Charting new particle physics with primordial GWs

Planck 2022
01.06.2022

Courtesy of Peera Simakachorn

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.

Yann Gouttenoire (Tel Aviv university)
with
Peera Simakachorn (DESY & U.Hamburg),
Géraldine Servant (DESY & U.Hamburg)

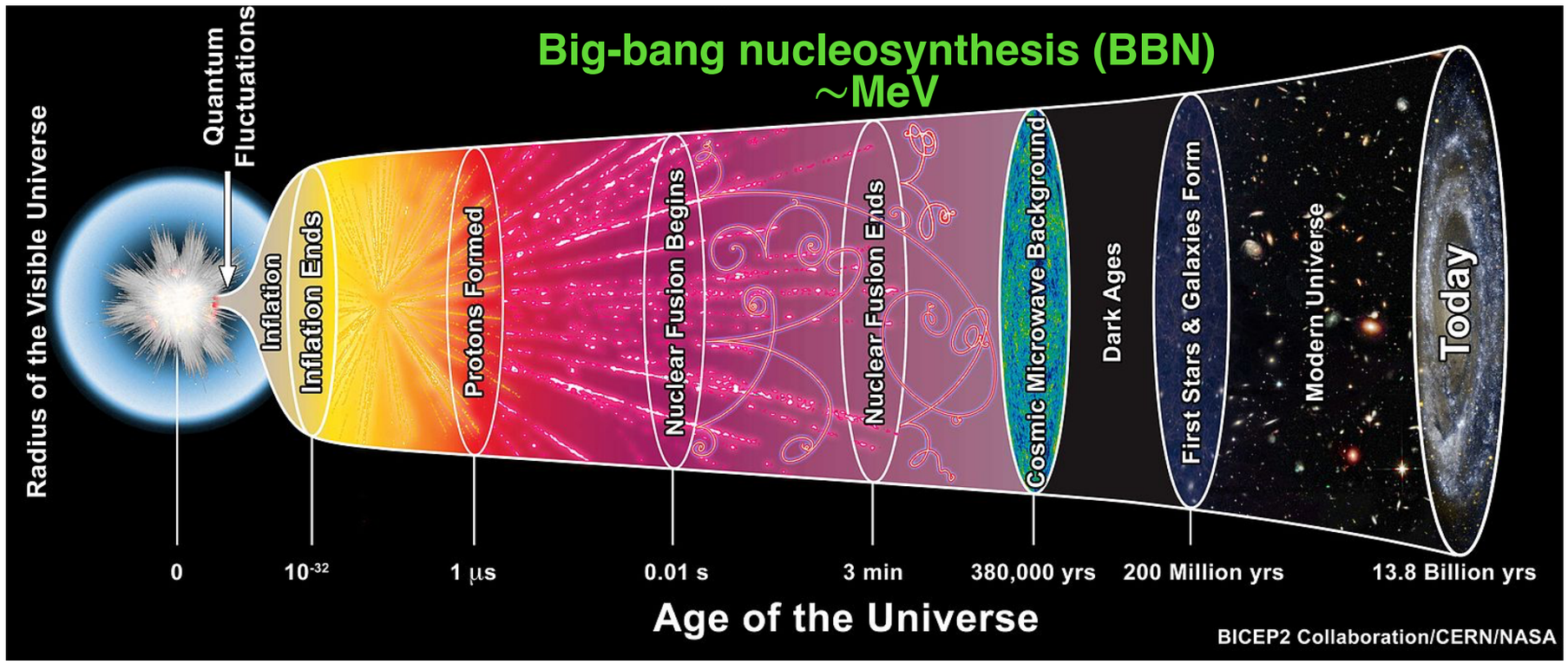
Funded by

Azrieli International Postdoctoral Fellows

Fondation Azrieli Foundation

History of the Universe

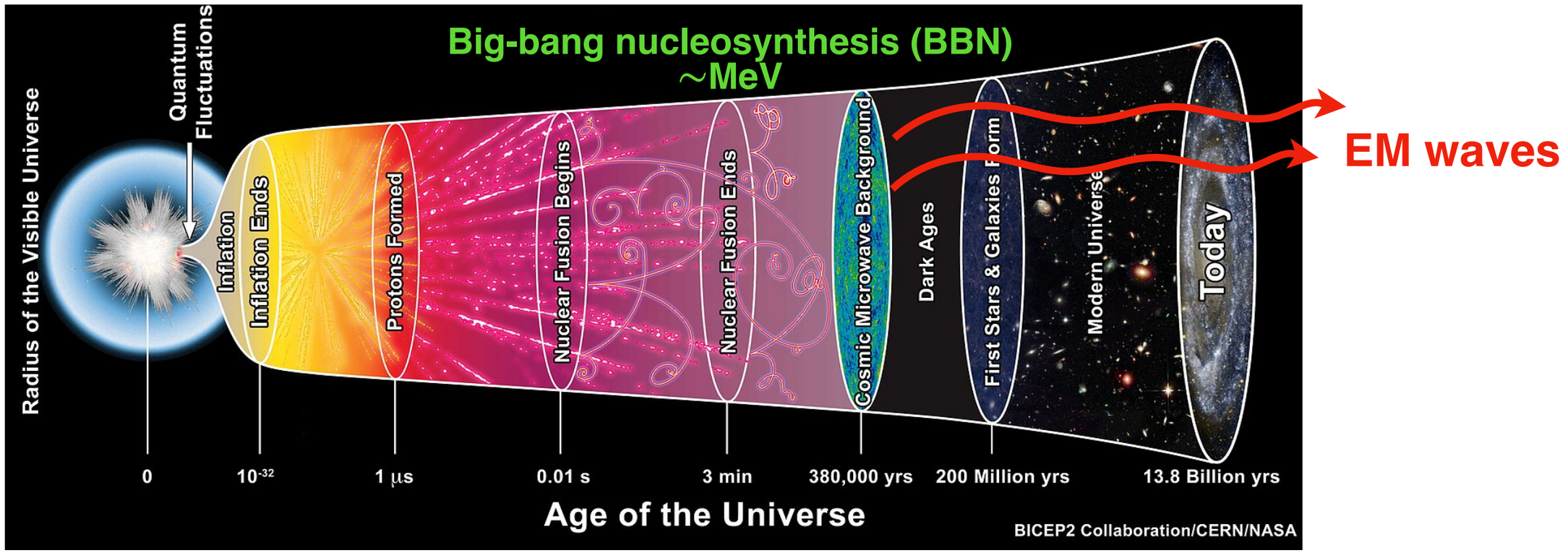
high energies ← low energies



History of the Universe

high energies ⟵ low energies

⟶ well-tested



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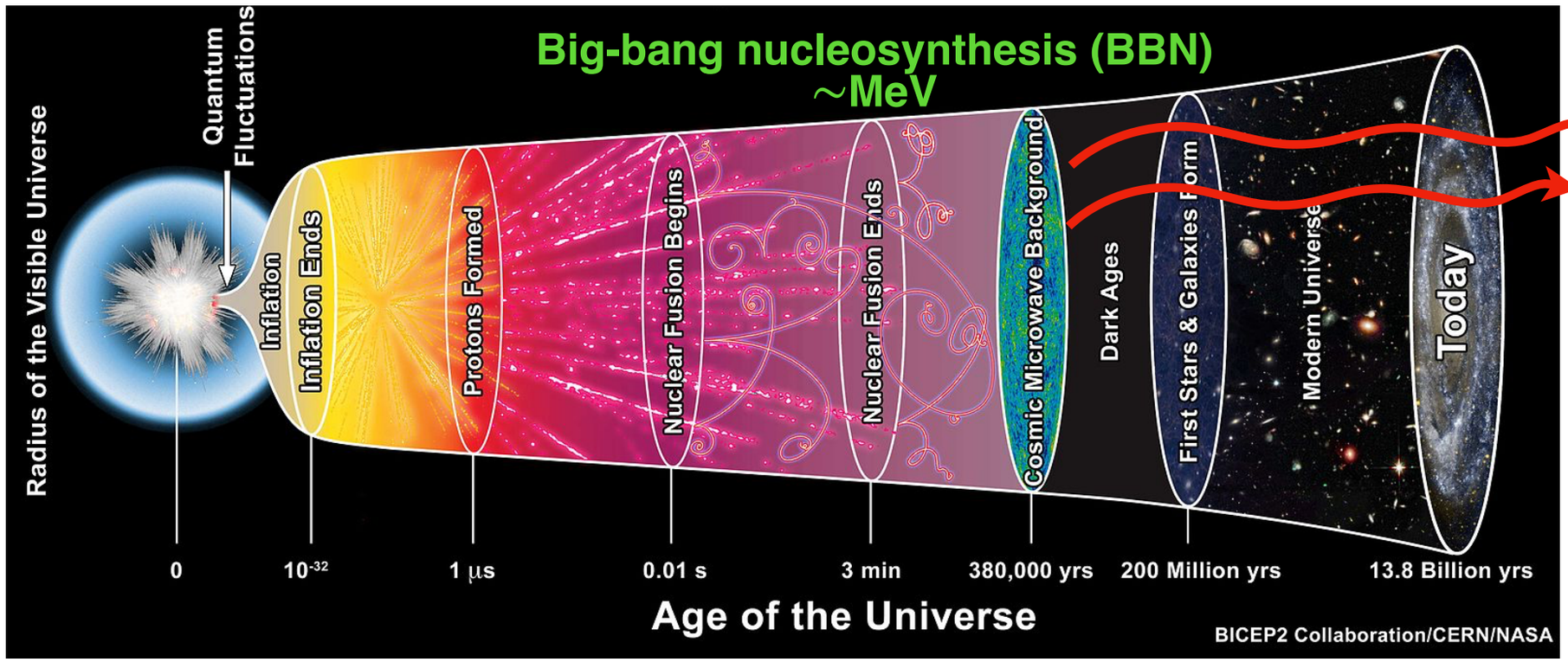

EM waves

Cosmological dark age

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

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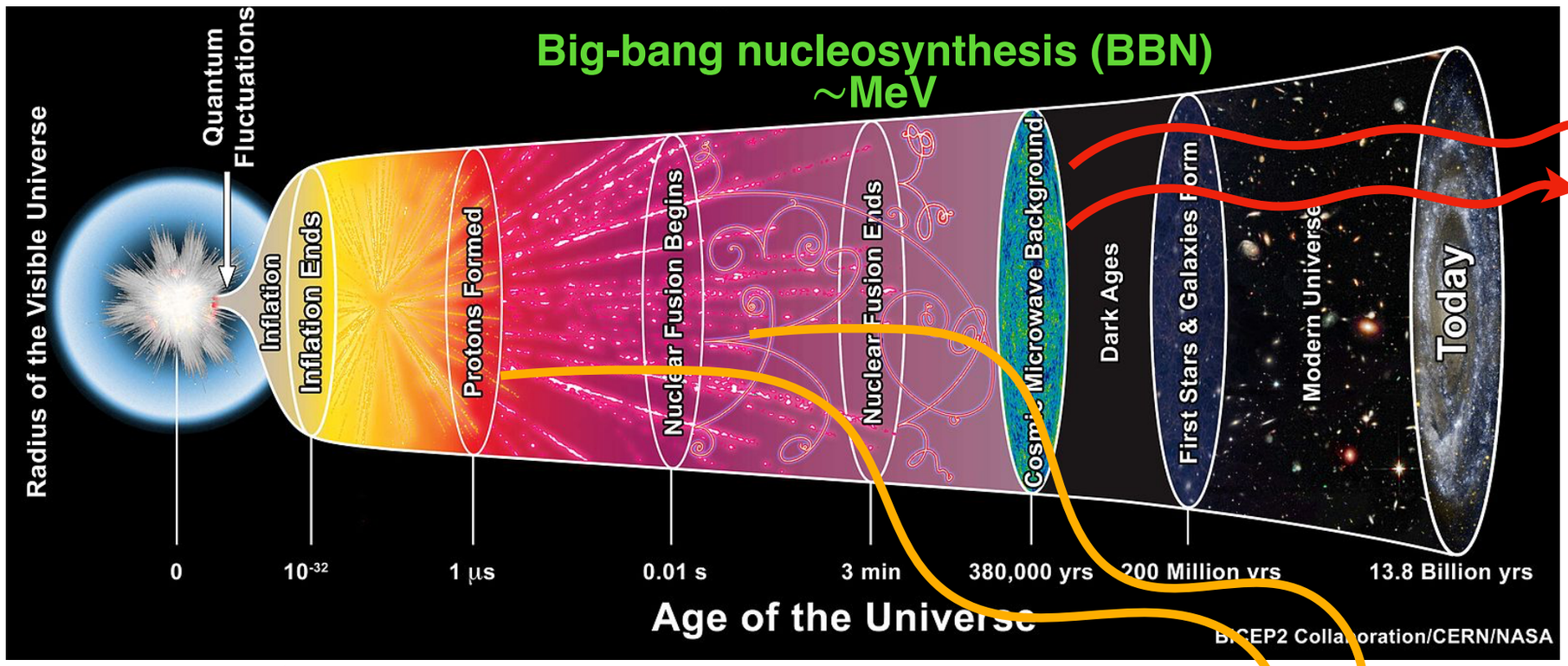


EM waves

Cosmological dark age

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

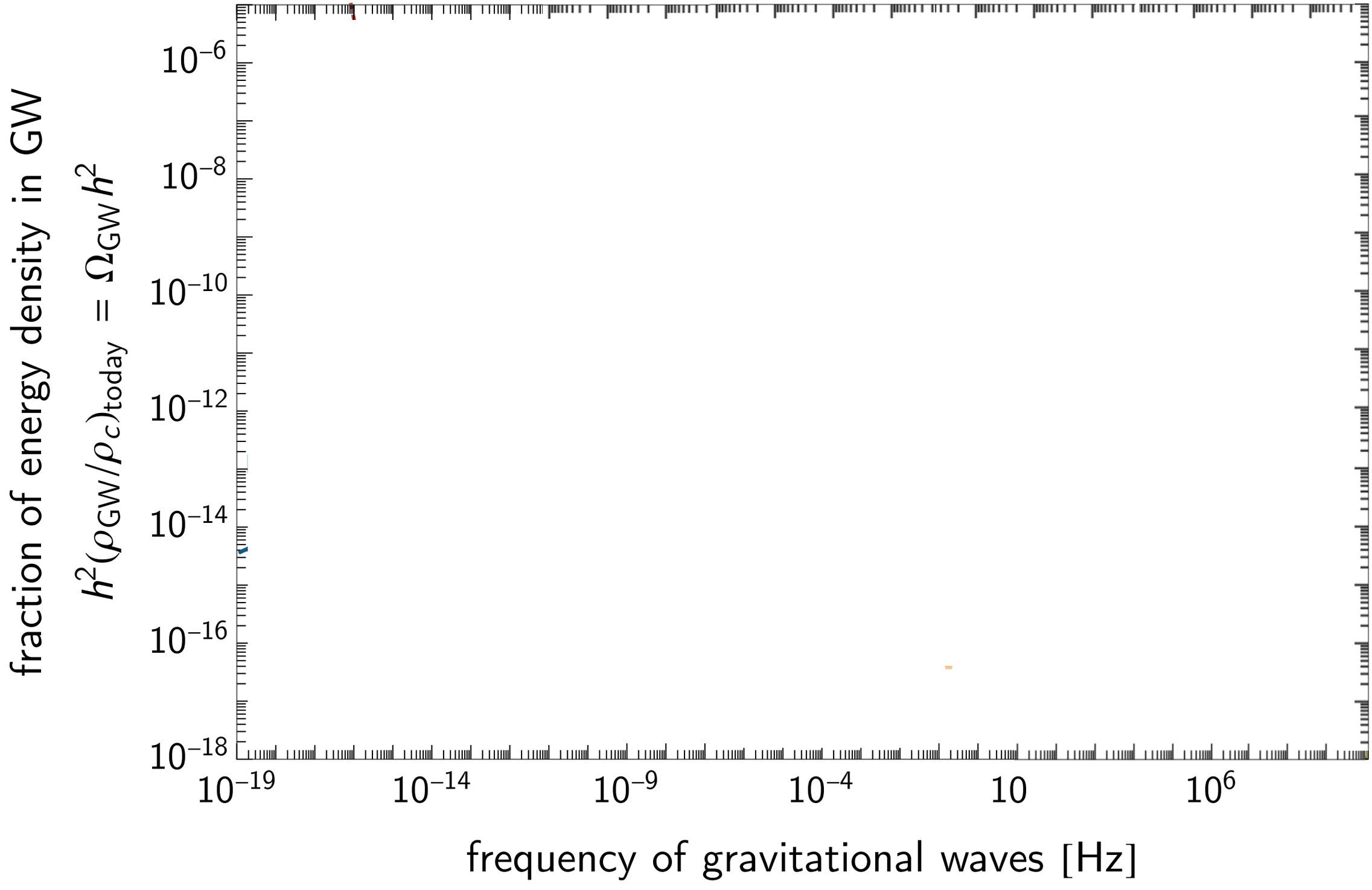
Primordial GW

(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 ($T \gtrsim$ MeV).

Future prospects of GW experiments



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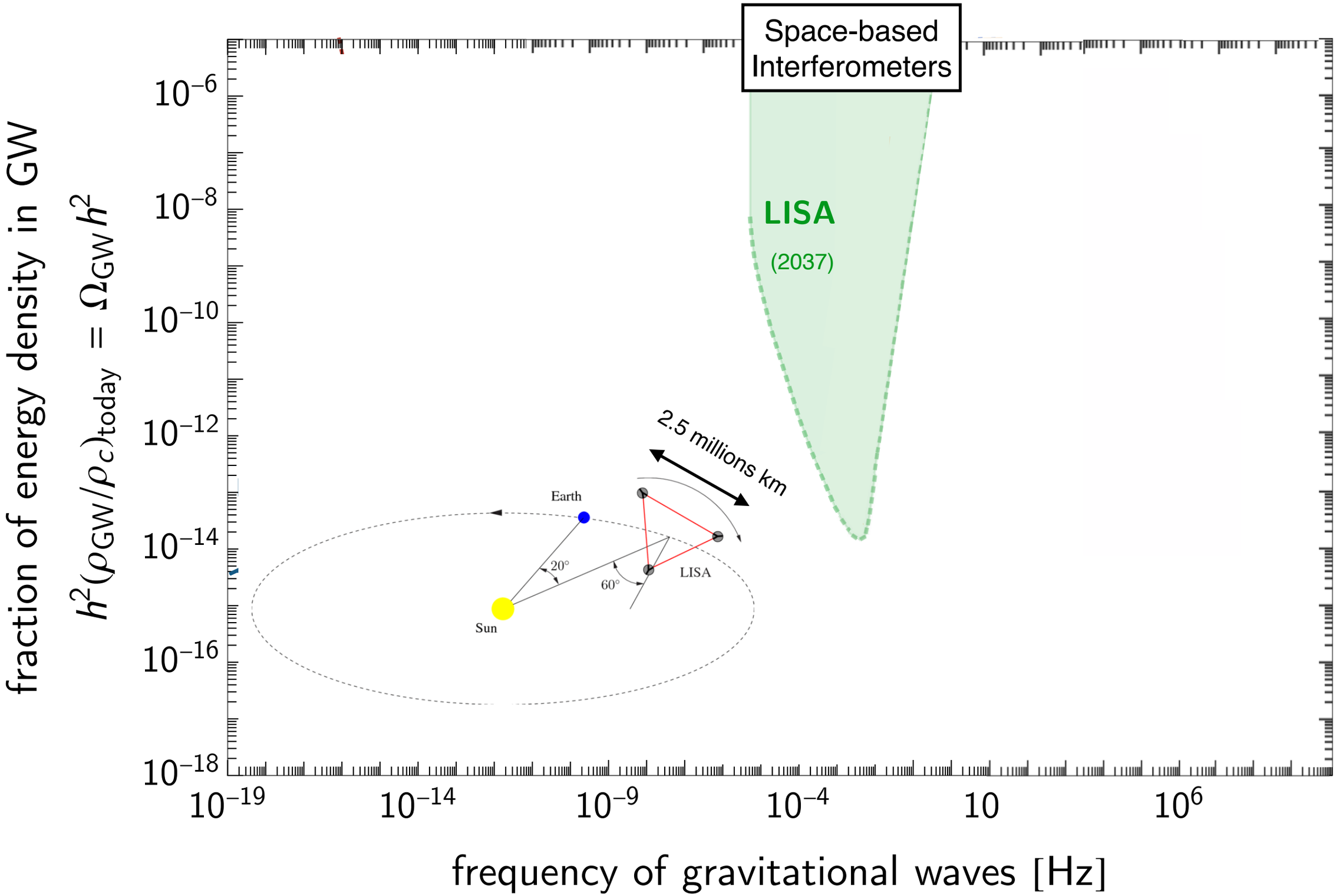

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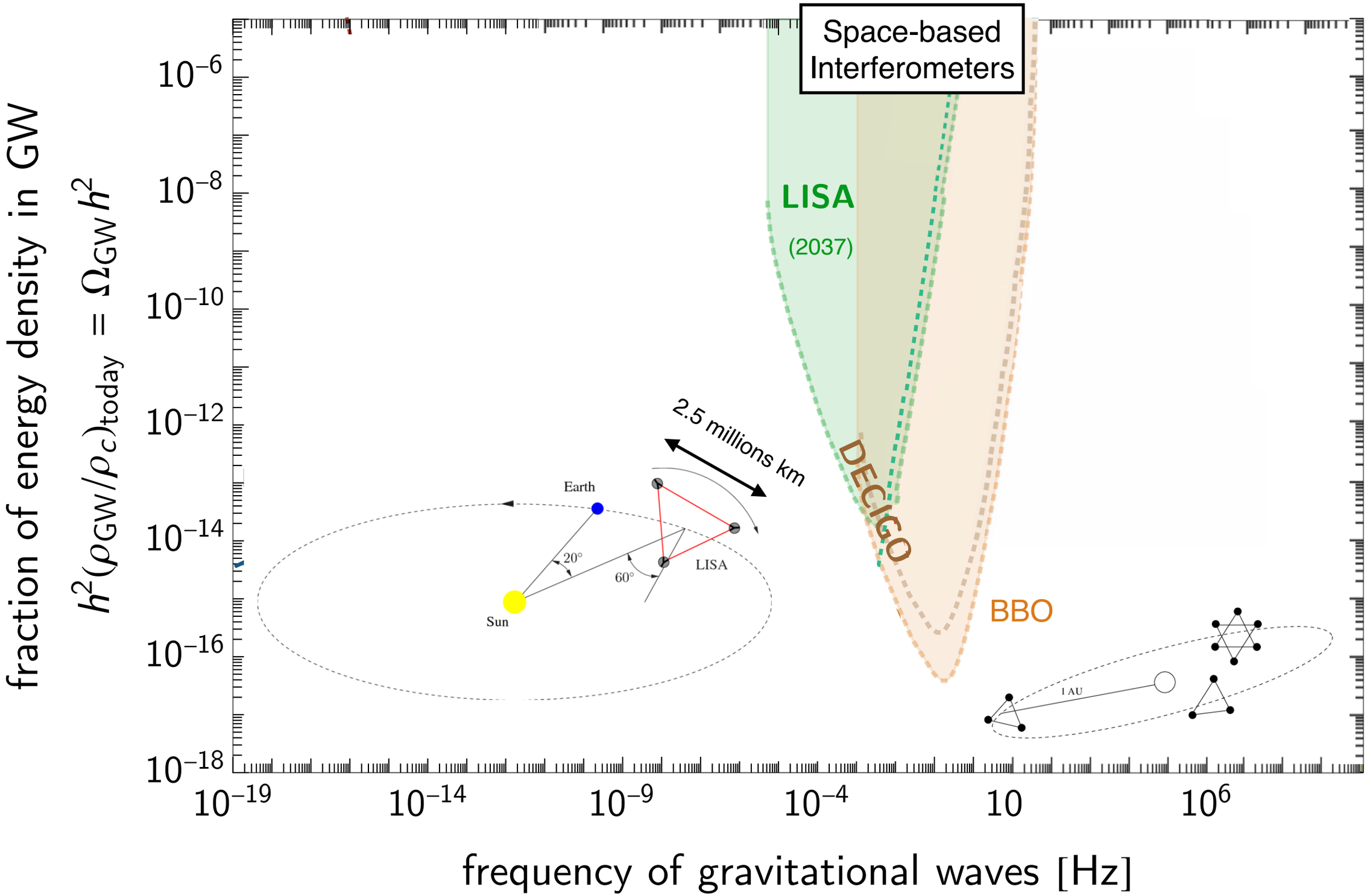

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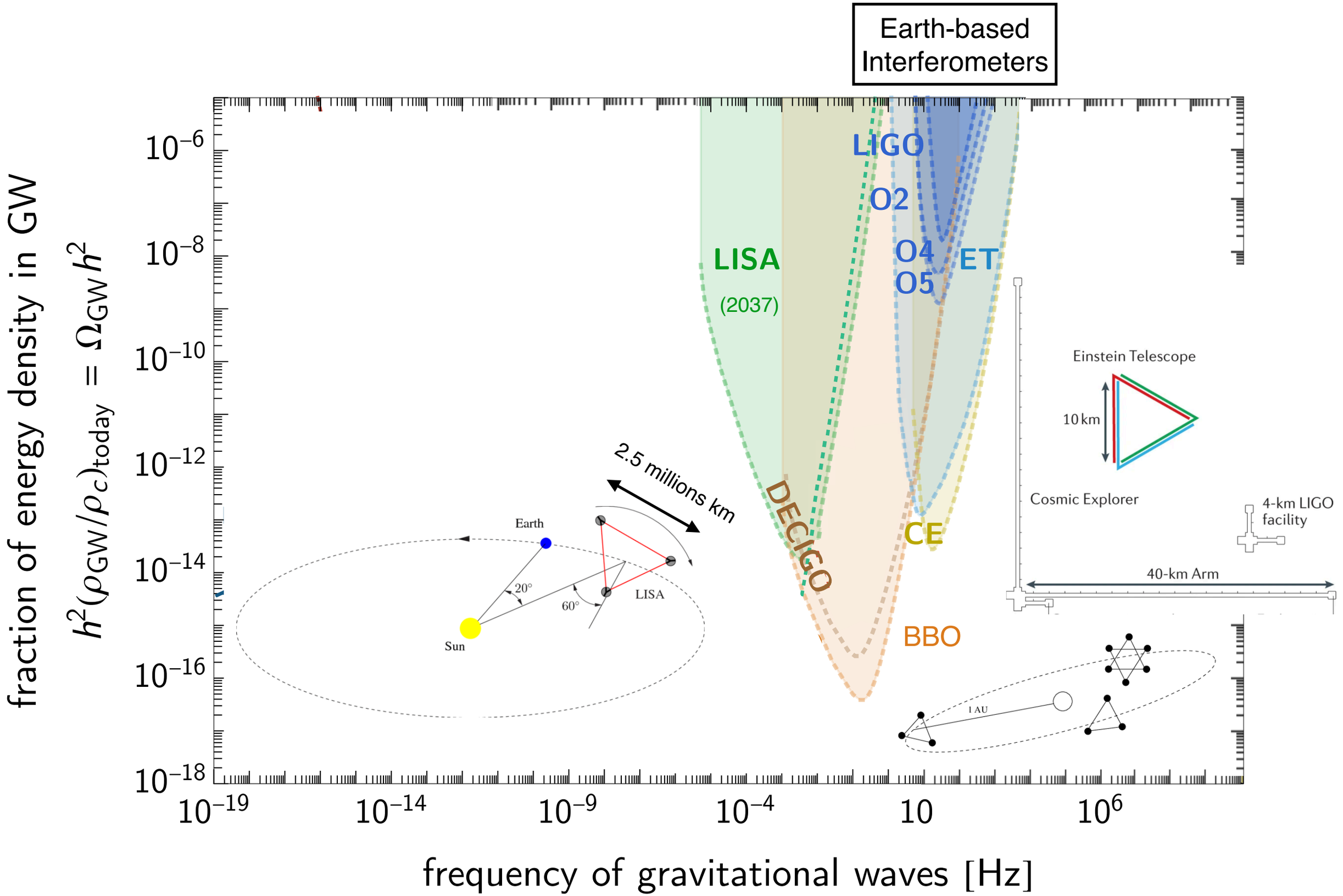

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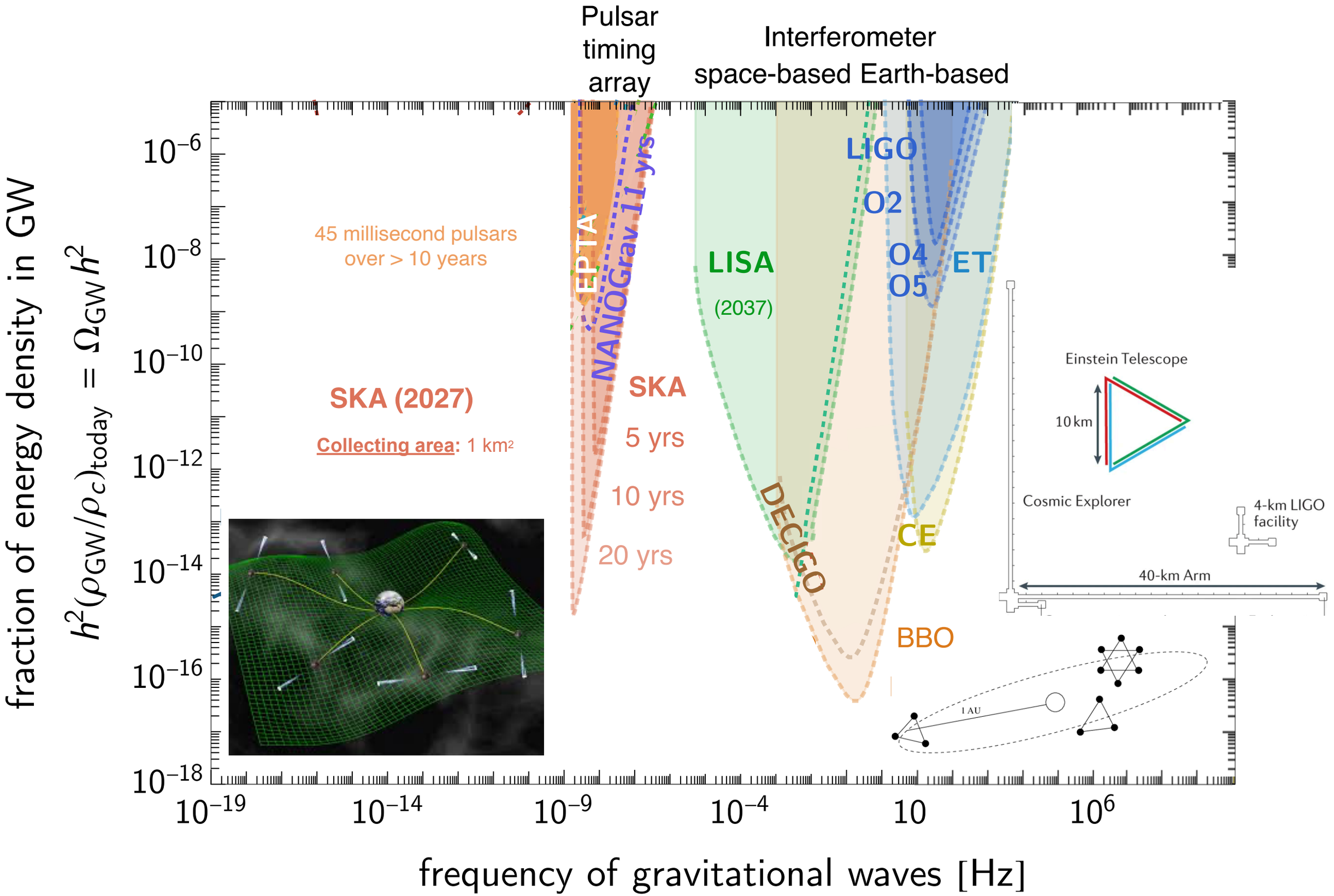

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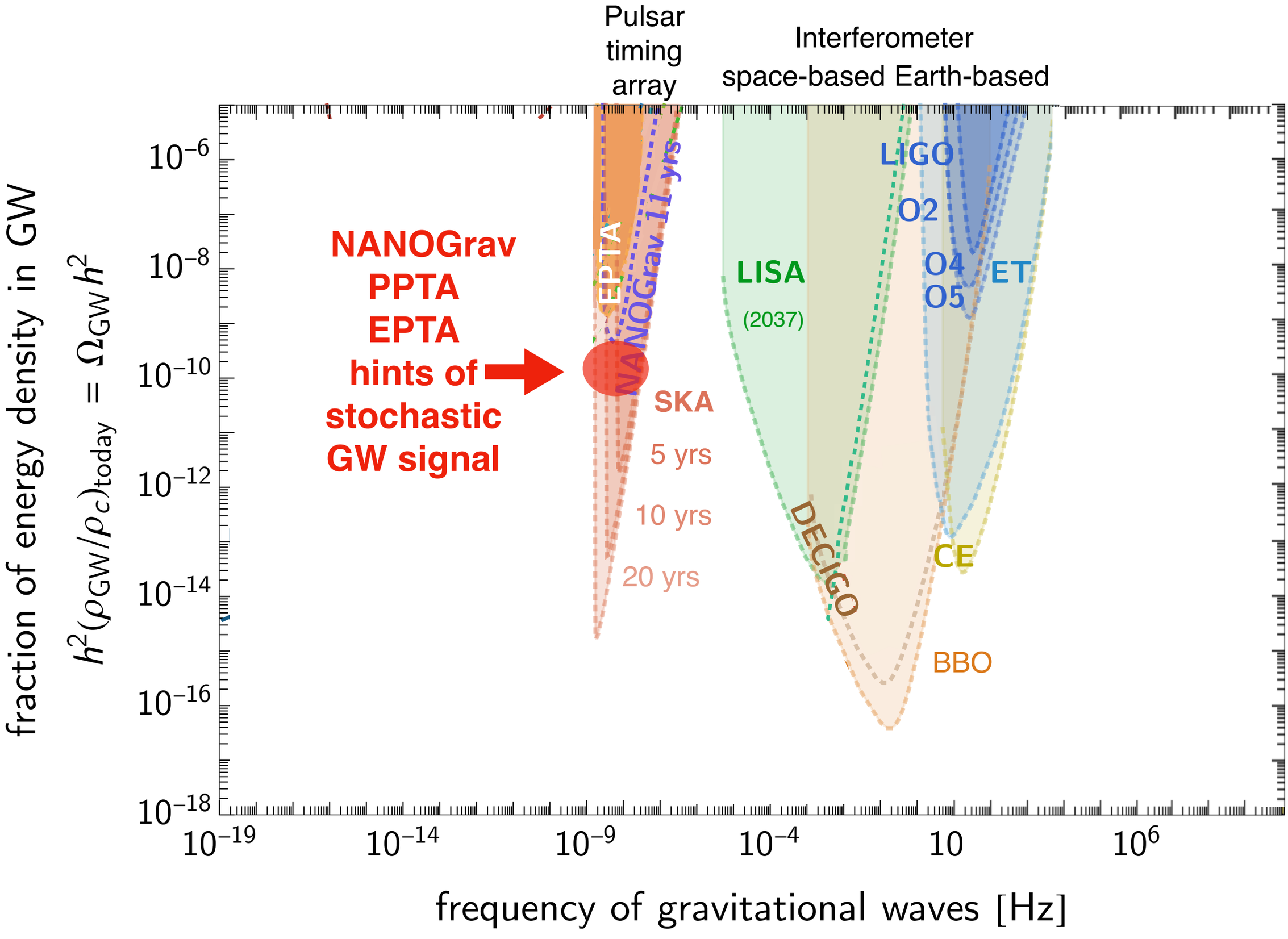

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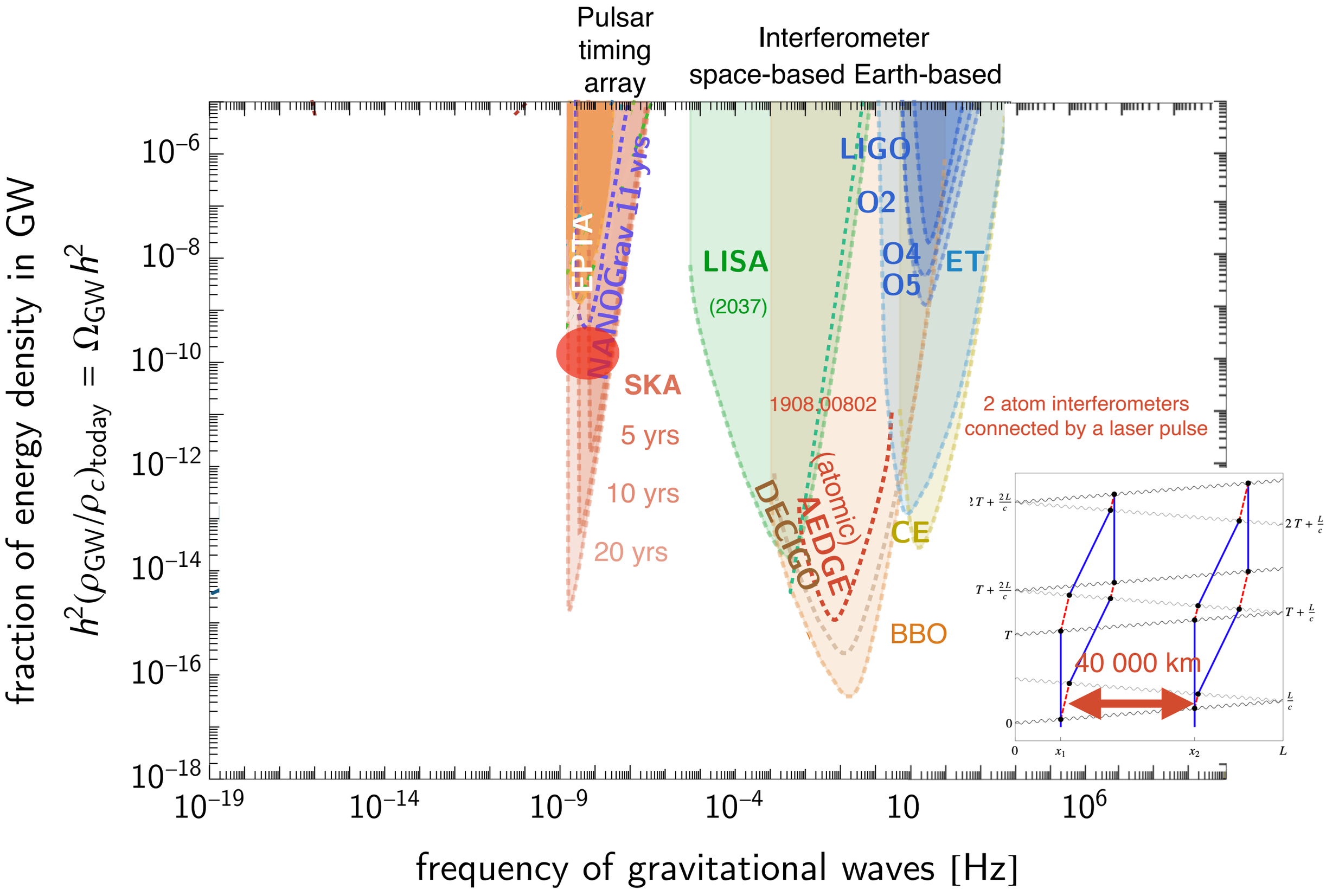

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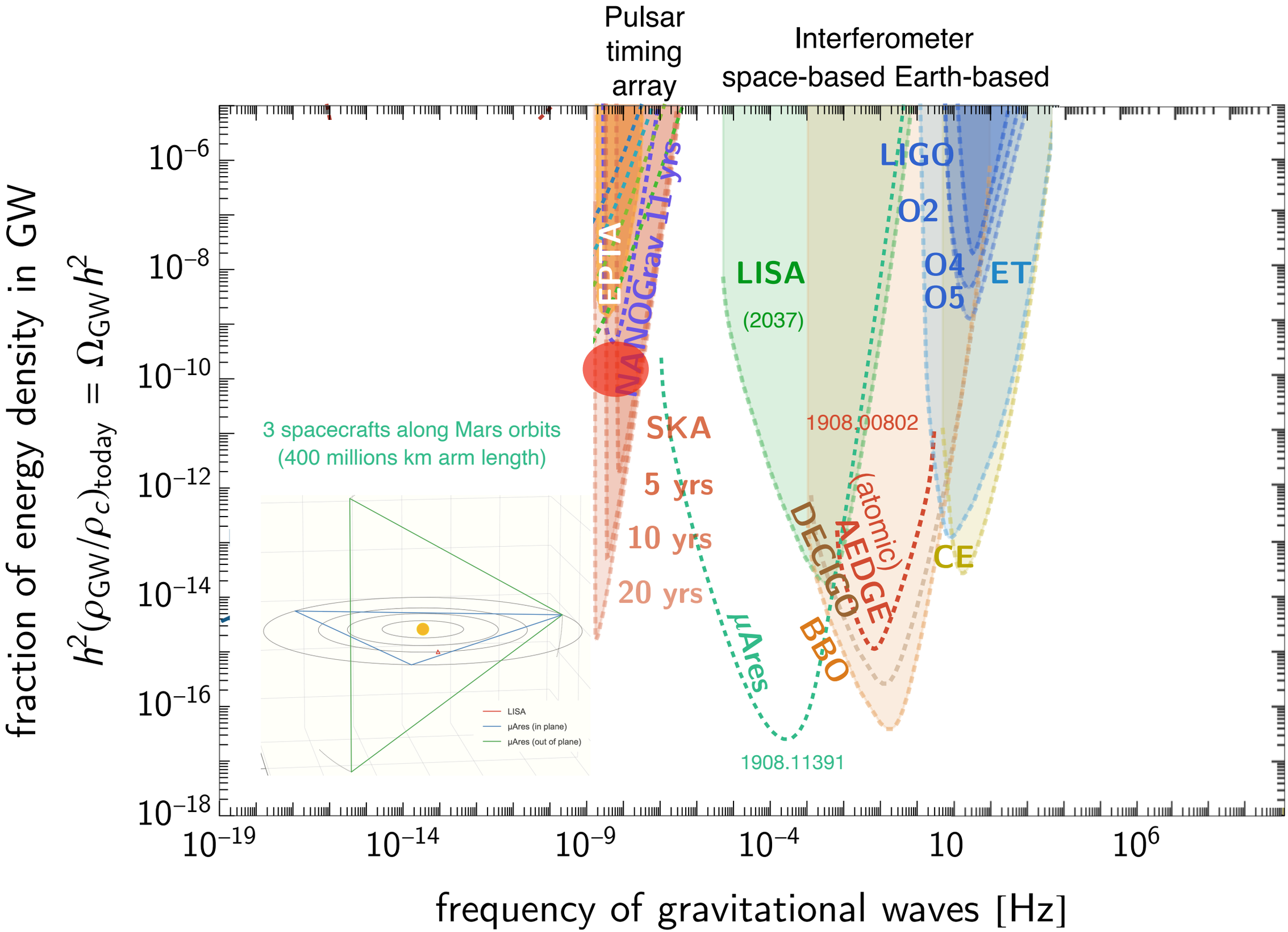

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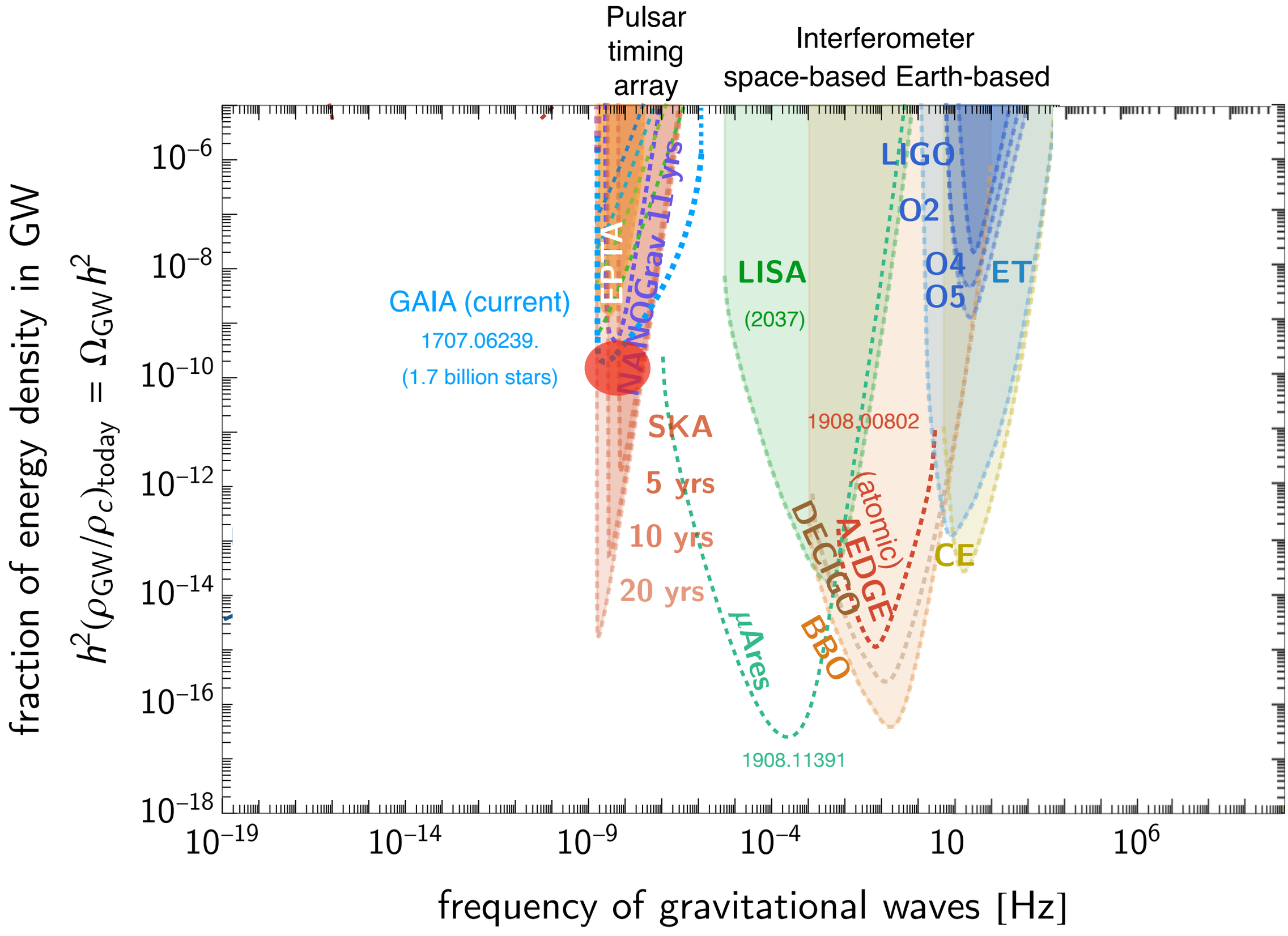

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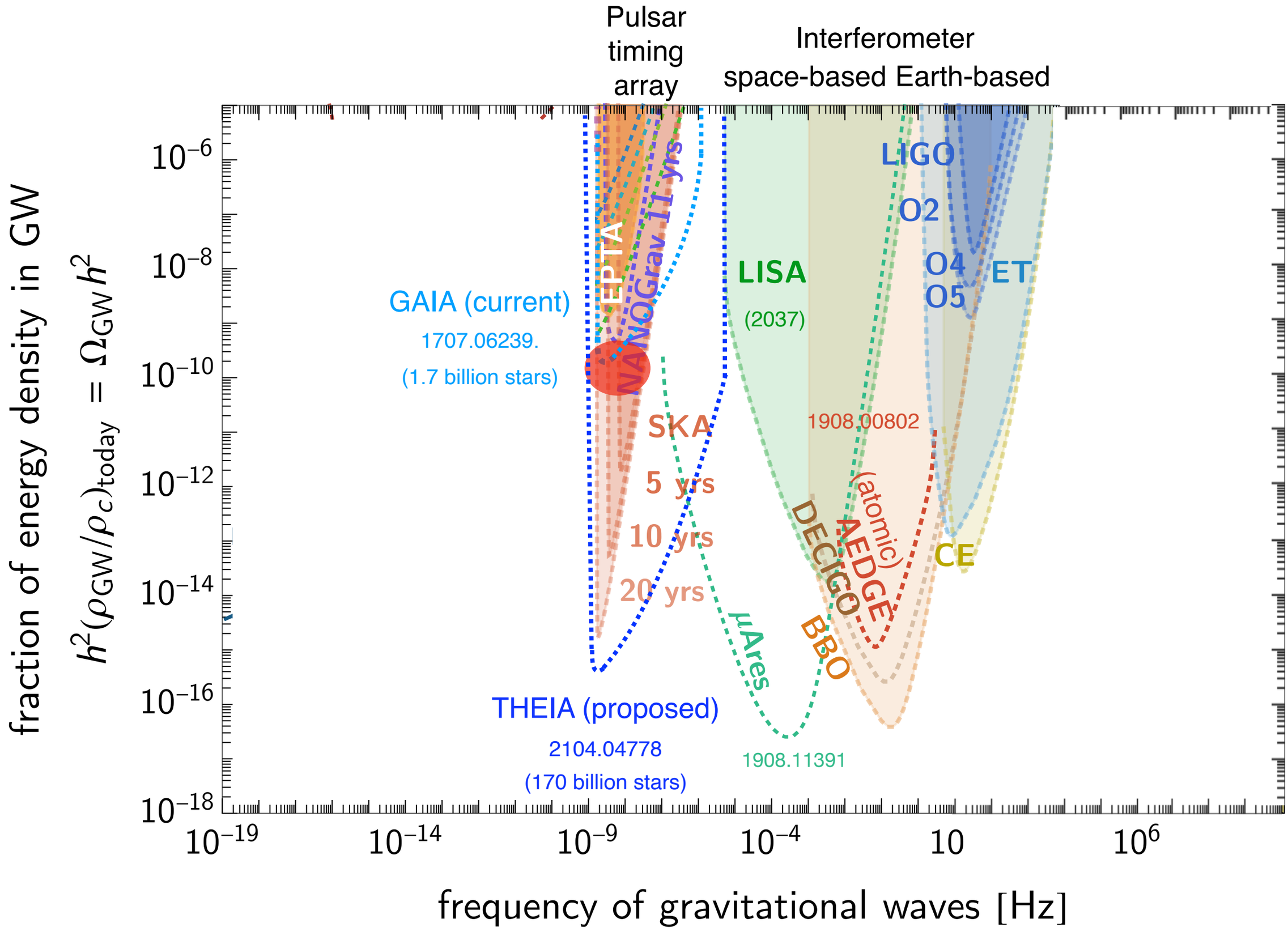

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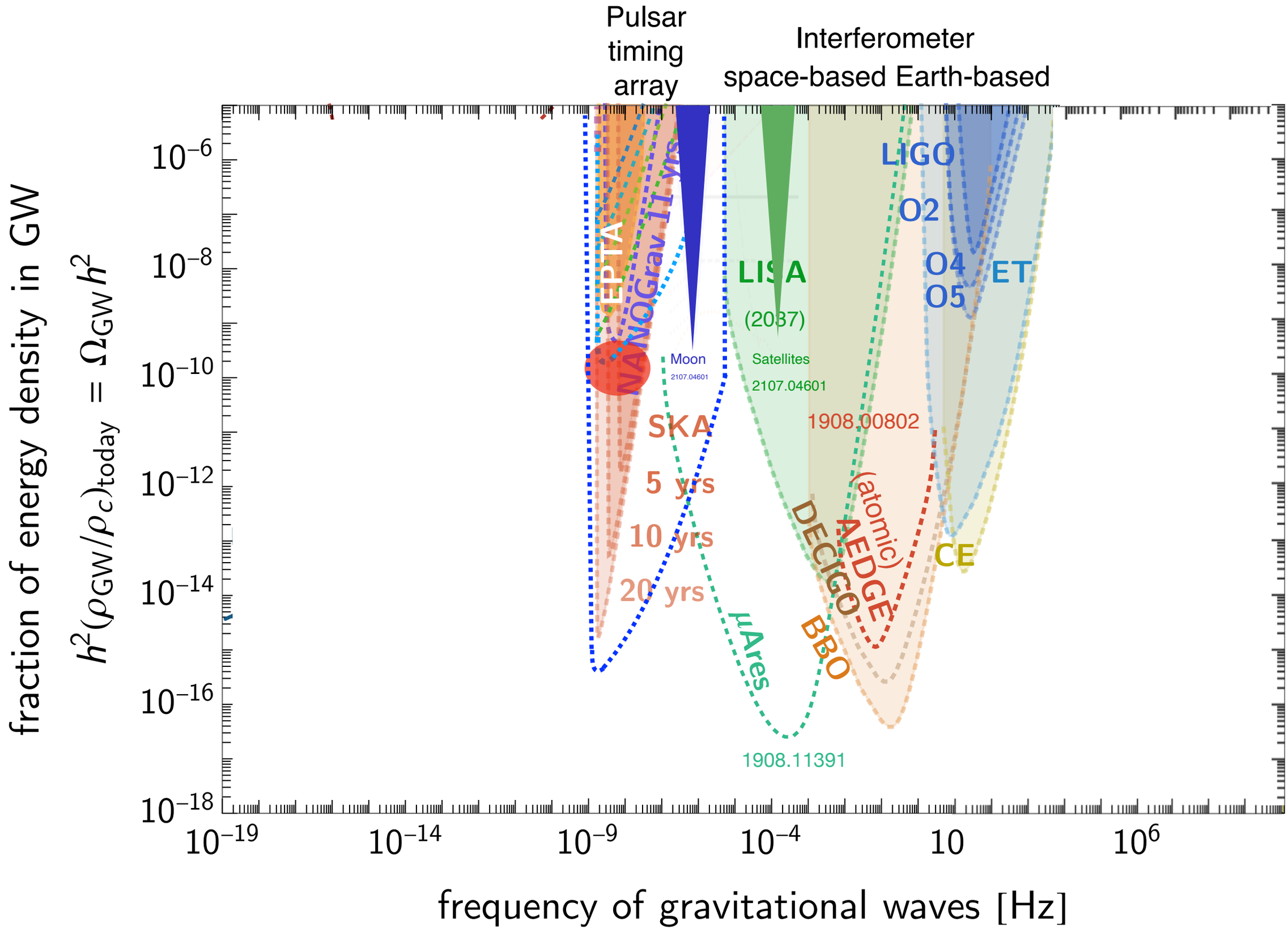

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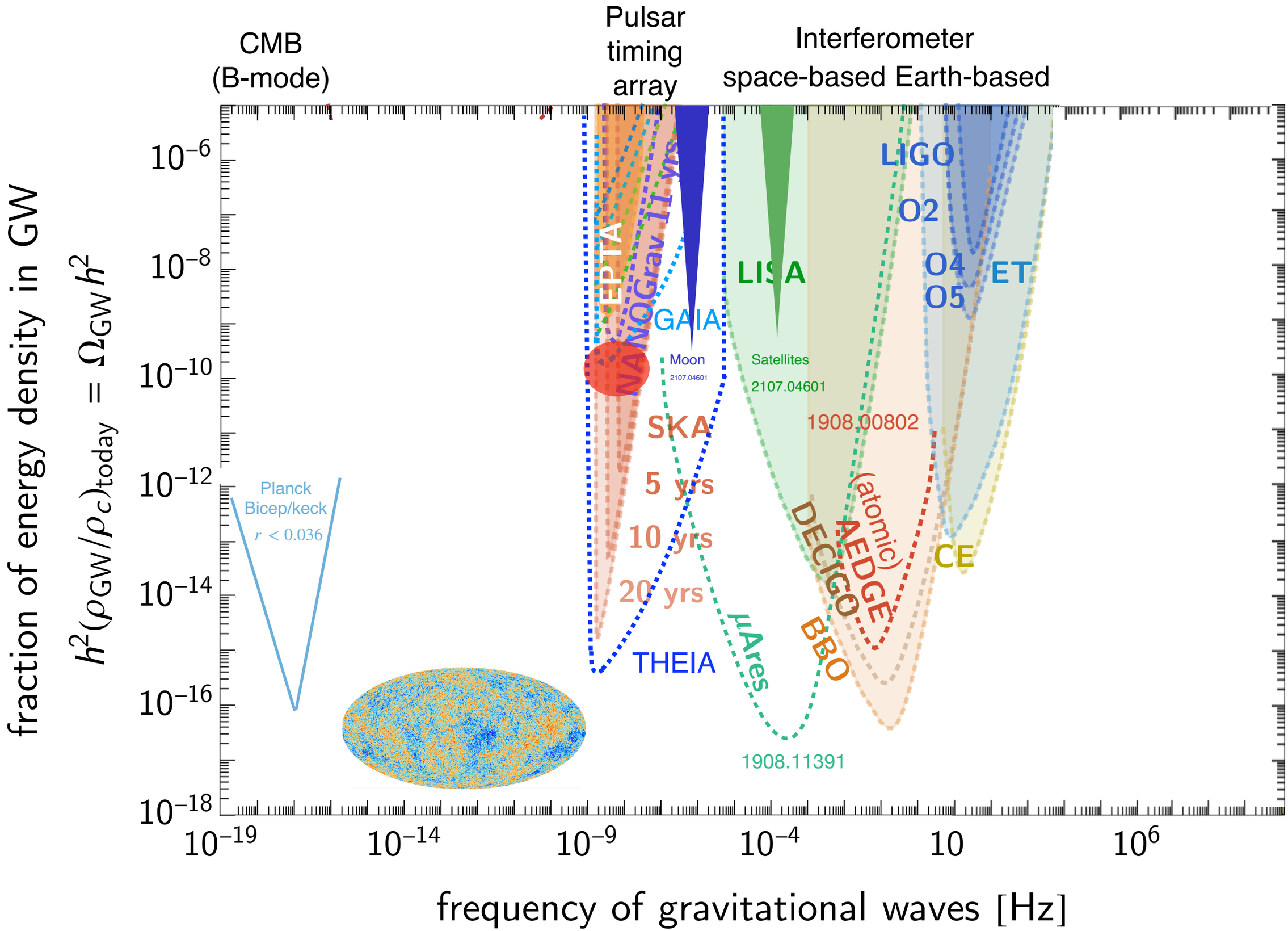

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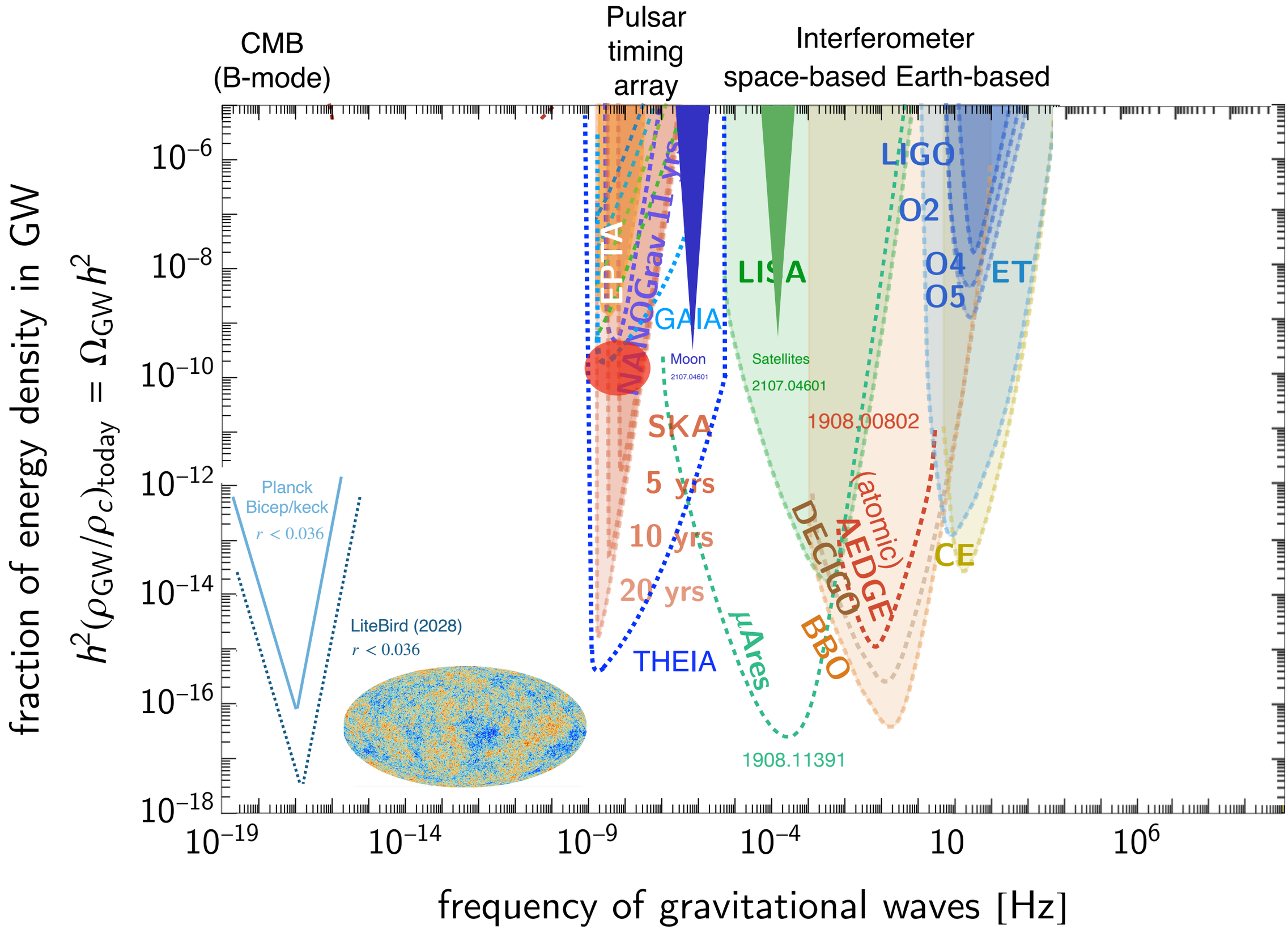

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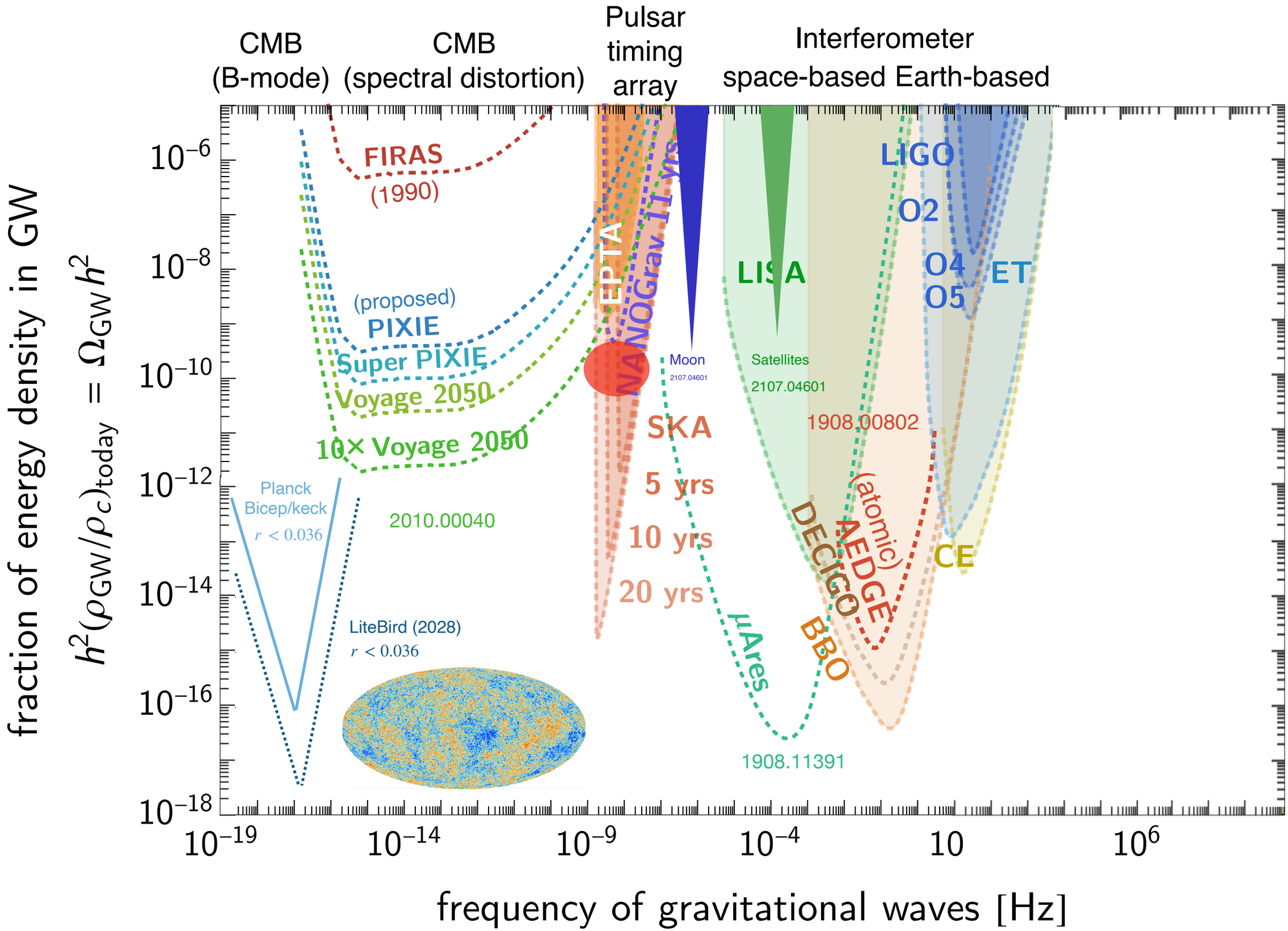

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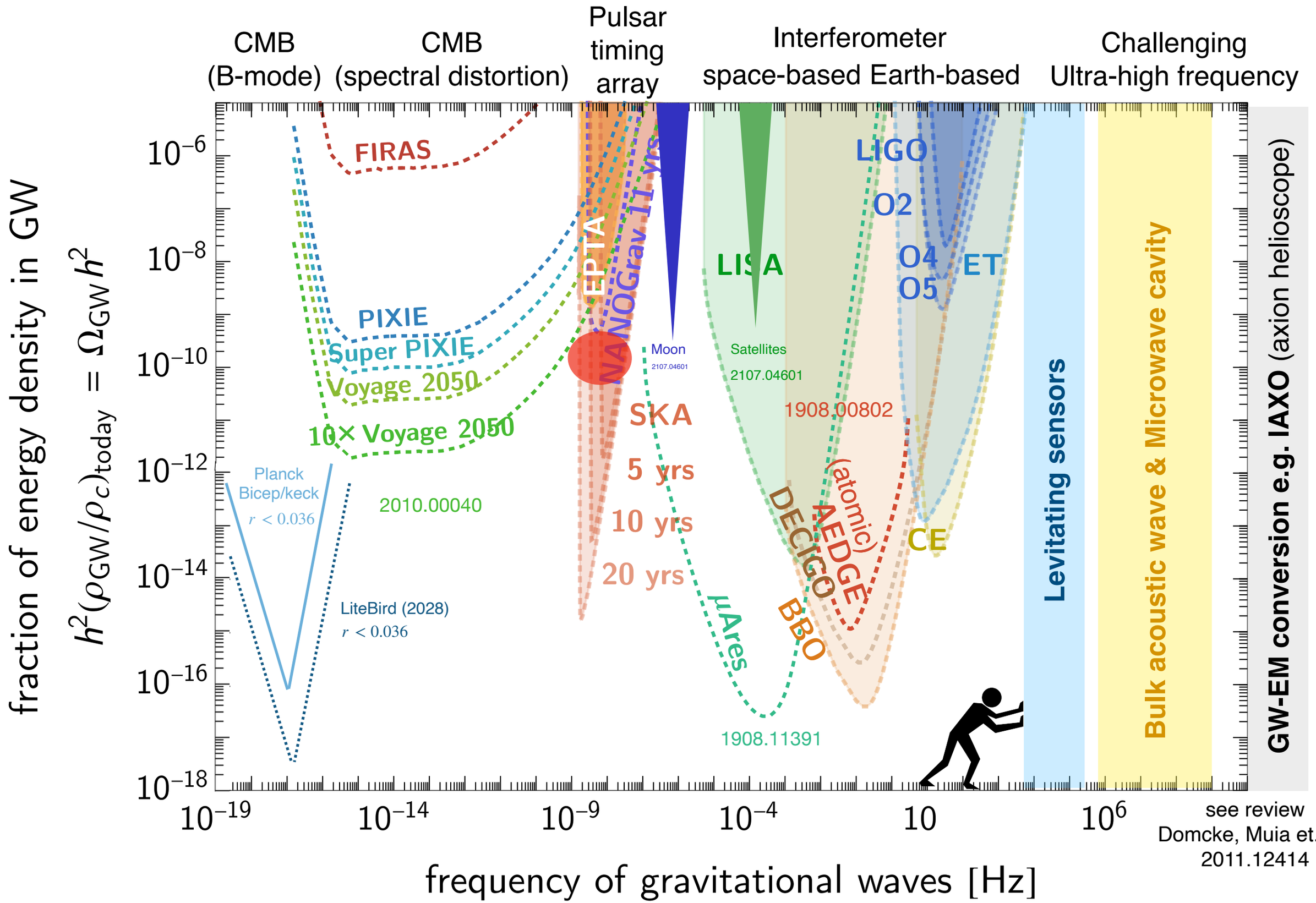

see review
Domcke, Muia et. al.,
2011.12414

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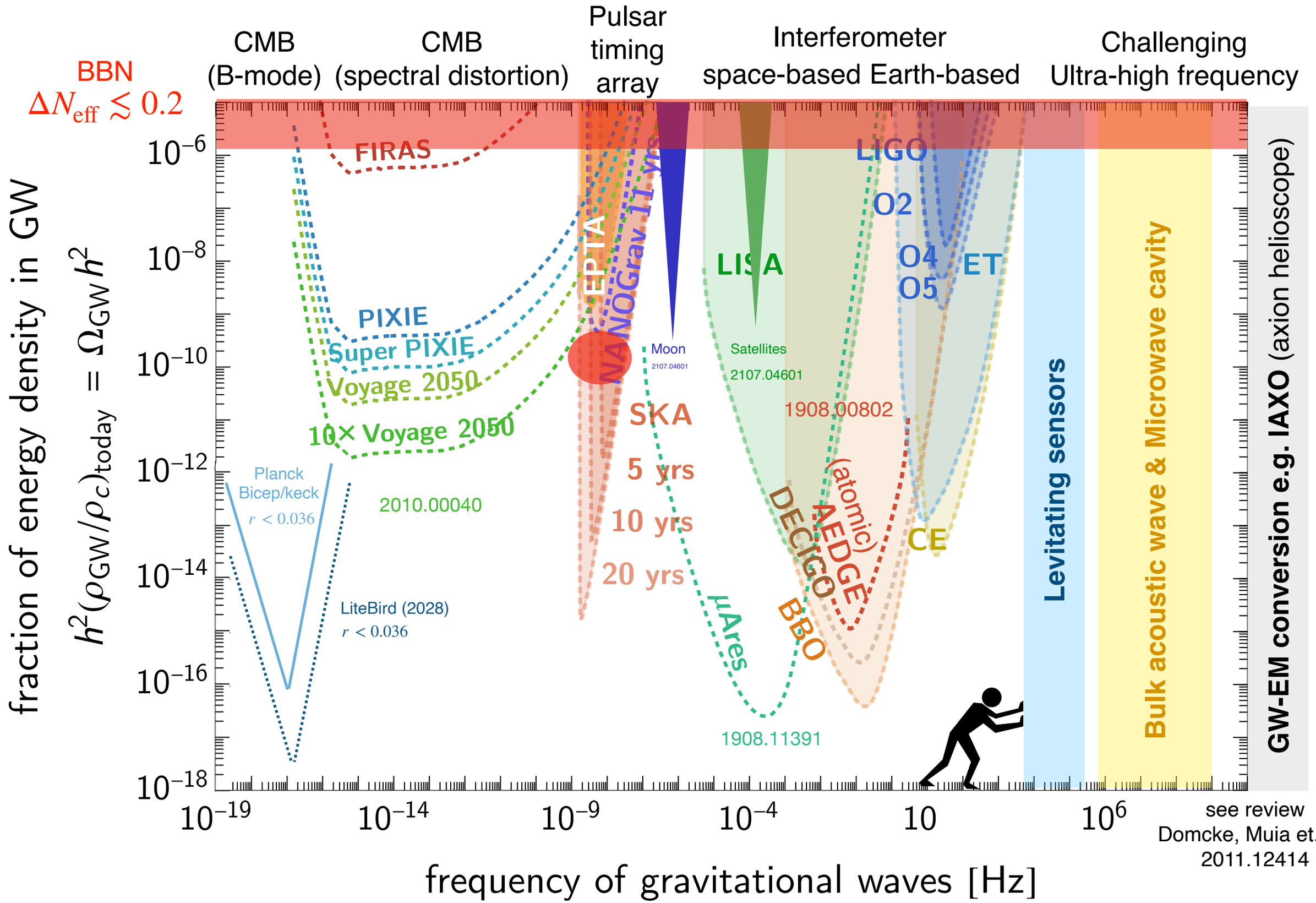

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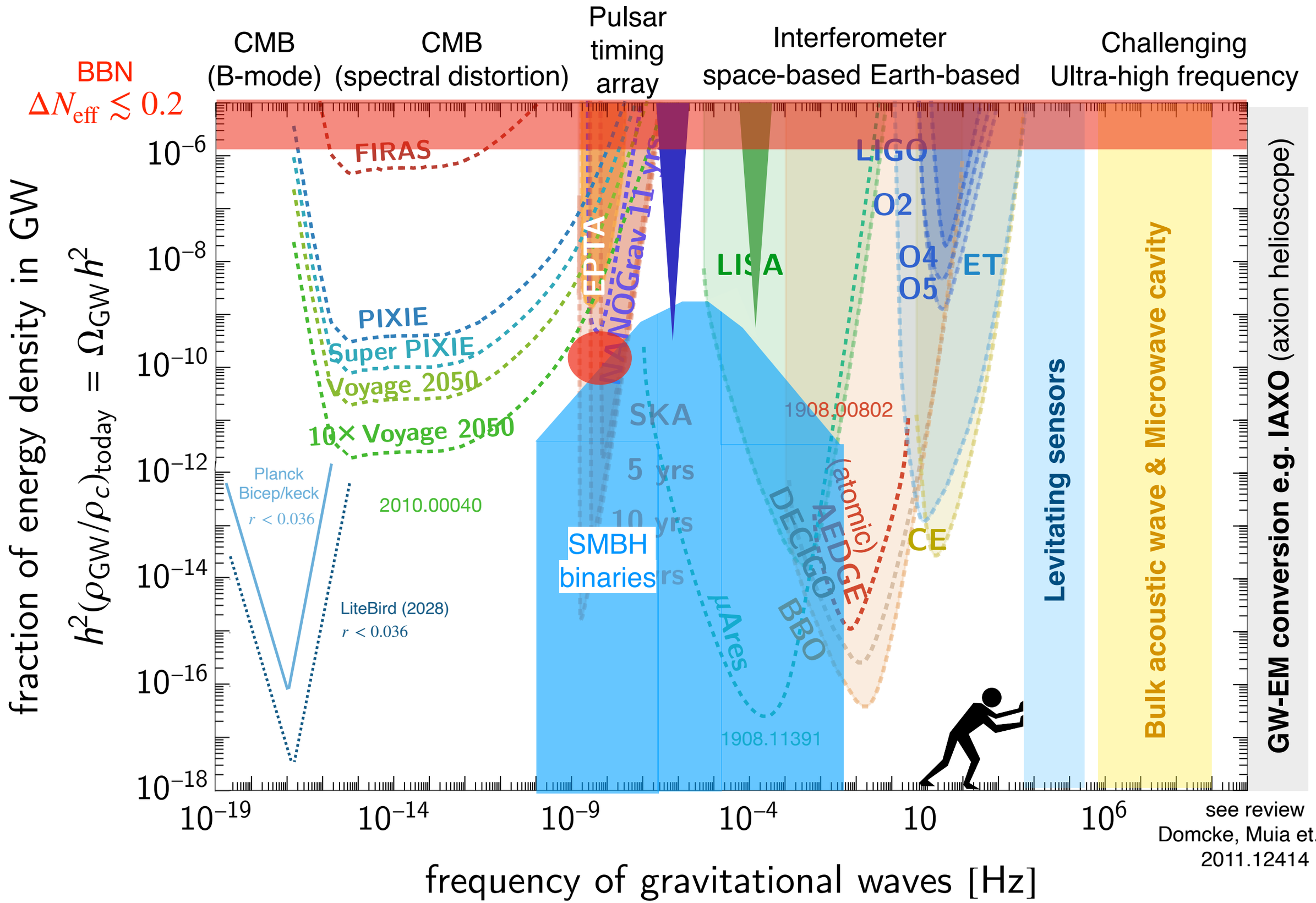
Astrophysical foreground



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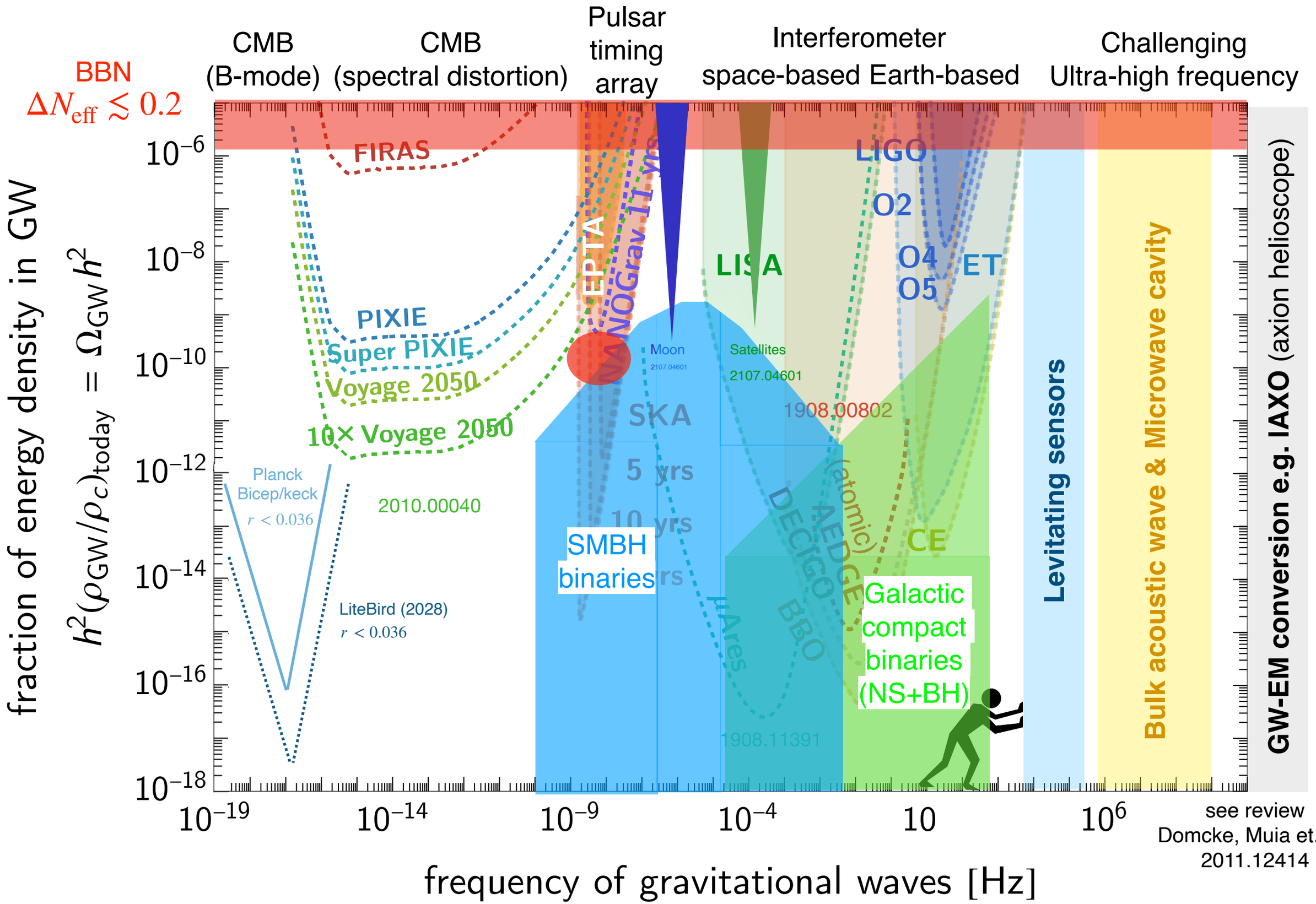

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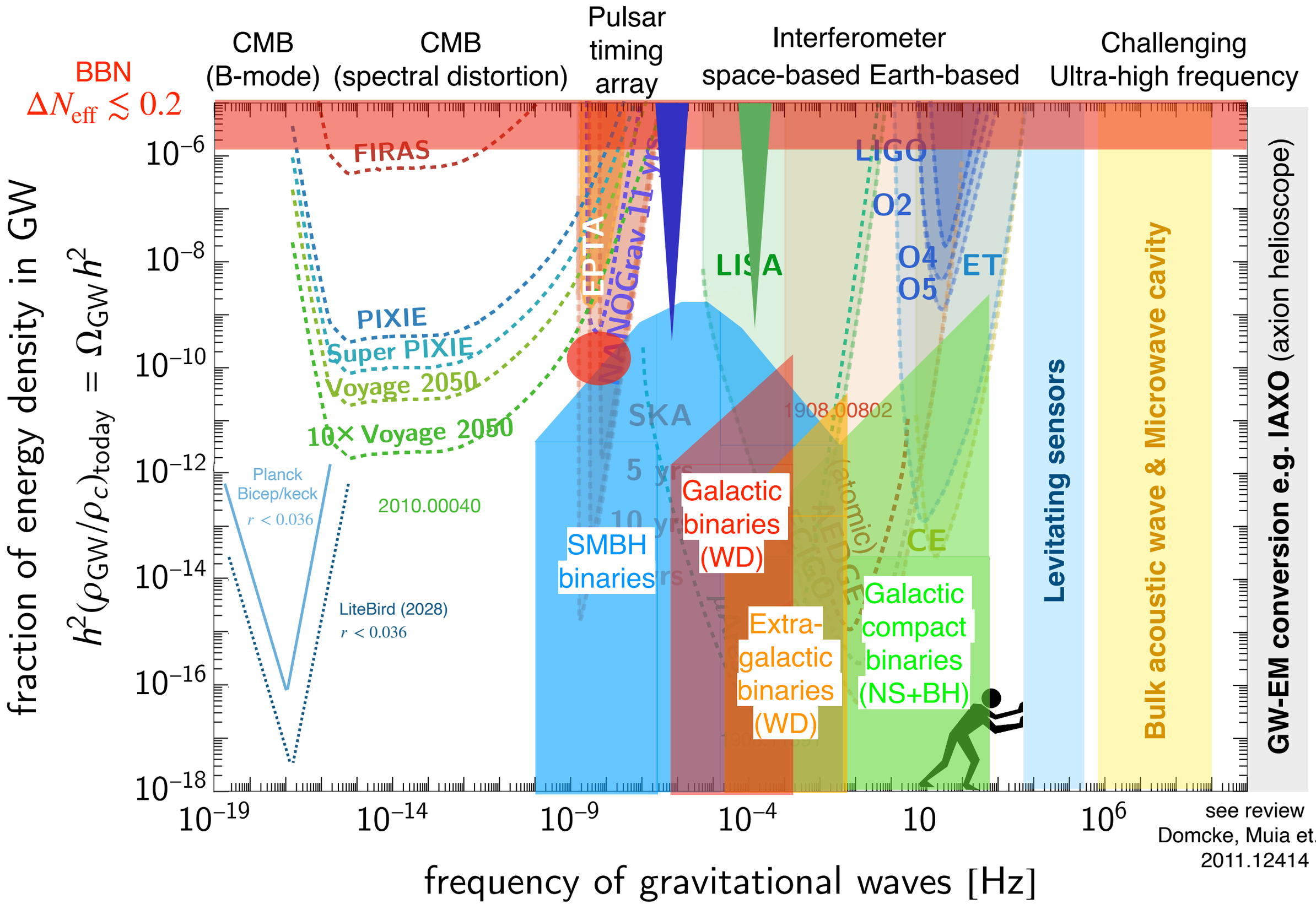

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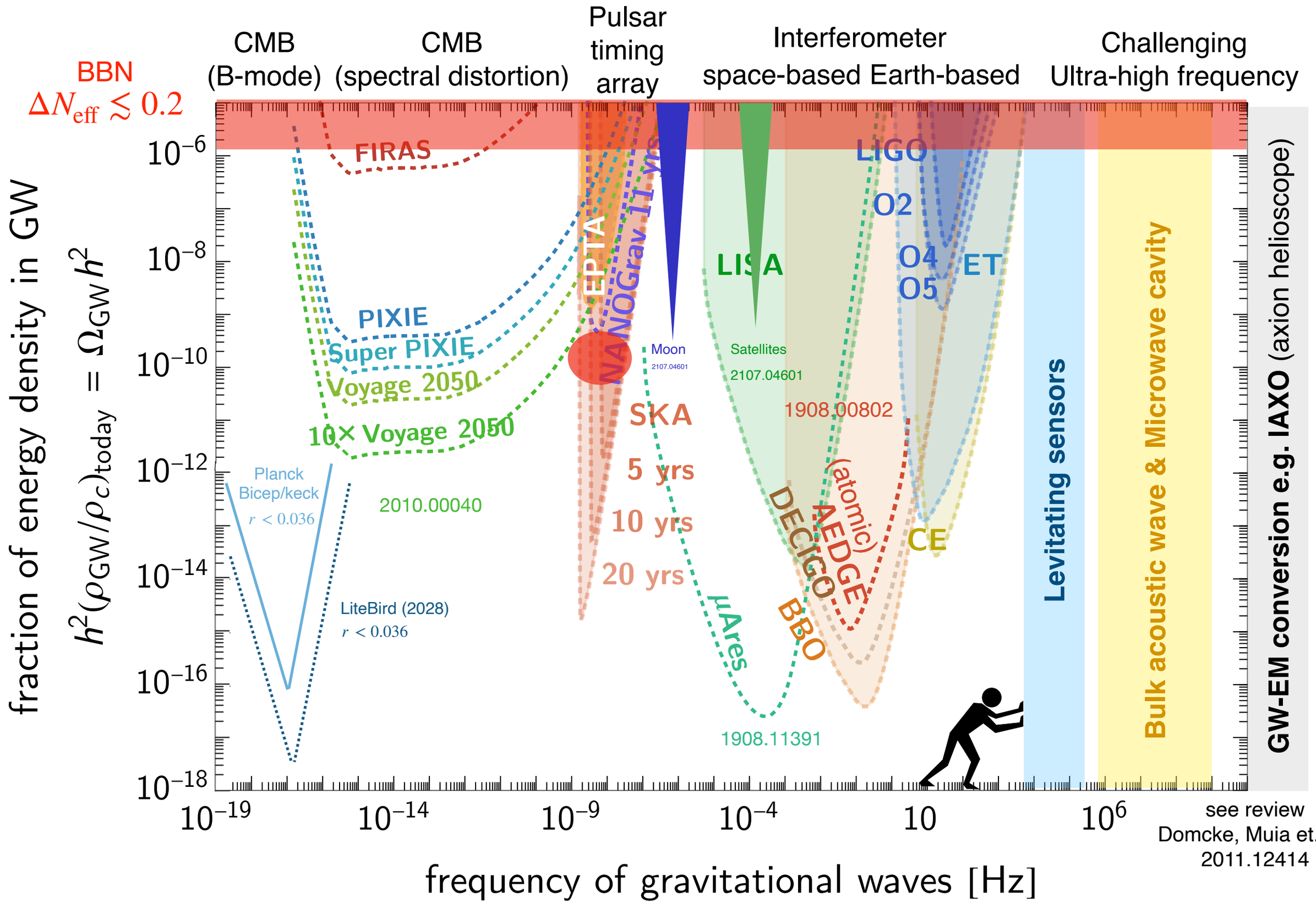

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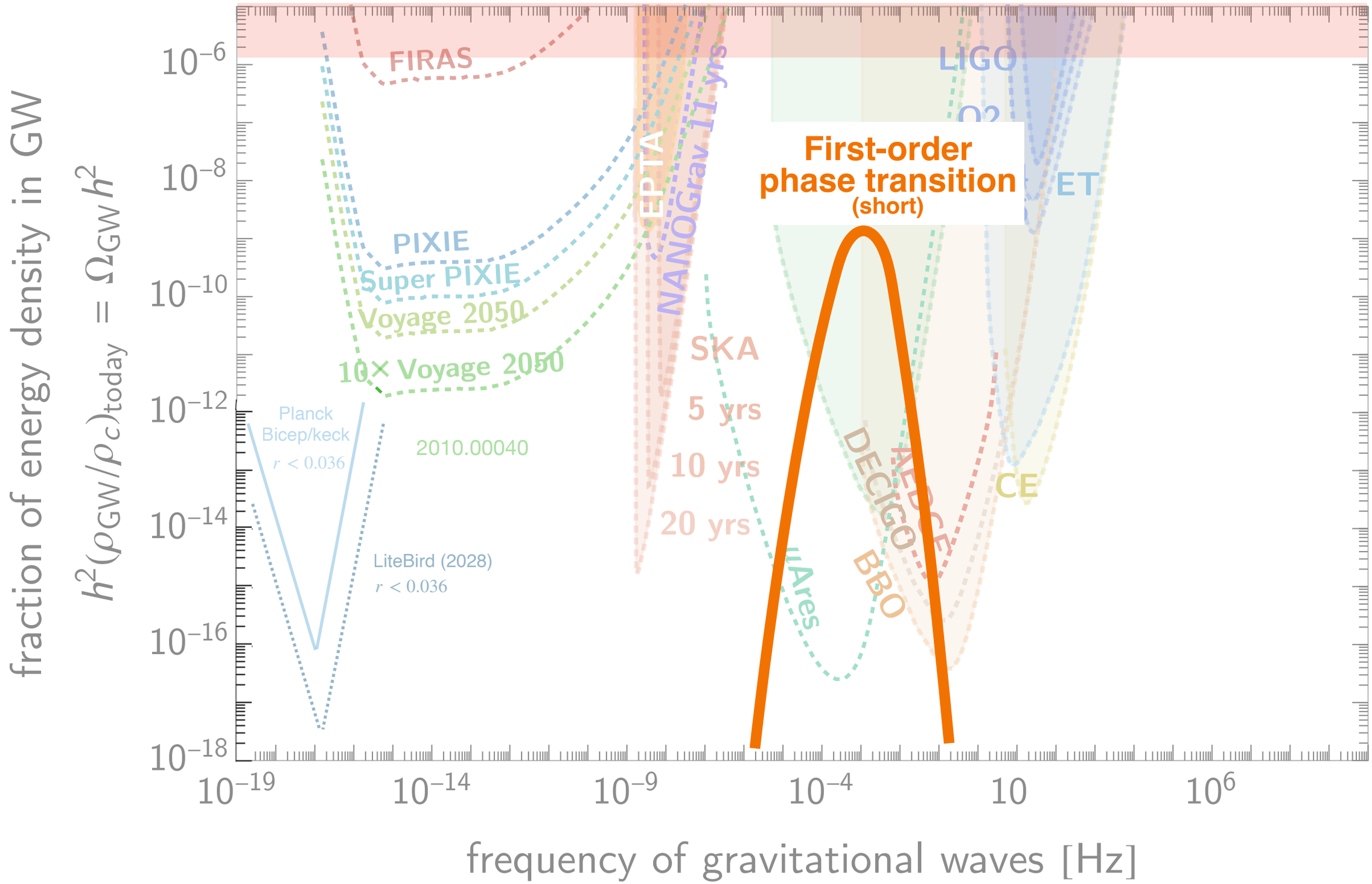
GW of primordial origins



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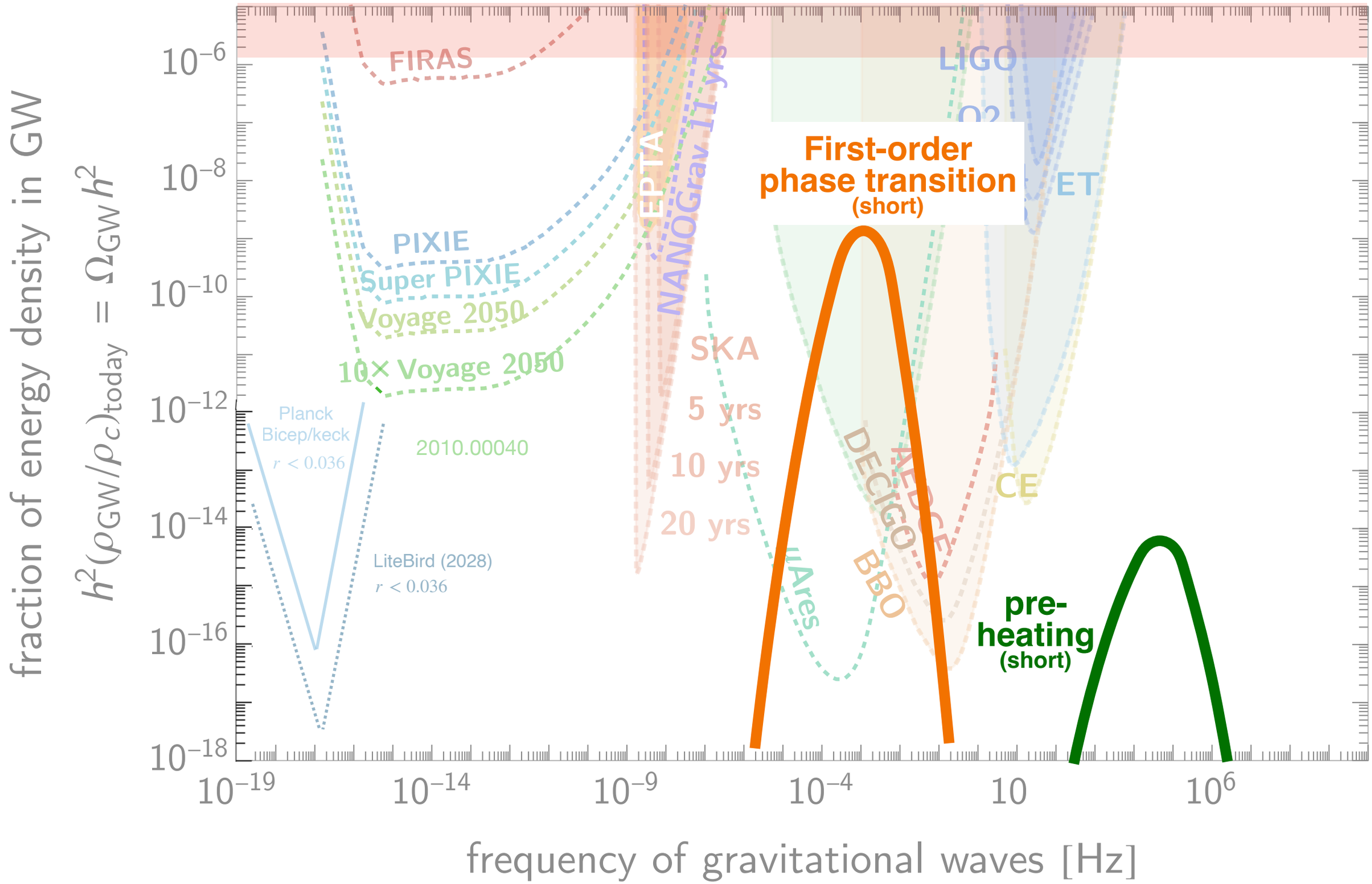

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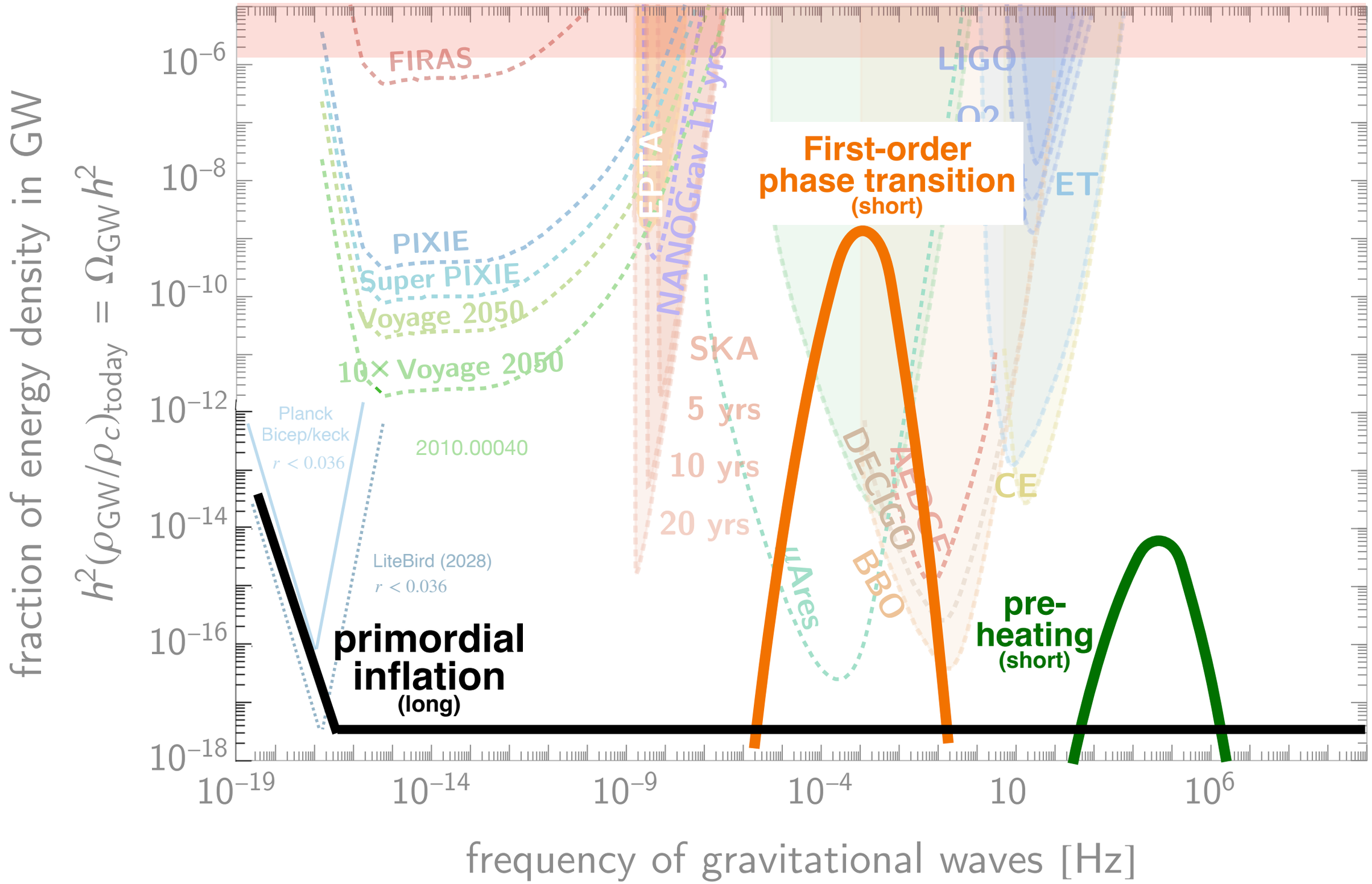

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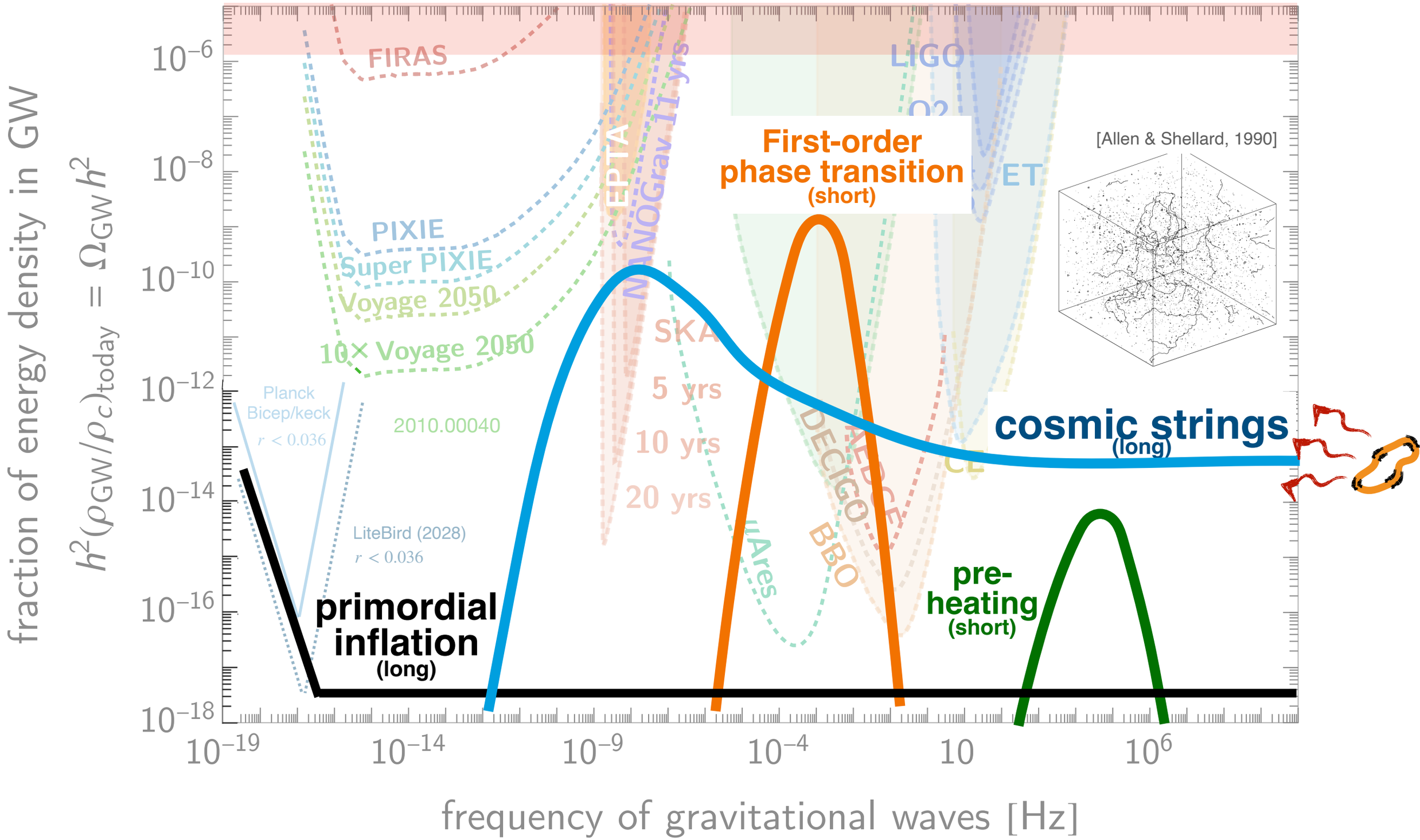

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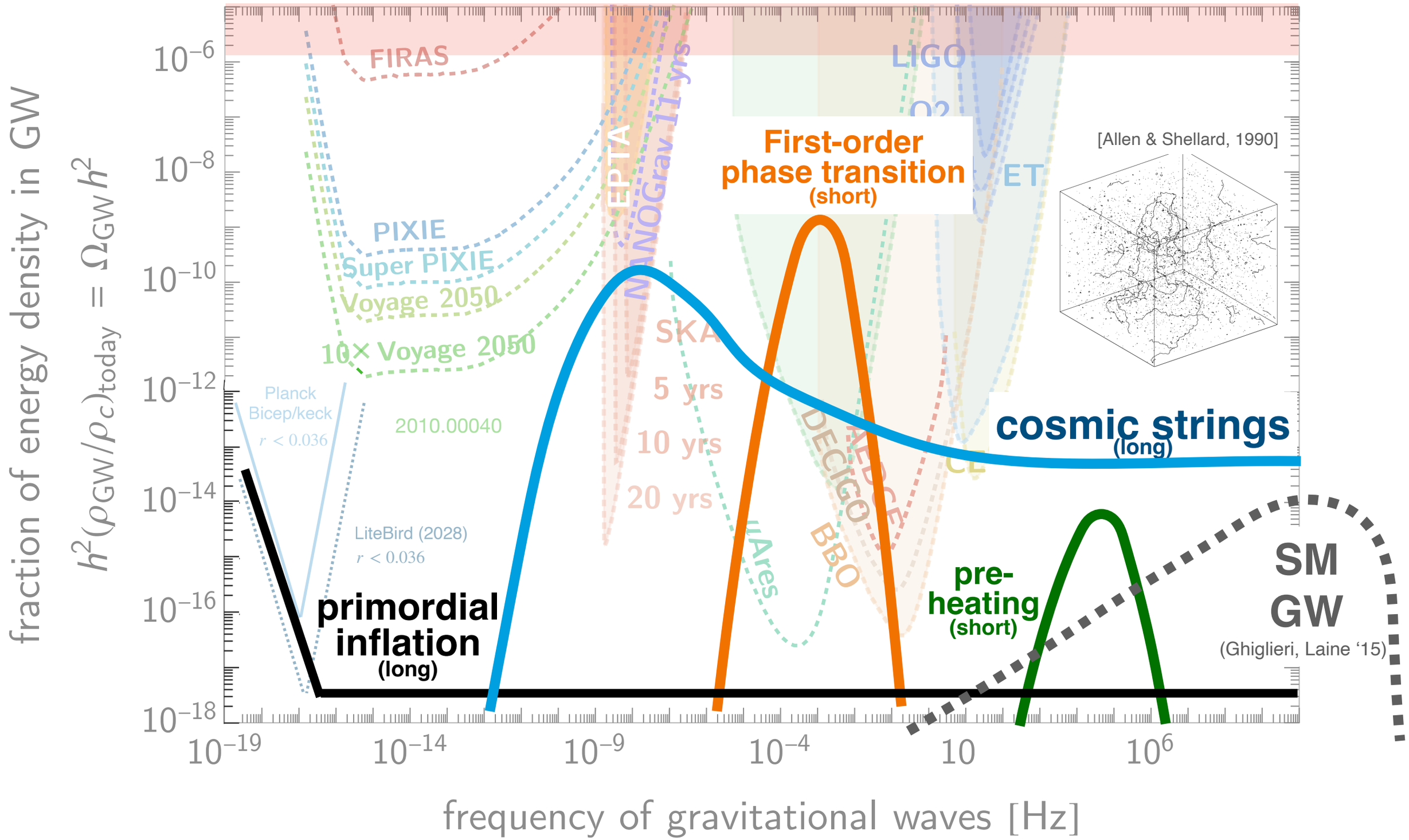
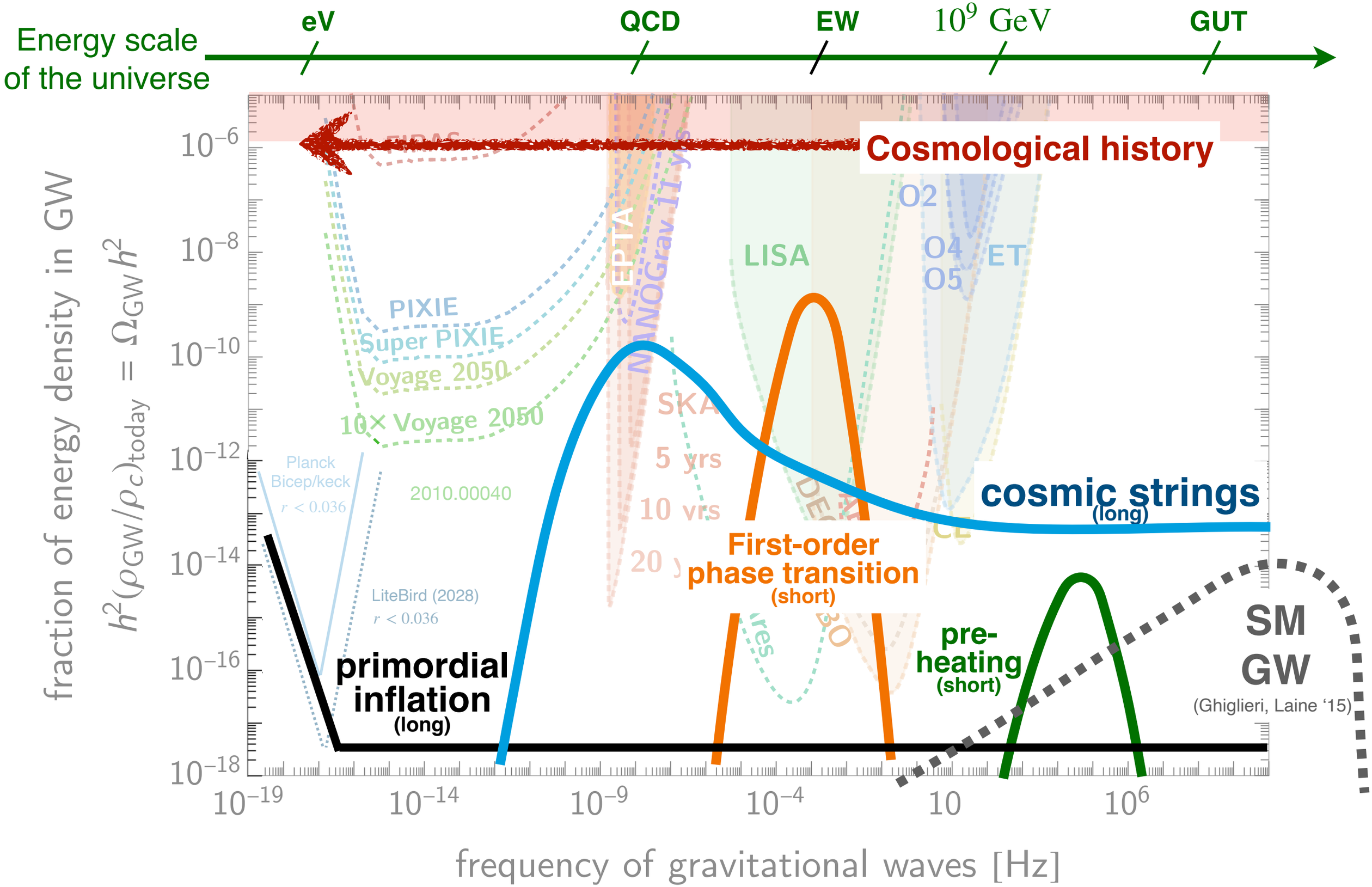


Cosmic Archeology



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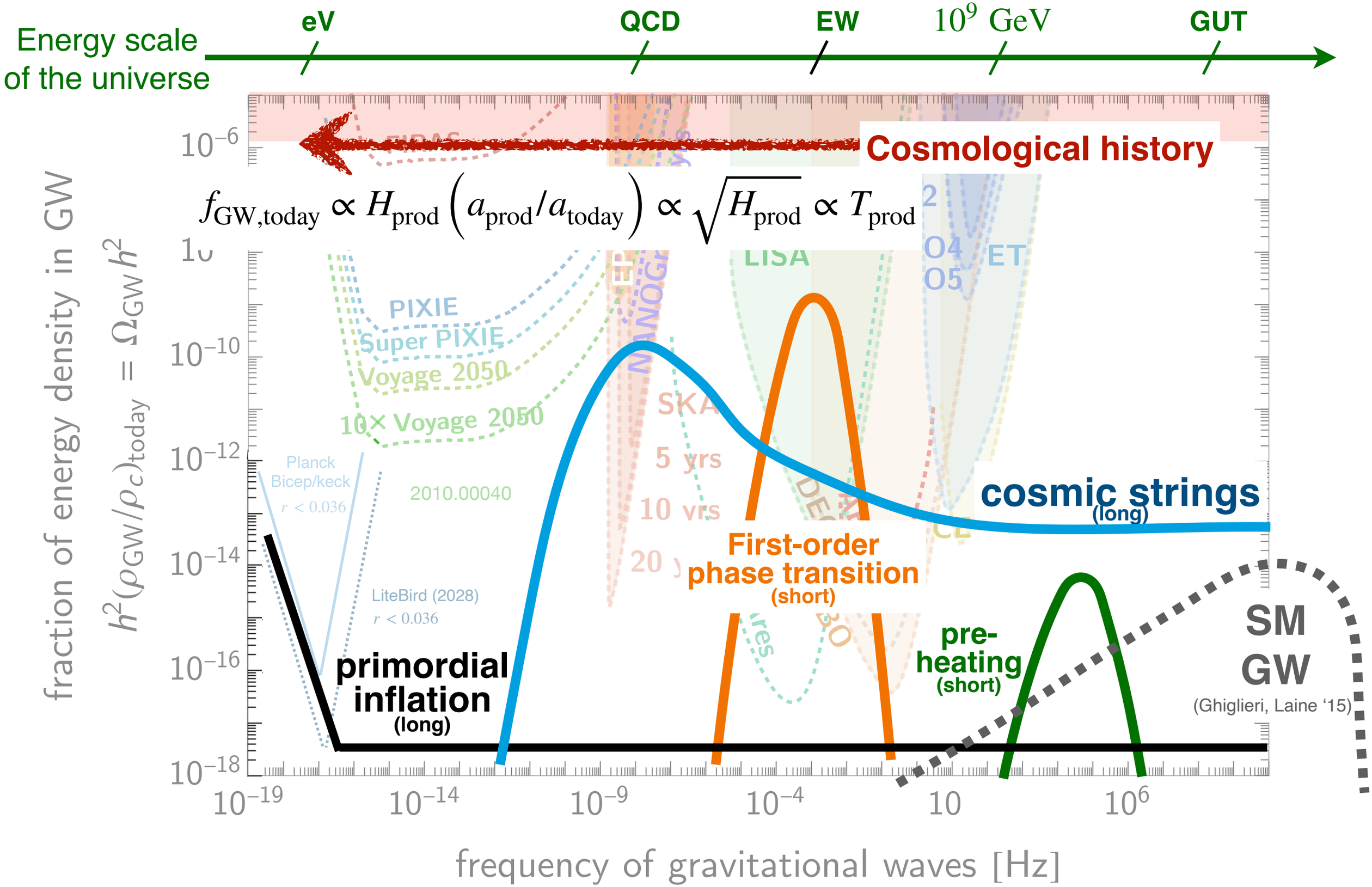

Cosmic Archeology

Energy scale of the universe

eV | QCD | EW | 10^9 GeV | GUT

Cosmological history

$$f_{\mathrm{GW,today}} \propto H_{\mathrm{prod}} \left(a_{\mathrm{prod}} / a_{\mathrm{today}} \right) \propto \sqrt{H_{\mathrm{prod}}} \propto T_{\mathrm{prod}}$$ **radiation dom.** $H^{-1/2} \propto a$

fraction of energy density in GW

$h^2(\rho_{\mathrm{GW}}/\rho_c)_{\mathrm{today}} = \Omega_{\mathrm{GW}} h^2$

10^{-6} 10^{-10} 10^{-12} 10^{-14} 10^{-16} 10^{-18}

PIXIE
Super PIXIE
Voyage 2050
10× Voyage 2050
Planck
Bicep/keck
$r < 0.036$
2010.00040
LiteBird (2028)
$r < 0.036$
primordial inflation (long)
SKA
5 yrs
10 yrs
20 yrs
LISA
O4
O5
ET
cosmic strings (long)
First-order phase transition (short)
pre-heating (short)
SM GW
(Ghiglieri, Laine '15)

10^{-19} 10^{-14} 10^{-9} 10^{-4} 10 10^{6}

frequency of gravitational waves [Hz]

Cosmic Archeology

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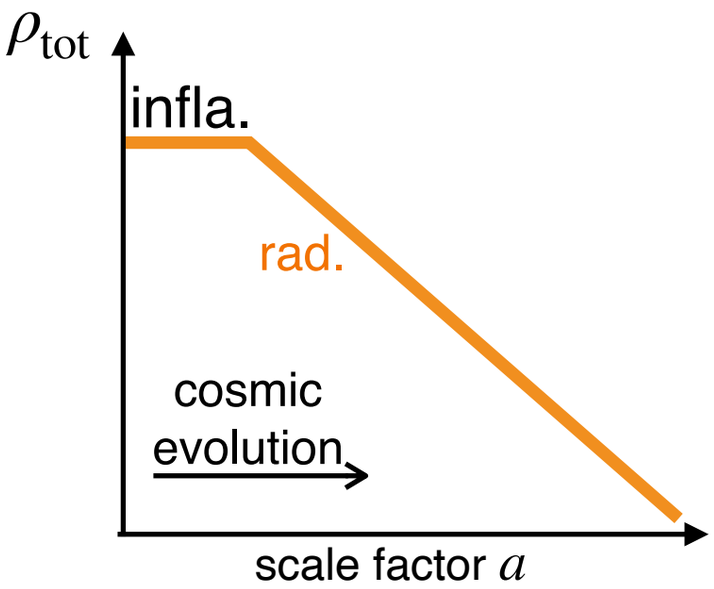
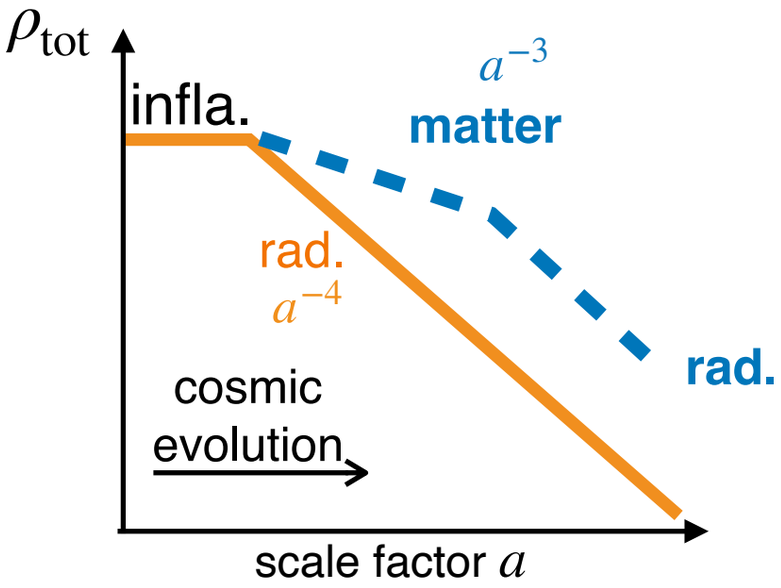
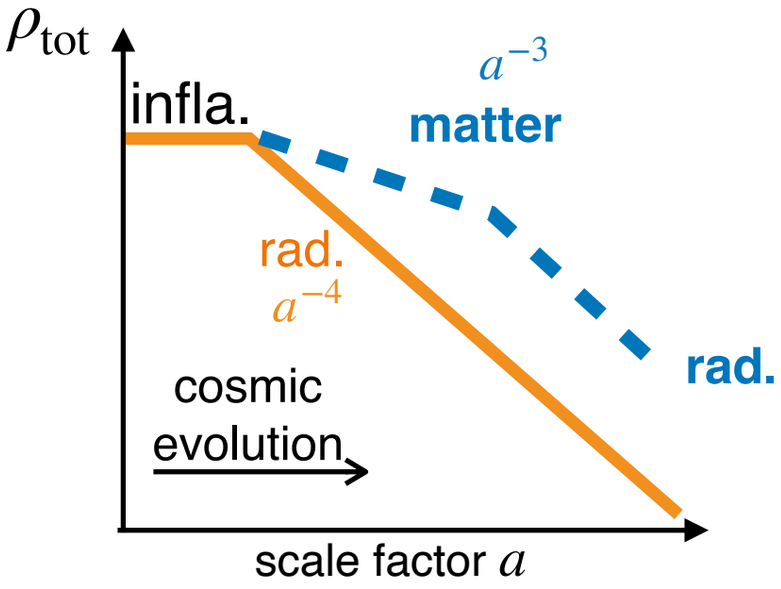

ρ_{tot}
infla.
rad.
cosmic
evolution
scale factor a

A) Post-inflationary dynamics



Inflation oscillation

A) Post-inflationary dynamics



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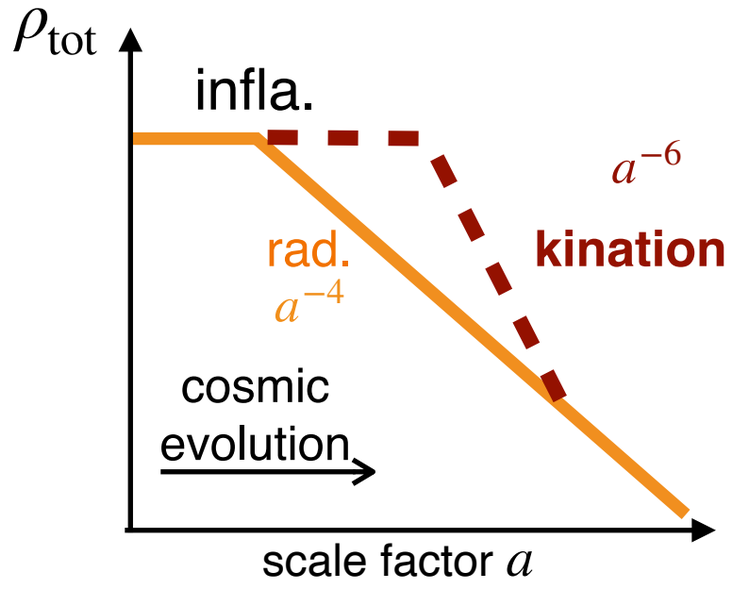

Quintessence inflation

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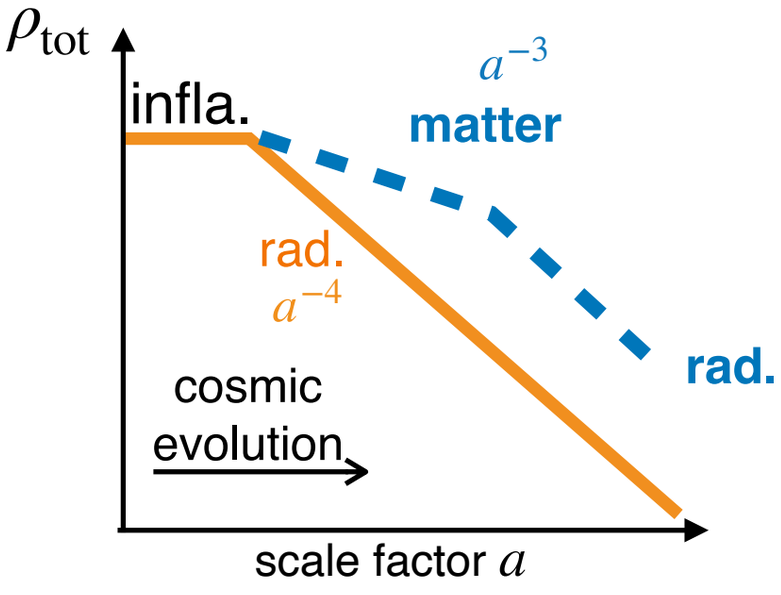

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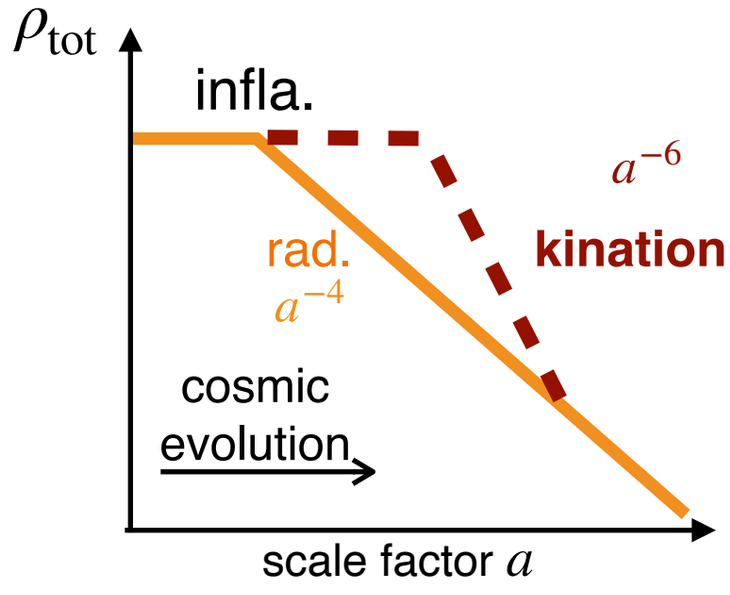

Quintessence inflation

B) Disconnected from inflation sector (this talk)

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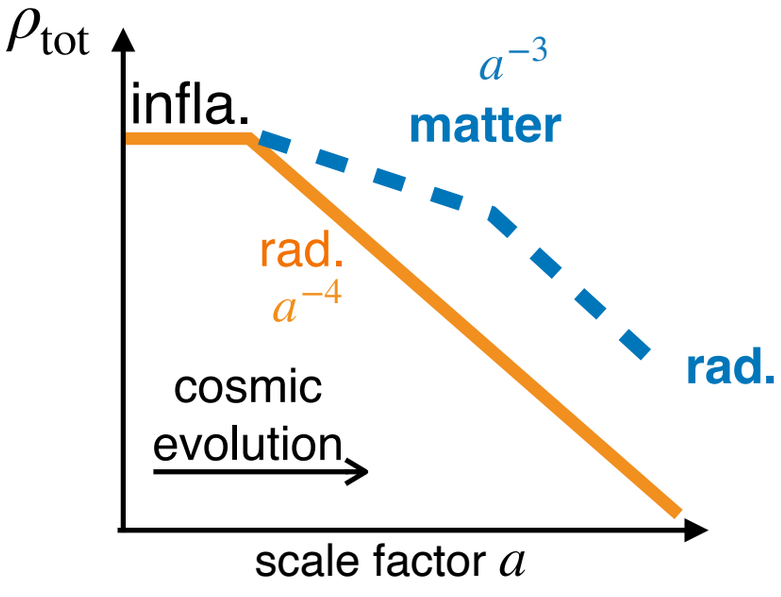

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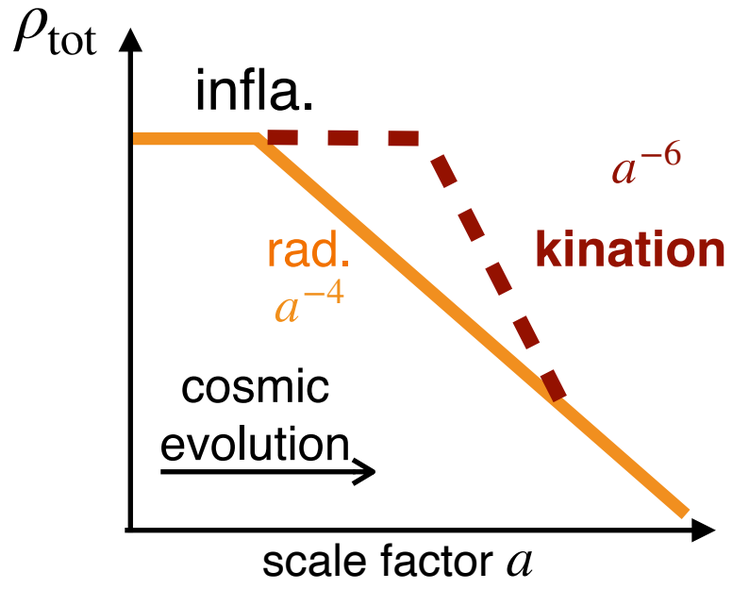

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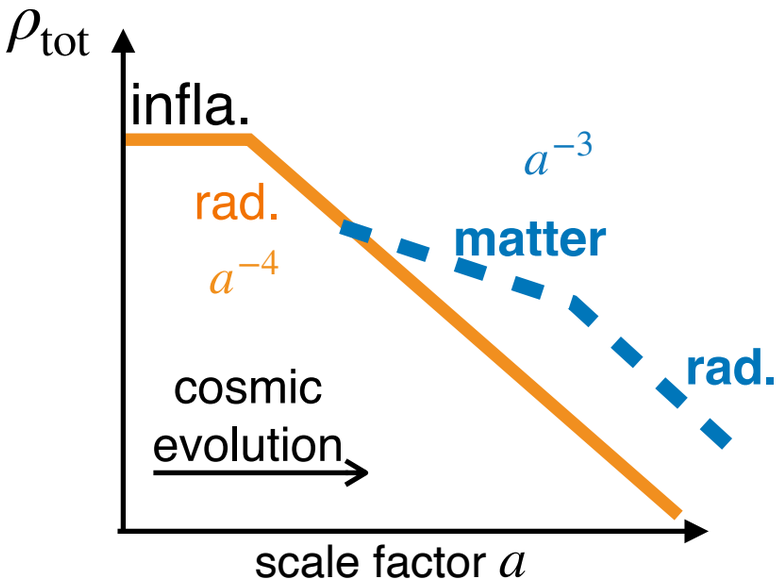
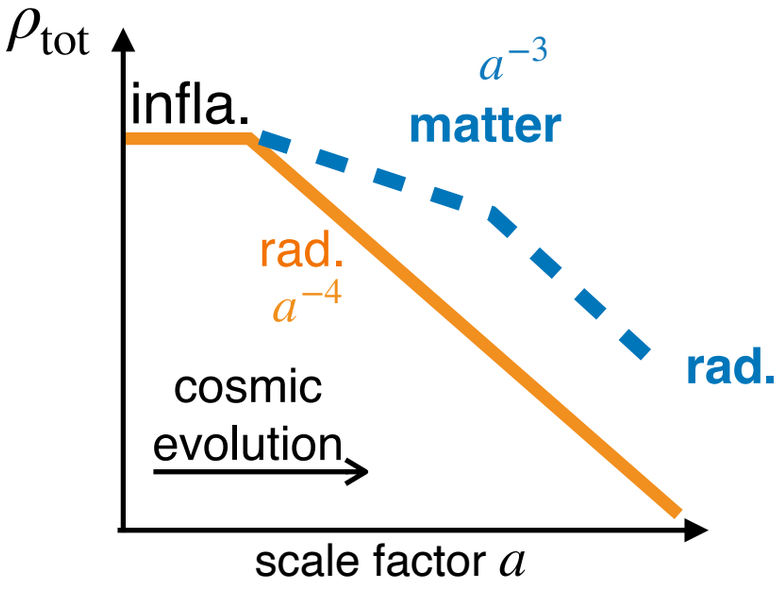


Heavy & unstable particles

A) Post-inflationary dynamics



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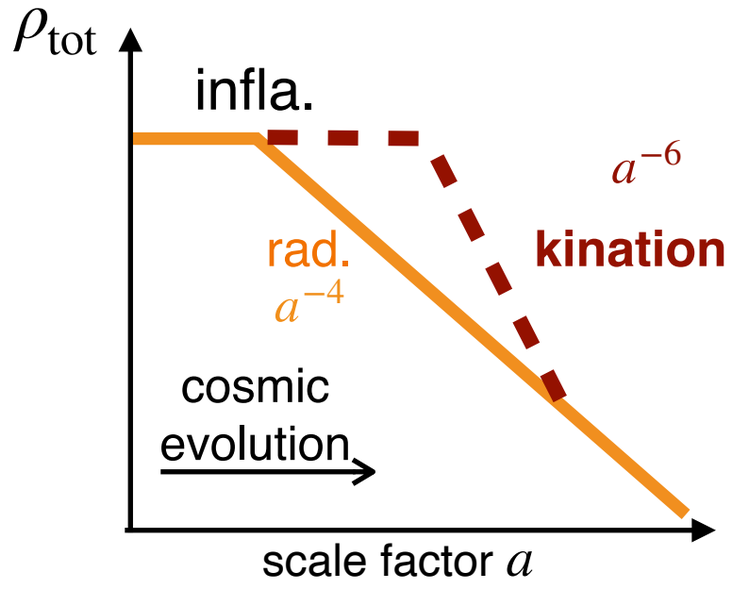

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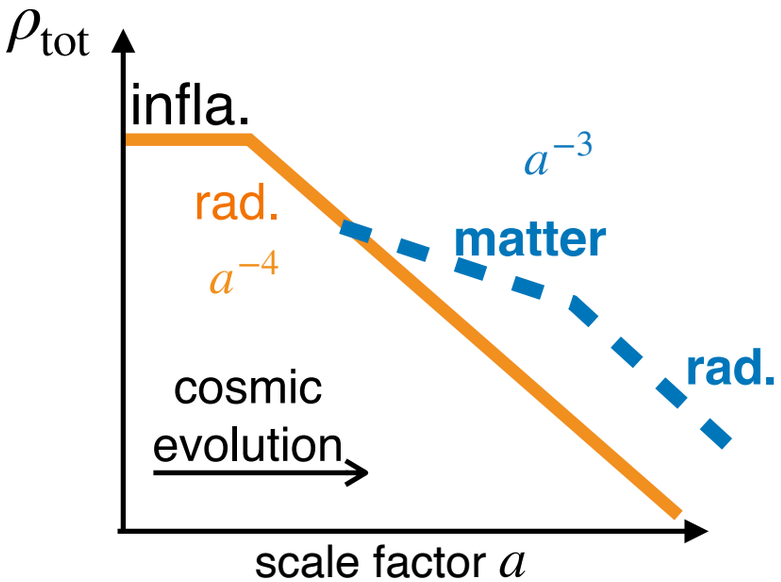

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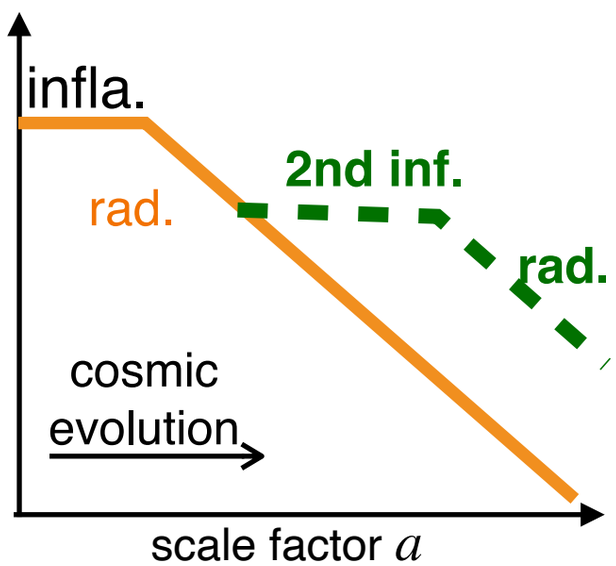
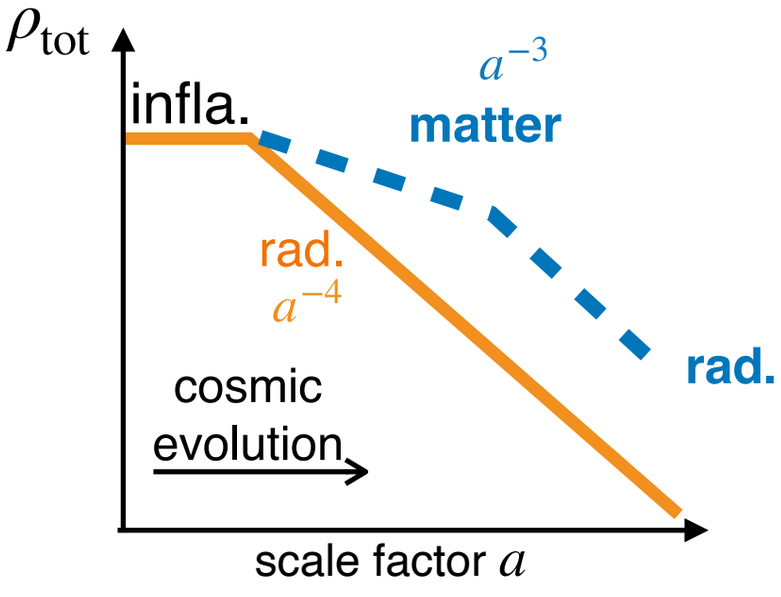


Supercool 1st-order phase transition

A) Post-inflationary dynamics



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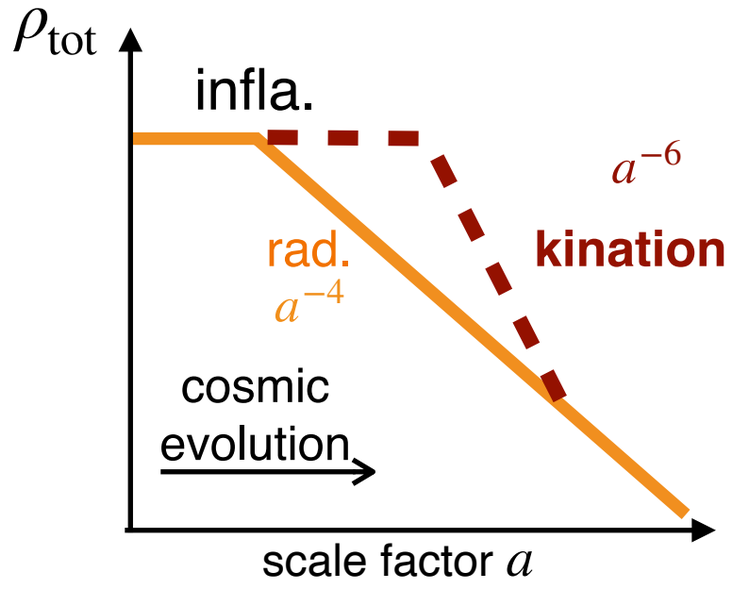

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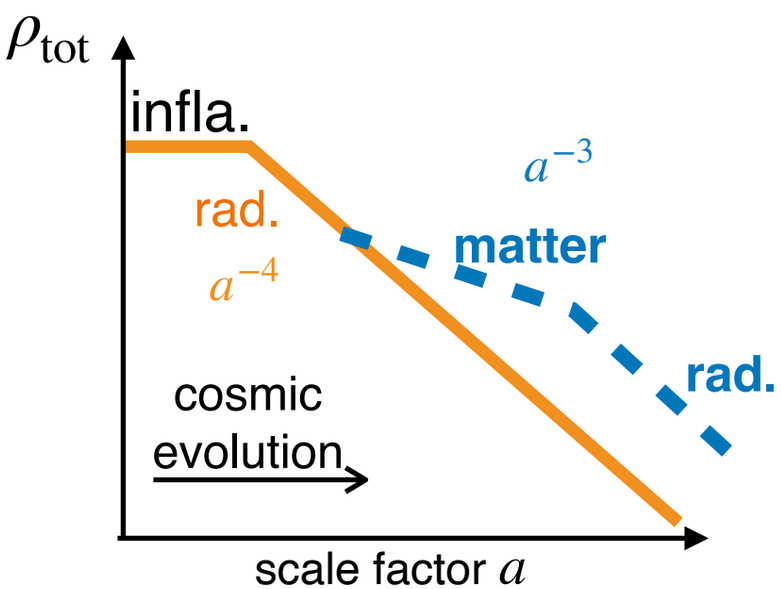

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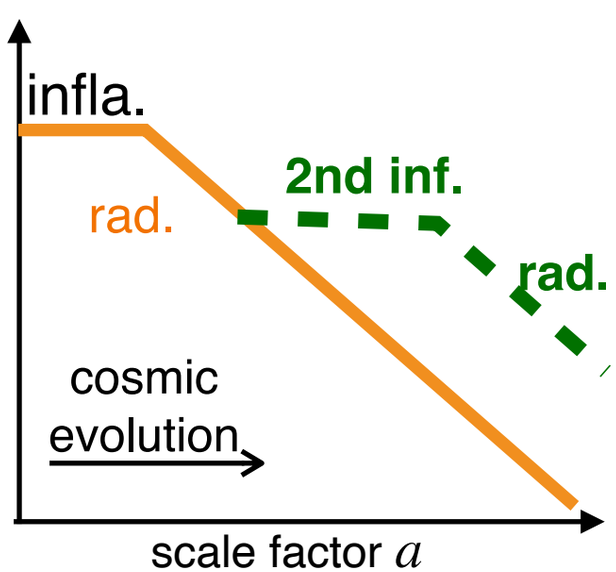

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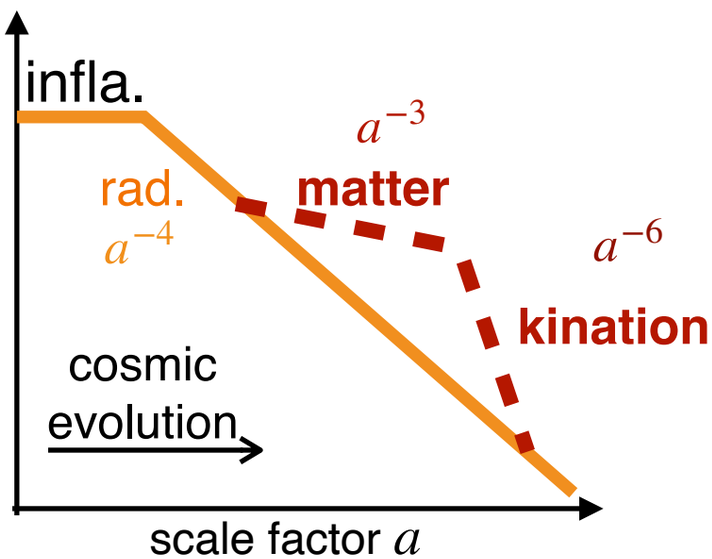
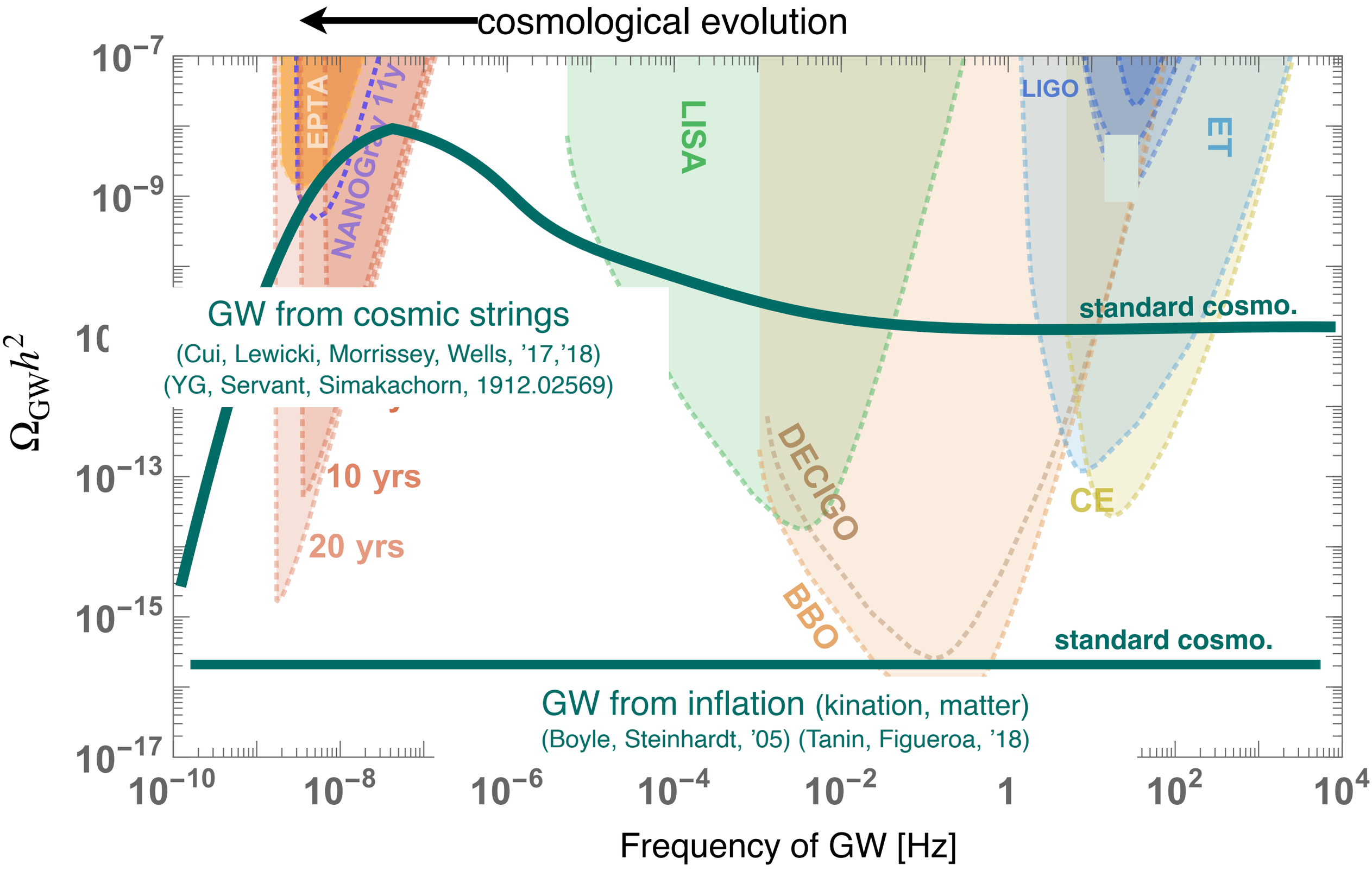


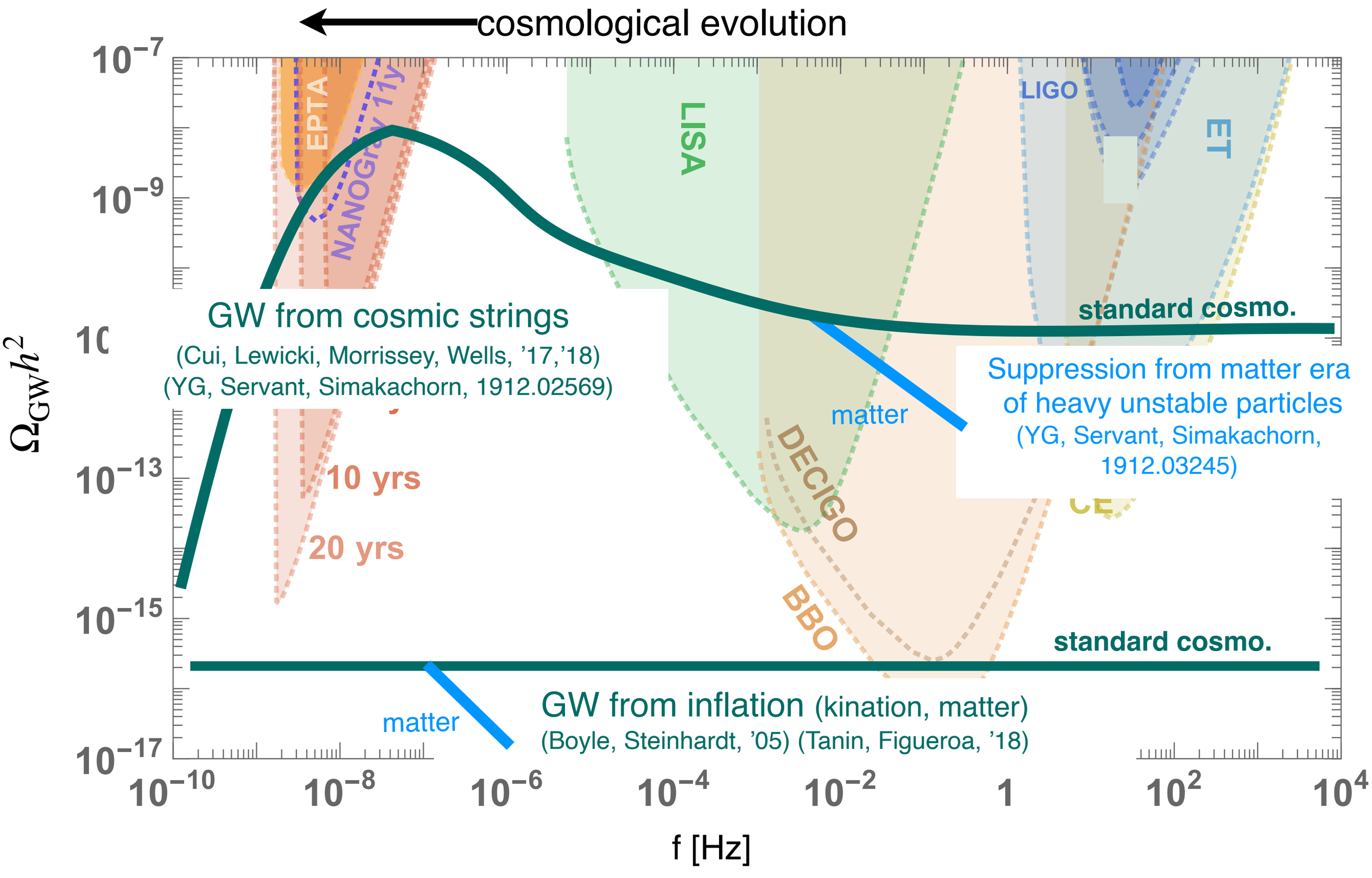
Rotating field

(Affleck-Dine)

Overview: Cosmic archeology with GW



Overview: Cosmic archeology with GW



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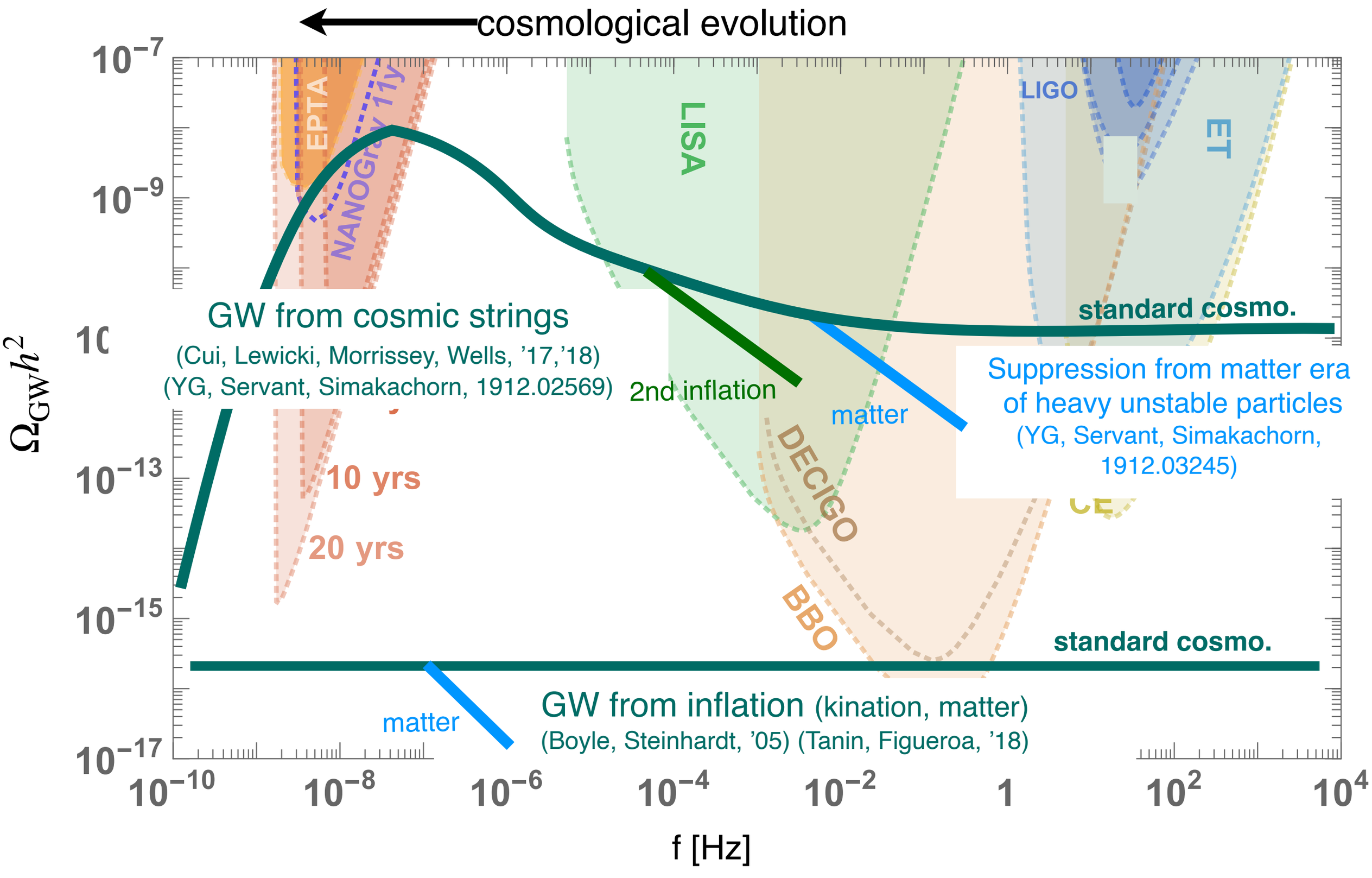

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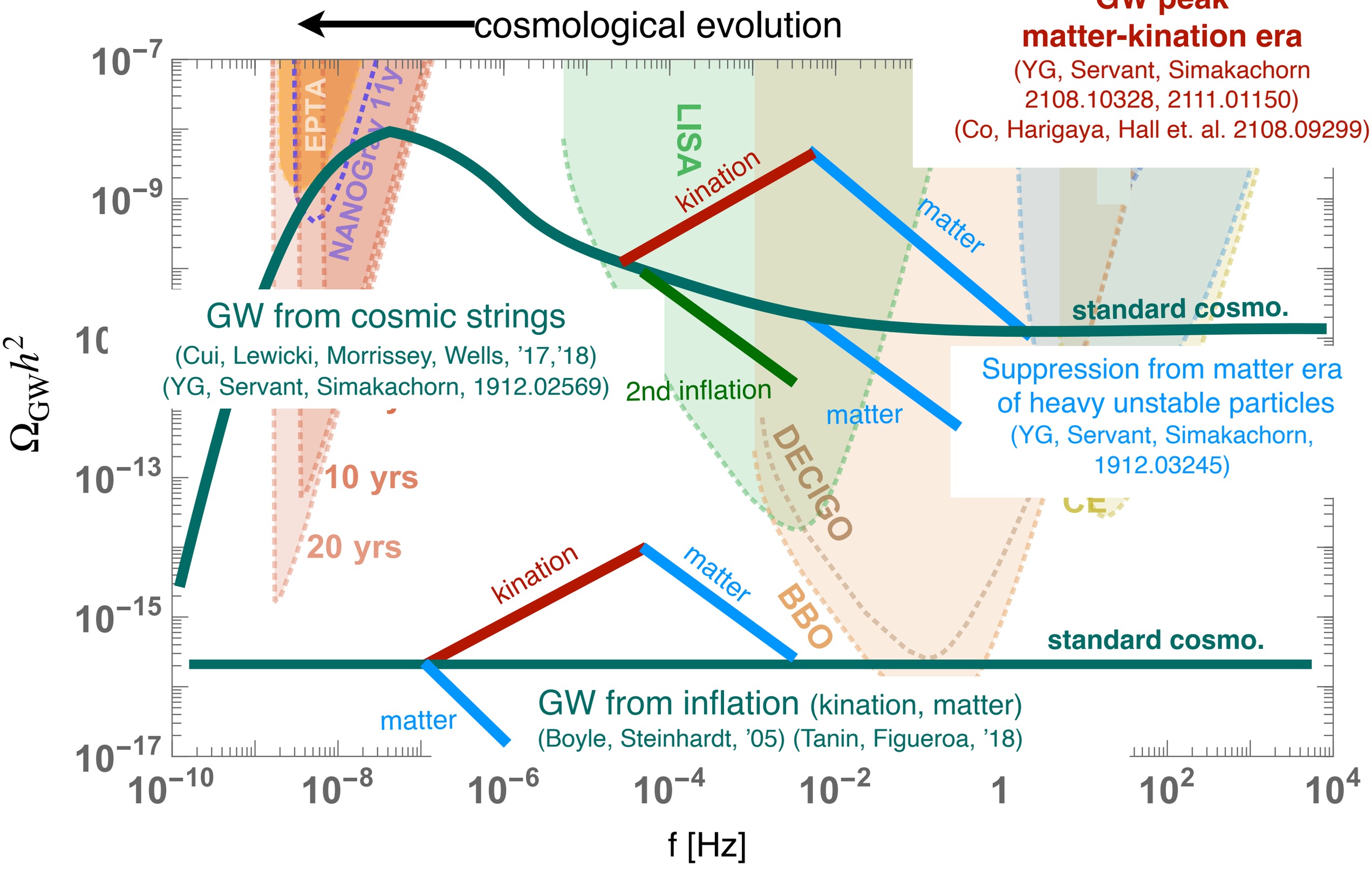


Overview: Cosmic archeology with GW

cosmological evolution

"GW peak"
matter-kination era
(YG, Servant, Simakachorn 2108.10328, 2111.01150)
(Co, Harigaya, Hall et. al. 2108.09299)

GW from cosmic strings
(Cui, Lewicki, Morrissey, Wells, '17,'18)
(YG, Servant, Simakachorn, 1912.02569)

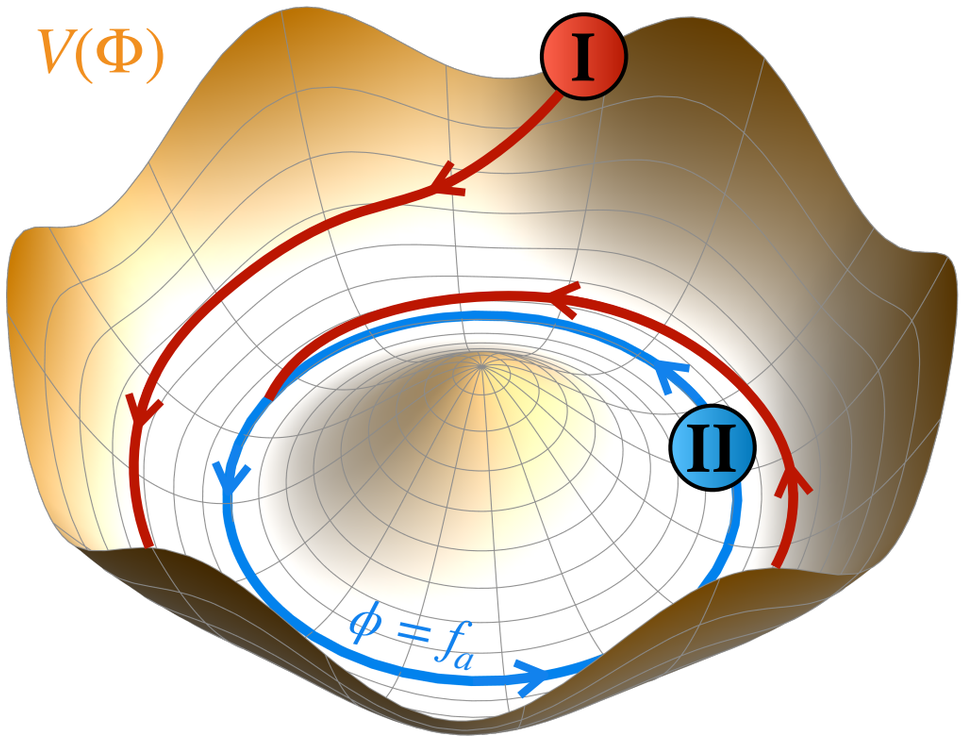
GW from inflation (kination, matter)
(Boyle, Steinhardt, '05) (Tanin, Figueroa, '18)

Suppression from matter era of heavy unstable particles
(YG, Servant, Simakachorn, 1912.03245)

EPTA
NANOGrav 11y
10 yrs
20 yrs
LISA
DECIGO
BBO
kination
matter
2nd inflation
standard cosmo.

$\Omega_{\rm GW}h^2$

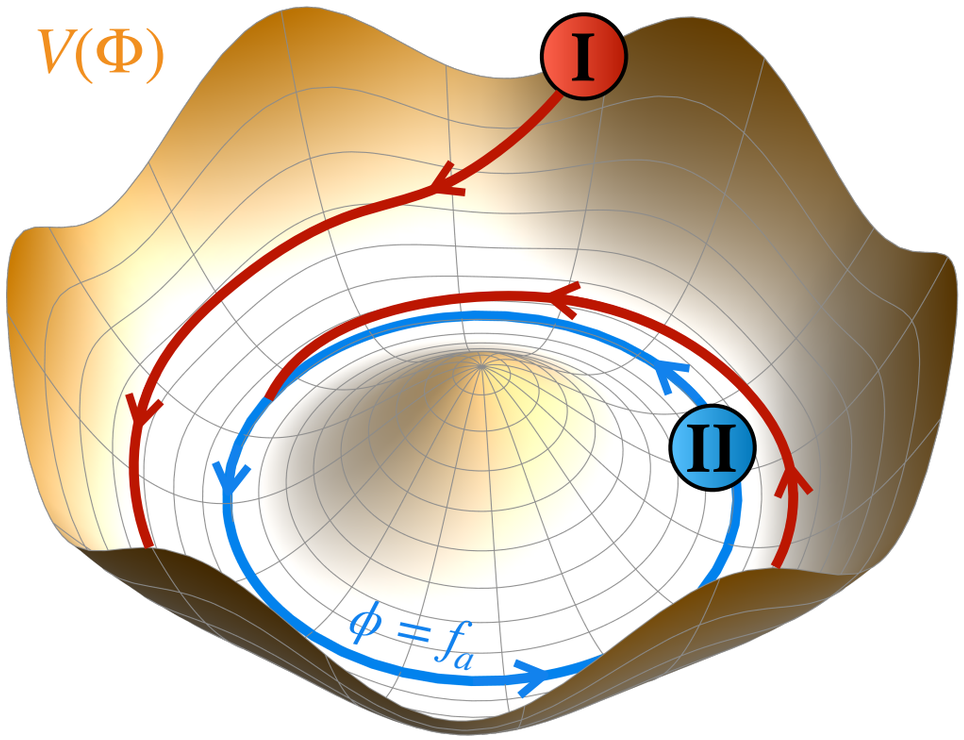
f [Hz]



Rotating complex scalar field

"Affleck-Dine Baryogenesis" (Affleck, Dine, 1985)

"Axiogenesis" (Co, Hall, Harigaya, et. al., '19)



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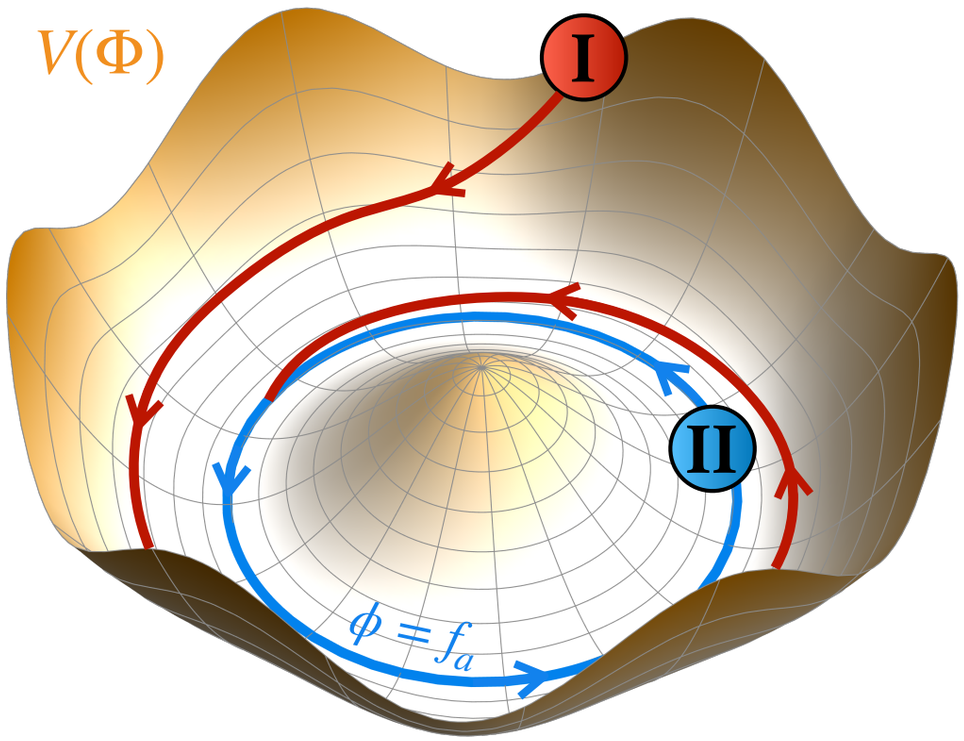

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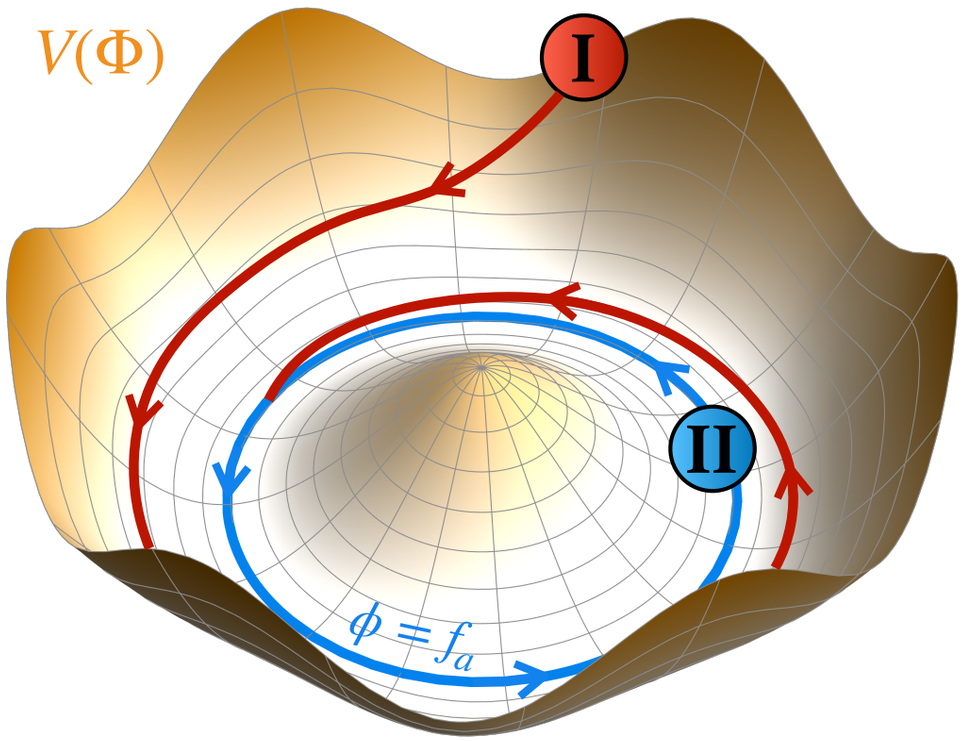
I. $U(1)$-symmetric (quadratic) potential
with spontaneous symmetry-breaking minimum

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

(generic in SUSY)



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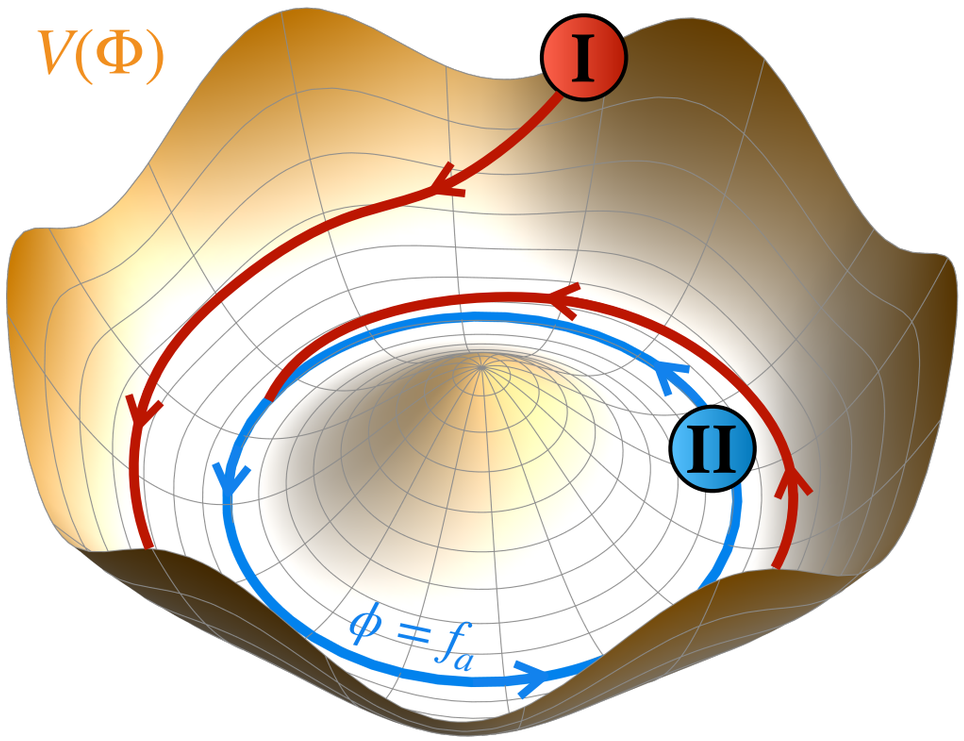
$$V_{\rm H} = - H^2 |\Phi|^2$$

(Dine, Randall, Thomas, 1995) (SUSY again)



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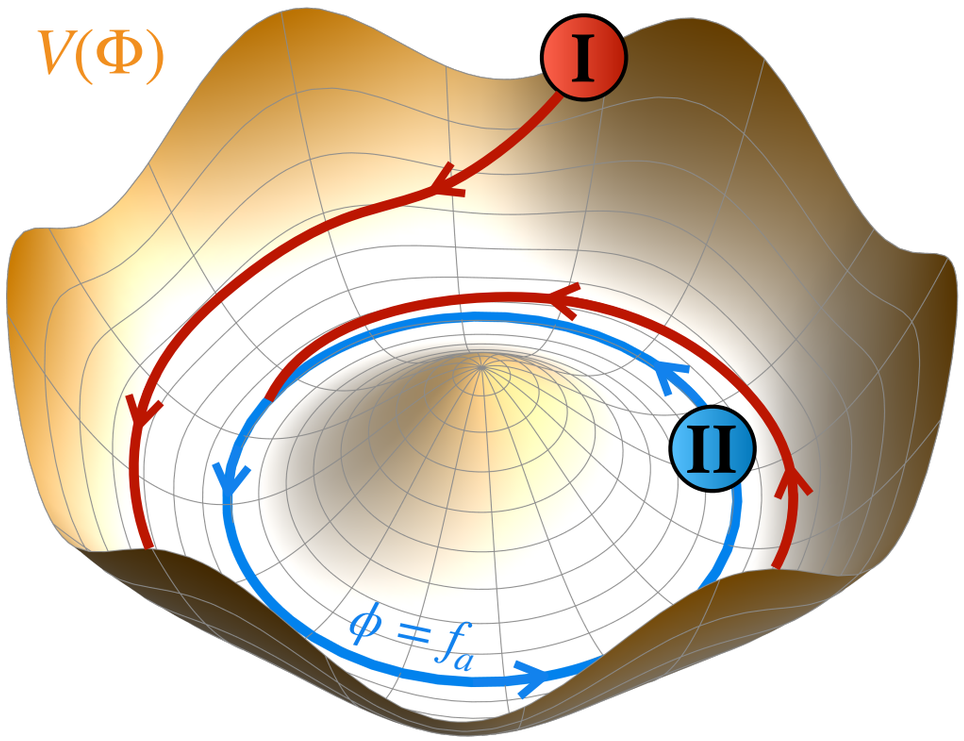
$$V(\Phi) = \Lambda_b^4 \left[\left(\frac{\Phi}{M_{\rm Pl}} \right)^l + \left(\frac{\Phi^\dagger}{M_{\rm Pl}} \right)^l \right]$$

(Neutron EDM bound $l \gtrsim 10$)



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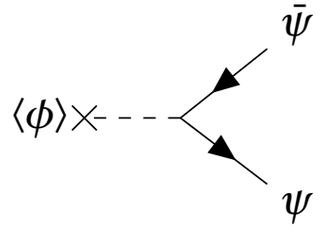
(Neutron EDM bound $l \gtrsim 10$)

IV. Damping of radial motion

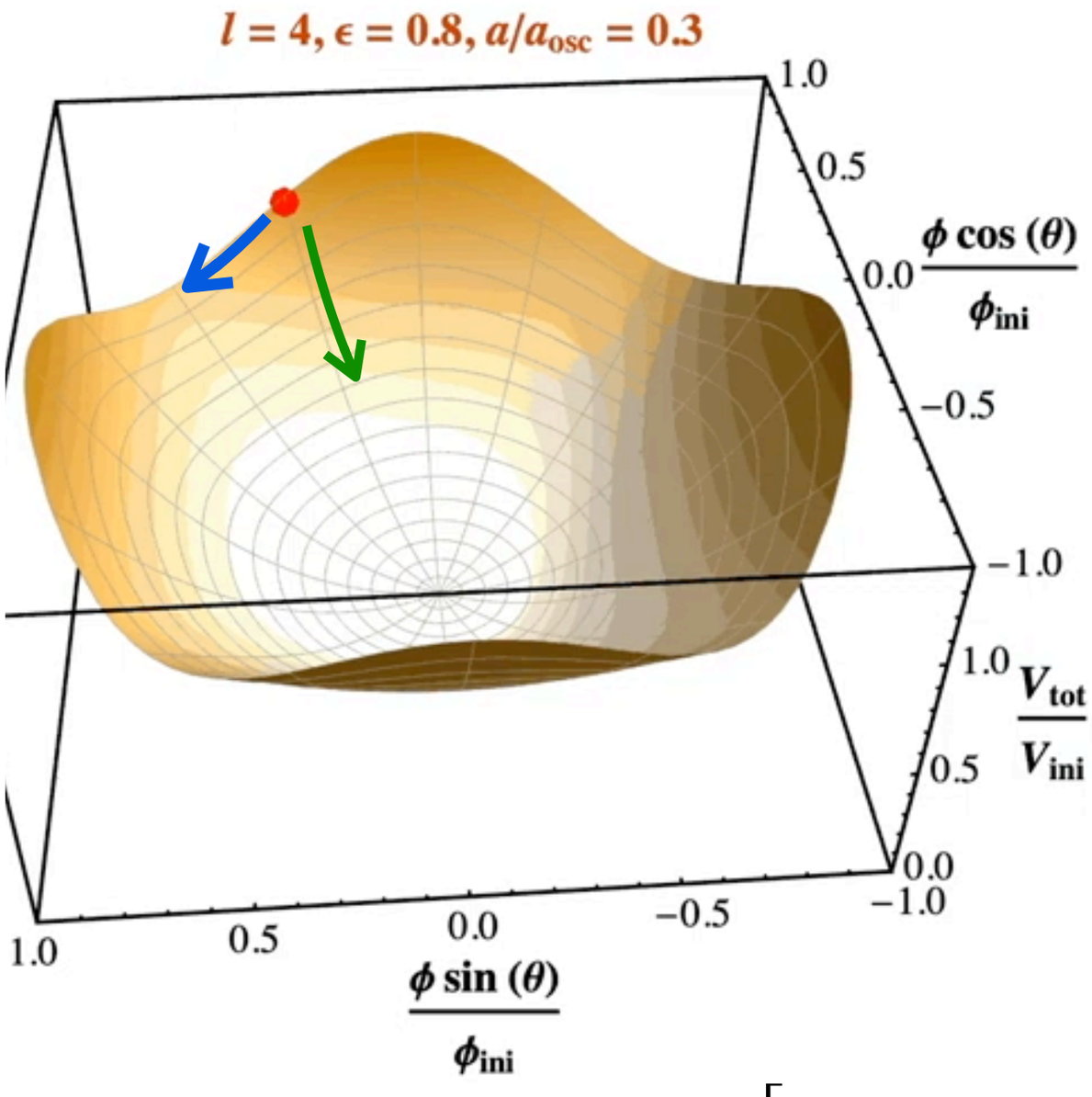
$$V_{\rm int} = \lambda_\psi \phi \bar{\psi} \psi$$



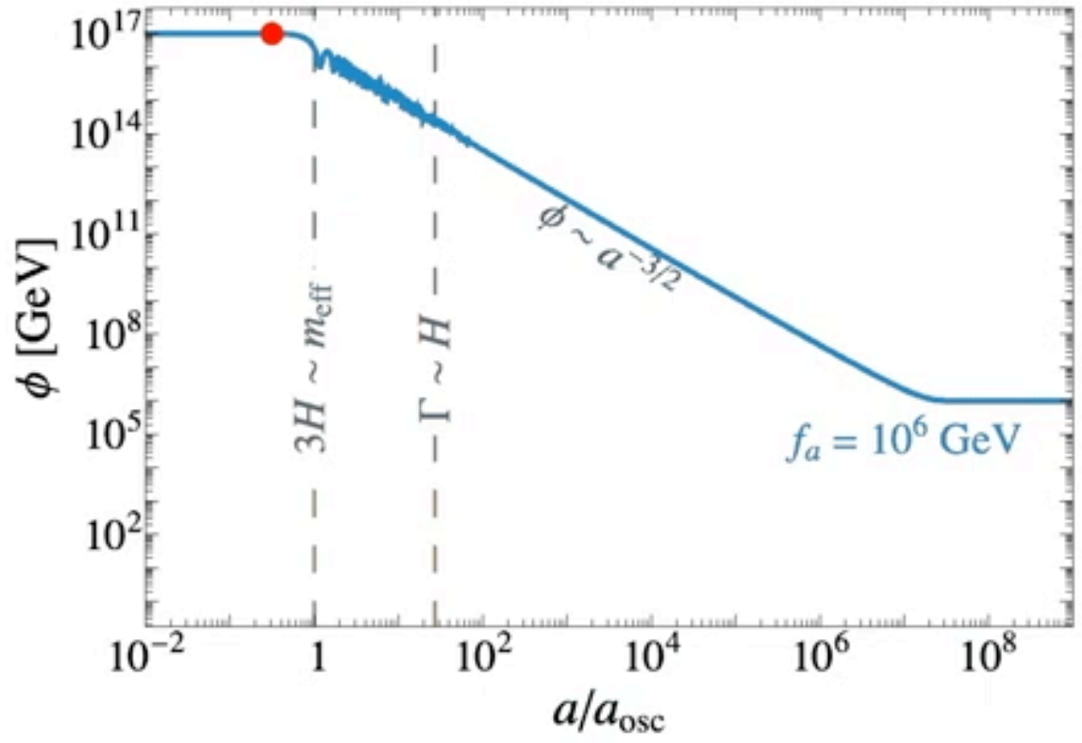
[Mukaida, Nakayama, '12 '13]

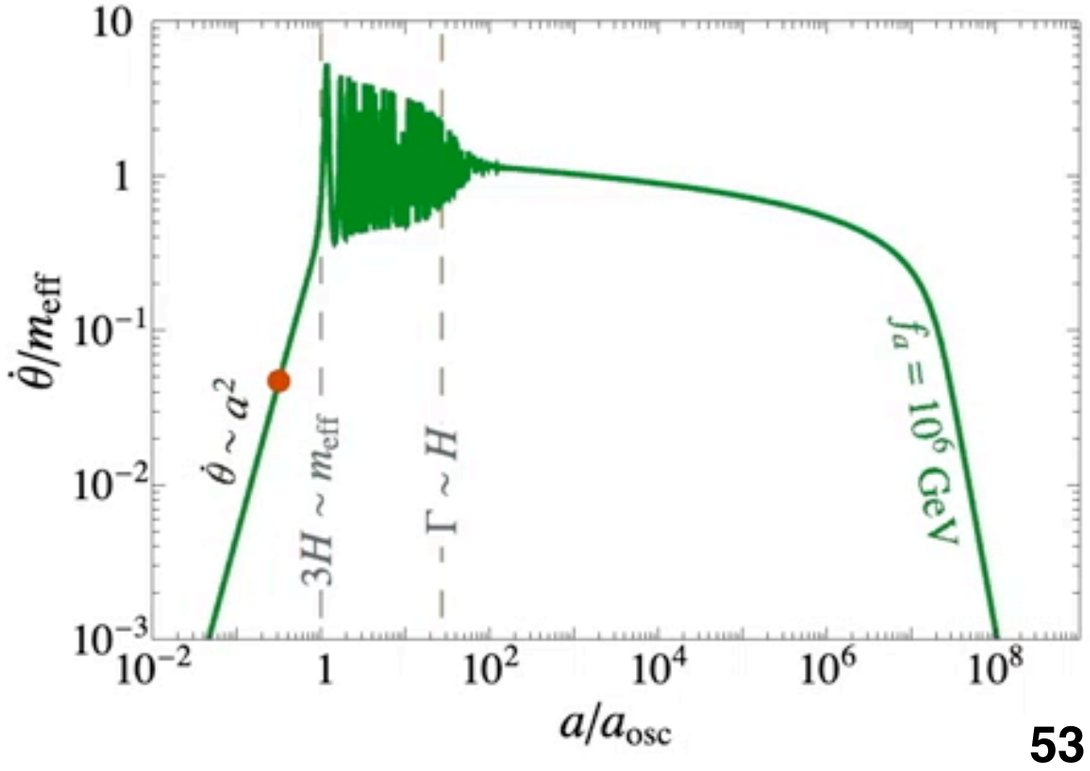
Ingredients I & II & III: scalar potential and large initial VEV

[YG, Servant, Simakachorn, 2111.01150]

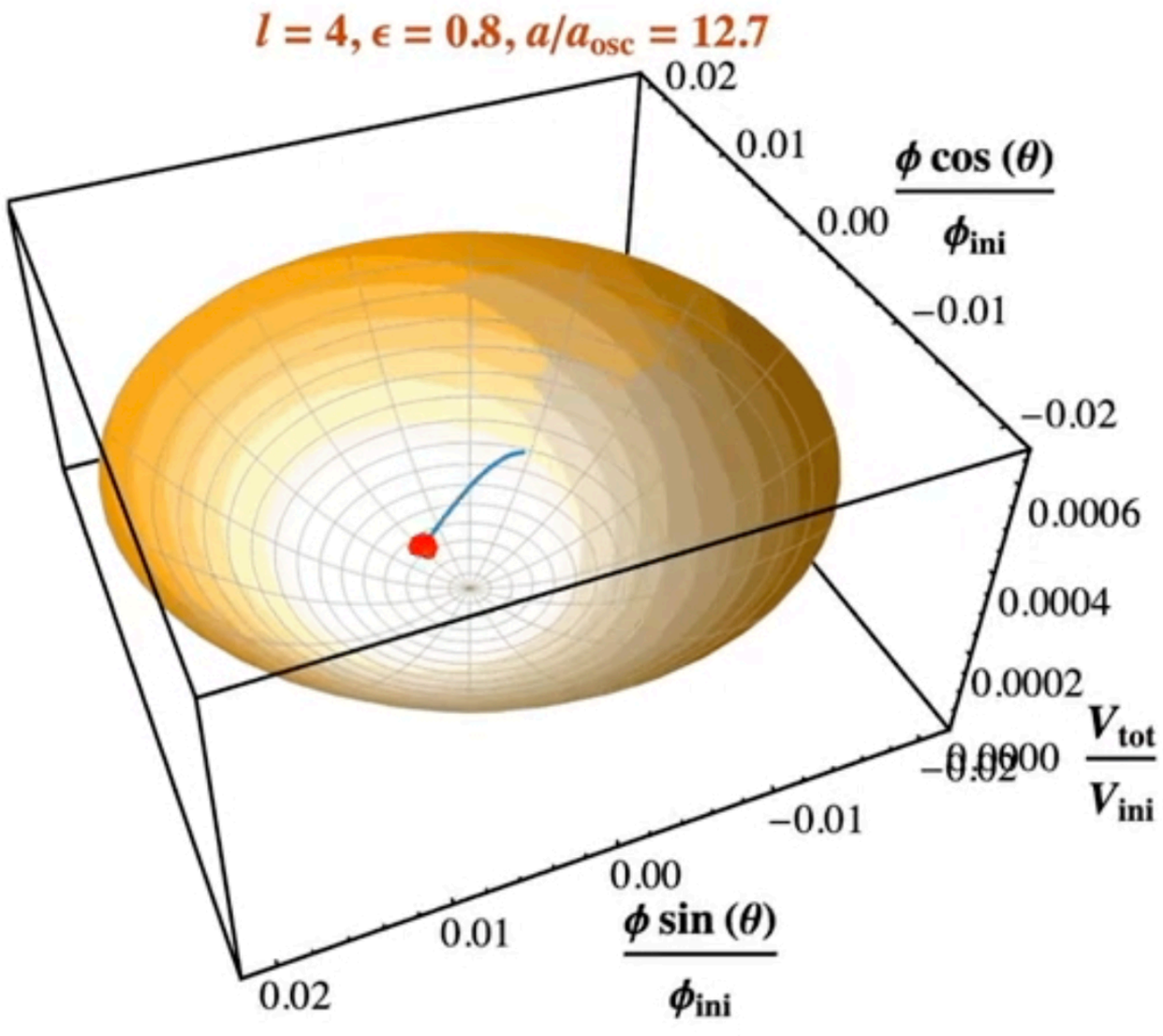


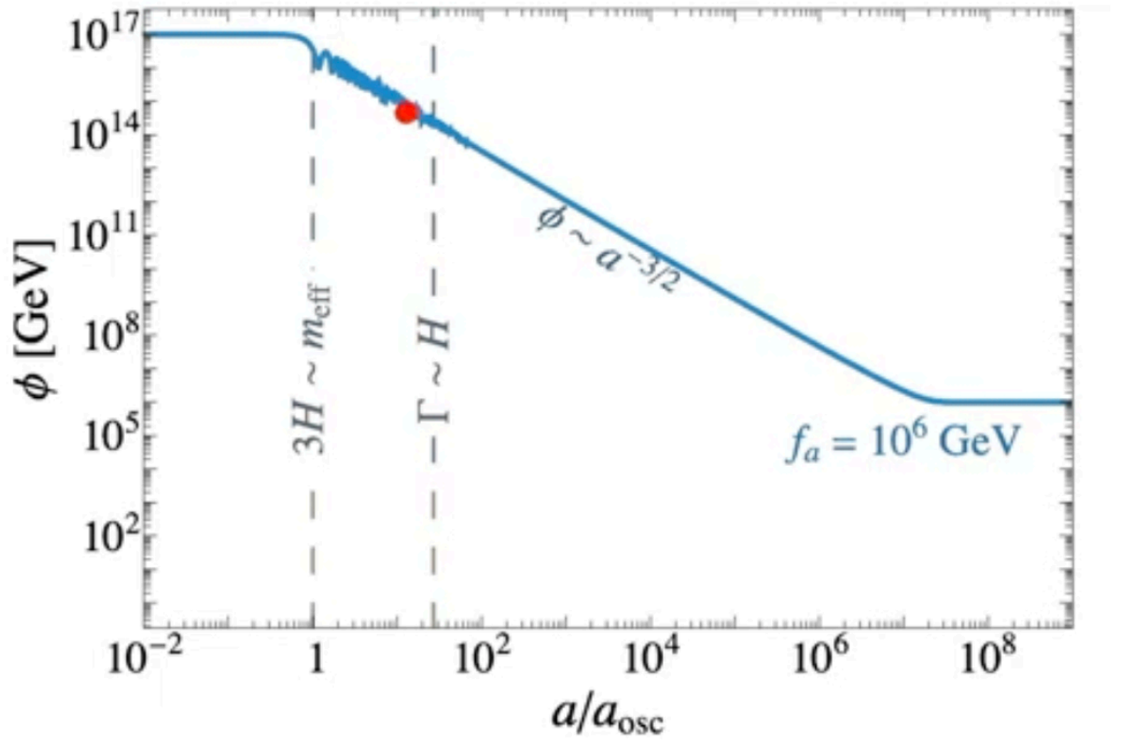
$$V(\Phi) = m_r^2 |\Phi|^2 \left[\log\left(\frac{|\Phi|^2}{f_a^2}\right) - 1\right] + \Lambda_b^4 \left[\left(\frac{\Phi}{M_{\rm Pl}}\right)^l + \left(\frac{\Phi^\dagger}{M_{\rm Pl}}\right)^l\right] - H^2 |\Phi|^2$$

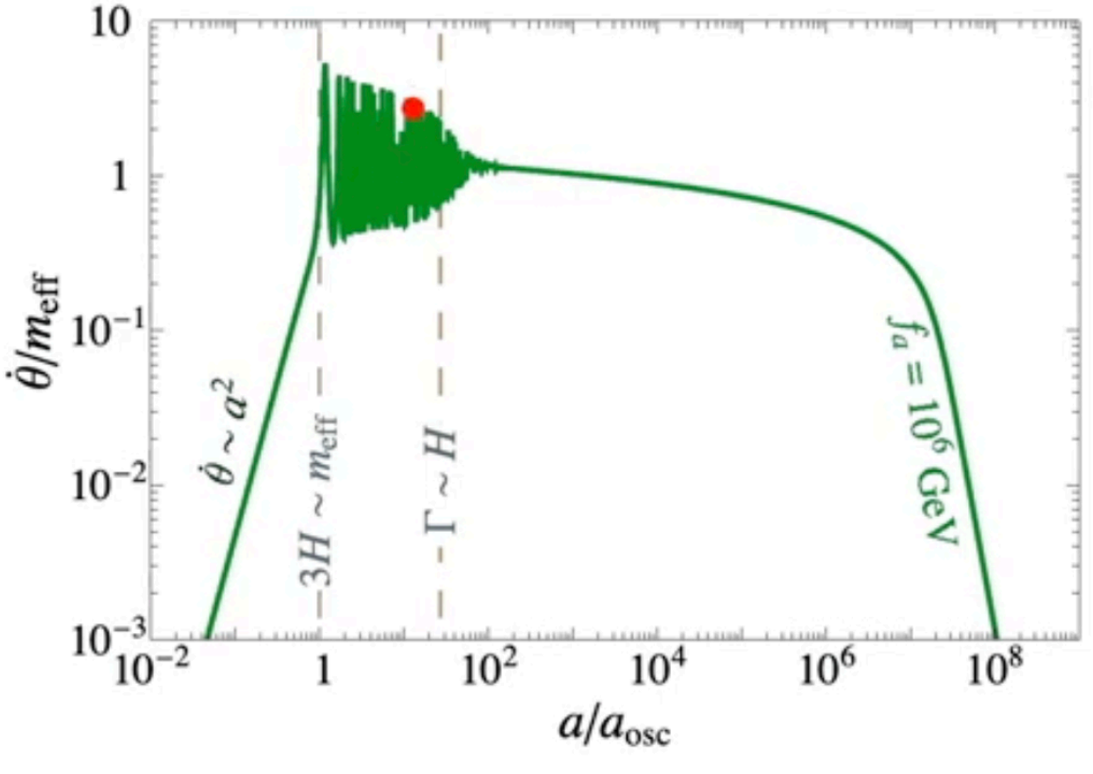




Ingredients IV: radial-motion damping







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

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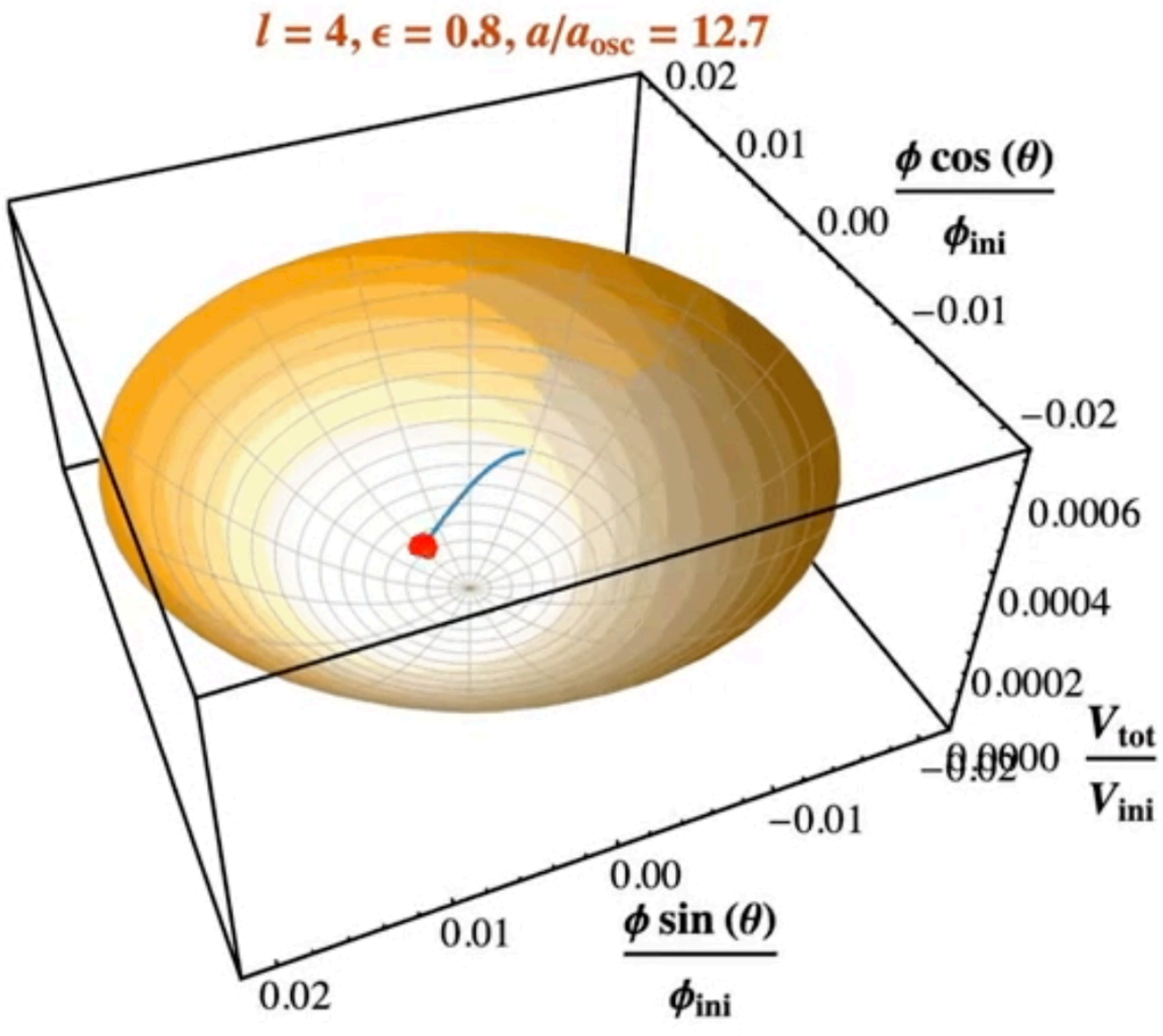

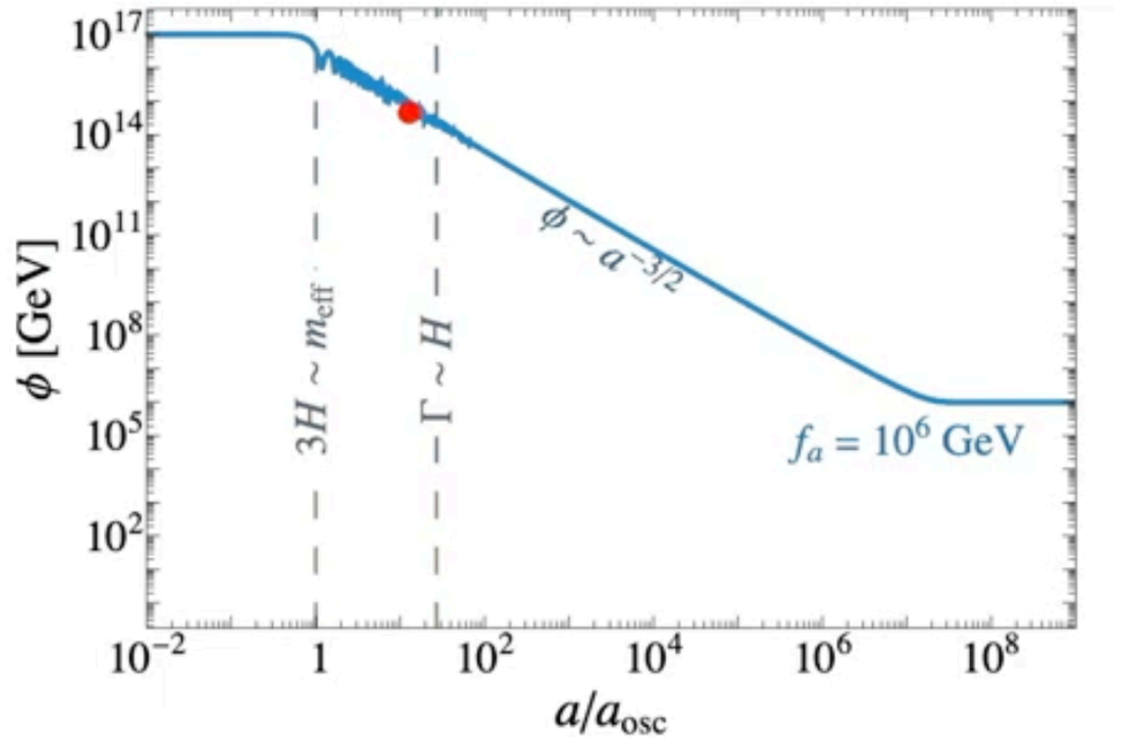

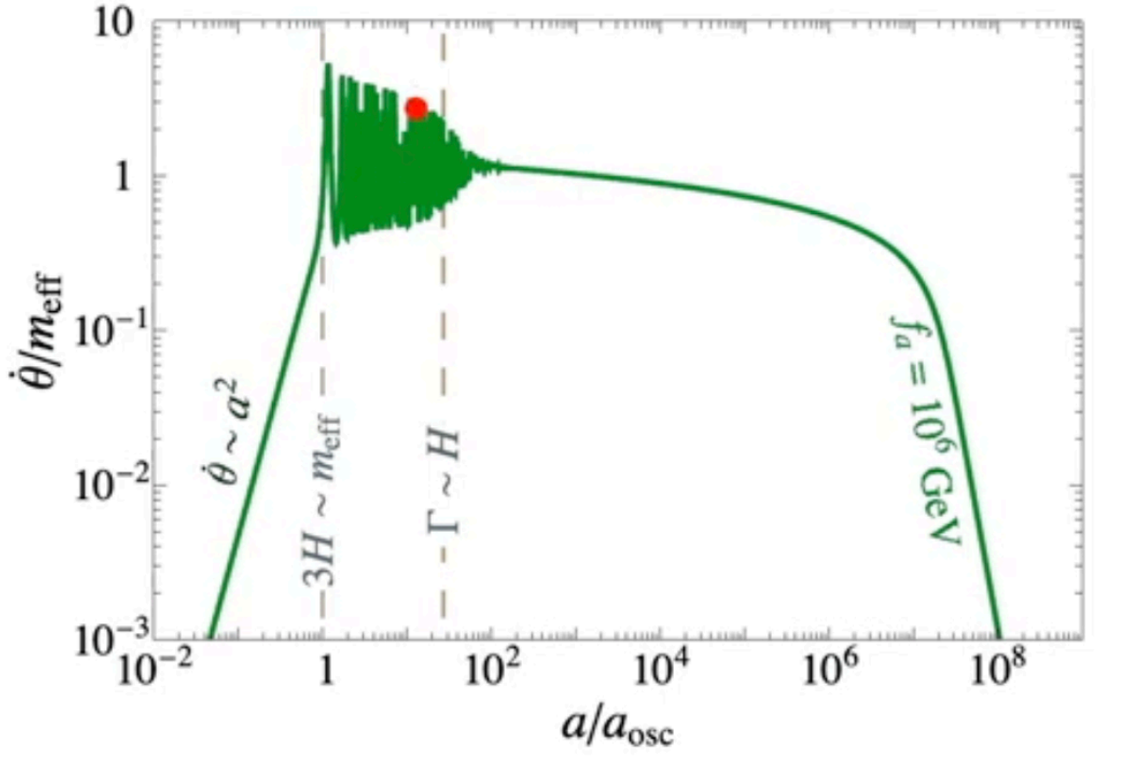

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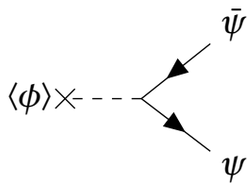
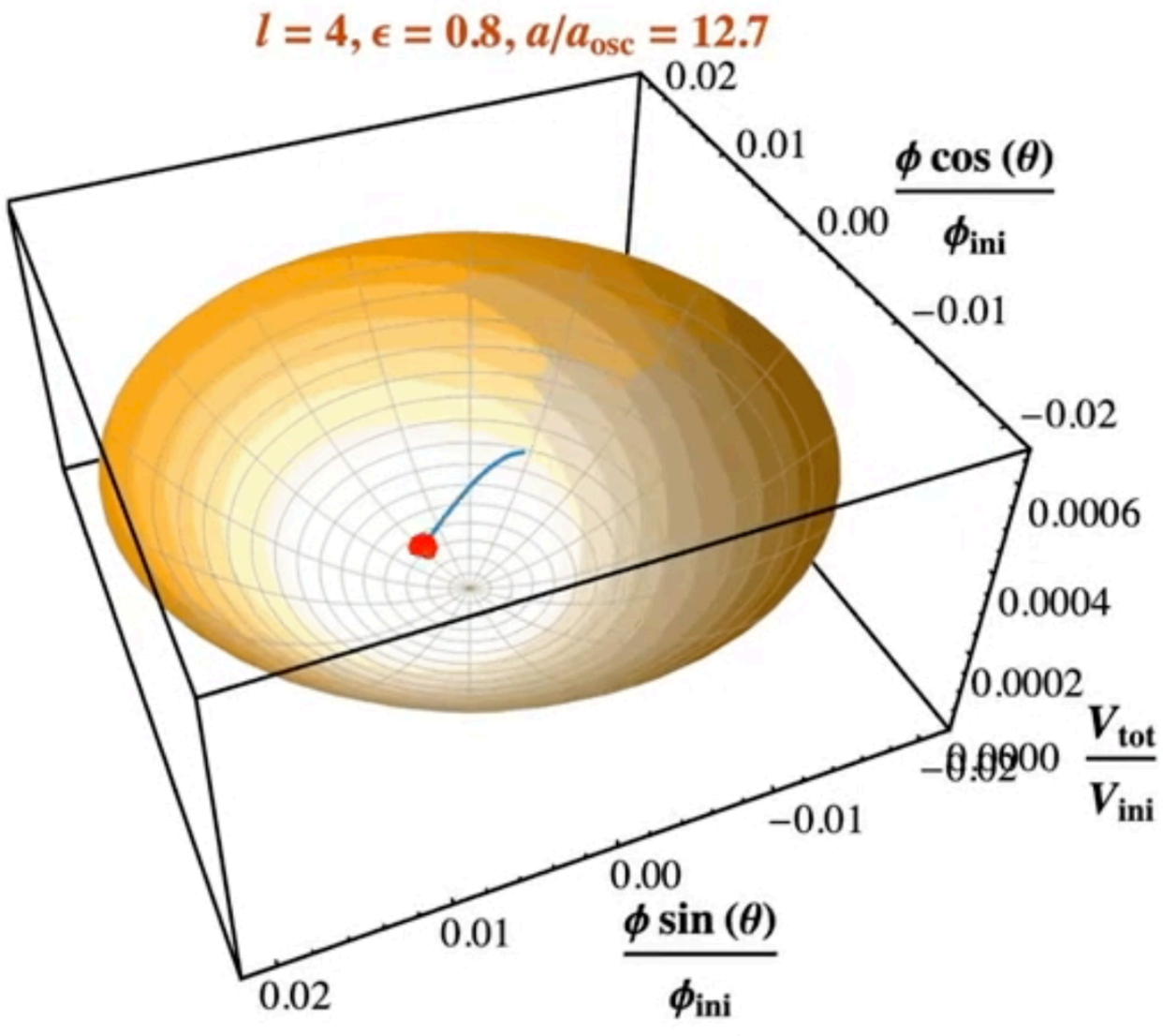
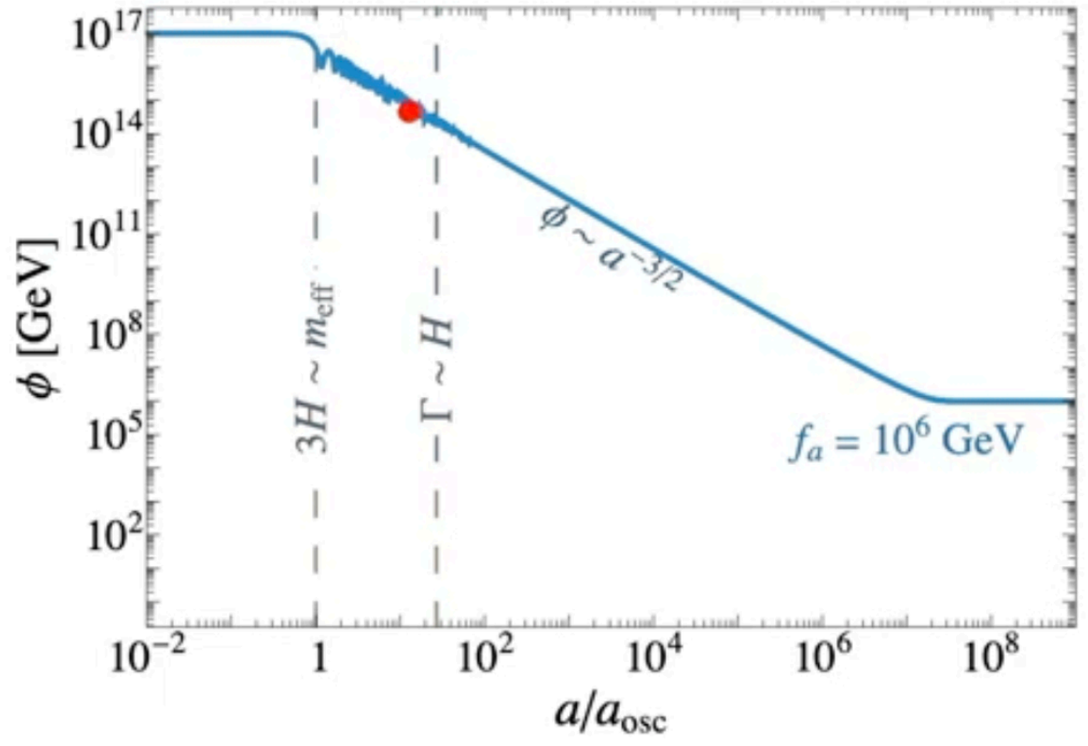
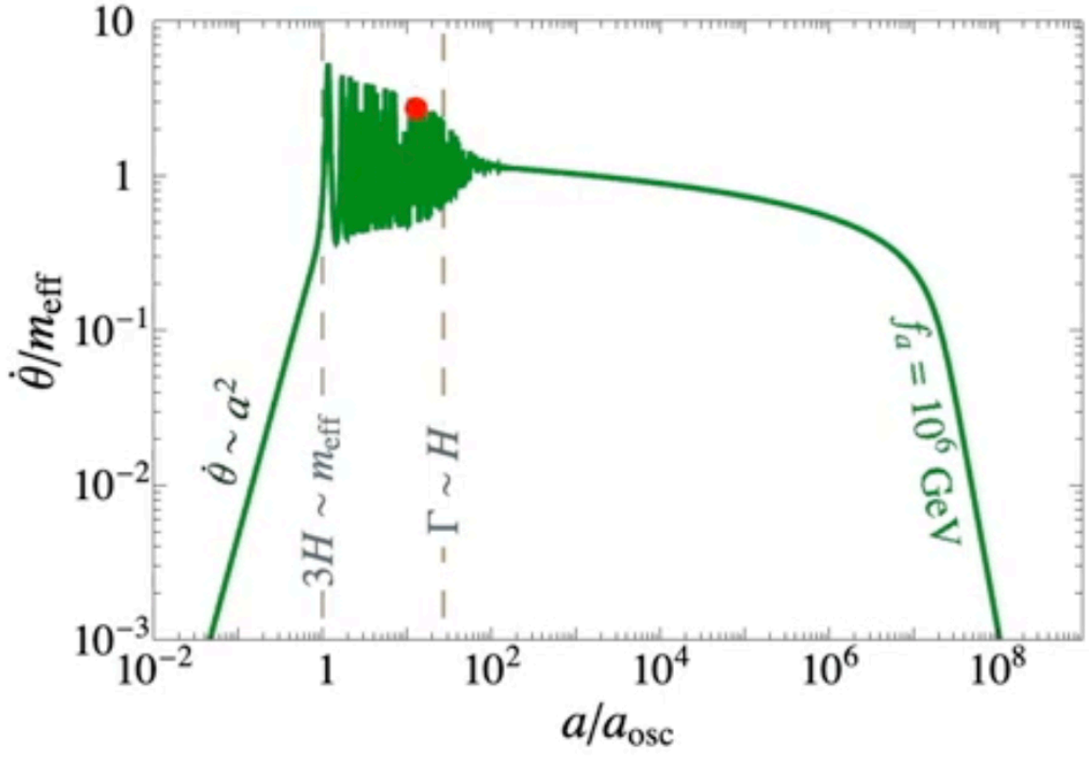


a:







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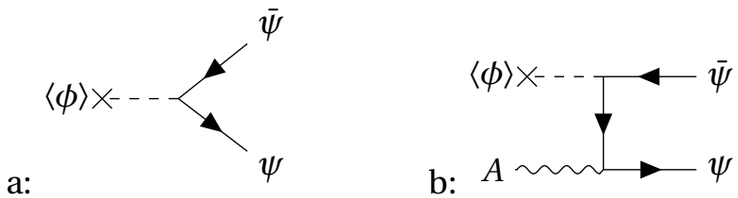

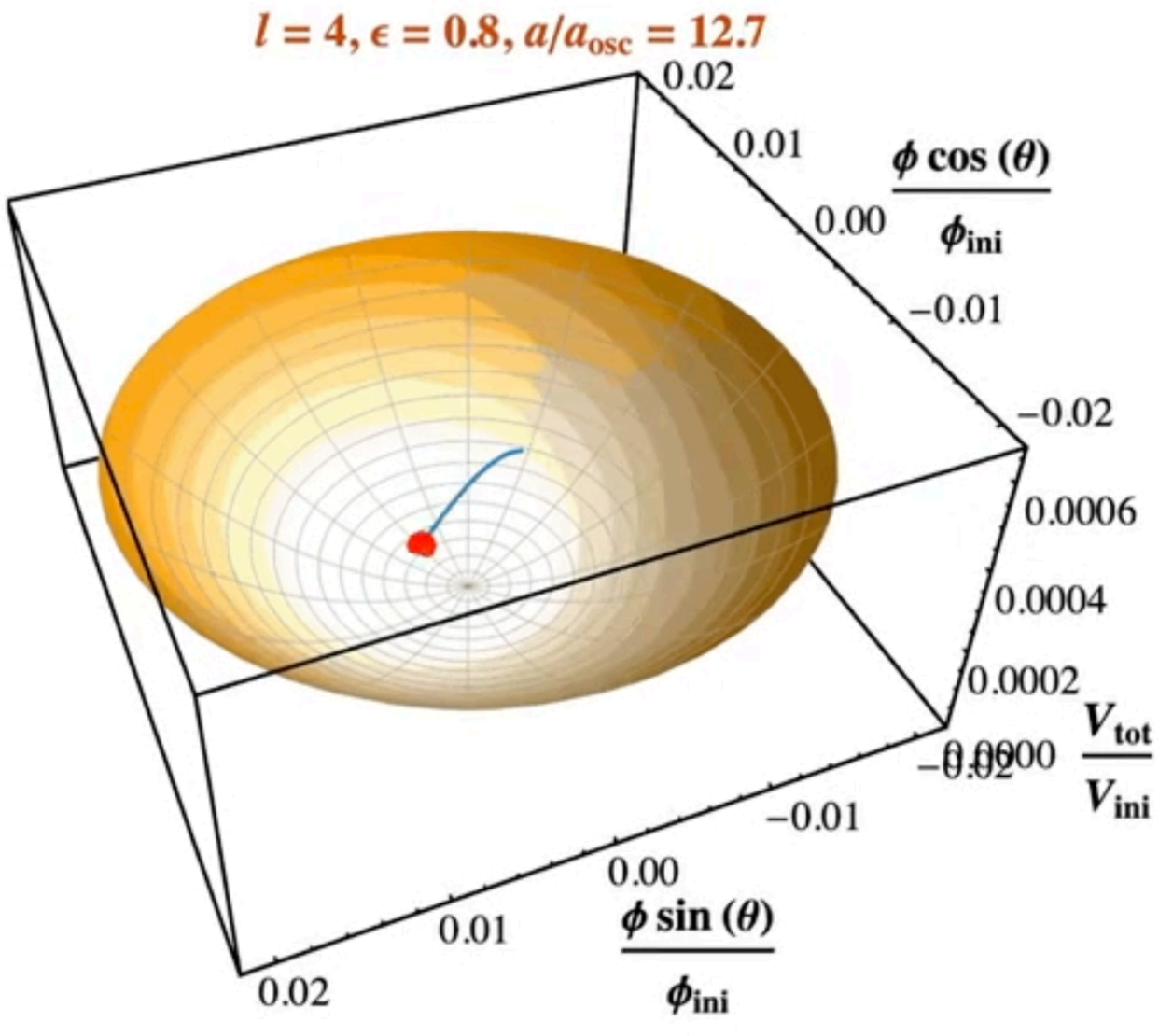

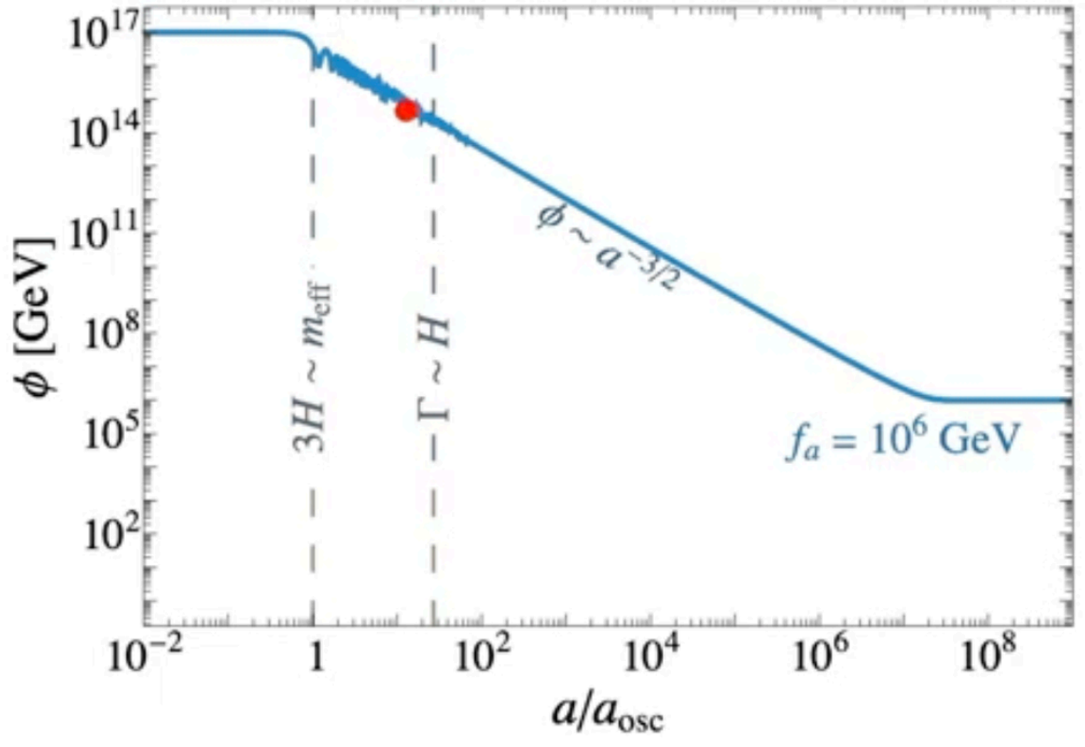

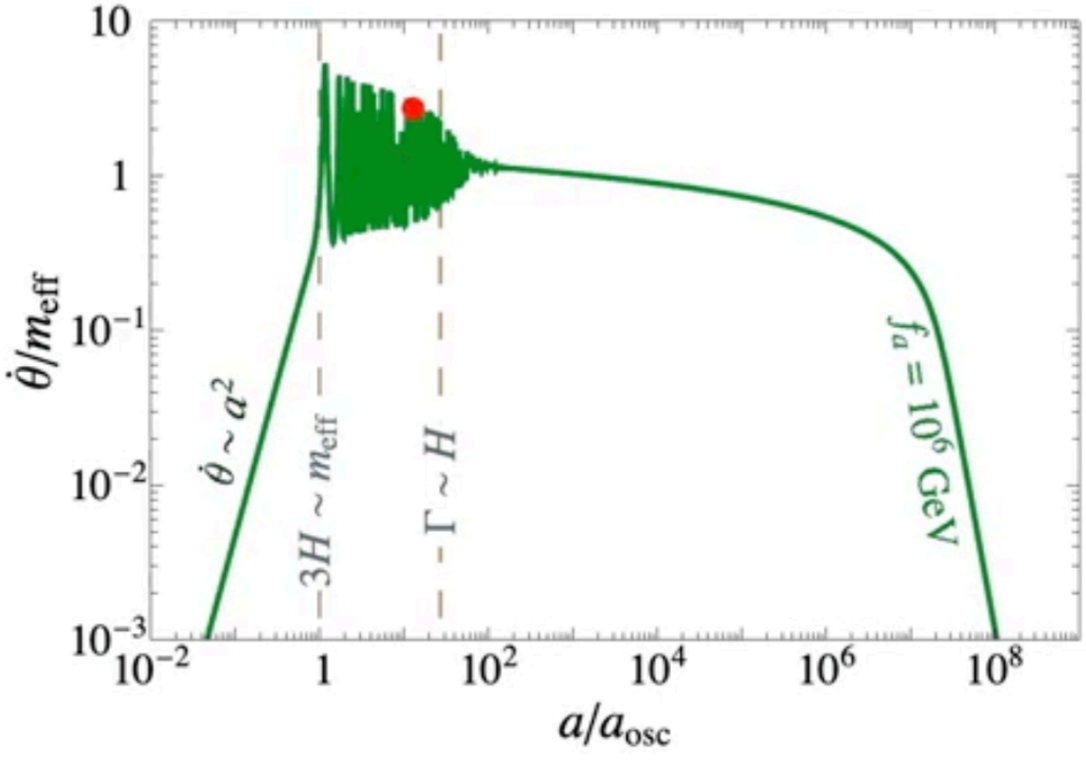

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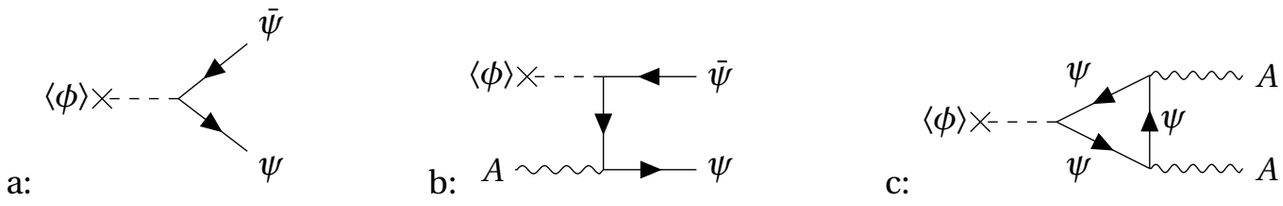

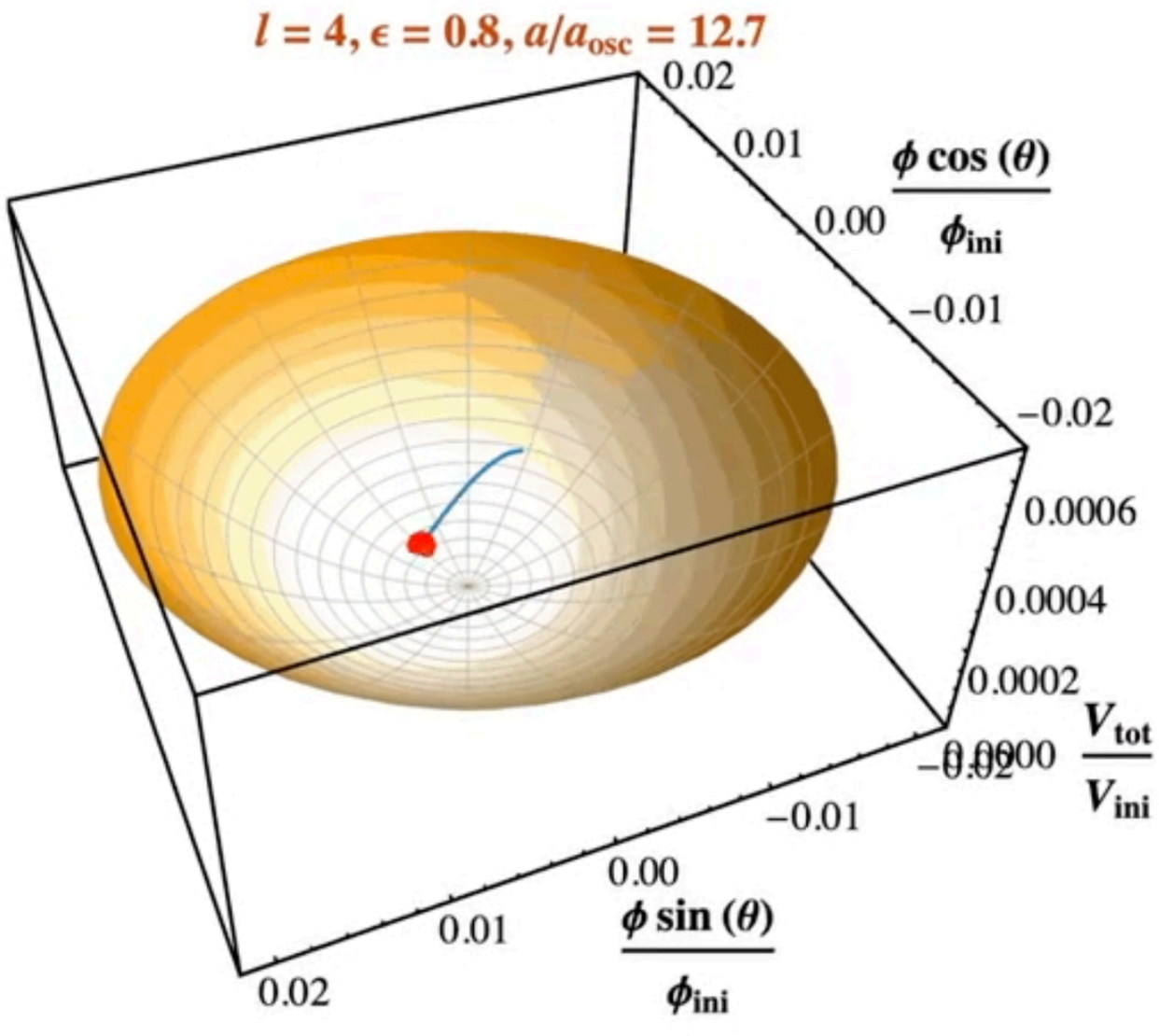

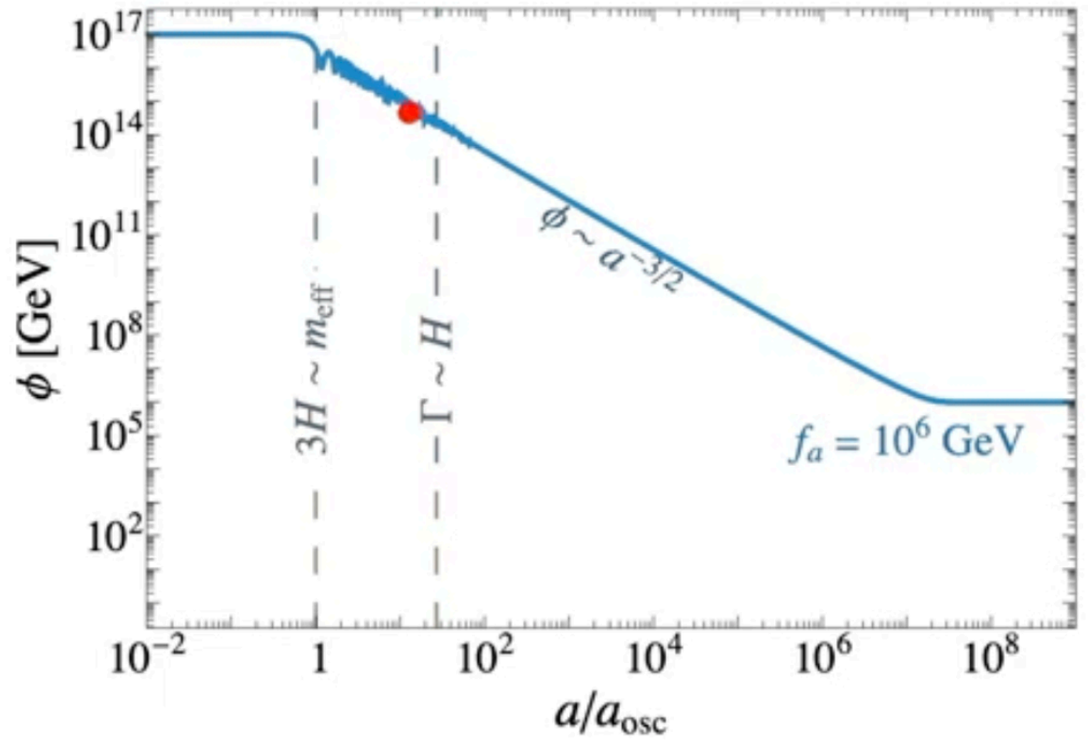

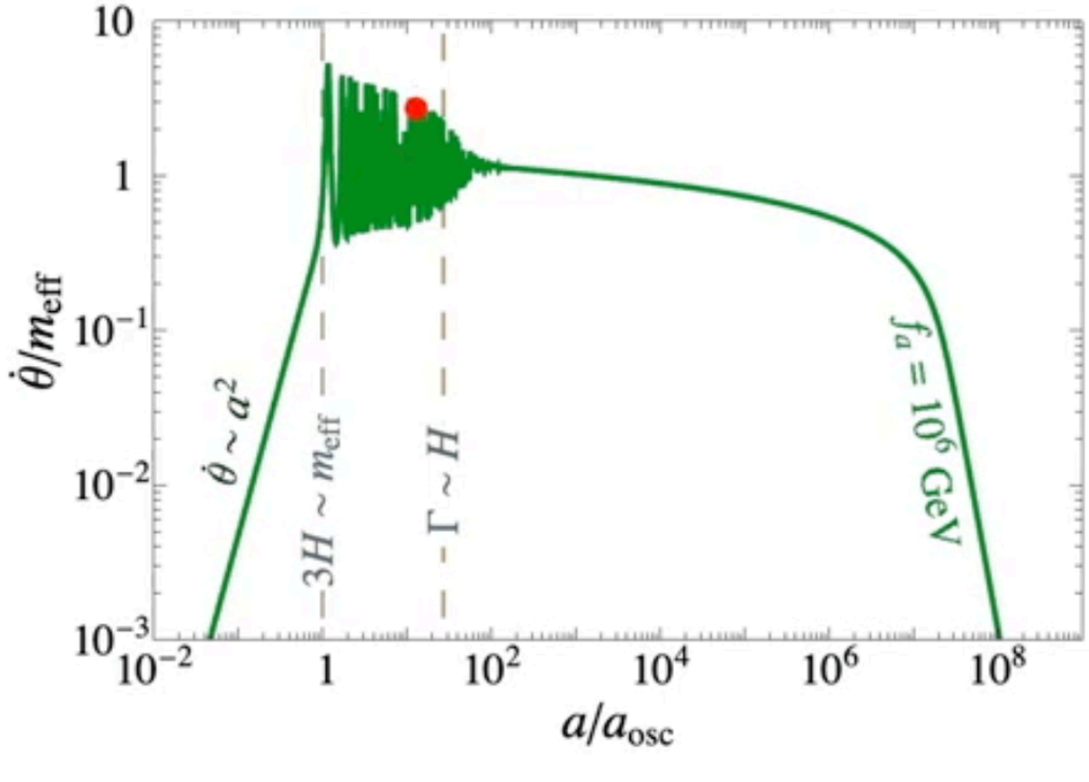

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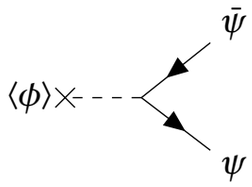
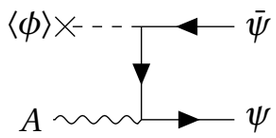
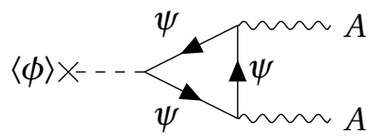
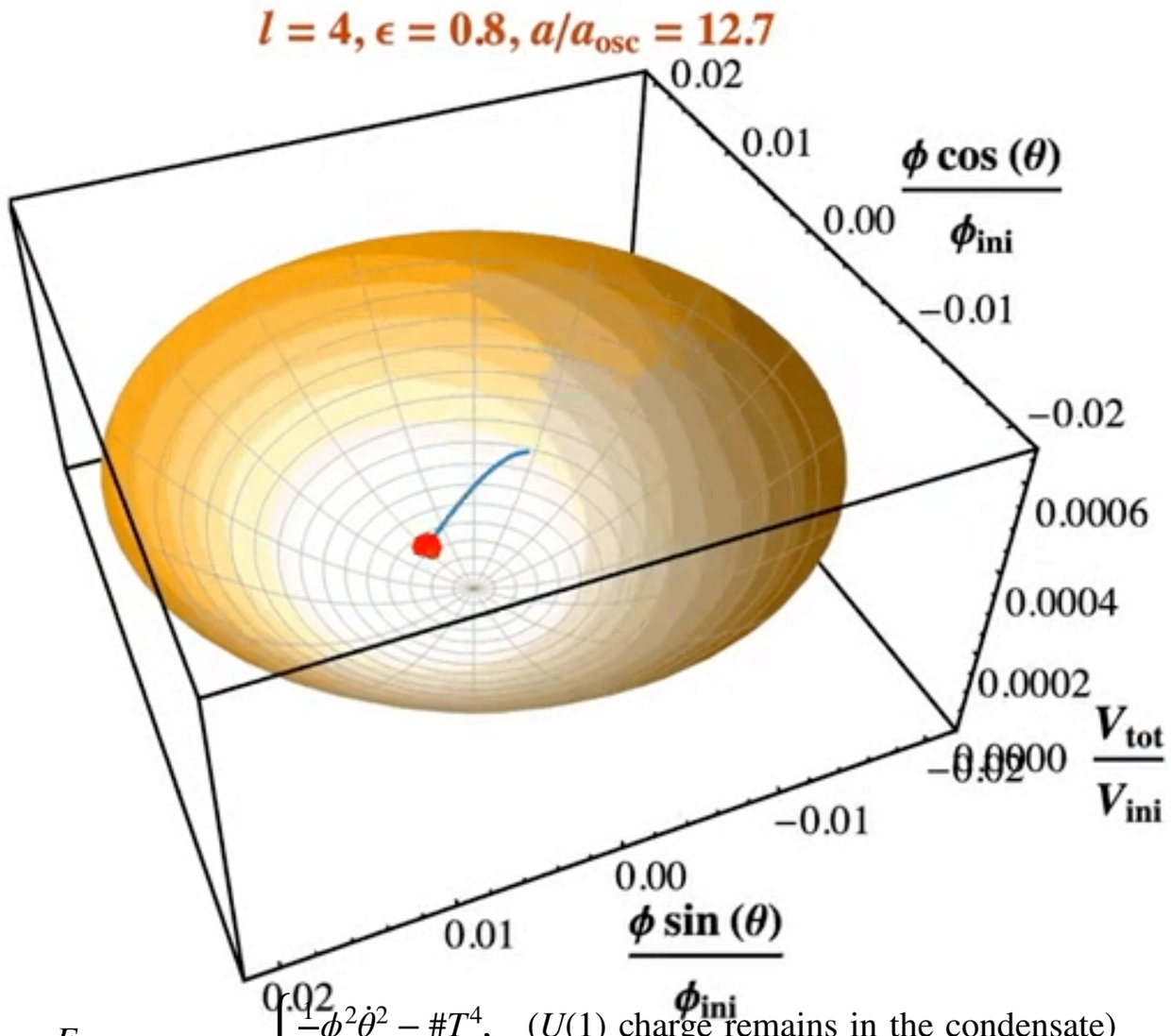
a: 

b: 

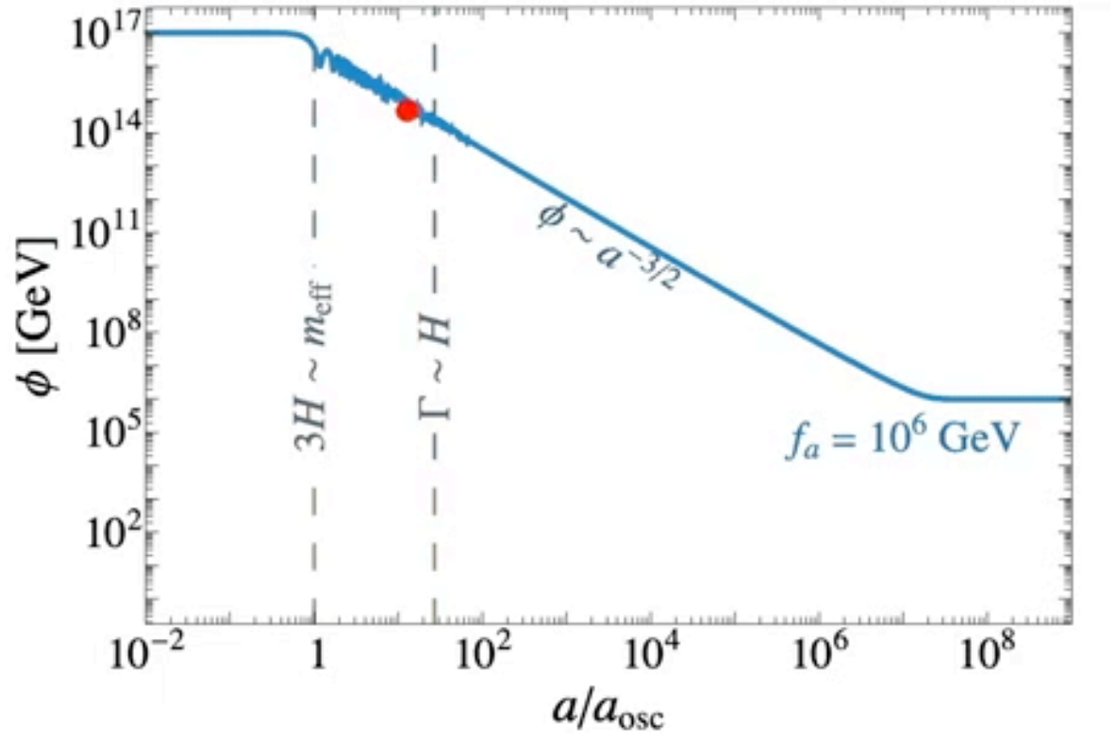
c: 

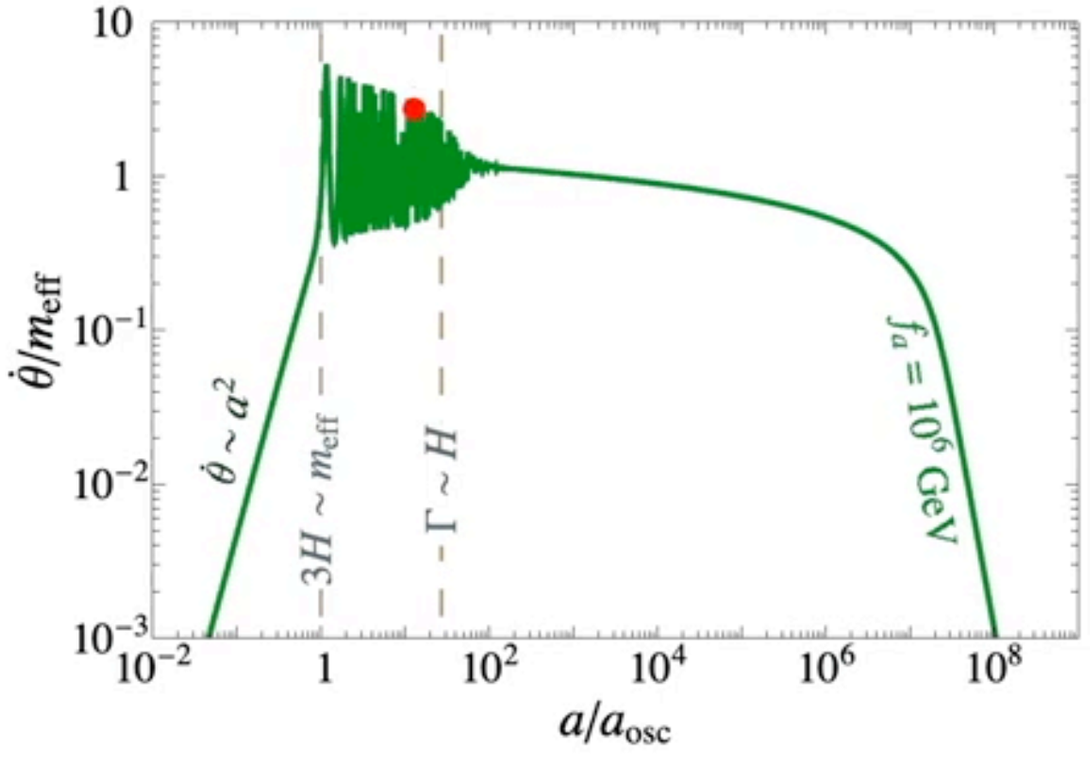


$$\frac{F}{V} = \rho - Ts = \begin{cases} \frac{1}{2}\phi^2\dot{\theta}^2 - \#T^4, & (U(1) \text{ charge remains in the condensate}) \\ \#\frac{\phi^4\dot{\theta}^2}{T^2} - \#T^4, & (U(1) \text{ charge transferred to the plasma}) \end{cases}$$

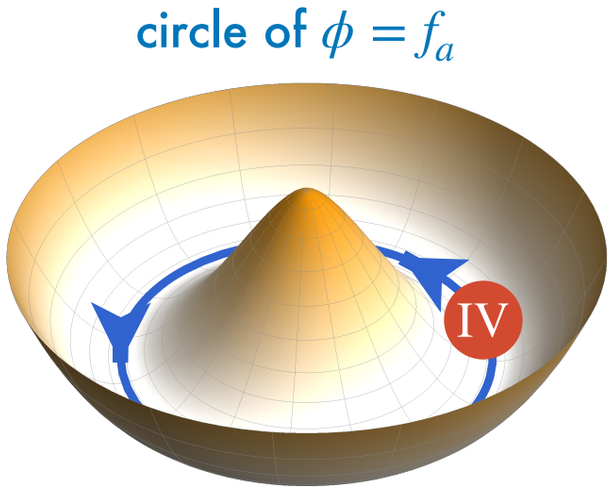
$(\rho \supset \mu n$ with $\mu = n/T^2$ and $n = \phi^2\dot{\theta})$

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





After reaching the bottom ⇒ kination era



Axion speed $\dot{\theta} \sim m_r$ (from $V''(\phi) \sim \dot{\theta}^2\phi$)

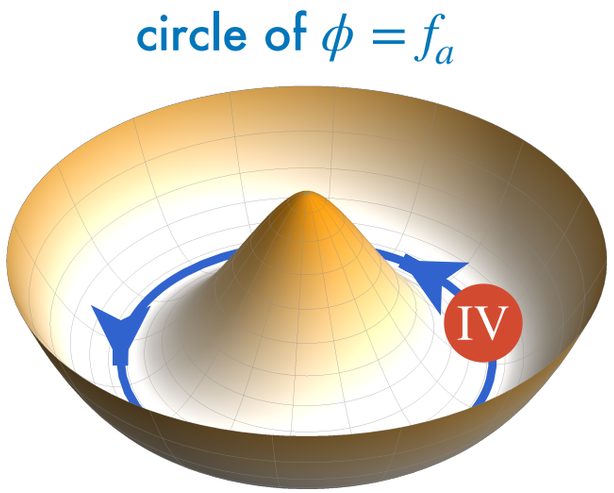
$$\frac{d}{dt}(a^3\phi^2\dot{\theta}) = 0 \;\Rightarrow \dot{\theta} \propto a^{-3}$$

Kinetic energy dominates

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

and behaves as kination.

After reaching the bottom ⇒ kination era



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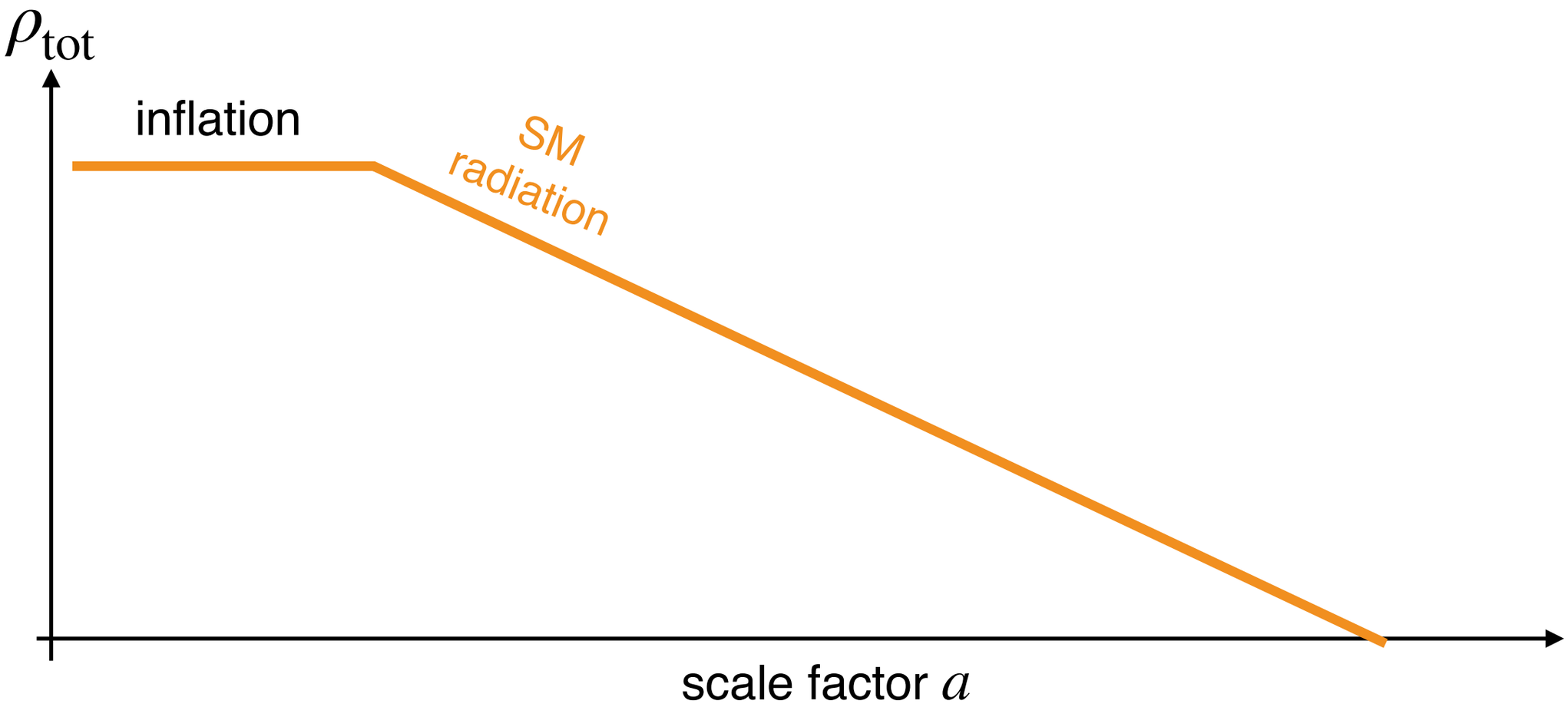

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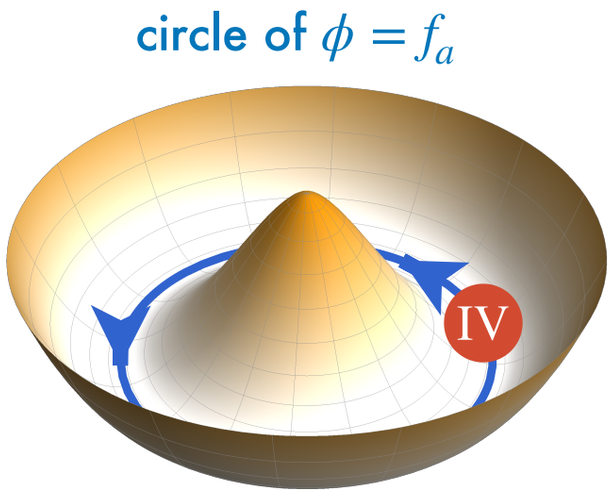

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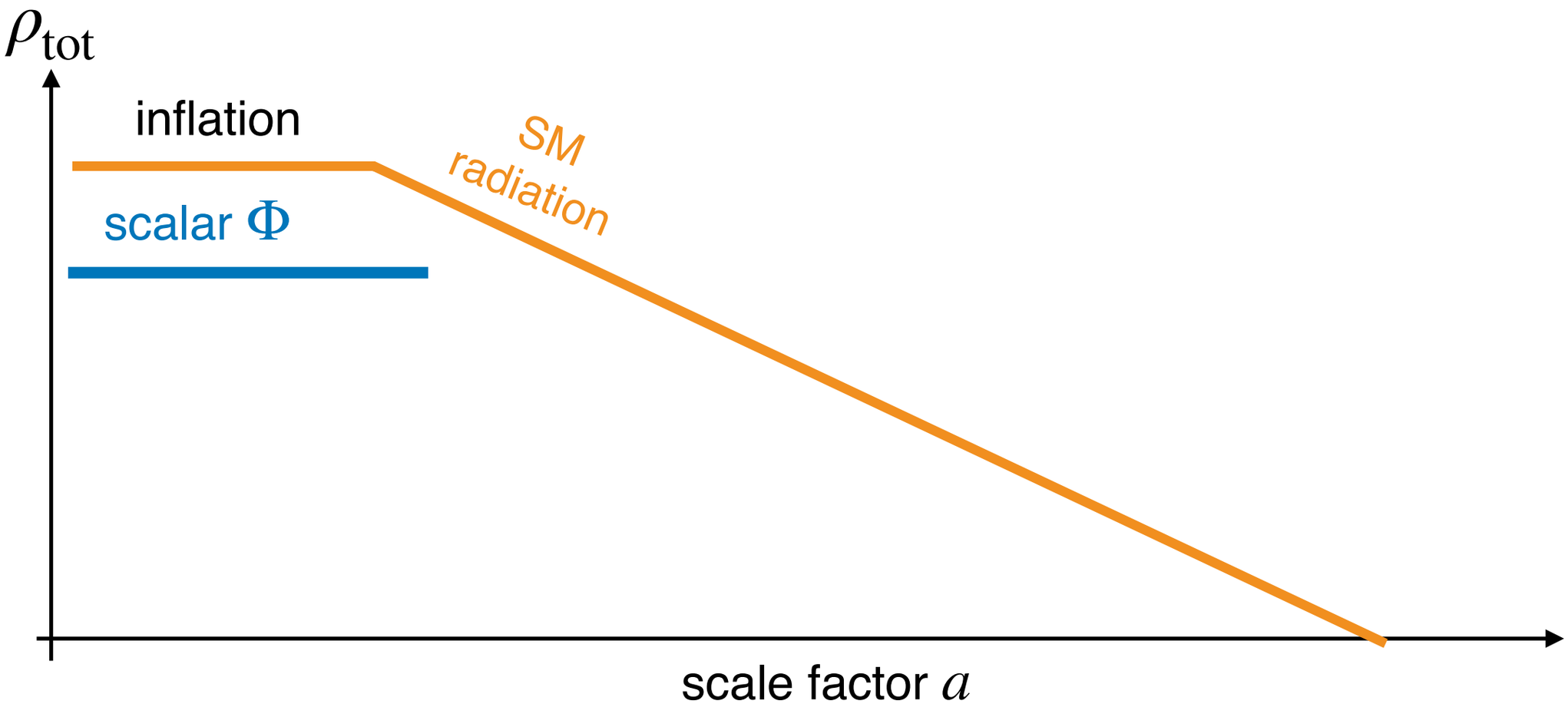

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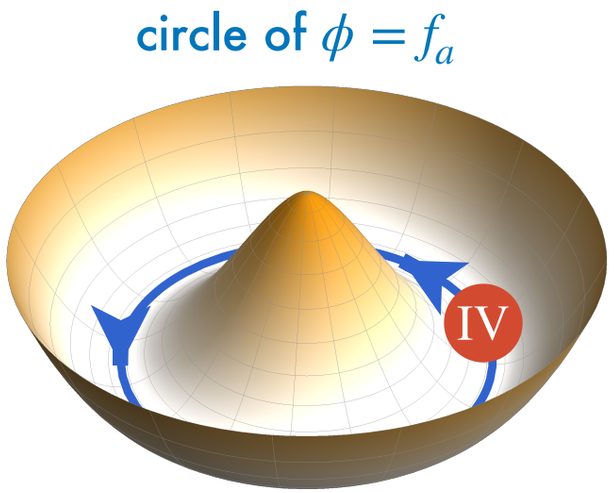

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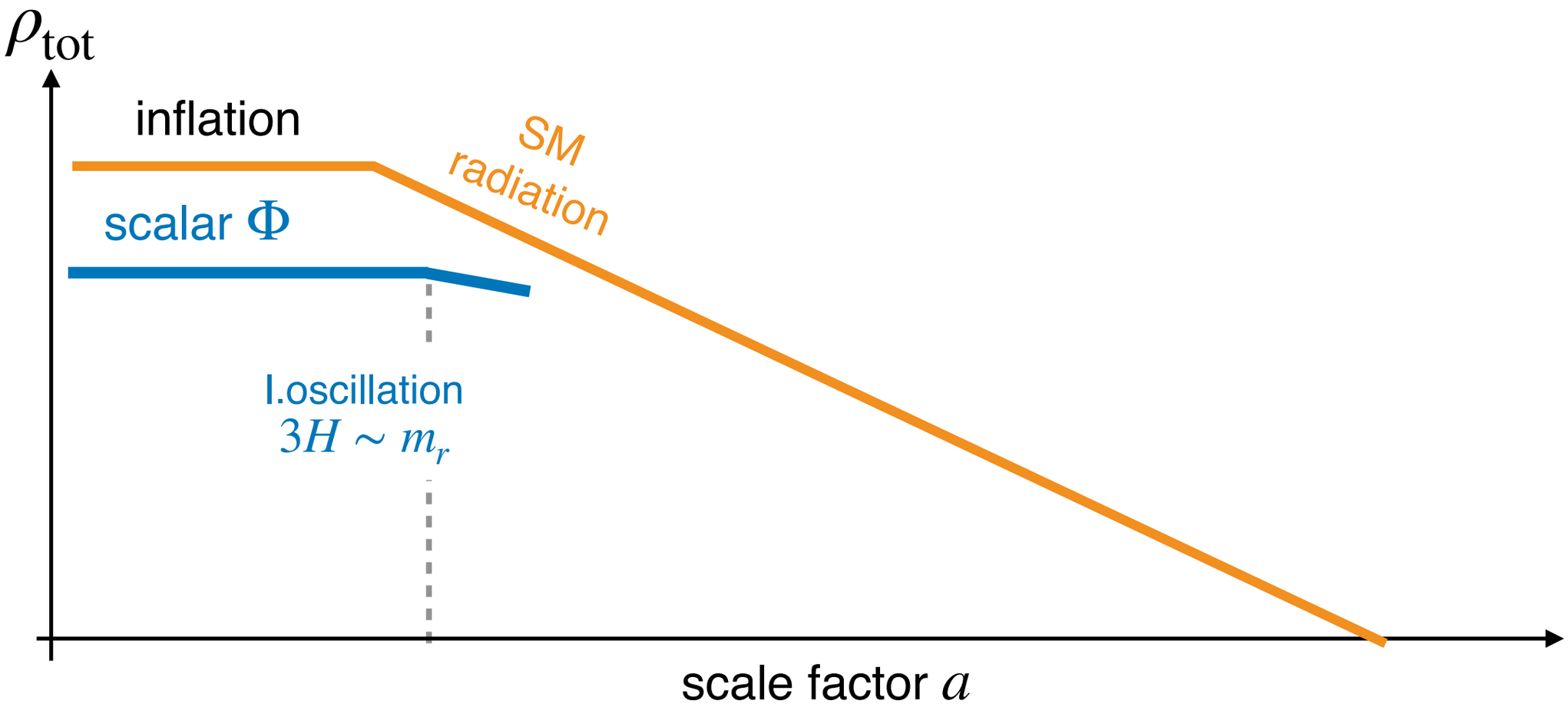
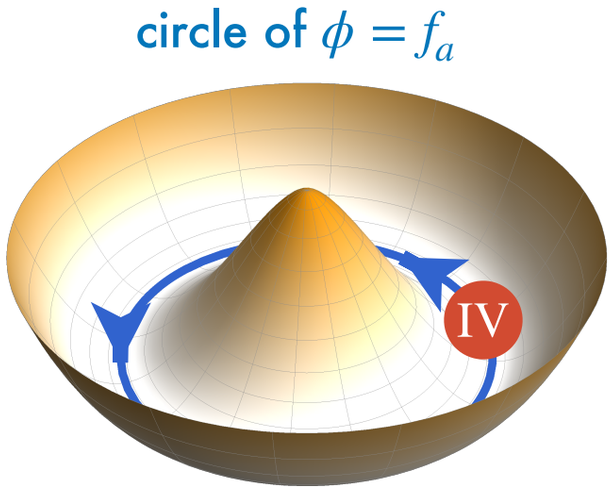


After reaching the bottom ⇒ kination era



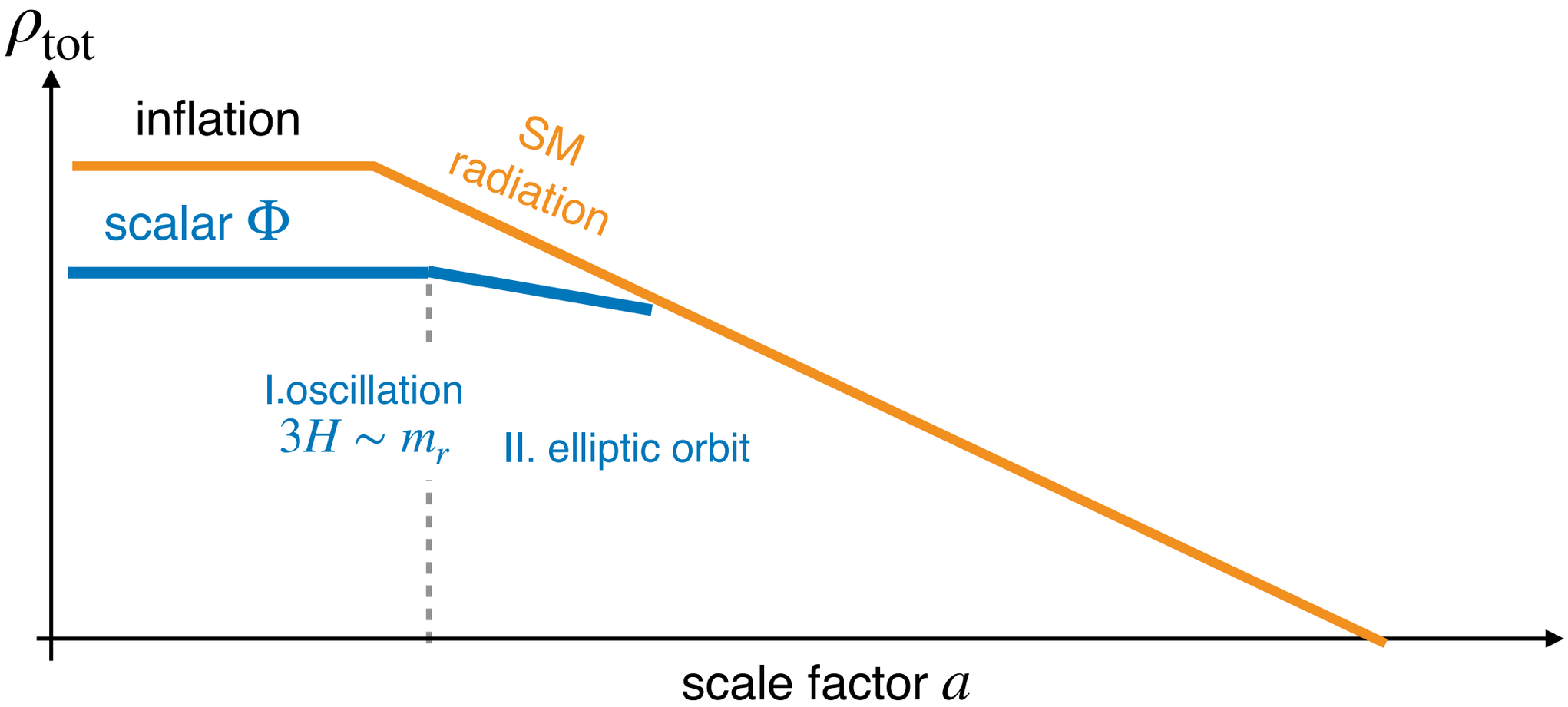
Axion speed $\dot{\theta} \sim m_r$ (from $V''(\phi) \sim \dot{\theta}^2\phi$)

$$\frac{d}{dt}(a^3\phi^2\dot{\theta}) = 0 \;\Rightarrow \dot{\theta} \propto a^{-3}$$

Kinetic energy dominates

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

and behaves as kination.



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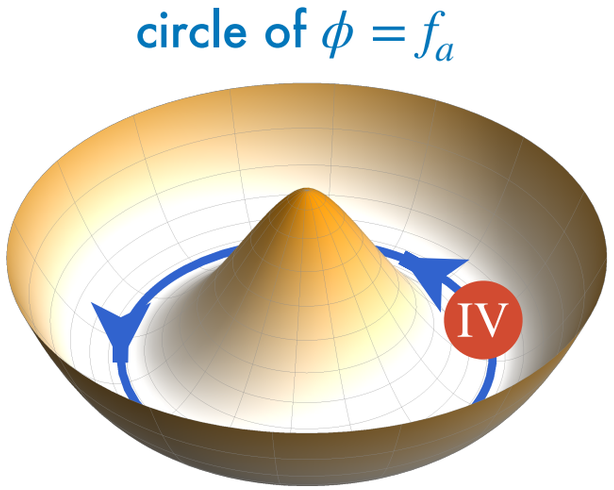

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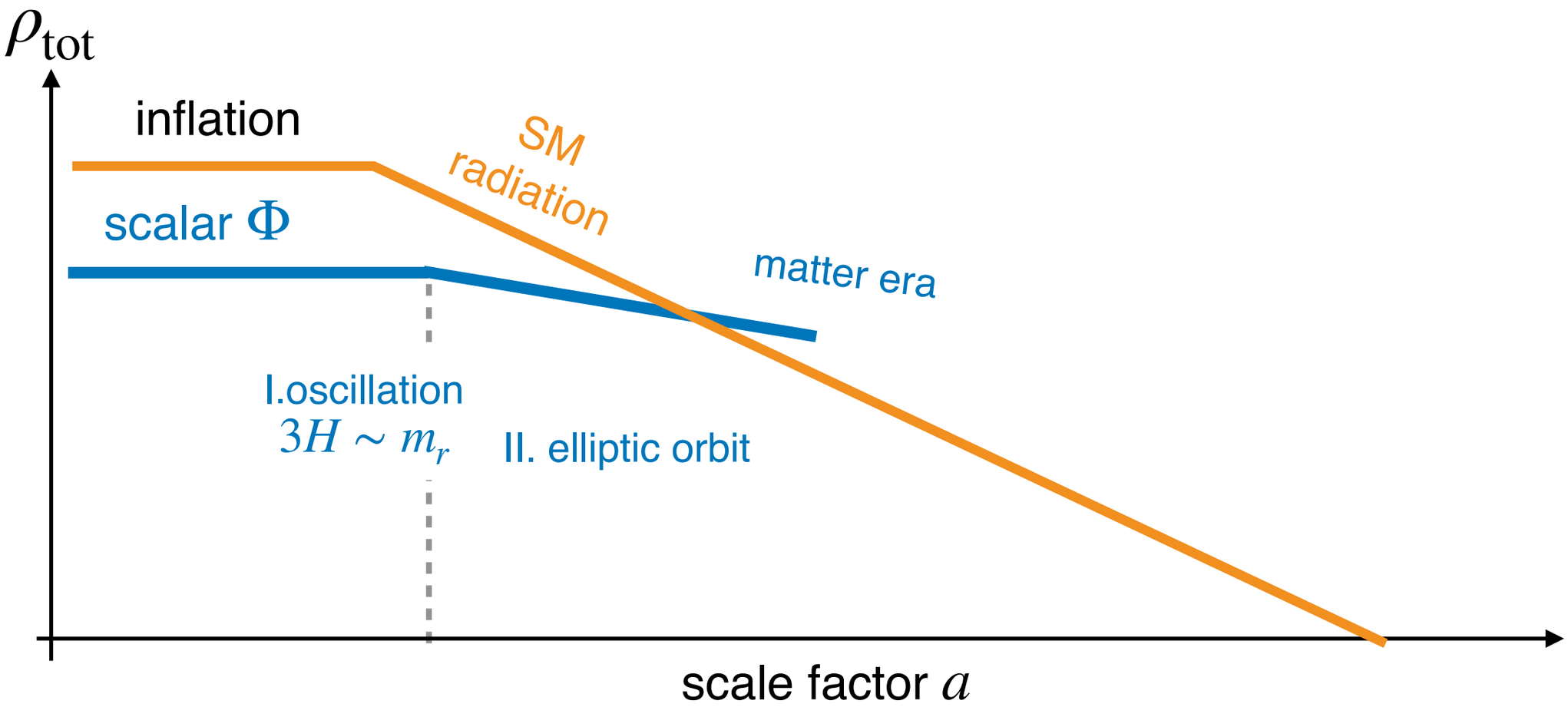

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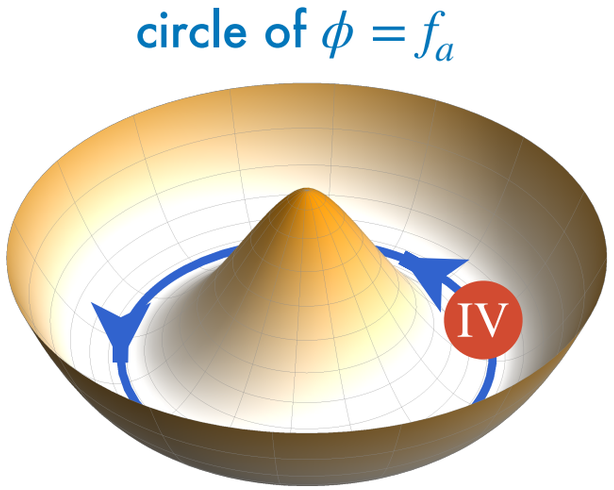

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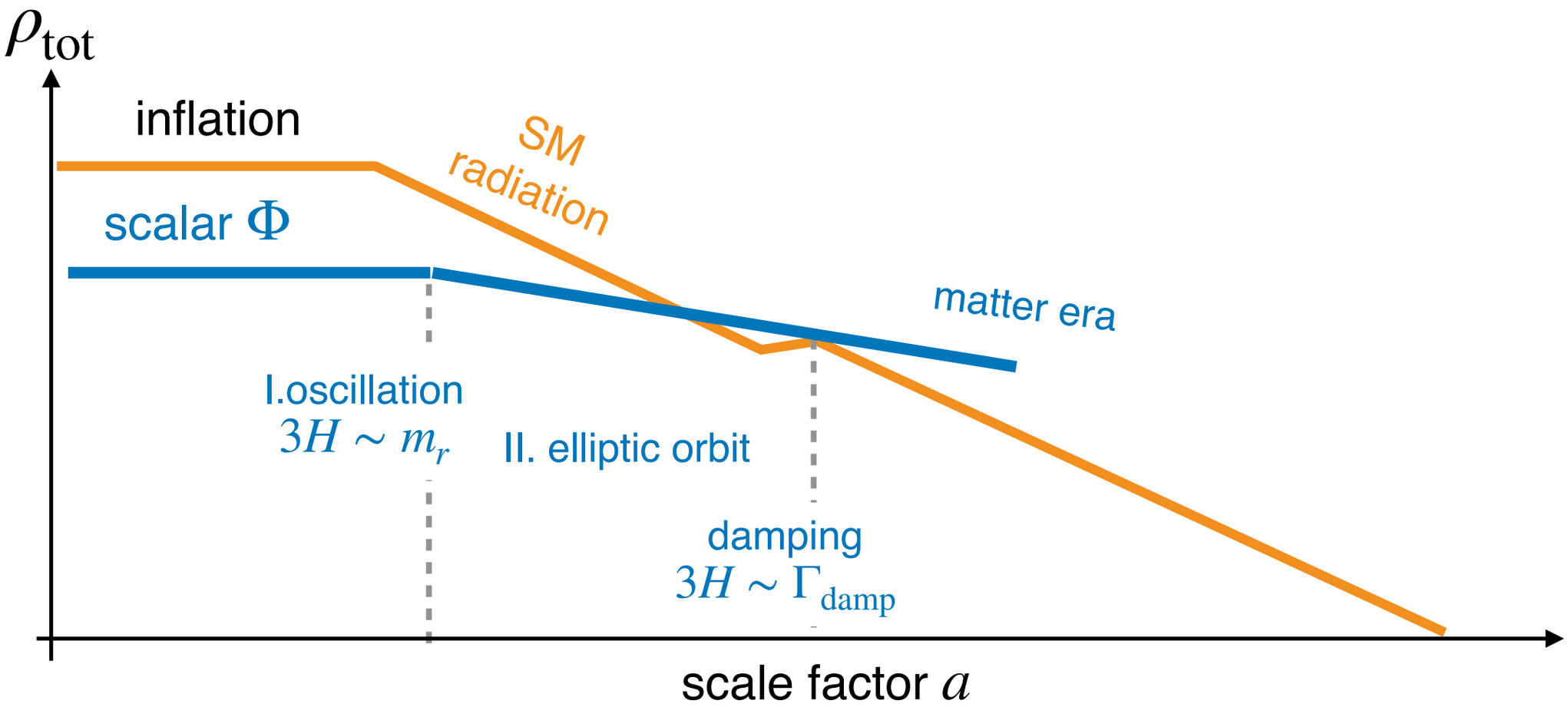

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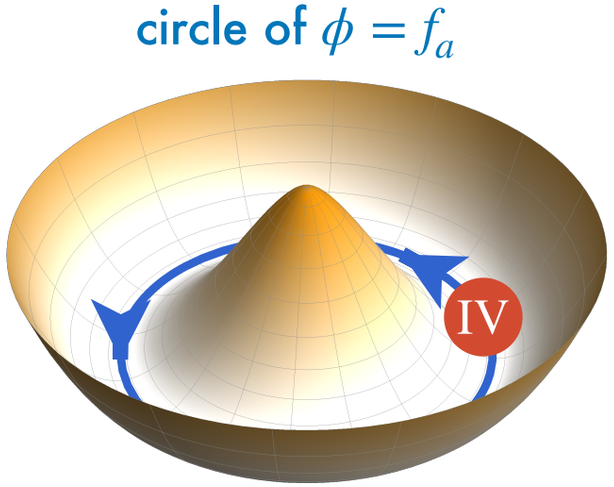

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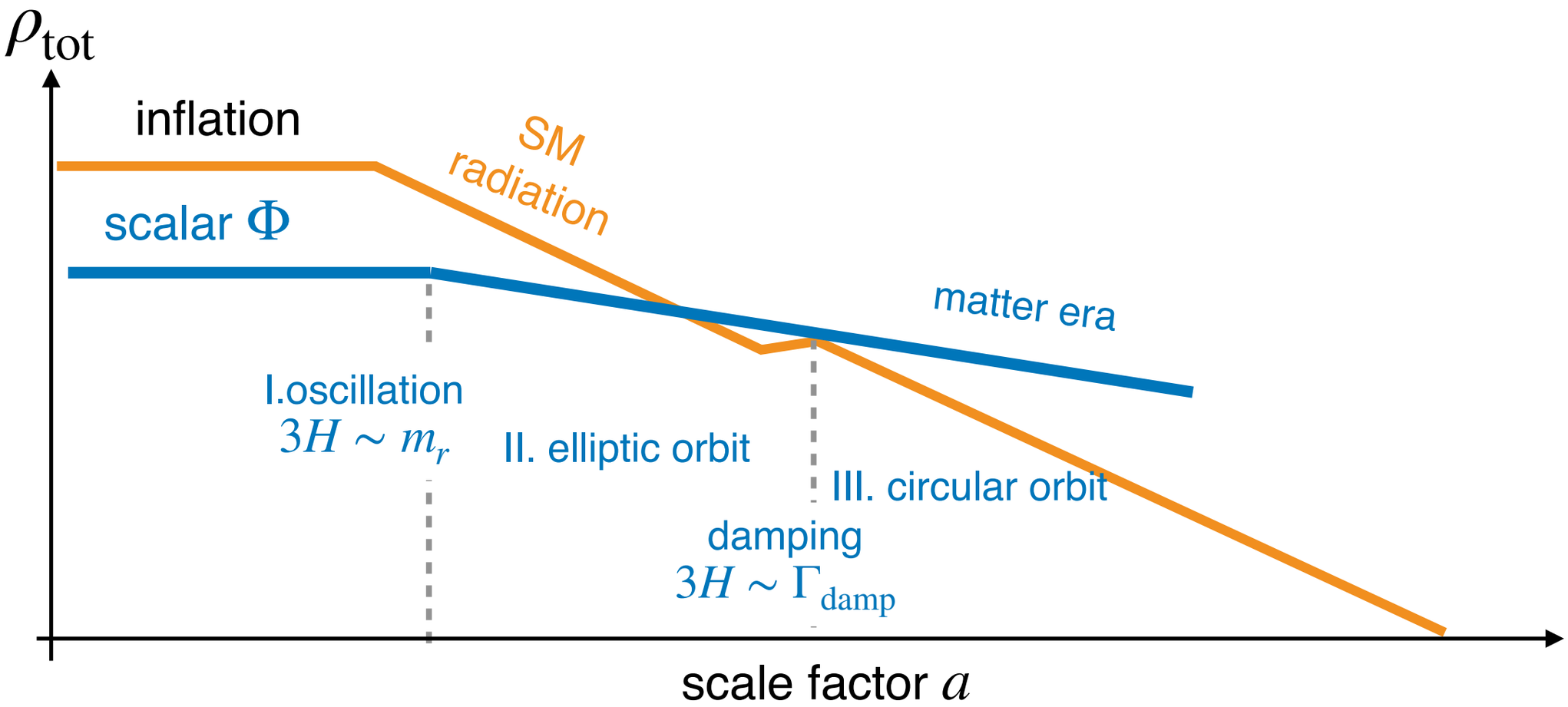

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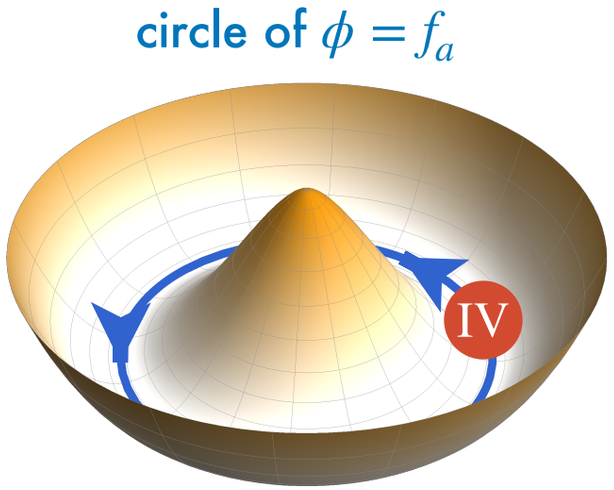

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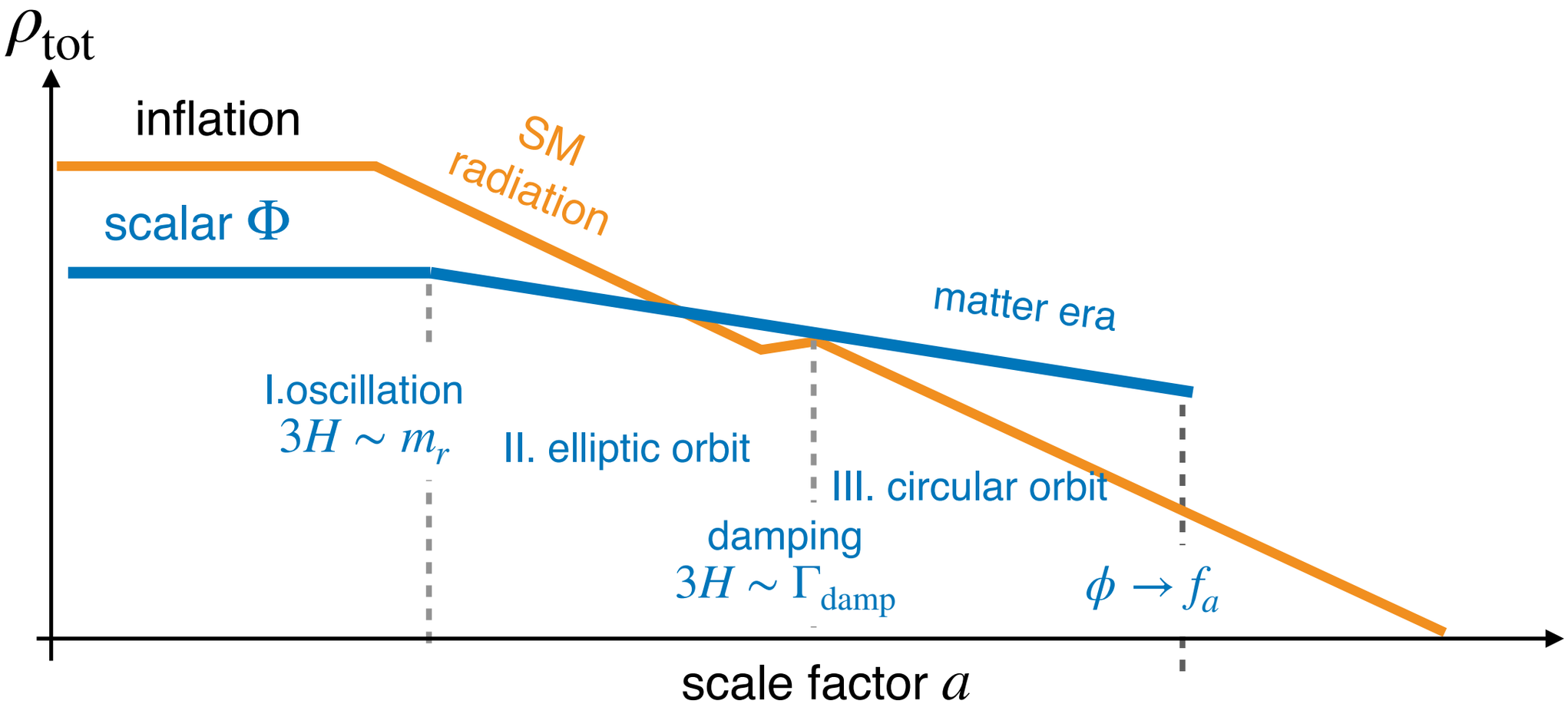

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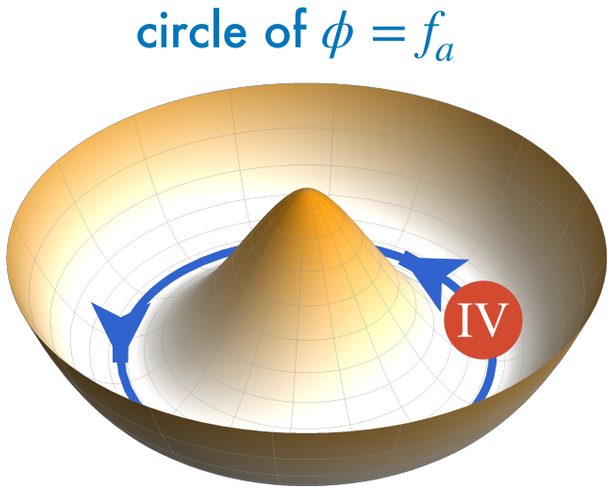

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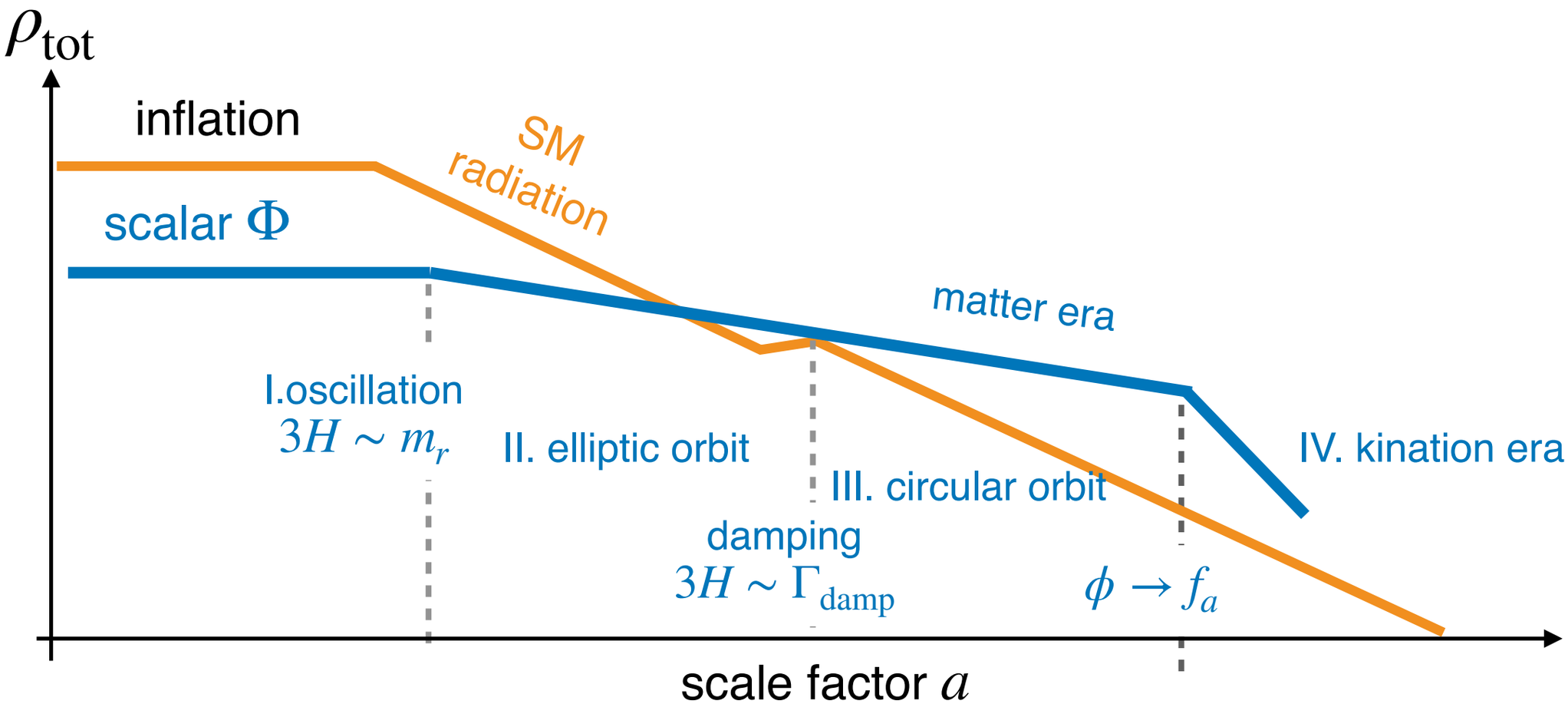

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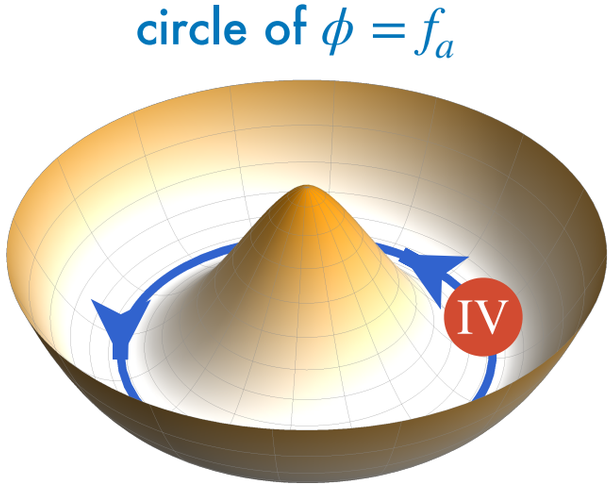

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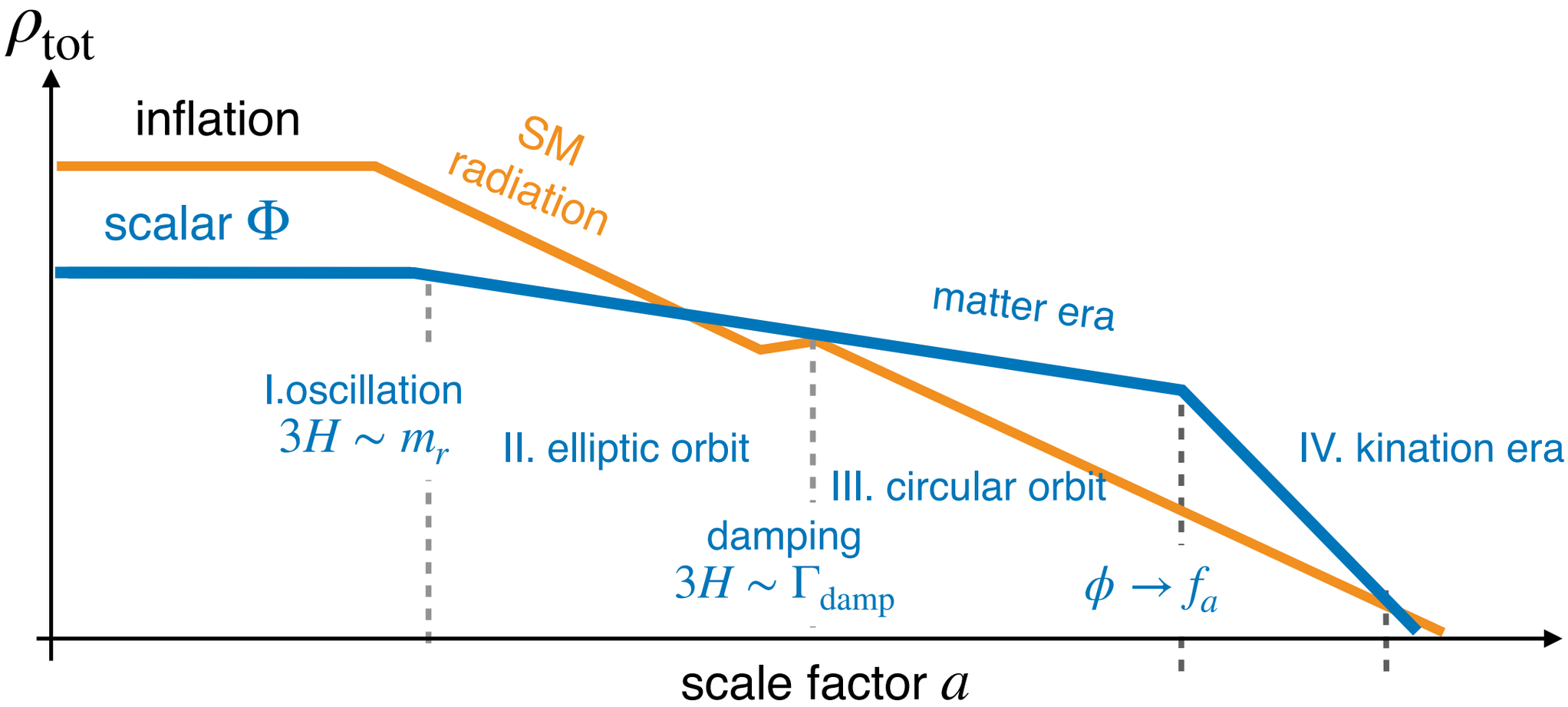

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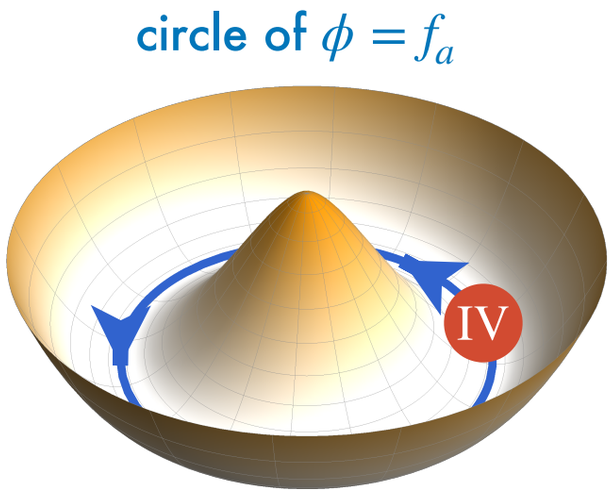

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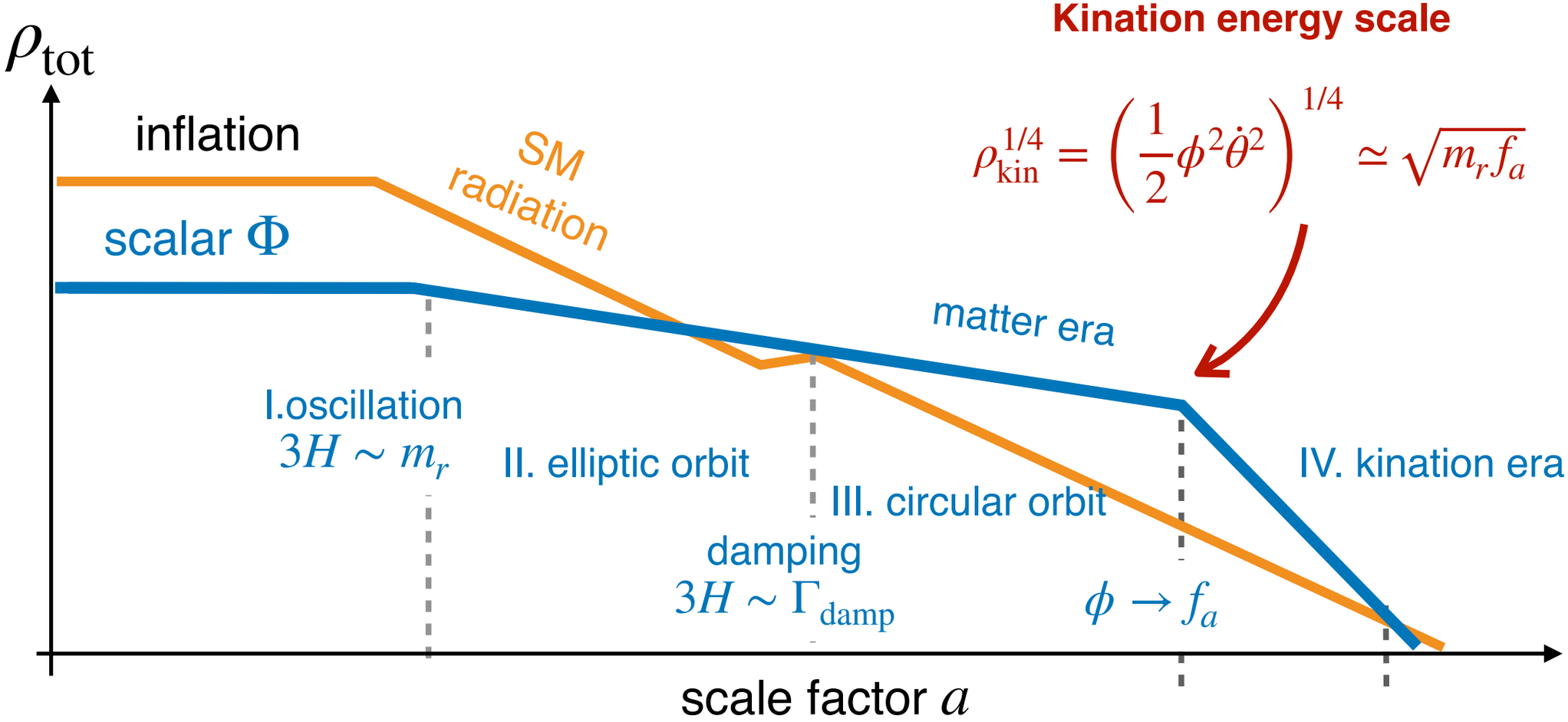
Kination energy scale

$$\rho_{\rm kin}^{1/4} = \left(\frac{1}{2}\phi^2\dot{\theta}^2\right)^{1/4} \simeq \sqrt{m_r f_a}$$



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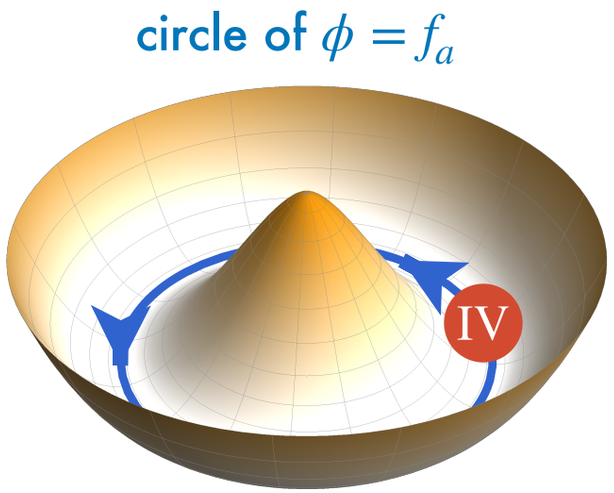

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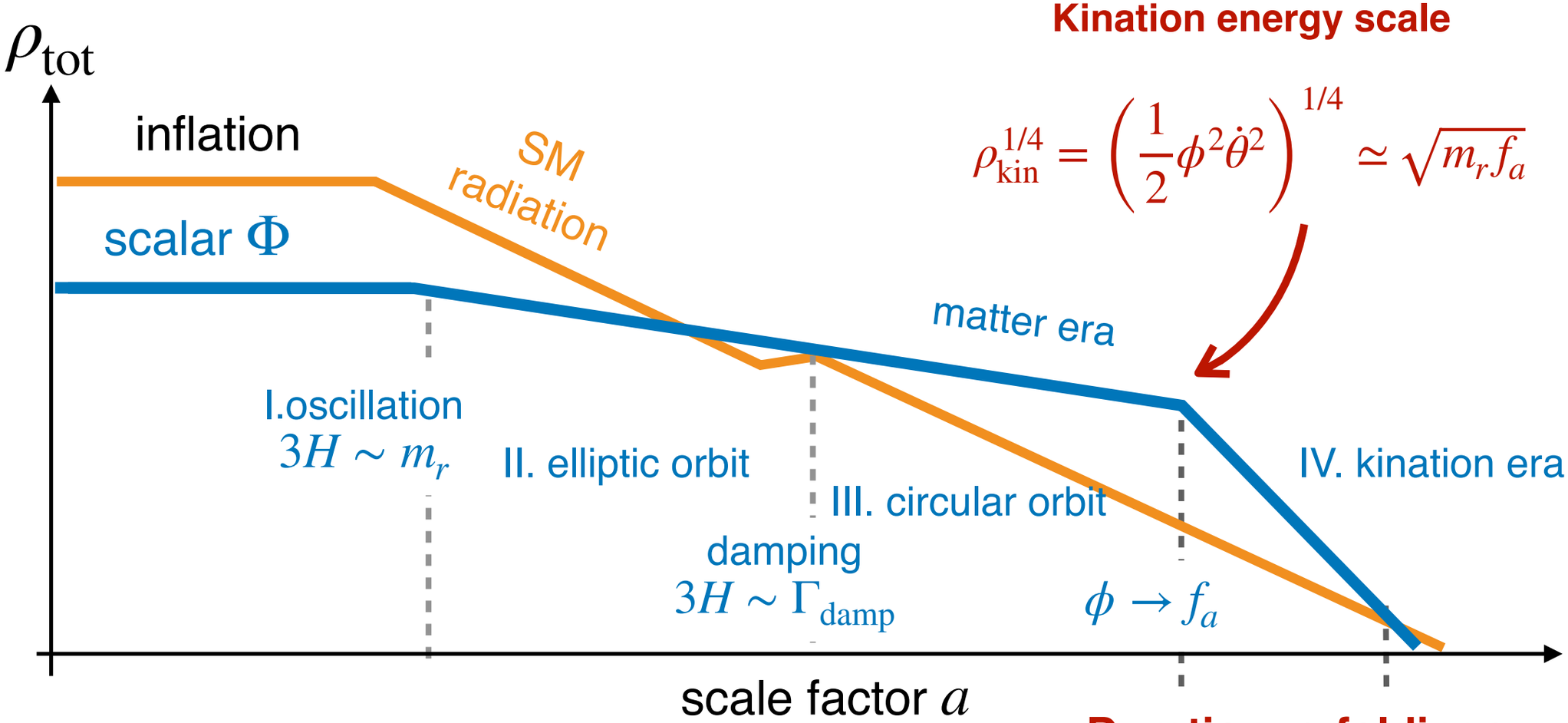

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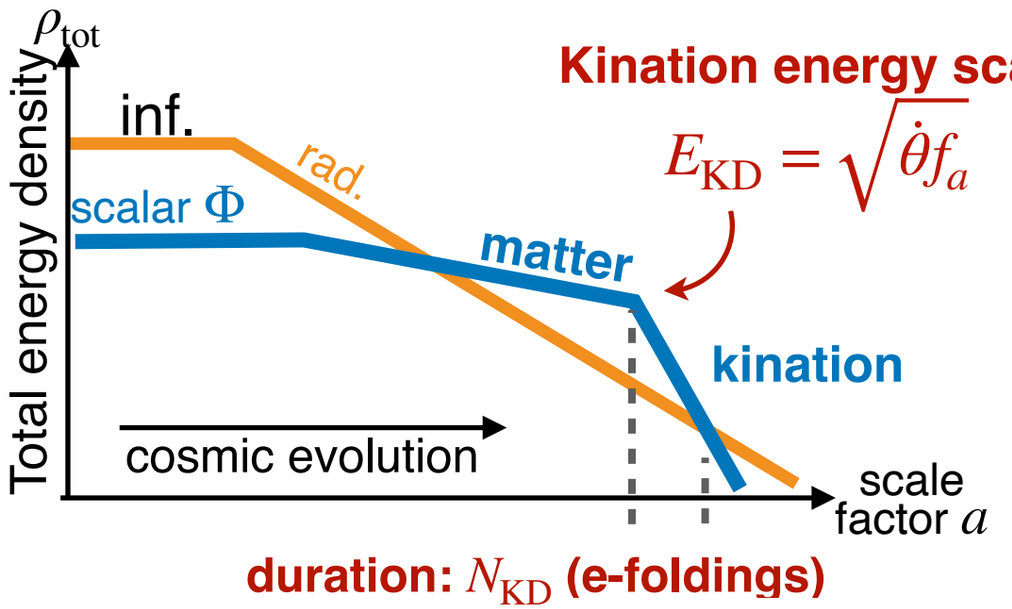
Duration: e-foldings

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

GW signature: a “Peak”

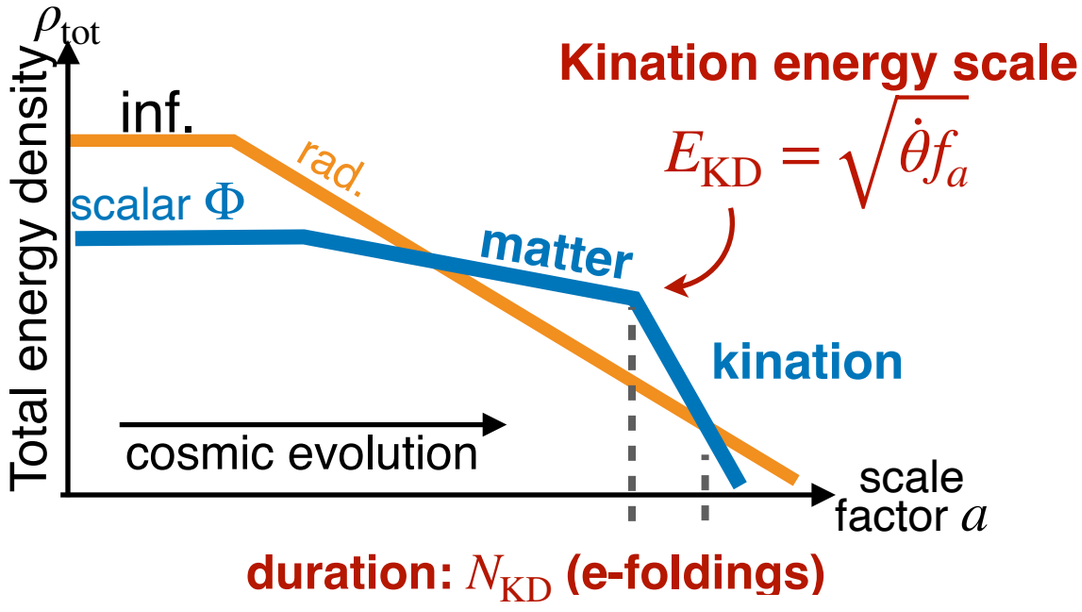


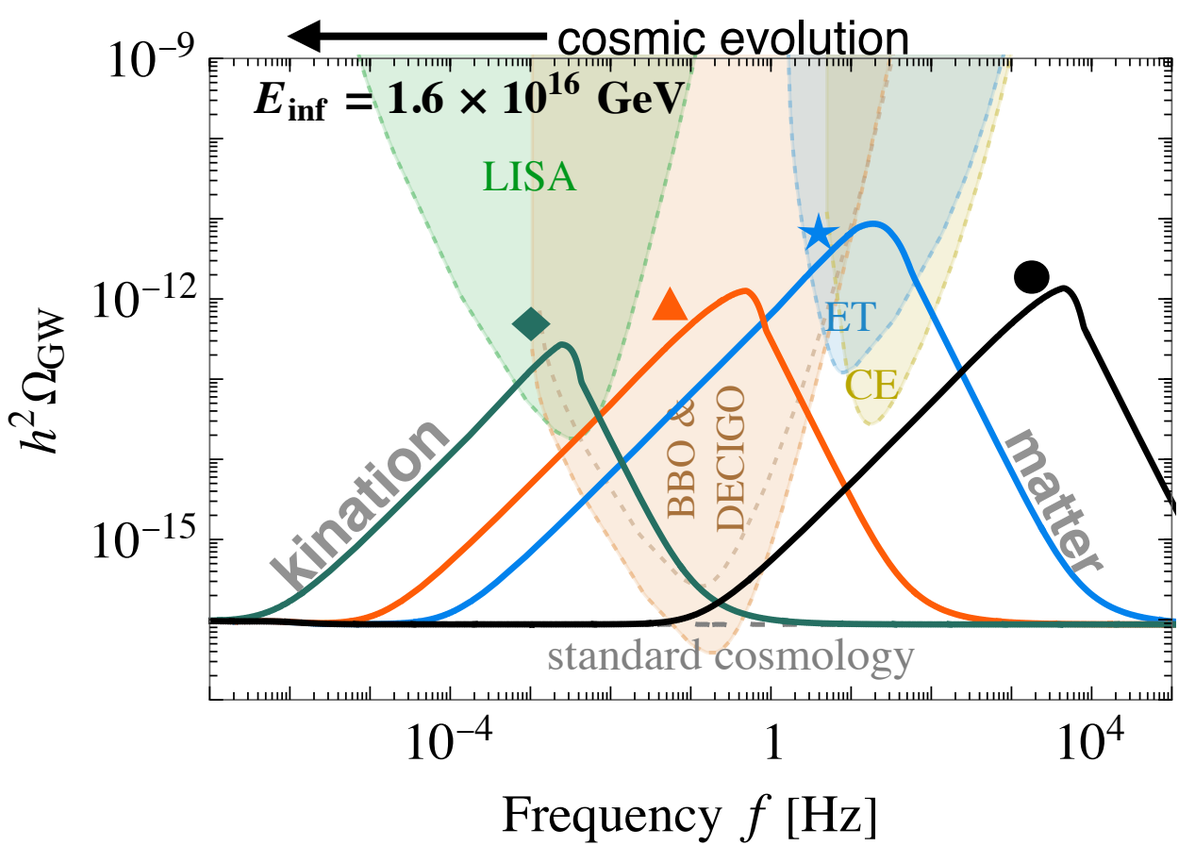
Kination energy scale

$$E_{\rm KD} = \sqrt{\dot{\theta} f_a}$$

duration: $N_{\rm KD}$ (e-foldings)

GW signature: a “Peak”





[YG, Servant, Simakachorn 2108.10328 & 2111.01150]

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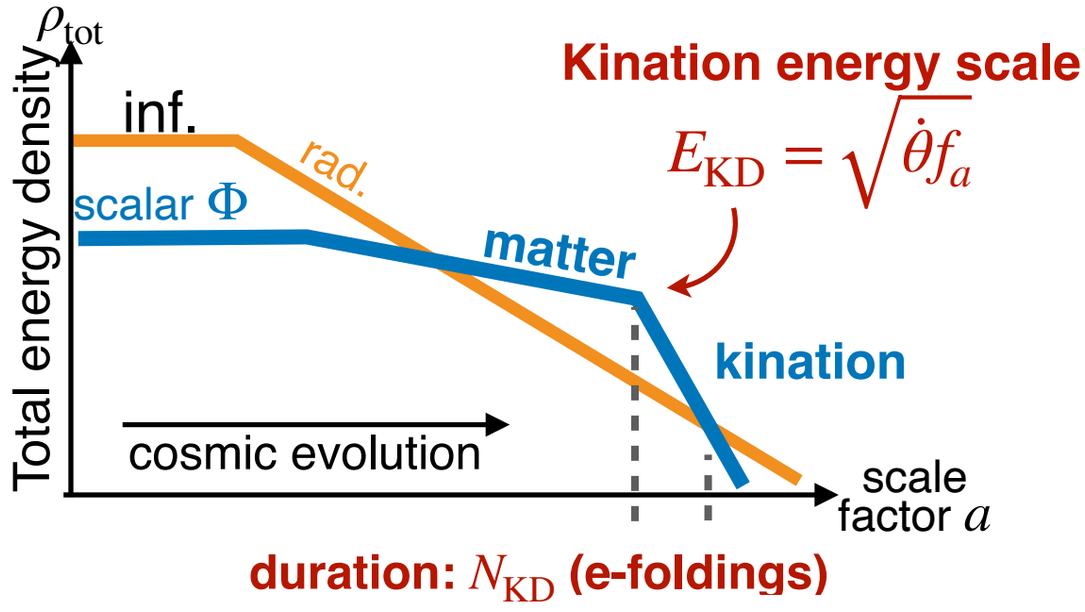

Peak position for GW from inflation.

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

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

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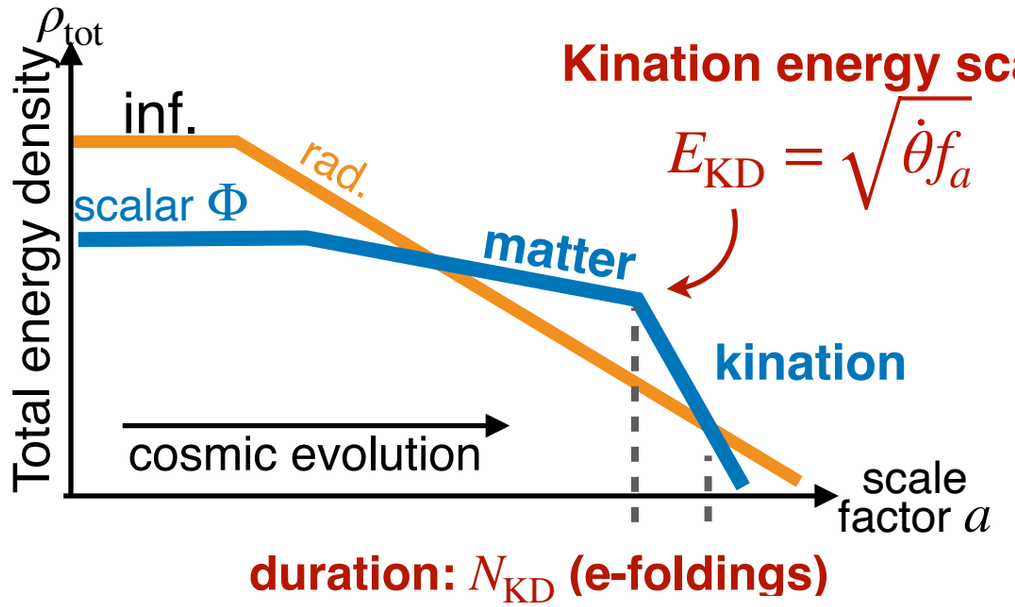

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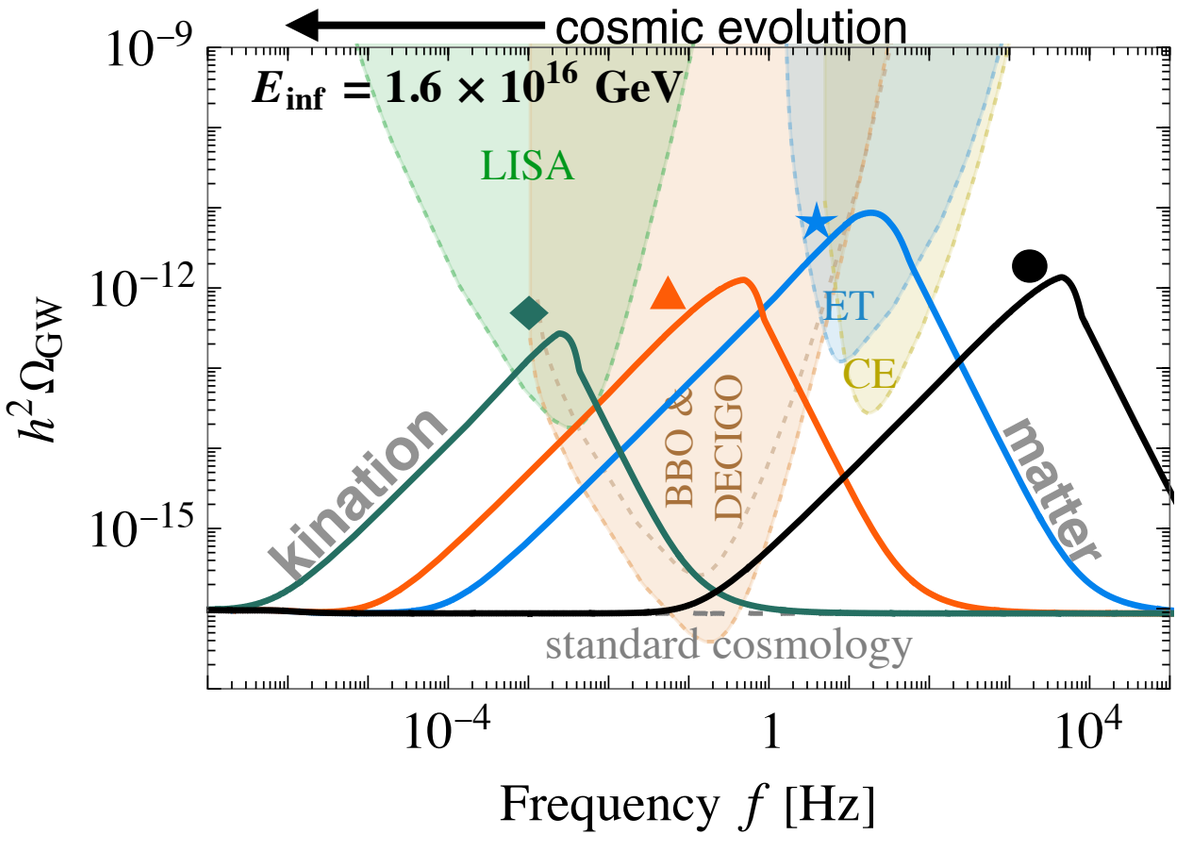
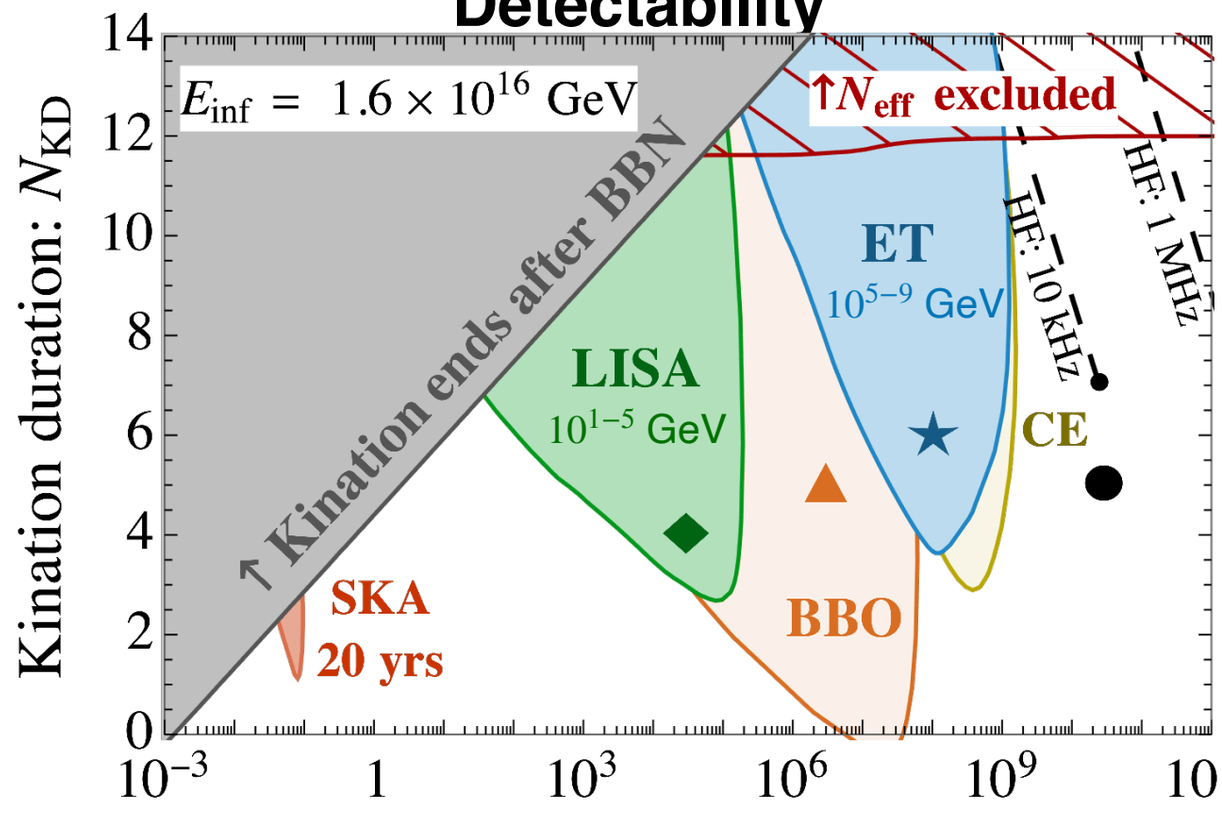


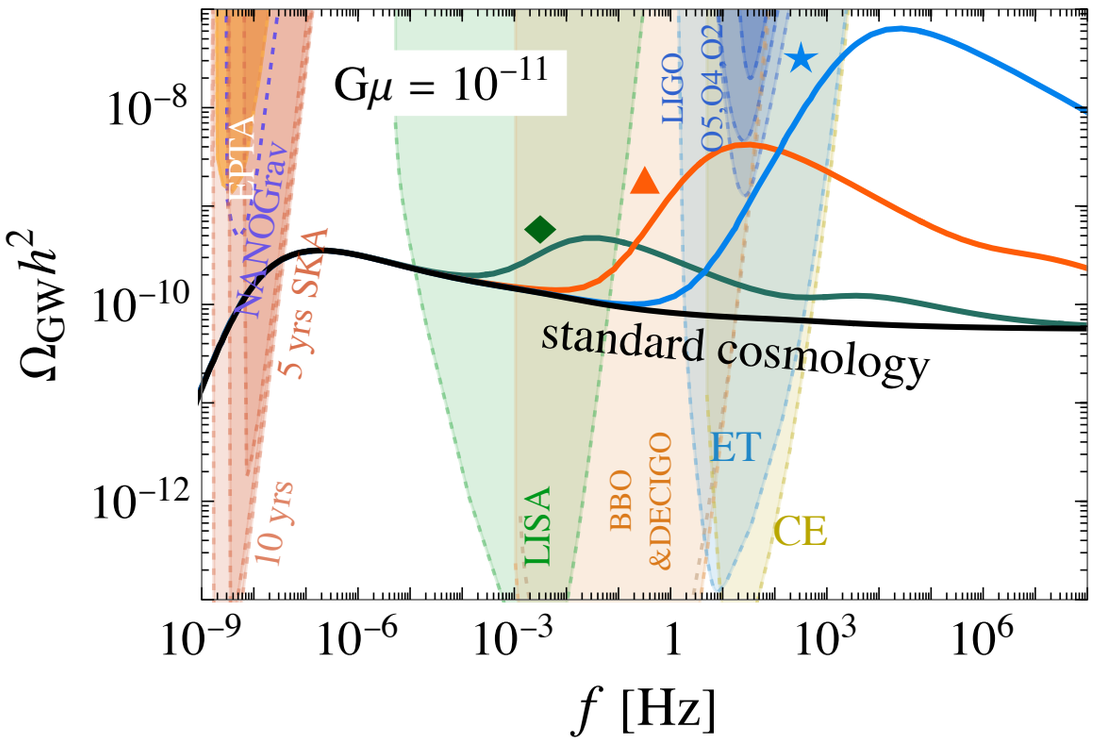
Detectability

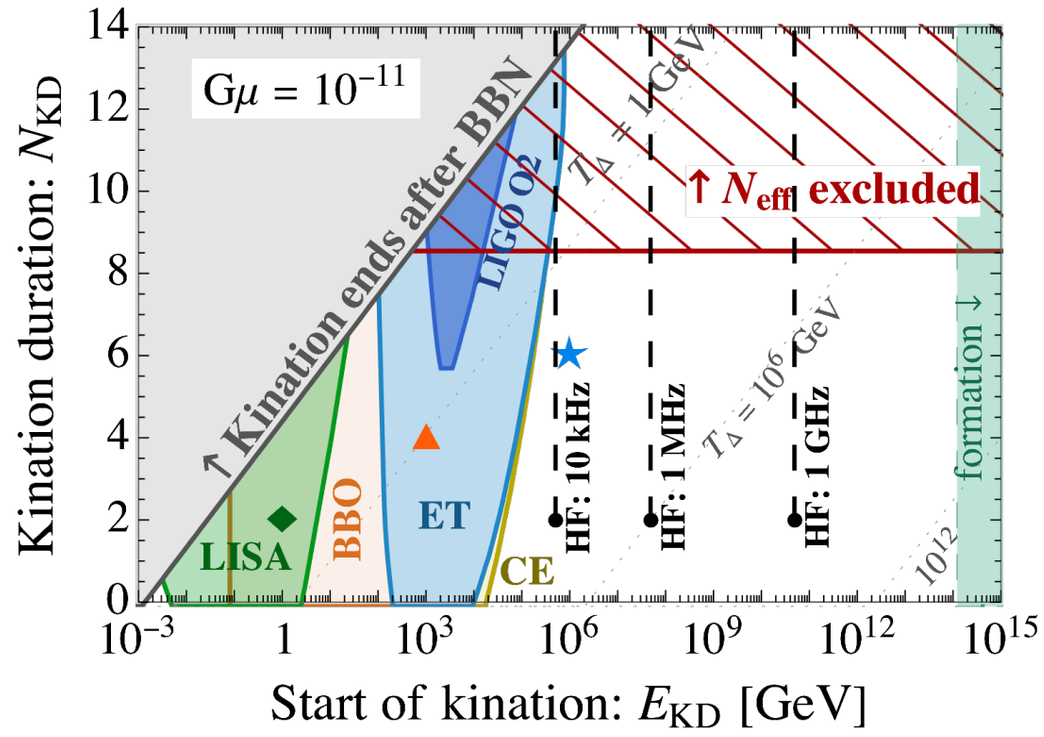


[YG, Servant, Simakachorn 2108.10328 & 2111.01150]

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

YG, Servant, Simakachorn, 2111.01150





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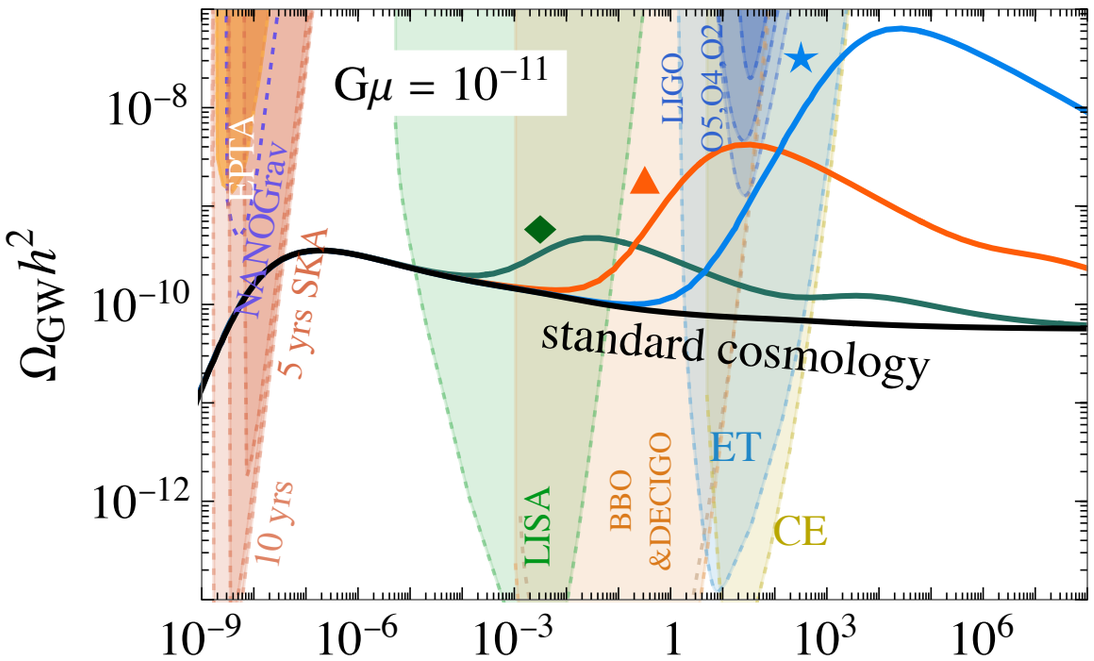
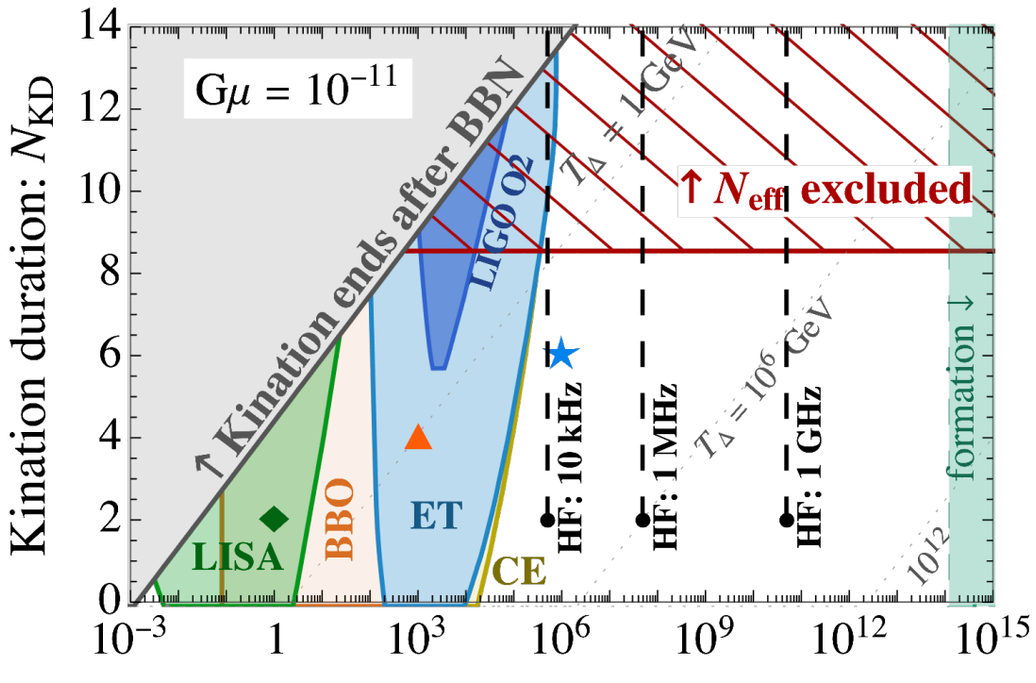
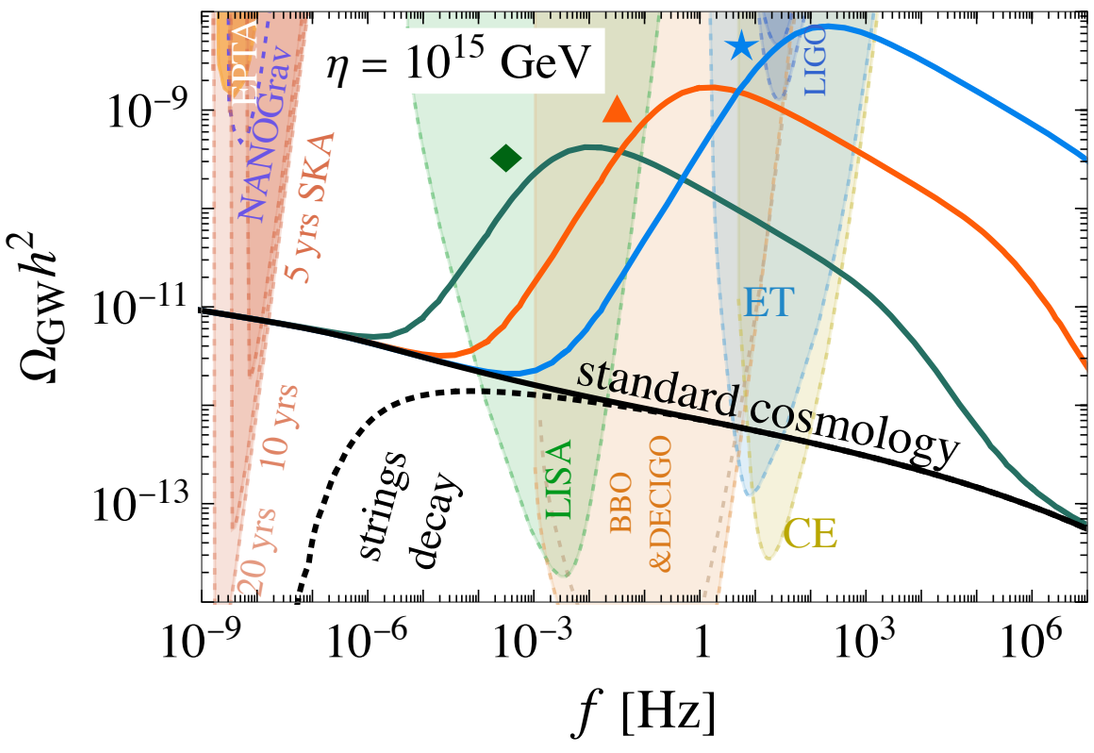
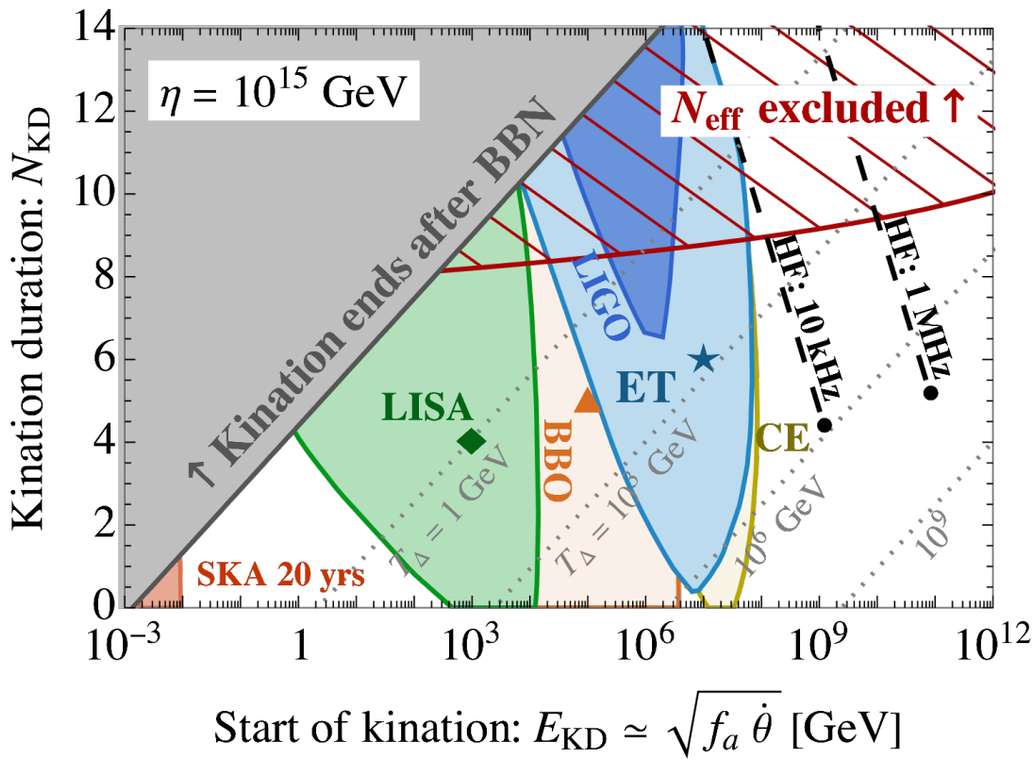
YG, Servant, Simakachorn, 2111.01150





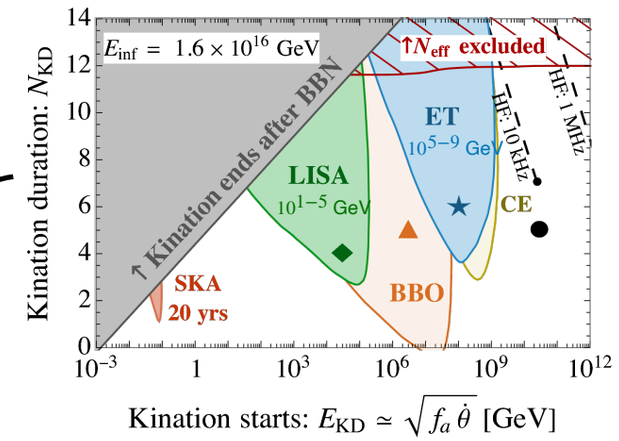
Global **cosmic strings** symmetry breaking scale $\simeq \eta$

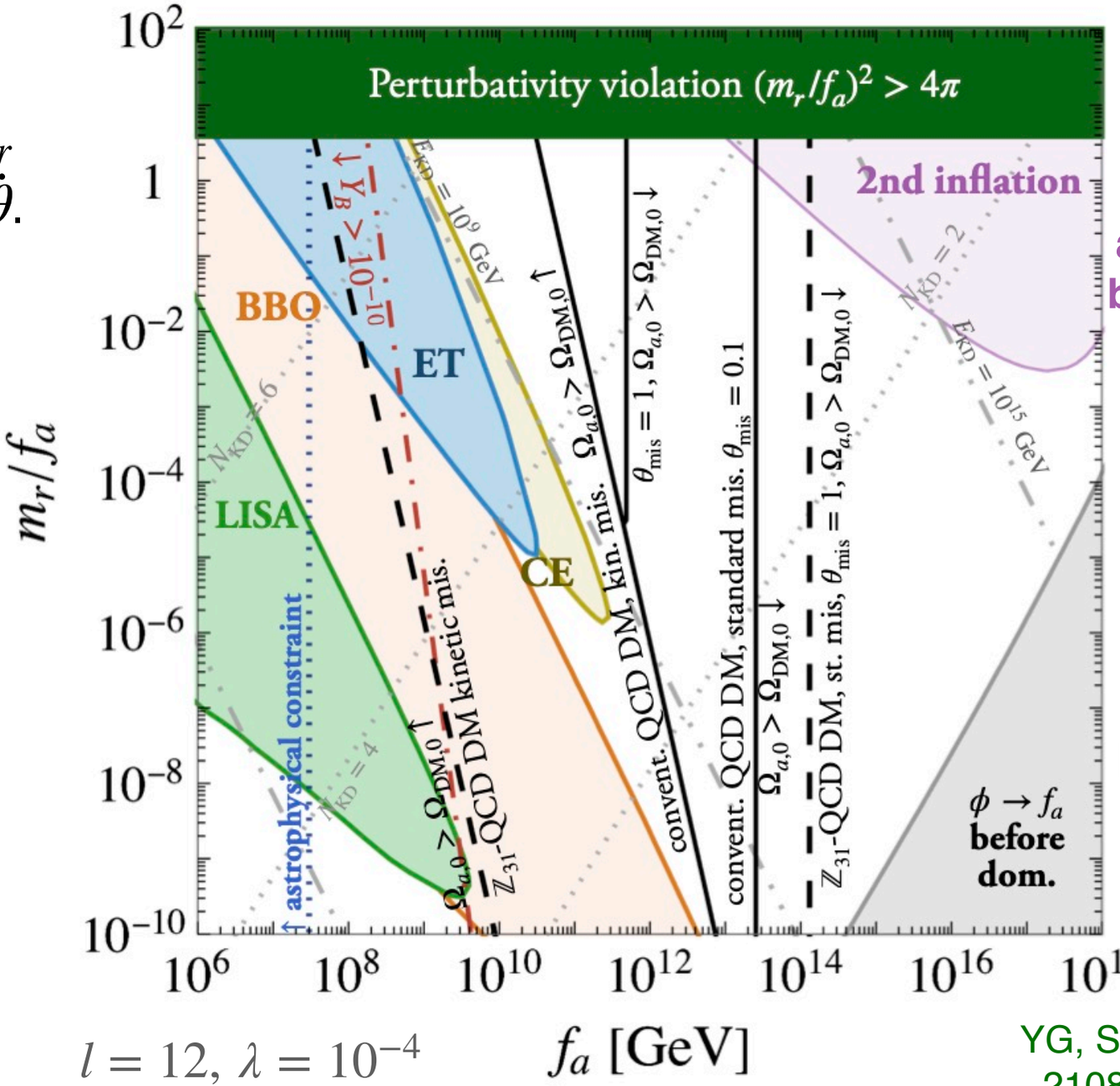




In terms of model parameters

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





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

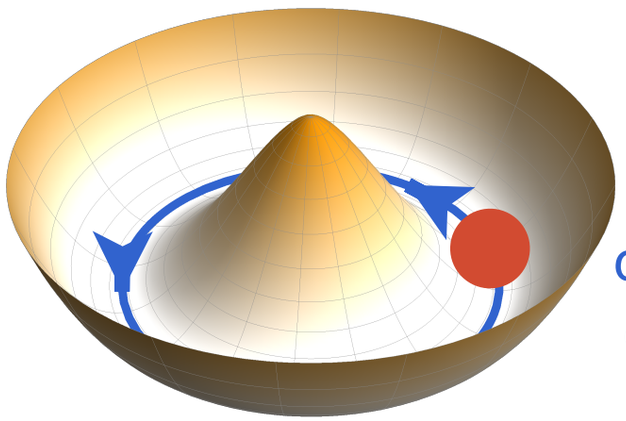
$m_r = \sqrt{V''}$

axion dominates before oscillation

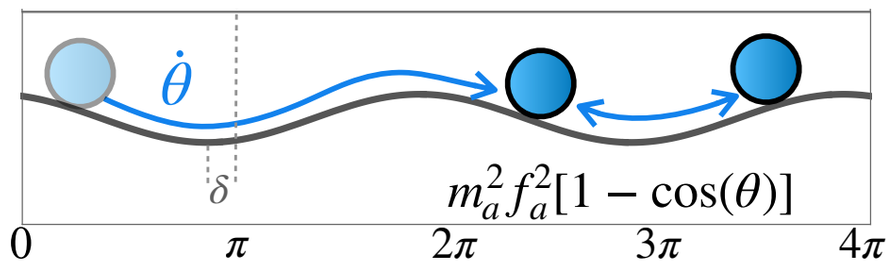
no kination

YG, Servant, Simakachorn, 2108.10328, 2111.01150

Axion Dark Matter



circle of
$\phi = f_a$



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

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

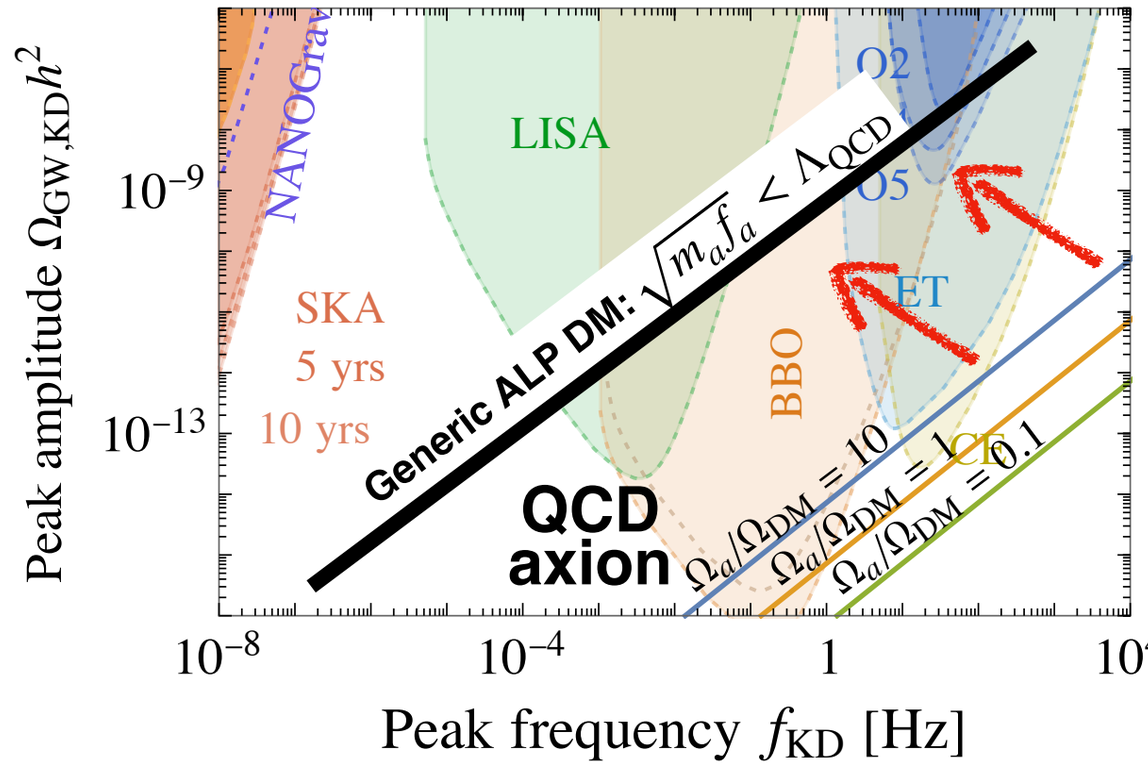
[Co, Harigaya, Hall, '19] [Chang, Cui, '19] [Fonseca, Morgante, Sato, Servant, '19] [Morgante, Ratzinger, Sato, Stefanek, '21]

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

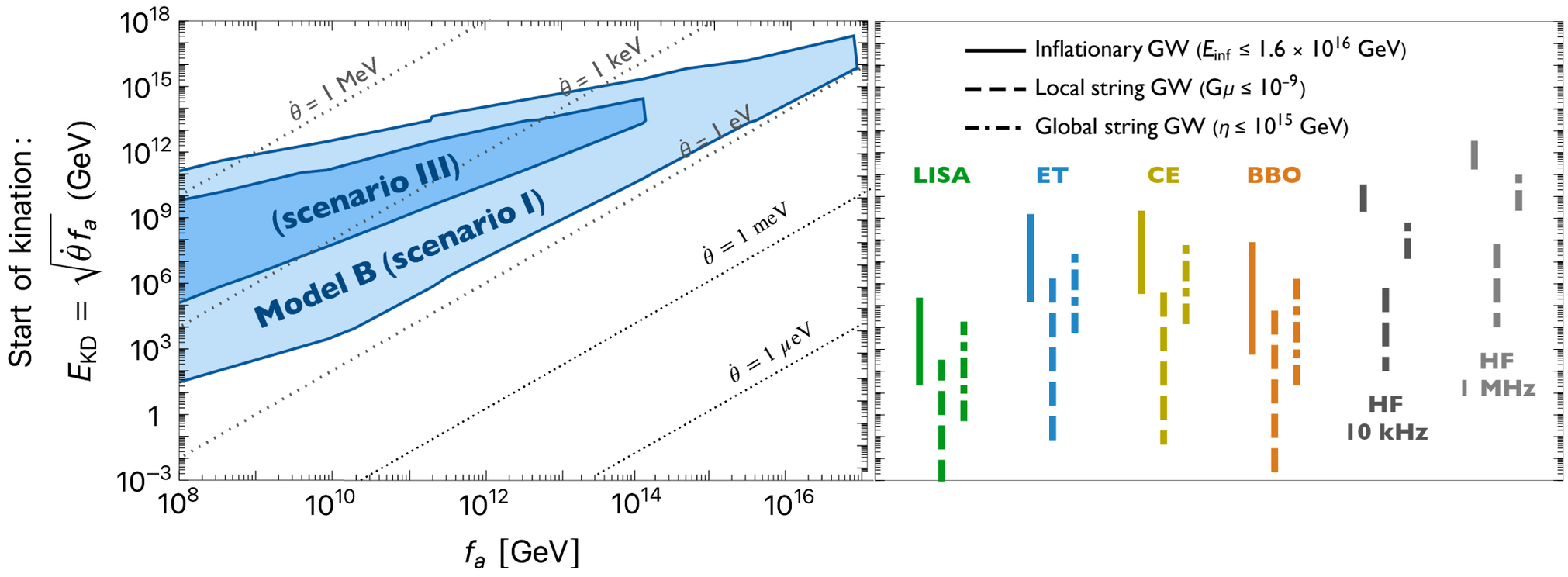
Cosmic archeology with GW from primordial inflation and cosmic strings

Early matter era — **Heavy & unstable particles** — $1\ \mathrm{s} \gtrsim \tau_X \gtrsim 10^{-17} s$

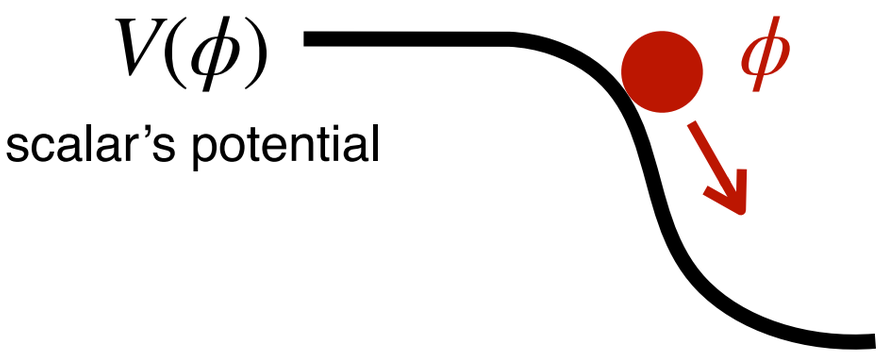
2nd inflation era — **Supercool 1st-order phase transition** — $10^{-2}\ \mathrm{GeV} \lesssim E_{\mathrm{inf}} \lesssim 10^{13}\ \mathrm{GeV}$

Intermediate kination era

Spinning axion



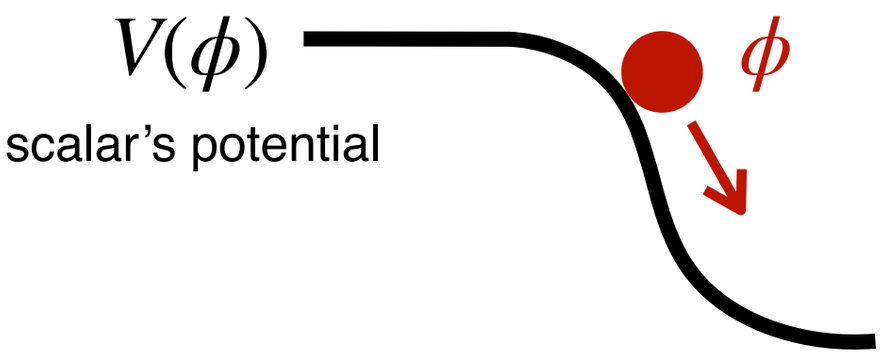
The simplest kination era



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

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

The simplest kination era



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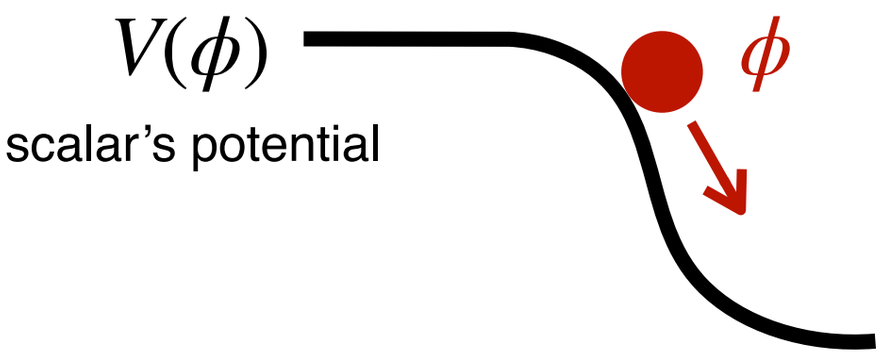
A scalar field dominates the universe with large kinetic energy,
"Kination" era. ($\rho_\phi \propto a^{-6}$)
[Spokoiny 1993, Joyce, 1997]

The simplest kination era



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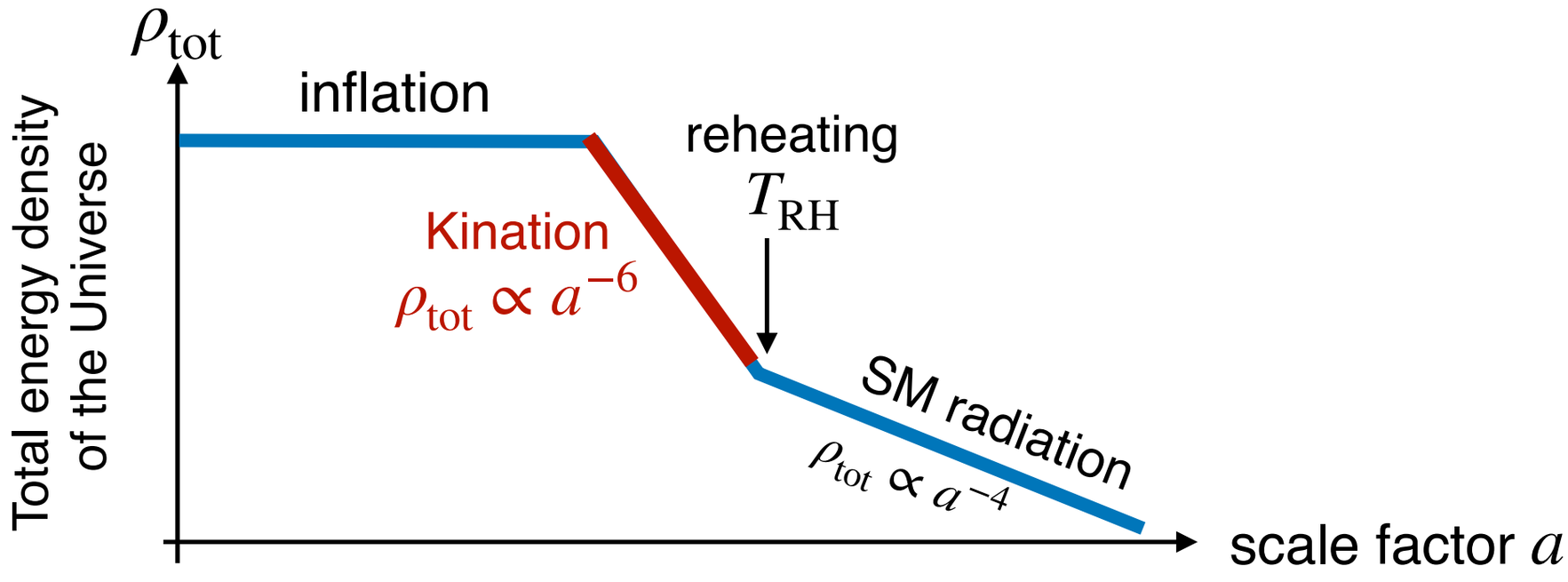
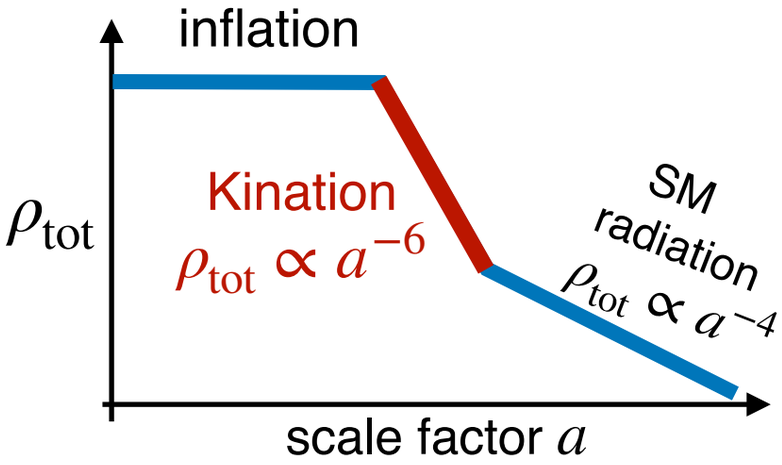
Maximum $\omega_\phi = 1$, when $E_{\rm kinetic} \gg E_{\rm potential}$

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



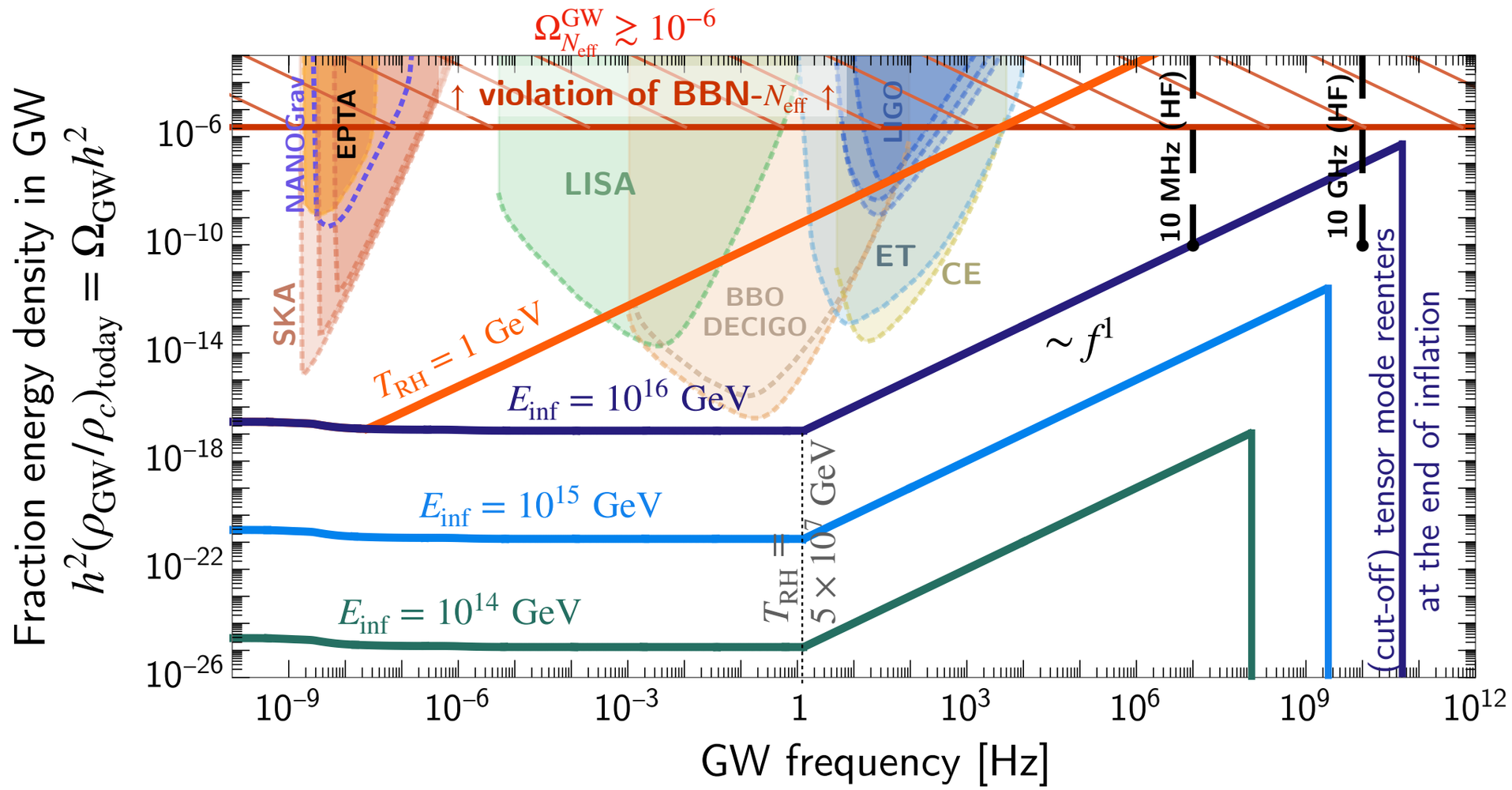


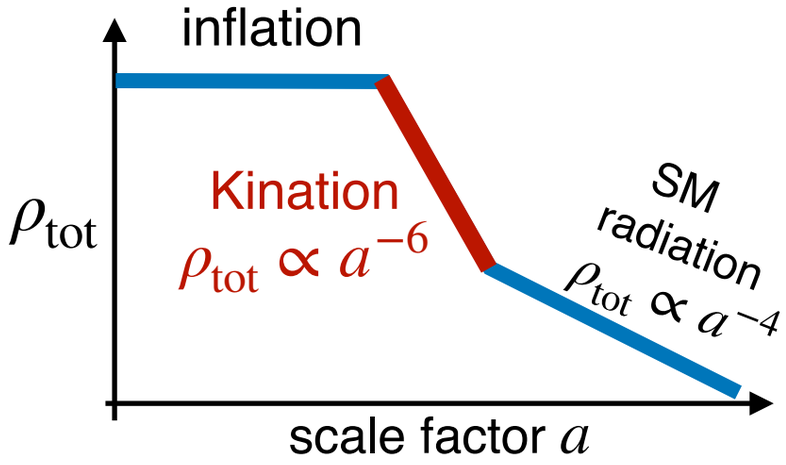
GW is an extra radiation.

Too much GW violate BBN/CMB bound:

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

A long kination after inflation cannot have observable signal.





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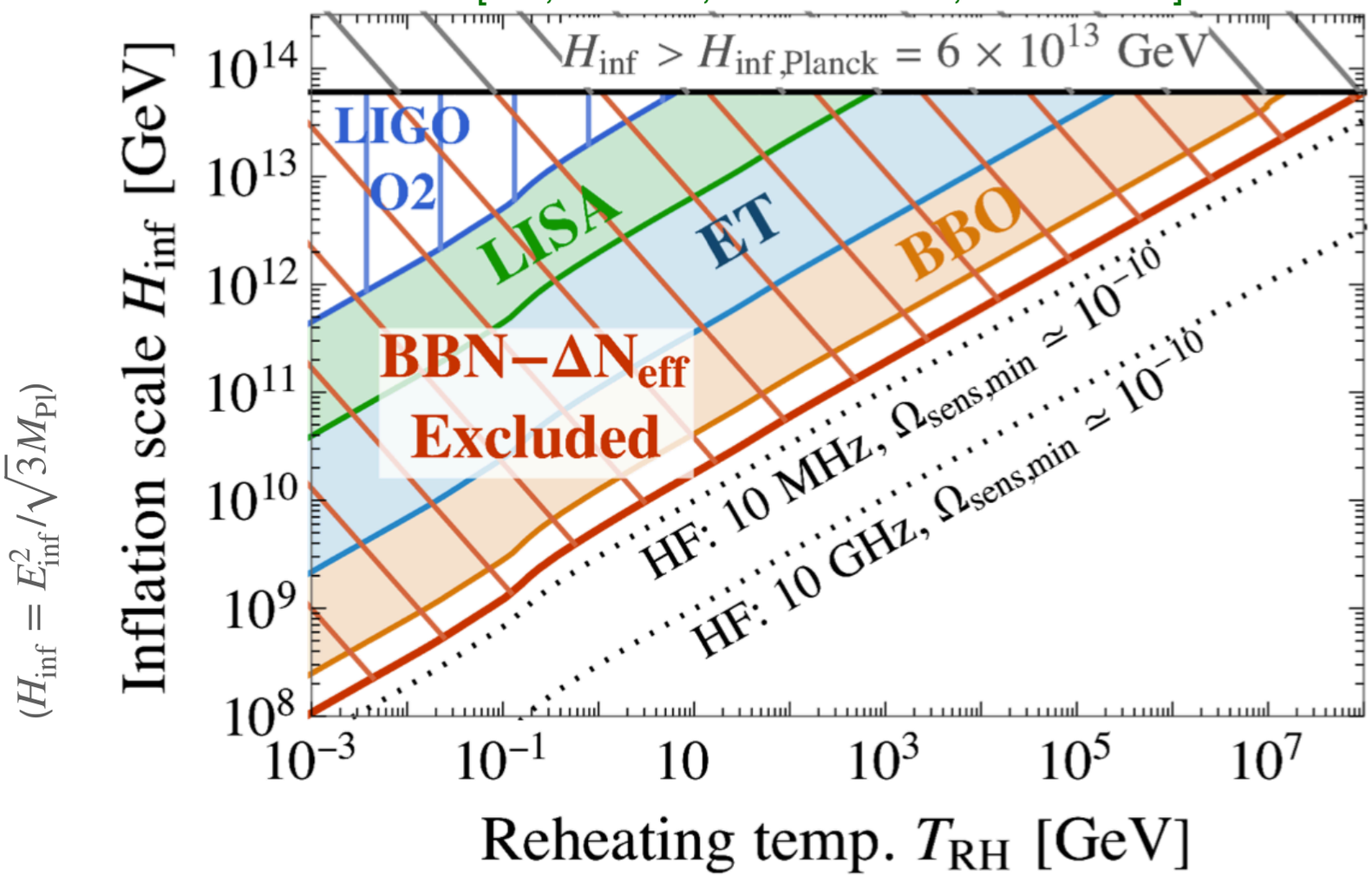
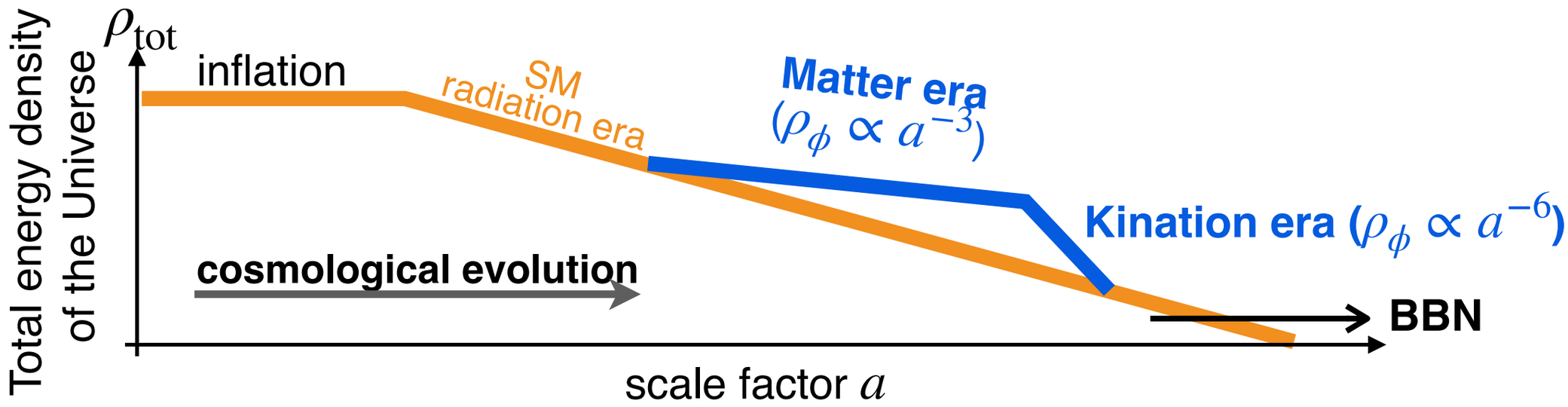
[YG, Servant, Simakachorn, 2111.01150]



What if instead kination occurs long after inflation ?

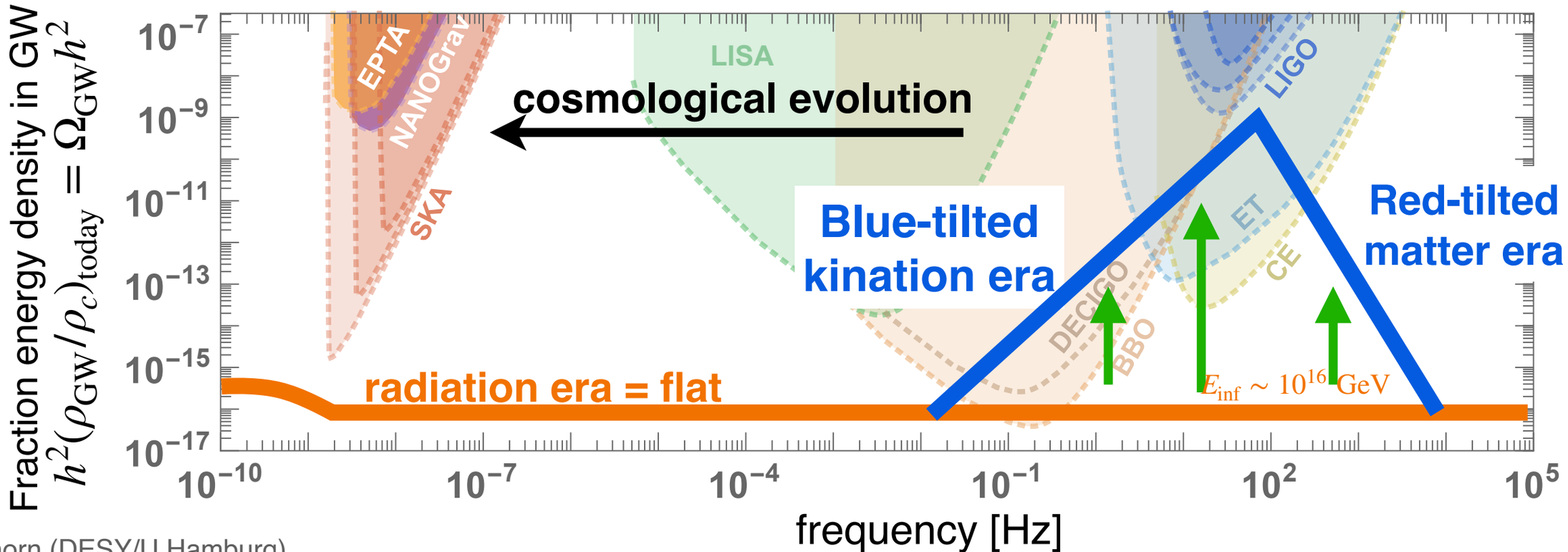


Spinning axion!

Peaked GW signature

[YG, Servant, Simakachorn, 2108.10328 & 2111.01150]

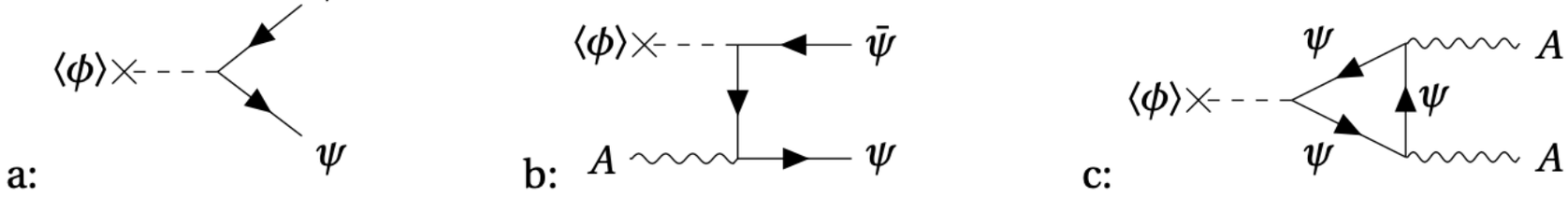
[Co, Harigaya, Hall, et. al., 2108.09299]



Number of e-folds of kination

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

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



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

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

Baryogenesis from a spinning axion

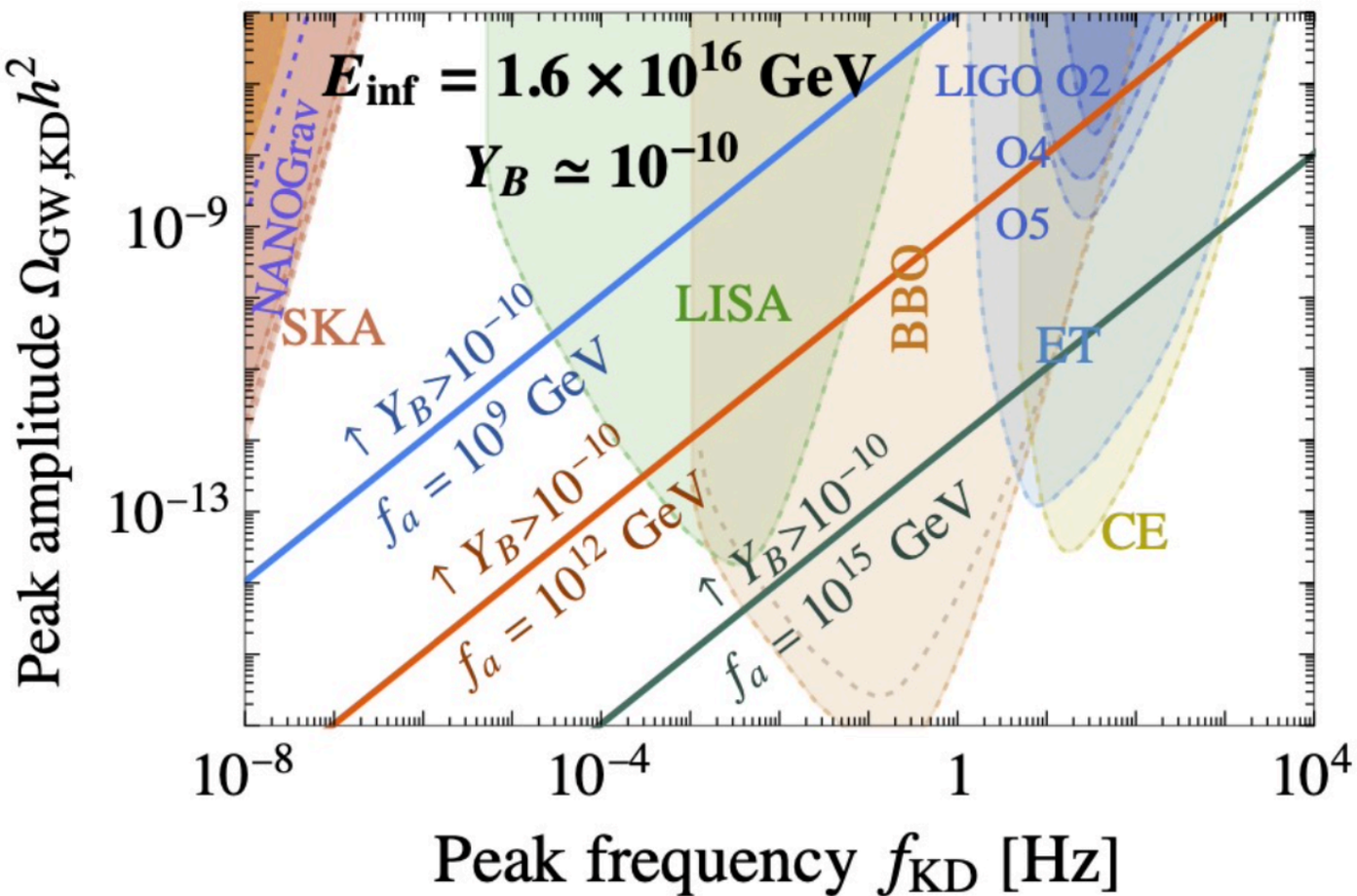
Standard "Axiogenesis" [Co, Harigaya, '19]

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

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

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

Gravitational waves from primordial inflation

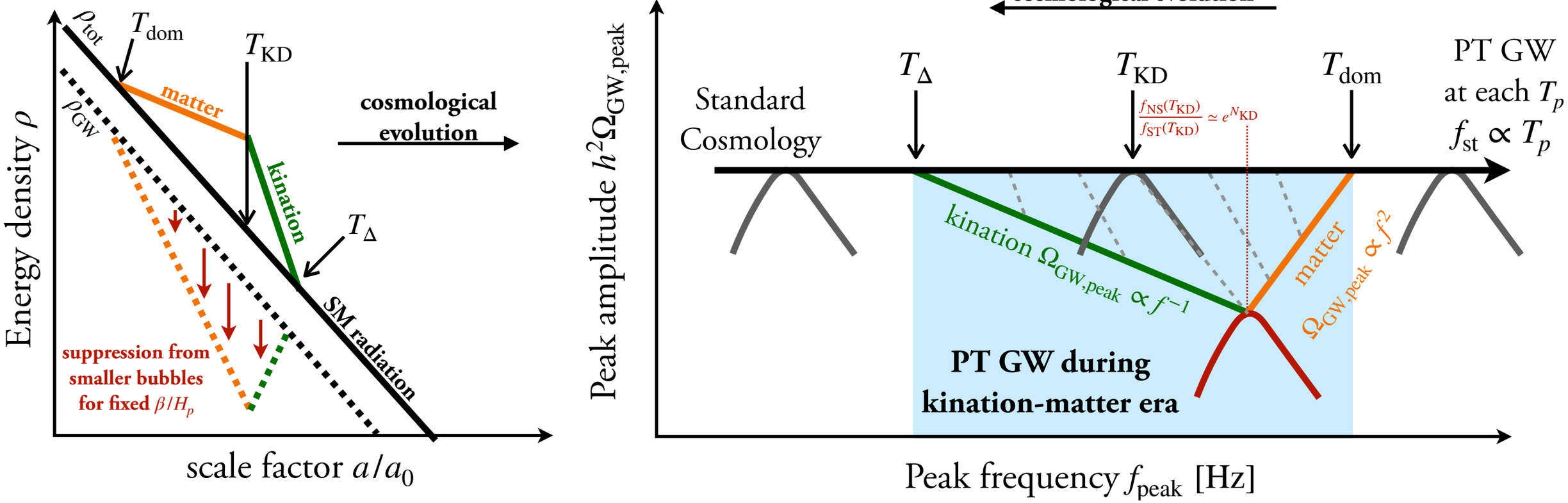


Effect on short-lasting GW

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)

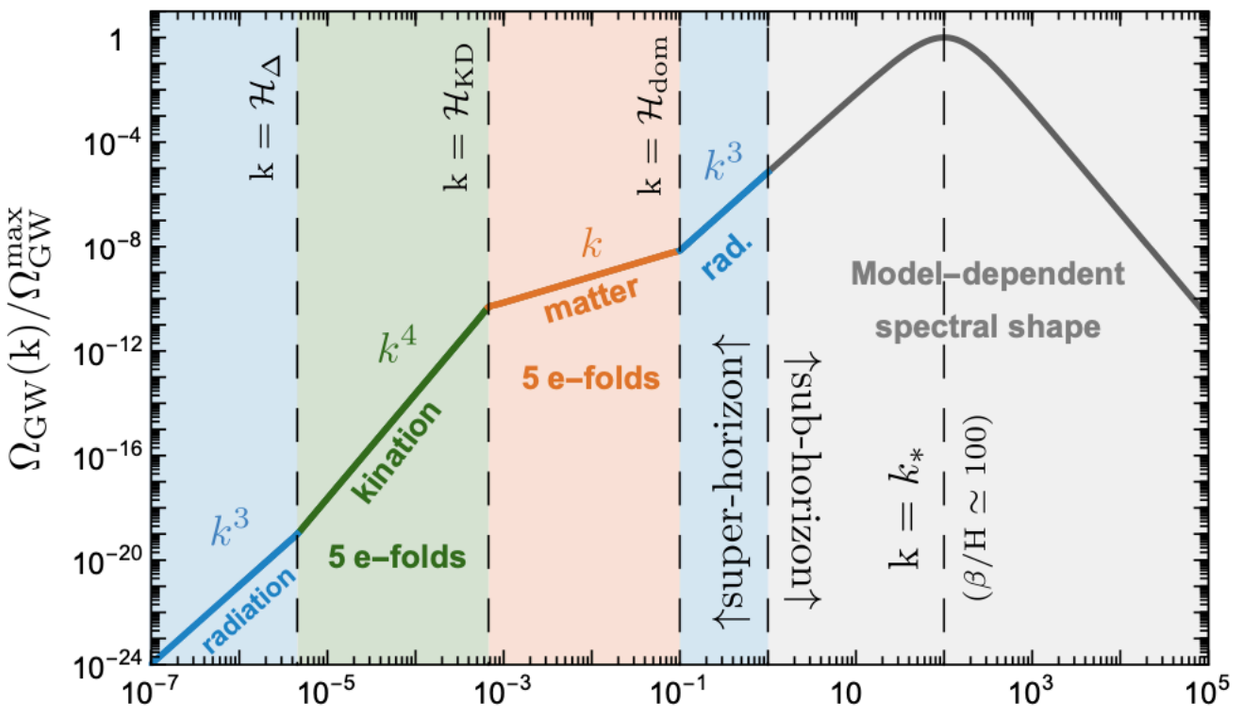


Super simplified argument: For fixed β/H_p,
the bubble size is fixed to be some fraction of Hubble horizon.
During the matter-kination era, Universe has smaller size, smaller bubbles, and thus weaker GW.

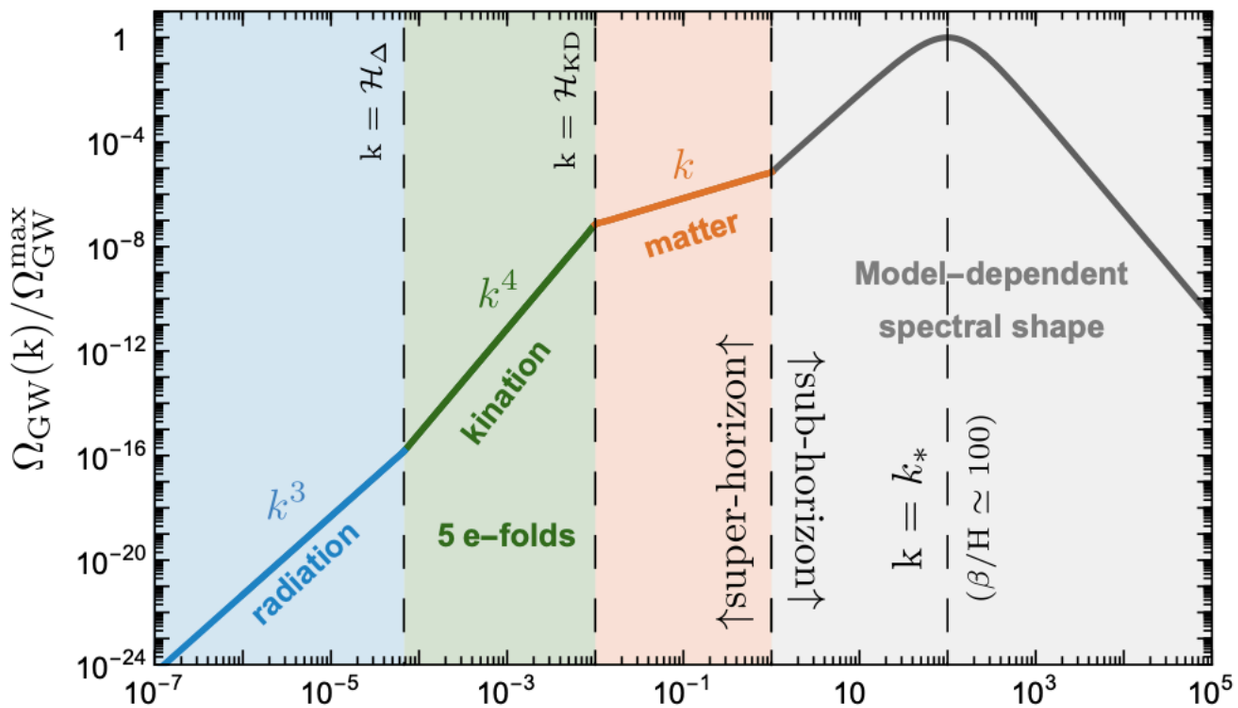
Other spectral distortions, e.g. causality tail [Hook, Marques-Tavares, Racco, '20]

GW from phase transition

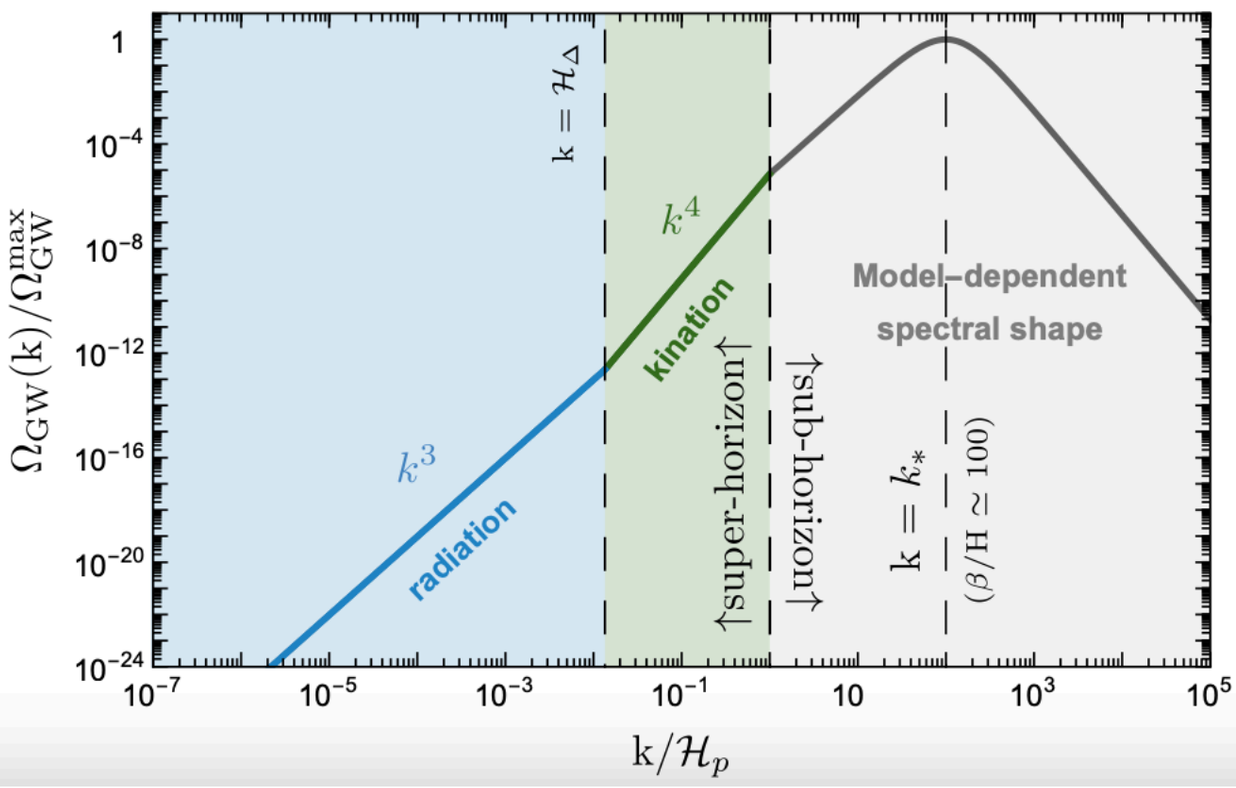
PT occuring before matter-kination era

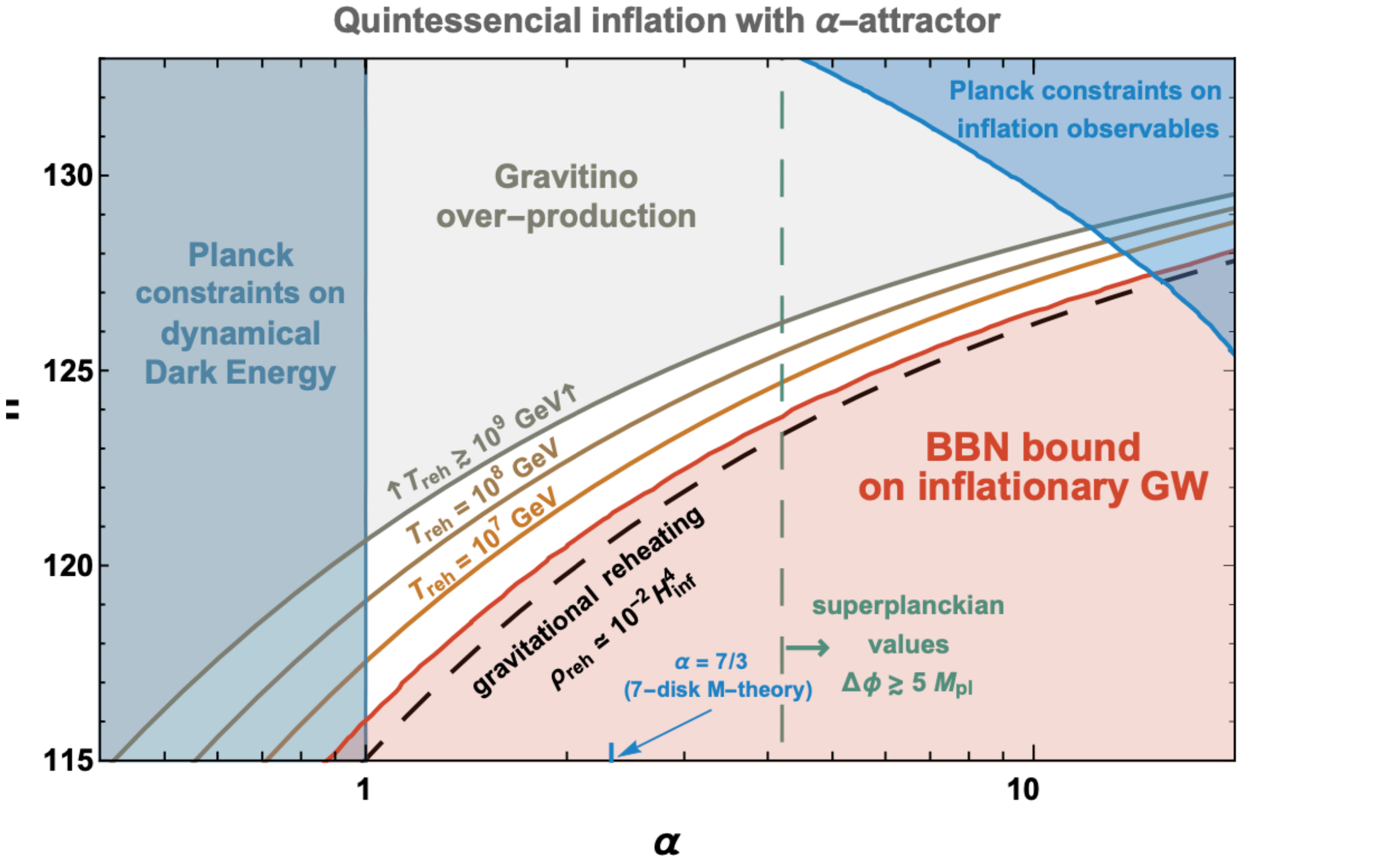


PT occuring during matter era



PT occuring during kination era



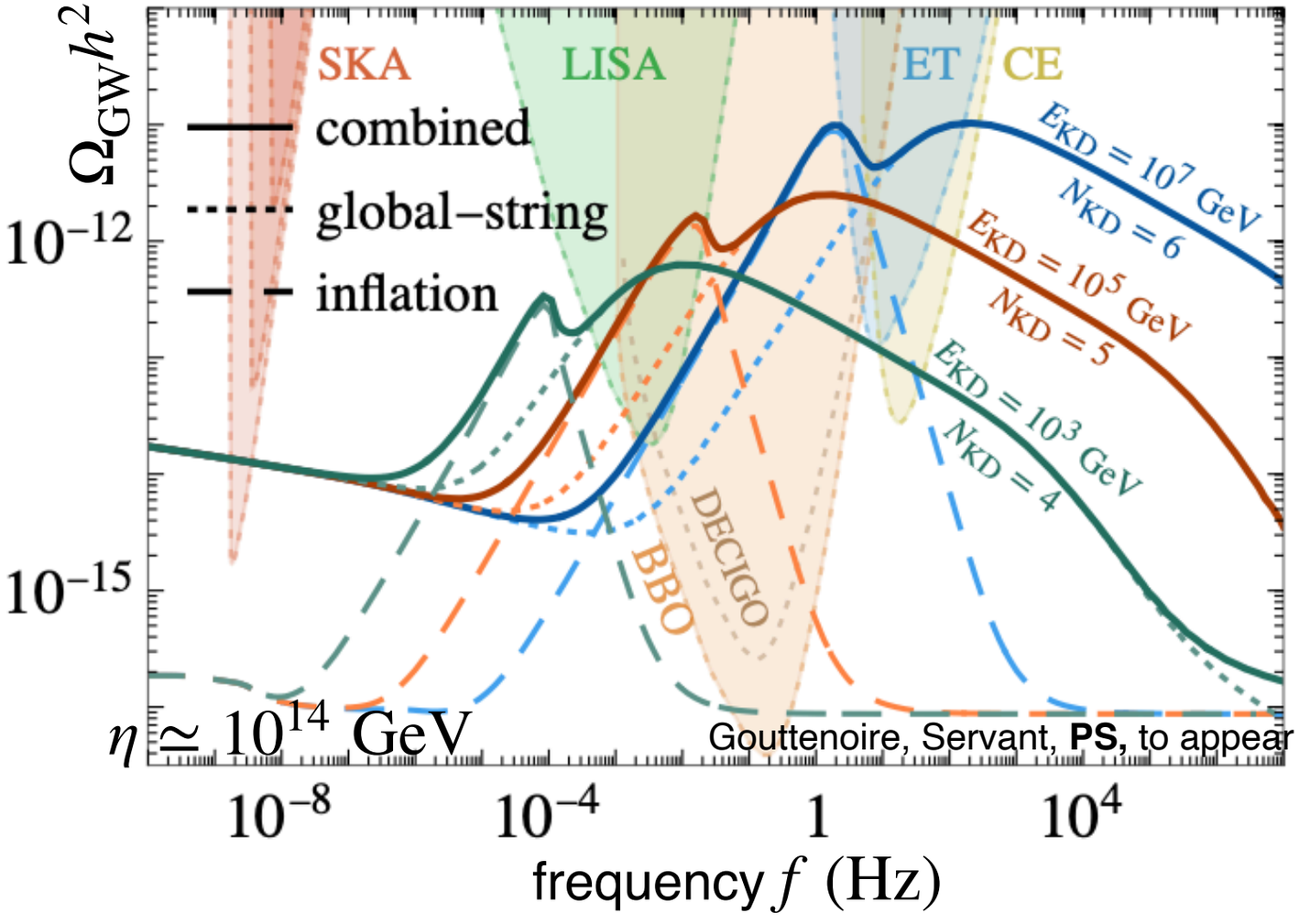

Quintessencial inflation with α–attractor
Planck constraints on inflation observables
Gravitino over–production
Planck constraints on dynamical Dark Energy
↑ $T_{reh} \gtrsim 10^9$ GeV↑
$T_{reh} = 10^8$ GeV
$T_{reh} = 10^7$ GeV
gravitational reheating
$\rho_{reh} \simeq 10^{-2} H_{inf}^4$
BBN bound on inflationary GW
superplanckian values
$\Delta\phi \gtrsim 5\, M_{pl}$
α = 7/3
(7–disk M–theory)
n
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: $\Omega_{\rm peak}^{\rm glob} h^2 \approx 10^{-14} \left(\frac{\eta}{10^{15}\ \text{GeV}} \right)^4 \left[\frac{\exp(2N_{\rm KD})}{10^4} \right] \log^3(\cdots$

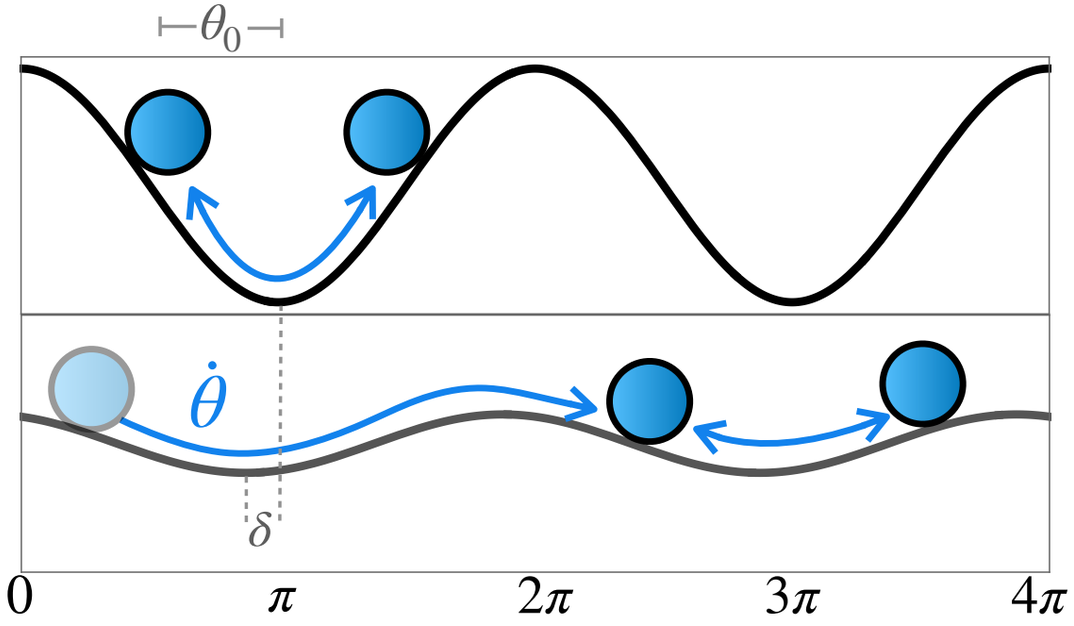


Fixed peak separation
$f_{\rm inf}/f_{\rm glob} = \mathcal{O}(10^{-2})$
[for loops' size: $(0.1)H^{-1}$]

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

Model A: trapped misalignment

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

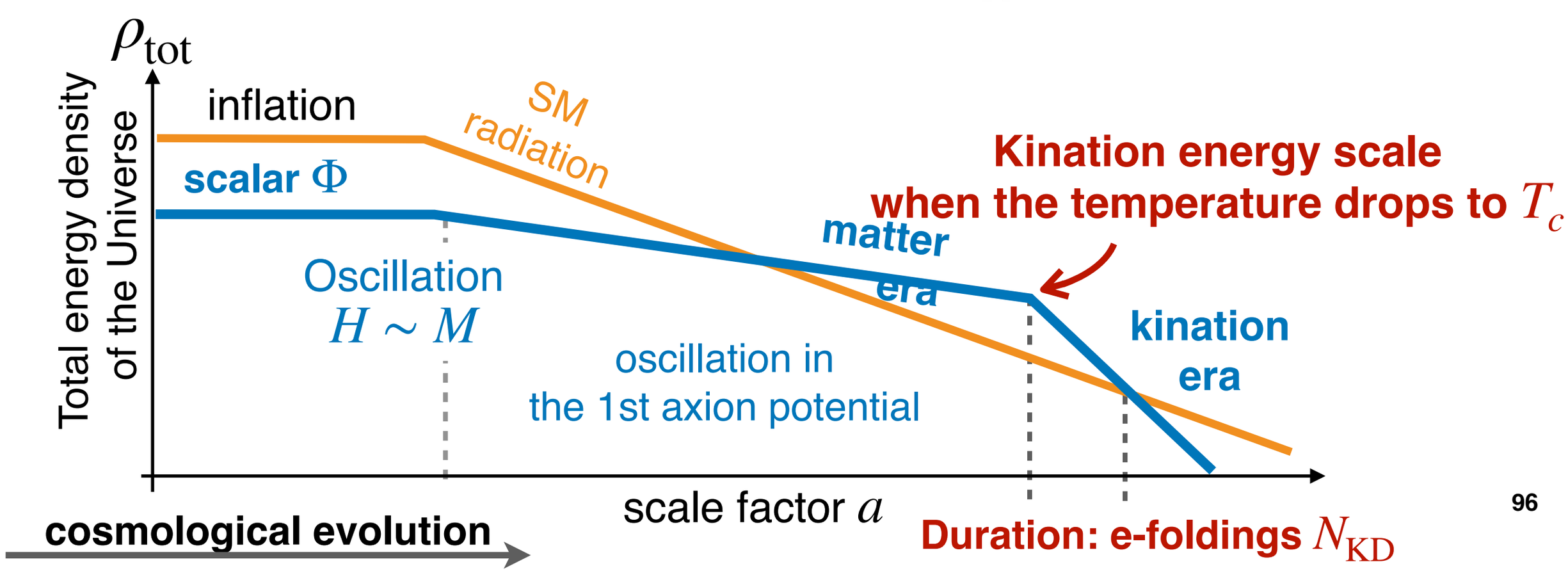


For $T \gtrsim T_c$, $V_{\rm high} \sim M^2 f_a^2 \cos(\theta)$
axion oscillates and behaves as matter.

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

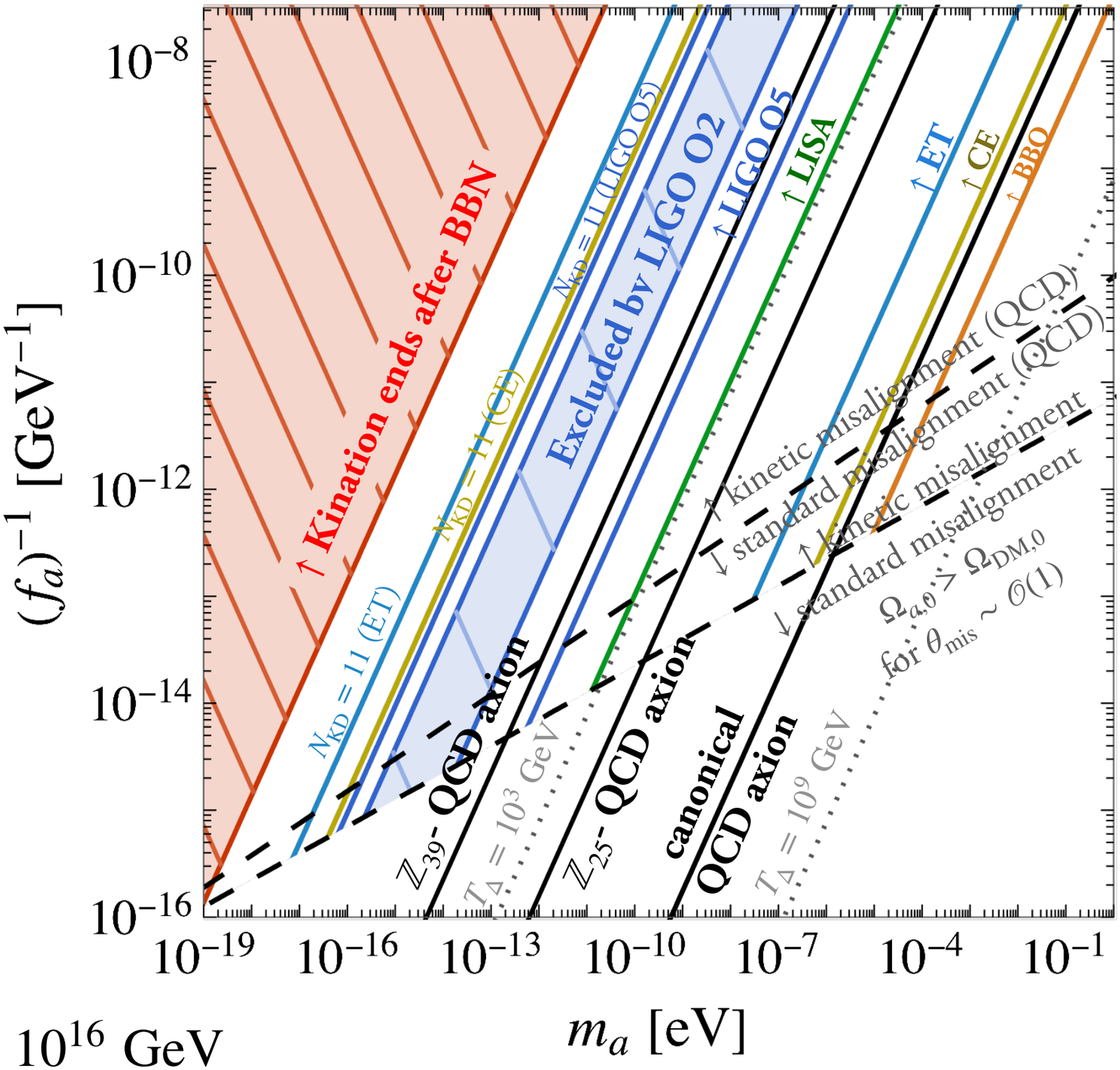
$$\dot{\theta}_c \sim \frac{T_c^{3/2} M^{1/4}}{M_{\rm Pl}^{3/4}}$$ and generates kination era.



Detectability in axion parameter spaces

$$\Omega_{a,0} = \Omega_{\mathrm{DM},0}$$

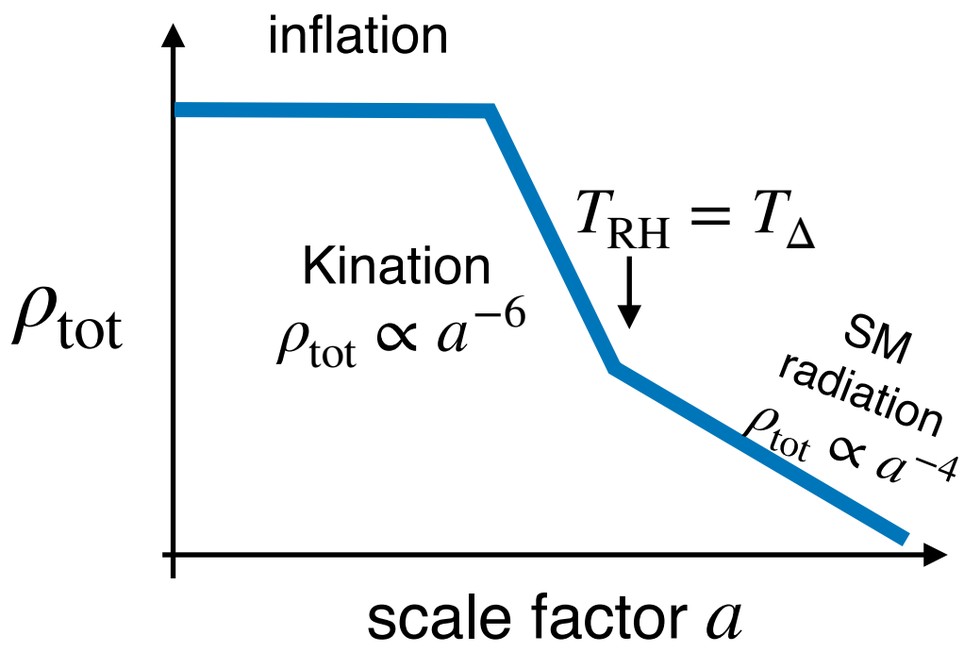
(Gouttenoire, Servant, **PS,** to appear)

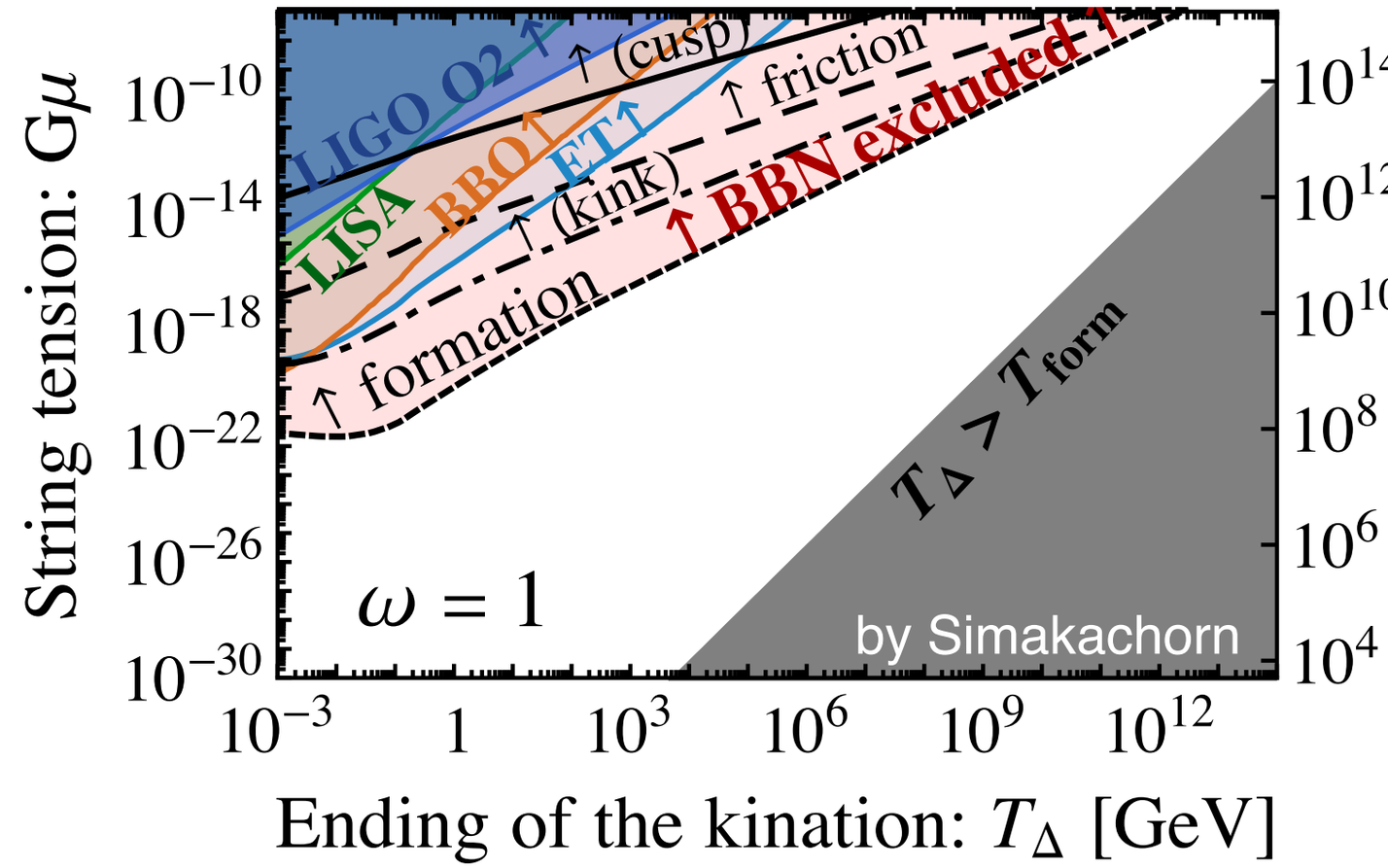


$E_{\mathrm{inf}} = 1.6 \times 10^{16}$ GeV

Long Kination ⇒ too much GW

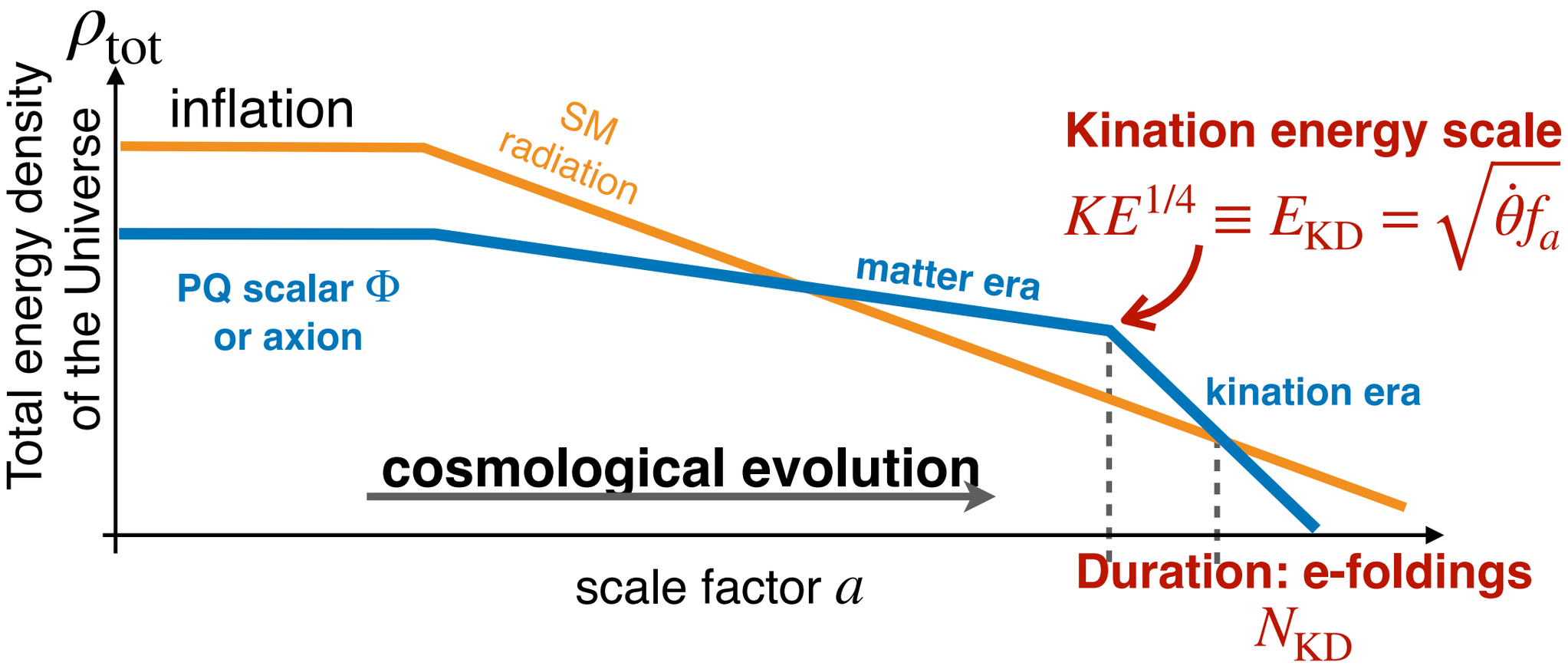
GW from local cosmic strings





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)