Charting new particle physics with primordial GWs

LIO & STAR workshop 2022
23.06.2022

based on
1912.02569 Cosmic-string GW (model-independent)
1912.03245 Cosmic-string GW probes heavy & unstable particles
2108.10328, 2111.01150
Primordial GWs probe kination era and axion physics.

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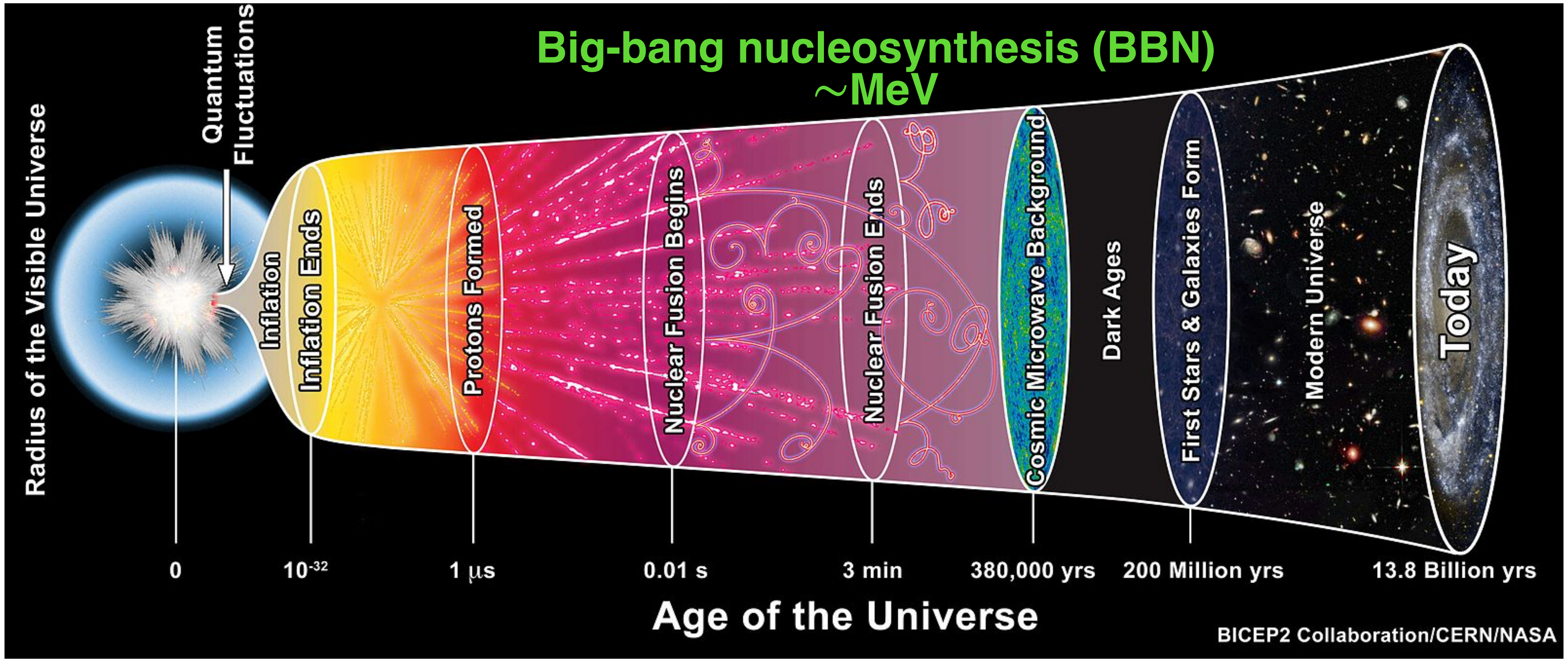
with
Peera Simakachorn (DESY & U.Hamburg),
Géraldine Servant (DESY & U.Hamburg)

Funded by
Azrieli International Postdoctoral Fellows
Fondation Azrieli Foundation

Courtesy of Peera Simakachorn

History of the Universe

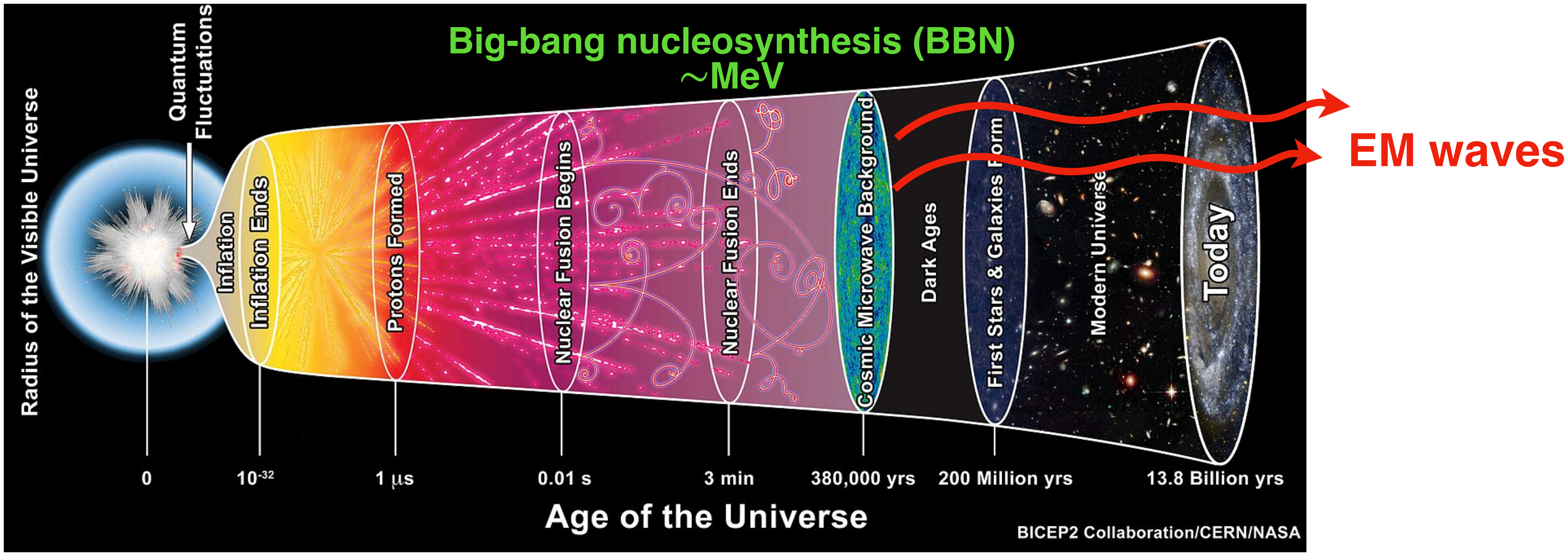
high energies ← low energies



History of the Universe

high energies ⟵ low energies

⟶ well-tested



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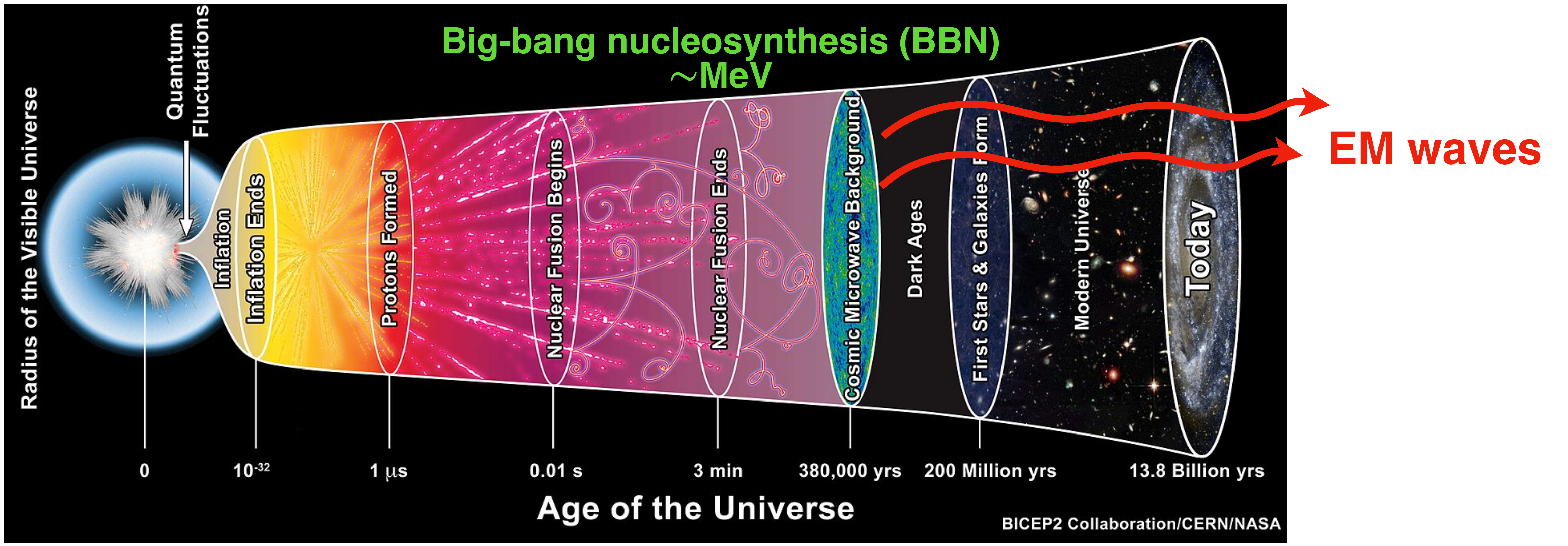

Cosmological dark age

inflation, reheating, phase transitions, baryogenesis, dark matter,…

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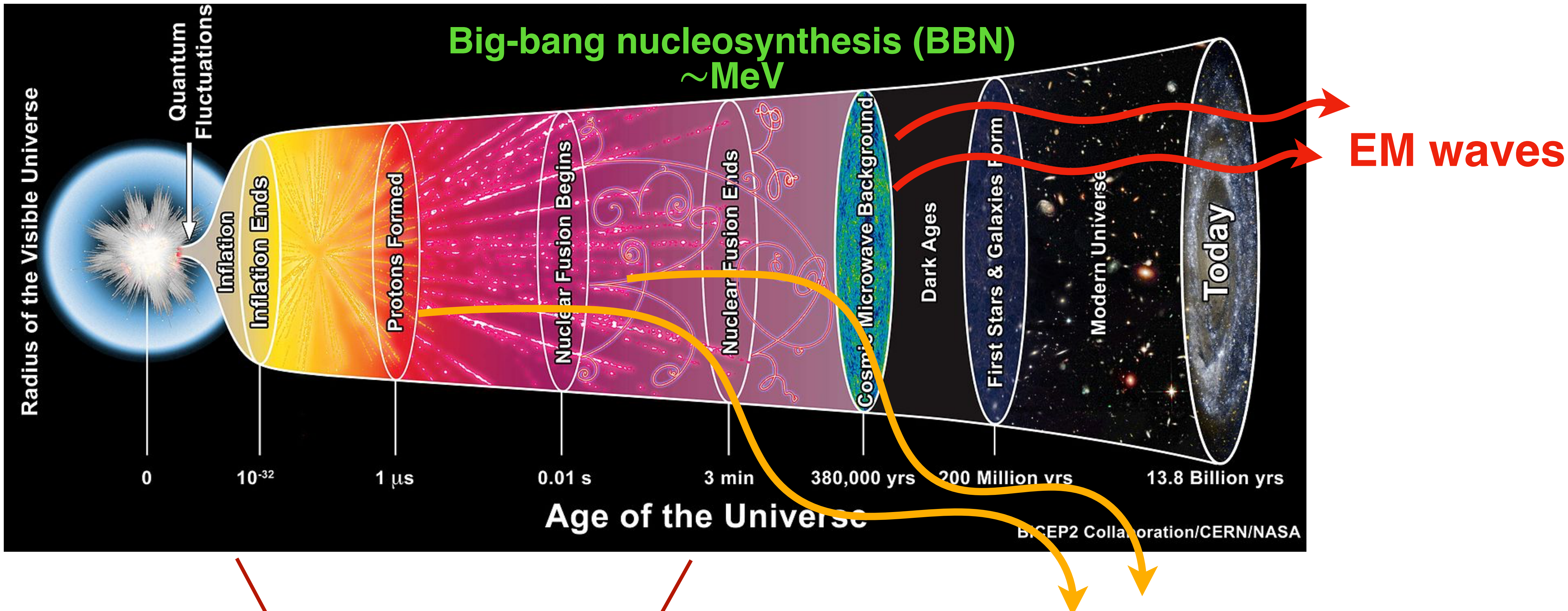

Cosmological dark age

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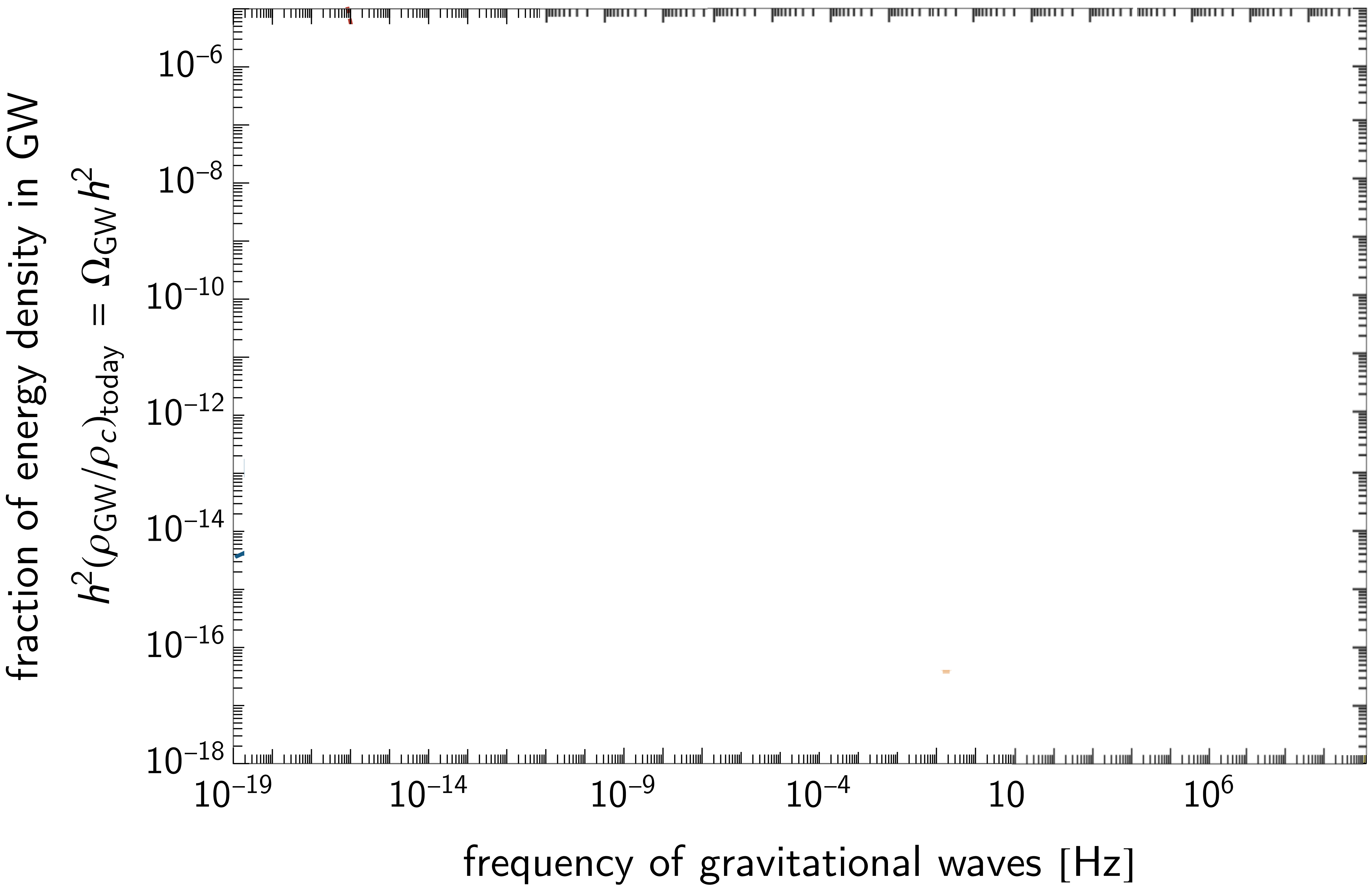
Primordial GW

(propagates freely after production)

$$\frac{\Gamma_{\rm GW}(T)}{H(T)} \sim \frac{G^2 T^5}{T^2/M_{\rm pl}} = \left(\frac{T}{M_{\rm pl}}\right)^3$$

GW as probes of pre-BBN Universe ($T \gtrsim \mathrm{MeV}$).

Future prospects of GW experiments



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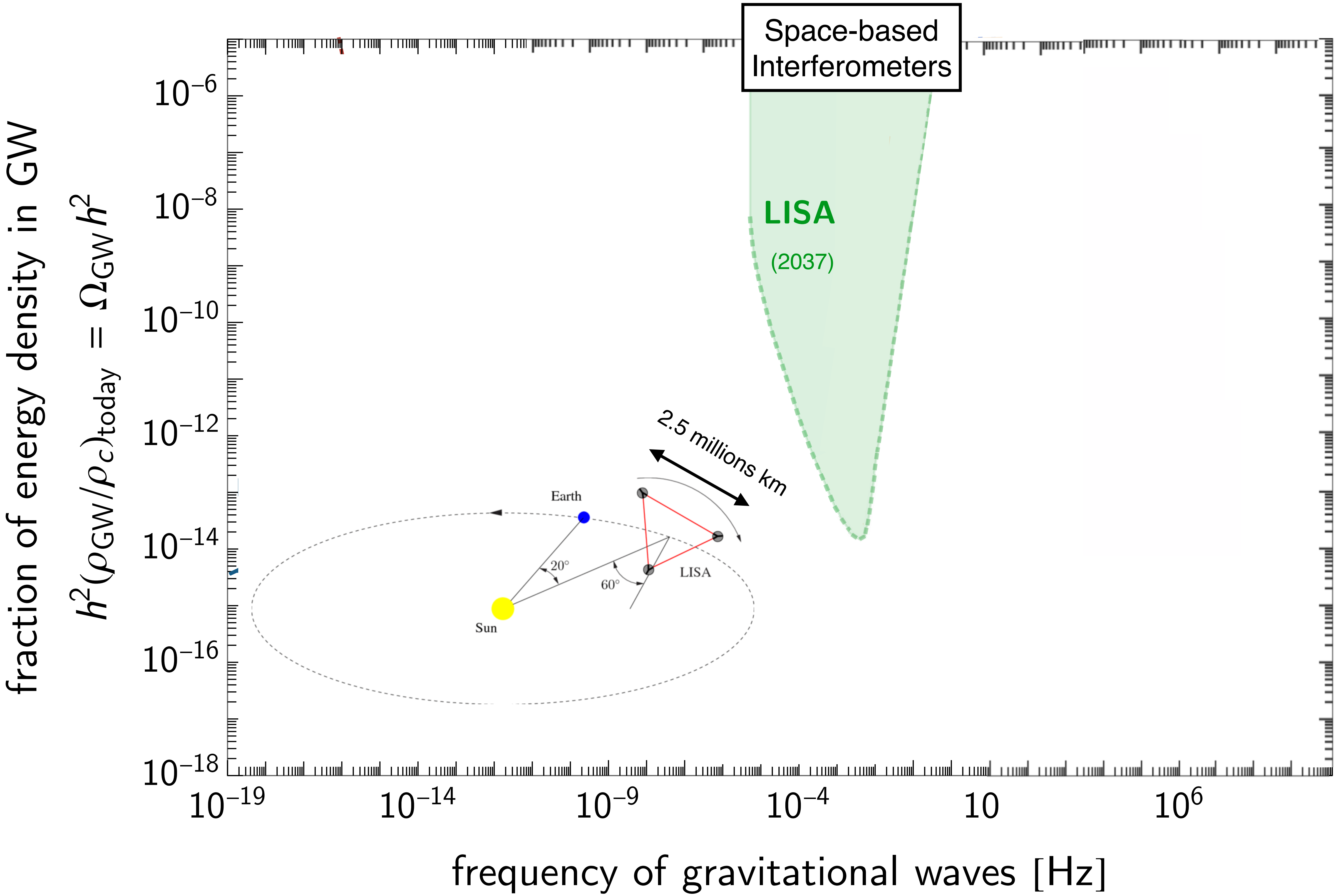

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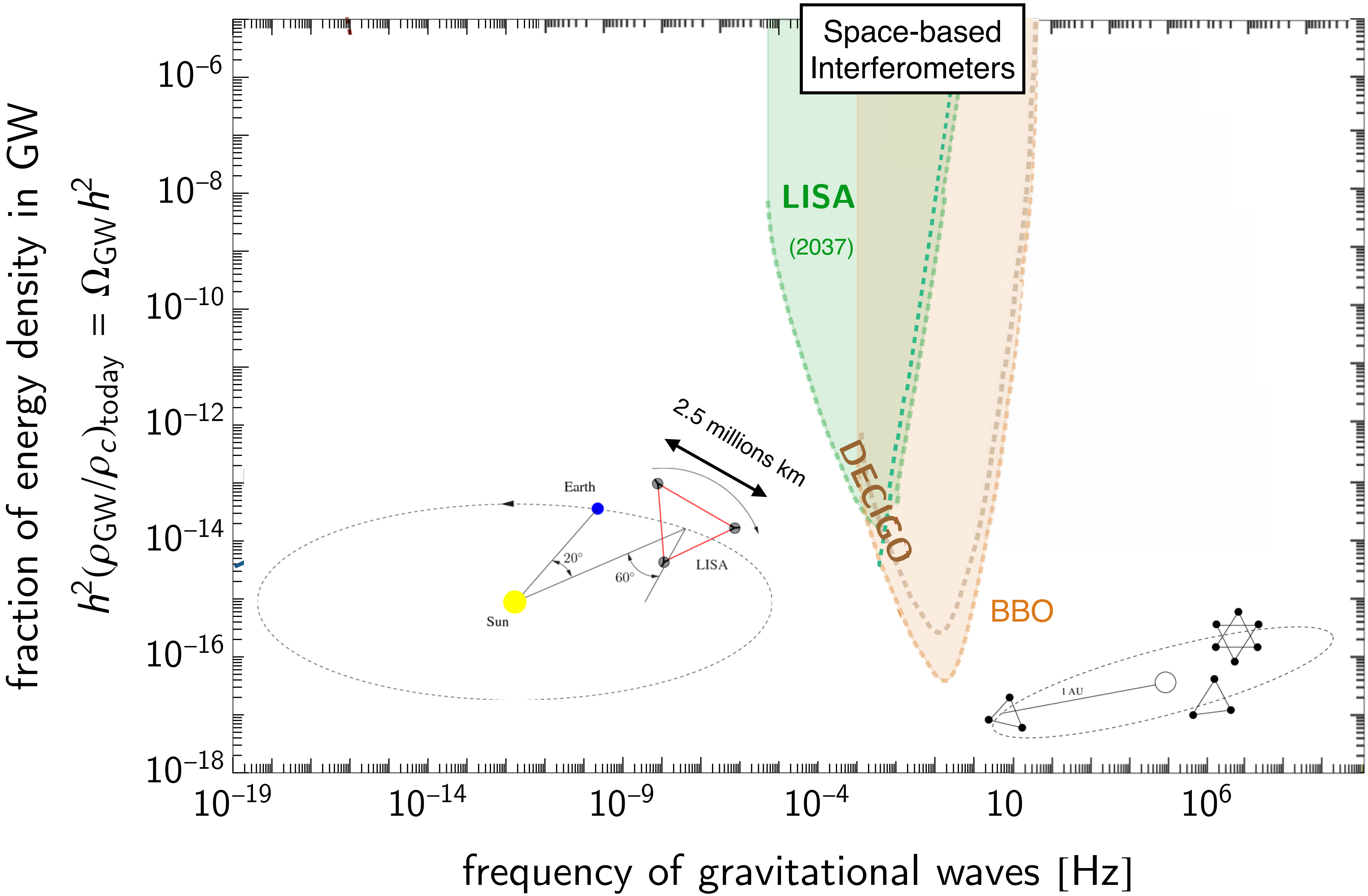

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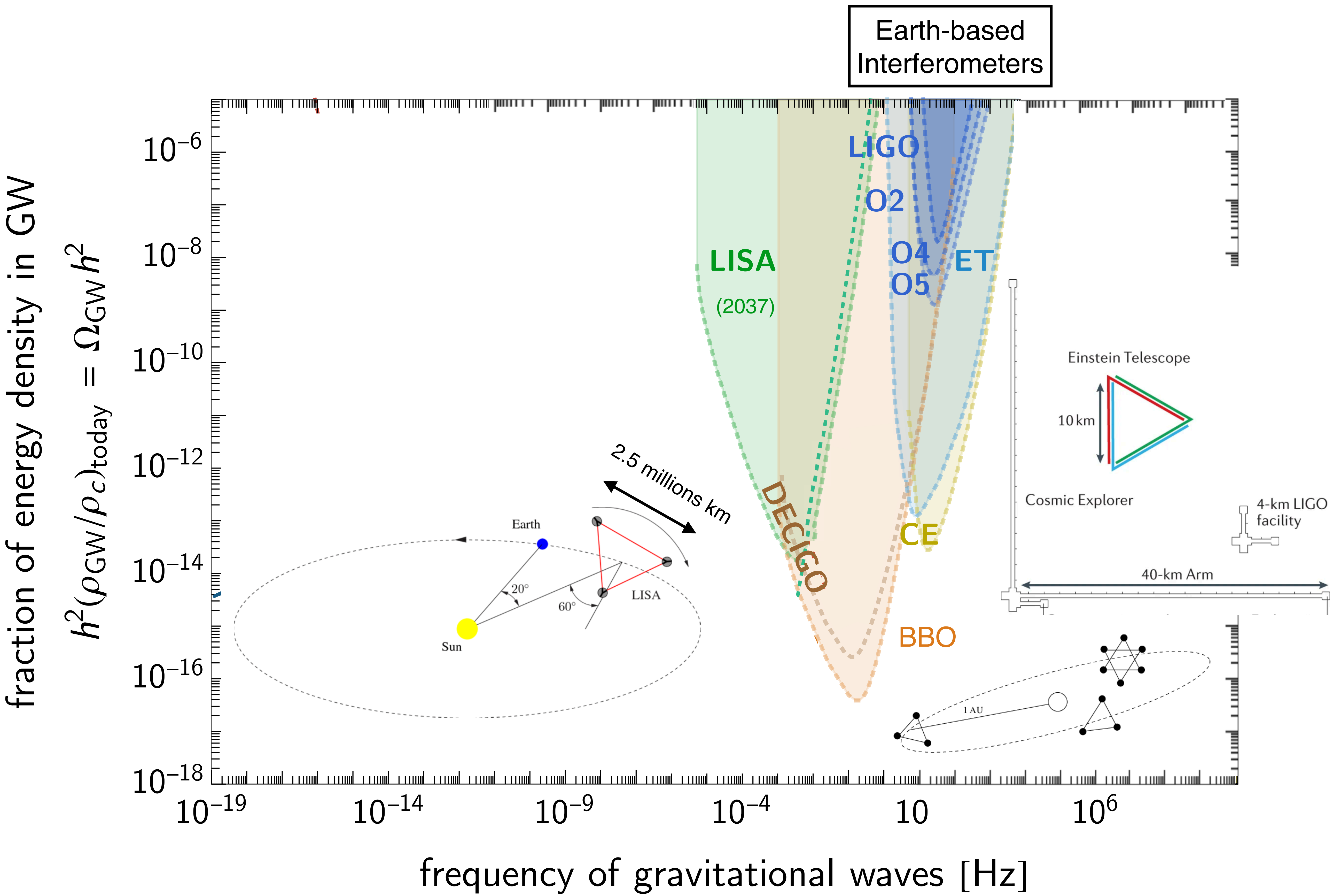

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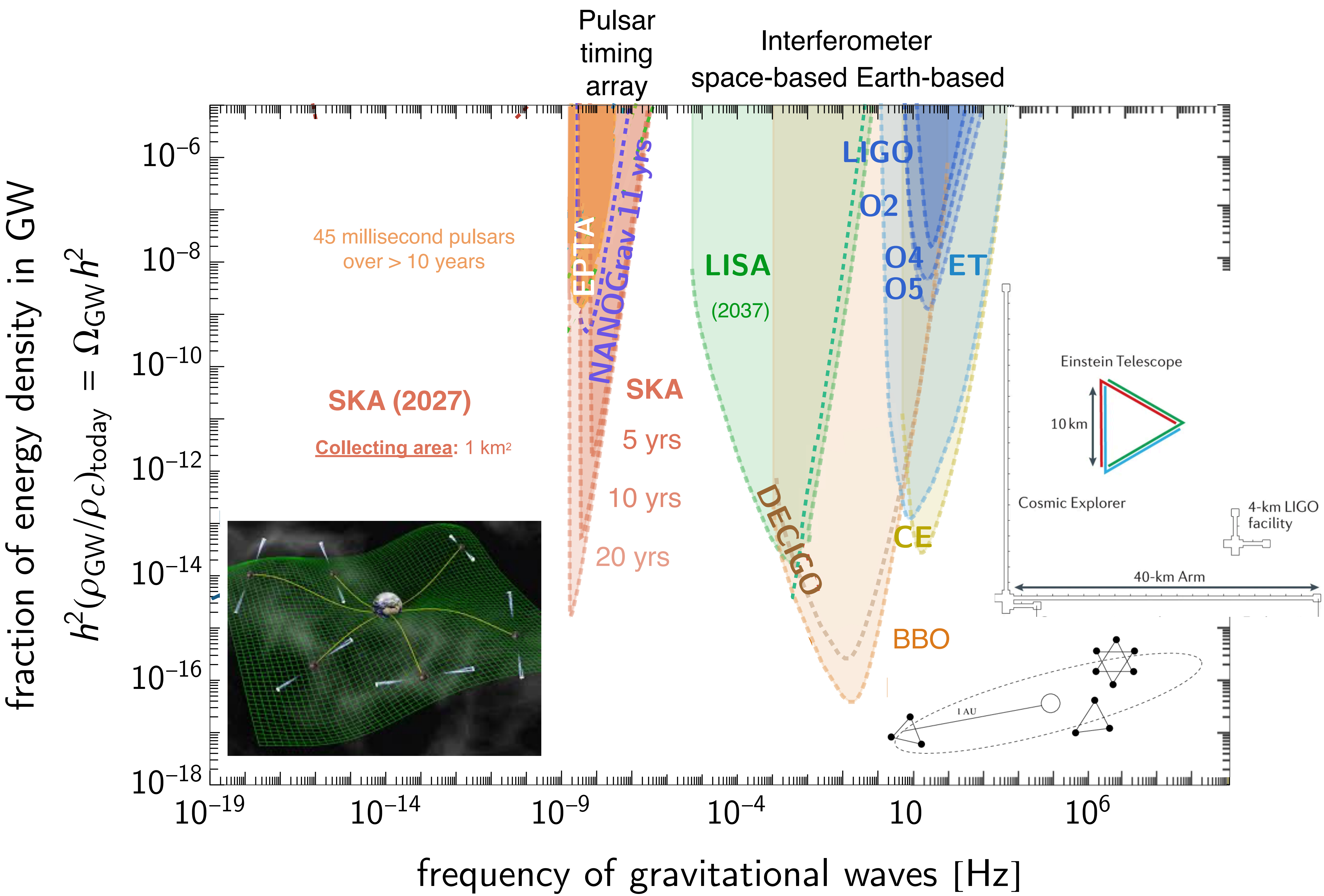

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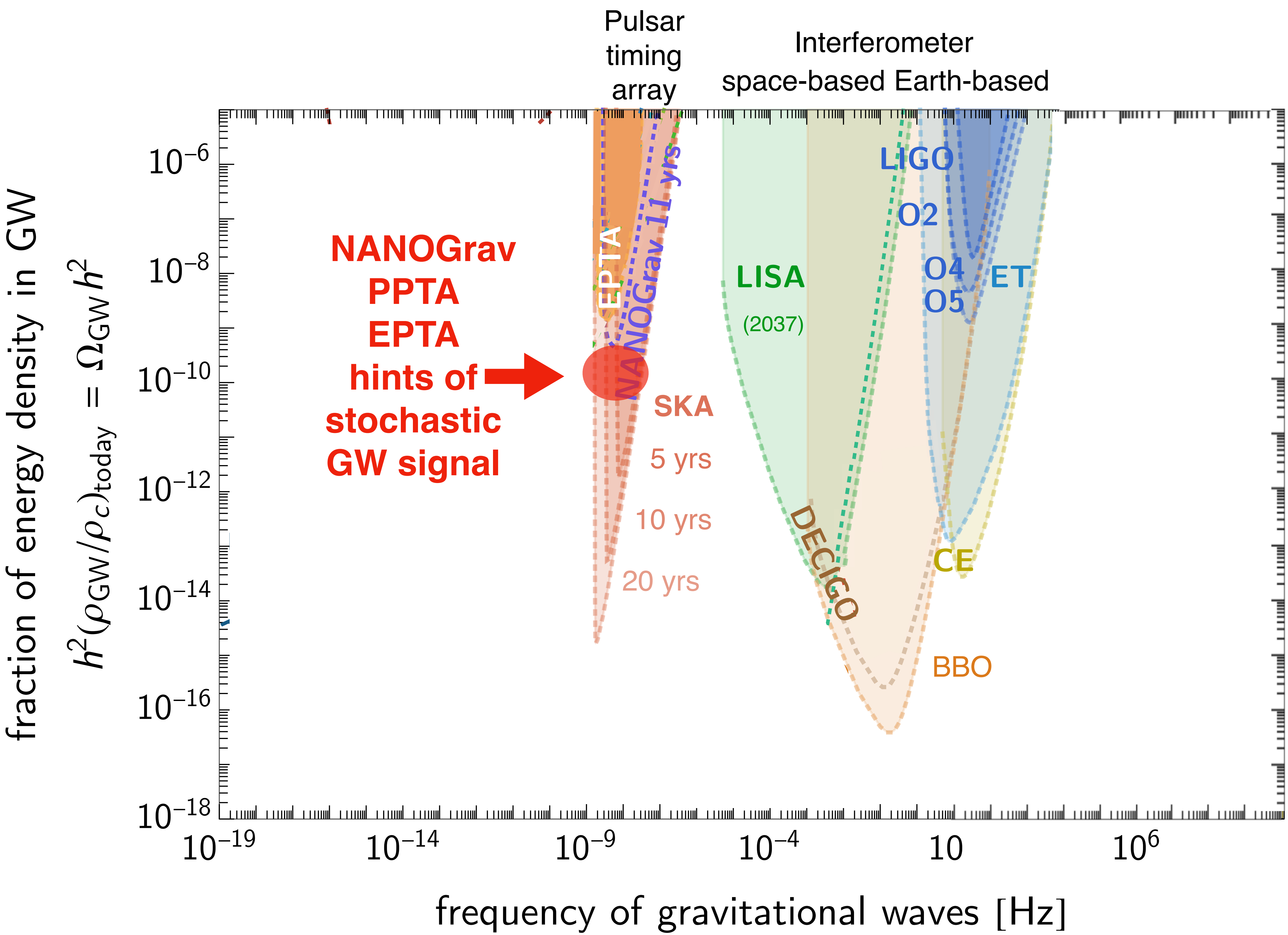

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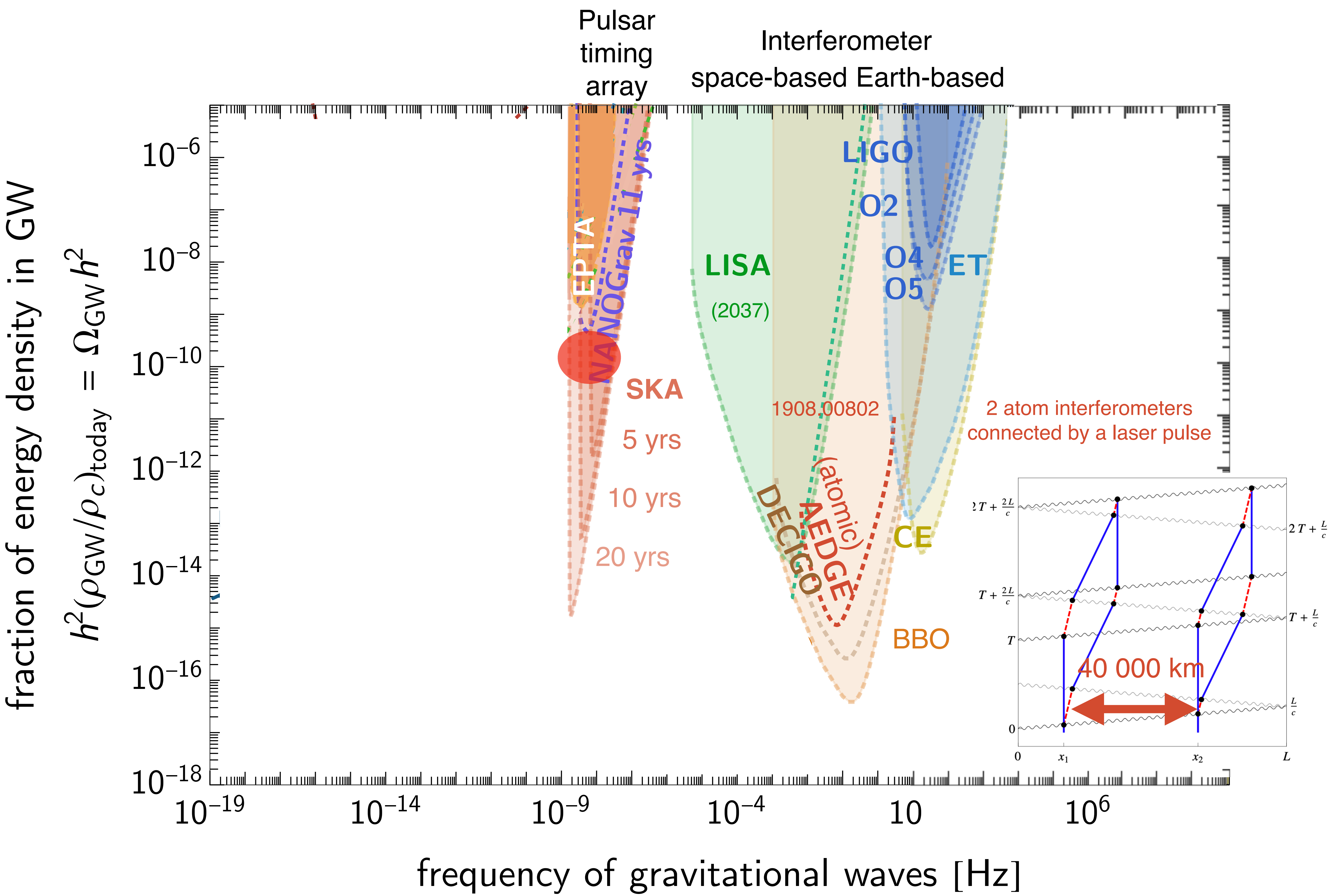

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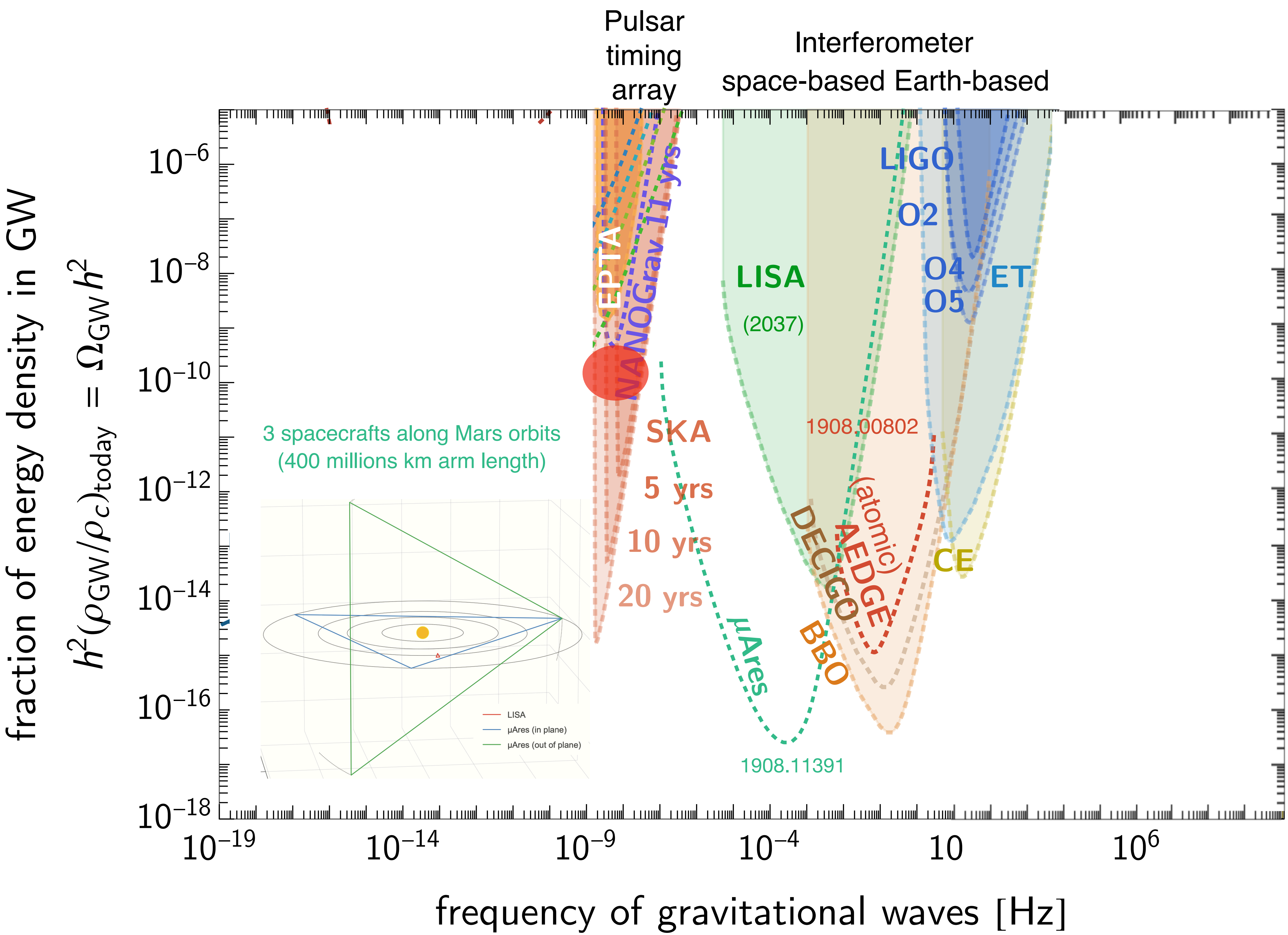

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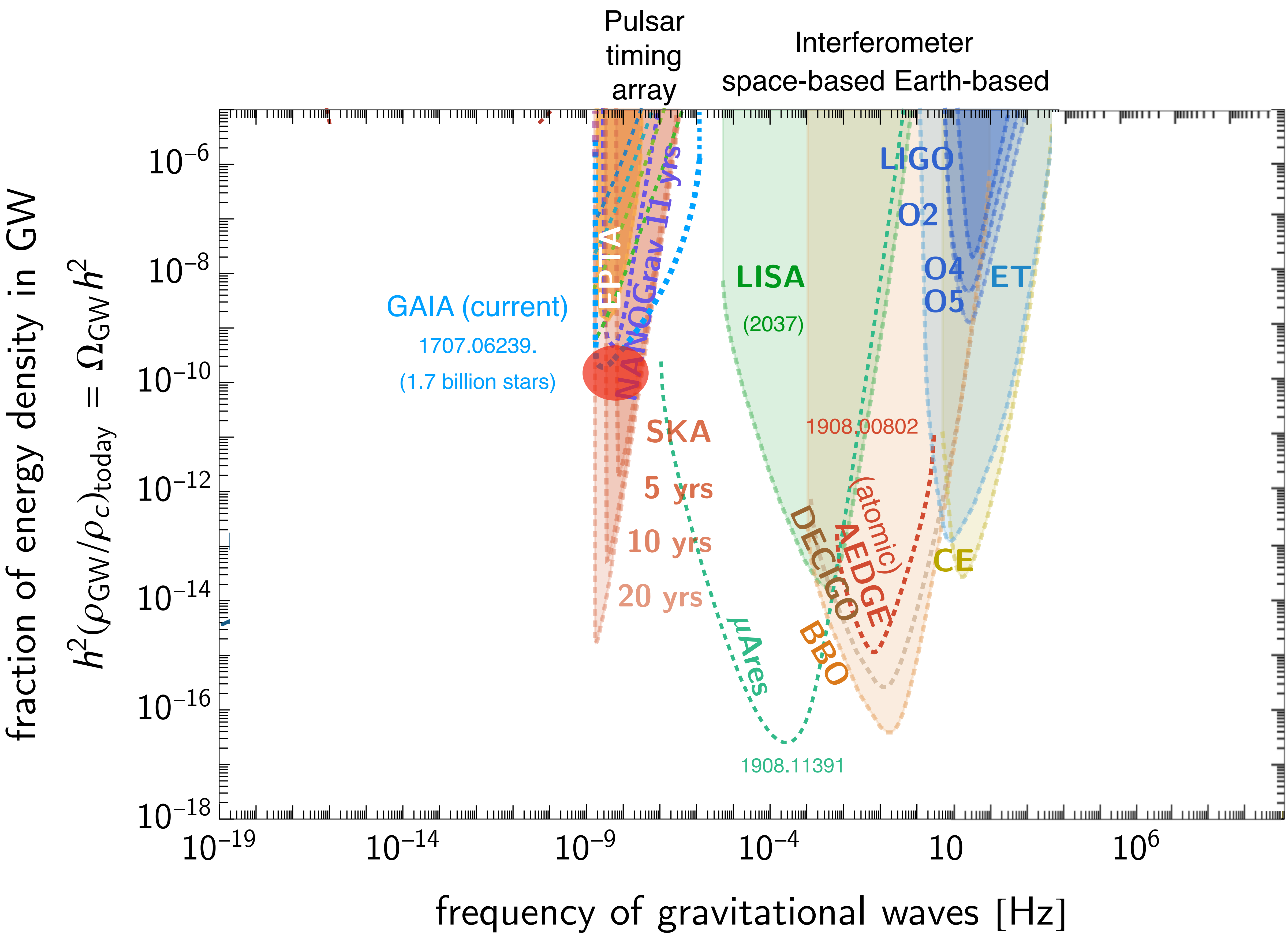

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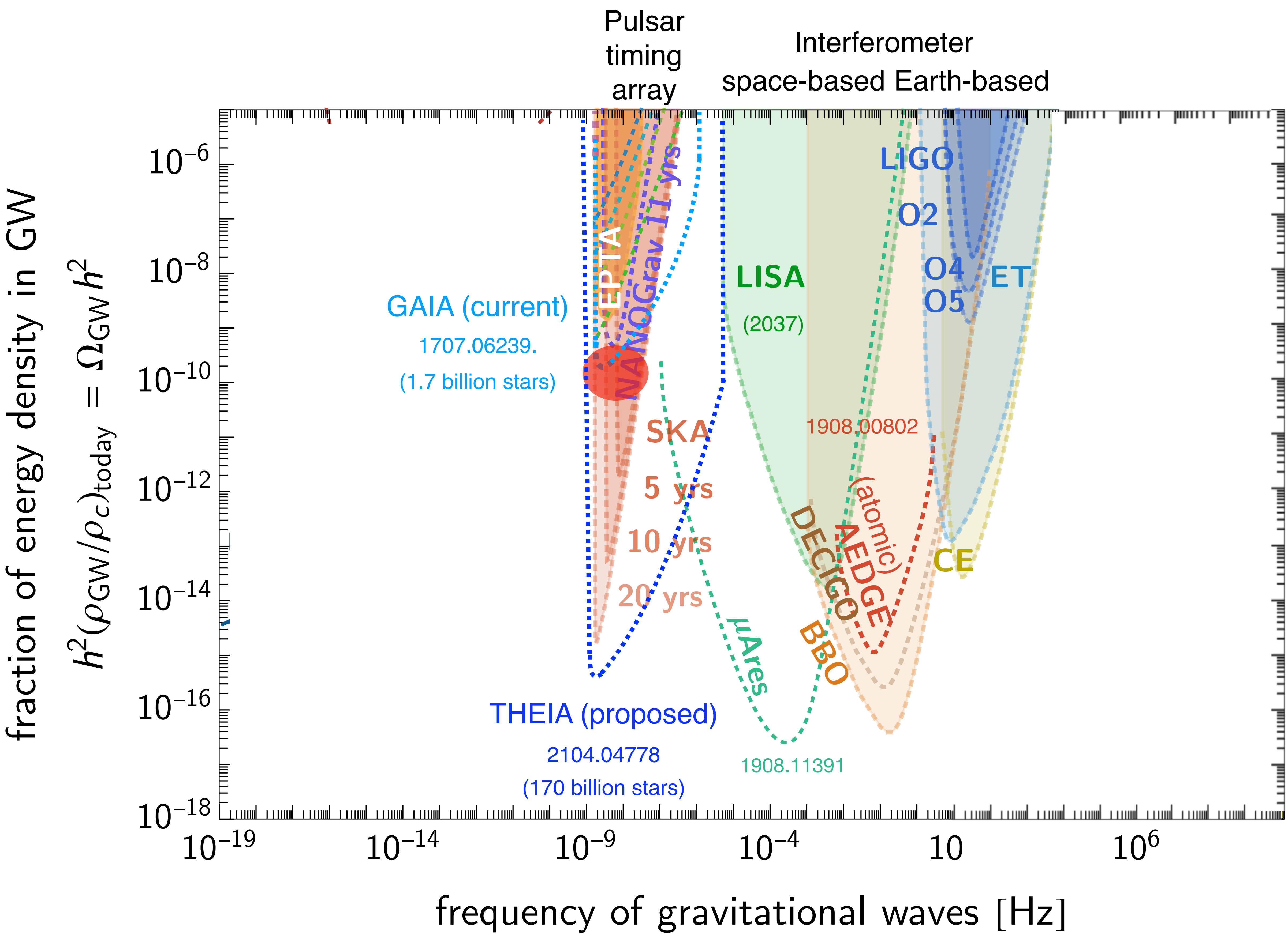

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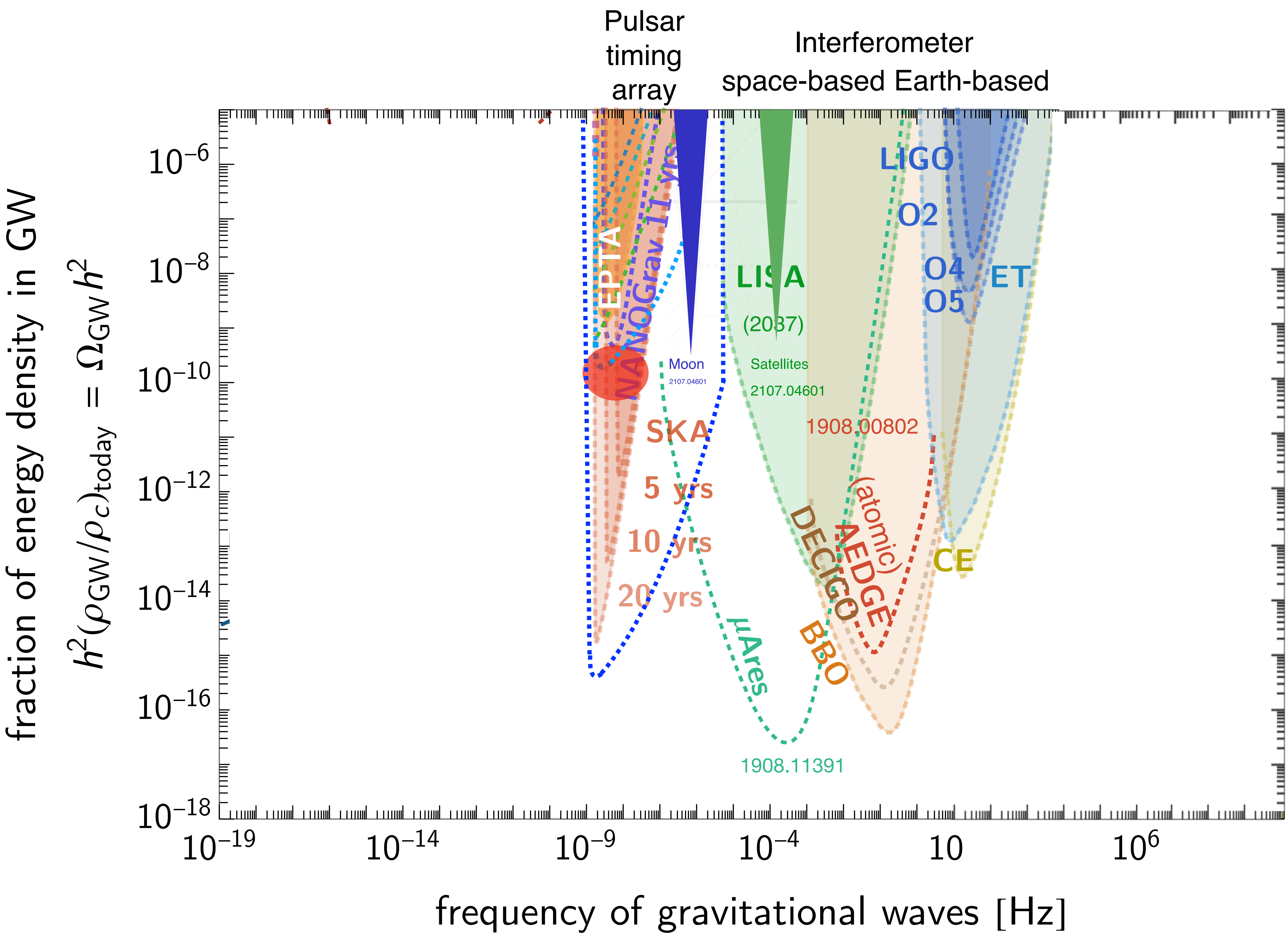

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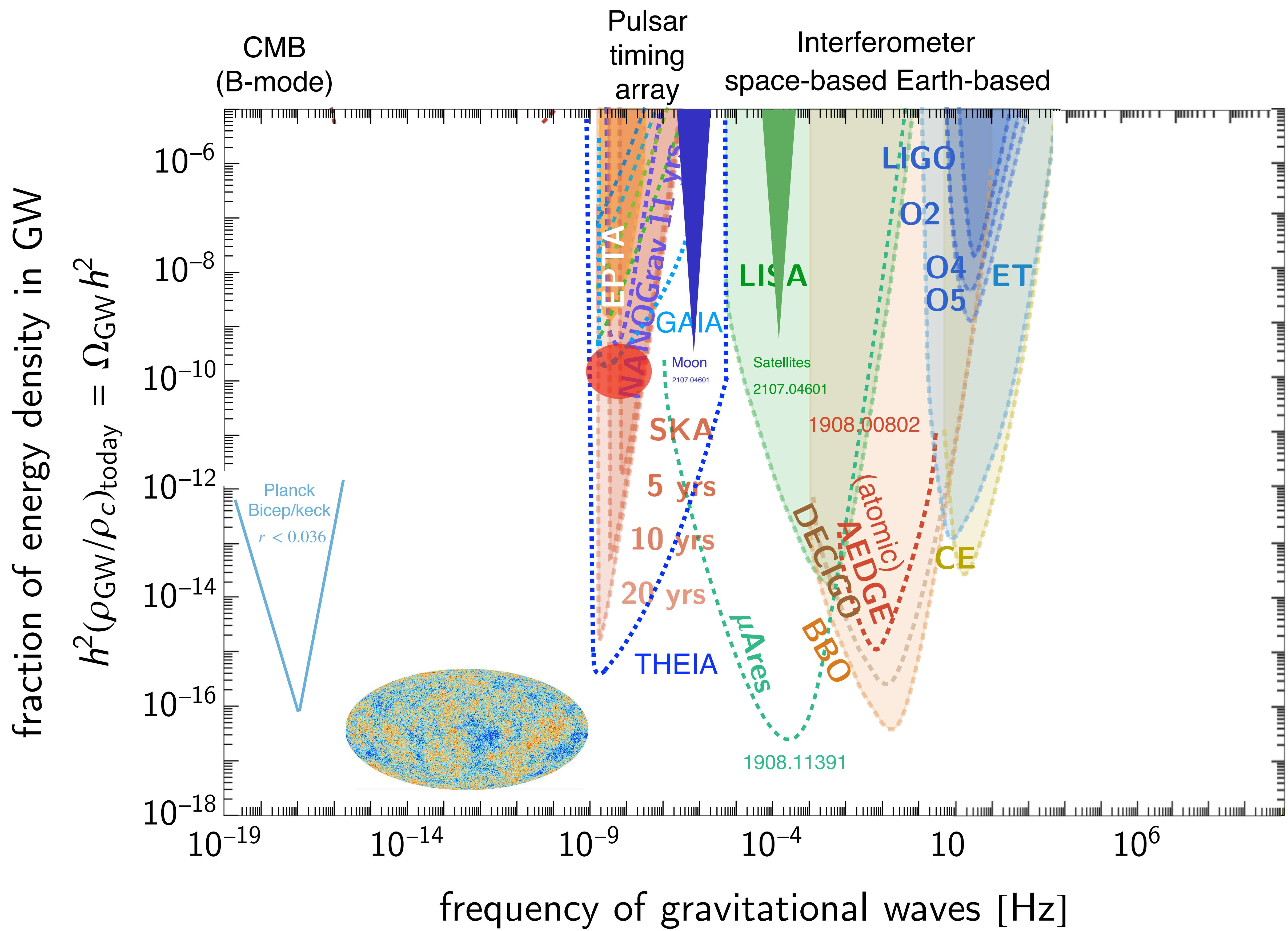

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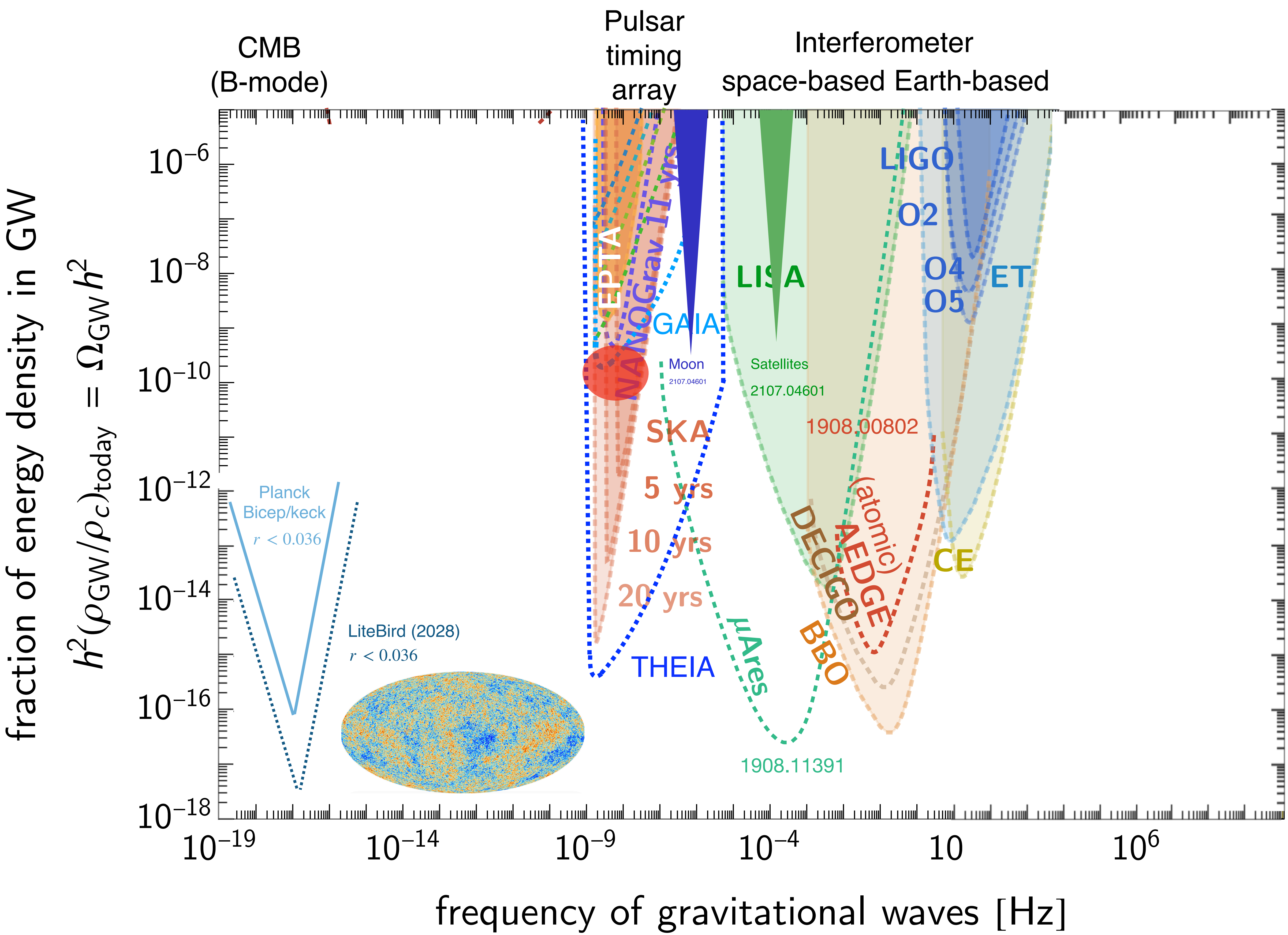

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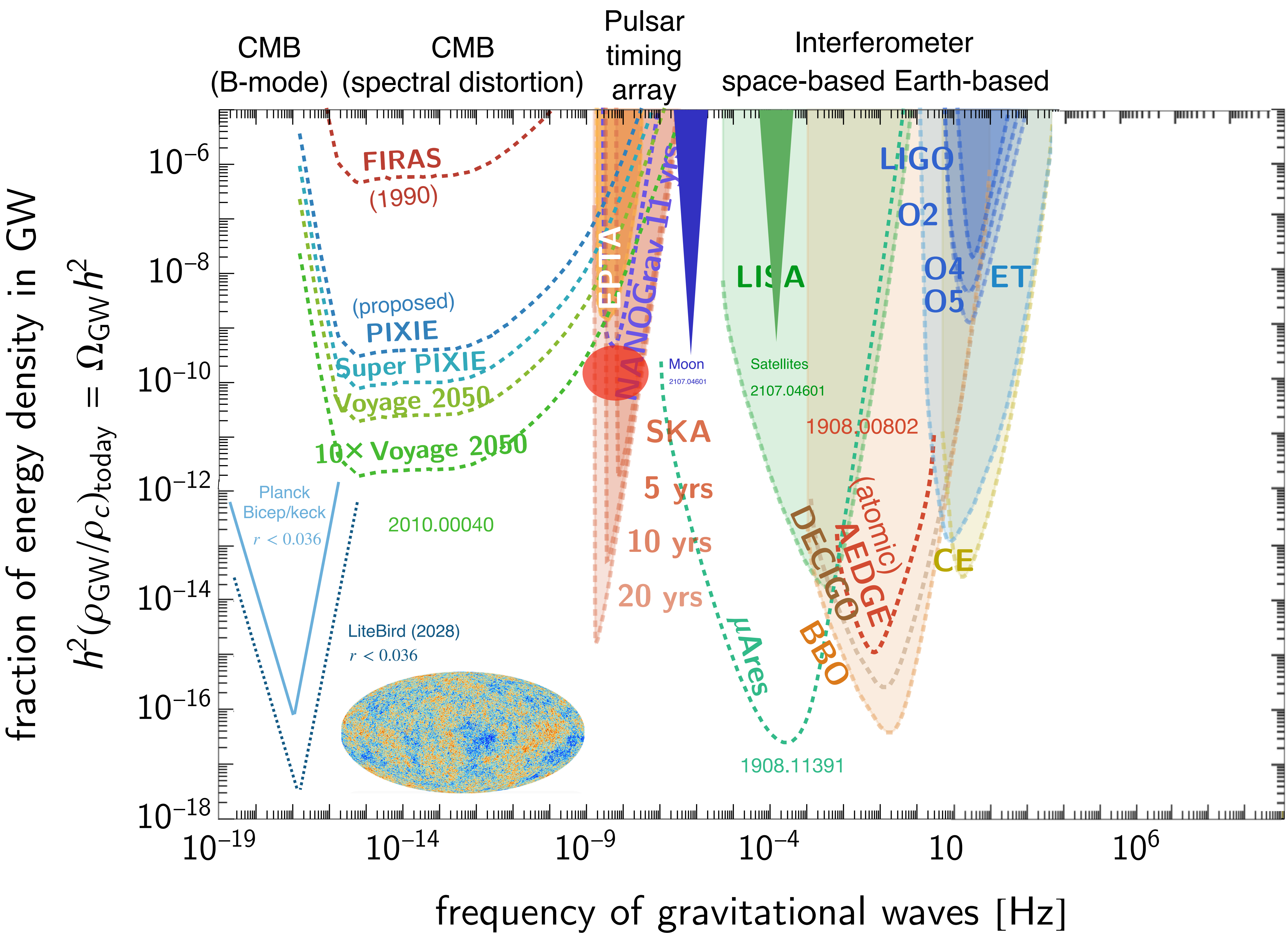

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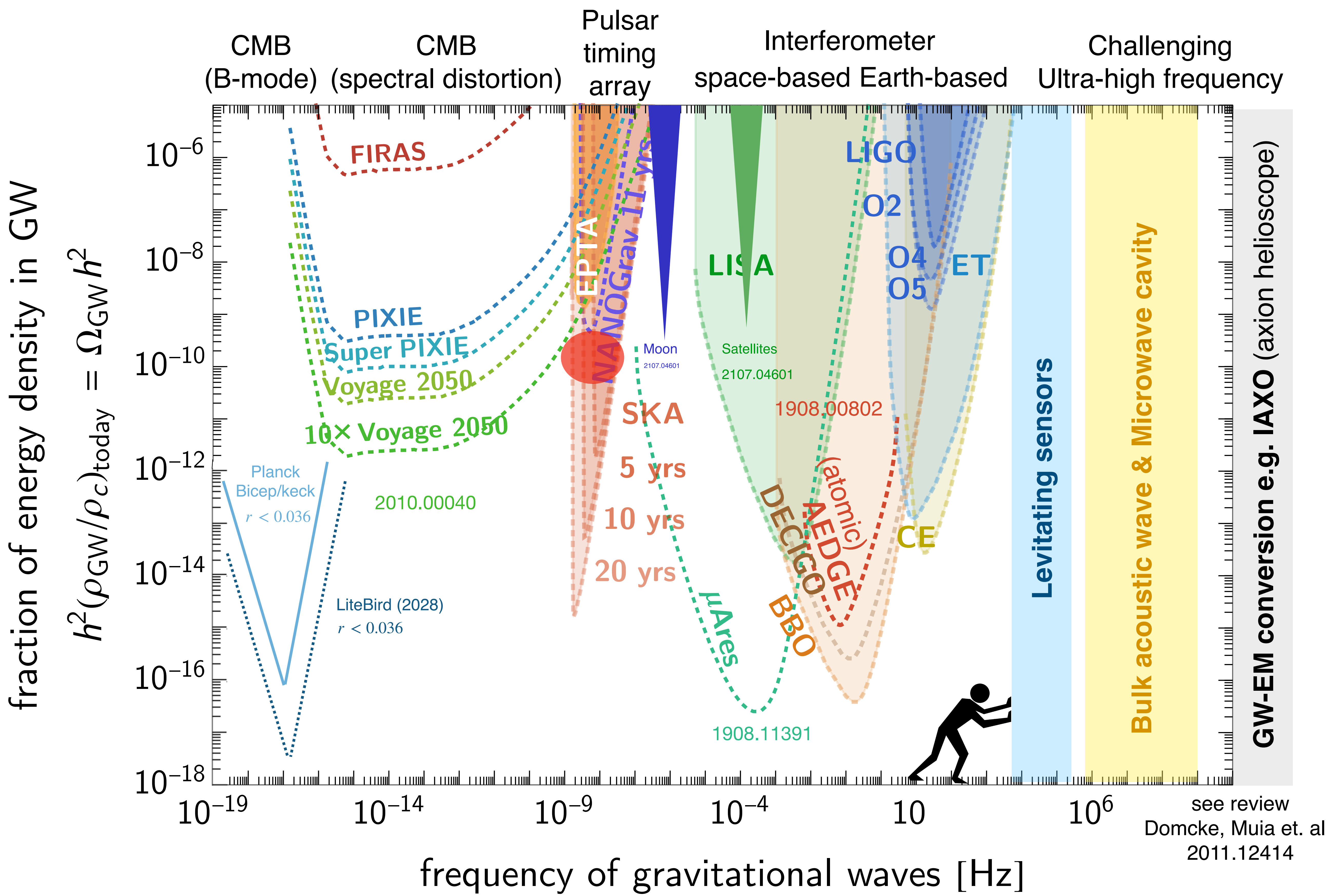

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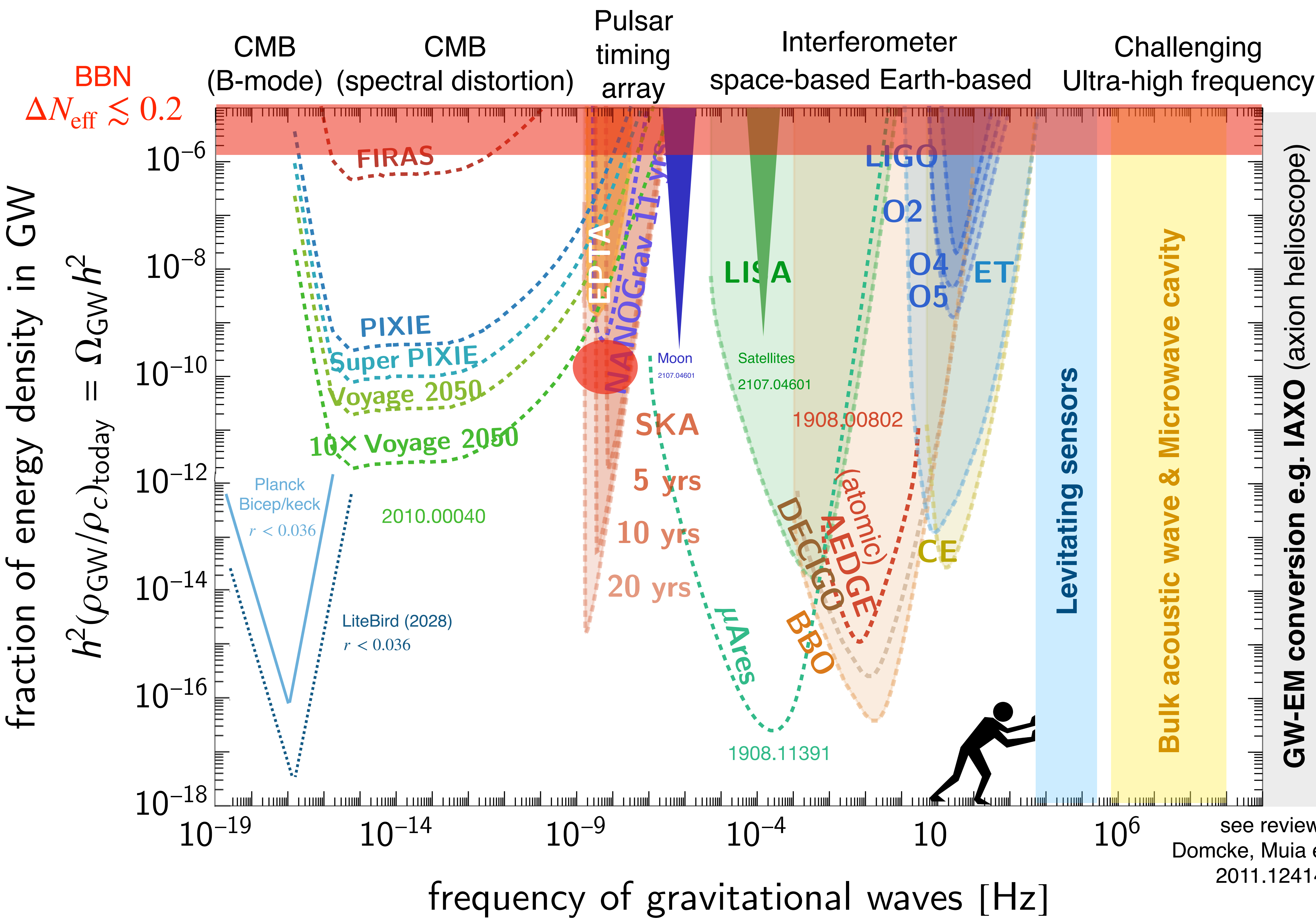
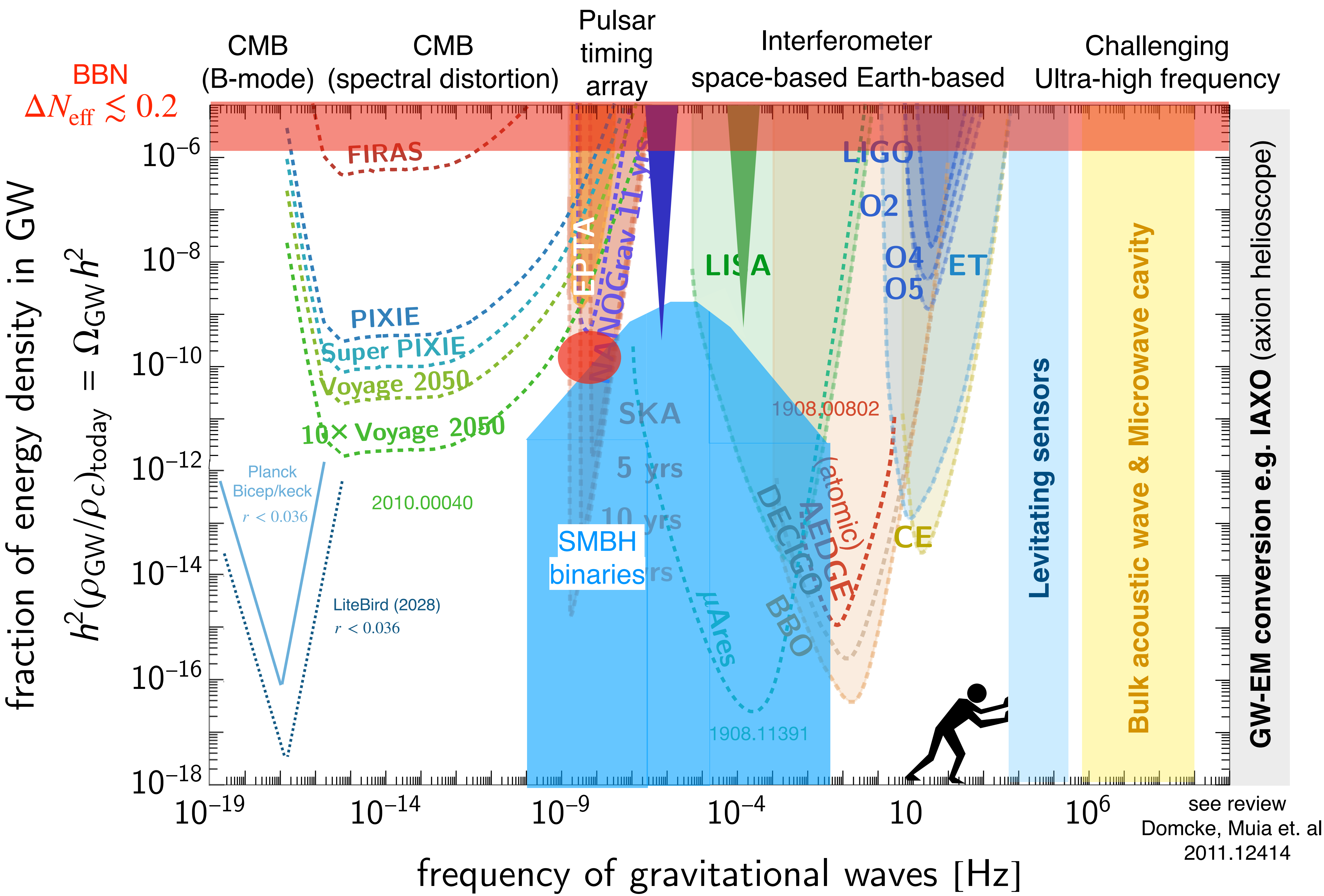


see review Domcke, Muia et. al., 2011.12414

Astrophysical foreground



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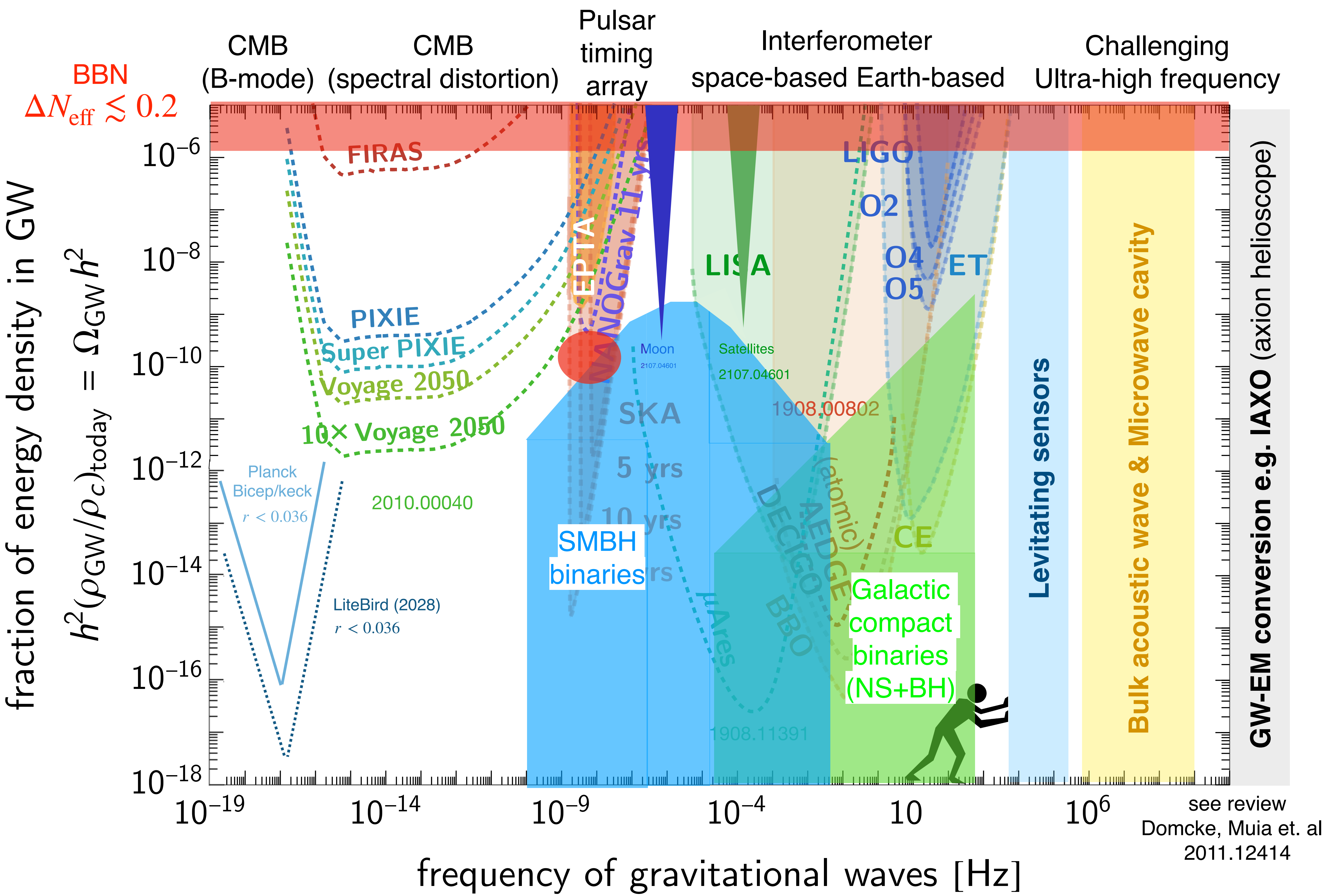

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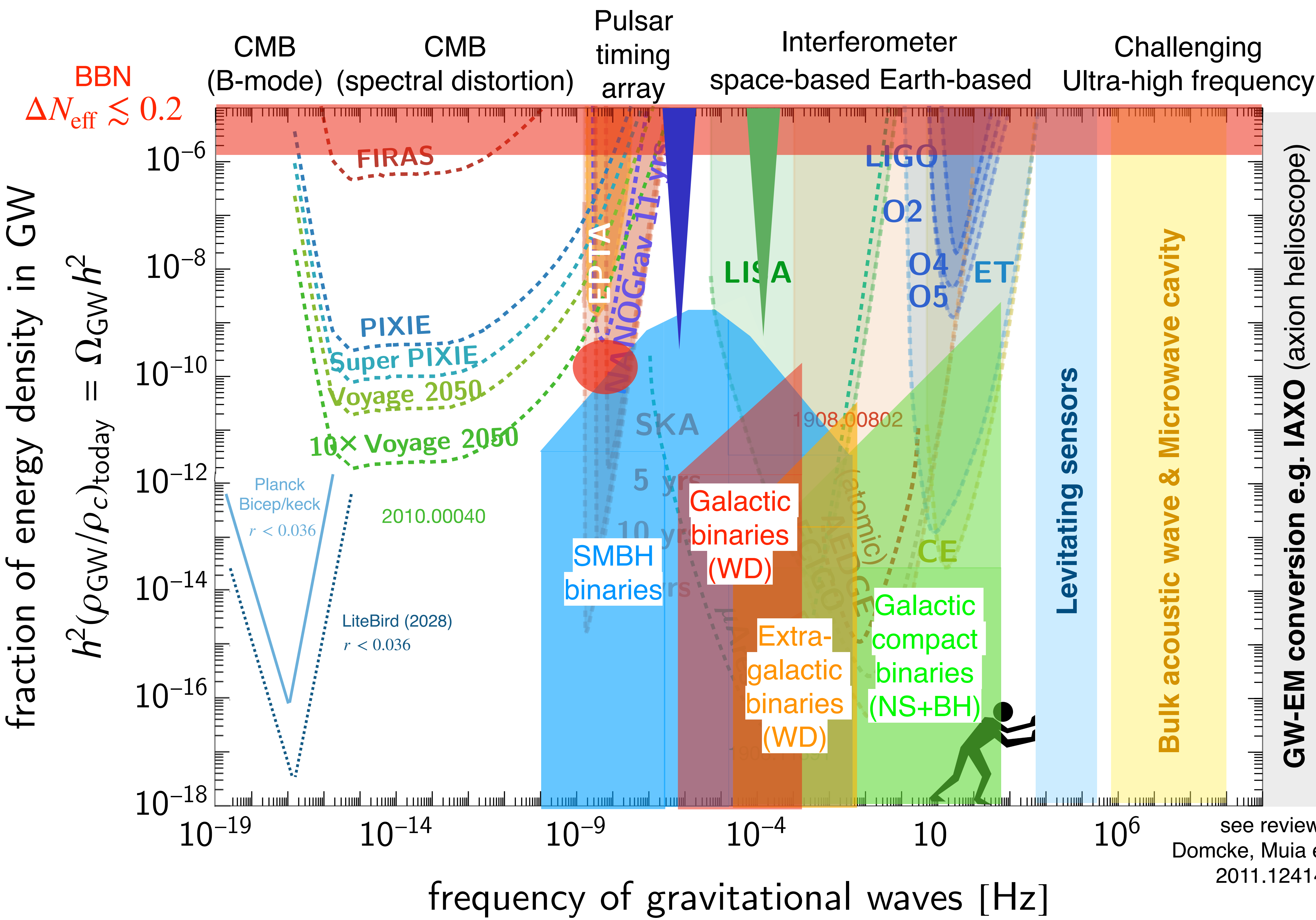

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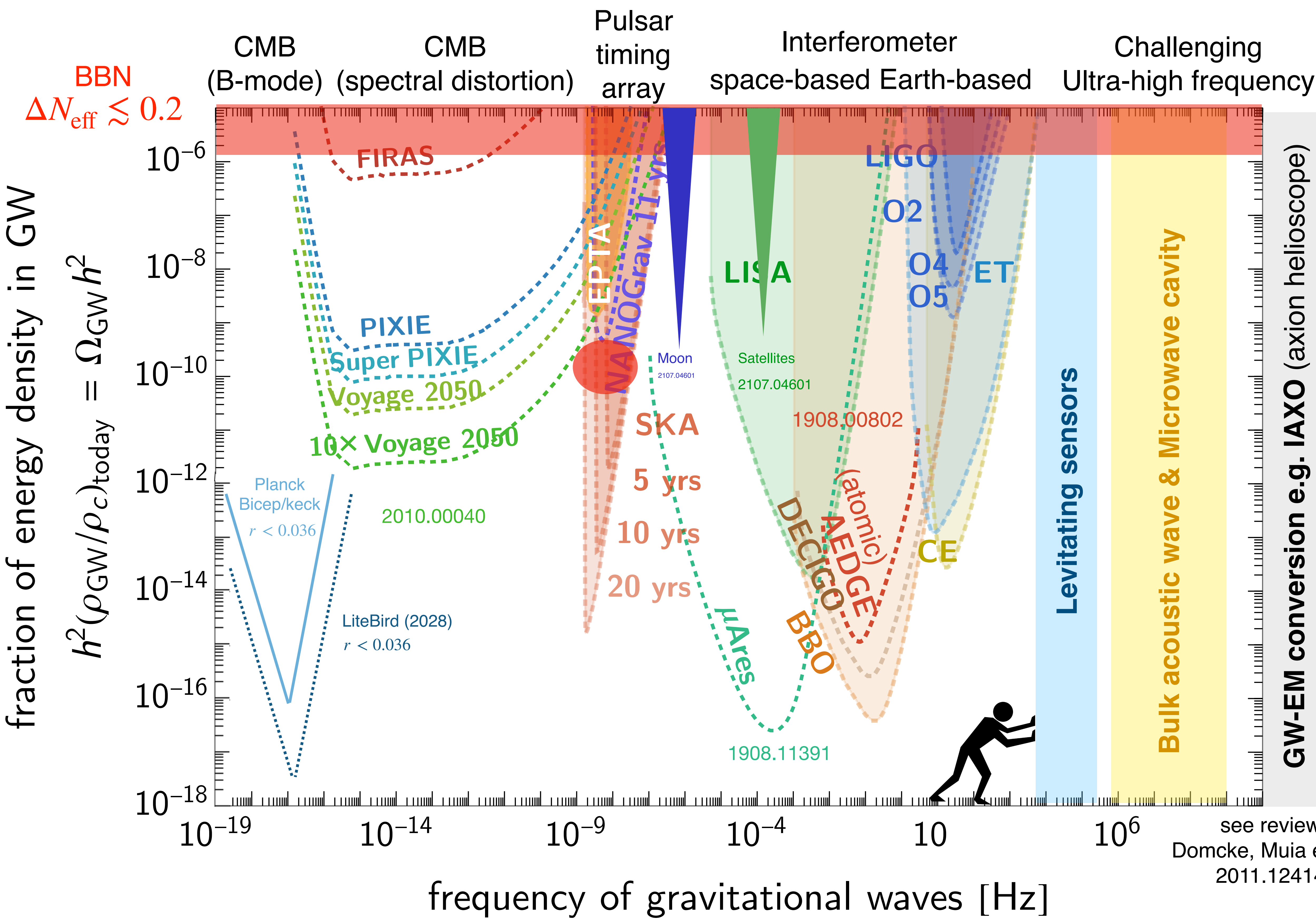

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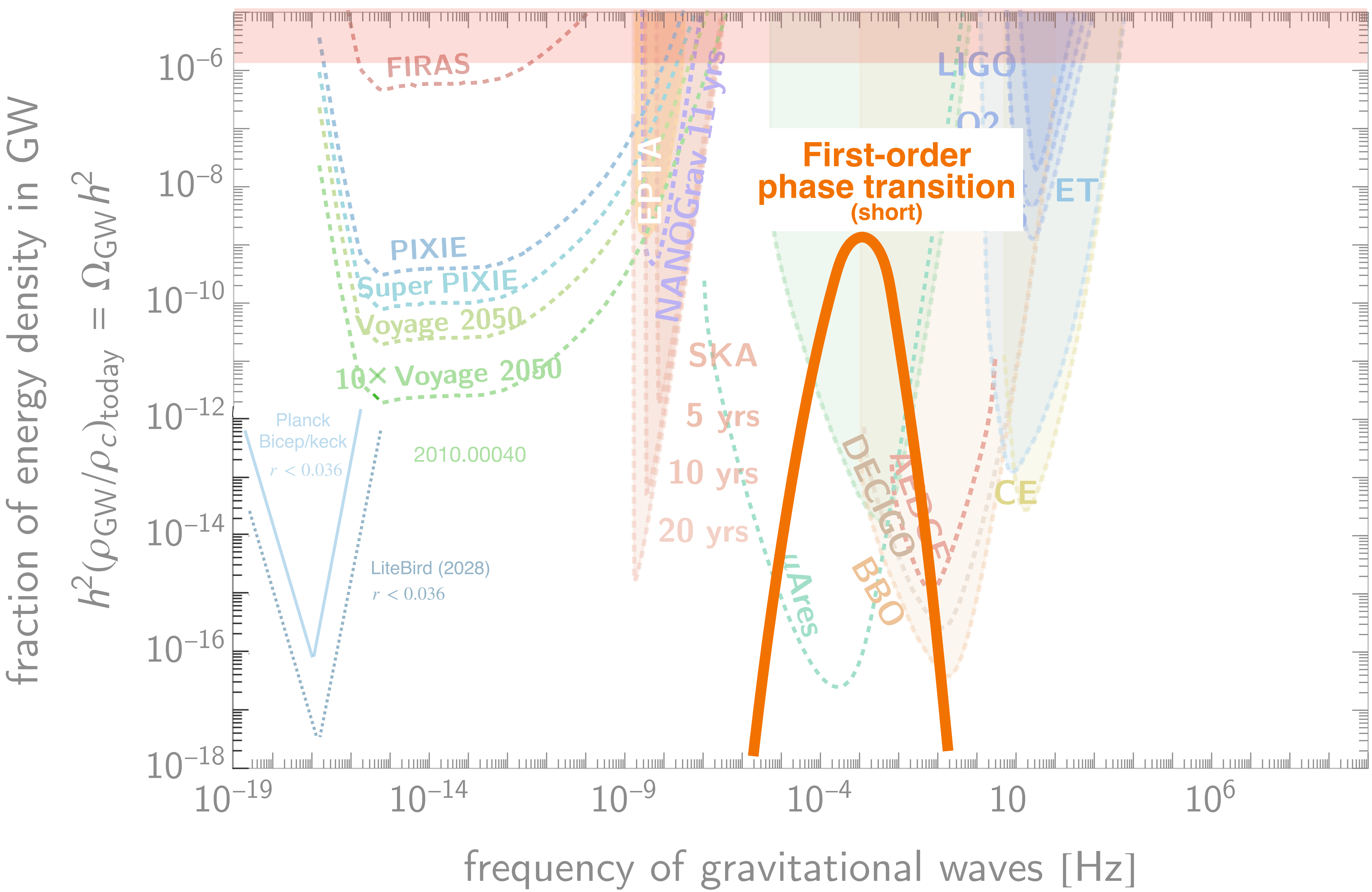
GW of primordial origins



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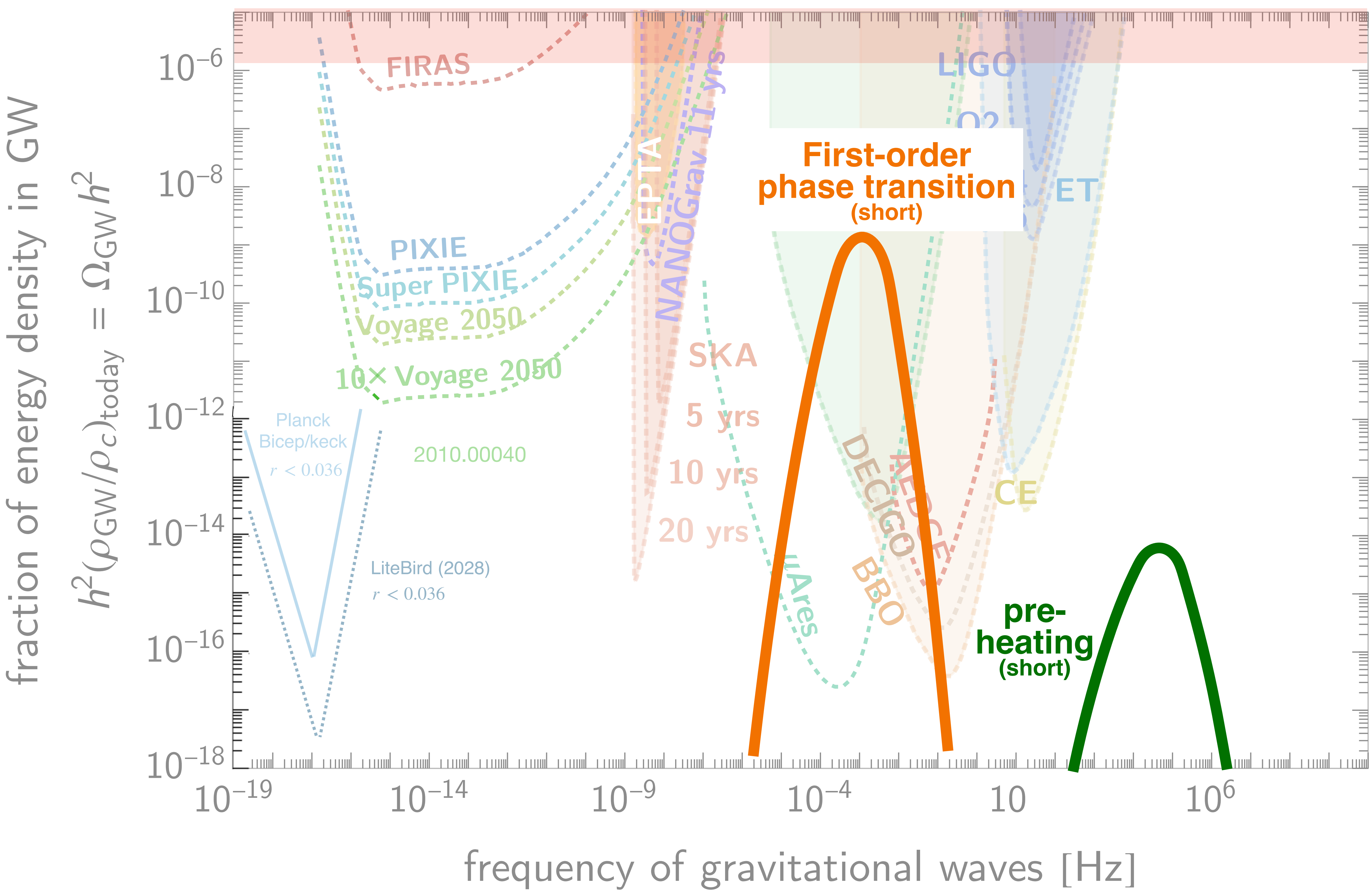

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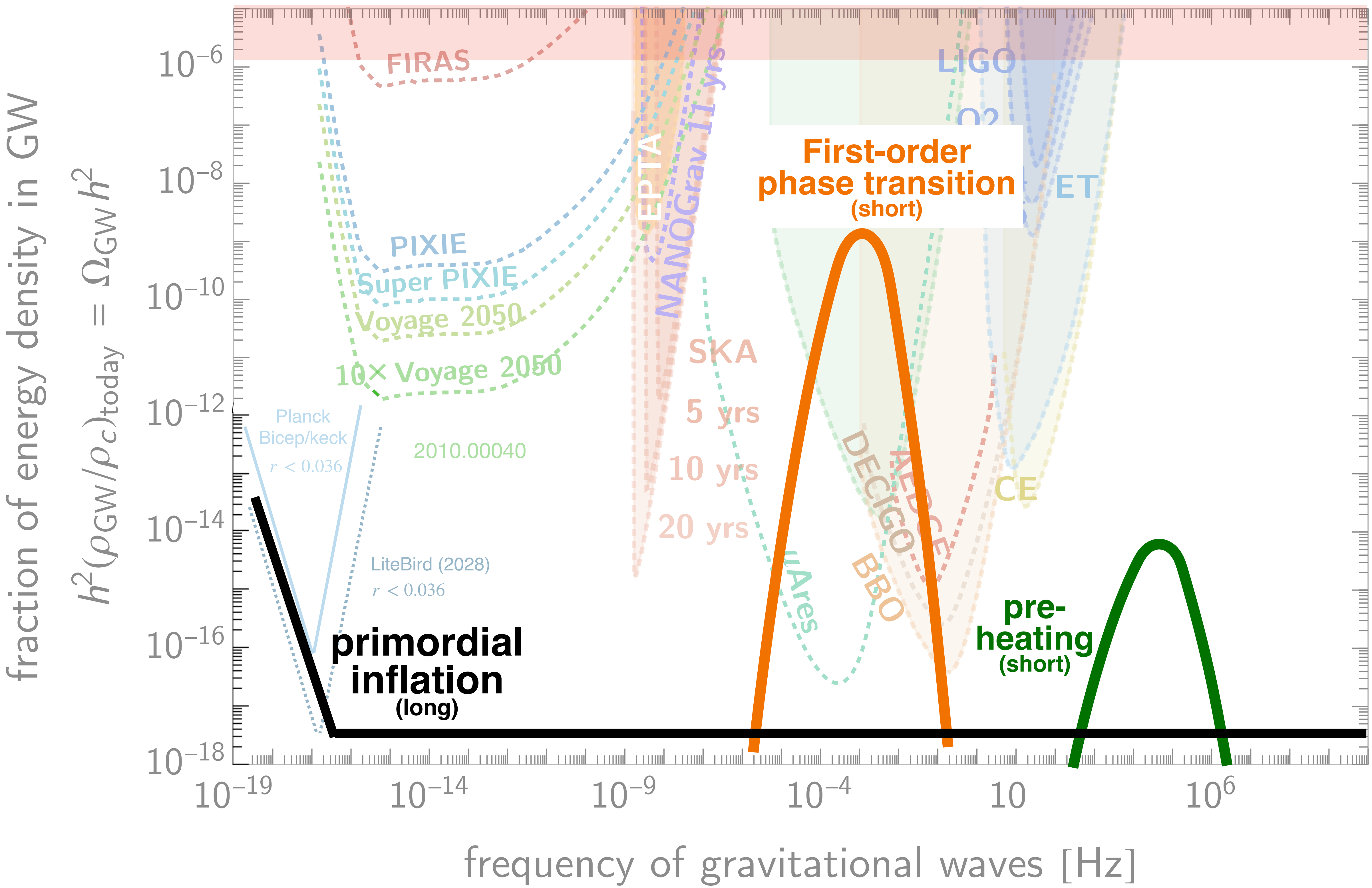

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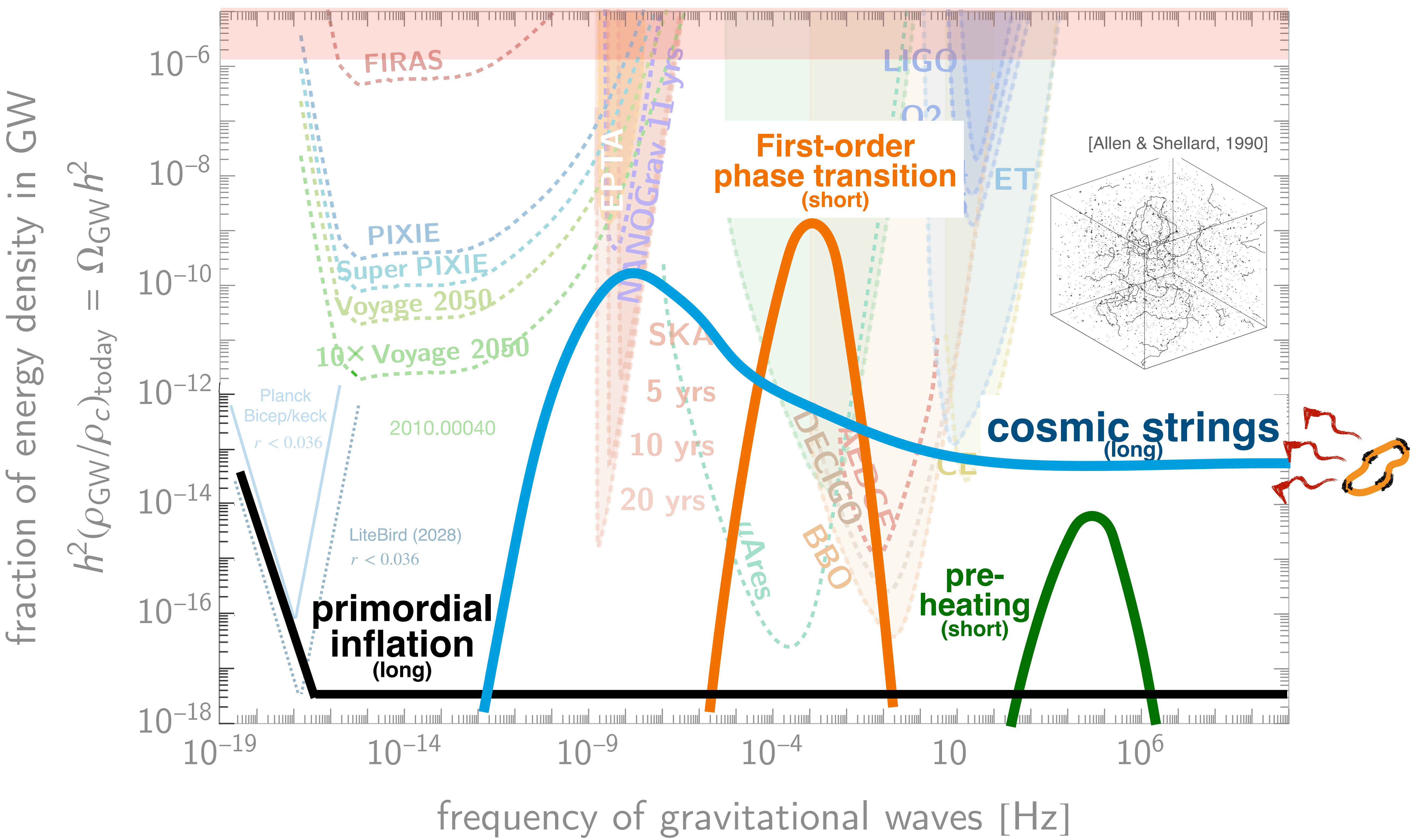

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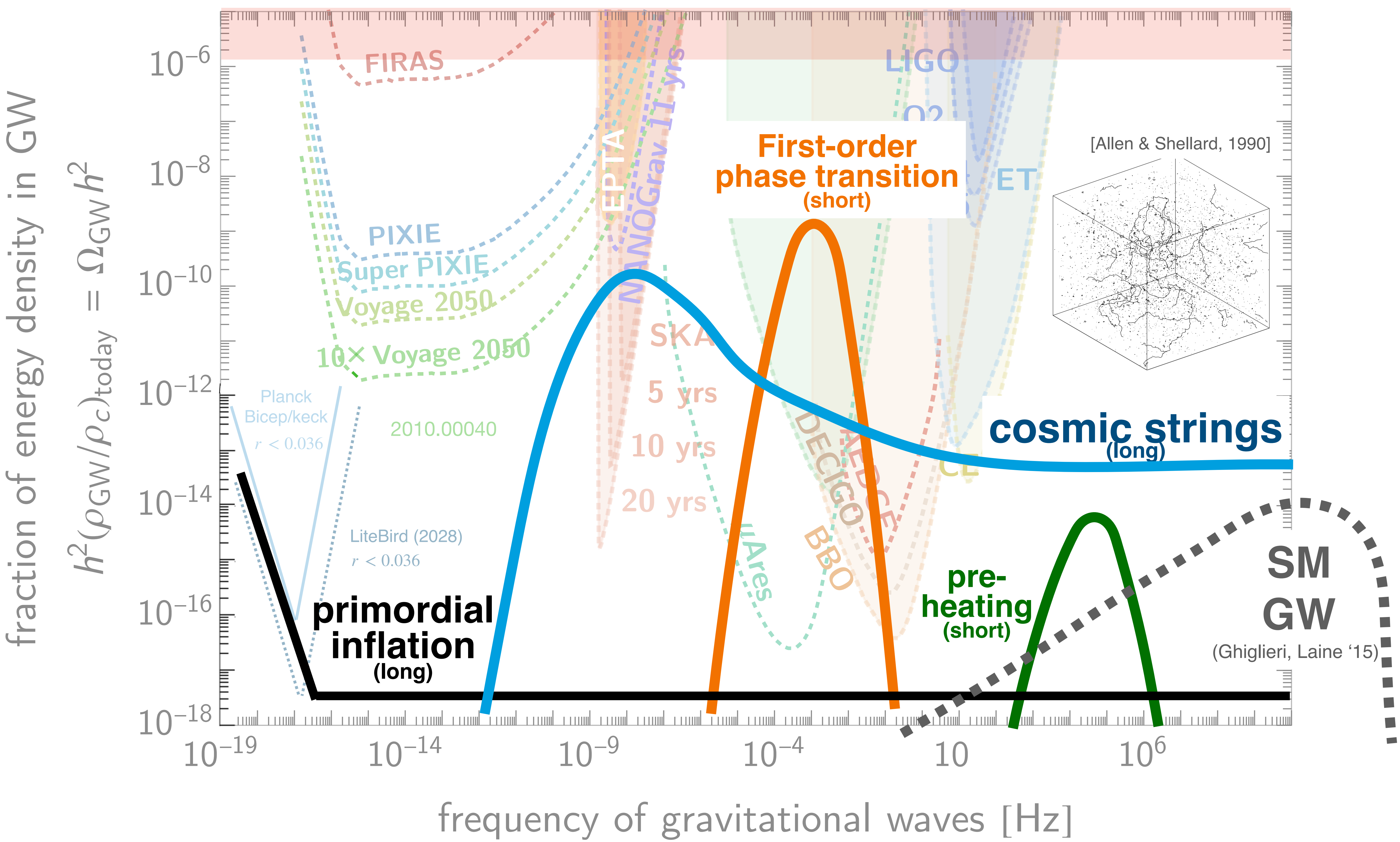
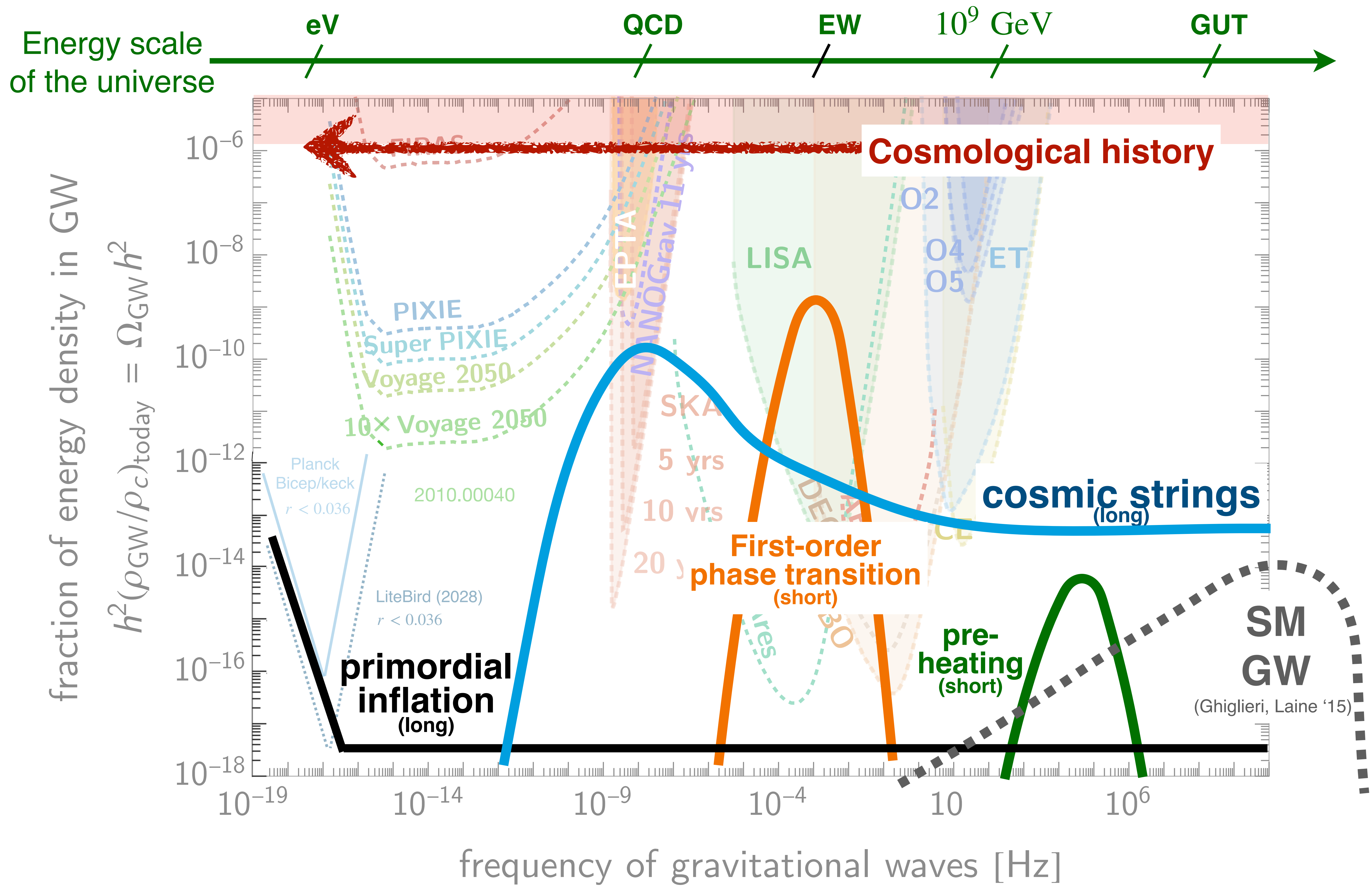


Cosmic Archeology



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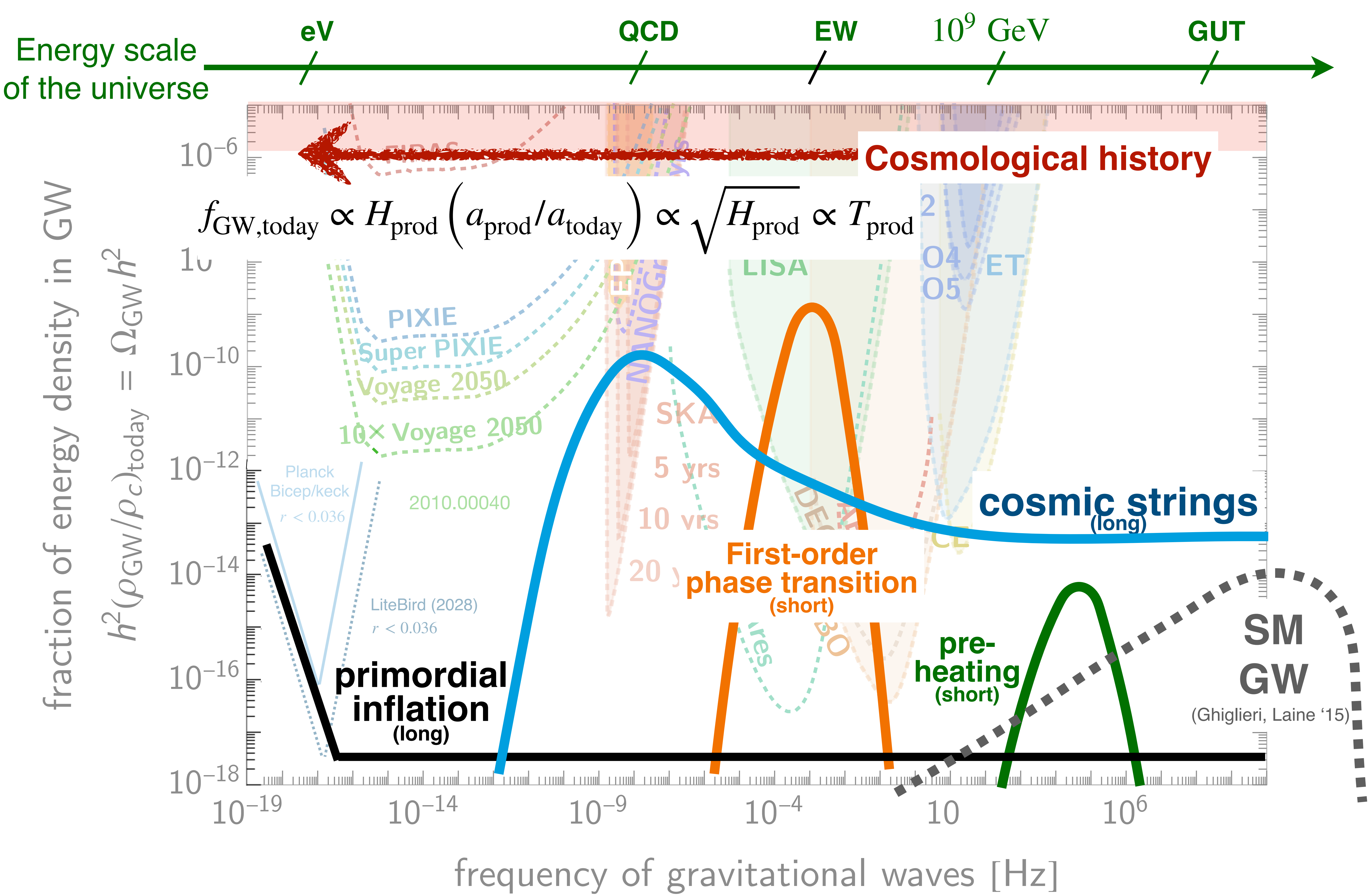
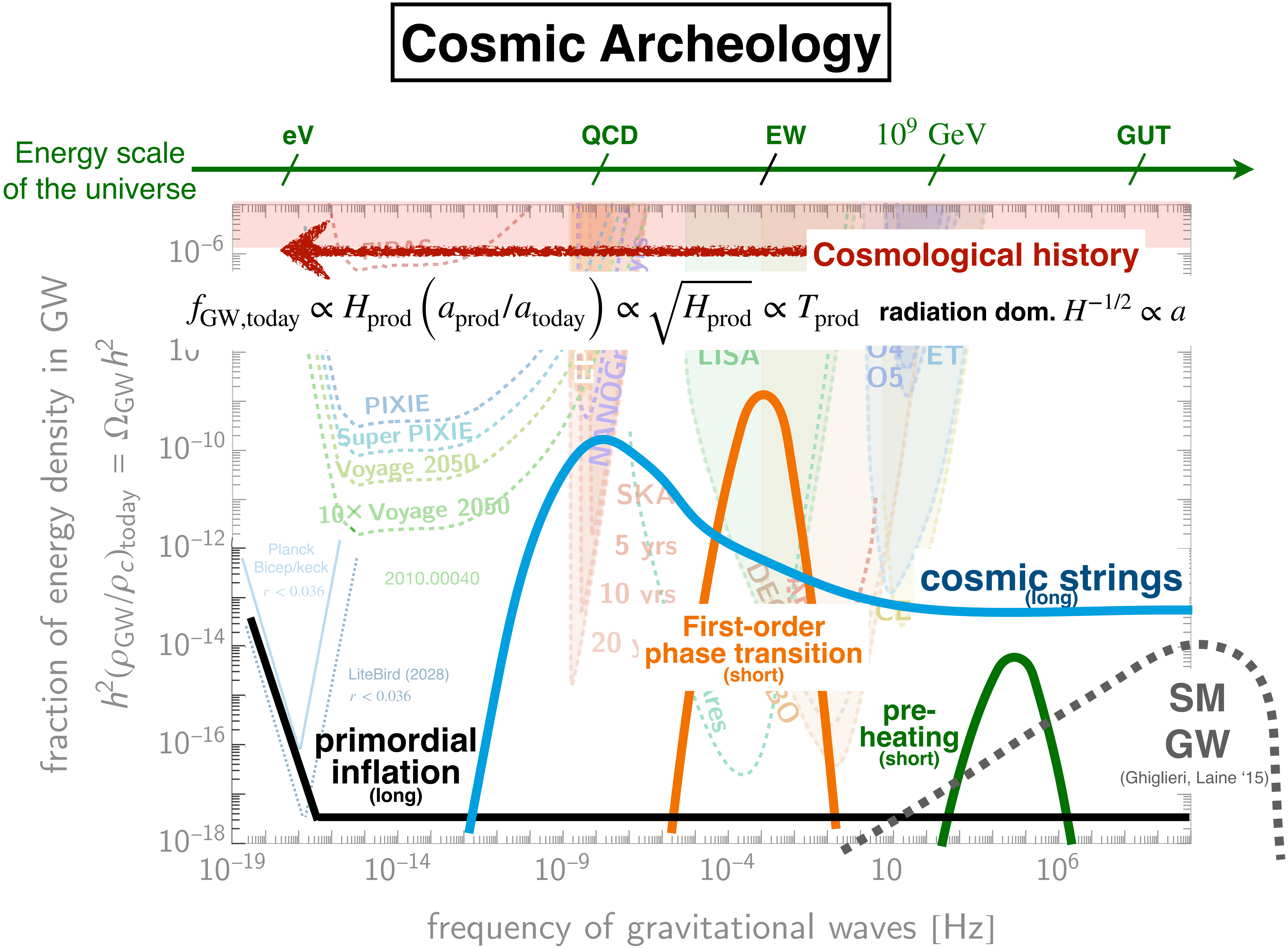
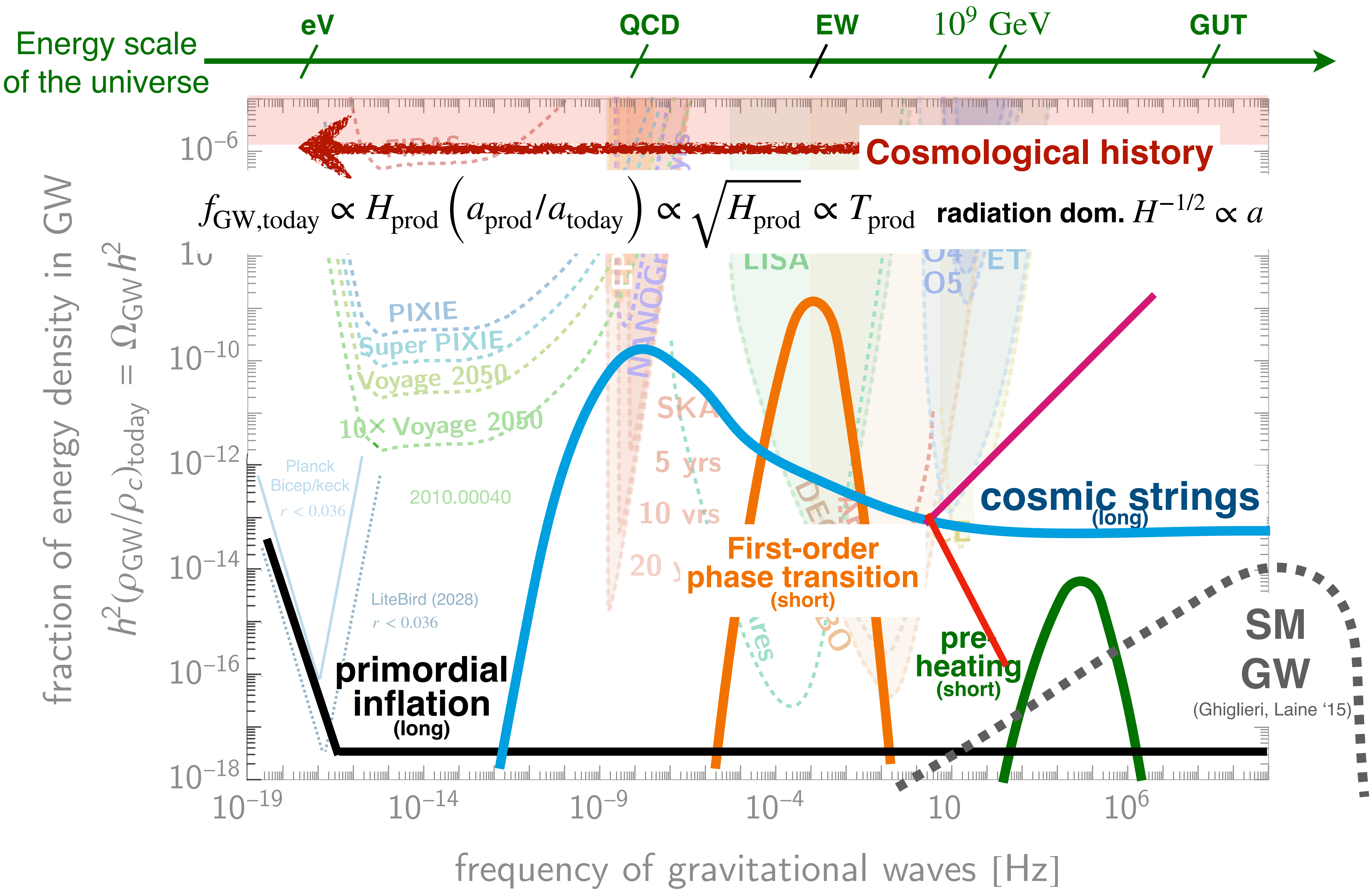


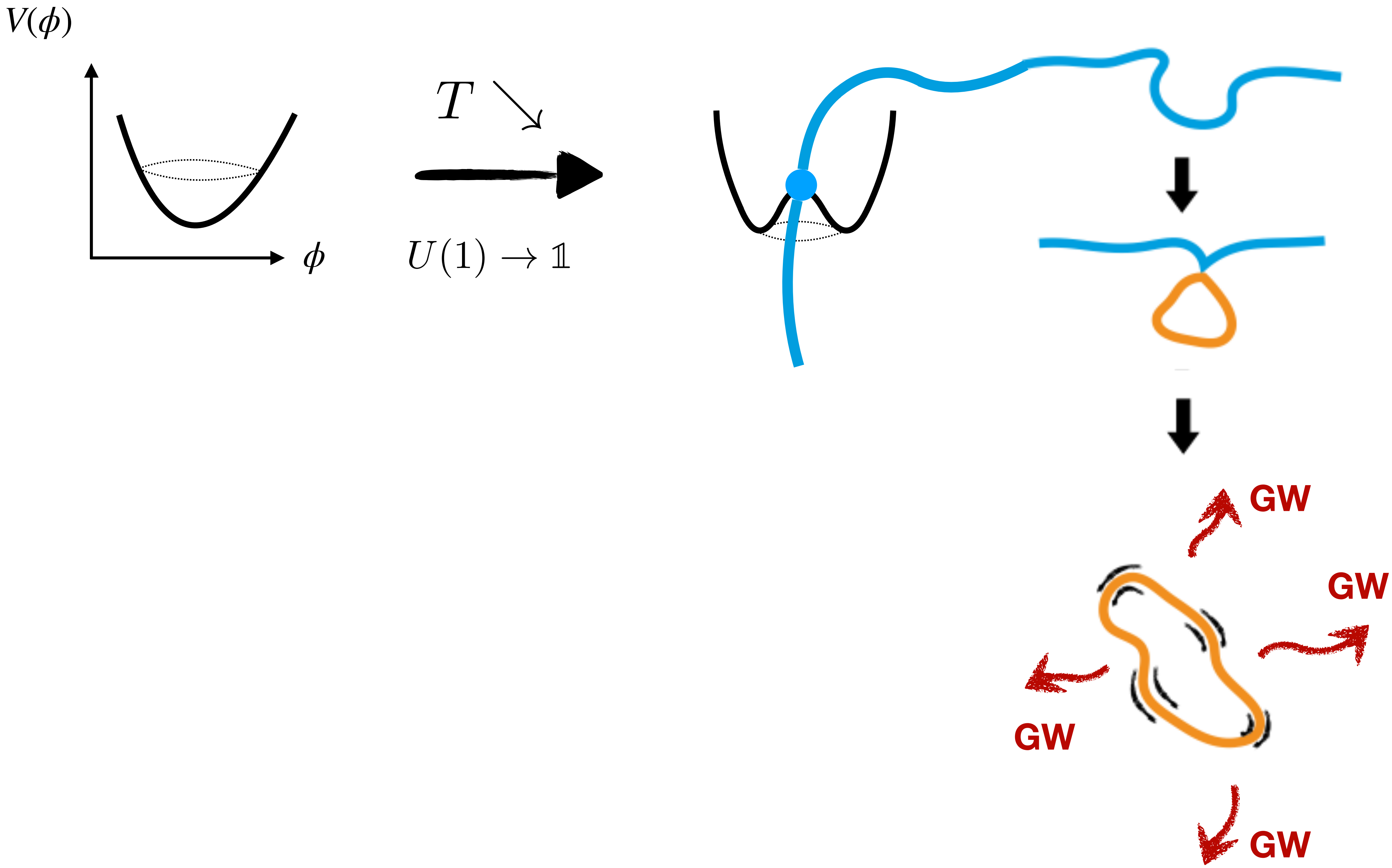

Cosmic Archeology
Energy scale of the universe
eV
QCD
EW
10^9 GeV
GUT
Cosmological history
$f_{\rm GW,today} \propto H_{\rm prod}\left(a_{\rm prod}/a_{\rm today}\right) \propto \sqrt{H_{\rm prod}} \propto T_{\rm prod}$
radiation dom. $H^{-1/2} \propto a$
fraction of energy density in GW
$h^2(\rho_{\rm GW}/\rho_c)_{\rm today} = \Omega_{\rm GW} h^2$
PIXIE
Super PIXIE
Voyage 2050
10× Voyage 2050
2010.00040
Planck
Bicep/keck
$r < 0.036$
LiteBird (2028)
$r < 0.036$
SKA
5 yrs
10 yrs
LISA
O5
ET
cosmic strings
(long)
First-order
phase transition
(short)
primordial
inflation
(long)
pre-
heating
(short)
SM
GW
(Ghiglieri, Laine '15)
10^{-6}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-19}
10^{-14}
10^{-9}
10^{-4}
10
10^{6}
frequency of gravitational waves [Hz]

Cosmic Archeology



Cosmic Strings

•



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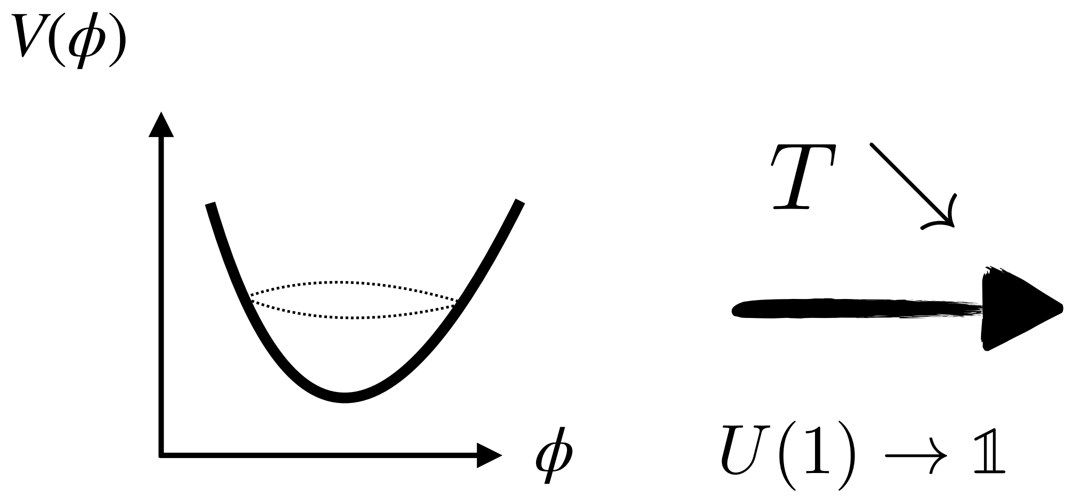
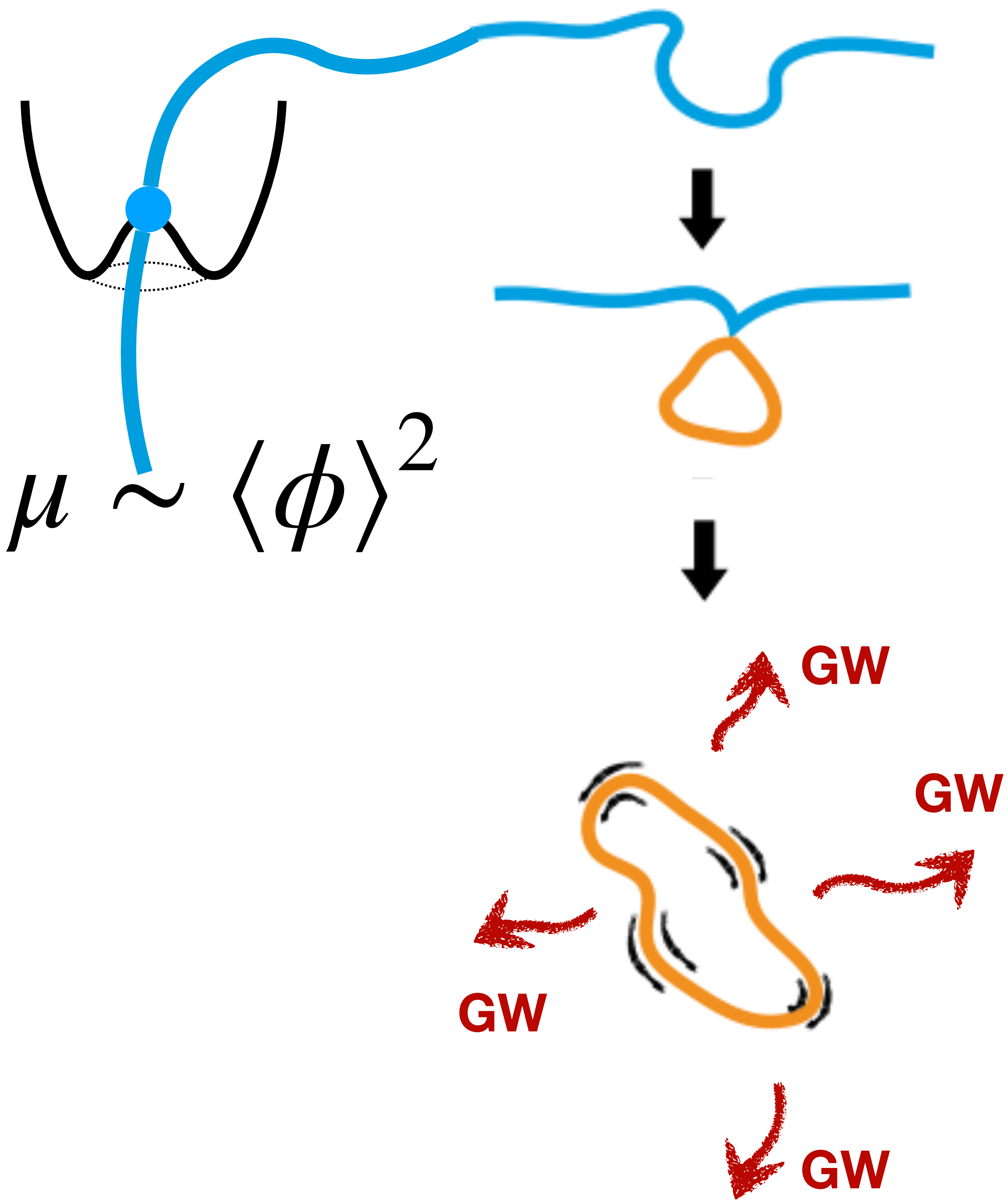
- 



- **1D classical objects:** $\mu \sim \langle \phi \rangle^2$

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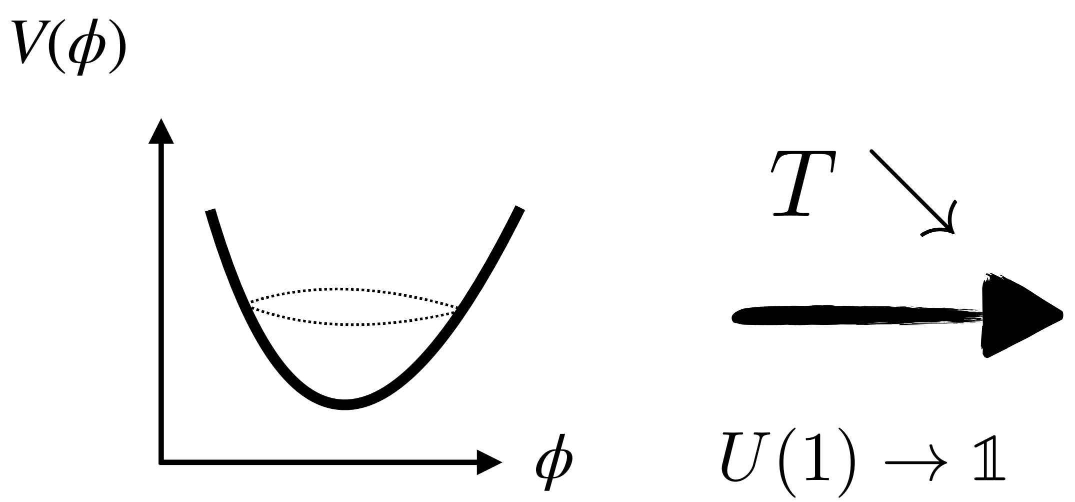
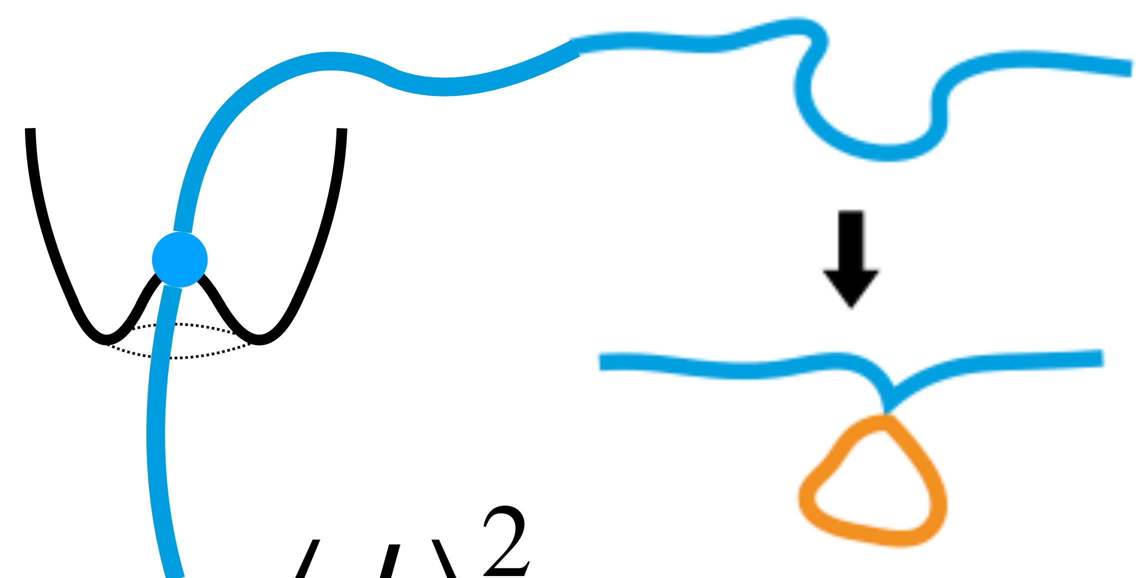
- 

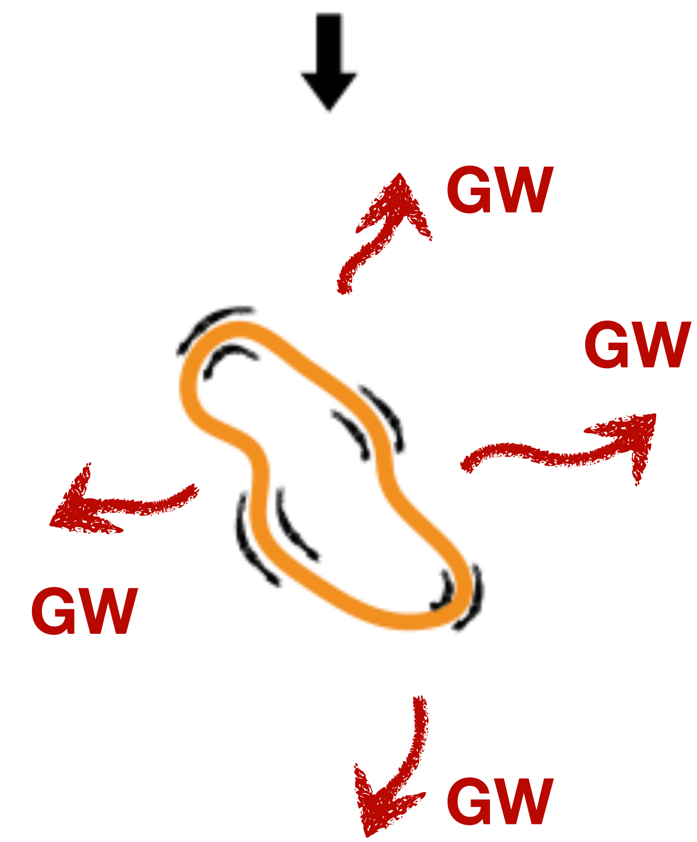


- **1D classical objects:** $\mu \sim \langle \phi \rangle^2$

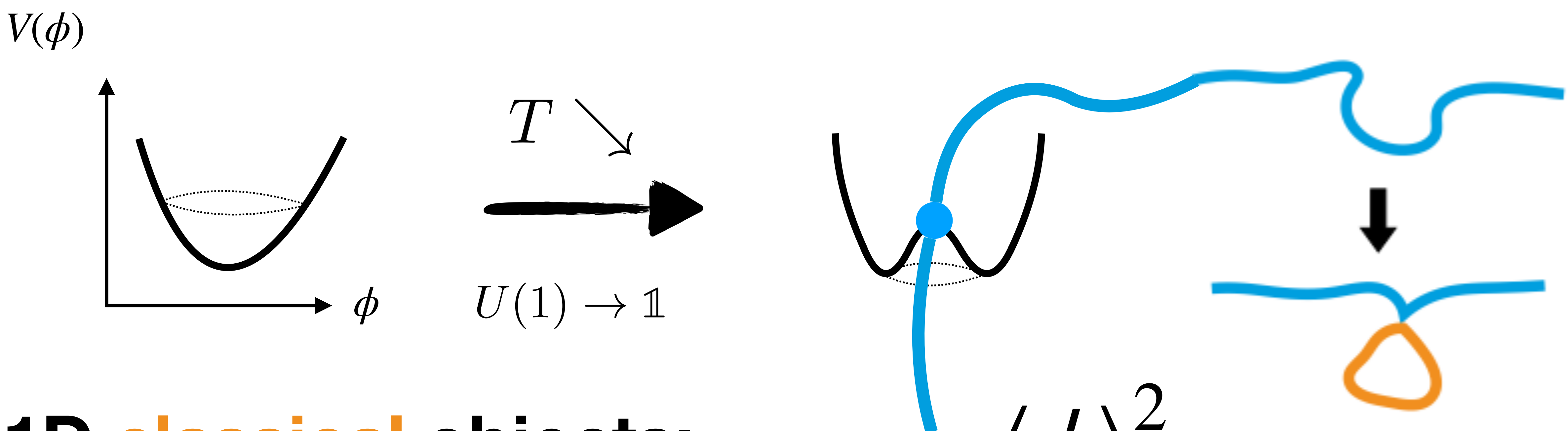
- **Loops emit GW power**

$$P_{\mathrm{GW}} = \Gamma\, G\mu^2 \qquad \Gamma = 50$$

→ **independent of loop length**



Cosmic Strings

- 

- **1D** **classical** **objects:** $\mu \sim \langle \phi \rangle^2$

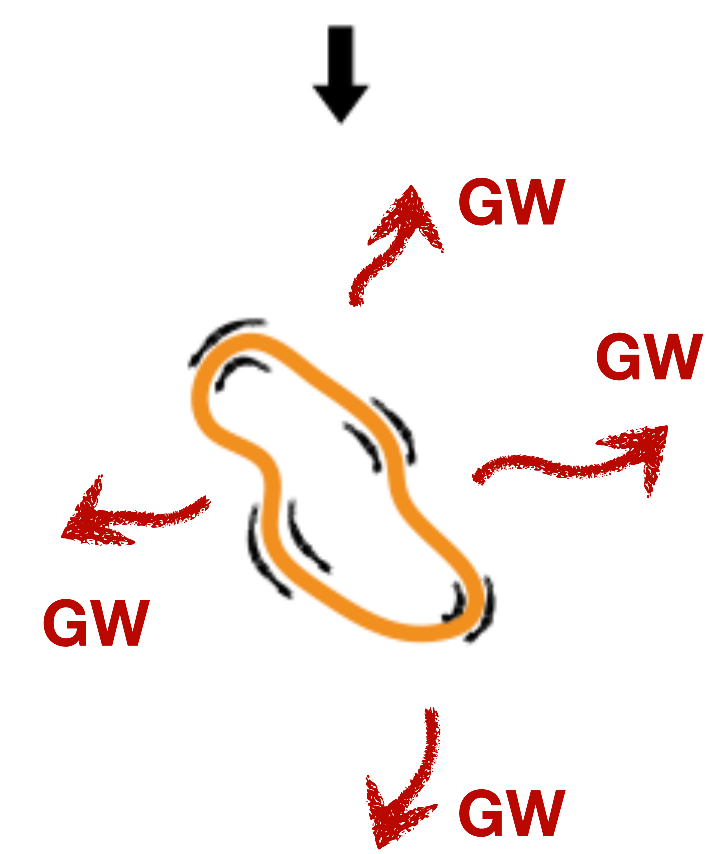
- **Loops** **emit GW power**

$$P_{\rm GW} = \Gamma\, G\mu^2 \qquad \Gamma = 50$$

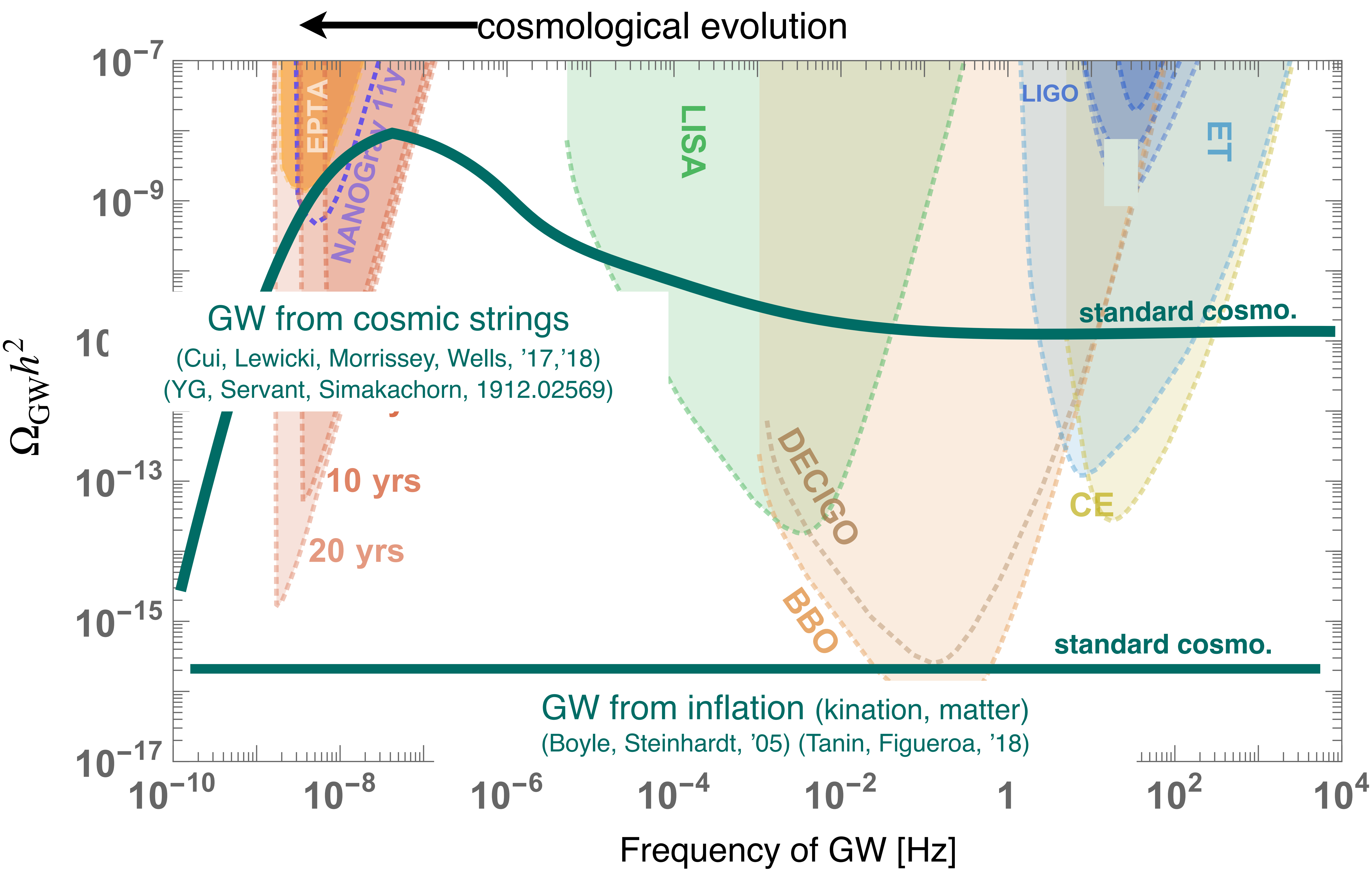
→ **independent of** **loop length**

- **Scaling regime:** $L \propto t$

→ $\Omega_{\rm CS} \simeq \text{constant}$



Overview: Cosmic archeology with GW



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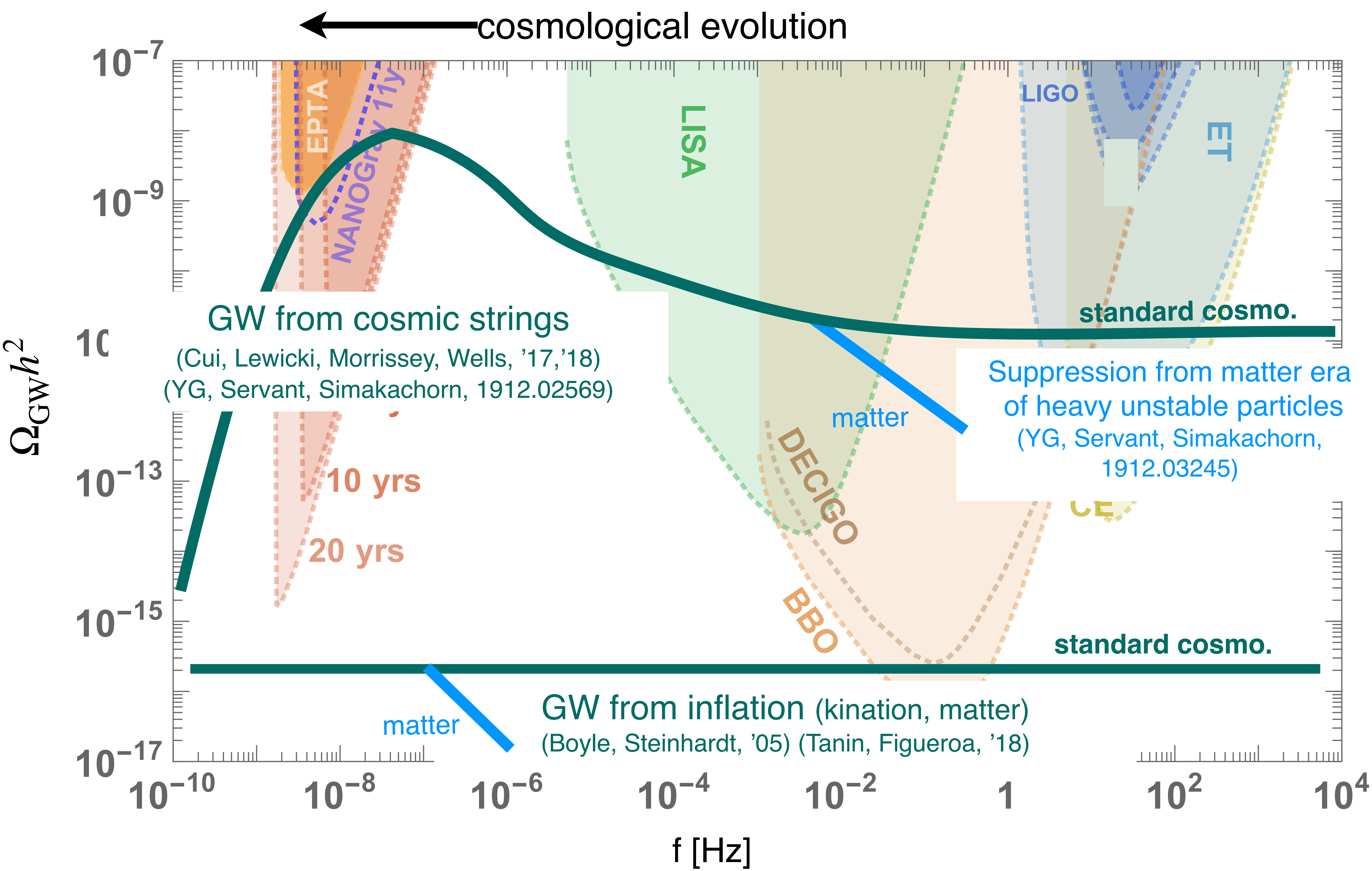

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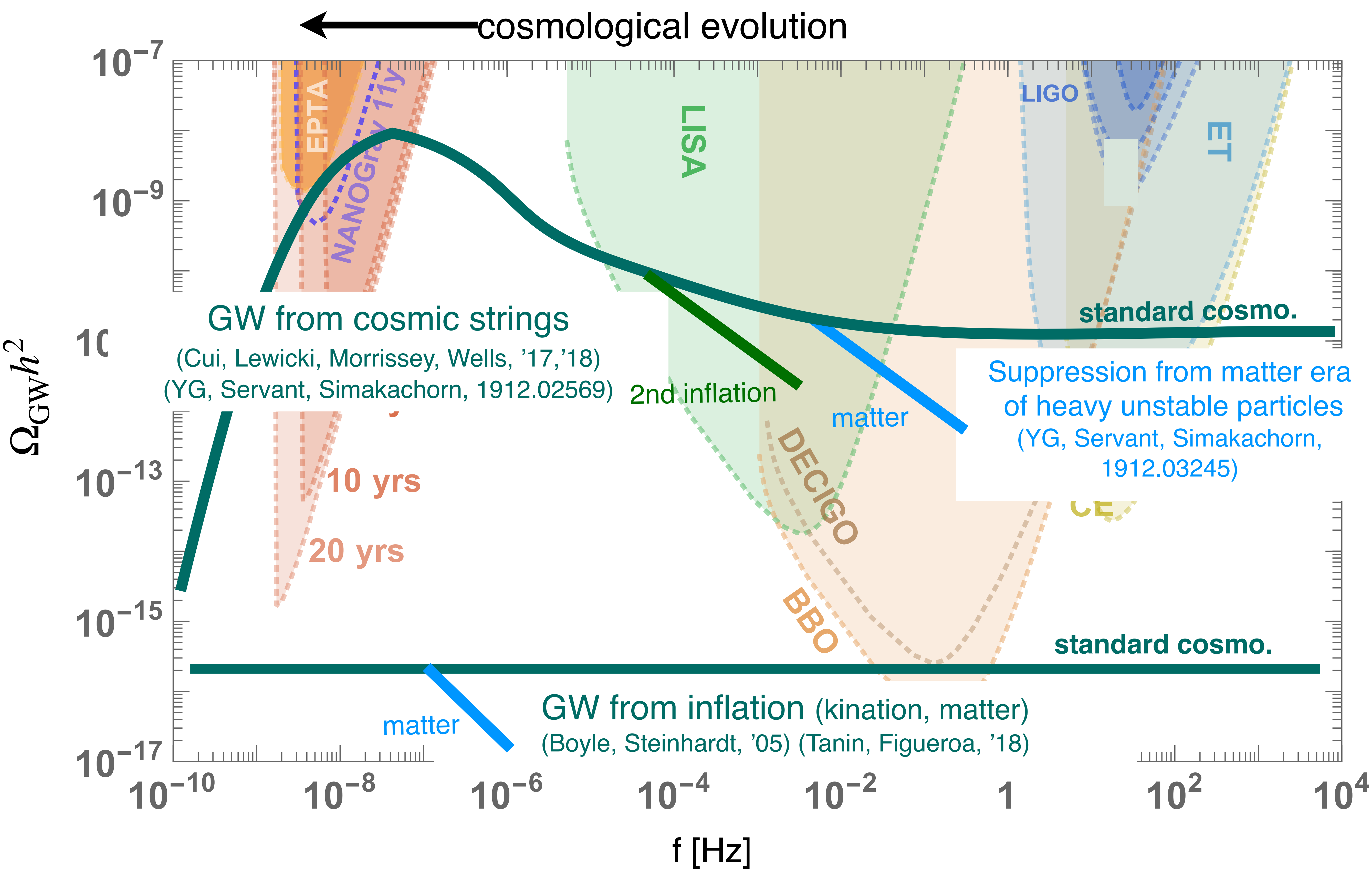

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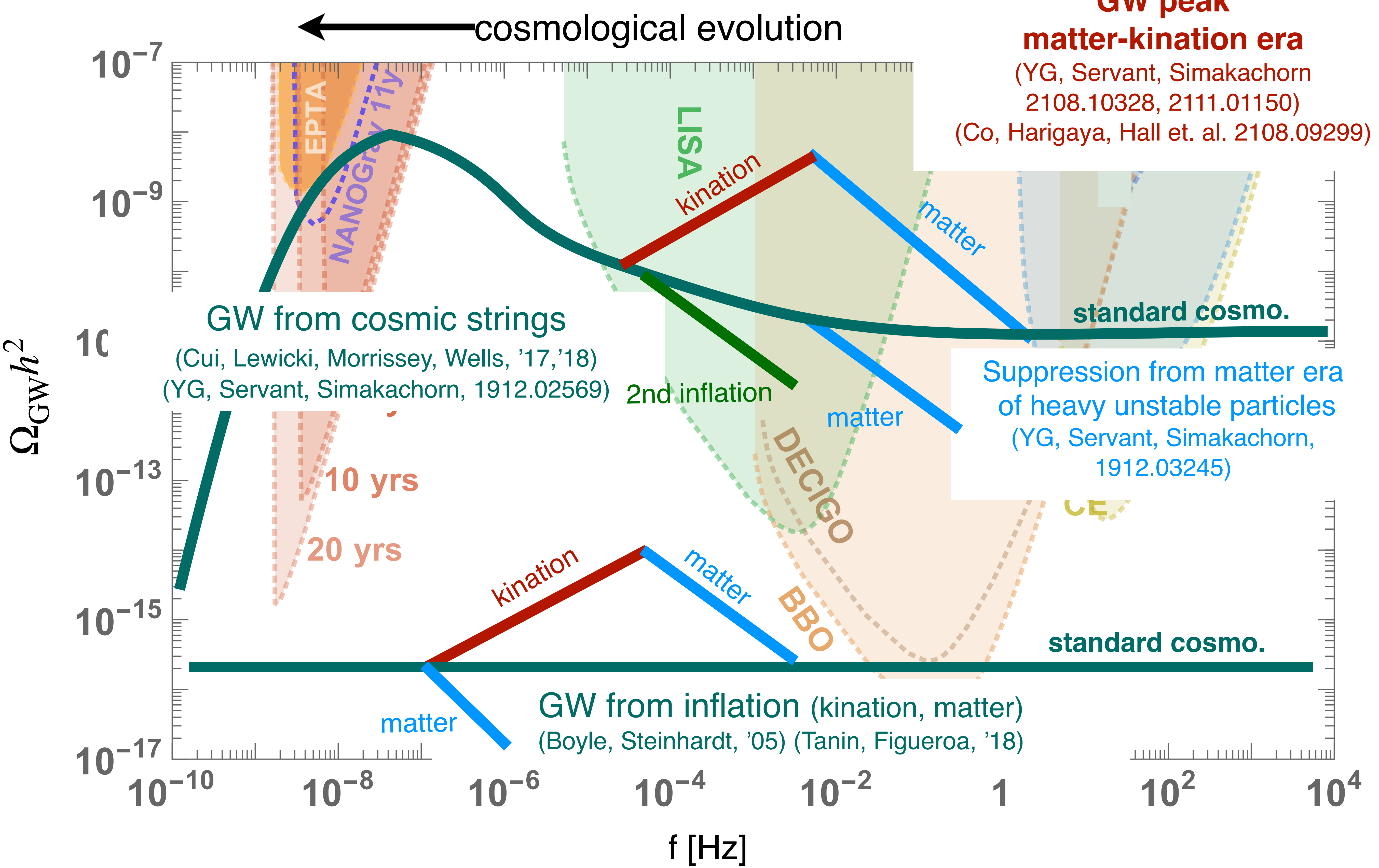
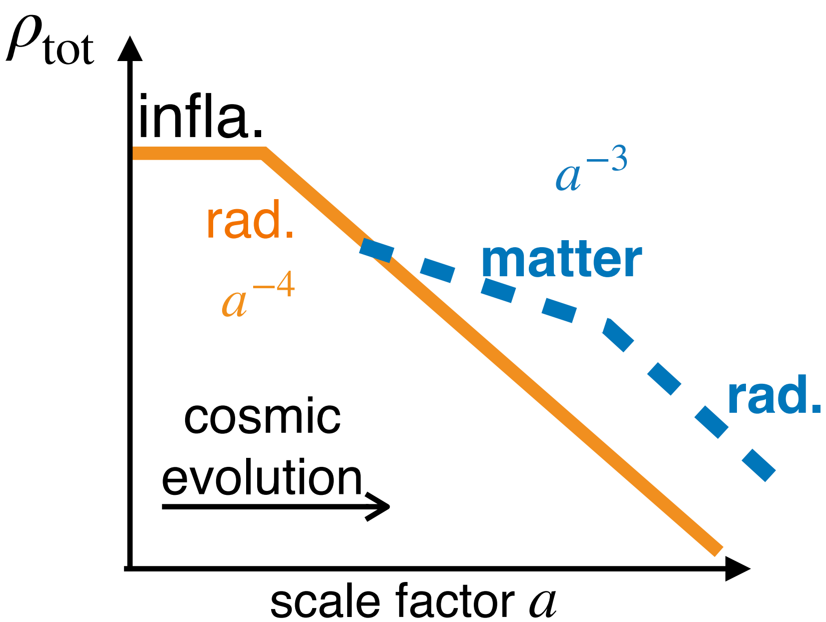
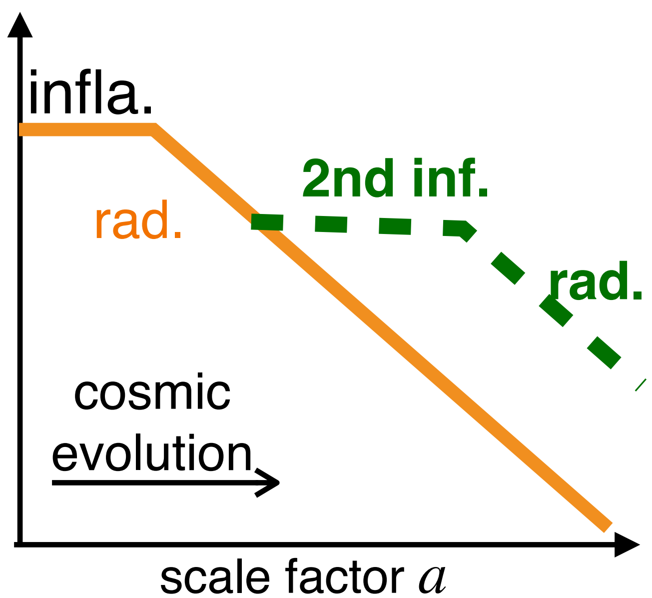


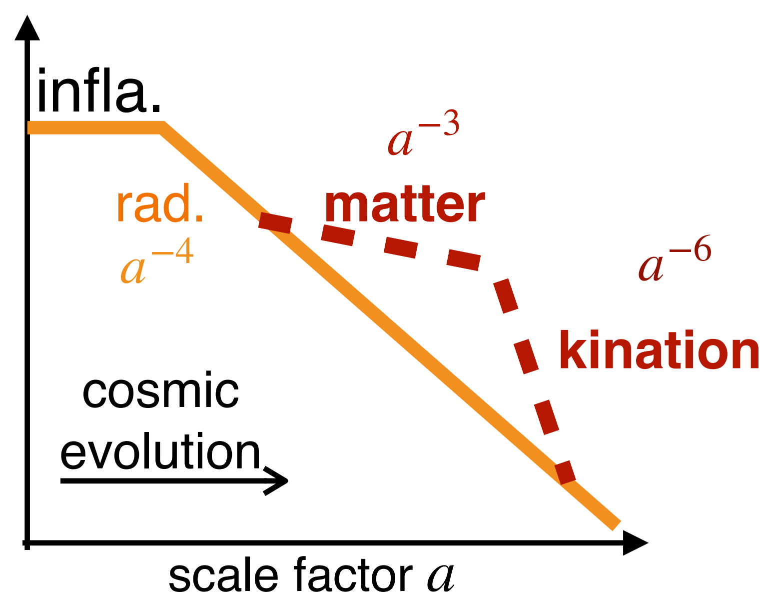
Non-standard cosmological eras



Heavy & unstable particles



Supercool 1st-order phase transition



Rotating field

(Affleck-Dine)

Plan

0. Intro

I. GW signature of non-standard era

II. Early matter era

Heavy & unstable particles

III. 2nd inflation era

Supercool 1st-order phase transition

IV. Intermediate kination era

Rotating axion!

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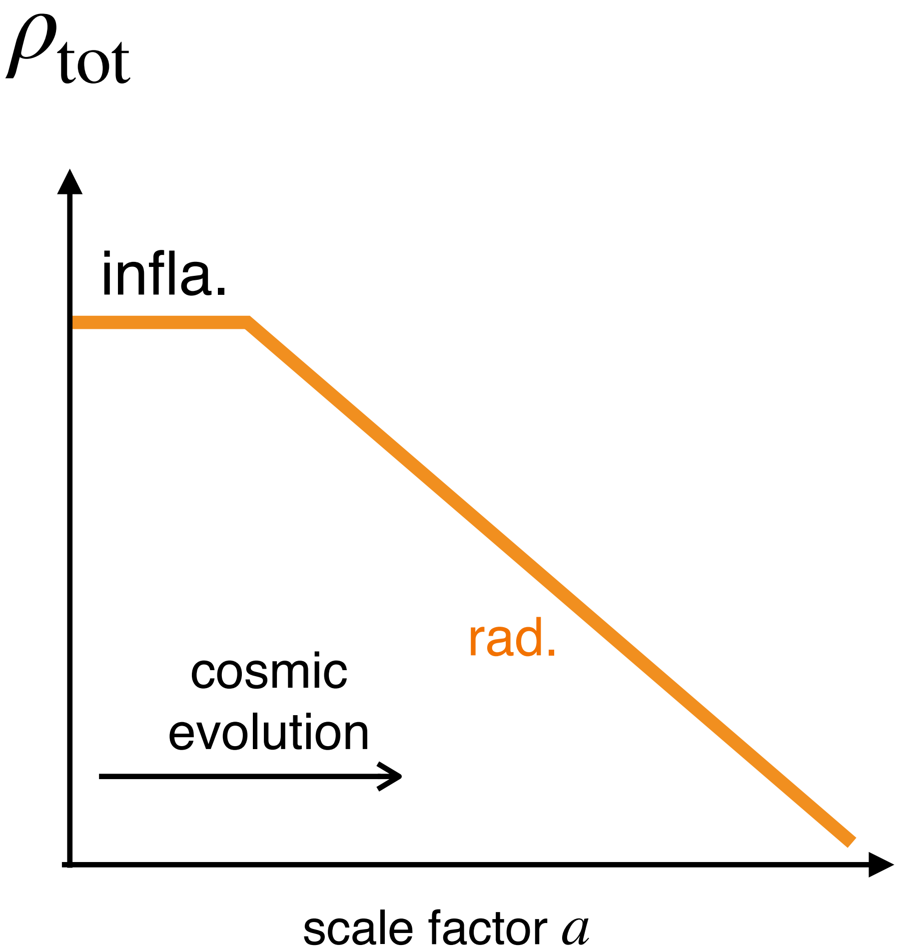
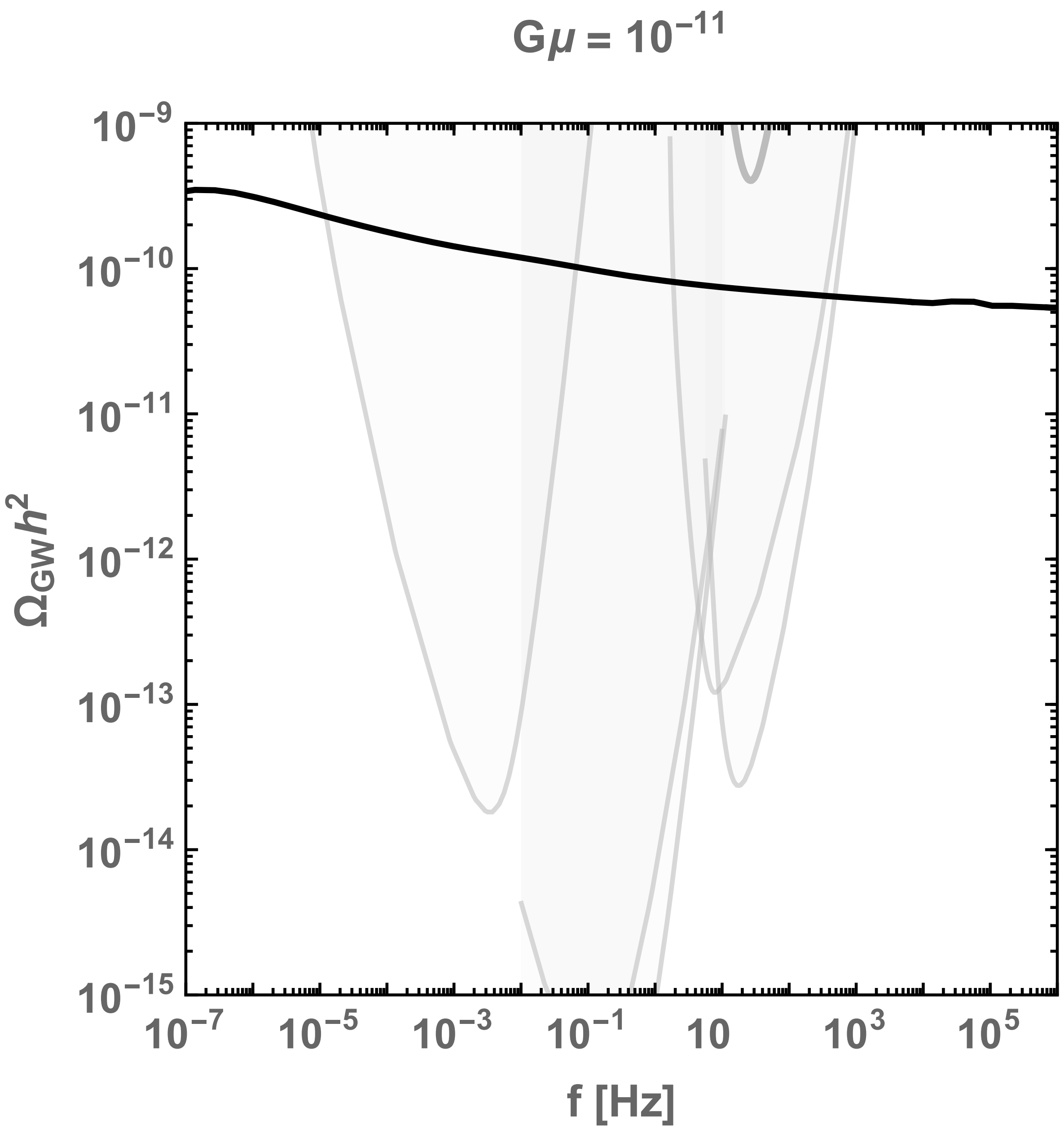
Non-standard Matter era

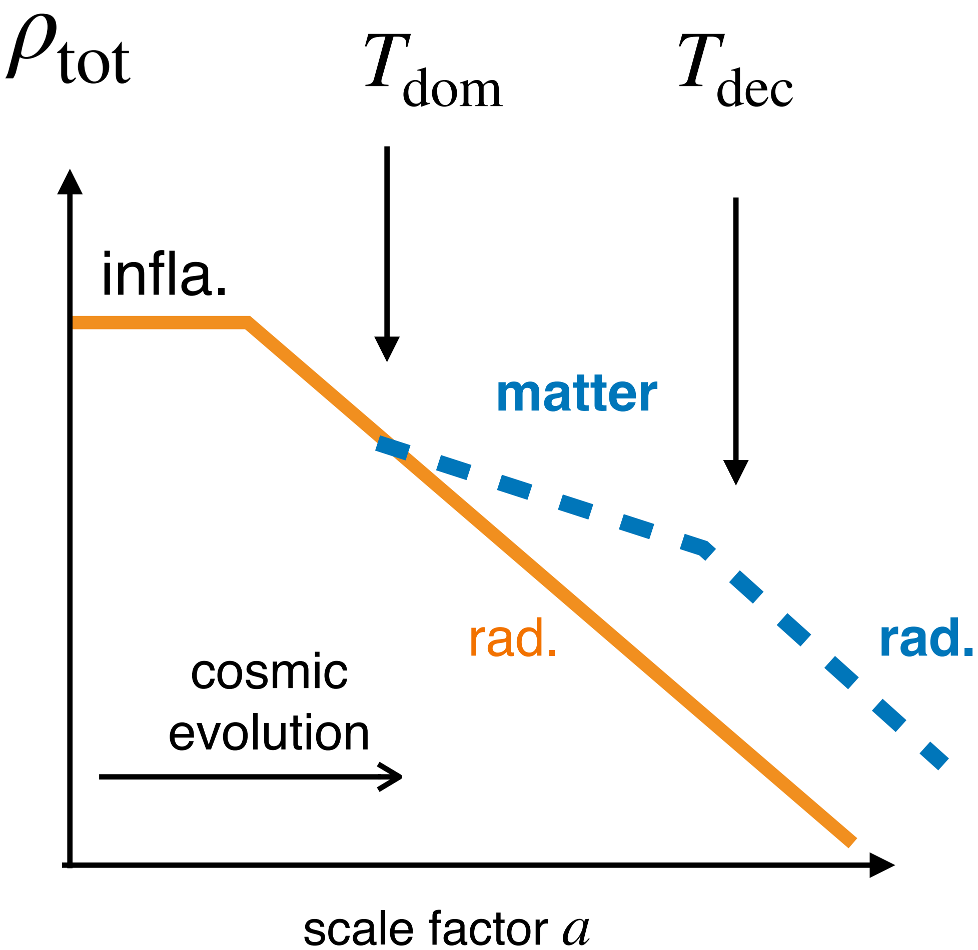
1912.03245





Non-standard Matter era

1912.03245



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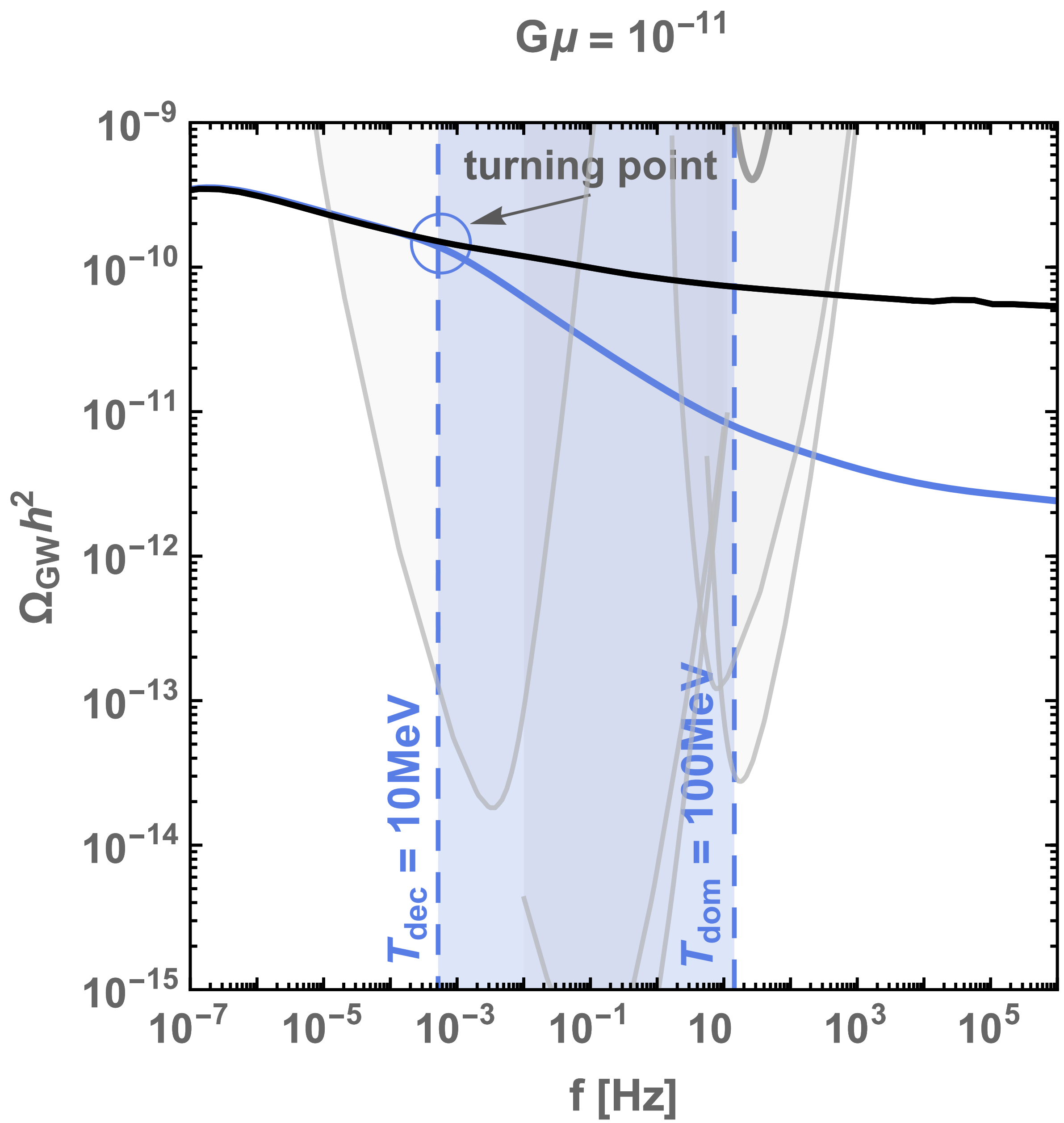

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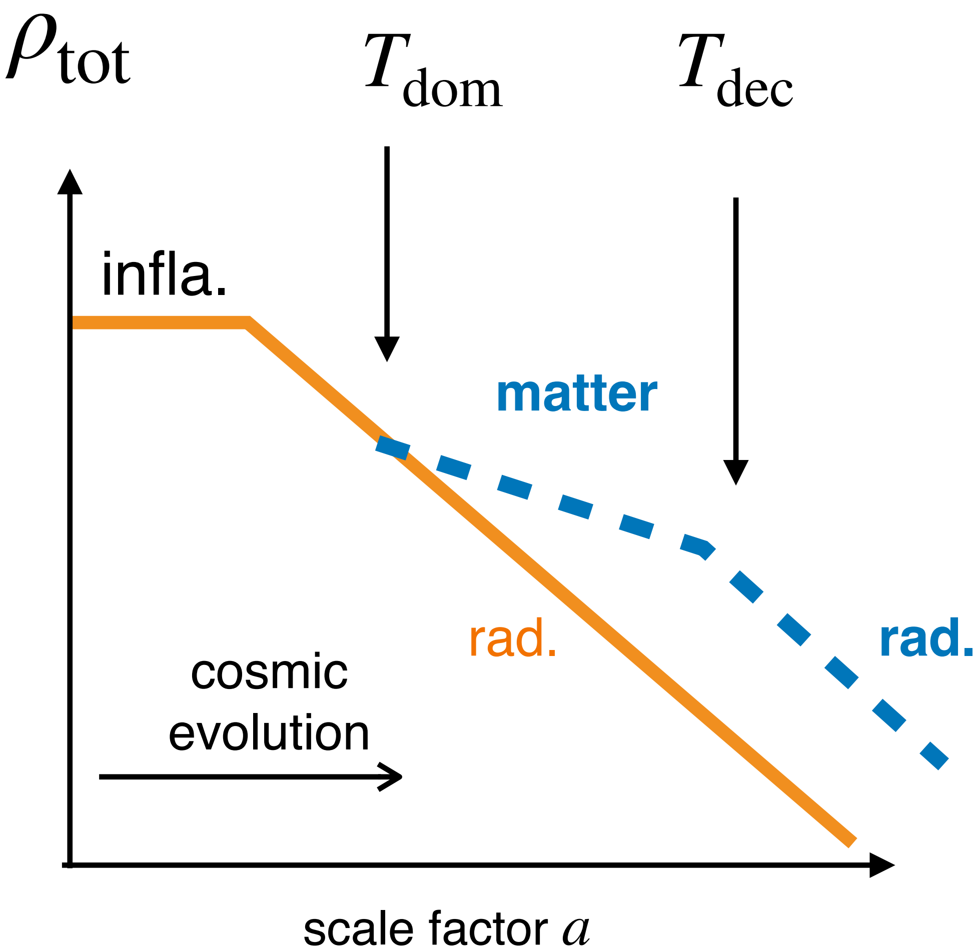
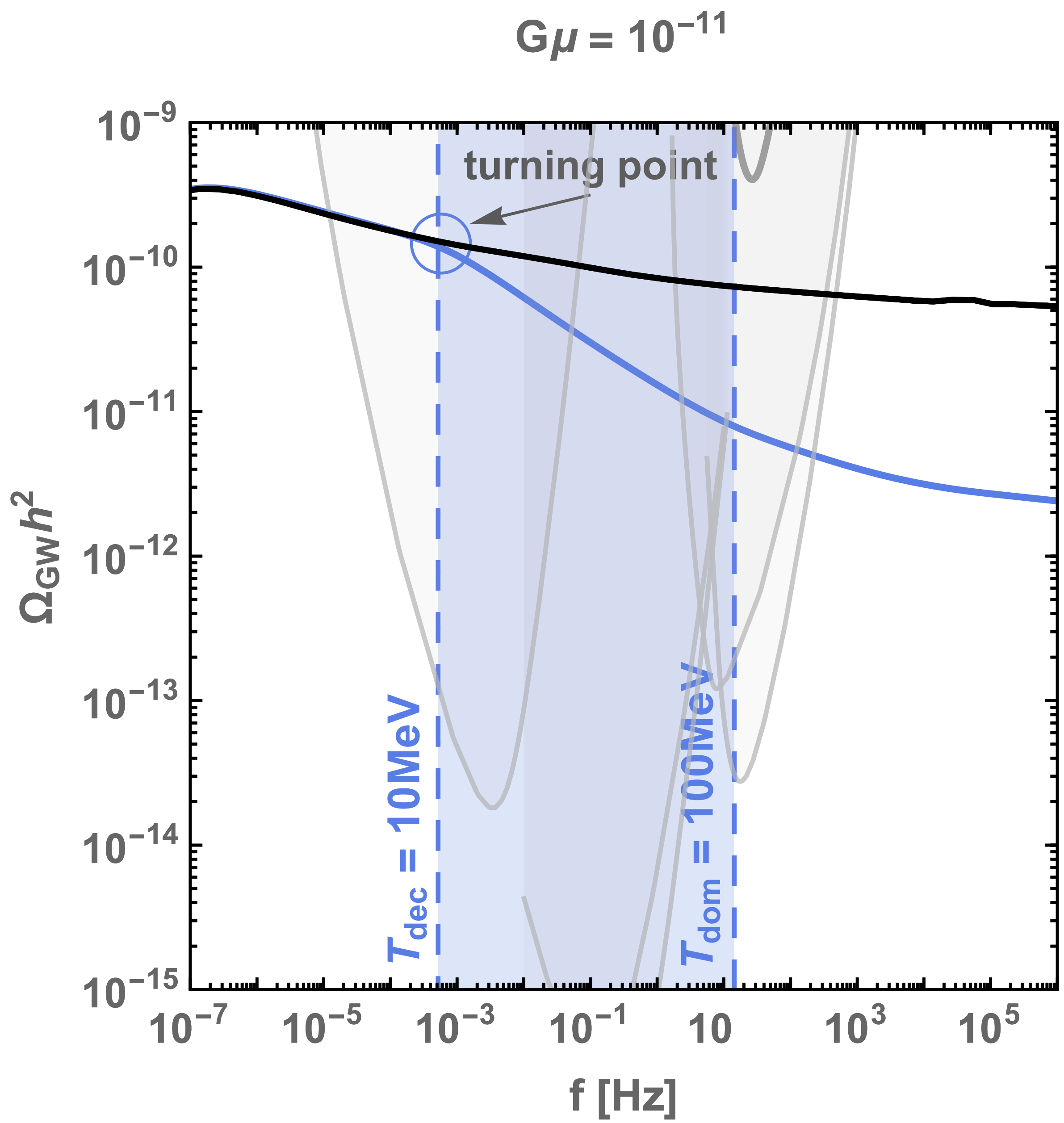




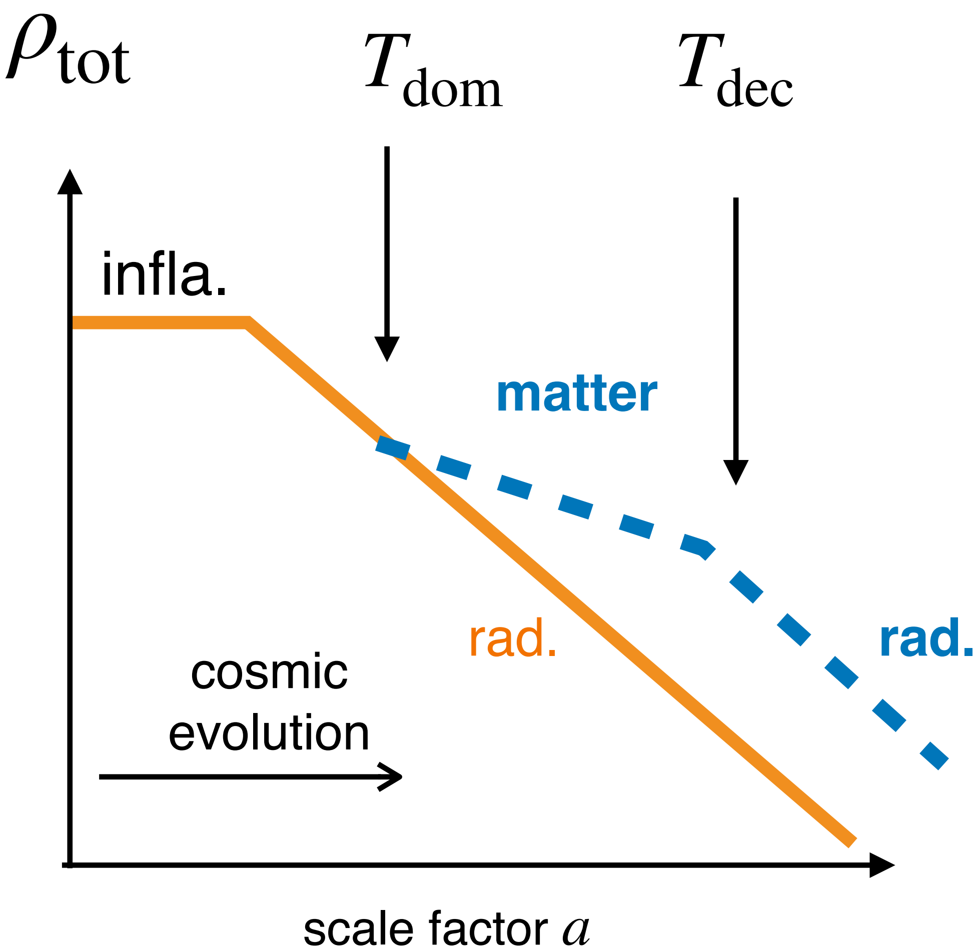
Heavy & unstable particles

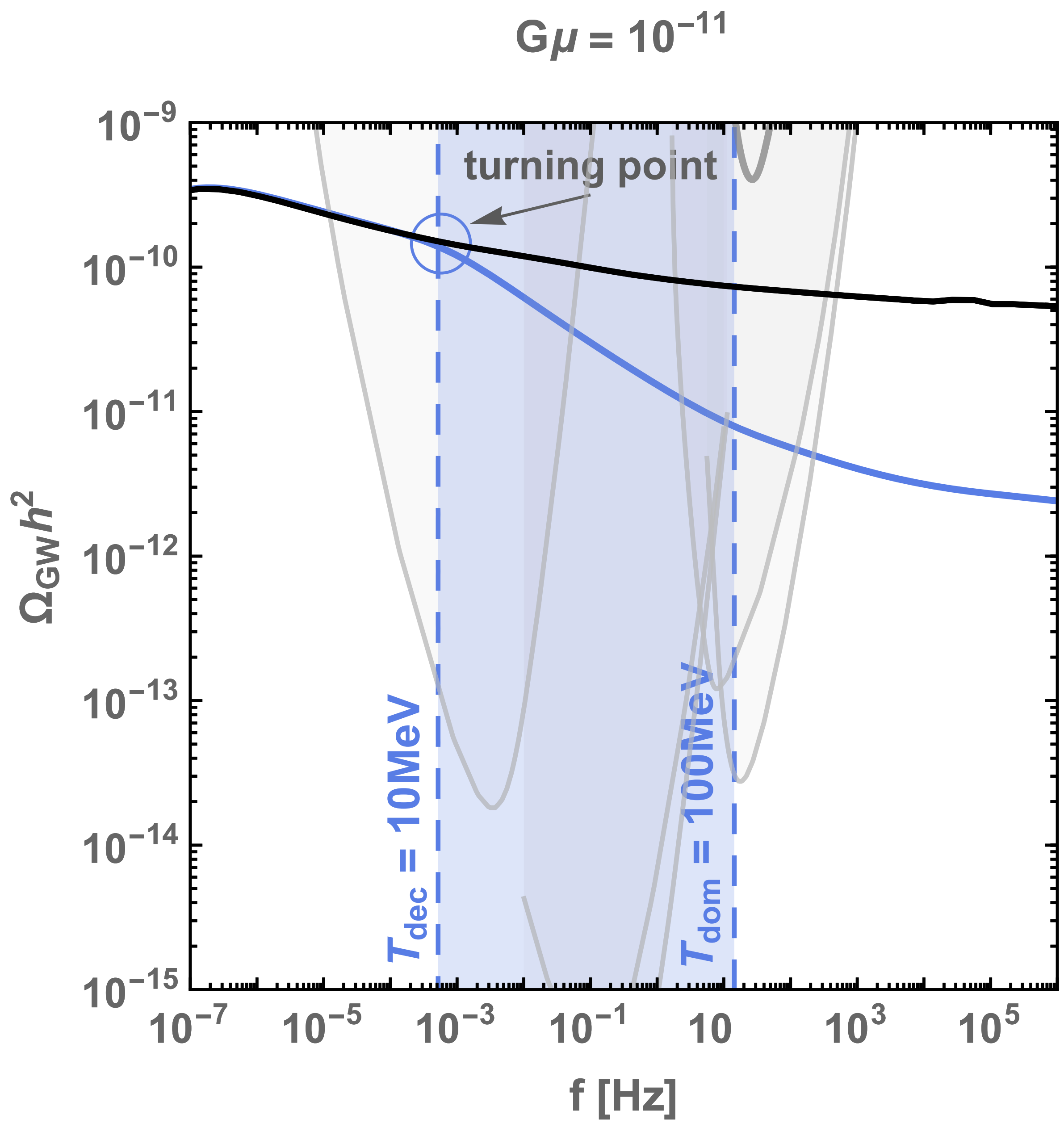
Examples:

I. Moduli from SUSY breaking

Non-standard Matter era

1912.03245





Heavy & unstable particles

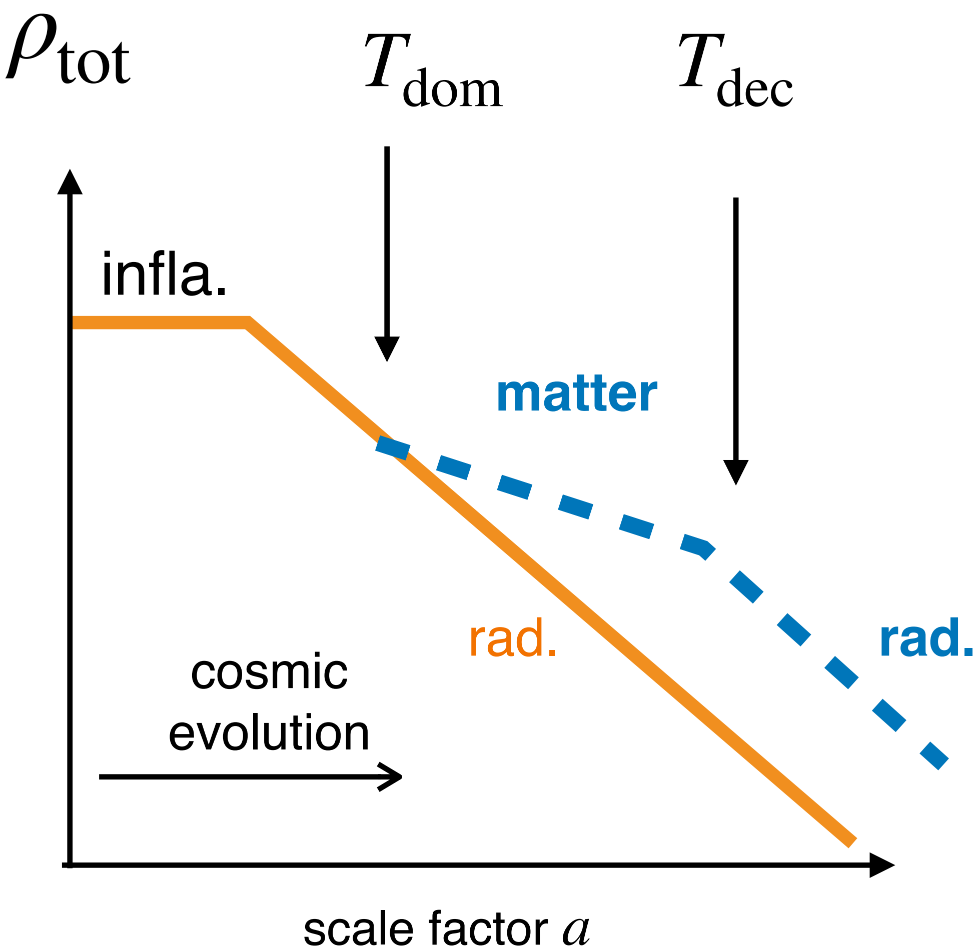
Examples:

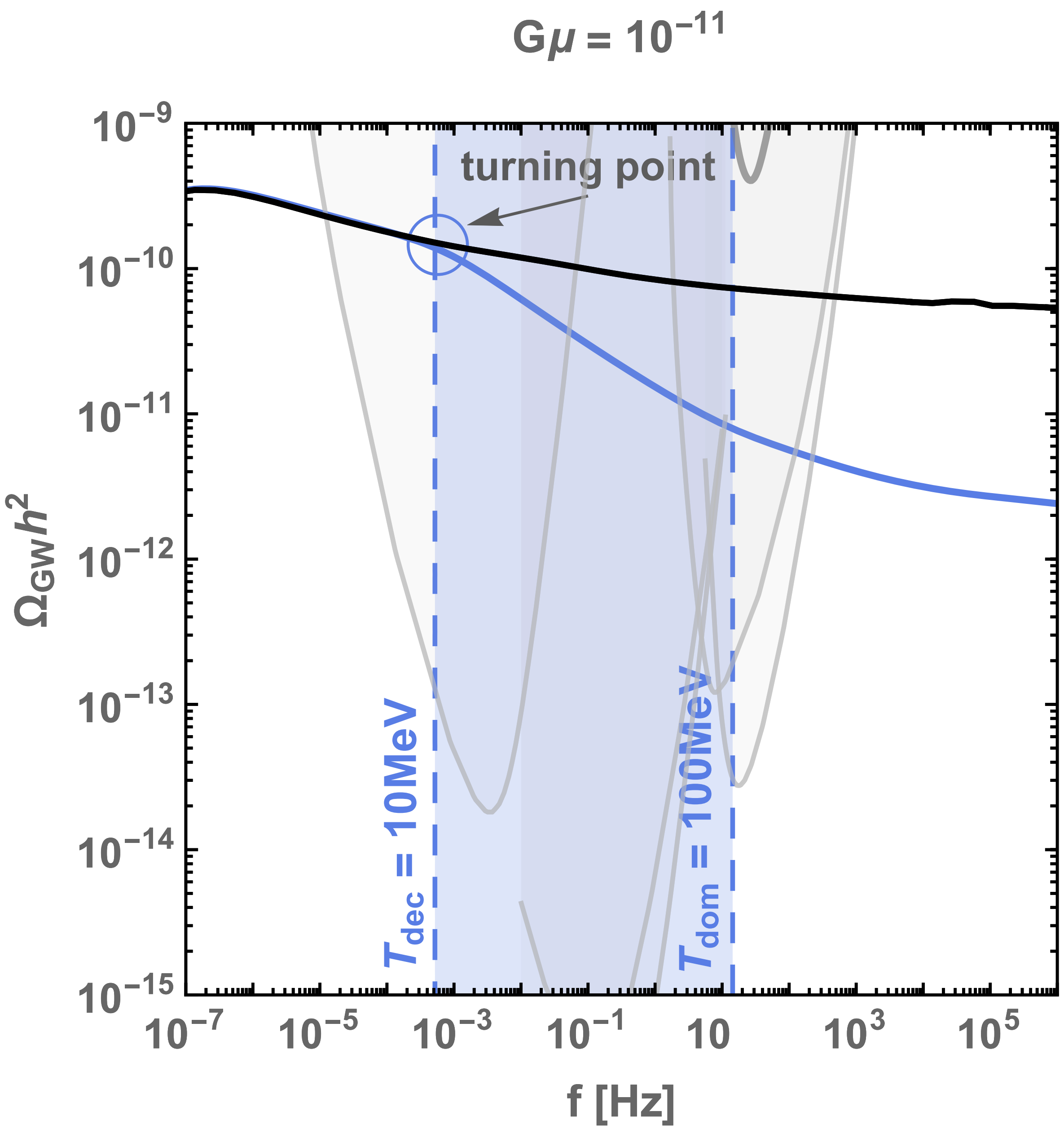
I. Moduli from SUSY breaking

II. Heavy long-lived U(1) dark photon

Non-standard Matter era

1912.03245





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III. Gravitationally-coupled heavy relic

Non-standard Matter era

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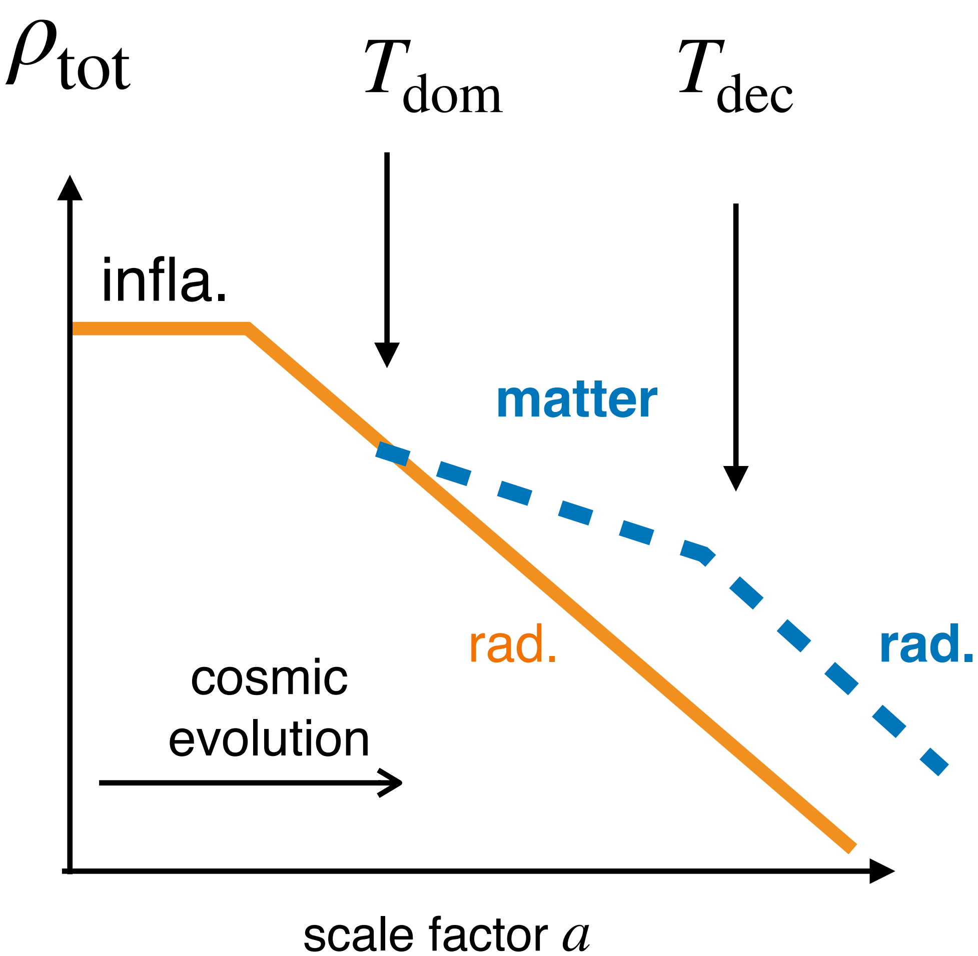

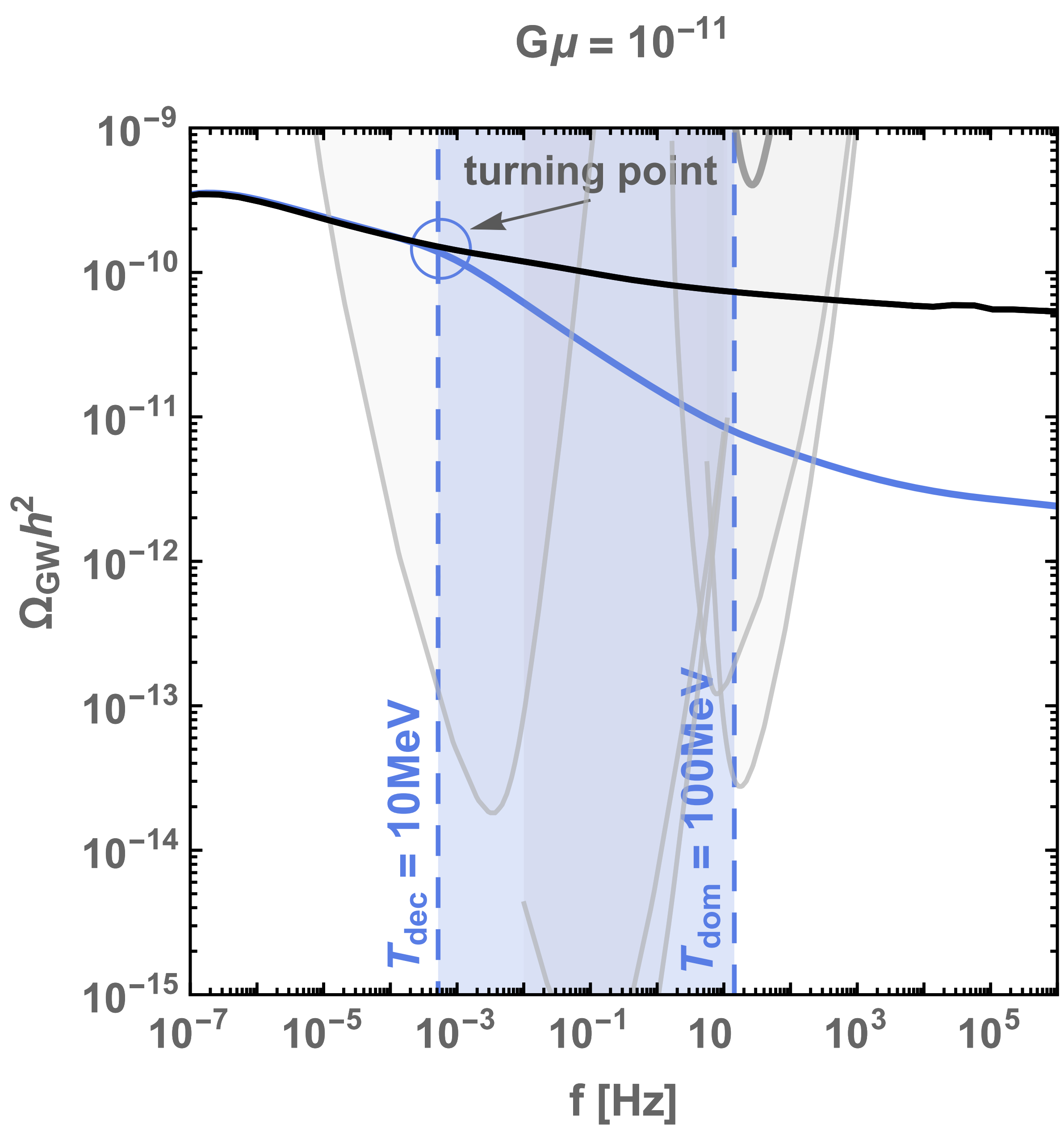

Heavy & unstable particles

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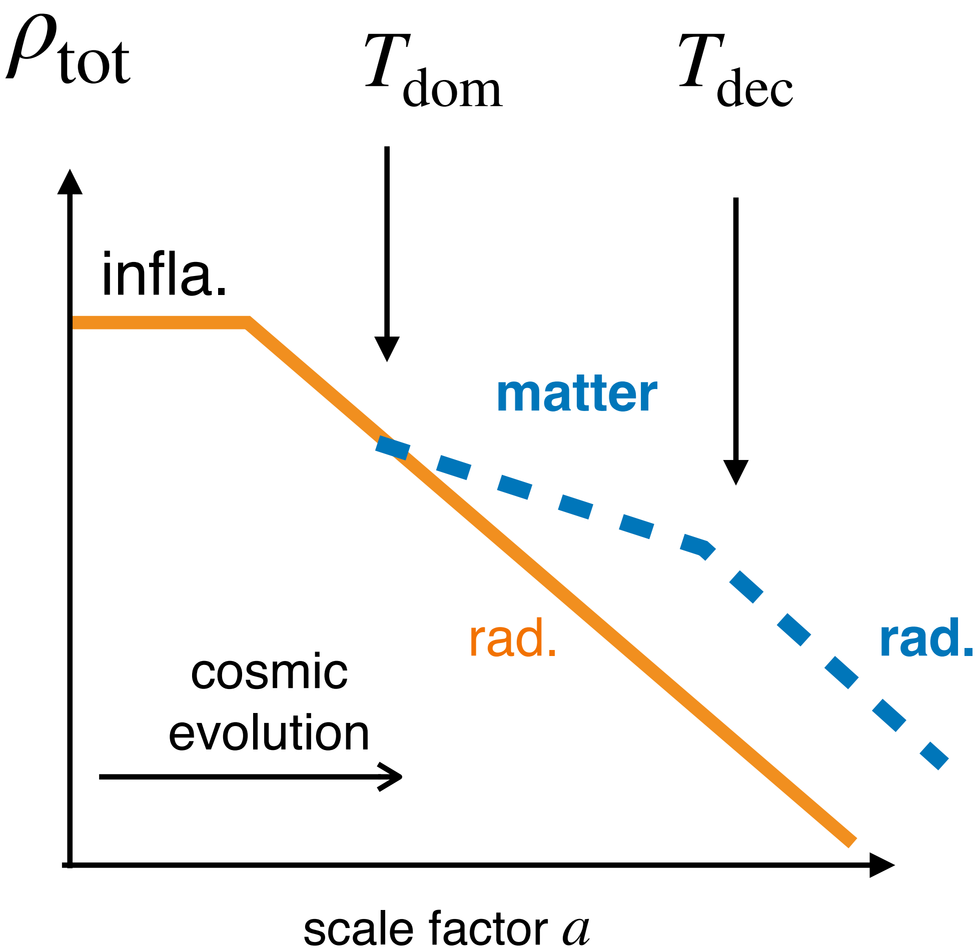
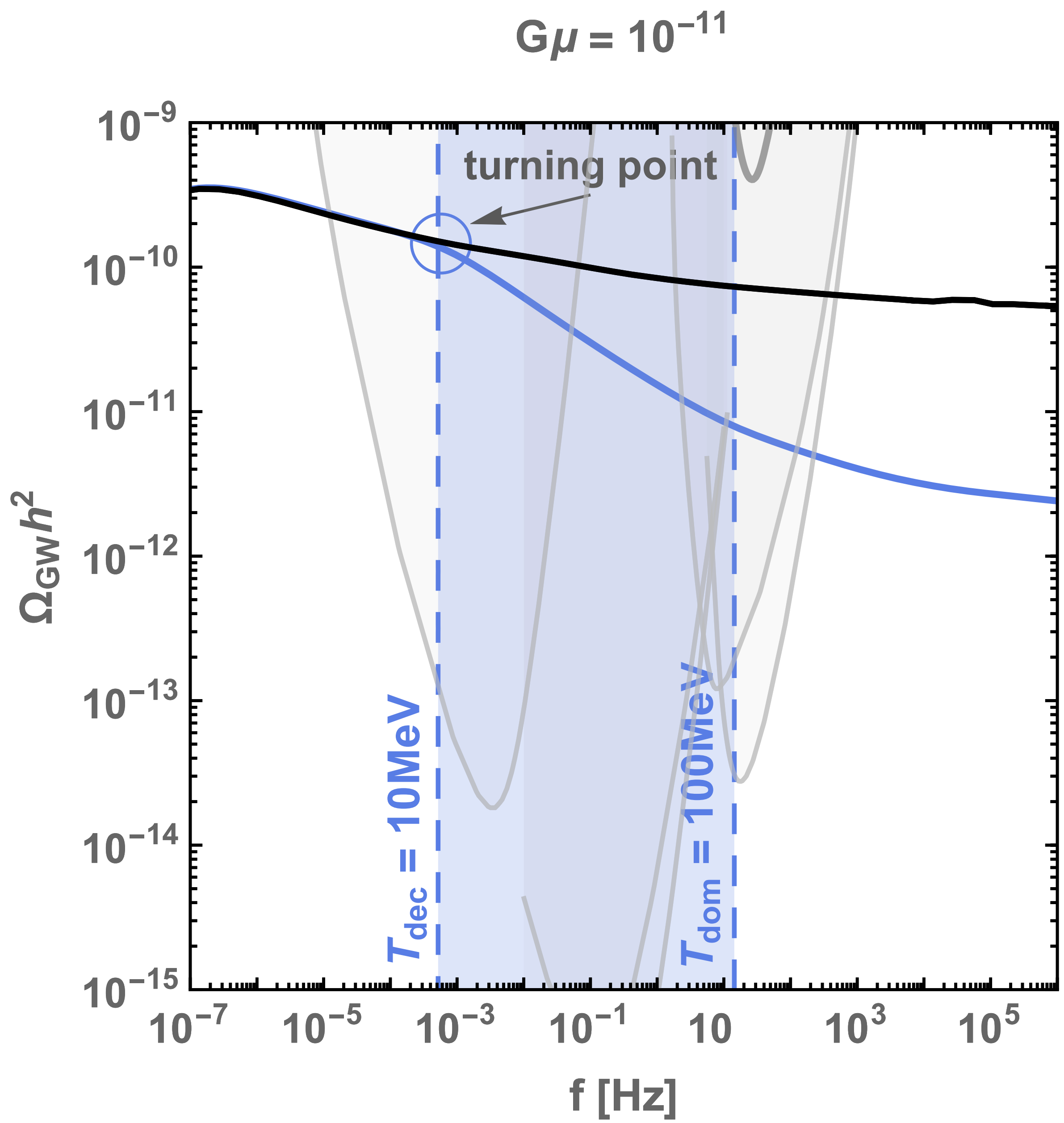
IV. Light PBH < 10^8 g

Non-standard Matter era

1912.03245





Heavy & unstable particles

Examples:

I. Moduli from SUSY breaking

II. Heavy long-lived U(1) dark photon

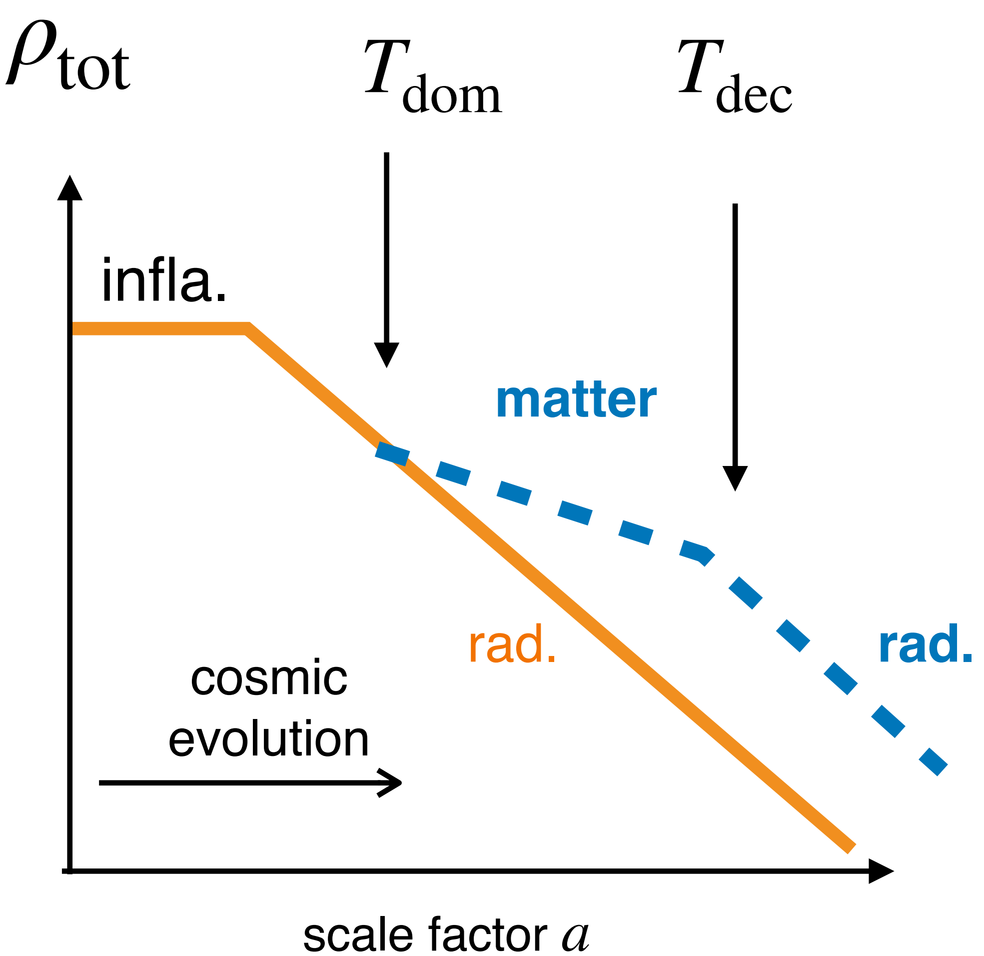
III. Gravitationally-coupled heavy relic

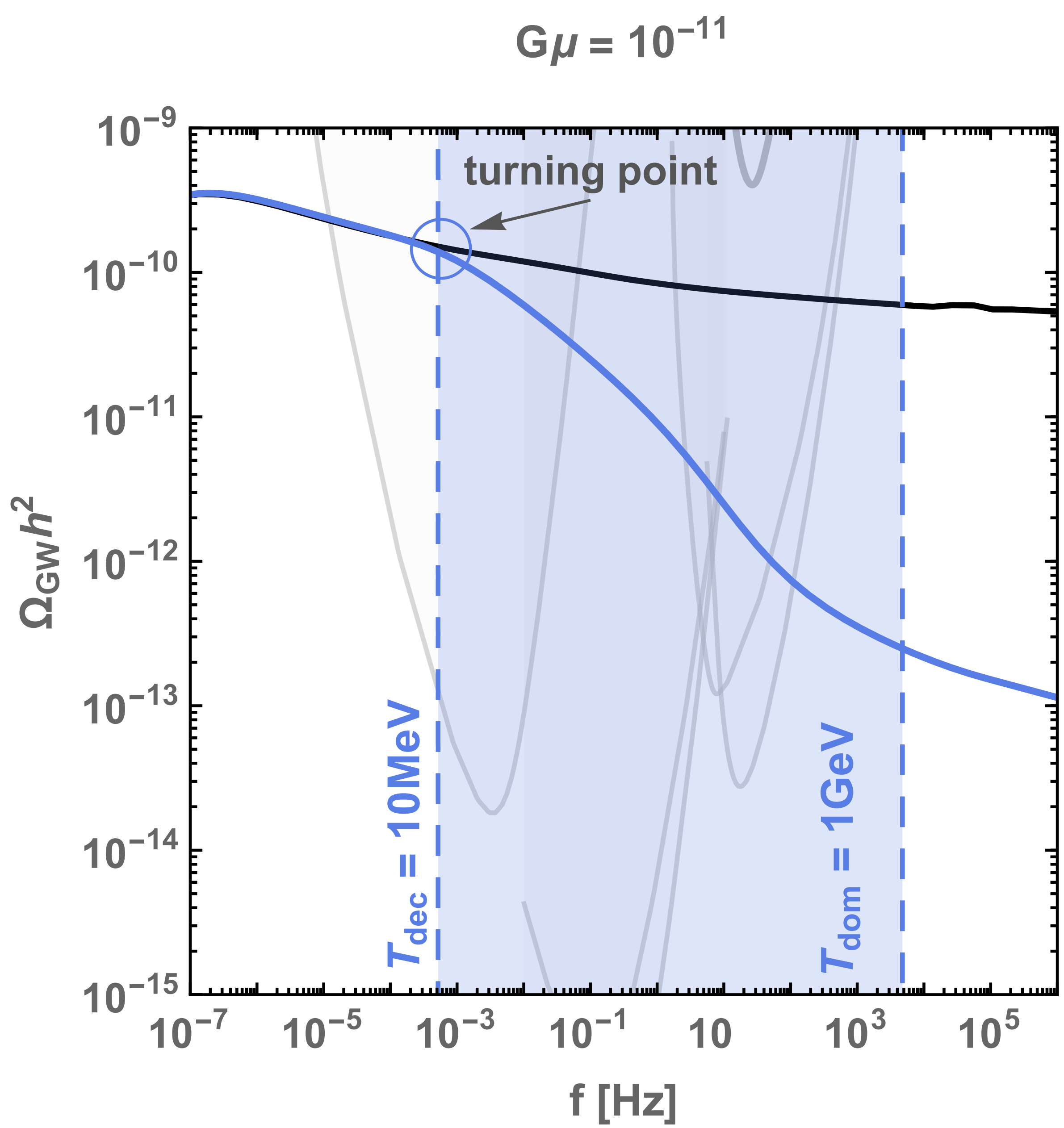
IV. Light PBH $< 10^8$ g

V. Heavy axion $>$ 0.1 GeV

Non-standard Matter era

1912.03245





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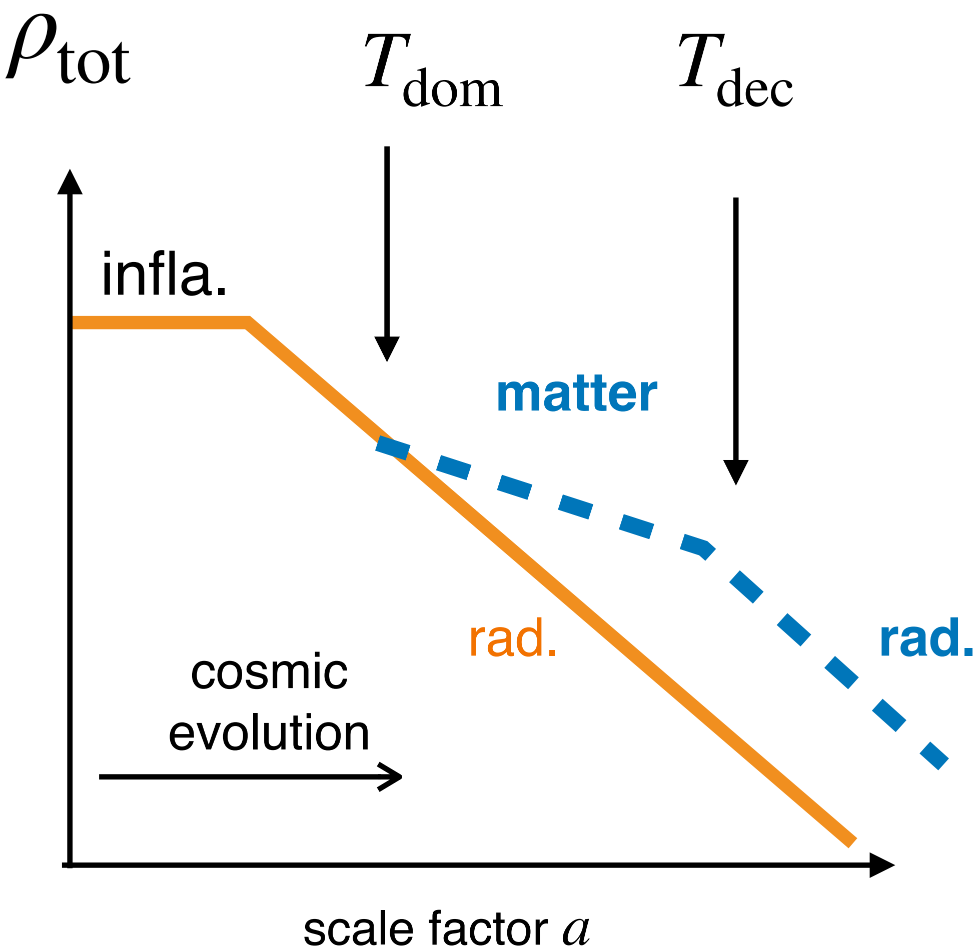

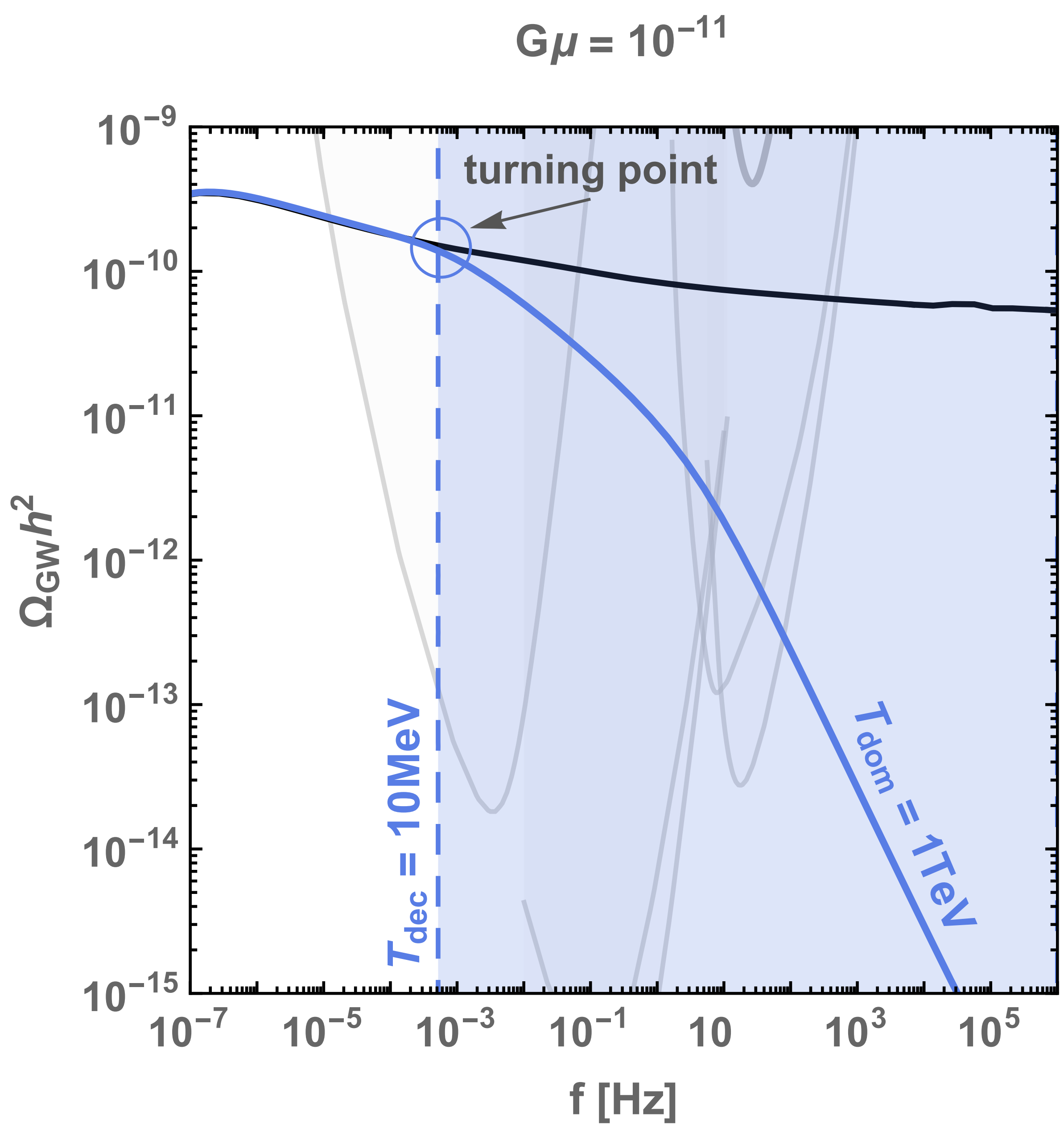

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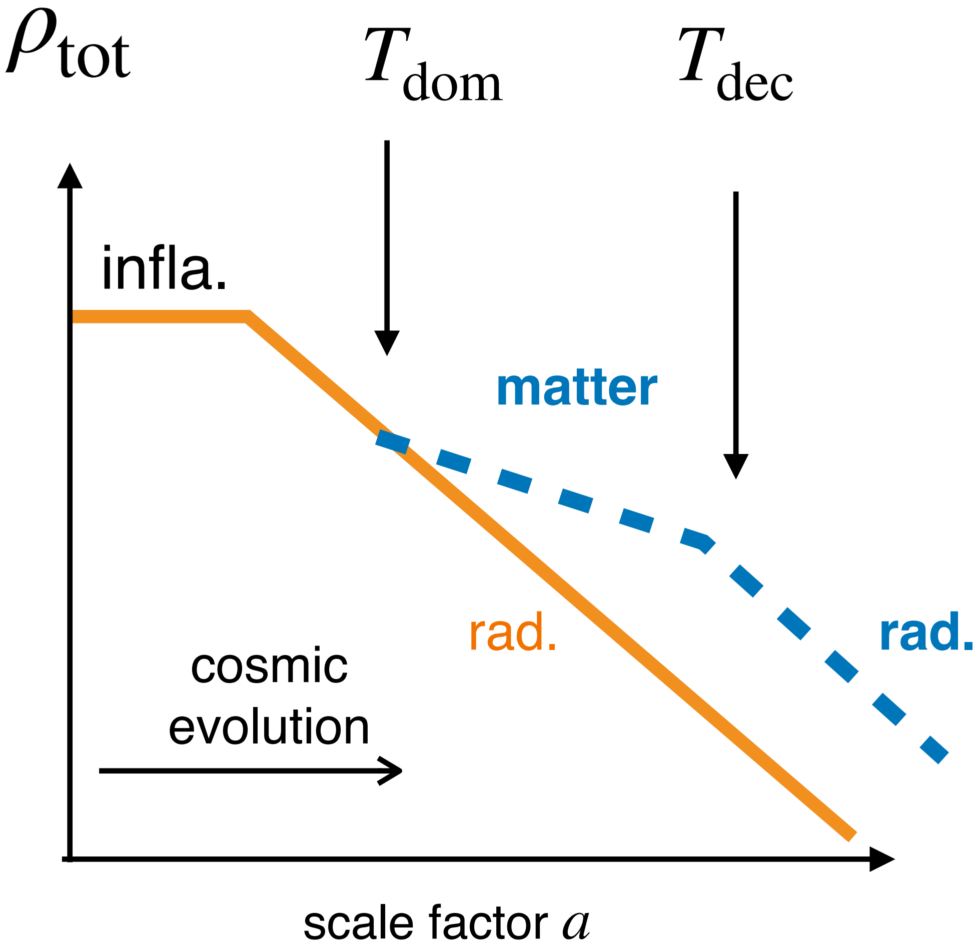

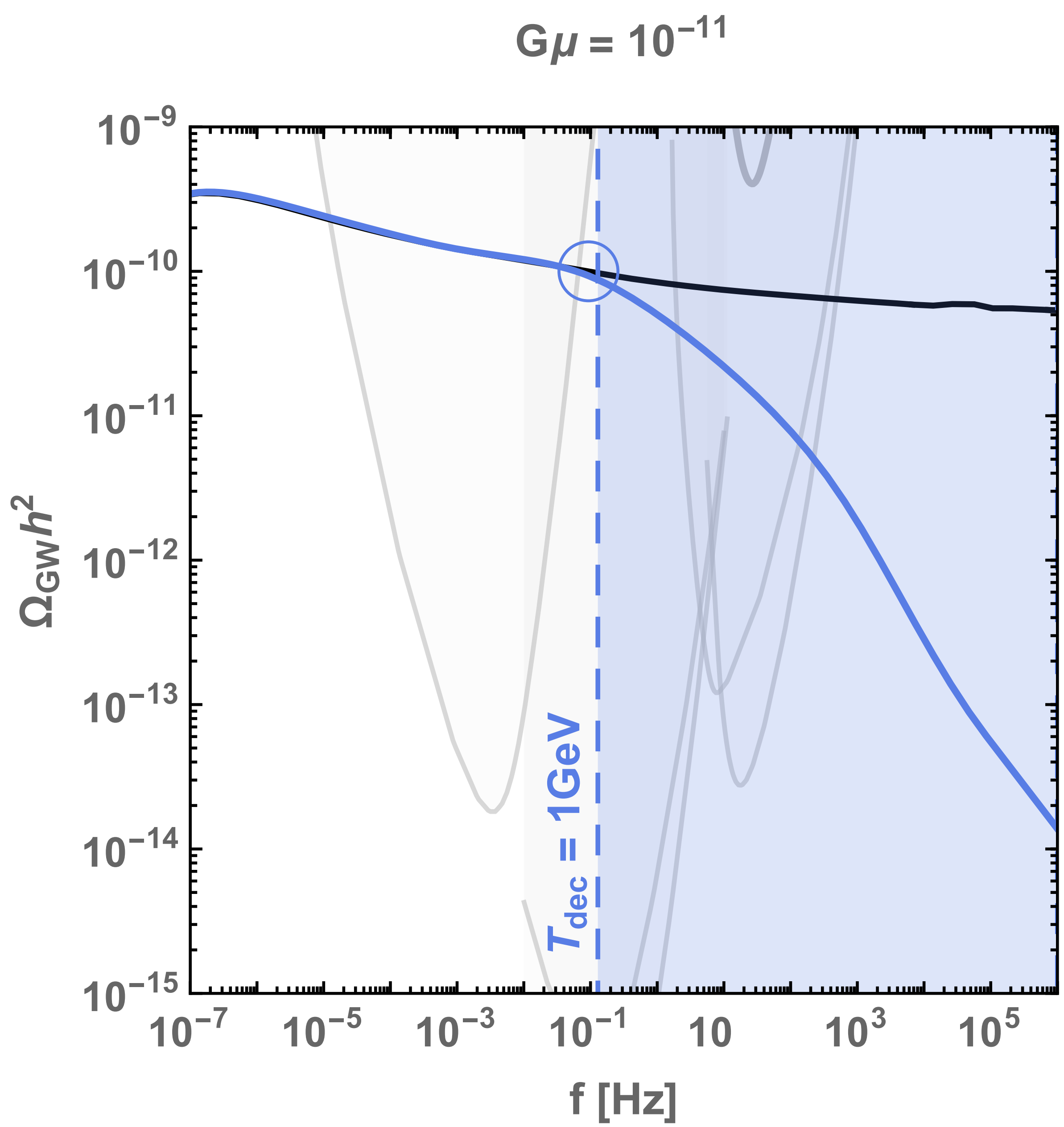

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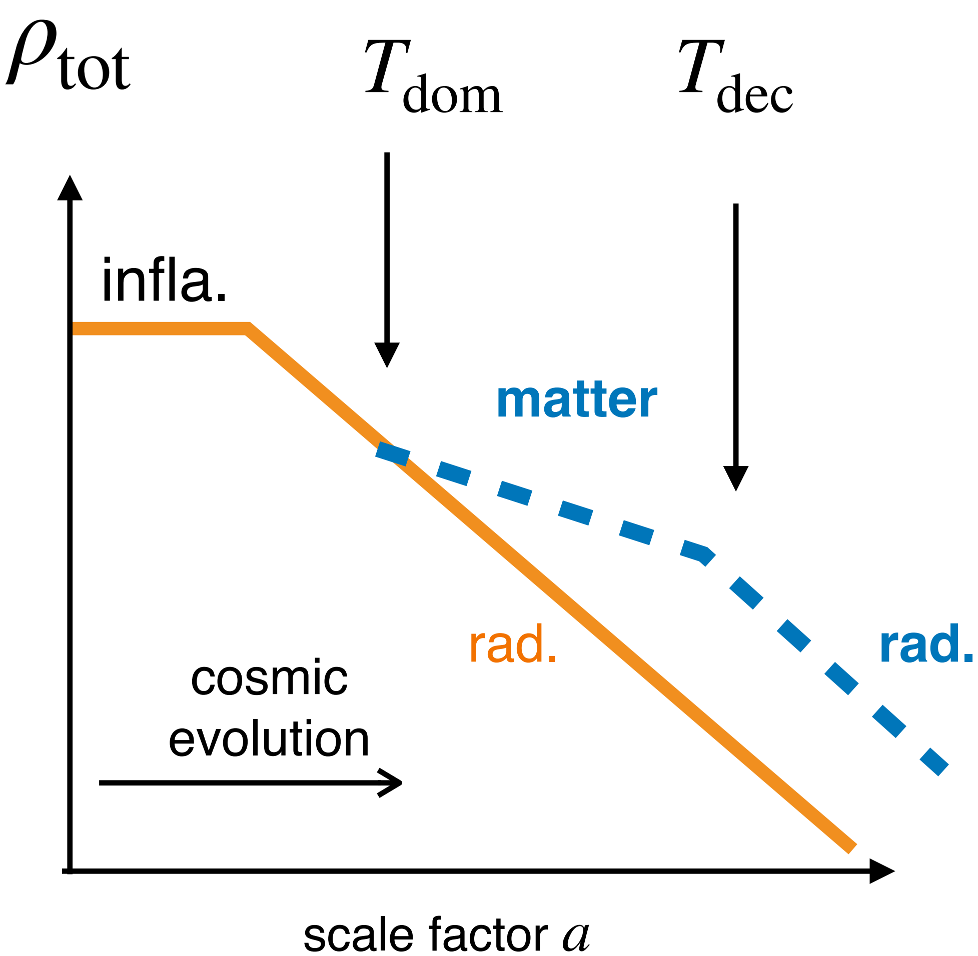

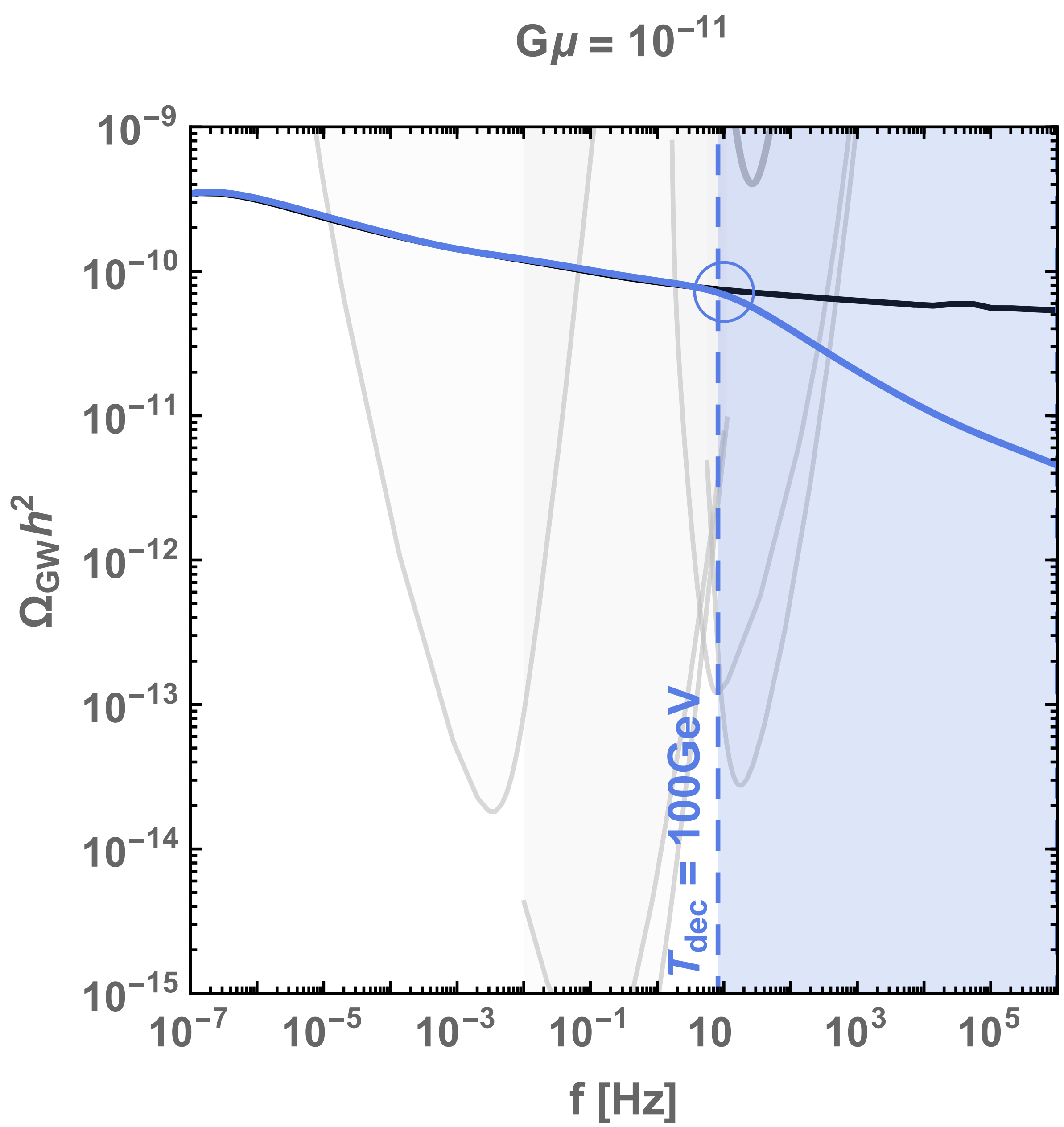

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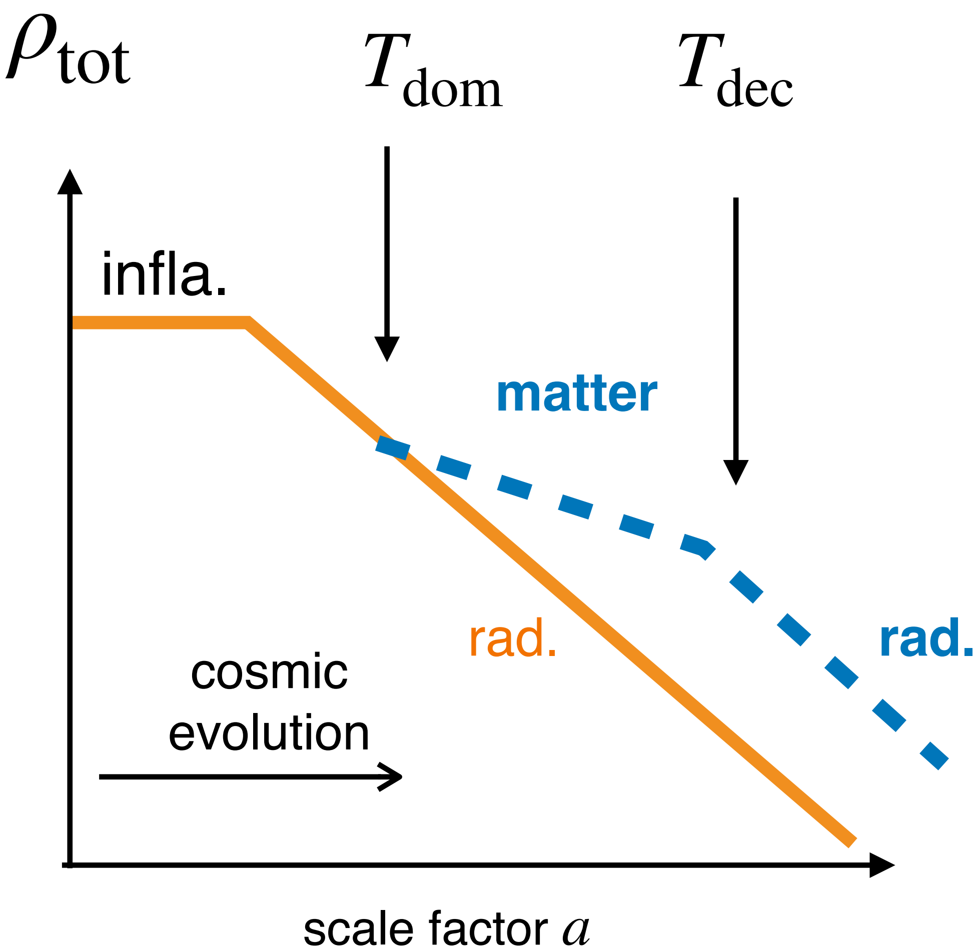

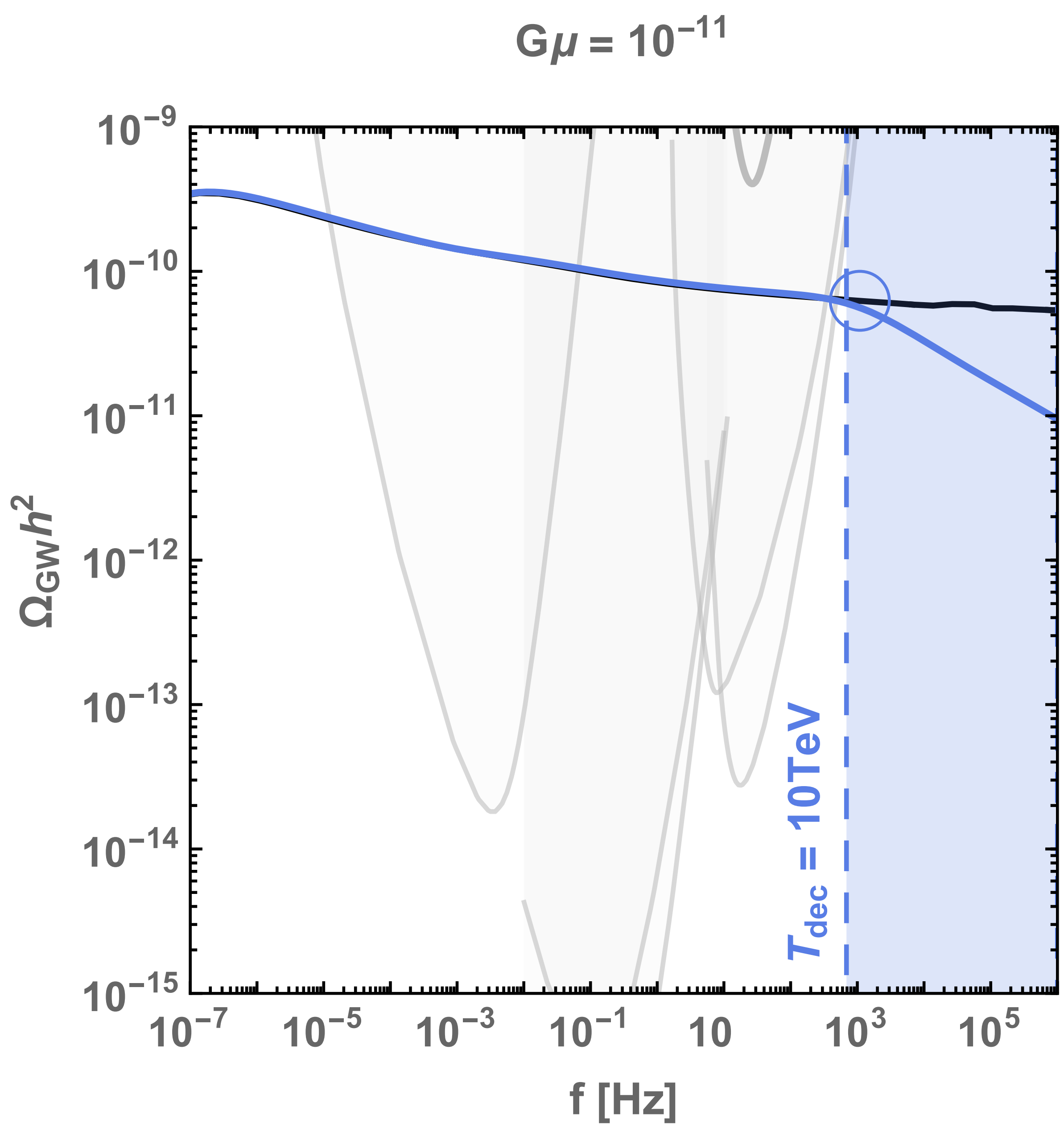

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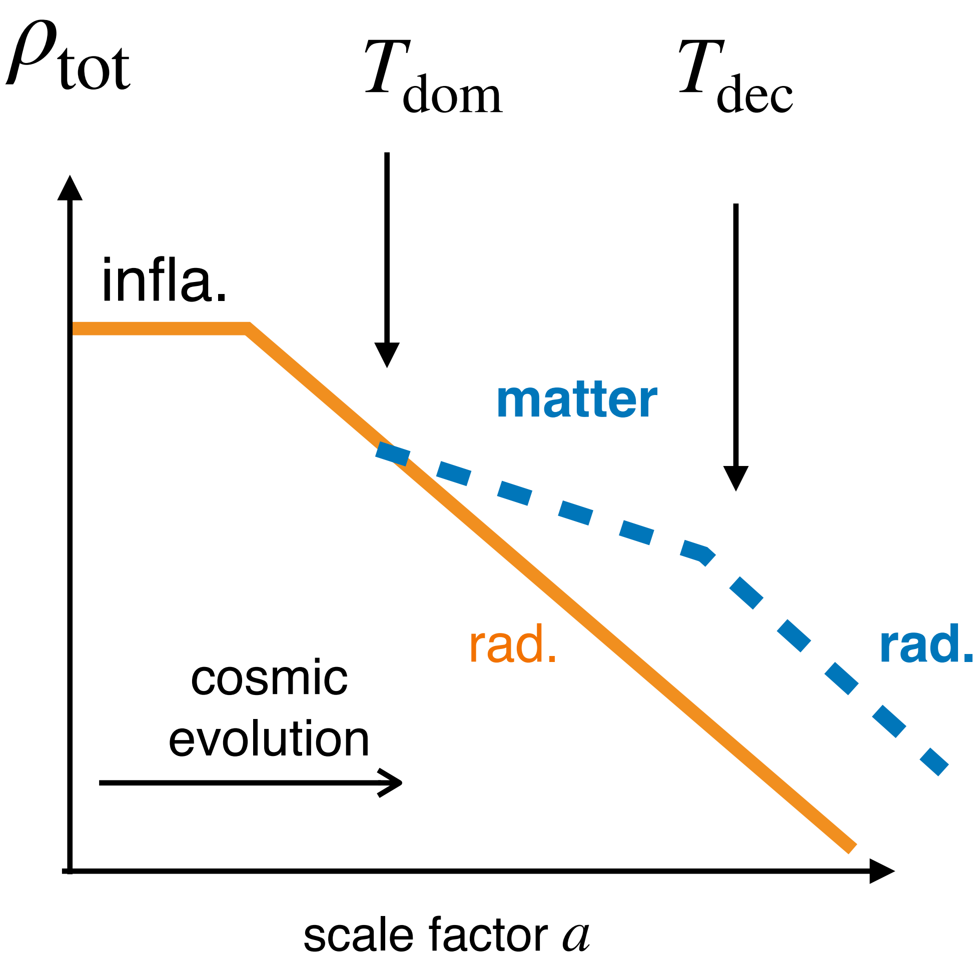

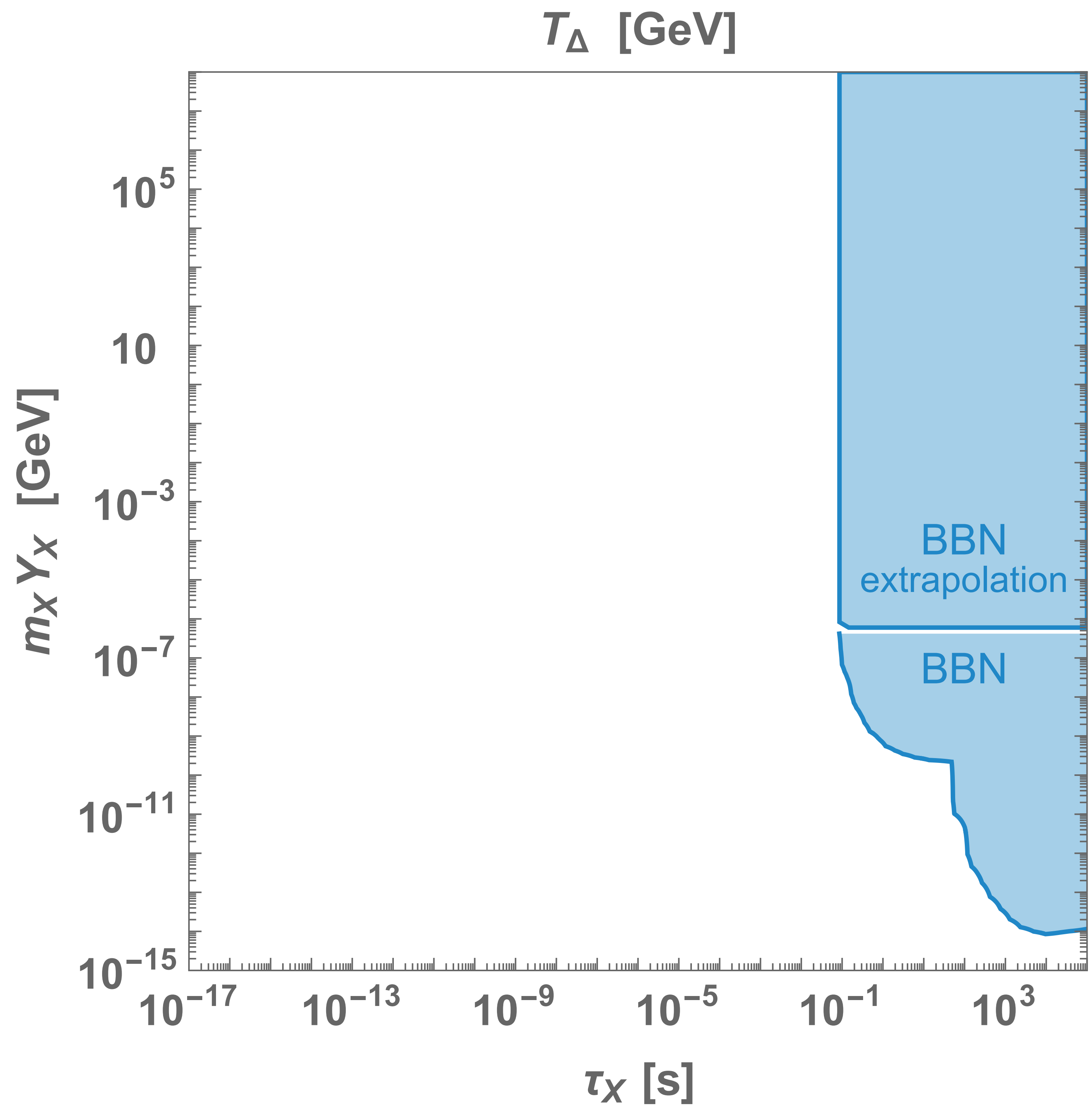

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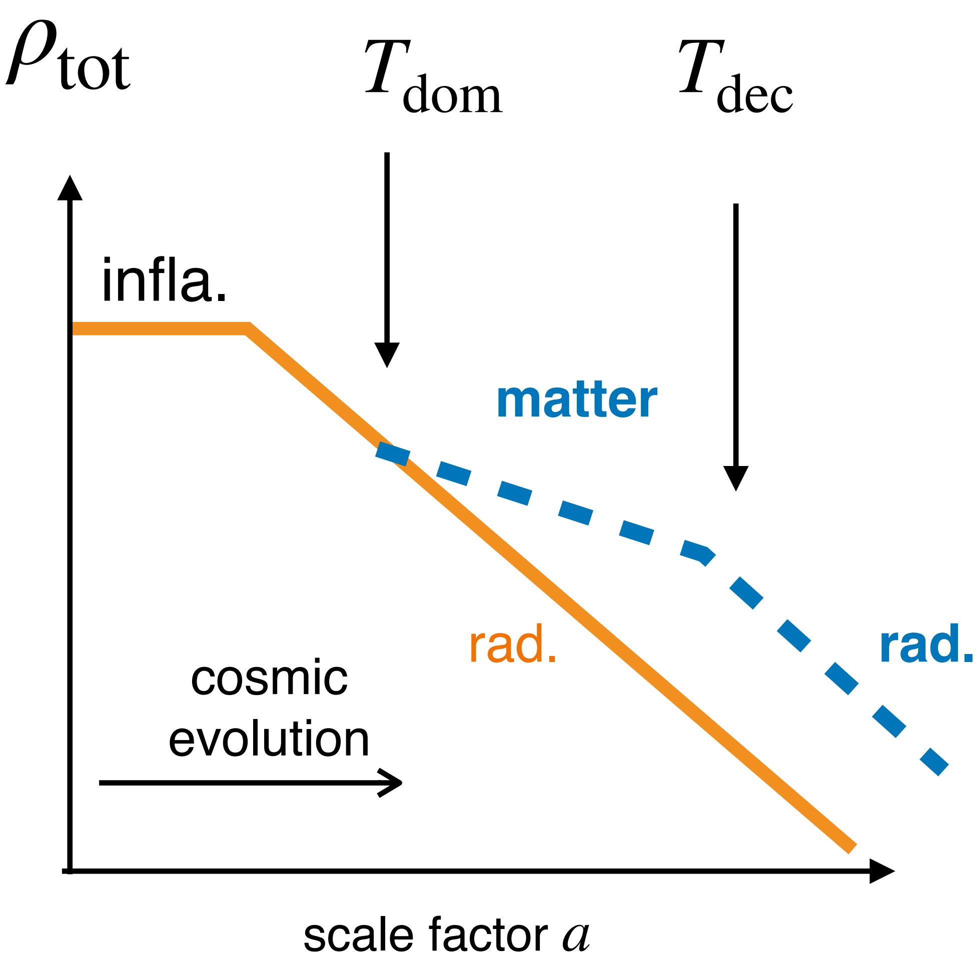

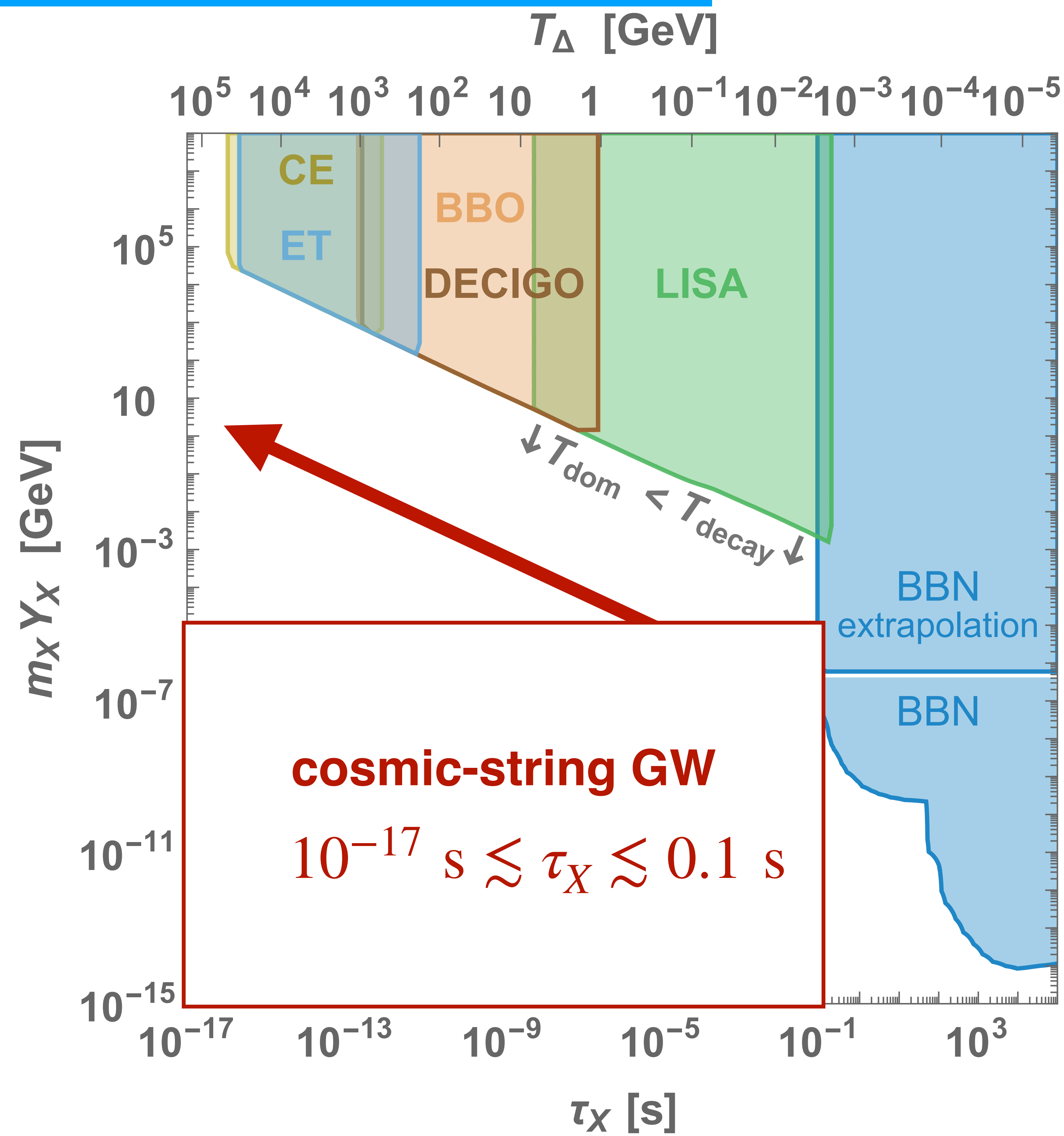

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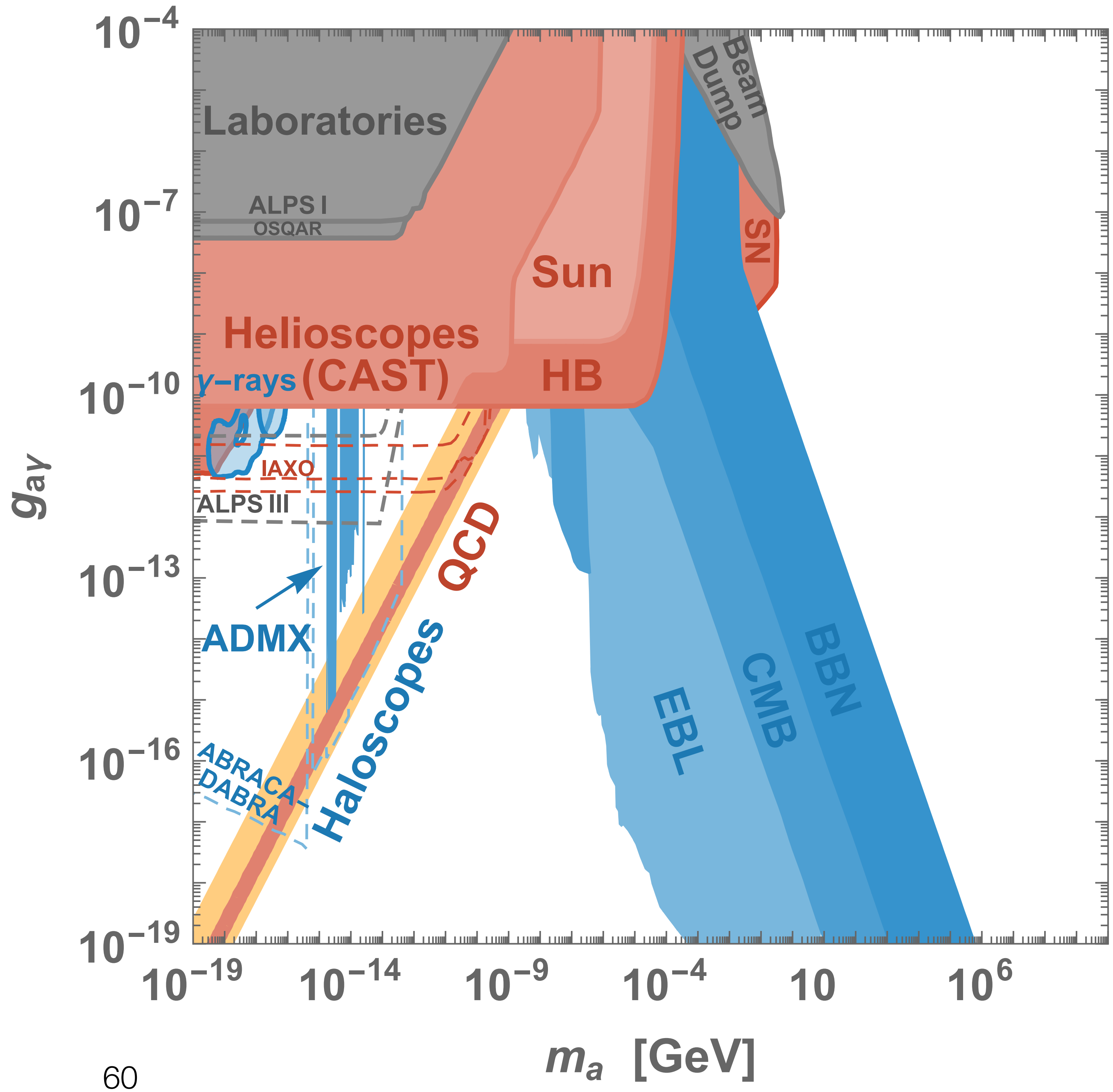
Example 1 : ALPs

$G\mu = 10^{-11}$ – $\Gamma_a = \dfrac{g_{a\gamma}^2\, m_a^3}{64\,\pi}$

- **Assume thermal abundance**

- **Decay rate**

$$\Gamma_a = \frac{g_{a\gamma}^2 m_a^3}{64\pi}$$



Example 1 : ALPs

→ **Assume thermal abundance**

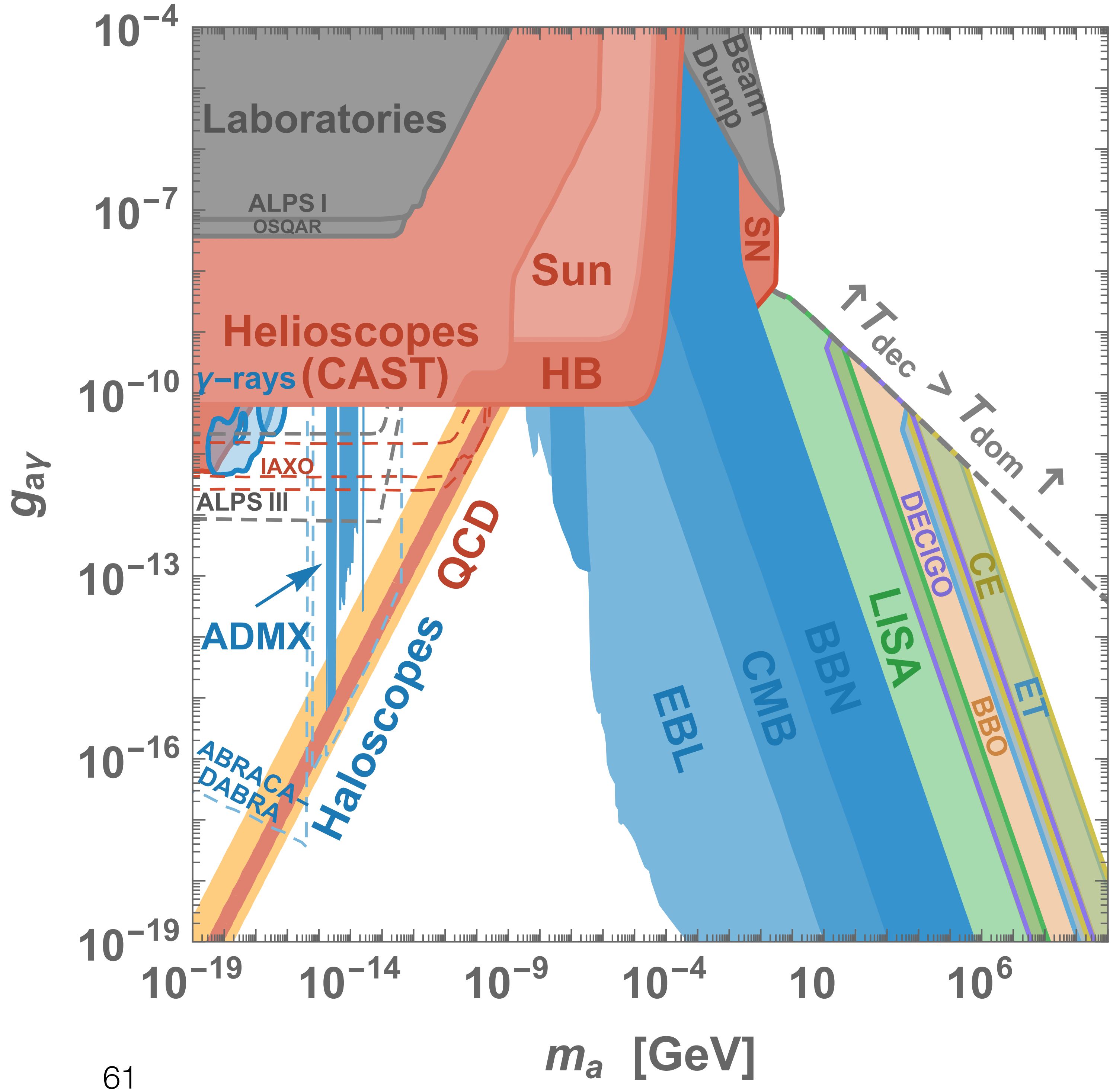
→ **Decay rate**

$$\Gamma_a = \frac{g_{a\gamma}^2 m_a^3}{64\pi}$$

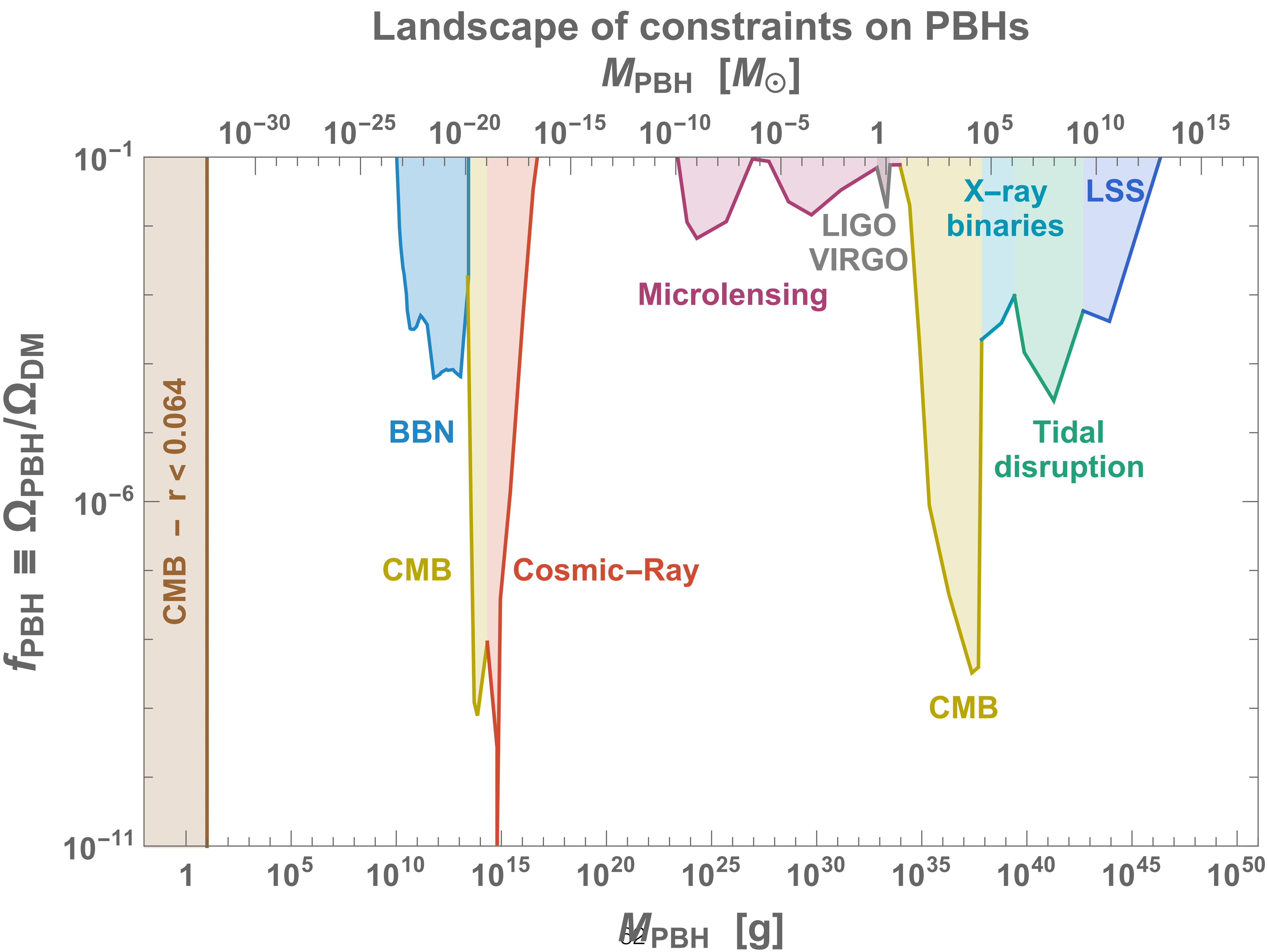
→ **Reach**

$$m_a \lesssim 10^{10}\ \mathrm{GeV}$$

$G\mu = 10^{-11}$ – $\Gamma_a = \dfrac{g_{a\gamma}^2\, m_a^3}{64\,\pi}$



Example 2 : PBHs



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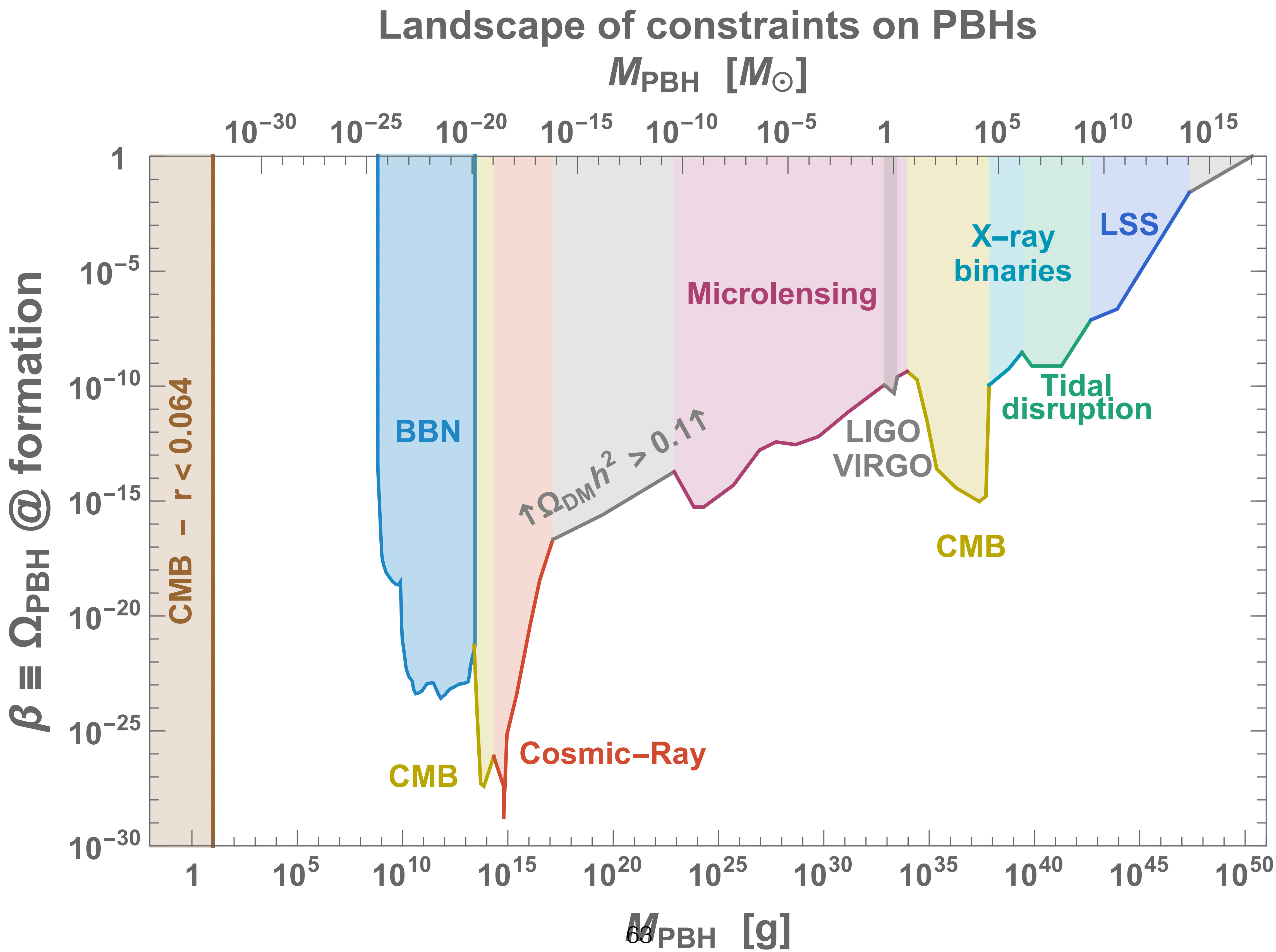

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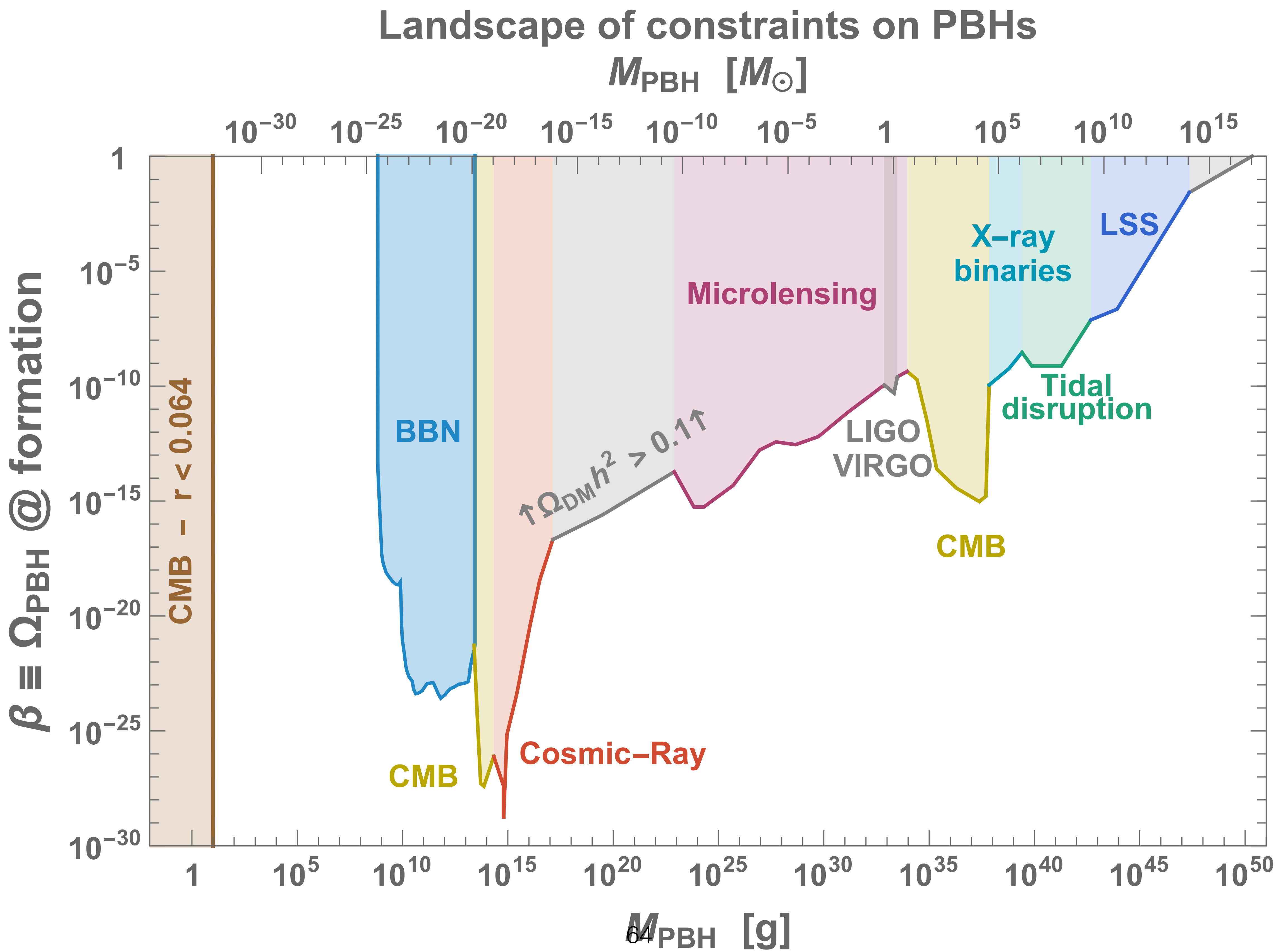

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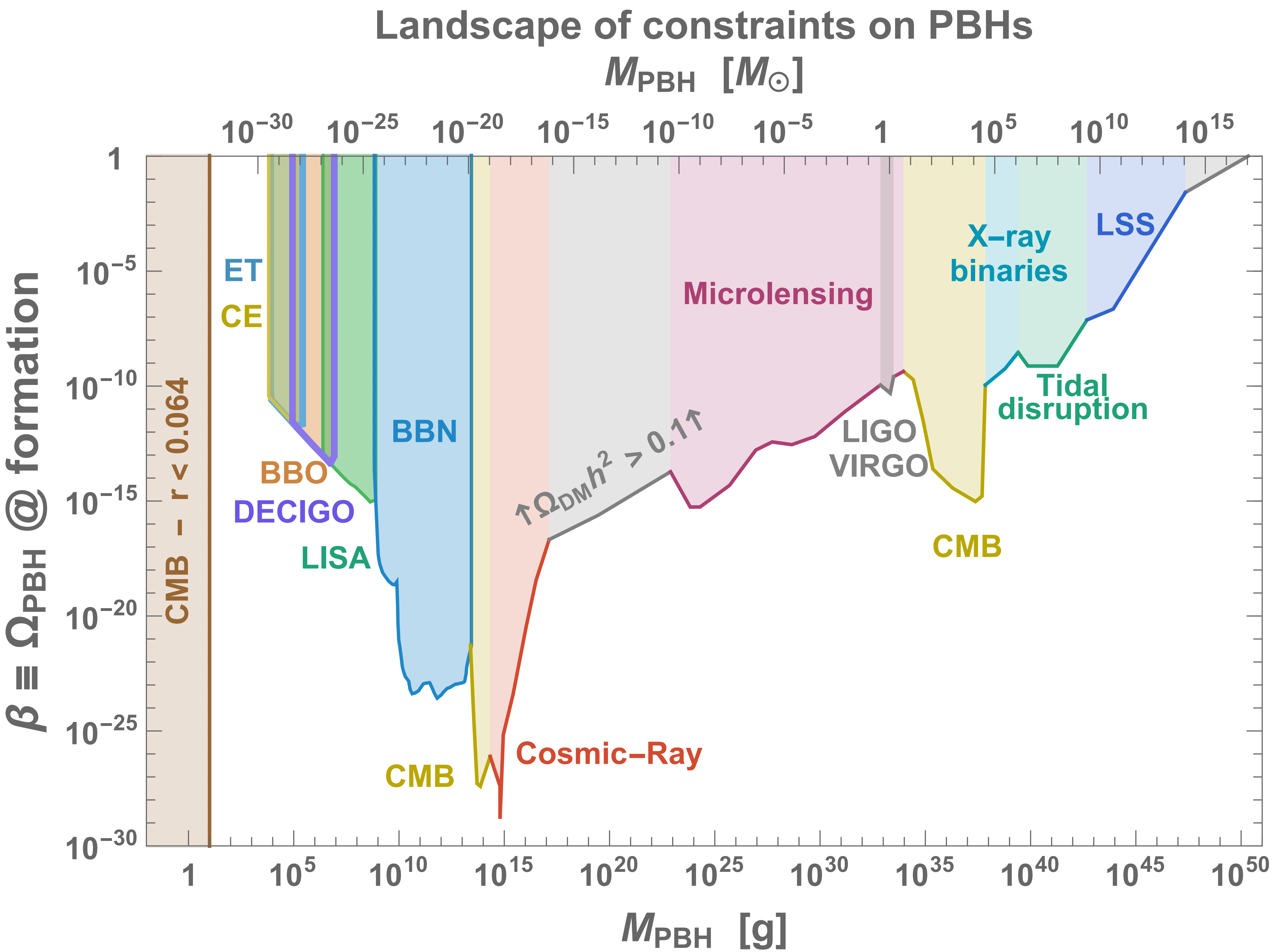
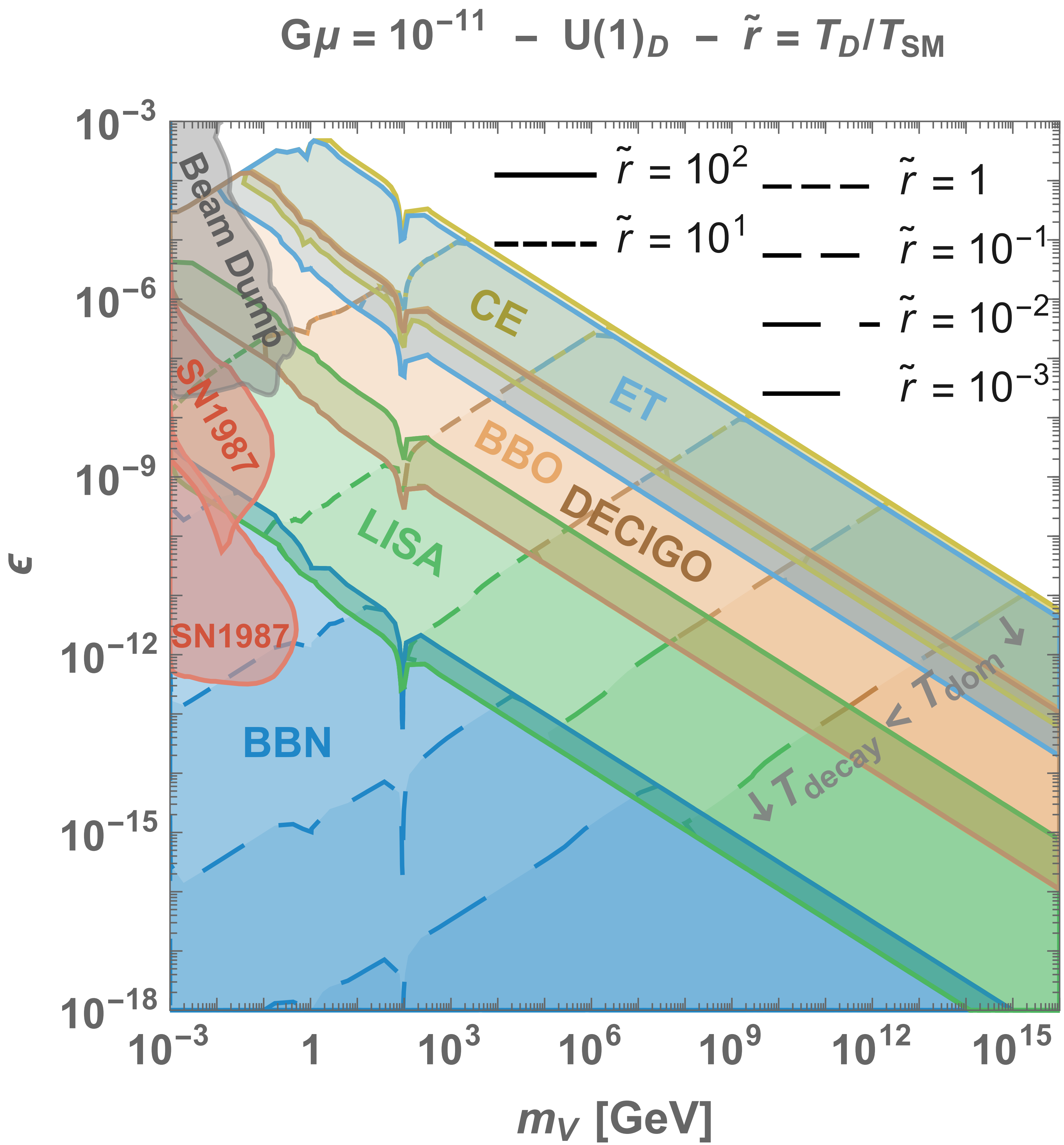


Example 3: Dark photon $U(1)_D$



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I. GW signature of non-standard era

II. Early matter era — Heavy & unstable particles

III. 2nd inflation era — Supercool 1st-order phase transition

IV. Intermediate kination era

Spinning axion!

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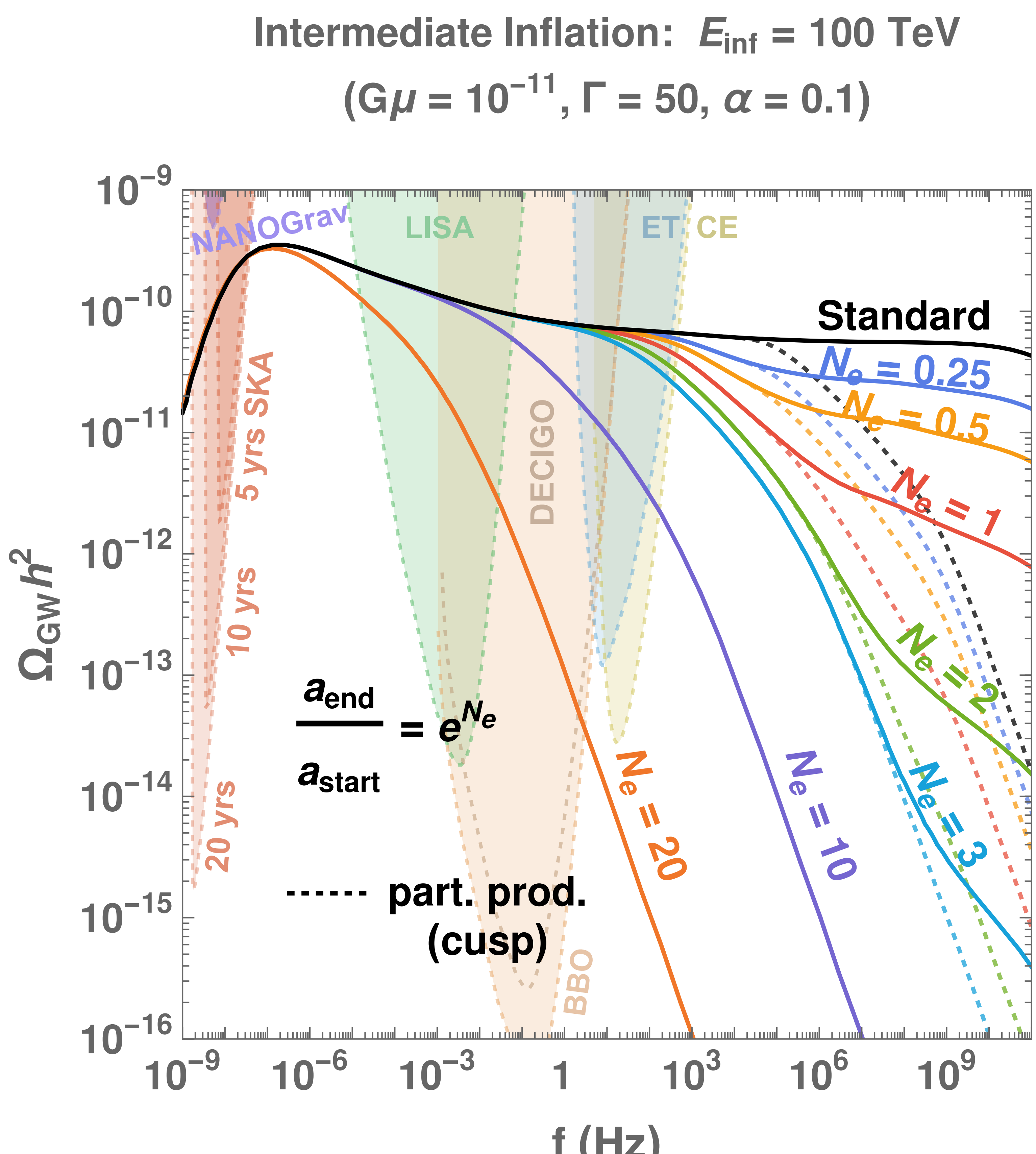
1912.03245

e.g. supercooled 1st order phase transition



Intermediate inflation era

1912.03245

e.g. supercooled 1st order phase transition

Creminelli, Nicolis, Rattazzi 01'
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Konstandin, Servant 11'
Iso, Serpico, Shimada 17'
Von Harling, Servant 17'
Bruggisser, Harling, Matsedonskyi, Servant 18'
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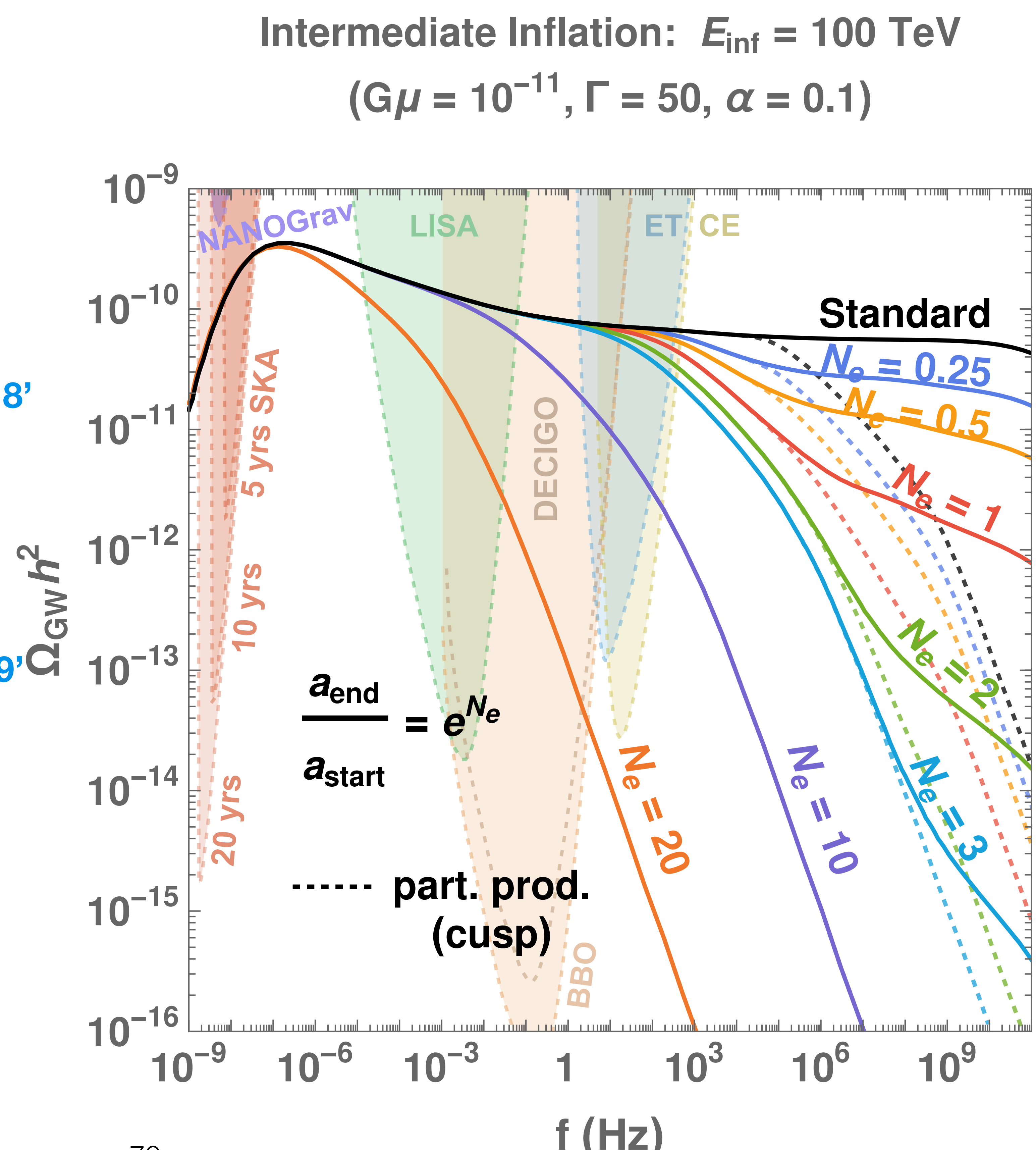

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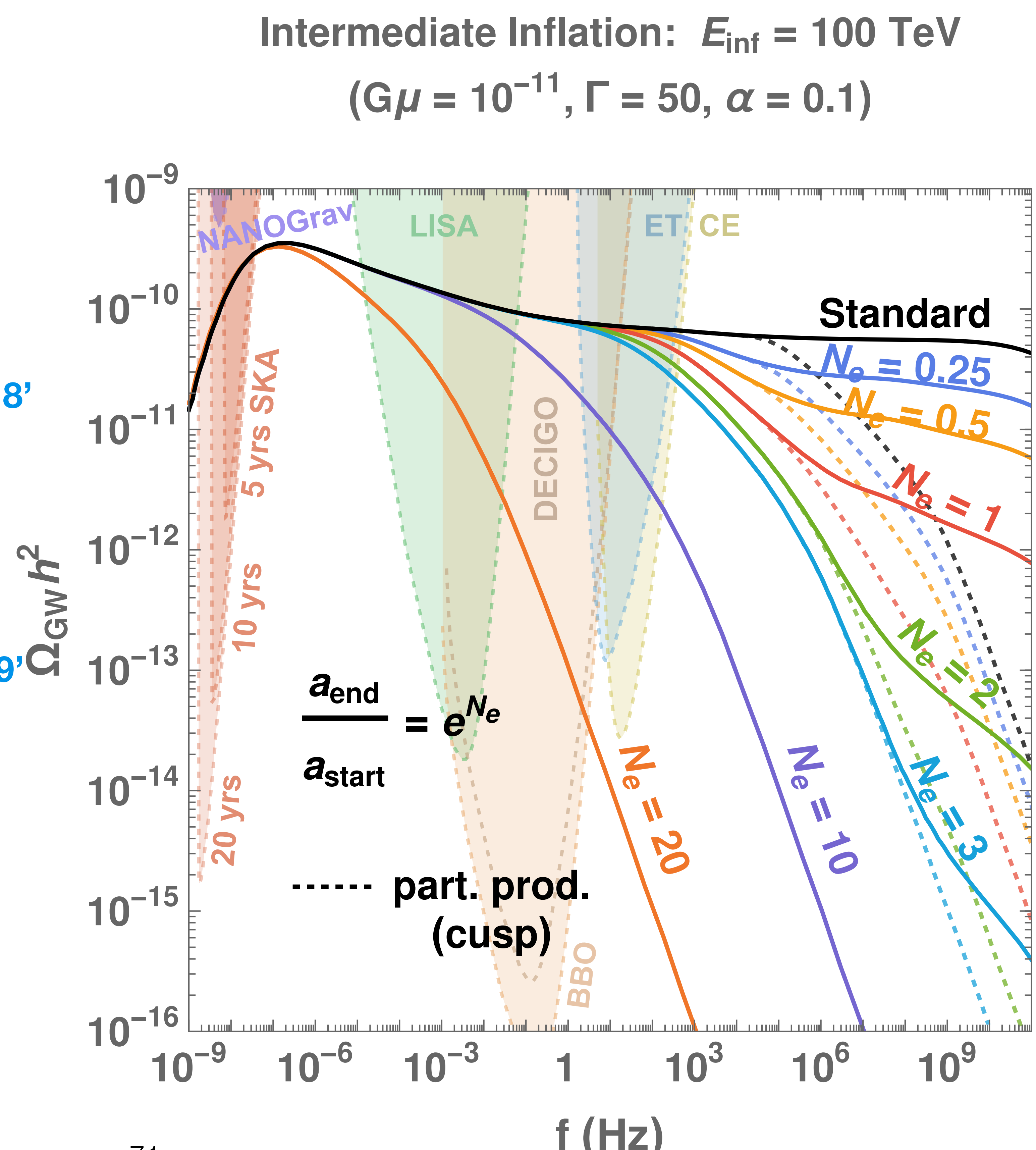
→ **Strings stretched outside the horizon**



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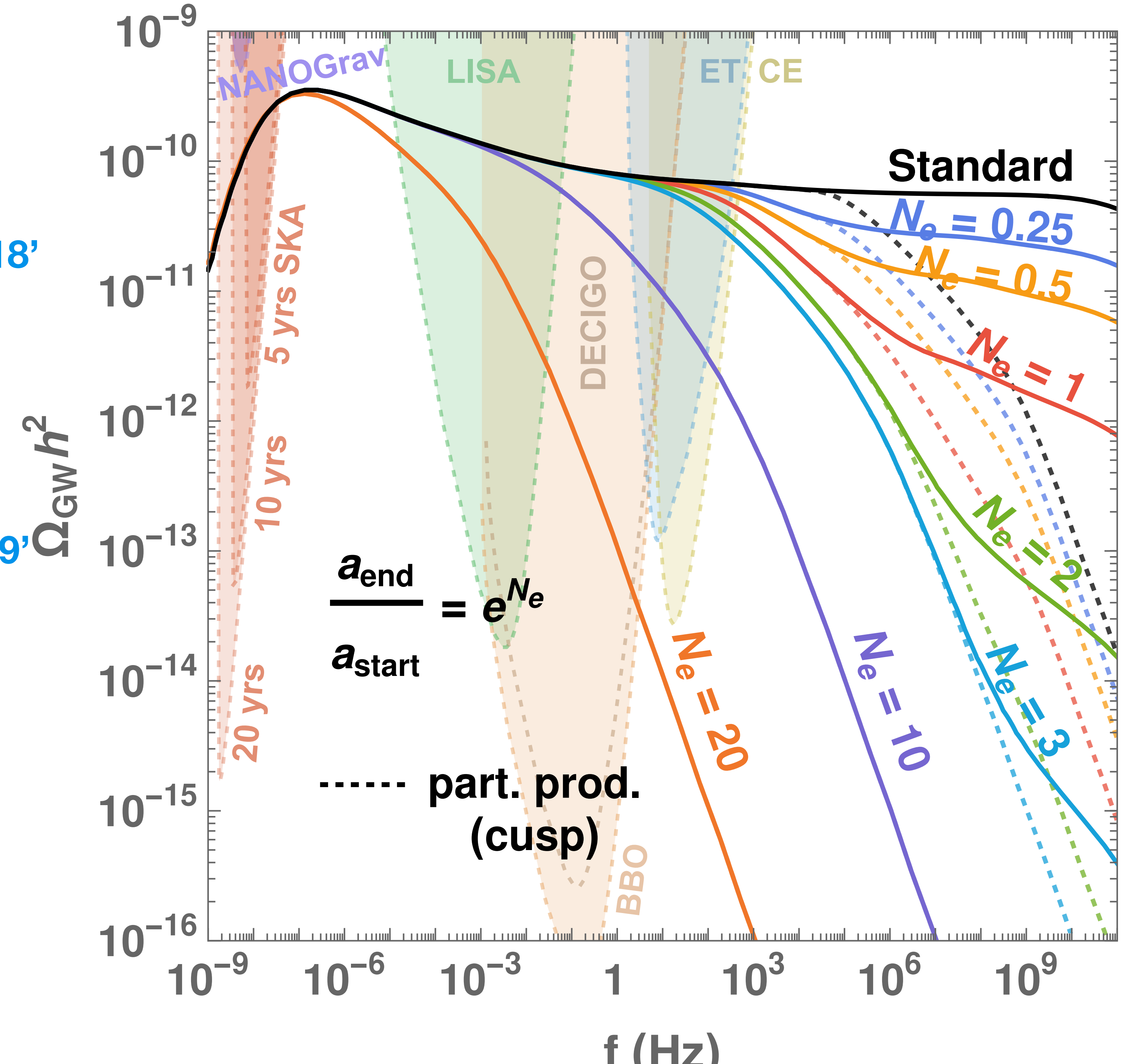

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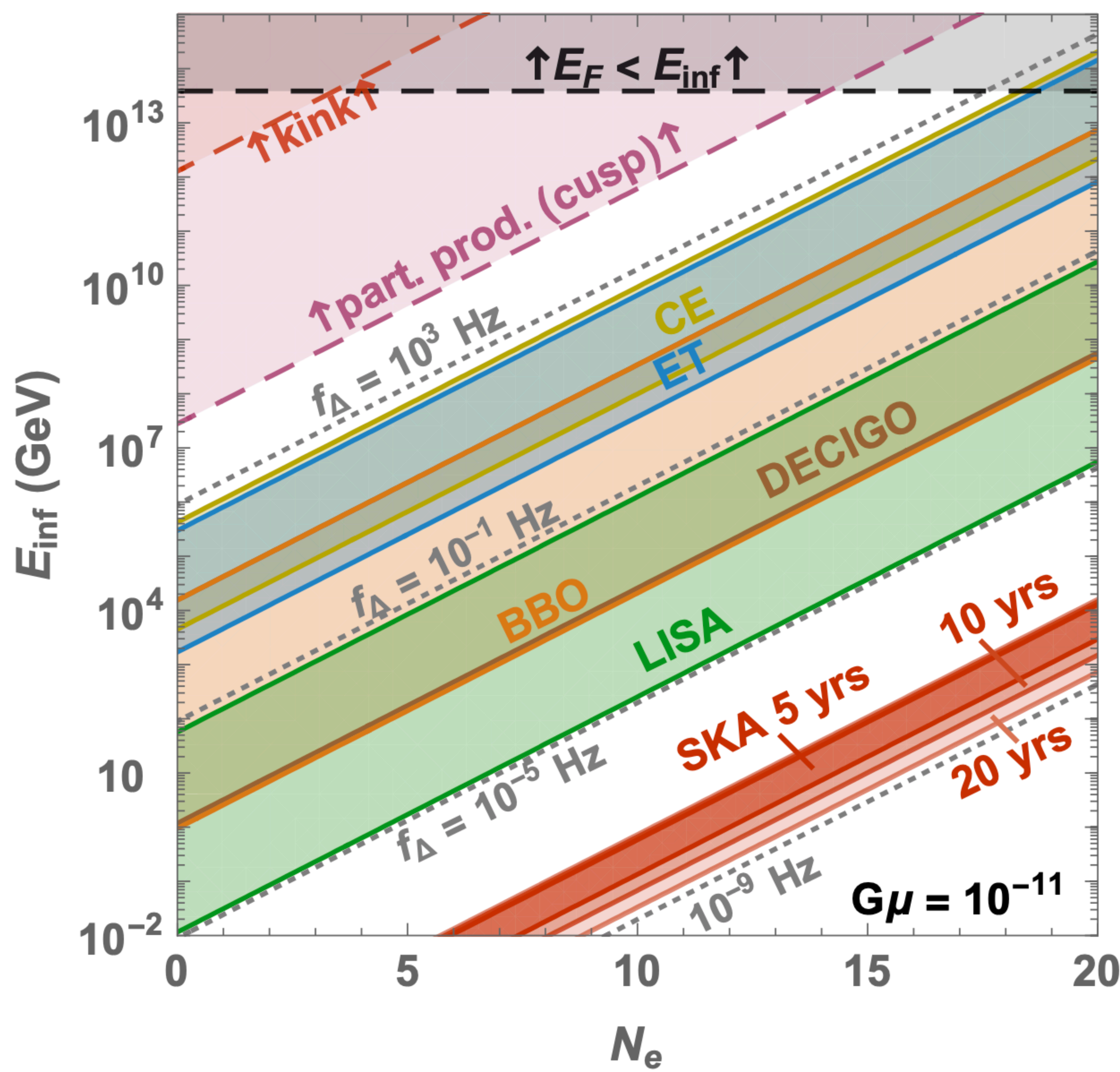

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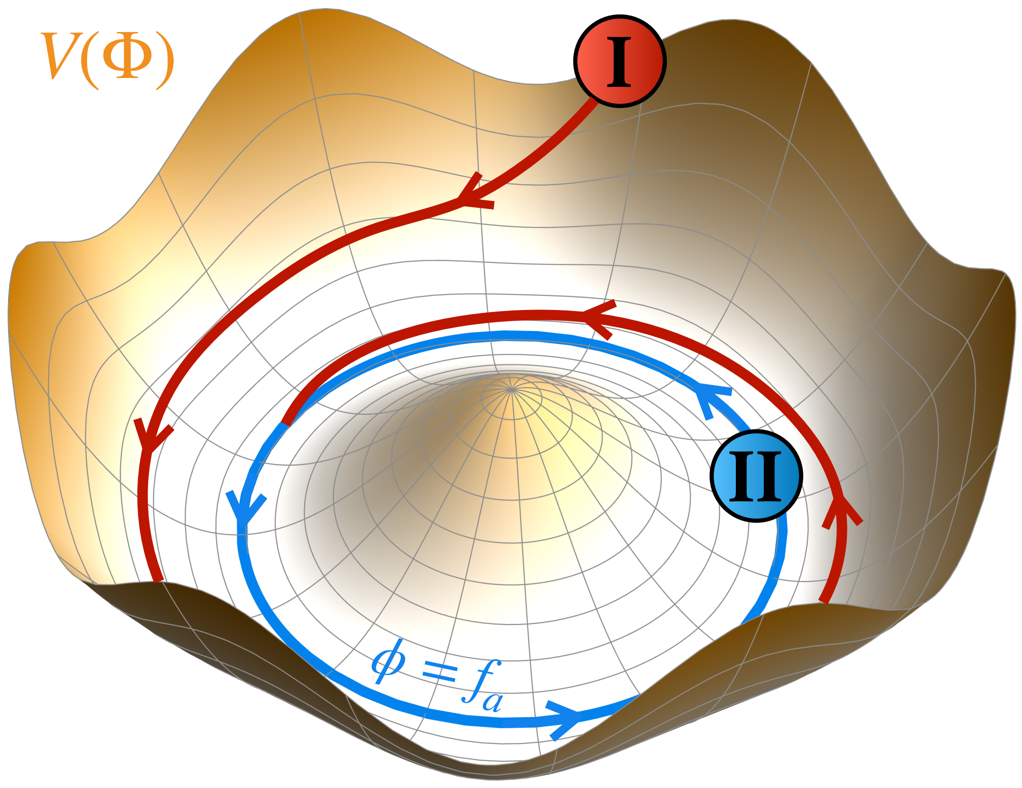
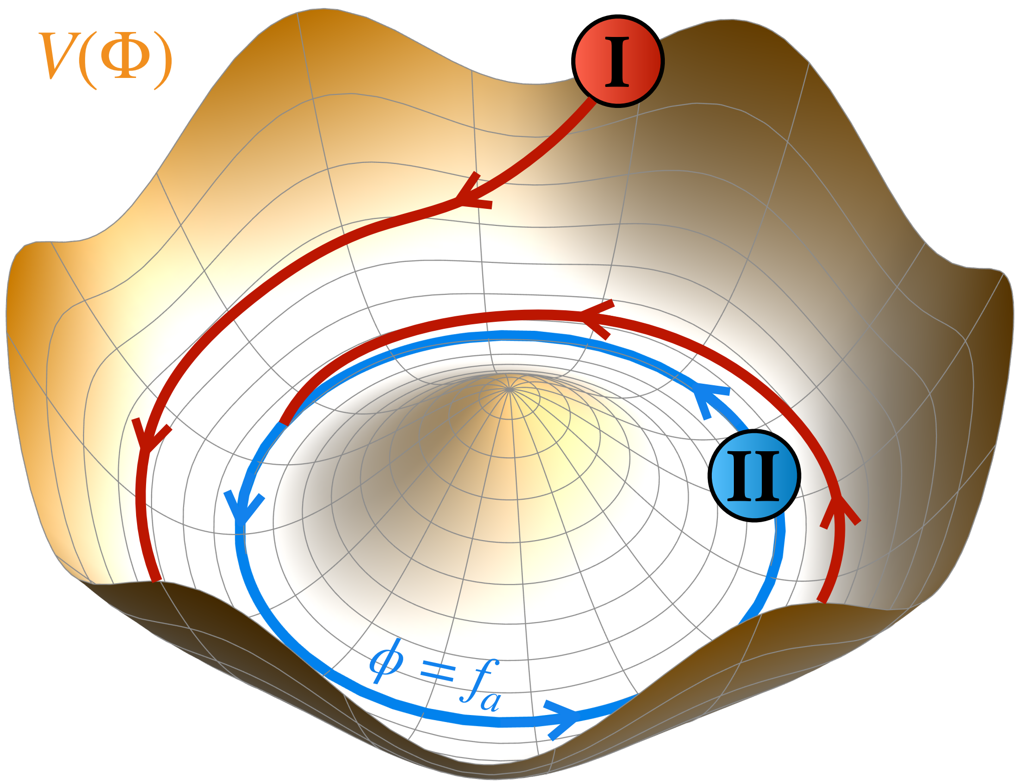


Rotating complex scalar field

“Affleck-Dine Baryogenesis” (Affleck, Dine, 1985)

“Axiogenesis” (Co, Hall, Harigaya, et. al., ’19)



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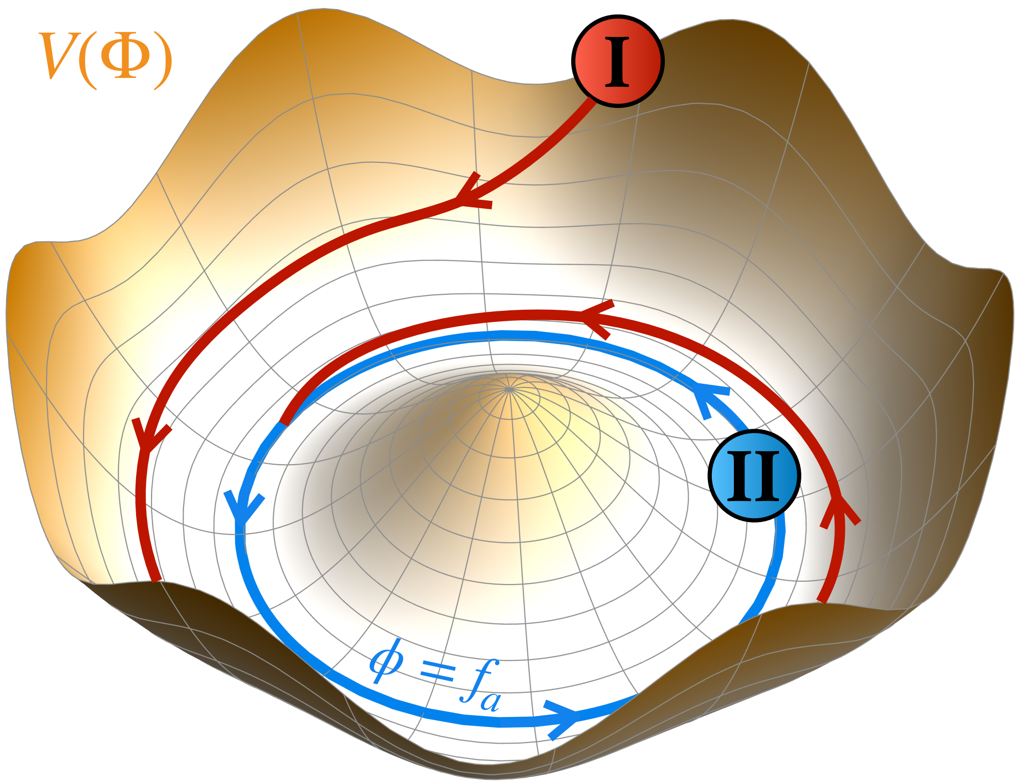

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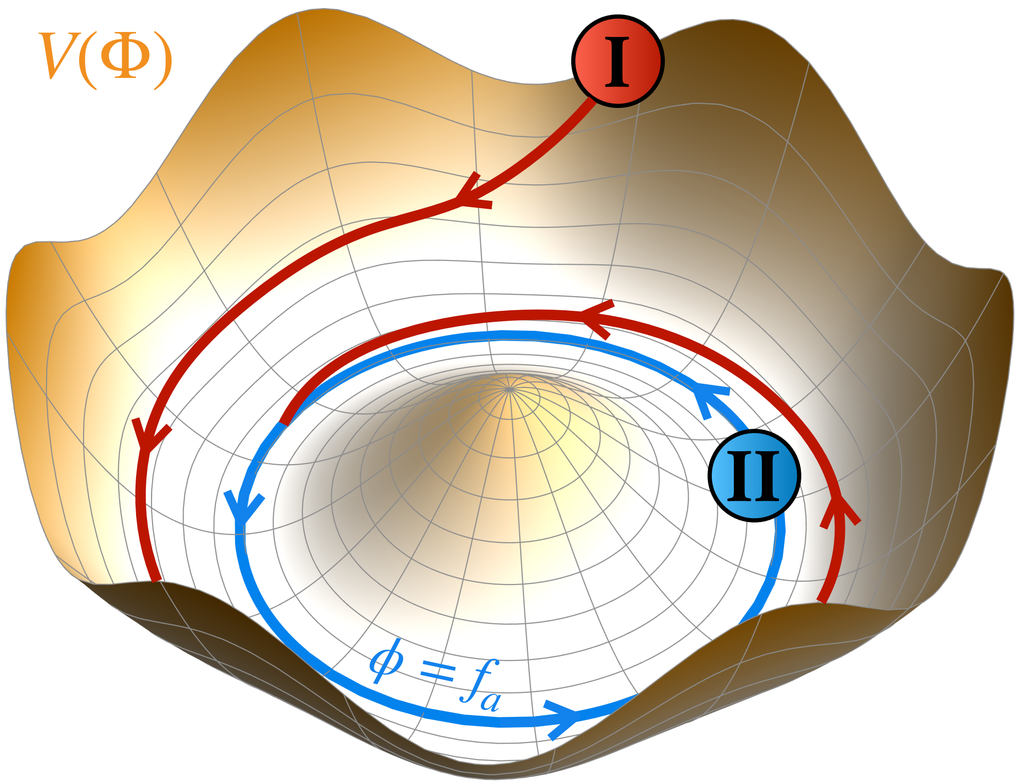
$$V(\Phi) = m_r^2 |\Phi|^2 \left[\log \left(\frac{|\Phi|^2}{f_a^2} \right) - 1 \right]$$

(generic in SUSY)



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$$V_{\rm H} = -H^2 |\Phi|^2$$

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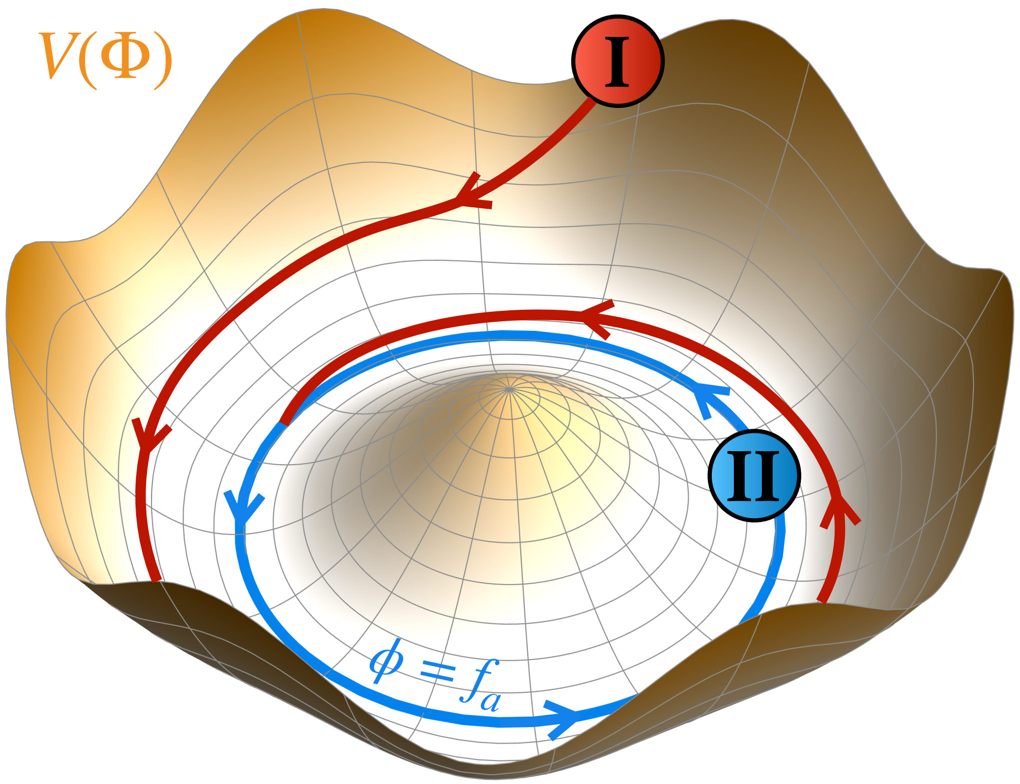

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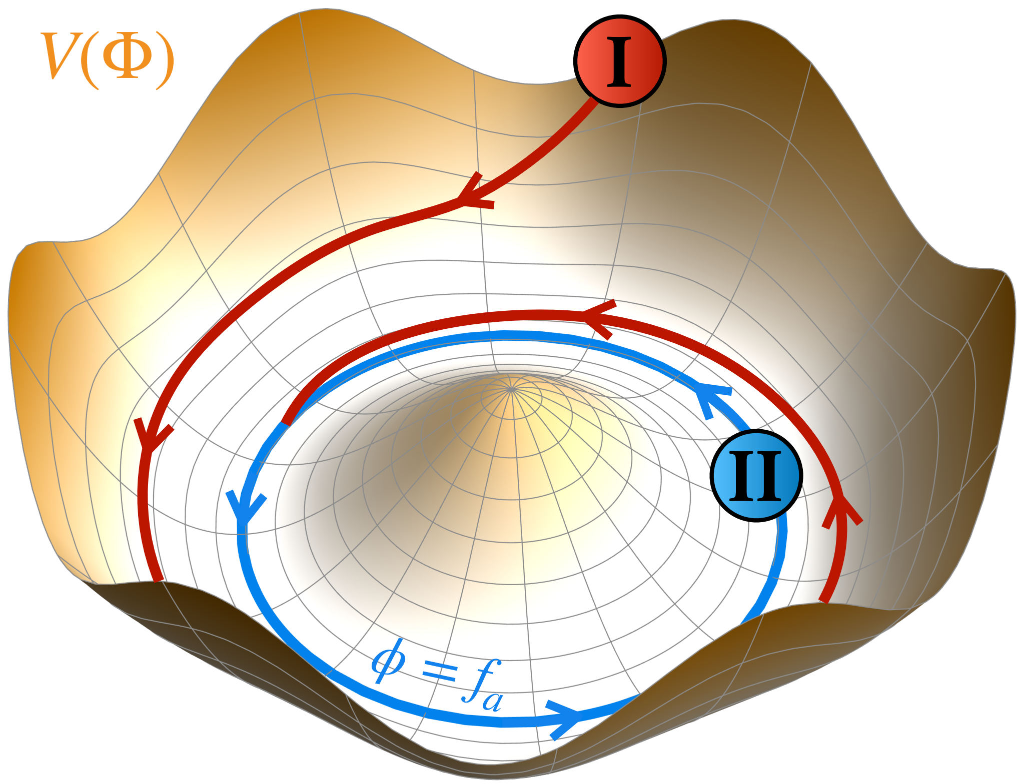
(Neutron EDM bound $l \gtrsim 10$)



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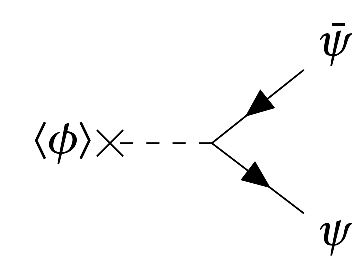
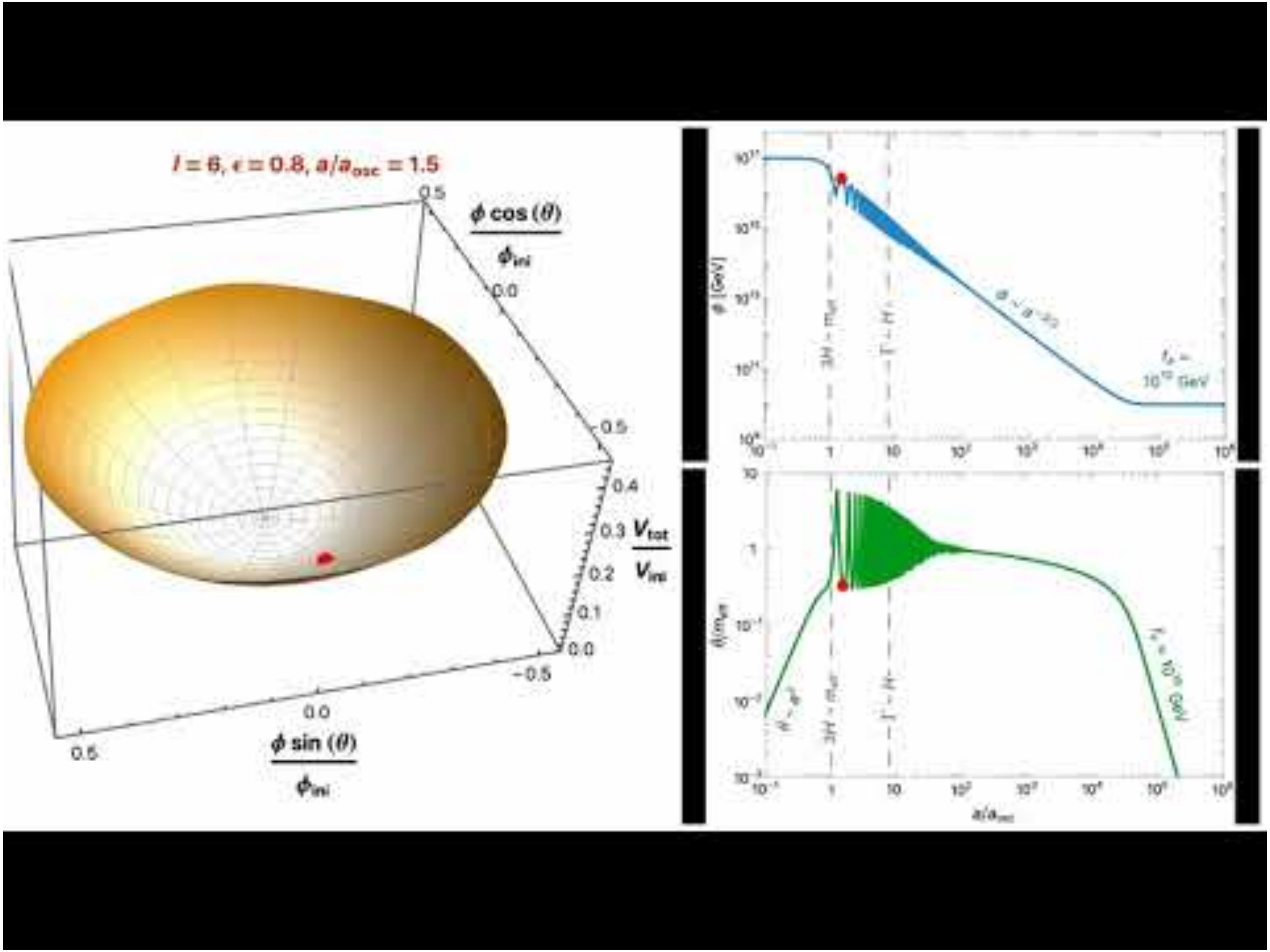
IV. Damping of radial motion

$$V_{\rm int} = \lambda_\psi \phi \bar{\psi} \psi$$



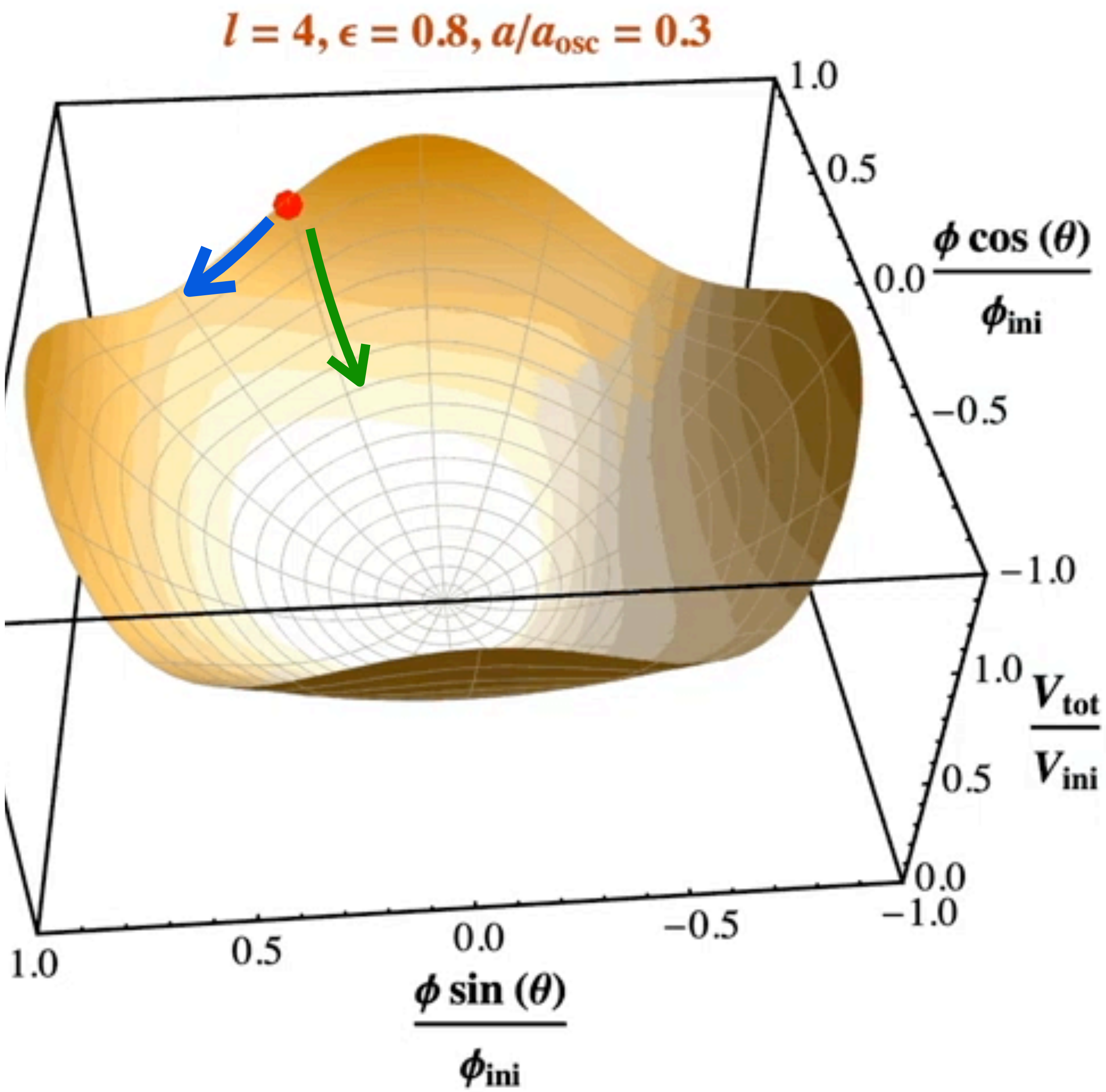
[Mukaida, Nakayama, '12 '13]

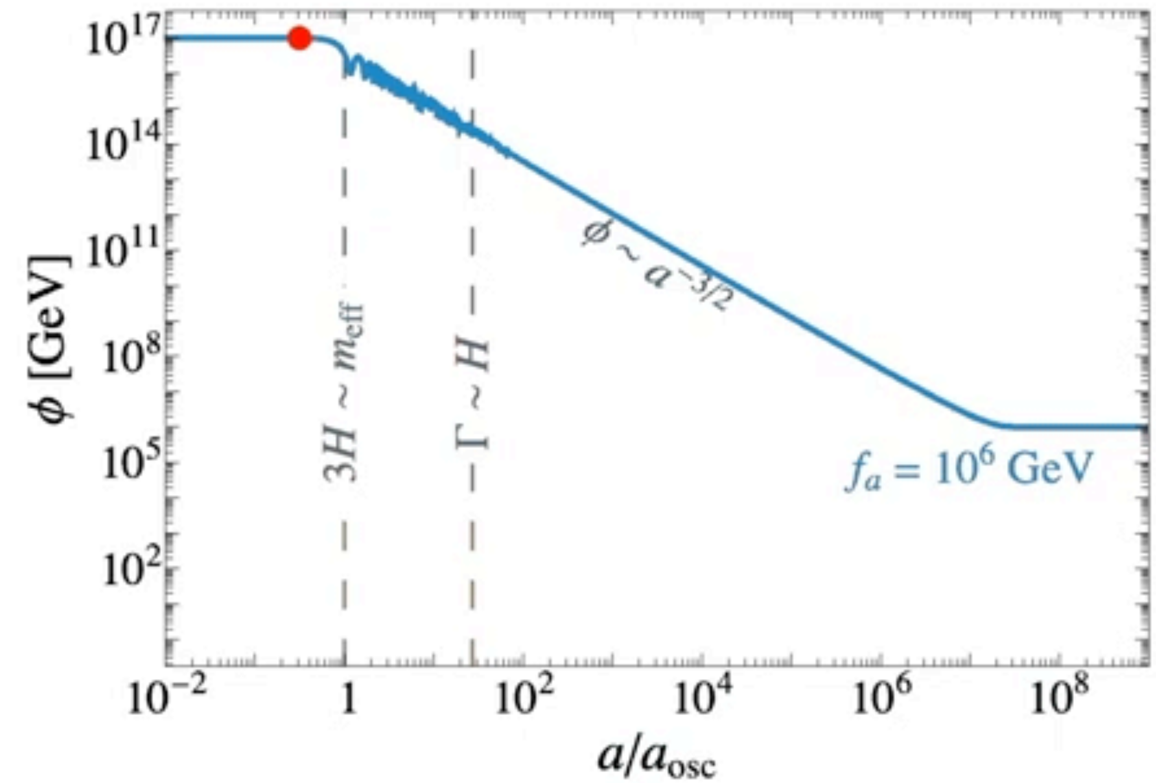


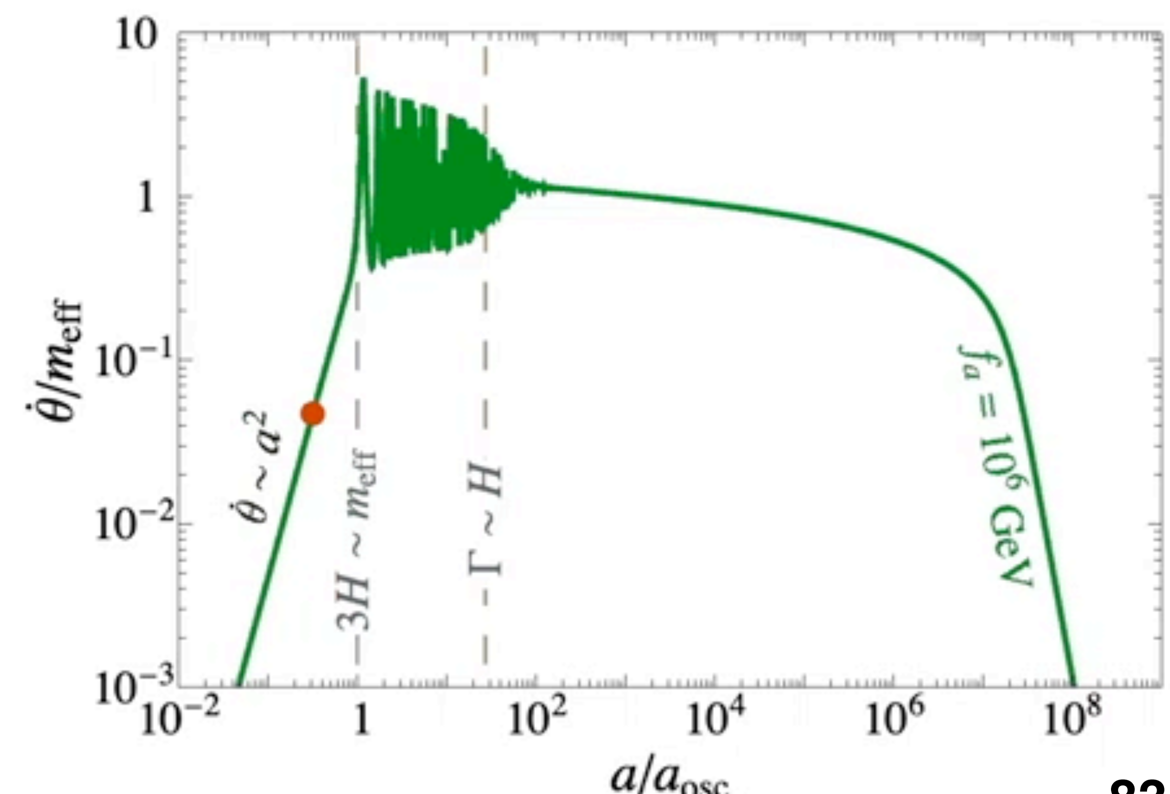
https://www.youtube.com/watch?v=RdCAgcvfFy0

Ingredients I & II & III: scalar potential and large initial VEV

[YG, Servant, Simakachorn, 2111.01150]



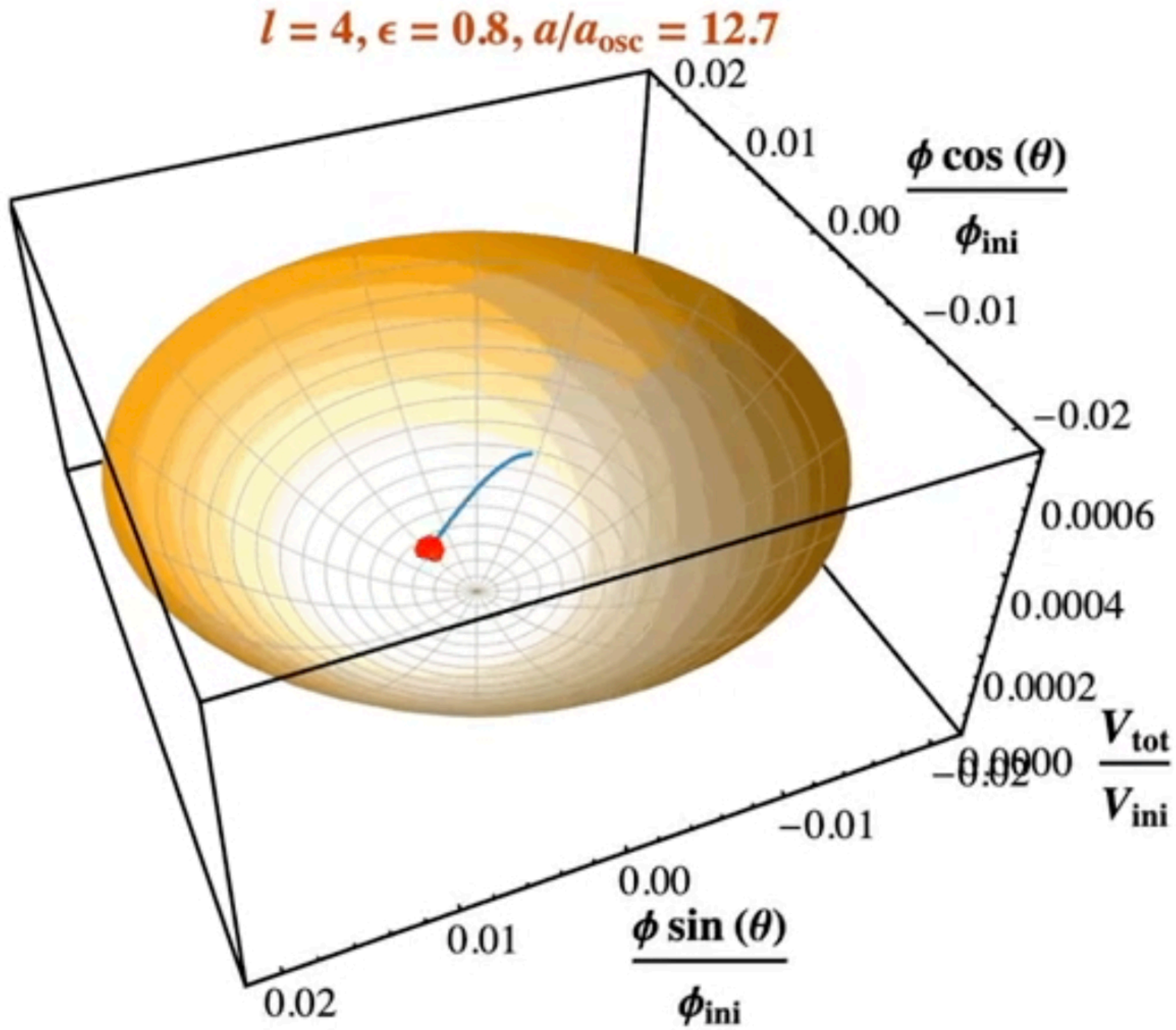


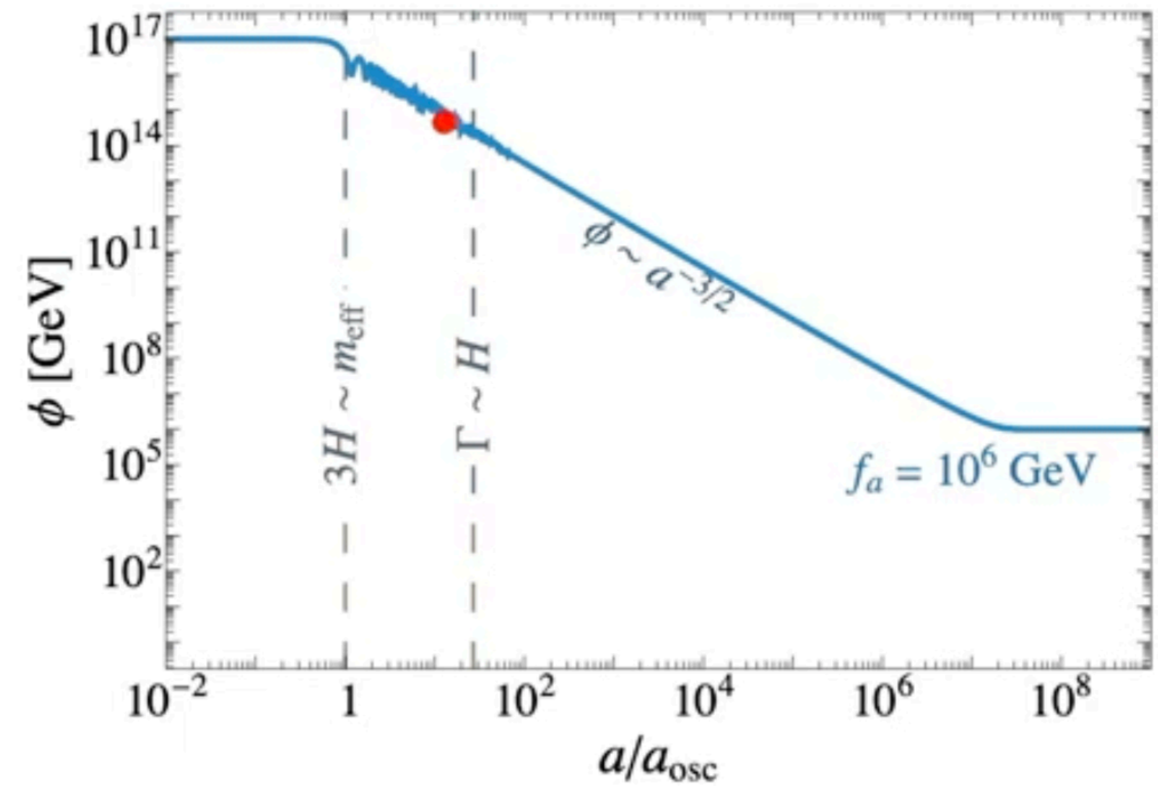


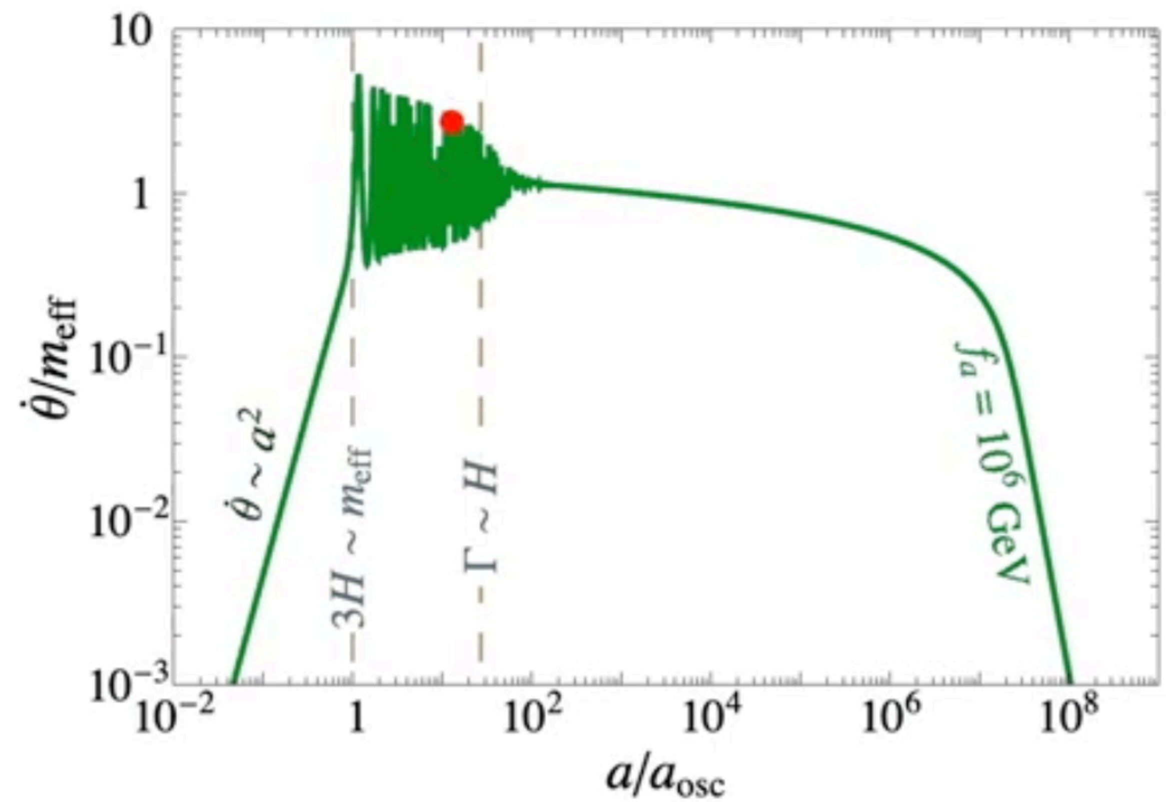
$$V(\Phi) = m_r^2 |\Phi|^2 \left[\log\left(\frac{|\Phi|^2}{f_a^2}\right) - 1\right] + \Lambda_b^4 \left[\left(\frac{\Phi}{M_{Pl}}\right)^l + \left(\frac{\Phi^\dagger}{M_{Pl}}\right)^l\right]$$

$$-H^2 |\Phi|^2$$

Ingredients IV: radial-motion damping







$V_{\rm int} = \lambda_\psi \phi \bar{\psi} \psi$

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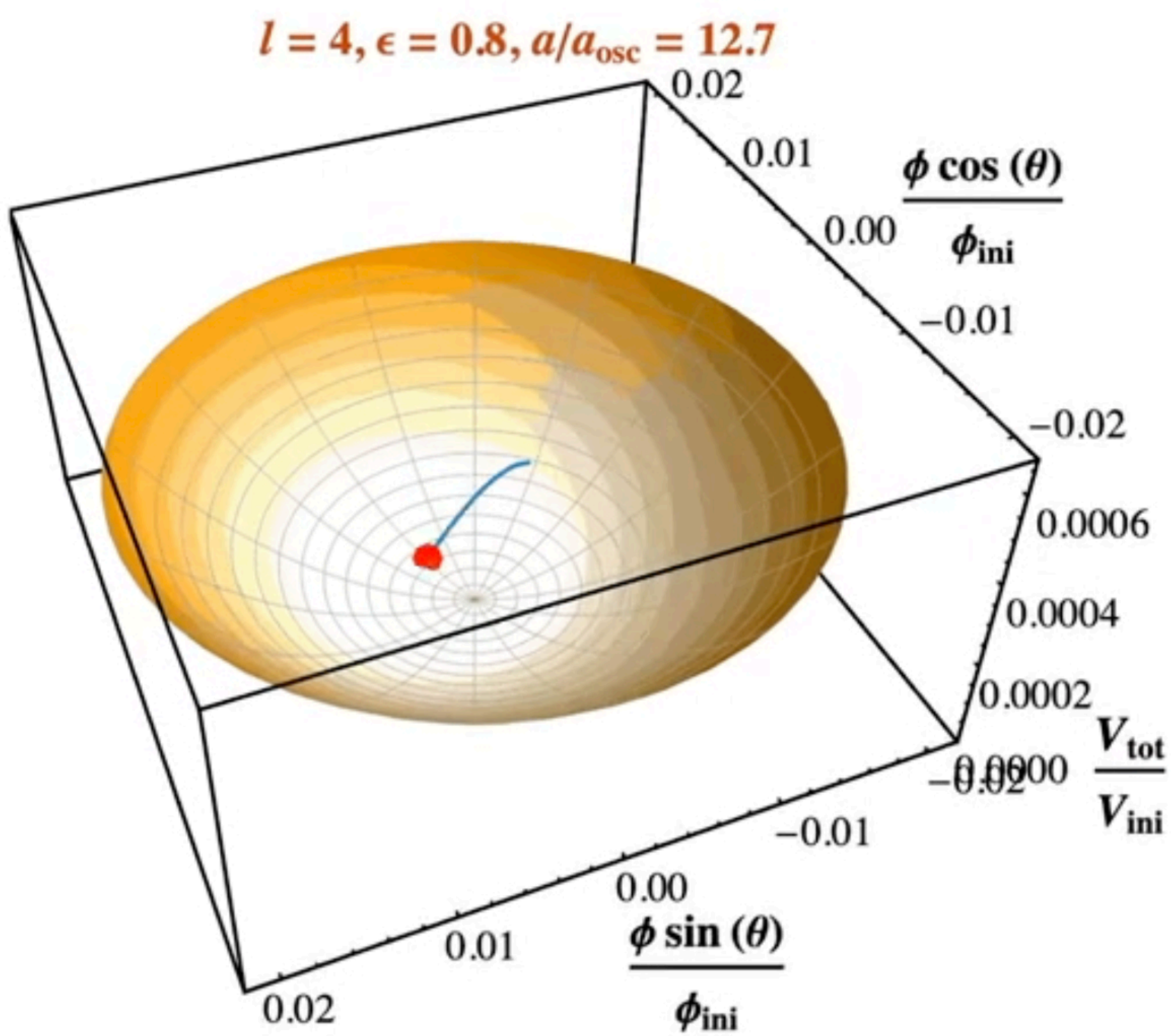

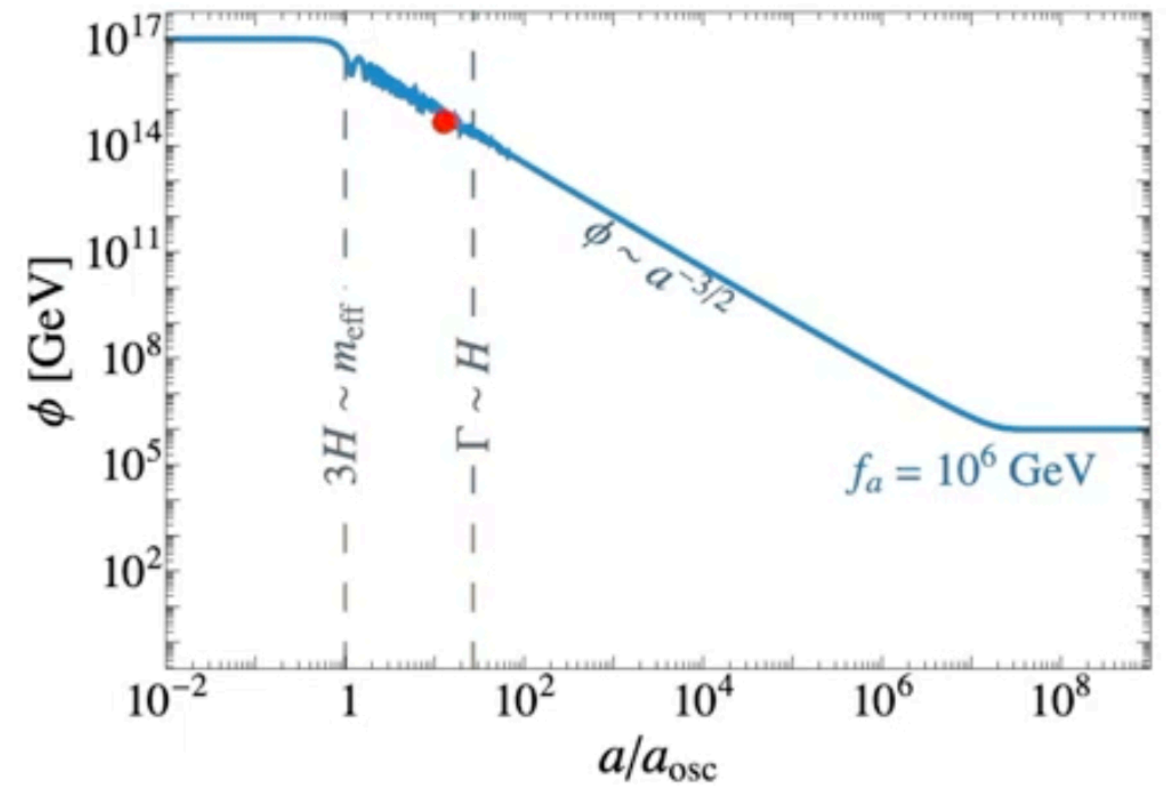

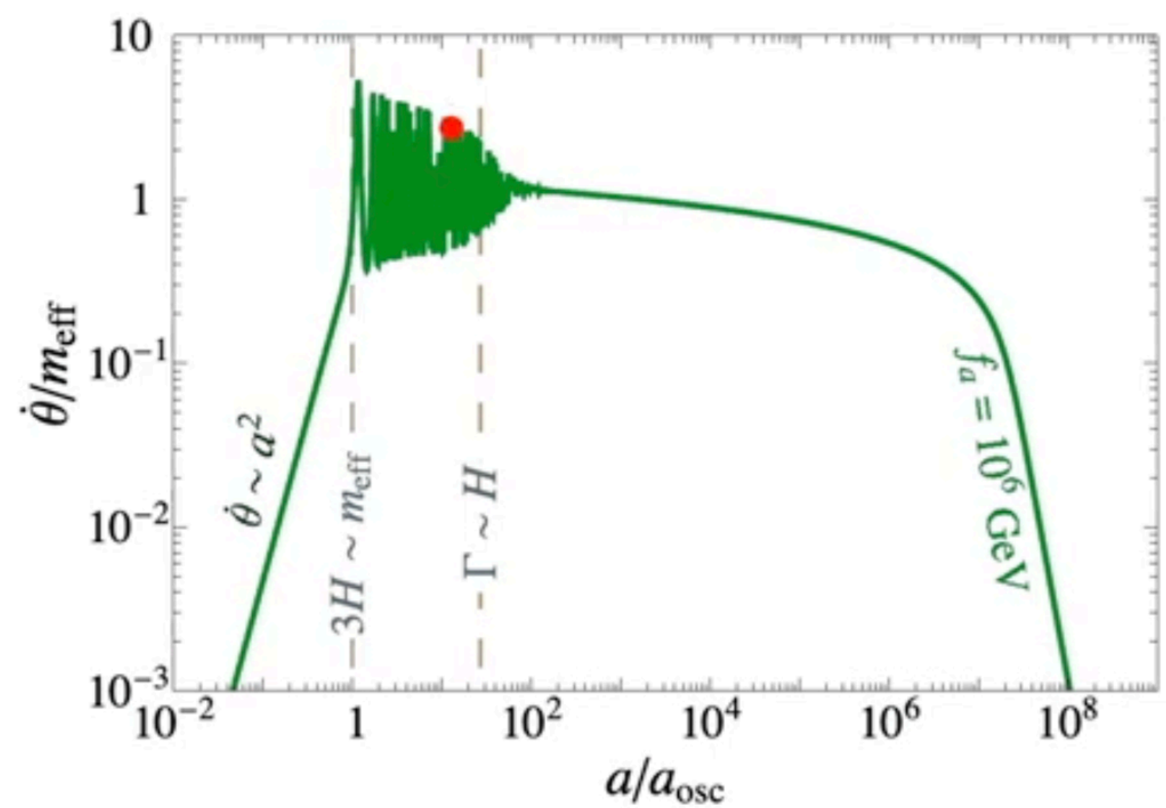

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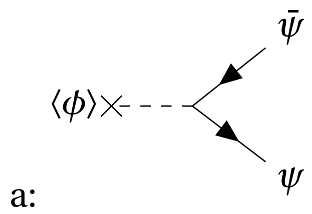

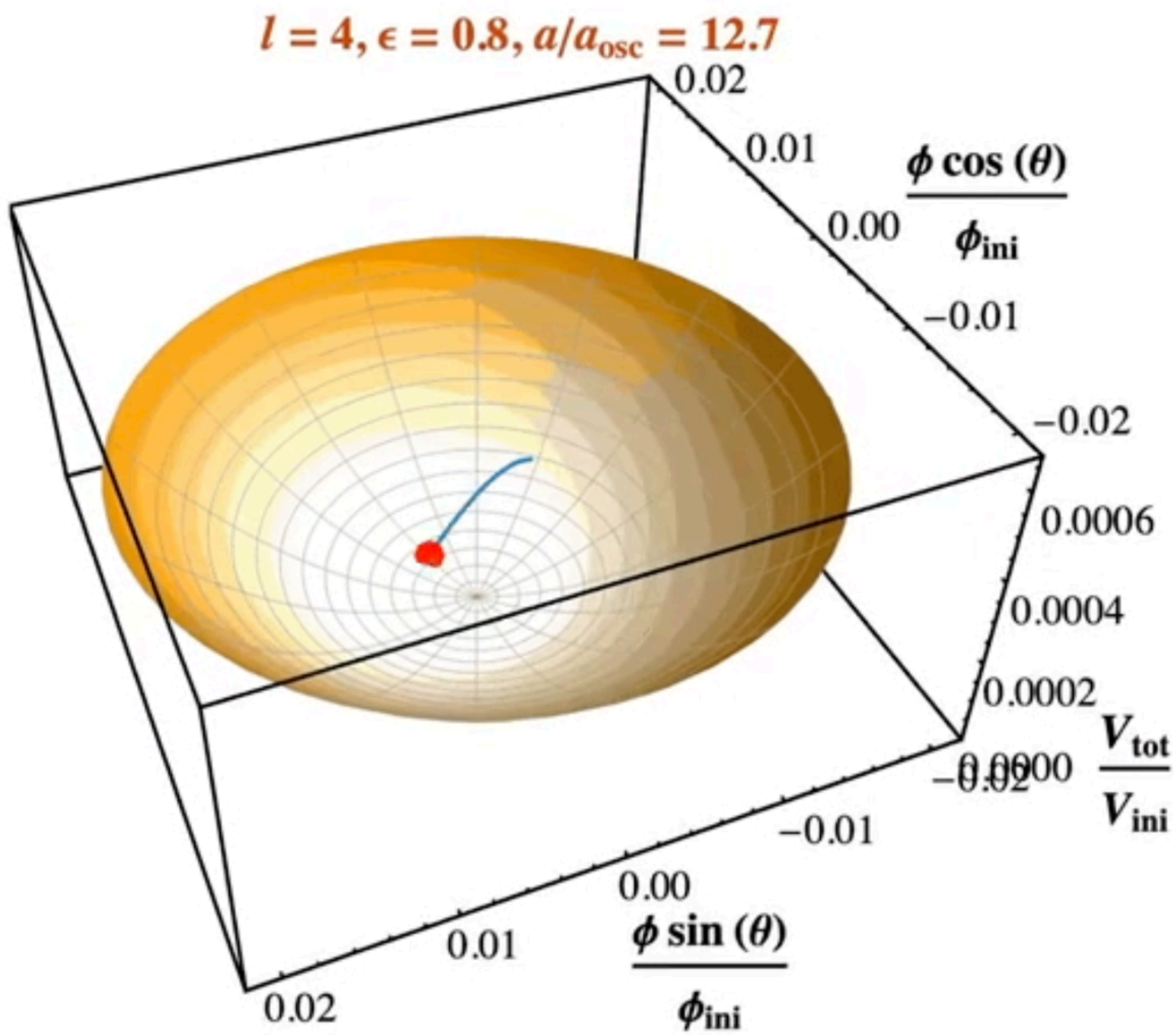

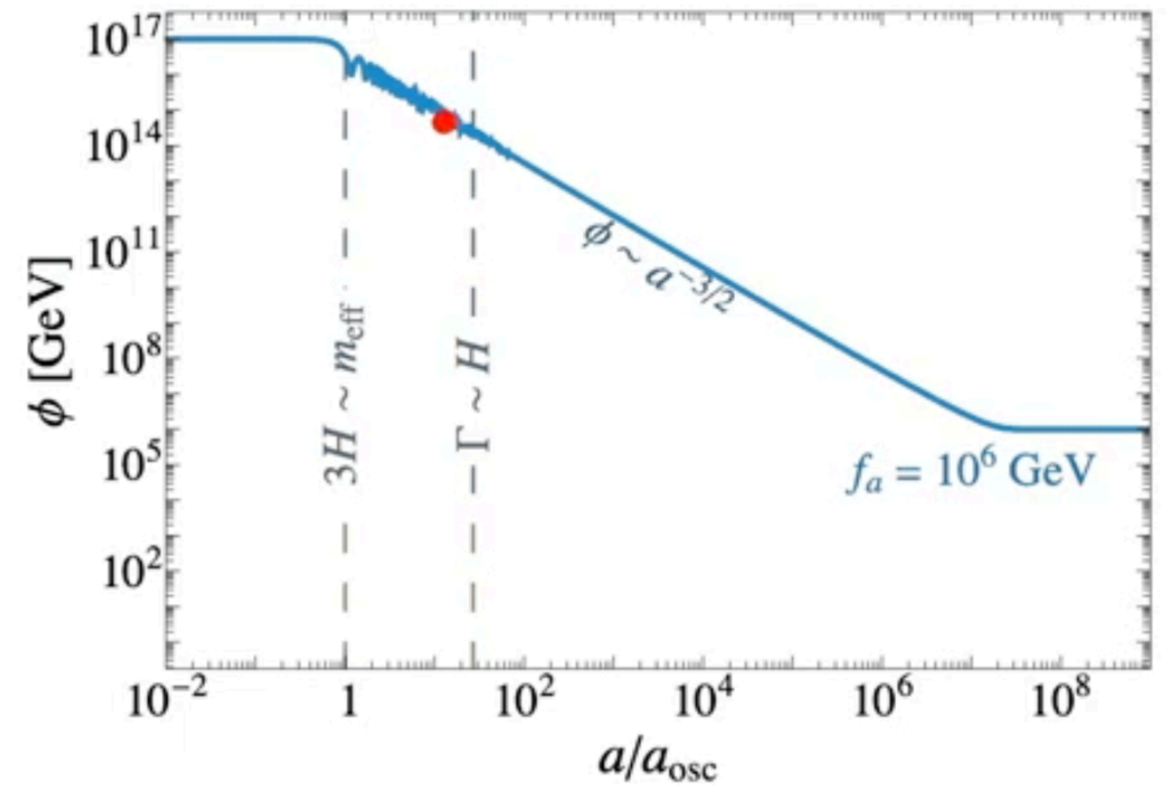

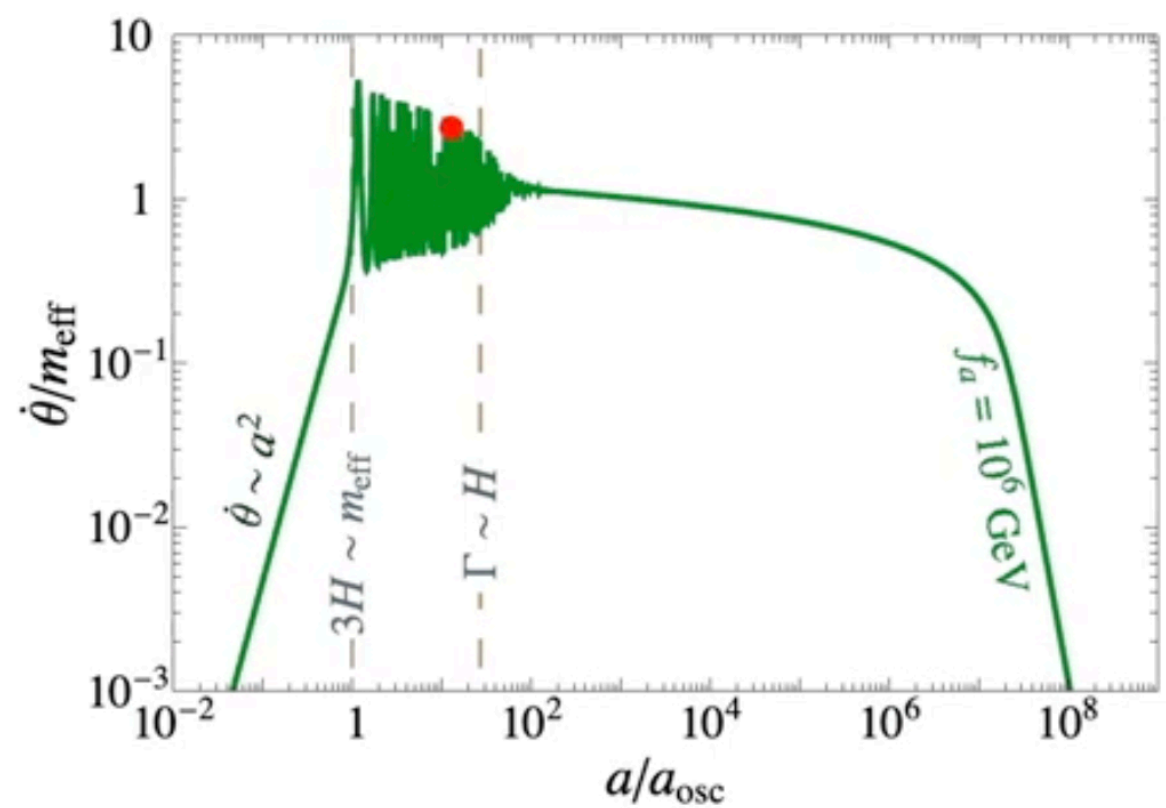

$$V_{\text{int}} = \lambda_\psi \phi \bar{\psi} \psi$$

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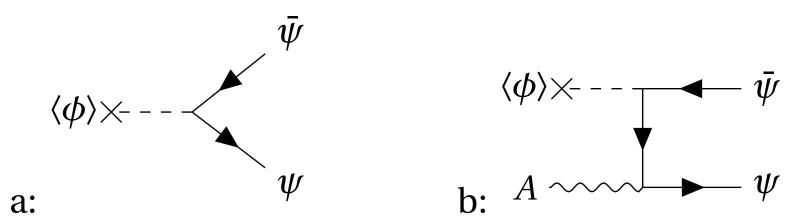

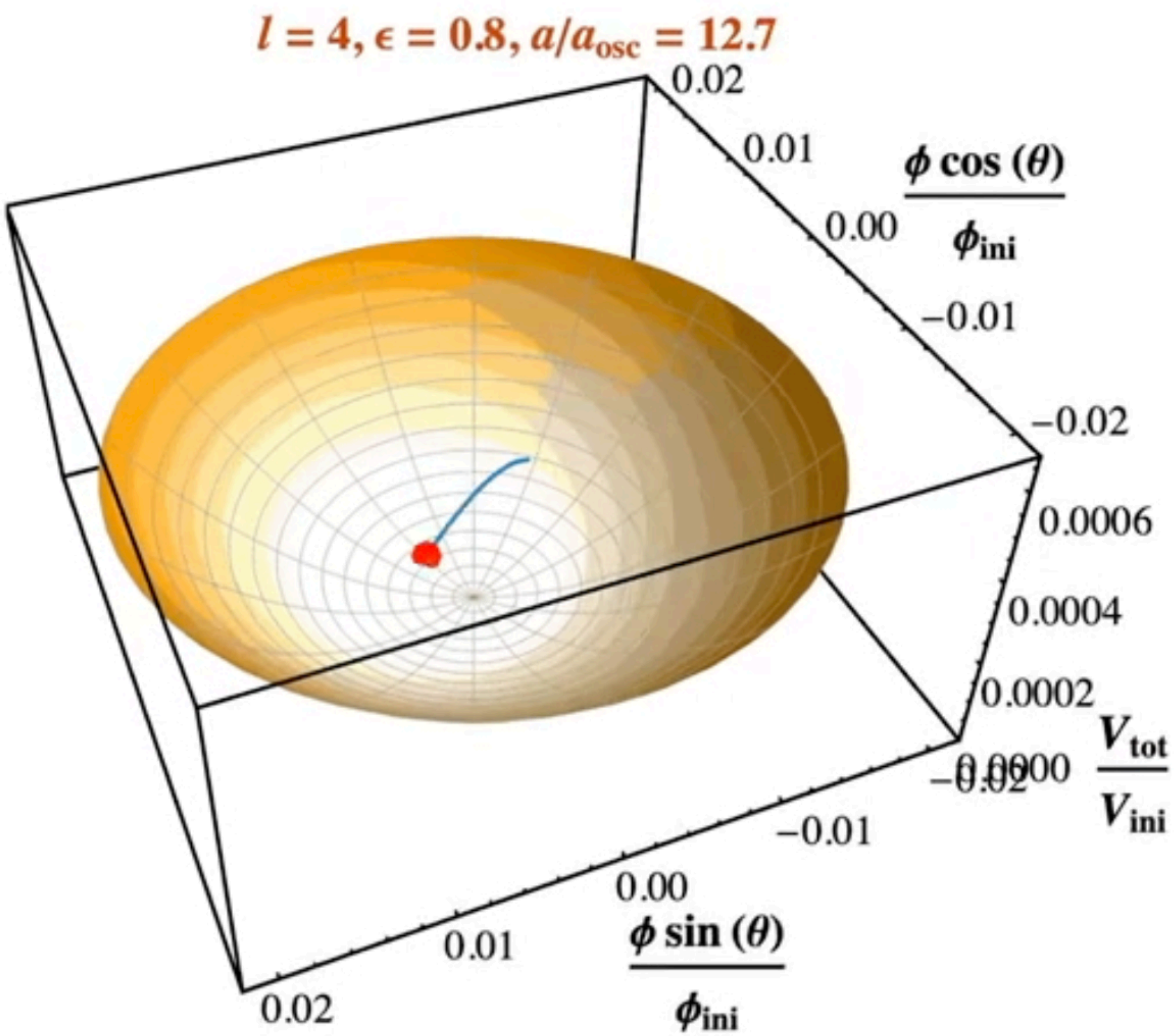

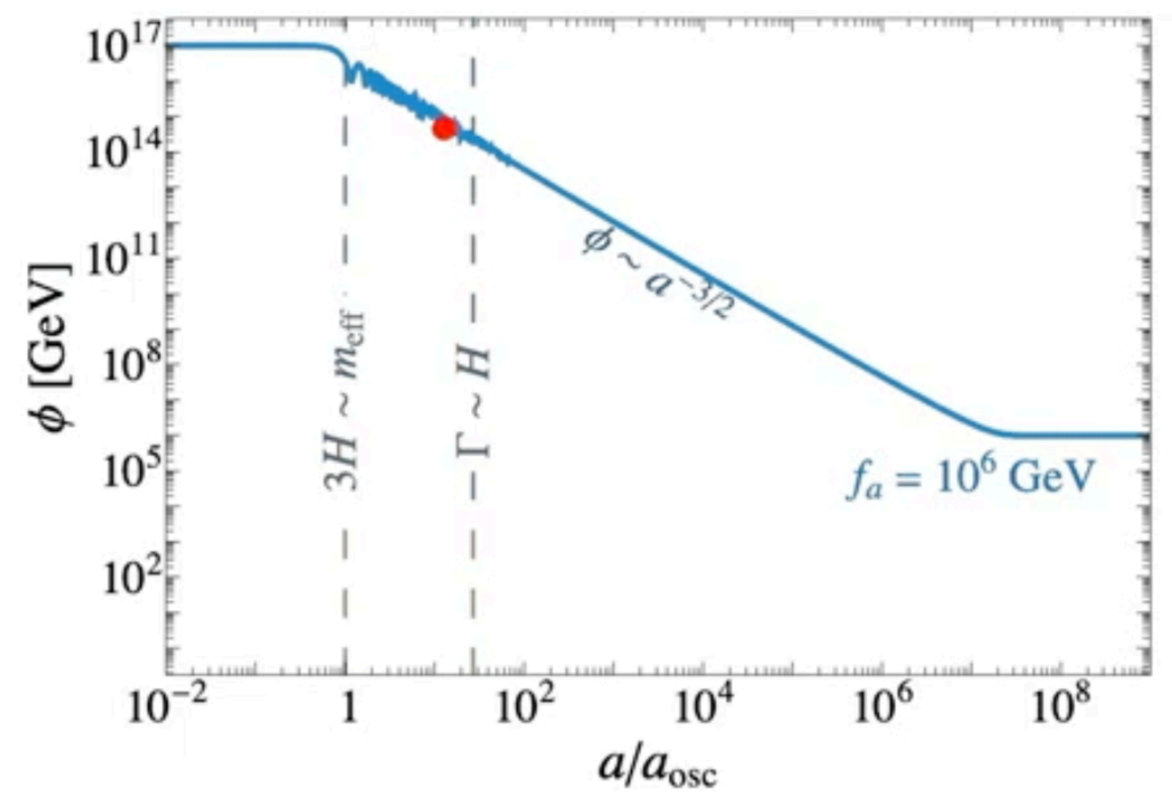

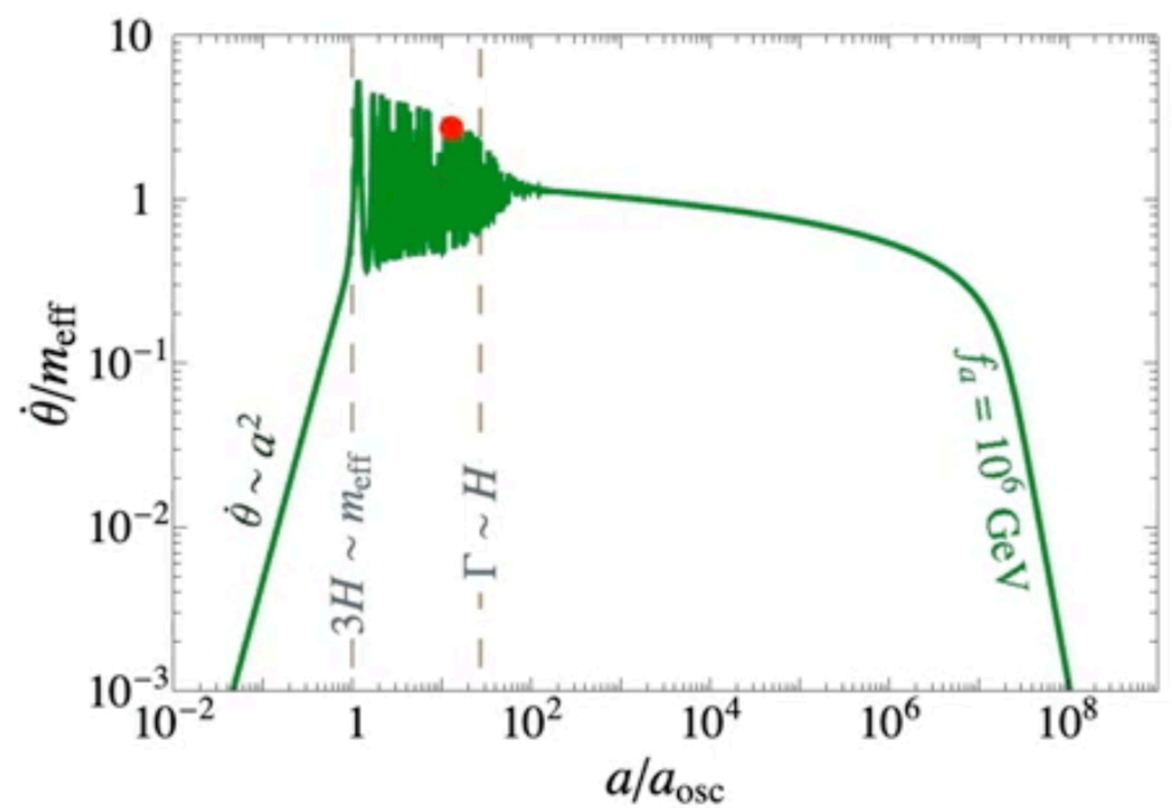

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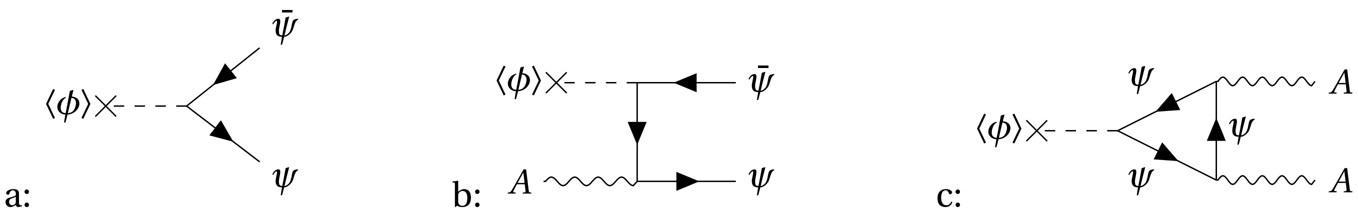

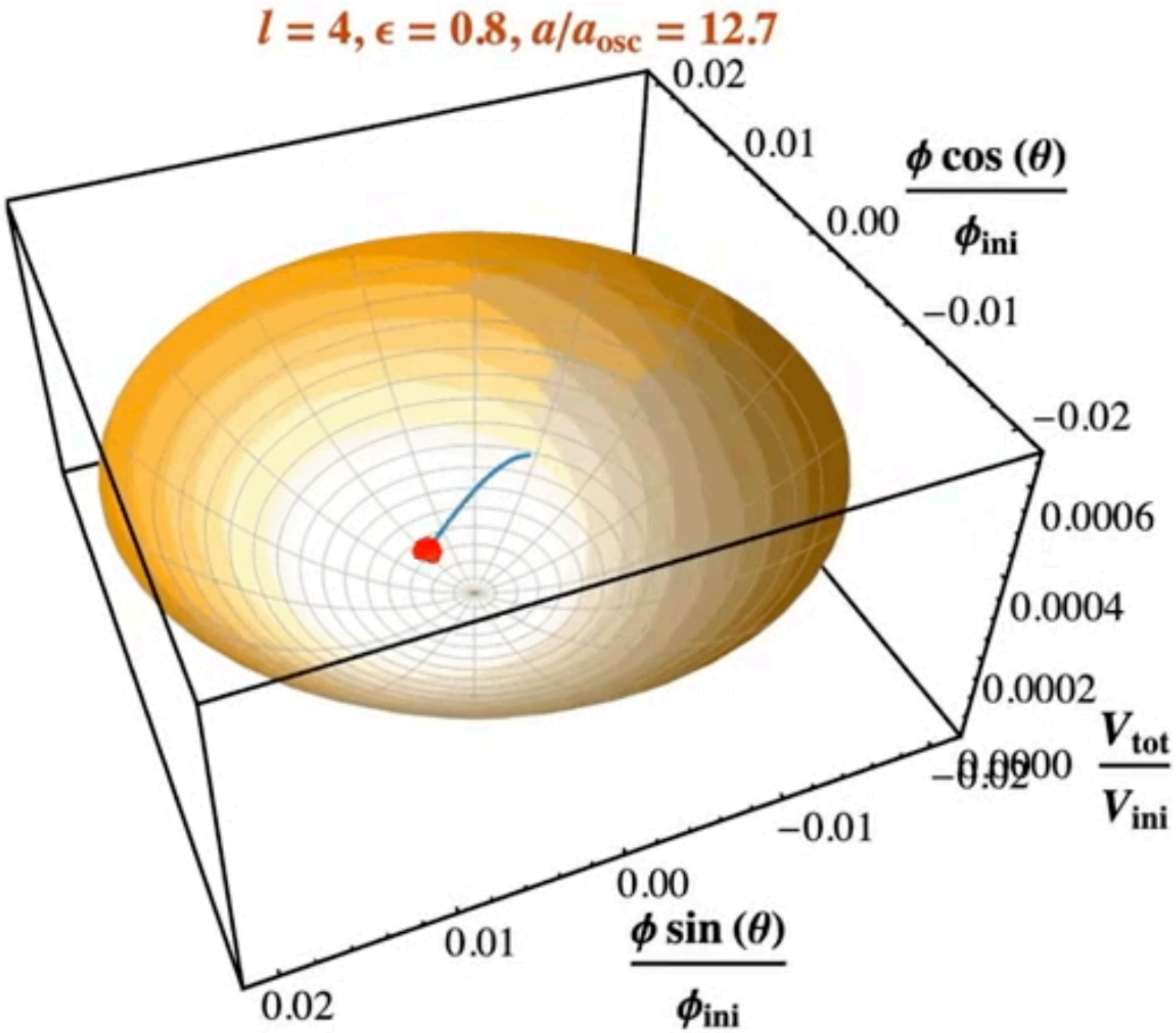

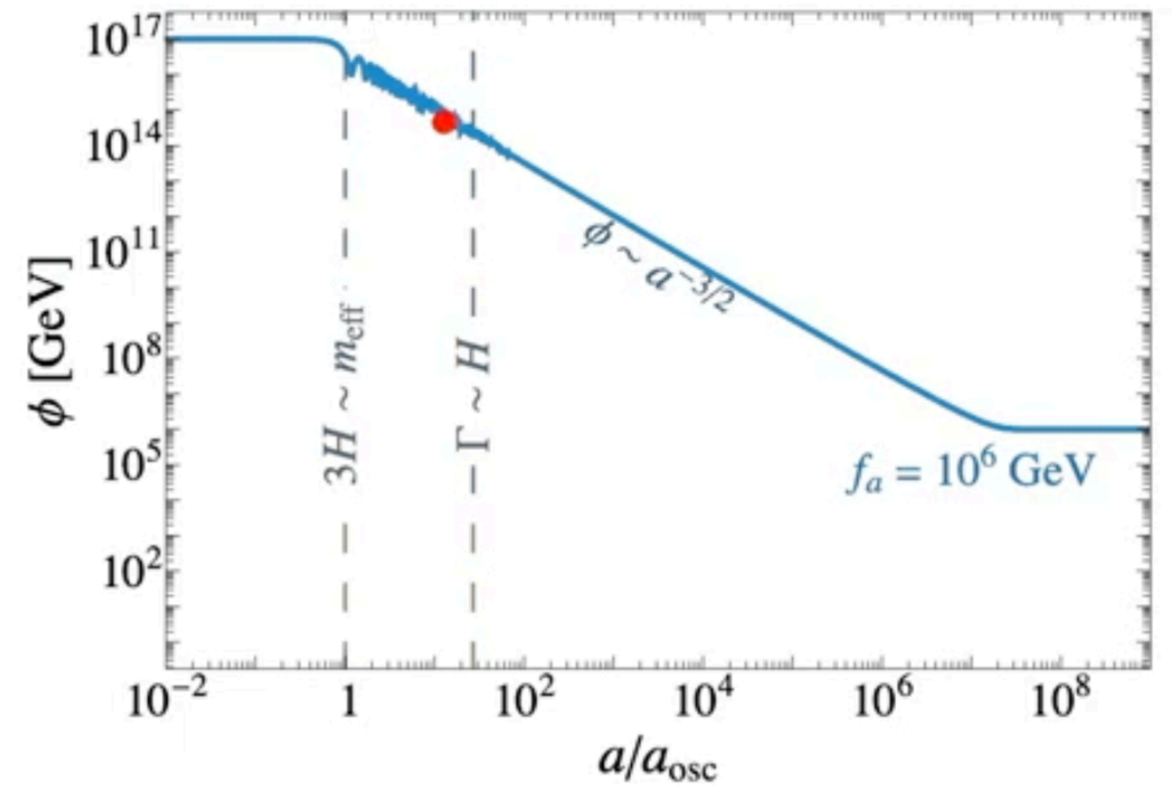

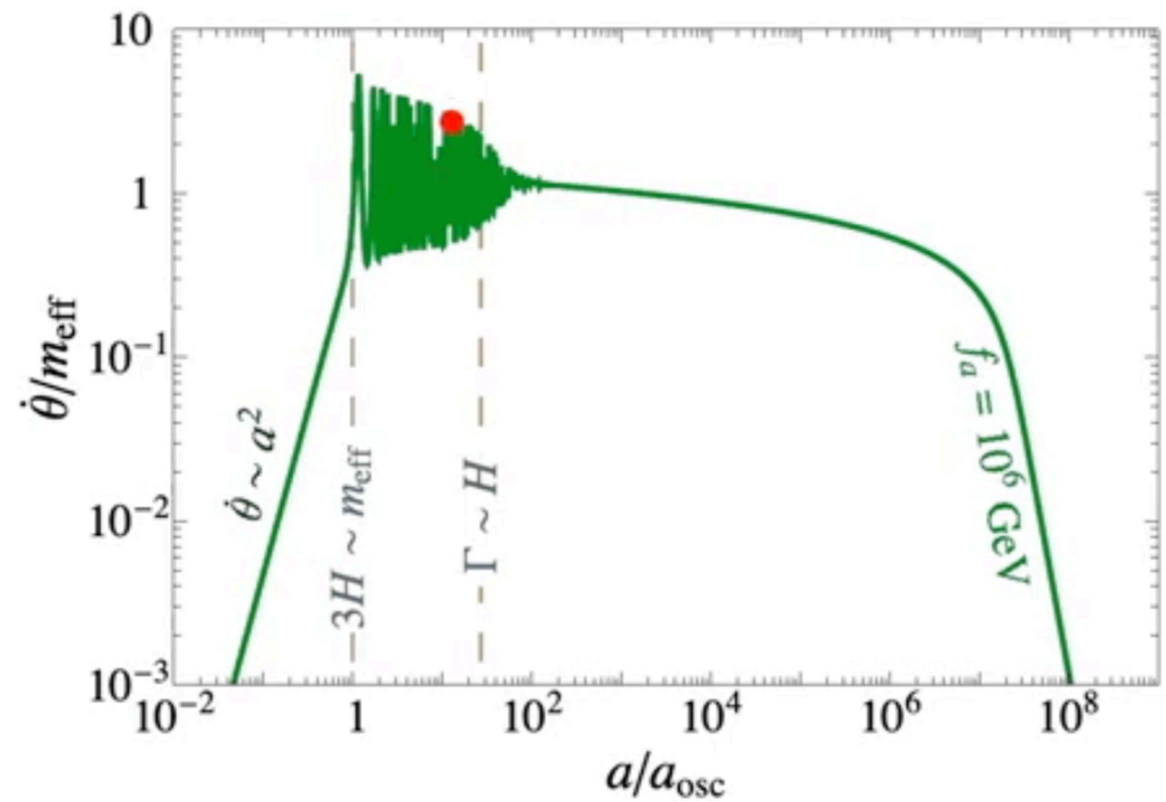

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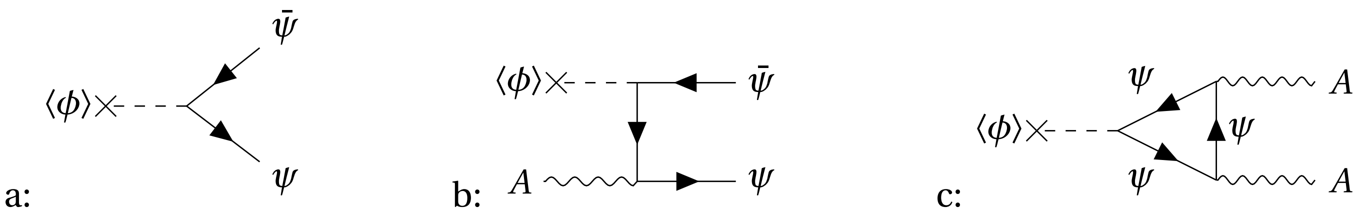
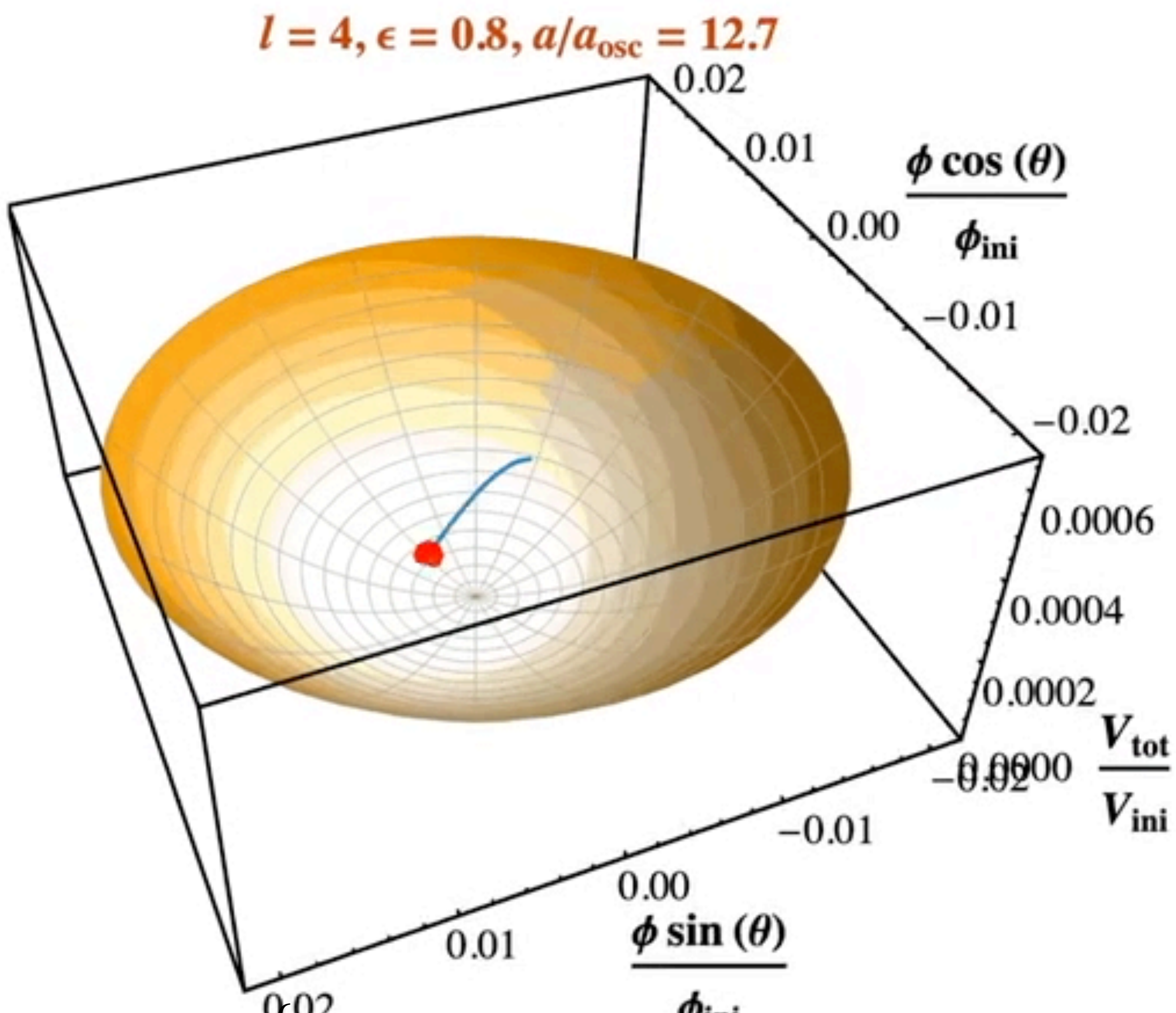
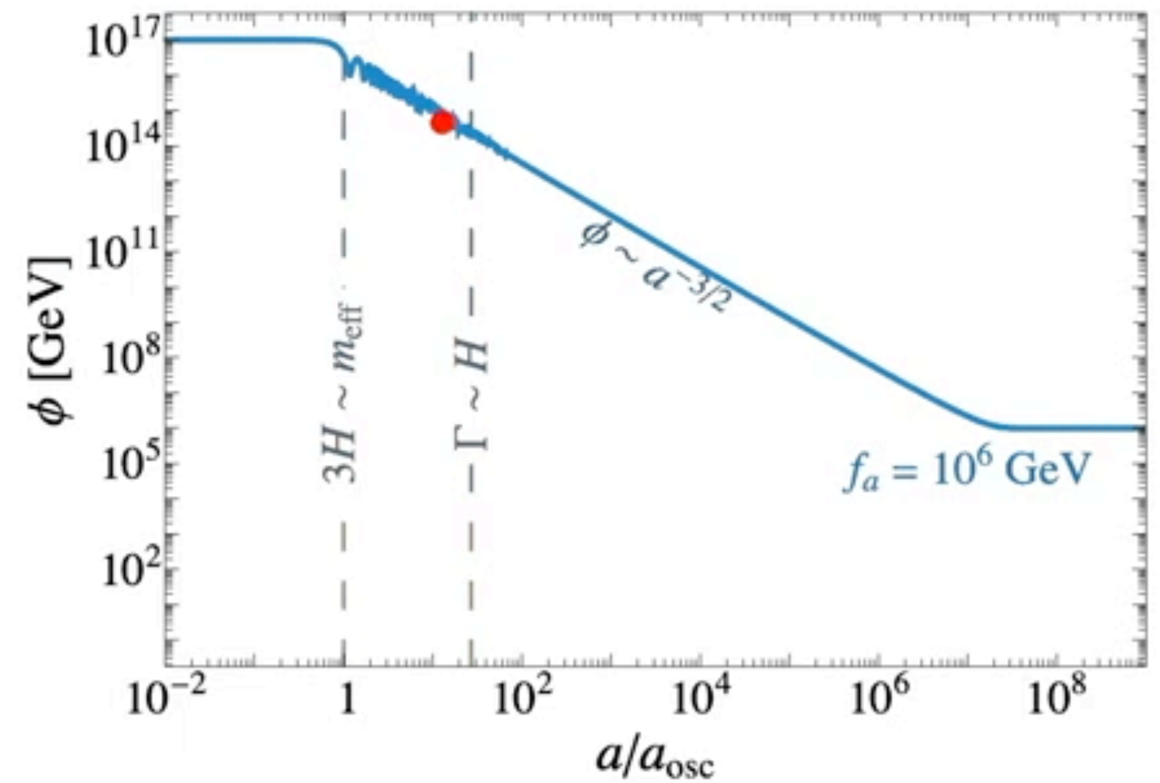
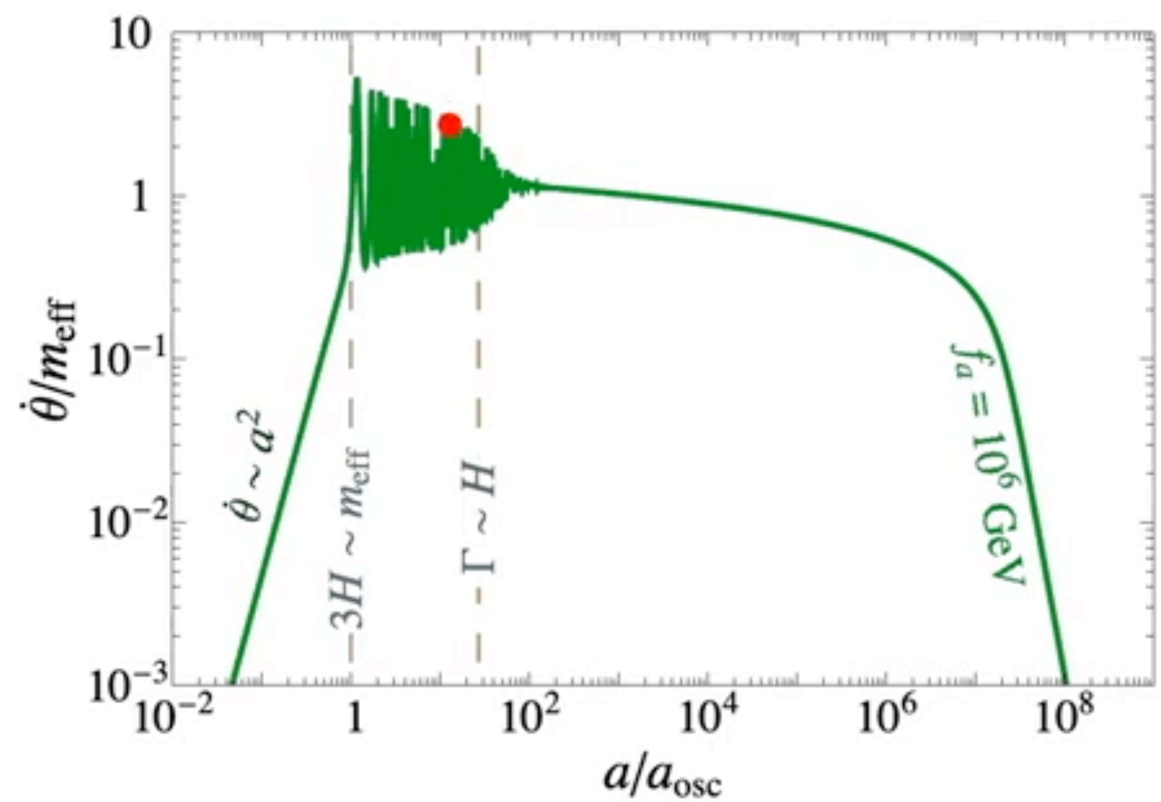






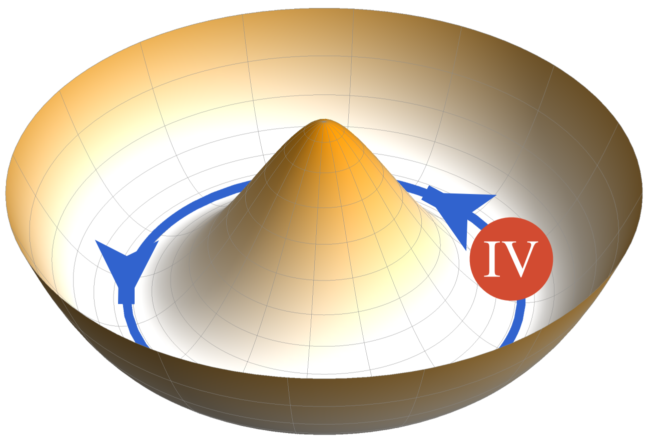


$$\frac{F}{V} = \rho - Ts = \begin{cases} \frac{1}{2}\phi^2\dot{\theta}^2 - \# T^4, & (U(1) \text{ charge remains in the condensate}) \\ \# \frac{\phi^4 \dot{\theta}^2}{T^2} - \# T^4, & (U(1) \text{ charge transferred to the plasma}) \end{cases}$$

$(\rho \supset \mu n$ with $\mu = n/T^2$ and $n = \phi^2 \dot{\theta})$

If $\phi \gg T \quad \Longrightarrow \quad U(1)$ charge remains in the condensate

After reaching the bottom ⇒ kination era



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Kinetic energy dominates

$$\rho_\Phi = KE \propto \dot{\theta}^2 \propto a^{-6}$$

and behaves as kination.

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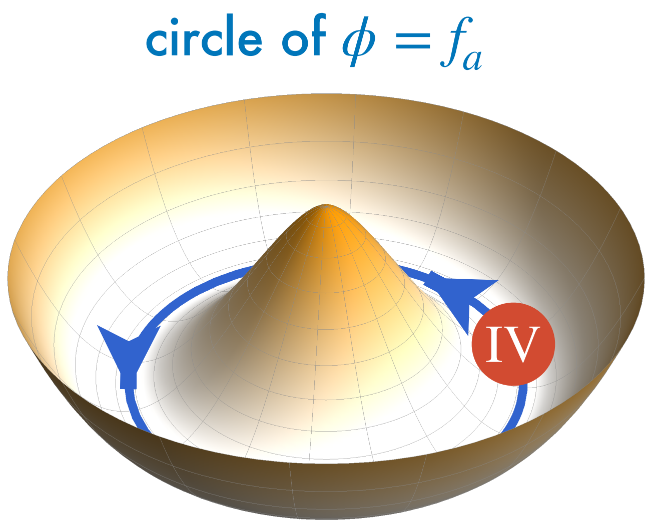

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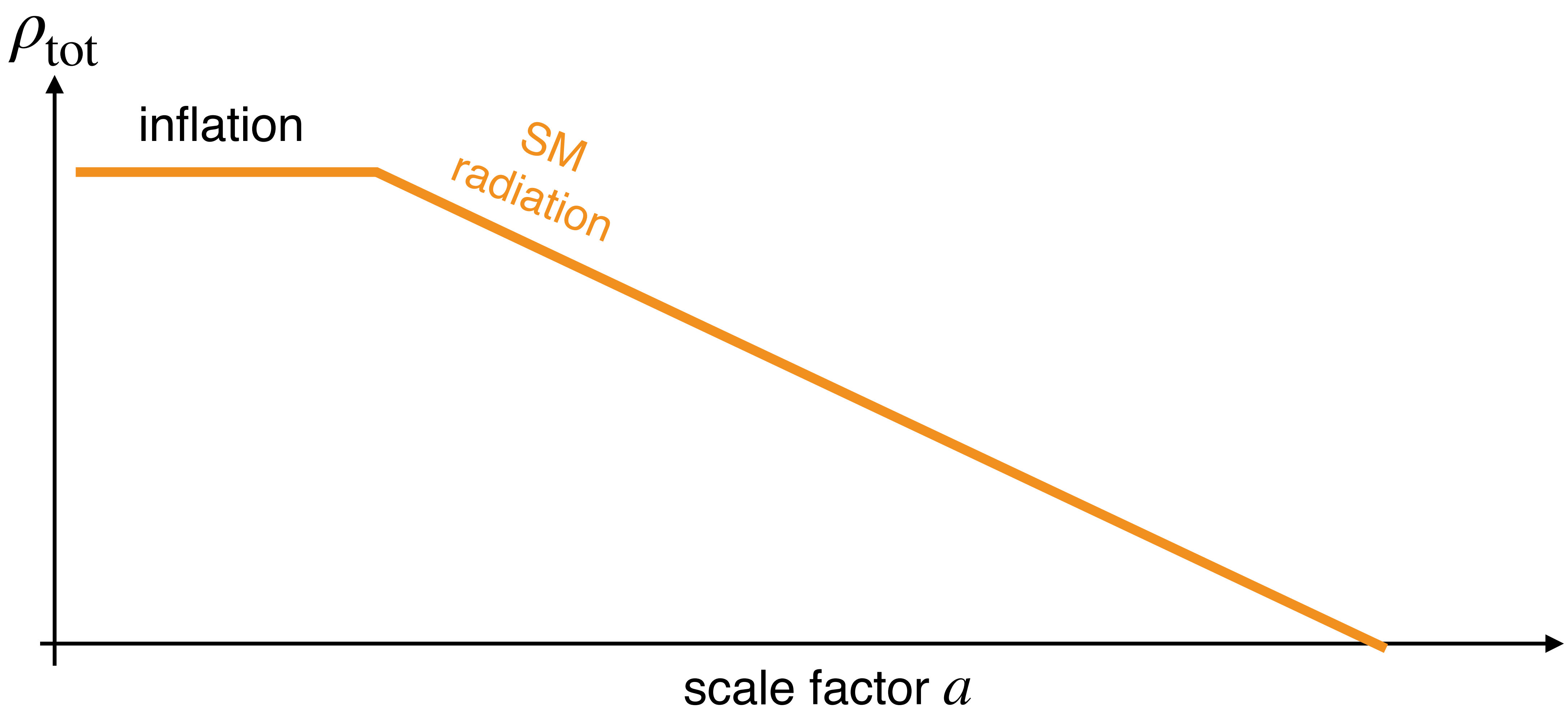

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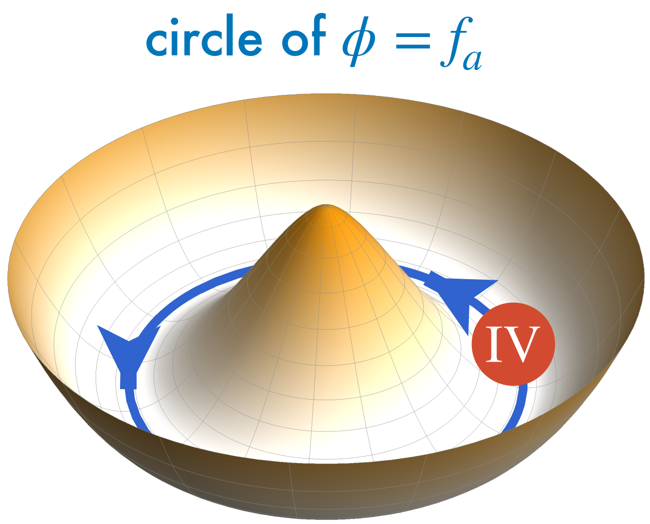

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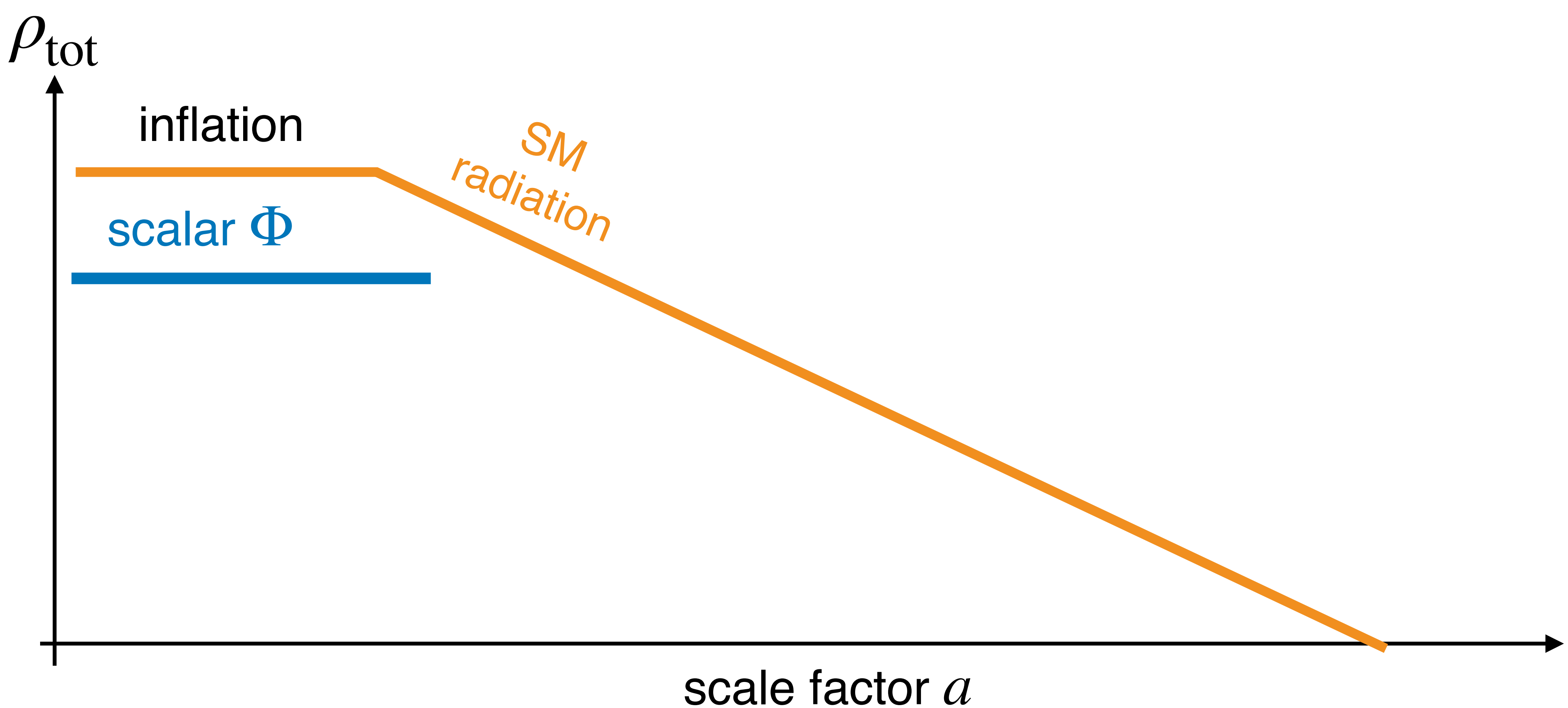

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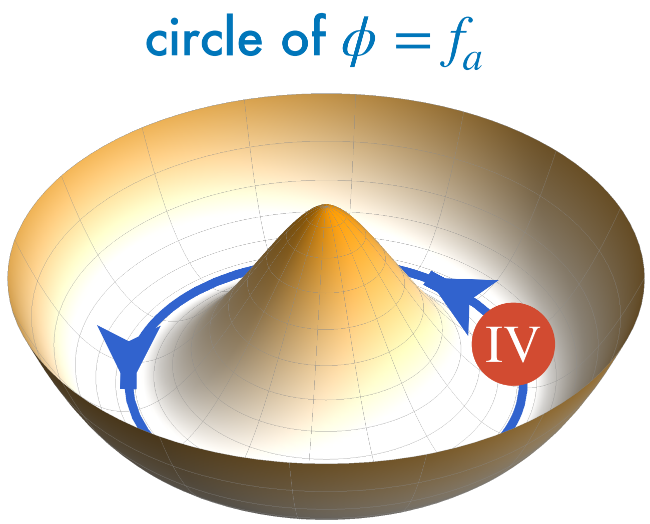

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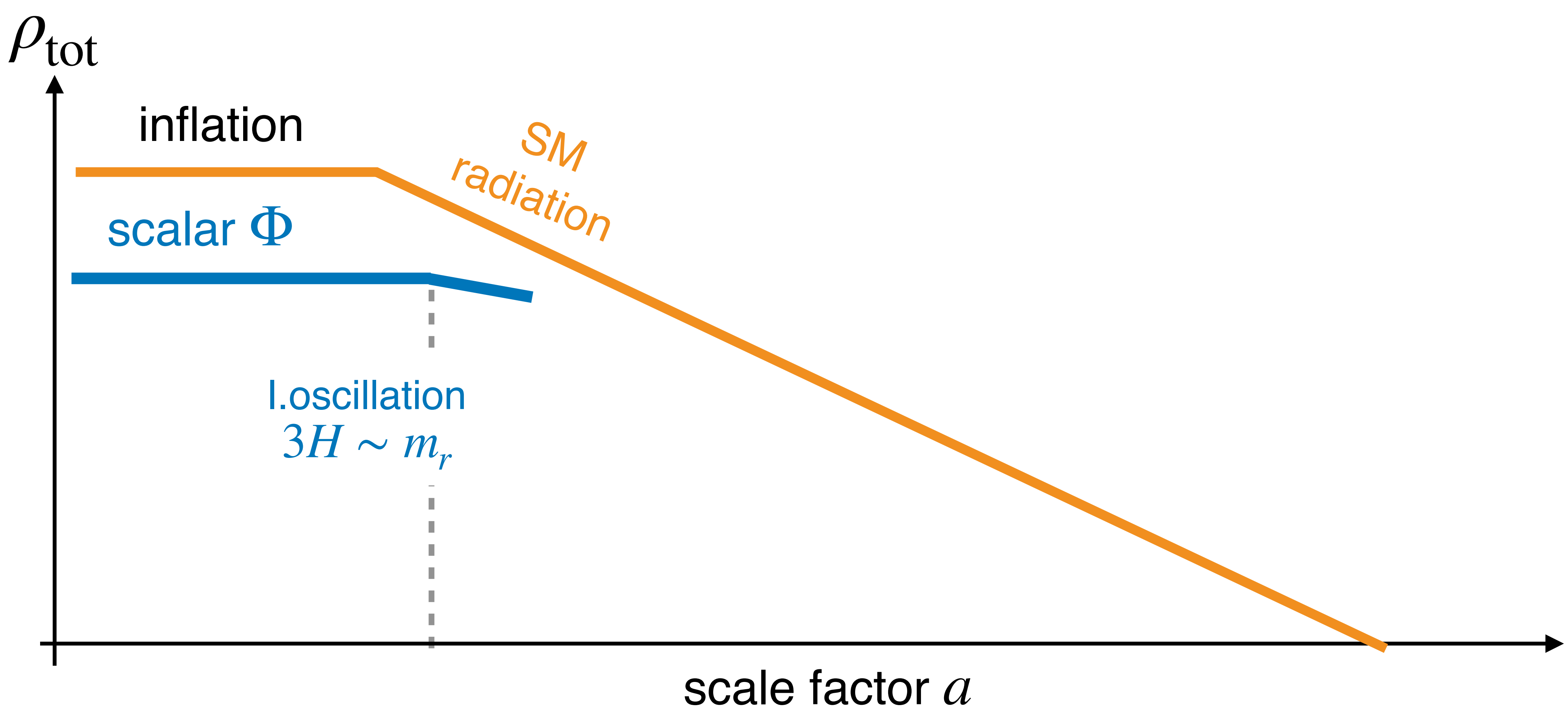

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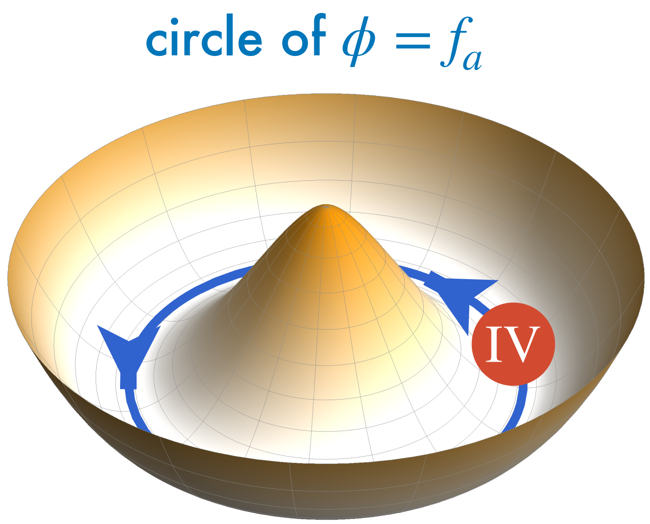

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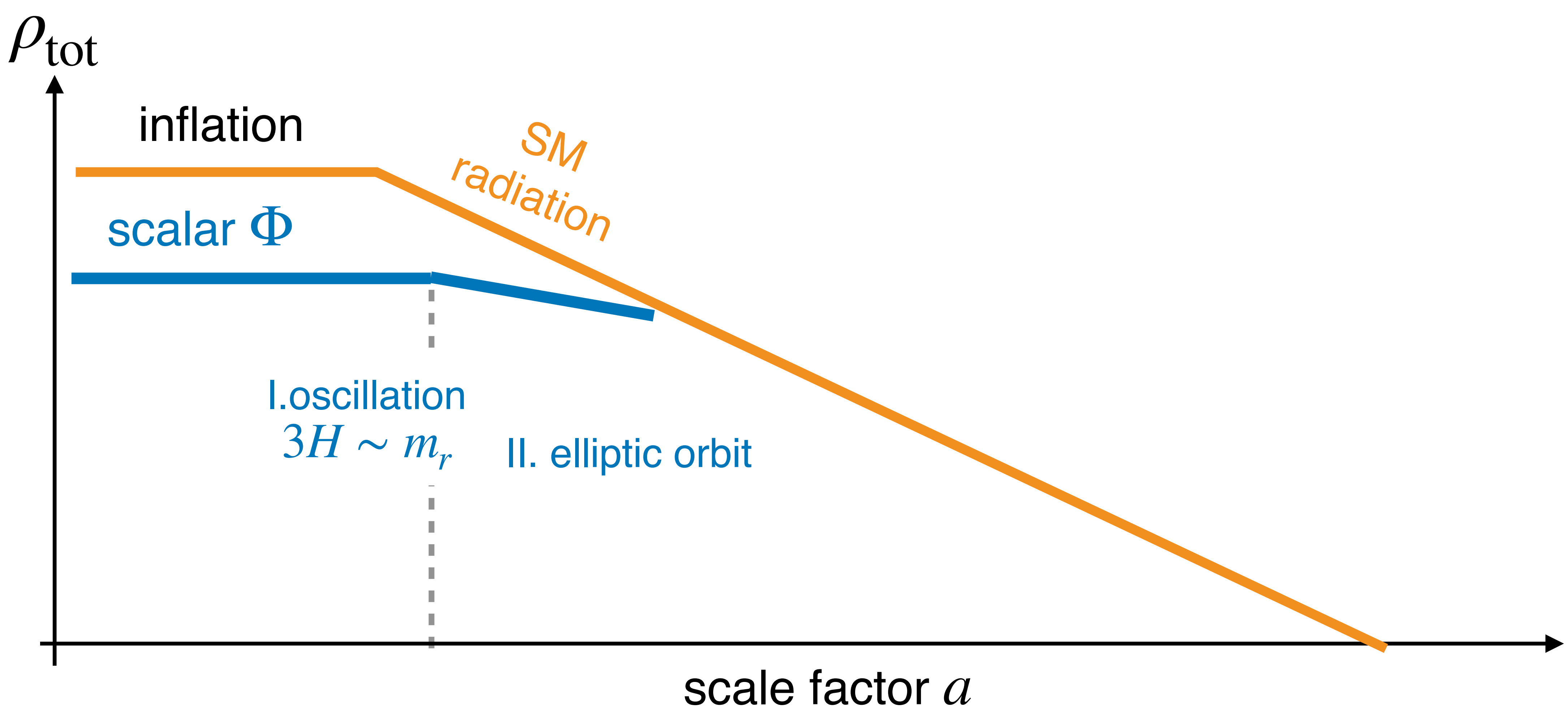

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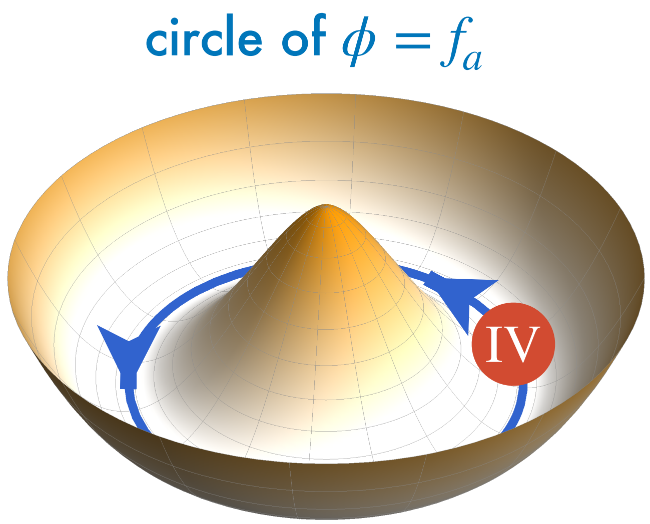

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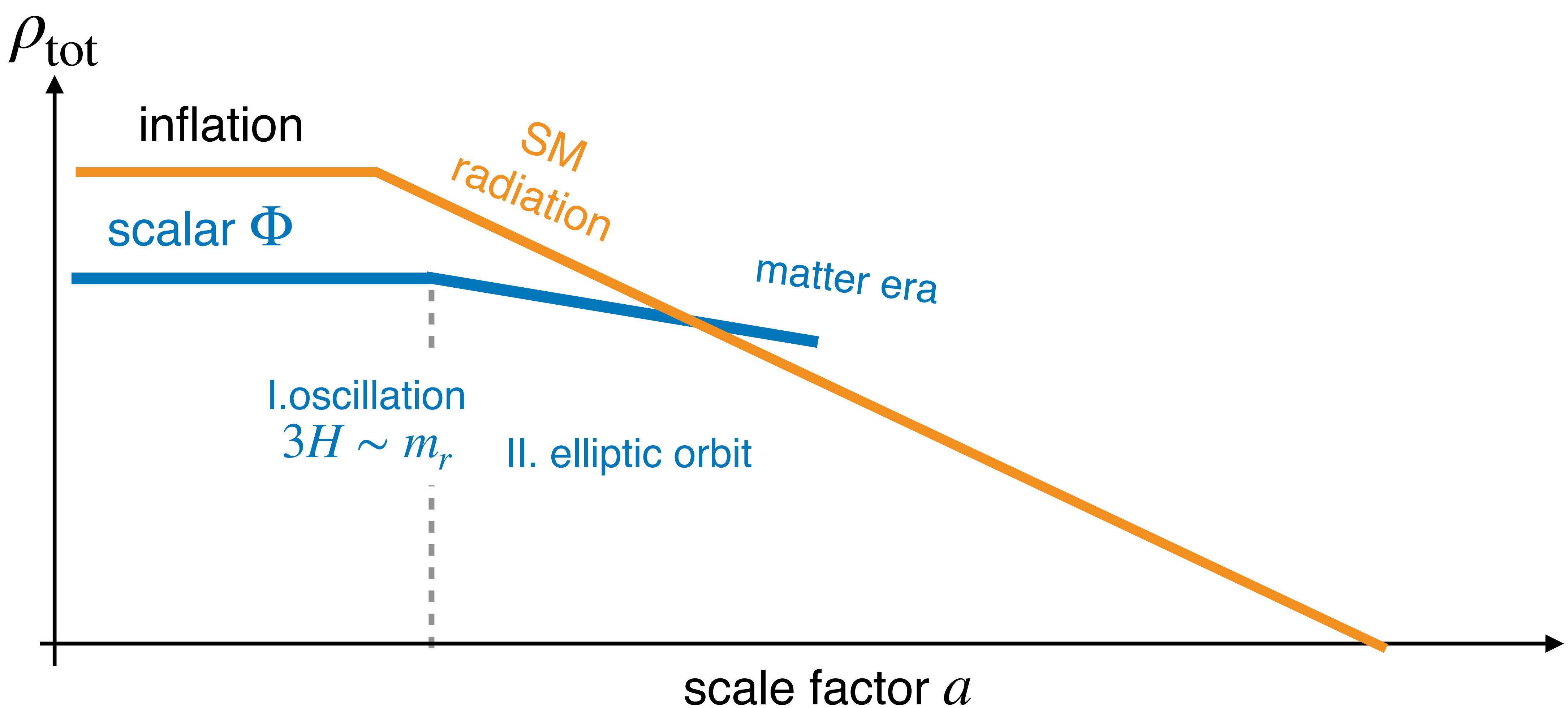

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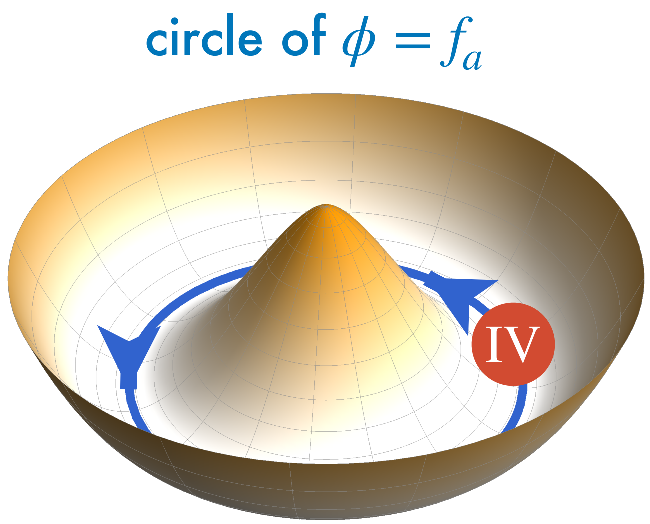

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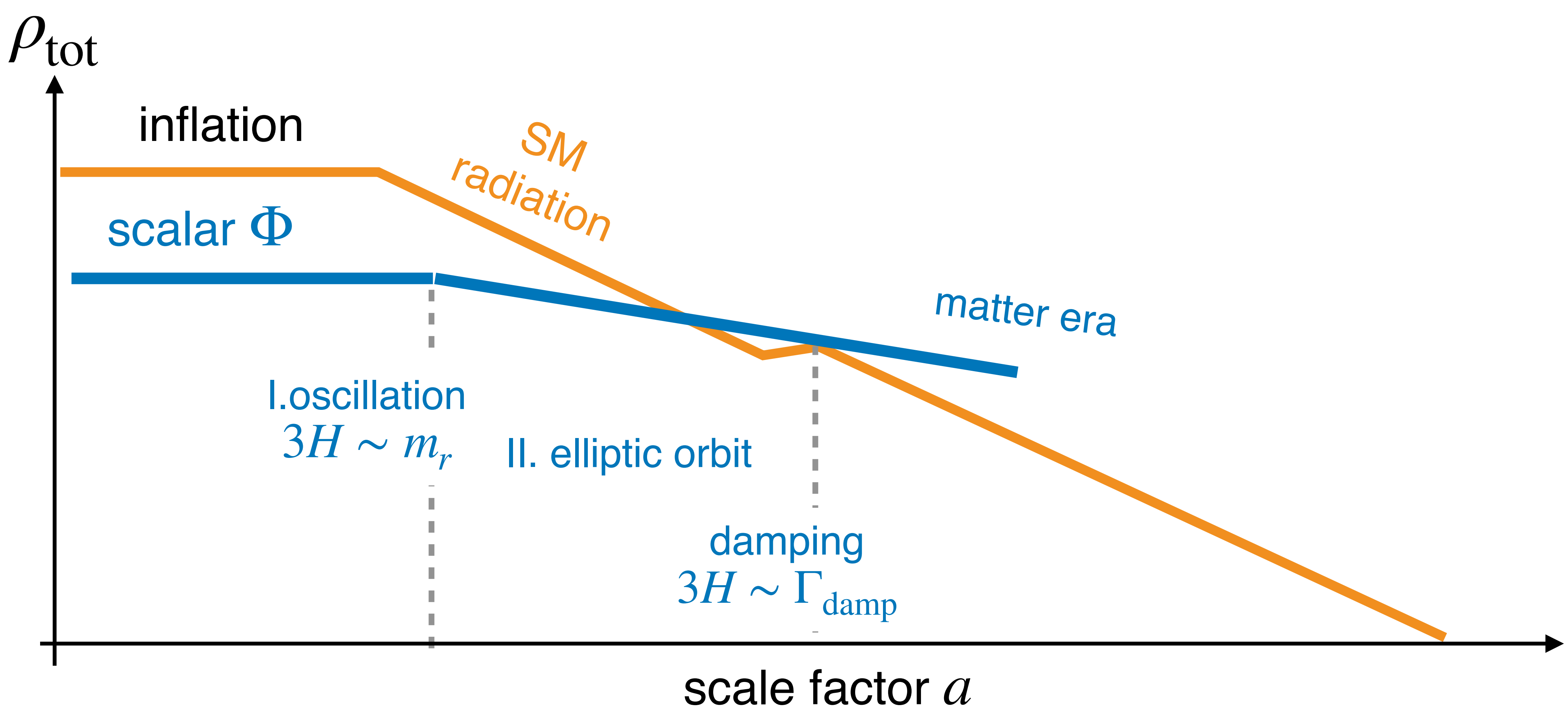

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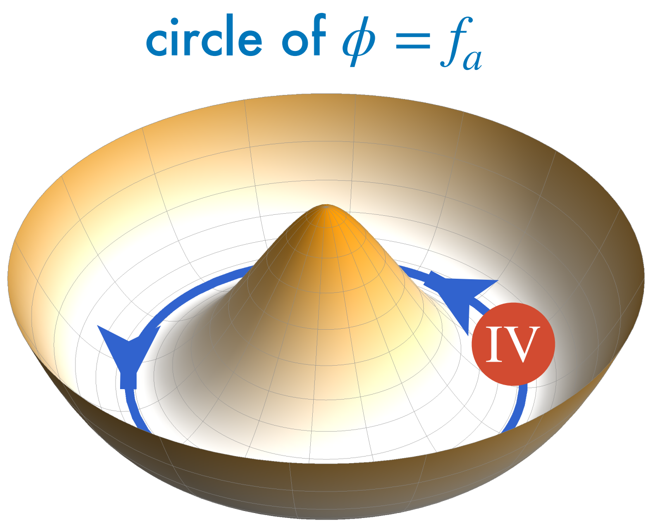

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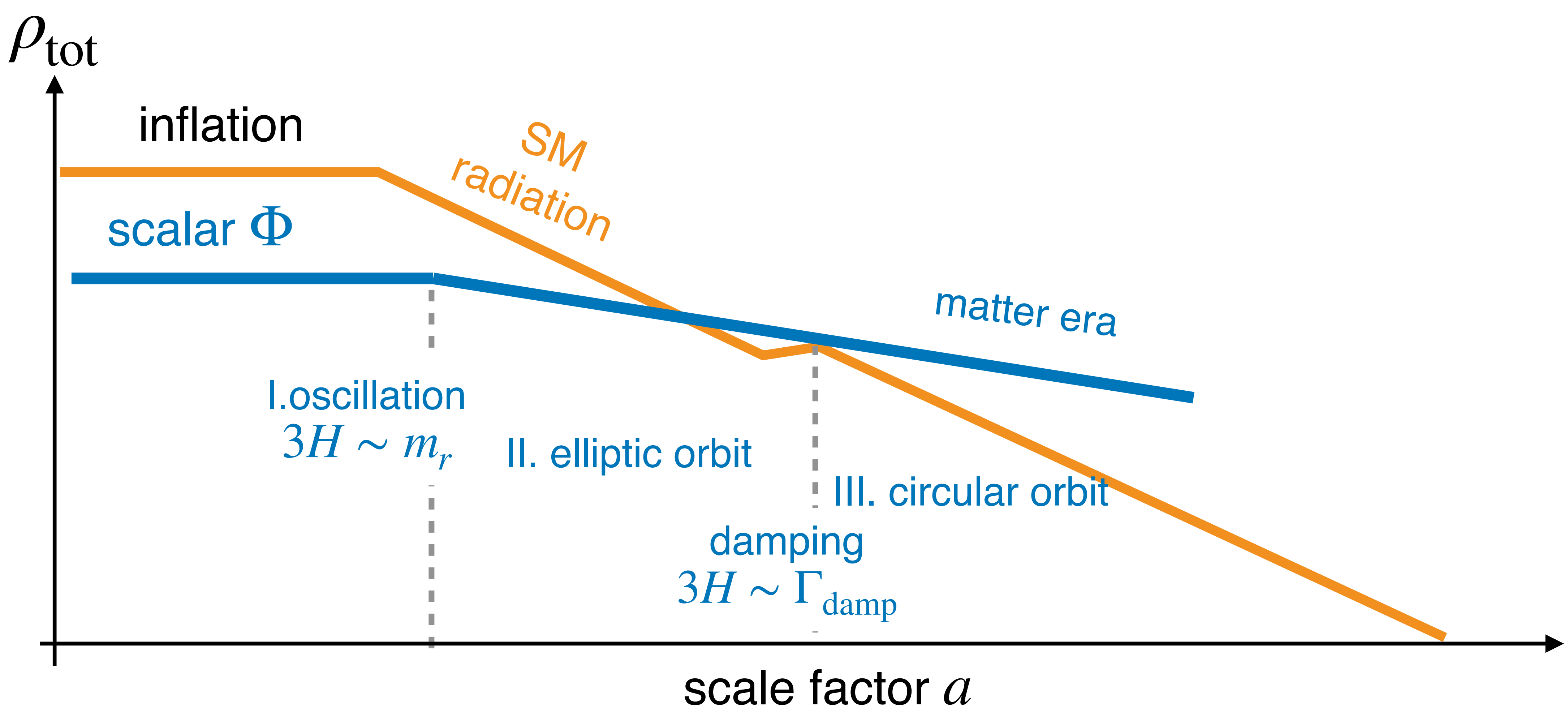

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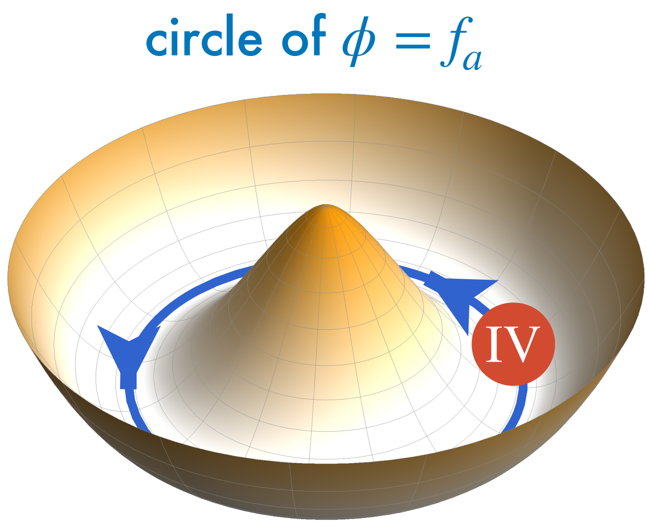

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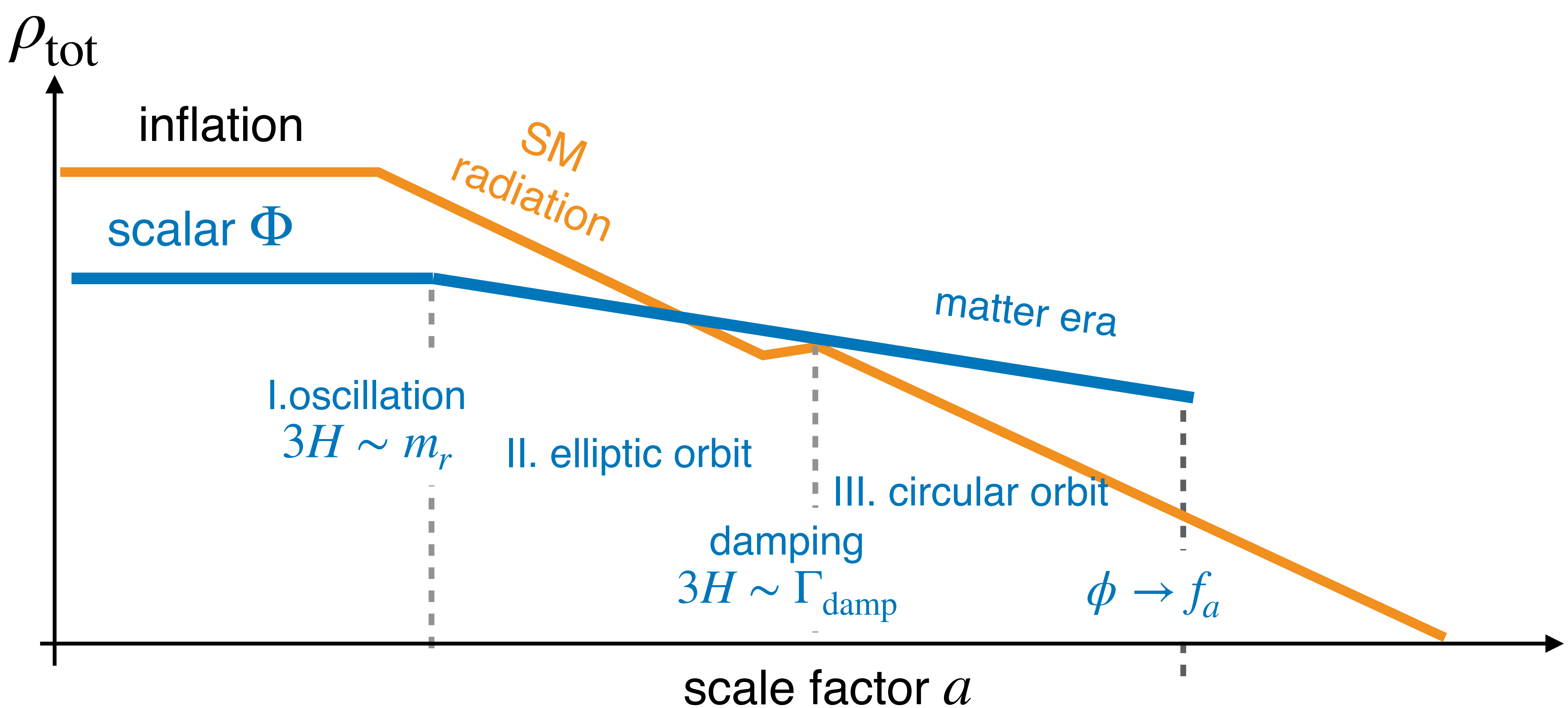

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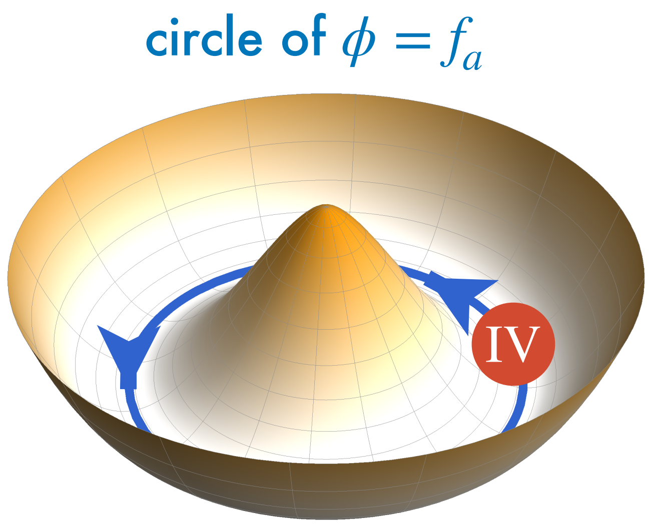

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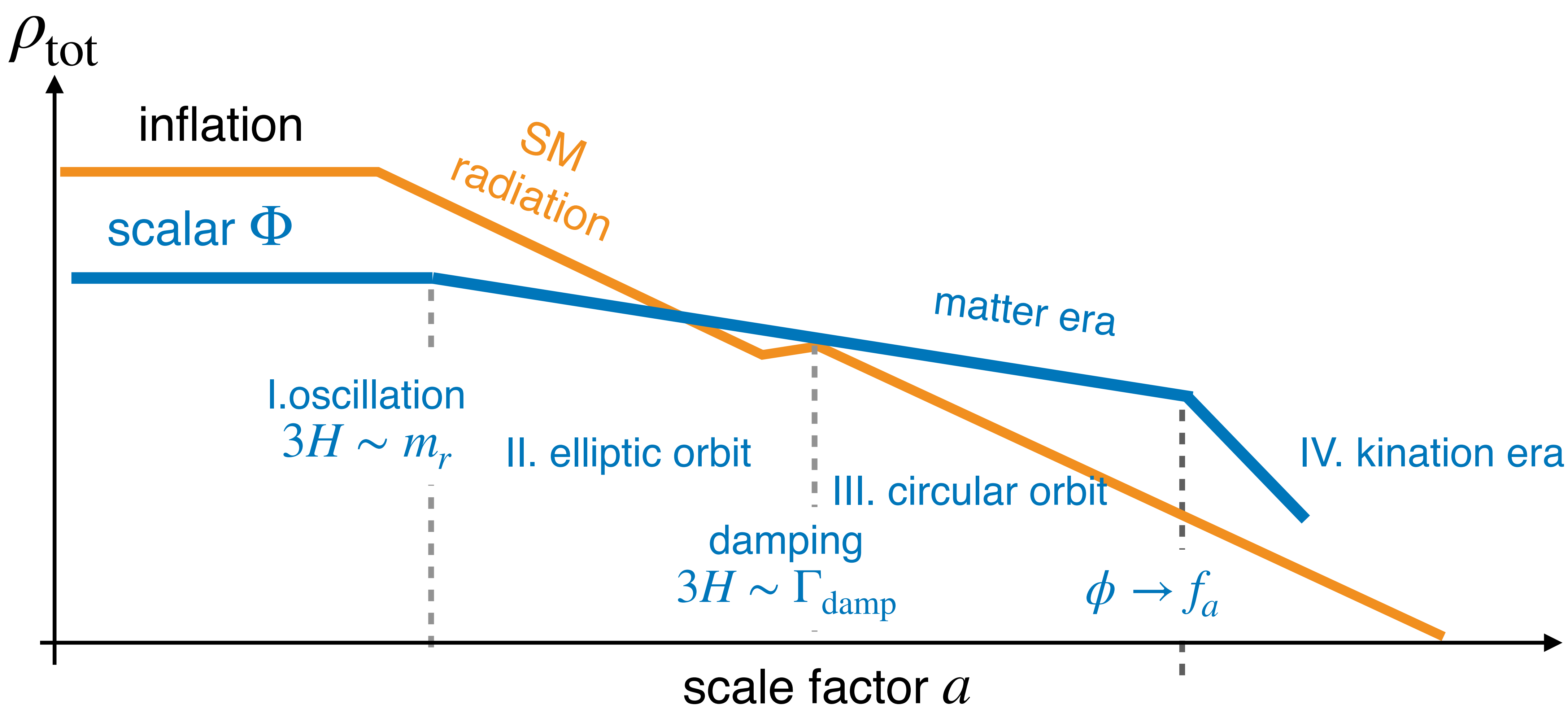

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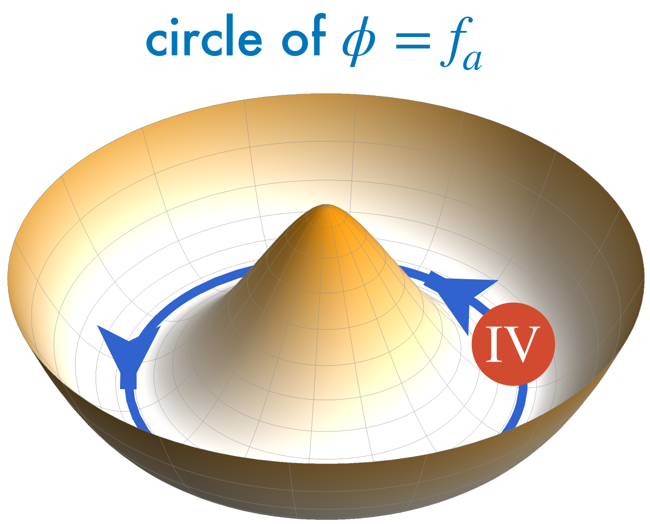

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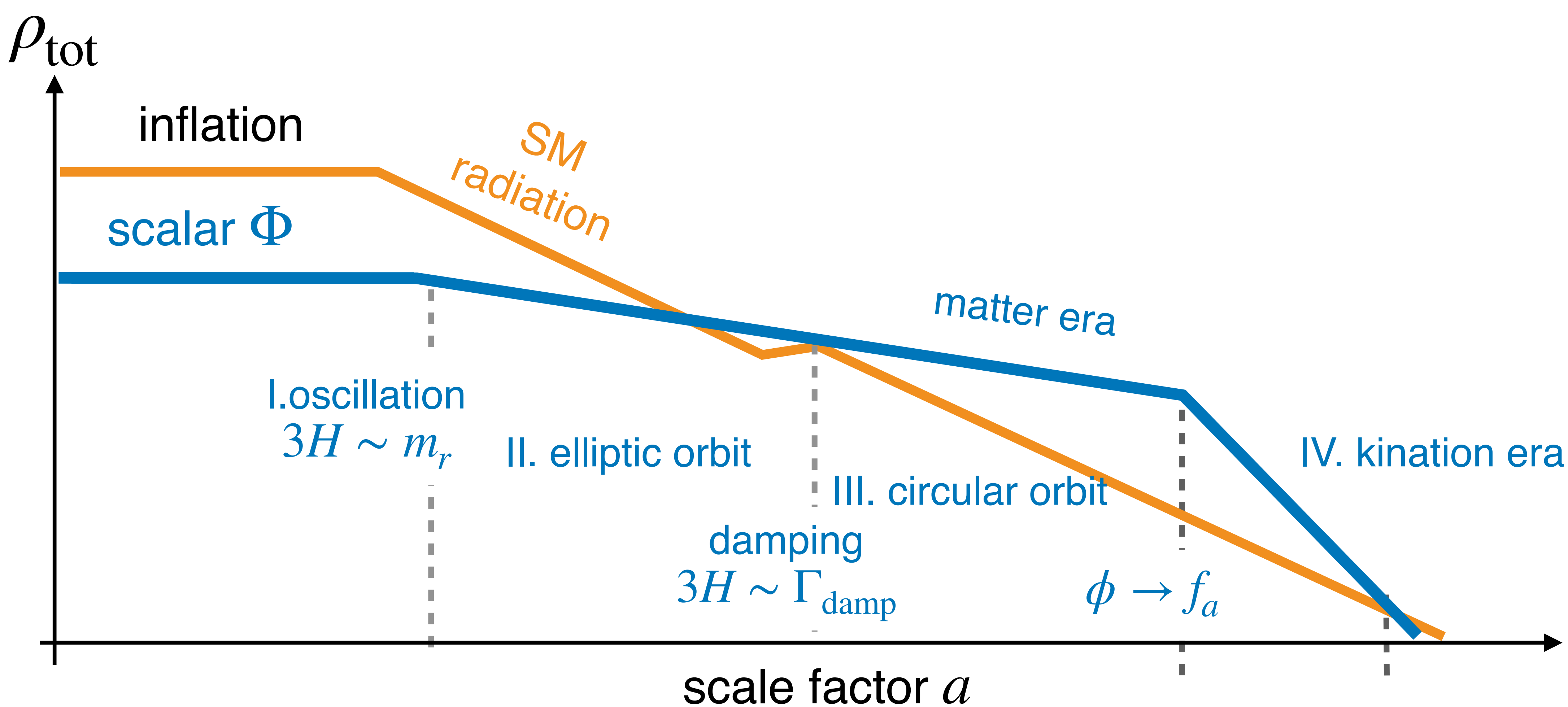

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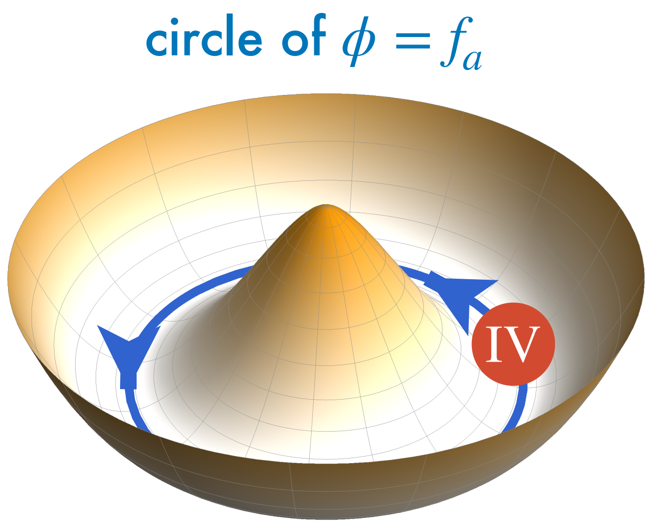

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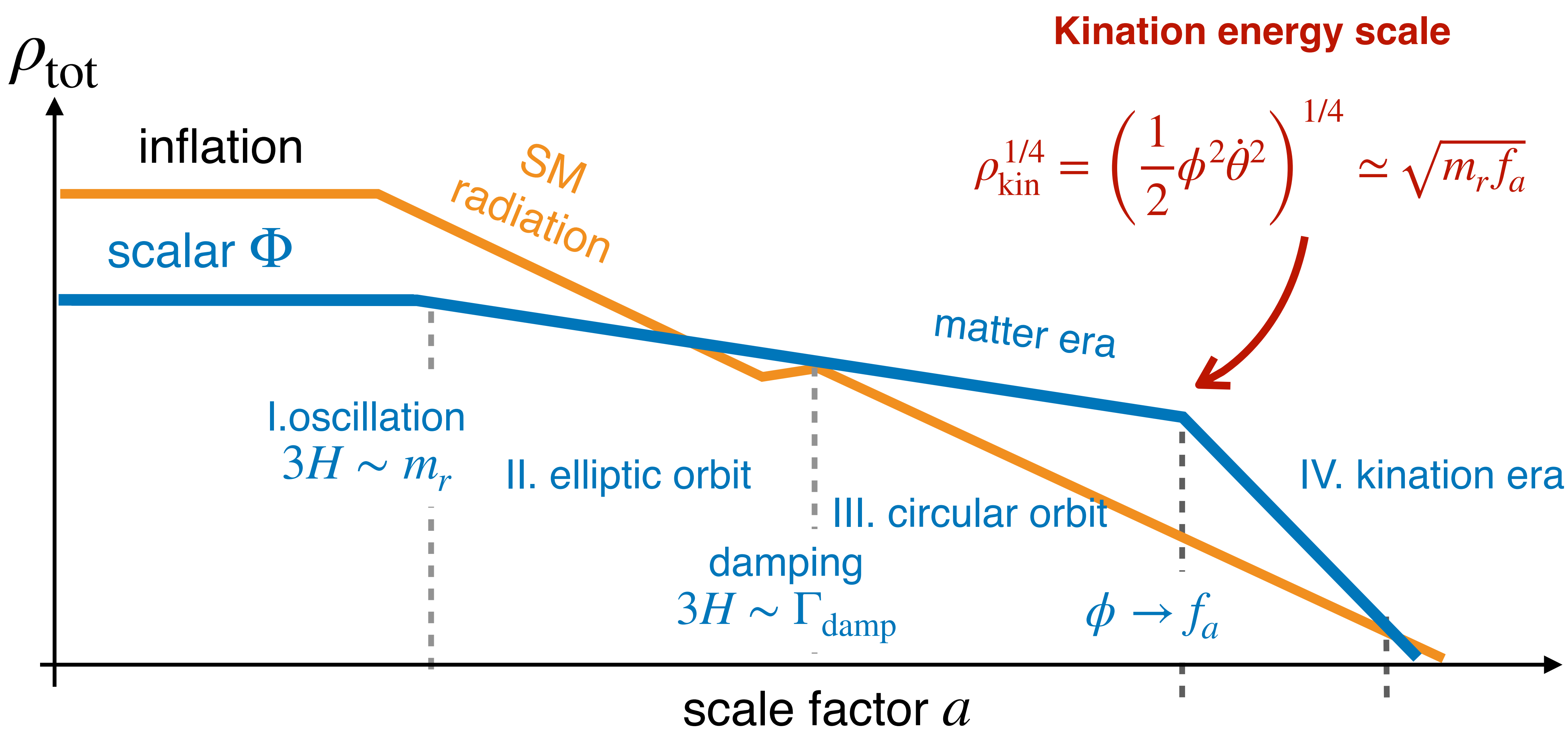

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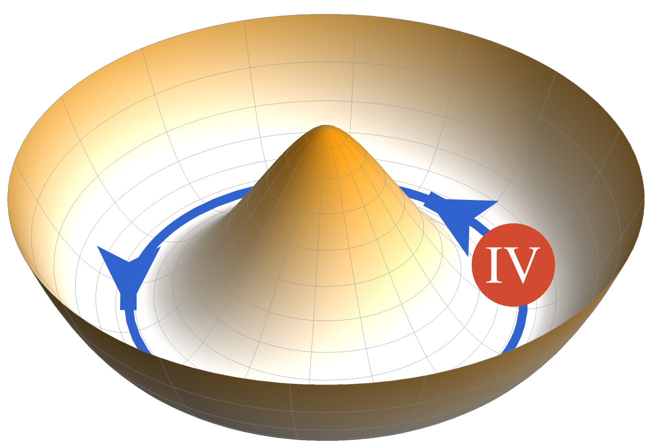

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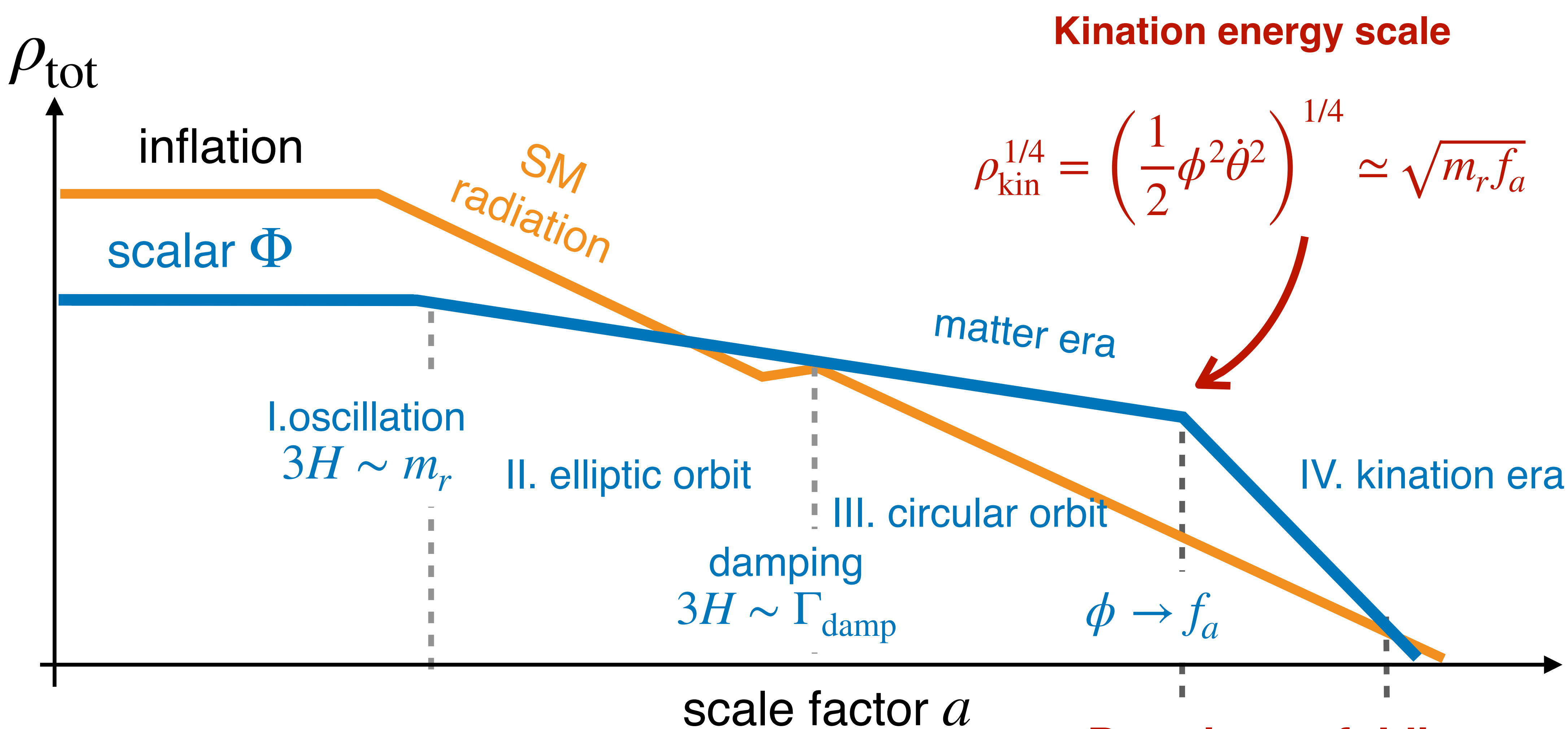
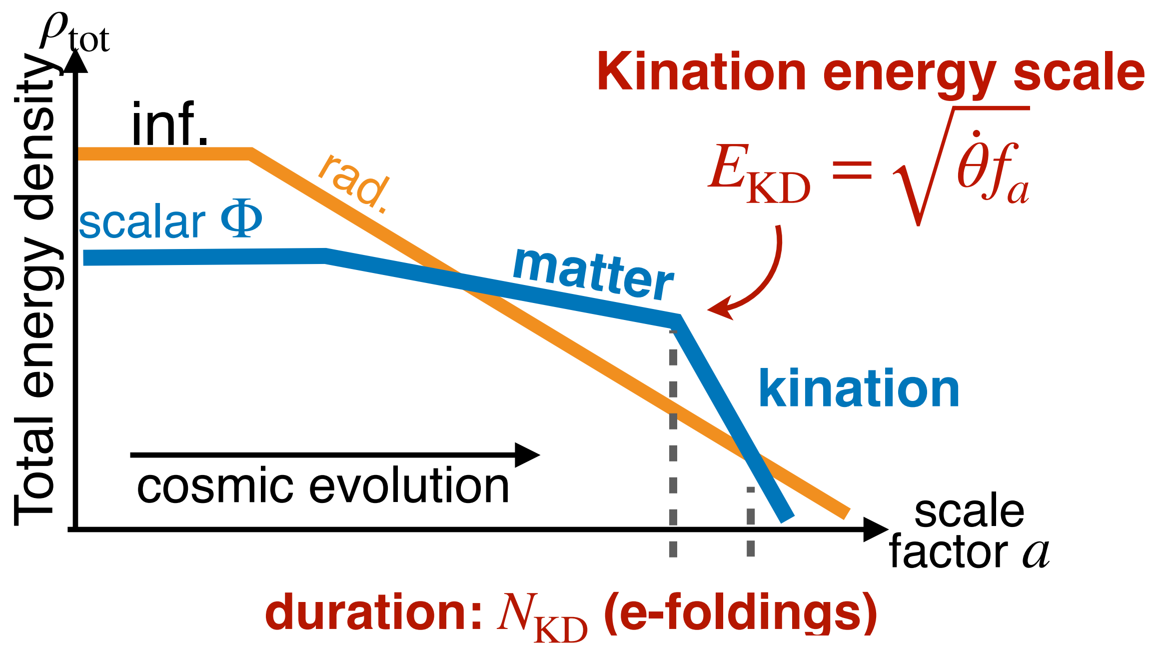


Duration: e-foldings

$$N_{\rm KD} = \frac{1}{6}\log\left(\frac{\rho_{\rm damp}}{\rho_{\rm kin}}\right)$$

GW signature: a "Peak"



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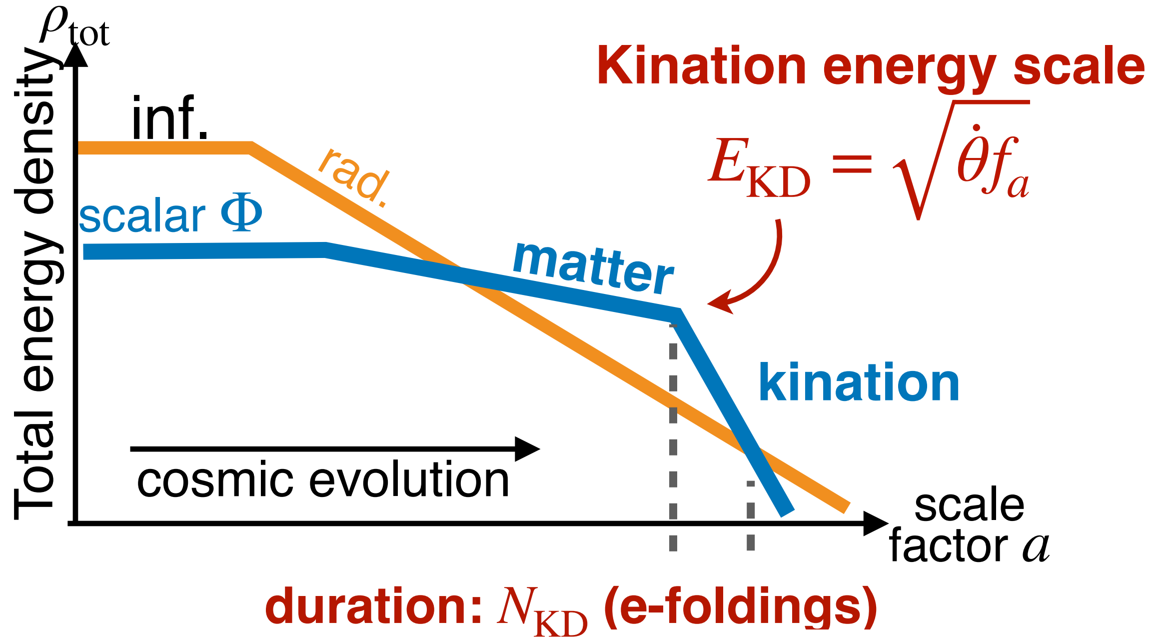

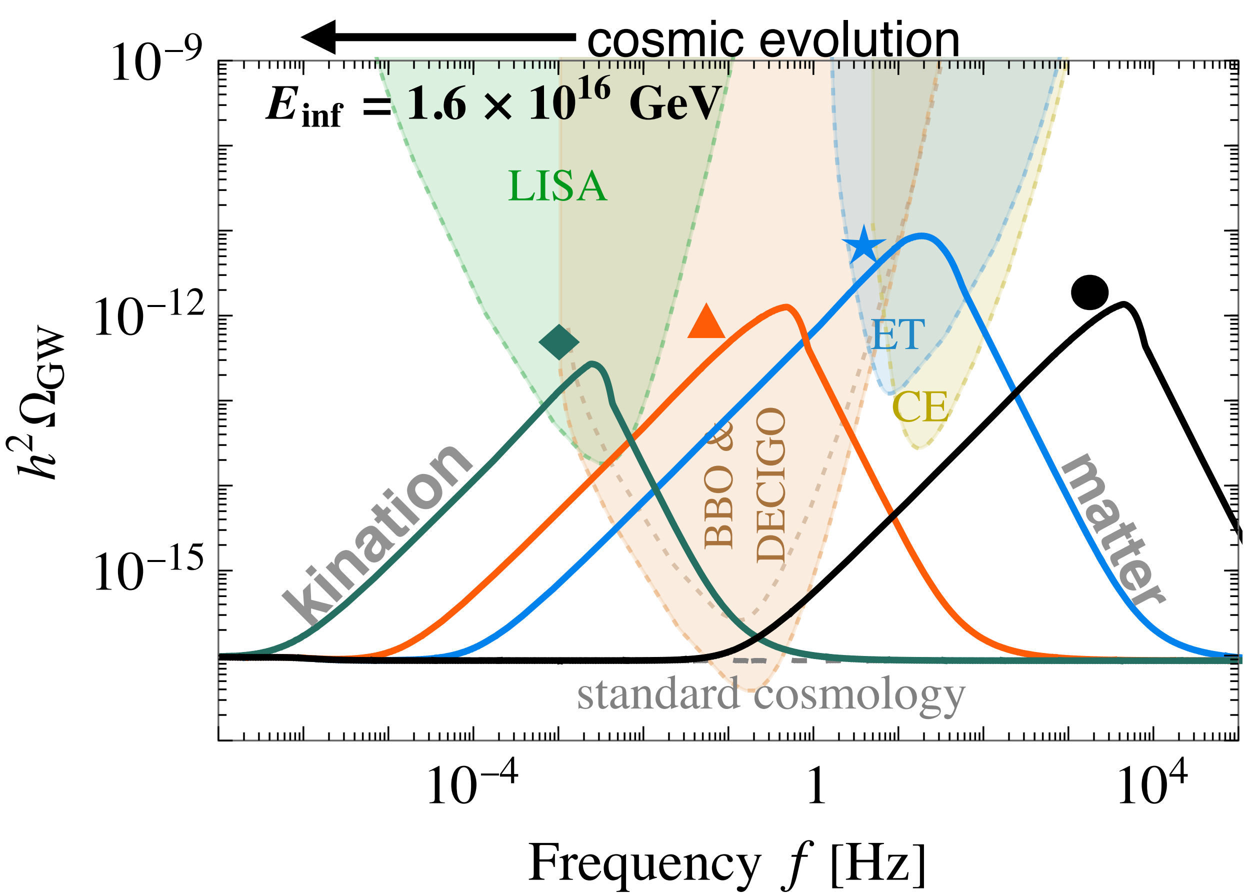

[YG, Servant, Simakachorn 2108.10328 & 2111.01150]

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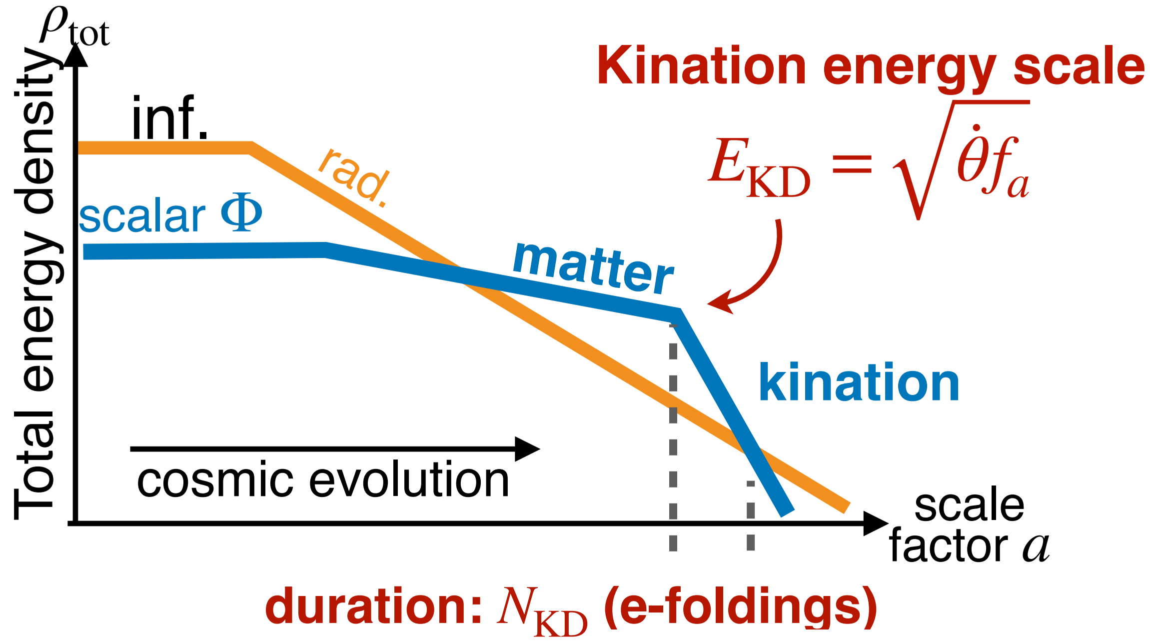
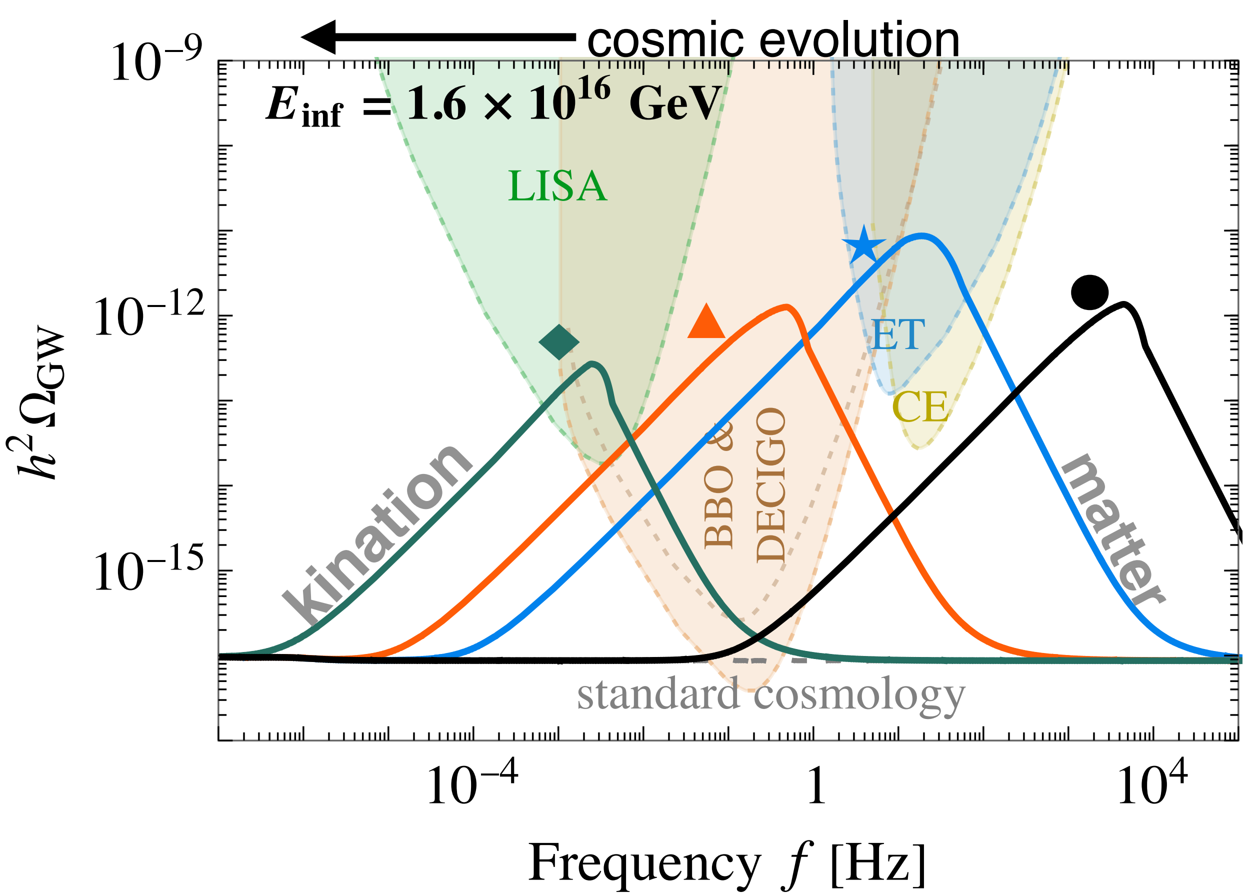


Peak position for GW from inflation.

$$f_{\rm peak} \approx 10\ \text{Hz} \left(\frac{E_{\rm KD}}{10^8\ \text{GeV}}\right) \left[\frac{\exp(N_{\rm KD}/2)}{10}\right]$$

$$\Omega_{\rm peak} h^2 \approx 10^{-12} \left(\frac{E_{\rm inf}}{1.6 \times 10^{16}\ \text{GeV}}\right)^4 \left[\frac{\exp(2N_{\rm KD})}{10^4}\right]$$



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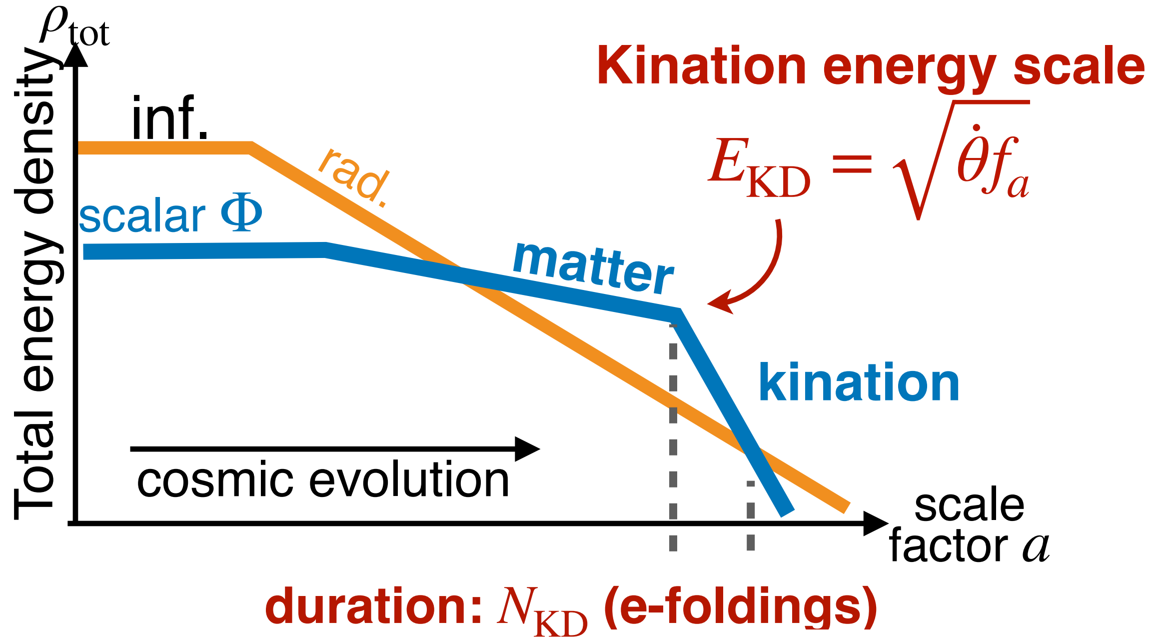

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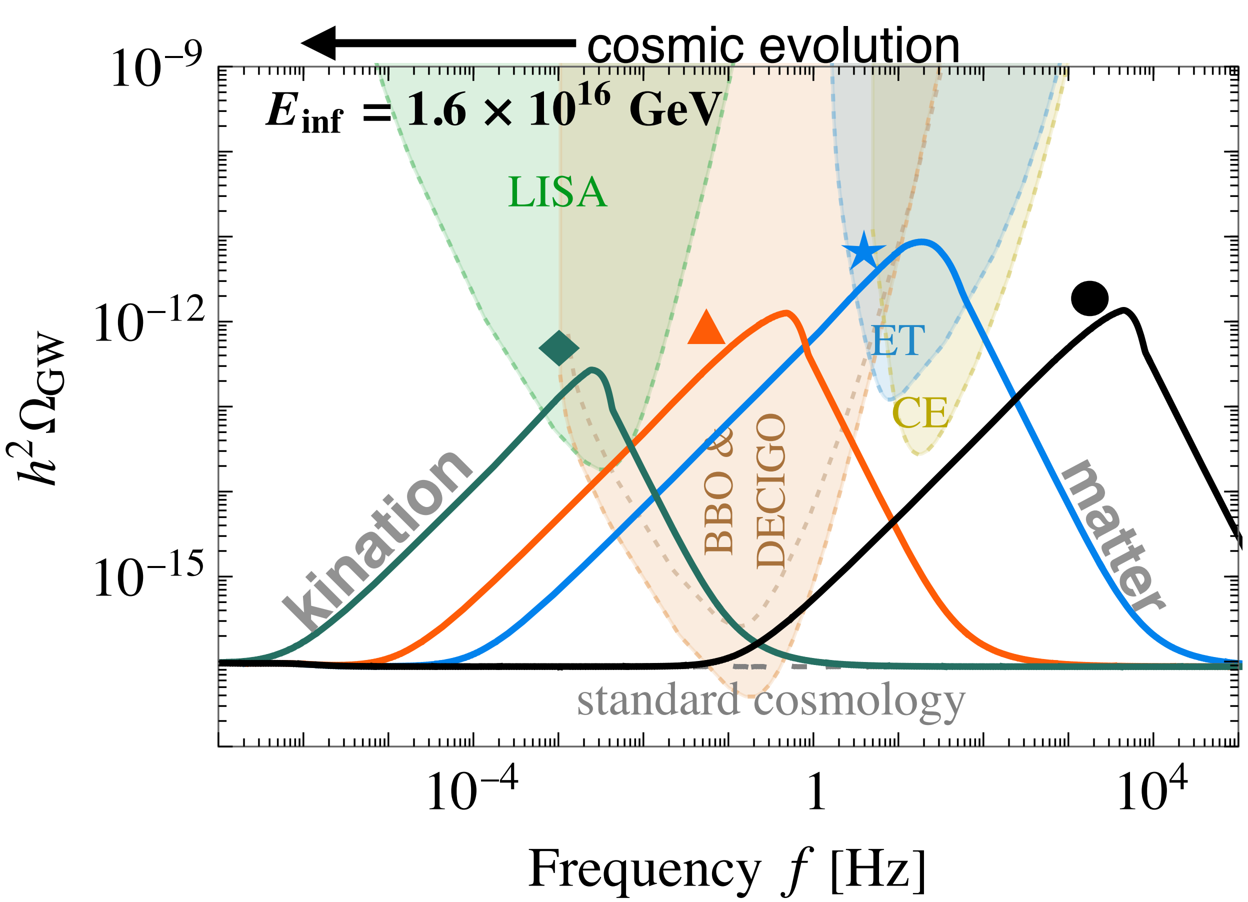
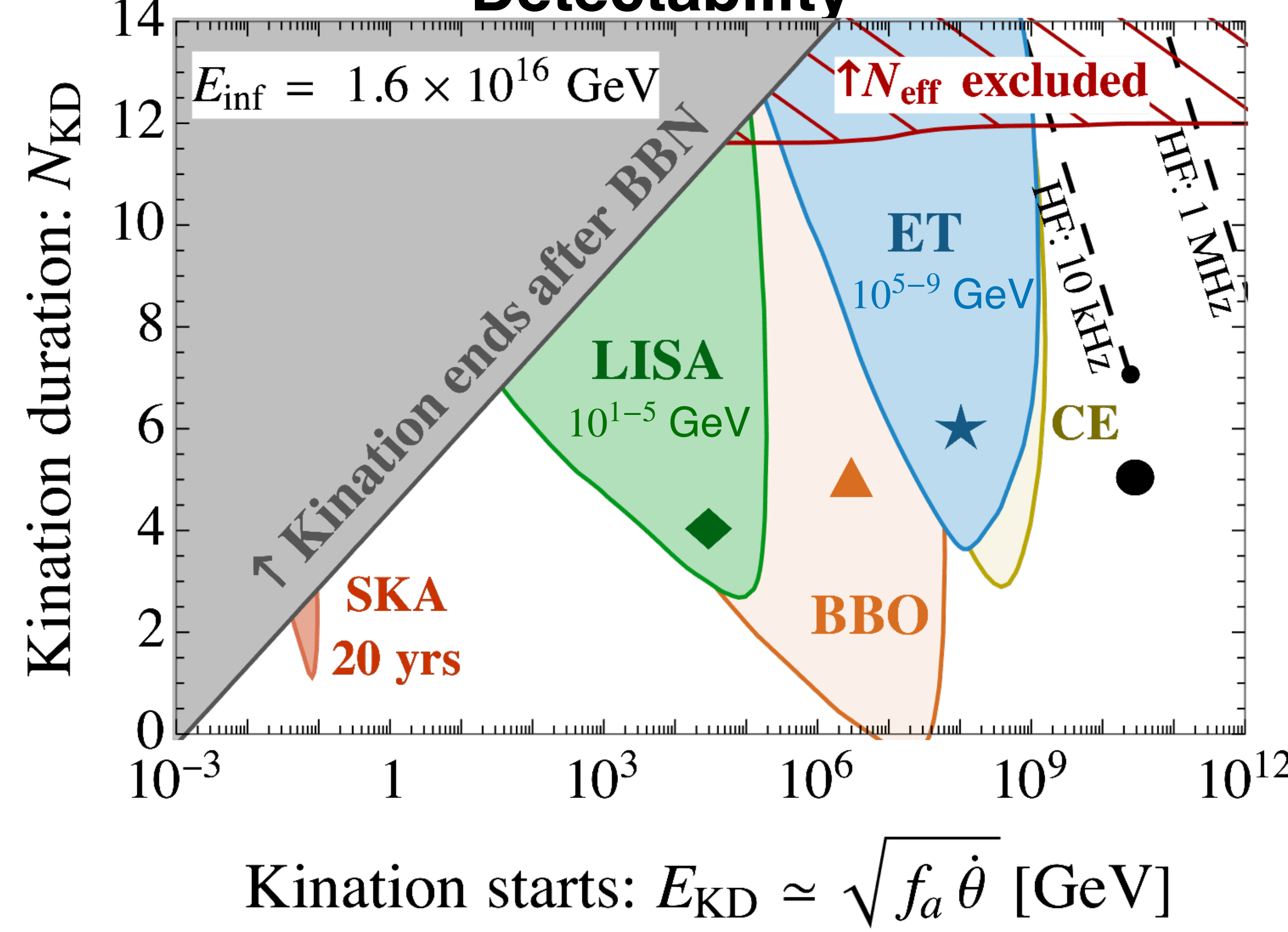


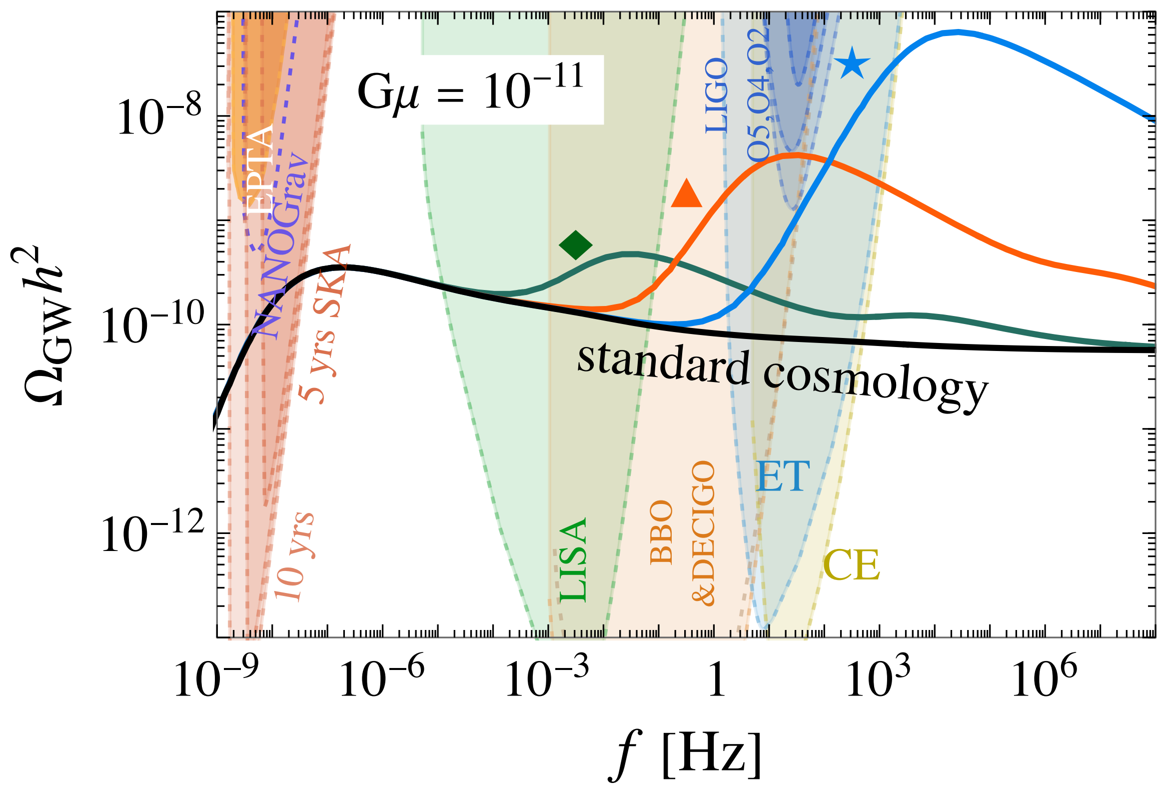
Detectability

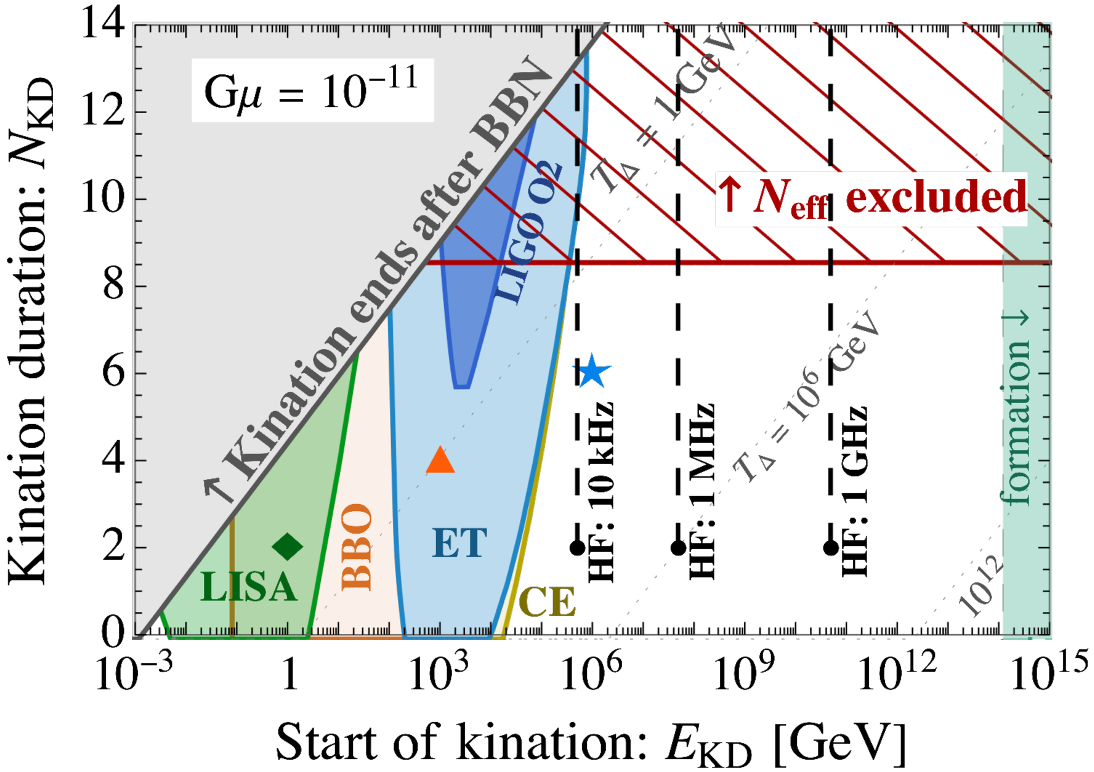


[YG, Servant, Simakachorn 2108.10328 & 2111.01150]

Local cosmic strings symmetry breaking scale $\simeq M_{\rm pl}\sqrt{G\mu}$

YG, Servant, Simakachorn, 2111.01150





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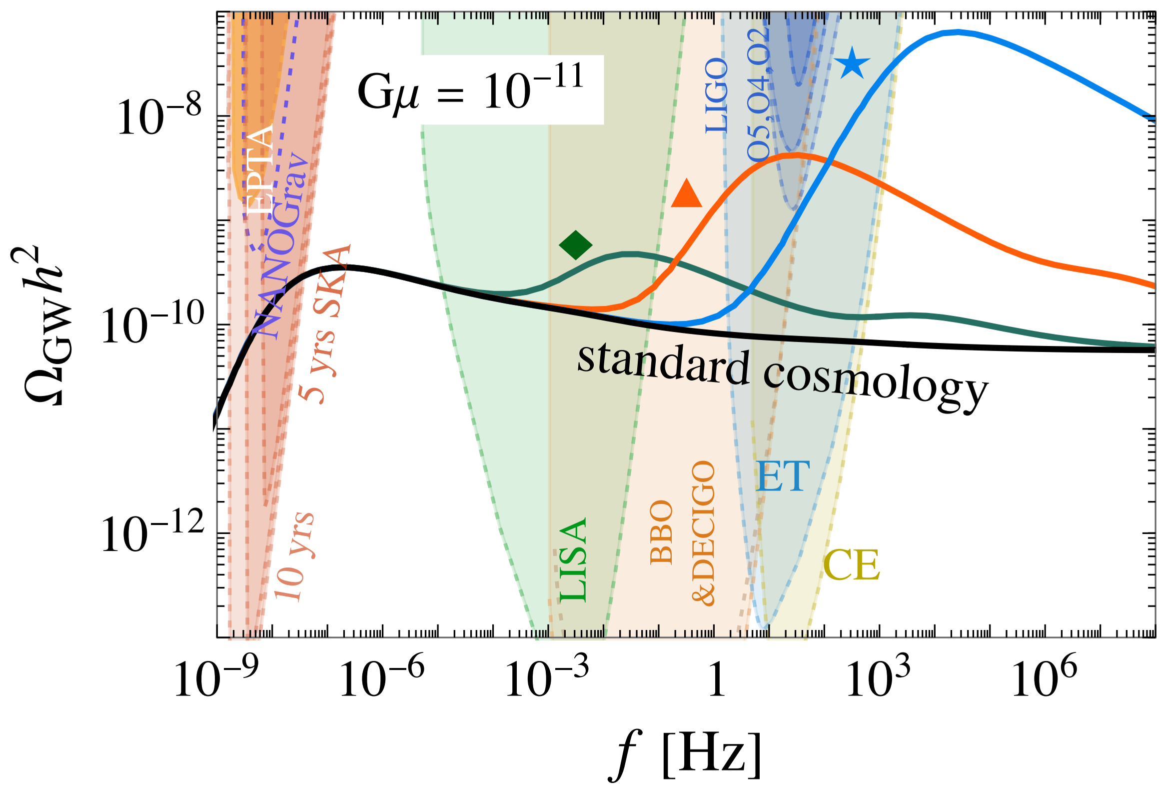
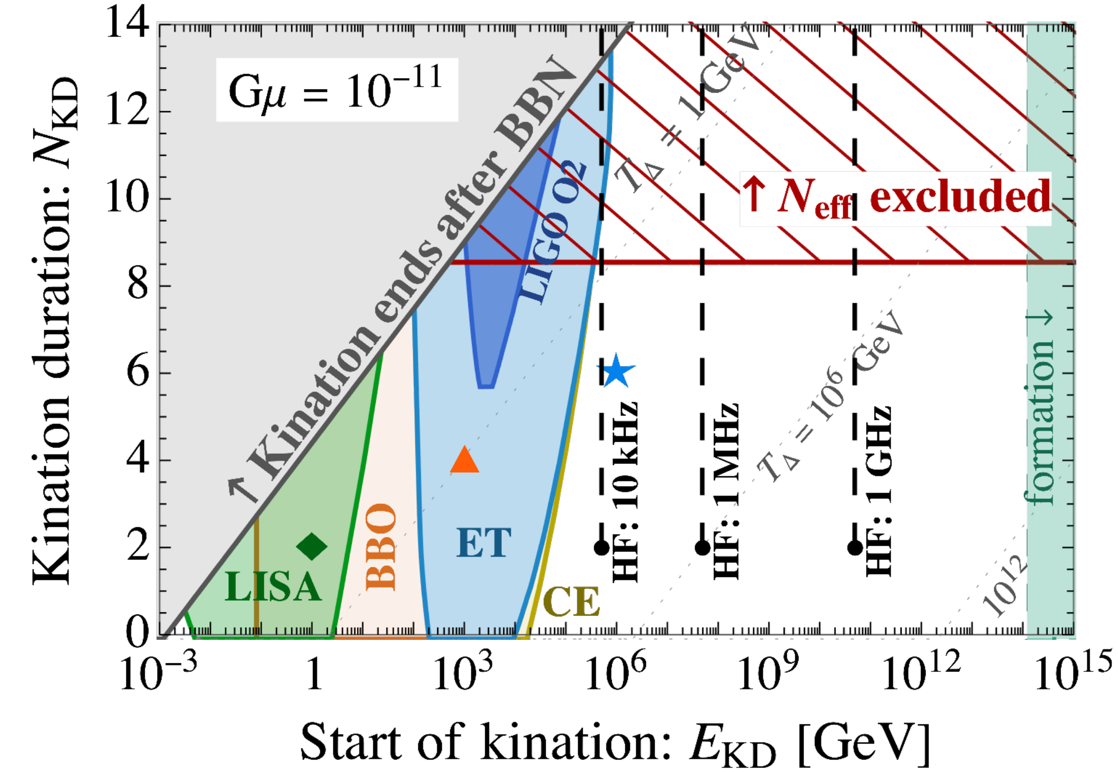
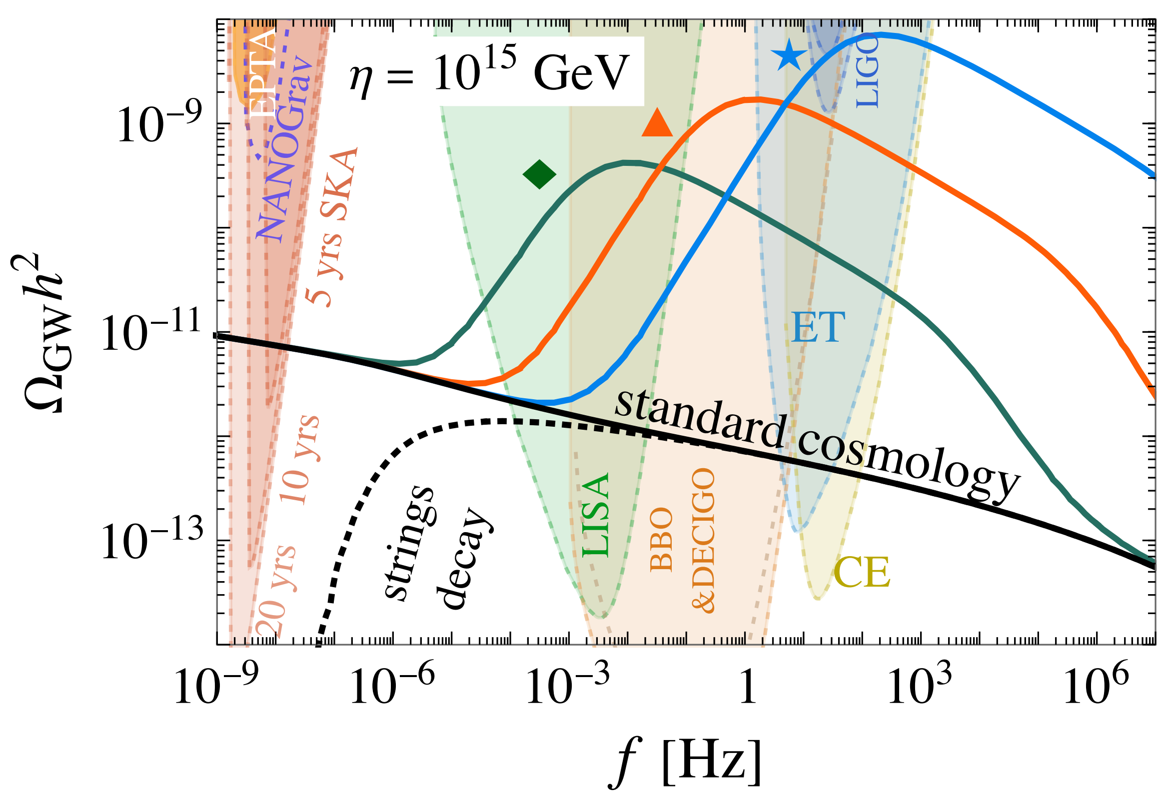
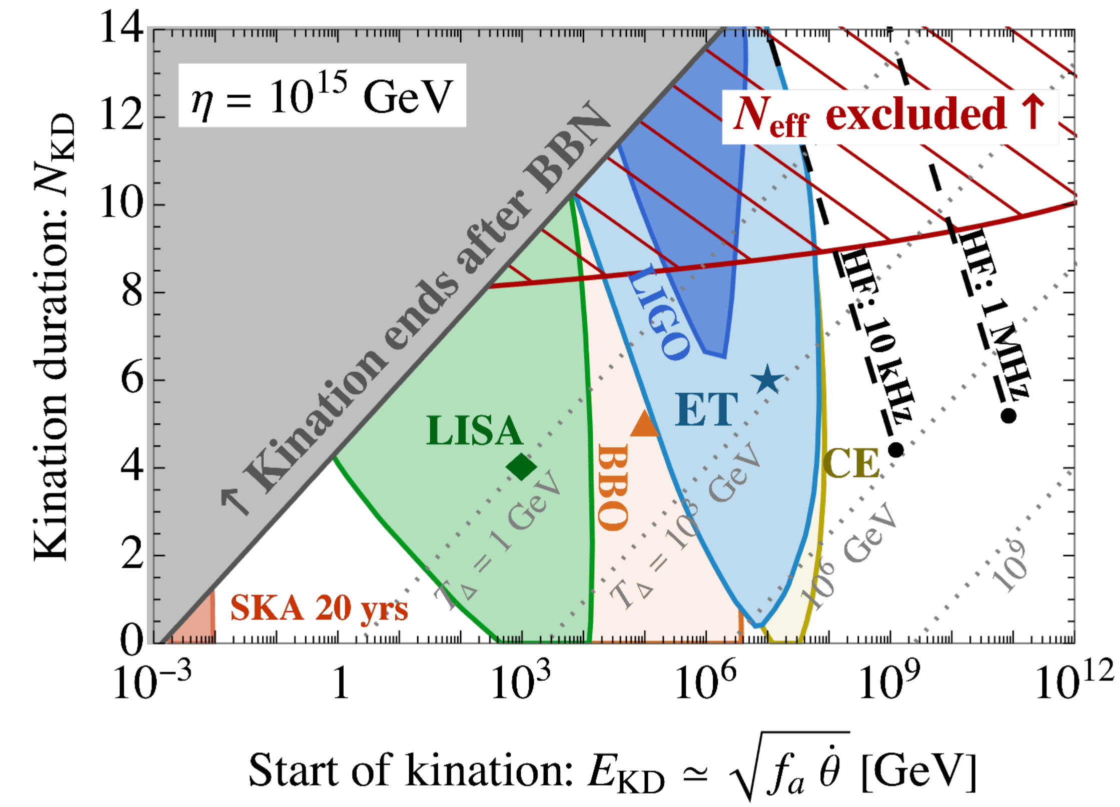
YG, Servant, Simakachorn, 2111.01150





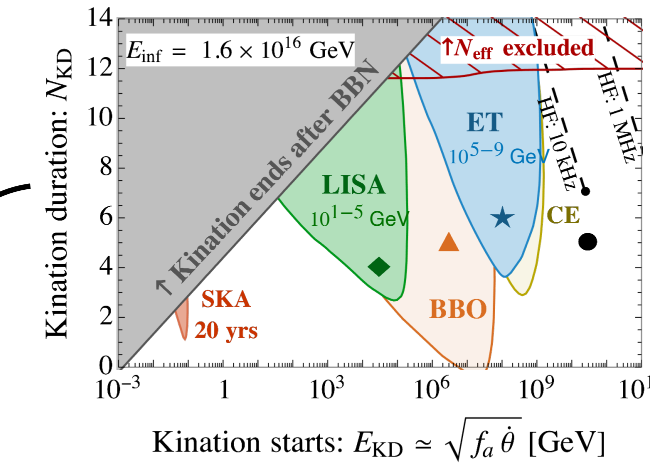
Global cosmic strings symmetry breaking scale $\simeq \eta$

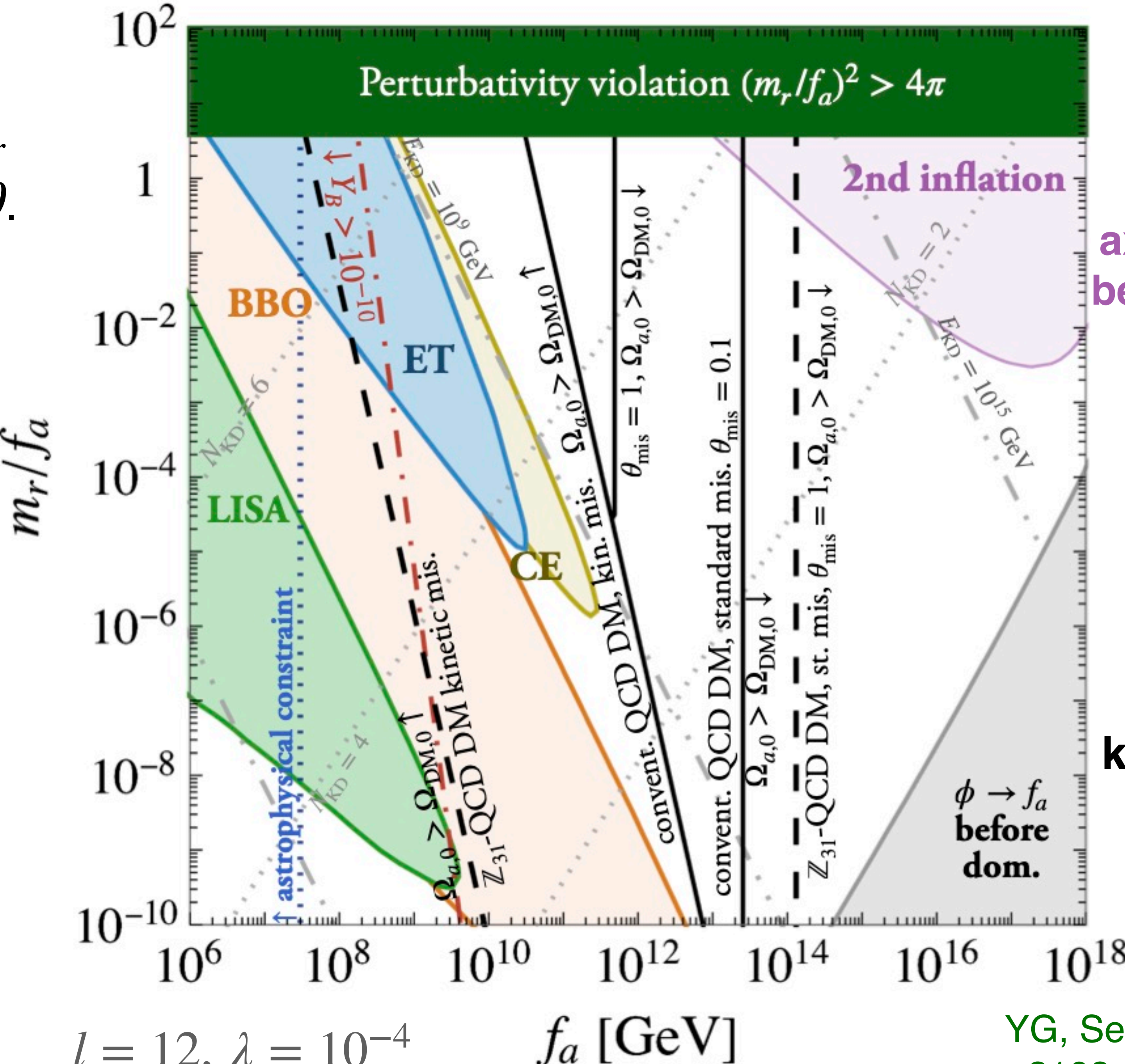




In terms of model parameters

Radial mode mass m_r controls axion speed $\dot{\theta}$.





axion dominates before oscillation

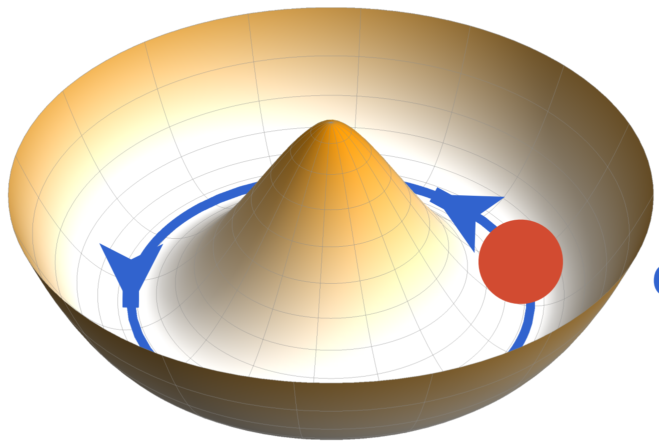
no kination

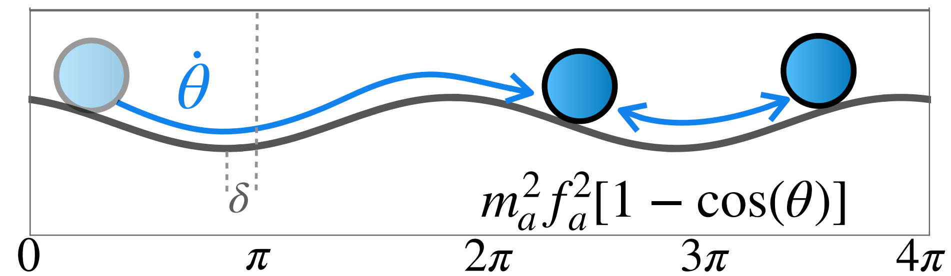
$l = 12,\ \lambda = 10^{-4}$

$m_r = \sqrt{V''}$

YG, Servant, Simakachorn, 2108.10328, 2111.01150

Axion Dark Matter





Kinetic energy red-shifts $\dot{\theta}^2 f_a^2 \propto a^{-6}$ until $\dot{\theta}^2 f_a^2 \simeq m_a^2 f_a^2$.

PQ charge in the spinning axion transfers to the axion number density via kinetic misalignment & axion fragmentation

[Co, Harigaya, Hall, '19]
[Chang, Cui, '19]
[Fonseca, Morgante, Sato, Servant, '19]
[Morgante, Ratzinger, Sato, Stefanek, '21]

$$\left.\frac{n_a}{s}\right|_0 \simeq \left.\frac{n_\theta}{s}\right|_{\rm KD} \equiv \frac{f_a^2 \dot{\theta}_{\rm KD}}{s_{\rm KD}}$$

QCD Axion Dark Matter

via kinetic misalignment & axion fragmentation $\left.\frac{n_a}{s}\right|_0 \simeq \left.\frac{n_\theta}{s}\right|_{\rm KD} \equiv \frac{f_a^2\dot\theta}{s_{\rm KD}}$

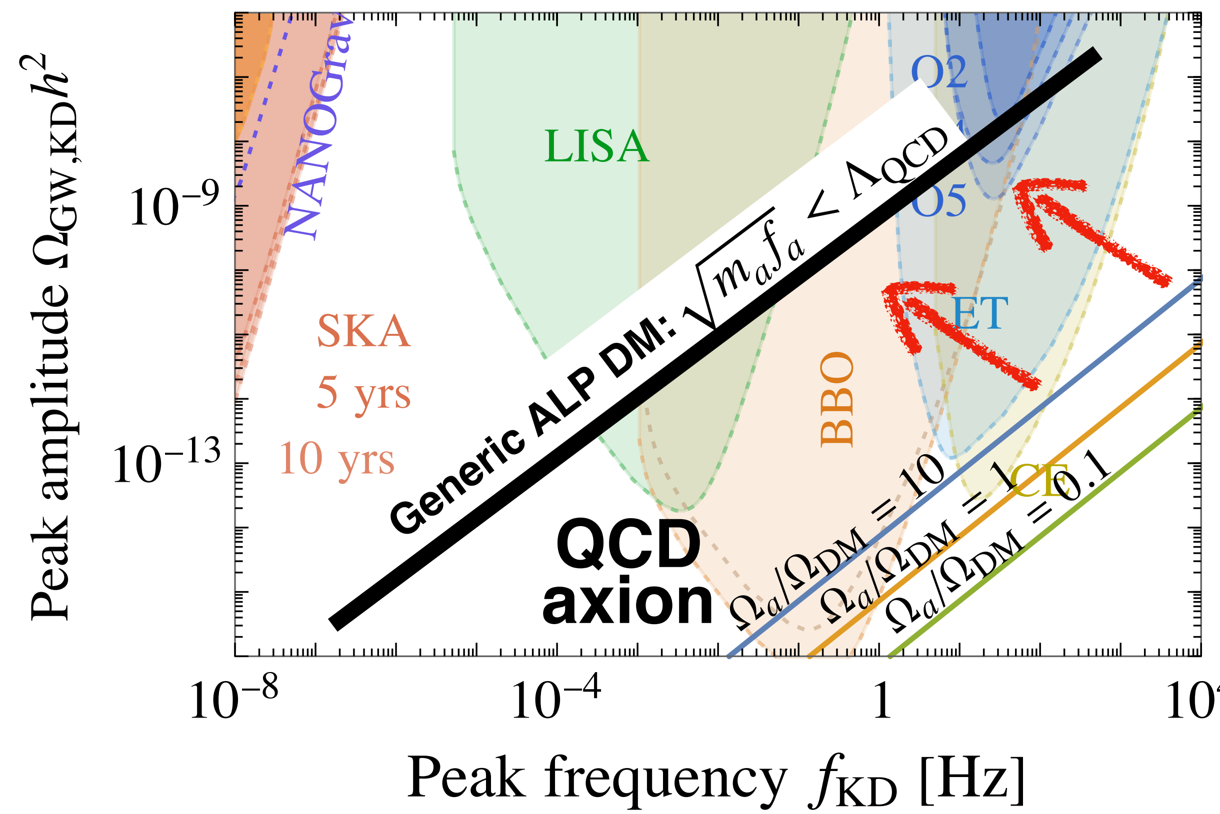
[Co, Harigaya, Hall, '19] [Fonseca, Morgante, Sato, Servant, '19]
[Chang, Cui, '19] [Morgante, Ratzinger, Sato, Stefanek, '21]

GW peak & Axion abundance

$$f_{\rm peak} \approx 10\ {\rm kHz}\left(\frac{\sqrt{m_a f_a}}{100\ {\rm MeV}}\right)^2\left(\frac{E_{\rm KD}}{10^9\ {\rm GeV}}\right)^{4/3}\left(\frac{\Omega_{a,0}}{\Omega_{\rm DM,0}}\right)^{1/3}$$

$$\Omega_{\rm peak}h^2 \approx 10^{-15}\left(\frac{f_{\rm KD}}{\rm Hz}\right)\left(\frac{E_{\rm inf}}{10^{16}\ {\rm GeV}}\right)^4\left(\frac{100\ {\rm MeV}}{\sqrt{m_a f_a}}\right)^2\left(\frac{\Omega_{a,0}}{\Omega_{\rm DM,0}}\right)$$

[YG, Servant, Simakachorn, 2111.01150]



The conventional QCD axion DM has no observable peak,
except BBO or HF experiments.

Observable signals for generic ALP DM and
QCD axion DM with lighter mass, e.g., from the $\mathbb{Z}_N$-axion.

[Hook, '18] & [Di Luzio, Gavela, Quilez, Ringwald, '21]

Conclusion

Cosmic archeology with GW from primordial inflation and cosmic strings

Early matter era

Heavy & unstable particles

$$1\ \mathrm{s} \gtrsim \tau_X \gtrsim 10^{-17} s$$

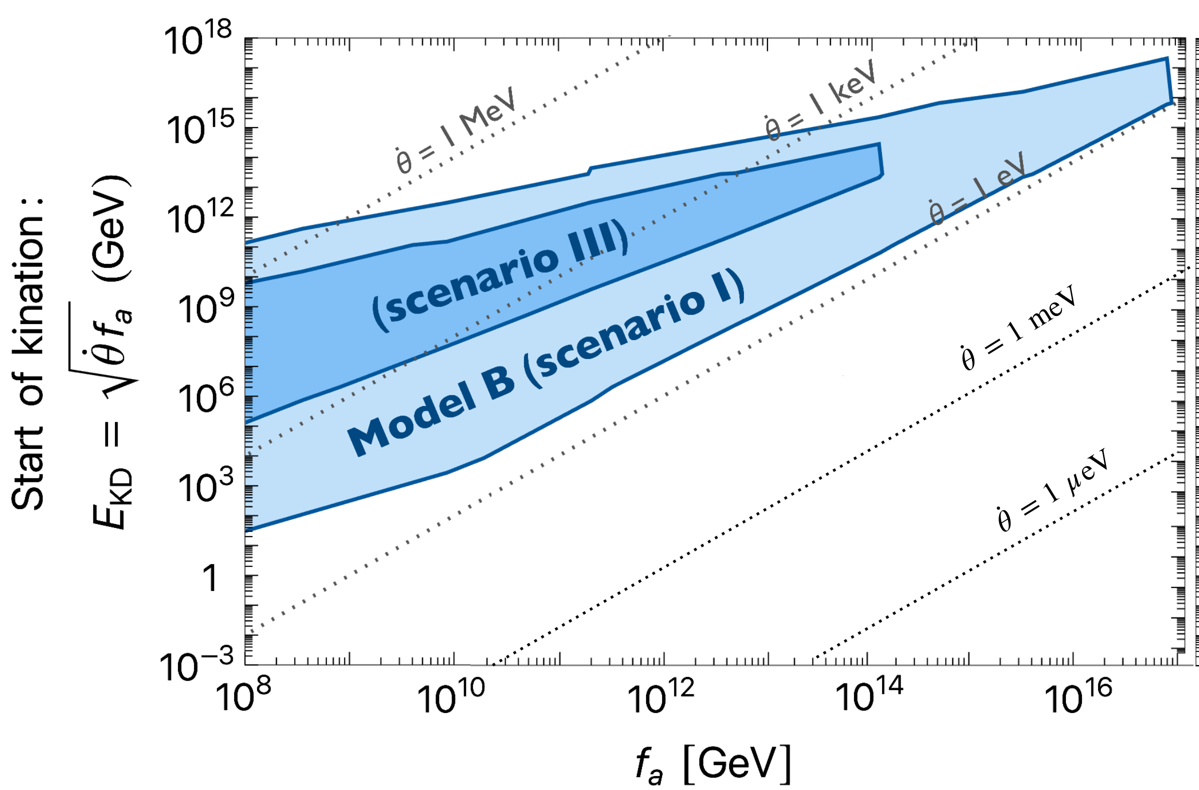
2nd inflation era

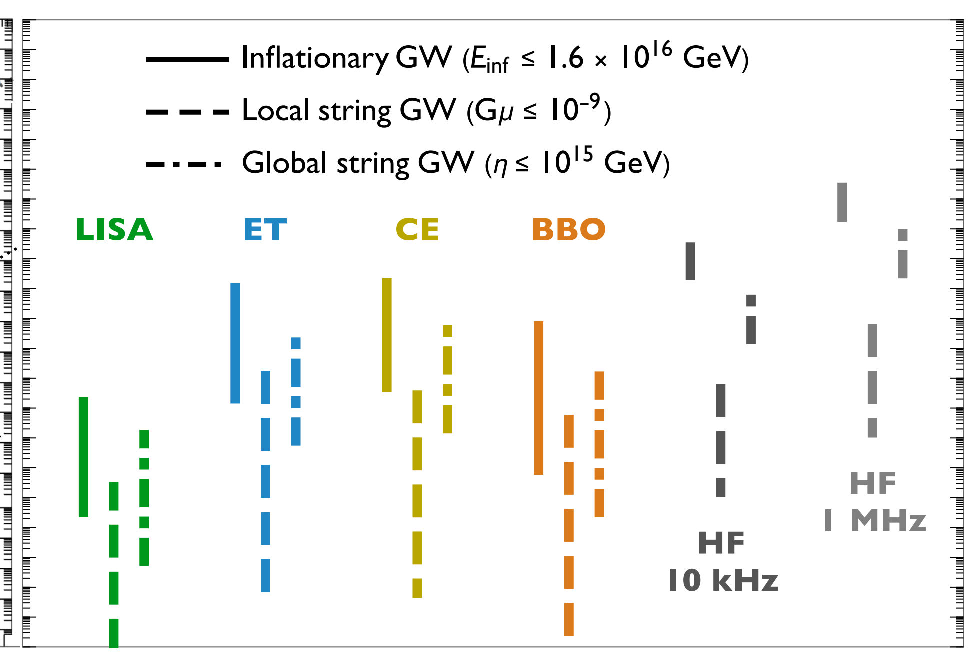
Supercool 1st-order phase transition

$$10^{-2}\ \mathrm{GeV} \lesssim E_{\mathrm{inf}} \lesssim 10^{13}\ \mathrm{GeV}$$

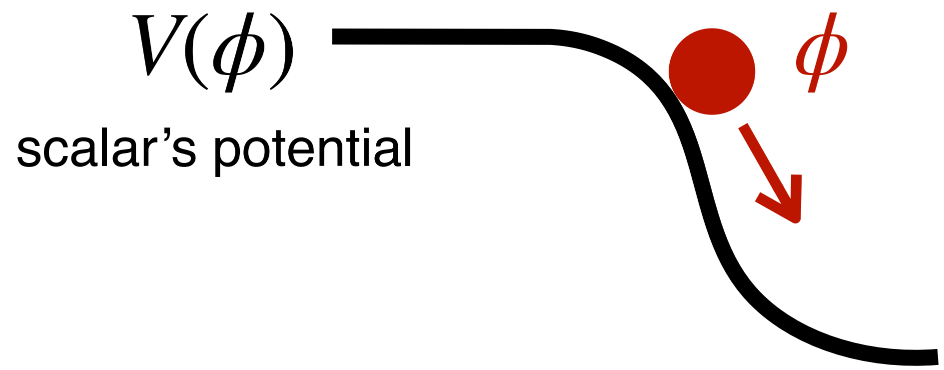
Intermediate kination era

Spinning axion





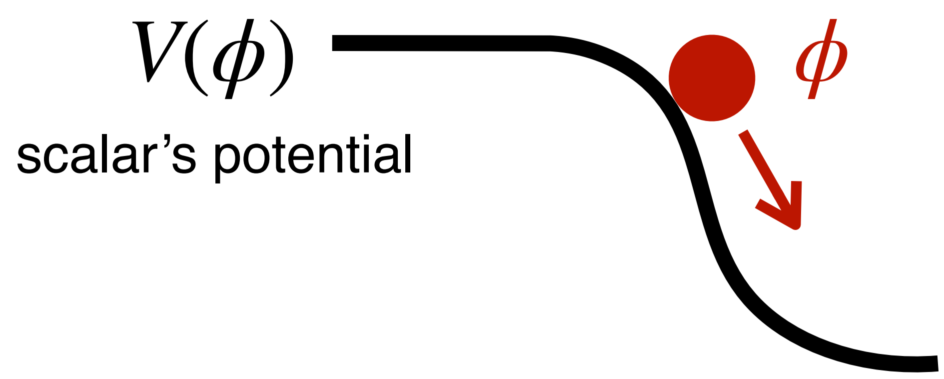
The simplest kination era



equation-of-state: $\omega_\phi = \dfrac{E_{\text{kinetic}} - E_{\text{potential}}}{E_{\text{kinetic}} + E_{\text{potential}}}$

Maximum $\omega_\phi = 1$, when $E_{\text{kinetic}} \gg E_{\text{potential}}$

The simplest kination era



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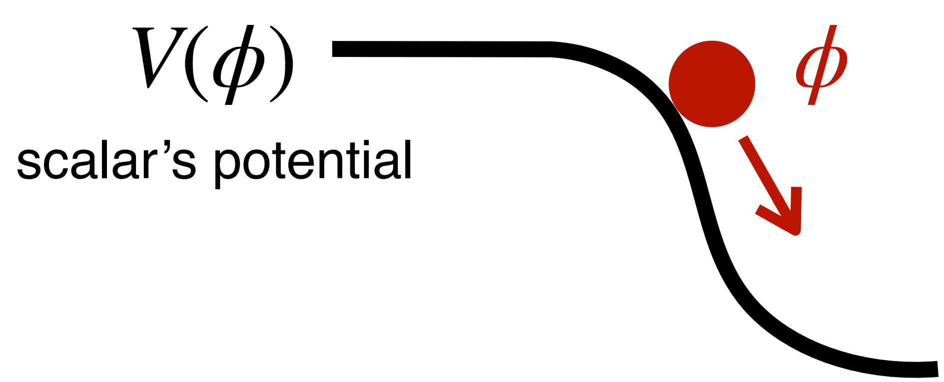
Maximum $\omega_\phi = 1$, when $E_{\text{kinetic}} \gg E_{\text{potential}}$

A scalar field dominates the universe with large kinetic energy,
"Kination" era. ($\rho_\phi \propto a^{-6}$)

[Spokoiny 1993, Joyce, 1997]

The simplest kination era



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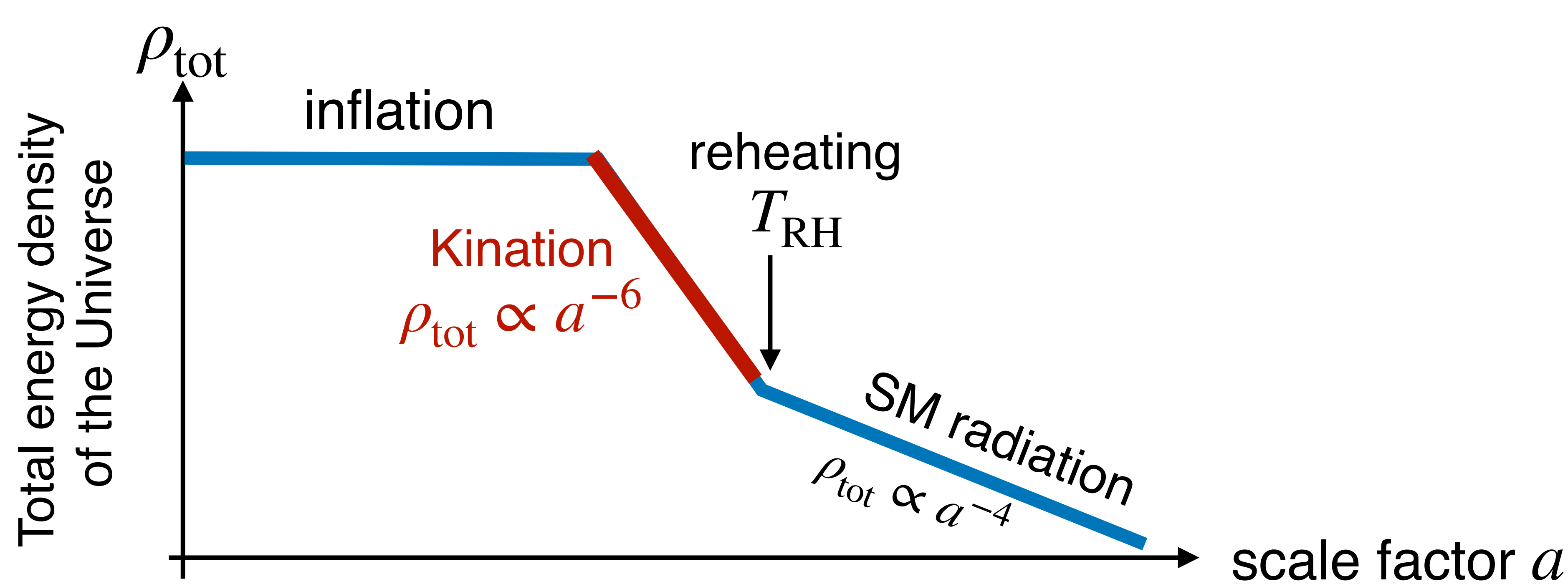
A scalar field dominates the universe with large kinetic energy,

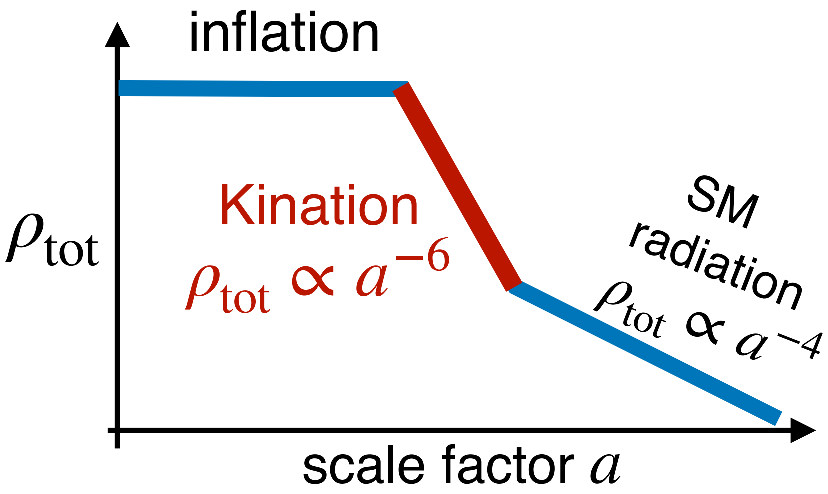
"Kination" era. ($\rho_\phi \propto a^{-6}$)

[Spokoiny 1993, Joyce, 1997]

Example: quintessential inflation

Peebles and Vilenkin 1998



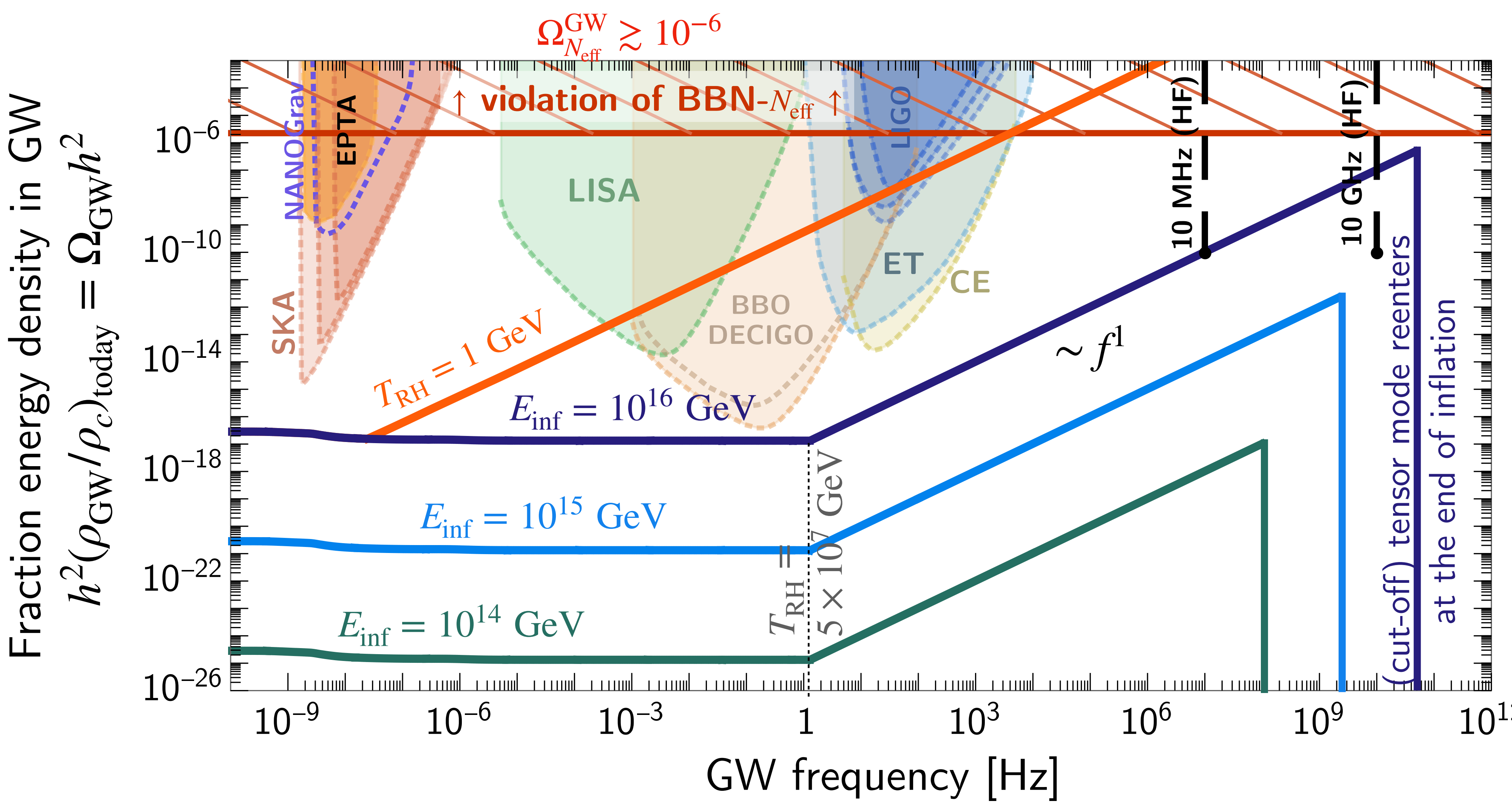


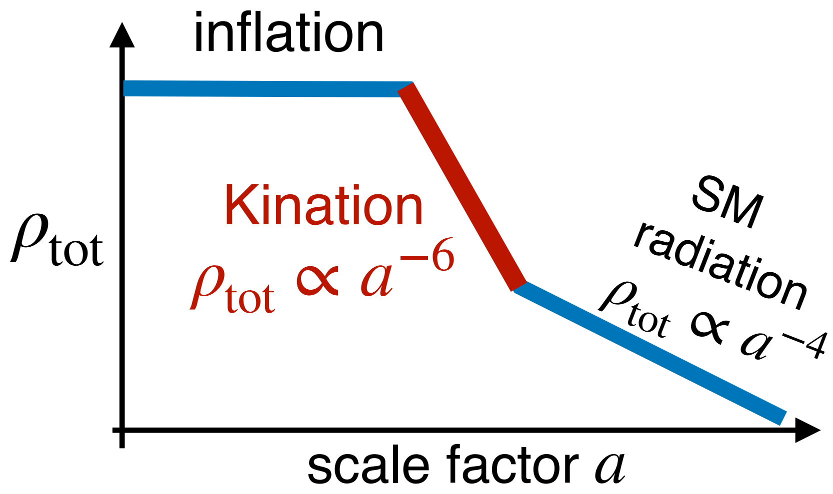
GW is an extra radiation.

Too much GW violate BBN/CMB bound:

$$\Delta N_{eff} \lesssim 0.2$$

A long kination after inflation cannot have observable signal.





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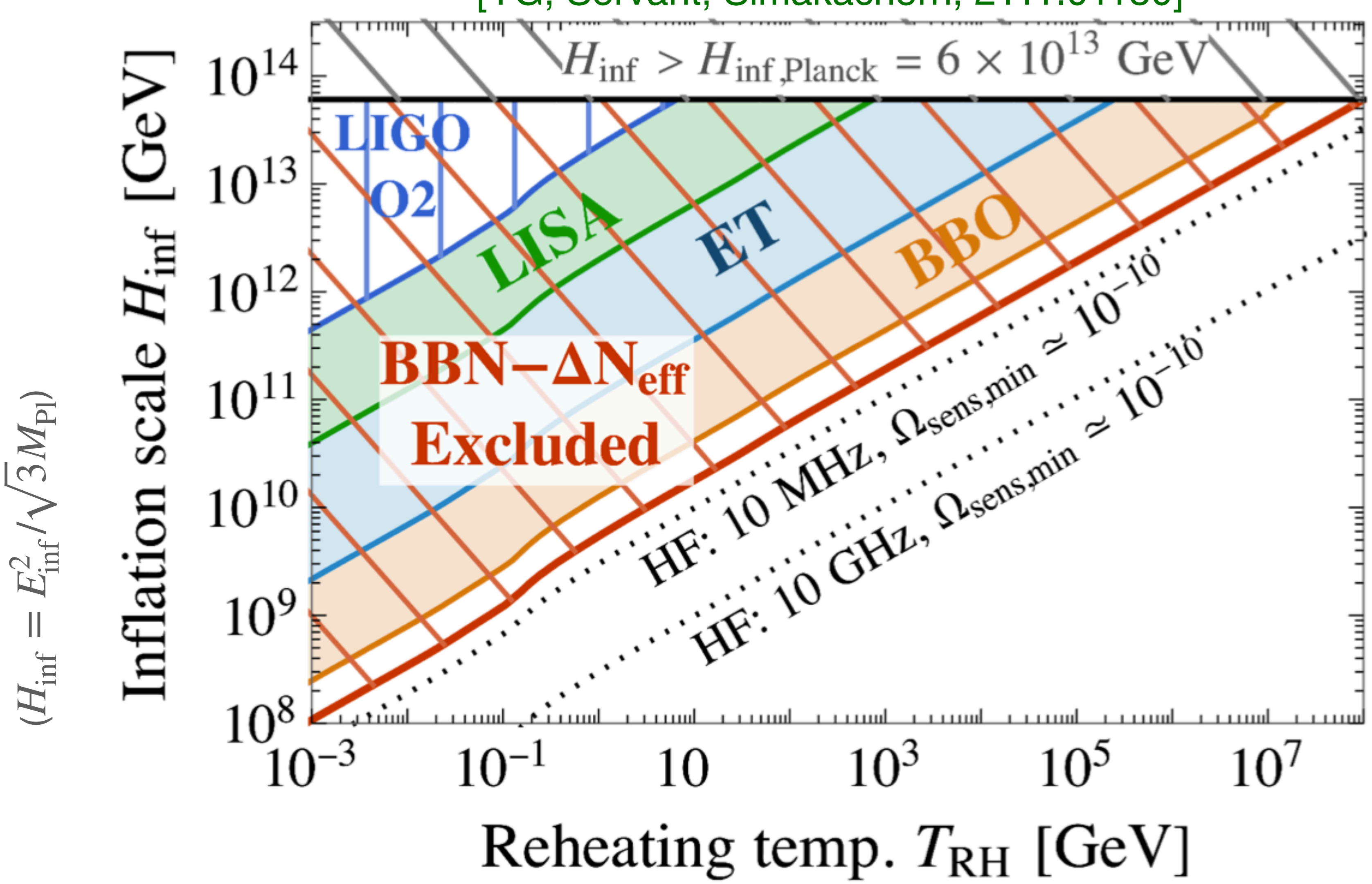
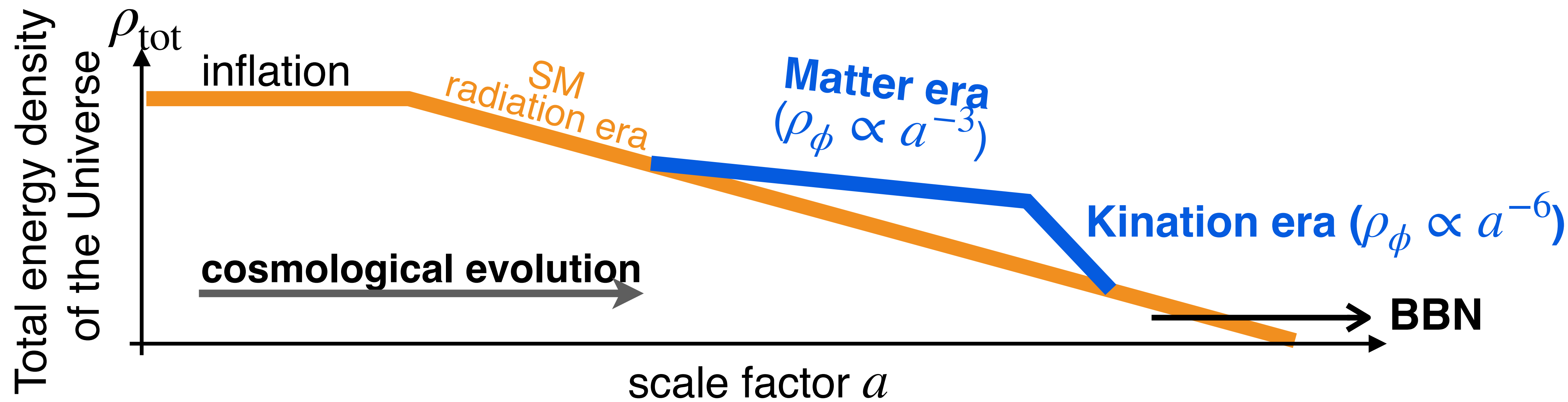
[YG, Servant, Simakachorn, 2111.01150]



What if instead kination occurs long after inflation ?

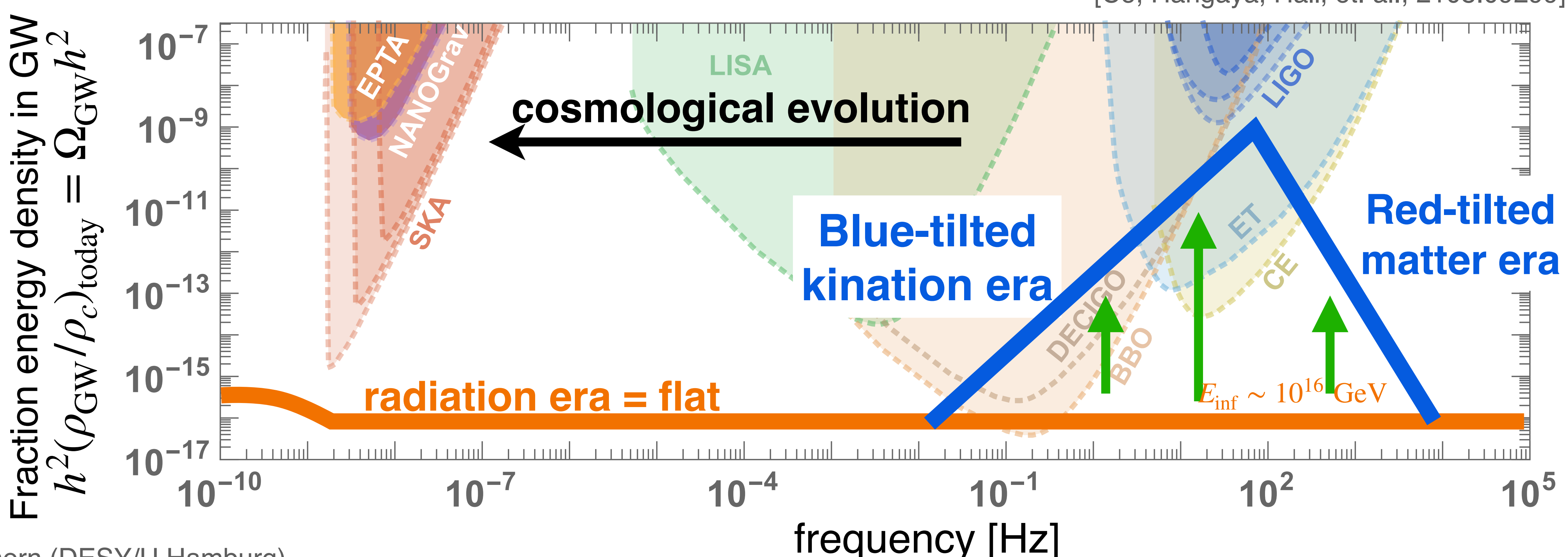


Spinning axion!

[YG, Servant, Simakachorn, 2108.10328 & 2111.01150]

[Co, Harigaya, Hall, et. al., 2108.09299]

Peaked GW signature

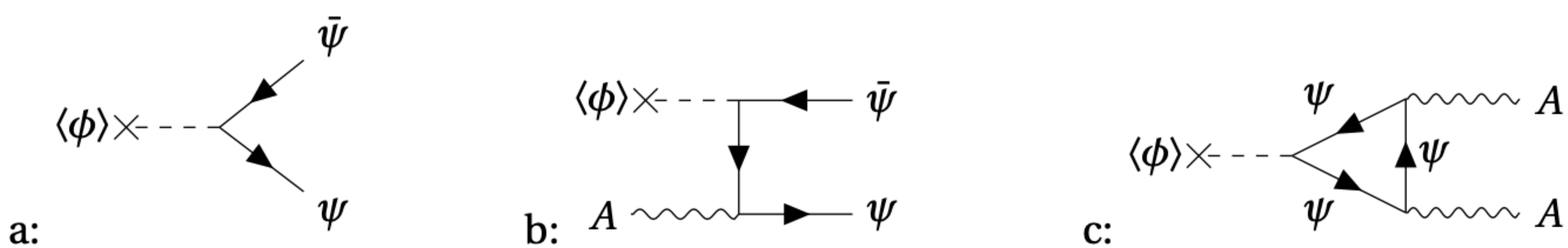


Number of e-folds of kination

$$\epsilon = \begin{cases} \frac{1}{\sqrt{2}} \frac{m_{r,\text{eff}}(f_a)}{m_{r,\text{eff}}(\phi_{\text{ini}})} \, l \sin l\theta_{\text{ini}}, & \text{if} \quad c > l-1, \\ \frac{1}{\sqrt{2}} \sqrt{\frac{c}{l-1}} \frac{m_{r,\text{eff}}(f_a)}{m_{r,\text{eff}}(\phi_{\text{ini}})} \, l \sin l\theta_{\text{ini}}, & \text{otherwise.} \end{cases}$$

$$\phi_{\text{ini}} = M_{\text{pl}} \left(\sqrt{c} \frac{m_{r,\text{eff}}(\phi_{\text{ini}})}{\lambda \sqrt{2l-2} M_{\text{pl}}} \right)^{\frac{1}{l-2}}.$$

$$\Gamma_\phi \simeq \begin{cases} \text{for } y_\psi \phi < T: \begin{cases} \text{for } m_{\psi,\text{th}} = g\,T > m_\phi/2, & \frac{y_\psi^2 \alpha T}{2\pi^2}, \\ \text{for } m_{\psi,\text{th}} = g\,T < m_\phi/2, & \frac{y_\psi^2 m_\phi}{8\pi}, \end{cases} \\ \text{for } y_\psi \phi > T: \quad b\alpha^2 \frac{\text{Max}[T,\, m_\phi]^3}{\phi^2} + \frac{y_\psi^2 m_\phi}{8\pi} \Theta(2m_\phi - y_\psi \phi). \end{cases} \tag{F.5}$$



$$e^{N_{\text{KD}}} = \left(\frac{\min(\rho_{\text{dom}}, \rho_{\text{damp}})}{\rho_{\text{KD},i}} \right)^{1/6} = \begin{cases} \sqrt{\frac{3}{2}} \left(\frac{m_{r,\text{eff}}(\phi_{\text{ini}})}{m_{r,\text{eff}}(f_a)} \frac{M_{\text{pl}}}{f_a} \right)^{1/3} \left(\frac{\phi_{\text{ini}}}{M_{\text{pl}}} \right)^{4/3} \epsilon^{2/3}, & \text{if } \rho_{\text{damp}} > \rho_{\text{dom}}, \\ \left(\frac{6 M_{\text{pl}}^2 \Gamma_{\text{damp}}^2}{f_a^2 m_{r,\text{eff}}^2(f_a)} \right)^{1/6} \epsilon^{2/3}, & \text{if } \rho_{\text{damp}} < \rho_{\text{dom}}. \end{cases} \tag{8.28}$$

$$\rho_{\text{damp}} > \rho_{\text{dom}} \quad \Longrightarrow \quad e^{N_{\text{KD}}} \simeq e^{8.2}\, \epsilon^{2/3} \left(\frac{10^9 \text{ GeV}}{f_a} \right)^{1/3} \left(\frac{m_{r,\text{eff}}(\phi_{\text{ini}})}{5 m_{r,\text{eff}}(f_a)} \right)^{1/3} \left(\frac{\phi_{\text{ini}}}{M_{\text{pl}}} \right)^{4/3},$$

Baryogenesis from a spinning axion

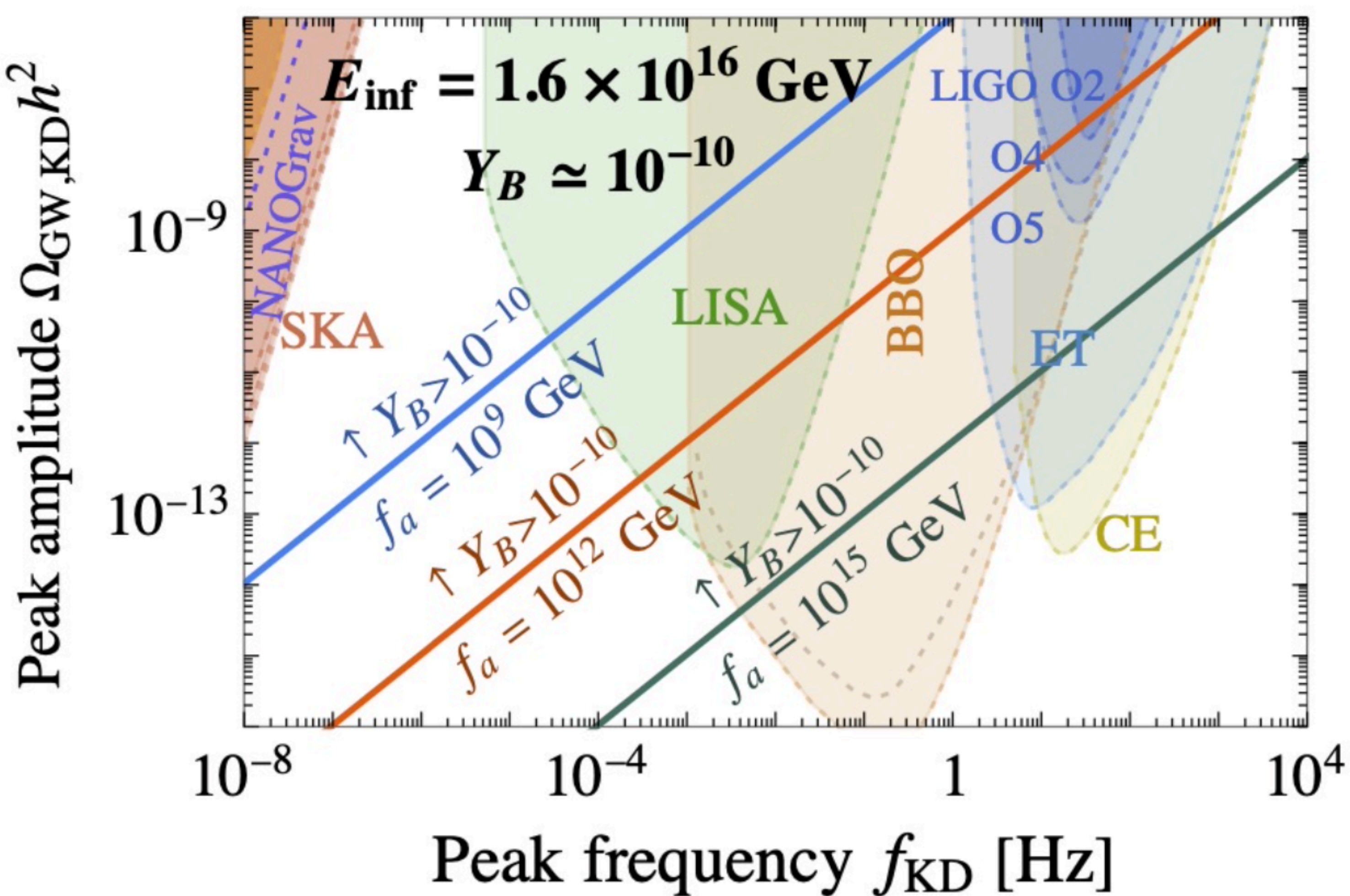
Standard "Axiogenesis" [Co, Harigaya, '19]

$U(1)_{\rm PQ}$-charge transfers to baryon number via $SU(3)_c$ and $SU(2)_L$ sphaleron.

$$Y_\theta = 692\left(\frac{0.1}{c_B}\right)\left(\frac{130\ \mathrm{GeV}}{T_{\rm ws}}\right)^2\left(\frac{f_a}{10^8\ \mathrm{GeV}}\right)^2\left(\frac{Y_B}{10^{-10}}\right).$$

$$E_{\rm KD} = (74\ \mathrm{TeV})\, G^{3/4}(T_{\rm KD})\left(\frac{c_B}{0.1}\right)\left(\frac{T_{\rm ws}}{130\ \mathrm{GeV}}\right)^2\left(\frac{10^8\ \mathrm{GeV}}{f_a}\right)\left(\frac{10^{-10}}{Y_B}\right)\exp\left(\frac{3N_{\rm KD}}{2}\right).$$

Gravitational waves from primordial inflation

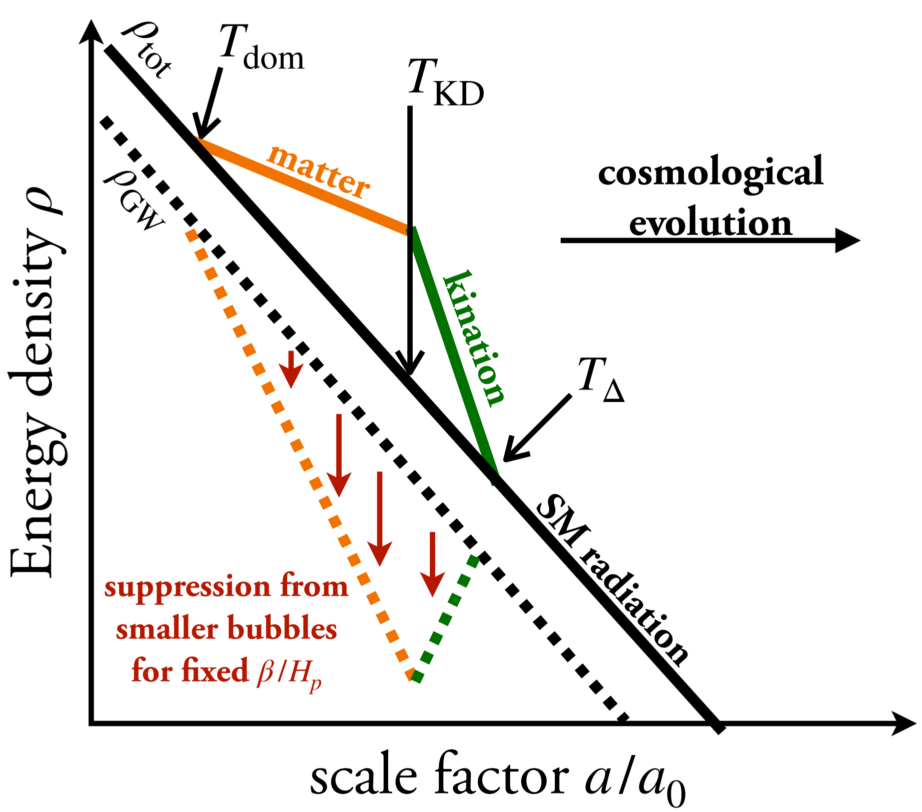


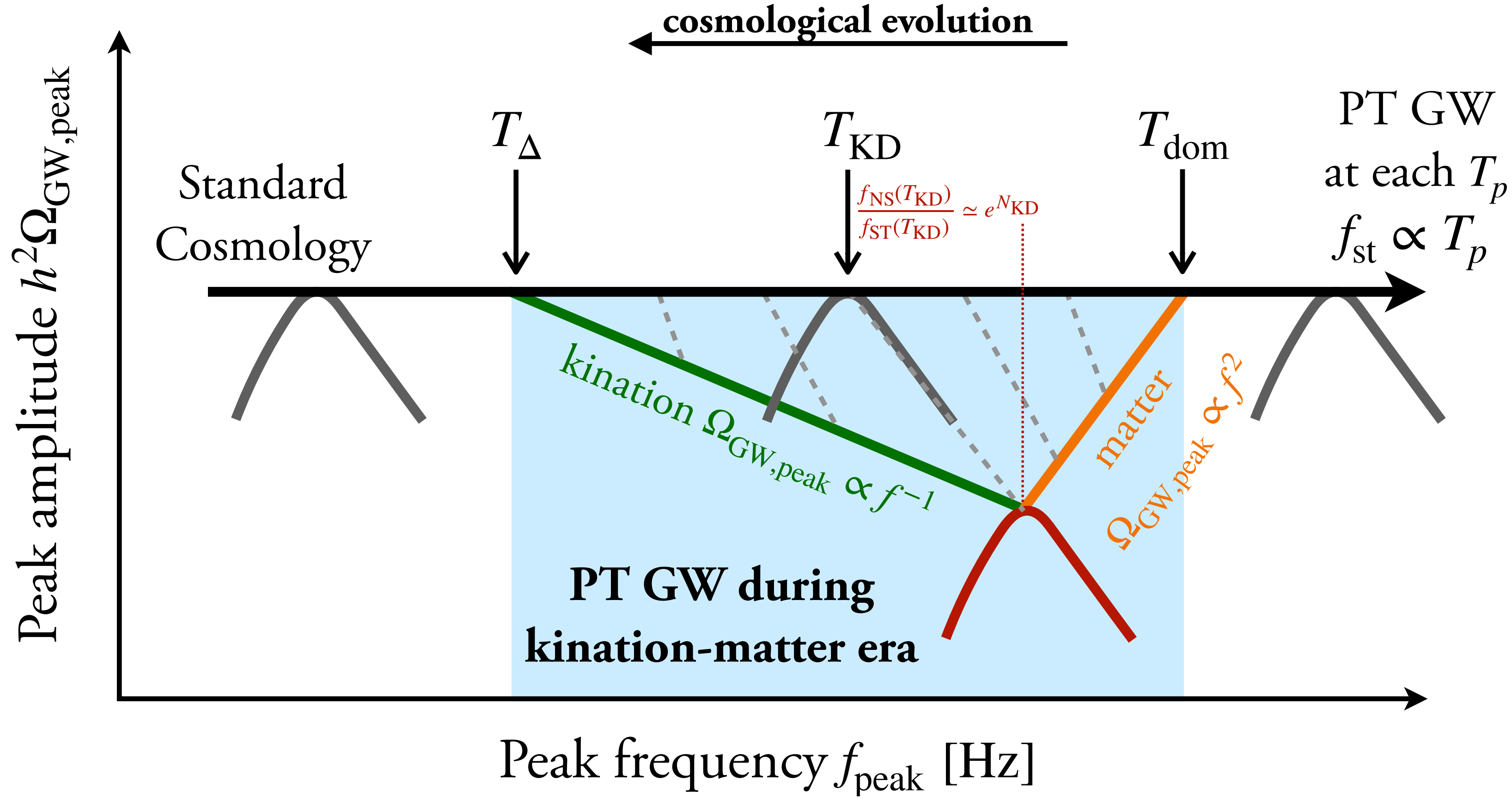
Effect on short-lasting GW

e.g. first-order phase transition

Thermal phase transition where the source of GW is the thermal plasma cannot have the enhancement.

(Gouttenoire, Servant, **PS,** to appear)





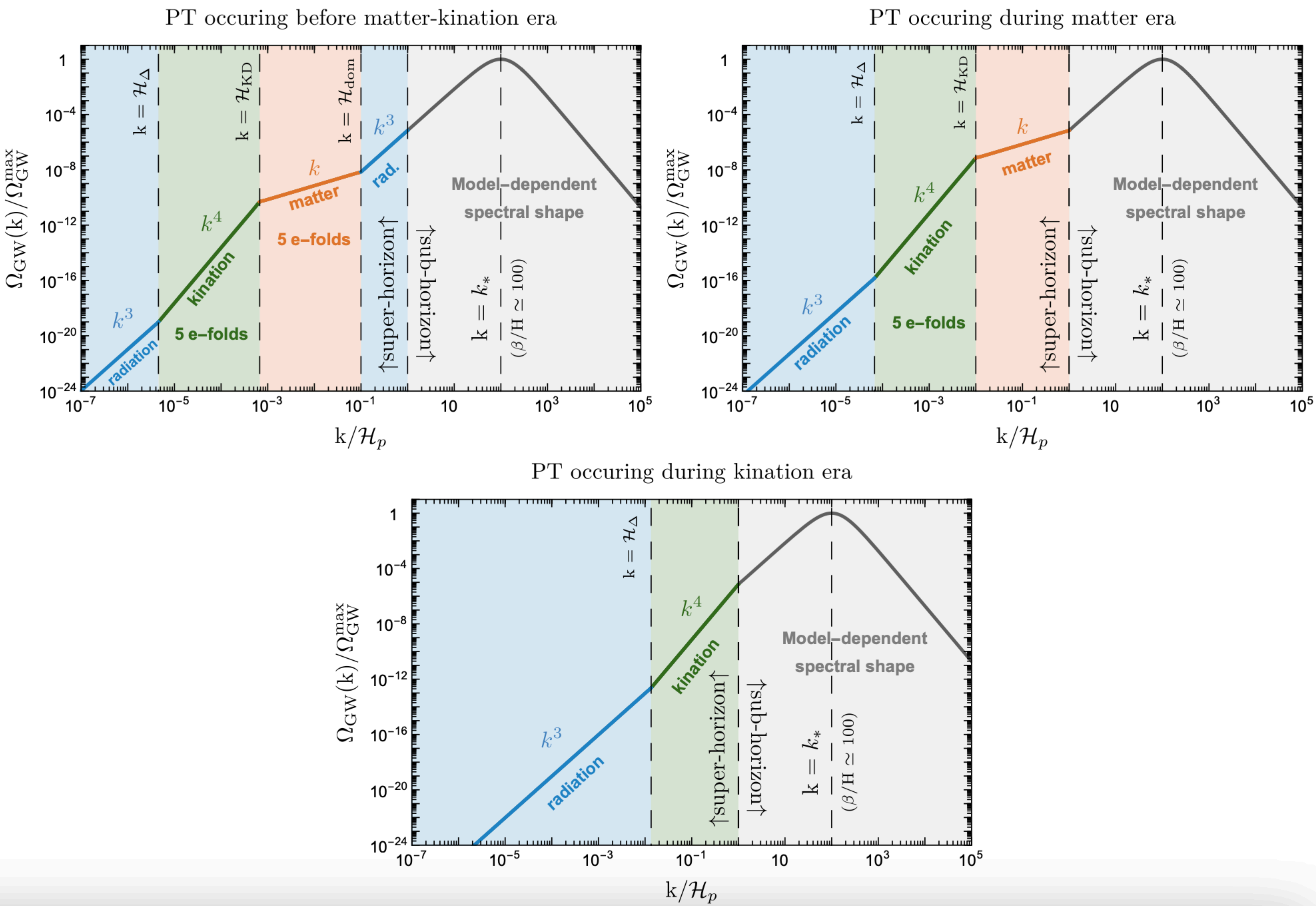
Super simplified argument: For fixed β/H_p,

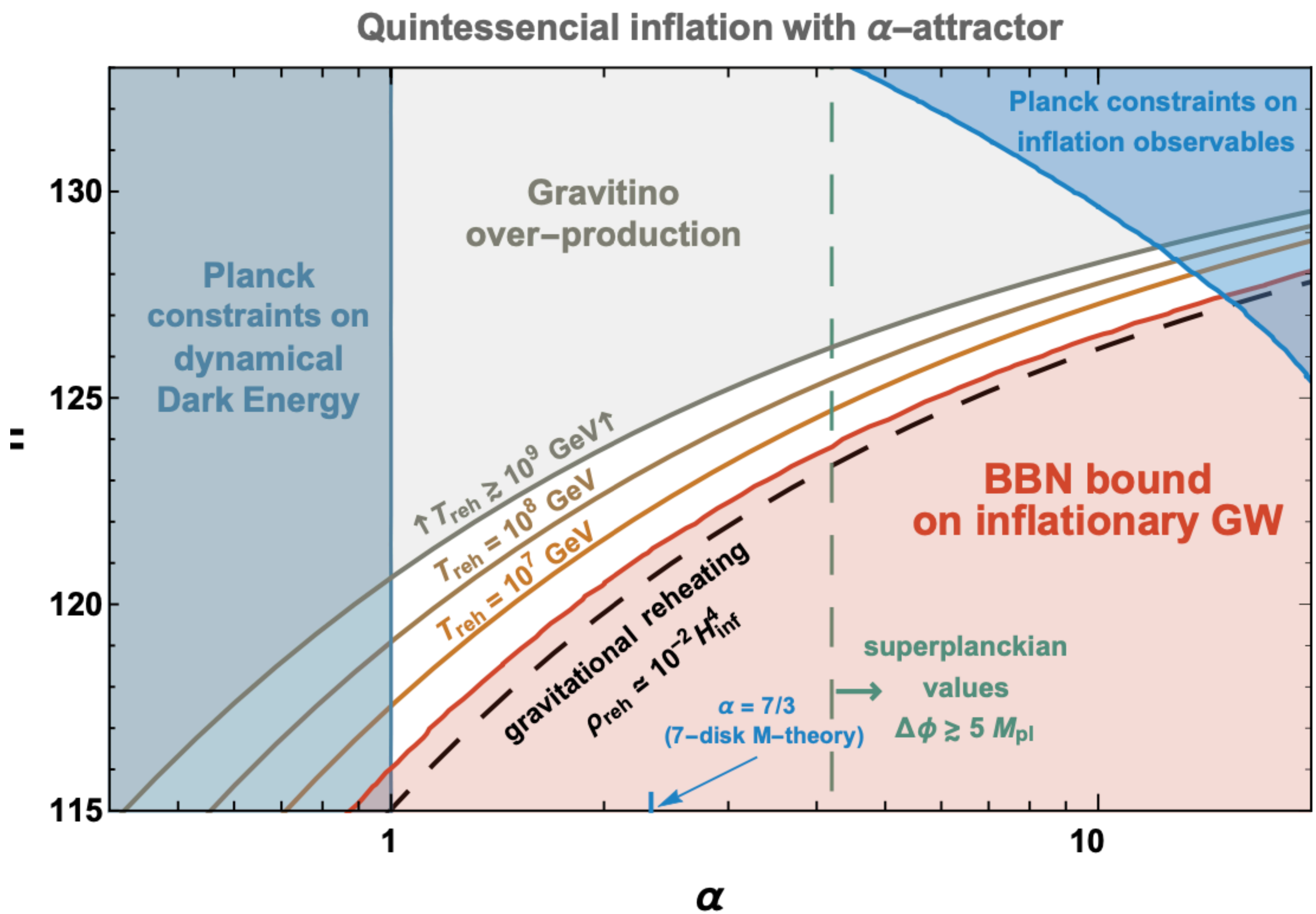
the bubble size is fixed to be some fraction of Hubble horizon.

During the matter-kination era, Universe has smaller size, smaller bubbles, and thus weaker GW.

Other spectral distortions, e.g. causality tail [Hook, Marques-Tavares, Racco, '20]

GW from phase transition





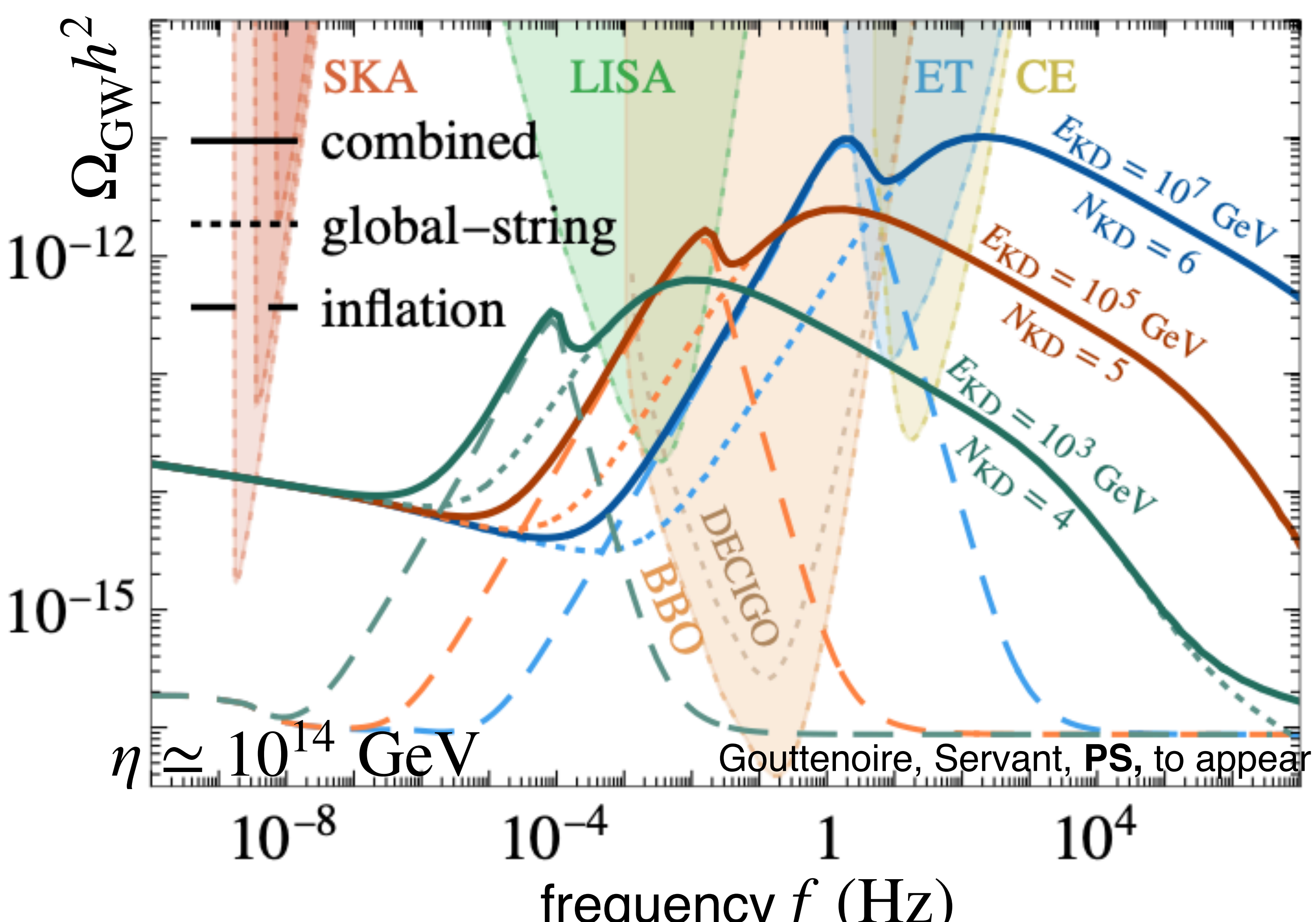
Quintessencial inflation with α–attractor
Planck constraints on dynamical Dark Energy
Gravitino over–production
Planck constraints on inflation observables
↑ $T_{reh} \gtrsim 10^9$ GeV↑
$T_{reh} = 10^8$ GeV
$T_{reh} = 10^7$ GeV
gravitational reheating
$\rho_{reh} \simeq 10^{-2} H_{inf}^4$
BBN bound on inflationary GW
superplanckian values
$\Delta\phi \gtrsim 5\ M_{pl}$
$\alpha = 7/3$
(7–disk M–theory)
130
125
120
115
1
10
α

Inflation + global cosmic strings

String network formed at energy scale η
continuously produces loops which decay into GW (and also particles.)

E.g. Axionic strings from PQ symmetry breaking with $\eta \sim f_a$.

eak amplitude from global strings: $\Omega^{\rm glob}_{\rm peak} h^2 \approx 10^{-14} \left(\frac{\eta}{10^{15}\ \rm GeV} \right)^4 \left[\frac{\exp(2N_{\rm KD})}{10^4} \right] \log^3(\cdots$

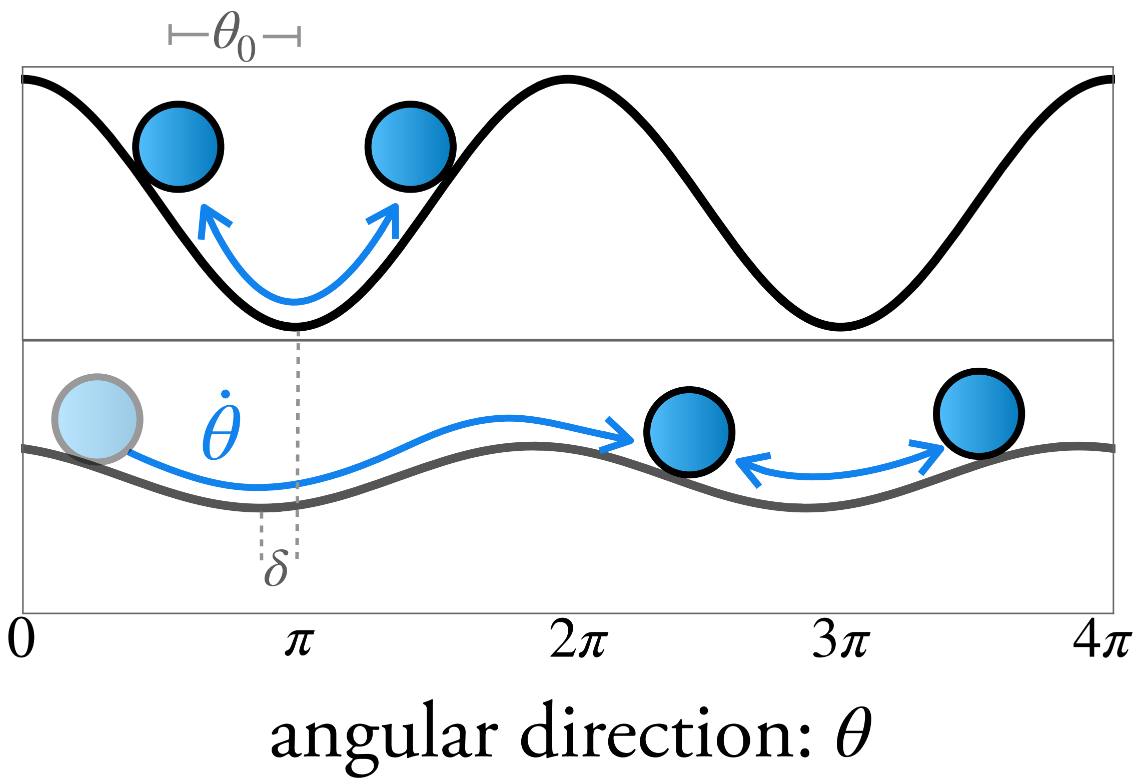


Fixed peak separation
$f_{\rm inf}/f_{\rm glob} = \mathcal{O}(10^{-2})$
[for loops' size: $(0.1)H^{-1}$]

With $E_{\rm inf} \sim 10^{16}$ GeV,
two-peak signature
for $10^{12} \lesssim \frac{\eta}{\rm GeV} \lesssim 10^{15}$.

Model A: trapped misalignment

Model A: Trapped misalignment [Di Luzio, Gavela, Quilez, Ringwald, '21]



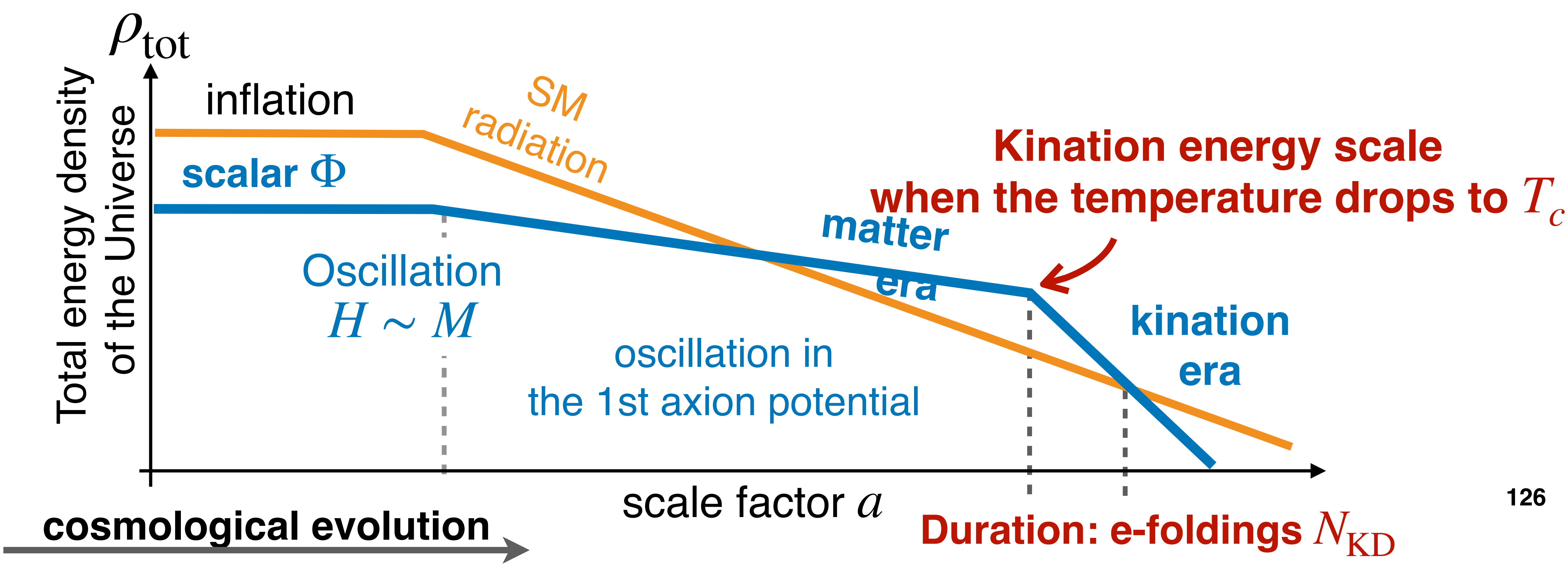
For $T \gtrsim T_c$, $V_{\rm high} \sim M^2 f_a^2 \cos(\theta)$

axion oscillates and behaves as matter.

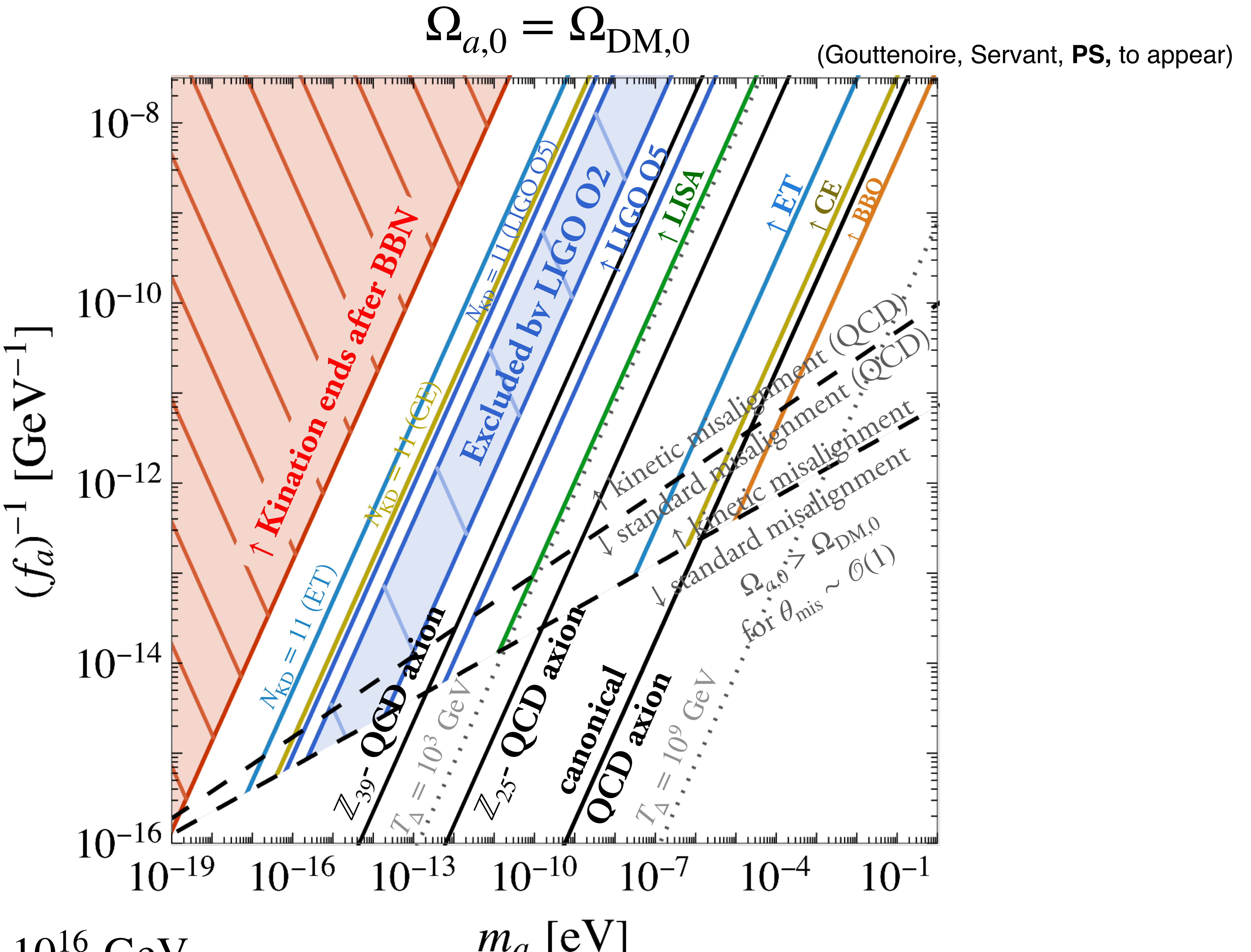
For $T \lesssim T_c$, $V_{\rm low} \sim m_a^2 f_a^2 \cos(\theta)$ with $M \gg m_a$

Axion rolls freely with large initial speed at T_c

$$\dot{\theta}_c \sim \frac{T_c^{3/2} M^{1/4}}{M_{\rm Pl}^{3/4}}$$ and generates kination era.



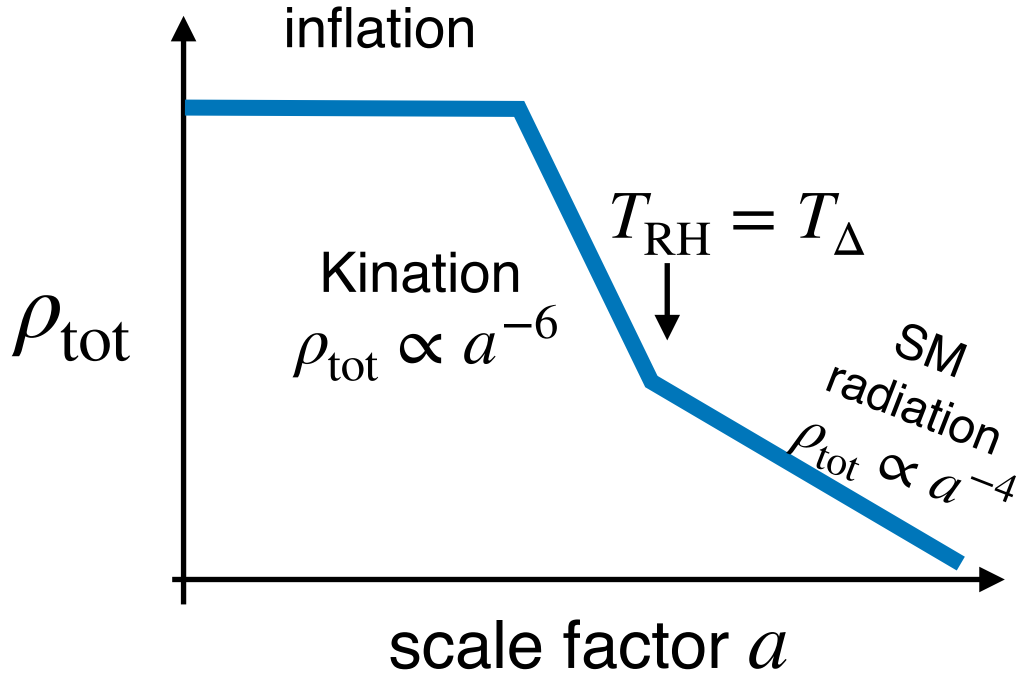
Detectability in axion parameter spaces

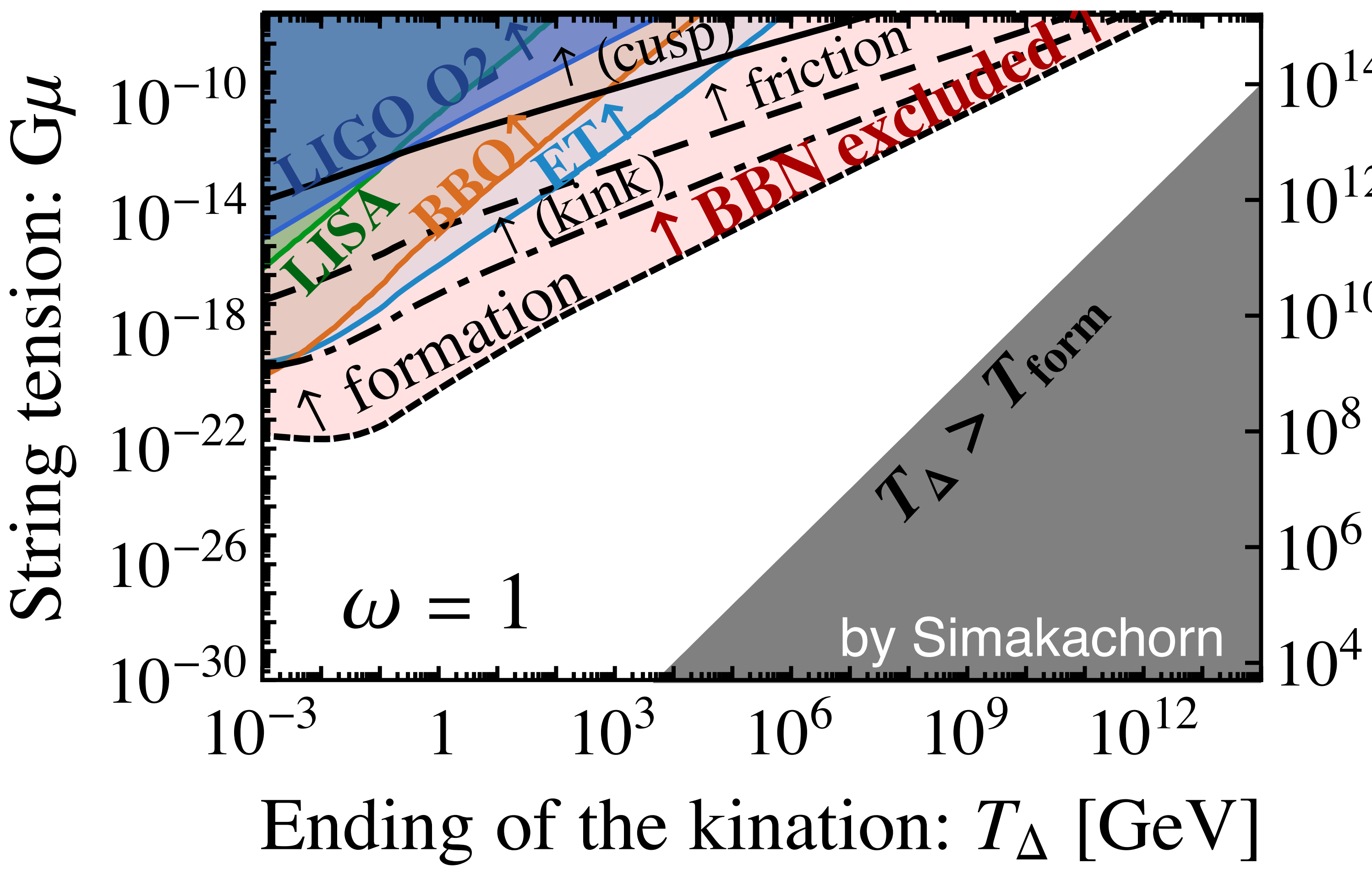


$E_{inf} = 1.6 \times 10^{16}$ GeV

Long Kination ⇒ too much GW

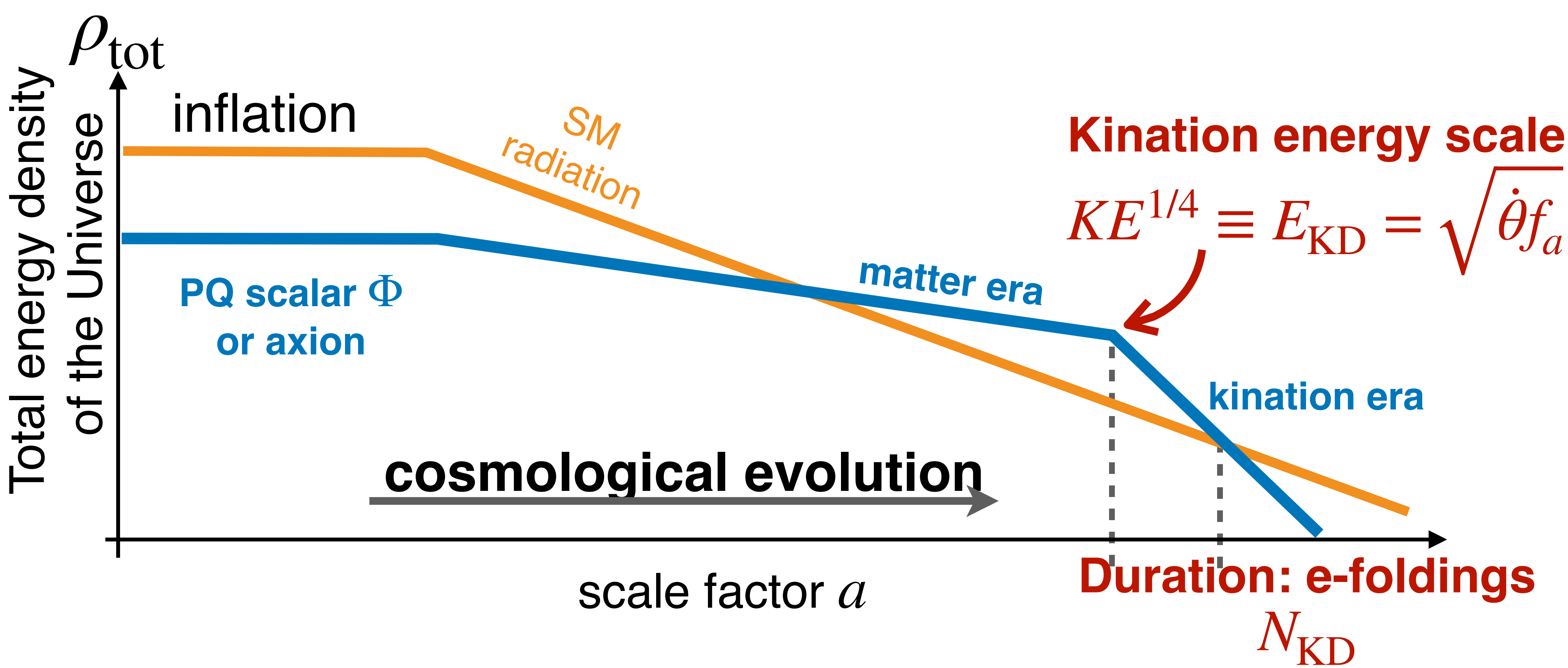
GW from local cosmic strings





The cut-off of the cosmic-string GW is crucial for the BBN constraint.
No well-motivated model that generates cosmic strings during kination ?

Model-independent kination from spinning axion



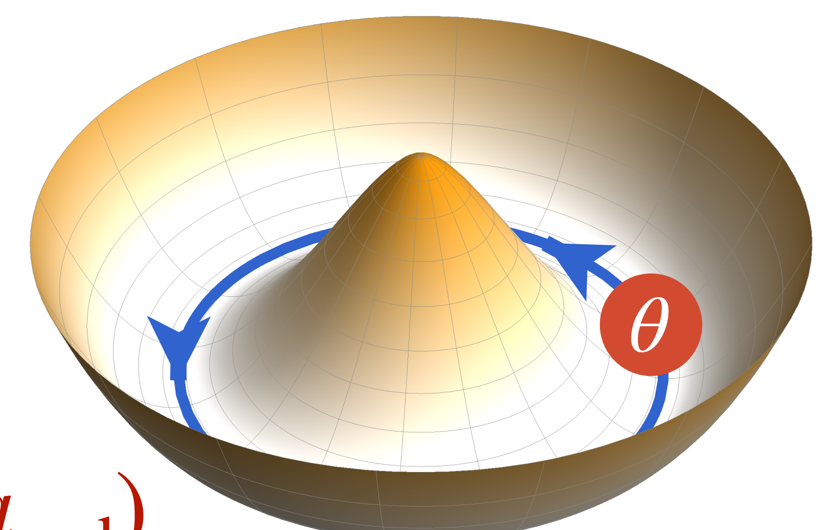
are characterized by
(given the spontaneous symmetry-breaking scale f_a)

1. **kination energy scale** $E_{\rm KD} = \sqrt{\dot{\theta} f_a}$

   (the spinning speed of axion $\dot{\theta}$ when kination starts)

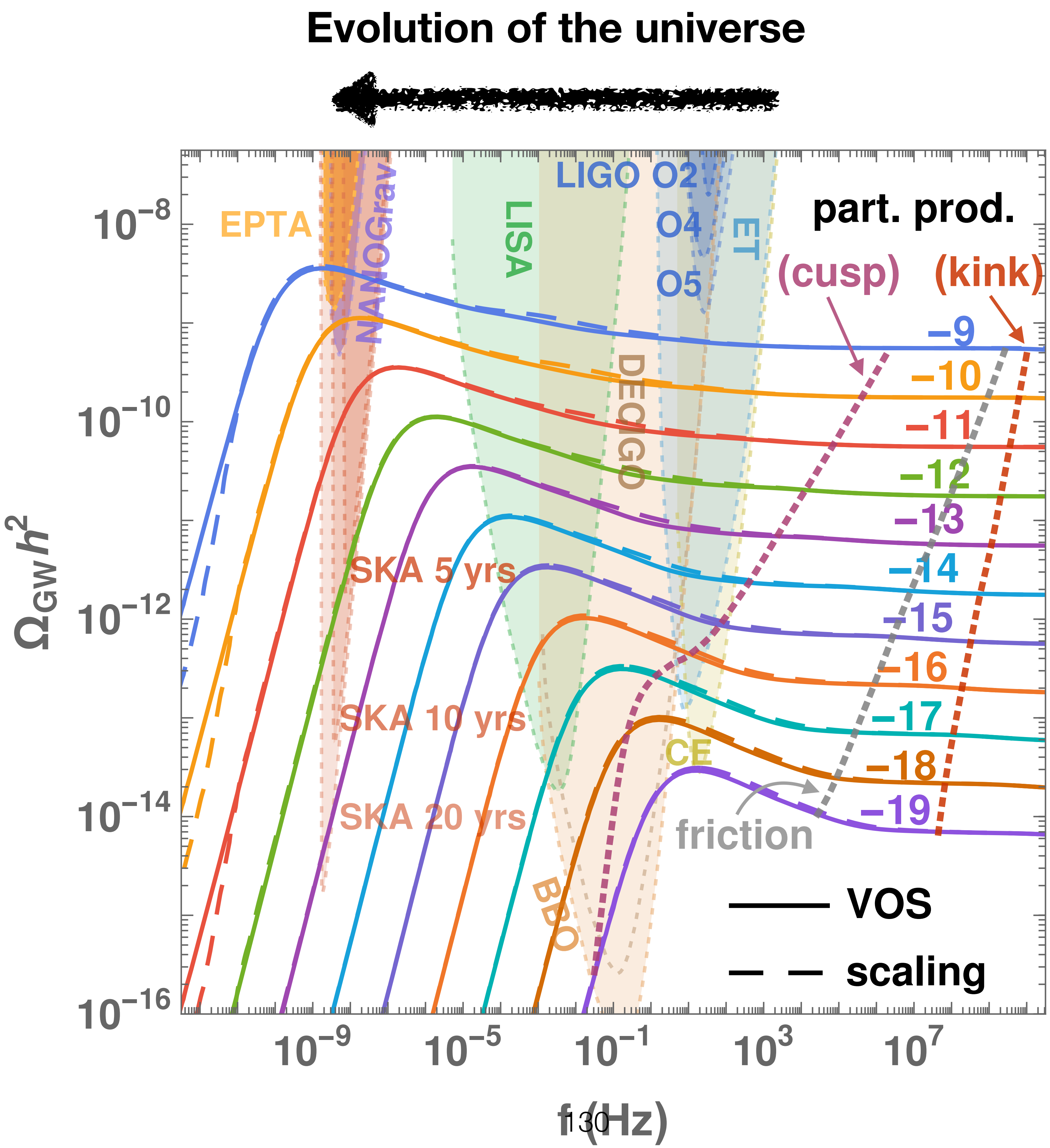
2. **the duration of kination era** $N_{\rm KD} = \log(a_{\rm start}/a_{\rm end})$

   (related to the beginning of the matter era)



circle of $\phi = f_a$

GW spectrum from Cosmic Strings



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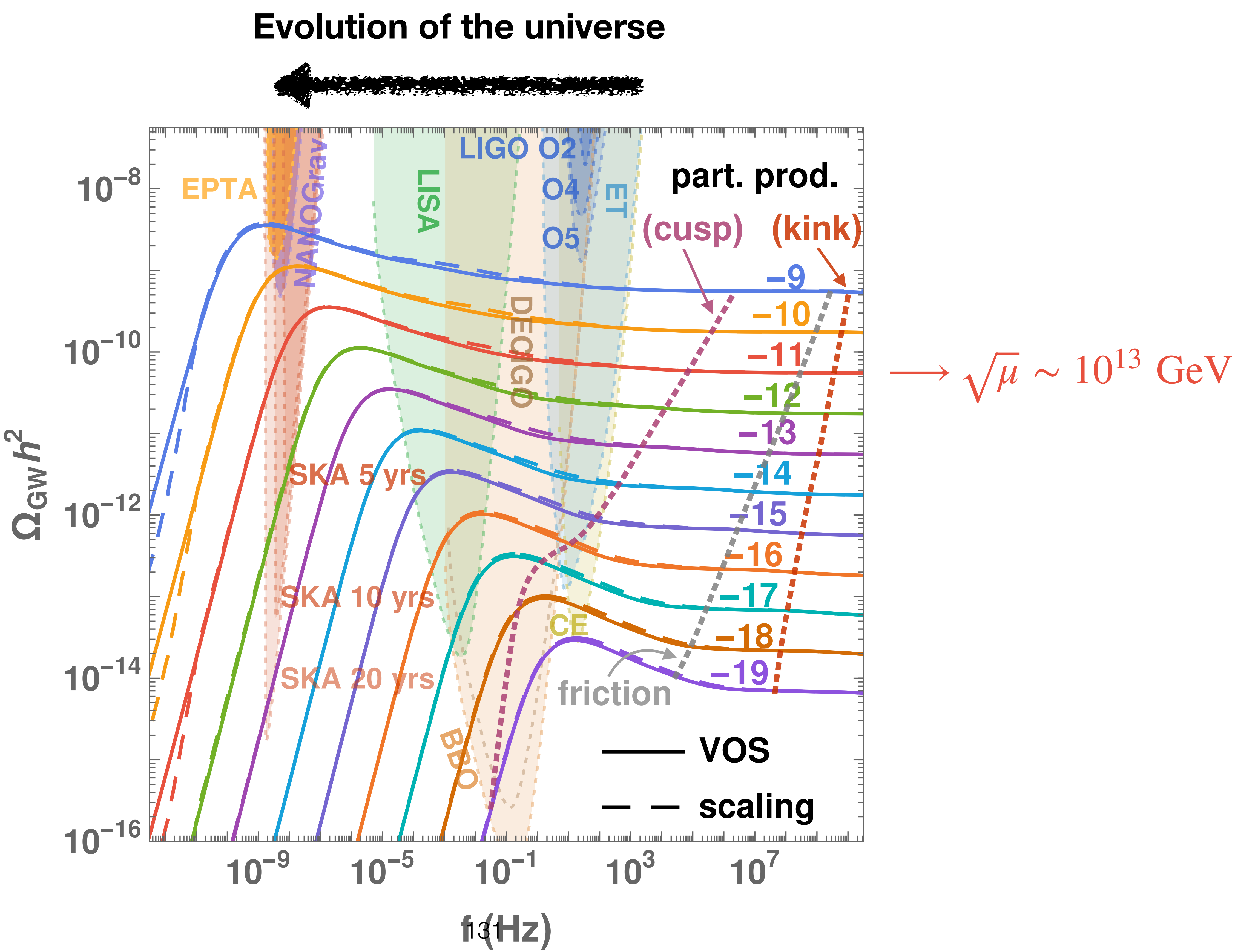

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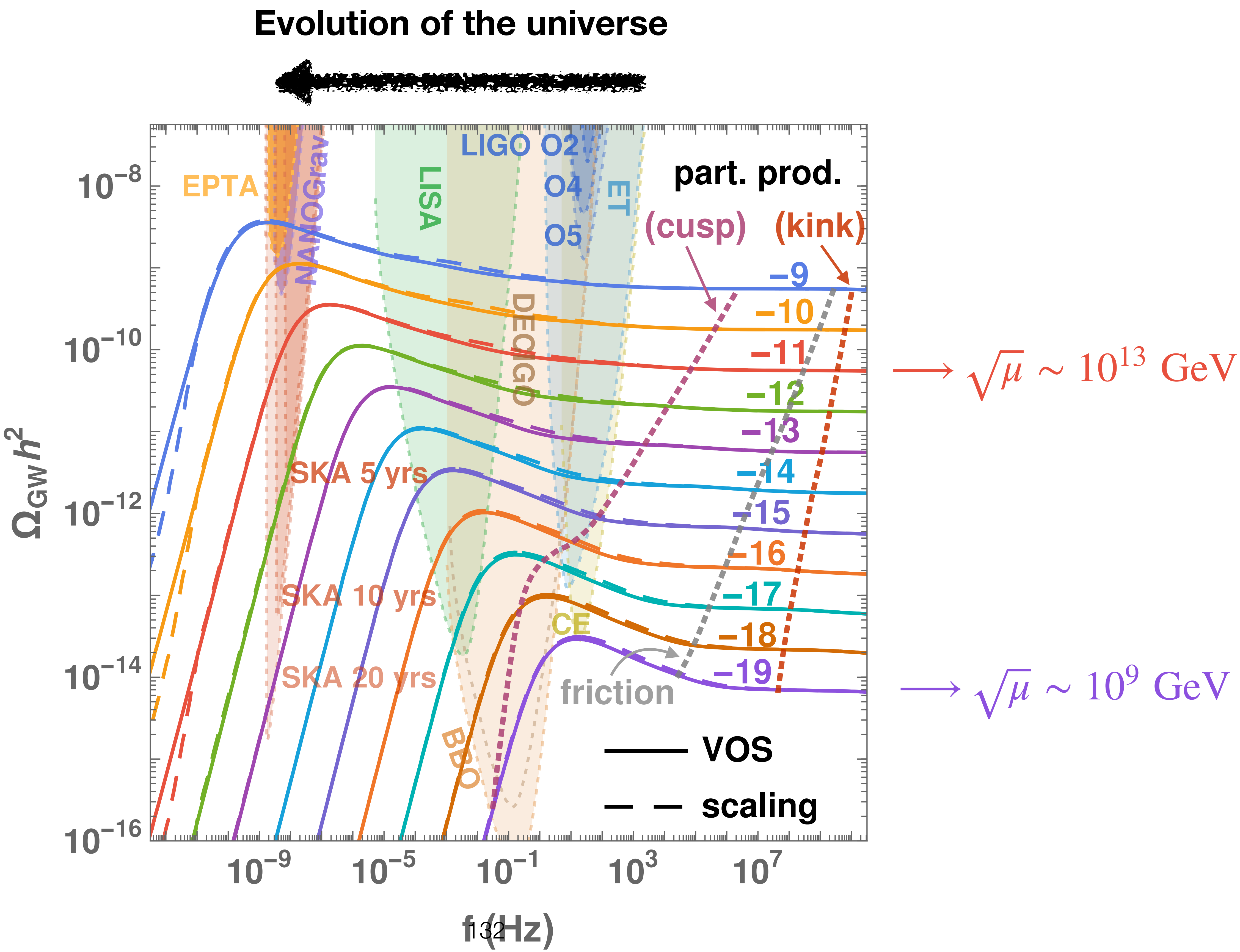

String network formation

- **Topological defects generated during spontaneous-symmetry-breaking with** $\pi_1(G/H) \neq 1$

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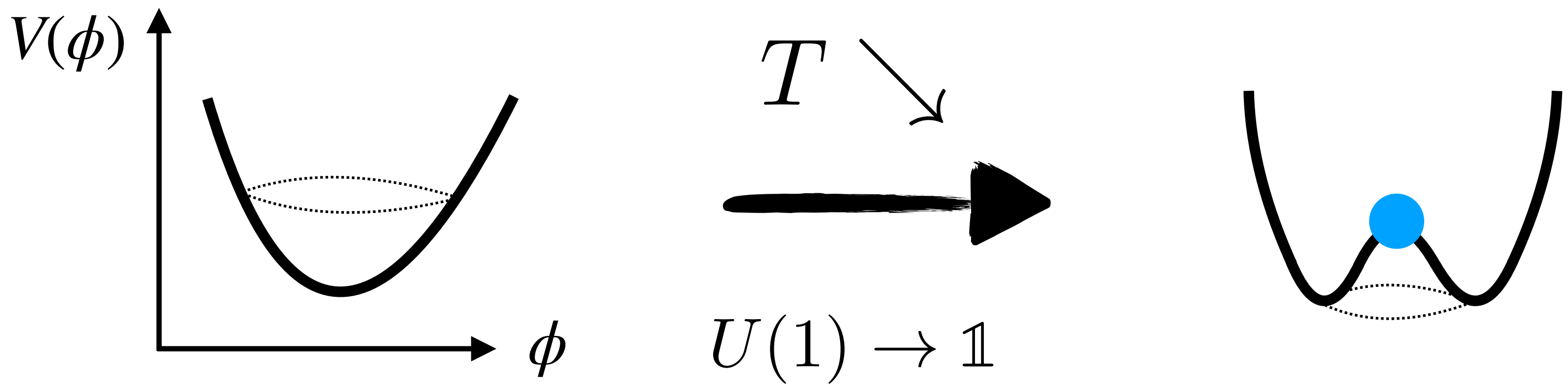

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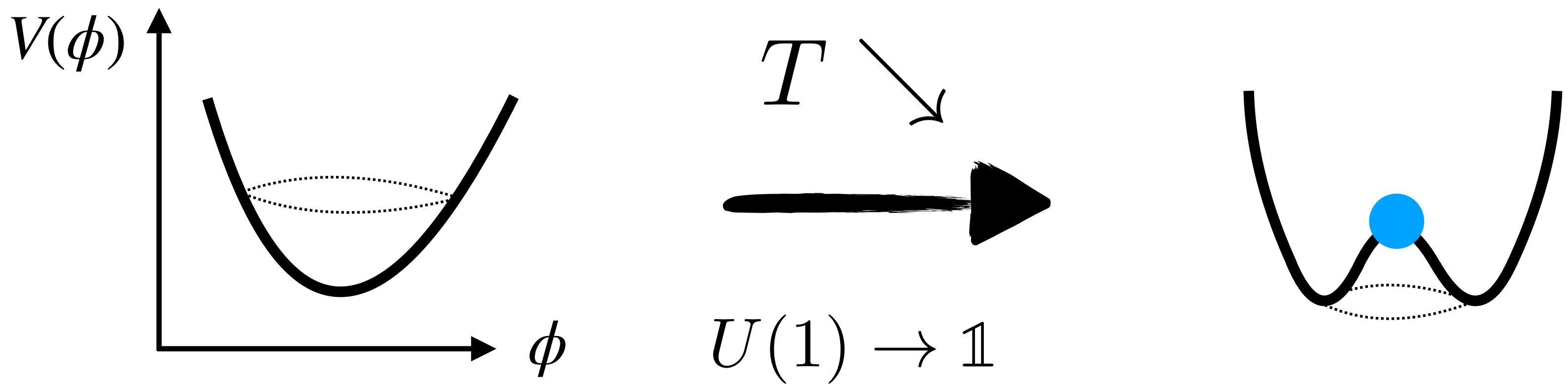
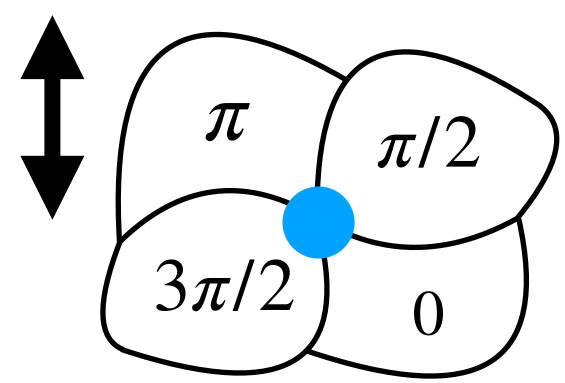
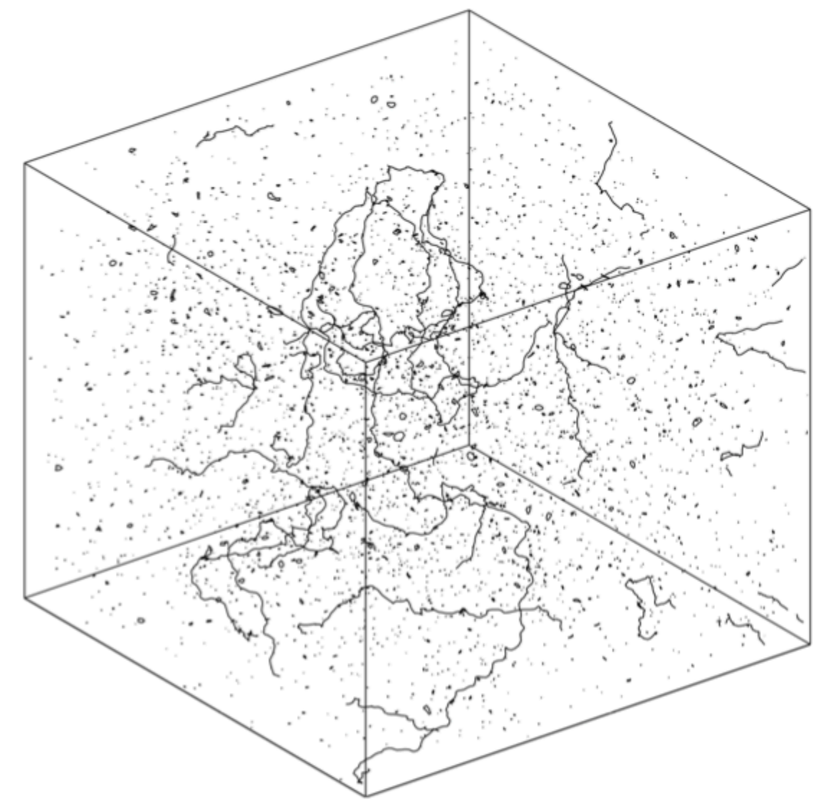


correlation length L



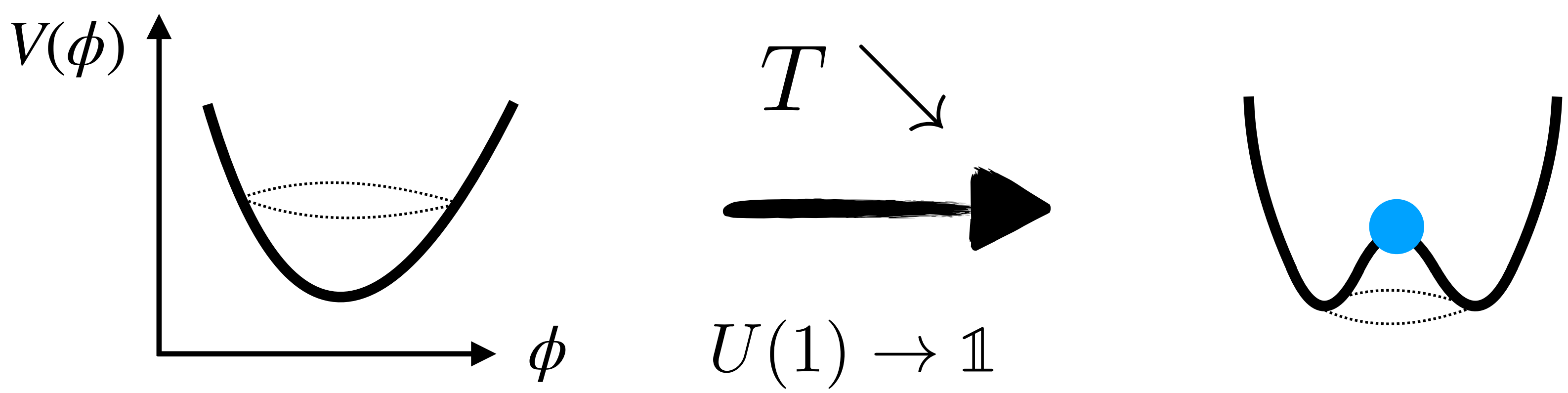
[Kibble 1976]

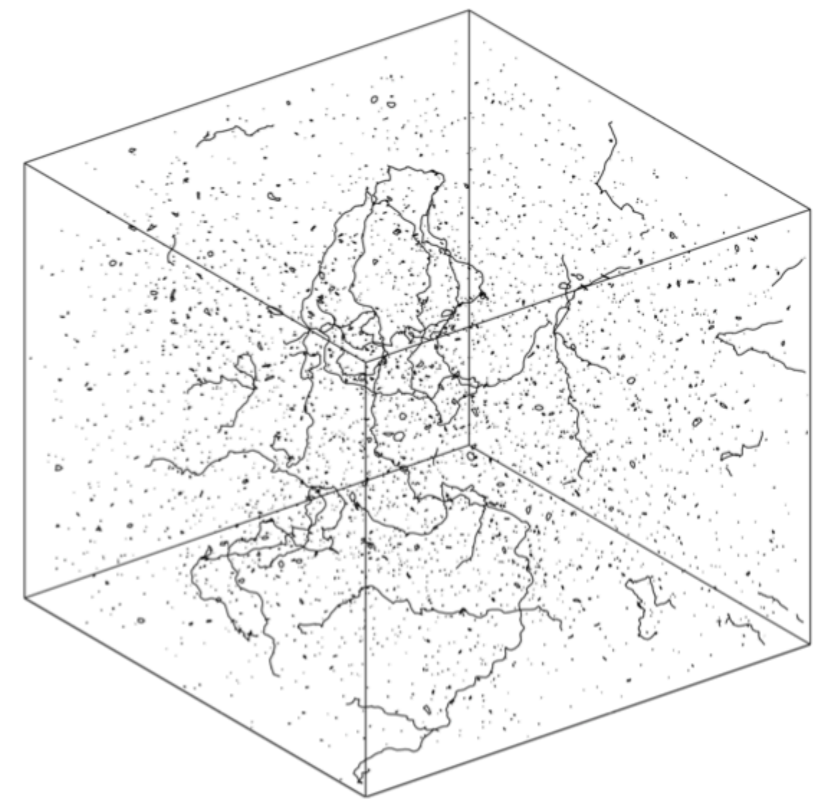


[Allen & Shellard 1990]

String network formation

- **Topological defects generated during spontaneous-symmetry-breaking with** $\pi_1(G/H) \neq 1$





[Allen & Shellard 1990]

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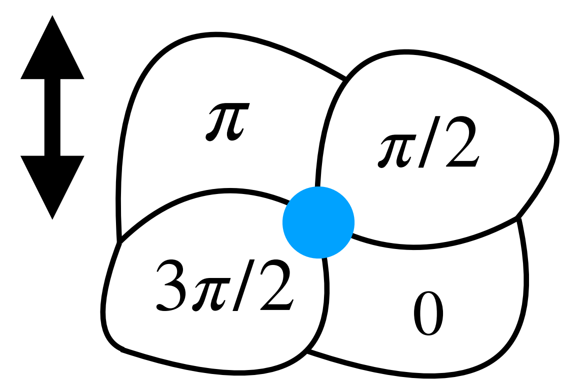
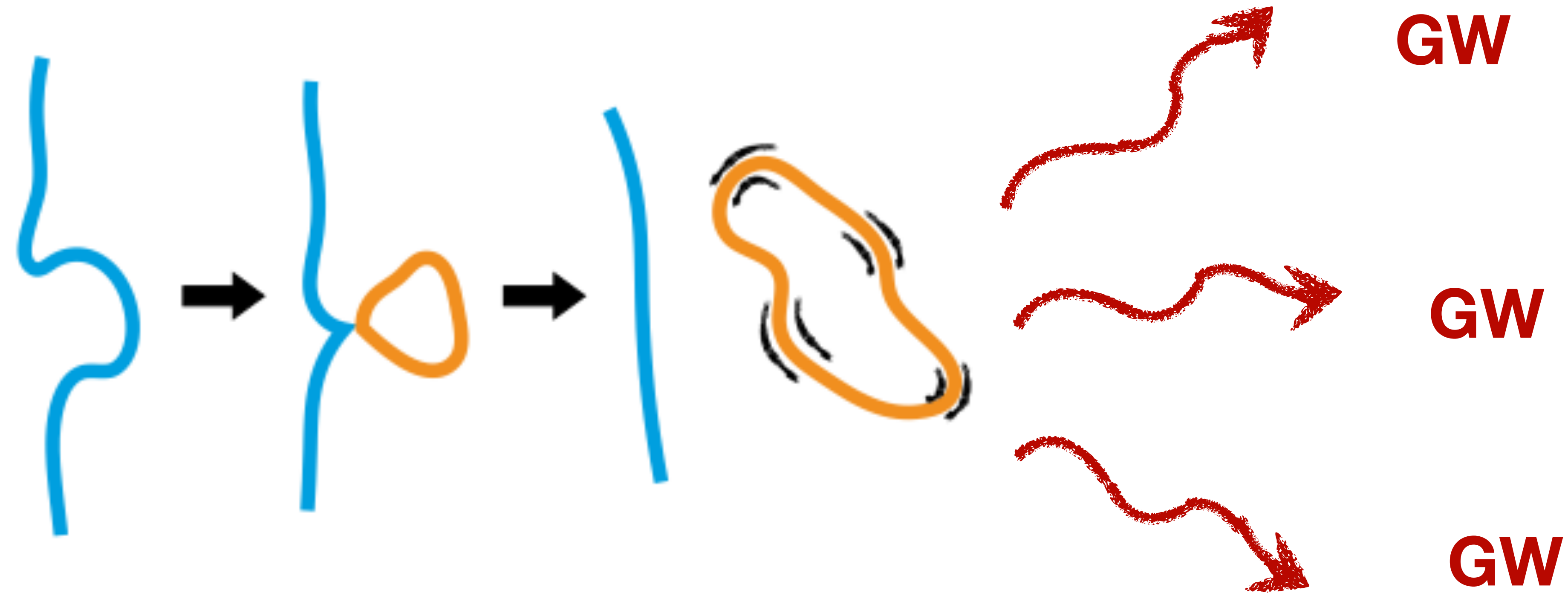


[Kibble 1976]

- **Nambu-Goto approximation**

→ **1D classical objects with tension:** $\mu \sim \langle \phi \rangle^2$

- **GW spectrum generated by string loops**



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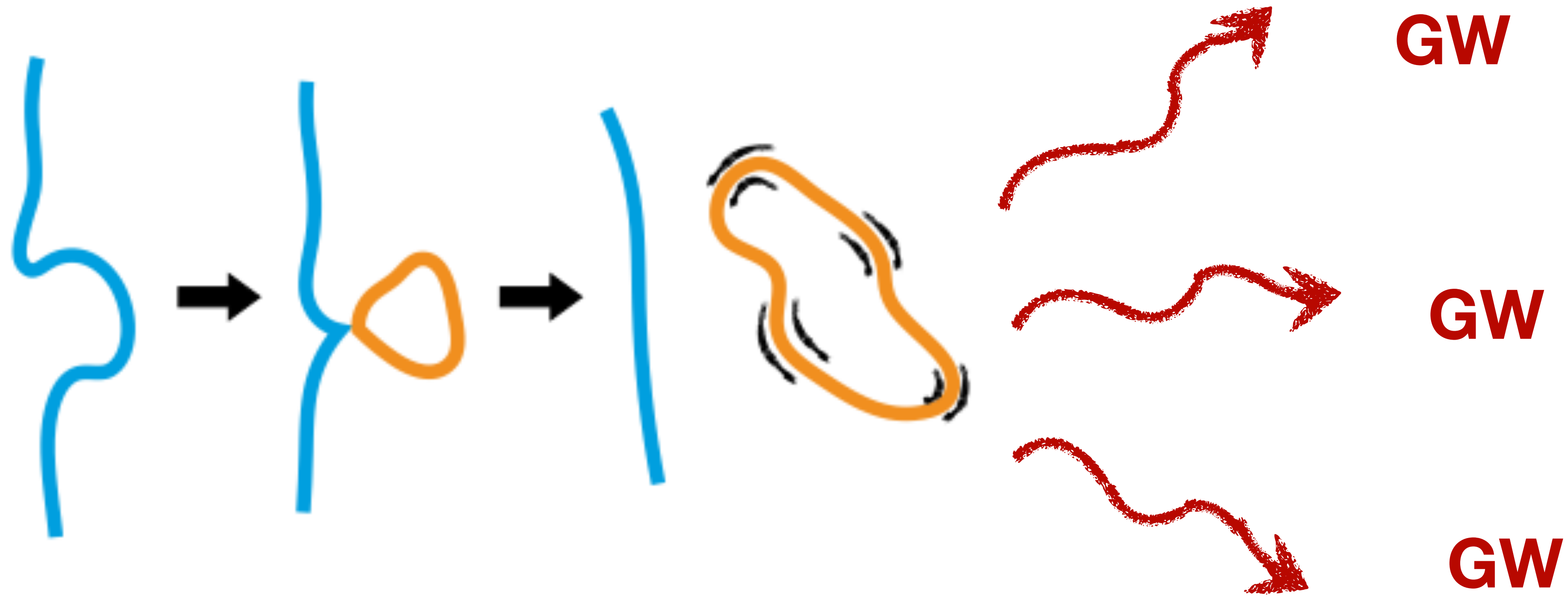
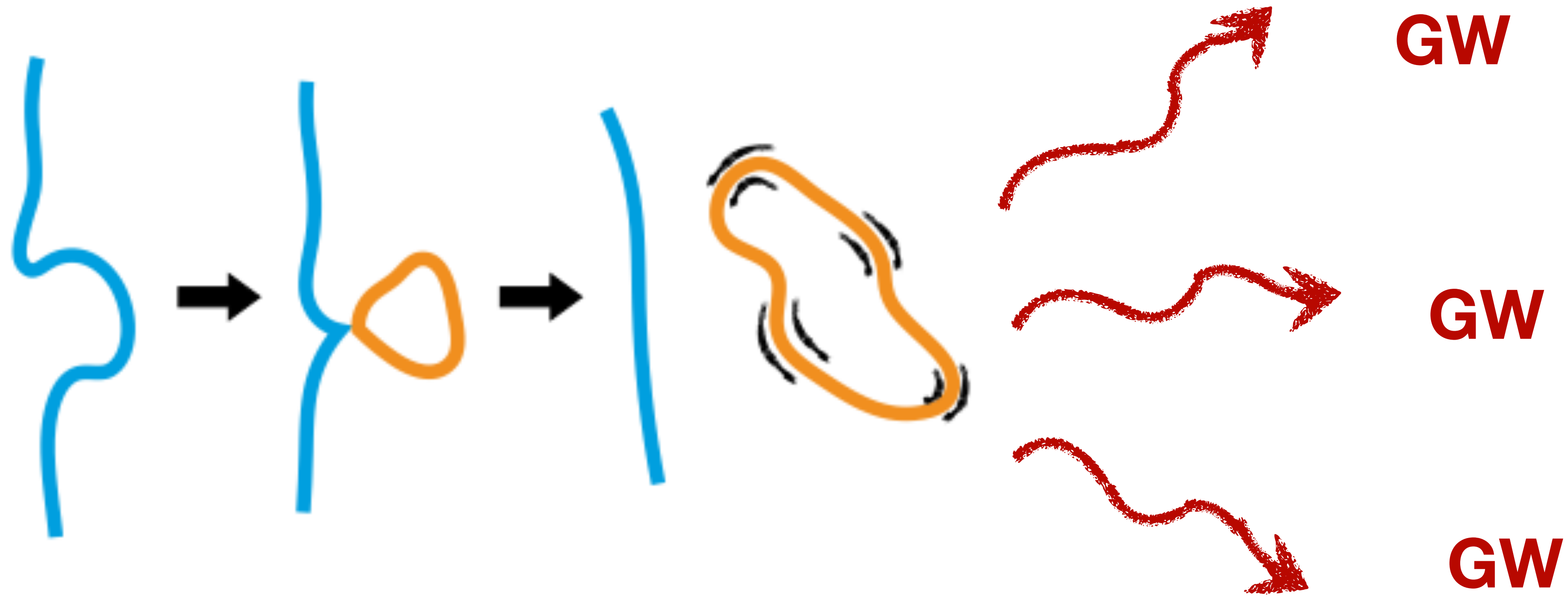


- **Assume LOCAL strings**

- GW spectrum generated by string loops



- Assume LOCAL strings

- GOAL: Use GW from string as a probe of the Early Universe