# Beyond the Standard Models with GW from Cosmic Strings

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DESY - Hamburg

[1912.02569]
[1912.03245]

With Peera Simakachorn and Géraldine Servant

DESY.

Virtual seminar at APC - Paris
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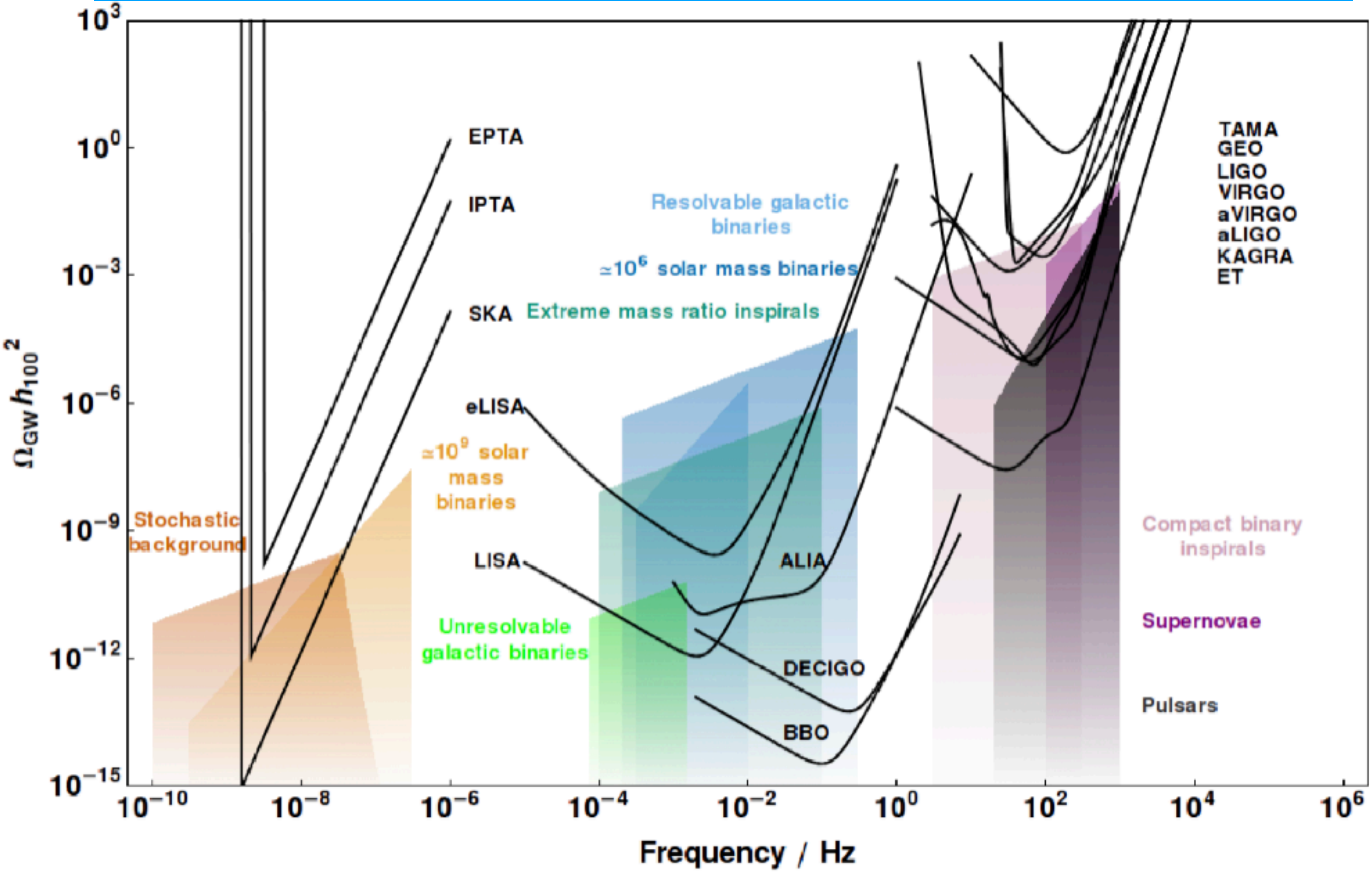
PIER

Picture from C. Ringeval

# Future prospects GW detection



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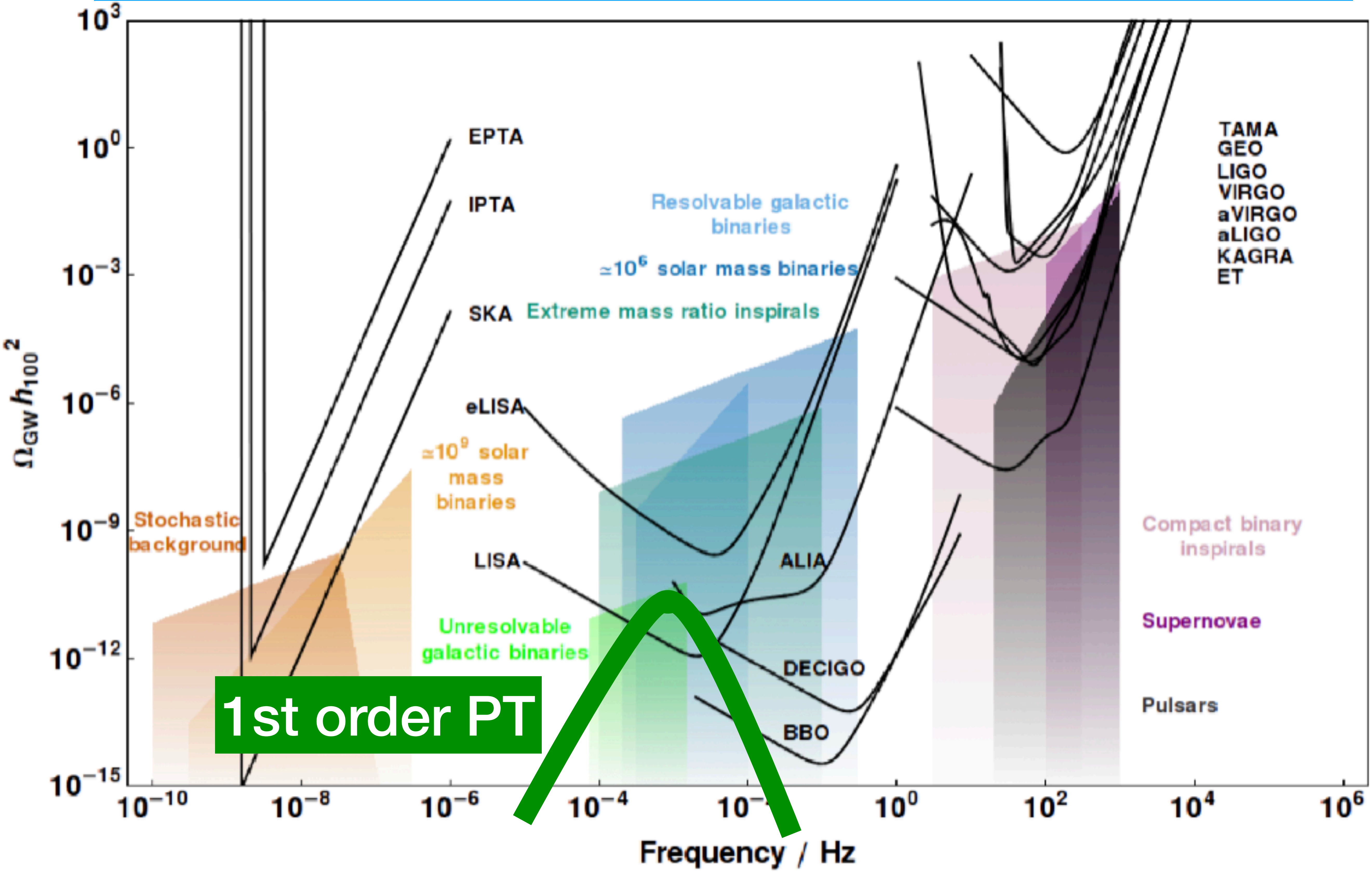

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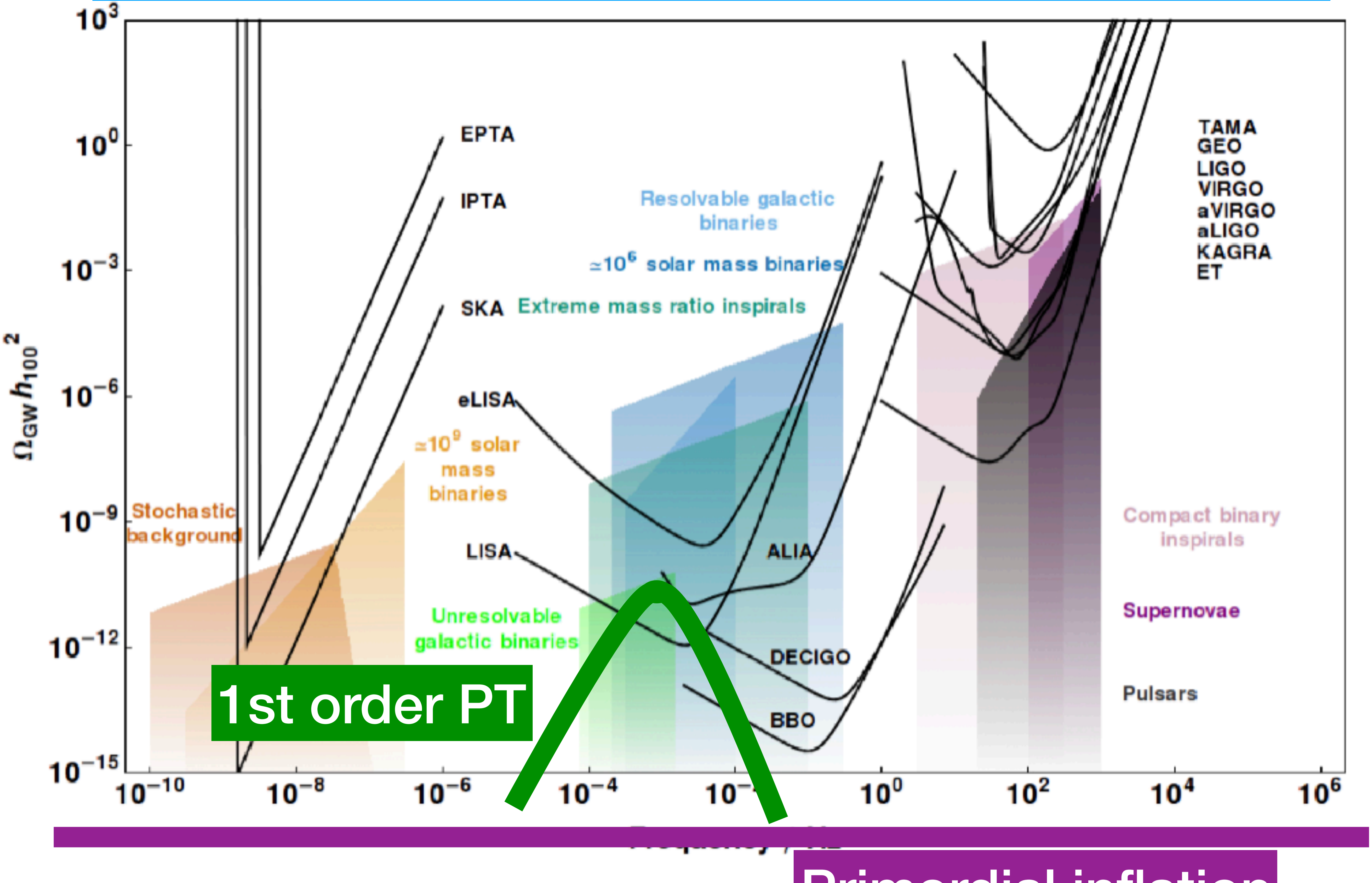

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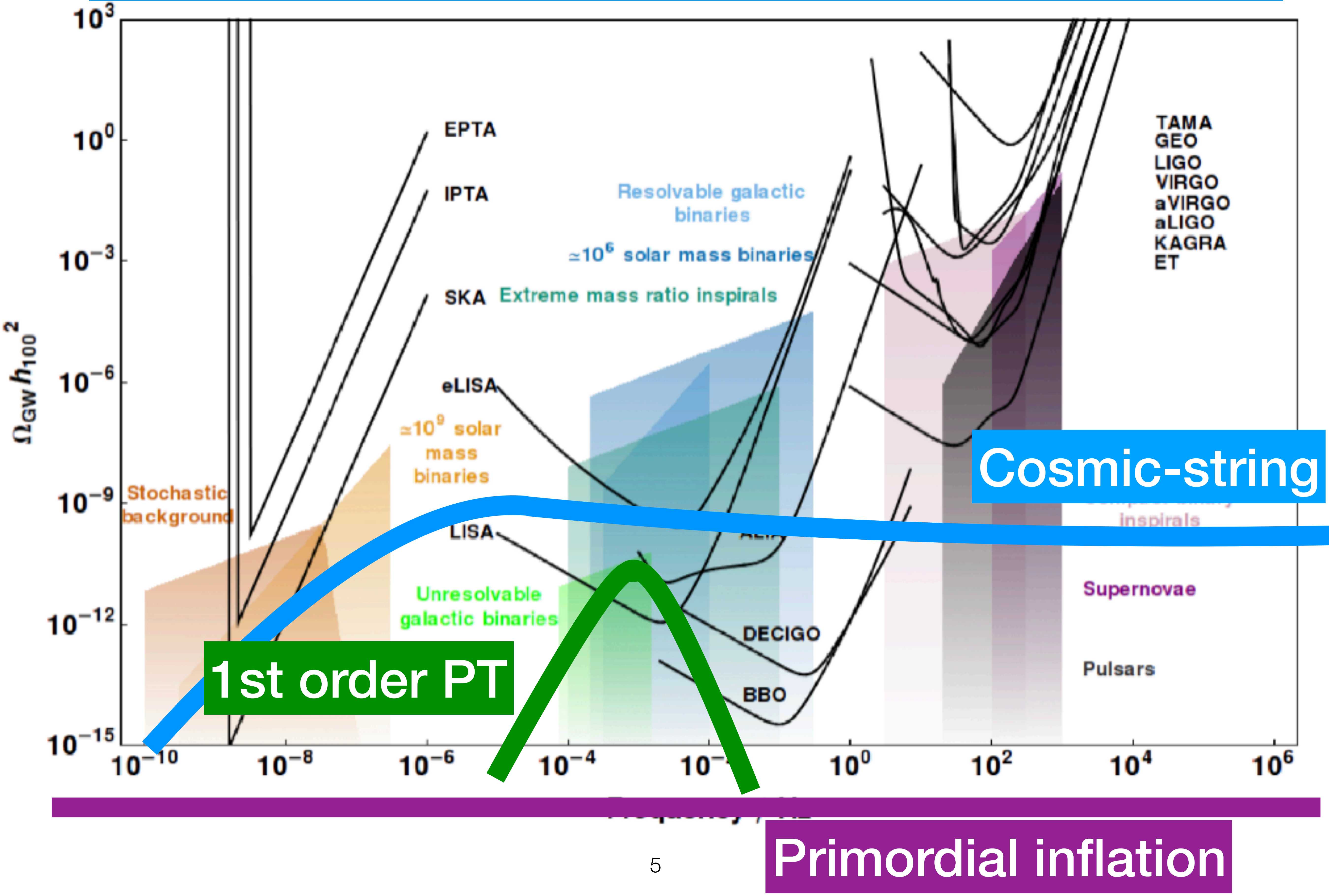

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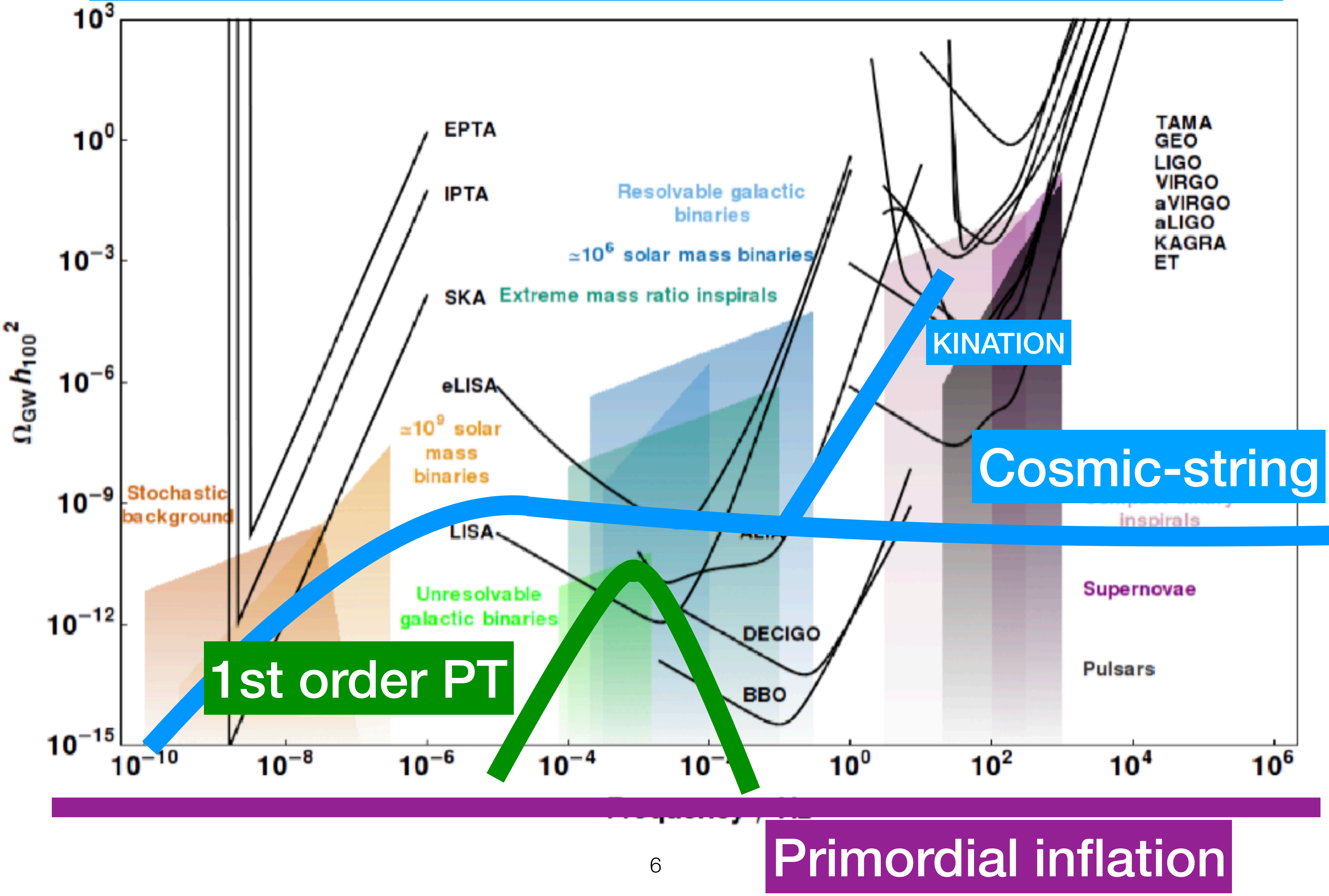

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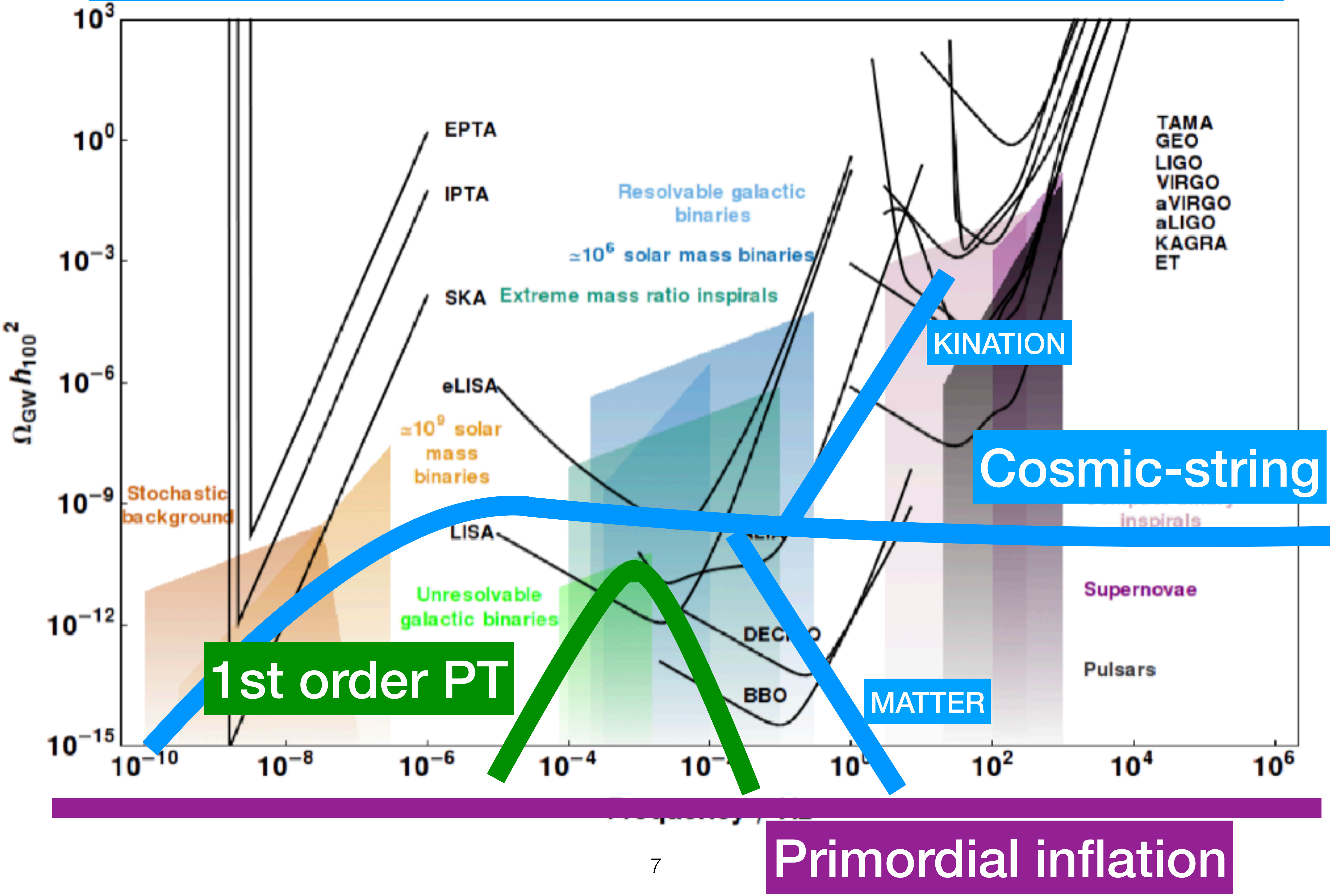

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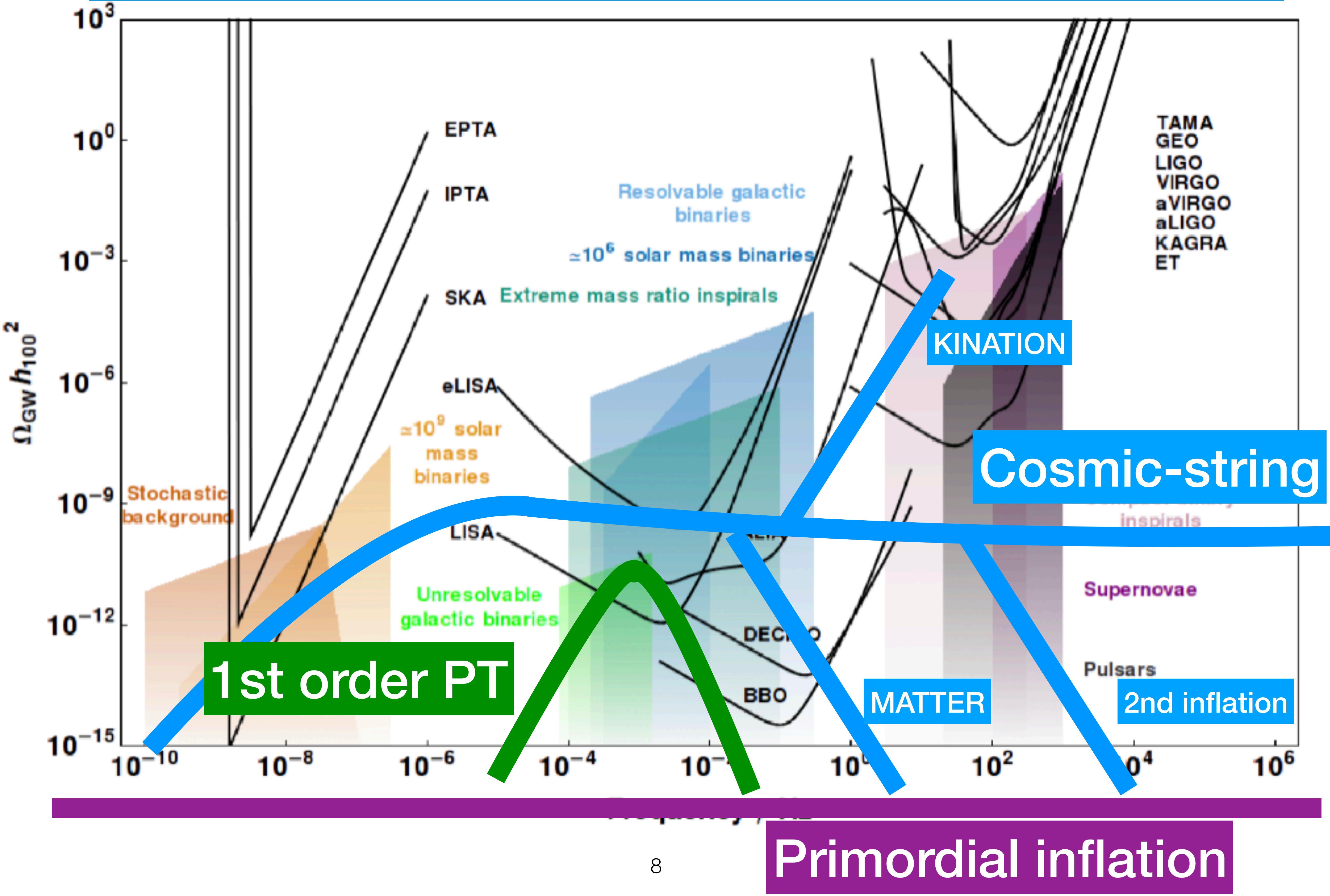

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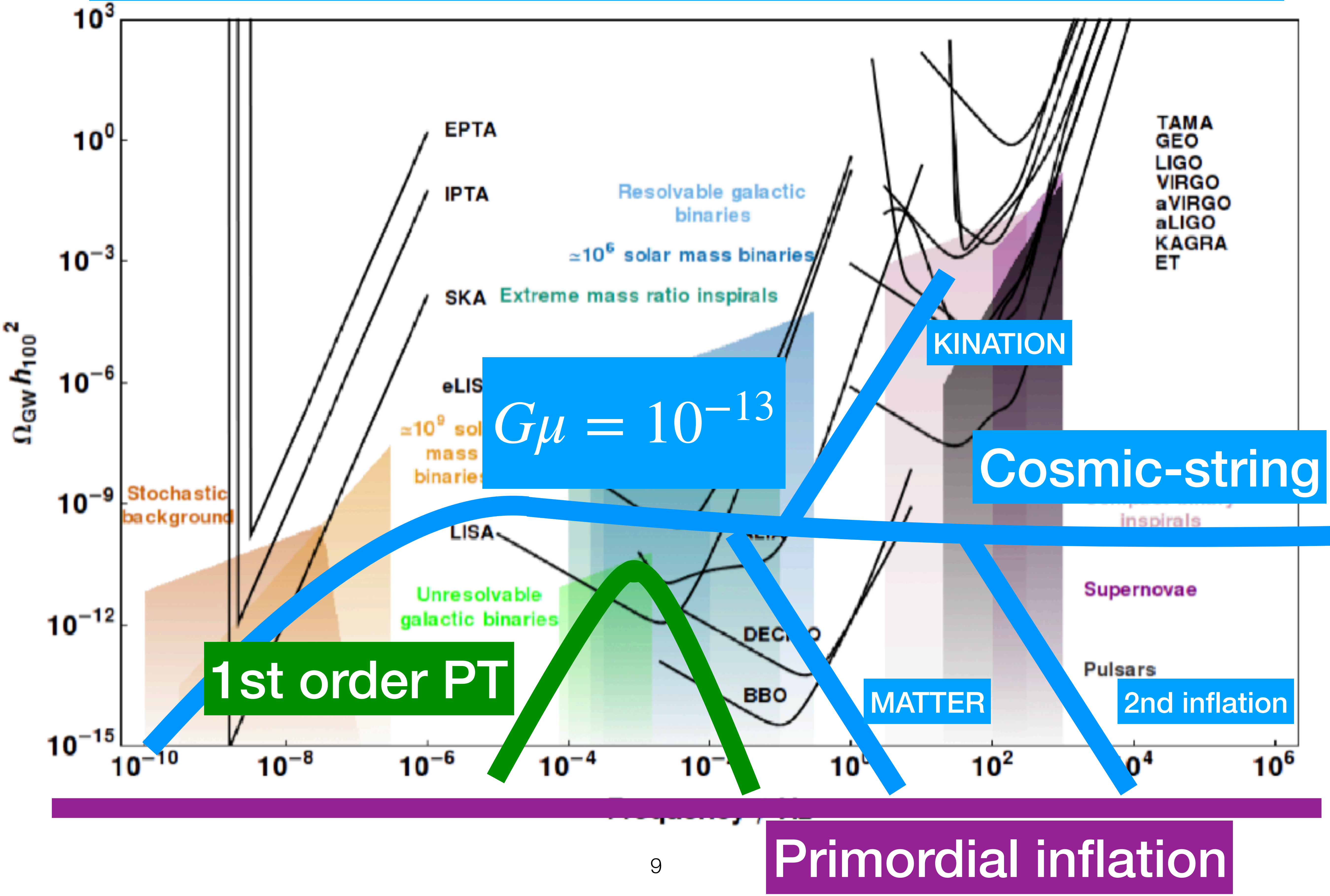

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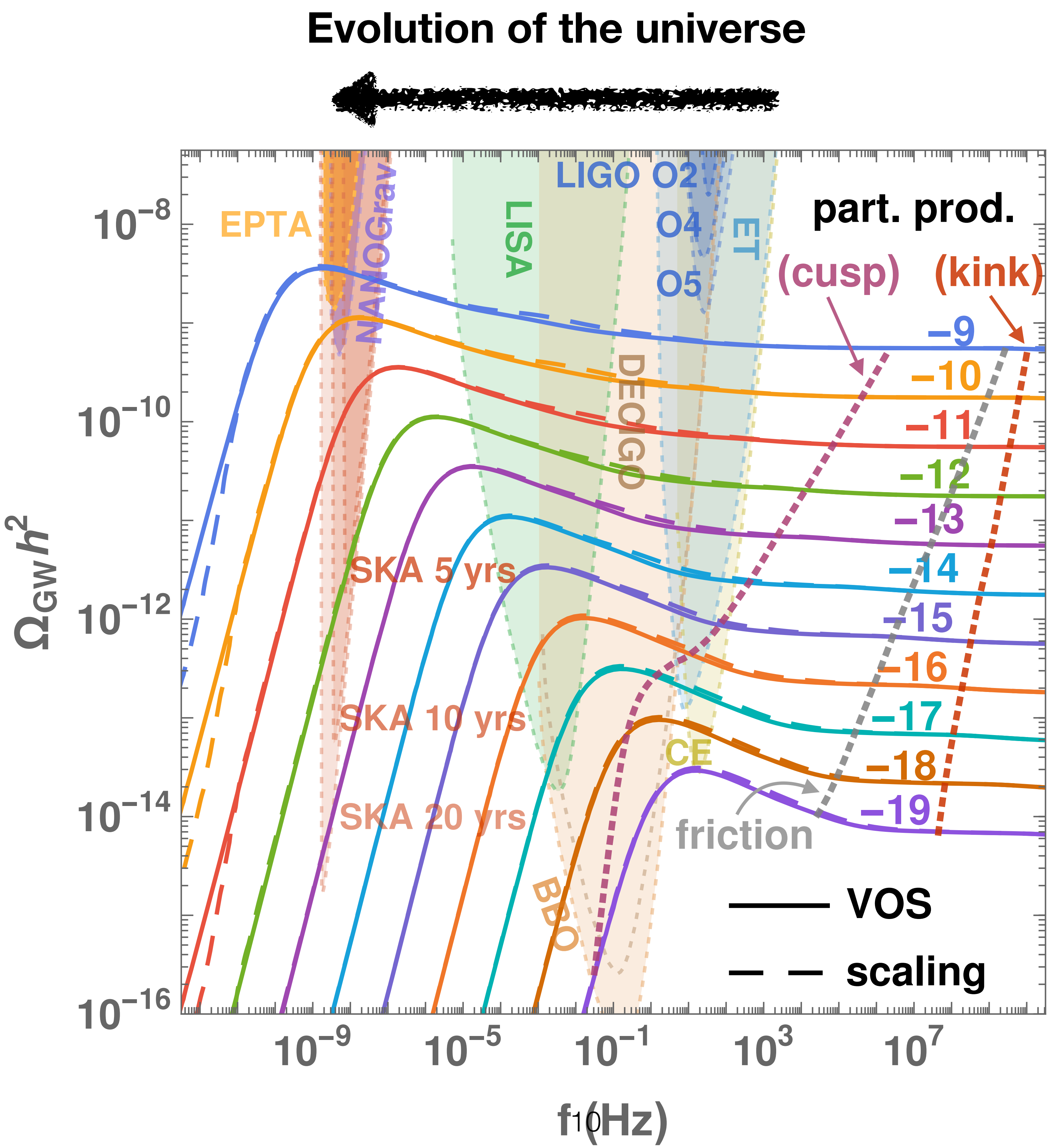
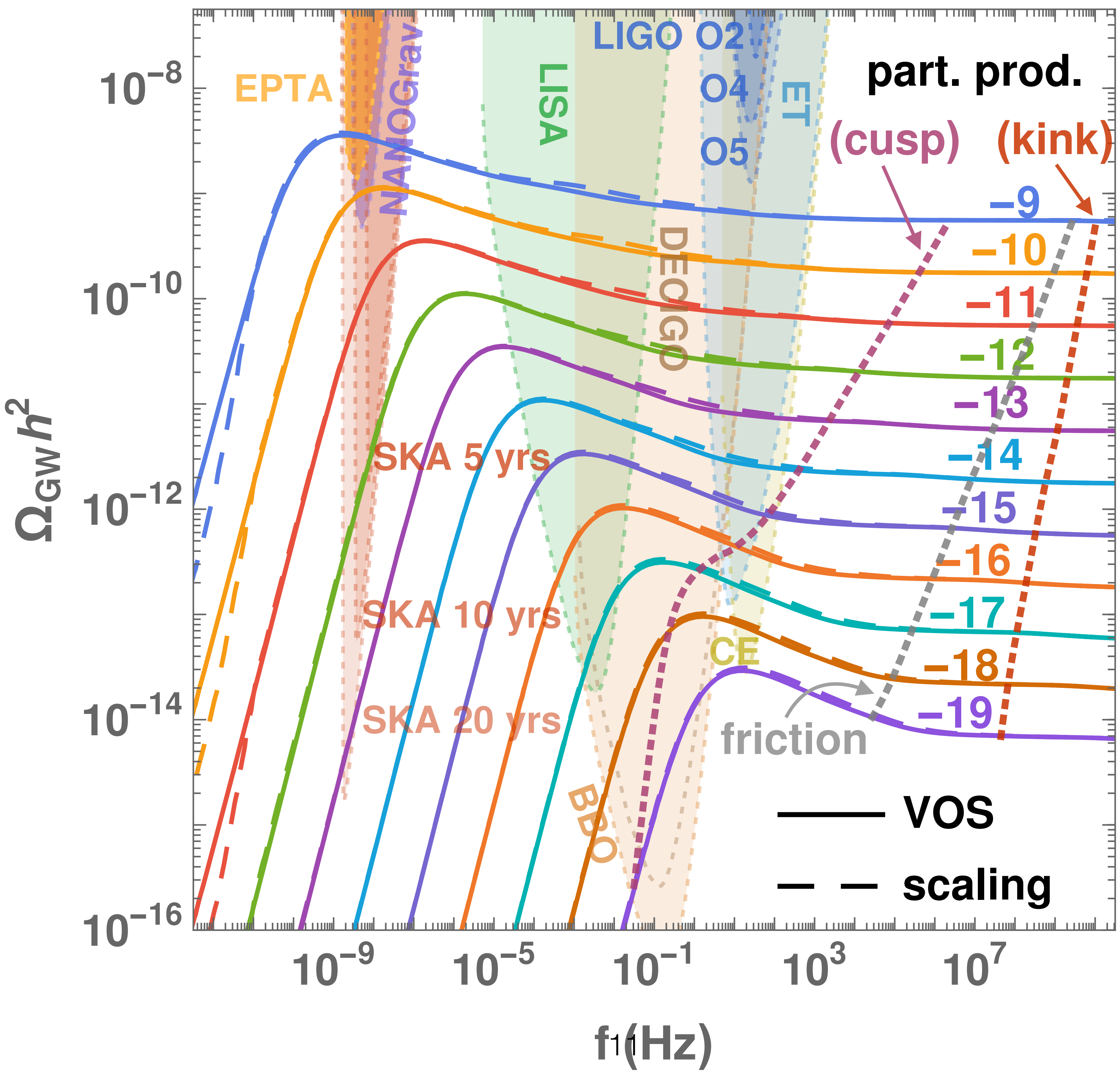


# GW spectrum from Cosmic Strings

**Evolution of the universe**




$\longrightarrow \sqrt{\mu} \sim 10^{13}$ GeV

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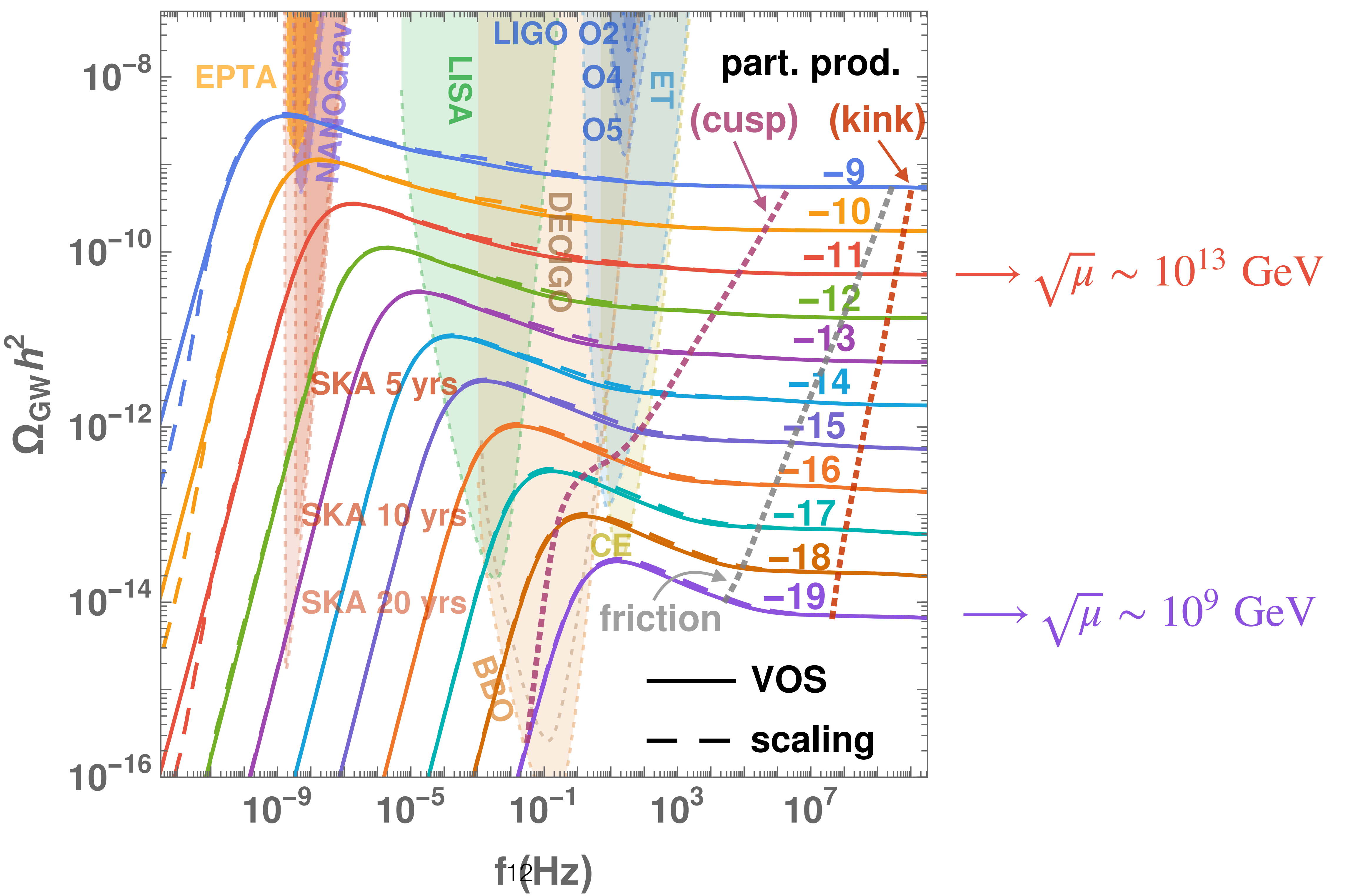

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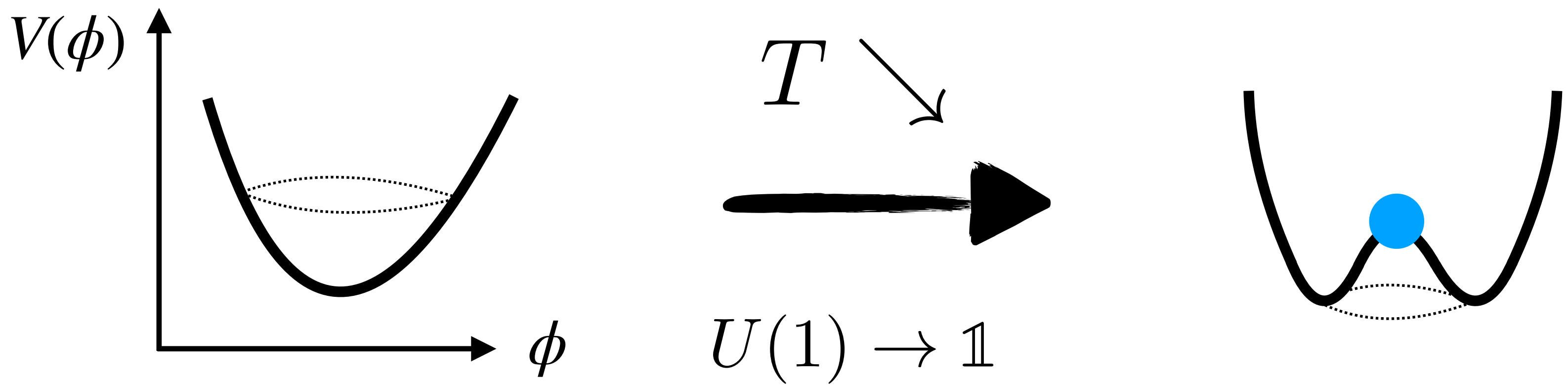

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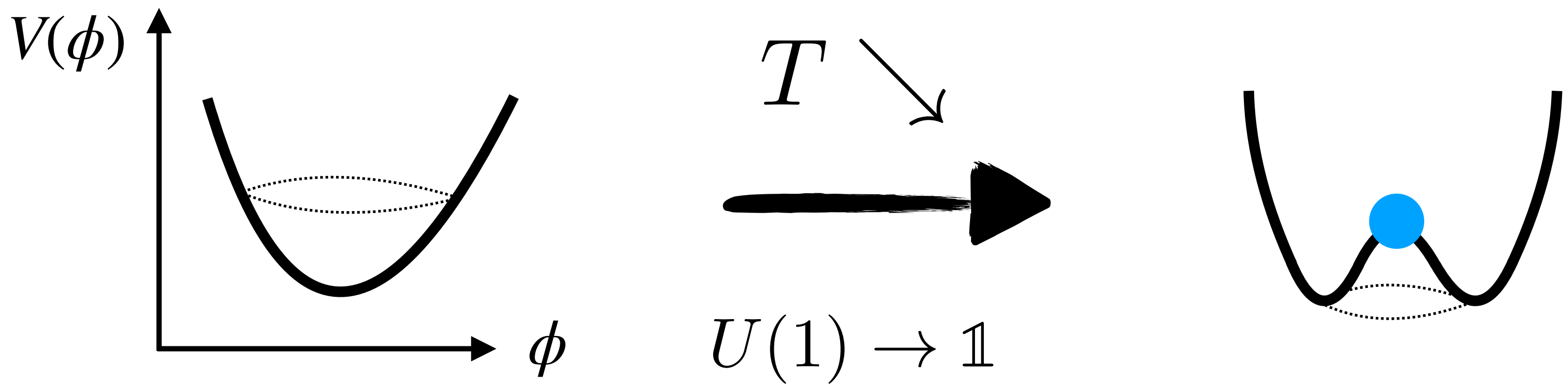


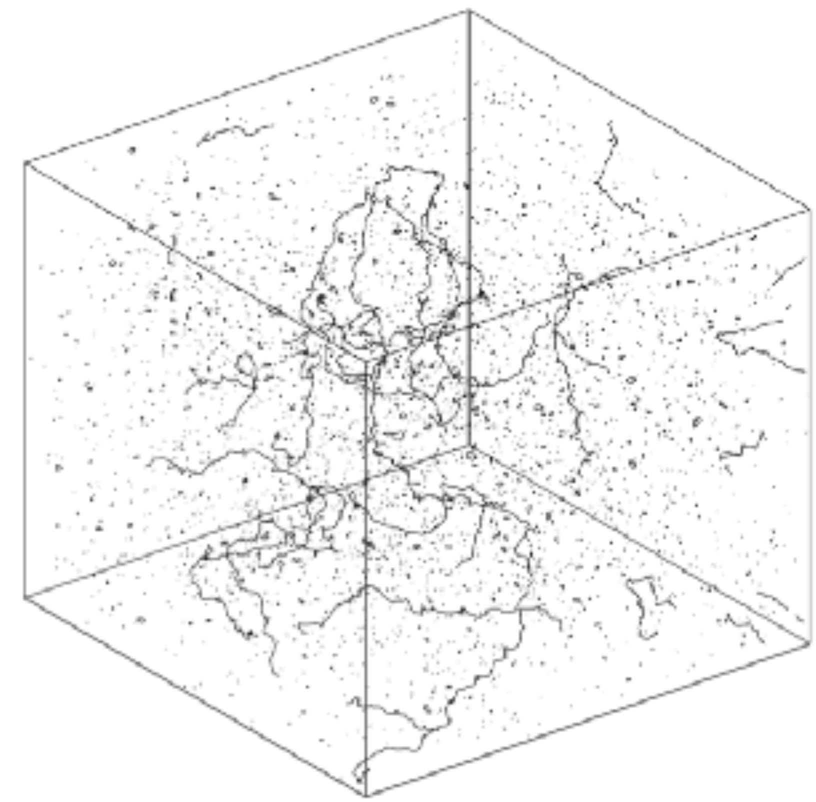

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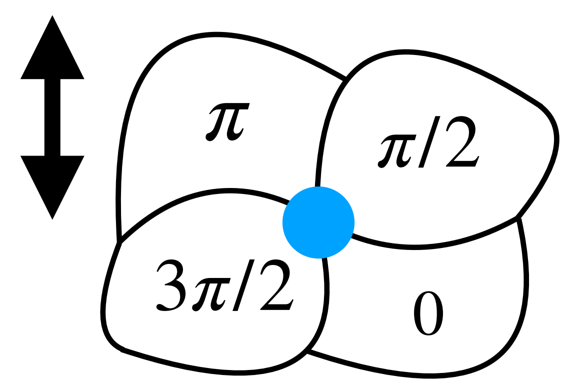


[Kibble 1976]

[Allen & Shellard 1990]

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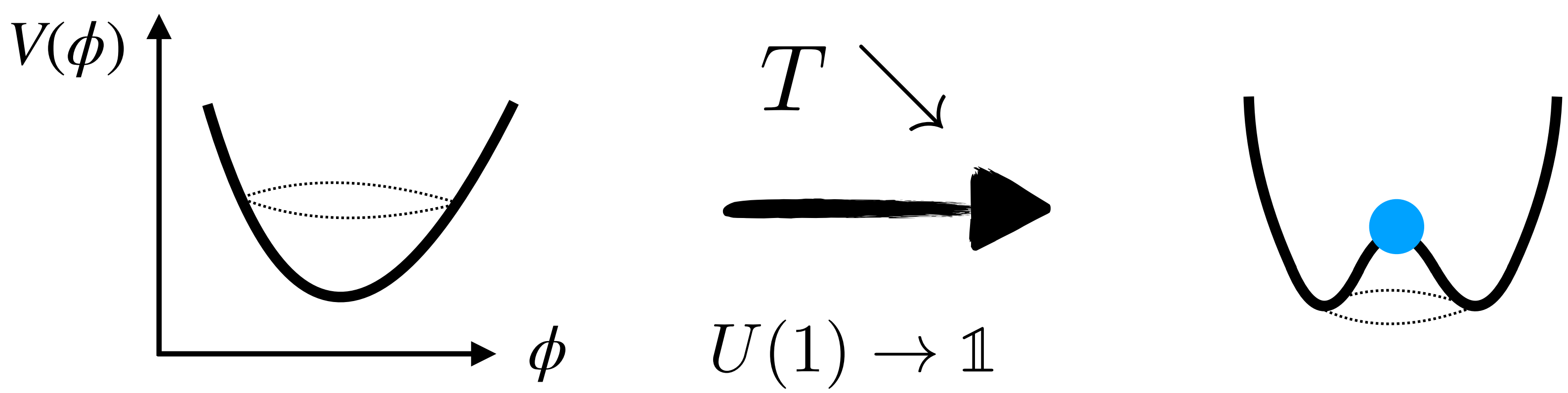


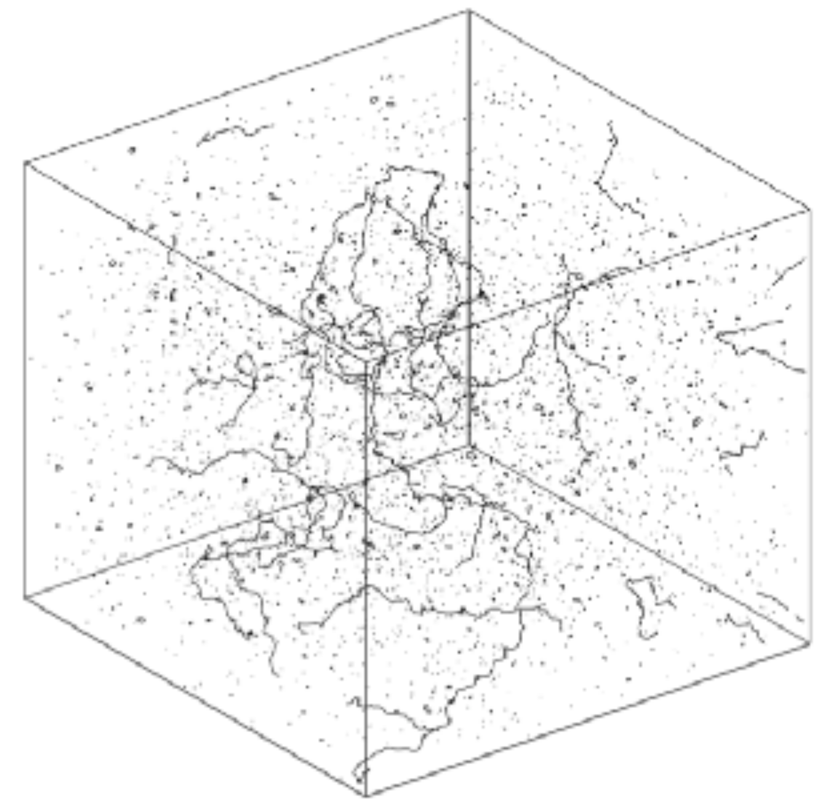

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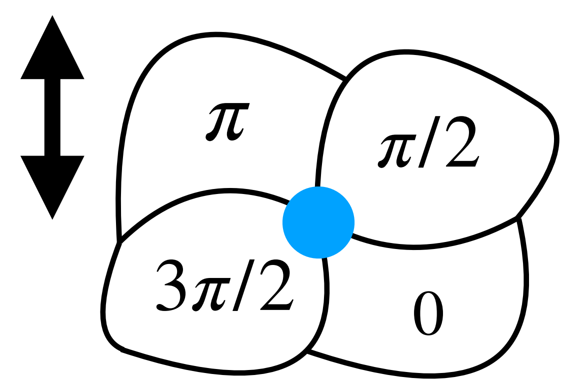
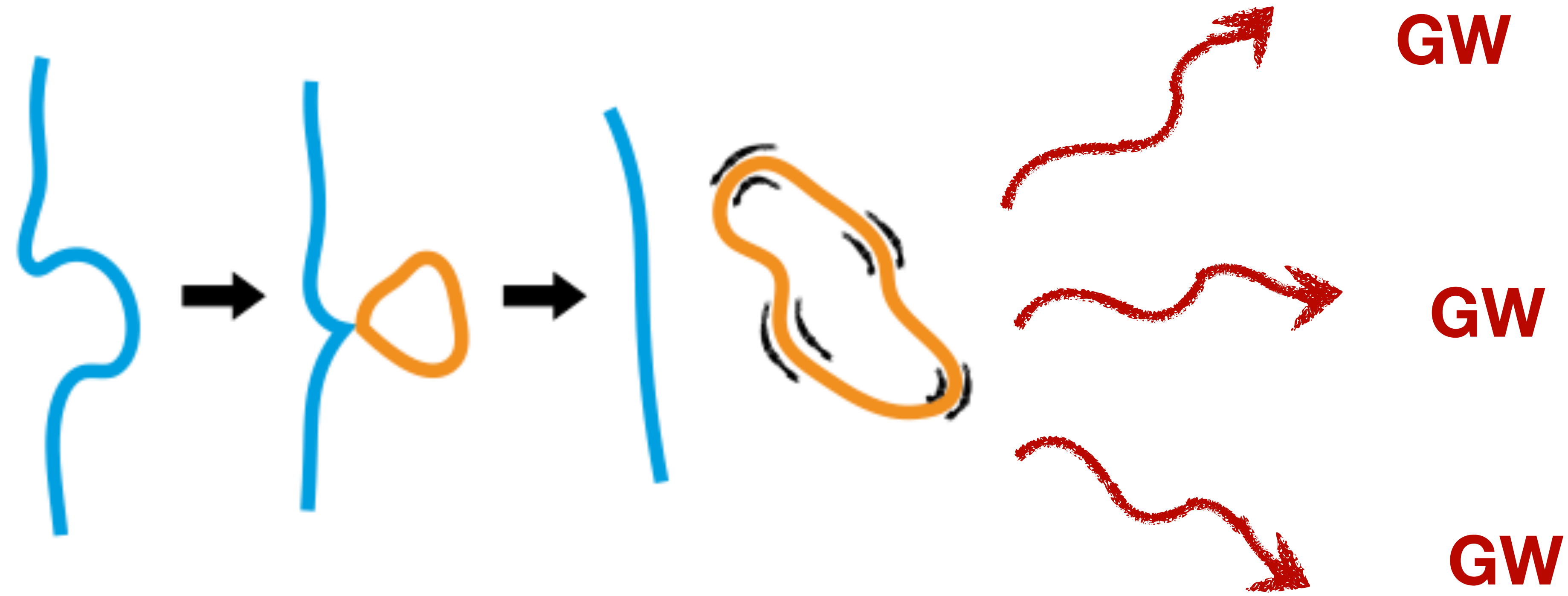



[Kibble 1976]

- **Nambu-Goto approximation**

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

- **GW spectrum generated by string loops**



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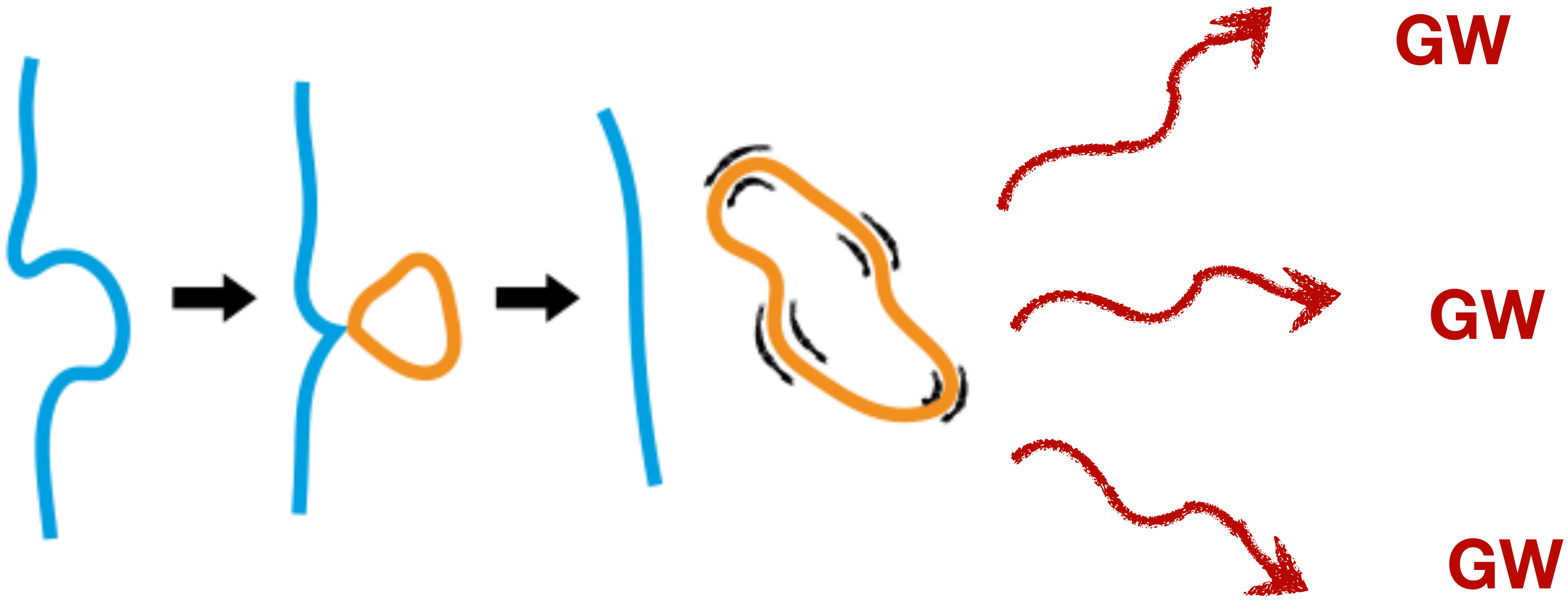


- Assume LOCAL strings

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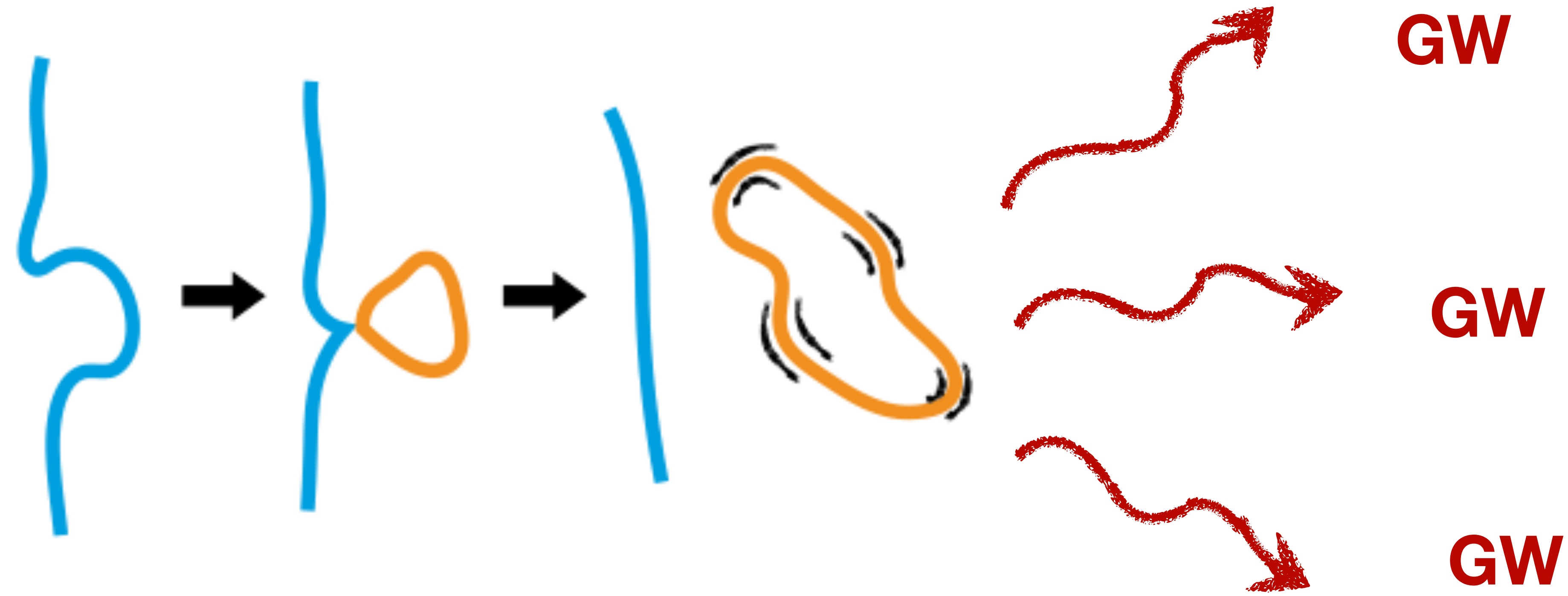


- Assume LOCAL strings

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

# Stucture of the talk

## A) GW spectrum from CS

- Scaling regime
- Number of loops
- Beyond Nambu-Goto: massive radiation

## B) Probe non-standard cosmology and particle physics

- Early Matter era induced by heavy unstable particle
  (e.g. superstring moduli, U(1) dark photon, ALPs, PBHs)

- Early intermediate inflation
  (e.g. supercool first order phase transition)

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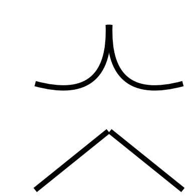
$$\tilde{f} = \frac{2k}{l}, \qquad k \in \mathbb{N}^+, \qquad P_{\rm GW}^{(k)}/P_{\rm GW}^{(1)} = \begin{cases} k^{-4/3} & \boxed{\text{cusps}} \\ k^{-5/3} & \text{kinks} \\ k^{-2} & \text{kink-kink collisions} \end{cases}$$



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$\Gamma = 50$ **(NG sim. Blanco-Pillado 17')**

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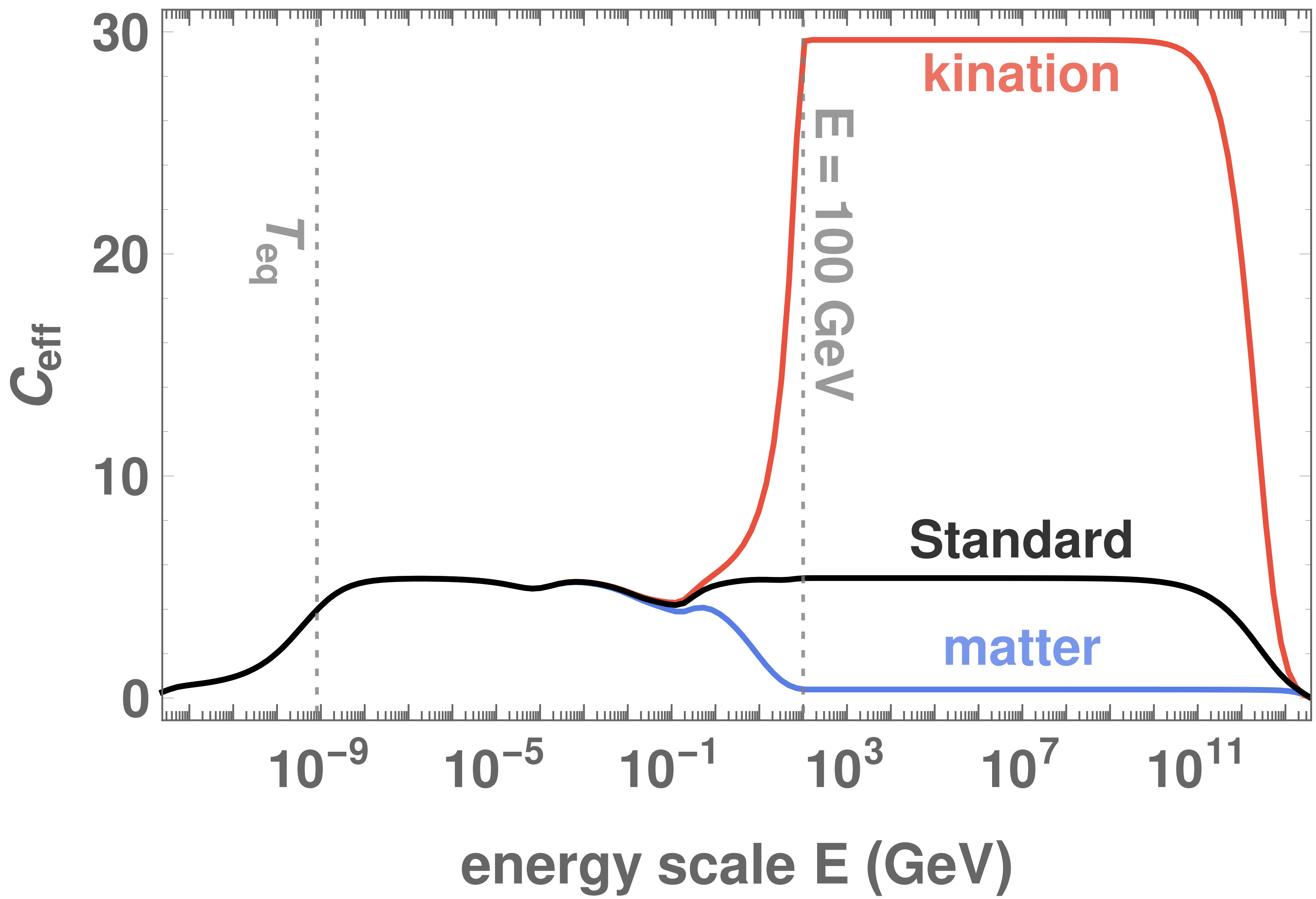

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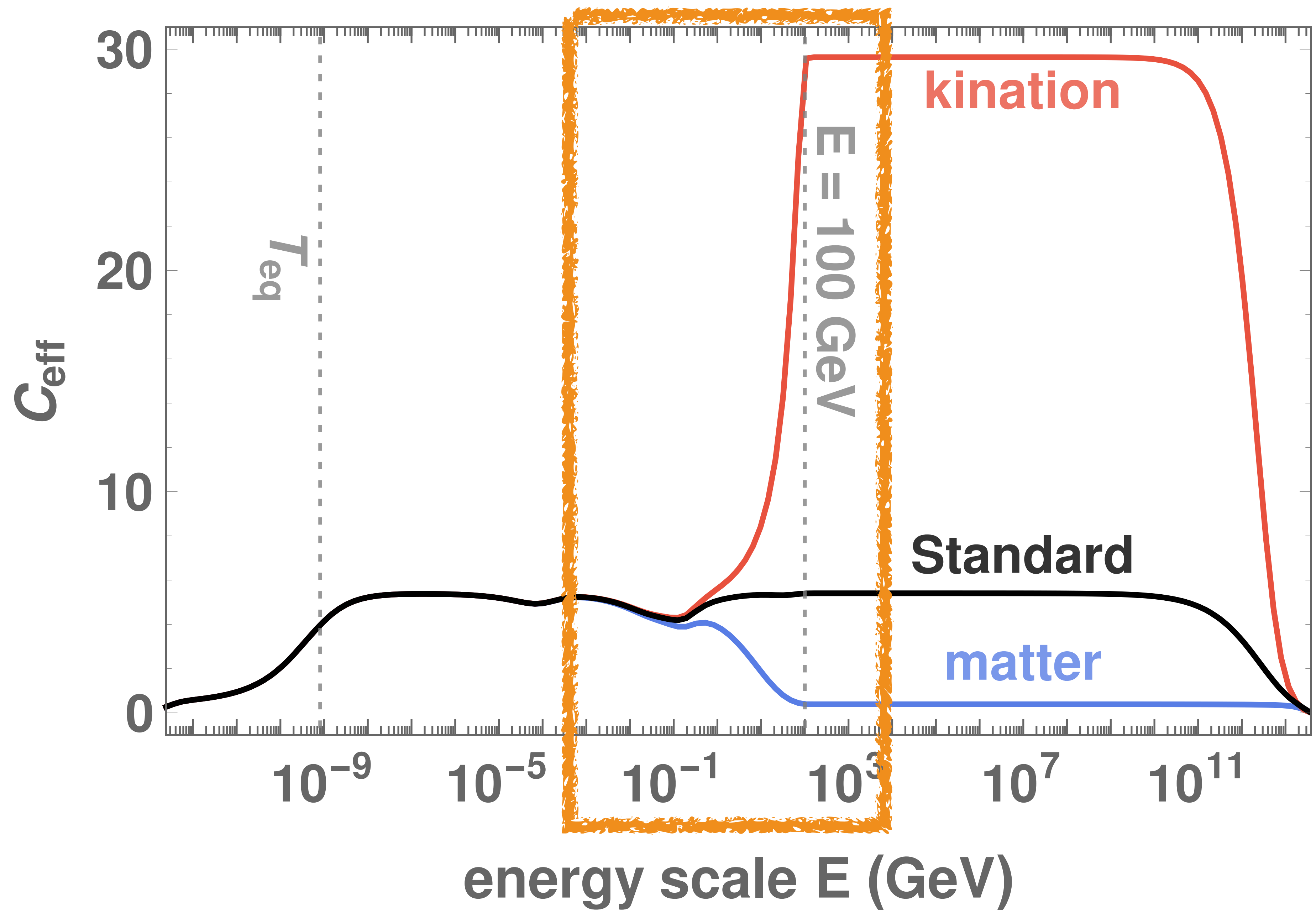

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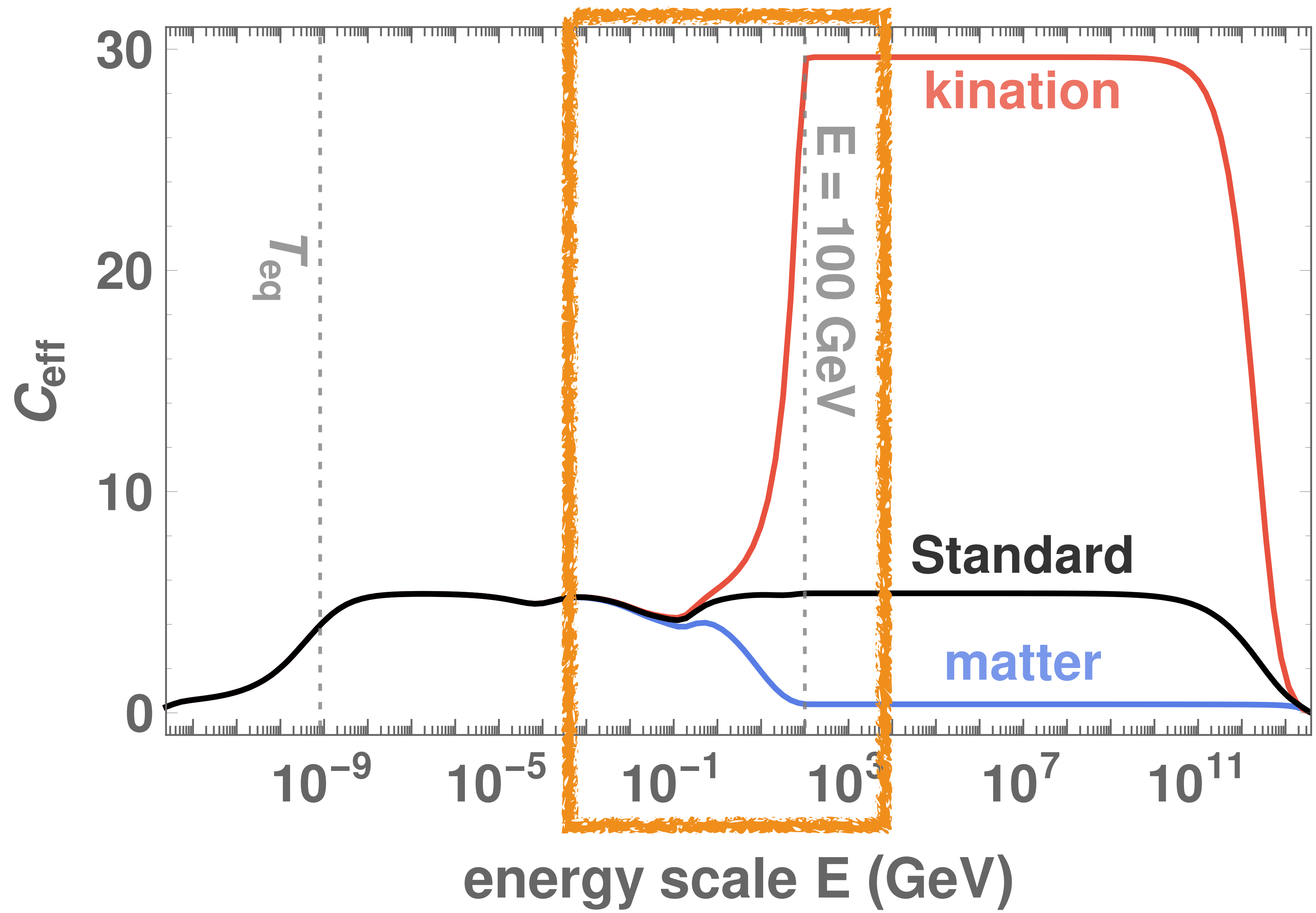


**Improvement with respect to Cui, Lewicki, Morrissey, Wells 17' and 18'**

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$t_i$ = loop formation time

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- **Our assumption:**

$$P(\alpha) = \delta(\alpha - 0.1)$$

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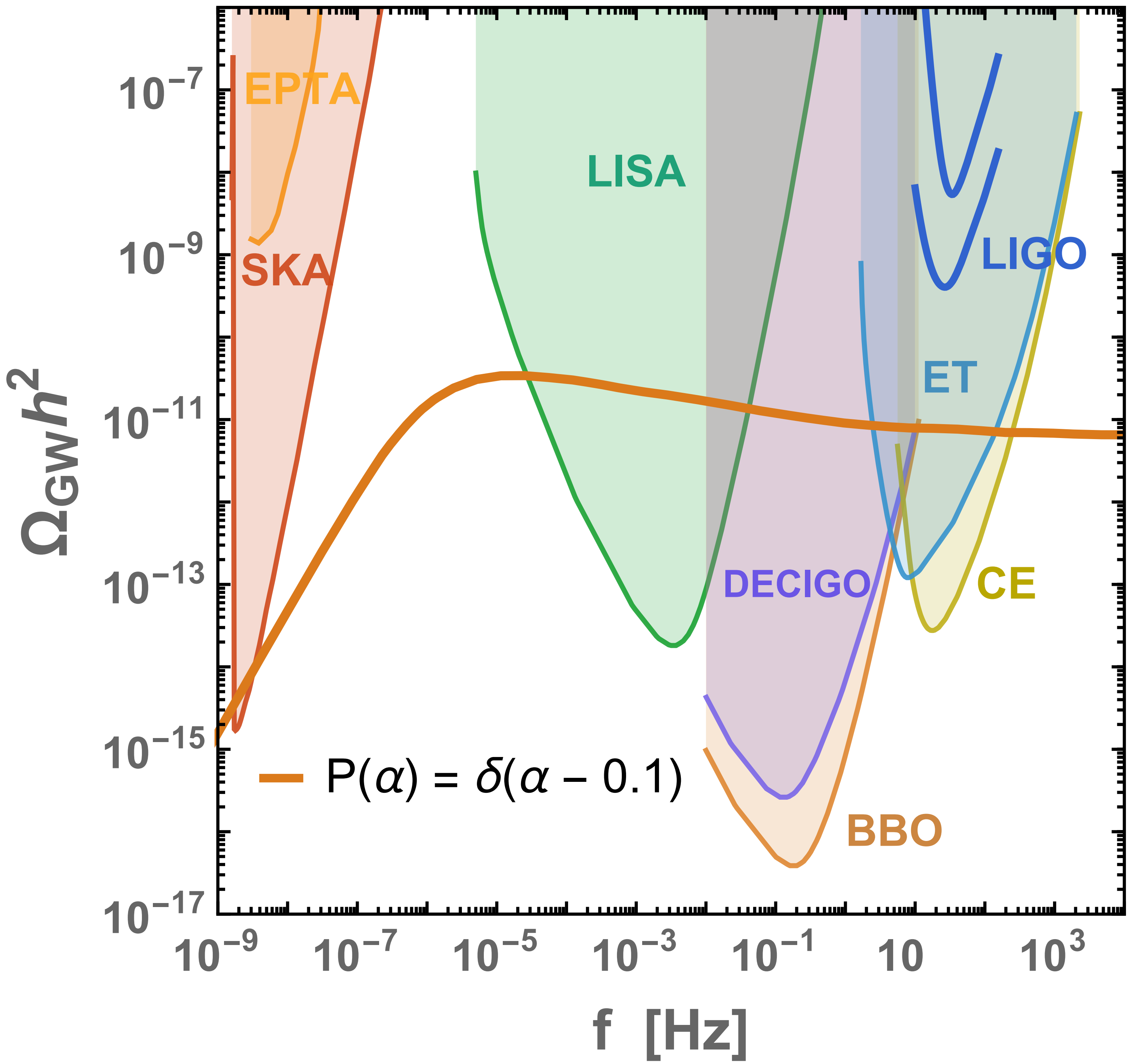

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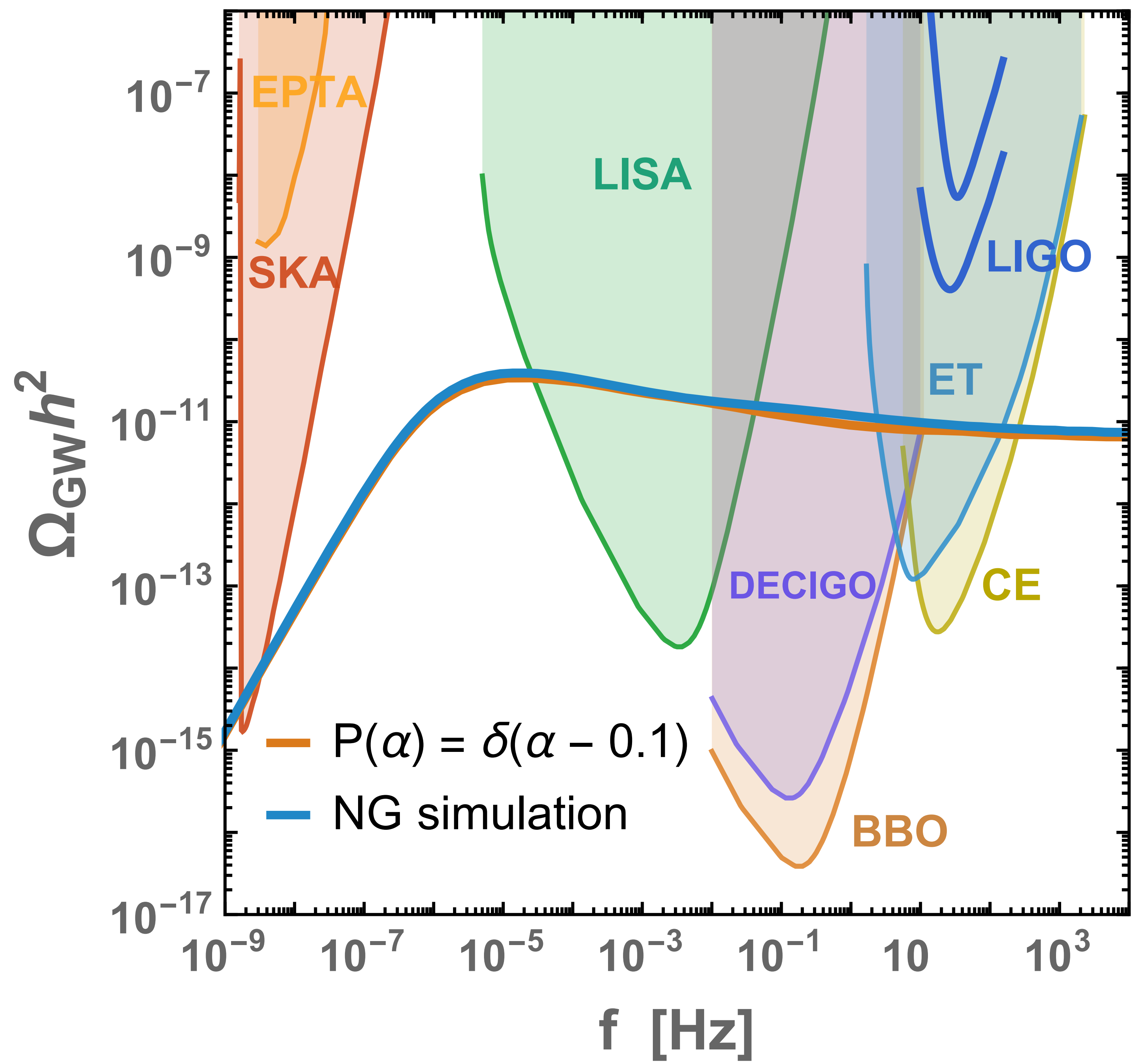

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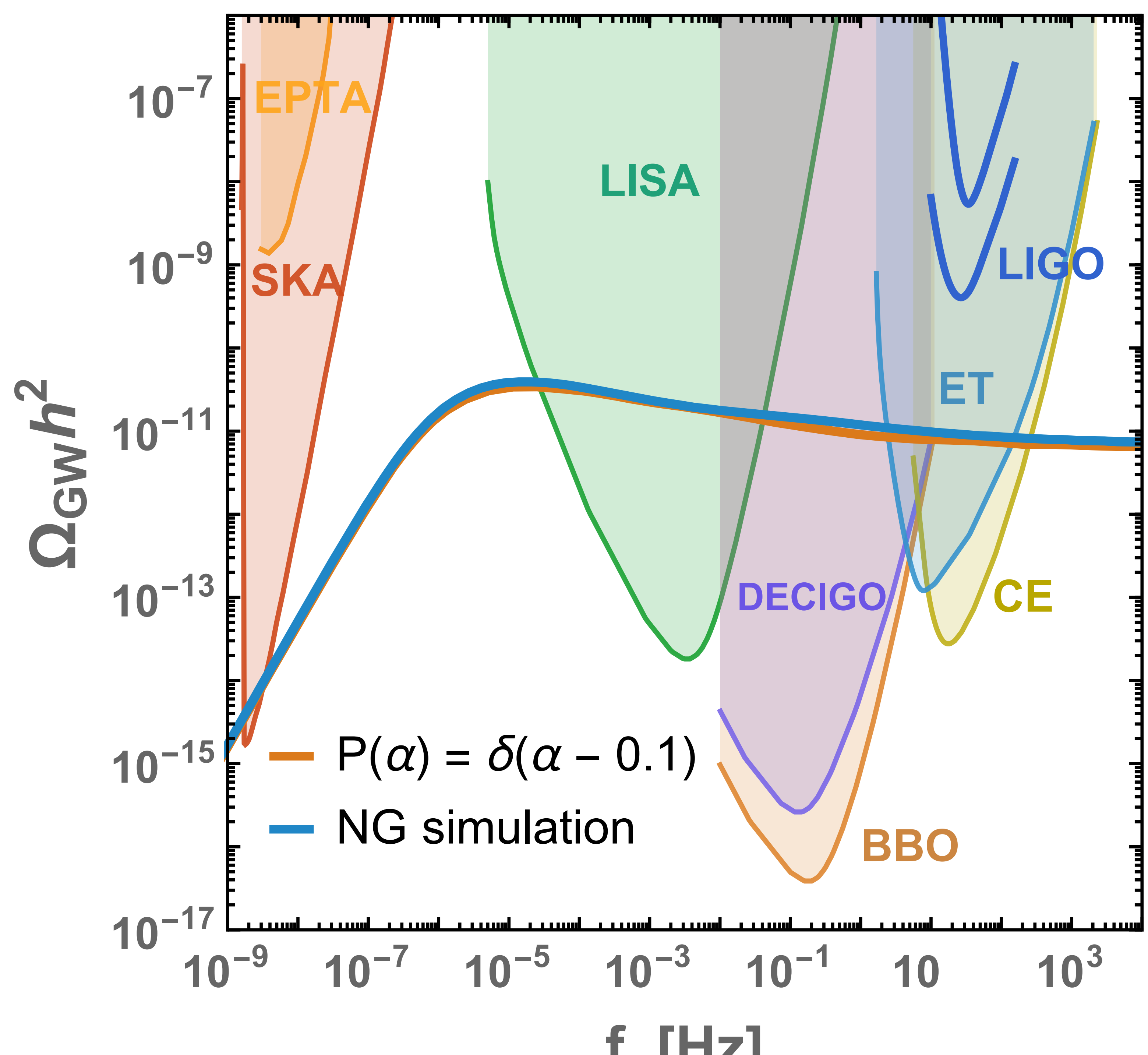

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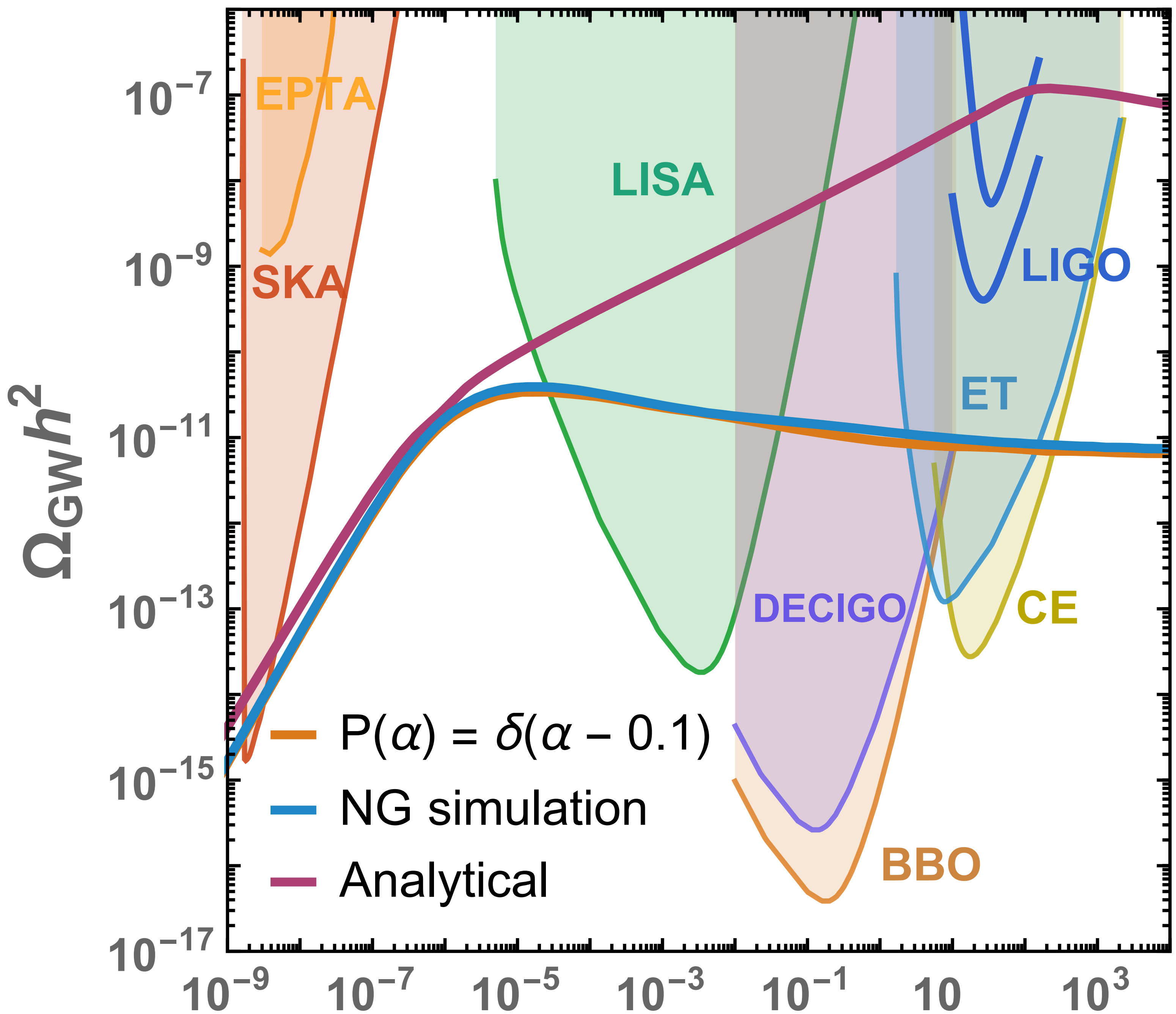


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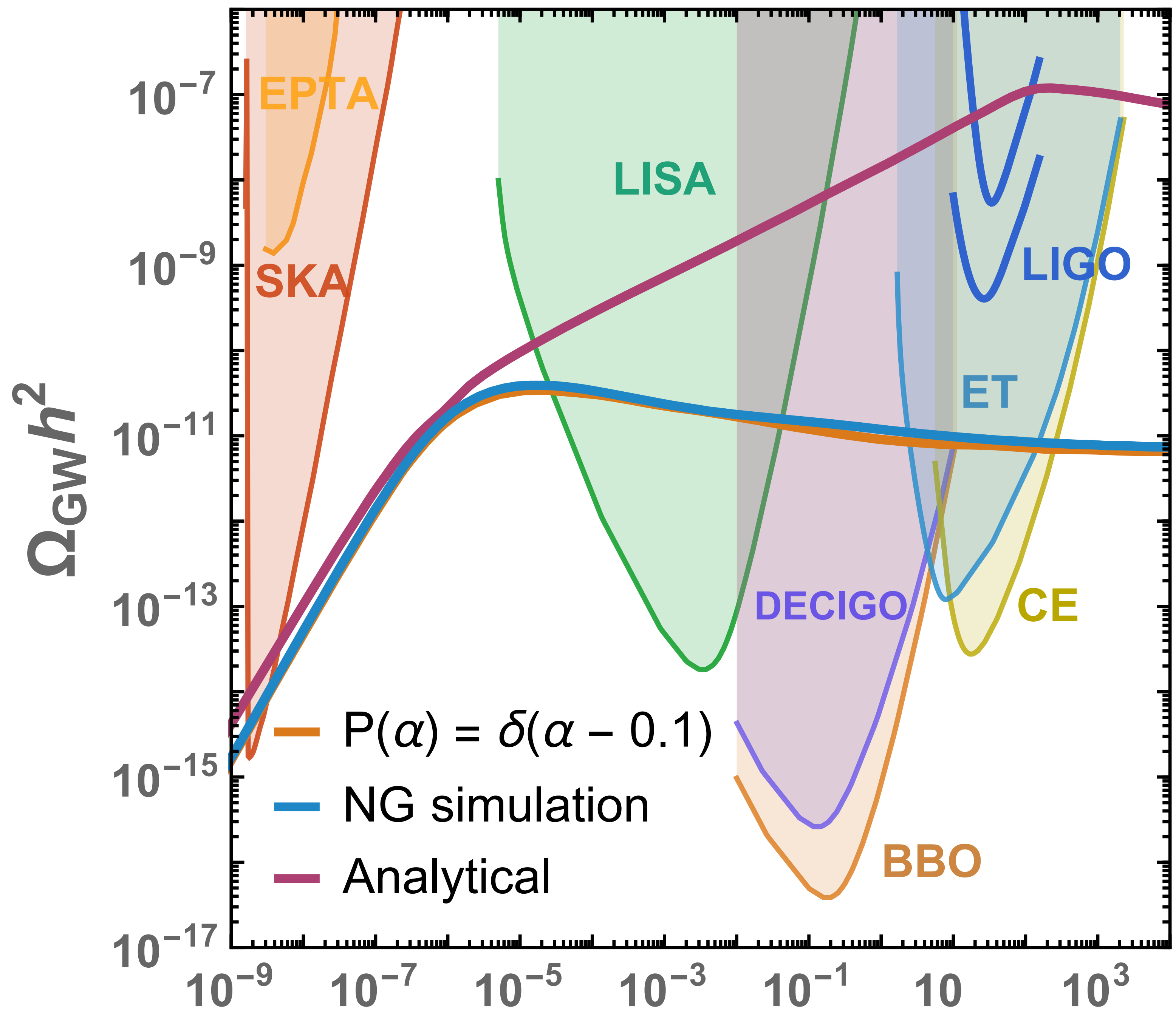


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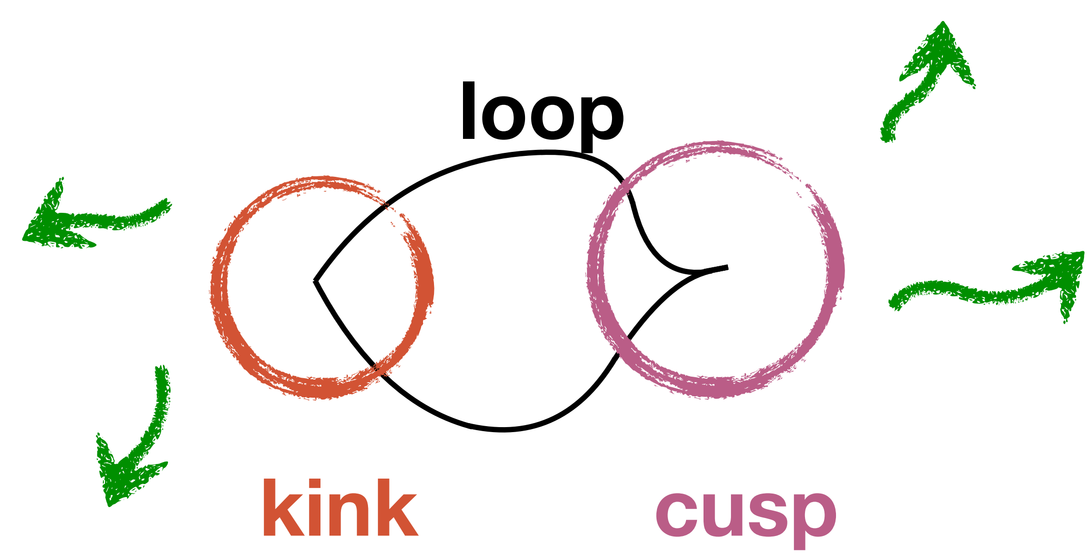
**Cosmological** **Microscopic**

- **NG approx. violated by small-scale structure**
  - → **Massive Particle production**



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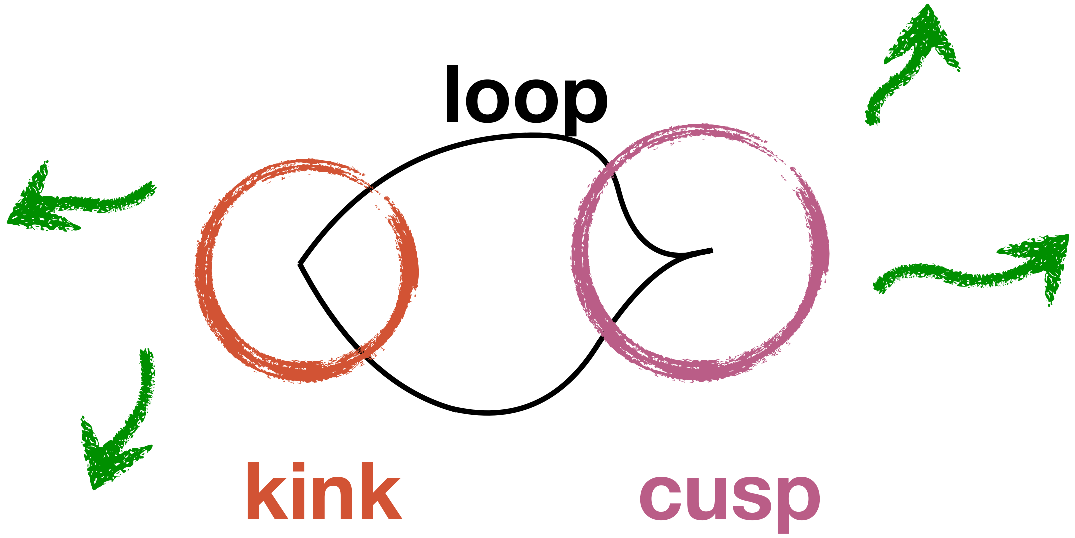

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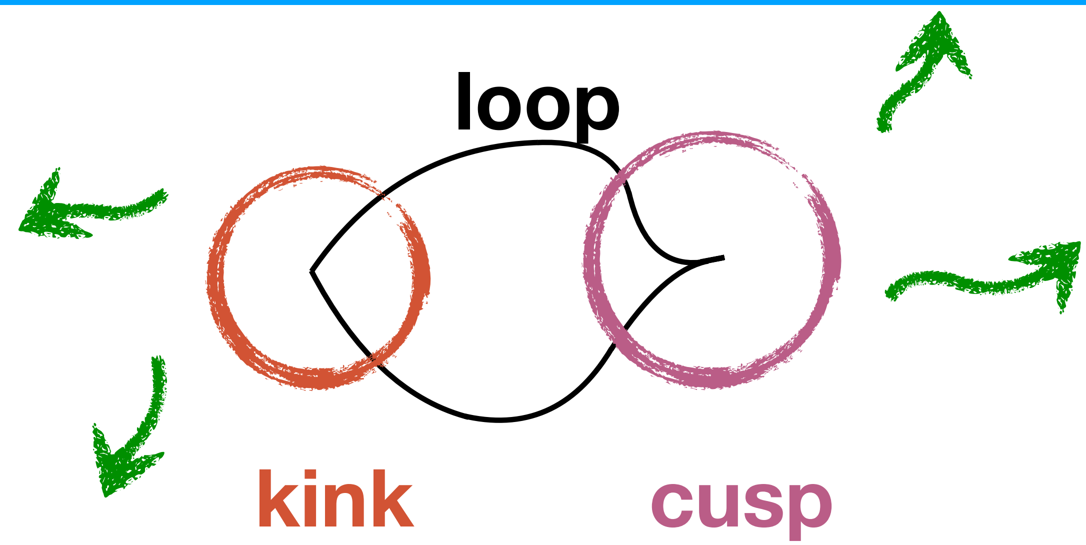


Blanco-Pillado, Olum 98'

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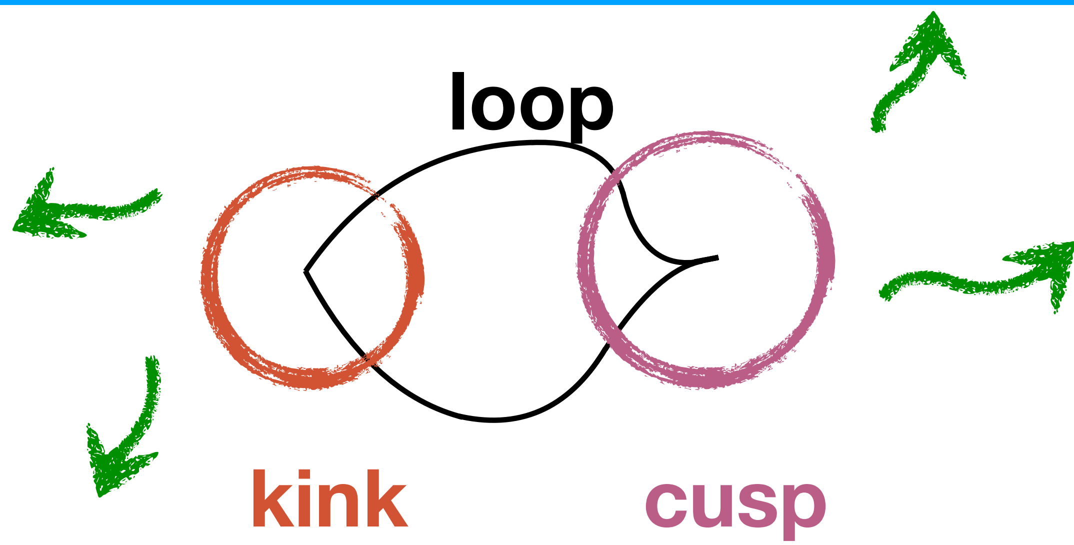


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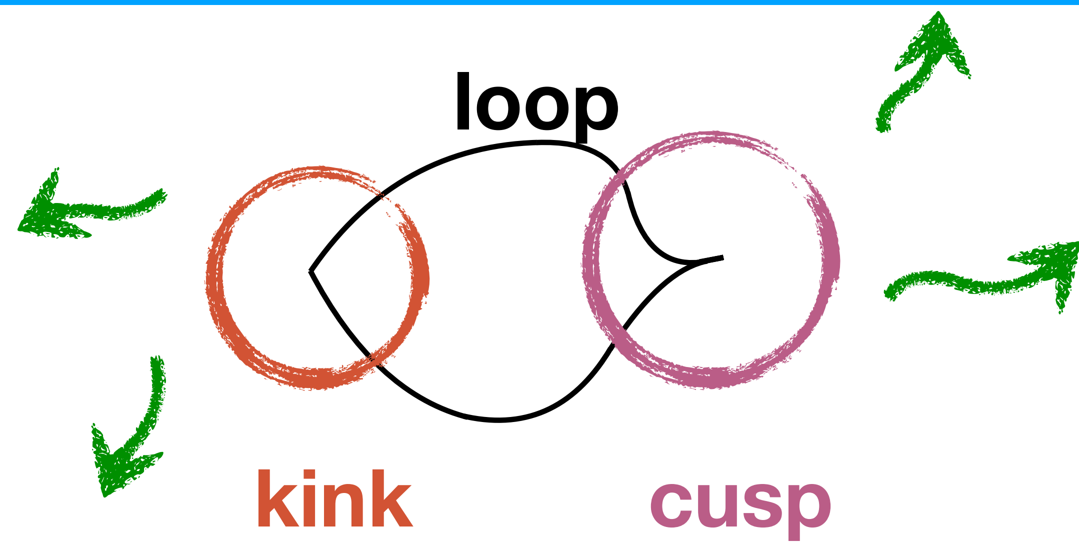


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→ **No GW emission when:** $P^{\text{part.}}_{\text{kink/cusp}} \gtrsim P_{\text{GW}} = \Gamma G \mu^2$

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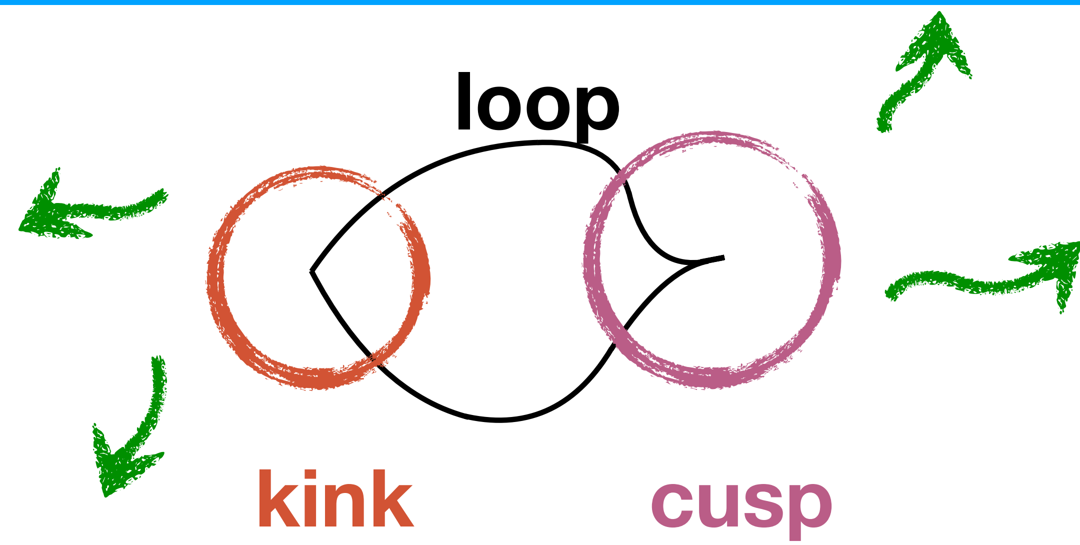


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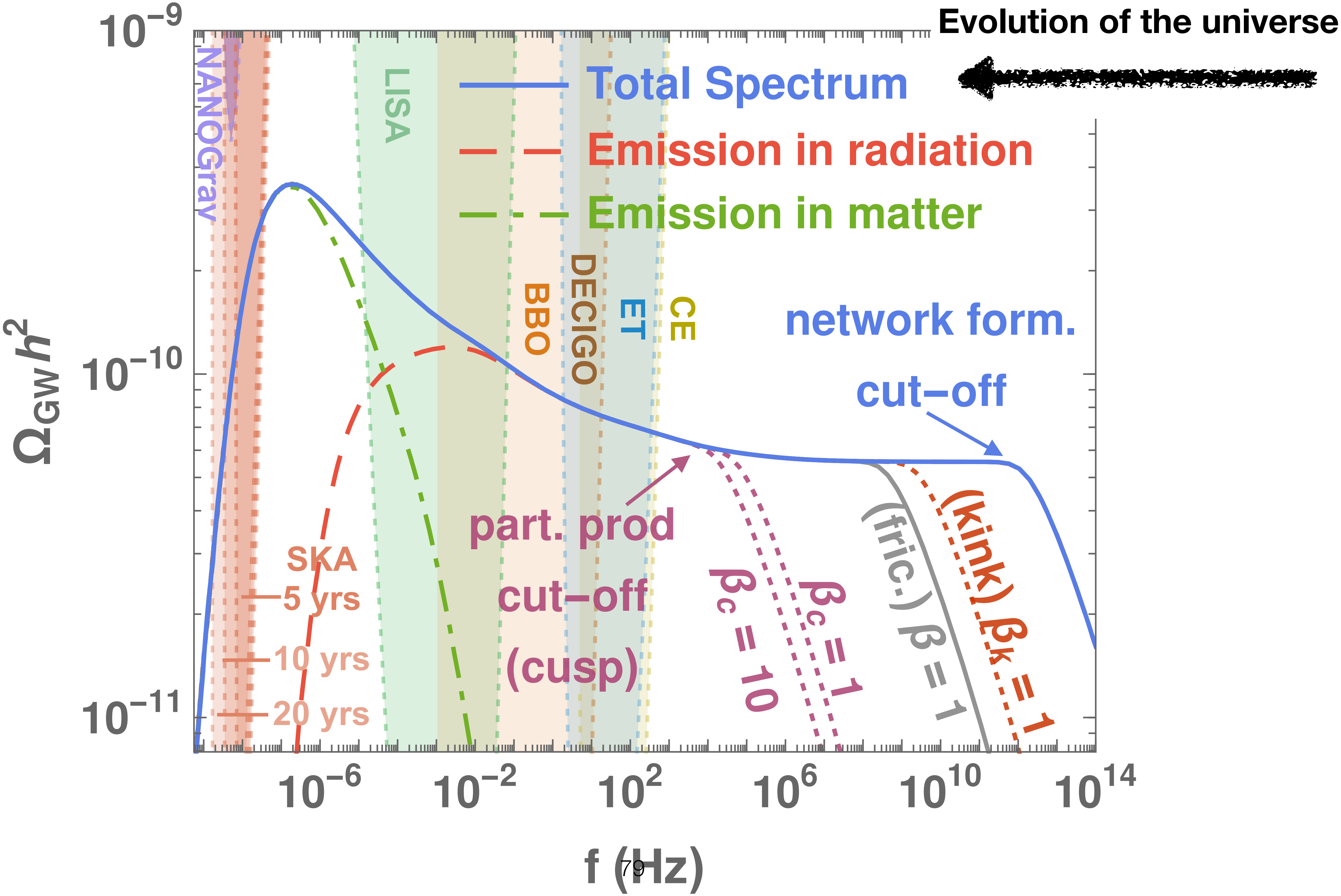
**Disagreement with Lattice Field Theory simulations from**

Hindmarsh et al. 97' / 08' / 17'

→ **Predict much more massive particles and no observable GW**

# GW spectrum from Cosmic Strings



# The GW spectrum

$t_i = \text{loop formation time}$

$\tilde{t} = \text{GW emission time}$

$$l(\tilde{t}) = \begin{cases} \frac{2k}{f}\frac{a(\tilde{t})}{a(t_0)}, \\ \alpha t_i - \Gamma G\mu(\tilde{t} - t_i). \end{cases}$$

**GW energy density redshift**

**Beyond NG approx: Massive radiation**

**Emitted power into GW**

$\Gamma = 50$ **(NG sim. Blanco-Pillado 17')**

$$\Omega_{\rm GW}(f) \simeq \sum_k \frac{1}{\rho_c}\int_{t_{\rm osc}}^{t_0} d\tilde{t} \int d\alpha \left[\frac{a(\tilde{t})}{a(t_0)}\right]^3 \cdot \Theta(t_i - \frac{l_*}{\alpha}) \cdot \frac{\Gamma G\mu^2}{k^{4/3}}$$

**Loop density redshift**

$$\times \left[\frac{a(t_i)}{a(\tilde{t})}\right]^3 \cdot \frac{dt_i}{d\tilde{f}} \cdot P(\alpha) \cdot \frac{\tilde{C}_{\rm eff}(t_i)}{\alpha\, t_i^4} \cdot \Theta(t_i - t_{\rm osc})$$

$t_{\rm osc} \equiv {\rm Min}[t_F,\, t_{\rm friction}]$

**Loop size distribution**

$$P(\alpha) = \delta(\alpha - 0.1)$$

**(NG sim. Blanco-Pillado 14')**

$$\frac{dn_{\rm loop}}{dt_i} = \frac{1}{\mu \times \alpha \times t_i}\frac{d\rho_{\rm loop}}{dt_i}$$

**Friction stops**

**Network is formed**

# Summary part A

- $P_{\mathrm{GW}} = \Gamma\, G\mu^2$ $\quad \Gamma = 50$ $\quad$ **independent of loop length**

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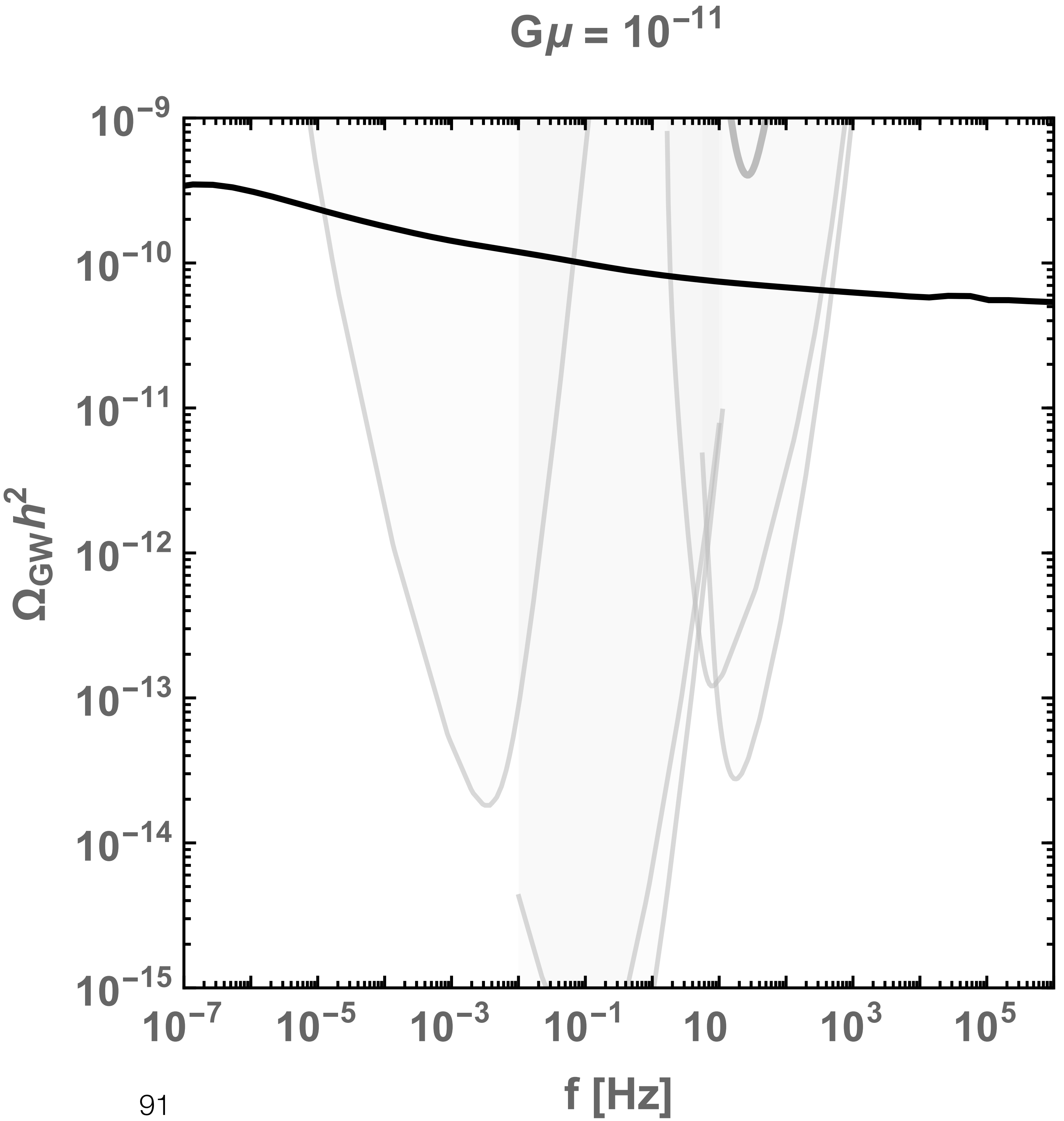
$\neq$ **Hindmarsh et al. 97' / 08' / 17'** **who predict no observable GW at all**

# B) Probe of non-standard cosmology and particle physics

→ **Early Matter era**

→ **Early intermediate inflation**

# Non-standard Matter era

# Non-standard Matter era

T

**Radiation**

$$T_{\rm dom} = \frac{4}{3} m_X Y_X$$

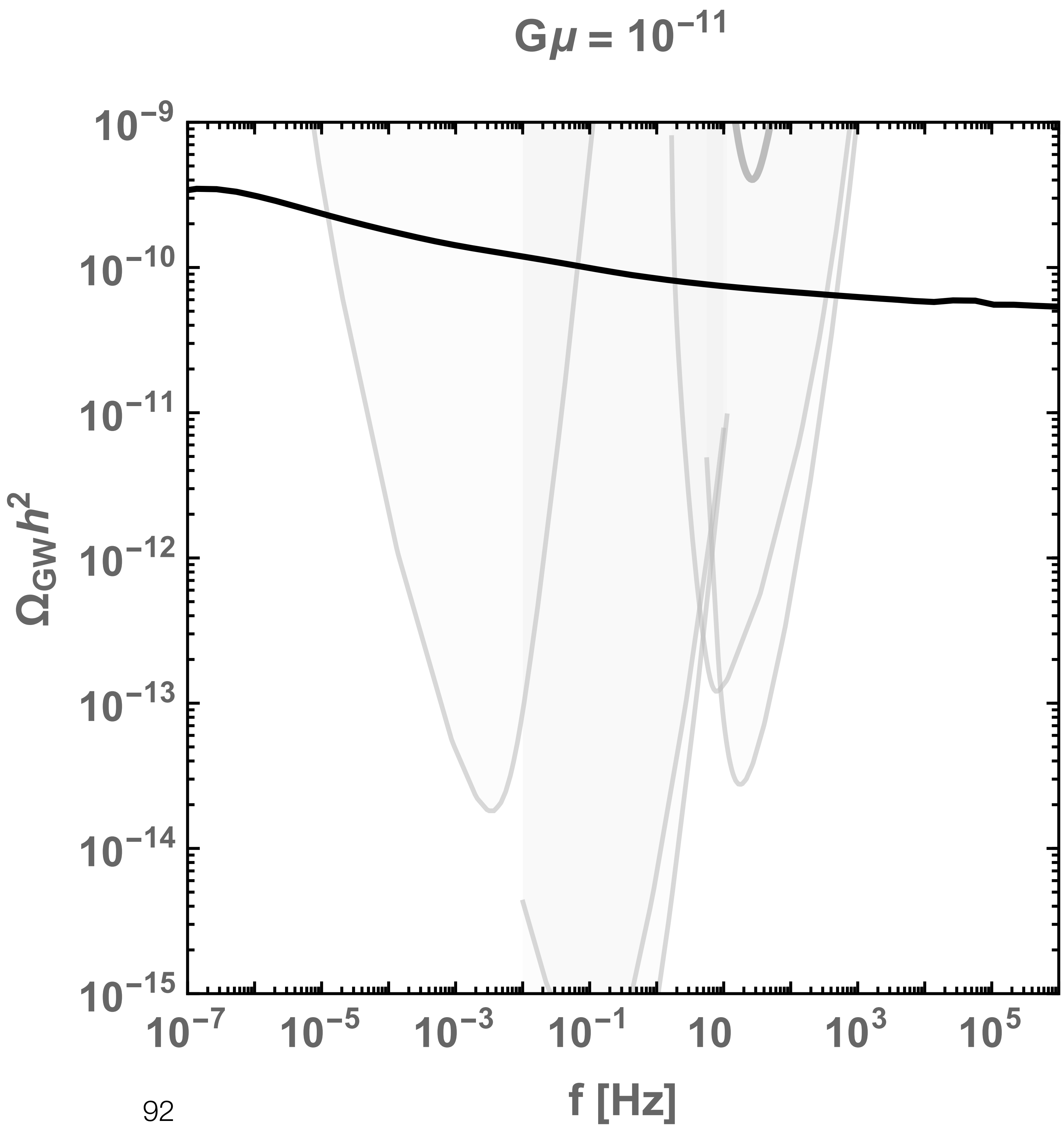
**Matter**

$$T_{\rm dec} \sim 1\ \mathrm{GeV} \left( \frac{10^{-7}\ \mathrm{s}}{\tau_X} \right)^{1/2}$$

**Radiation**

$$T_{\rm BBN} \sim 1\ \mathrm{MeV}$$

**Already constrained**



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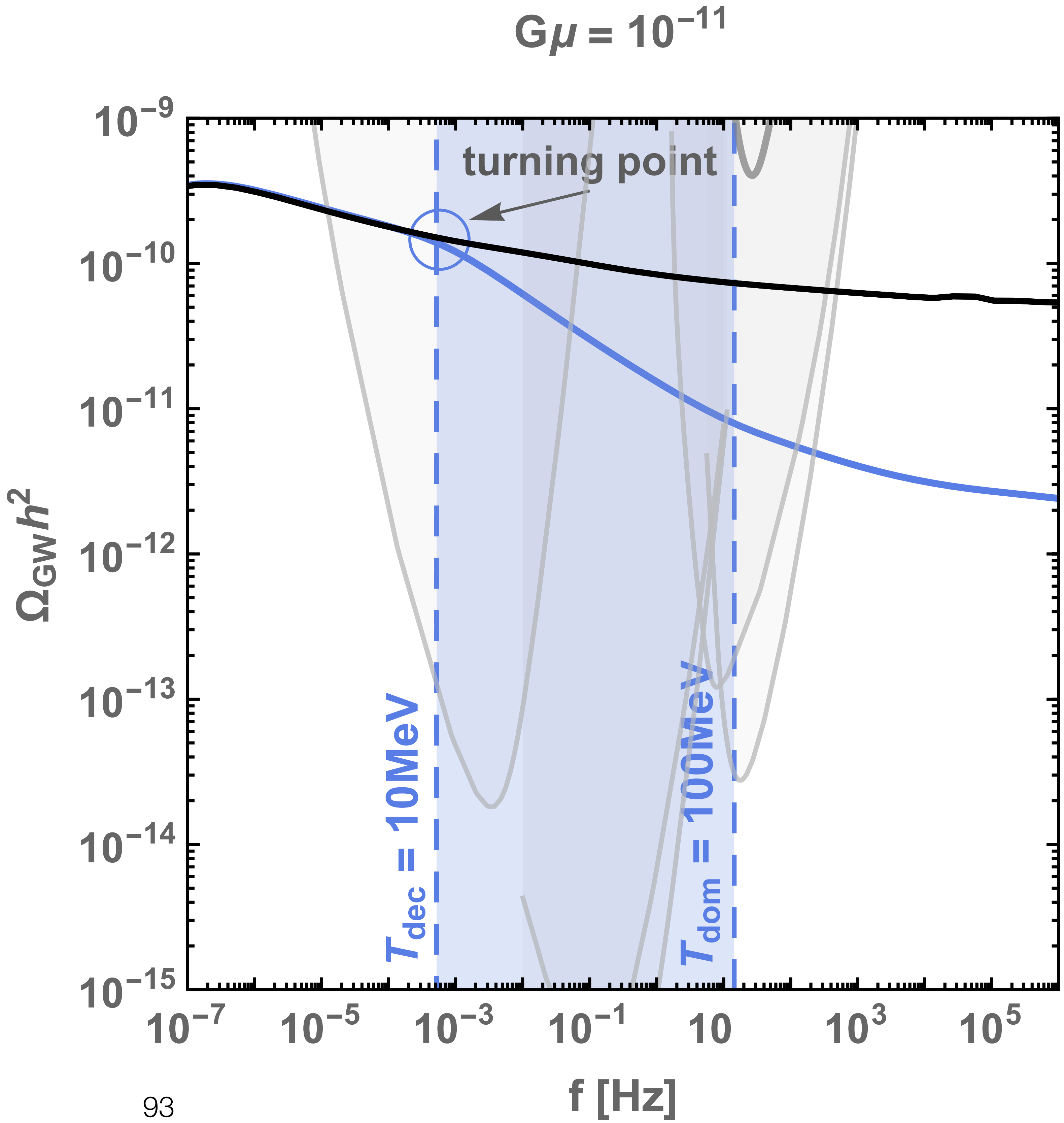

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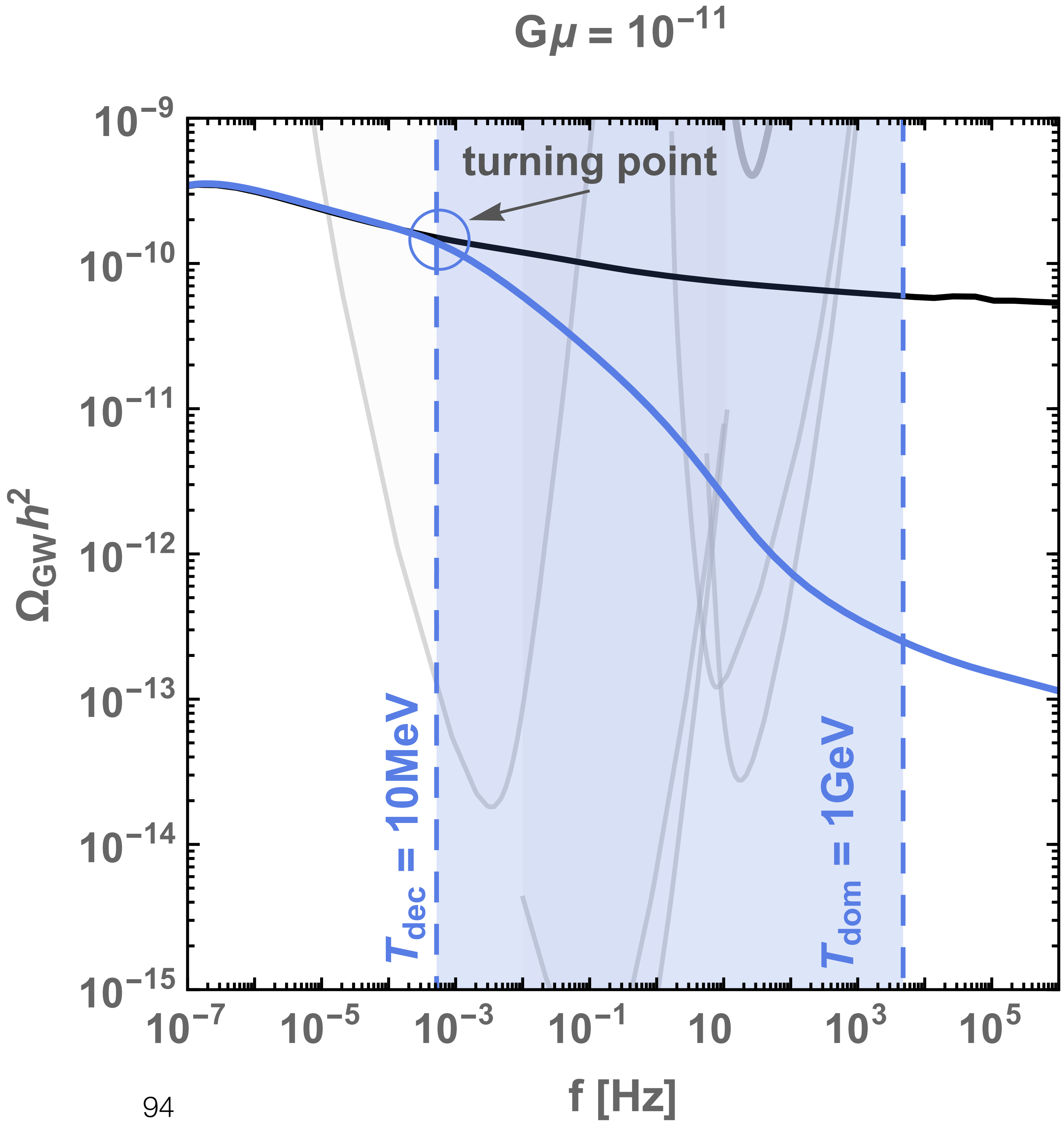

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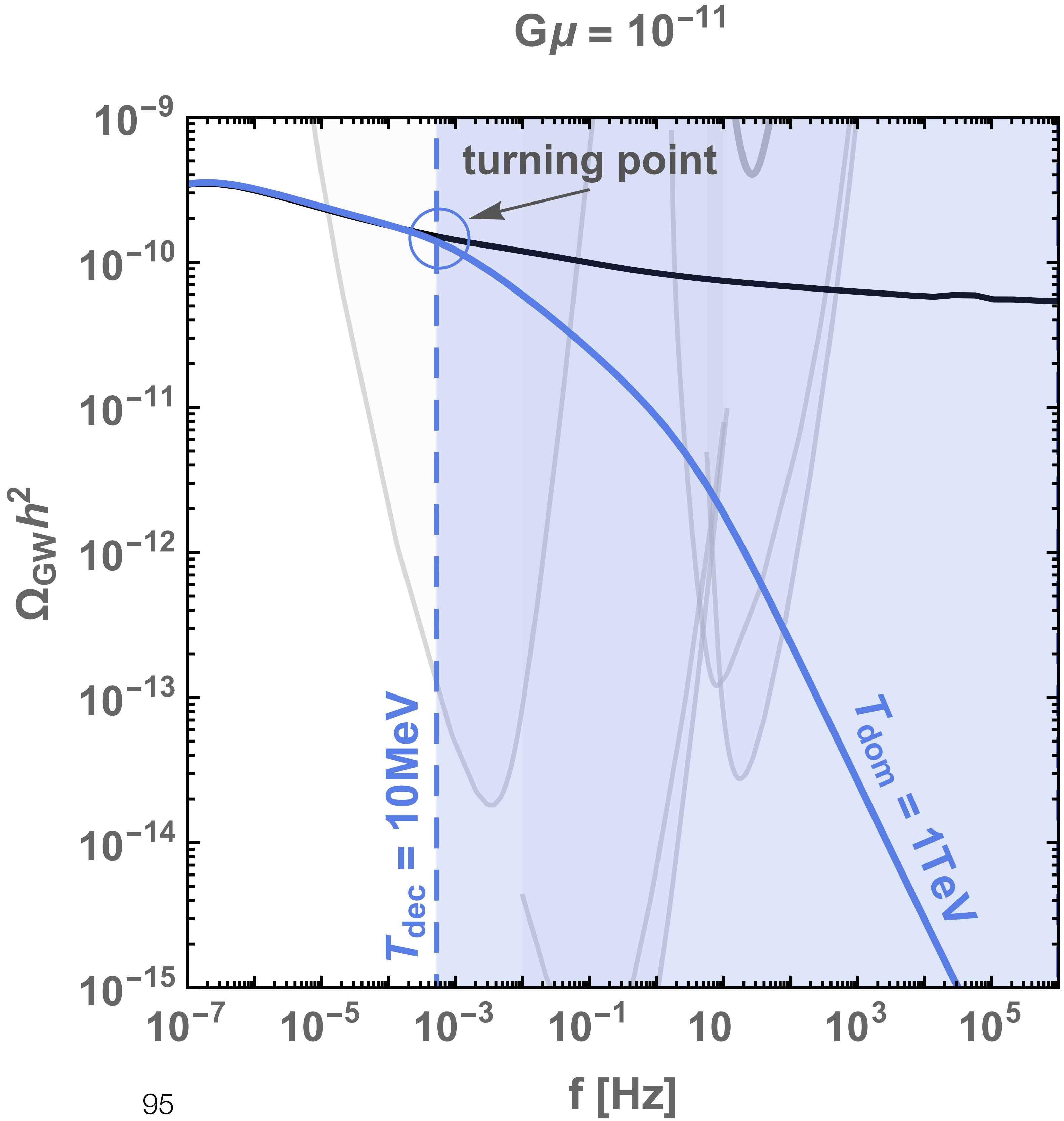

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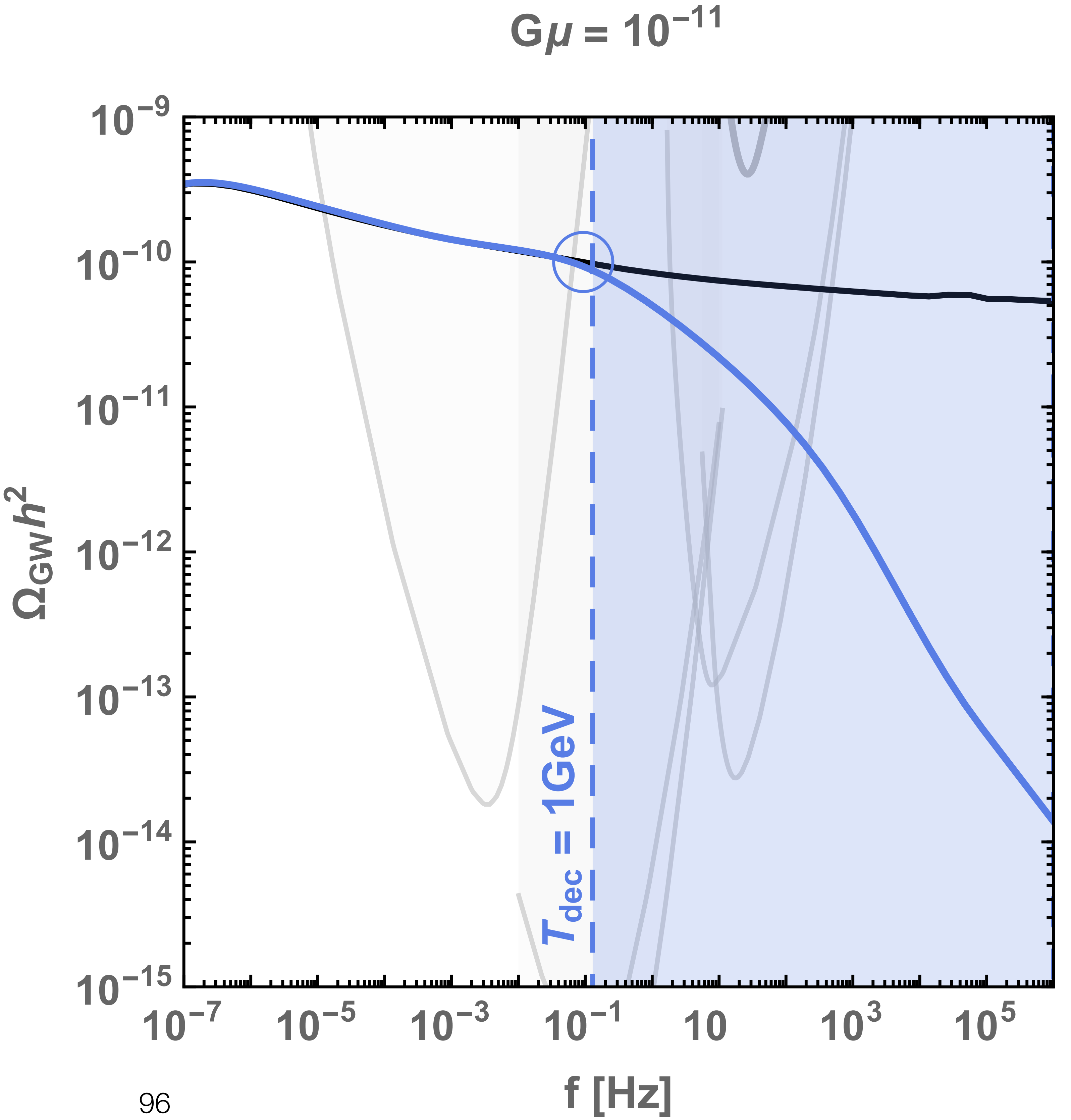

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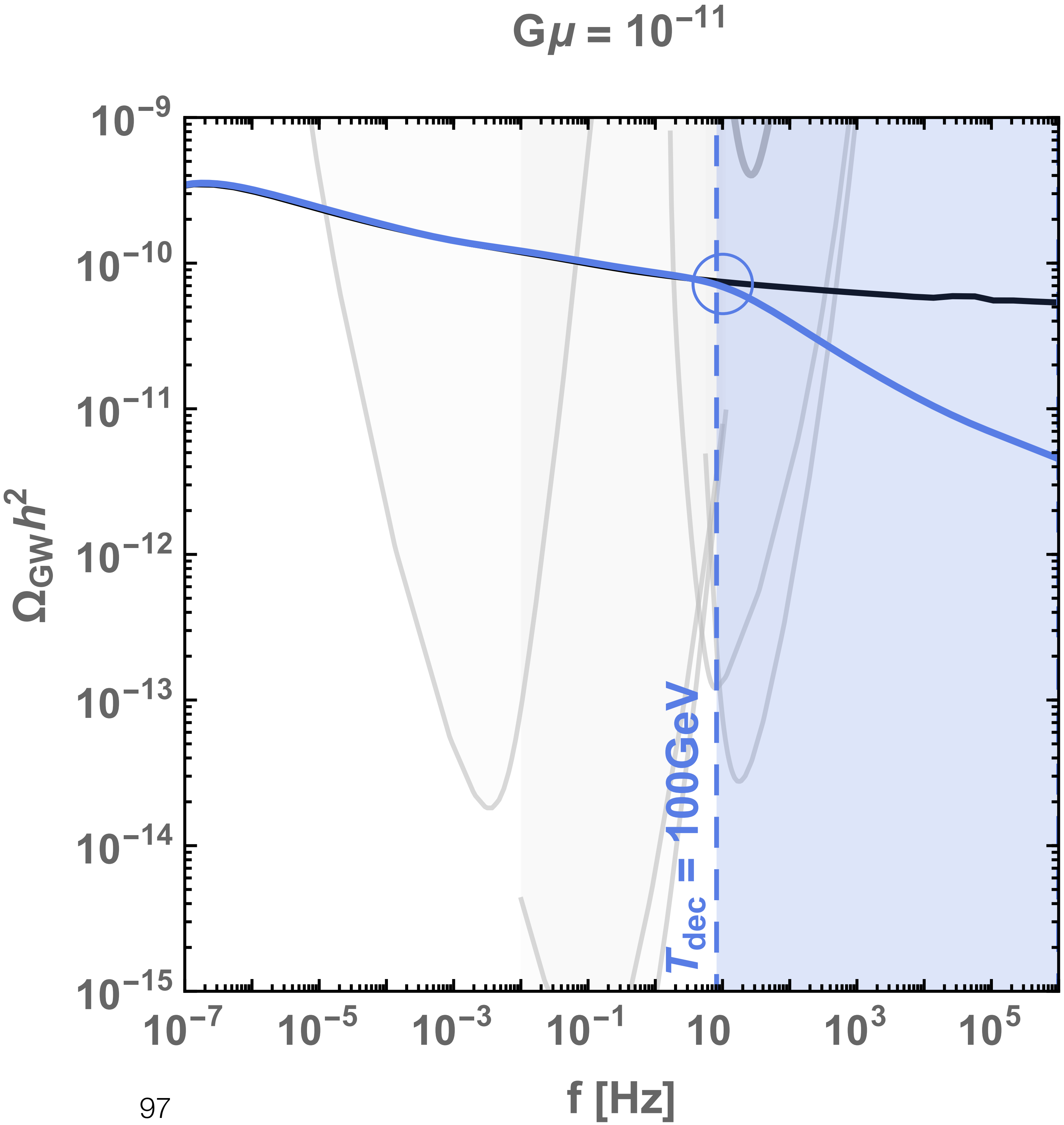

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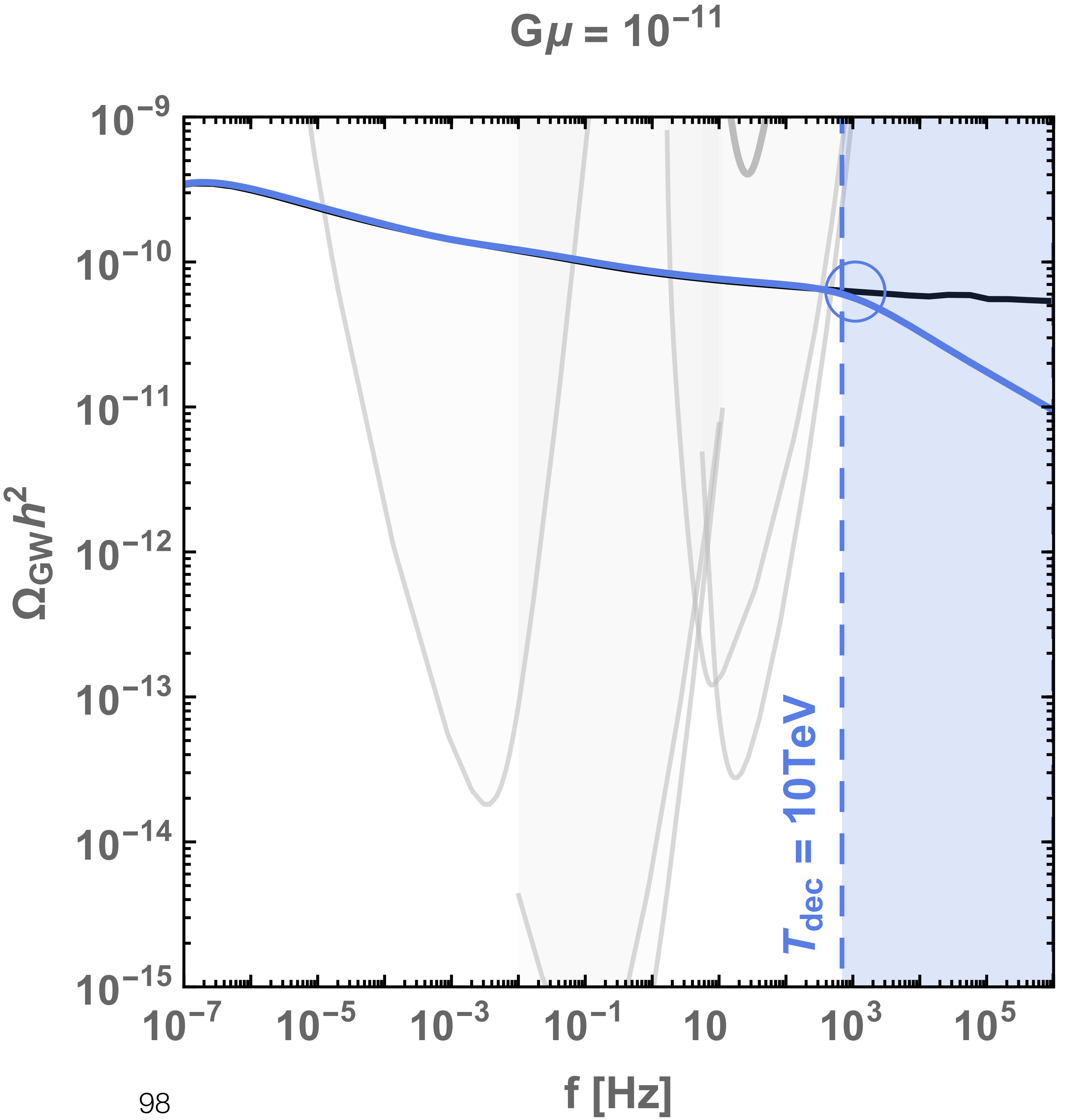

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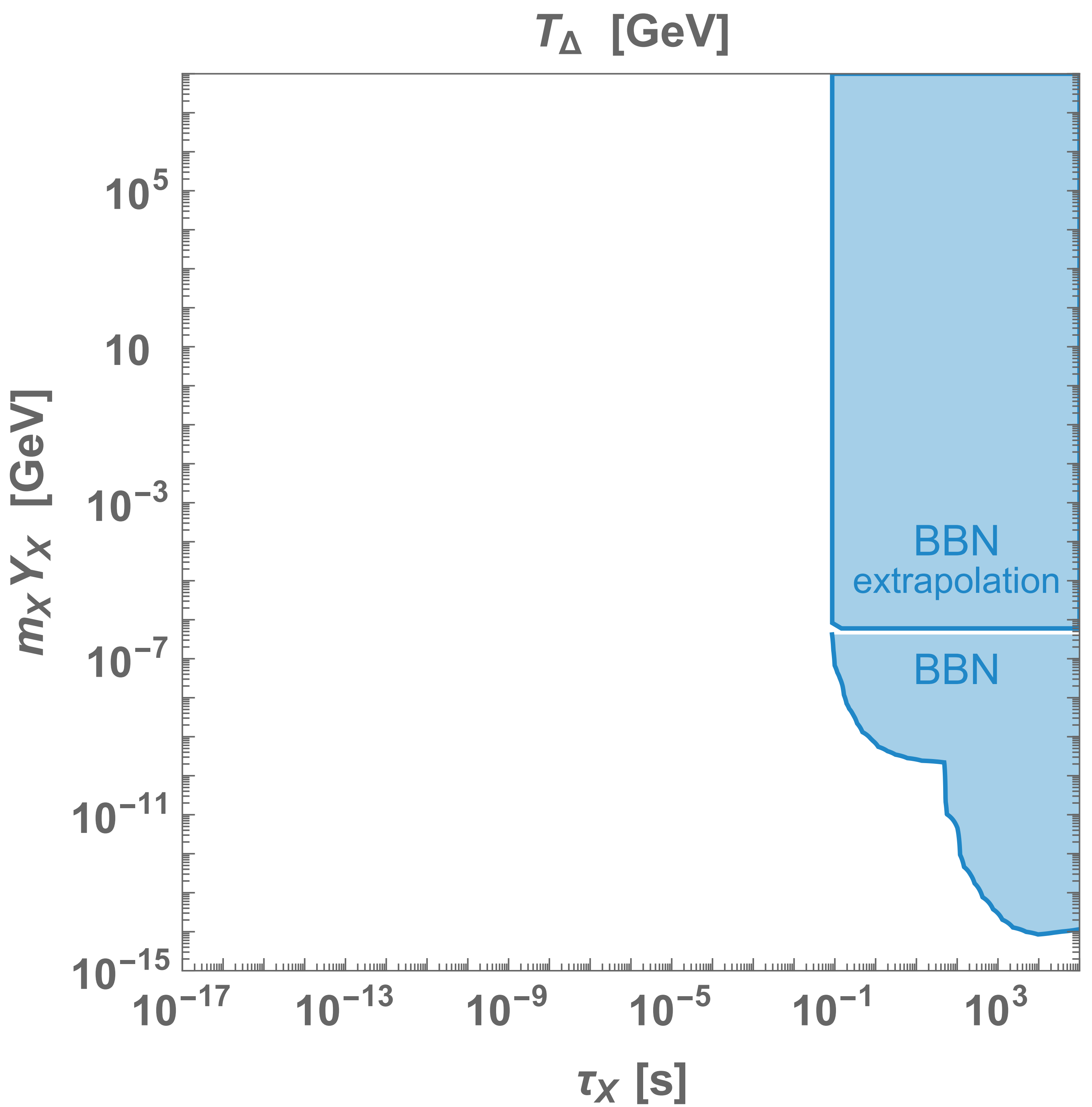

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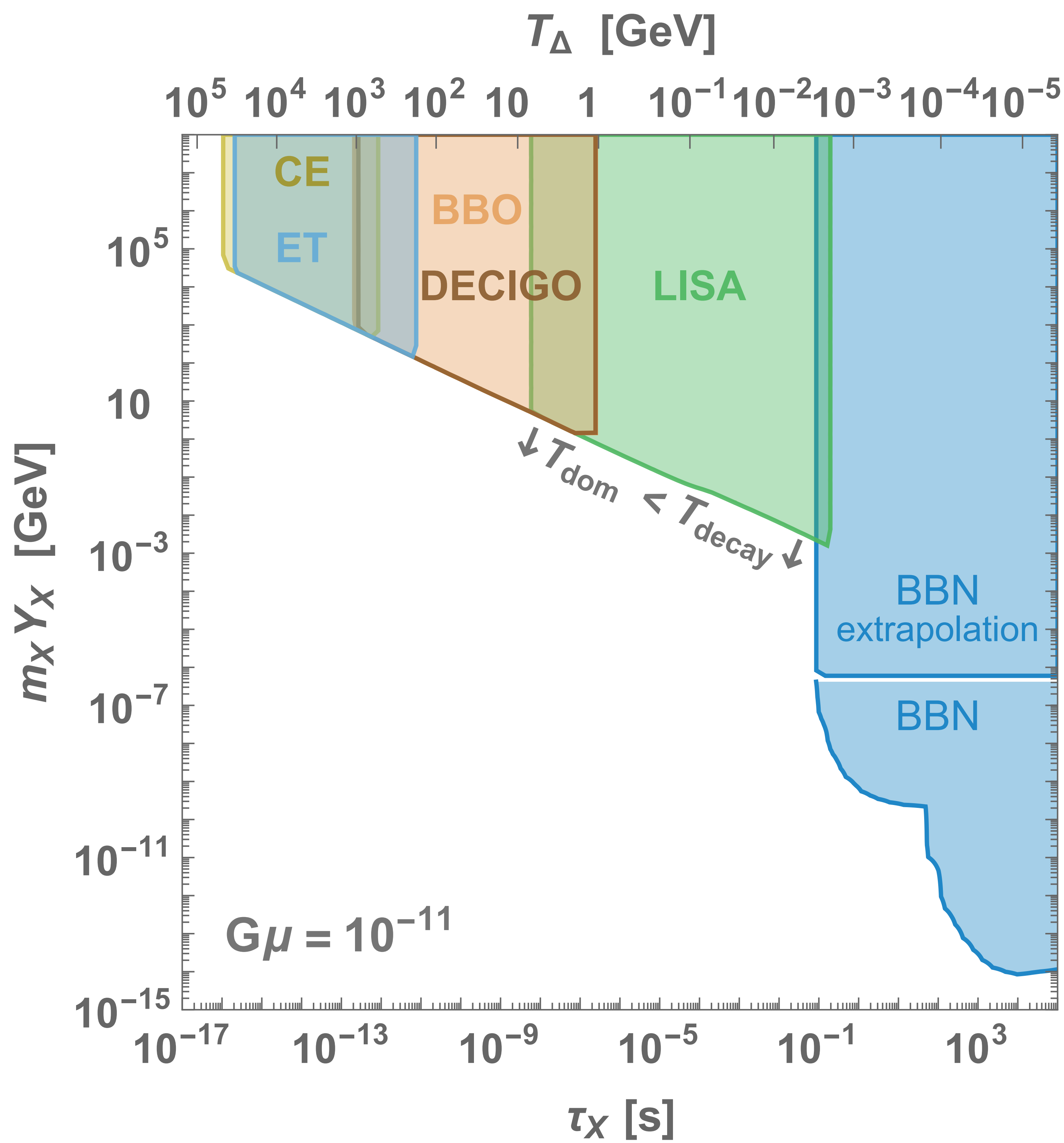

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**Beyond Nambu-Goto approx.**

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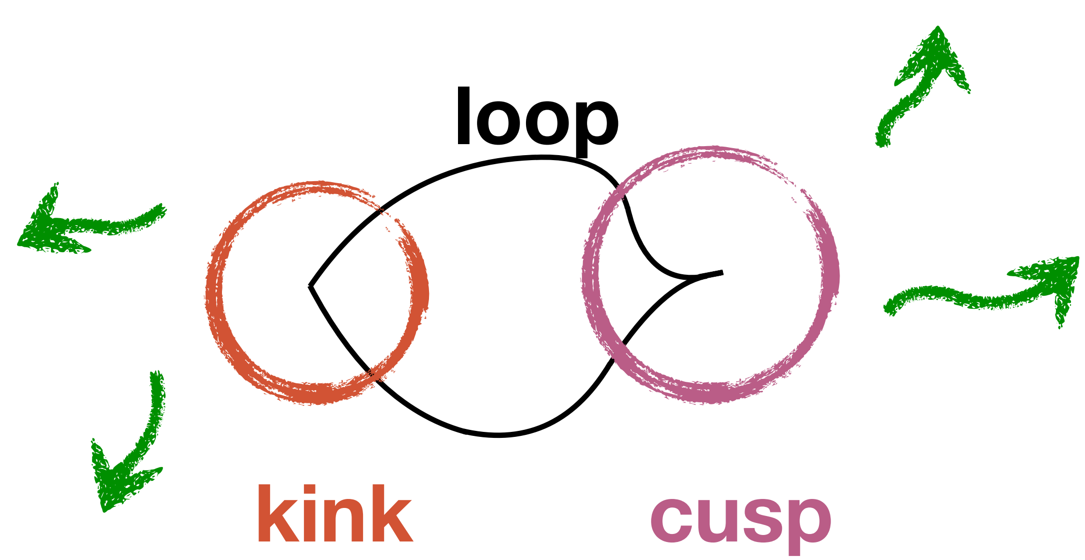


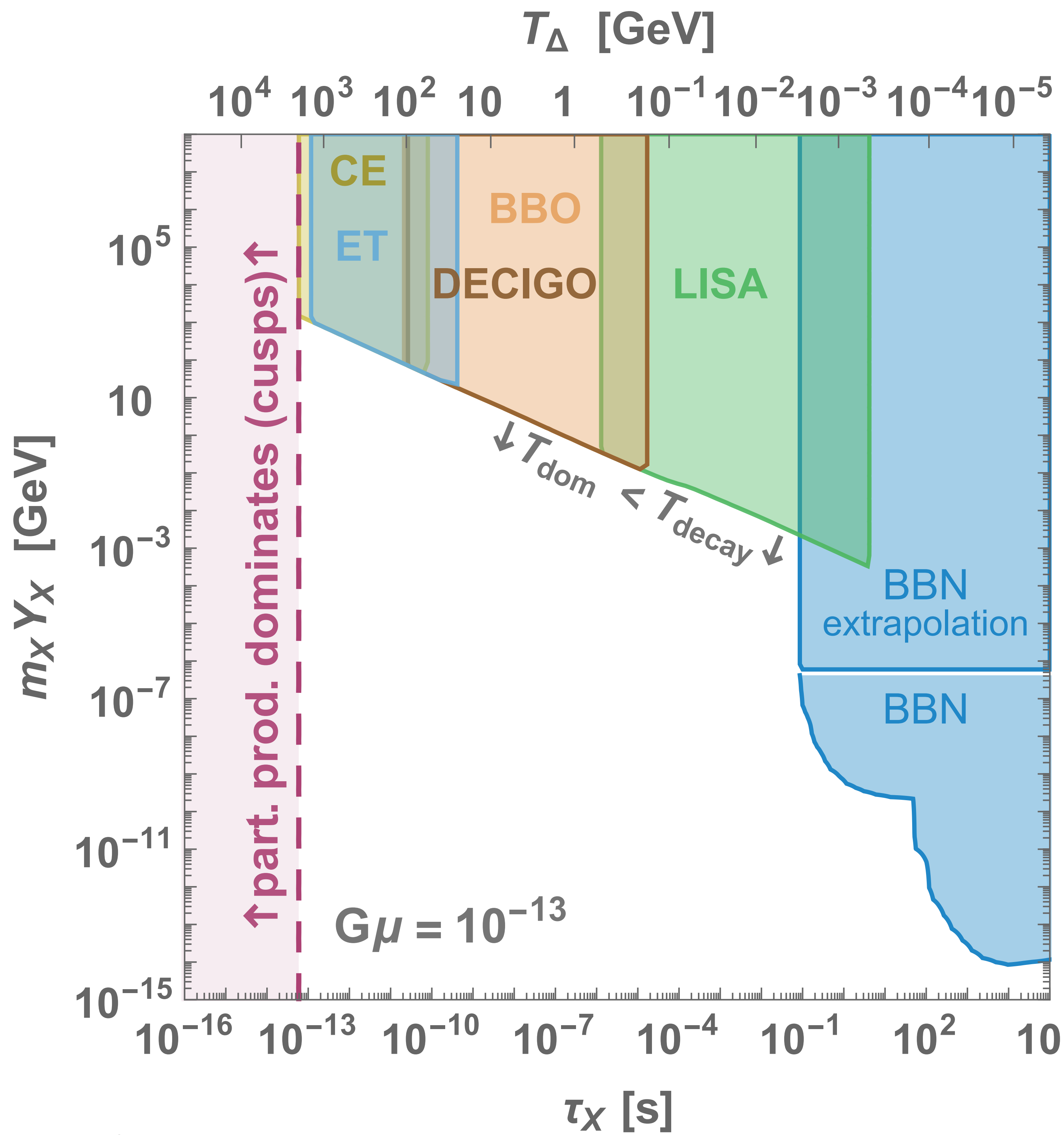

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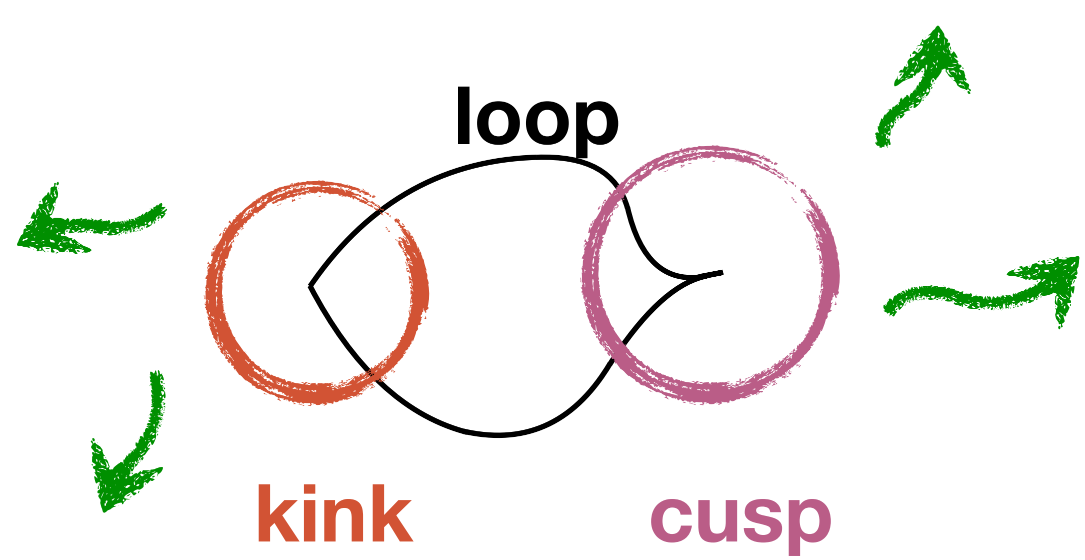


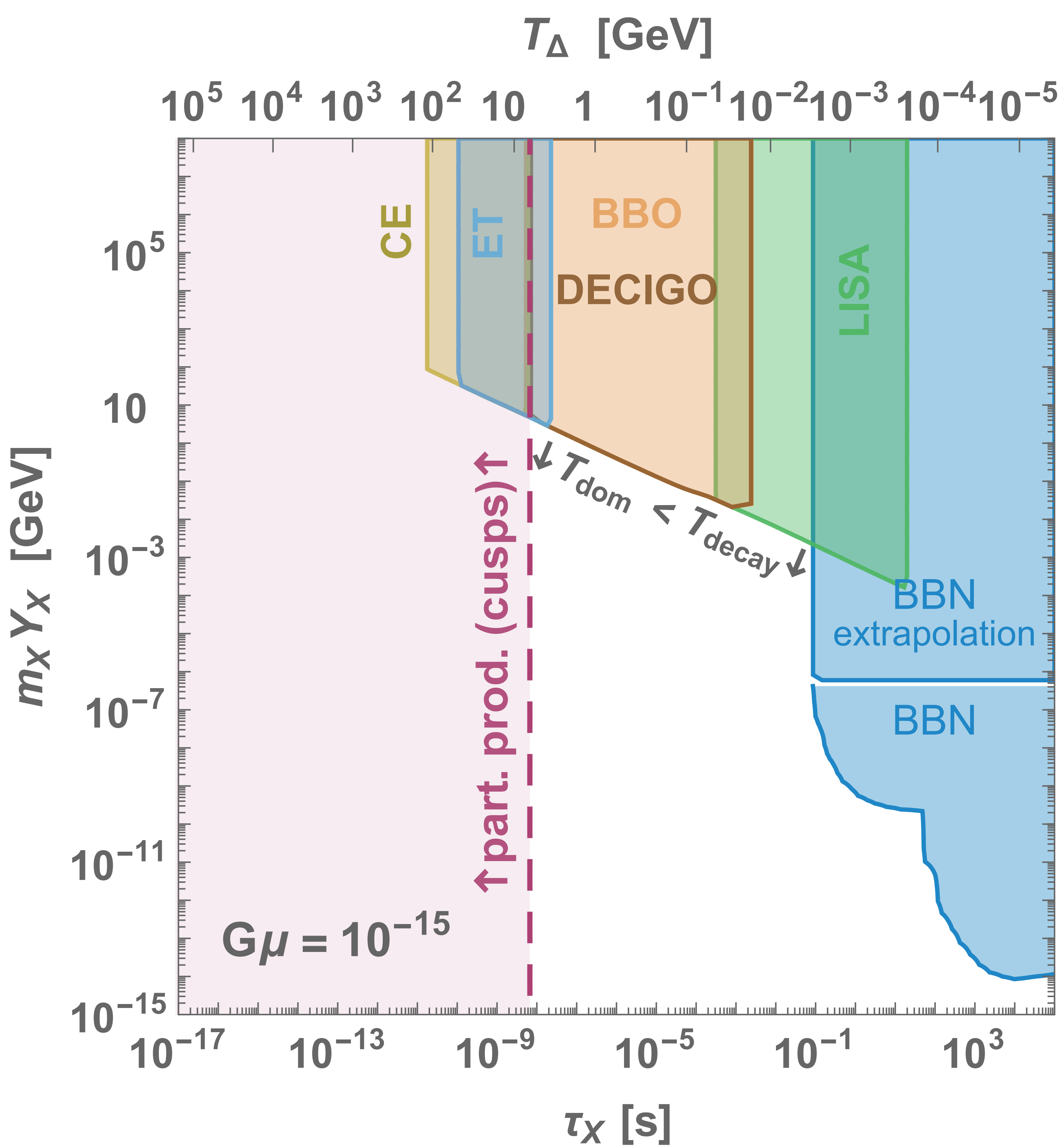

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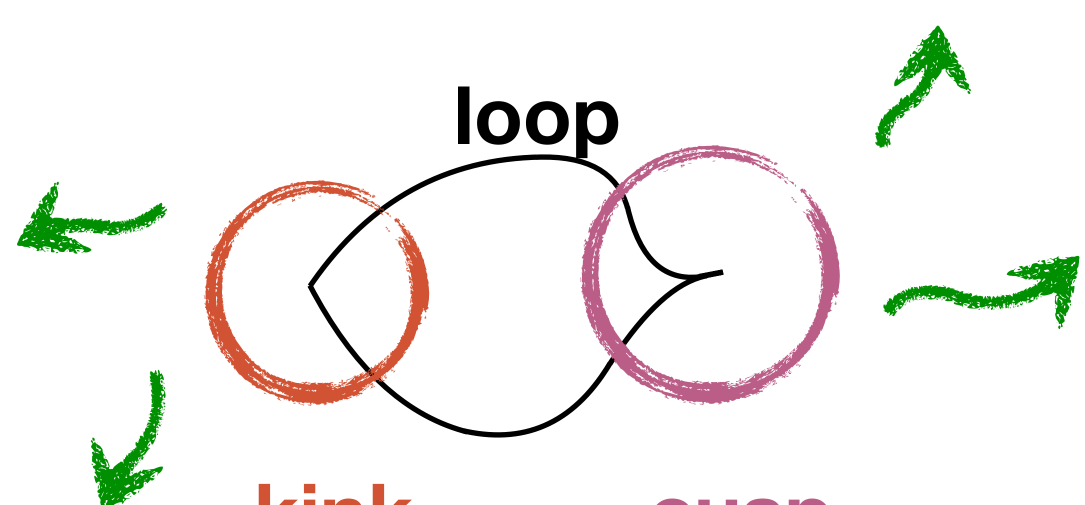


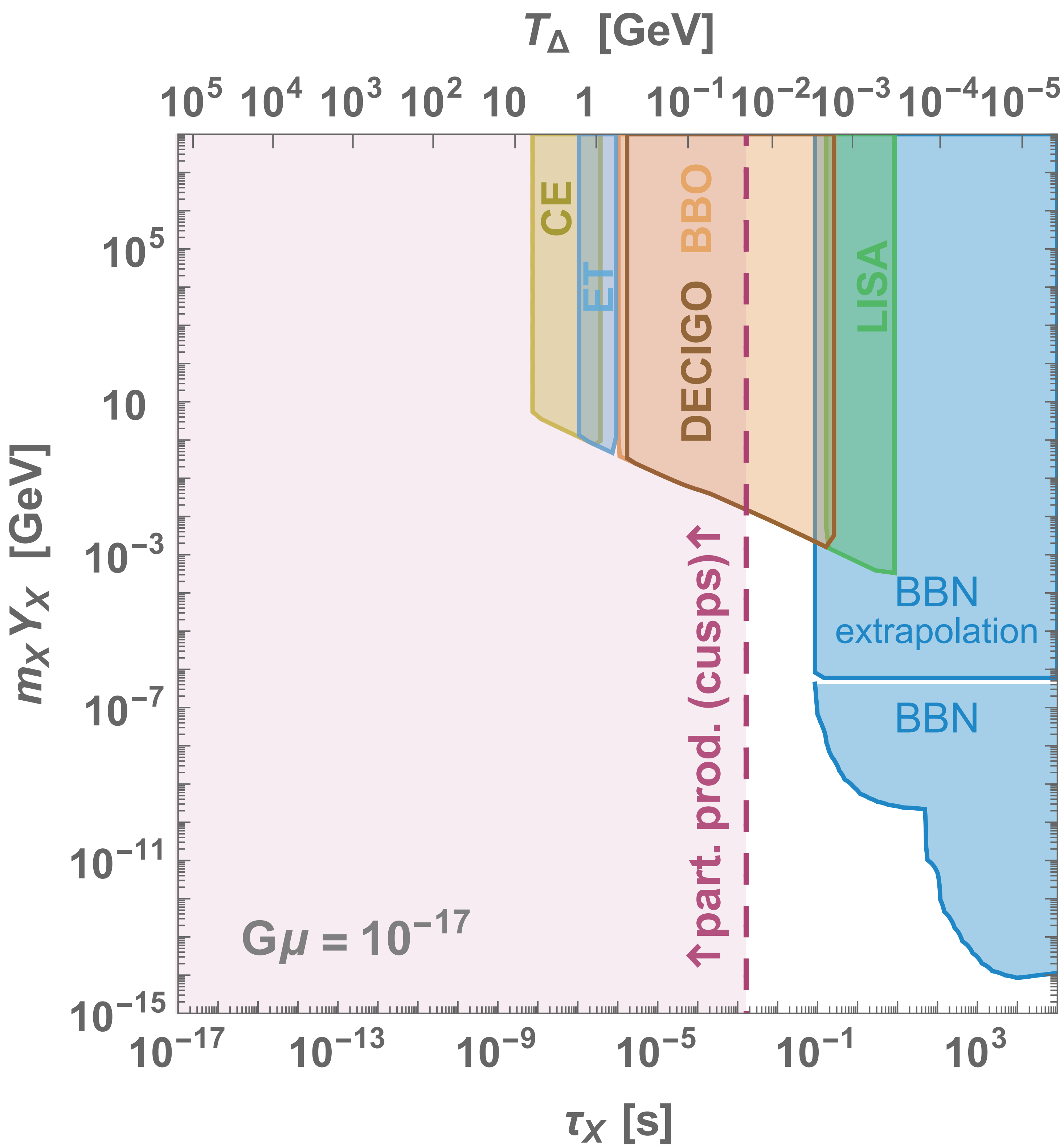

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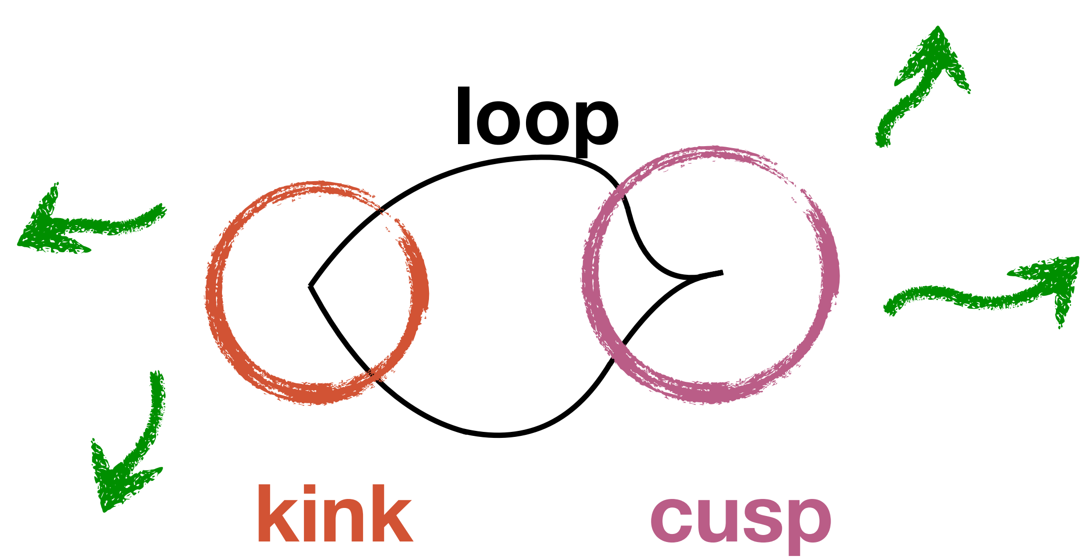


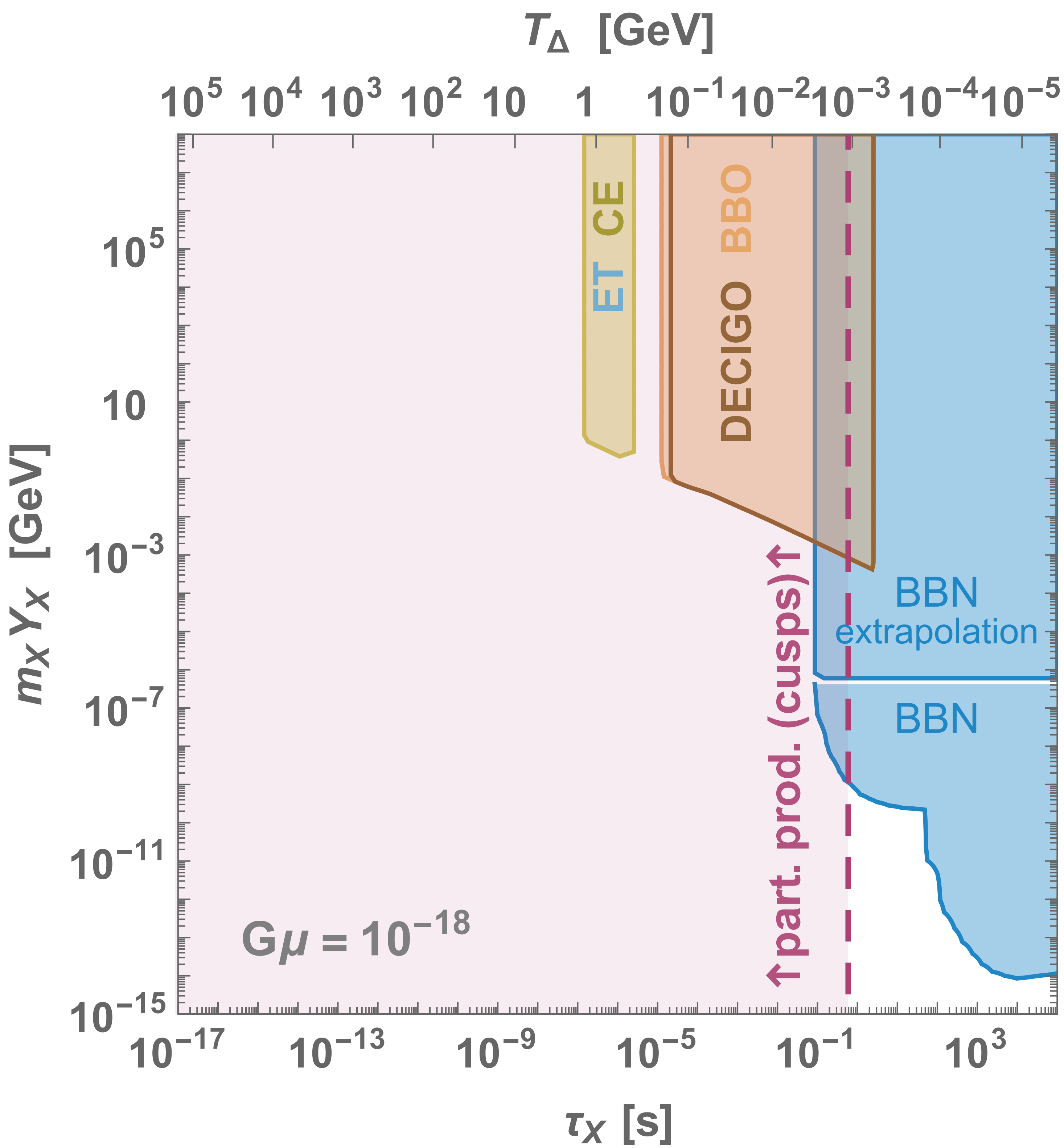

# 1) Planck-suppressed decay

**Planck-suppressed interactions**

$$\tau_X \simeq \frac{c}{8\pi}\frac{m_X^3}{M_{\rm pl}^2}$$

**Ex 1: scalar oscillating moduli**

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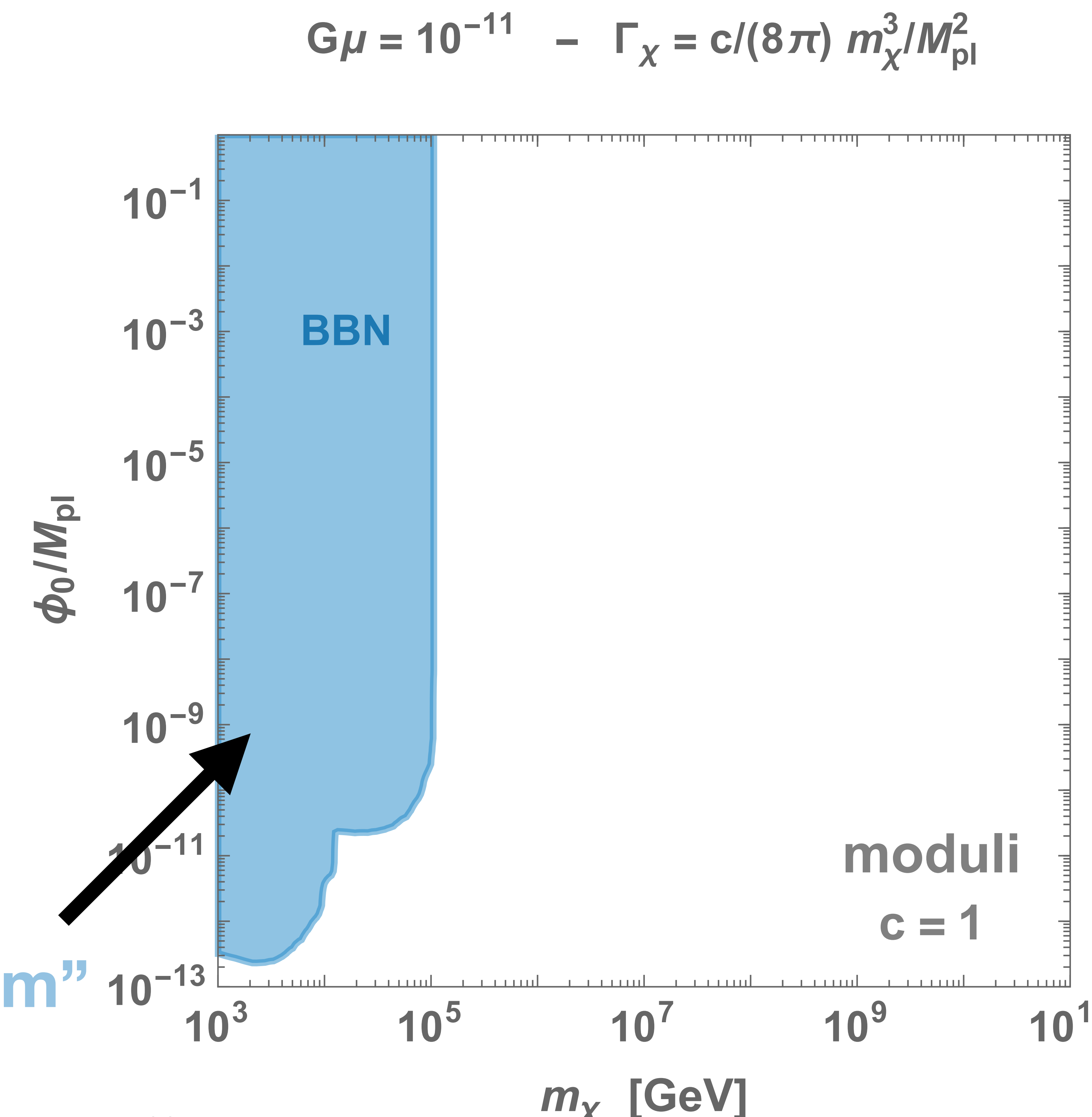


"Moduli problem"

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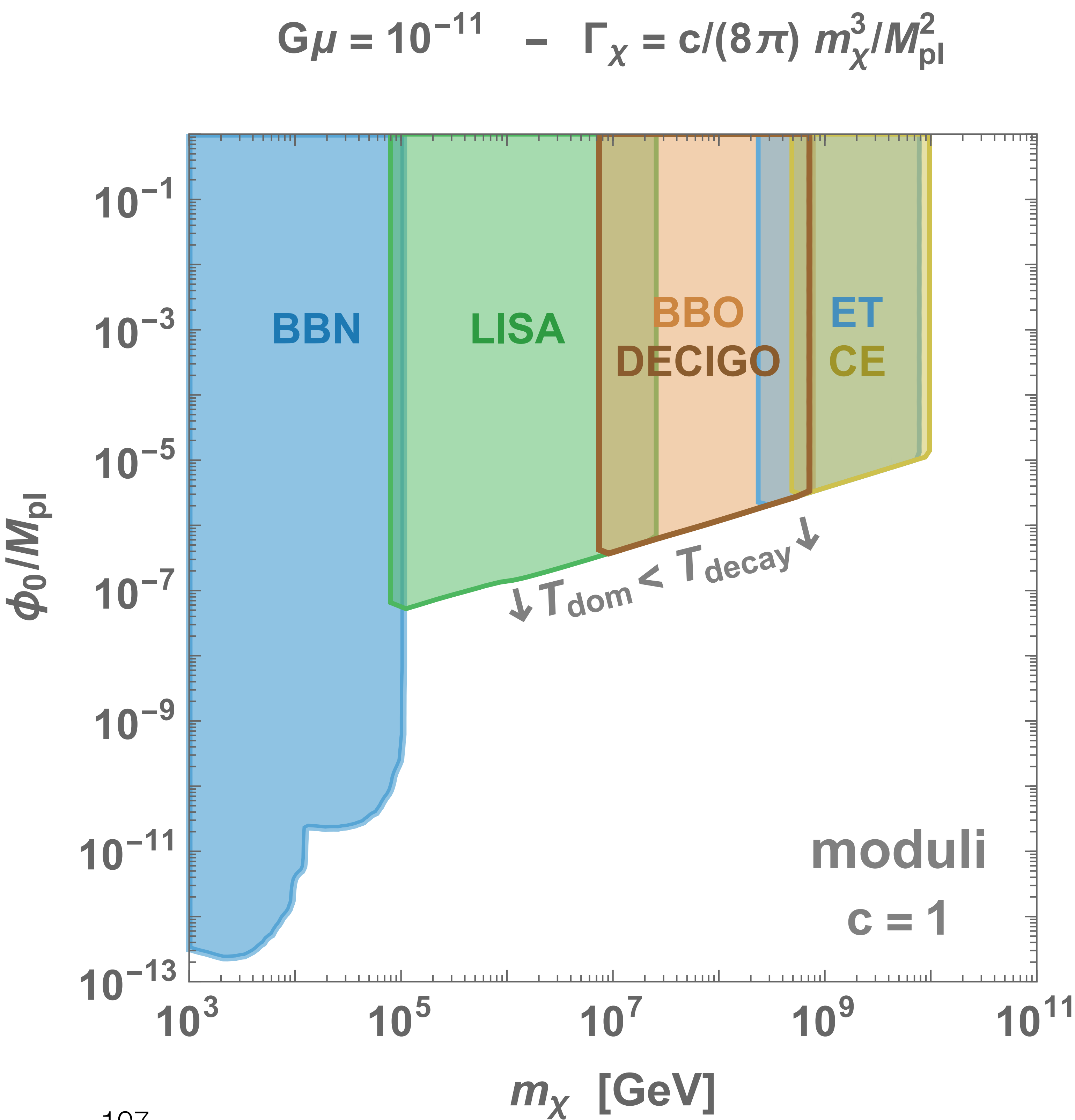

# Probe superstring theories up to $10^{10}$ GeV!

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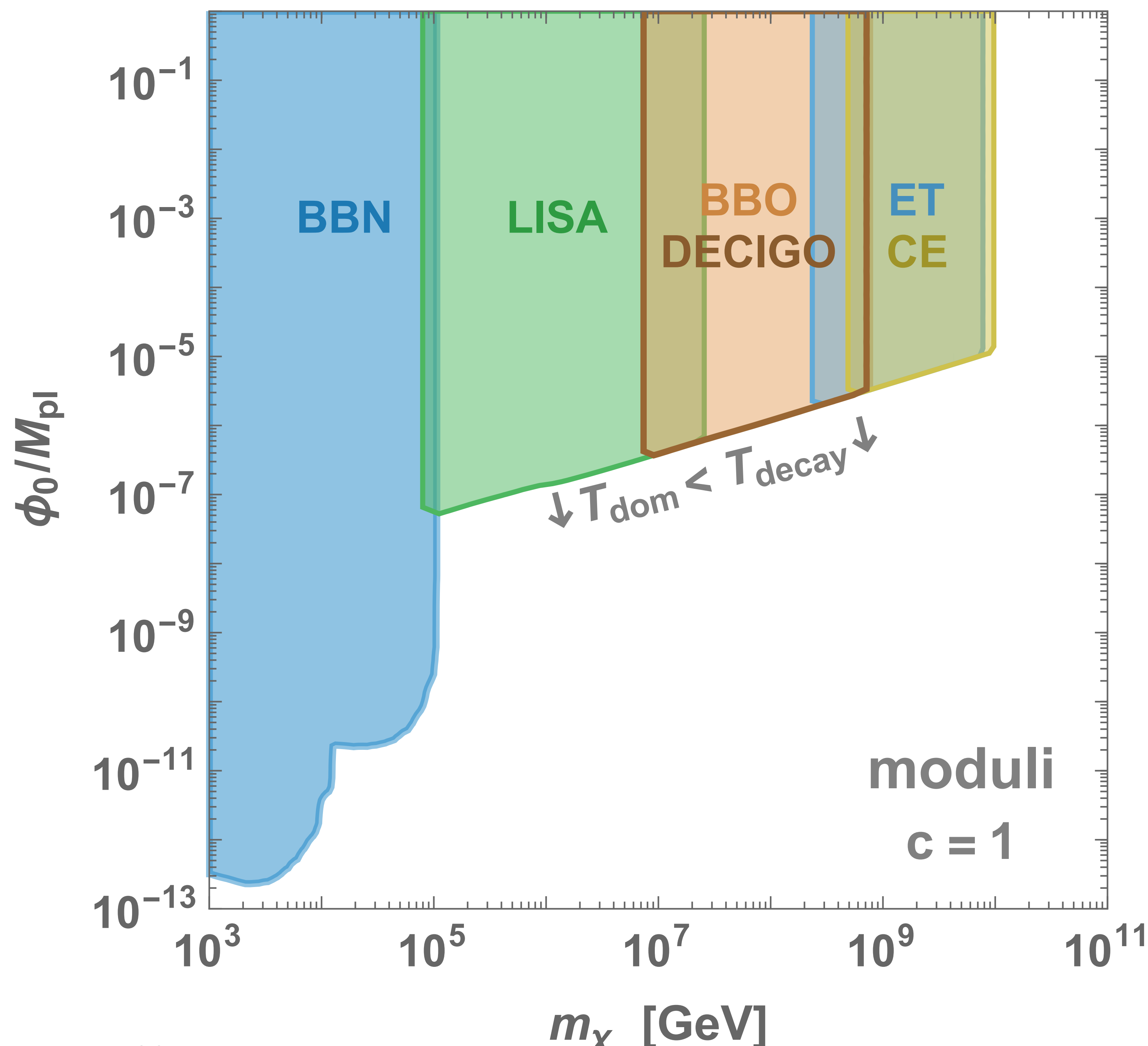

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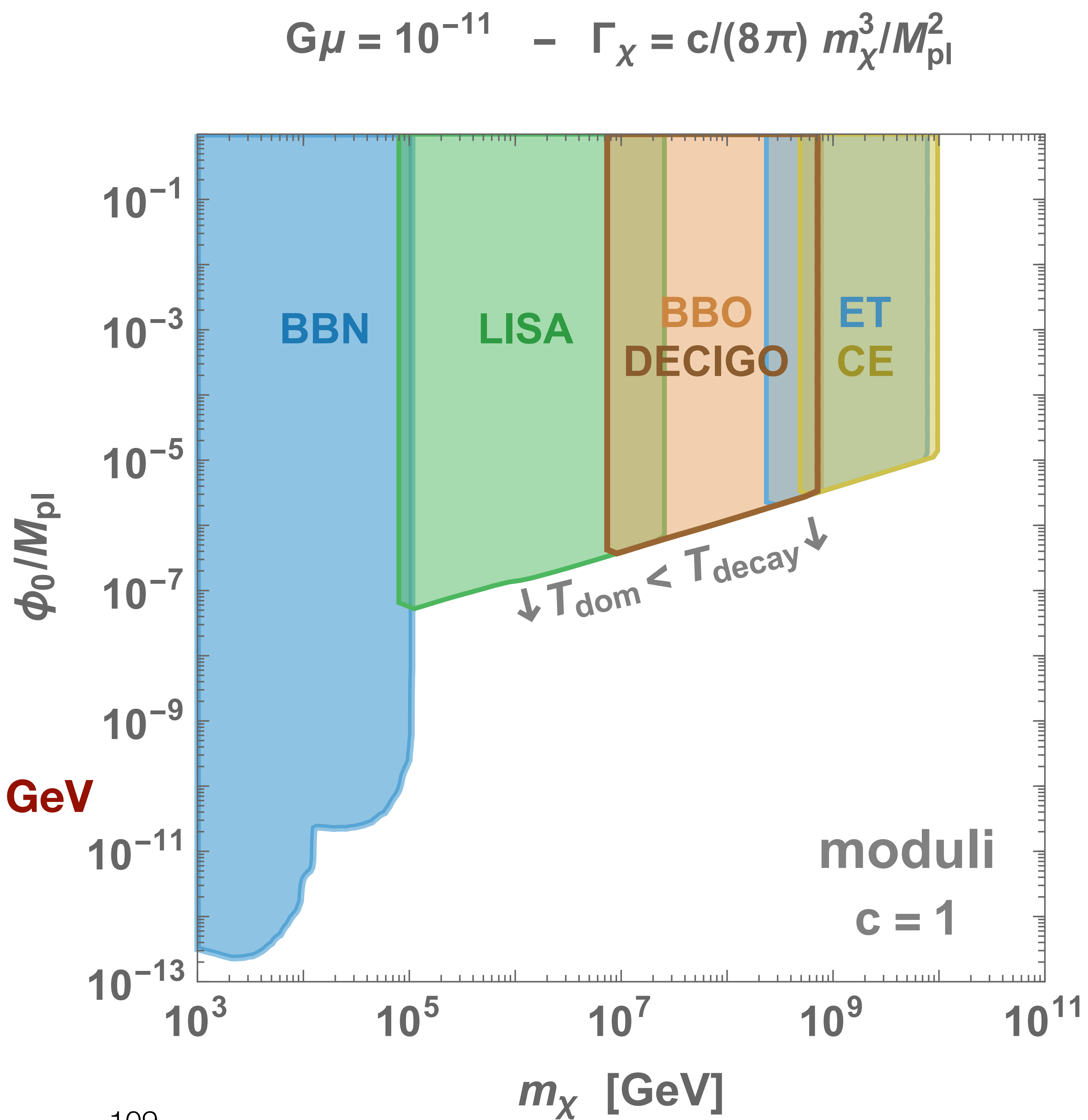

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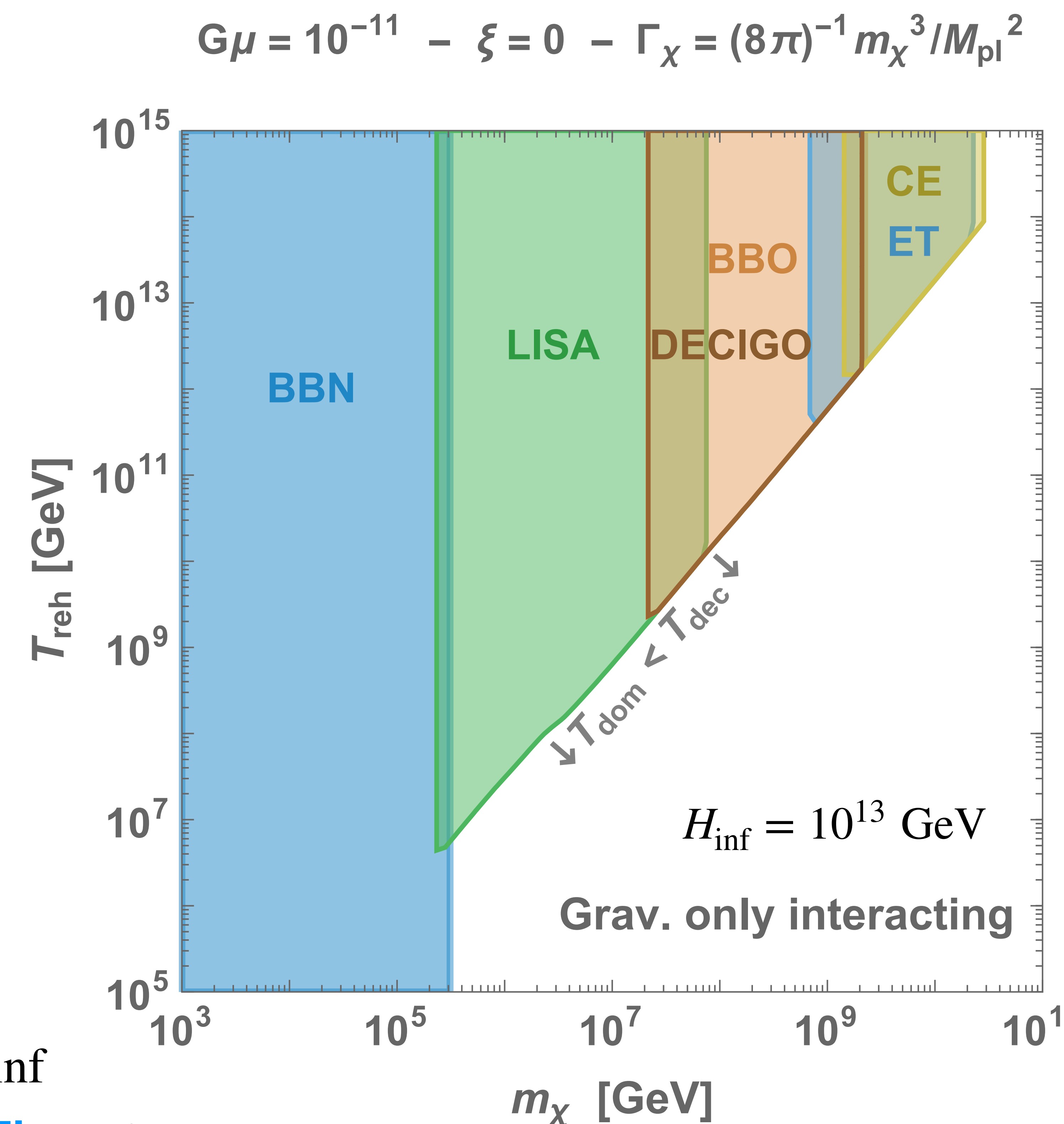
**Ex 2: gravitationally-only interacting scalar**

$$\rho_X \simeq H_{\rm reh}^2 H_{\rm inf}^2 \quad if \quad m_X \leq H_{\rm inf}$$

Kolb, Long 17'



# 2) Dark photon $U(1)_D$

- **Massive dark photon**
  **+**
  **Kinetic mixing**

$$\mathscr{L} \supset \epsilon F_Y F_D$$

- **Width**

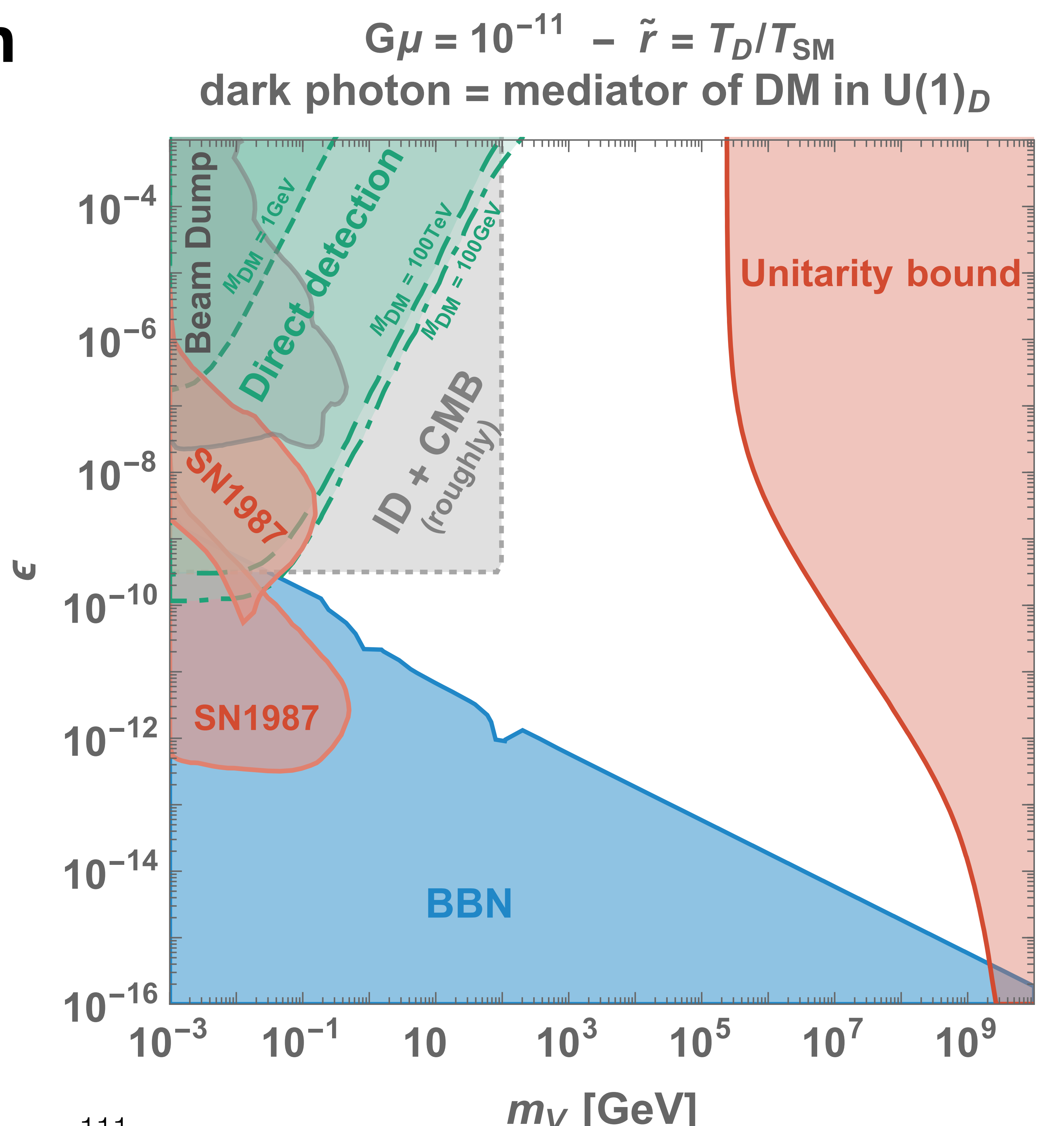
$$\Gamma_V \sim \epsilon \, m_V$$

- **DM mediator**

- **Entropy injection**

Berlin, Hooper, Krnjaic 16'

Cirelli, YG, Petraki, Sala 18'



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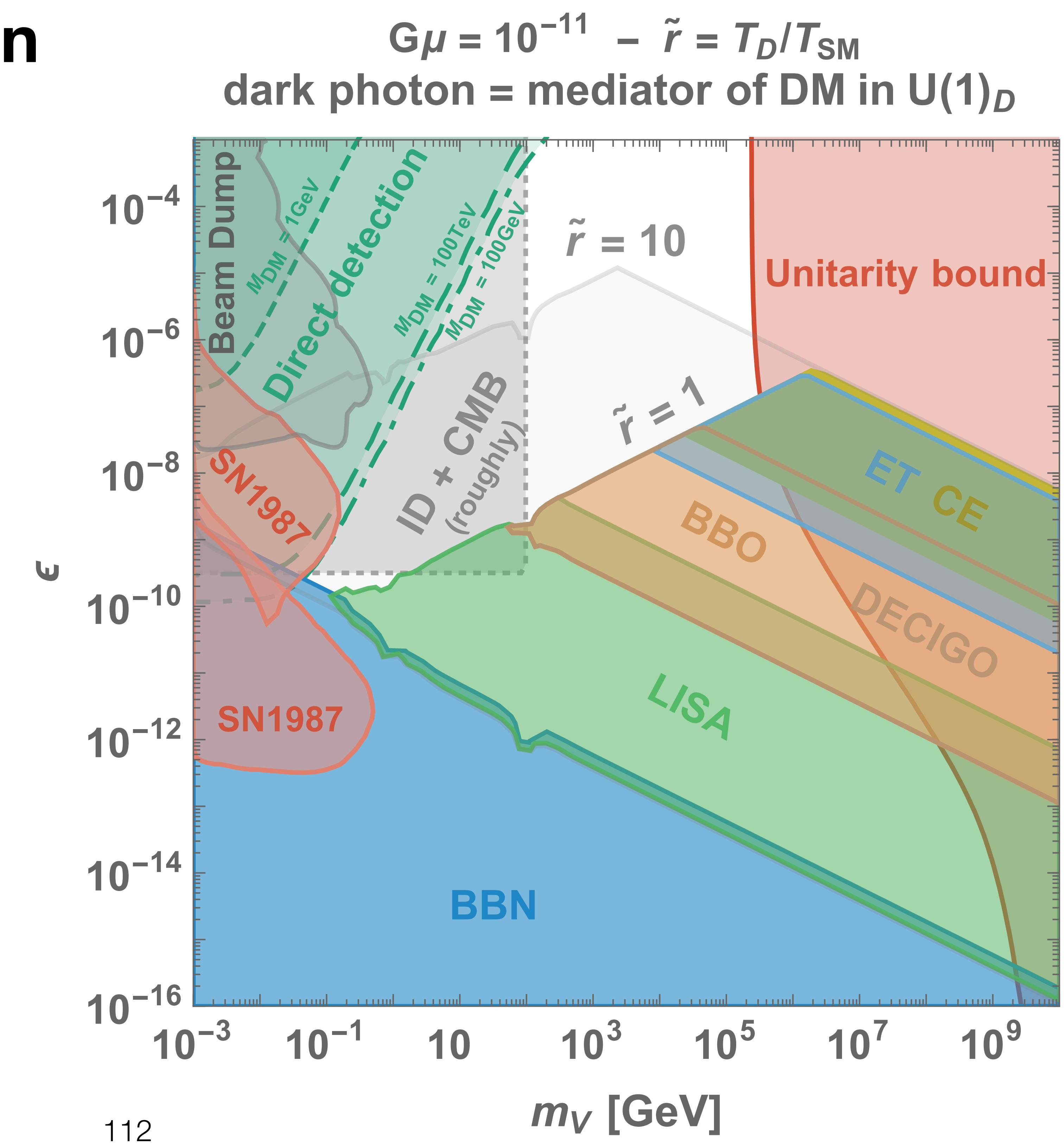

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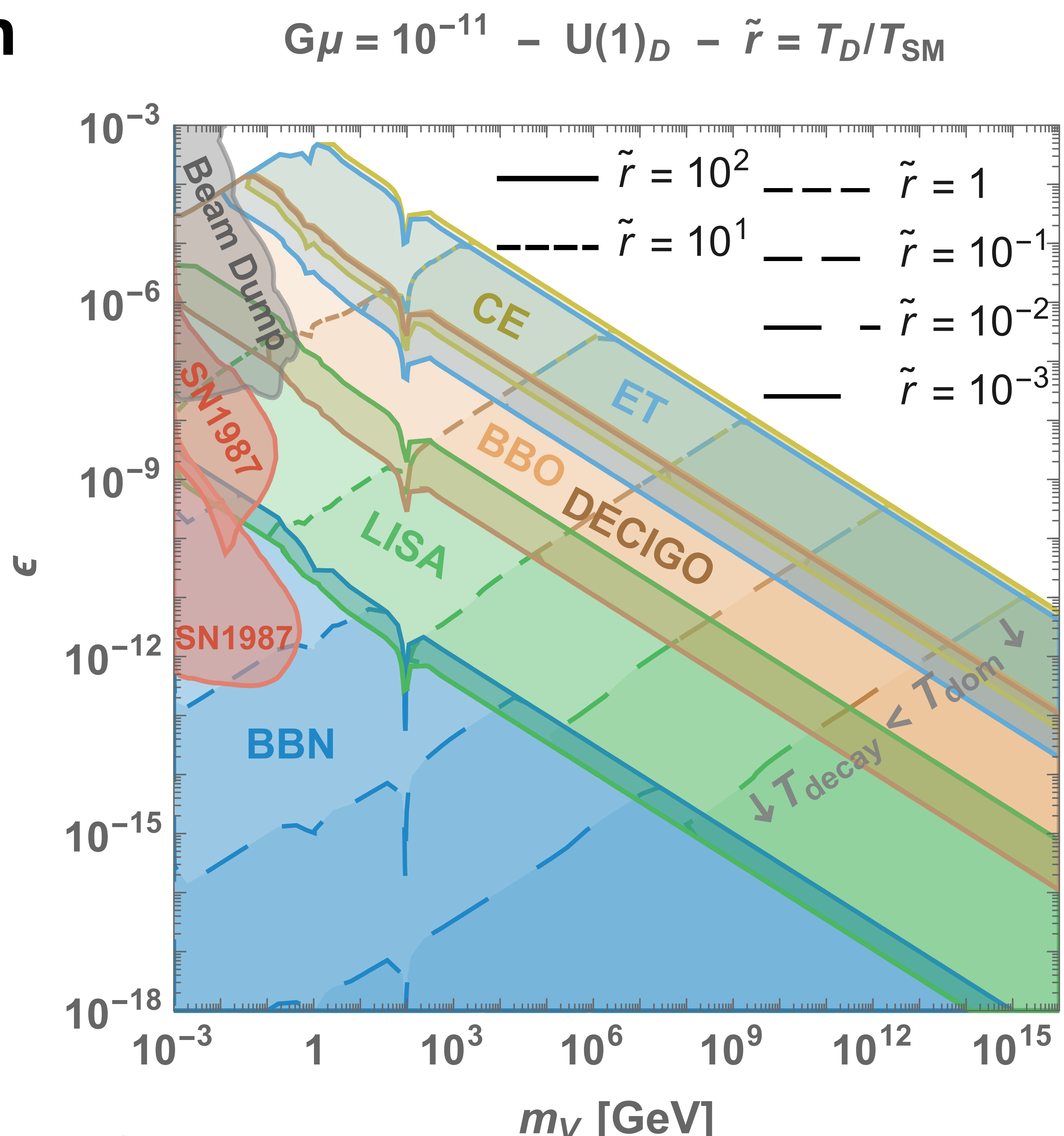
**Abundance fixed by**

$$r \equiv \frac{T_D}{T_{SM}}$$



# 3) ALPs

→ **Assume thermal abundance**

→ **Decay rate**

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

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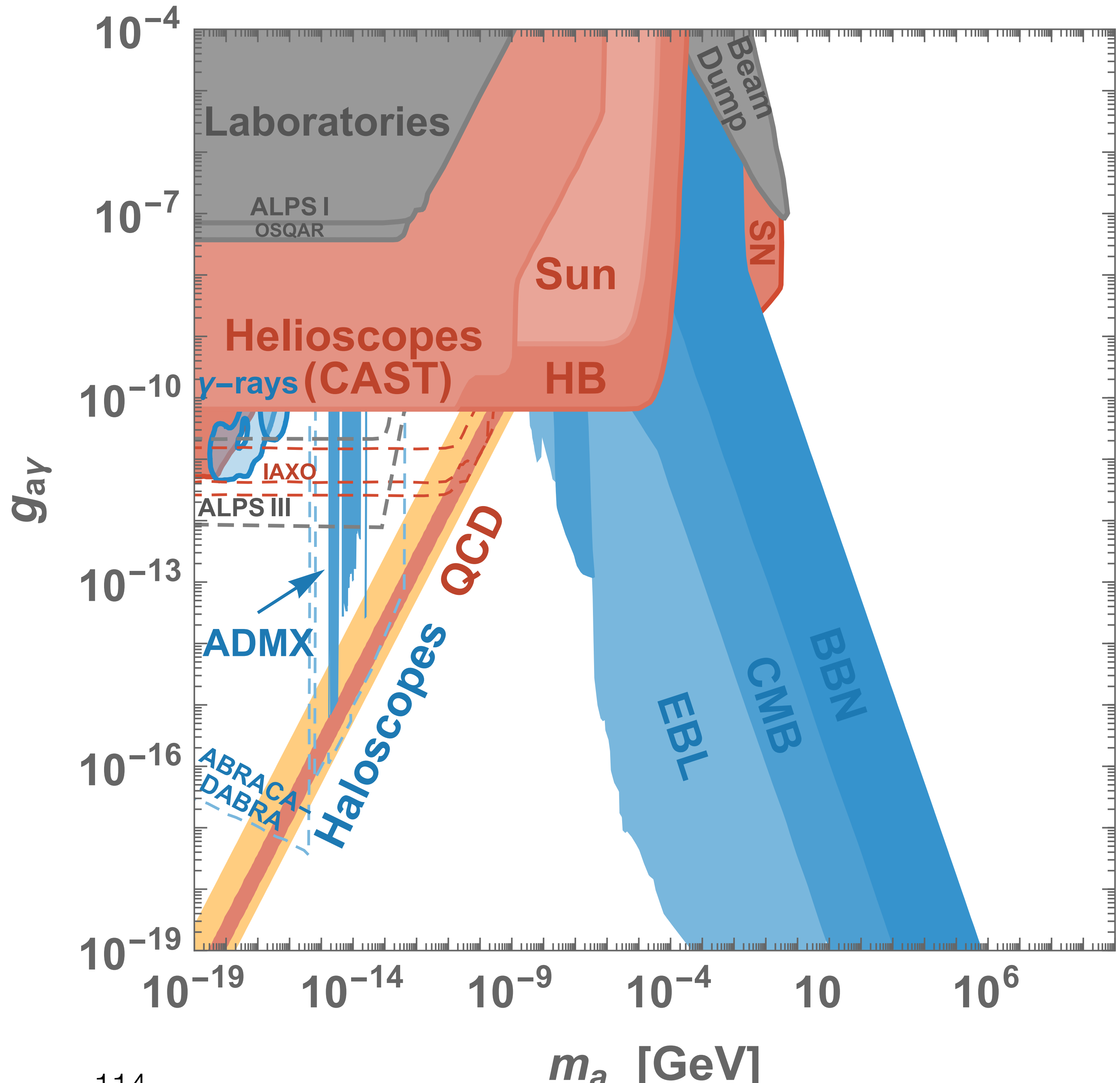

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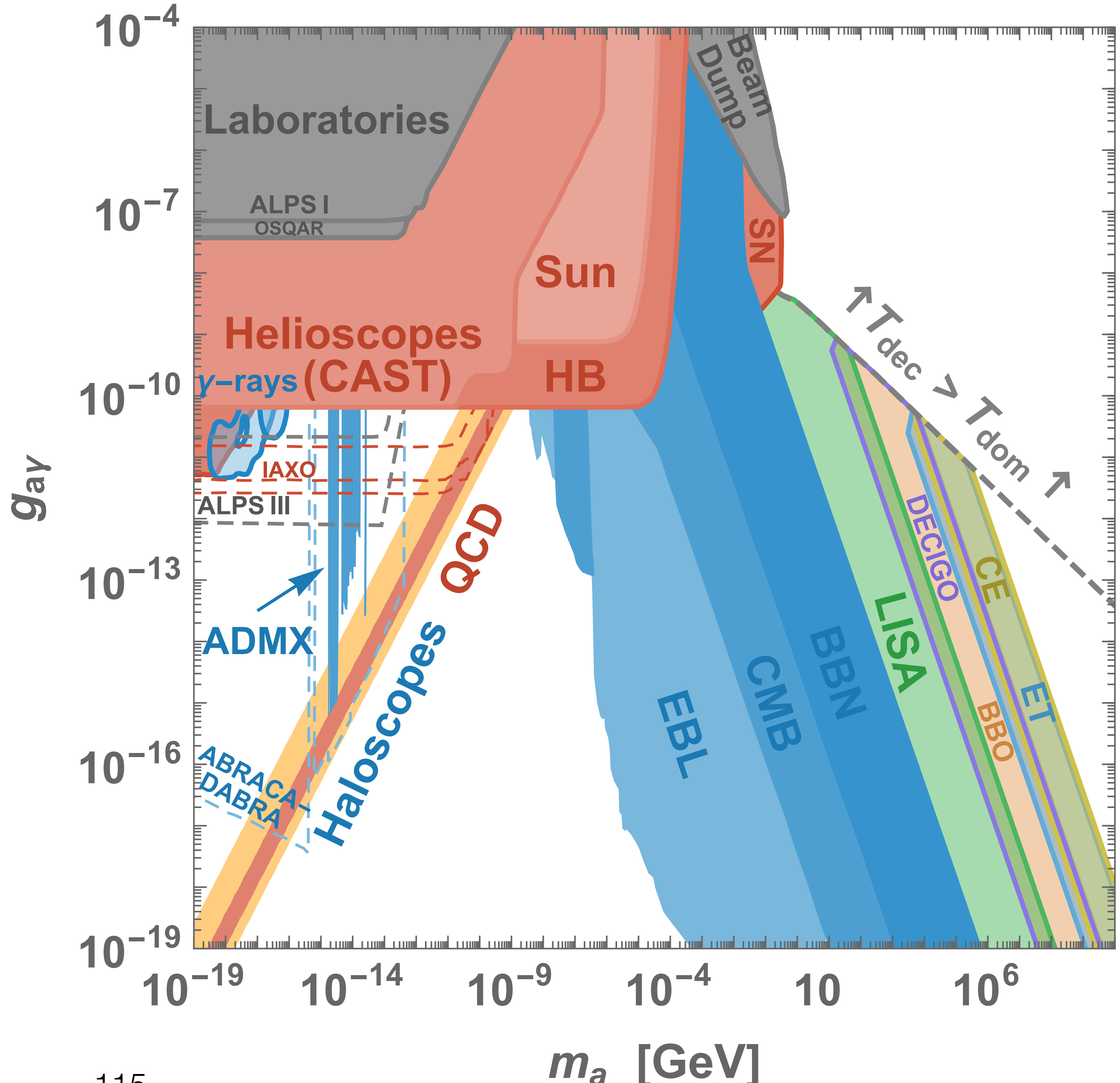
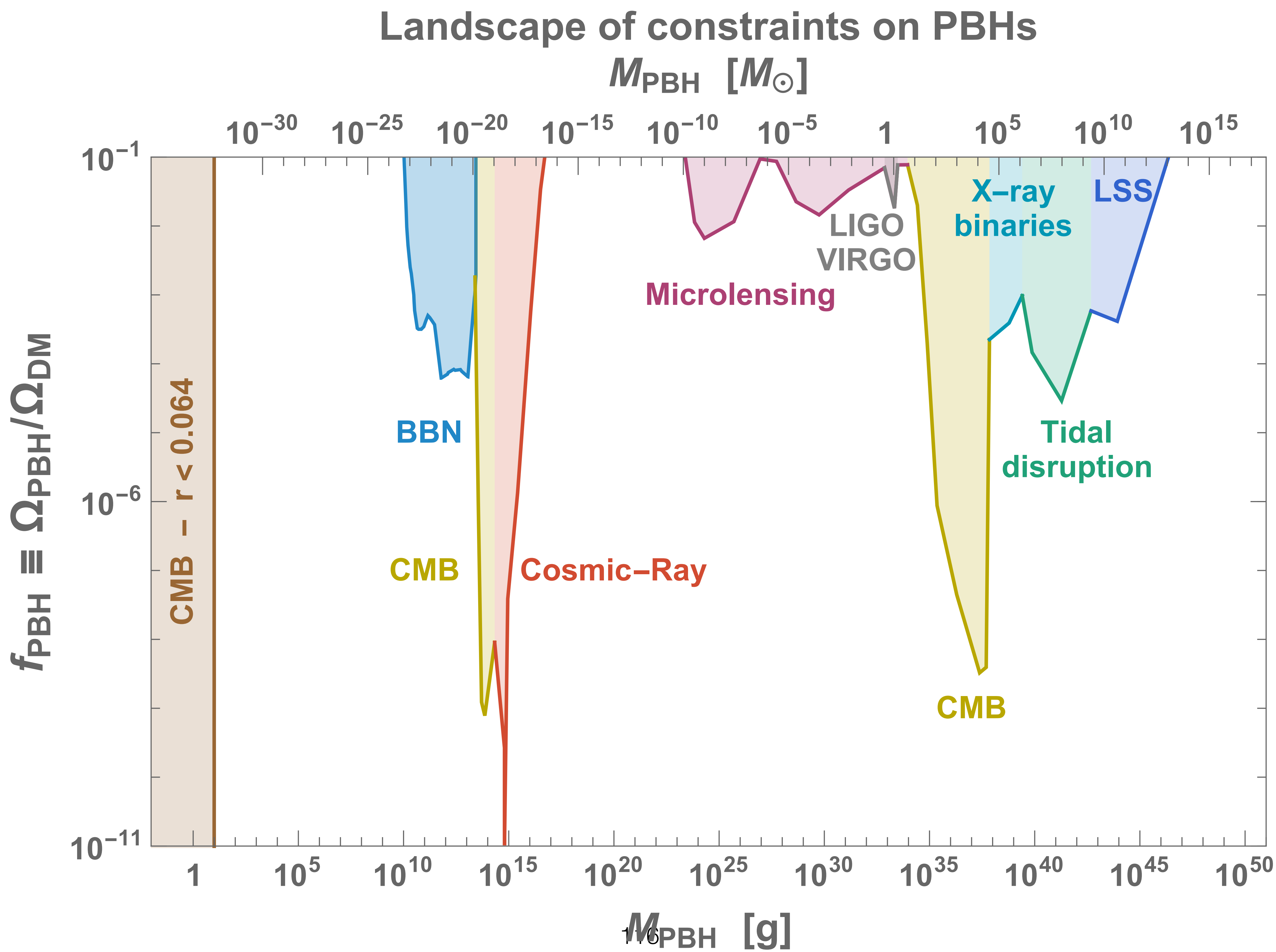
- **Reach**

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

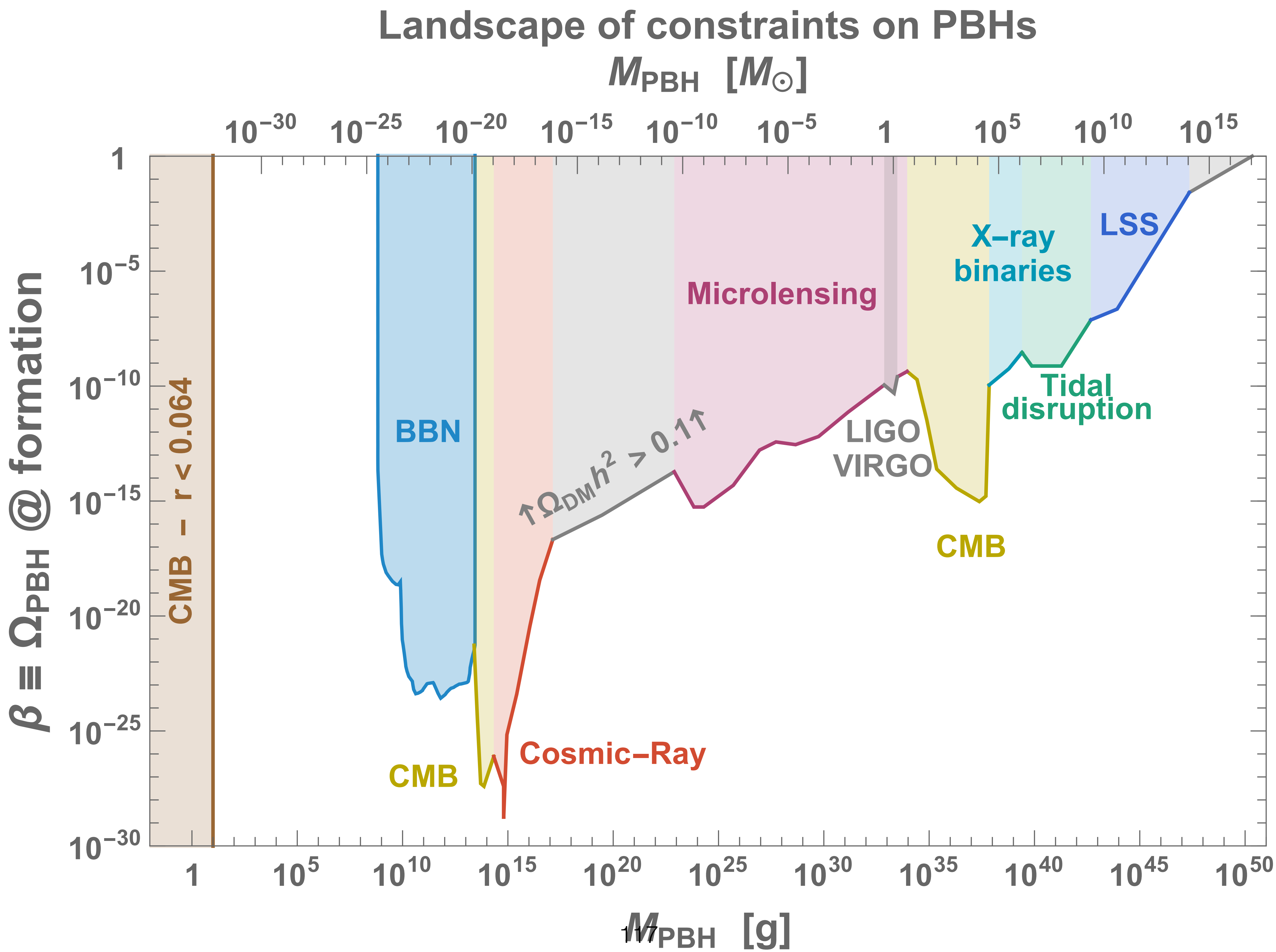


# 4) PBHs



Landscape of constraints on PBHs
M_PBH [M_⊙]
10^−30
10^−25
10^−20
10^−15
10^−10
10^−5
1
10^5
10^10
10^15
10^−1
10^−6
10^−11
f_PBH ≡ Ω_PBH/Ω_DM
CMB – r < 0.064
BBN
CMB
Cosmic–Ray
Microlensing
LIGO
VIRGO
X–ray
binaries
LSS
Tidal
disruption
CMB
1
10^5
10^10
10^15
10^20
10^25
10^30
10^35
10^40
10^45
10^50
M_PBH [g]

# 4) PBHs



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$10^{-5}$
1
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$10^{10}$
$10^{15}$
$\beta \equiv \Omega_{PBH}$ @ formation
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$10^{-10}$
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CMB – r < 0.064
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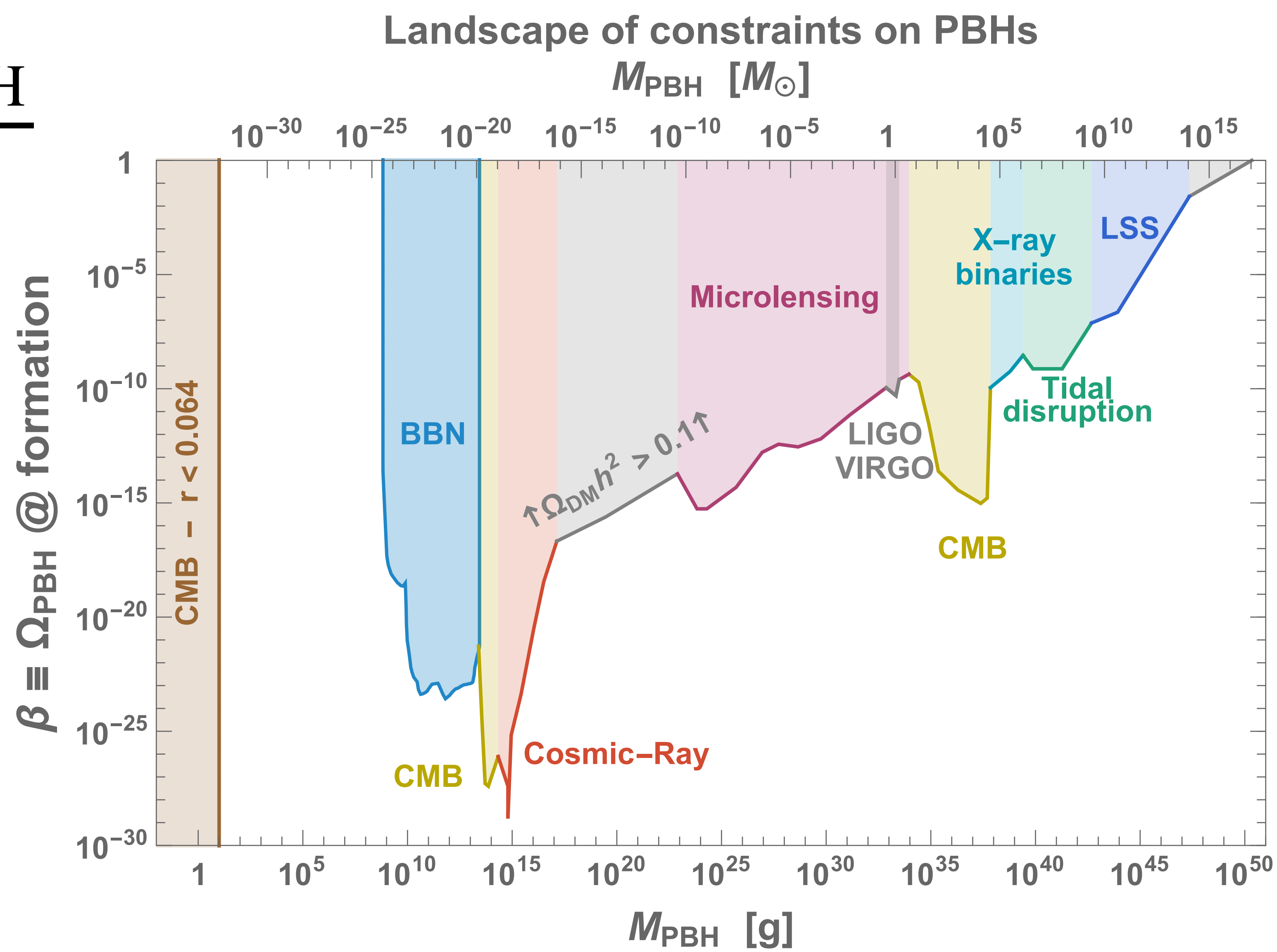
# 4) PBHs

**PBHs abundance**

$$\beta \equiv \frac{\rho_{\rm PBH}(t_i)}{\rho_{\rm tot}(t_i)} = \frac{4M_{\rm PBH}}{T_i}\frac{n_{\rm PBH}}{s}$$



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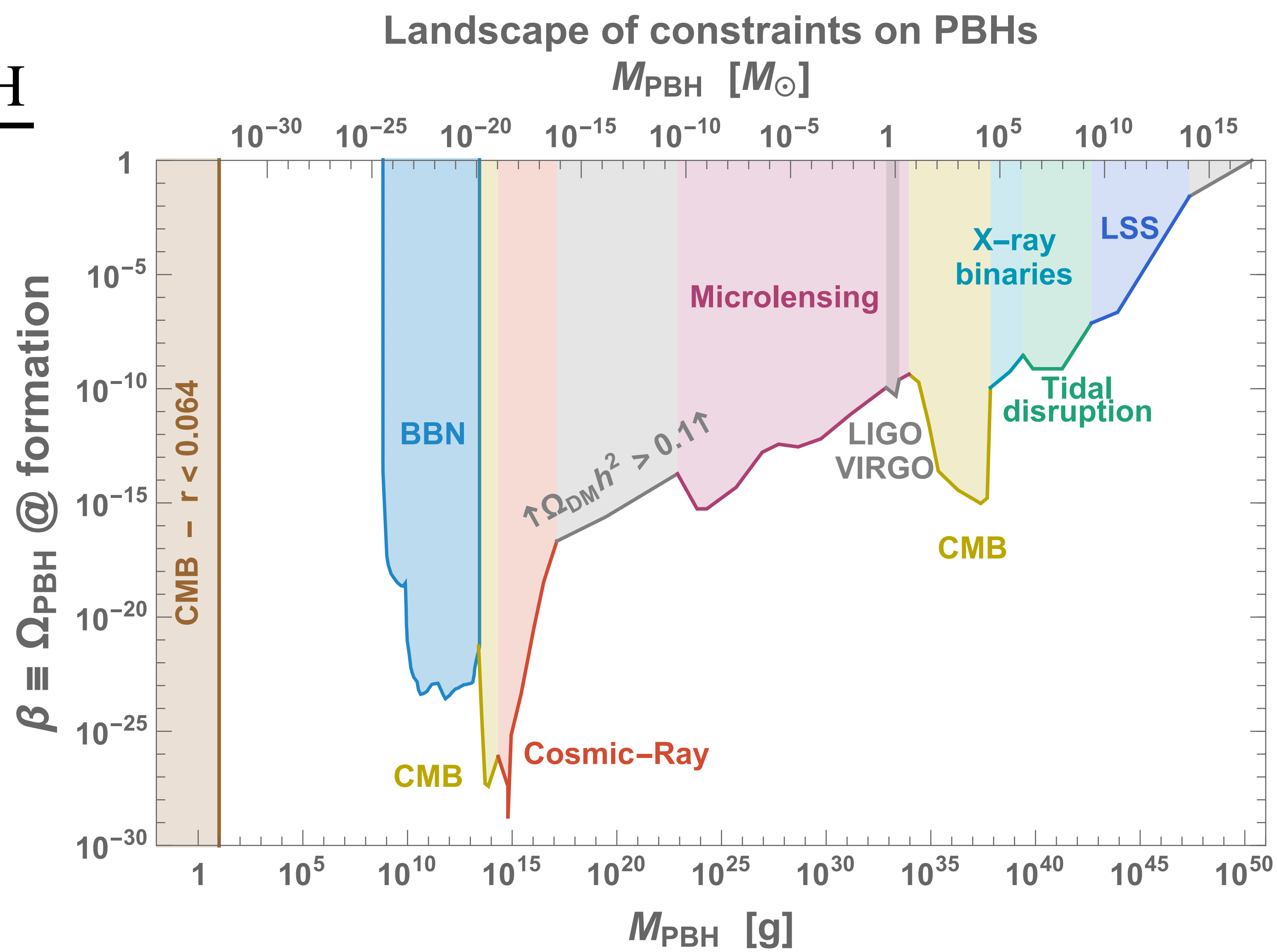

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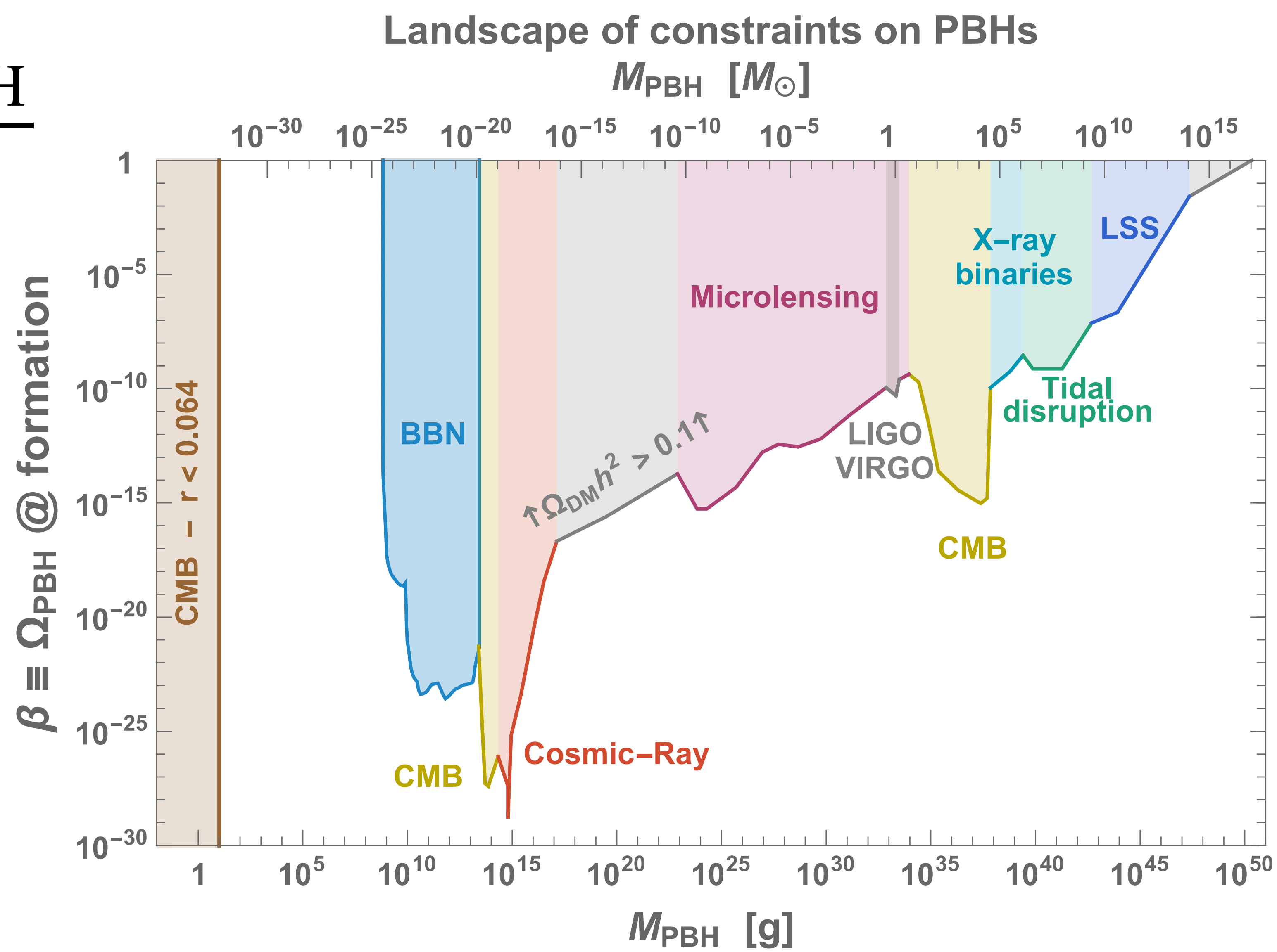


## Lifetime

$$\tau_{\rm PBH} \sim 10^{64}\left(\frac{M}{M_{\rm sun}}\right)^3 \ \text{yr}$$

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**Lifetime**

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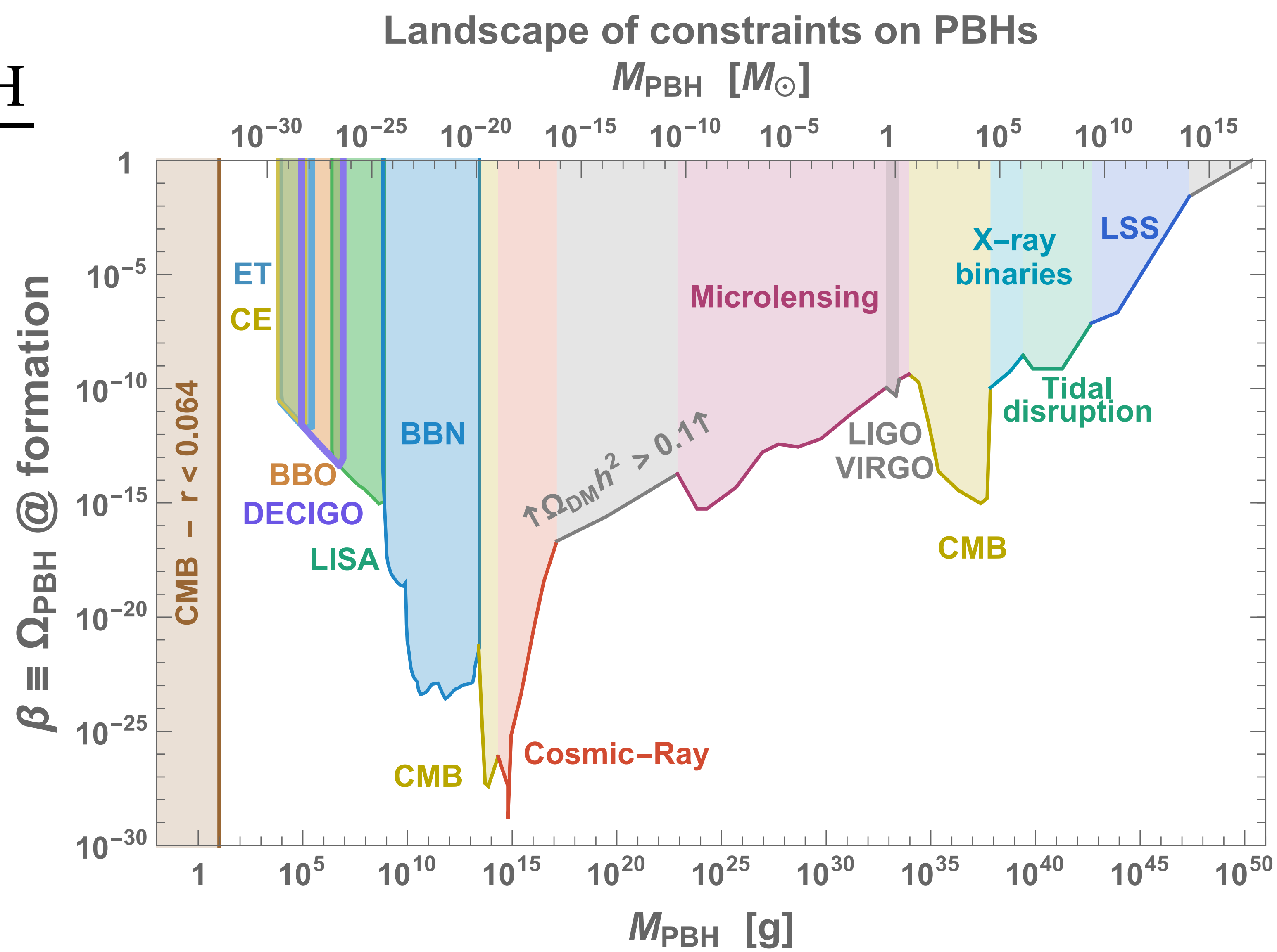
**Reach**

$$10^3 \ g \lesssim M_{\rm PBH} \lesssim 10^9 \ g$$



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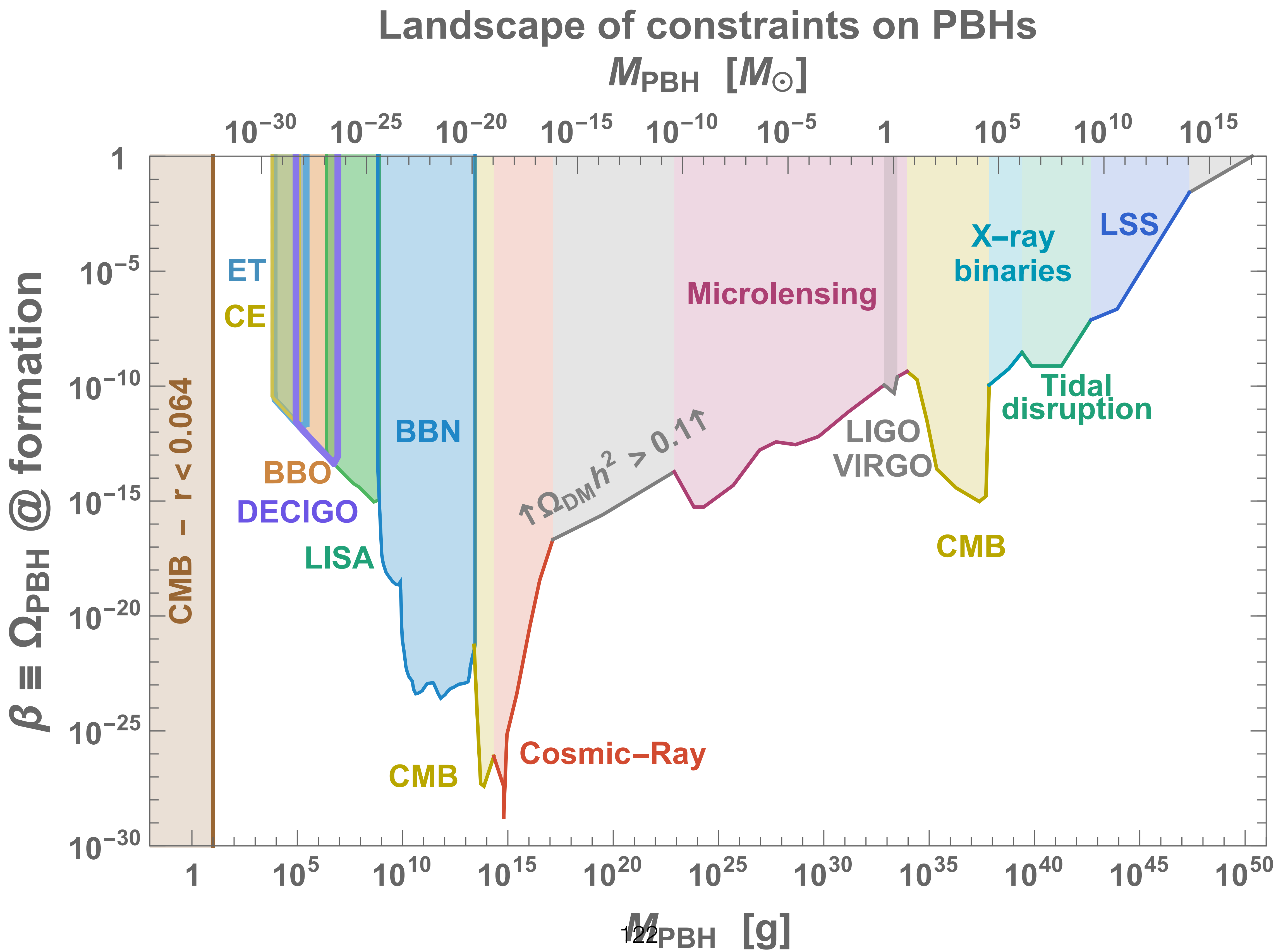

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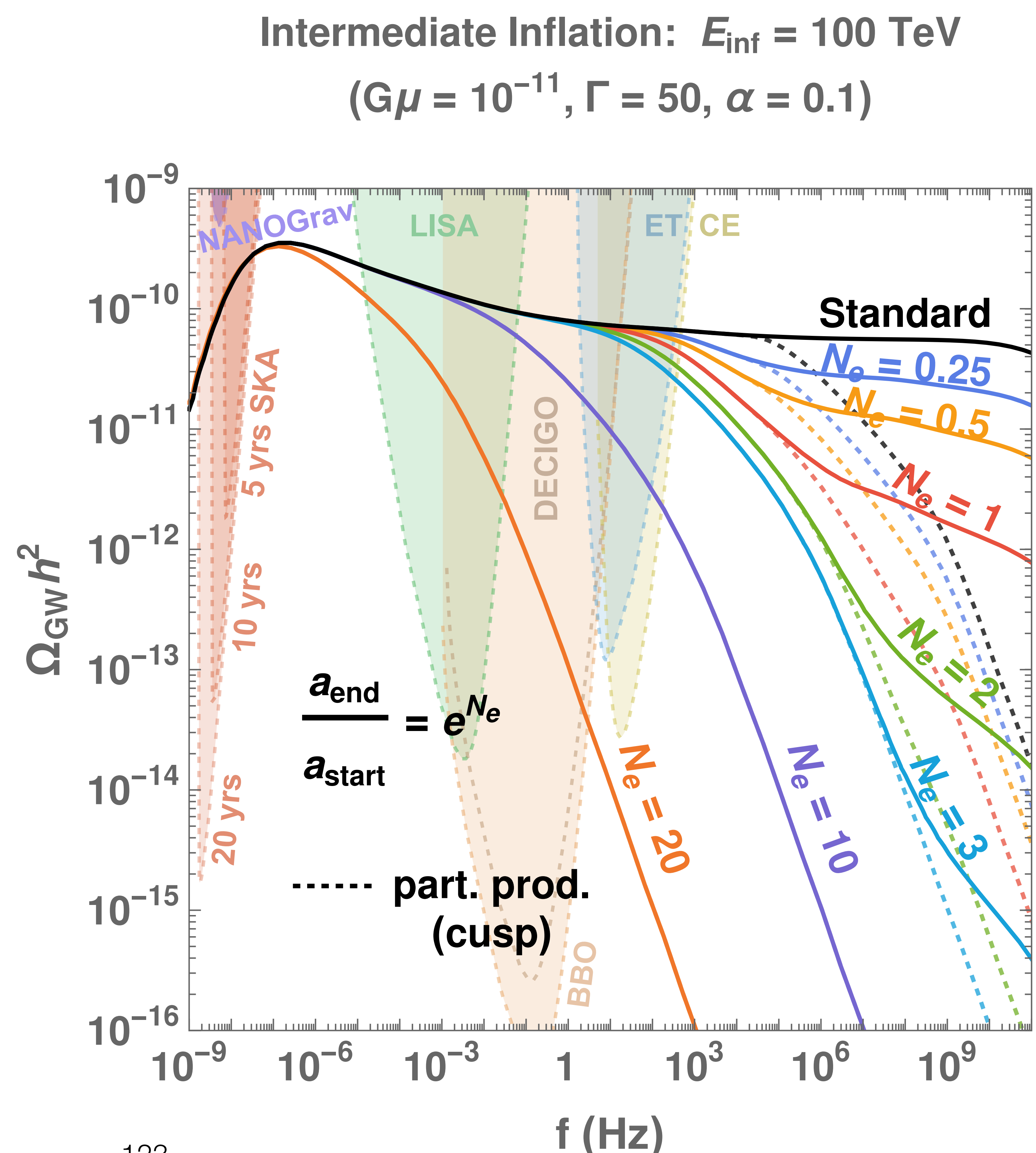
# Intermediate inflation era

**e.g. supercooled 1st order phase transition**



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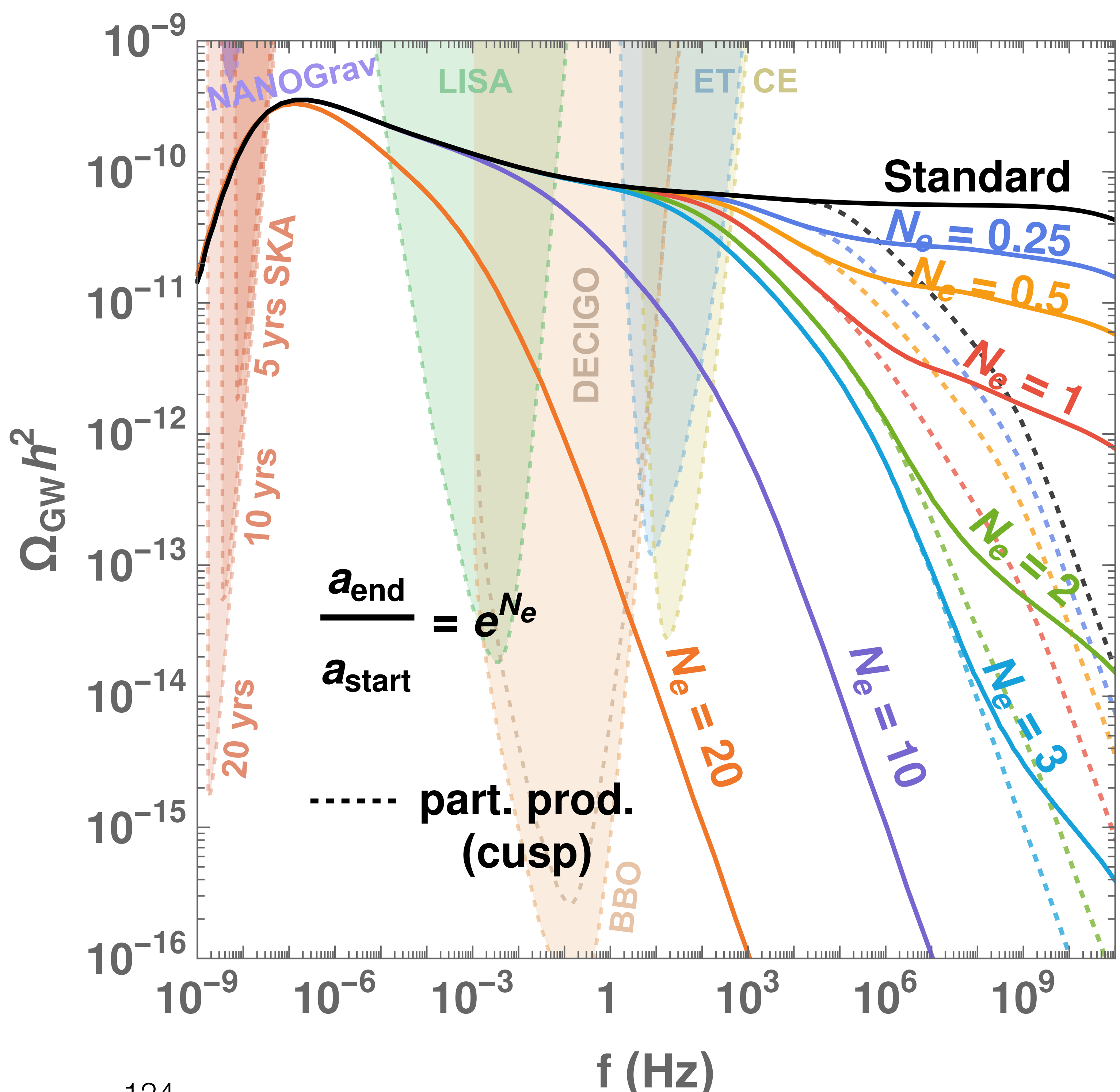

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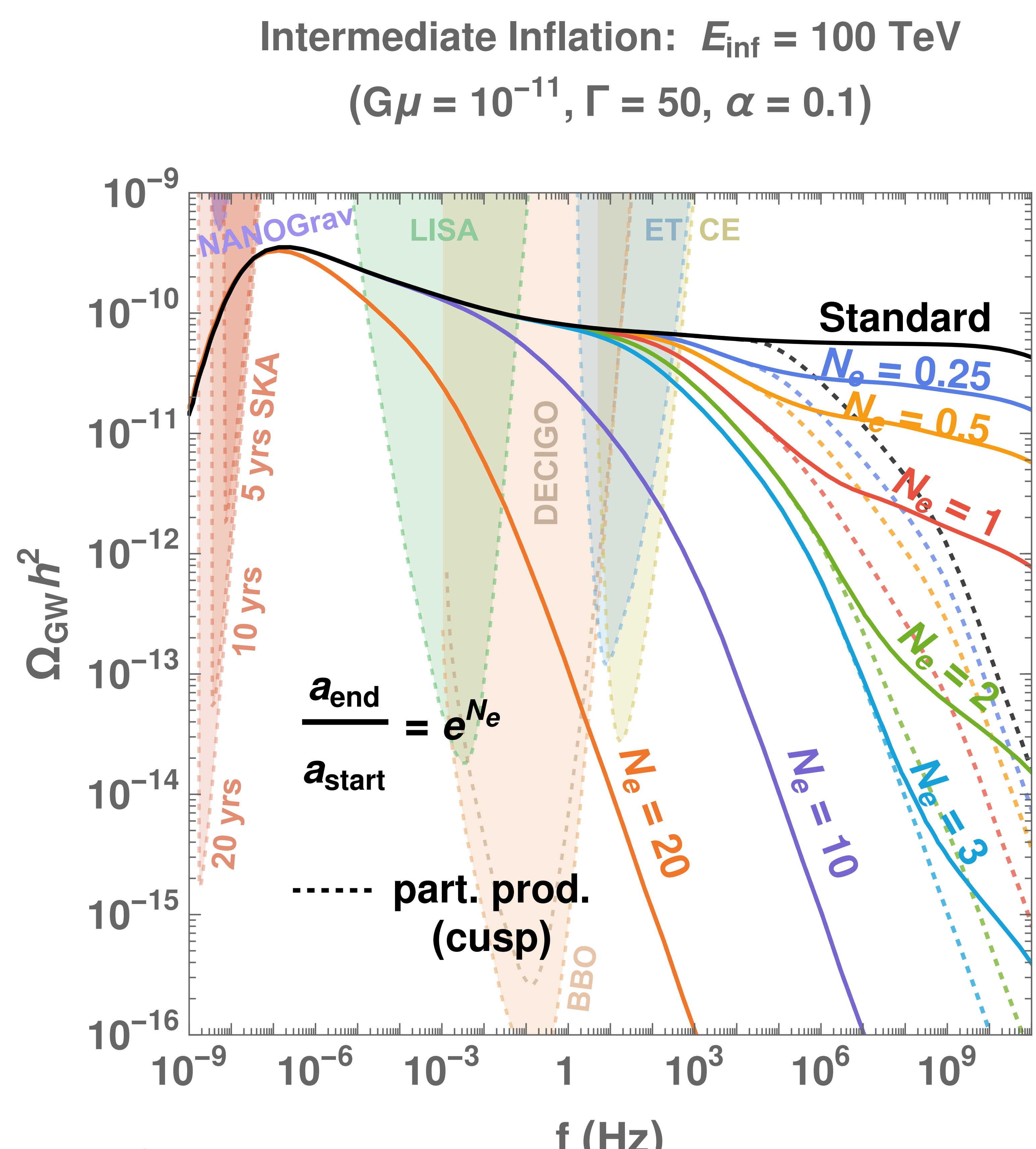

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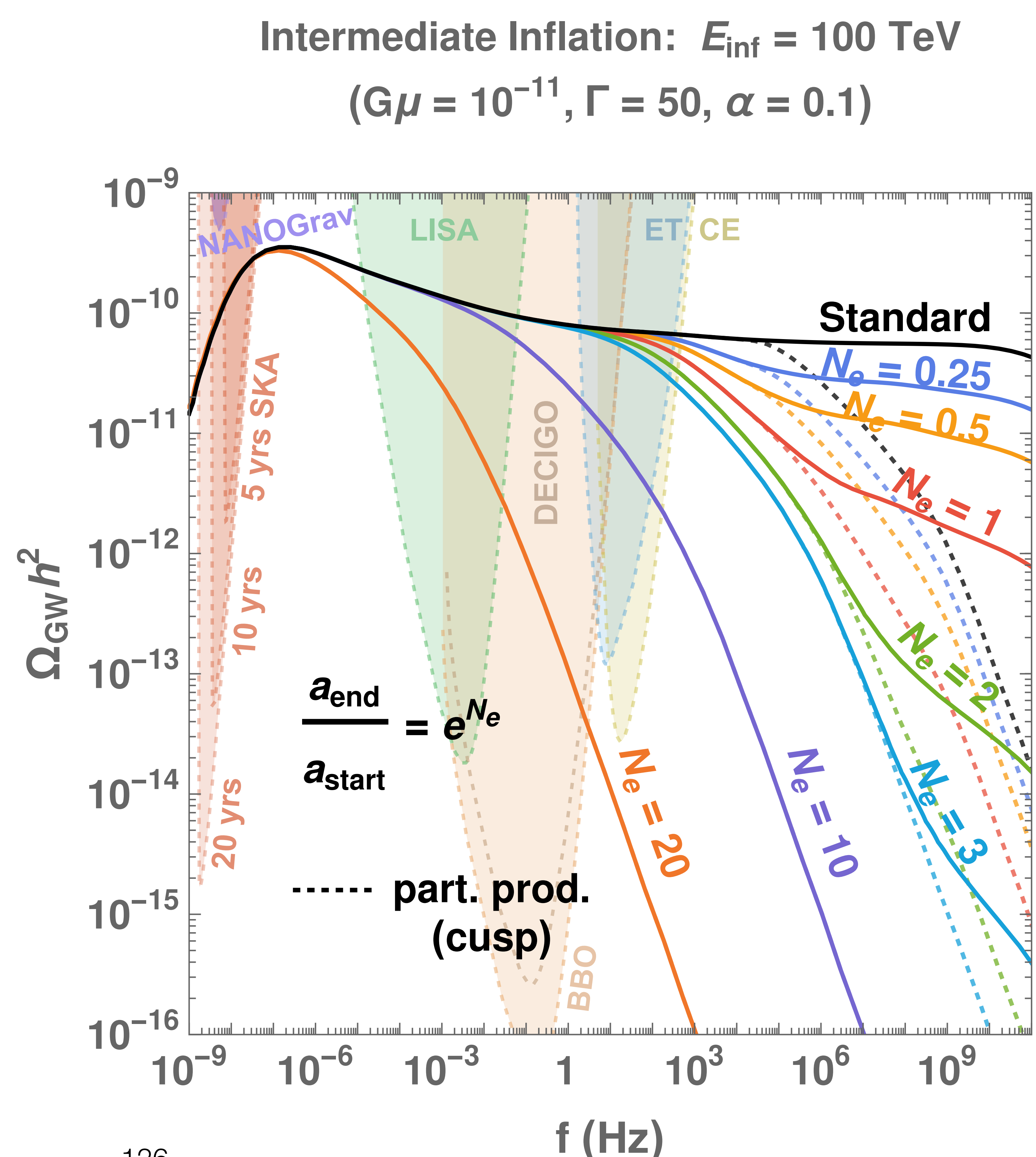

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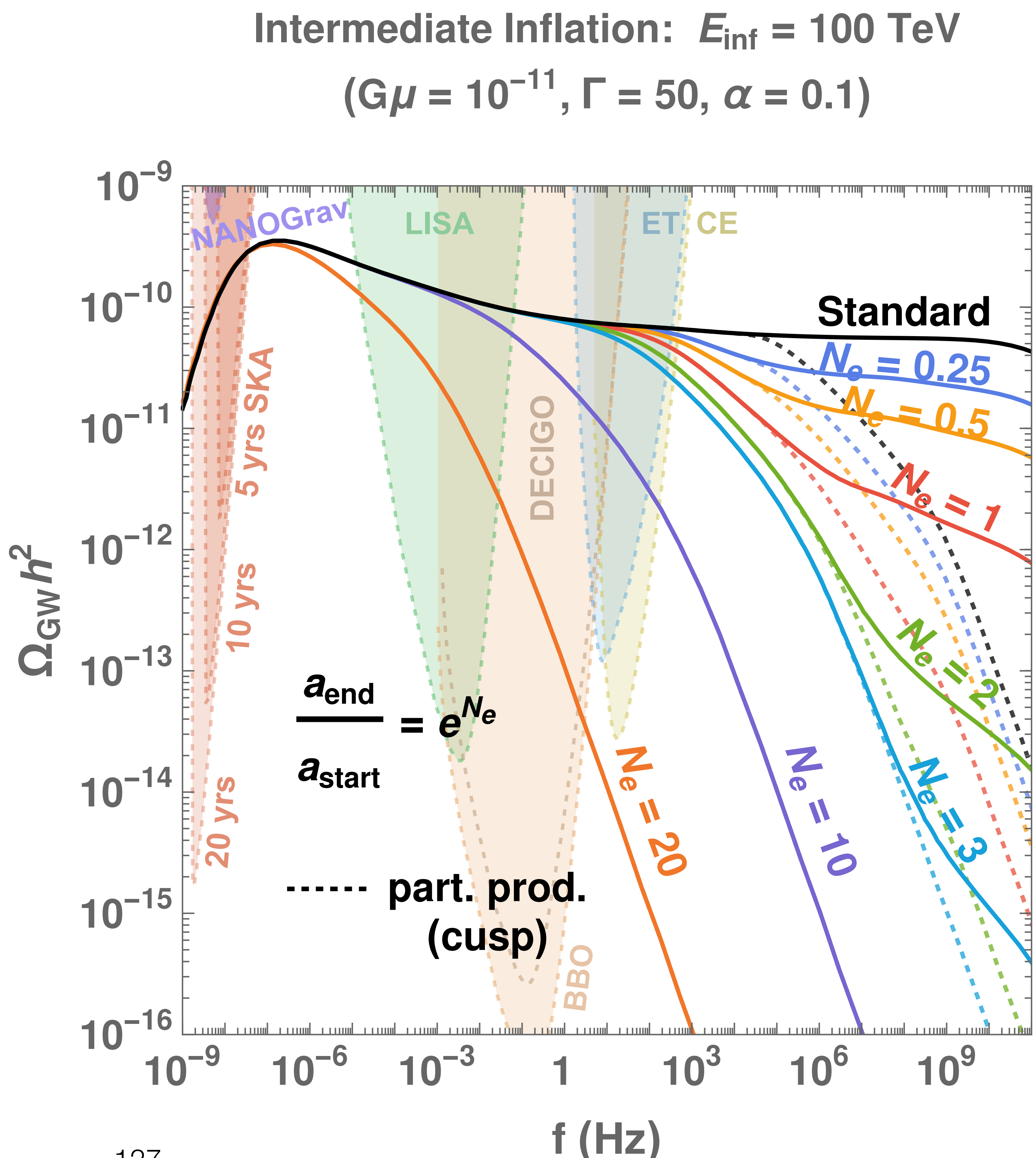

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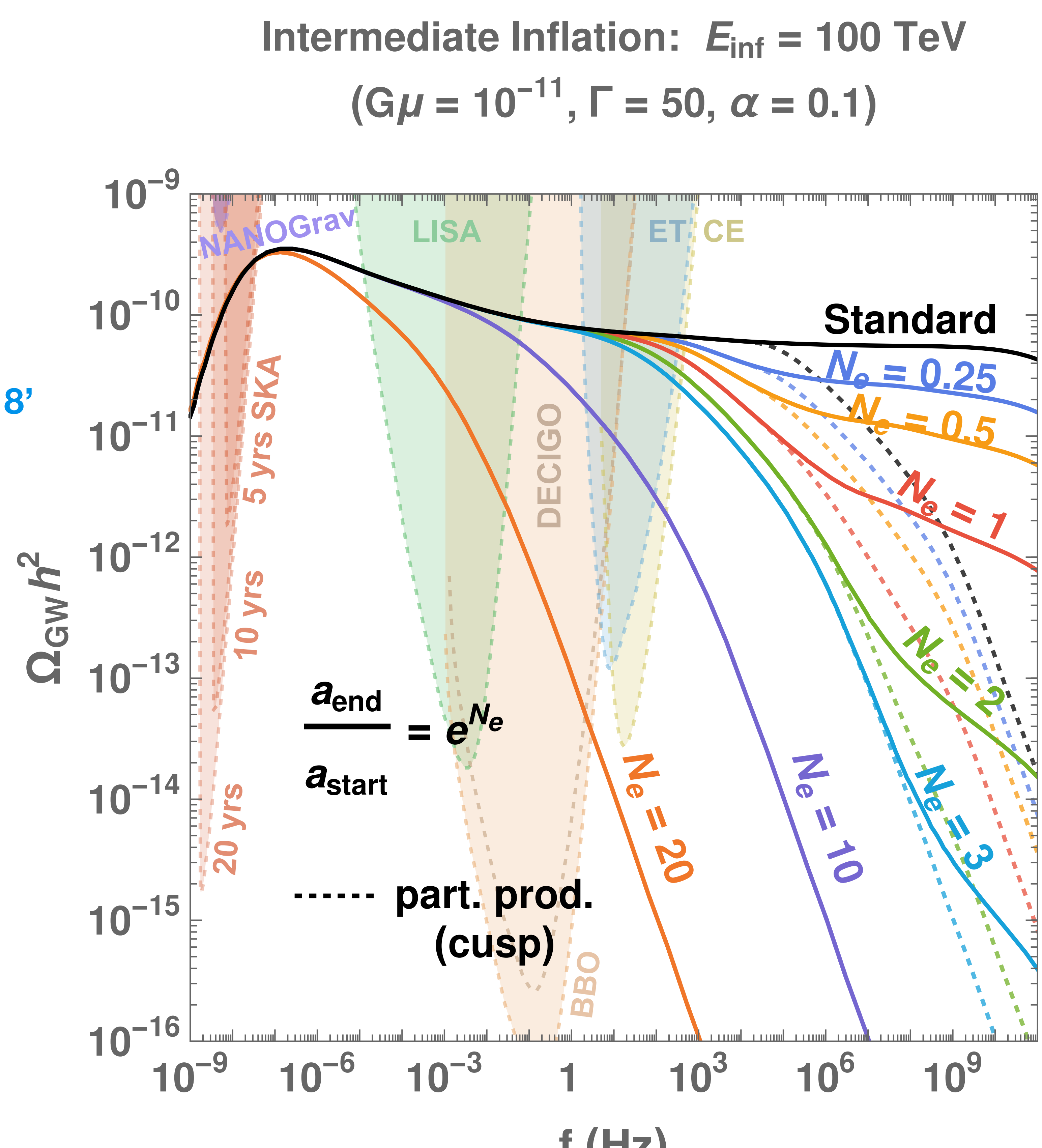

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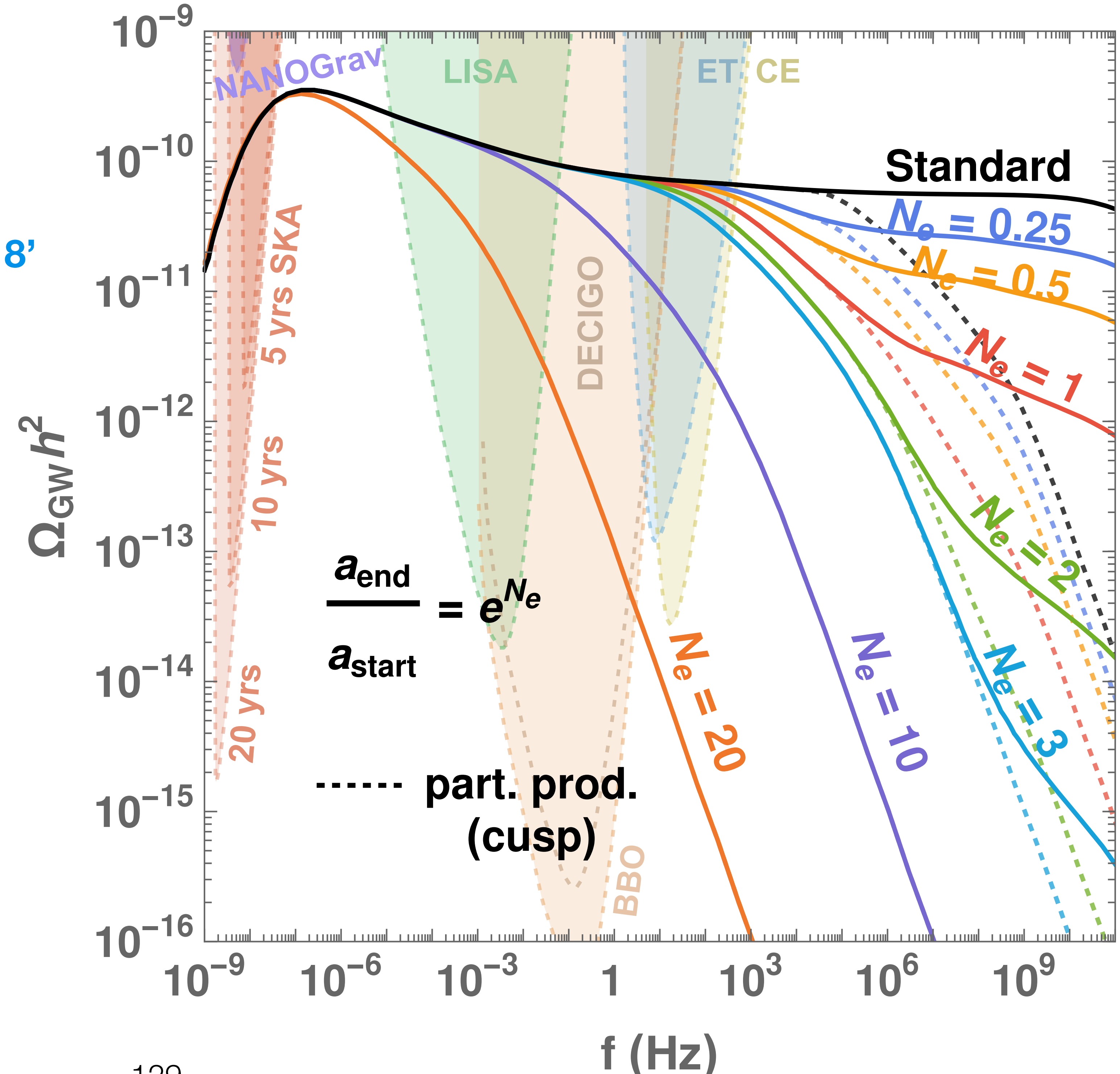

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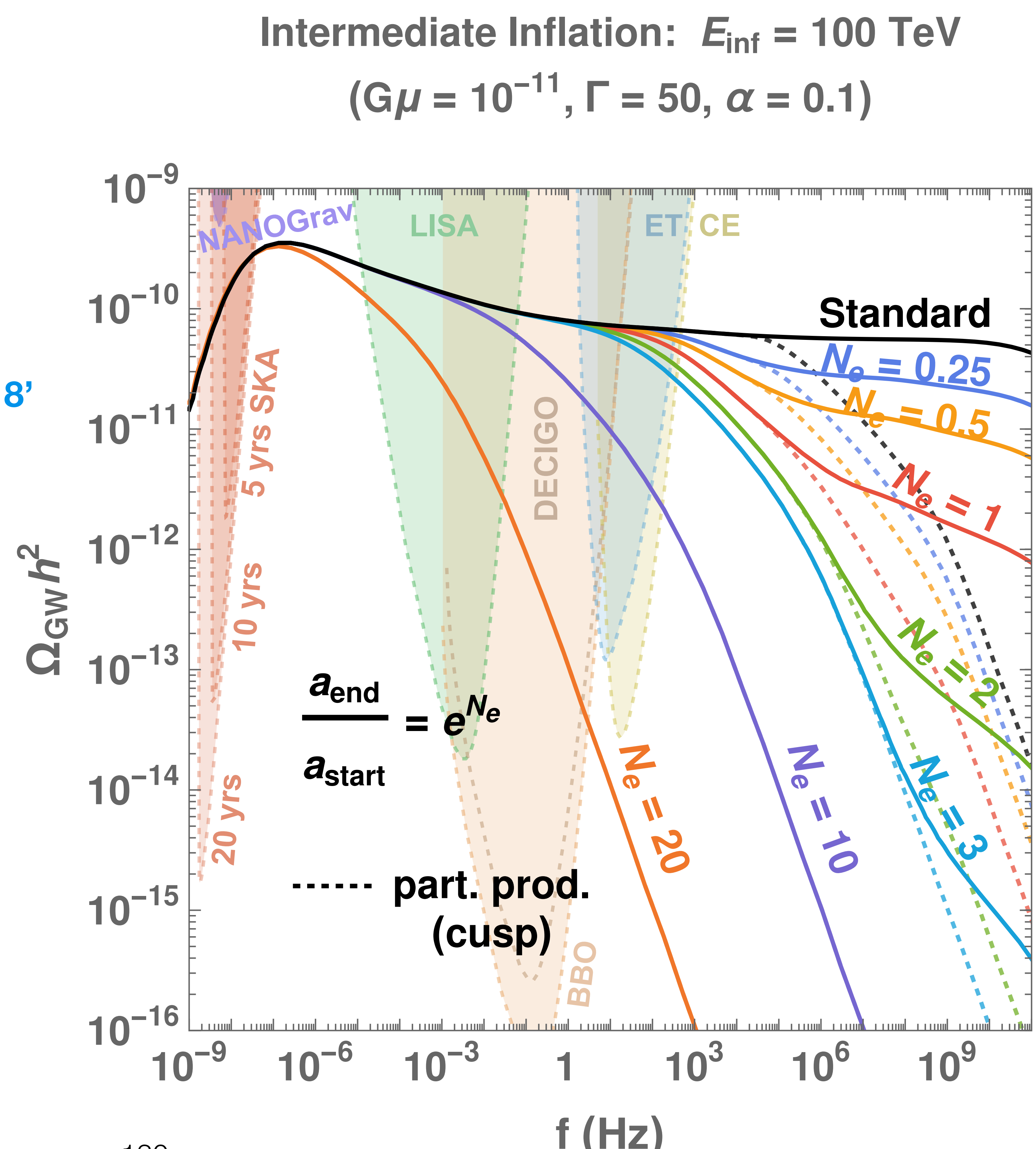

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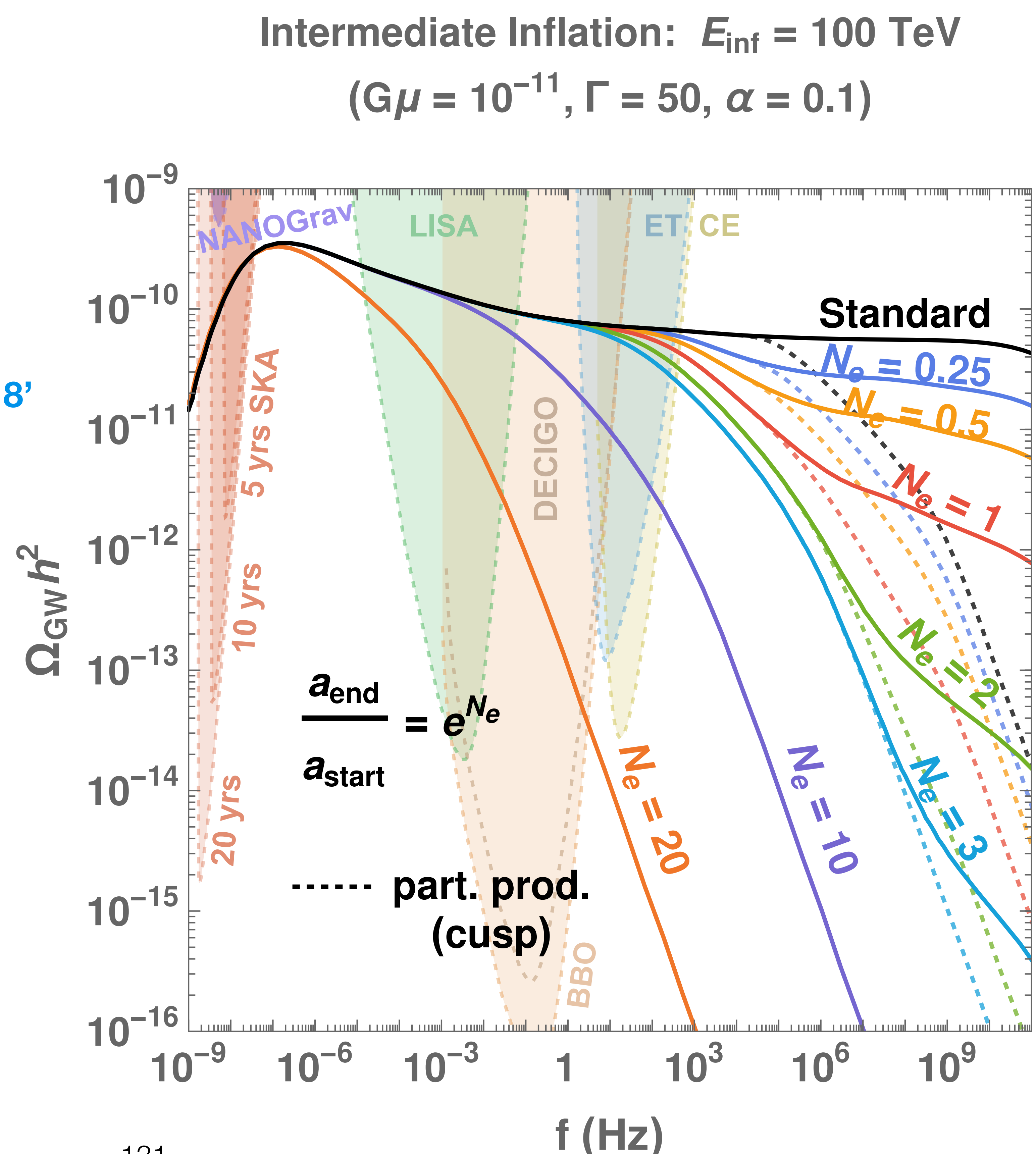

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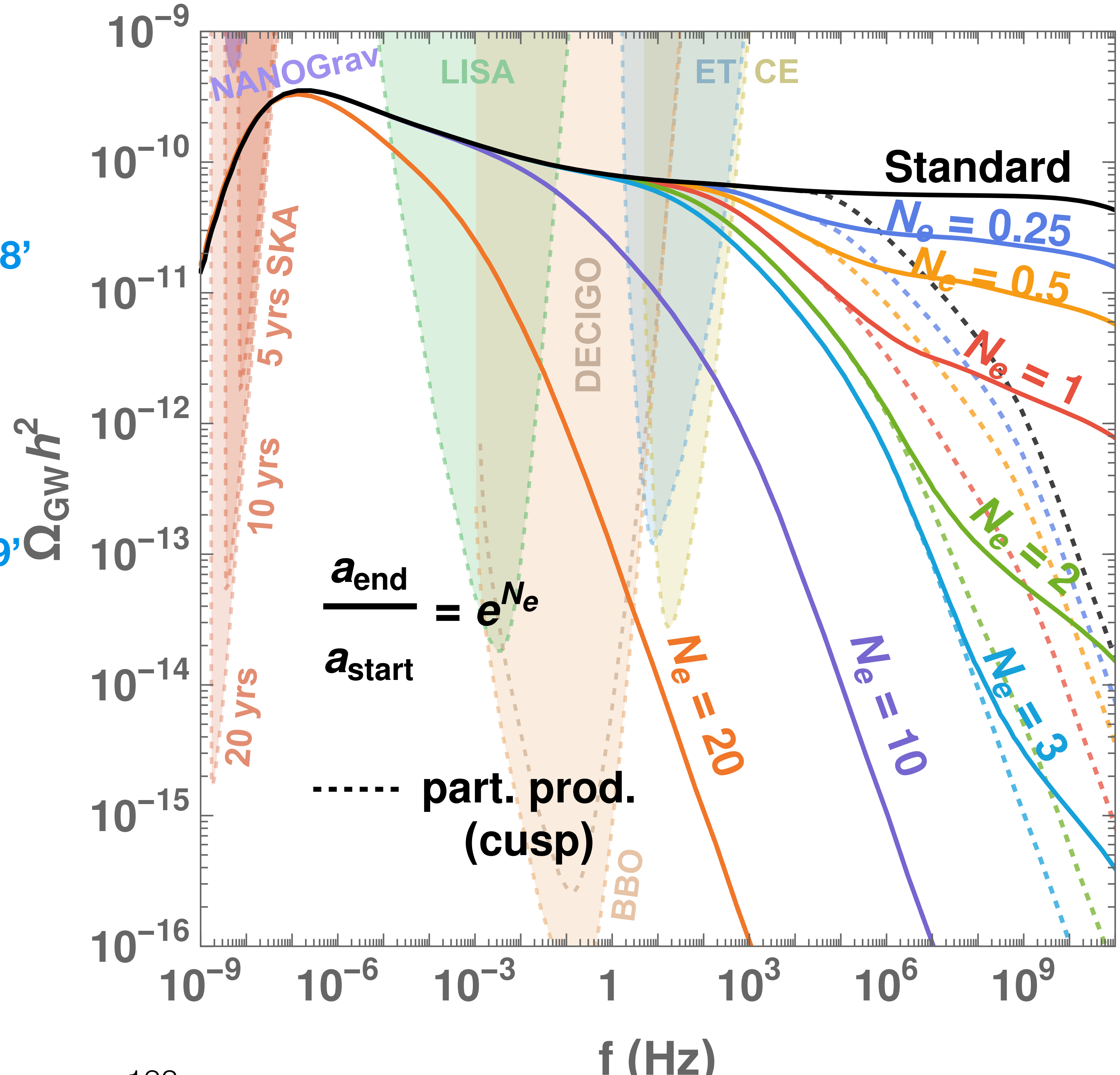

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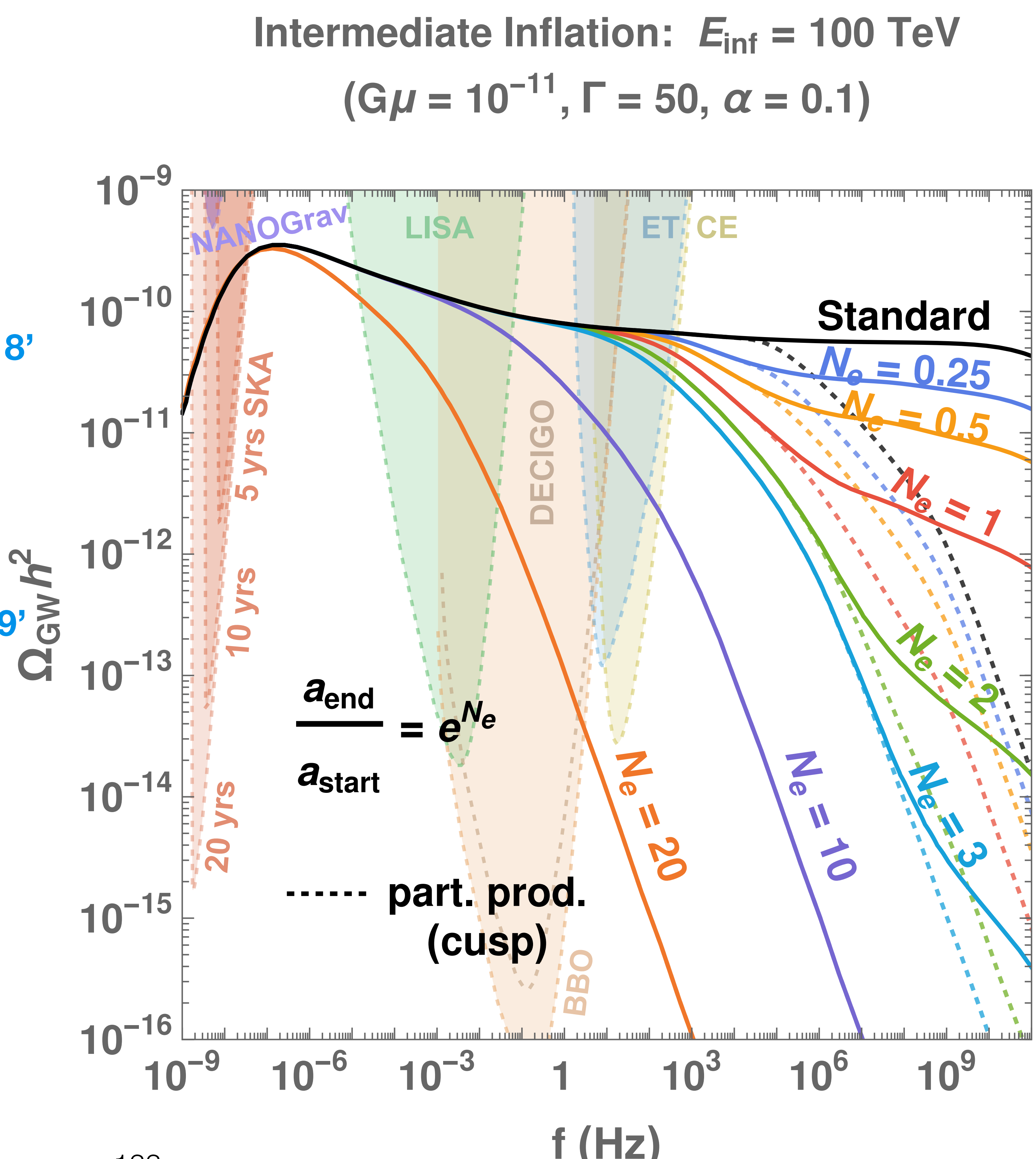
→ **Correlation length stretched outside Hubble horizon**



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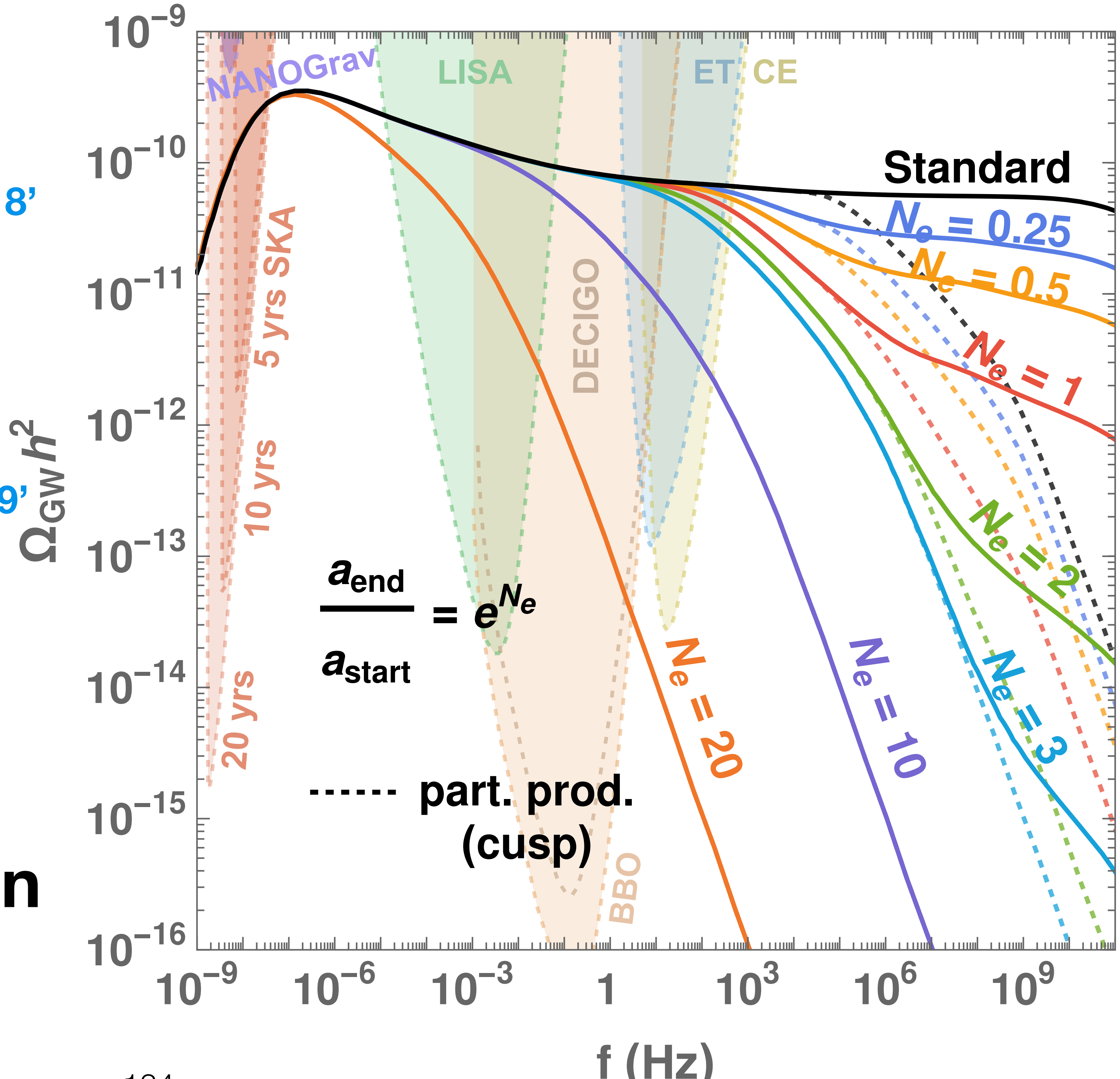

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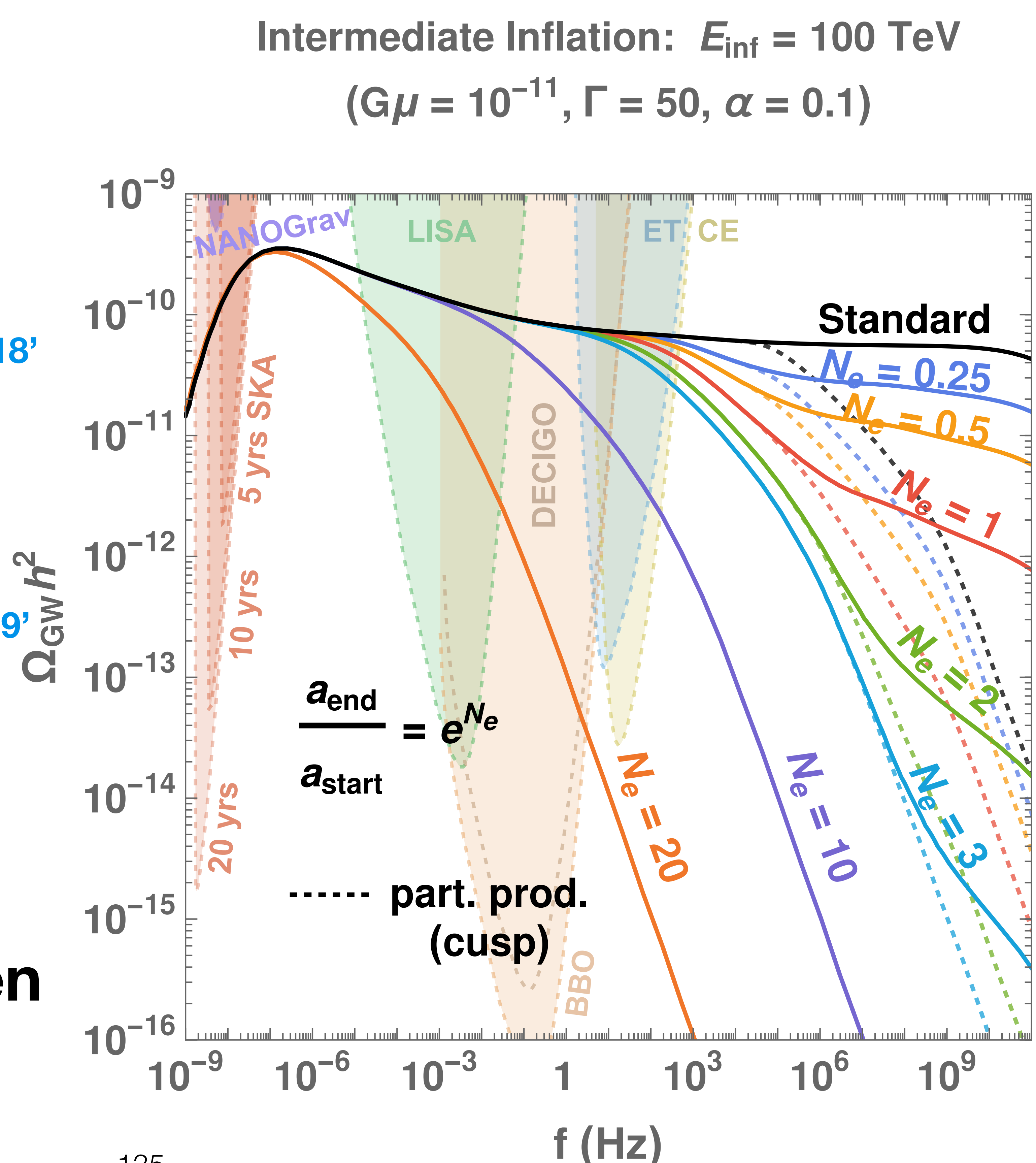
→ **Correlation length stretched outside Hubble horizon**

→ **Loop formation frozen**

→ **Takes Ne additional e-folds to re-enter**



# Intermediate inflation era

**Scaling: L ∝ t**

$a_{\rm start}$

**Inflation: L ∝ a**

$a_{\rm end} = a_{\rm start}\, e^{N_e}$

**L ∝ a (L >> t)**

$a_{\rm re-enter} = a_{\rm start}\, e^{2N_e}$

**Scaling: L ∝ t**

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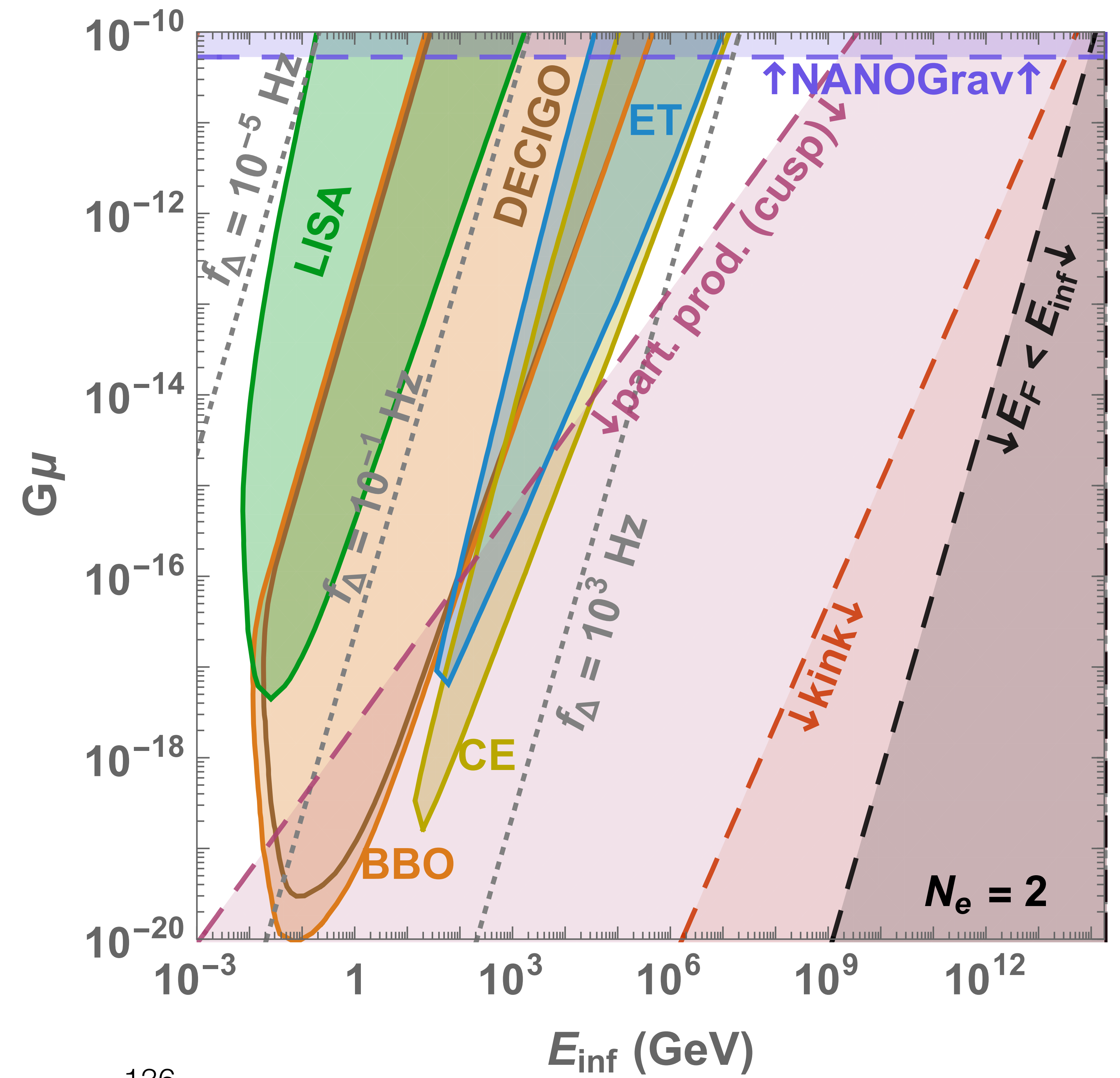

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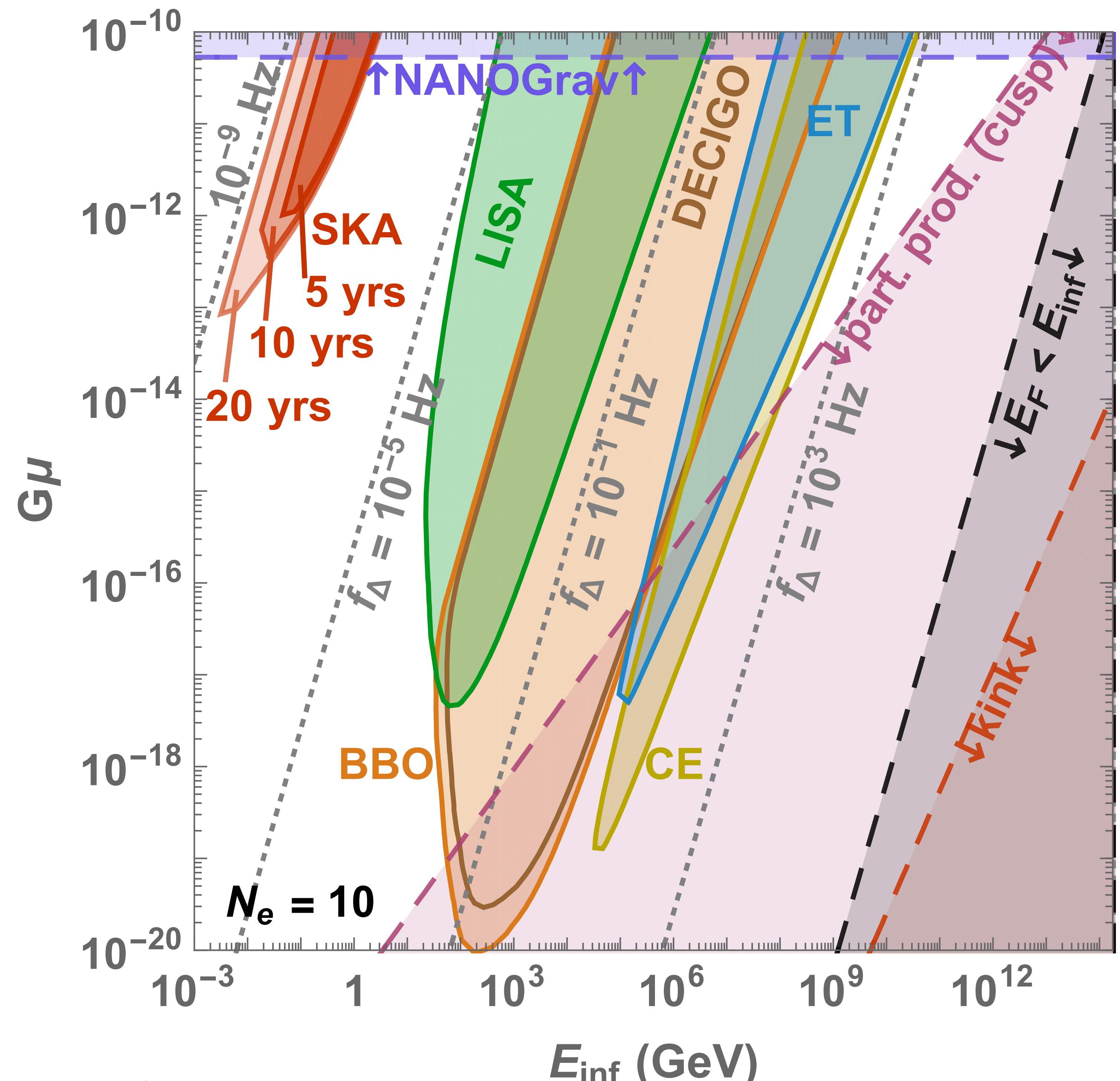

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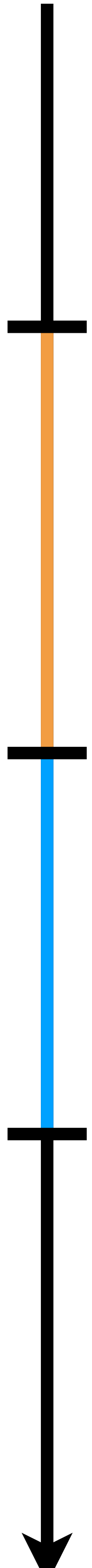

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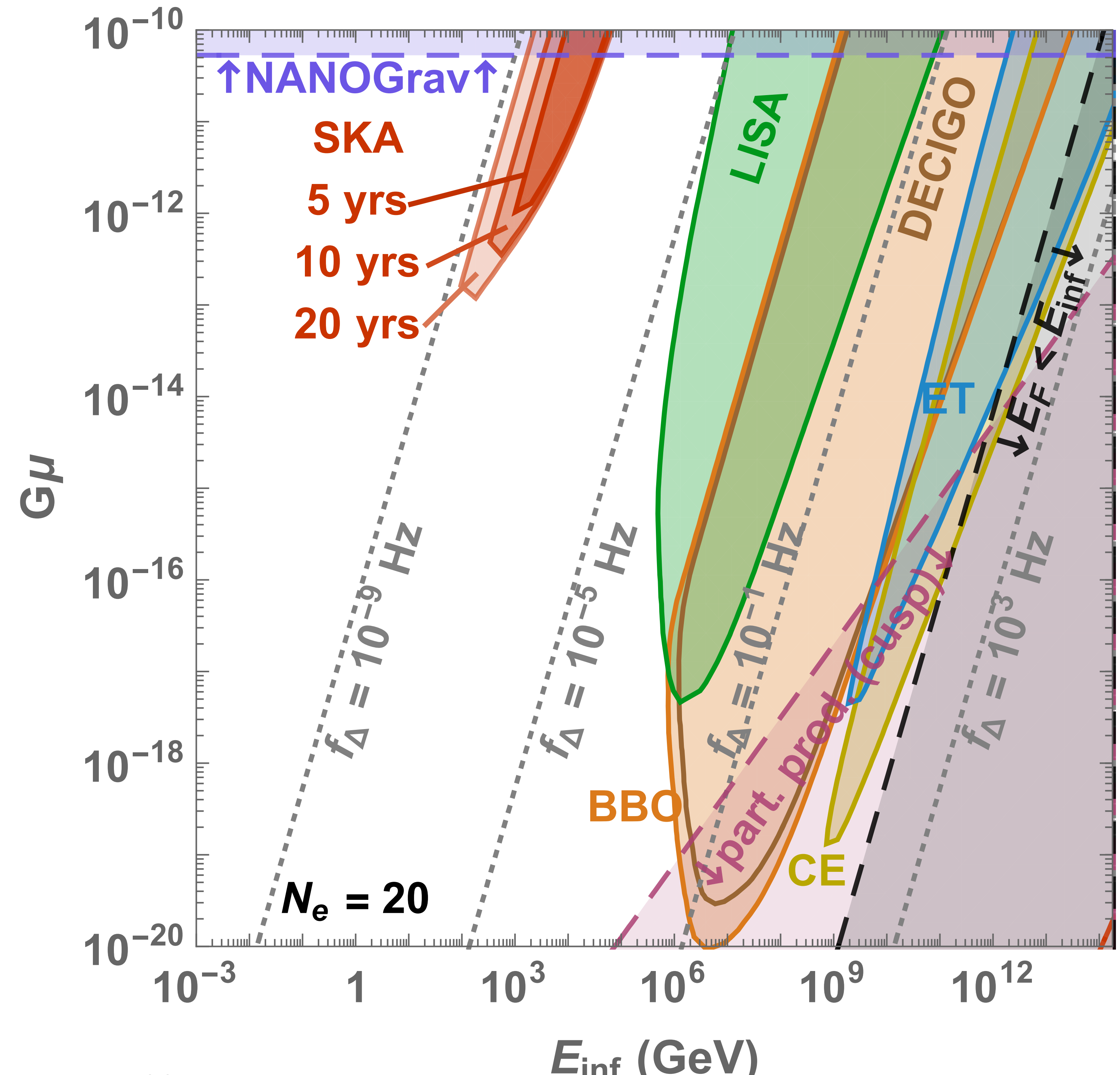

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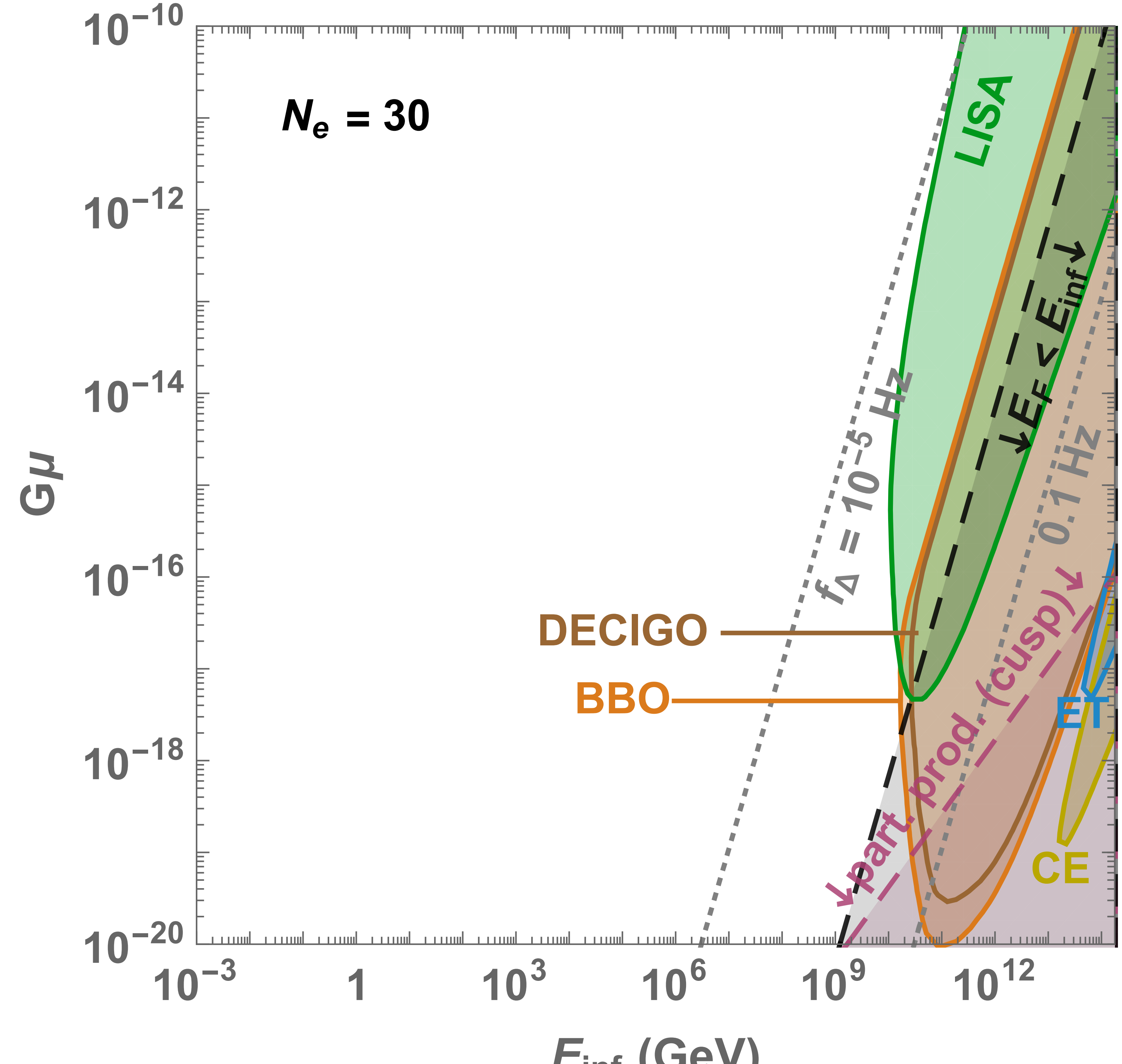

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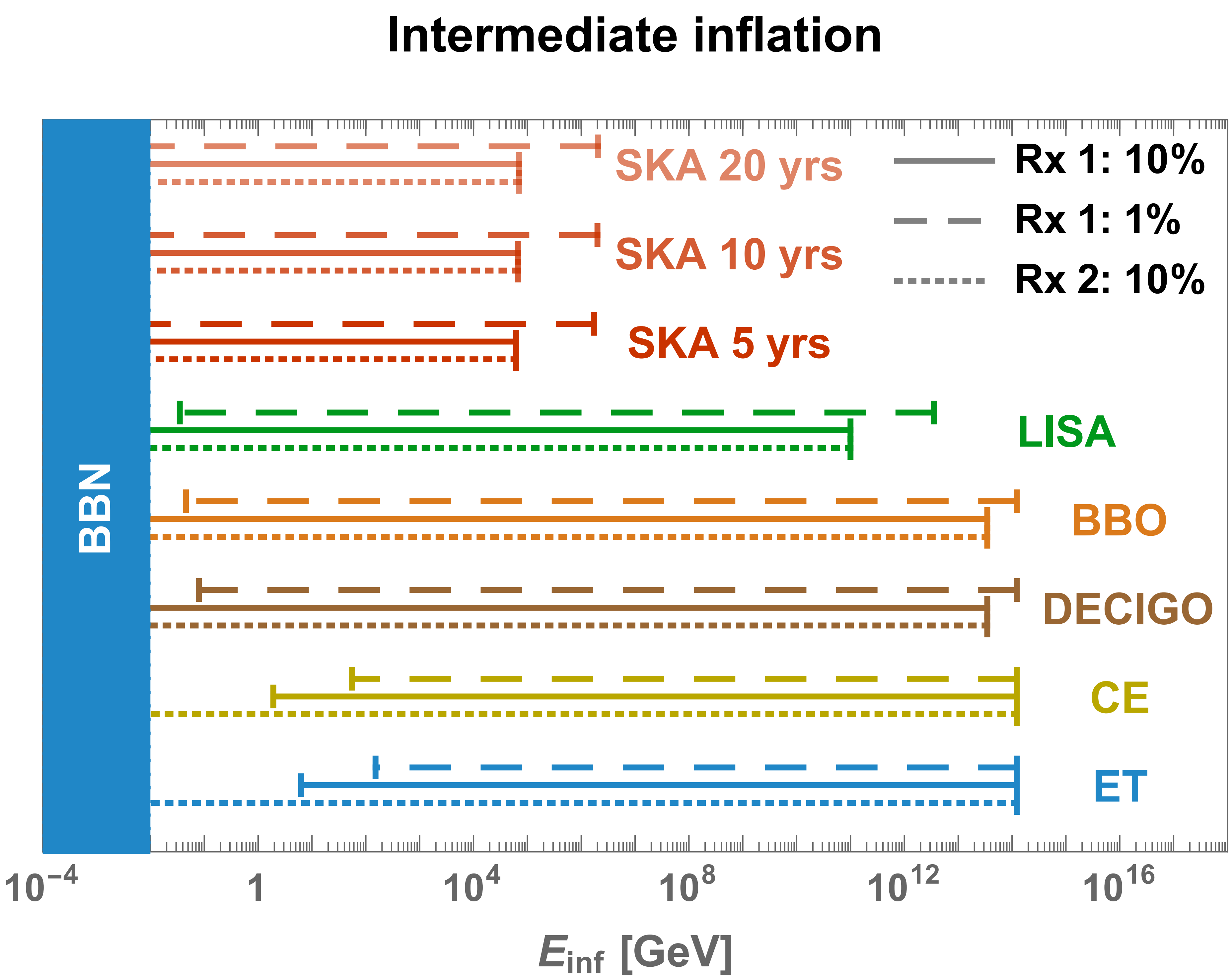


# CONCLUSION

- **Scaling regime and beyond, loop size distribution, massive radiation..**

- **NS matter era caused by heavy cold relic**

**Model-independent:** $1\ \mathrm{s} \gtrsim \tau_X \gtrsim 10^{-17} s$

**Probe superstring scales and ALPs mass up to** $10^{10}\ \mathrm{GeV}$

**Dark photon:** $\epsilon \geq 10^{-18}$ and $\mathrm{m_X} \lesssim 10^{16}\ \mathrm{GeV}$

**PBH:** $10^3\ g \lesssim M_{\mathrm{PBH}} \lesssim 10^9\ \mathrm{g}$

- **Second inflation:** $10^{-2}\ \mathrm{GeV} \lesssim E_{\mathrm{inf}} \lesssim 10^{13}\ \mathrm{GeV}$

**Reach larger scales due to freezing effects during Ne e-folds after inflation**

# Metastable cosmic string

$$SO(10) \to G_{\rm SM} \times U(1)_{\rm B-L} \to G_{\rm SM},$$

$\pi_2(G/H) \neq 1$ **Monopoles**

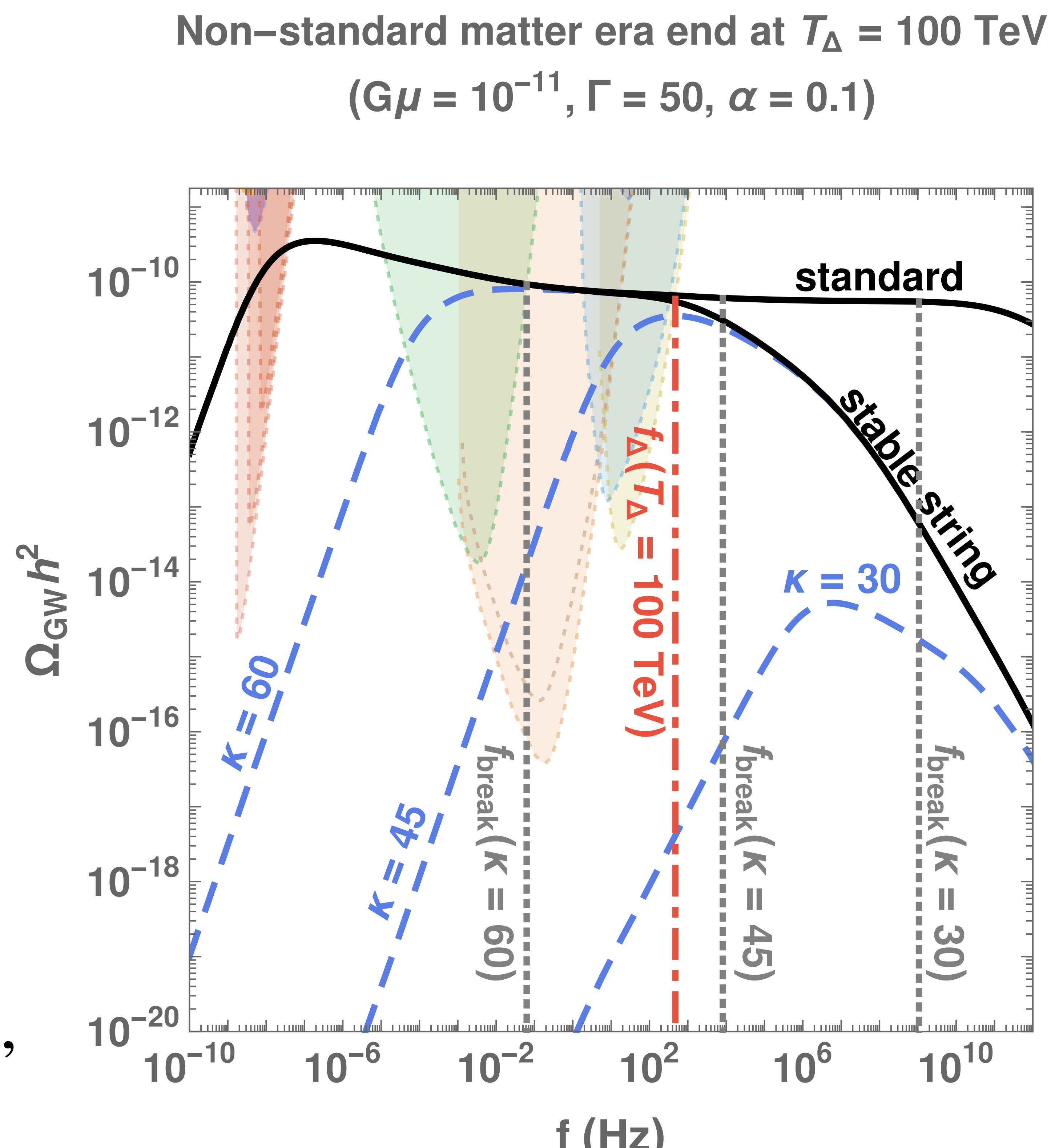
$\pi_1(G/H) \neq 1$ **Cosmic-strings**

$\pi_1(G/H) = 1$

$$S \longrightarrow SM + \bar{M}S$$

$$\text{with rate} \quad \Gamma_{\rm d} = \frac{\mu}{2\pi}\exp(-\pi\kappa),$$

$$\kappa \equiv m^2/\mu \gtrsim 1$$



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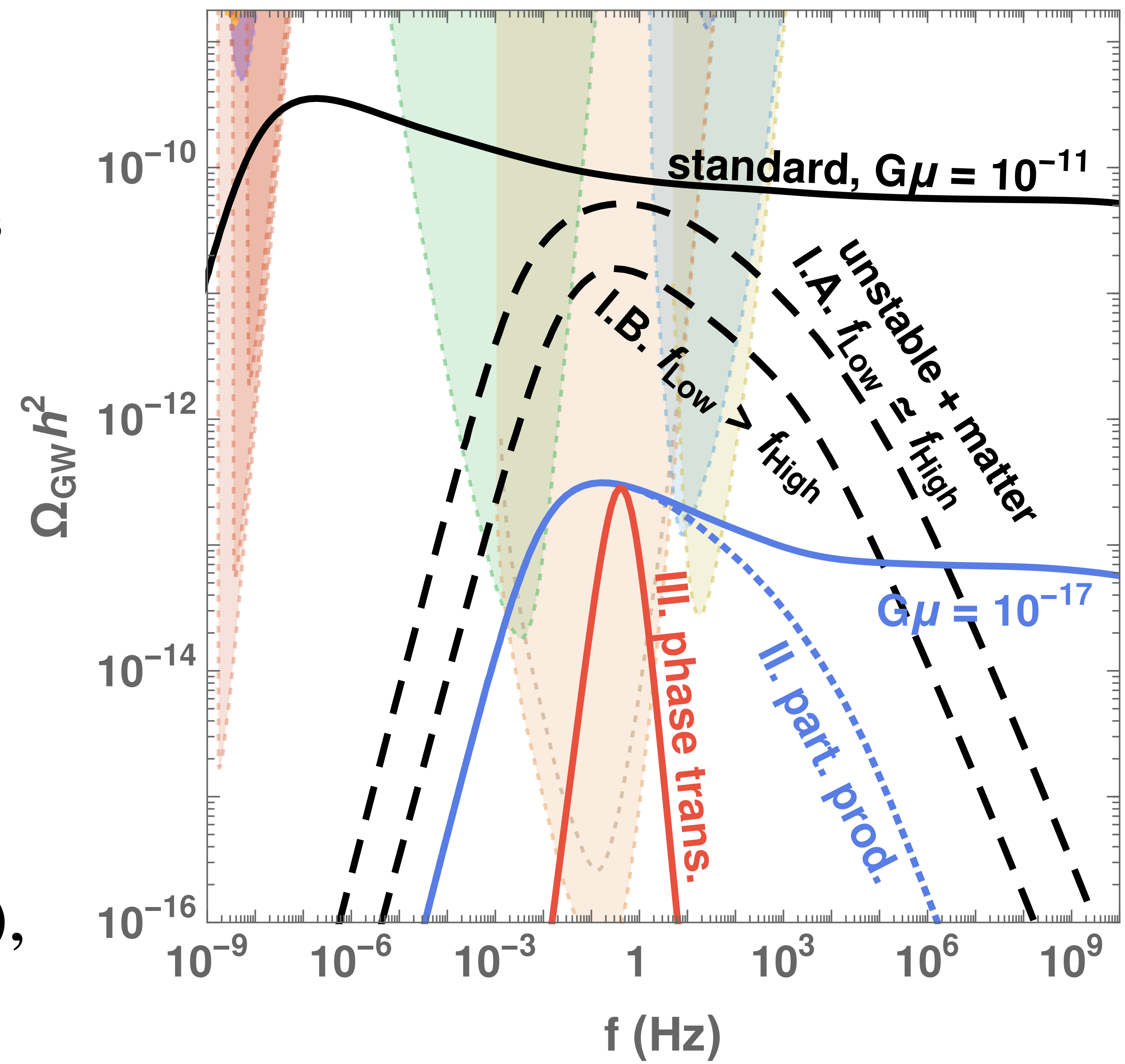


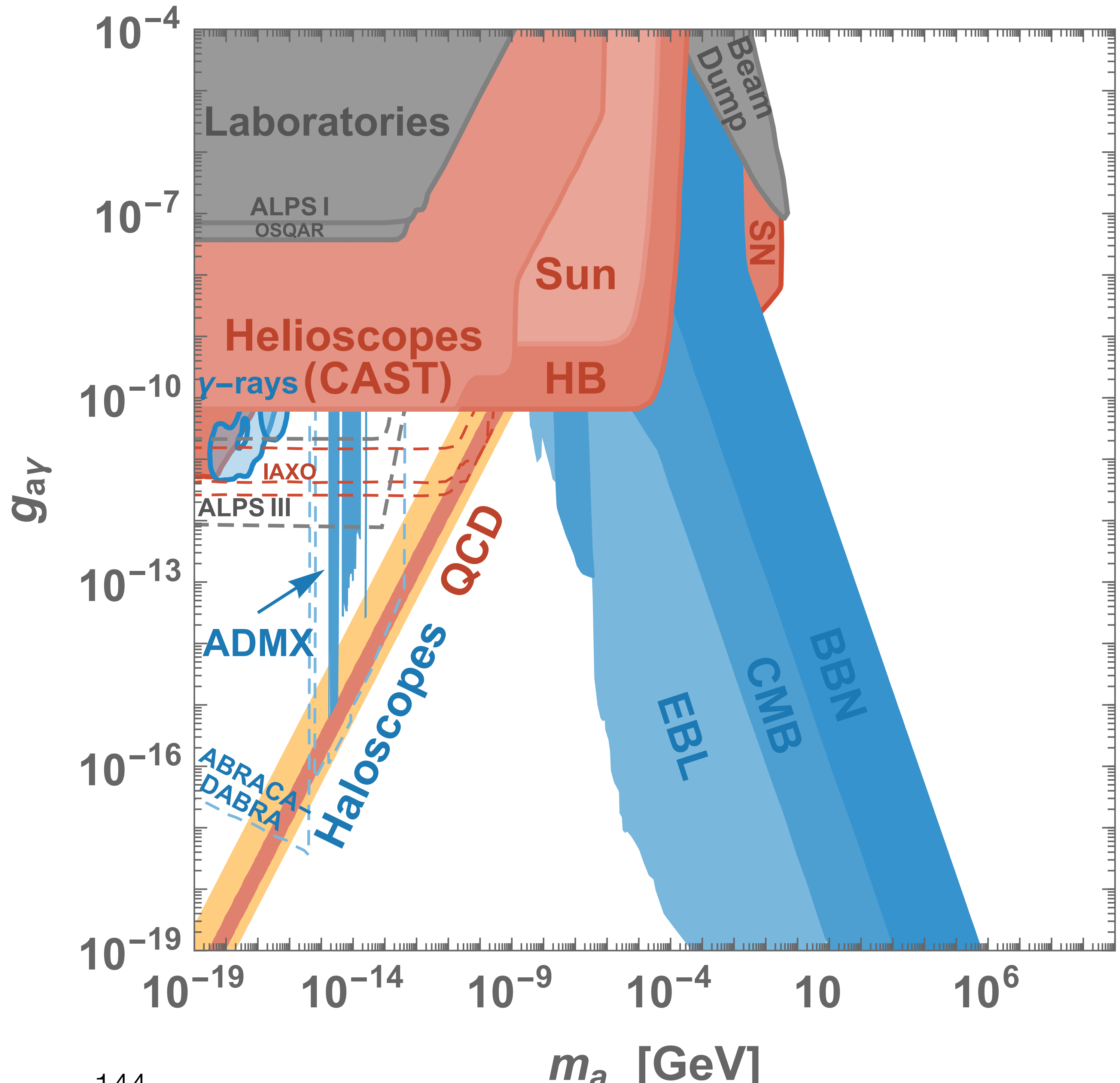
# 3) ALPs

→ **Assume thermal abundance**

→ **Decay rate**

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

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



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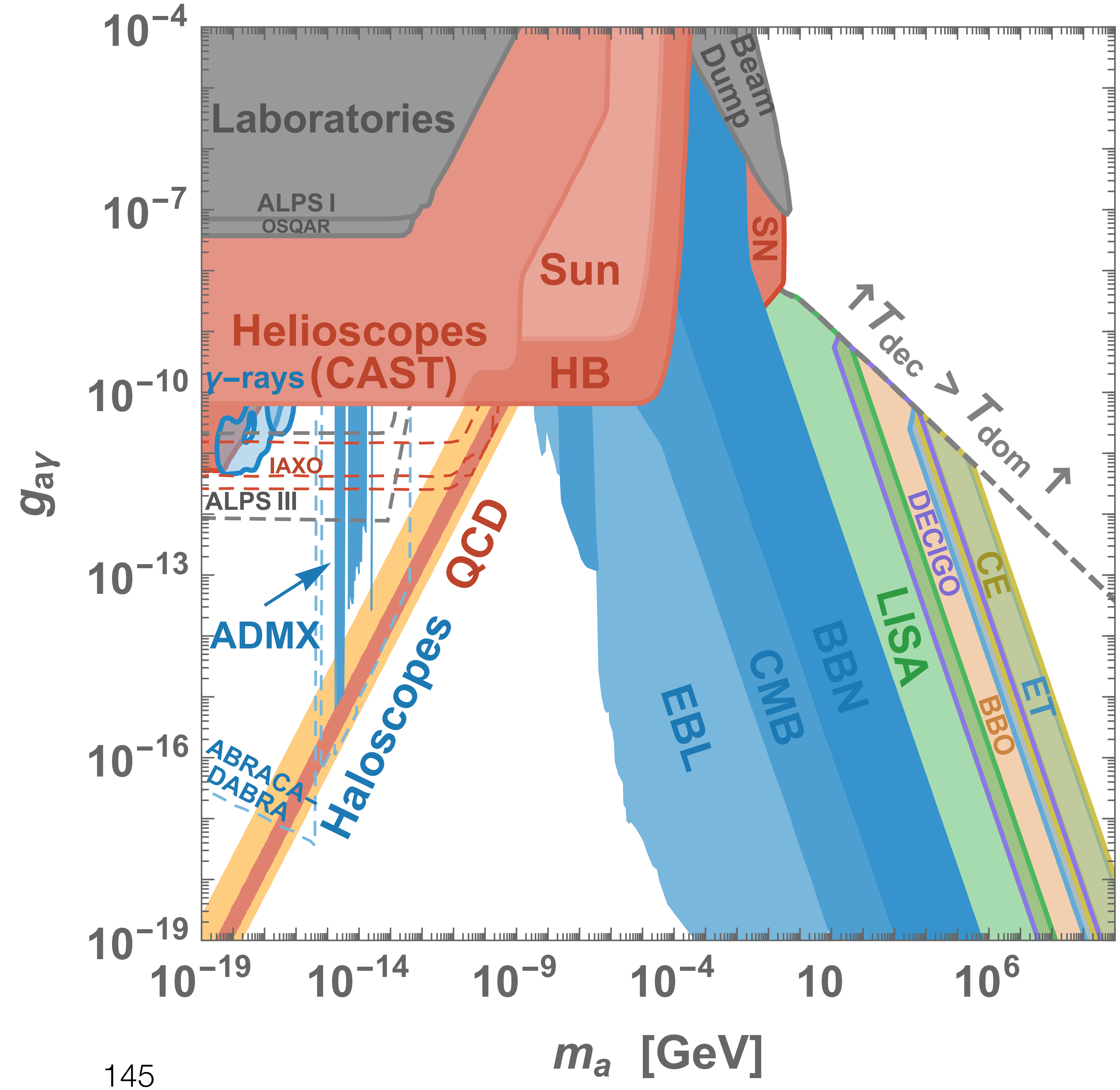
$$m_a \lesssim 10^{10}\ \text{GeV}$$



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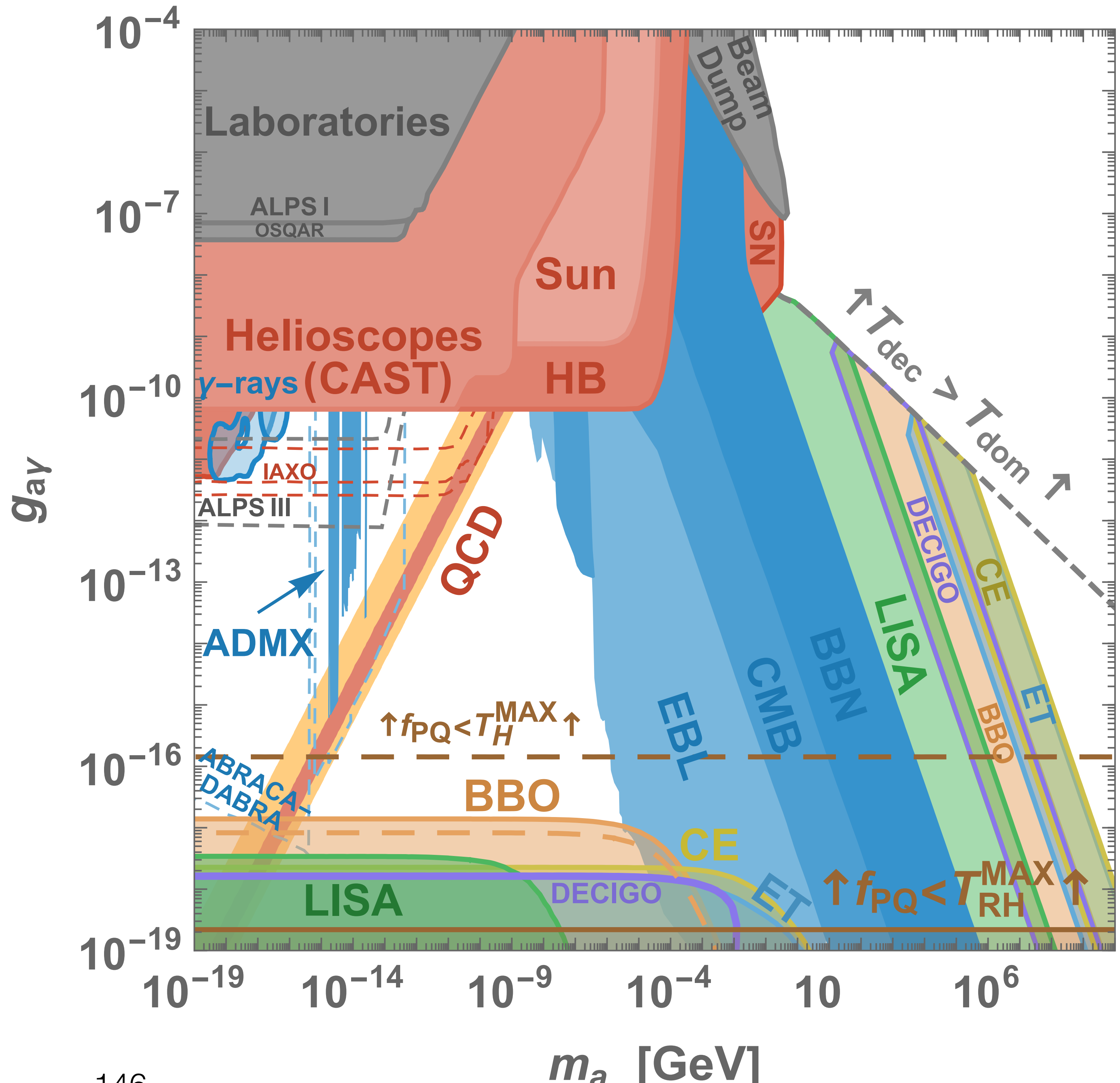

# Temperature - frequency relation

- **Remember for 1st order PT:**

→ **"LISA is a window on TeV"**

$$f \sim 10 H_* \left(\frac{a_*}{a_0}\right) \quad \longrightarrow \quad f = (1.9\ \mathrm{mHz}) \left(\frac{\mathrm{T}_*}{1\ \mathrm{TeV}}\right)\left(\frac{\mathrm{g}_*}{100}\right)^{1/4}$$

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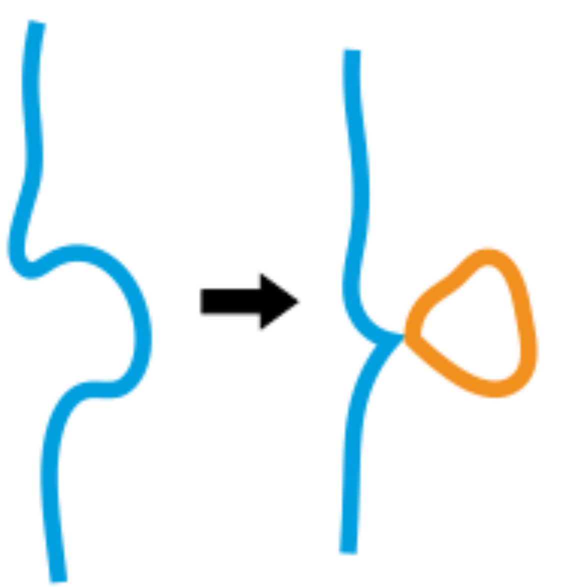
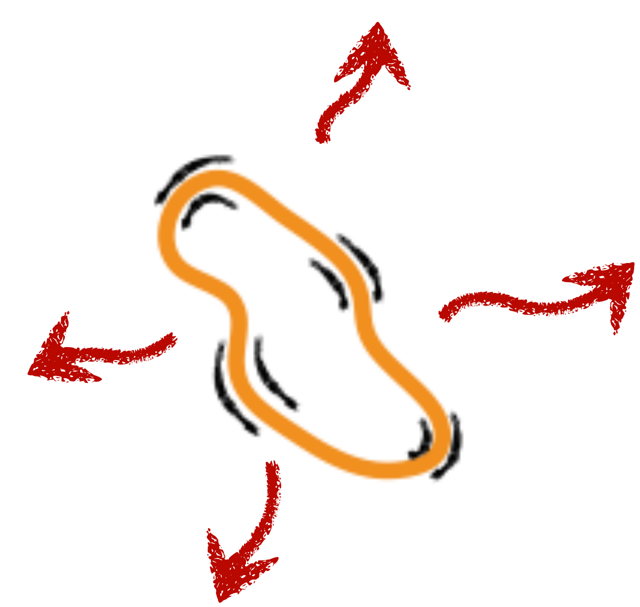


**Loop formation at $t_i$**

$$t_* \sim t_i / G\mu$$



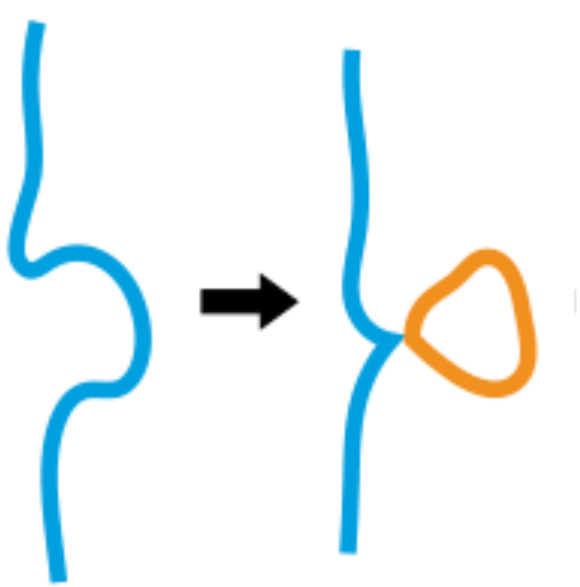
**GW emission at $t_*$**

# Temperature - frequency relation

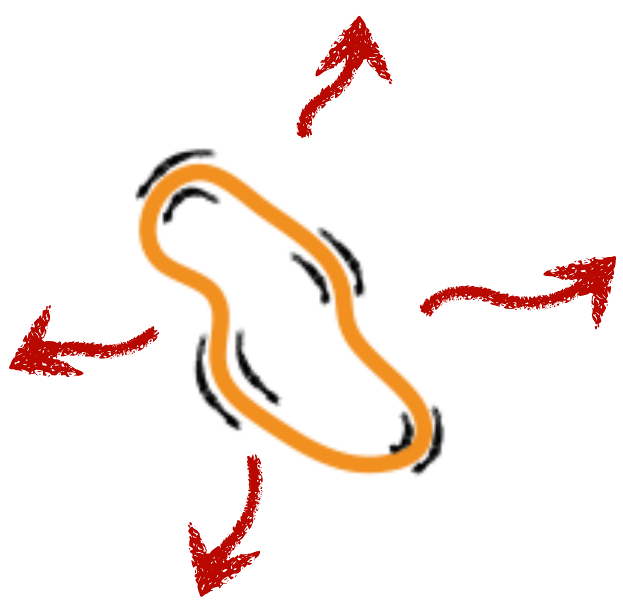
- **Remember for 1st order PT:**

→ **"LISA is a window on ~~TeV~~"** $\left(\frac{T_i}{0.1\ \mathrm{GeV}}\right)$

$$f \sim 10 H_* \left(\frac{a_*}{a_0}\right)\left(\frac{1}{G\mu}\right)^{1/2} \longrightarrow \qquad f = (1.9\ \mathrm{mHz}) \left(\frac{\mathrm{T}_*}{1\ \mathrm{TeV}}\right)\left(\frac{\mathrm{g}_*}{100}\right)^{1/4}$$



$t_* \sim t_i / G\mu$



**Loop formation at $t_i$** **GW emission at $t_*$**

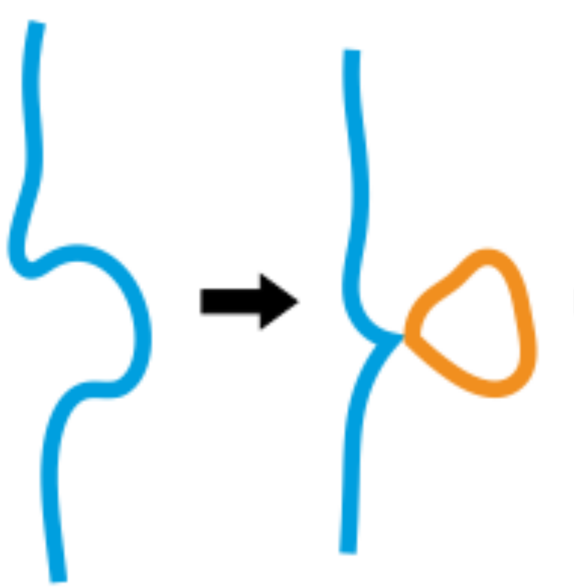
# Temperature - frequency relation

- **Remember for 1st order PT:**

**Einstein Telescope**

→ **"~~LISA~~ is a window on $\boxed{\text{TeV}}$"** $\left(\frac{T_i}{0.1\ \text{GeV}}\right)$

$$f \sim 10 H_* \left(\frac{a_*}{a_0}\right)\left(\frac{1}{G\mu}\right)^{1/2} \longrightarrow \qquad f = (1.9\ \text{mHz})\left(\frac{\text{T}_*}{1\ \text{TeV}}\right)\left(\frac{\text{g}_*}{100}\right)^{1/4}$$



$$\xrightarrow{\;t_* \sim t_i/G\mu\;}$$

**Loop formation at $t_i$** **GW emission at $t_*$**

# String network evolution

➜ **Velocity-dependent One-Scale (VOS) model** $\bar{v}$ $\rho_\infty = \dfrac{\mu}{L^2}$

$$\frac{d\bar{v}}{dt} = (1-\bar{v}^2)\left[\frac{k(\bar{v})}{L} - 2H\bar{v}\right]$$

**Newton's law**
**Curvature VS Hubble expansion**

$$\frac{d\rho_\infty}{dt} = -2H(1+\bar{v}^2)\rho_\infty \boxed{-\tilde{c}\,\bar{v}\frac{\rho_\infty}{L}}$$

**Energy conservation**
**Hubble exp. VS loop formation**

➜ **Thermal friction:** $\dfrac{\bar{v}^2}{l_d} \equiv 2H\bar{v}^2 + \dfrac{\bar{v}^2}{l_f}$ with $\mathrm{l_f} \equiv \dfrac{\mu}{\sigma\,\rho} = \dfrac{\mu}{\beta \mathrm{T}^3}$

**Negligible for T lower than:** $T_{\mathrm{friction}} \sim 40\ \mathrm{PeV}\dfrac{\mathrm{G}\mu}{10^{-15}}$

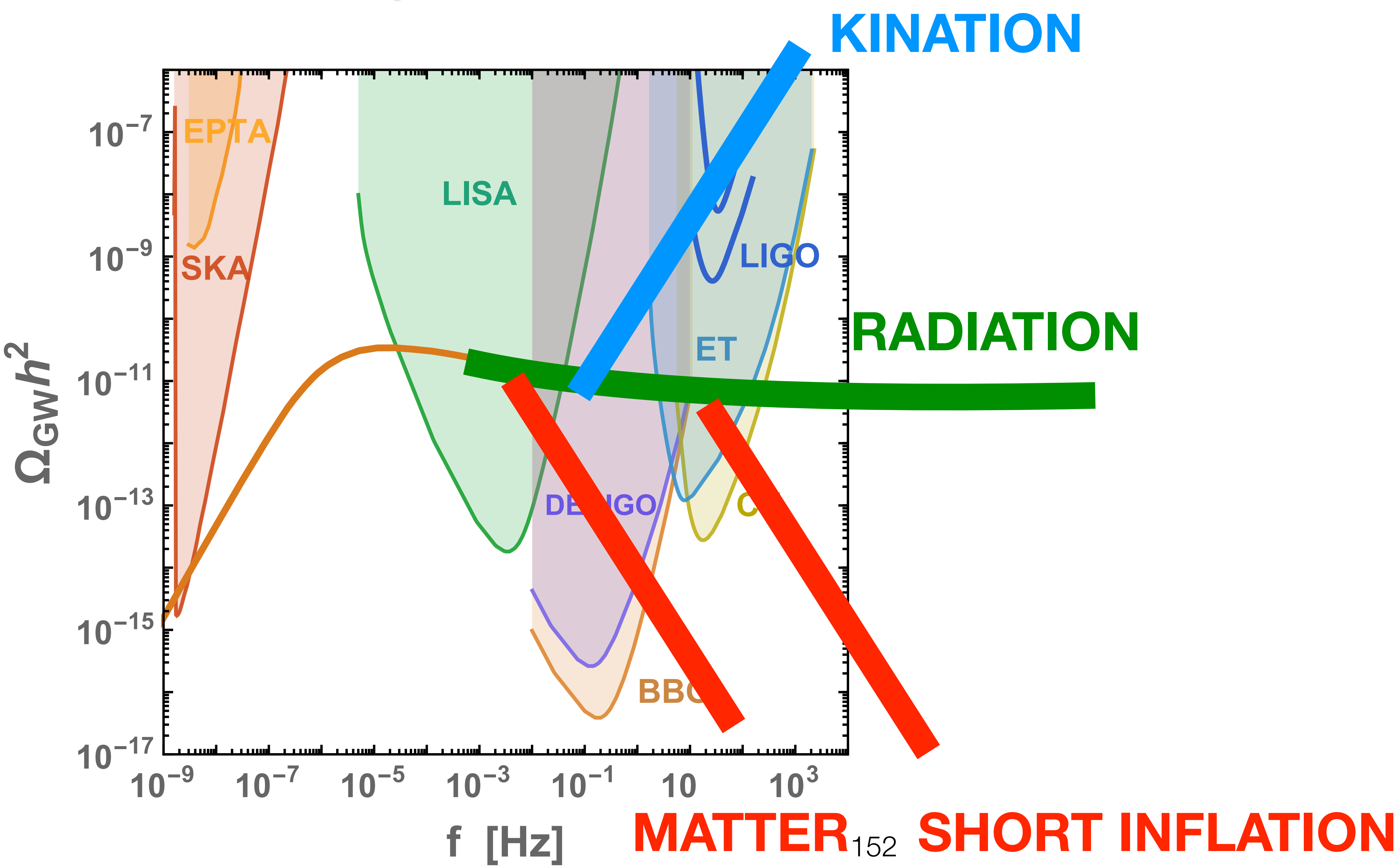
**Compare with network formation:** $T_{\mathrm{F}} \sim \sqrt{\mu} \sim 10^{11}\ \mathrm{GeV}\left(\dfrac{G\mu}{10^{-15}}\right)^{1/2}.$

**GW energy density redshift**

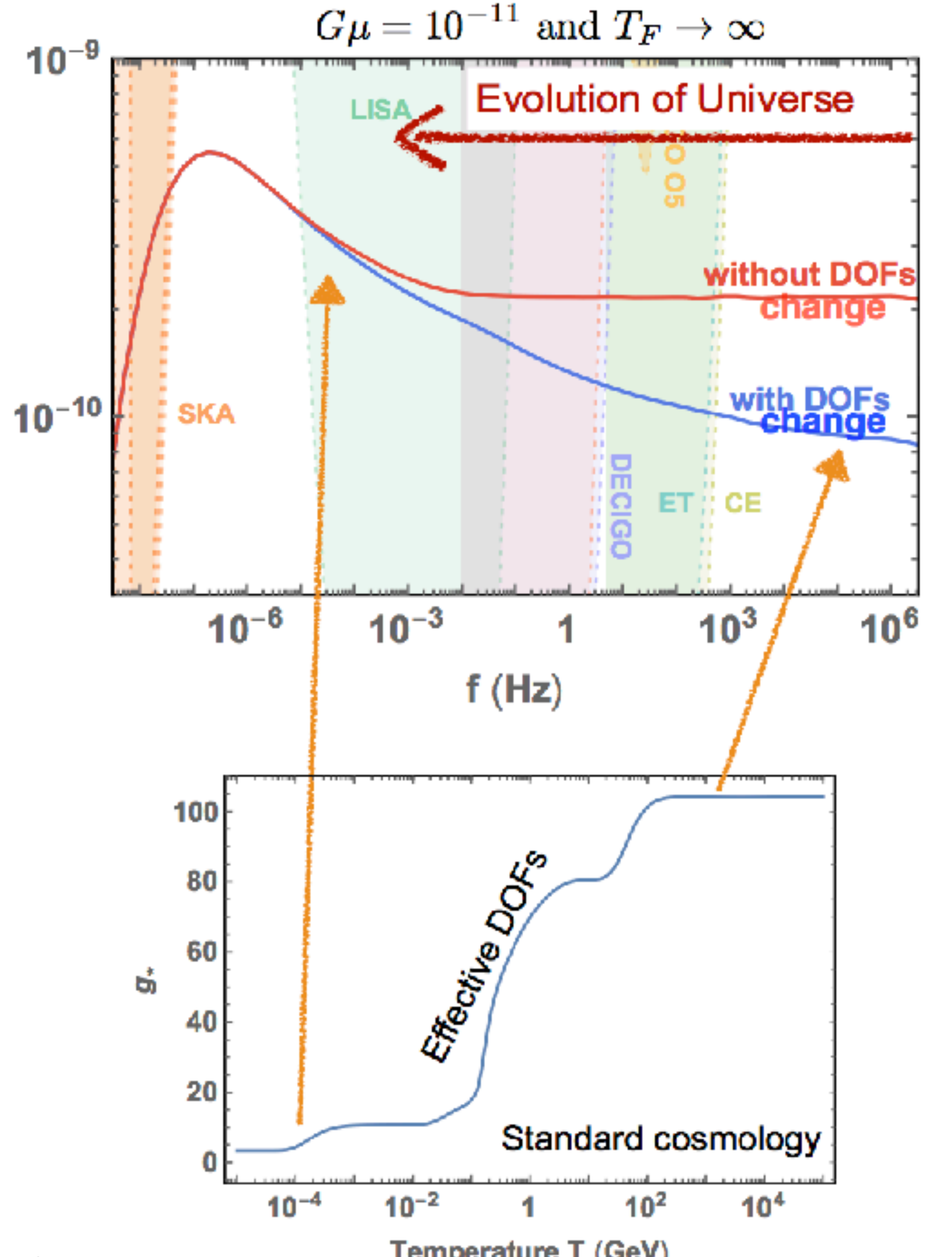
**Loop density redshift**

$$\Omega_{\rm GW}(f) \simeq \sum_k \frac{1}{\rho_c}\int_{t_{\rm osc}}^{t_0} d\tilde{t} \int d\alpha \left[\frac{a(\tilde{t})}{a(t_0)}\right]^3 \cdot \Theta\!\left(t_i - \frac{l_*}{\alpha}\right) \cdot \frac{\Gamma G\mu^2}{k^{4/3}}$$

$$\times \left[\frac{a(t_i)}{a(\tilde{t})}\right]^3 \cdot \frac{dt_i}{d\tilde{f}} \cdot P(\alpha) \cdot \frac{\tilde{C}_{\rm eff}(t_i)}{\alpha\, t_i^4} \cdot \Theta(t_i - t_{\rm osc})$$



# Change in DOFs



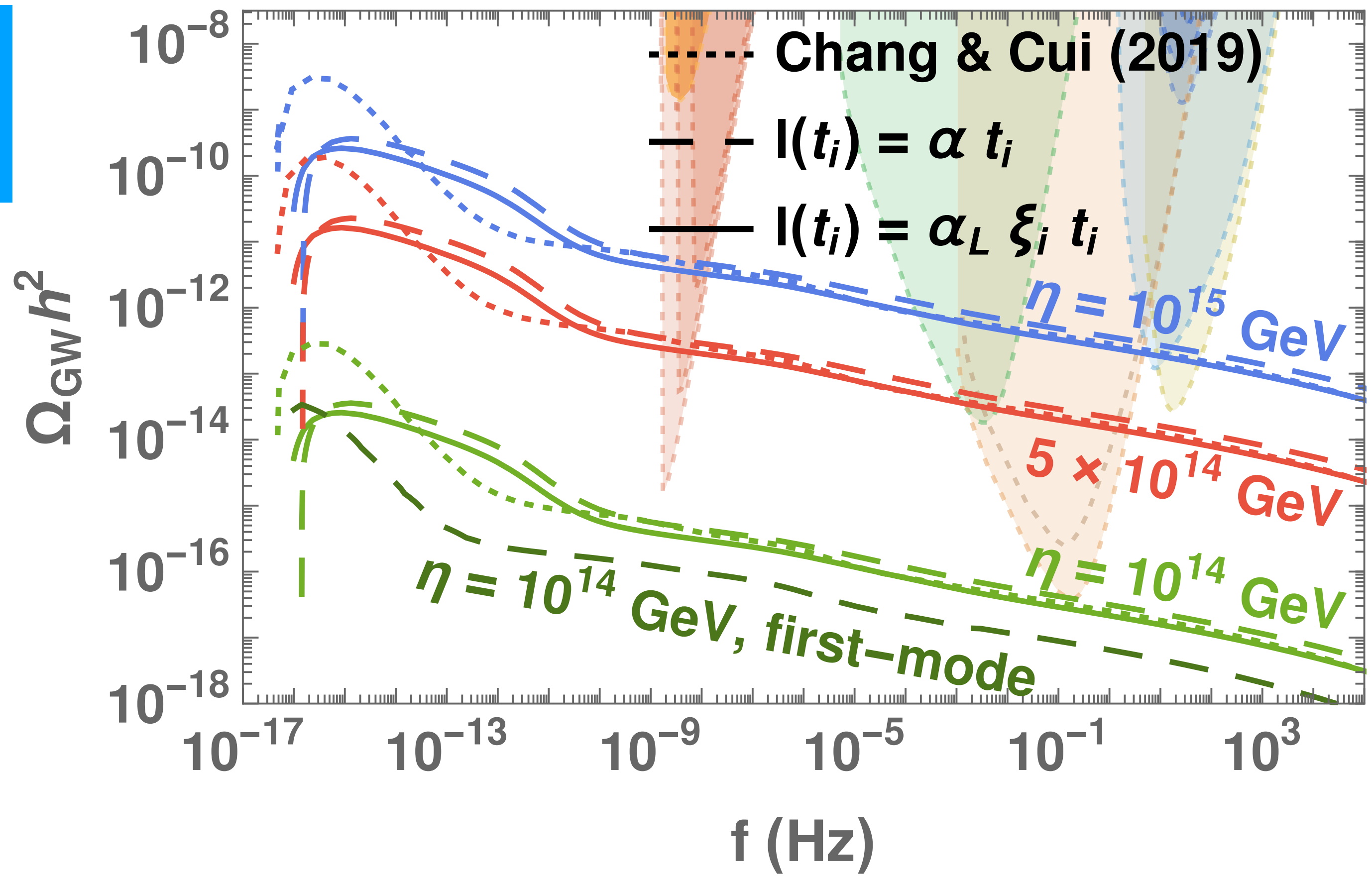

**Decay of relativistic particles**

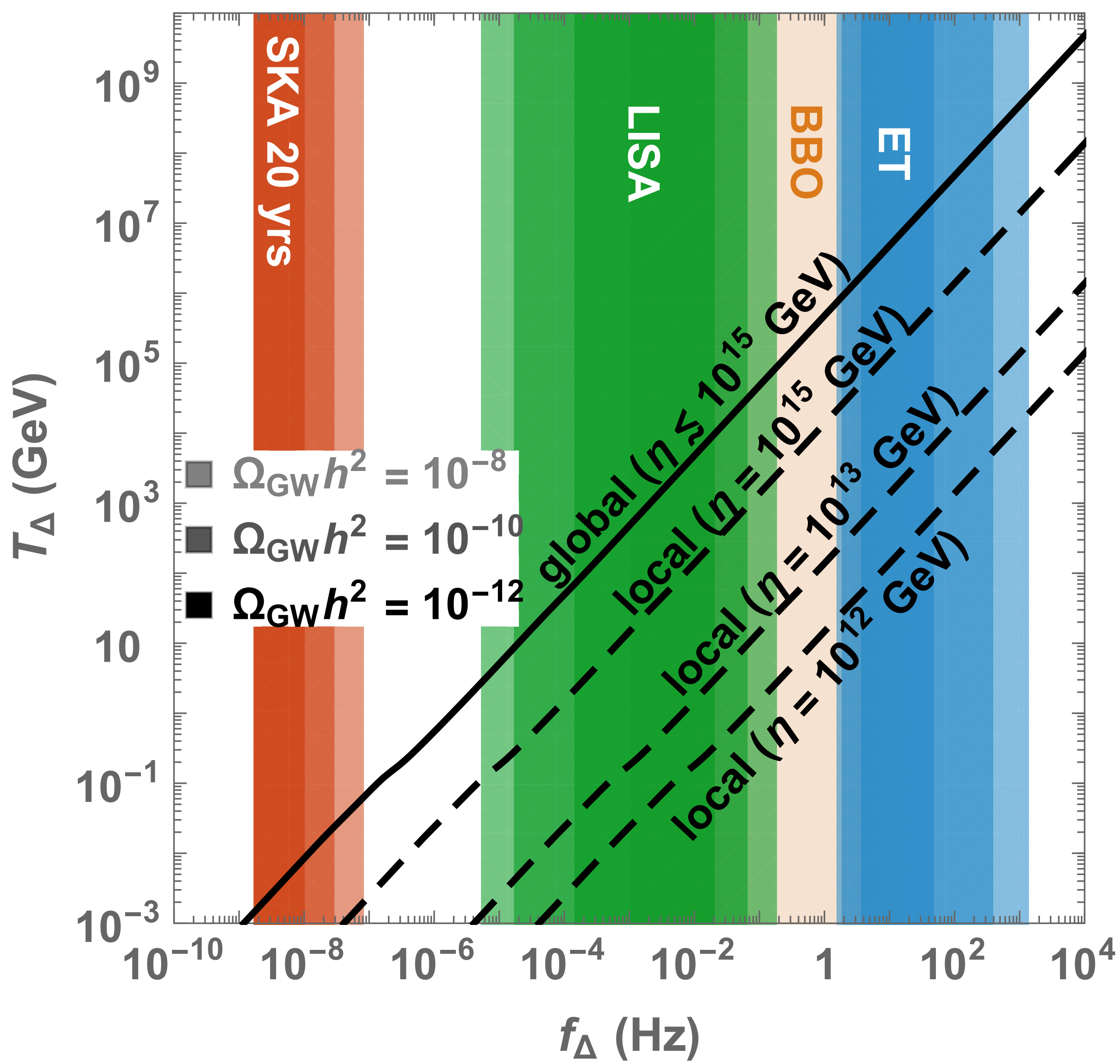
➜ **Deviation from** $a \propto t^{1/2}$

# Global strings

$$f\Big|_{\text{global}}(T_*) \sim \sqrt{G\mu}\ \times\ f\Big|_{\text{local}}(T_*)$$

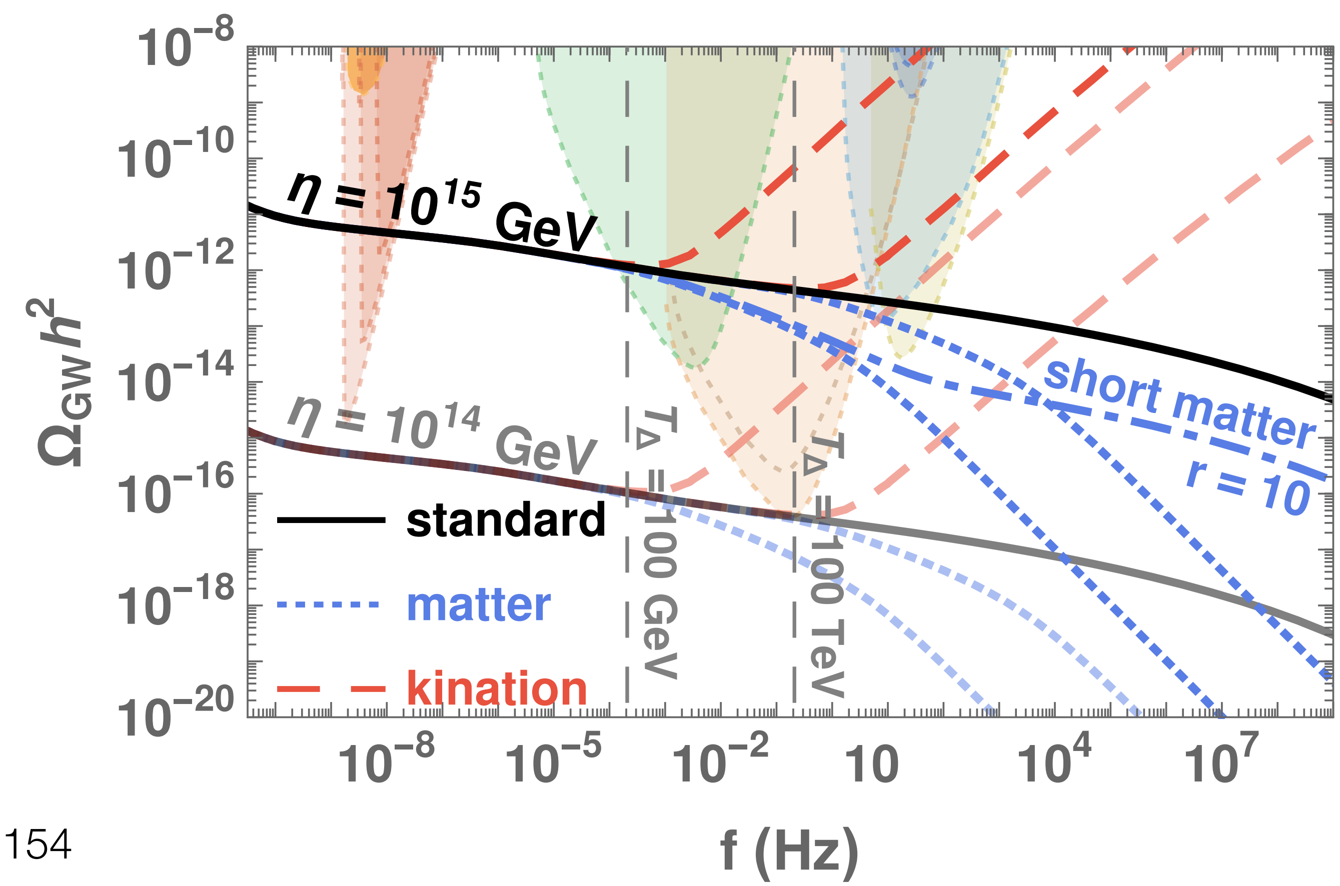
$$\Omega_{\text{GW}}\Big|_{\text{global}} \sim (G\mu)^{3/2}\ \times\ \Omega_{\text{GW}}\Big|_{\text{local}}$$



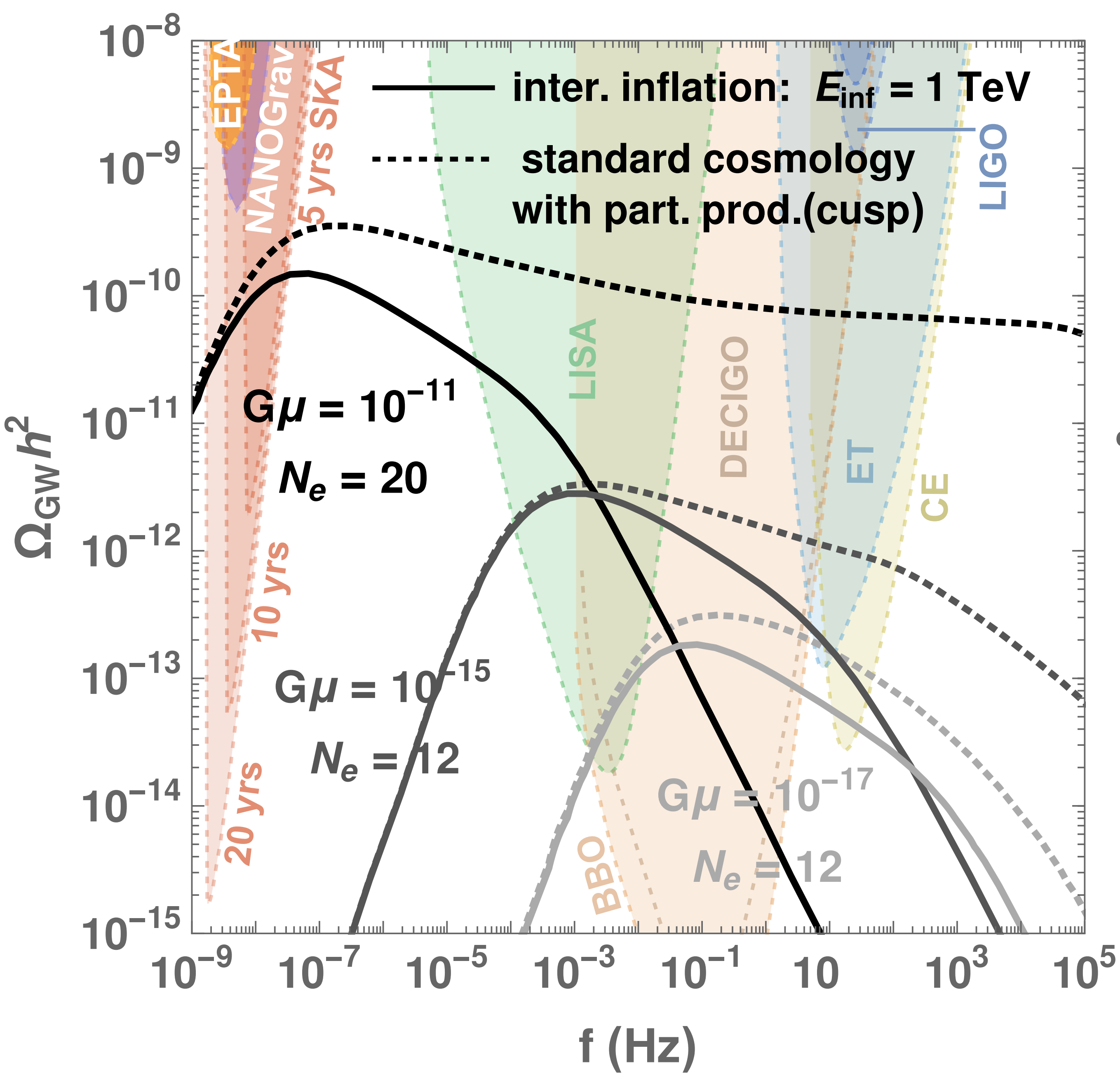




Non−standard cosmo.

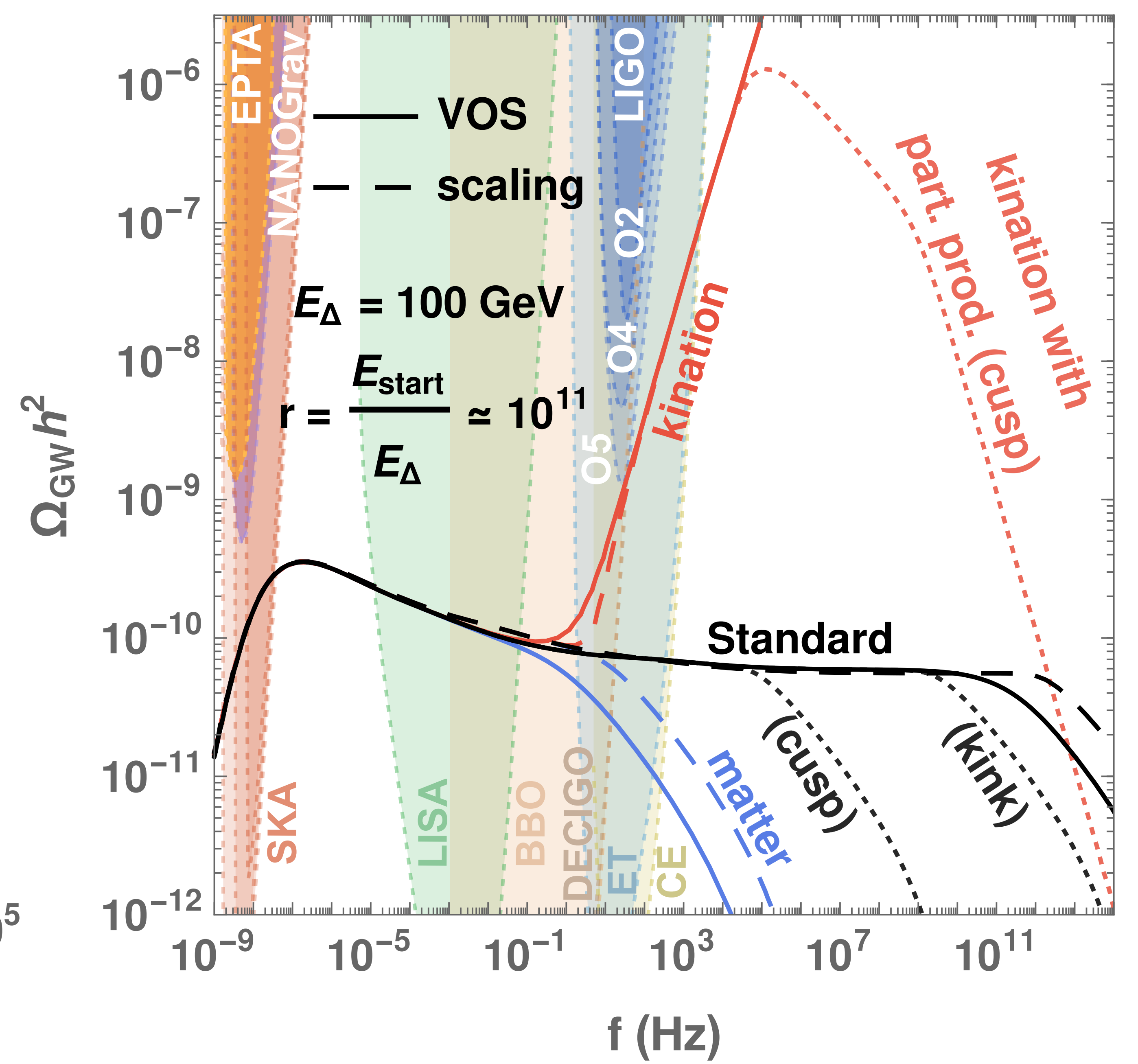
global strings: $\Gamma = 50$, $\alpha = 0.1$



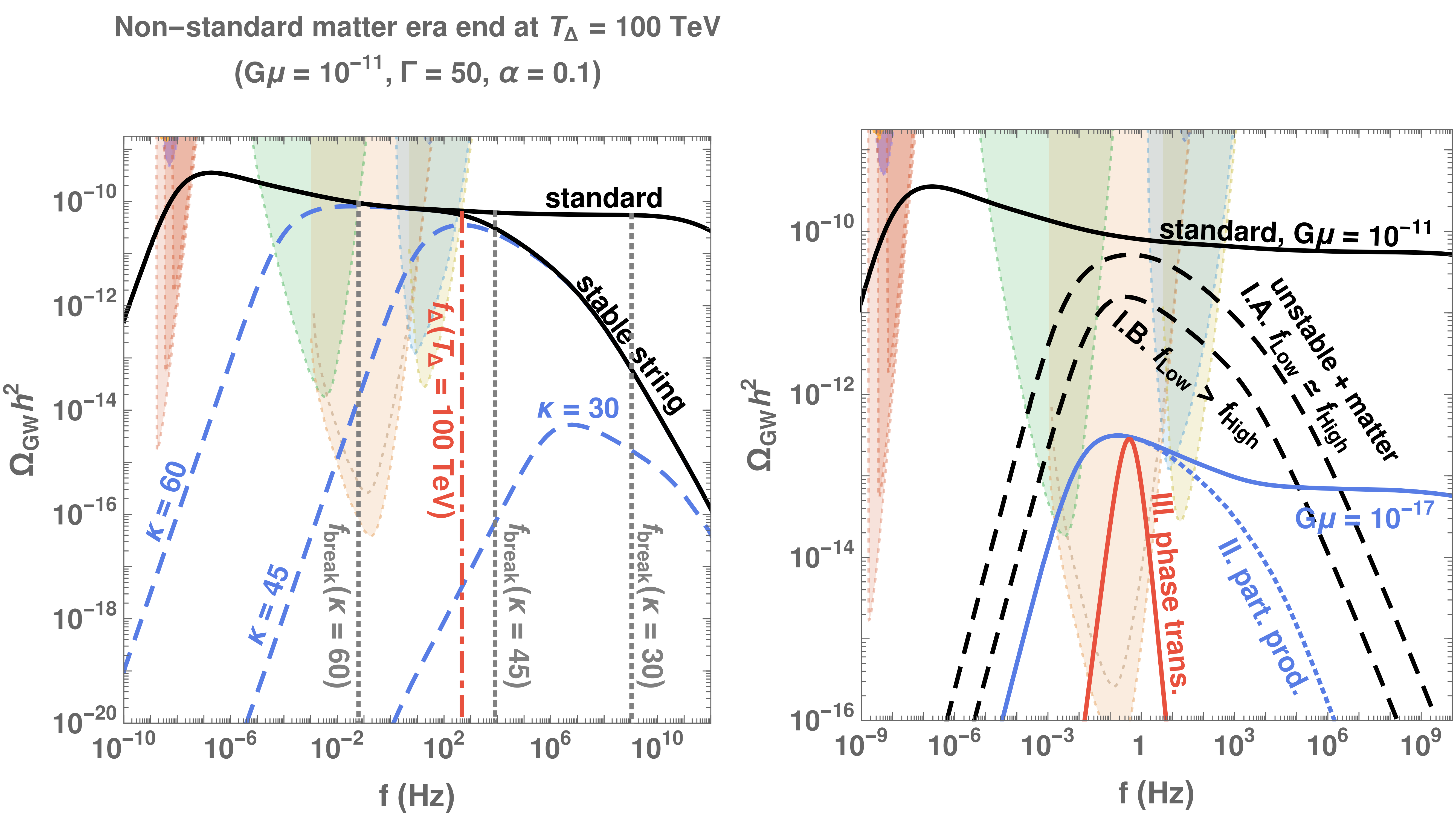
# Peak-like spectrum



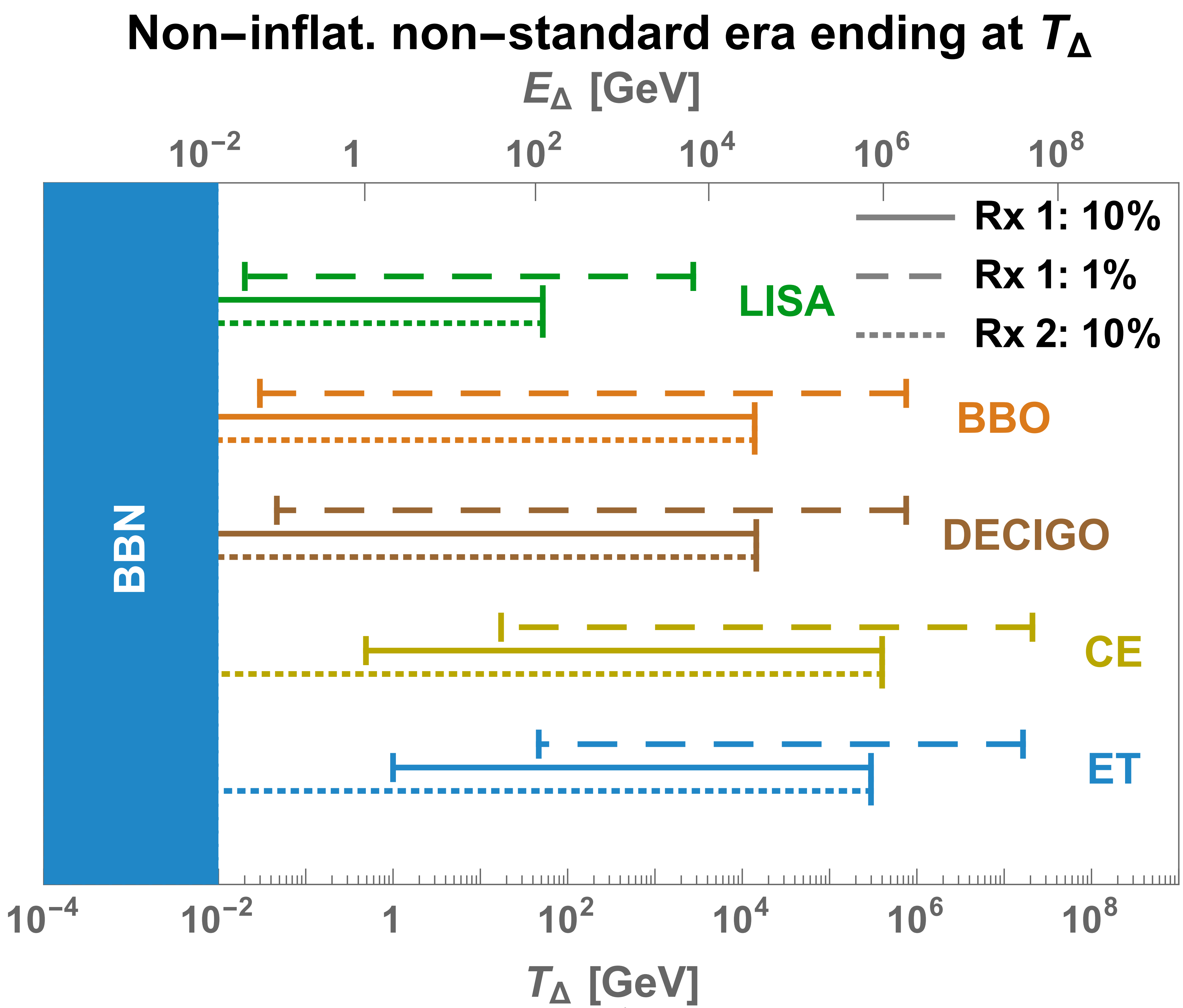

Non–standard cosmo. before rad. era
($G\mu = 10^{-11}$, $\Gamma = 50$, $\alpha = 0.1$)



# Peak-like spectrum



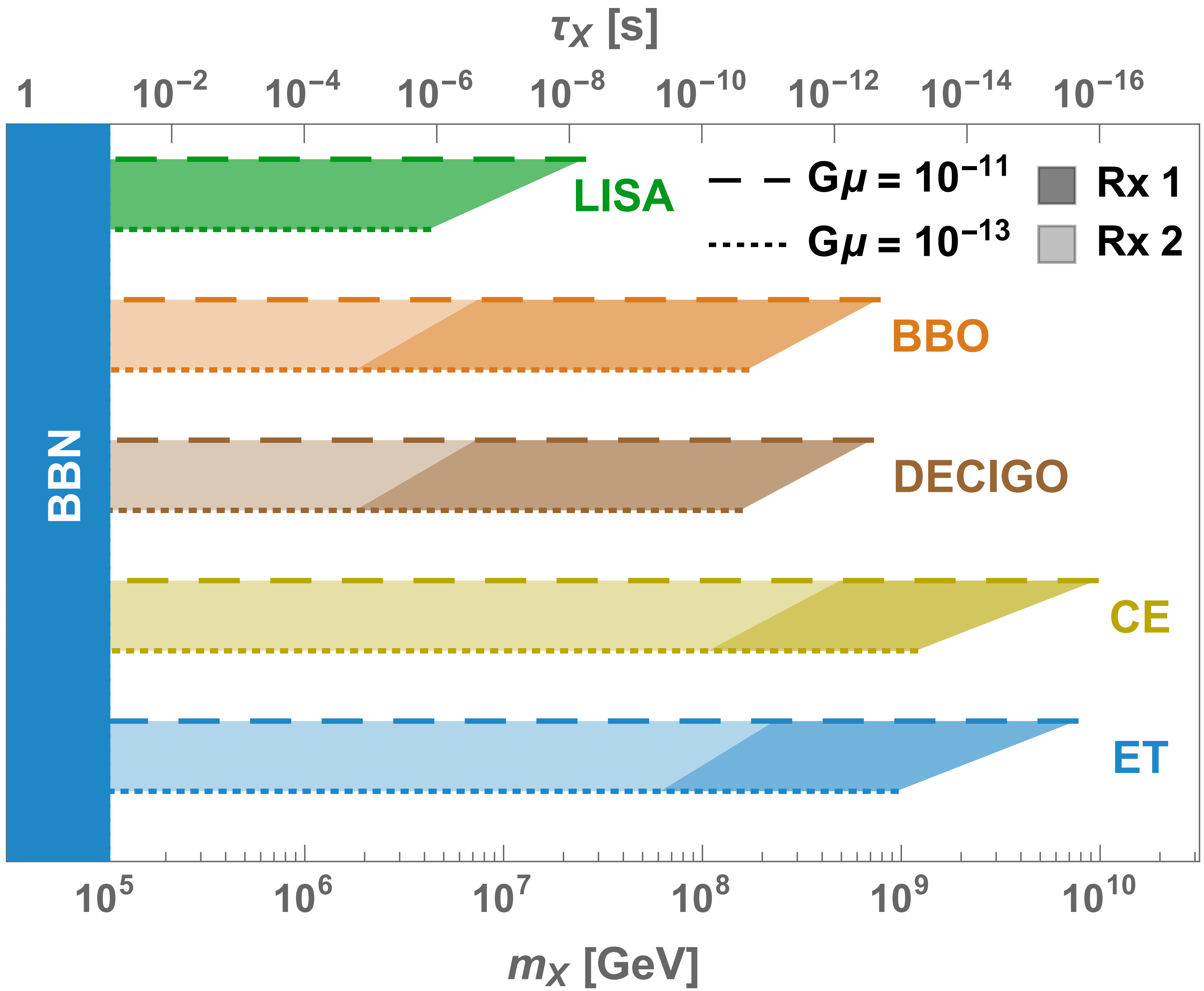
# Money plots



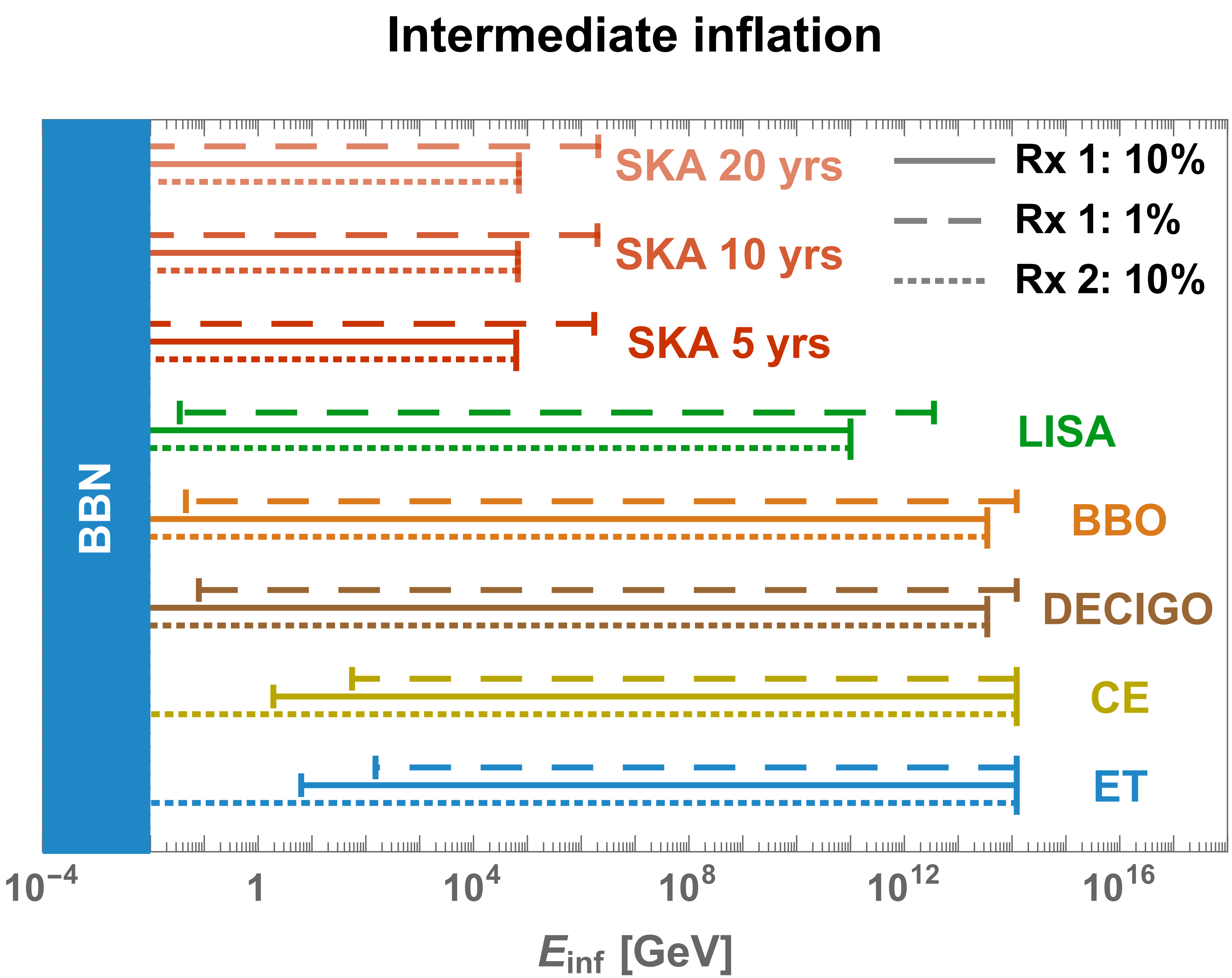
Non–inflat. non–standard era ending at $T_\Delta$
$E_\Delta$ [GeV]
$10^{-2}$
1
$10^2$
$10^4$
$10^6$
$10^8$
Rx 1: 10%
Rx 1: 1%
Rx 2: 10%
LISA
BBO
DECIGO
CE
ET
BBN
$10^{-4}$
$10^{-2}$
1
$10^2$
$10^4$
$10^6$
$10^8$
$T_\Delta$ [GeV]

# Money plots

$$\Gamma_X \simeq (8\pi)^{-1}\, m_X^3 \,/\, M_{\rm pl}^2$$

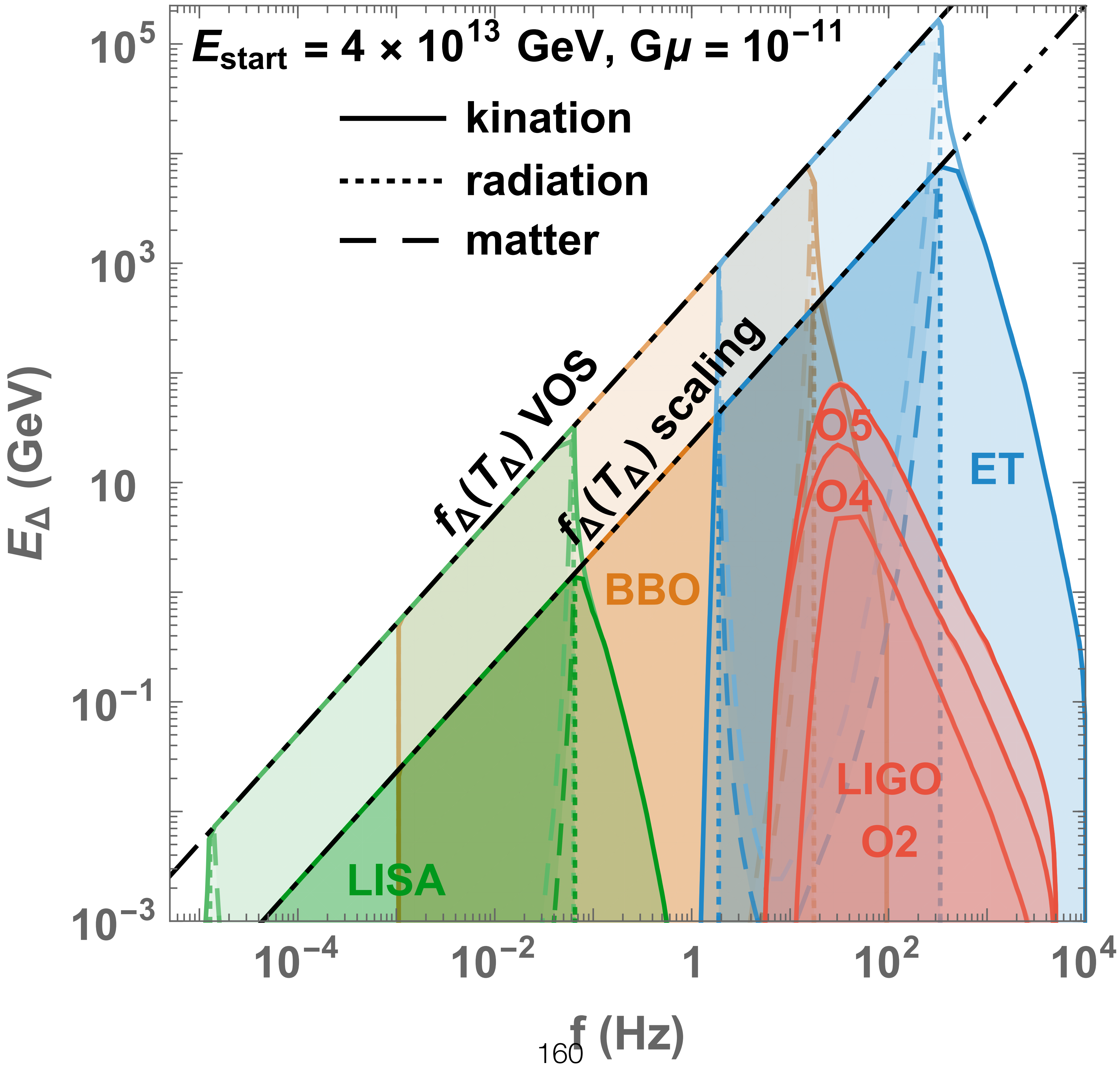


# Money plots

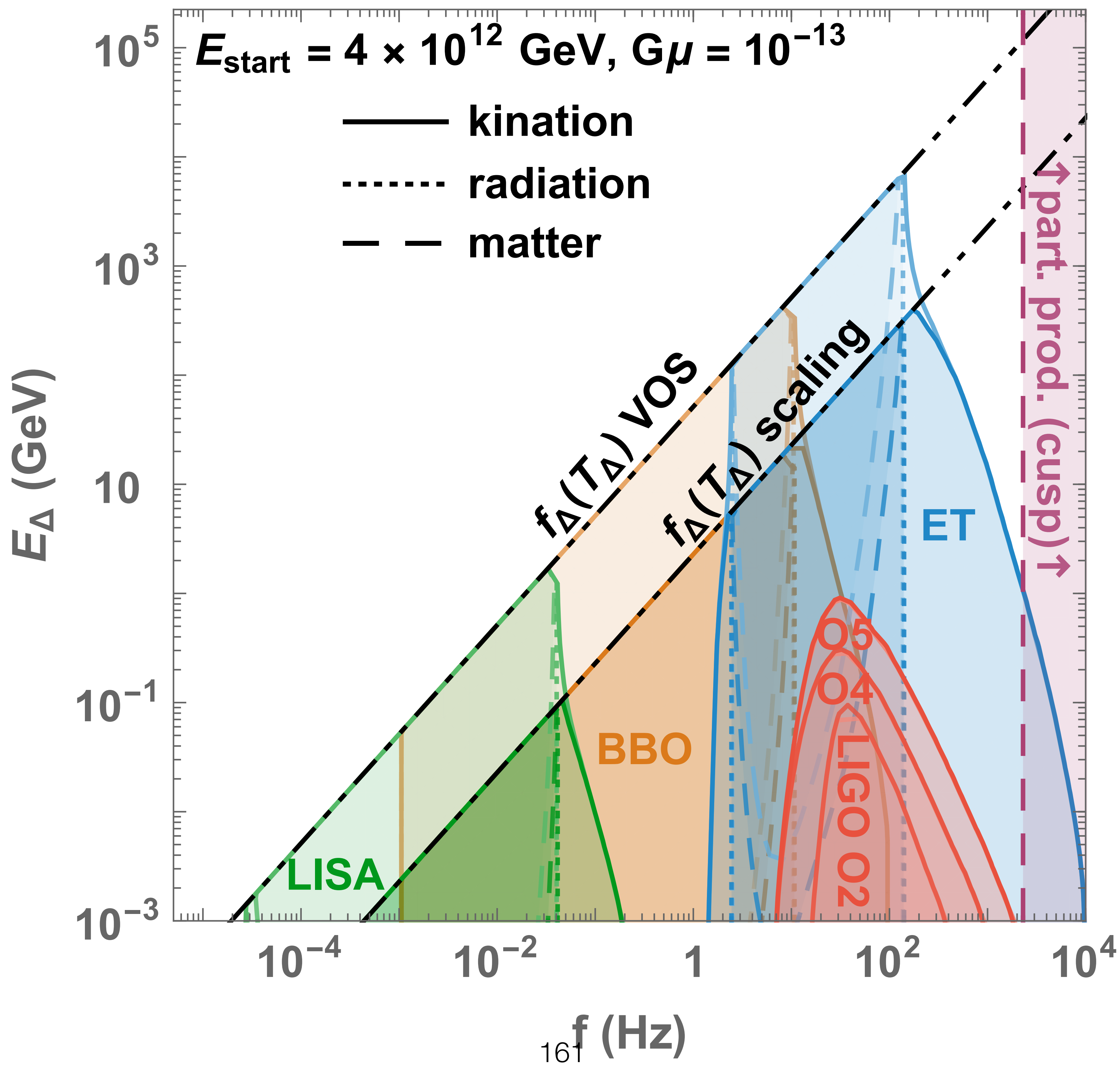


Intermediate inflation
SKA 20 yrs
SKA 10 yrs
SKA 5 yrs
LISA
BBO
DECIGO
CE
ET
BBN
Rx 1: 10%
Rx 1: 1%
Rx 2: 10%
$10^{-4}$
1
$10^{4}$
$10^{8}$
$10^{12}$
$10^{16}$
$E_{\rm inf}$ [GeV]

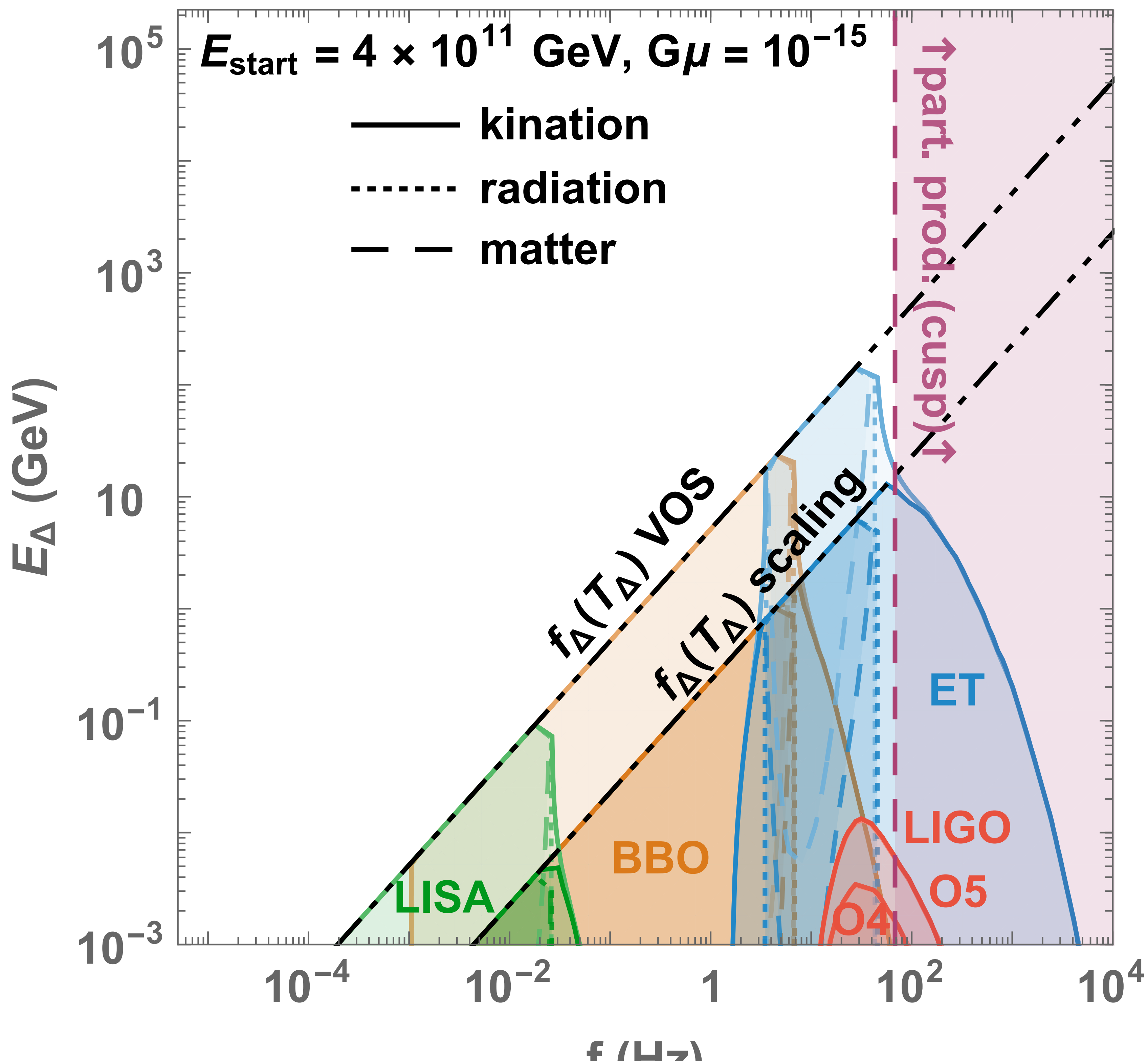
# VOS vs Scaling



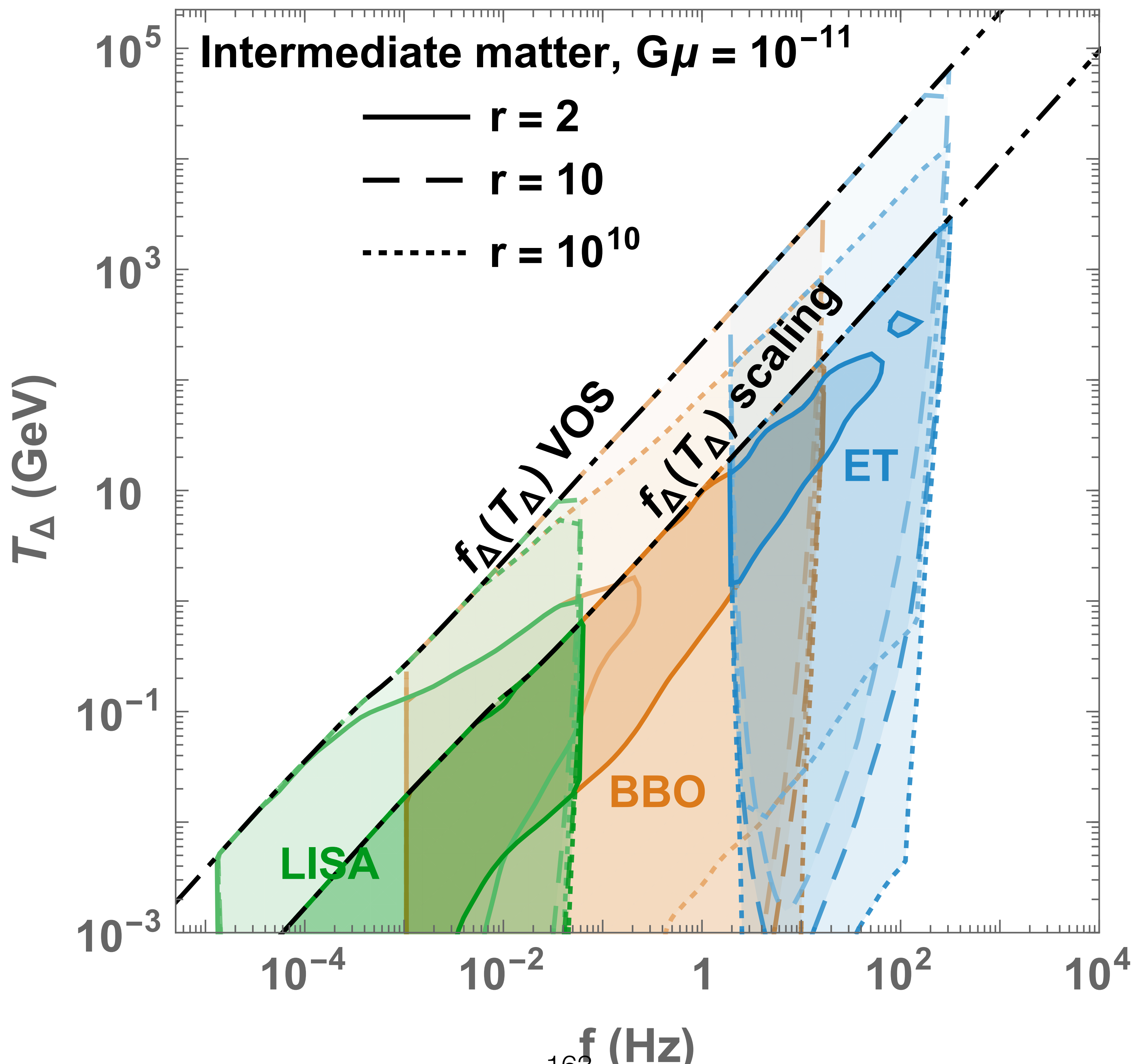
# VOS vs Scaling



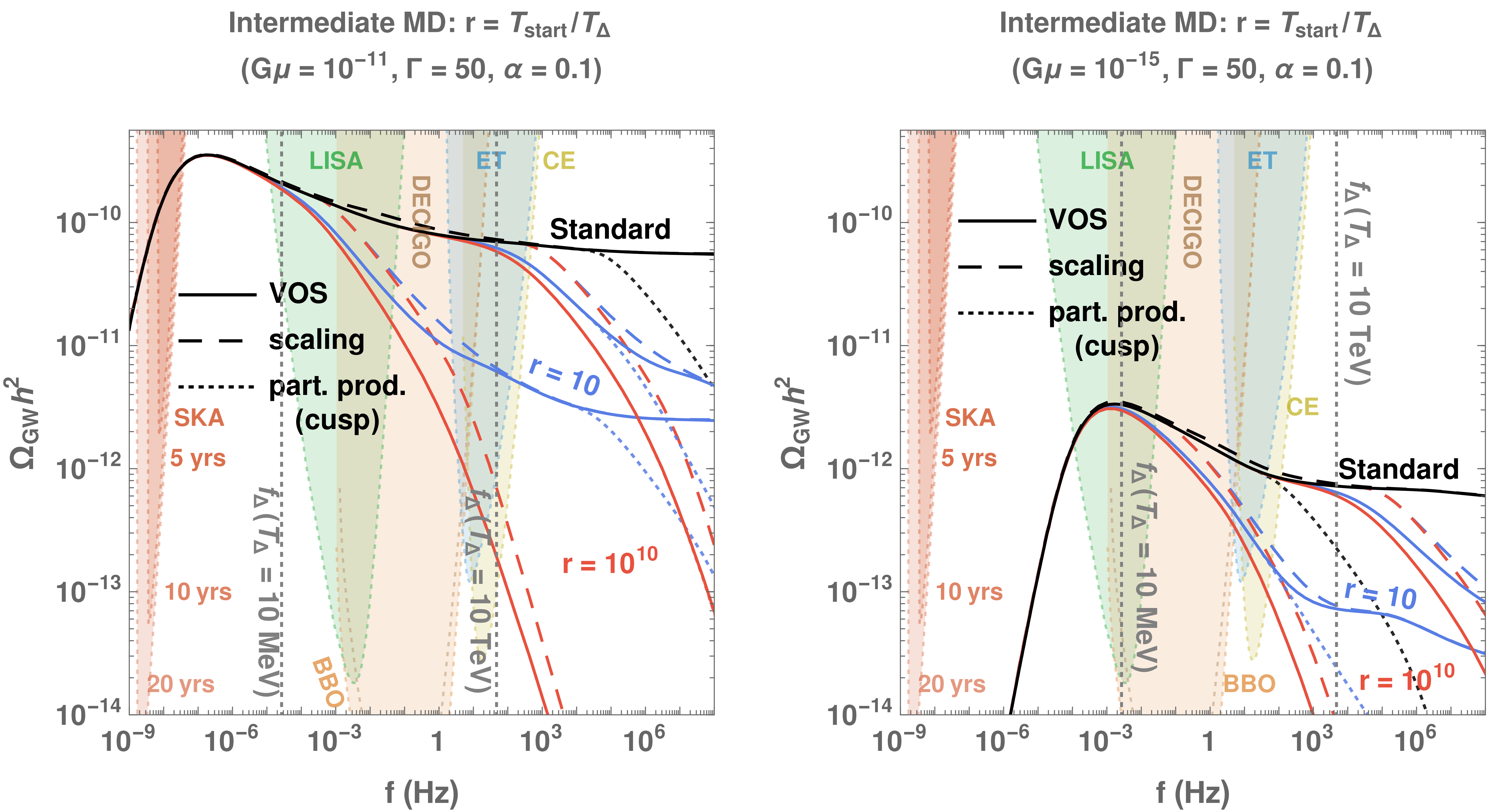
# VOS vs Scaling



# VOS vs Scaling



# VOS vs Scaling



# Intermediate inflation era

**Scaling:** **L ∝ t**

$a_{\rm start}$

**Inflation:** **L ∝ a**

$$a_{\rm end} = a_{\rm start}\, e^{N_e}$$

**L ∝ a** **( L >> t )**

$$a_{\rm re-enter} = a_{\rm start}\, e^{2N_e}$$

**Scaling:** **L ∝ t**

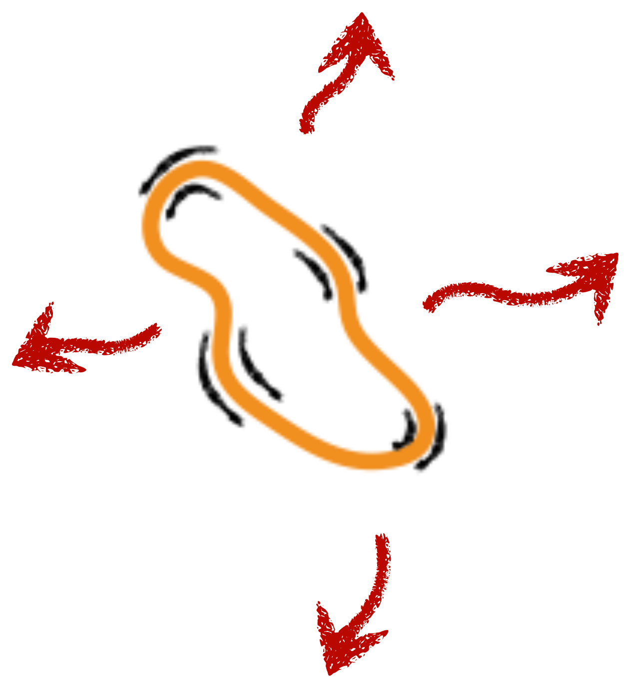
**a**

# Consequences of scaling regime:

- Long-standing source of GW

  From network formation until today

  $\neq$ GW from 1st order PT



- Flat GW spectrum during radiation

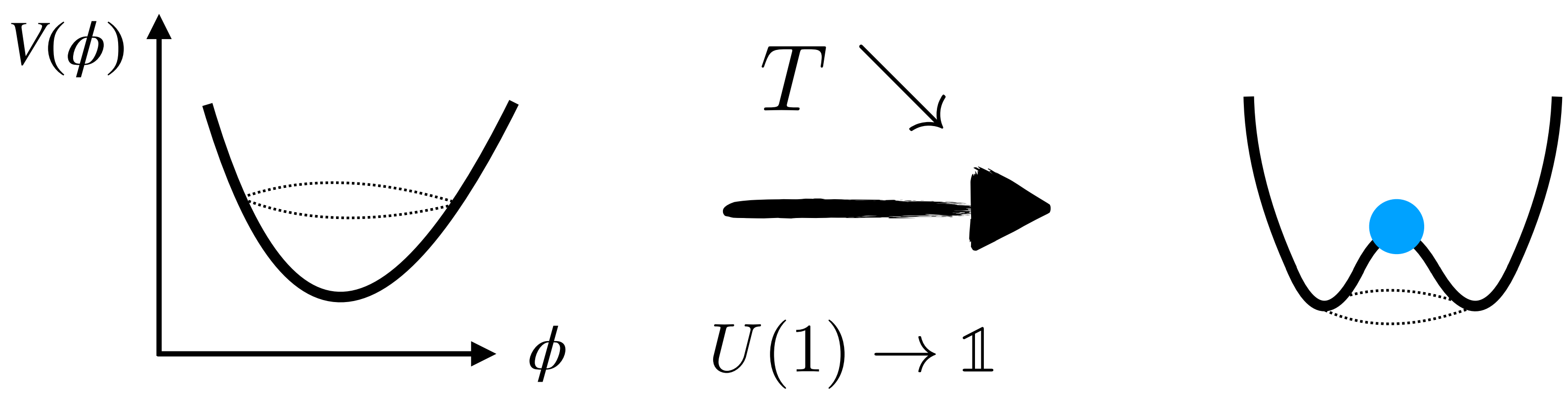
Freq $\nearrow$ ➔ Loops smaller

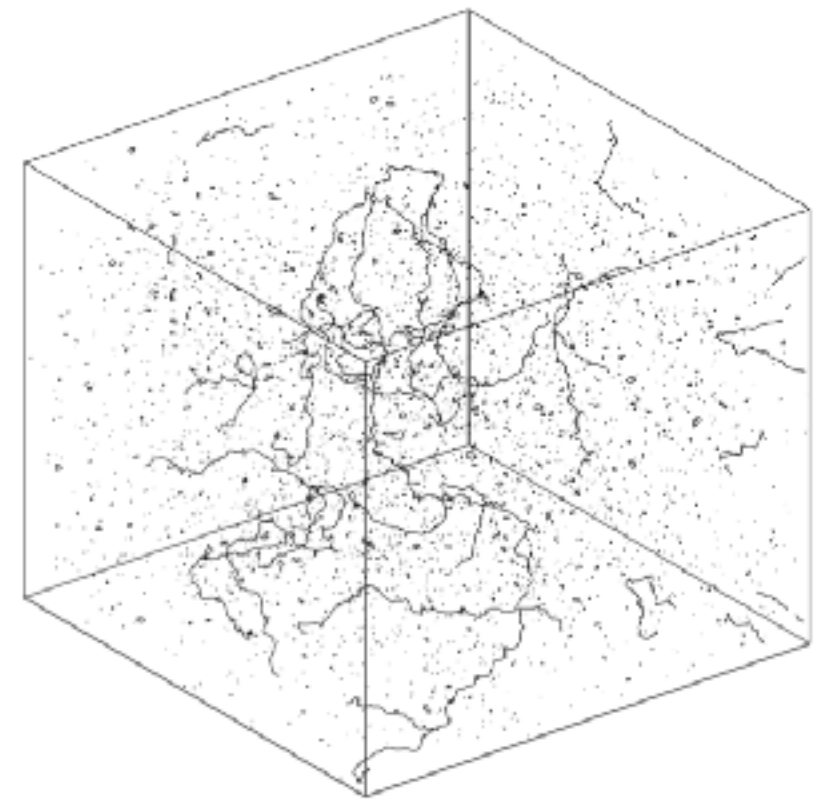
➔ $\begin{cases} \text{Loops produced earlier} \rightarrow \text{more loops} \\ \text{GW emission earlier} \rightarrow \text{more redshift} \end{cases}$

➔ 2nd Conspiracy

# String network formation

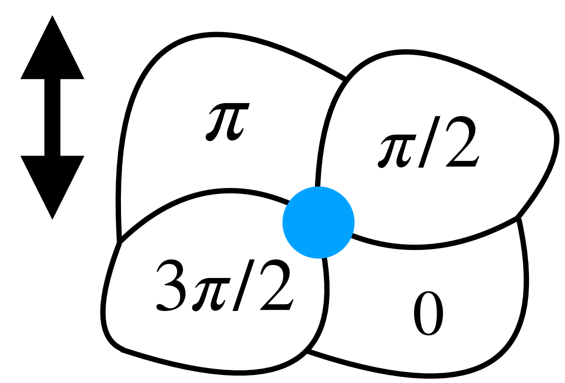
- **Can be topological defects generated during spontaneous-symmetry-breaking** [Kibble 1976]



[Allen & Shellard 1990]

**correlation length** $L$




- **Nambu-Goto approximation**

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

# String network evolution

**Energy density:** $\rho_\infty = \mu/L^2$

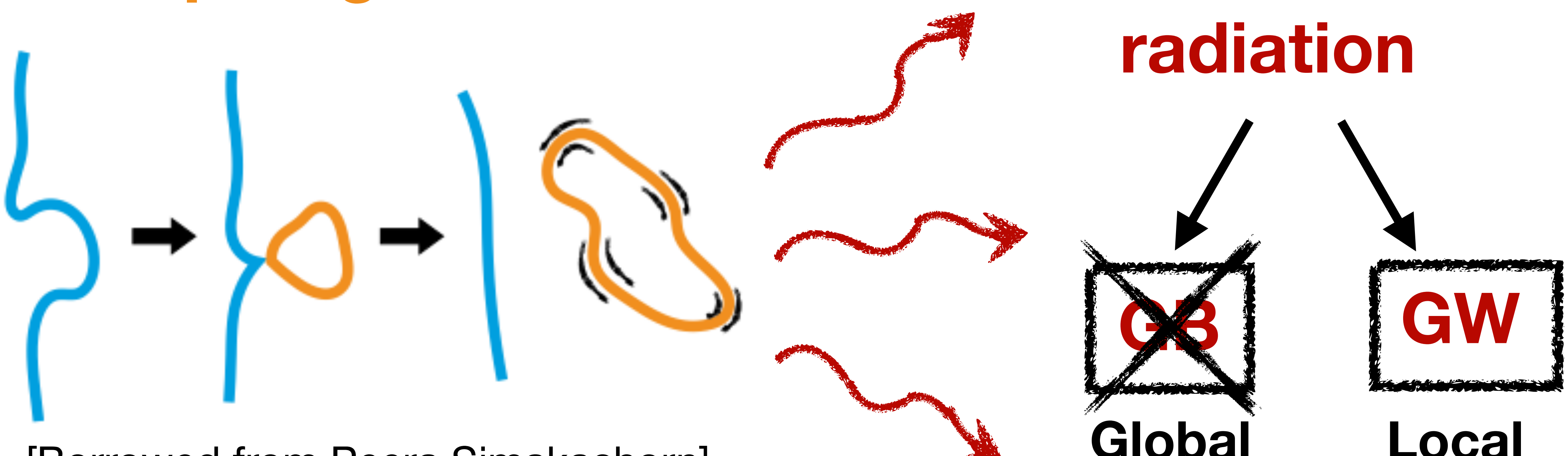
- **Two competing dynamics:**

1) **Hubble expansion:** $L \propto a \rightarrow \rho_\infty \propto a^{-2}$

→ **Would over-close the universe**

2) **Loop fragmentation:**

**Massless radiation**




[Borrowed from Peera Simakachorn]

# String network evolution

Energy density: $\rho_\infty = \mu/L^2$

- Two competing dynamics:

1) Hubble expansion: $L \propto a \rightarrow \rho_\infty \propto a^{-2}$

→ Would over-close the universe

2) Loop fragmentation:

- Conspiracy between 1) and 2)

→ Scaling regime: $L \propto t$

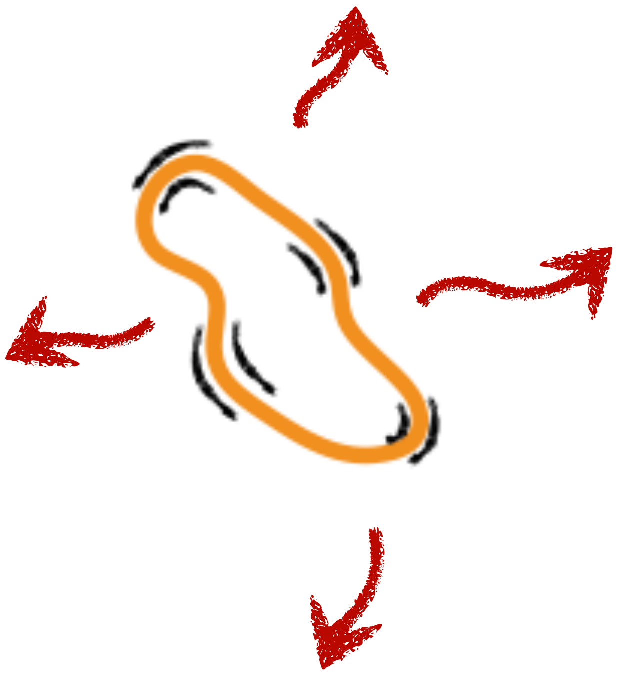
→ $$\rho_\infty \propto \begin{cases} a^{-4} & \text{during radiation} \\ a^{-3} & \text{during matter} \end{cases}$$

# Consequences of scaling regime:

- **Long-standing source of GW**

  **From network formation until today**

  $\neq$ **GW from 1st order PT**

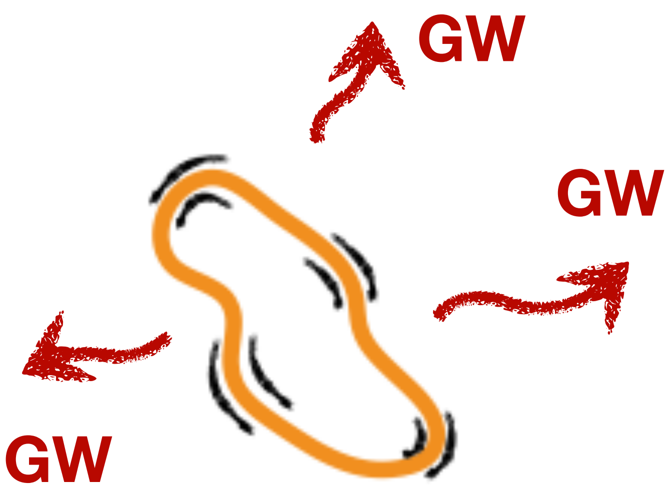


- **Flat GW spectrum during radiation**

  ➔ **Conspiracy between number of loops and redshift factor**

  ➔ **Deviation from flat in matter, kination, inflation..**

# GW spectrum from Cosmic Strings




- **Emitted power into GW**

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

$$\Gamma = 50$$

- **Current bound by pulsar arrays :**

$G\mu \gtrsim 10^{-11} \to \langle\phi\rangle \gtrsim 10^{13}$ GeV

- **Reach of future interferometer:**

$G\mu = 10^{-19} \to \langle\phi\rangle \simeq 10^{9}$ GeV