# Primordial Black Holes: Recent Highlights

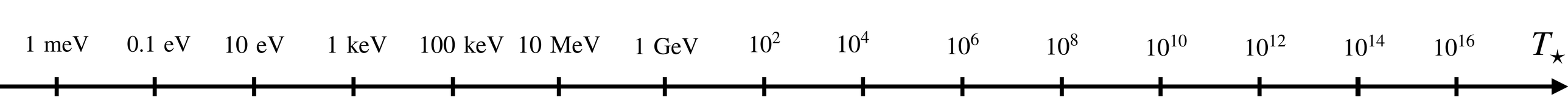
**Yann Gouttenoire**

*Institute of Astrophysics in Paris*

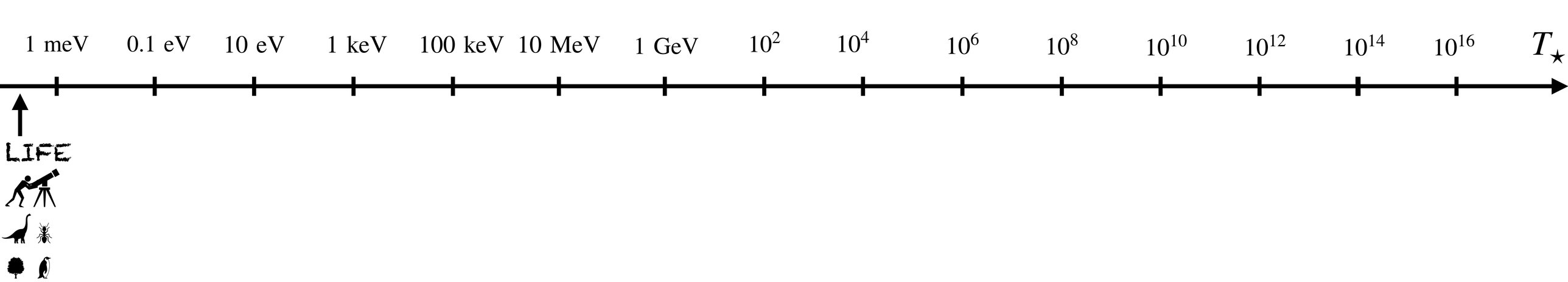
**11th March 2026**

**RPP 2026 - Montpellier**





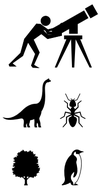

What we do know about the History of our Universe




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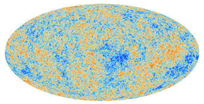
1 meV 0.1 eV 10 eV 1 keV 100 keV 10 MeV 1 GeV $10^2$ $10^4$ $10^6$ $10^8$ $10^{10}$ $10^{12}$ $10^{14}$ $10^{16}$ $T_\star$

LIFE

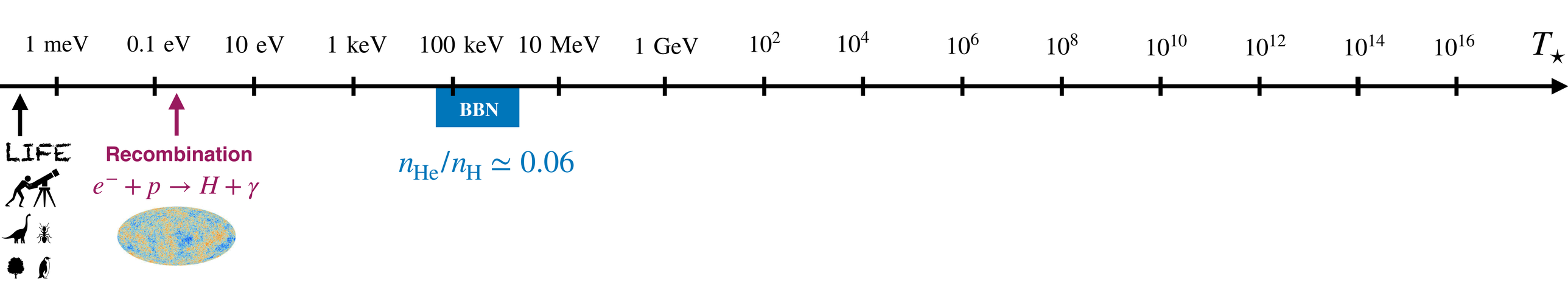


**Recombination**

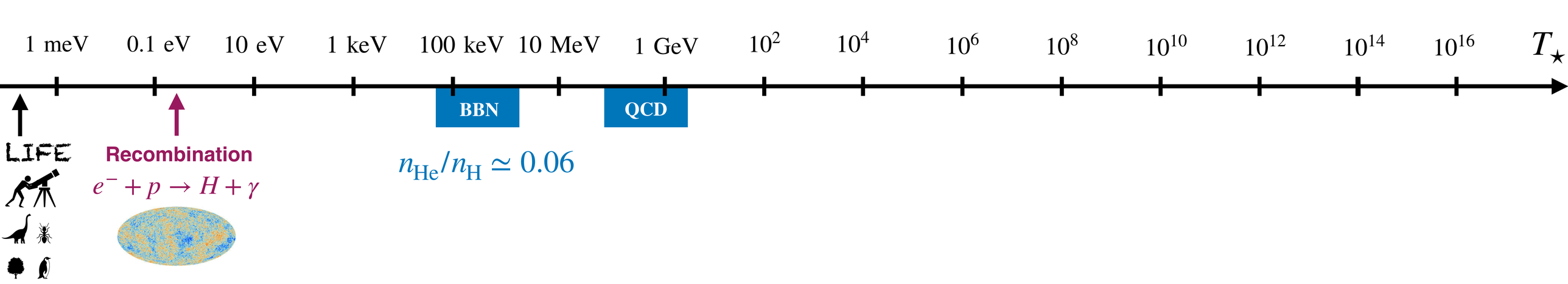
$e^- + p \rightarrow H + \gamma$



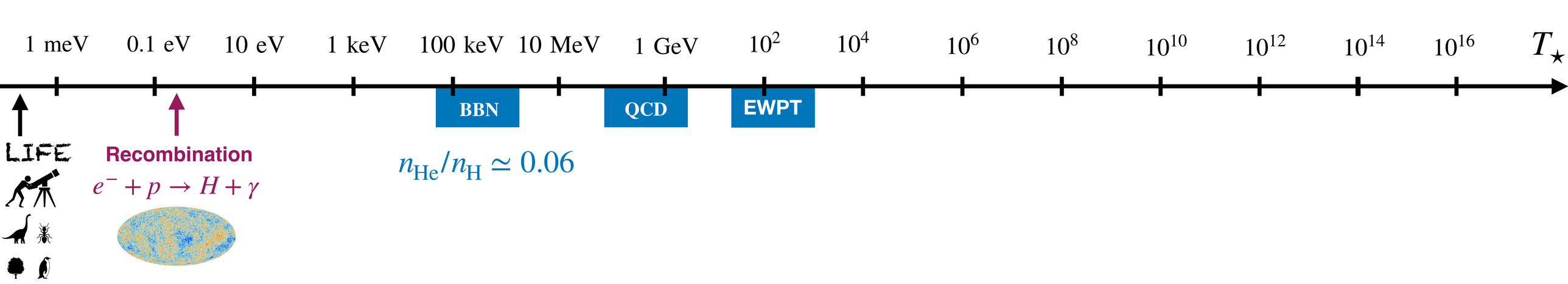
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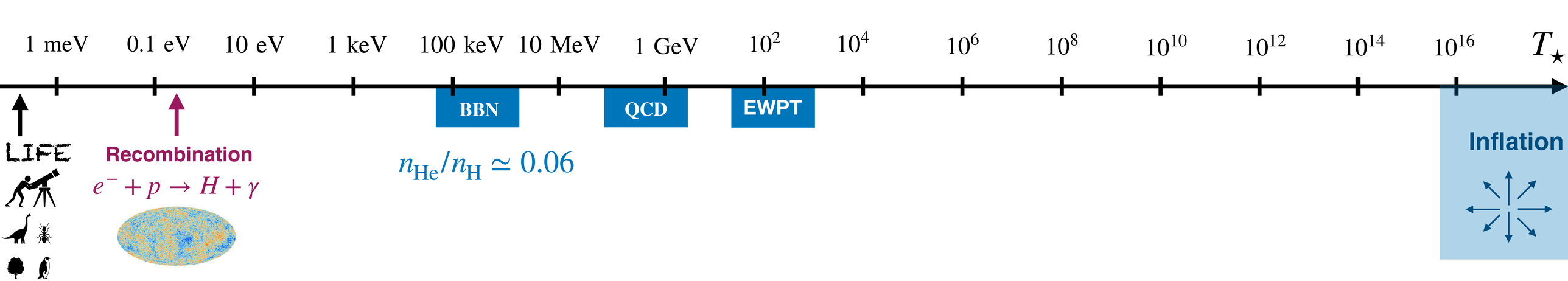

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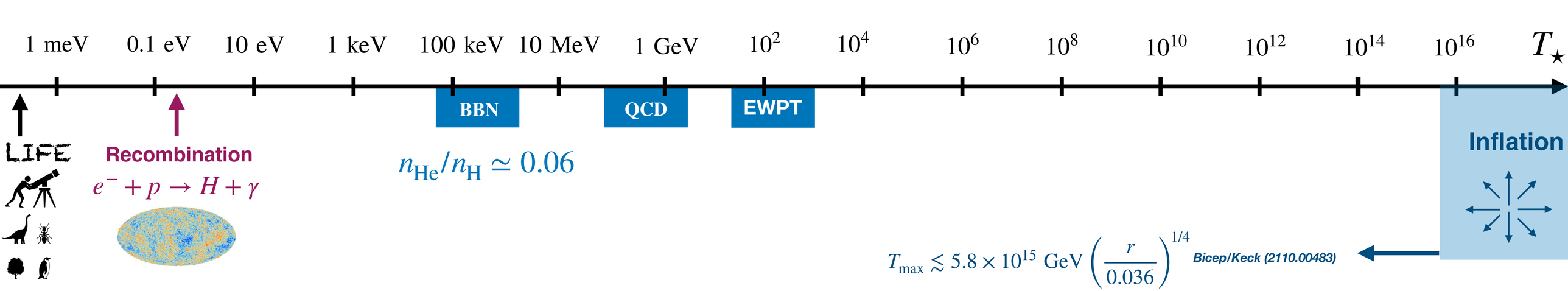

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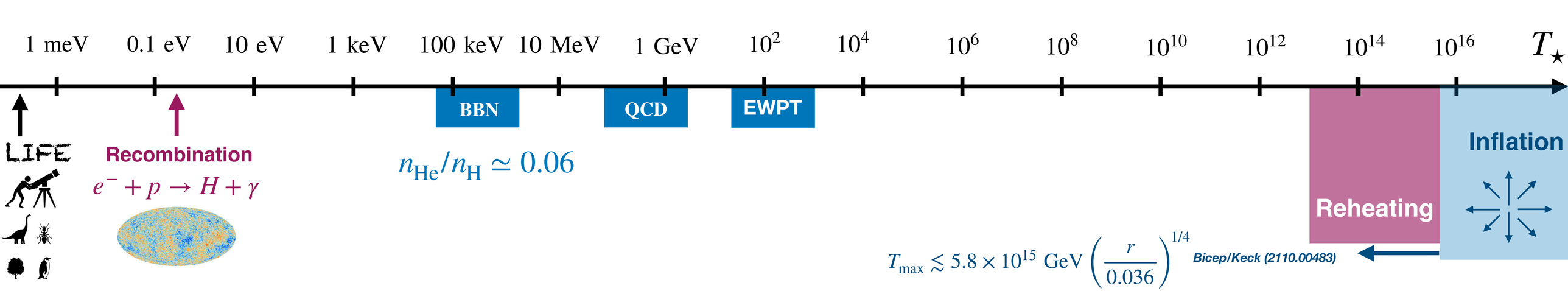

What we do know about the History of our Universe



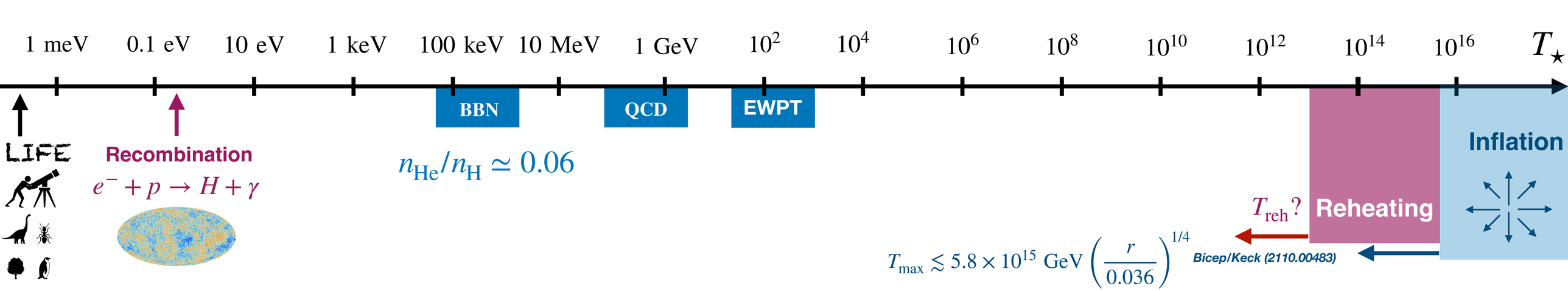

What we do know about the History of our Universe



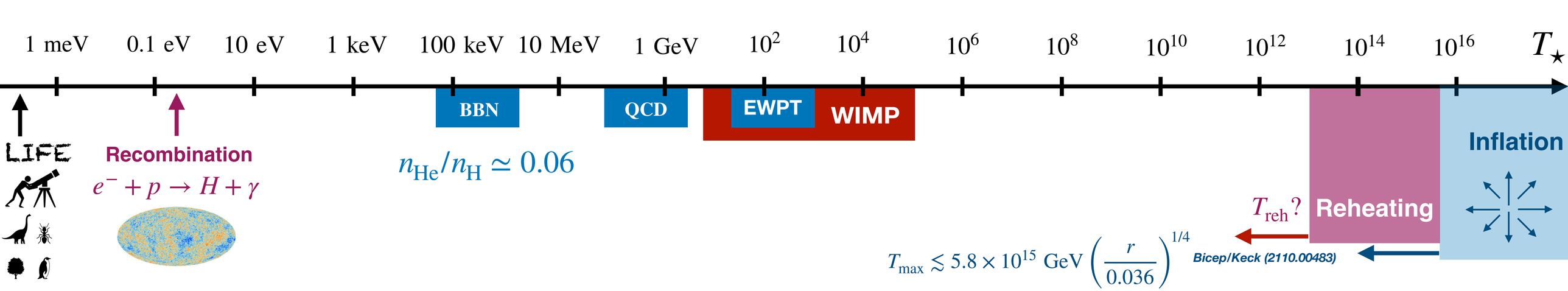

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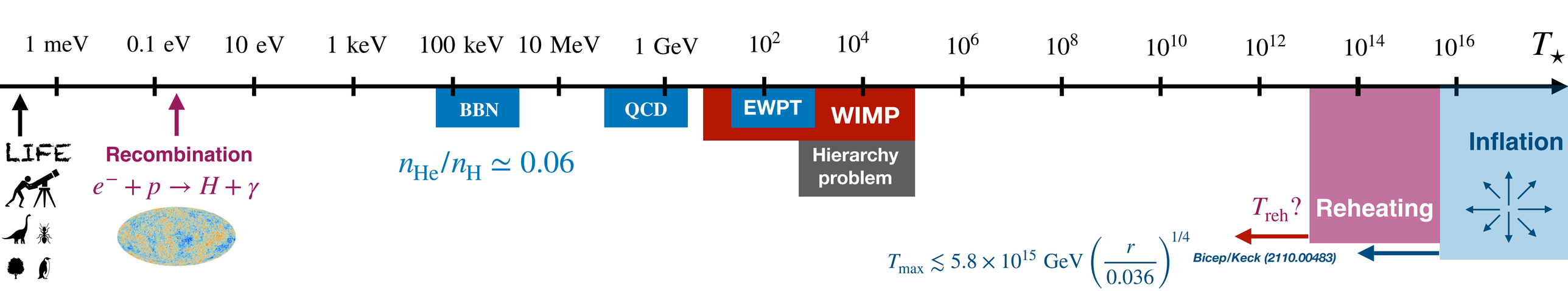

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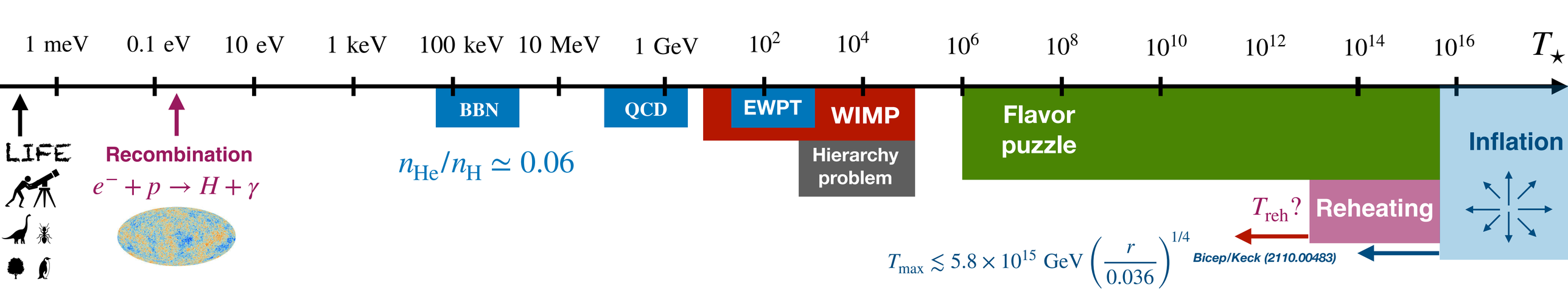

What we don't know about the History of our Universe



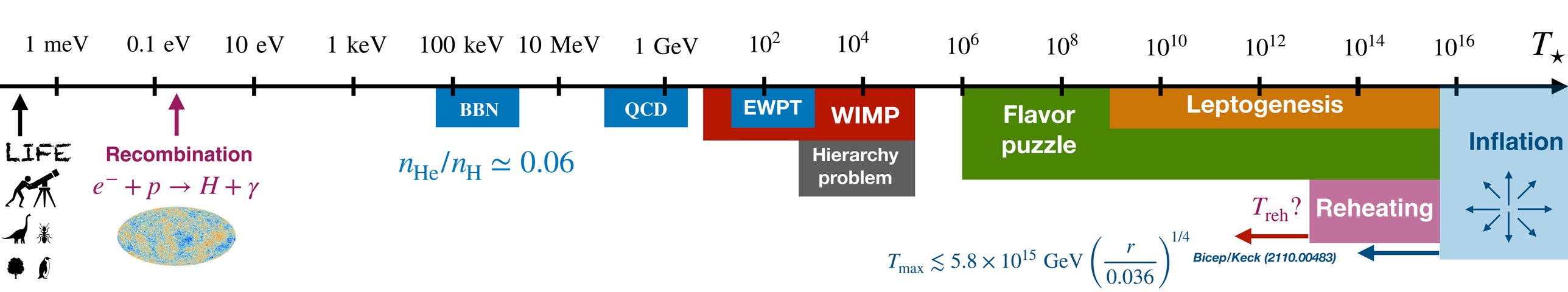

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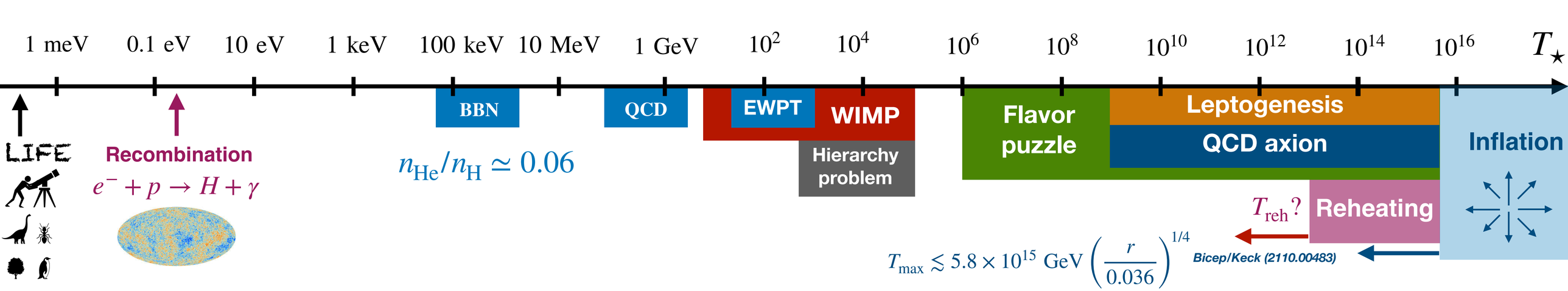

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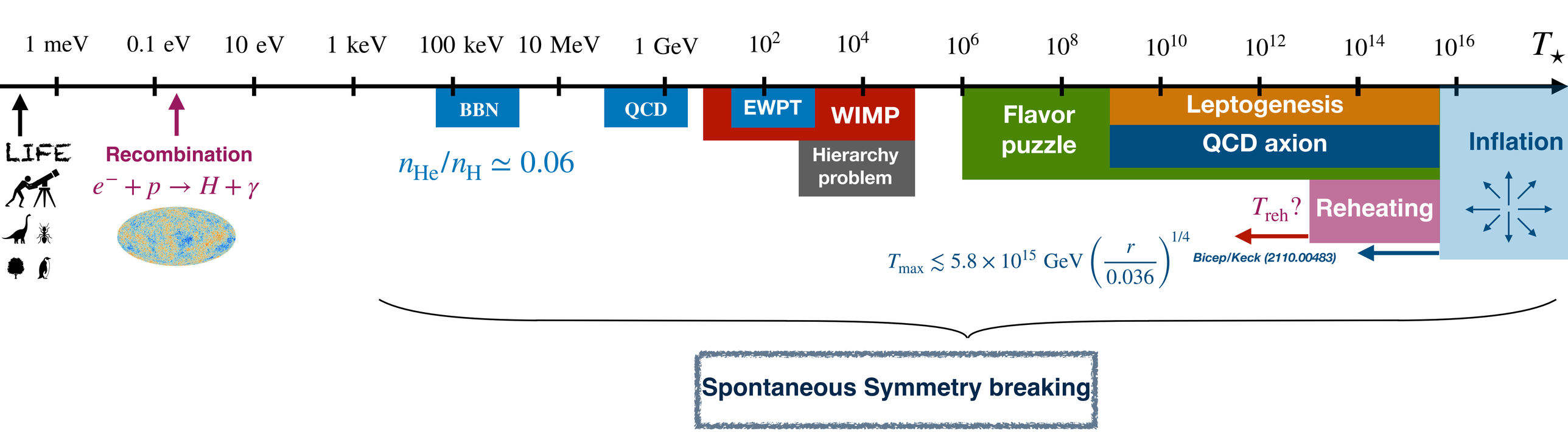

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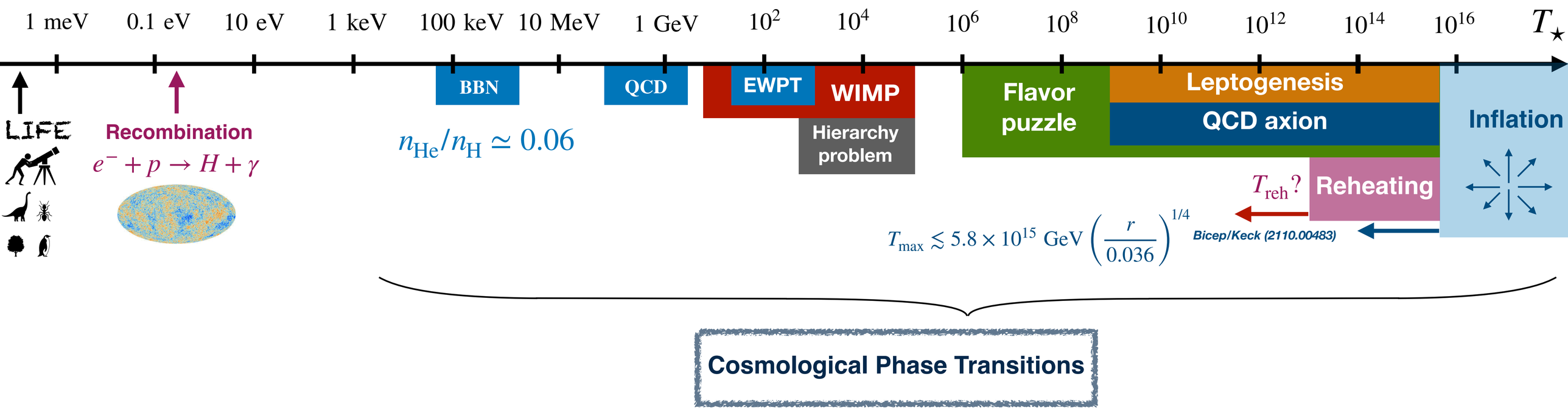



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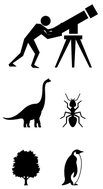

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1 meV
0.1 eV
10 eV
1 keV
100 keV
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1 GeV
$10^2$
$10^4$
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$10^{10}$
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$10^{14}$
$10^{16}$
$T_\star$
LIFE
Recombination
$e^- + p \to H + \gamma$
BBN
$n_{\rm He}/n_{\rm H} \simeq 0.06$
QCD
EWPT
WIMP
Hierarchy problem
Flavor puzzle
Leptogenesis
QCD axion
Inflation
$T_{\rm reh}$?
Reheating
$T_{\rm max} \lesssim 5.8 \times 10^{15}\ {\rm GeV} \left(\frac{r}{0.036}\right)^{1/4}$
Bicep/Keck (2110.00483)
Spontaneous Symmetry breaking


1 meV
0.1 eV
10 eV
1 keV
100 keV
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$10^2$
$10^4$
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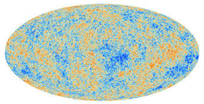
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LIFE



**Recombination**

$e^- + p \to H + \gamma$



**BBN**

$n_{\rm He}/n_{\rm H} \simeq 0.06$

**QCD**

**EWPT** **WIMP**

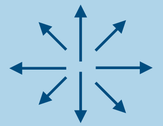
**Hierarchy problem**

**Flavor puzzle**

**Leptogenesis**

**QCD axion**

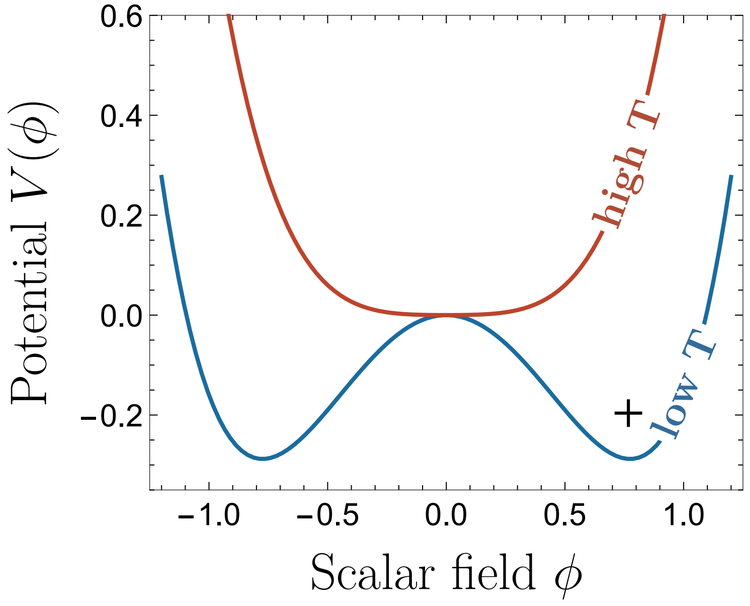
**Inflation**

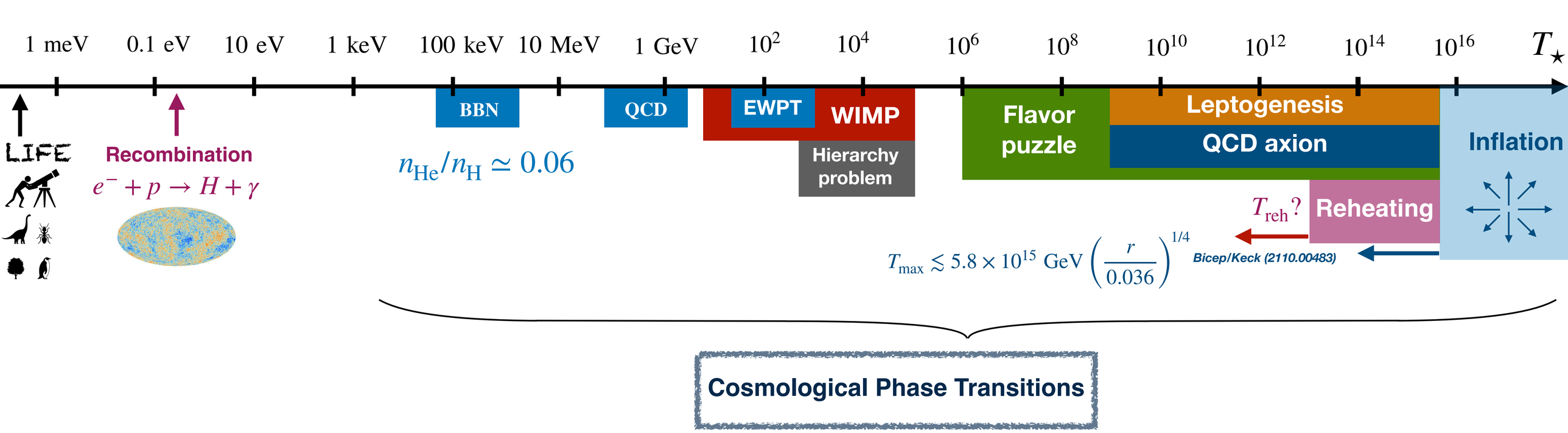


$T_{\rm reh}$? **Reheating**

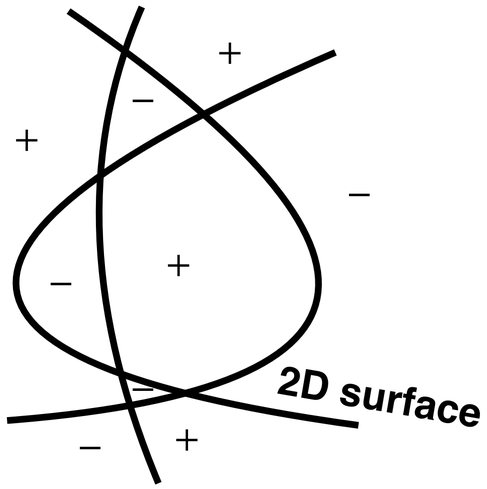
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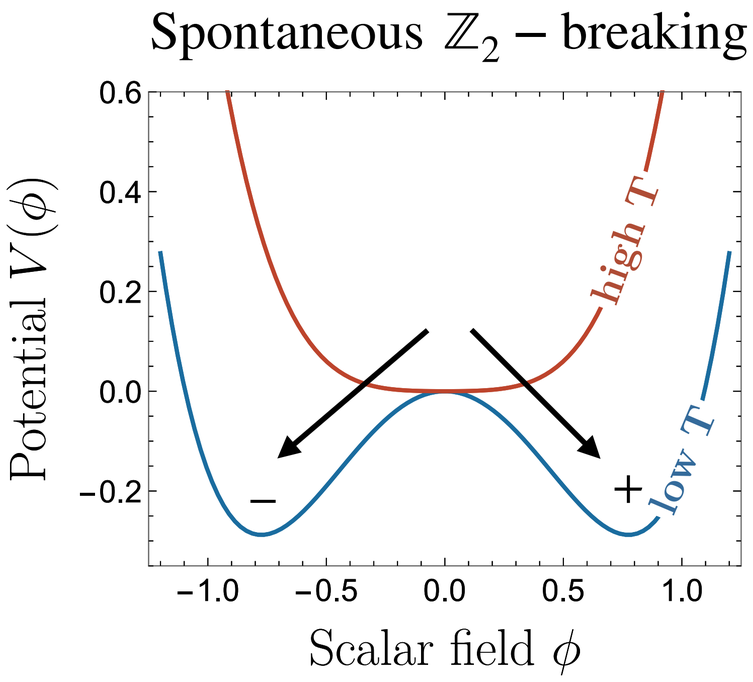
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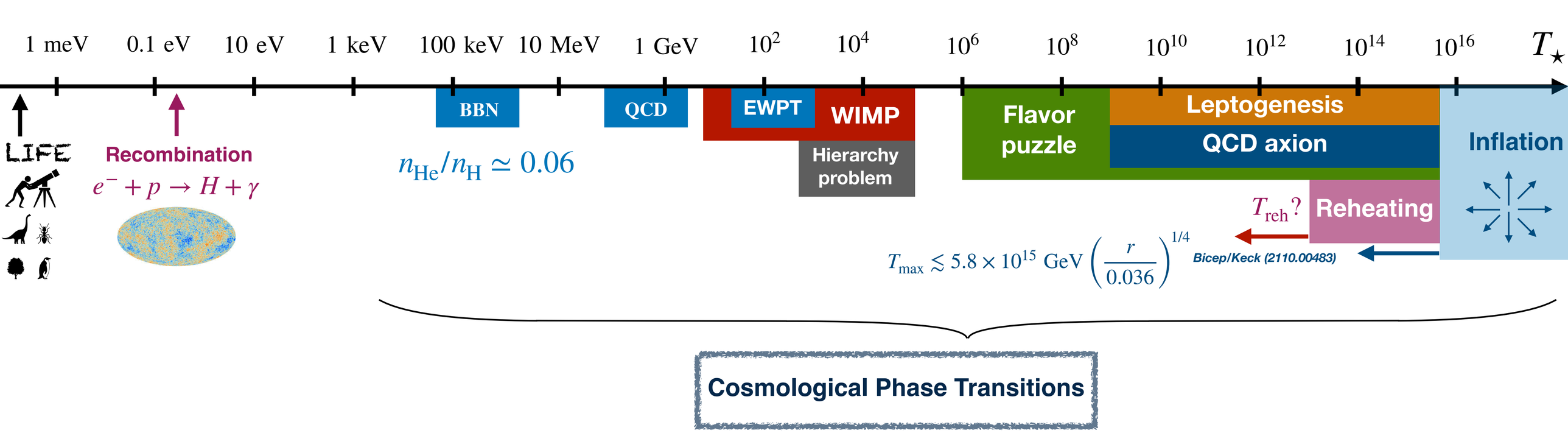


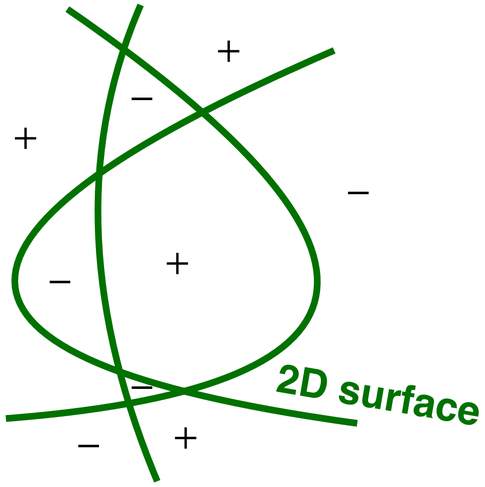


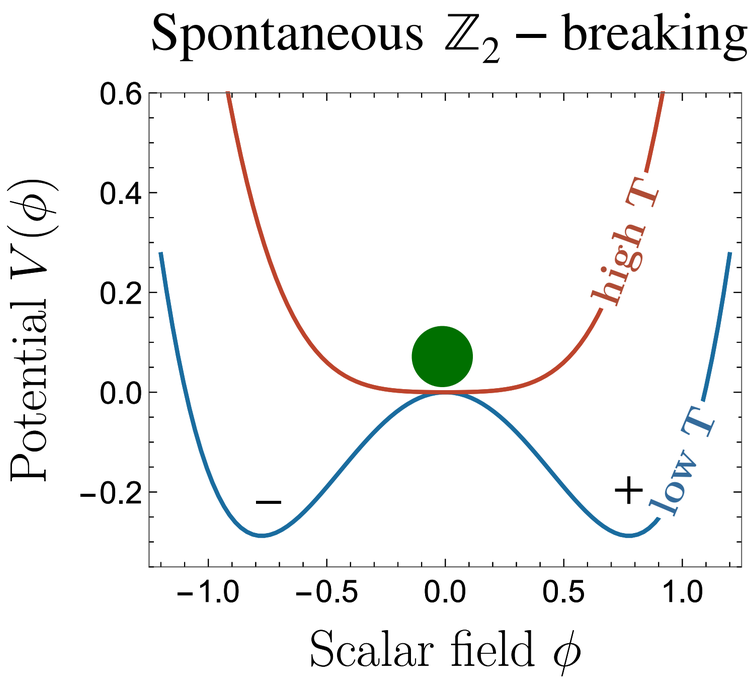

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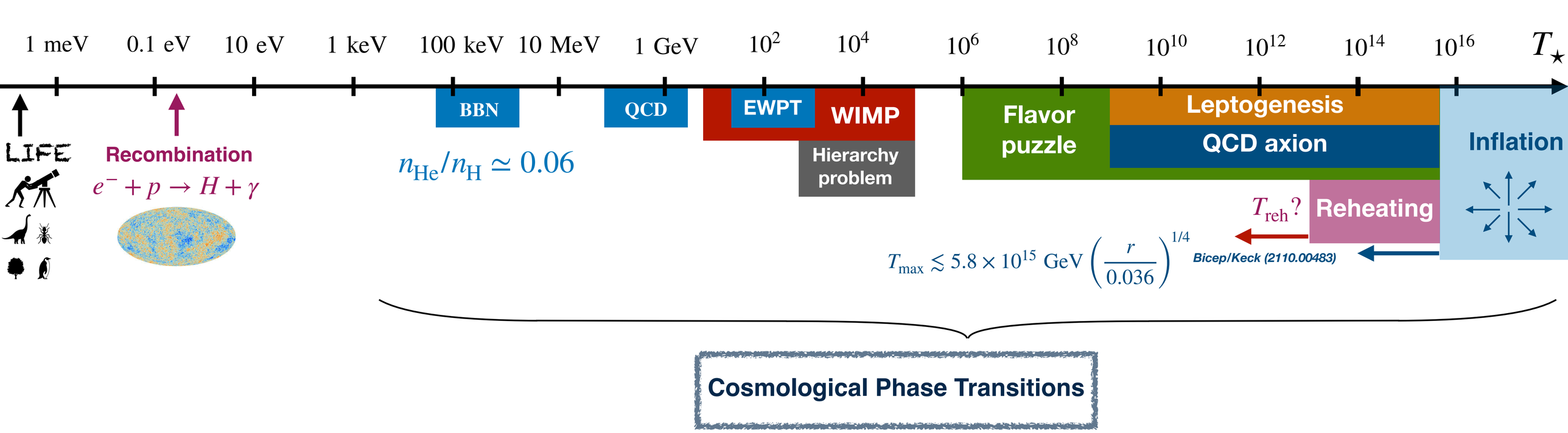


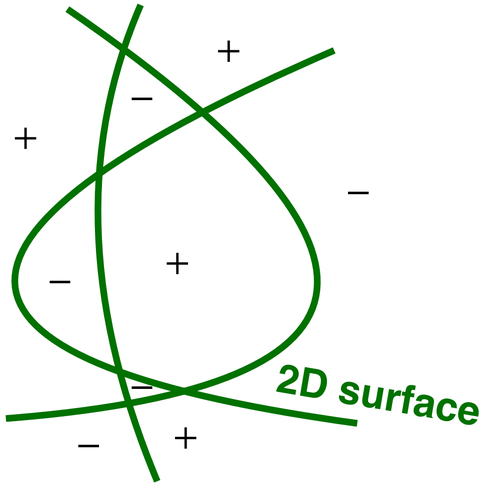



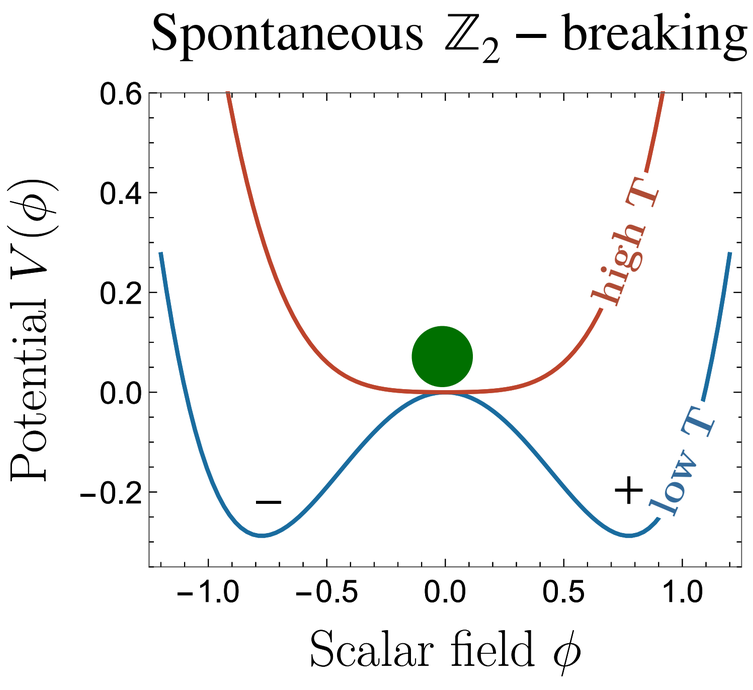

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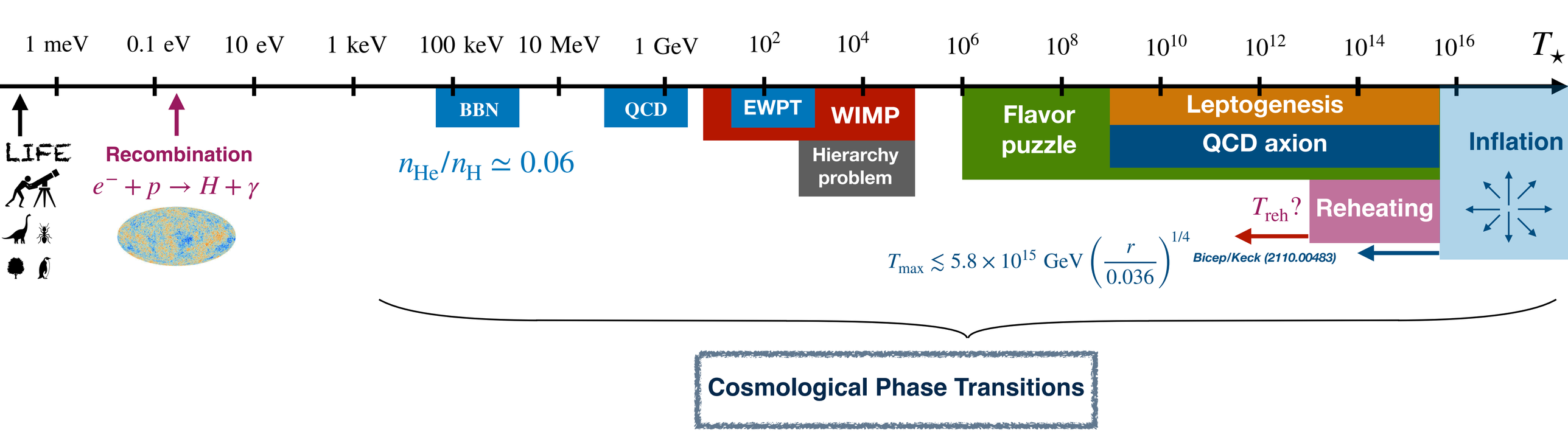

+
−
+
−
+
−
+
−
+
2D surface


Spontaneous $\mathbb{Z}_2$ – breaking
Potential $V(\phi)$
0.6
0.4
0.2
0.0
−0.2
high T
low T
−
+
−1.0
−0.5
0.0
0.5
1.0
Scalar field $\phi$

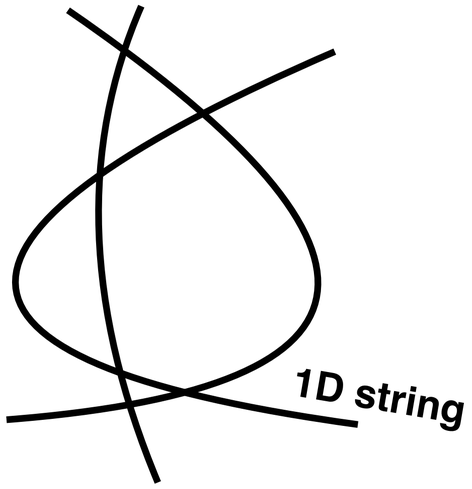

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+
−
+
−
+
−
+
−
+
2D surface

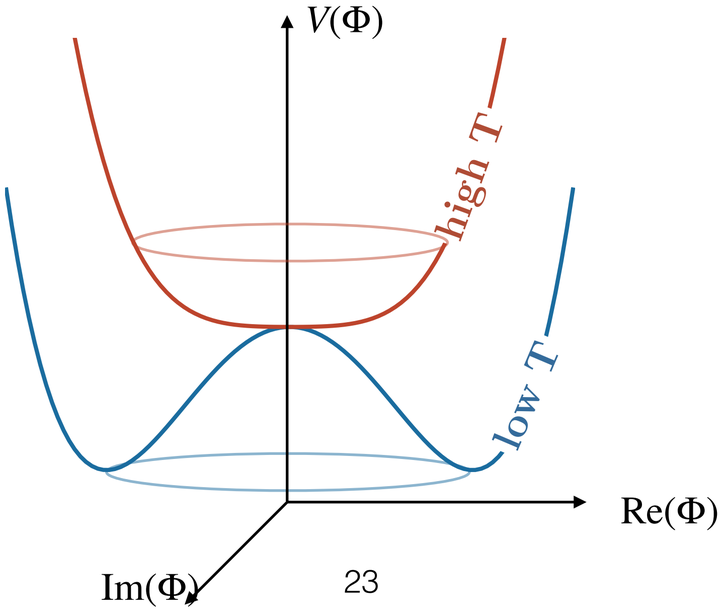

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+
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0.0
0.5
1.0
Scalar field $\phi$

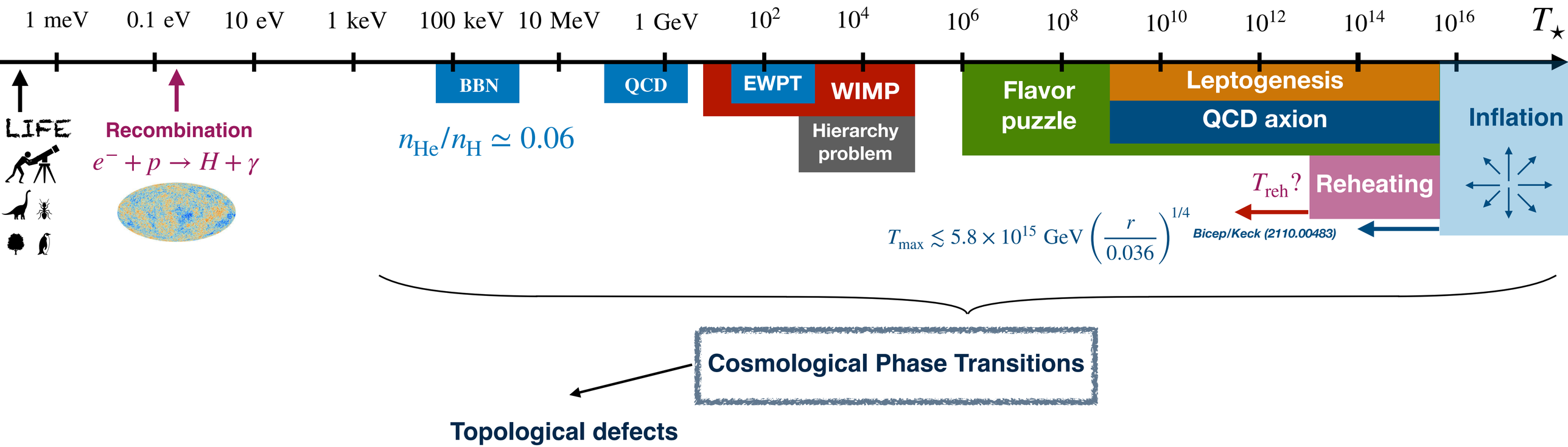


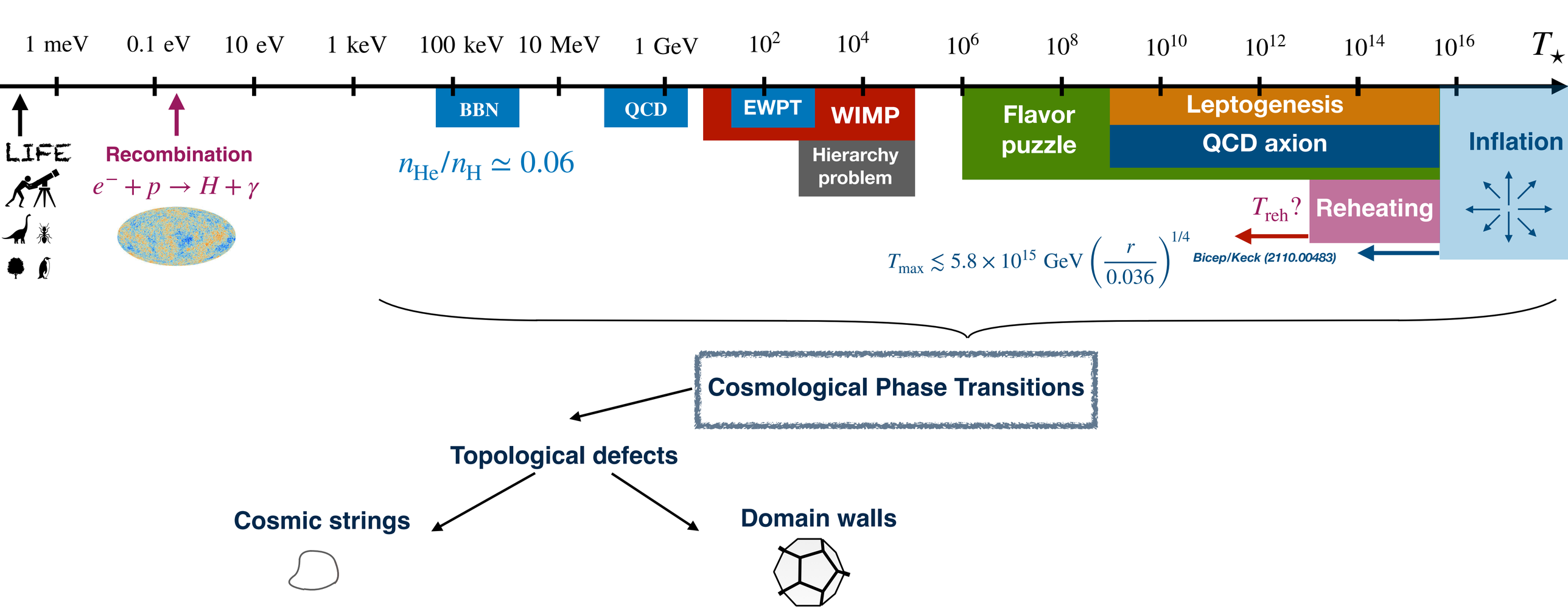

**Cosmological Phase Transitions**




Spontaneous U(1) – breaking




1 meV
0.1 eV
10 eV
1 keV
100 keV
10 MeV
1 GeV
$10^2$
$10^4$
$10^6$
$10^8$
$10^{10}$
$10^{12}$
$10^{14}$
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Cosmological Phase Transitions
Topological defects

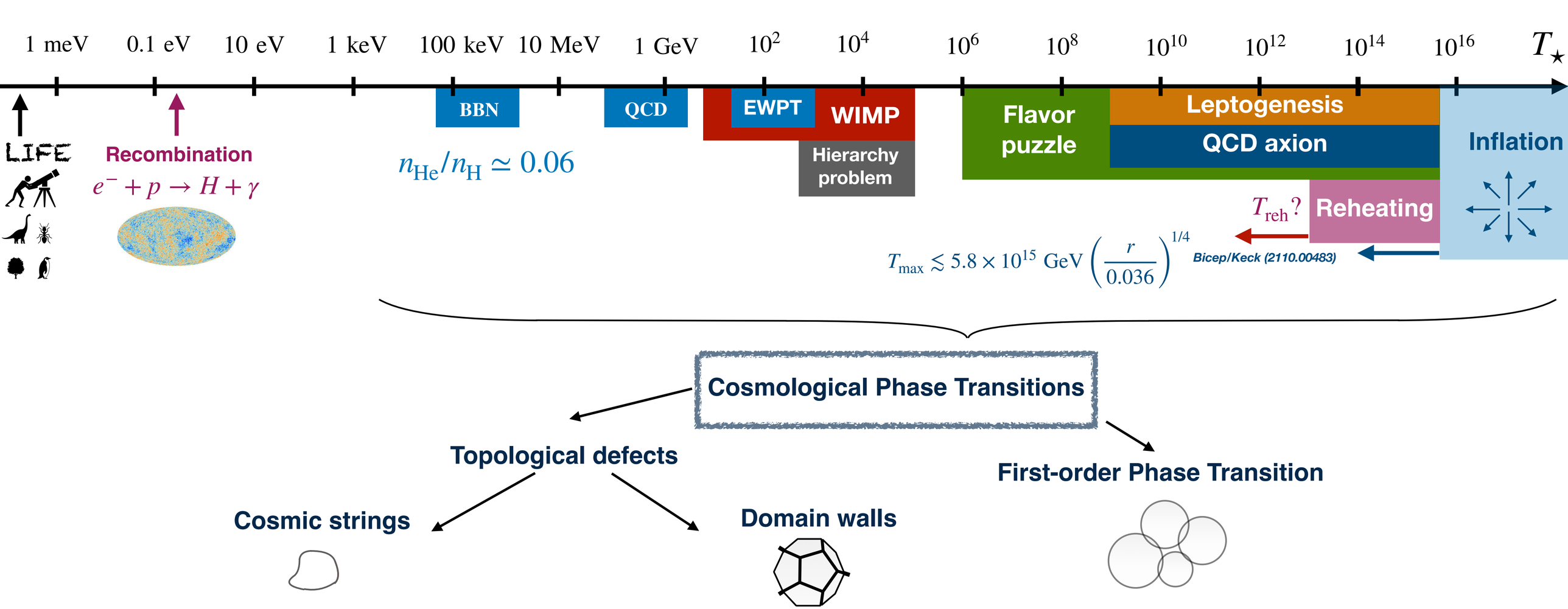



**Cosmological Phase Transitions**

**Topological defects**

**Cosmic strings**

**Domain walls**



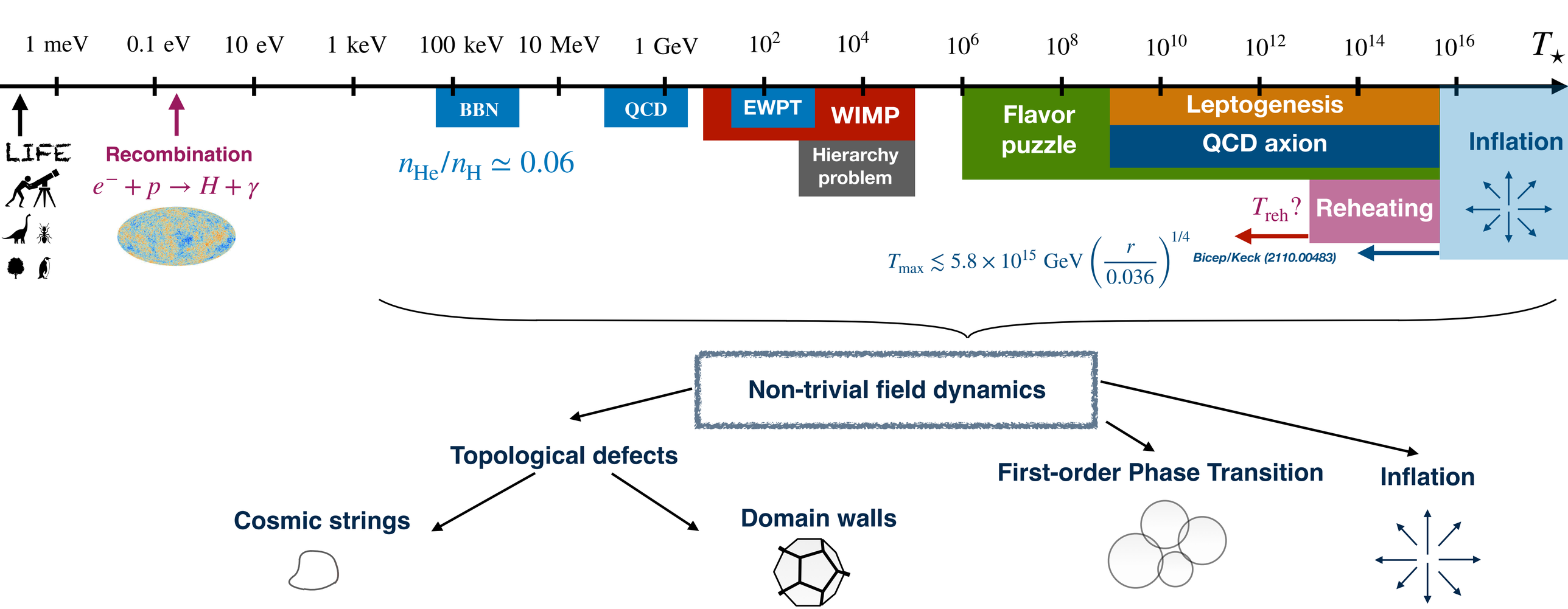

**Cosmological Phase Transitions**

**Topological defects**

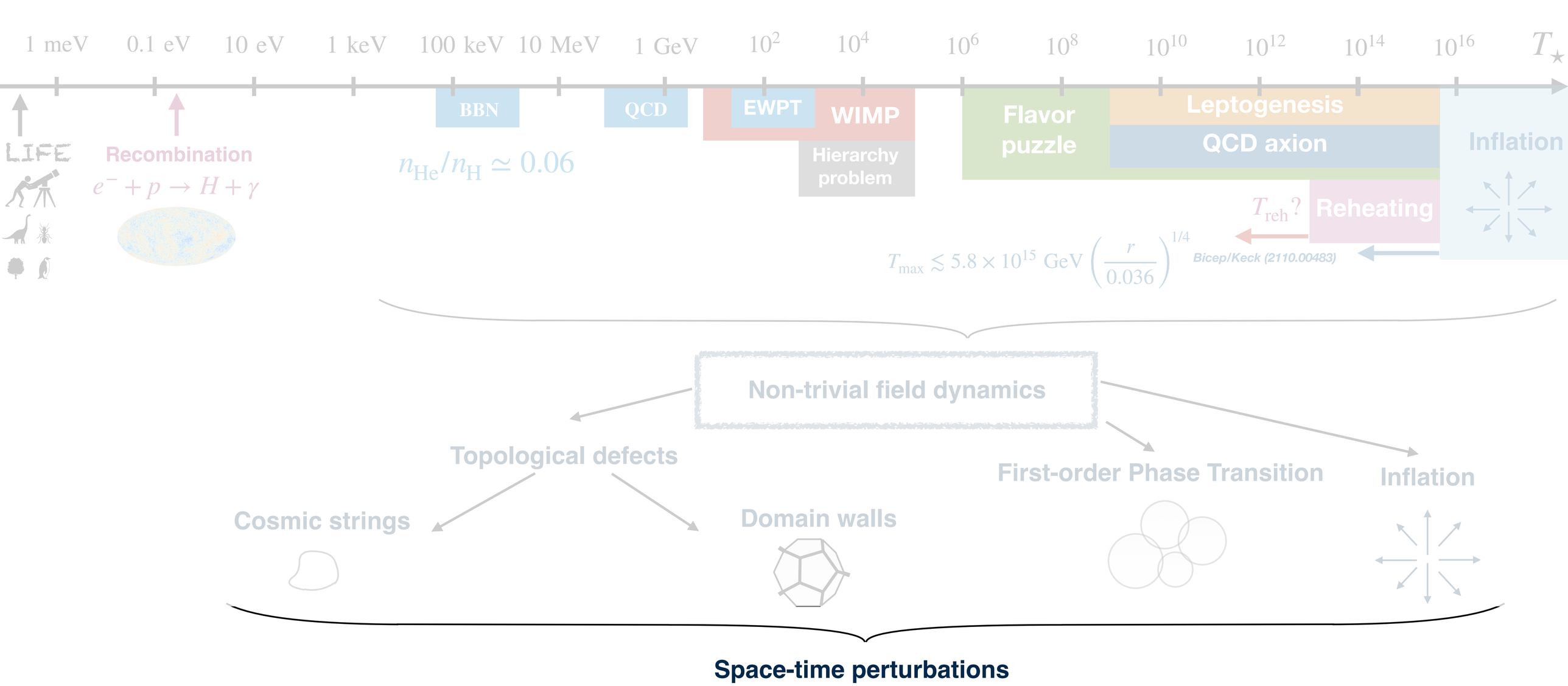
**Cosmic strings**

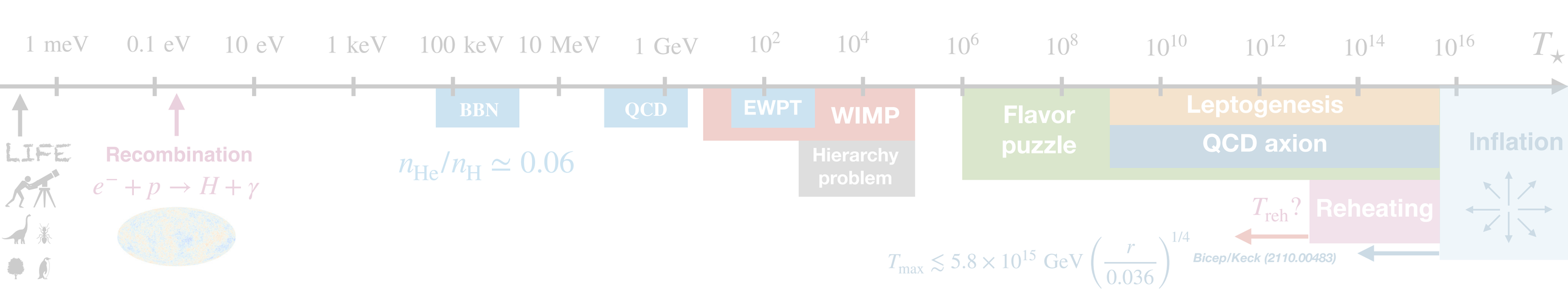
**Domain walls**

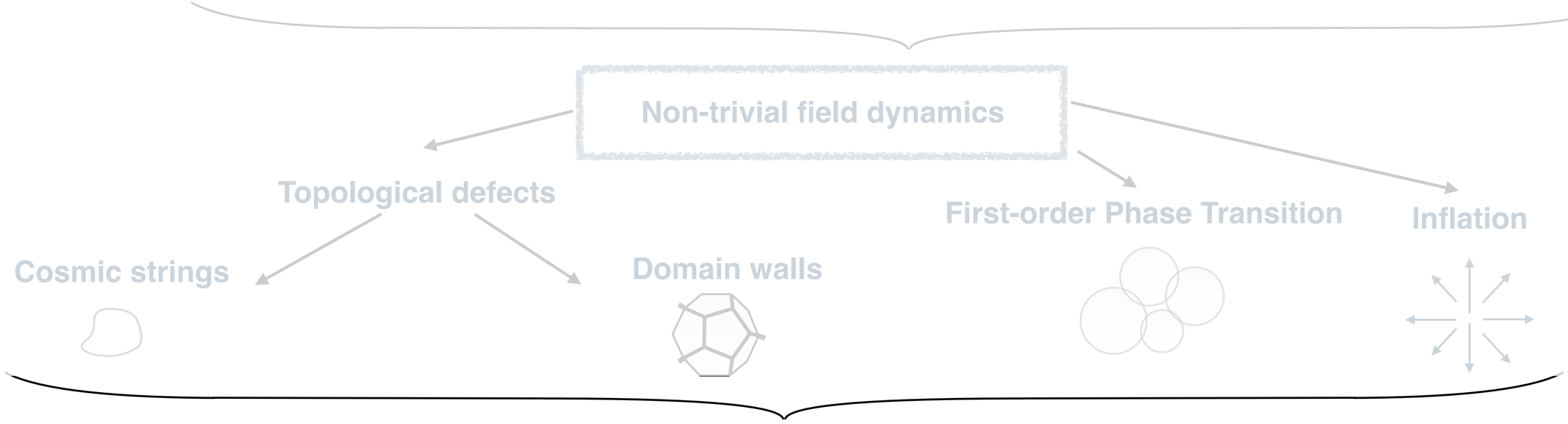
**First-order Phase Transition**


1 meV
0.1 eV
10 eV
1 keV
100 keV
10 MeV
1 GeV
$10^2$
$10^4$
$10^6$
$10^8$
$10^{10}$
$10^{12}$
$10^{14}$
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Non-trivial field dynamics
Topological defects
Cosmic strings
Domain walls
First-order Phase Transition
Inflation


1 meV
0.1 eV
10 eV
1 keV
100 keV
10 MeV
1 GeV
$10^2$
$10^4$
$10^6$
$10^8$
$10^{10}$
$10^{12}$
$10^{14}$
$10^{16}$
$T_\star$
LIFE
Recombination
$e^- + p \to H + \gamma$
BBN
$n_{\rm He}/n_{\rm H} \simeq 0.06$
QCD
EWPT
WIMP
Hierarchy problem
Flavor puzzle
Leptogenesis
QCD axion
Inflation
$T_{\rm reh}$?
Reheating
$T_{\rm max} \lesssim 5.8 \times 10^{15}\ {\rm GeV} \left(\frac{r}{0.036}\right)^{1/4}$
Bicep/Keck (2110.00483)
Non-trivial field dynamics
Topological defects
Cosmic strings
Domain walls
First-order Phase Transition
Inflation
Space-time perturbations




**Space-time perturbations**

**Gravitational Waves (GWs)**

$h_{ij}(\vec{x}, t)$

1 meV 0.1 eV 10 eV 1 keV 100 keV 10 MeV 1 GeV $10^2$ $10^4$ $10^6$ $10^8$ $10^{10}$ $10^{12}$ $10^{14}$ $10^{16}$ $T_\star$

BBN QCD EWPT WIMP Hierarchy problem Flavor puzzle Leptogenesis QCD axion Inflation

LIFE

Recombination

$e^- + p \to H + \gamma$

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*Bicep/Keck (2110.00483)*

**Non-trivial field dynamics**

**Topological defects**

**Cosmic strings**

**Domain walls**

**First-order Phase Transition**

**Inflation**

**Space-time perturbations**

**Scalar Curvature**

$\mathscr{R}(\vec{x}, t)$

**Gravitational Waves (GWs)**

$h_{ij}(\vec{x}, t)$

1 meV 0.1 eV 10 eV 1 keV 100 keV 10 MeV 1 GeV $10^2$ $10^4$ $10^6$ $10^8$ $10^{10}$ $10^{12}$ $10^{14}$ $10^{16}$ $T_\star$

LIFE

Recombination

$e^- + p \to H + \gamma$

BBN

$n_{\rm He}/n_{\rm H} \simeq 0.06$

QCD

EWPT

WIMP

Hierarchy problem

Flavor puzzle

Leptogenesis

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Inflation

$T_{\rm reh}$?

Reheating

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*Bicep/Keck (2110.00483)*

**Non-trivial field dynamics**

**Topological defects**

**Cosmic strings**

**Domain walls**

**First-order Phase Transition**

**Inflation**

**Space-time perturbations**

**Primordial Black Holes (PBHs)**

*(Shibata & Sasaki 1999)*

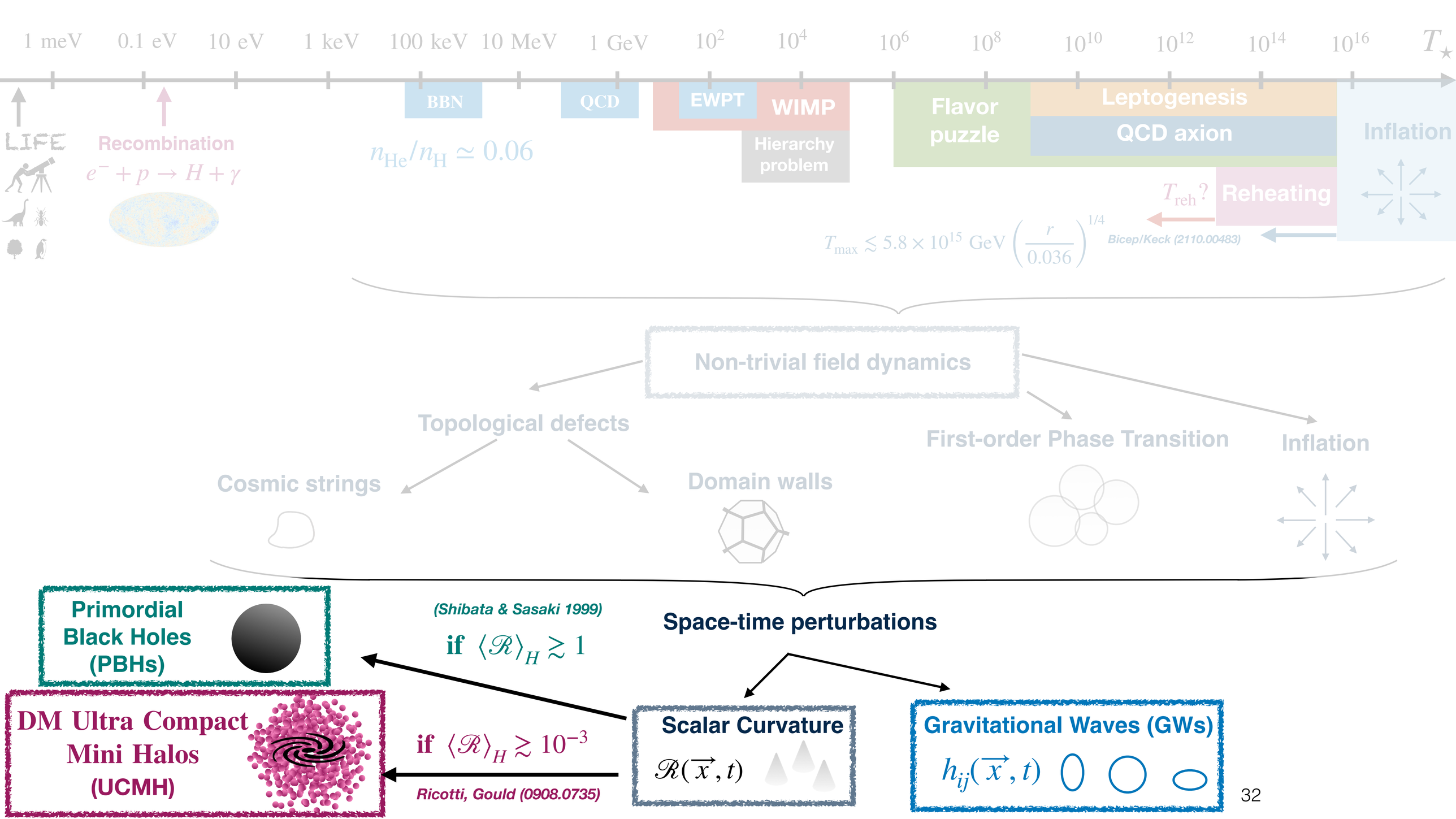
**if** $\langle \mathscr{R} \rangle_H \gtrsim 1$

**Scalar Curvature**

$\mathscr{R}(\vec{x}, t)$

**Gravitational Waves (GWs)**

$h_{ij}(\vec{x}, t)$


1 meV
0.1 eV
10 eV
1 keV
100 keV
10 MeV
1 GeV
$10^2$
$10^4$
$10^6$
$10^8$
$10^{10}$
$10^{12}$
$10^{14}$
$10^{16}$
$T_\star$
BBN
QCD
EWPT
WIMP
Hierarchy problem
Flavor puzzle
Leptogenesis
QCD axion
Inflation
LIFE
Recombination
$e^- + p \to H + \gamma$
$n_{\rm He}/n_{\rm H} \simeq 0.06$
$T_{\rm reh}$?
Reheating
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Bicep/Keck (2110.00483)
Non-trivial field dynamics
Topological defects
Cosmic strings
Domain walls
First-order Phase Transition
Inflation
Primordial Black Holes (PBHs)
(Shibata & Sasaki 1999)
if $\langle \mathscr{R} \rangle_H \gtrsim 1$
Space-time perturbations
DM Ultra Compact Mini Halos (UCMH)
if $\langle \mathscr{R} \rangle_H \gtrsim 10^{-3}$
Ricotti, Gould (0908.0735)
Scalar Curvature
$\mathscr{R}(\vec{x}, t)$
Gravitational Waves (GWs)
$h_{ij}(\vec{x}, t)$

# Plan of the talk

# Plan of the talk

1)

**Gravitational Waves (GWs)**

$h_{ij}(\vec{x}, t)$

# Plan of the talk

1) **Gravitational Waves (GWs)**

$h_{ij}(\vec{x}, t)$

2) **Primordial Black Holes (PBHs)**



# Plan of the talk

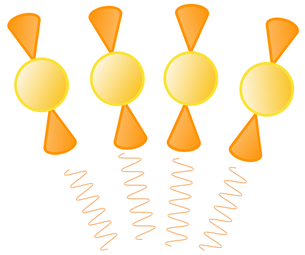
1) **Gravitational Waves (GWs)**

$h_{ij}(\vec{x}, t)$

2) **Primordial Black Holes (PBHs)**



3) **What is the PTA signal ?**



# Plan of the talk

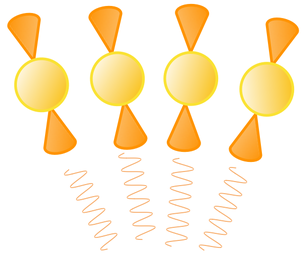
1) Gravitational Waves (GWs)

$h_{ij}(\vec{x}, t)$

2) Primordial Black Holes (PBHs)



3) What is the PTA signal ?



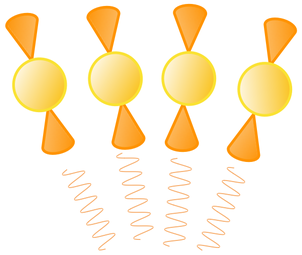
# Plan of the talk

1) Gravitational Waves (GWs) $h_{ij}(\vec{x}, t)$

2) Primordial Black Holes (PBHs)



3) What is the PTA signal ?



# Plan of the talk

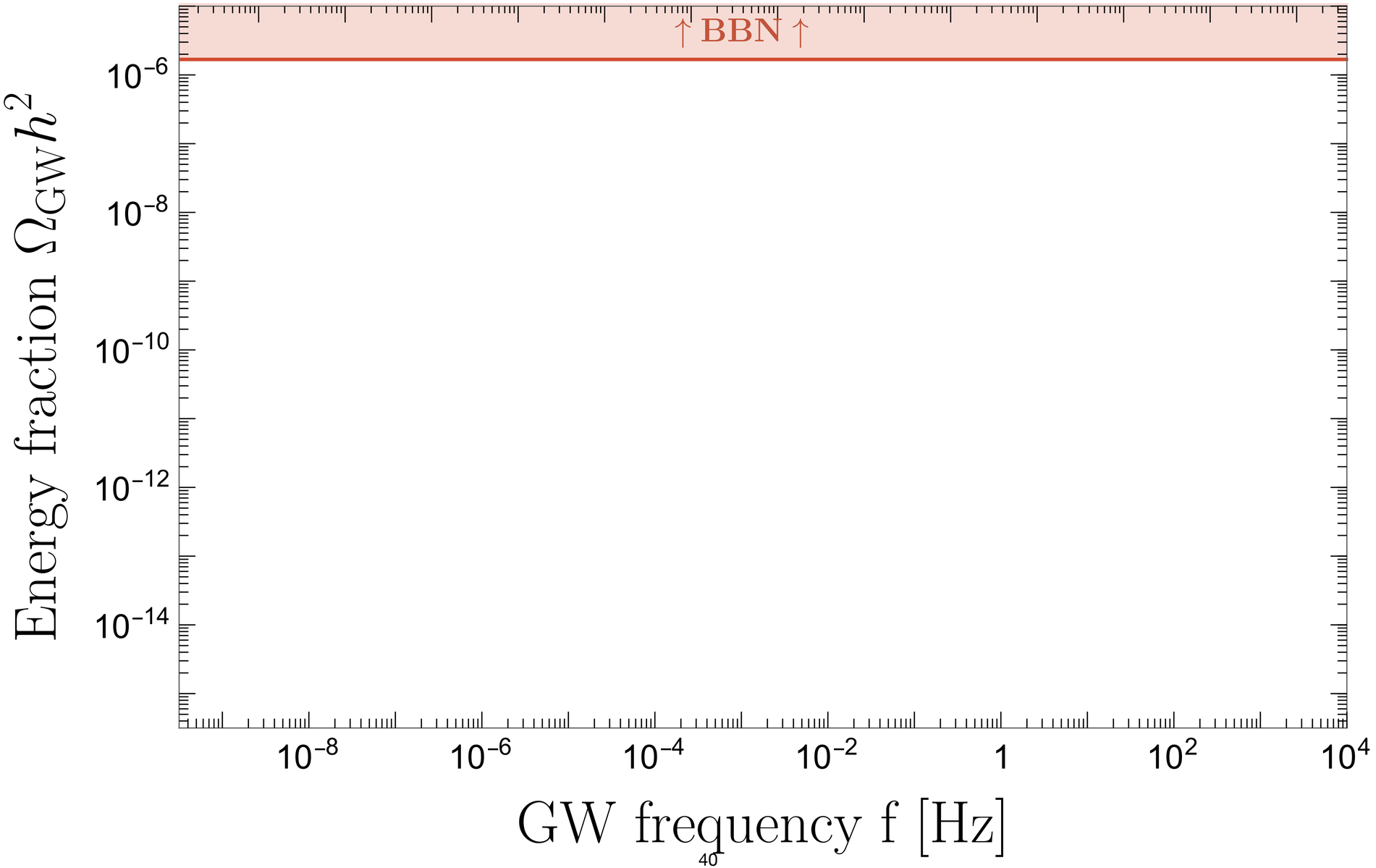
1) Gravitational Waves (GWs)

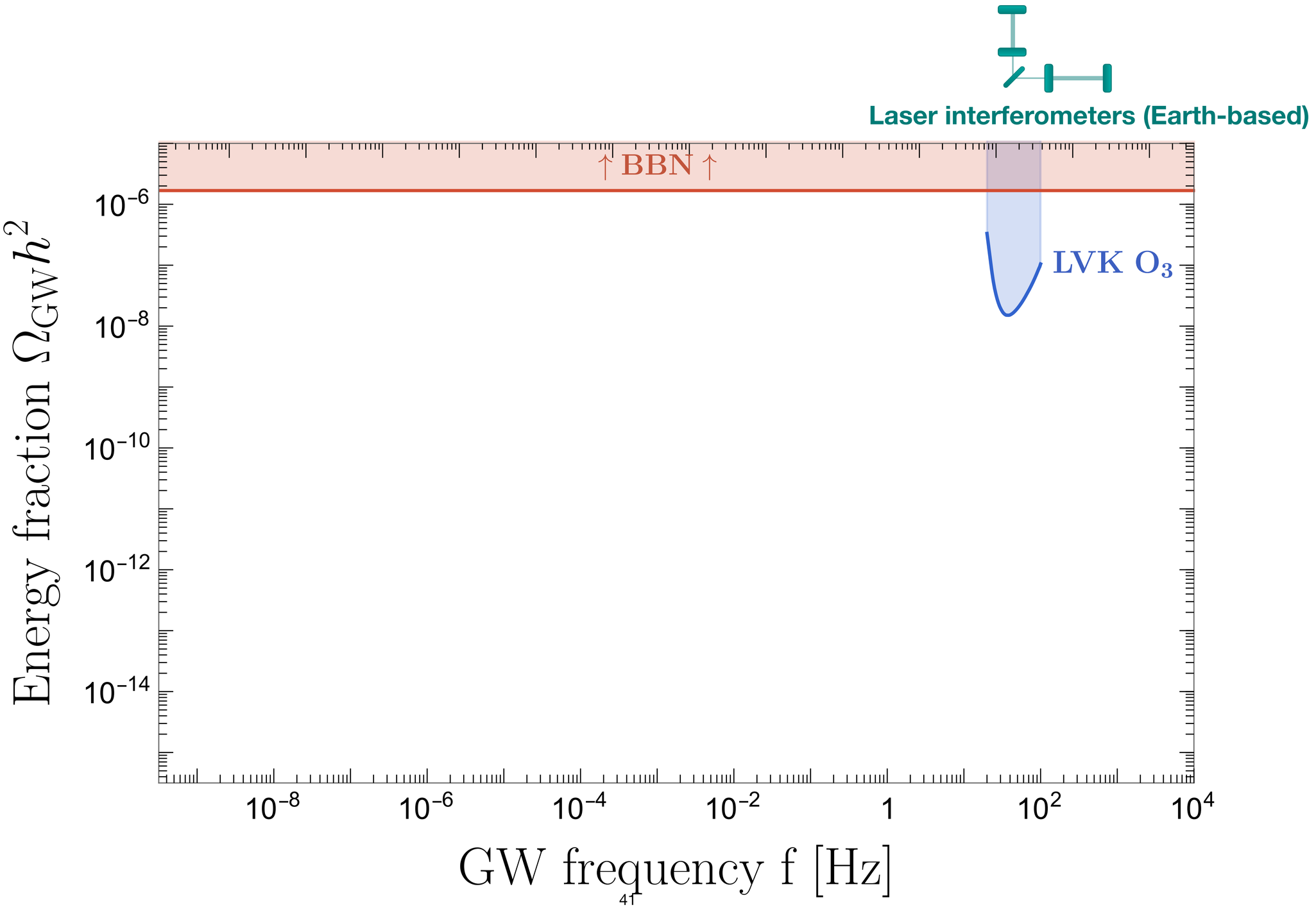
$h_{ij}(\vec{x}, t)$

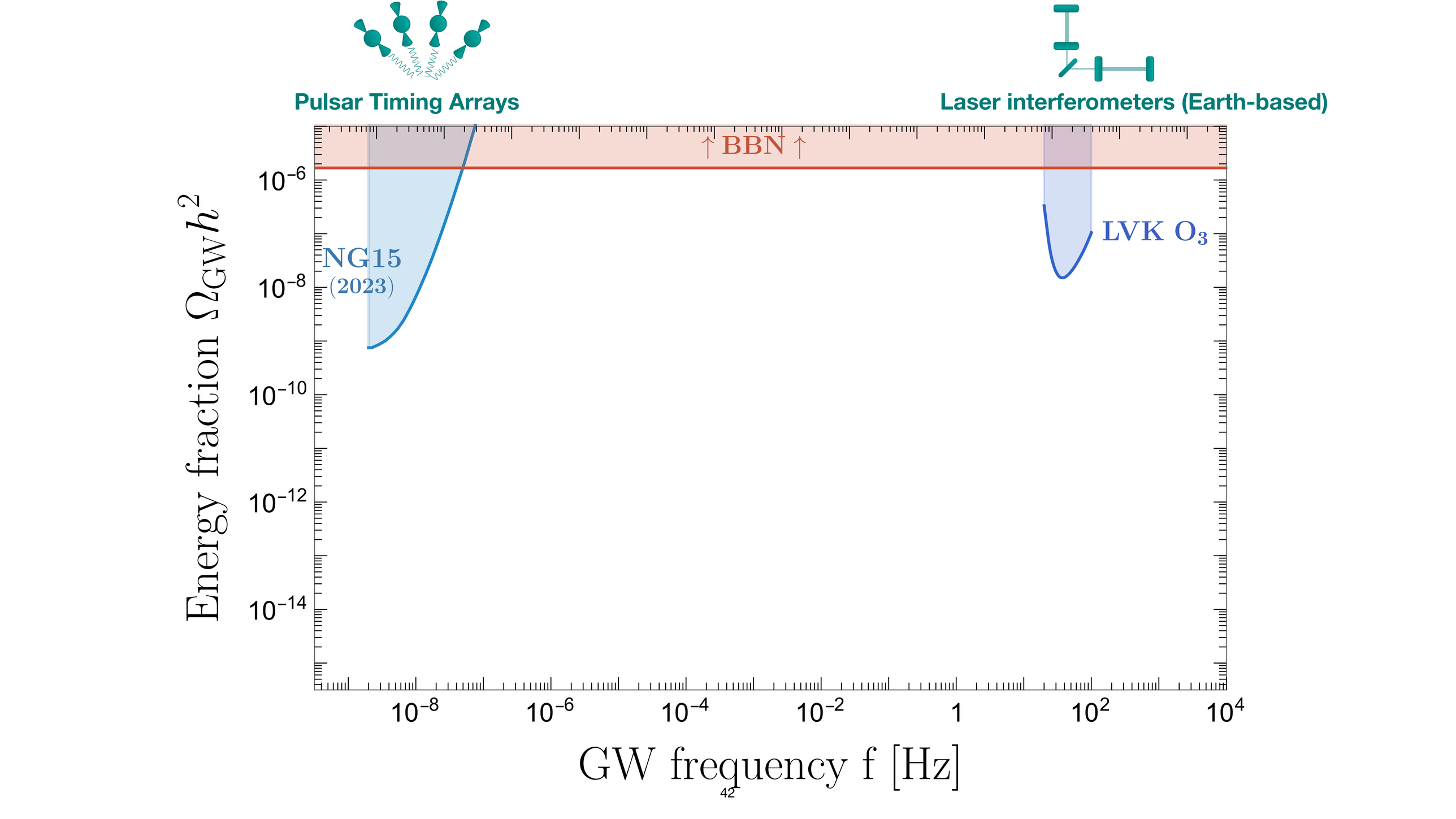
2) Primordial Black Holes (PBHs)

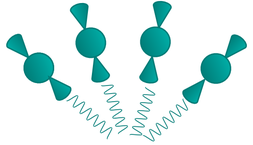


3) What is the PTA signal ?

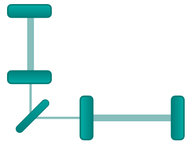

↑ BBN ↑
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
$10^{-14}$
Energy fraction $\Omega_{\rm GW}h^2$
$10^{-8}$
$10^{-6}$
$10^{-4}$
$10^{-2}$
1
$10^{2}$
$10^{4}$
GW frequency f [Hz]


Laser interferometers (Earth-based)
↑ BBN ↑
LVK O3
Energy fraction $\Omega_{\rm GW}h^2$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
$10^{-14}$
$10^{-8}$
$10^{-6}$
$10^{-4}$
$10^{-2}$
1
$10^{2}$
$10^{4}$
GW frequency f [Hz]

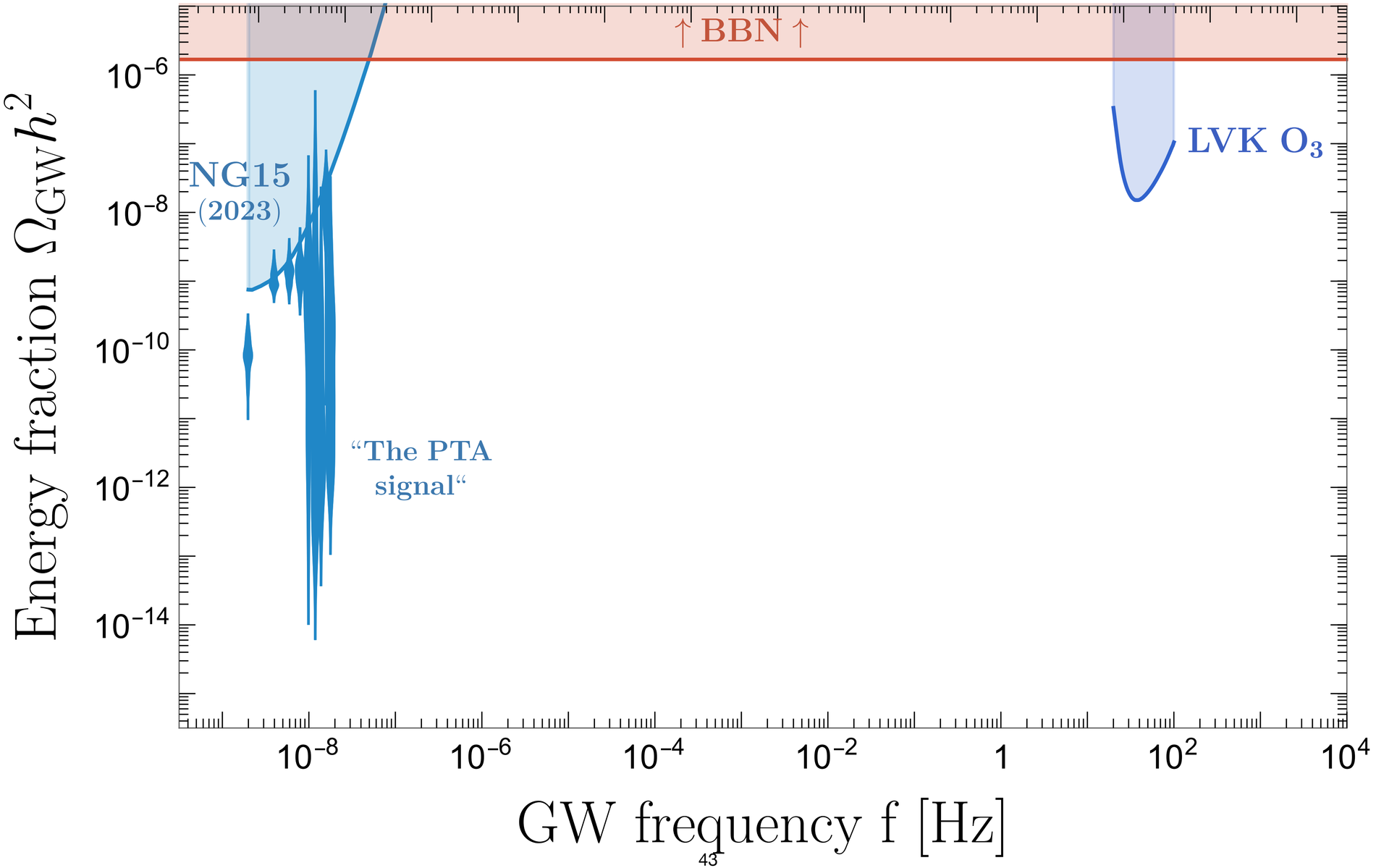

Pulsar Timing Arrays
Laser interferometers (Earth-based)
↑ BBN ↑
NG15
(2023)
LVK O3
Energy fraction $\Omega_{\rm GW}h^2$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
$10^{-14}$
$10^{-8}$
$10^{-6}$
$10^{-4}$
$10^{-2}$
1
$10^{2}$
$10^{4}$
GW frequency f [Hz]

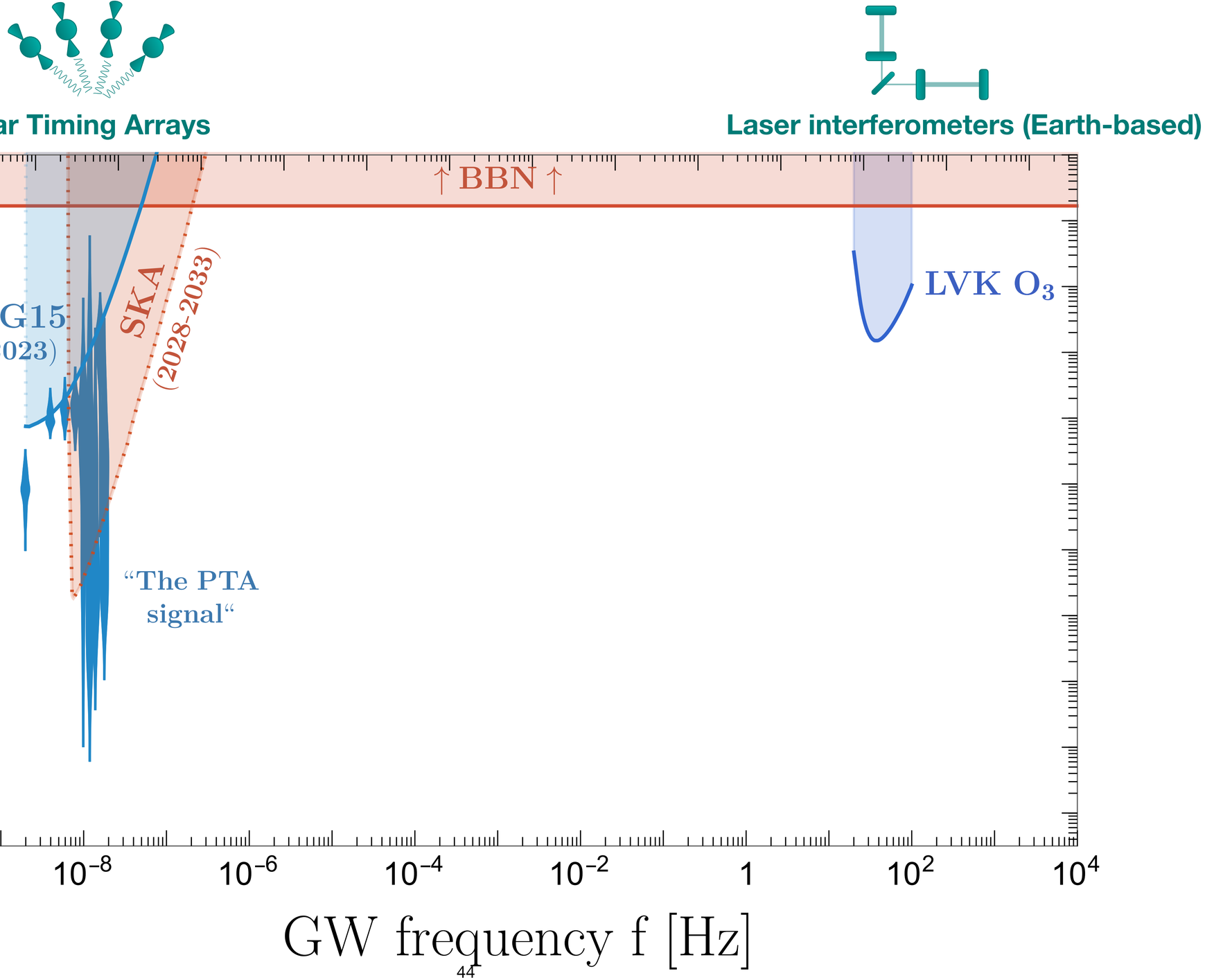


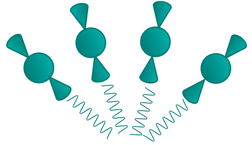
Pulsar Timing Arrays



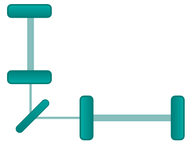
Laser interferometers (Earth-based)



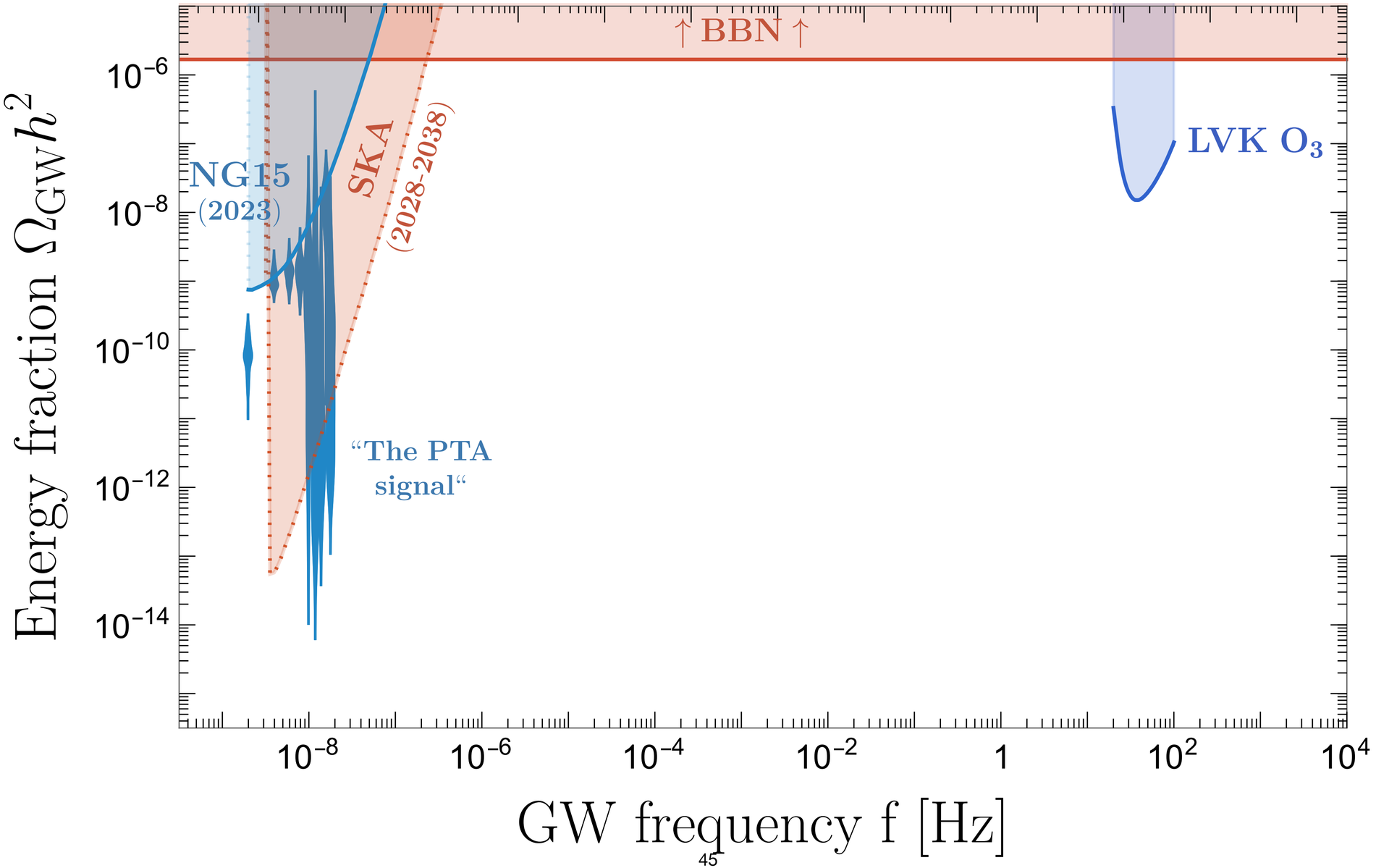

Pulsar Timing Arrays
Laser interferometers (Earth-based)
↑ BBN ↑
NG15
(2023)
SKA
(2028-2033)
LVK O3
"The PTA
signal"
Energy fraction $\Omega_{\rm GW}h^2$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
$10^{-14}$
$10^{-8}$
$10^{-6}$
$10^{-4}$
$10^{-2}$
1
$10^{2}$
$10^{4}$
GW frequency f [Hz]

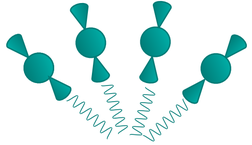


Pulsar Timing Arrays

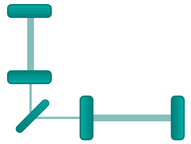


Laser interferometers (Earth-based)

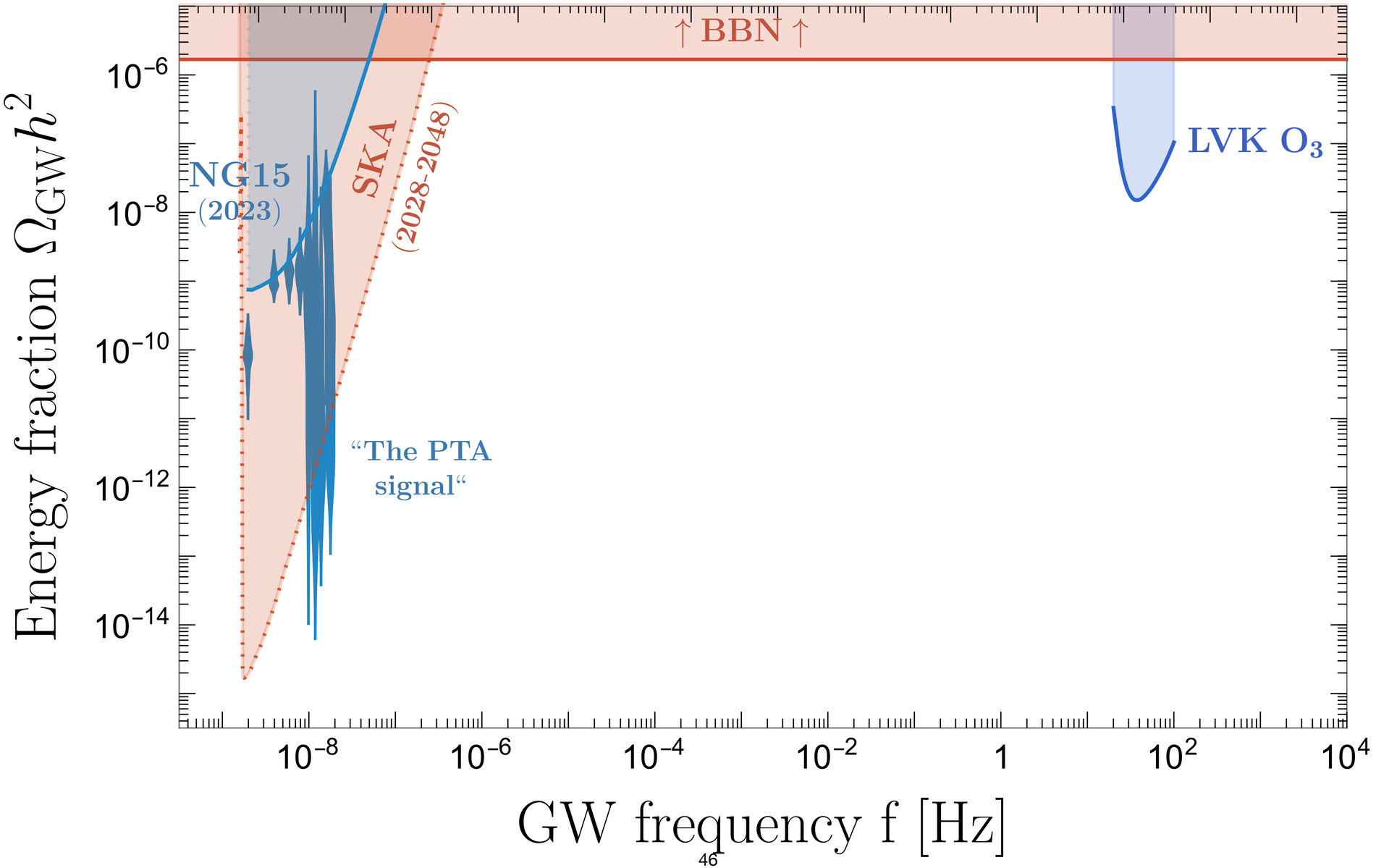


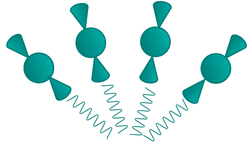


Pulsar Timing Arrays

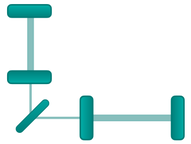


Laser interferometers (Earth-based)

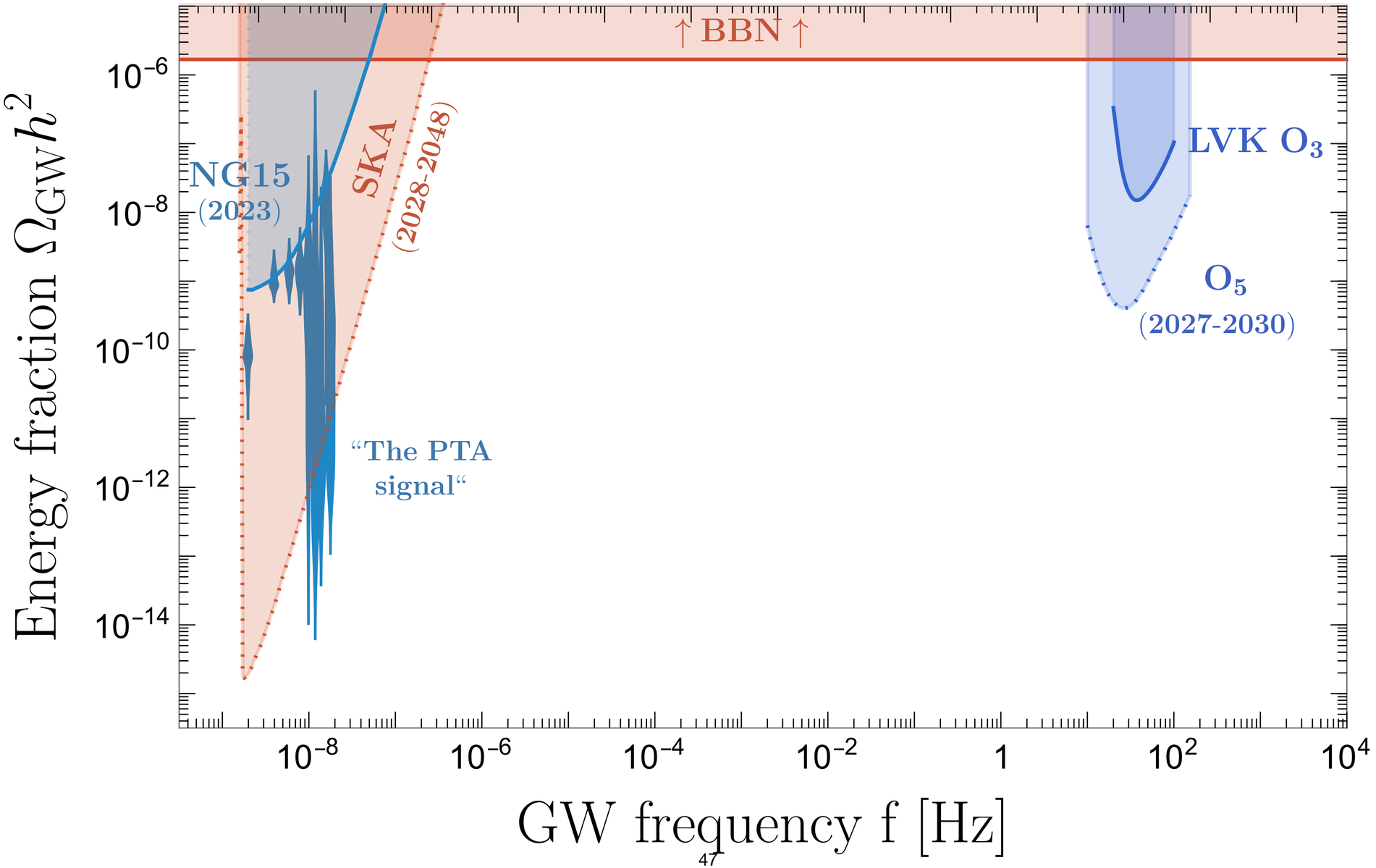


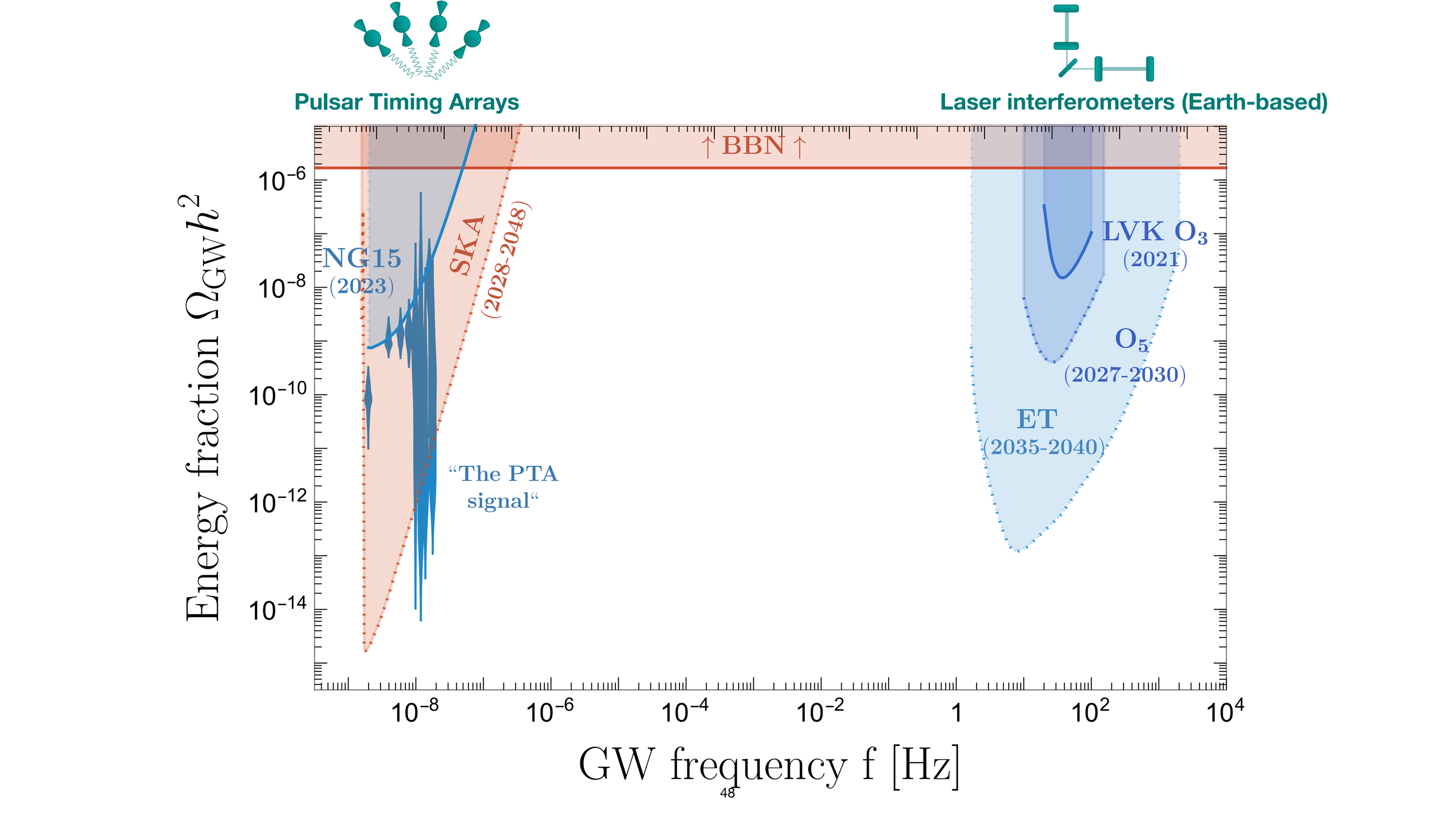


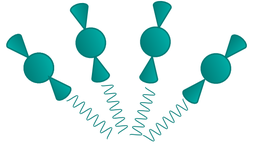
Pulsar Timing Arrays



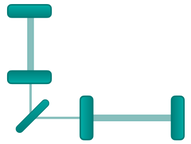
Laser interferometers (Earth-based)



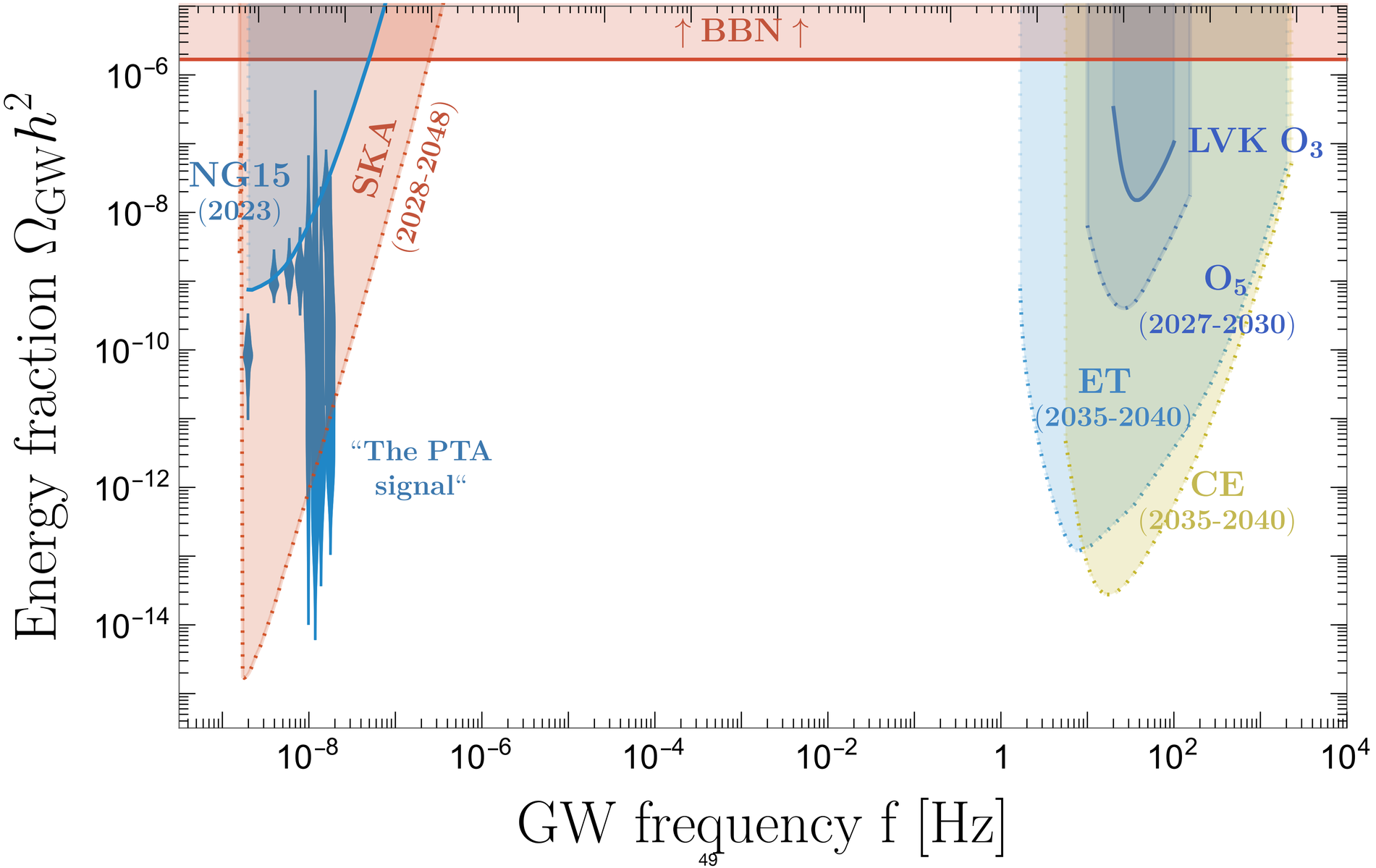

Pulsar Timing Arrays
Laser interferometers (Earth-based)
↑ BBN ↑
NG15
(2023)
SKA
(2028-2048)
"The PTA
signal"
LVK O3
(2021)
O5
(2027-2030)
ET
(2035-2040)
Energy fraction $\Omega_{\rm GW}h^2$
GW frequency f [Hz]
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
$10^{-14}$
$10^{-8}$
$10^{-6}$
$10^{-4}$
$10^{-2}$
1
$10^{2}$
$10^{4}$

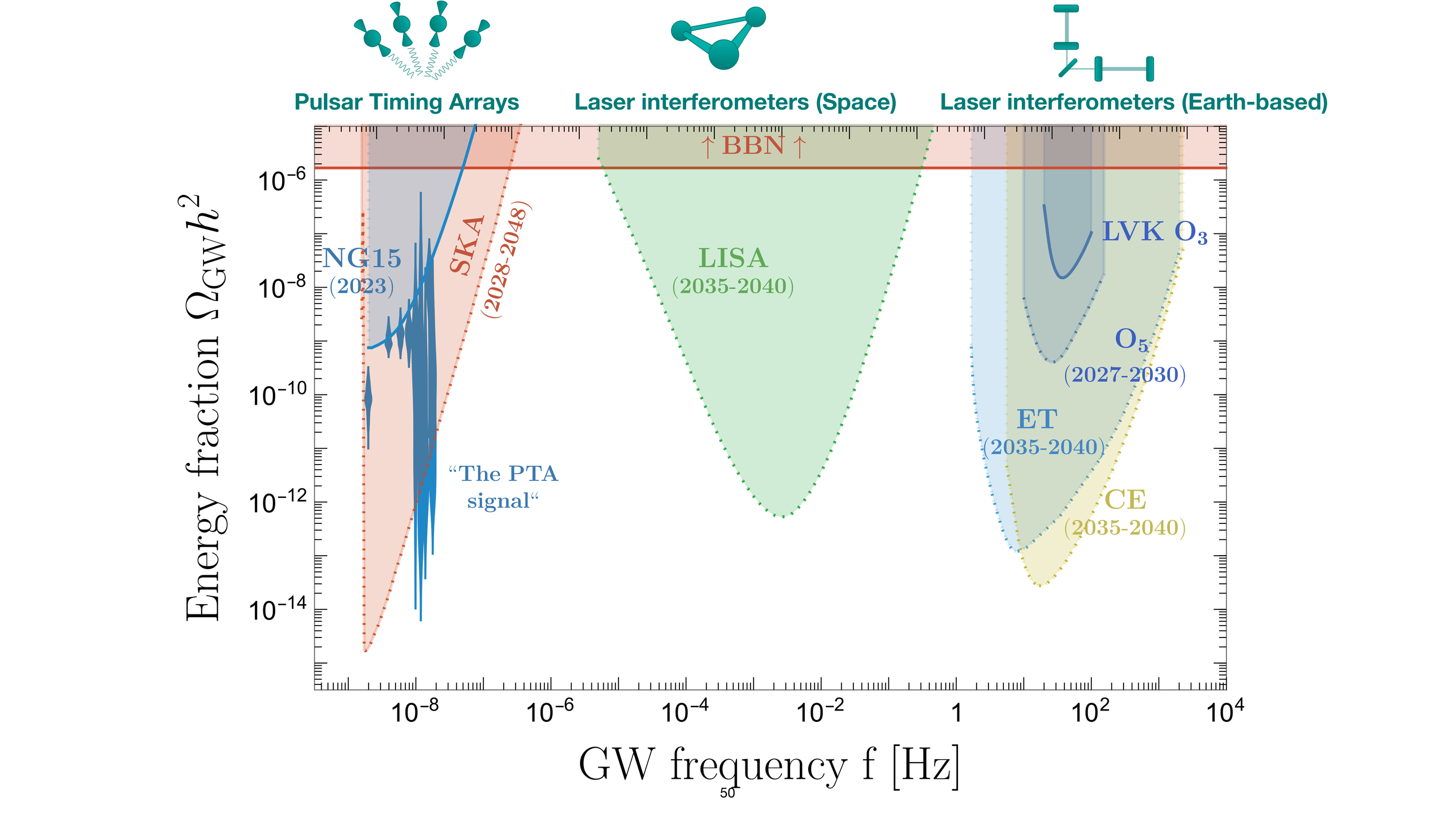


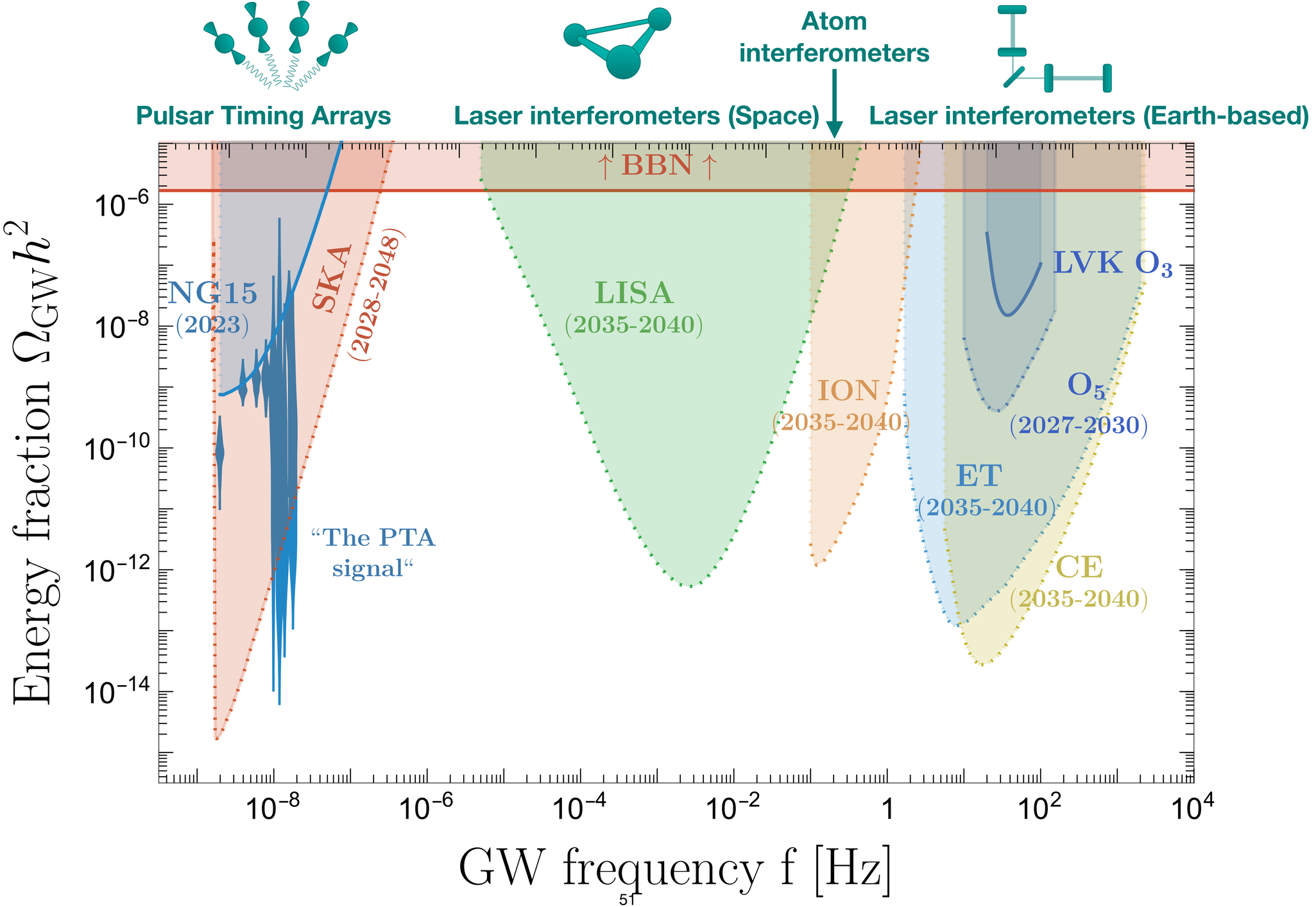
Pulsar Timing Arrays

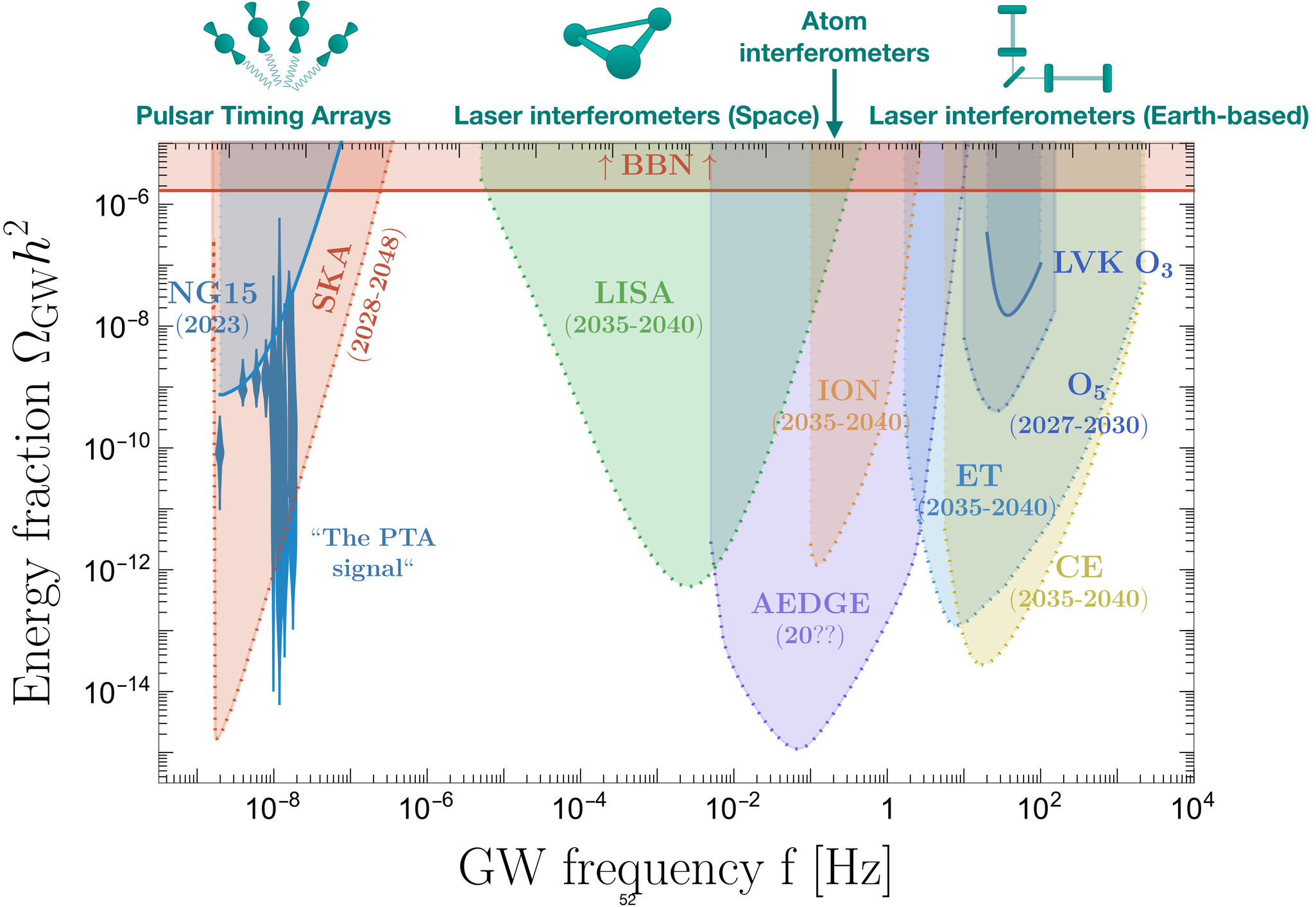


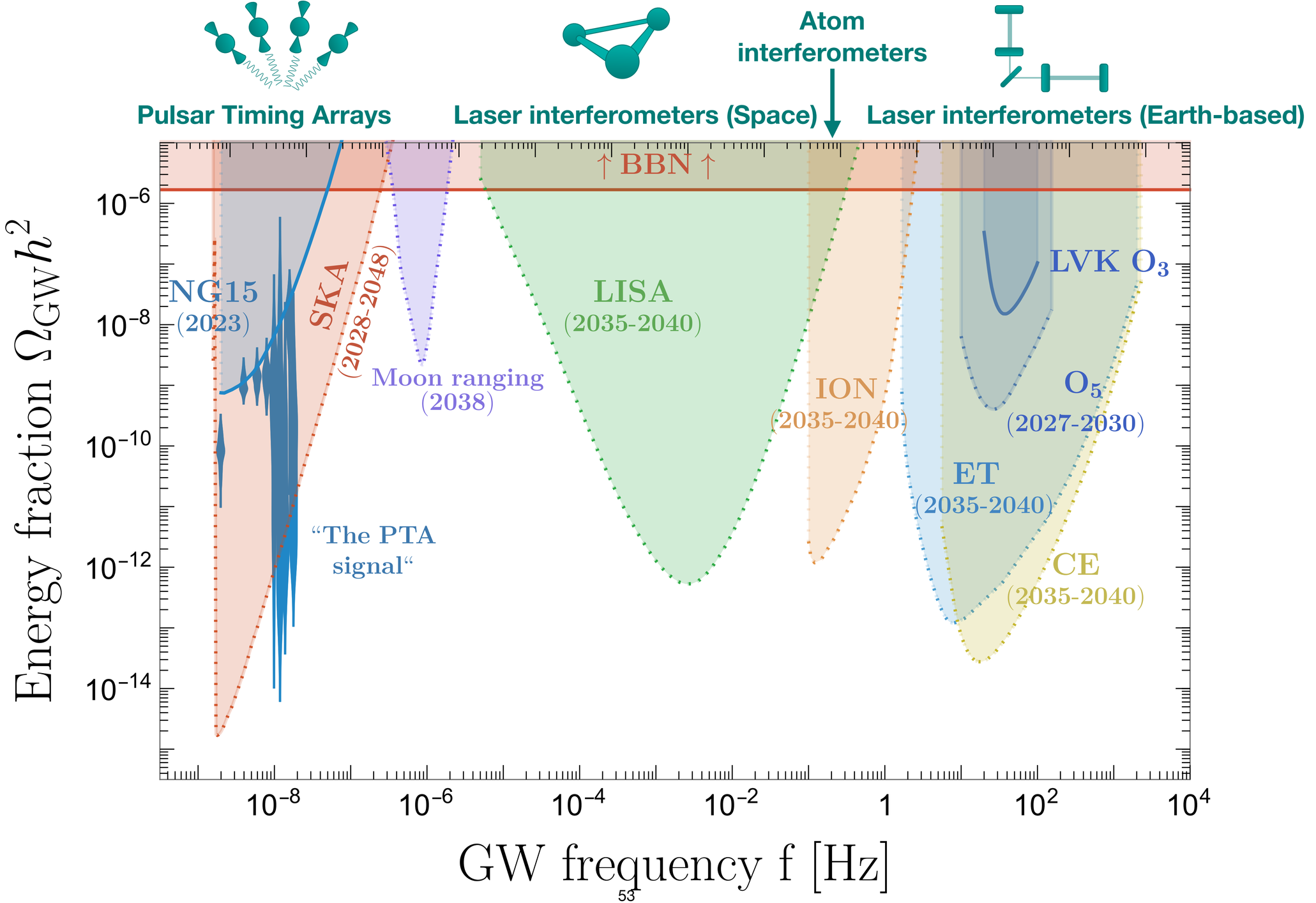
Laser interferometers (Earth-based)

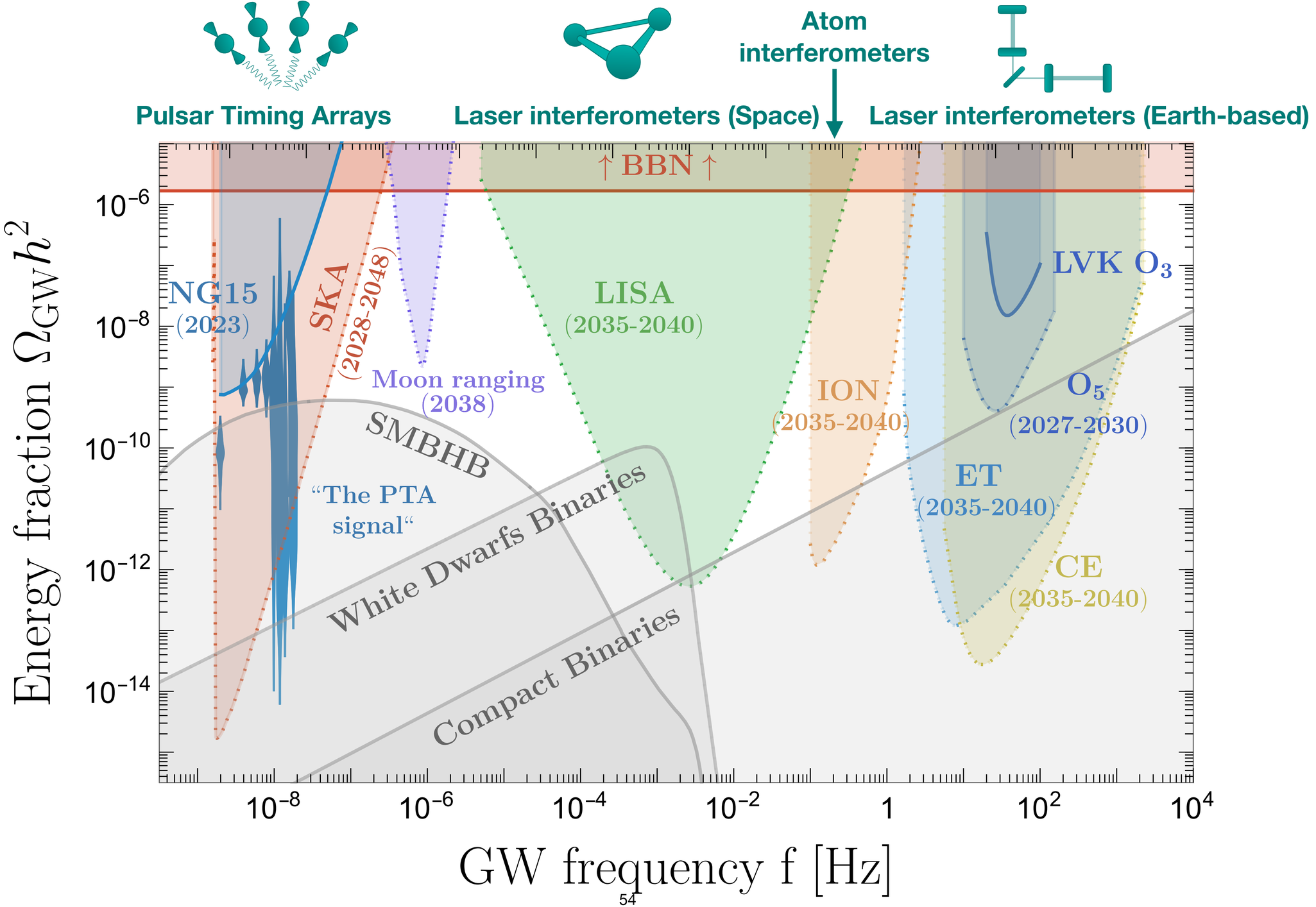



Pulsar Timing Arrays
Laser interferometers (Space)
Laser interferometers (Earth-based)
↑ BBN ↑
NG15
(2023)
SKA
(2028-2048)
LISA
(2035-2040)
LVK O3
O5
(2027-2030)
ET
(2035-2040)
CE
(2035-2040)
"The PTA
signal"
Energy fraction $\Omega_{\rm GW}h^2$
GW frequency f [Hz]
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
$10^{-14}$
$10^{-8}$
$10^{-6}$
$10^{-4}$
$10^{-2}$
1
$10^{2}$
$10^{4}$


Pulsar Timing Arrays
Laser interferometers (Space)
Atom interferometers
Laser interferometers (Earth-based)
↑ BBN ↑
NG15 (2023)
SKA (2028-2048)
LISA (2035-2040)
ION (2035-2040)
LVK O3
O5 (2027-2030)
ET (2035-2040)
CE (2035-2040)
"The PTA signal"
Energy fraction $\Omega_{\rm GW}h^2$
GW frequency f [Hz]
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
$10^{-14}$
$10^{-8}$
$10^{-6}$
$10^{-4}$
$10^{-2}$
1
$10^{2}$
$10^{4}$

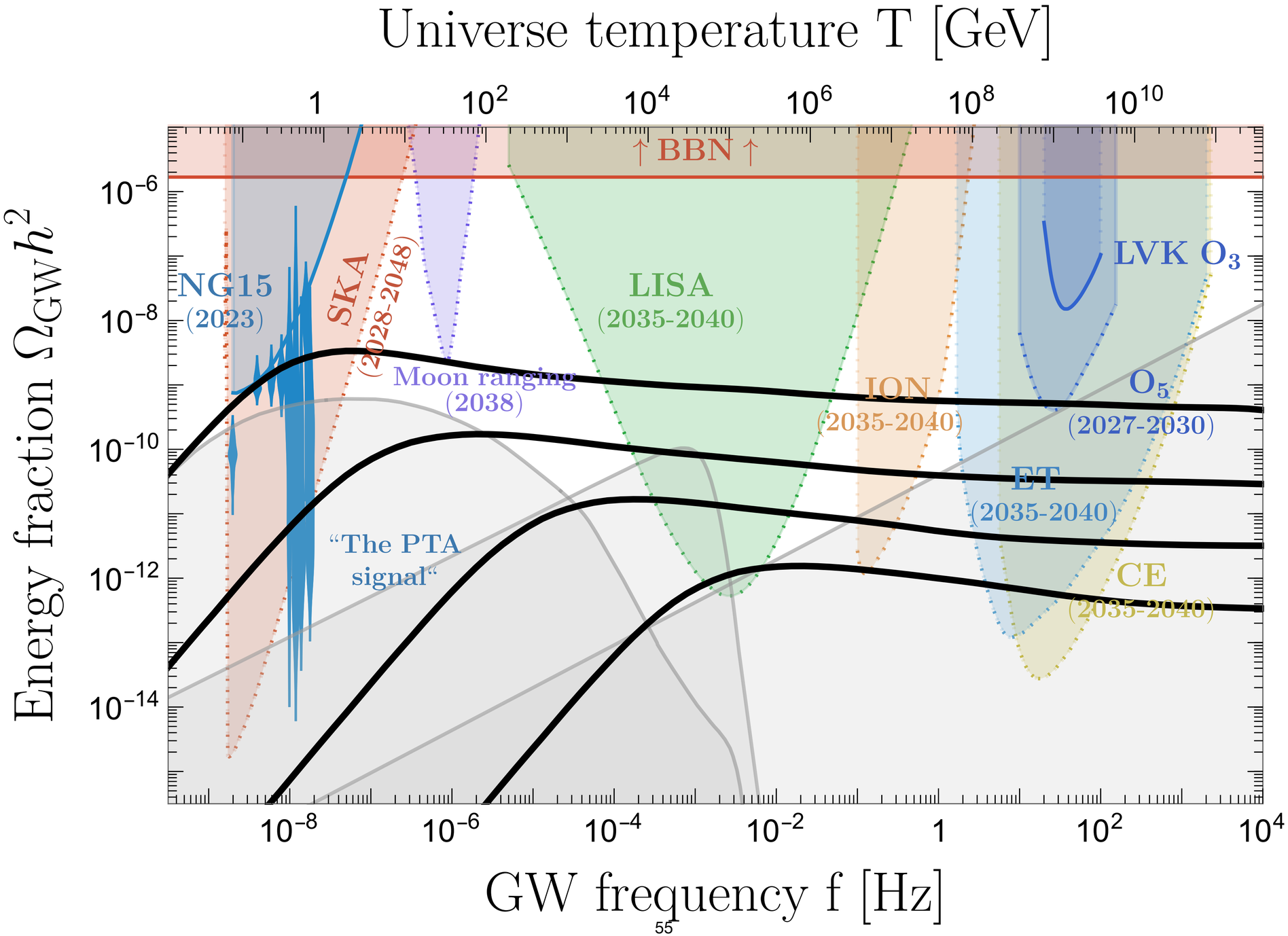

Pulsar Timing Arrays
Laser interferometers (Space)
Atom interferometers
Laser interferometers (Earth-based)
↑ BBN ↑
NG15 (2023)
SKA (2028-2048)
"The PTA signal"
LISA (2035-2040)
ION (2035-2040)
AEDGE (20??)
LVK O3
O5 (2027-2030)
ET (2035-2040)
CE (2035-2040)
Energy fraction $\Omega_{GW}h^2$
GW frequency f [Hz]
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
$10^{-14}$
$10^{-8}$
$10^{-6}$
$10^{-4}$
$10^{-2}$
1
$10^{2}$
$10^{4}$


Pulsar Timing Arrays
Laser interferometers (Space)
Atom interferometers
Laser interferometers (Earth-based)
↑ BBN ↑
NG15 (2023)
SKA (2028-2048)
Moon ranging (2038)
LISA (2035-2040)
ION (2035-2040)
LVK O3
O5 (2027-2030)
ET (2035-2040)
CE (2035-2040)
"The PTA signal"
Energy fraction $\Omega_{\rm GW}h^2$
GW frequency f [Hz]
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
$10^{-14}$
$10^{-8}$
$10^{-6}$
$10^{-4}$
$10^{-2}$
1
$10^{2}$
$10^{4}$


Pulsar Timing Arrays
Laser interferometers (Space)
Atom interferometers
Laser interferometers (Earth-based)
↑ BBN ↑
NG15 (2023)
SKA (2028-2048)
Moon ranging (2038)
LISA (2035-2040)
ION (2035-2040)
LVK O3
O5 (2027-2030)
ET (2035-2040)
CE (2035-2040)
SMBHB
"The PTA signal"
White Dwarfs Binaries
Compact Binaries
Energy fraction $\Omega_{GW}h^2$
GW frequency f [Hz]
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
$10^{-14}$
$10^{-8}$
$10^{-6}$
$10^{-4}$
$10^{-2}$
1
$10^{2}$
$10^{4}$

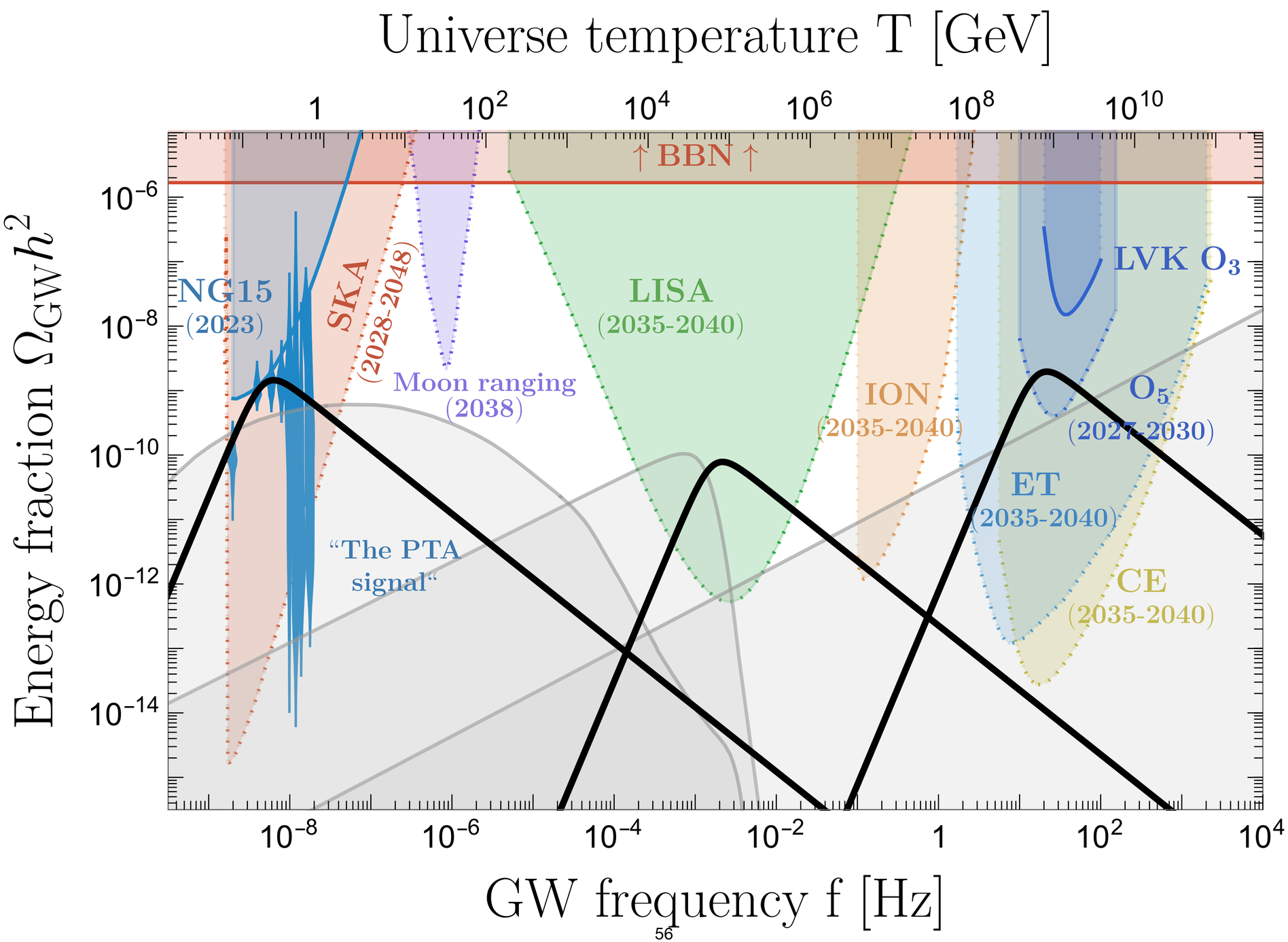
## Cosmic strings



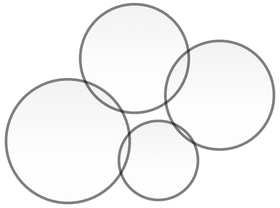


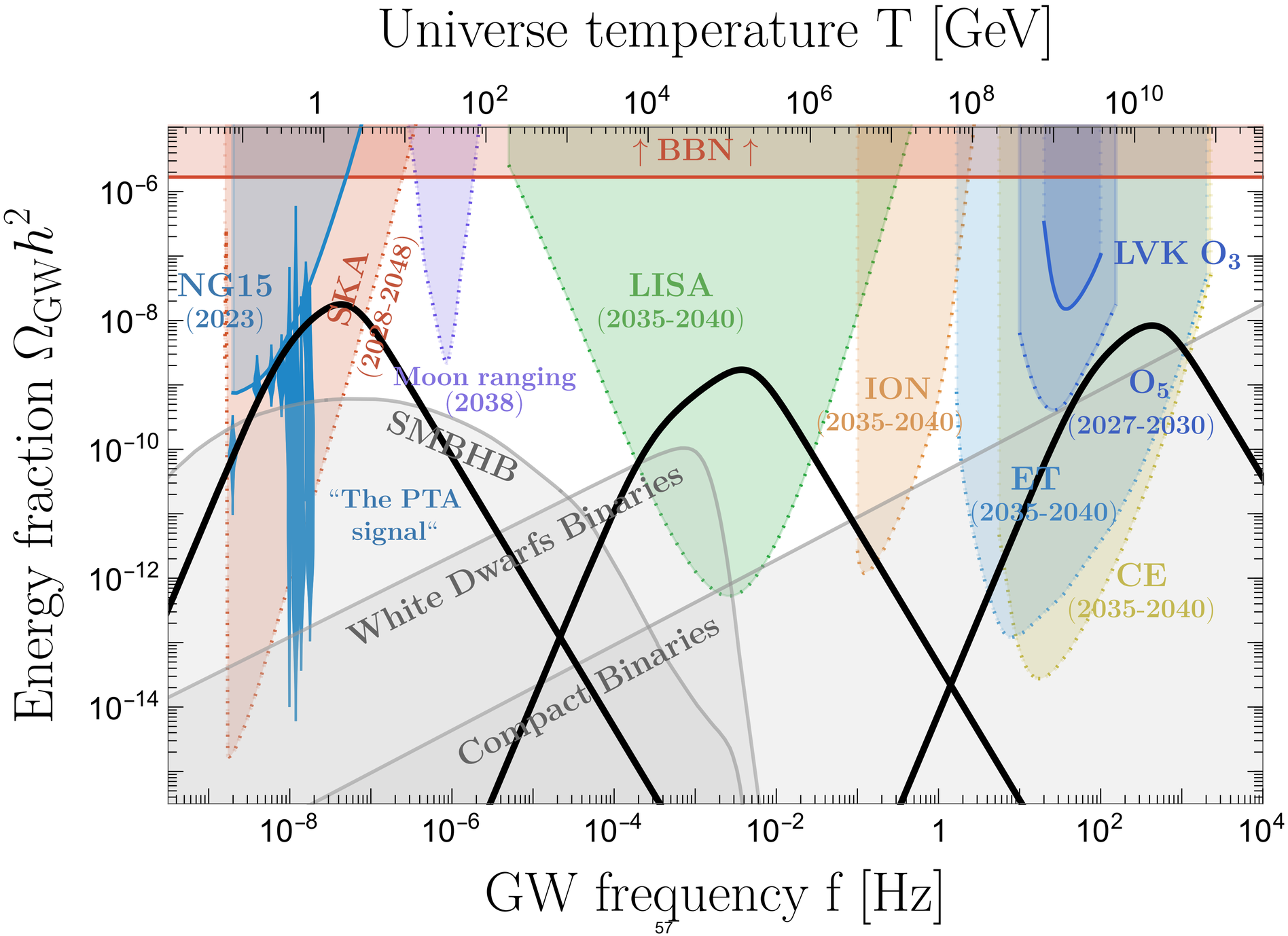
## Domain walls





**First-order phase transition**

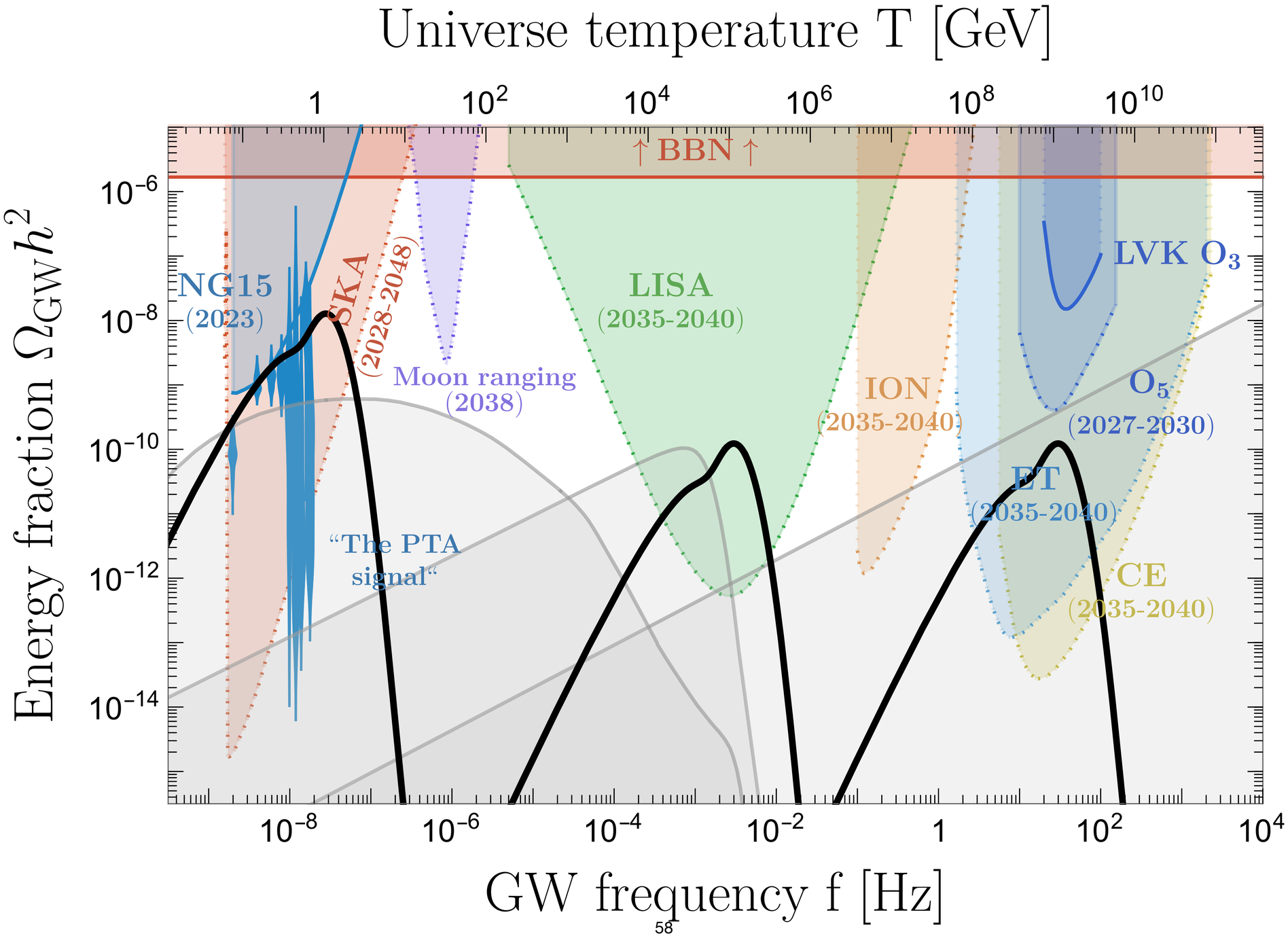




## Curvature peaks



**Produce GW at 2nd order in perturbation theory**

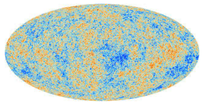


1 meV 0.1 eV 10 eV 1 keV 100 keV 10 MeV 1 GeV $10^2$ $10^4$ $10^6$ $10^8$ $10^{10}$ $10^{12}$ $10^{14}$ $10^{16}$ $T_\star$

LIFE

Recombination

$e^- + p \to H + \gamma$



BBN

$n_{\rm He}/n_{\rm H} \simeq 0.06$

QCD

EWPT

WIMP

Hierarchy problem

Flavor puzzle

Leptogenesis

QCD axion

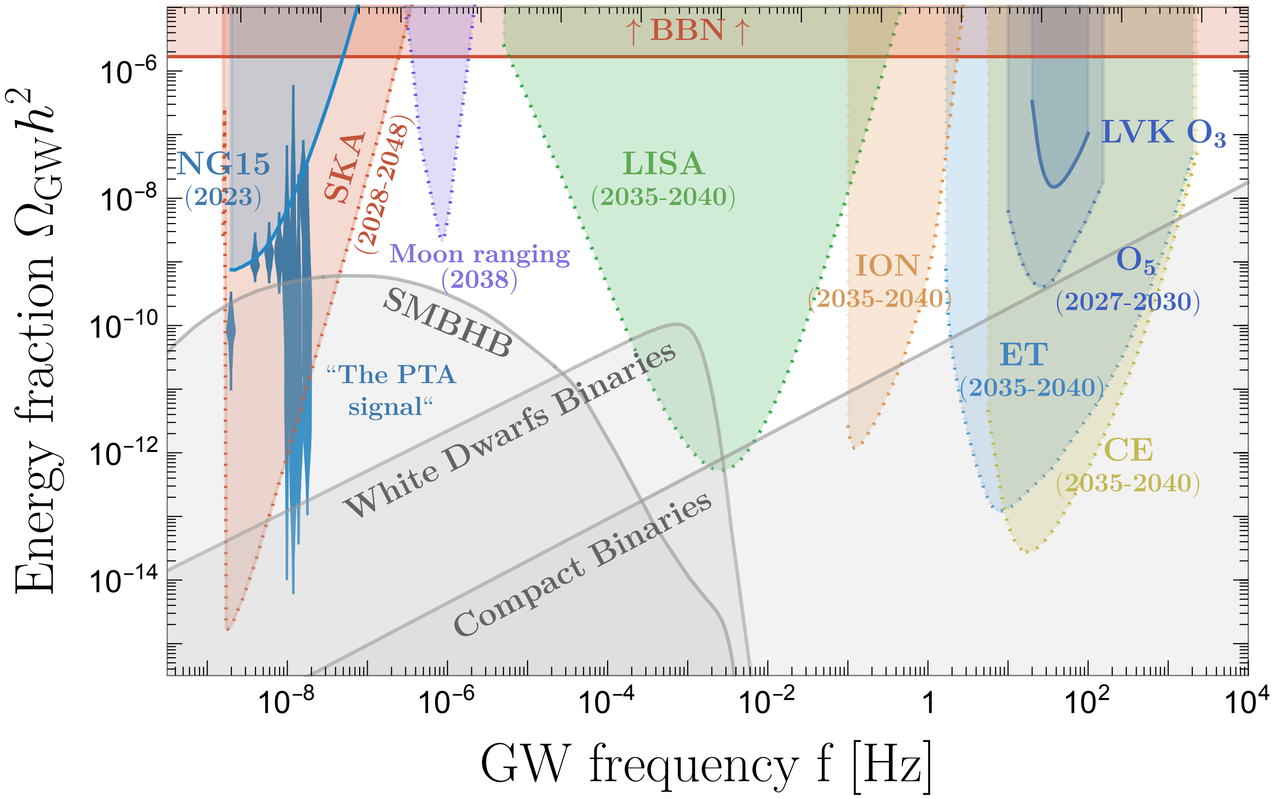
Inflation

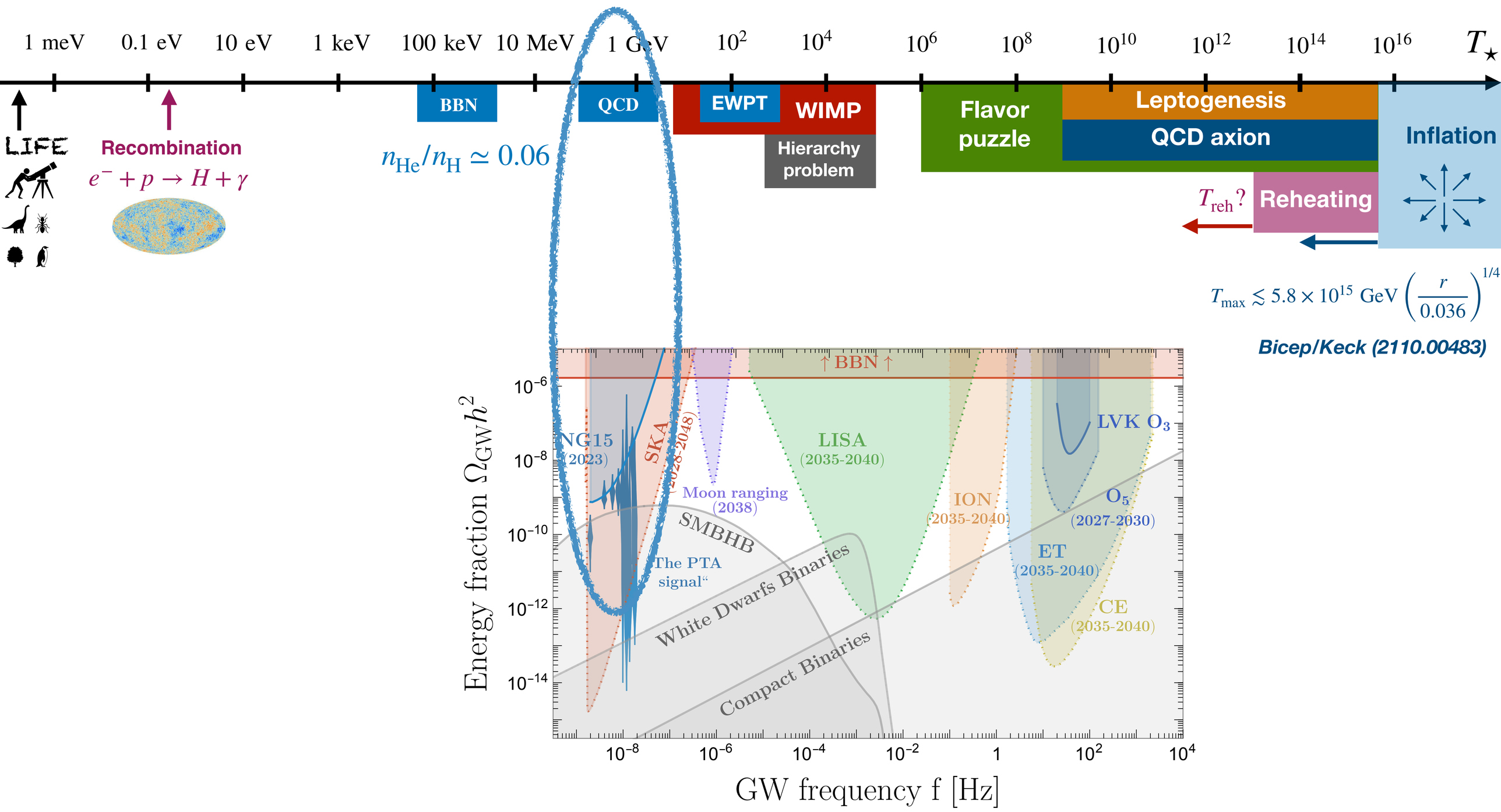
$T_{\rm reh}$?

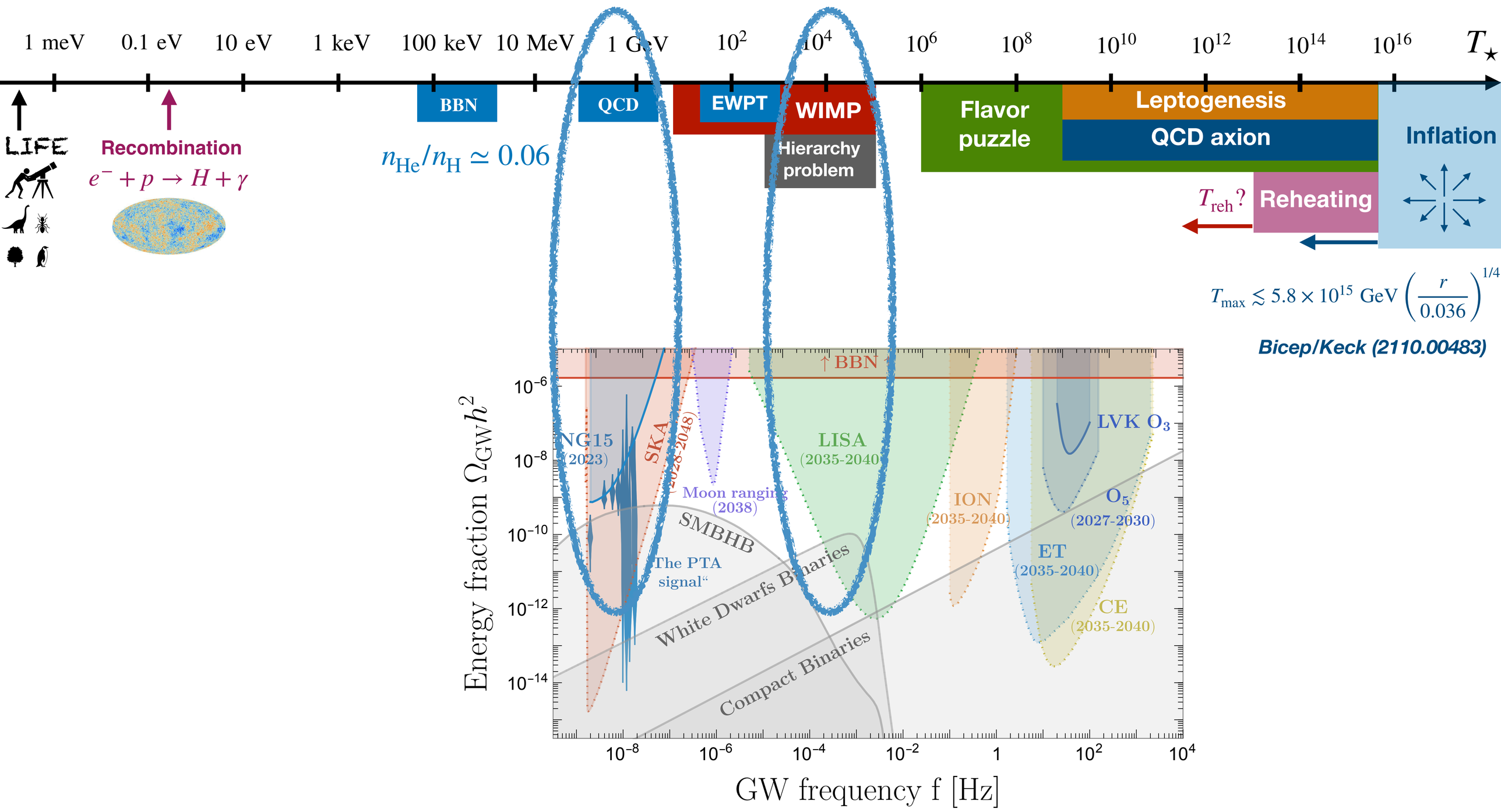
Reheating

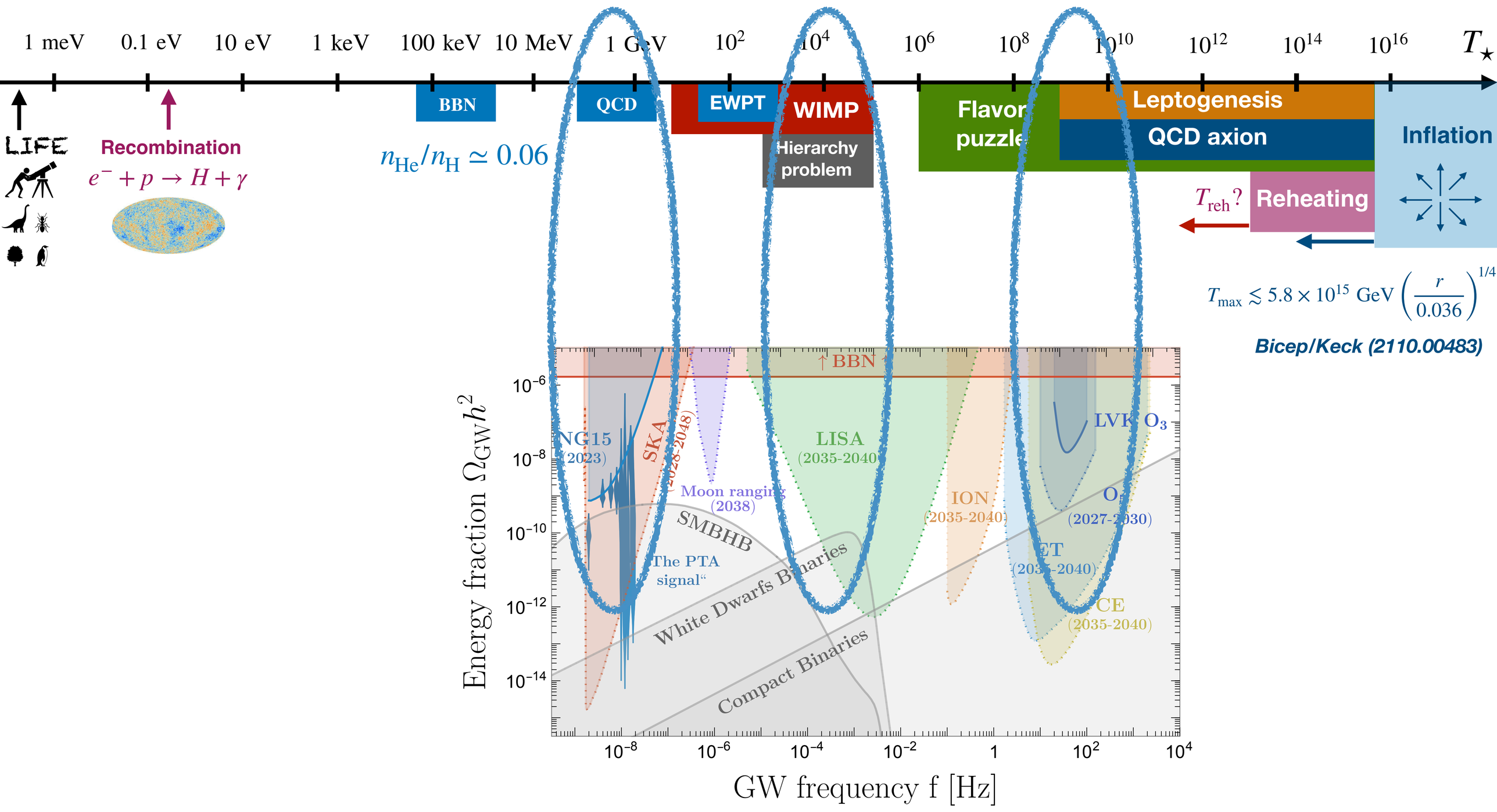
$$T_{\rm max} \lesssim 5.8 \times 10^{15}\ {\rm GeV} \left(\frac{r}{0.036}\right)^{1/4}$$

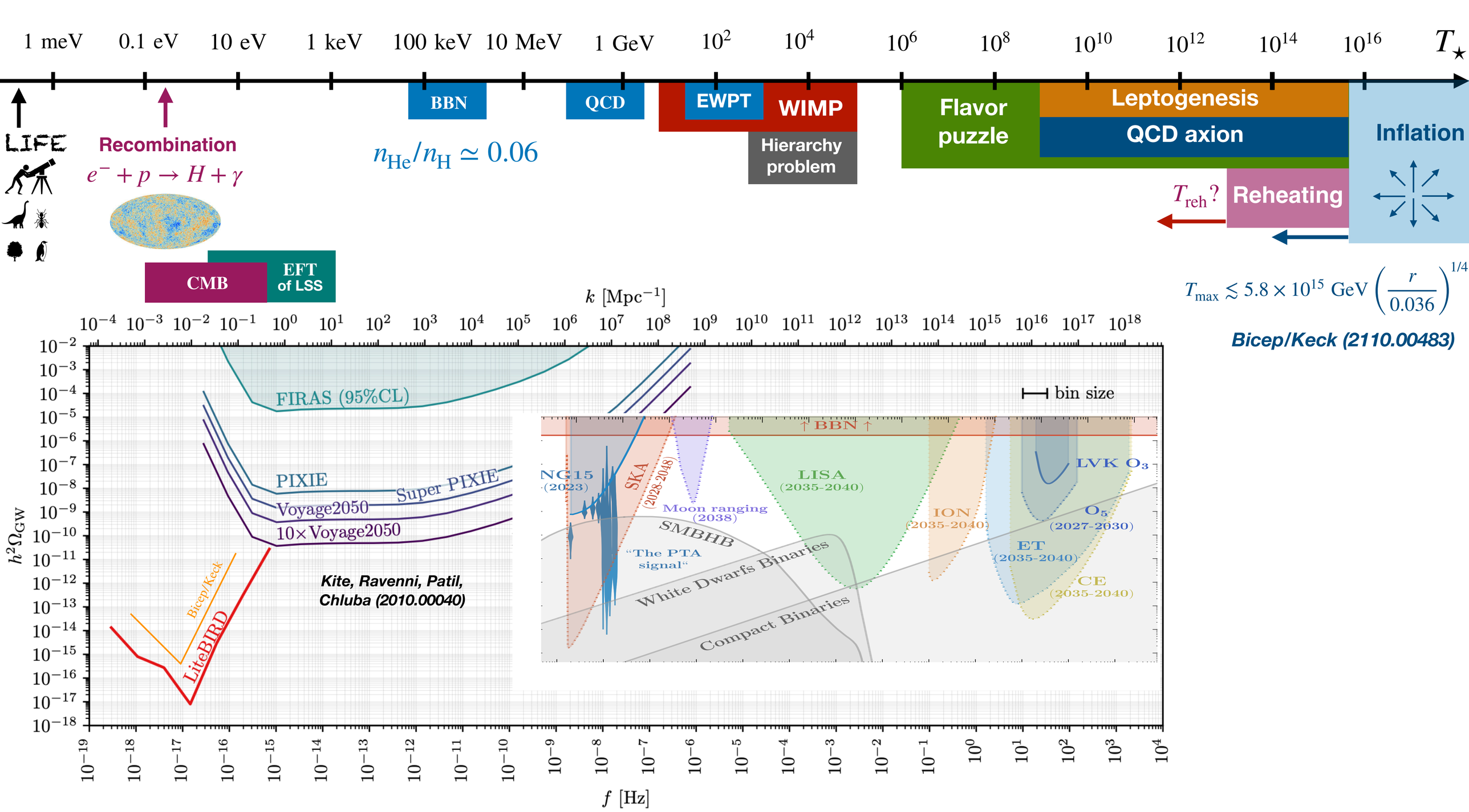
***Bicep/Keck (2110.00483)***

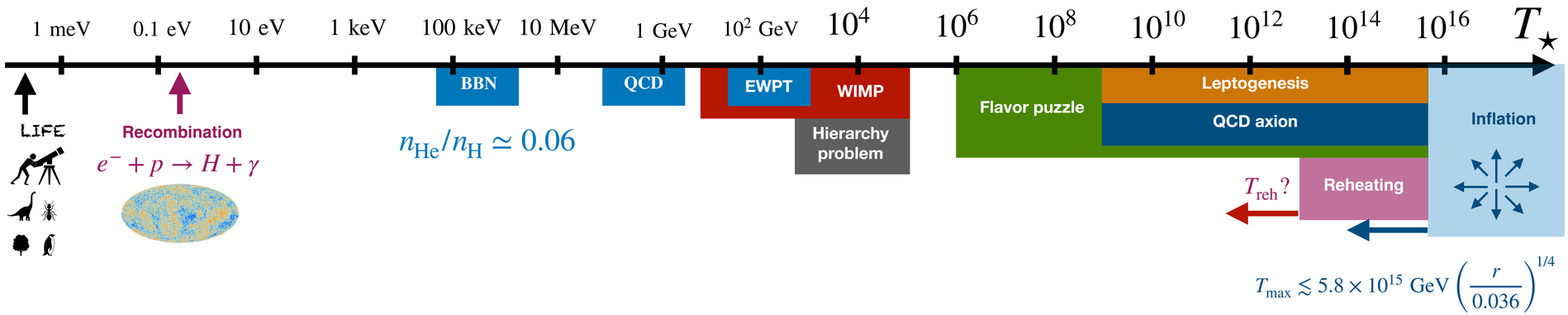



1 meV
0.1 eV
10 eV
1 keV
100 keV
10 MeV
1 GeV
$10^2$
$10^4$
$10^6$
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$10^{10}$
$10^{12}$
$10^{14}$
$10^{16}$
$T_\star$
LIFE
Recombination
$e^- + p \to H + \gamma$
BBN
$n_{\rm He}/n_{\rm H} \simeq 0.06$
QCD
EWPT
WIMP
Hierarchy problem
Flavor puzzle
Leptogenesis
QCD axion
Inflation
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Reheating
$T_{\rm max} \lesssim 5.8 \times 10^{15}\ {\rm GeV} \left(\frac{r}{0.036}\right)^{1/4}$
Bicep/Keck (2110.00483)
↑ BBN ↑
NG15 (2023)
SKA (2028-2048)
Moon ranging (2038)
LISA (2035-2040)
ION (2035-2040)
LVK $O_3$
$O_5$ (2027-2030)
ET (2035-2040)
CE (2035-2040)
SMBHB
The PTA signal"
White Dwarfs Binaries
Compact Binaries
Energy fraction $\Omega_{\rm GW}h^2$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
$10^{-14}$
$10^{-8}$
$10^{-6}$
$10^{-4}$
$10^{-2}$
1
$10^2$
$10^4$
GW frequency f [Hz]


1 meV
0.1 eV
10 eV
1 keV
100 keV
10 MeV
1 GeV
$10^2$
$10^4$
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$10^8$
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$10^2$
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Bicep/Keck (2110.00483)
Energy fraction $\Omega_{\rm GW} h^2$
GW frequency f [Hz]
BBN
NG15 (2023)
SKA (2028-2048)
Moon ranging (2038)
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$O_4$ (2027-2030)
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White Dwarfs Binaries
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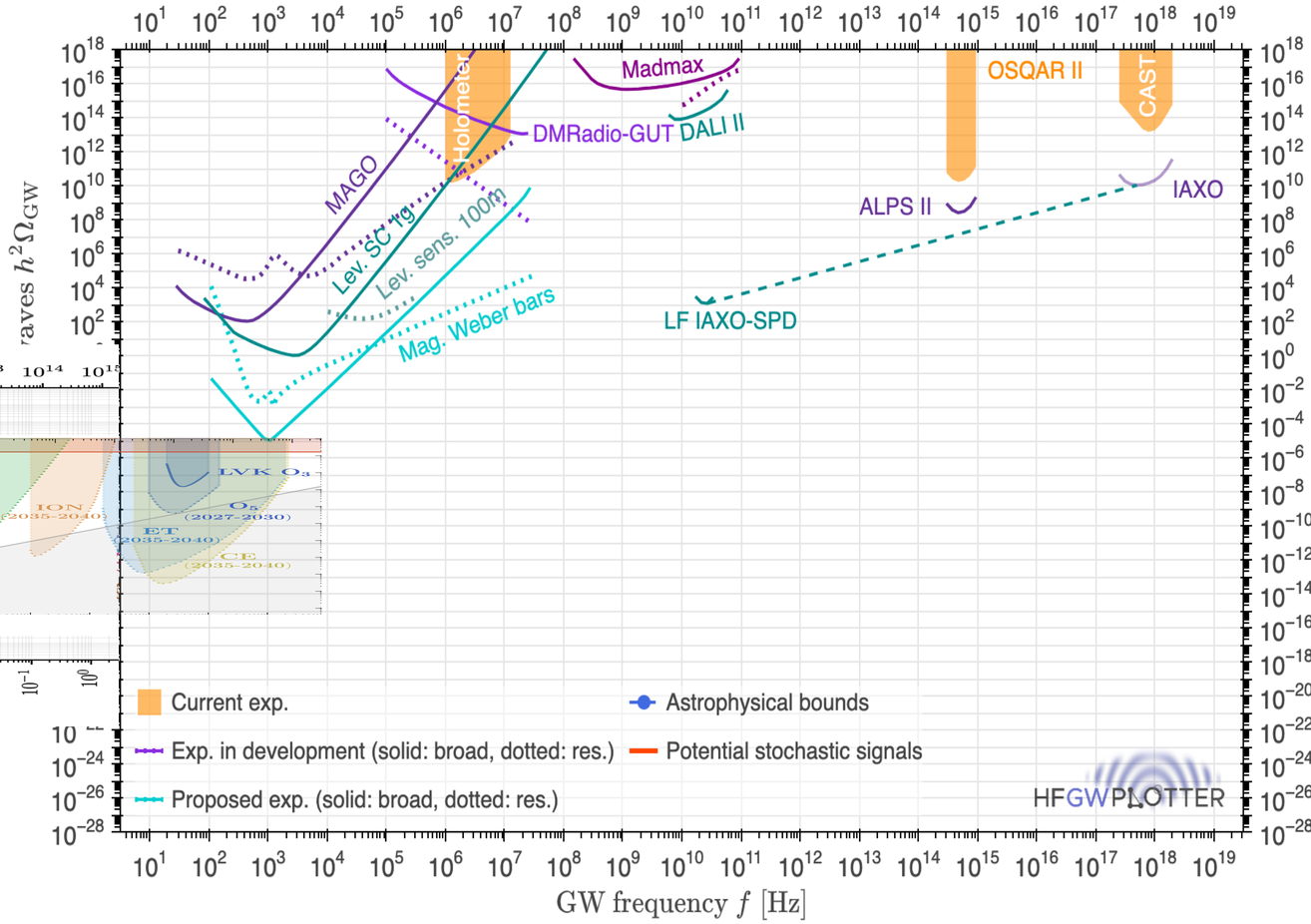

1 meV
0.1 eV
10 eV
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$10^2$
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Leptogenesis
QCD axion
Inflation
$T_{\rm reh}$?
Reheating
CMB
EFT of LSS
$T_{\rm max} \lesssim 5.8 \times 10^{15}$ GeV $\left(\frac{r}{0.036}\right)^{1/4}$
Bicep/Keck (2110.00483)
$k$ [Mpc$^{-1}$]
$h^2\Omega_{\rm GW}$
$f$ [Hz]
FIRAS (95%CL)
PIXIE
Super PIXIE
Voyage2050
10×Voyage2050
Bicep/Keck
LiteBIRD
Kite, Ravenni, Patil, Chluba (2010.00040)
bin size
↑ BBN ↑
NG15 (2023)
SKA (2028-2048)
Moon ranging (2038)
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LVK $O_3$
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White Dwarfs Binaries
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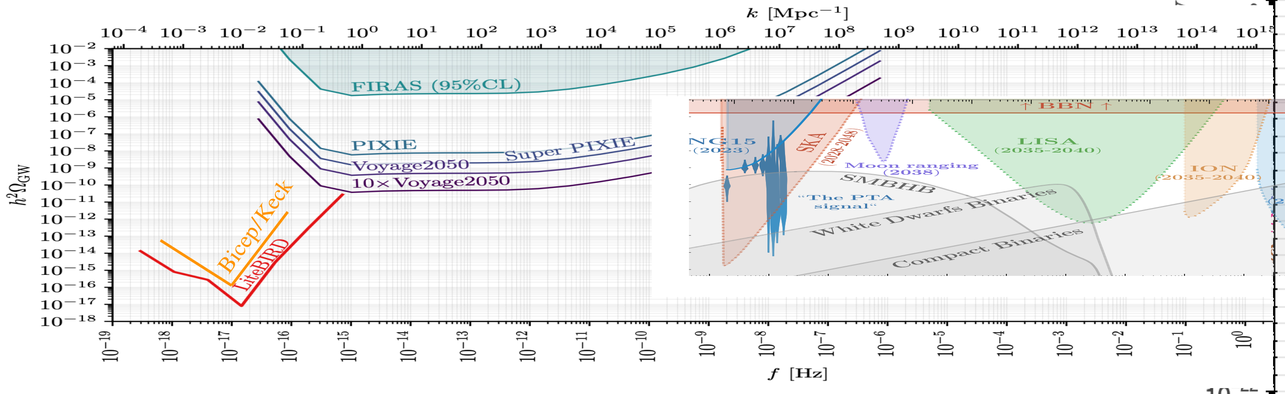

$$T_{\rm max} \lesssim 5.8 \times 10^{15}\ {\rm GeV} \left(\frac{r}{0.036}\right)^{1/4}$$

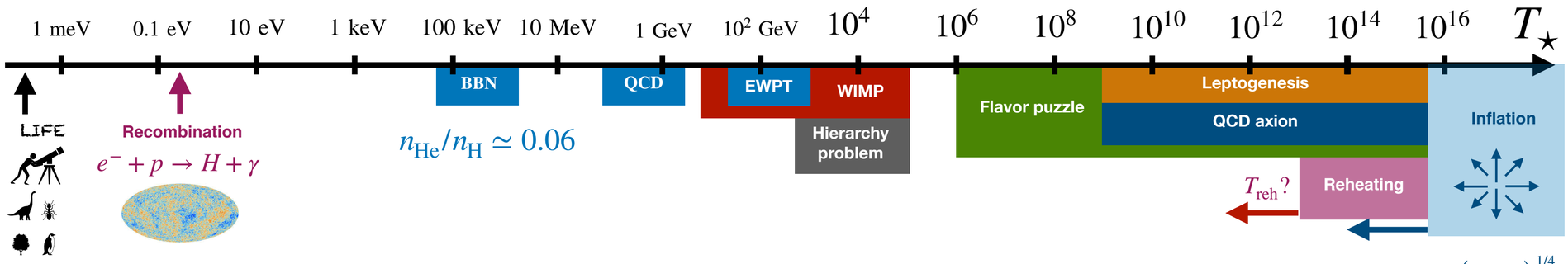
*Bicep/Keck (2110.00483)*

***GWPlotter: Muia, Ringwald, Tamarit (2501.11723)***




***Kite, Ravenni, Patil, Chluba (2010.00040)***

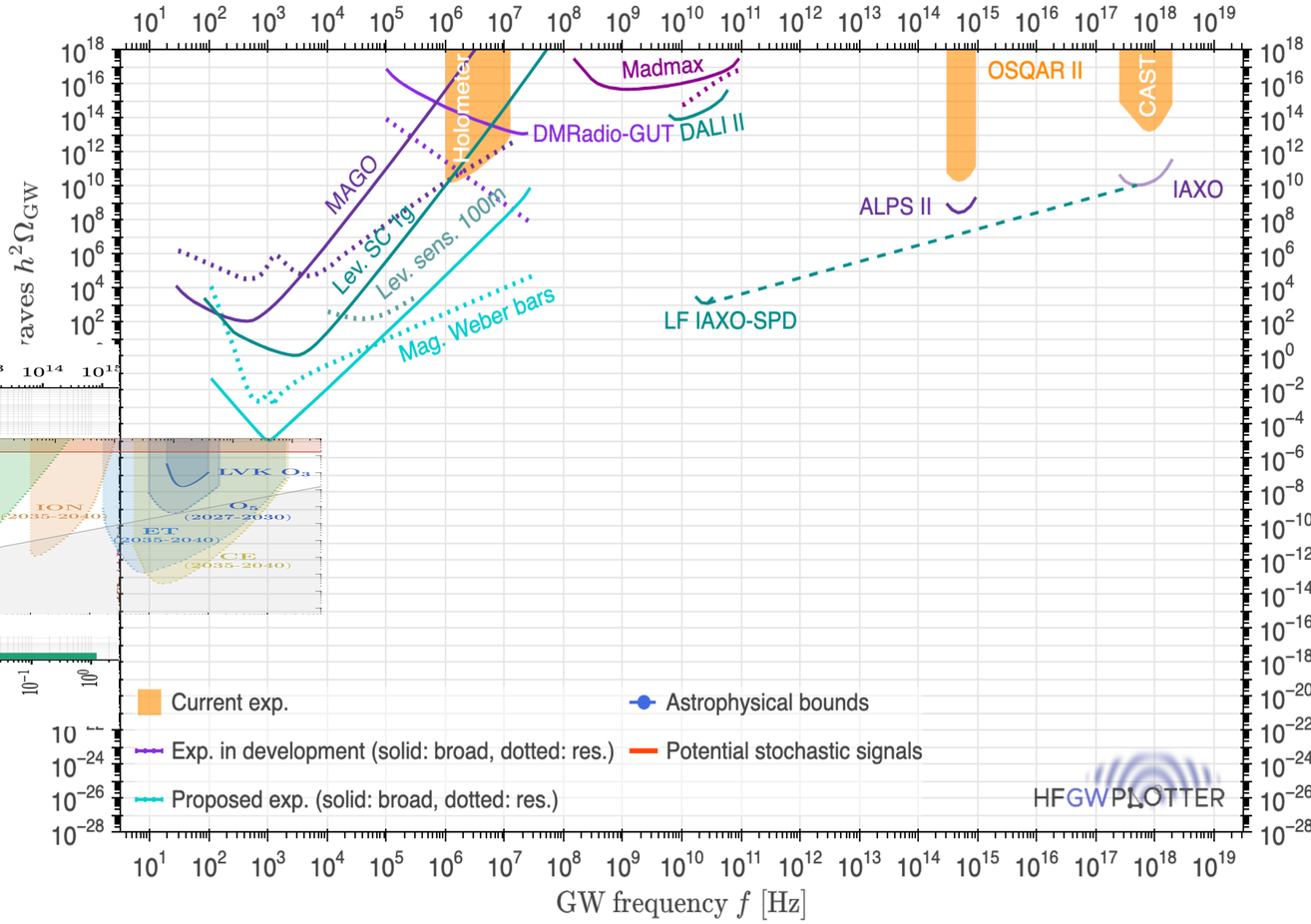




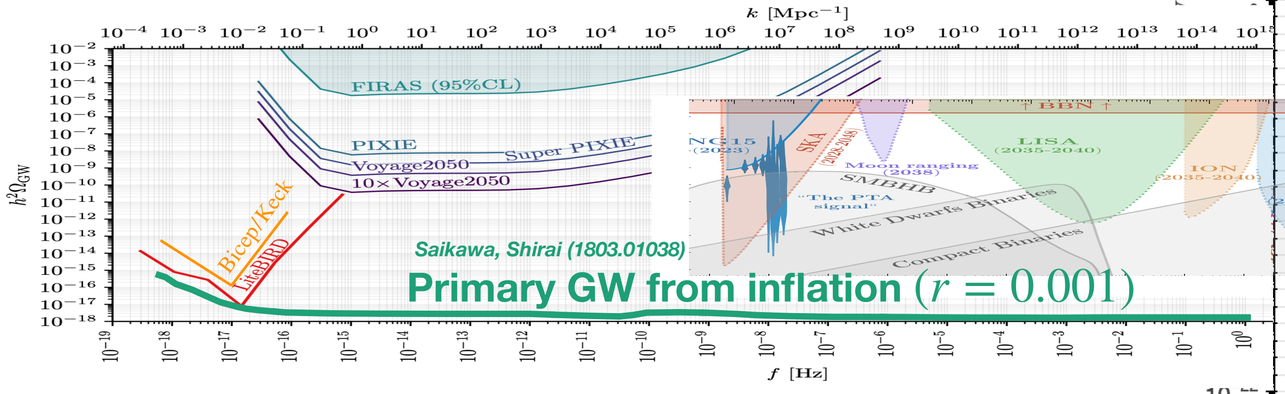

$$T_{\rm max} \lesssim 5.8 \times 10^{15}\ {\rm GeV} \left(\frac{r}{0.036}\right)^{1/4}$$

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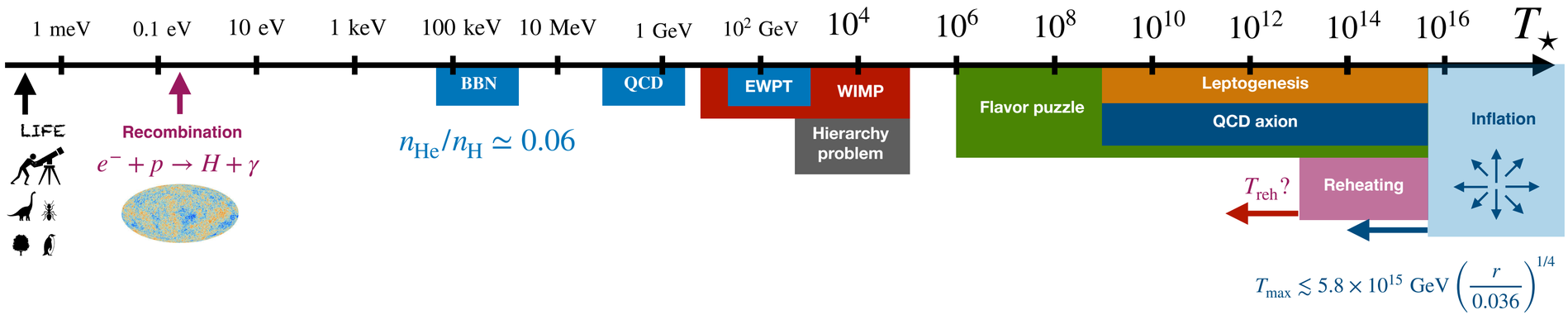



*Kite, Ravenni, Patil, Chluba (2010.00040)*




*Saikawa, Shirai (1803.01038)*

**Primary GW from inflation ($r = 0.001$)**

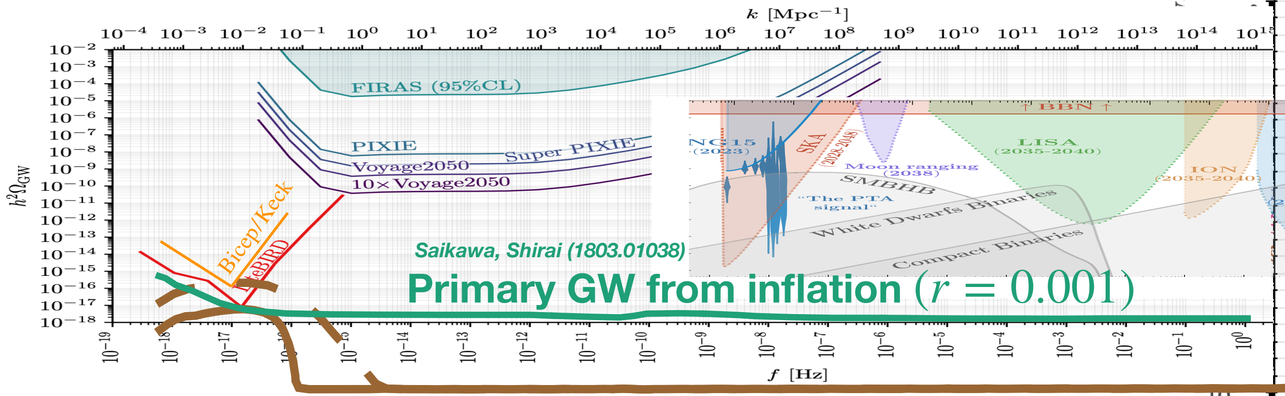



$$T_{\rm max} \lesssim 5.8 \times 10^{15}\ {\rm GeV} \left(\frac{r}{0.036}\right)^{1/4}$$

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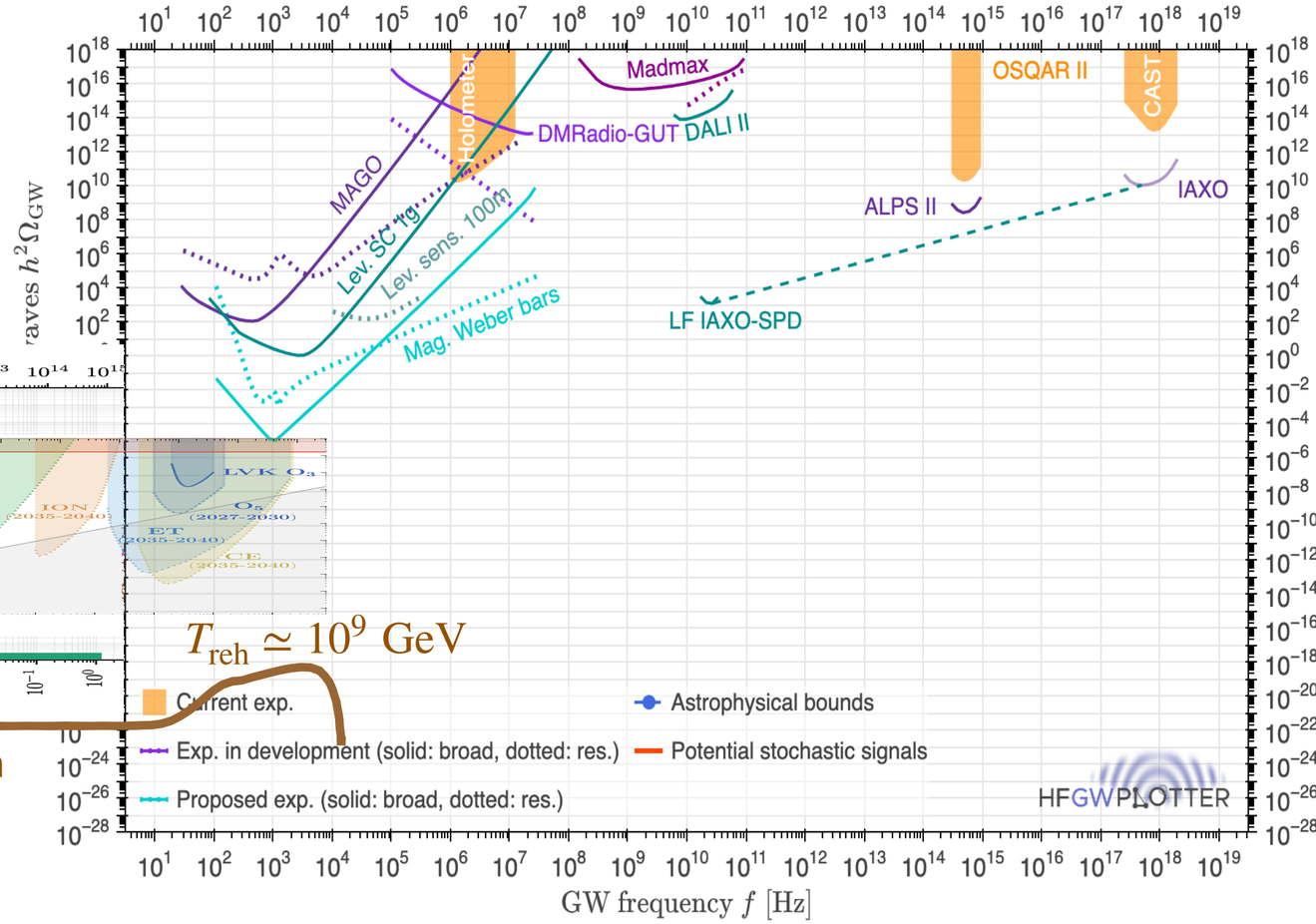
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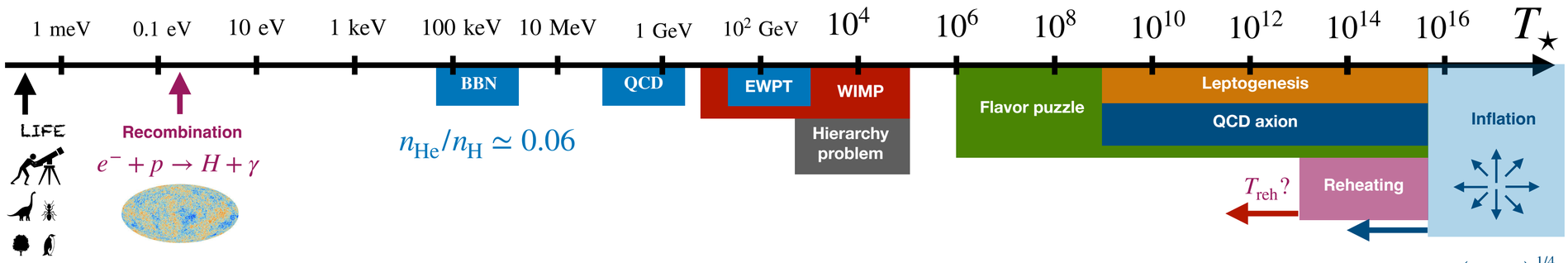
**Primary GW from inflation ($r = 0.001$)**




**Irreducible secondary GW from inflation**

**(Only depend on $\mathcal{A}_{\mathcal{R}} \simeq 2.1 \times 10^{-9}$ and is independent of r)**

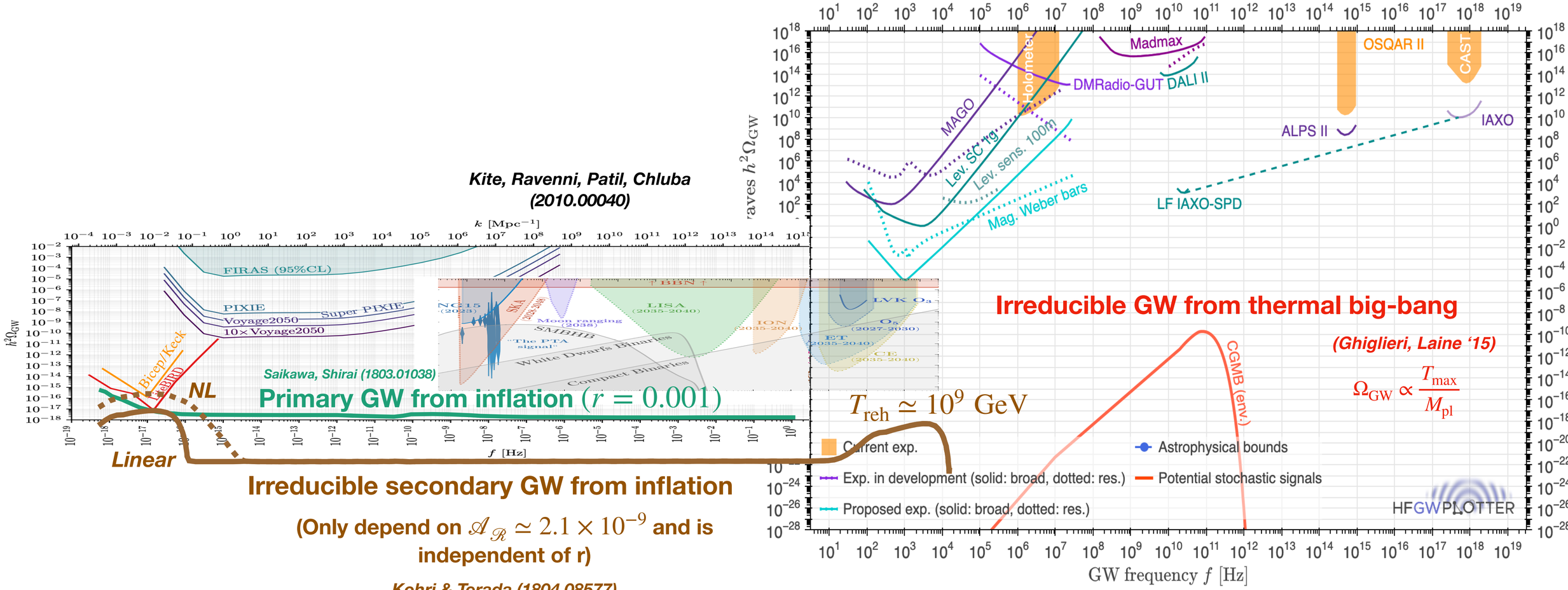
*Kohri & Terada (1804.08577)*




$$T_{\rm max} \lesssim 5.8 \times 10^{15}\ {\rm GeV} \left(\frac{r}{0.036}\right)^{1/4}$$

*Bicep/Keck (2110.00483)*

***GWPlotter: Muia, Ringwald, Tamarit (2501.11723)***




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**Primary GW from inflation ($r = 0.001$)**




**Irreducible secondary GW from inflation**

**(Only depend on $\mathscr{A}_{\mathscr{R}} \simeq 2.1 \times 10^{-9}$ and is independent of r)**

***Kohri & Terada (1804.08577)***

# Plan of the talk

1) Gravitational Waves (GWs)

$h_{ij}(\vec{x}, t)$

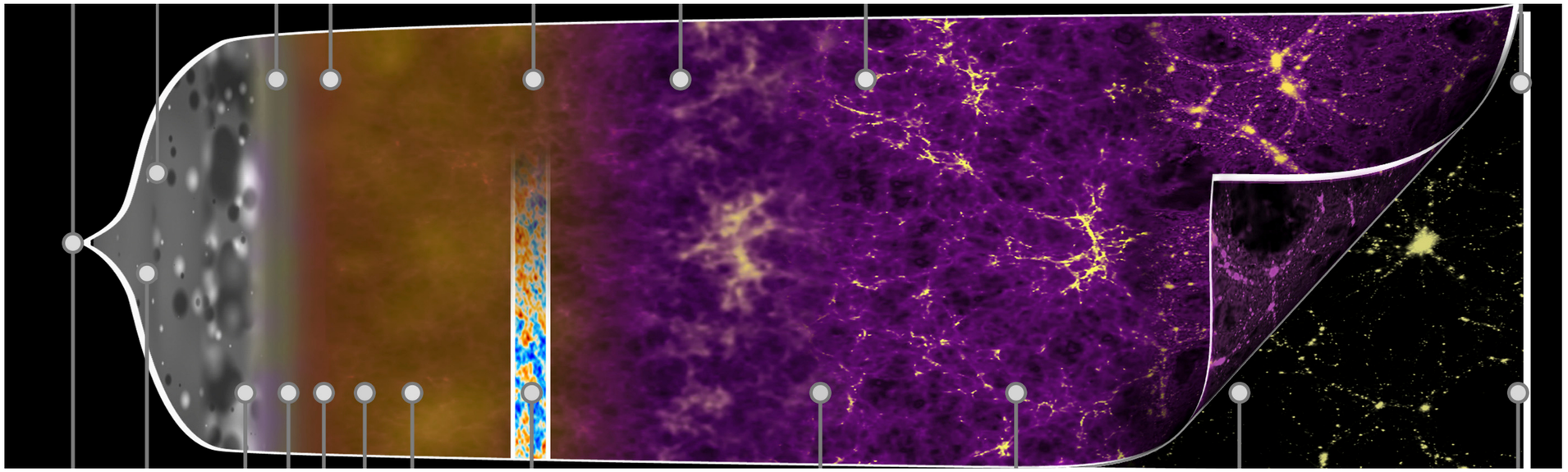
2) Primordial Black Holes (PBHs)



3) What is the PTA signal ?

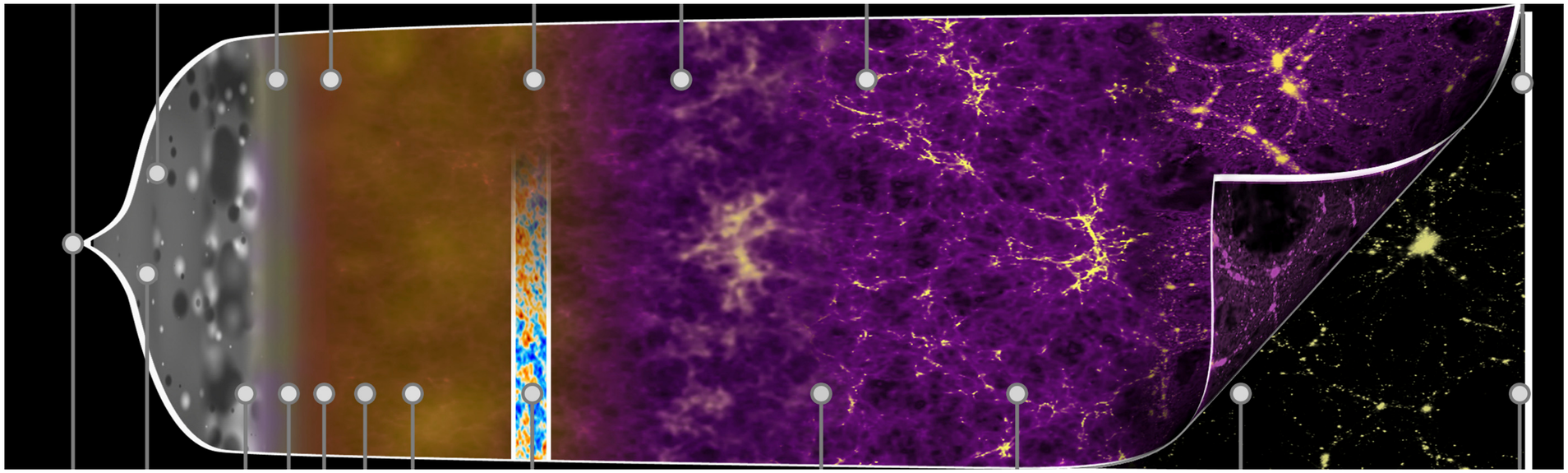
# What are Primordial Black Holes ?

# What are Primordial Black Holes ?



Star formation

# What are Primordial Black Holes ?

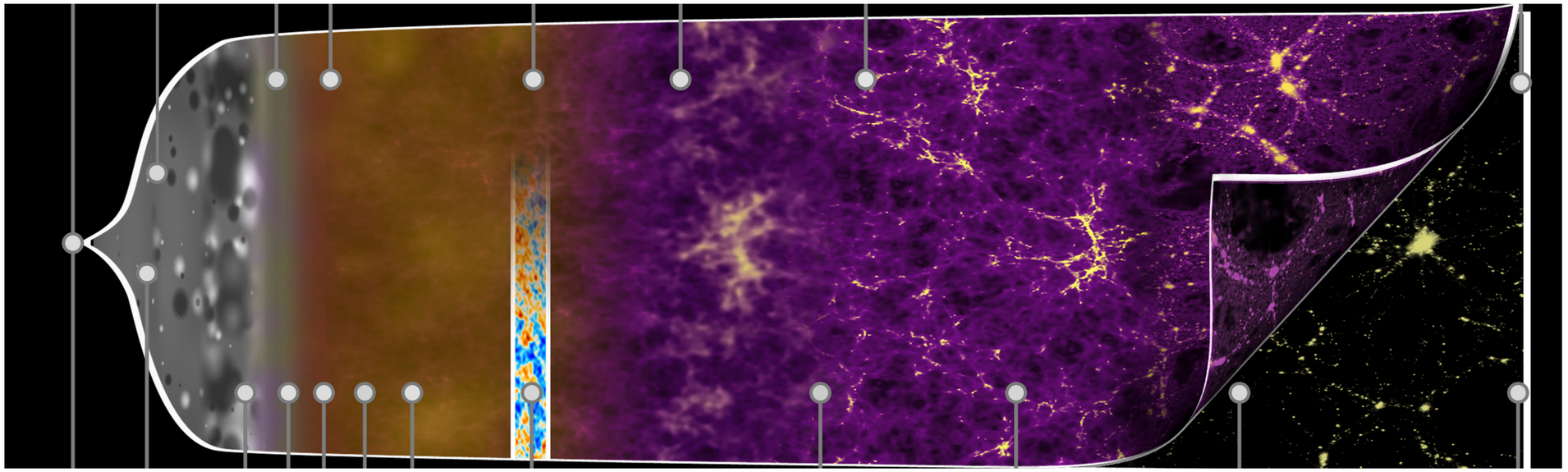


PBH formation

Star formation

**in presence of large inhomogeneities:**

# What are Primordial Black Holes ?



**PBH formation**

**Star formation**

**in presence of large inhomogeneities:**

**1)** $\delta\rho/\rho \sim 1$

**2)** horizon size

*Hawking (1971)*

1) $\delta\rho/\rho \sim 1$
2) horizon size

⇒ Where do this come from ?

**Friedmann's equation :**

$$H^2 = \frac{8\pi G}{3}\rho$$

1) $\delta\rho/\rho \sim 1$
2) horizon size

⇒ Where do this come from ?

**Friedmann's equation :**

$$H^{-3} \times H^2 = \frac{8\pi G}{3}\rho \times H^{-3}$$

1) $\delta\rho/\rho \sim 1$
2) horizon size

⇒ Where do this come from ?

**Friedmann's equation :**

$$H^{-1} = 2G \times \frac{4\pi H^{-3}}{3}\rho$$

1) $\delta\rho/\rho \sim 1$
2) horizon size

⇒ Where do this come from ?

**Friedmann's equation :**

$$H^{-1} = 2G \times \frac{4\pi H^{-3}}{3}\rho$$

$$\equiv R_{\mathrm{H}} \qquad \equiv M_{\mathrm{H}}$$

1) $\delta\rho/\rho \sim 1$
2) horizon size

⇒ Where do this come from ?

**Friedmann's equation :**

$$R_{\mathrm{H}} = 2GM_{\mathrm{H}}$$

1) $\delta\rho/\rho \sim 1$
2) horizon size

⇒ Where do this come from ?

**Friedmann's equation :**

$$R_{\mathrm{H}} = 2GM_{\mathrm{H}}$$



**Schwarschild's equation**

1) $\delta\rho/\rho \sim 1$
2) horizon size

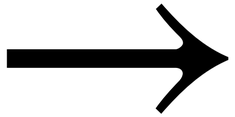
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**Schwarschild's equation**



**Hubble patches are on the edge to collapse into black holes**

1) $\delta\rho/\rho \sim 1$
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⇒ Where do this come from ?

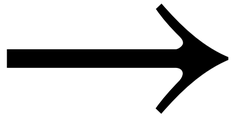
**Friedmann's equation :**

$$\frac{R_{\mathrm{H}} - 2GM_{\mathrm{H}}}{R_H} \gtrsim 0.45$$

Radiation pressure



**Schwarschild's equation**



**Hubble patches are on the edge to collapse into black holes**

1) $\delta\rho/\rho \sim 1$
2) horizon size

⇒ Where do this come from ?

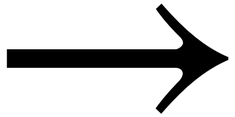
**Friedmann's equation :**

$$\frac{\langle \delta\rho \rangle_H}{\rho} \gtrsim 0.45$$

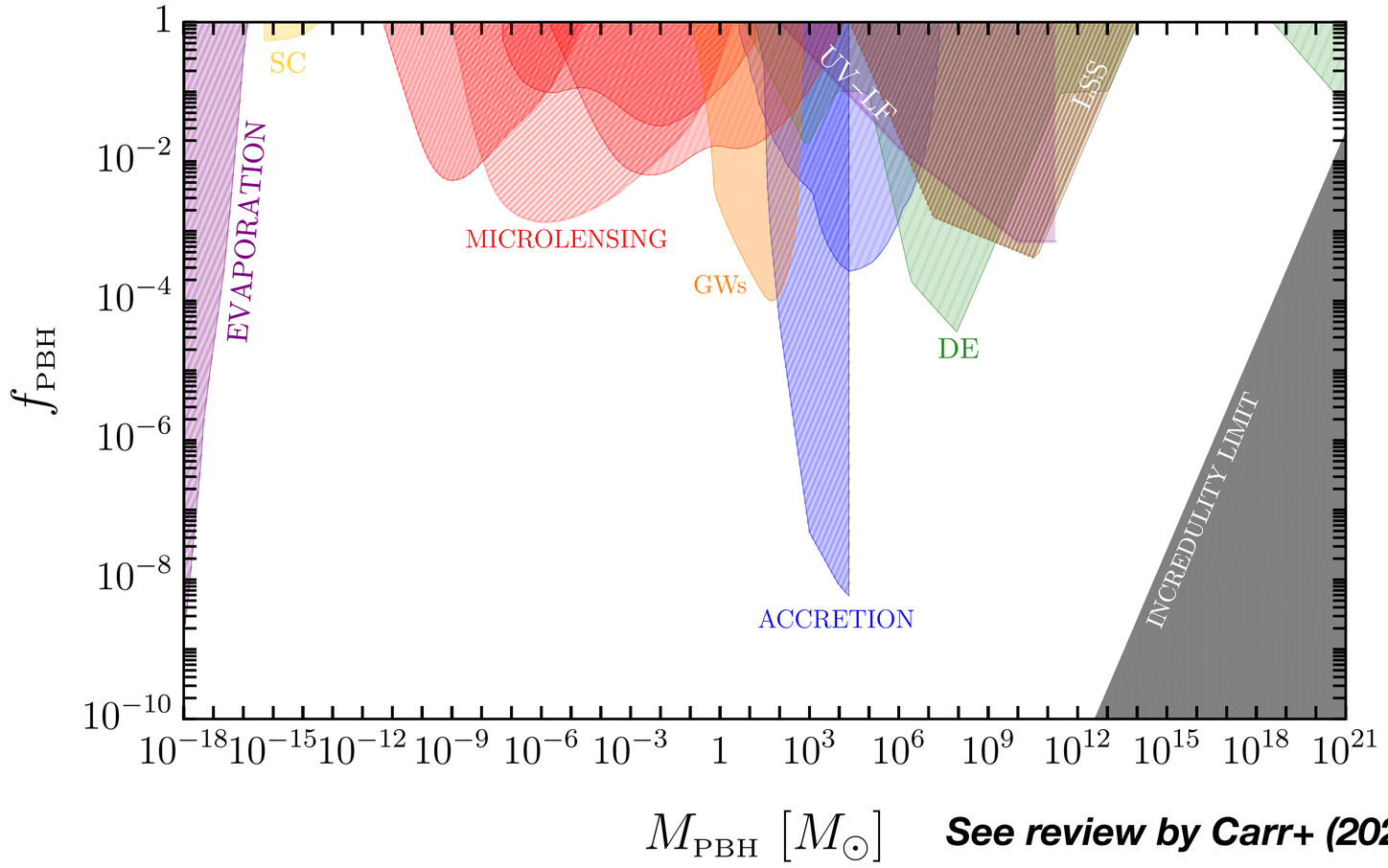
Radiation pressure



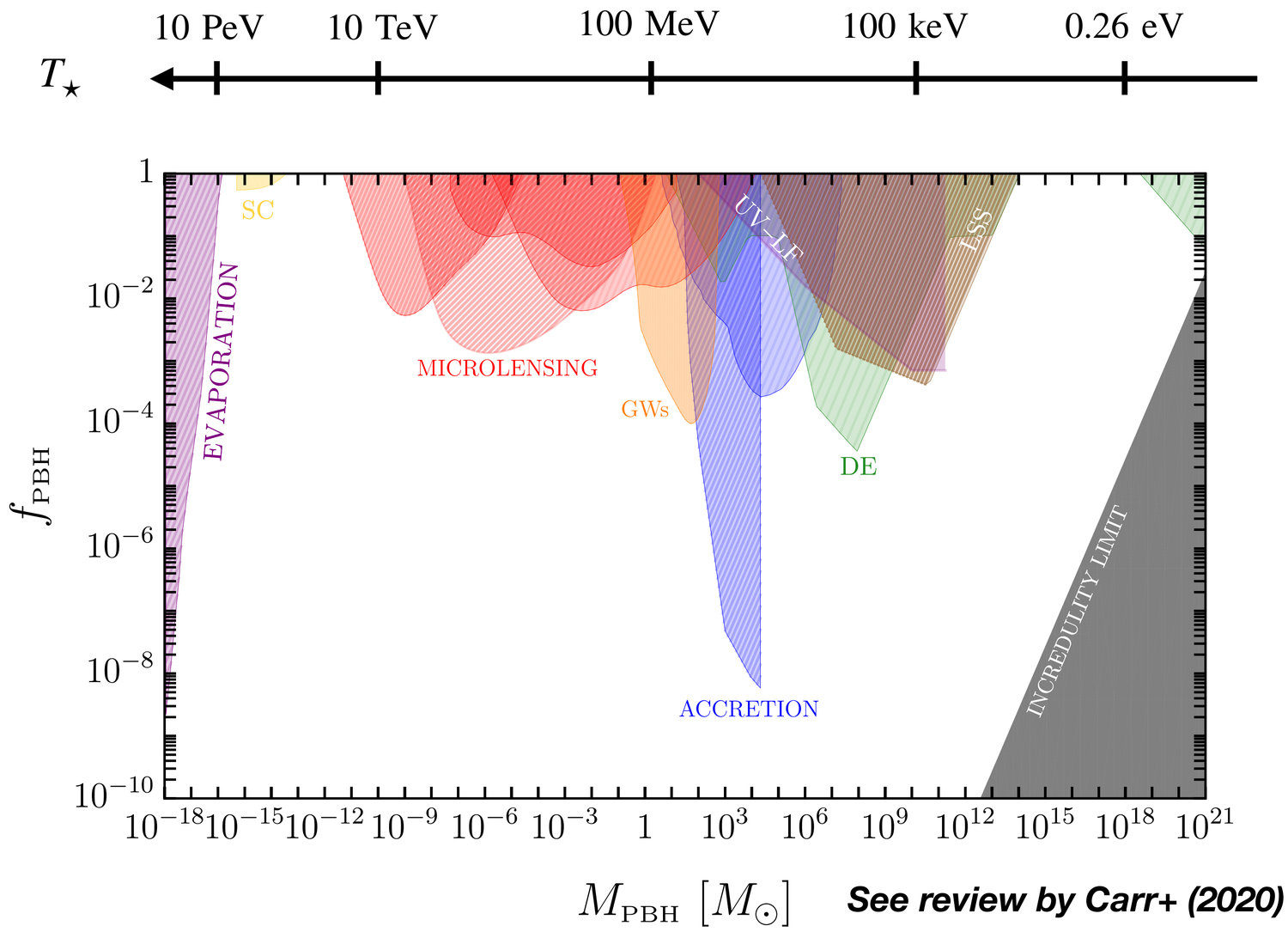
**Schwarschild's equation**



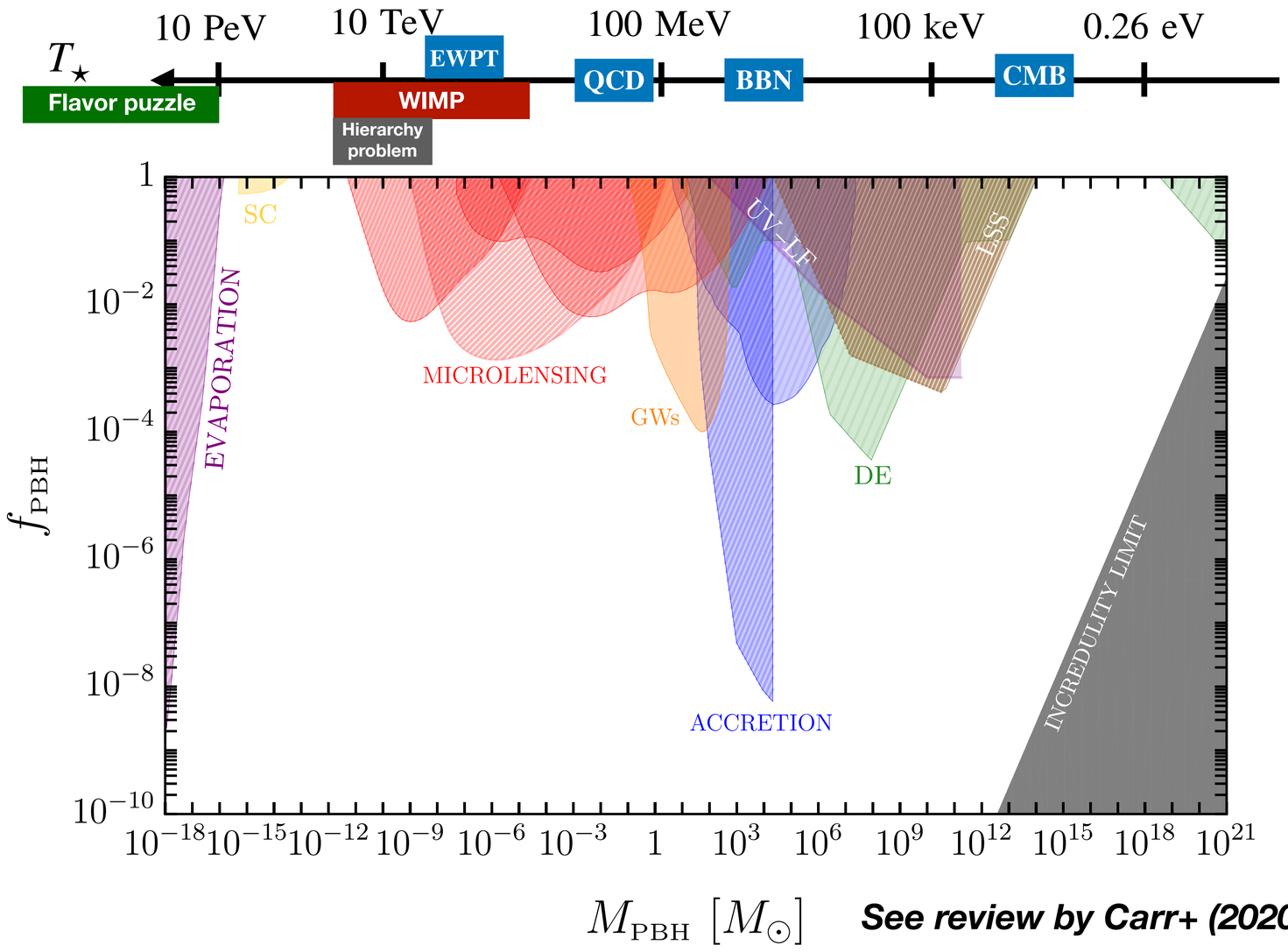
**Hubble patches are on the edge to collapse into black holes**



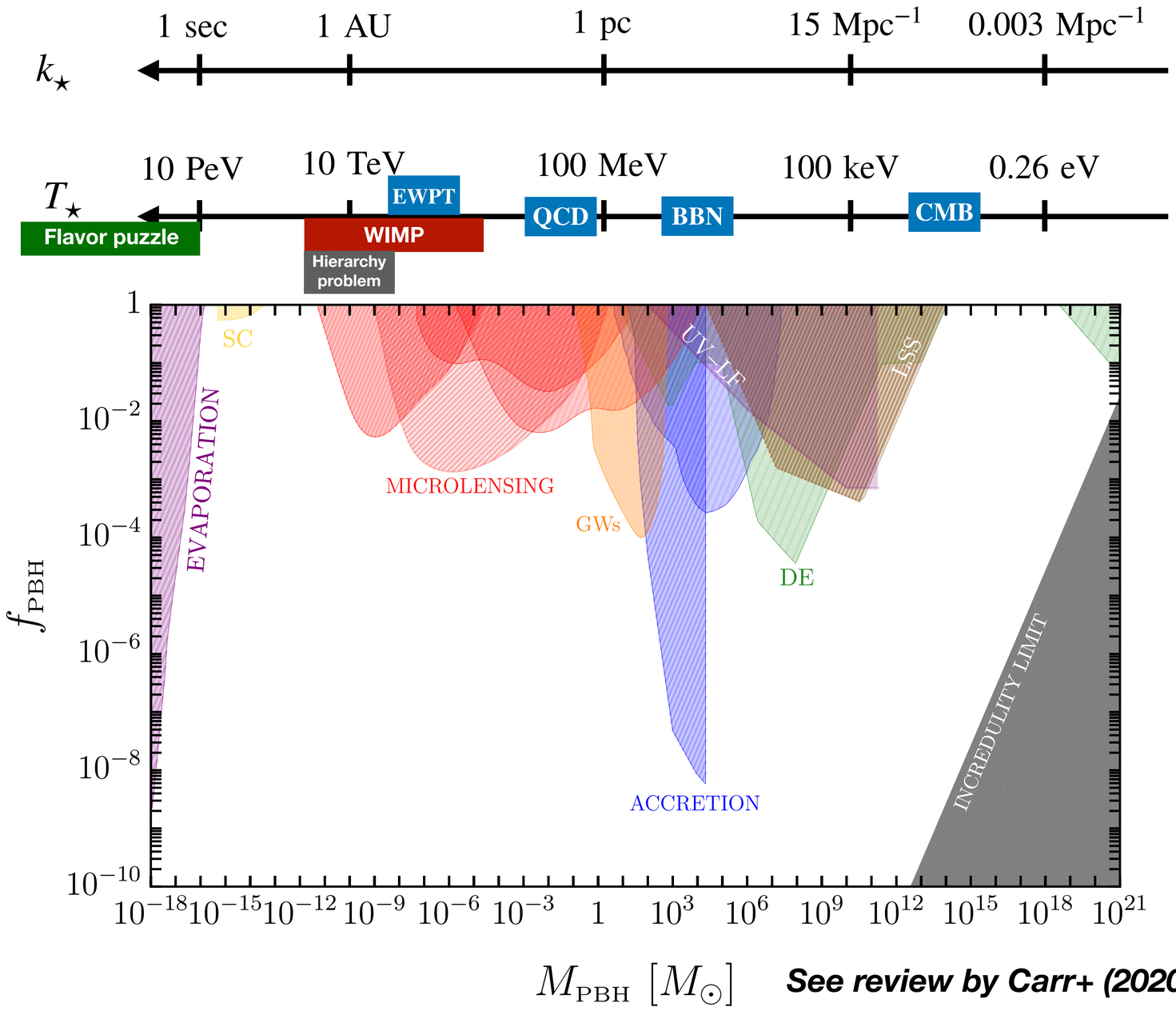

***See review by Carr+ (2020)***




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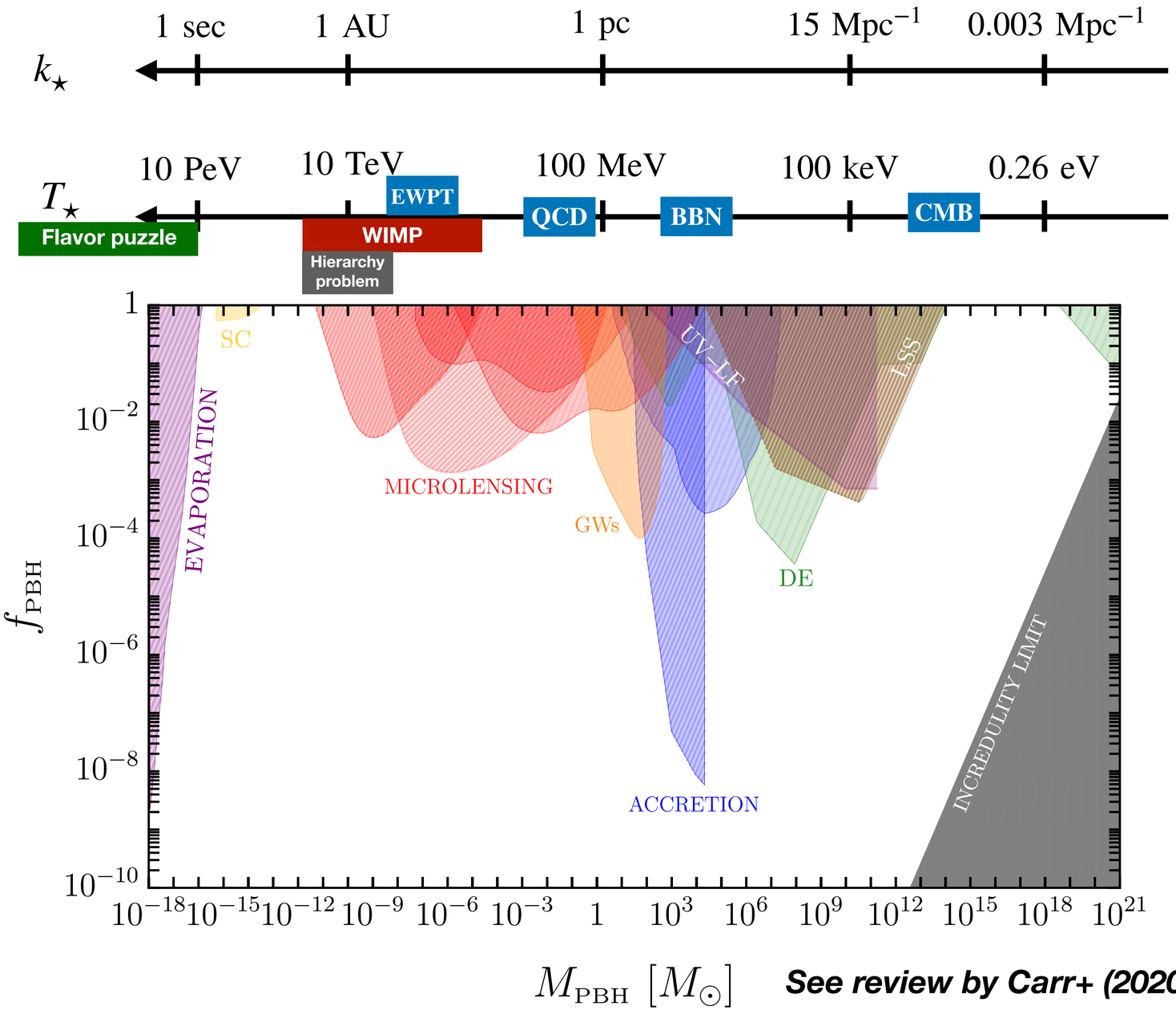

***See review by Carr+ (2020)***

# Lyman – $\alpha$

**Effective Field Theory Constraints on Primordial Black Holes from the High-Redshift Lyman-$\alpha$ Forest**


Mikhail M. Ivanov[1,*] and Sokratis Trifinopoulos[1,2,3,†]

[1] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[2] *Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland*
[3] *Physik-Institut, Universität Zürich, 8057 Zürich, Switzerland*


***See review by Carr+ (2020)***

# Lyman – $\alpha$

**Effective Field Theory Constraints on Primordial Black Holes from the High-Redshift Lyman-$\alpha$ Forest**


Mikhail M. Ivanov[1,*] and Sokratis Trifinopoulos[1,2,3,†]

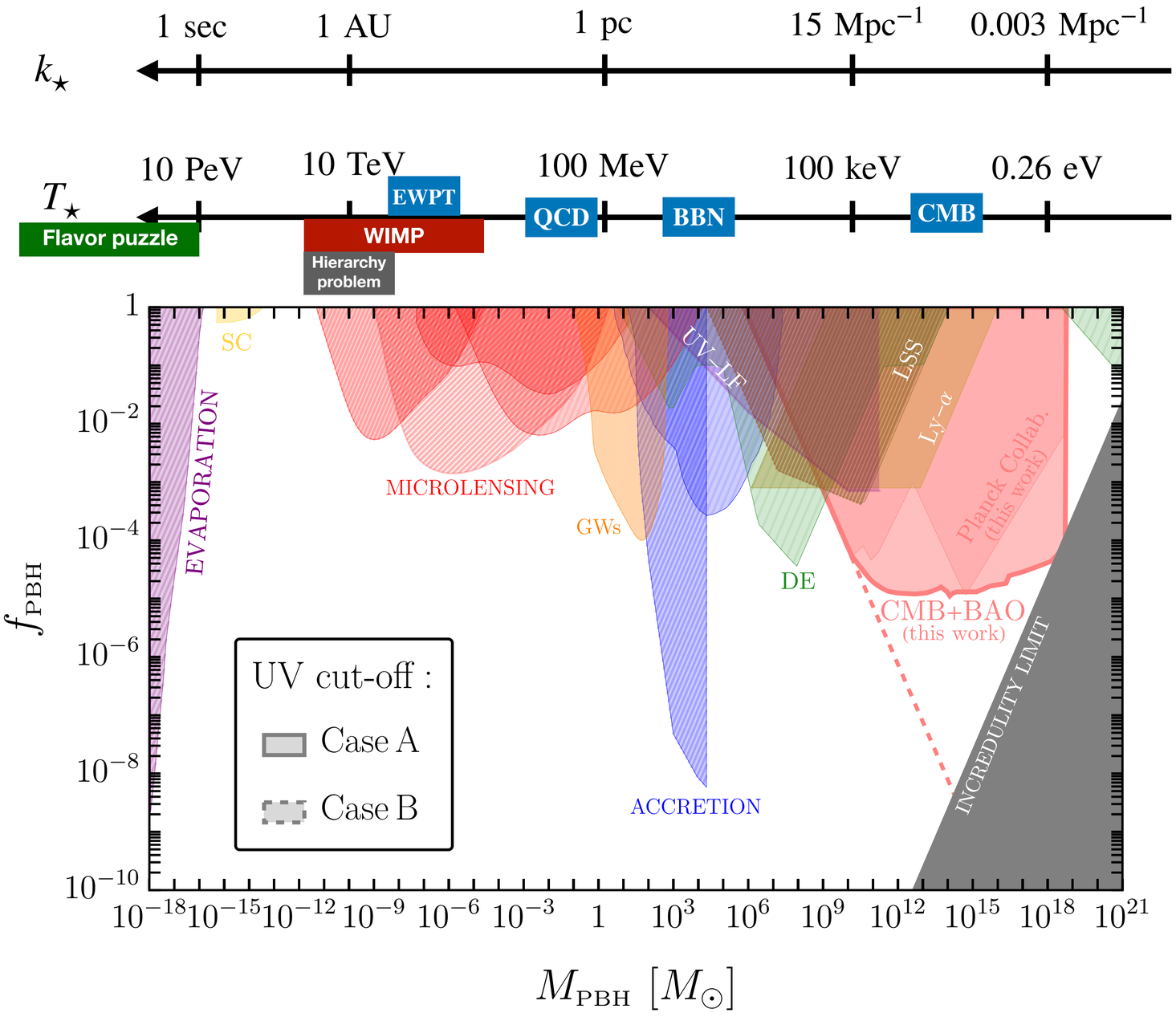
[1] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
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# CMB + BAO

**Closing the Mass Window for Stupendously Large Black Holes**


Christopher Gerlach,[1,*] Yann Gouttenoire,[1,†] Antonio J. Iovino,[2,3,‡] and Nicholas Leister[1,§]

[1] *PRISMA$^+$ Cluster of Excellence & Mainz Institute for Theoretical Physics, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany*
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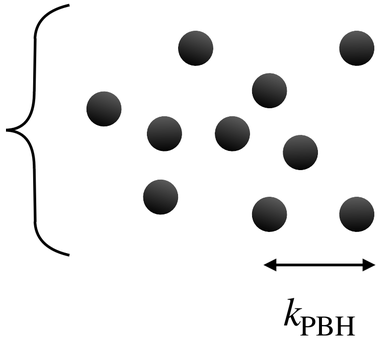

## CMB + BAO

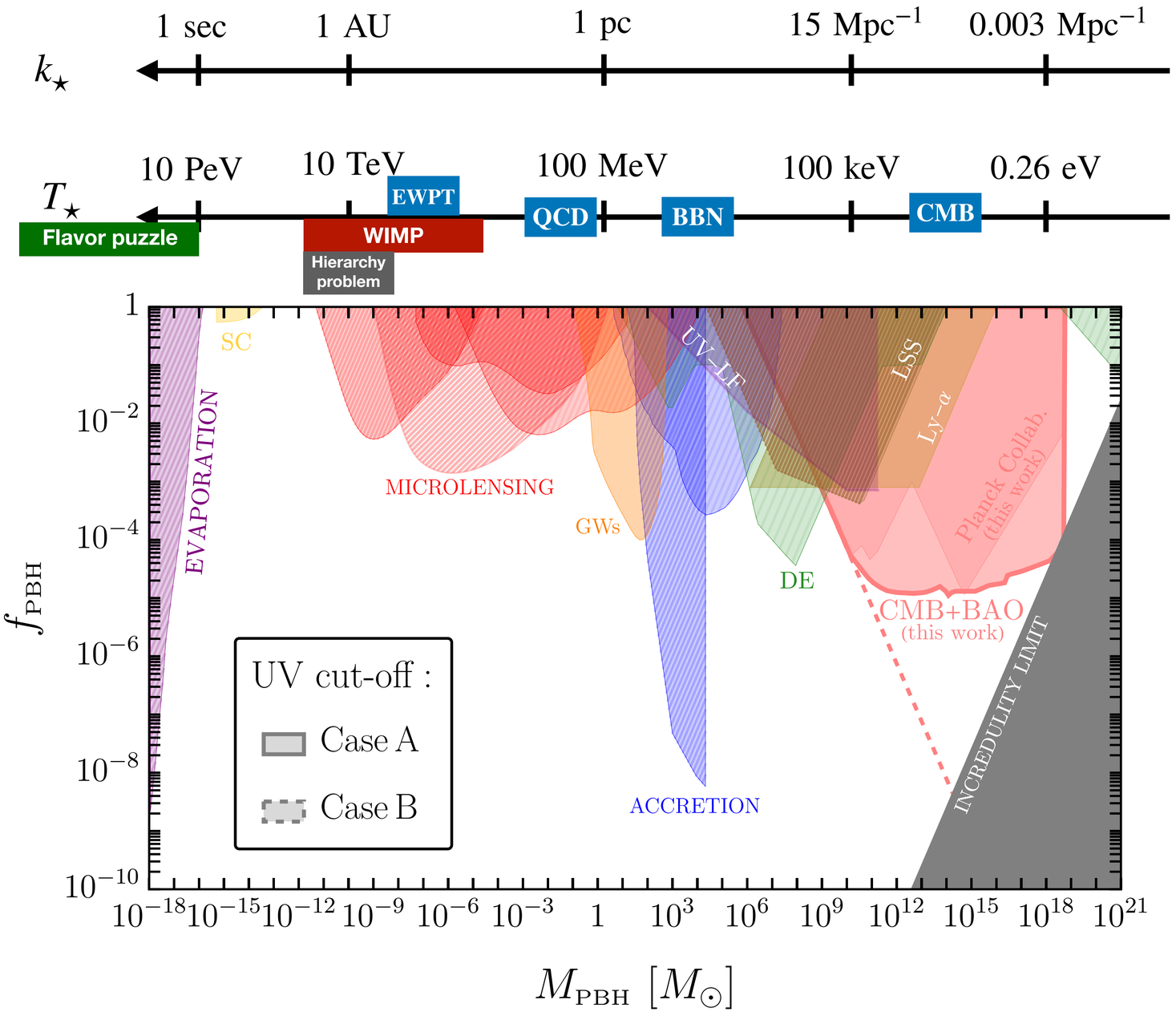
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**Gas of PBHs**



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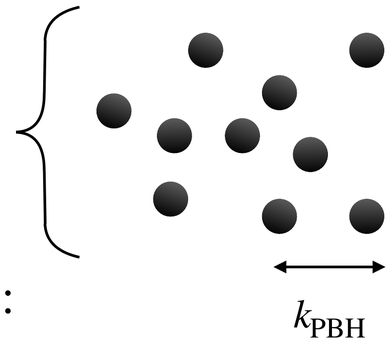

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**Gas of PBHs**

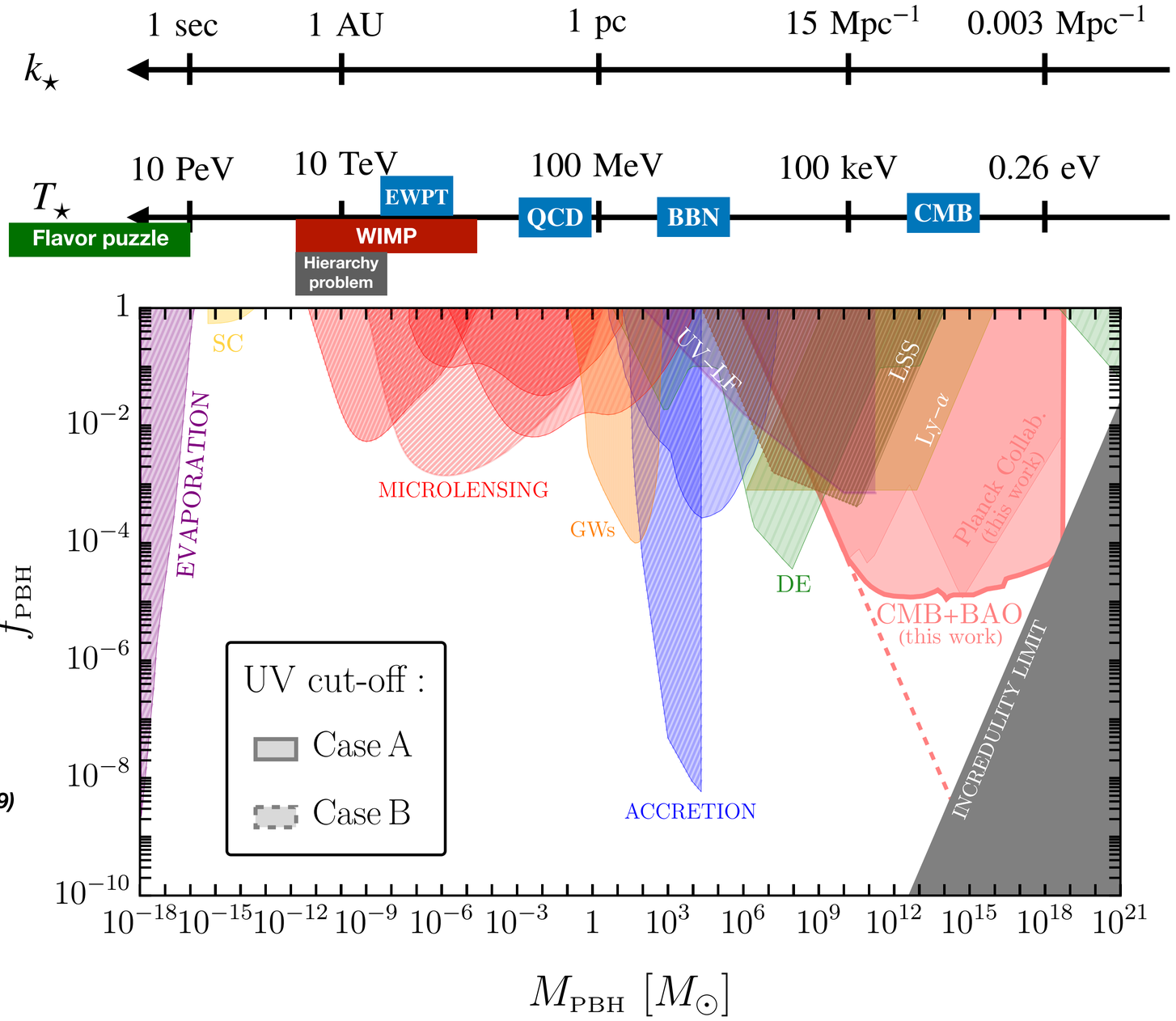



**Poisson noise :**

$$\mathscr{P}_\delta = f_{\rm PBH}^2 \left(\frac{k}{k_{\rm PBH}}\right)^3 \Theta(k_{\rm cut} - k)$$

*Inman, Ali-Haïmoud (1907.08129)*

**⇒ source isocurvatures**



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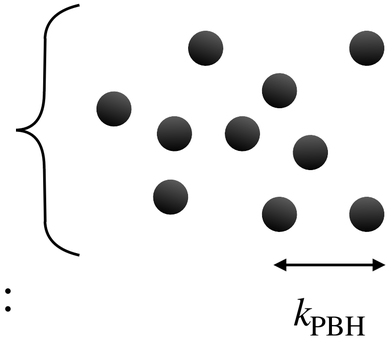

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**Gas of PBHs**



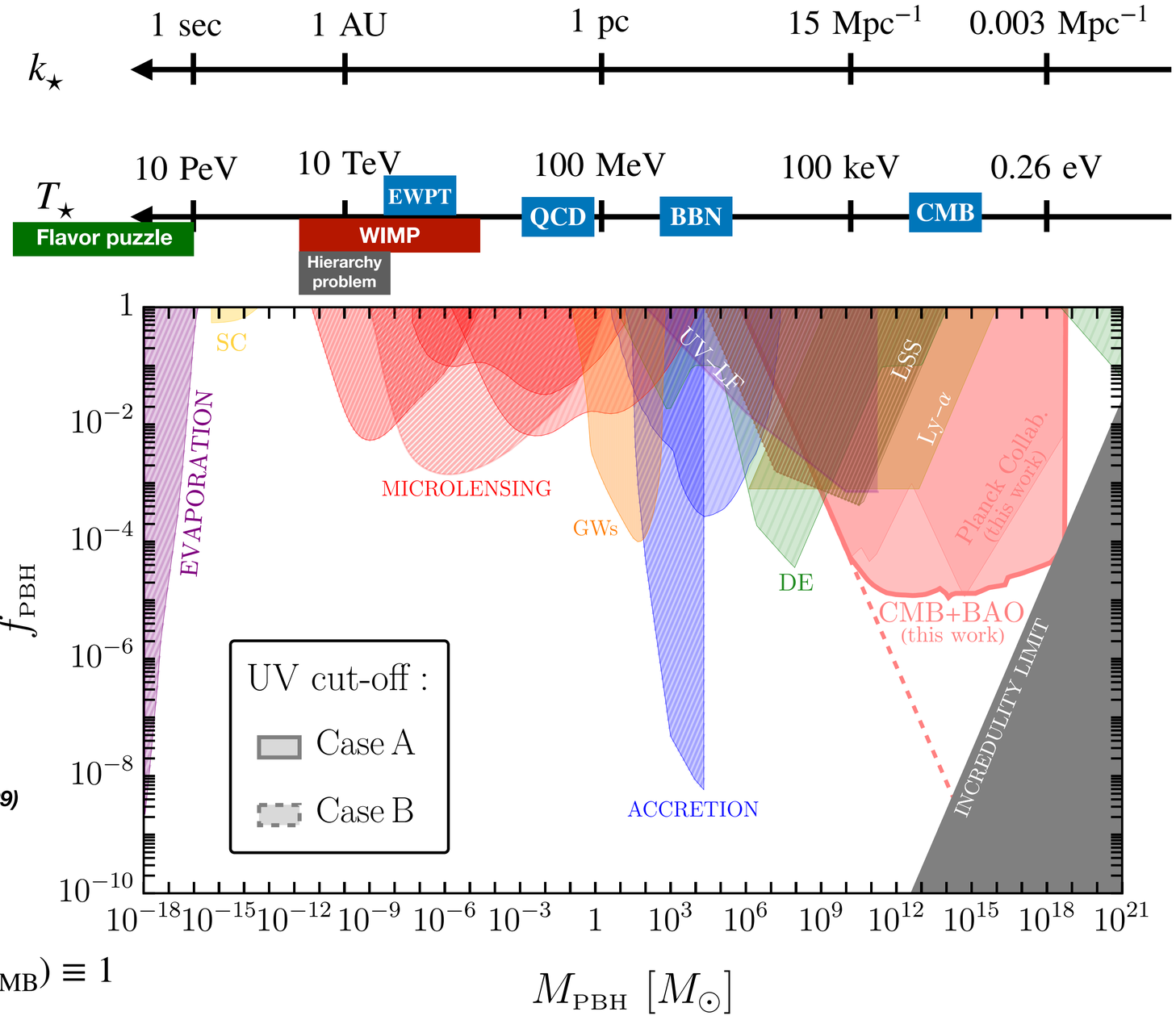

**Poisson noise :**

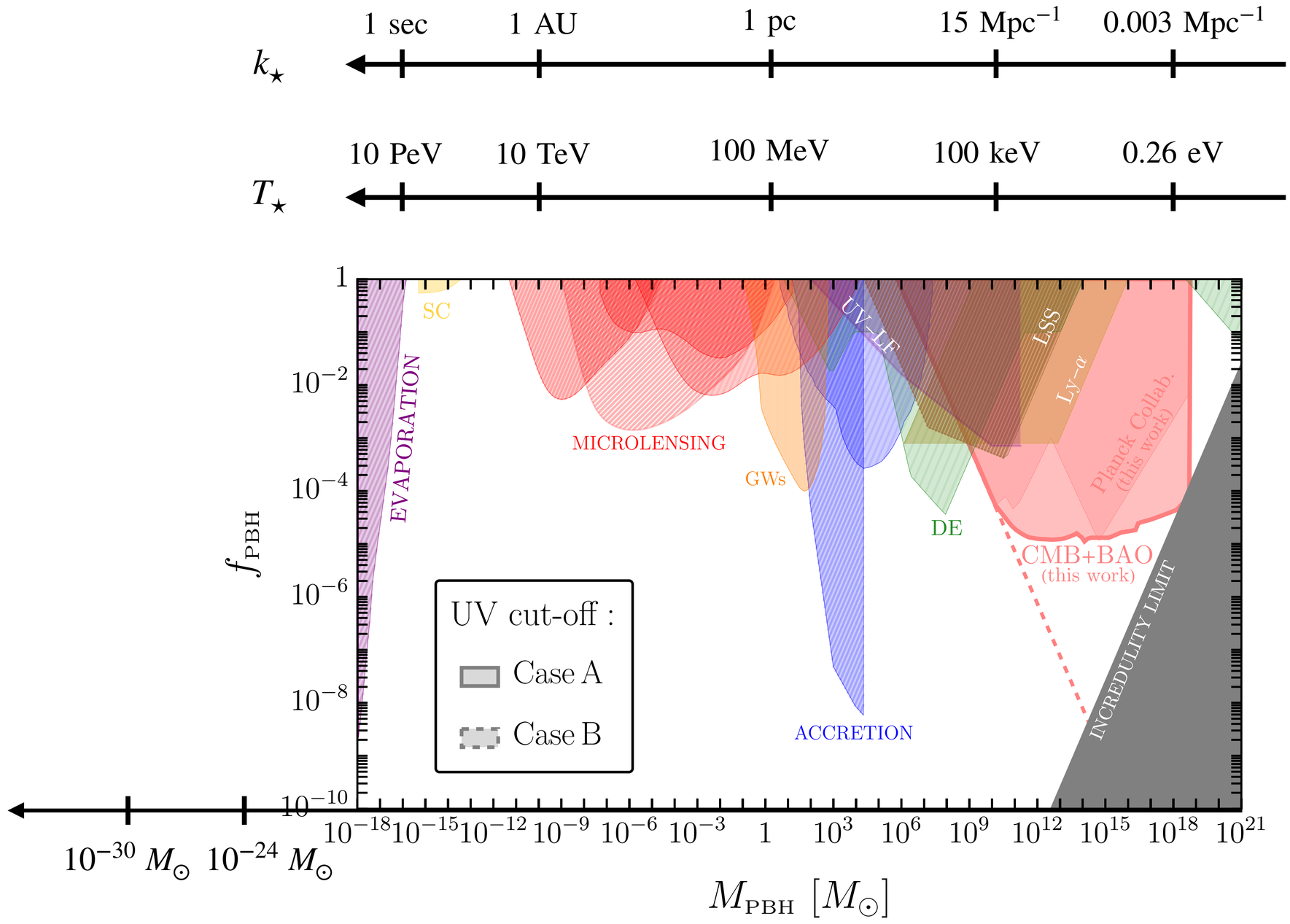
$$\mathscr{P}_\delta = f_{\rm PBH}^2 \left(\frac{k}{k_{\rm PBH}}\right)^3 \Theta(k_{\rm cut} - k)$$

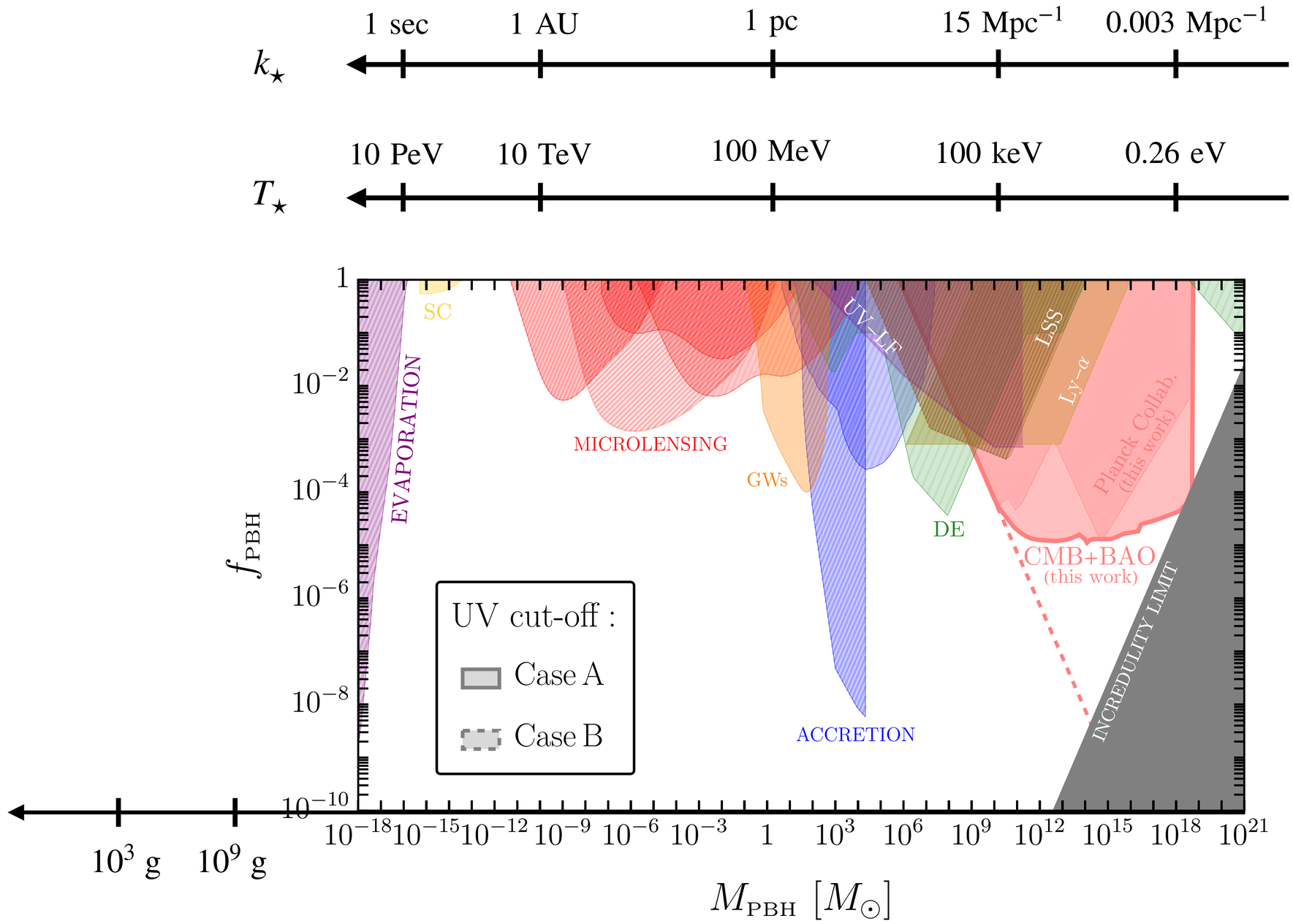
*Inman, Ali-Haïmoud (1907.08129)*

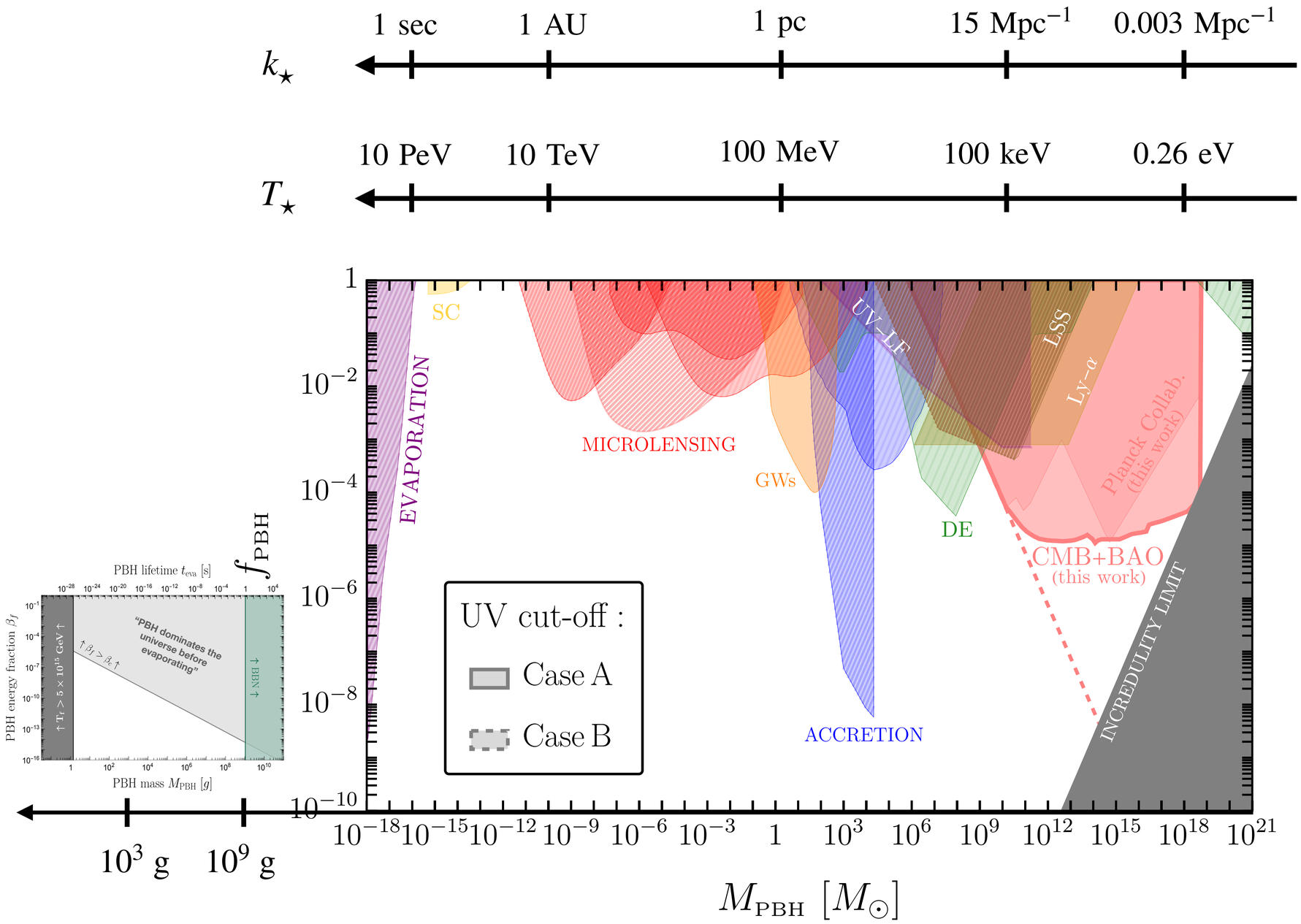
**⇒ source isocurvatures**

$$k_{\rm cut} = \begin{cases} k_{\rm PBH}, & \text{(solid line)} \\ k_{\rm NL}, & \text{(dashed line)} \end{cases} \quad \text{with} \quad \delta_{\rm DM}(k_{\rm NL}, t_{\rm CMB}) \equiv 1$$



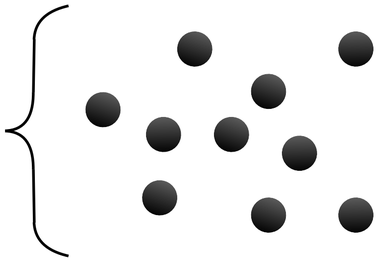

1 sec
1 AU
1 pc
15 Mpc$^{-1}$
0.003 Mpc$^{-1}$
$k_\star$
10 PeV
10 TeV
100 MeV
100 keV
0.26 eV
$T_\star$
1
$10^{-2}$
$10^{-4}$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$f_{\rm PBH}$
SC
EVAPORATION
MICROLENSING
GWs
UV_LF
ACCRETION
DE
LSS
Ly-$\alpha$
Planck Collab.
(this work)
CMB+BAO
(this work)
INCREDULITY LIMIT
UV cut-off :
Case A
Case B
$10^{-18}$ $10^{-15}$ $10^{-12}$ $10^{-9}$ $10^{-6}$ $10^{-3}$ 1 $10^{3}$ $10^{6}$ $10^{9}$ $10^{12}$ $10^{15}$ $10^{18}$ $10^{21}$
$10^{-30}\,M_\odot$ $10^{-24}\,M_\odot$
$M_{\rm PBH}\ [M_\odot]$

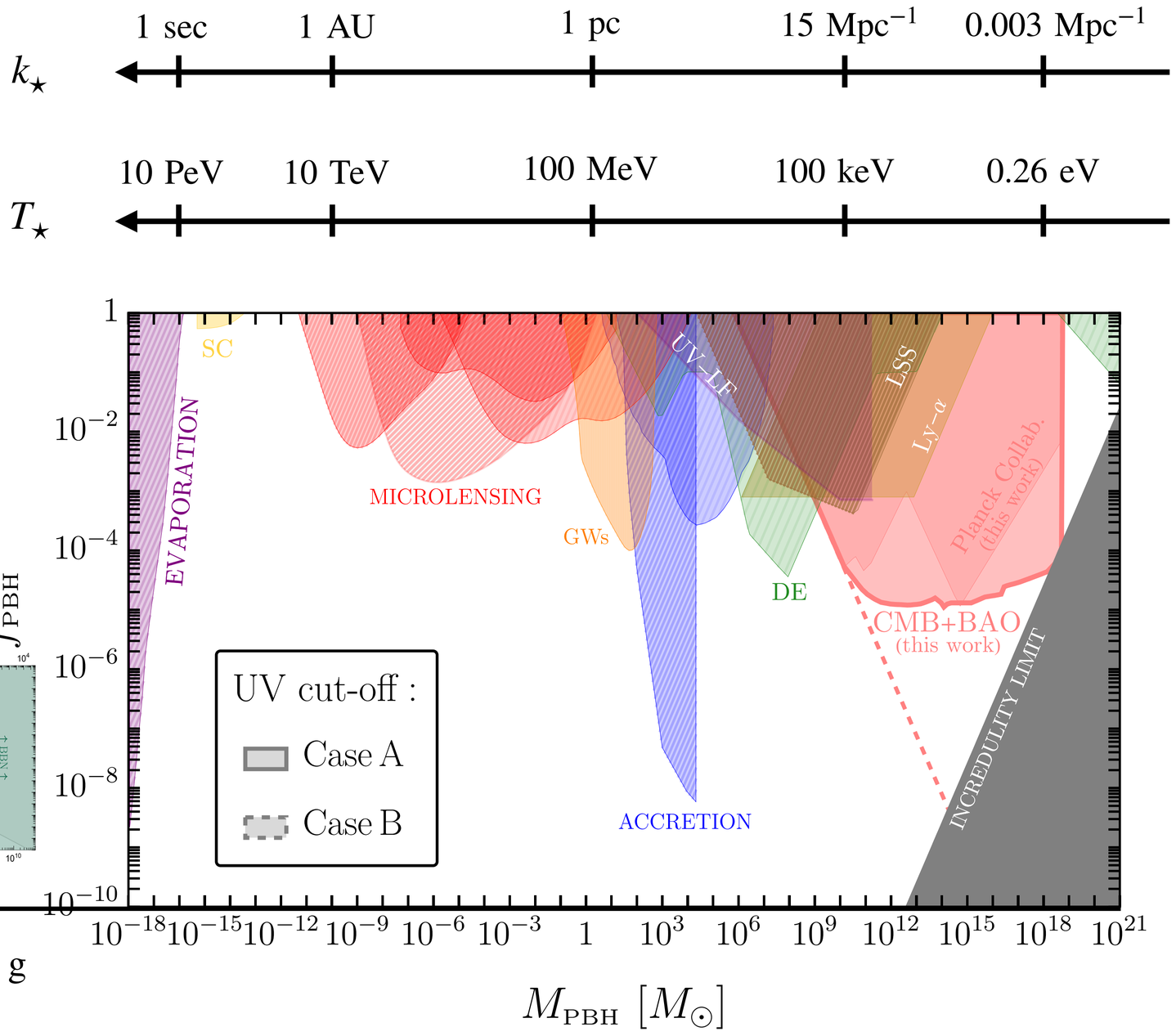

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(this work)
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INCREDULITY LIMIT
ACCRETION
UV cut-off :
Case A
Case B
$M_{\rm PBH}\ [M_\odot]$
$10^3$ g
$10^9$ g
PBH lifetime $t_{\rm eva}$ [s]
PBH energy fraction $\beta_f$
PBH mass $M_{\rm PBH}$ [$g$]
"PBH dominates the universe before evaporating"
BBN

# Ultra-light PBHs

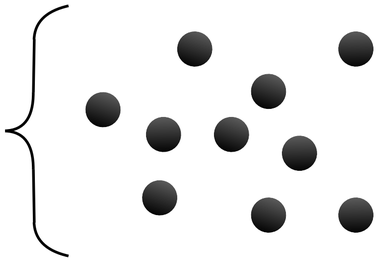
**Gas of evaporating PBHs**

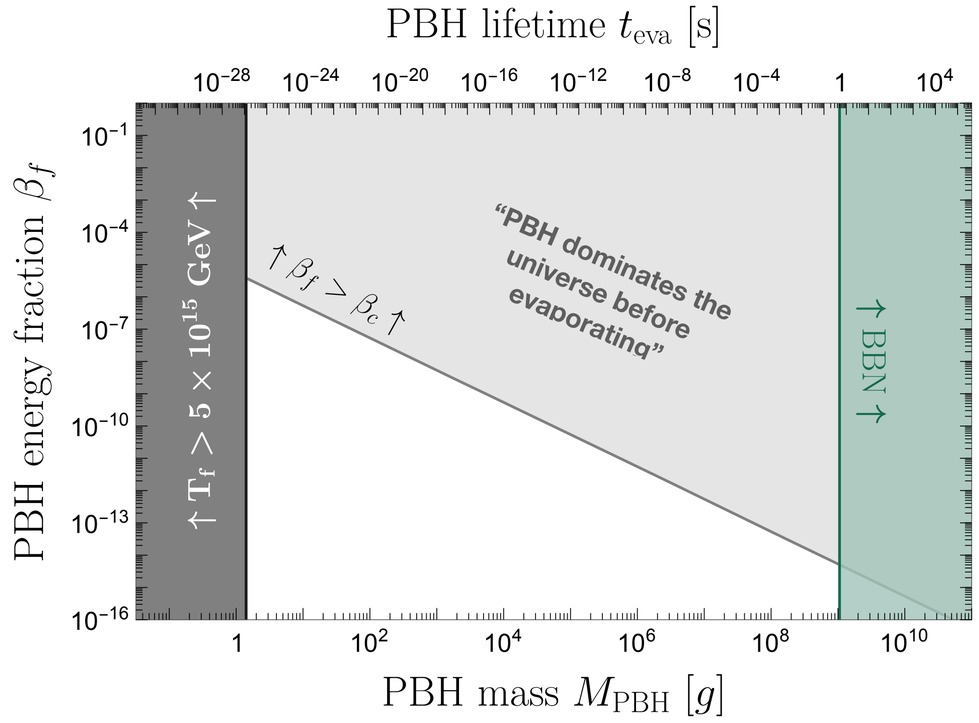


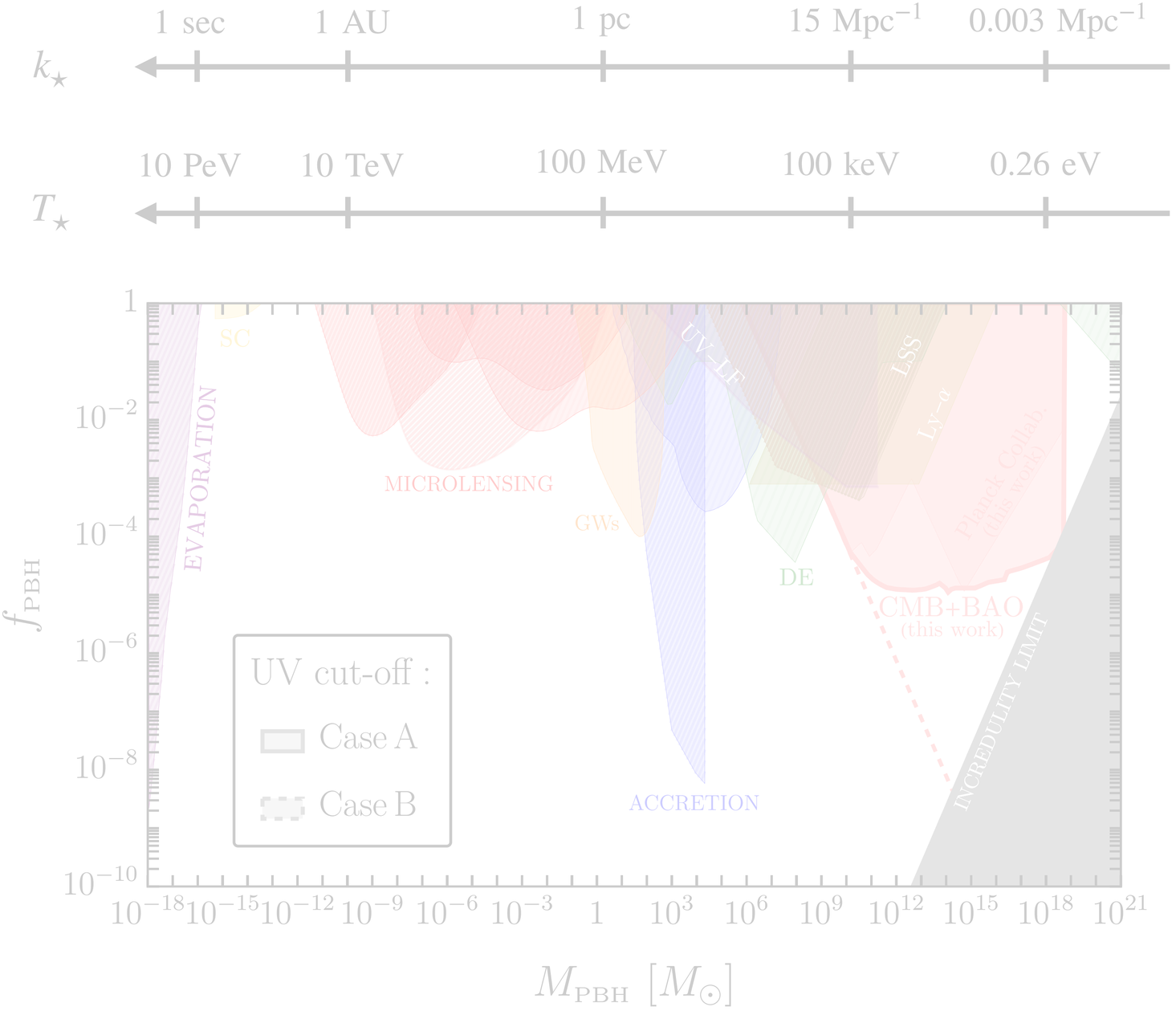


# Ultra-light PBHs

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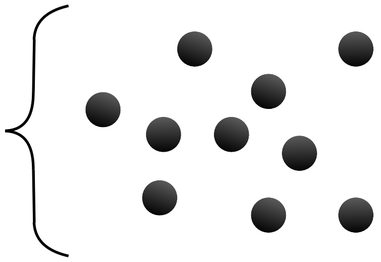


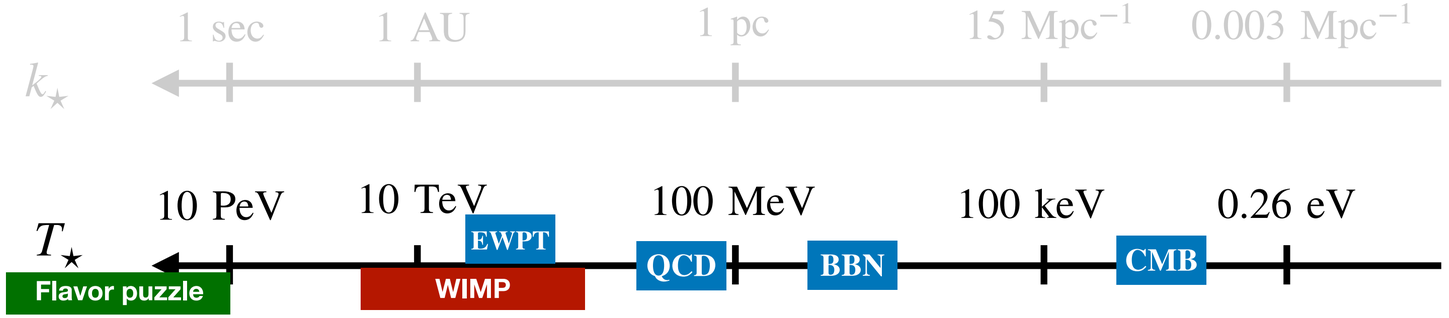


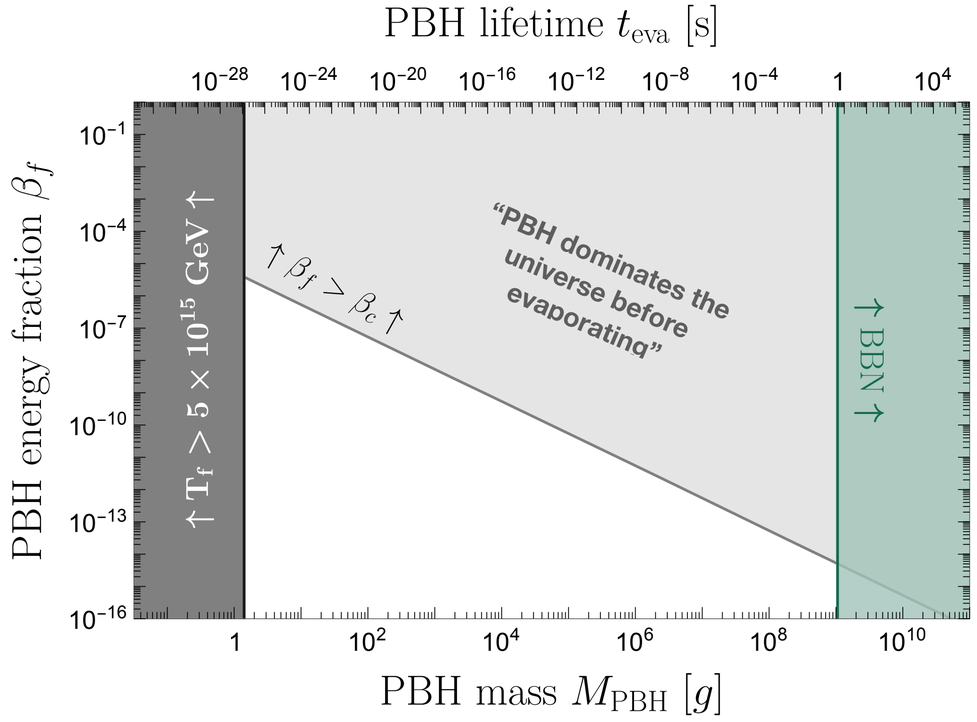



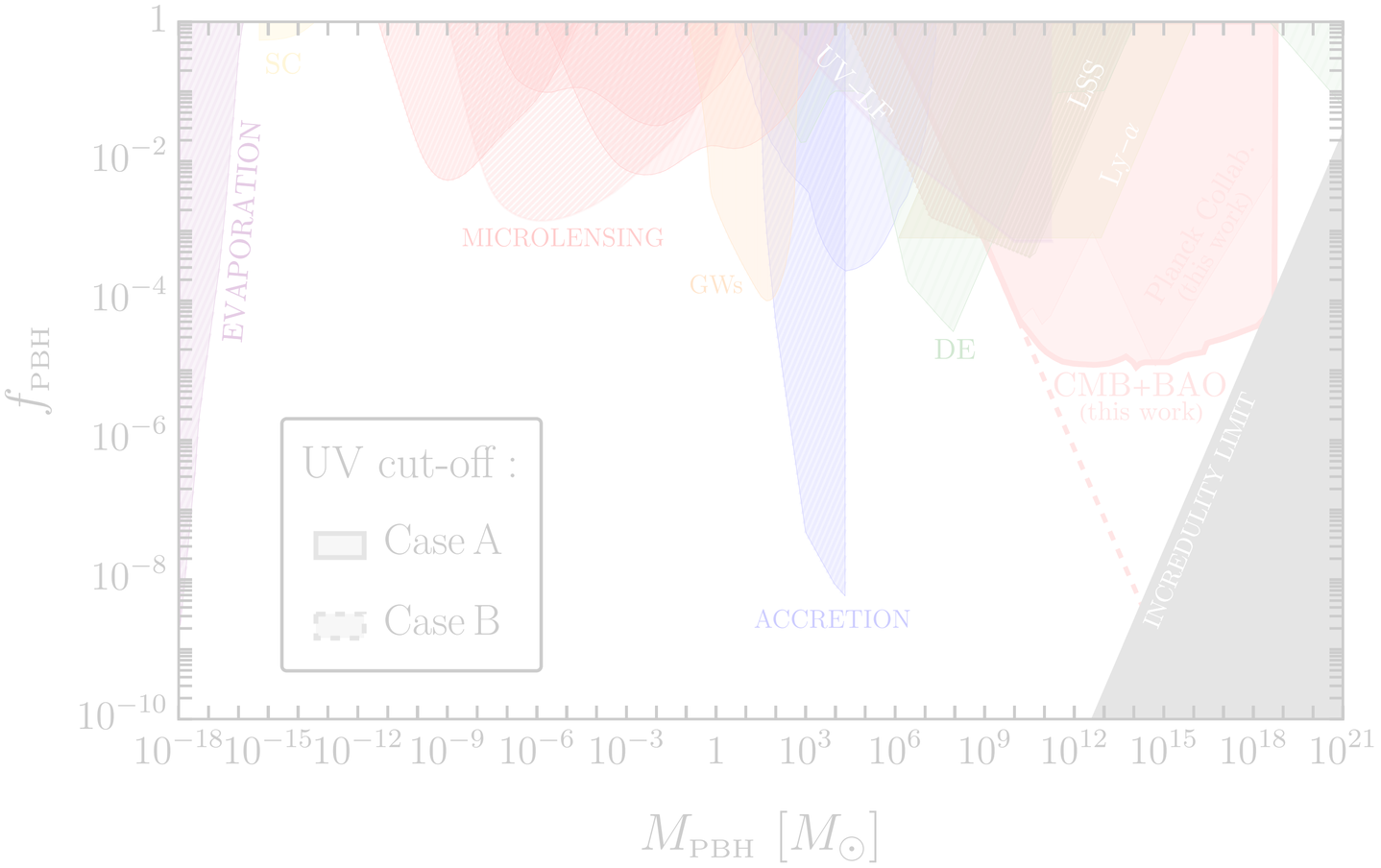
# Ultra-light PBHs

**Gas of evaporating PBHs**



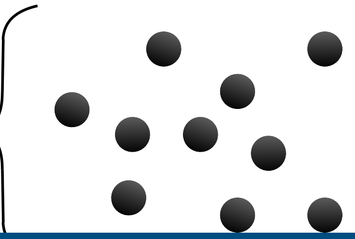


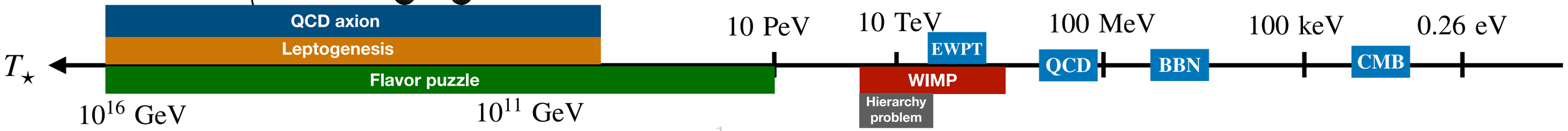



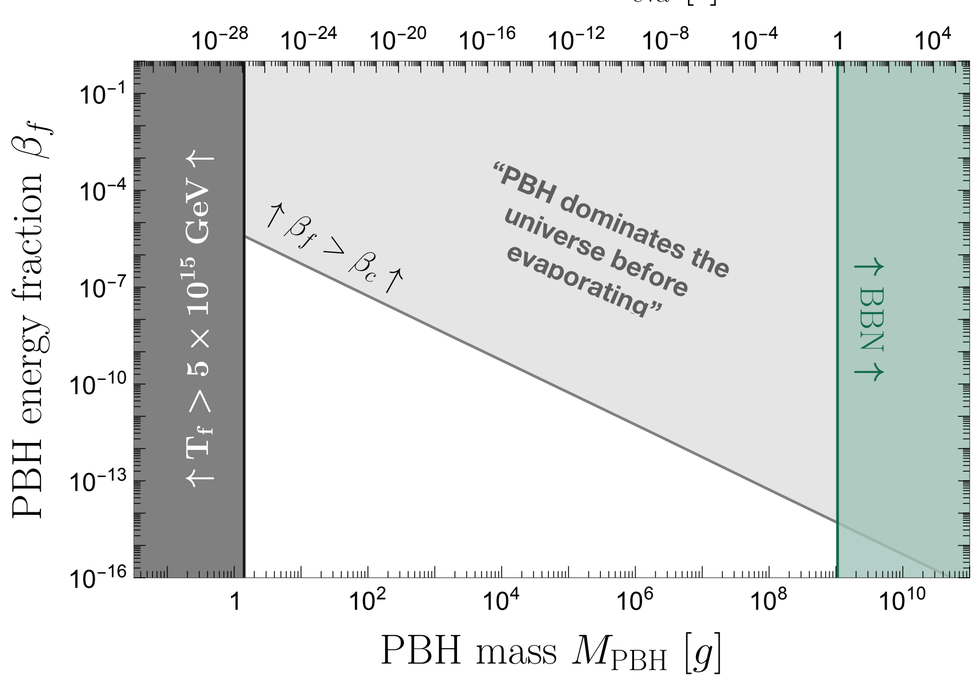



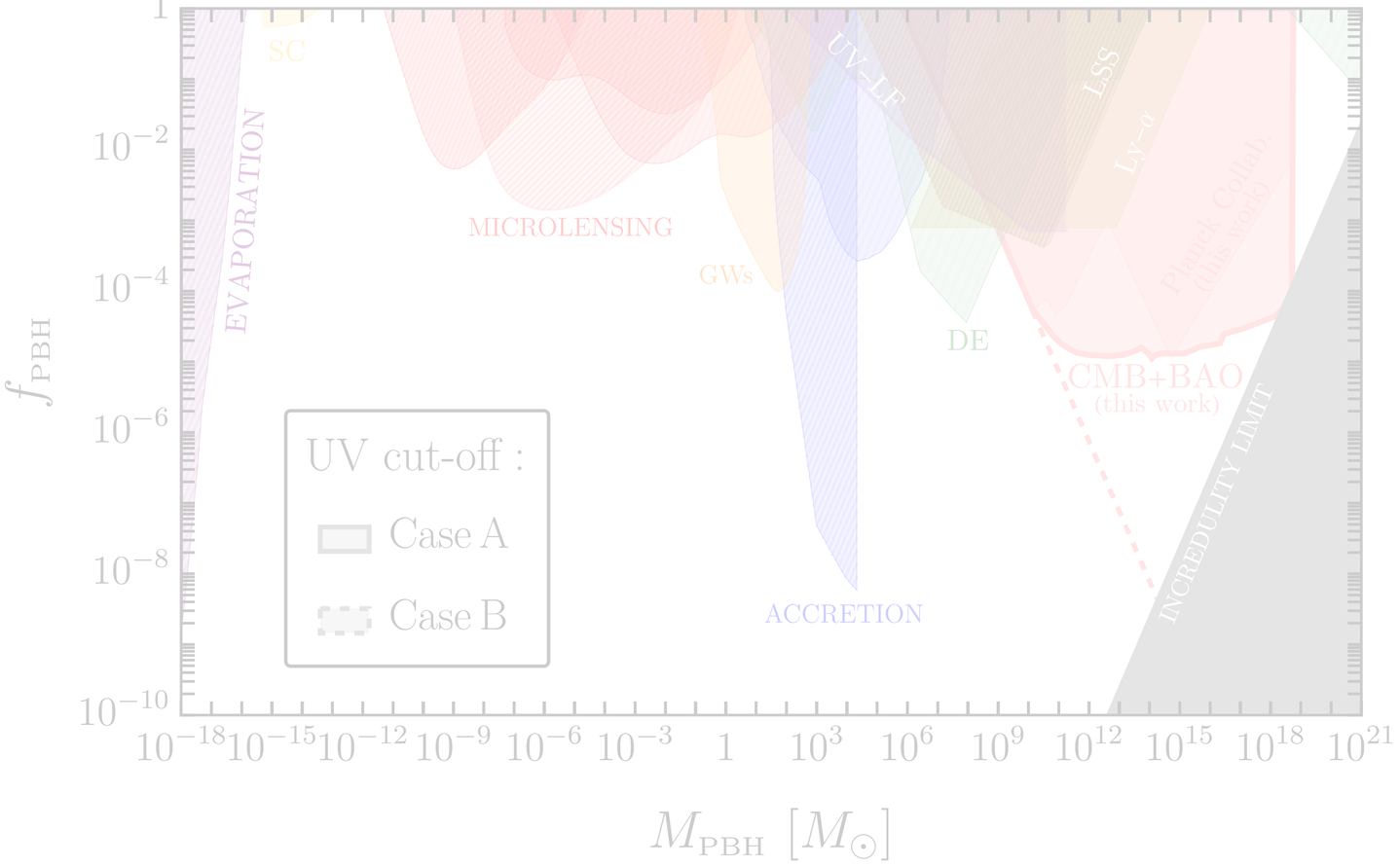
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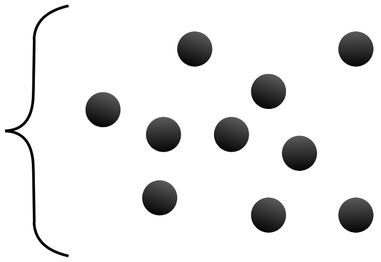


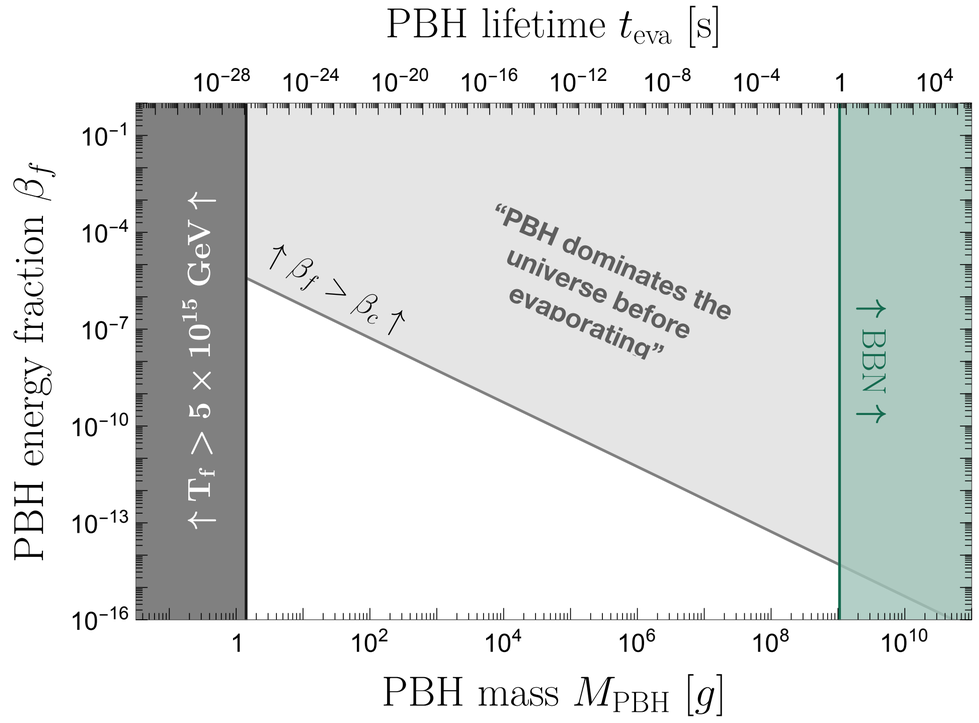



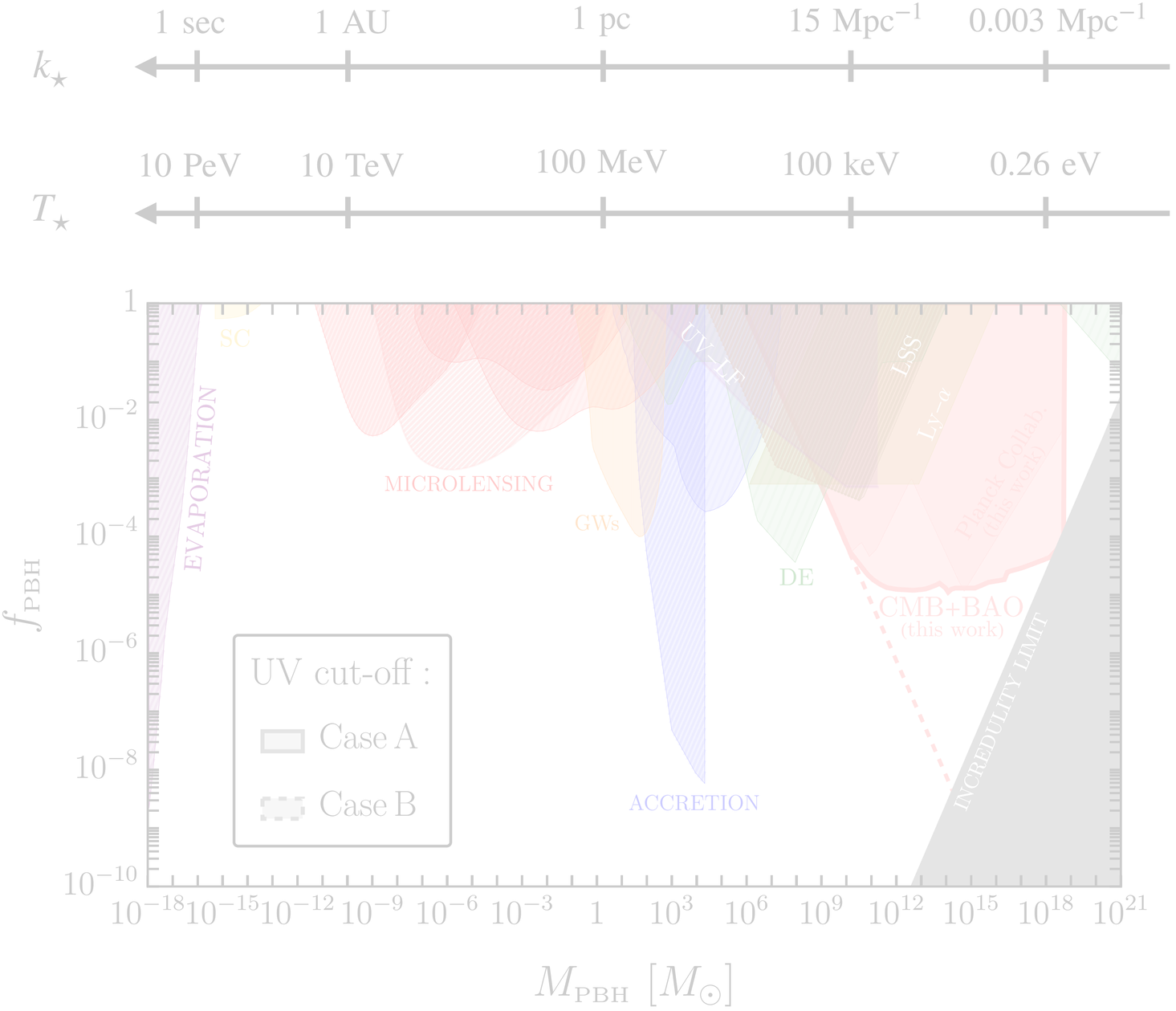



# Ultra-light PBHs

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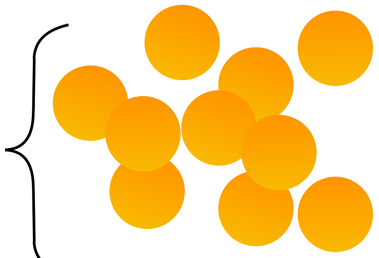


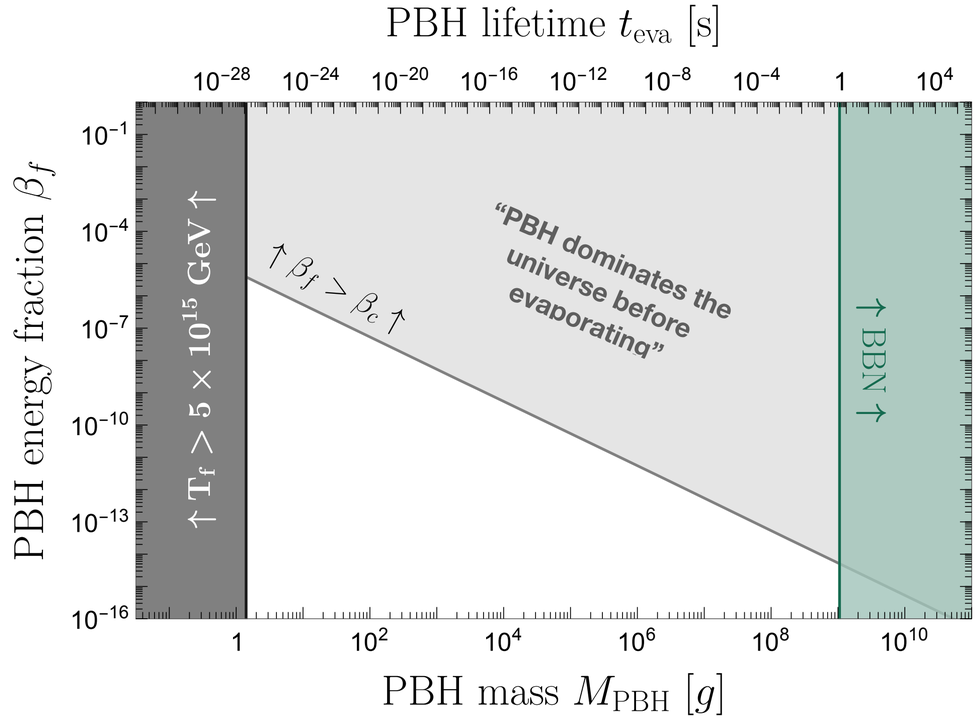


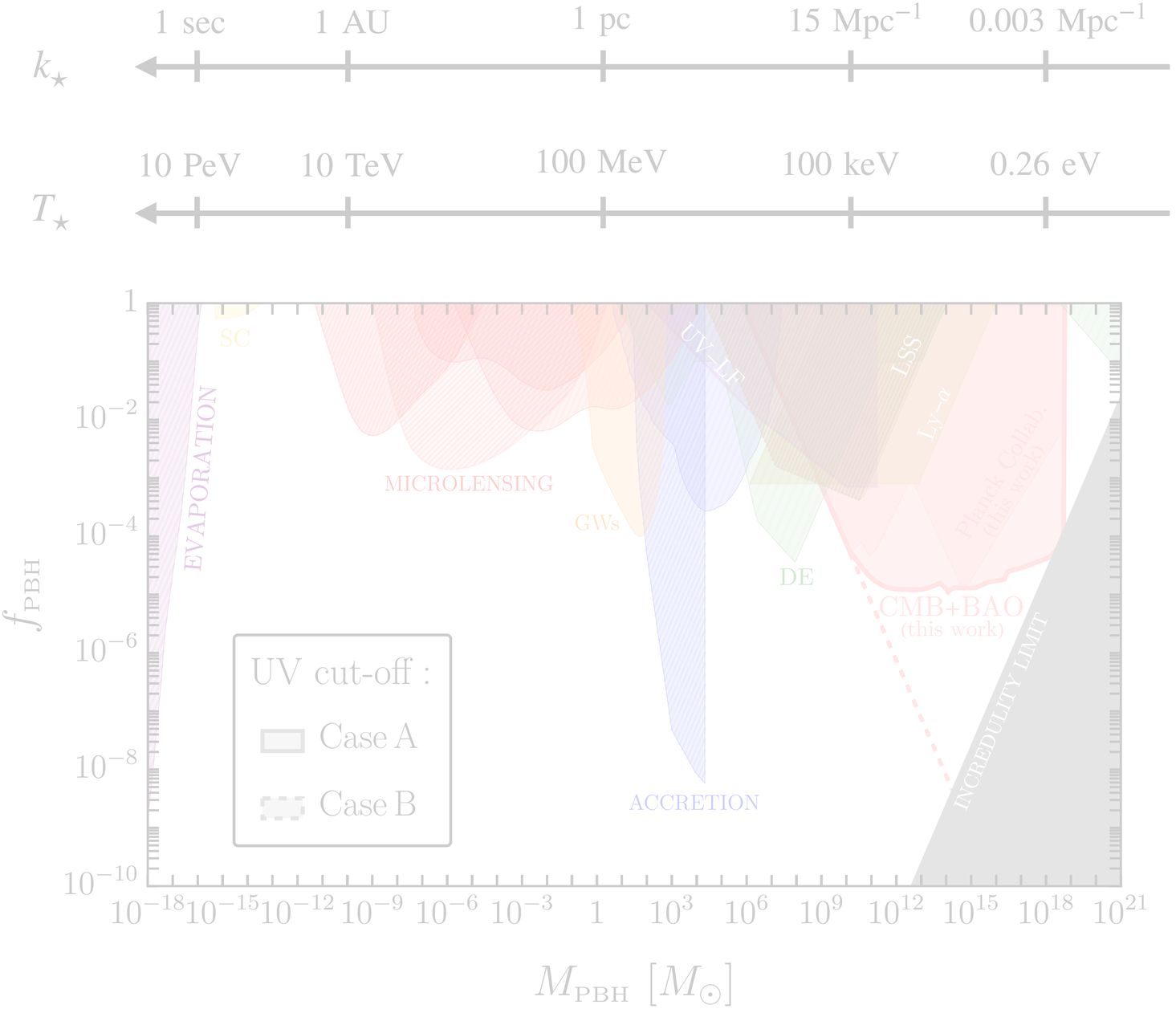



**Evaporation**

**Gas of evaporating PBHs**

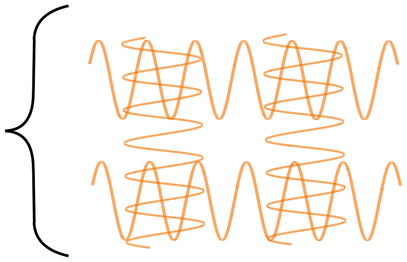


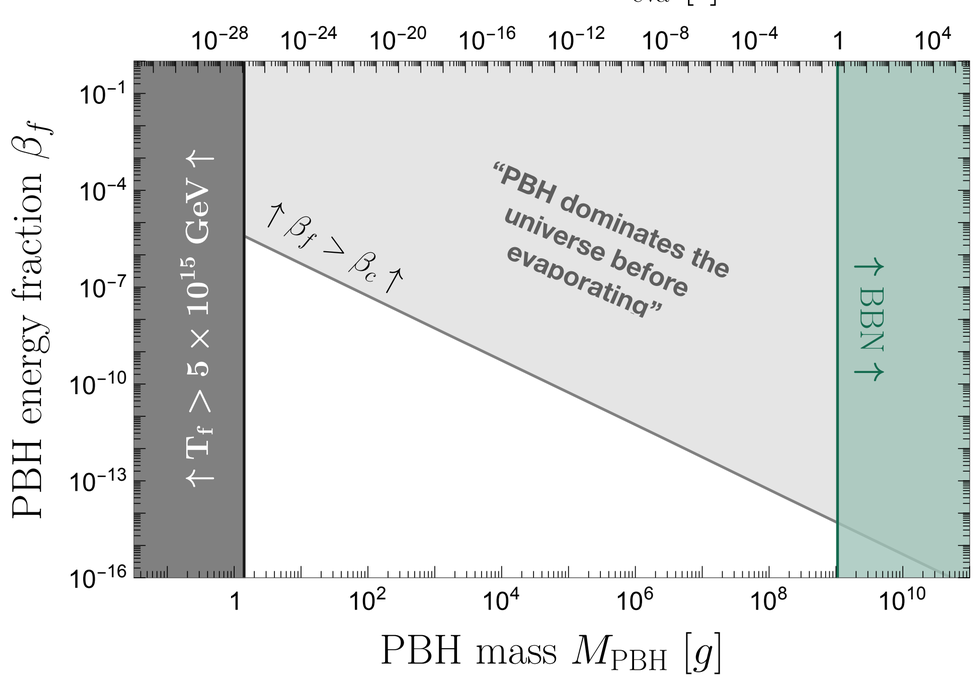


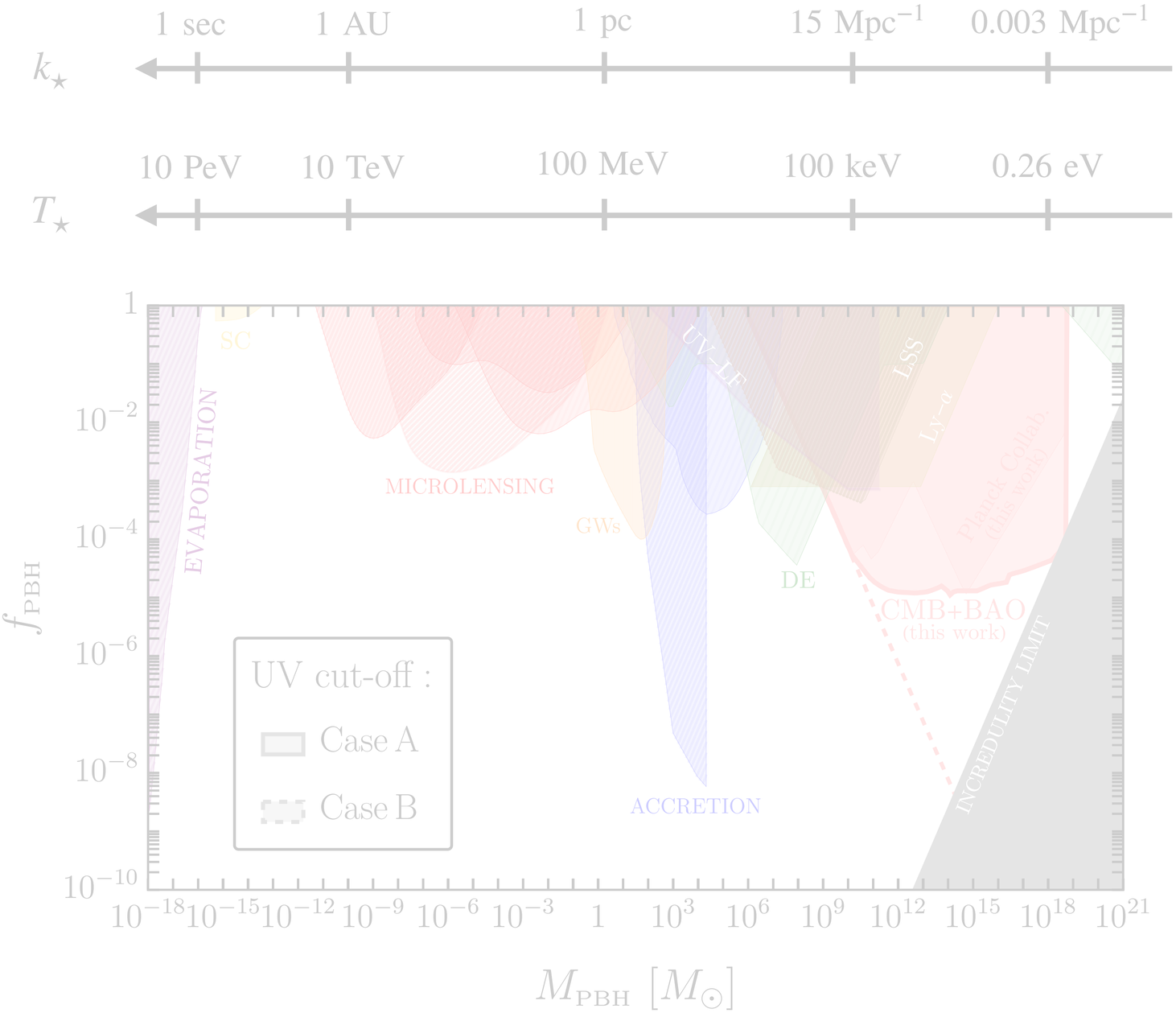



# Evaporation ⇒ Sound waves

**Gas of evaporating PBHs**

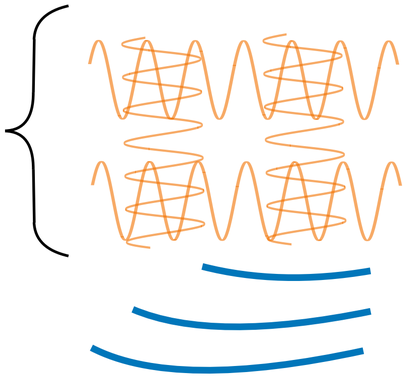




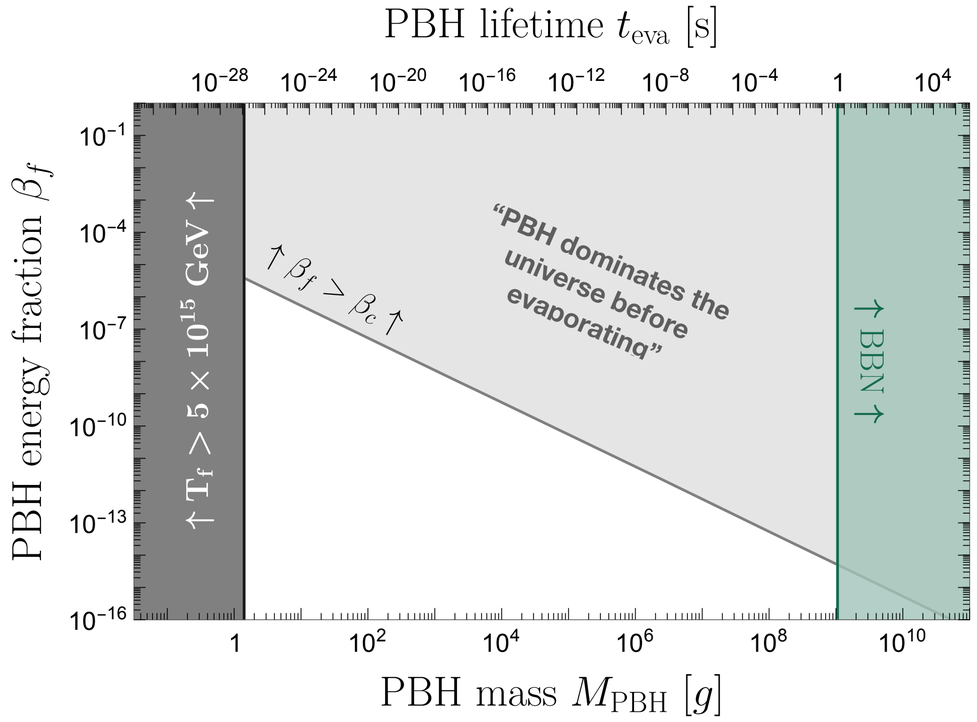
## Evaporation ⇒ Sound waves

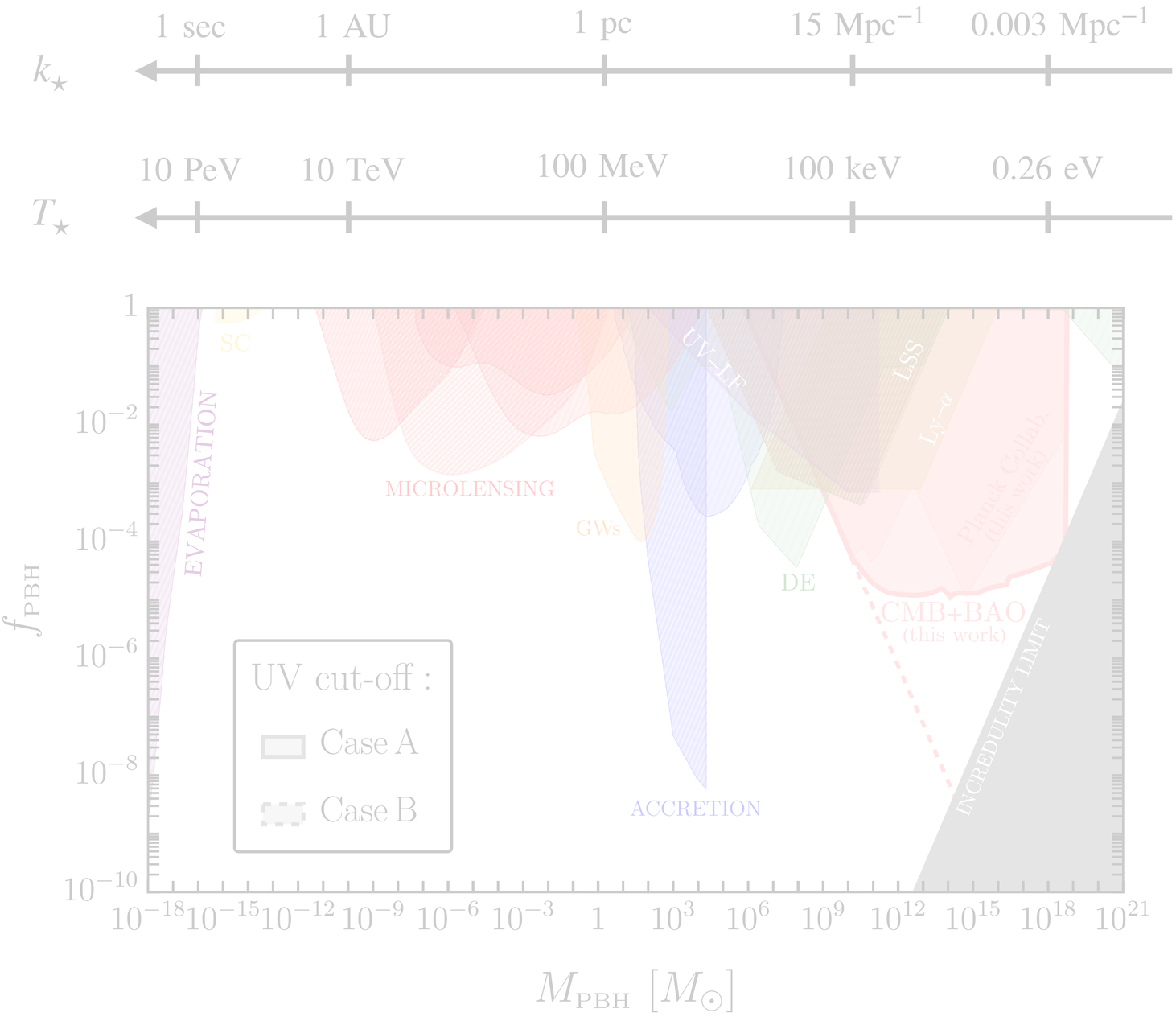
**Gas of evaporating PBHs**



*Inomata, Kawasaki, Mukaida, Terada, Yanagida (2003.10455)*

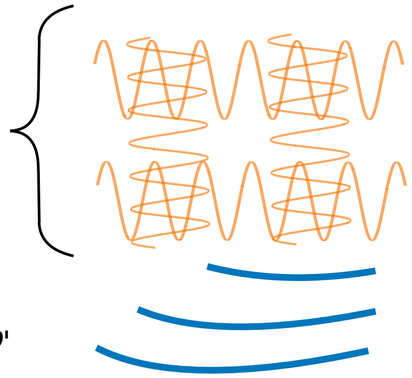
## Poltergeist GWs



# Evaporation ⇒ Sound waves

**Gas of evaporating PBHs**



*Inomata, Kawasaki, Mukaida, Terada, Yanagida (2003.10455)*

*Papanikolaou, Vennin, Langlois 20'*

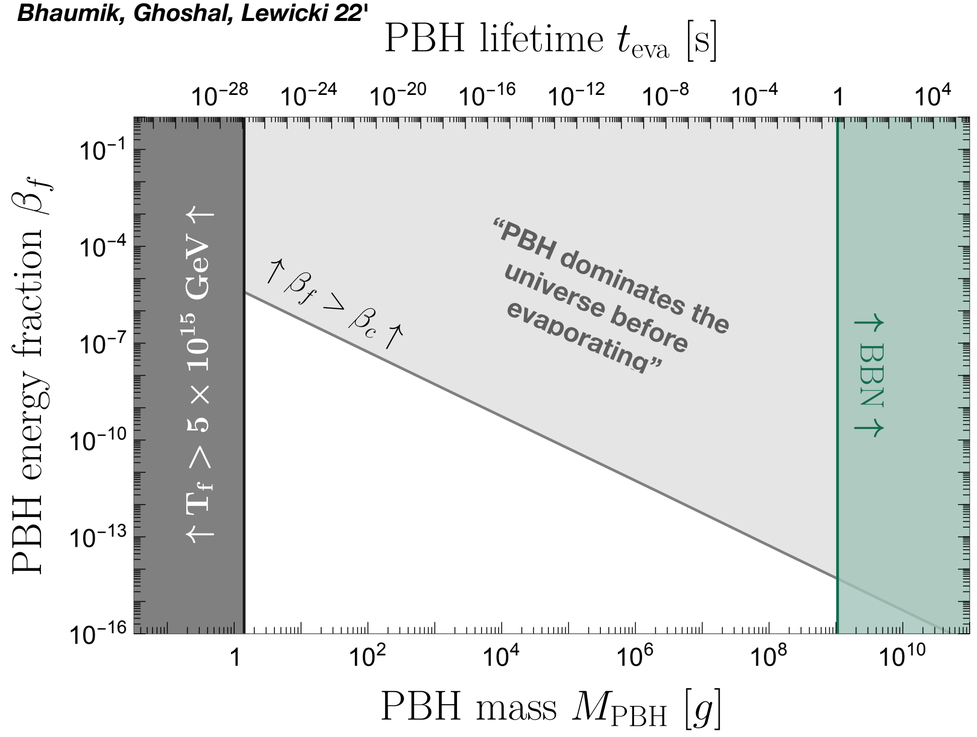
*Domenech, Lin, Sasaki 20'*

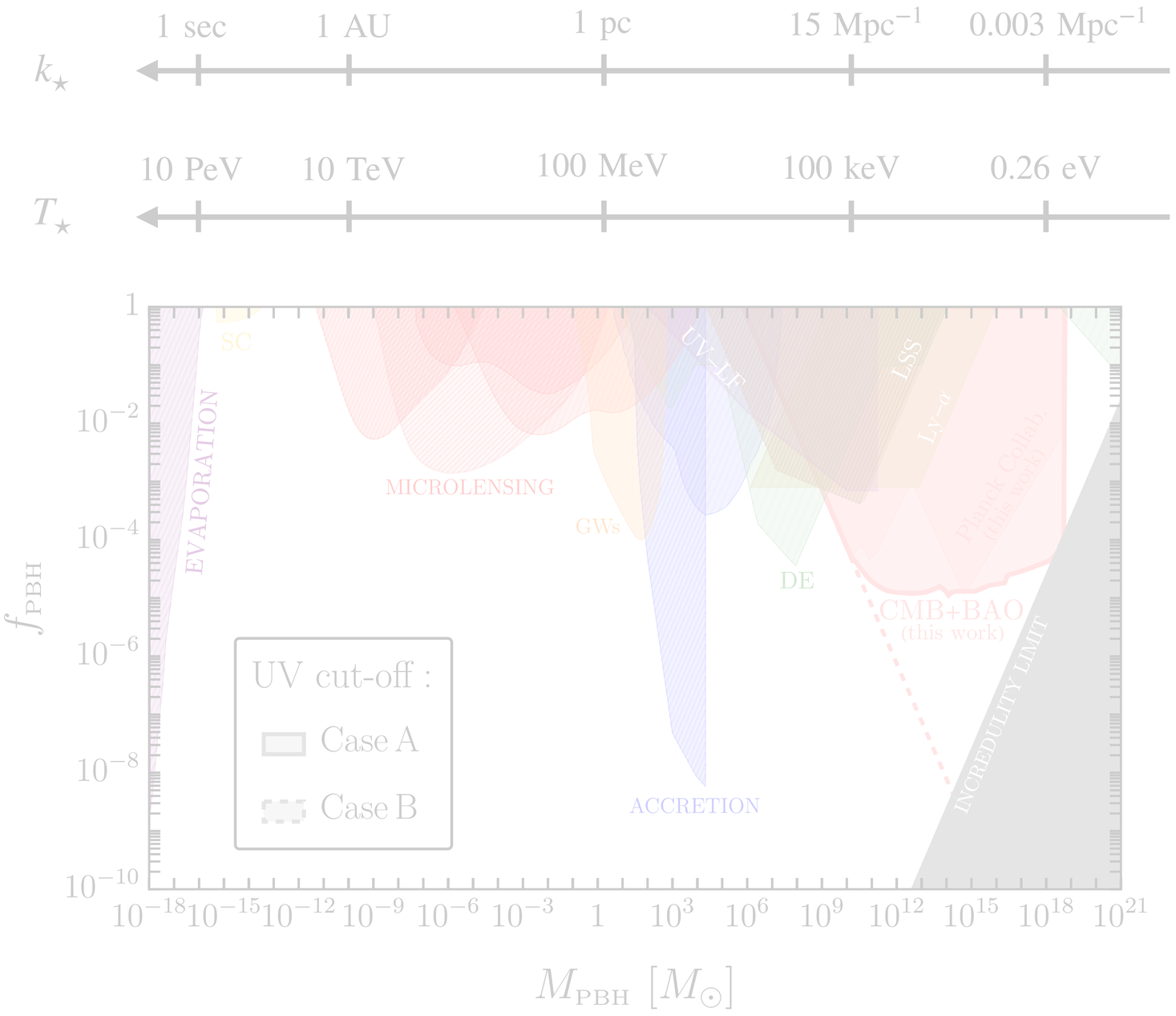
*Domenech, Takhistov, Sasaki 21'*

*Domenech, Trankle 24'*

*Bhaumik, Ghoshal, Lewicki 22'*

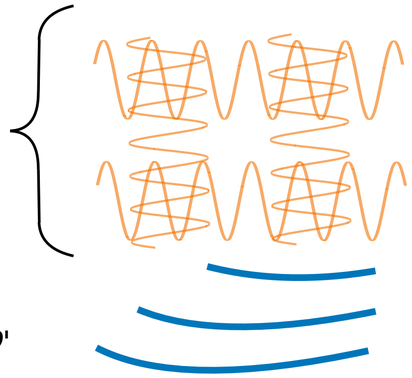
**Poltergeist GWs**



# Evaporation ⇒ Sound waves

**Gas of evaporating PBHs**



*Inomata, Kawasaki, Mukaida, Terada, Yanagida (2003.10455)*

*Papanikolaou, Vennin, Langlois 20'*

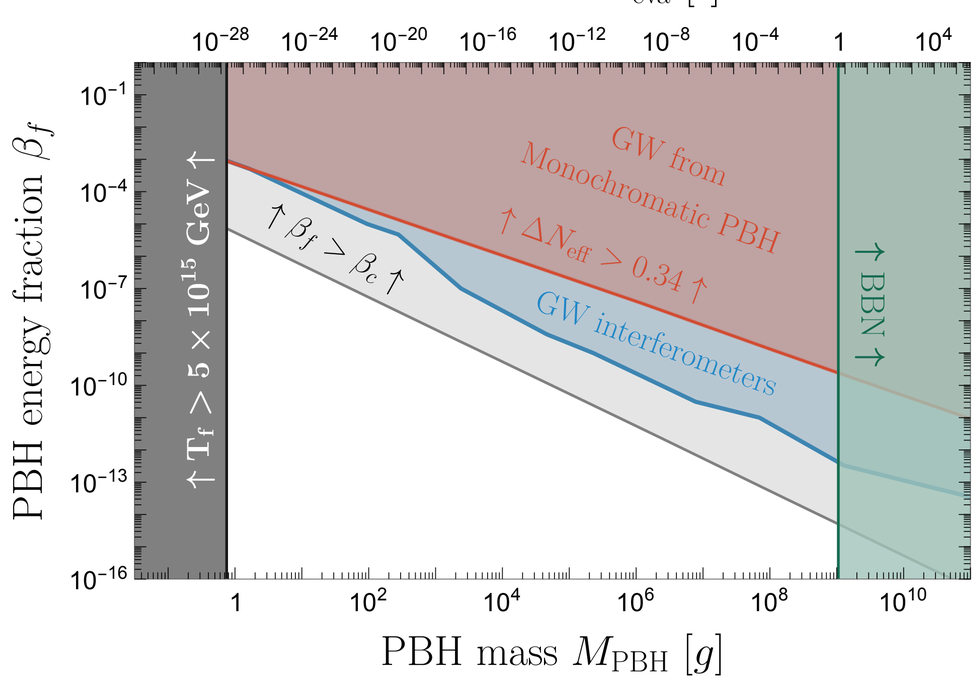
*Domenech, Lin, Sasaki 20'*

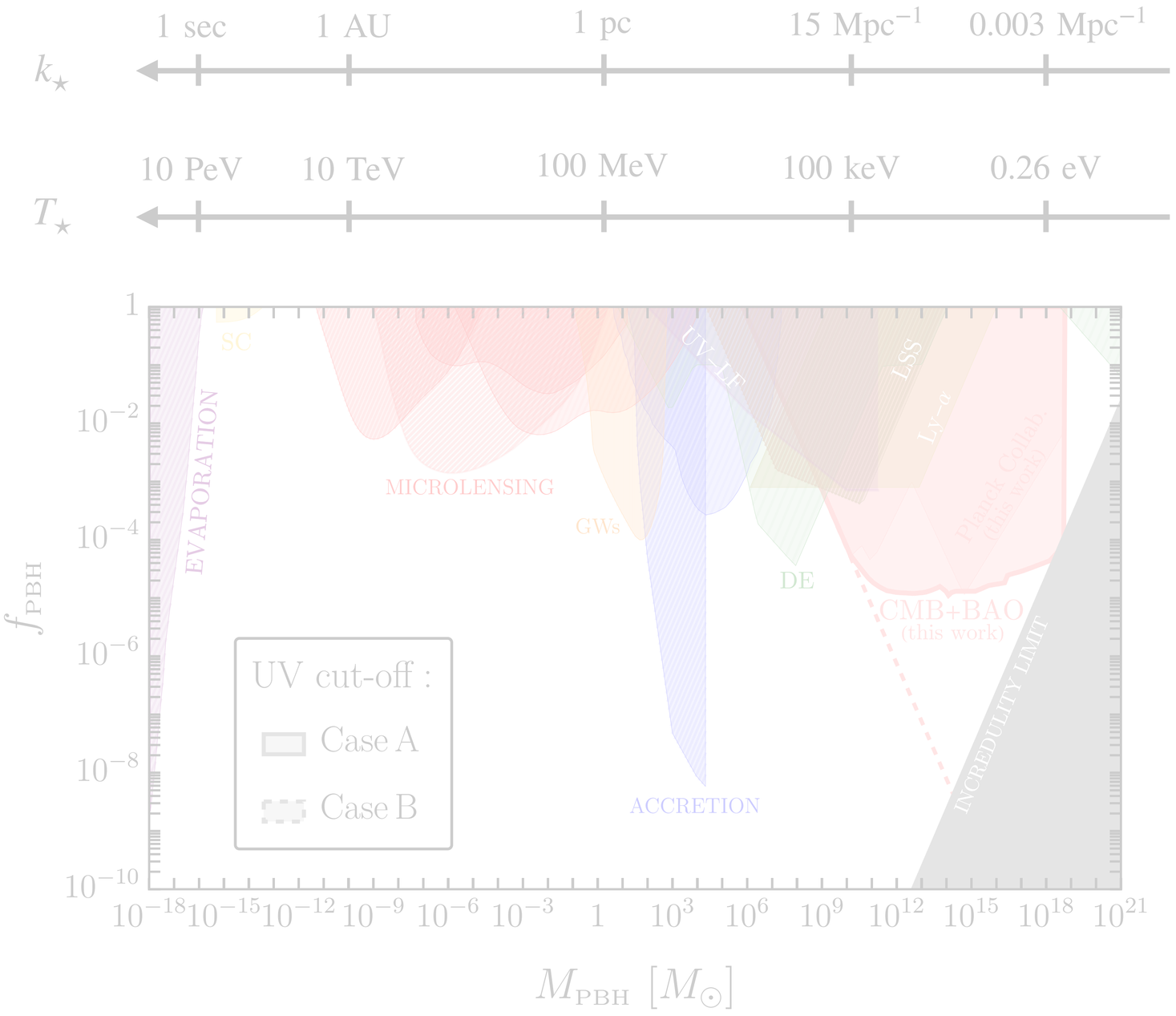
*Domenech, Takhistov, Sasaki 21'*

*Domenech, Trankle 24'*

*Bhaumik, Ghoshal, Lewicki 22'*

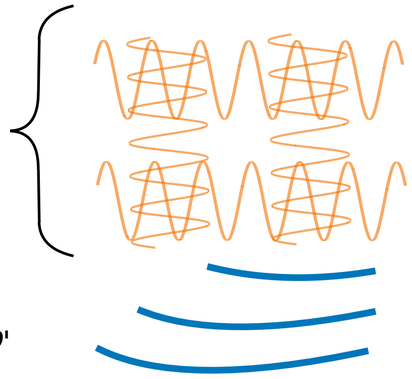
**Poltergeist GWs**



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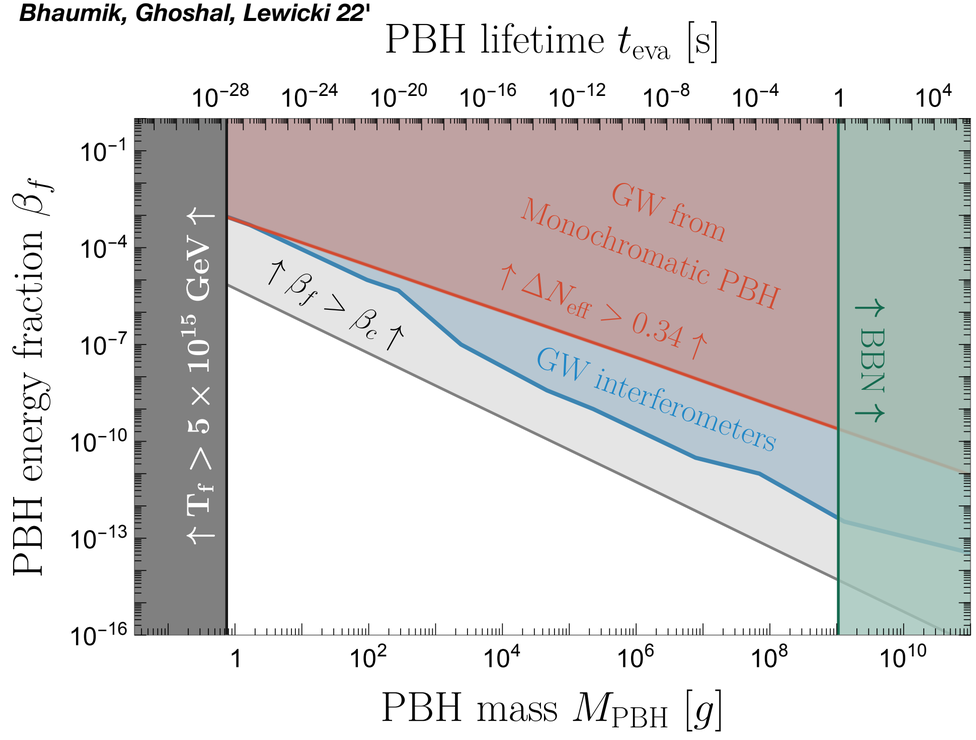
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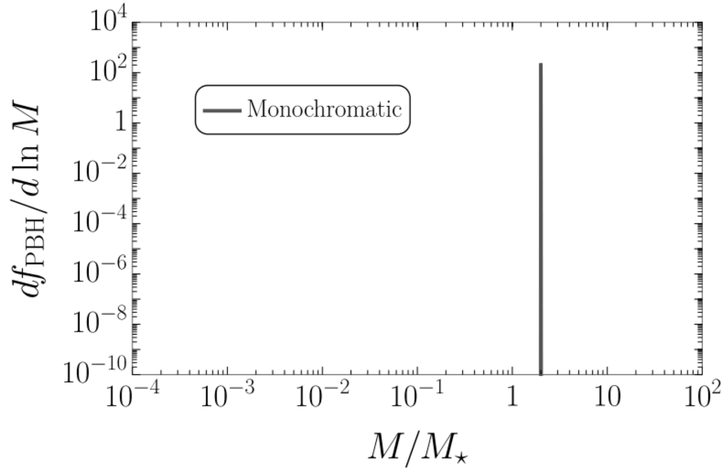



# Opening the Window for Ultra-Light Primordial Black Holes

**In preparation (26XX.XXXX)**

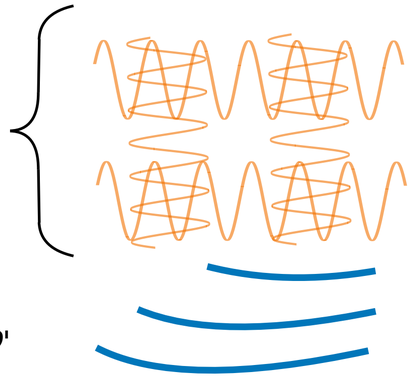

Yann Gouttenoire, Nicholas Leister, Pedro Schwaller

*PRISMA+ Cluster of Excellence & MITP, Johannes Gutenberg University, 55099 Mainz, Germany*

**Evaporation ⇒ Sound waves**

**Gas of evaporating PBHs**



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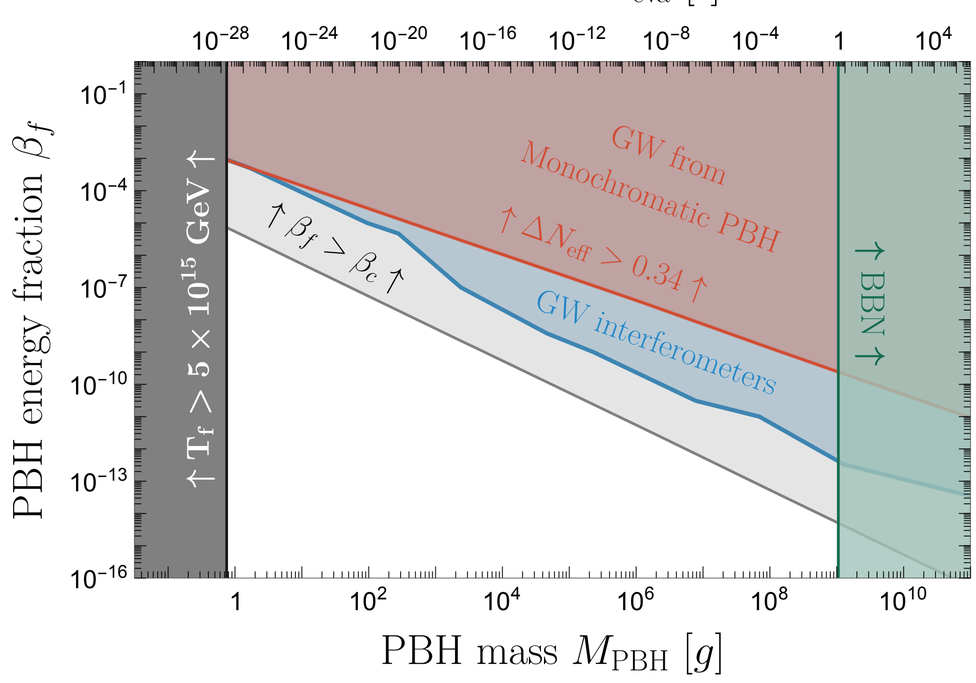
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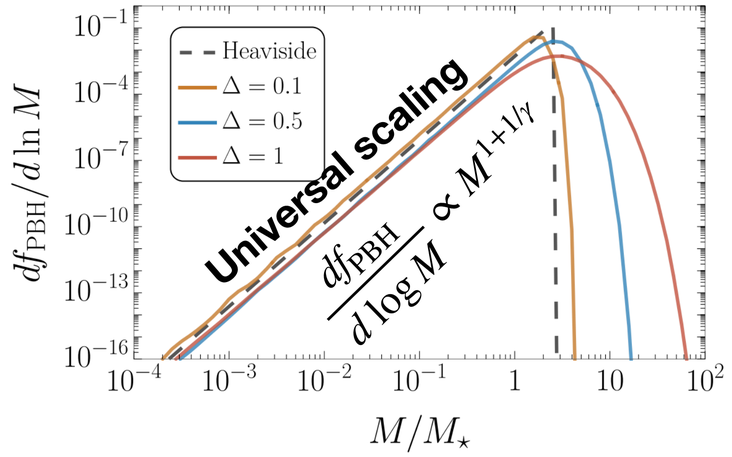


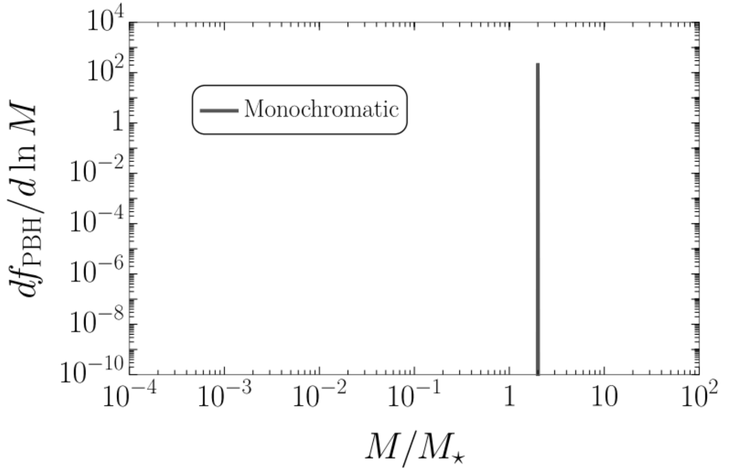

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$$M_{\rm PBH} = M_{\rm H}(\delta - \delta_c)^\gamma$$

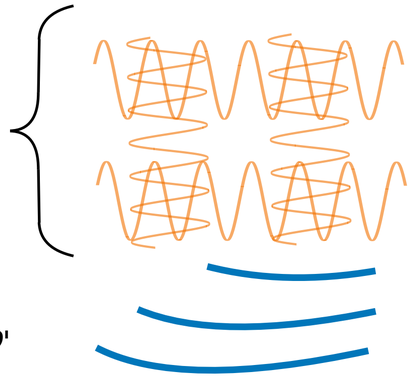
$$\gamma \simeq 0.36$$

**Choptuik's law**

***(Choptuik 93')***

**Evaporation ⇒ Sound waves**

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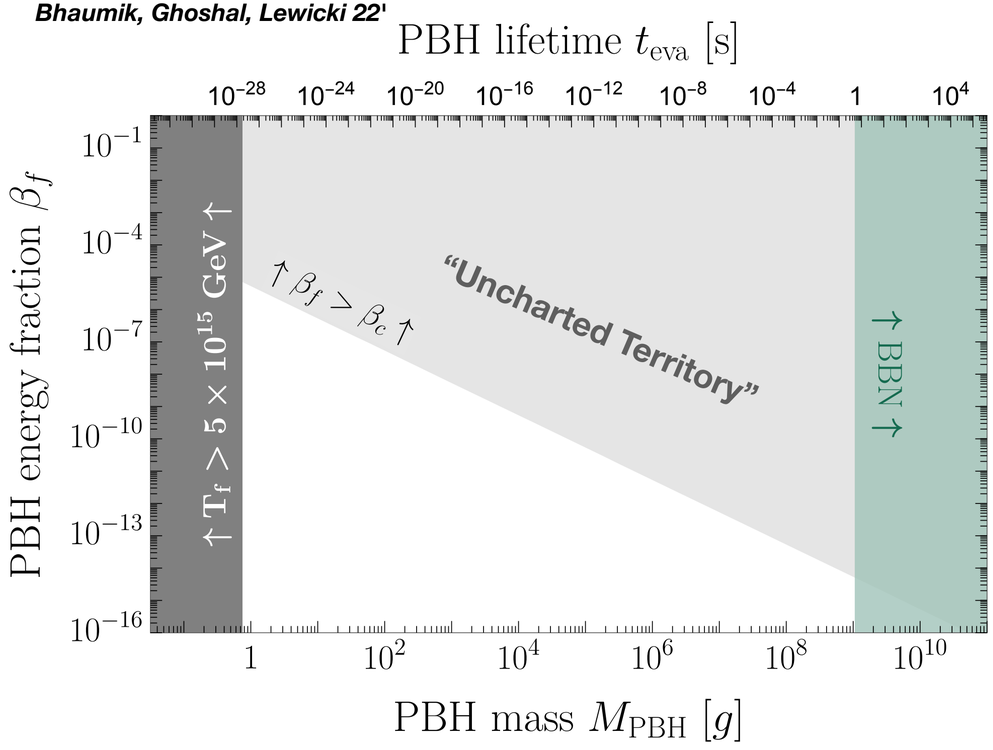
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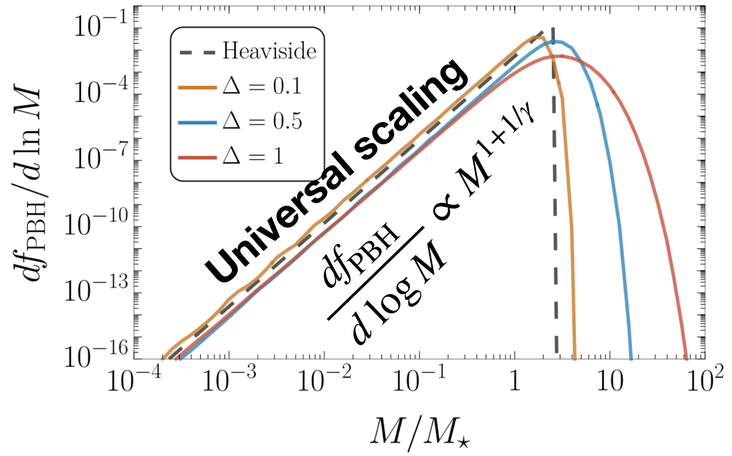


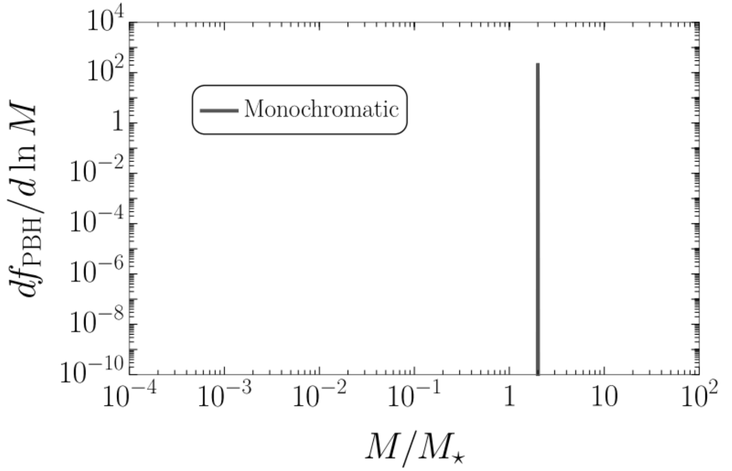

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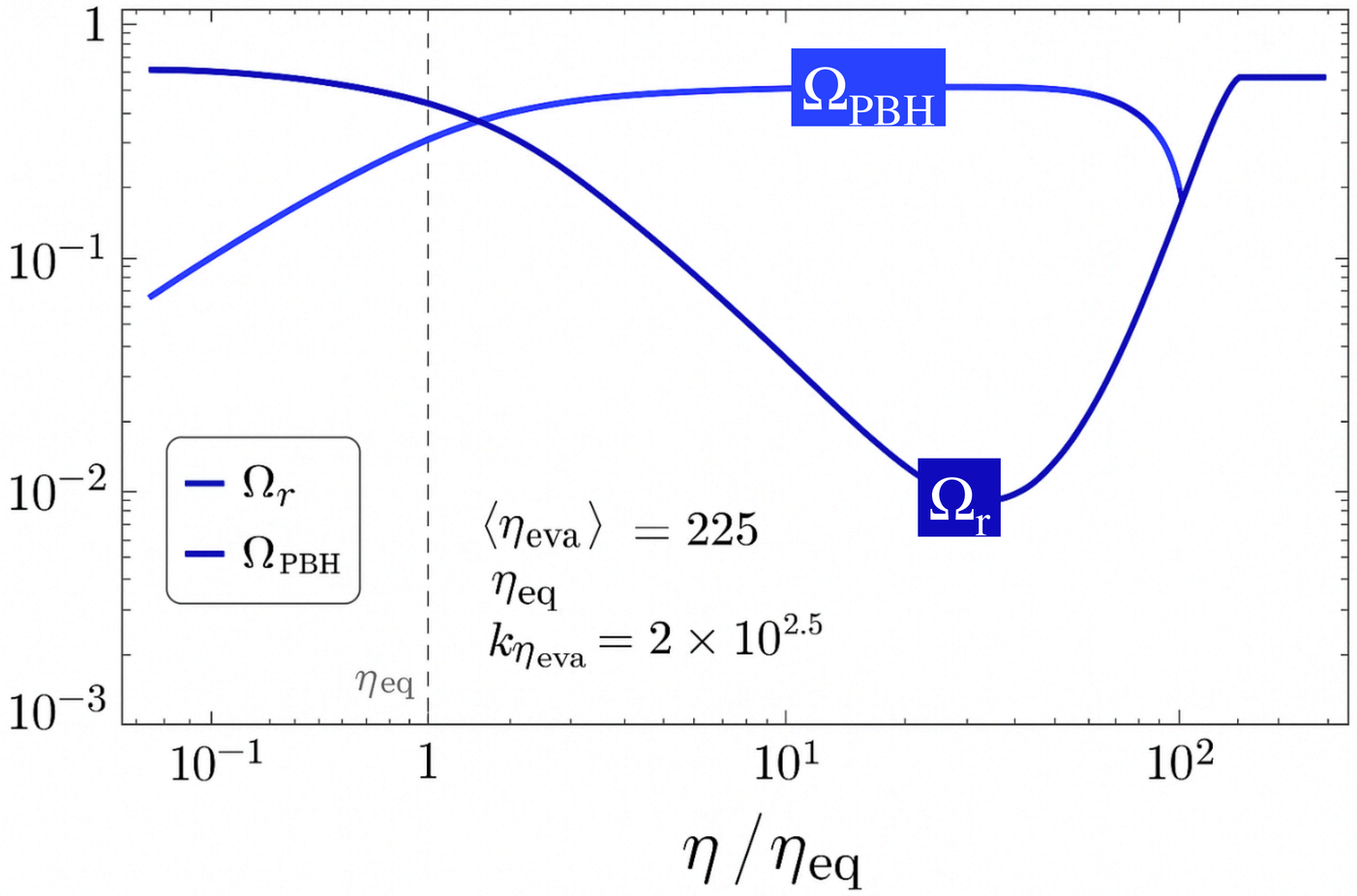
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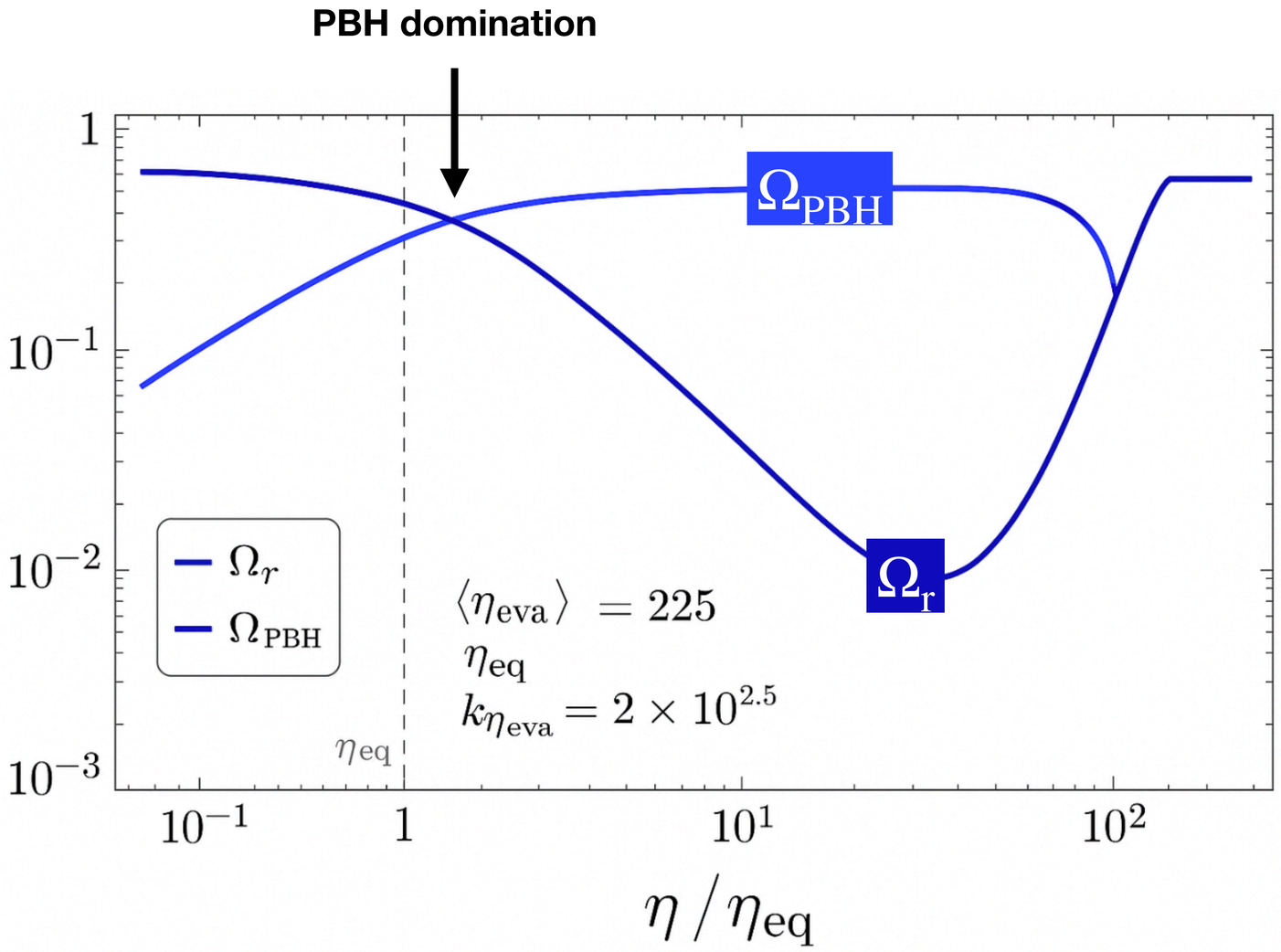
Background equations

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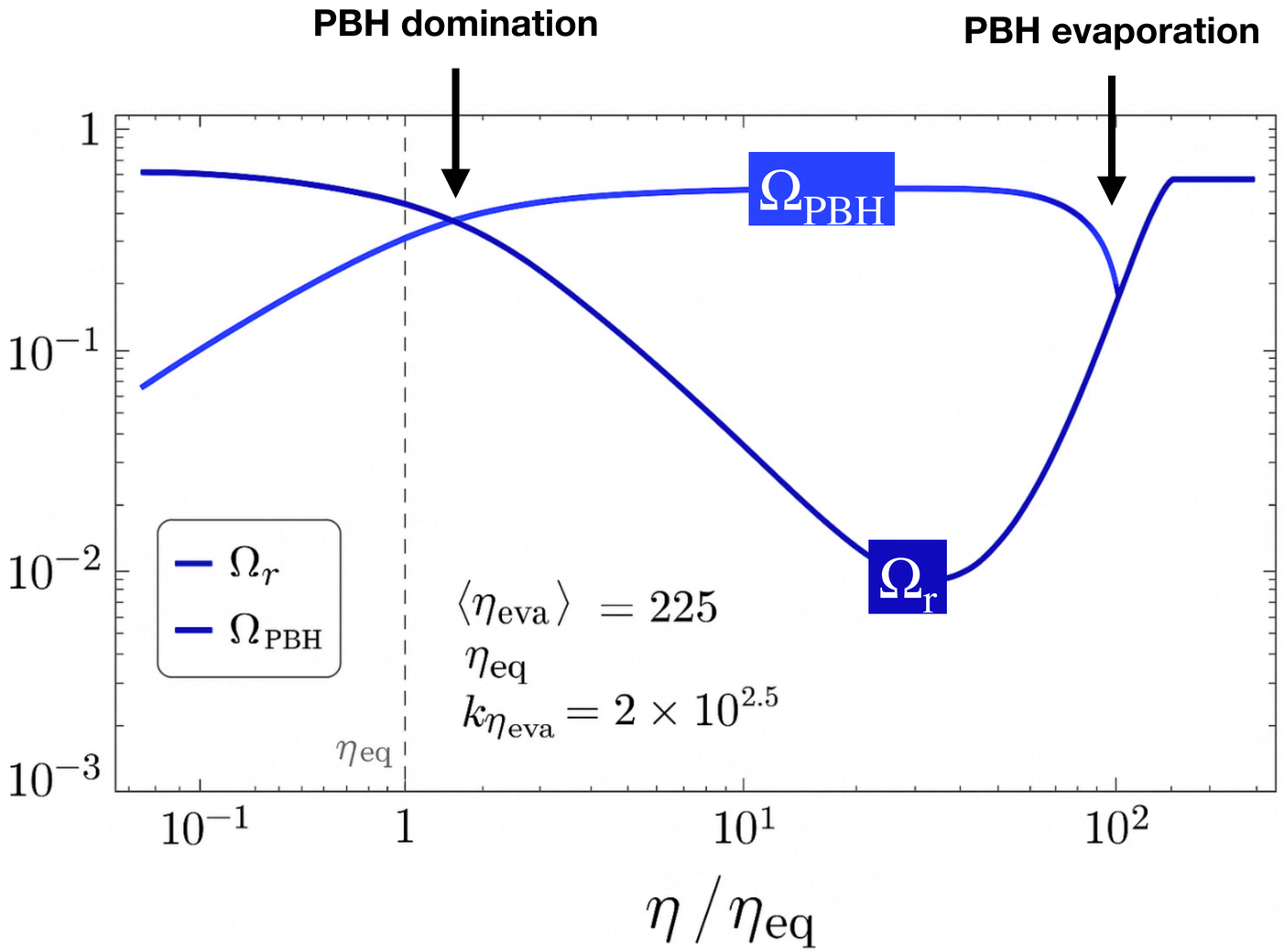
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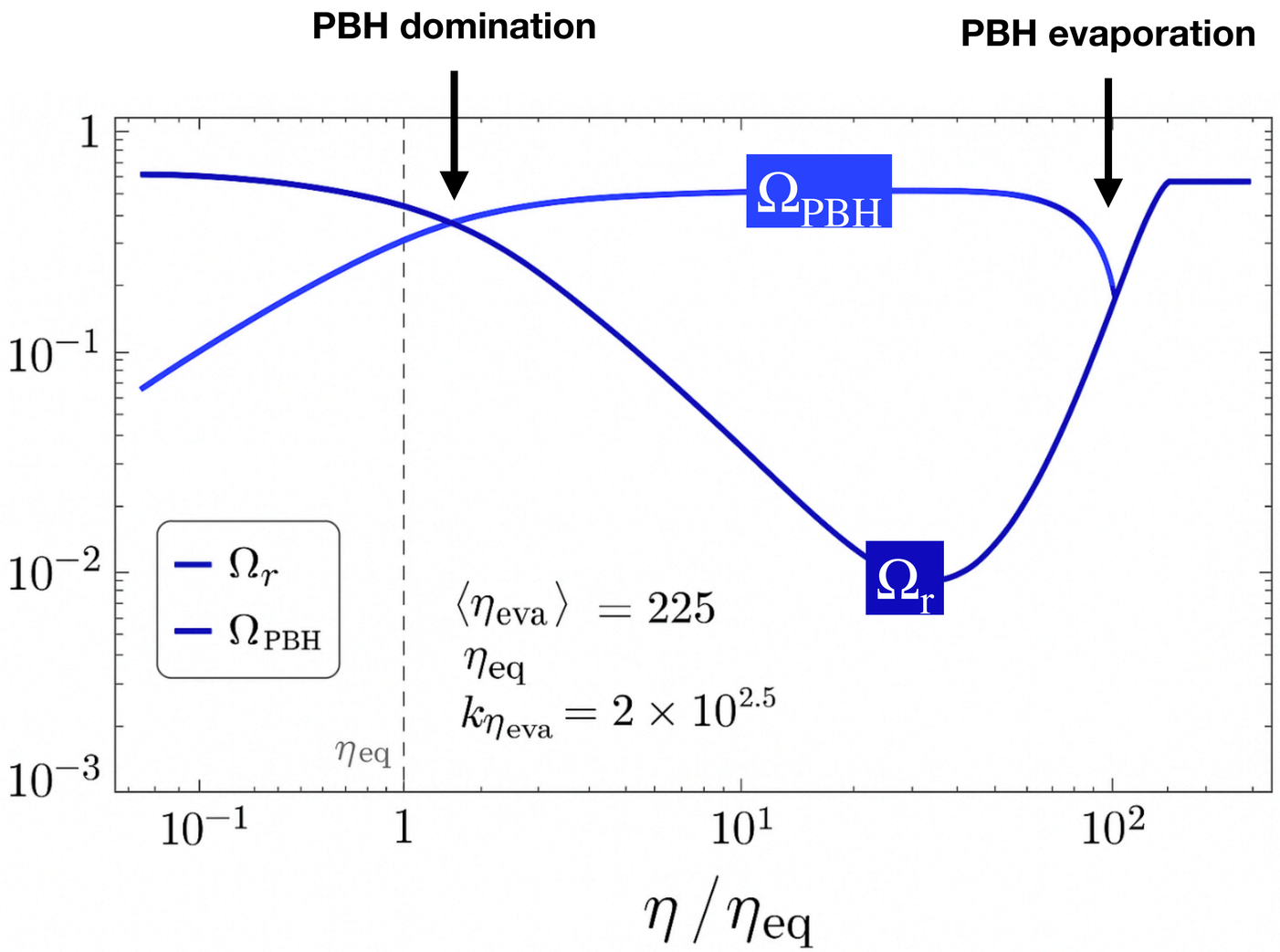
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$$G_{\mu\nu} = \frac{8\pi G}{3} T_{\mu\nu}$$

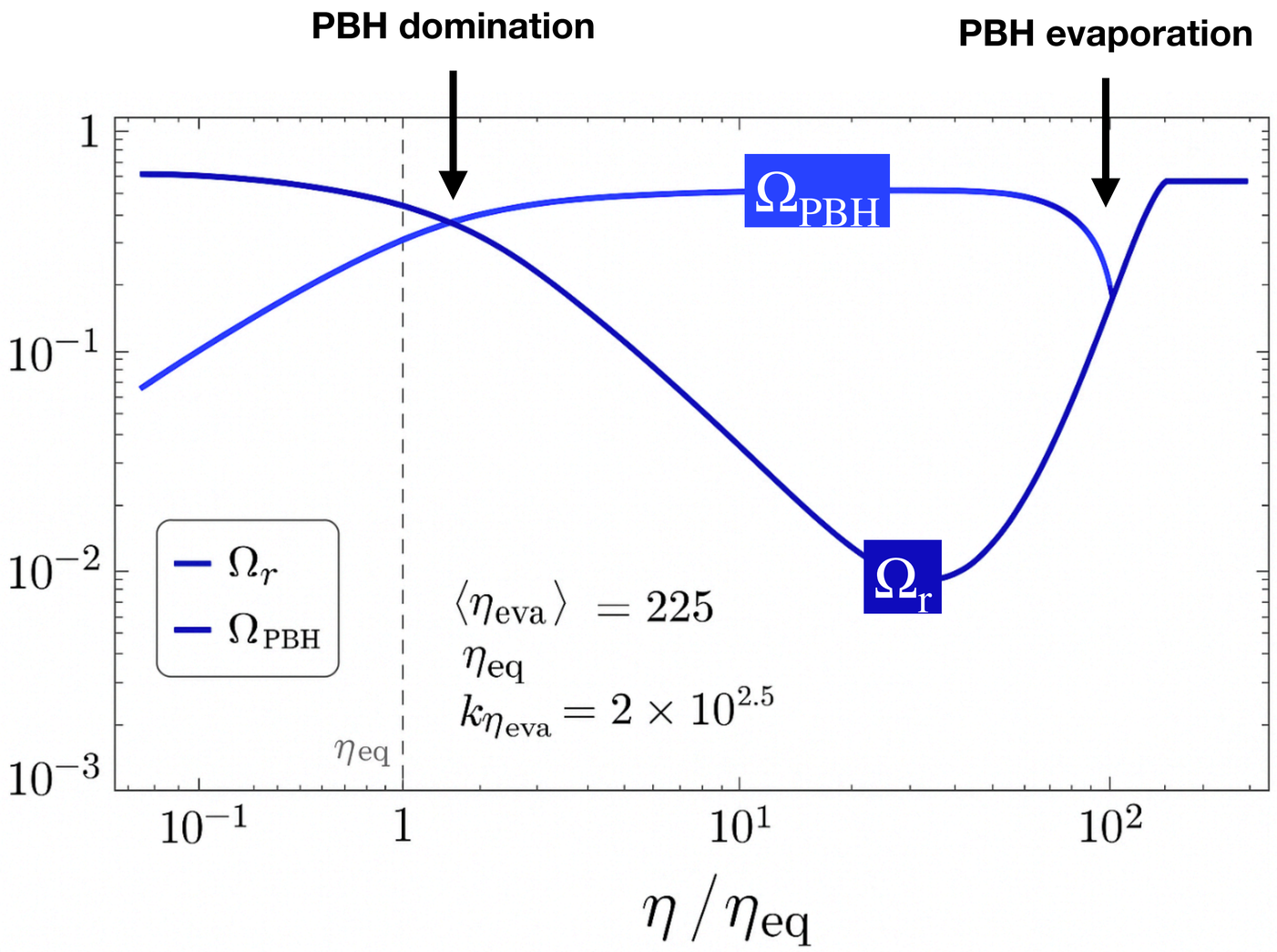


$$ds^2 = a^2(\eta)\left[(1+2\Phi)\,d\eta^2 - (1-2\Phi)\,\delta_{ij}\,dx^i dx^j\right]$$

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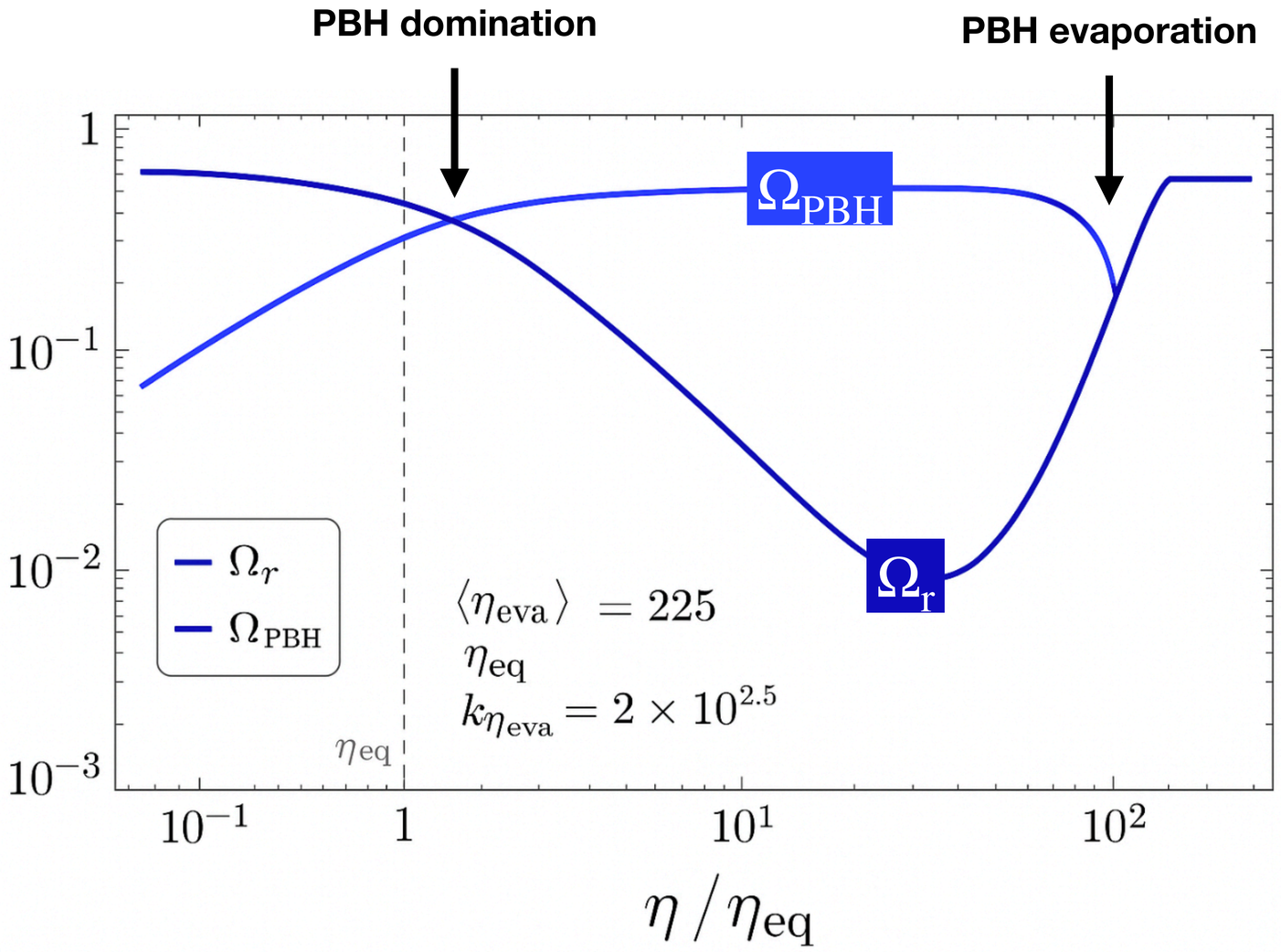
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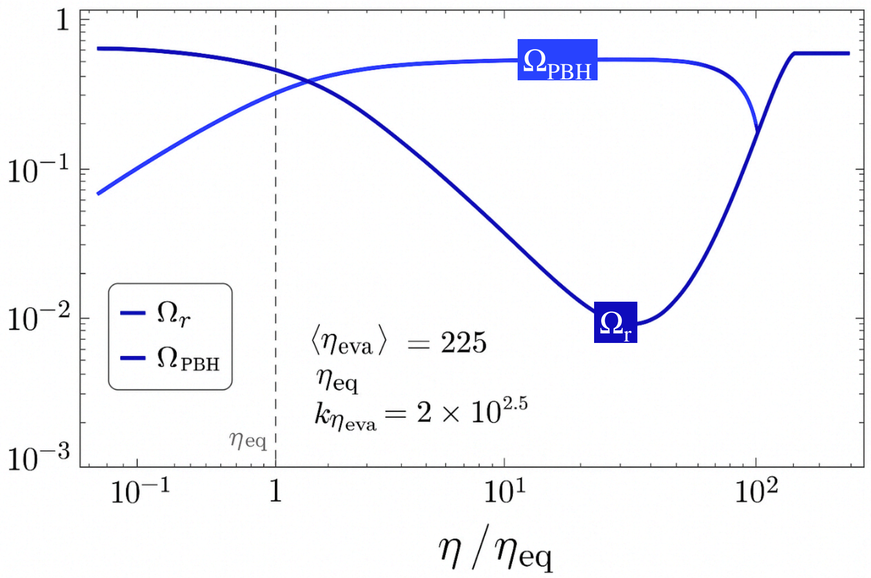
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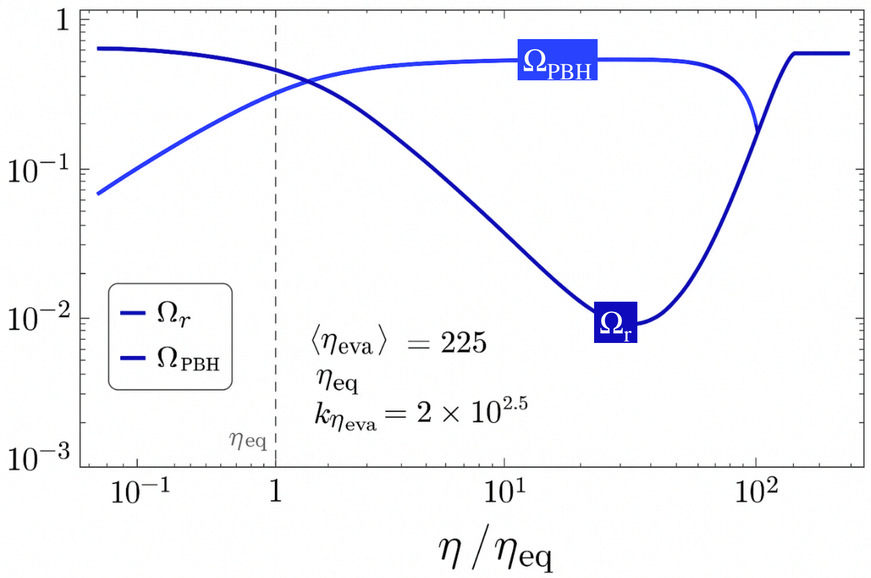
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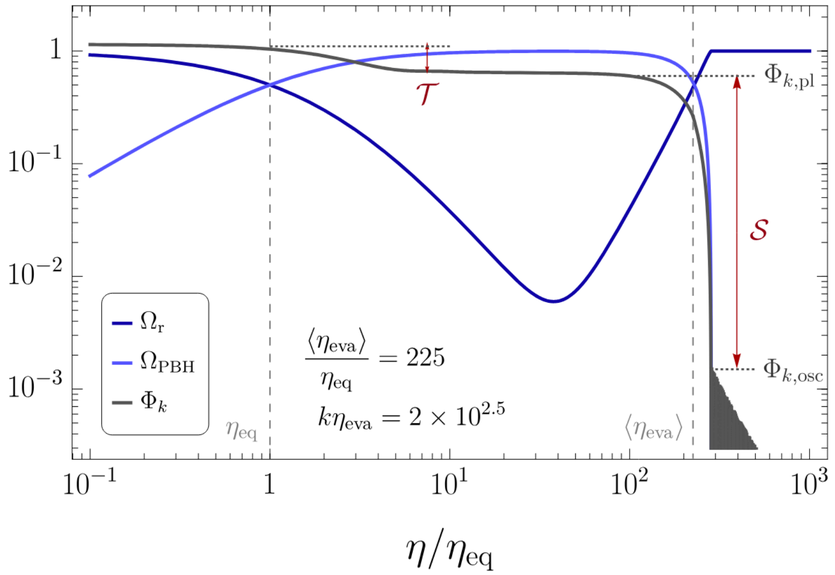
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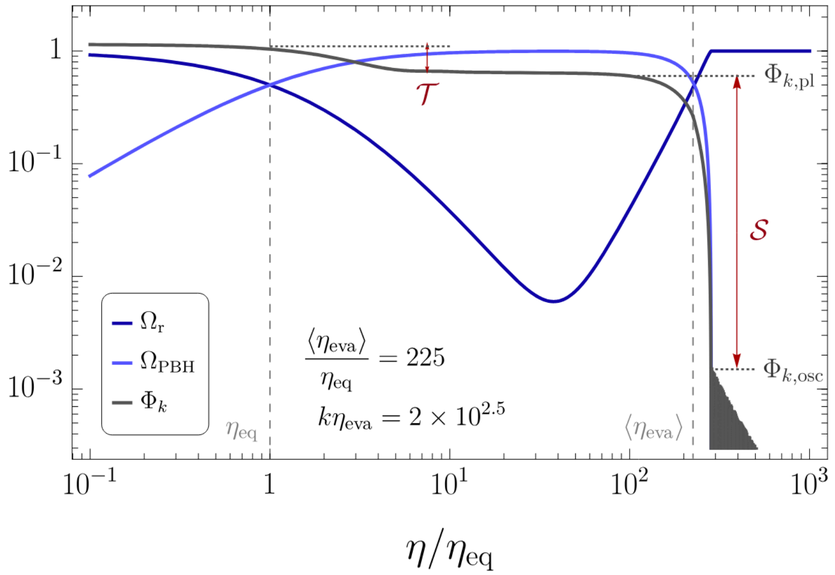
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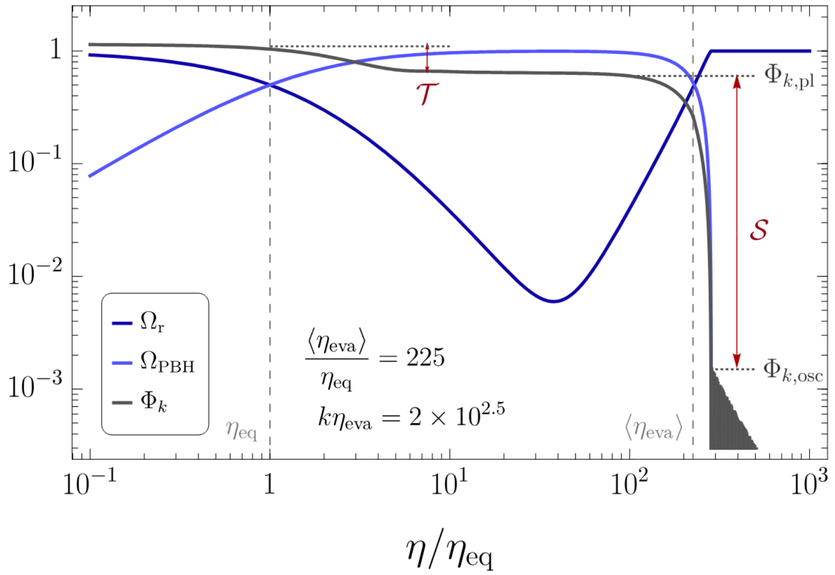
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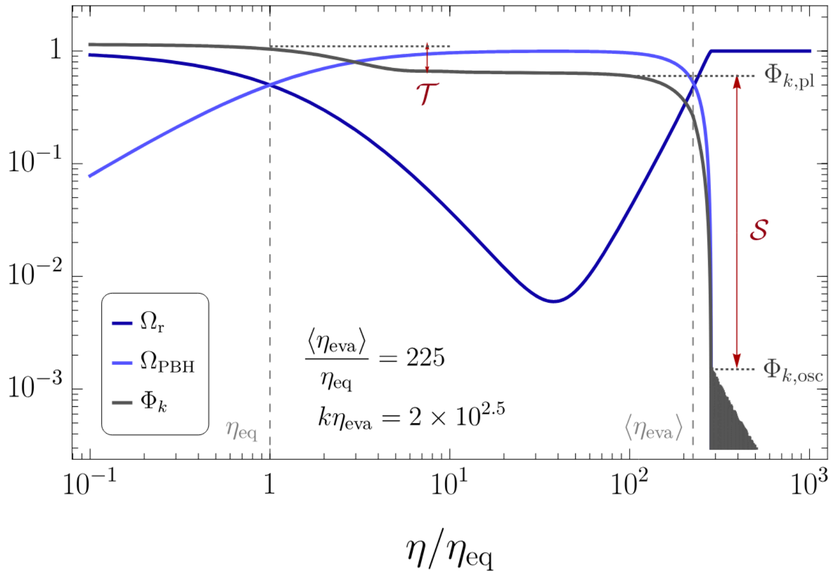
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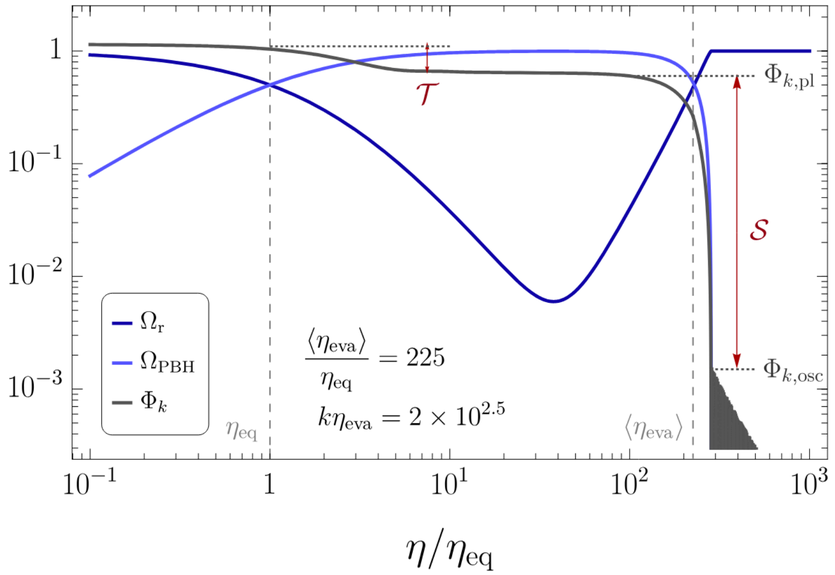
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Scalar perturbation equation

$$k^2\Phi \simeq \frac{3}{2}\mathscr{H}^2\left(\frac{\rho_{\rm PBH}}{\rho_{\rm tot}}\delta_{\rm PBH} + \frac{\rho_{\rm rad}}{\rho_{\rm tot}}\delta_{\rm r}\right)$$

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$$ds^2 = a^2(\eta)\left[(1+2\Phi)\,d\eta^2 - (1-2\Phi)\,\delta_{ij}\,dx^i dx^j\right]$$

$$T^{\mu}_{\ \nu} = \begin{pmatrix} \bar{\rho}+\delta\rho & -(\bar{\rho}+\bar{p})\,v_j \\ (\bar{\rho}+\bar{p})\,v^i & -(\bar{p}+\delta p)\,\delta^i_{\ j} \end{pmatrix}$$

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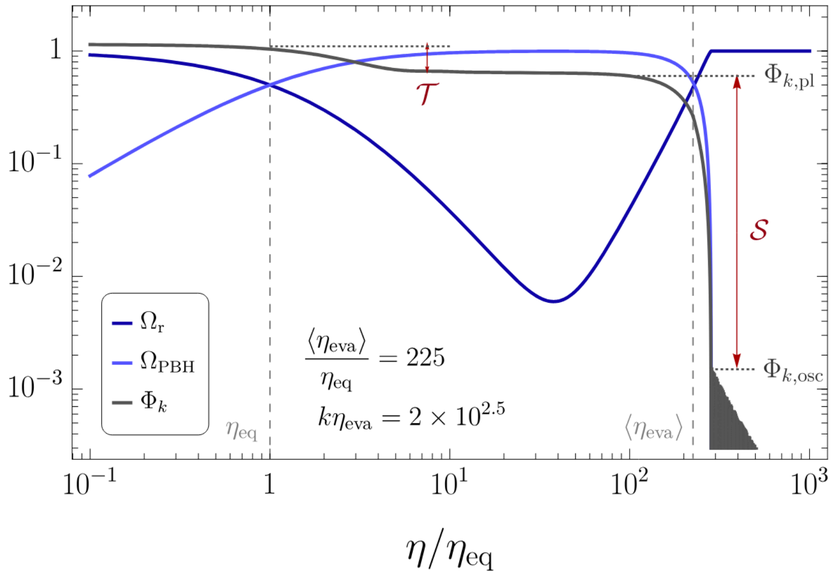
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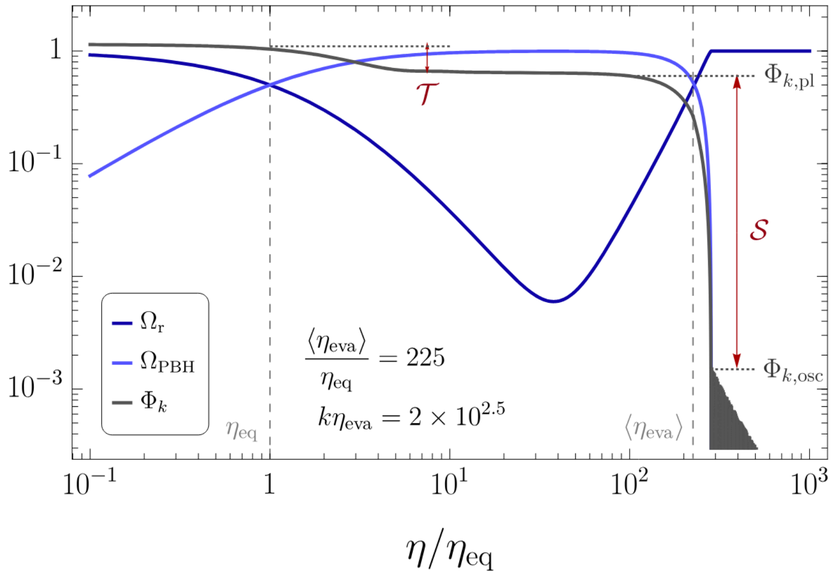
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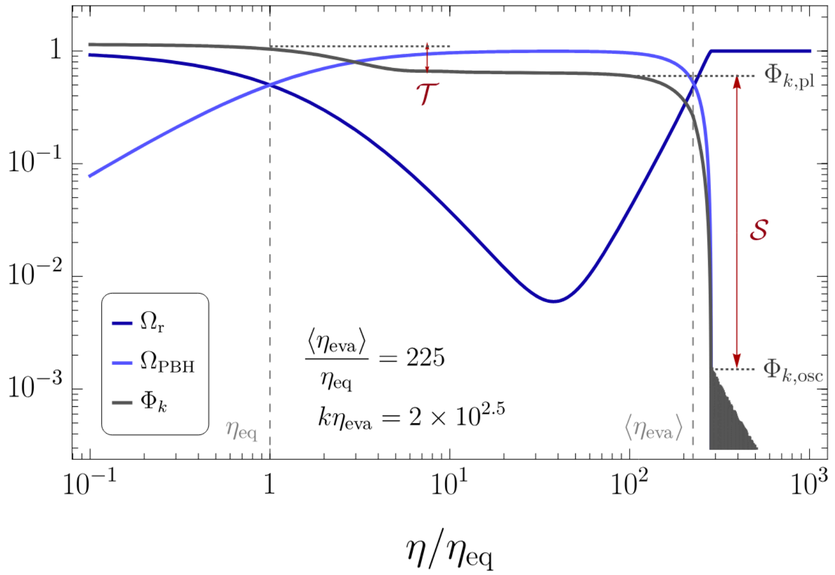
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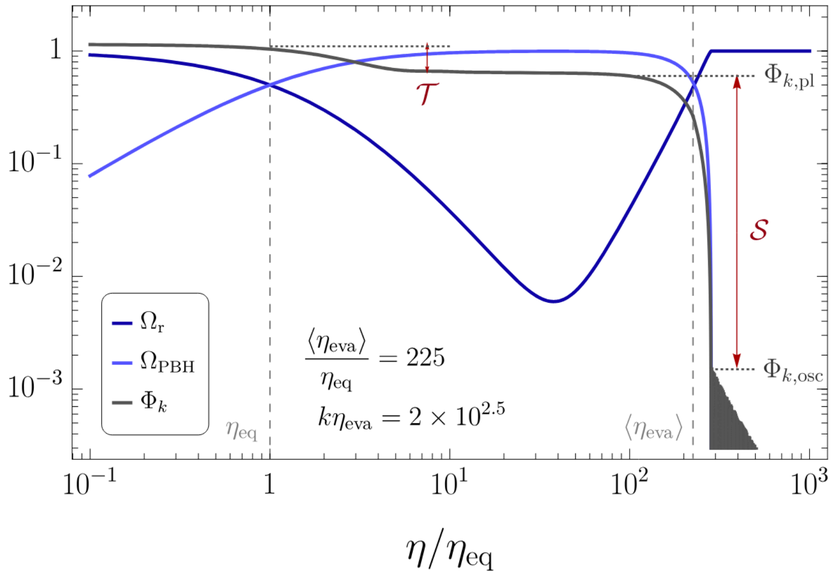
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Background equations

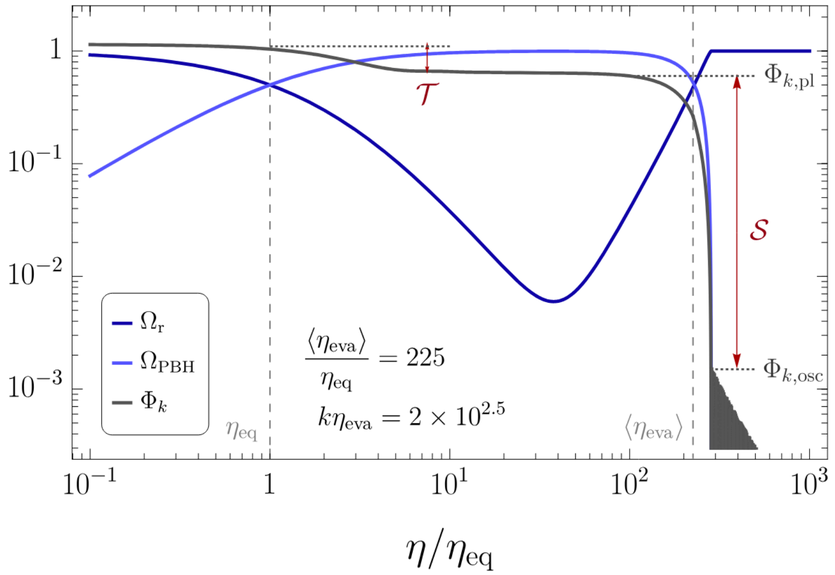
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time



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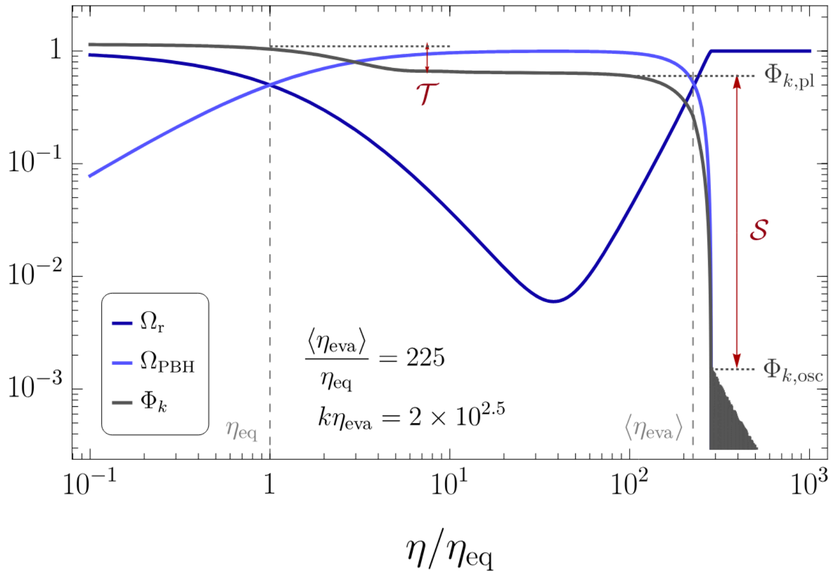
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## Scalar perturbation equation

$$k^2\Phi \simeq \frac{3}{2}\mathcal{H}^2\left(\frac{\rho_{\rm PBH}}{\rho_{\rm tot}}\delta_{\rm PBH} + \frac{\rho_{\rm rad}}{\rho_{\rm tot}}\delta_{\rm r}\right)$$

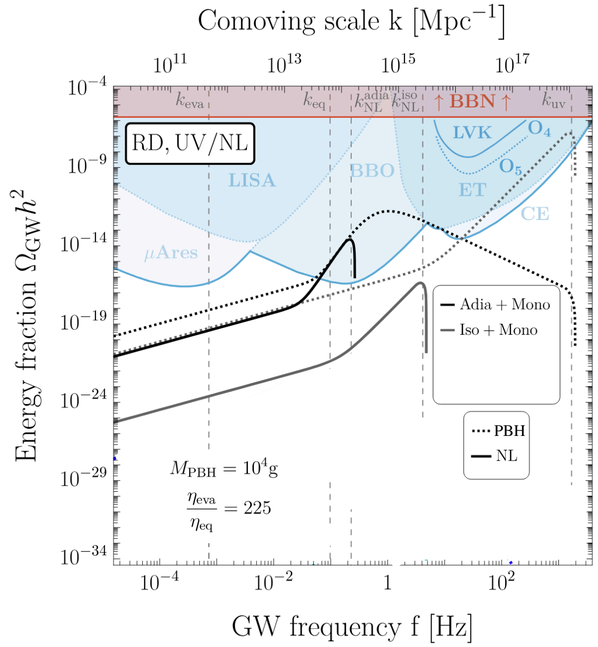
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time




## Tensor perturbation equation

$$\Box h_{ij} = \partial_i\Phi\partial_j\Phi$$



$$ds^2 = a^2(\eta)\left[(1+2\Phi)\,d\eta^2 - (1-2\Phi)\,\delta_{ij}\,dx^i dx^j\right]$$

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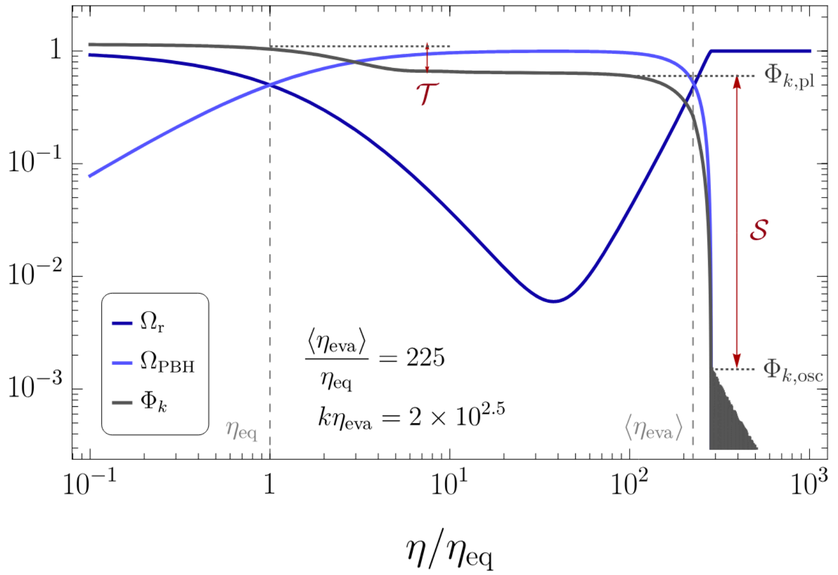
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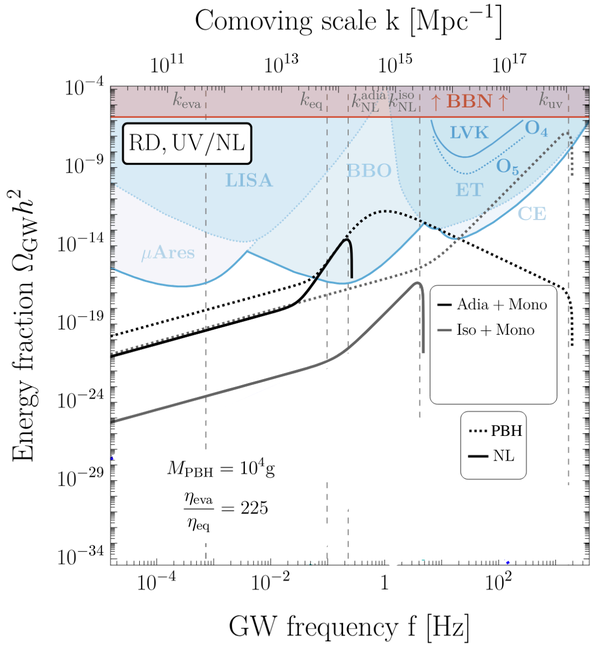
time




Tensor perturbation equation

$$\Box h_{ij} = \partial_i\Phi\partial_j\Phi$$

$$\mathscr{P}_\Phi = \Theta(k_{\rm cut} - k)\begin{cases} \mathscr{P}_{\rm adia}(k) \\ \dfrac{3}{2}\left(\dfrac{\mathcal{H}}{k}\right)^2 f^2_{\rm PBH}\left(\dfrac{k}{k_{\rm PBH}}\right)^3 \end{cases}$$



$$ds^2 = a^2(\eta)\left[(1+2\Psi)\,d\eta^2 - (1-2\Phi)\,\delta_{ij}\,dx^i dx^j\right]$$

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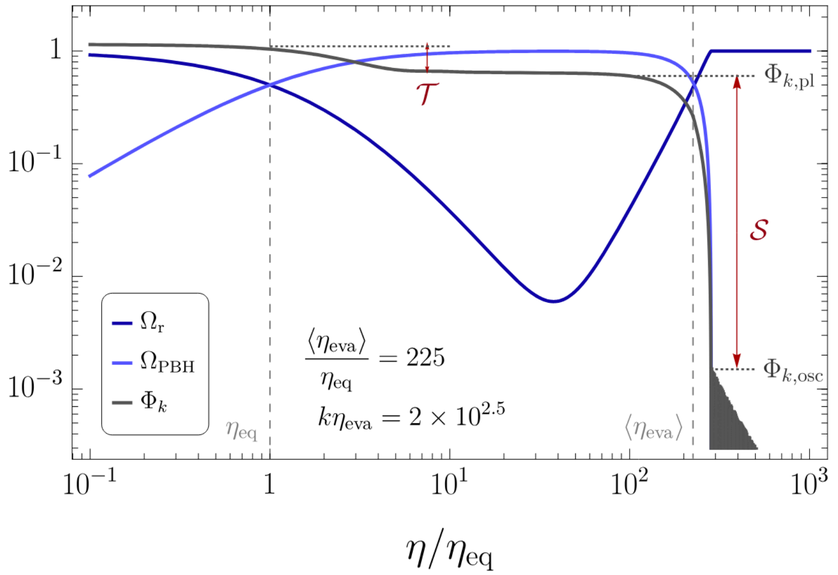
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time ↓

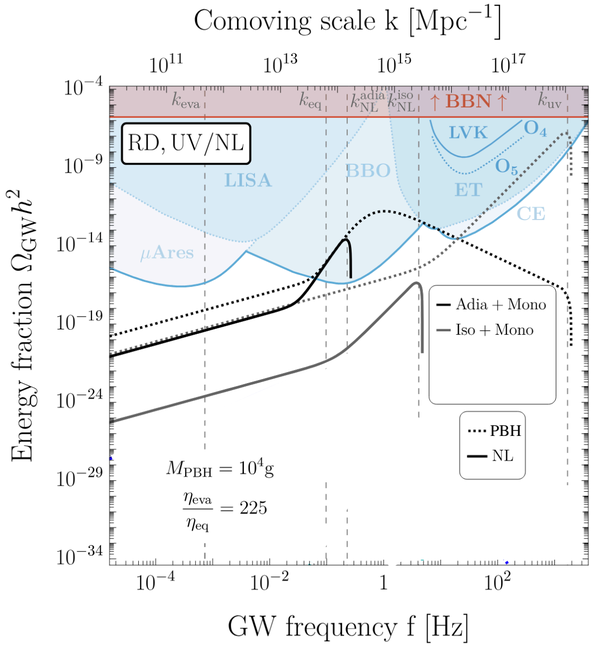



## Tensor perturbation equation

$$\Box h_{ij} = \partial_i\Phi\partial_j\Phi$$

$$\mathscr{P}_\Phi = \Theta(k_{\rm cut} - k)\begin{cases} \mathscr{P}_{\rm adia}(k) \\ \dfrac{3}{2}\left(\dfrac{\mathcal{H}}{k}\right)^2 f^2_{\rm PBH}\left(\dfrac{k}{k_{\rm PBH}}\right)^3 \end{cases}$$

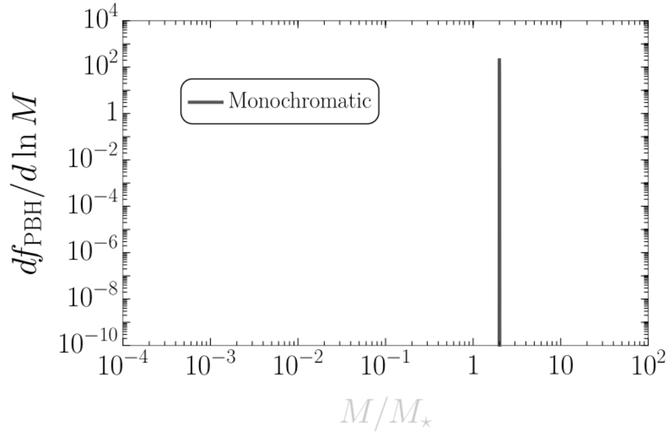
$$k_{\rm cut} = \begin{cases} k_{\rm PBH}, & \text{(dashed line)} \\ k_{\rm NL}, & \text{(solid line)} \end{cases}$$

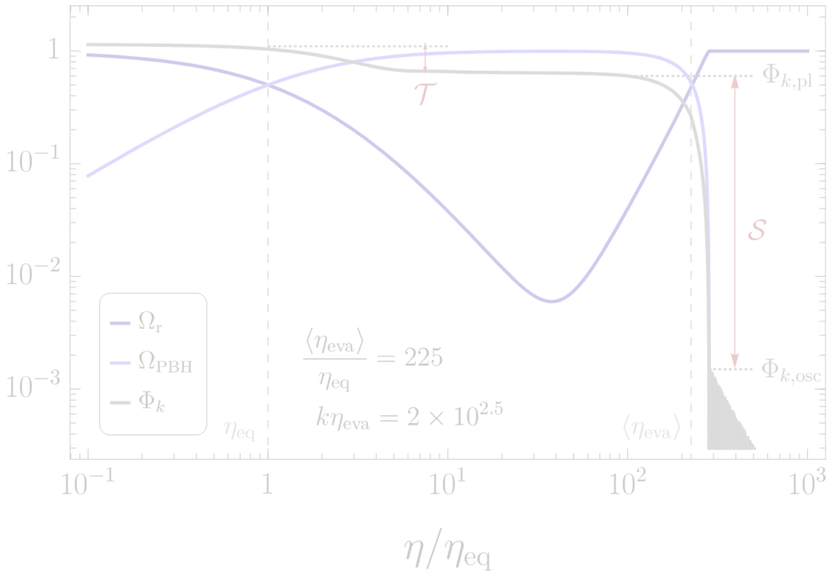


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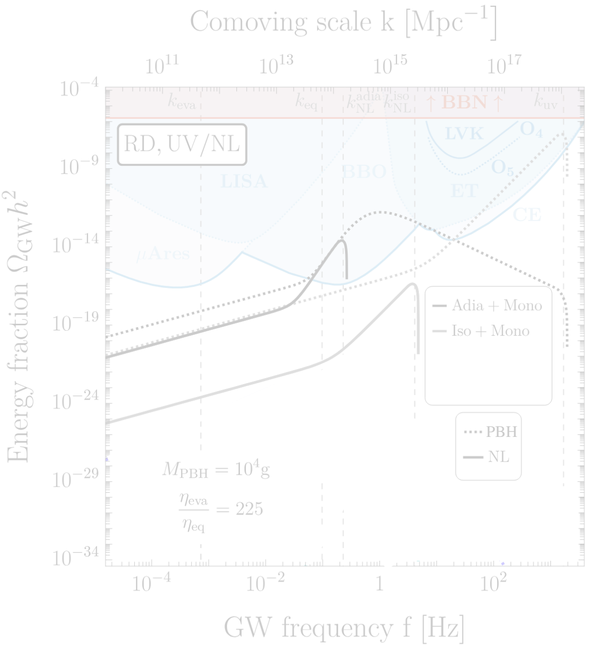




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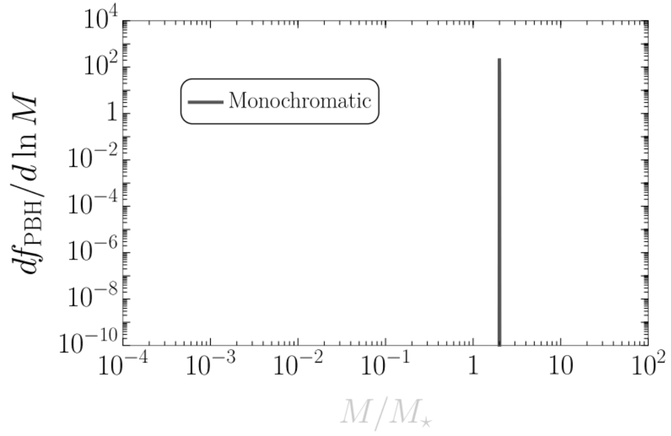
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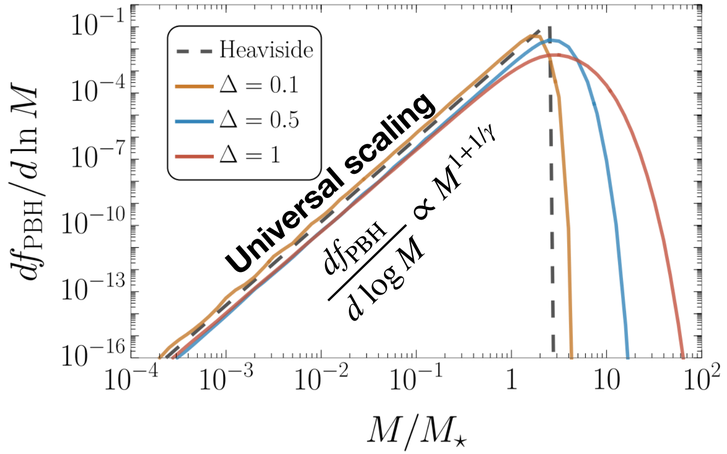
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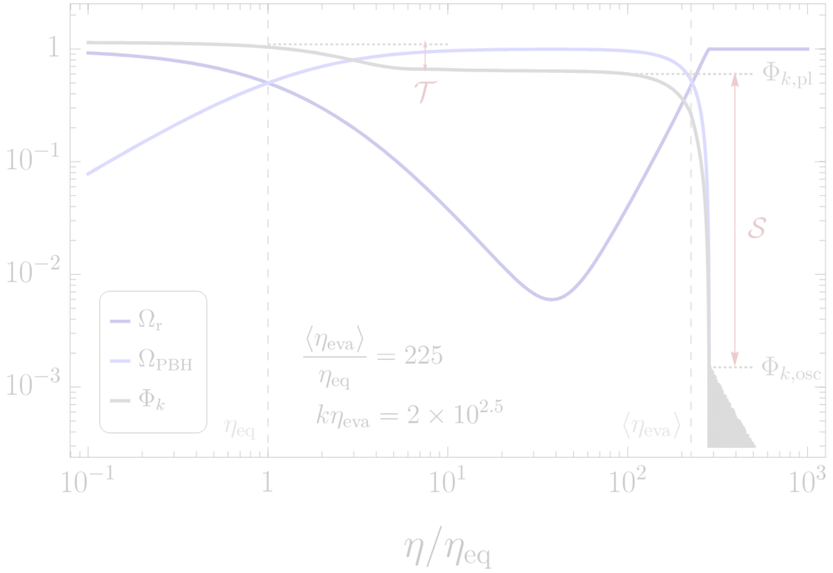
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$\Longrightarrow$



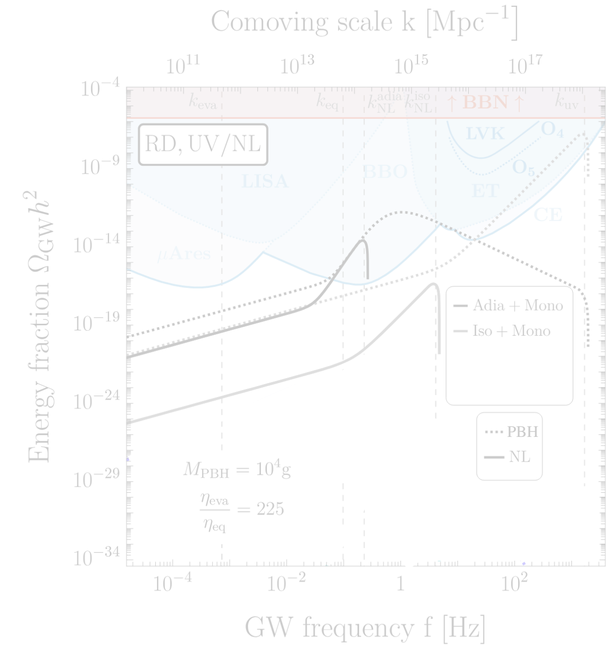




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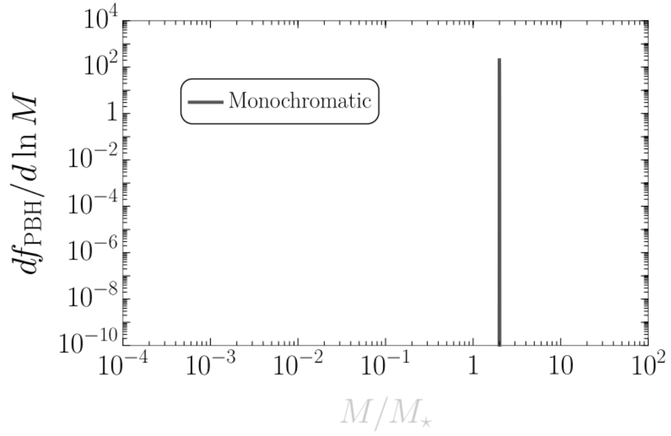


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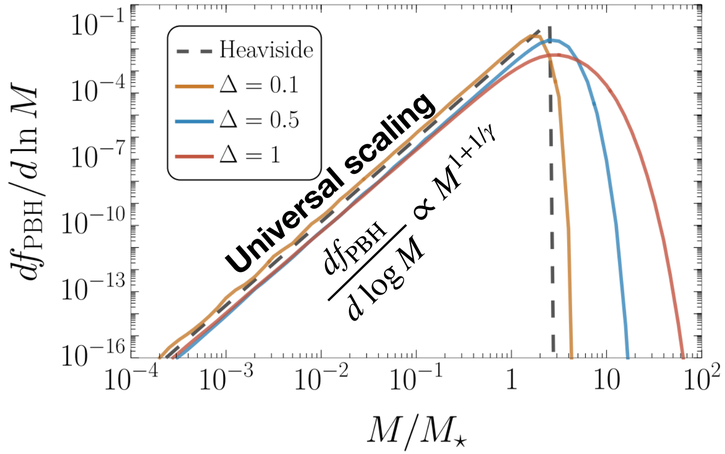
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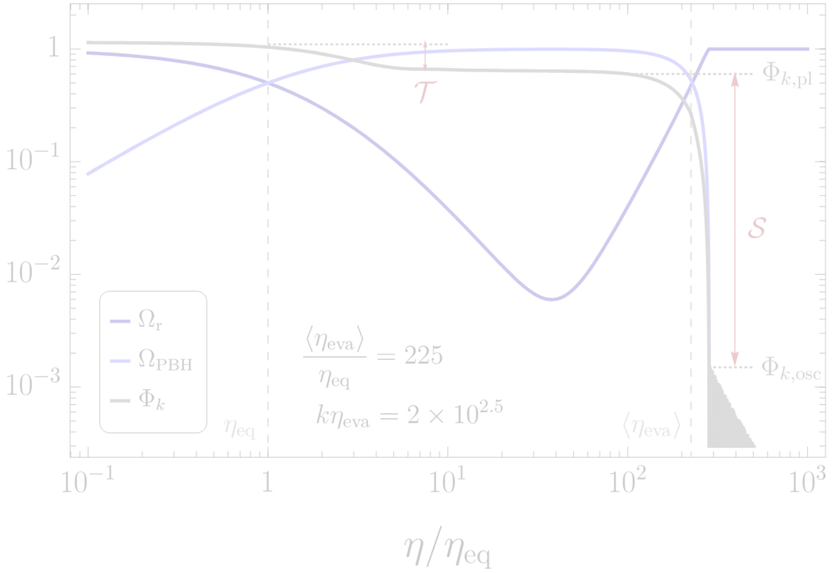
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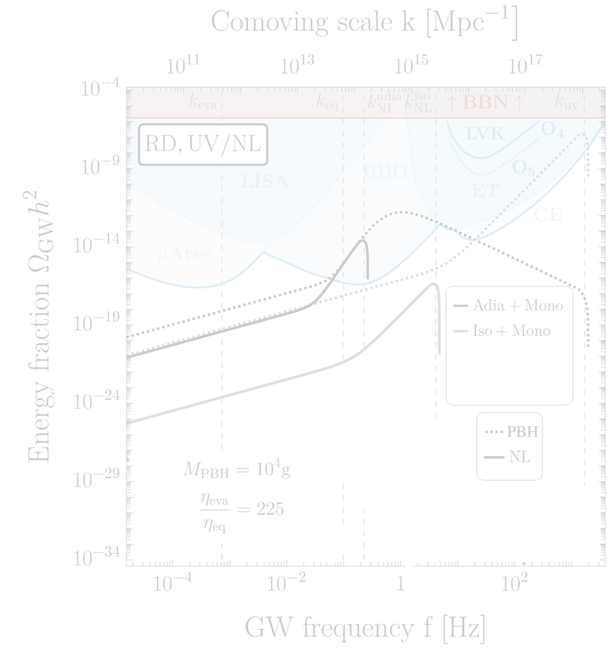




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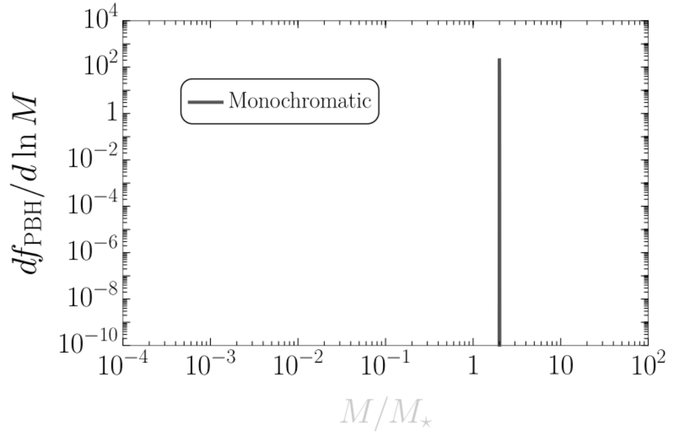
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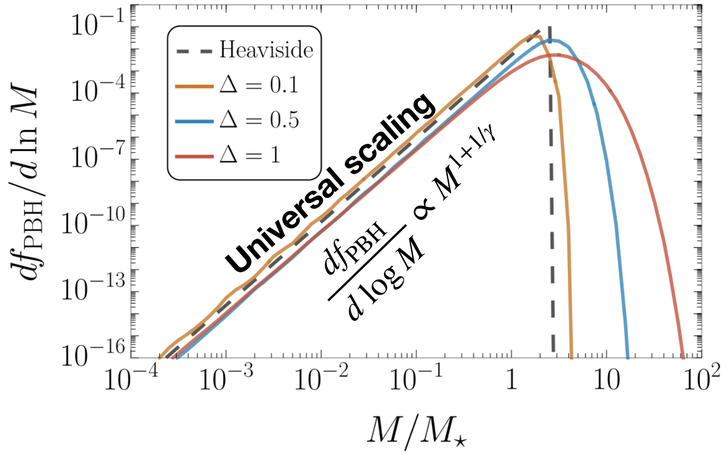
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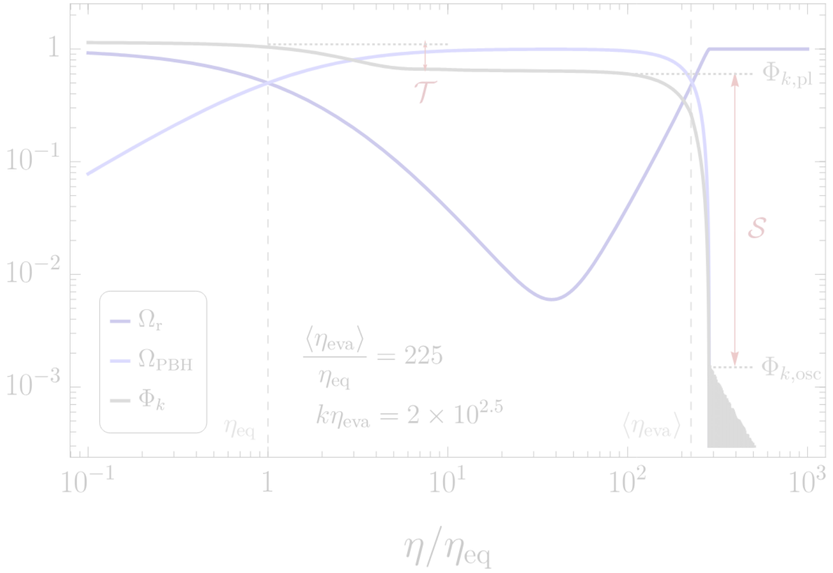
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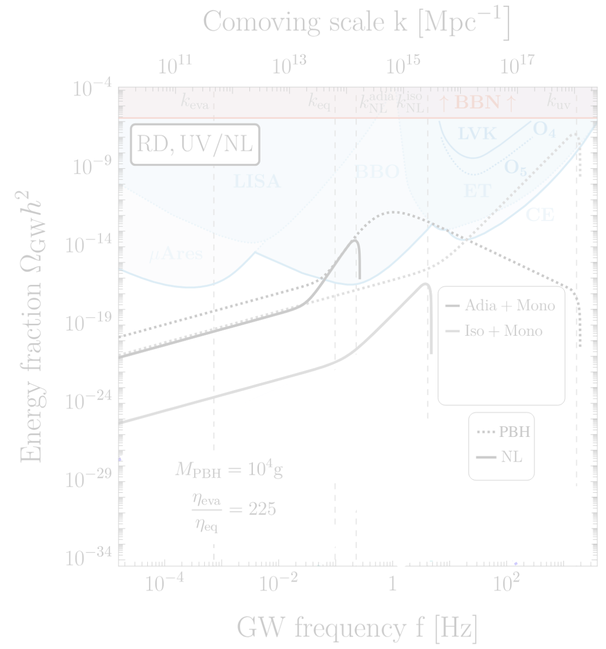




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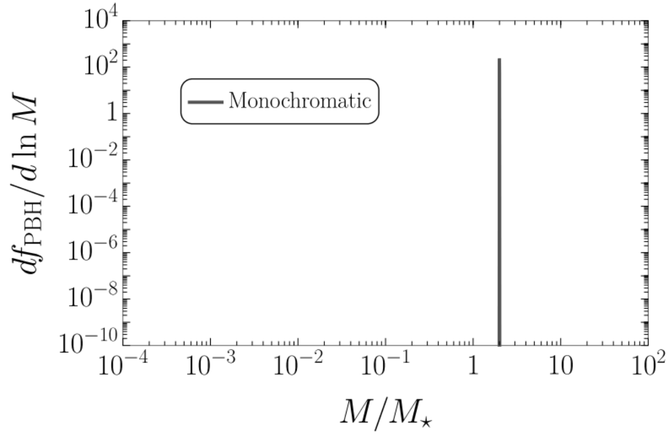
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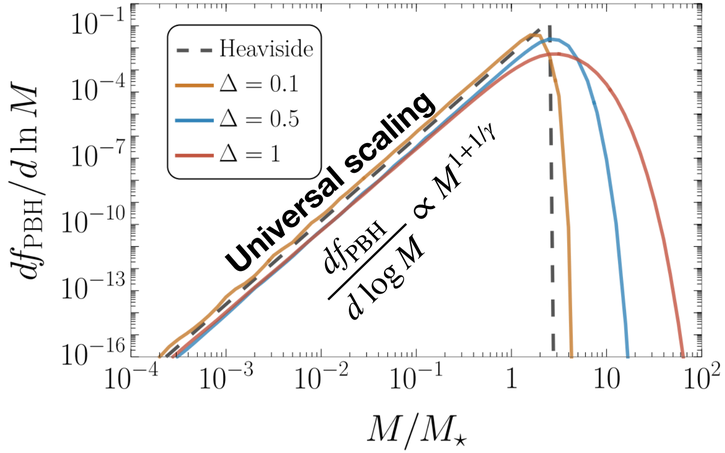
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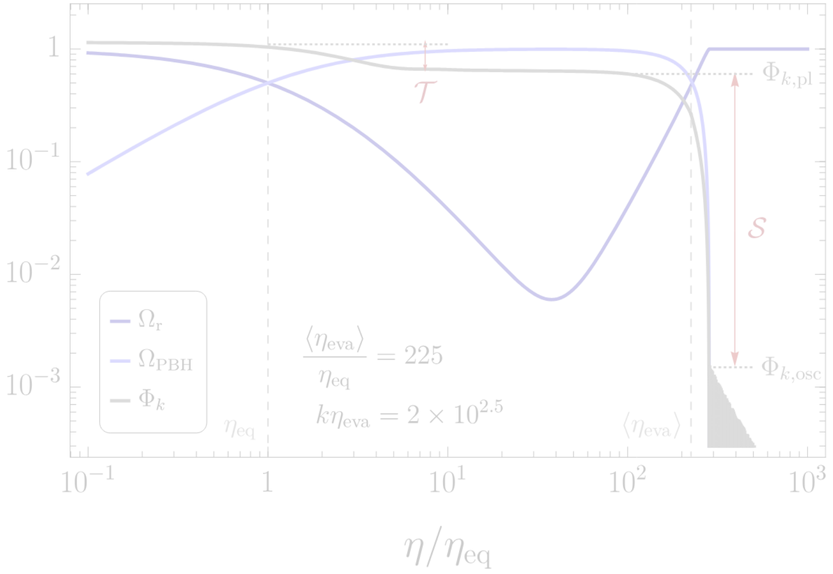
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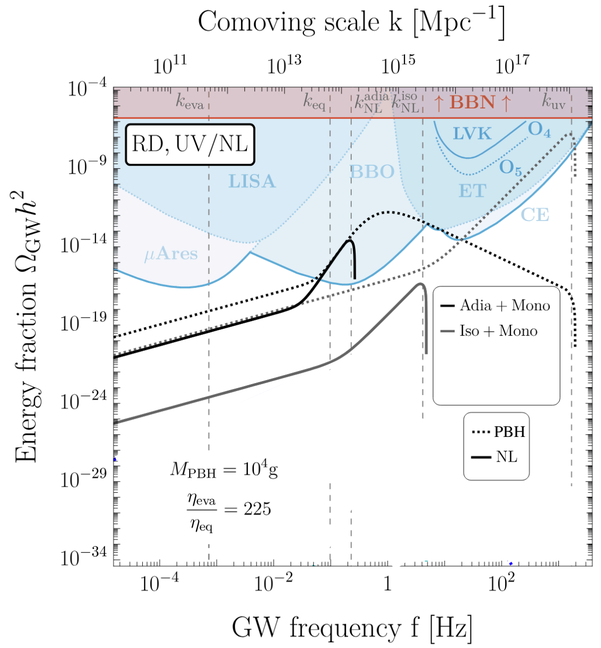




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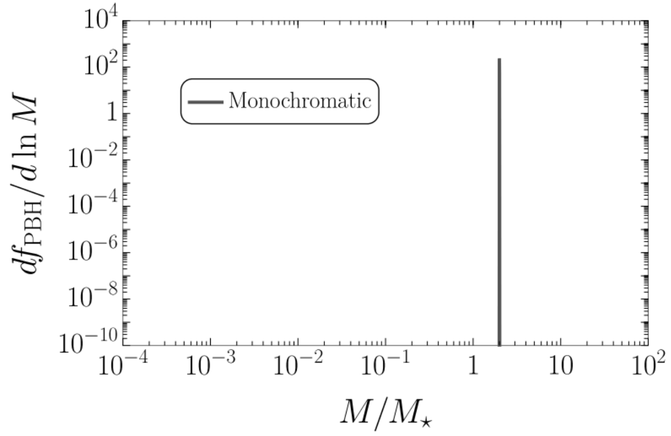
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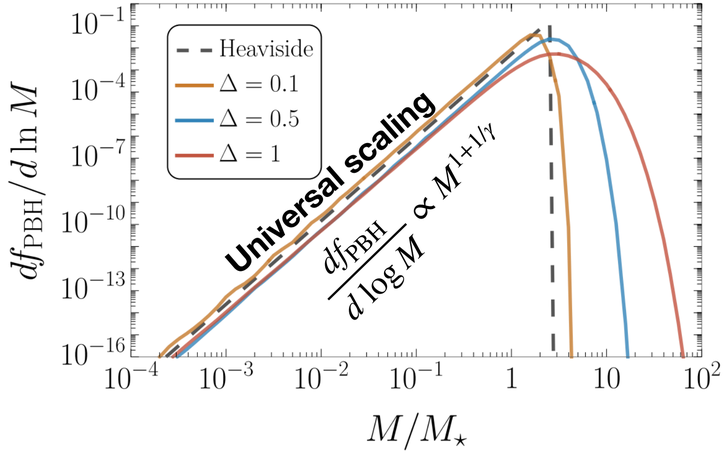
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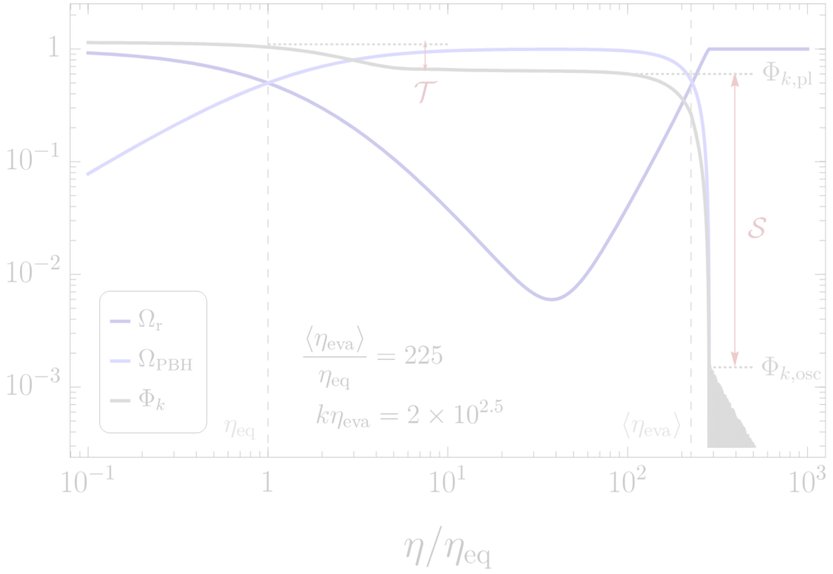
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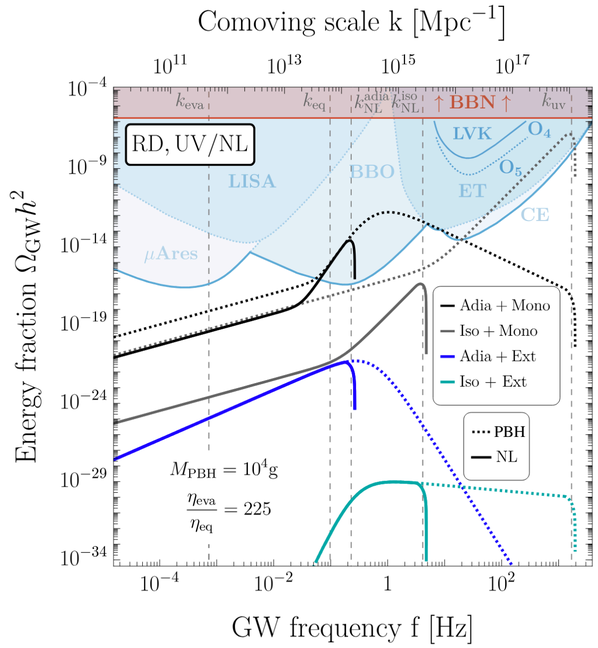



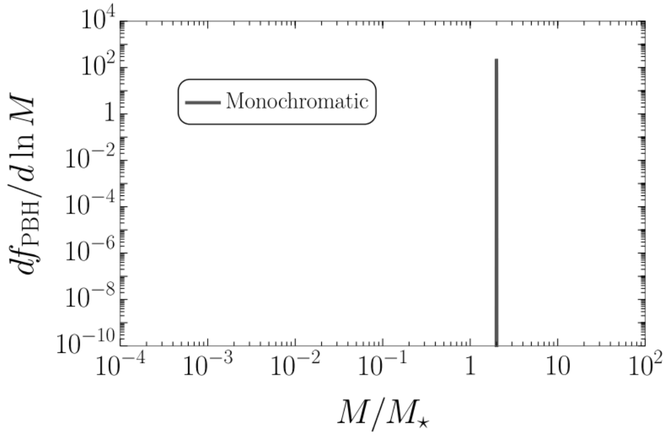

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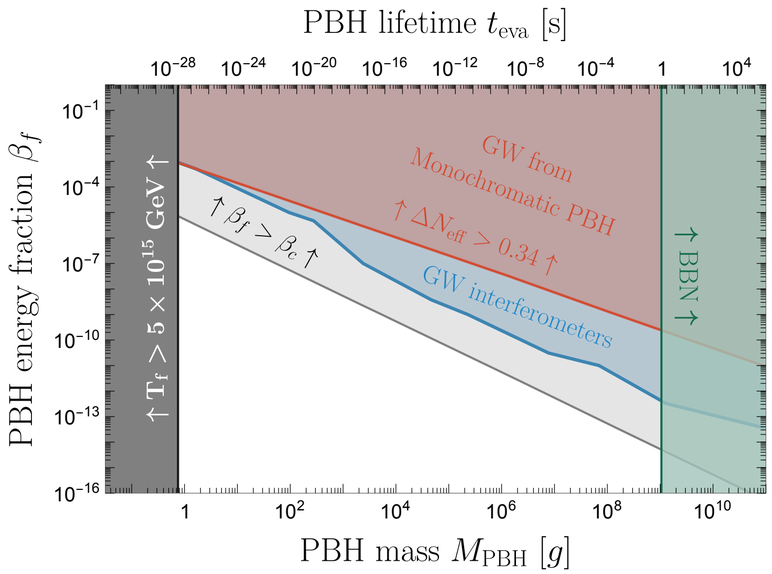
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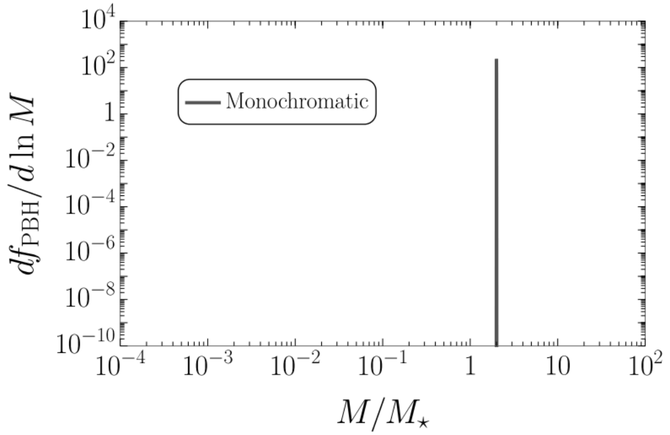
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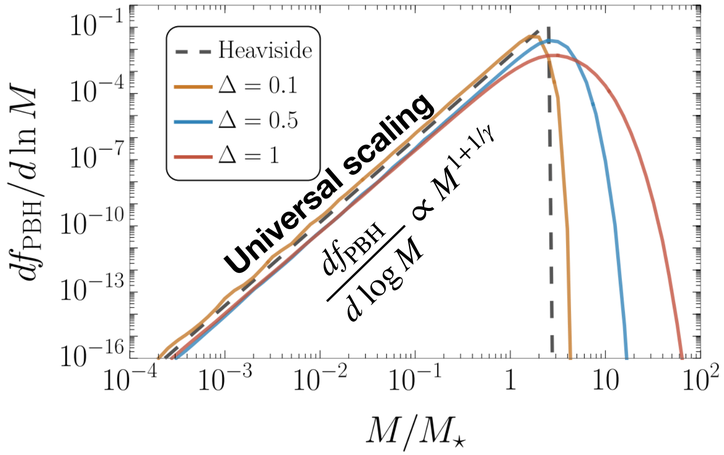



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**Choptuik's law**

***(Choptuik 93')***




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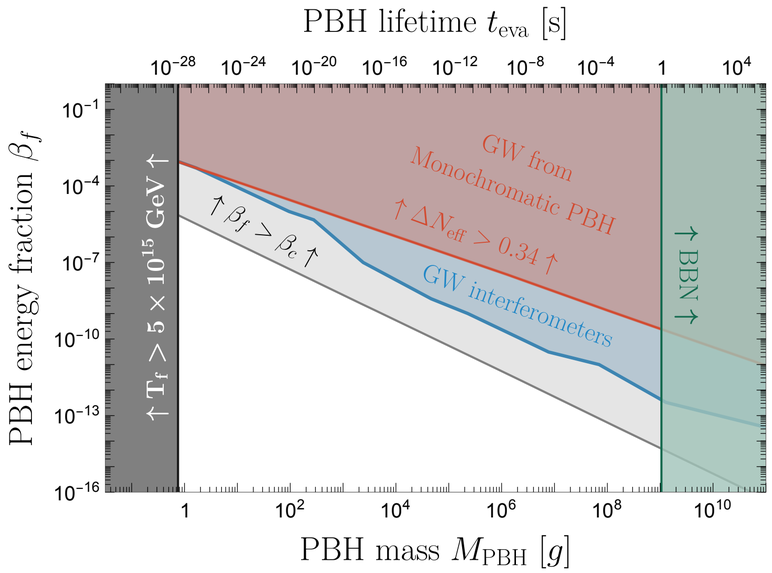
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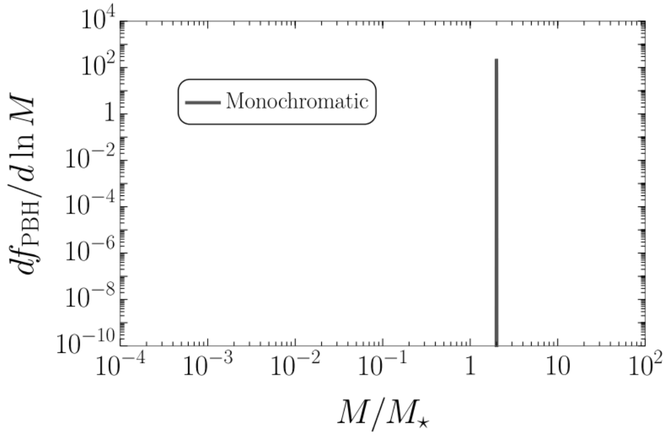
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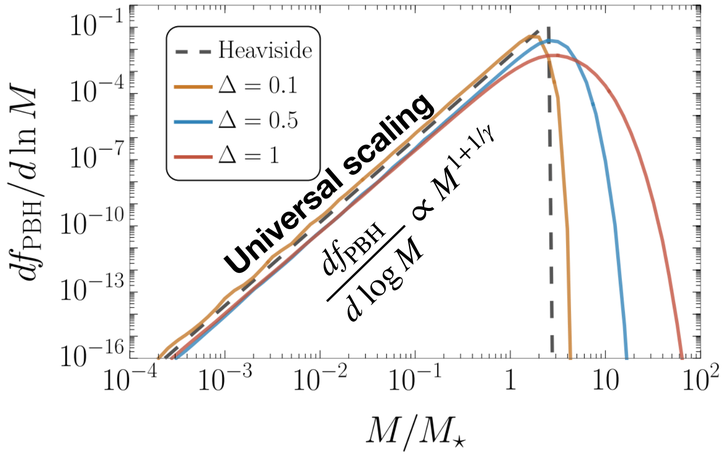



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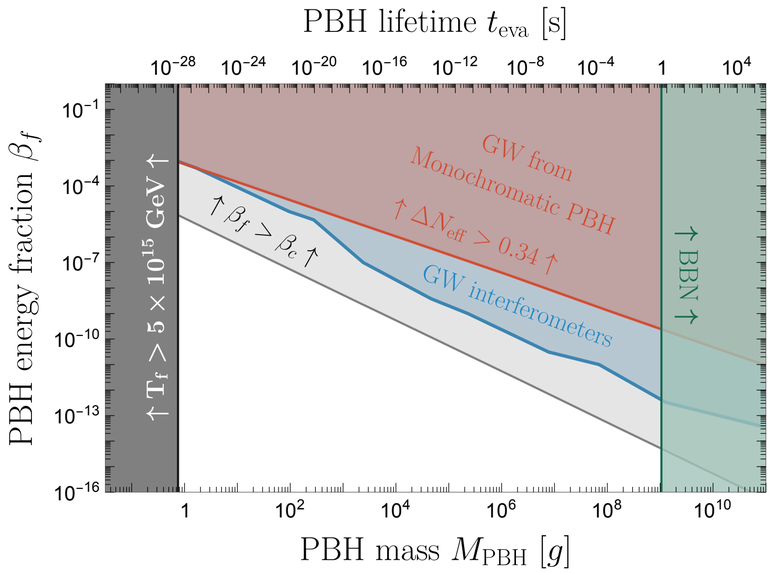
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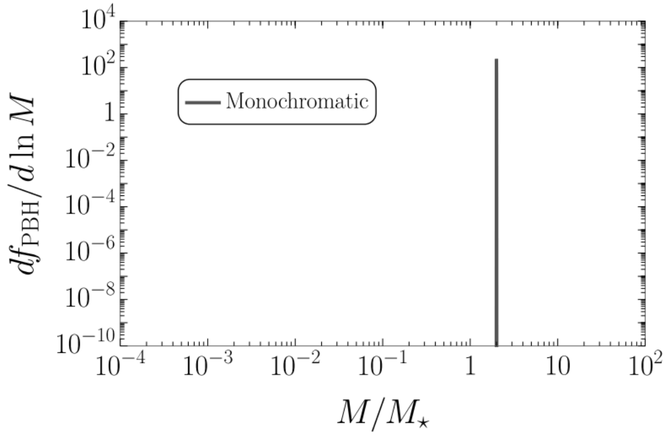



## Opening the Window for Ultra-Light Primordial Black Holes

**In preparation (26XX.XXXX)**


Yann Gouttenoire, Nicholas Leister, Pedro Schwaller

*PRISMA+ Cluster of Excellence & MITP, Johannes Gutenberg University, 55099 Mainz, Germany*

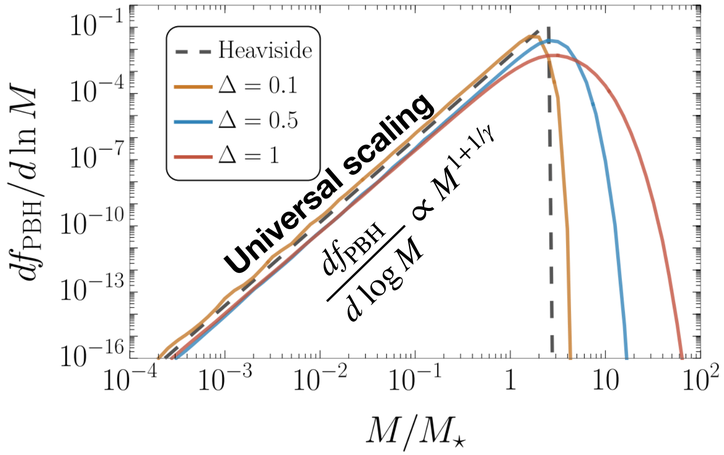



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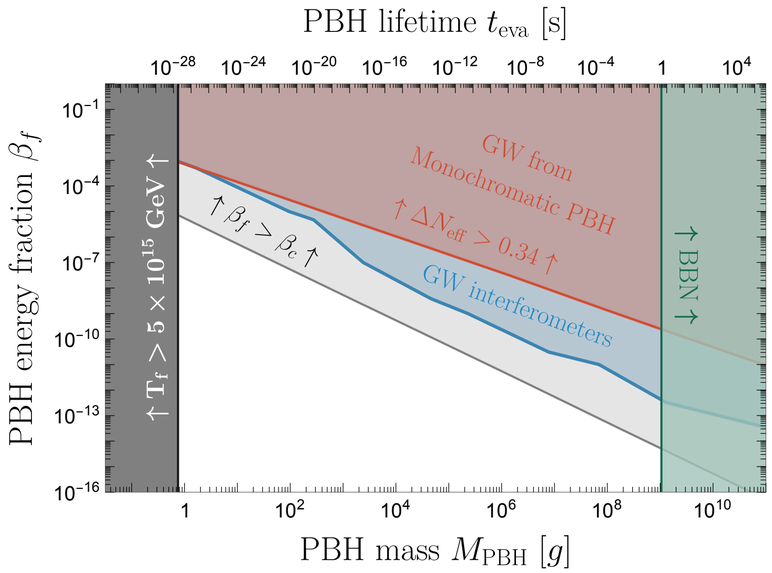
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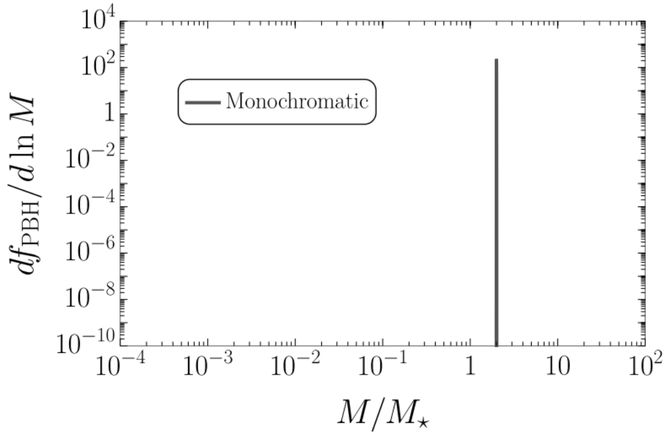



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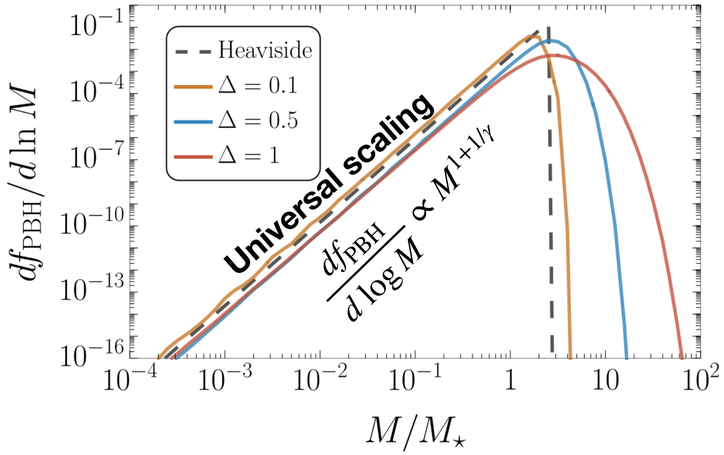



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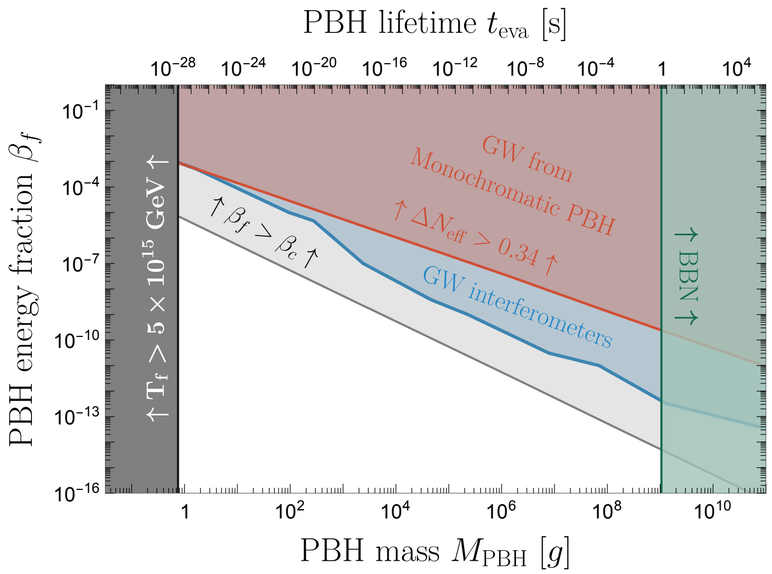
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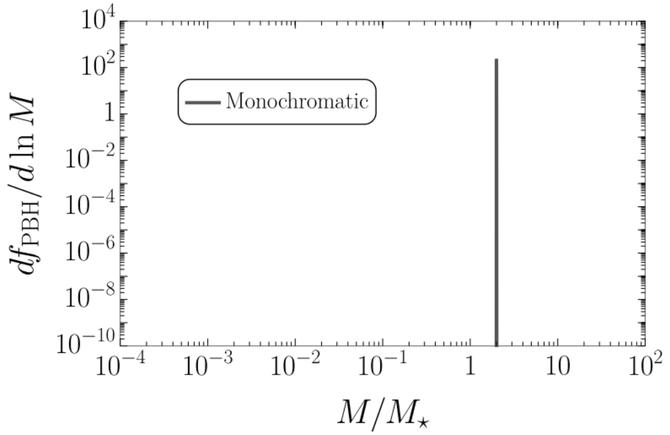
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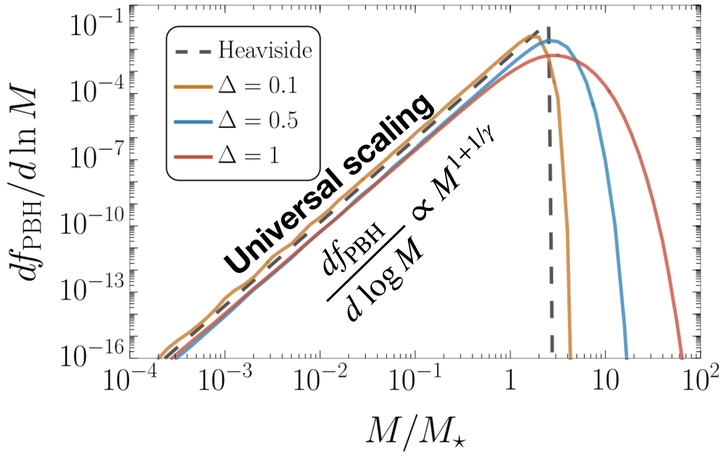



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***Inomata, Kawasaki, Mukaida, Terada, Yanagida (2003.10455)***

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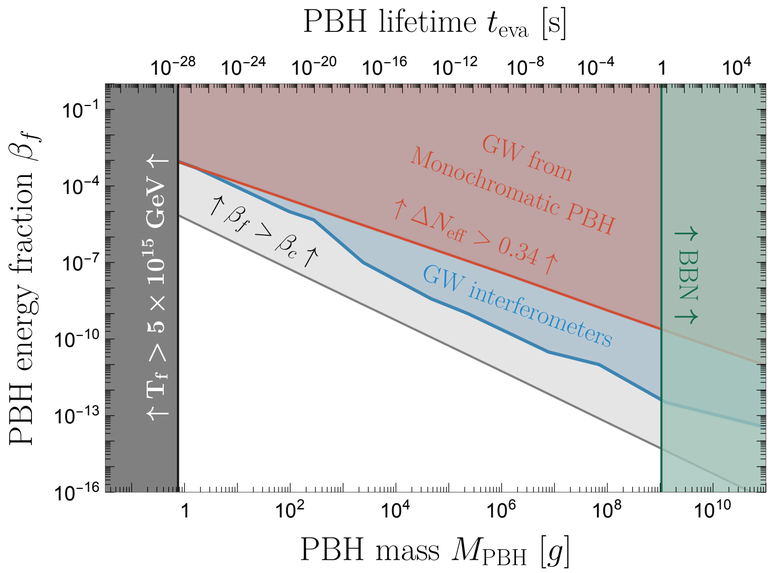
***Domenech, Lin, Sasaki 20'***

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***Domenech, Trankle 24'***

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$$k_{\rm cut} = k_{\rm NL} \quad \text{(conservative)}$$



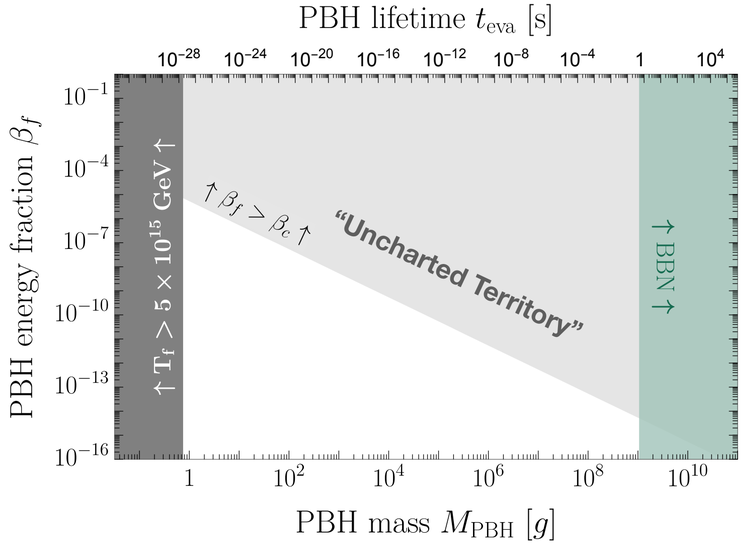

**Opening the Window for Ultra-Light Primordial Black Holes**

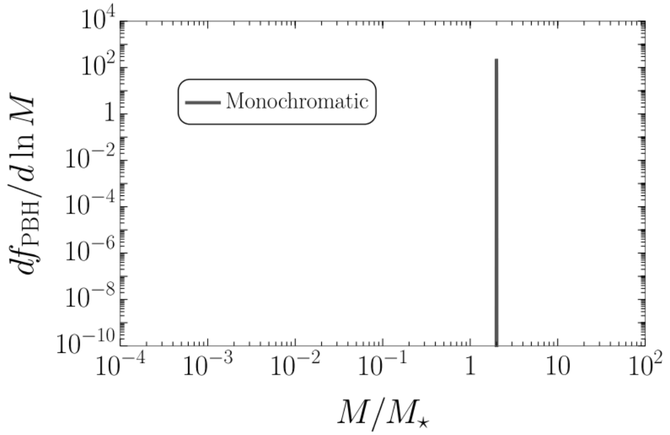
**In preparation (26XX.XXXX)**


Yann Gouttenoire, Nicholas Leister, Pedro Schwaller

*PRISMA+ Cluster of Excellence & MITP, Johannes Gutenberg University, 55099 Mainz, Germany*


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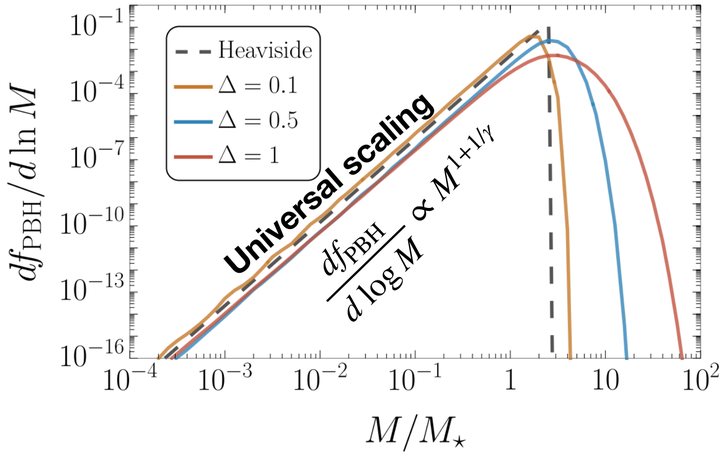



$$\gamma \simeq 0.36$$

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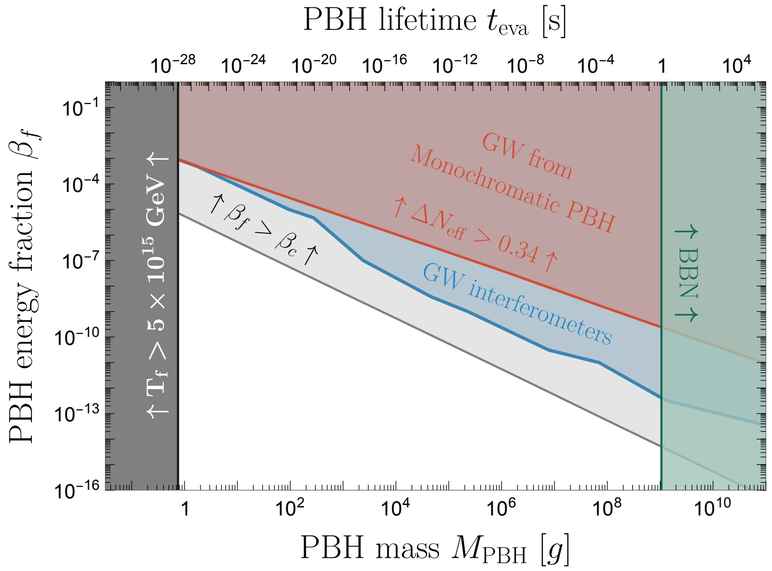
## Opening the Window for Ultra-Light Primordial Black Holes

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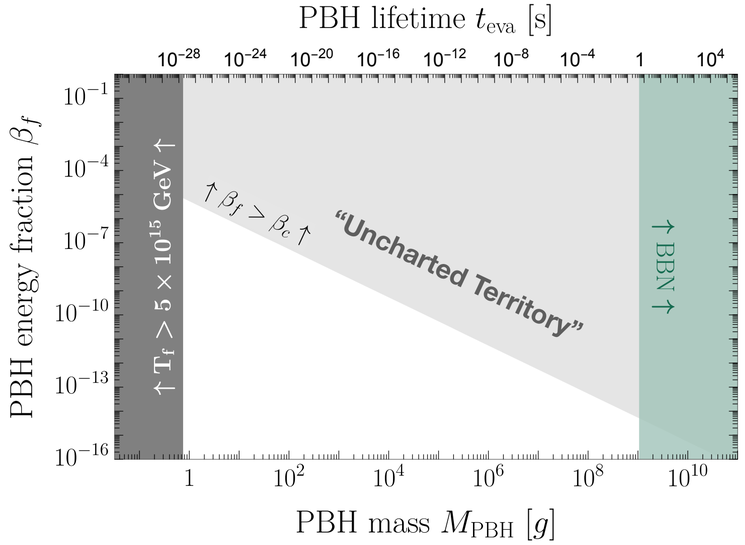

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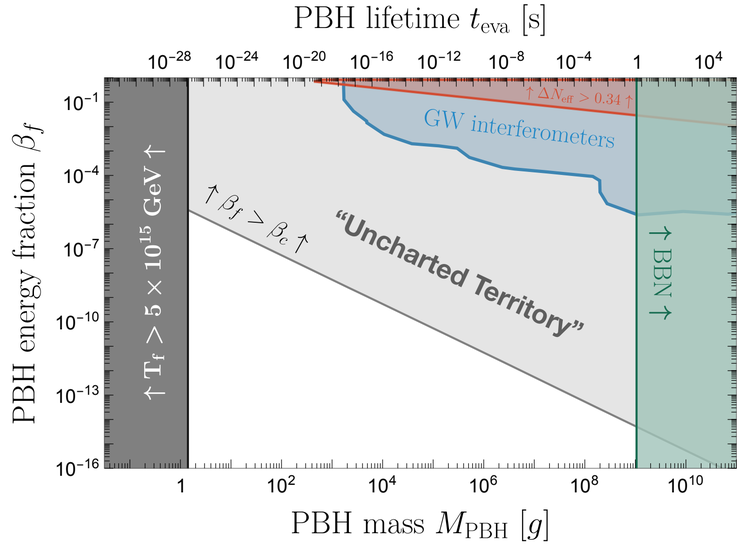

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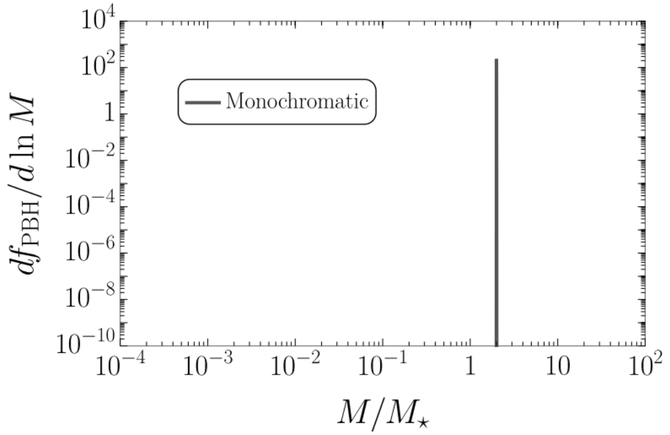



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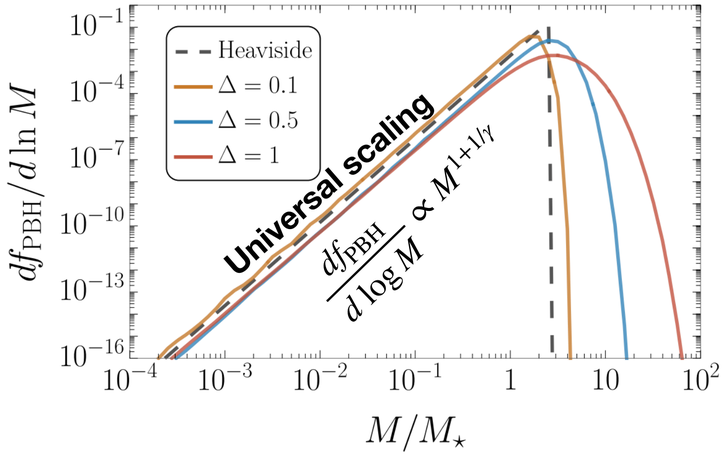



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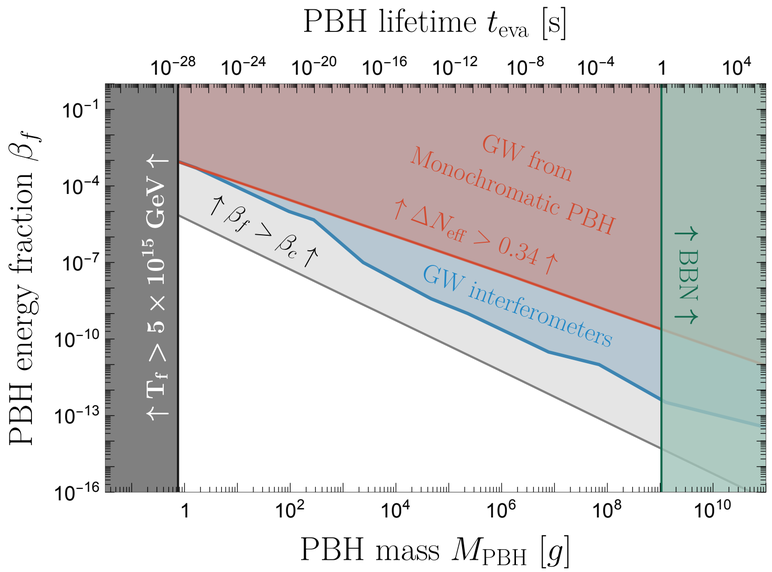
## Opening the Window for Ultra-Light Primordial Black Holes

**In preparation (26XX.XXXX)**

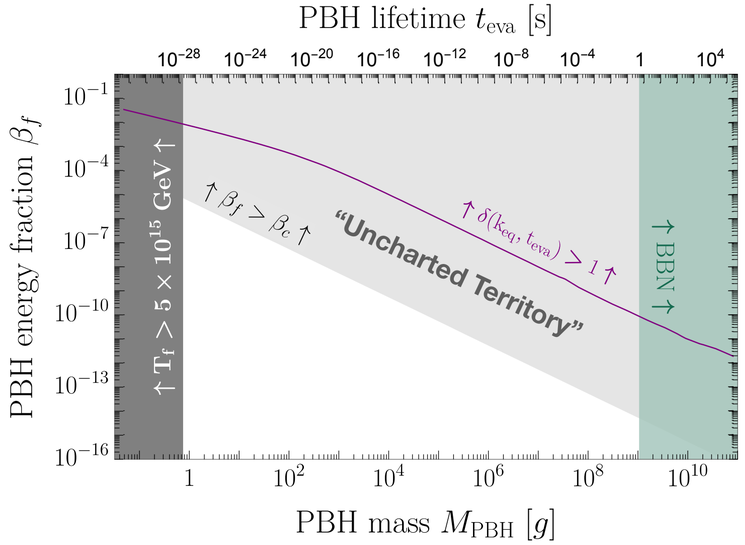

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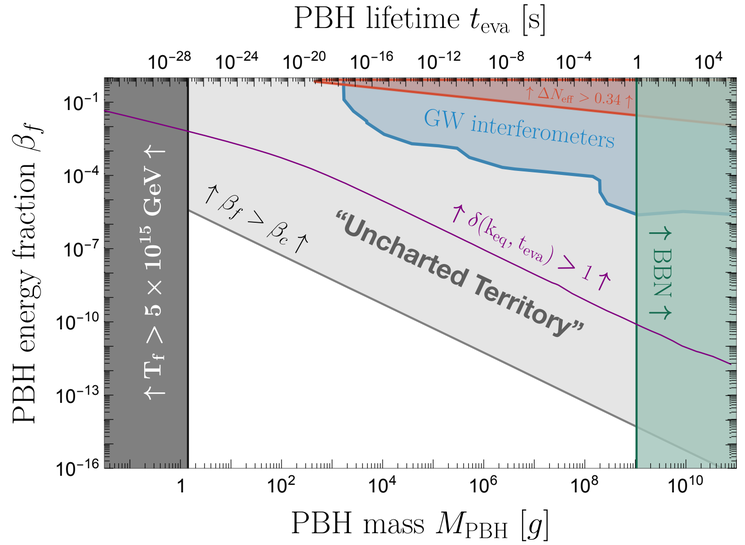

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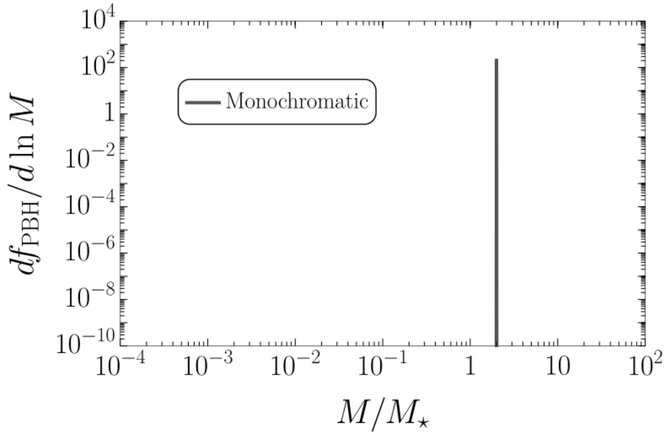



$k_{\rm cut} = k_{\rm NL}$ (conservative)




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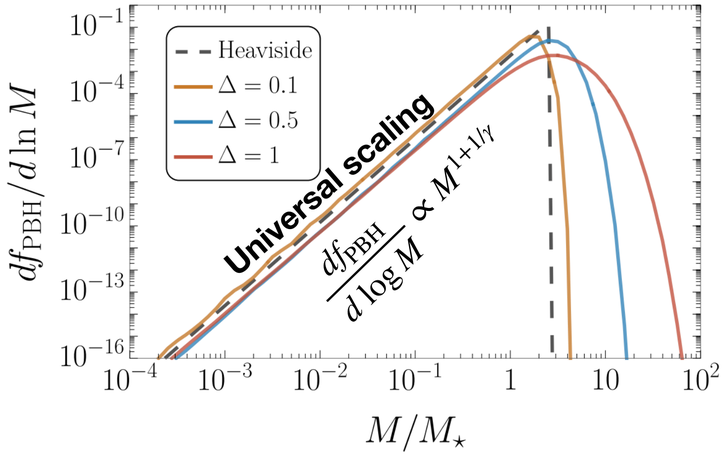



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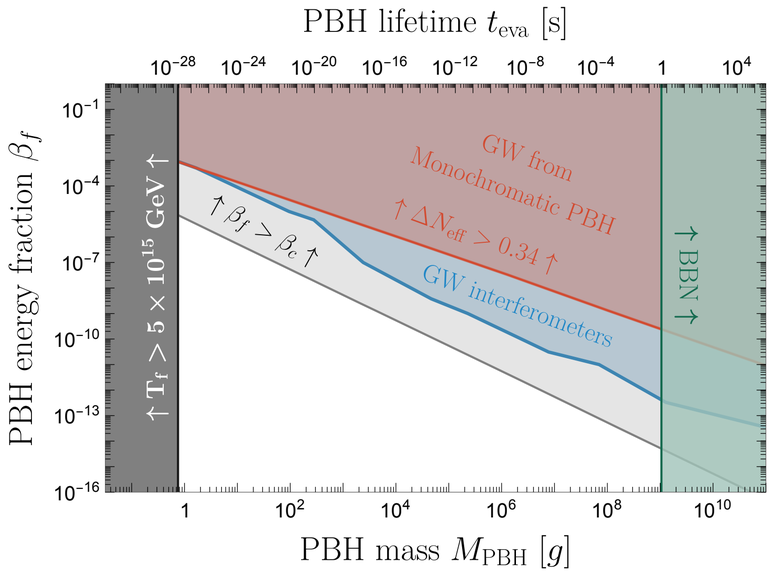
## Opening the Window for Ultra-Light Primordial Black Holes

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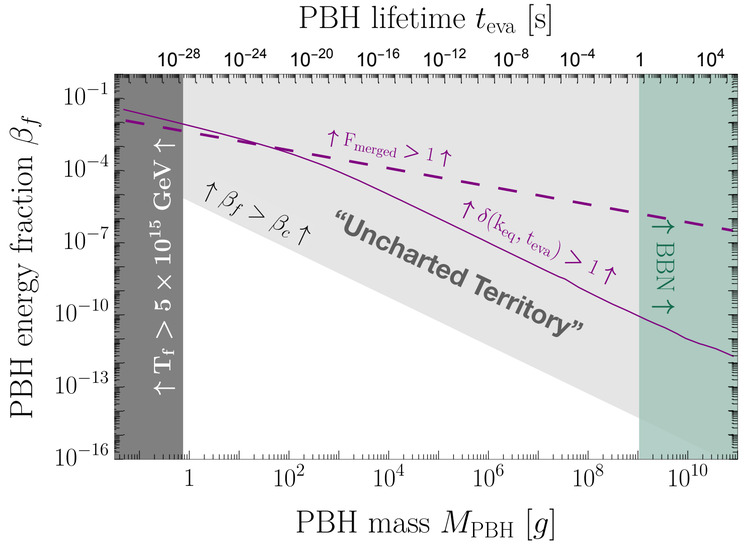

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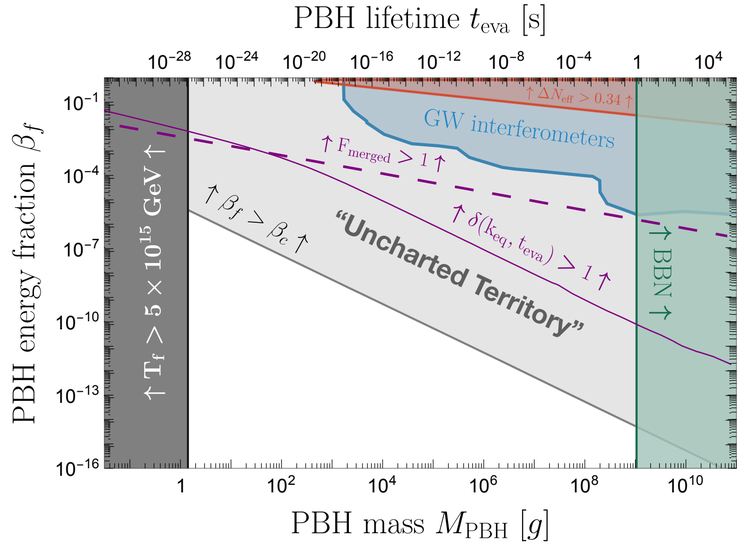

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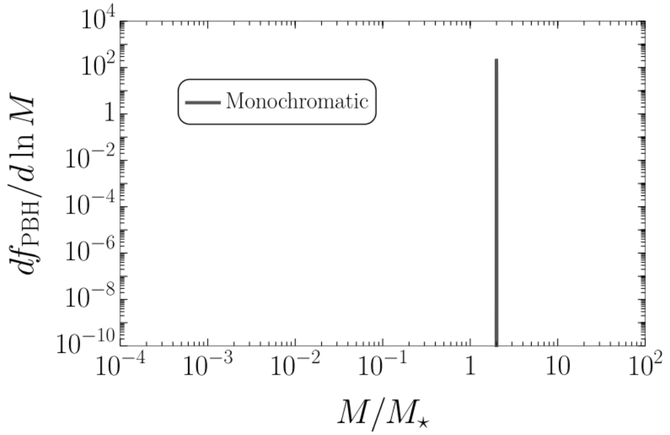



$k_{\rm cut} = k_{\rm NL}$ (conservative)




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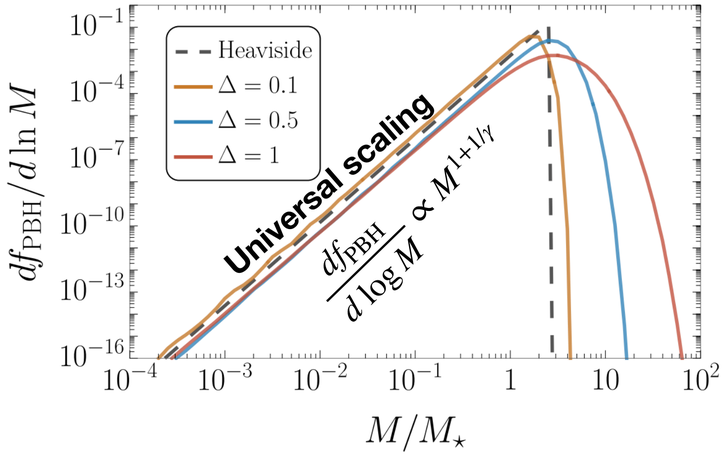



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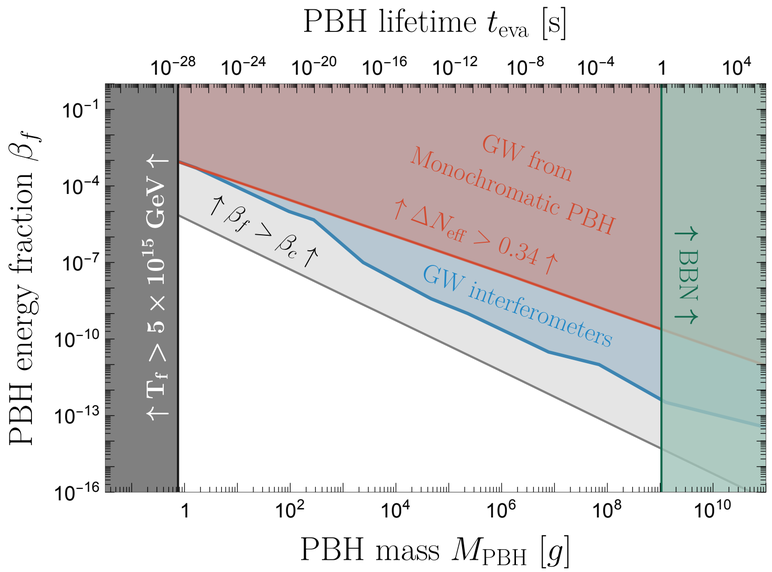
**Opening the Window for Ultra-Light Primordial Black Holes**

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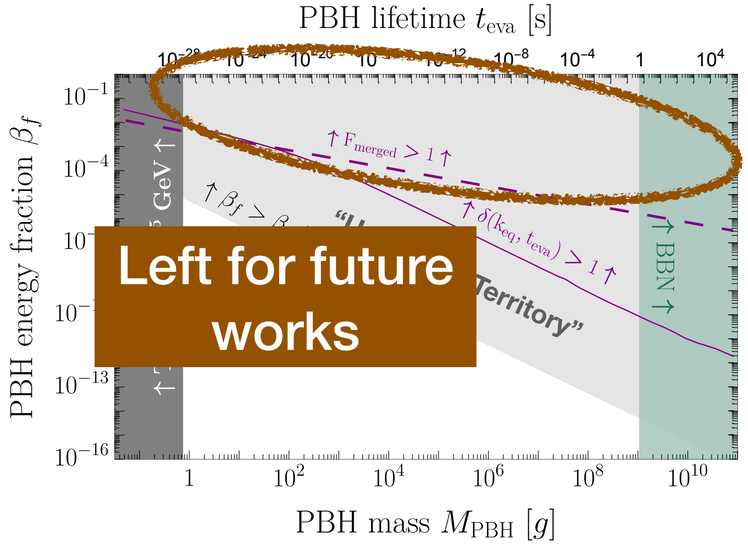

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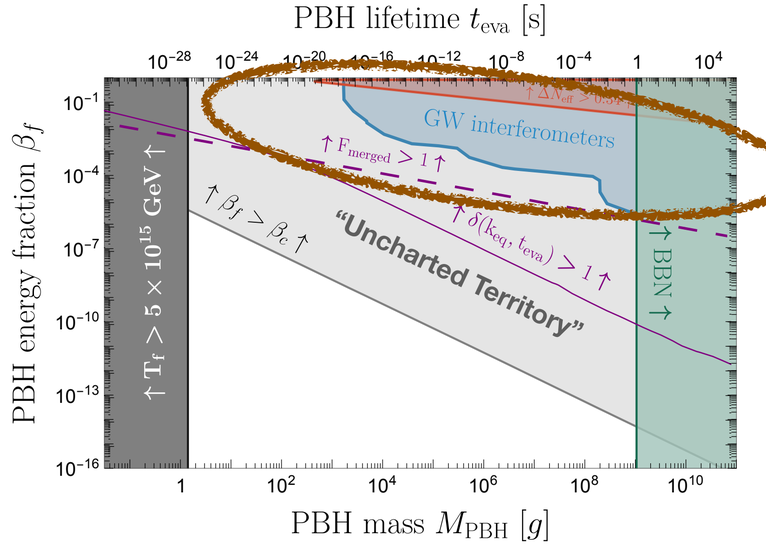



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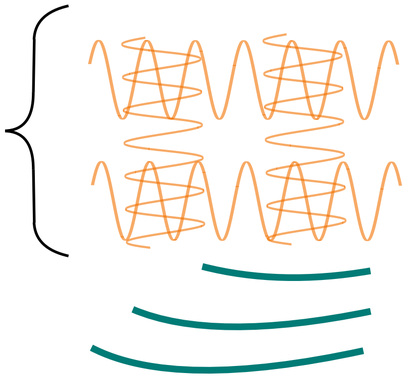

**Left for future works**

$k_{\rm cut} = k_{\rm PBH}$ (aggressive)



**Evaporation ⇒ Sound waves**

**Gas of evaporating PBHs**



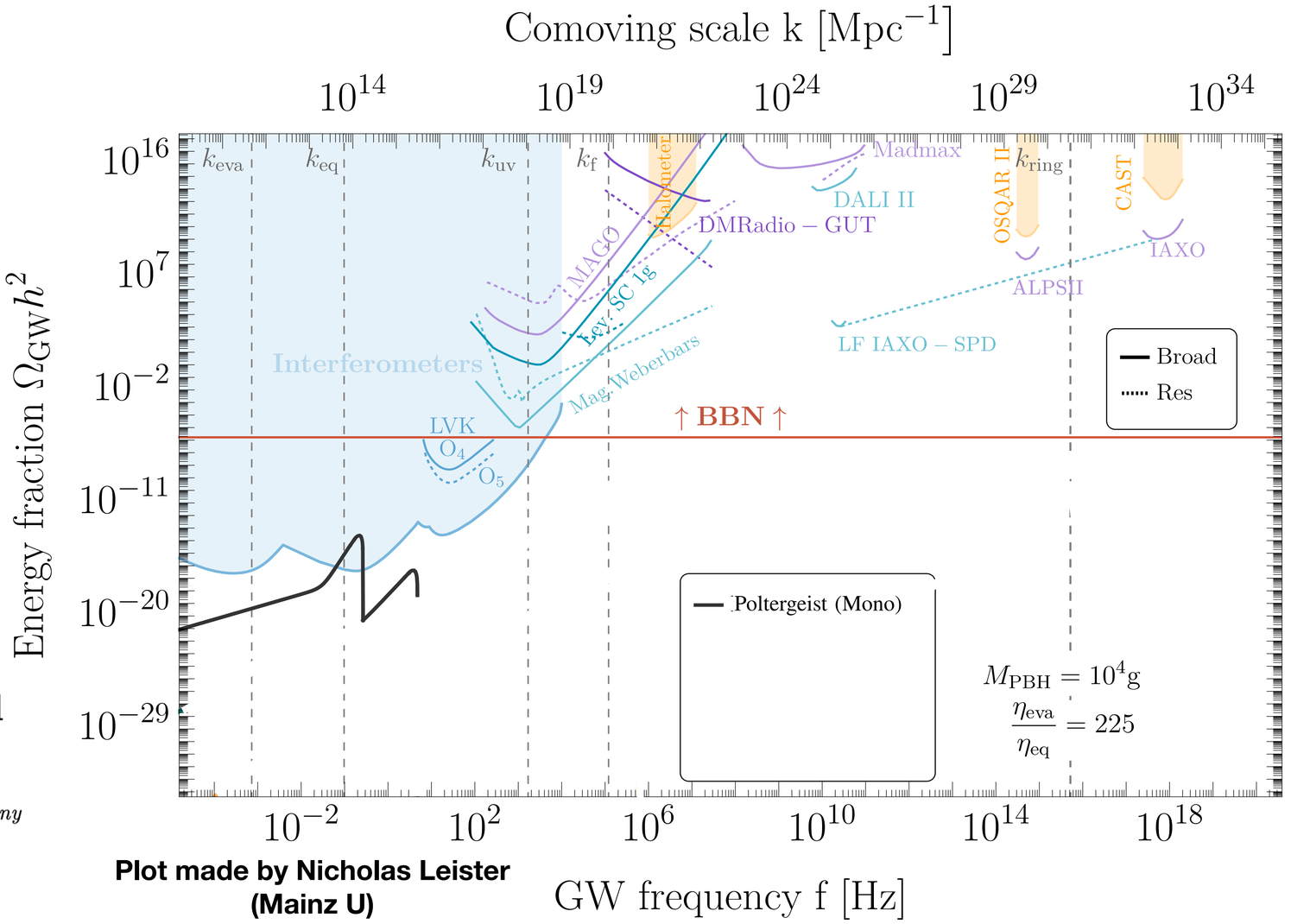
*Inomata, Kawasaki, Mukaida, Terada, Yanagida (2003.10455)*

**Poltergeist GWs**

**Gravitational Waves from Ultra-Light Primordial Black Holes**

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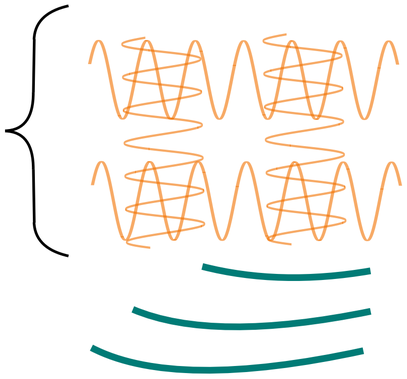
**In preparation (26XX.XXXX)**




**Plot made by Nicholas Leister (Mainz U)**

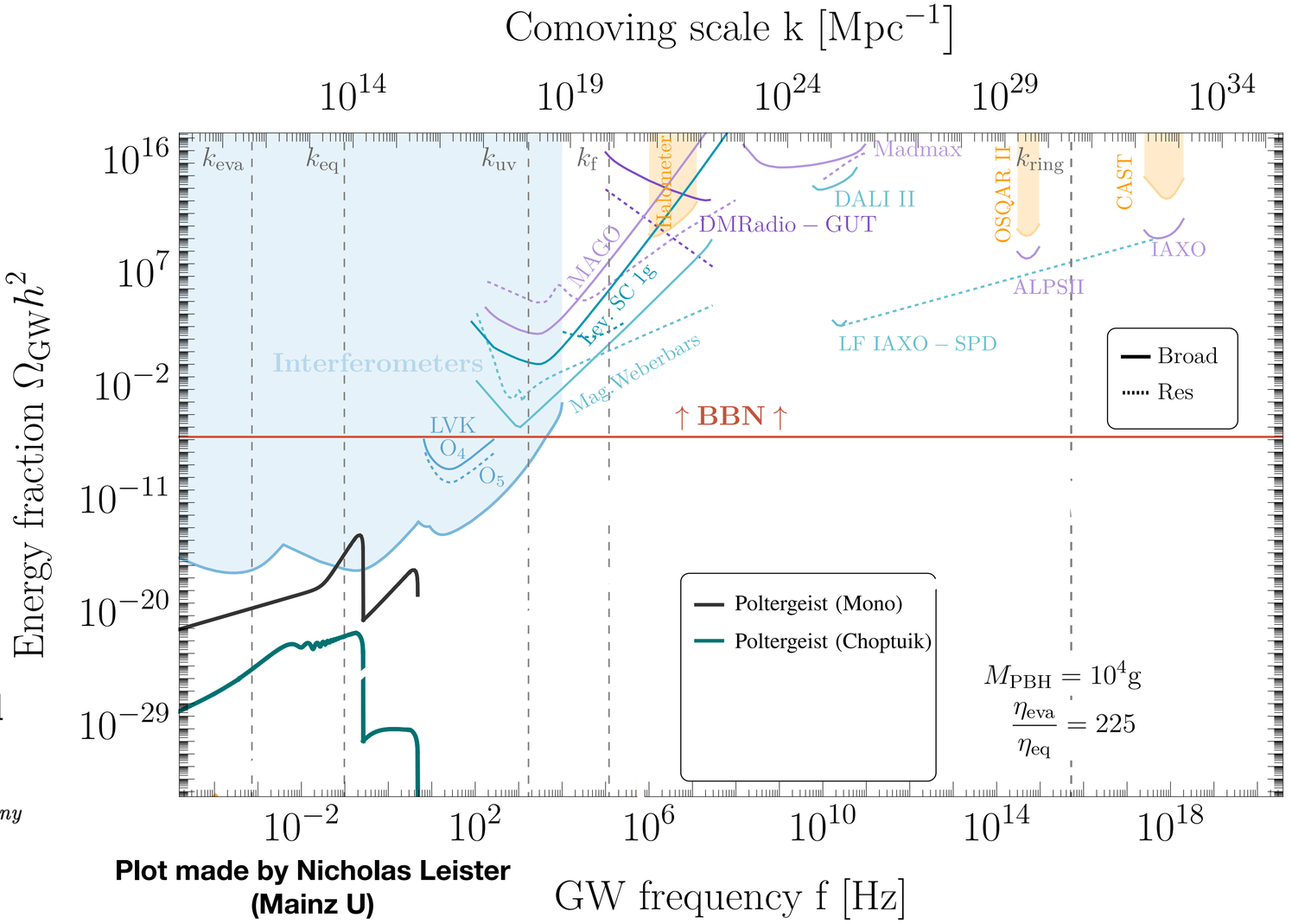
**Evaporation ⇒ Sound waves**

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**Poltergeist GWs**




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## Gravitational Waves from Ultra-Light Primordial Black Holes

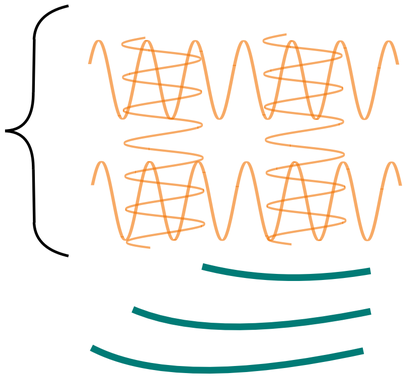

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**In preparation (26XX.XXXX)**

## Evaporation ⇒ Sound waves

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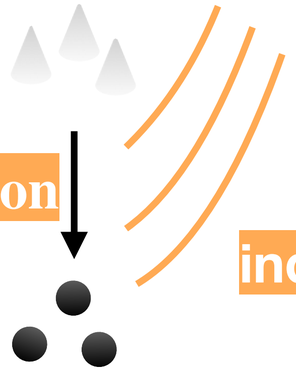


*Inomata, Kawasaki, Mukaida, Terada, Yanagida (2003.10455)*

**Poltergeist GWs**

## Scalar Curvature

$\mathscr{R}(\vec{x}, t)$



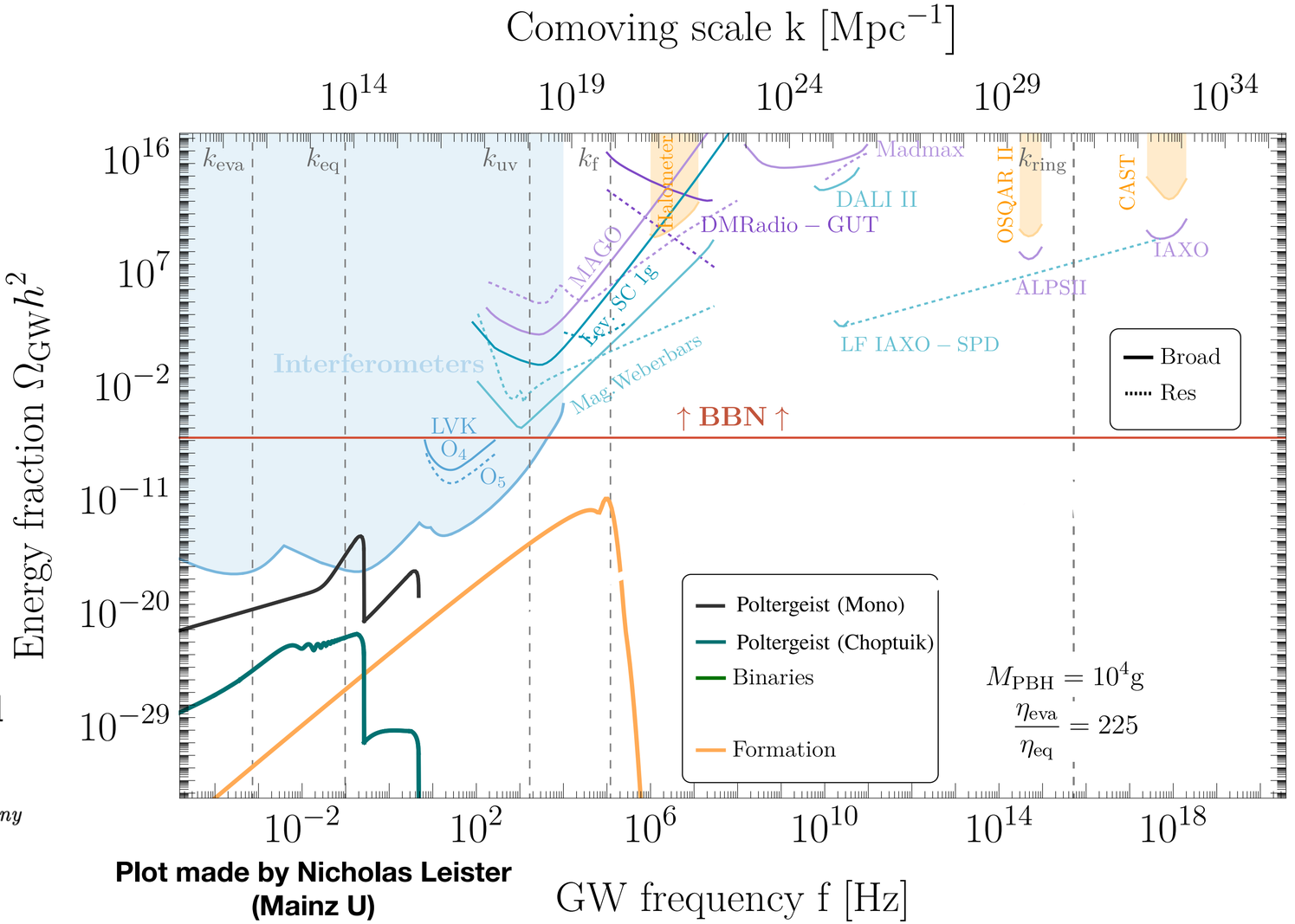
**PBH formation**

**Scalar-induced GW**

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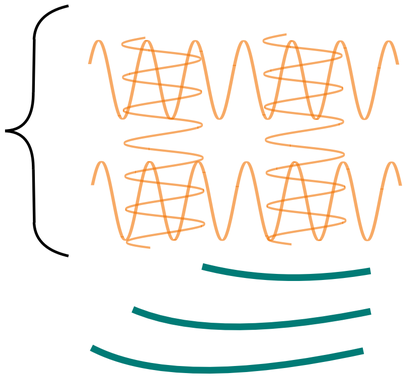
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**Plot made by Nicholas Leister (Mainz U)**

## Evaporation ⇒ Sound waves

**Gas of evaporating PBHs**

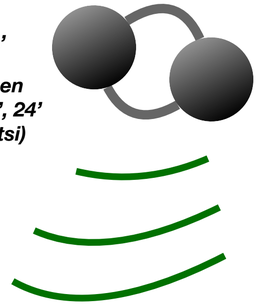


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**Poltergeist GWs**

*Sasaki review 18'*

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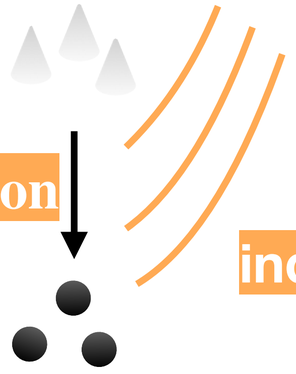
**GW from binaries**

## Scalar Curvature

$\mathscr{R}(\vec{x}, t)$

**PBH formation**

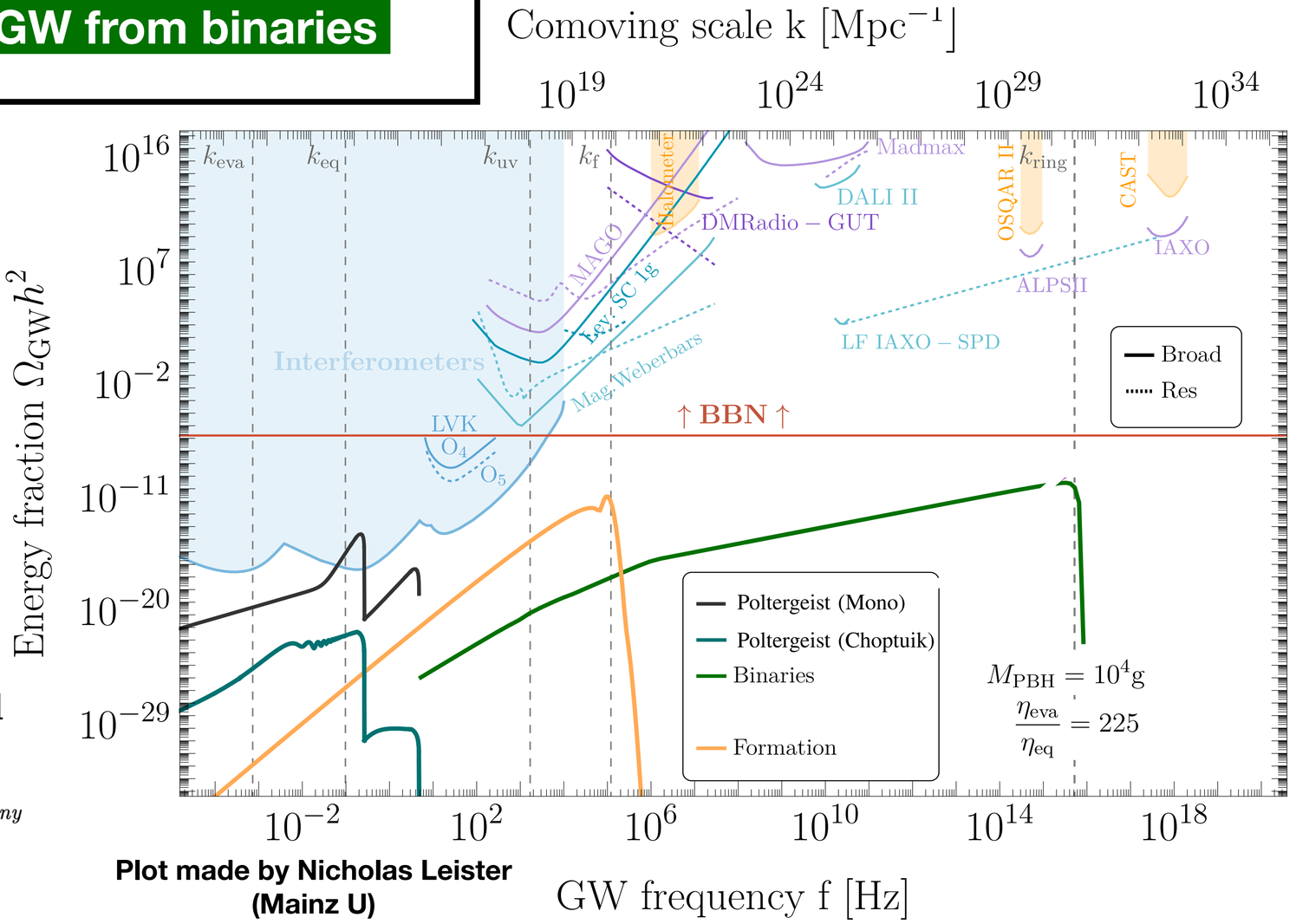
**Scalar-induced GW**



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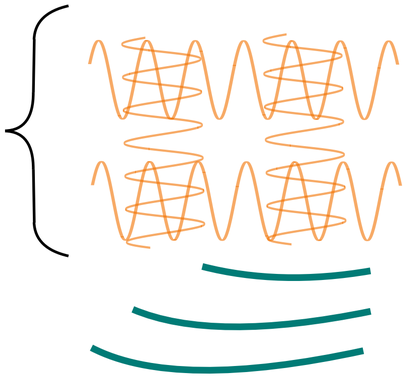
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**Plot made by Nicholas Leister (Mainz U)**

## Evaporation ⇒ Sound waves

Gas of evaporating PBHs

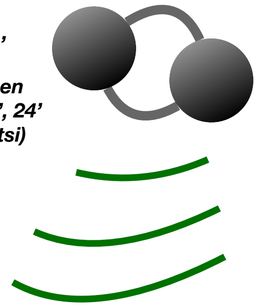


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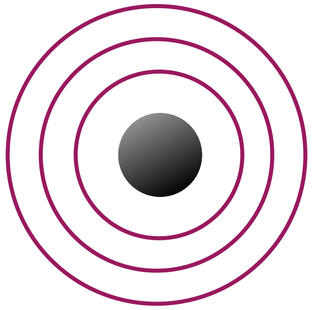
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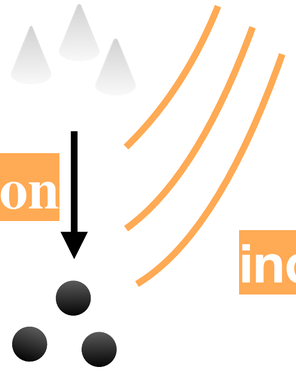
**GW from binaries**



**GW from Hawking evaporation**

### Scalar Curvature

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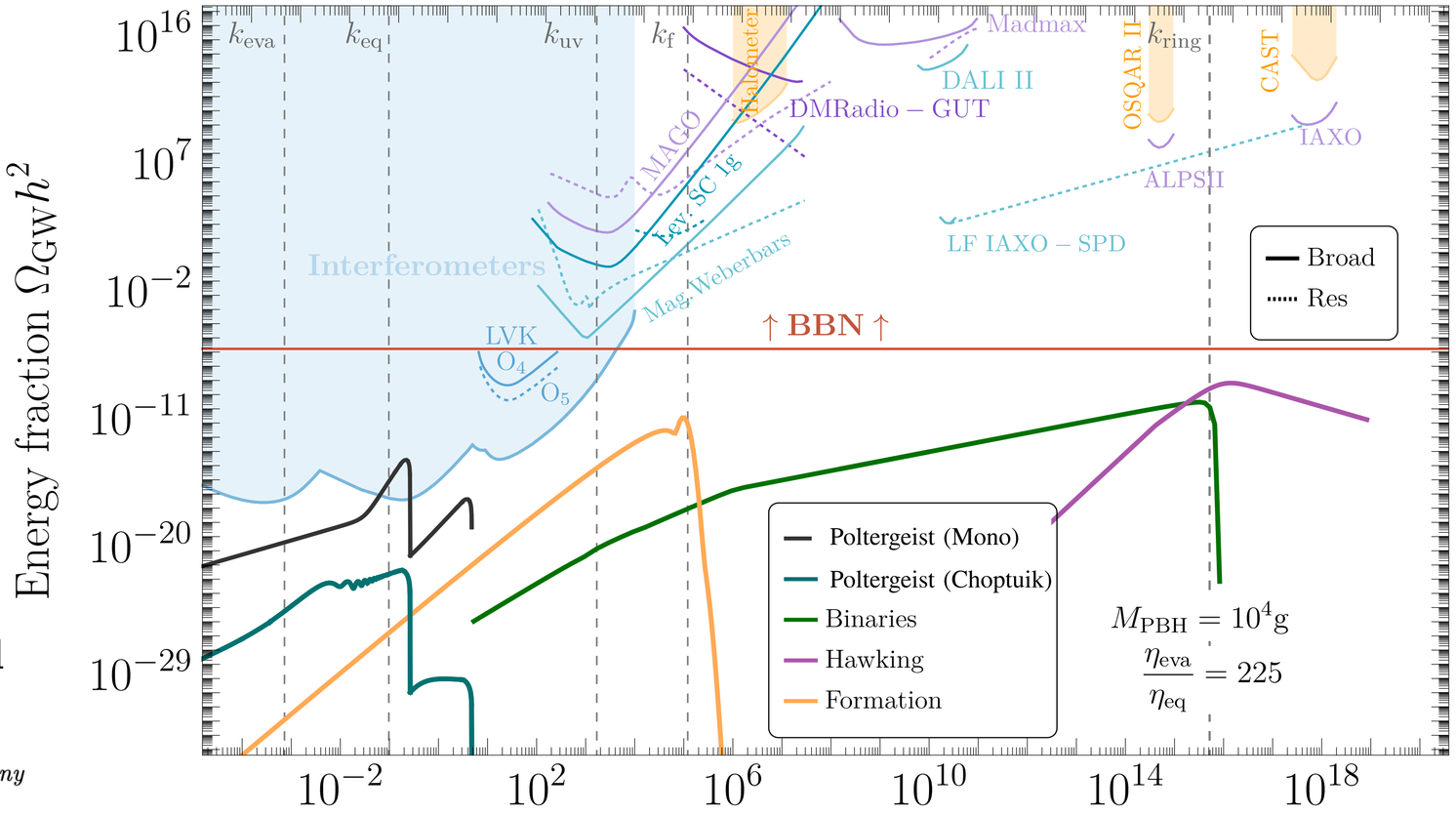
**PBH formation**

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## Gravitational Waves from Ultra-Light Primordial Black Holes

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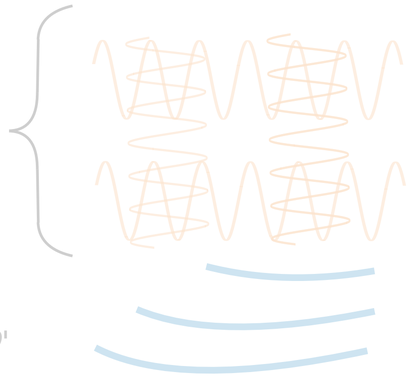
**In preparation (26XX.XXXX)**




**Plot made by Nicholas Leister (Mainz U)**

## Evaporation ⇒ Sound waves

Gas of evaporating PBHs



Inomata, Kawasaki, Mukaida, Terada, Yanagida (2003.10455)

Papanikolaou, Vennin, Langlois 20'

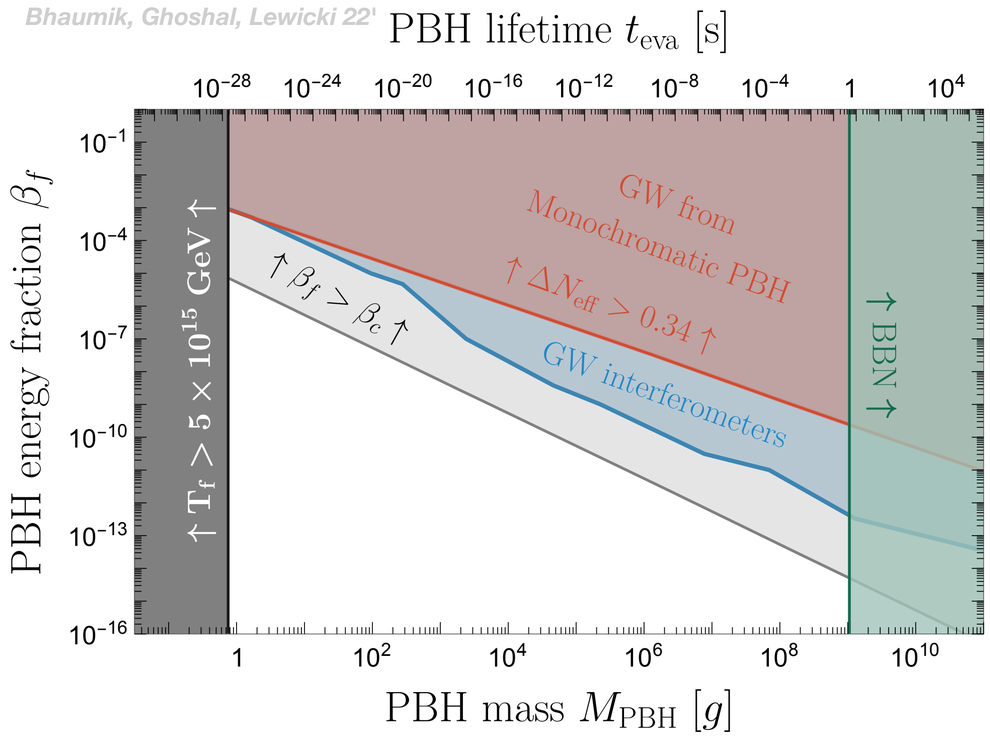
Domenech, Lin, Sasaki 20'

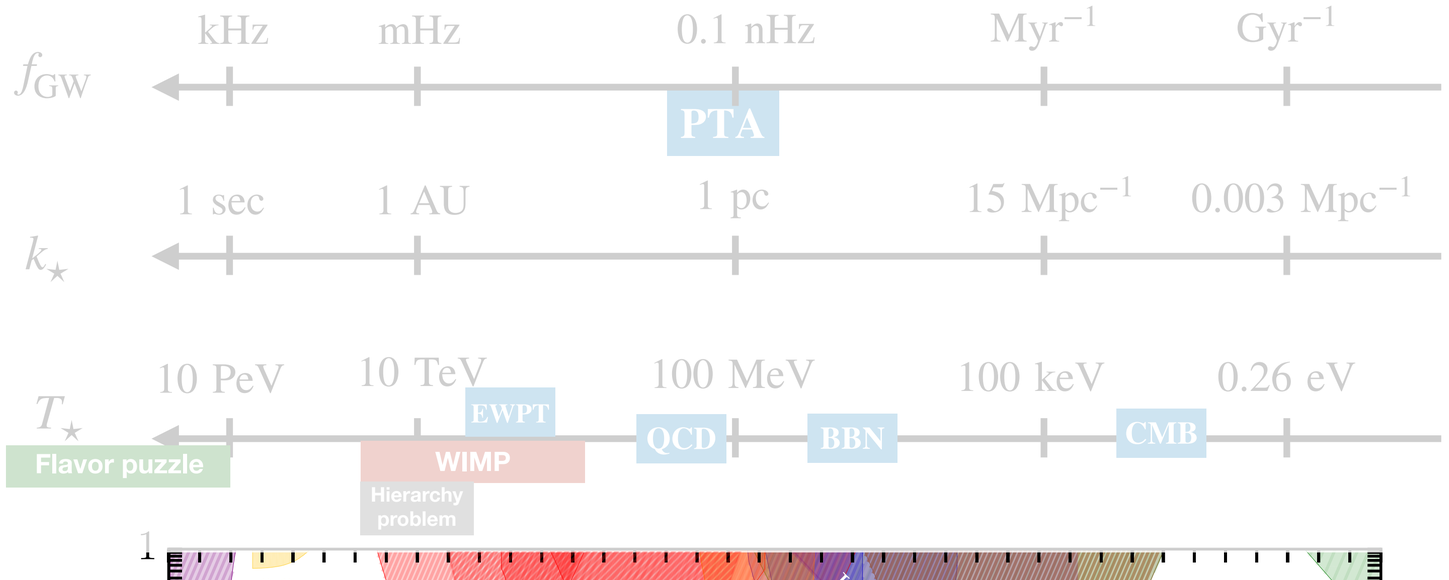
Domenech, Takhistov, Sasaki 21'

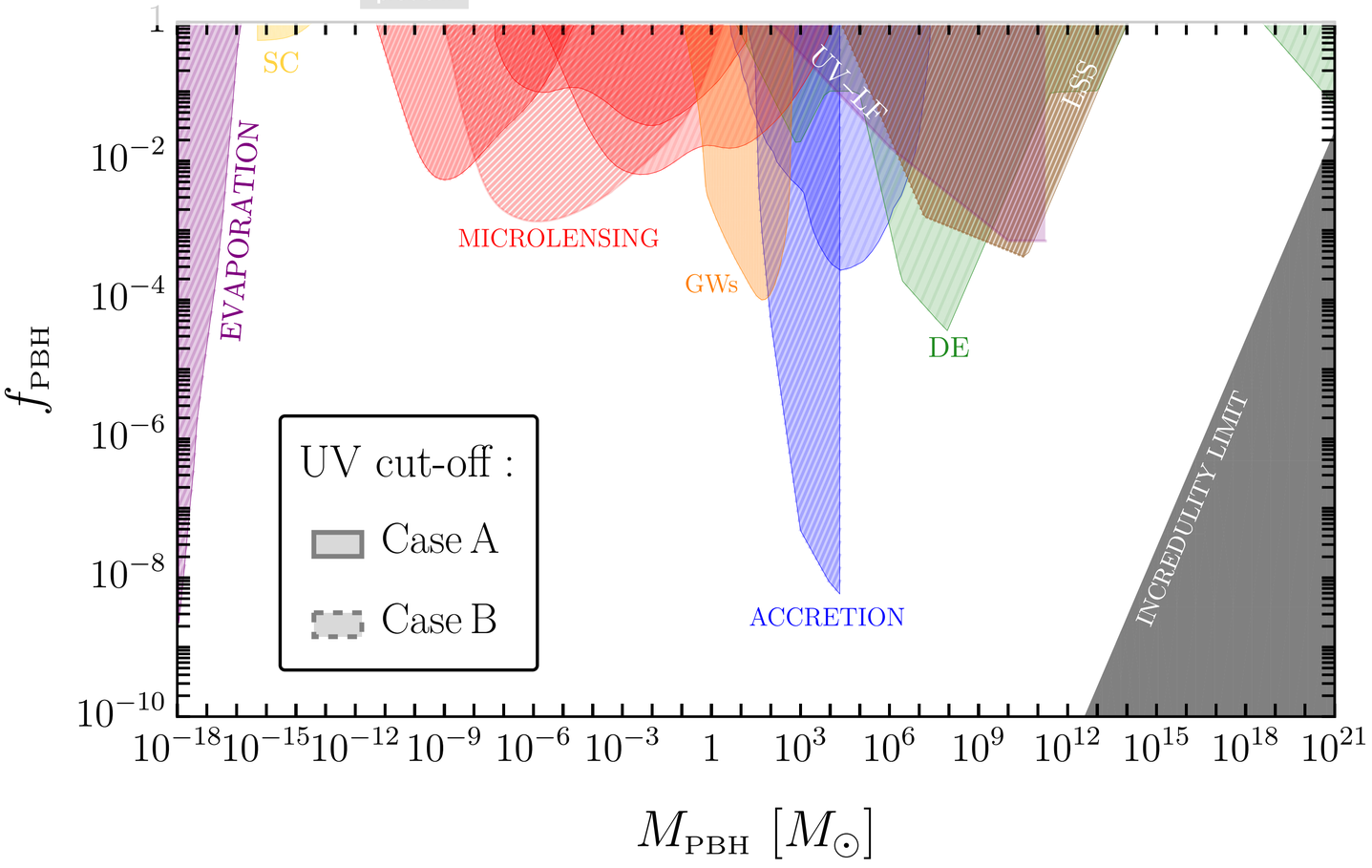
Domenech, Trankle 24'

Bhaumik, Ghoshal, Lewicki 22'

## Poltergeist GWs

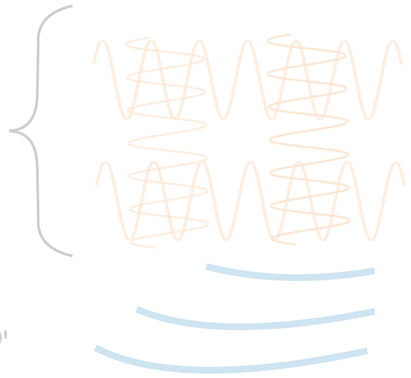


## Evaporation ⇒ Sound waves

Gas of evaporating PBHs



Inomata, Kawasaki, Mukaida, Terada, Yanagida (2003.10455)

Papanikolaou, Vennin, Langlois 20'

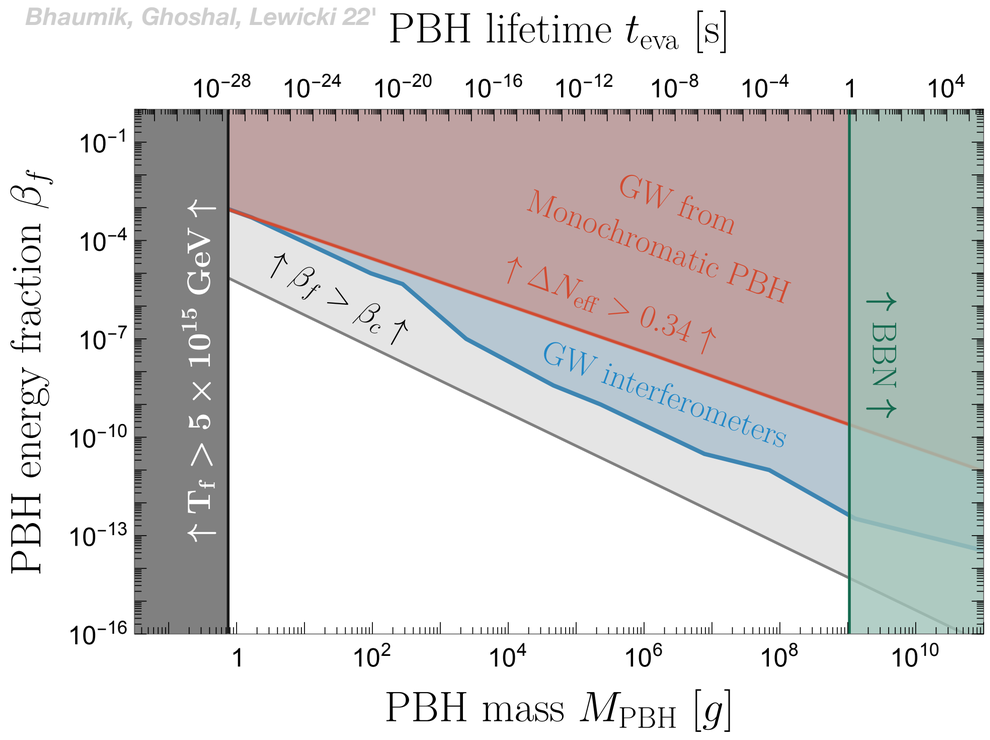
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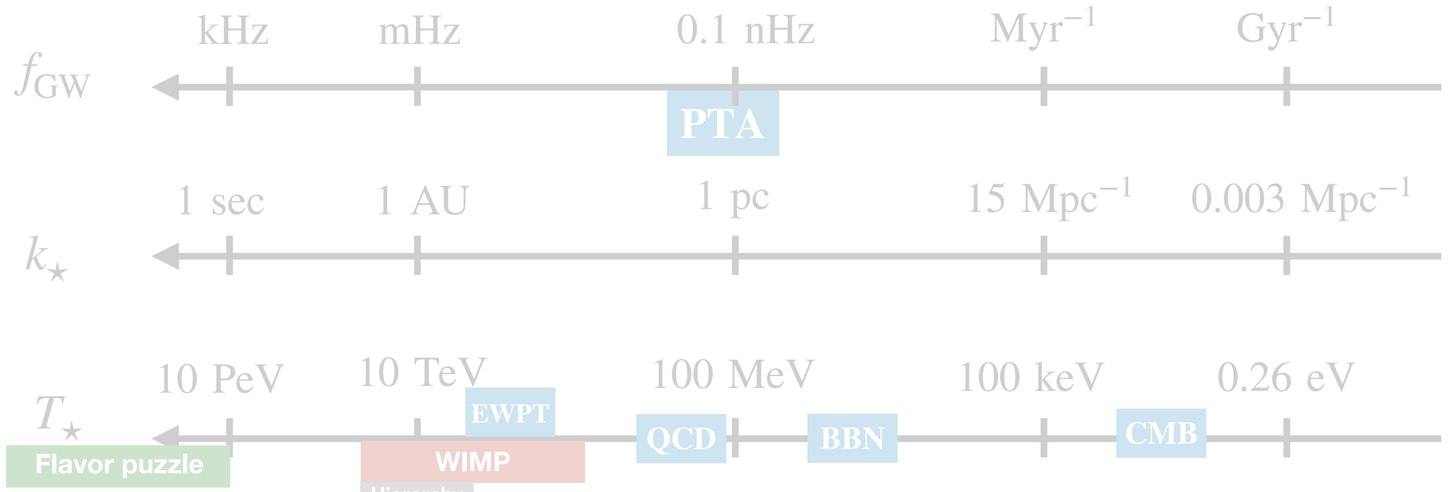
Domenech, Takhistov, Sasaki 21'

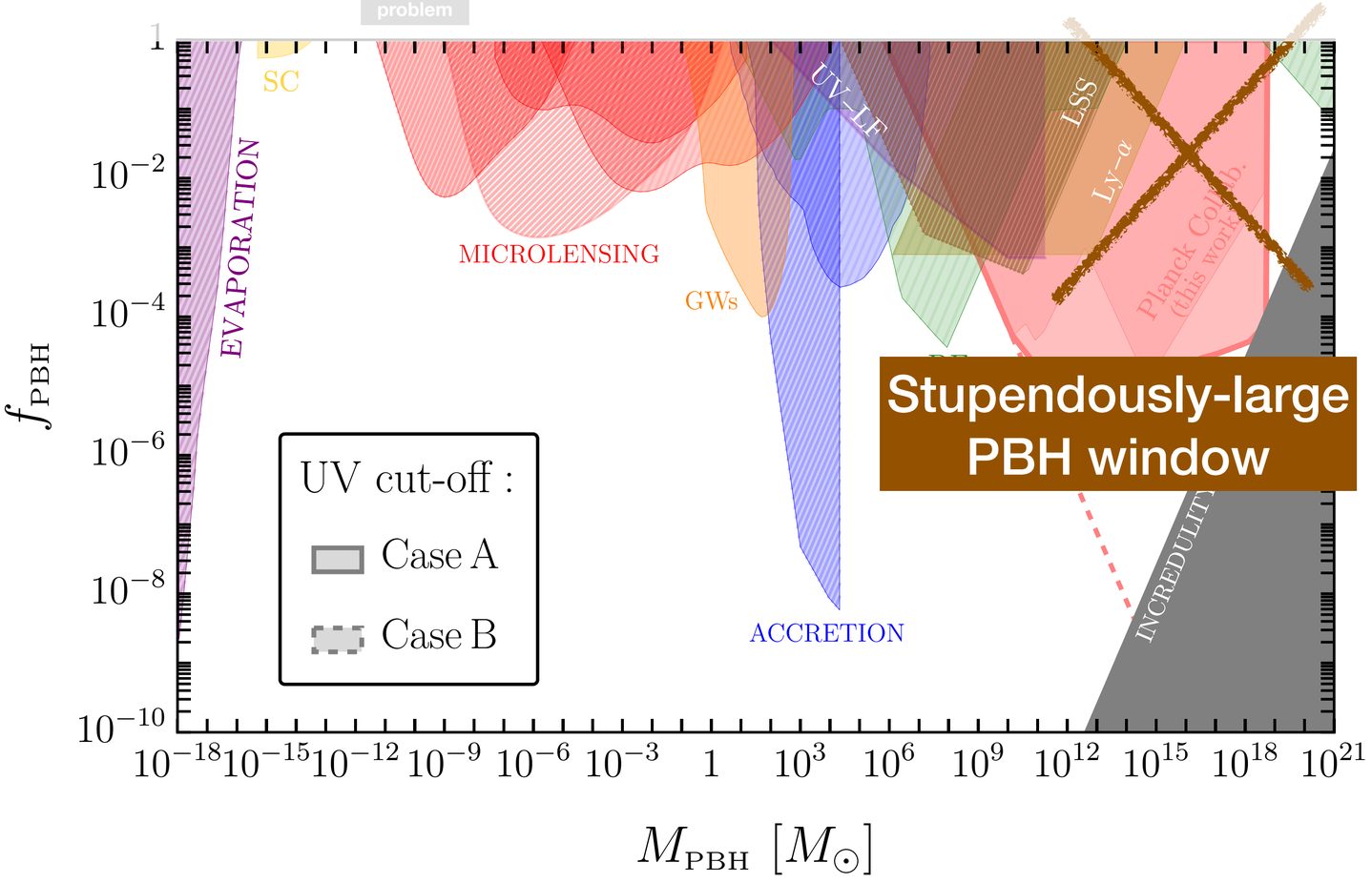
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## Poltergeist GWs

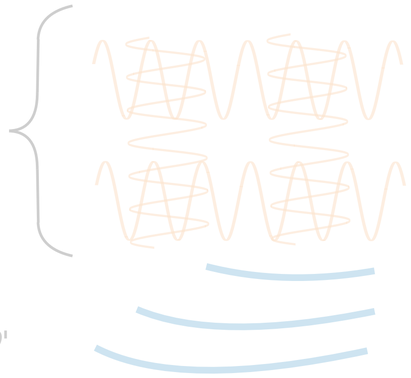


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Gas of evaporating PBHs



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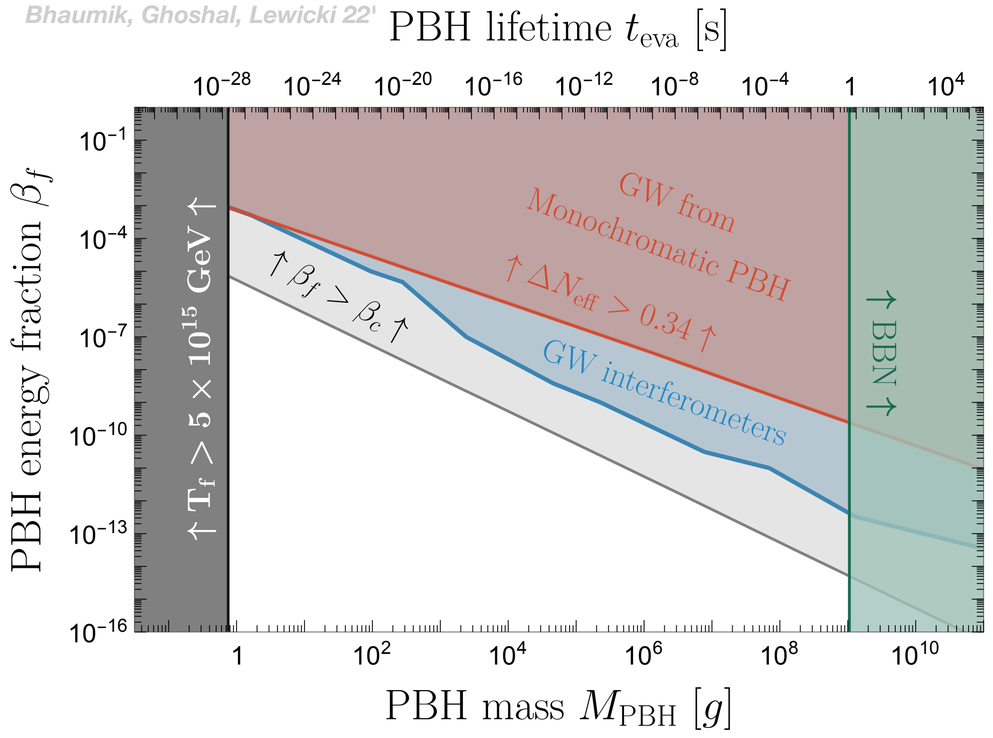
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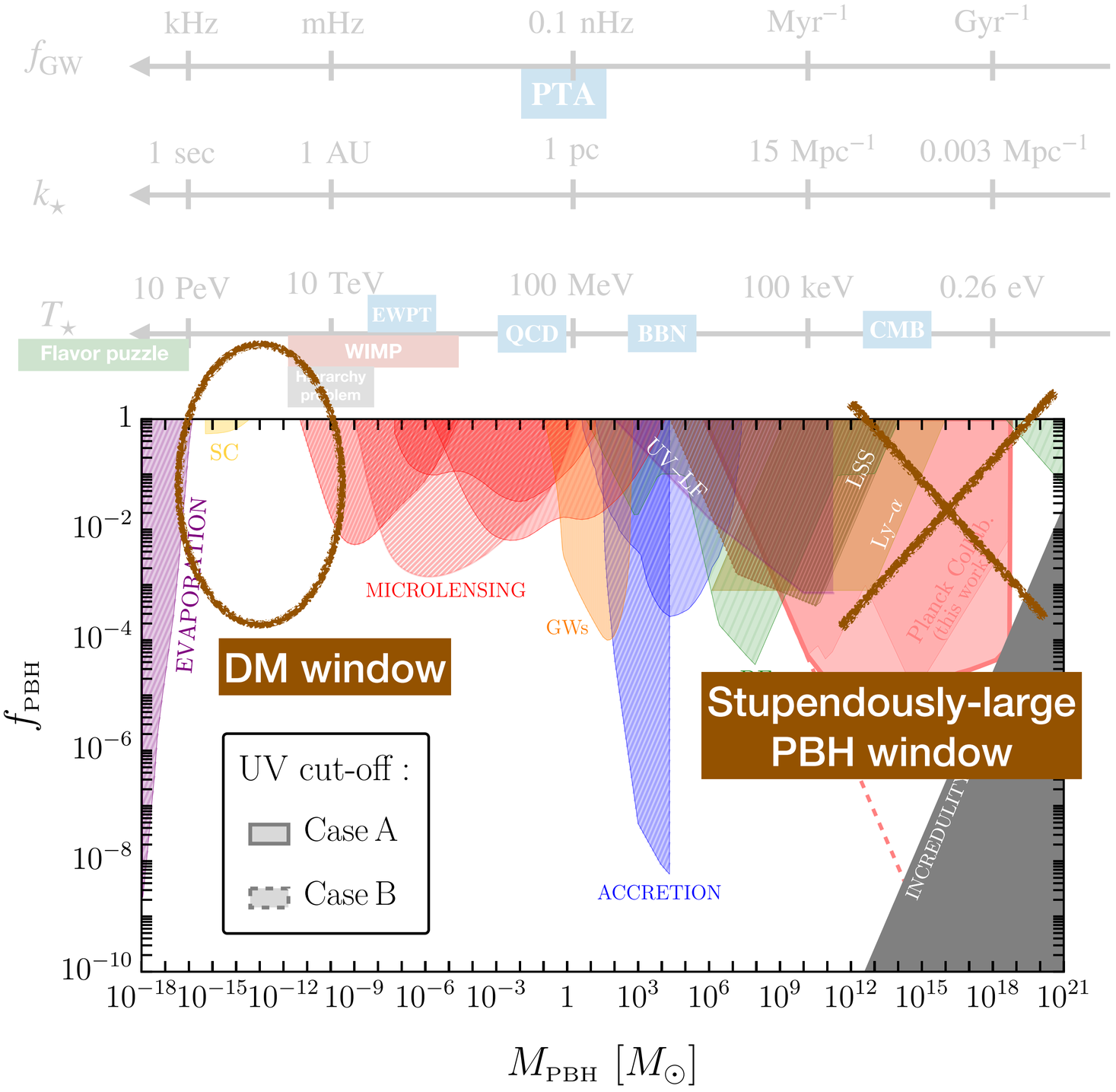
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Poltergeist GWs



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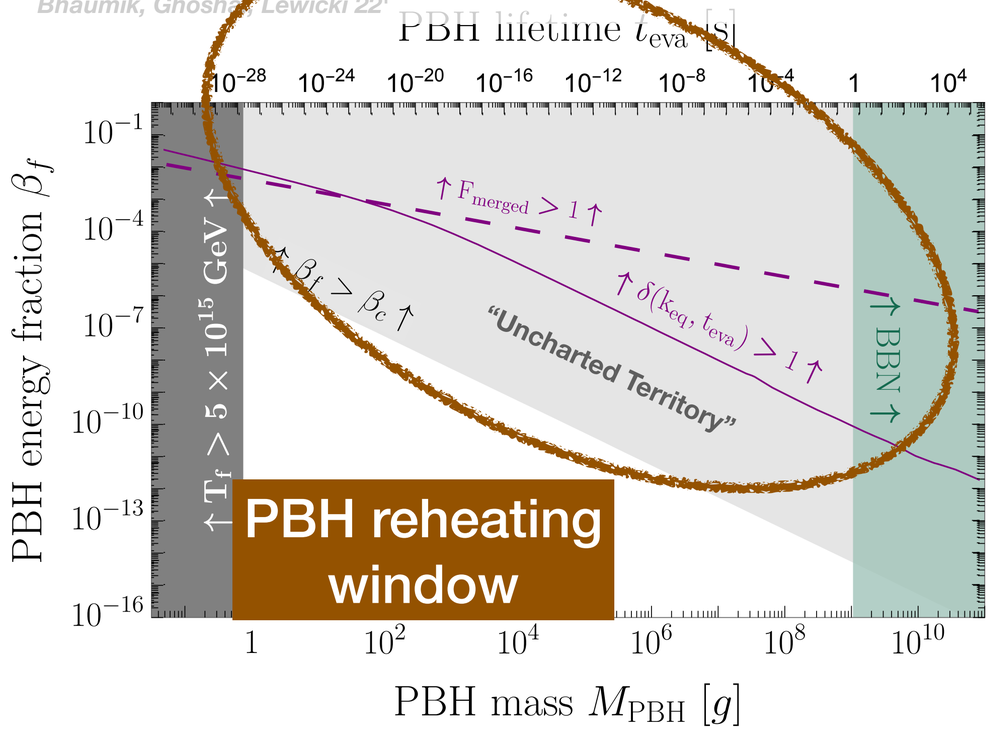
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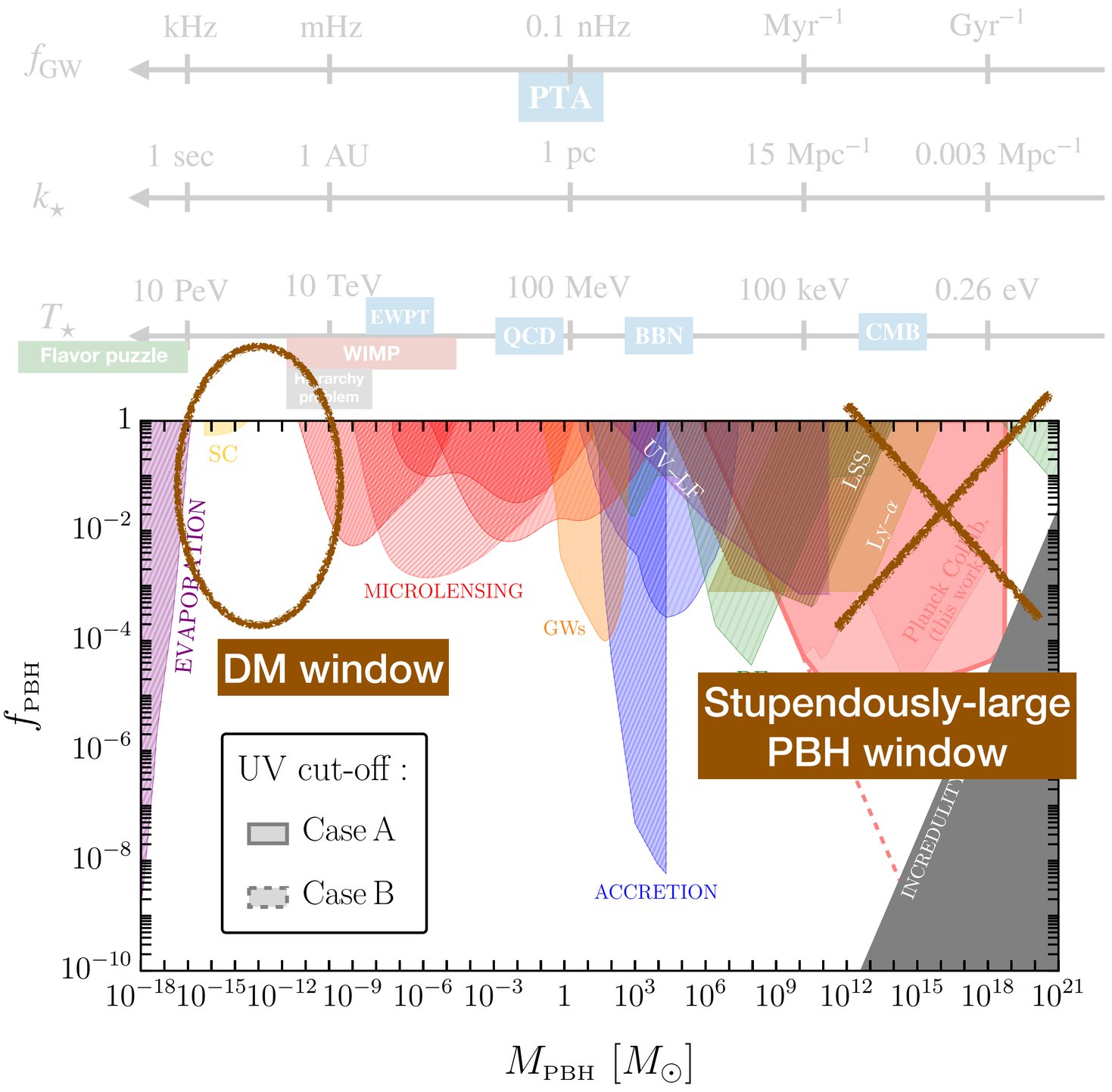
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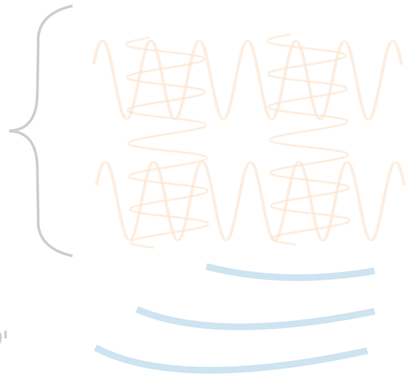
## Poltergeist GWs



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Gas of evaporating PBHs



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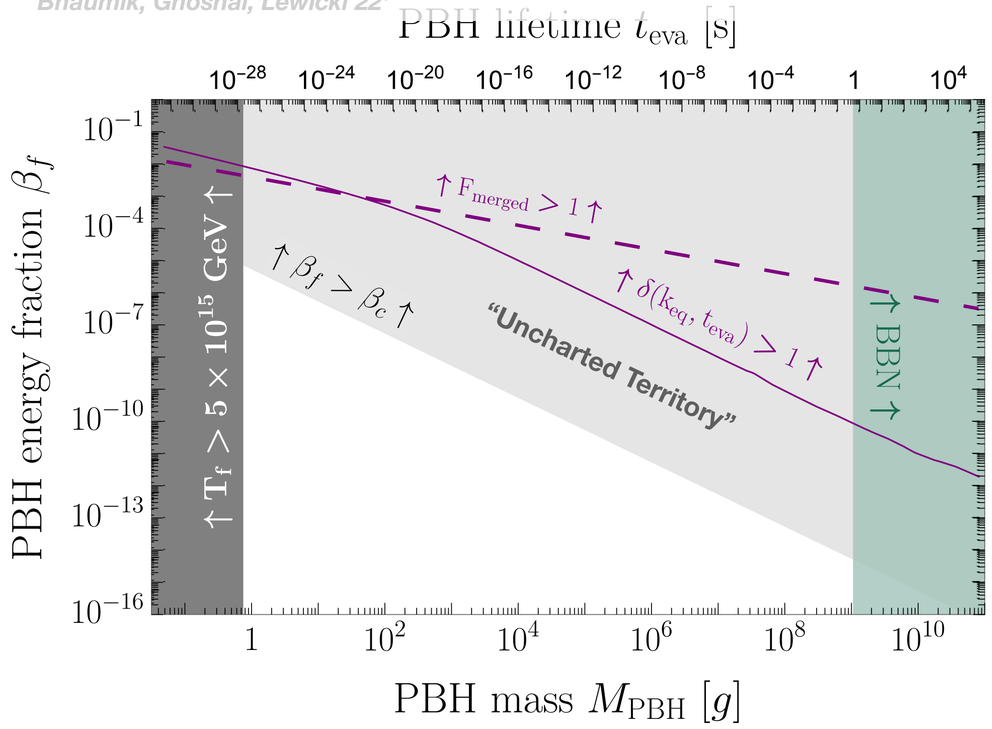
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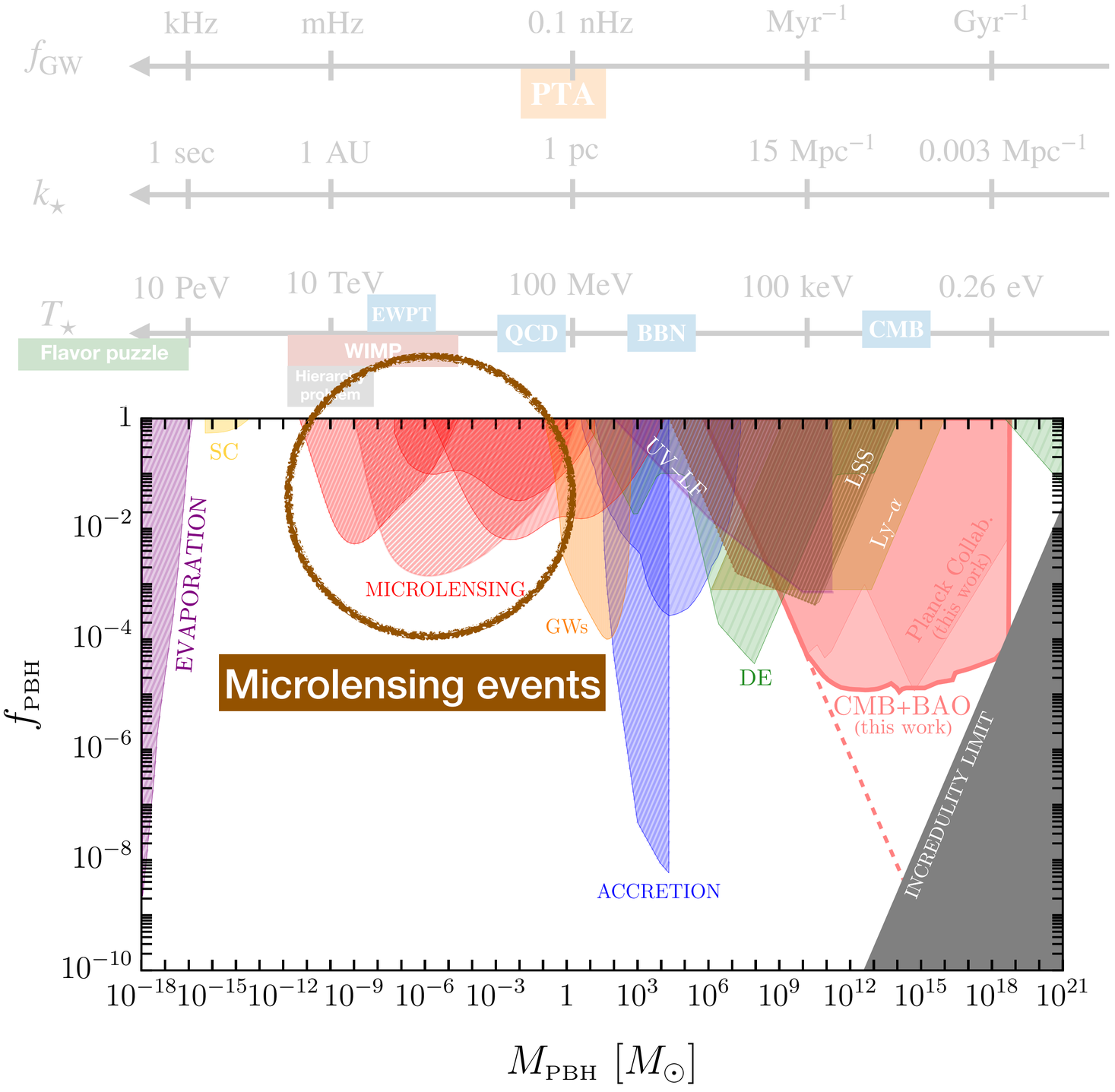
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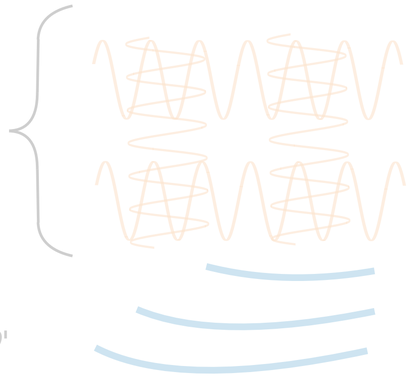
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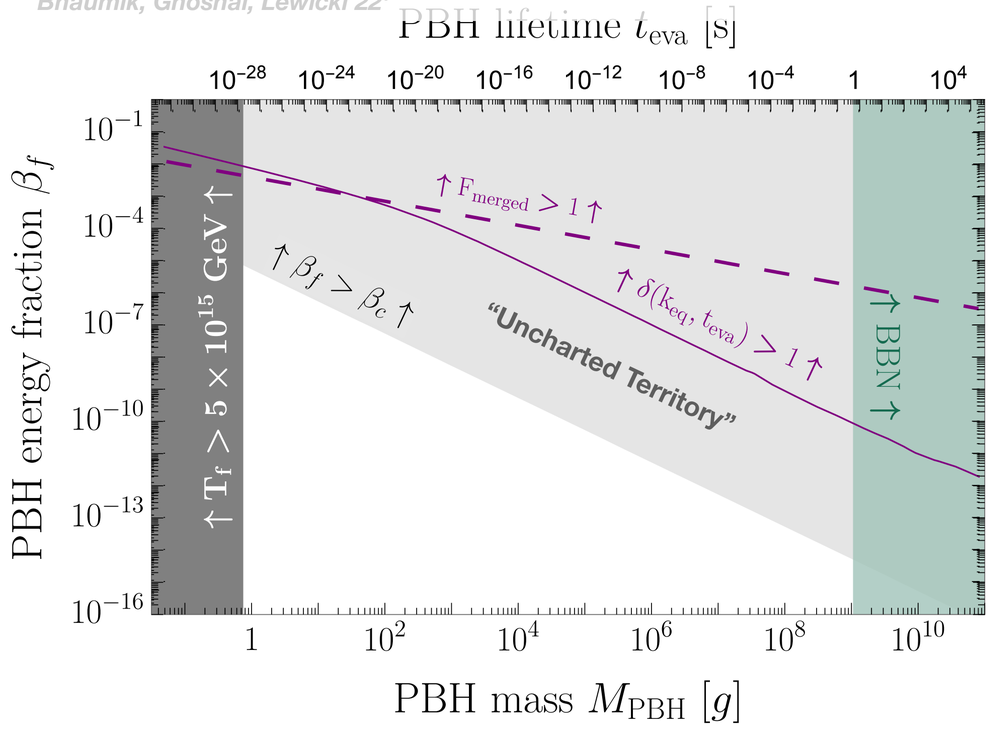
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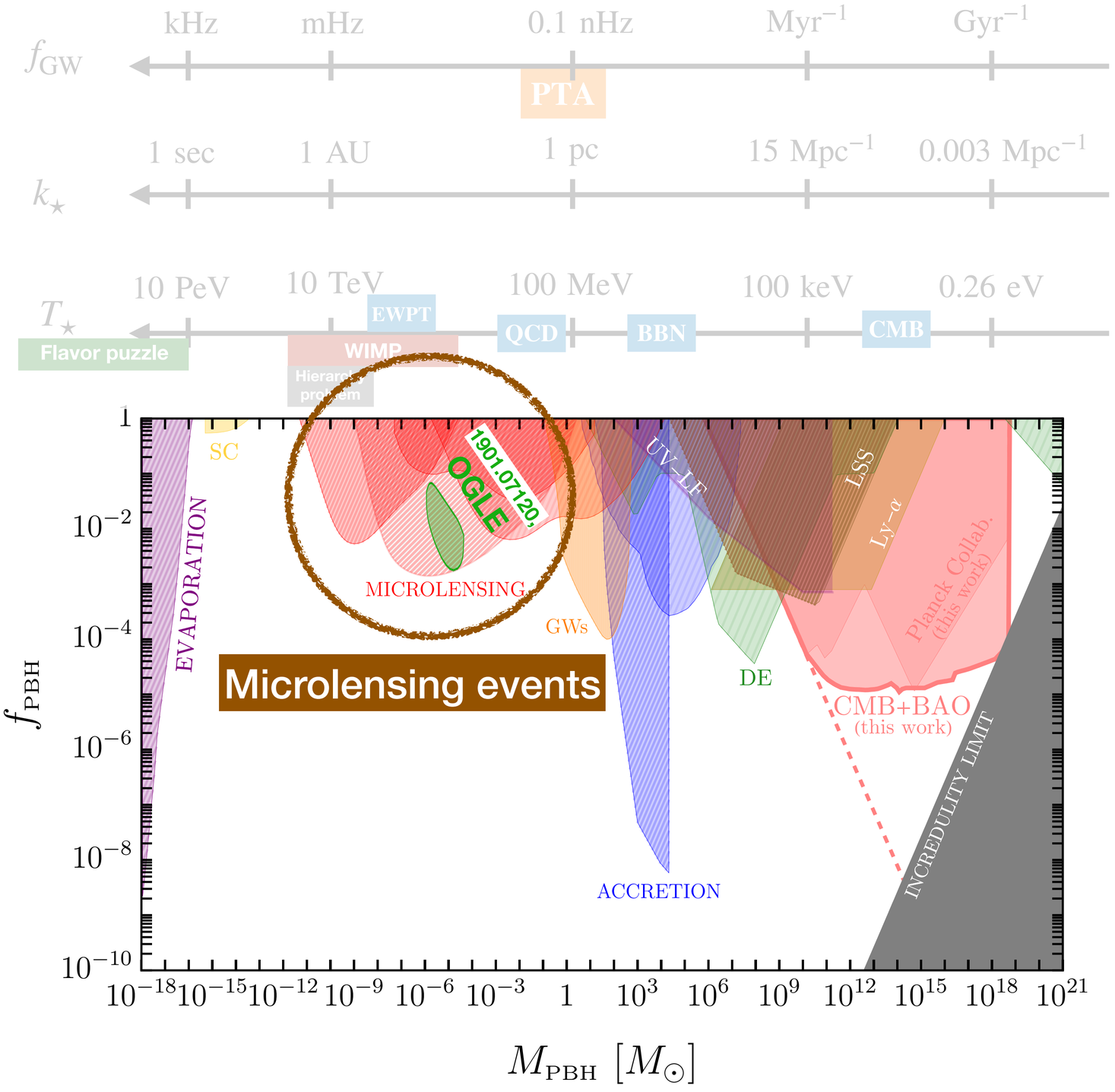
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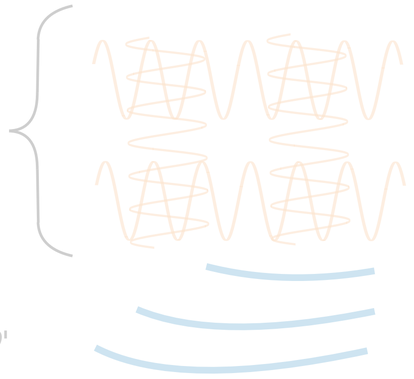
## Poltergeist GWs



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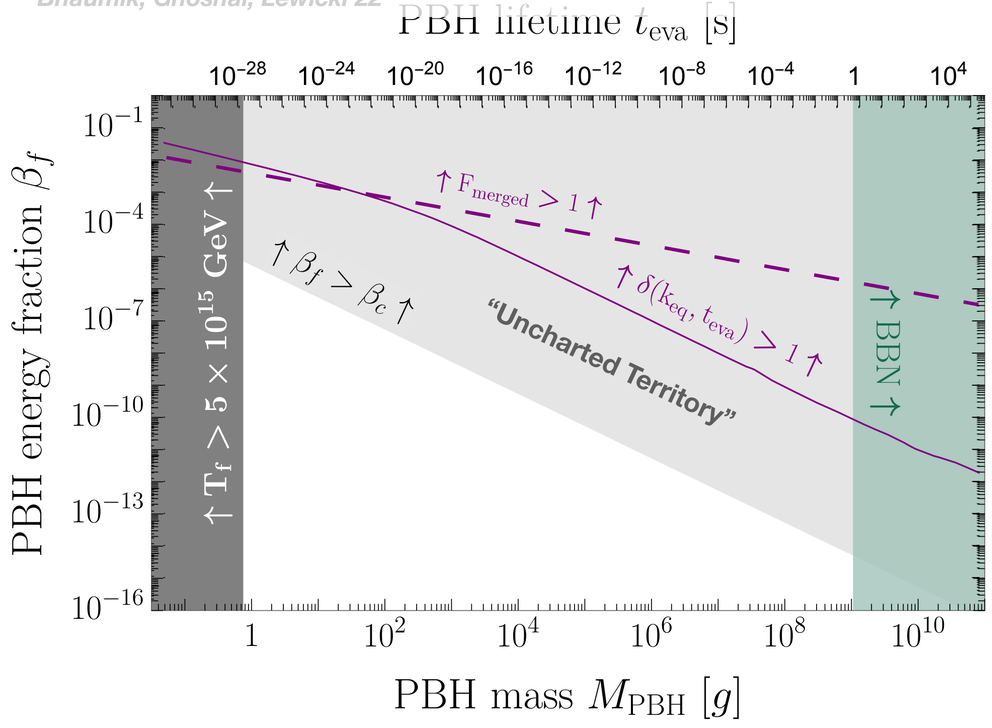
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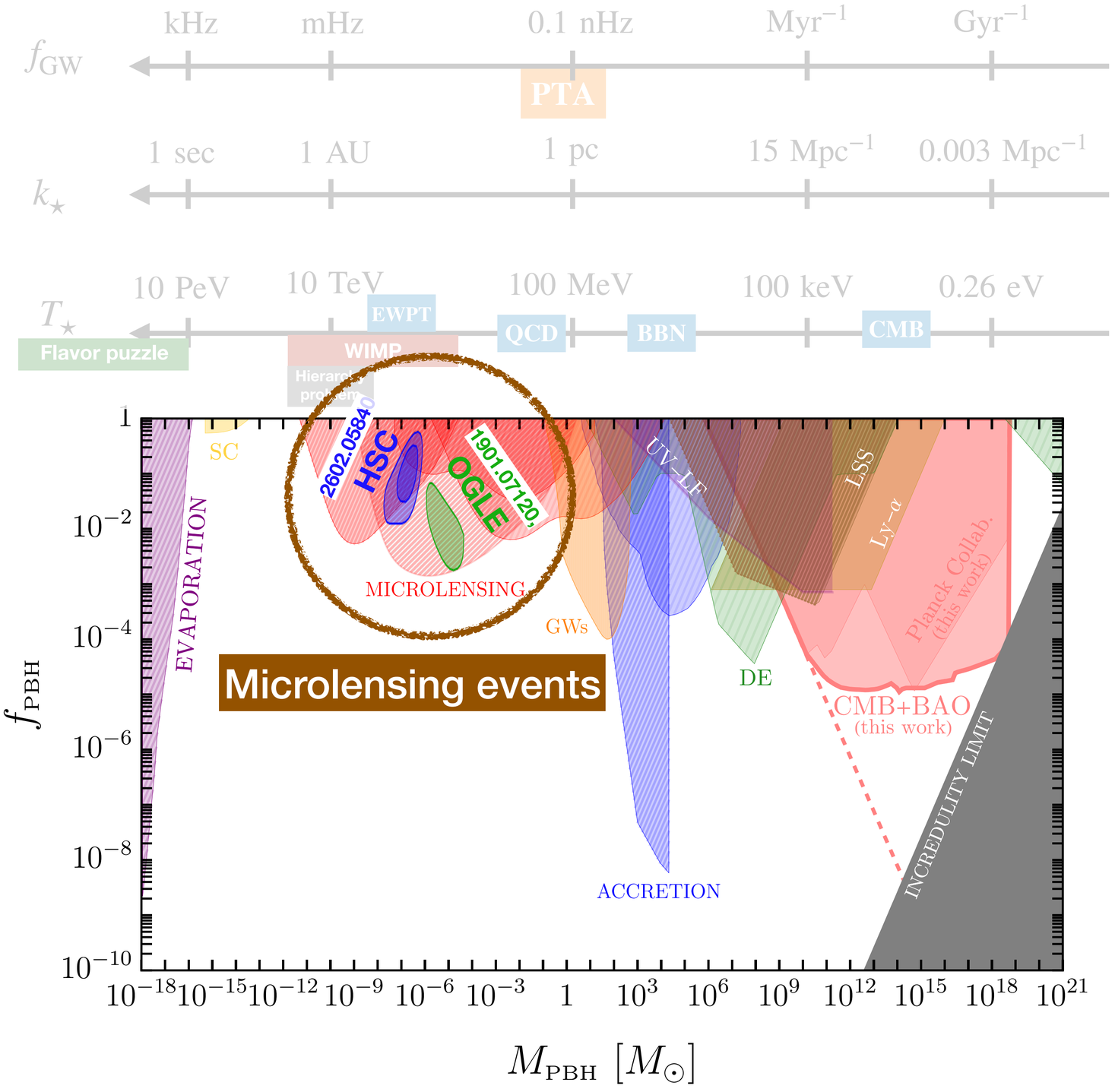
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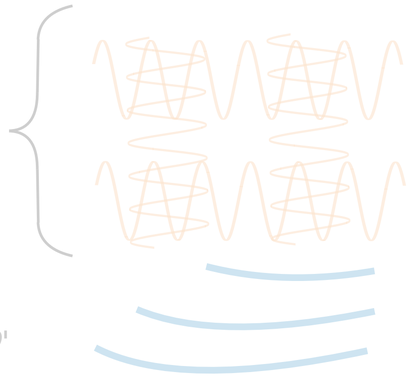
## Poltergeist GWs



## Evaporation ⇒ Sound waves

Gas of evaporating PBHs



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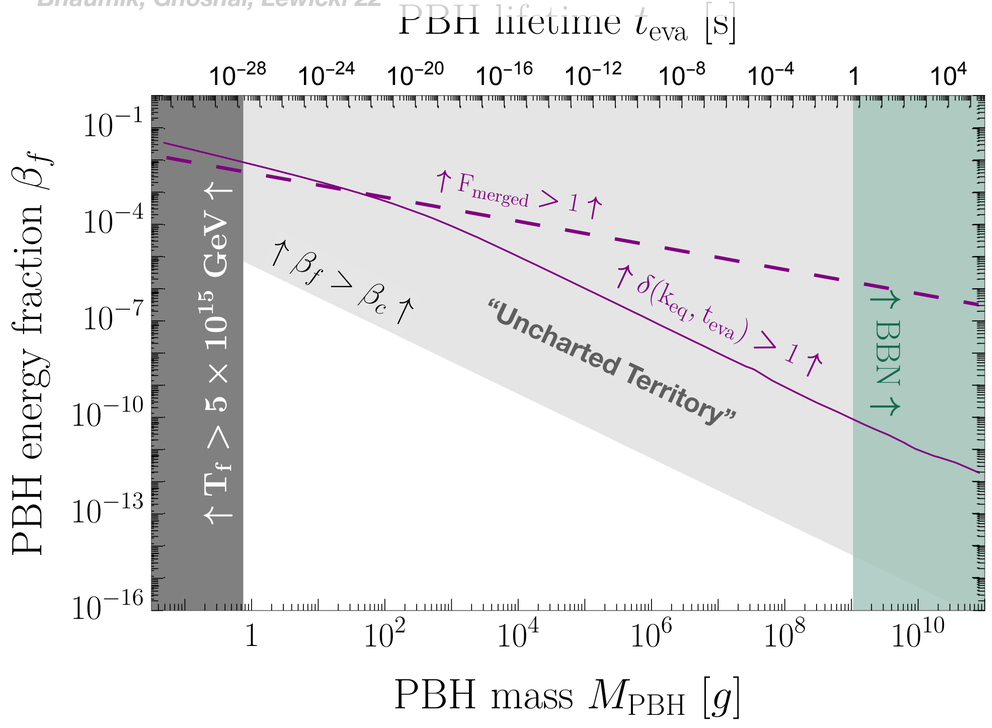
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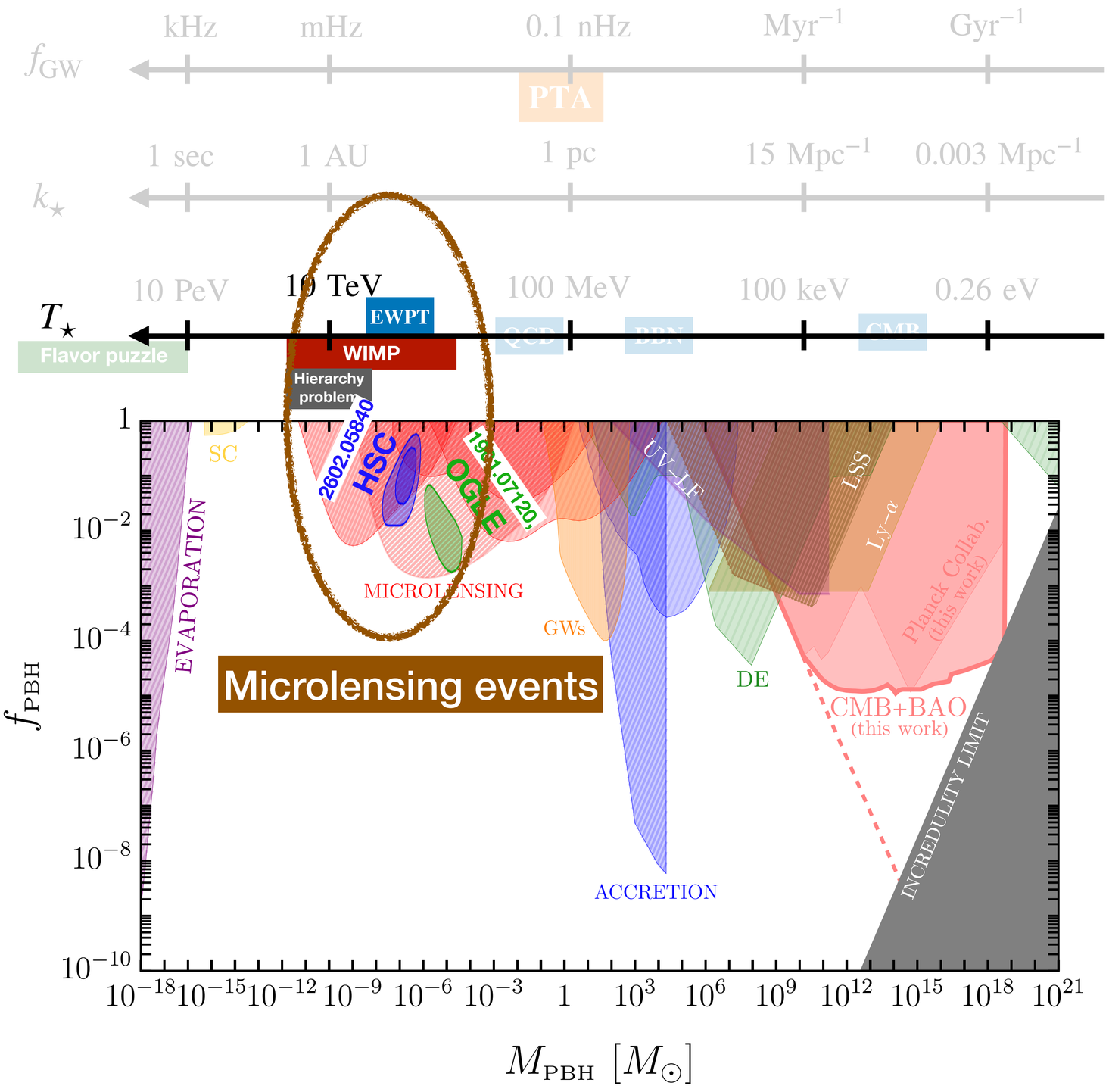
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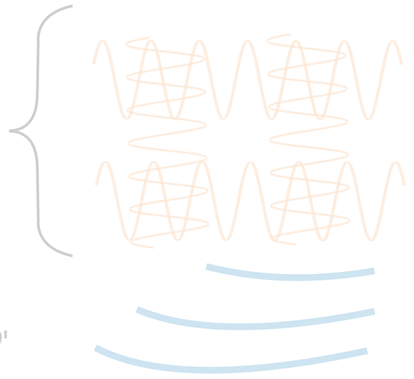
## Poltergeist GWs



**Evaporation ⇒ Sound waves**

Gas of evaporating PBHs



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*Papanikolaou, Vennin, Langlois 20'*

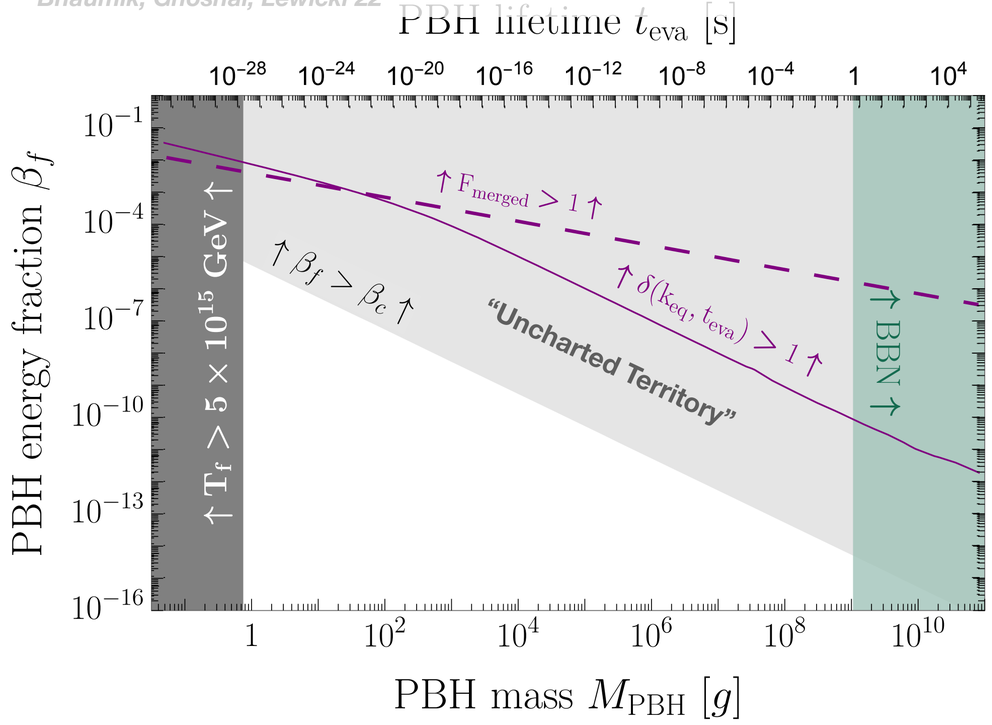
*Domenech, Lin, Sasaki 20'*

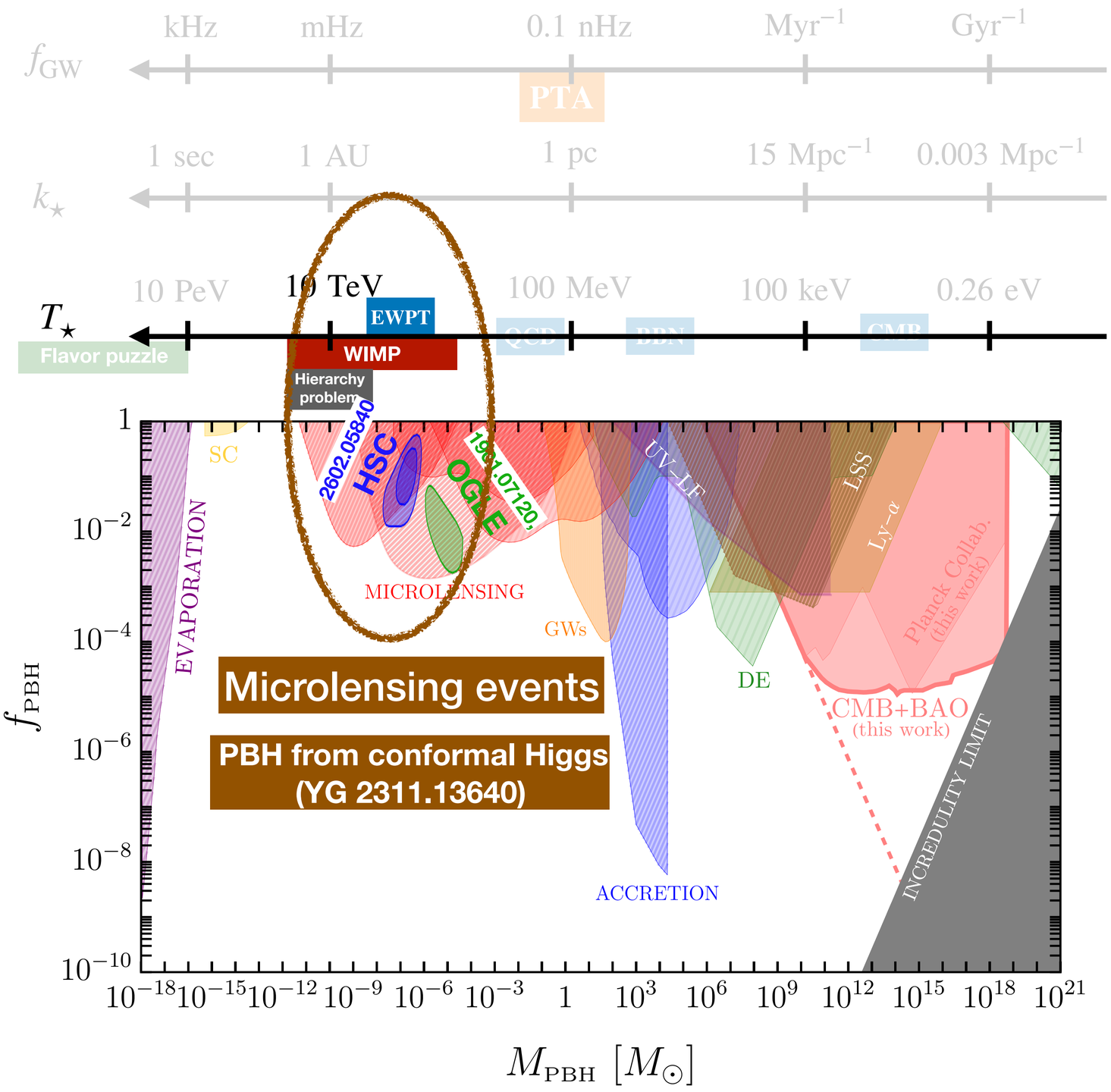
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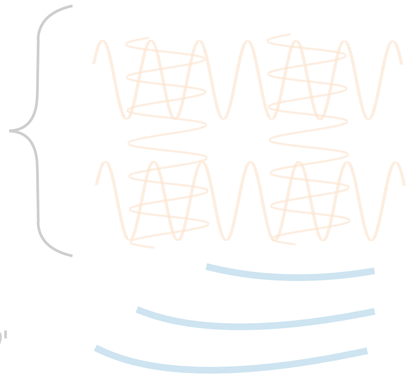
**Poltergeist GWs**



## Evaporation ⇒ Sound waves

Gas of evaporating PBHs



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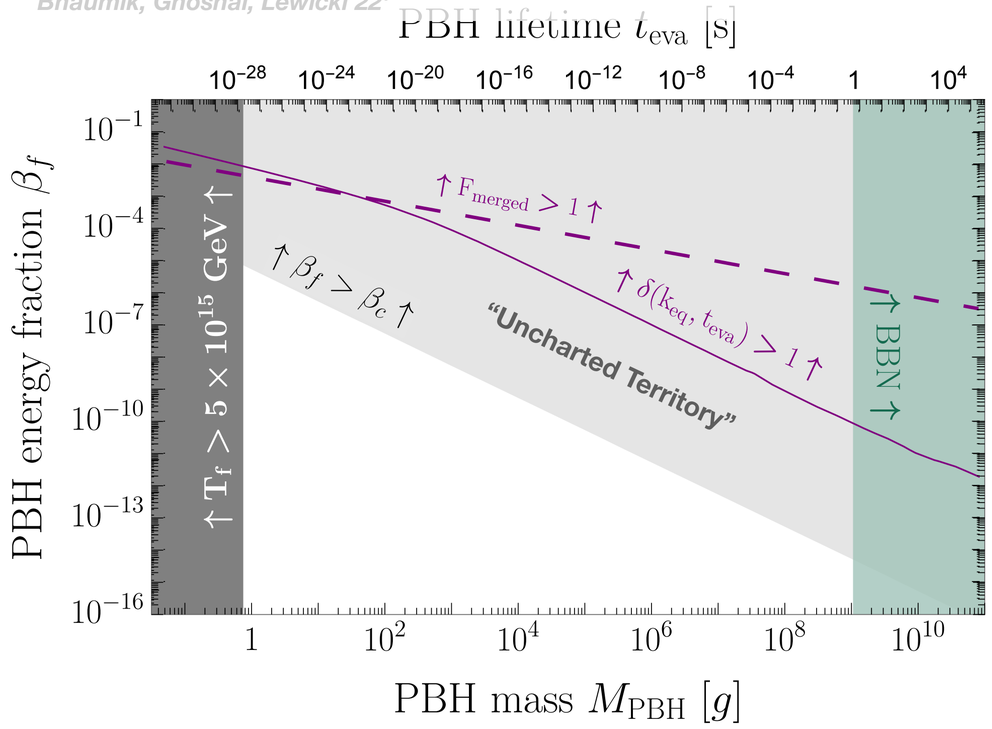
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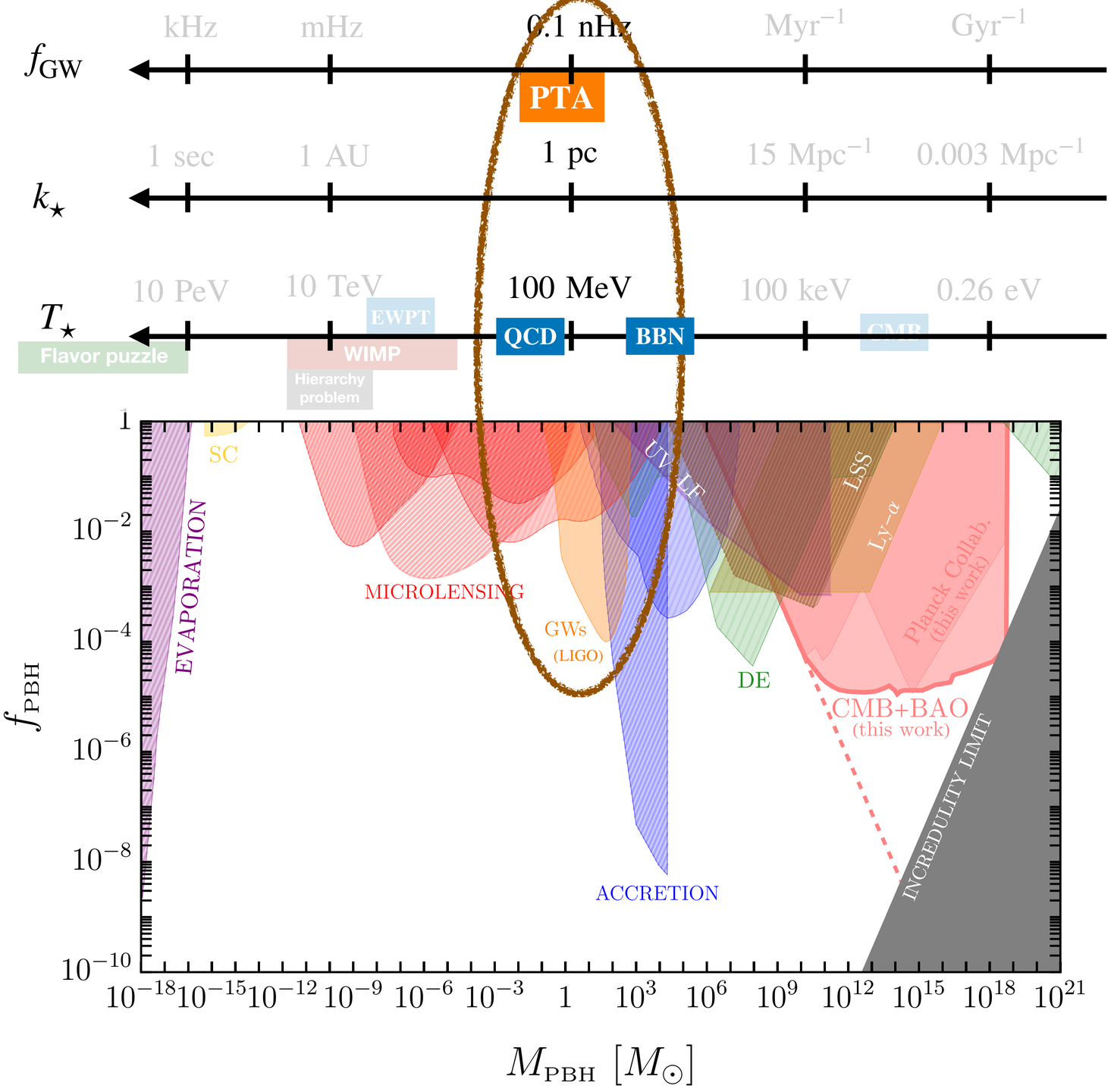
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## Poltergeist GWs



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Gas of evaporating PBHs

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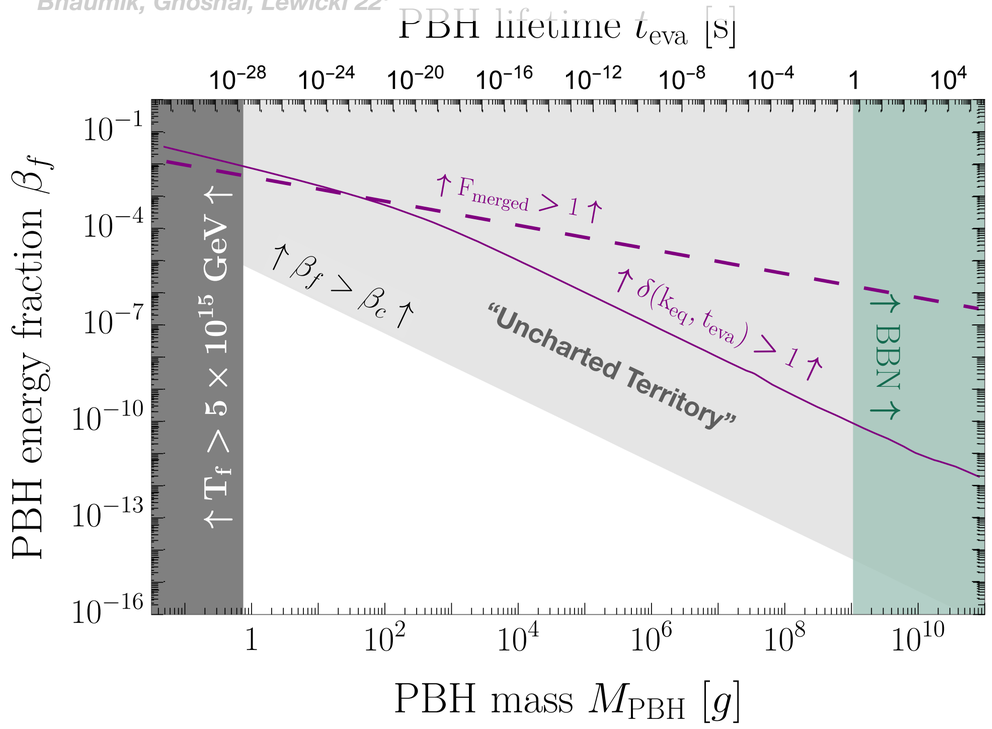
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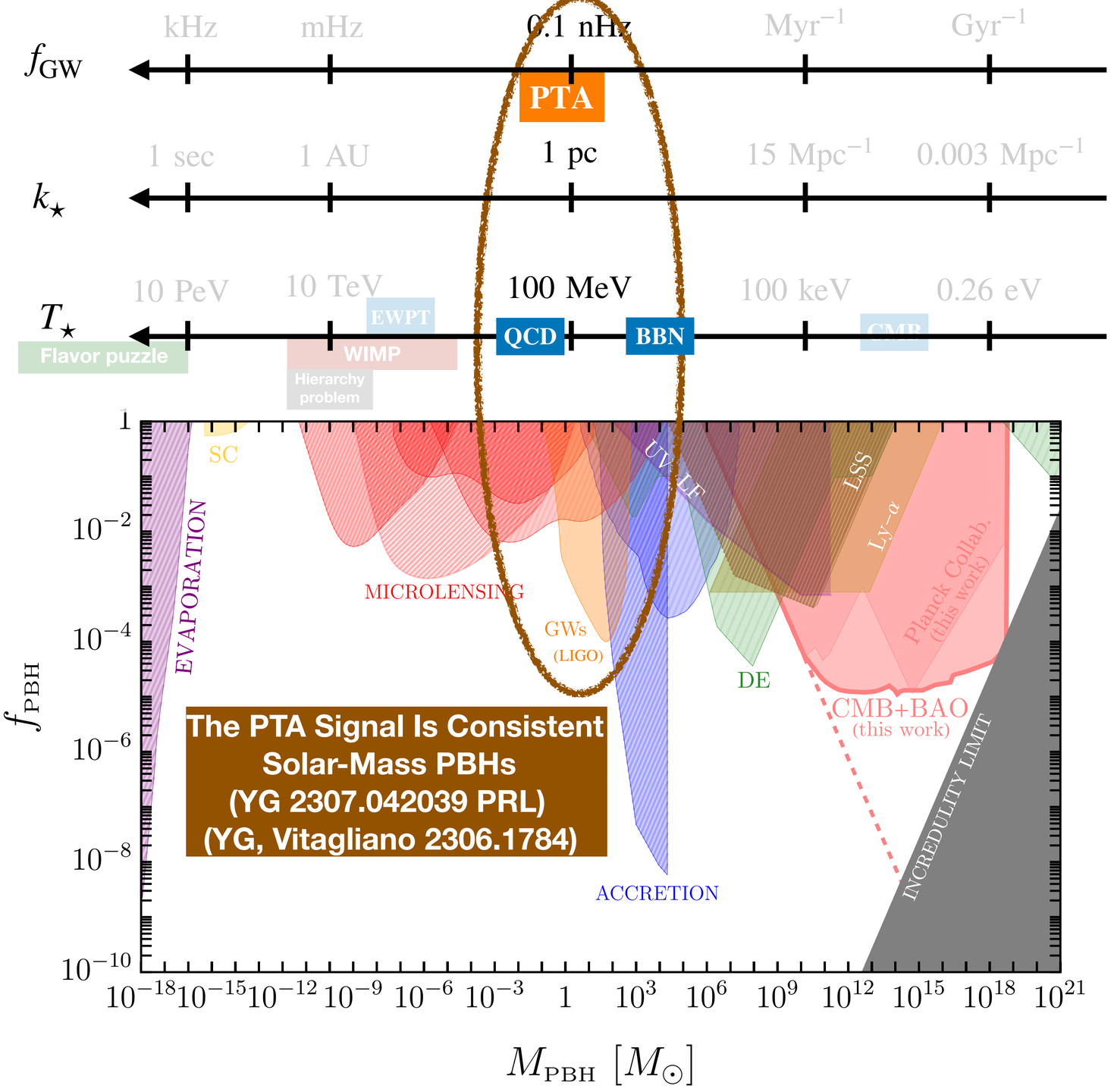
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## Poltergeist GWs



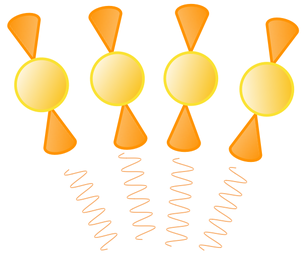



# Plan of the talk

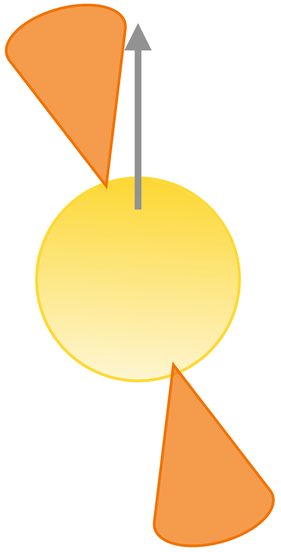
1) Gravitational Waves (GWs) $h_{ij}(\vec{x}, t)$

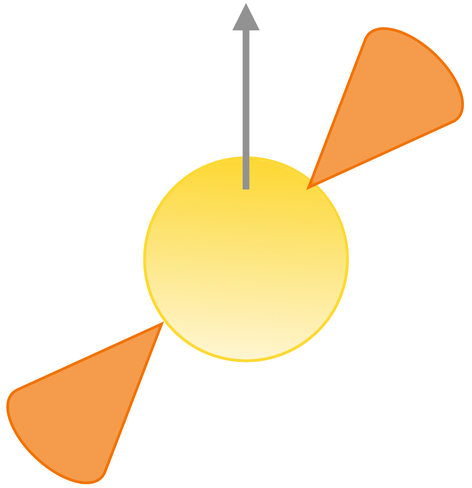
2) Primordial Black Holes (PBHs)

3) What is the PTA signal ?



# Pulsar Timing Arrays (PTA)







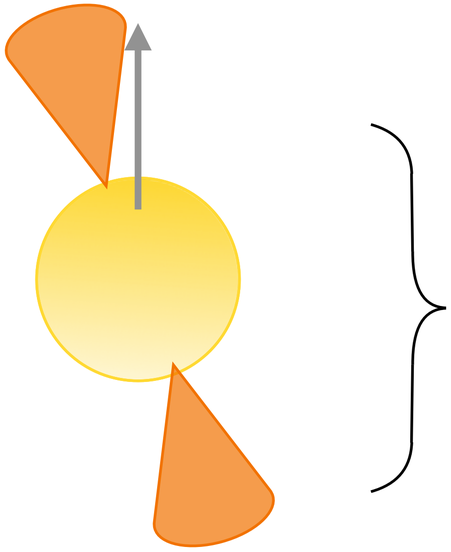
The New York Times

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## *The Cosmos Is Thrumming With Gravitational Waves, Astronomers Find*

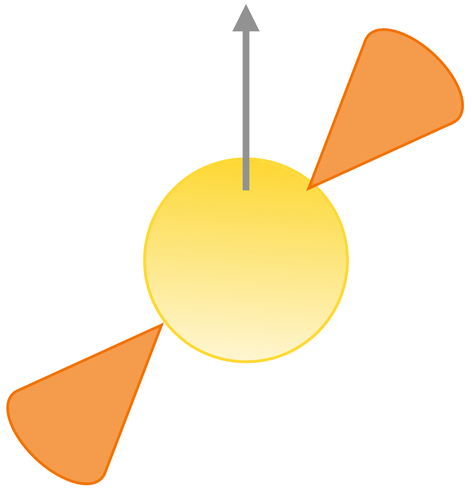


# Pulsar Timing Arrays (PTA)



$1\ M_\odot$





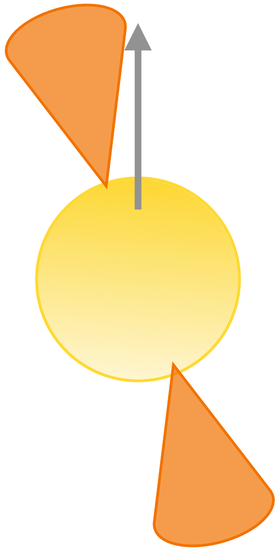
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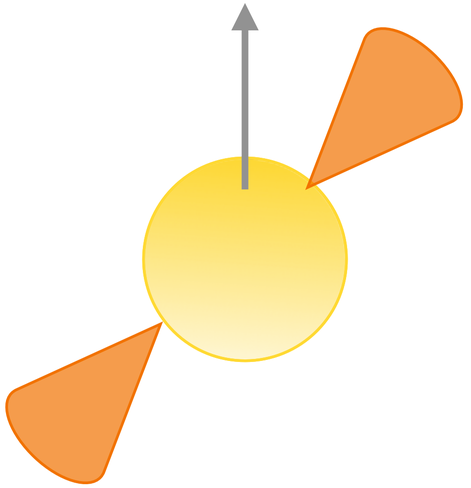


# Pulsar Timing Arrays (PTA)



$1\ M_\odot$

10 km





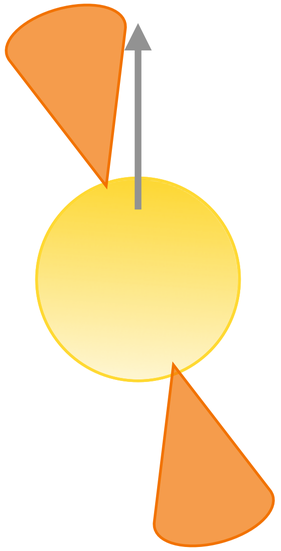
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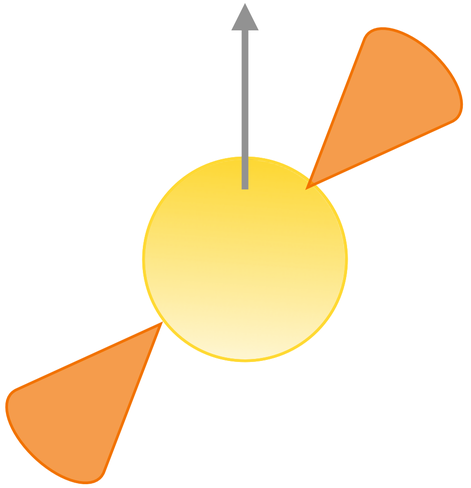
# Pulsar Timing Arrays (PTA)



$1\ M_\odot$

10 km

500 rotations/s





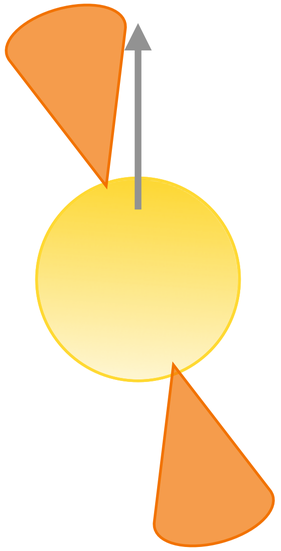
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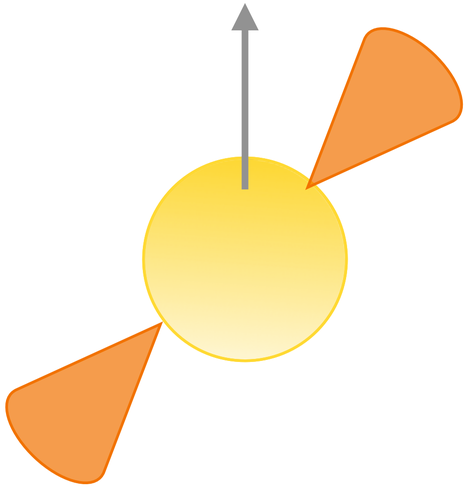
# Pulsar Timing Arrays (PTA)



$1\ M_\odot$

10 km

500 rotations/s



1 kpc



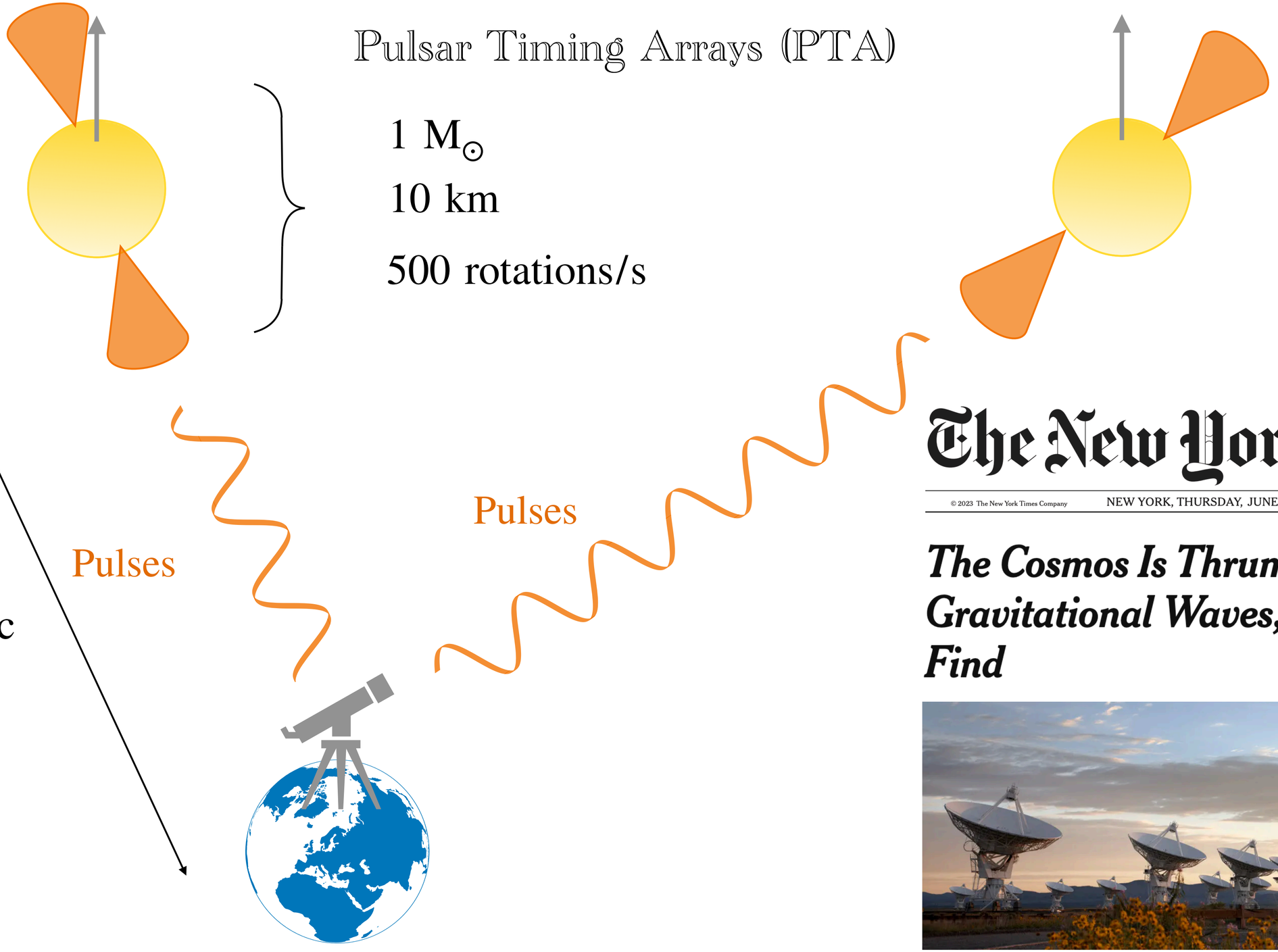
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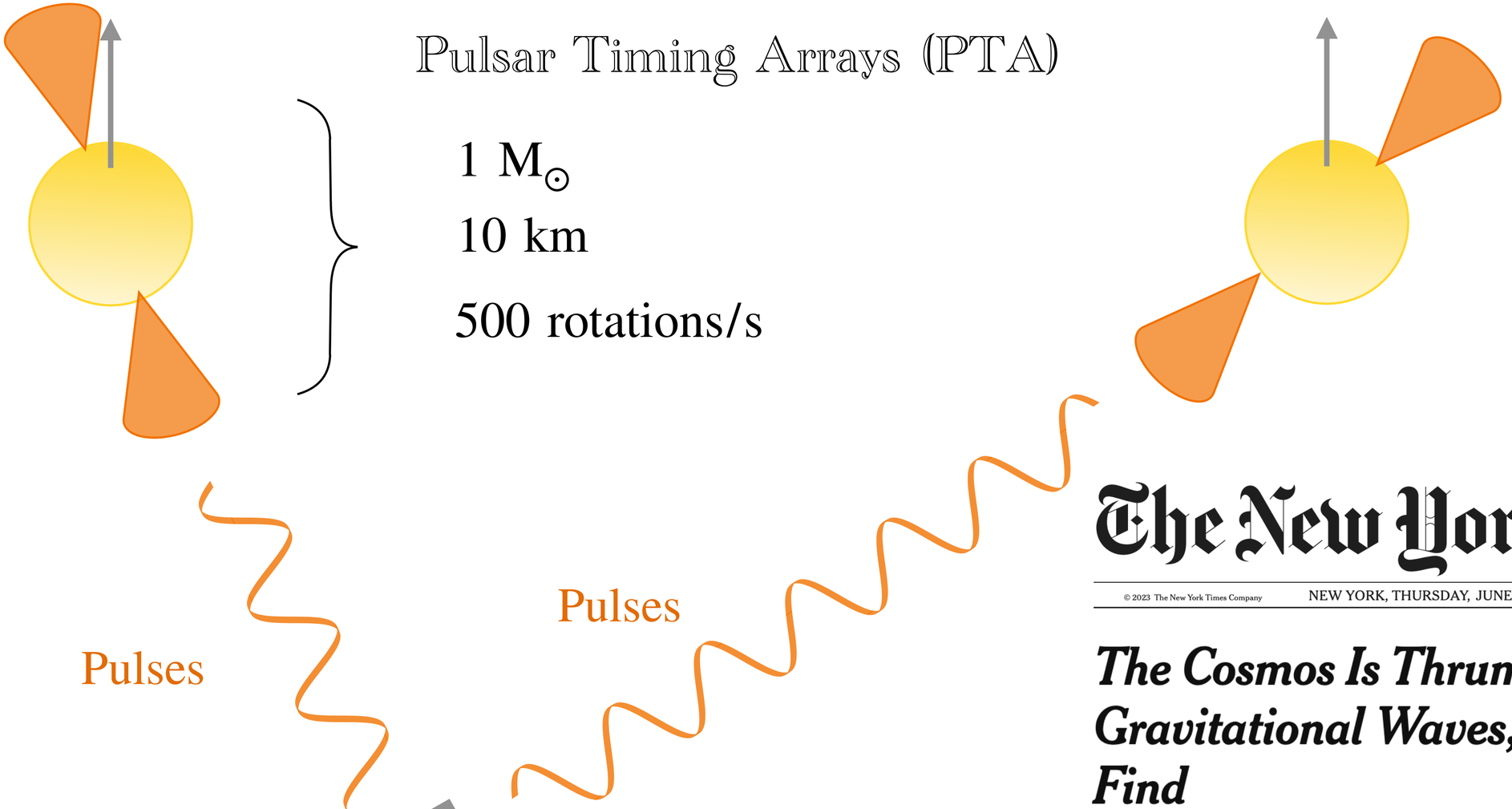

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# Pulsar Timing Arrays (PTA)

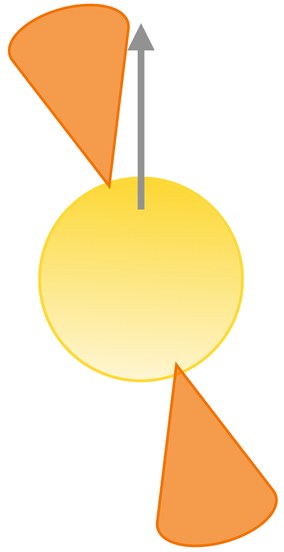


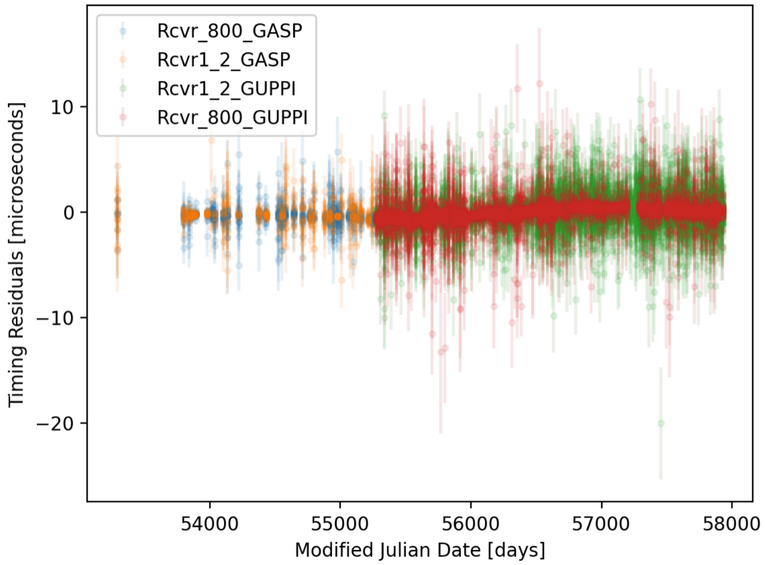

The New York Times

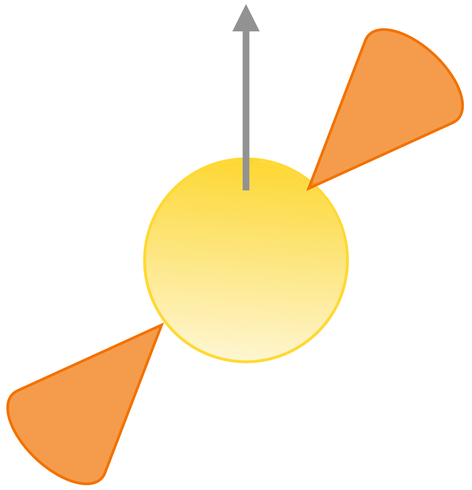
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## *The Cosmos Is Thrumming With Gravitational Waves, Astronomers Find*







Pulses

Pulses

Gravitational

Waves

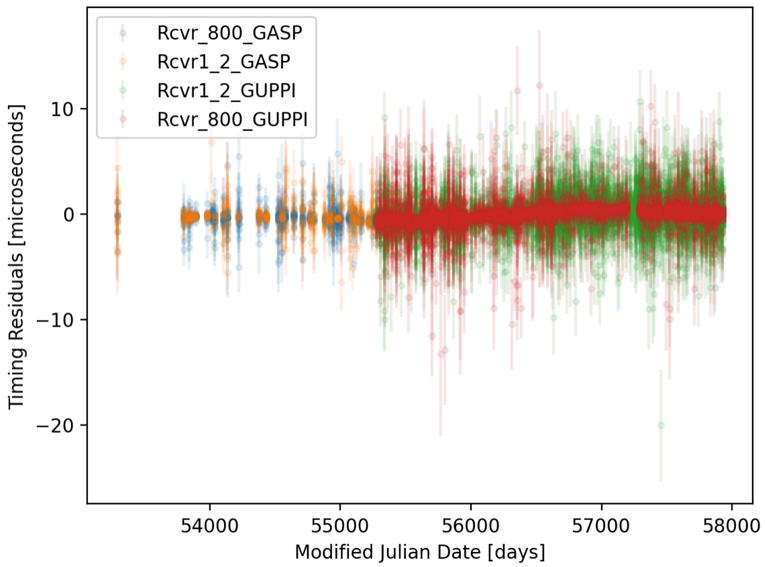


The New York Times

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# *The Cosmos Is Thrumming With Gravitational Waves, Astronomers Find*





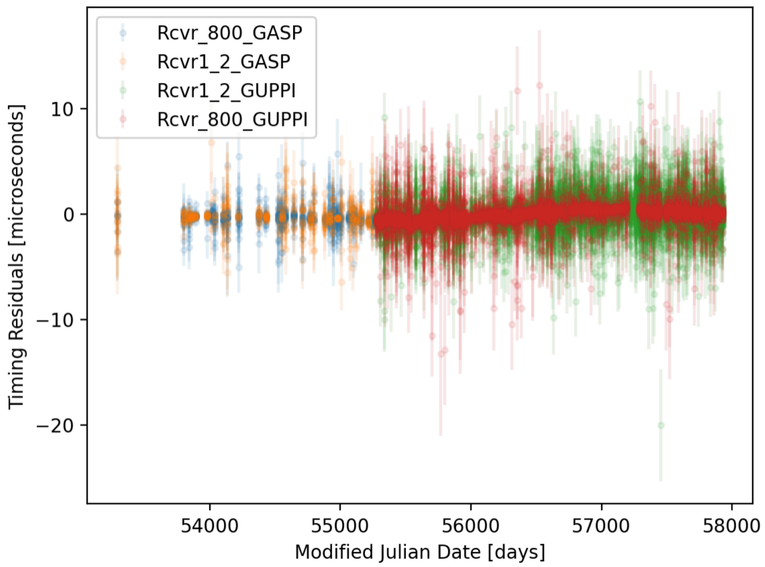

Pulses

Pulses

Gravitational

Waves

Solar system systematics



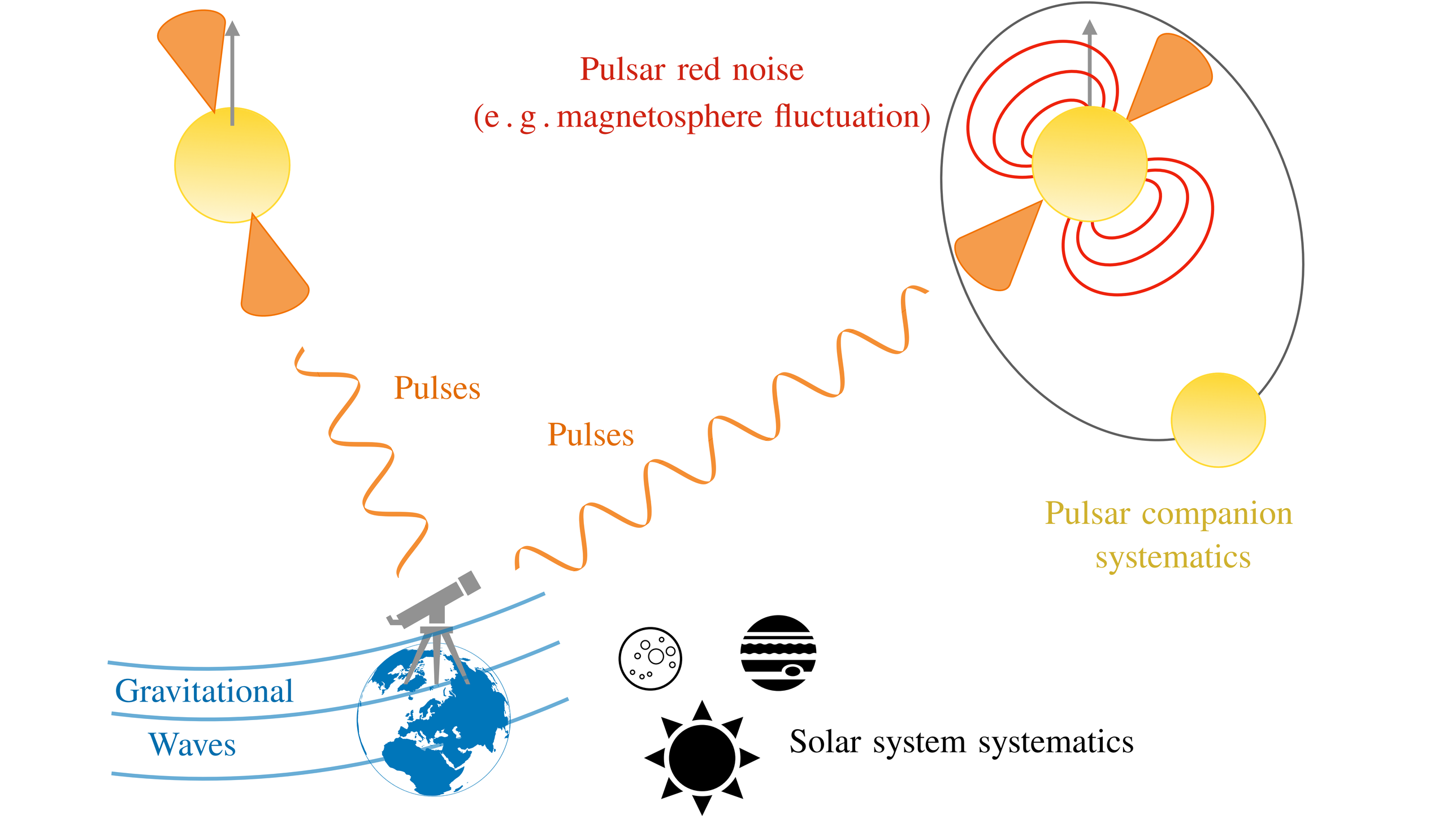

Pulses

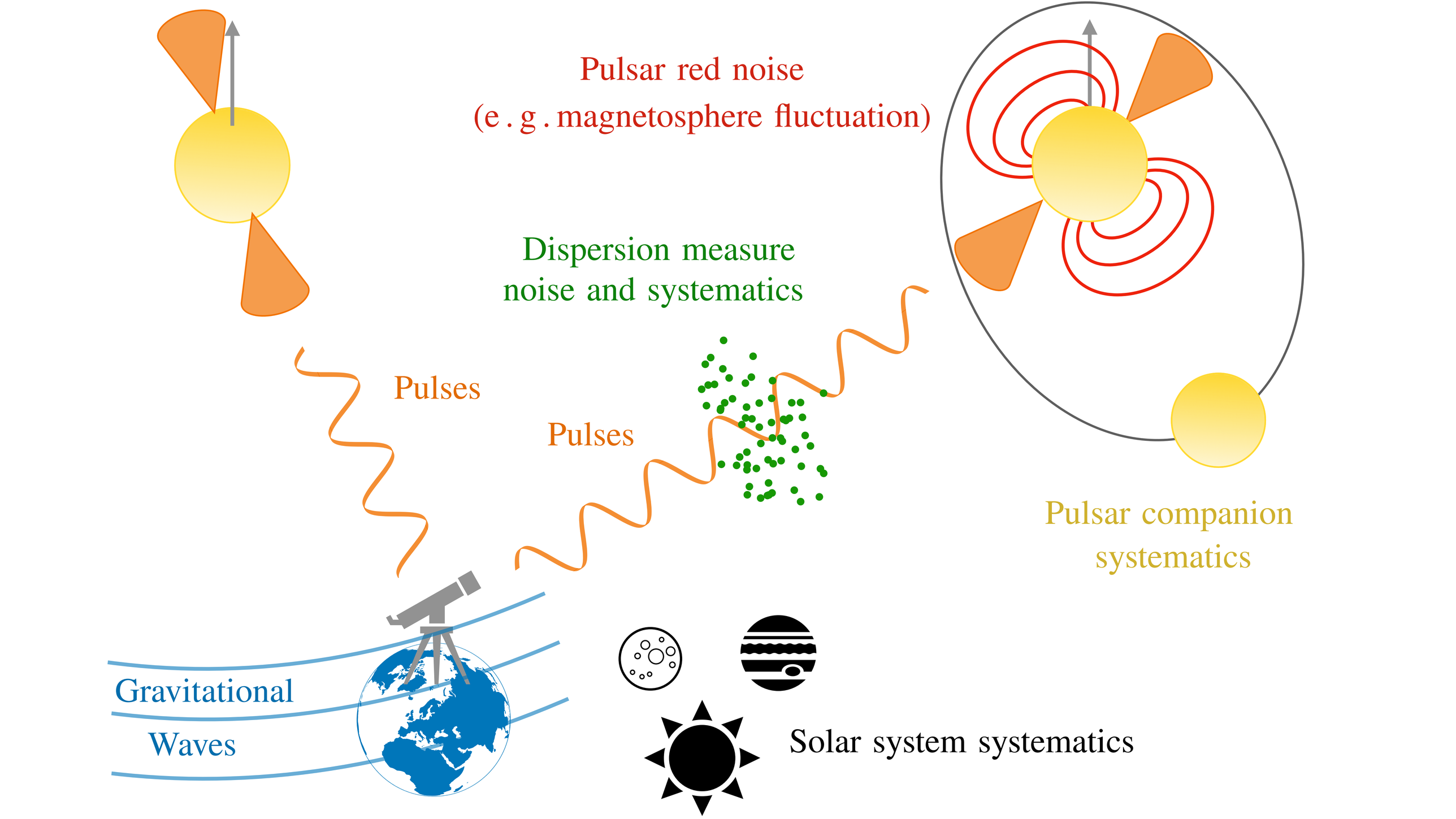
Pulses

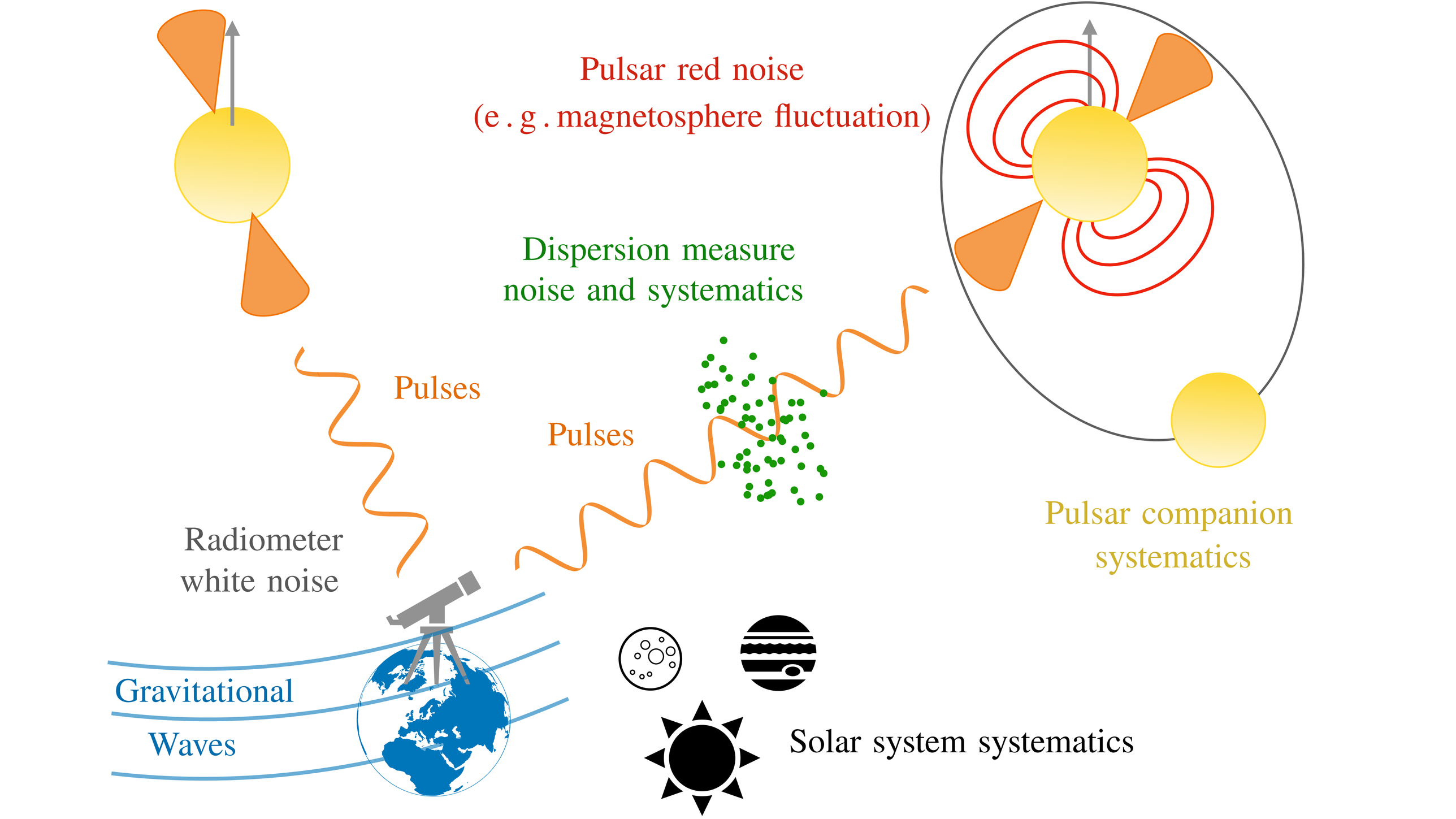
Pulsar companion systematics

Gravitational Waves

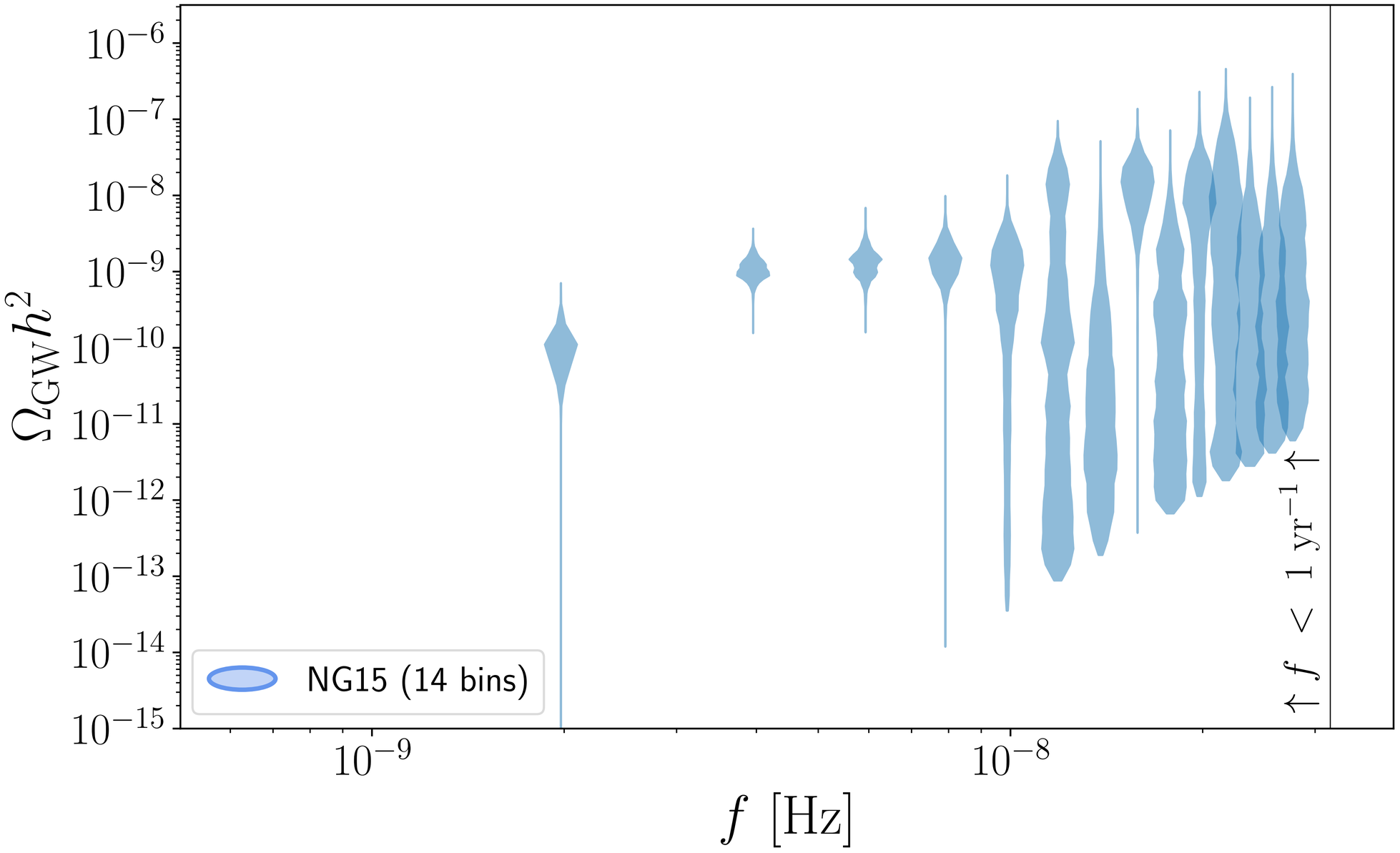
Solar system systematics


Pulsar red noise
(e . g . magnetosphere fluctuation)
Pulses
Pulses
Pulsar companion
systematics
Gravitational
Waves
Solar system systematics

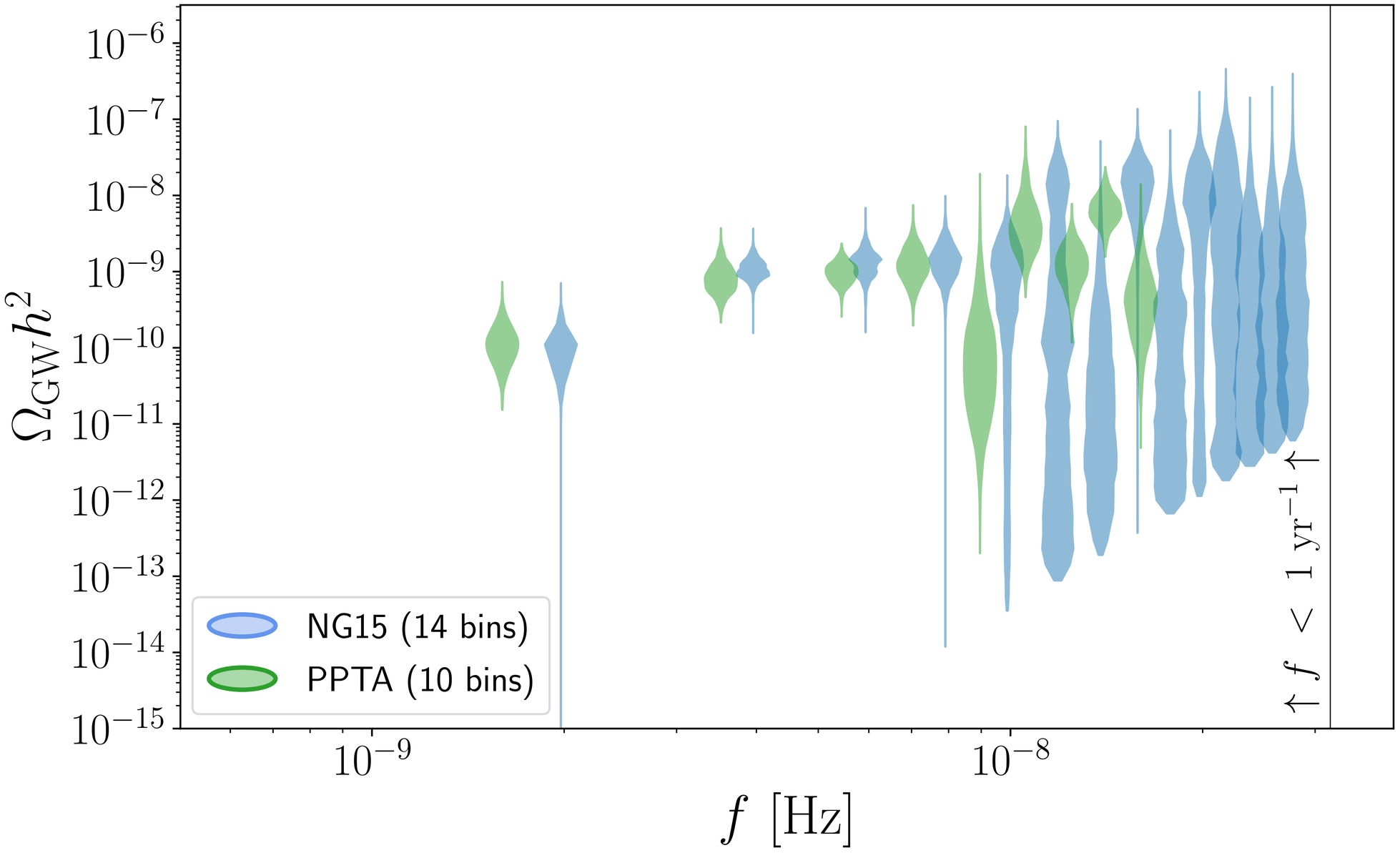

Pulsar red noise
(e . g . magnetosphere fluctuation)
Dispersion measure
noise and systematics
Pulses
Pulses
Pulsar companion
systematics
Gravitational
Waves
Solar system systematics


Pulsar red noise
(e . g . magnetosphere fluctuation)
Dispersion measure
noise and systematics
Pulses
Pulses
Radiometer
white noise
Pulsar companion
systematics
Gravitational
Waves
Solar system systematics

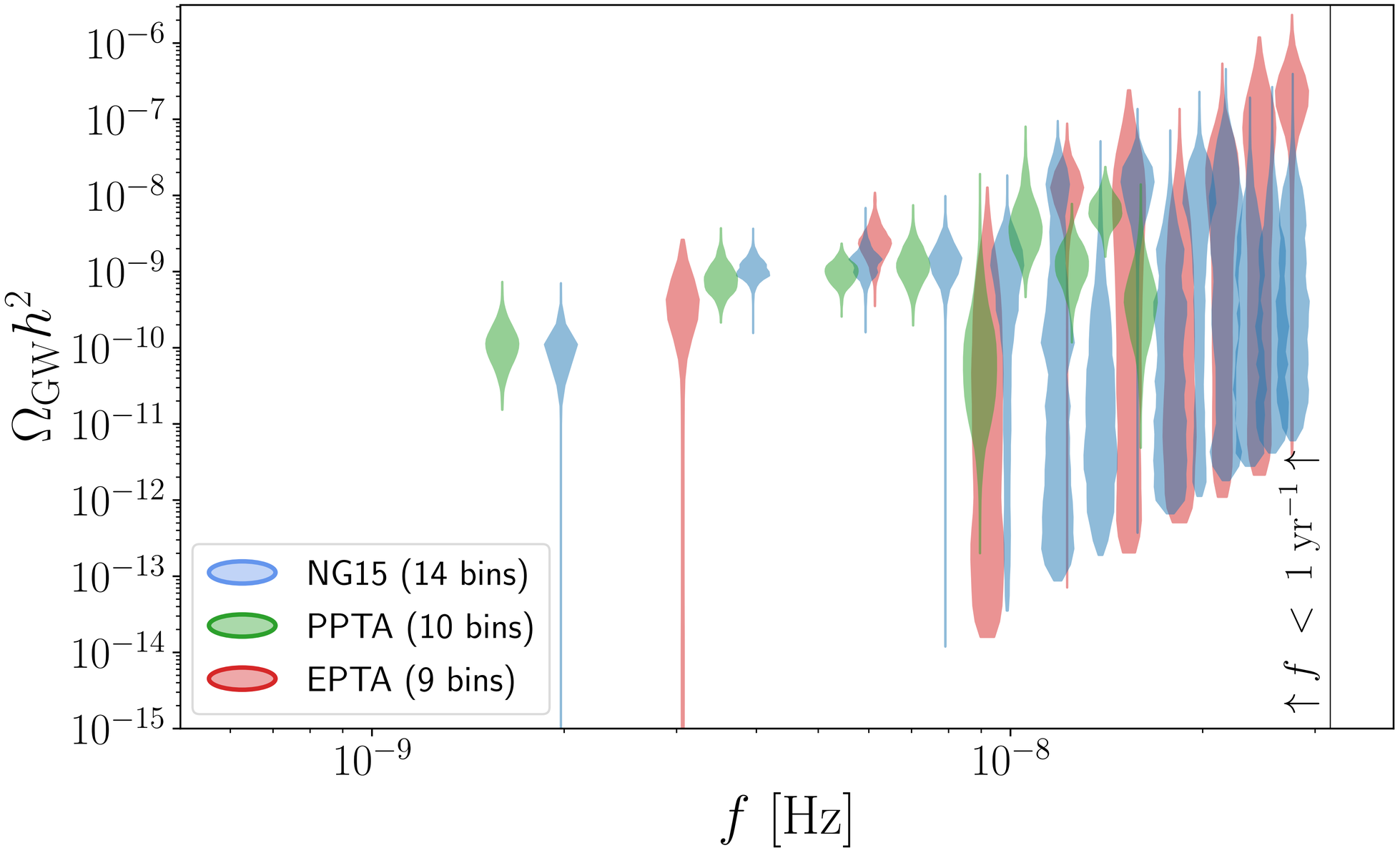
# Discovery of the first stochastic GW background by Pulsar Timing Arrays (PTA)



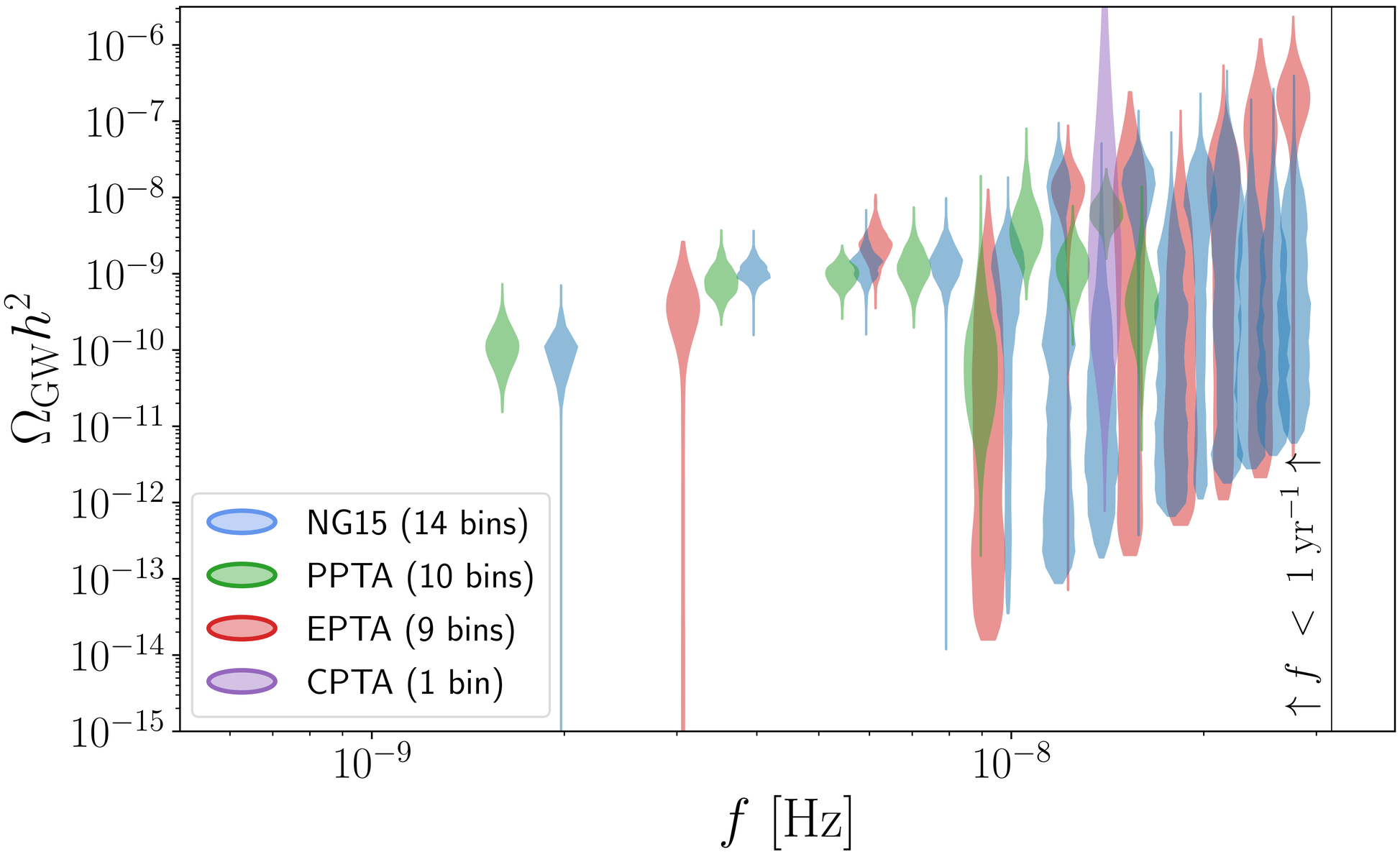
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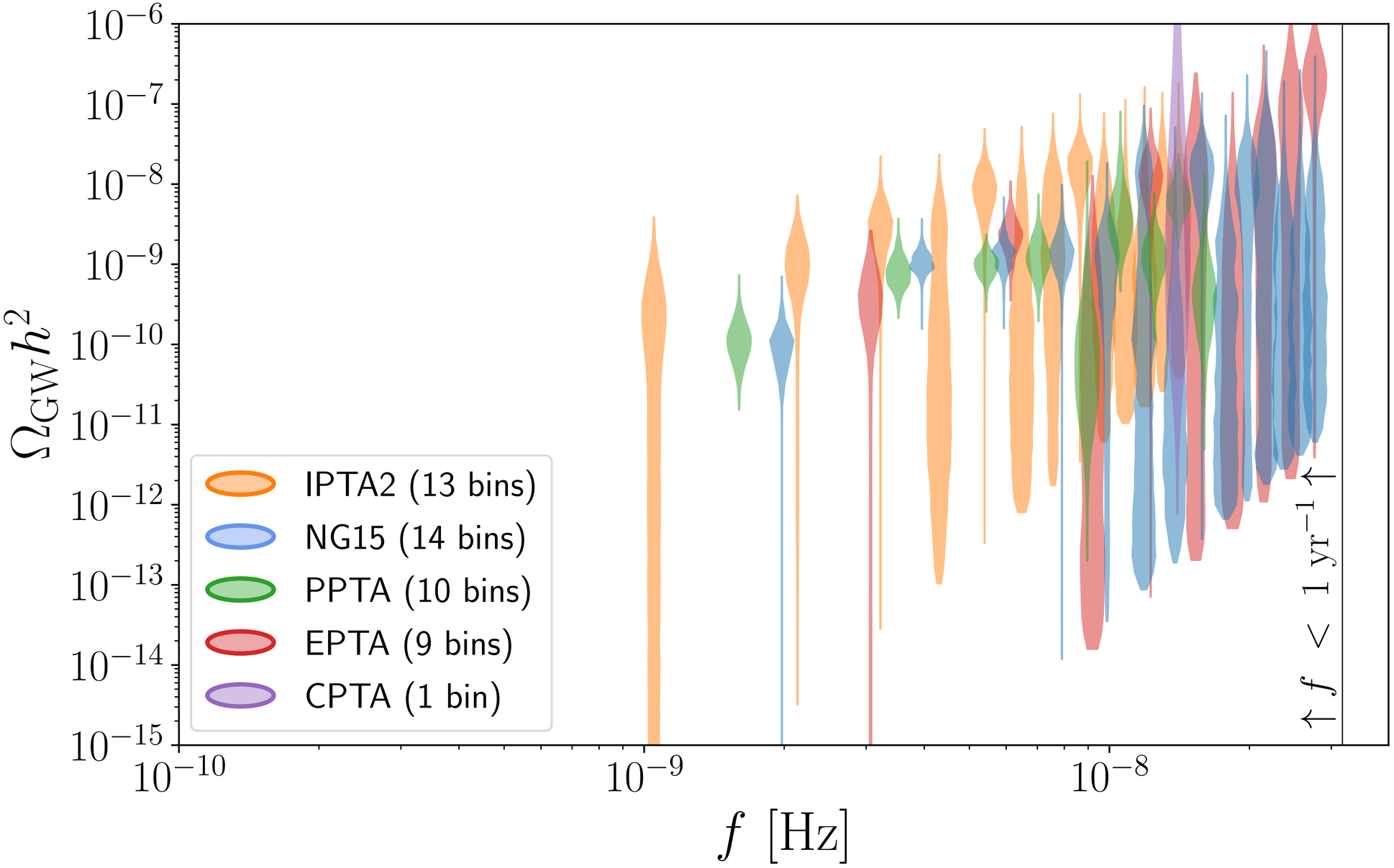
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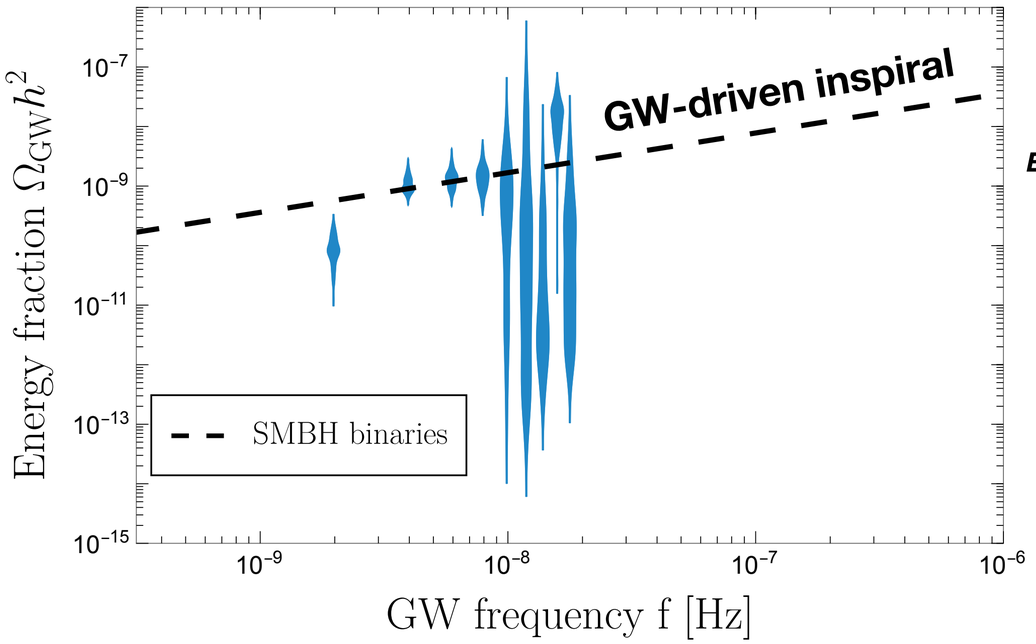
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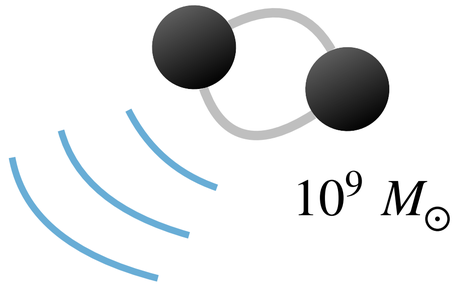


# Pulsar Timing Arrays (PTA)

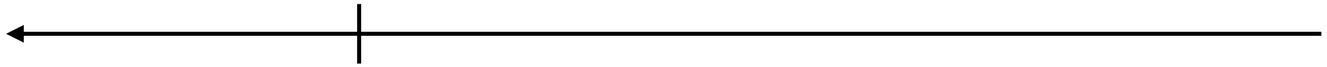



***Ellis, Fairbairn, Hutsi, Raidal, Urrutia, Vaskonen, Veermäe (23', 24')***

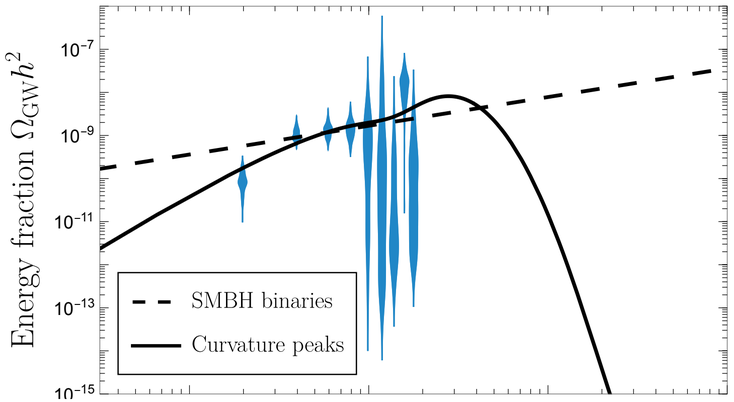
Supermassive black holes binaries




Gravitational Waves



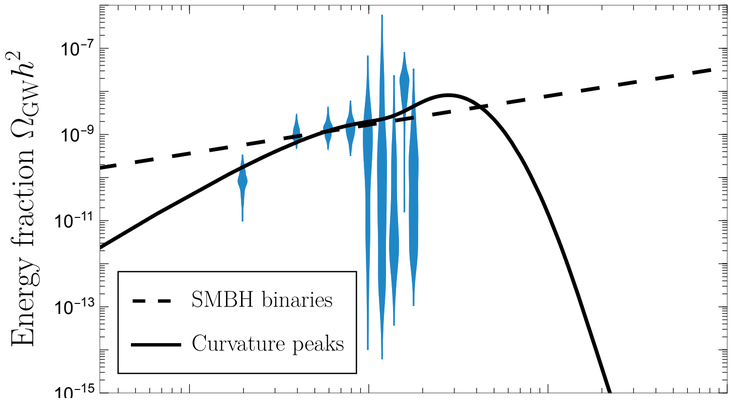
***Reviews:*** ***Madge et al (2306.14856), Figueroa et al (2307.02399), Ellis et al (2308.08546)***




## Curvature peaks

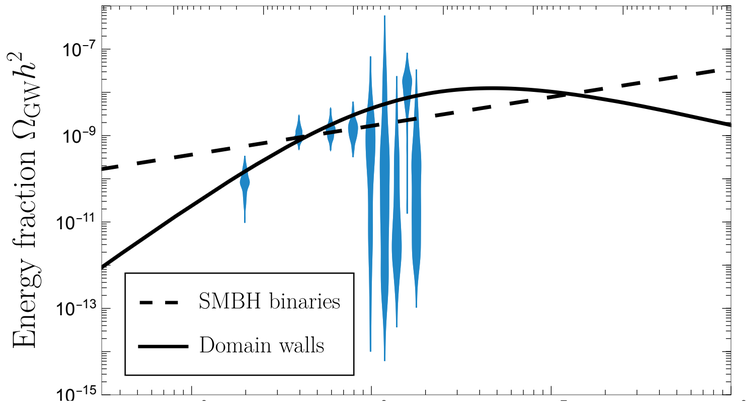
***Kohri, Terada (2009.11853)***
***Vaskonen, Veermae (2009.07832),***
***Franciolini, Iovino, Vaskonen, Vermae (2306.17143)***
***Cecchini, Franciolini, Pieroni (2503.10805)***
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## Curvature peaks

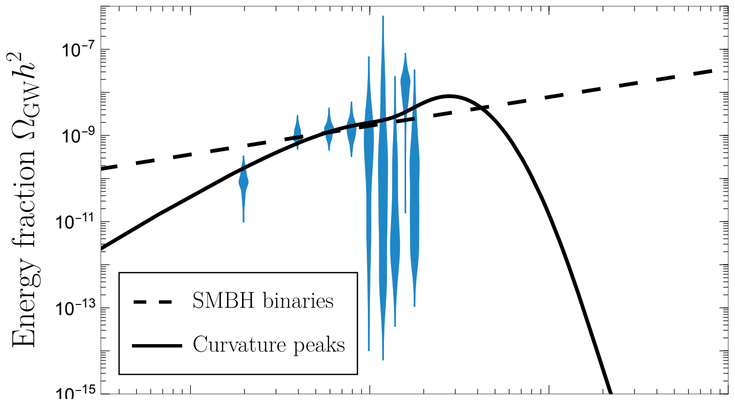
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***...***




## Domain wall networks

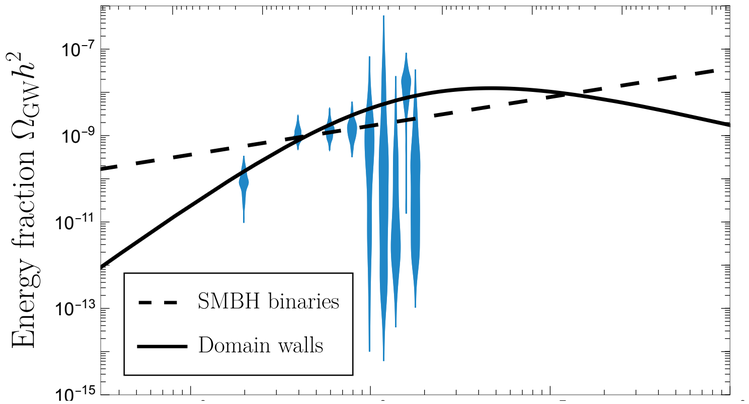
***Ferreira, Notari, Pujolas, Rompineve (2204.04228)***
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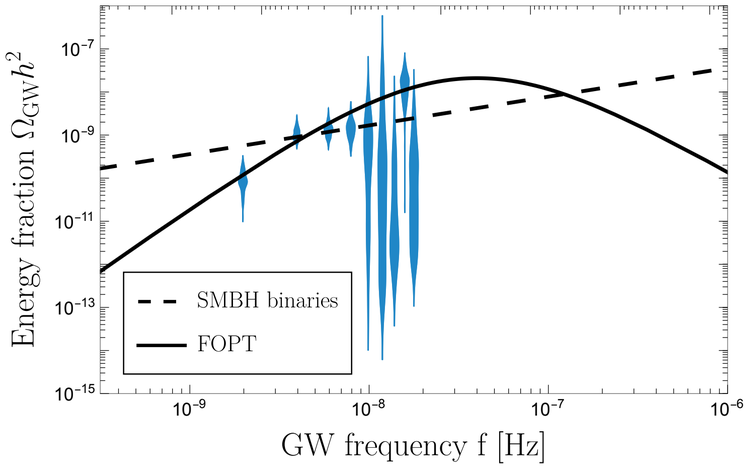

## Curvature peaks

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## Domain wall networks

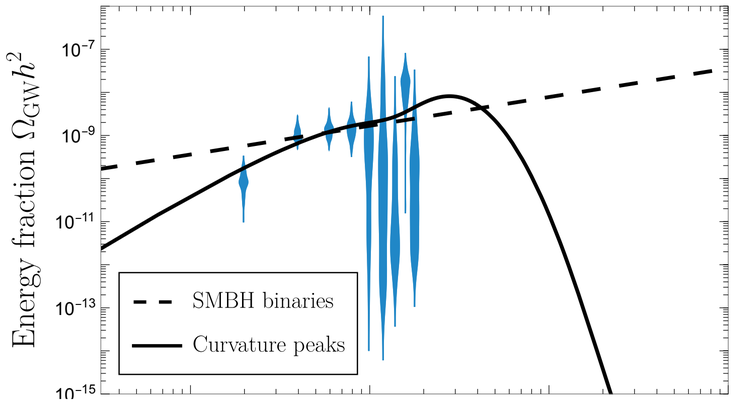
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## First-order phase transitions

***Roper Pol et al. (2201.05630)***
***Ghoshal, White et al. (2307.02259)***
***YG (2307.04239)***
**Lewicki, Toczek, Vaskonen (2402.04158)**
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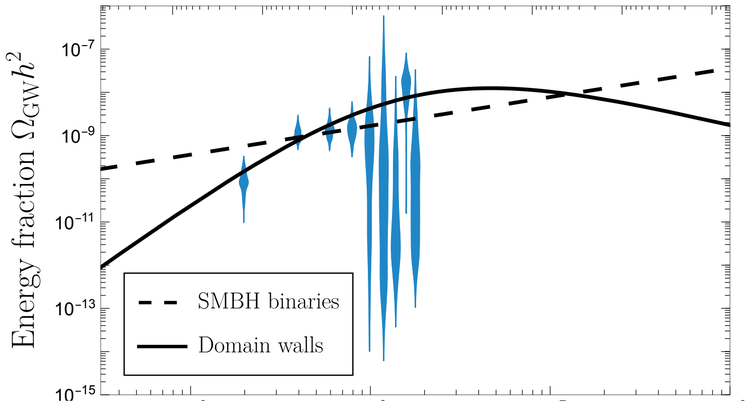



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PBH

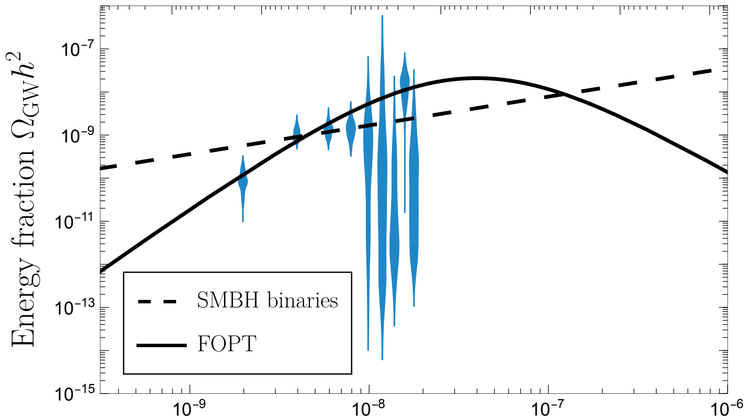



## Domain wall networks

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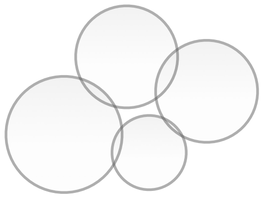


PBH

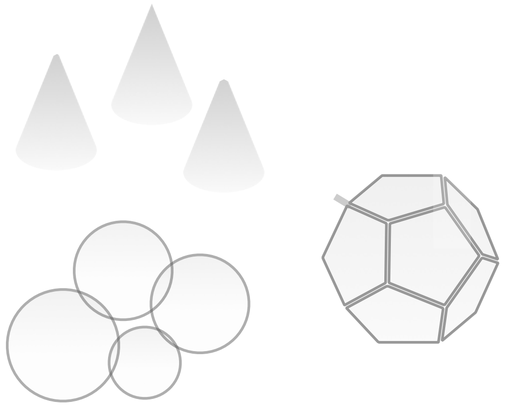



## First-order phase transitions

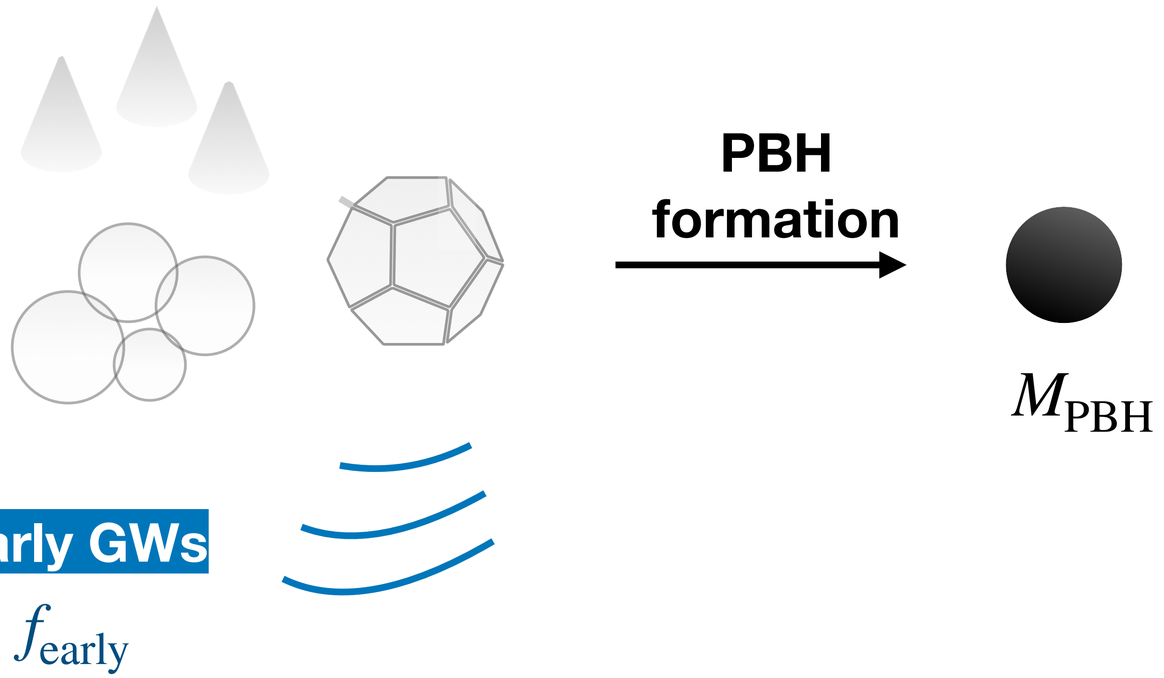
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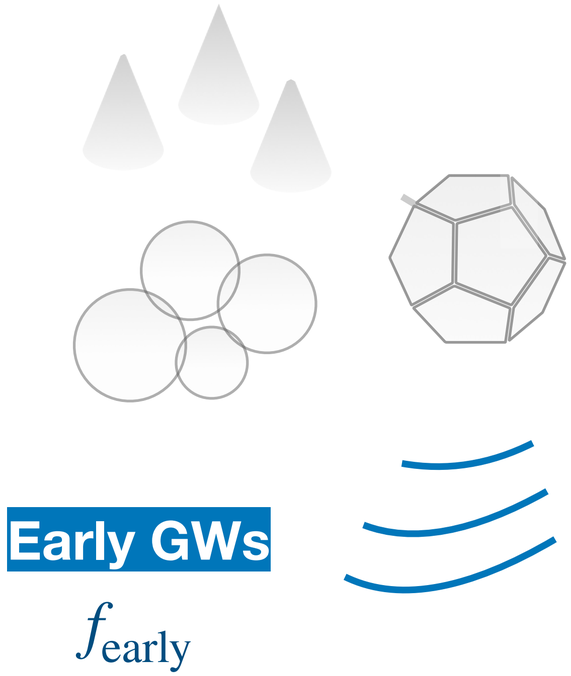


PBH




Early GWs
$f_{\mathrm{early}}$


PBH
formation
$M_{\mathrm{PBH}}$
Early GWs
$f_{\mathrm{early}}$

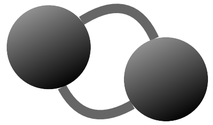


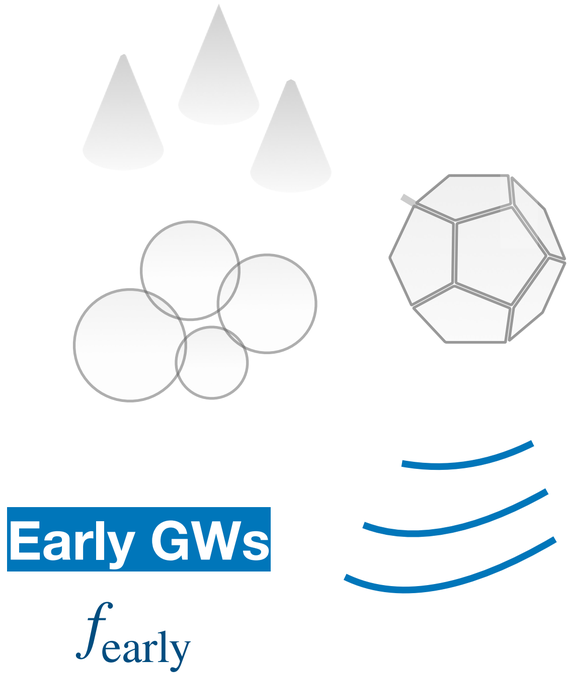

**PBH formation**



$M_{\rm PBH}$

**Binary formation**



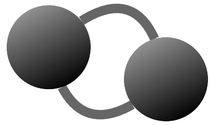


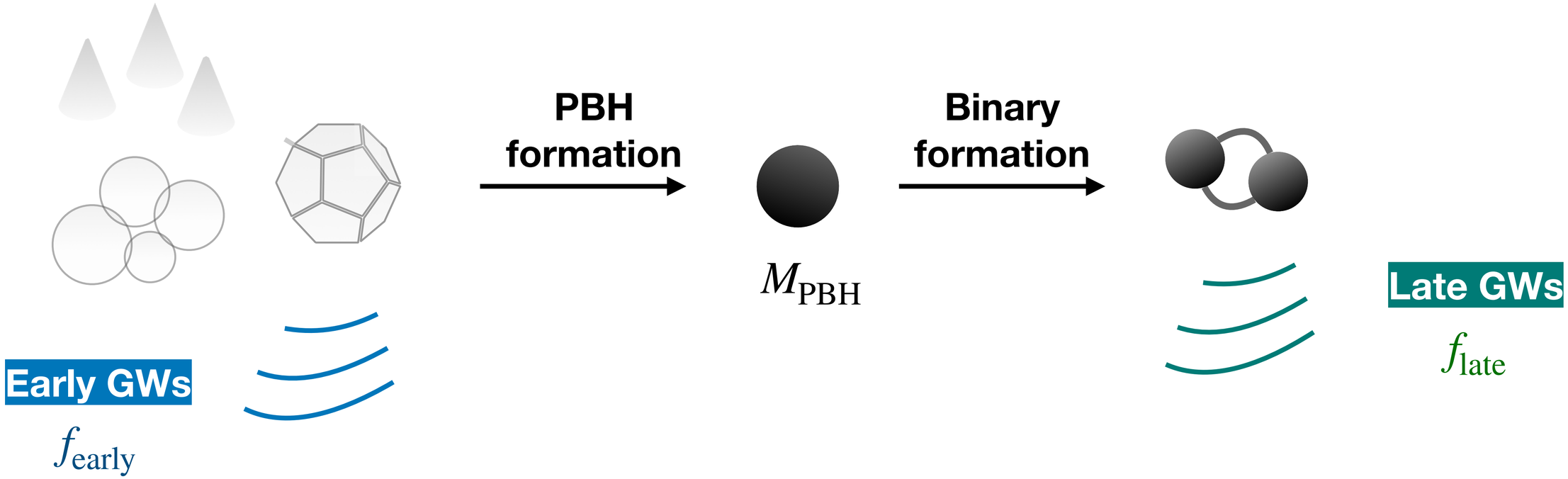

**PBH formation**



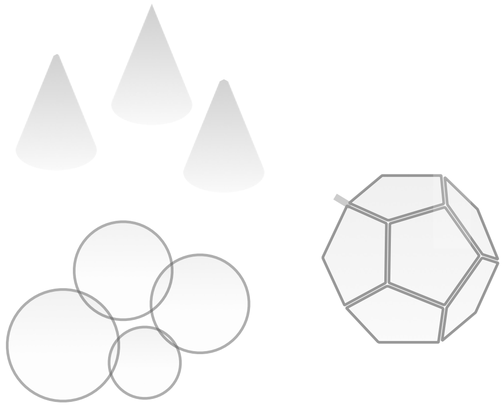
$M_{\rm PBH}$

**Binary formation**




PBH
formation
Binary
formation
$M_{\mathrm{PBH}}$
Early GWs
$f_{\mathrm{early}}$
Late GWs
$f_{\mathrm{late}}$

$$\left(\frac{f_{\rm early}}{3\ {\rm nHz}}\right) \simeq \epsilon_\star \left(\frac{4\ M_\odot}{M_{\rm PBH}}\right)^{1/2} \simeq \epsilon_\star \left(\frac{f_{\rm late}}{1\ {\rm kHz}}\right)^{1/2} \qquad \left(\epsilon_\star \equiv \frac{k_\star}{\mathscr{H}_\star}\right)$$



**Early GWs**

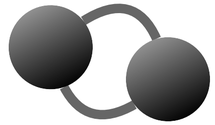
$f_{\rm early}$

**PBH formation**



$M_{\rm PBH}$

**Binary formation**

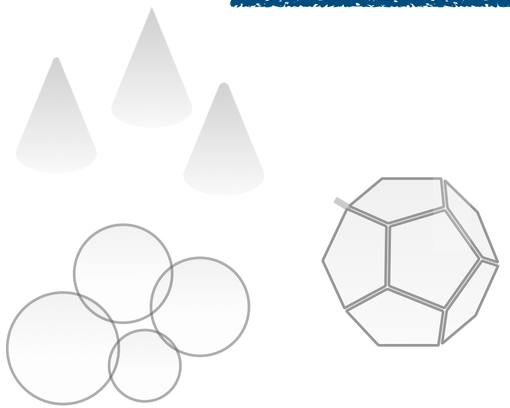




**Late GWs**

$f_{\rm late}$

$$\left(\frac{f_{\rm early}}{3\ {\rm nHz}}\right) \simeq \epsilon_\star \left(\frac{4\ M_\odot}{M_{\rm PBH}}\right)^{1/2} \simeq \epsilon_\star \left(\frac{f_{\rm late}}{1\ {\rm kHz}}\right)^{1/2} \qquad \left(\epsilon_\star \equiv \frac{k_\star}{\mathscr{H}_\star}\right)$$



**Early GWs**

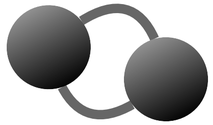
$f_{\rm early}$

**PBH formation**



$M_{\rm PBH}$

**Binary formation**

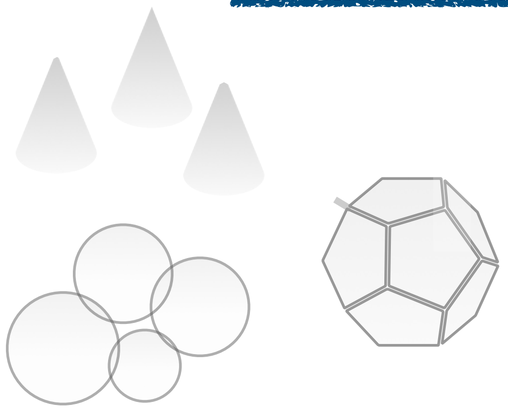




**Late GWs**

$f_{\rm late}$

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**Early GWs**

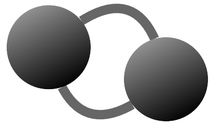
$f_{\rm early}$

**PBH formation**



$M_{\rm PBH}$

**Binary formation**

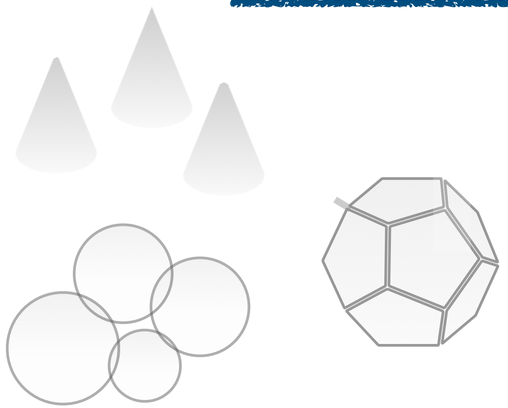




**Late GWs**

$f_{\rm late}$

$$\left(\frac{f_{\rm early}}{3\ {\rm nHz}}\right) \simeq \epsilon_\star \left(\frac{4\ M_\odot}{M_{\rm PBH}}\right)^{1/2} \simeq \epsilon_\star \left(\frac{f_{\rm late}}{1\ {\rm kHz}}\right)^{1/2} \qquad \left(\epsilon_\star \equiv \frac{k_\star}{\mathscr{H}_\star}\right)$$

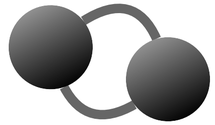


**PBH formation**



$M_{\rm PBH}$

**Binary formation**





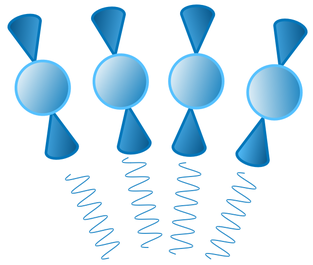
**Late GWs**

$f_{\rm late}$

**Early GWs**

$f_{\rm early}$

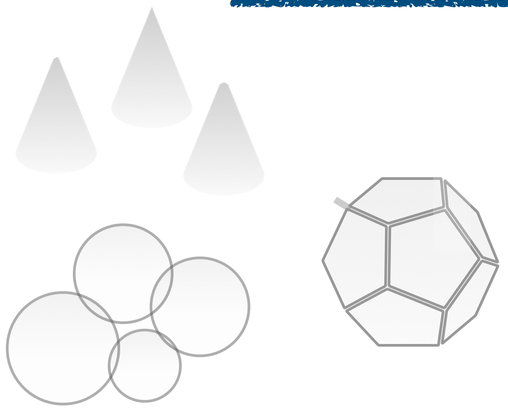




**Pulsar Timing Arrays**
**(NG15, EPTA, PPTA, CPTA, . . . )**

**nHz GW**

$$\left(\frac{f_{\rm early}}{3\ {\rm nHz}}\right) \simeq \epsilon_\star \left(\frac{4\ M_\odot}{M_{\rm PBH}}\right)^{1/2} \simeq \epsilon_\star \left(\frac{f_{\rm late}}{1\ {\rm kHz}}\right)^{1/2} \qquad \left(\epsilon_\star \equiv \frac{k_\star}{\mathscr{H}_\star}\right)$$

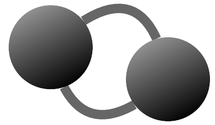


PBH formation



$M_{\rm PBH}$

Binary formation



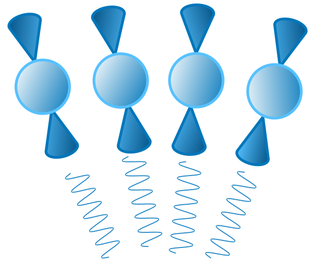


**Late GWs**

$f_{\rm late}$

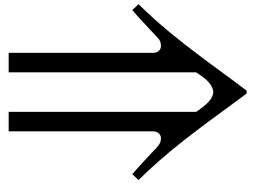
**Early GWs**

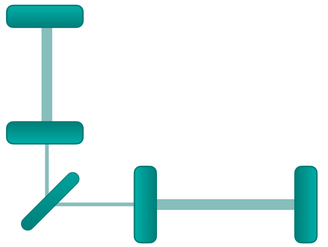
$f_{\rm early}$



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**(NG15, EPTA, PPTA, CPTA, . . . )**

**nHz GW**

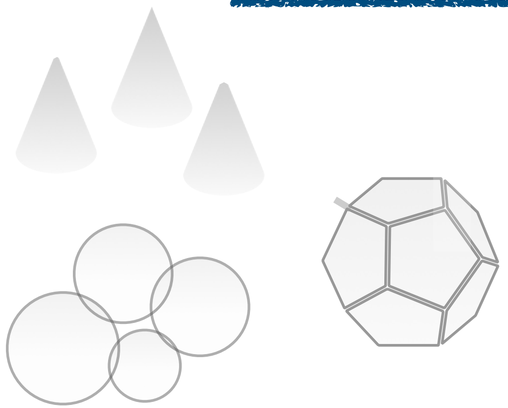




**Earth-based Laser Interferometers**
**(LVK $O_4$, $O_5$, ET, CE)**

**kHz GW**

$$\left(\frac{f_{\rm early}}{3\ {\rm nHz}}\right) \simeq \epsilon_\star \left(\frac{4\ M_\odot}{M_{\rm PBH}}\right)^{1/2} \simeq \epsilon_\star \left(\frac{f_{\rm late}}{1\ {\rm kHz}}\right)^{1/2} \qquad \left(\epsilon_\star \equiv \frac{k_\star}{\mathscr{H}_\star}\right)$$

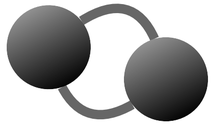


**PBH formation**



$M_{\rm PBH}$

**Binary formation**



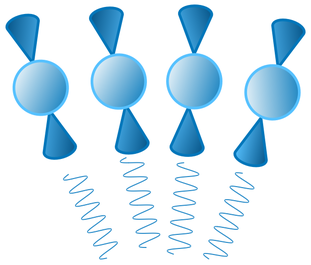


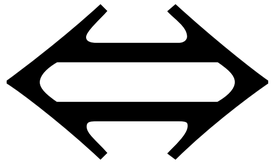
**Late GWs**

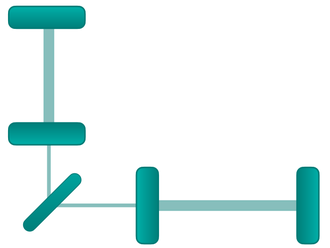
$f_{\rm late}$

**Early GWs**

$f_{\rm early}$





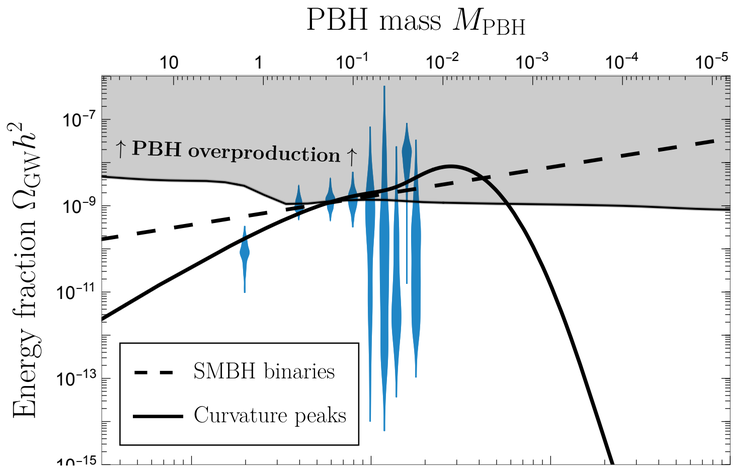


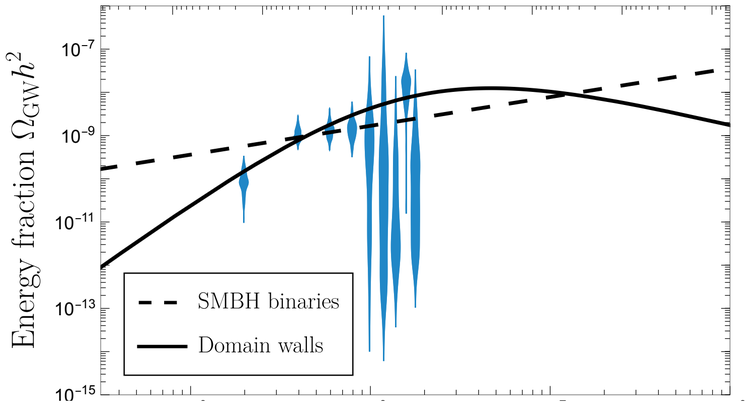
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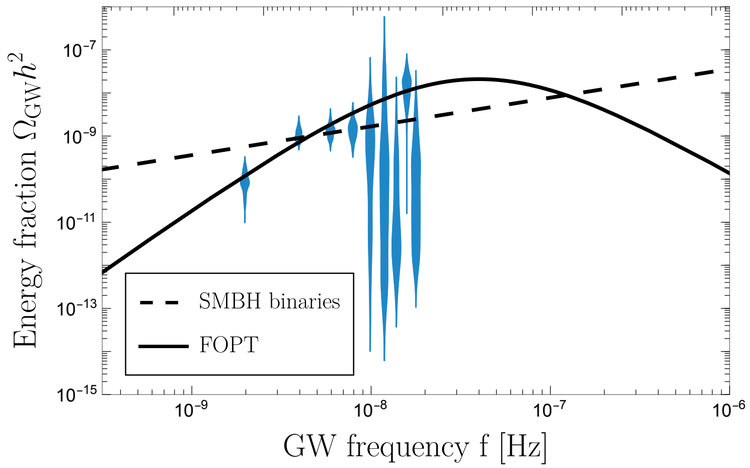
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## Curvature peaks

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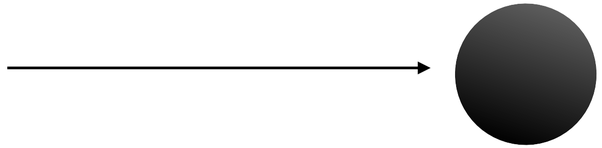
*Clesse, Dandoy, Verma (2412.15989)*

*Except if negative non-Gaussianities*

*Franciolini, Iovino, Vaskonen, Veermae (2306.17143)*

*YG, Trifinopoulos, Vanvlasselaer (2508.19328)*





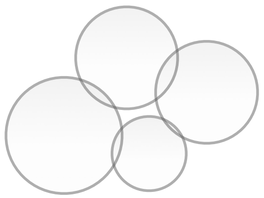
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*Blasi, Mariotti, Rase, Sevrin (2306.17830)*
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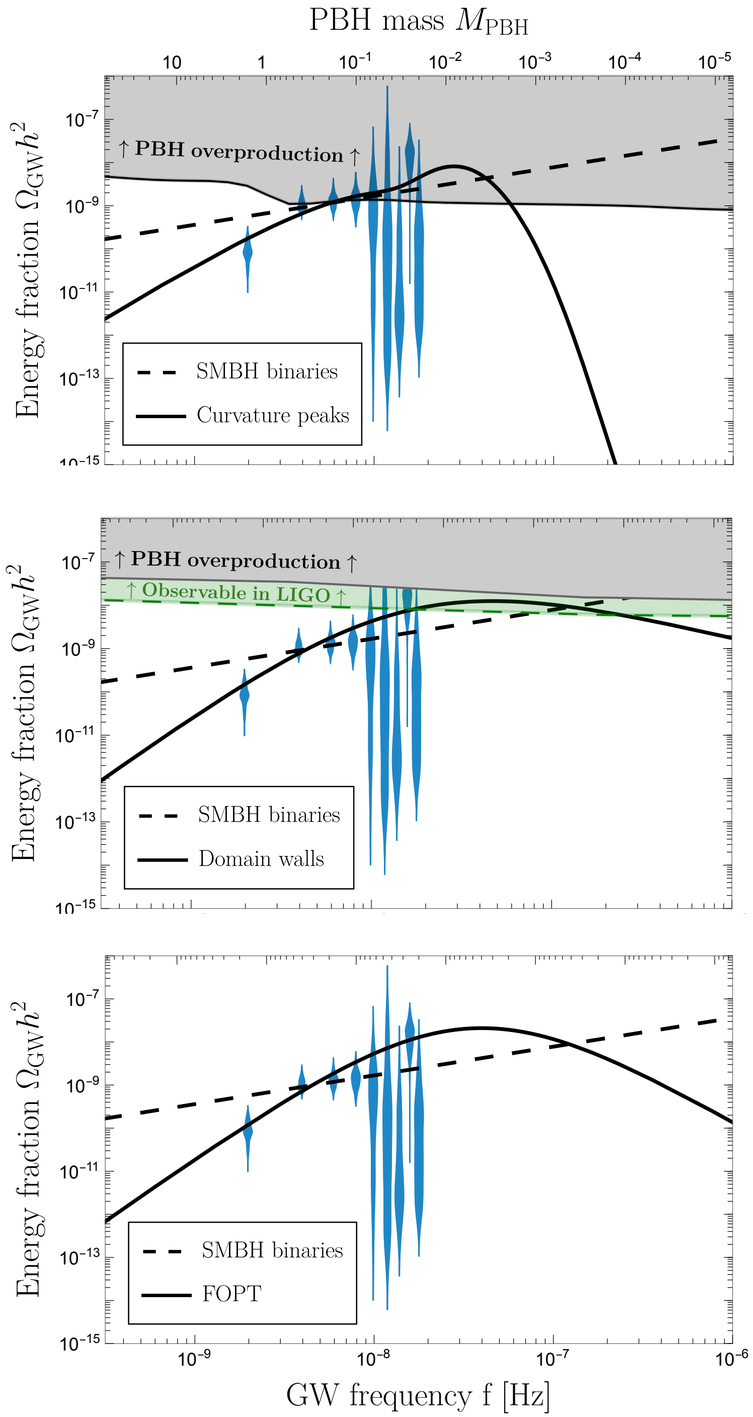


## First-order phase transitions

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*YG (2307.04239)*
**Lewicki, Toczek, Vaskonen (2402.04158)**
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**...**



***Reviews:*** ***Madge et al (2306.14856), Figueroa et al (2307.02399), Ellis et al (2308.08546)***




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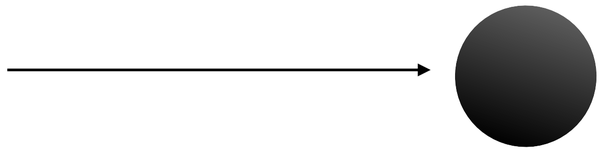
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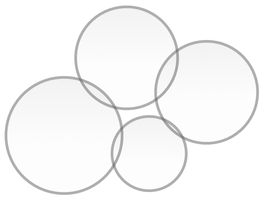
**Produce solar-mass PBH**

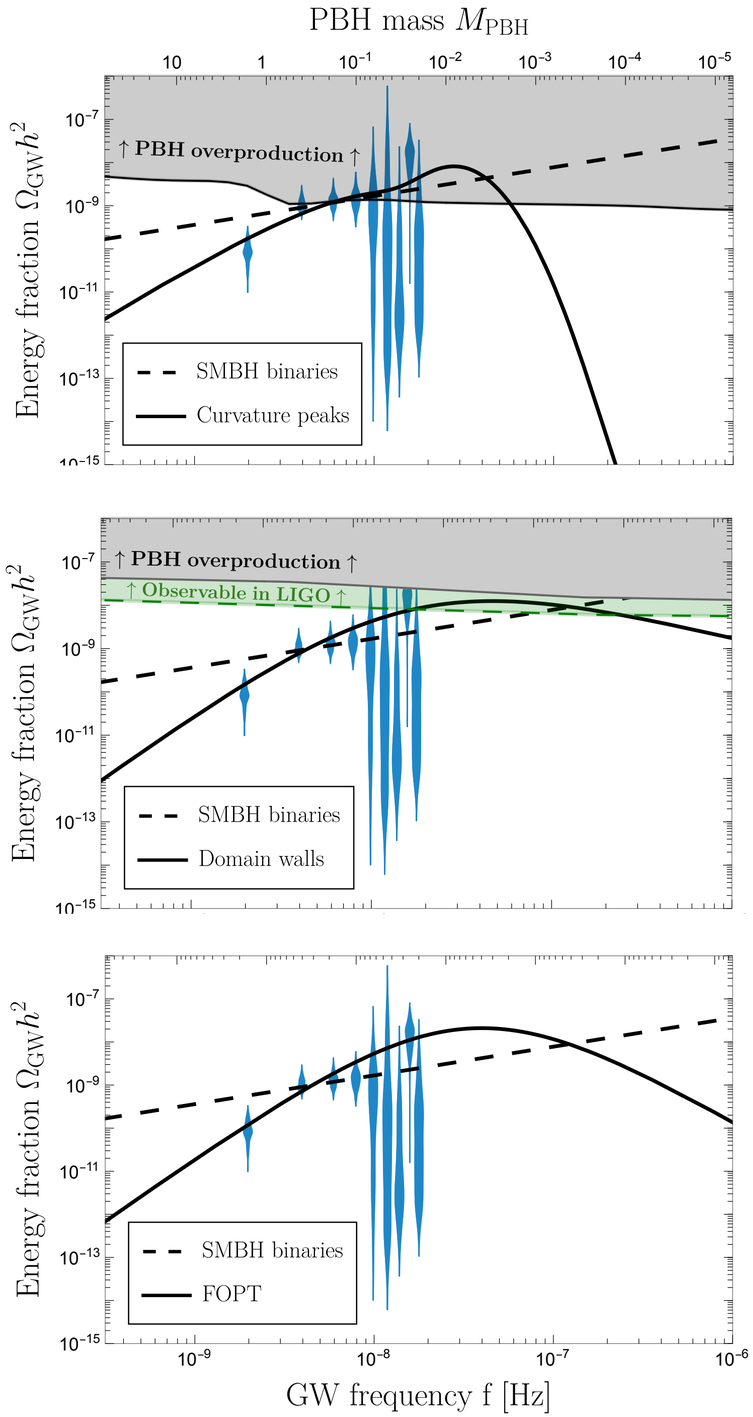
***YG, Vitagliano 2306.17841***



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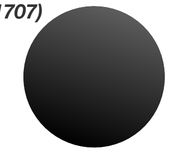
**Produce solar-mass PBH**

***YG, Vitagliano 2306.17841***



*Ferrer, Masso, Panico, Pujolas, Rompineve (1807.01707)*
*Ferreira, Notari, Pujolas, Rompineve (2401.14331)*

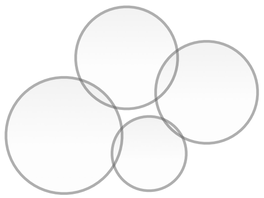
***YG,Vitagliano, 2311.07670***

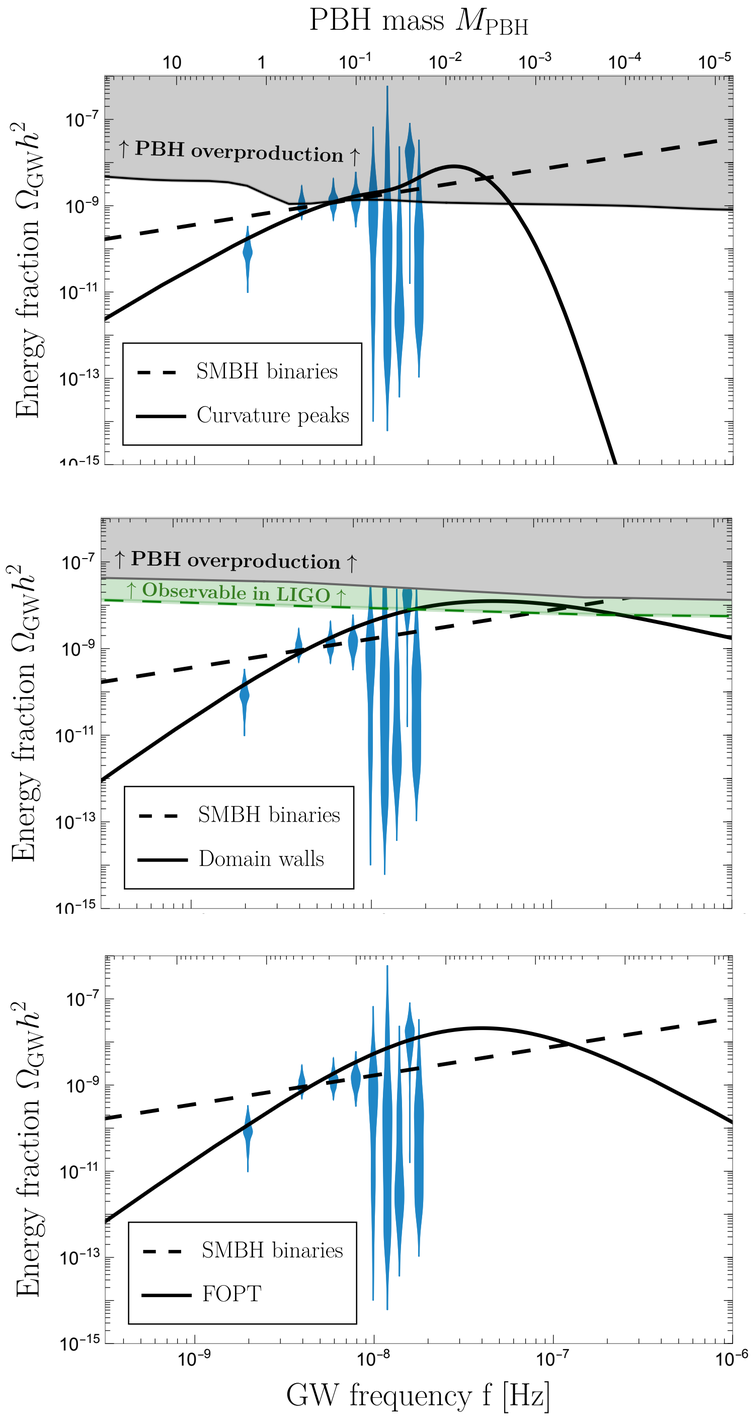


PBH

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**...**





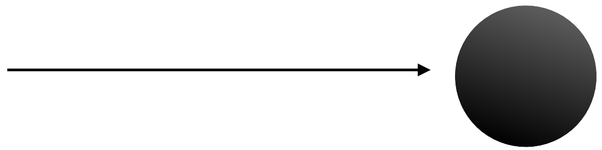

***Reviews:*** ***Madge et al (2306.14856), Figueroa et al (2307.02399), Ellis et al (2308.08546)***

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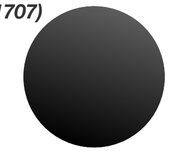
**Produce solar-mass PBH**

***YG, Vitagliano 2306.17841***



*Ferrer, Masso, Panico, Pujolas, Rompineve (1807.01707)*
*Ferreira, Notari, Pujolas, Rompineve (2401.14331)*

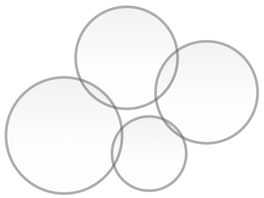
***YG,Vitagliano, 2311.07670***

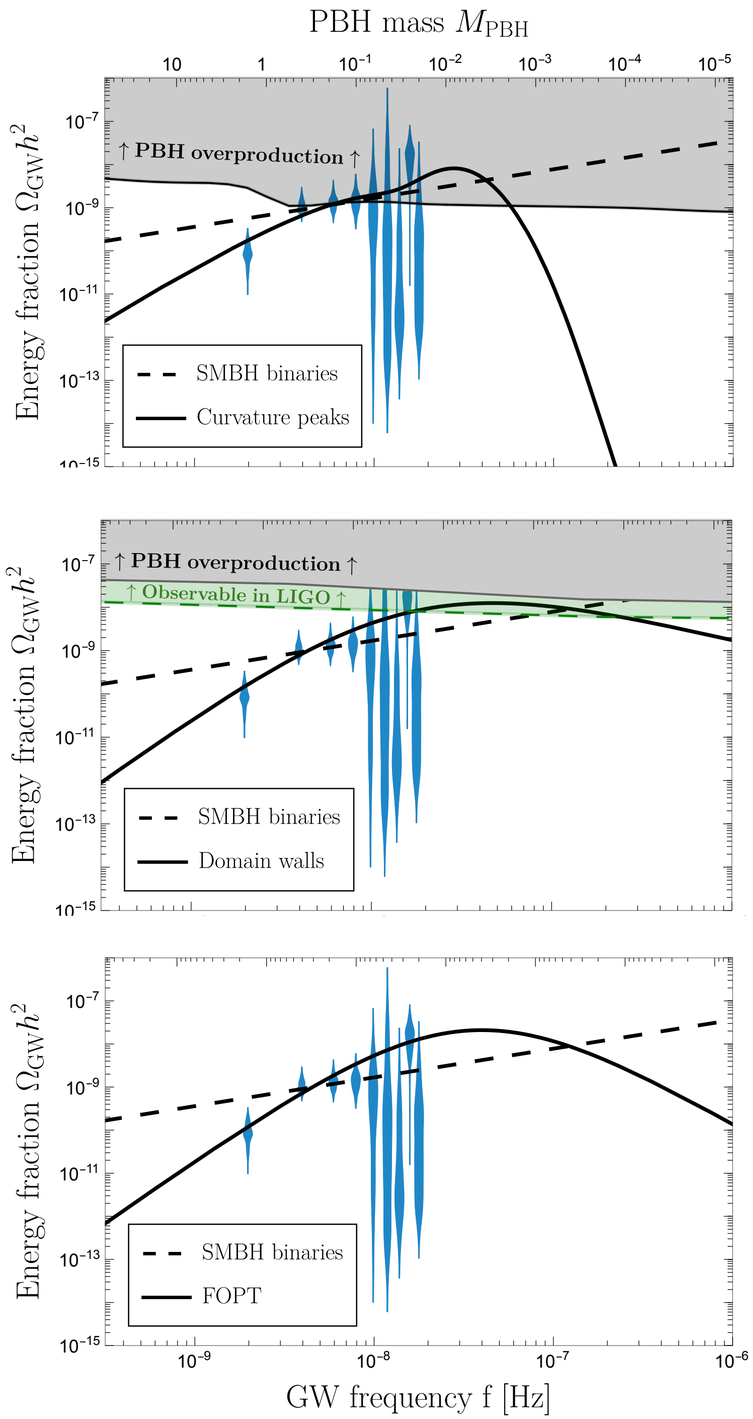


PBH

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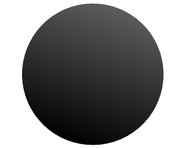



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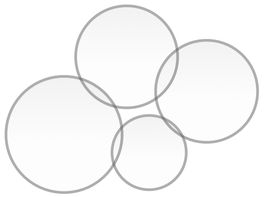


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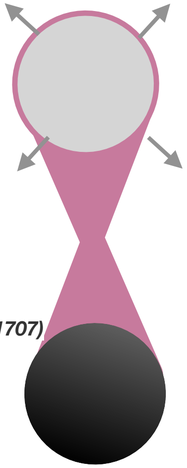


***Reviews:*** ***Madge et al (2306.14856),***
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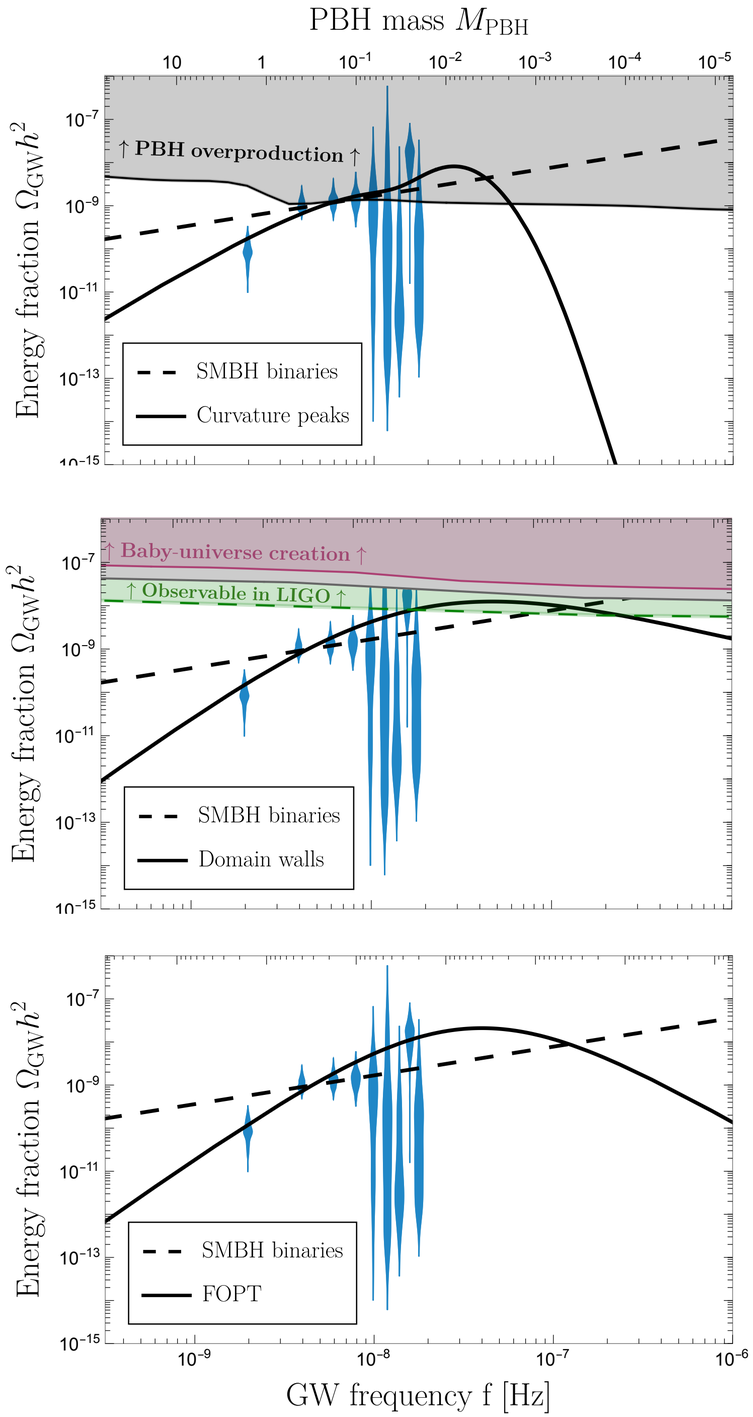
Baby-universe

*Deng, Garriga, Vilenkin (1612.03753)*

Wormhole



PBH

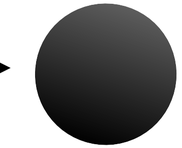



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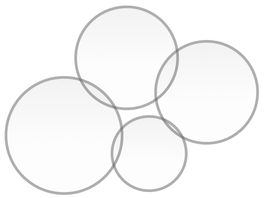


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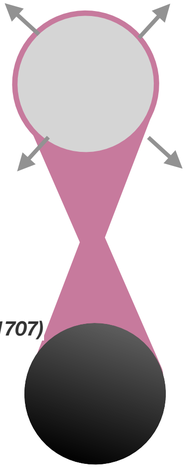


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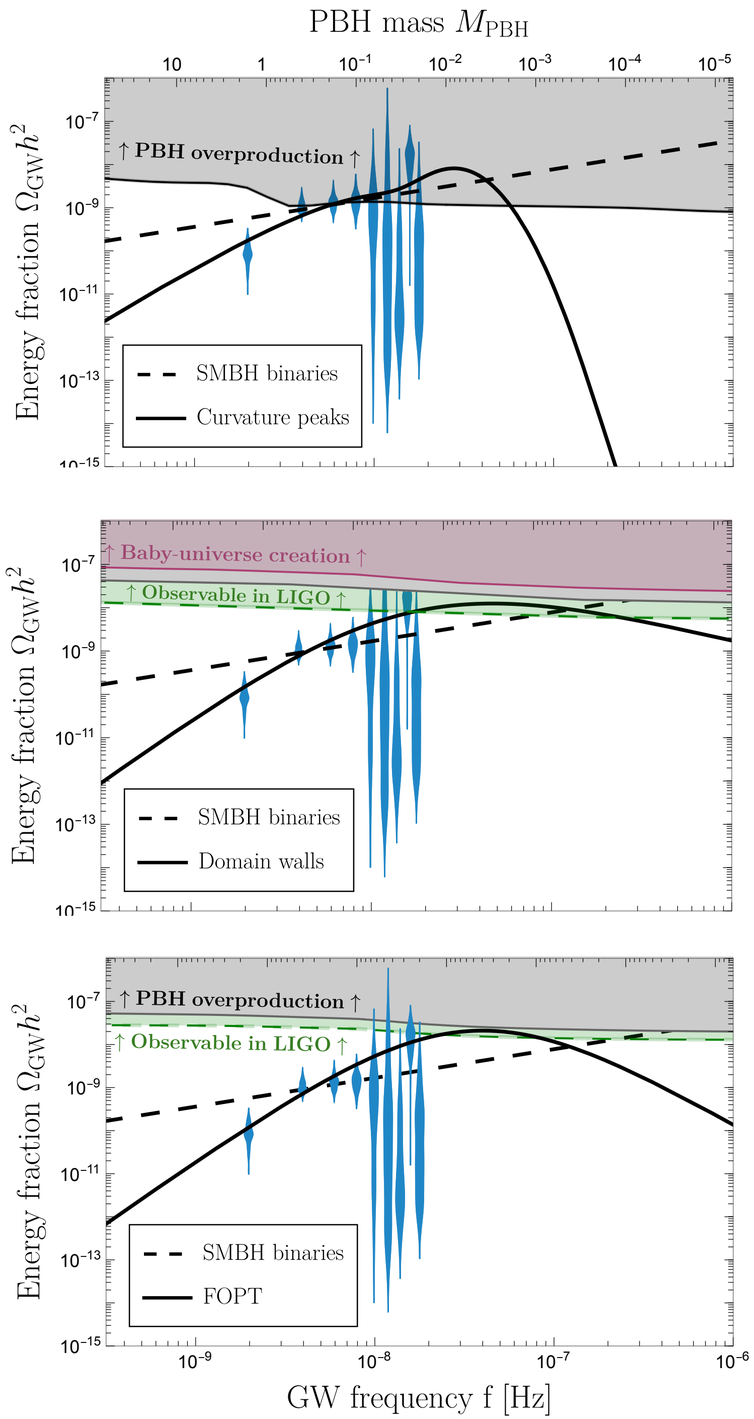
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*Vaskonen, Veermae (2009.07832),*
*De Luca, Franciolini, Riotto (2009.08268)*
*Clesse, Dandoy, Verma (2412.15989)*

*Except if negative non-Gaussianities*

*Franciolini, Iovino, Vaskonen, Veermae (2306.17143)*
*YG, Trifinopoulos, Vanvlasselaer (2508.19328)*

## Domain wall networks

*Ferreira, Notari, Pujolas, Rompineve (2204.04228)*
*Blasi, Mariotti, Rase, Sevrin (2306.17830)*
*...*

**Produce solar-mass PBH**

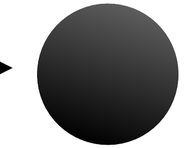
*YG, Vitagliano 2306.17841*

## First-order phase transitions

*Roper Pol et al. (2201.05630)*
*Ghoshal, White et al. (2307.02259)*
*YG (2307.04239)*
Lewicki, Toczek, Vaskonen (2402.04158)
Hoefken Zink et al. (2501.15649)
...

***Reviews:* Madge et al (2306.14856), Figueroa et al (2307.02399), Ellis et al (2308.08546)**





Baby-universe

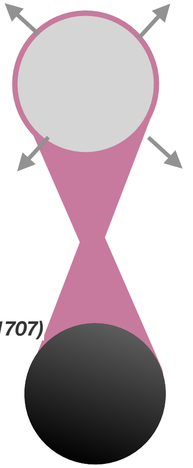
*Deng, Garriga, Vilenkin (1612.03753)*

Wormhole

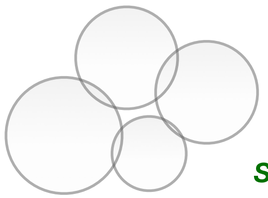


*Ferrer, Masso, Panico, Pujolas, Rompineve (1807.01707)*
*Ferreira, Notari, Pujolas, Rompineve (2401.14331)*

*YG,Vitagliano, 2311.07670*



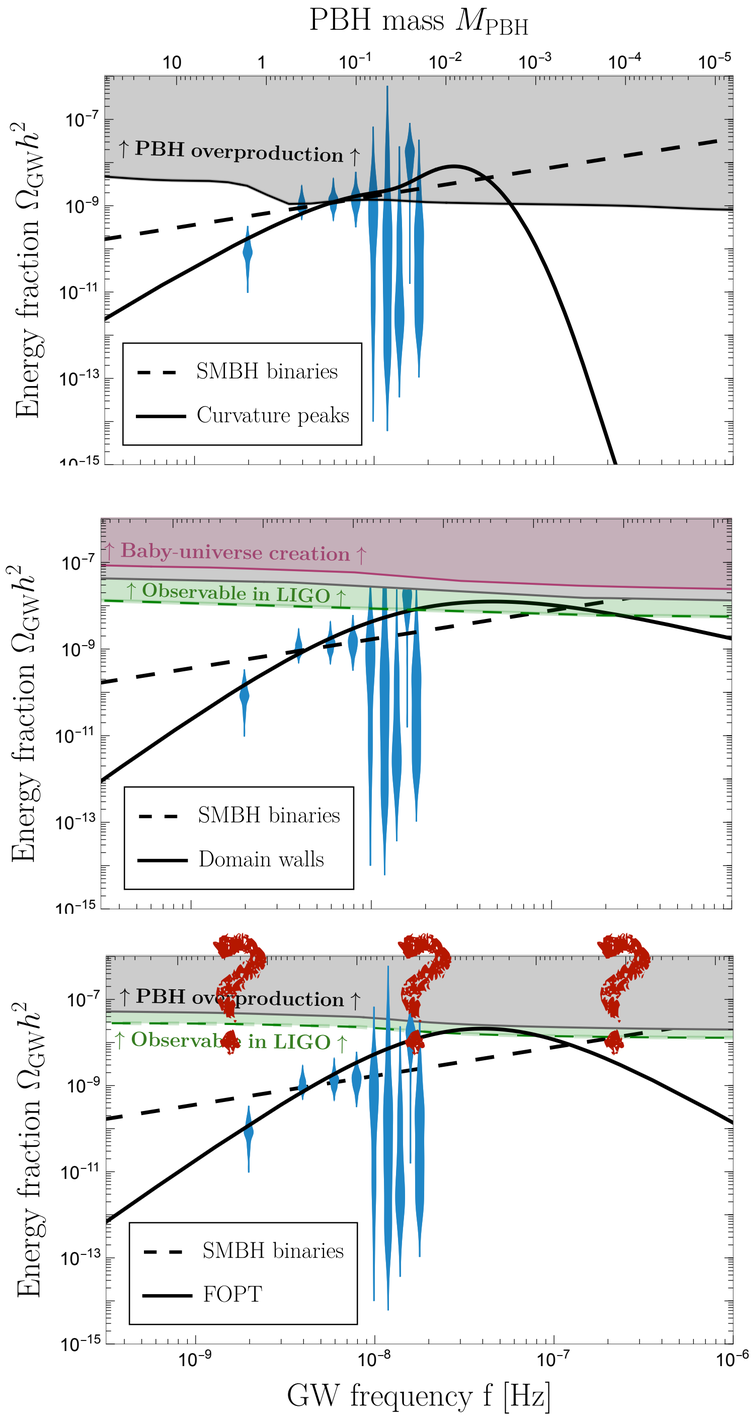
PBH



*YG&Volansky 2023,*
*YG (2307.04239)*



*Sasaki+ 1982, Bian+ 2021, Lu+ 2022,*
*Lewicki, Toczek, Vaskonen 2023,*
*Baldes+ 2023,*
*Lewicki, Toczek, Vaskonen 2024, .....*




## Curvature peaks

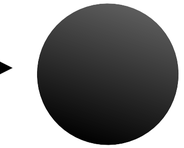
**Overproduce PBH**

*Chen, Yuan, Huang (1910.12239)*
*Kohri, Terada (2009.11853)*
*Inomata, Kawasaki, Mukaida, Yanagida (2011.01270)*
*Vaskonen, Veermae (2009.07832),*
*De Luca, Franciolini, Riotto (2009.08268)*
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## Domain wall networks

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*...*

**Produce solar-mass PBH**

*YG, Vitagliano 2306.17841*



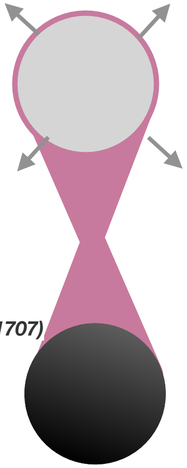
*Ferrer, Masso, Panico, Pujolas, Rompineve (1807.01707)*
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*YG,Vitagliano, 2311.07670*

## Baby-universe

*Deng, Garriga, Vilenkin (1612.03753)*

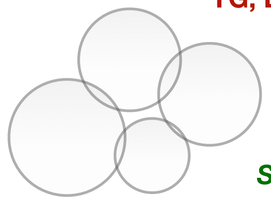
## Wormhole



PBH

## First-order phase transitions

*Roper Pol et al. (2201.05630)*
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Hoefken Zink et al. (2501.15649)
...



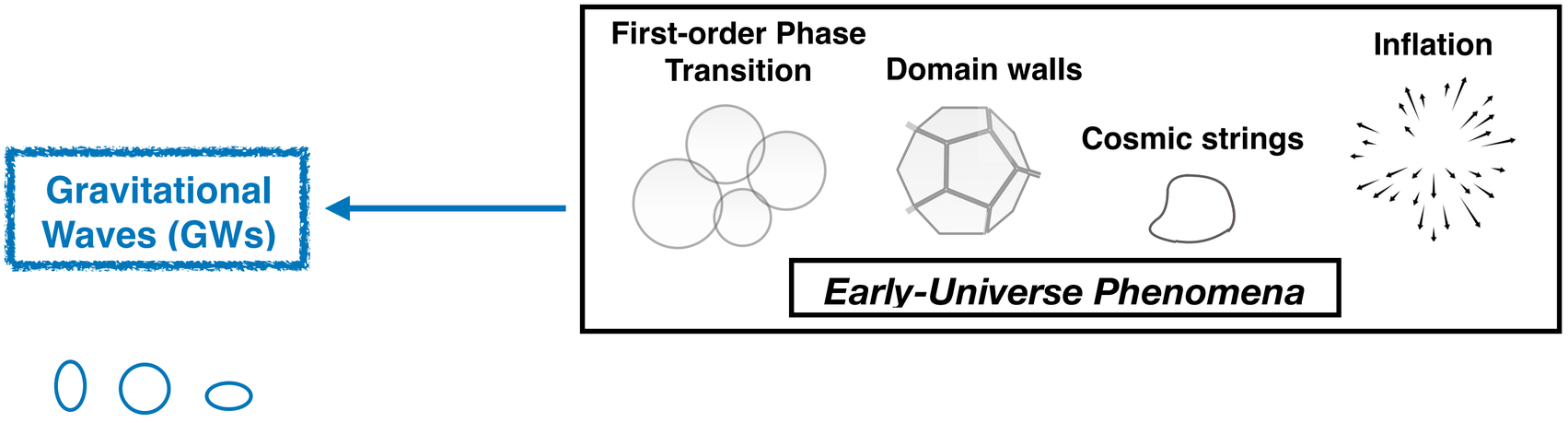
**Franciolini, YG, Jinno, 2503.01962**
**YG, Lewicki, Toczek, Vaskonen (in preparation)**

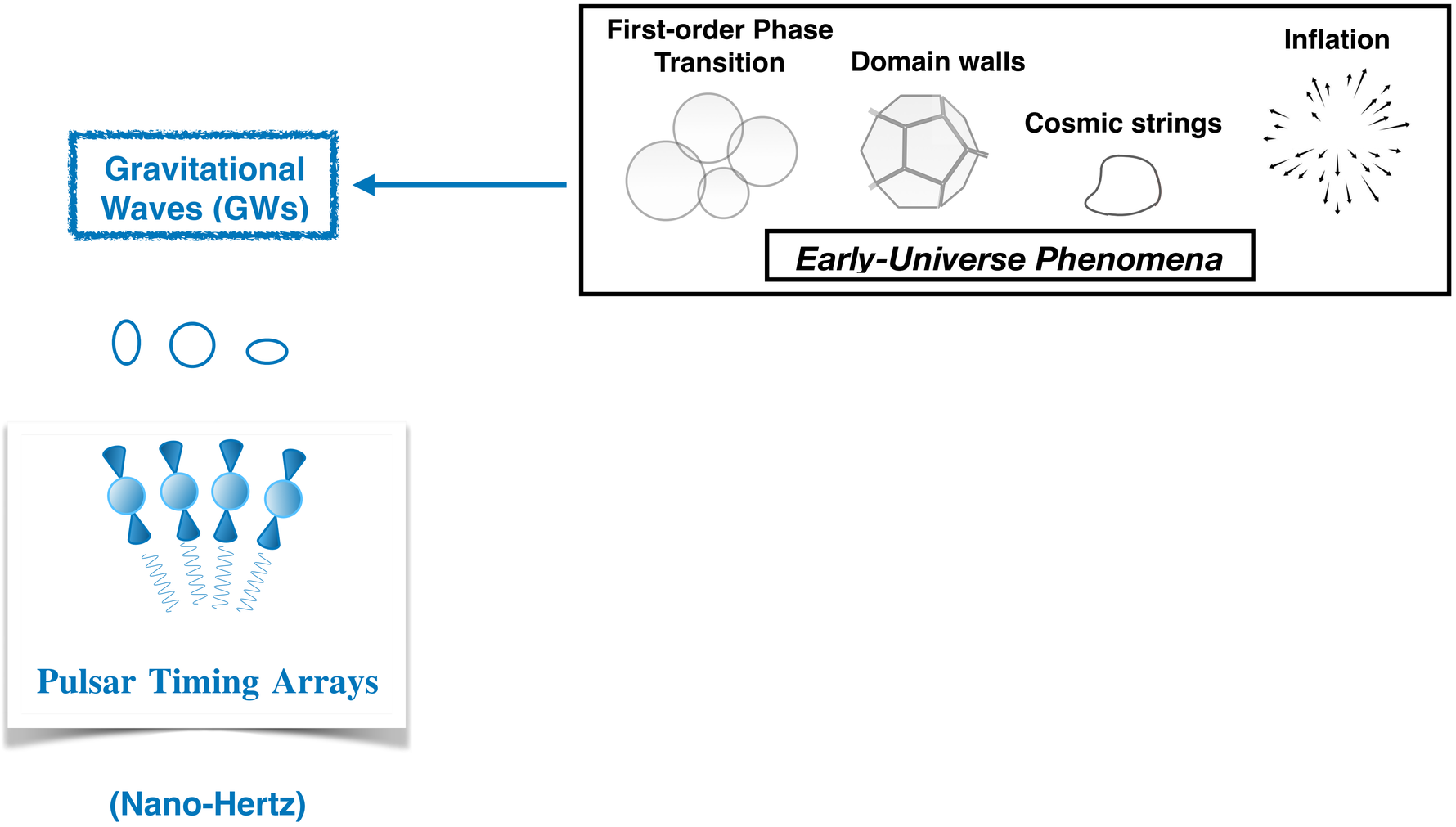
*YG&Volansky 2023,*
*YG (2307.04239)*



*Sasaki+ 1982, Bian+ 2021, Lu+ 2022,*
*Lewicki, Toczek, Vaskonen 2023,*
*Baldes+ 2023,*
*Lewicki, Toczek, Vaskonen 2024, .....*

***Reviews:** Madge et al (2306.14856),*
*Figueroa et al (2307.02399),*
*Ellis et al (2308.08546)*


First-order Phase Transition
Domain walls
Inflation
Cosmic strings
Early-Universe Phenomena
Gravitational Waves (GWs)


First-order Phase Transition
Domain walls
Inflation
Cosmic strings
Early-Universe Phenomena
Gravitational Waves (GWs)
Pulsar Timing Arrays
(Nano-Hertz)

First-order Phase Transition

Domain walls

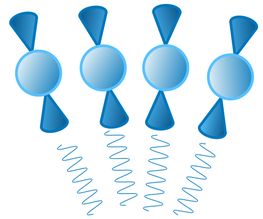
Inflation

Cosmic strings

*Early-Universe Phenomena*

**Gravitational Waves (GWs)**



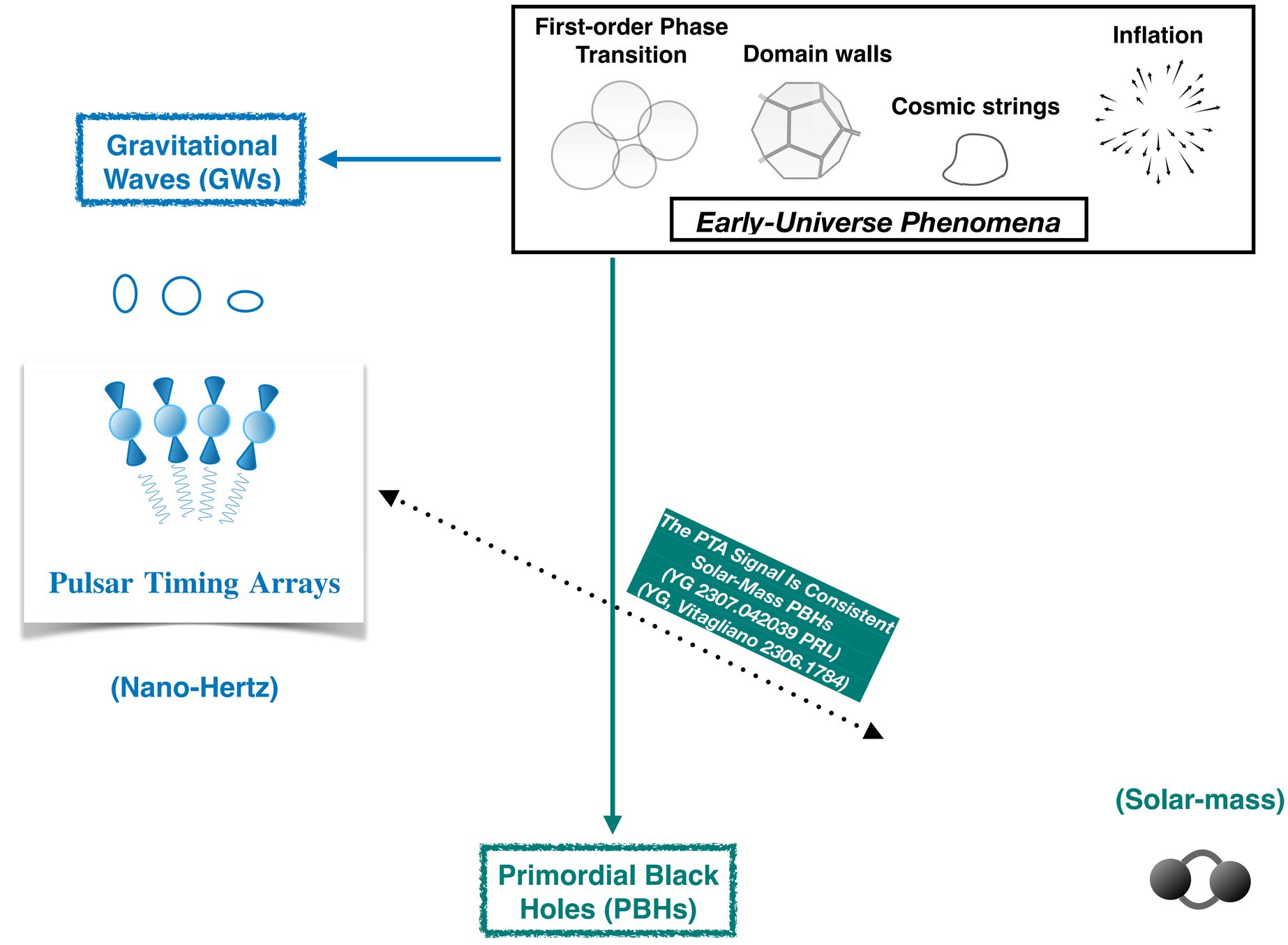


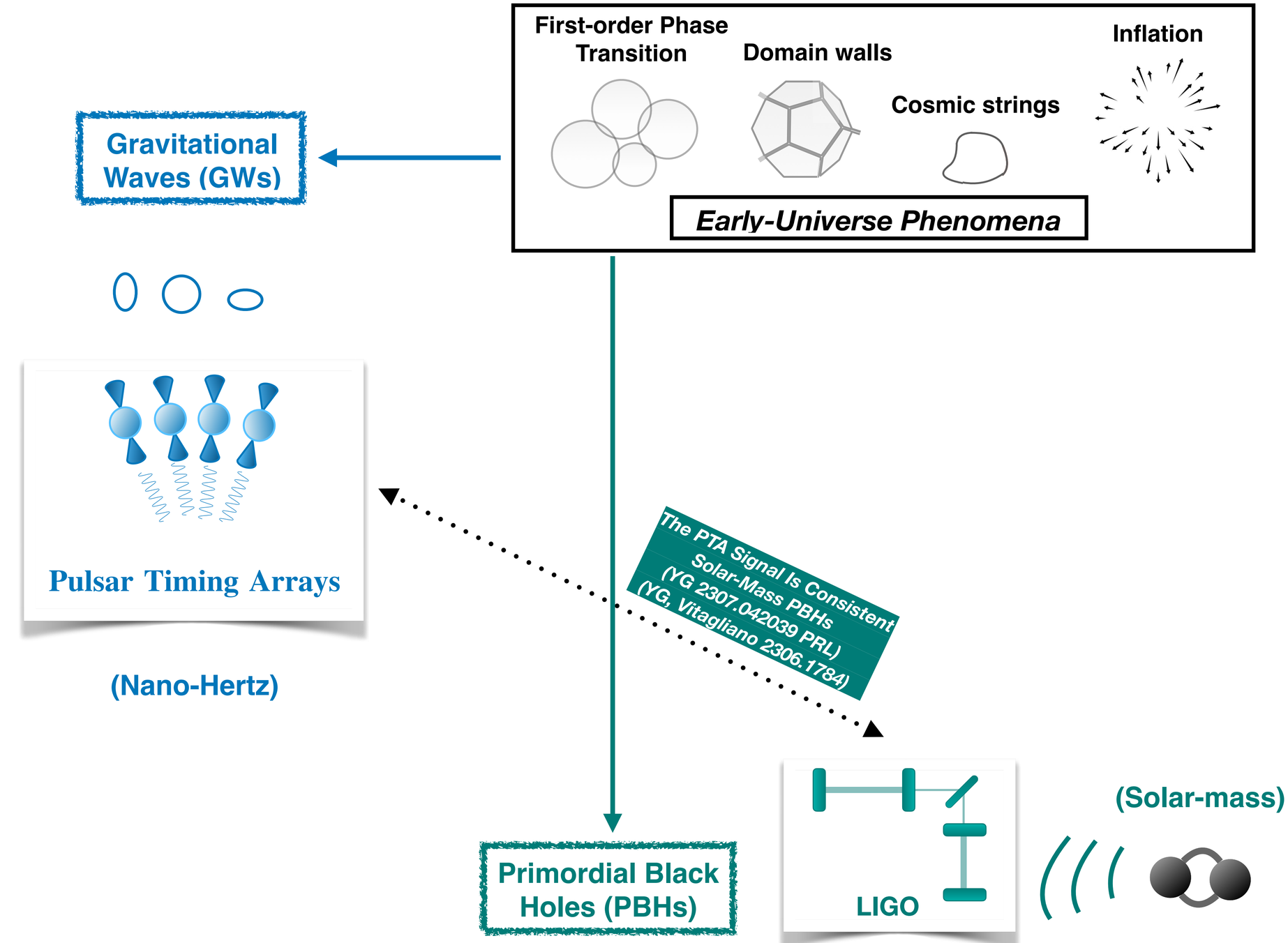
**Pulsar Timing Arrays**

**(Nano-Hertz)**

**Primordial Black Holes (PBHs)**




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The PTA Signal Is Consistent
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(YG, Vitagliano 2306.1784)
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First-order Phase Transition

Domain walls

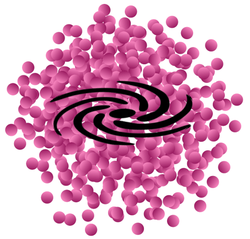
Inflation

Cosmic strings

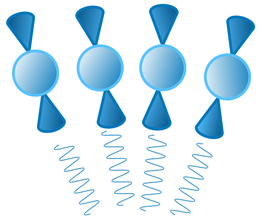
*Early-Universe Phenomena*

Gravitational Waves (GWs)

Ultra-Compact Mini-Halos (UCMHs)







Pulsar Timing Arrays

(Nano-Hertz)

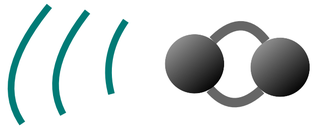
The PTA Signal Is Consistent Solar-Mass PBHs (YG 2307.042039 PRL) (YG, Vitagliano 2306.1784)

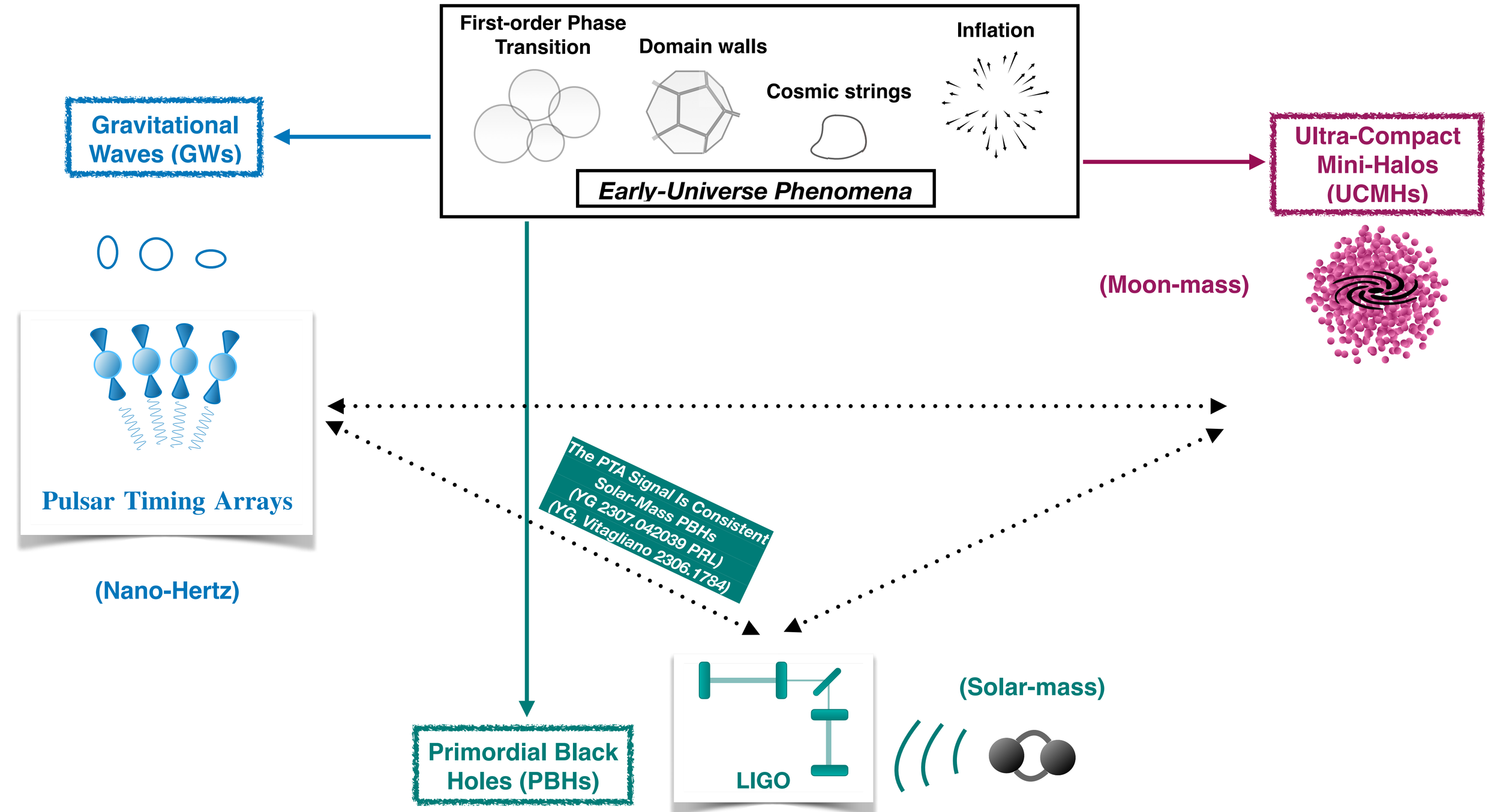
Primordial Black Holes (PBHs)

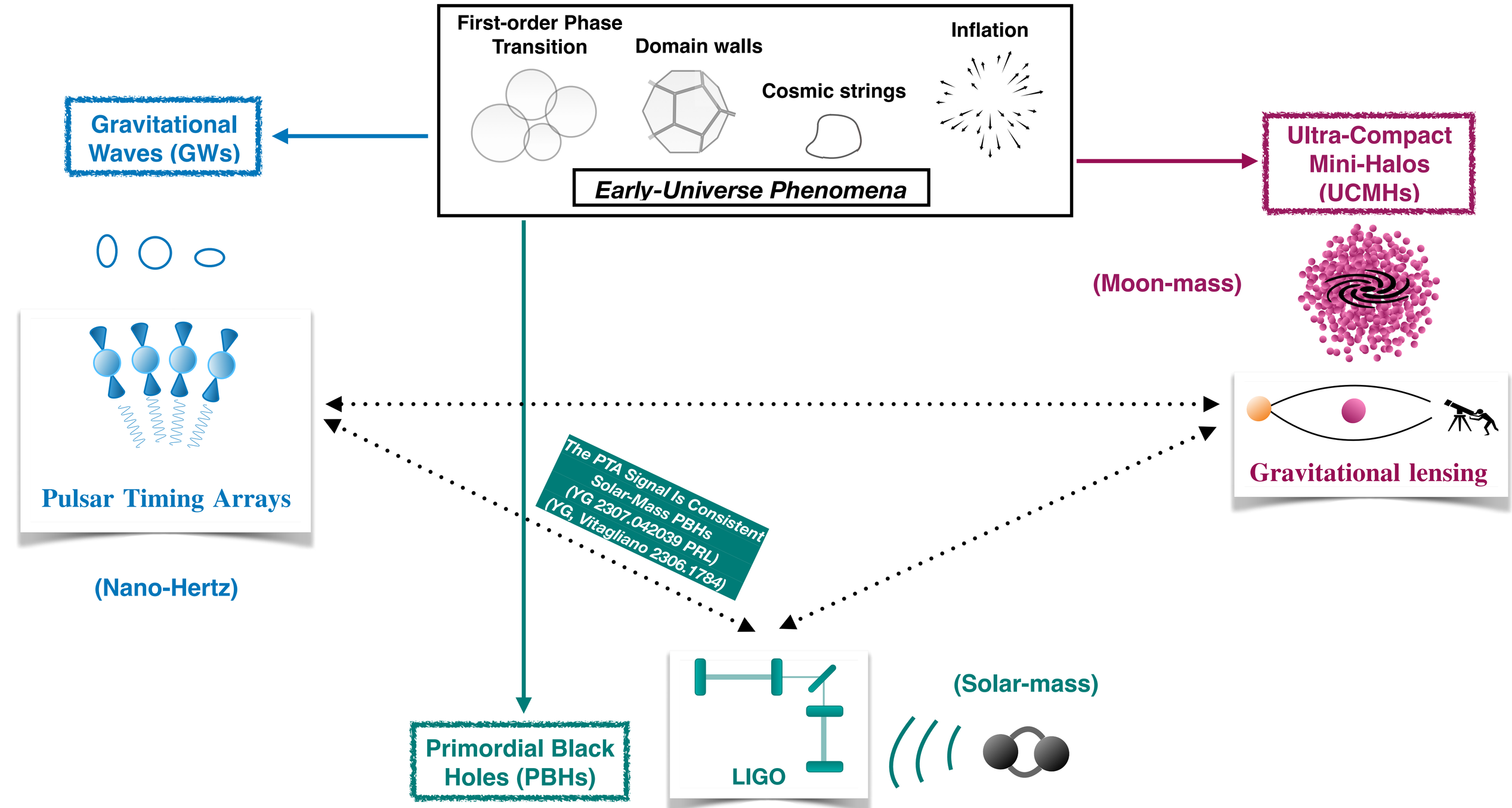


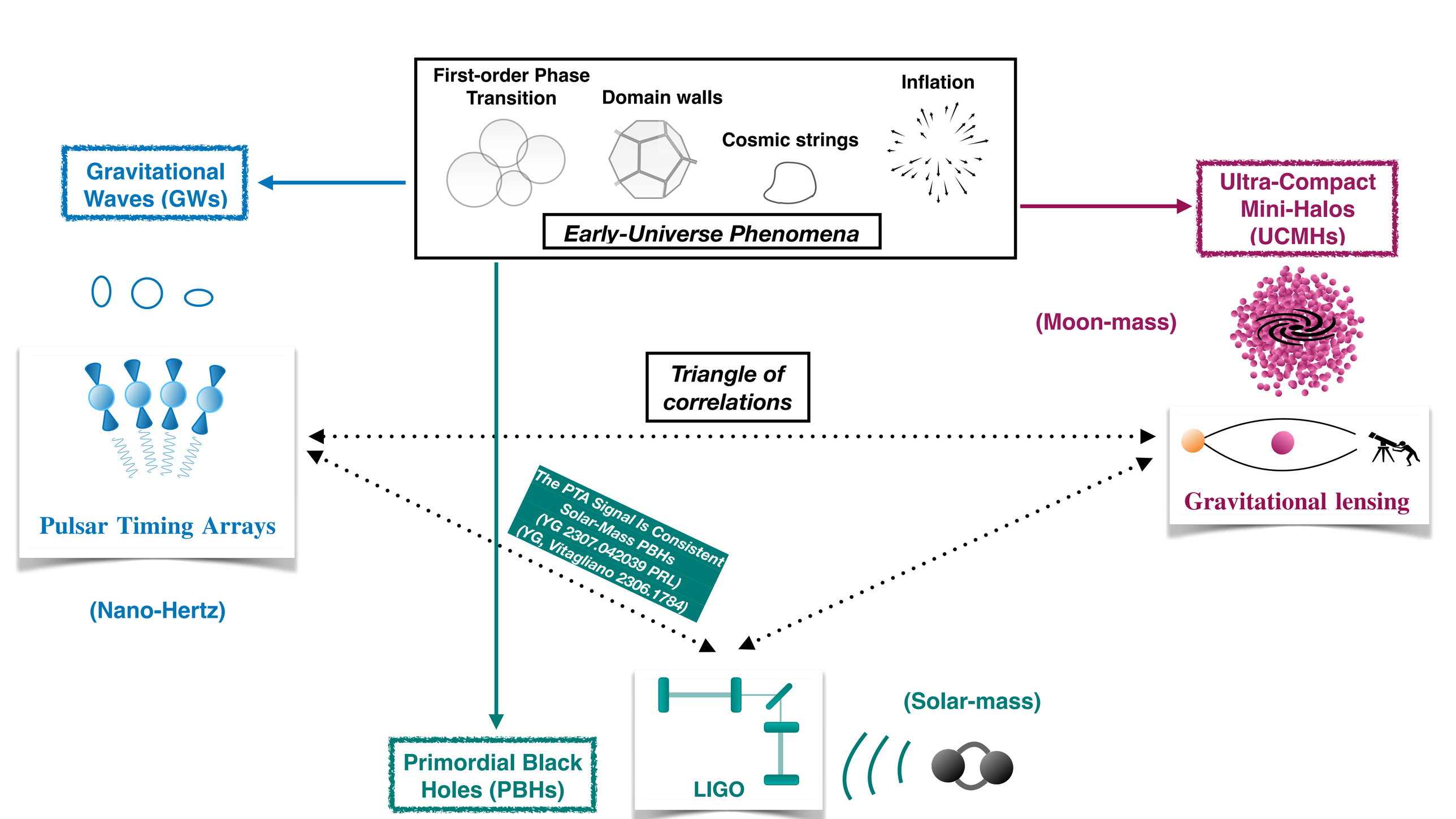
LIGO

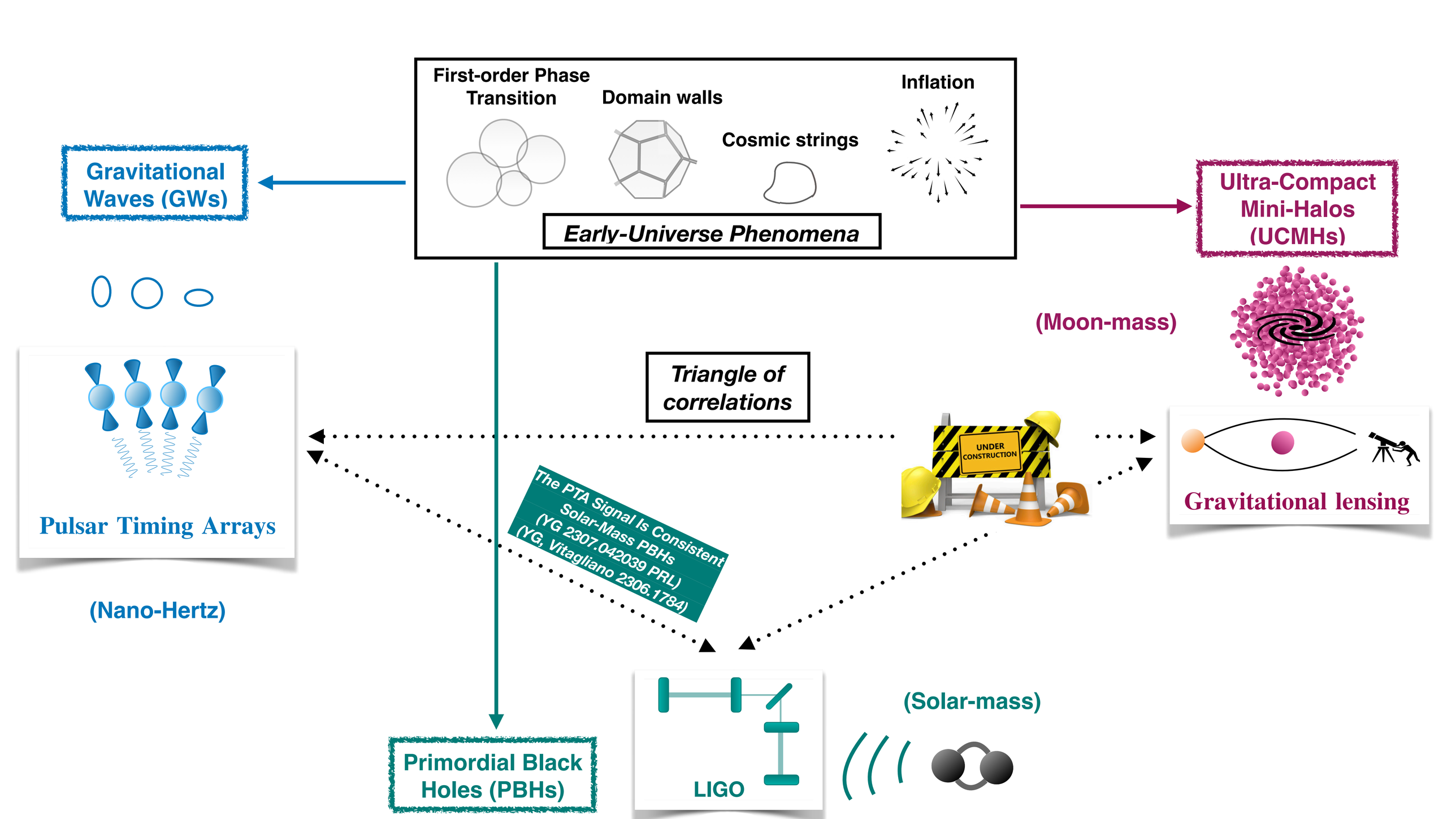
(Solar-mass)

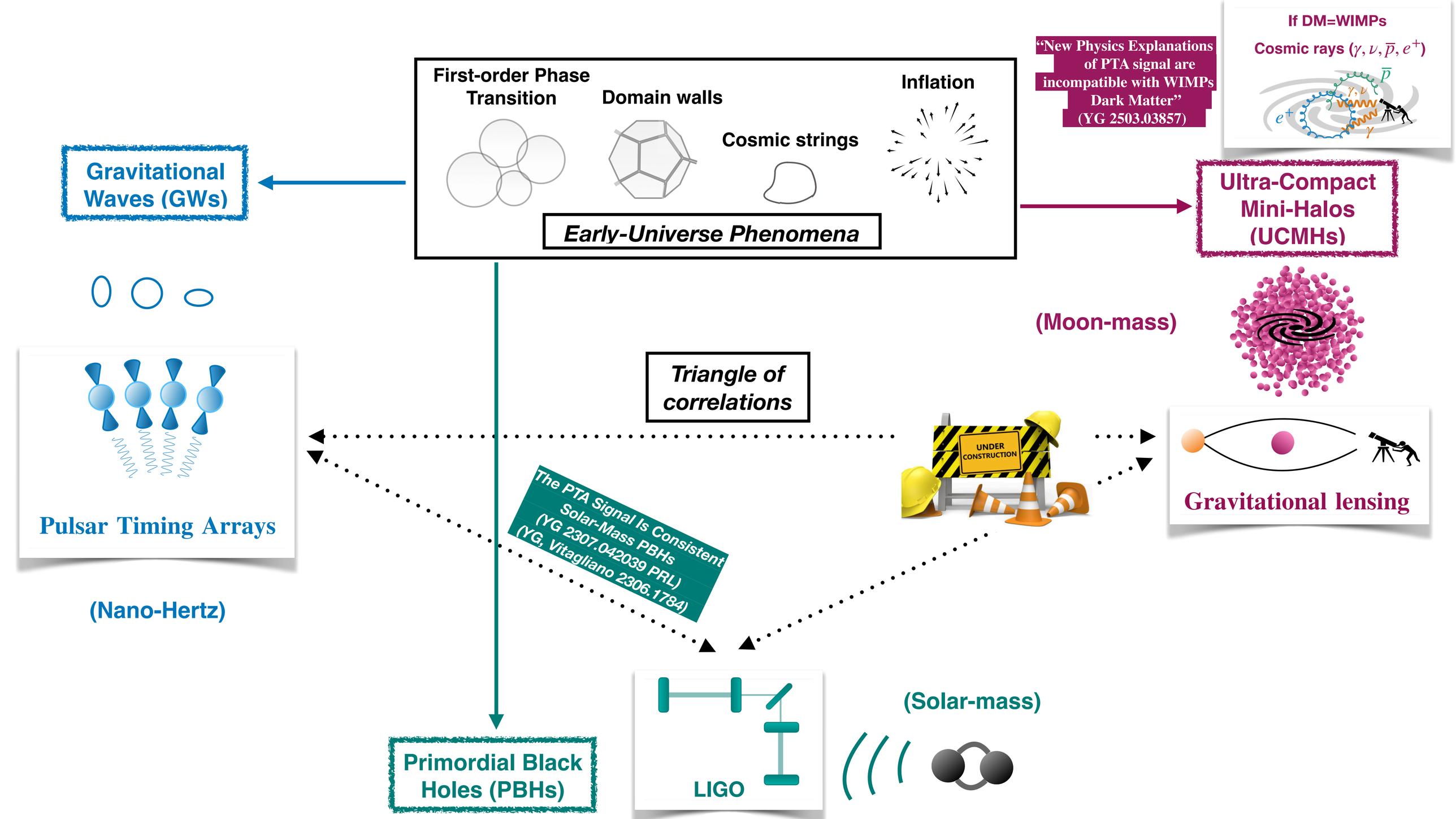



First-order Phase Transition
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Ultra-Compact Mini-Halos (UCMHs)
(Moon-mass)
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UNDER CONSTRUCTION
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"New Physics Explanations of PTA signal are incompatible with WIMPs Dark Matter" (YG 2503.03857)
If DM=WIMPs
Cosmic rays ($\gamma, \nu, \bar{p}, e^+$)
(Moon-mass)
Pulsar Timing Arrays
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UNDER CONSTRUCTION
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LIGO
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First-order Phase Transition

Domain walls

Cosmic strings

Inflation

*Early-Universe Phenomena*

**Gravitational Waves (GWs)**

**Pulsar Timing Arrays**

**(Nano-Hertz)**

**Primordial Black Holes (PBHs)**

*Triangle of correlations*

The PTA Signal Is Consistent Solar-Mass PBHs (YG 2307.042039 PRL) (YG, Vitagliano 2306.1784)

LIGO

**(Solar-mass)**

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If DM=WIMPs

Cosmic rays ($\gamma, \nu, \overline{p}, e^+$)

**Ultra-Compact Mini-Halos (UCMHs)**

**(Moon-mass)**

UNDER CONSTRUCTION

**Gravitational lensing**

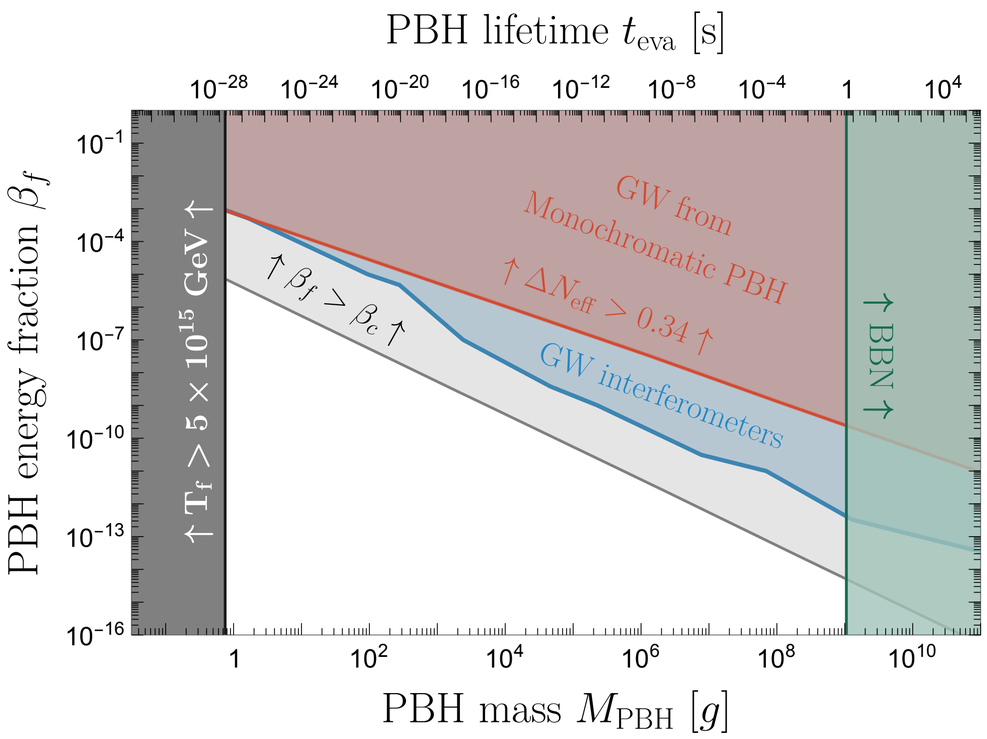
**Pulsar Timing Arrays**

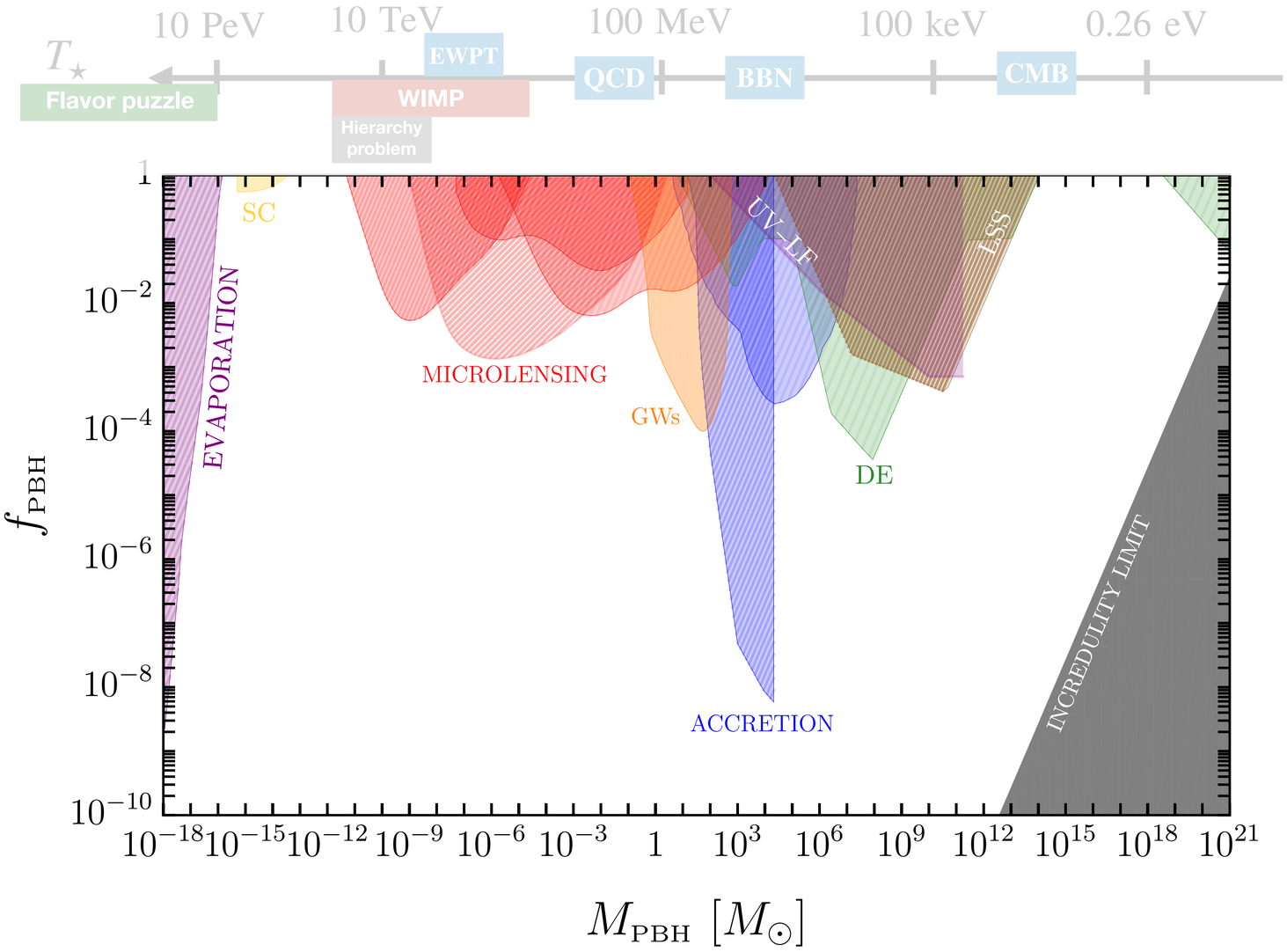
1) Doppler drift

2) Shapiro shift

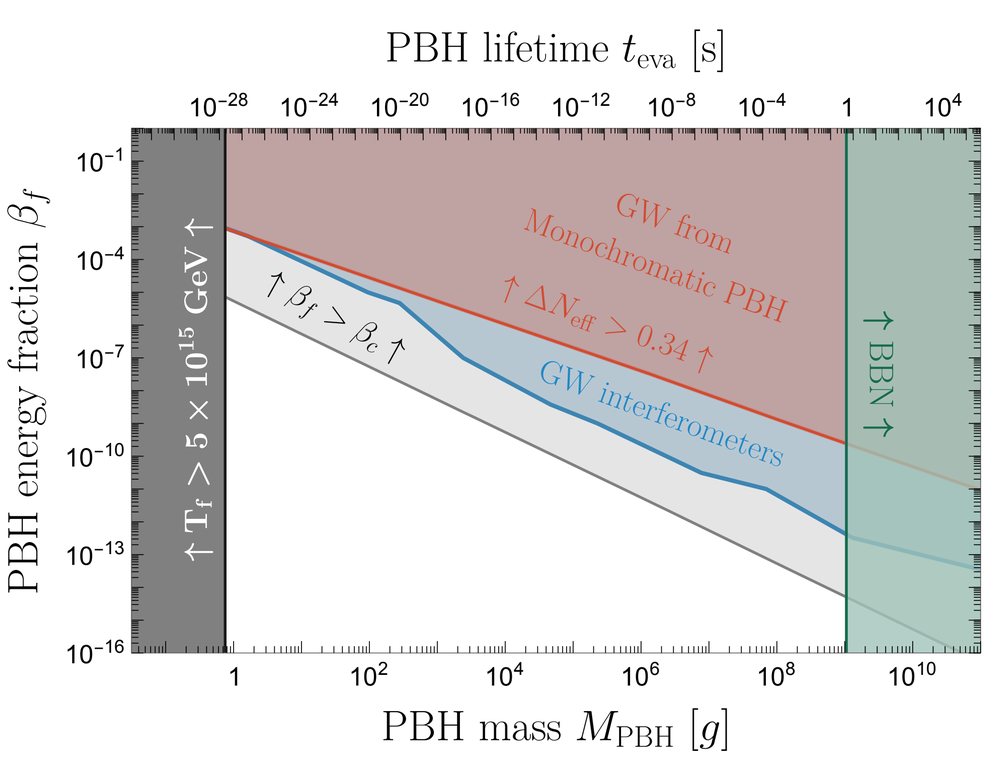
# Summary

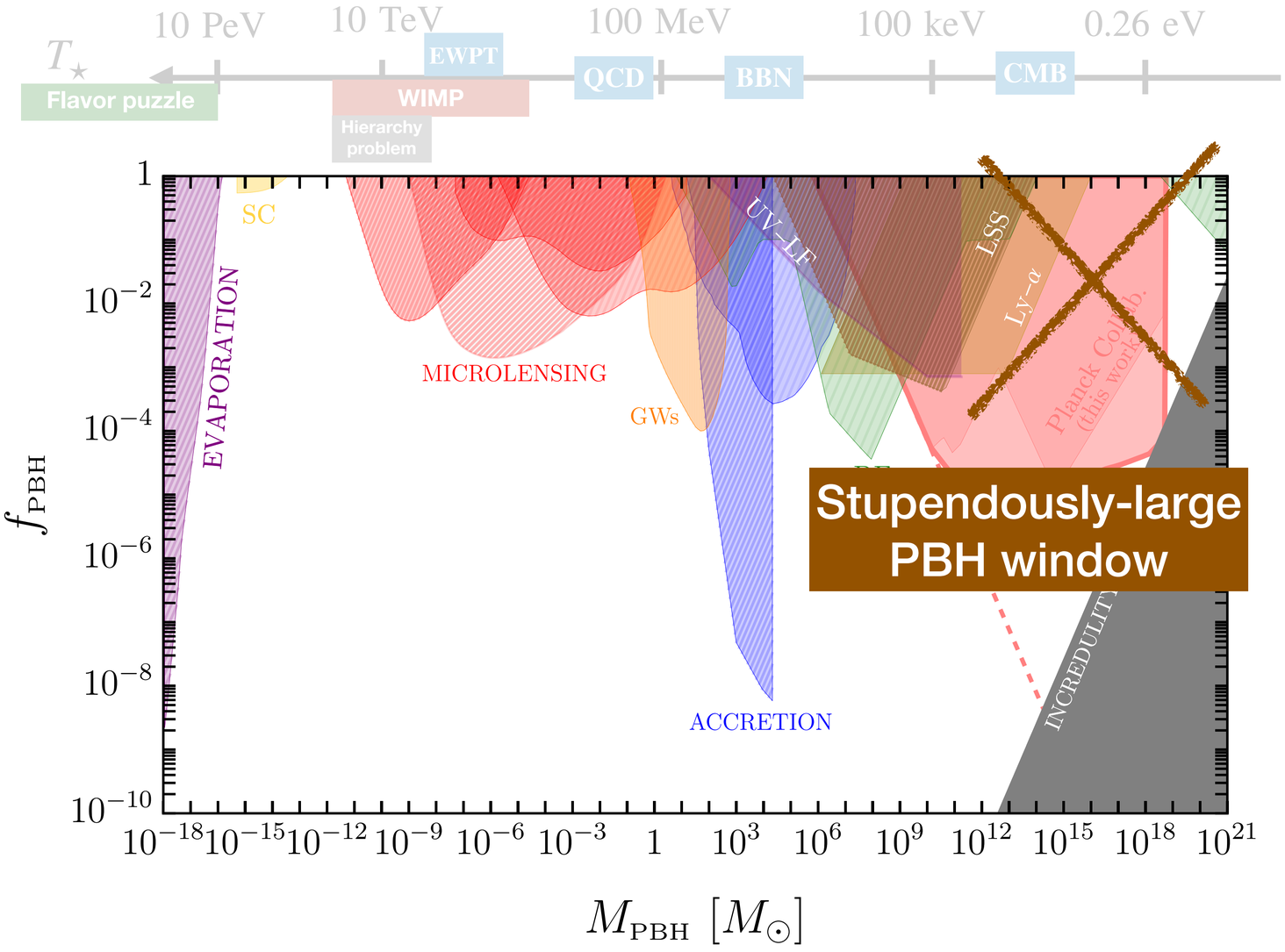
# Summary


PBH lifetime $t_{\rm eva}$ [s]
$10^{-28}$ $10^{-24}$ $10^{-20}$ $10^{-16}$ $10^{-12}$ $10^{-8}$ $10^{-4}$ 1 $10^{4}$
PBH energy fraction $\beta_f$
$10^{-1}$ $10^{-4}$ $10^{-7}$ $10^{-10}$ $10^{-13}$ $10^{-16}$
$\uparrow T_f > 5\times10^{15}$ GeV $\uparrow$
GW from Monochromatic PBH
$\uparrow \Delta N_{\rm eff} > 0.34 \uparrow$
$\uparrow \beta_f > \beta_c \uparrow$
GW interferometers
$\uparrow$ BBN $\uparrow$
1 $10^{2}$ $10^{4}$ $10^{6}$ $10^{8}$ $10^{10}$
PBH mass $M_{\rm PBH}$ $[g]$

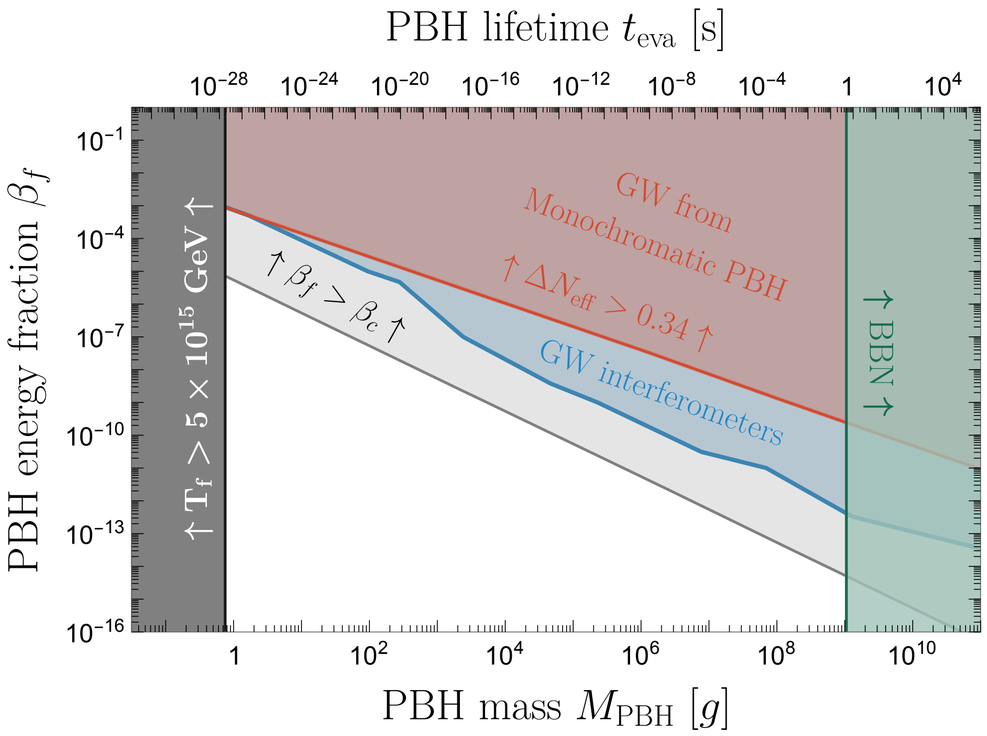

10 PeV
10 TeV
100 MeV
100 keV
0.26 eV
$T_\star$
Flavor puzzle
EWPT
WIMP
Hierarchy problem
QCD
BBN
CMB
1
$10^{-2}$
$10^{-4}$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$f_{\rm PBH}$
SC
EVAPORATION
MICROLENSING
GWs
UV-LF
DE
LSS
ACCRETION
INCREDULITY LIMIT
$10^{-18}$ $10^{-15}$ $10^{-12}$ $10^{-9}$ $10^{-6}$ $10^{-3}$ 1 $10^{3}$ $10^{6}$ $10^{9}$ $10^{12}$ $10^{15}$ $10^{18}$ $10^{21}$
$M_{\rm PBH}$ $[M_\odot]$

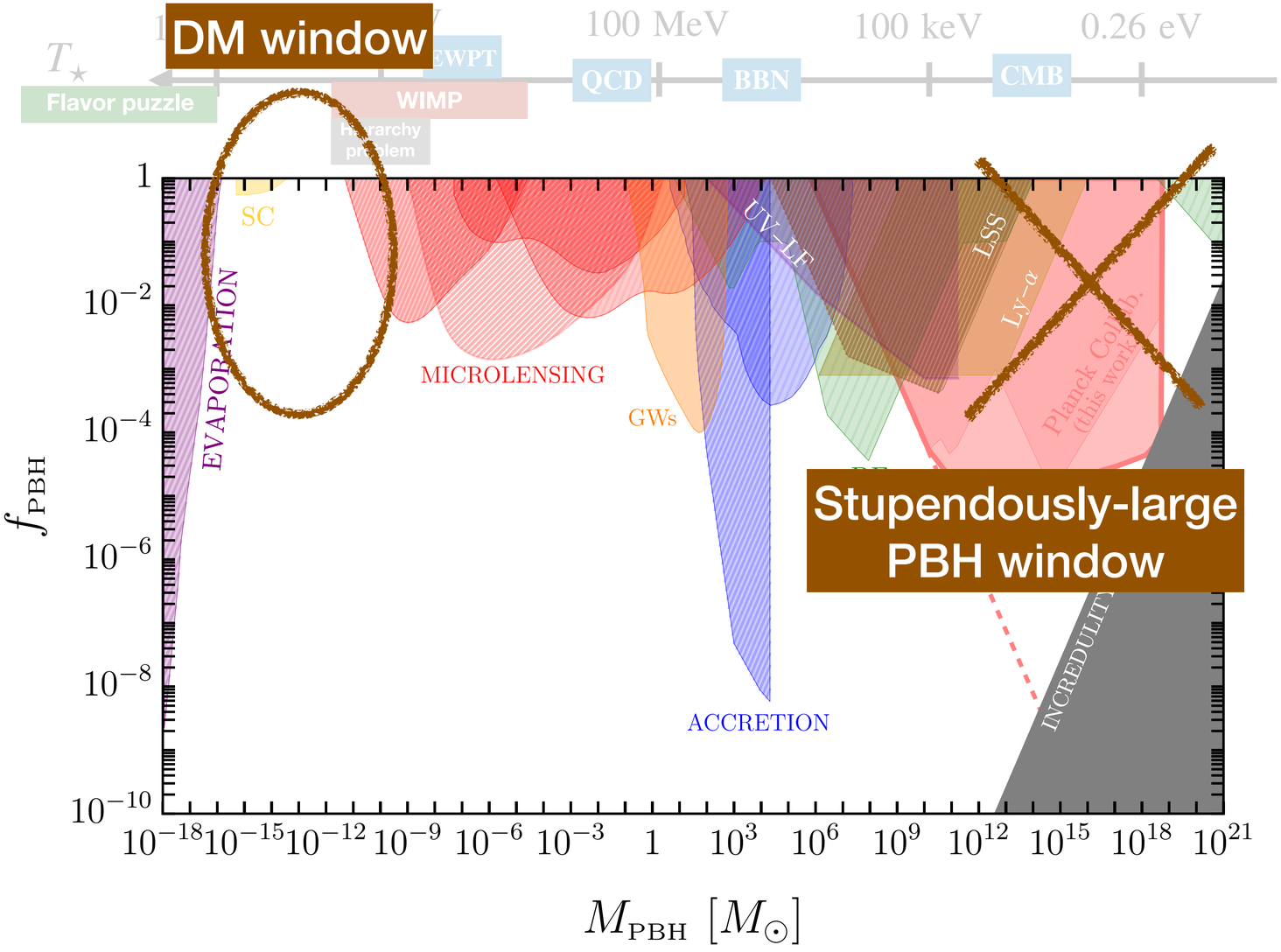
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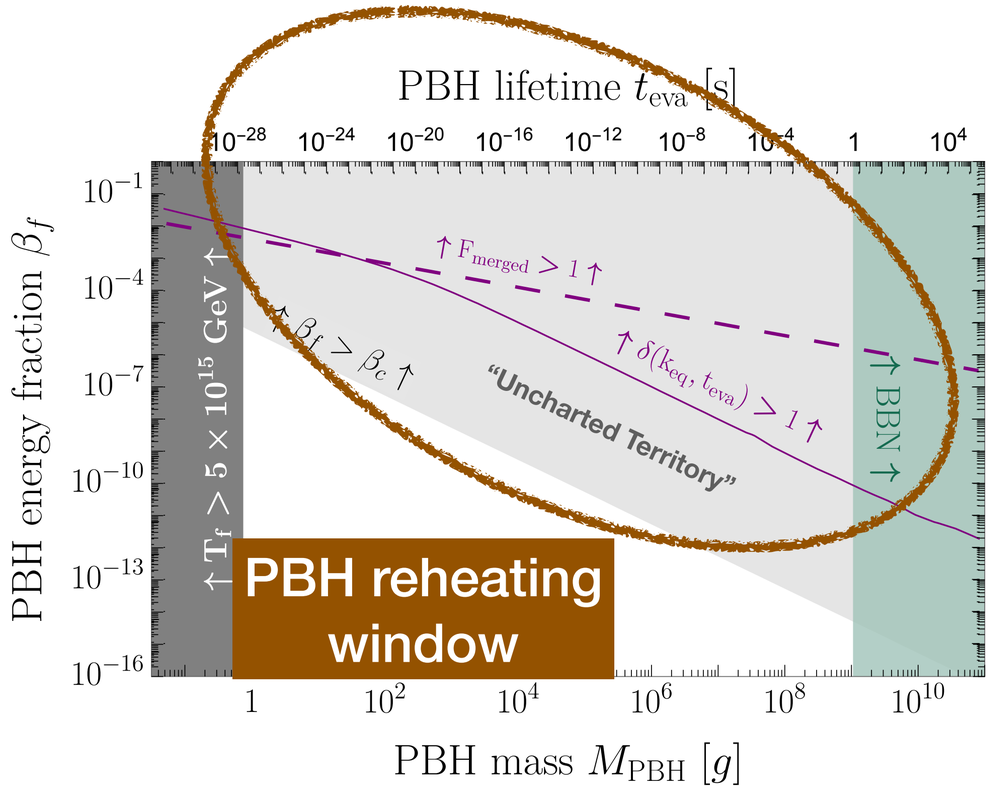

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SC
EVAPORATION
MICROLENSING
GWs
UV-LF
LSS
Ly-$\alpha$
Planck Collab. (this work)
ACCRETION
INCREDULITY
Stupendously-large PBH window
$10^{-18}$ $10^{-15}$ $10^{-12}$ $10^{-9}$ $10^{-6}$ $10^{-3}$ 1 $10^{3}$ $10^{6}$ $10^{9}$ $10^{12}$ $10^{15}$ $10^{18}$ $10^{21}$
$M_{\rm PBH}$ $[M_\odot]$

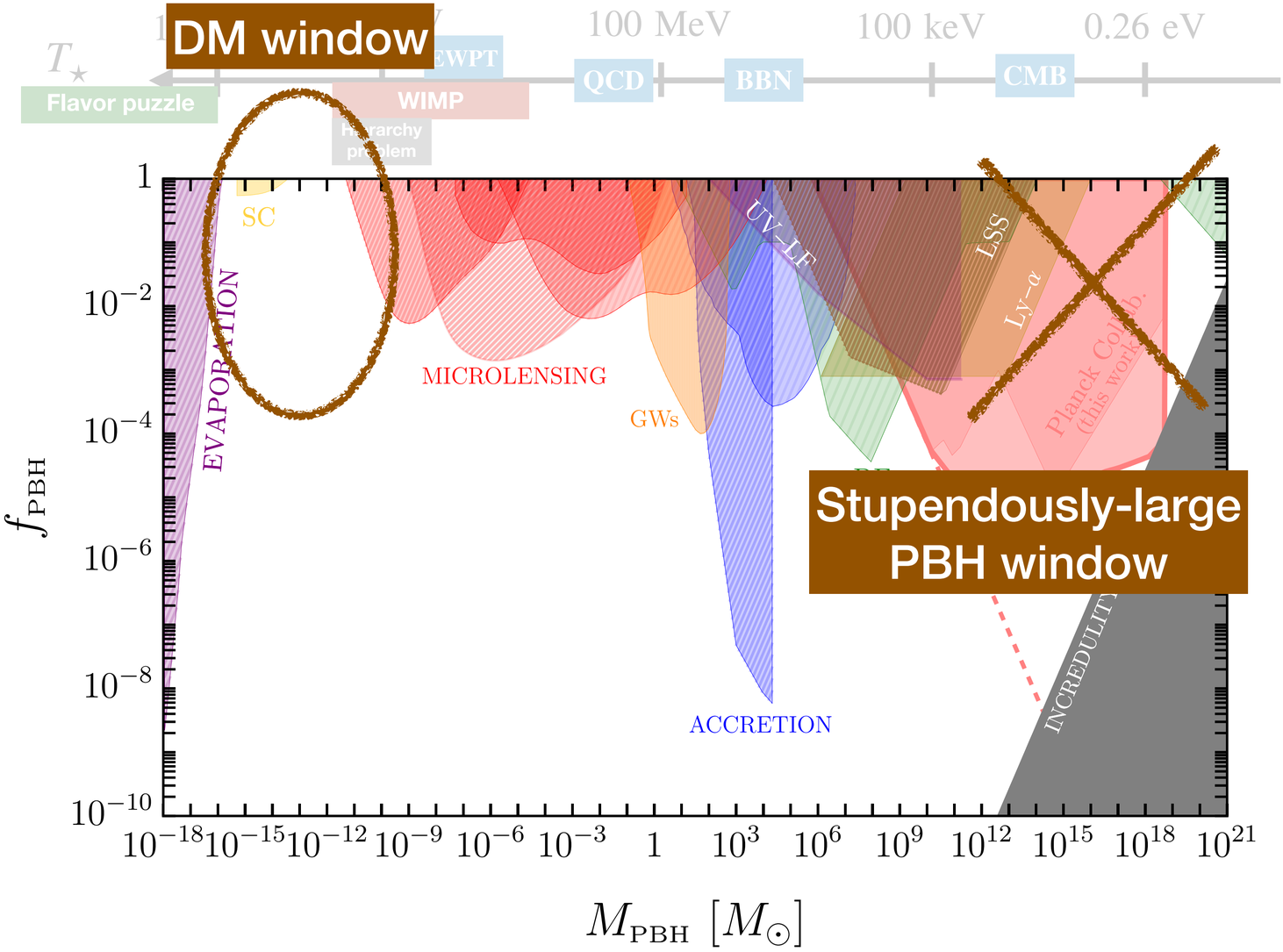
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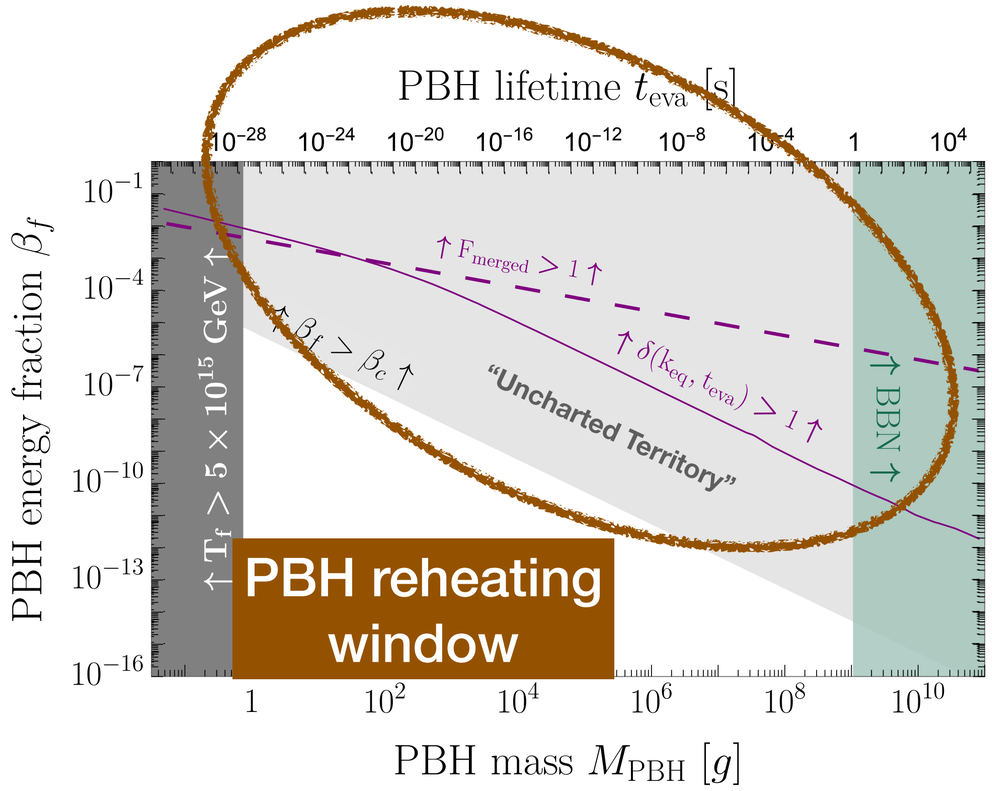

DM window
Stupendously-large PBH window
$T_\star$
100 MeV
100 keV
0.26 eV
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ACCRETION
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$f_{\rm PBH}$
$M_{\rm PBH}$ $[M_\odot]$

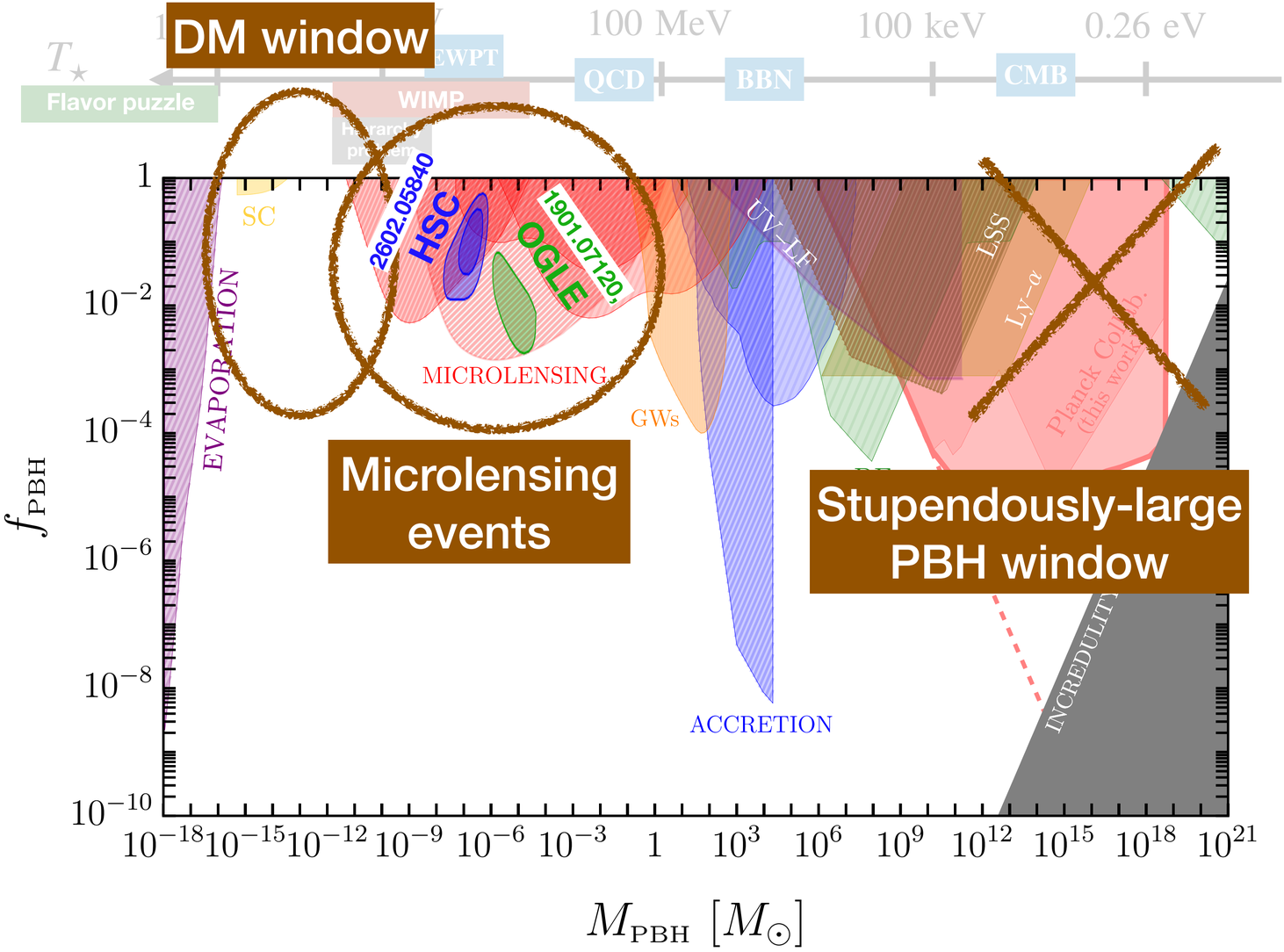
# Summary


PBH lifetime $t_{\rm eva}$ [s]
$10^{-28}$ $10^{-24}$ $10^{-20}$ $10^{-16}$ $10^{-12}$ $10^{-8}$ $10^{-4}$ 1 $10^{4}$
PBH energy fraction $\beta_f$
$10^{-1}$ $10^{-4}$ $10^{-7}$ $10^{-10}$ $10^{-13}$ $10^{-16}$
$\uparrow T_f > 5\times10^{15}$ GeV $\uparrow$
$\uparrow F_{\rm merged} > 1 \uparrow$
$\uparrow \beta_f > \beta_c \uparrow$
$\uparrow \delta(k_{\rm eq}, t_{\rm eva}) > 1 \uparrow$
"Uncharted Territory"
$\uparrow$ BBN $\uparrow$
1 $10^{2}$ $10^{4}$ $10^{6}$ $10^{8}$ $10^{10}$
PBH mass $M_{\rm PBH}$ $[g]$
PBH reheating window

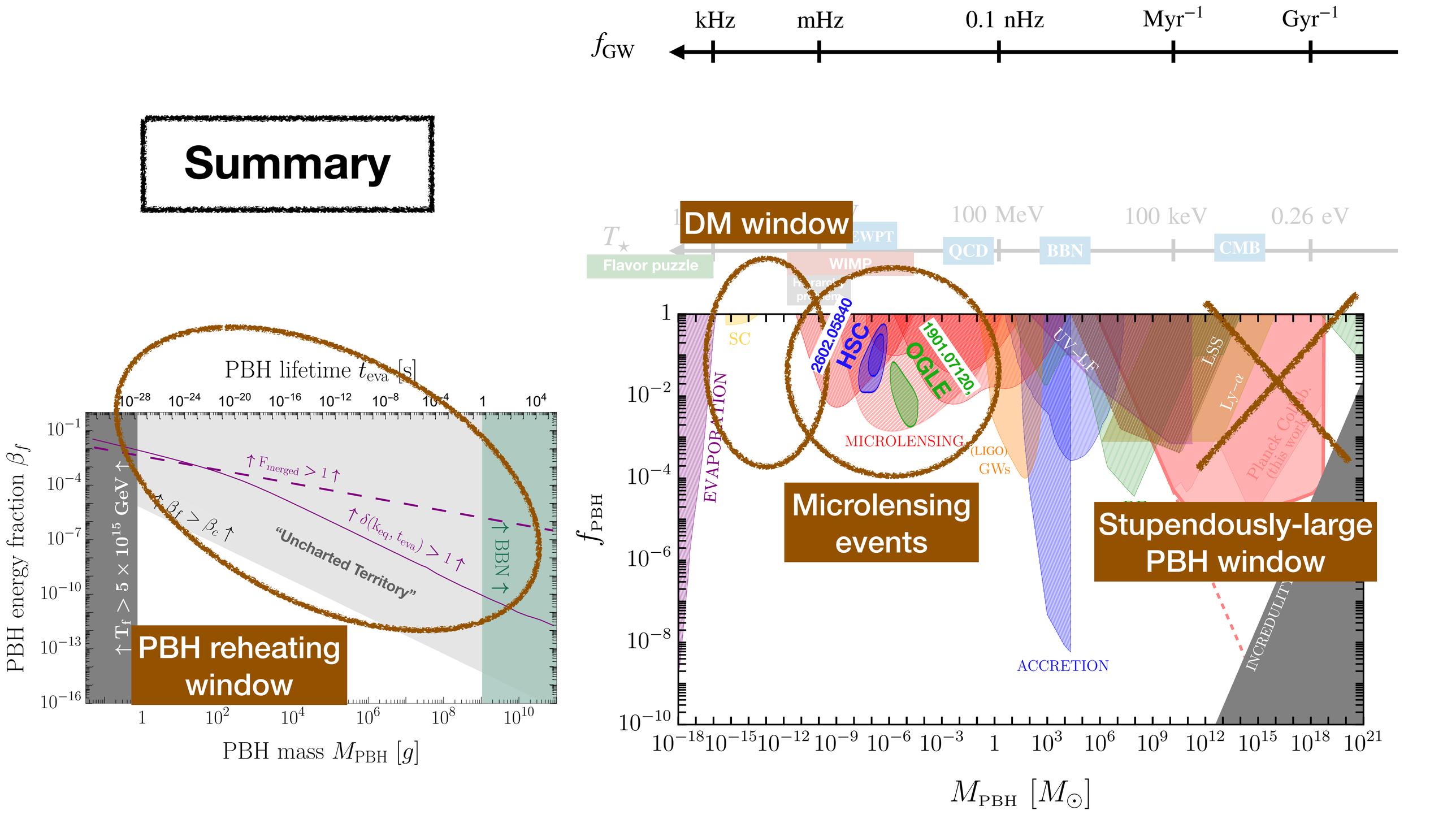

DM window
$T_\star$
100 MeV
100 keV
0.26 eV
Flavor puzzle
EWPT
WIMP
QCD
BBN
CMB
1
$10^{-2}$
$10^{-4}$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$f_{\rm PBH}$
SC
EVAPORATION
MICROLENSING
GWs
UV-LF
LSS
Ly-$\alpha$
Planck Collab. (this work)
ACCRETION
INCREDULITY
Stupendously-large PBH window
$10^{-18}$ $10^{-15}$ $10^{-12}$ $10^{-9}$ $10^{-6}$ $10^{-3}$ 1 $10^{3}$ $10^{6}$ $10^{9}$ $10^{12}$ $10^{15}$ $10^{18}$ $10^{21}$
$M_{\rm PBH}$ $[M_\odot]$

# Summary

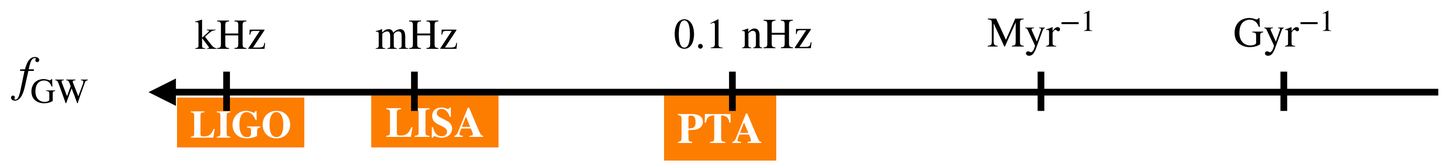

PBH lifetime $t_{\rm eva}$ [s]
$10^{-28}$ $10^{-24}$ $10^{-20}$ $10^{-16}$ $10^{-12}$ $10^{-8}$ $10^{-4}$ 1 $10^{4}$
PBH energy fraction $\beta_f$
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$\uparrow T_f > 5\times10^{15}$ GeV $\uparrow$
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$\uparrow \delta(k_{\rm eq}, t_{\rm eva}) > 1 \uparrow$
"Uncharted Territory"
$\uparrow$ BBN $\uparrow$
1 $10^{2}$ $10^{4}$ $10^{6}$ $10^{8}$ $10^{10}$
PBH mass $M_{\rm PBH}$ $[g]$
PBH reheating window

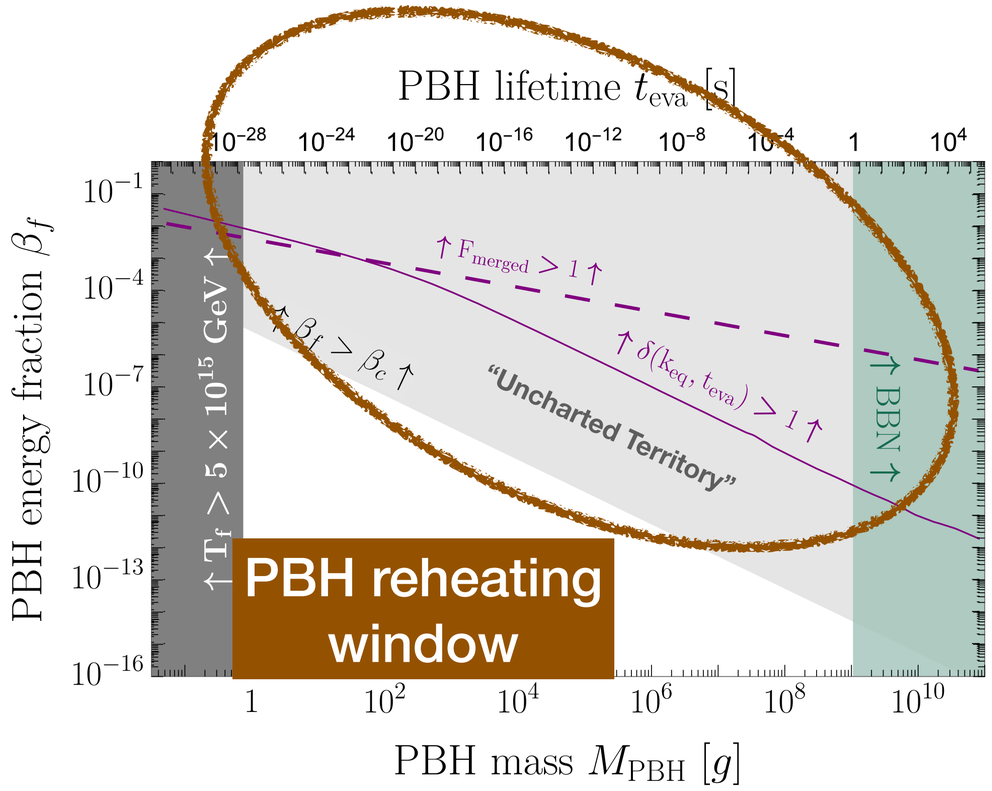

DM window
$T_\star$
100 MeV
100 keV
0.26 eV
Flavor puzzle
EWPT
QCD
BBN
CMB
WIMP
SC
2602.05840
HSC
OGLE
1901.07120,
MICROLENSING
EVAPORATION
GWs
UV LF
LSS
Ly-$\alpha$
Planck Collab. (this work)
ACCRETION
INCREDULITY
Microlensing events
Stupendously-large PBH window
$f_{\rm PBH}$
1 $10^{-2}$ $10^{-4}$ $10^{-6}$ $10^{-8}$ $10^{-10}$
$10^{-18}$ $10^{-15}$ $10^{-12}$ $10^{-9}$ $10^{-6}$ $10^{-3}$ 1 $10^{3}$ $10^{6}$ $10^{9}$ $10^{12}$ $10^{15}$ $10^{18}$ $10^{21}$
$M_{\rm PBH}$ $[M_\odot]$

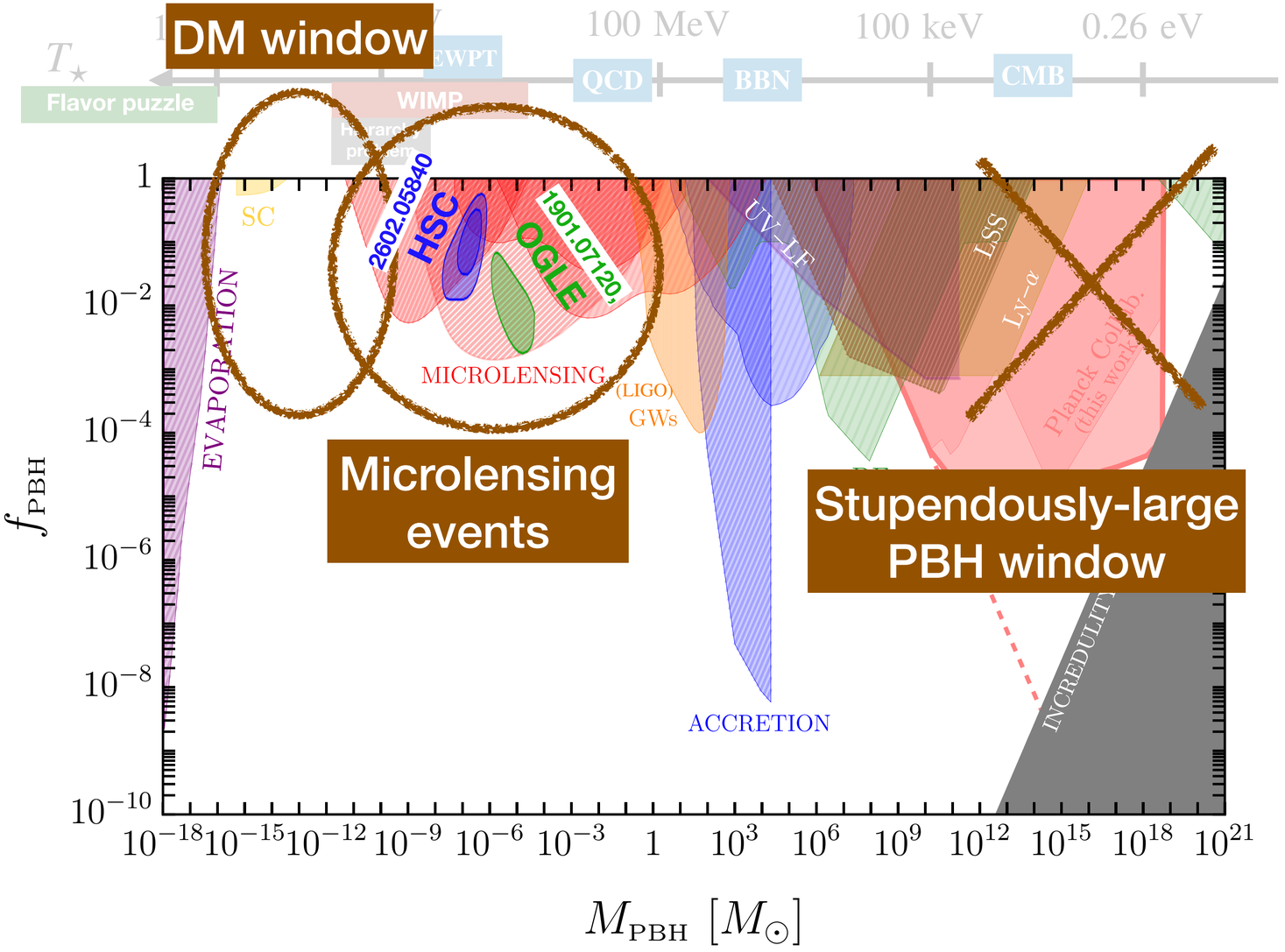
# Summary


kHz
mHz
0.1 nHz
Myr$^{-1}$
Gyr$^{-1}$
$f_{\rm GW}$
DM window
100 MeV
100 keV
0.26 eV
$T_\star$
Flavor puzzle
EWPT
QCD
BBN
CMB
WIMP
SC
2602.05840
HSC
OGLE
1901.07120,
MICROLENSING
EVAPORATION
(LIGO)
GWs
UV LF
LSS
Ly-$\alpha$
Planck Collab.
(this work)
ACCRETION
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Microlensing events
Stupendously-large PBH window
$f_{\rm PBH}$
$M_{\rm PBH}$ $[M_\odot]$
PBH lifetime $t_{\rm eva}$ [s]
PBH energy fraction $\beta_f$
PBH mass $M_{\rm PBH}$ $[g]$
$\uparrow T_f > 5\times10^{15}$ GeV $\uparrow$
$\uparrow F_{\rm merged} > 1 \uparrow$
$\uparrow \beta_f > \beta_c \uparrow$
$\uparrow \delta(k_{\rm eq}, t_{\rm eva}) > 1 \uparrow$
"Uncharted Territory"
$\uparrow$ BBN $\uparrow$
PBH reheating window

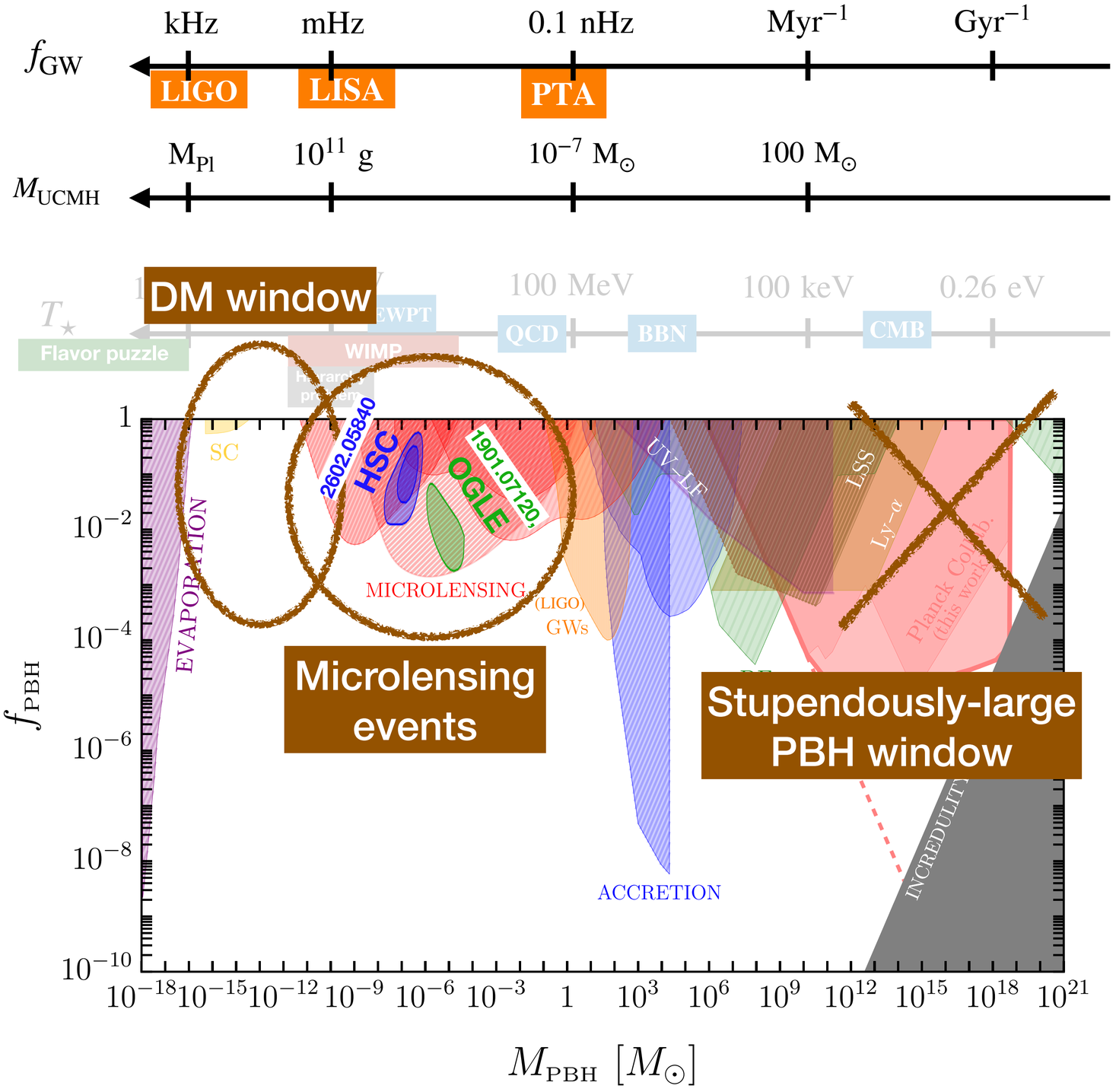
# Summary

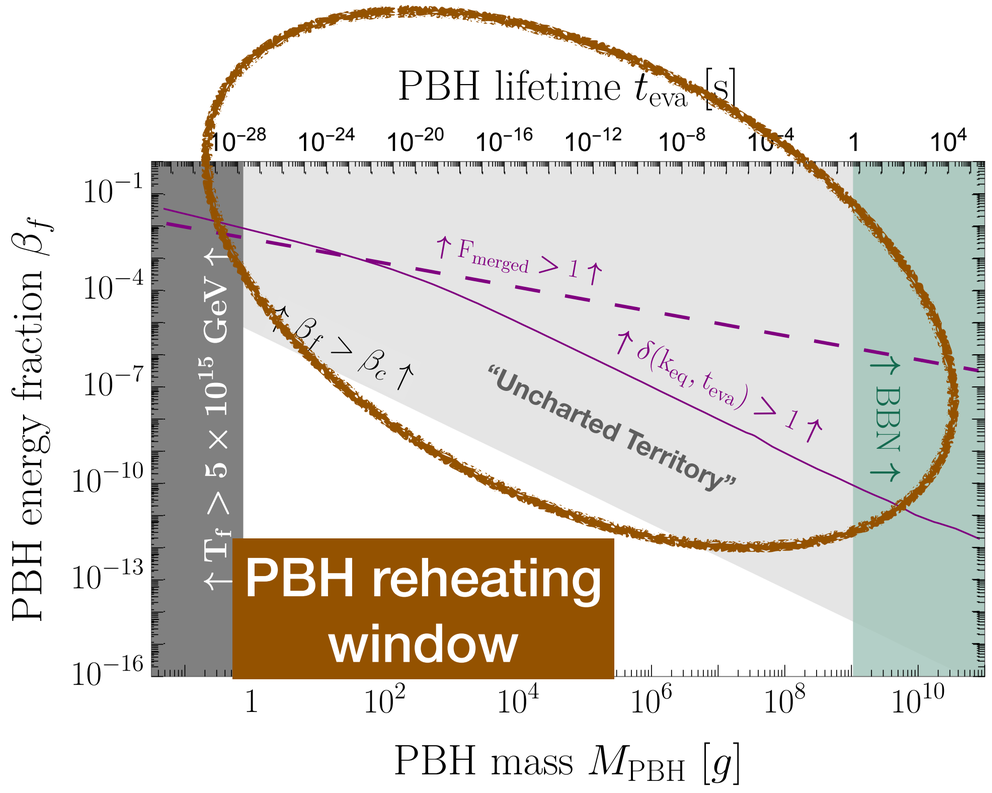

kHz
mHz
0.1 nHz
Myr$^{-1}$
Gyr$^{-1}$
$f_{\rm GW}$
LIGO
LISA
PTA


PBH lifetime $t_{\rm eva}$ [s]
$10^{-28}$ $10^{-24}$ $10^{-20}$ $10^{-16}$ $10^{-12}$ $10^{-8}$ $10^{-4}$ 1 $10^{4}$
PBH energy fraction $\beta_f$
$10^{-1}$ $10^{-4}$ $10^{-7}$ $10^{-10}$ $10^{-13}$ $10^{-16}$
$\uparrow T_f > 5\times10^{15}$ GeV $\uparrow$
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"Uncharted Territory"
$\uparrow$ BBN $\uparrow$
1 $10^{2}$ $10^{4}$ $10^{6}$ $10^{8}$ $10^{10}$
PBH mass $M_{\rm PBH}$ $[g]$
PBH reheating window

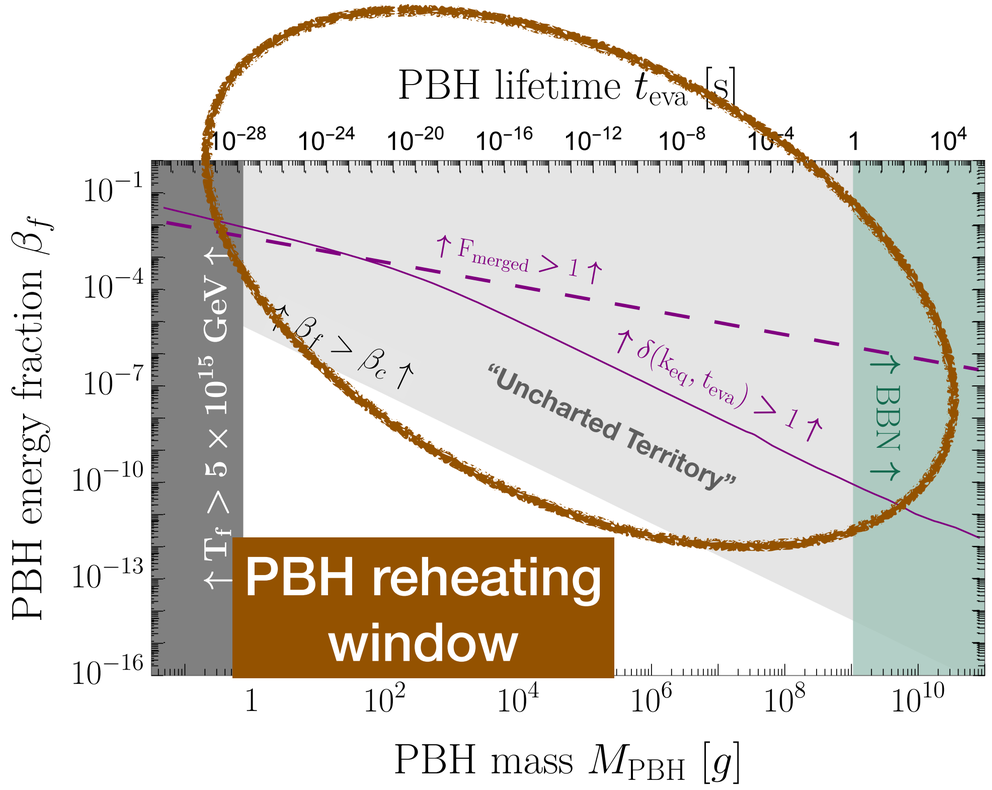

DM window
$T_\star$
100 MeV
100 keV
0.26 eV
Flavor puzzle
EWPT
QCD
BBN
CMB
WIMP
1
$10^{-2}$
$10^{-4}$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$f_{\rm PBH}$
SC
2602.05840
HSC
OGLE
1901.07120,
MICROLENSING
(LIGO) GWs
EVAPORATION
UV LF
LSS
Ly-$\alpha$
Planck Collab. (this work)
ACCRETION
INCREDULITY
Microlensing events
Stupendously-large PBH window
$10^{-18}$ $10^{-15}$ $10^{-12}$ $10^{-9}$ $10^{-6}$ $10^{-3}$ 1 $10^{3}$ $10^{6}$ $10^{9}$ $10^{12}$ $10^{15}$ $10^{18}$ $10^{21}$
$M_{\rm PBH}$ $[M_\odot]$

# Summary

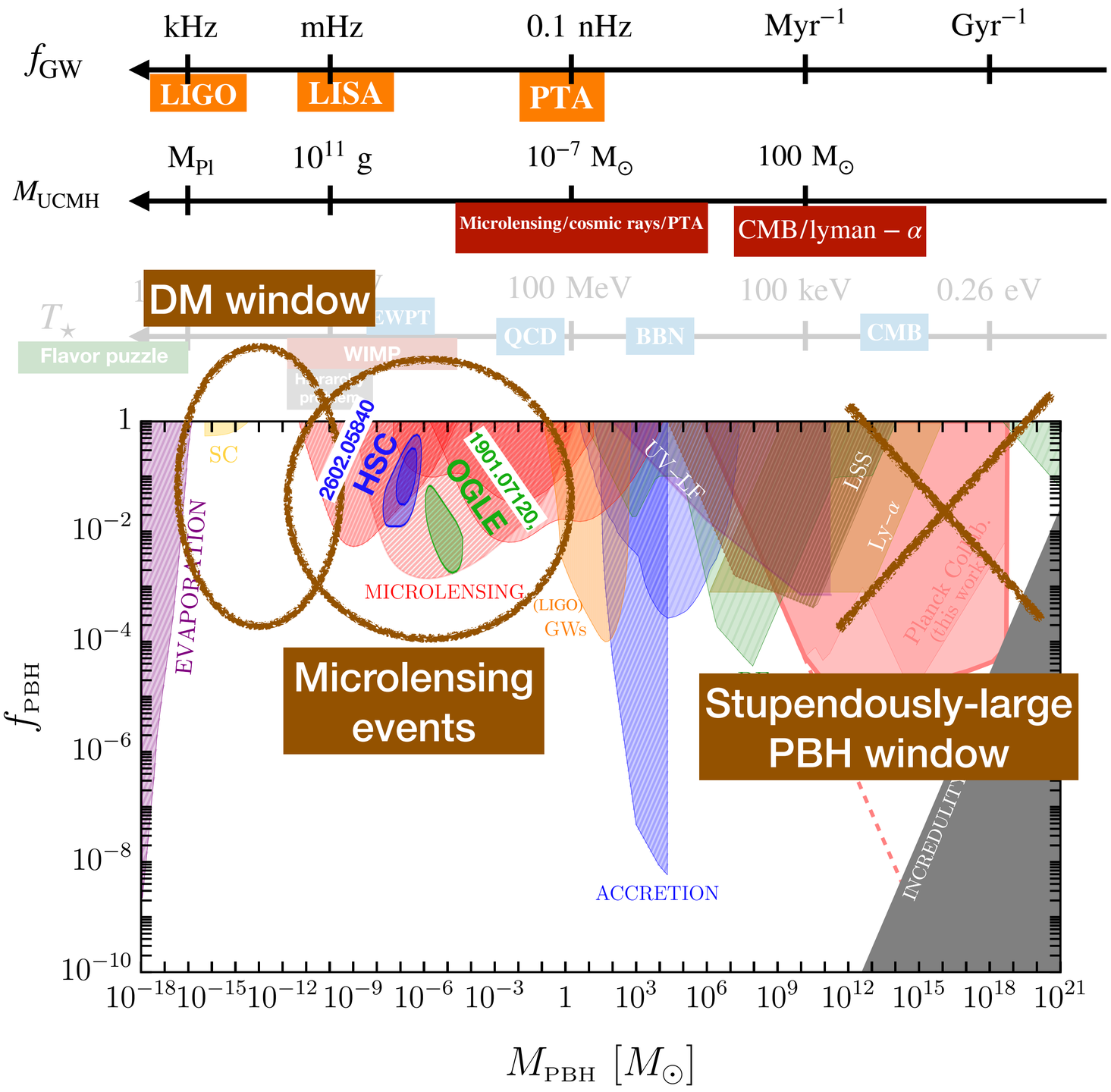

$f_{\rm GW}$
kHz
mHz
0.1 nHz
$\rm Myr^{-1}$
$\rm Gyr^{-1}$
LIGO
LISA
PTA
$M_{\rm UCMH}$
$M_{\rm Pl}$
$10^{11}$ g
$10^{-7}$ $M_\odot$
100 $M_\odot$
$T_\star$
100 MeV
100 keV
0.26 eV
Flavor puzzle
EWPT
QCD
BBN
CMB
WIMP
DM window
SC
EVAPORATION
2602.05840
HSC
OGLE
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MICROLENSING
(LIGO)
GWs
UV LF
LSS
Ly-$\alpha$
Planck Collab.
(this work)
ACCRETION
INCREDULITY
Microlensing events
Stupendously-large PBH window
$f_{\rm PBH}$
$M_{\rm PBH}$ $[M_\odot]$


PBH lifetime $t_{\rm eva}$ [s]
PBH energy fraction $\beta_f$
PBH mass $M_{\rm PBH}$ $[g]$
$\uparrow T_f > 5\times10^{15}$ GeV $\uparrow$
$\uparrow F_{\rm merged} > 1 \uparrow$
$\uparrow \beta_f > \beta_c \uparrow$
$\uparrow \delta(k_{\rm eq}, t_{\rm eva}) > 1 \uparrow$
"Uncharted Territory"
$\uparrow$ BBN $\uparrow$
PBH reheating window

# Summary




**PBH reheating window**

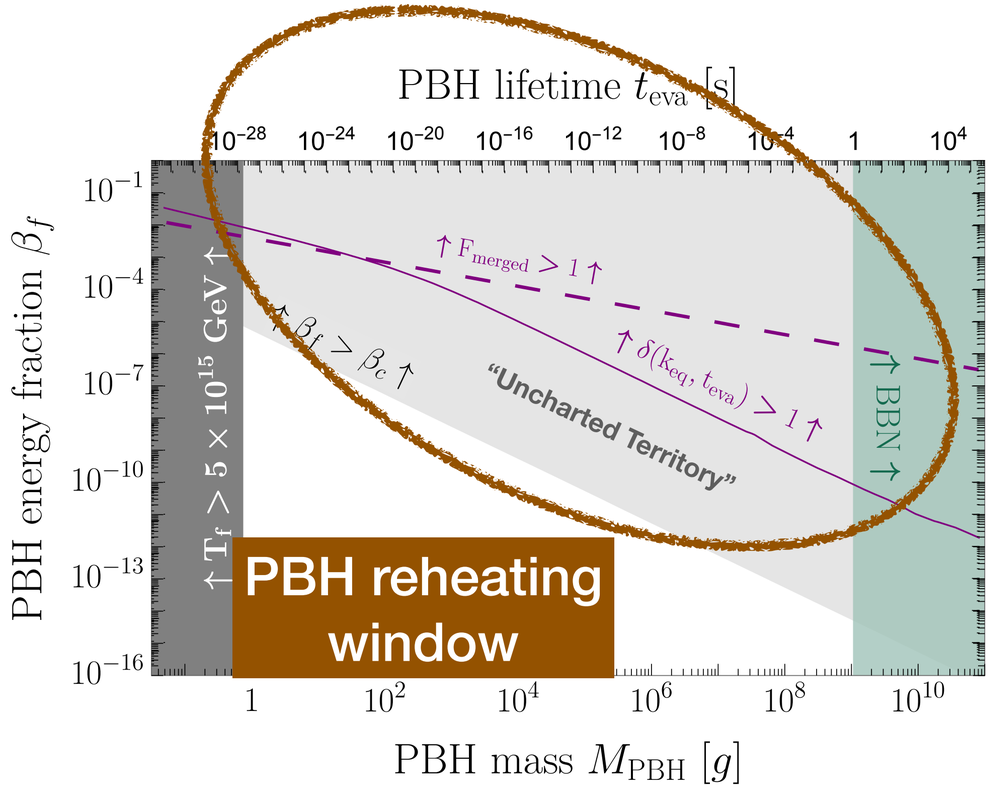



**DM window**

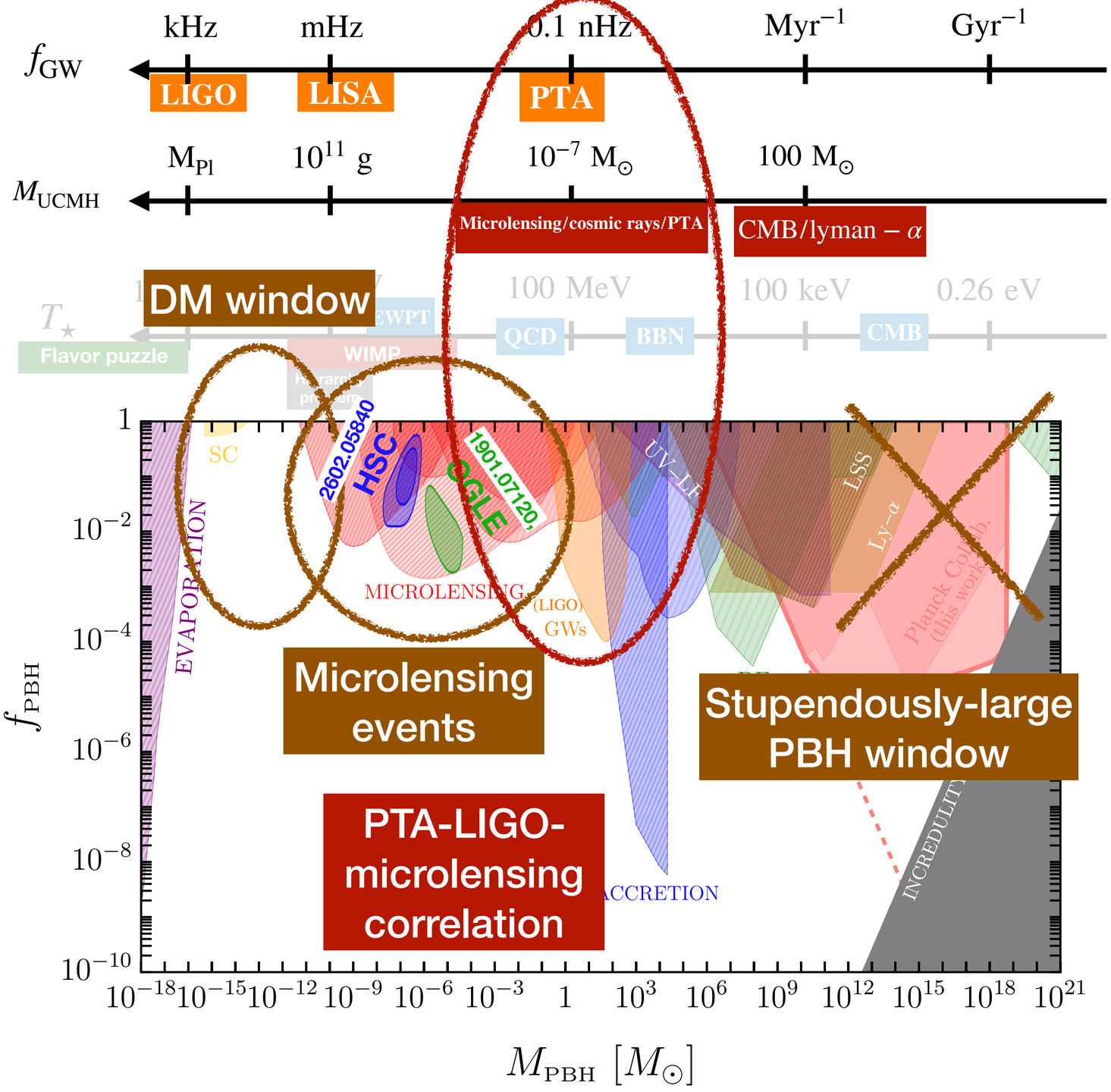
**Microlensing events**

**Stupendously-large PBH window**

# Summary




**PBH reheating window**




**Microlensing events**

**Stupendously-large PBH window**

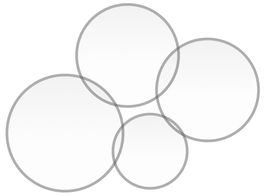
**PTA-LIGO-microlensing correlation**



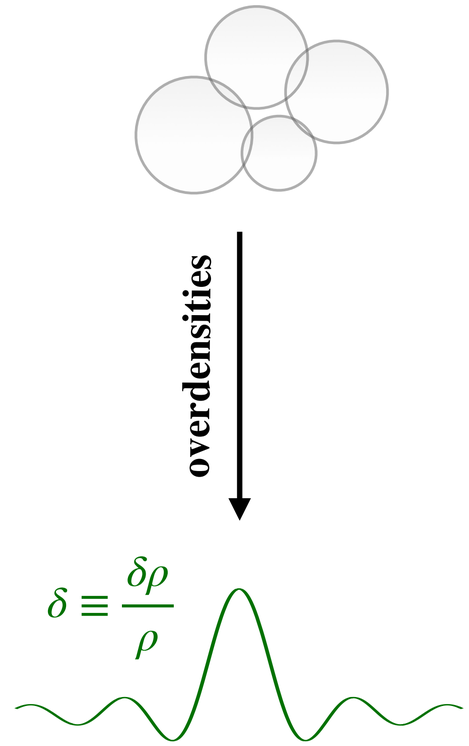

Organized by Michael Baker, Christian Byrnes, Joaquim Iguaz Juan, Andrea Thamm, and Yann Gouttenoire

***Register here until 20 March 2026***

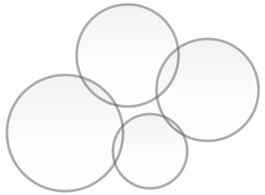
First-order
phase transition



First-order
phase transition

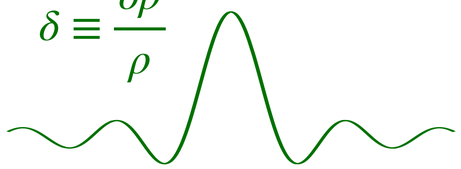


First-order
phase transition



**overdensities**

$$\delta \equiv \frac{\delta\rho}{\rho}$$

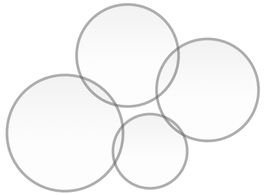


$$\delta^{(F)} \gtrsim 5$$



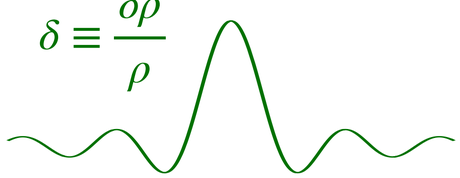
PBH

First-order
phase transition



overdensities

$\delta \equiv \frac{\delta\rho}{\rho}$



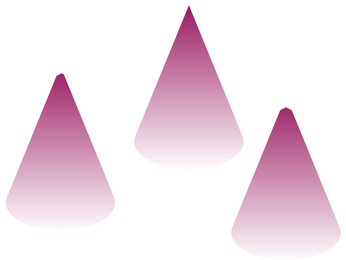
$\delta^{(F)} \gtrsim 5$



PBH

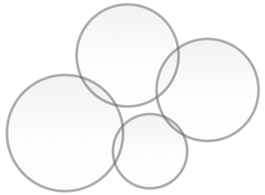
$\mathscr{R} \simeq \frac{9}{40}\delta^{(F)}$

Franciolini, YG, Jinno
2503.01962



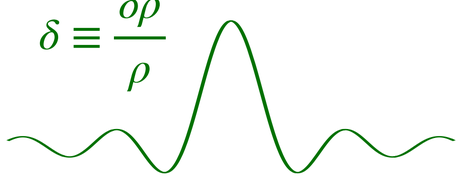
Curvature peaks $\mathscr{R}$

First-order
phase transition



overdensities

$\delta \equiv \frac{\delta\rho}{\rho}$



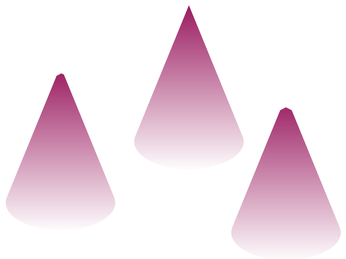
$\mathscr{R} \gtrsim 1$



PBH

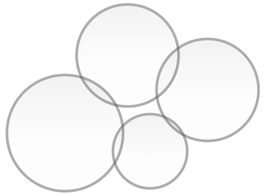
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Franciolini, YG, Jinno
2503.01962



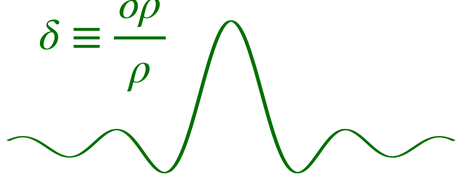
Curvature peaks $\mathscr{R}$

First-order
phase transition



overdensities

$\delta \equiv \frac{\delta\rho}{\rho}$



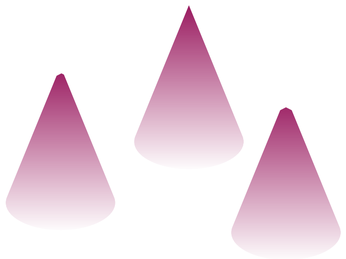
$\mathscr{R} \gtrsim 1$

PBH

$\mathscr{R} \simeq \frac{9}{40}\delta^{(F)}$

Franciolini, YG, Jinno
2503.01962

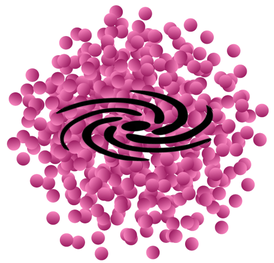
Curvature peaks $\mathscr{R}$



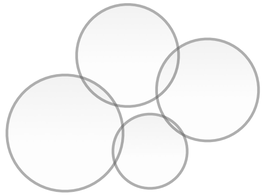
$\mathscr{R} \gtrsim 10^{-3}$

YG
2503.03857

**Ultra-compact
Mini-Halo**

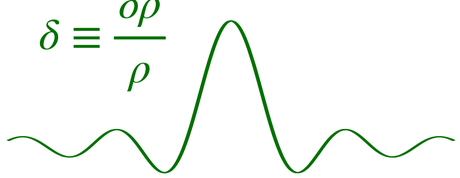


First-order
phase transition



overdensities

$\delta \equiv \frac{\delta\rho}{\rho}$



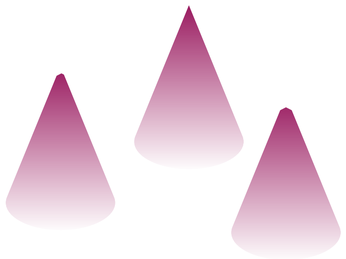
$\mathscr{R} \gtrsim 1$

PBH

$\mathscr{R} \simeq \frac{9}{40}\delta^{(F)}$

Franciolini, YG, Jinno
2503.01962

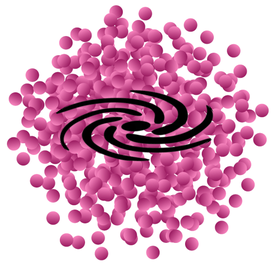
Curvature peaks $\mathscr{R}$



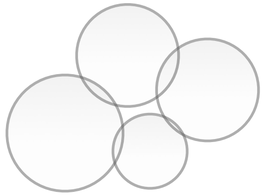
$\mathscr{R} \gtrsim 10^{-3}$

YG
2503.03857

**Ultra-compact
Mini-Halo**

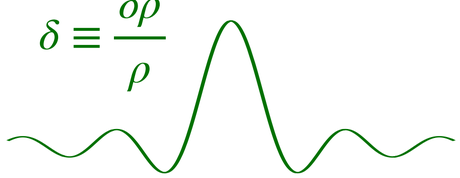


First-order
phase transition



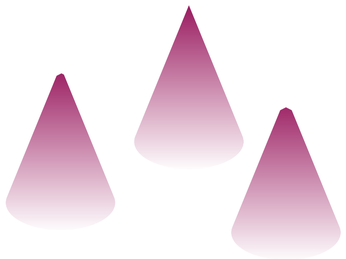
overdensities

$\delta \equiv \frac{\delta\rho}{\rho}$



$\mathscr{R} \simeq \frac{9}{40}\delta^{(F)}$

Franciolini, YG, Jinno
2503.01962



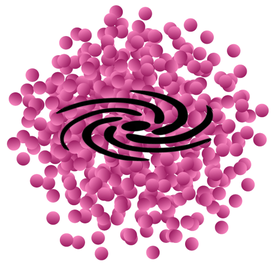
Curvature peaks $\mathscr{R}$

$\mathscr{R} \gtrsim 10^{-3}$

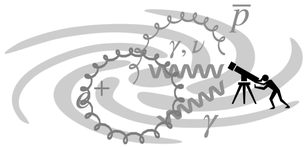
YG
2503.03857

$\mathscr{R} \gtrsim 1$

**Ultra-compact Mini-Halo**



**DM=WIMPs**




**Cosmic-rays**

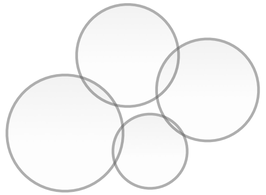


PBH

YG
2503.03857

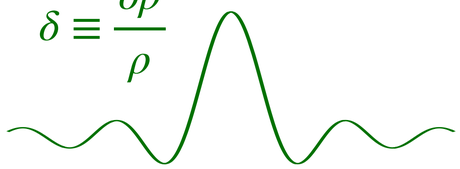
**"New Physics Explanations of PTA signal are incompatible with WIMPs Dark Matter"**

First-order
phase transition



**overdensities**

$\delta \equiv \frac{\delta\rho}{\rho}$



$\mathscr{R} \simeq \frac{9}{40}\delta^{(F)}$

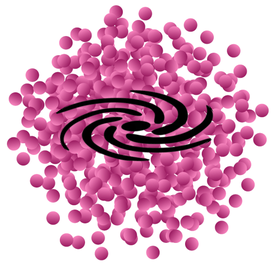
Franciolini, YG, Jinno
2503.01962

Curvature peaks $\mathscr{R}$

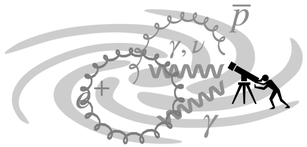
$\mathscr{R} \gtrsim 10^{-3}$

YG
2503.03857

**Ultra-compact Mini-Halo**



**DM=WIMPs**

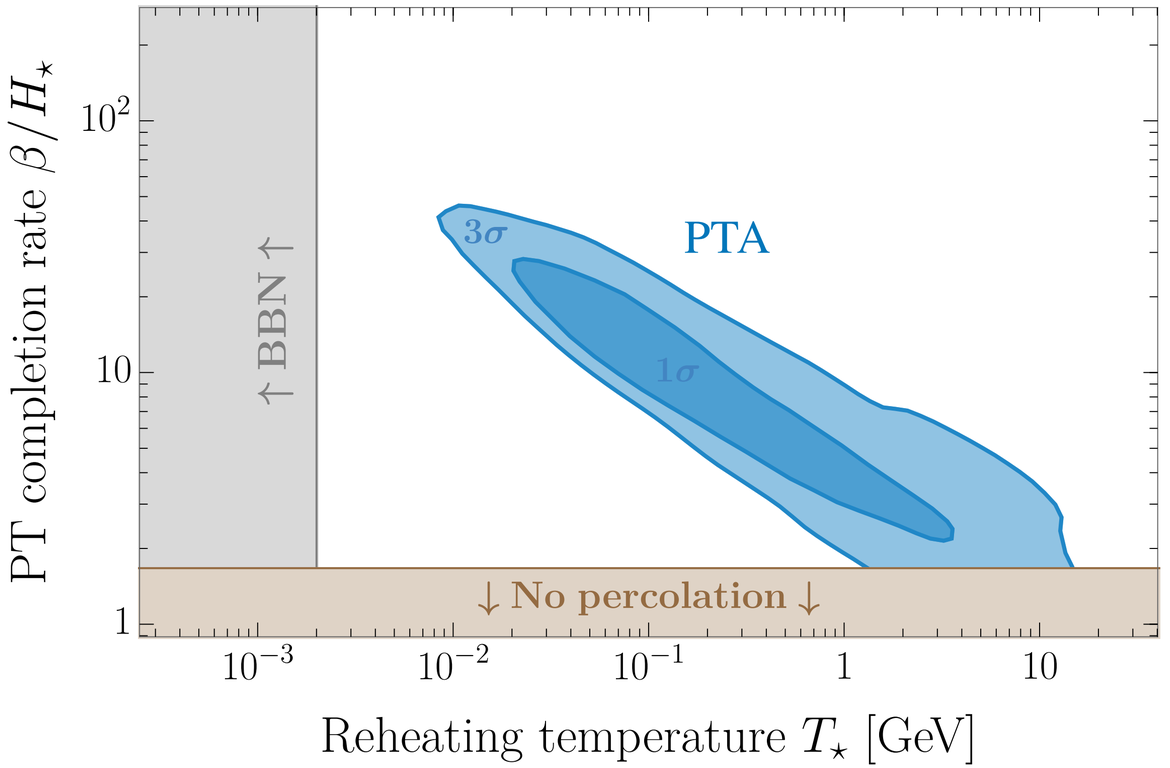



**Cosmic-rays**

$\mathscr{R} \gtrsim 1$



PBH



YG
2503.03857

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First-order
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Franciolini, YG, Jinno
2503.01962

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2503.03857

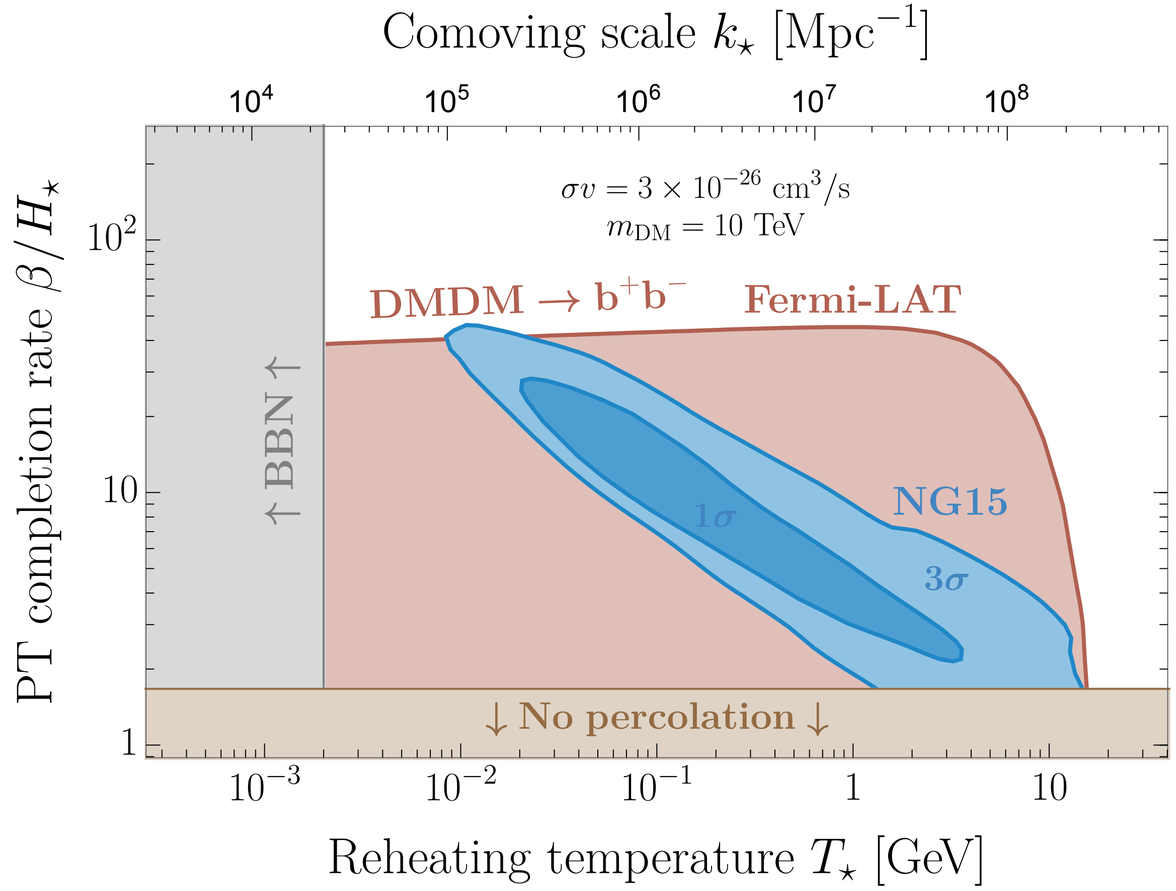
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Mini-Halo

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Franciolini, YG, Jinno
2503.01962

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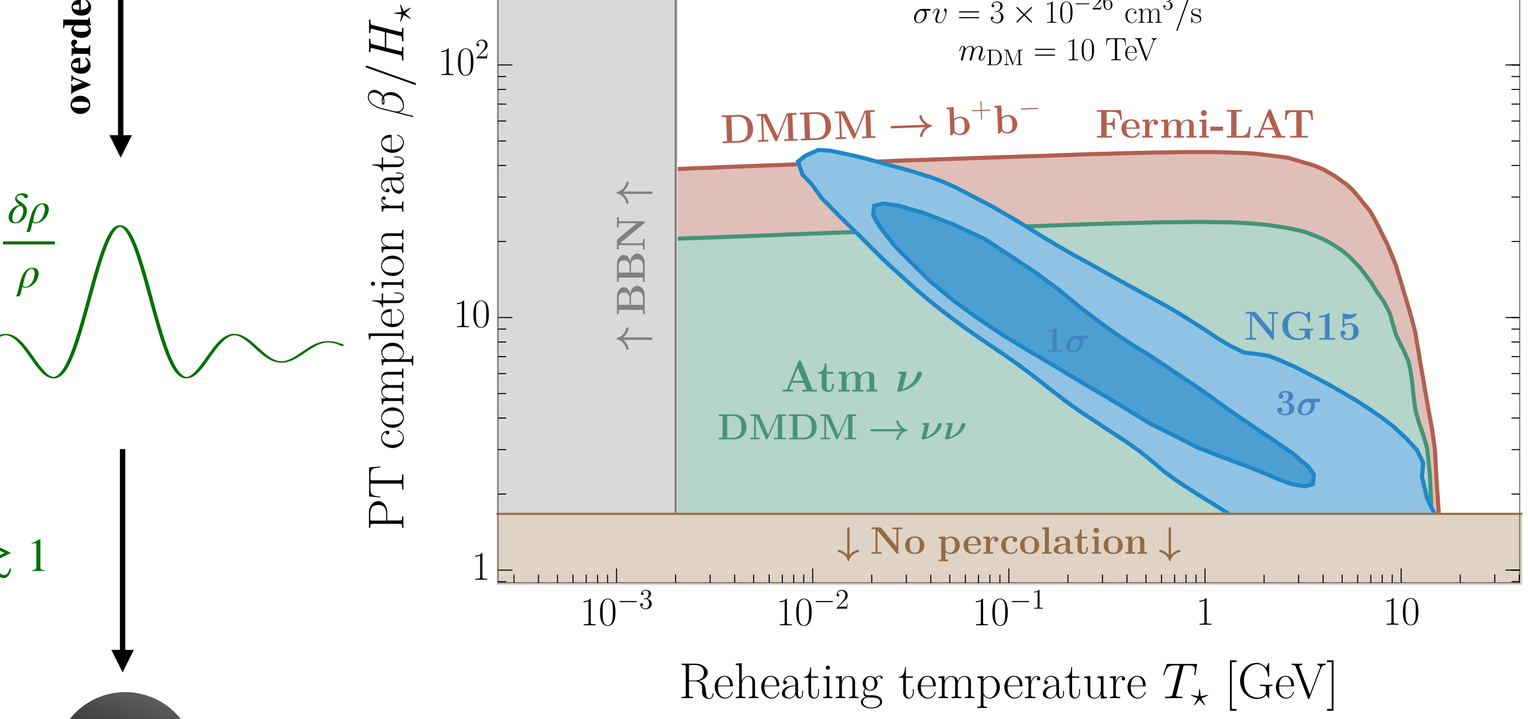
Ultra-compact
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YG
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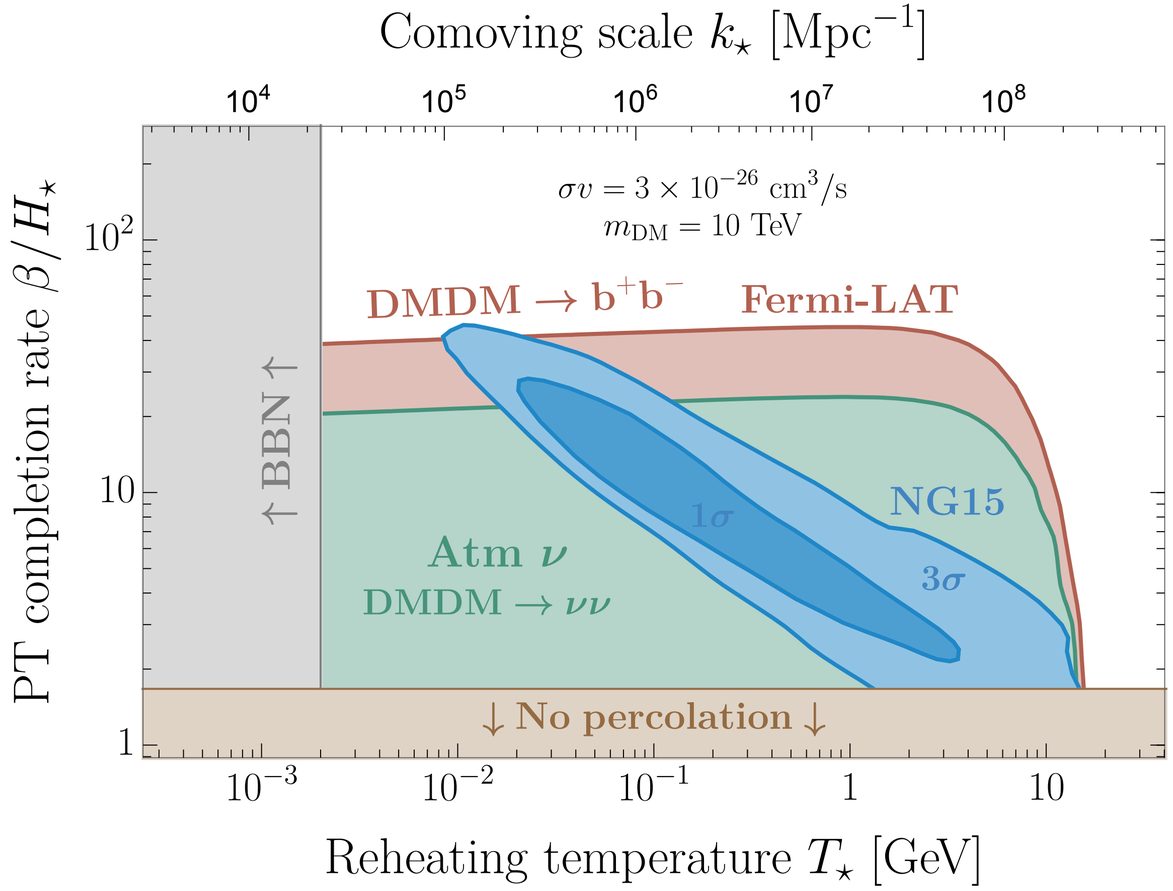
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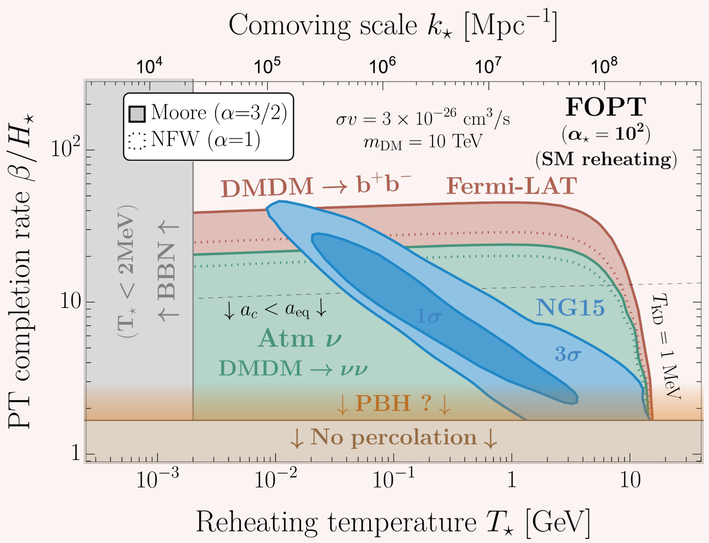
**"New Physics Explanations of PTA signal are incompatible with WIMPs Dark Matter"**




**Same conclusion for : 1) Curvature Peaks from inflation**

**2) Domain Wall Networks**

# First-order Phase Transition




$$\mathscr{P}_{\mathscr{R}}(k) = \left(\frac{\alpha_\star}{1+\alpha_\star}\right)^2 \left(\frac{H_\star}{\beta}\right)^2 \frac{a_1 (k_p/\beta)^3}{\left(a_2 + (k_p/\beta)^2\right)^3}$$

$$k_p = k_\star / a_\star$$

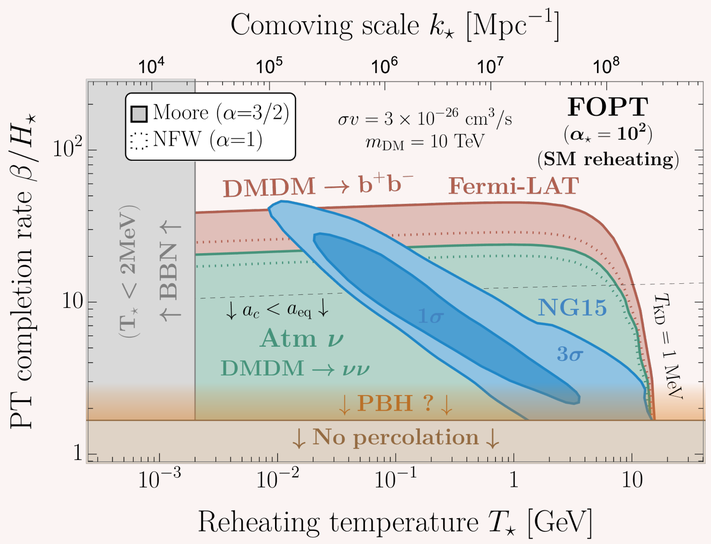
***Franciolini, YG, Jinno 2503.01962***

***Elor, Jinno, Kumar, McGehee, Tsai, 2311.16222 (PRL)***

**YG 2503.03857**

**“New Physics Explanations of PTA signal are incompatible with WIMPs Dark Matter”**

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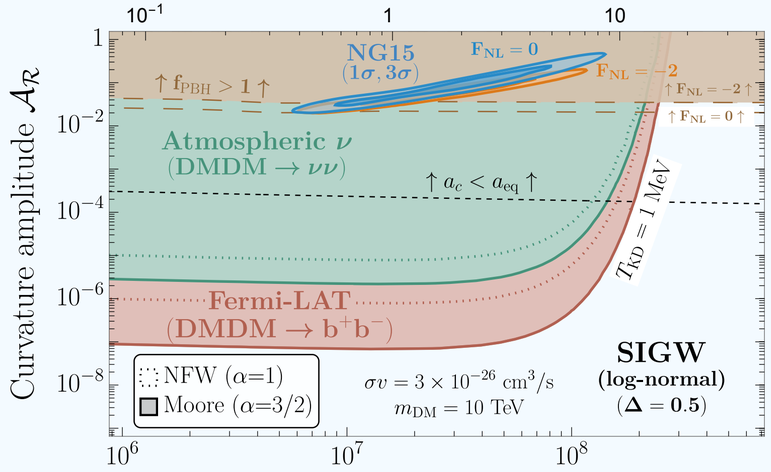
**YG 2503.03857**

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## Gaussian curvature peaks

$$\mathscr{P}_{\mathscr{R}}(k) = \frac{\mathscr{A}_{\mathscr{R}}}{\sqrt{2\pi}\Delta} \exp\left[-\frac{\log^2(k/k_\star)}{2\Delta^2}\right]$$

Horizon crossing temperature $T_\star$ [GeV]

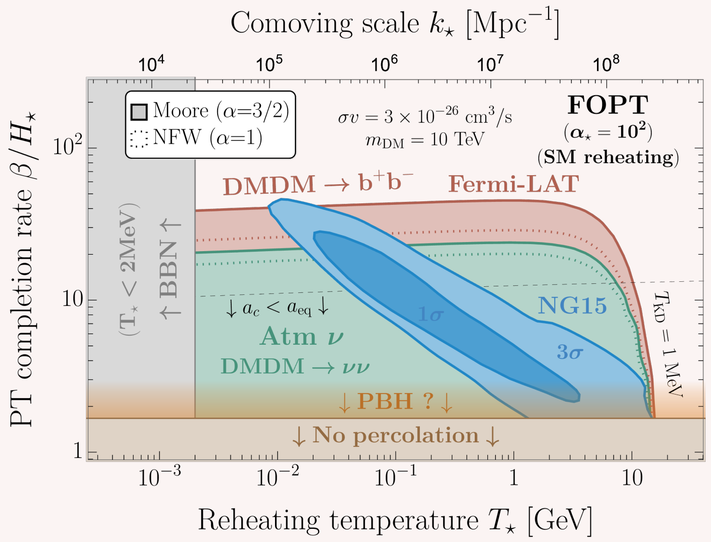



***See also Nakama, Suyama, Kohri, Hiroshima (1712.08820)***

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*Franciolini, YG, Jinno 2503.01962*

*Elor, Jinno, Kumar, McGehee, Tsai, 2311.16222 (PRL)*

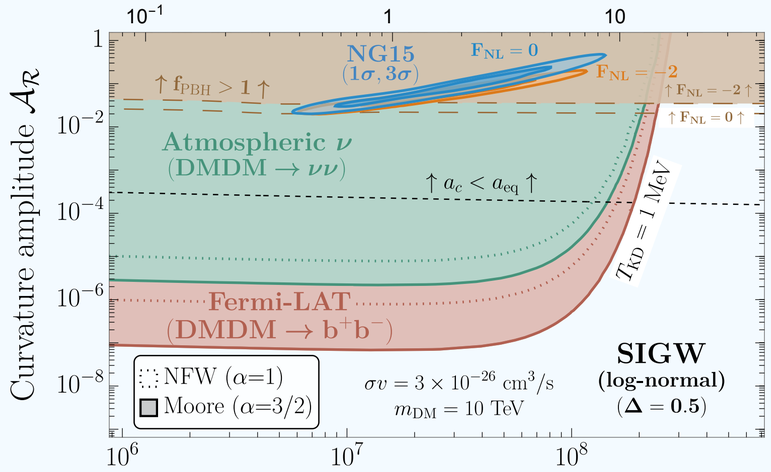
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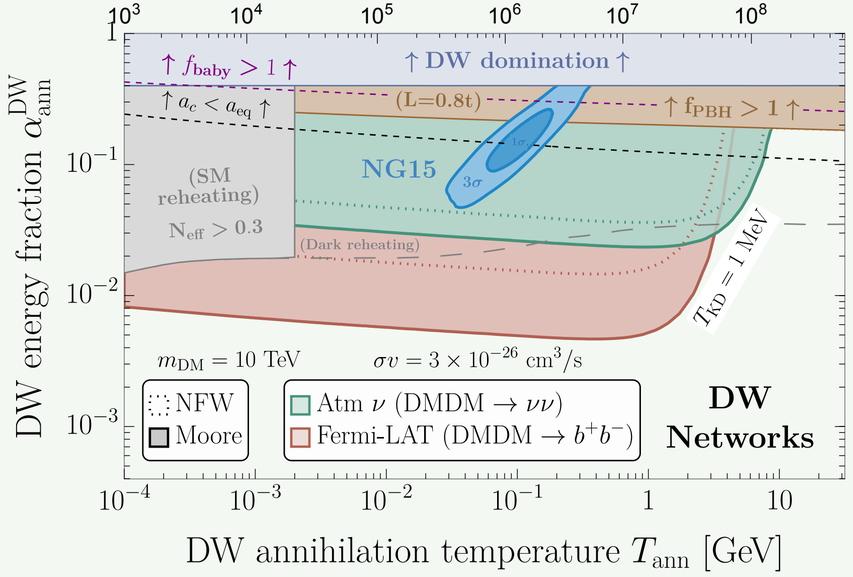
## Domain Wall Networks

$$\mathscr{P}_{\mathscr{R}}(k) = \frac{\alpha_{\rm V}^2}{2\pi} \frac{(k_p L_{\rm ann})^3}{\left[4 + (k_p L_{\rm ann})^2\right]^2}$$

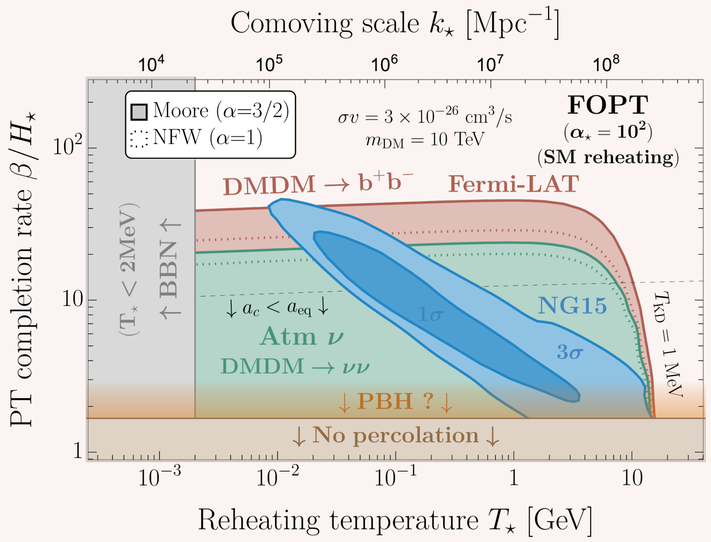
$$\alpha_V = V_{\rm bias}/\rho_{\rm rad}\Big|_{t=t_{\rm ann}}$$




$$L_{\rm ann} \sim t_{\rm ann}$$



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***Franciolini, YG, Jinno 2503.01962***

***Elor, Jinno, Kumar, McGehee, Tsai, 2311.16222 (PRL)***

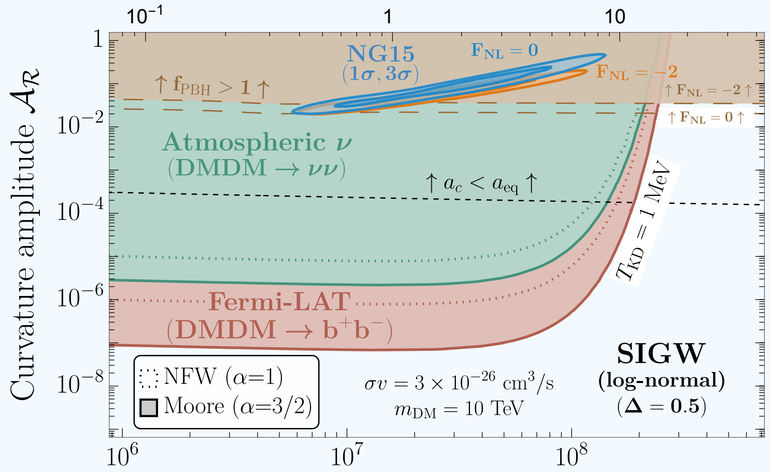
**YG 2503.03857**

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## Domain Wall Networks

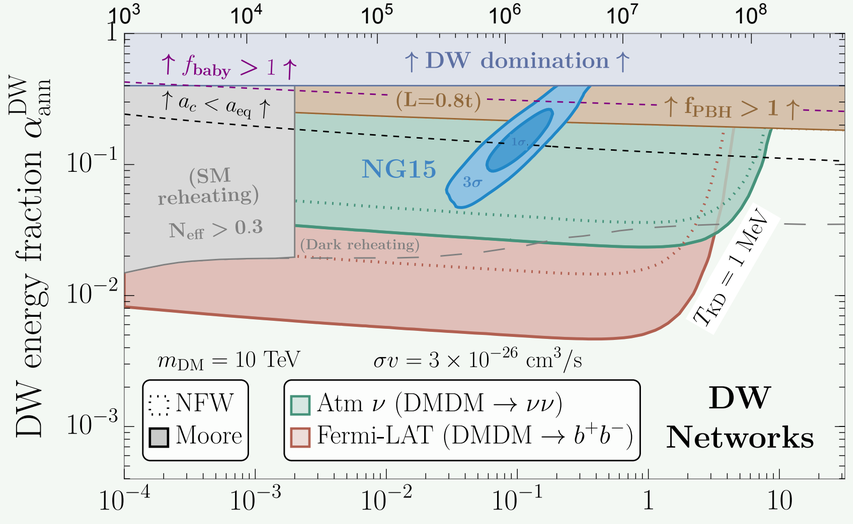
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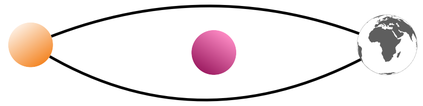

$$L_{\rm ann} \sim t_{\rm ann}$$

Comoving scale $k_{\rm ann}$ [Mpc$^{-1}$]




# Thank you

***Next step:*** ***Get rid of WIMPs assumption with Gravitational Lensing***



**HSC microlensing and lensed Quasars**

***(in preparation)***

**See also *Delos, Franciolini 2301.13171***

Lewicki, Toczek, Vaskonen, 2402.04158, PRL

(deltaPT)

Franciolini, YG, Jinno 2503.01962

Neglect effects from bubble walls

Lewicki, Toczek, Vaskonen 2305.04924

Flores, Kusenko, Sasaki 2402.13341

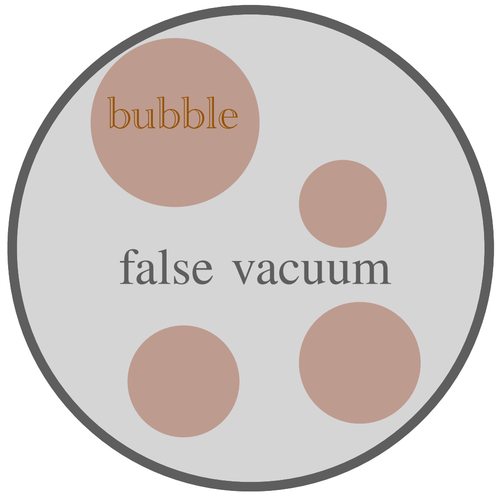
Hashino, Kanemura, Takahashi,
Tanaka, Yoo 2501.11040

Suggest bubble walls could be important



YG, Lewicki, Toczek, Vaskonen, 26XX.XXXXX

Account for momentum flux from bubble walls




deltaPT

