

Gravitational Probes of the Early Universe

Yann Gouttenoire

15th October 2025

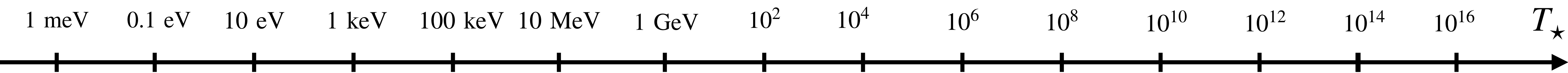
TUG (Théorie, Univers et Gravitation)



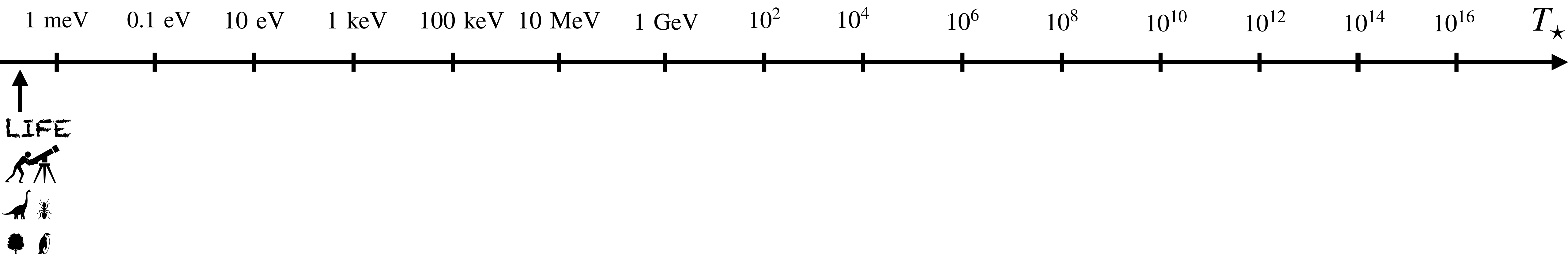
February 2026



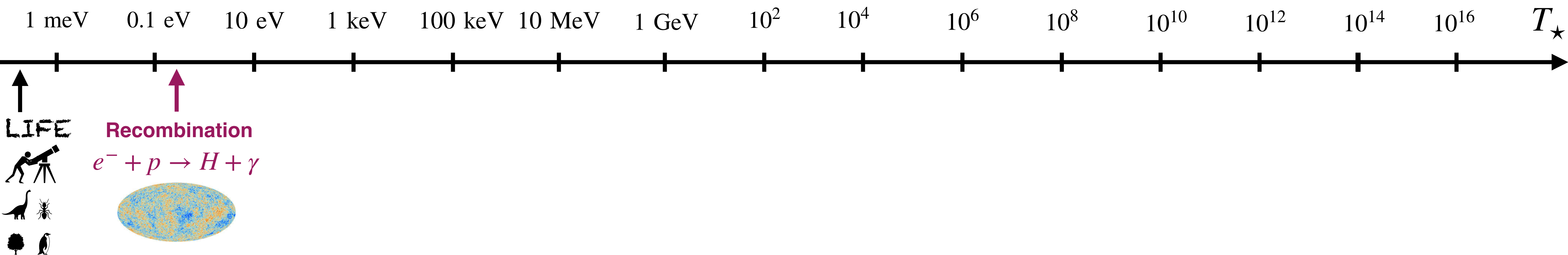
Institute of Astrophysics in Paris



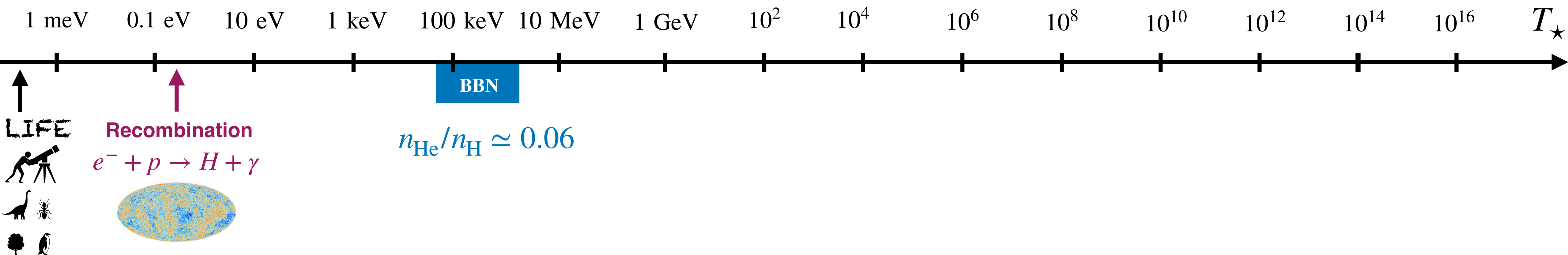
What we do know about the
History of our Universe



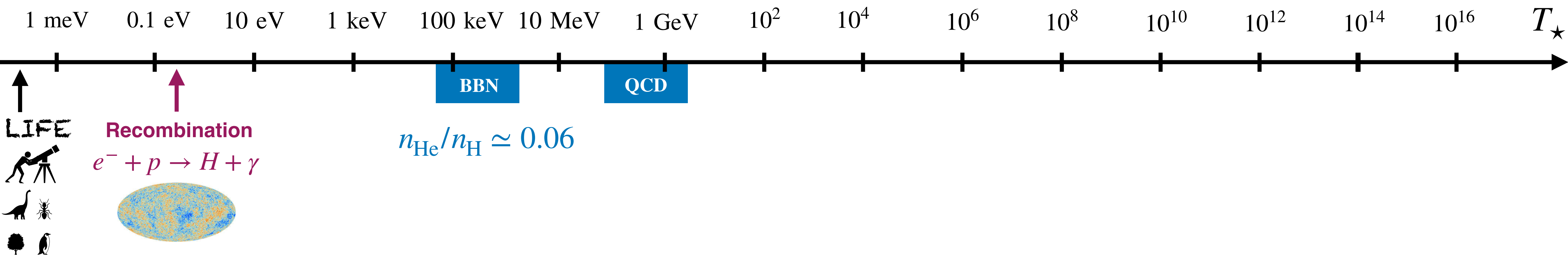
What we do know about the
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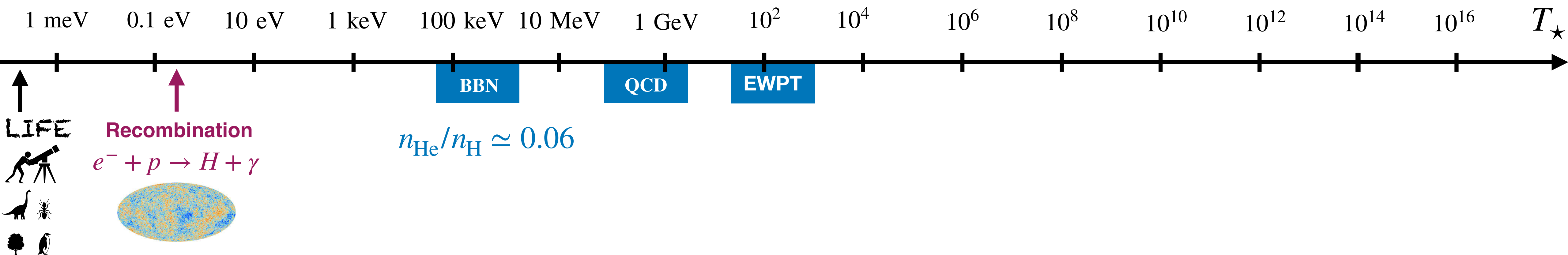
What we do know about the
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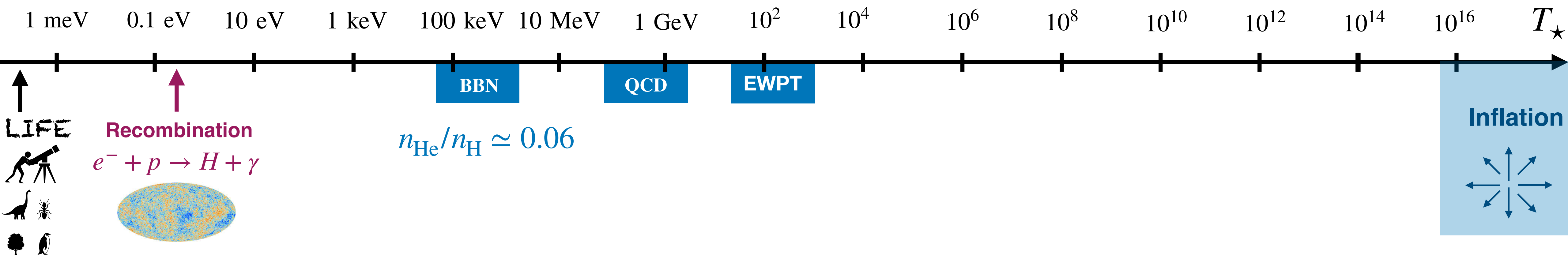
What we do know about the
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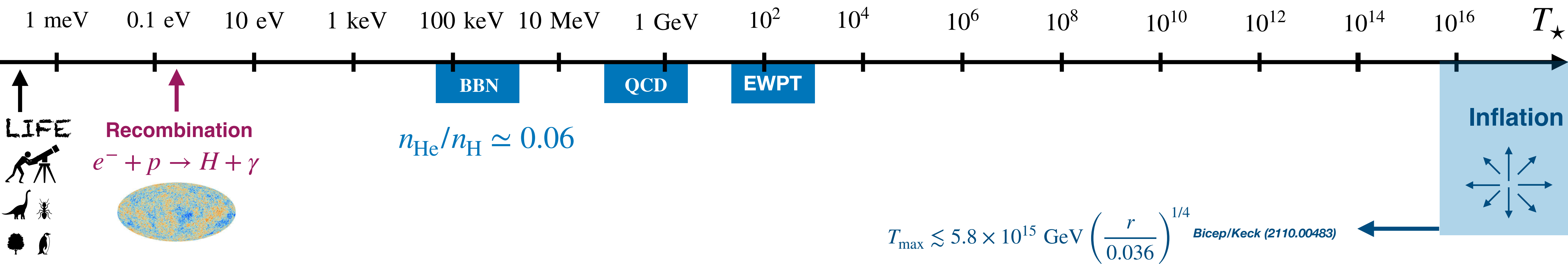
What we do know about the
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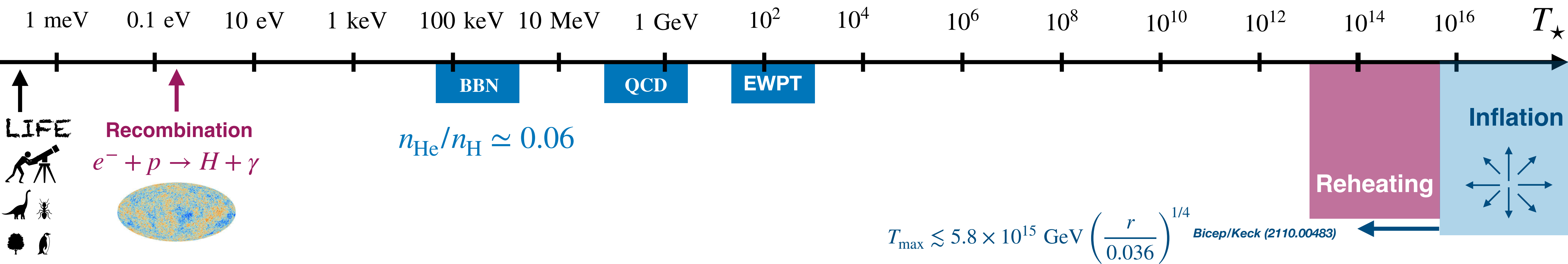
What we do know about the
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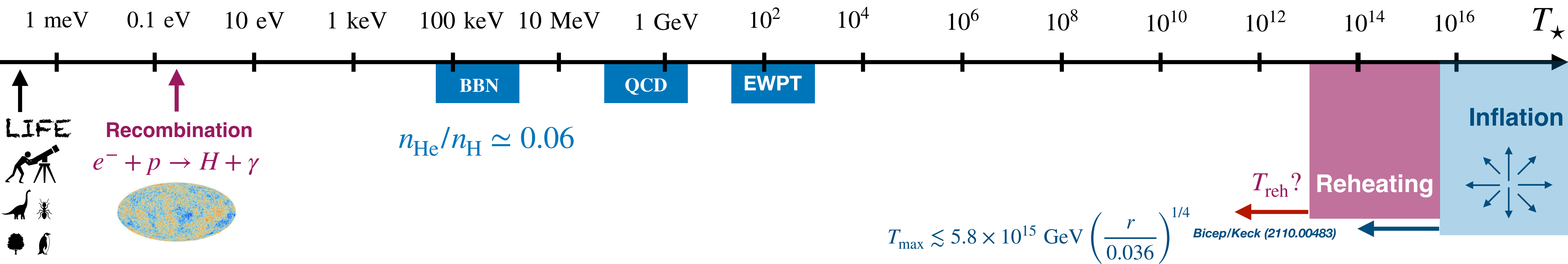
What we do know about the
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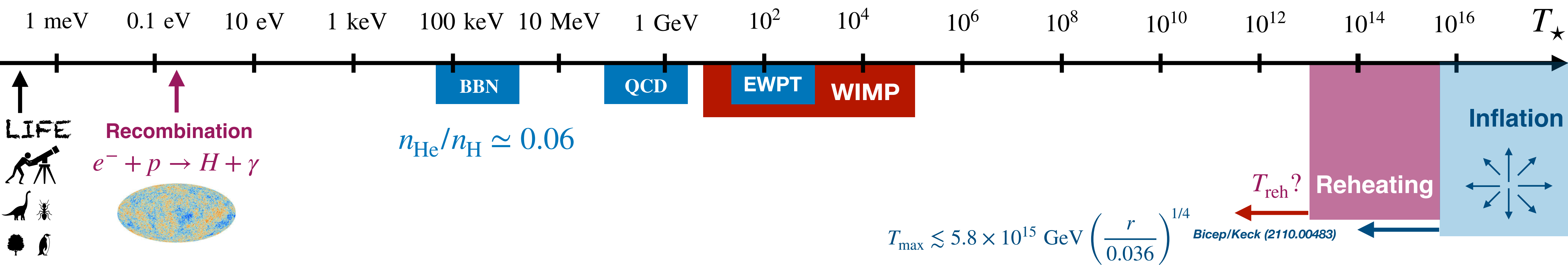
What we do know about the
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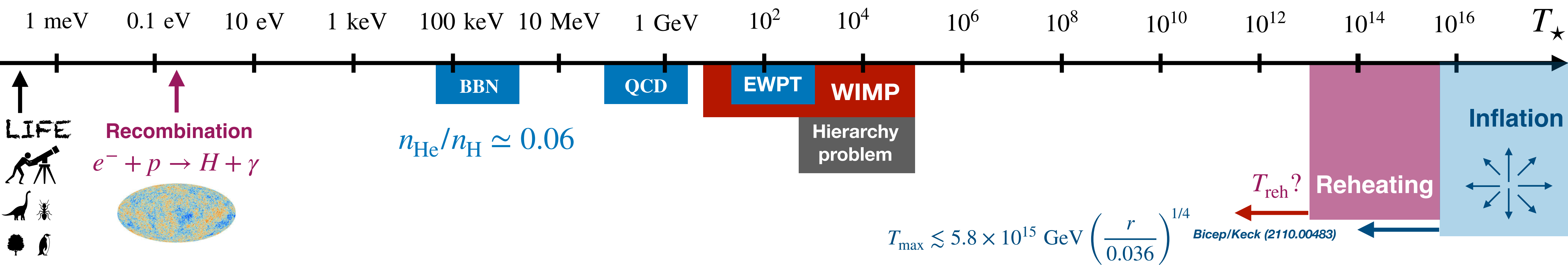
What we do know about the
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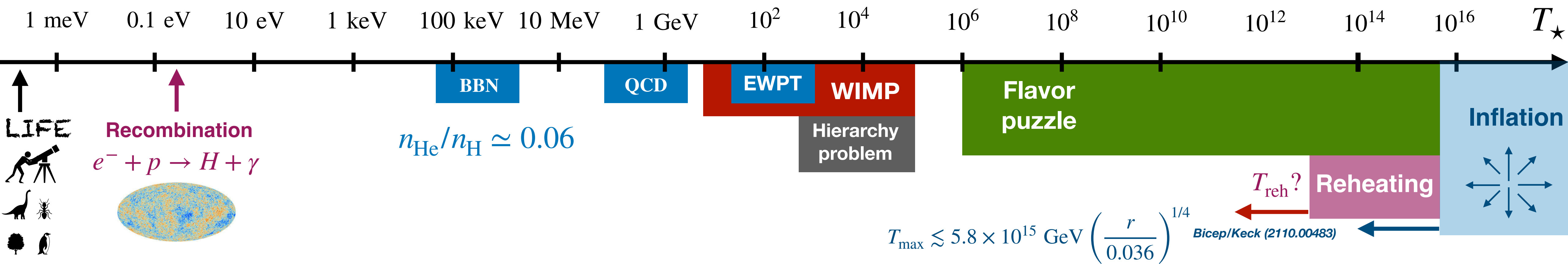
What we **don't** know about the
History of our Universe



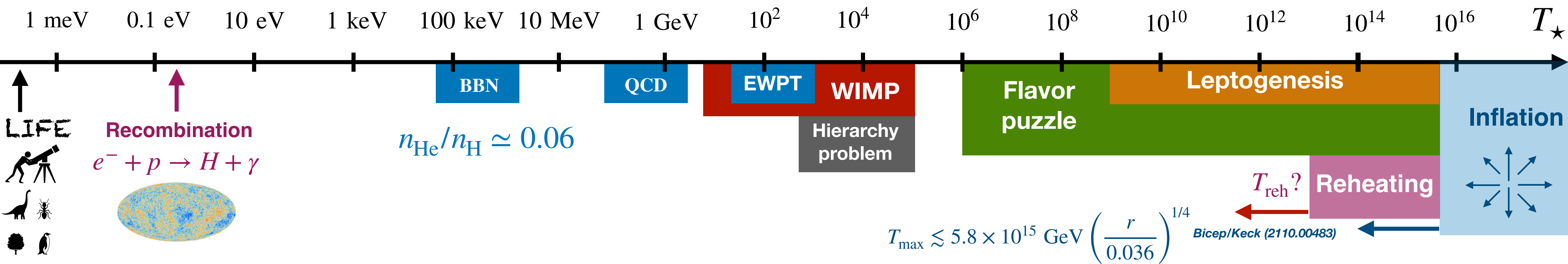
What we **don't** know about the
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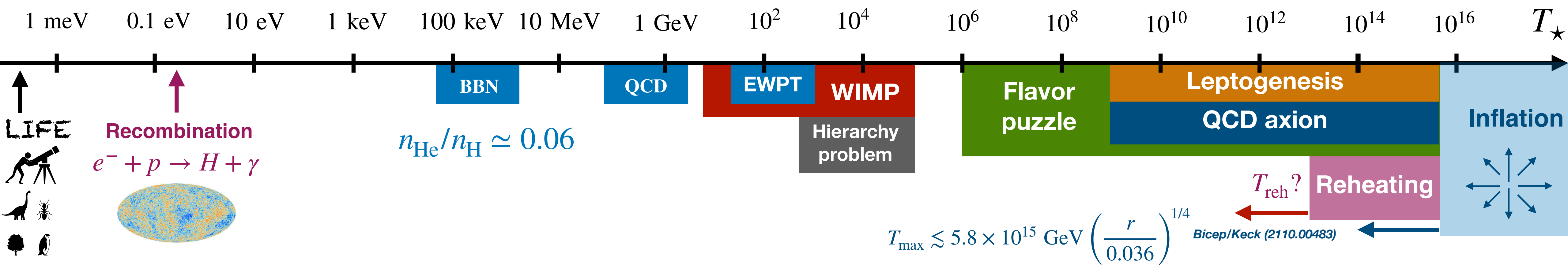
What we **don't** know about the
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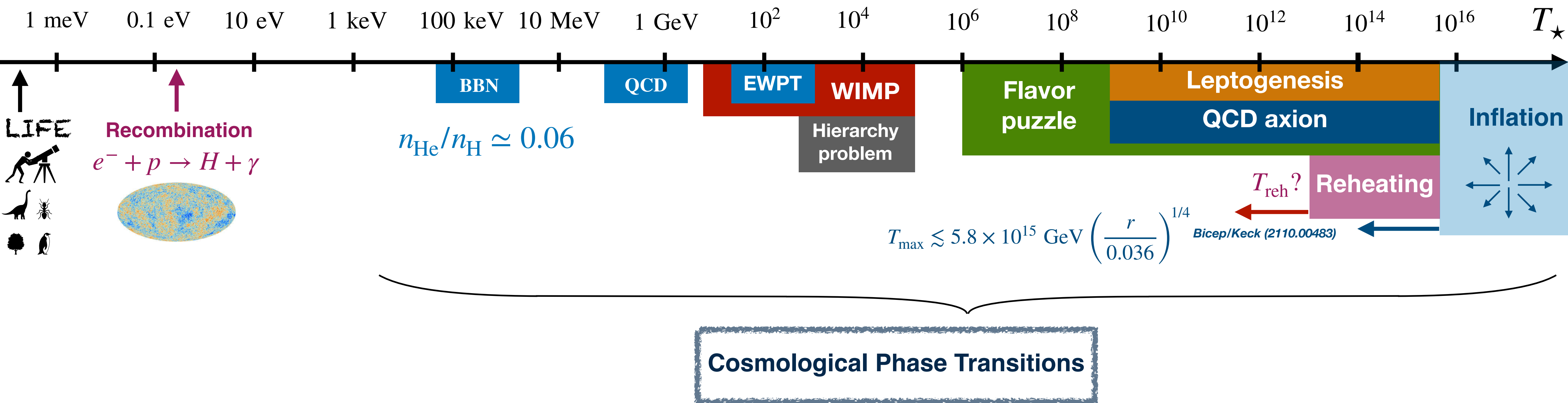
What we **don't** know about the History of our Universe

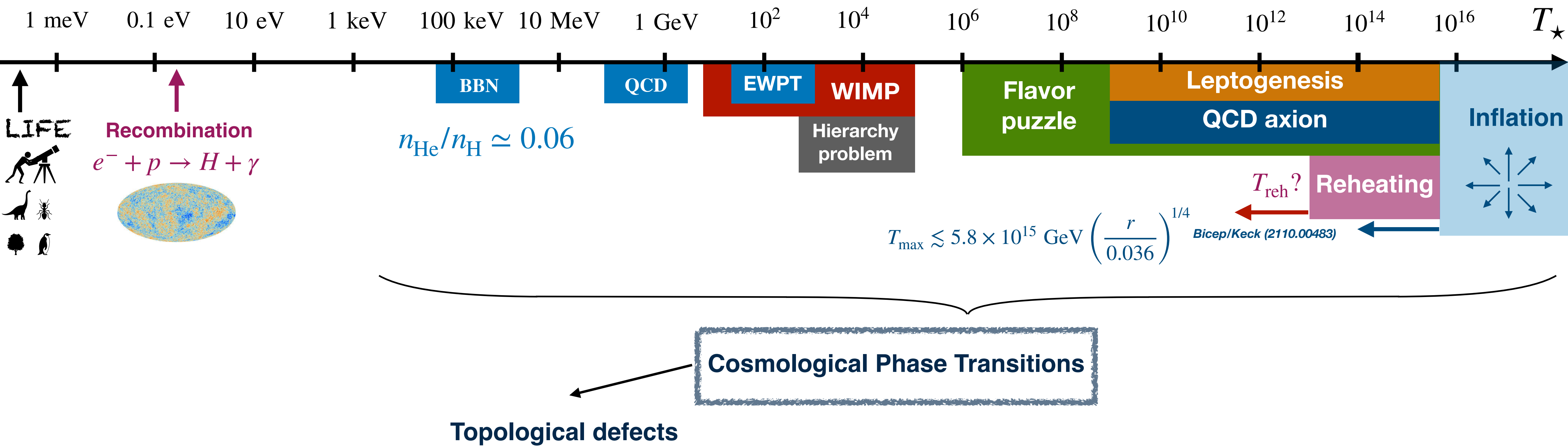


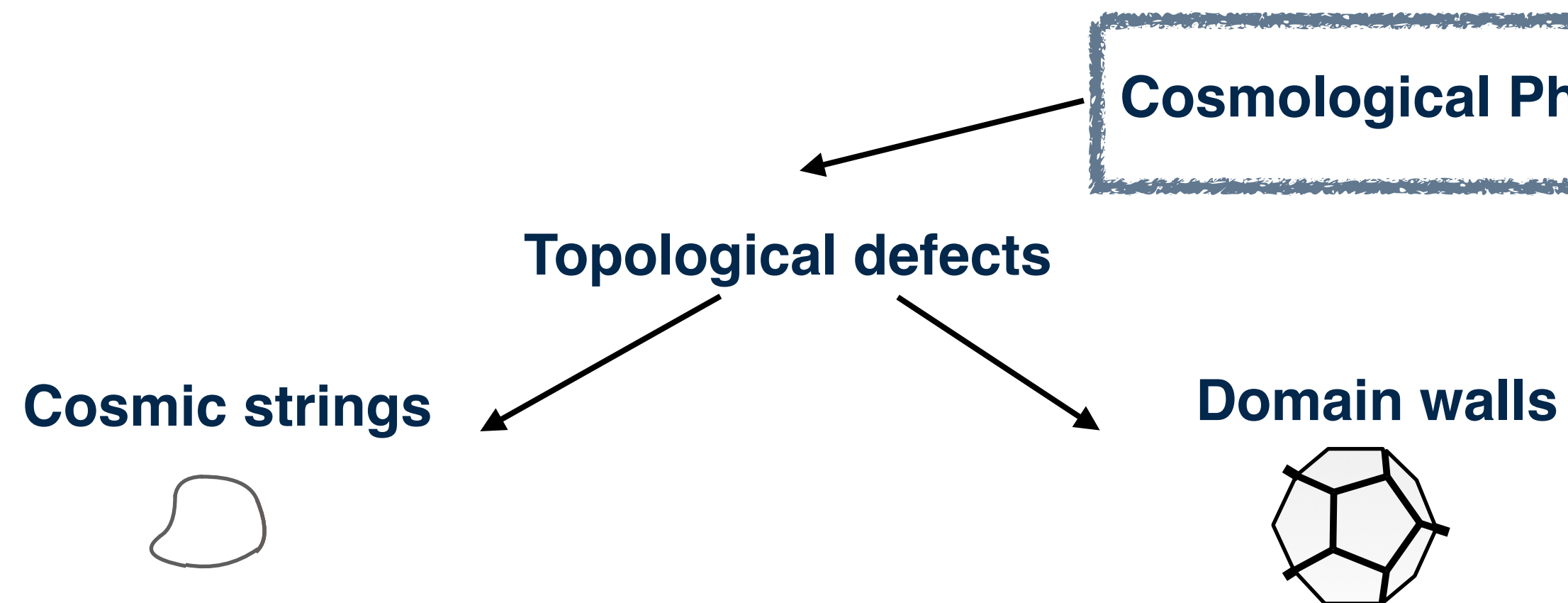
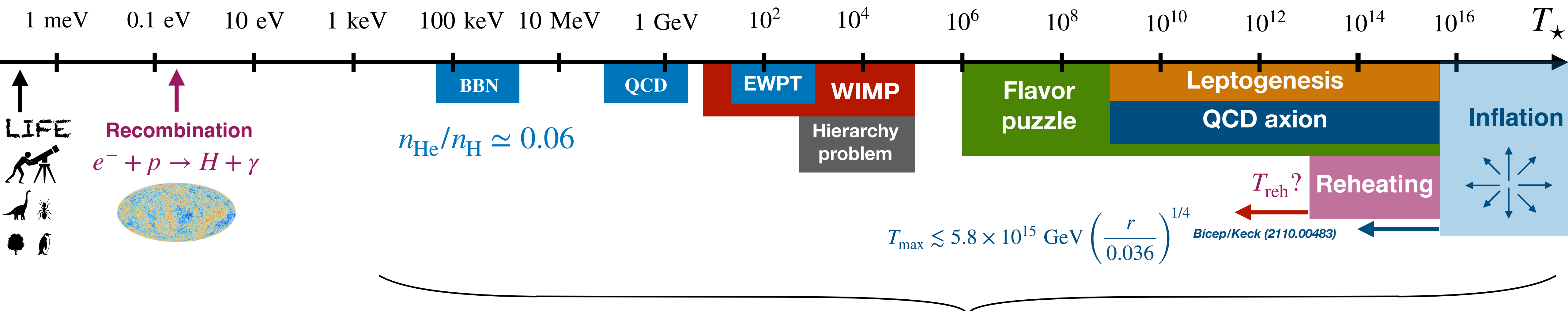
What we **don't** know about the History of our Universe

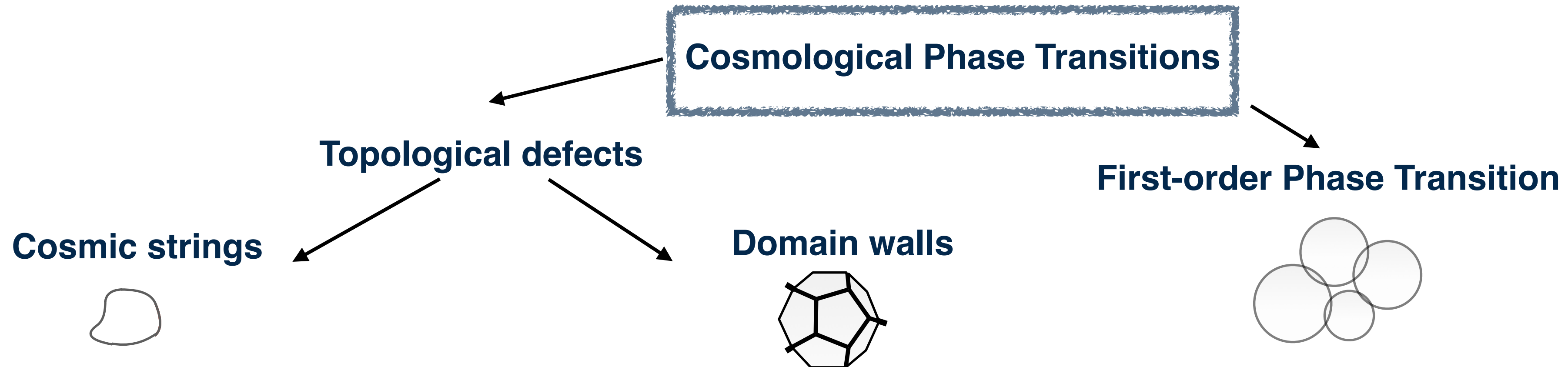
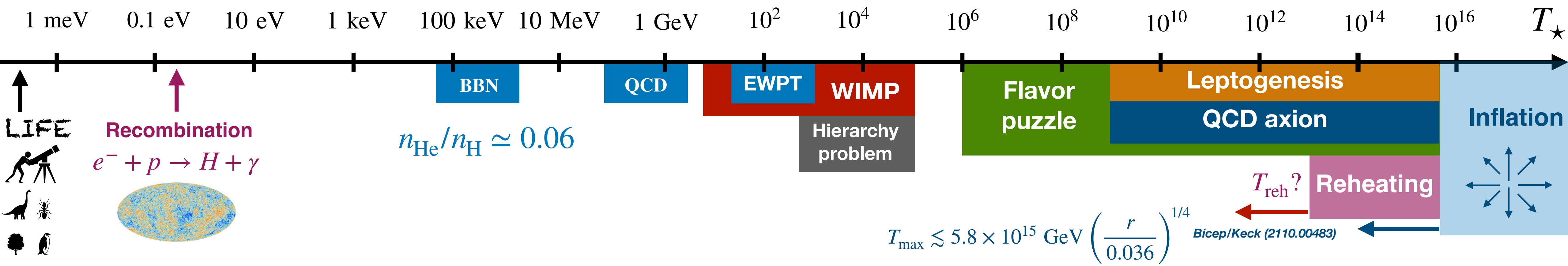


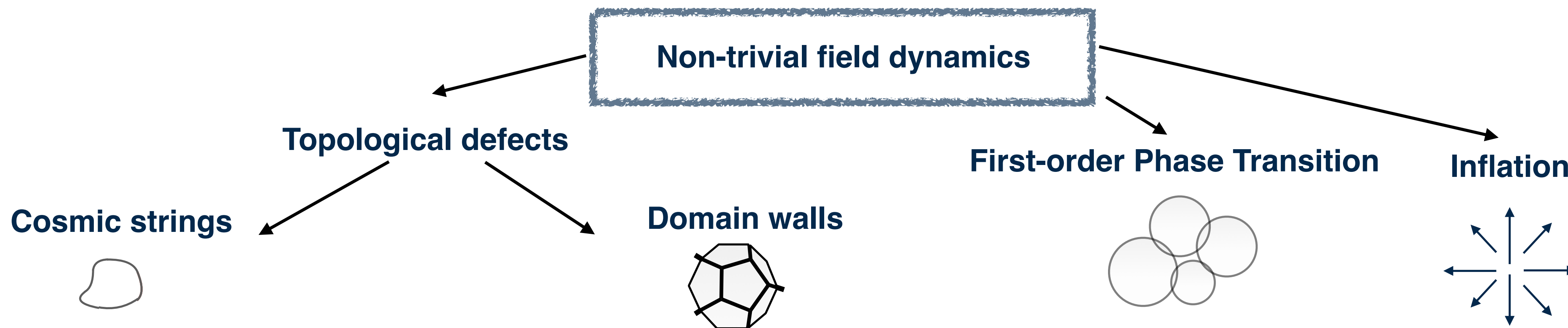
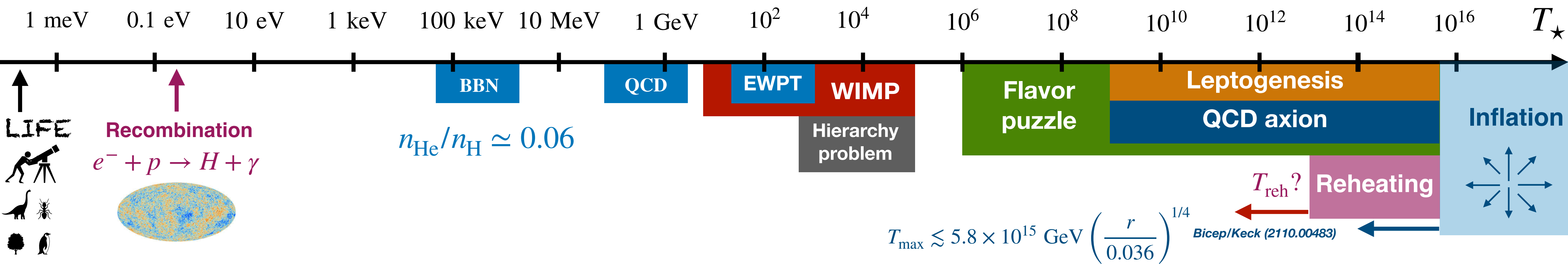
What we **don't** know about the History of our Universe

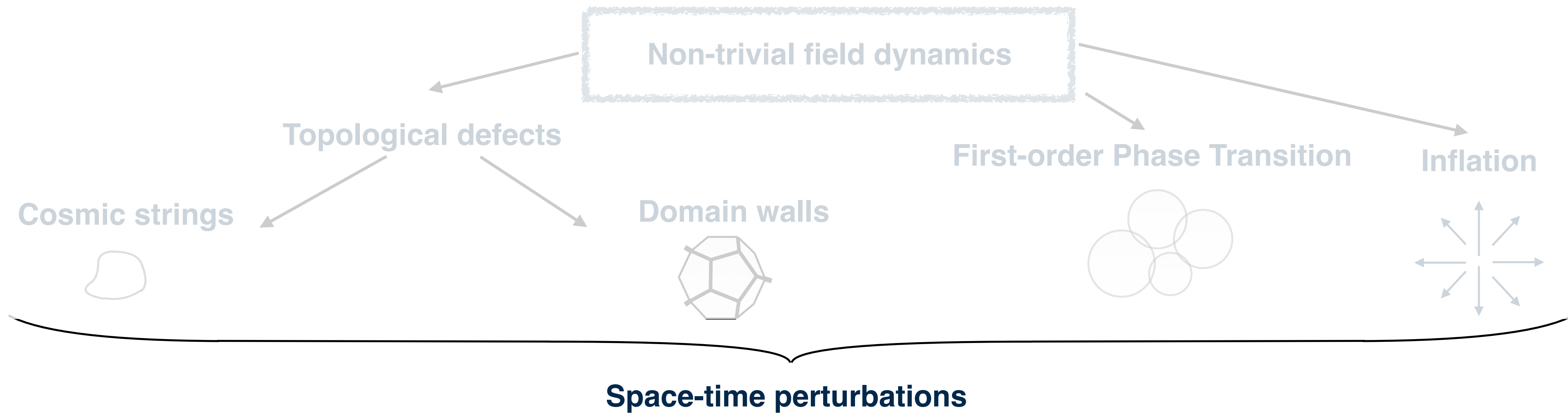
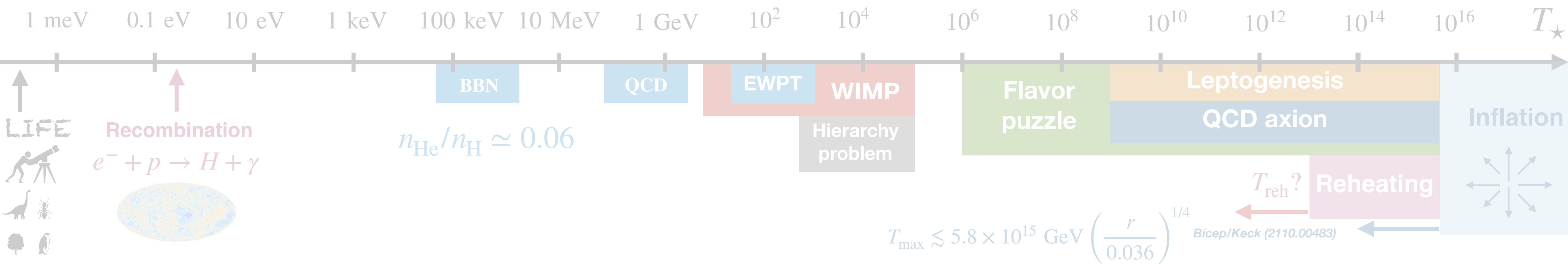


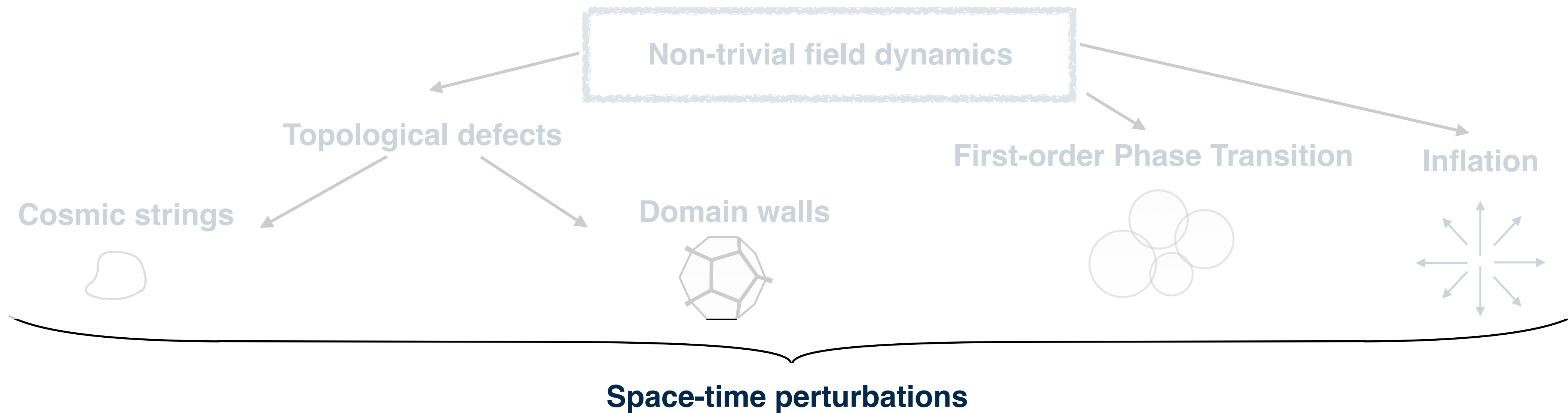
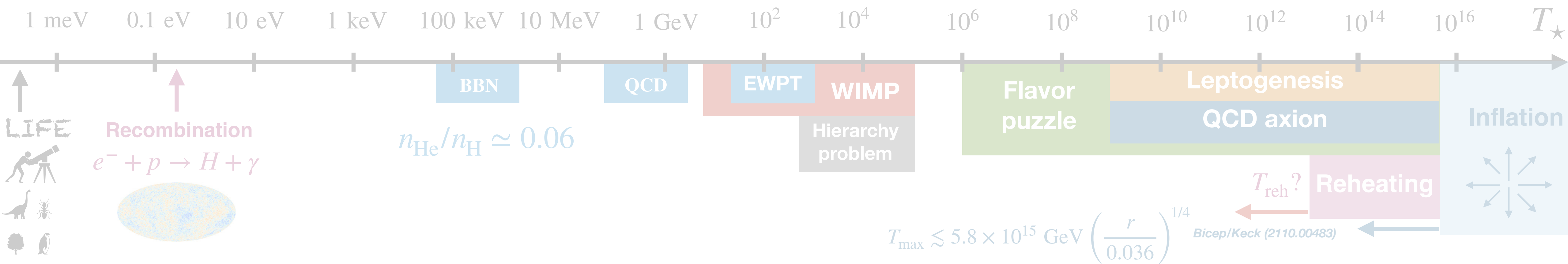






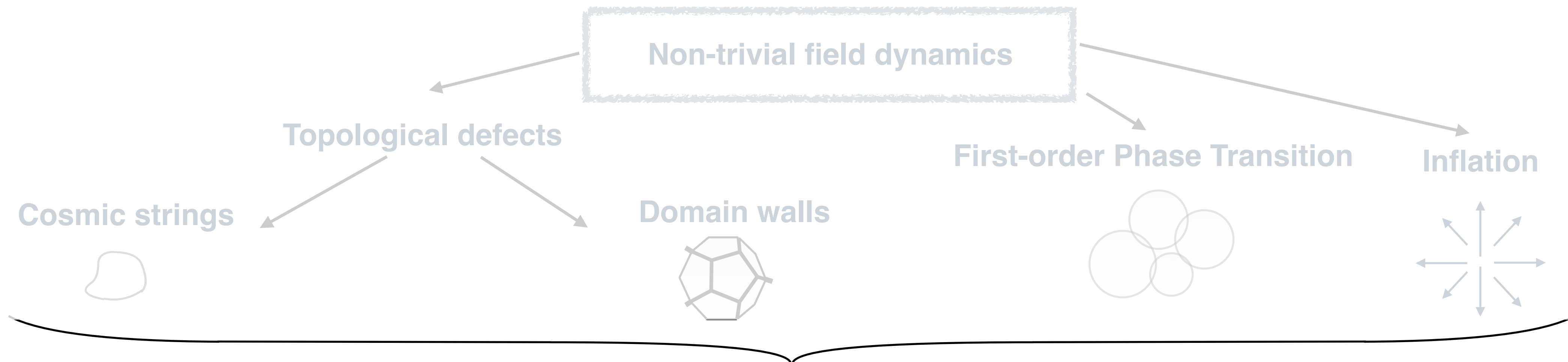
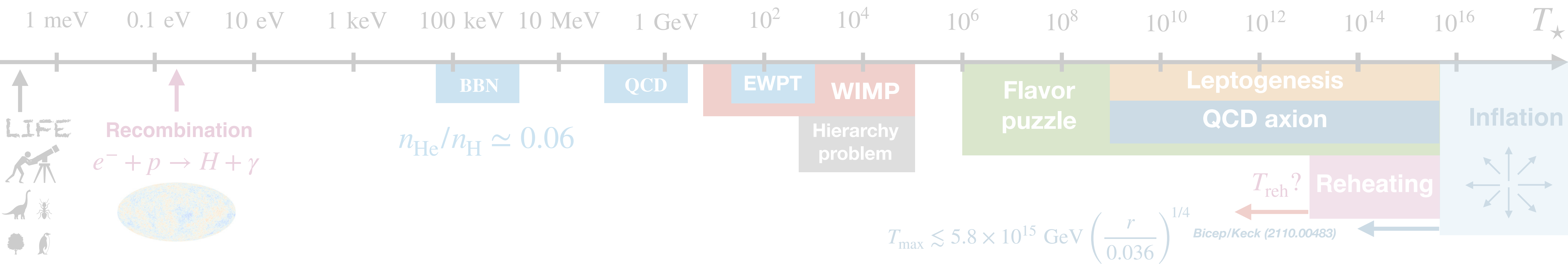




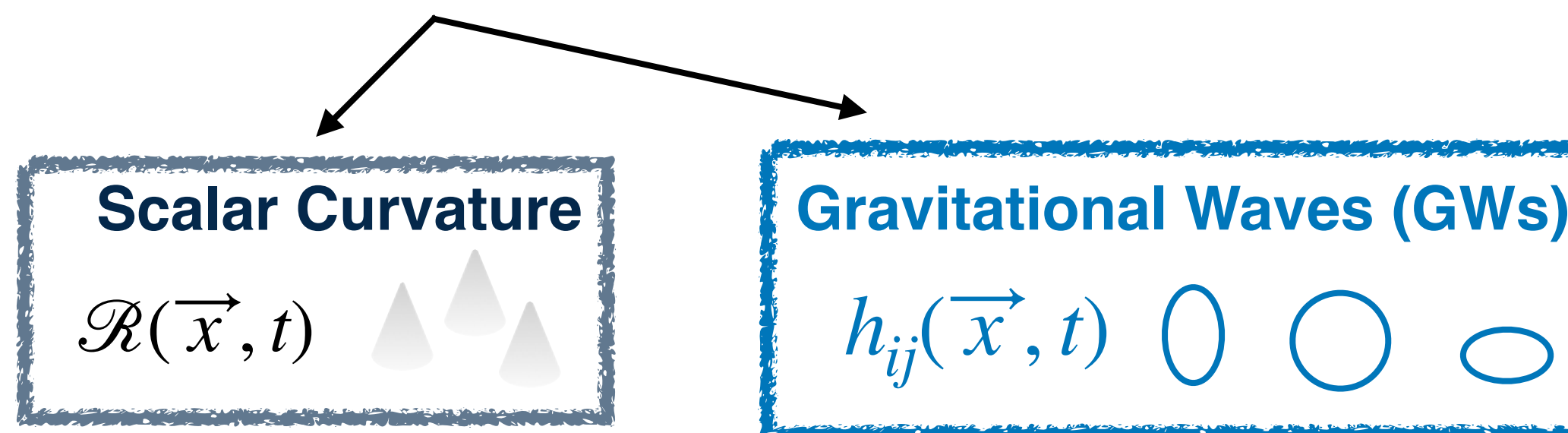


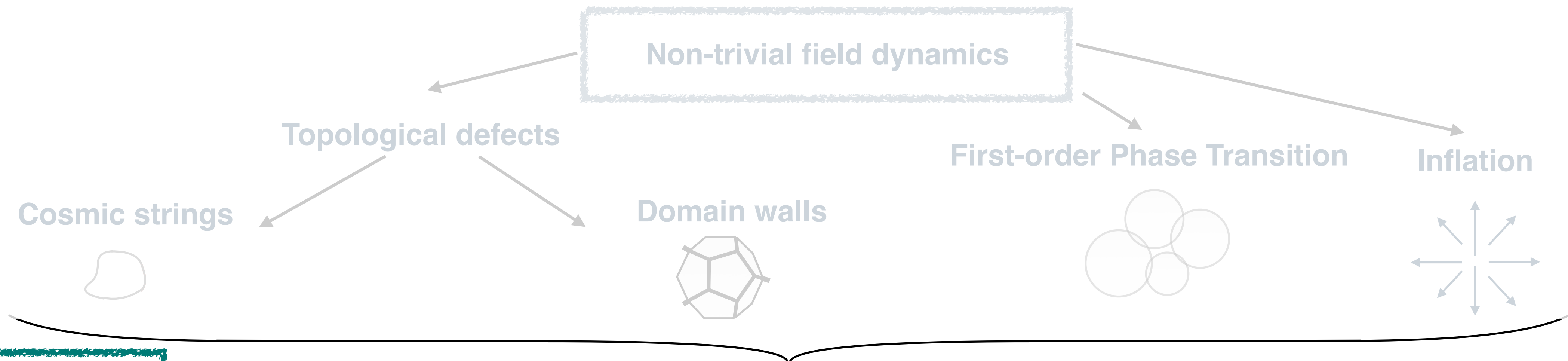
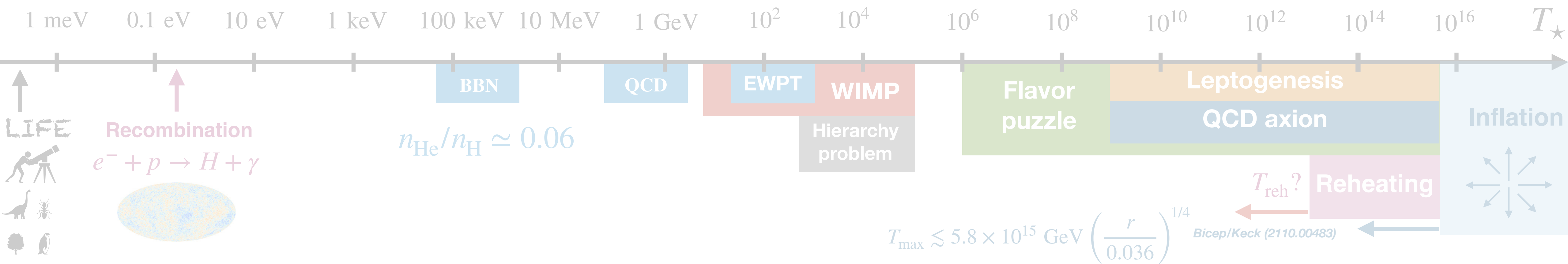
Gravitational Waves (GWs)

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



Space-time perturbations





Primordial Black Holes (PBHs)

(Shibata & Sasaki 1999)

if $\langle \mathcal{R} \rangle_H \gtrsim 0.1$

Space-time perturbations

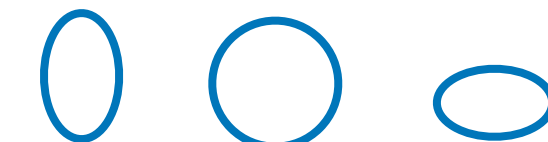
Scalar Curvature

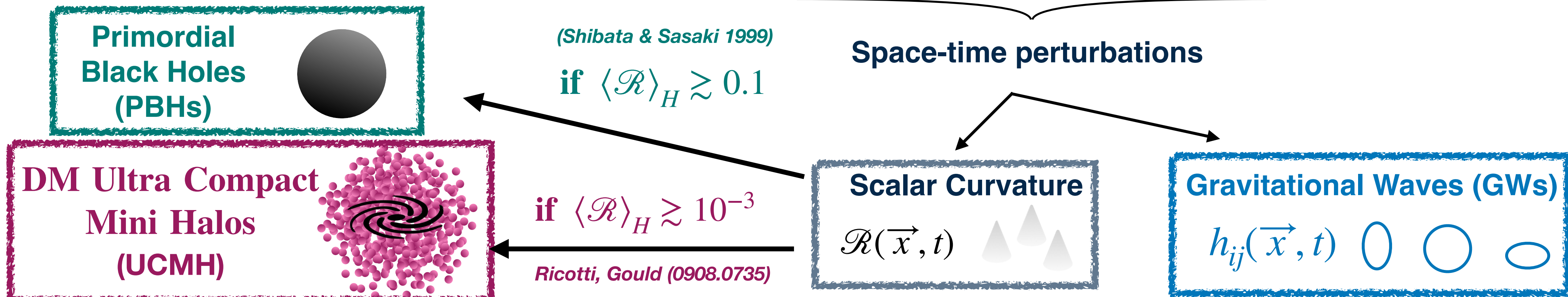
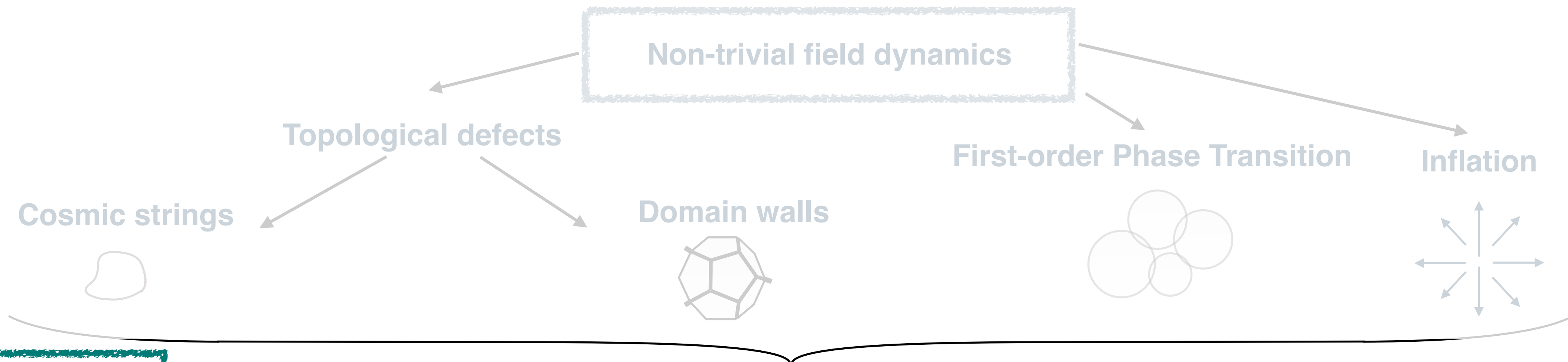
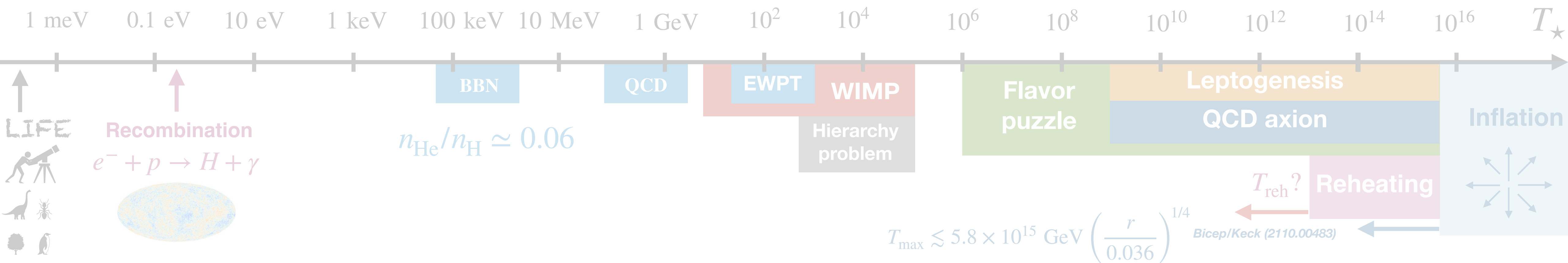
$\mathcal{R}(\vec{x}, t)$



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

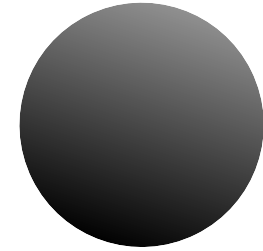
1)

Gravitational Waves (GWs)

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

2)

Primordial
Black Holes
(PBHs)



Plan of the talk

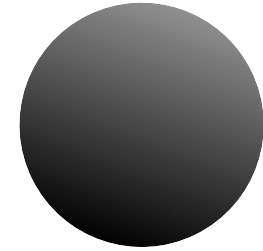
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Gravitational Waves (GWs)

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

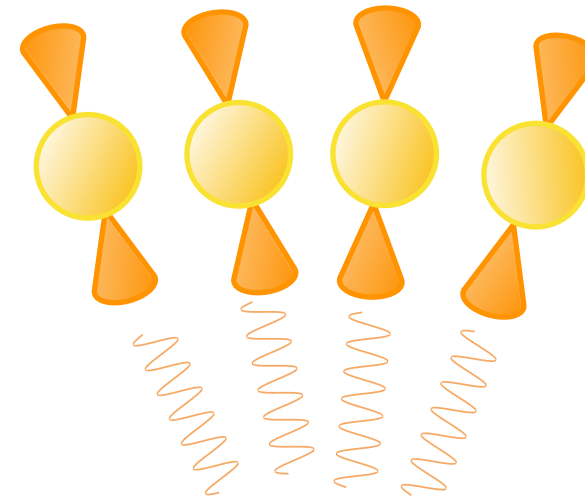
2)

Primordial
Black Holes
(PBHs)



3)

What is the PTA
signal ?



Plan of the talk

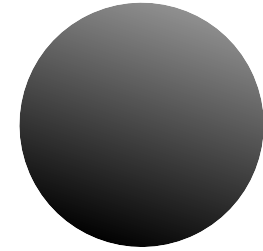
1)

Gravitational Waves (GWs)

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

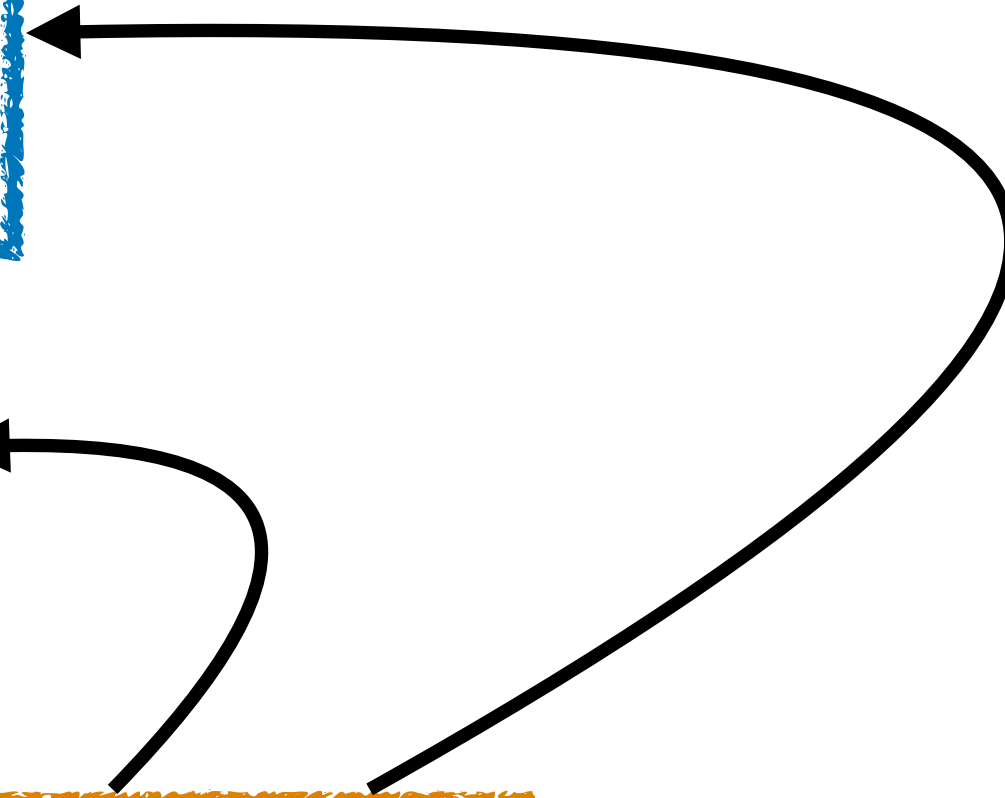
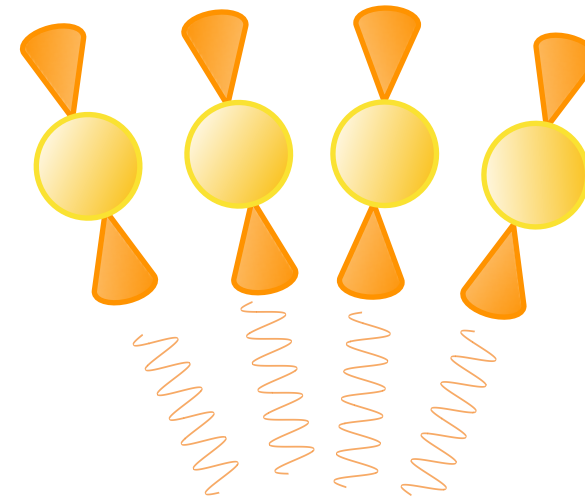
2)

Primordial
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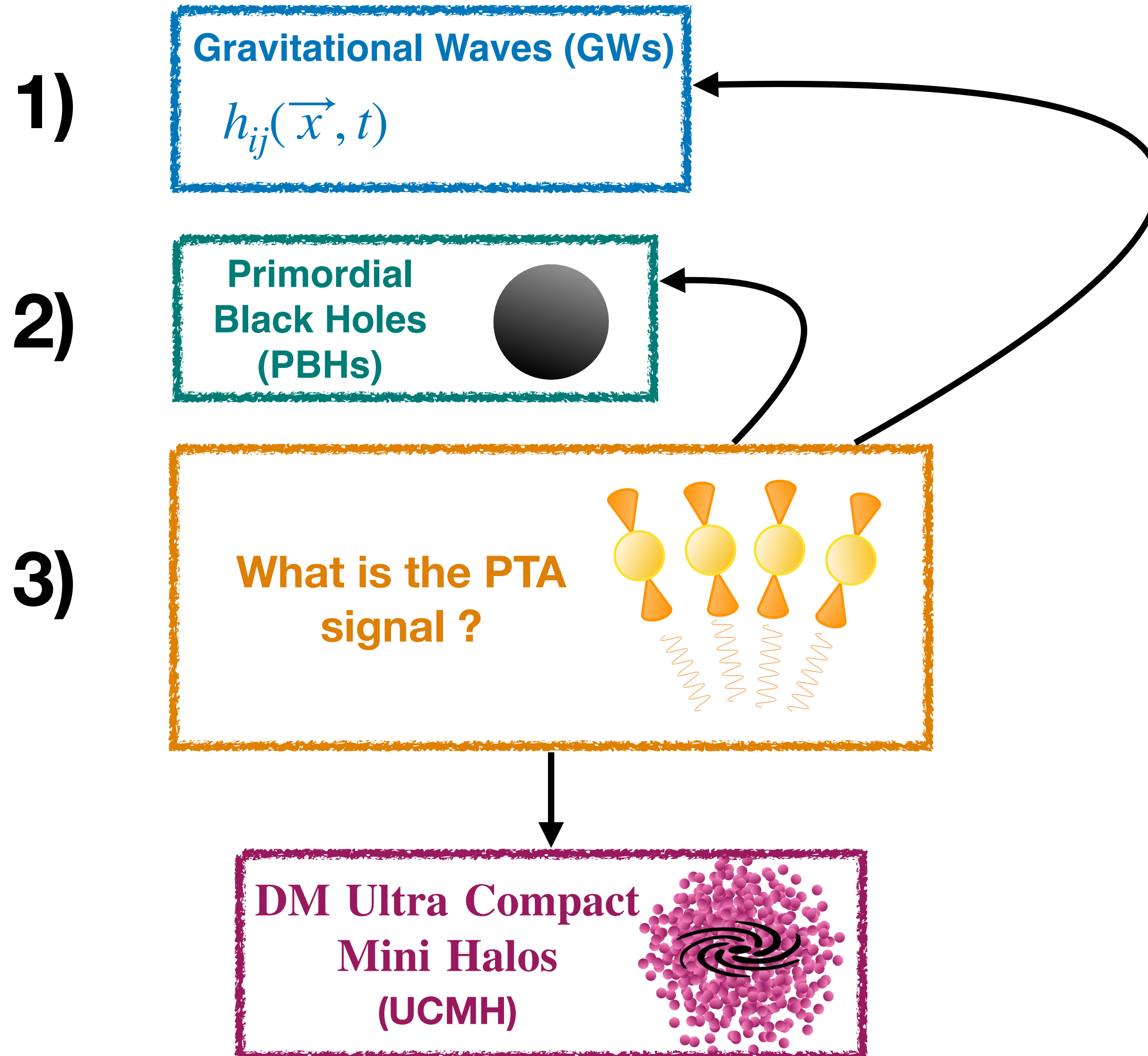


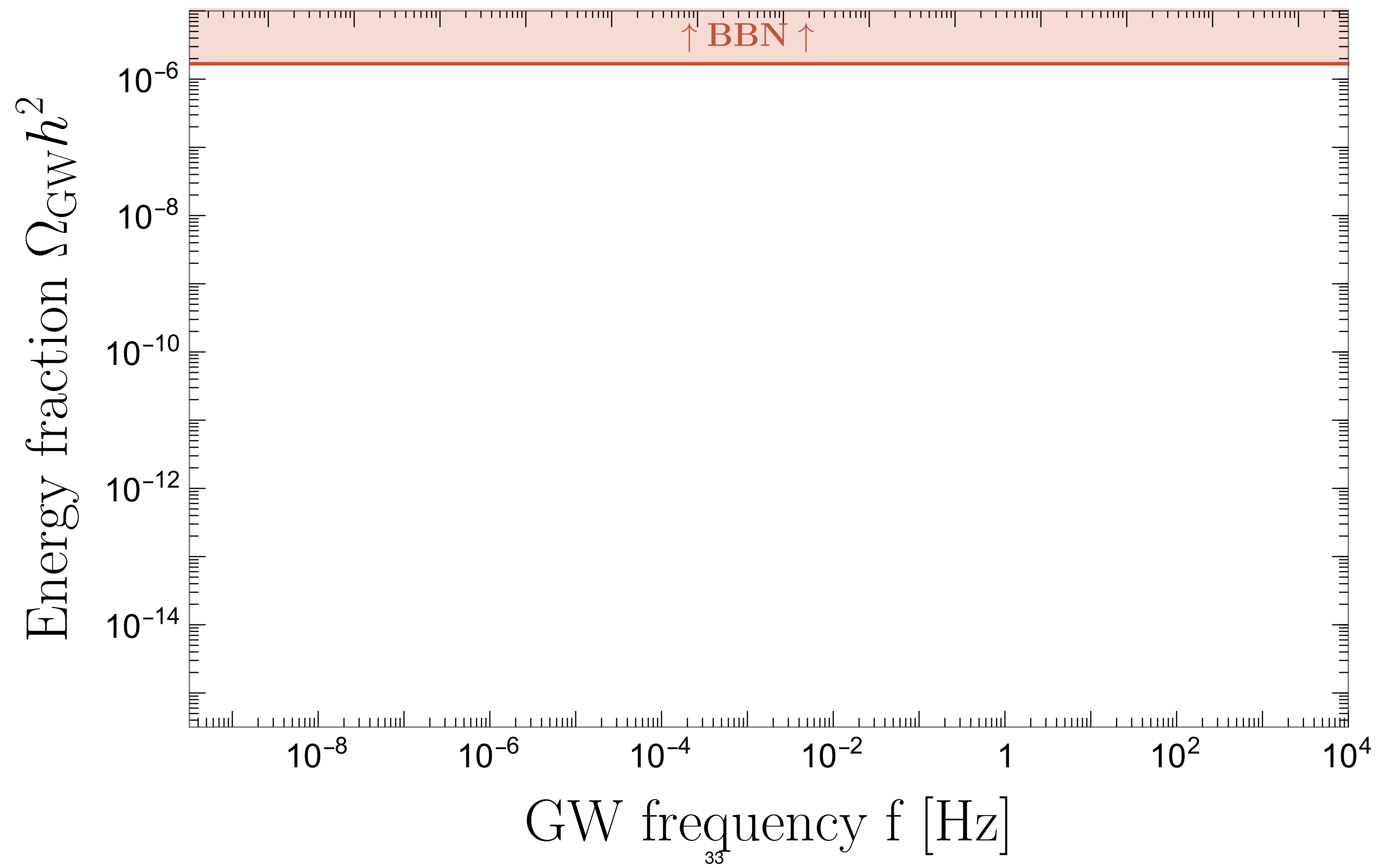
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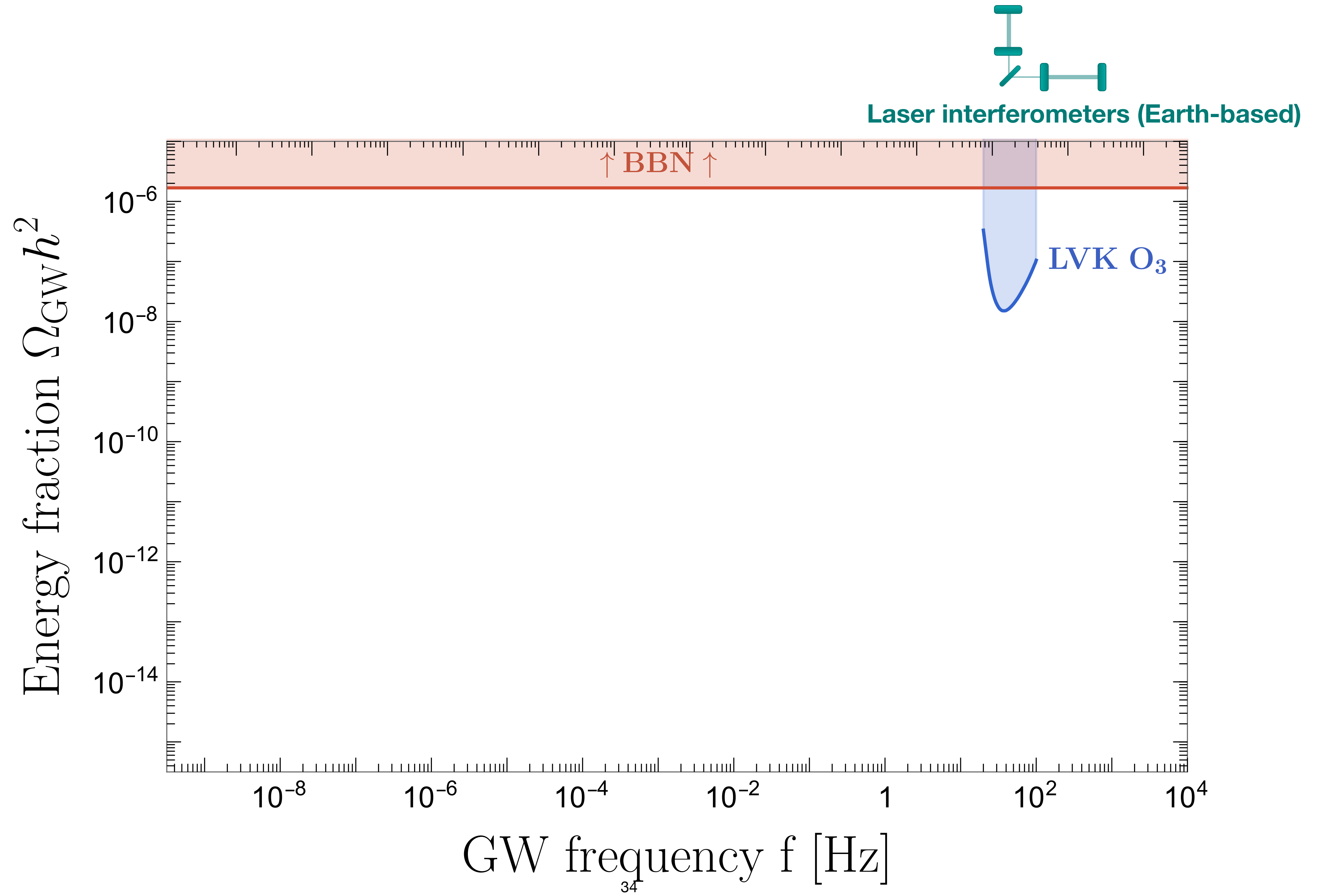
What is the PTA
signal ?

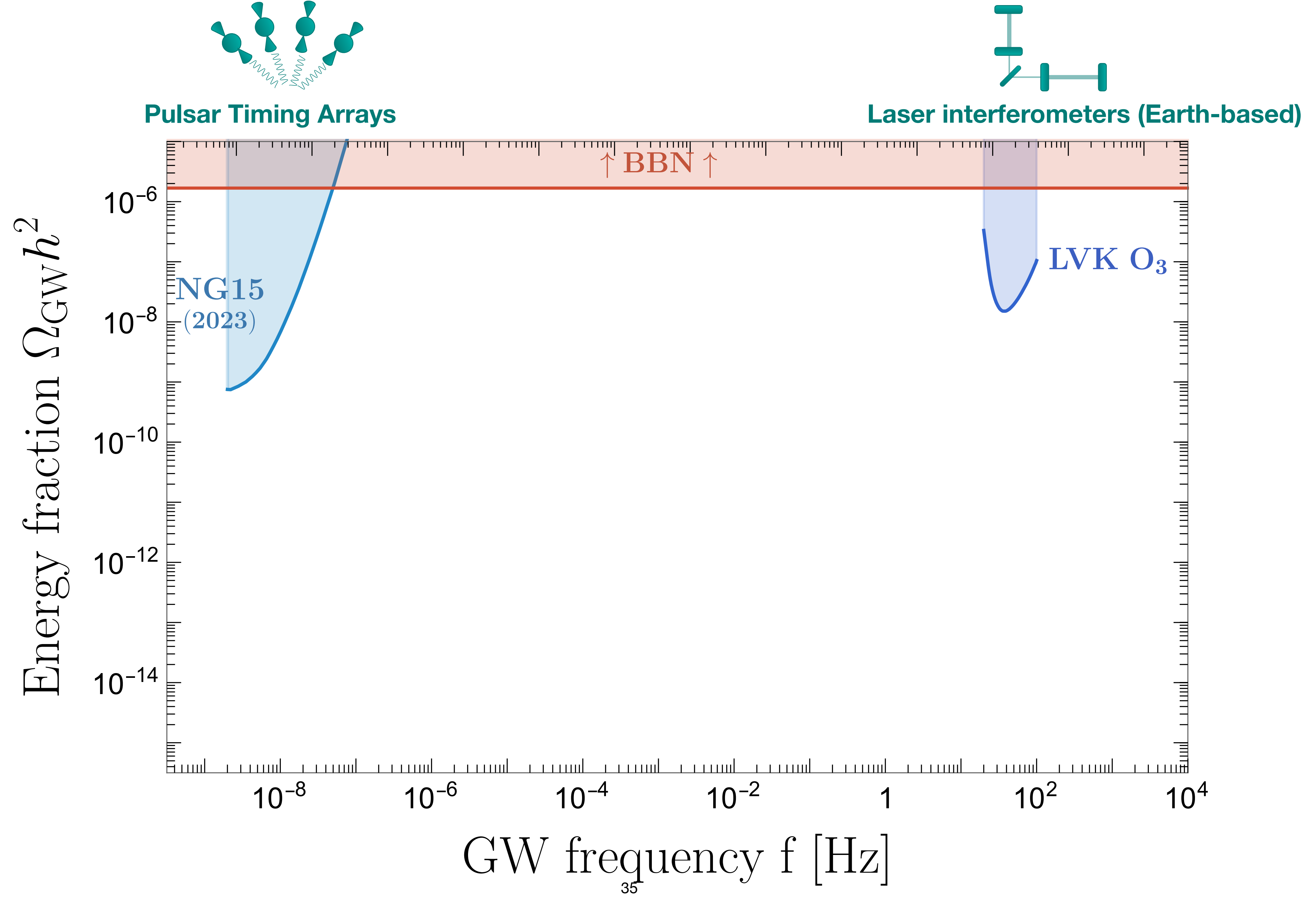


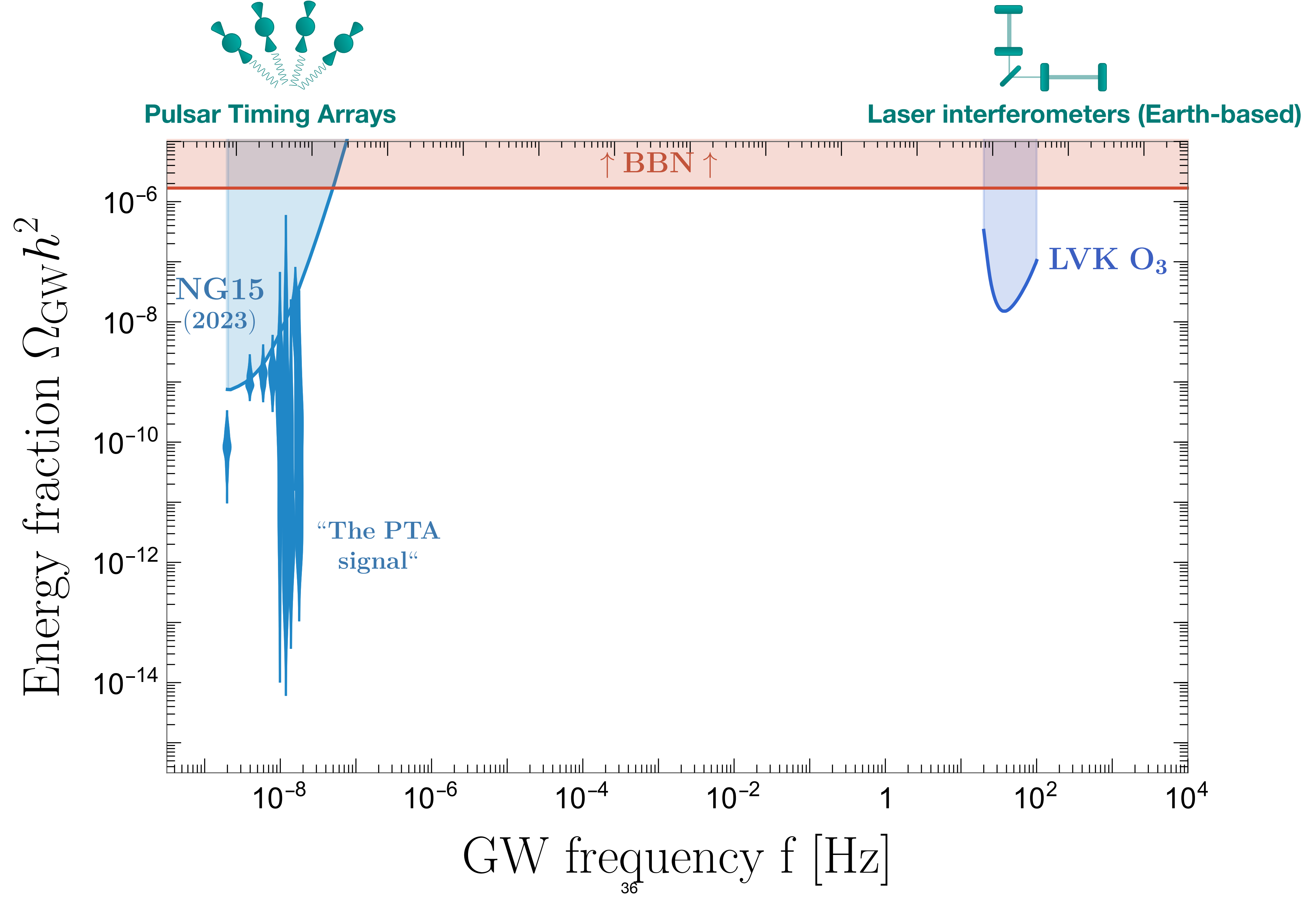
Plan of the talk

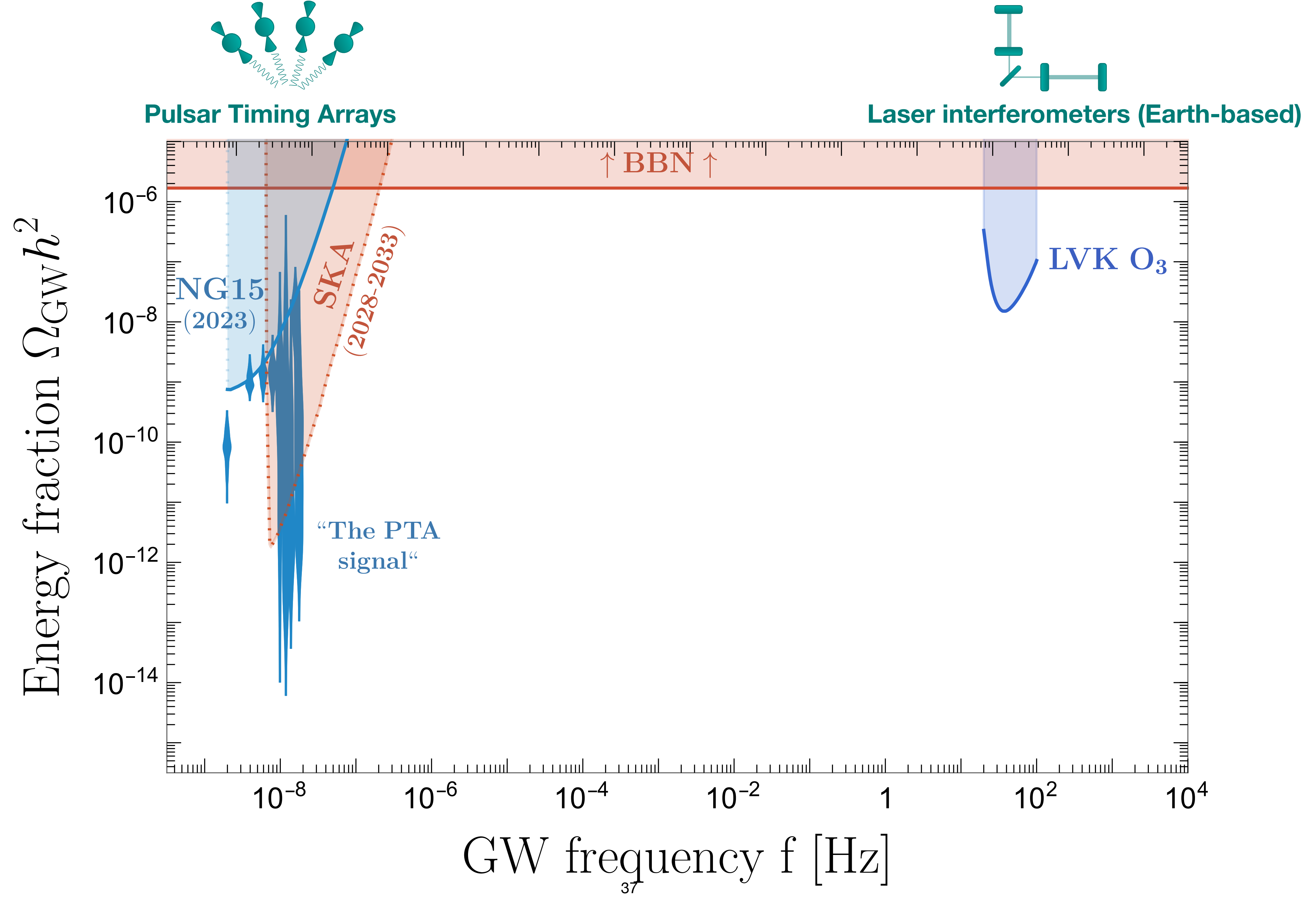


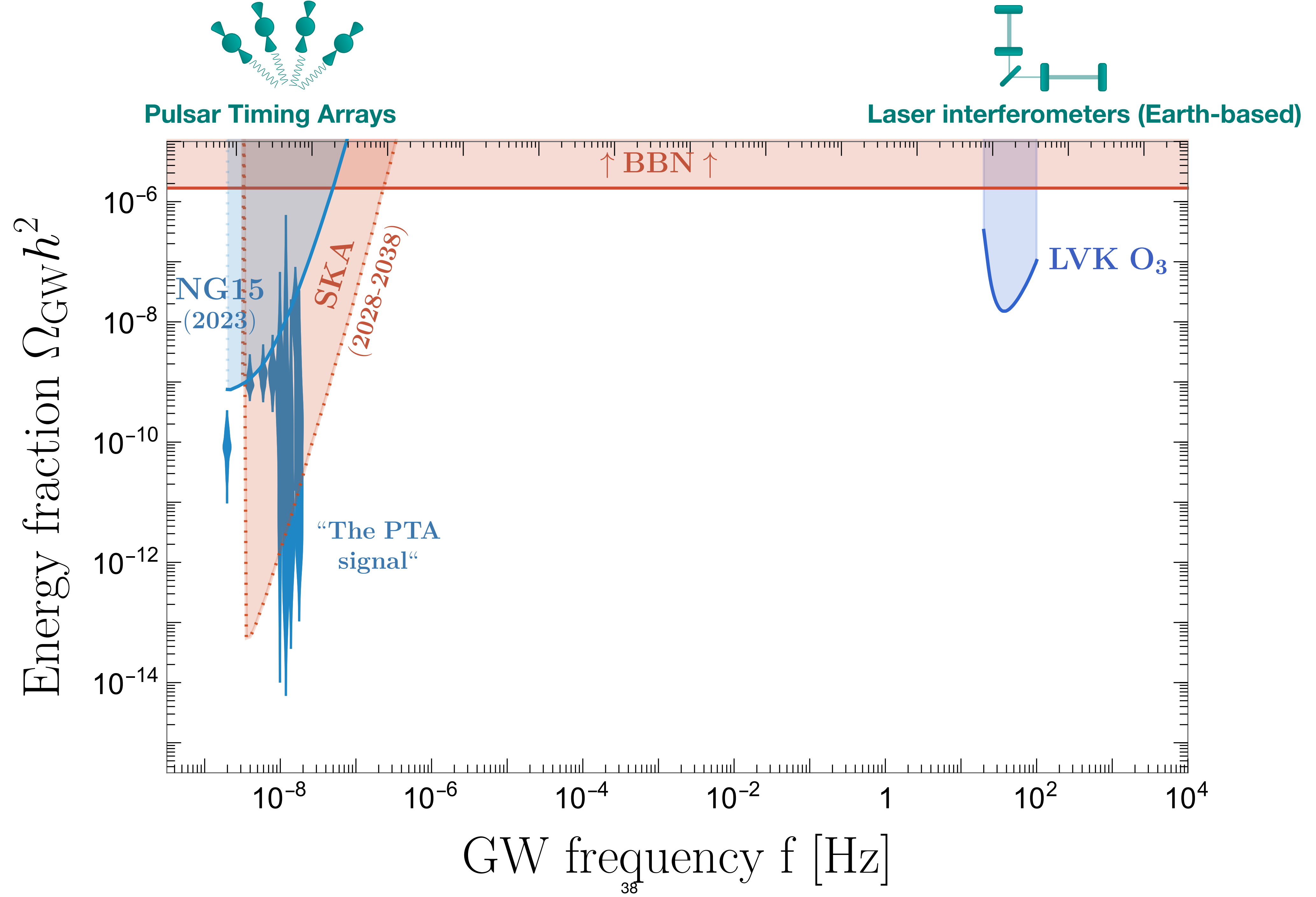


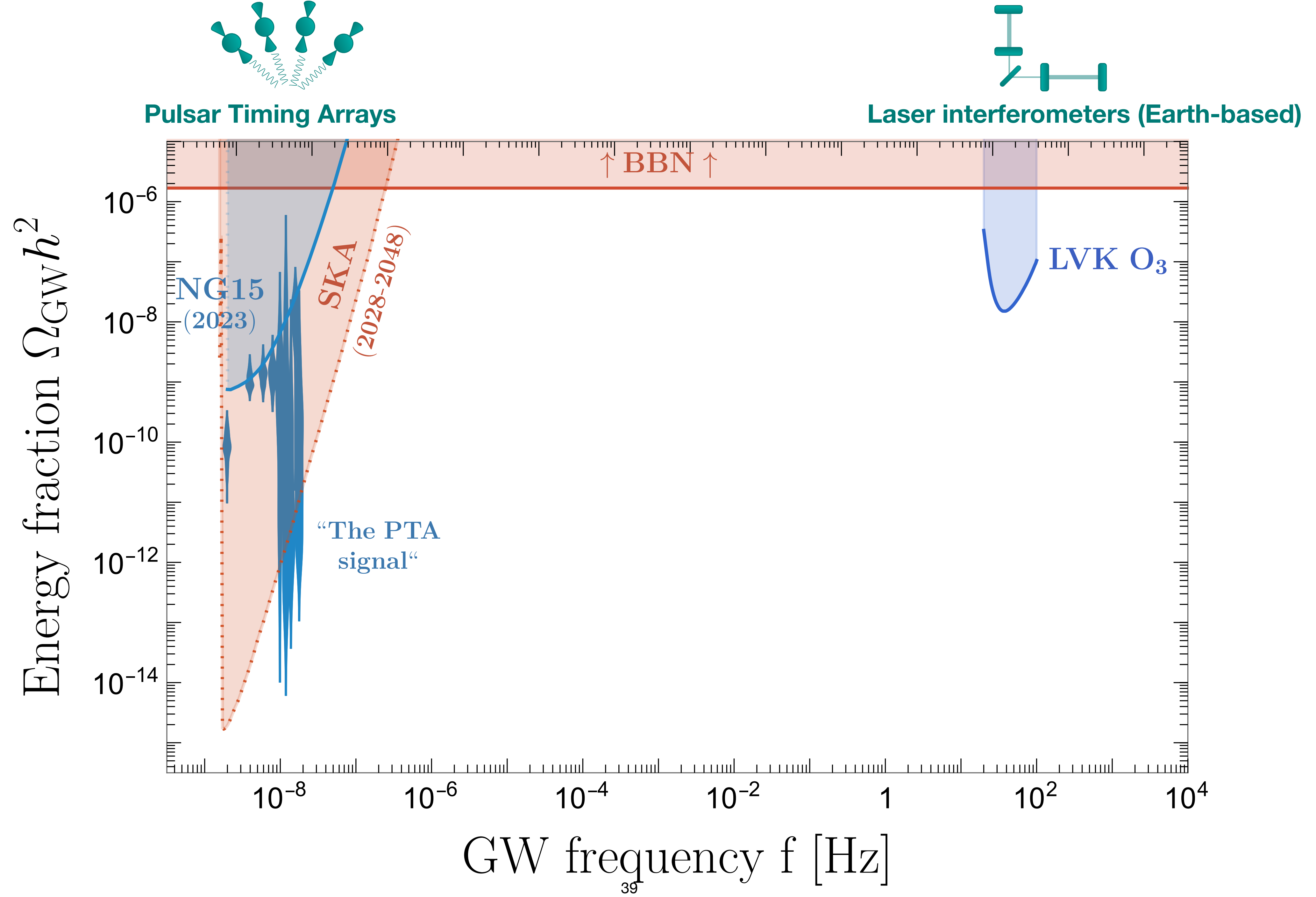


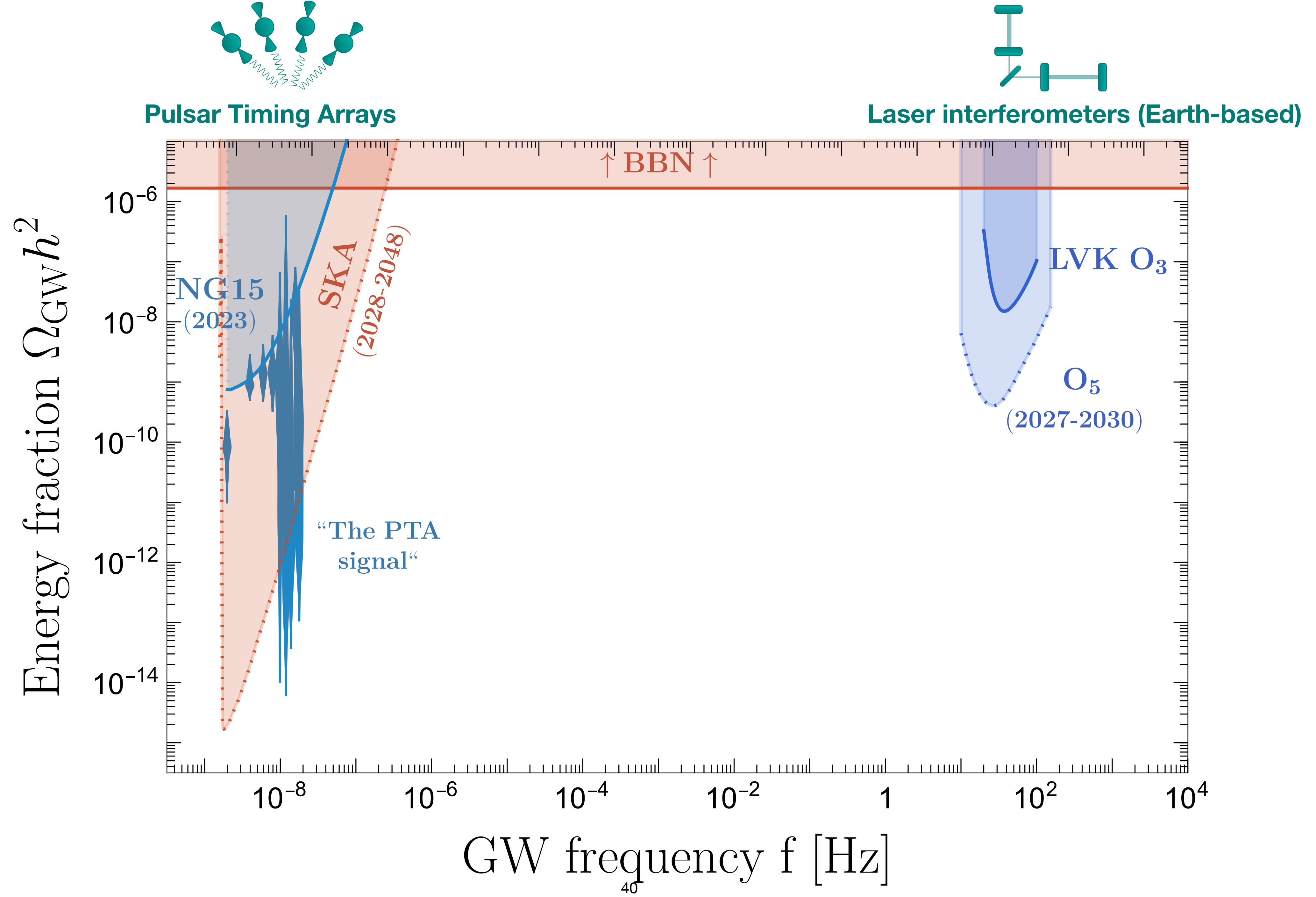


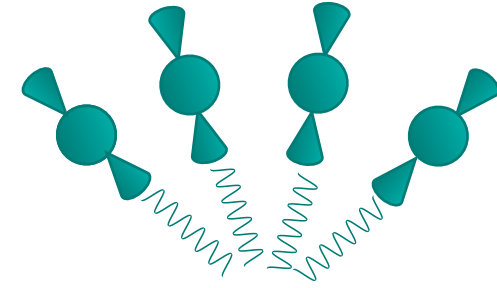




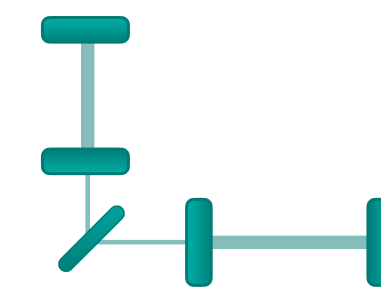




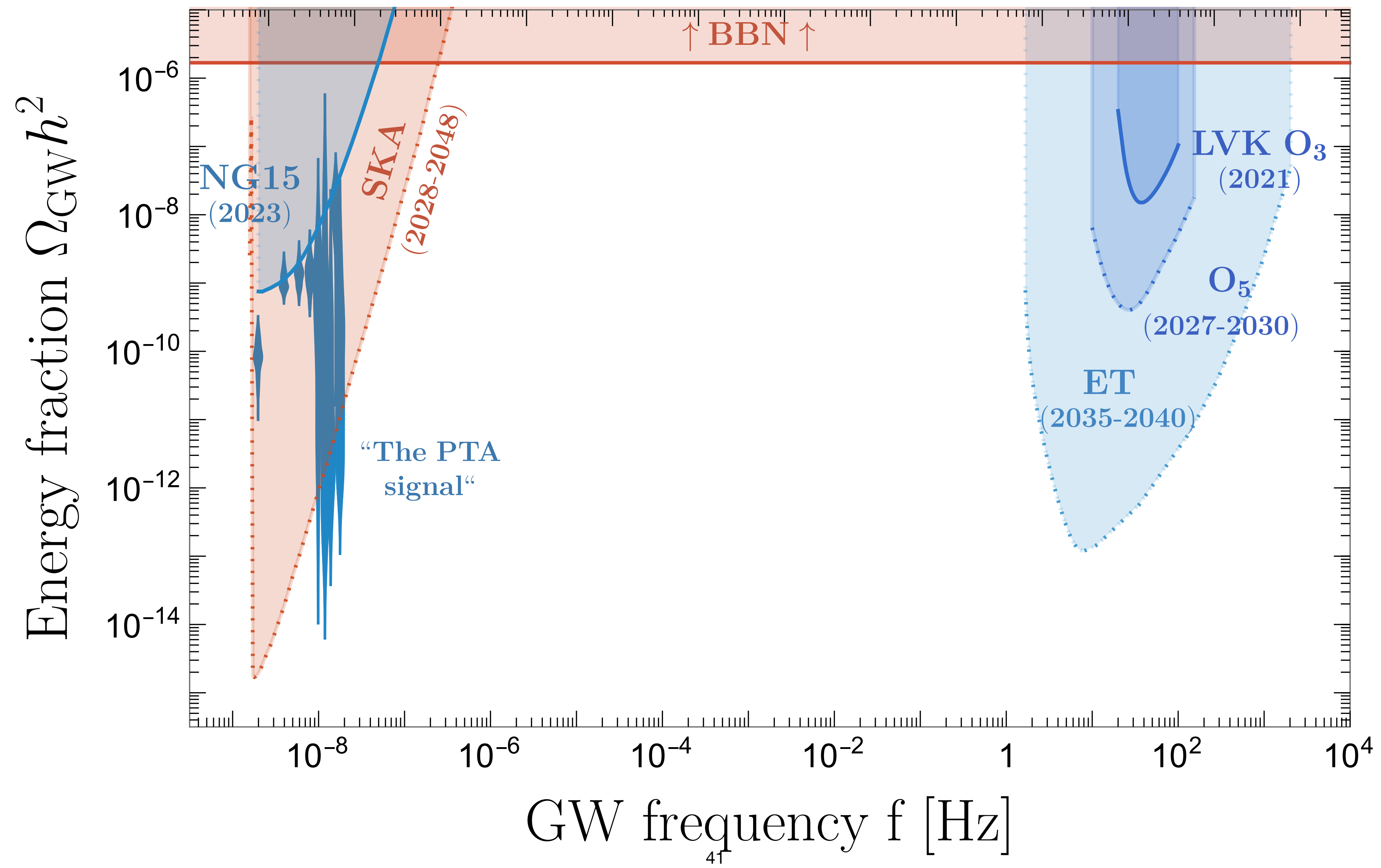


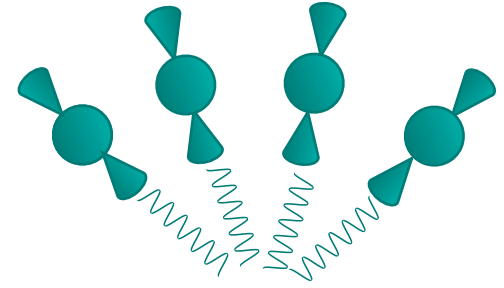


Pulsar Timing Arrays

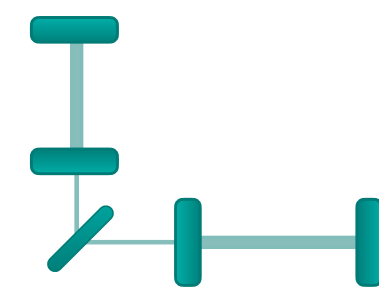


Laser interferometers (Earth-based)

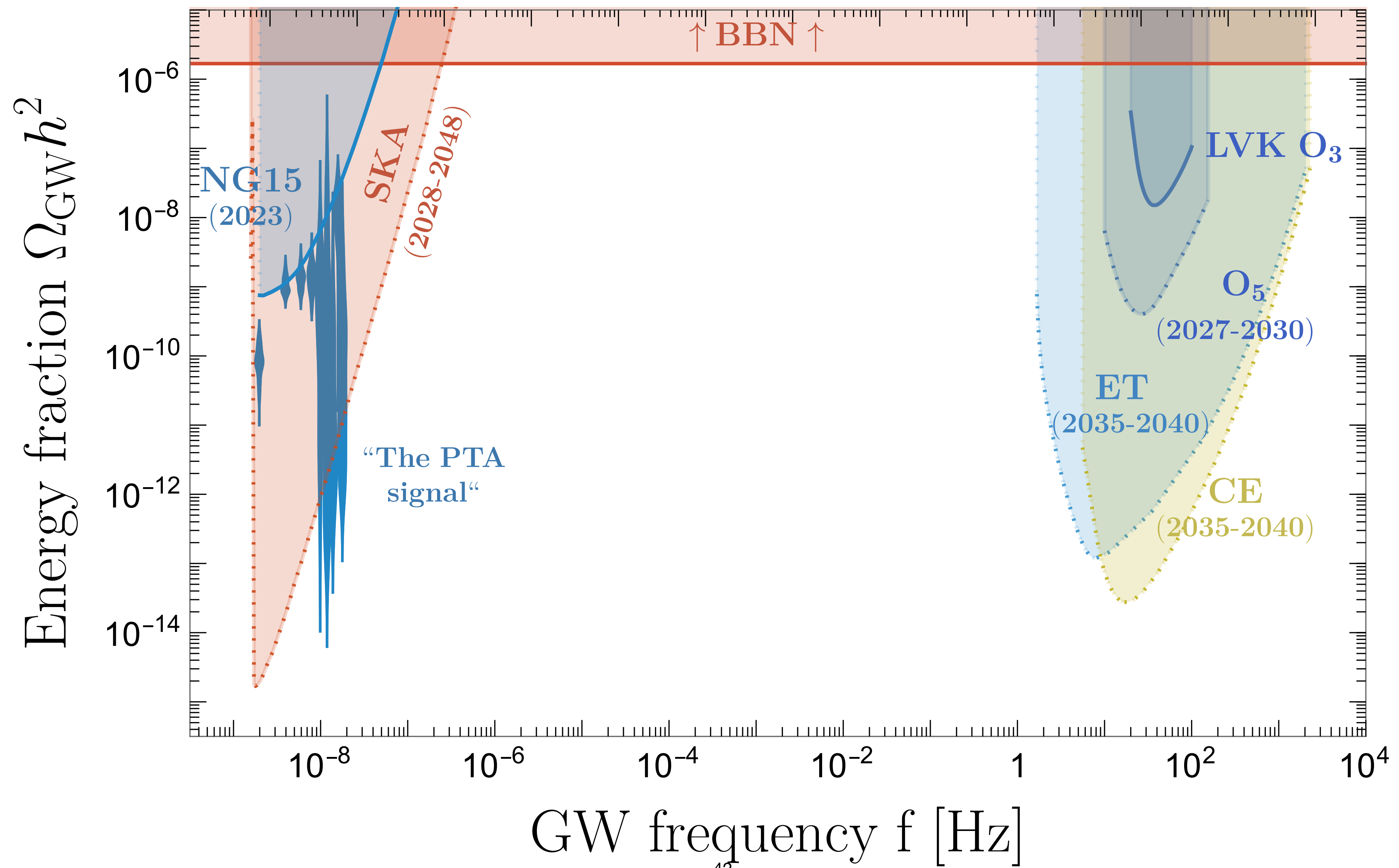


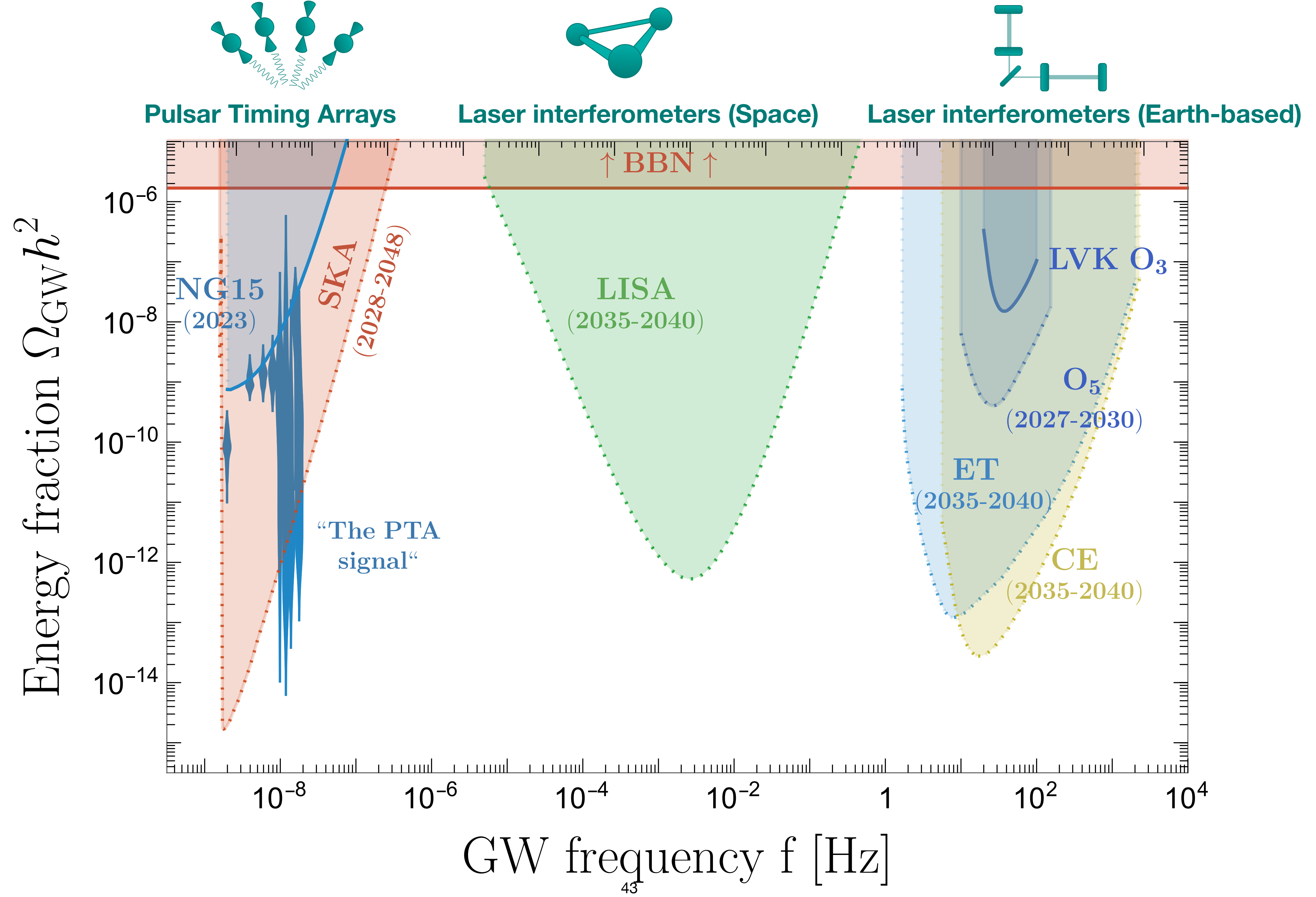


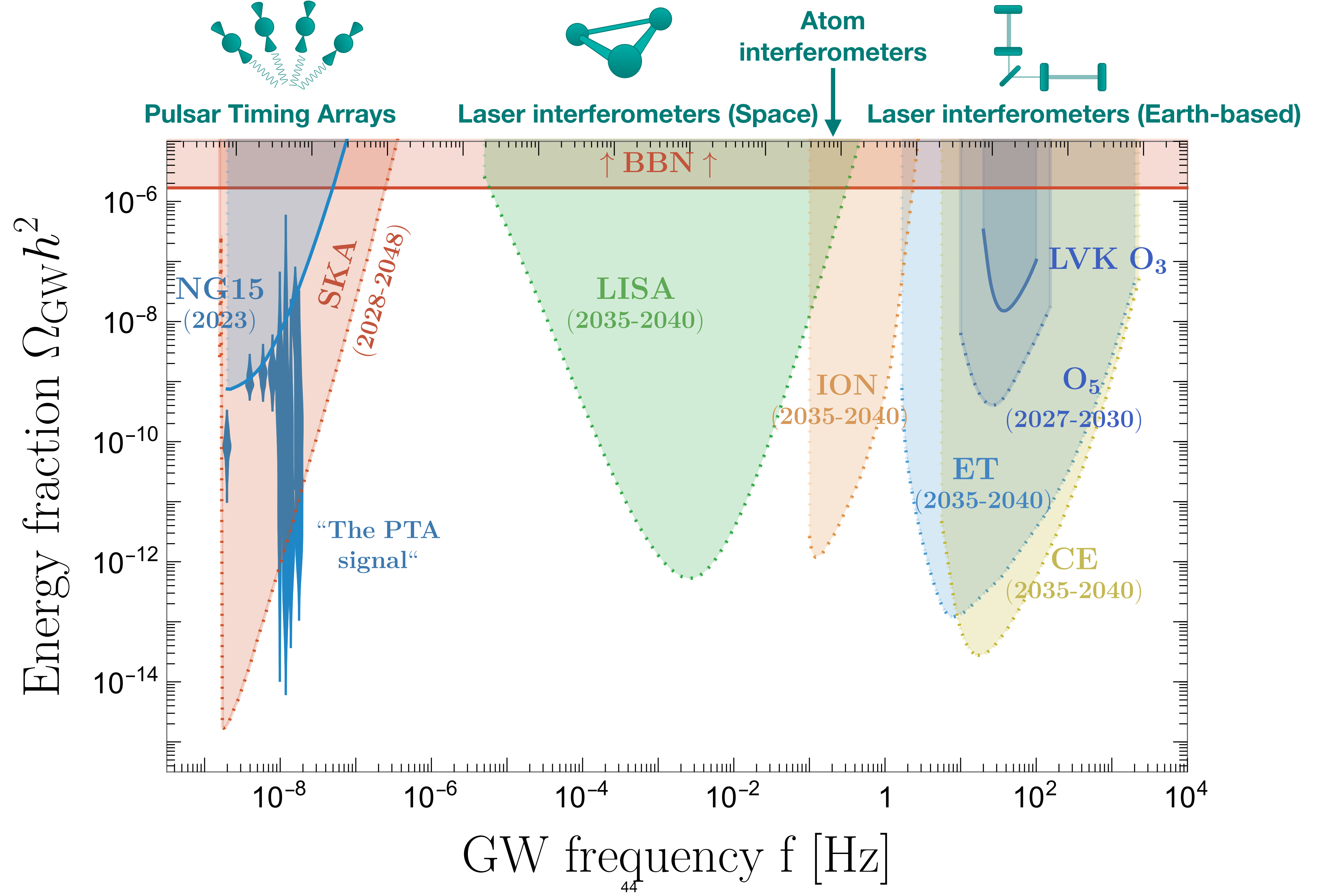
Pulsar Timing Arrays

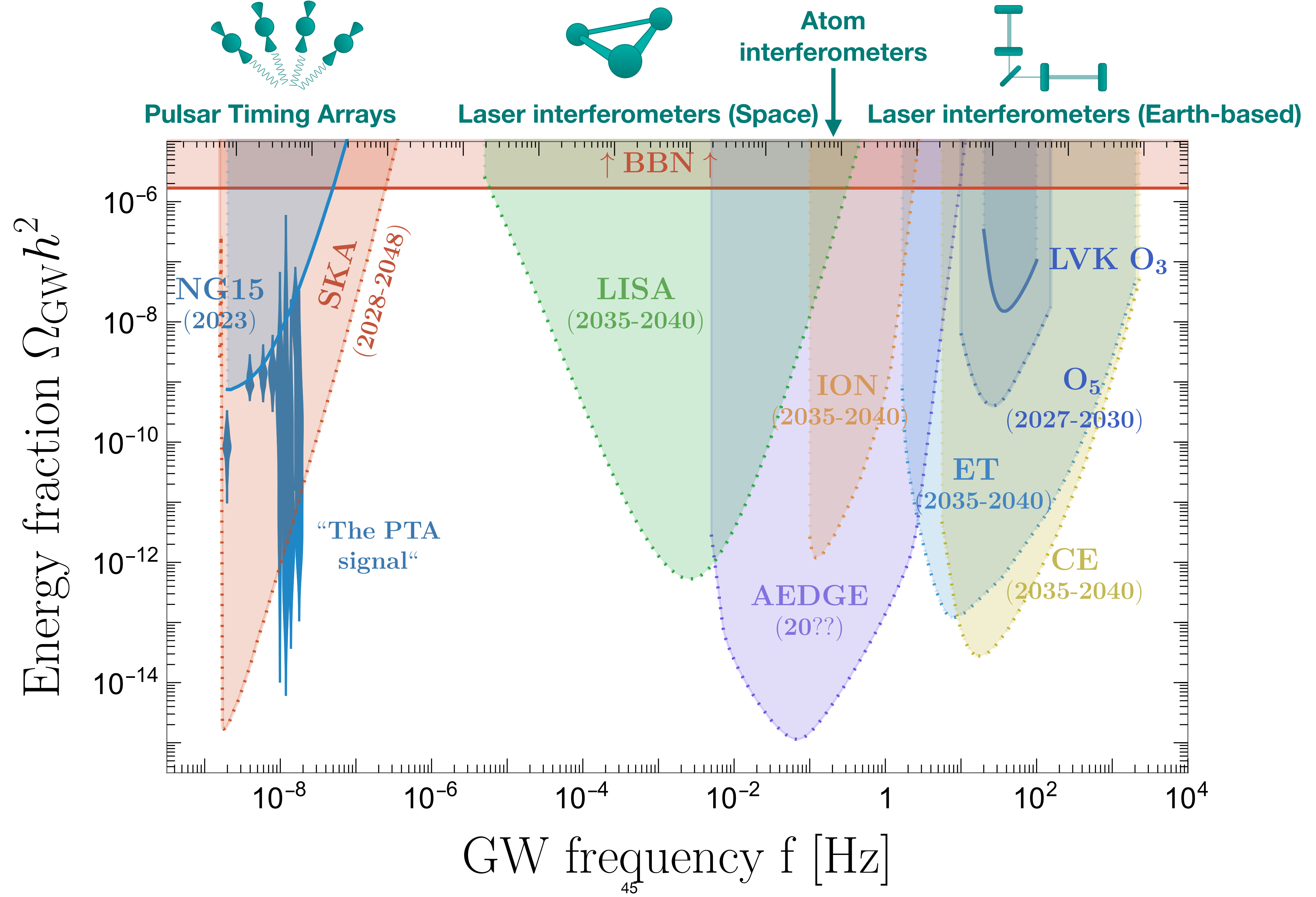


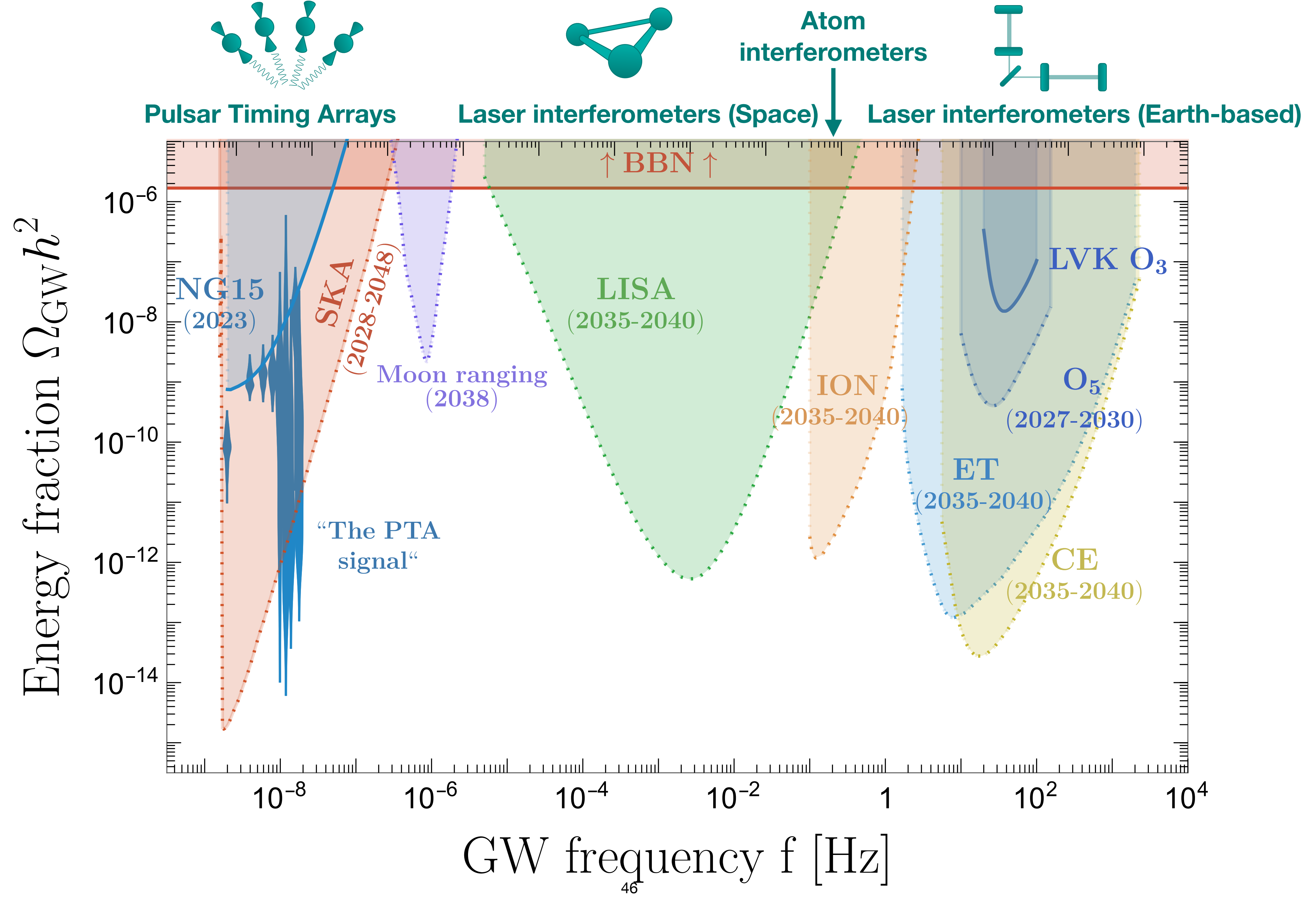
Laser interferometers (Earth-based)

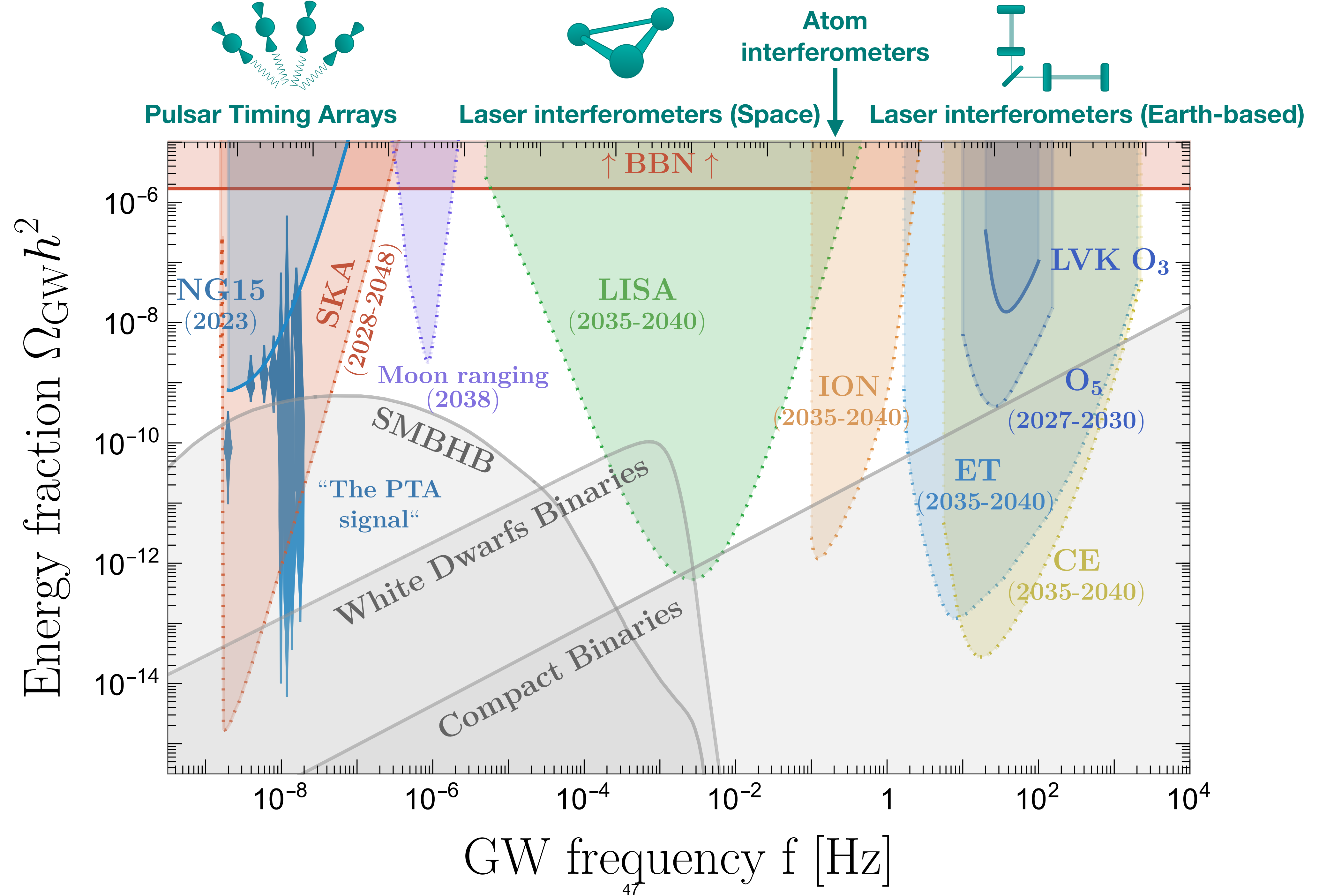




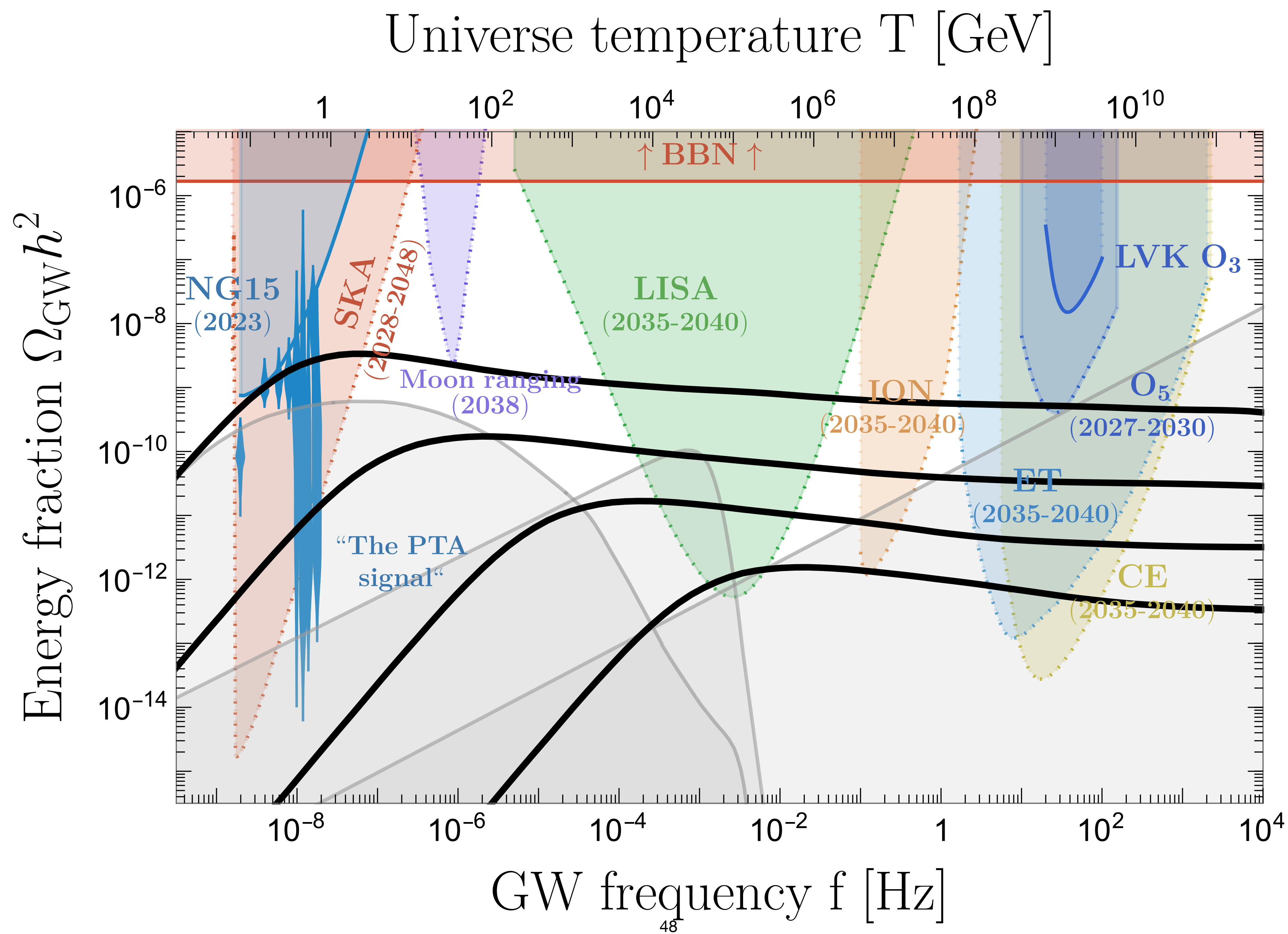
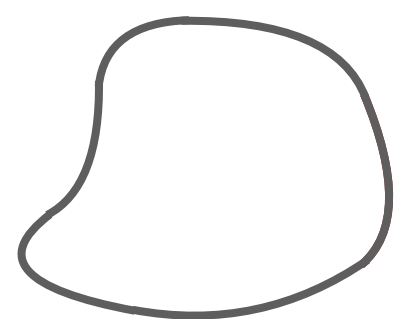




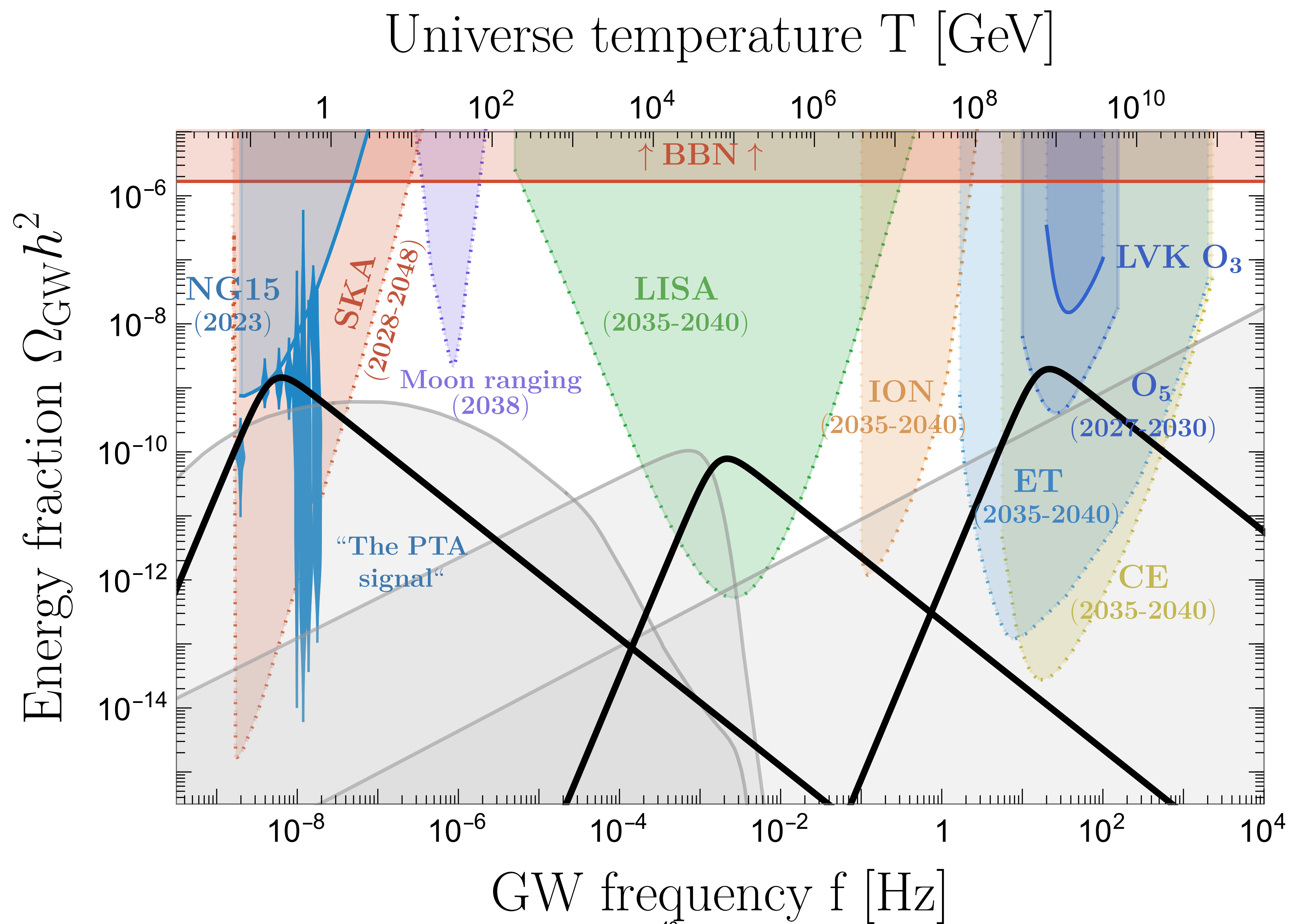
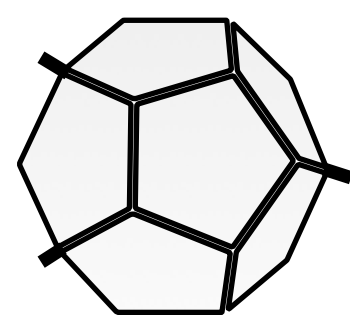




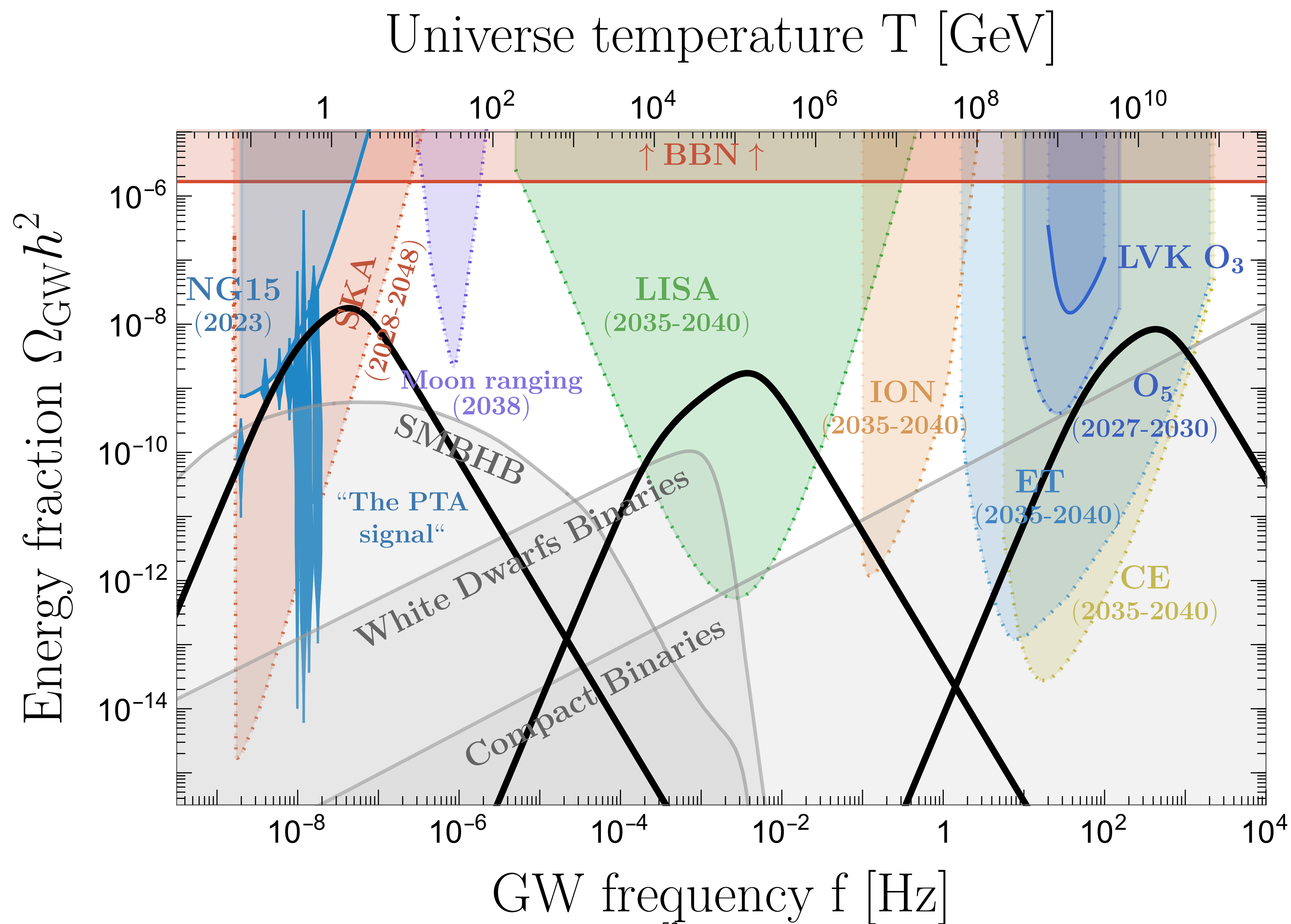
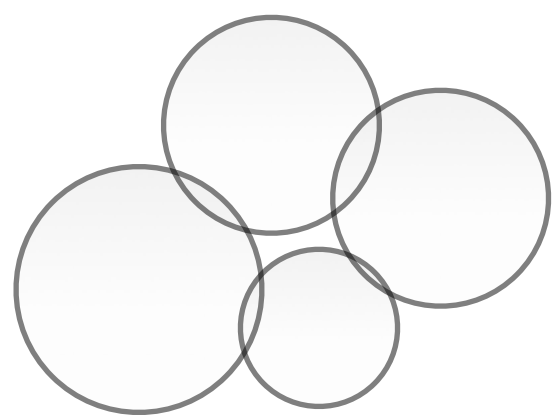
Cosmic strings



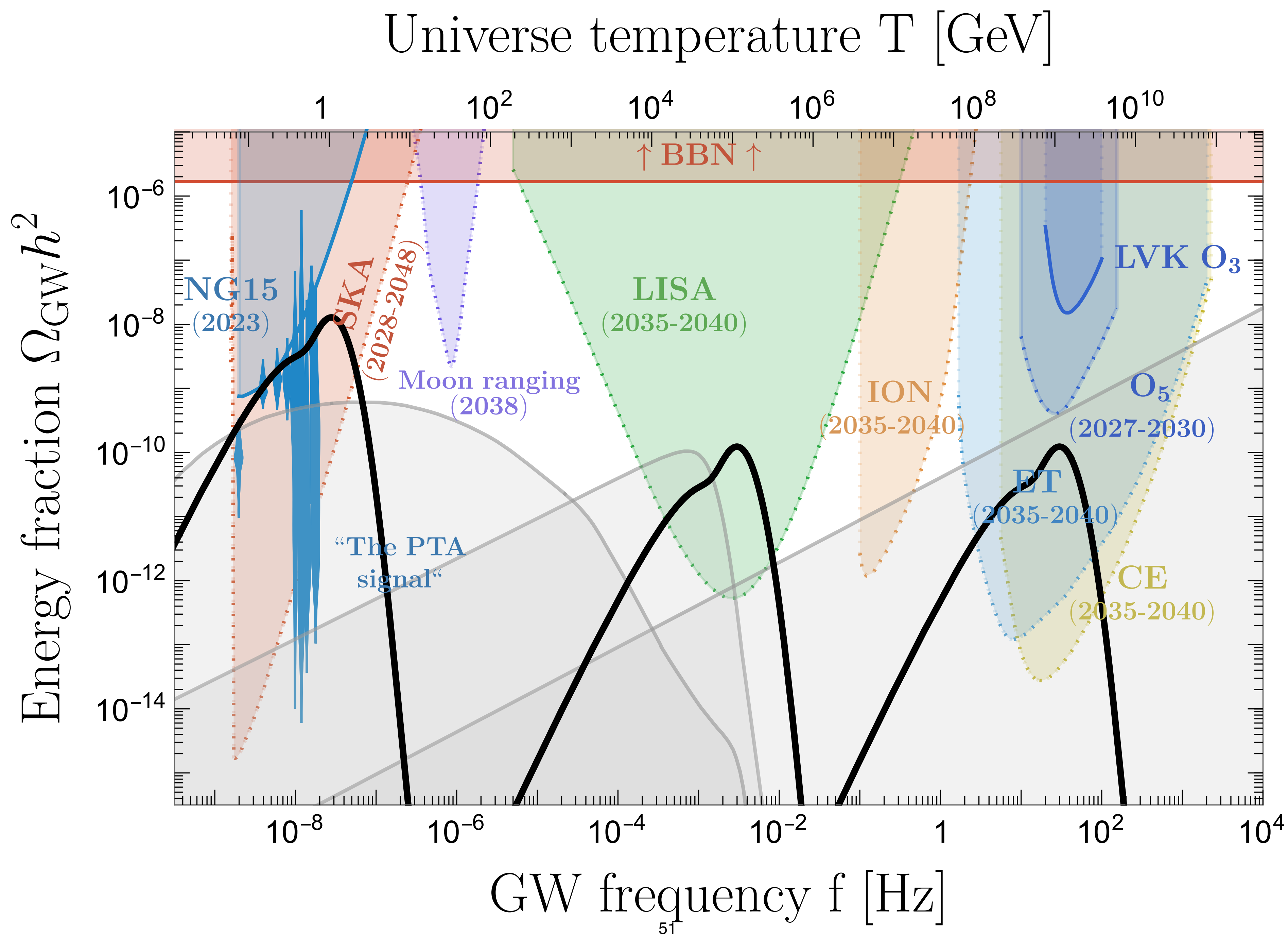
Domain walls

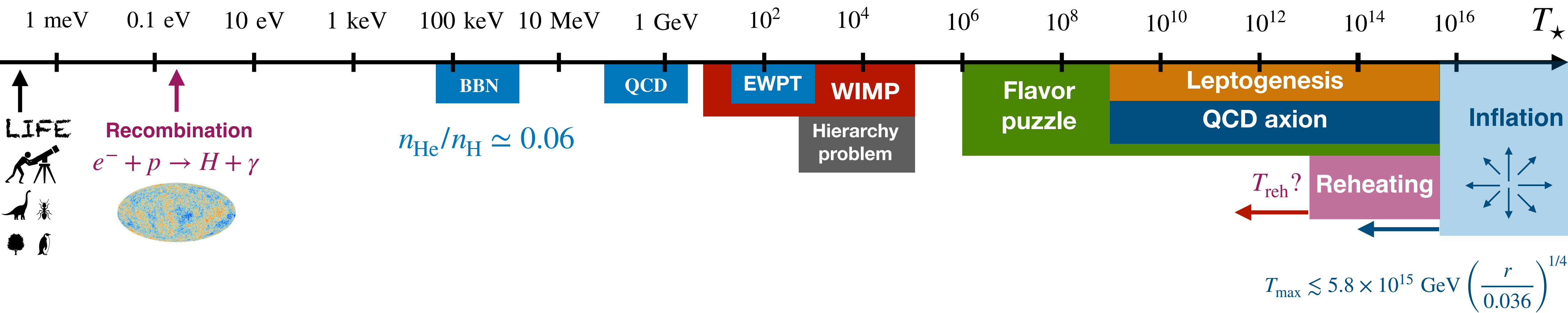


**First-order
phase transition**

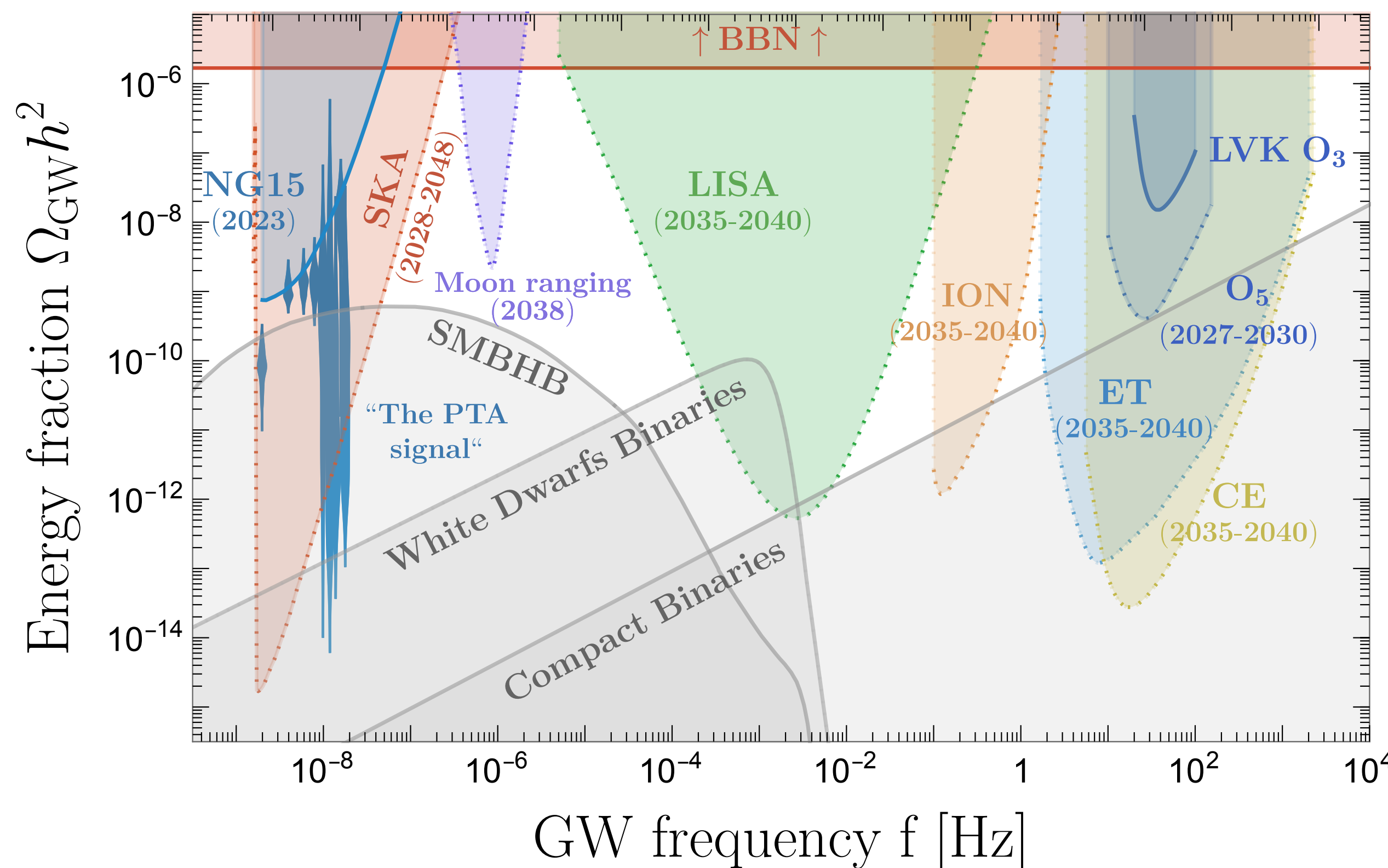


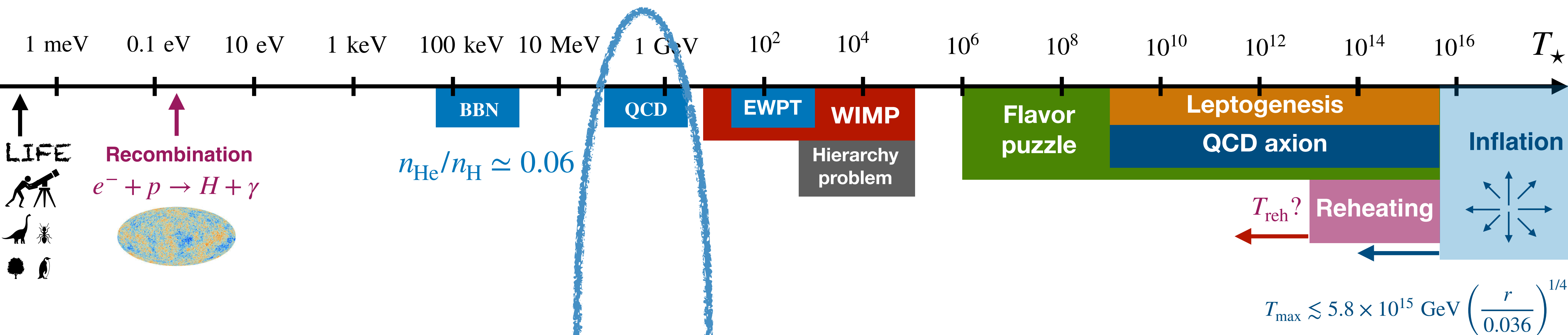
GW frequency f [Hz]





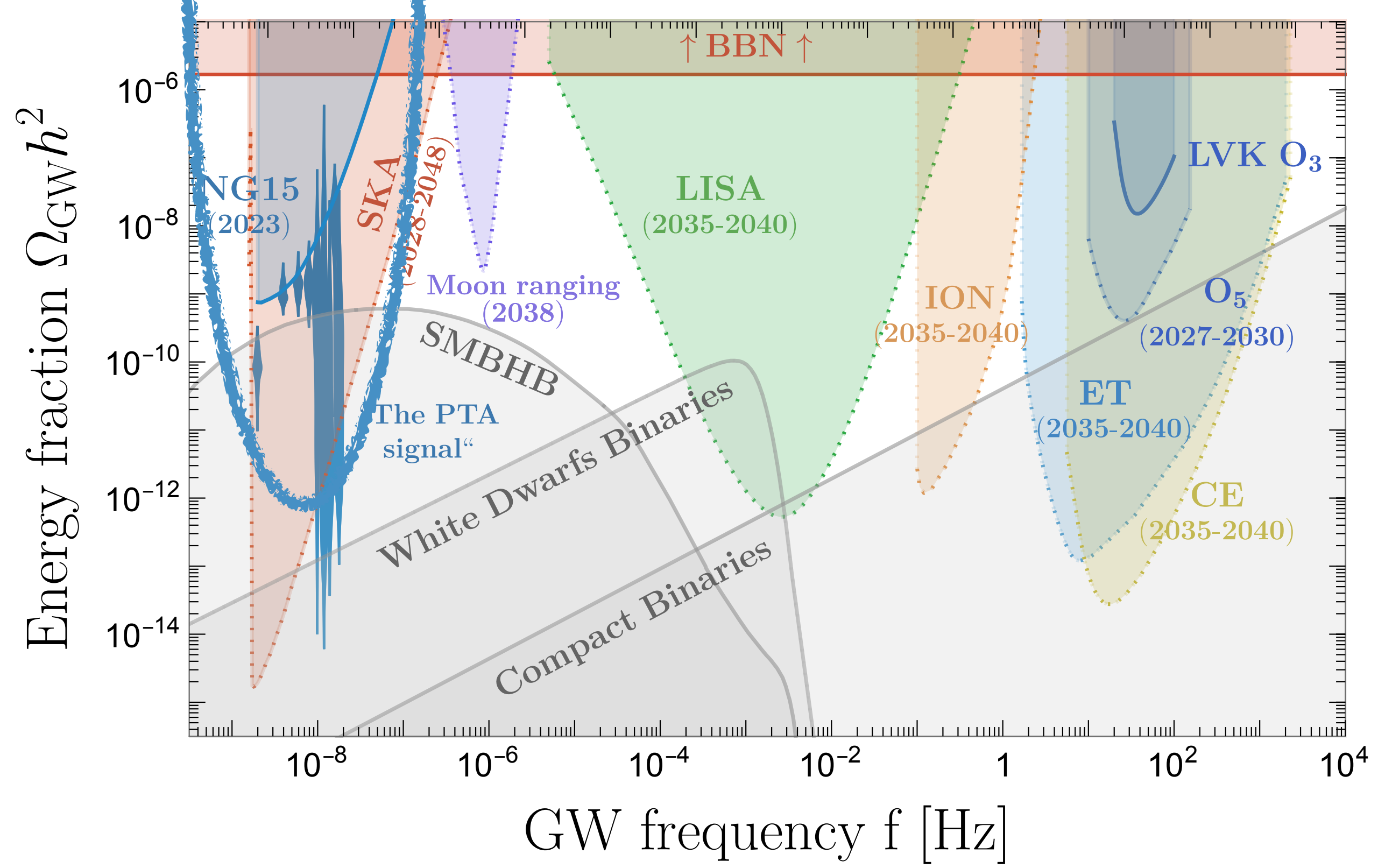
Bicep/Keck (2110.00483)

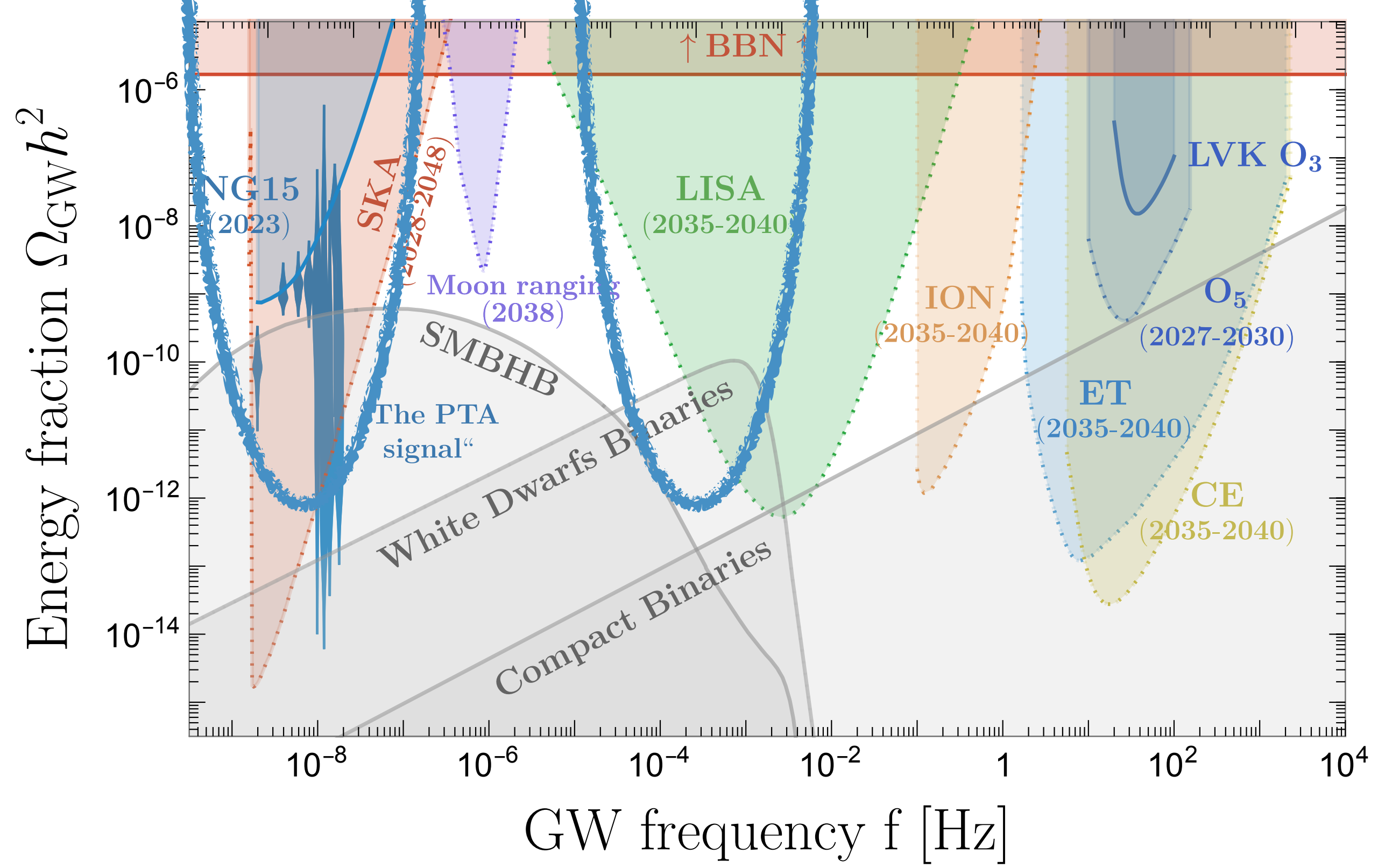
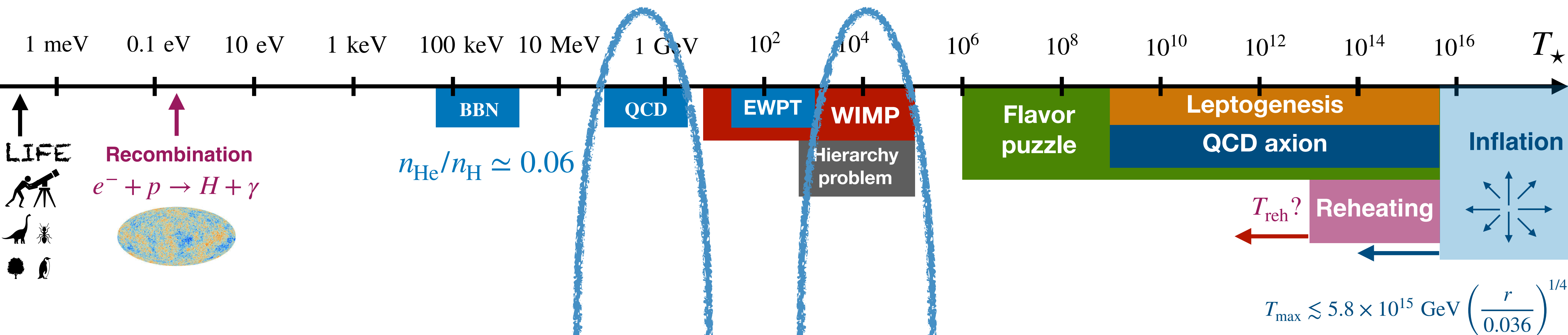




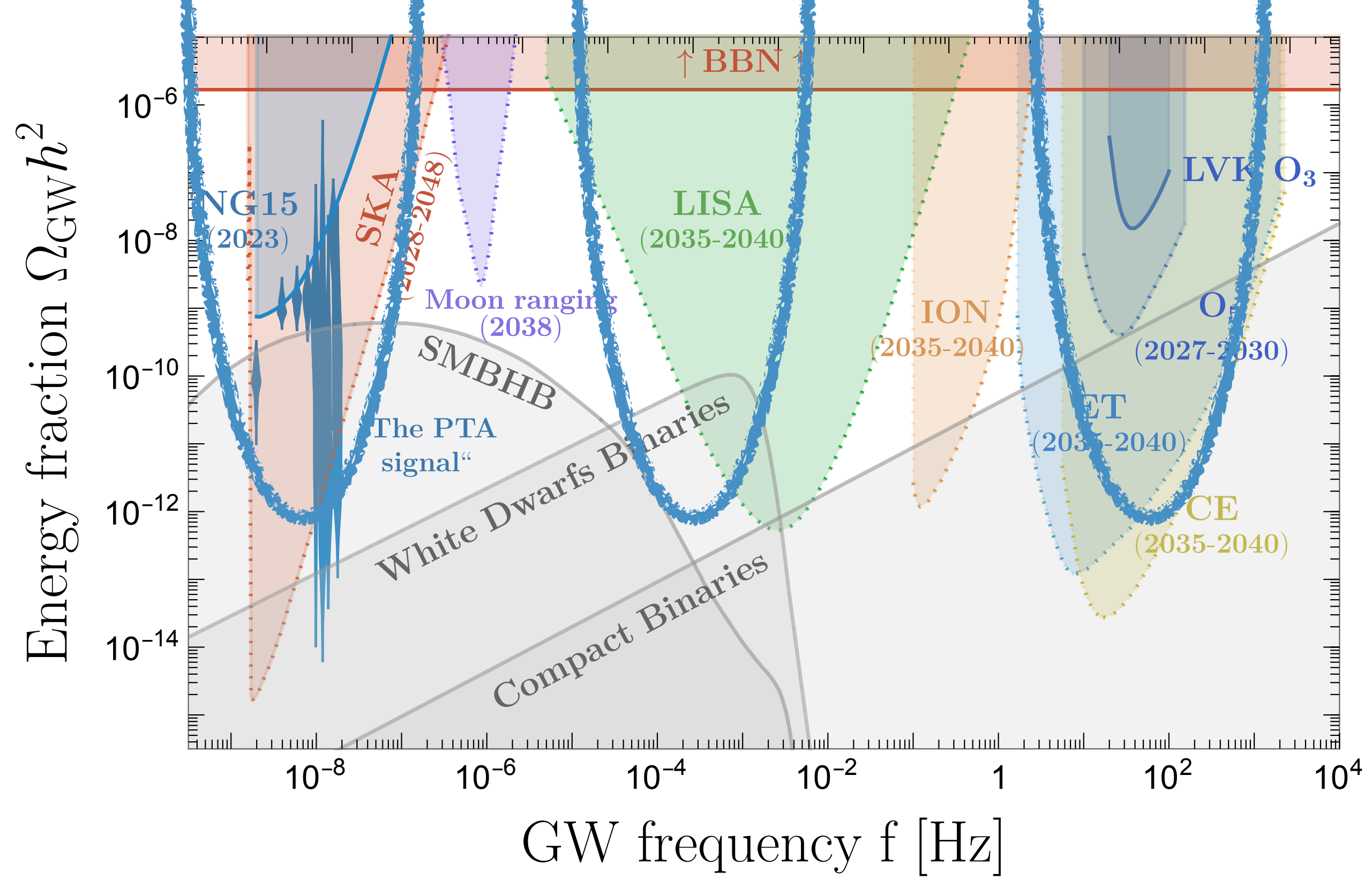
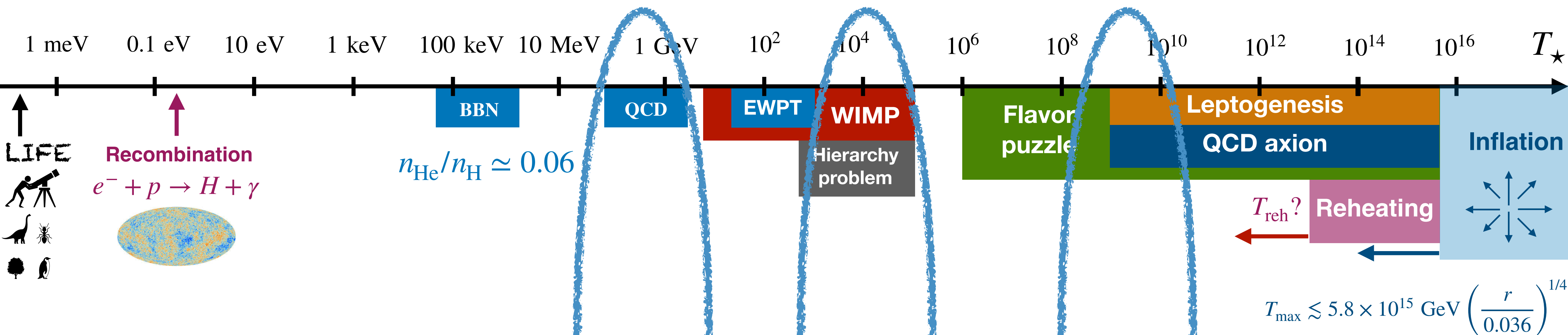
$$T_{\text{max}} \lesssim 5.8 \times 10^{15} \text{ GeV} \left(\frac{r}{0.036} \right)^{1/4}$$

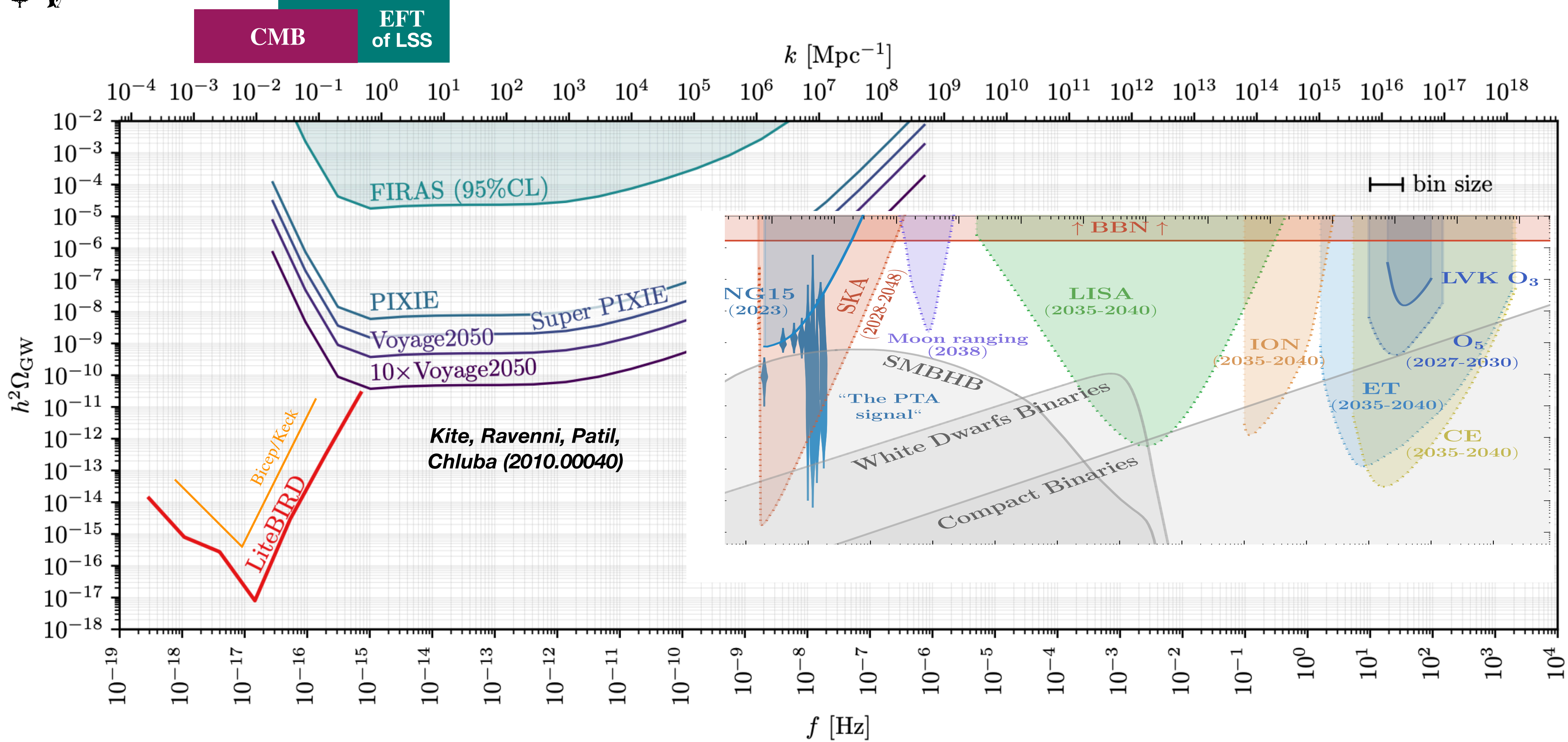
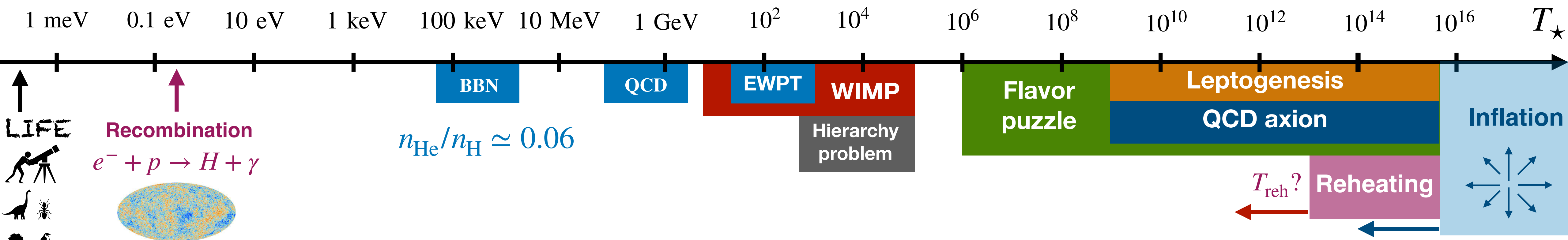
Bicep/Keck (2110.00483)





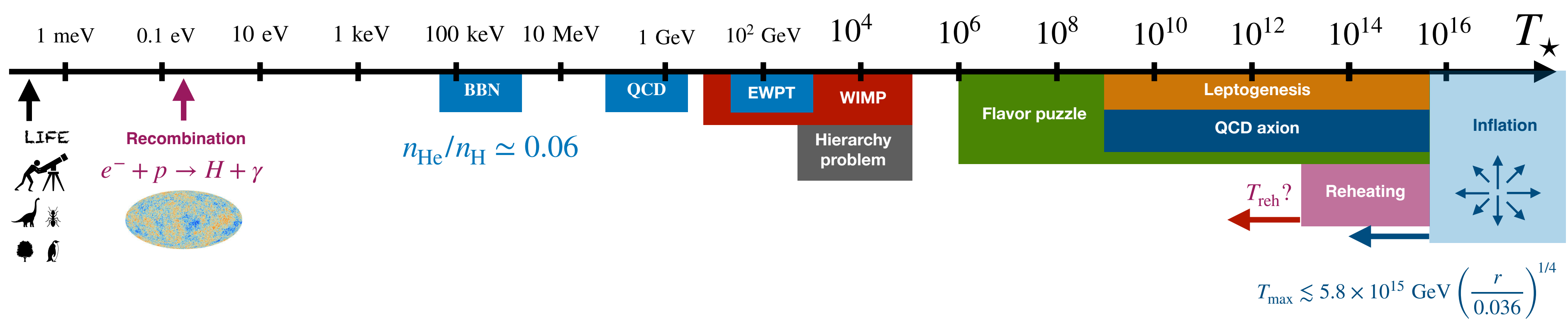
Bicep/Keck (2110.00483)





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

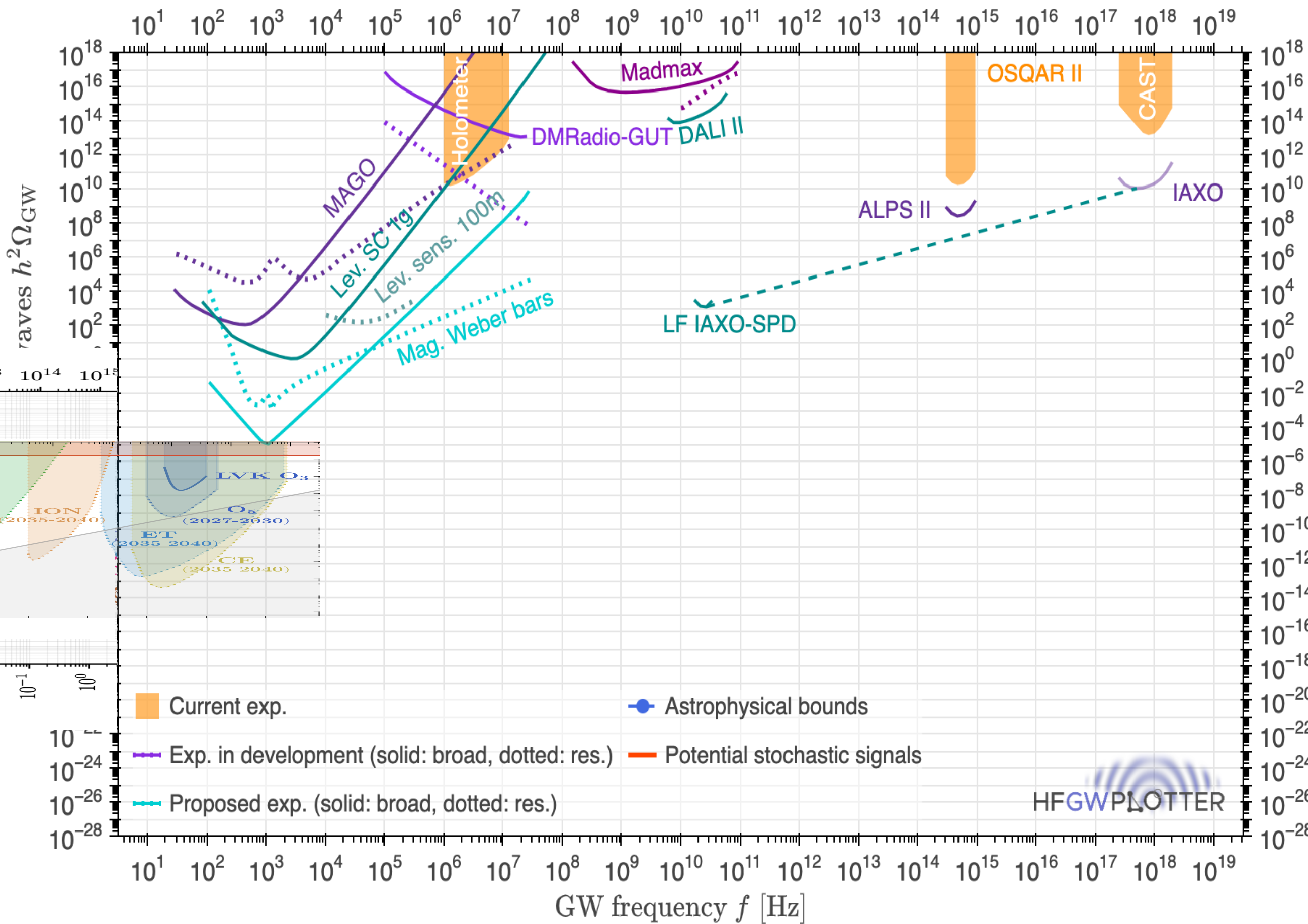
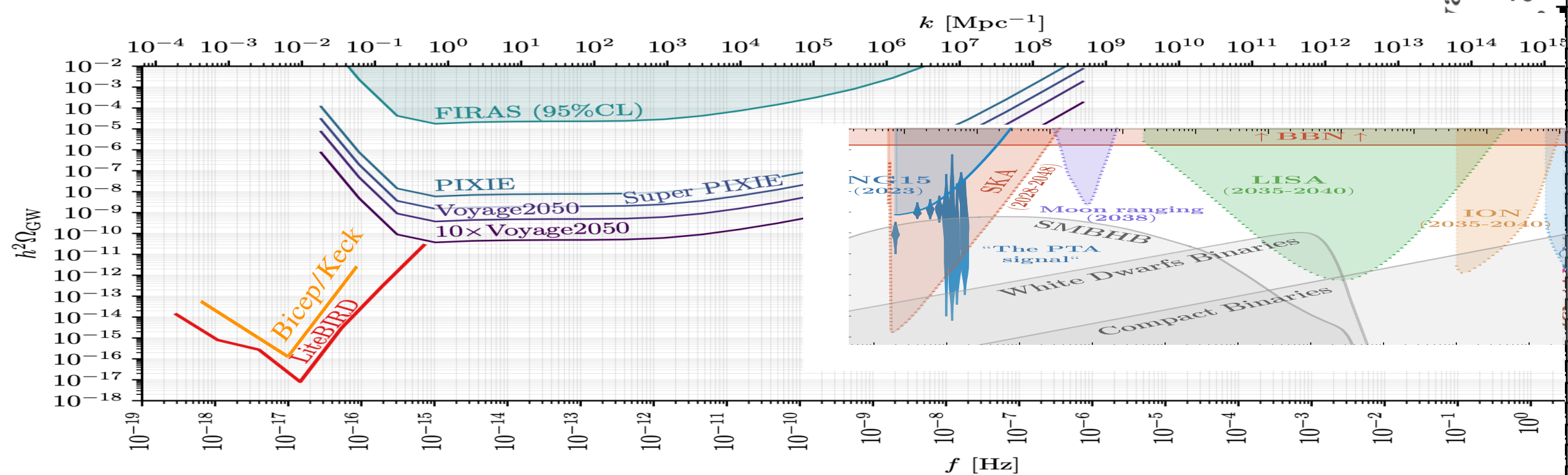
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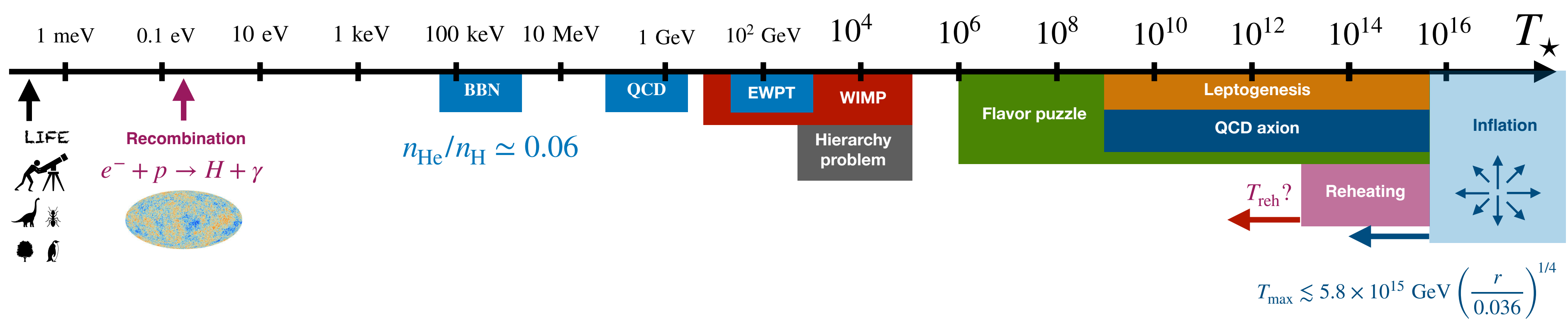
Bicep/Keck (2110.00483)

GWPlotter: Muia, Ringwald, Tamarit (2501.11723)

Kite, Ravenni, Patil, Chluba (2010.00040)



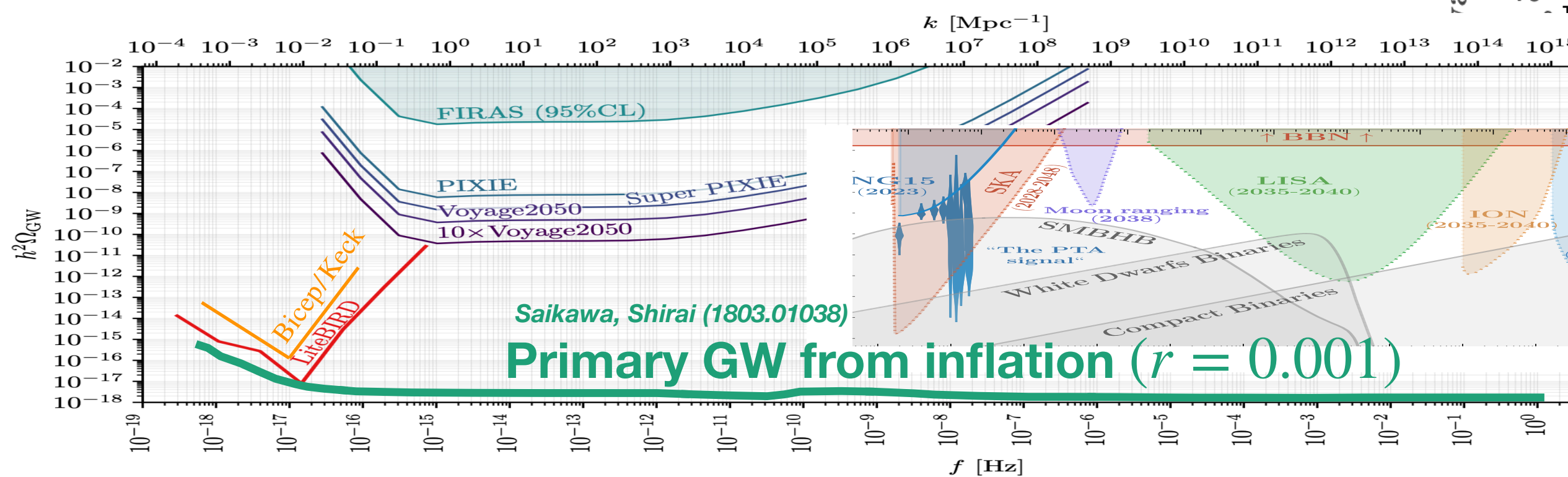
HFGWPLOTTER



Bicep/Keck (2110.00483)

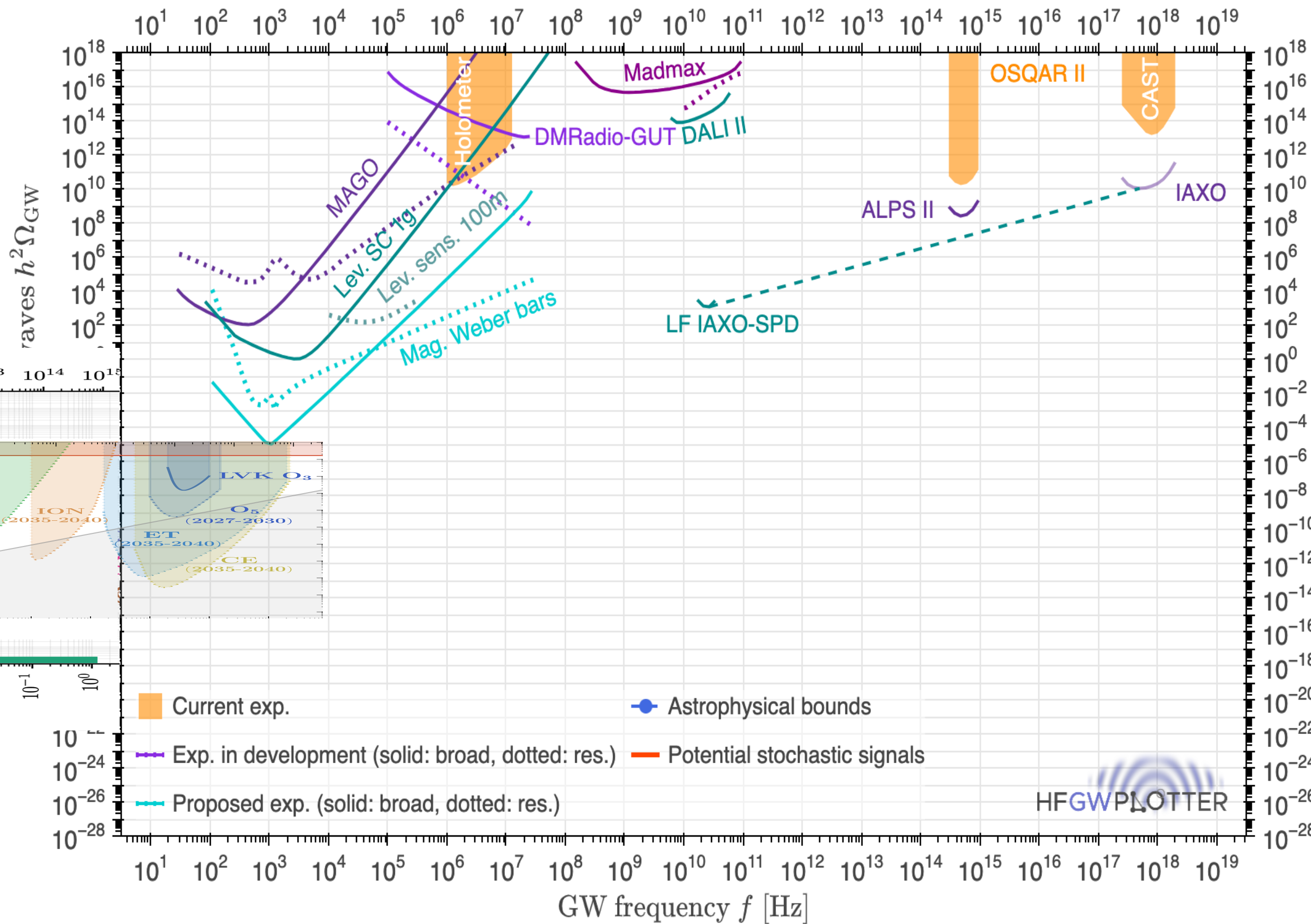
GWPlotter: Muia, Ringwald, Tamarit (2501.11723)

Kite, Ravenni, Patil, Chluba (2010.00040)

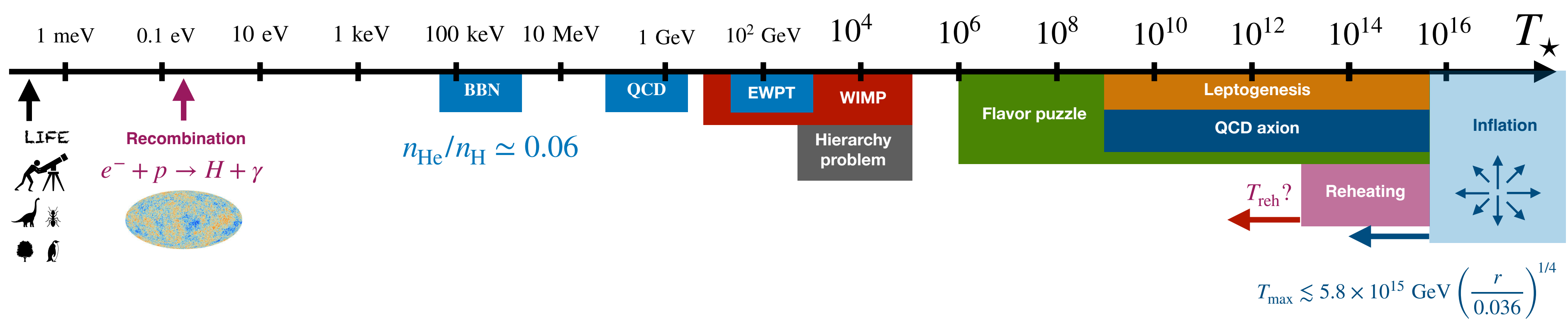


Saikawa, Shirai (1803.01038)

Primary GW from inflation ($r = 0.001$)



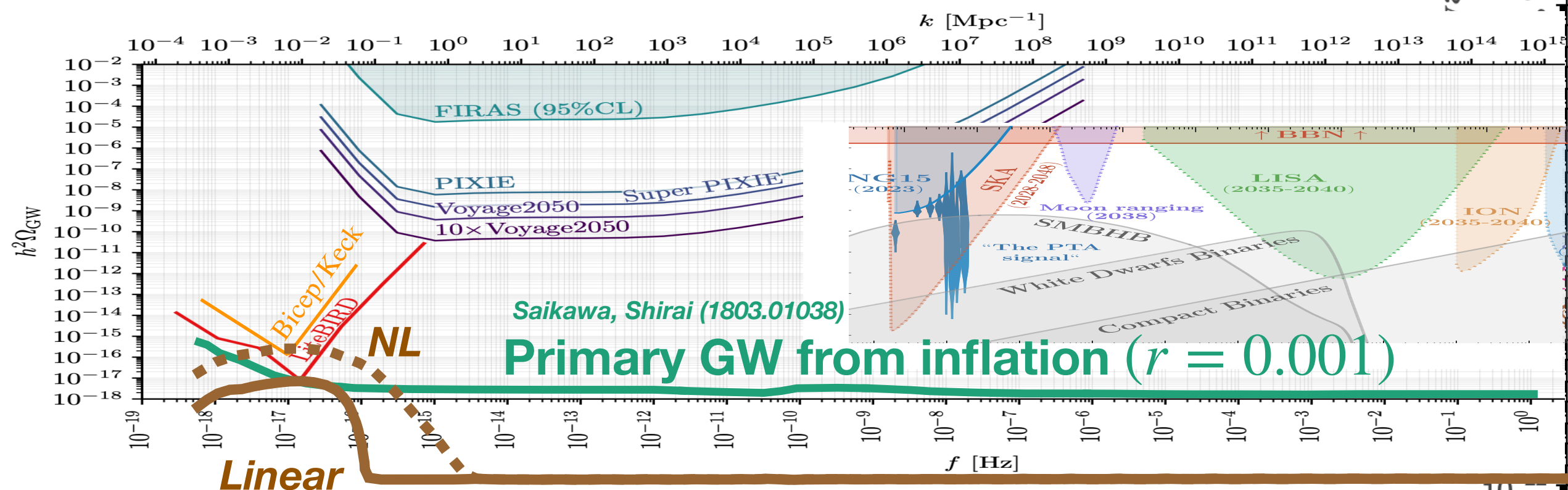
HFGW PLOTTER



Bicep/Keck (2110.00483)

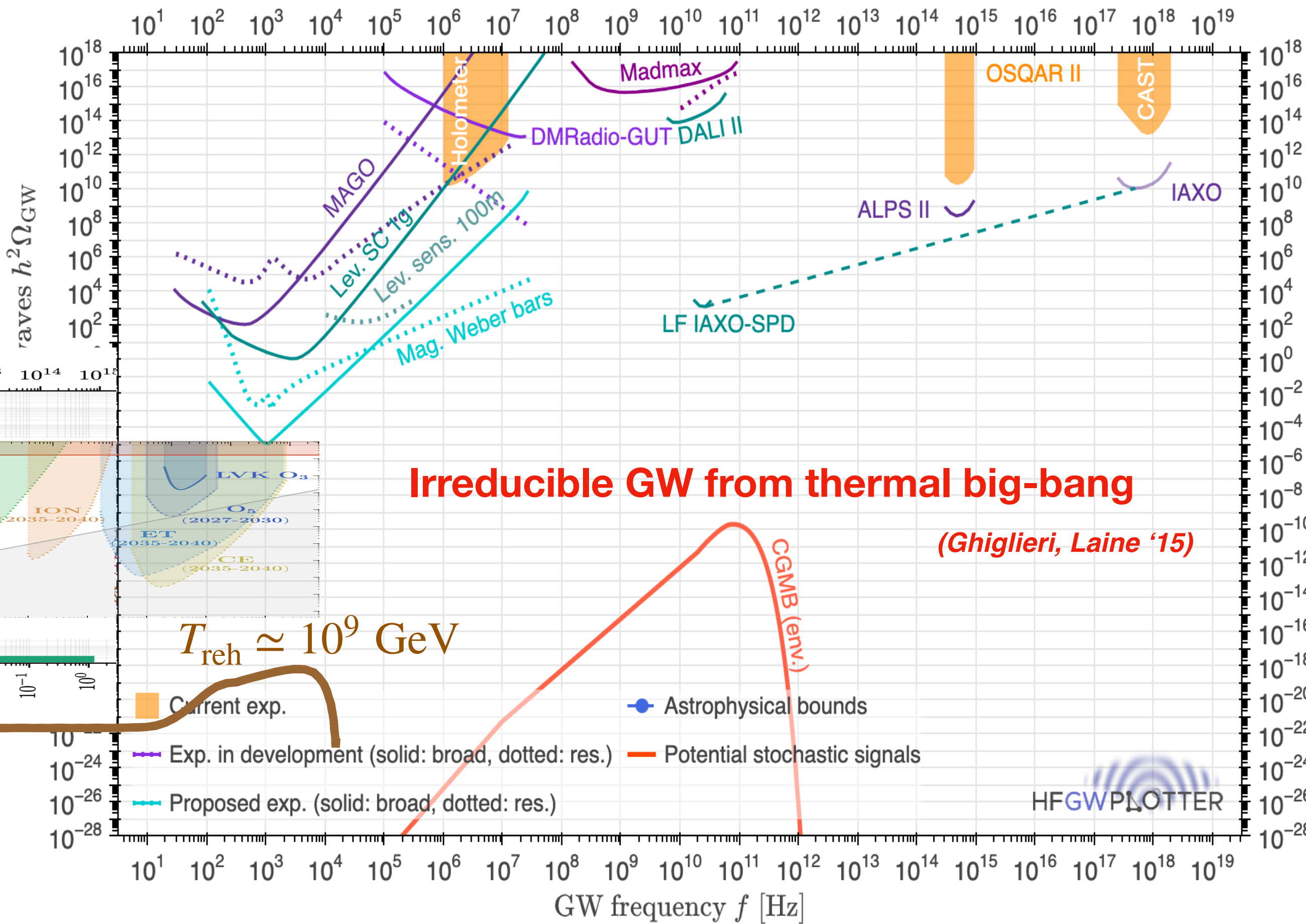
GWPlotter: Muia, Ringwald, Tamarit (2501.11723)

Kite, Ravenni, Patil, Chluba (2010.00040)



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)



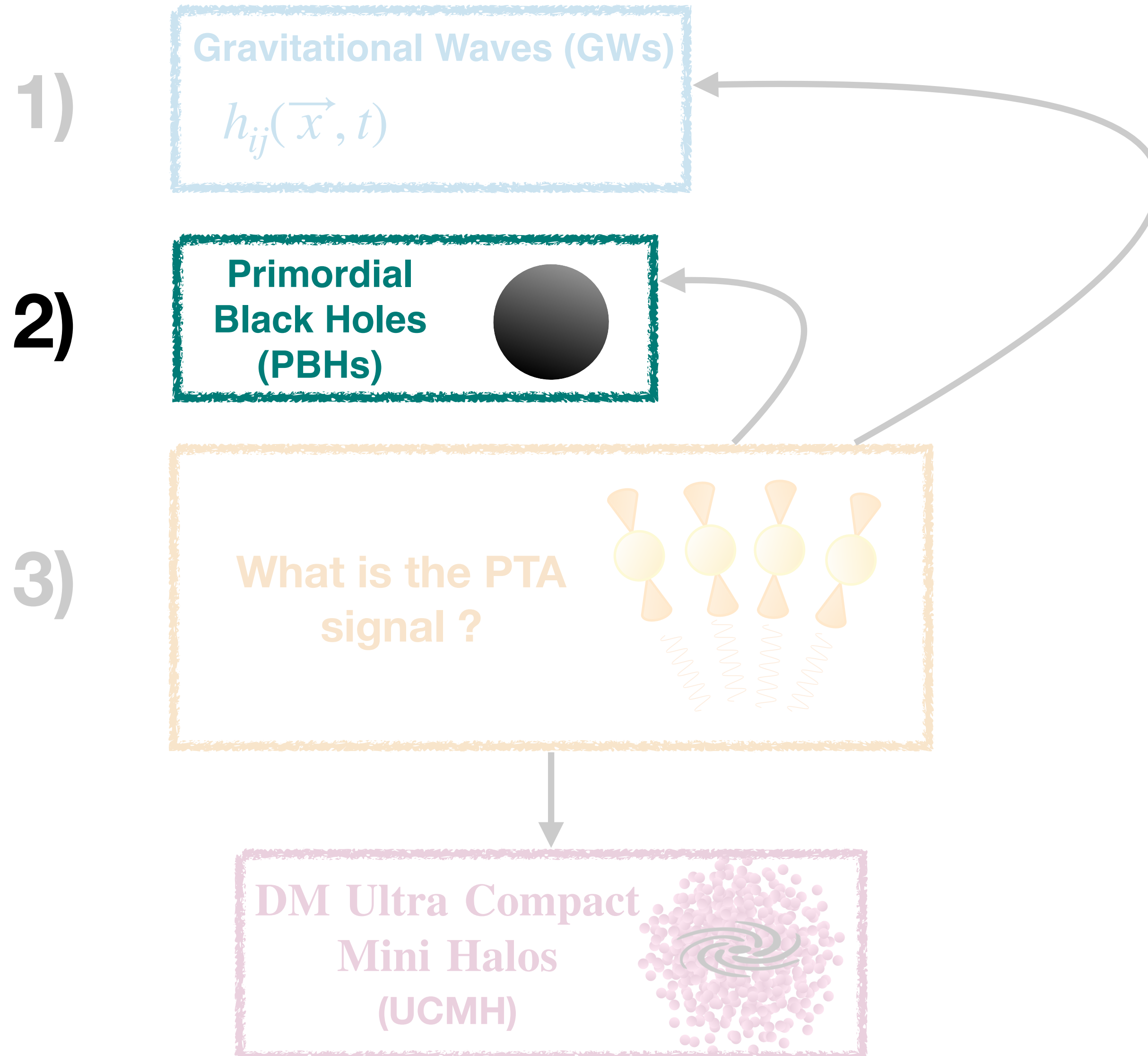
Irreducible GW from thermal big-bang

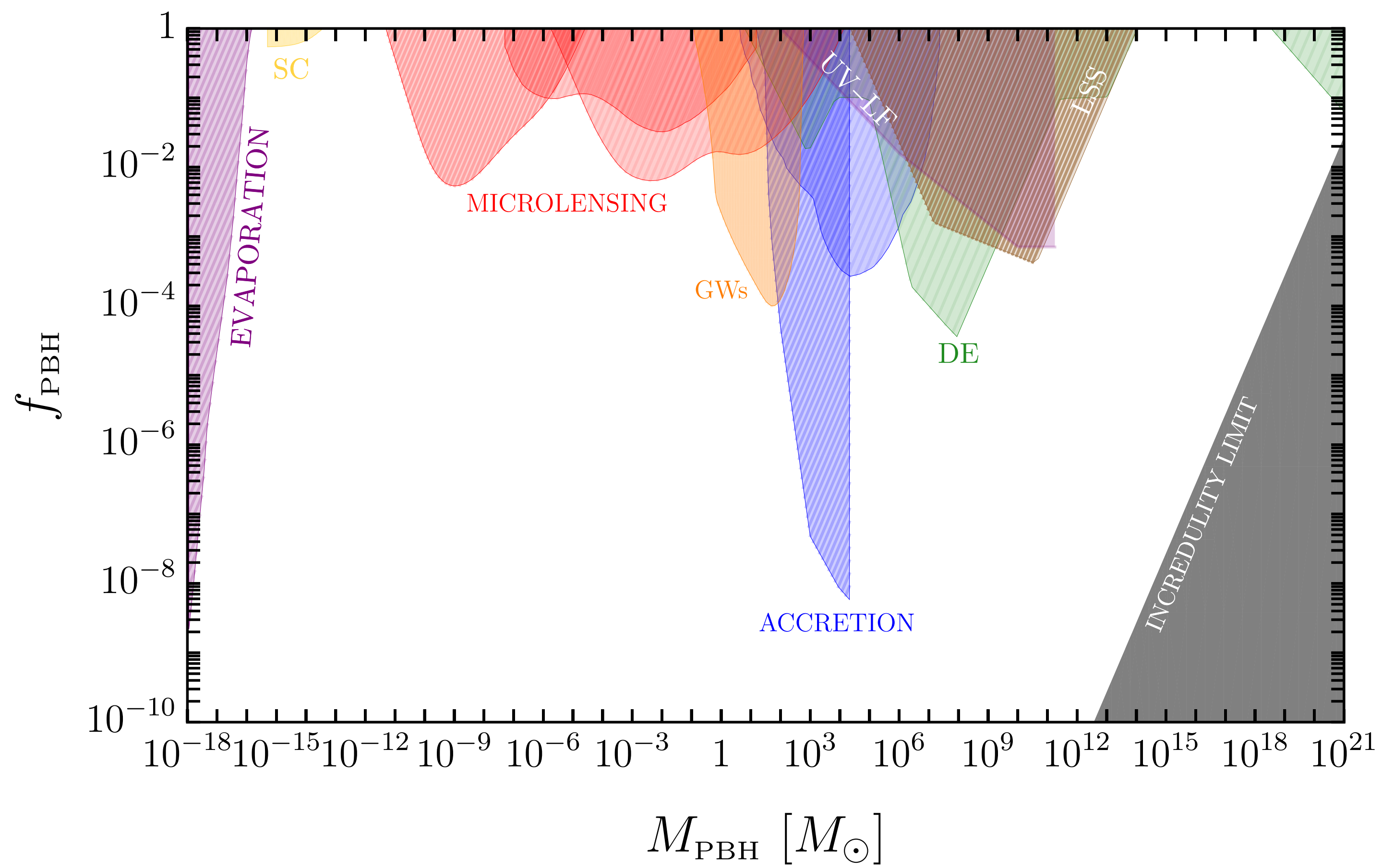
(Ghiglieri, Laine '15)

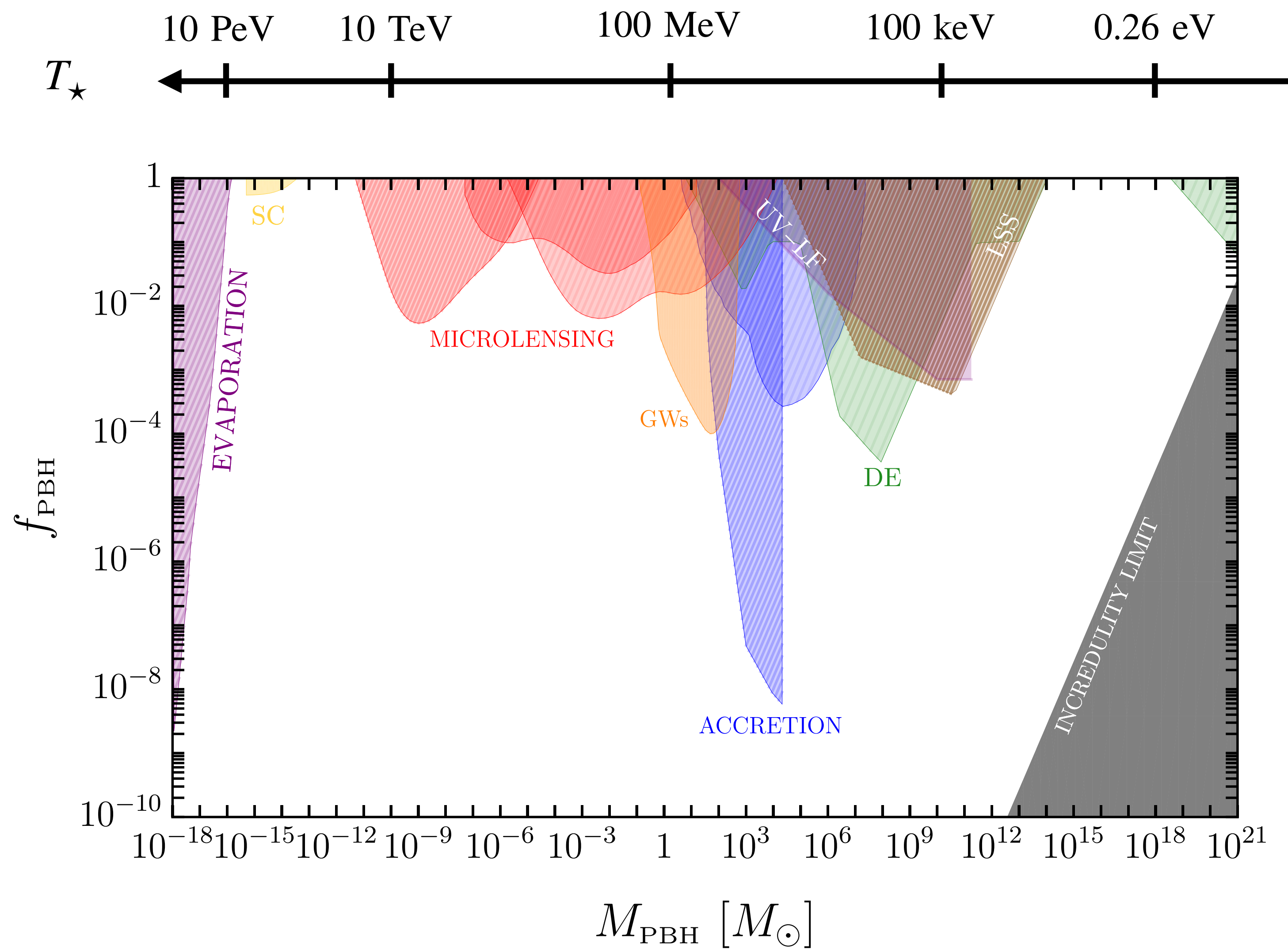
$T_{\text{reh}} \simeq 10^9 \text{ GeV}$

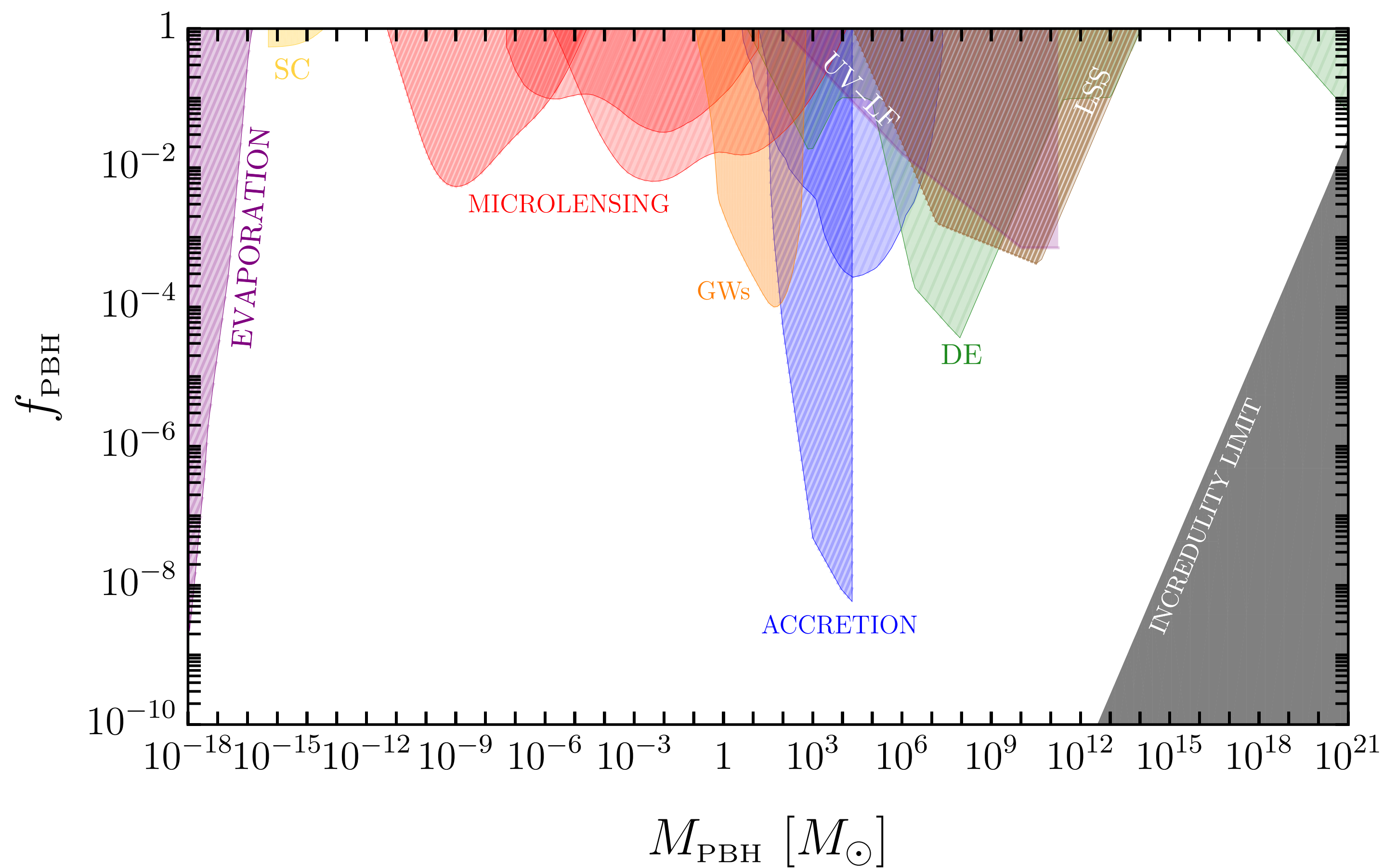
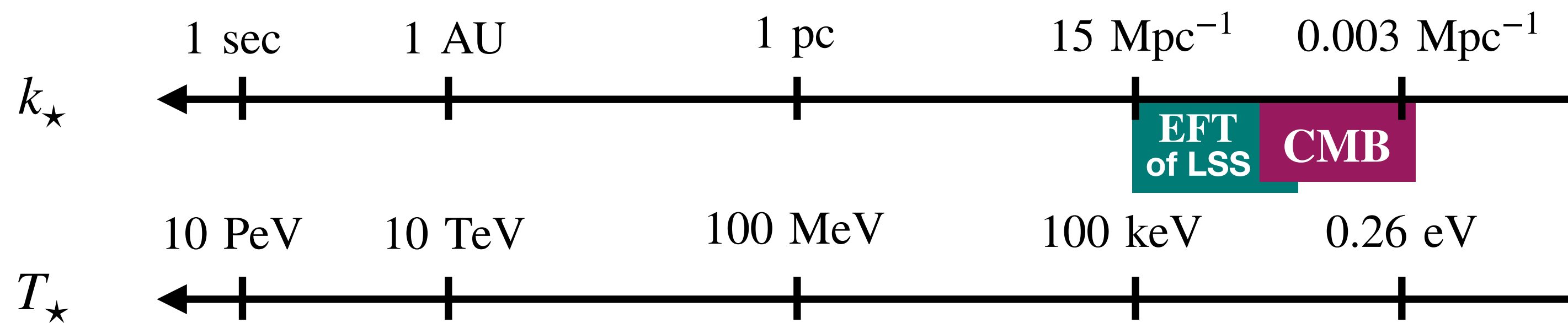
HFGWPLOTTER

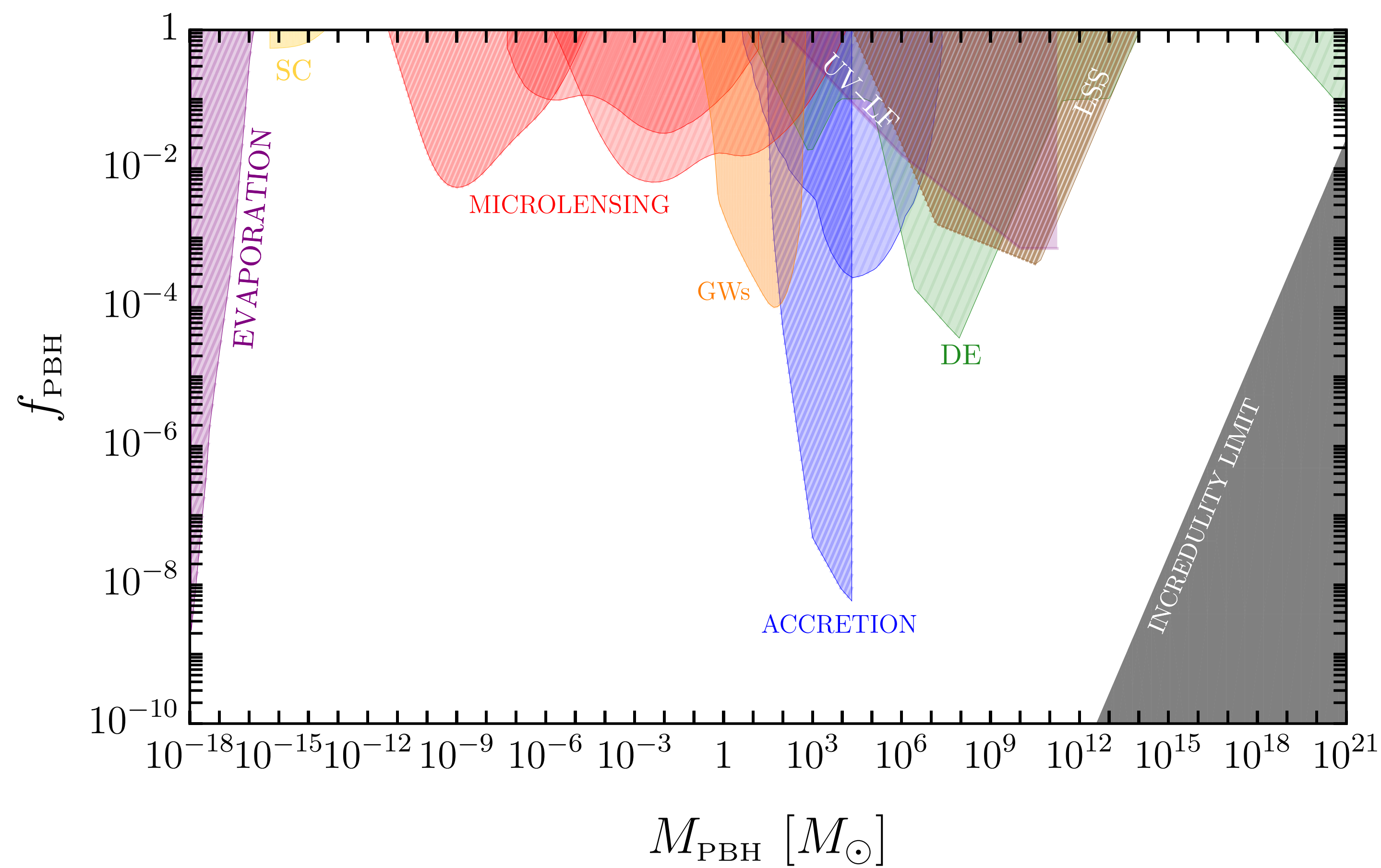
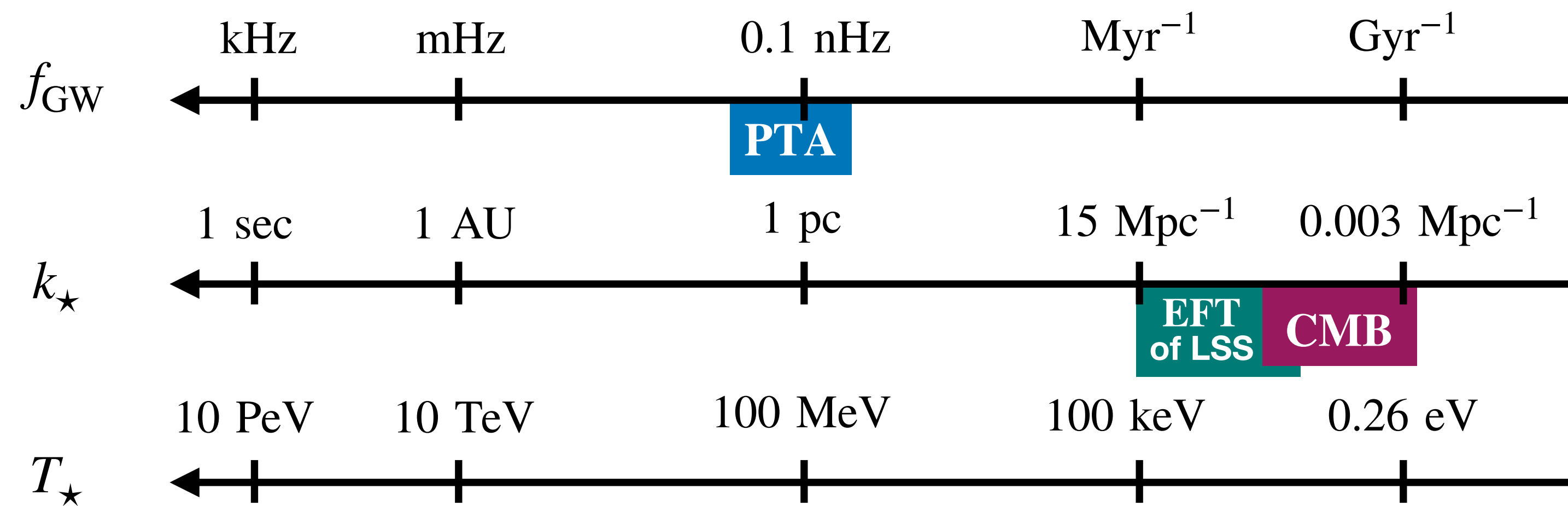
Plan of the talk











Lyman α

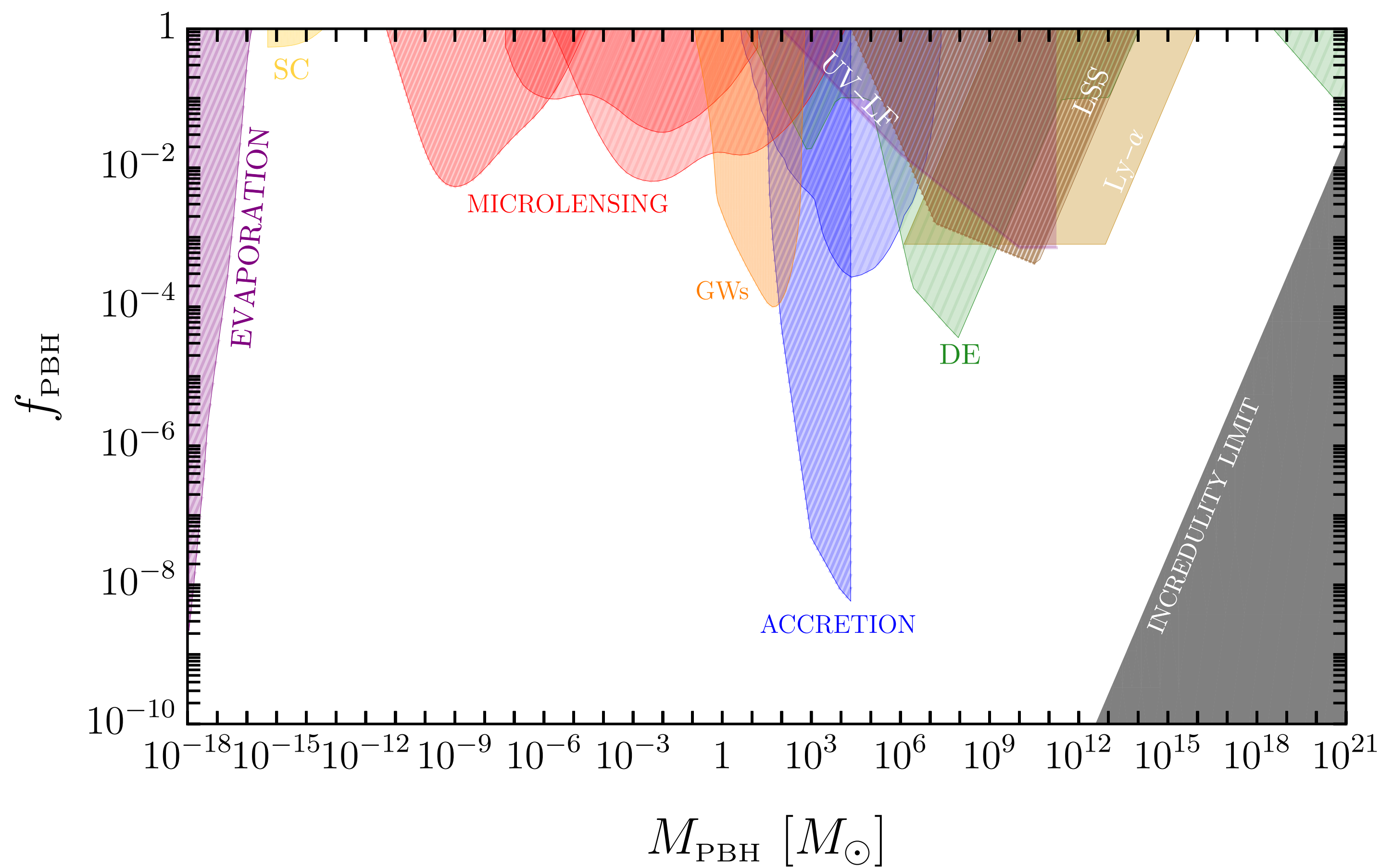
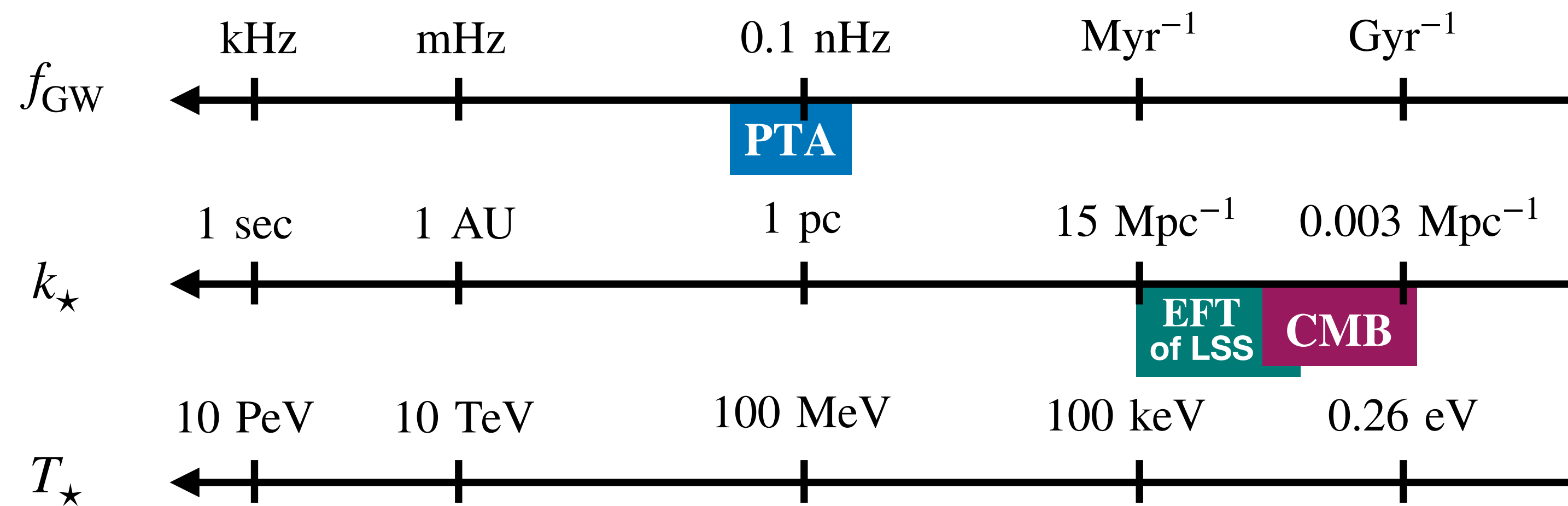
Effective Field Theory Constraints on Primordial Black Holes from the High-Redshift Lyman- α Forest

Mikhail M. Ivanov^{1,*} and Sokratis Trifinopoulos^{1,2,3,†}

¹Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

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Lyman α

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CMB + BAO

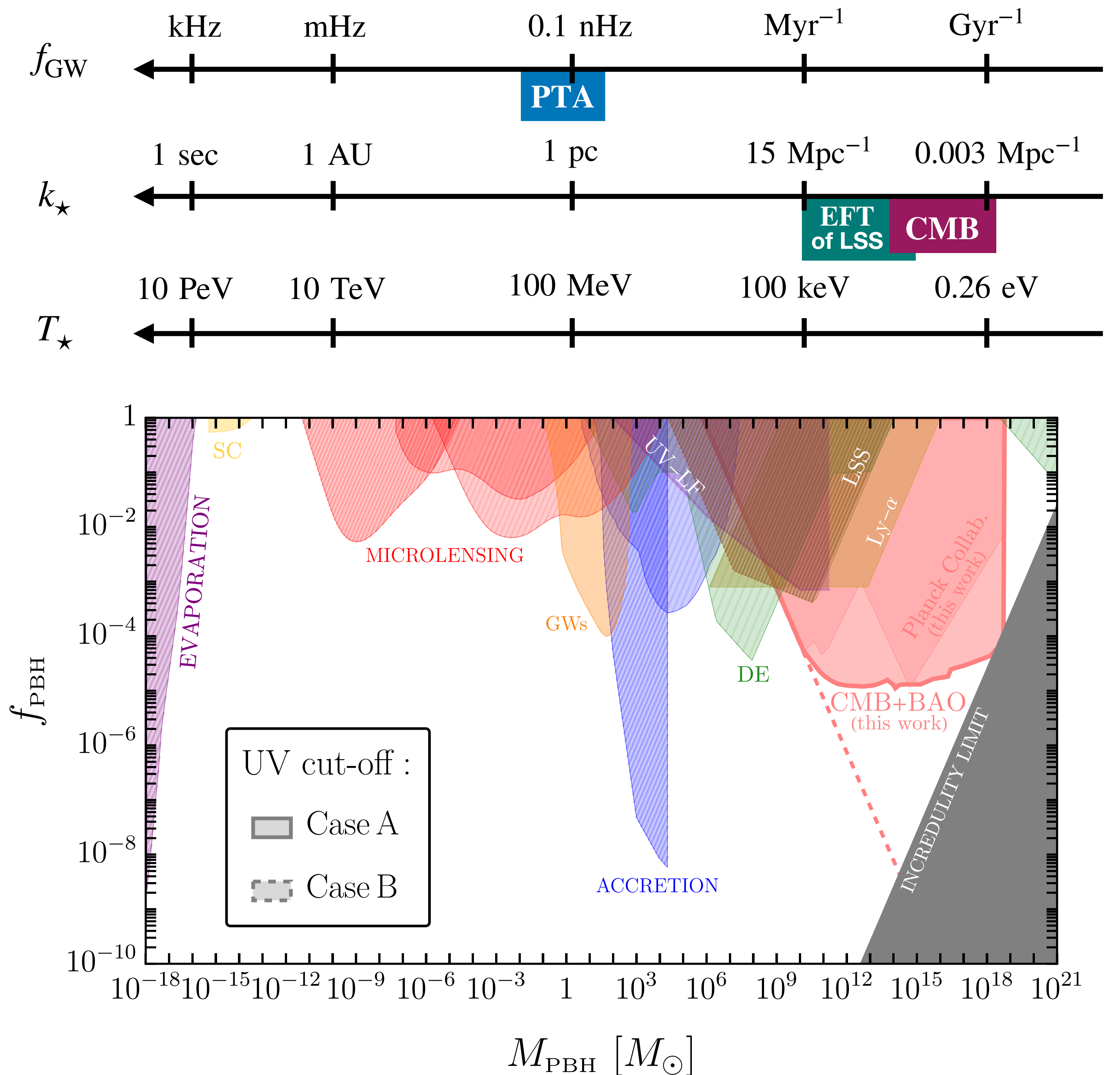
Closing the Mass Window for Stupendously Large Black Holes

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,
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Lyman α

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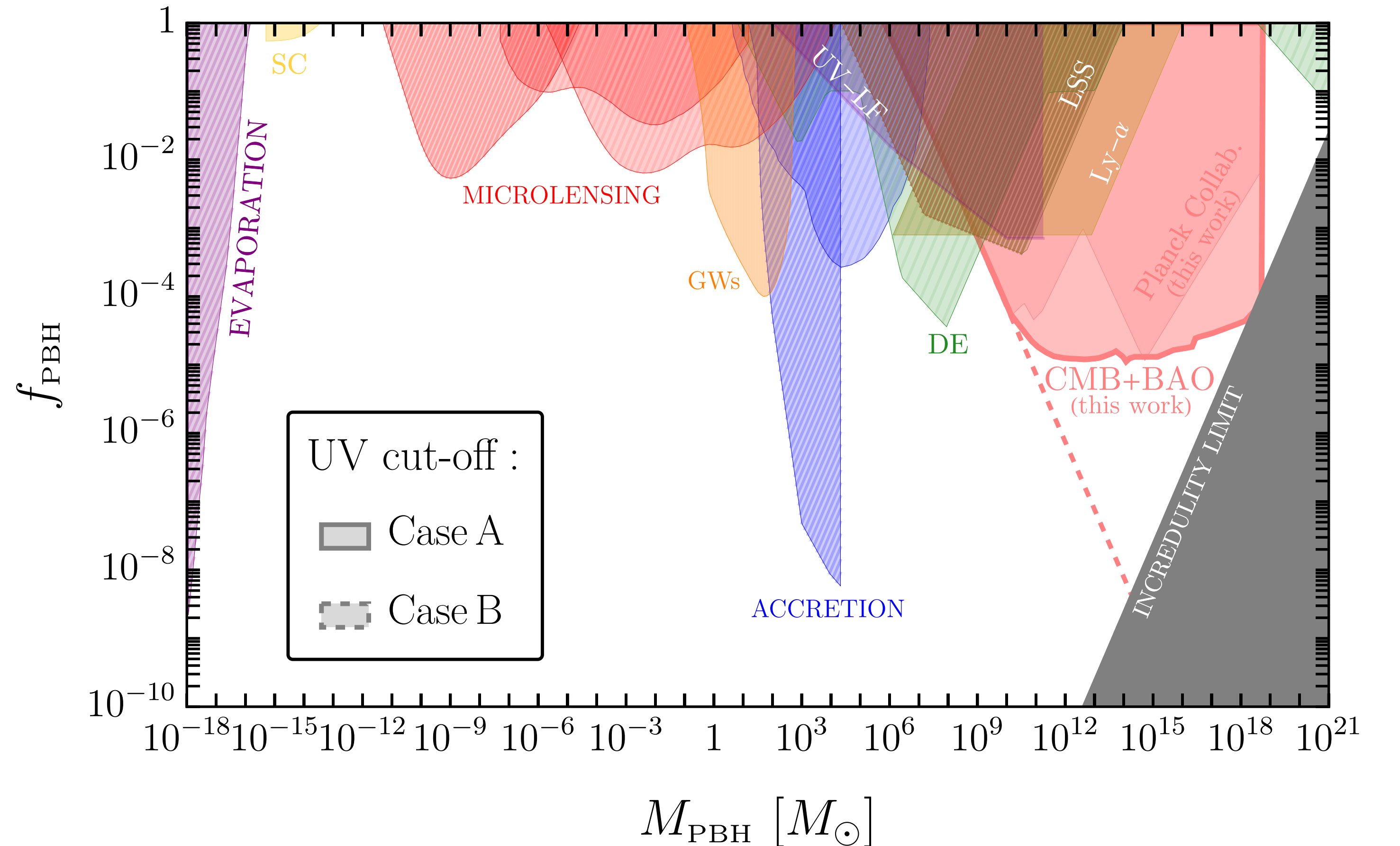
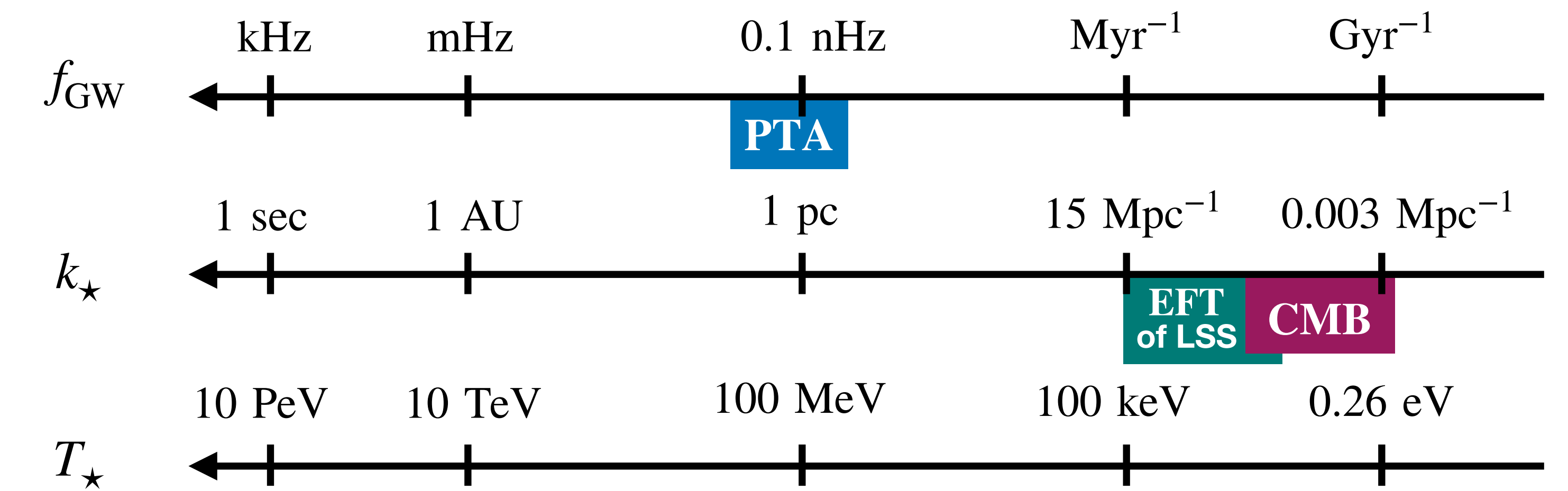
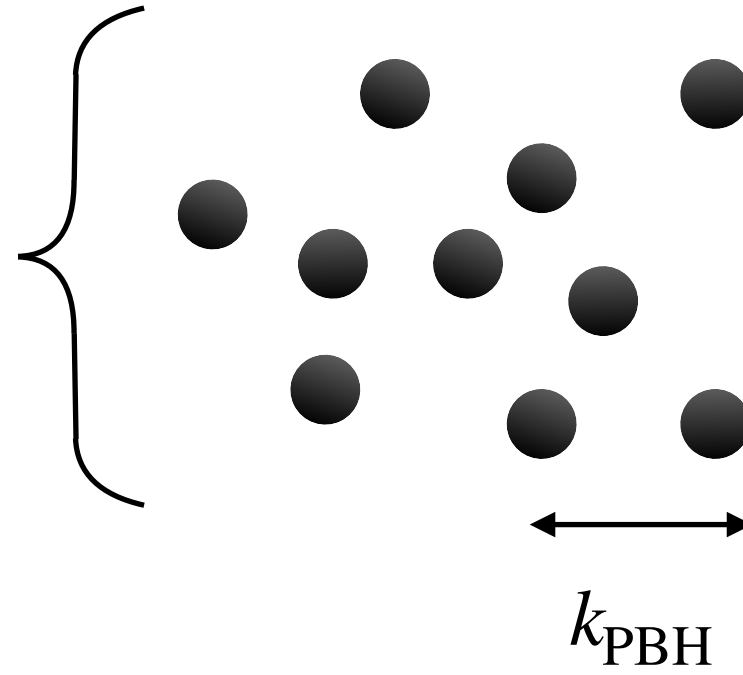
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Gas of PBHs



Lyman – α

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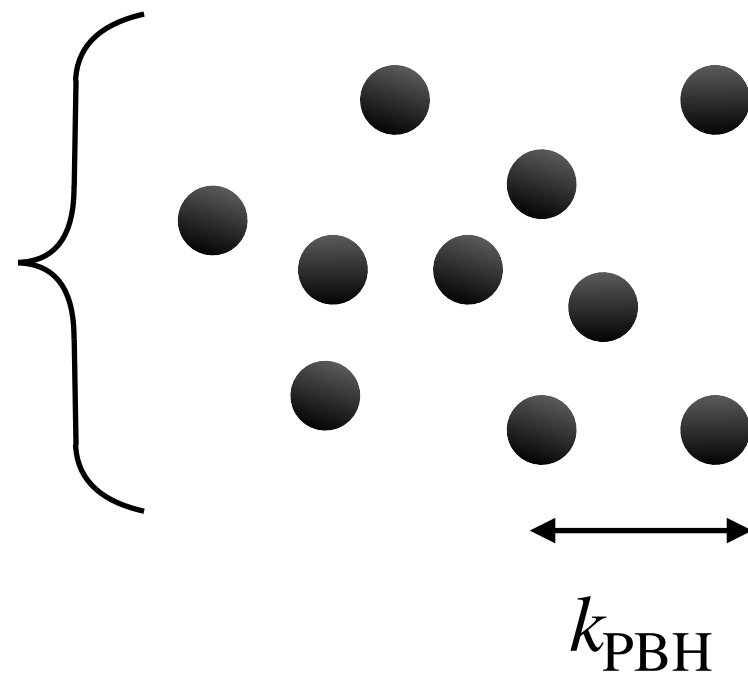
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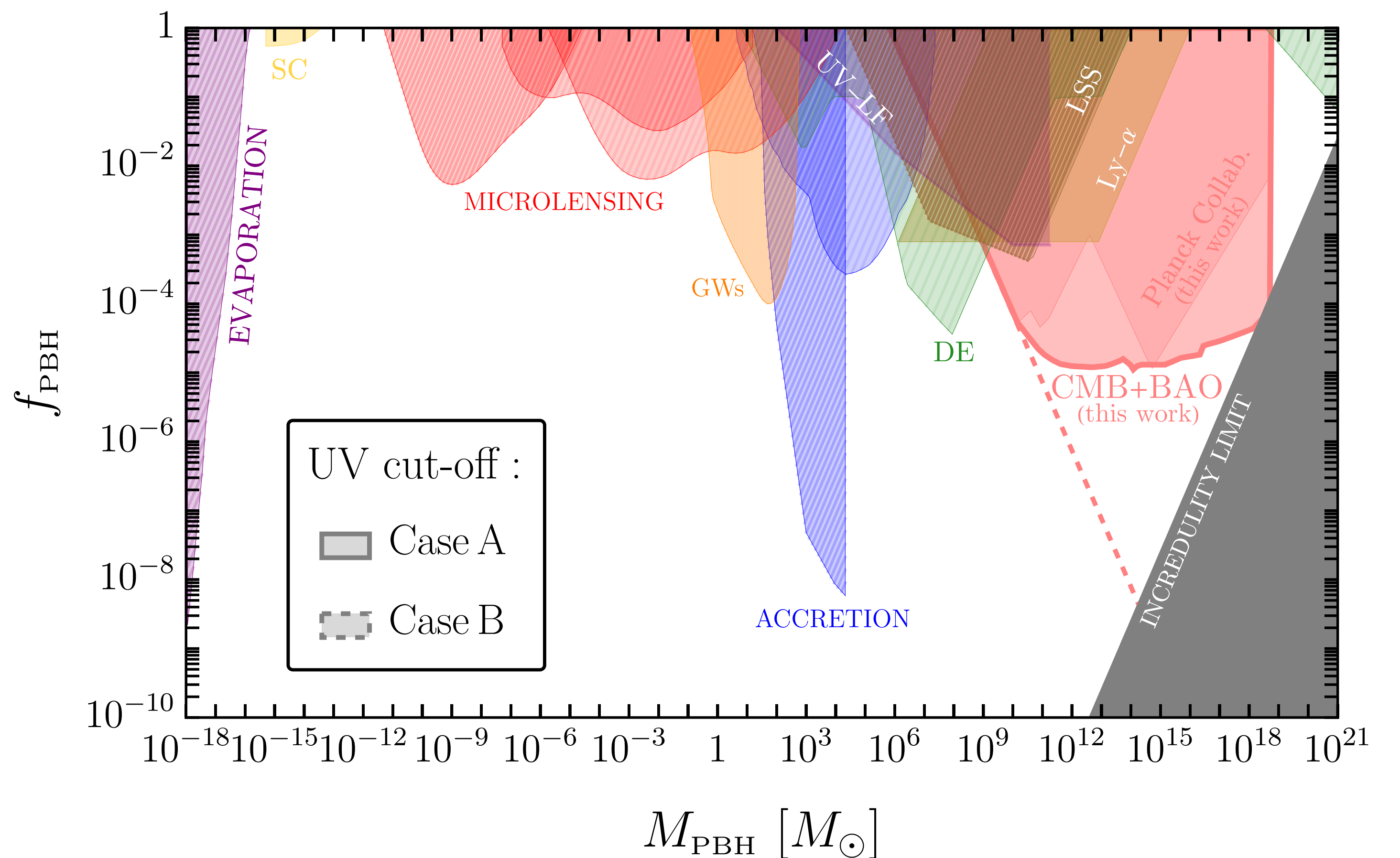
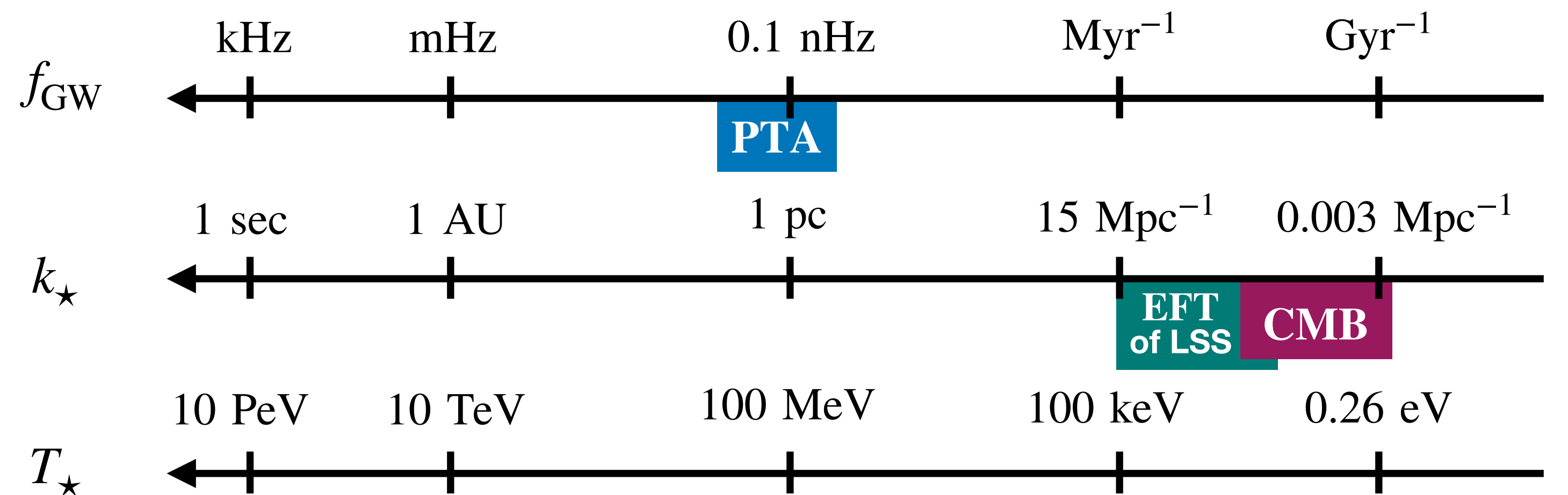
³*Department of Theoretical Physics and Gravitational Wave Science Center,
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Gas of PBHs



Poisson noise :

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



Lyman – α

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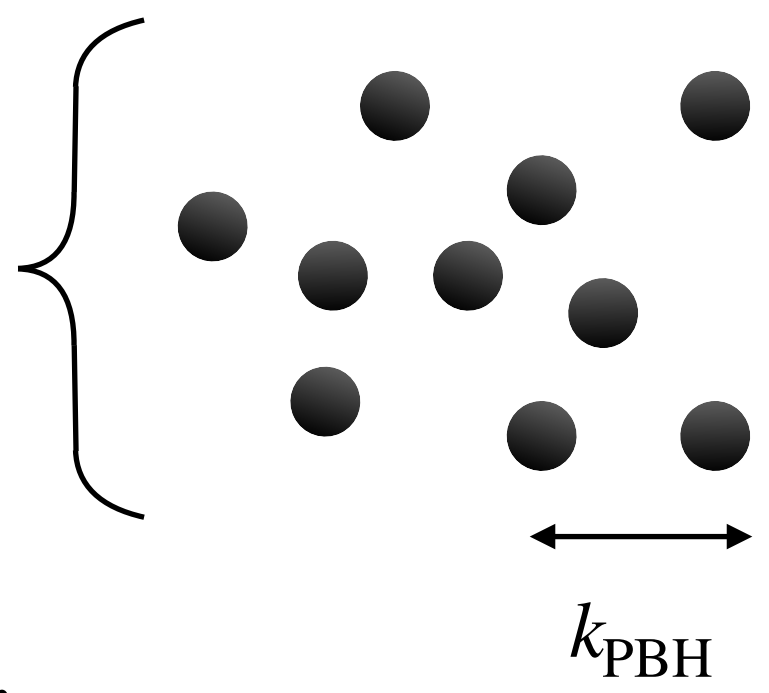
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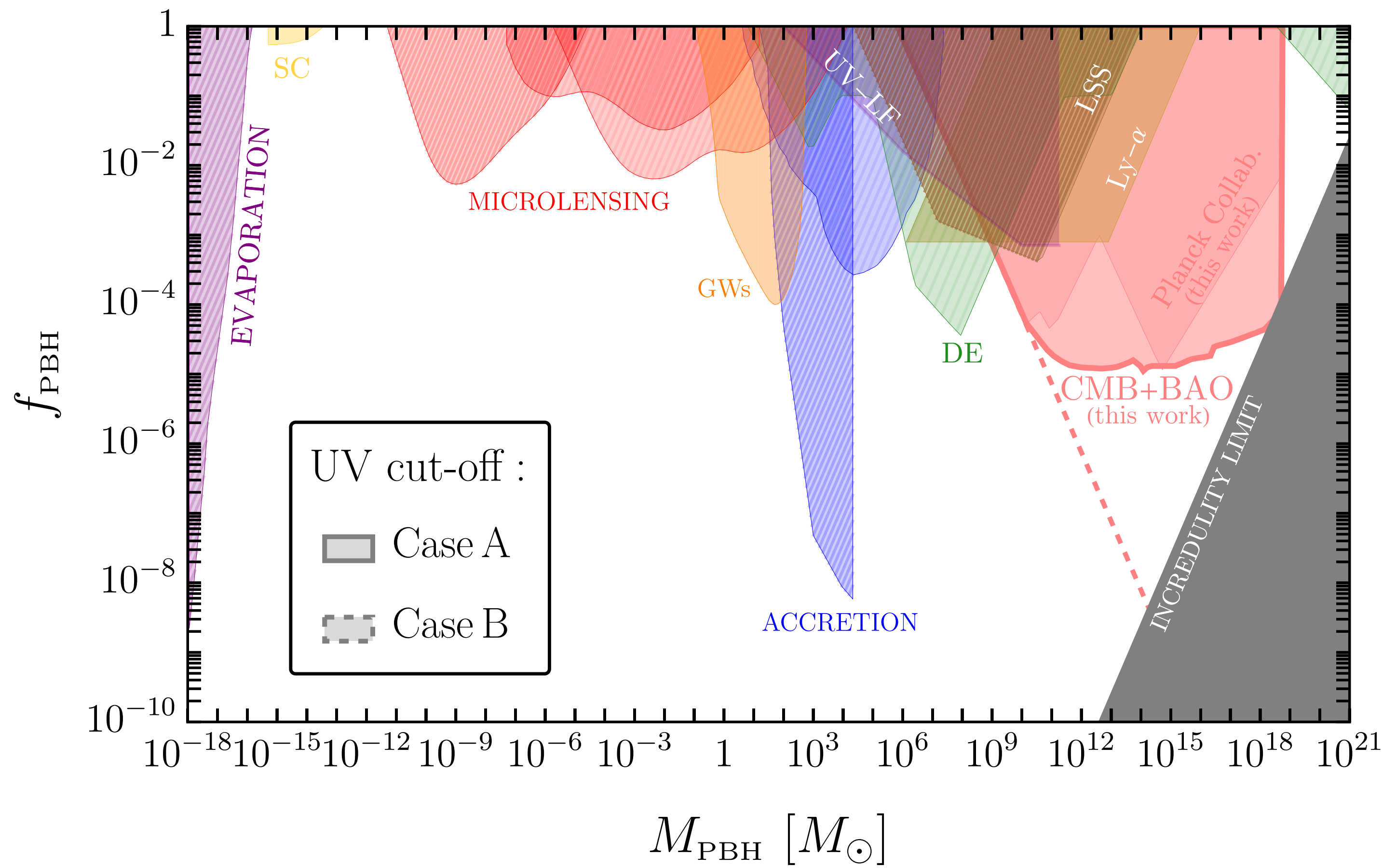
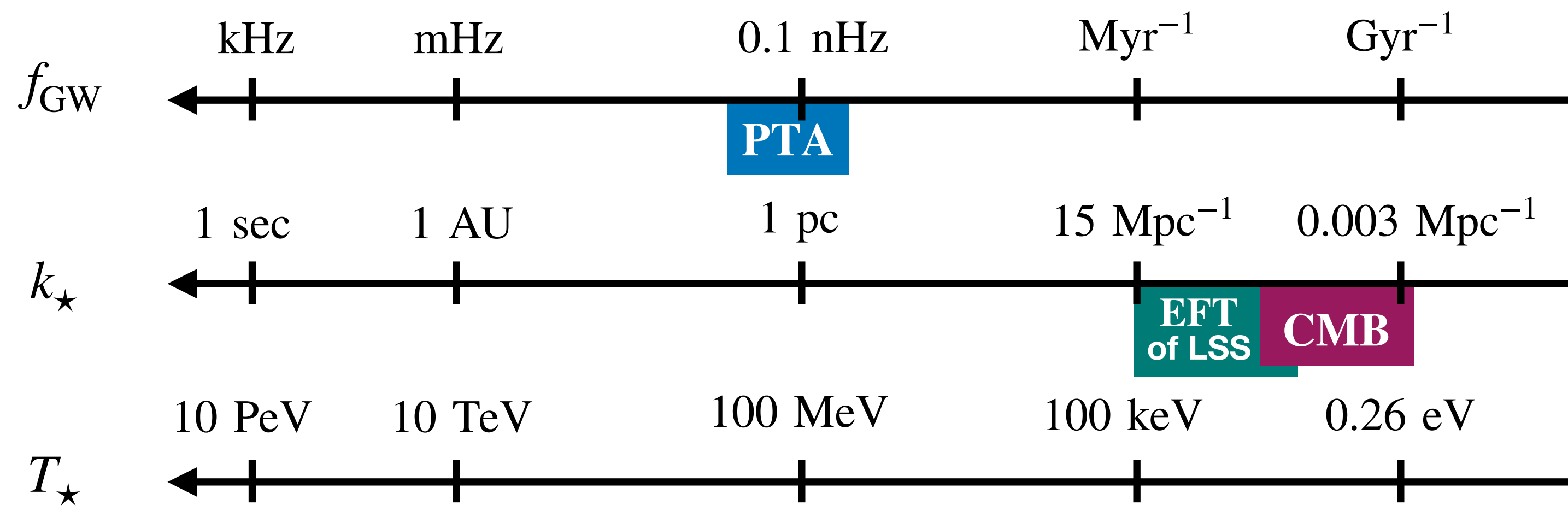
Gas of PBHs



Poisson noise :

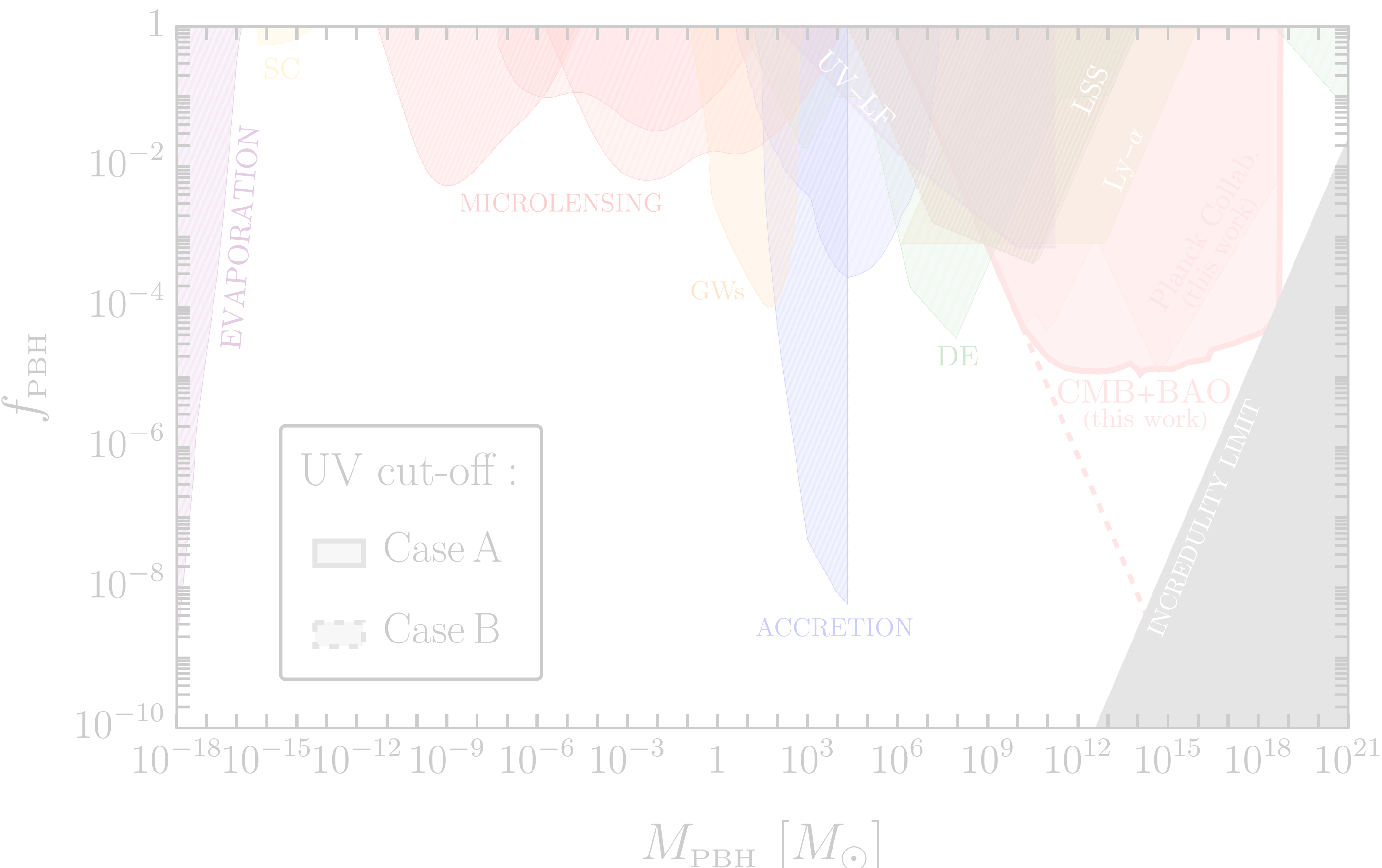
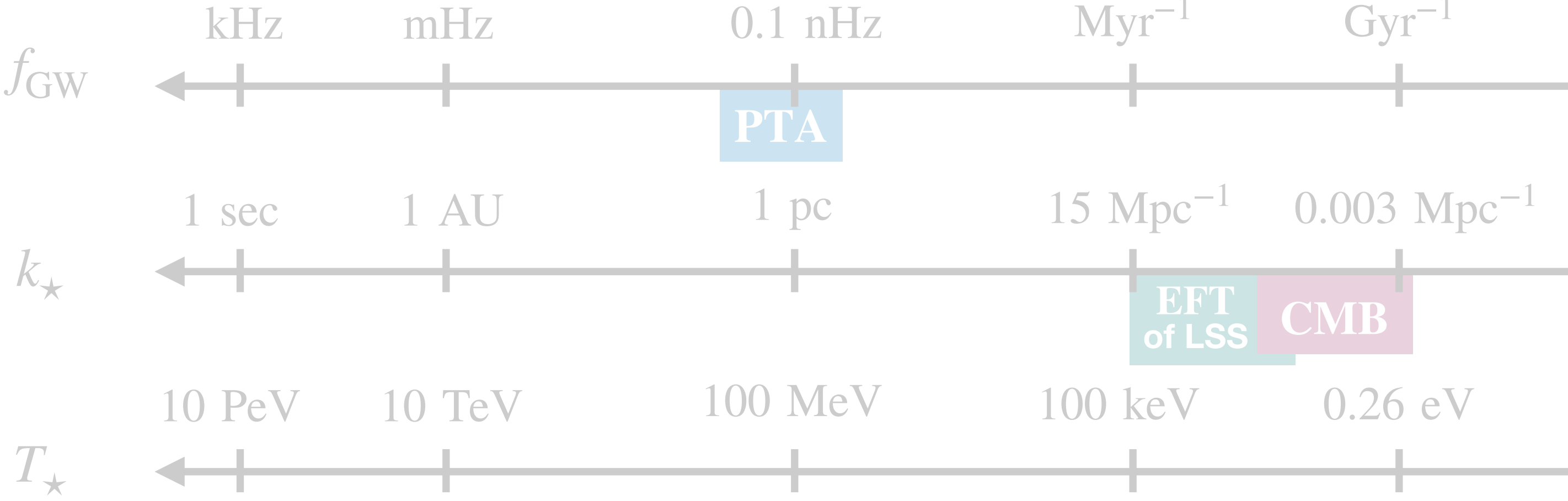
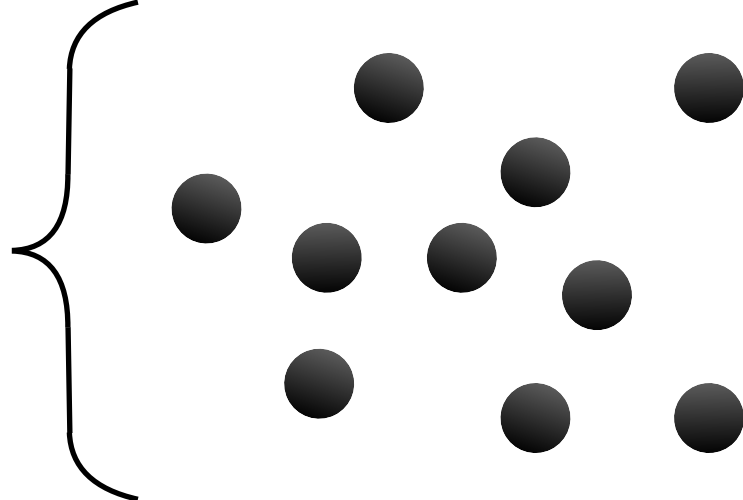
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⇒ source isocurvatures



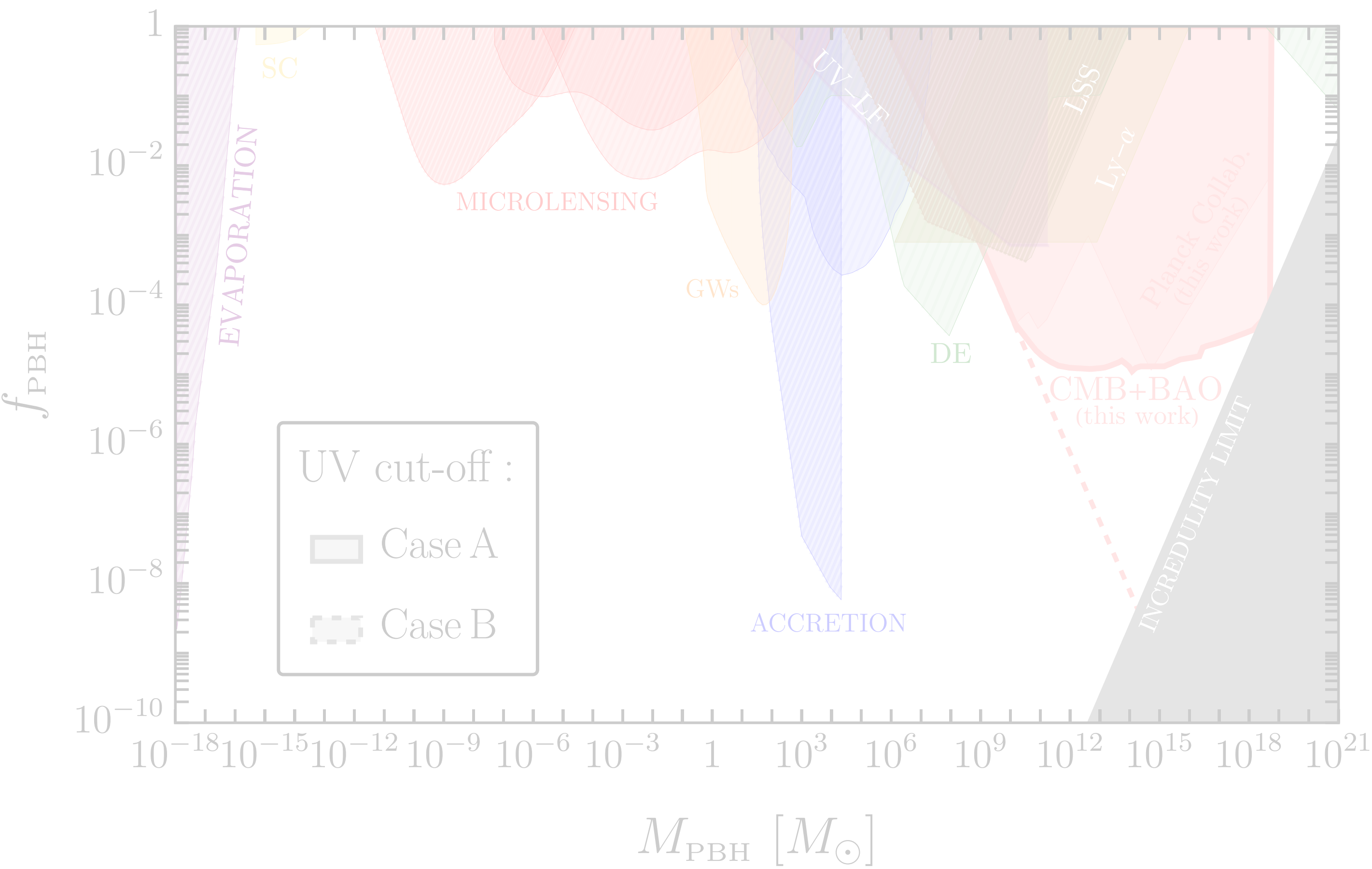
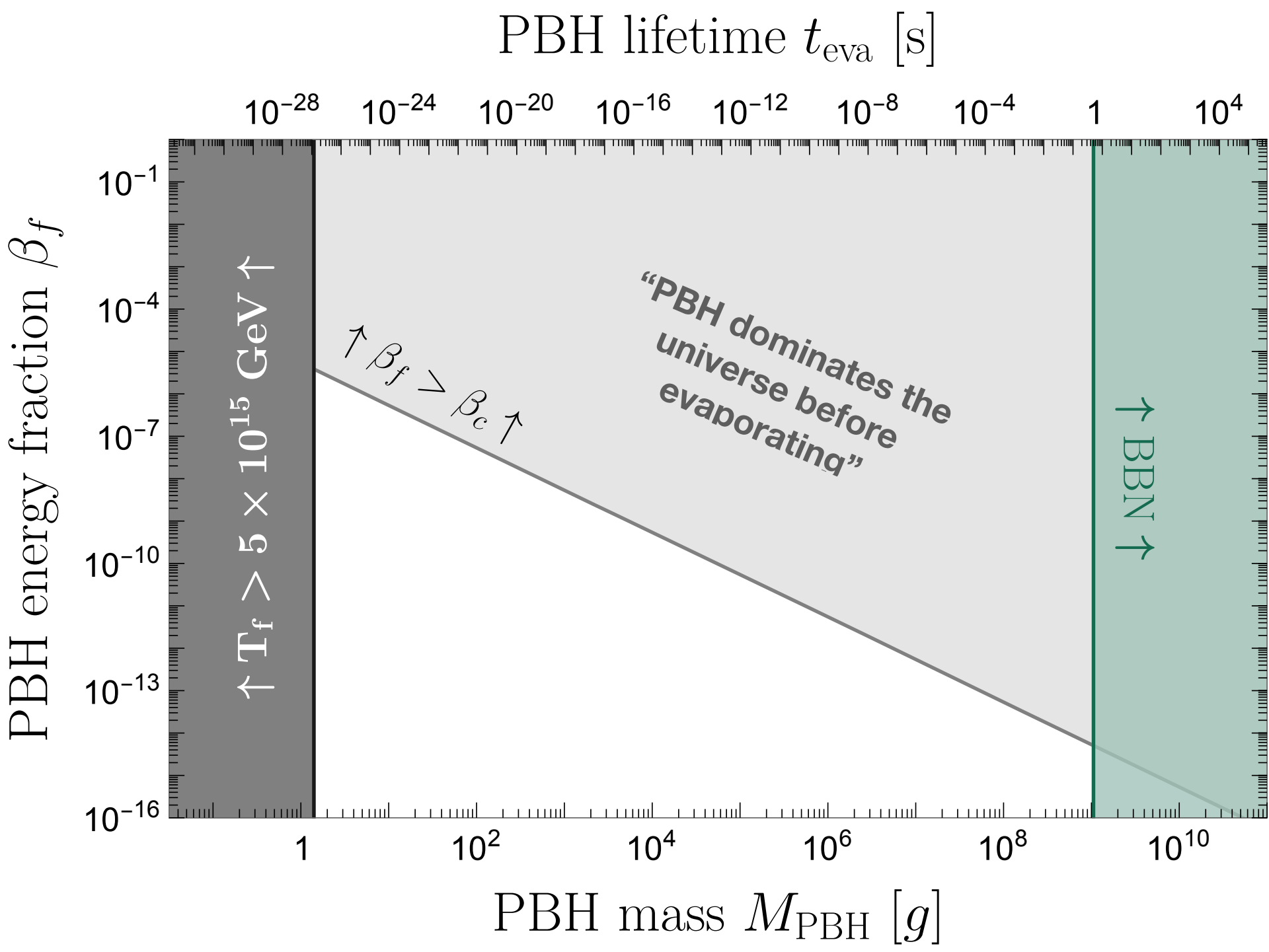
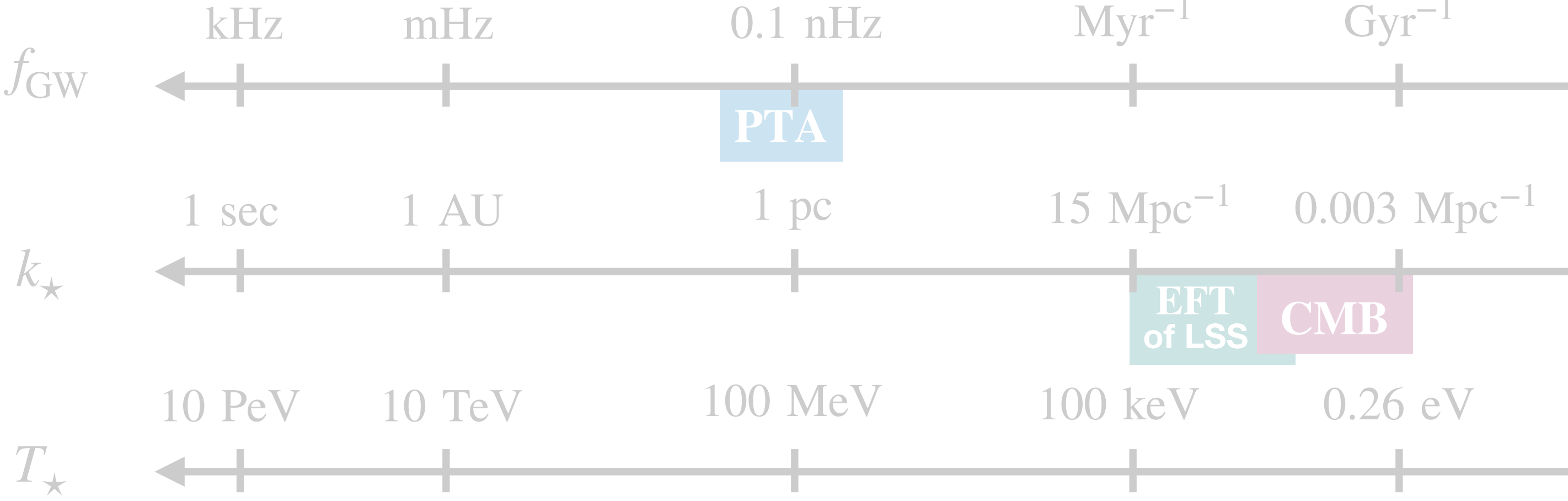
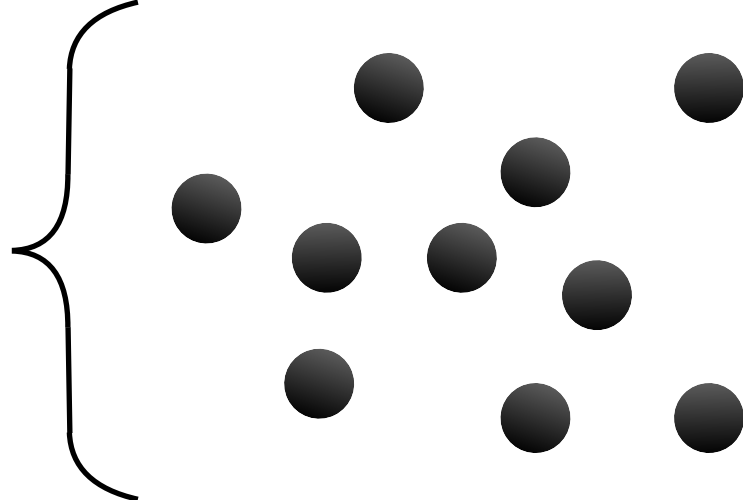
Ultra-light PBHs

Gas of
evaporating PBHs



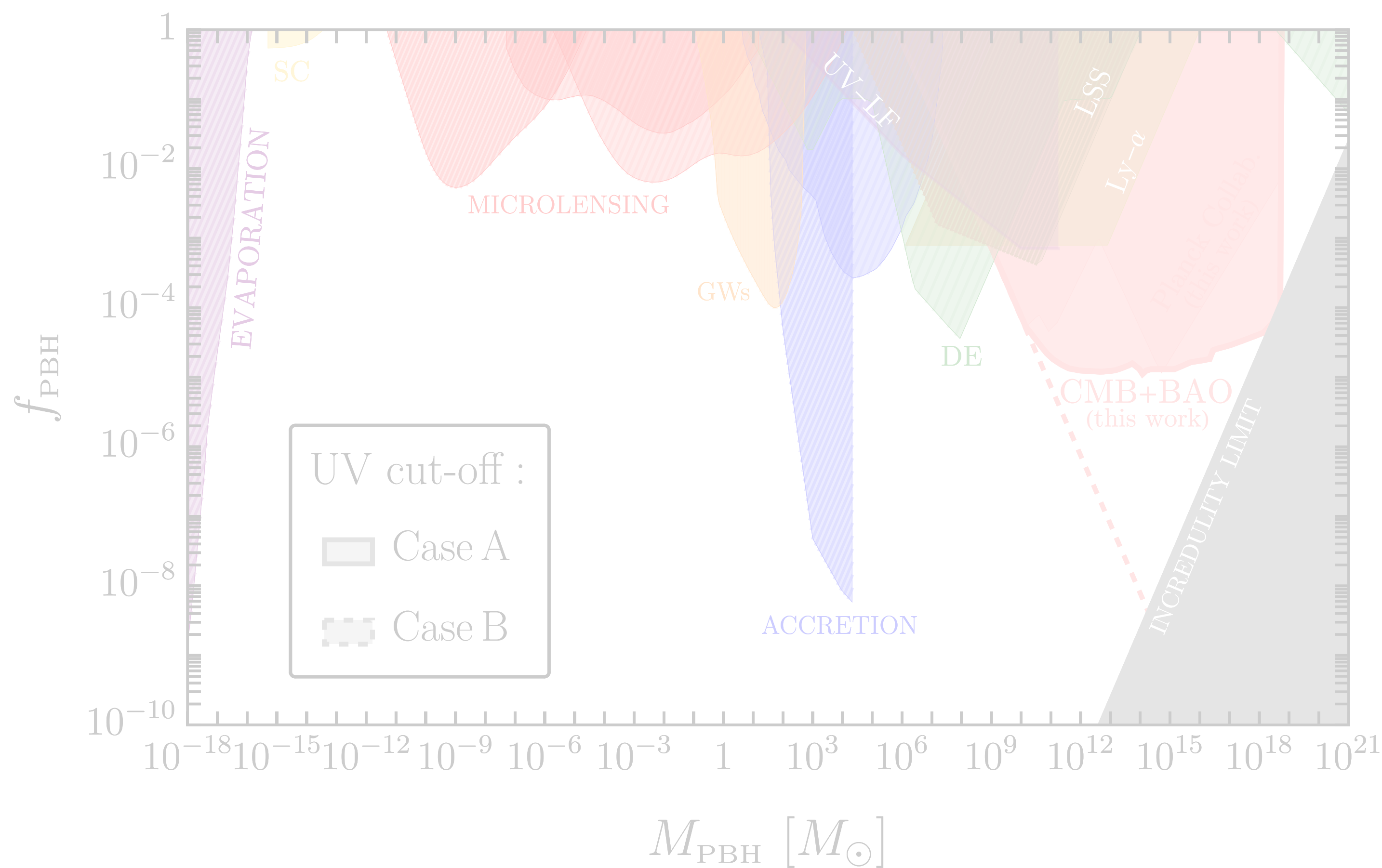
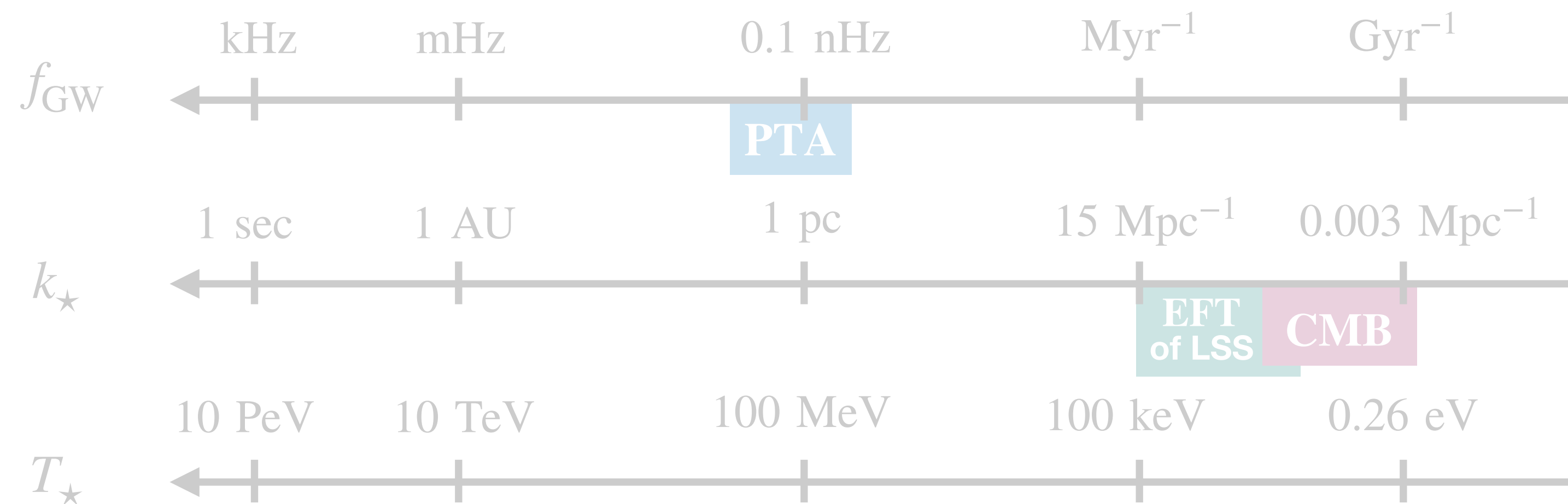
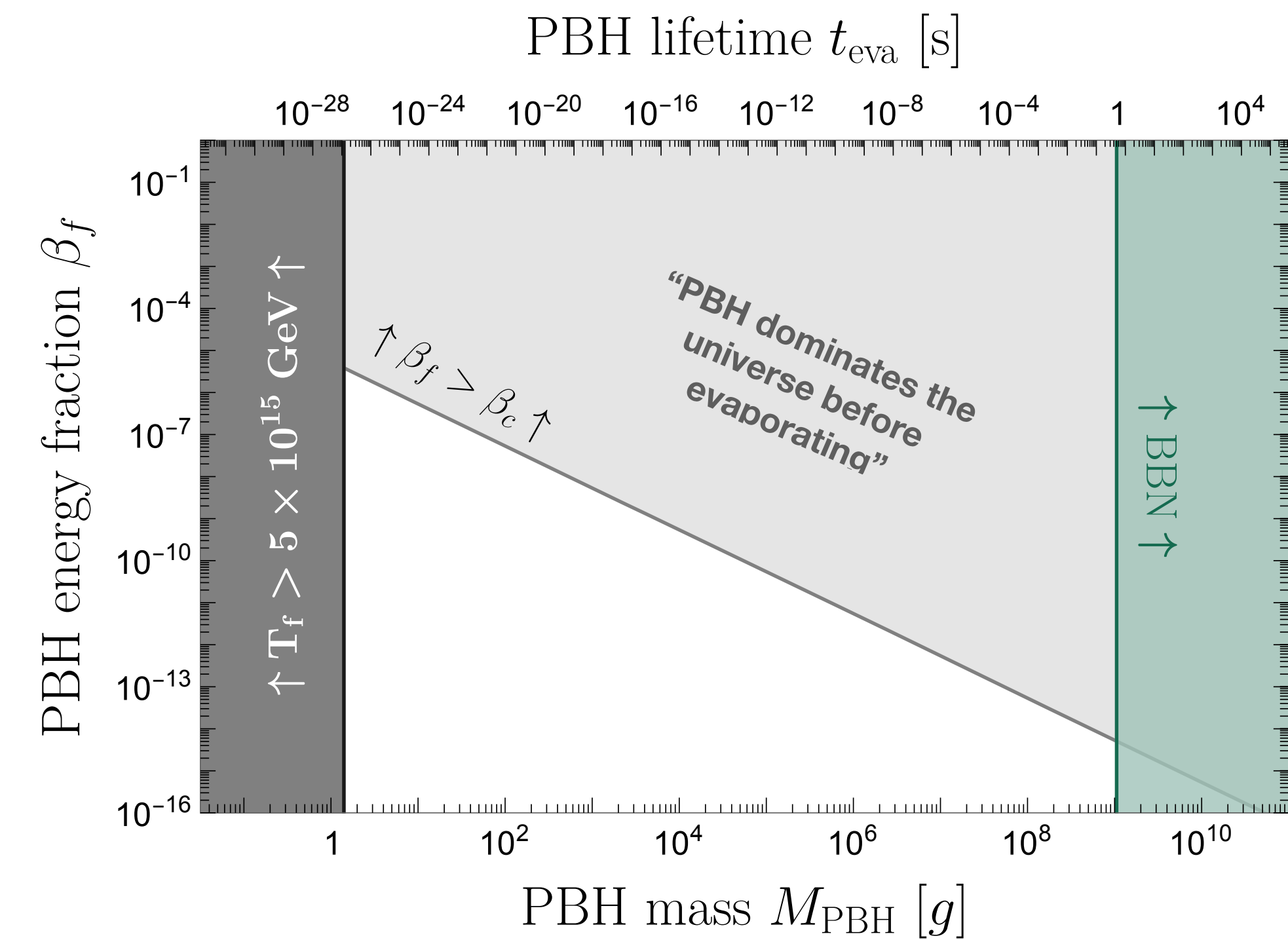
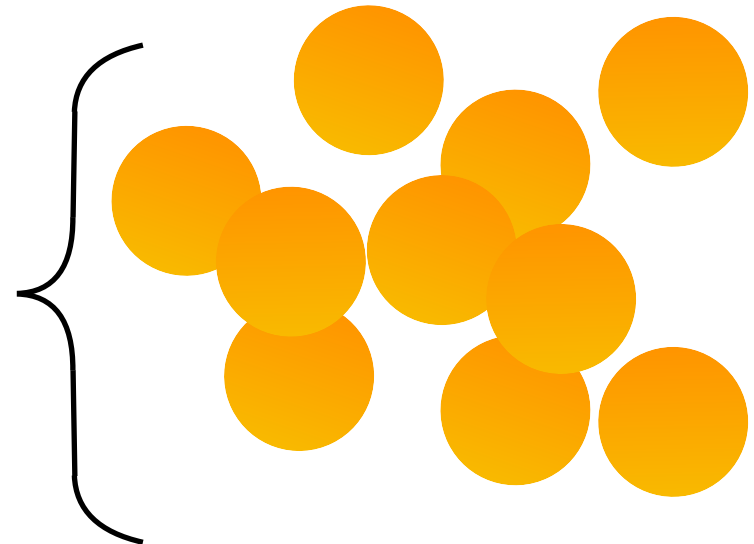
Ultra-light PBHs

Gas of
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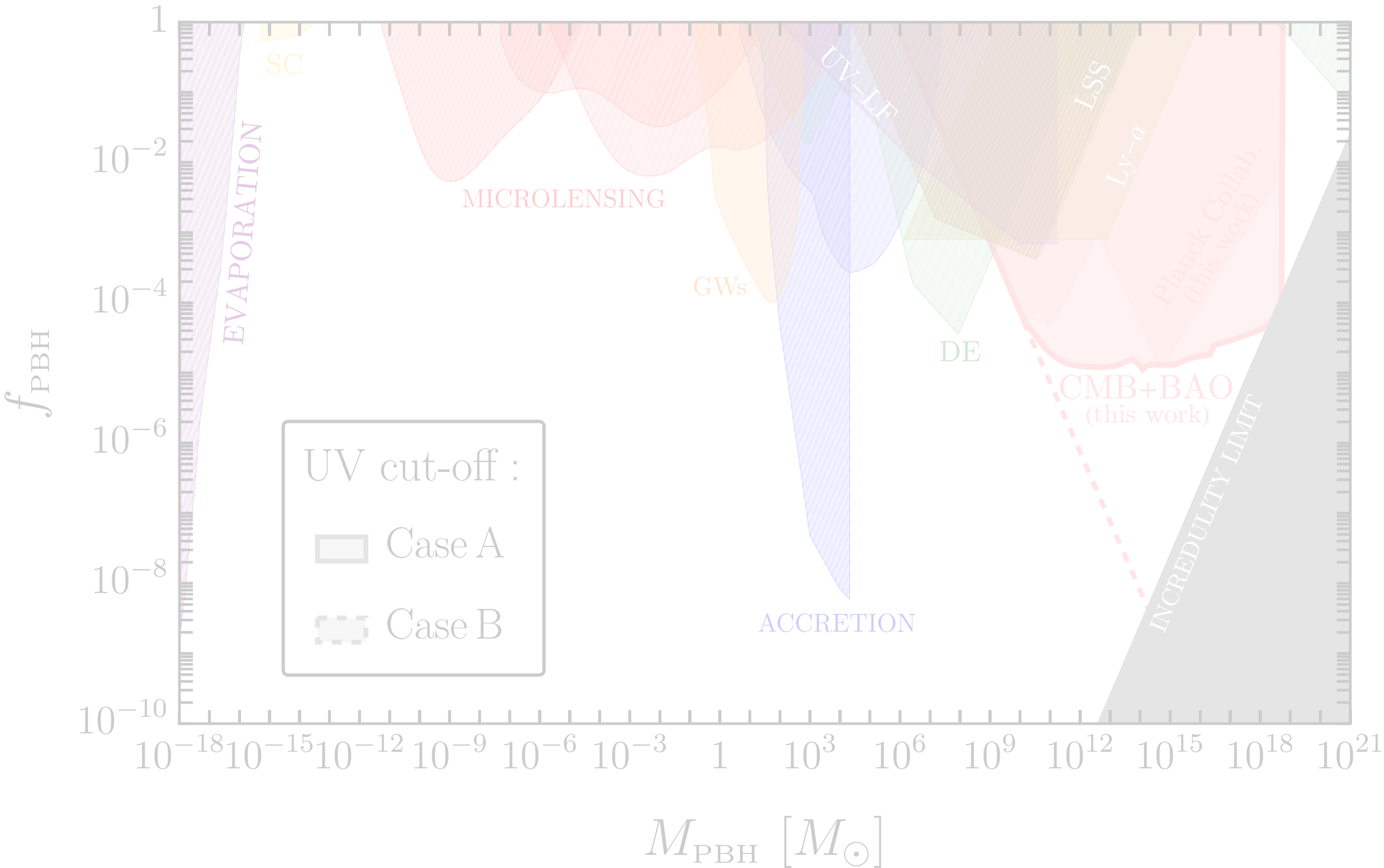
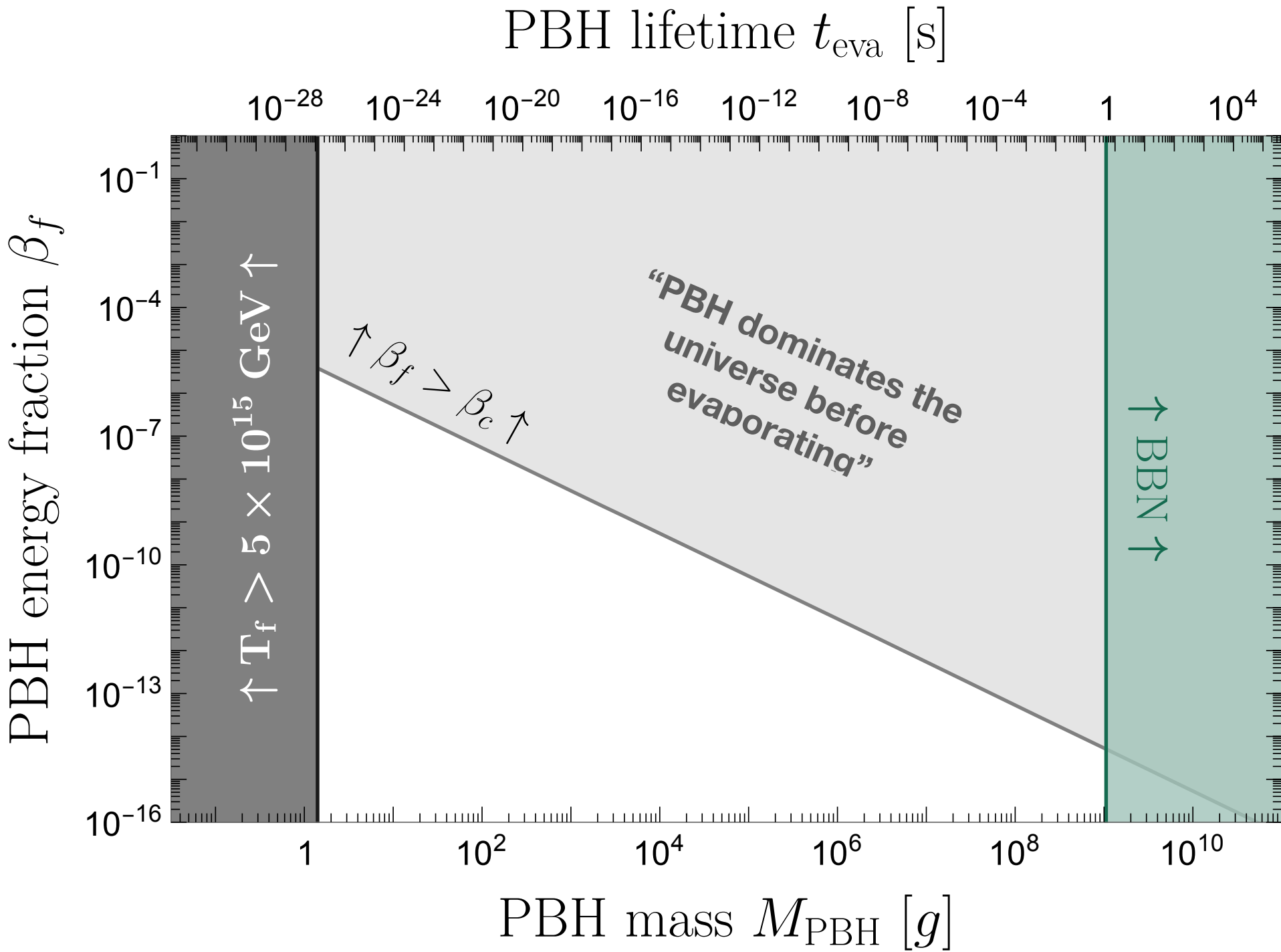
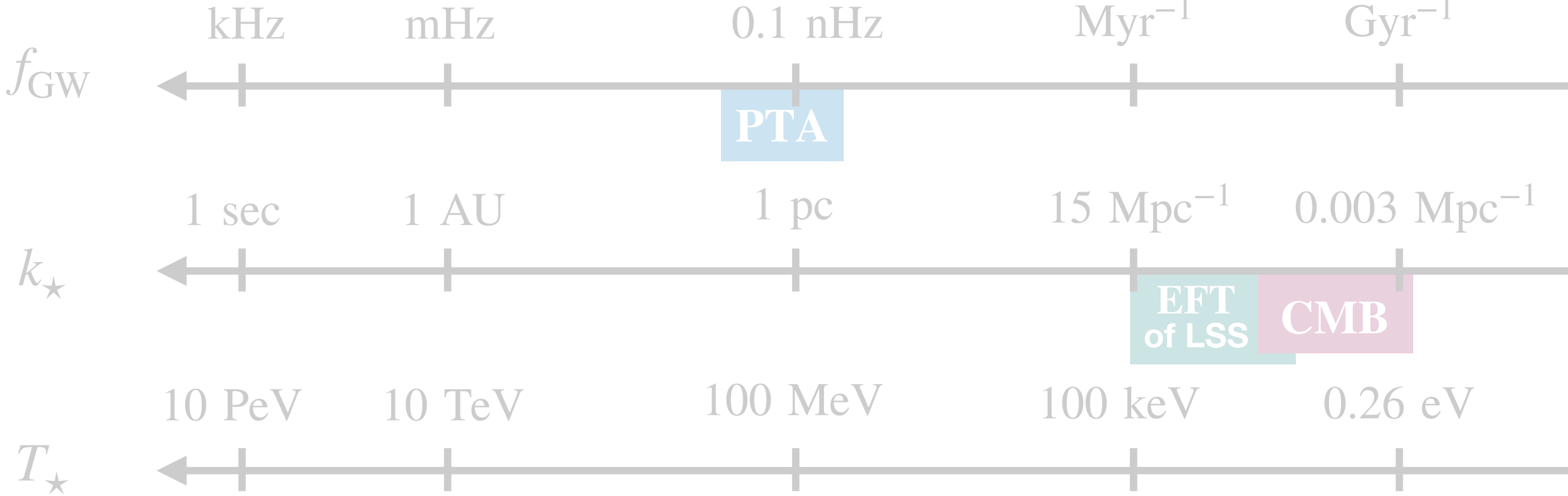
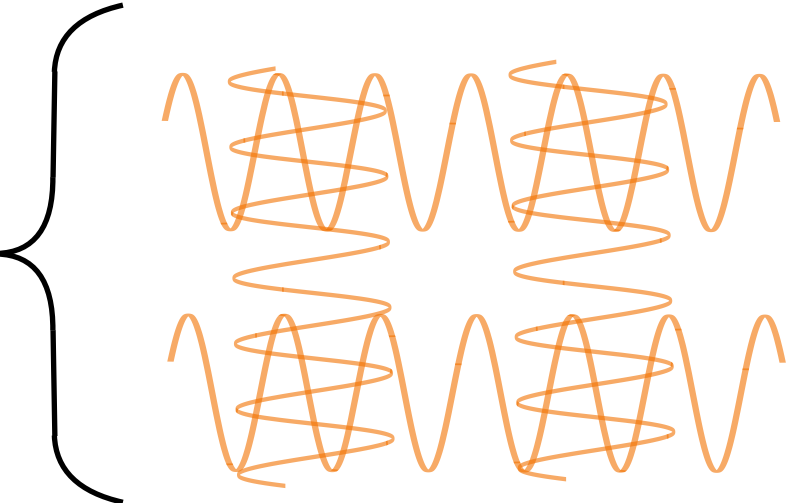
**Gas of
evaporating PBHs**

Evaporation



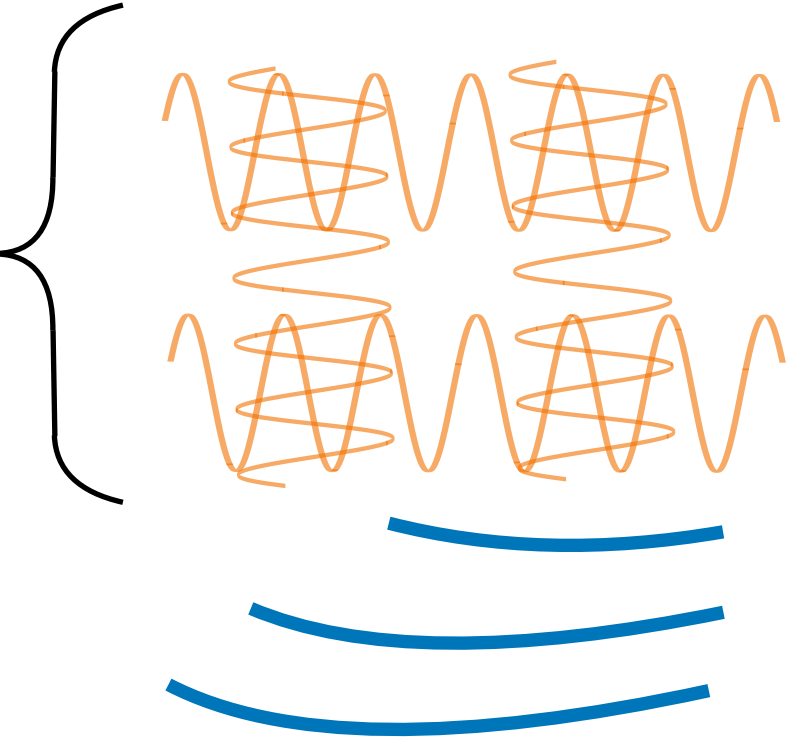
Evaporation $\Rightarrow$ Sound waves

Gas of
evaporating PBHs



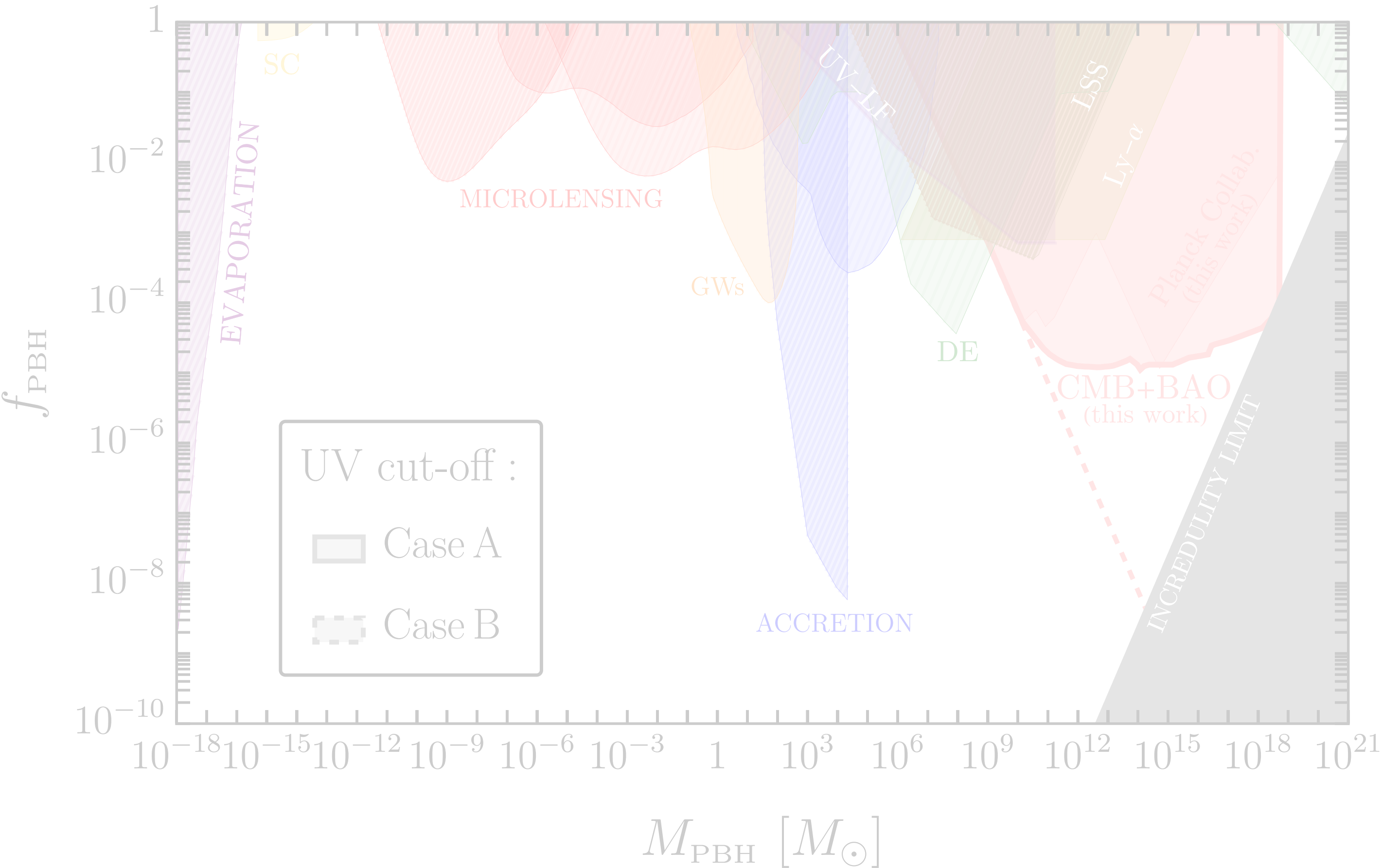
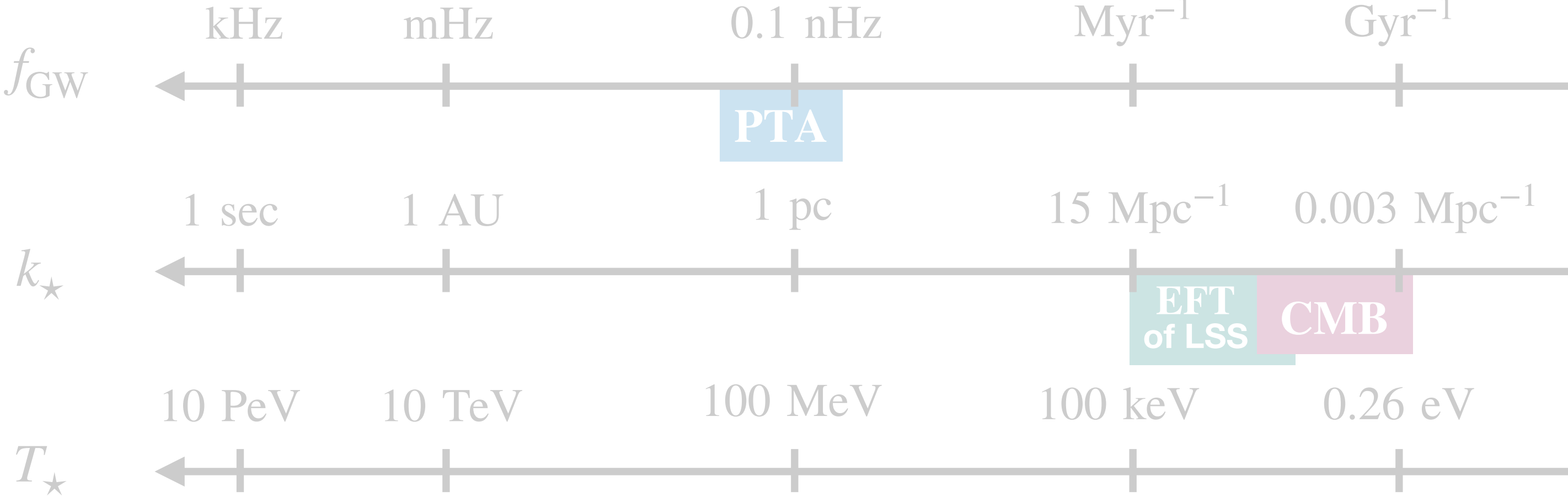
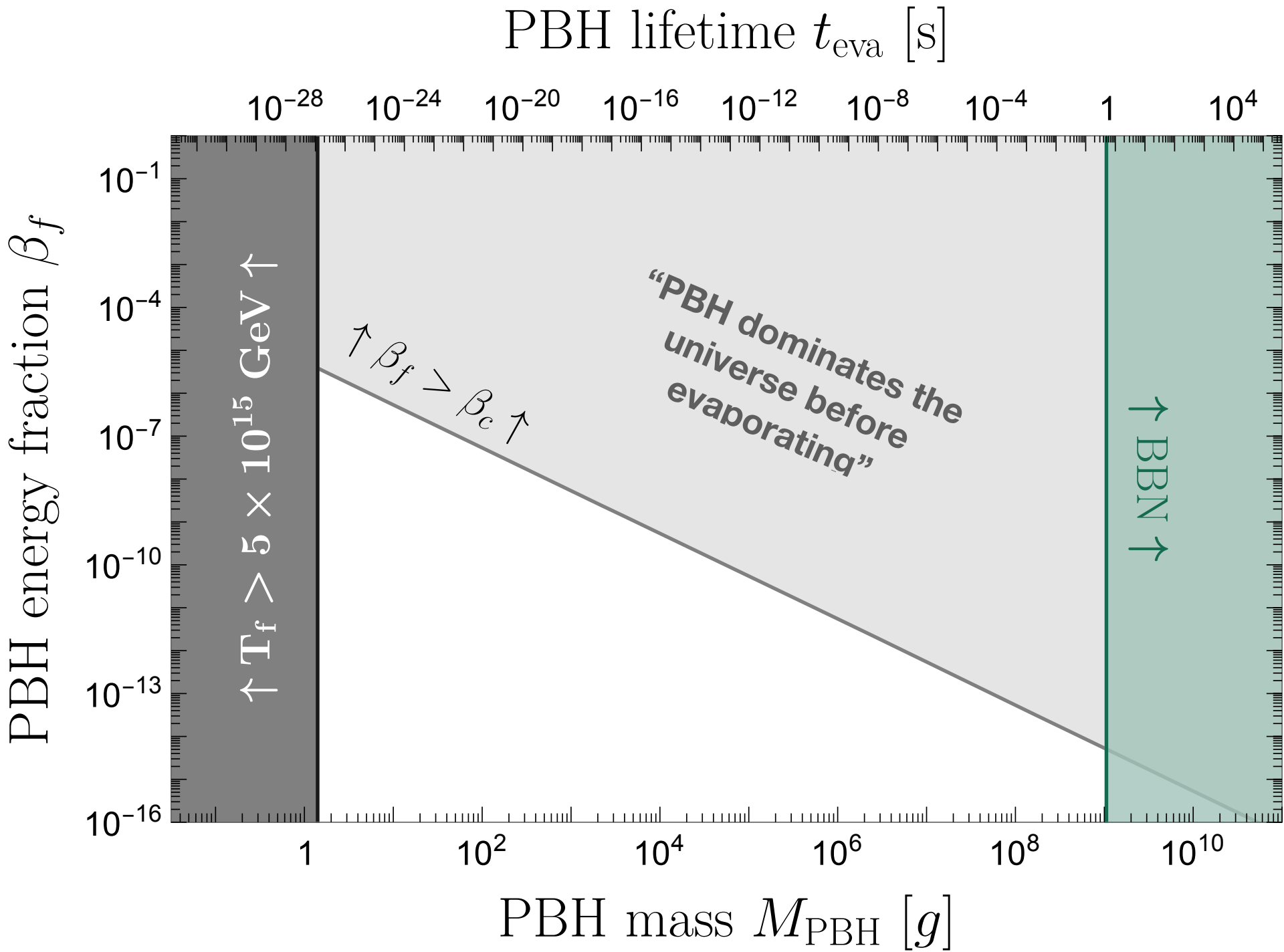
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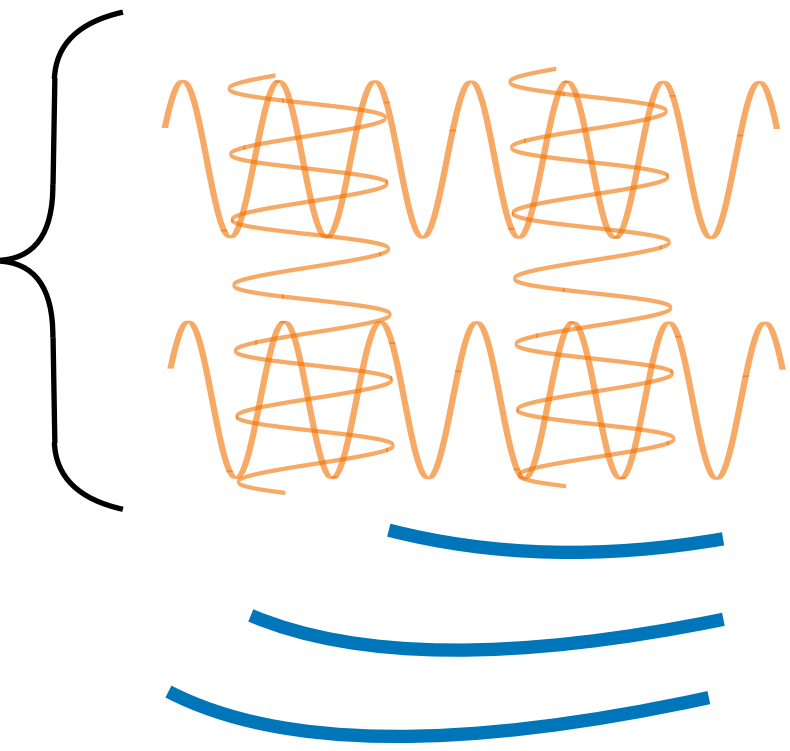
Poltergeist GWs

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



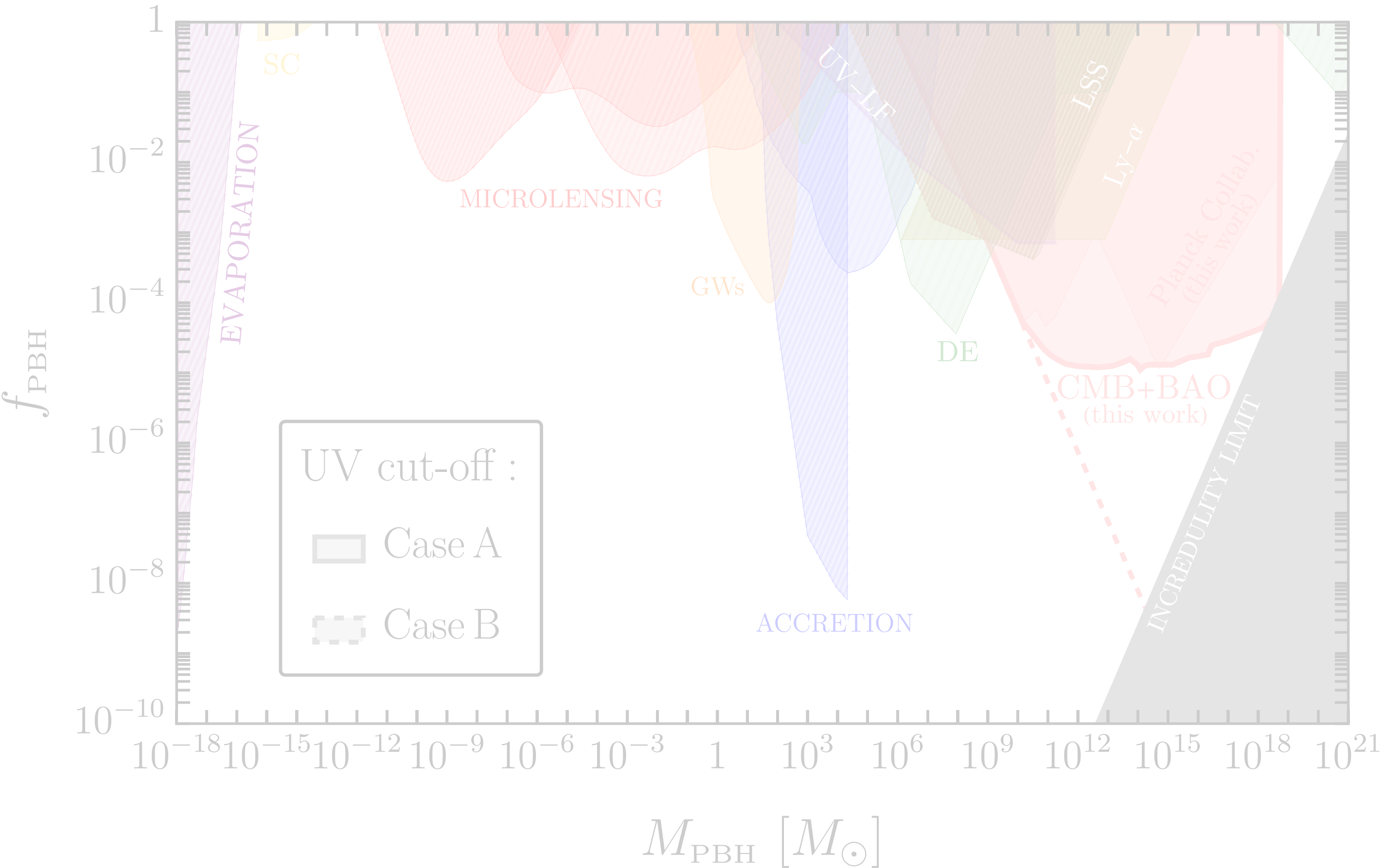
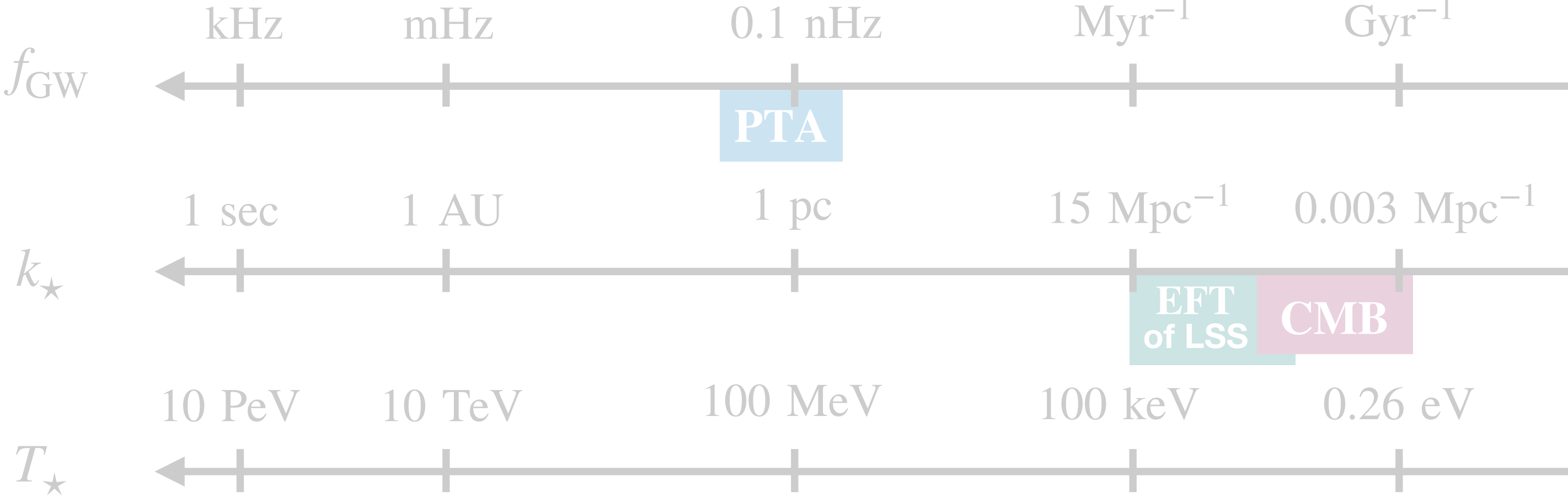
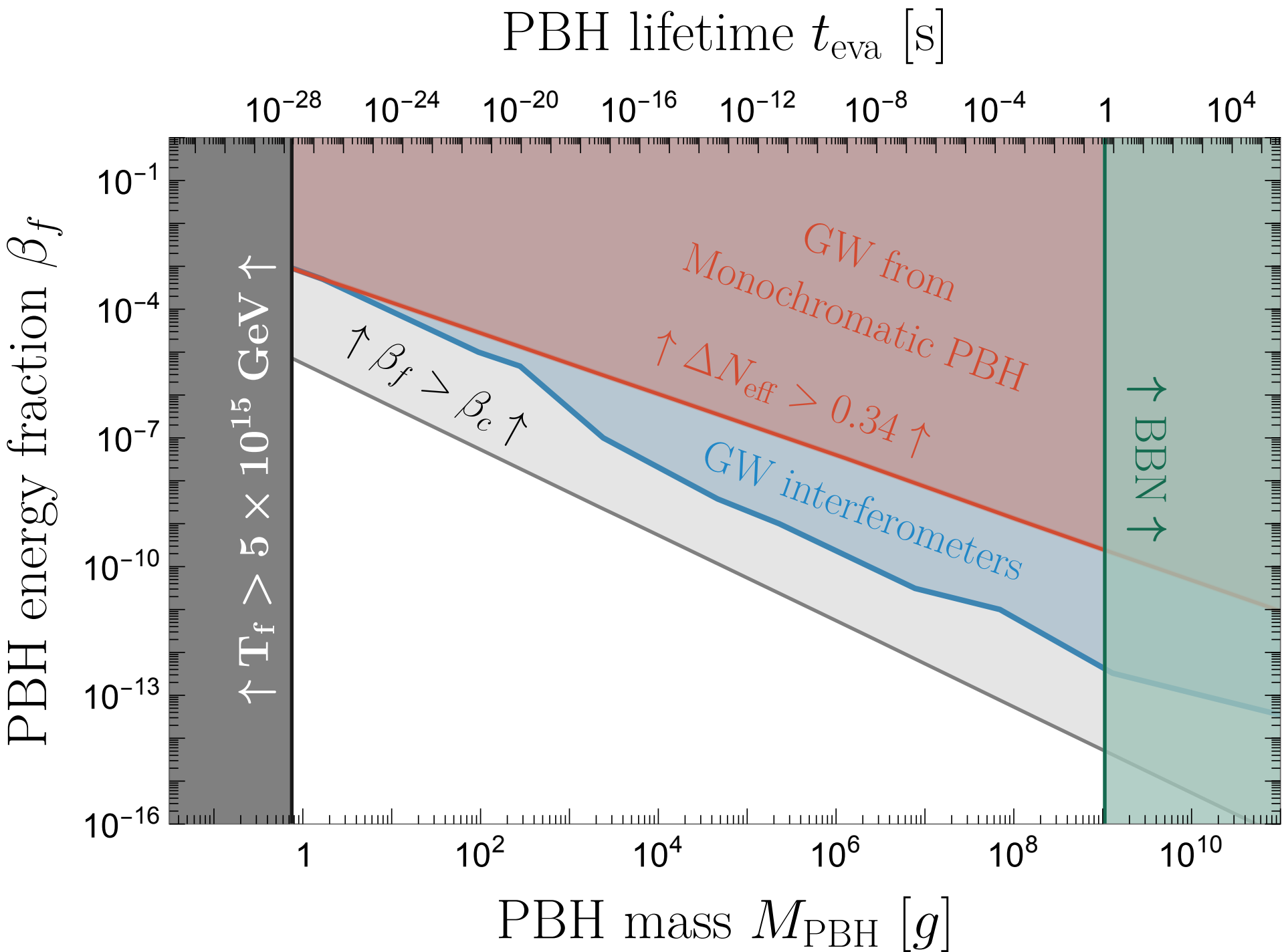
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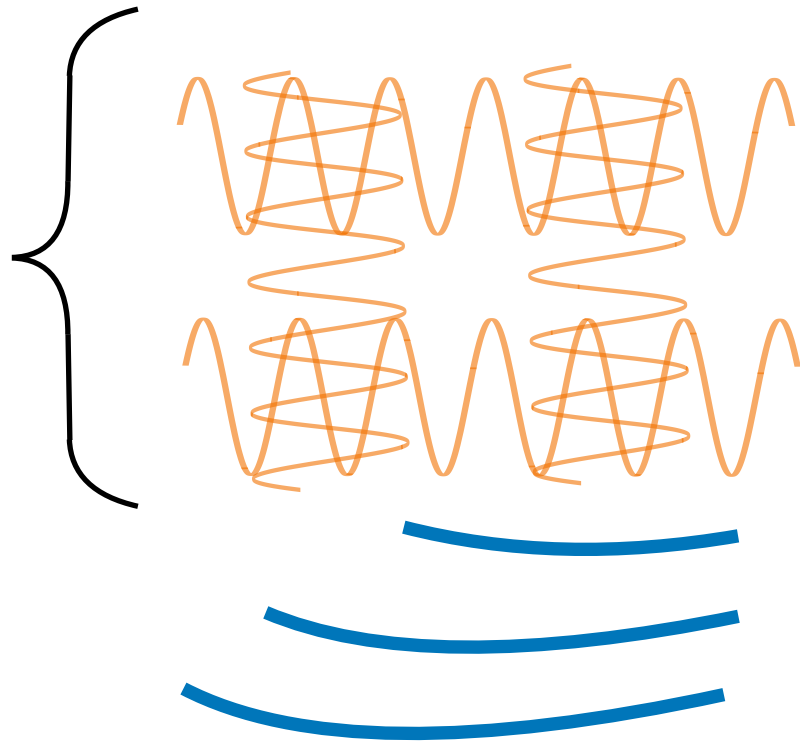
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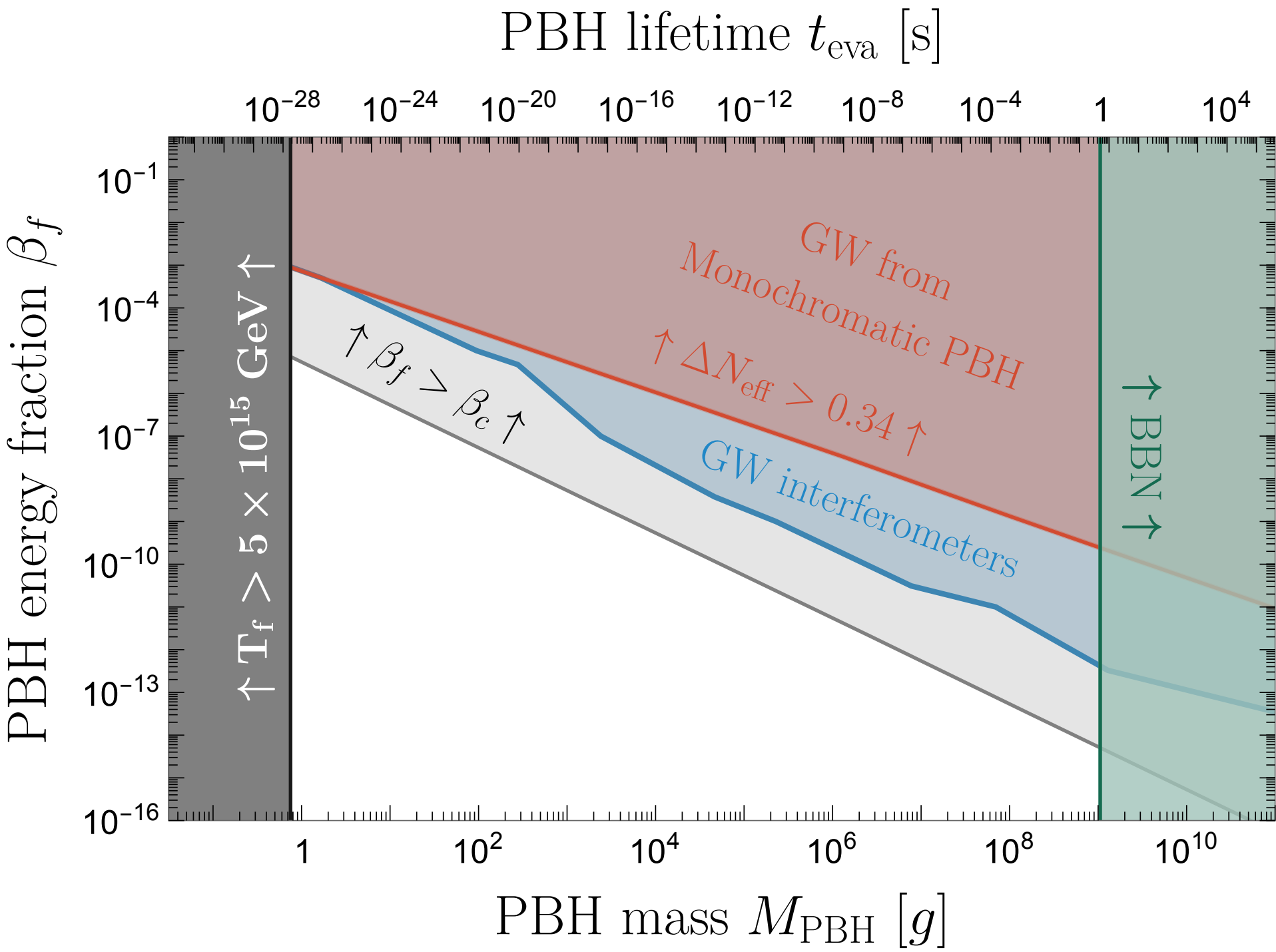
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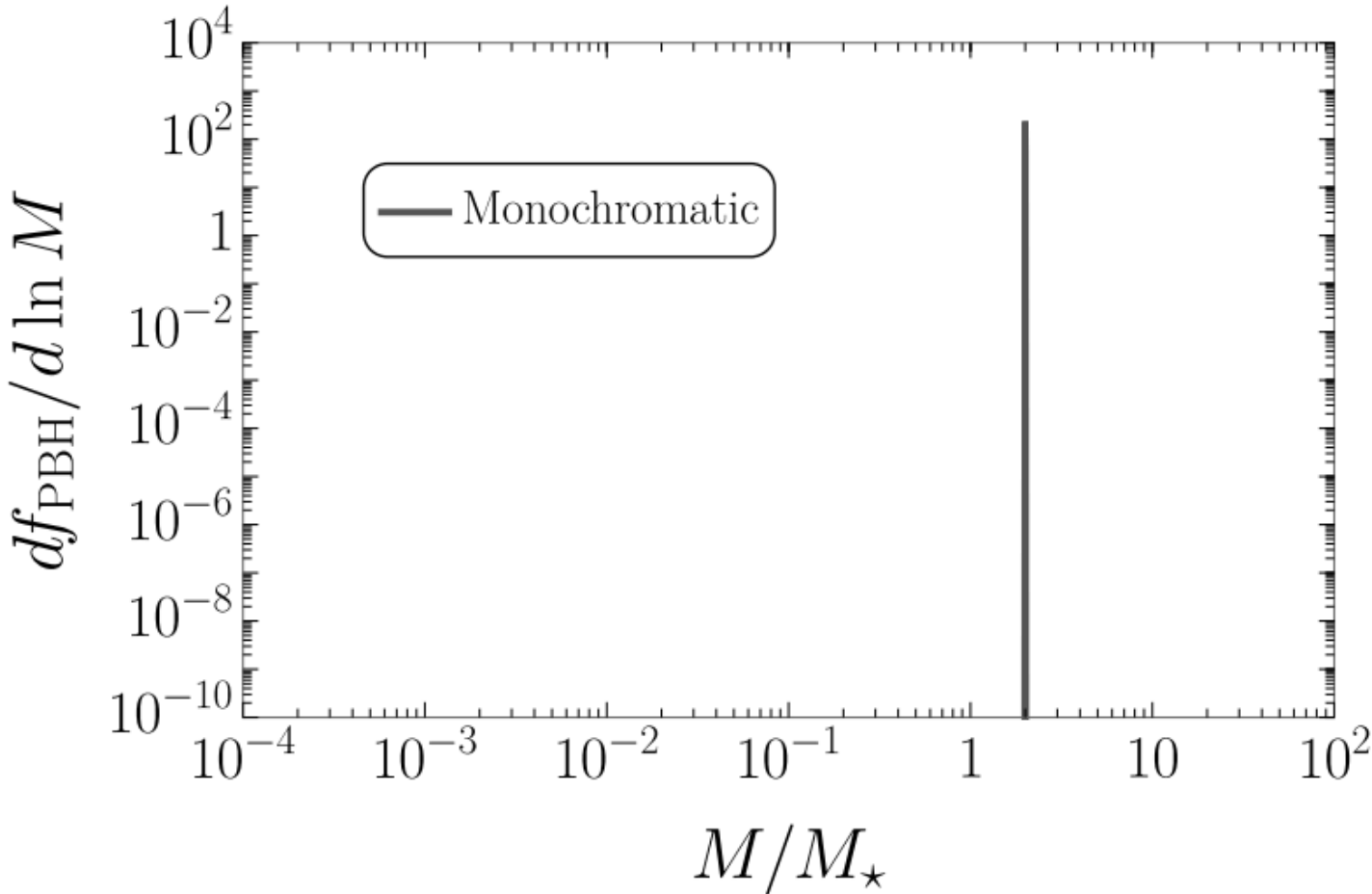


Opening the Window for Ultra-Light Primordial
Black Holes

In preparation (25XX.XXXX)

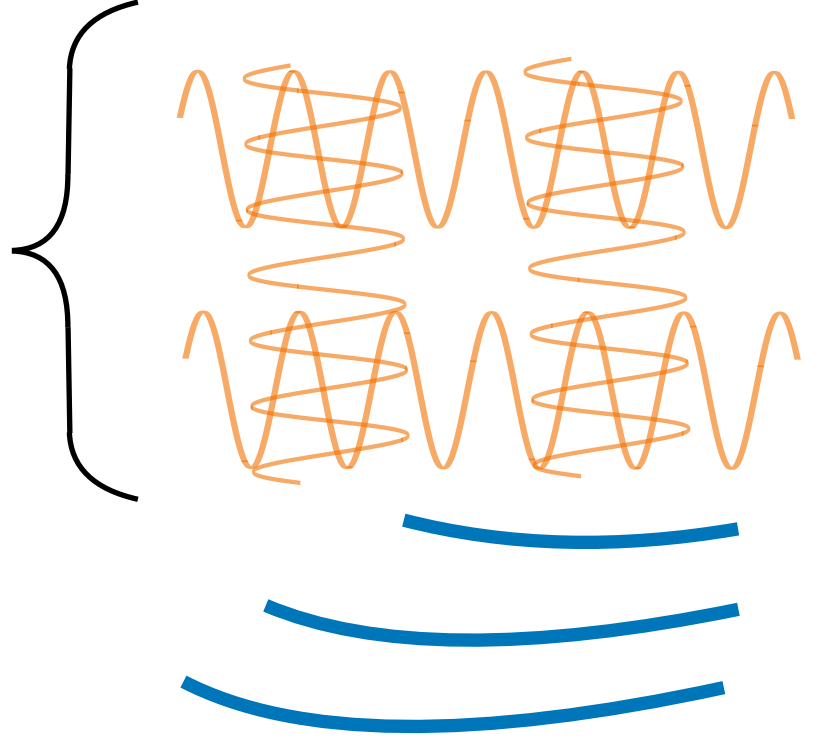
Yann Gouttenoire, Nicholas Leister, Pedro Schwaller

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



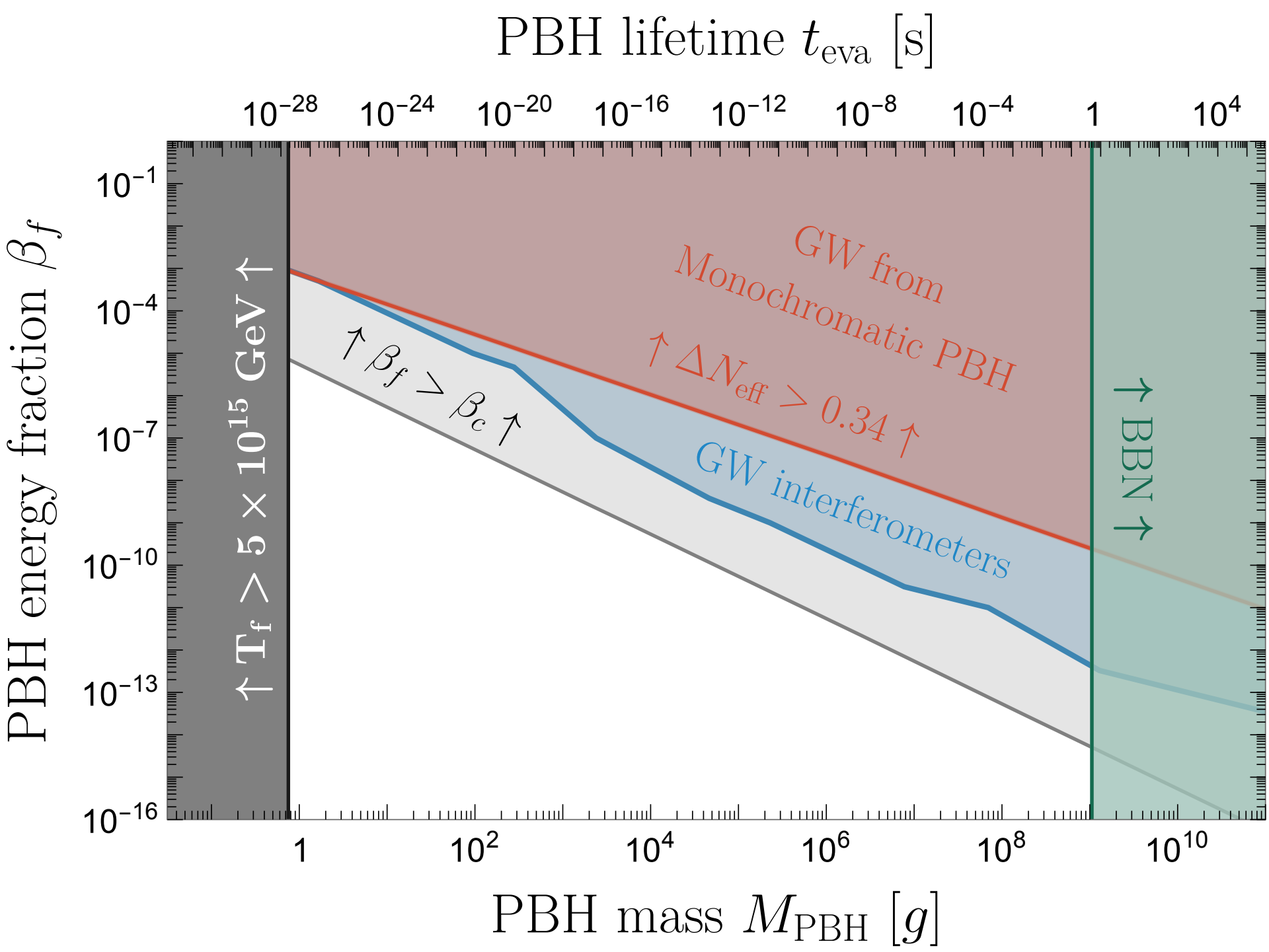
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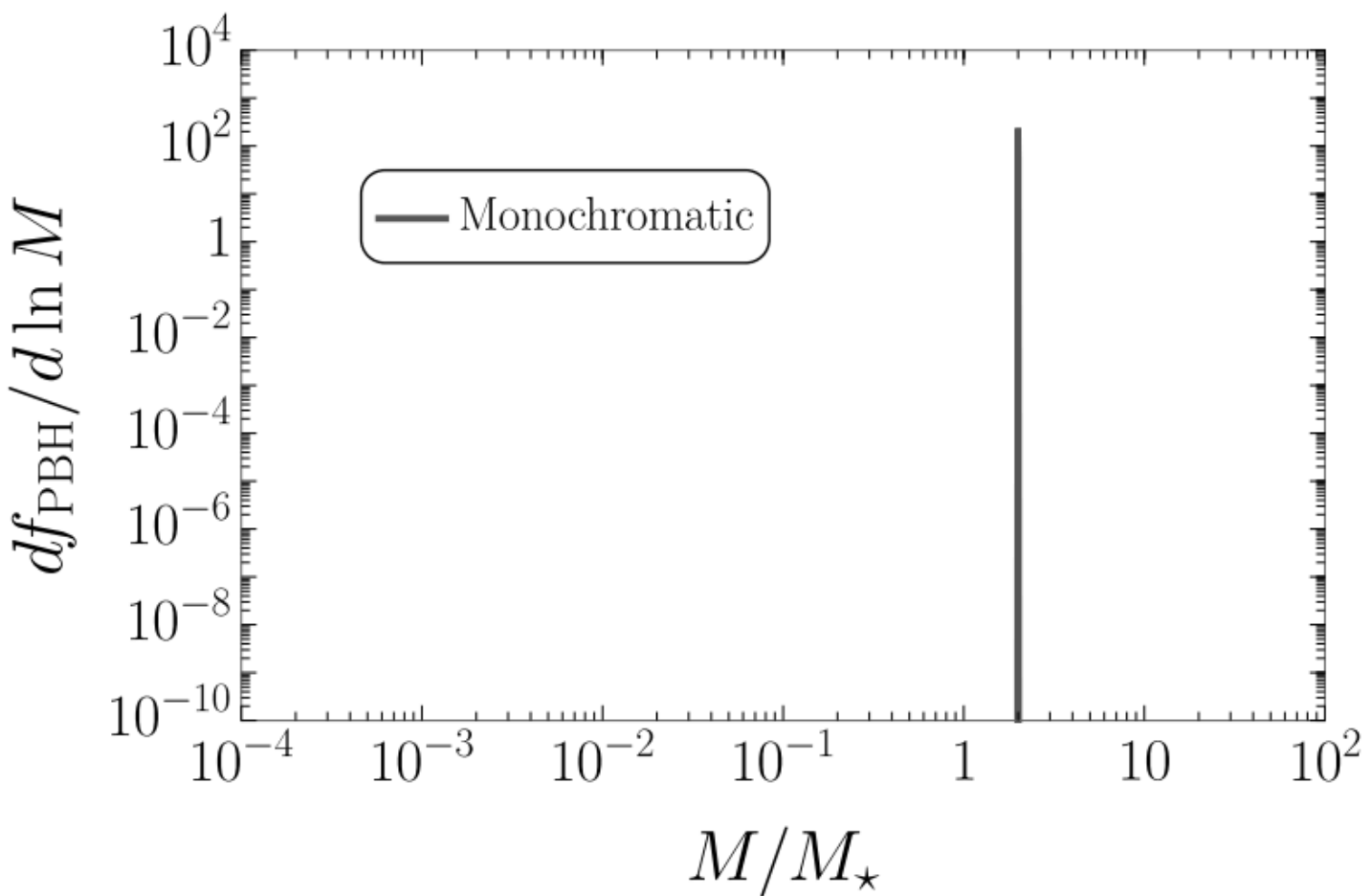
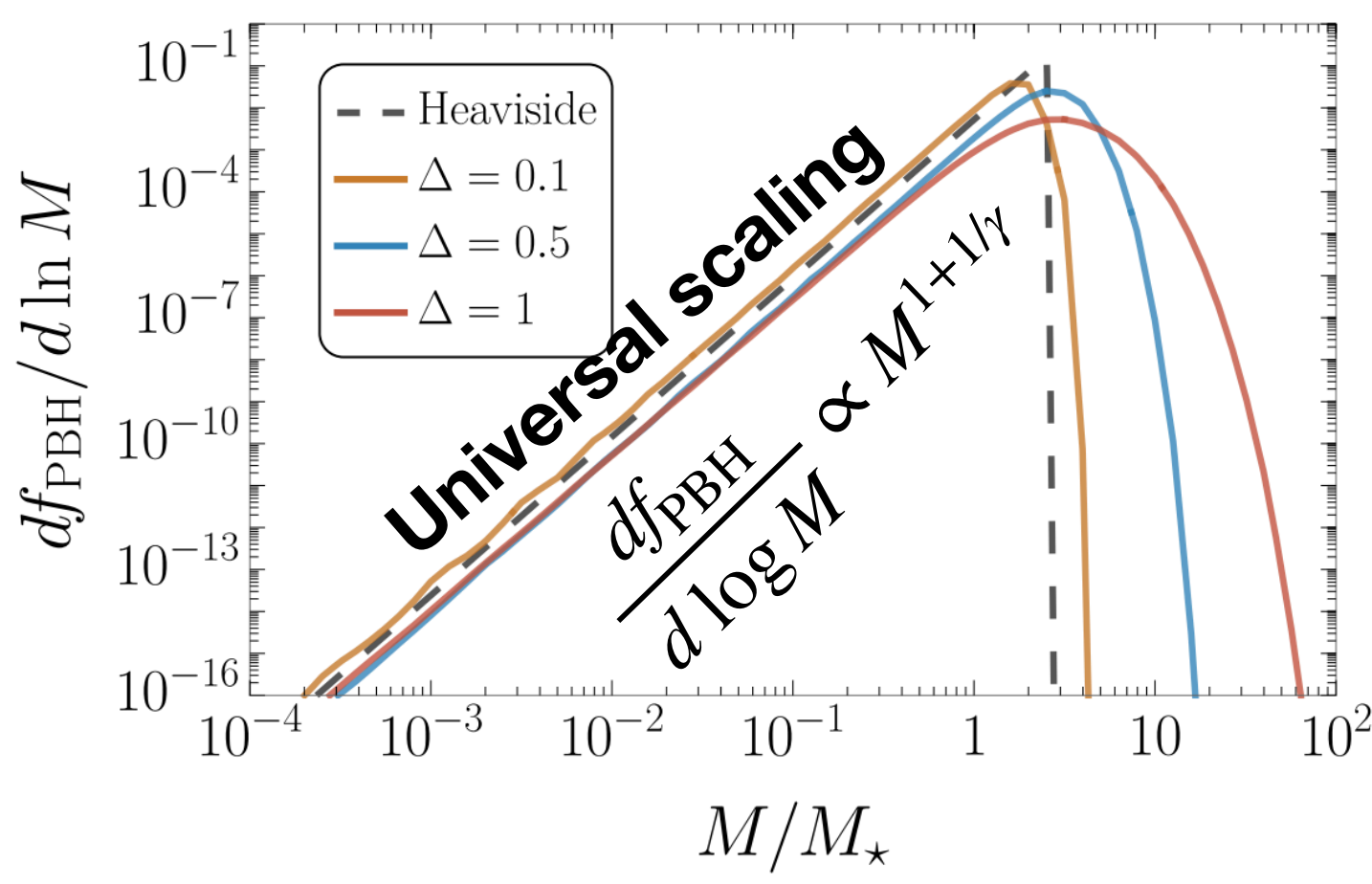


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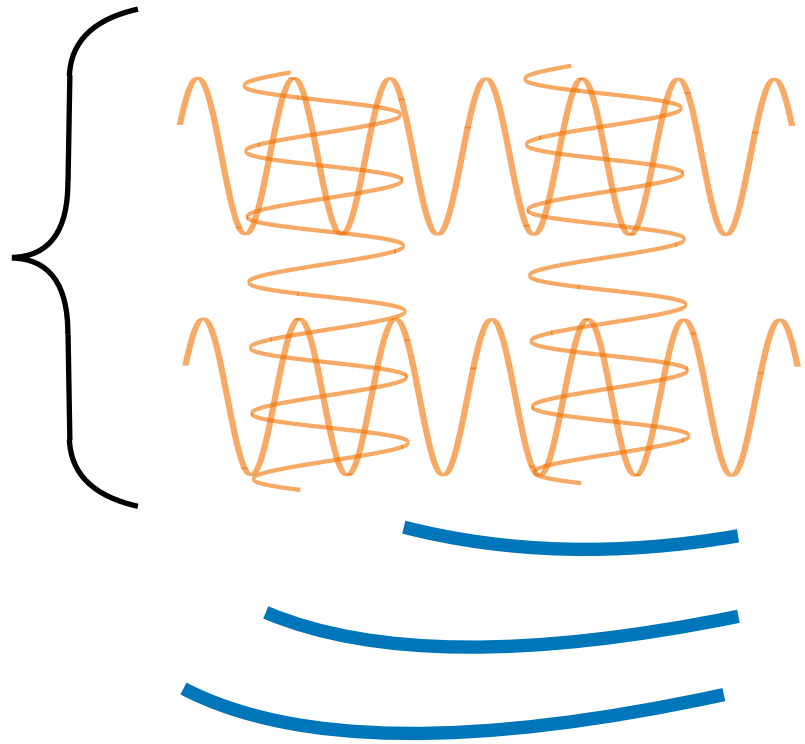
$$M_{\text{PBH}} = M_{\text{H}}(\delta - \delta_c)^\gamma$$

$$\gamma \simeq 0.36$$

Choptuik's law
(Choptuik 93')

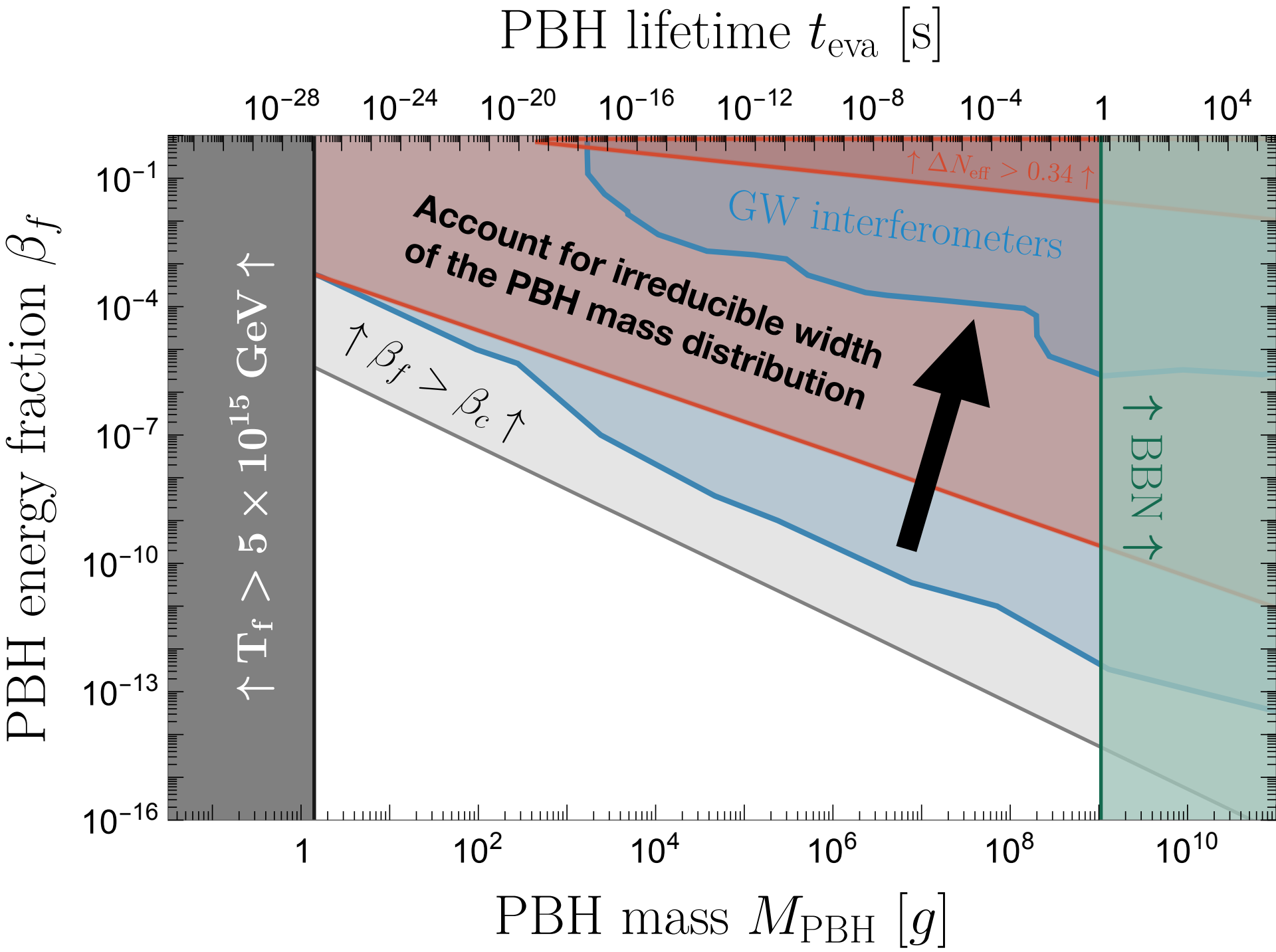
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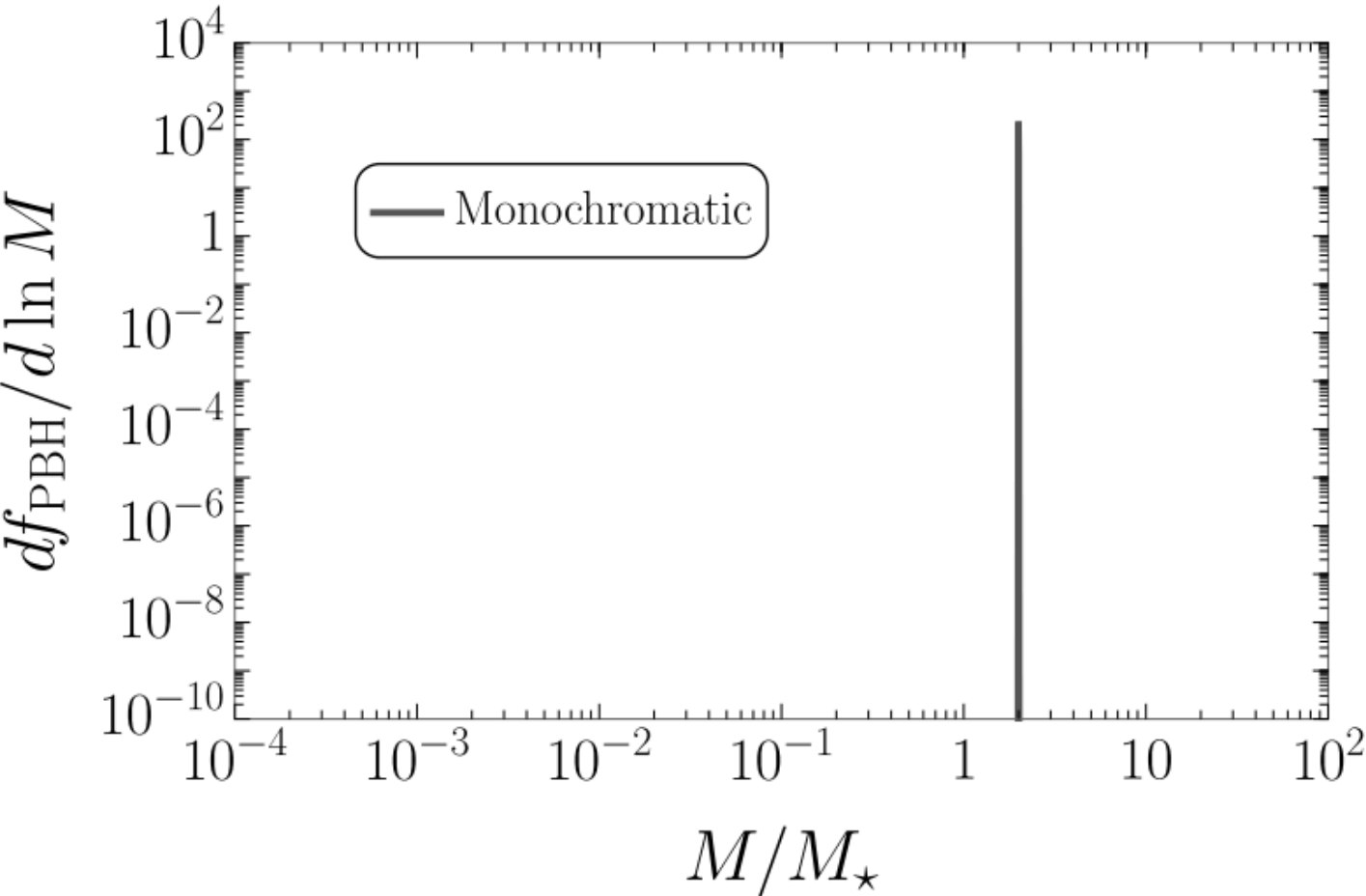
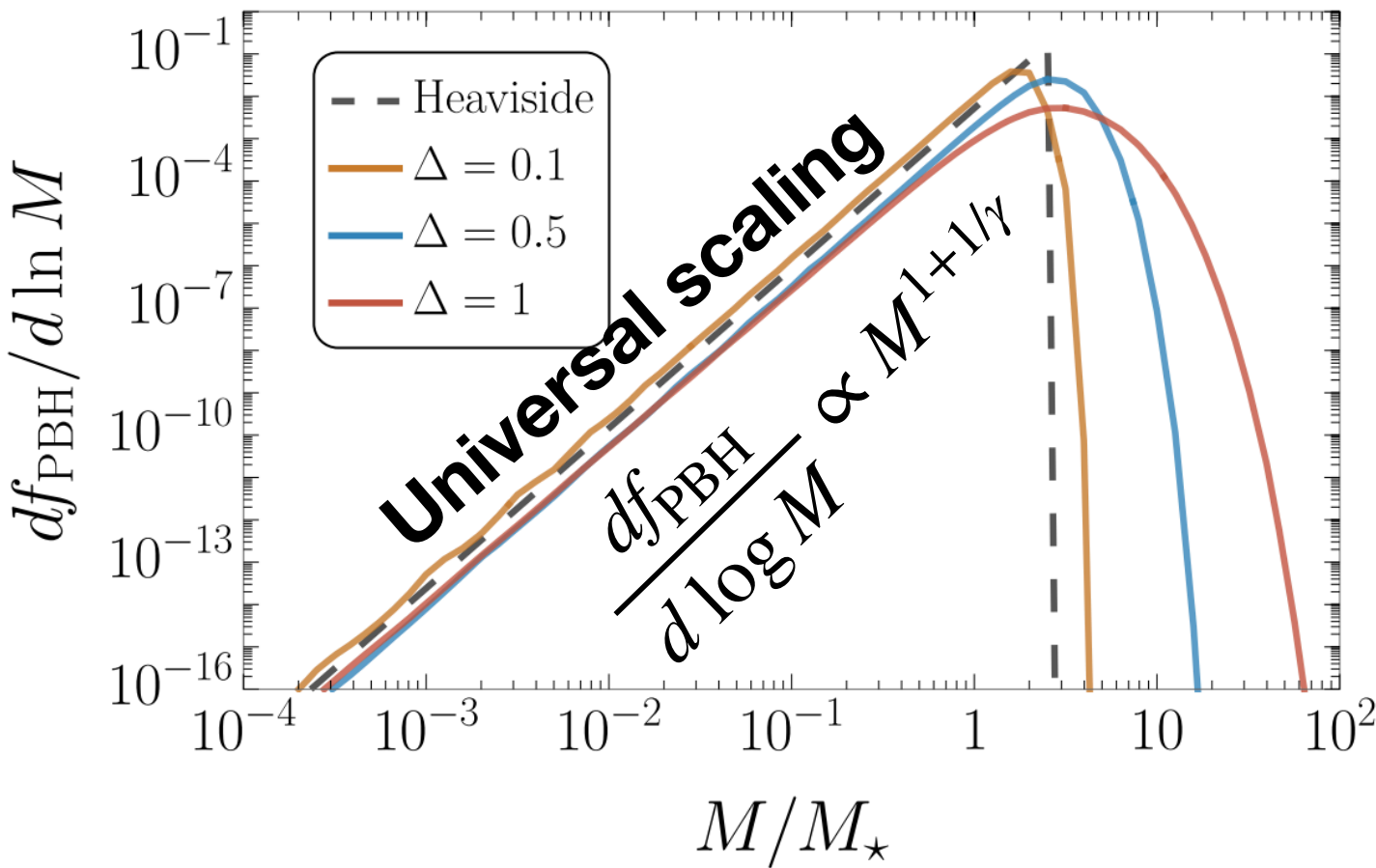


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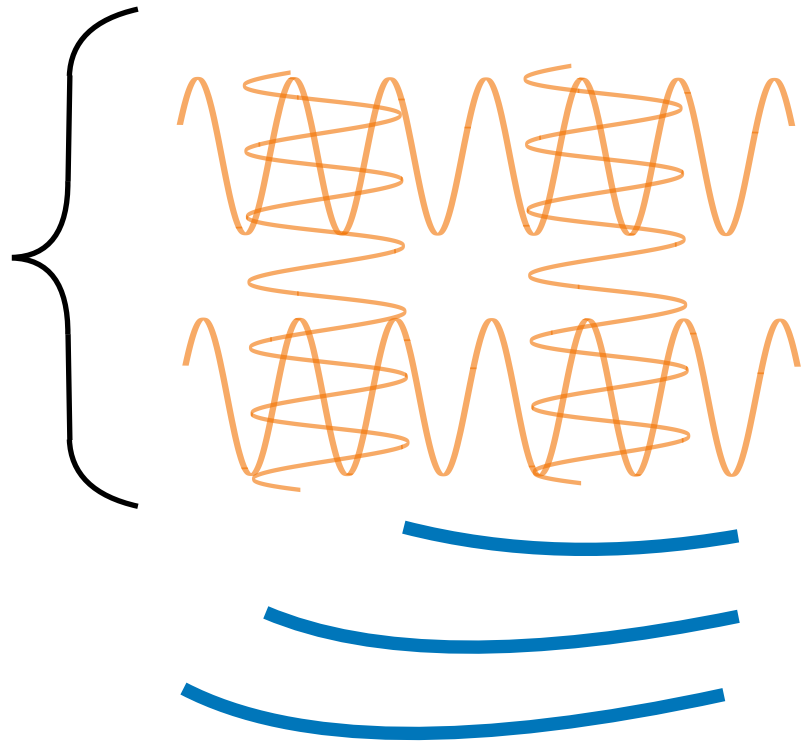
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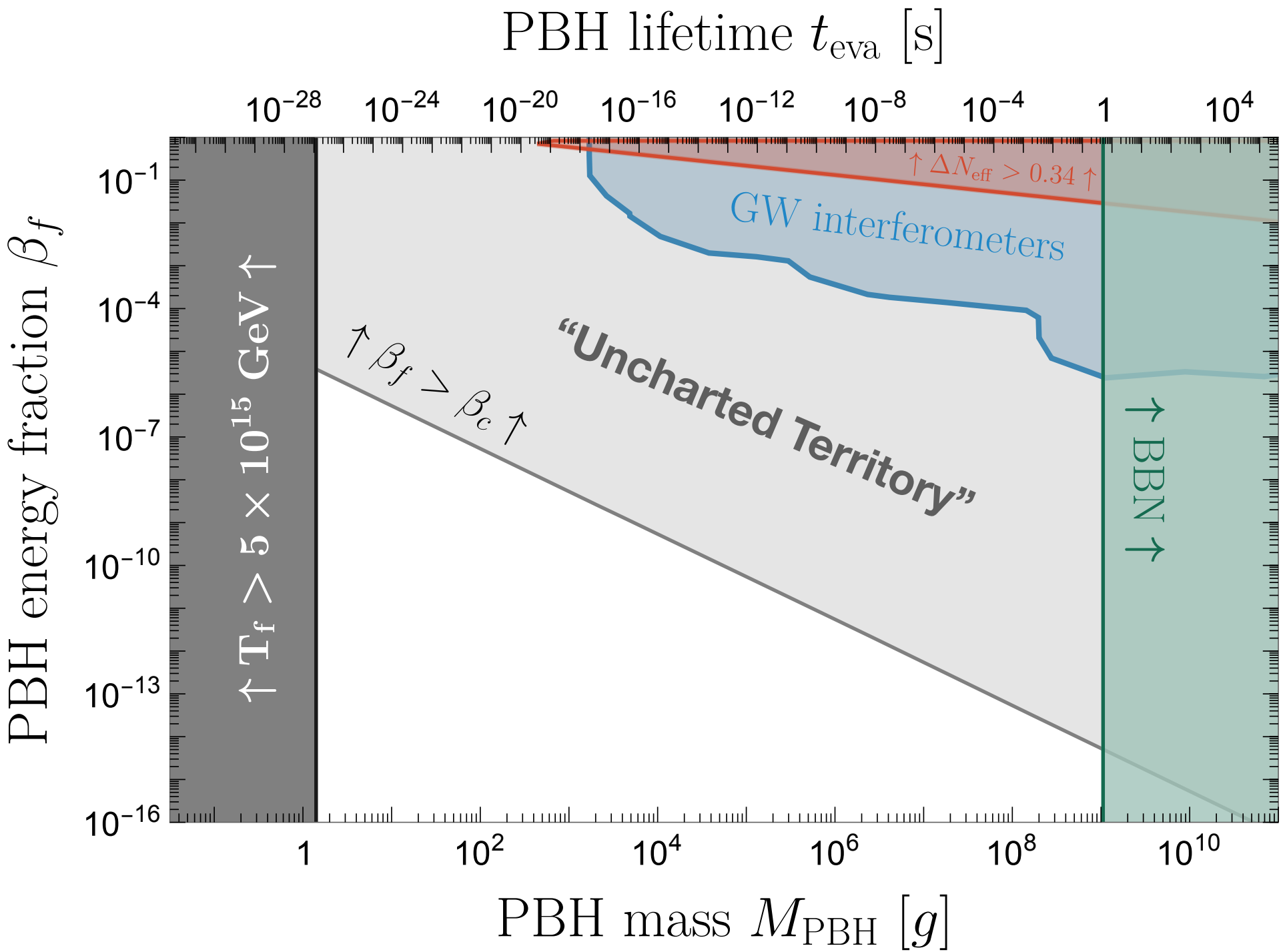
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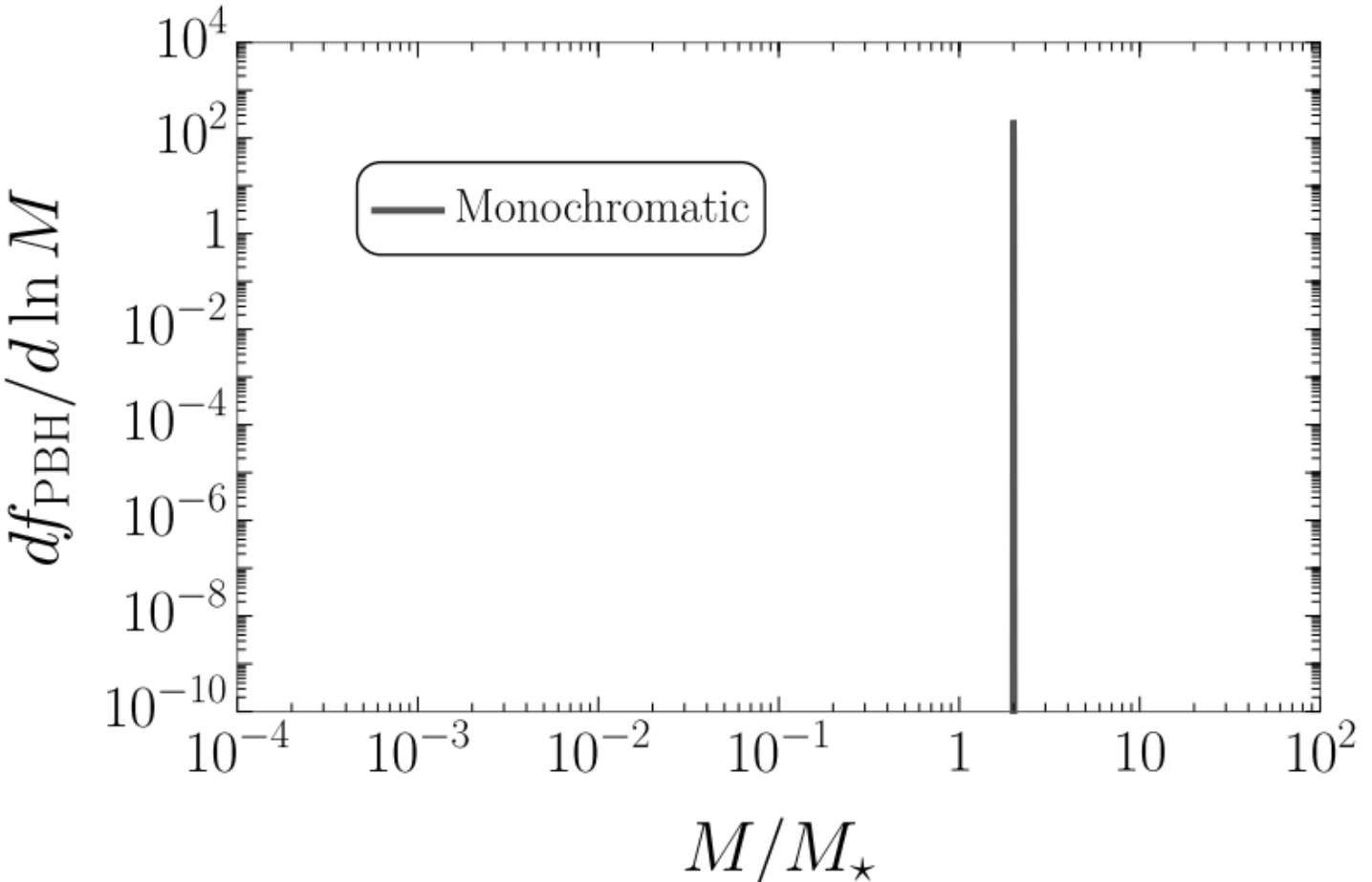
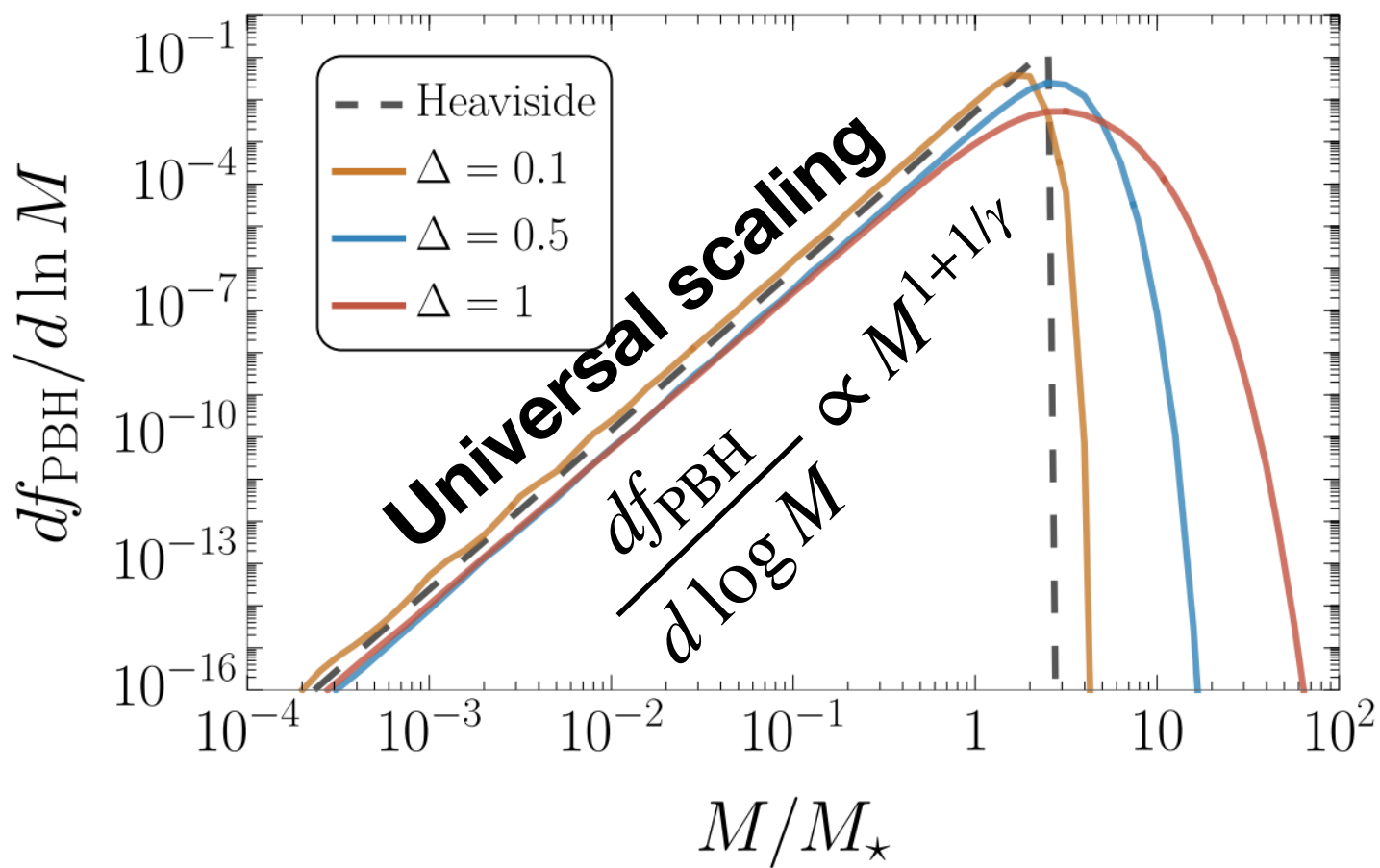


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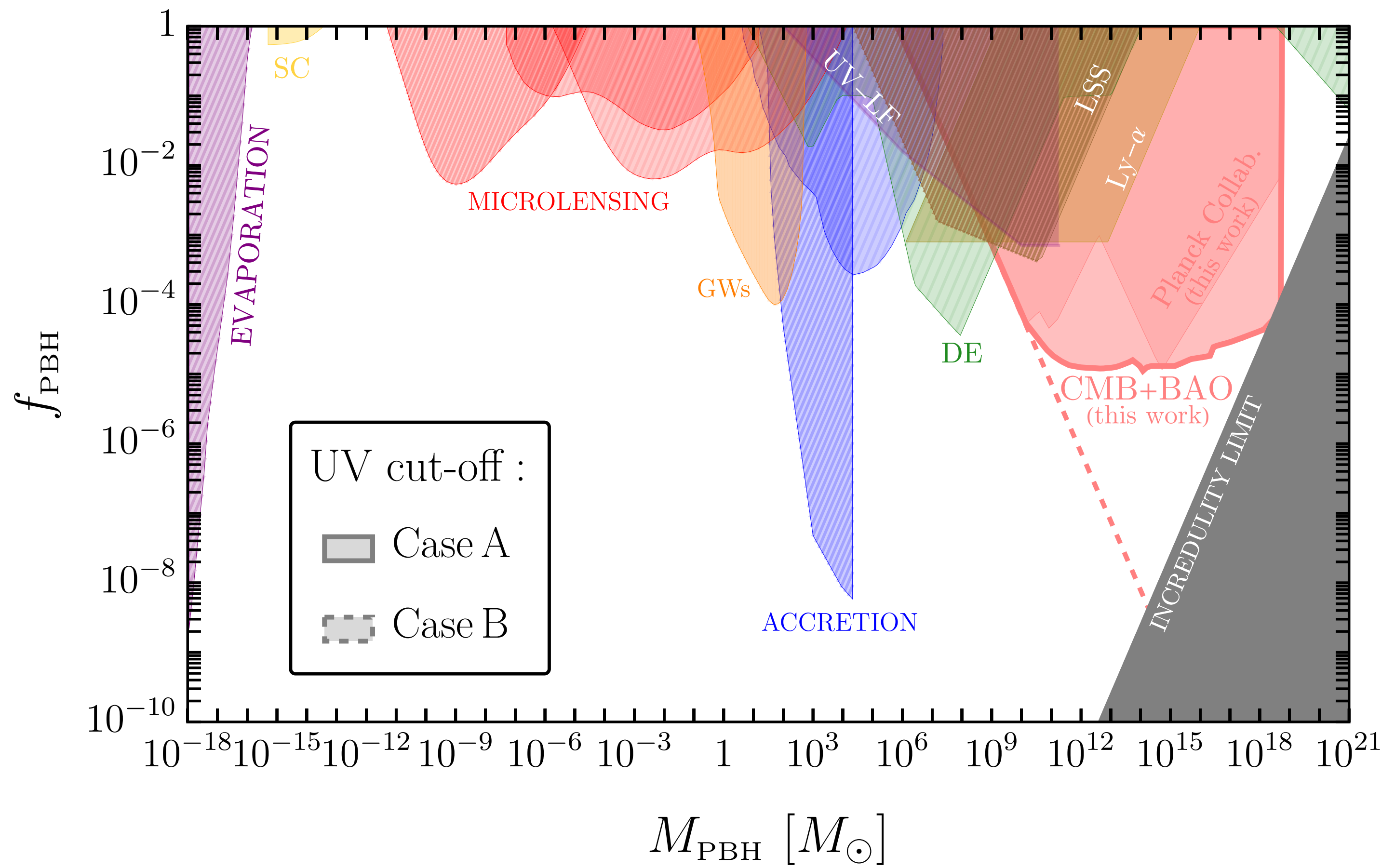
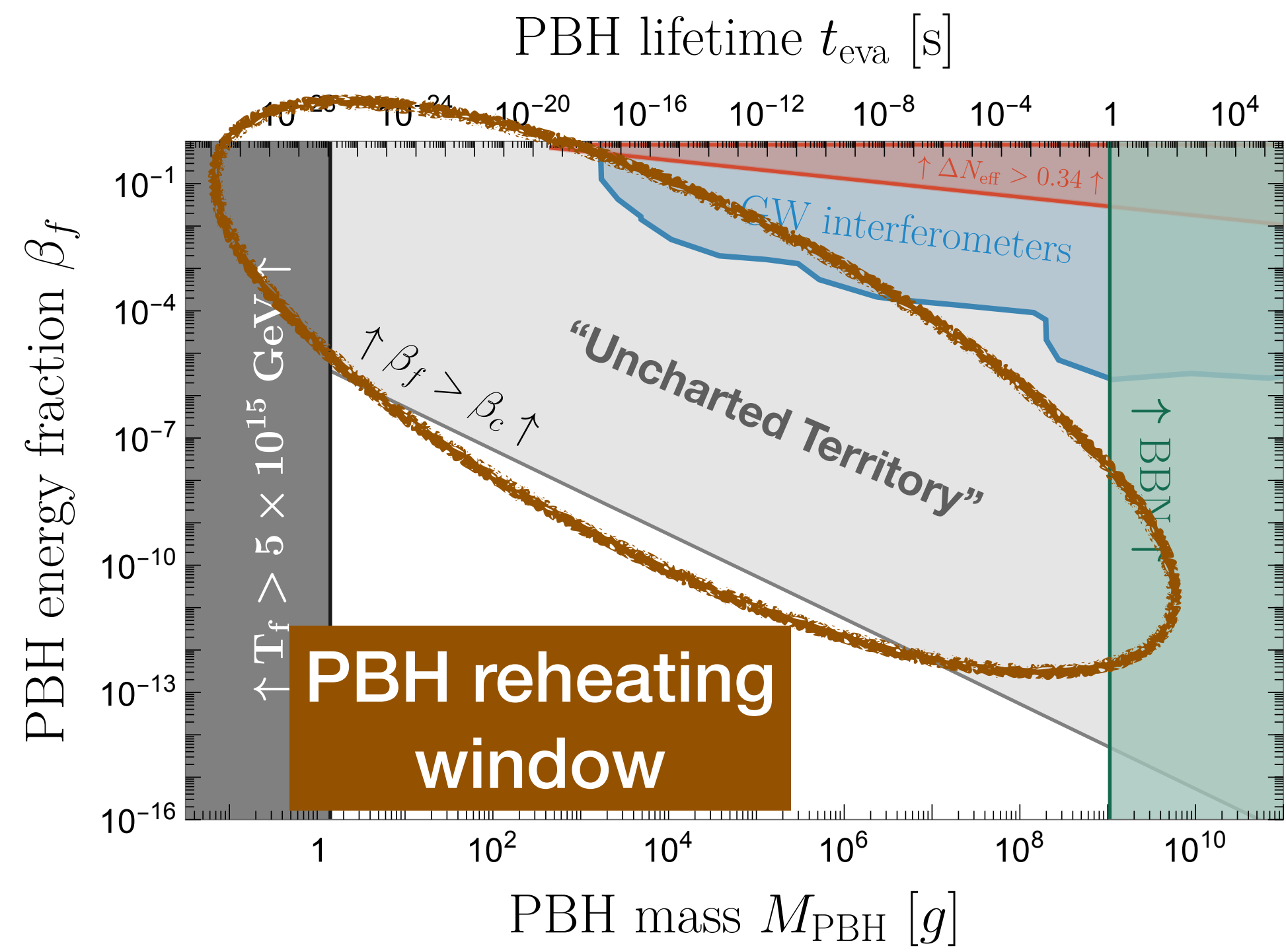
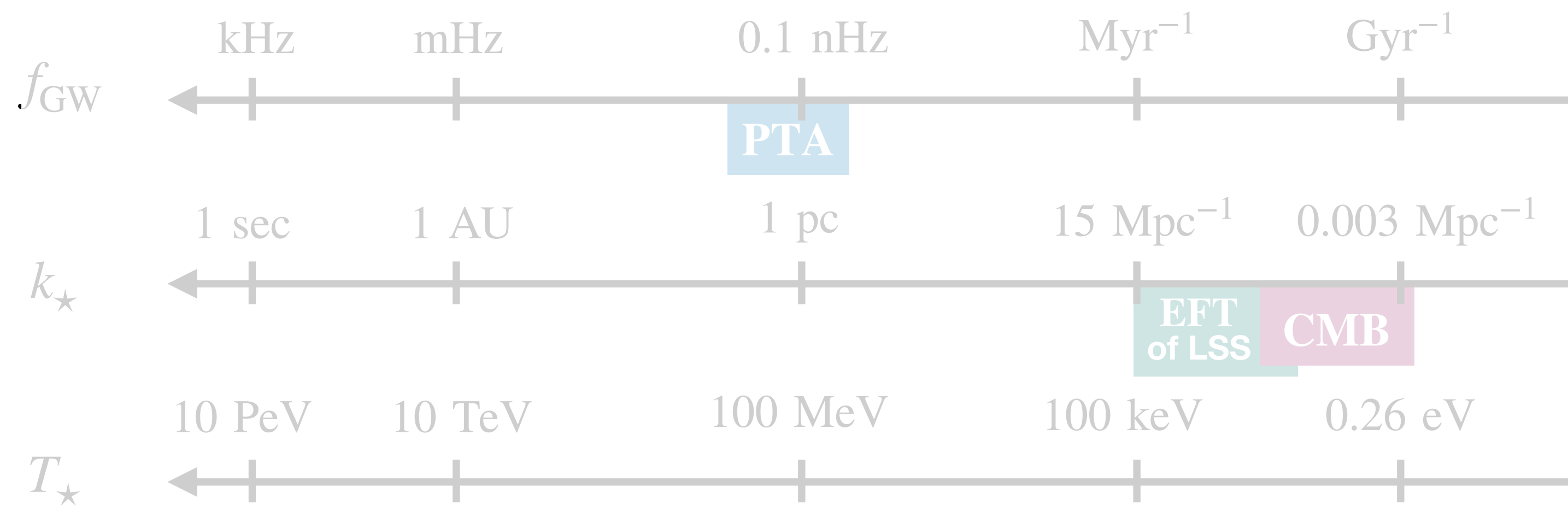
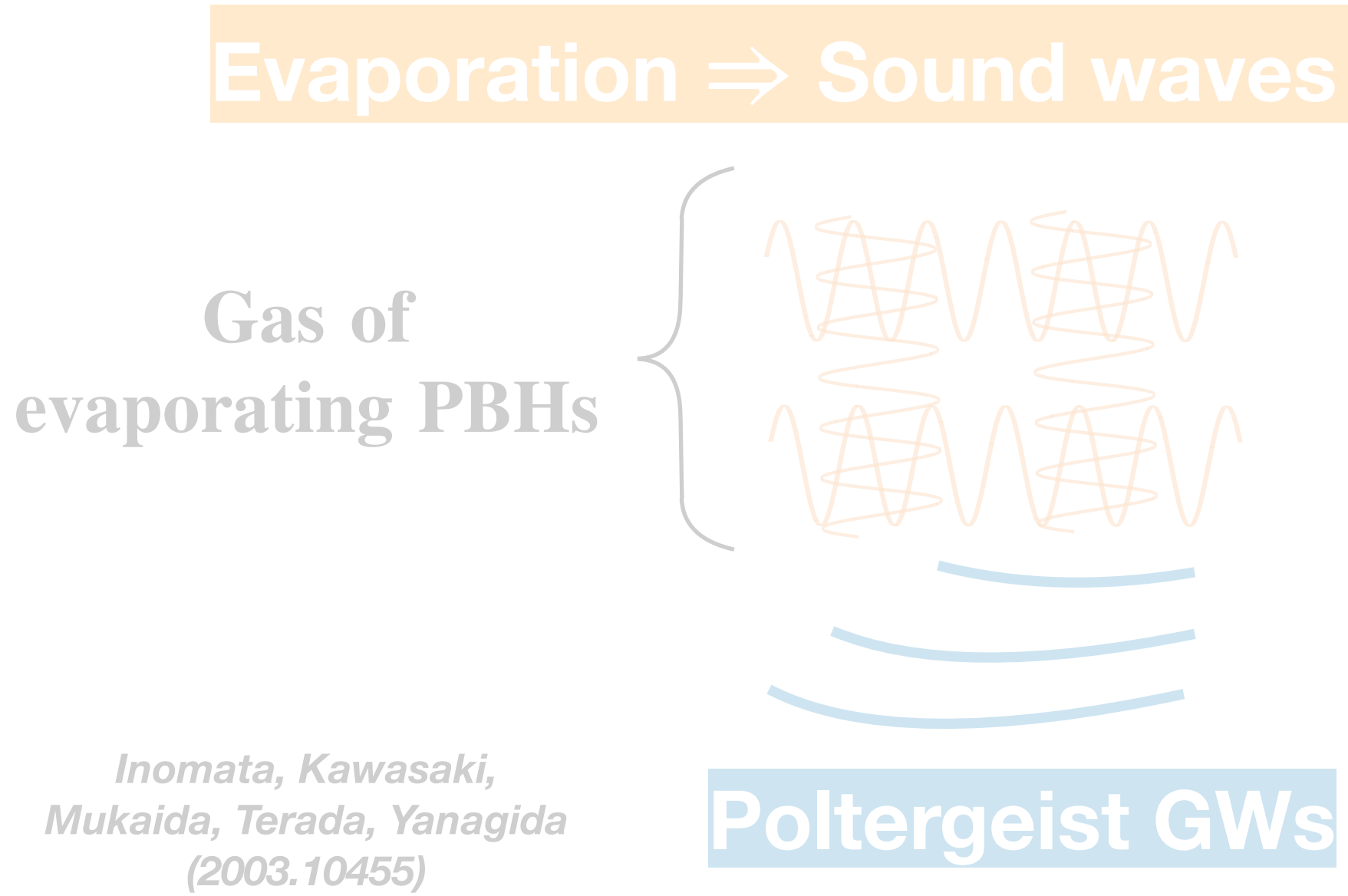
PRISMA+ Cluster of Excellence & MITP, Johannes Gutenberg University, 55099 Mainz, Germany

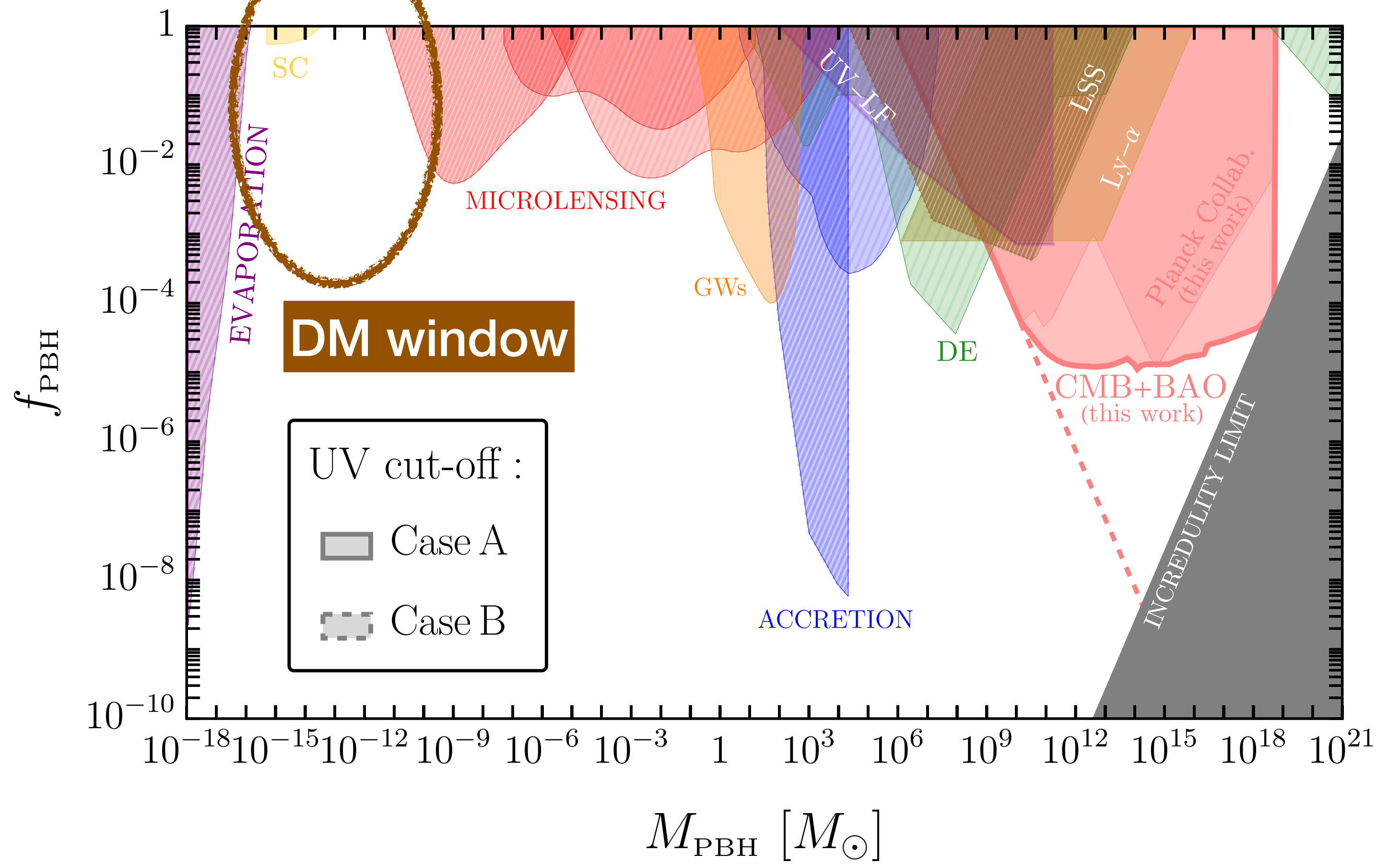
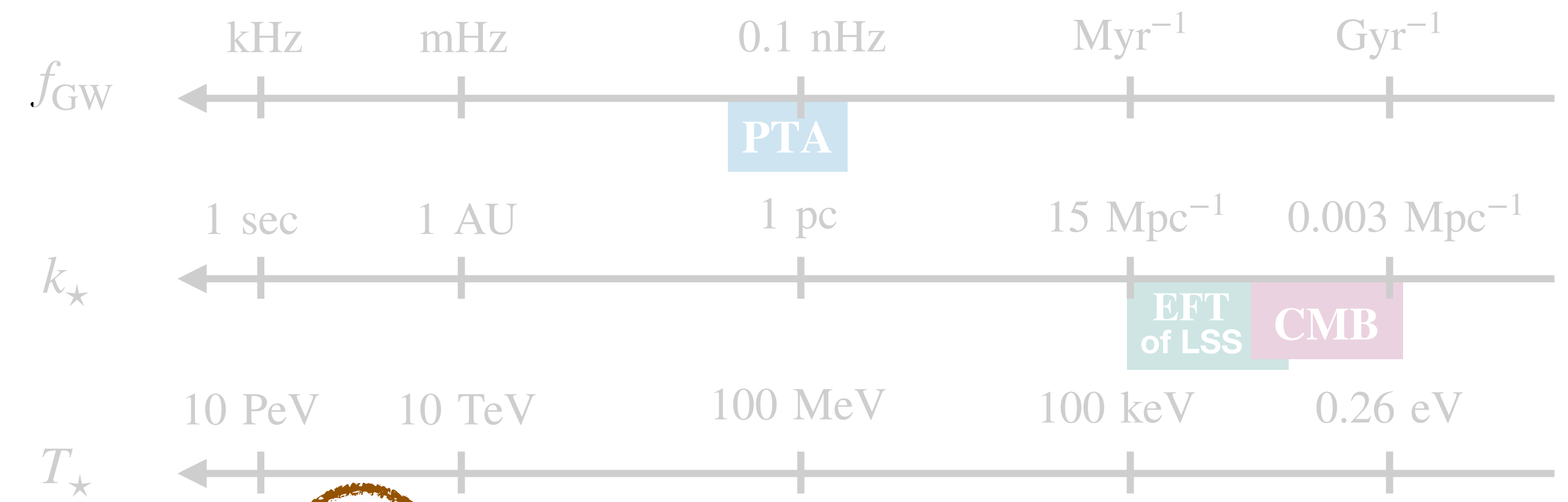
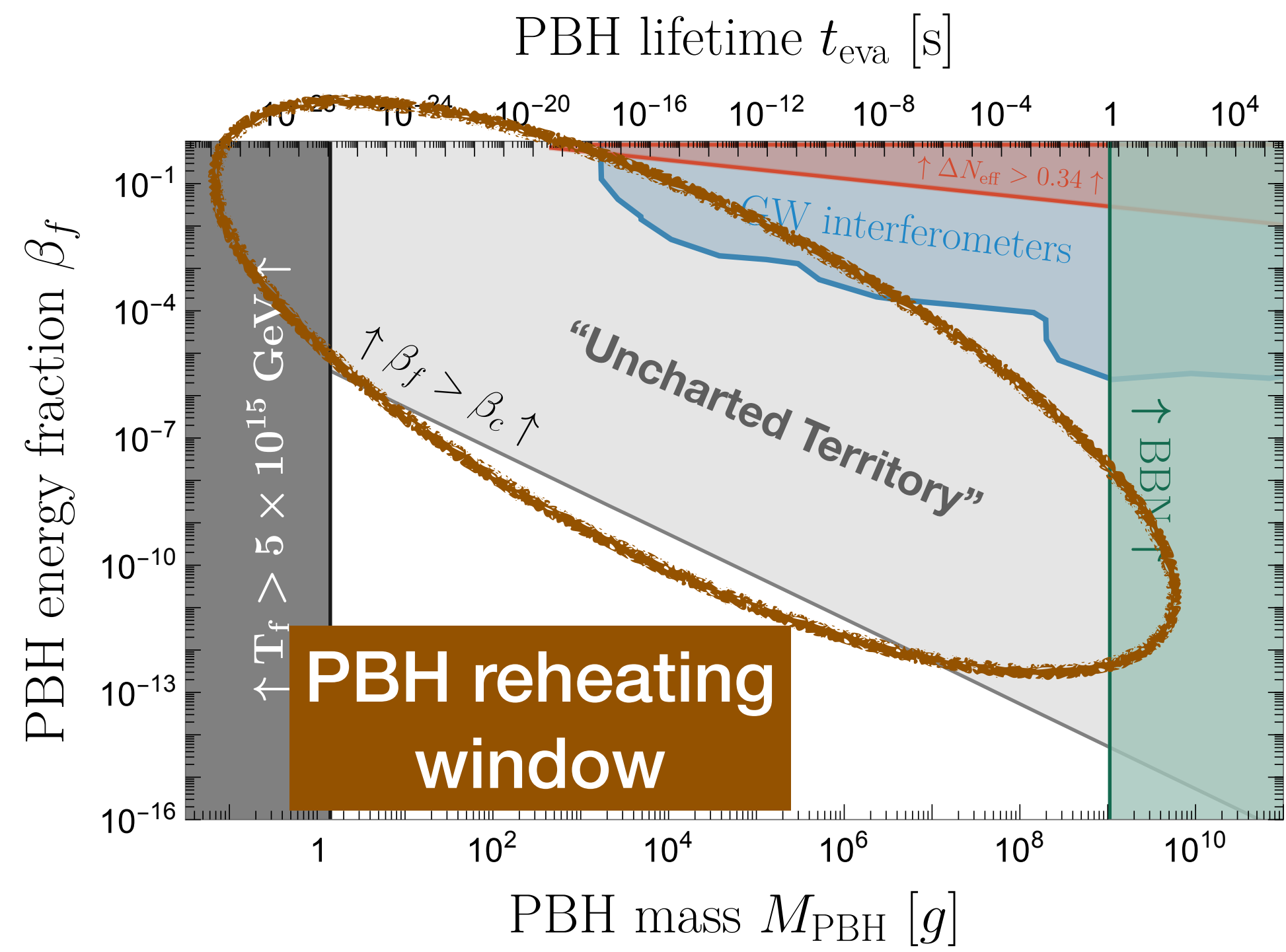
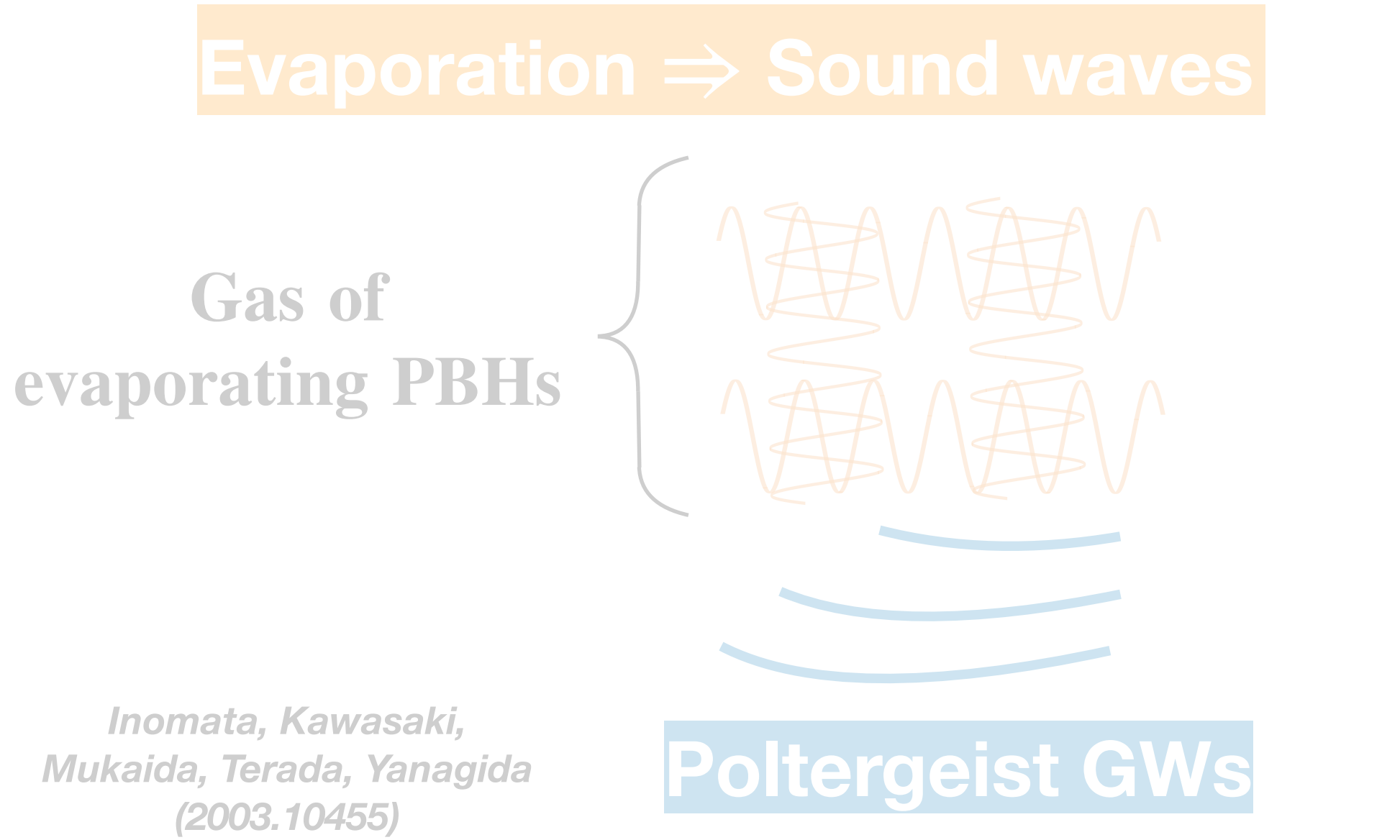


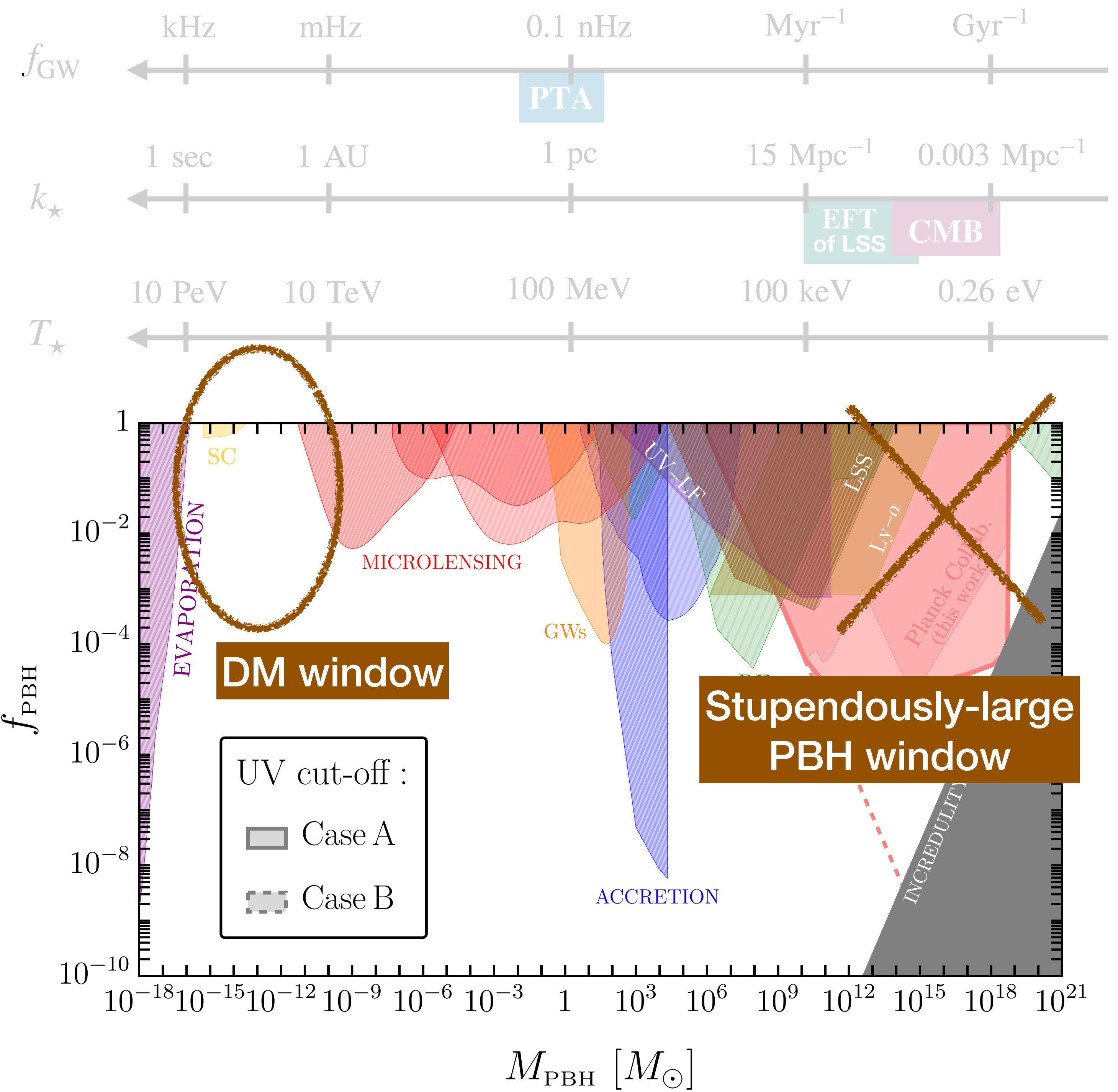
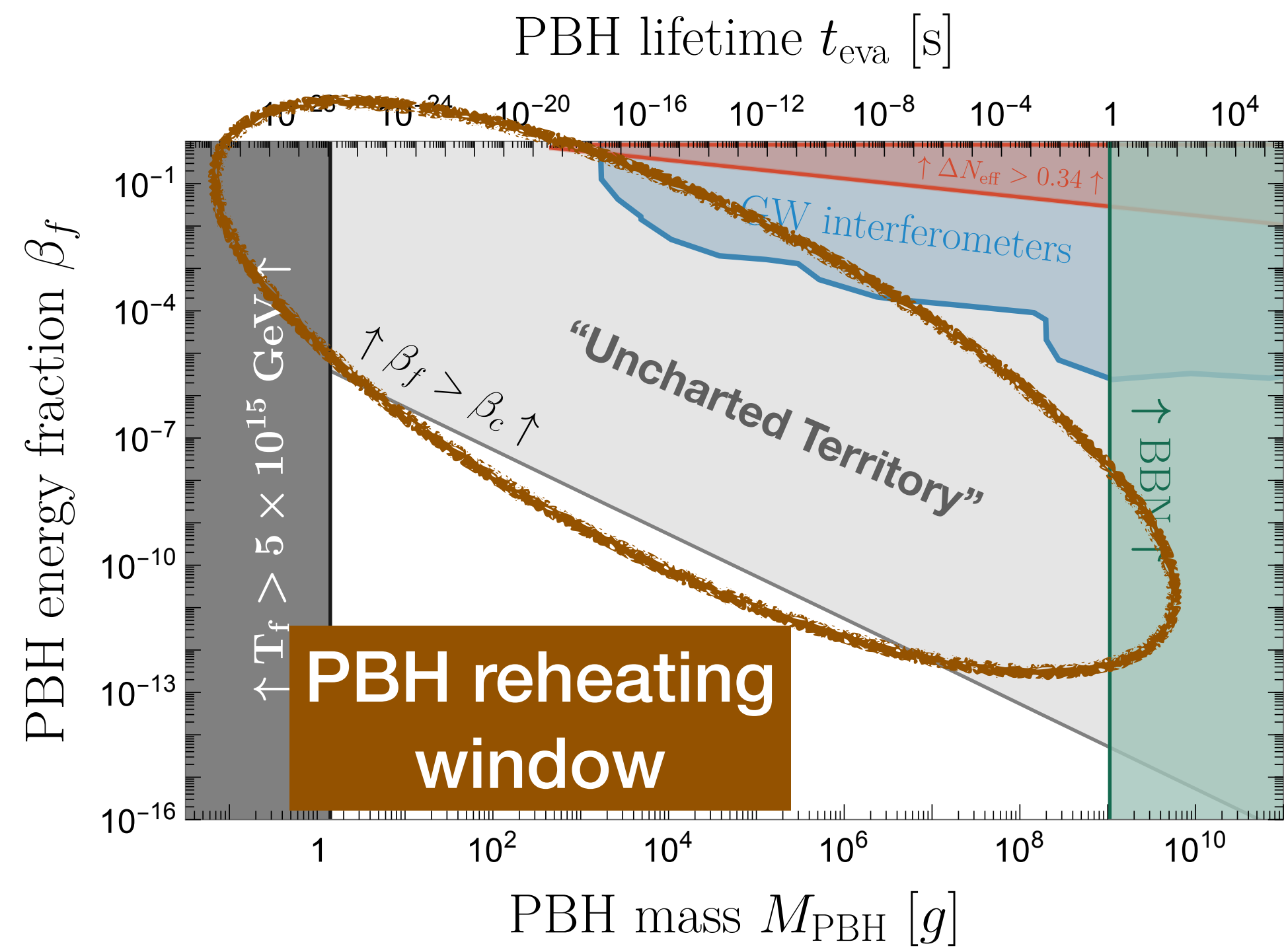
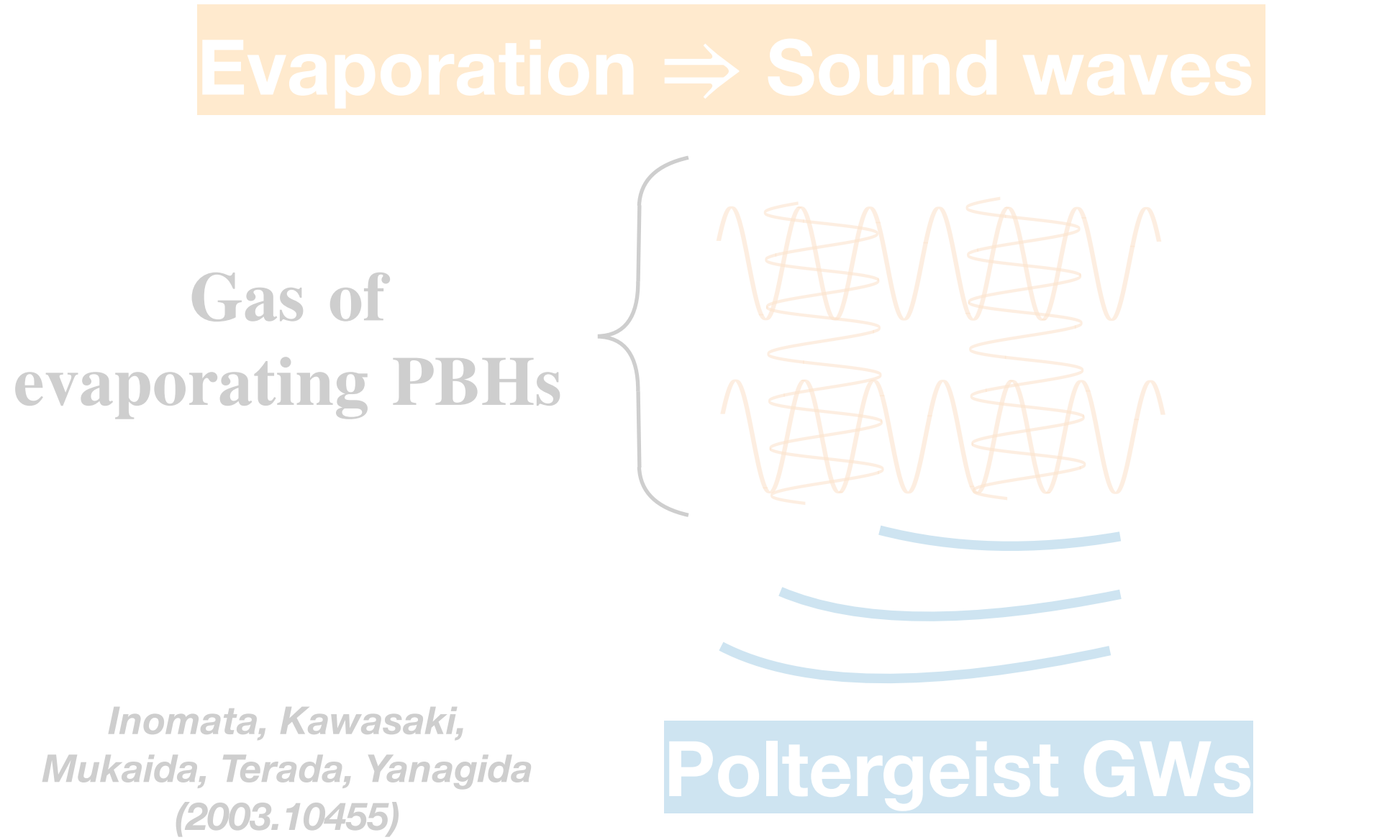
$M_{\text{PBH}} = M_{\text{H}}(\delta - \delta_c)^\gamma$

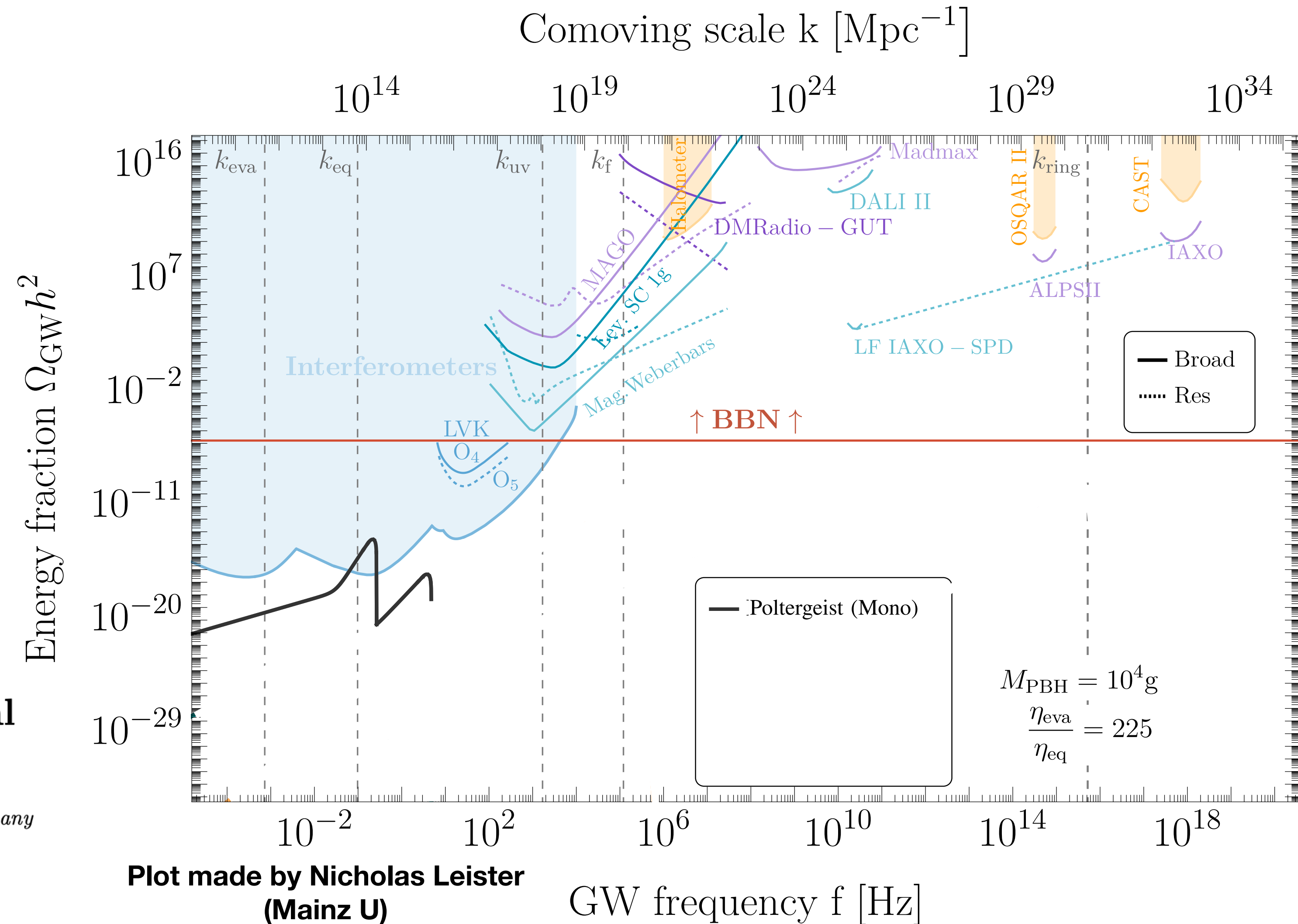
$\gamma \simeq 0.36$

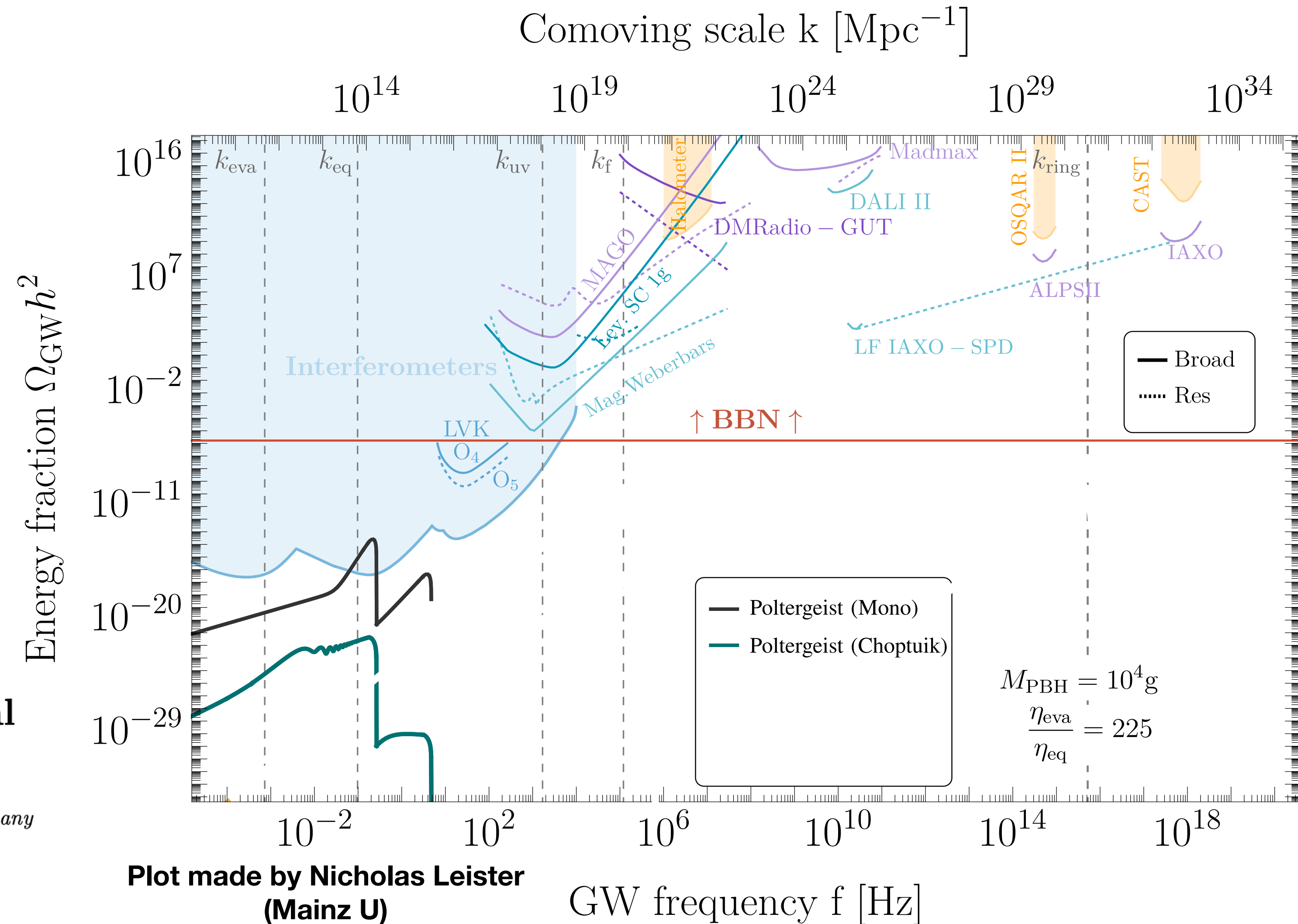
Choptuik's law
(Choptuik 93')



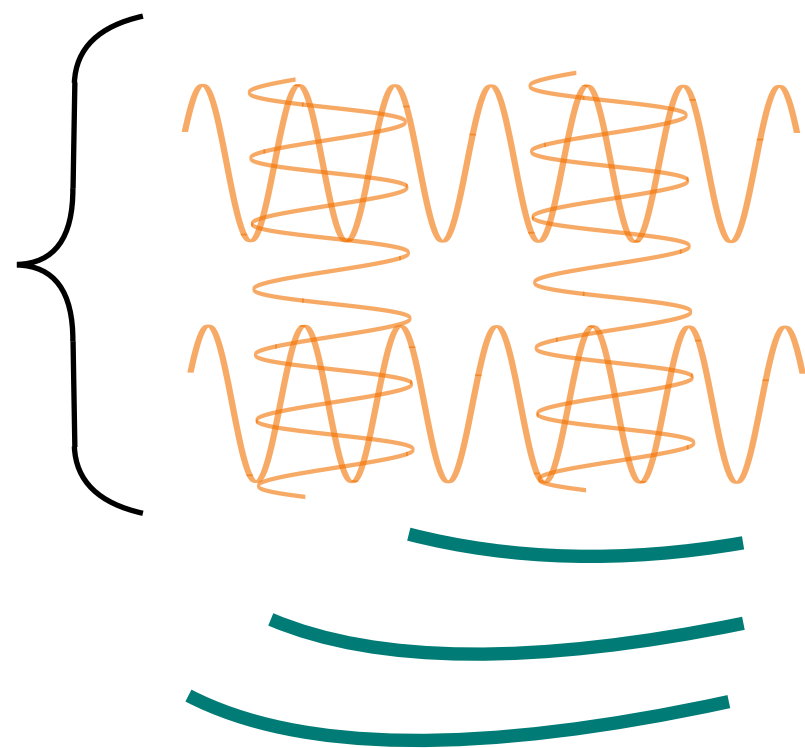








Gas of evaporating PBHs



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

Poltergeist GWs

Scalar Curvature

$$\mathcal{R}(\overrightarrow{x}, t)$$

PBH formation

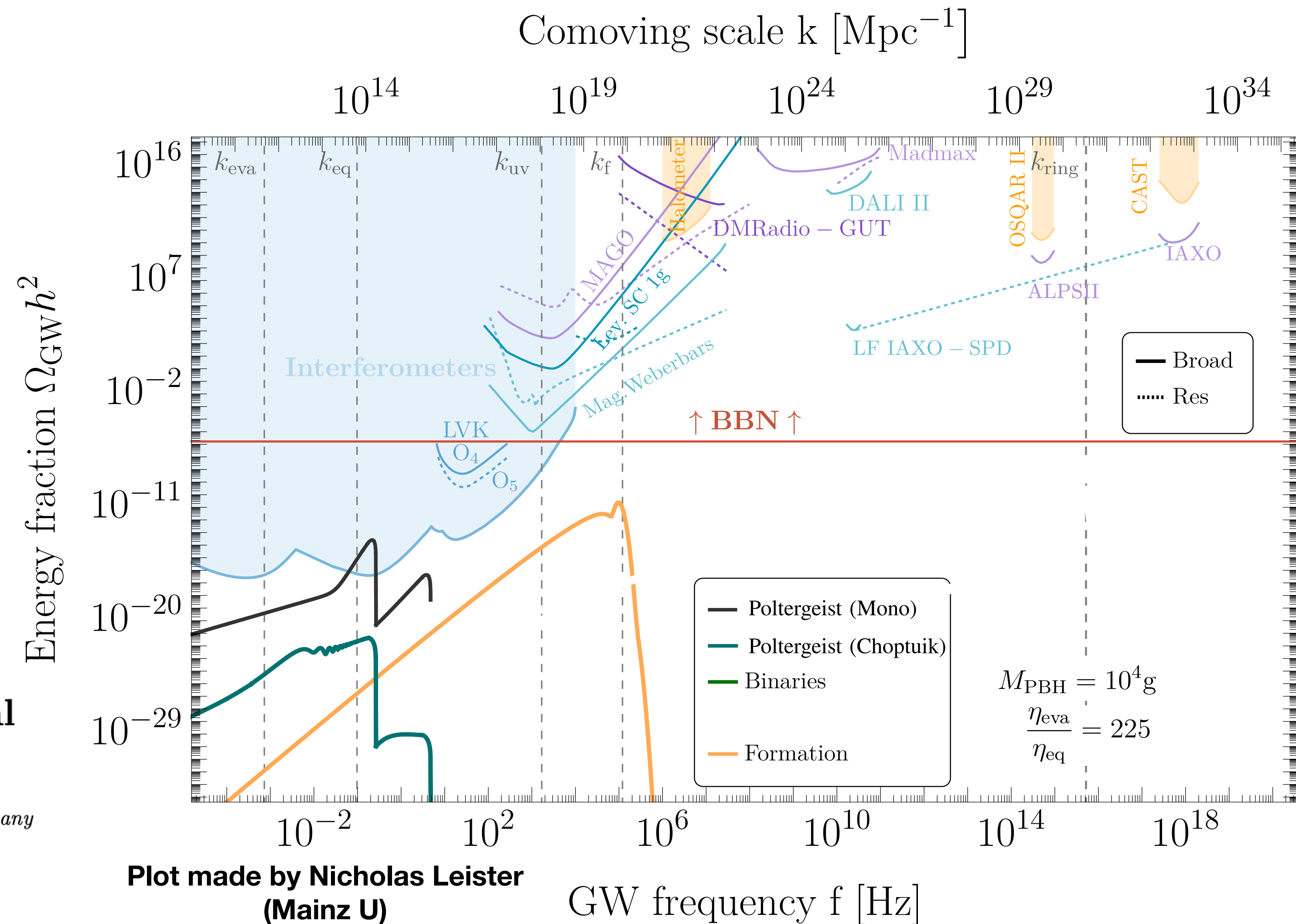
Scalar-induced GW

Gravitational Waves from Ultra-Light Primordial Black Holes

Yann Gouttenoire, Nicholas Leister, Pedro Schwaller

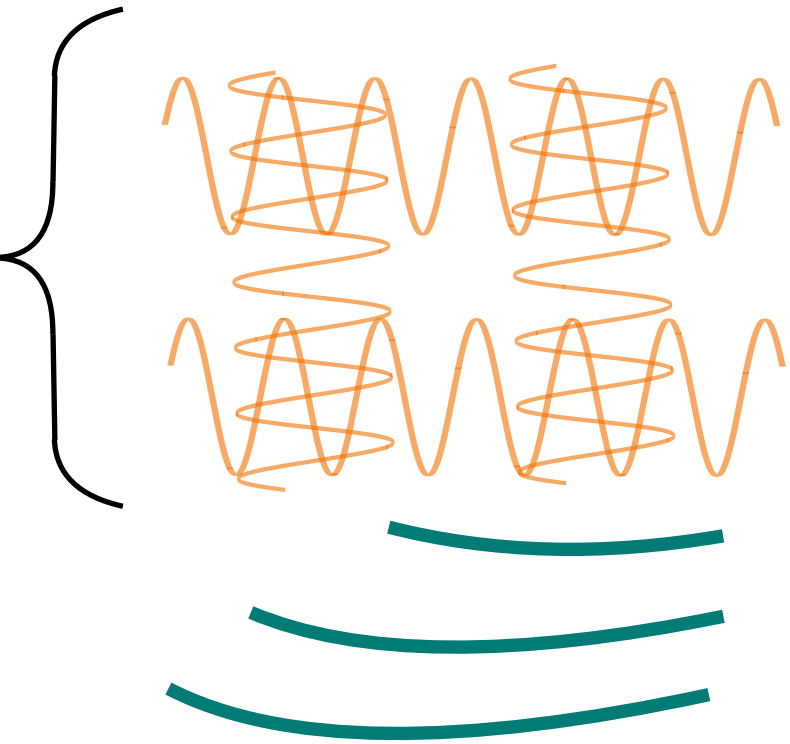
PRISMA+ Cluster of Excellence & MITP, Johannes Gutenberg University, 55099 Mainz, Germany

In preparation (25XX.XXXX)



Evaporation $\Rightarrow$ Sound waves

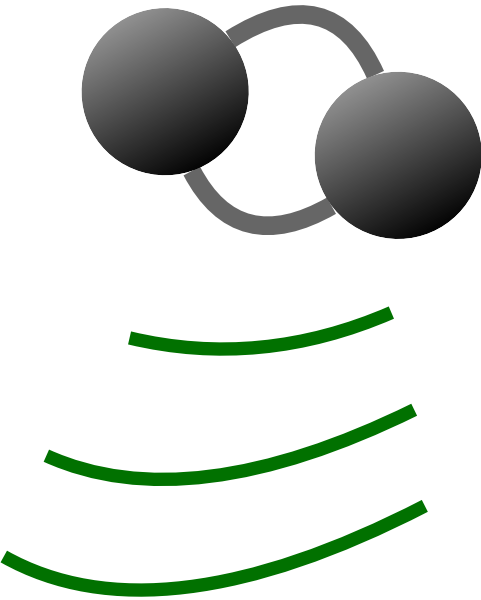
Gas of
evaporating PBHs



Poltergeist GWs

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

GW from binaries

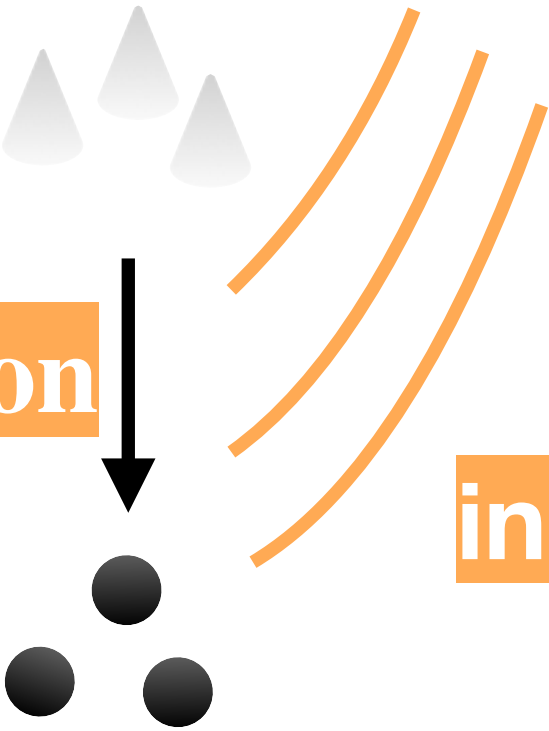


Comoving scale k [Mpc^{-1}]

10^{19} 10^{24} 10^{29} 10^{34}

Scalar Curvature

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



PBH formation

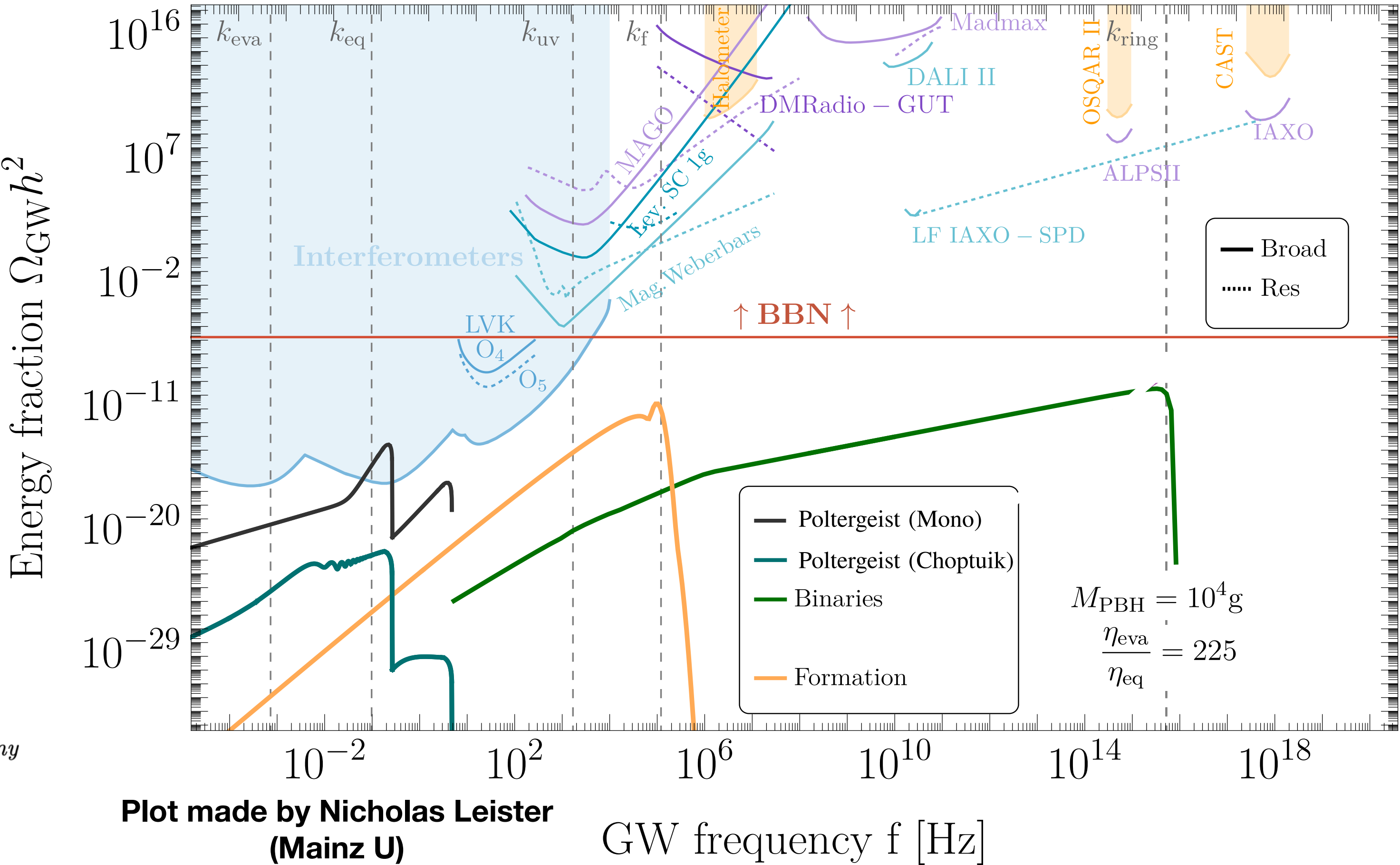
Scalar-
induced GW

Gravitational Waves from Ultra-Light Primordial
Black Holes

Yann Gouttenoire, Nicholas Leister, Pedro Schwaller

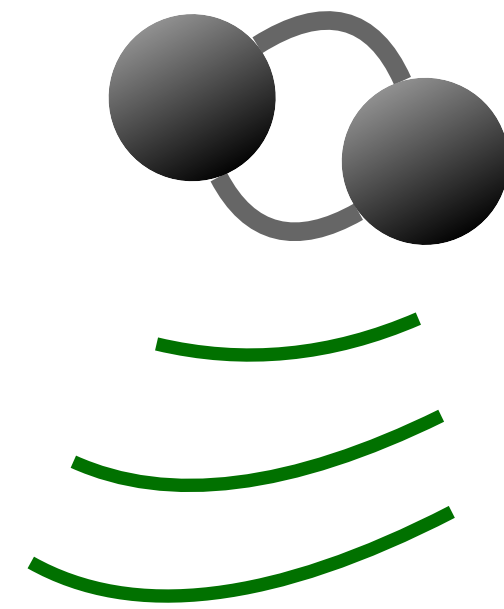
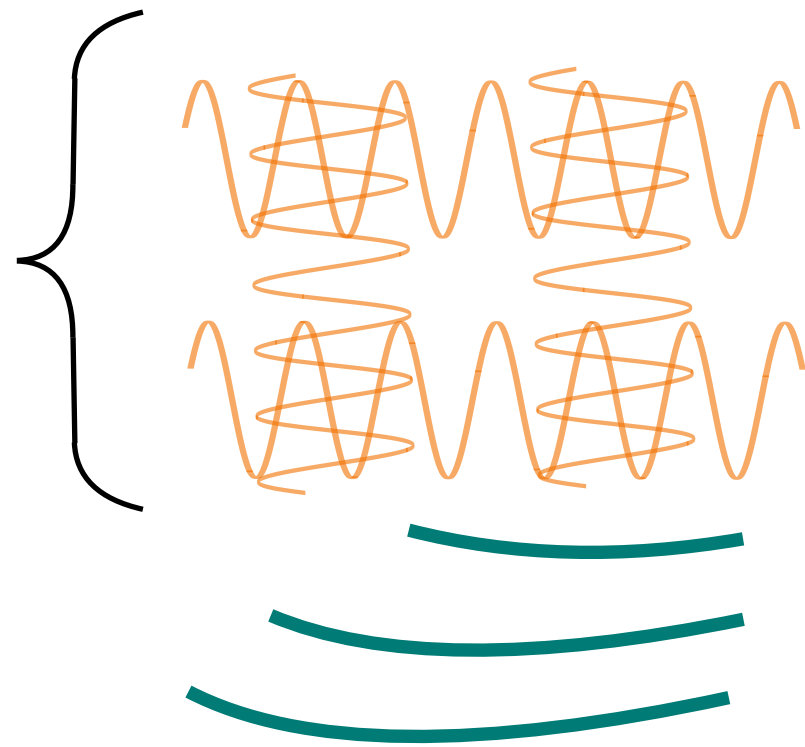
PRISMA+ Cluster of Excellence & MITP, Johannes Gutenberg University, 55099 Mainz, Germany

In preparation (25XX.XXXX)

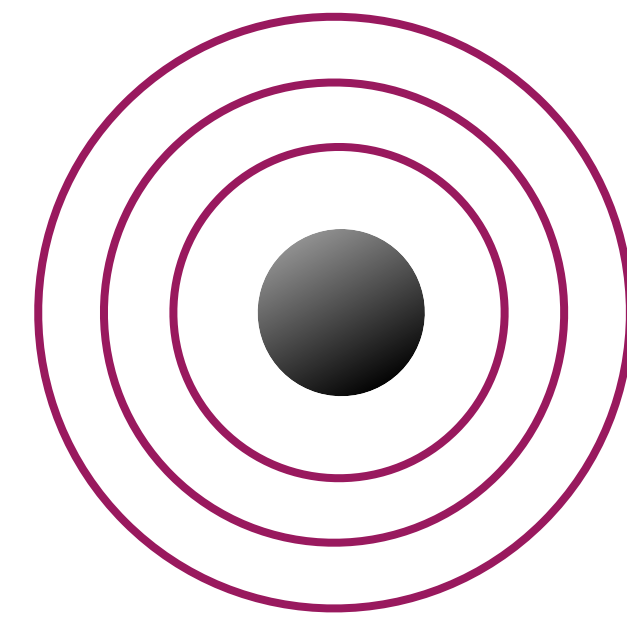


Poltergeist GWs

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

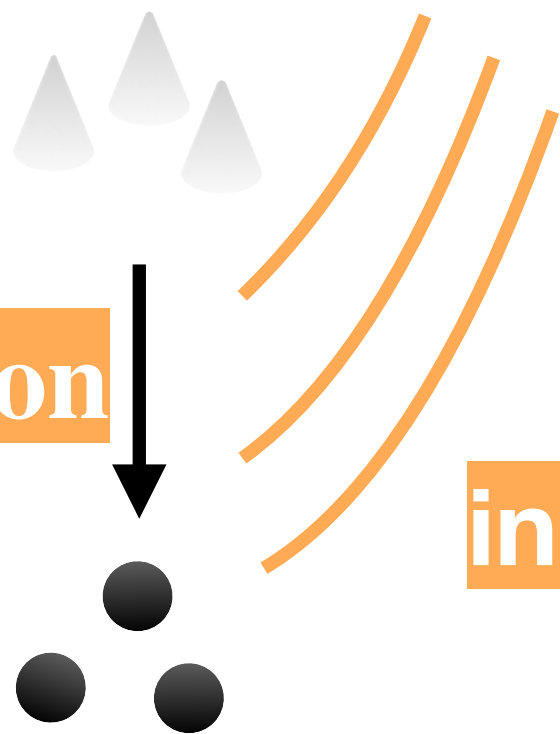


GW from binaries



GW from Hawking evaporation

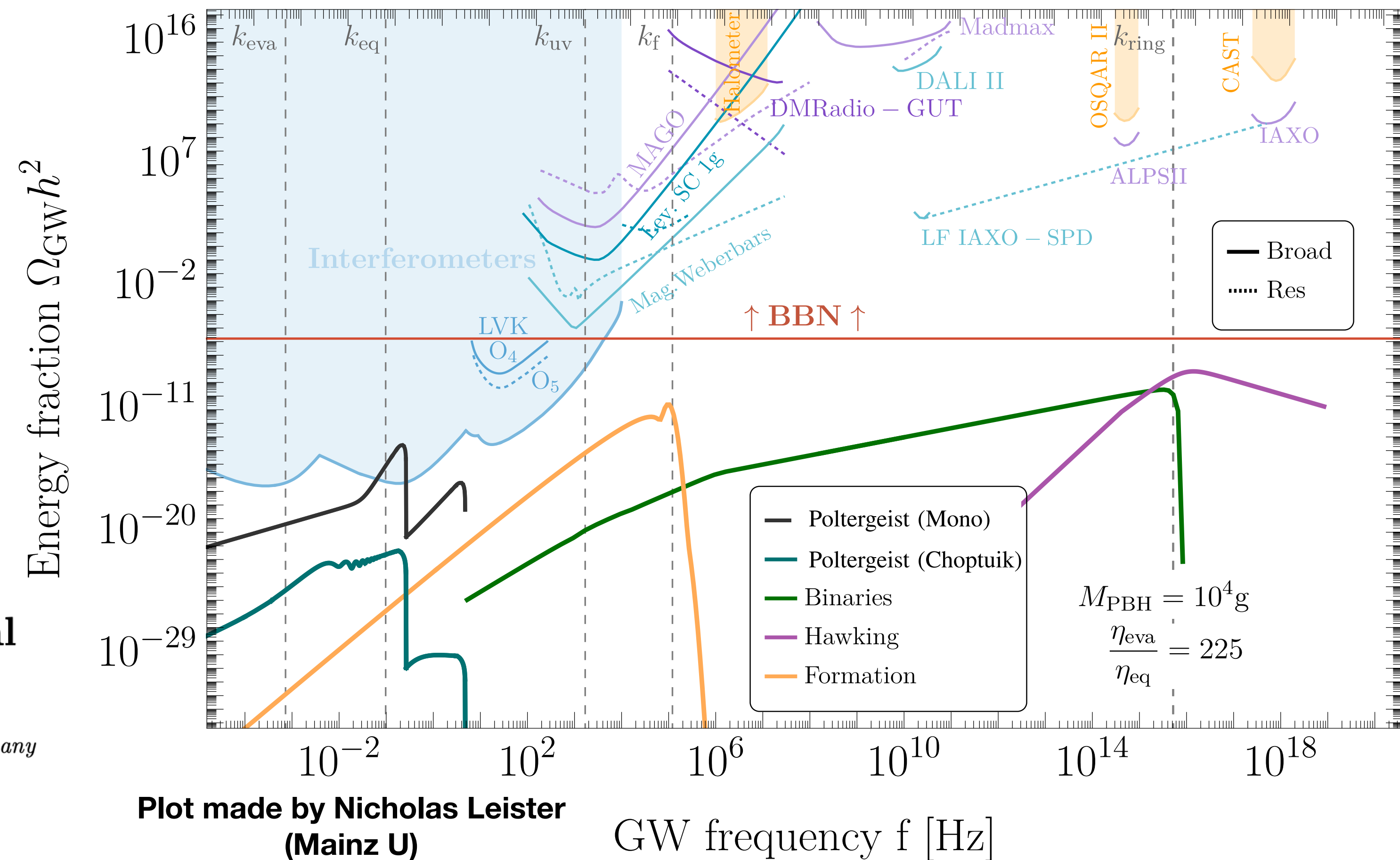
Scalar-induced GW



Yann Gouttenoire, Nicholas Leister, Pedro Schwaller

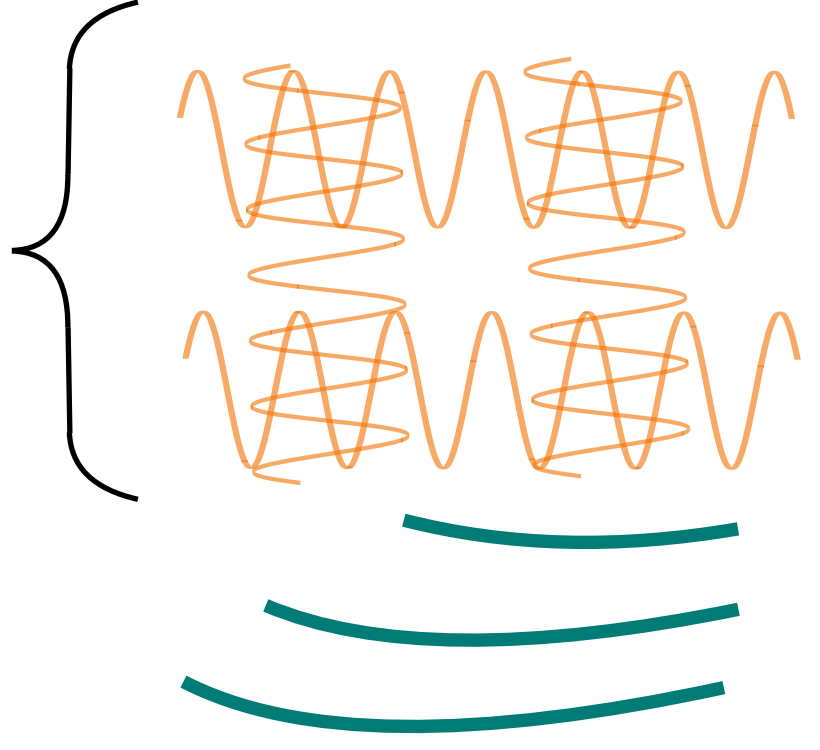
PRISMA+ Cluster of Excellence & MITP, Johannes Gutenberg University, 55099 Mainz, Germany

In preparation (25XX.XXXX)



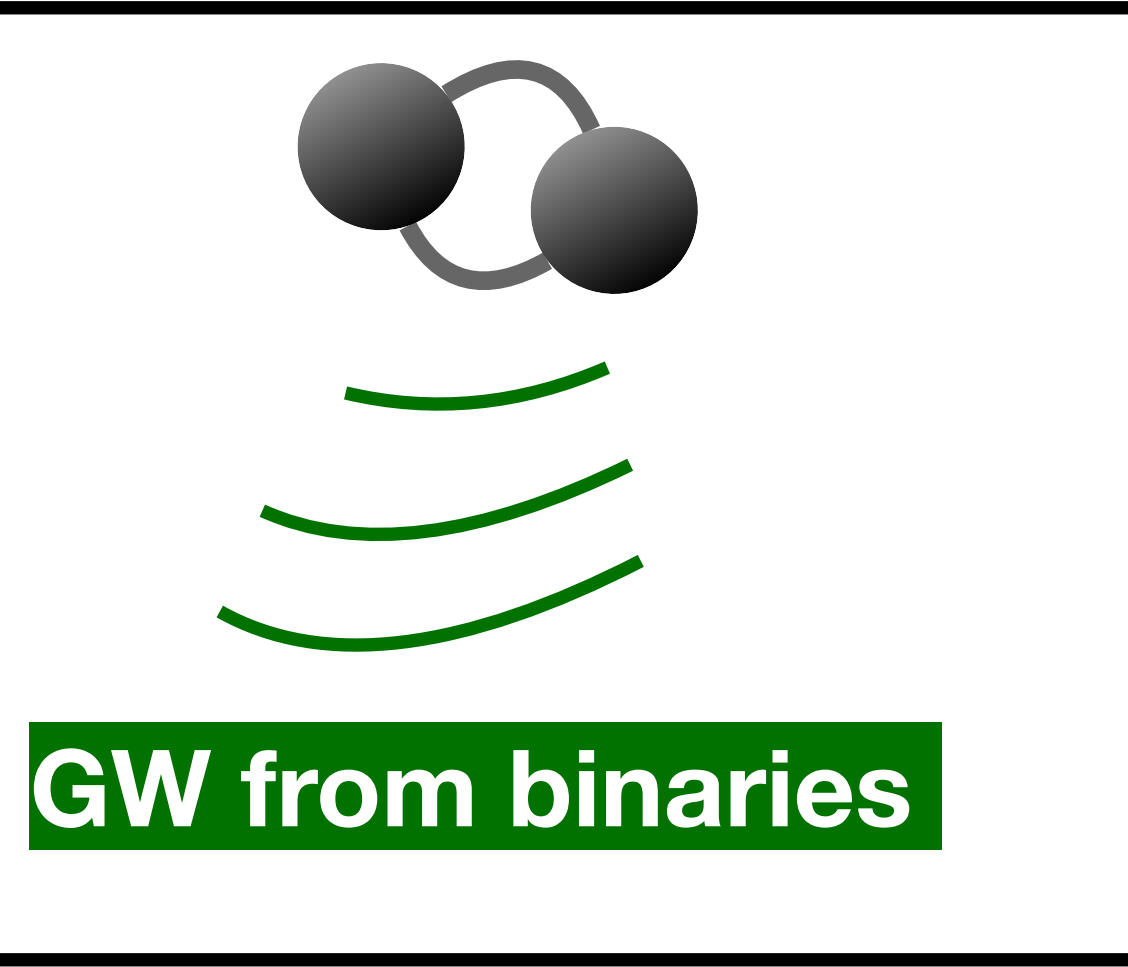
Evaporation $\Rightarrow$ Sound waves

Gas of
evaporating PBHs



Poltergeist GWs

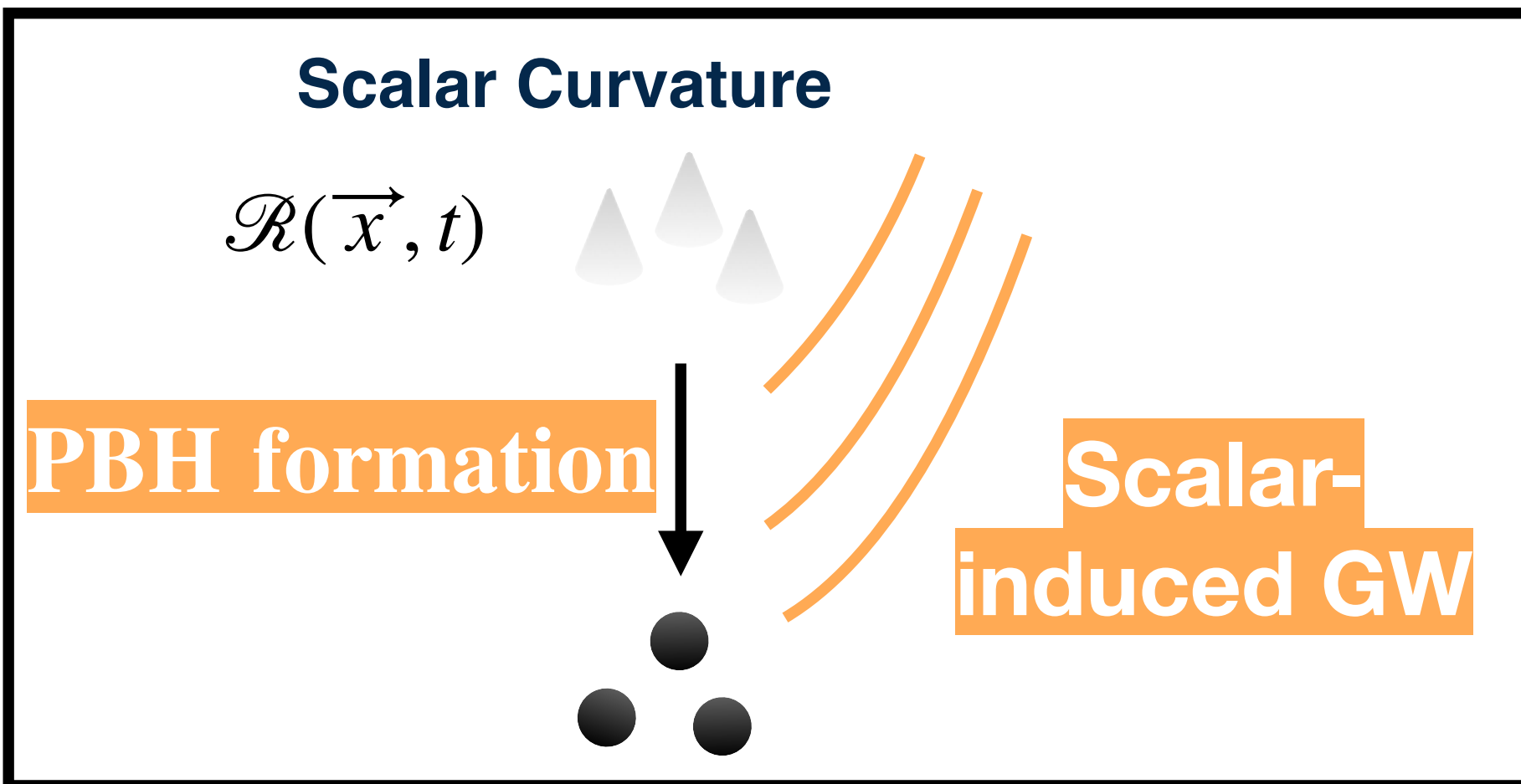
Inomata, Kawasaki,
Mukaida, Terada, Yanagida
(2003.10455)



GW from binaries



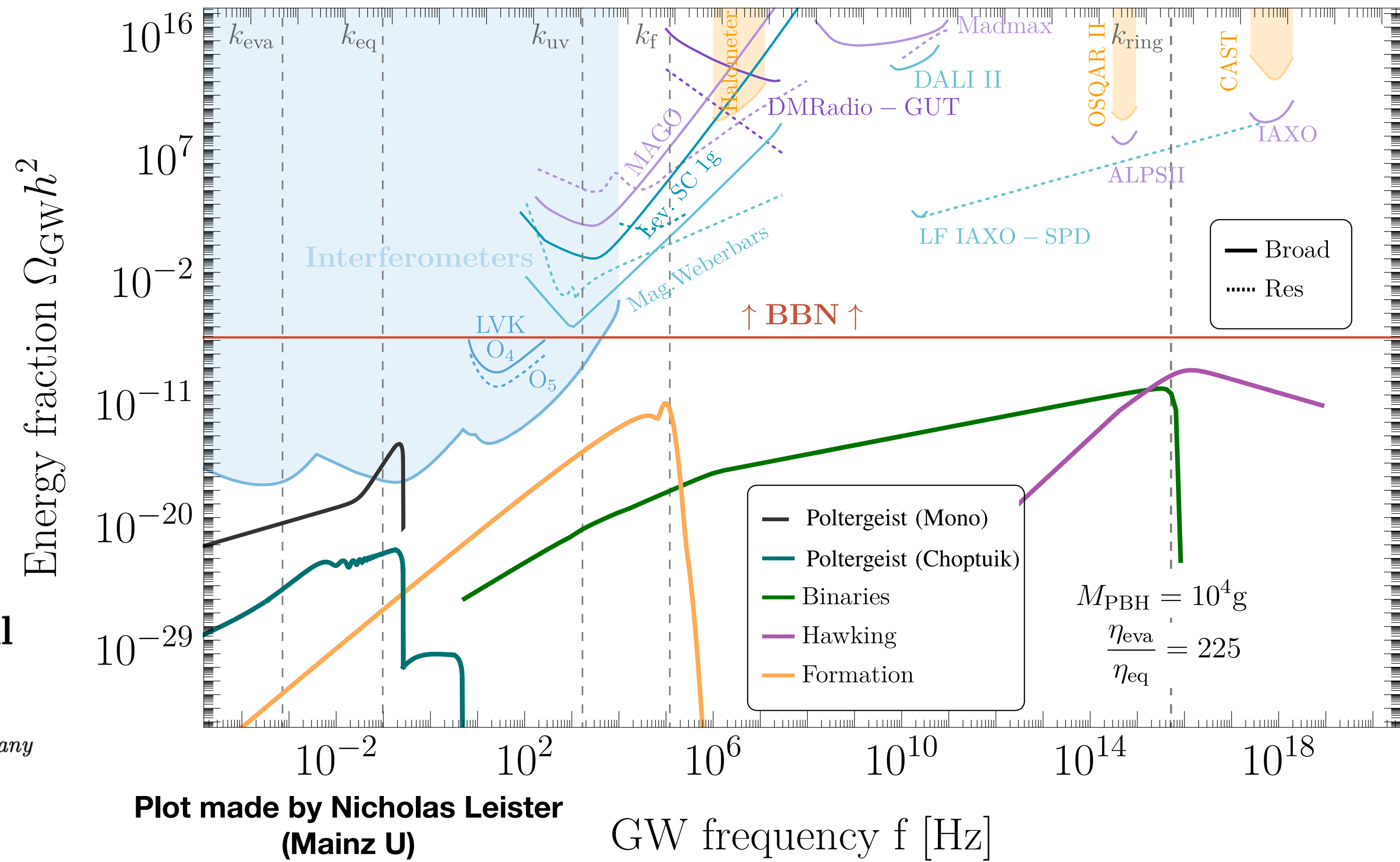
GW from Hawking
evaporation

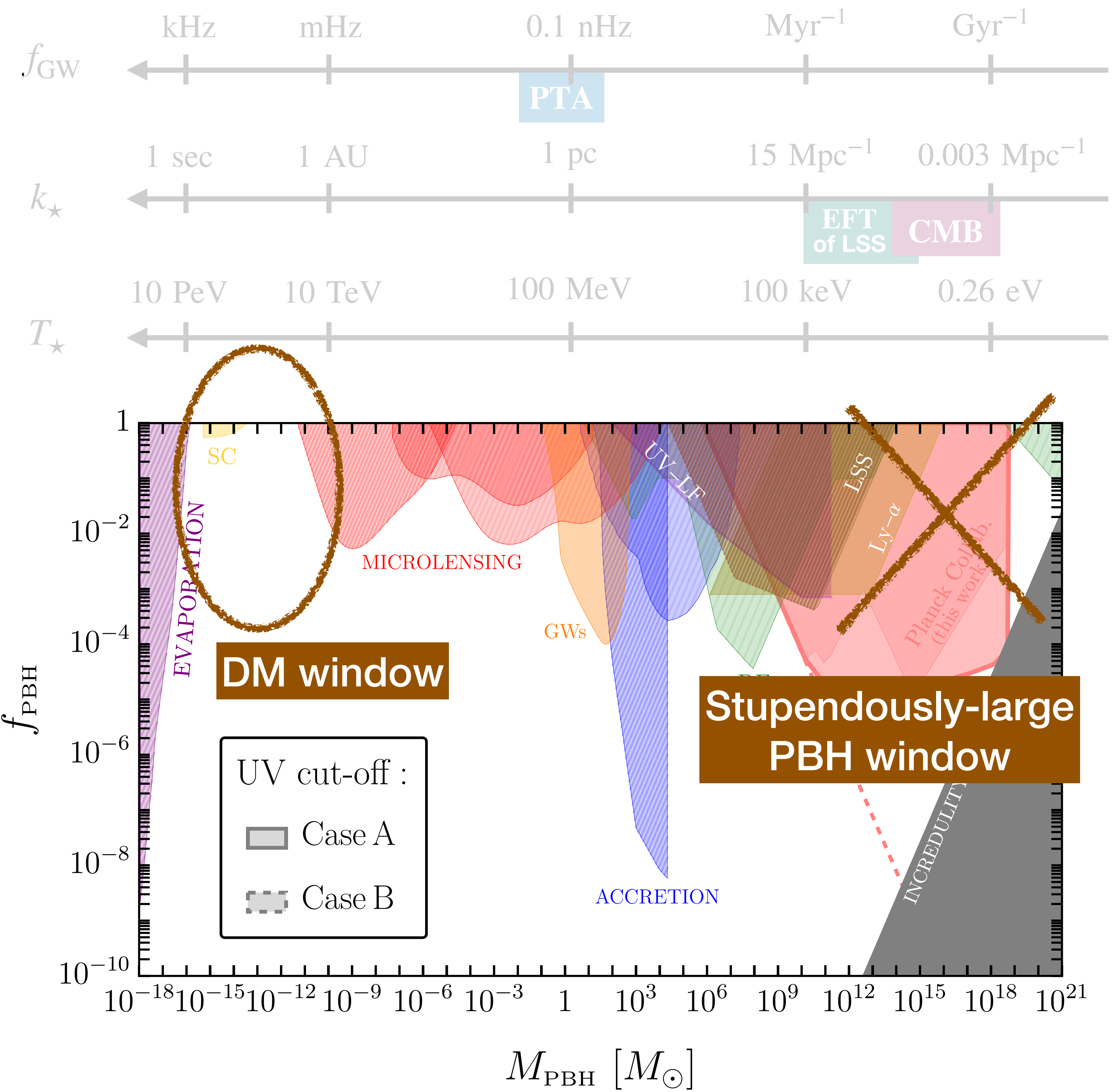
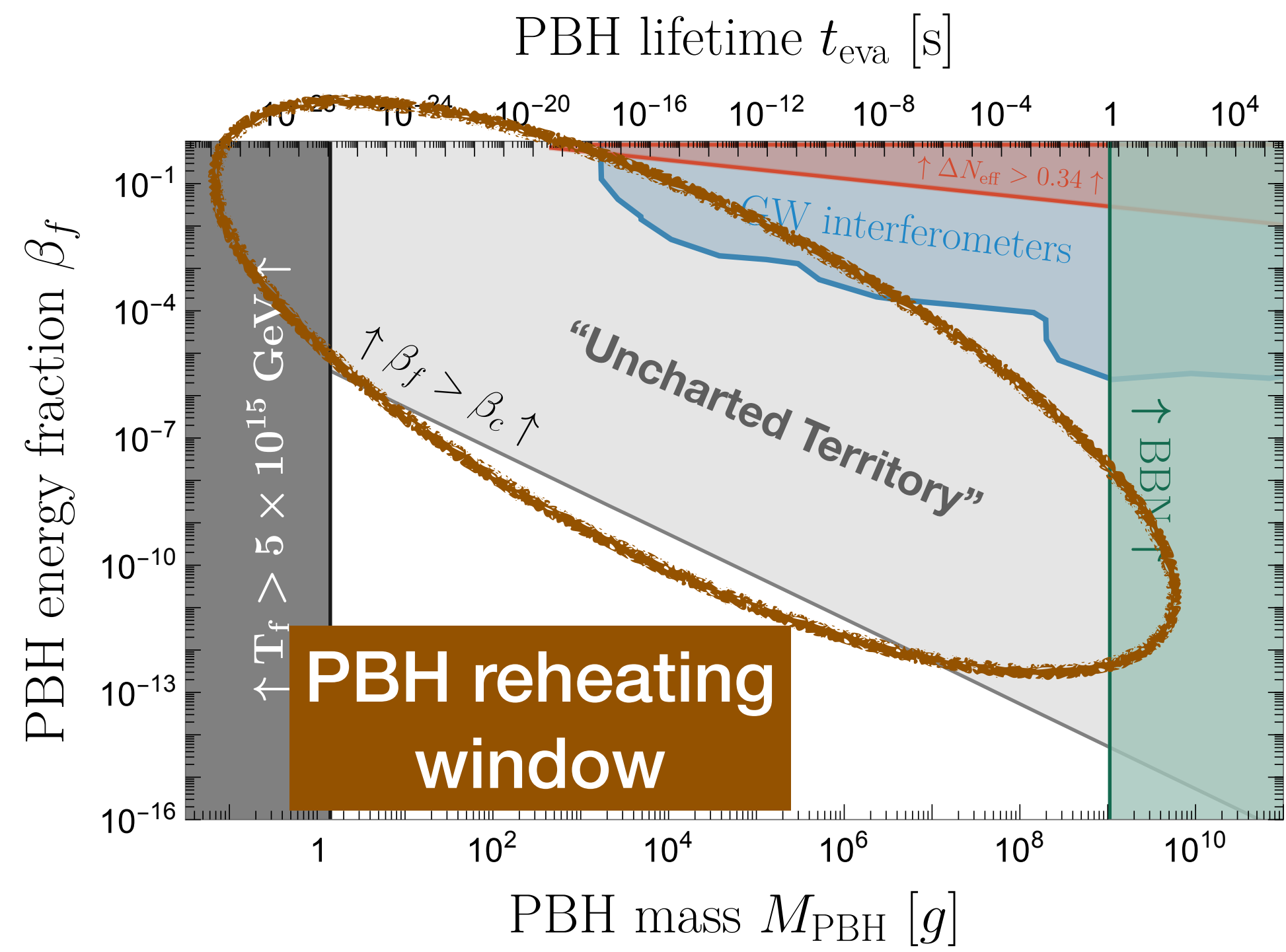
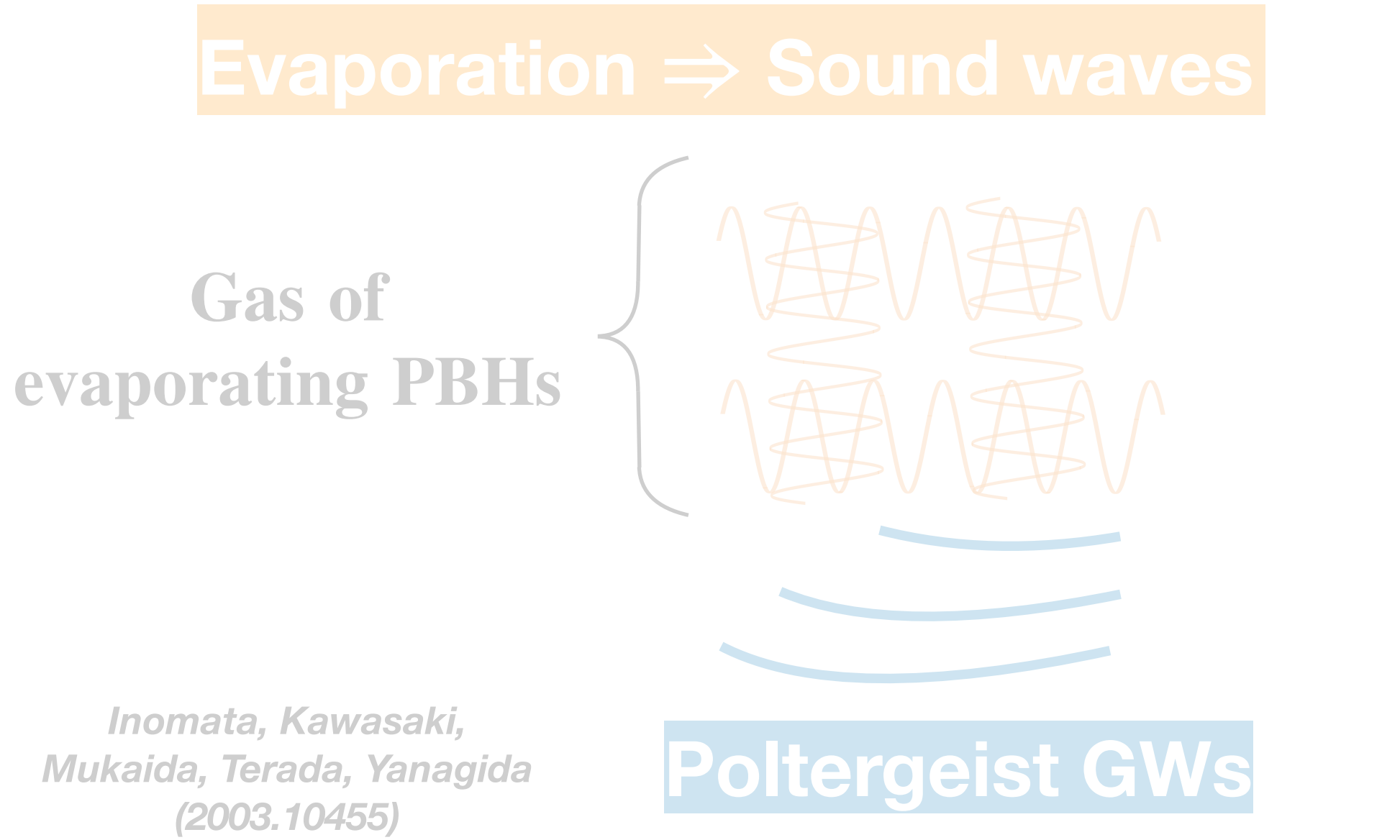


Gravitational Waves from Ultra-Light Primordial
Black Holes

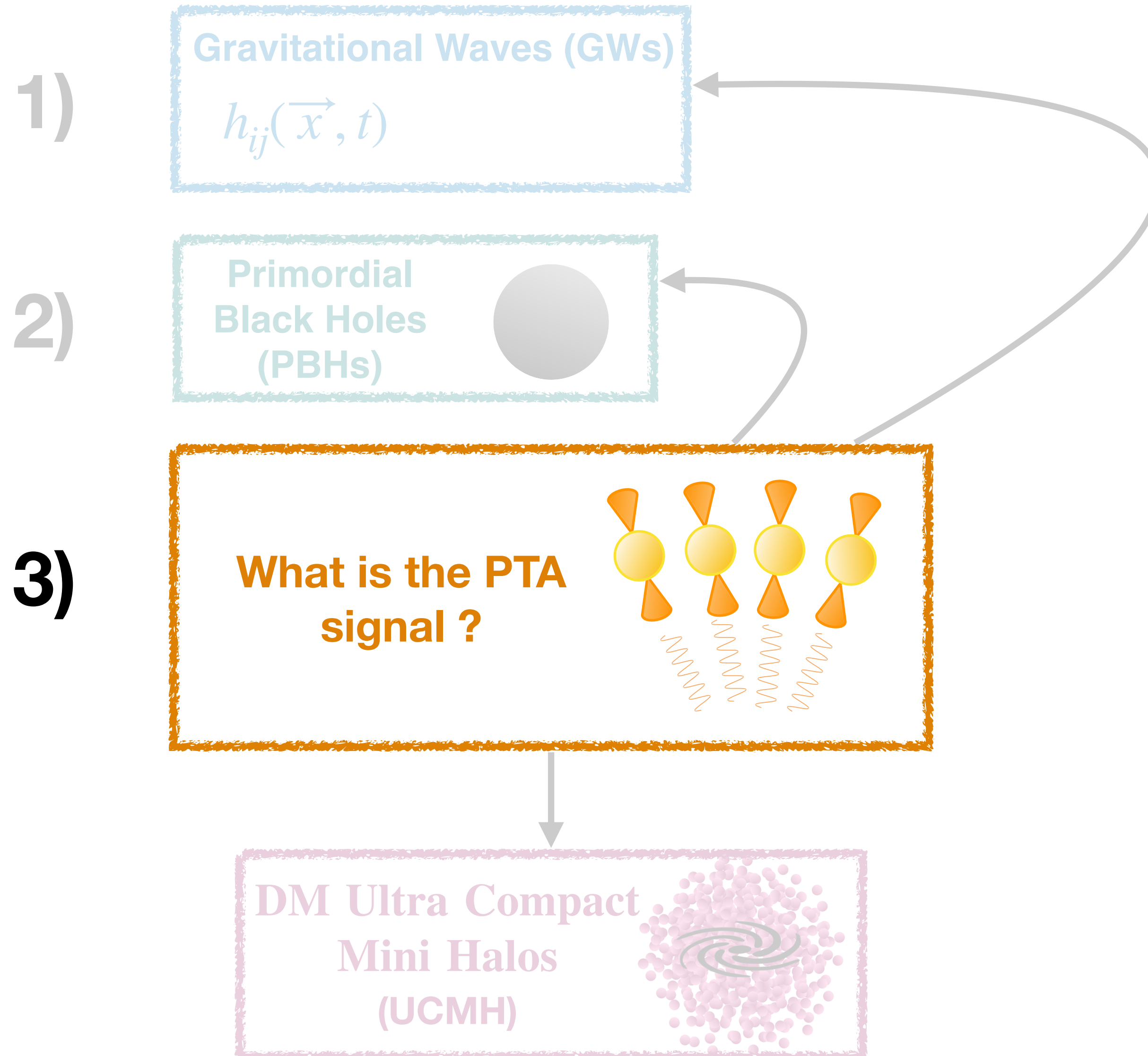
Yann Gouttenoire, Nicholas Leister, Pedro Schwaller
PRISMA+ Cluster of Excellence & MITP, Johannes Gutenberg University, 55099 Mainz, Germany

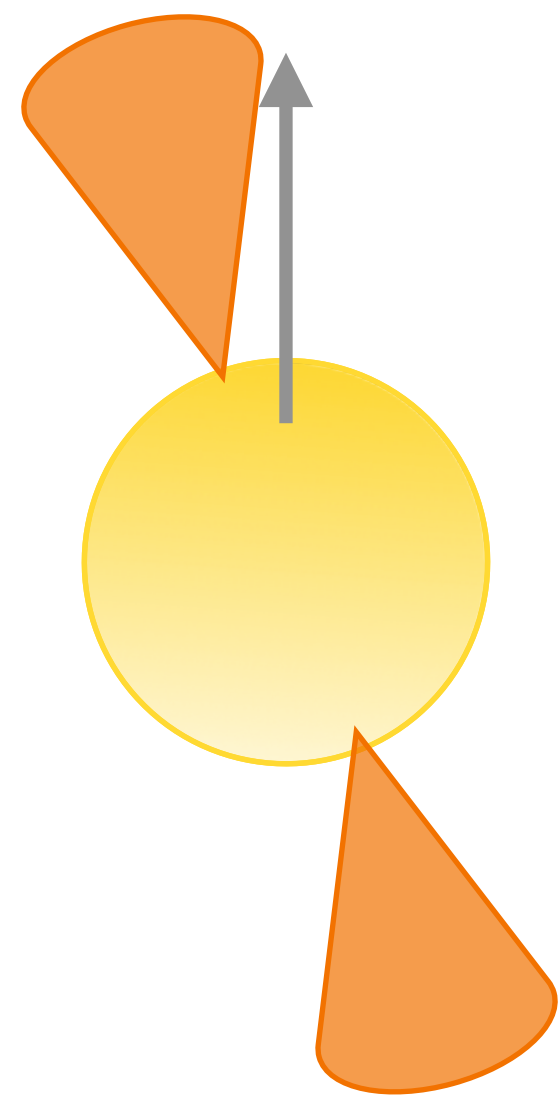
In preparation (25XX.XXXX)



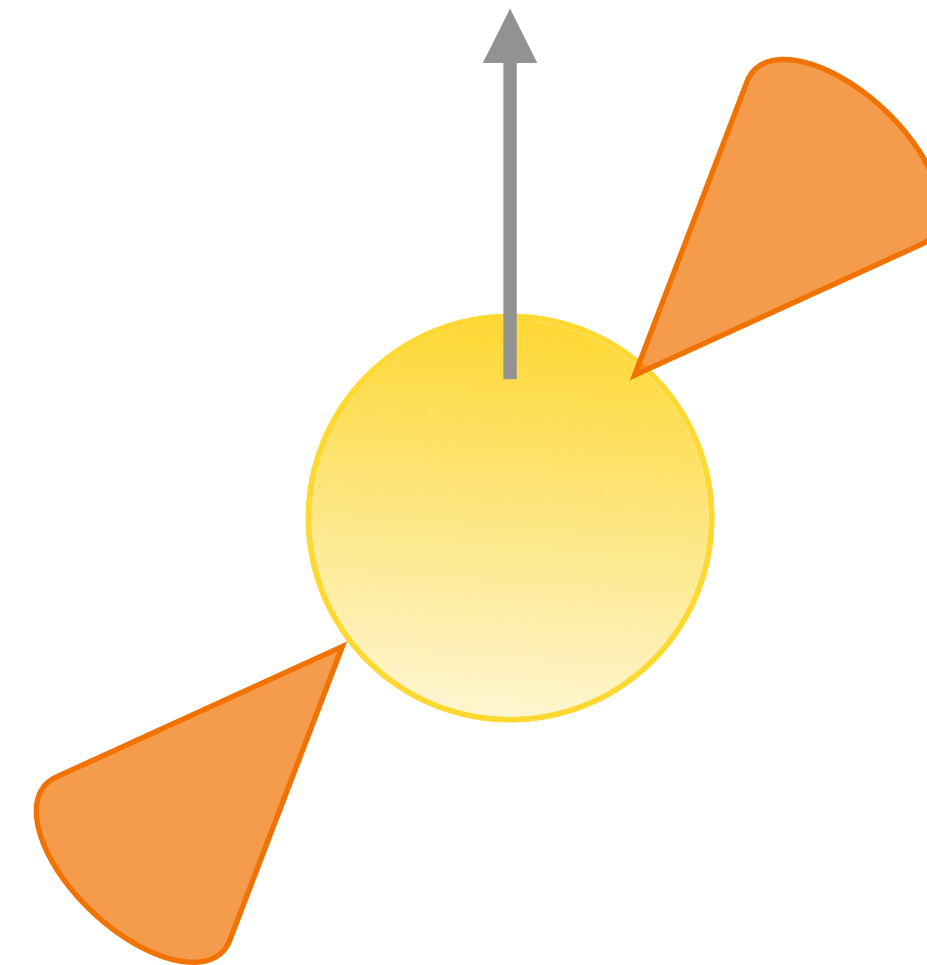


Plan of the talk





Pulsar Timing Arrays (PTA)



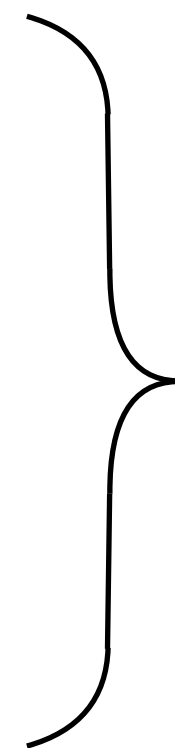
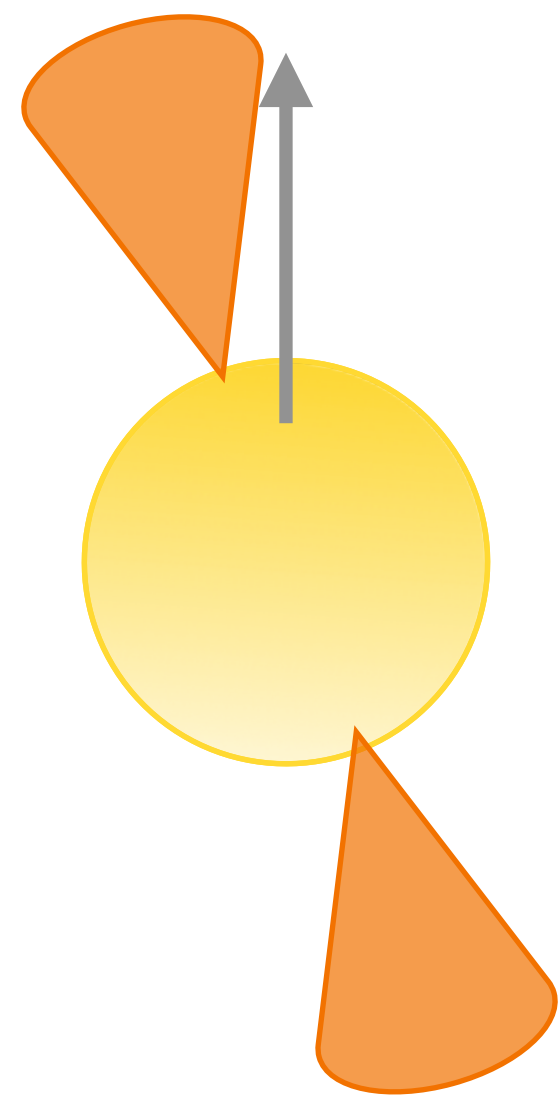
The New York Times

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NEW YORK, THURSDAY, JUNE 29, 2023

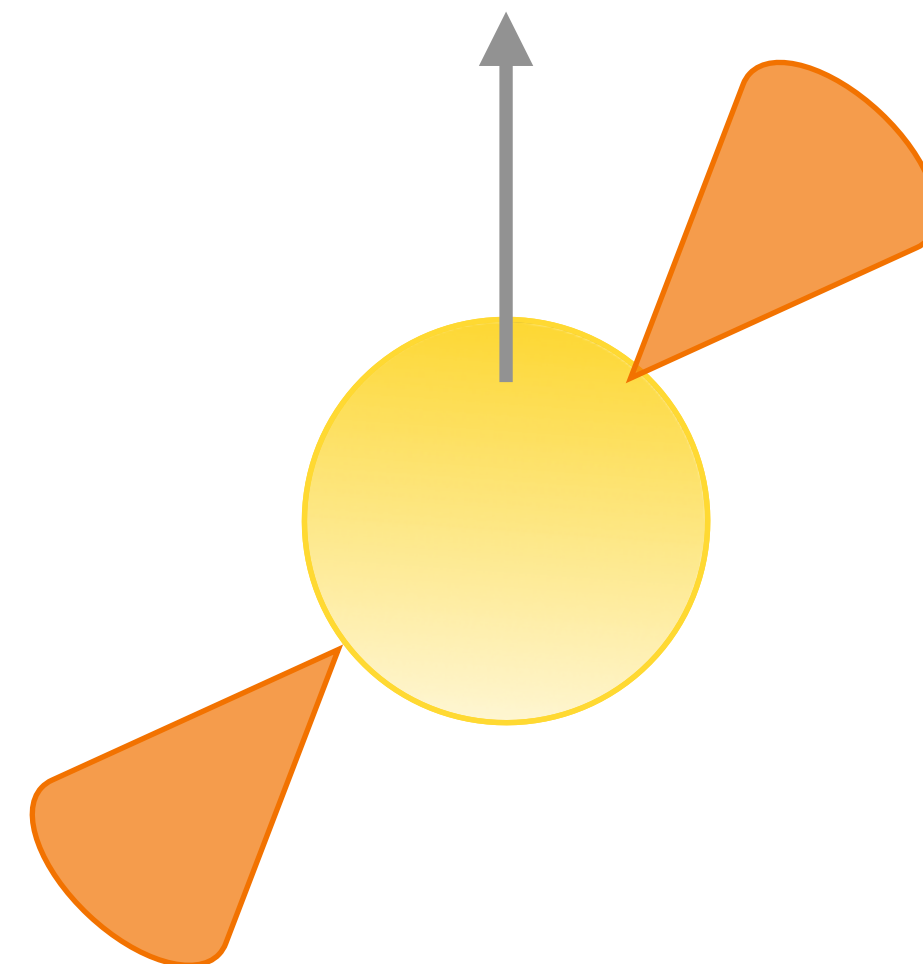
The Cosmos Is Thrumming With Gravitational Waves, Astronomers Find





Pulsar Timing Arrays (PTA)

$1 M_{\odot}$



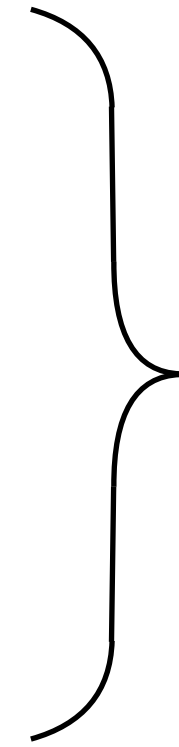
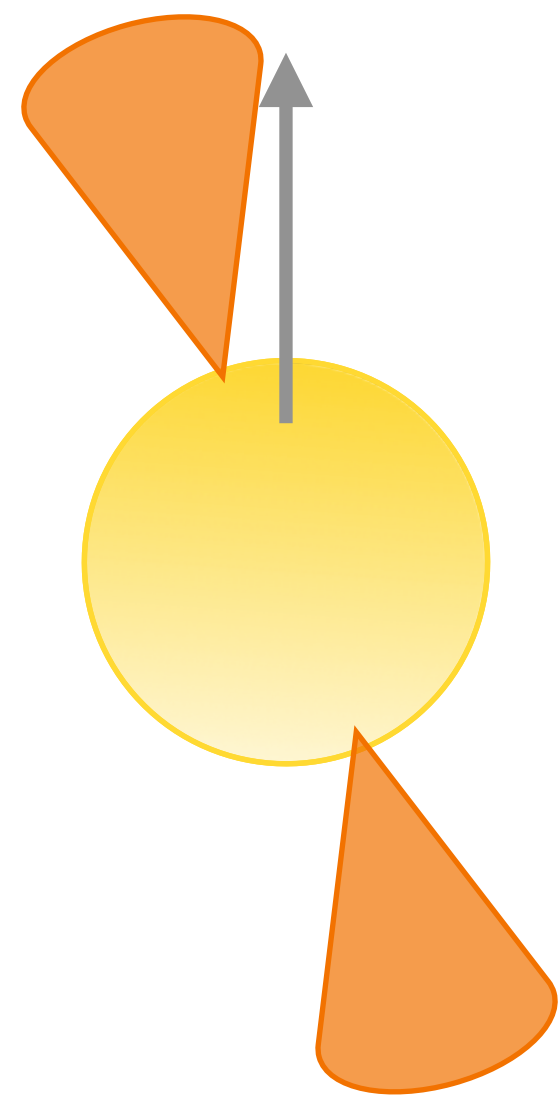
The New York Times

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Find***

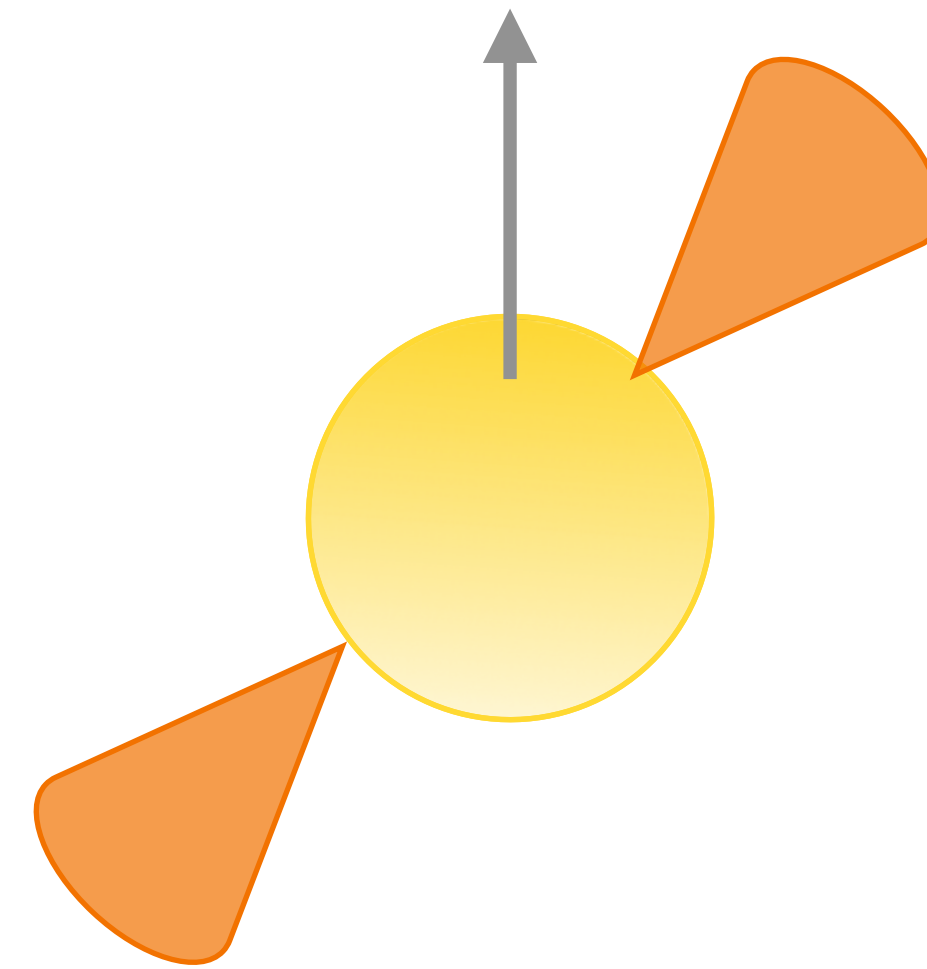




Pulsar Timing Arrays (PTA)

1 $M_{\odot}$

10 km



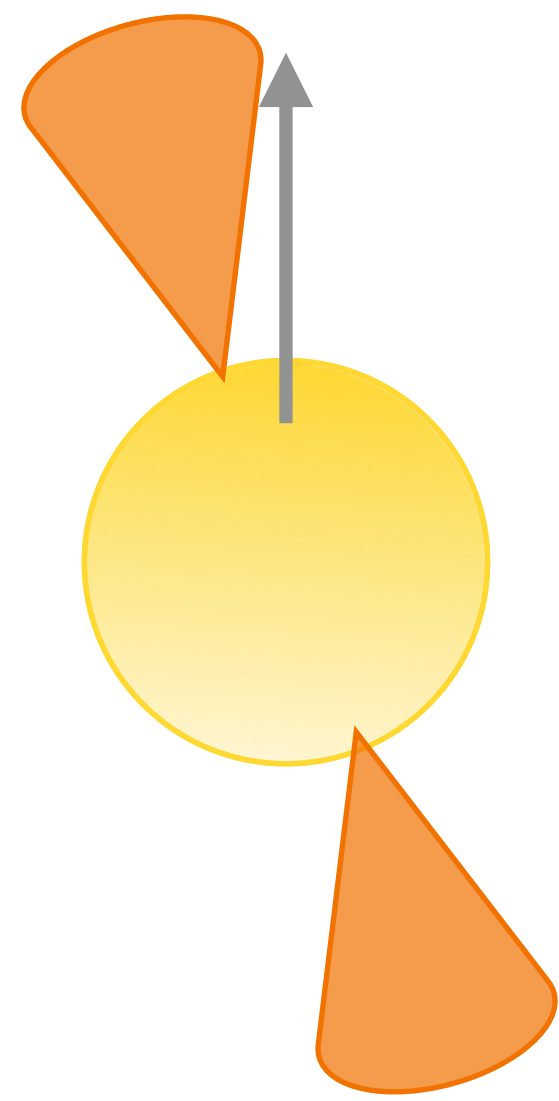
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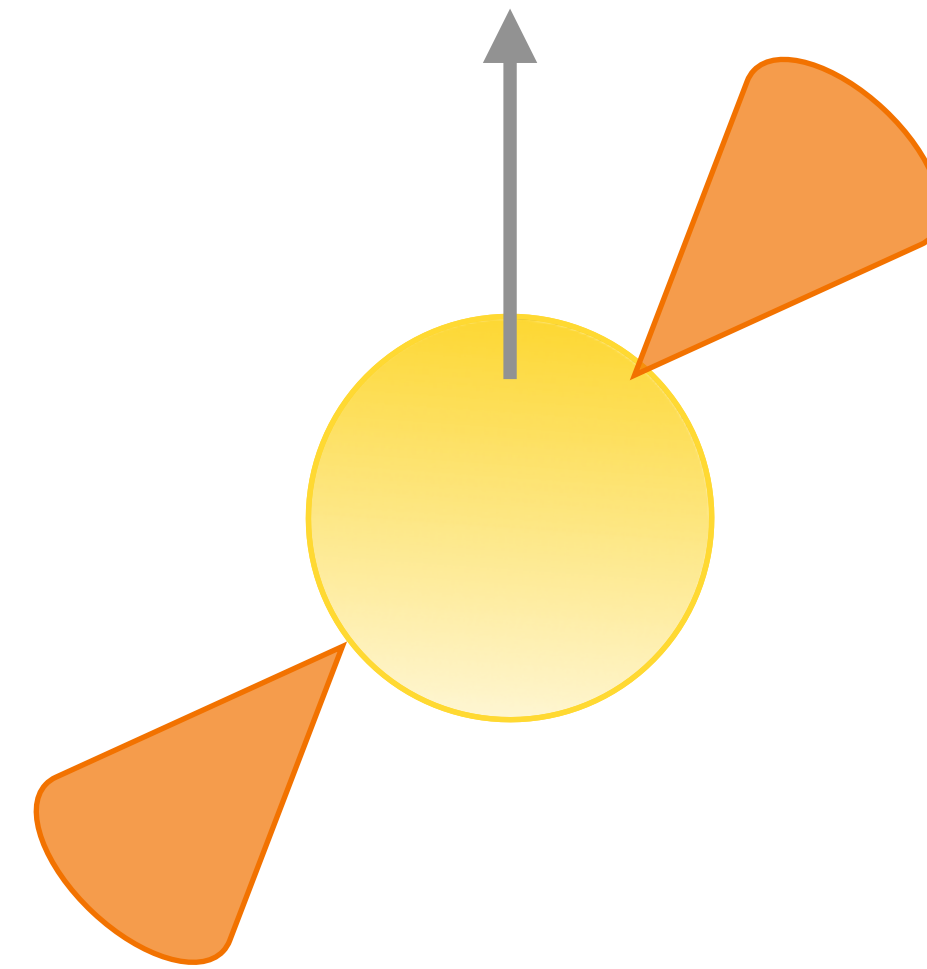
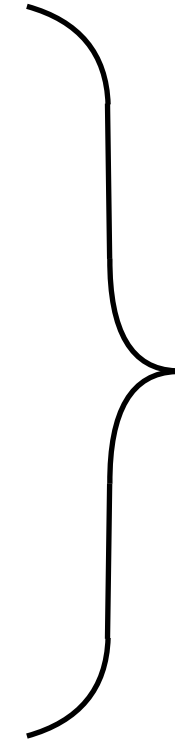


Pulsar Timing Arrays (PTA)

1 $M_{\odot}$

10 km

500 rotations/s



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The Cosmos Is Thrumming With Gravitational Waves, Astronomers Find



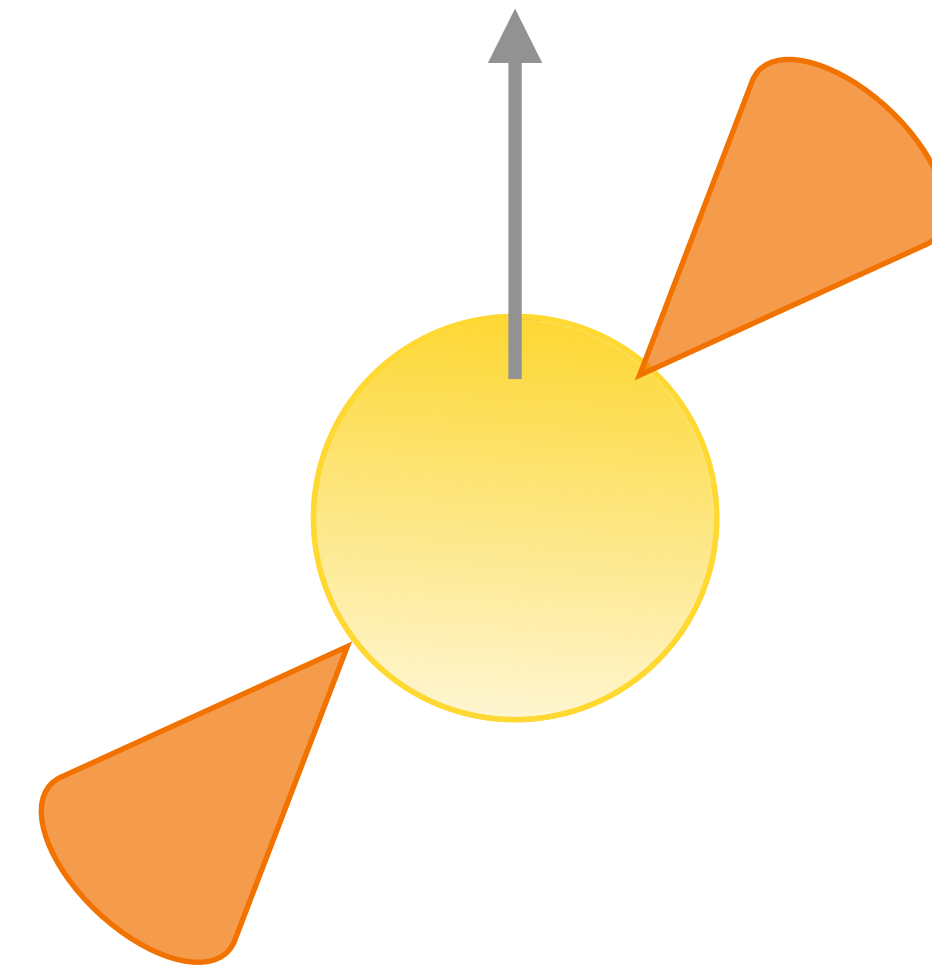
Pulsar Timing Arrays (PTA)

1 M_⊙

10 km

500 rotations/s

1 kpc



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Pulsar Timing Arrays (PTA)

1 $M_{\odot}$

10 km

500 rotations/s

Pulses

Pulses

1 kpc



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Gravitational Waves, Astronomers
Find***



Pulsar Timing Arrays (PTA)

1 M_⊙
10 km
500 rotations/s

Pulses

Pulses

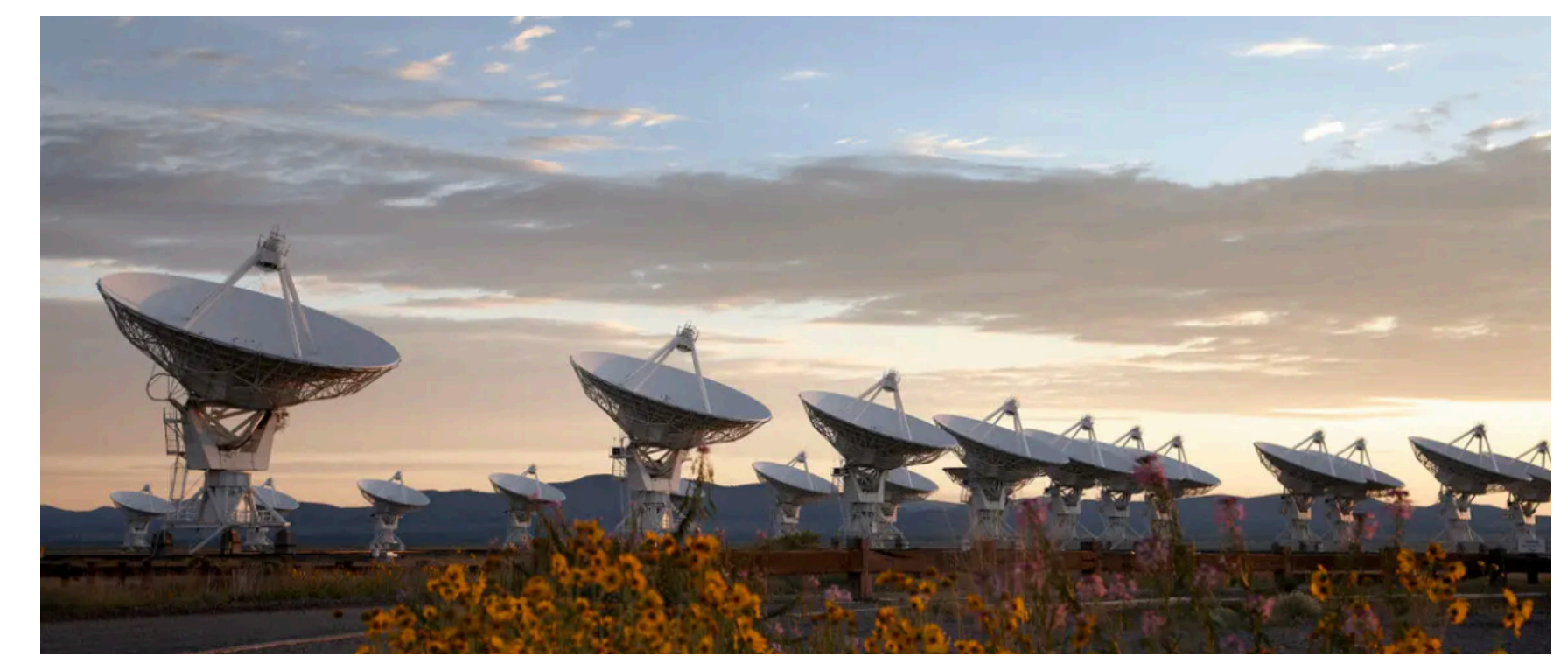
Gravitational
Waves

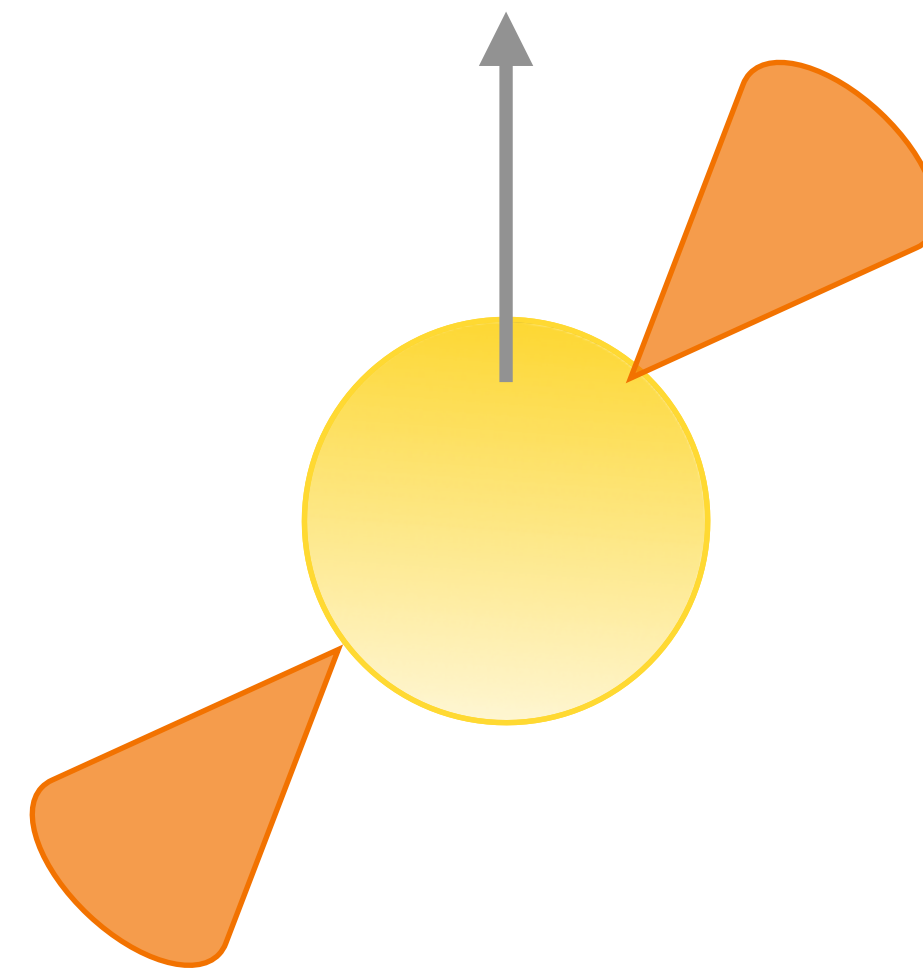
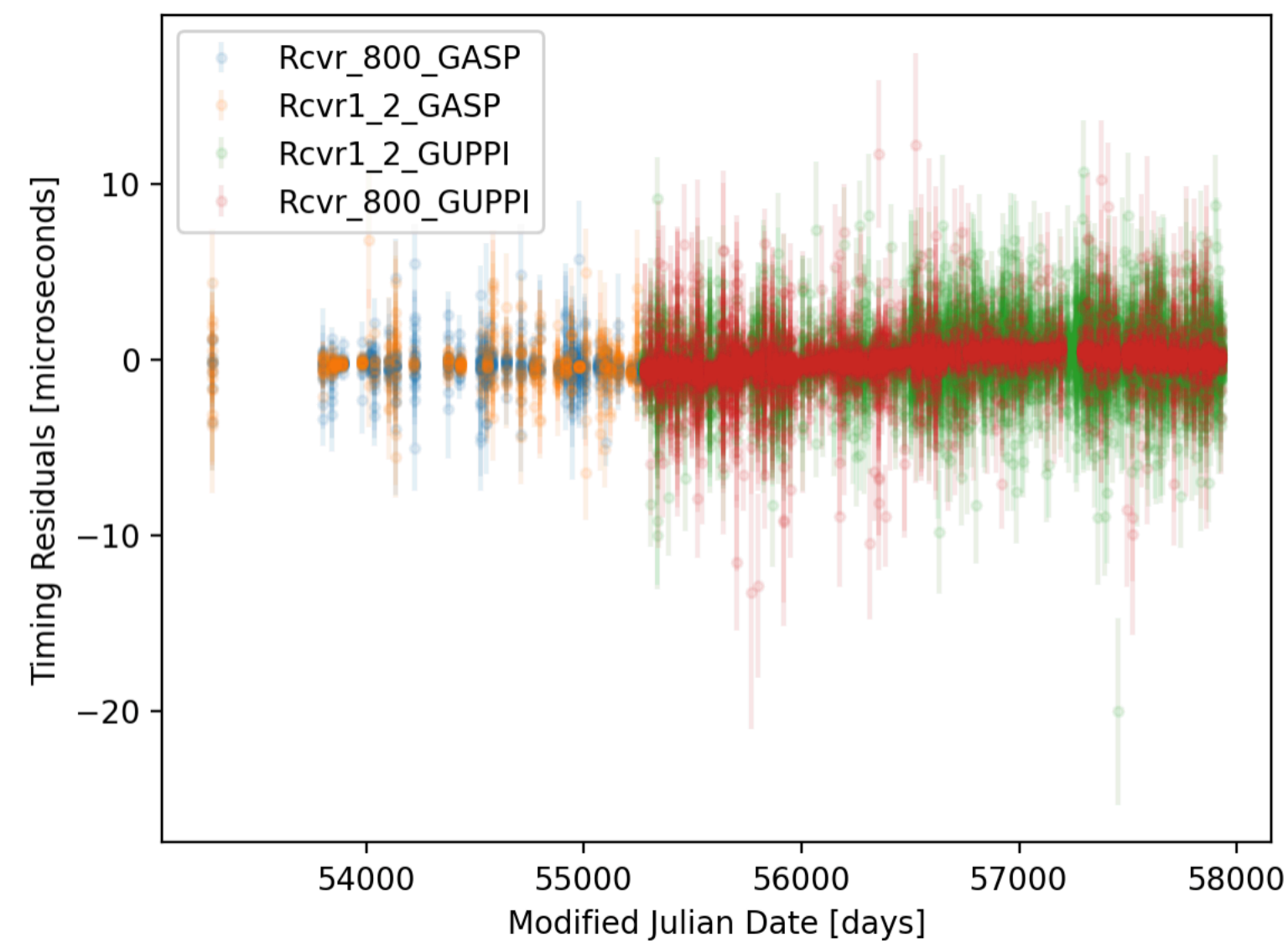
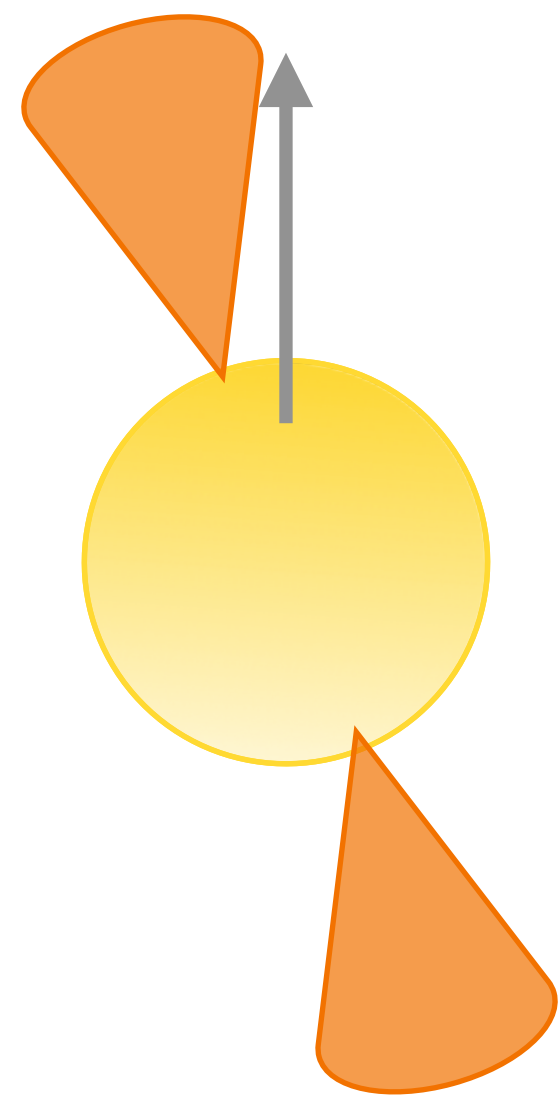


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The Cosmos Is Thrumming With Gravitational Waves, Astronomers Find





Pulses

Pulses

Gravitational
Waves



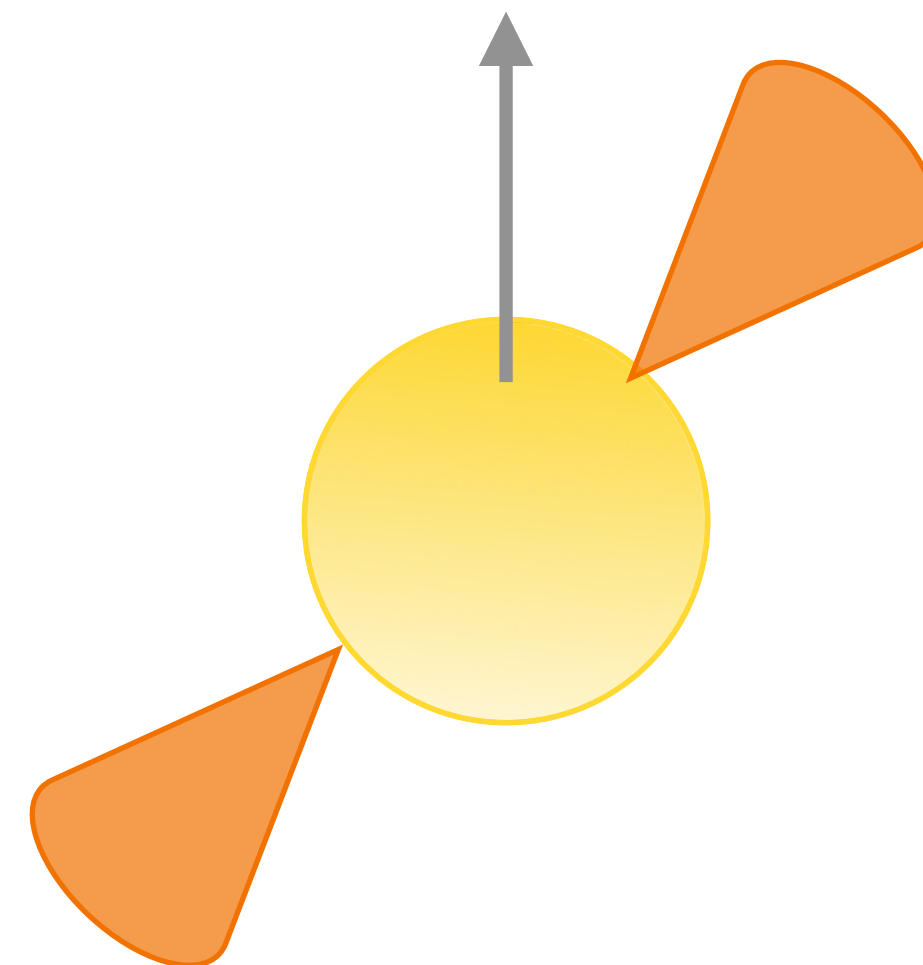
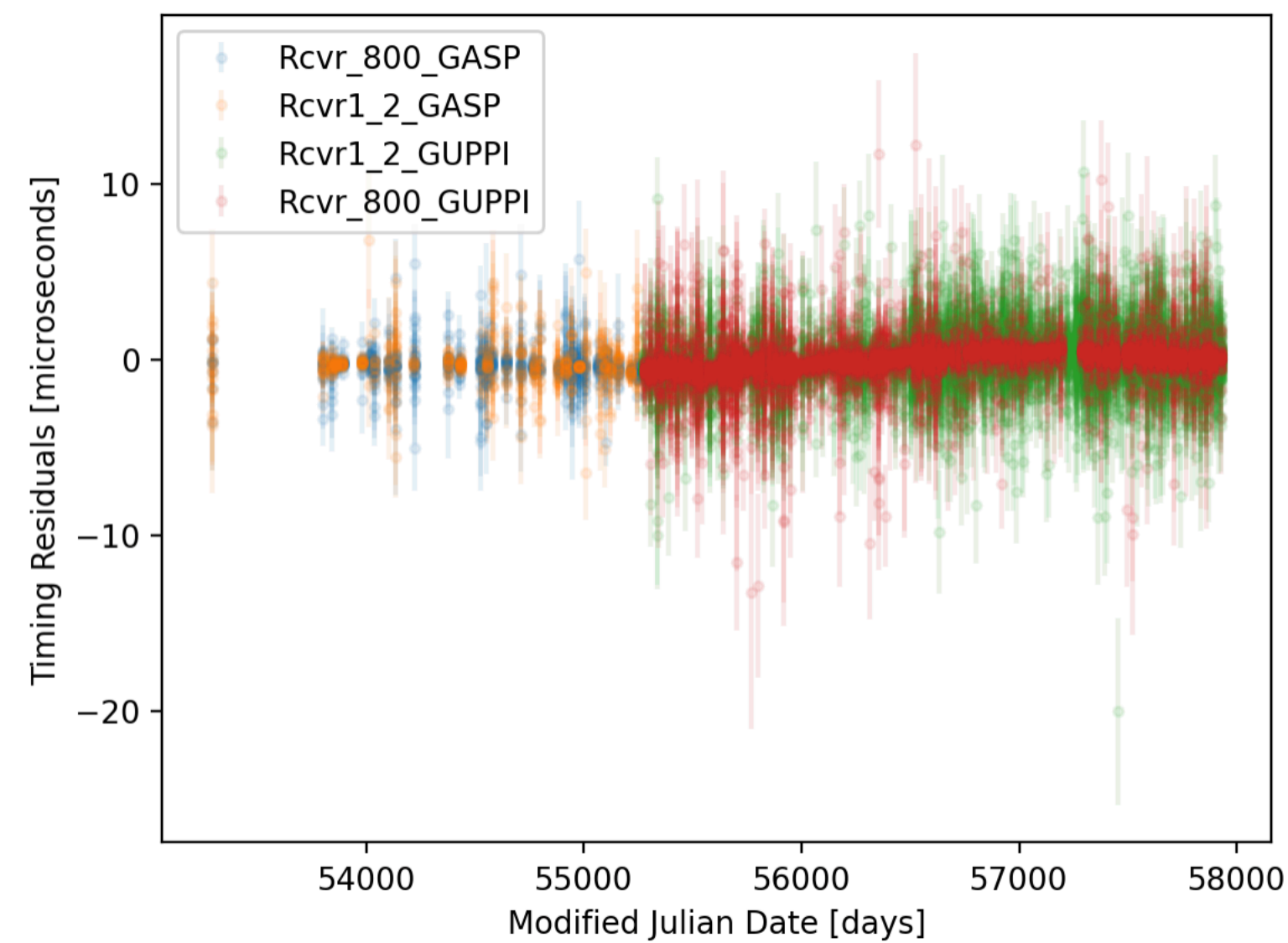
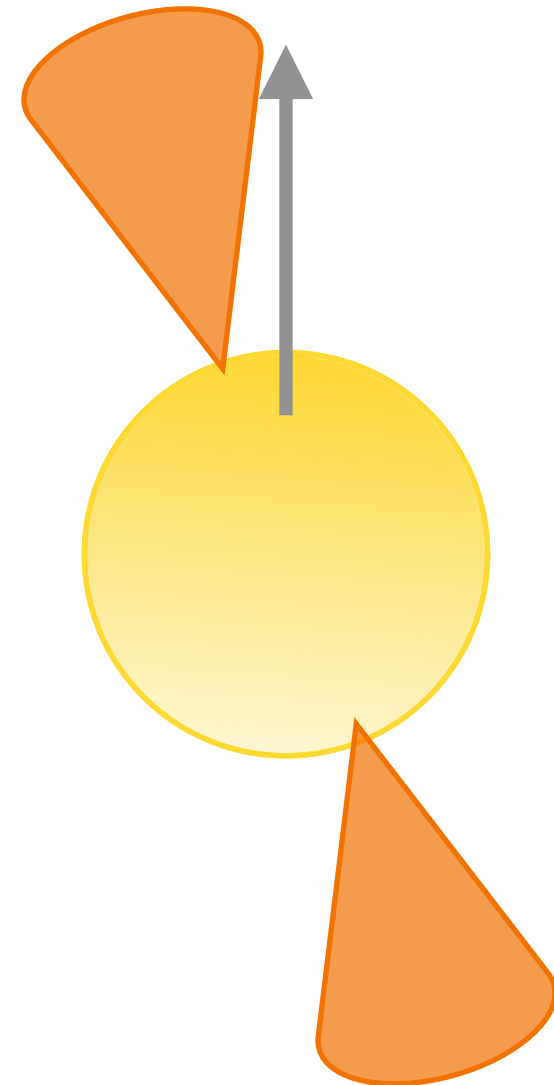
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The Cosmos Is Thrumming With Gravitational Waves, Astronomers Find

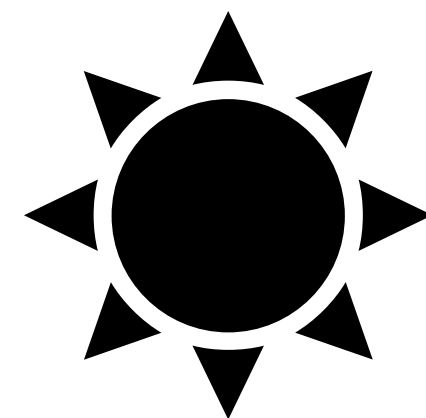
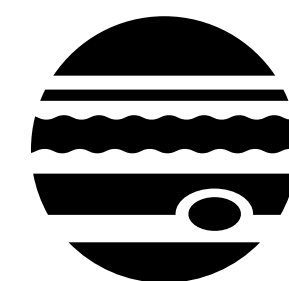
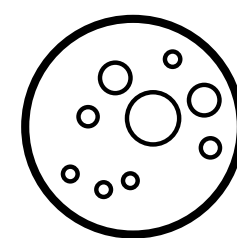




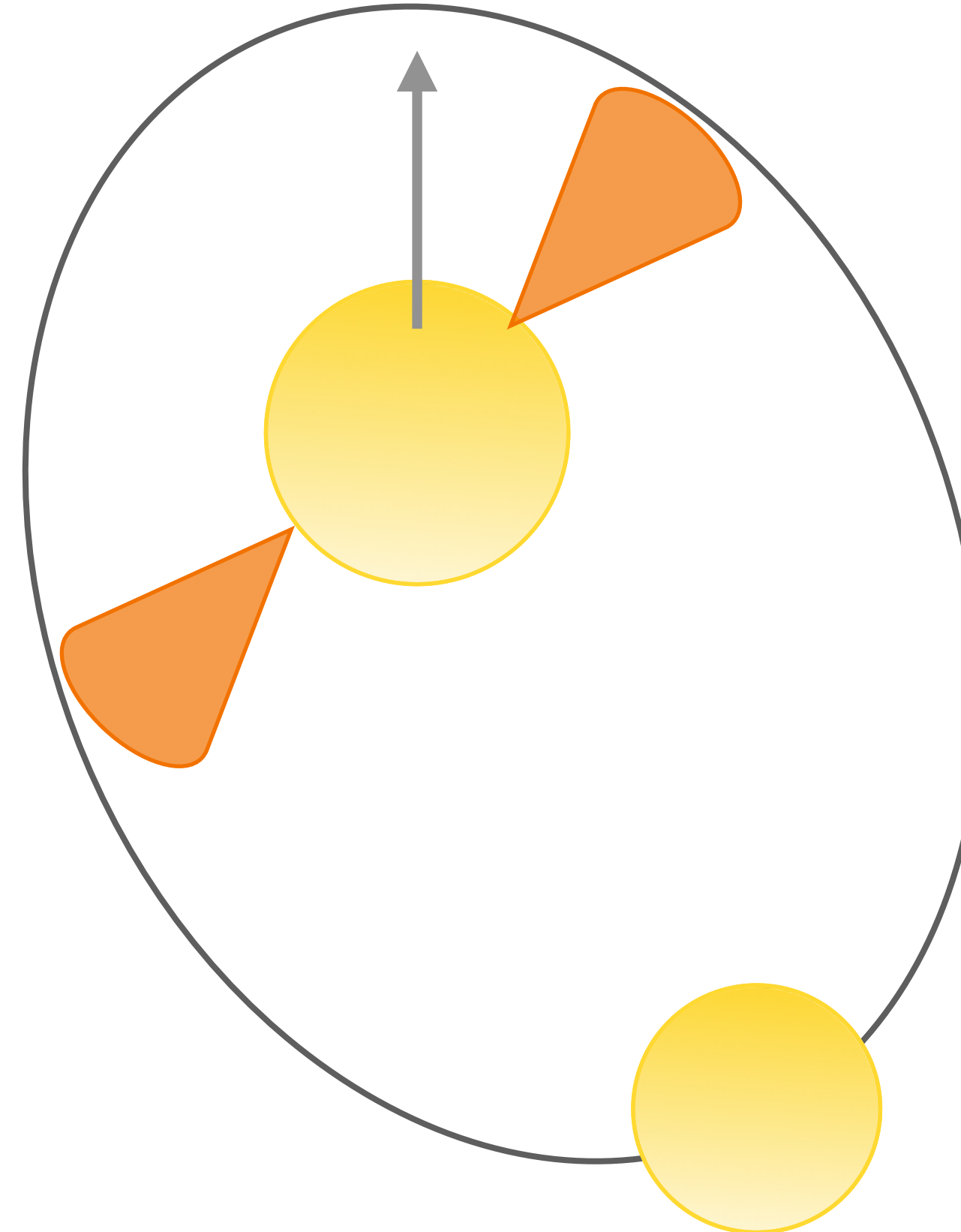
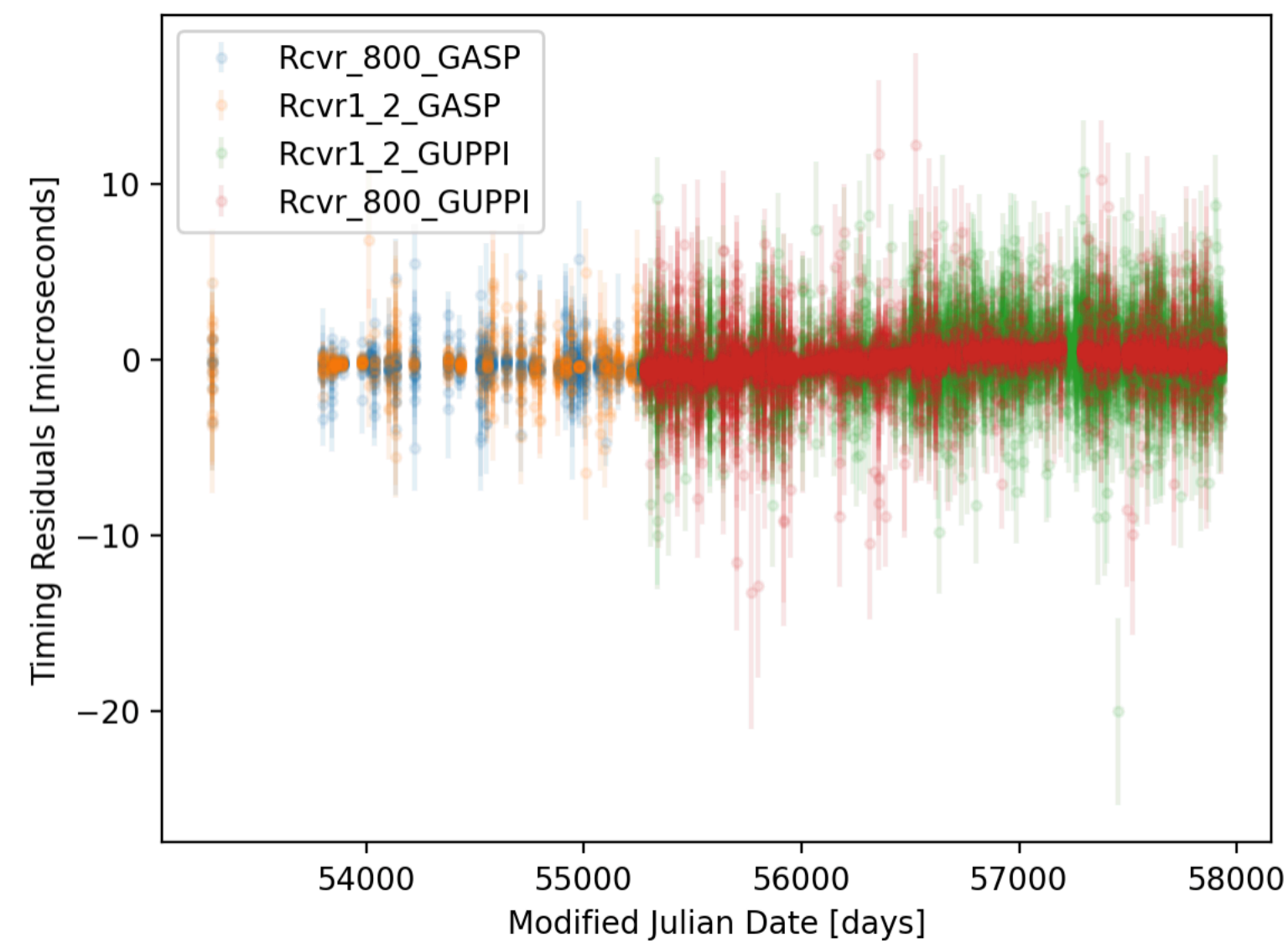
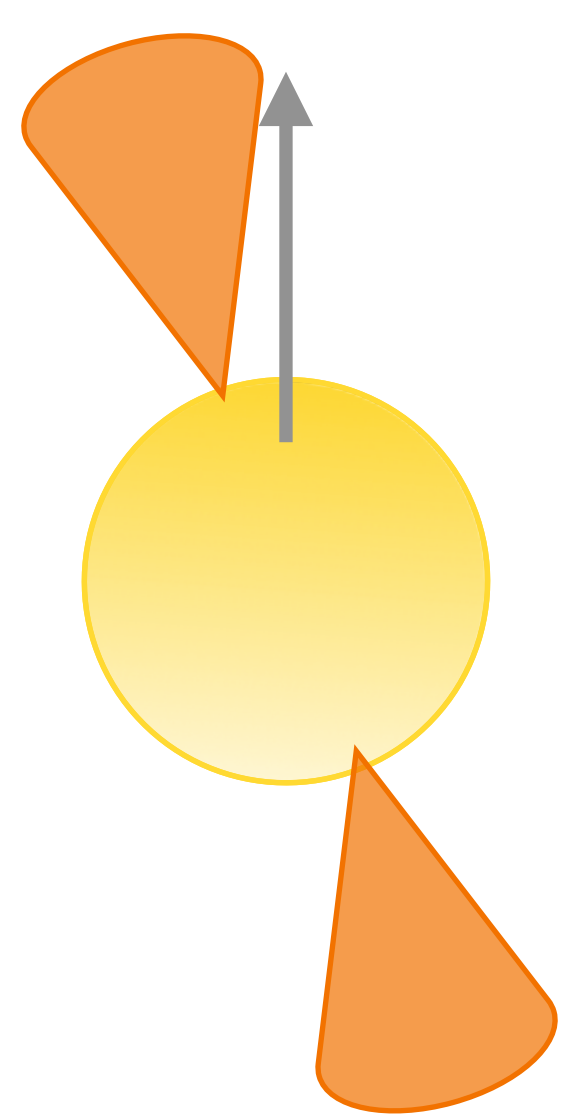
Pulses

Pulses

Gravitational
Waves



Solar system systematics

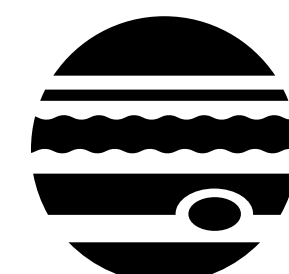
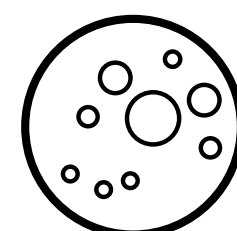


Pulses

Pulses

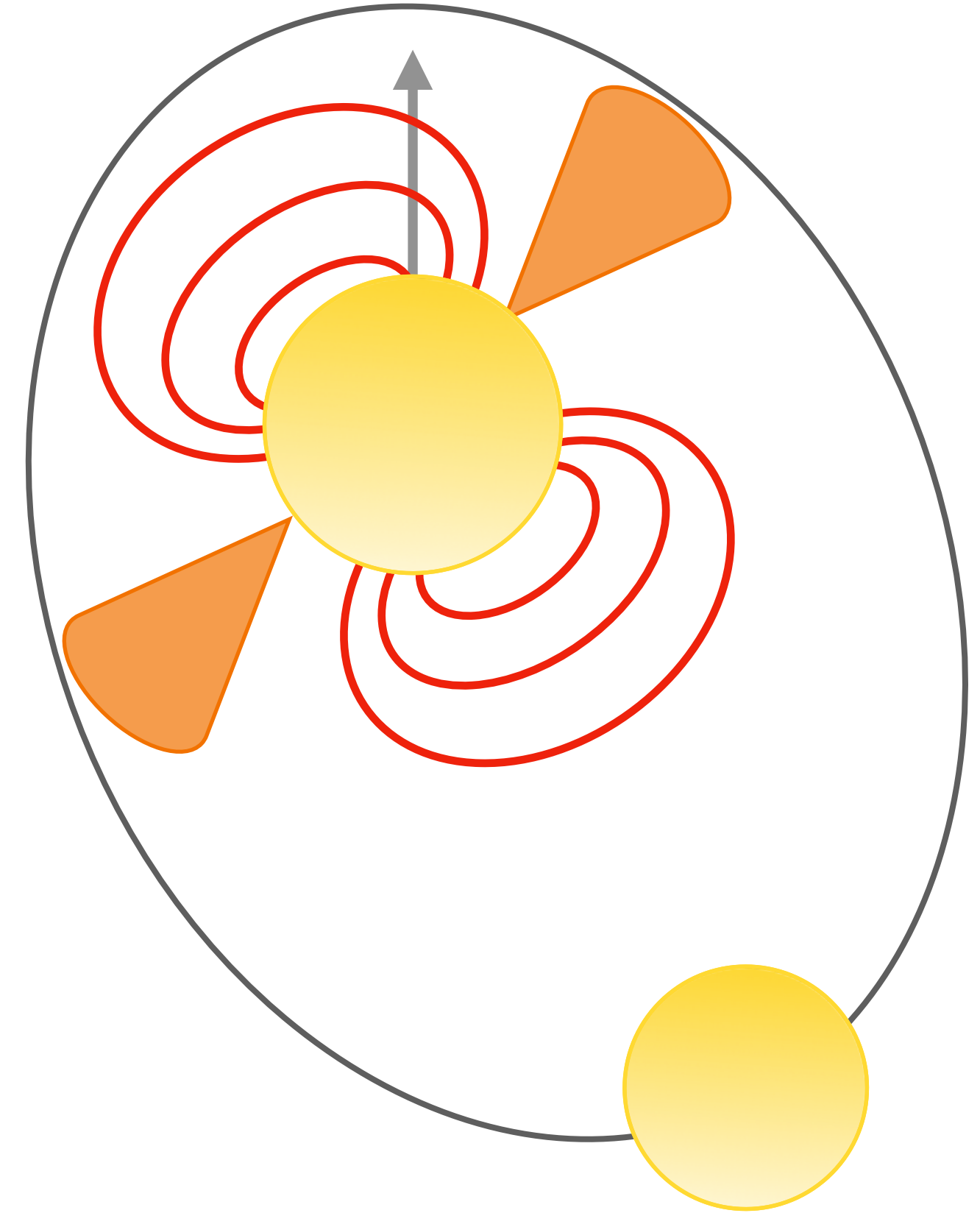
Pulsar companion
systematics

Gravitational
Waves



Solar system systematics

Pulsar red noise
(e . g . magnetosphere fluctuation)

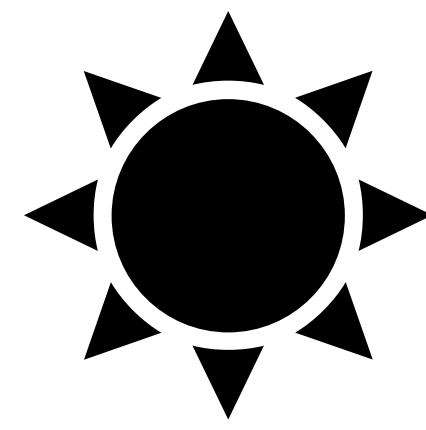
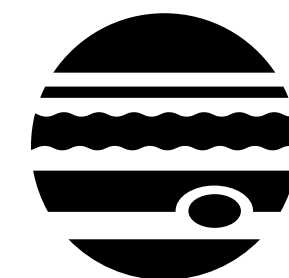
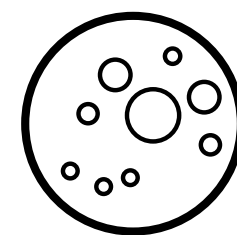


Pulsar companion
systematics

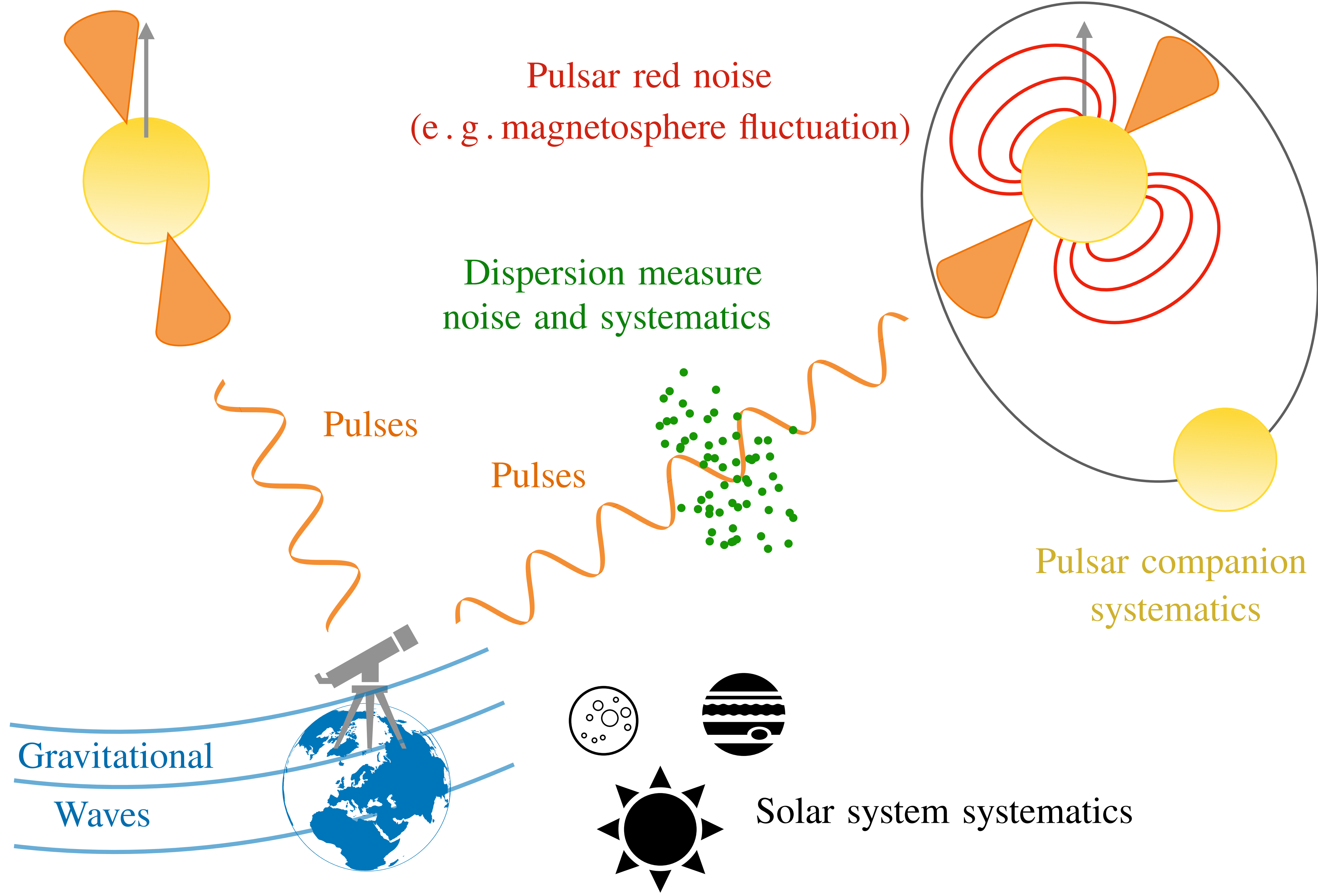
Pulses

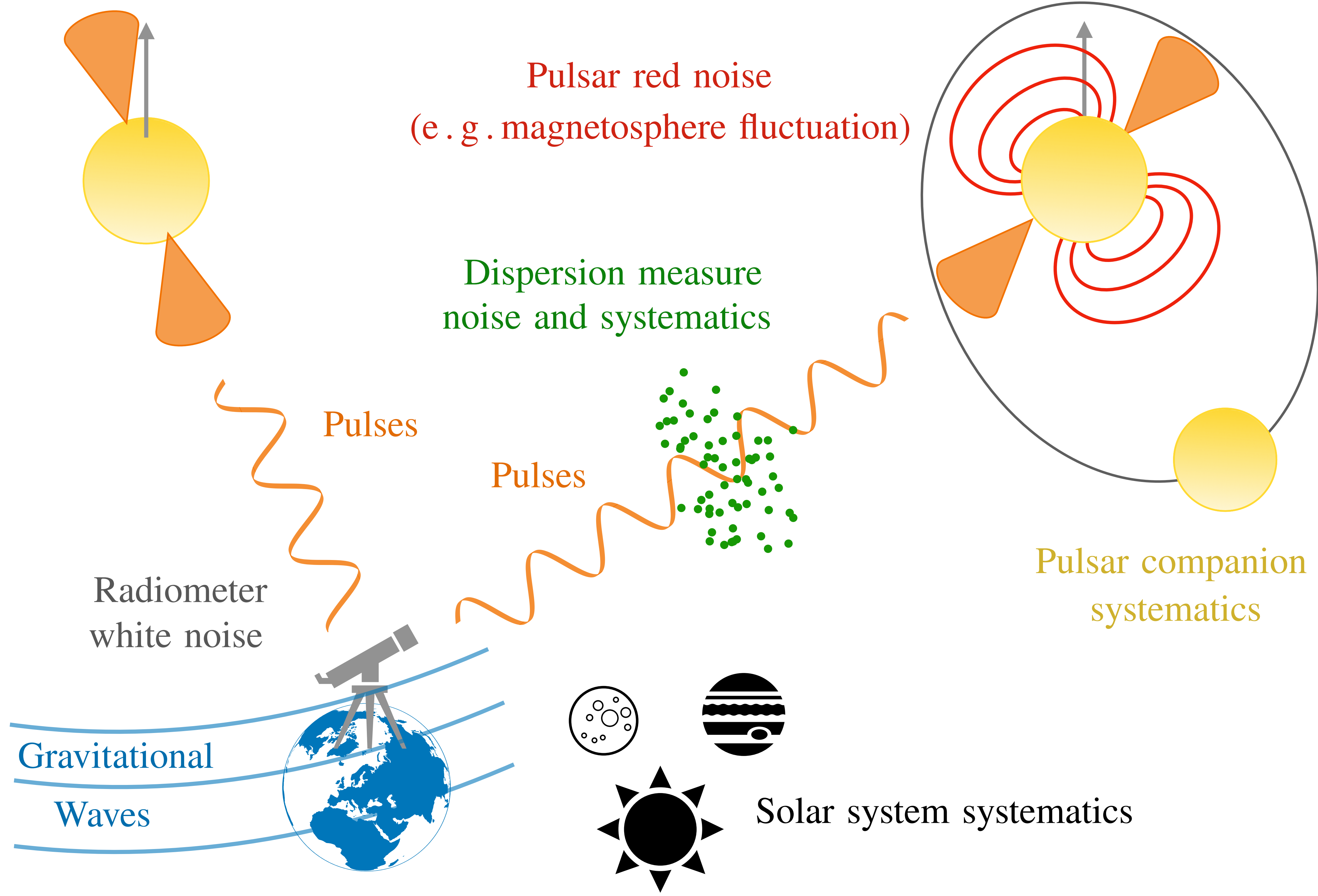
Pulses

Gravitational
Waves

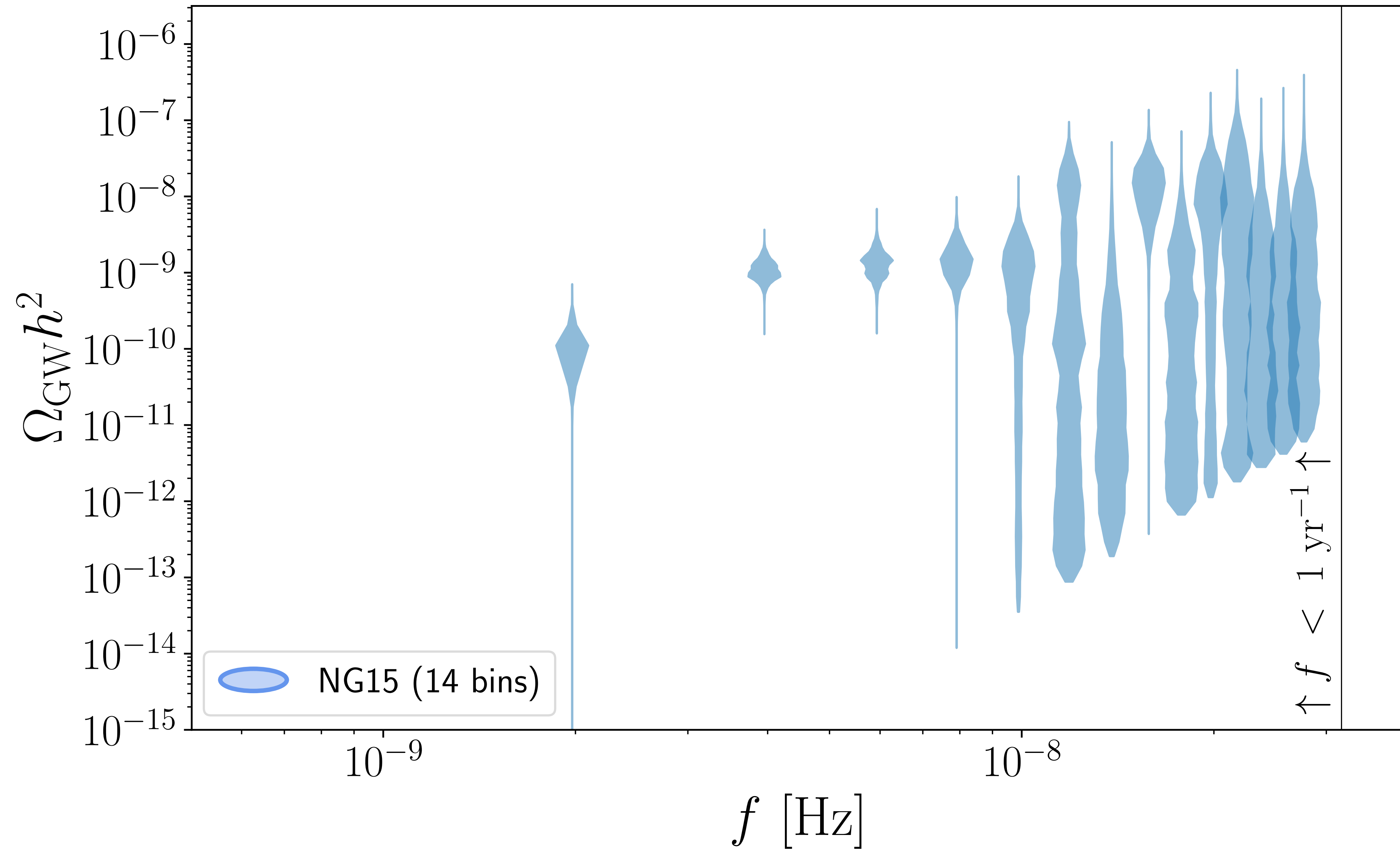


Solar system systematics

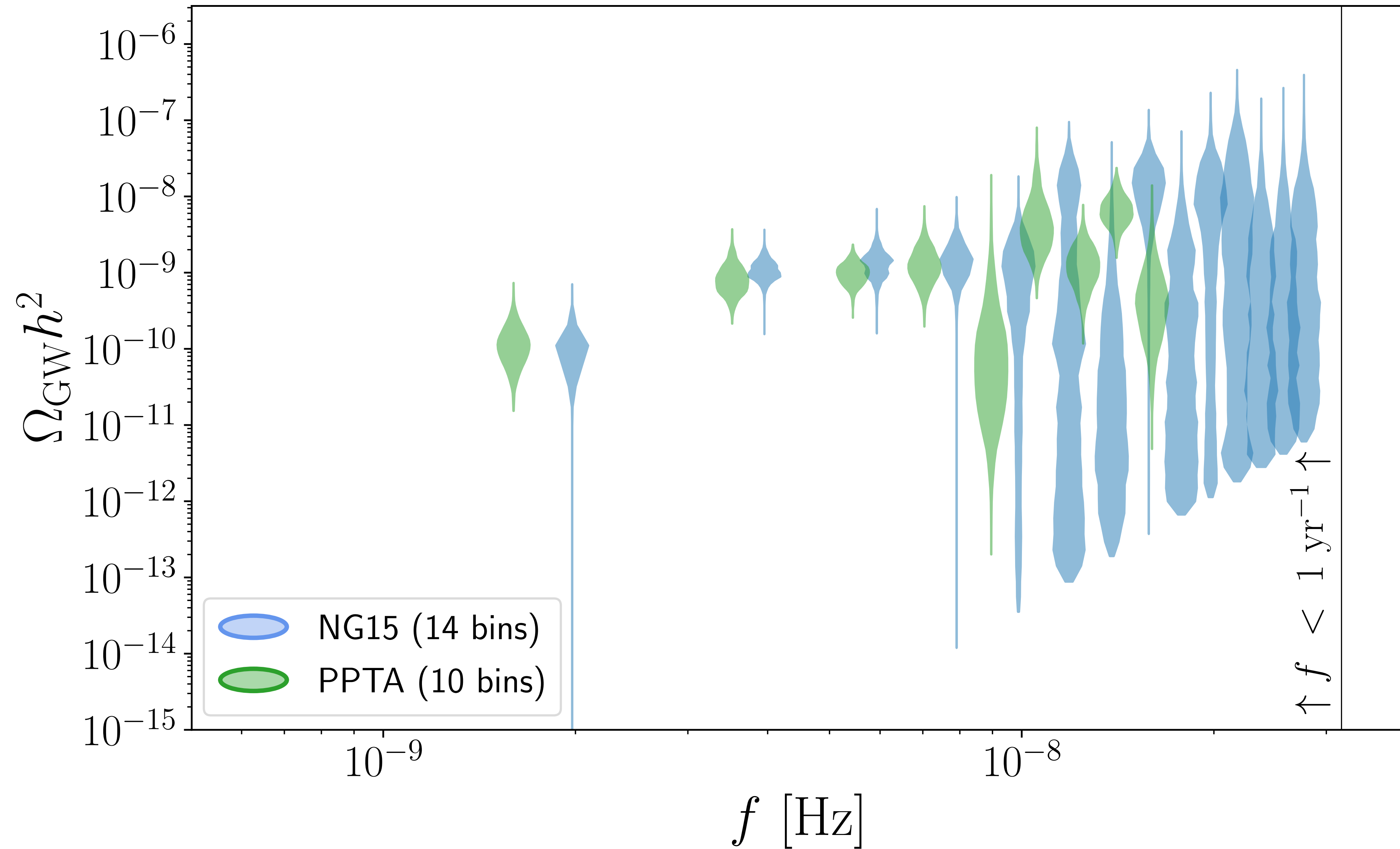




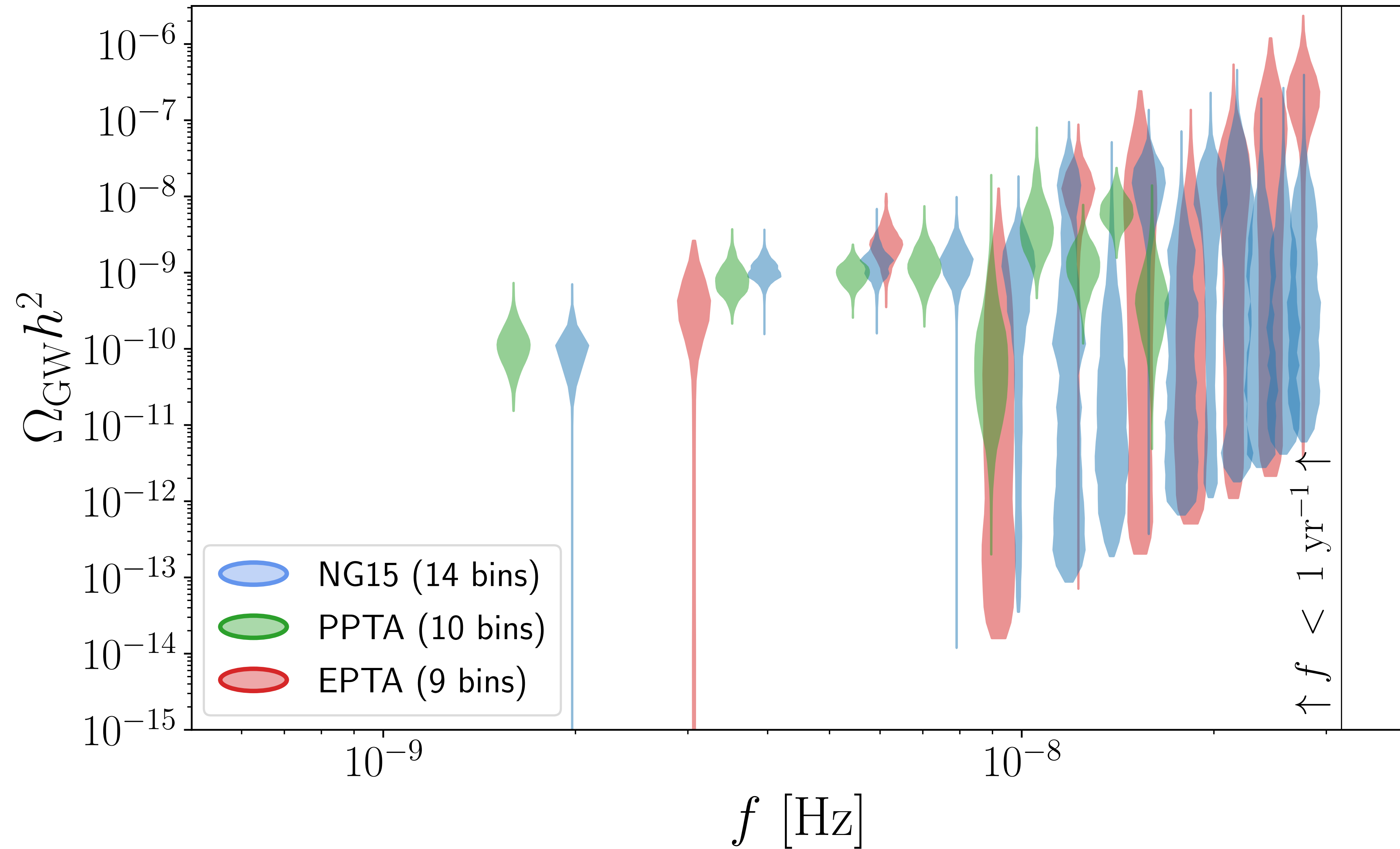
Discovery of the first stochastic GW background by Pulsar Timing Arrays (PTA)



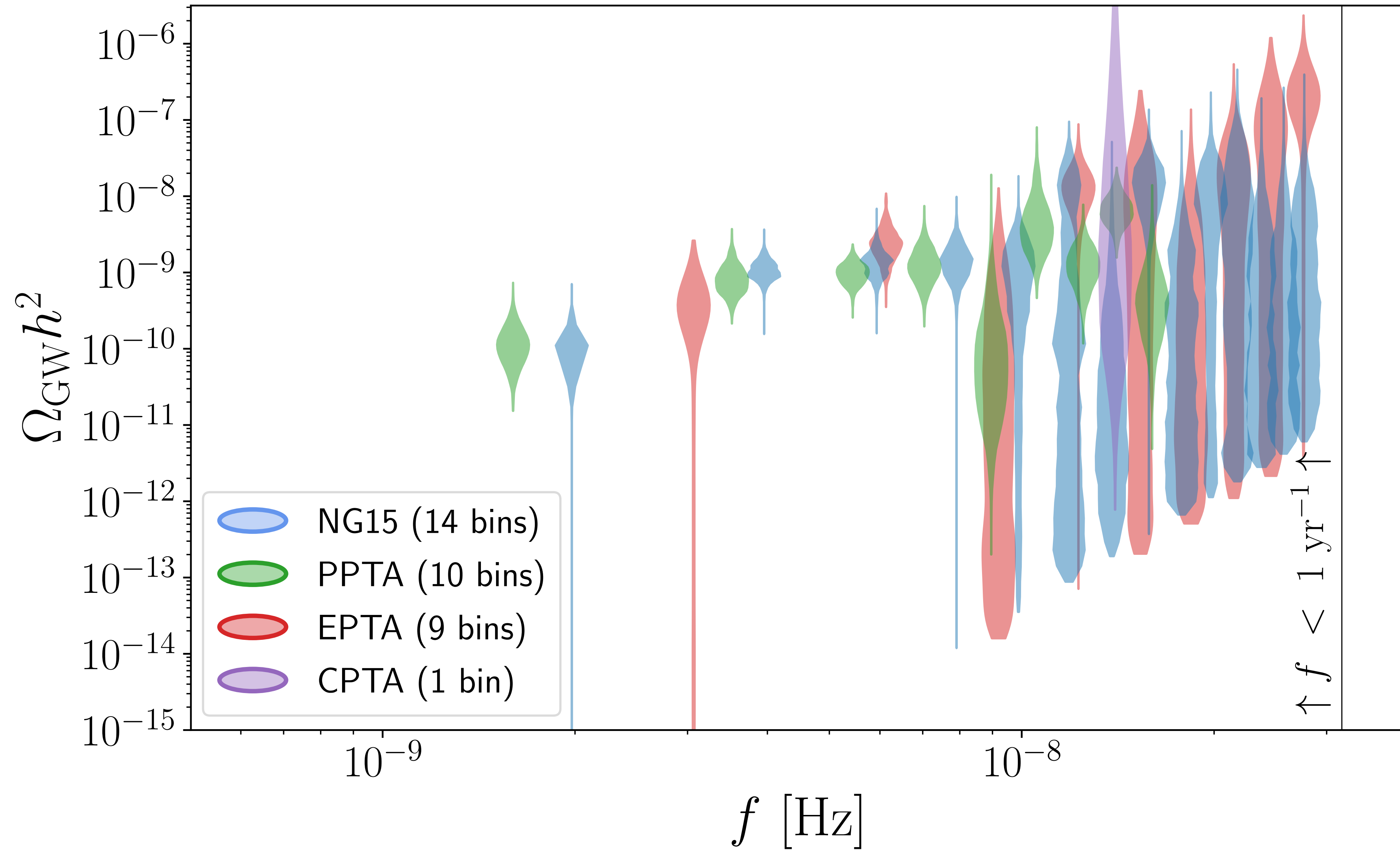
Discovery of the first stochastic GW background by Pulsar Timing Arrays (PTA)



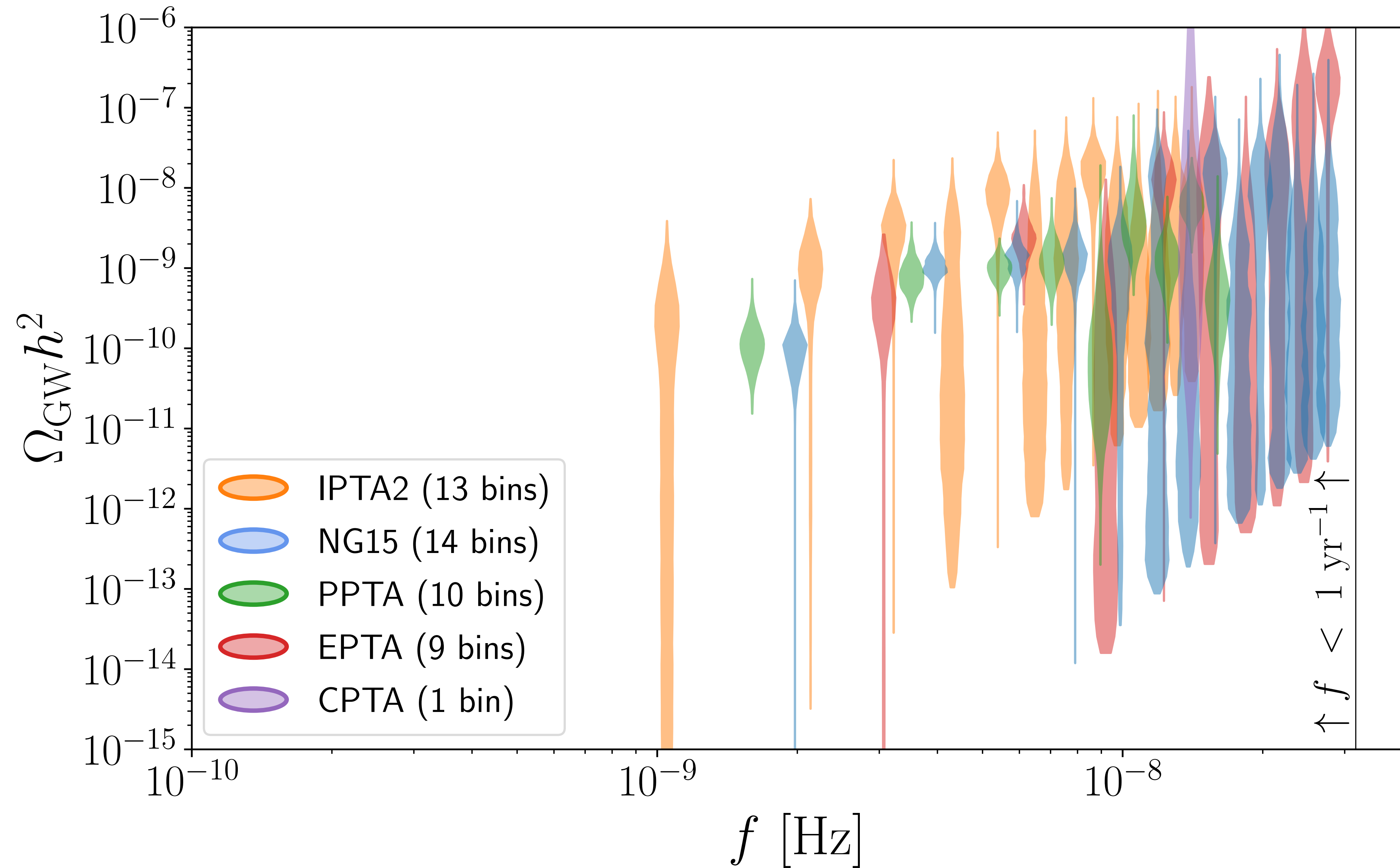
Discovery of the first stochastic GW background by Pulsar Timing Arrays (PTA)



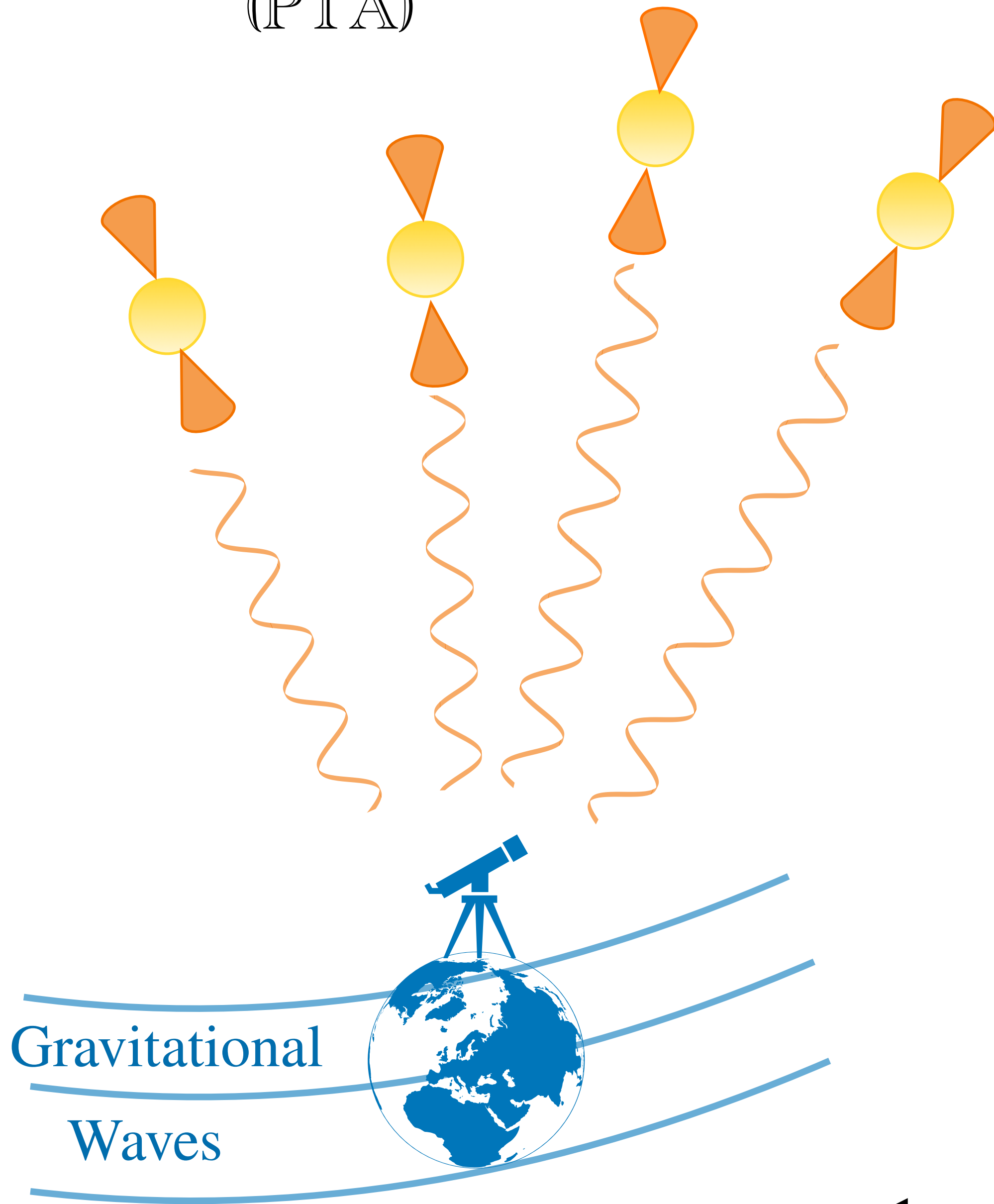
Discovery of the first stochastic GW background by Pulsar Timing Arrays (PTA)



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

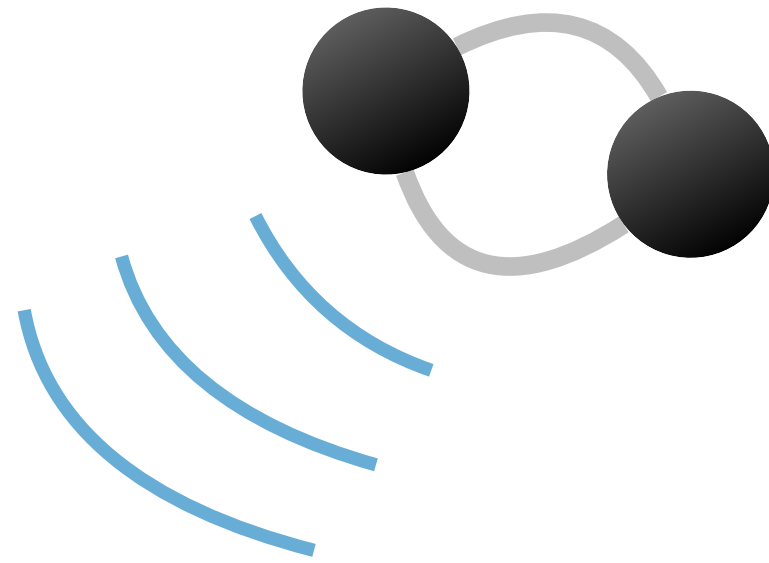


Pulsar Timing Arrays
(PTA)

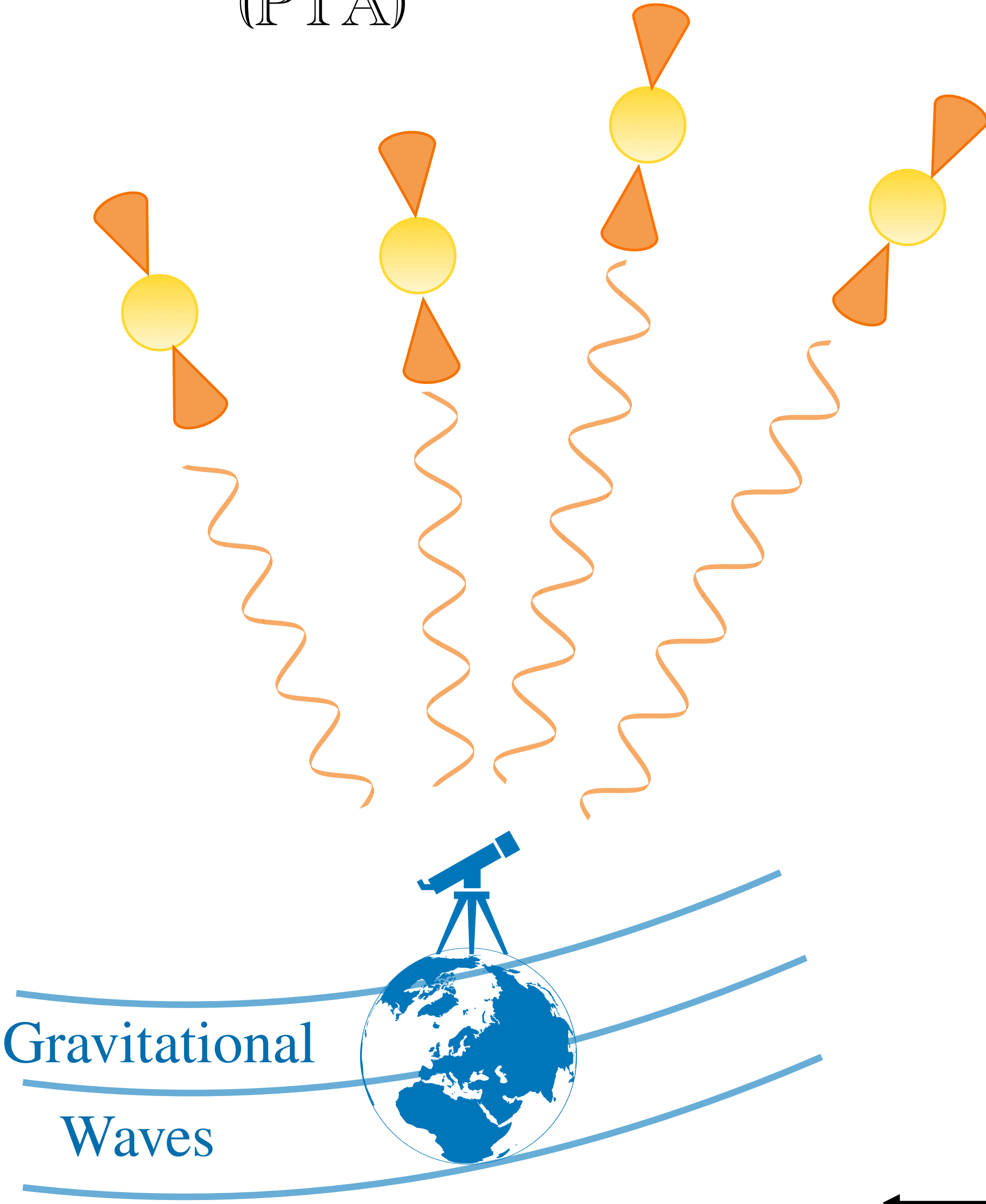


Gravitational
Waves

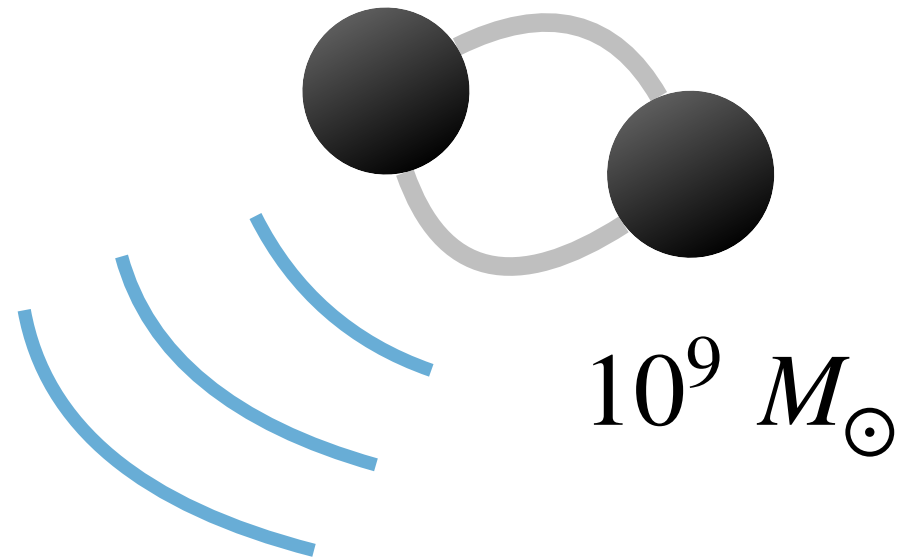
Supermassive
black holes binaries



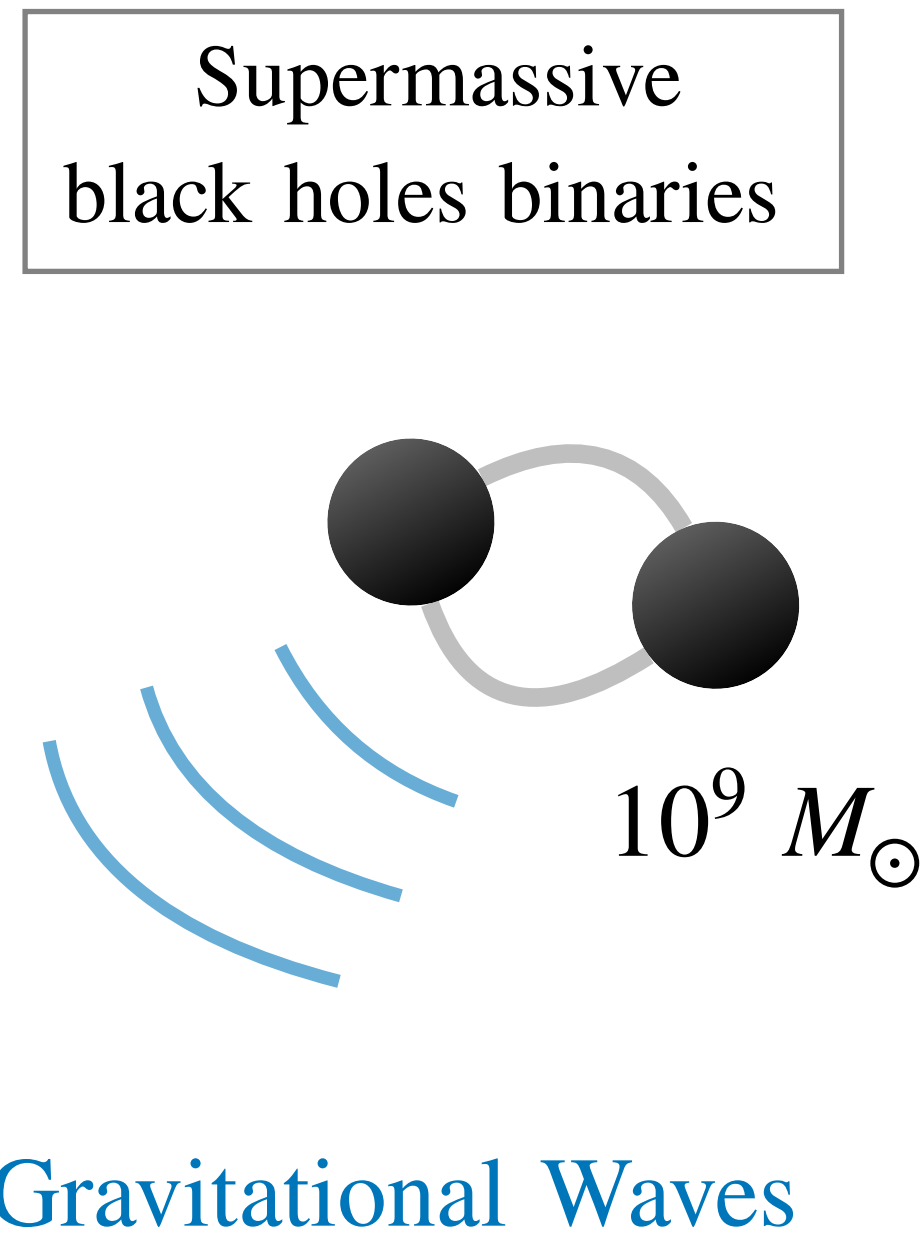
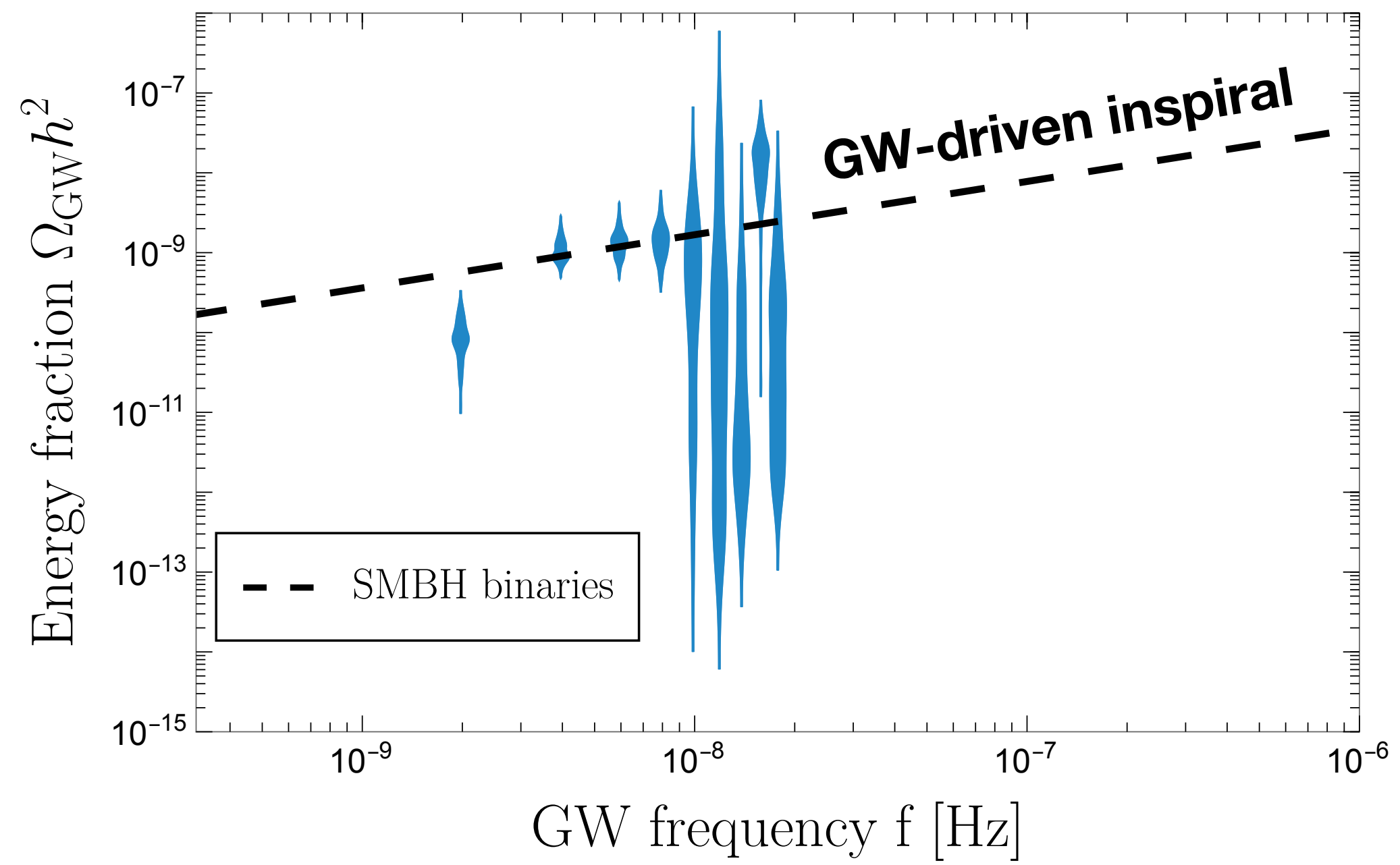
Pulsar Timing Arrays (PTA)

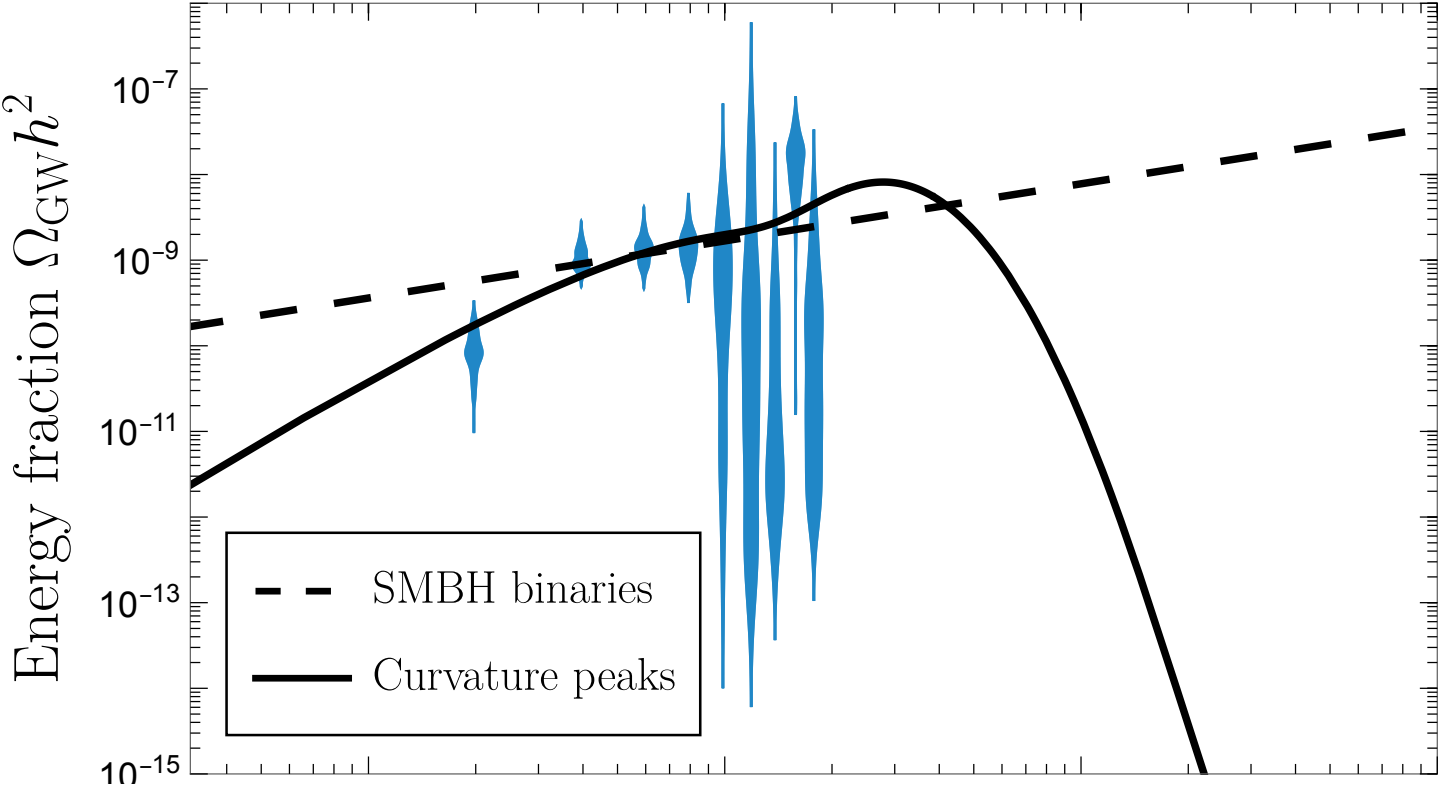


Supermassive
black holes binaries



Pulsar Timing Arrays (PTA)



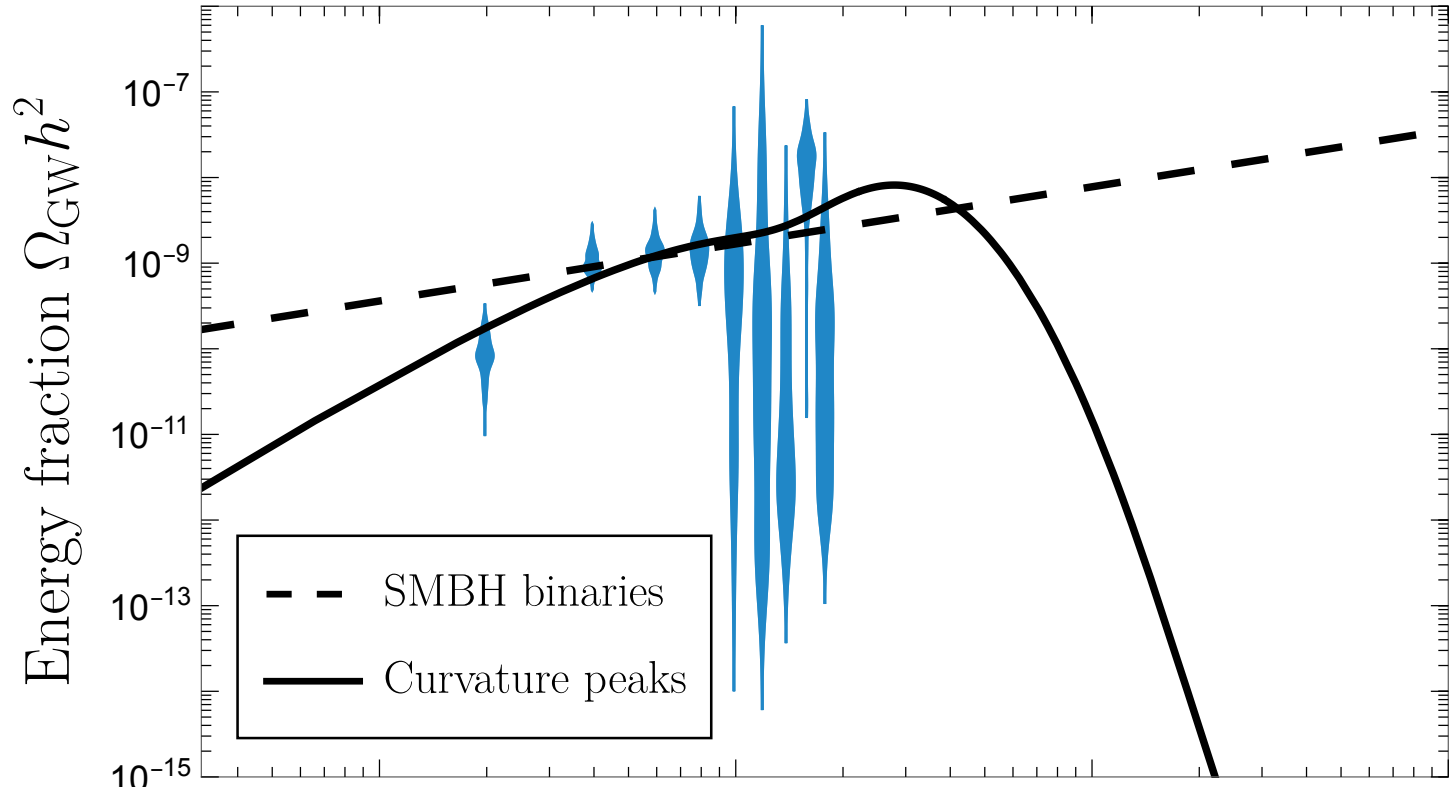


Curvature peaks

Kohri, Terada (2009.11853)
Vaskonen, Veermäe (2009.07832),
Franciolini, Vaskonen, Vermae (2306.17143)
Cecchini, Franciolini, Pieroni (2503.10805)
...

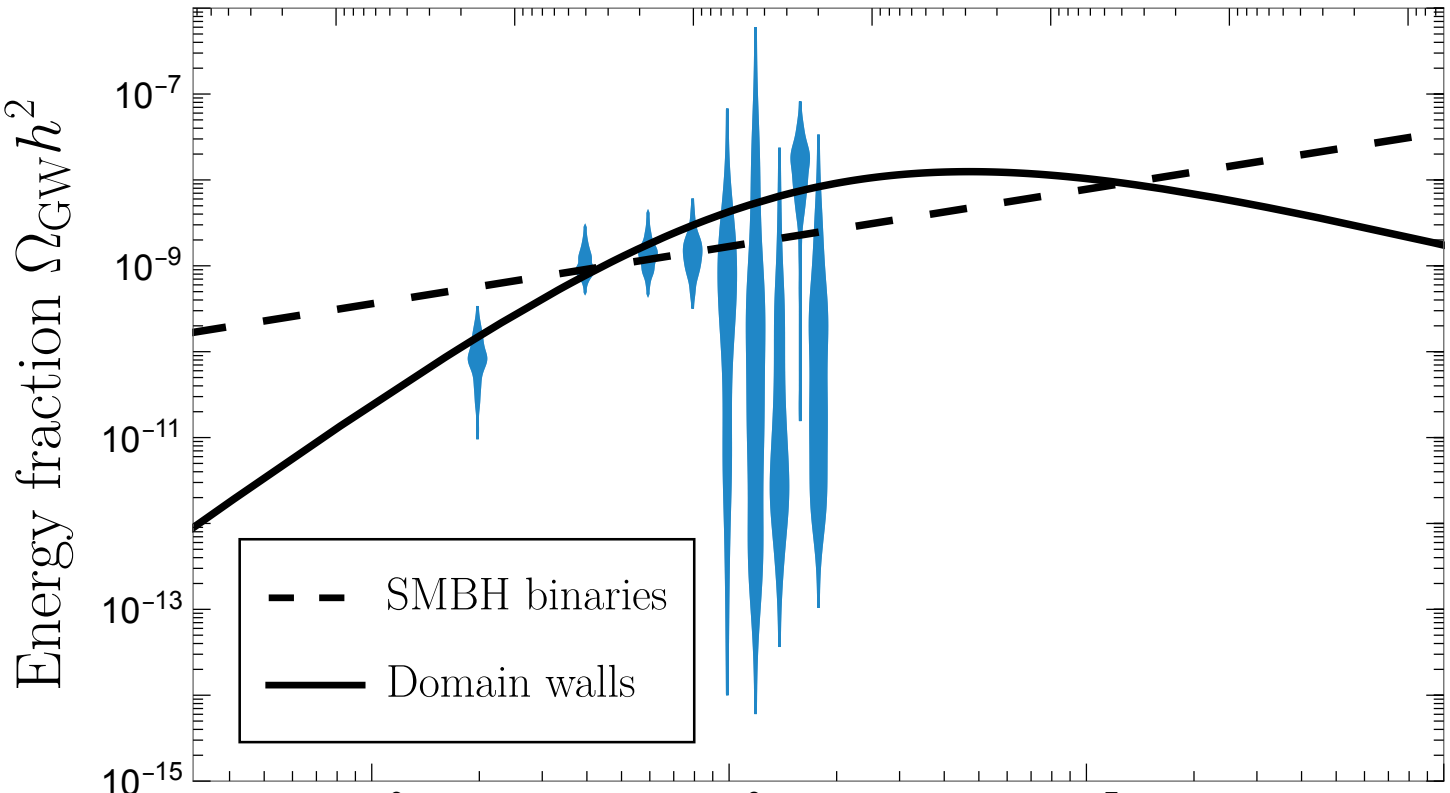


Reviews: Madge et al (2306.14856),
Figueroa et al (2307.02399),
Ellis et al (2308.08546)



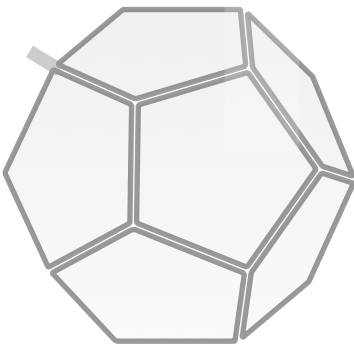
Curvature peaks

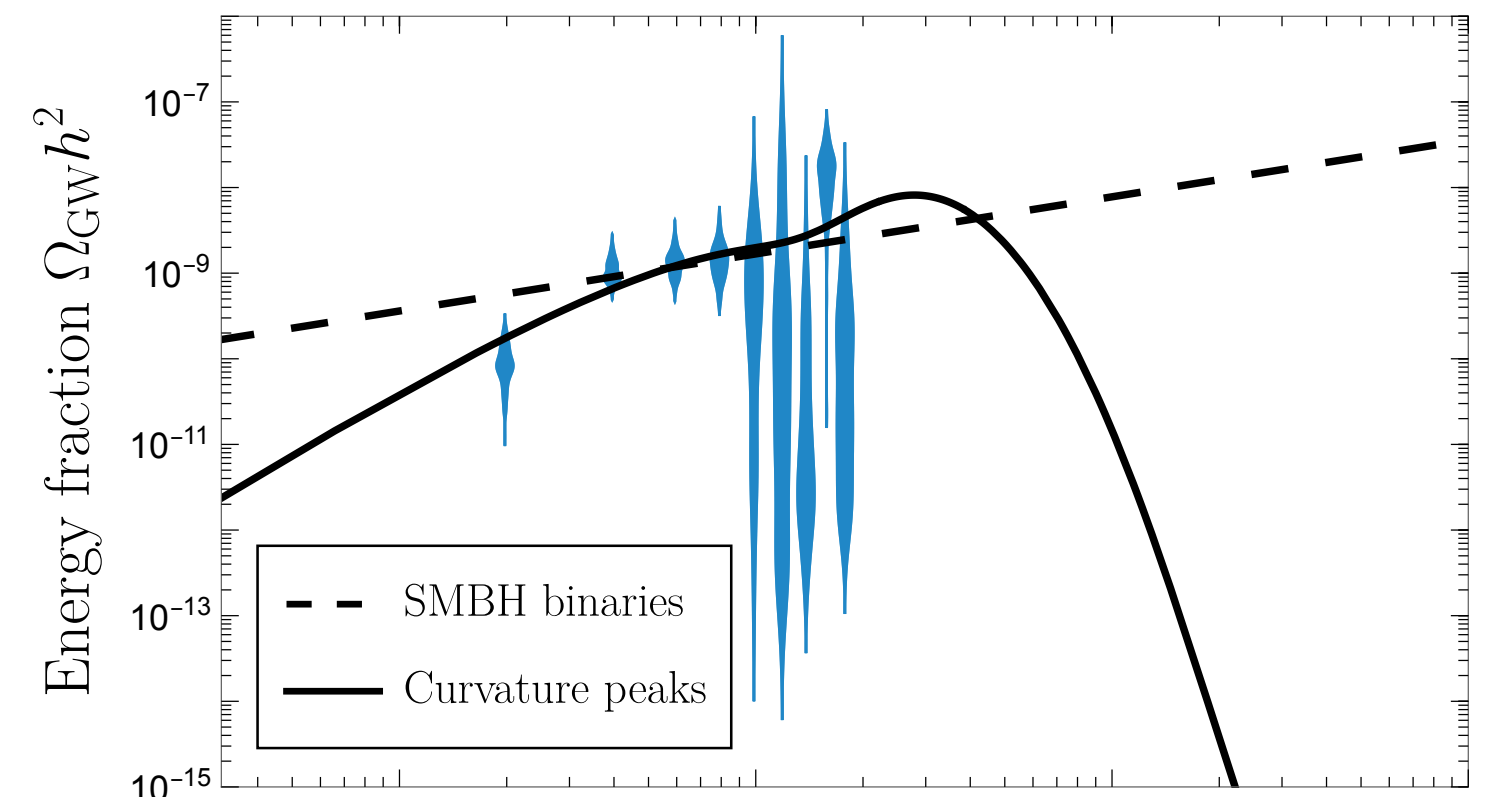
Kohri, Terada (2009.11853)
Vaskonen, Veermäe (2009.07832),
Franciolini, Vaskonen, Vermae (2306.17143)
Cecchini, Franciolini, Pieroni (2503.10805)
...



Domain wall networks

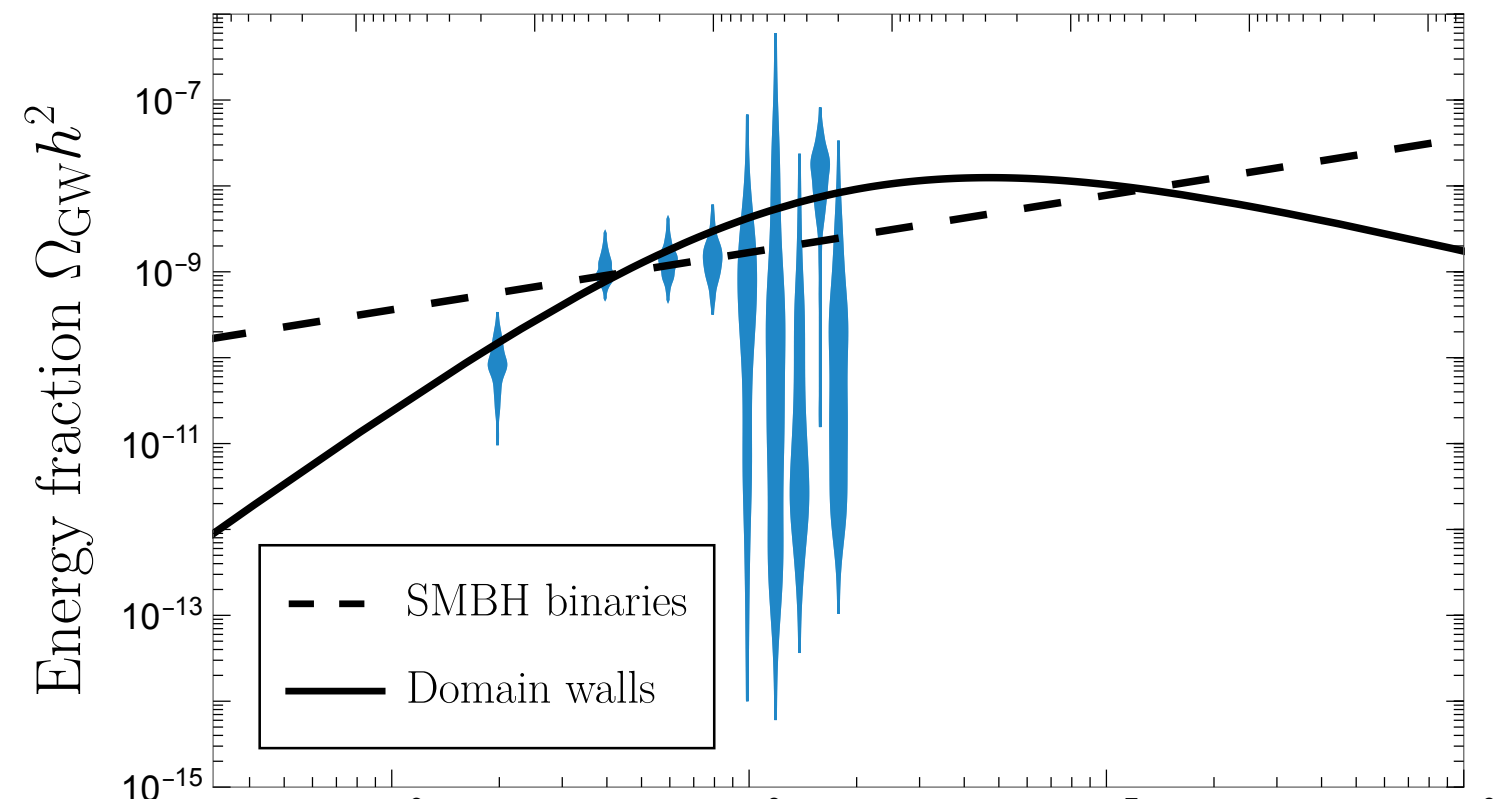
Ferreira, Notari, Pujolas, Rompineve (2204.04228)
Blasi, Mariotti, Rase, Sevrin (2306.17830)
...





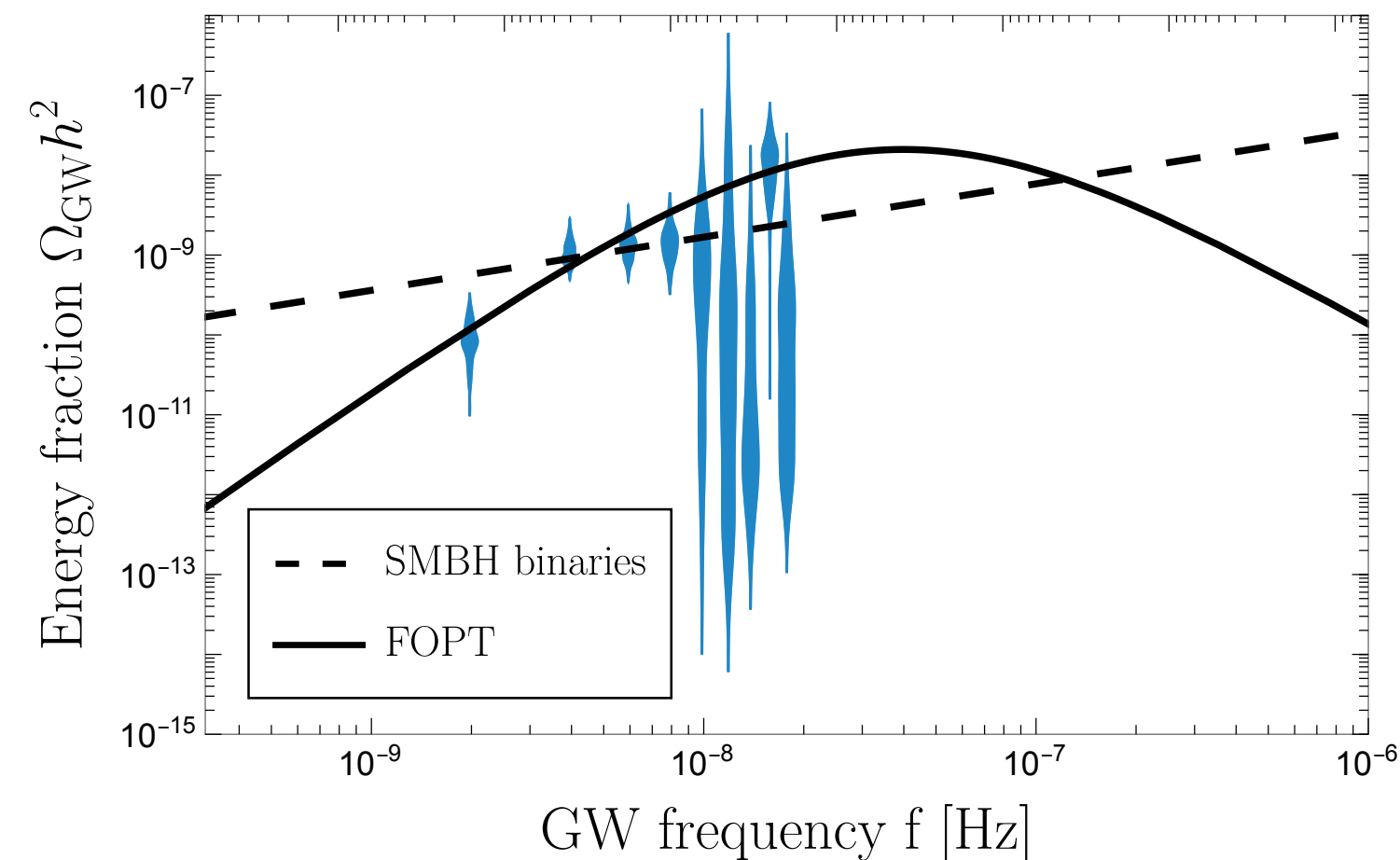
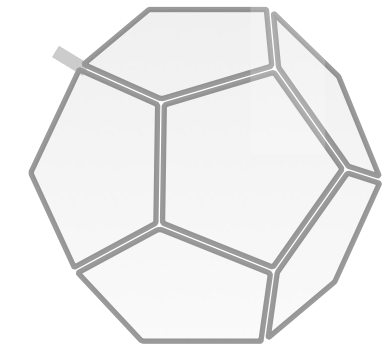
Curvature peaks

Kohri, Terada (2009.11853)
Vaskonen, Veermäe (2009.07832),
Franciolini, Vaskonen, Vermae (2306.17143)
Cecchini, Franciolini, Pieroni (2503.10805)
...



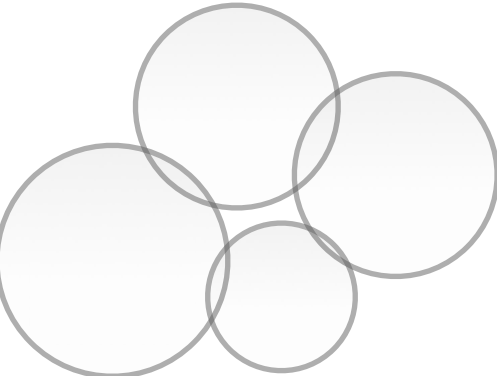
Domain wall networks

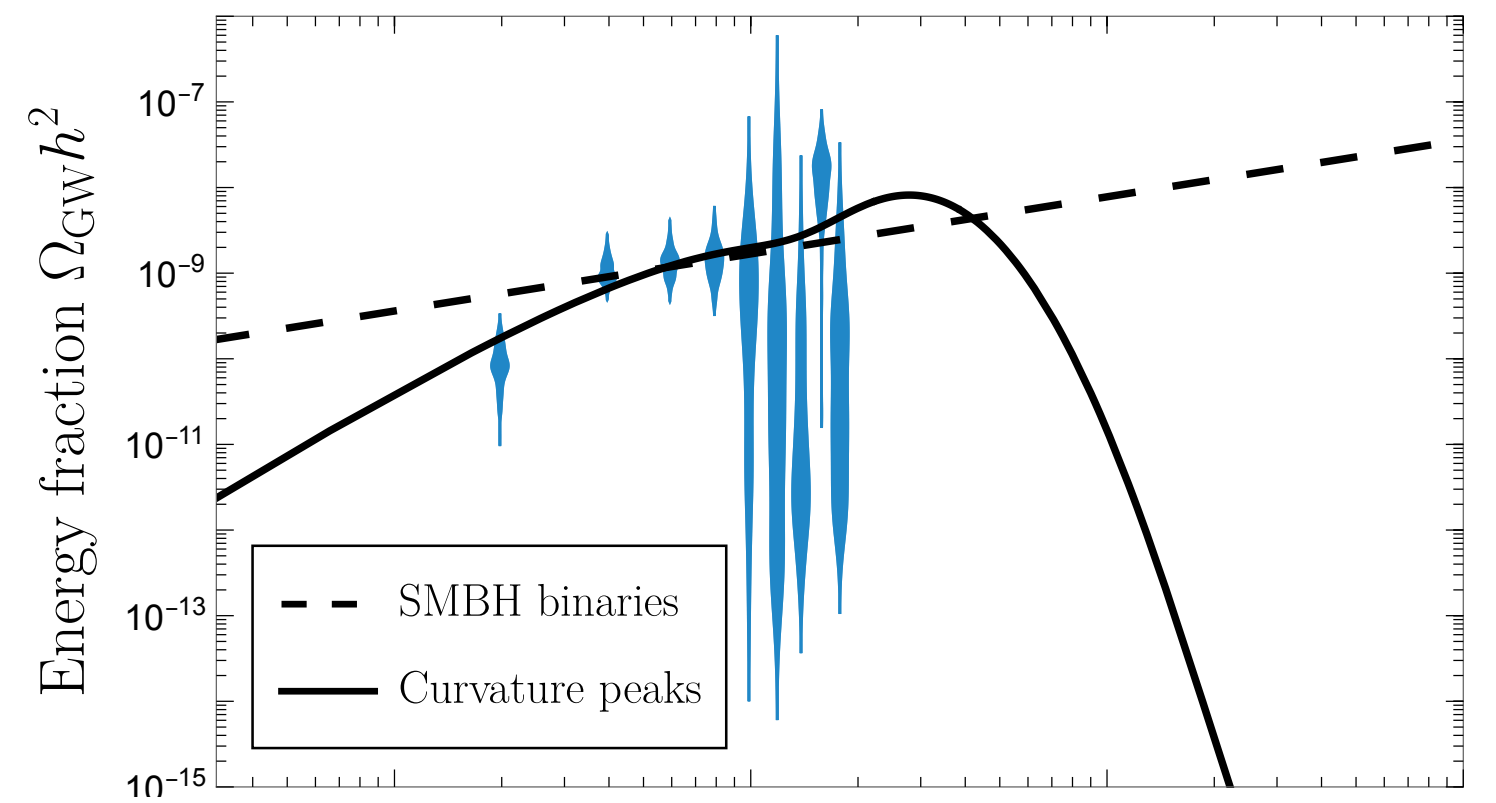
Ferreira, Notari, Pujolas, Rompineve (2204.04228)
Blasi, Mariotti, Rase, Sevrin (2306.17830)
...



First-order phase transitions

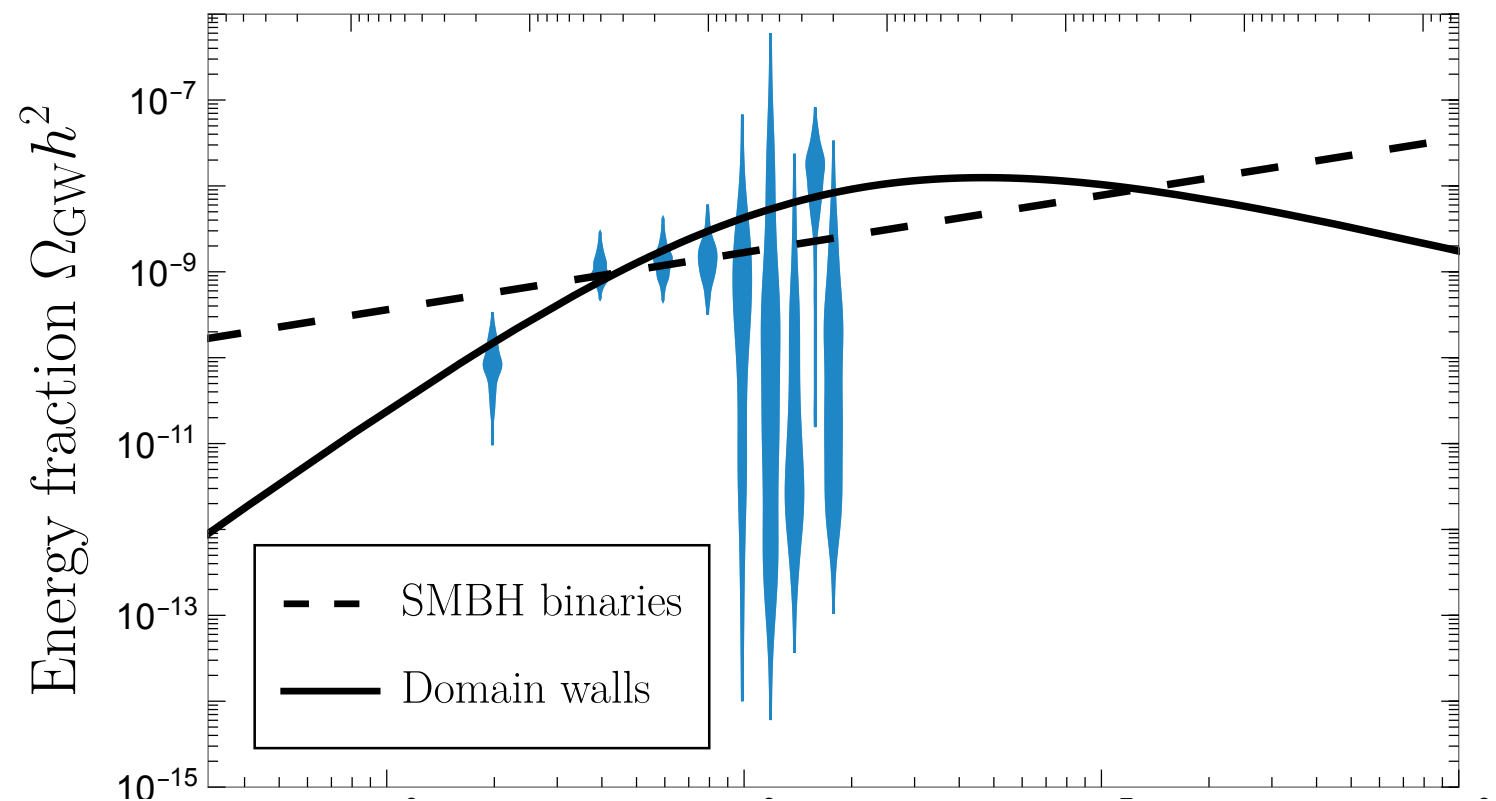
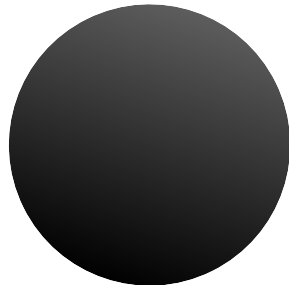
Roper Pol et al. (2201.05630)
Ghoshal, White et al. (2307.02259)
YG (2307.04239)
Lewicki, Toczek, Vaskonen (2402.04158)
Hoefken Zink et al. (2501.15649)
...





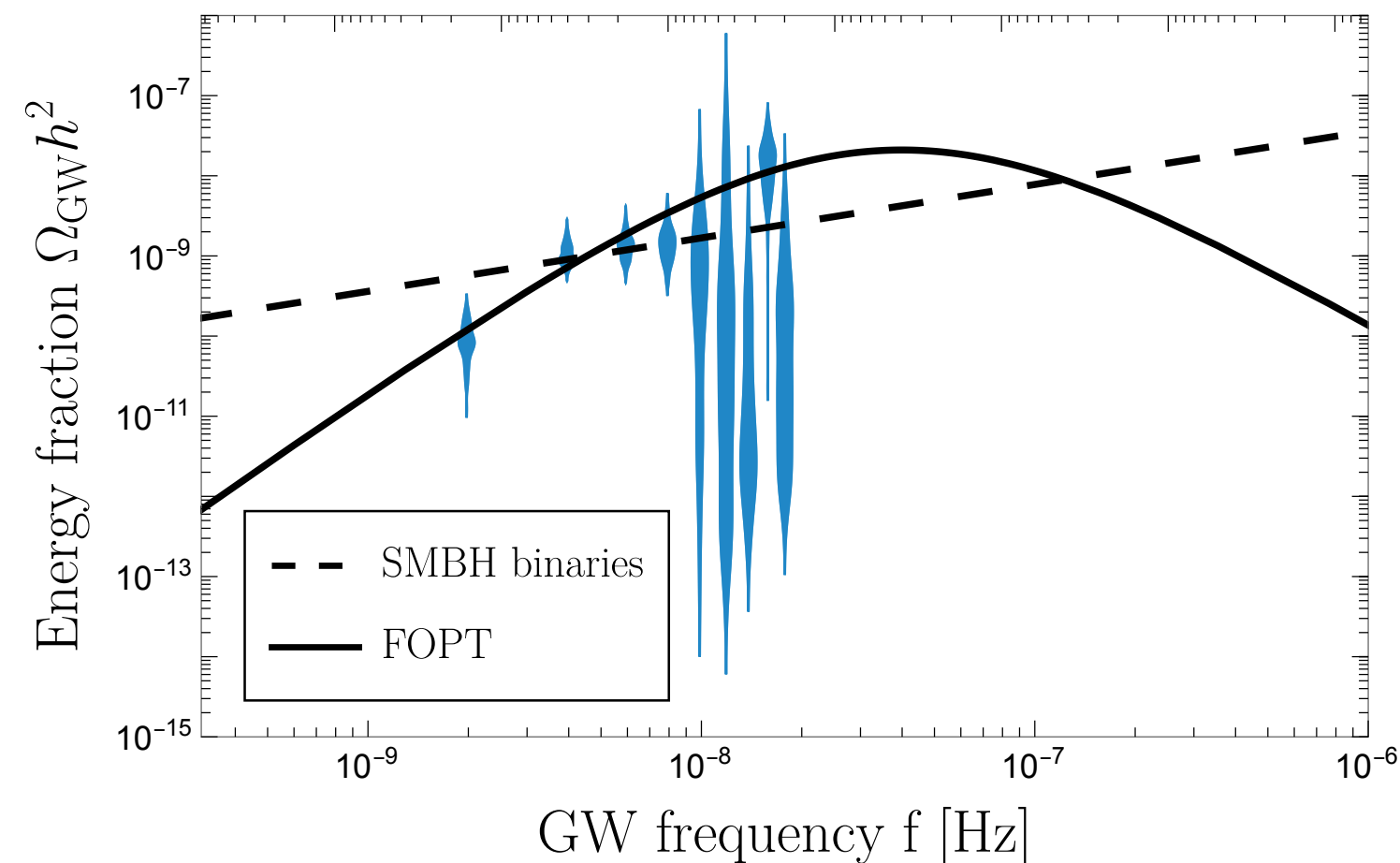
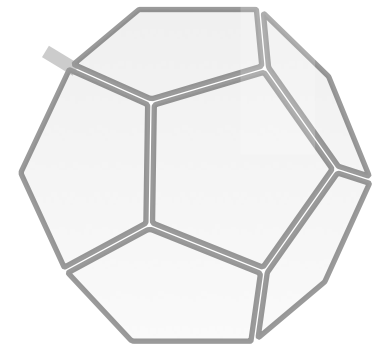
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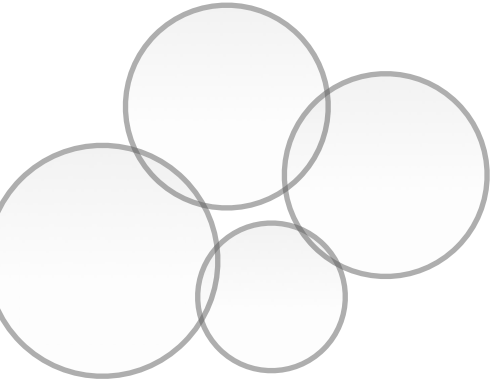
Domain wall networks

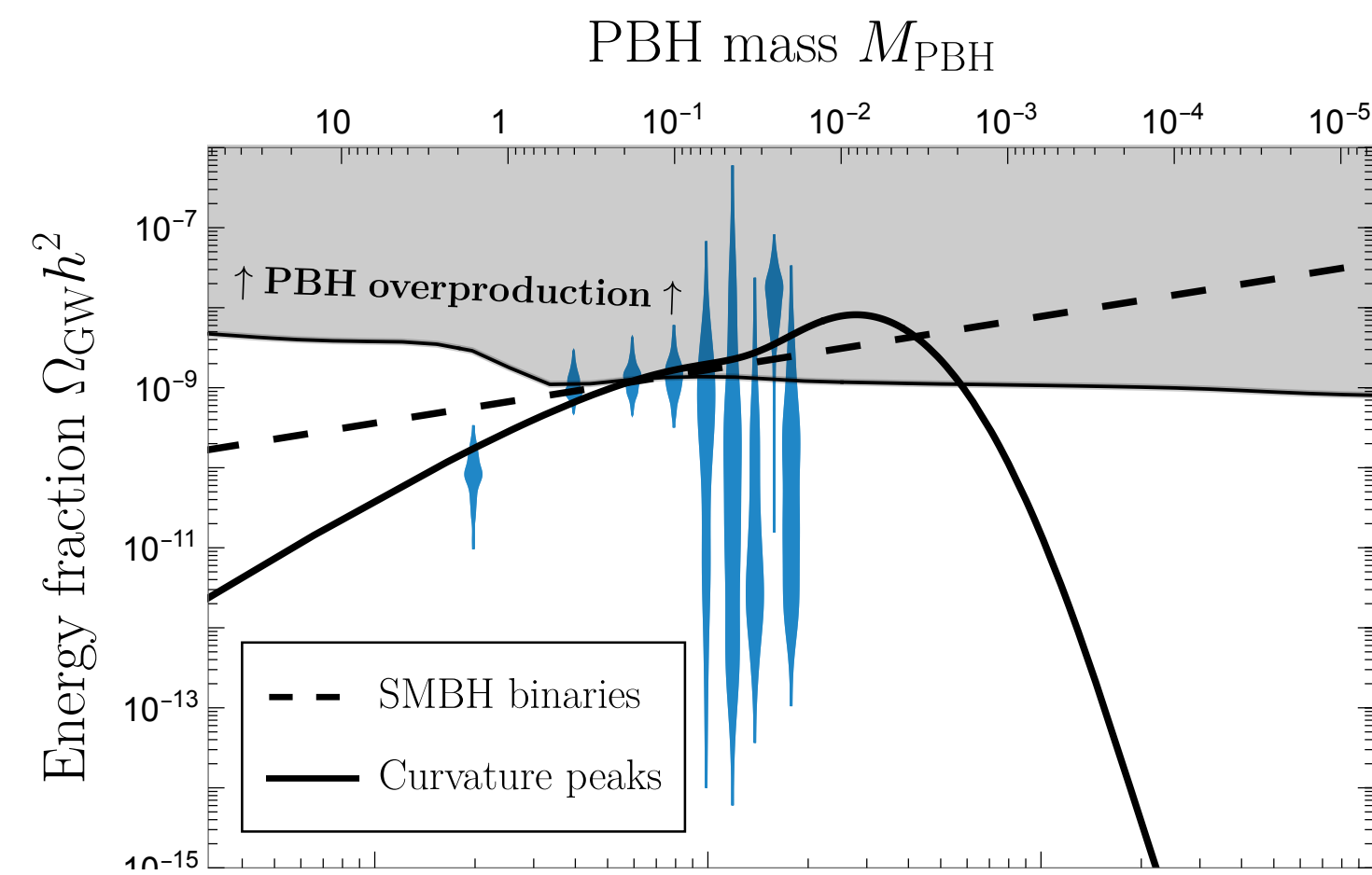
Ferreira, Notari, Pujolas, Rompineve (2204.04228)
Blasi, Mariotti, Rase, Sevrin (2306.17830)
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First-order phase transitions

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Hoefken Zink et al. (2501.15649)
...





Curvature peaks

Overproduce PBH

Chen, Yuan, Huang (1910.12239)

Kohri, Terada (2009.11853)

Inomata, Kawasaki, Mukaida, Yanagida (2011.01270)

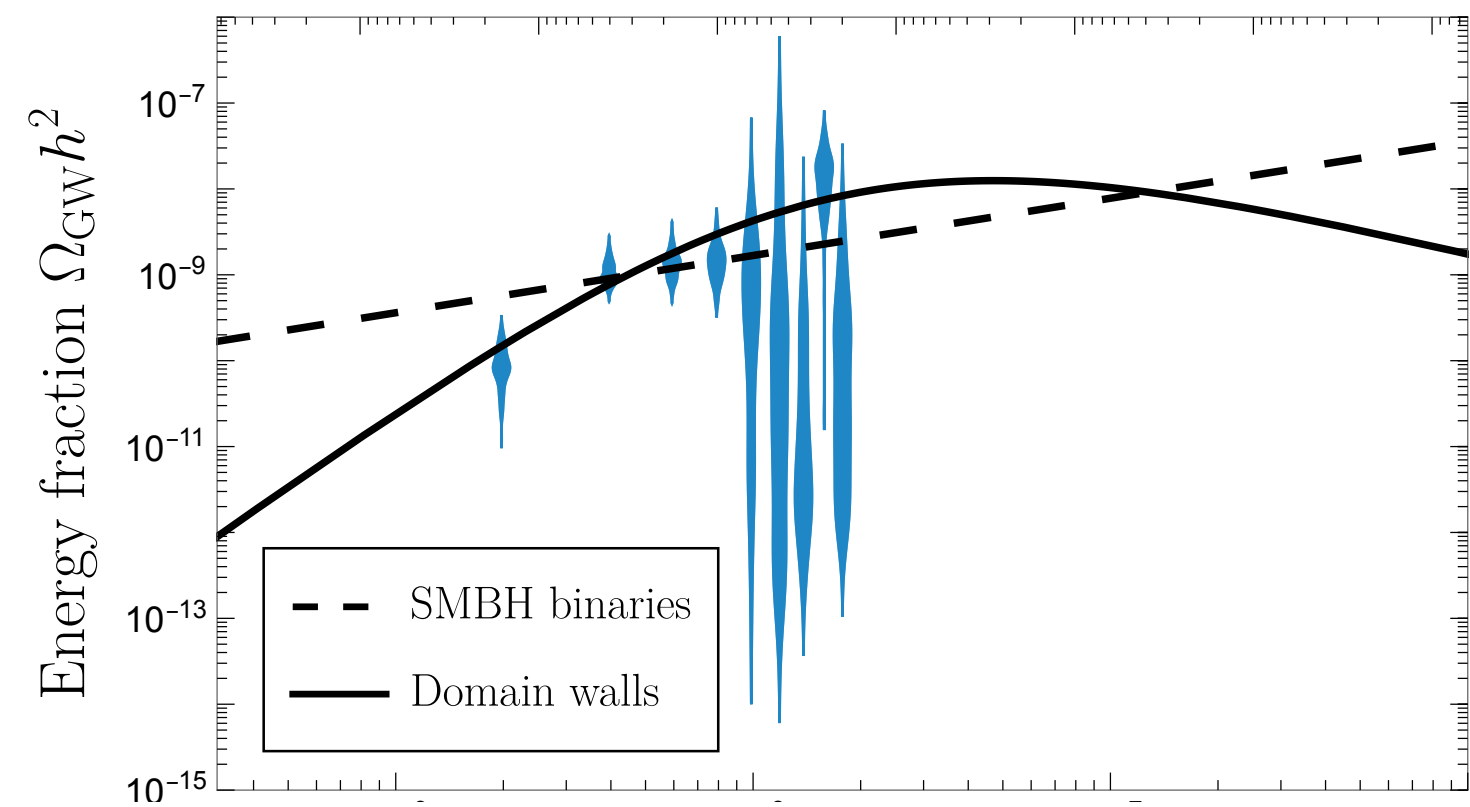
Vaskonen, Veermae (2009.07832),

De Luca, Franciolini, Riotto (2009.08268)

Except if negative non-Gaussianities

Franciolini, Vaskonen, Vermae (2306.17143)

YG, Trifinopoulos, Vanvlasselaer (2508.19328)

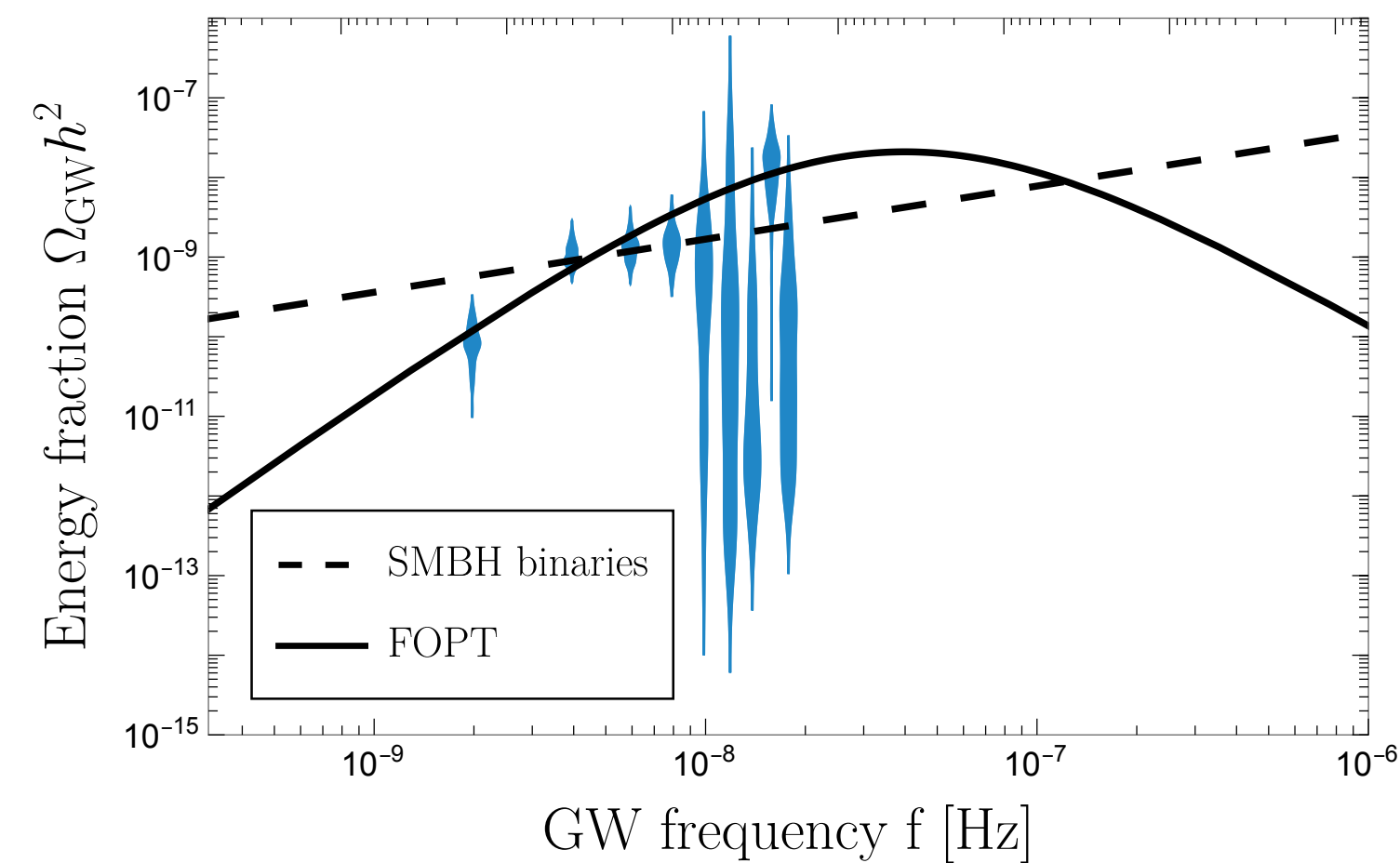
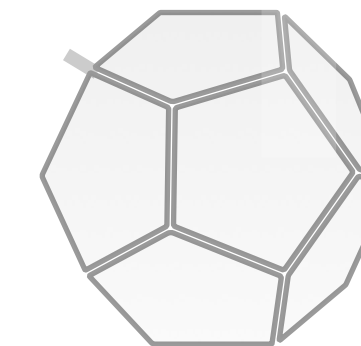


Domain wall networks

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...



First-order phase transitions

Roper Pol et al. (2201.05630)

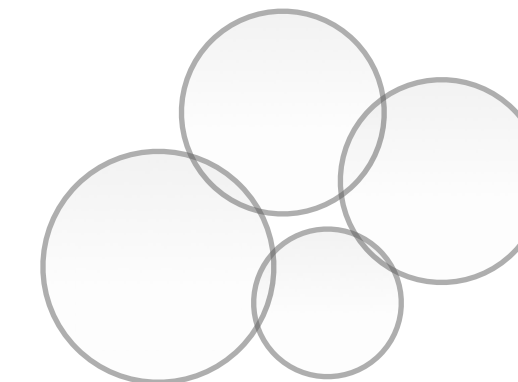
Ghoshal, White et al. (2307.02259)

YG (2307.04239)

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Reviews: Madge et al (2306.14856),

Figueroa et al (2307.02399),

Ellis et al (2308.08546)

Scalar Curvature

$$\mathcal{R}(\overrightarrow{x}, t)$$

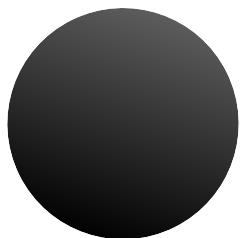


Scalar Curvature

$$\mathcal{R}(\overrightarrow{x}, t)$$



**PBH
formation**
→

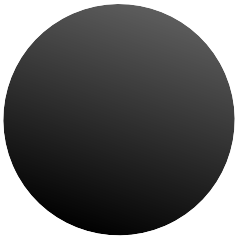


Scalar Curvature

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



**PBH
formation**



**GW from PBH
Formation**



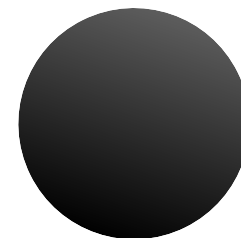
$$M_{\text{PBH}} = \frac{4\pi}{3} H_{\star}^{-3} \rho_{\star} \simeq M_{\odot} \left(\frac{2\pi}{H_{\star}/f_{\star}} \right)^2 \left(\frac{6.2 \text{ nHz}}{f_{\text{form}}} \right)^2$$

Scalar Curvature

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



**PBH
formation**



**GW from PBH
Formation**



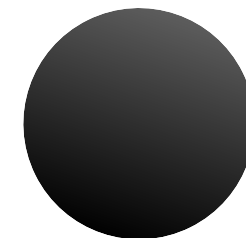
$$M_{\text{PBH}} = \frac{4\pi}{3} H_{\star}^{-3} \rho_{\star} \simeq M_{\odot} \left(\frac{2\pi}{H_{\star}/f_{\star}} \right)^2 \left(\frac{6.2 \text{ nHz}}{f_{\text{form}}} \right)^2$$

Scalar Curvature

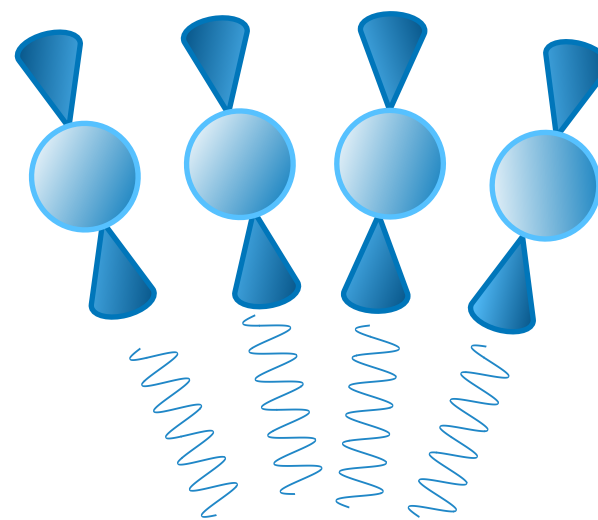
$\mathcal{R}(\vec{x}, t)$



**PBH
formation**



**GW from PBH
Formation**



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

nHz GW

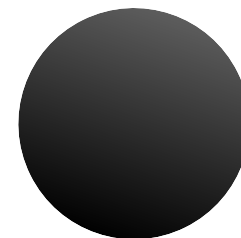
$$M_{\text{PBH}} = \frac{4\pi}{3} H_{\star}^{-3} \rho_{\star} \simeq M_{\odot} \left(\frac{2\pi}{H_{\star}/f_{\star}} \right)^2 \left(\frac{6.2 \text{ nHz}}{f_{\text{form}}} \right)^2$$

Scalar Curvature

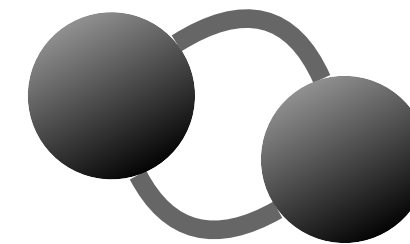
$\mathcal{R}(\vec{x}, t)$



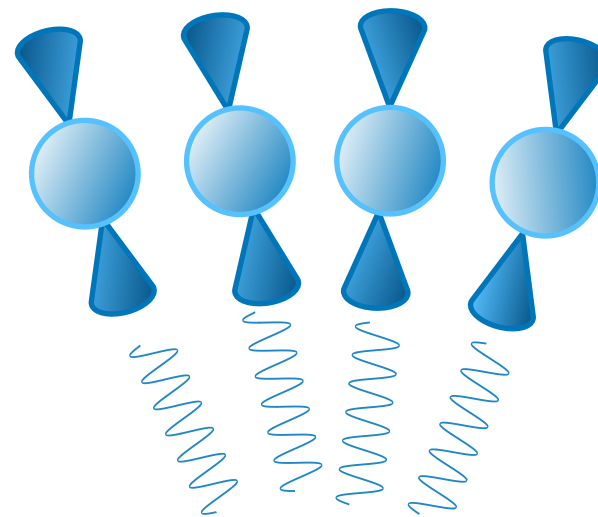
**PBH
formation**



**Binary
formation**



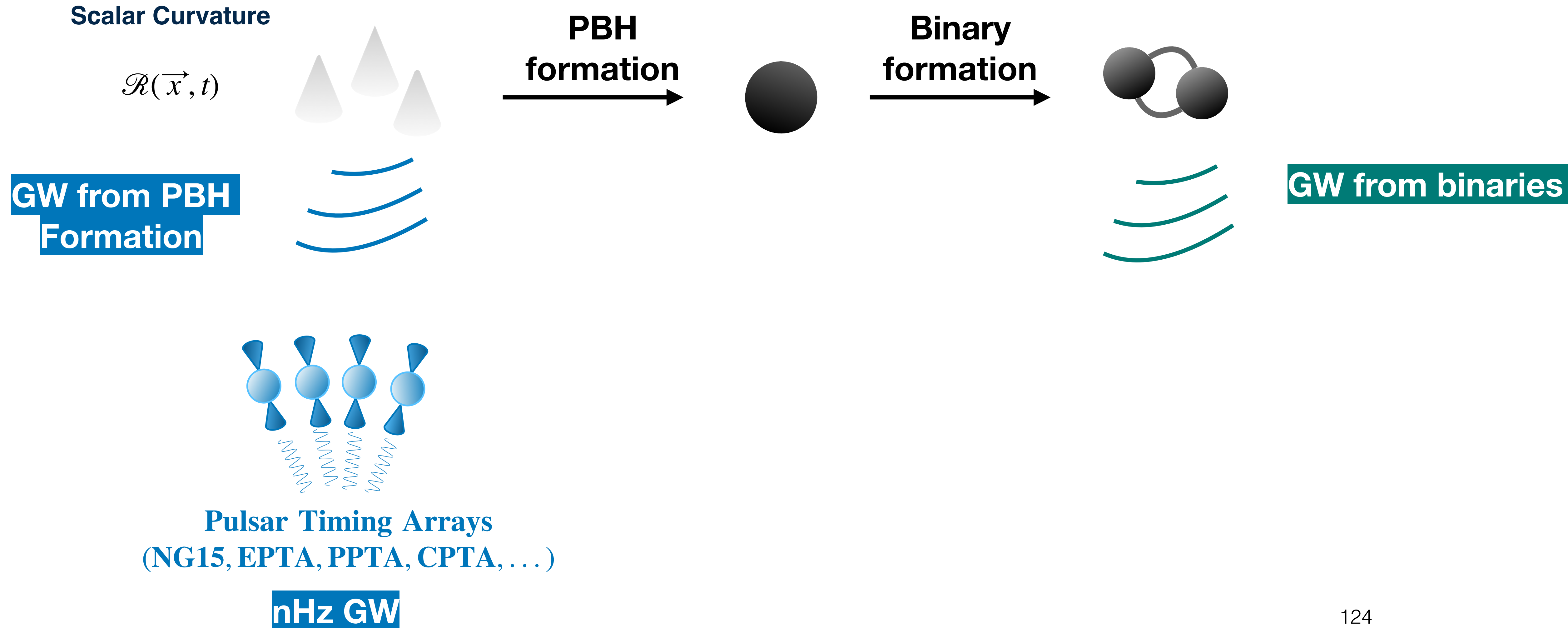
**GW from PBH
Formation**



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

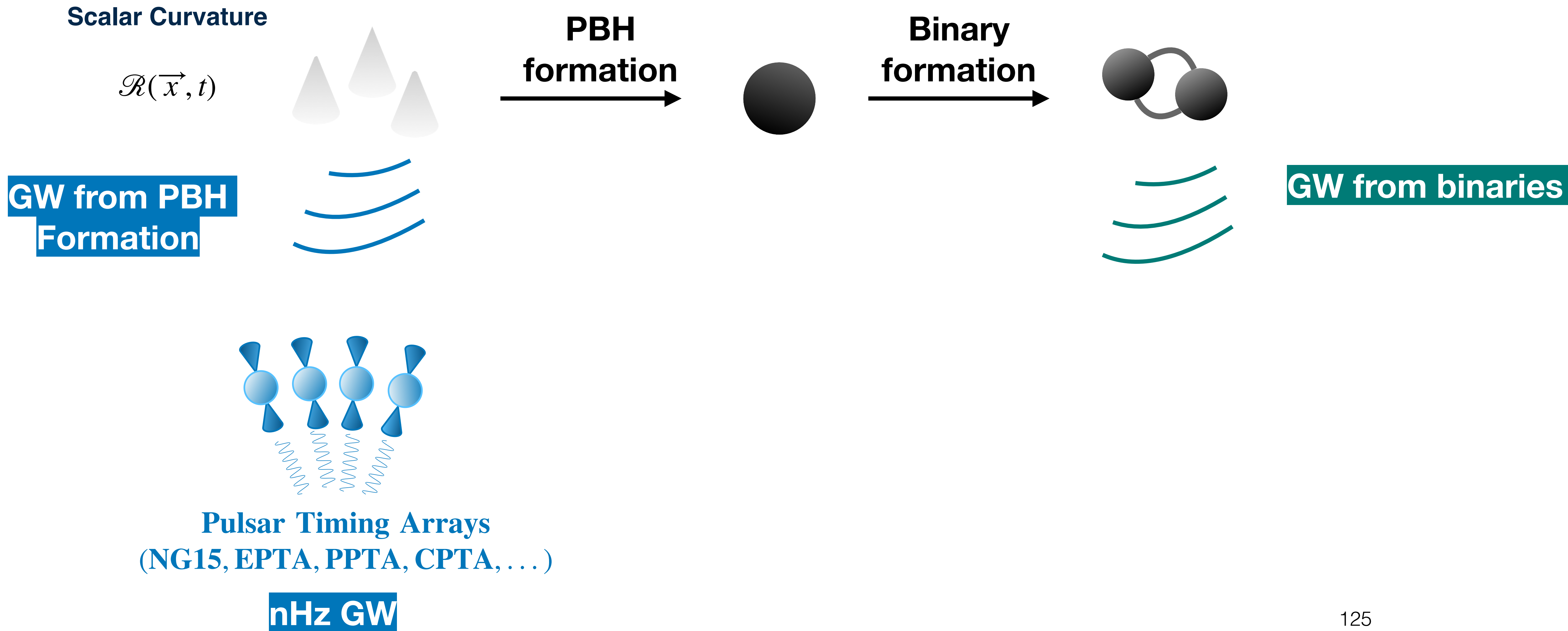
nHz GW

$$M_{\text{PBH}} = \frac{4\pi}{3} H_{\star}^{-3} \rho_{\star} \simeq M_{\odot} \left(\frac{2\pi}{H_{\star}/f_{\star}} \right)^2 \left(\frac{6.2 \text{ nHz}}{f_{\text{form}}} \right)^2$$



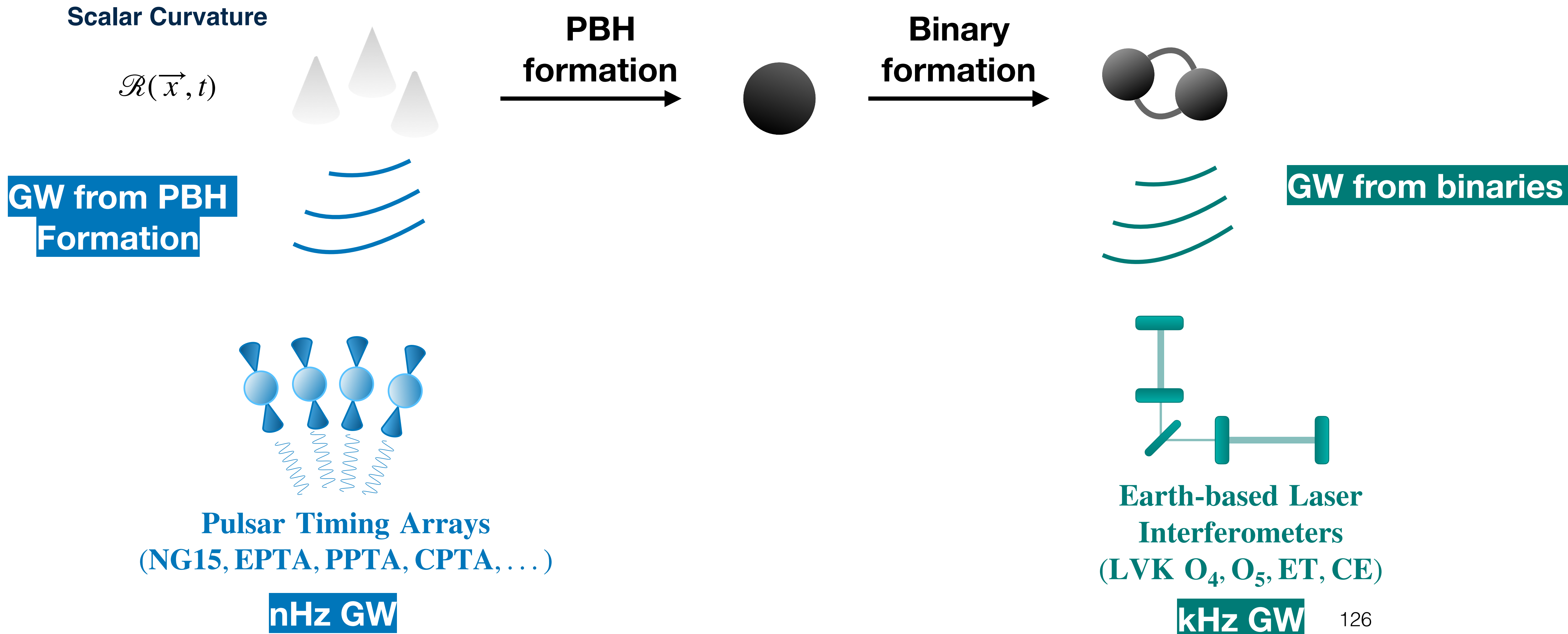
$$M_{\text{PBH}} = \frac{4\pi}{3} H_{\star}^{-3} \rho_{\star} \simeq M_{\odot} \left(\frac{2\pi}{H_{\star}/f_{\star}} \right)^2 \left(\frac{6.2 \text{ nHz}}{f_{\text{form}}} \right)^2$$

$$f_{\text{merg}} \sim \frac{M_{\text{pl}}^2}{\pi M_{\text{PBH}}} \sim 3 \text{ kHz} \left(\frac{M_{\odot}}{M_{\text{PBH}}} \right)$$



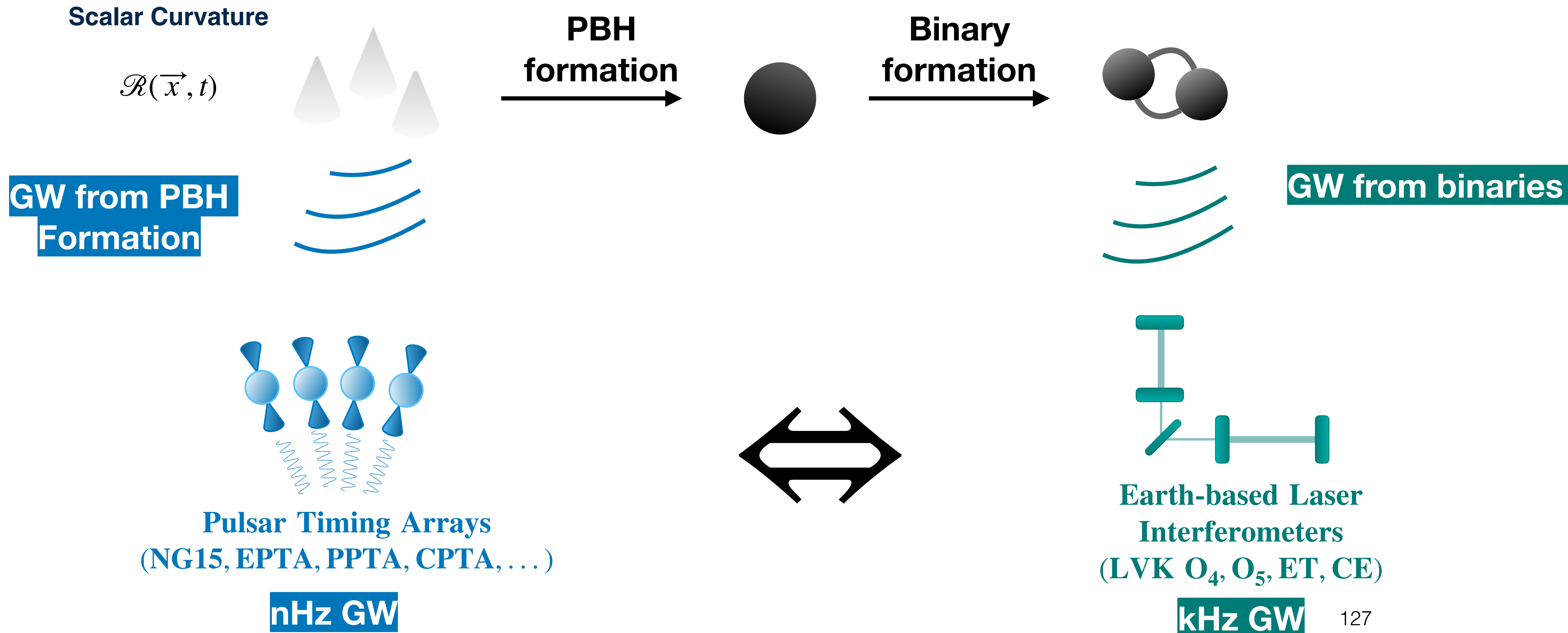
$$M_{\text{PBH}} = \frac{4\pi}{3} H_{\star}^{-3} \rho_{\star} \simeq M_{\odot} \left(\frac{2\pi}{H_{\star}/f_{\star}} \right)^2 \left(\frac{6.2 \text{ nHz}}{f_{\text{form}}} \right)^2$$

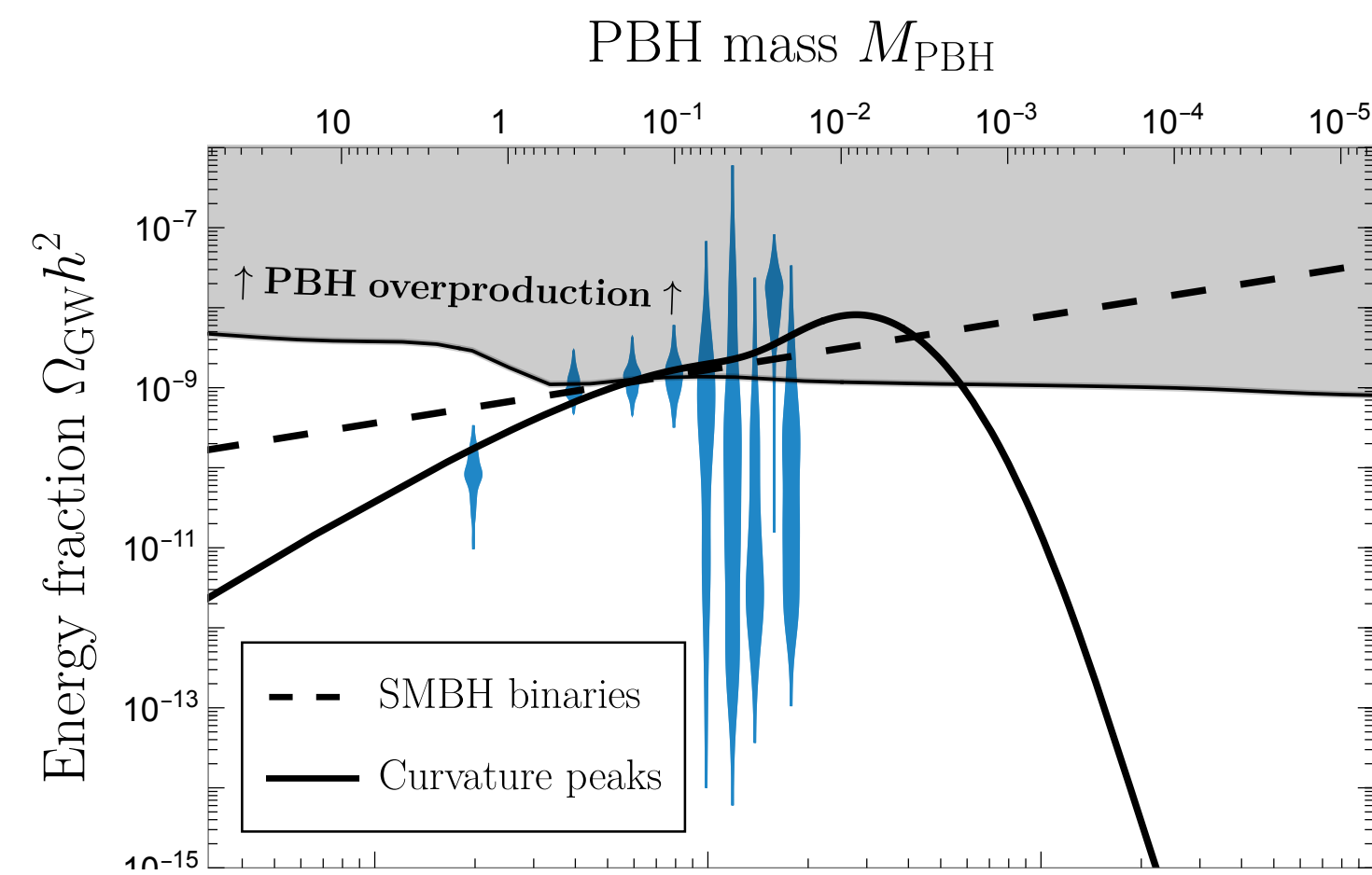
$$f_{\text{merg}} \sim \frac{M_{\text{pl}}^2}{\pi M_{\text{PBH}}} \sim 3 \text{ kHz} \left(\frac{M_{\odot}}{M_{\text{PBH}}} \right)$$



$$M_{\text{PBH}} = \frac{4\pi}{3} H_{\star}^{-3} \rho_{\star} \simeq M_{\odot} \left(\frac{2\pi}{H_{\star}/f_{\star}} \right)^2 \left(\frac{6.2 \text{ nHz}}{f_{\text{form}}} \right)^2$$

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Curvature peaks

Overproduce PBH

Chen, Yuan, Huang (1910.12239)

Kohri, Terada (2009.11853)

Inomata, Kawasaki, Mukaida, Yanagida (2011.01270)

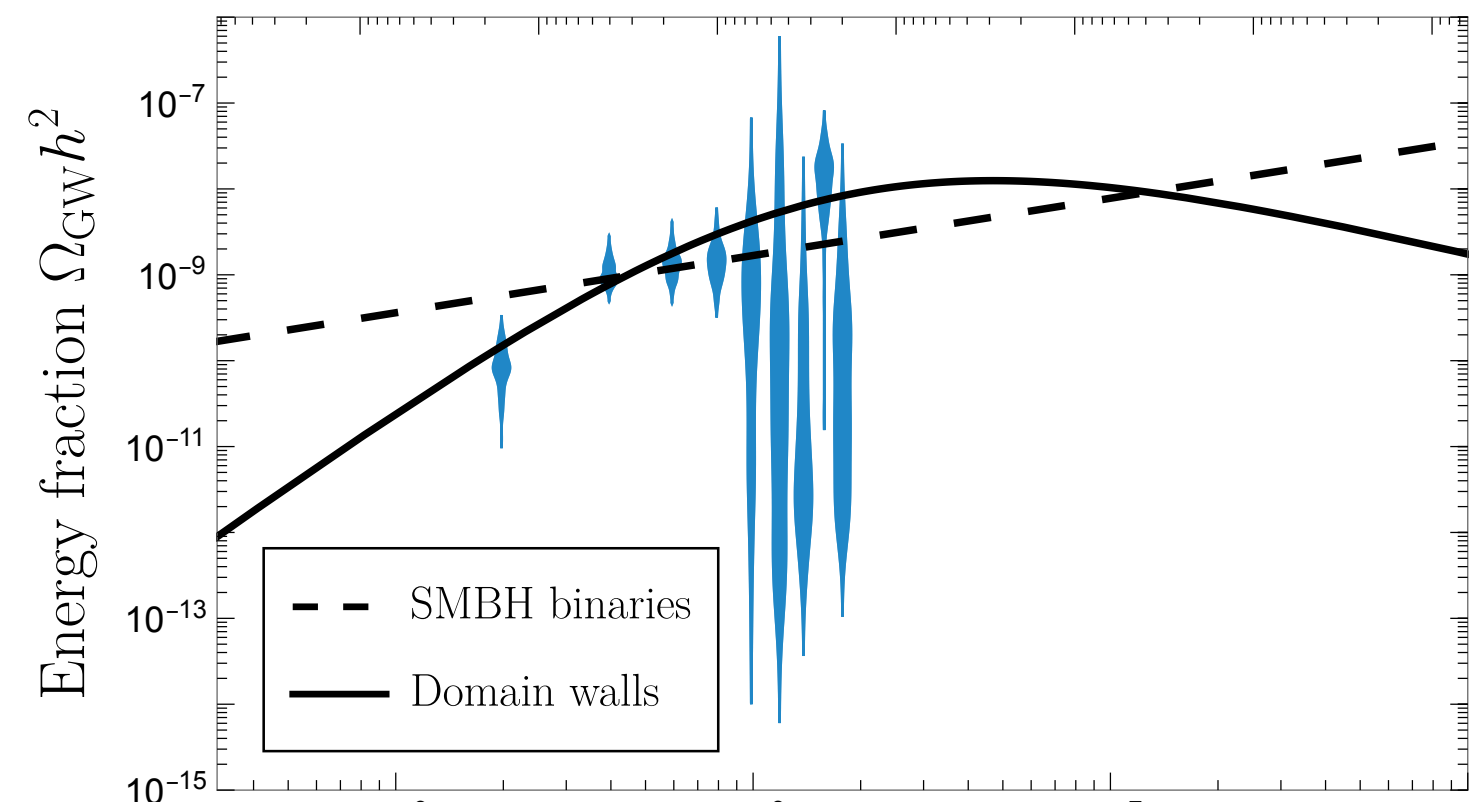
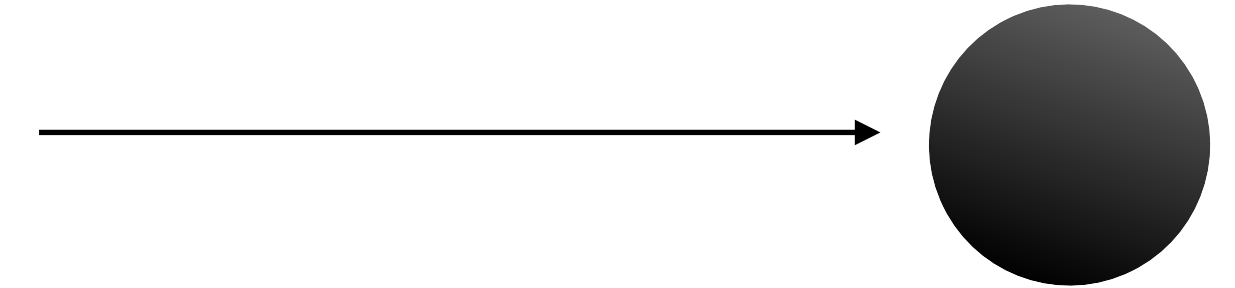
Vaskonen, Veermae (2009.07832),

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Except if negative non-Gaussianities

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YG, Trifinopoulos, Vanvlasselaer (2508.19328)

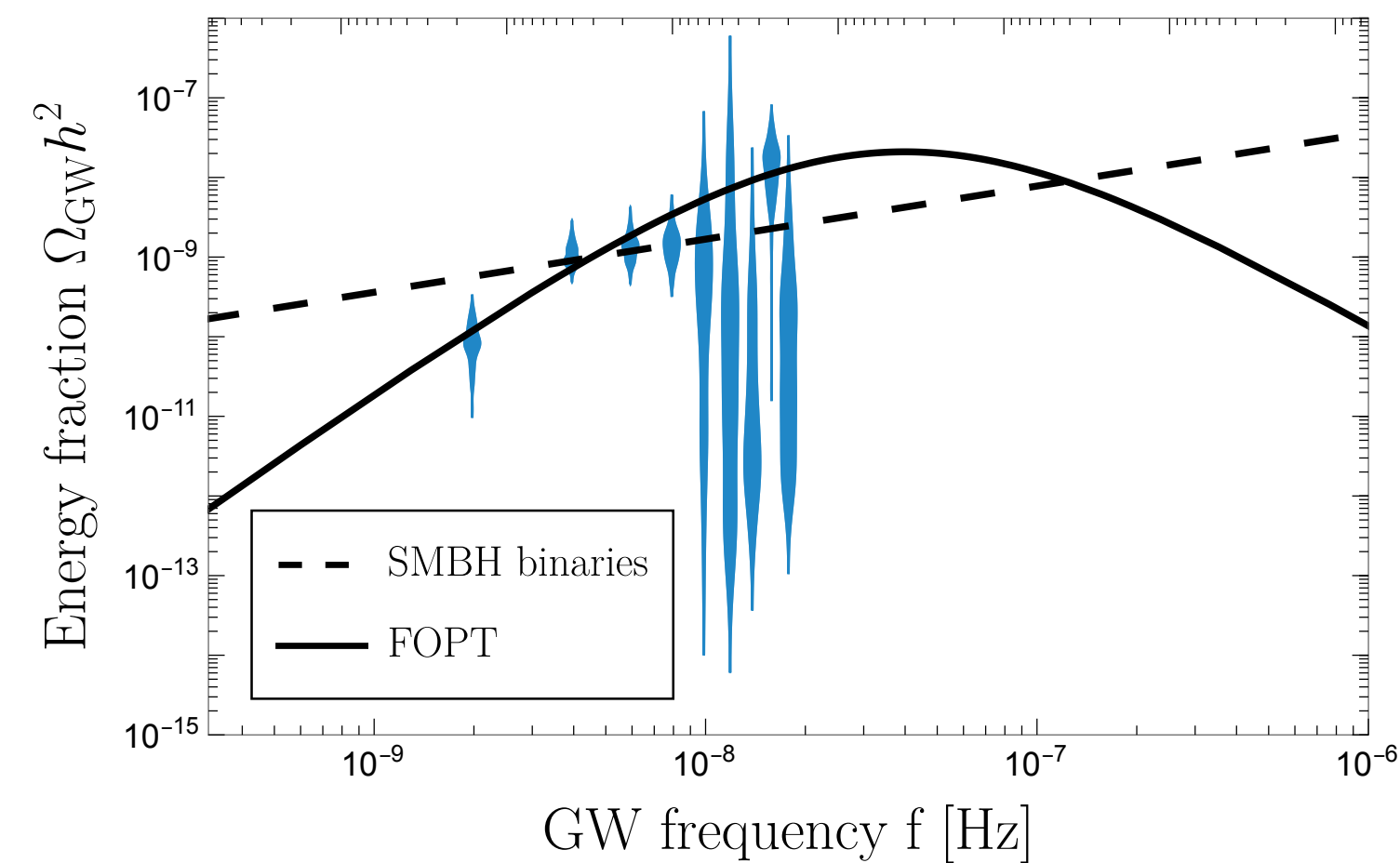
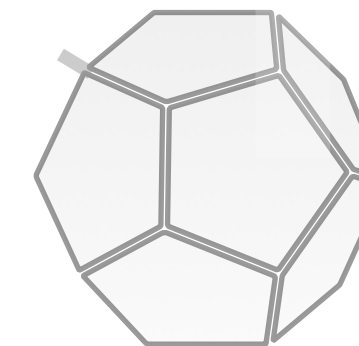


Domain wall networks

Ferreira, Notari, Pujolas, Rompineve (2204.04228)

Blasi, Mariotti, Rase, Sevrin (2306.17830)

...



First-order phase transitions

Roper Pol et al. (2201.05630)

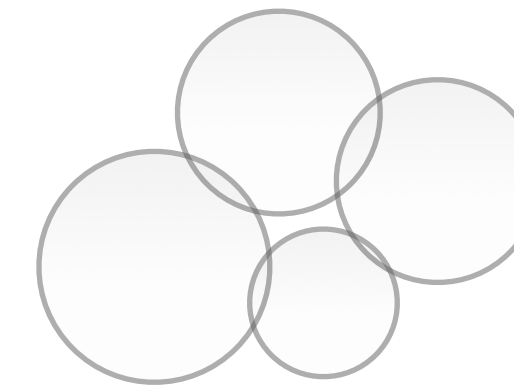
Ghoshal, White et al. (2307.02259)

YG (2307.04239)

Lewicki, Toczek, Vaskonen (2402.04158)

Hoefken Zink et al. (2501.15649)

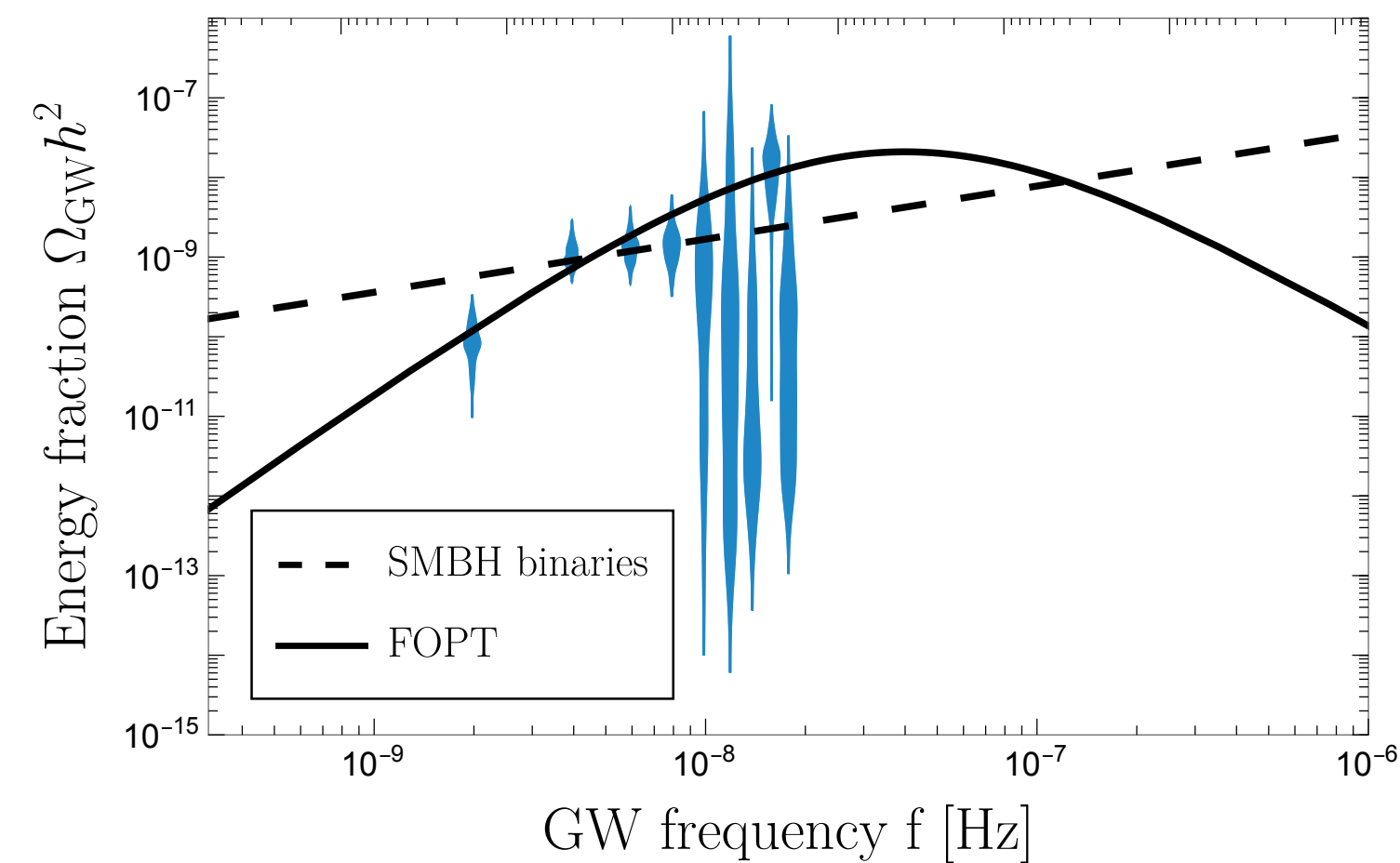
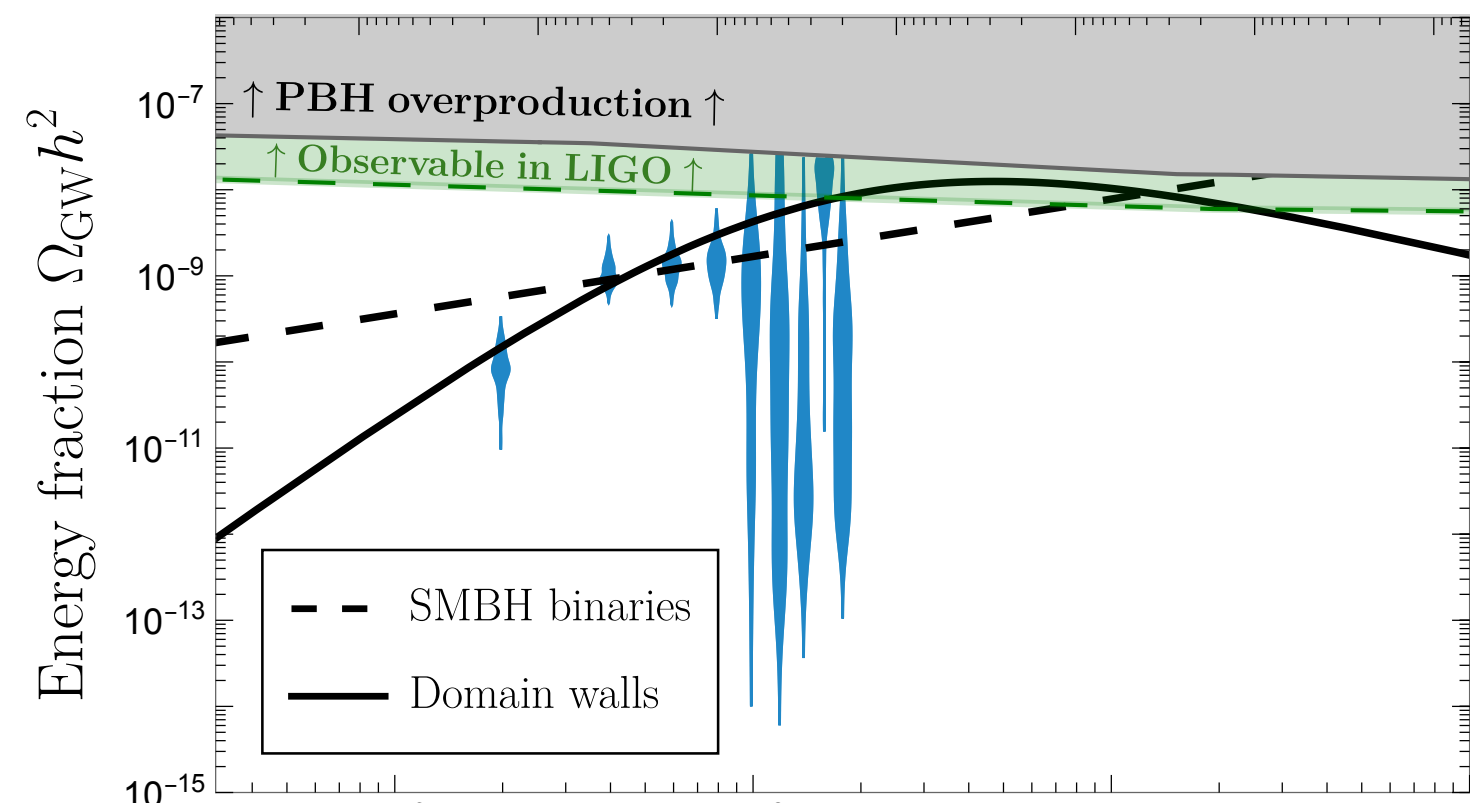
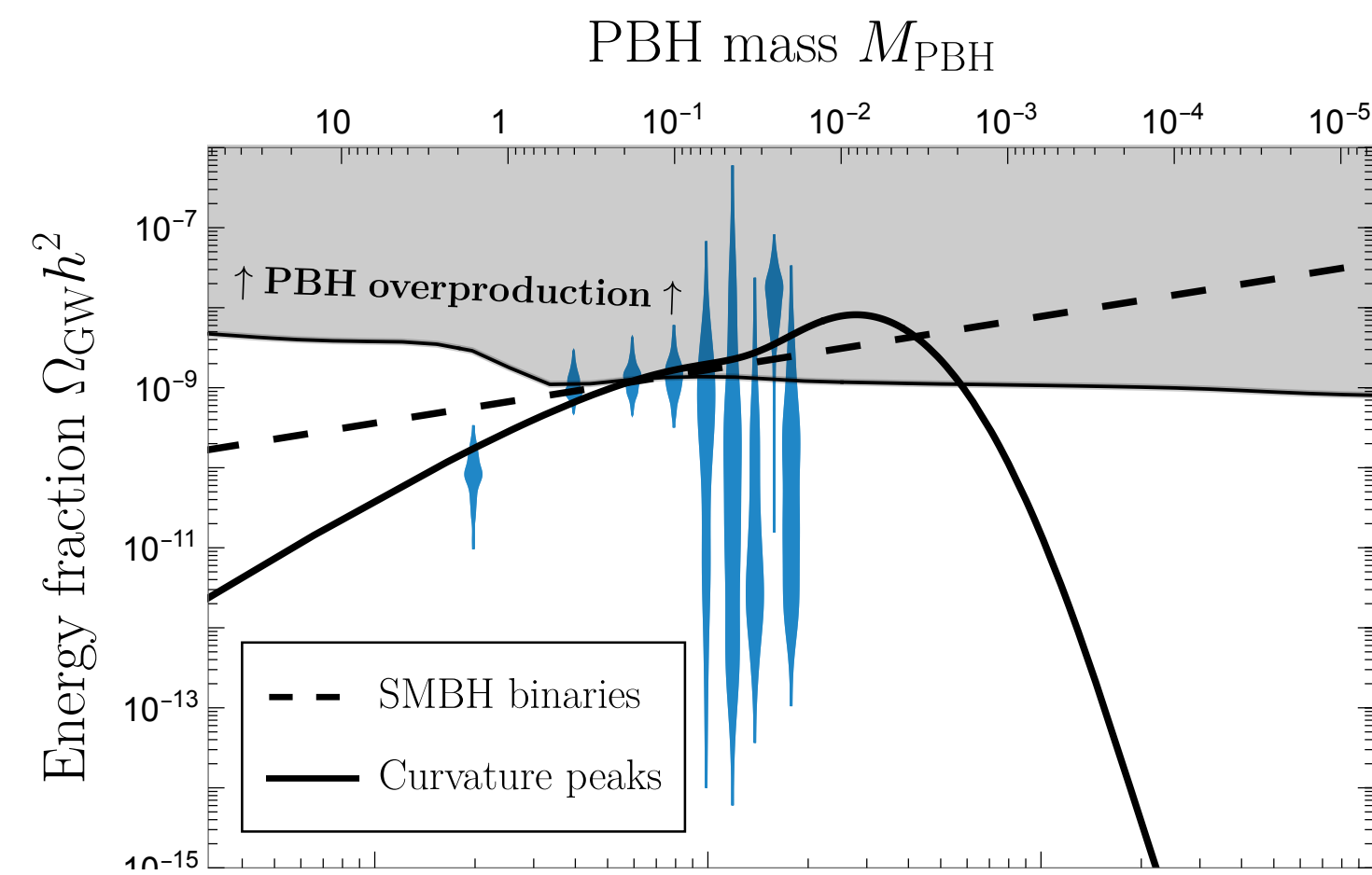
...



Reviews: *Madge et al (2306.14856),*

Figuerola et al (2307.02399),

Ellis et al (2308.08546)



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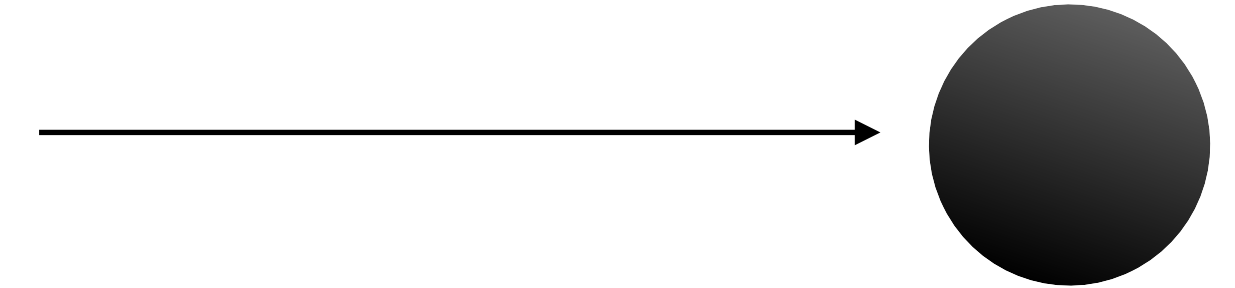
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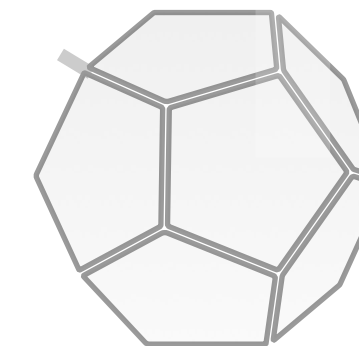
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Produce sub-solar-mass PBH

YG, Vitagliano 2306.17841



First-order phase transitions

Roper Pol et al. (2201.05630)

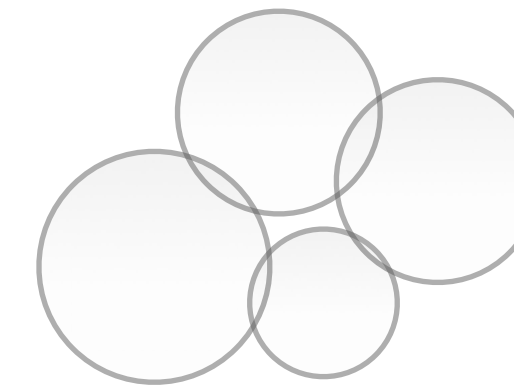
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YG (2307.04239)

Lewicki, Toczek, Vaskonen (2402.04158)

Hoefken Zink et al. (2501.15649)

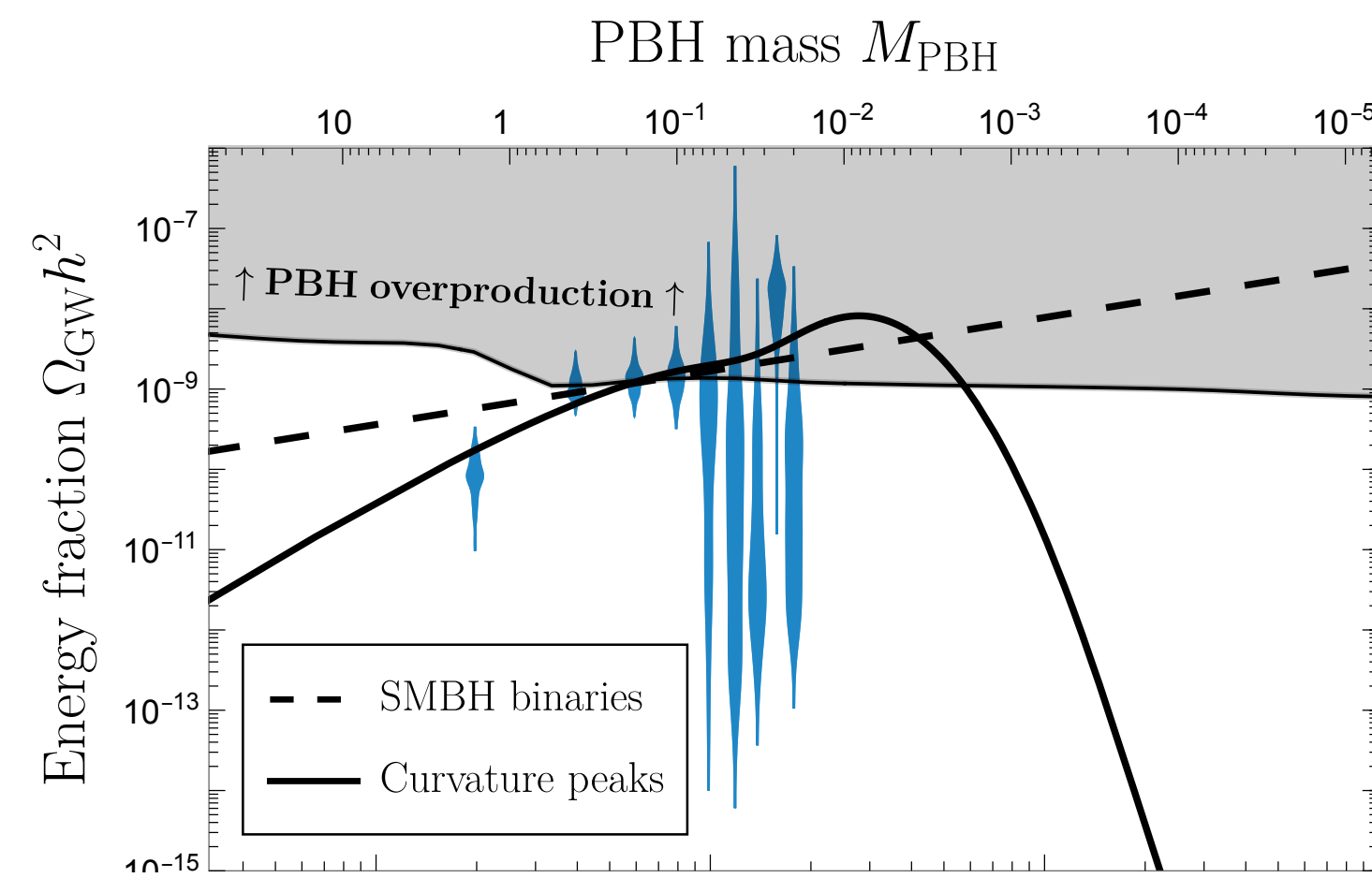
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Reviews: Madge et al (2306.14856),

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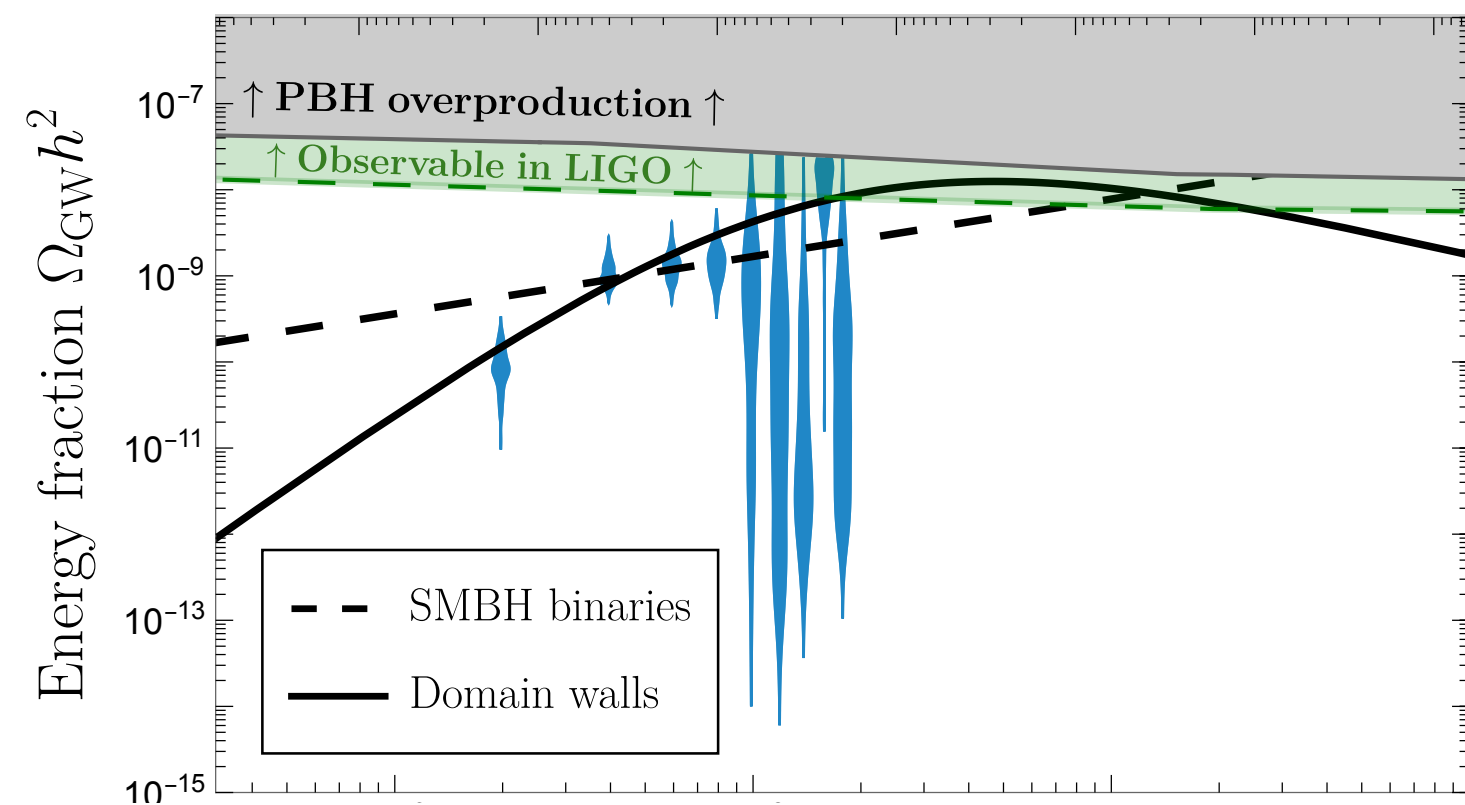
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Domain wall networks

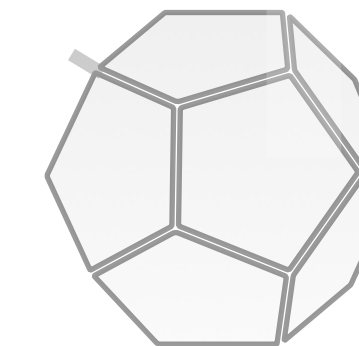
Ferreira, Notari, Pujolas, Rompineve (2204.04228)

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...

Produce sub-solar-mass PBH

YG, Vitagliano 2306.17841

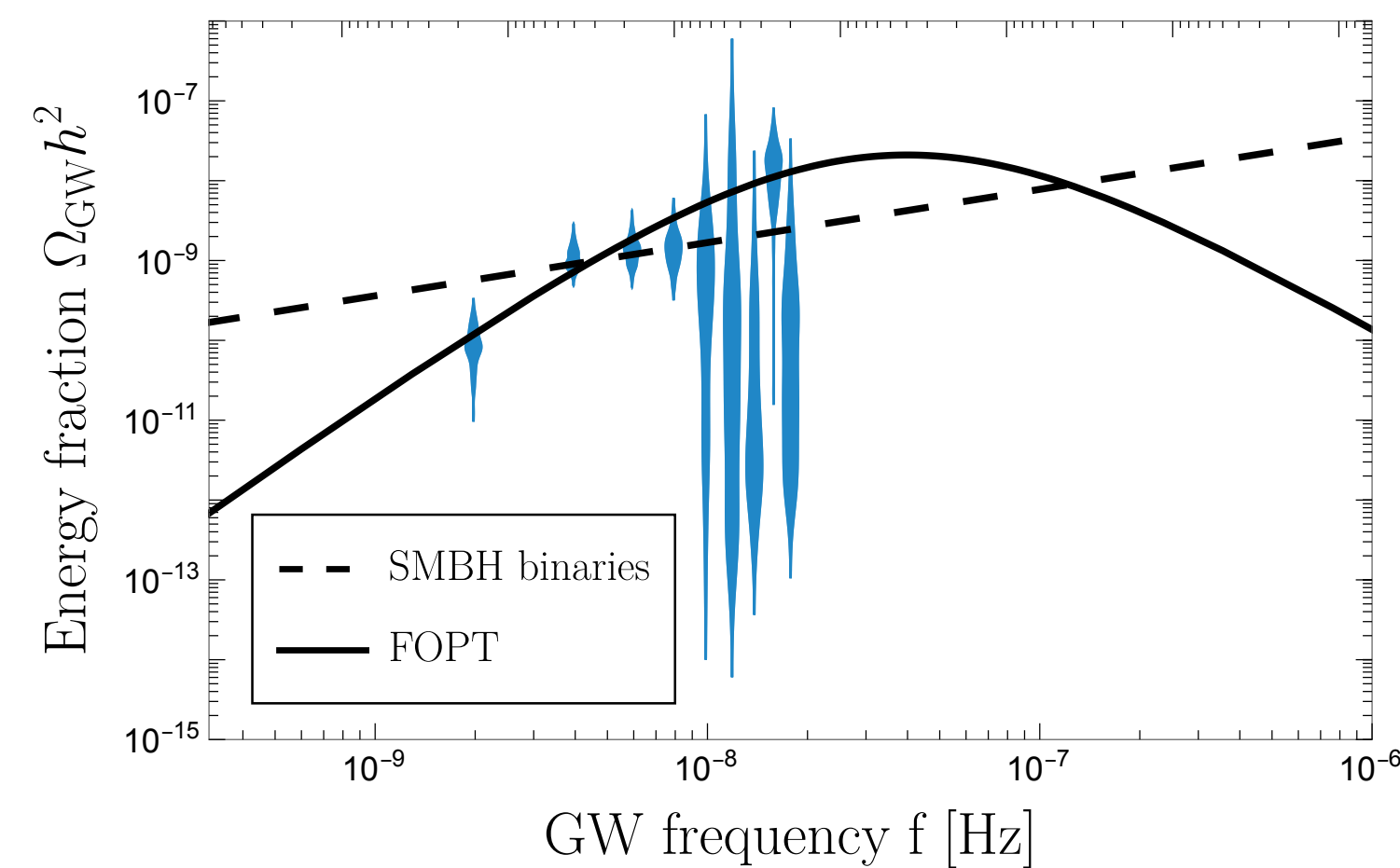


Ferrer, Masso, Panico, Pujolas, Rompineve (1807.01707)

Ferreira, Notari, Pujolas, Rompineve (2401.14331)

YG, Vitagliano, 2311.07670

PBH



First-order phase transitions

Roper Pol et al. (2201.05630)

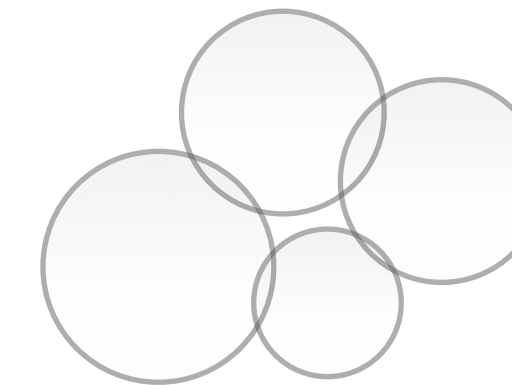
Ghoshal, White et al. (2307.02259)

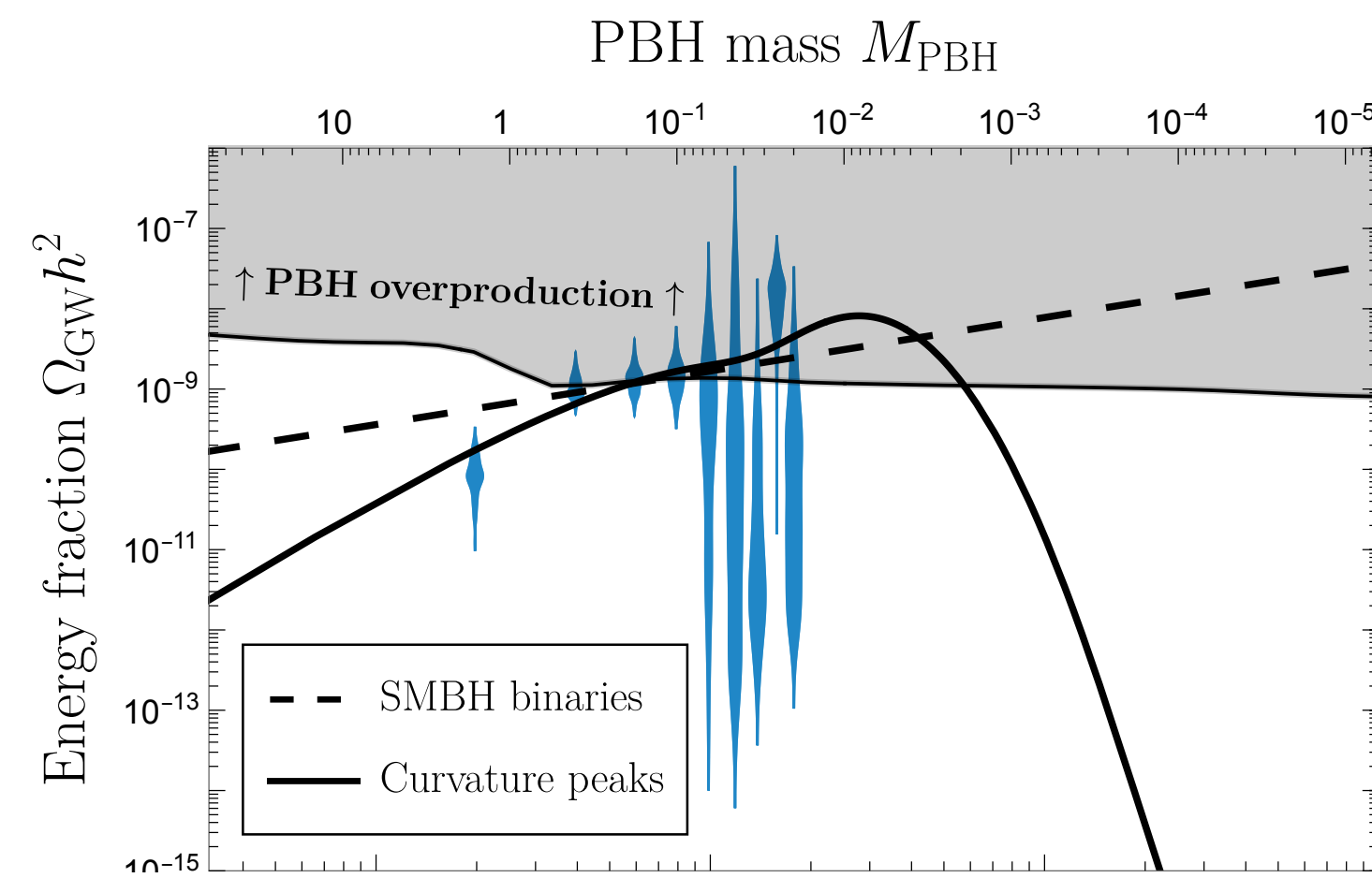
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Lewicki, Toczek, Vaskonen (2402.04158)

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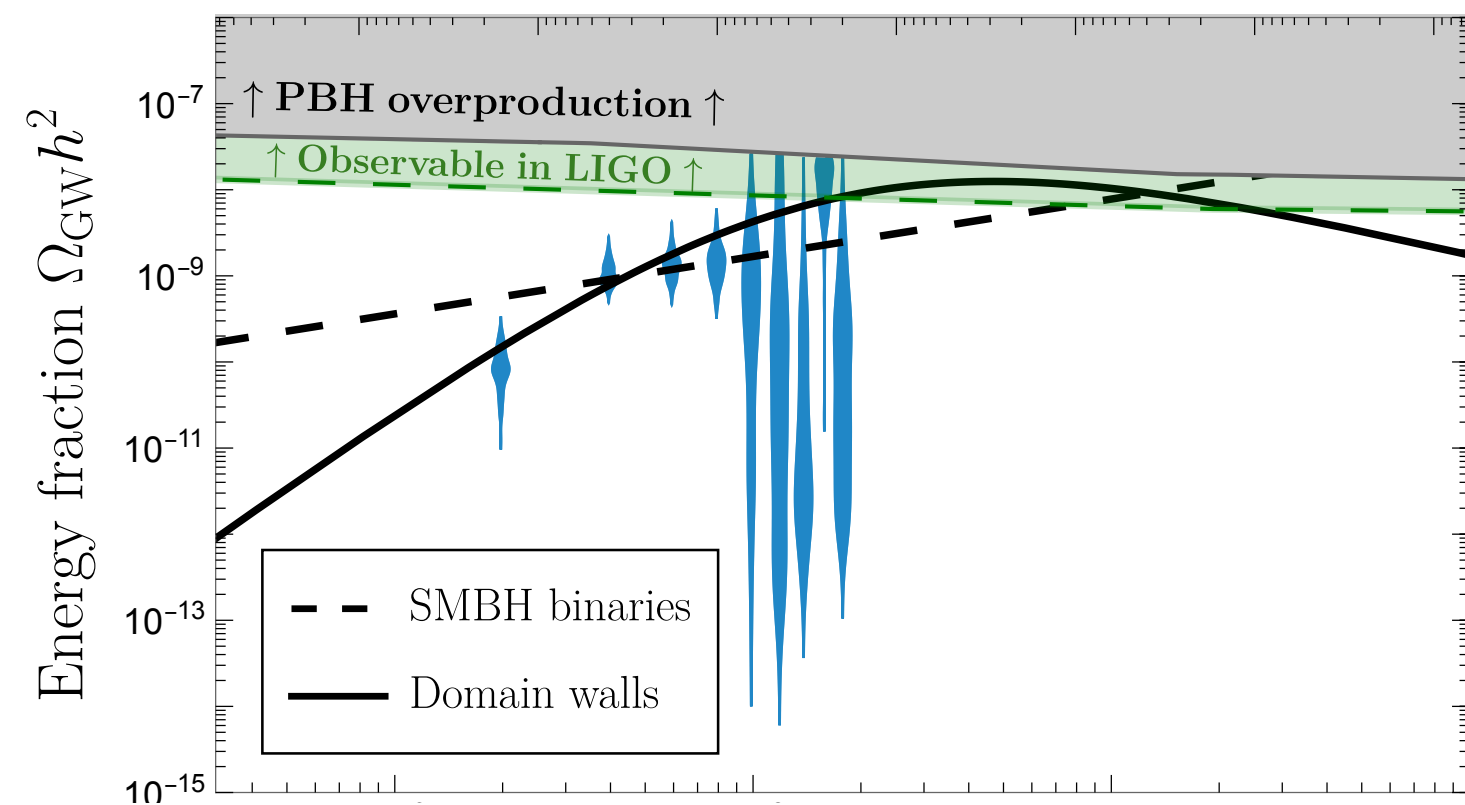
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Domain wall networks

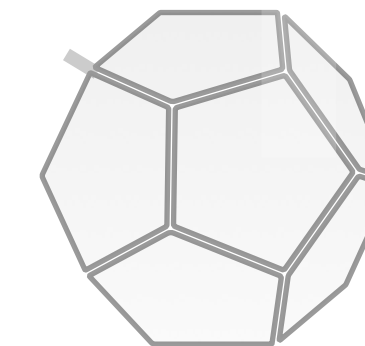
Ferreira, Notari, Pujolas, Rompineve (2204.04228)

Blasi, Mariotti, Rase, Sevrin (2306.17830)

...

Produce sub-solar-mass PBH

YG, Vitagliano 2306.17841



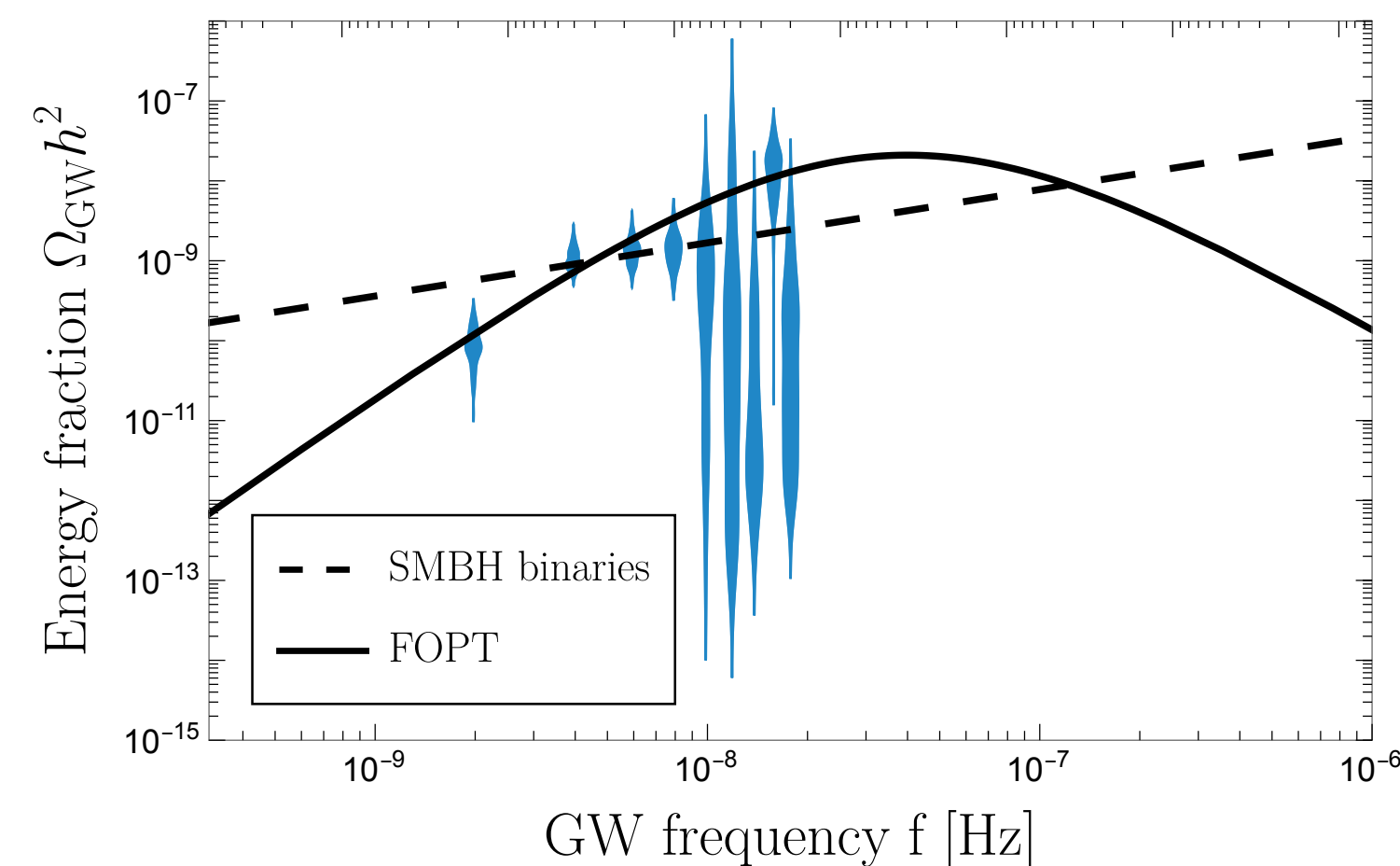
Ferrer, Masso, Panico, Pujolas, Rompineve (1807.01707)
Ferreira, Notari, Pujolas, Rompineve (2401.14331)

YG, Vitagliano, 2311.07670

**1) Solve DW trajectory
in full GR**

2) Percolation theory

PBH



First-order phase transitions

Roper Pol et al. (2201.05630)

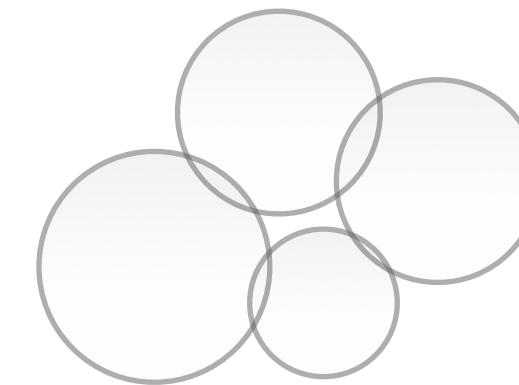
Ghoshal, White et al. (2307.02259)

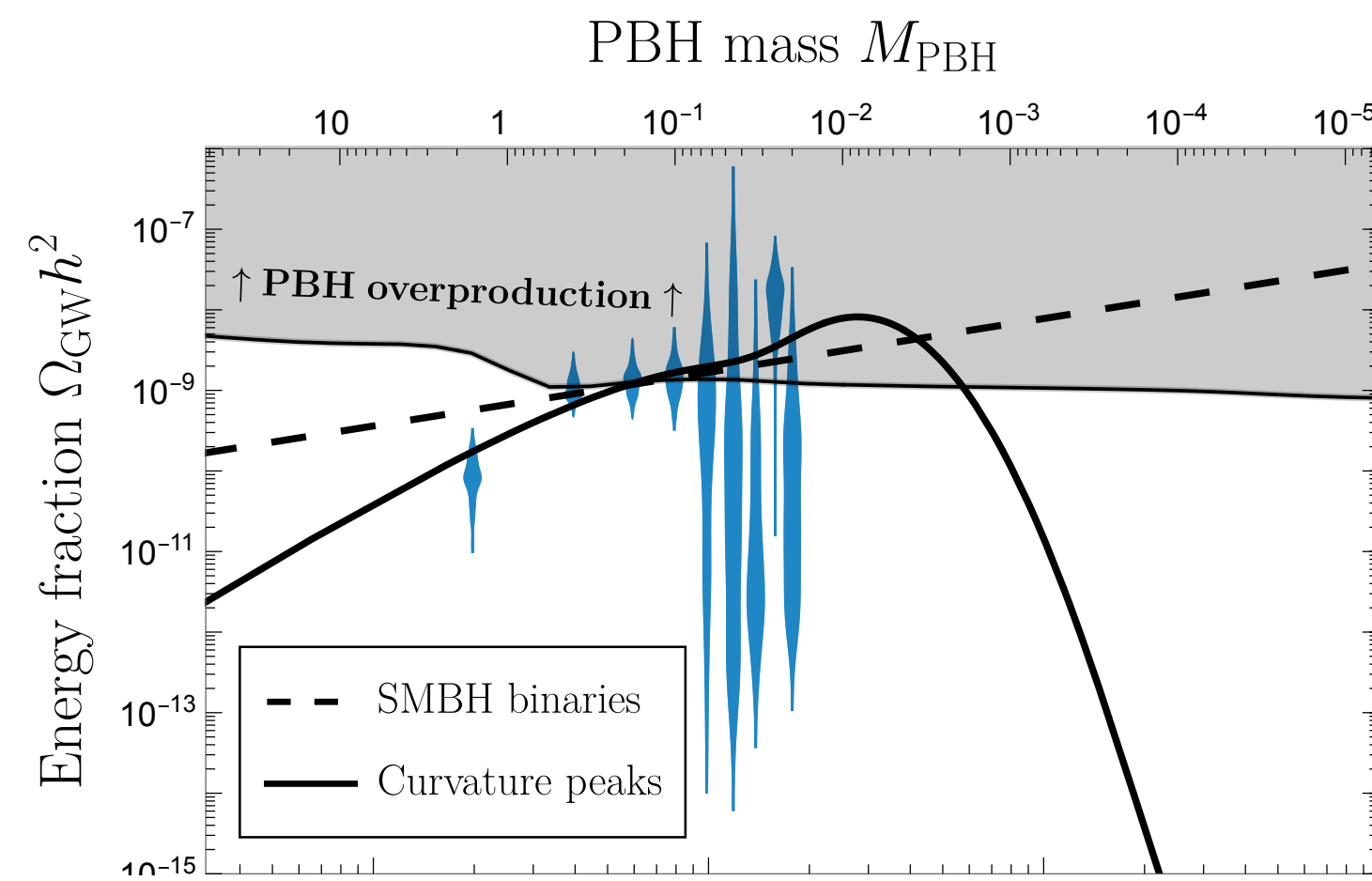
YG (2307.04239)

Lewicki, Toczek, Vaskonen (2402.04158)

Hoefken Zink et al. (2501.15649)

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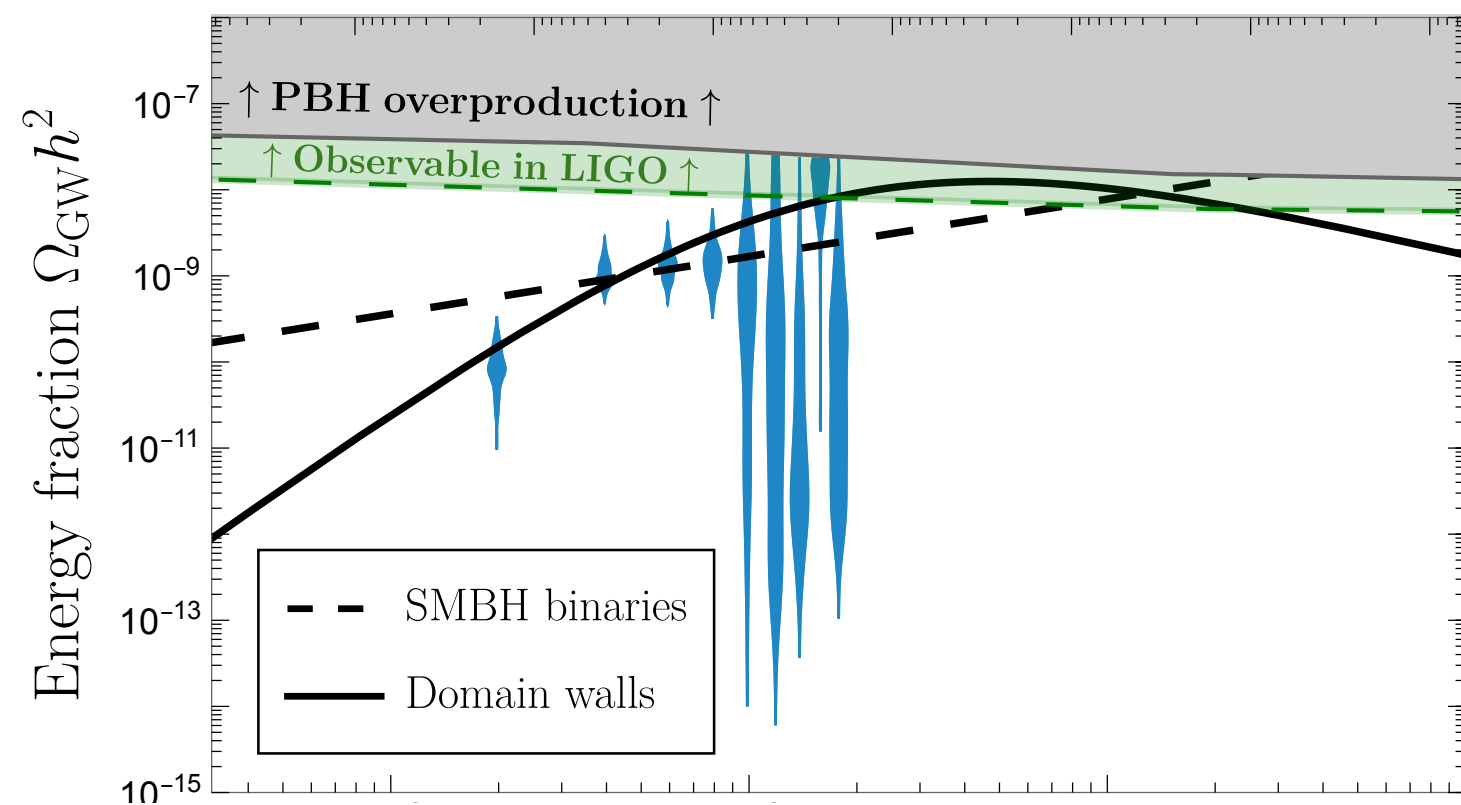
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Franciolini, Vaskonen, Vermae (2306.17143)

YG, Trifinopoulos, Vanvlasselaer (2508.19328)



Domain wall networks

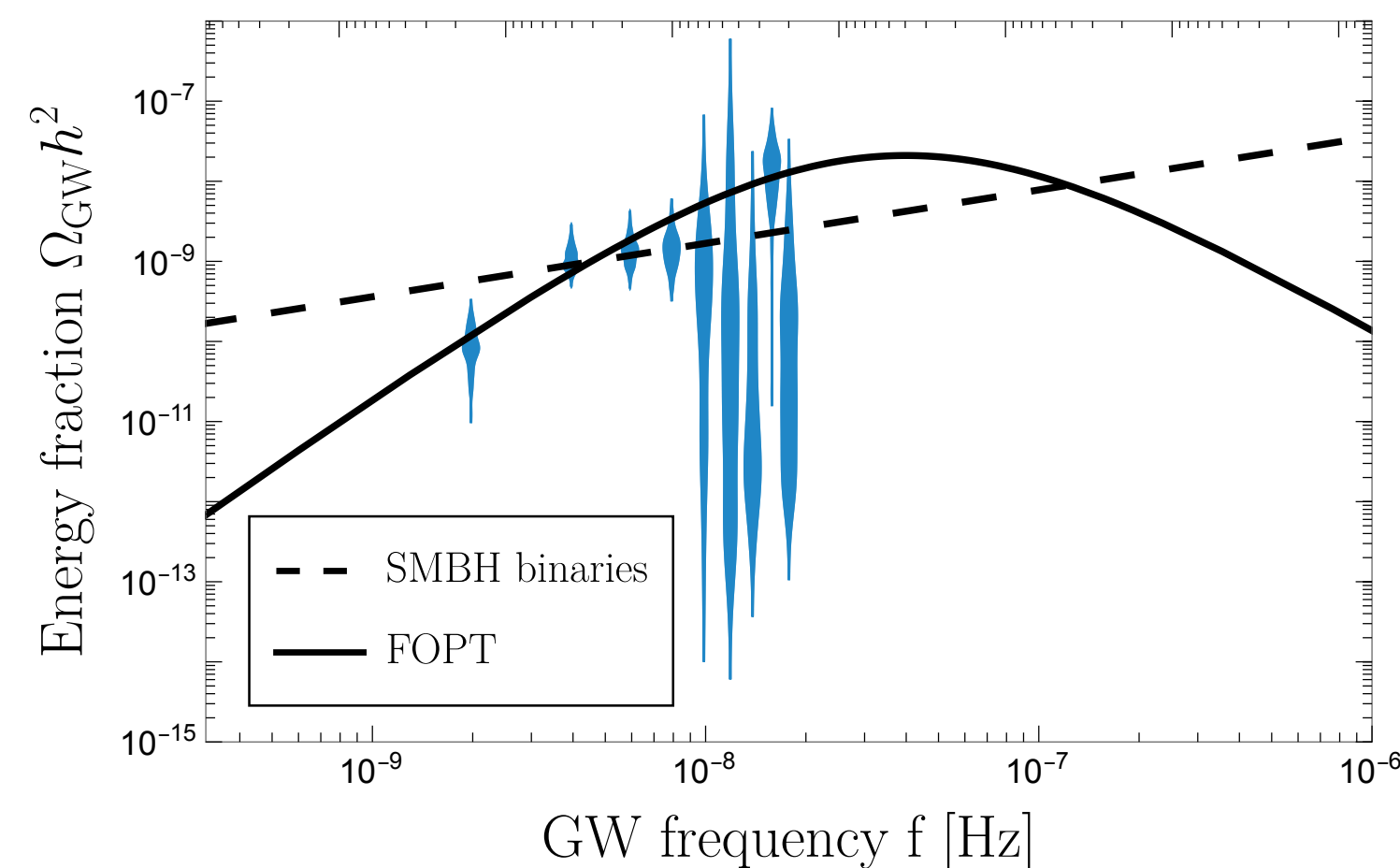
Ferreira, Notari, Pujolas, Rompineve (2204.04228)

Blasi, Mariotti, Rase, Sevrin (2306.17830)

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Produce sub-solar-mass PBH

YG, Vitagliano 2306.17841



First-order phase transitions

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Ghoshal, White et al. (2307.02259)

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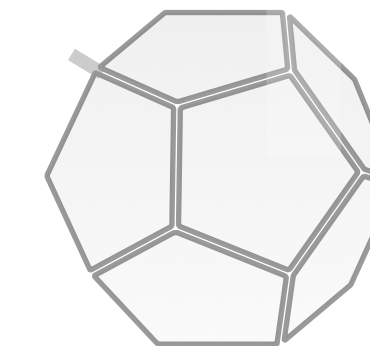
...



Baby-universe

Deng, Garriga, Vilenkin (1612.03753)

Wormhole



Ferrer, Masso, Panico, Pujolas, Rompineve (1807.01707)

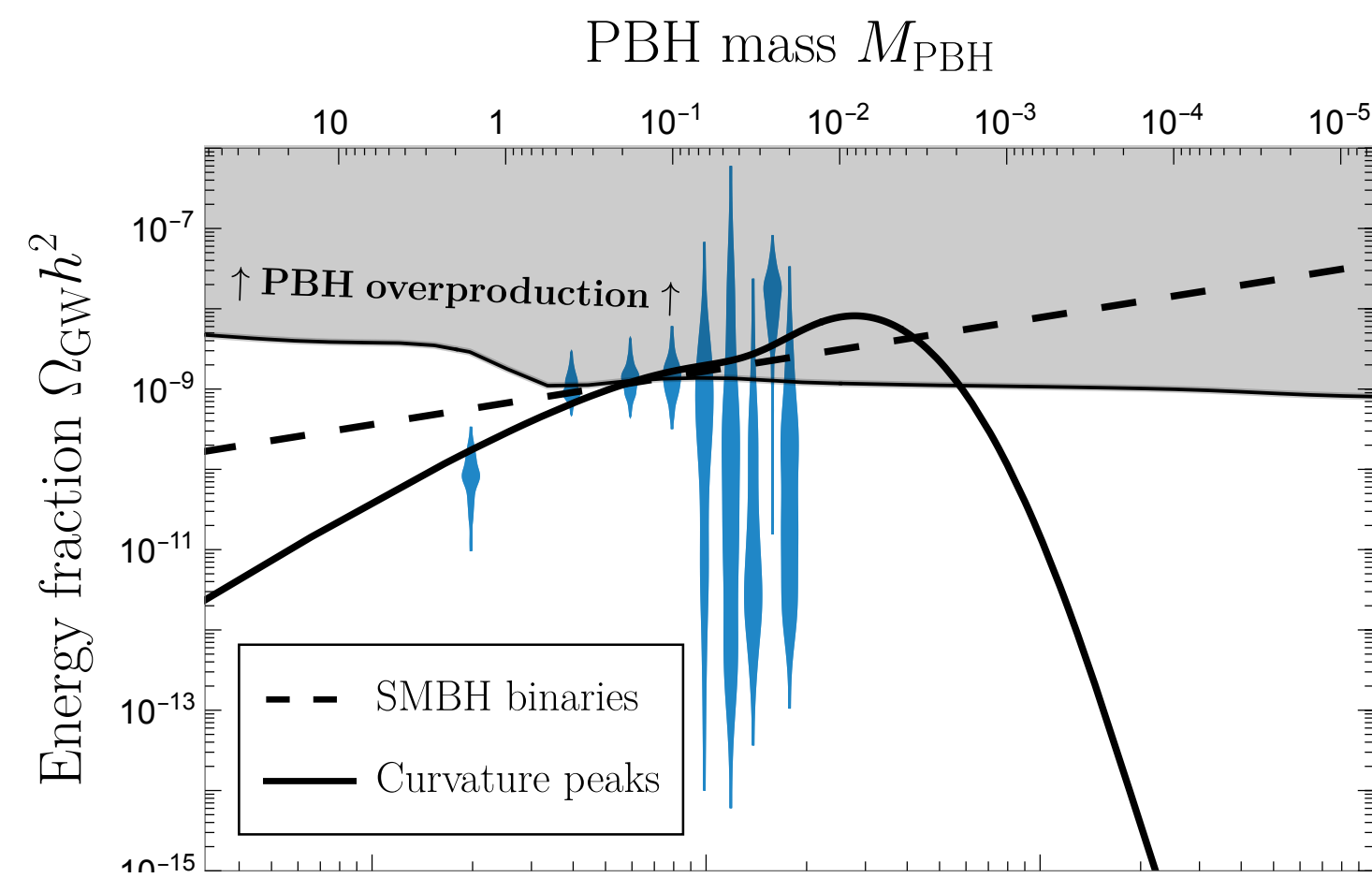
Ferreira, Notari, Pujolas, Rompineve (2401.14331)

YG, Vitagliano, 2311.07670

1) Solve DW trajectory
in full GR

2) Percolation theory

PBH

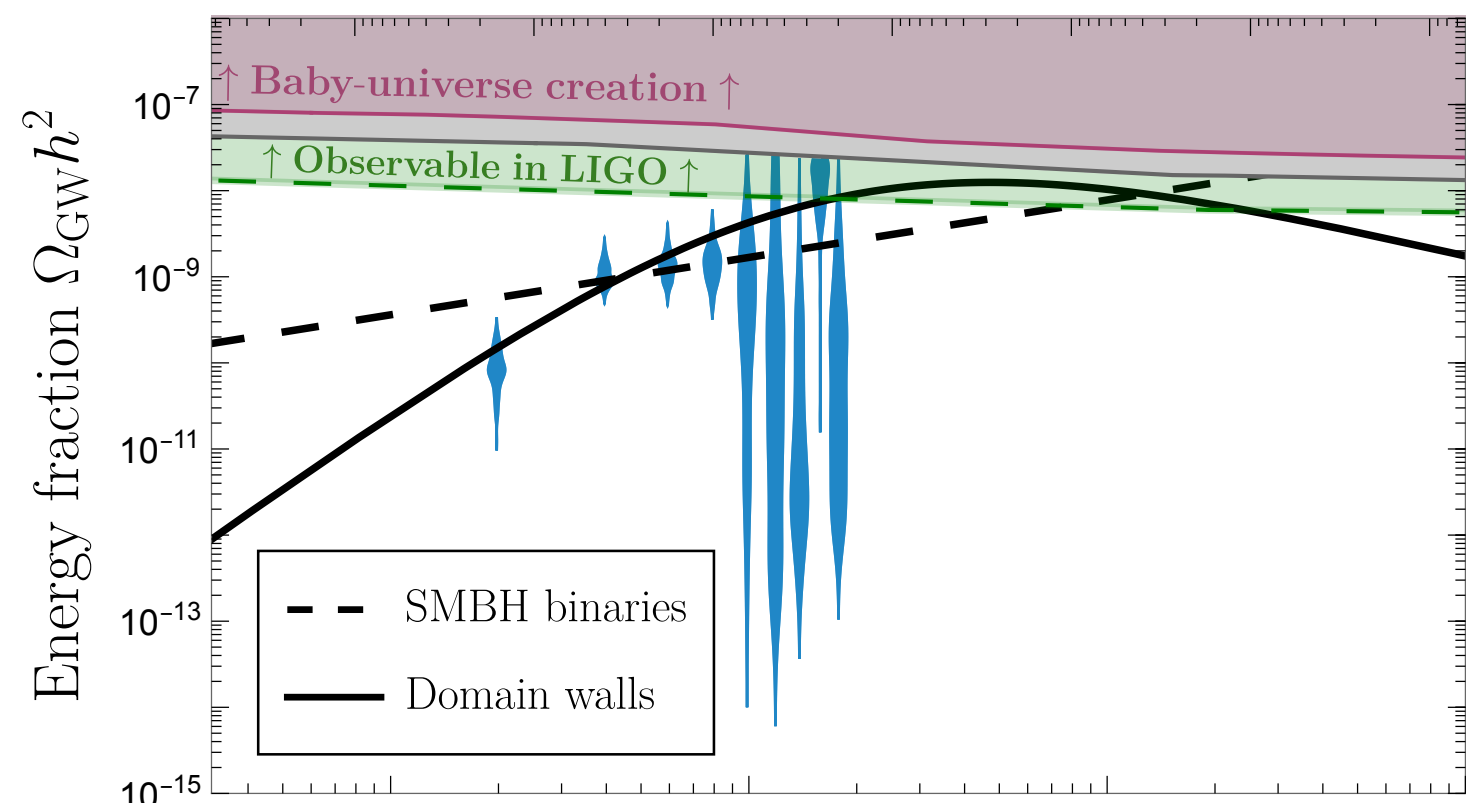


Curvature peaks

Overproduce PBH
Chen, Yuan, Huang (1910.12239)
Kohri, Terada (2009.11853)
Inomata, Kawasaki, Mukaida, Yanagida (2011.01270)
Vaskonen, Veermae (2009.07832),
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Except if negative non-Gaussianities
Franciolini, Vaskonen, Vermae (2306.17143)
YG, Trifinopoulos, Vanvlasselaer (2508.19328)

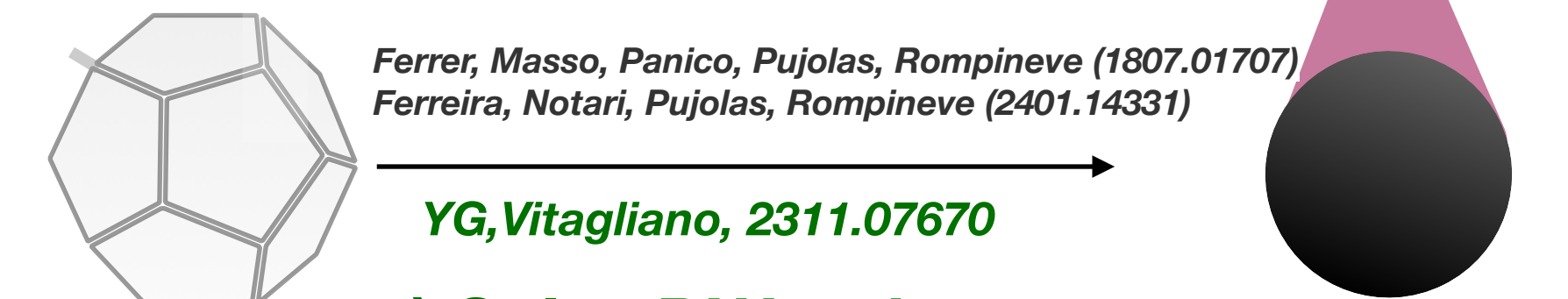


Reviews: *Madge et al (2306.14856),*
Figueroa et al (2307.02399),
Ellis et al (2308.08546)



Domain wall networks

Ferreira, Notari, Pujolas, Rompineve (2204.04228)
Blasi, Mariotti, Rase, Sevrin (2306.17830)
 ...
Produce sub-solar-mass PBH
YG, Vitagliano 2306.17841



Deng, Garriga, Vilenkin (1612.03753)

Wormhole

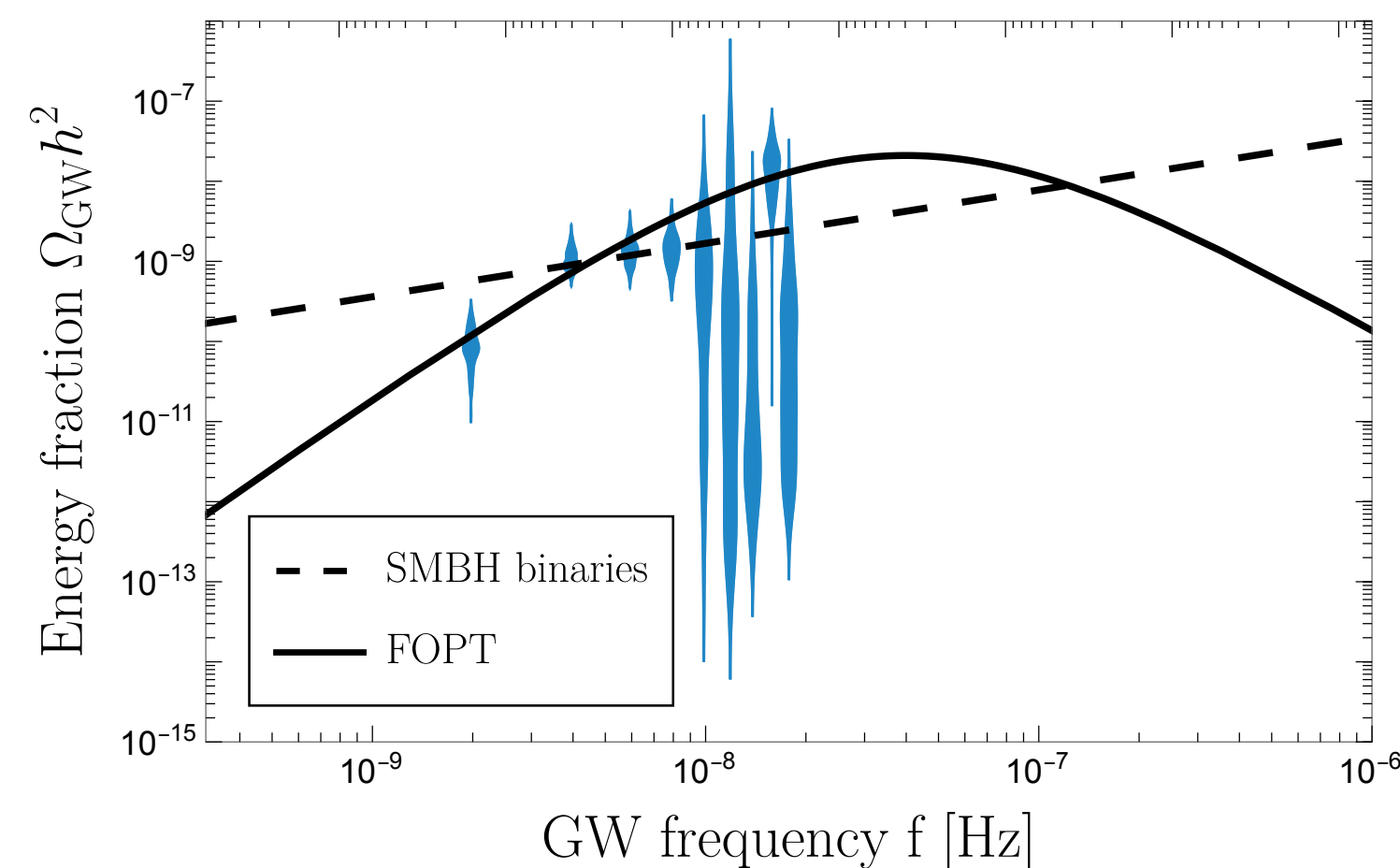
Ferrer, Masso, Panico, Pujolas, Rompineve (1807.01707)
Ferreira, Notari, Pujolas, Rompineve (2401.14331)

YG, Vitagliano, 2311.07670

**1) Solve DW trajectory
in full GR**

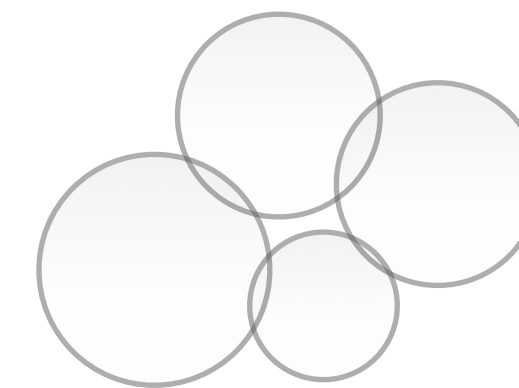
2) Percolation theory

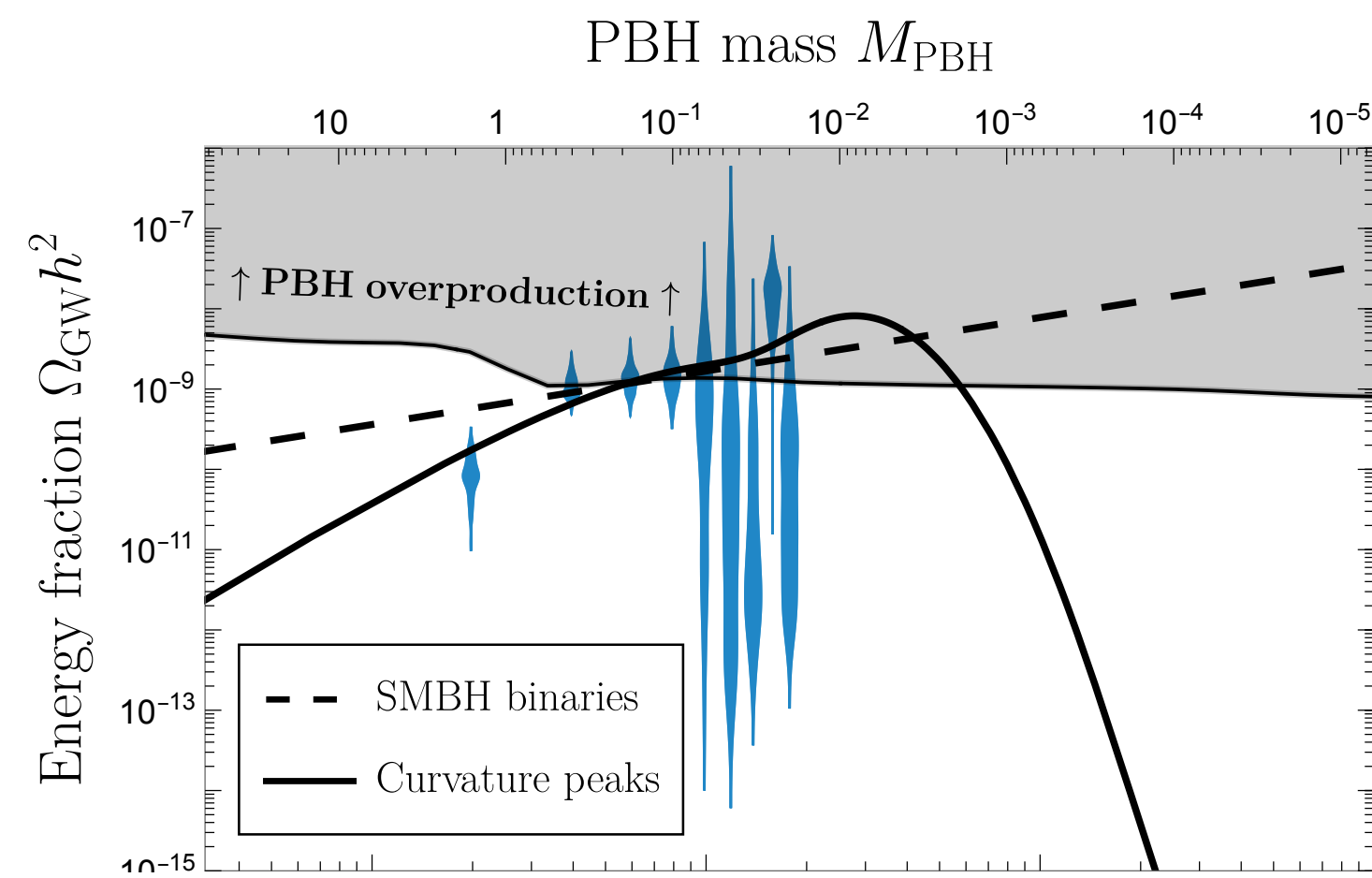
PBH



First-order phase transitions

Roper Pol et al. (2201.05630)
Ghoshal, White et al. (2307.02259)
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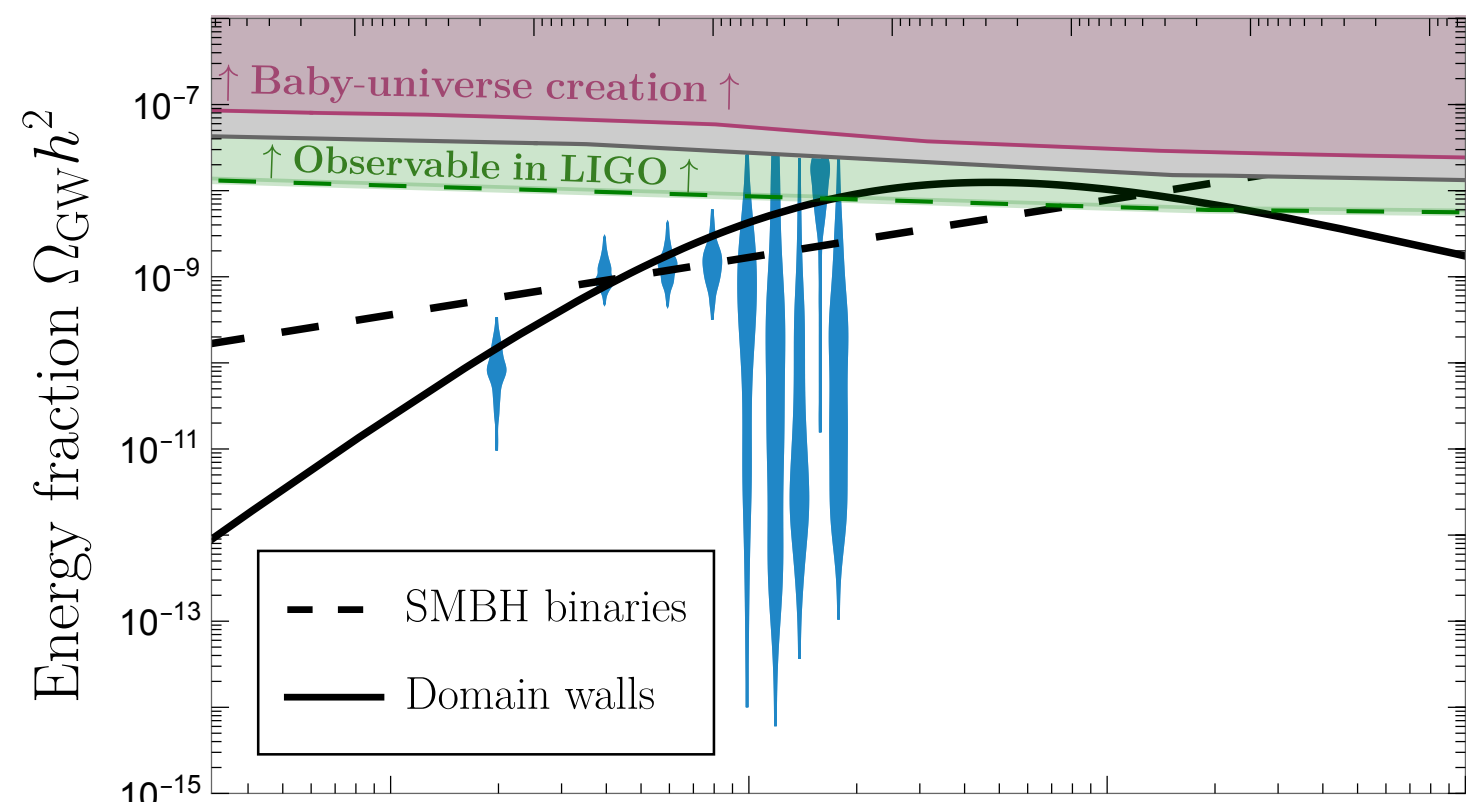
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Baby-universe

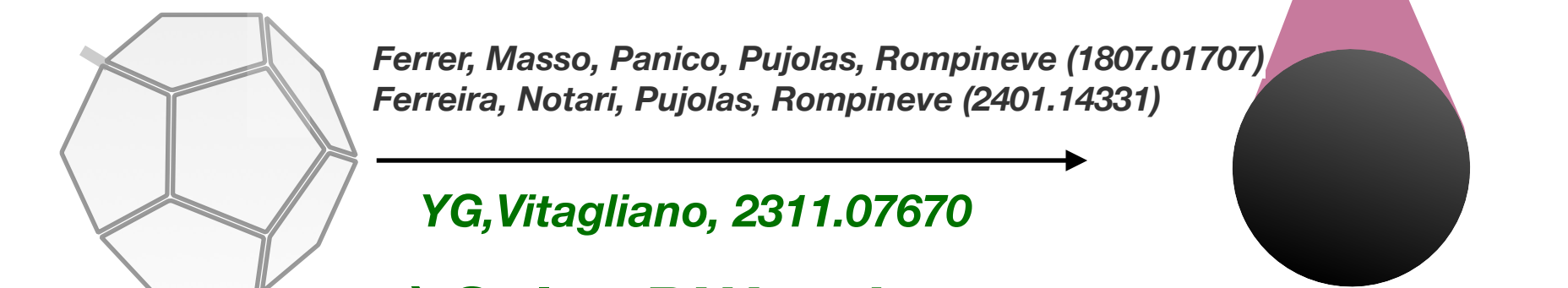


Domain wall networks

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Produce sub-solar-mass PBH

YG, Vitagliano 2306.17841



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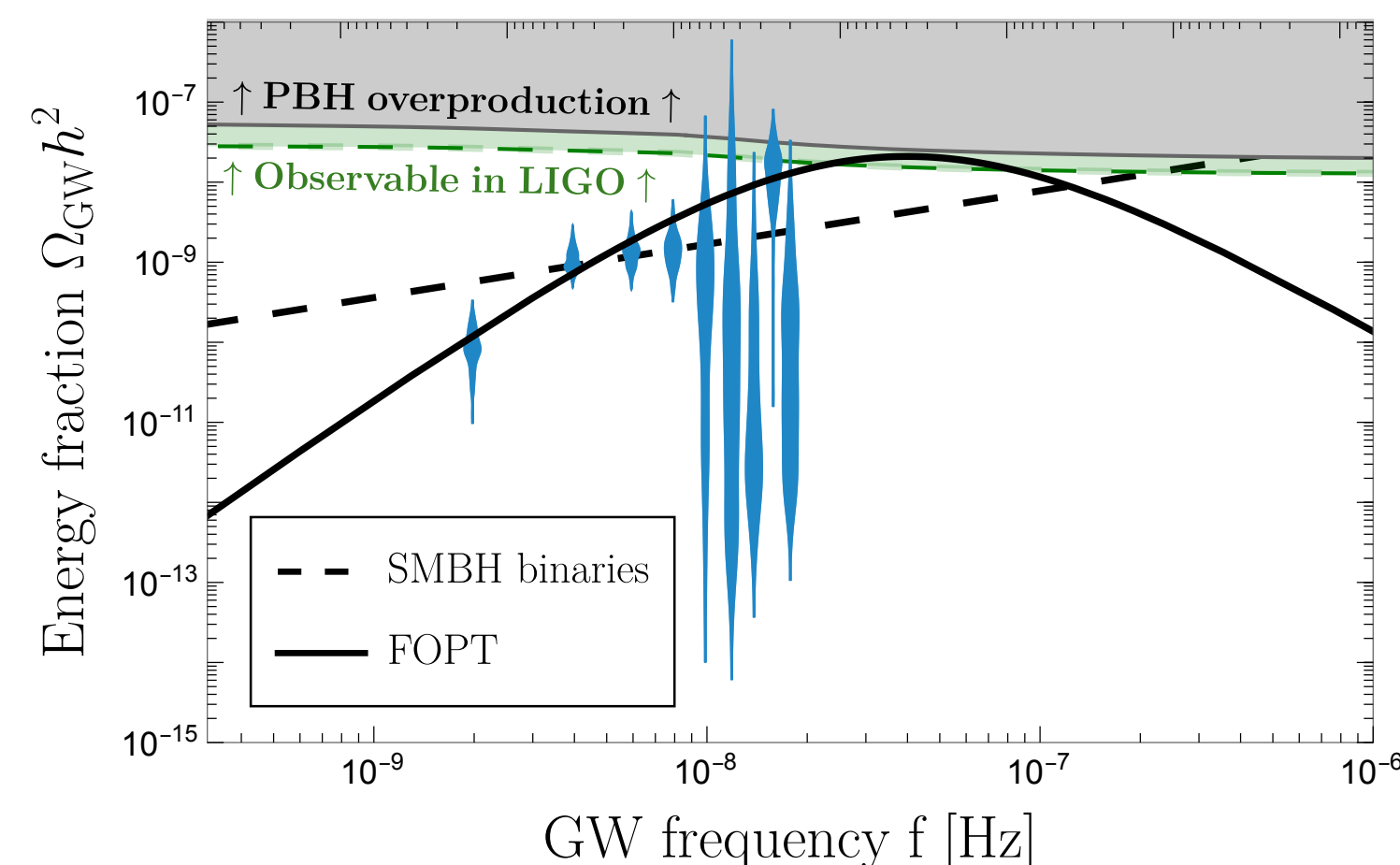
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YG, Vitagliano, 2311.07670

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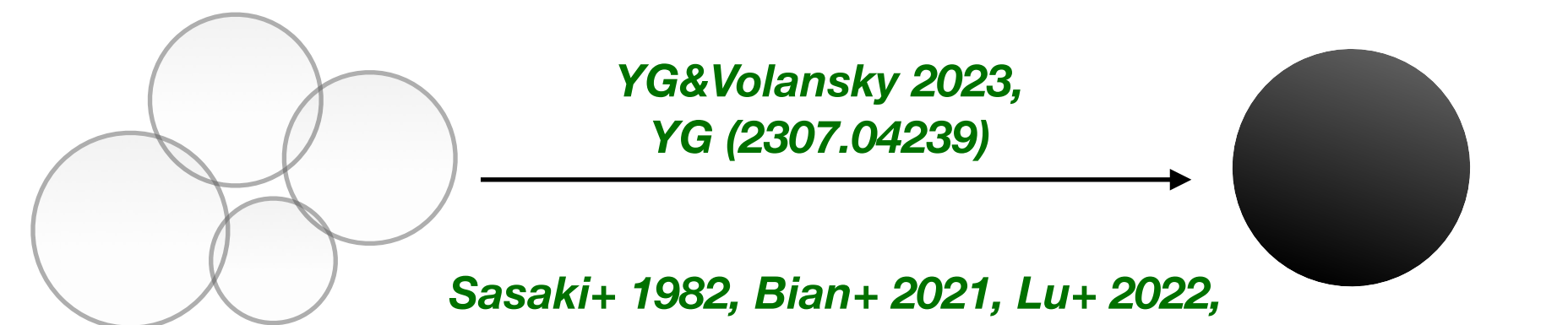
2) Percolation theory

PBH



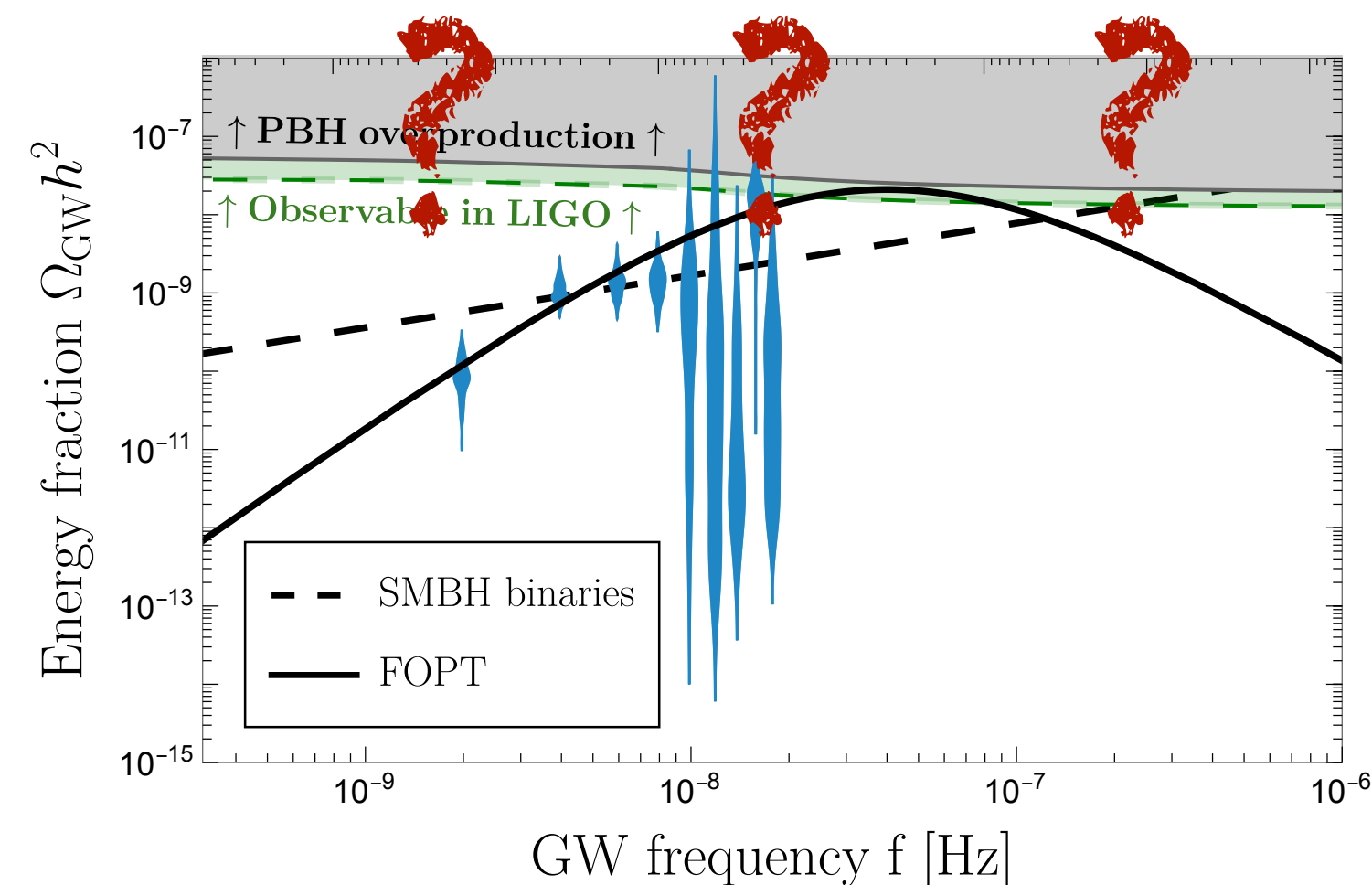
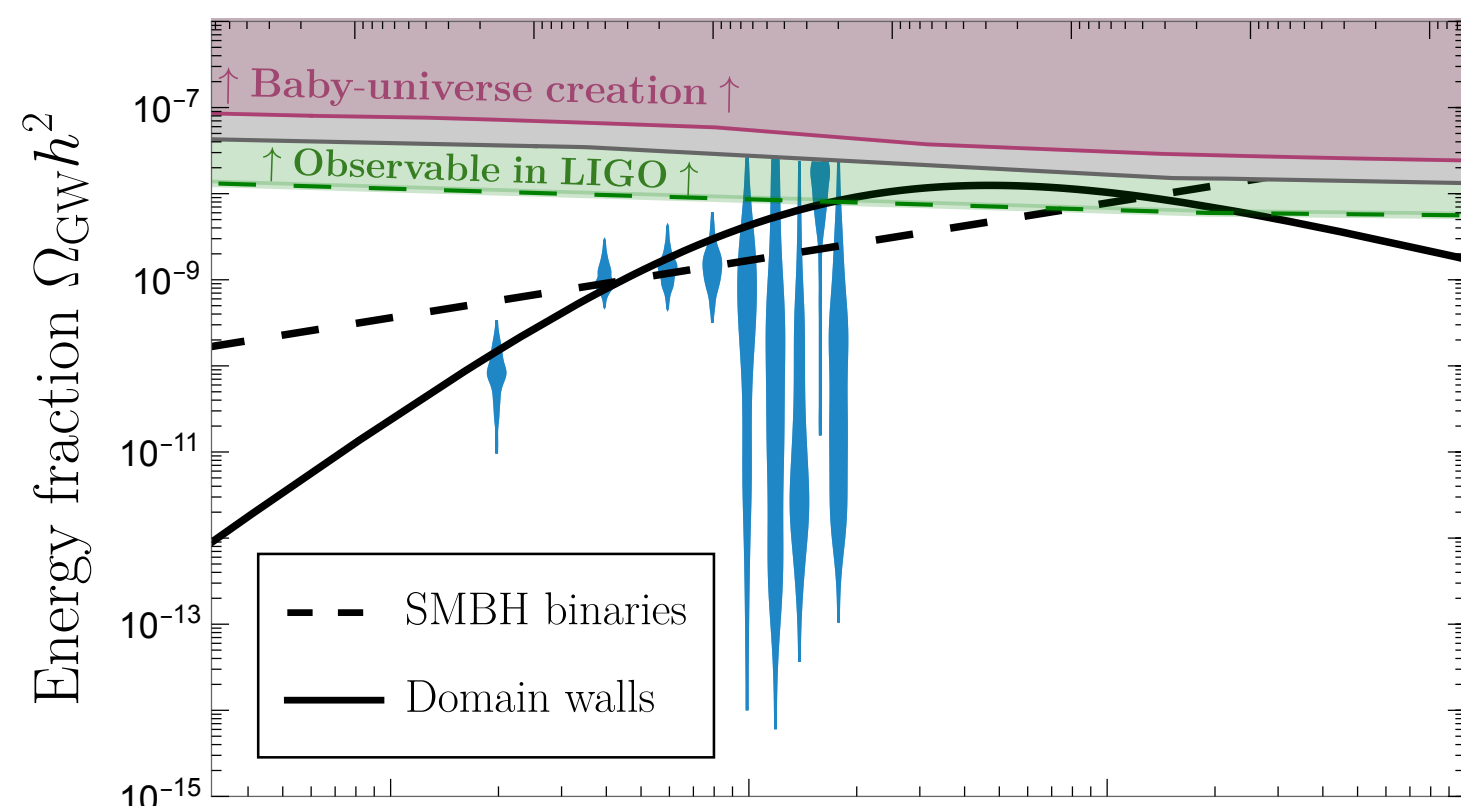
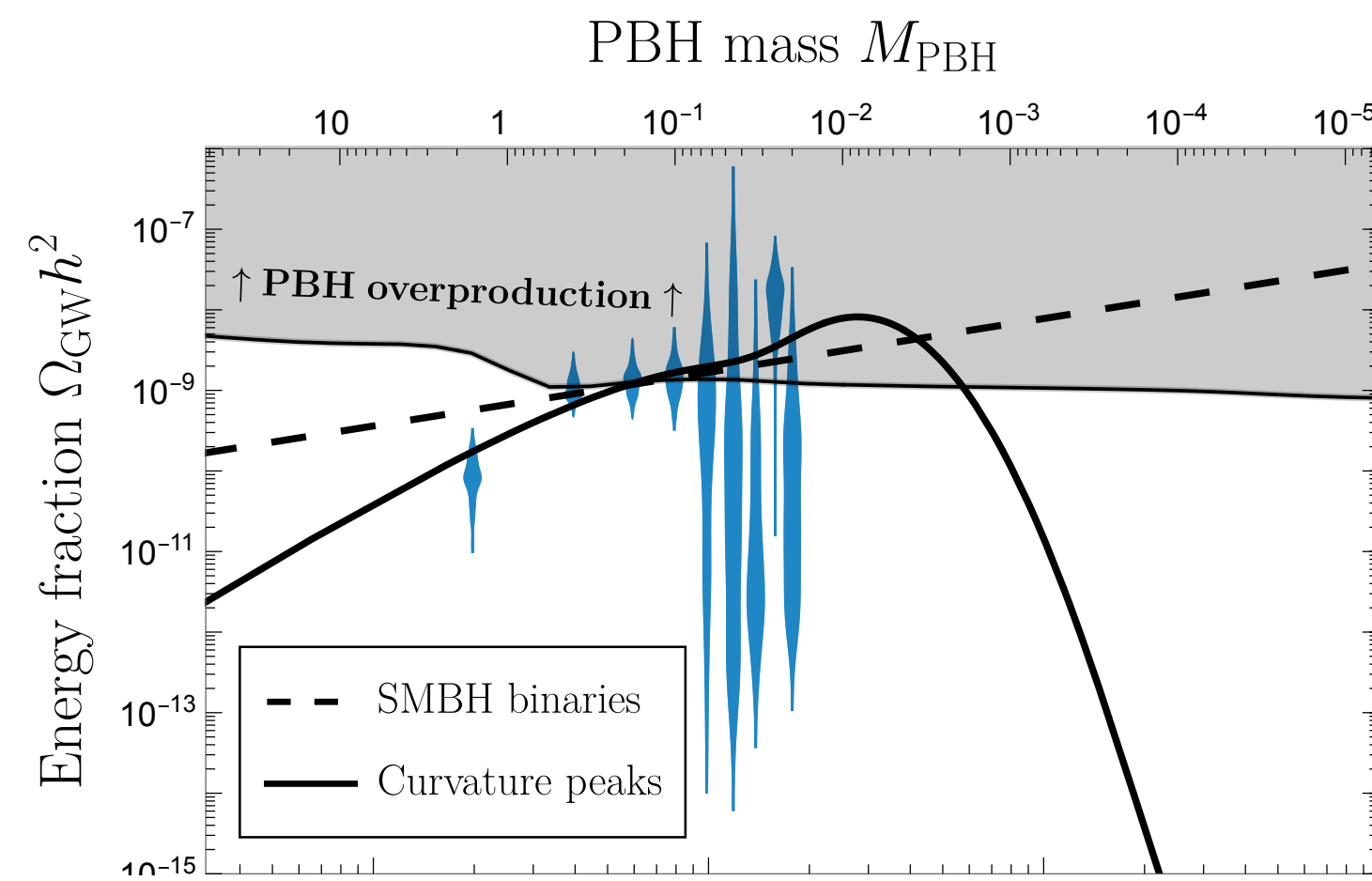
First-order phase transitions

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Lewicki, Toczec, Vaskonen (2402.04158)
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*YG&Volansky 2023,
 YG (2307.04239)*

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



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Produce sub-solar-mass PBH

YG, Vitagliano 2306.17841

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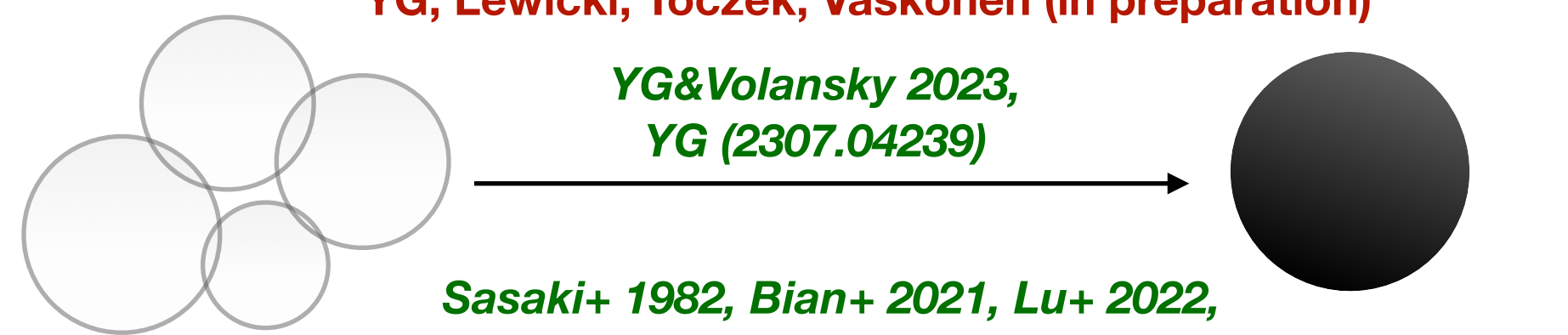
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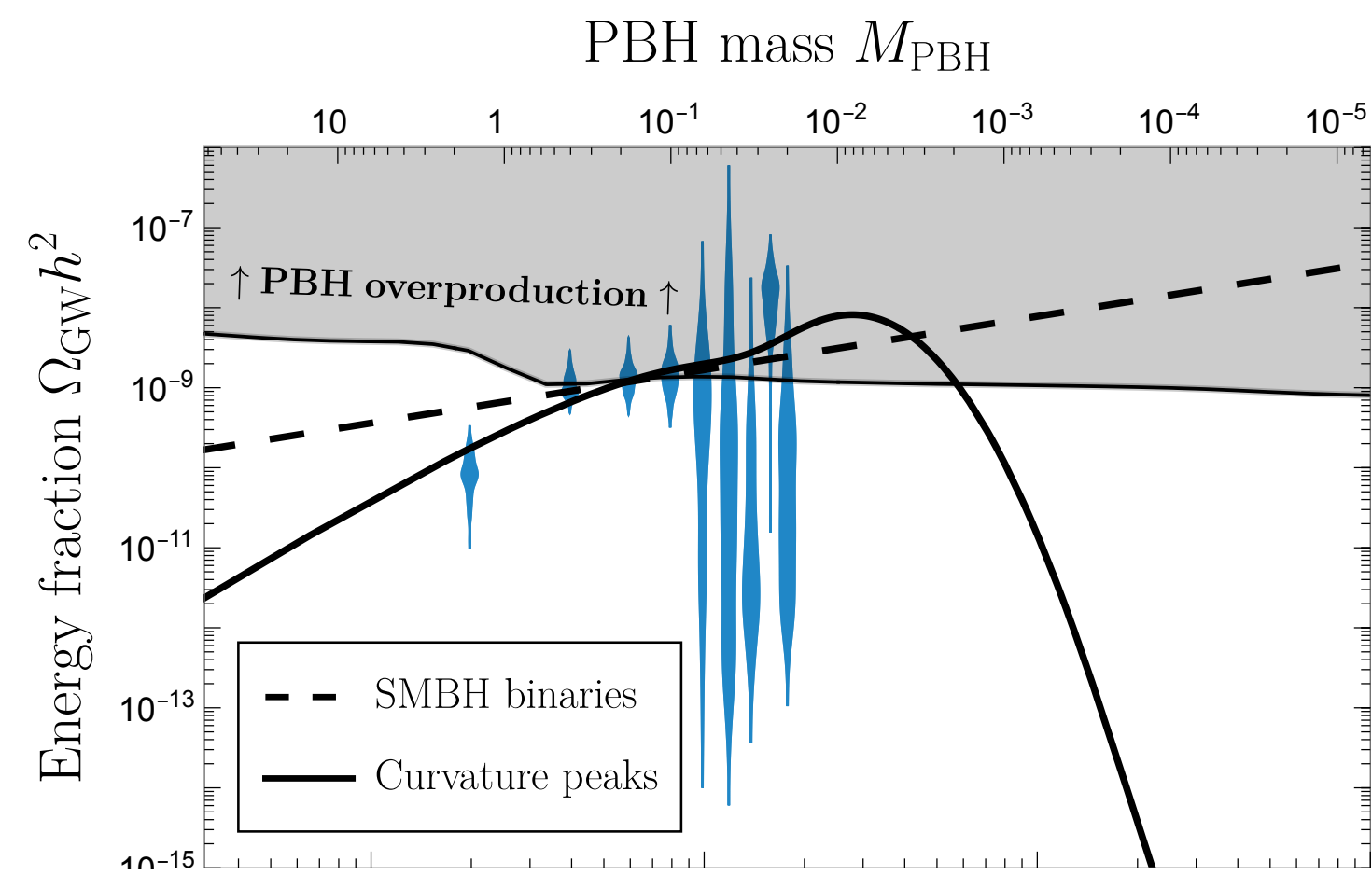
Franciolini, YG, Jinno, 2503.01962

YG, Lewicki, Toczec, Vaskonen (in preparation)

*YG&Volansky 2023,
YG (2307.04239)*

*Sasaki+ 1982, Bian+ 2021, Lu+ 2022,
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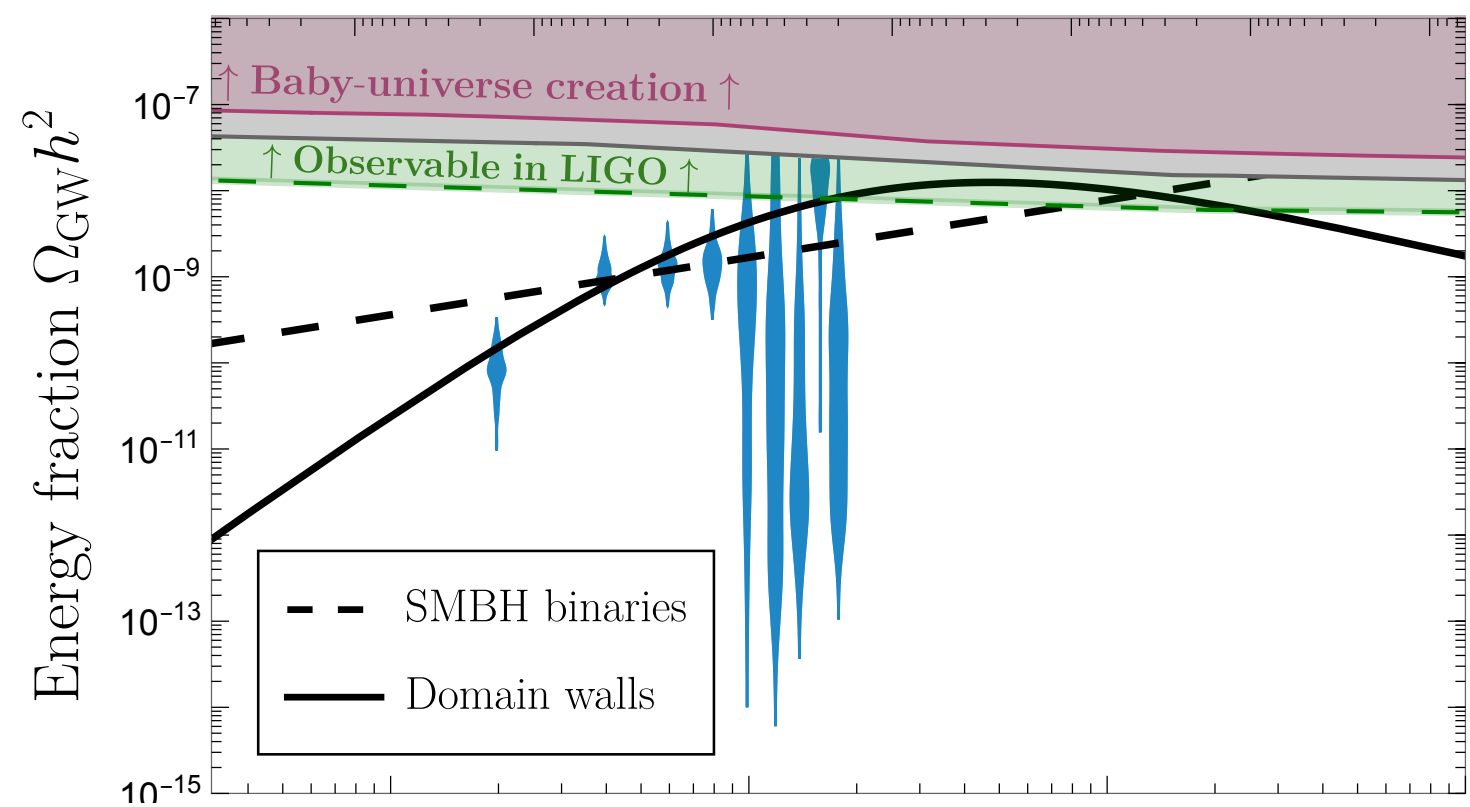
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Domain wall networks

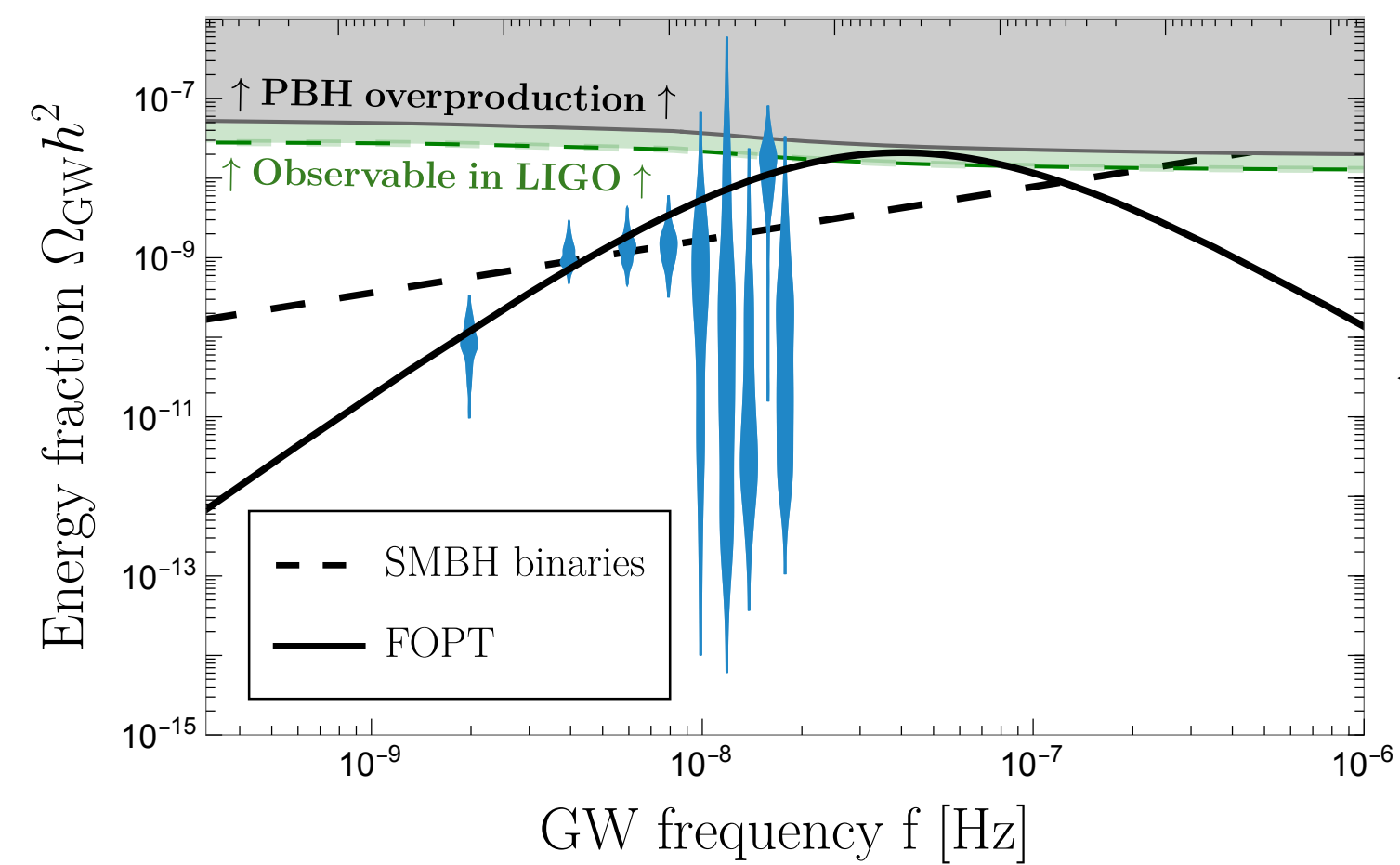
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Produce sub-solar-mass PBH

YG, Vitagliano 2306.17841



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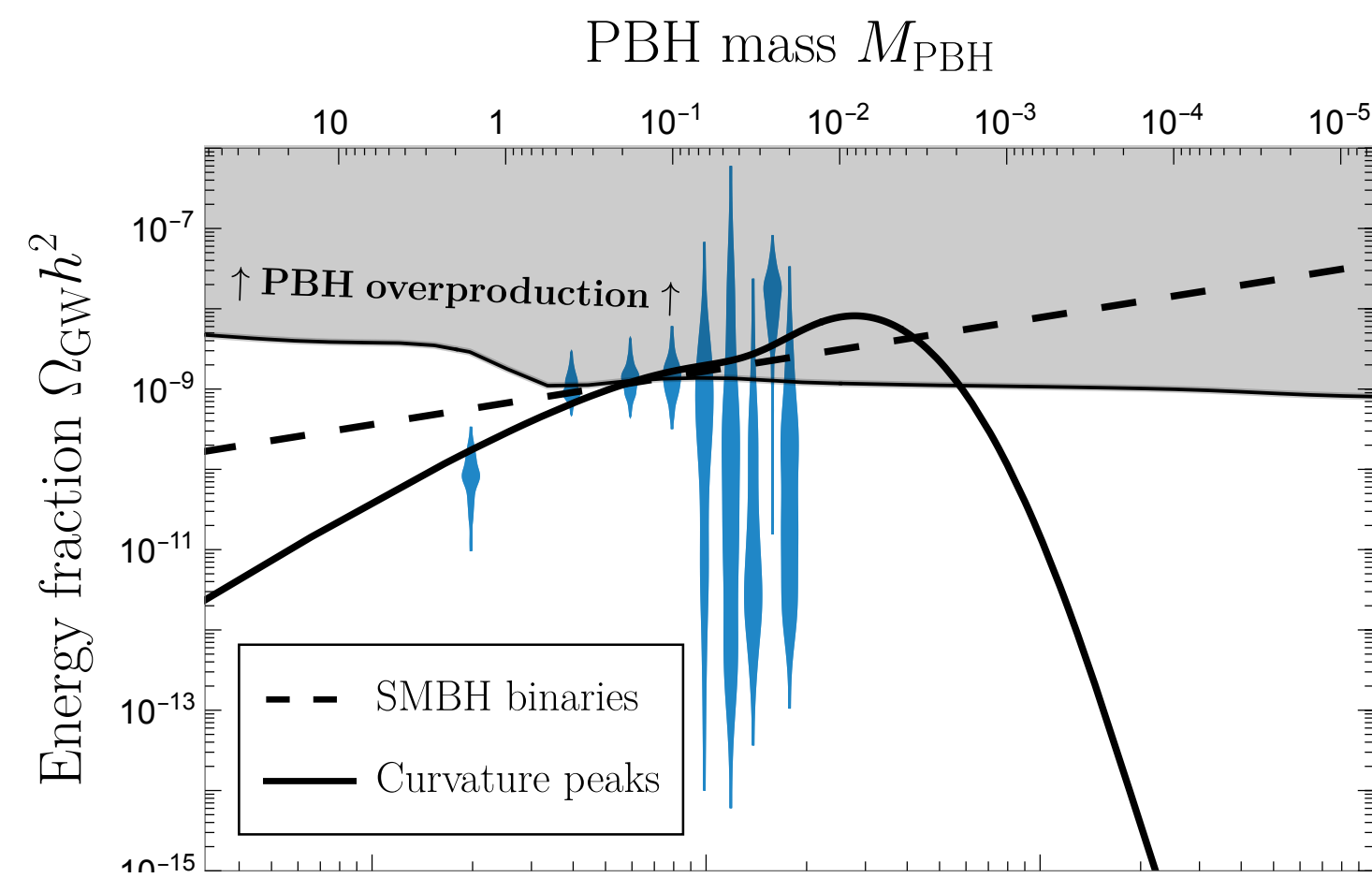
Scalar Curvature

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

YG 2503.03857

Franciolini, YG, Jinno,

2503.01962



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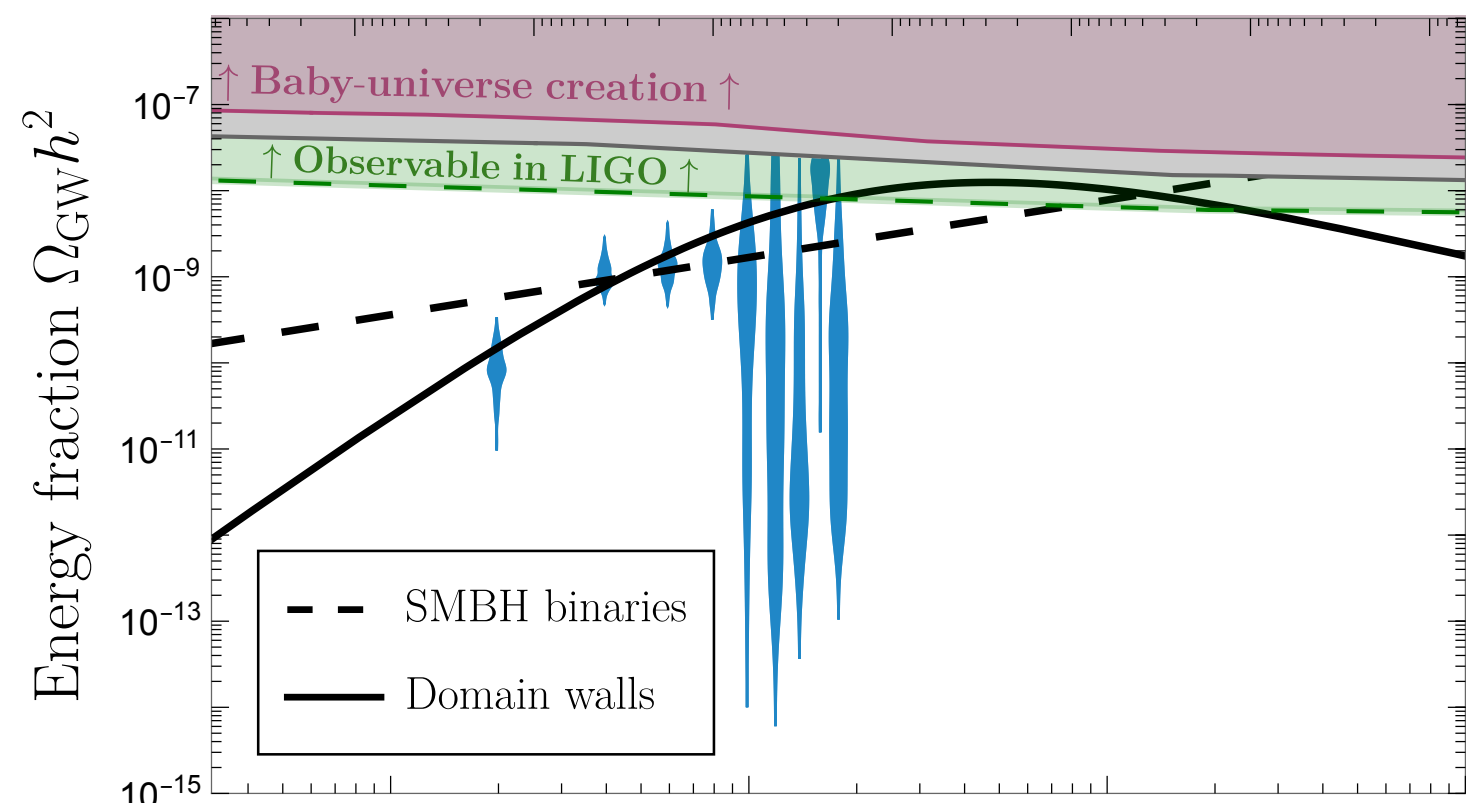
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Domain wall networks

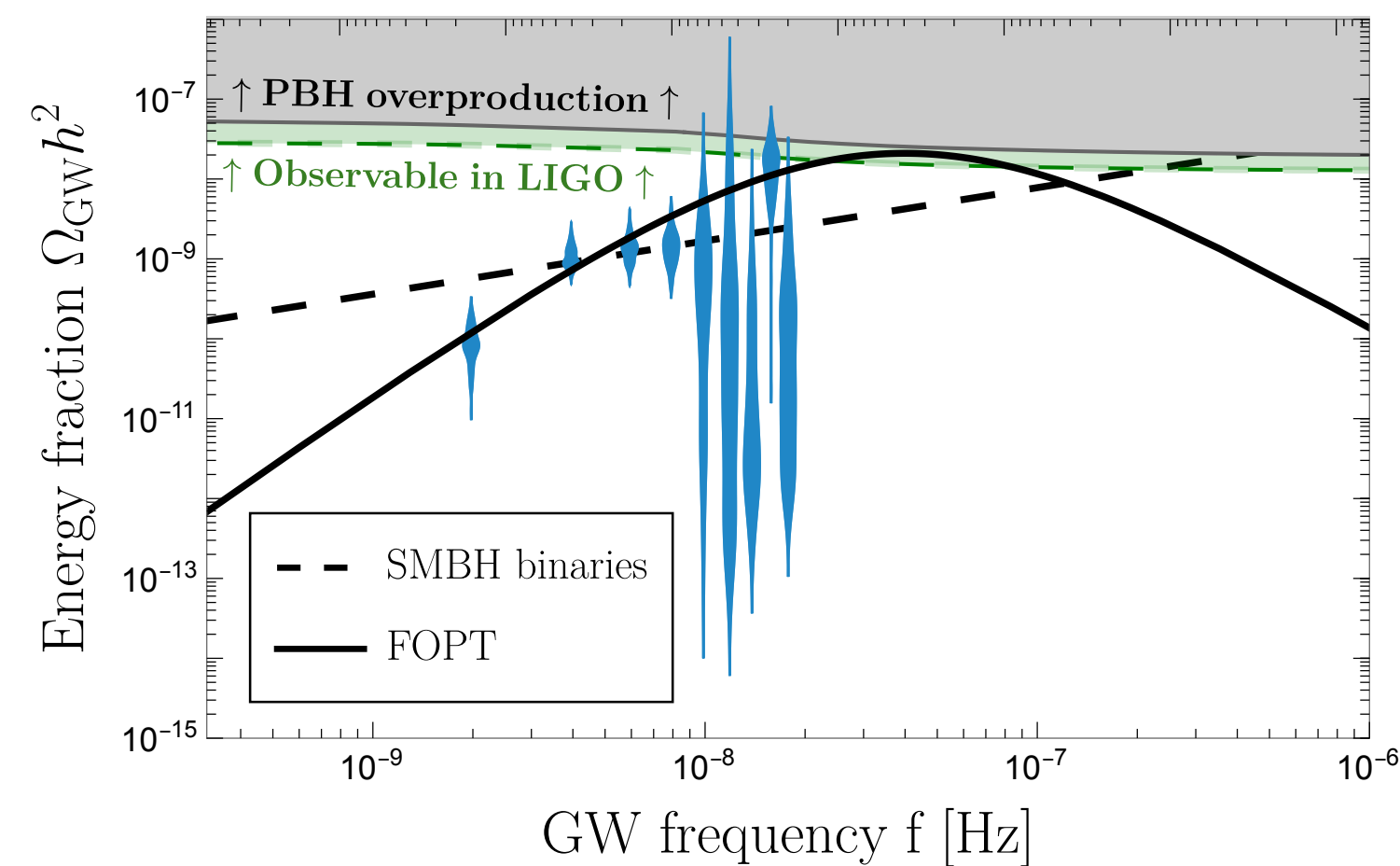
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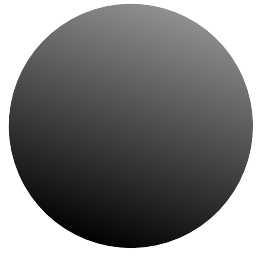
YG (2307.04239)

Lewicki, Toczek, Vaskonen (2402.04158)

Hoefken Zink et al. (2501.15649)

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**Primordial
Black Holes
(PBHs)**

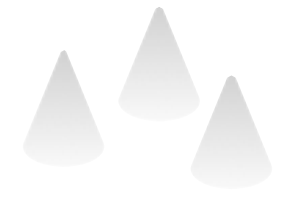


if $\langle \mathcal{R} \rangle_H \gtrsim 0.1$

(Shibata & Sasaki 1999)

Scalar Curvature

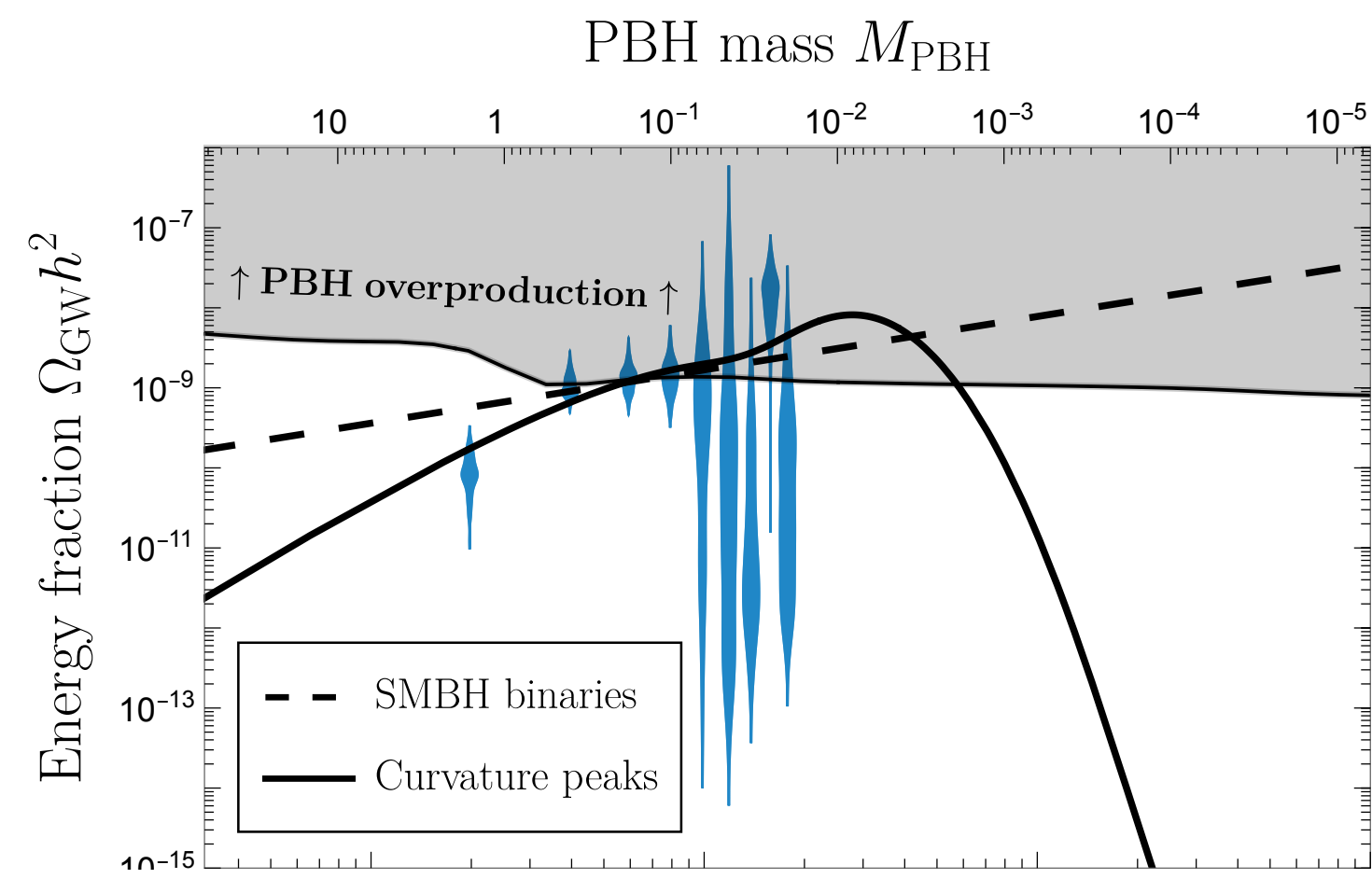
$\mathcal{R}(\vec{x}, t)$



YG 2503.03857

Franciolini, YG, Jinno,

2503.01962



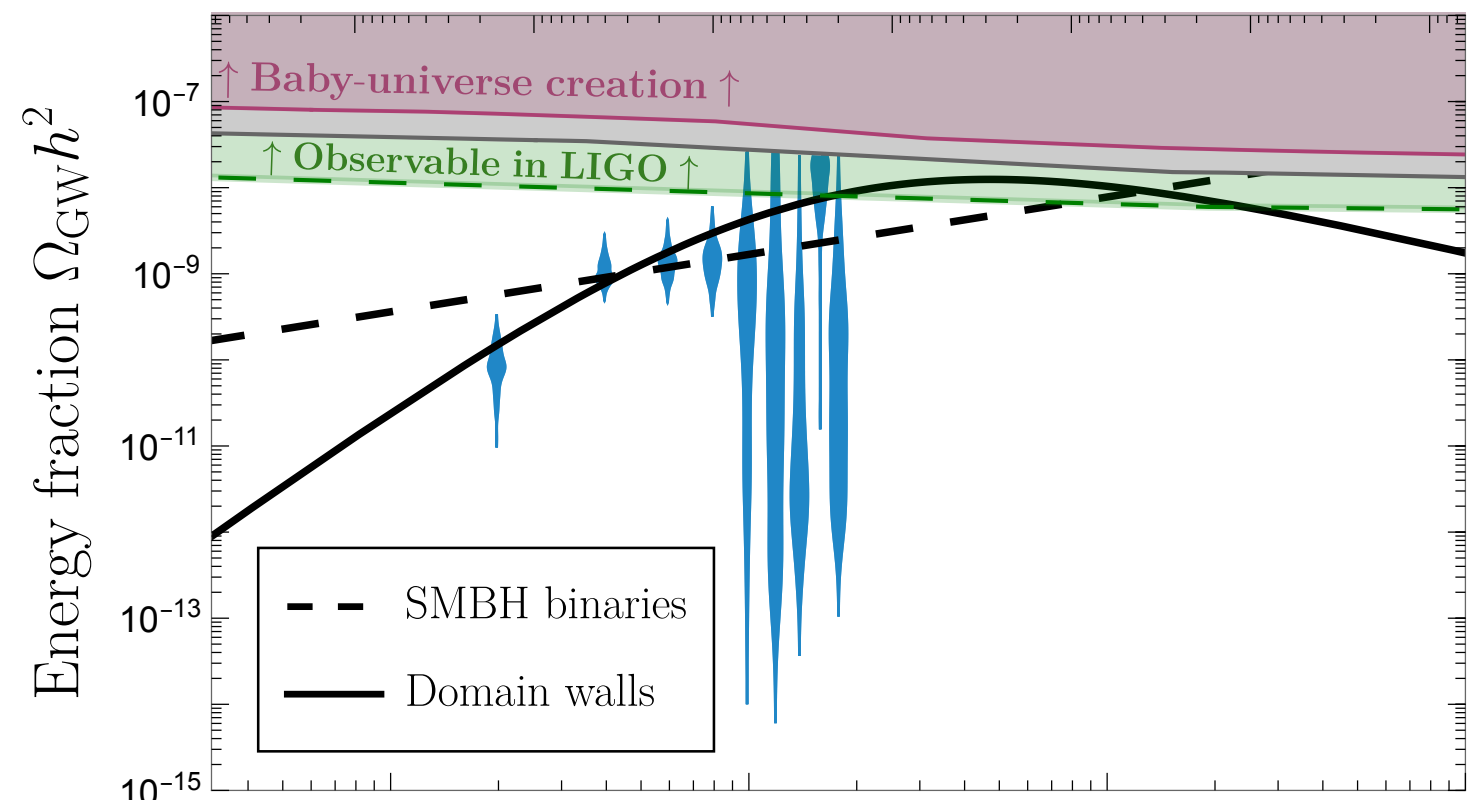
Curvature peaks

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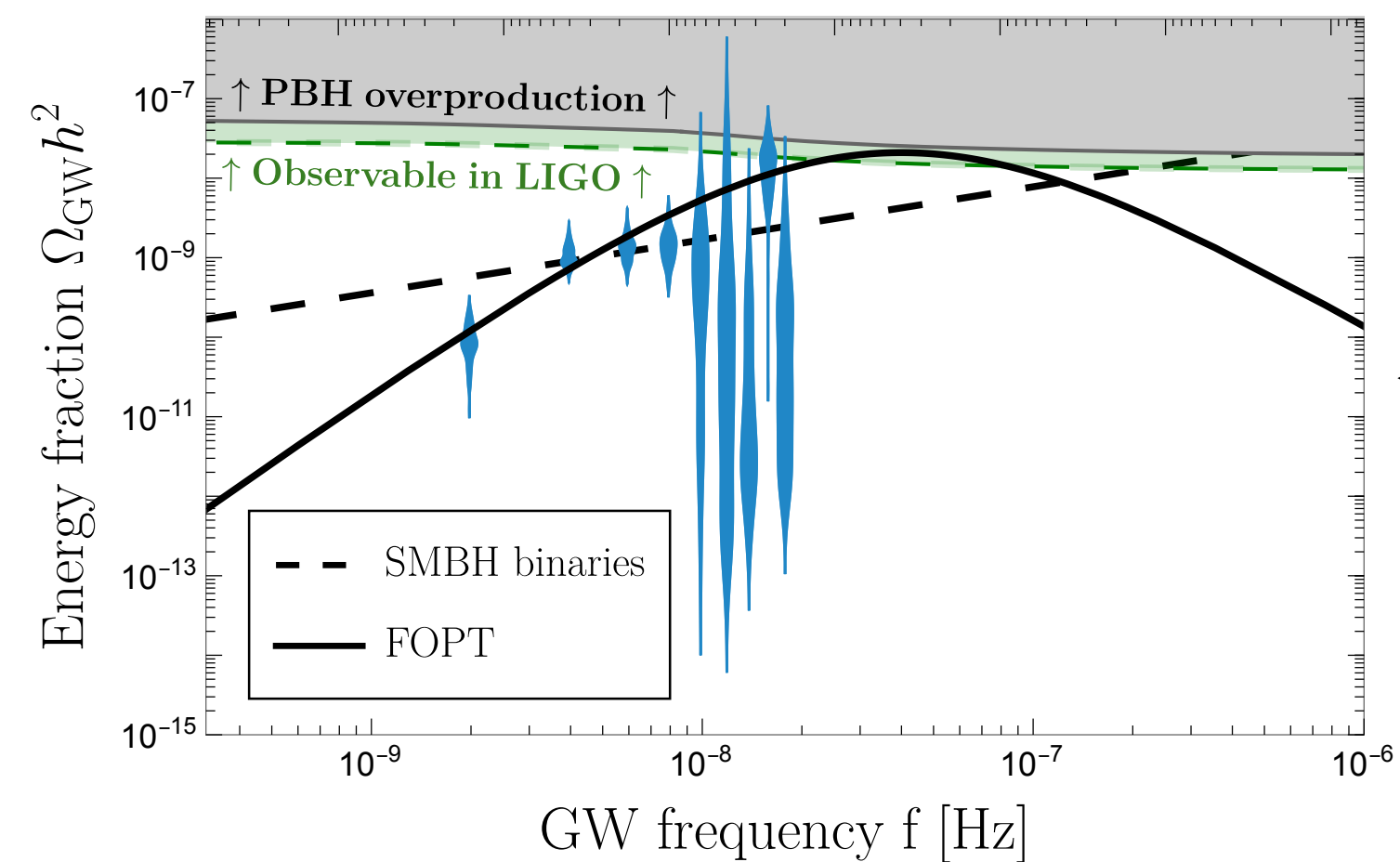


Domain wall networks

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Produce sub-solar-mass PBH

YG, Vitagliano 2306.17841



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if $\langle \mathcal{R} \rangle_H \gtrsim 0.1$

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Scalar Curvature

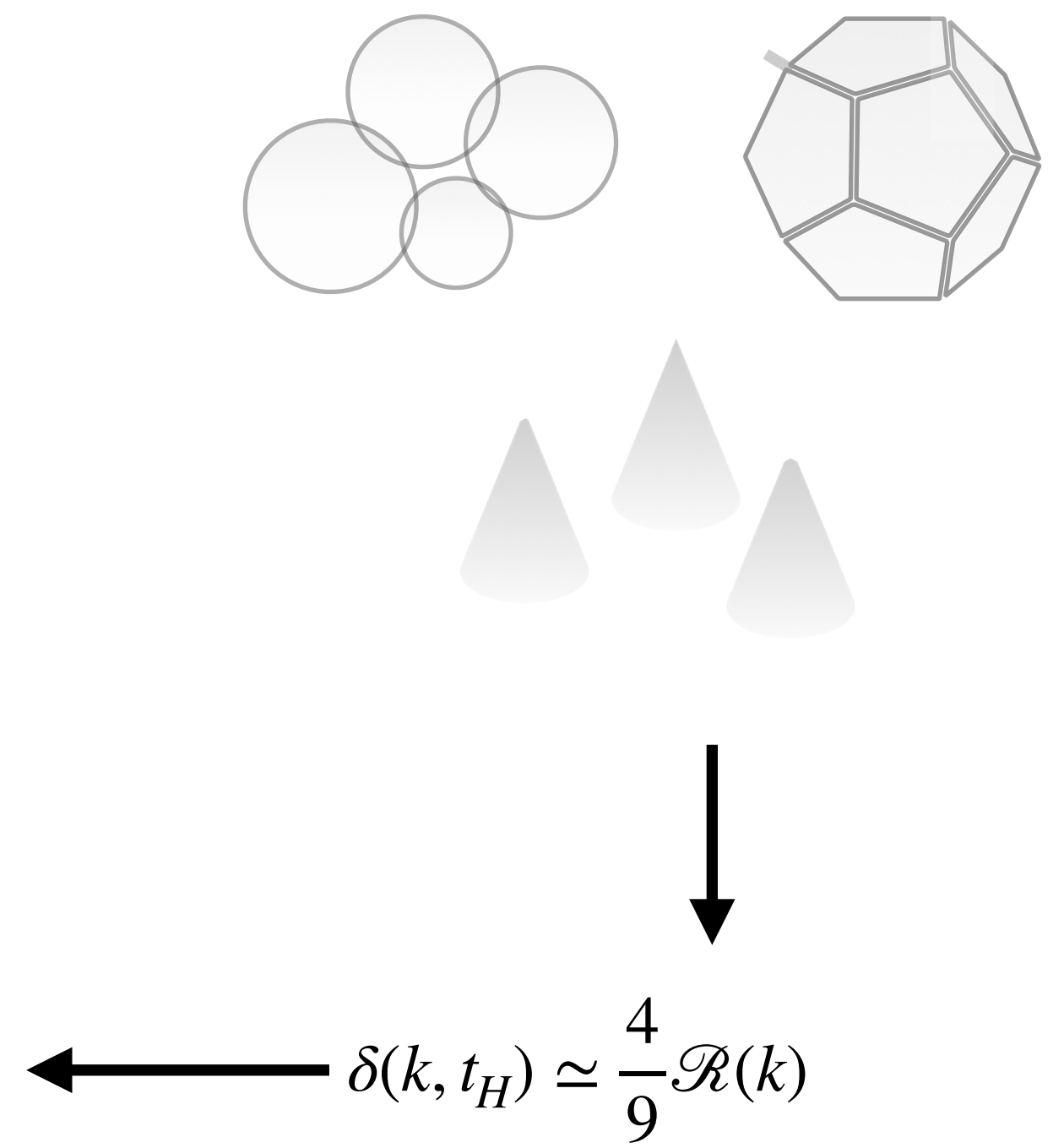
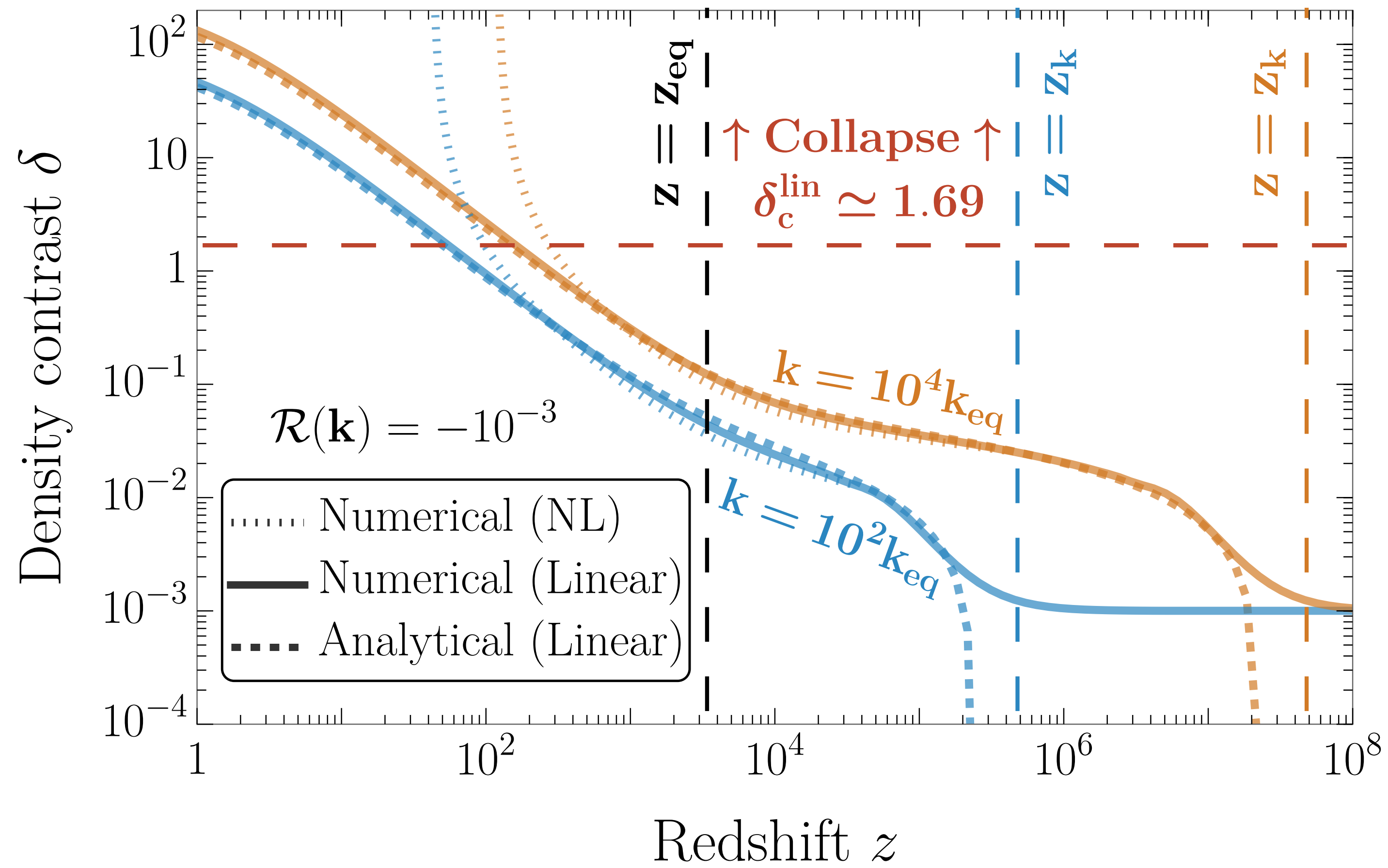
$\mathcal{R}(\vec{x}, t)$

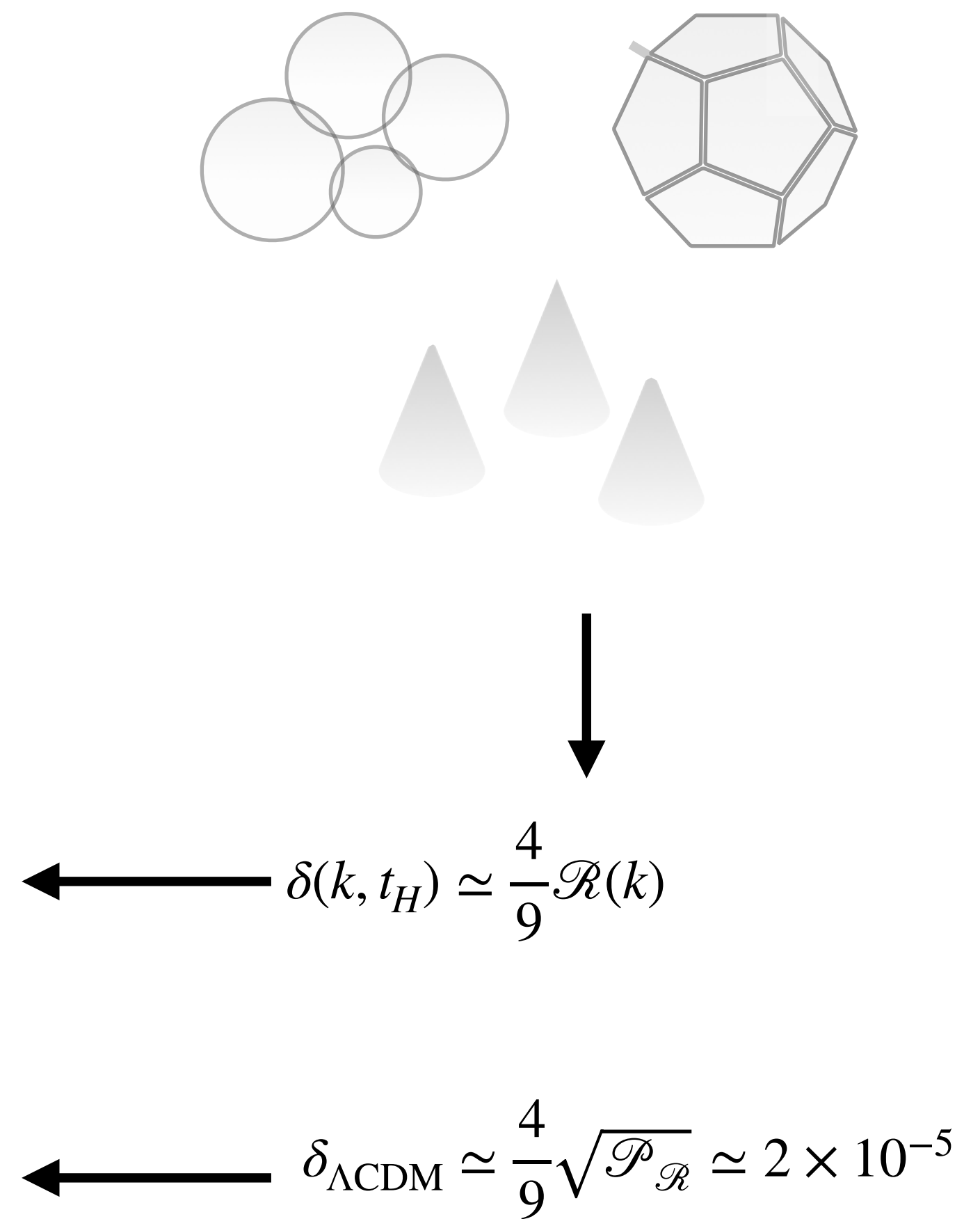
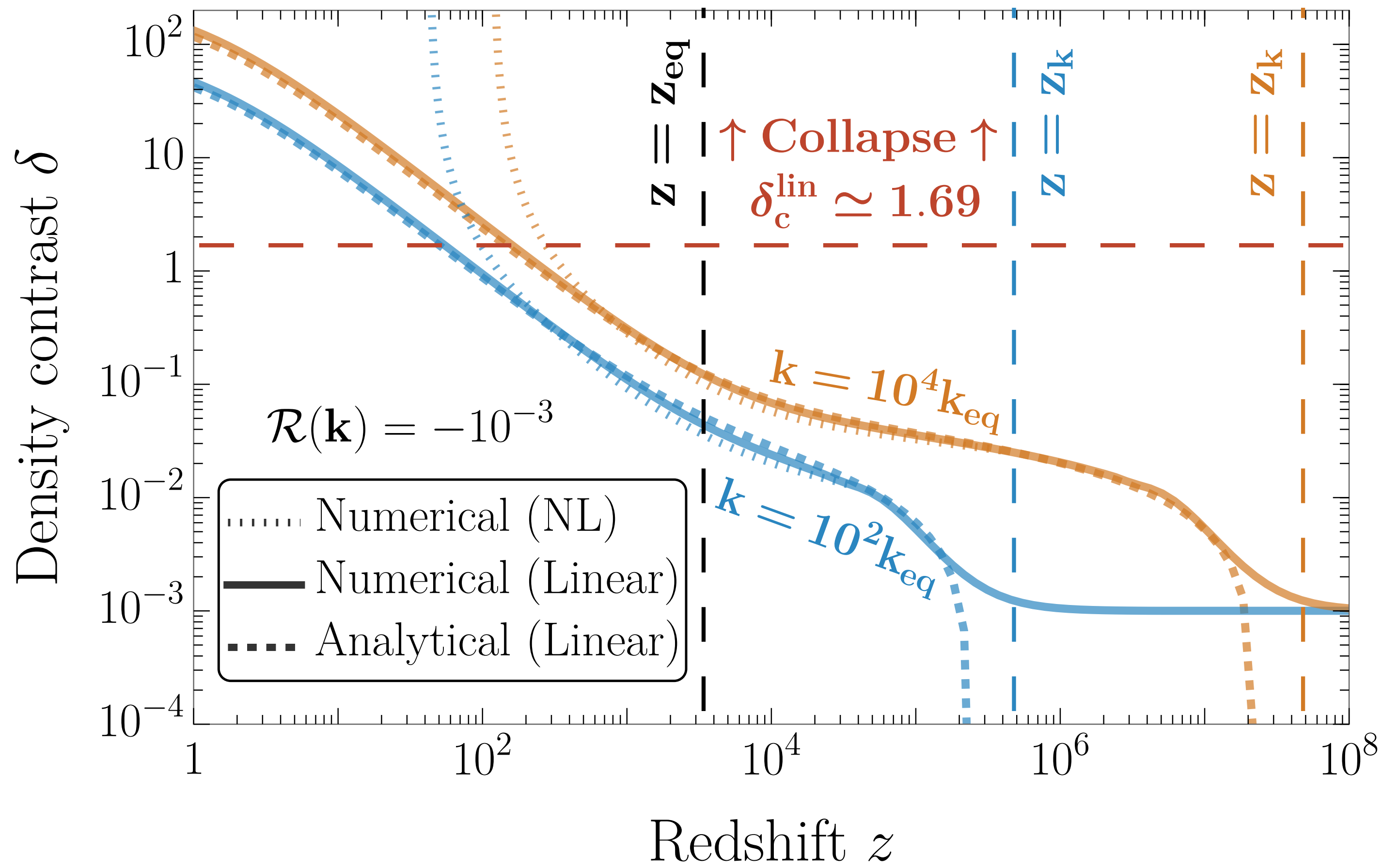
YG 2503.03857
Franciolini, YG, Jinno,
2503.01962

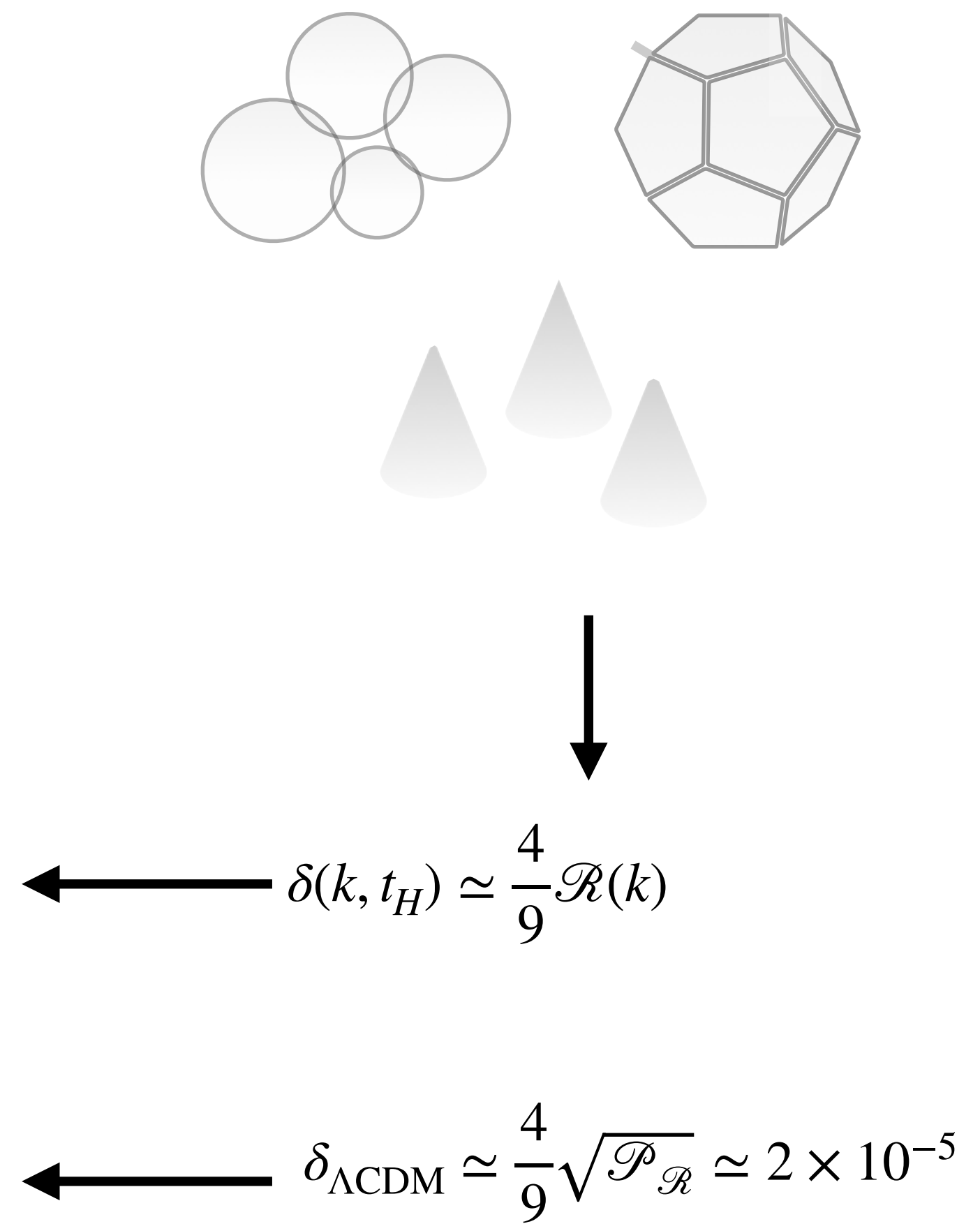
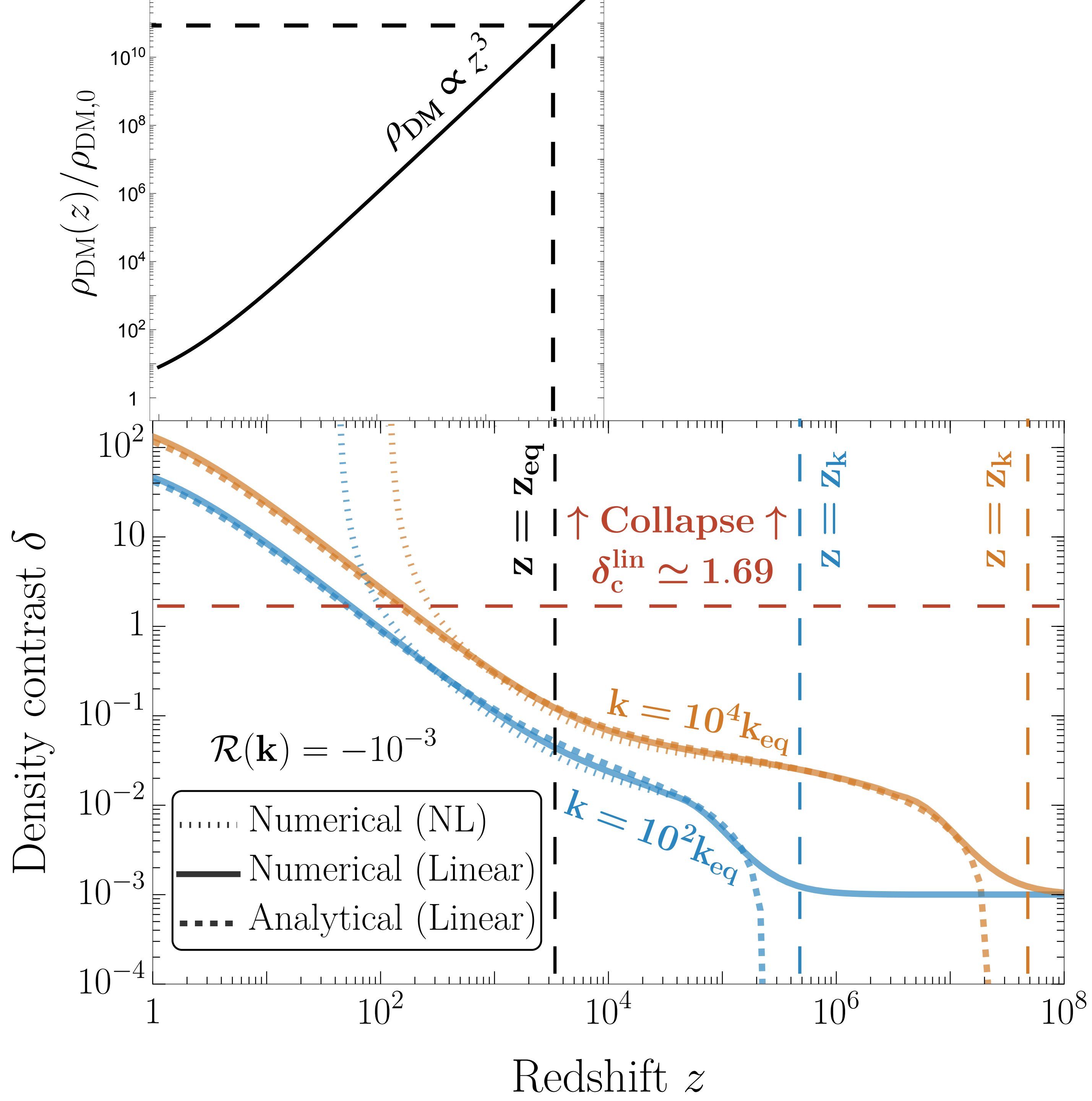
if $\langle \mathcal{R} \rangle_H \gtrsim 10^{-3}$

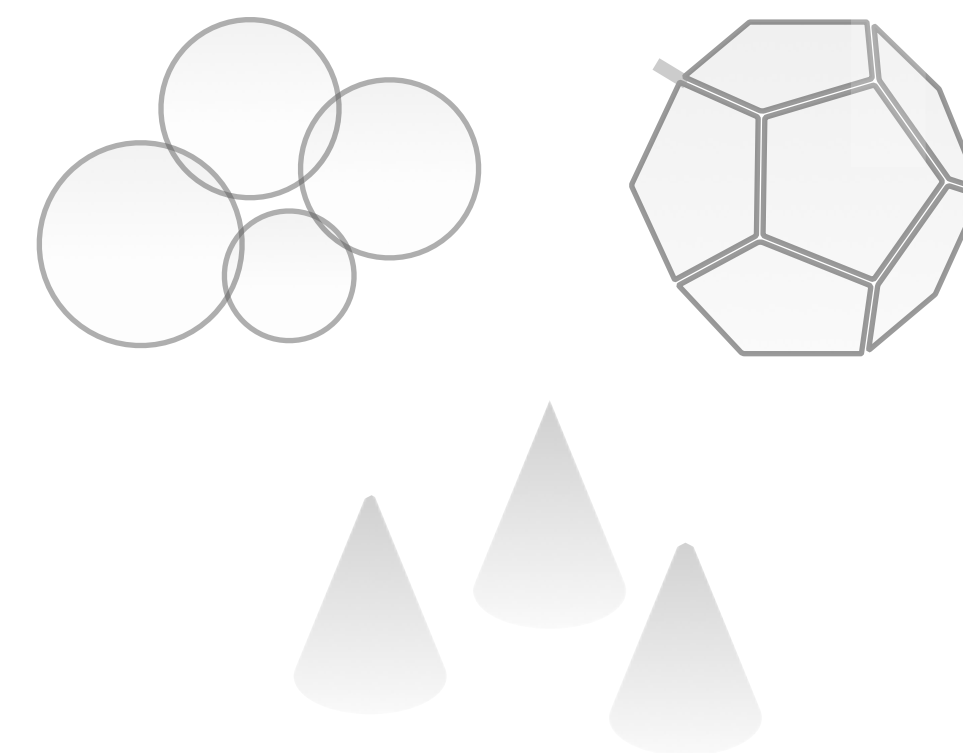
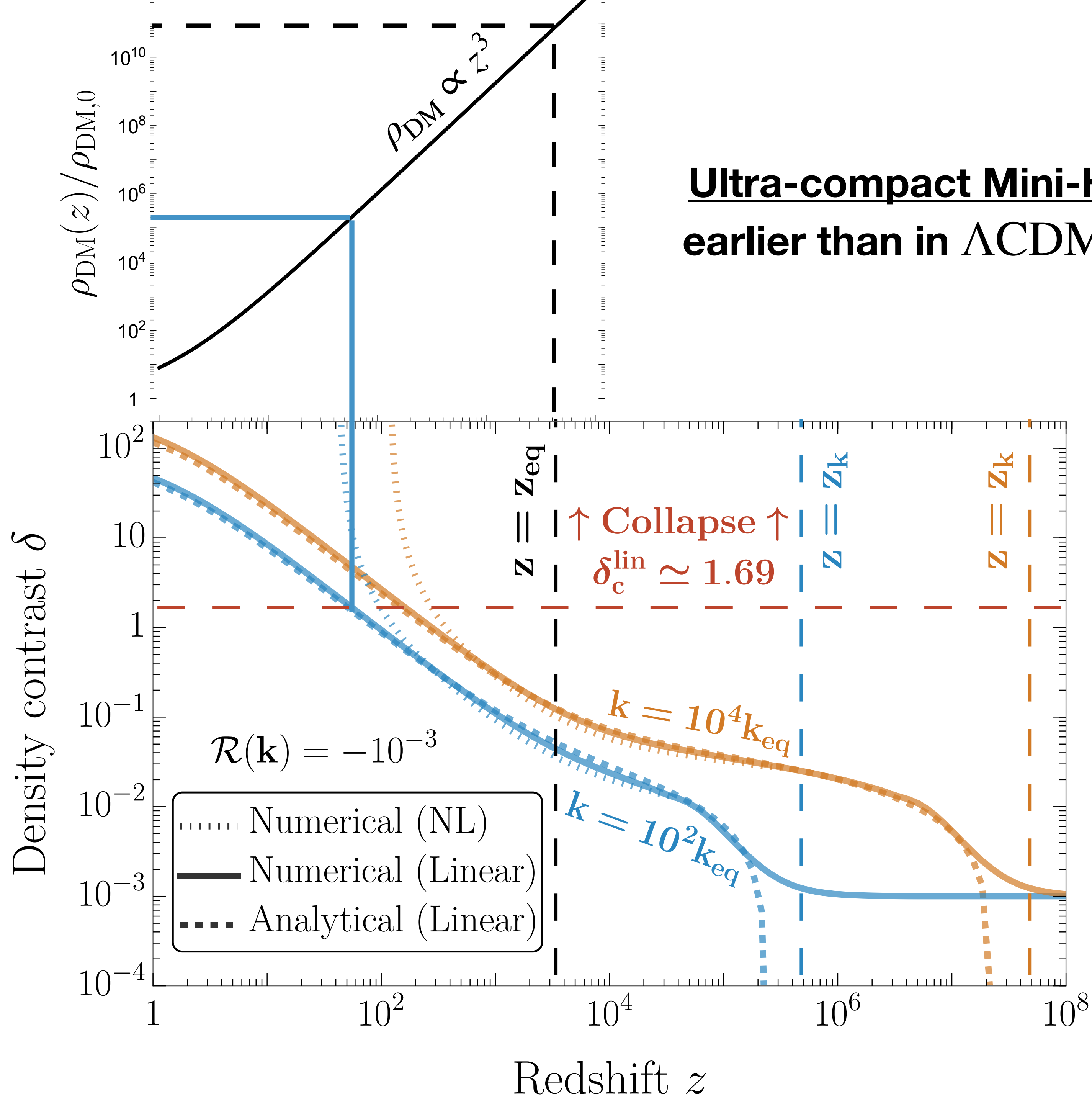
Ricotti, Gould (0908.0735)

**DM Ultra Compact
Mini Halos
(UCMH)**



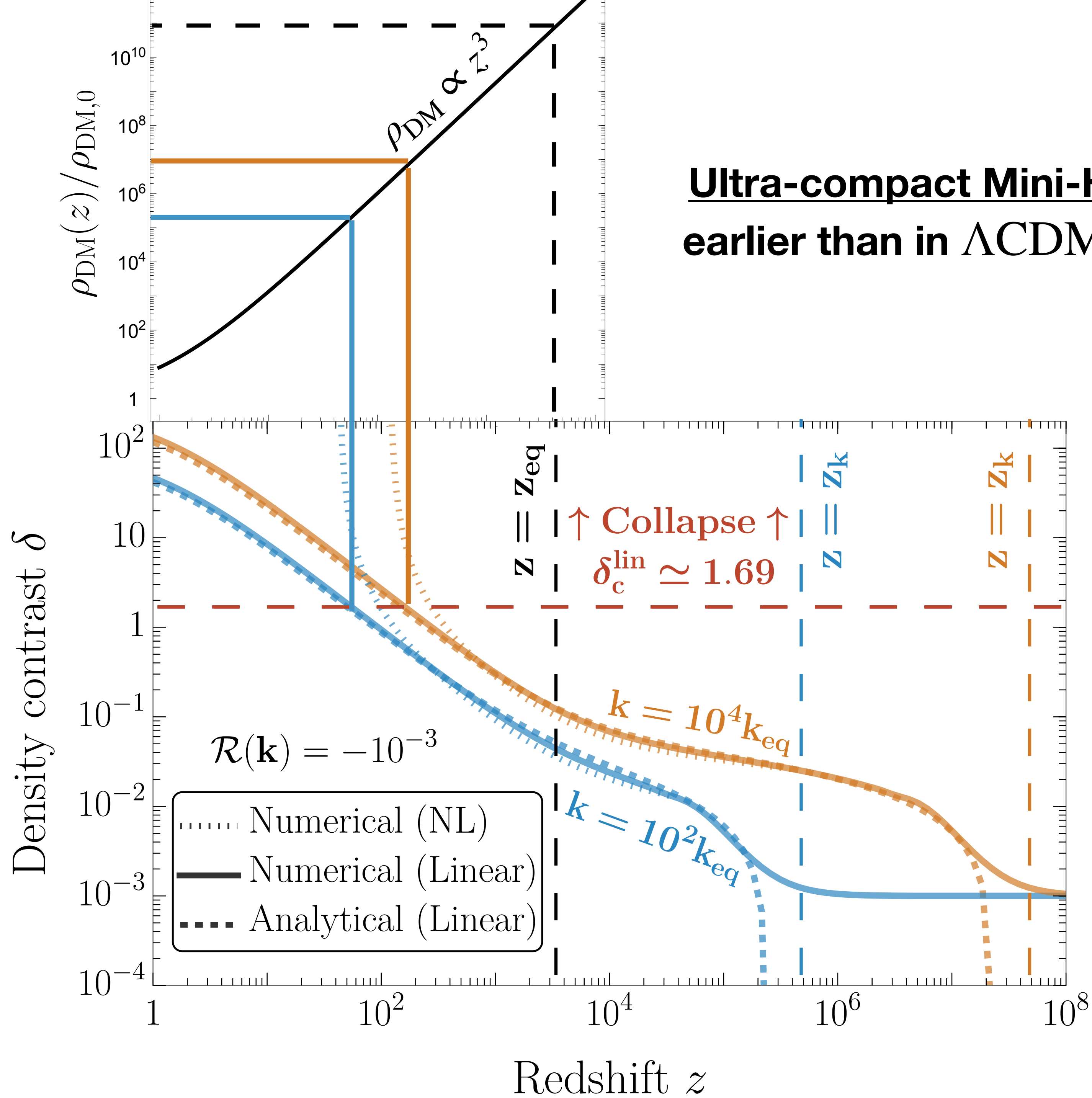




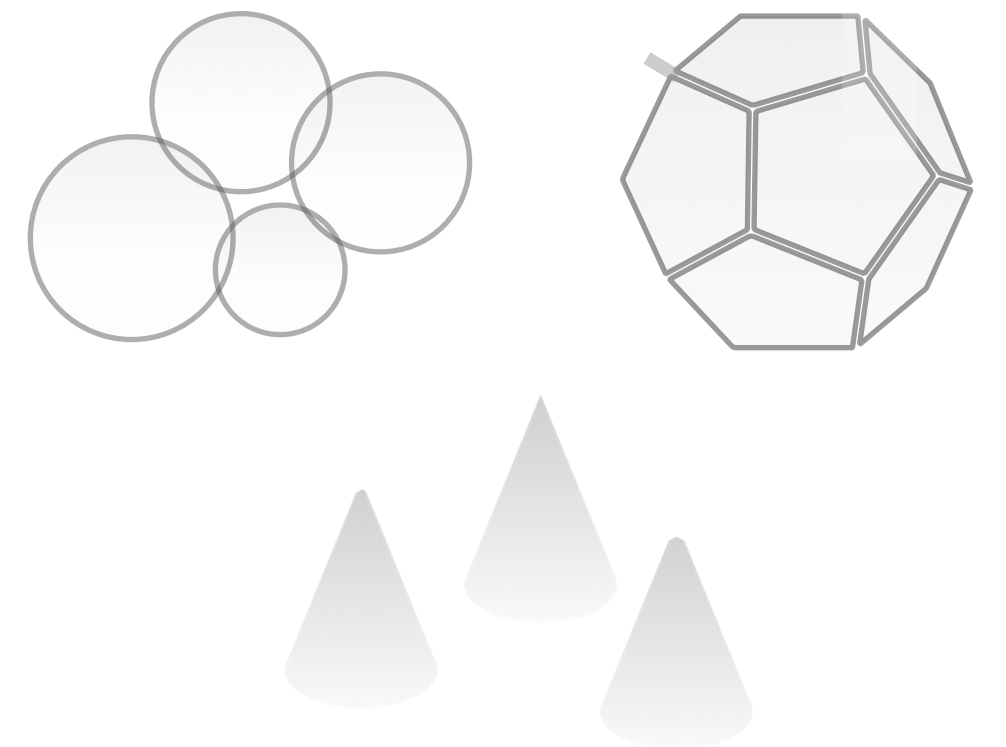


$\delta(k, t_H) \simeq \frac{4}{9} \mathcal{R}(k)$

$\delta_{\Lambda\text{CDM}} \simeq \frac{4}{9} \sqrt{\mathcal{P}_{\mathcal{R}}} \simeq 2 \times 10^{-5}$



Ultra-compact Mini-Halo: DM halo that formed earlier than in Λ CDM and therefore are denser

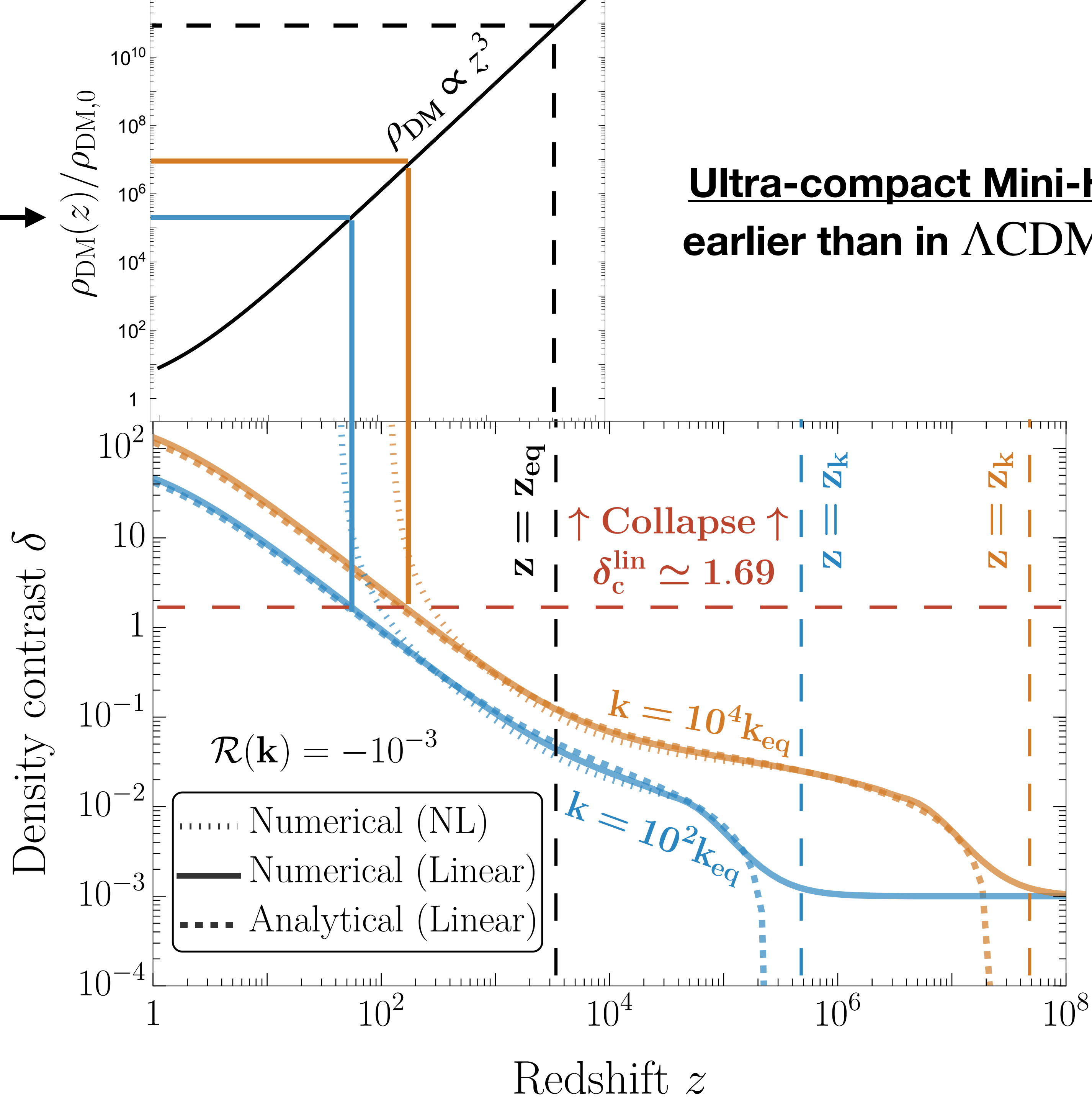


$\delta(k, t_H) \simeq \frac{4}{9} \mathcal{R}(k)$

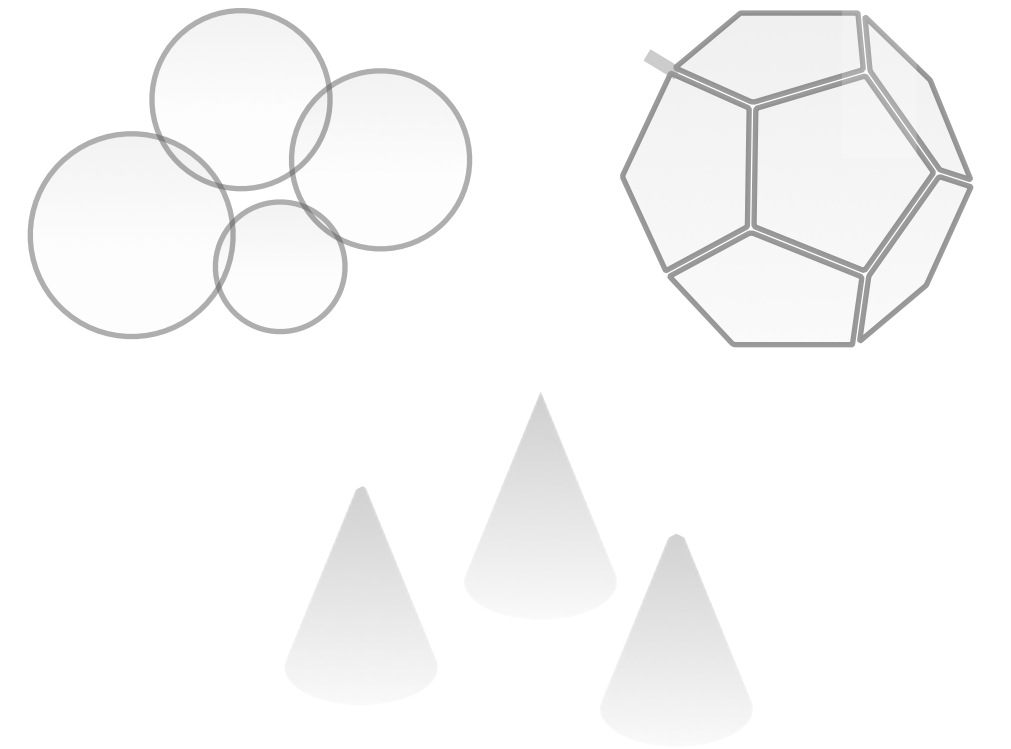
$\delta_{\Lambda\text{CDM}} \simeq \frac{4}{9} \sqrt{\mathcal{P}_{\mathcal{R}}} \simeq 2 \times 10^{-5}$

$$\rho_{\odot} \simeq 0.3 \text{ GeV/cm}^3$$

$$\simeq 2 \times 10^5 \rho_{\text{DM},0}$$



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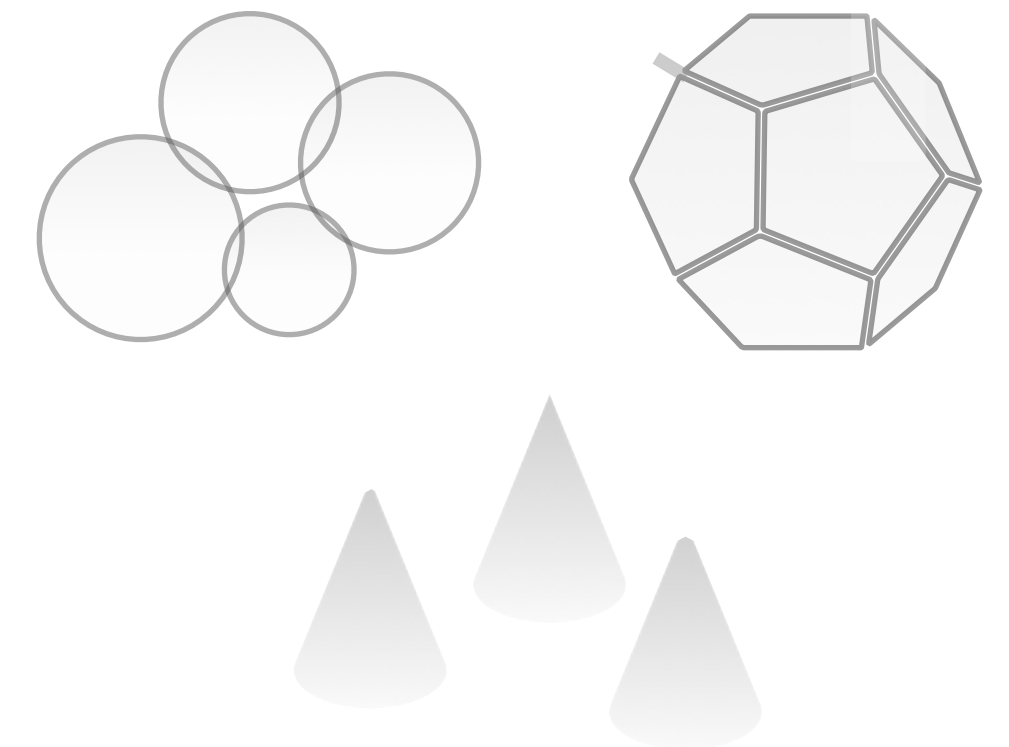
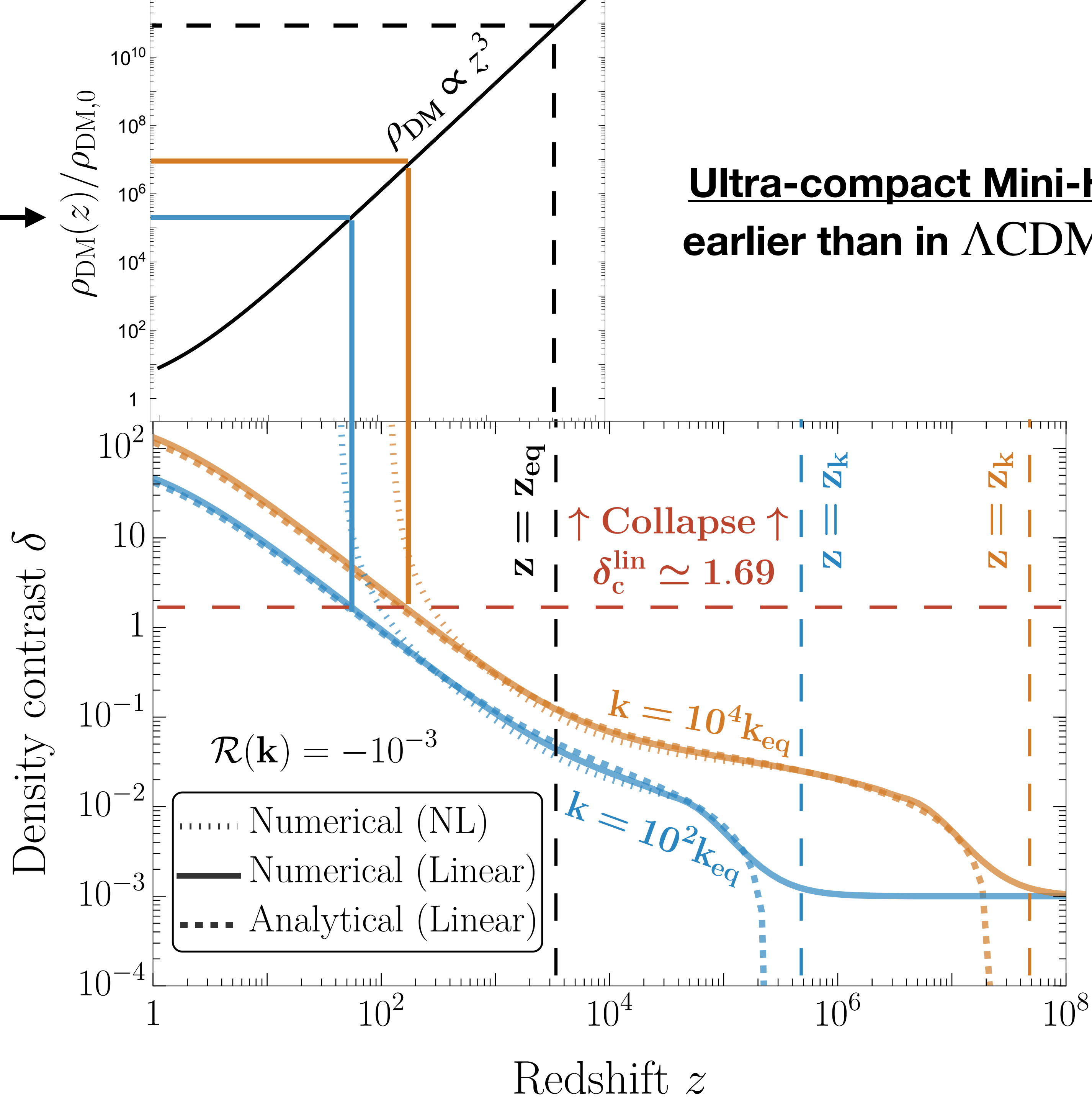
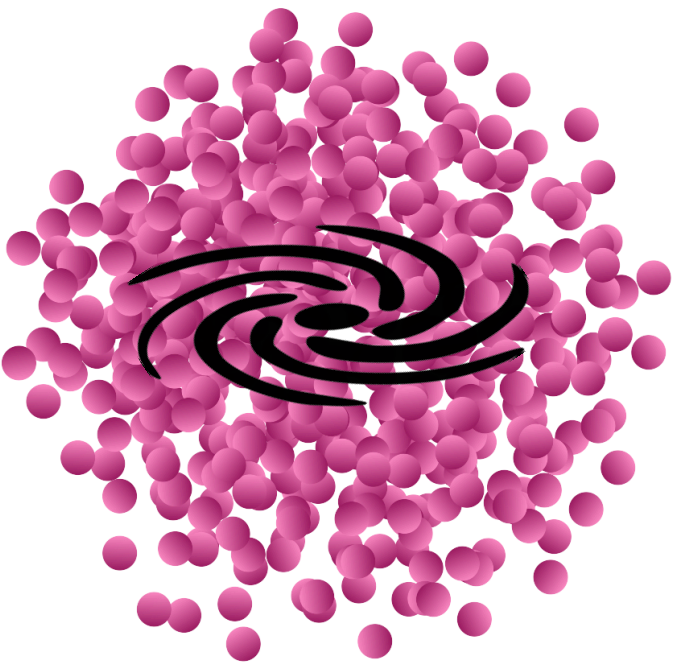


$$\delta(k, t_H) \simeq \frac{4}{9} \mathcal{R}(k)$$

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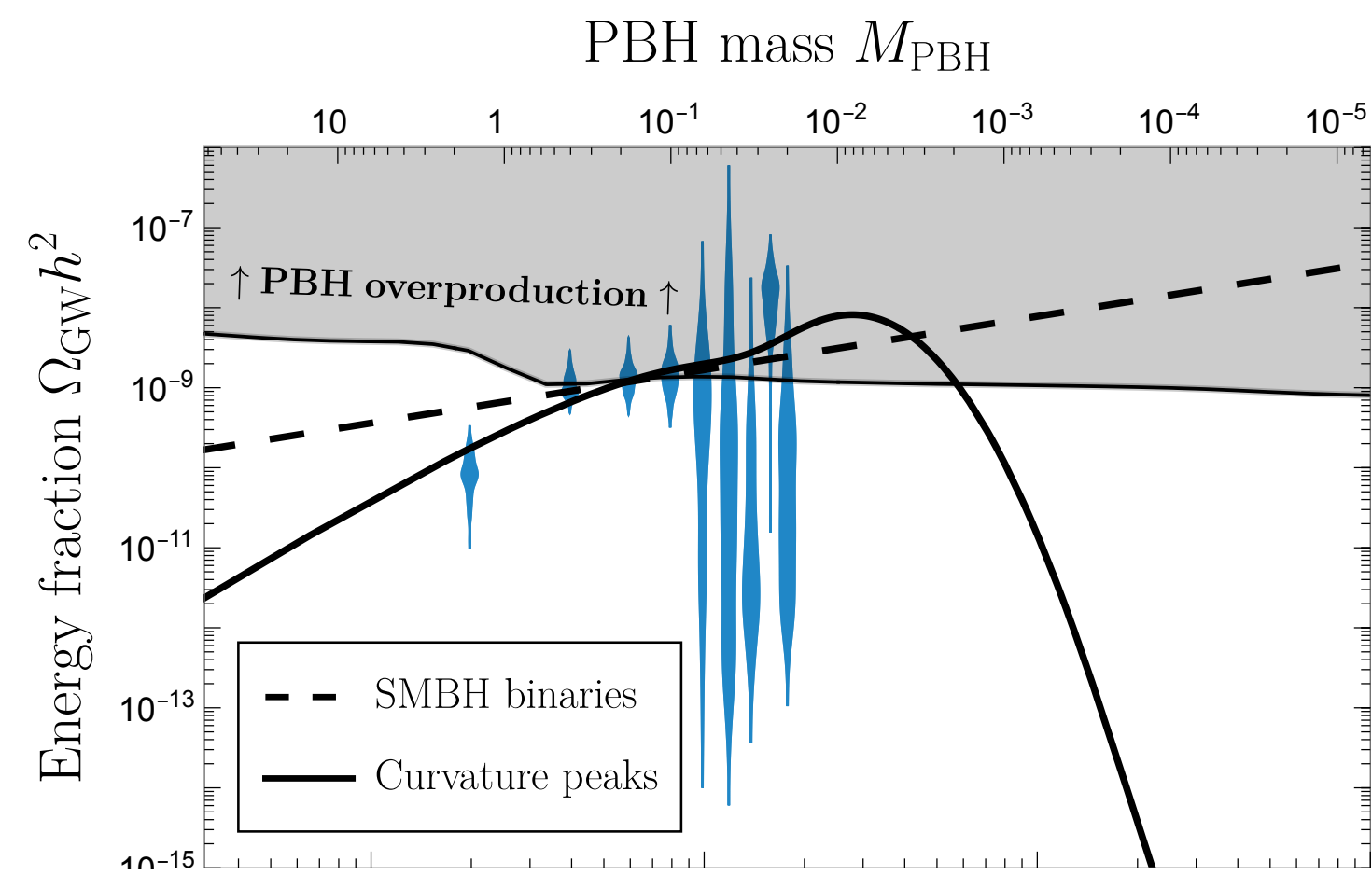
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Curvature peaks

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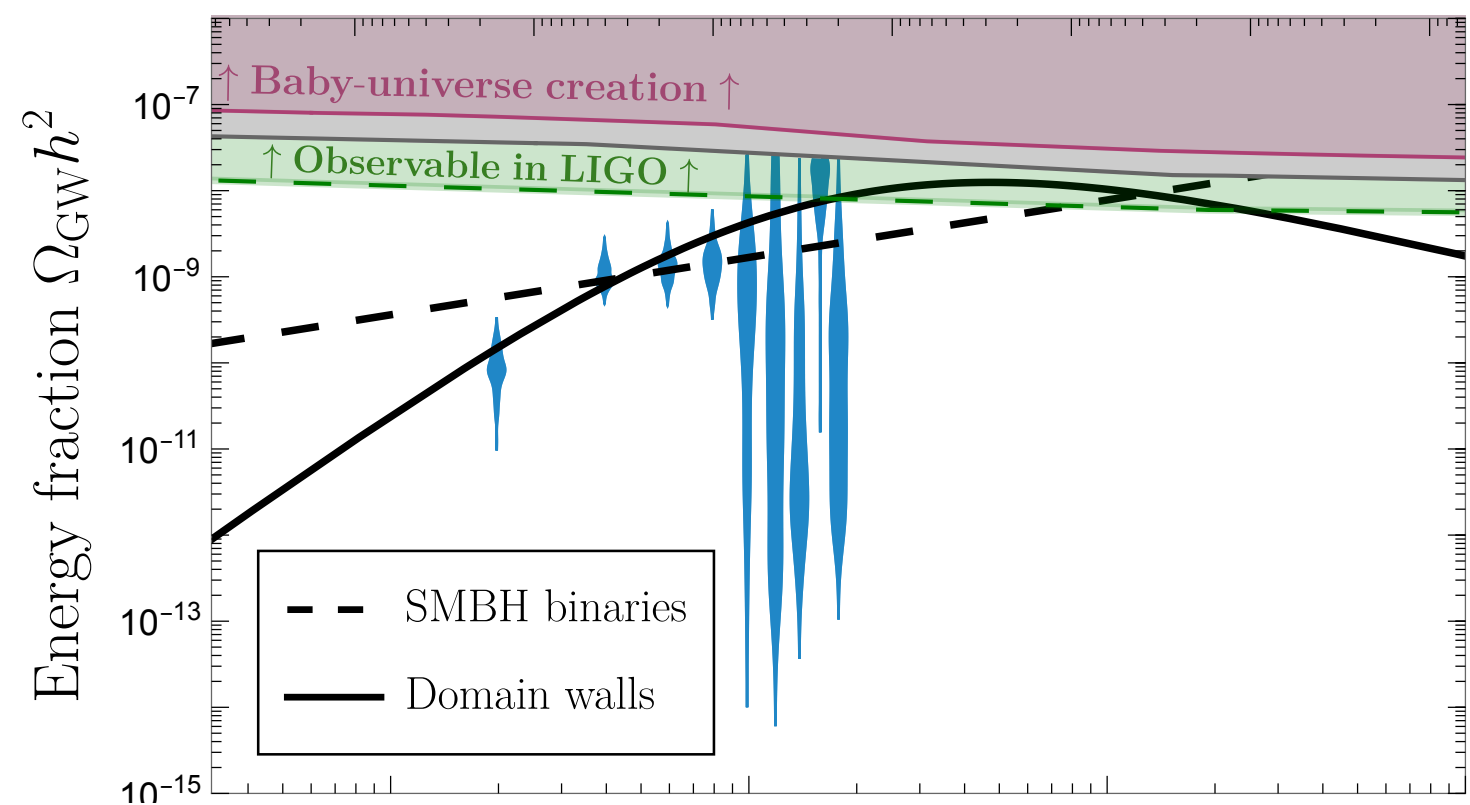
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Domain wall networks

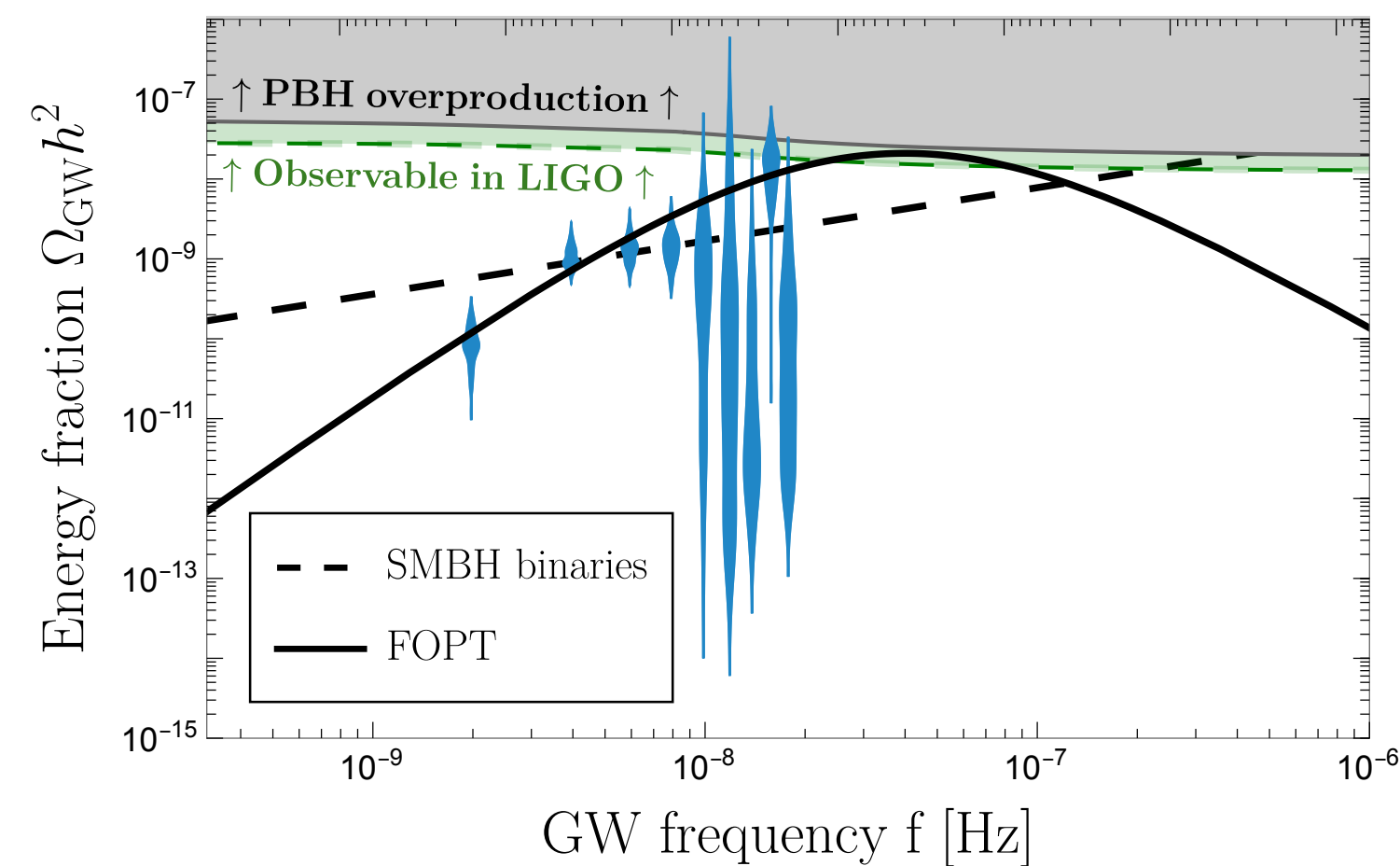
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...

Produce sub-solar-mass PBH

YG, Vitagliano 2306.17841



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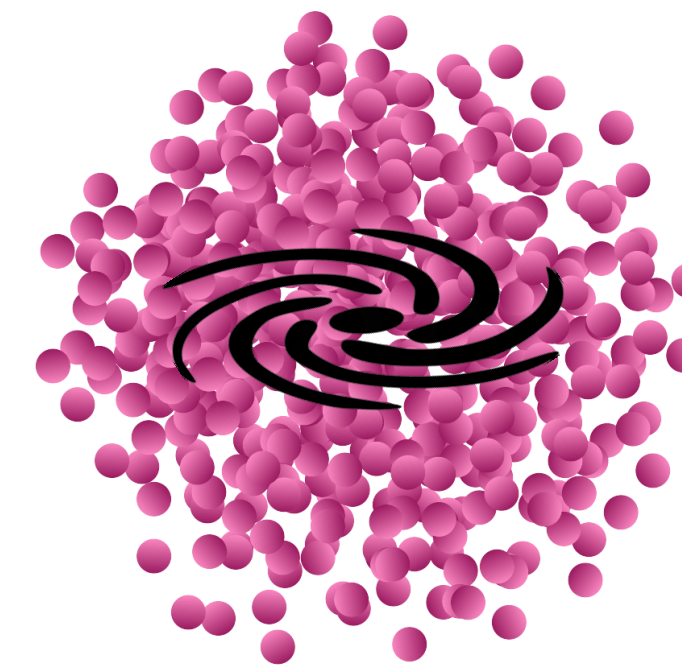
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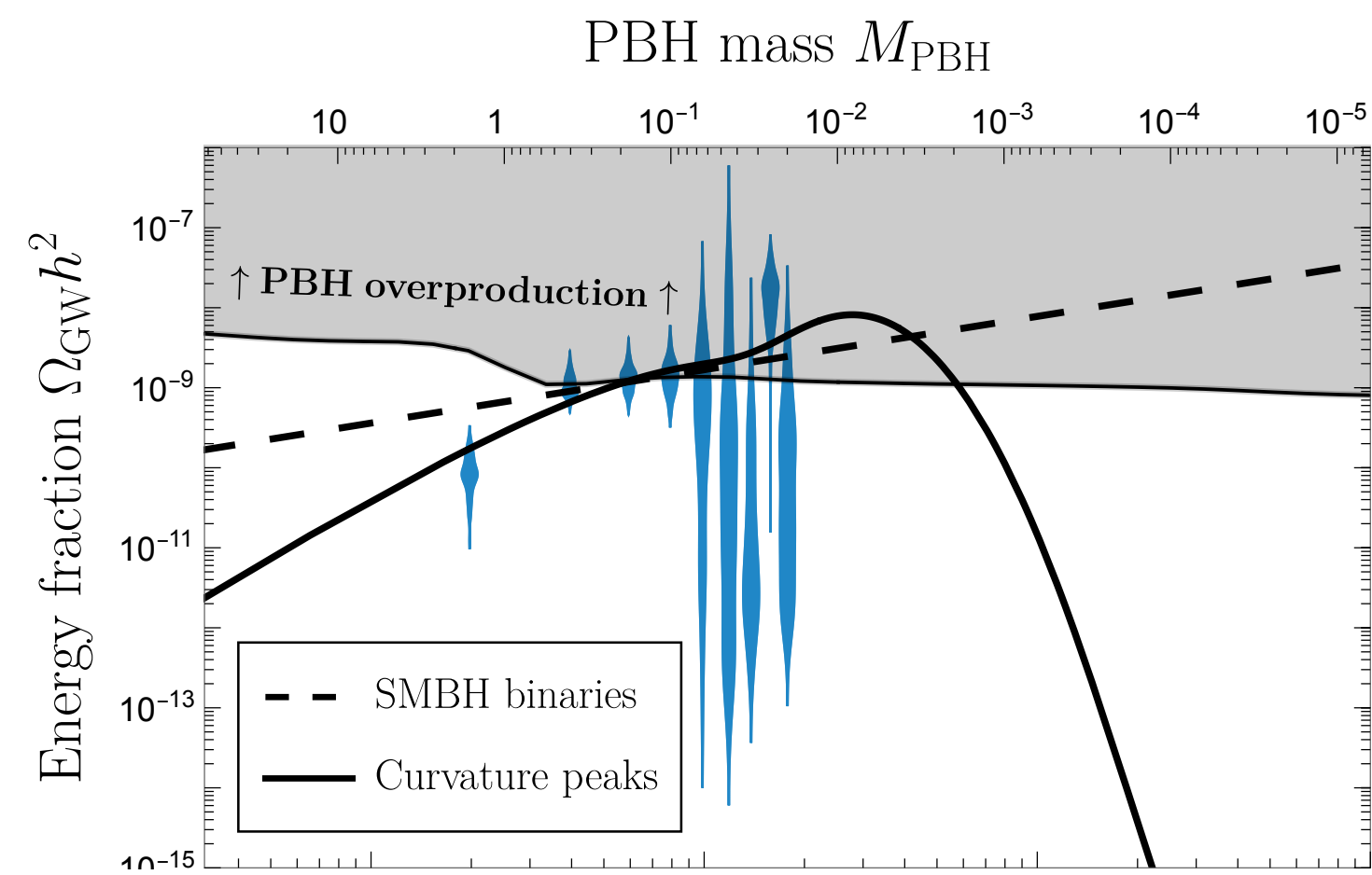
...



DM Ultra Compact Mini Halos

$$R_{\text{UCMH}} \sim 200 \text{ AU} \left(\frac{1000}{z_{\text{collapse}}} \right)$$

$$M_{\text{UCMH}} \sim 10^{-7} M_{\odot}$$



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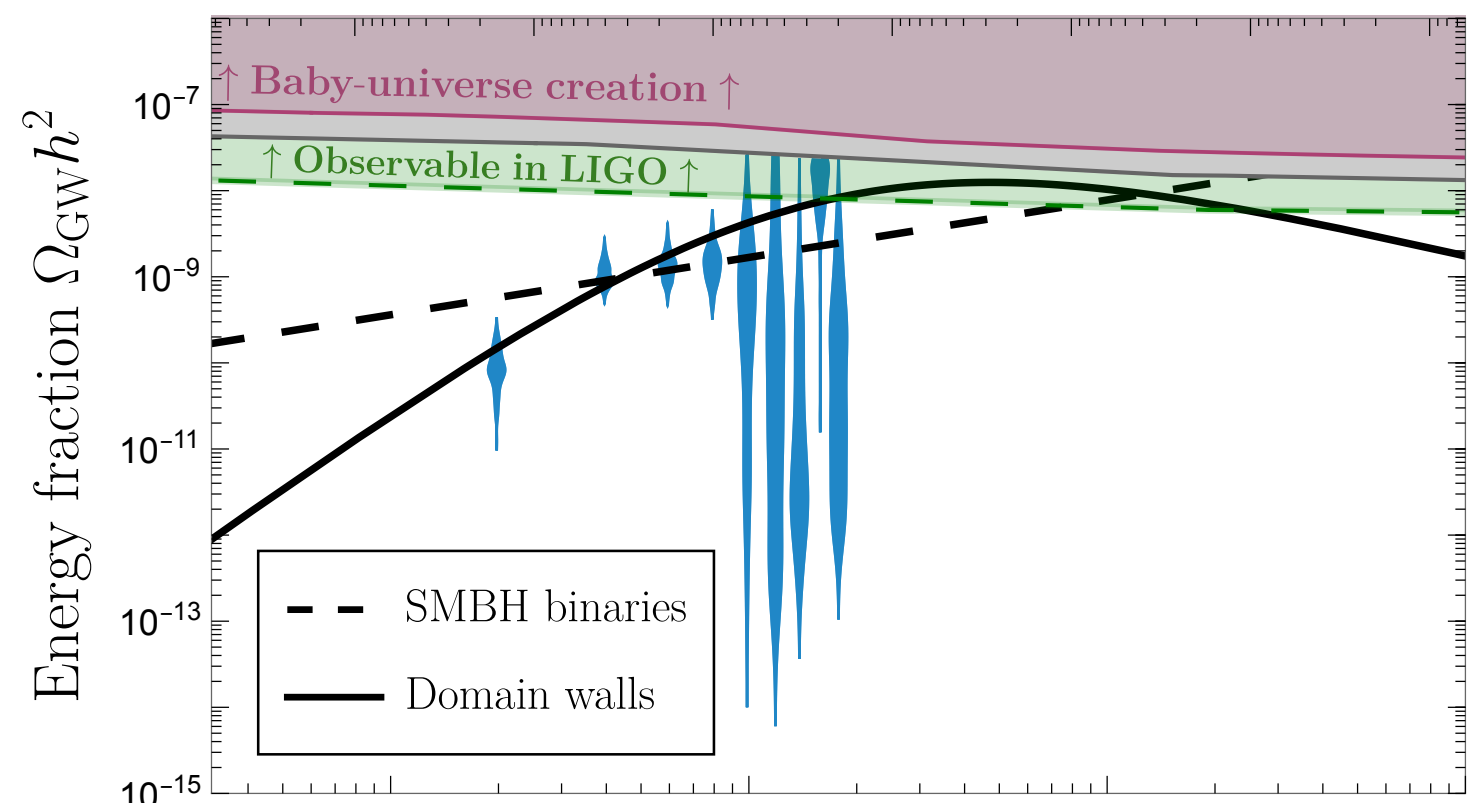
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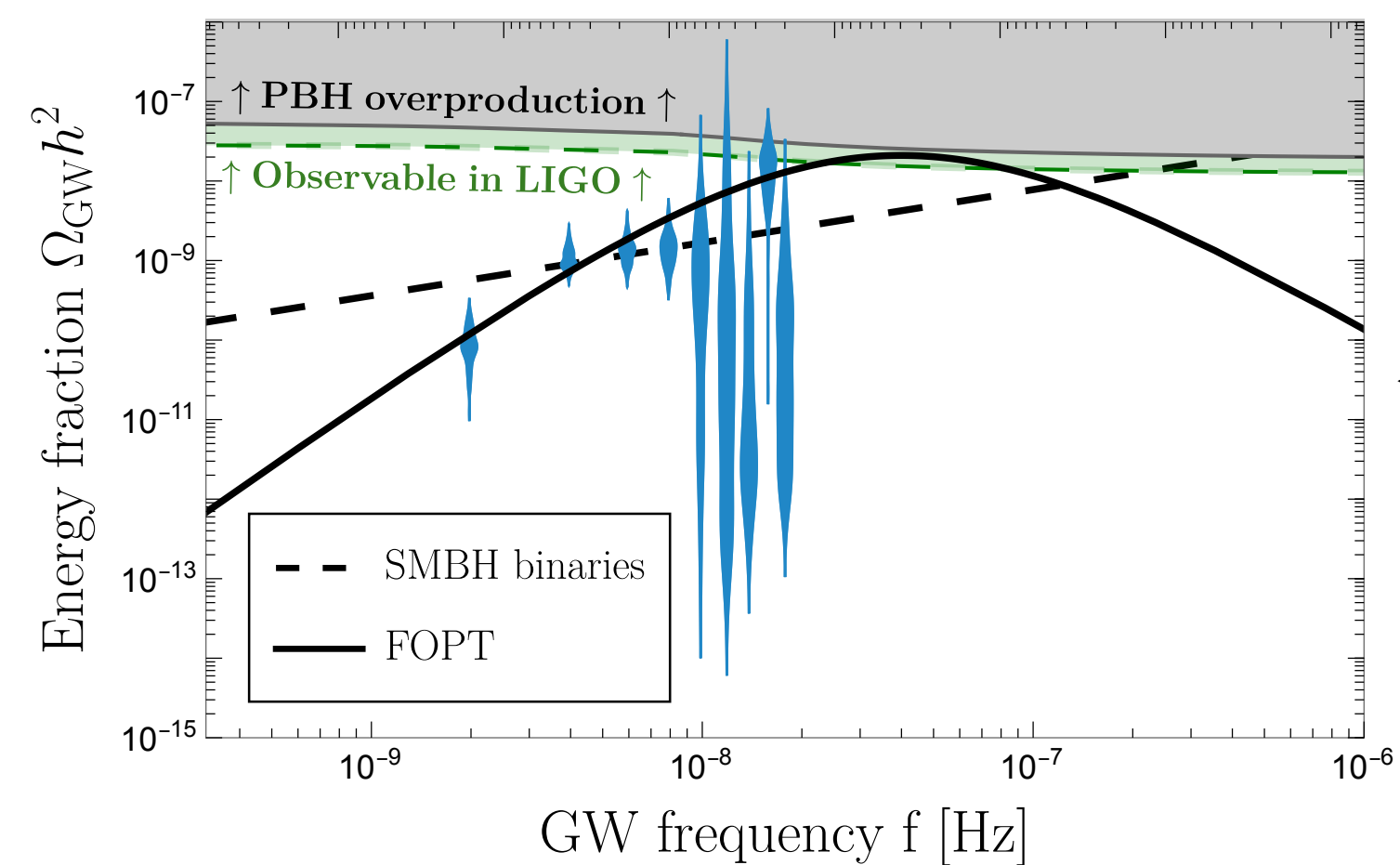
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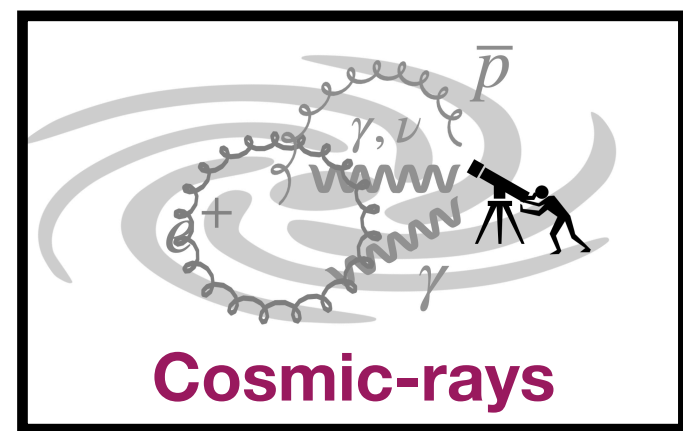
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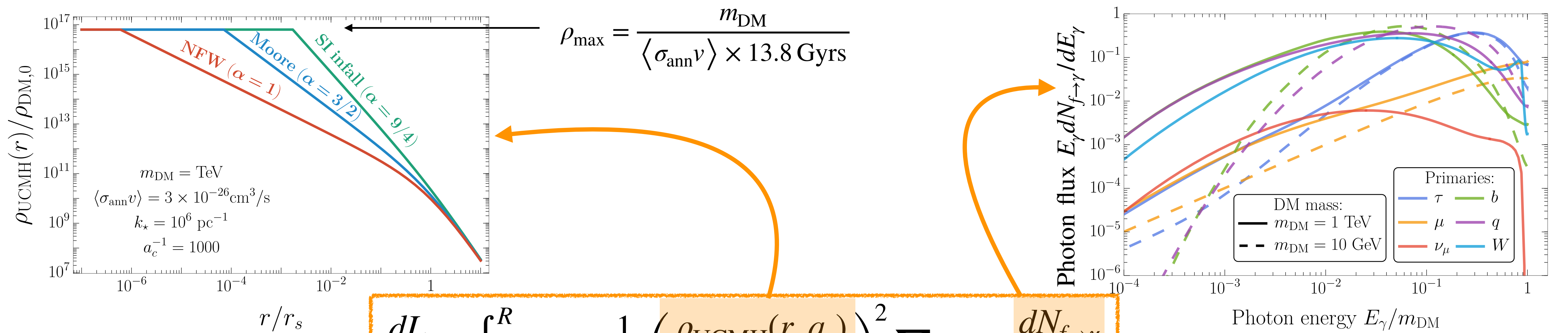
...



if DM=WIMPs

YG 2503.03857





$$\frac{dL}{dE} = \int_0^R 4\pi r^2 dr \frac{1}{2} \left(\frac{\rho_{\text{UCMH}}(r, a_c)}{m_{\text{DM}}} \right)^2 \sum_f \langle\sigma_f v\rangle \frac{dN_{f \rightarrow \gamma}}{dE}$$

YG 2503.03857

$$\frac{d^2 \mathcal{F}_\gamma(\theta)}{d\Omega dE} = \int_0^\infty \frac{ds}{4\pi} \frac{\rho_{\text{DM}}(s, \theta)}{\bar{\rho}_{\text{DM},0}} \times \int_0^\infty da_c \int_0^\infty \frac{dR}{R} \frac{dn}{da_c} \times \frac{dL[(1+z_e)E, a_c, R]}{dE}$$

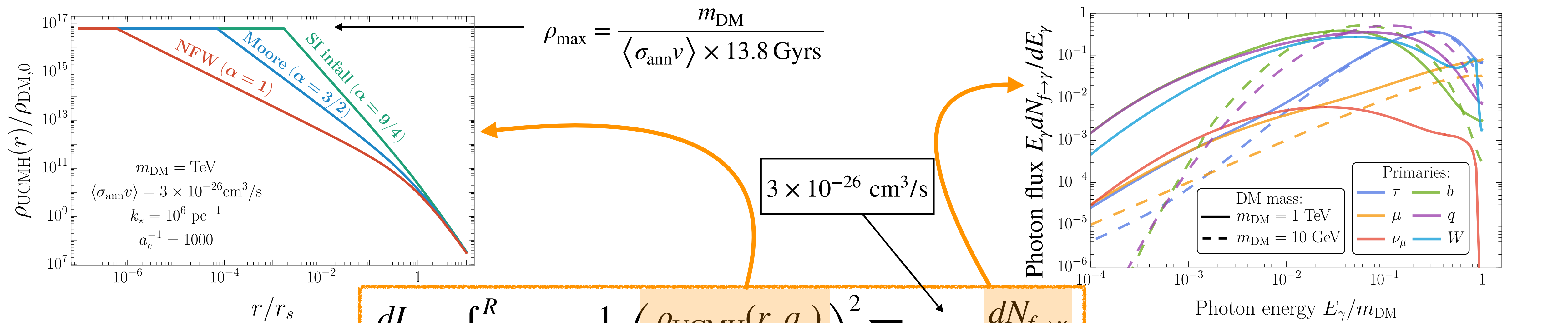
Press – Schechter theory

$$\rho_{\text{DM}}(s, \theta) = \rho_{\text{MW}} \left[\sqrt{s^2 + r_\odot^2 - 2r_\odot s \cos \theta} \right] + \frac{e^{-\tau(E, z_e)}}{(1+z_e)^3} \bar{\rho}_{\text{DM},0}$$

$$\frac{dn(R, a_c)}{da_c} \simeq R^{-3} \sqrt{\frac{2}{\pi}} \frac{\nu_c}{a_c} \exp\left(-\frac{\nu_c^2}{2}\right) \quad \nu_c \equiv \frac{\delta_{\text{min}}(a_c)}{\sigma_0(R)} \quad \delta_{\text{min}} \simeq 10^{-4} \frac{a_c^{-1}}{100}$$

$$\sigma_0^2(R) = \frac{16}{81} \int_0^\infty \frac{dk}{k} \tilde{W}(k, R)^2 (kR)^4 T(k, R)^2 \mathcal{P}_{\mathcal{R}}(k, t_H)$$

$$T(k, R) \rightarrow T(k, R) \times \exp\left[-\frac{1}{2} \left(\frac{k}{k_D}\right)^2\right] \quad k_D \simeq \frac{1.7 \times 10^8}{\text{Mpc}} \left(\frac{m_{\text{DM}}}{1 \text{ TeV}}\right)^{1/2} \left(\frac{T_{\text{KD}}}{30 \text{ MeV}}\right)^{1/2}$$



$$\frac{d^2 \mathcal{F}_{\gamma}(\theta)}{d\Omega dE}$$

$$=$$

$$\int_0^{\infty} \frac{ds}{4\pi} \frac{\rho_{\text{DM}}(s, \theta)}{\bar{\rho}_{\text{DM},0}}$$

$$\times$$

$$\int_0^{\infty} da_c \int_0^{\infty} \frac{dR}{R} \frac{dn}{da_c}$$

$$\times$$

$$\frac{dL[(1+z_e)E, a_c, R]}{dE}$$

Press – Schechter theory

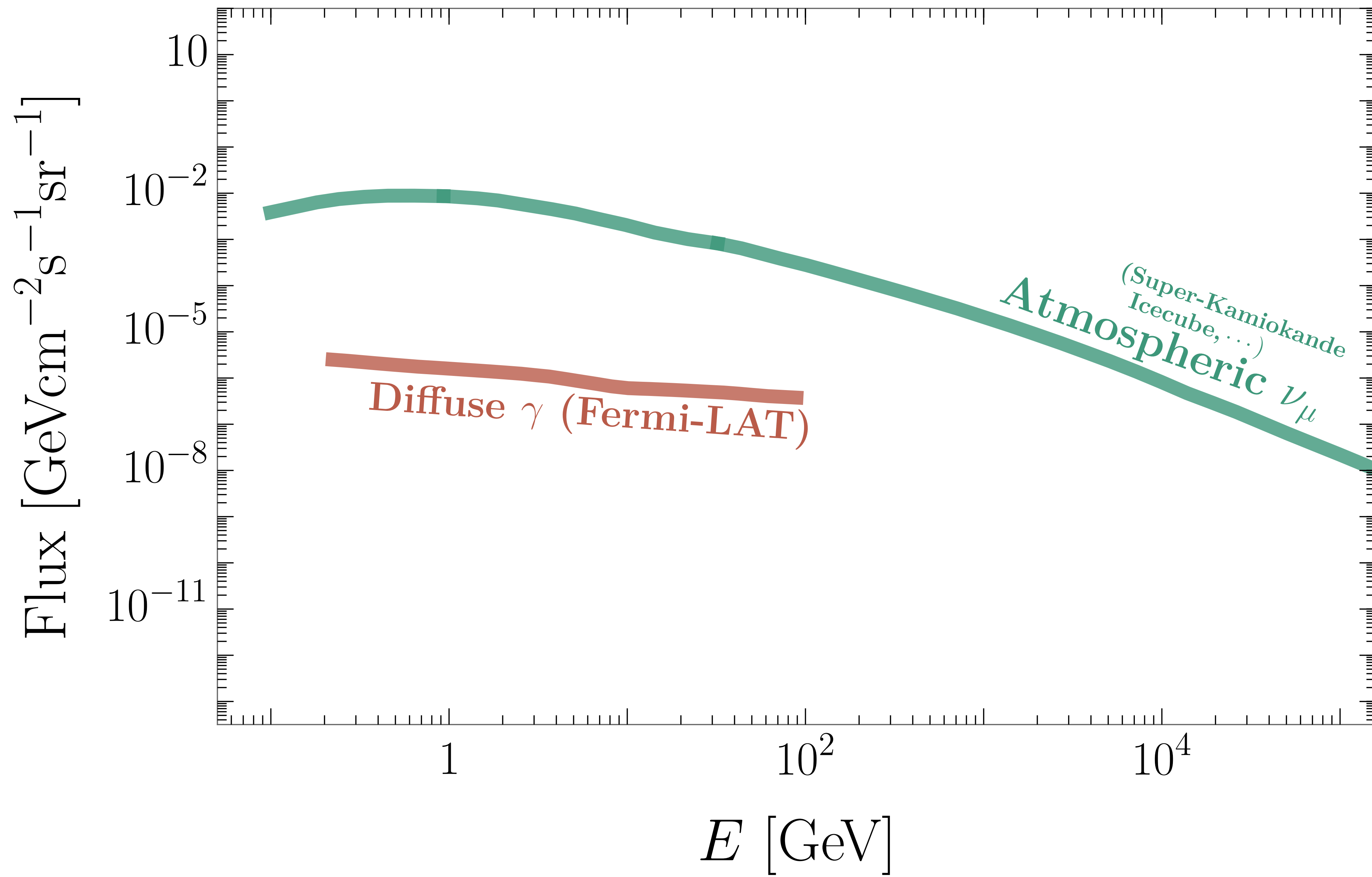
$$\frac{dn(R, a_c)}{da_c} \simeq R^{-3} \sqrt{\frac{2}{\pi}} \frac{\nu_c}{a_c} \exp\left(-\frac{\nu_c^2}{2}\right) \quad \nu_c \equiv \frac{\delta_{\min}(a_c)}{\sigma_0(R)} \quad \delta_{\min} \simeq 10^{-4} \frac{a_c^{-1}}{100}$$

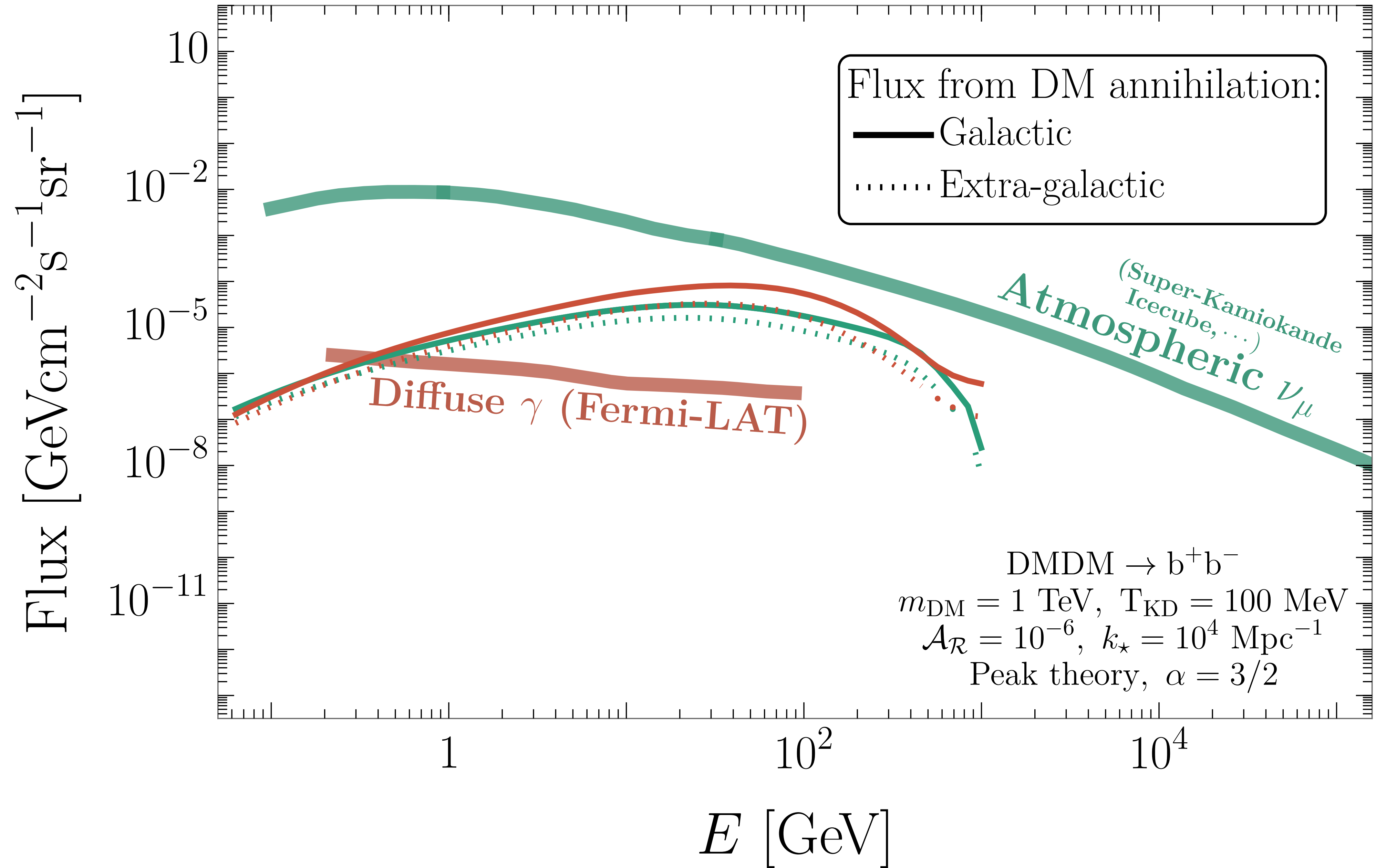
$$\sigma_0^2(R) = \frac{16}{81} \int_0^{\infty} \frac{dk}{k} \tilde{W}(k, R)^2 (kR)^4 T(k, R)^2 \mathcal{P}_{\mathcal{R}}(k, t_H)$$

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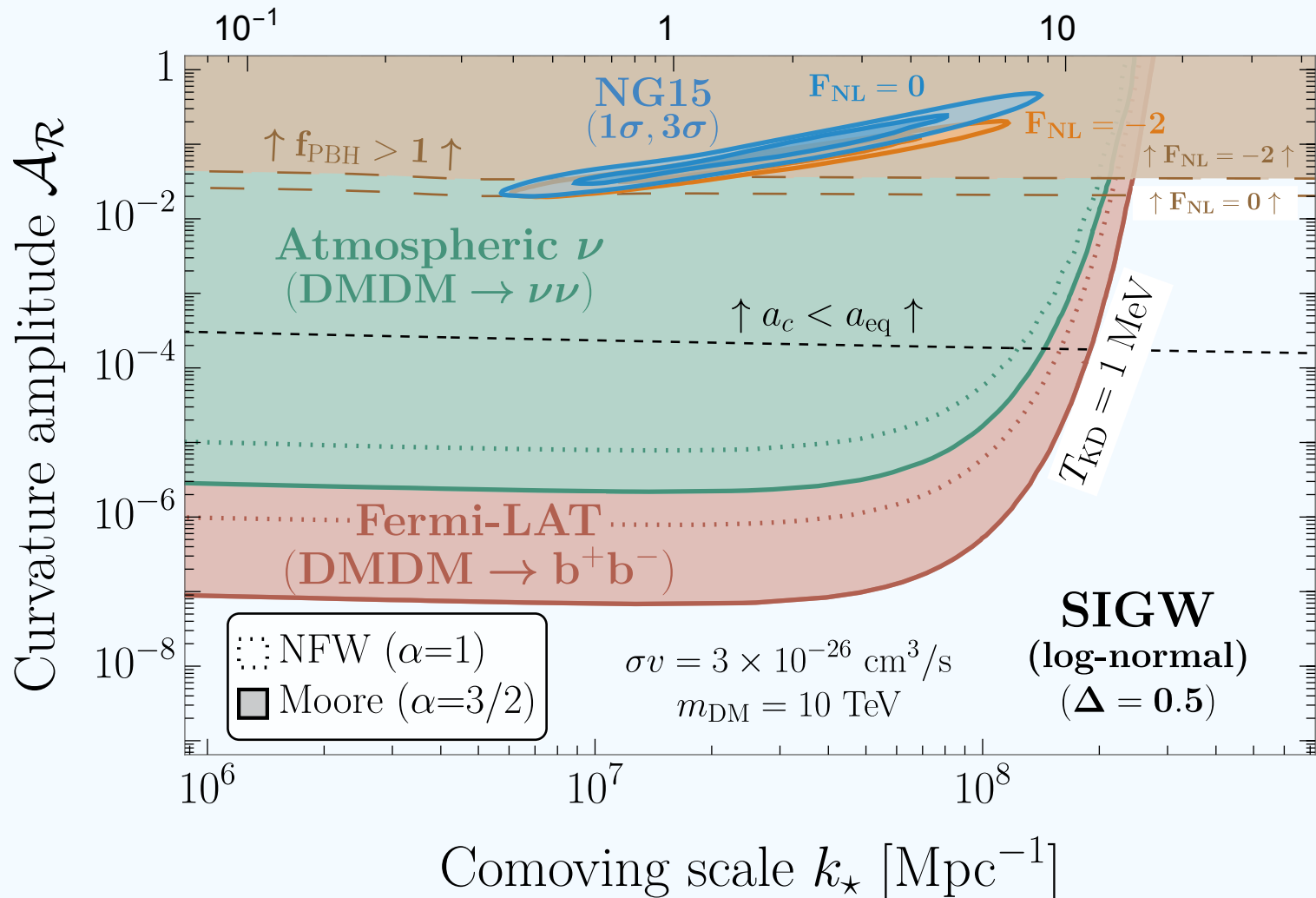


“New Physics Explanations of PTA
signal are incompatible with WIMPs
Dark Matter”

Gaussian curvature peaks

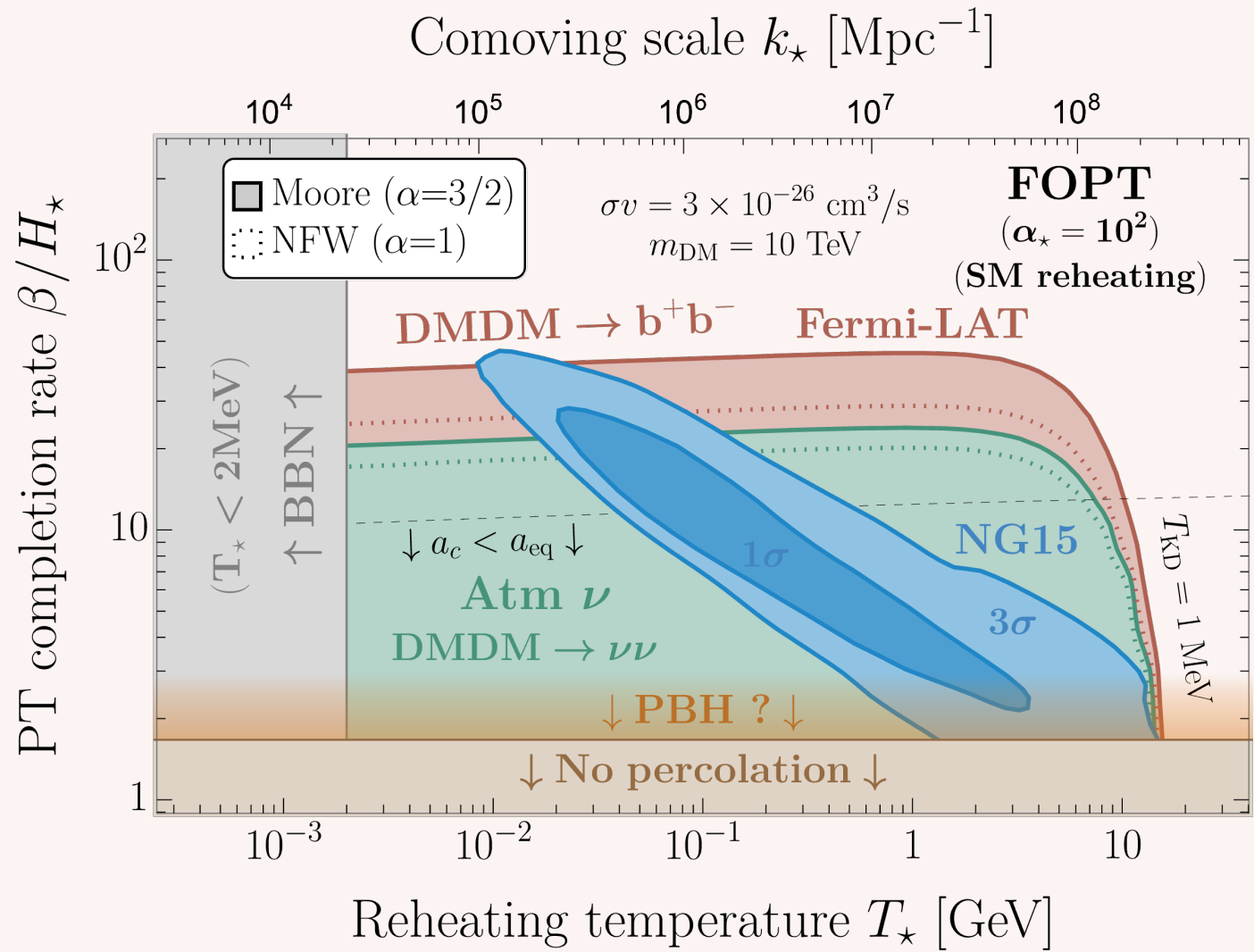
$$\mathcal{P}_{\mathcal{R}}(k) = \frac{\mathcal{A}_{\mathcal{R}}}{\sqrt{2\pi}\Delta} \exp\left[-\frac{\log^2(k/k_{\star})}{2\Delta^2}\right]$$

Horizon crossing temperature $T_{\star}$ [GeV]



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

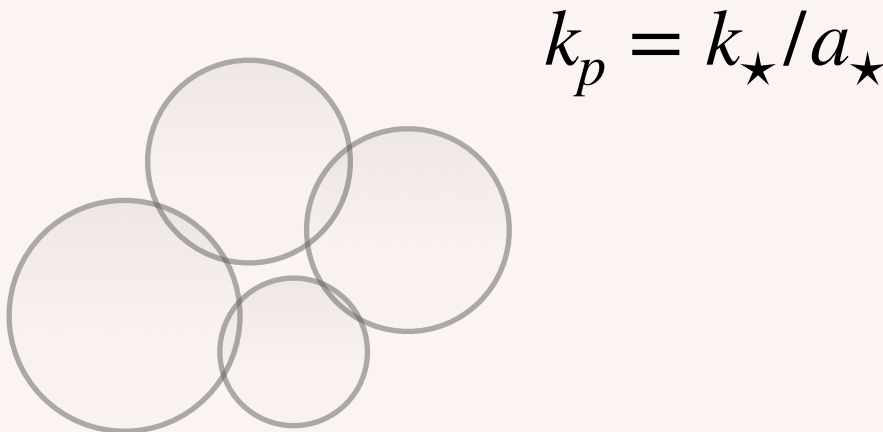
First-order Phase Transition



Franciolini, YG, Jinno
2503.01962

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

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

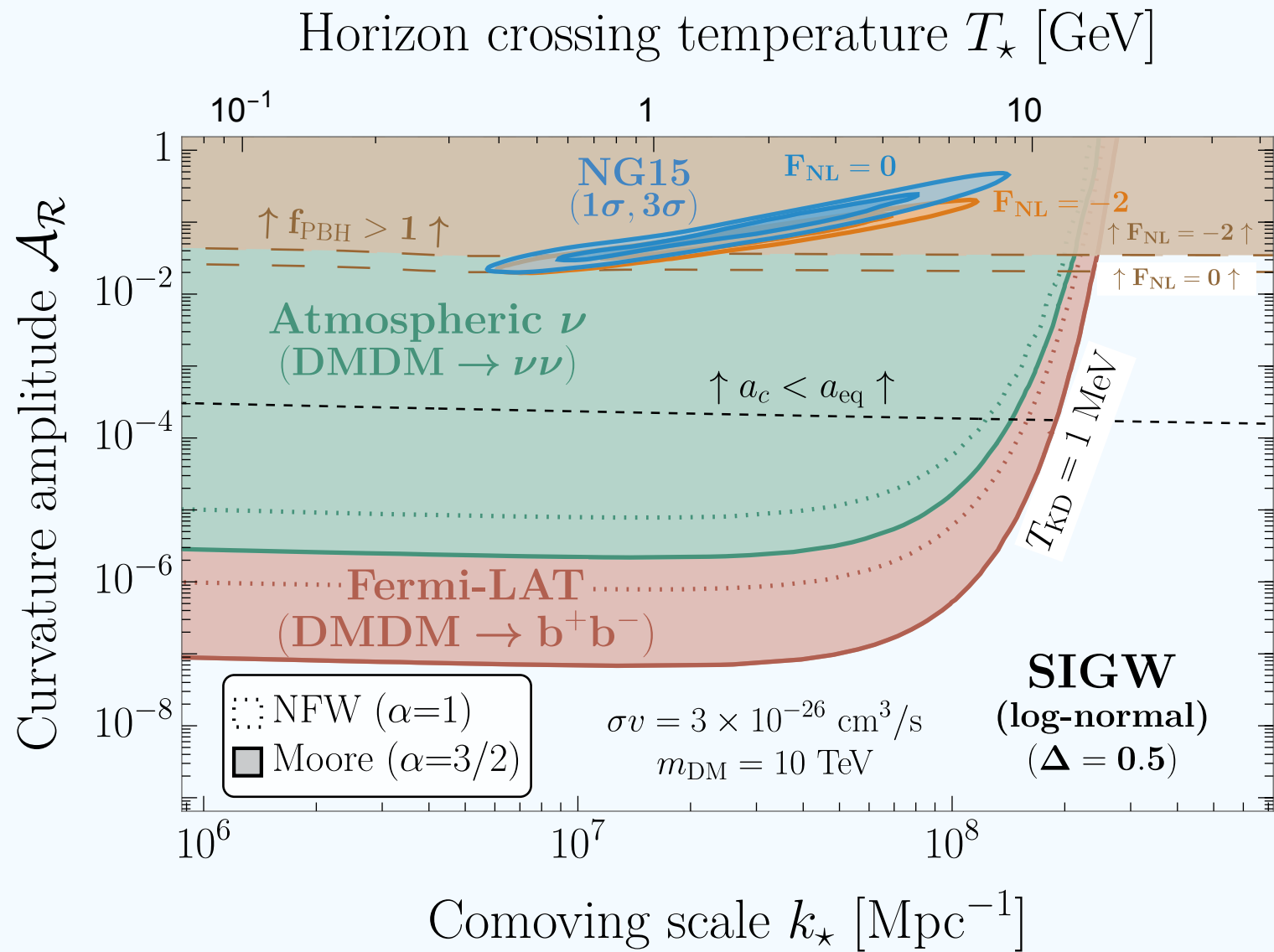


YG 2503.03857

“New Physics Explanations of PTA
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Dark Matter”

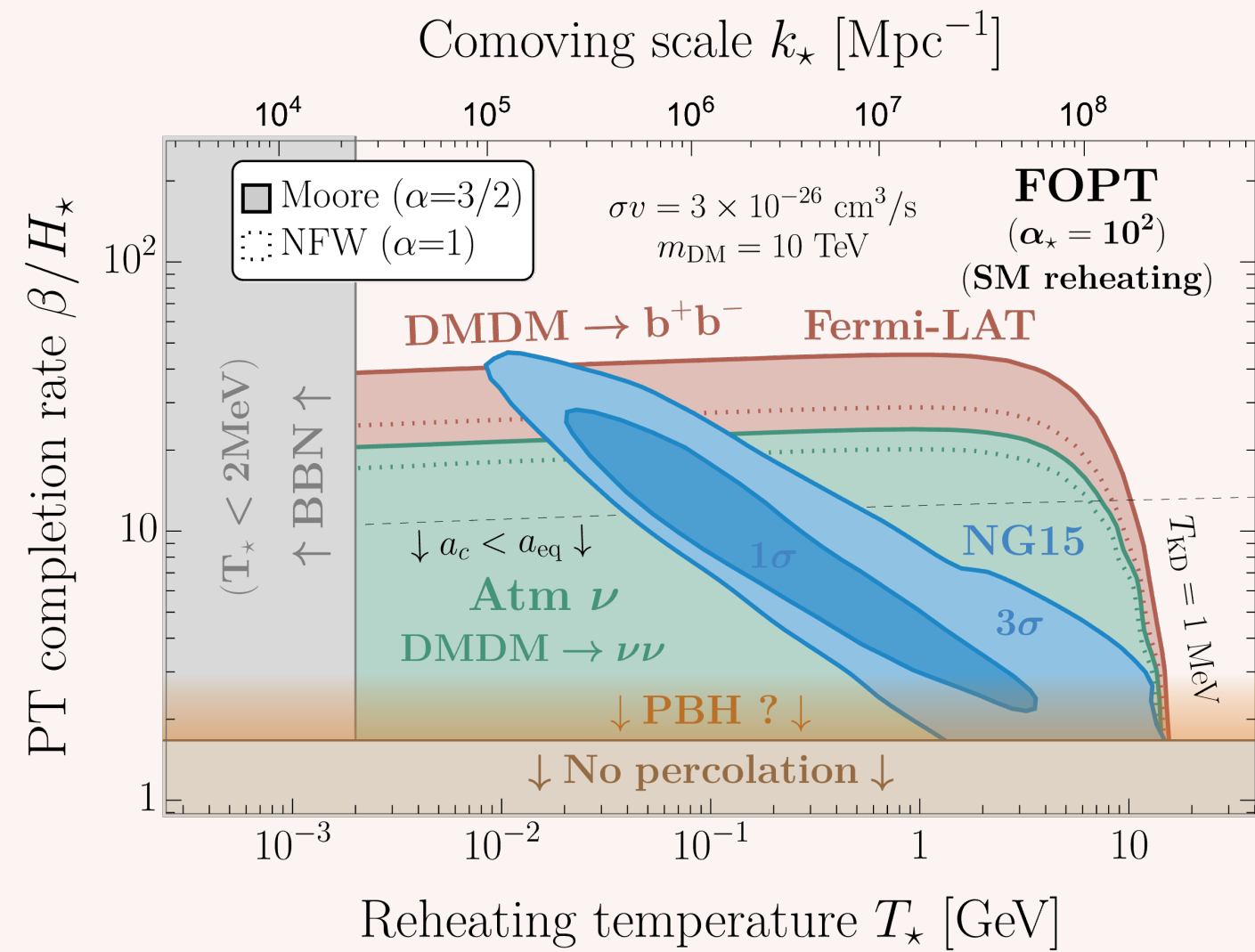
Gaussian curvature peaks

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



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

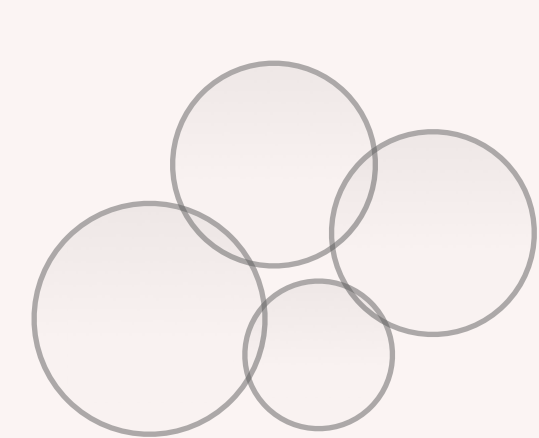
First-order Phase Transition



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

Franciolini, YG, Jinno
2503.01962

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



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

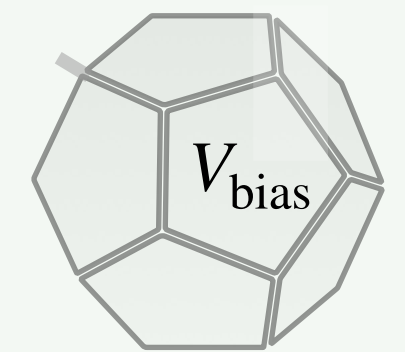
YG 2503.03857

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

Domain Wall Networks

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{\alpha_V^2}{2\pi} \frac{(k_p L_{\text{ann}})^3}{\left[4 + (k_p L_{\text{ann}})^2 \right]^2}$$

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



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

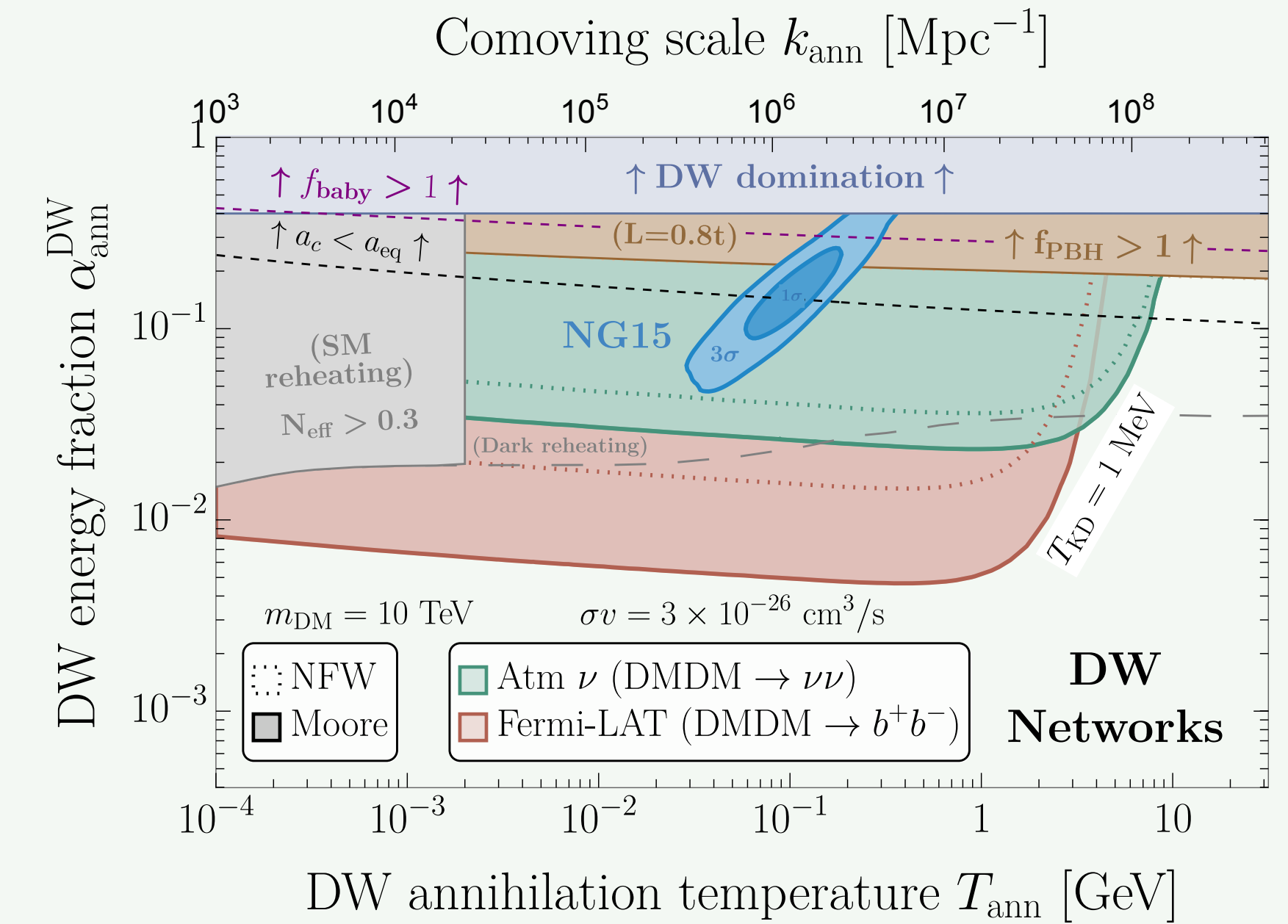
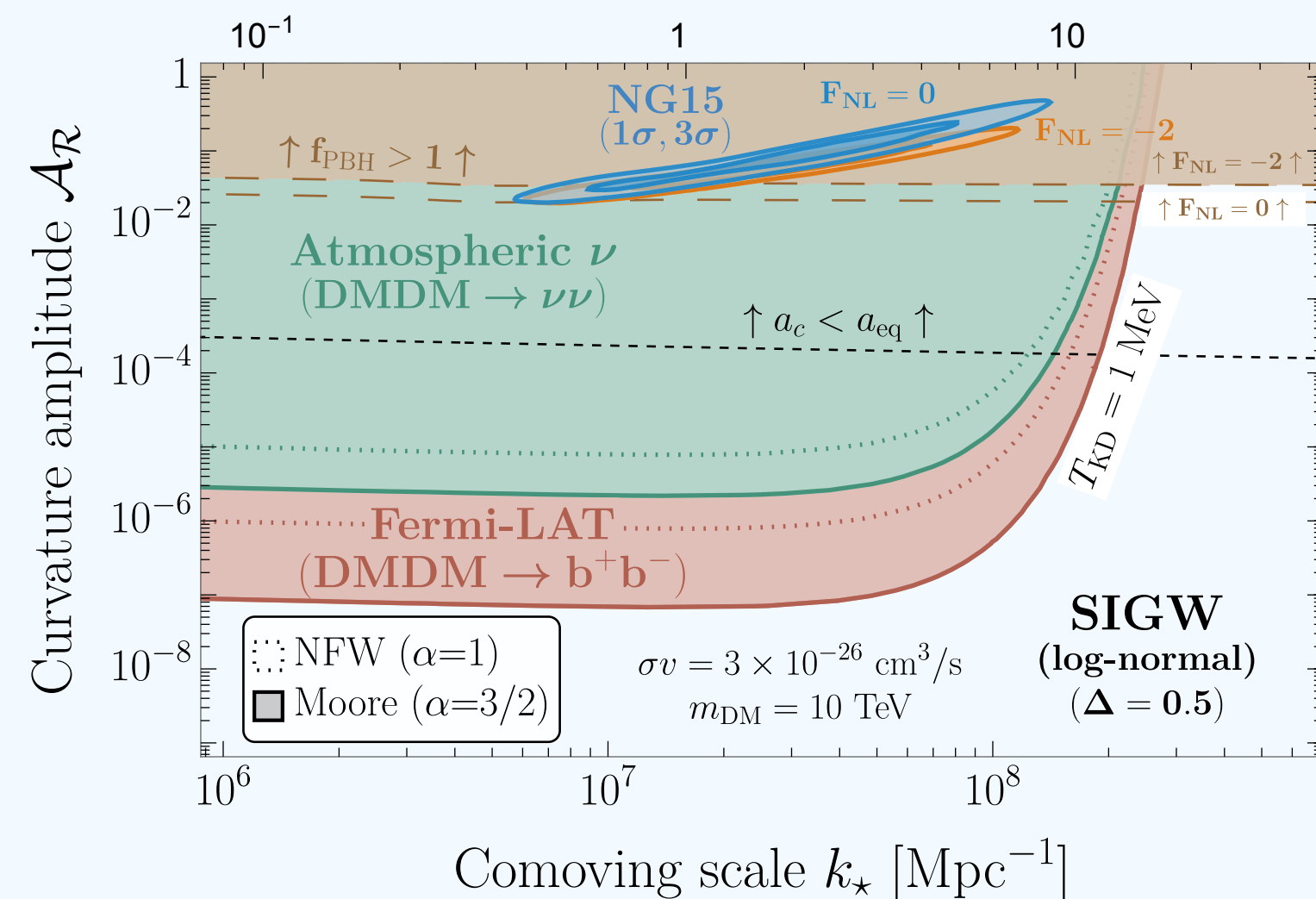
Gaussian curvature peaks

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

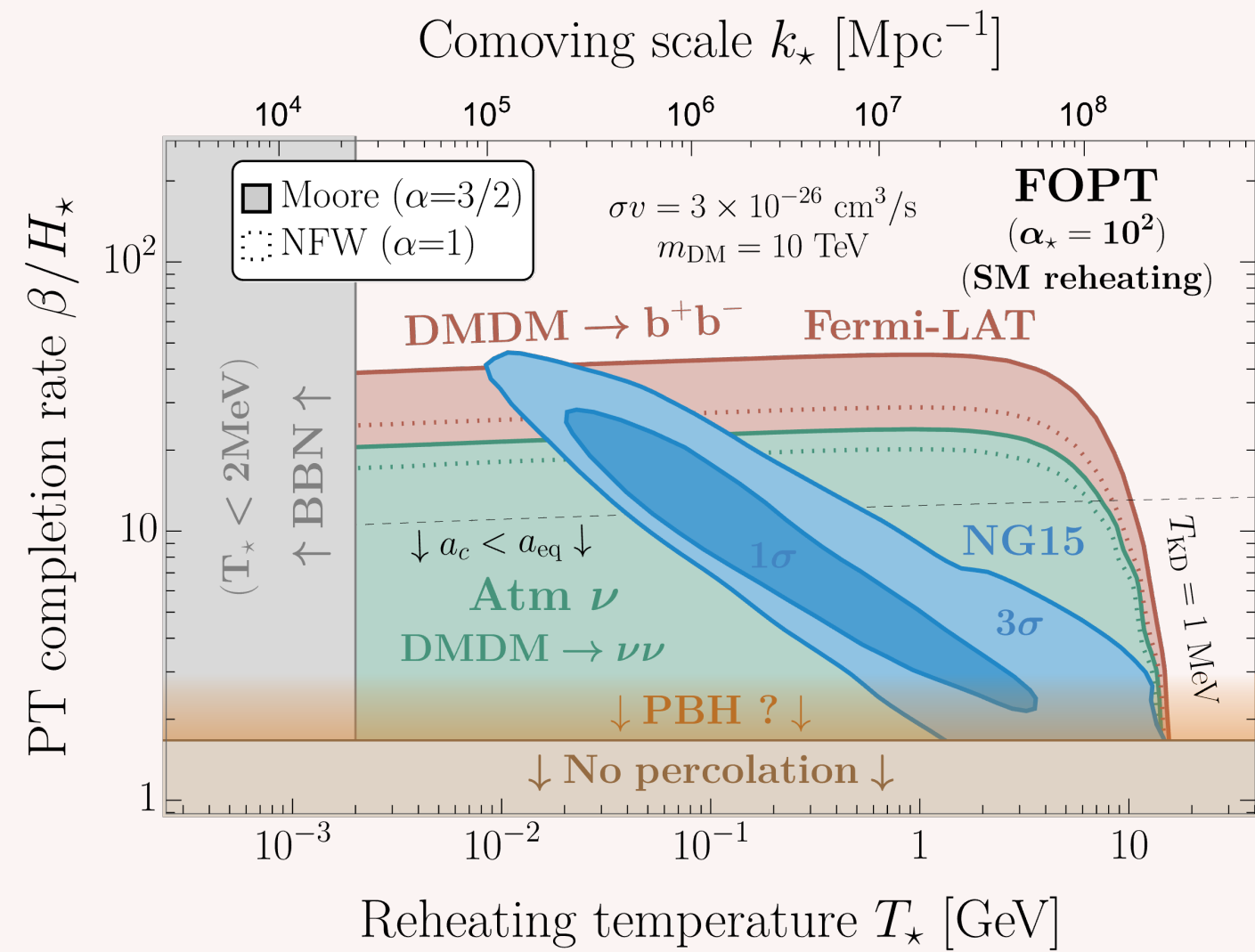
Horizon crossing temperature $T_\star$ [GeV]



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



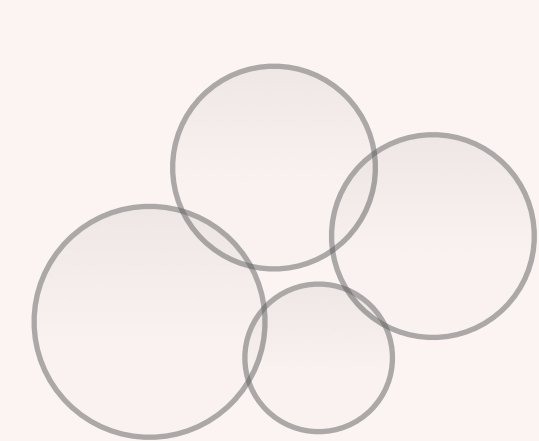
First-order Phase Transition



Franciolini, YG, Jinno
2503.01962

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

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



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

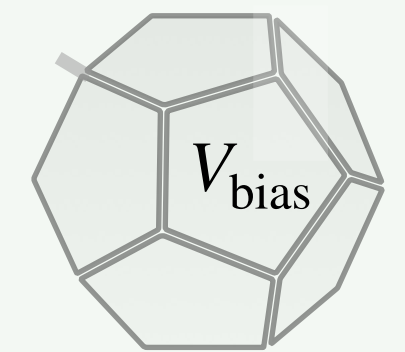
YG 2503.03857

“New Physics Explanations of PTA
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Dark Matter”

Domain Wall Networks

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

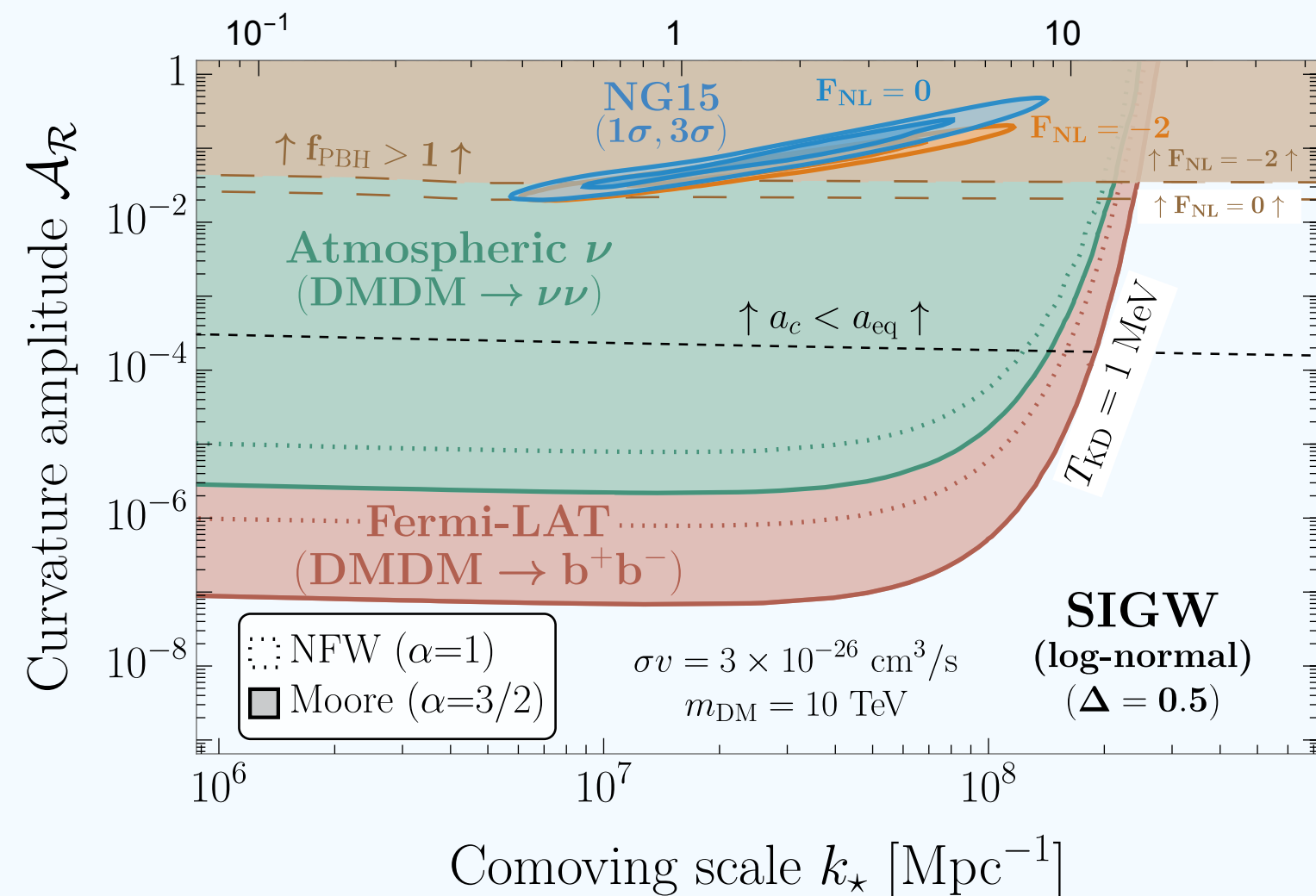


$$L_{\text{ann}} \sim t_{\text{ann}}$$

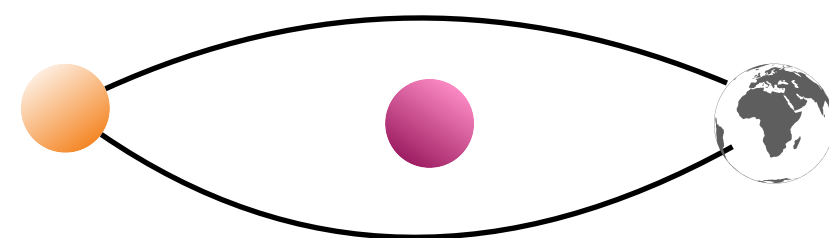
Gaussian curvature peaks

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

Horizon crossing temperature $T_\star$ [GeV]

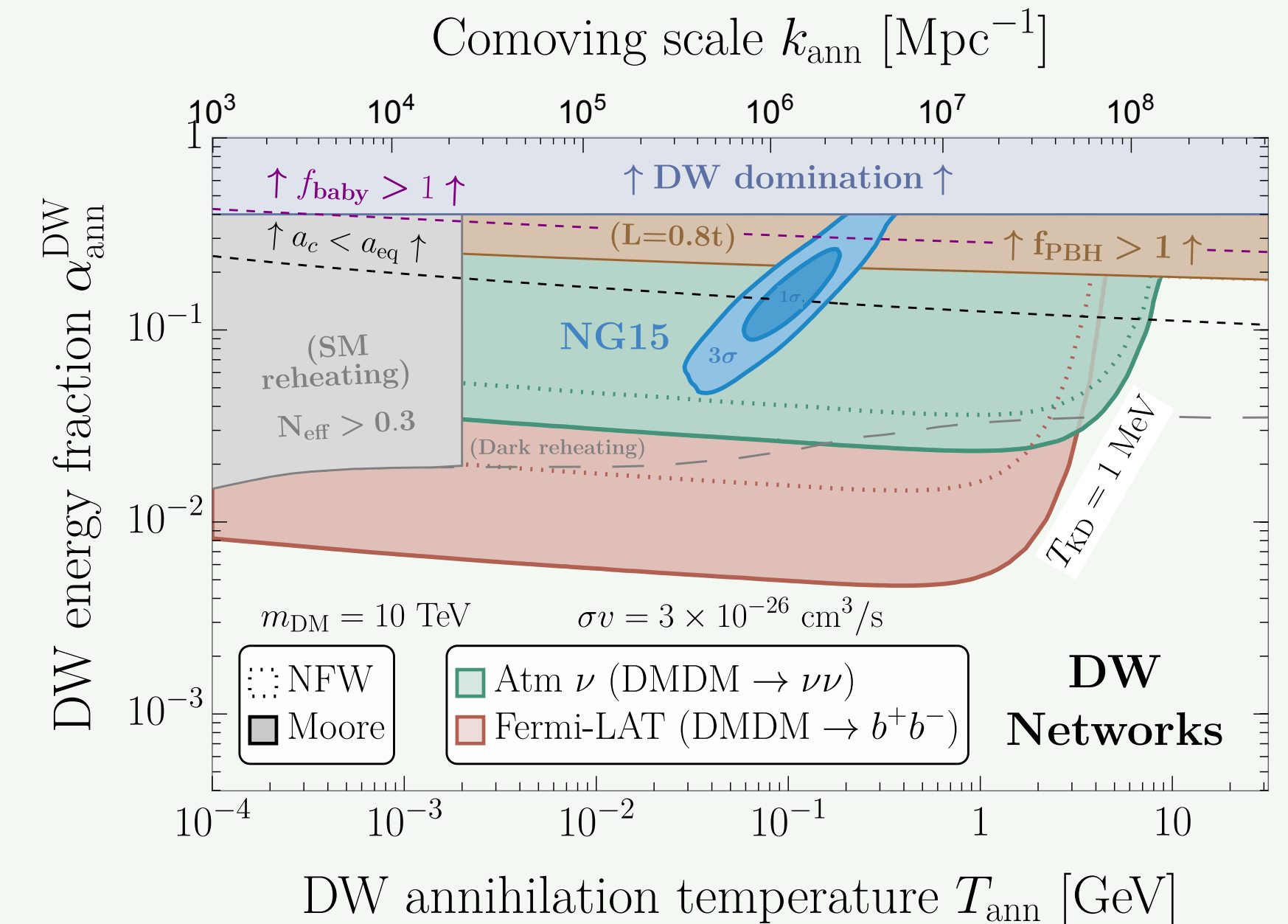


**Next step: Get rid of WIMPs
assumption with
Gravitational Lensing**

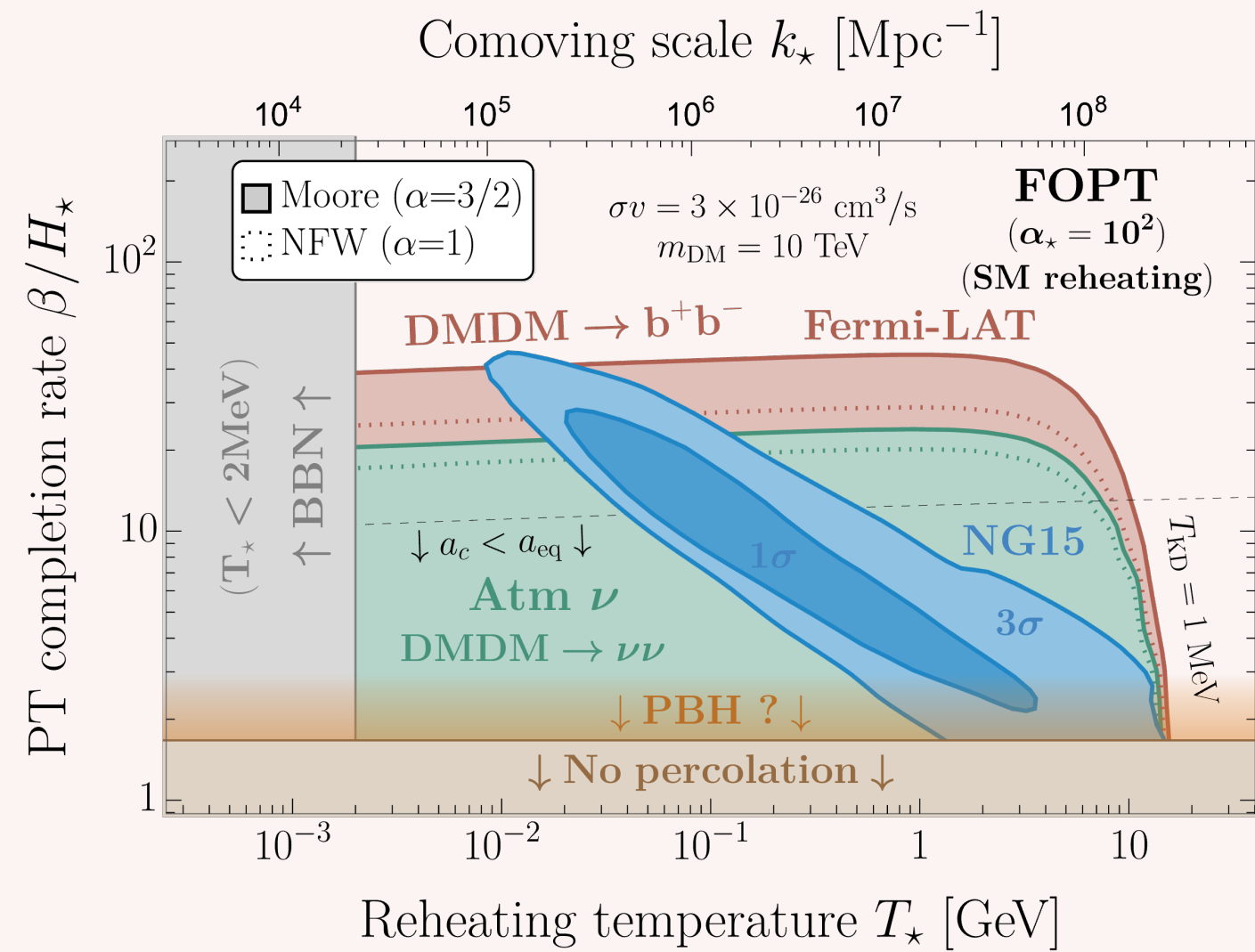


**HSC microlensing
(in preparation)
Lensed Quasars
(in preparation)**

(with Sten Delos)



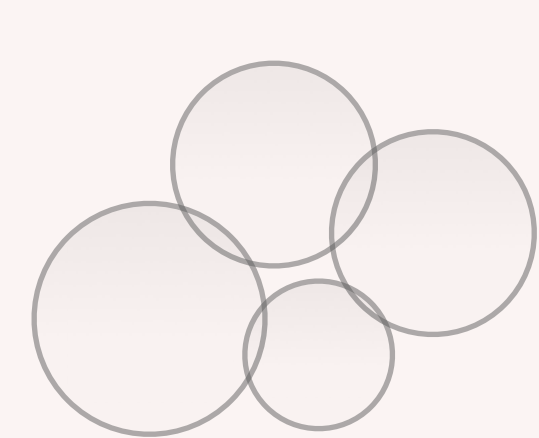
First-order Phase Transition



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

Franciolini, YG, Jinno
2503.01962

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



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

YG 2503.03857

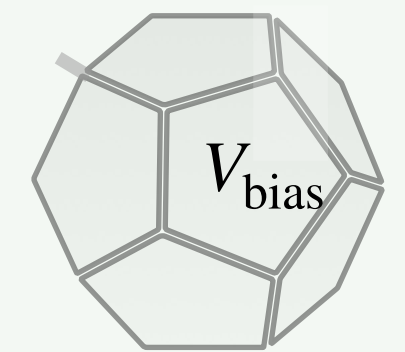
“New Physics Explanations of PTA
signal are incompatible with WIMPs
Dark Matter”

Thank you

Domain Wall Networks

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{\alpha_V^2}{2\pi} \frac{(k_p L_{\text{ann}})^3}{\left[4 + (k_p L_{\text{ann}})^2 \right]^2}$$

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

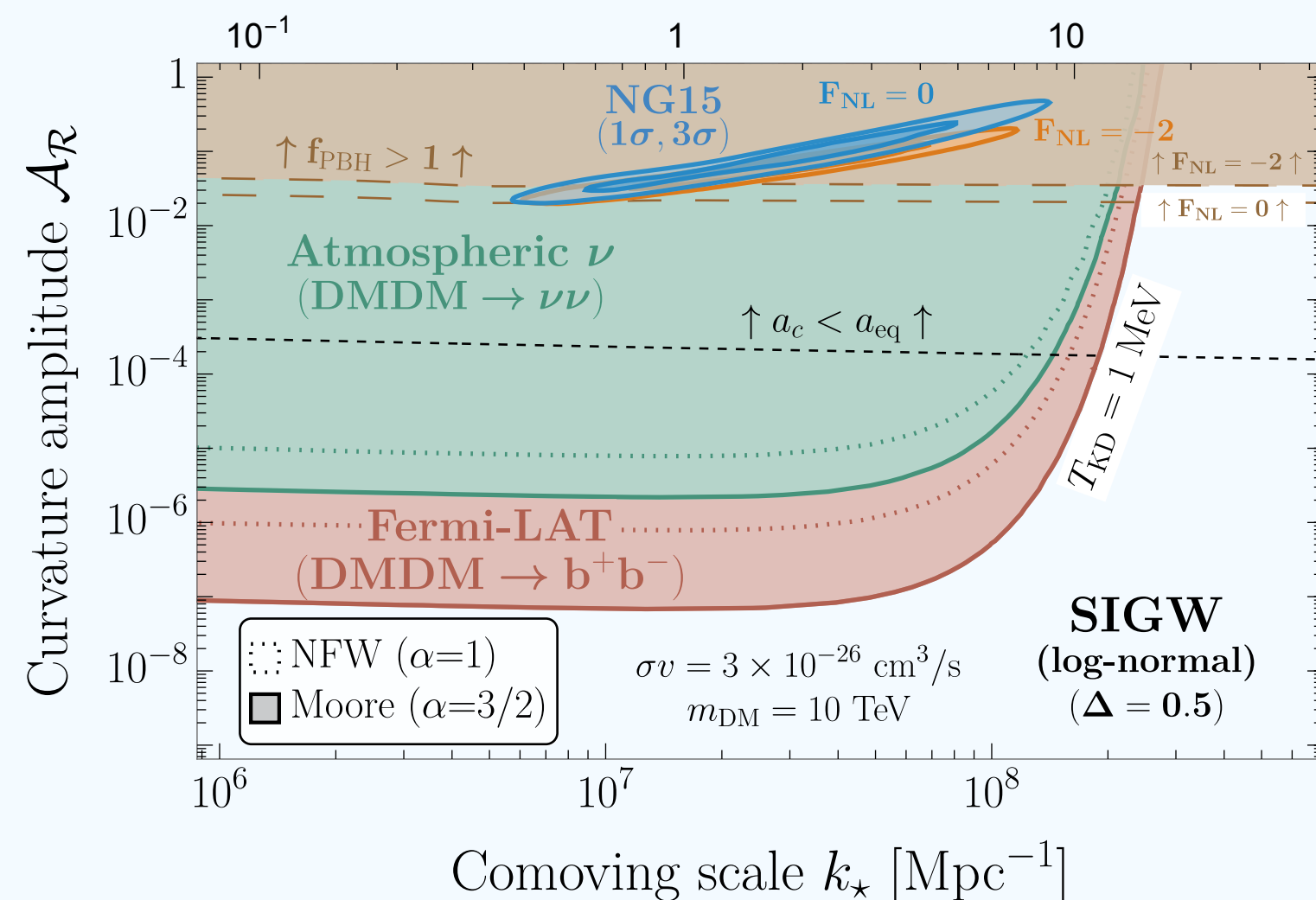


$$L_{\text{ann}} \sim t_{\text{ann}}$$

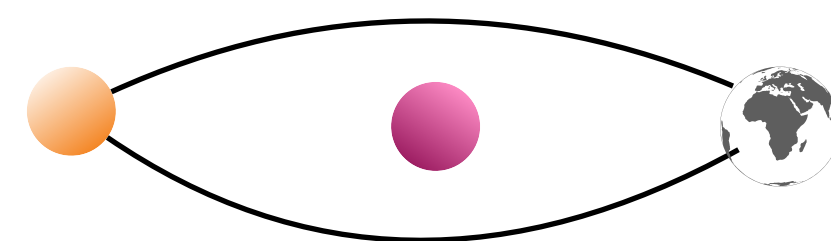
Gaussian curvature peaks

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

Horizon crossing temperature $T_\star$ [GeV]

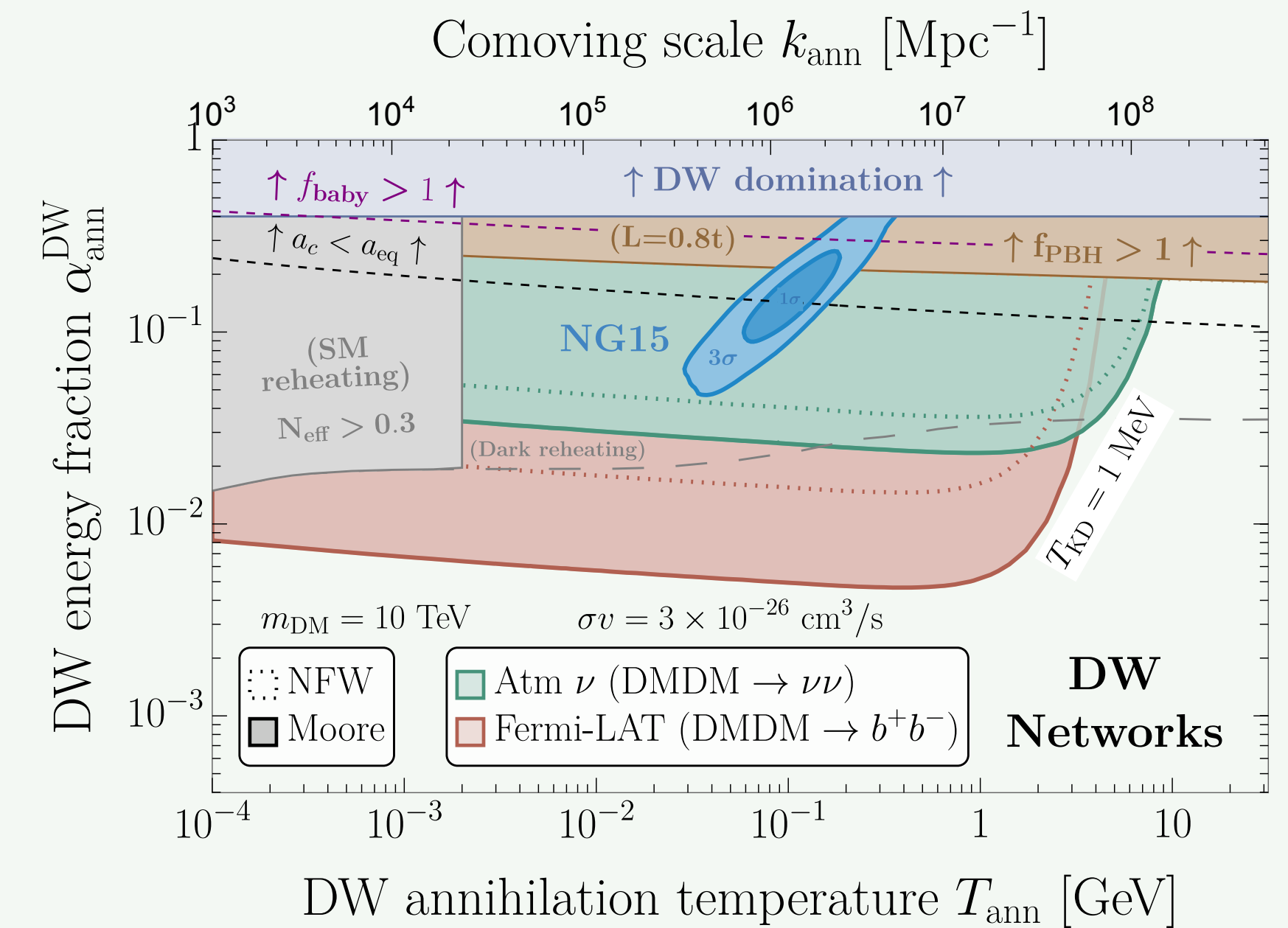


Next step: Get rid of WIMPs
assumption with
Gravitational Lensing

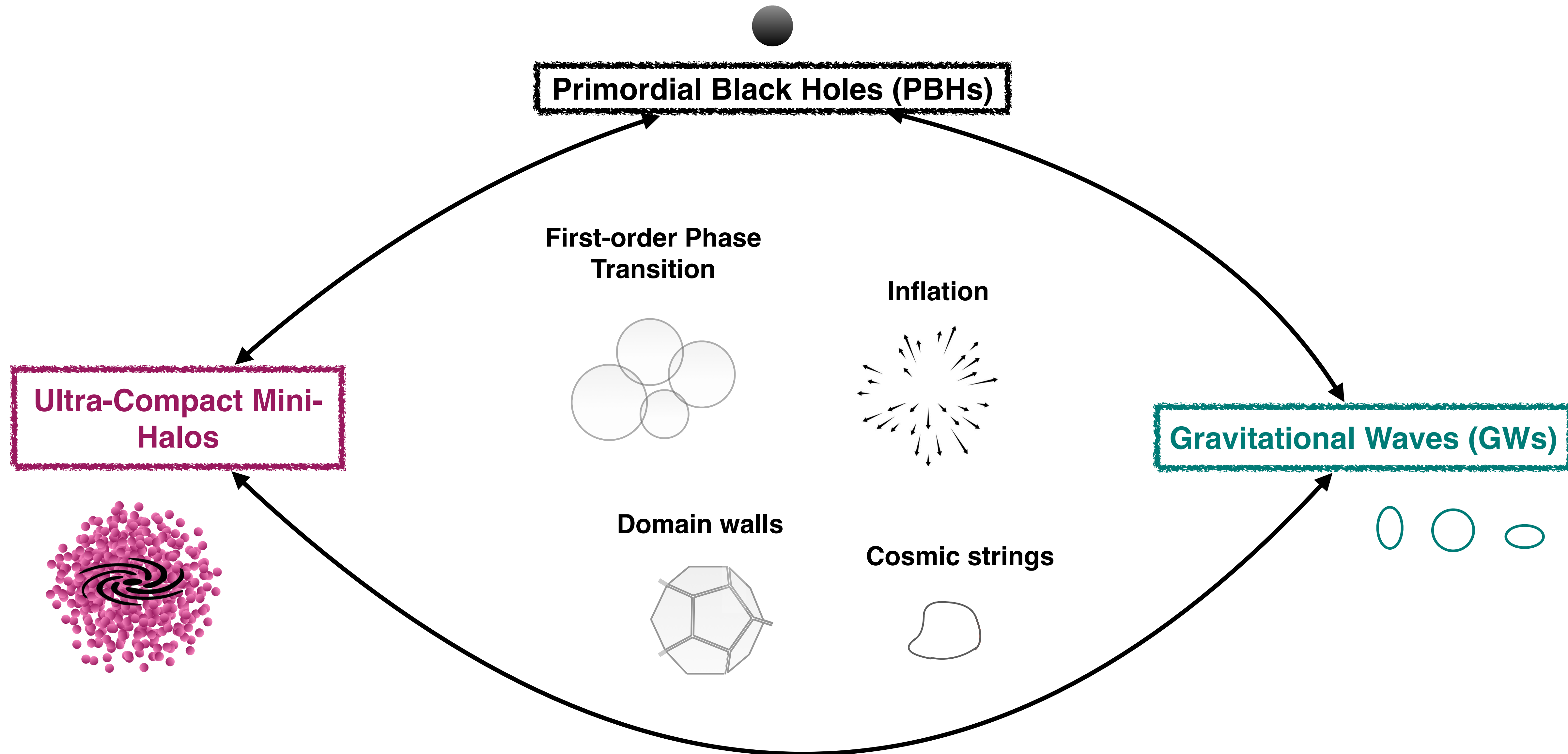


HSC microlensing
(in preparation)
Lensed Quasars
(in preparation)

(with Sten Delos)



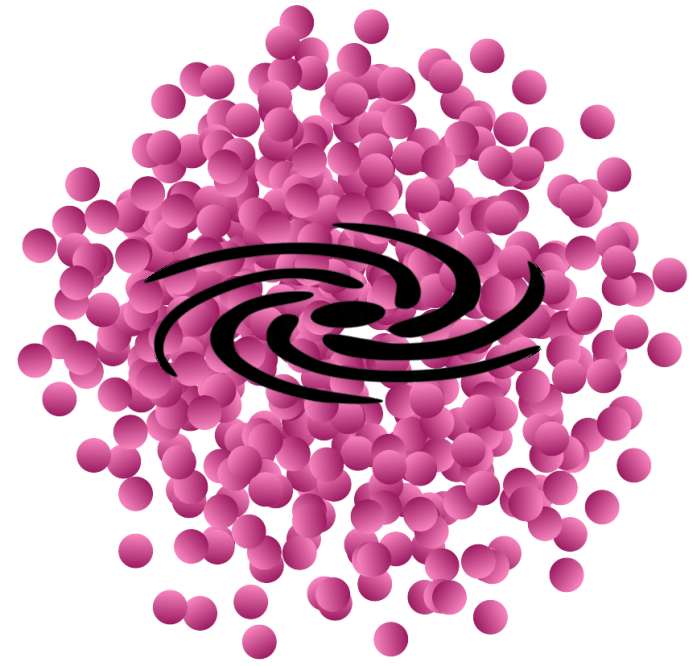
What can we learn from cross-correlation ?



DM Ultra Compact Mini Halos

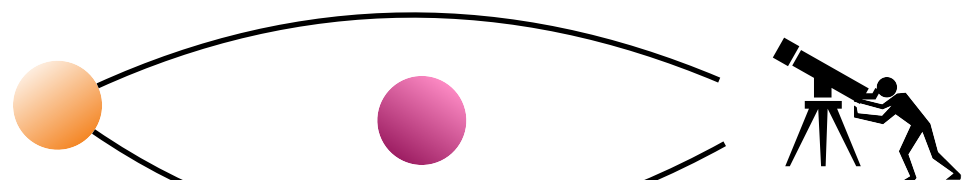
$$R_{\text{UCMH}} \sim 200 \text{ AU} \left(\frac{1000}{z_{\text{collapse}}} \right)$$

$$M_{\text{UCMH}} \sim 10^{-7} M_{\odot}$$



In preparation
(with Sten Delos)

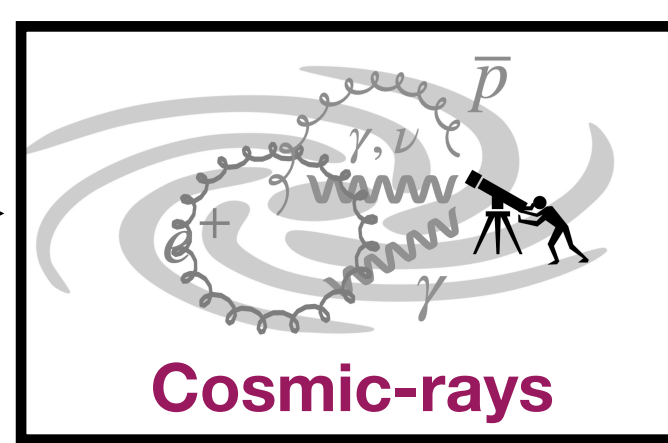
Gravitational Lensing



HSC microlensing
(in preparation)
Lensed Quasars
(in preparation)

if DM=WIMPs

YG 2503.03857



Cosmic-rays

$$\mathcal{R} \gtrsim 0.1$$

YG, Volansky 2305.04942

YG 2307.04239 (PRL)

Franciolini, YG, Jinno 2503.01962

YG, Vitagliano 2306.17841, 2311.07670

New Physics around $T_{\star} \sim 0.1 \text{ GeV}$:

1) Curvature peaks

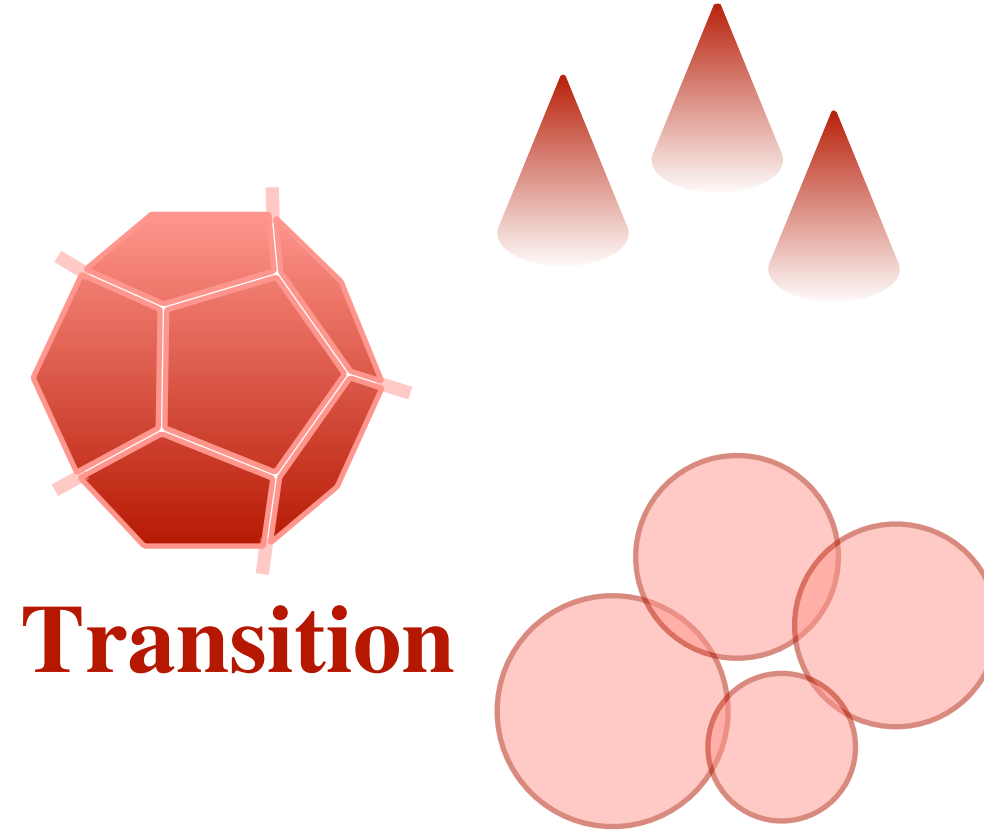
$$\mathcal{A}_{\mathcal{R}} \gtrsim 0.01$$

2) Domain Walls

$$\alpha_{\star} \gtrsim 0.1$$

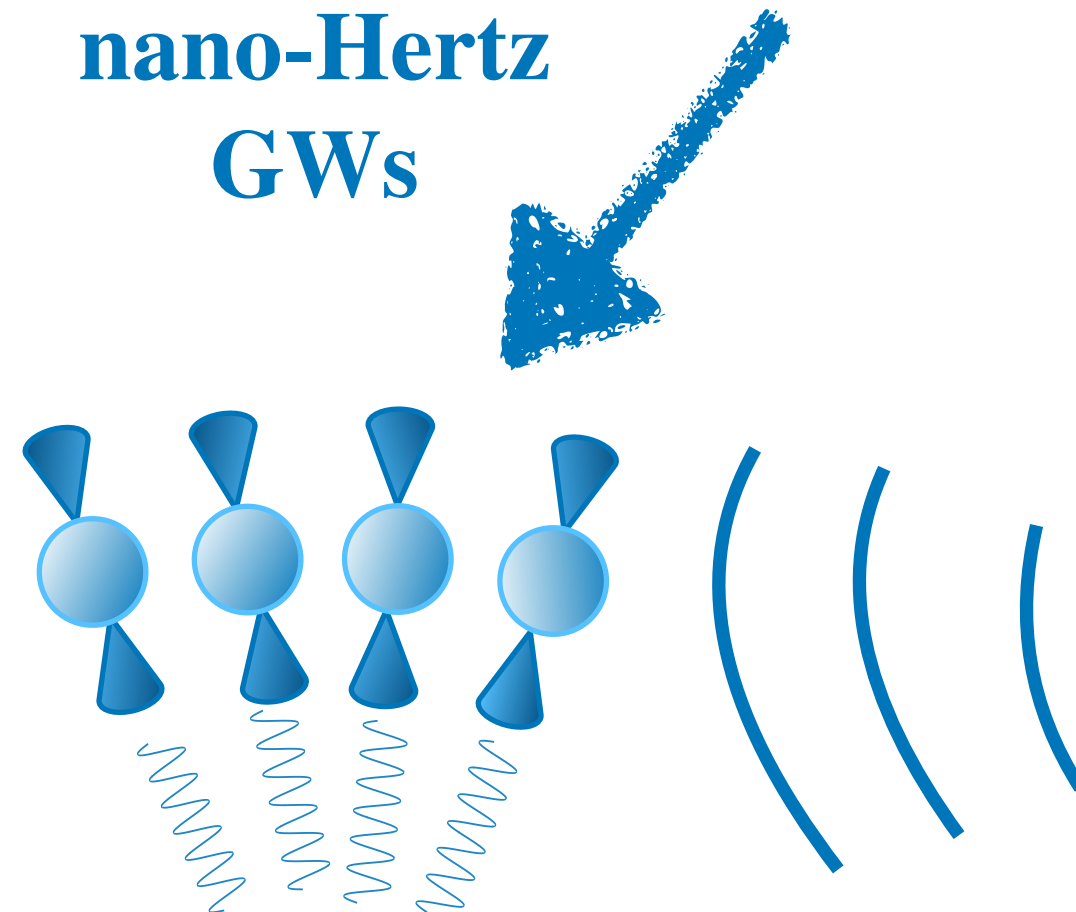
3) First Order Phase Transition

$$\beta/H_{\star} \lesssim 30$$

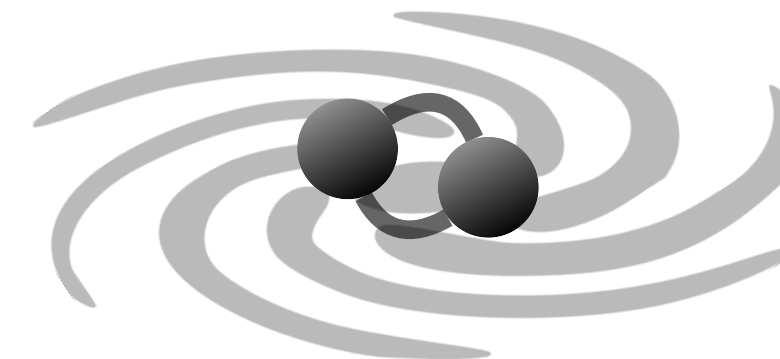


$$\mathcal{R} \gtrsim 10^{-3}$$

nano-Hertz
GWs



Astrophysical interpretation:

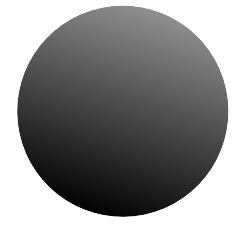


Super Massive Black Holes
Binary Mergers

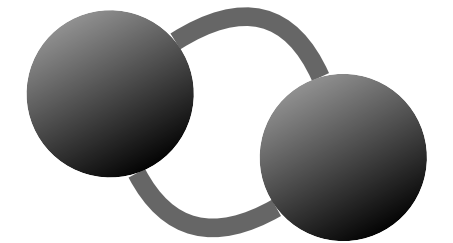
$$M_{\text{SMBH}} \sim 10^9 M_{\odot}$$

Primordial Black Holes

$$M_{\text{PBH}} \sim M_{\odot}$$



Binary
formation



kilo-Hertz
GWs

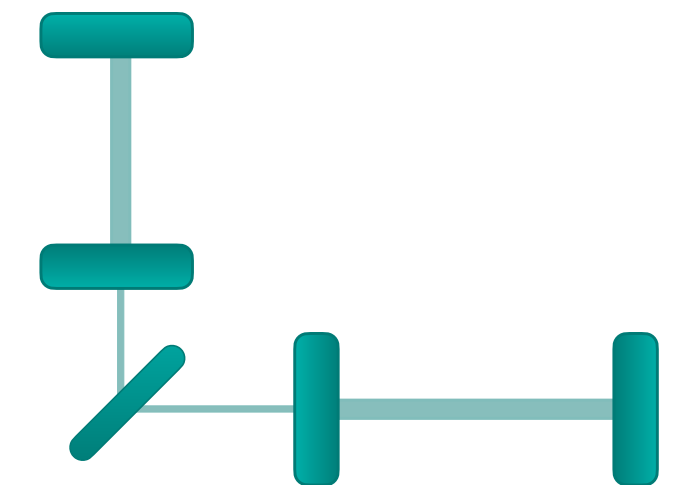


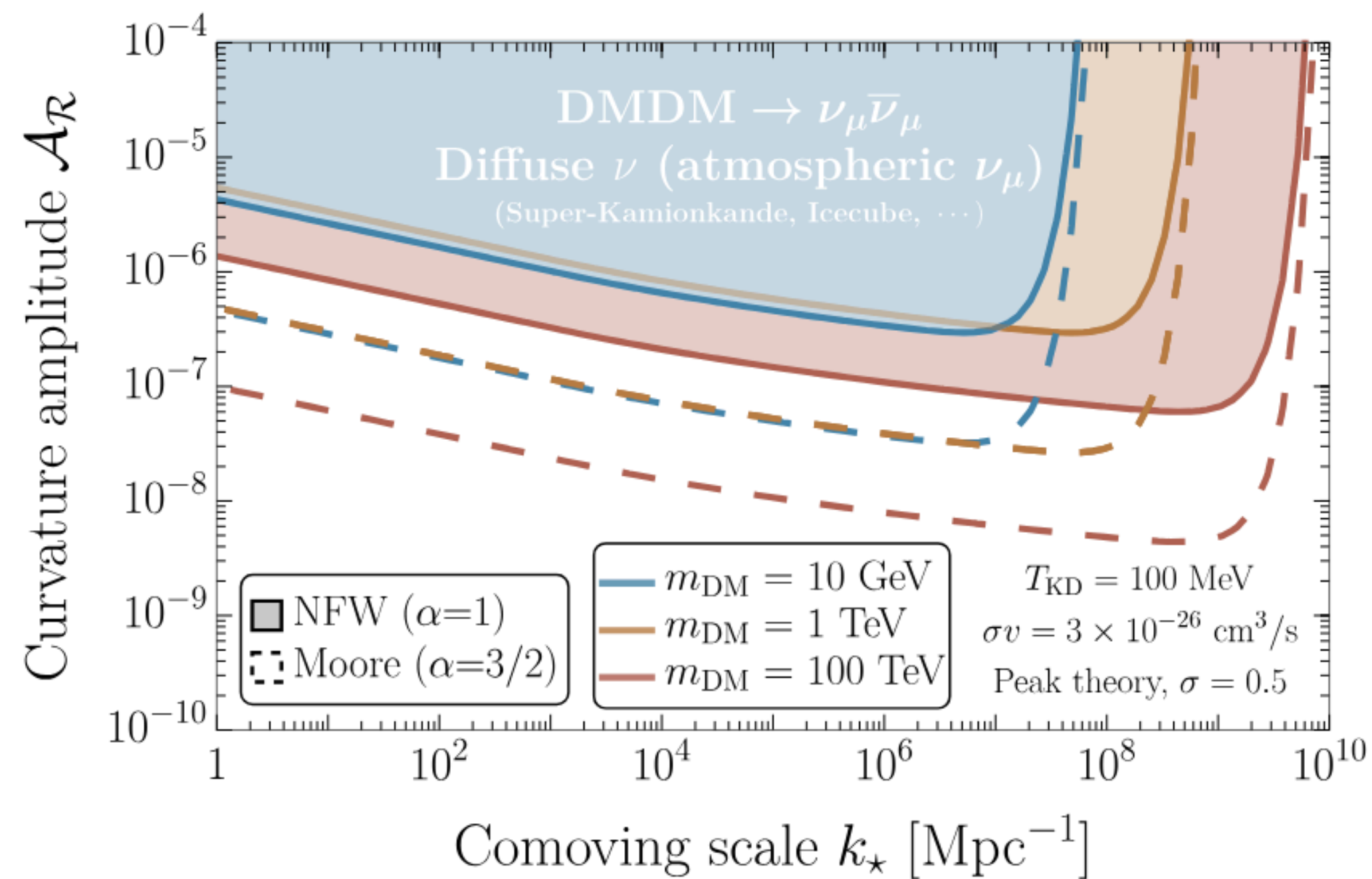
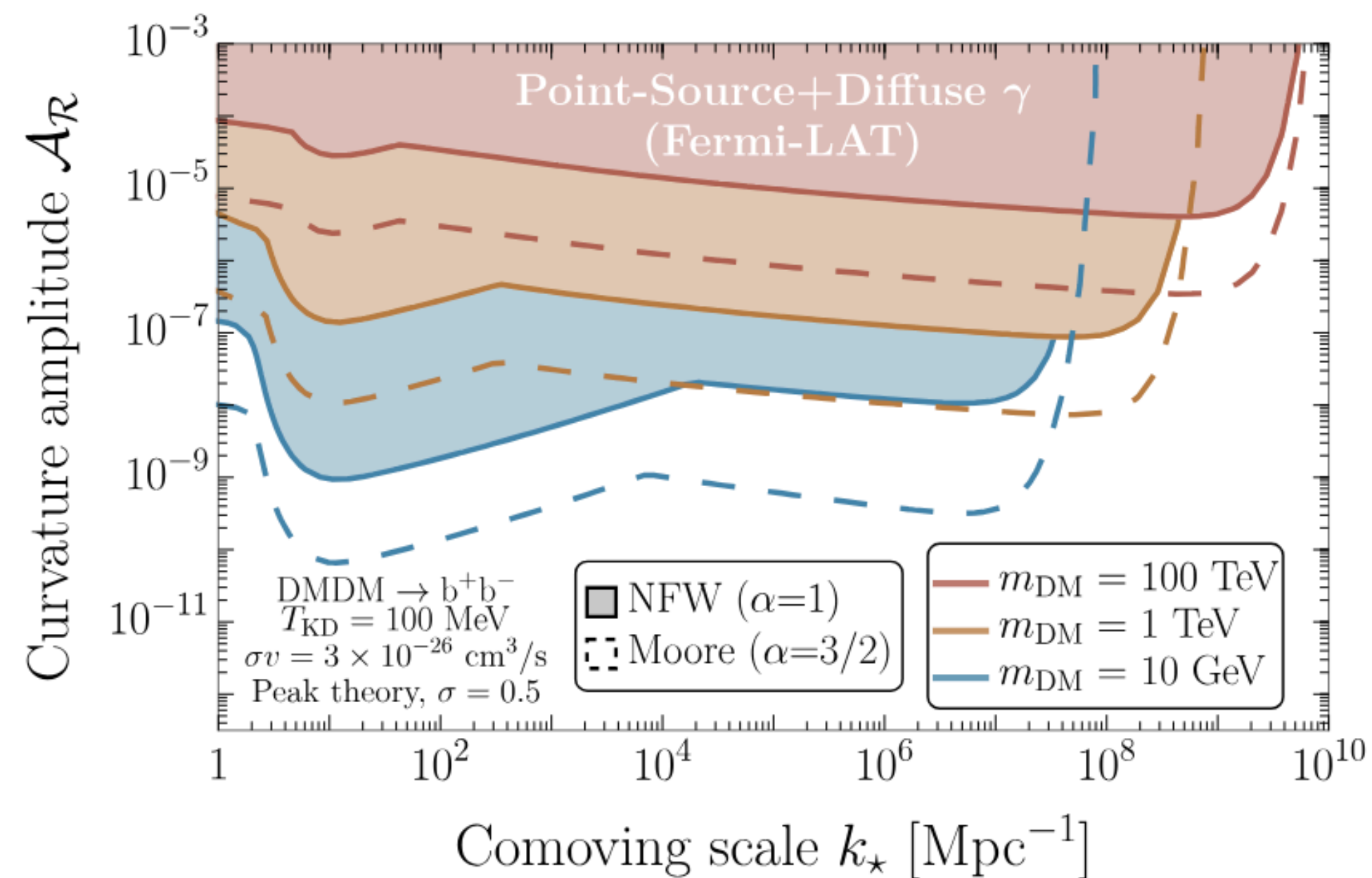
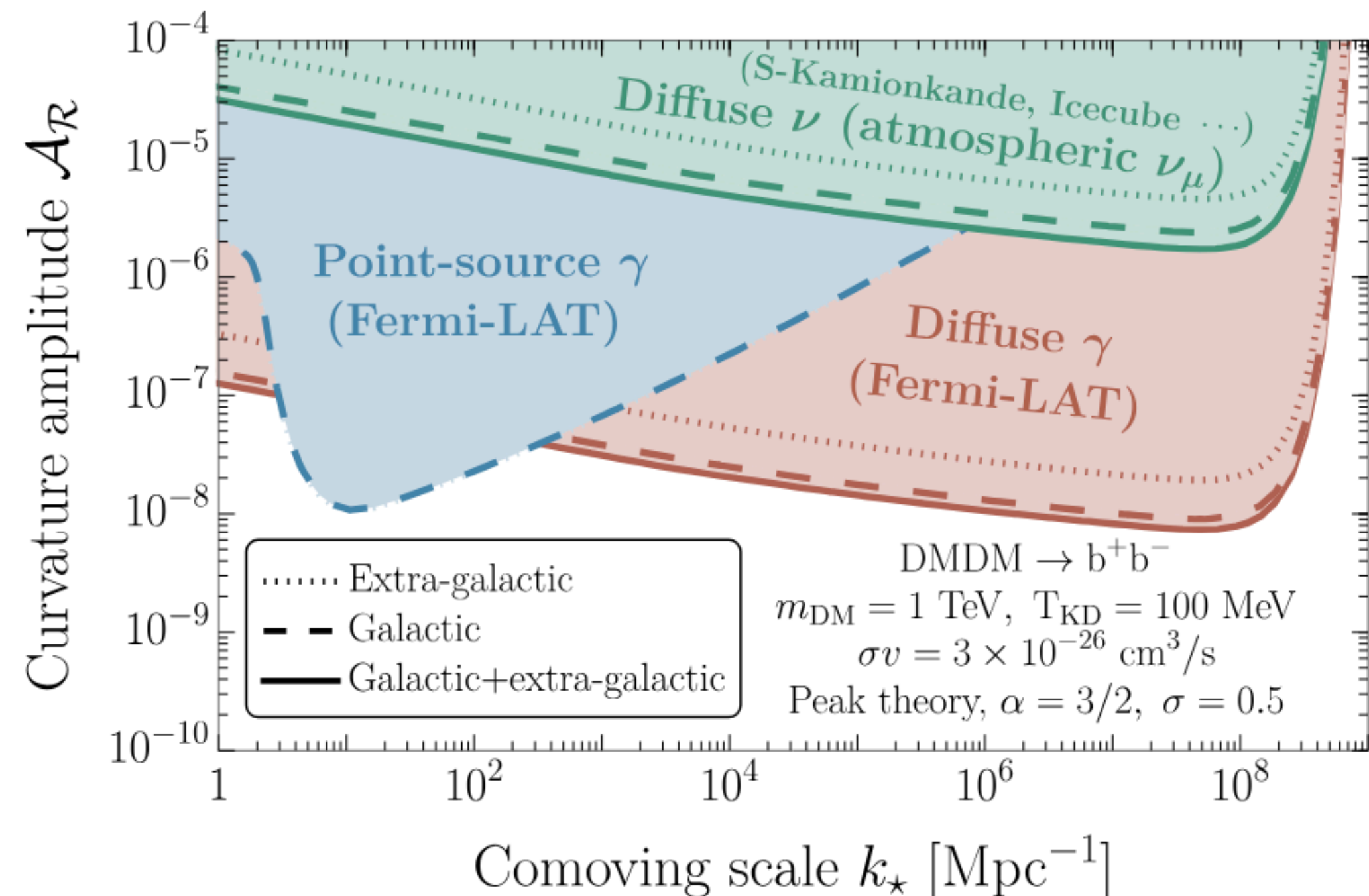
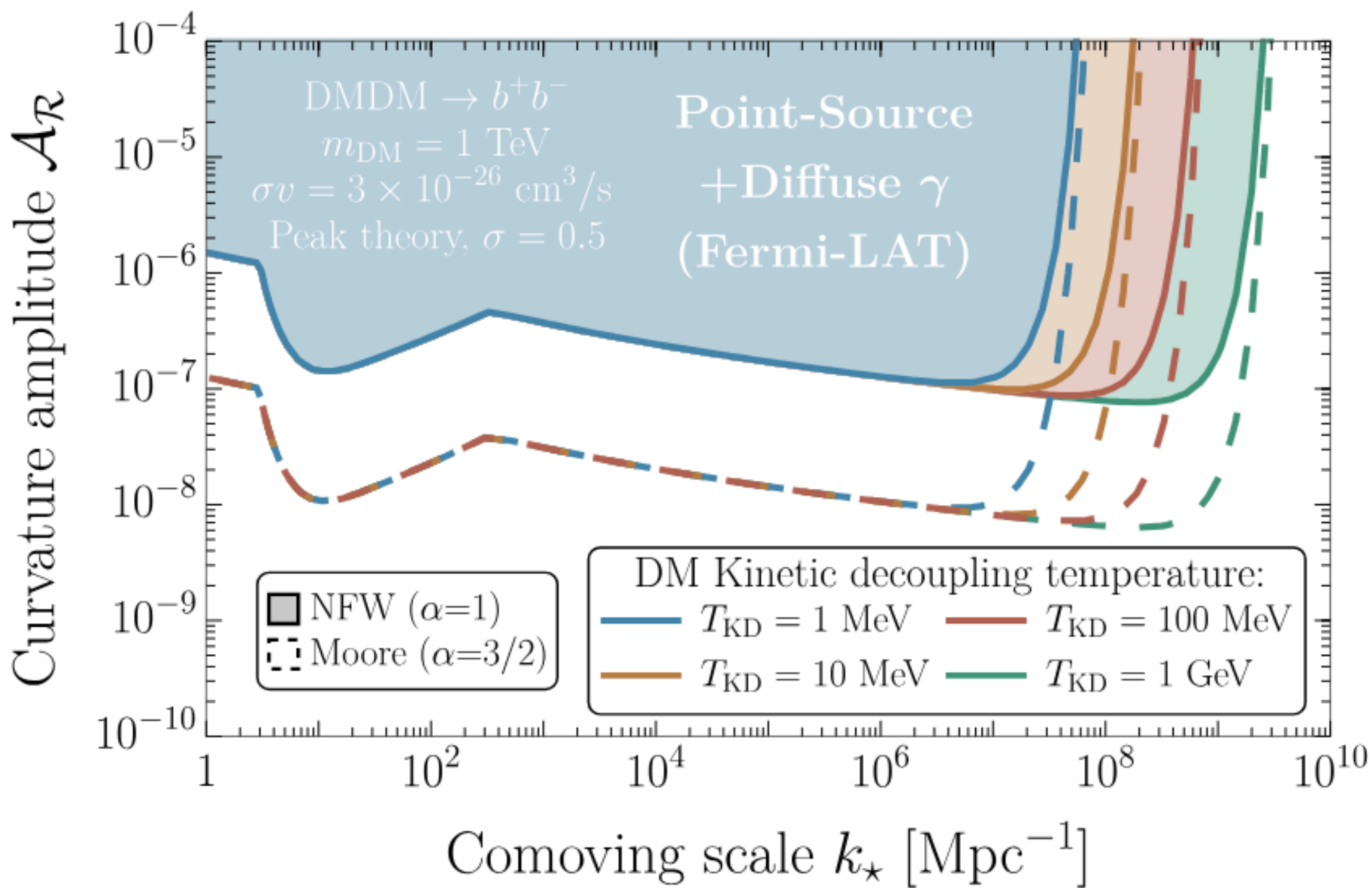
Pulsar Timing Arrays
(NG15, EPTA, PPTA, CPTA, ...)

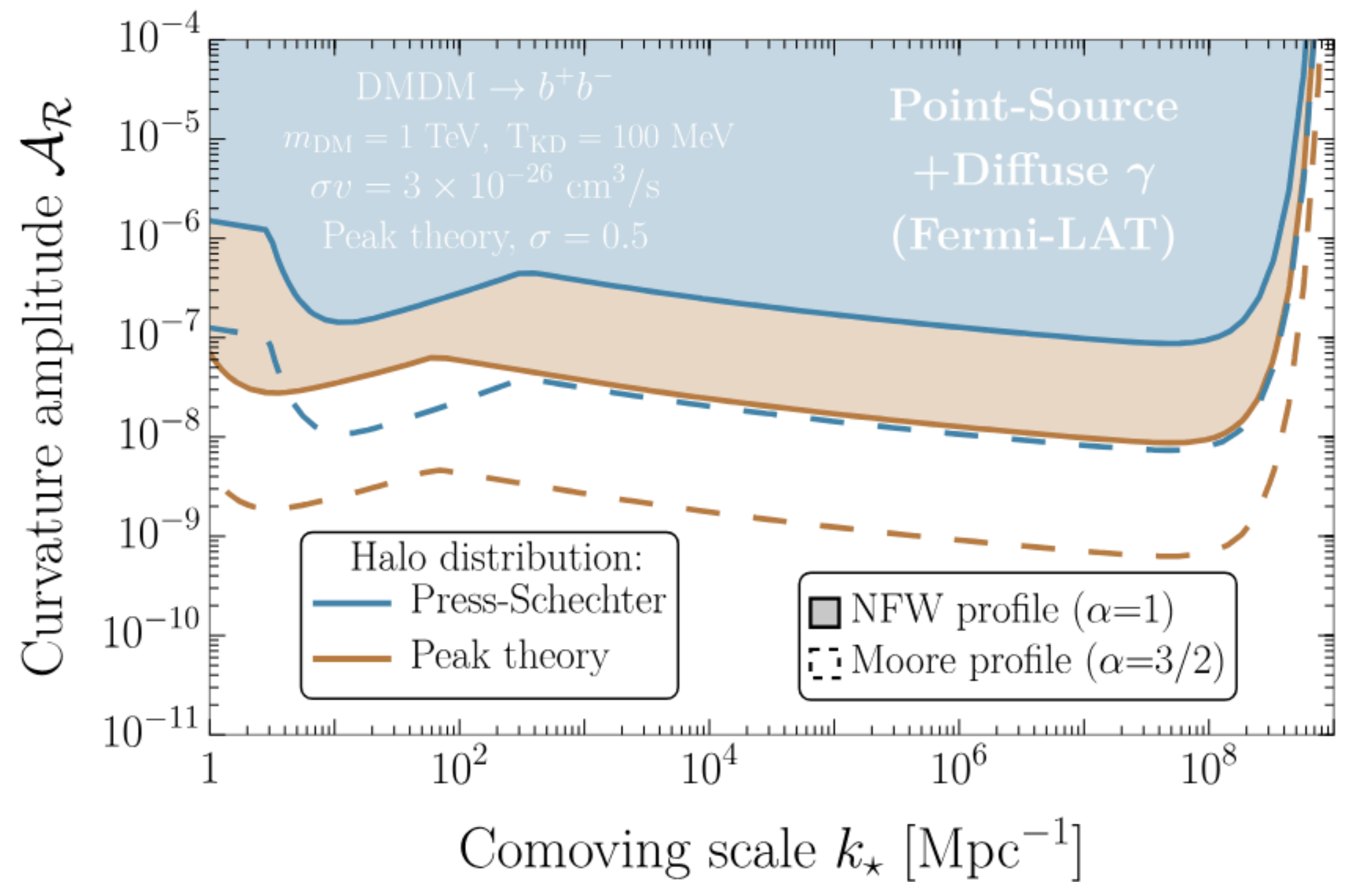
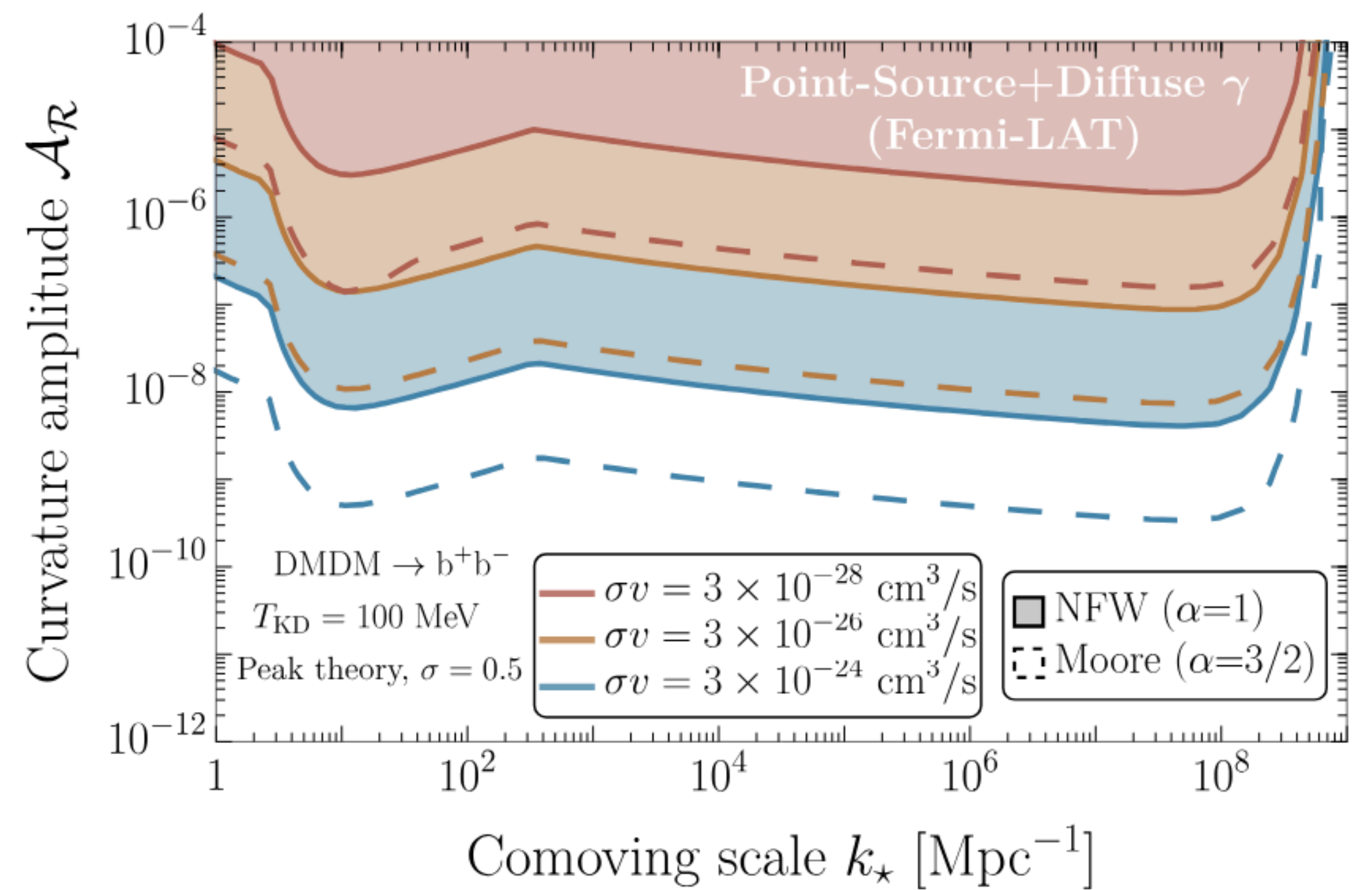
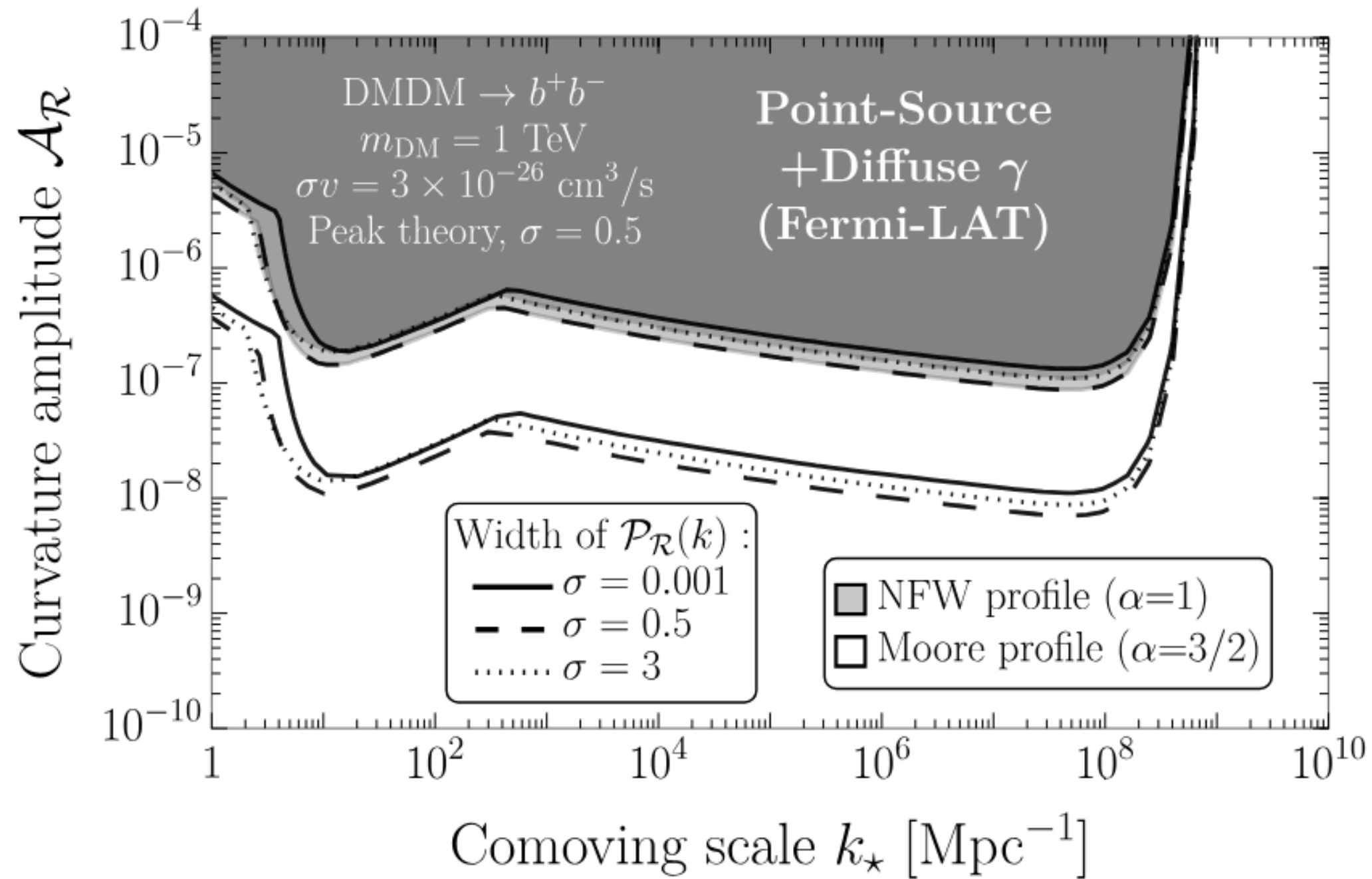
Data correlation

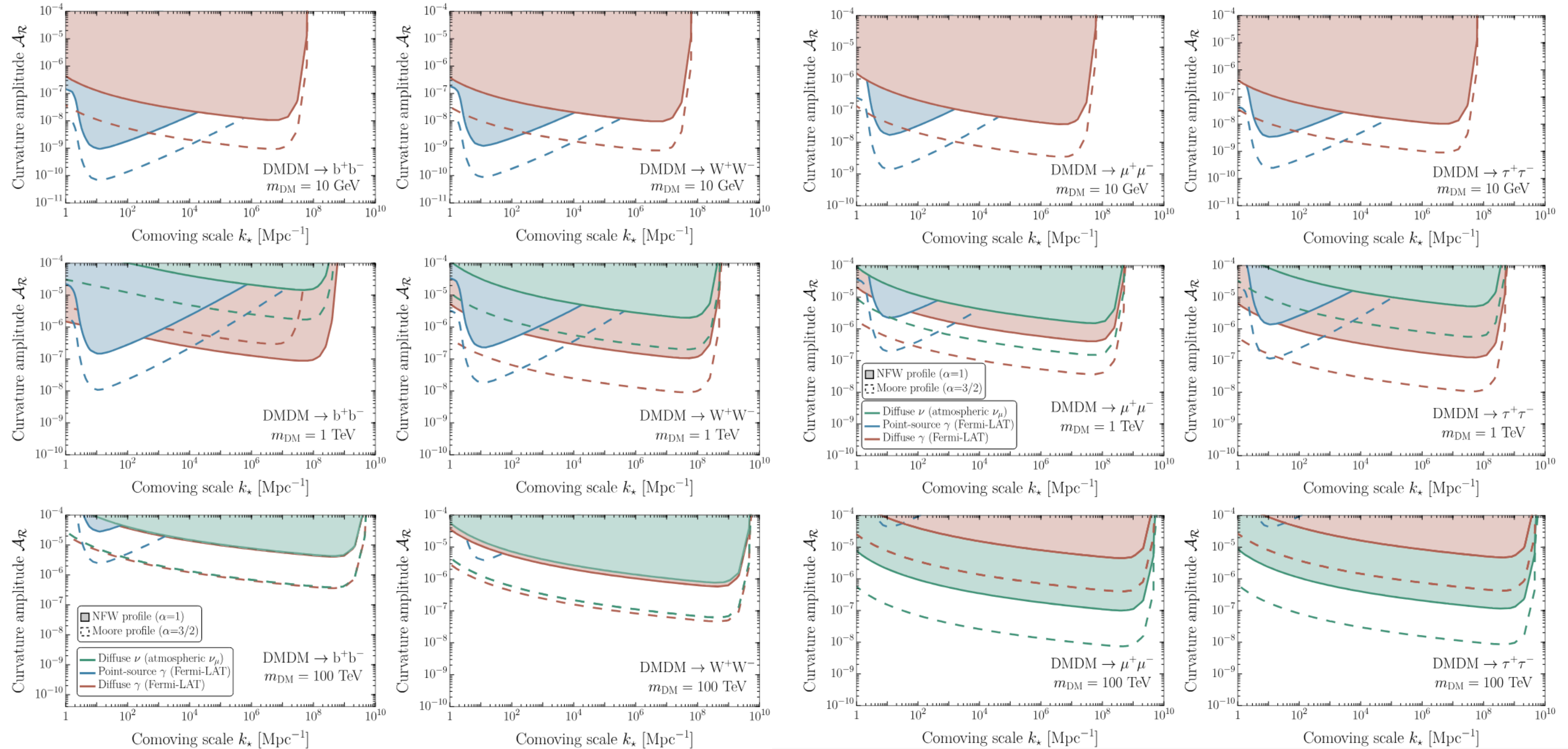
YG, Trifinopoulos, Vanvlasselaer (2508.19328)

Earth-based Laser
Interferometers
(LVK O₄, O₅, ET, CE)

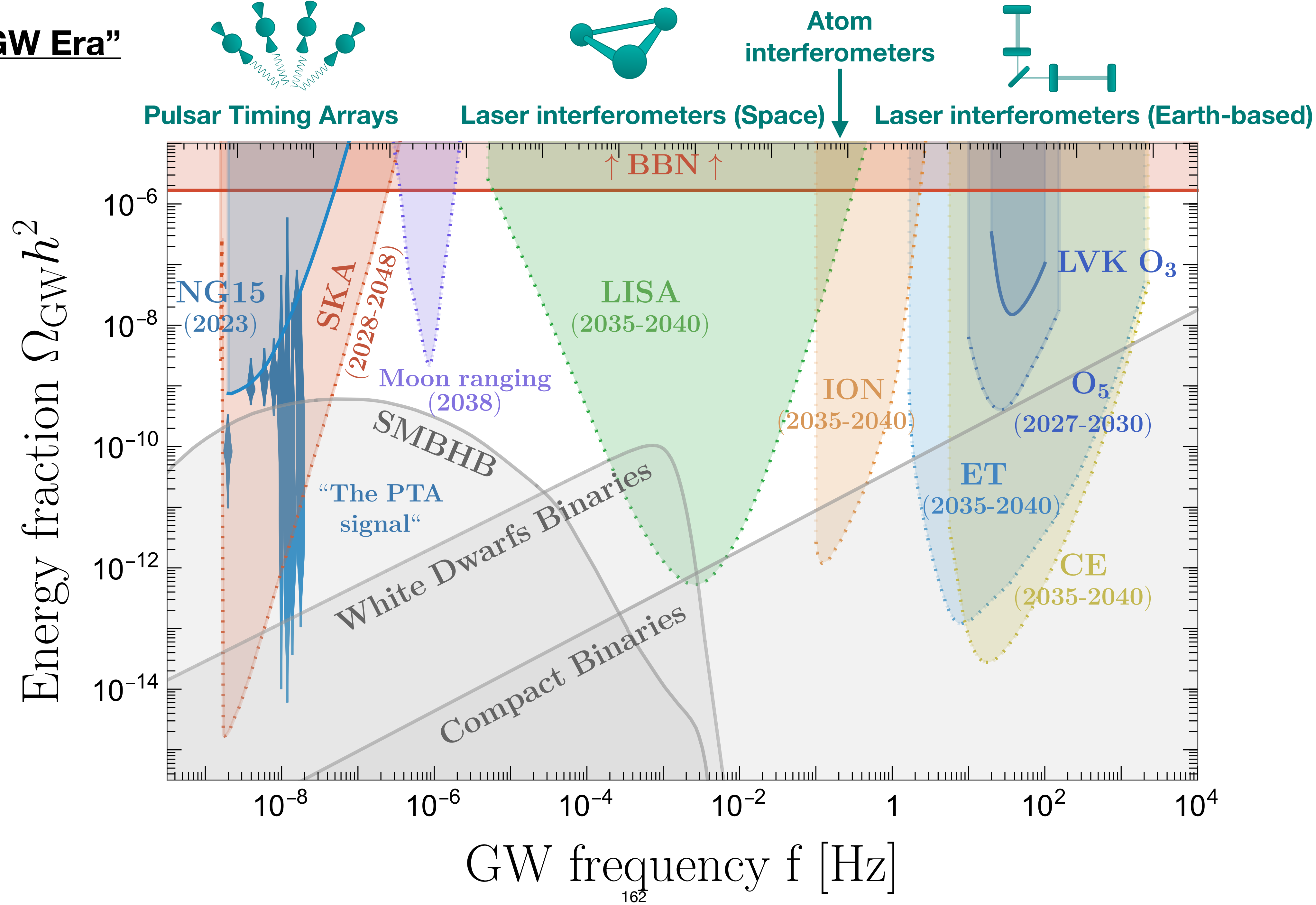


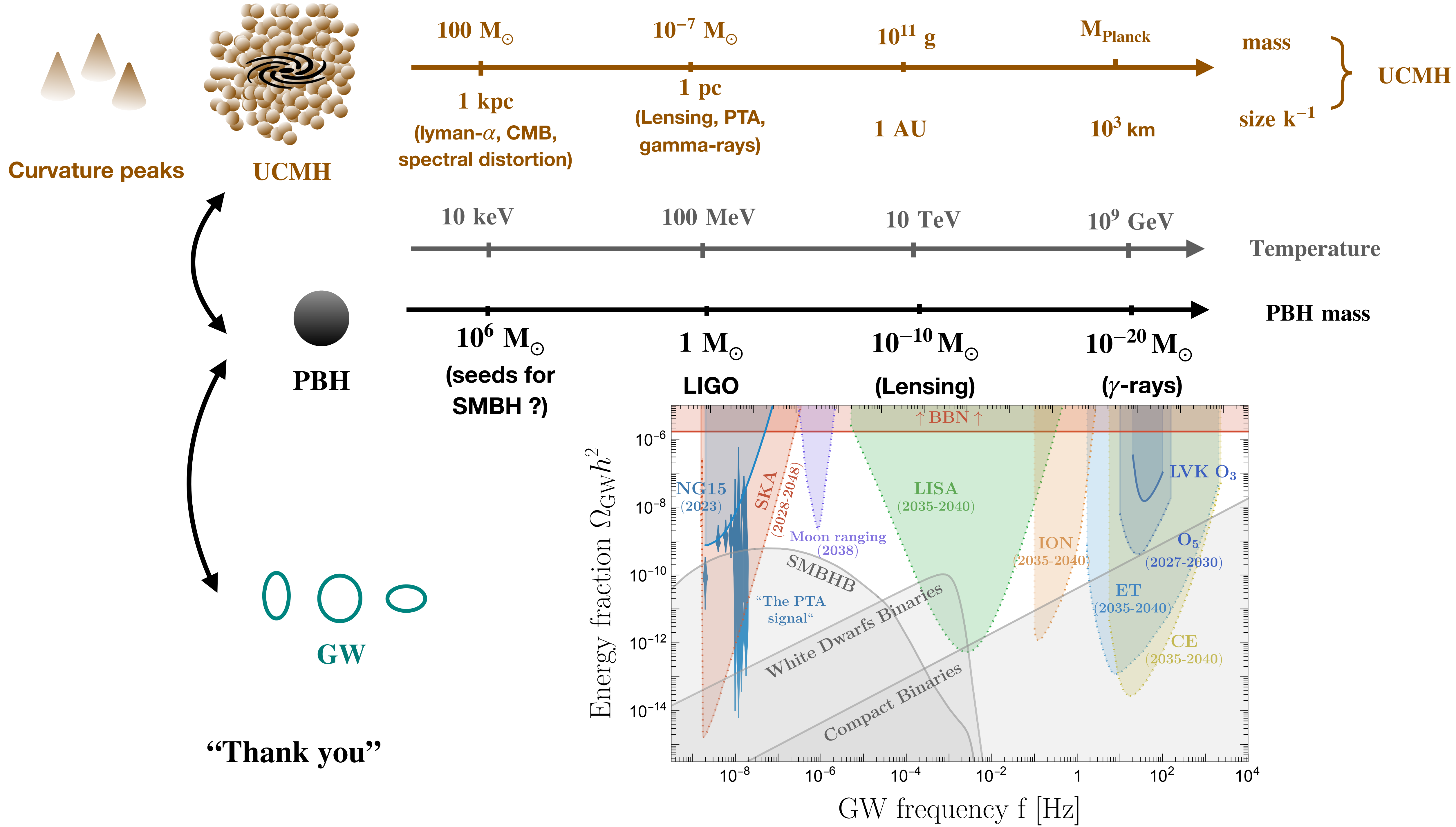


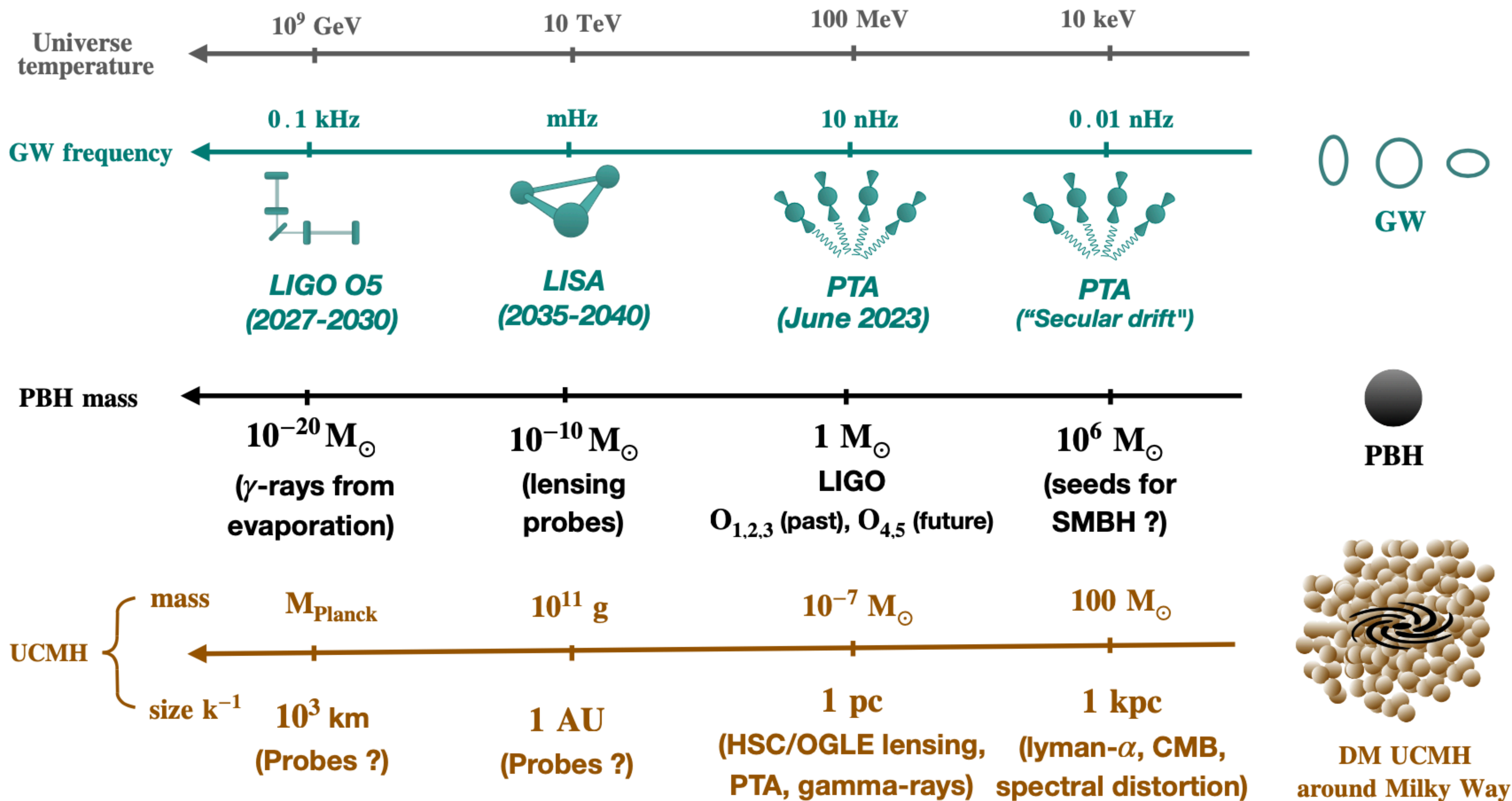


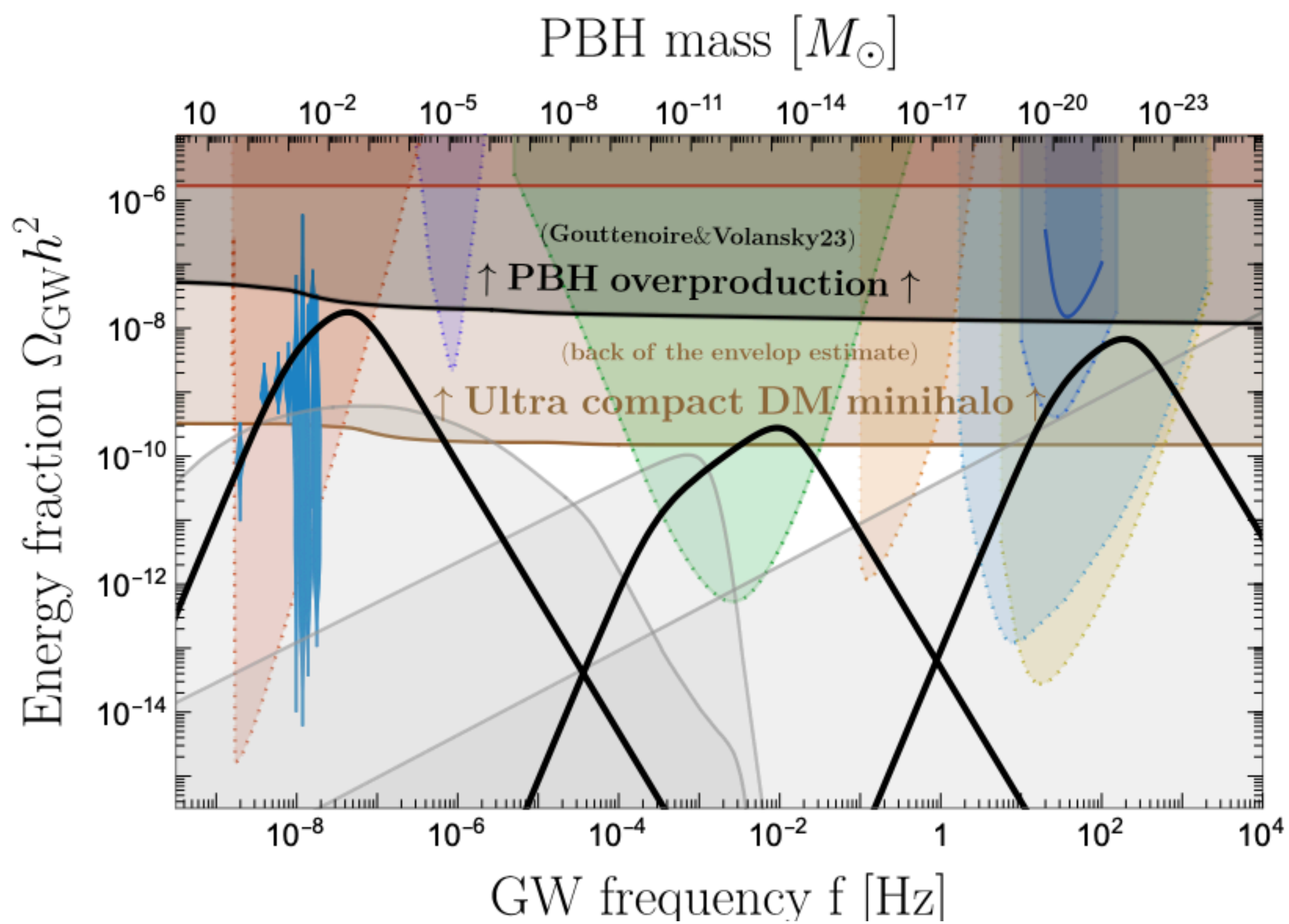


“The GW Era”



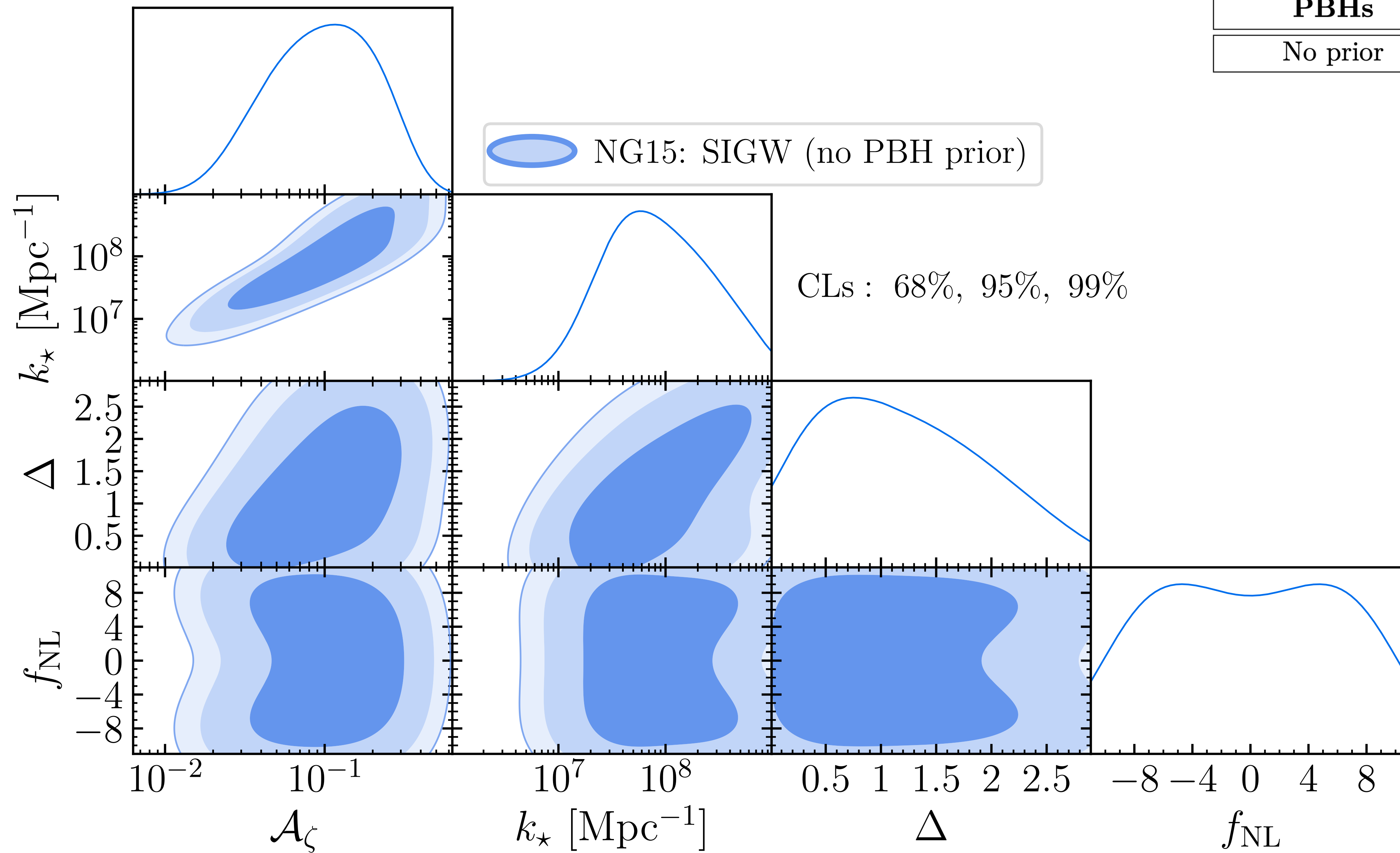




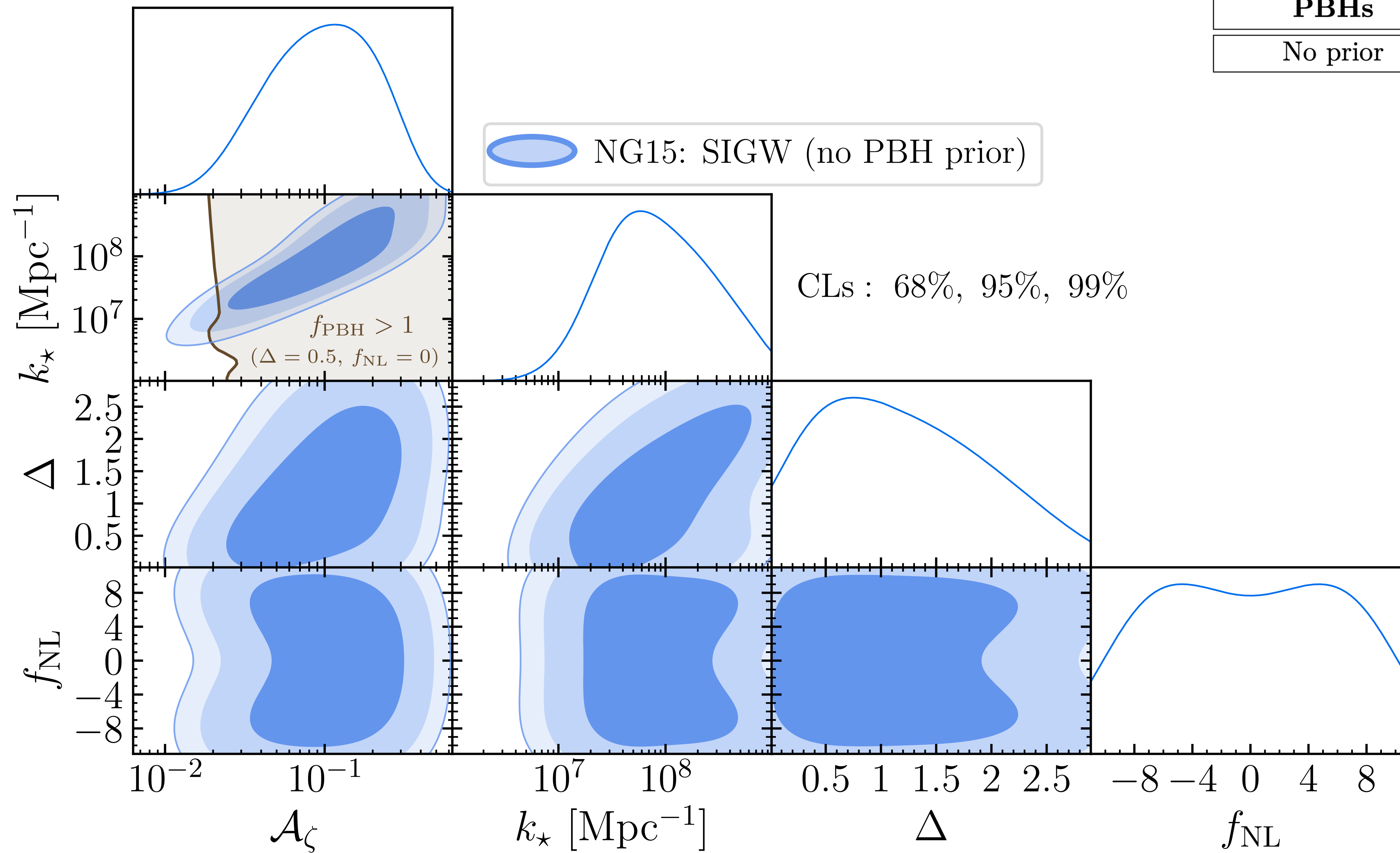


Prior on PBHs		Model X = SMBH only	Model Y	$\text{Log}_{10} \mathcal{B}_{Y,X} (\pm 0.10)$			
				Threshold statistics			Peak theory
				$f_{\text{NL}} = 0$	$f_{\text{NL}} = -2$	$ f_{\text{NL}} < 10$	
No prior		free amplitude	SIGW	1.67	1.74	1.74	1.67
			SIGW+SMBH	1.57	1.64	1.64	1.57
		GWOnly-Ext	SIGW	2.17	2.28	2.33	2.17
			SIGW+SMBH	2.05	2.16	2.22	2.05
Astrophysical		free amplitude	SIGW	-1.46	-0.70	-1.33	-3.34
			SIGW+SMBH	-0.08	-0.01	-0.11	-0.10
		GWOnly-Ext	SIGW	-0.90	-0.14	-0.75	-2.78
			SIGW+SMBH	0.05	0.20	0.06	-0.01
Sub-solar	CE	free amplitude	SIGW	-0.01	0.77	0.07	-2.20
			SIGW+SMBH	0.34	0.81	0.32	0.05
		GWOnly-Ext	SIGW	0.55	1.33	0.66	-1.64
			SIGW+SMBH	0.72	1.31	0.74	0.17
	ET	free amplitude	SIGW	0.16	0.95	0.23	-2.05
			SIGW+SMBH	0.45	0.96	0.42	0.09
		GWOnly-Ext	SIGW	0.72	1.51	0.82	-1.49
			SIGW+SMBH	0.86	1.48	0.87	0.23
	LVK O5	free amplitude	SIGW	0.62	1.40	0.69	-1.50
			SIGW+SMBH	0.74	1.36	0.72	0.20
		GWOnly-Ext	SIGW	1.18	1.96	1.28	-0.94
			SIGW+SMBH	1.21	1.90	1.25	0.37
	LVK O4	free amplitude	SIGW	0.66	1.59	0.79	-1.24
			SIGW+SMBH	0.77	1.52	0.79	0.24
		GWOnly-Ext	SIGW	1.22	2.15	1.37	-0.68
			SIGW+SMBH	1.27	2.06	1.33	0.40

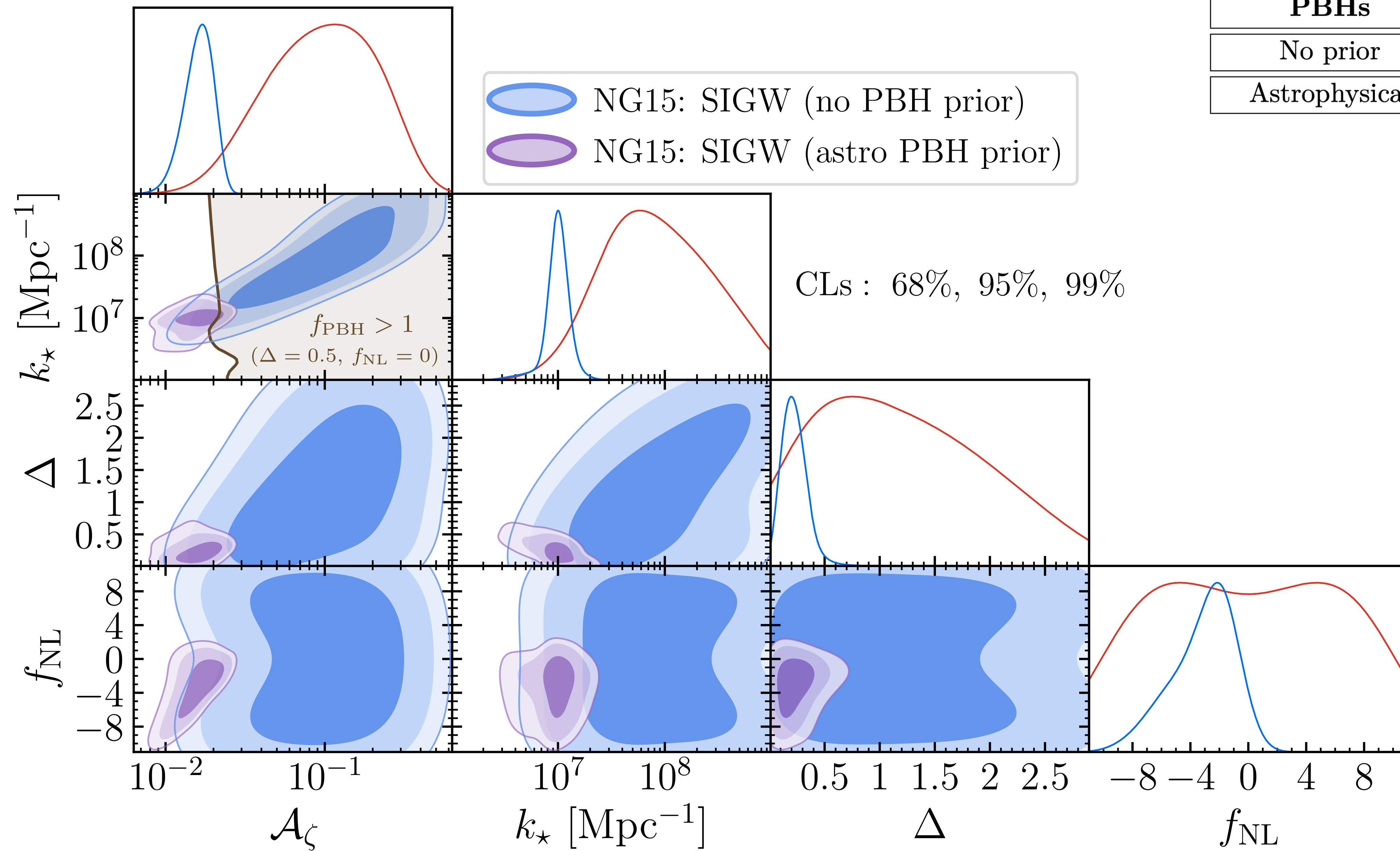
Prior on PBHs	SIGW / SMBH	
	$f_{\text{NL}} = 0$	$f_{\text{NL}} = -2$
No prior	2.17	2.28

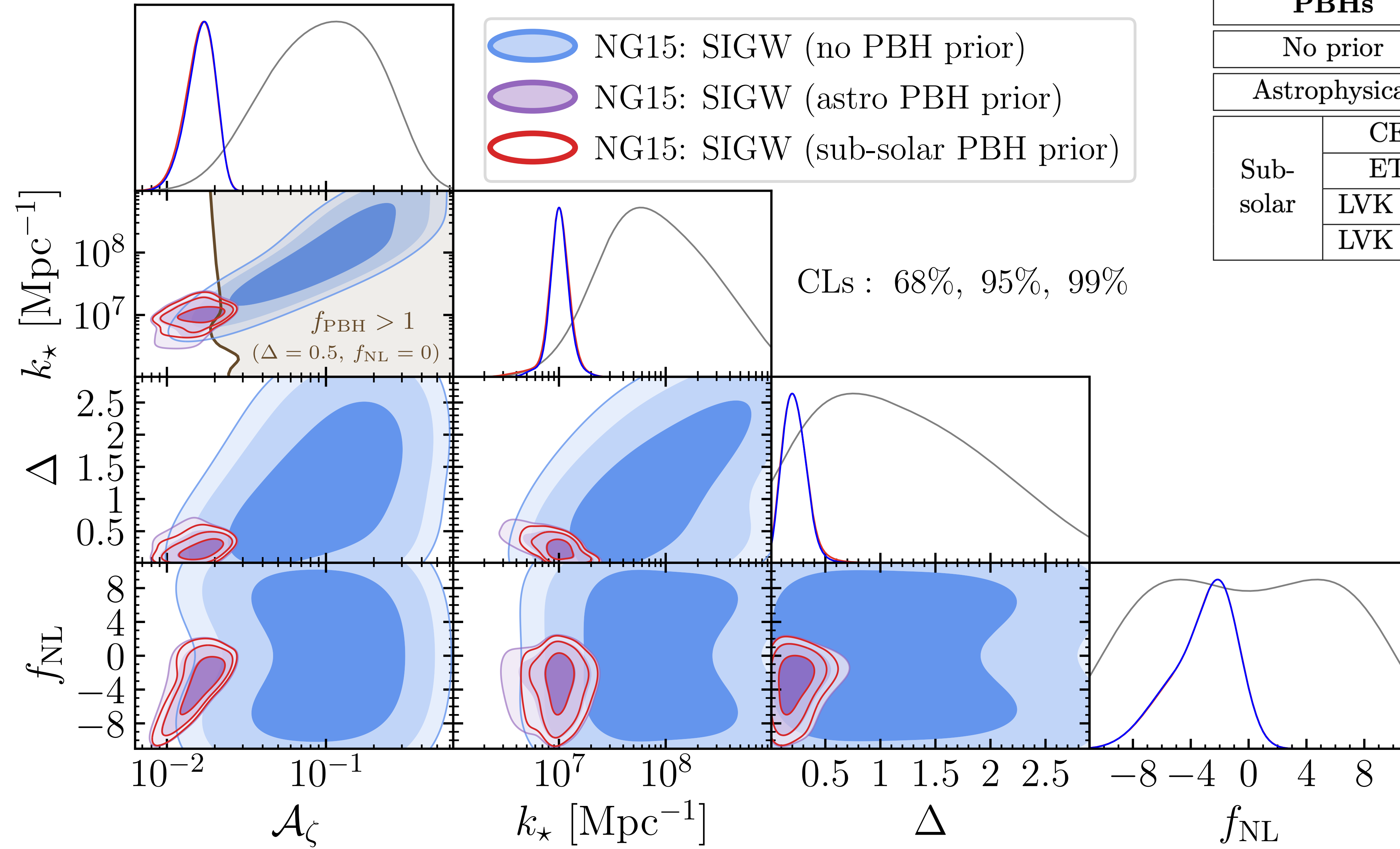


Prior on PBHs	SIGW / SMBH	
	$f_{\text{NL}} = 0$	$f_{\text{NL}} = -2$
No prior	2.17	2.28

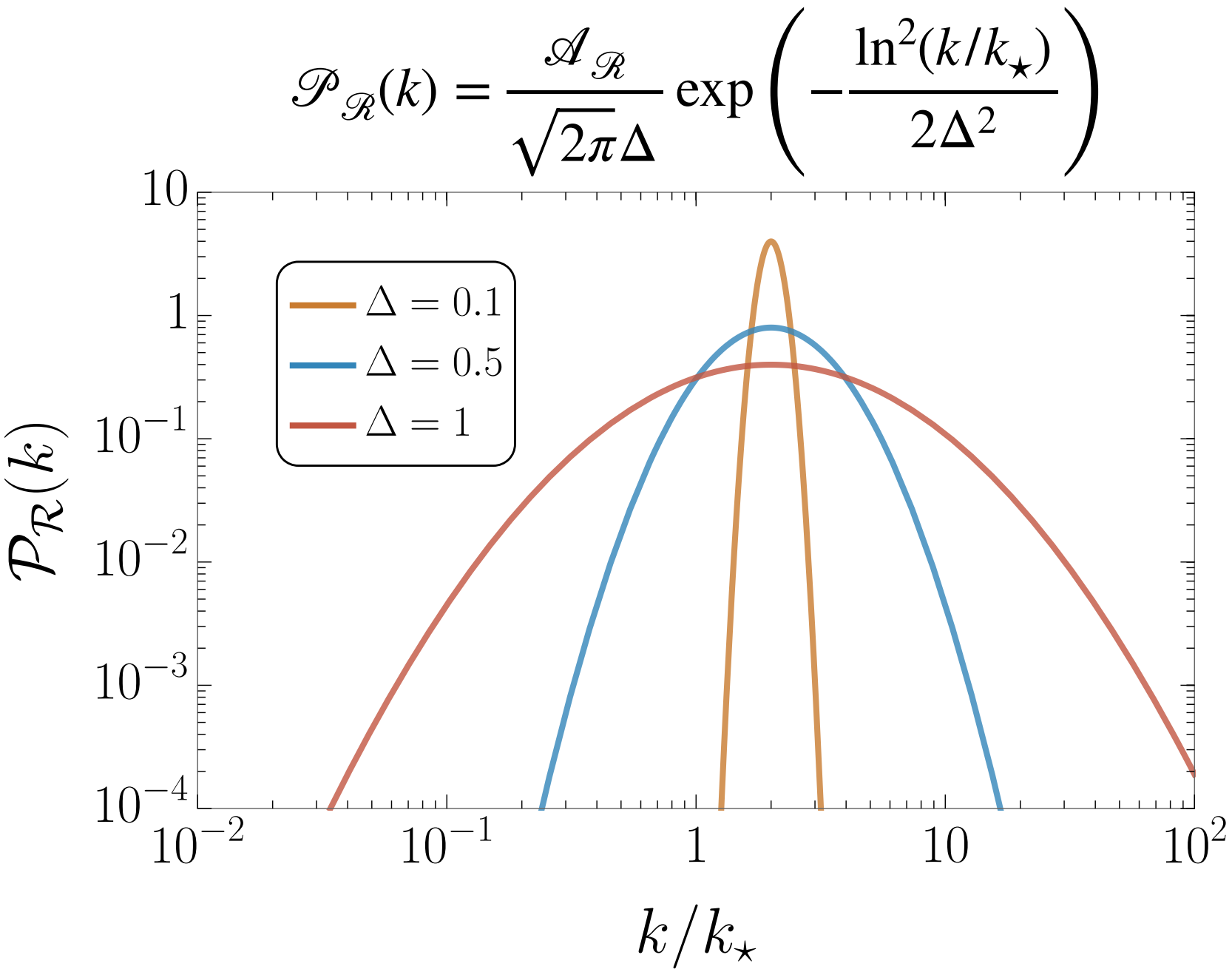


Prior on PBHs	SIGW / SMBH	
	$f_{\text{NL}} = 0$	$f_{\text{NL}} = -2$
No prior	2.17	2.28
Astrophysical	−0.90	−0.14





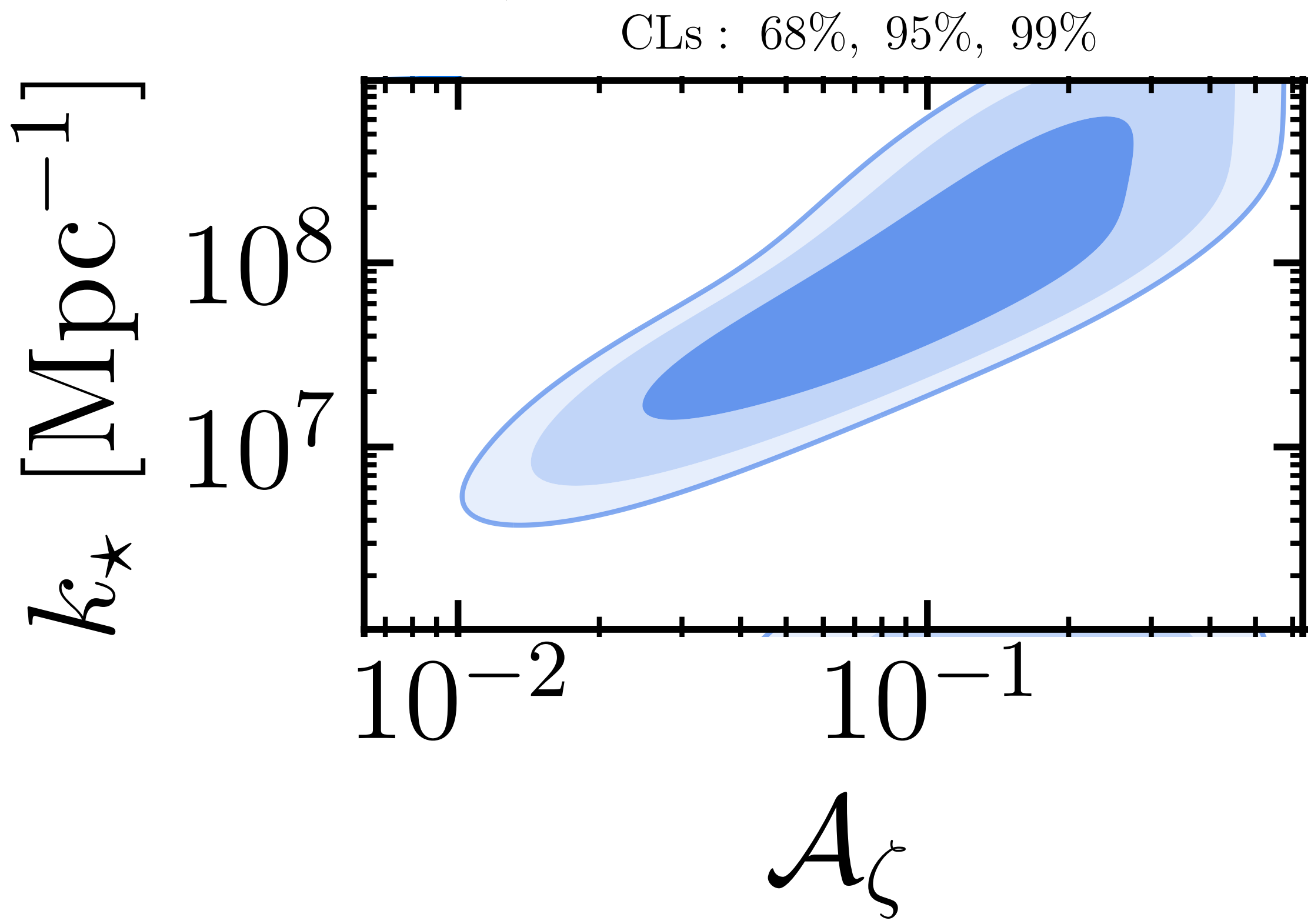
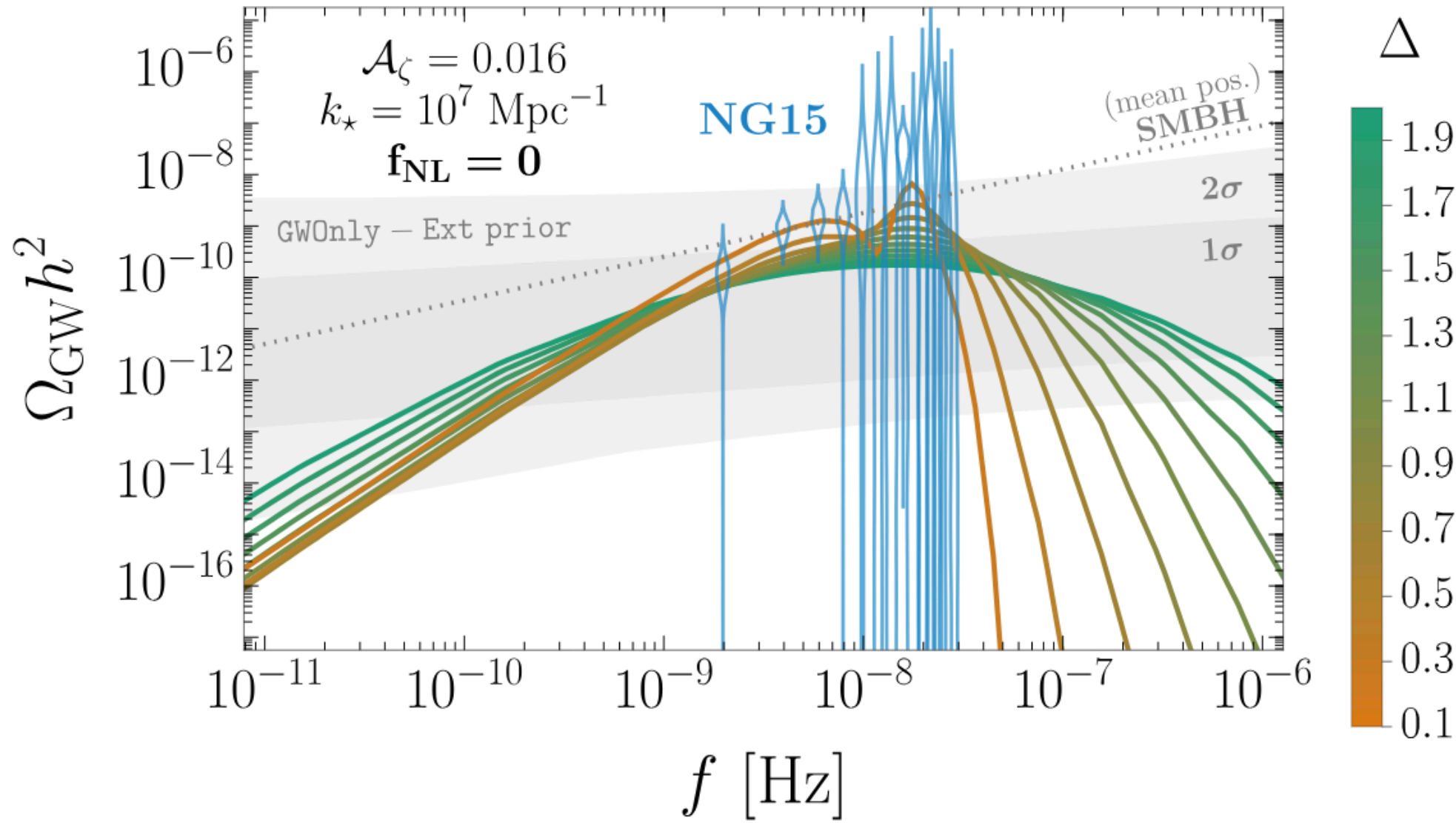
Prior on PBHs		SIGW / SMBH	
		$f_{\text{NL}} = 0$	$f_{\text{NL}} = -2$
No prior		2.17	2.28
Astrophysical		-0.90	-0.14
Sub-solar	CE	0.55	1.33
	ET	0.72	1.51
	LVK O5	1.18	1.96
	LVK O4	1.22	2.15



$\mathcal{P}_h(k) \sim \mathcal{P}_{\mathcal{R}}^2(k)$

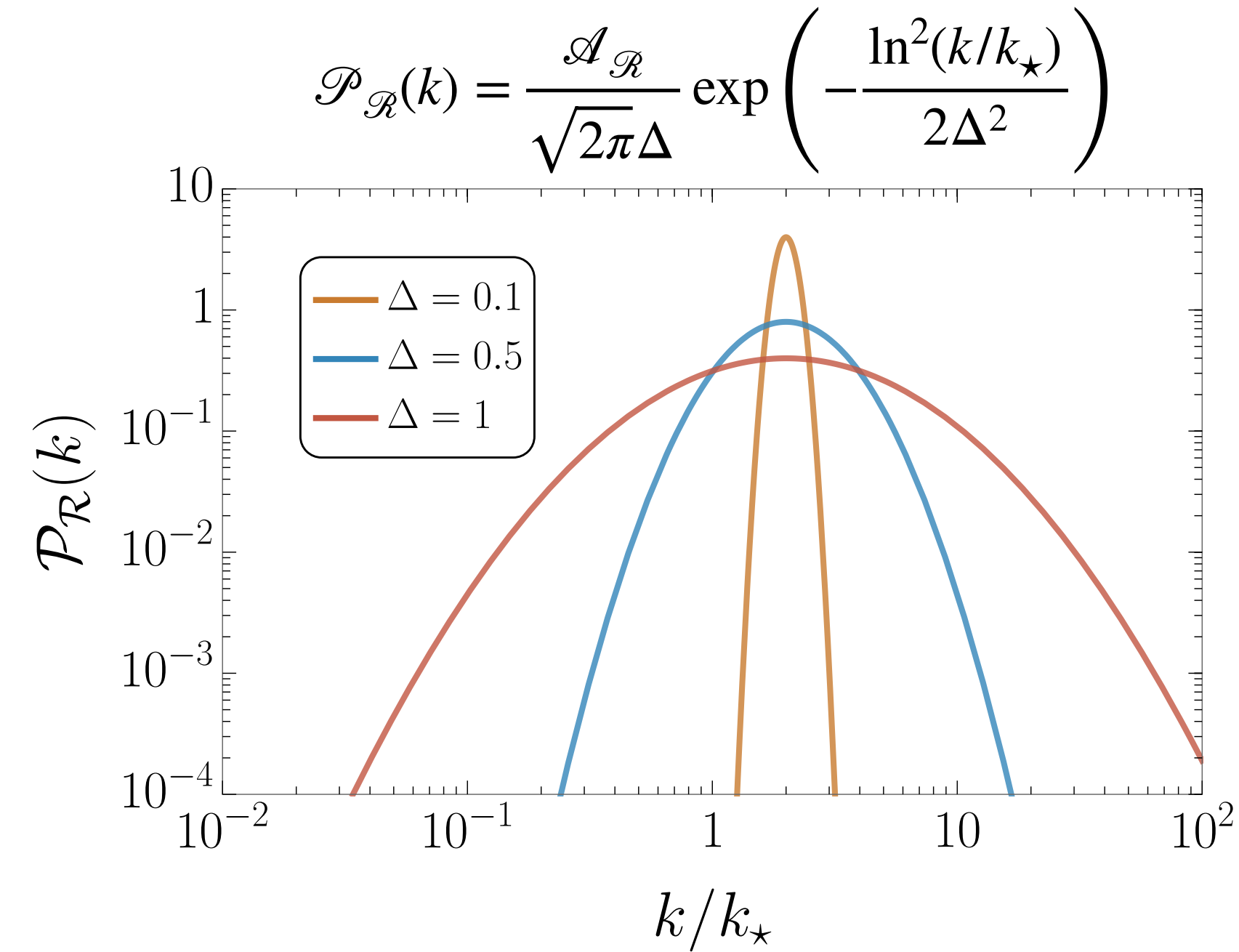
→

Scalar induced GW



NG15: SIGW (no PBH prior)

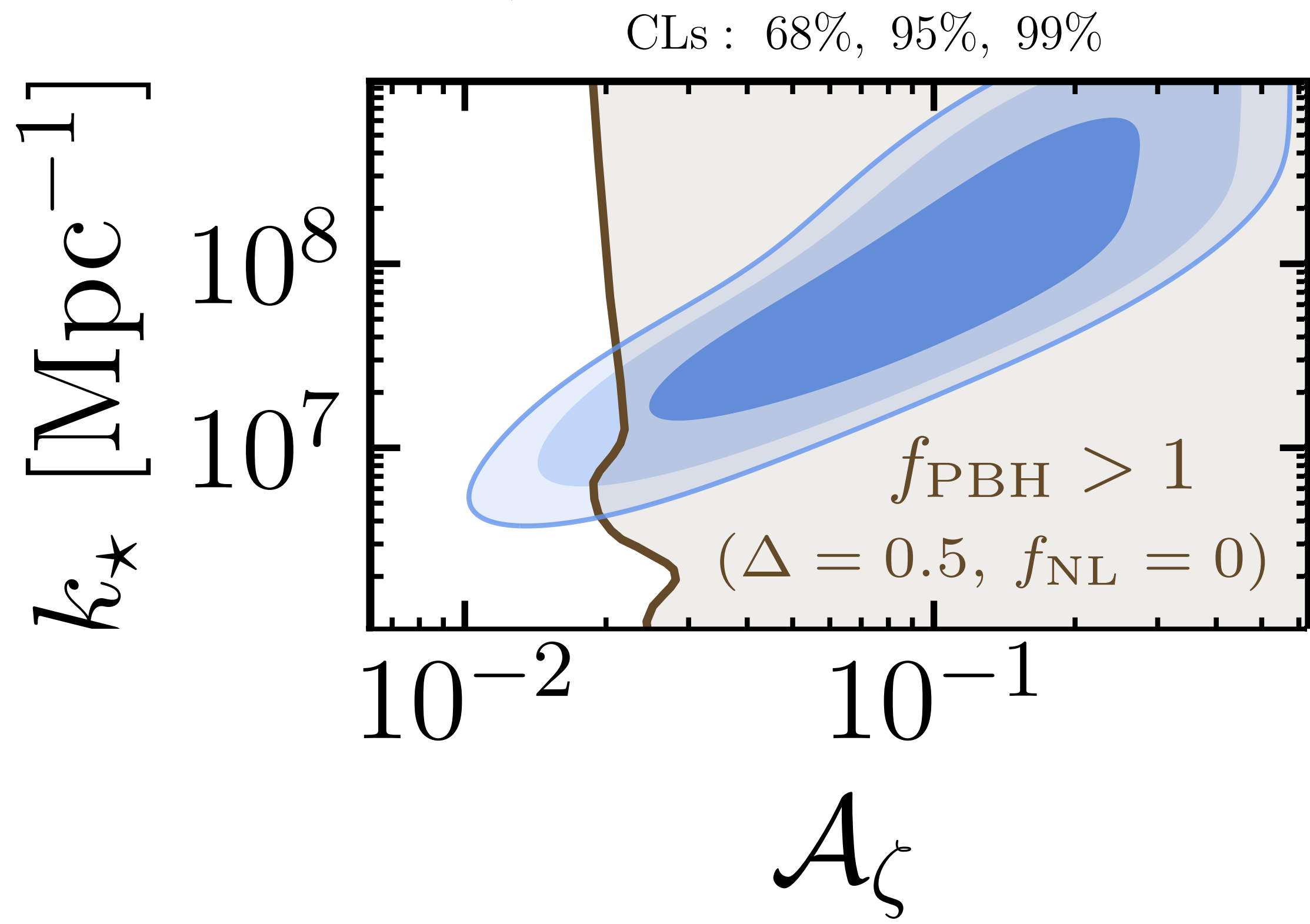
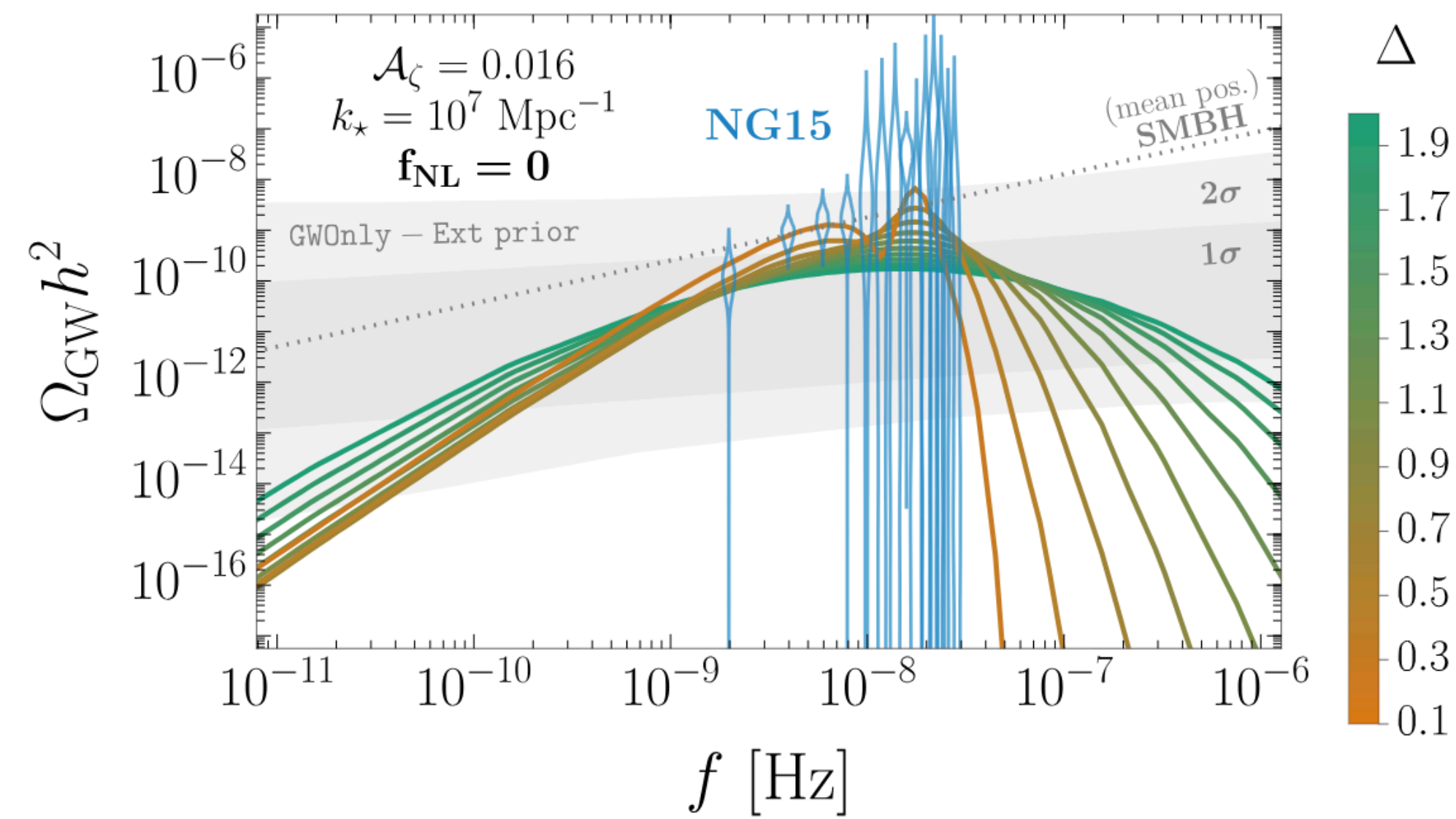
Prior on PBHs	SIGW / SMBH	
	$f_{\text{NL}} = 0$	$f_{\text{NL}} = -2$
No prior	2.17	2.28



$\mathcal{P}_h(k) \sim \mathcal{P}_{\mathcal{R}}^2(k)$

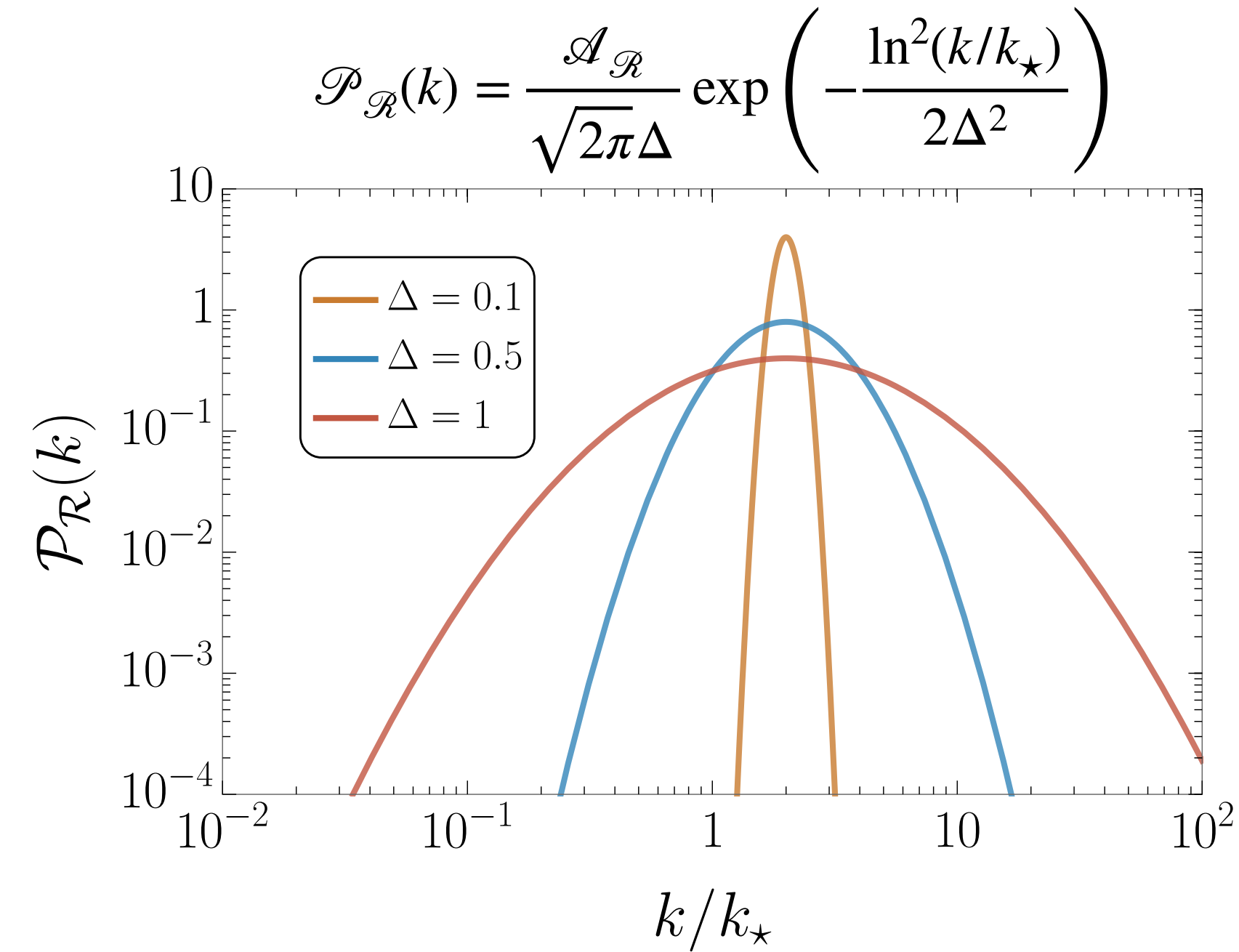
→

Scalar induced GW



NG15: SIGW (no PBH prior)

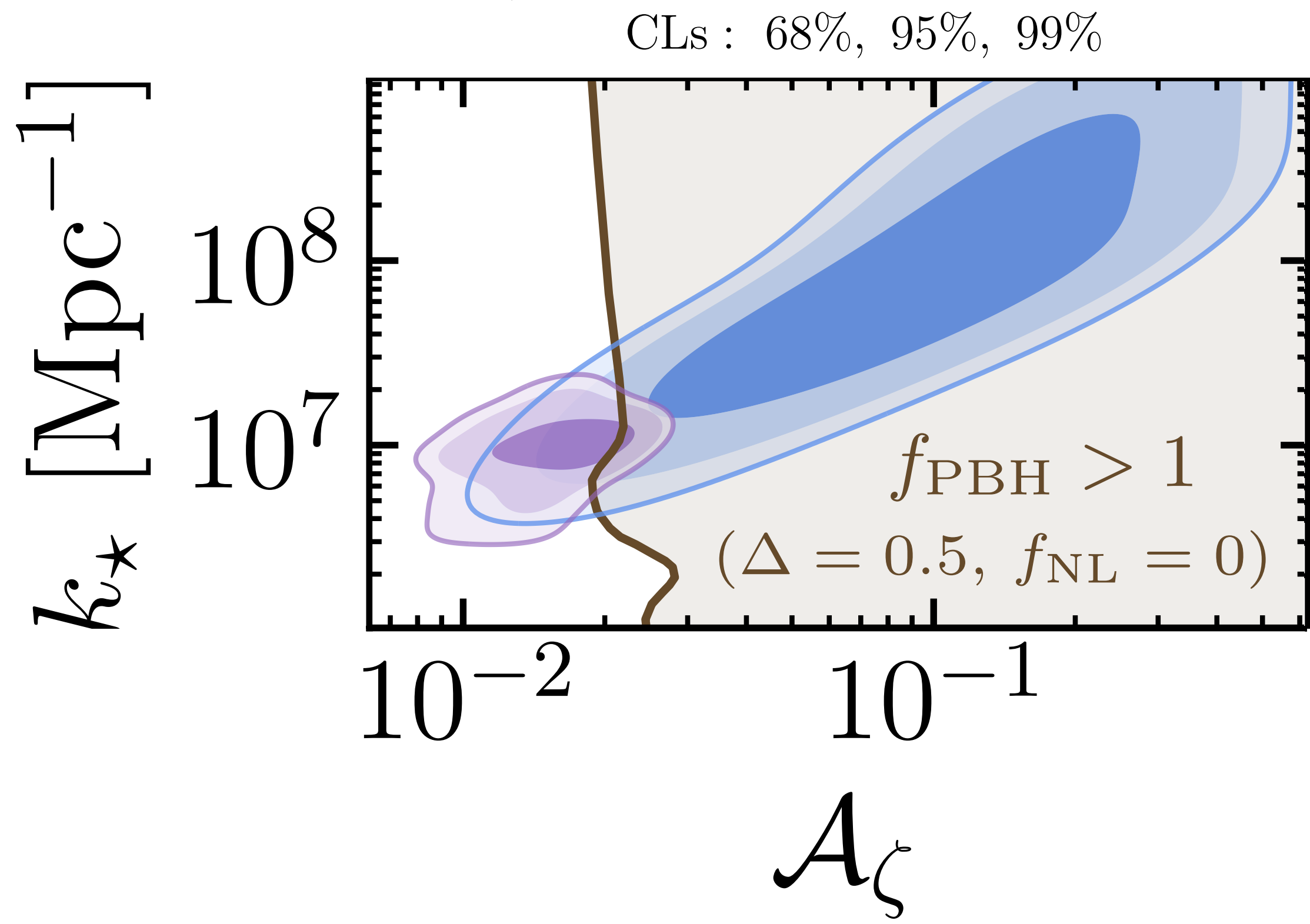
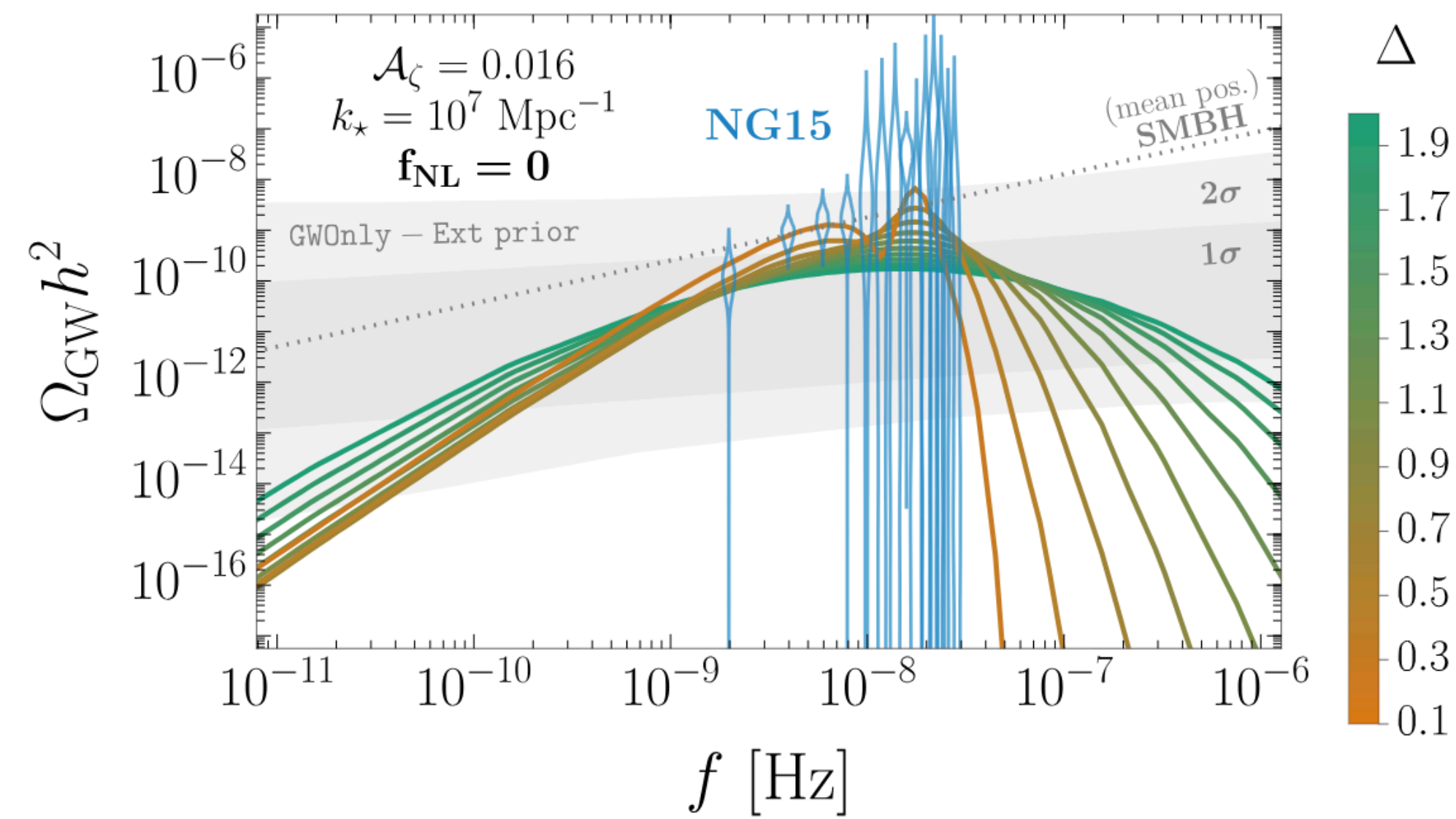
Prior on PBHs	SIGW / SMBH	
	$f_{\text{NL}} = 0$	$f_{\text{NL}} = -2$
No prior	2.17	2.28



$\mathcal{P}_h(k) \sim \mathcal{P}_{\mathcal{R}}^2(k)$

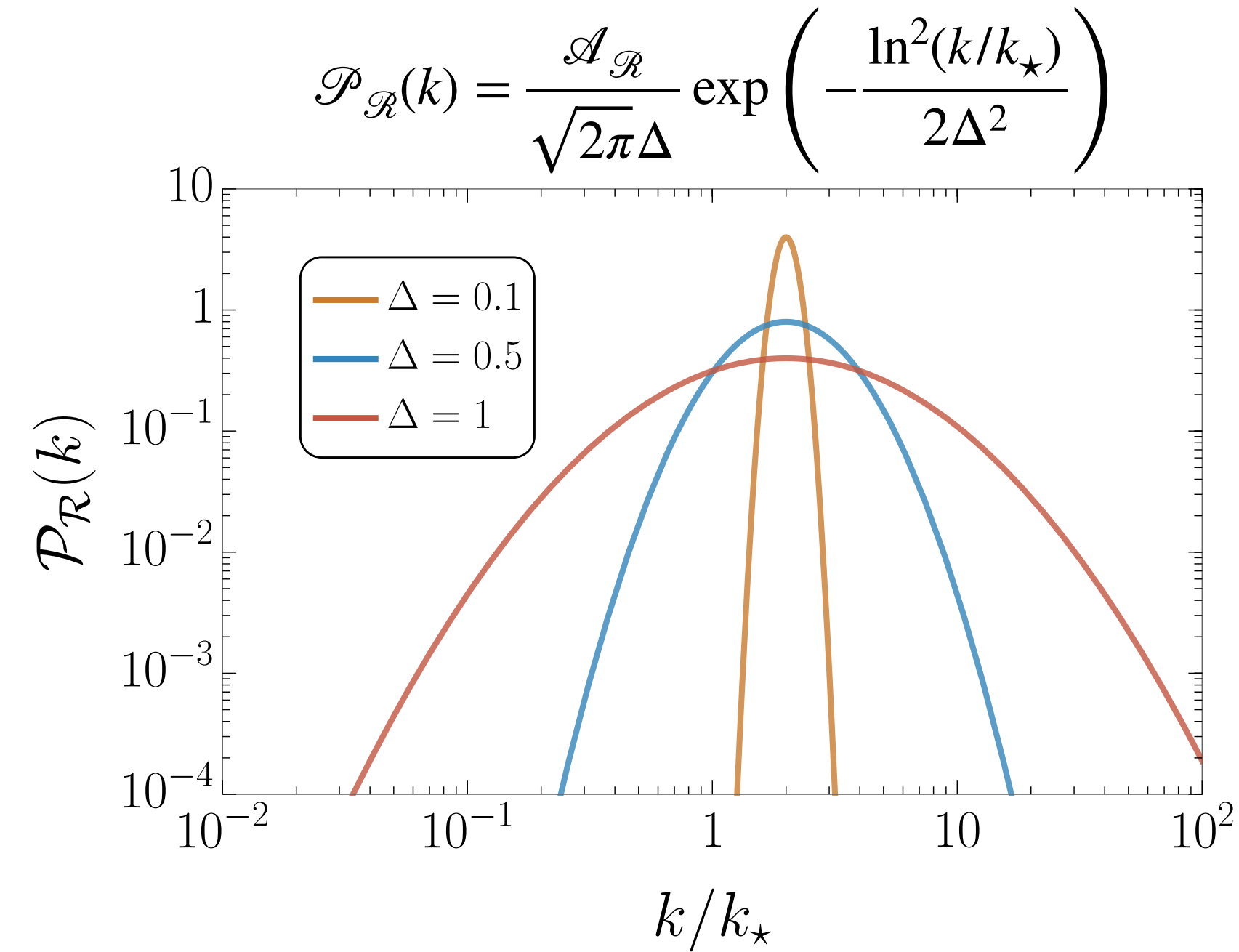
→

Scalar induced GW



- NG15: SIGW (no PBH prior)
- NG15: SIGW (astro PBH prior)

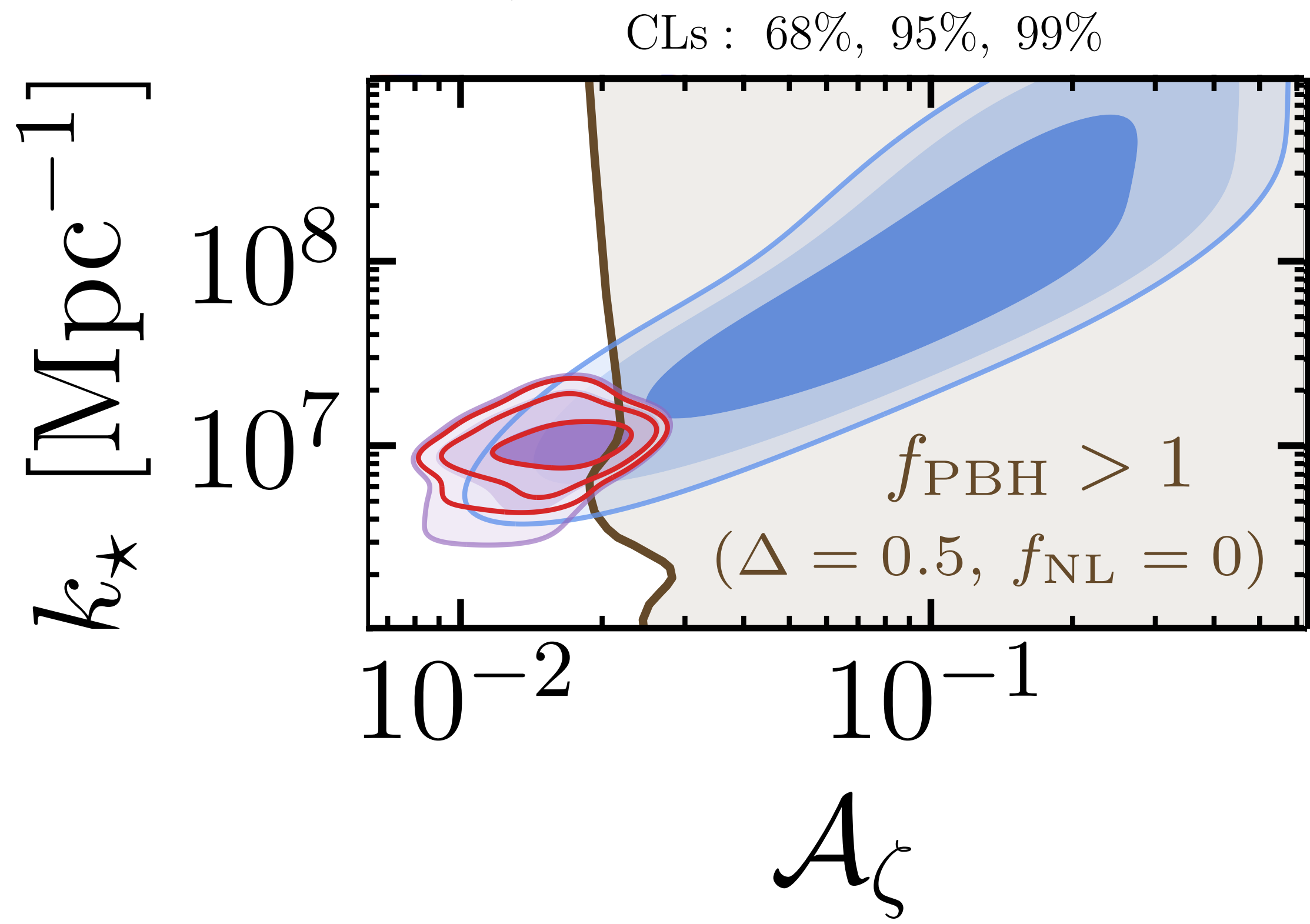
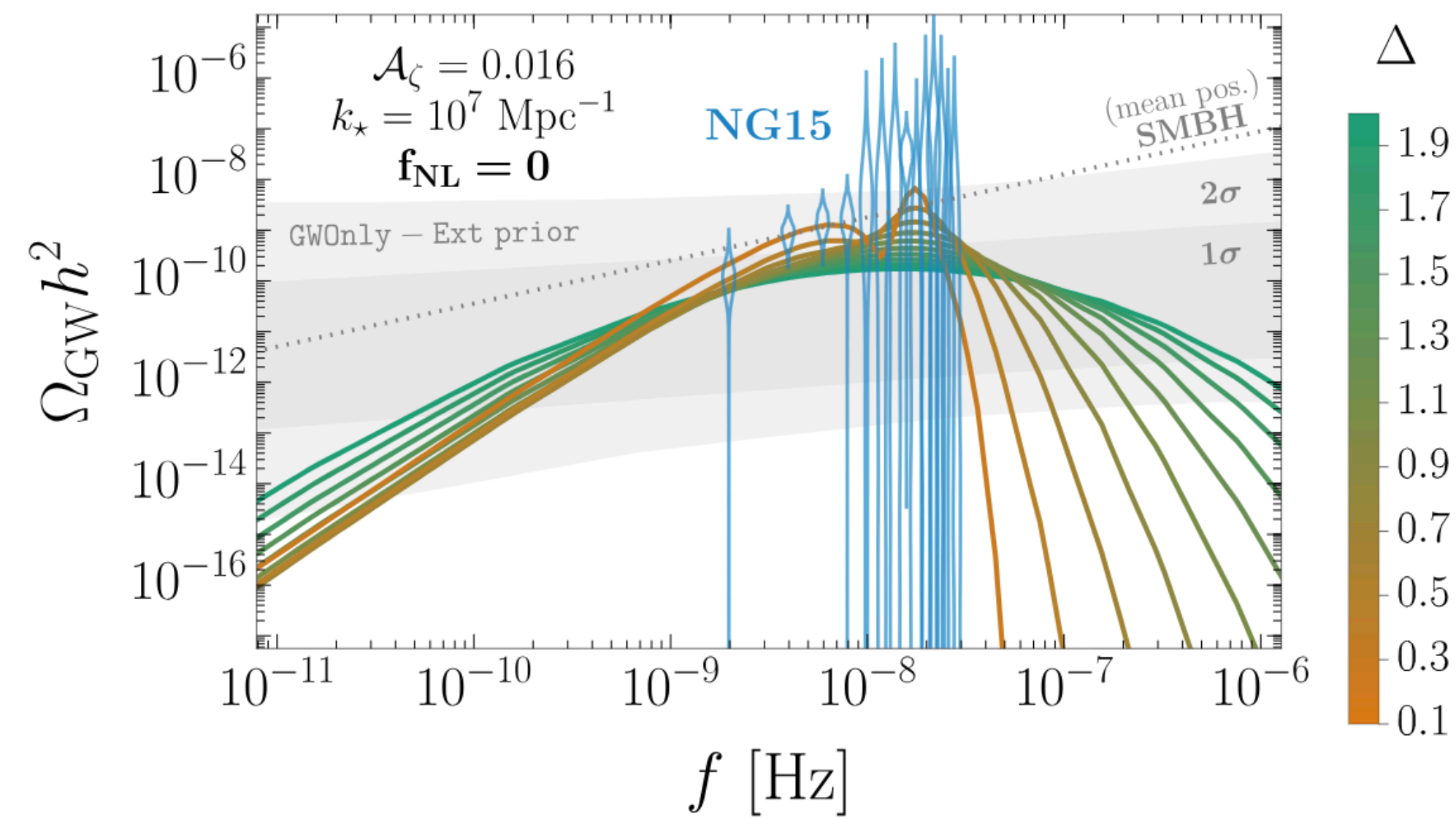
Prior on PBHs	SIGW / SMBH	
	$f_{\text{NL}} = 0$	$f_{\text{NL}} = -2$
No prior	2.17	2.28
Astrophysical	-0.90	-0.14



$\mathcal{P}_h(k) \sim \mathcal{P}_{\mathcal{R}}^2(k)$

→

Scalar induced GW

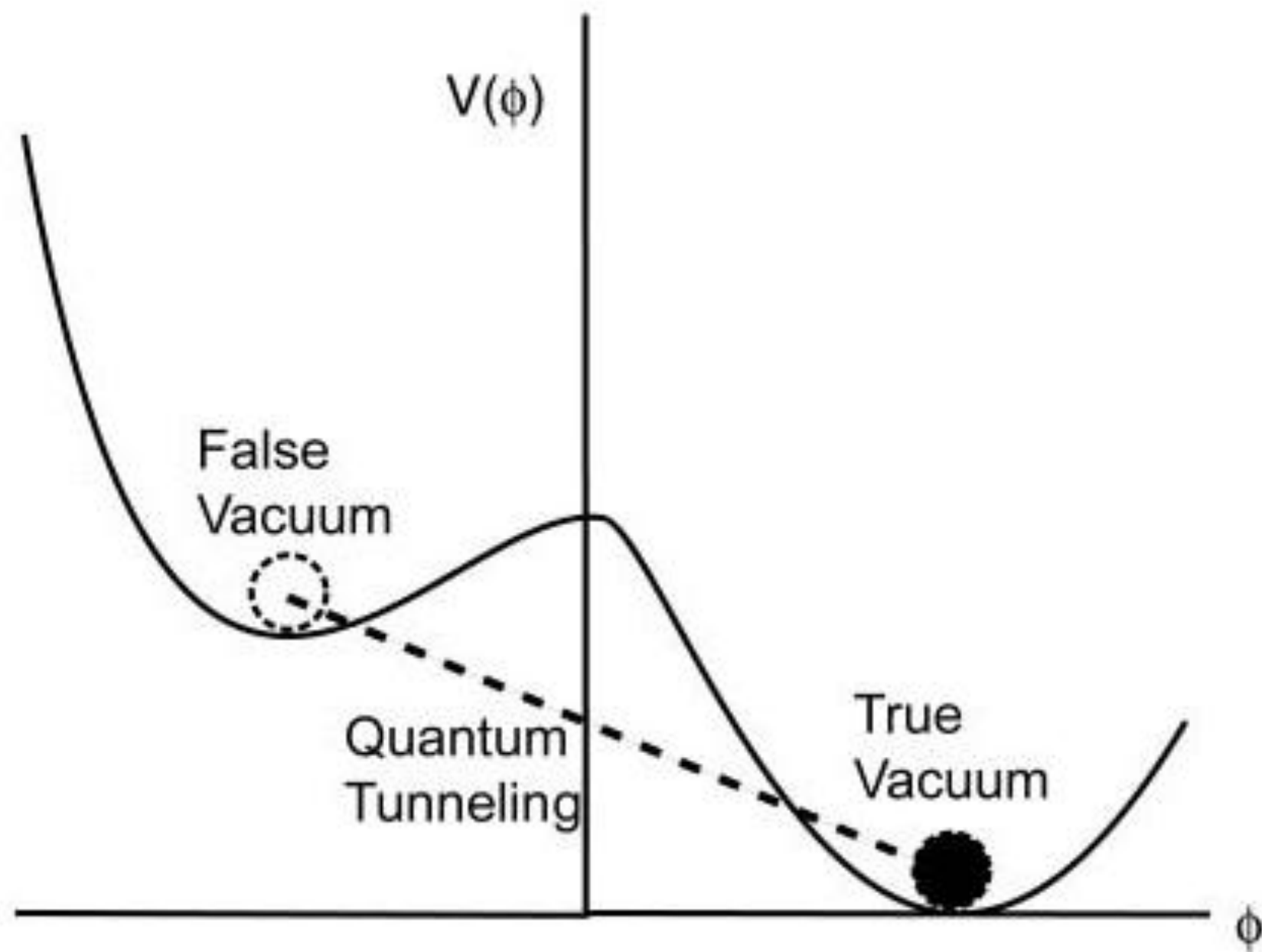


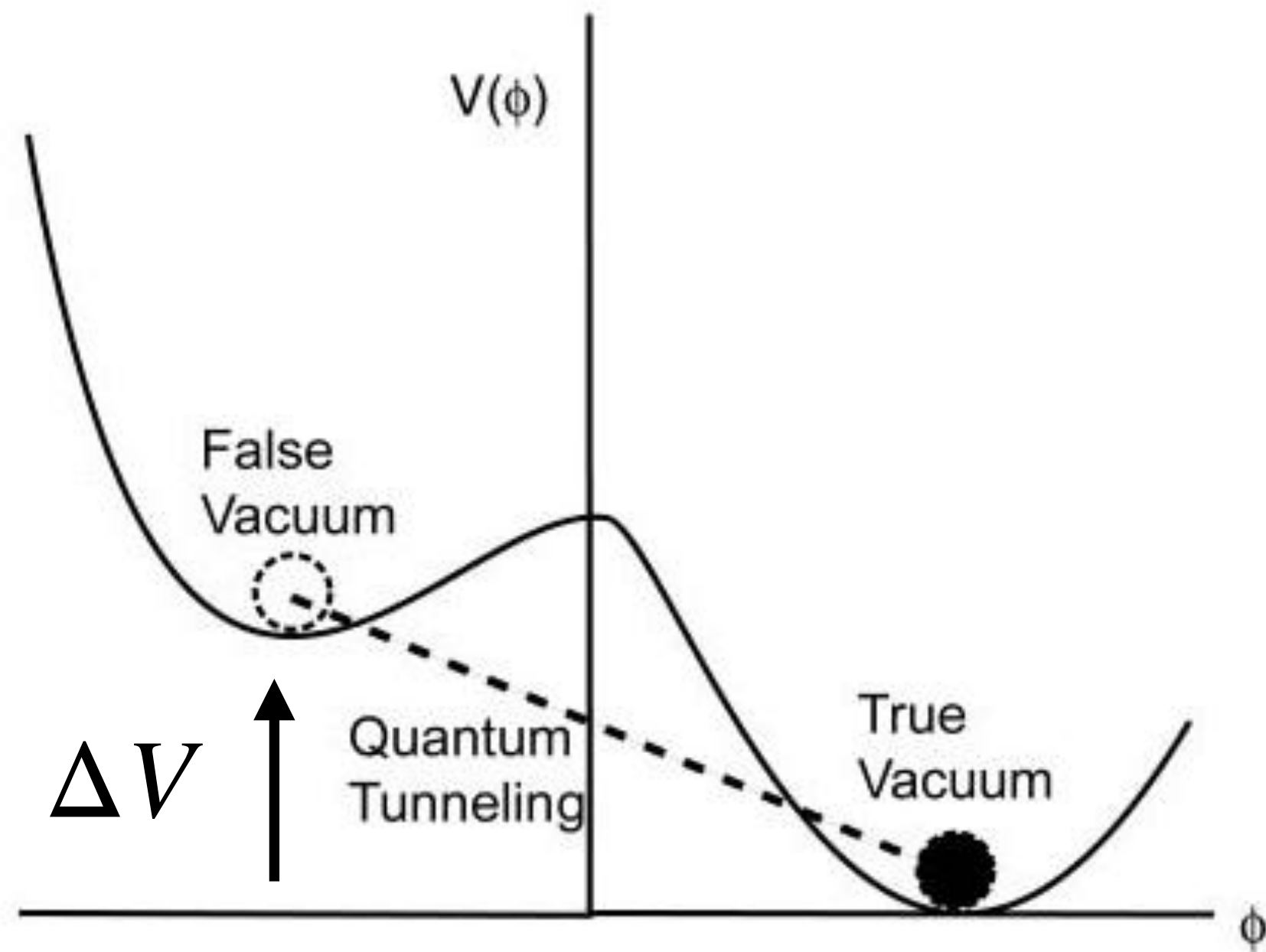
- NG15: SIGW (no PBH prior)
- NG15: SIGW (astro PBH prior)
- NG15: SIGW (sub-solar PBH prior)

Prior on PBHs		SIGW / SMBH	
		$f_{\text{NL}} = 0$	$f_{\text{NL}} = -2$
No prior		2.17	2.28
Astrophysical		−0.90	−0.14
Sub-solar	CE	0.55	1.33
	ET	0.72	1.51
	LVK O5	1.18	1.96
	LVK O4	1.22	2.15

PBHs from 1stOPT

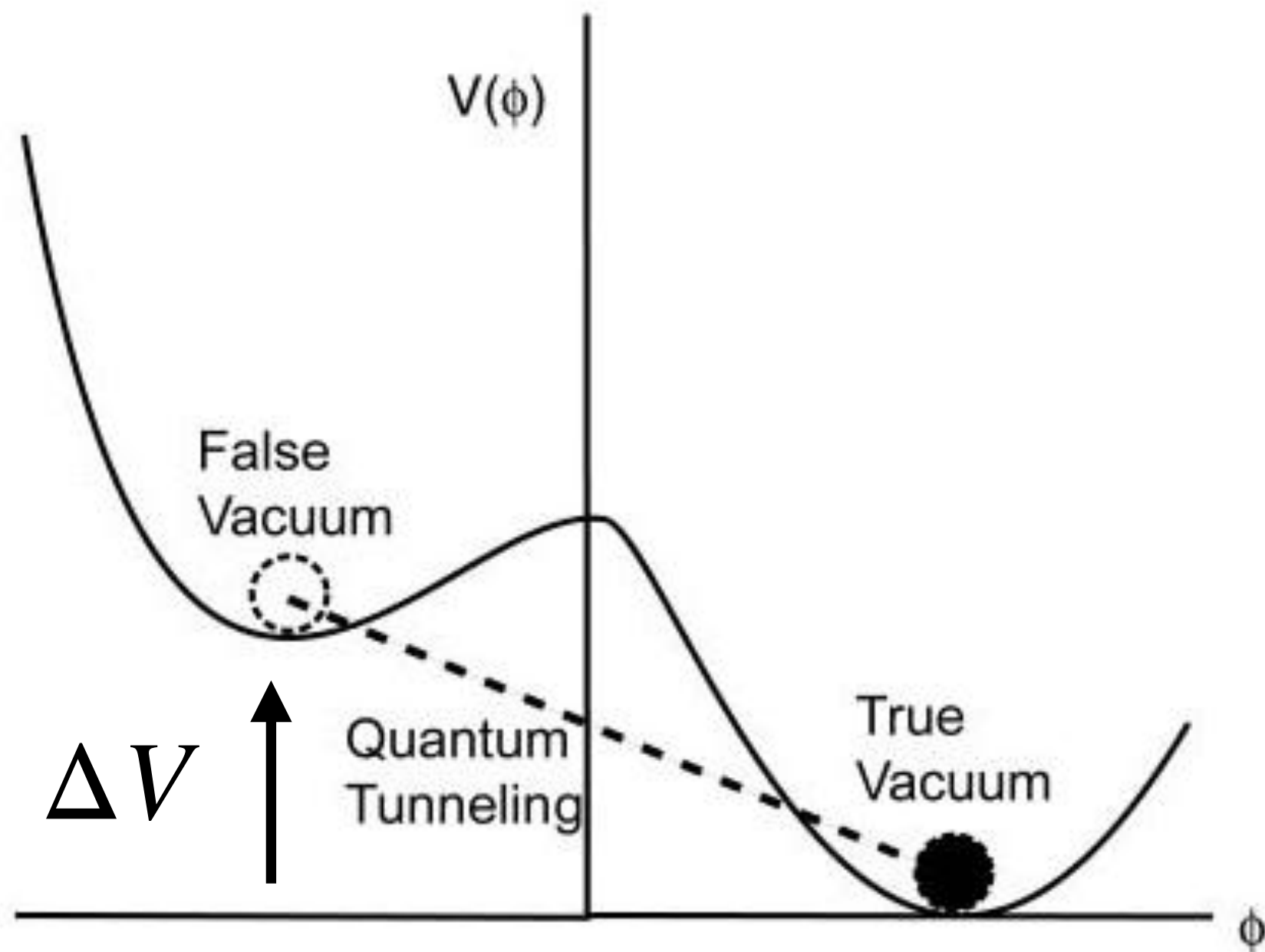
YG, Volansky 2305:04942





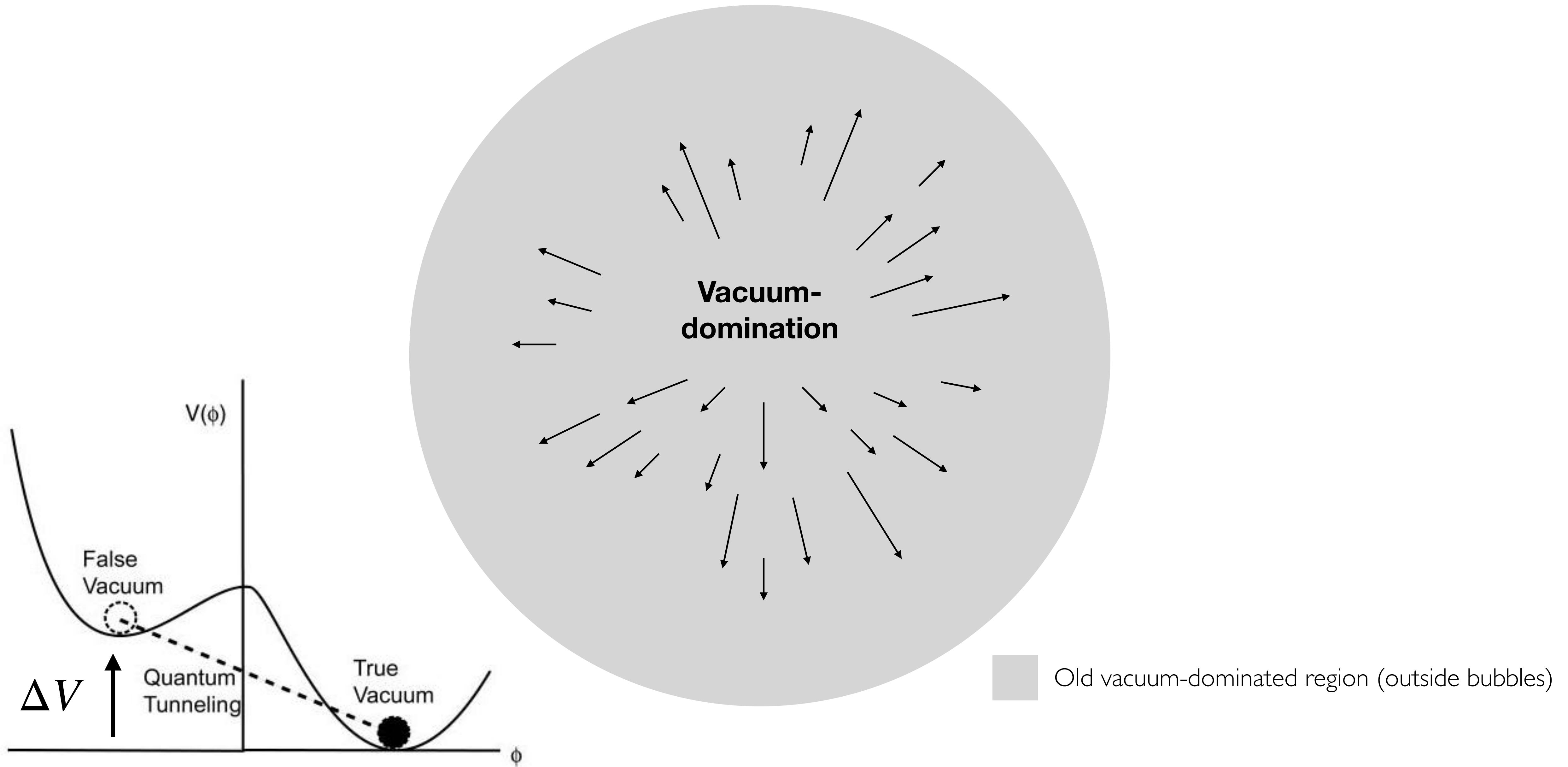
Strong 1st order PT:

$$\Delta V \gg \rho_{\text{rad}}$$



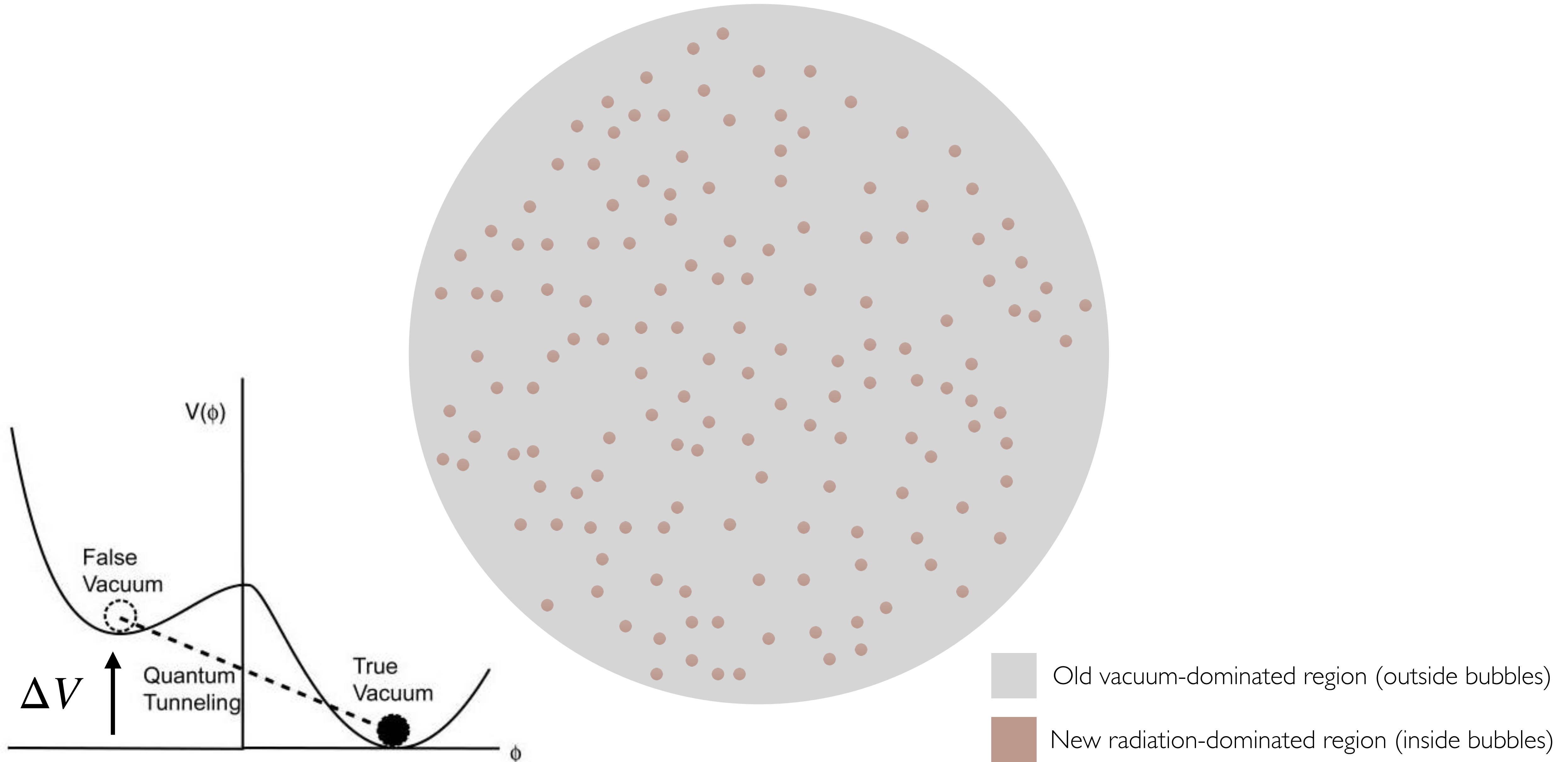
PBHs from 1stOPT

YG, Volansky 2305:04942



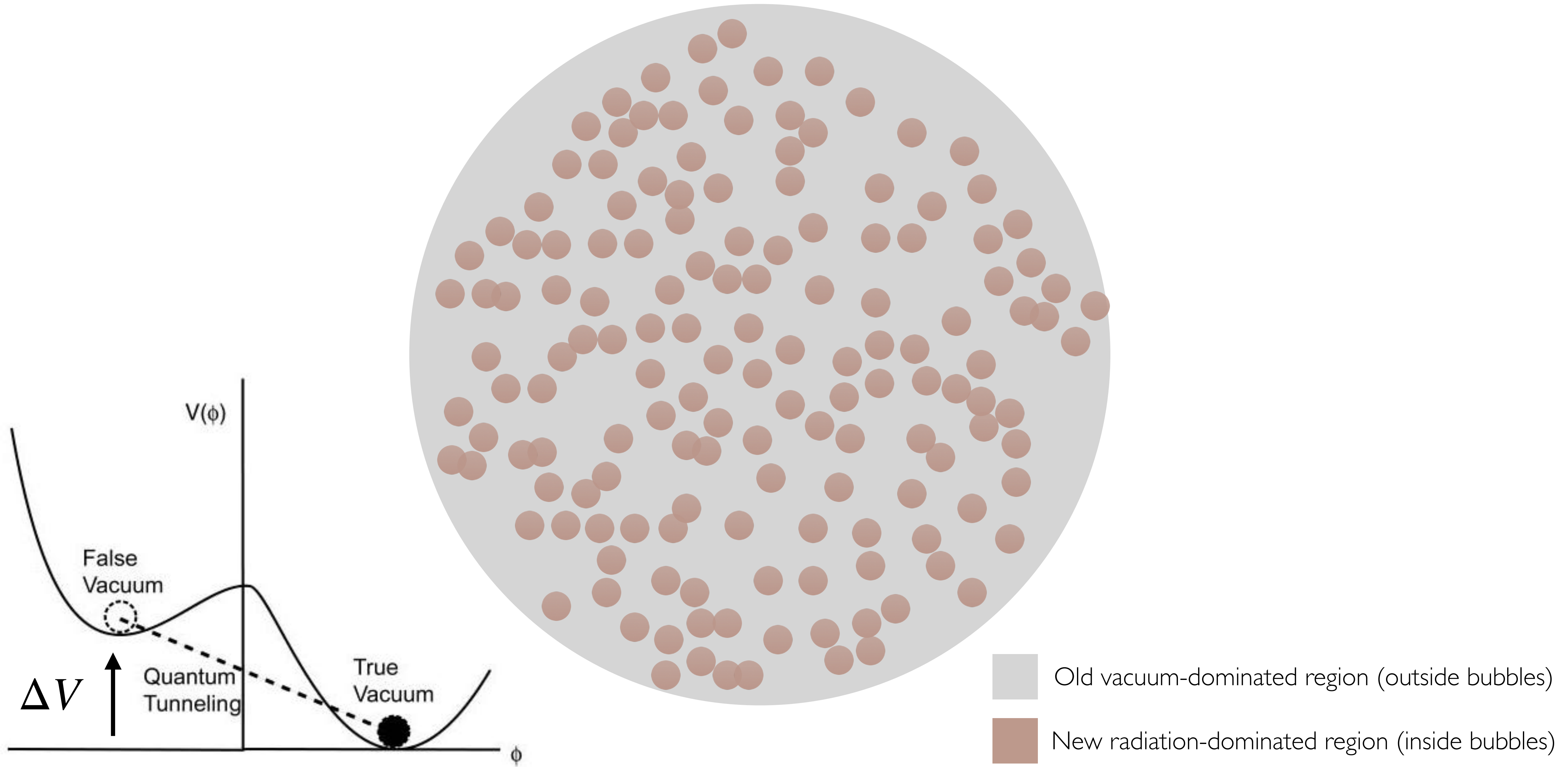
PBHs from 1stOPT

YG, Volansky 2305:04942



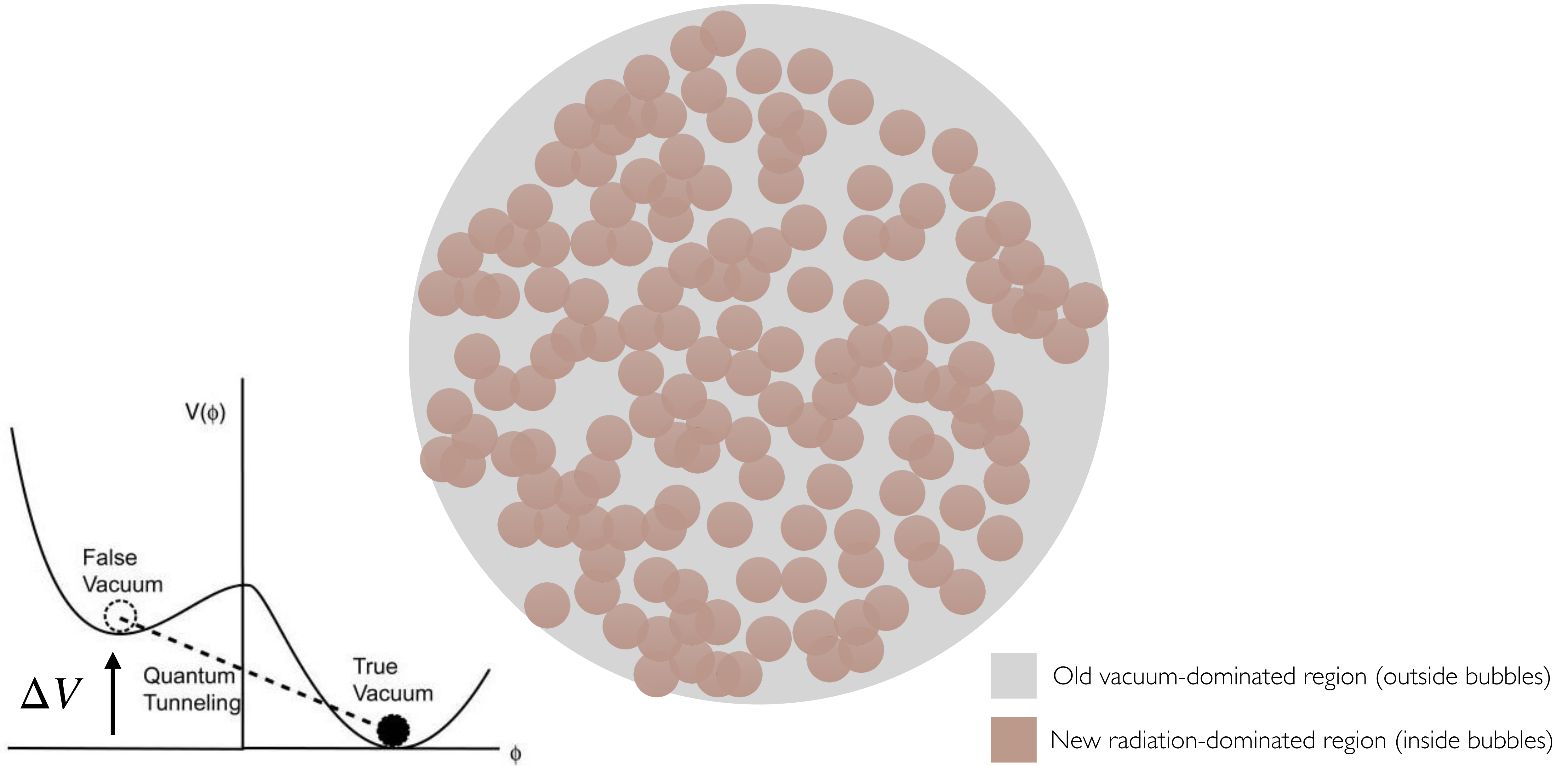
PBHs from 1stOPT

YG, Volansky 2305:04942



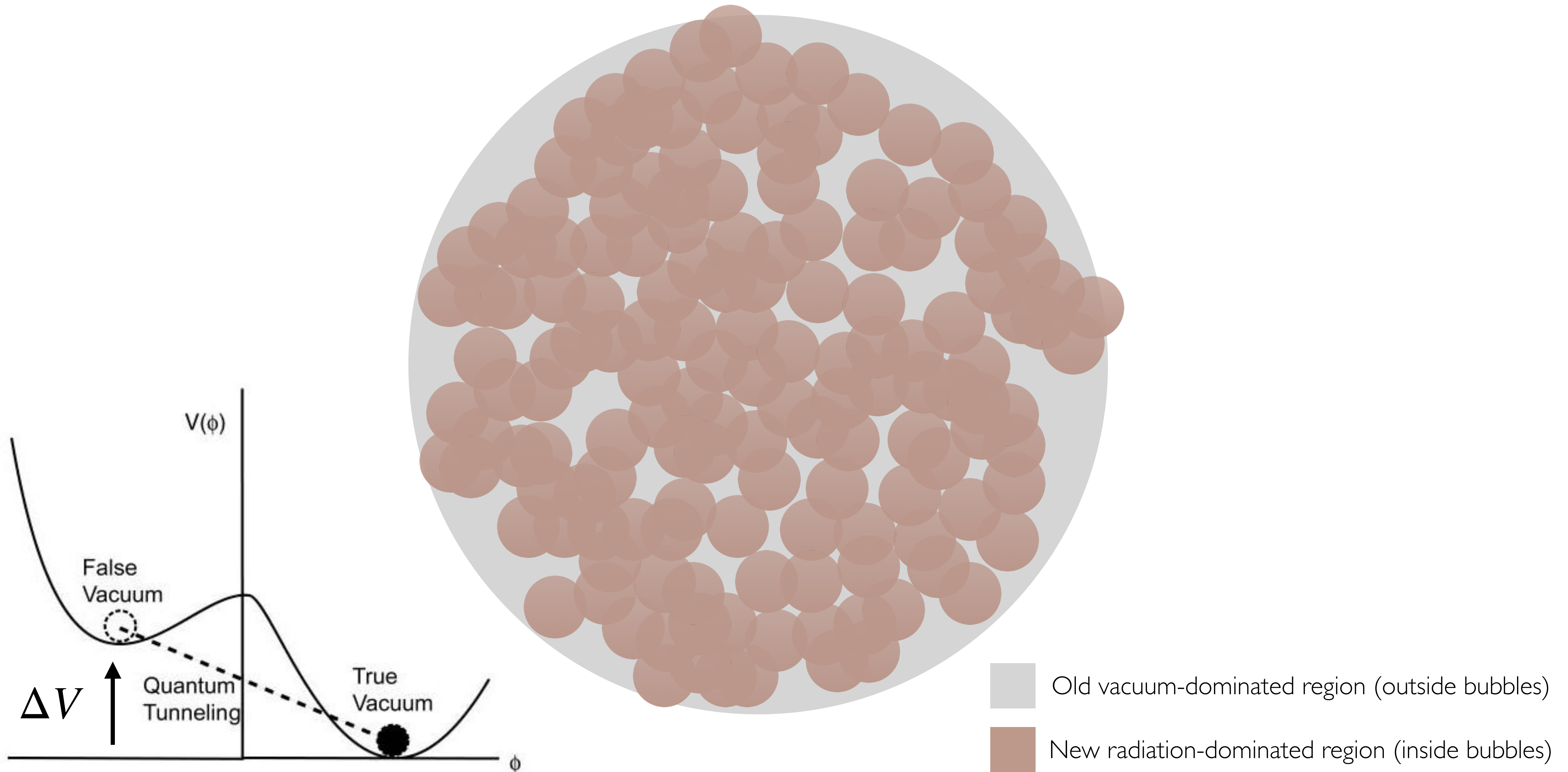
PBHs from 1stOPT

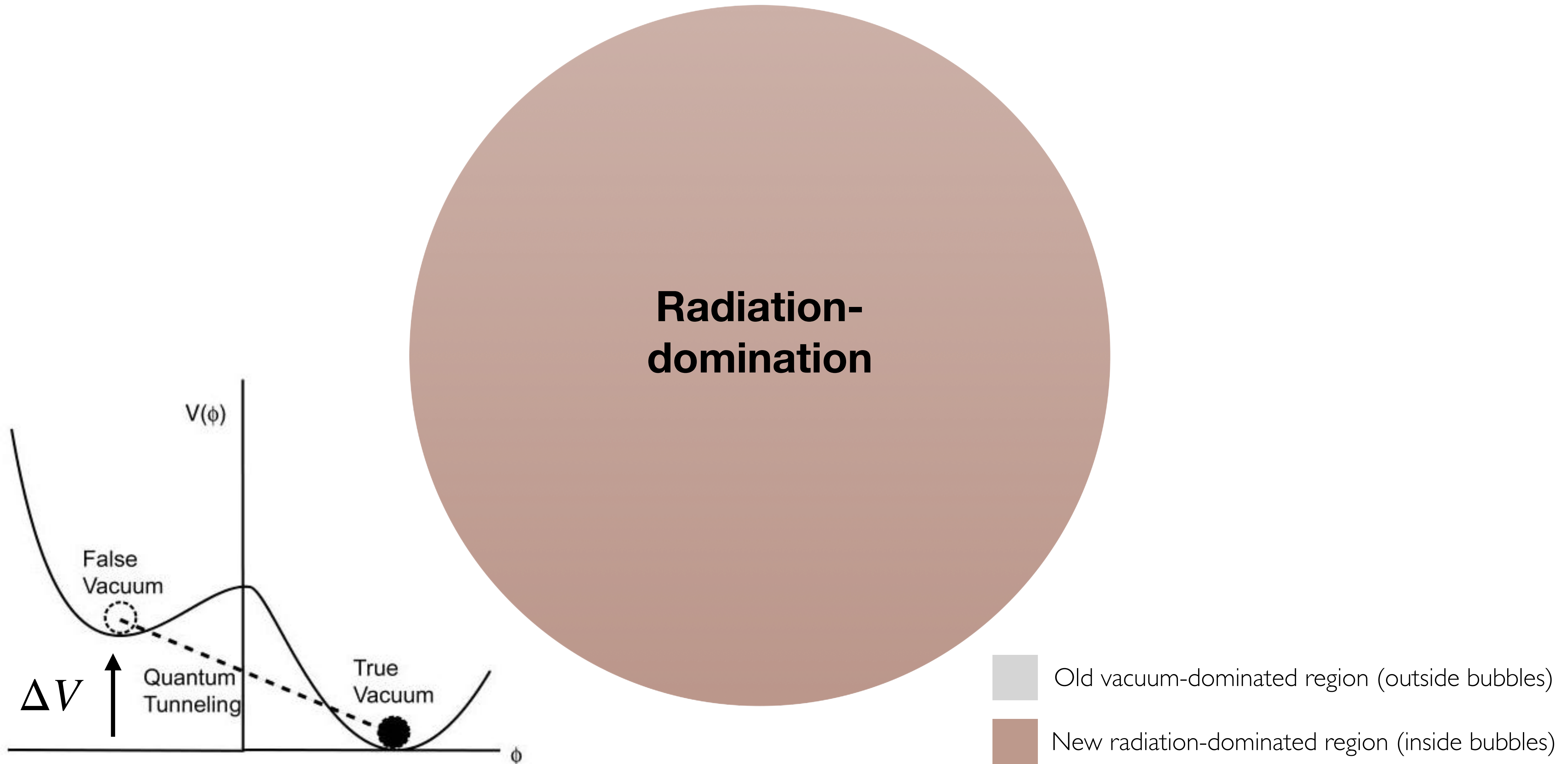
YG, Volansky 2305:04942



PBHs from 1stOPT

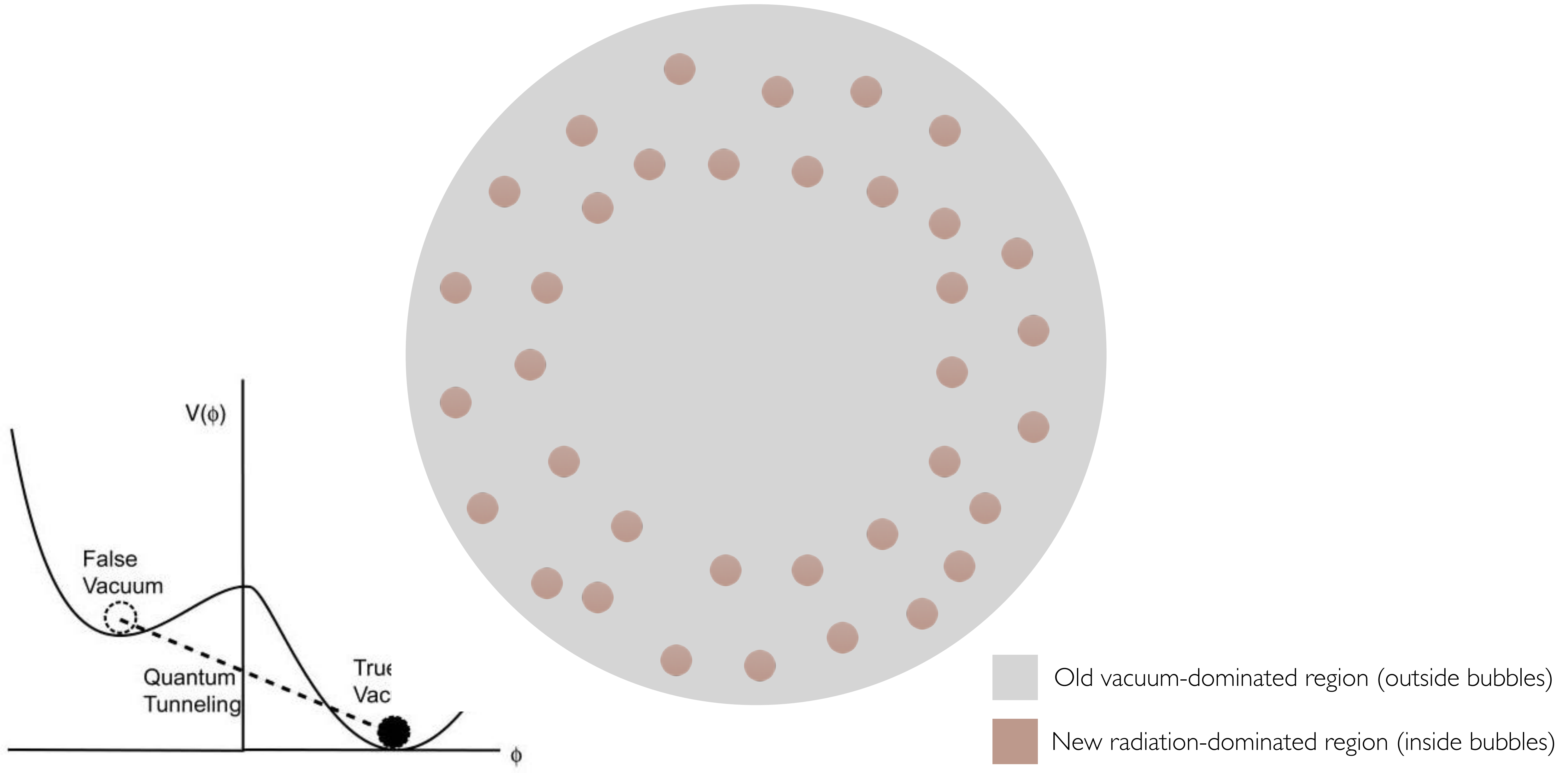
YG, Volansky 2305:04942





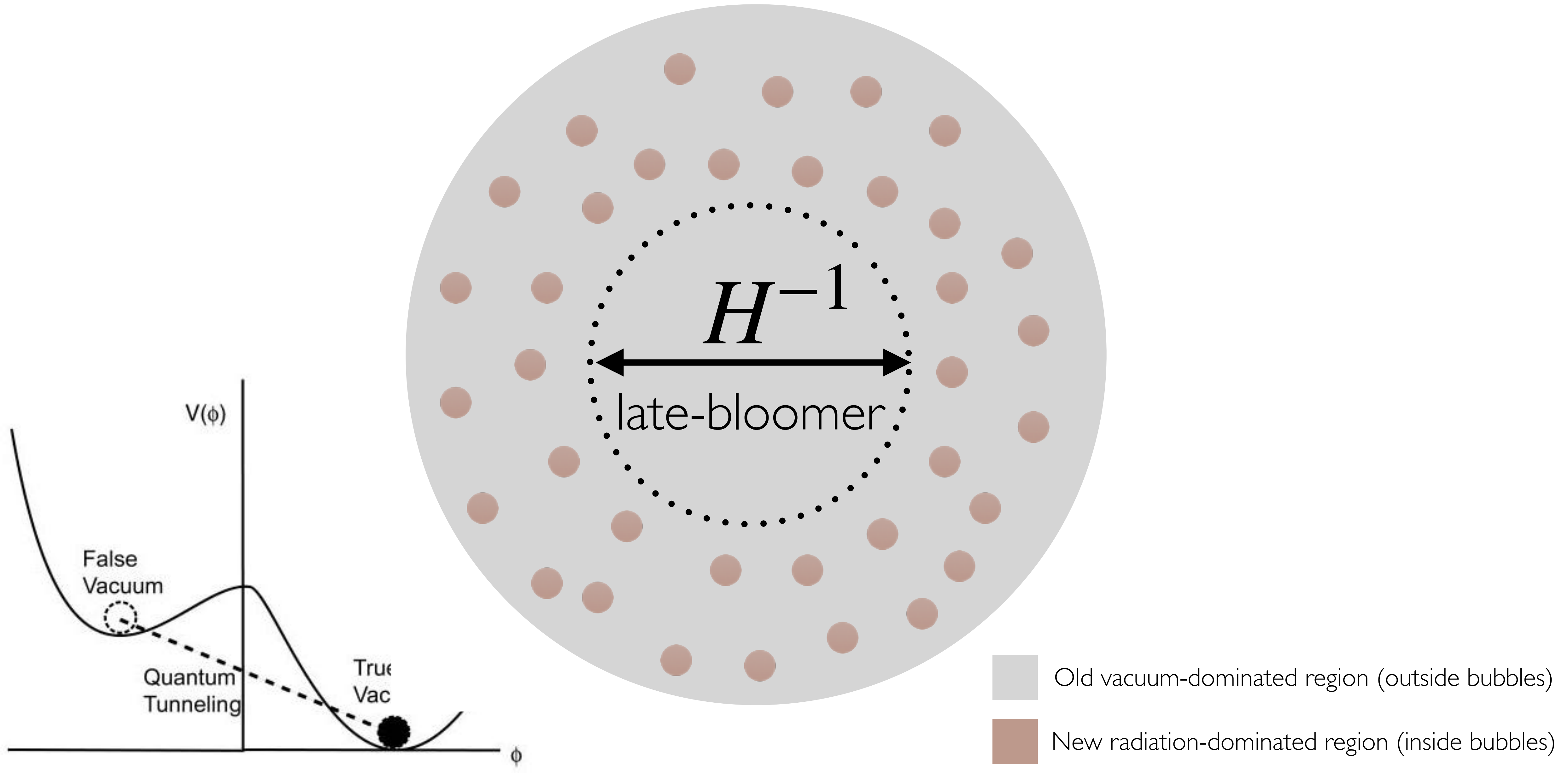
PBHs from 1stOPT

YG, Volansky 2305:04942



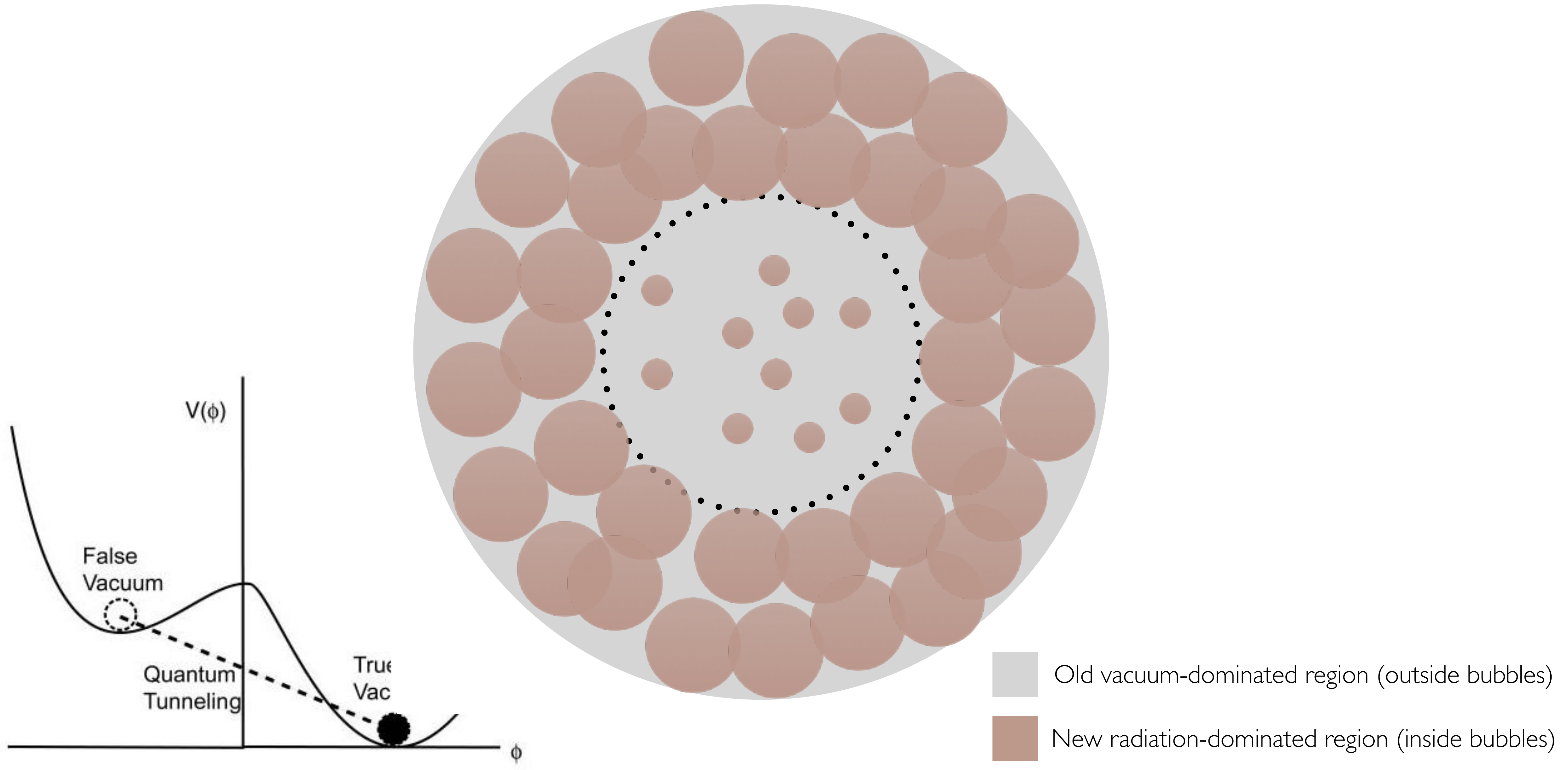
PBHs from 1stOPT

YG, Volansky 2305:04942



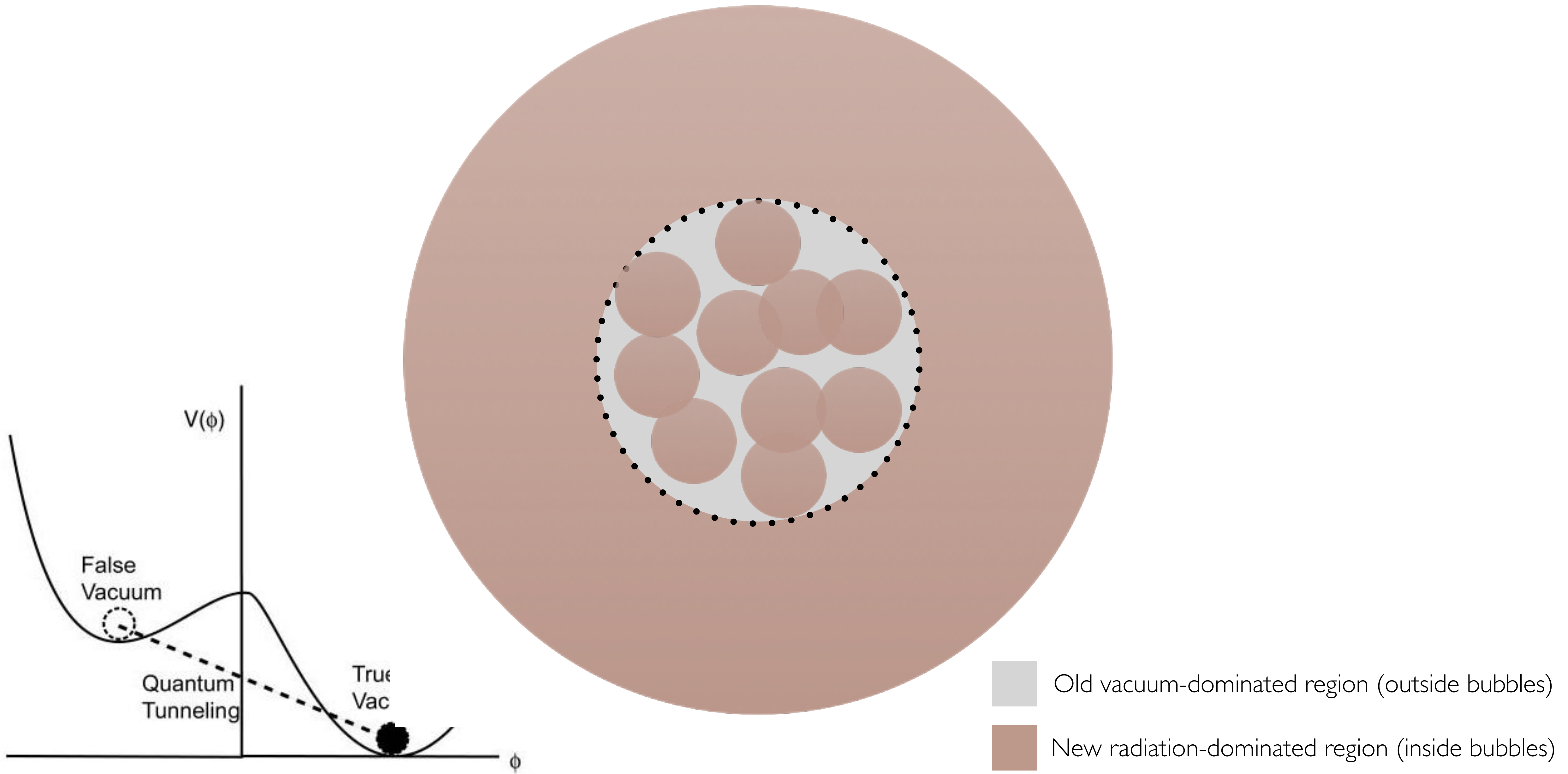
PBHs from 1stOPT

YG, Volansky 2305:04942



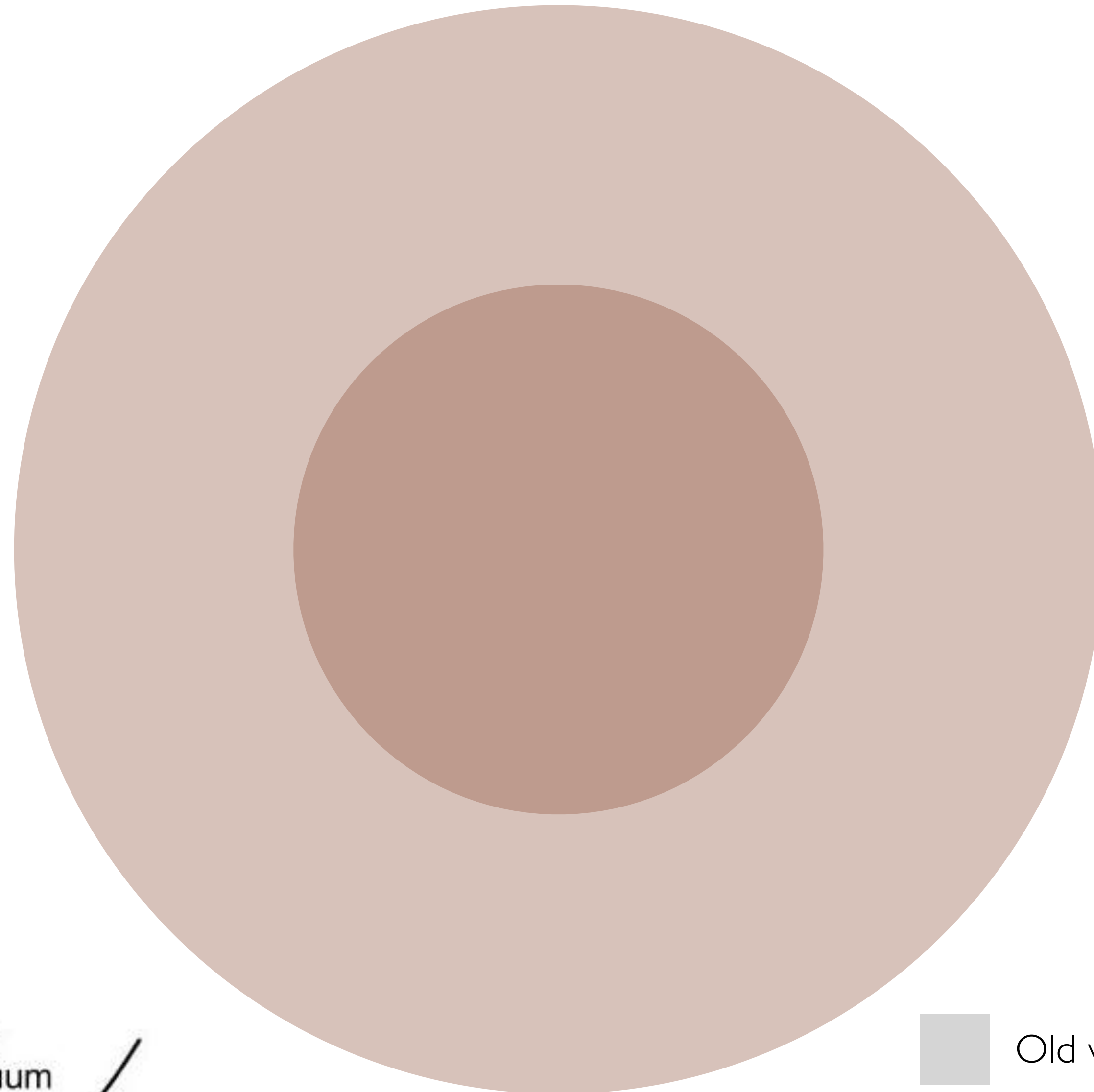
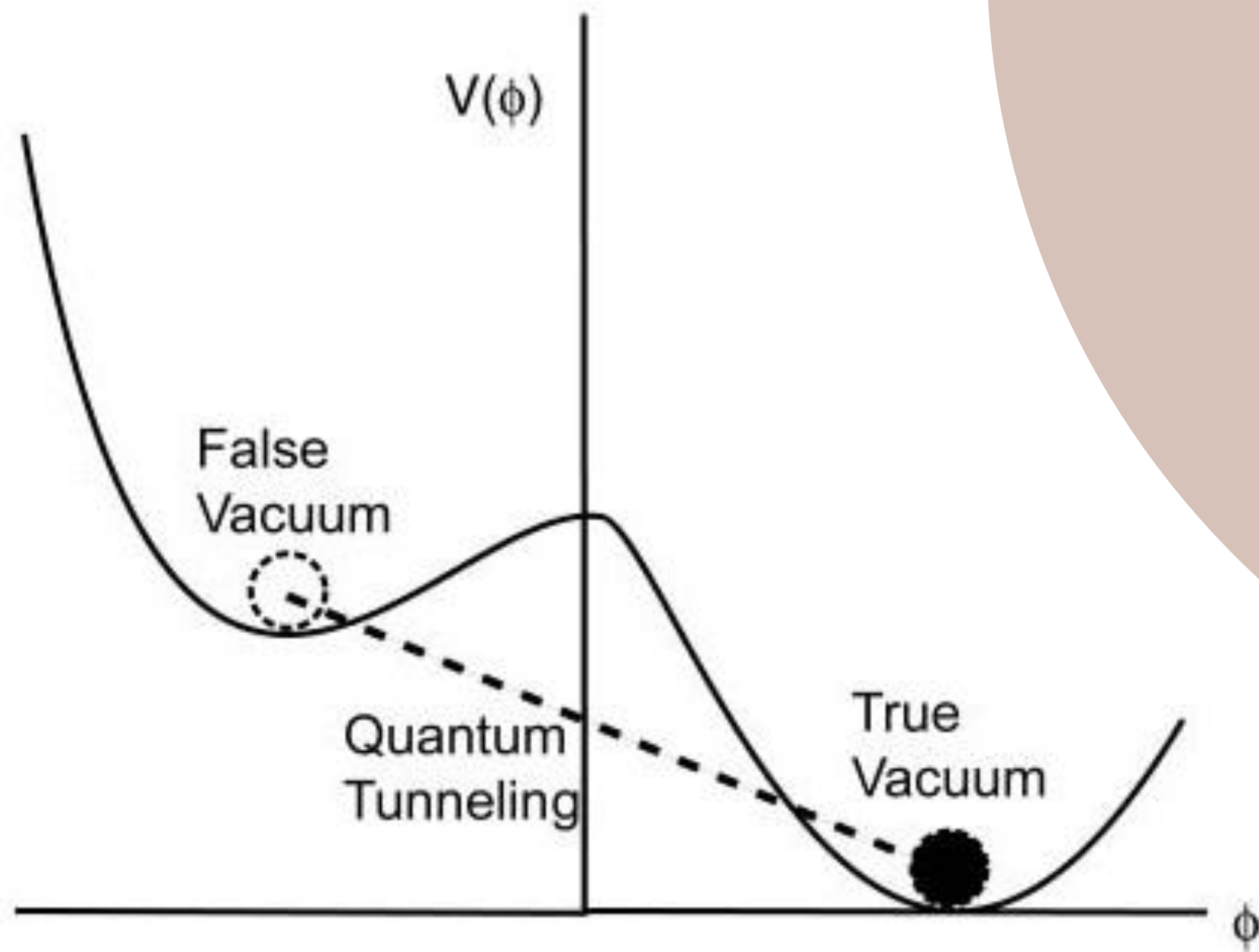
PBHs from 1stOPT

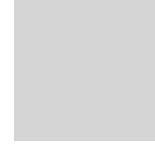
YG, Volansky 2305:04942



PBHs from 1stOPT

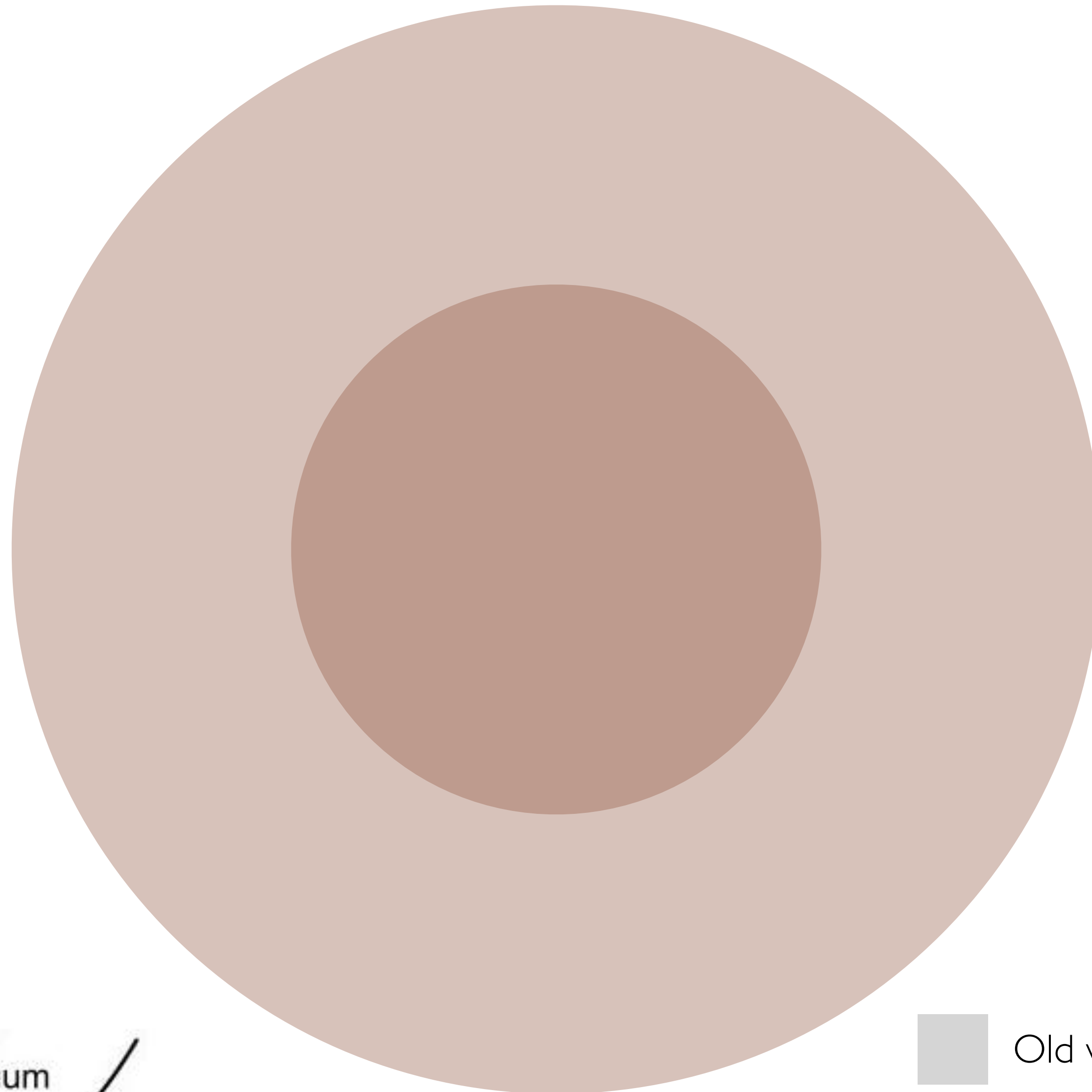
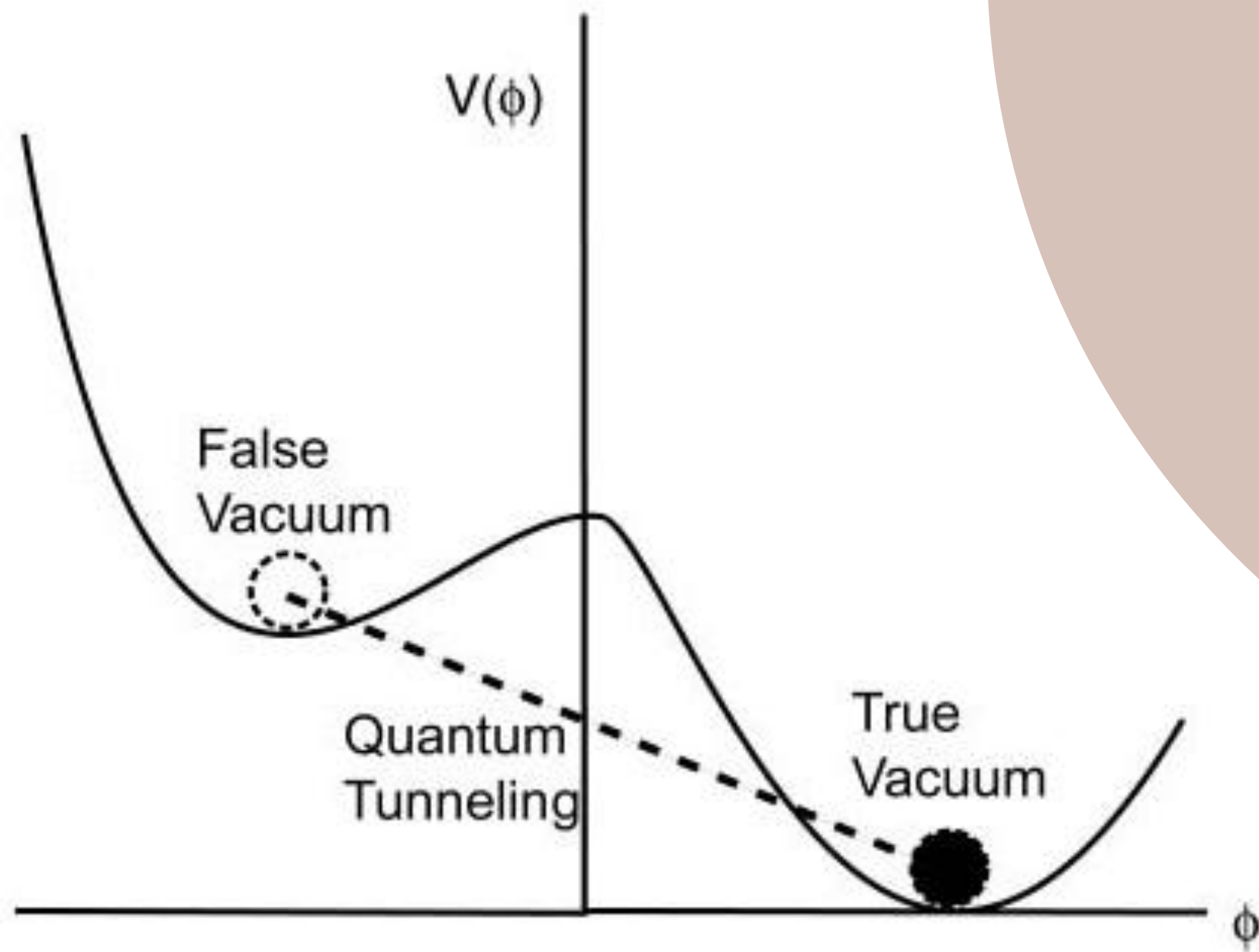
YG, Volansky 2305:04942



-  Old vacuum-dominated region (outside bubbles)
-  New radiation-dominated region (inside bubbles)

if

$$\delta\rho/\rho \gtrsim 0.50.$$



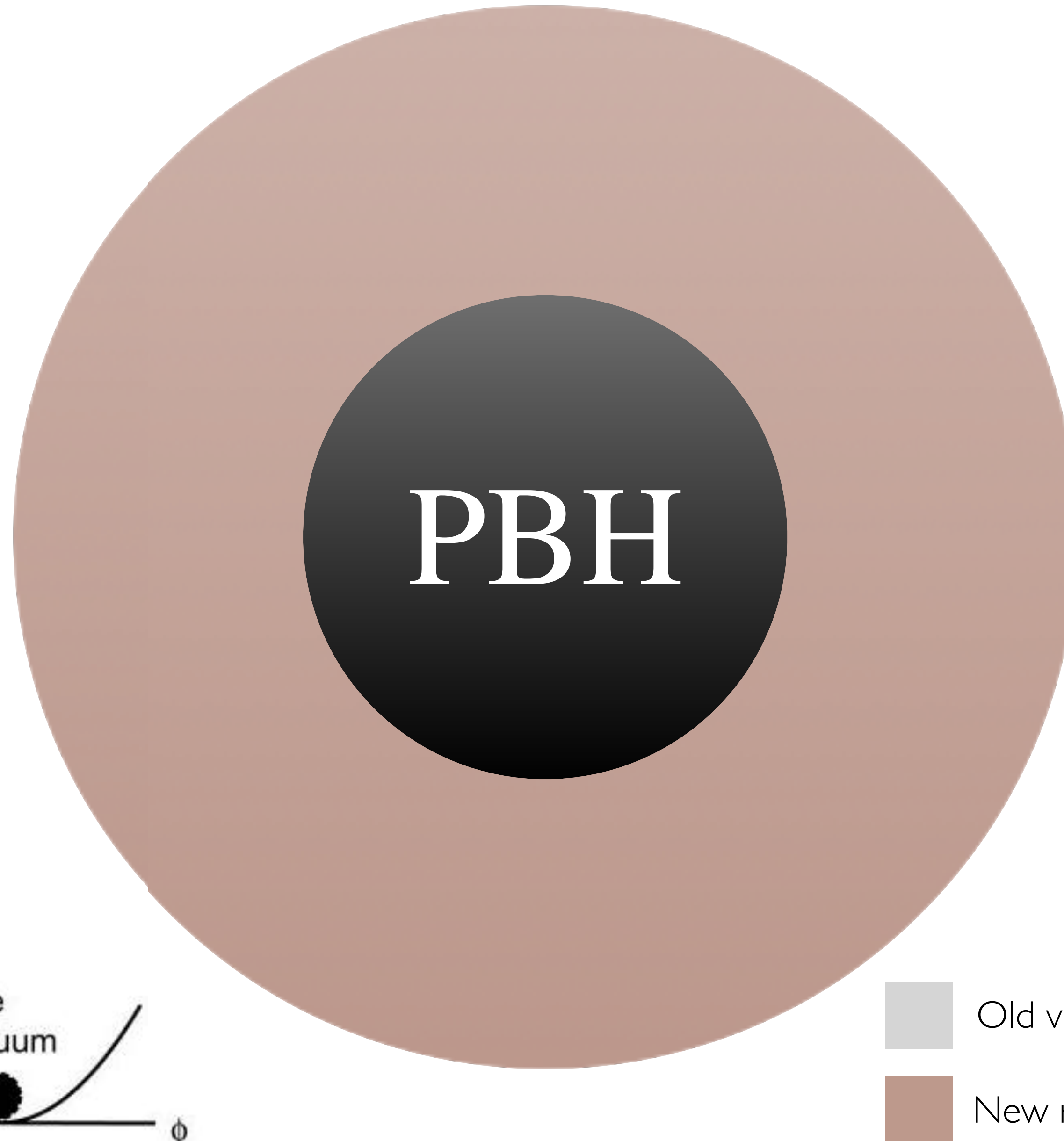
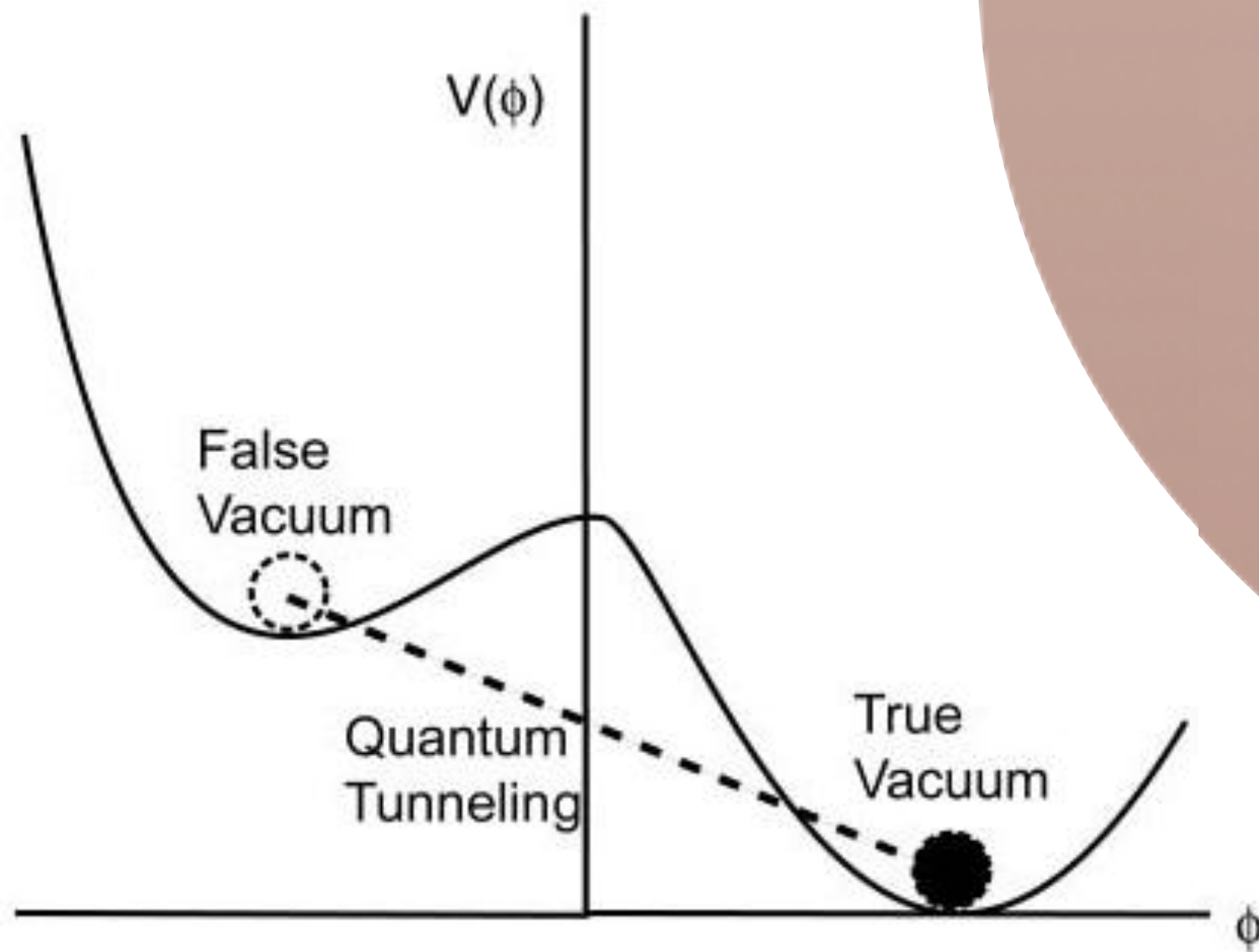
-  Old vacuum-dominated region (outside bubbles)
-  New radiation-dominated region (inside bubbles)

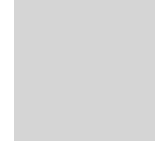
if

$$\delta\rho/\rho \gtrsim 0.50.$$

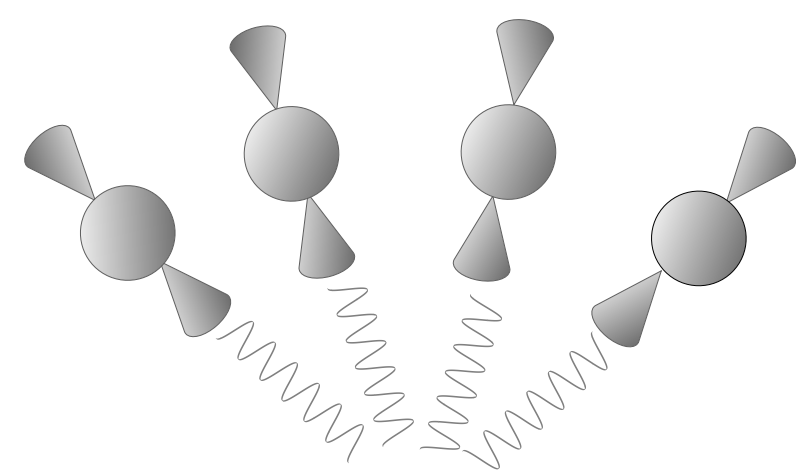
then

PBH



-  Old vacuum-dominated region (outside bubbles)
-  New radiation-dominated region (inside bubbles)

Pulsar Timing Arrays
(PTA)



Bian+ 2021, Lu+ 2022, Lewicki+ 2023,
YG&Volansky 2023, Baldes+ 2023, Lewicki+ PRL 2024,
.....

$$\delta\dot{\rho} + 3H(\delta\rho + \delta p) = 0$$

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

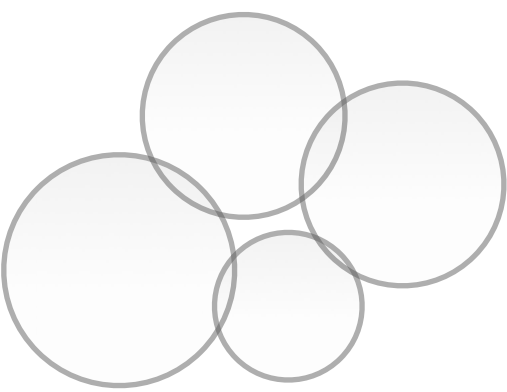
Spatially-flat gauge
 $\Phi = 0$

~~$ds^2 = (1 + 2\Phi) dt^2 - a^2(1 - 2\Phi) d\mathbf{x}^2$~~
INhomogeneously expanding universe

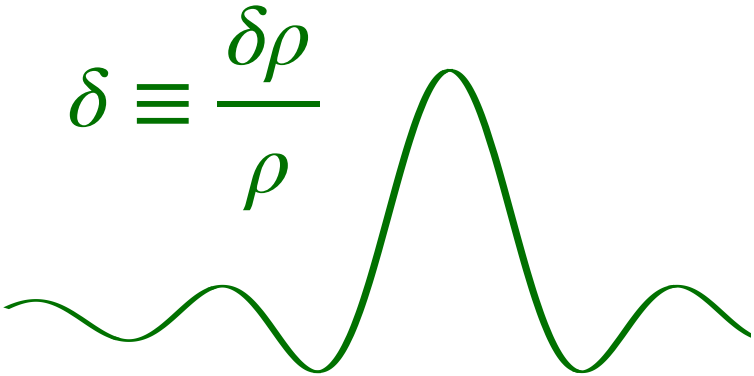
(GWs)
Gravitational
Waves



First-order
phase transition



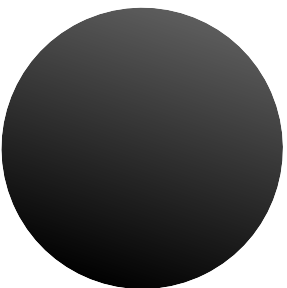
overdensities



collapses if

$$\delta \gtrsim 0.5$$

Key result :
Spatially-flat gauge
 $\delta \gtrsim 5$



PBH

Musco 1809.02127
Escriva, Germani, Sheth 1907.13311

Comoving gauge

Franciolini, YG, Jinno, 2503.01962

