Ultrahigh–frequency GW backgrounds from "Cosmic Strings"

Peera Simakachorn

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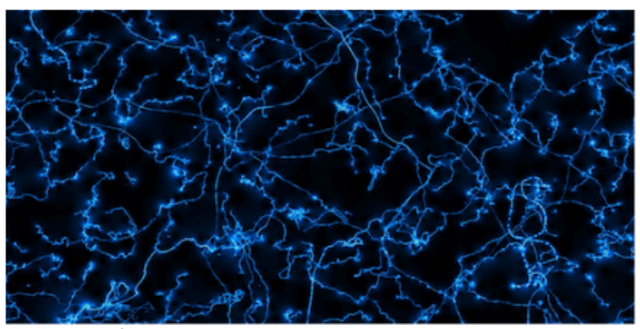
with

Géraldine Servant (U. Hamburg and DESY)

based on

Phys. Rev. D 109, 103538 [arXiv: 2312.09281]

Featured in Physics | Editors' Suggestion



C. Ringeval/Louvain University

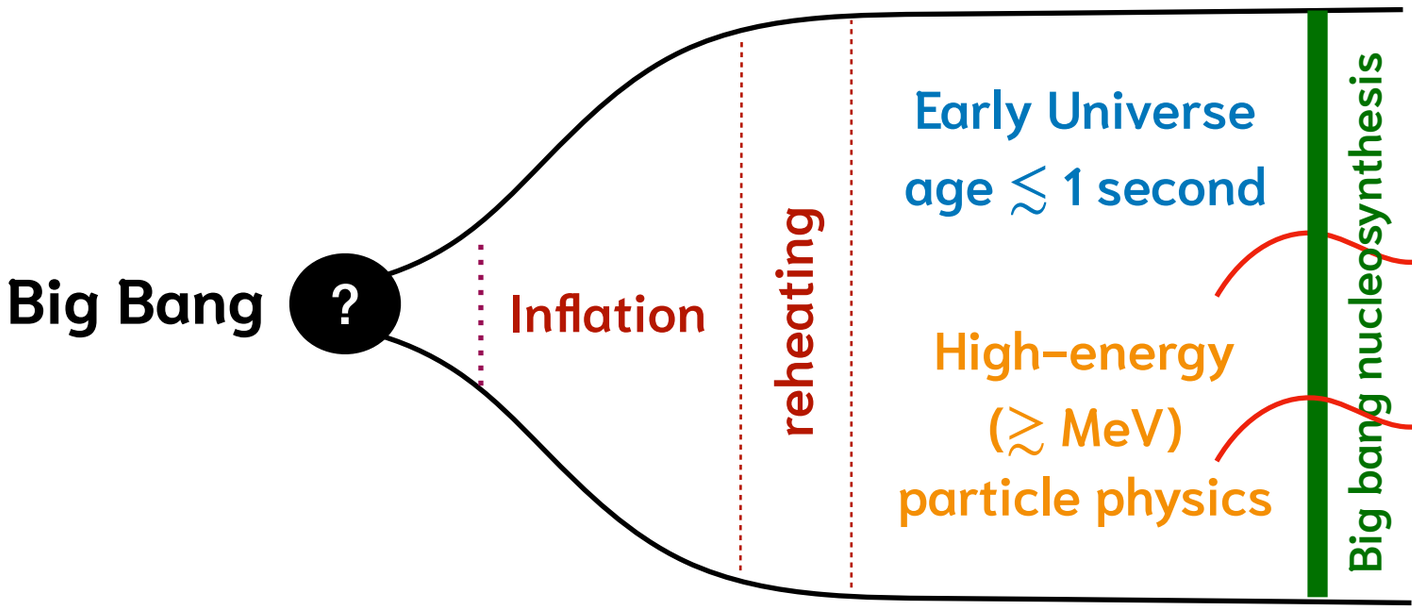
Physics NEWS AND COMMENTARY

Cosmic Strings' Imprints in High-Frequency Gravitational Waves

May 23, 2024

PLANCK 2024, Lisbon (06.06.2024)

Gravitational waves (GWs) as tools for charting the early-Universe cosmology and high-energy particle physics.



(See also e,g., talks by Stefan Antusch, Stephen King, and many others.)

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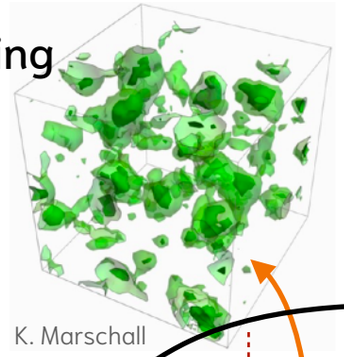
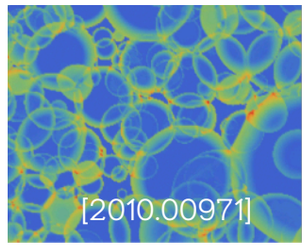
Many GW sources...(mostly BSM physics)

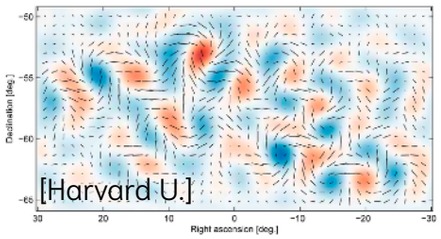
Preheating





1st-order phase trans.

Quantum fluctuation



Big Bang ?

Inflation

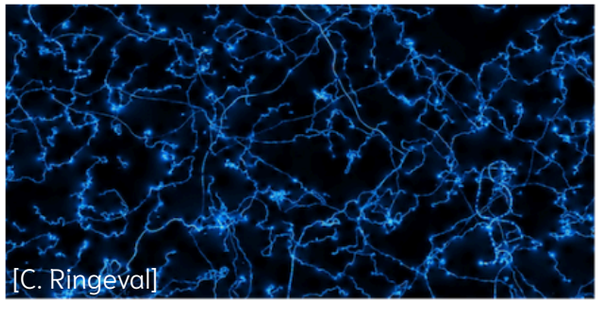
reheating

Early Universe
age $\lesssim$ 1 second

High-energy
($\gtrsim$ MeV)
particle physics

Big bang nucleosynthesis

GW



Cosmic strings

and other topological defects

(e.g., from Grand Unified Theories, Axions)

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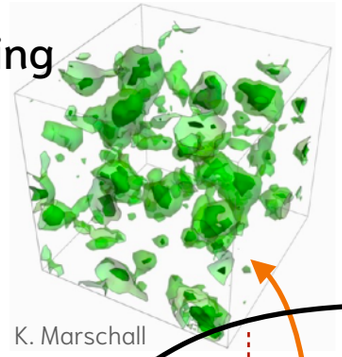

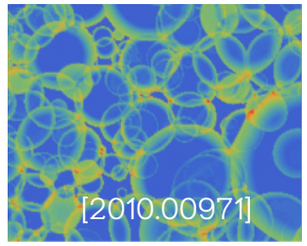

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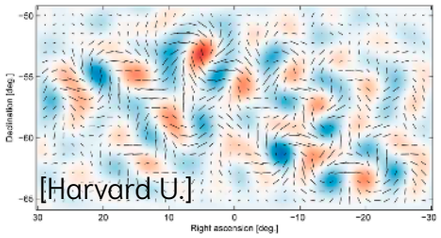

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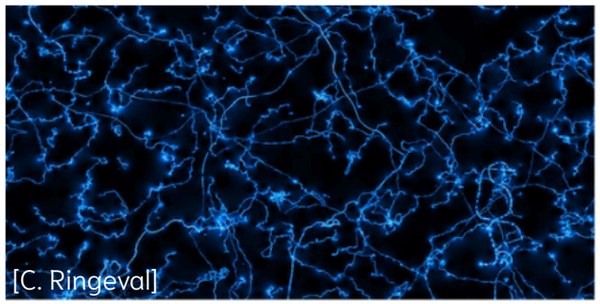

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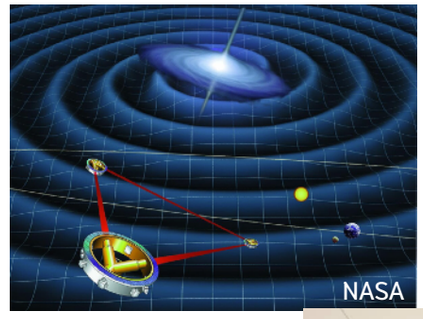
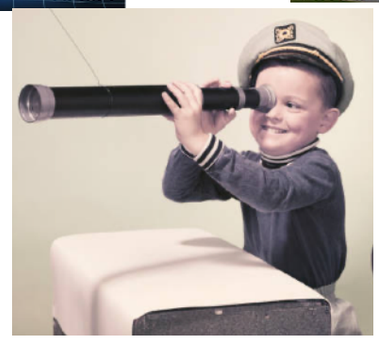
Many ways to detect...

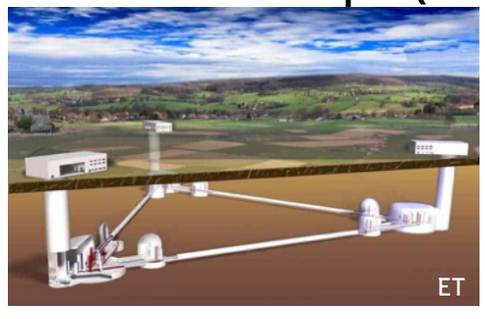
LISA



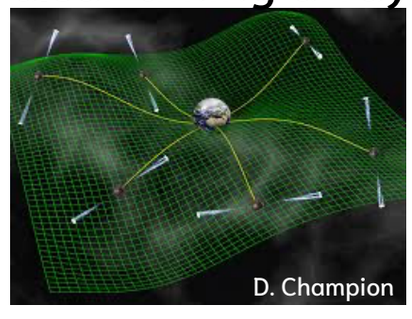
LIGO/VIRGO/KAGRA



Einstein Telescope (ET)



Pulsar timing arrays



NANOGrav, EPTA, PPTA, ...

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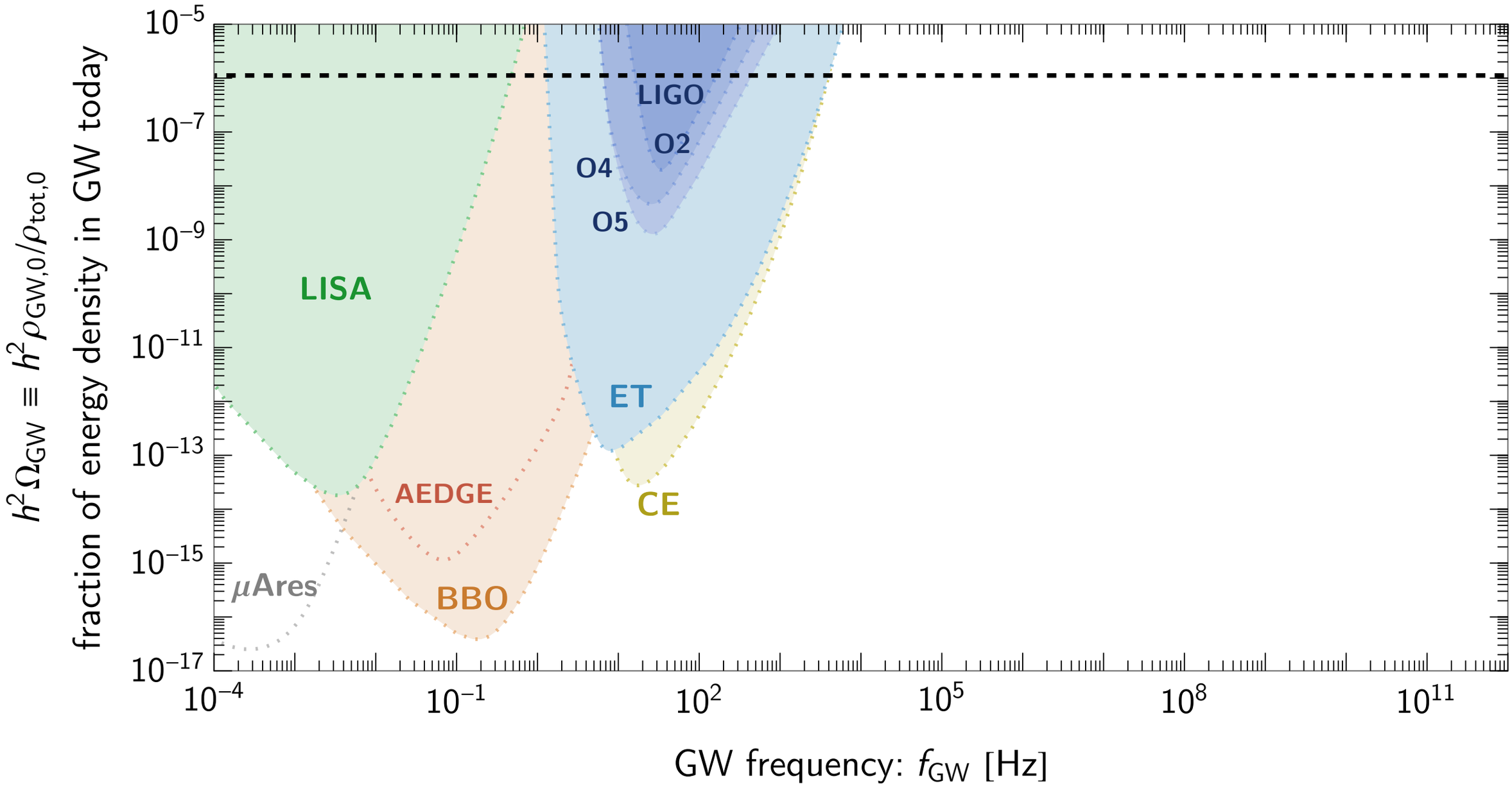
Gravitational–Wave Landscape



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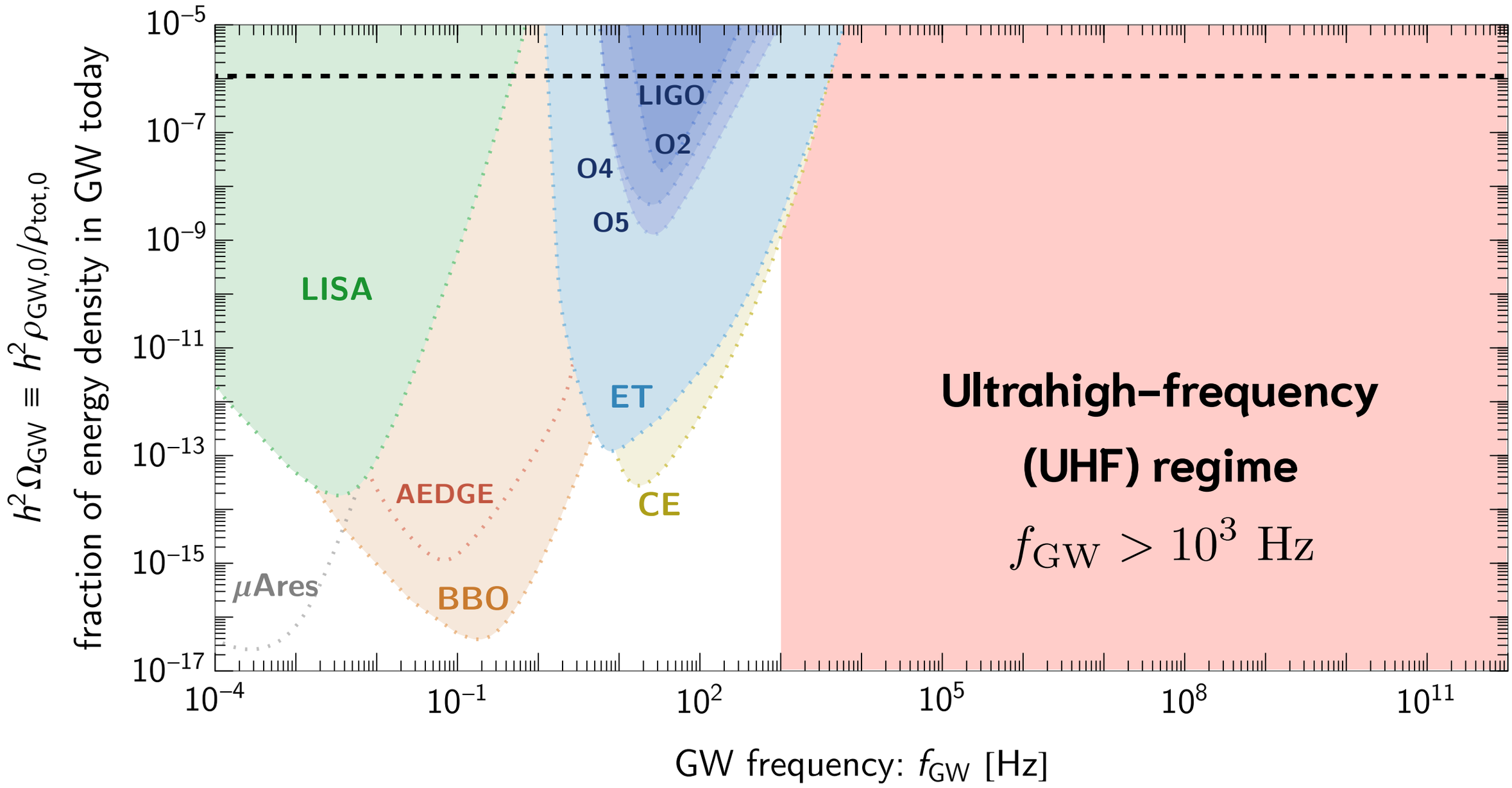

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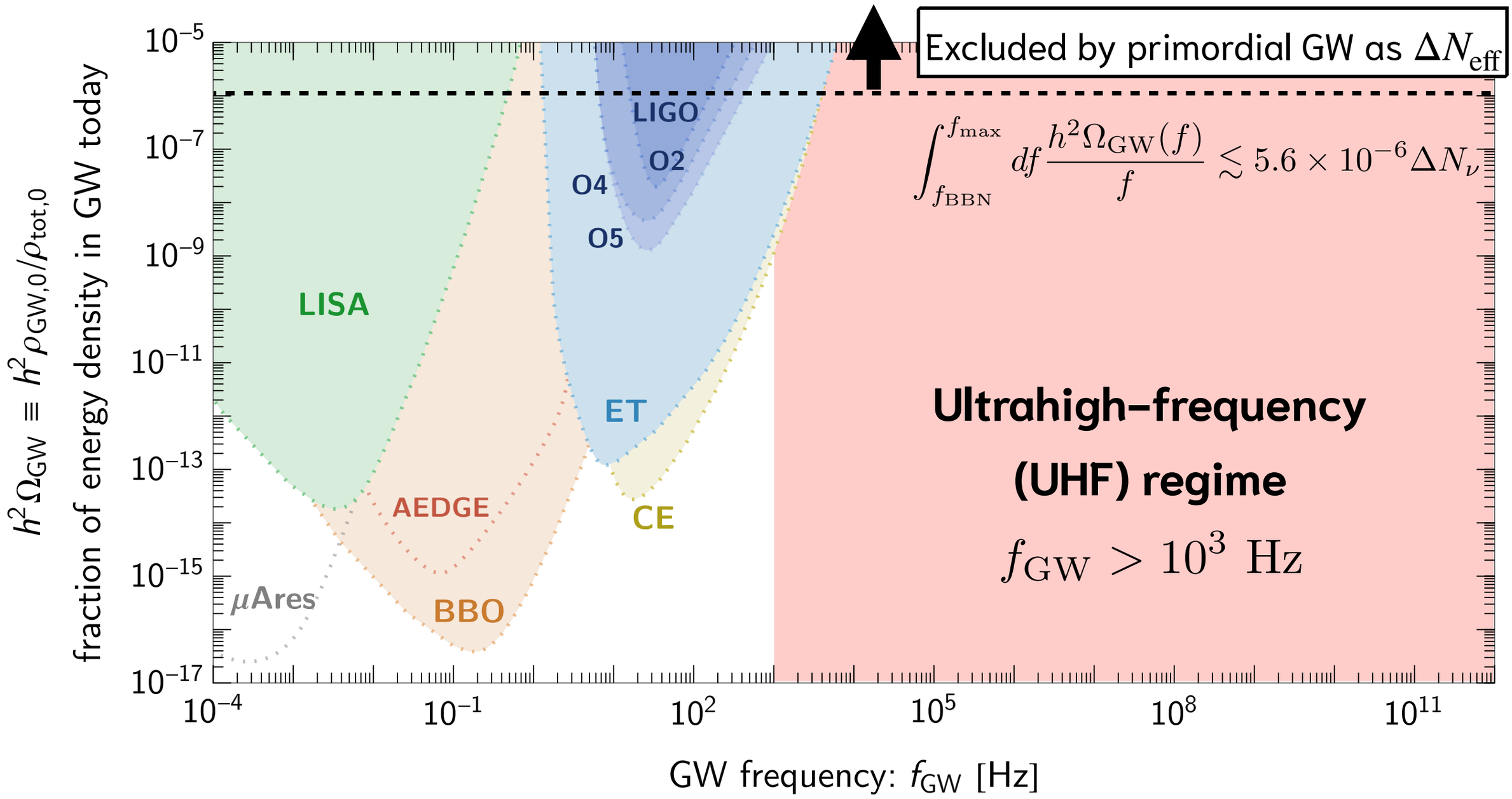

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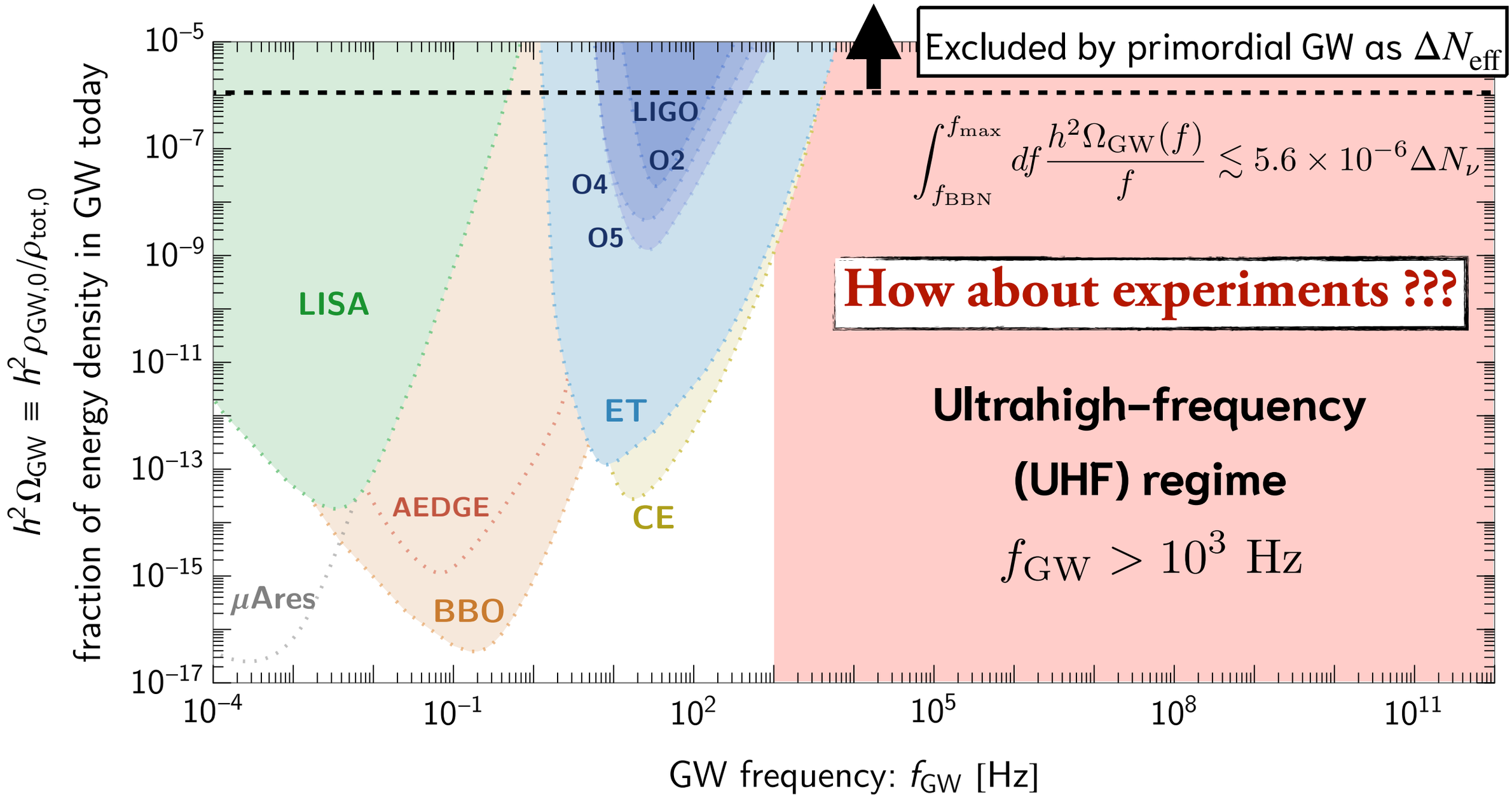
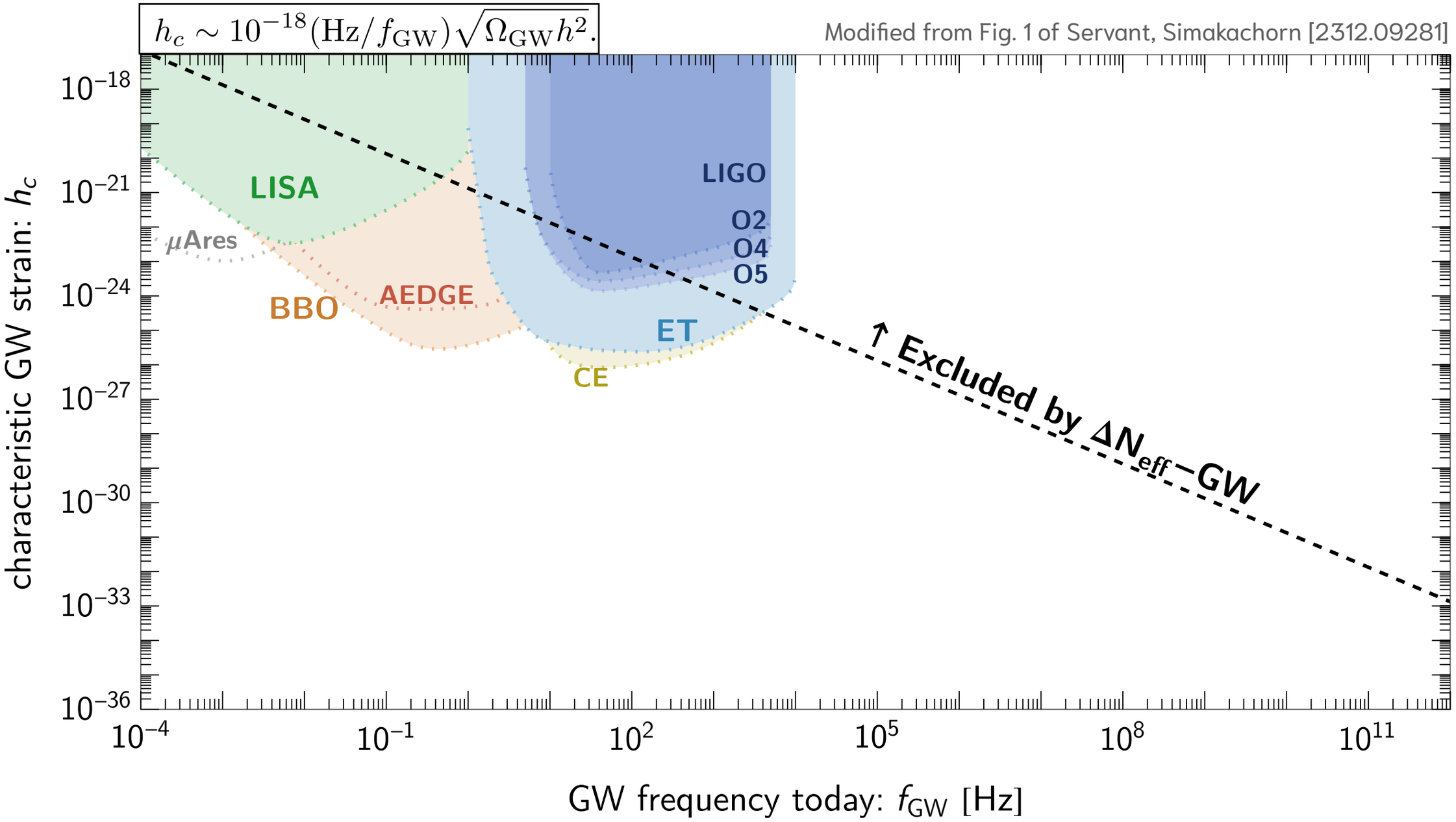


Current status of UHF GW experiments



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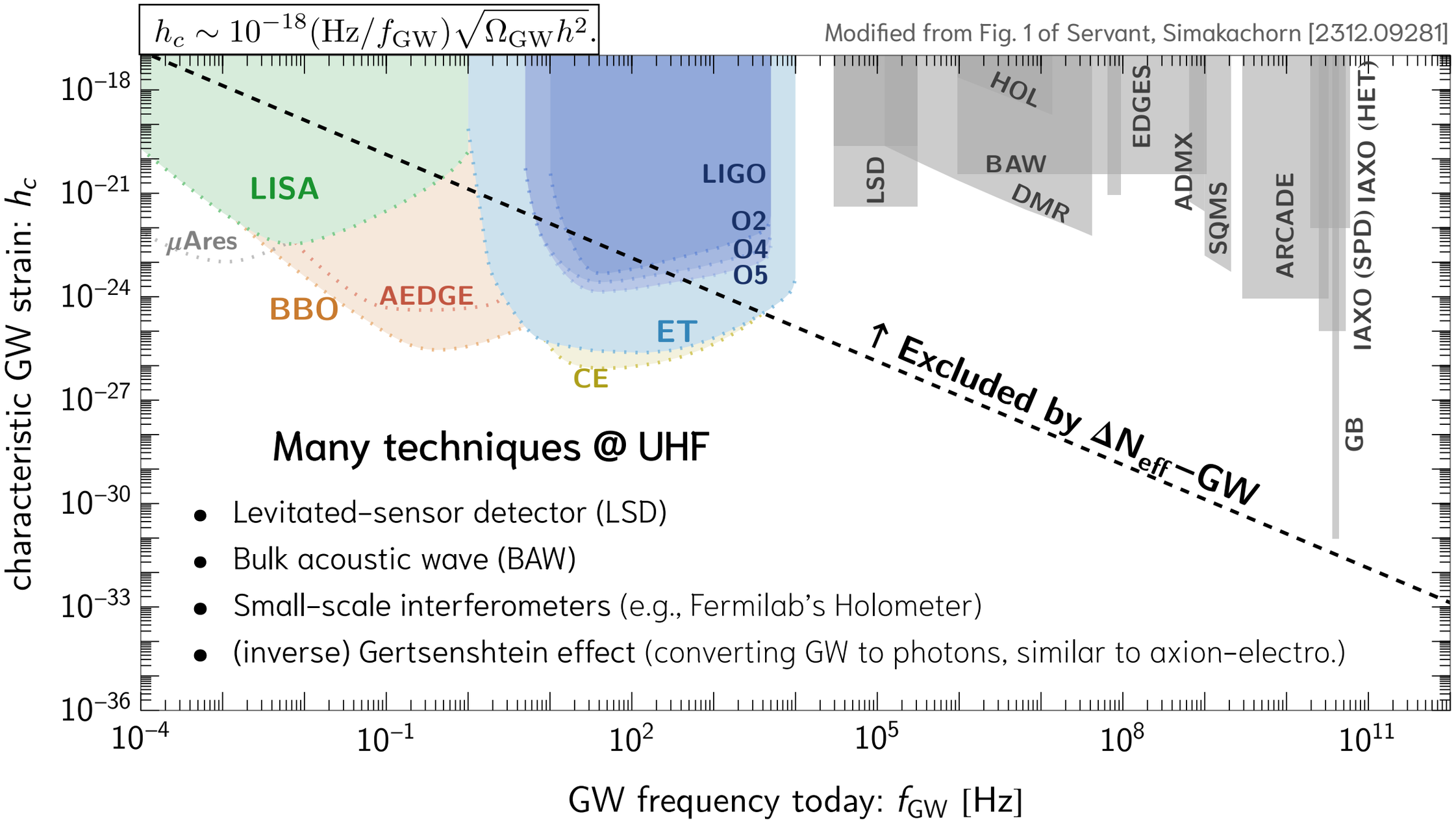

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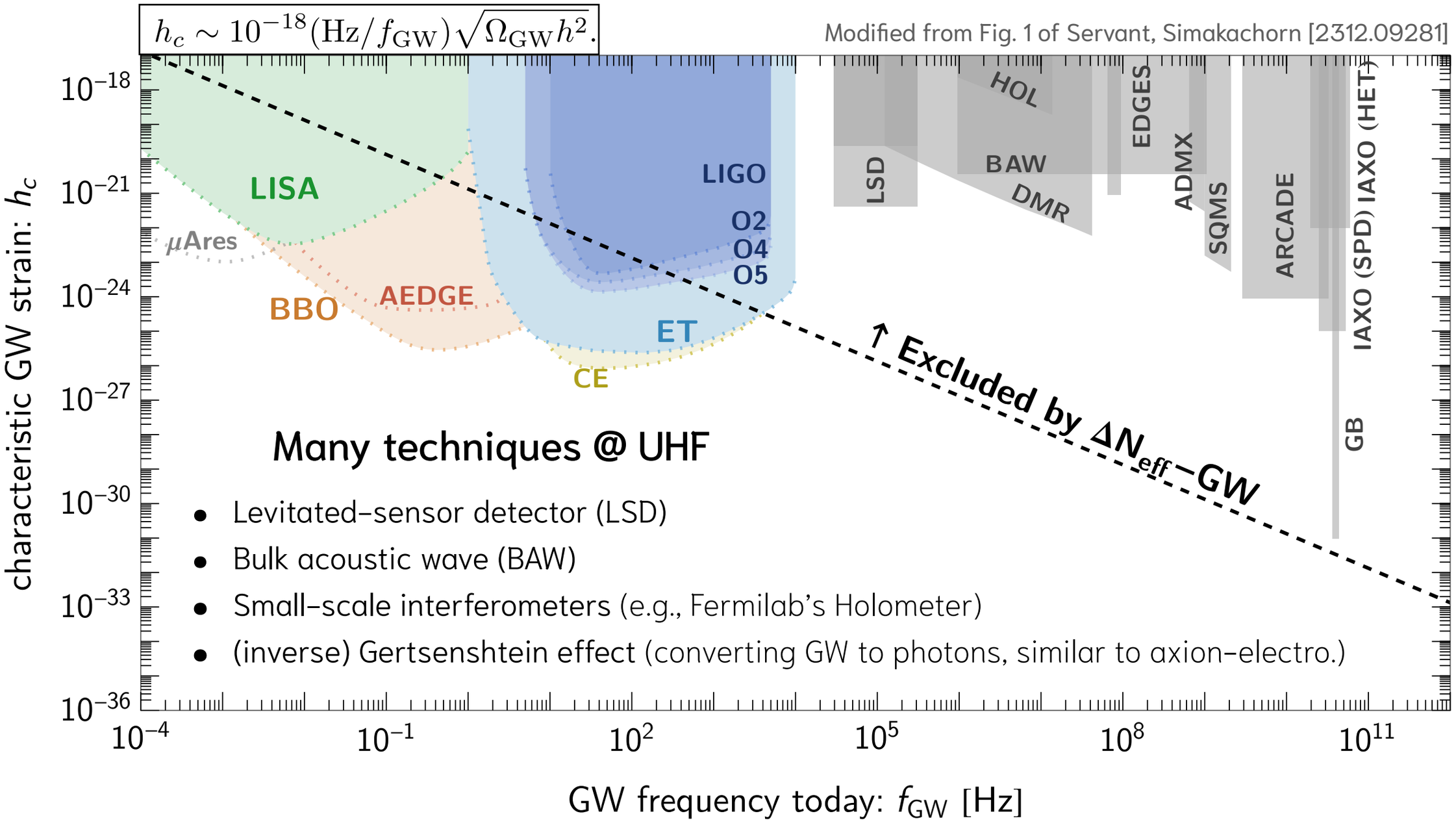


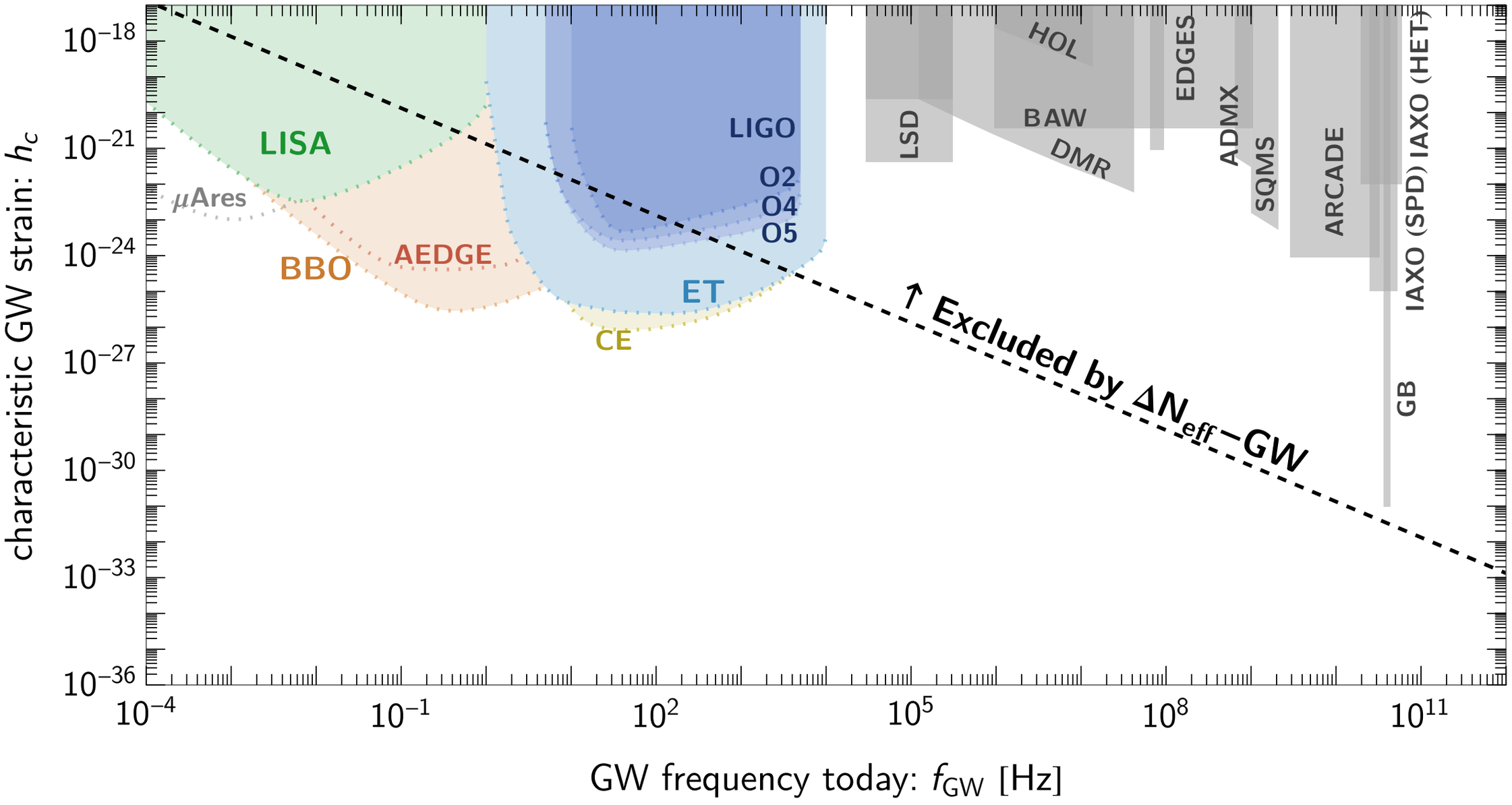
The ΔN_{eff}-GW bound is so far the strongest, but one should keep thinking because…

UHF regime = A golden window for new physics

Reasons:

- UHF window is clean from standard astro signals (e.g., from binaries of massive objects).

Servant, Simakachorn [2312.09281]



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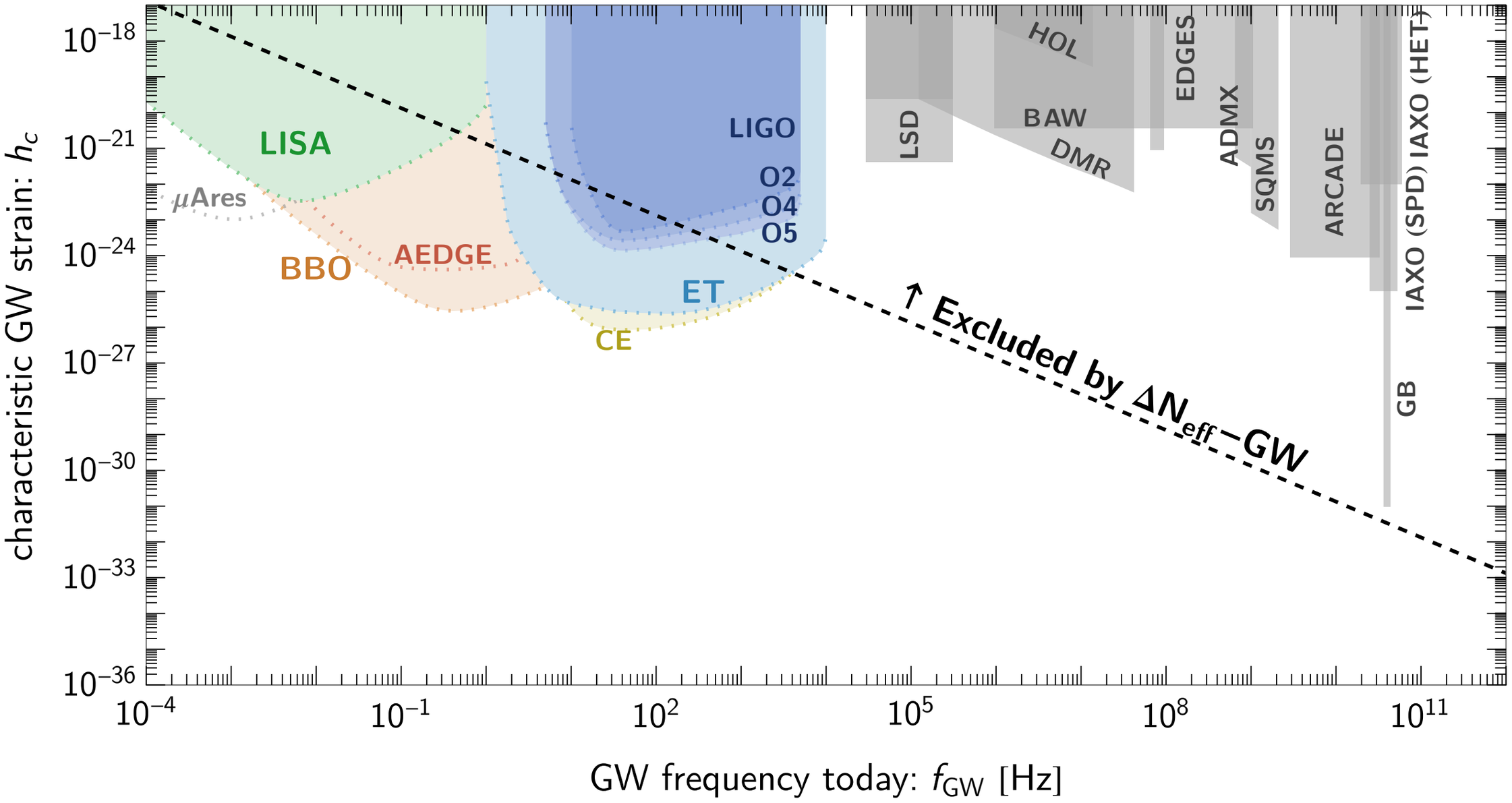

- **Signals from well-motivated sources, both SM and BSM @ ultrahigh energies**

$$f_{\rm GW} = f_{{\rm GW},e}\left(\frac{a_e}{a_0}\right) \simeq 1\ {\rm kHz}\left[\frac{H^{-1}(T)}{\lambda_{\rm GW}}\right]\left(\frac{T}{10^{10}\ {\rm GeV}}\right),$$

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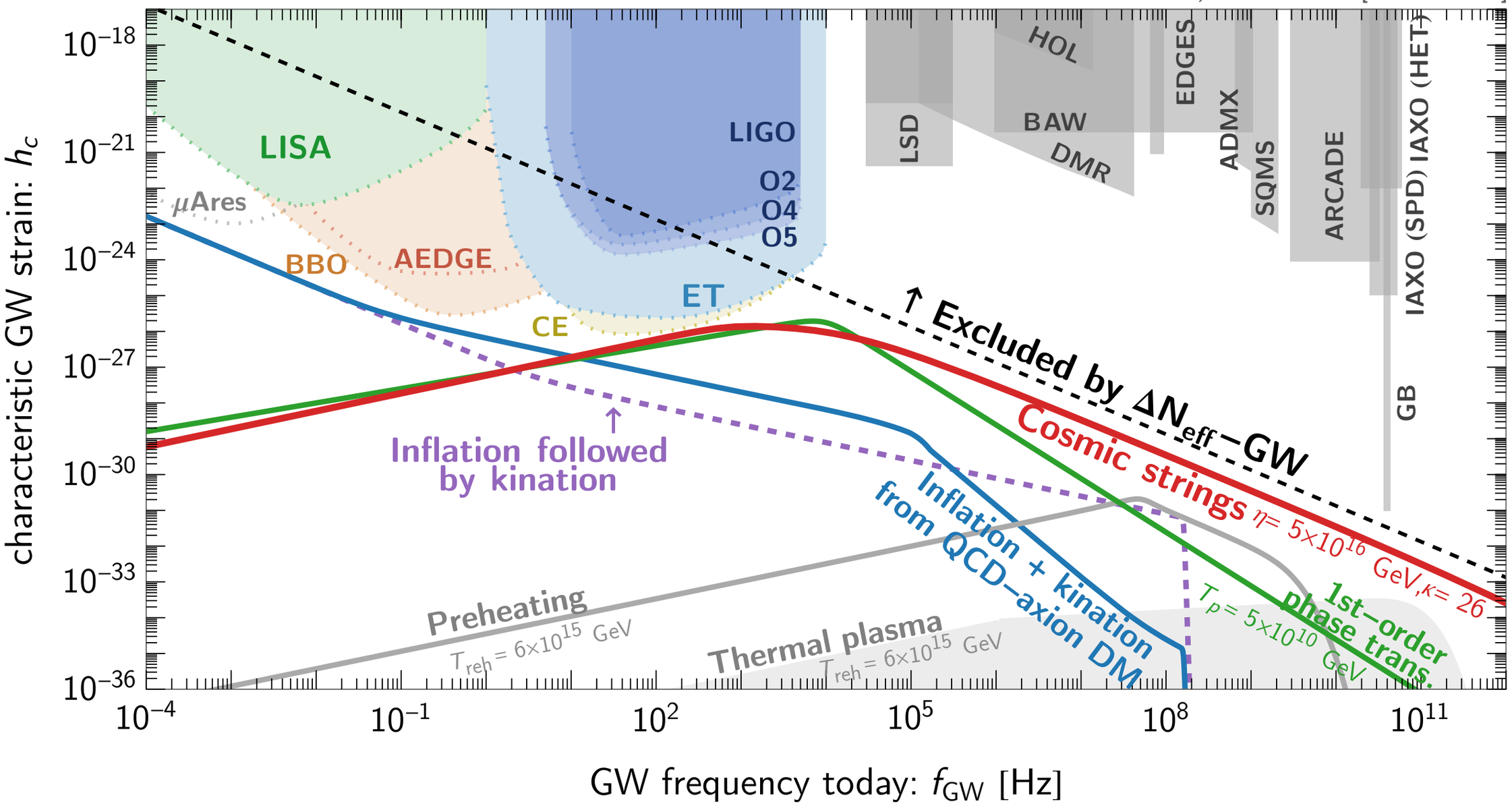

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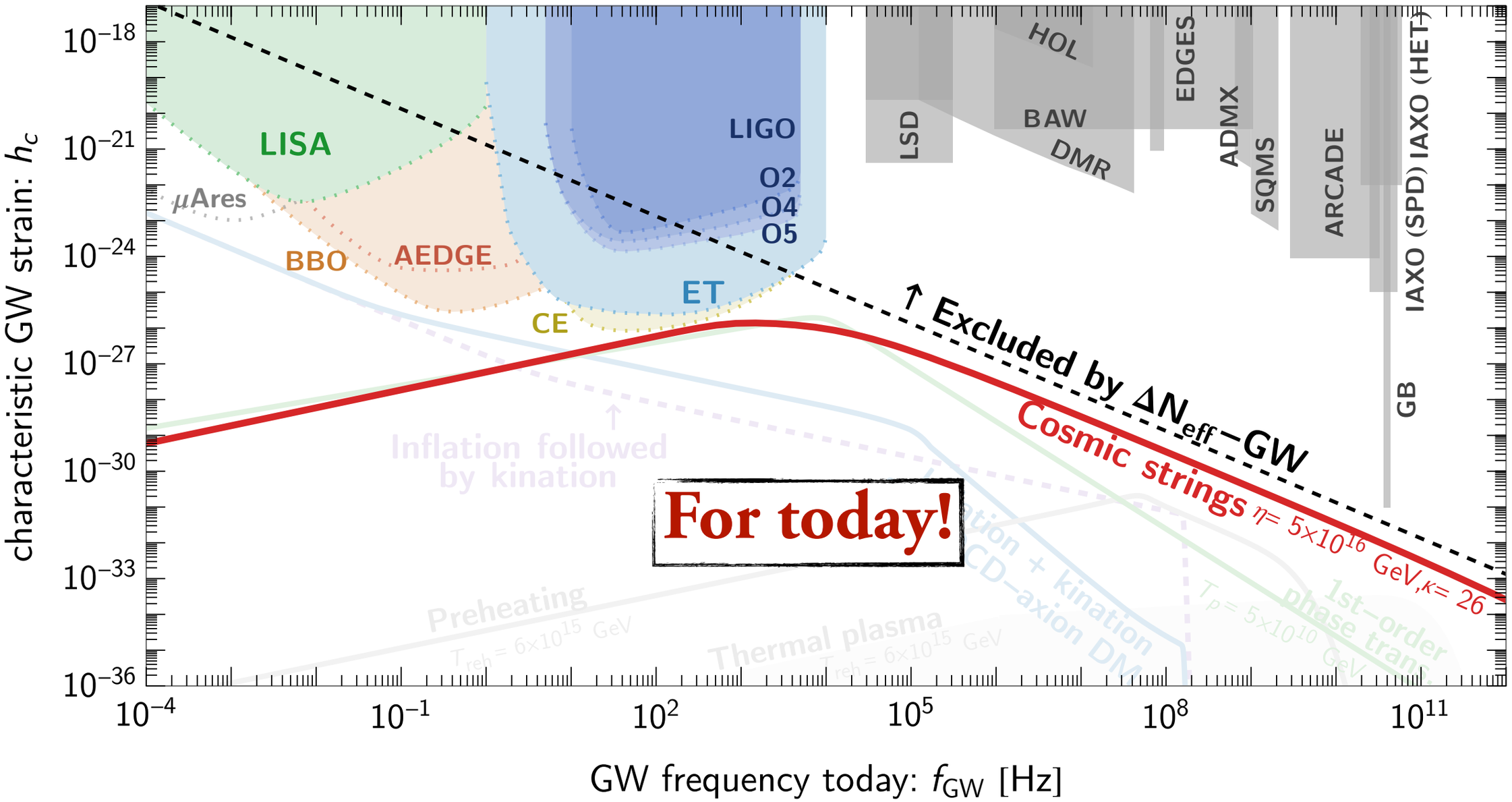

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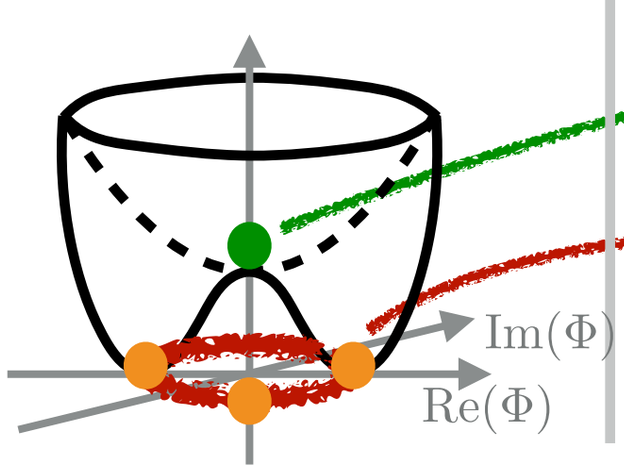
Cosmic strings and their GW background (GWB)

Recent reviews, e.g., LISA cosmo [1909.00819], Gouttenoire, Servant, Simakachorn [1912.02569], Sousa '23

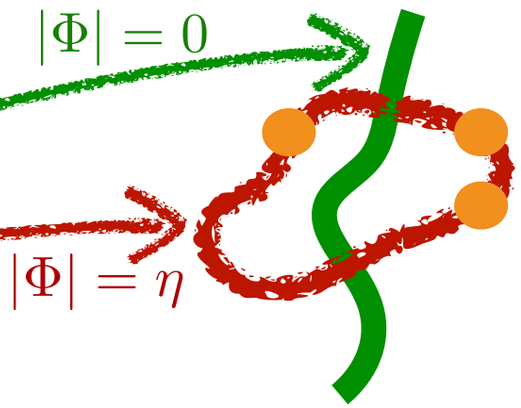
<u>field space</u>

e.g., $V(\Phi) \simeq \lambda(|\Phi|^2 - \eta^2)^2$

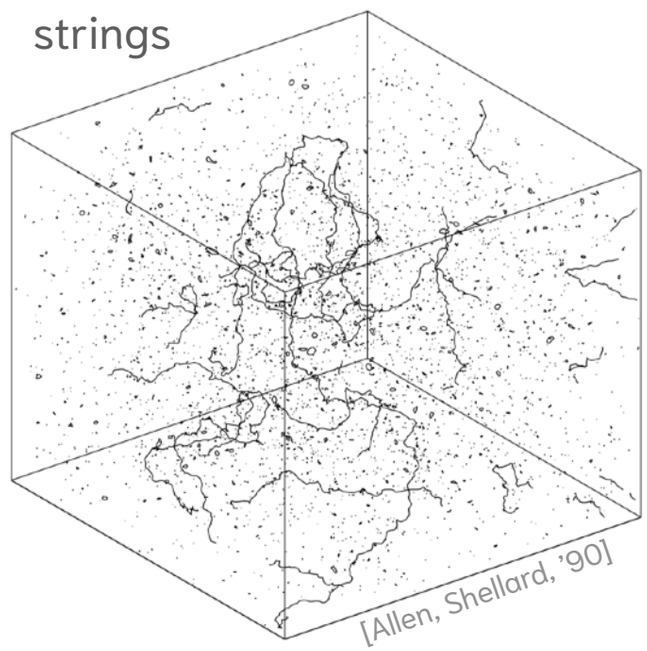


<u>physical space</u>

String's width $w \simeq m_\Phi^{-1} \simeq (\sqrt{\lambda}\eta)^{-1}$



Network of strings



A topological defect from spontaneous (global or local) symmetry breaking at the energy scale η
[Kibble, '76]

At late times, string's width ≪ horizon size ⇨ **1D object**

String tension: $G\mu \simeq \left(\frac{\eta}{m_{\rm Pl}}\right)^2 \simeq 7 \times 10^{-7} \left(\frac{\eta}{10^{16}\ \mathrm{GeV}}\right)^2$

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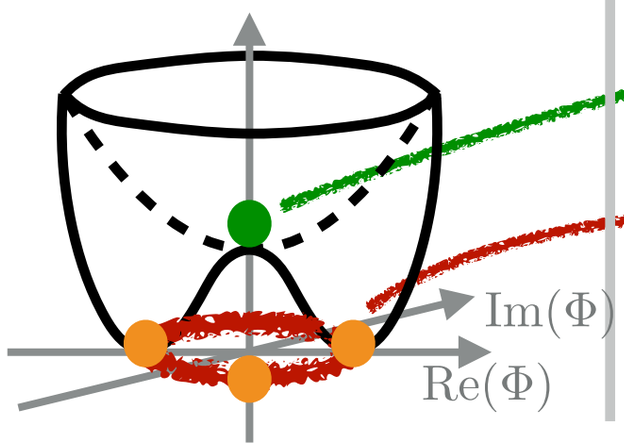

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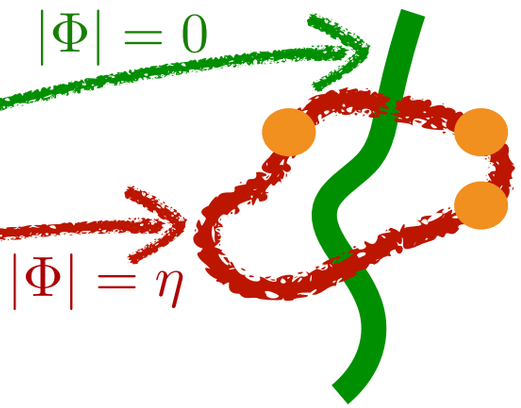

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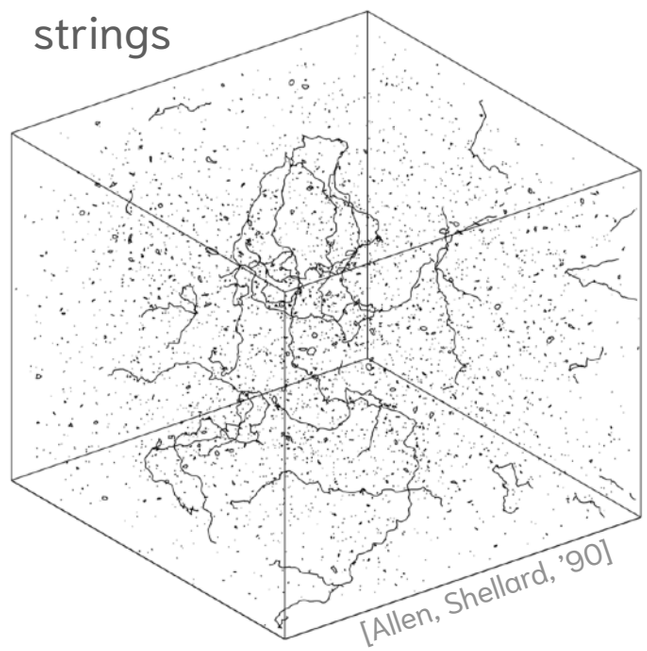

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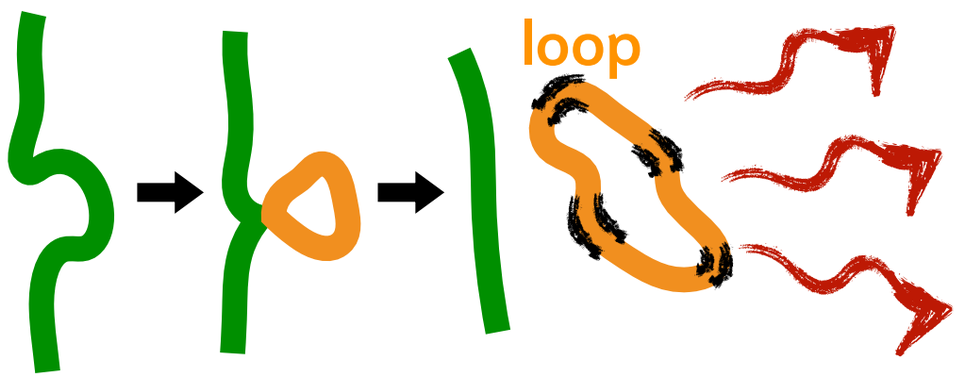


GW emission from loops

(+ particle production for global strings)

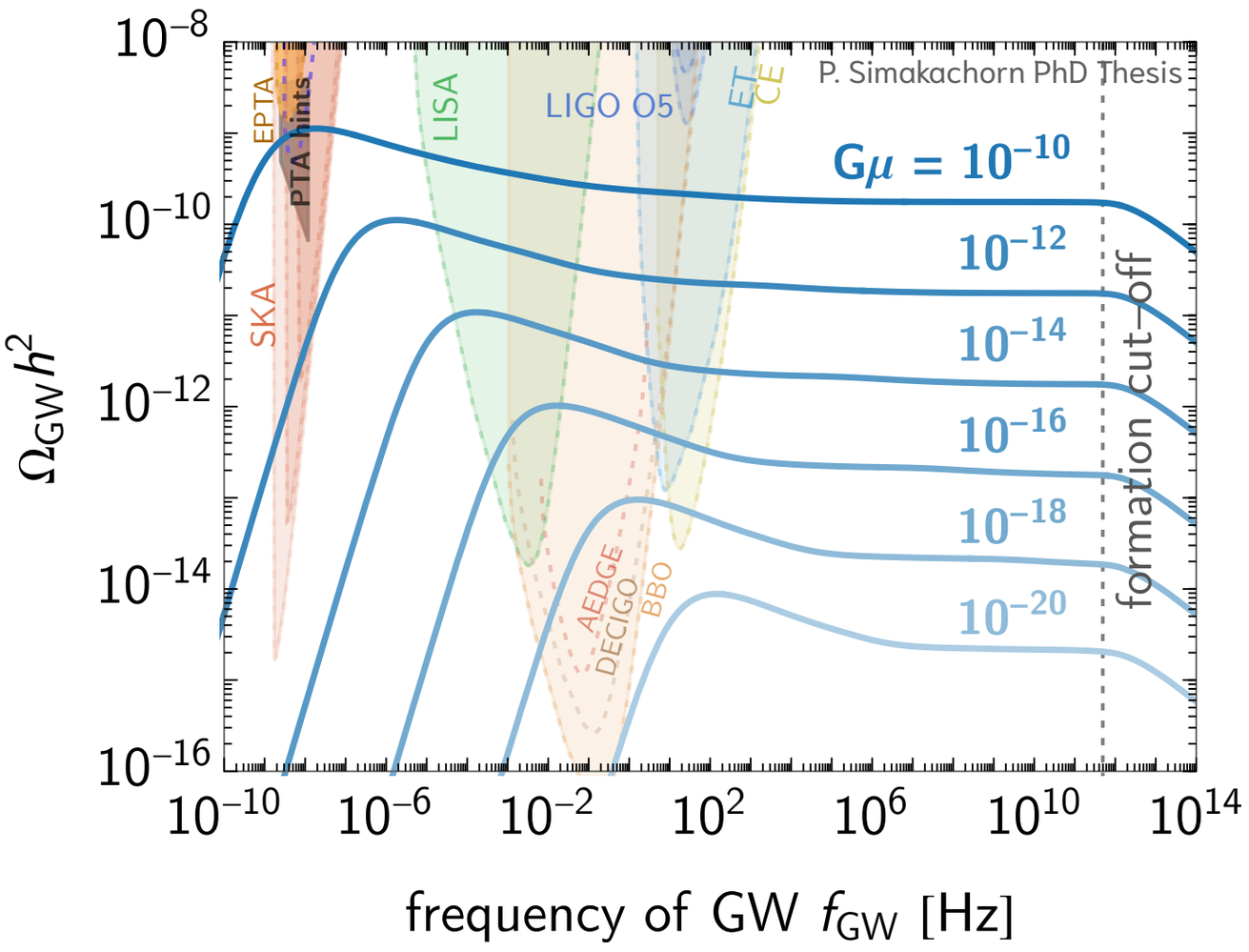
Local strings! and their GWB

Recent reviews, e.g., LISA cosmo [1909.00819], Gouttenoire, Servant, Simakachorn [1912.02569], Sousa '23

$$\Omega_{\rm GW}(f_{\rm GW}) = \frac{1}{\rho_{c,0}} \sum_{k=1}^{k_{\rm max}} \frac{2k}{f_{\rm GW}} \cdot \Gamma^{(k)} G\mu^2 \int_{t_{\rm form}}^{t_0} n_{\rm loop}(\tilde{t}) \left[\frac{a(\tilde{t})}{a(t_0)}\right]^5 d\tilde{t},$$

GW from a loop

# of loops produced along cosmic history (from production time until today)



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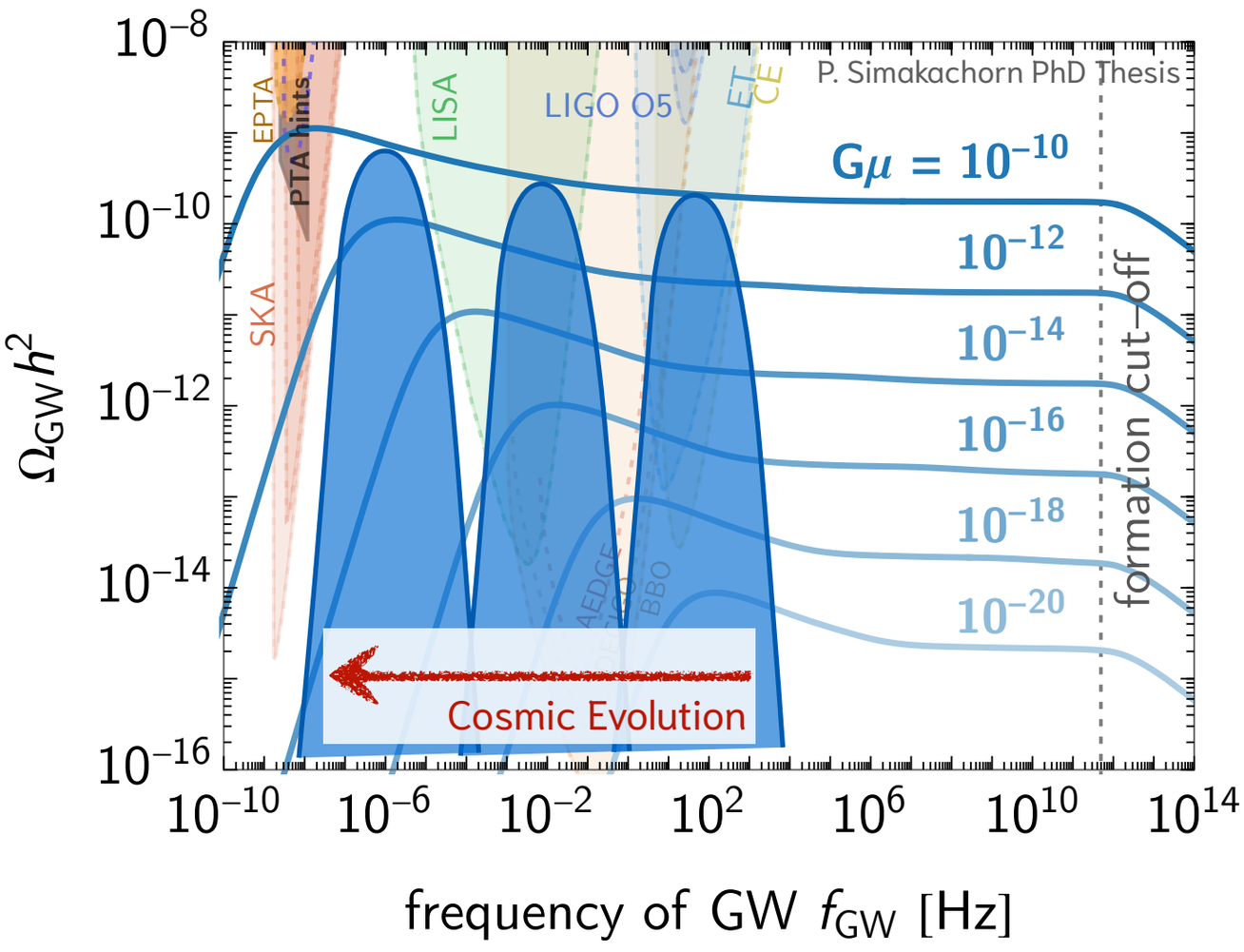

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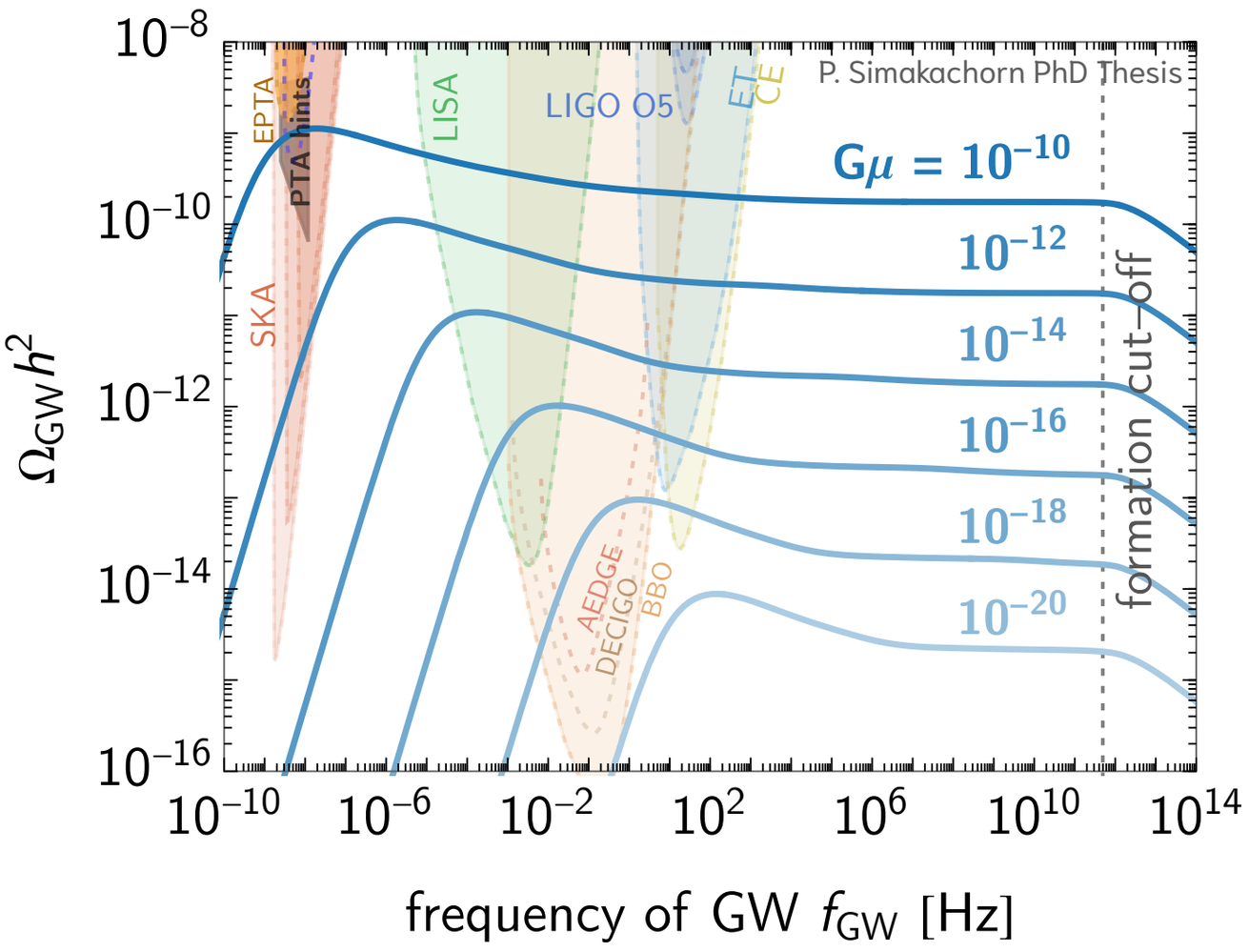

Not so large UHF signals due to observations @ low-frequency.

LVK (LIGO–VIRGO–KAGRA) @ ~10 Hz

$$\Omega_{\rm GW}h^2 \lesssim 10^{-8} \Rightarrow G\mu \lesssim 10^{-7}$$

PTA (pulsar-timing arrays) @ ~ nHz

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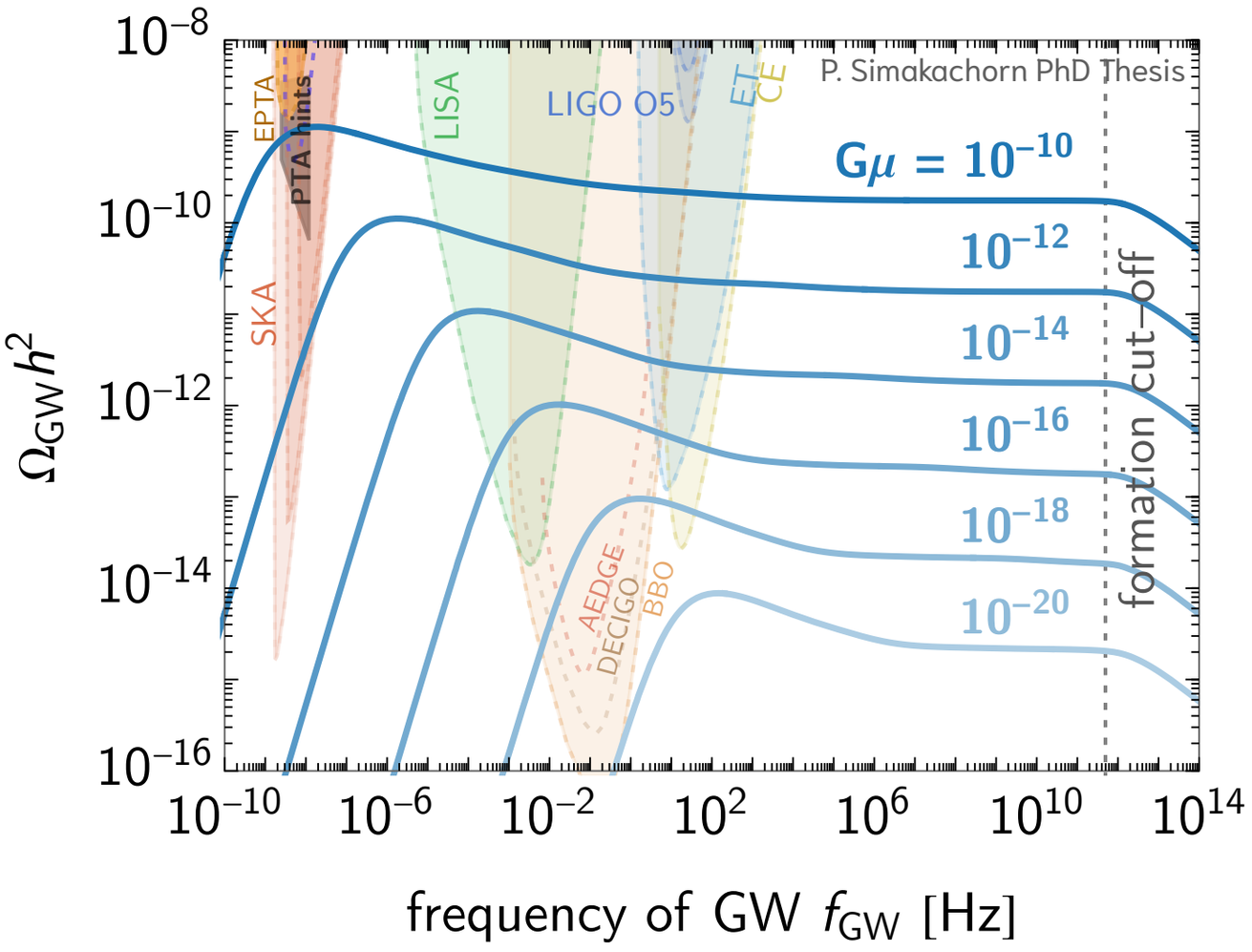

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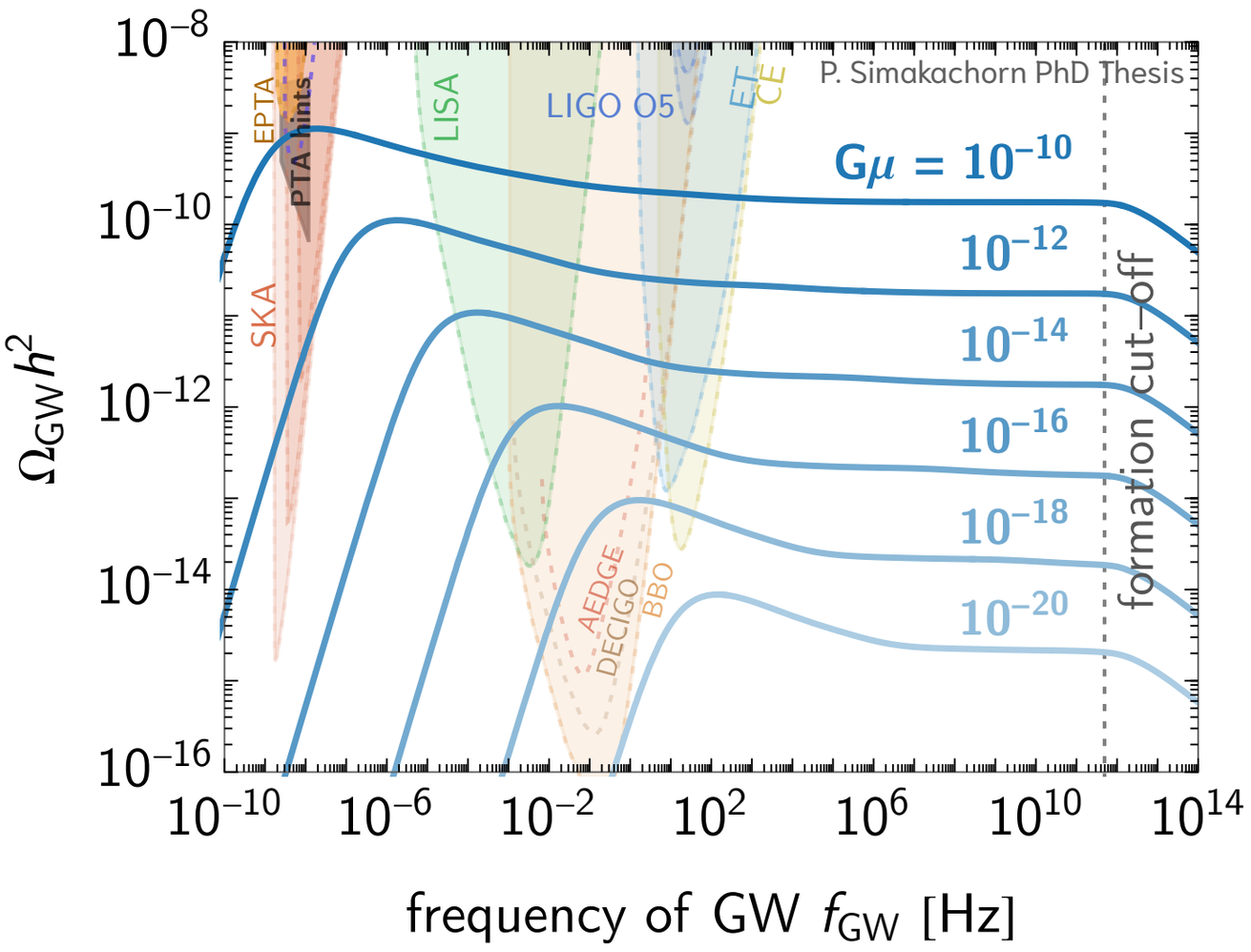

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These low-frequency constraints do not apply if strings shut down the GW production at later times.

String network decays!

Metastable cosmic strings

(Also see talks of S. Antusch and S. King)

Multiple-step phase transitions ⇒ Hybrid defects

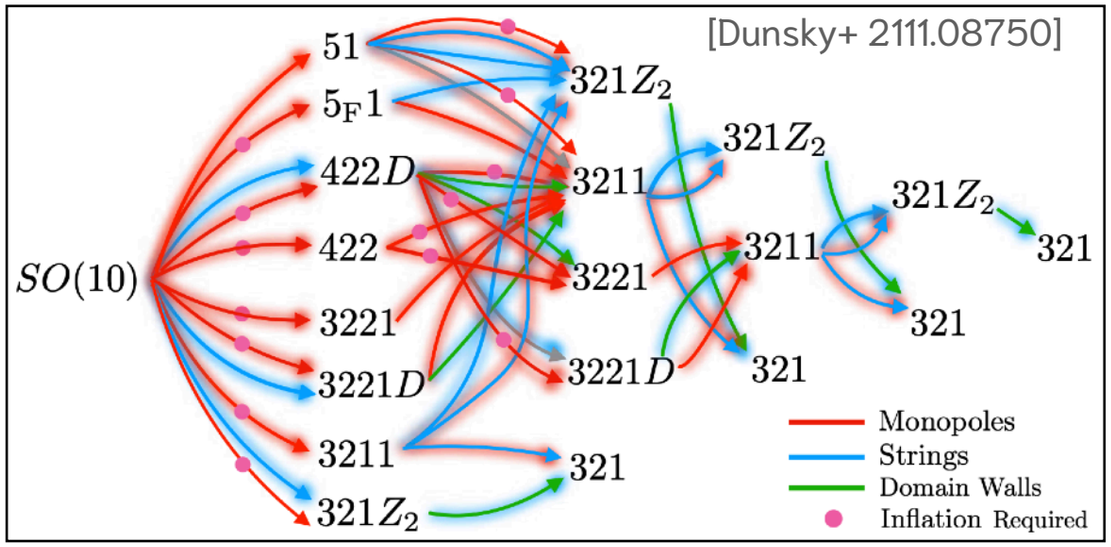
E.g., Grand unified theories, hybrid inflation models, post-inflationary axion

Buchmüller, Domcke, Schmitz+ [1912.03695, 2102.08923, 2107.04578, 2307.04691]
King, Pascoli, Turner, Zhou [2005.13549, 2106.15634]
Murayama+ [1908.03227, 2111.08750]

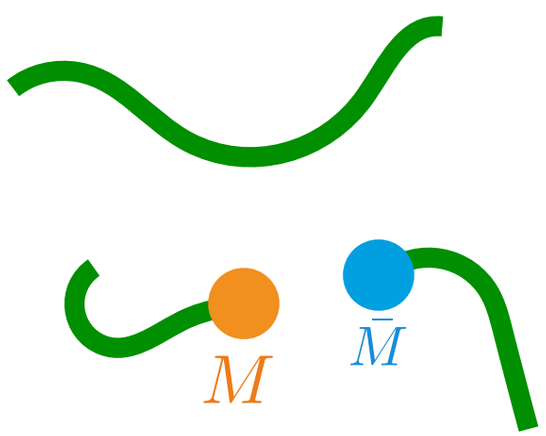
Vilenkin, Everett '82
Hiramatsu+ [1012.4558, 1202.5851]

and many others...

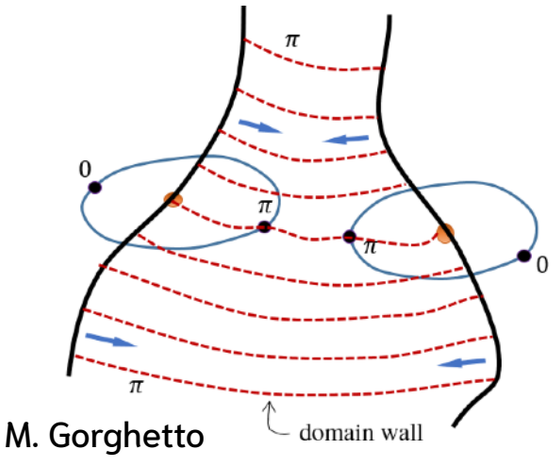
[Dunsky+ 2111.08750]



string-monopole



String-domain wall



M. Gorghetto

See also decaying defects

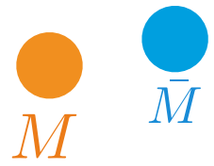
via Hubble-induced phase transition [see the talk by Javier Rubio]

Kamada, Yamada [1407.2882] Bettoni, Domènech, Rubio [1810.11117]

Example of metastable cosmic strings

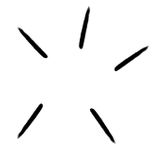
energy scale

Symmetry breaking #1



Monopole formation @ energy scale m_M

Inflation



Diluting monopoles,
otherwise monopole domination.

Symmetry breaking #2

String formation @ energy scale η

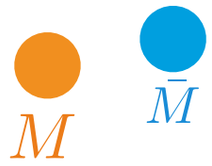
Decay of strings

Monopole nucleation and strings decay

Example of metastable cosmic strings

energy scale

Symmetry breaking #1



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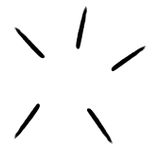

Diluting monopoles,
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Symmetry breaking #2

String formation @ energy scale η

Decay of strings

Monopole nucleation and strings decay

Nucleation rate per unit length:

(assuming thin strings and point-like monopole)
Vilenkin '82, Preskill, Vilenkin '93 Monin,+ '08
Beyond thin soliton approx. :
Dvali+ 2210.14947, Chitose+ 2312.15662

$$\Gamma_d = \frac{\mu}{2\pi} e^{-\pi\kappa} \quad \text{with} \quad \sqrt{\kappa} \equiv \frac{m_M}{\eta} \left[\frac{\text{monopole scale}}{\text{string scale}} \right] > 1$$

happens when $\Gamma_d l(t_{\rm brk}) = H(t_{\rm brk})$

Example of metastable cosmic strings

energy scale

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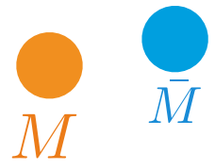

Monopole formation @ energy scale m_M

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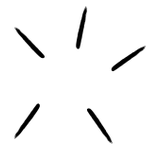

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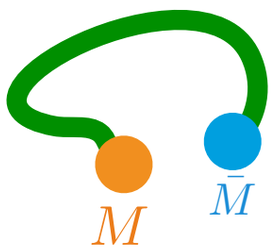
Two effects on loops:

$$n_{\rm loop}^{\rm brk} = n_{\rm loop}^{\rm stable} \Theta(t_{\rm brk} - t_i) e^{-\Gamma_d [l(t - t_{\rm brk}) \cdots]}$$



1. Shut off loops production

2. Depleting loop number density

dominant factor to suppress GWB

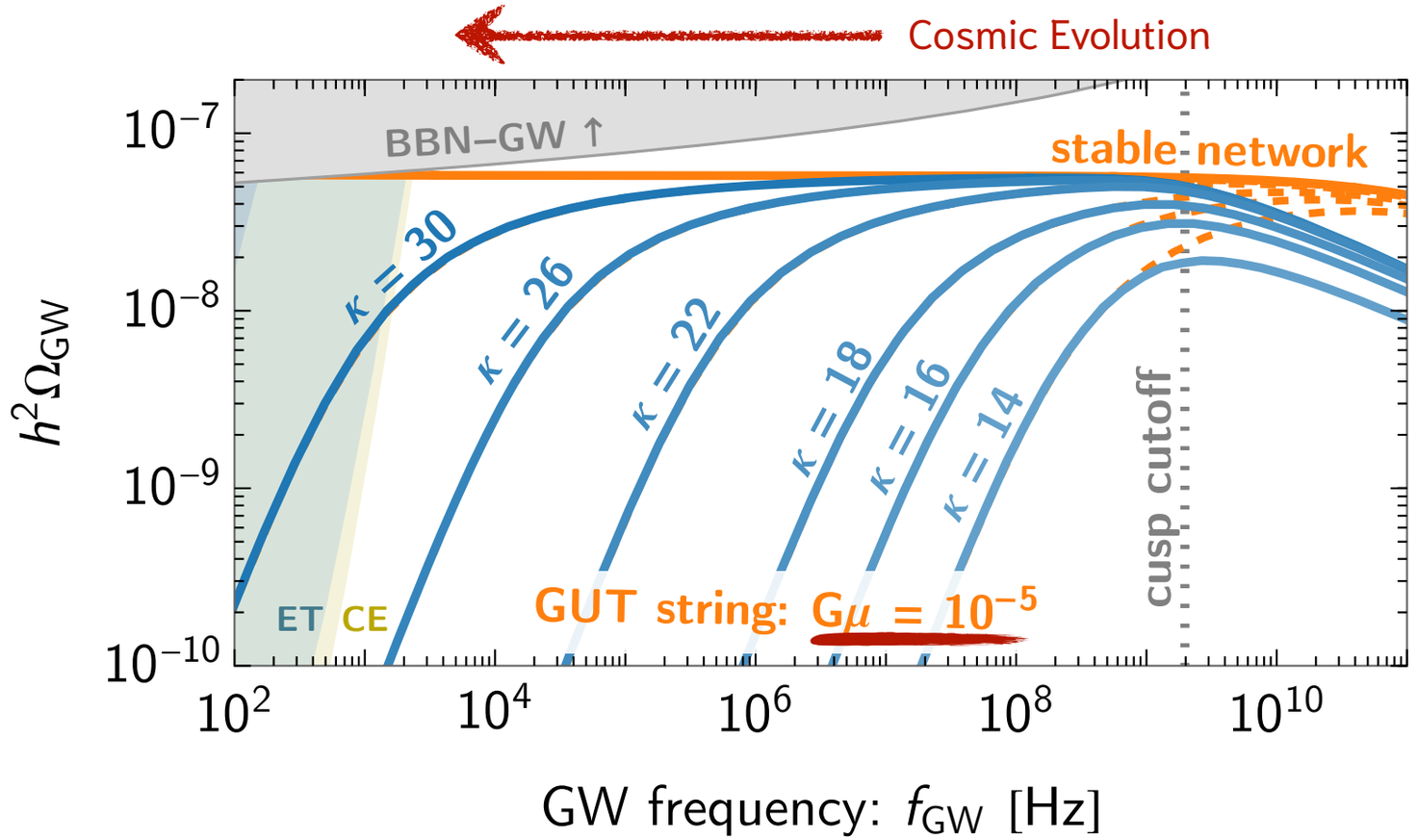
Large GWB @ UHF from metastable cosmic strings

Servant, Simakachorn [2312.09281]

Strings get cut @ late times ⇒
suppressed GW at low-frequencies

Infrared (IR) cutoff:

$$f_{\rm GW}^{\rm meta} \simeq {\rm MHz}\left(10^{-5}/G\mu\right)^{\frac{1}{2}} e^{-\frac{\pi}{4}(\kappa-25)}$$



The GWB can saturate the $\Delta N_{\rm eff}$–GW bound,
even if no signal is observed at sub-kHz experiments.

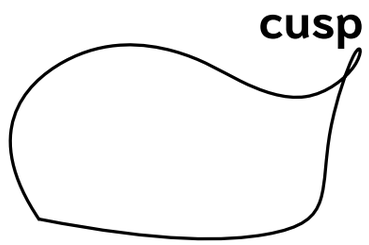
Any UHF experiment with sensitivity
slightly better than $\Delta N_{\rm eff}$–GW bound probes into GUT-scale physics.

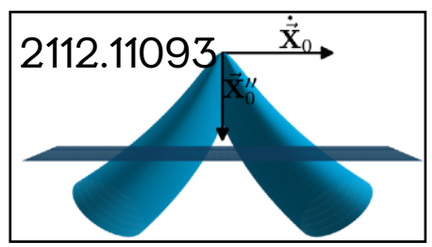
Other signatures of particle physics @ UHF: UV cutoffs

UHF signal from smaller loops at earlier times.

$$f_{\rm GW} \simeq 50\ {\rm kHz} \left[\frac{T}{10^{10}\ {\rm GeV}}\right] \left[\frac{10^{-5}}{G\mu}\right]^{\frac{1}{2}} \qquad l_{\rm loop} \sim H^{-1} \sim 10^{-10}\ {\rm GeV} \left[\frac{10^{14}\ {\rm GeV}}{T}\right]^2$$

1D description breaks e.g.,
small-scale structures (e.g., cusp and kink).





$$\left.\frac{dE}{dt}\right|_{\rm cusp} \sim \lambda^{-\frac{1}{4}} \frac{\mu^{3/4}}{l_{\rm loop}^{1/2}}$$

E.g. GW emission is inefficiently due to particle production from cusps if

$$f_{\rm GW} > f_{\rm GW}^{\rm cusp} \simeq {\rm GHz}\ \lambda^{1/8} \left(\frac{G\mu}{10^{-5}}\right)^{3/4}$$

scalar self-coupling

$$V(\Phi) \simeq \lambda(|\Phi|^2 - \eta^2)^2$$
$$w \simeq m_\Phi^{-1} \simeq (\sqrt{\lambda}\eta)^{-1}$$

Other UV cutoffs: the network formation, thermal friction, and particle production from kinks.

Auclair, Steer, Vachaspati [1911.12066], Gouttenoire, Servant, Simakachorn [1912.02569], Servant, Simakachorn [2312.09281]

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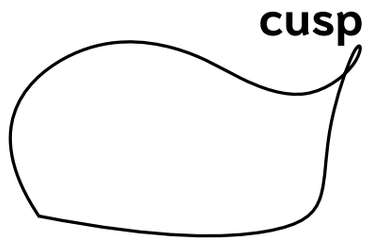
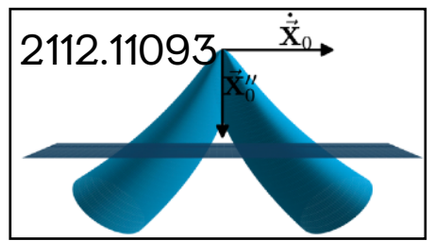
UV cutoff in the GW spectrum.





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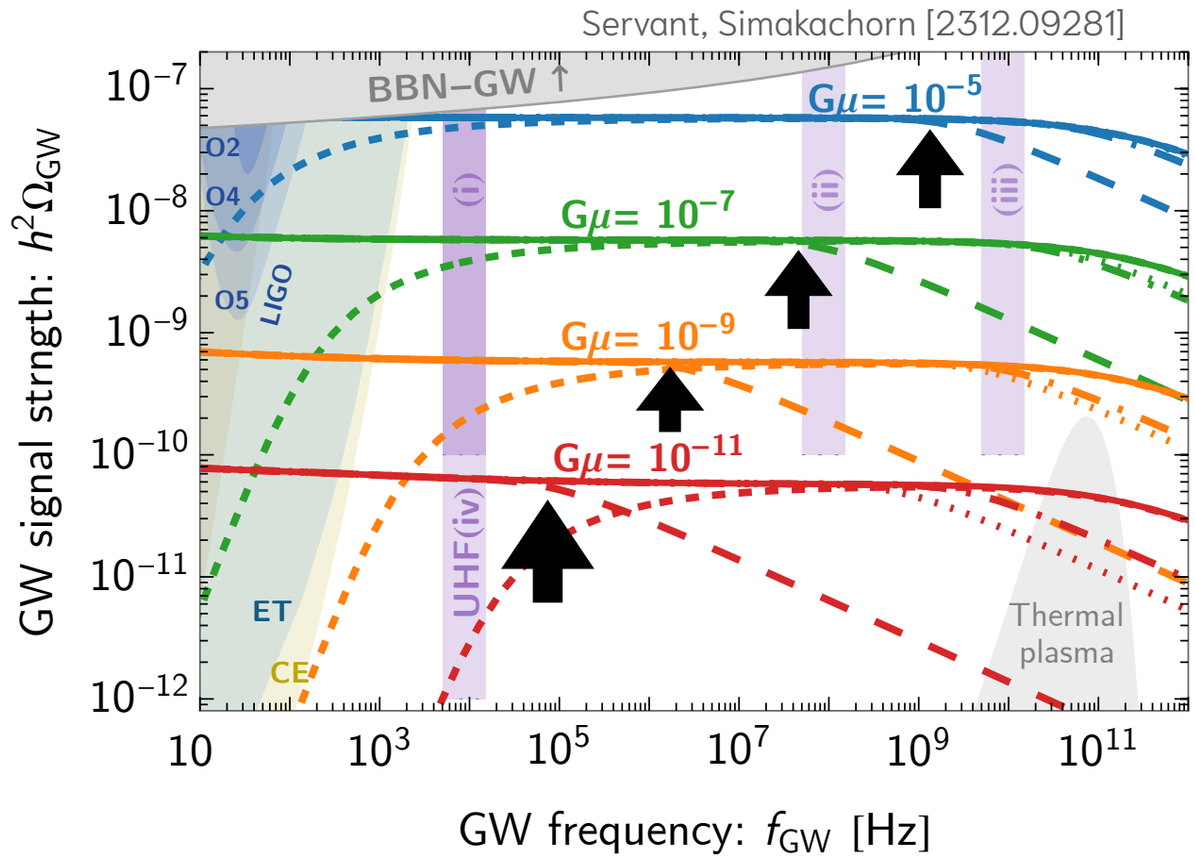
Servant, Simakachorn [2312.09281]



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Reconstruction of the scalar potential via GW

Servant, Simakachorn [2312.09281]

UV cutoff in the GW spectrum
e.g., from cusp,
moves with the string's fatness

$$w \simeq m_\Phi^{-1} \simeq (\sqrt{\lambda}\eta)^{-1}$$

$$f_{\rm GW}^{\rm cusp} \simeq {\rm GHz}\, \lambda^{1/8} \left(\frac{G\mu}{10^{-5}}\right)^{3/4}$$

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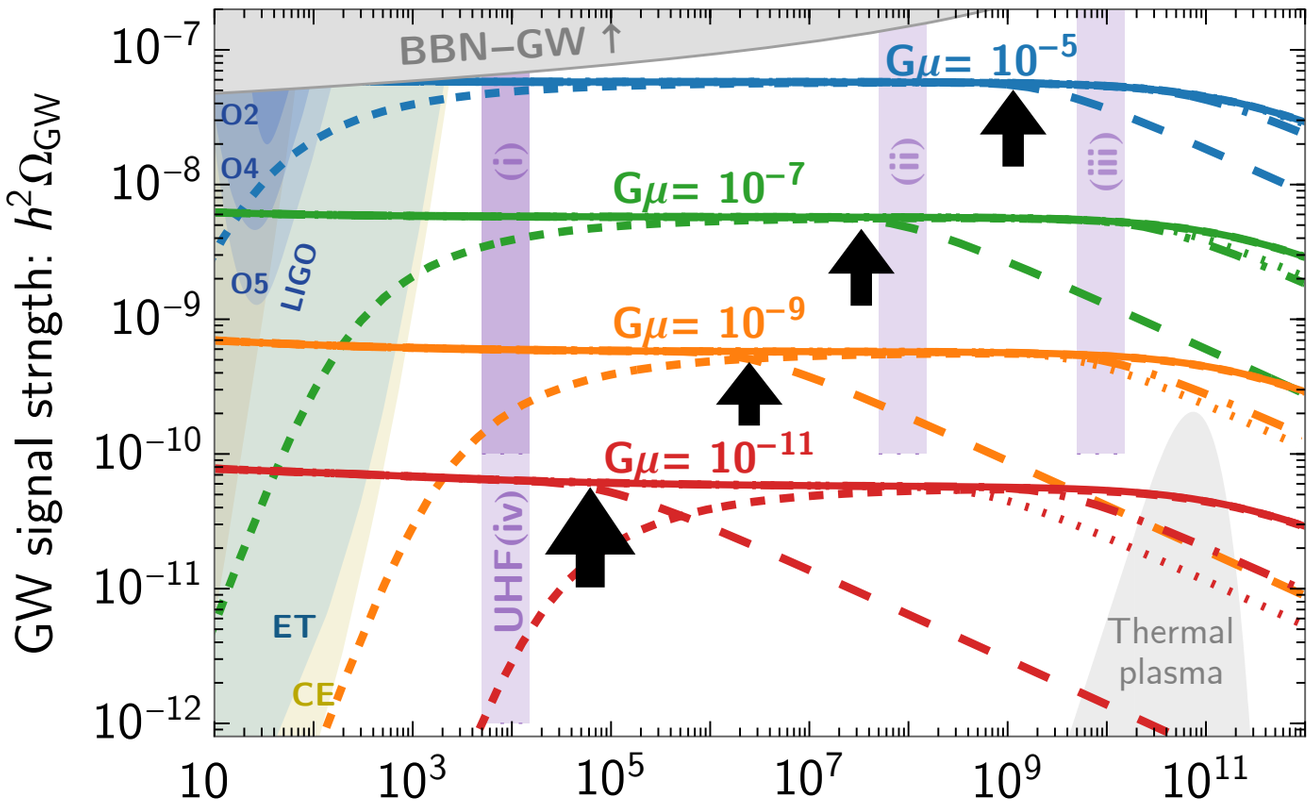


How to extract the UV cutoff if GWB is detected.

- Detect directly the cutoff (need some luck)
- Several detectors at different frequencies.
  Detect the flat part and the UV slope, ⇒ UV cutoff at the intersection (more generic)

Conclusion

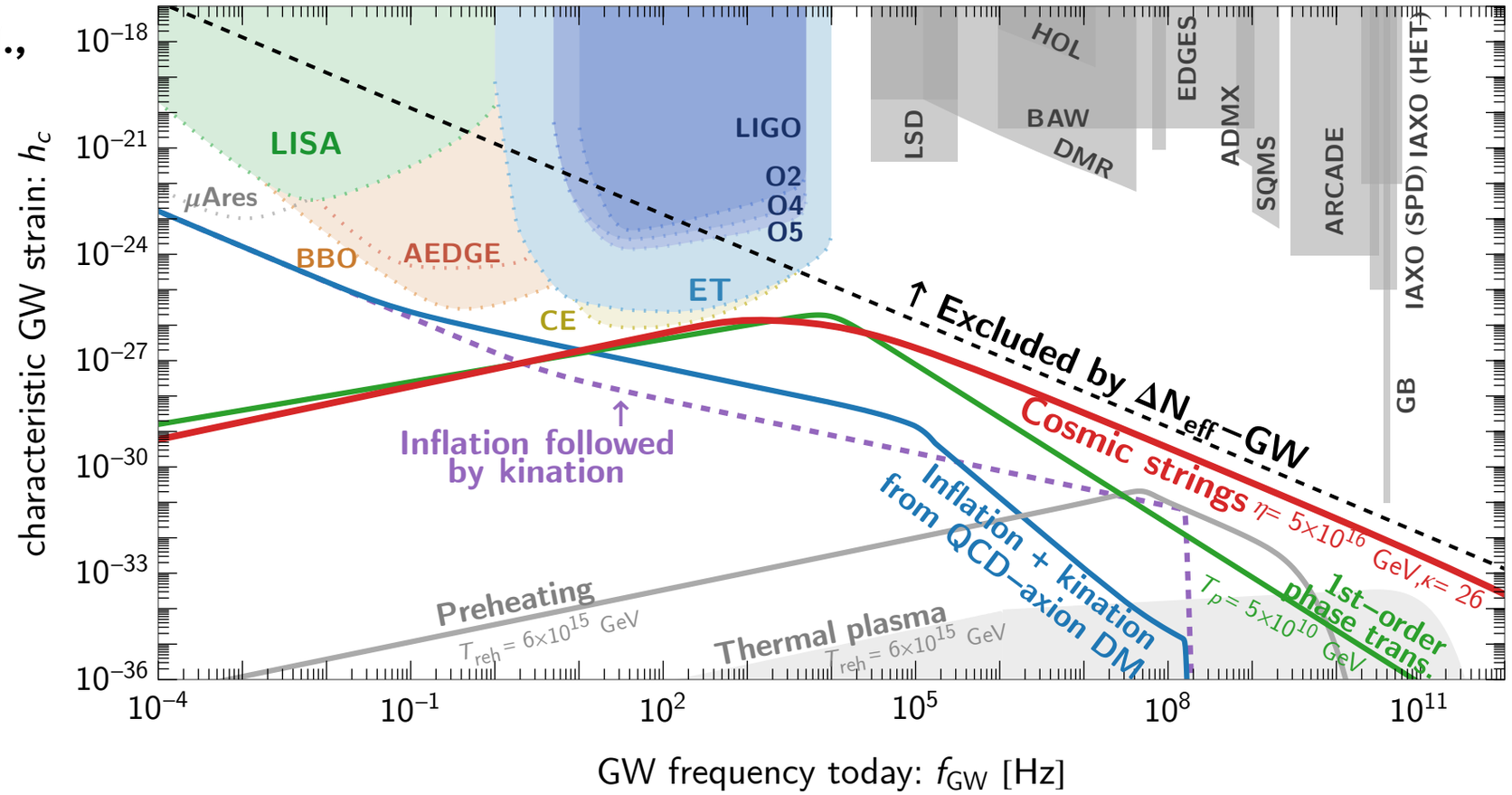
UHF regime (beyond kHz) =

A golden window for new physics (above 10^{10} GeV)

So far...the theoretical $\Delta N_{\rm eff}$–GW bound is the strongest.

But any experiment slightly more sensitive than this bound
will probe into the Universe at ultrahigh energy scales.

E.g.,



Large UHF signal from metastable strings.

The reconstruction of scalar potential (e.g., self–coupling λ) is possible via the observed UV cutoff in the spectrum!

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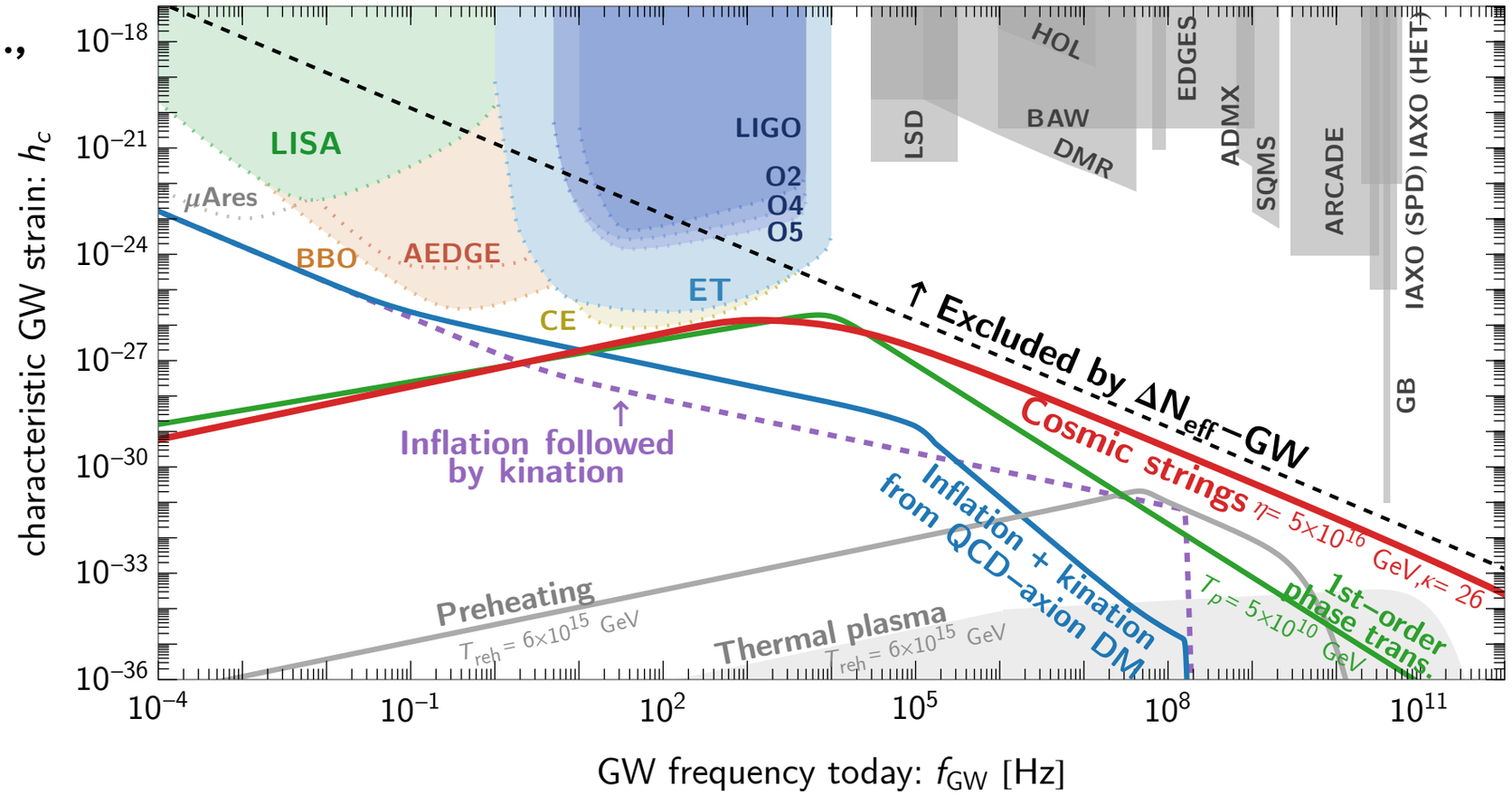

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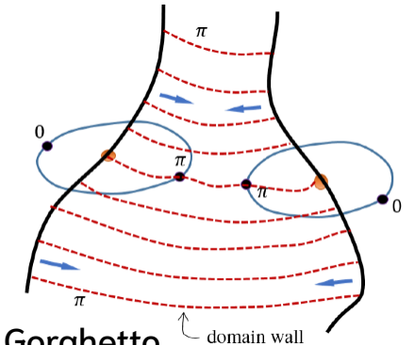
Servant, Simakachorn [2312.09281]

We also look at global strings or axionic strings…

Axionic (or global) strings

String–domain wall



$\Omega_{\rm GW} \propto \eta^4$ or f_a^4 with f_a: Peccei–Quinn symmetry–breaking scale

Strings attache to domain walls and collapse: $T_{\rm dec} \sim 10^9\ {\rm GeV}\sqrt{m_a/{\rm GeV}}$

Light axion ($m_a \lesssim 10^{-22}$ eV)

⇒ ~stable strings

Small UHF signal

- $\Delta N_{\rm eff}$–Goldstone bound

$$f_a \lesssim \mathcal{O}(1-3)\times 10^{15}\ {\rm GeV}$$

Cui, Chang '21, Hardy, Nicoleuscu, Gorghetto '21

- Pulsar–timing arrays

$$f_a \lesssim 2.8\times 10^{15}\ {\rm GeV}$$

Servant, Simakachorn [2307.03121]

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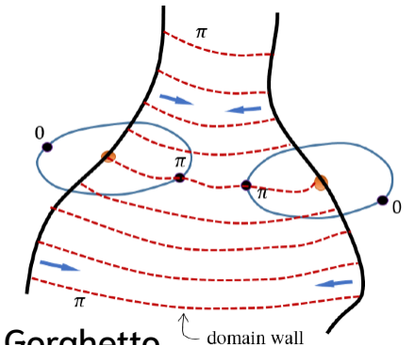

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Servant, Simakachorn [2307.03121]

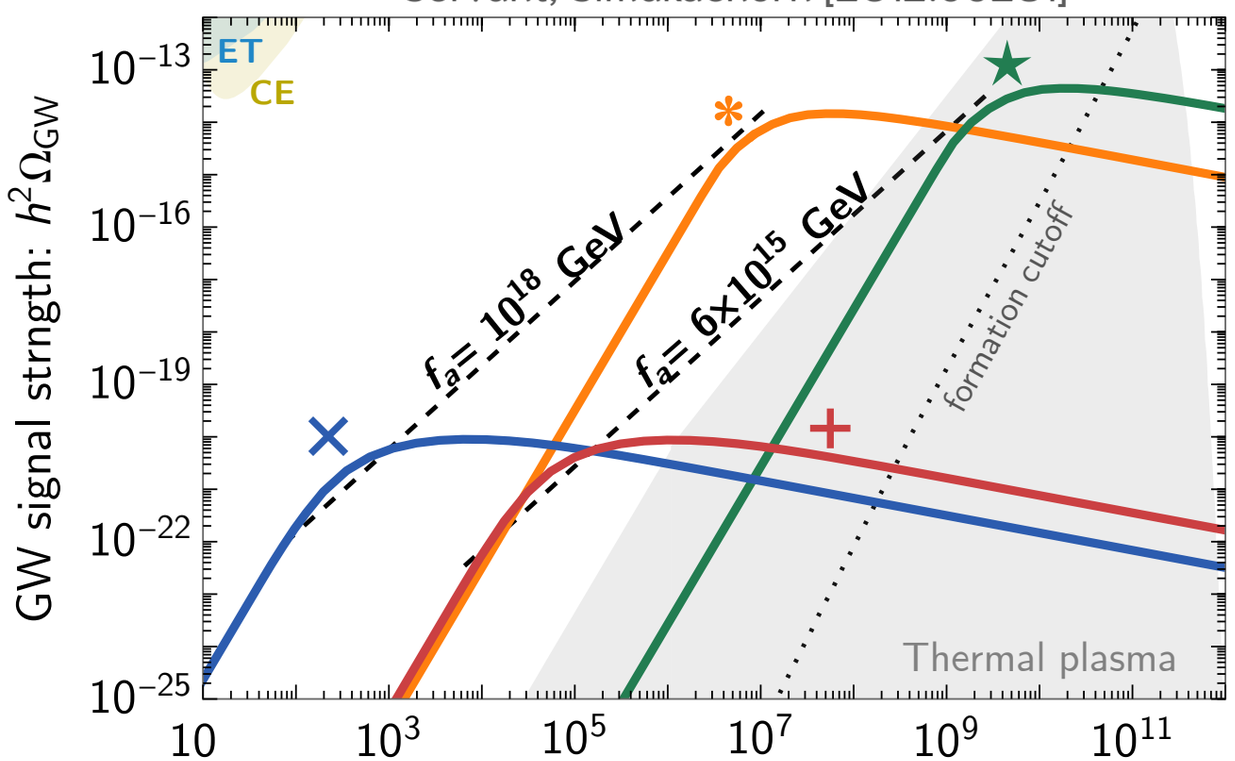
Heavy axion ($m_a \gtrsim$ GeV)

⇒ IR cutoff in UHF

Small signal, even for **large** f_a.

GWB is diluted by matter domination from axions produced from string collapse.

Servant, Simakachorn [2312.09281]



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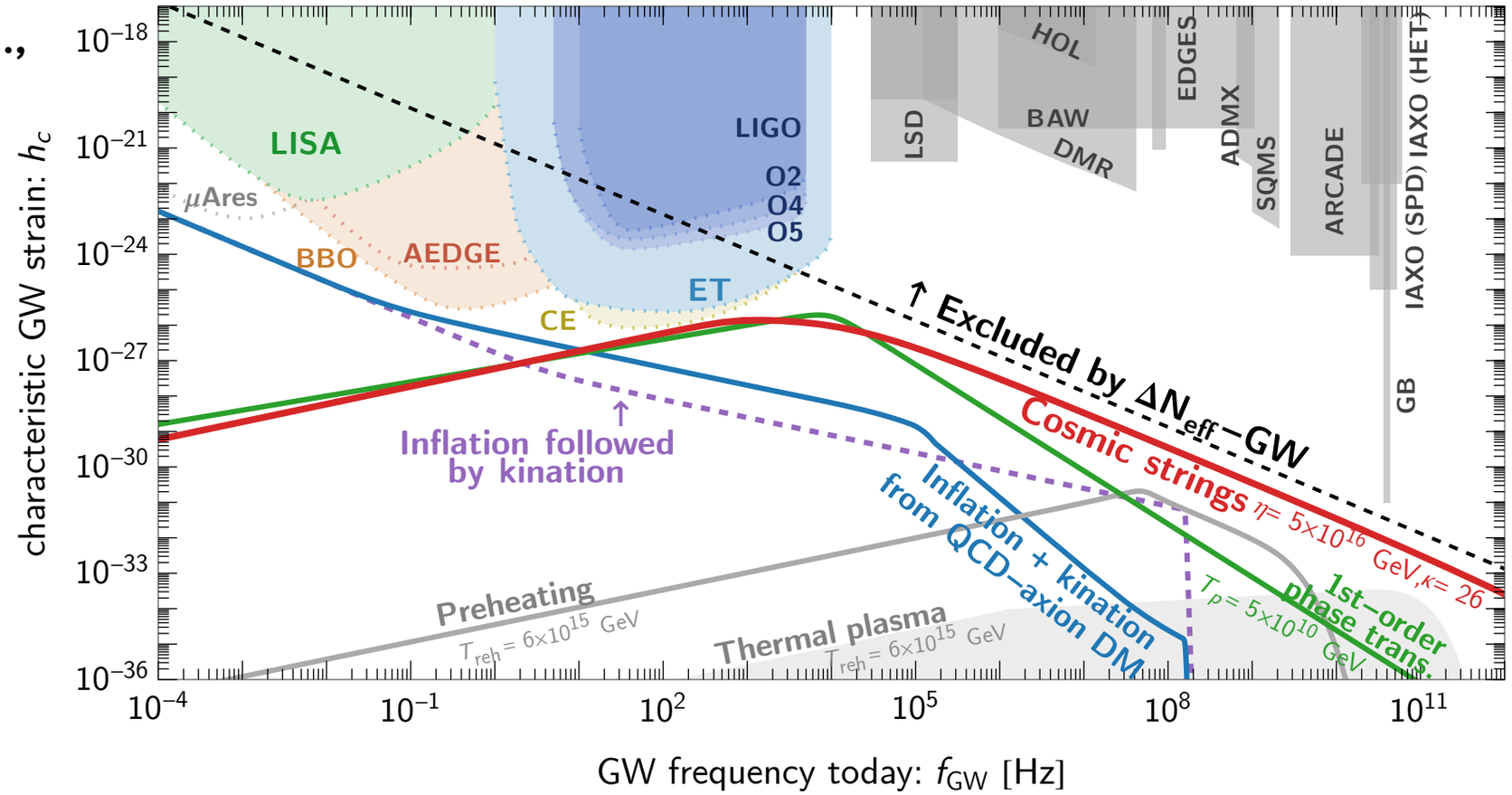


Large UHF signal from metastable strings.

The reconstruction of scalar potential (e.g., self–coupling λ) is possible via the observed UV cutoff in the spectrum!

Servant, Simakachorn [2312.09281]

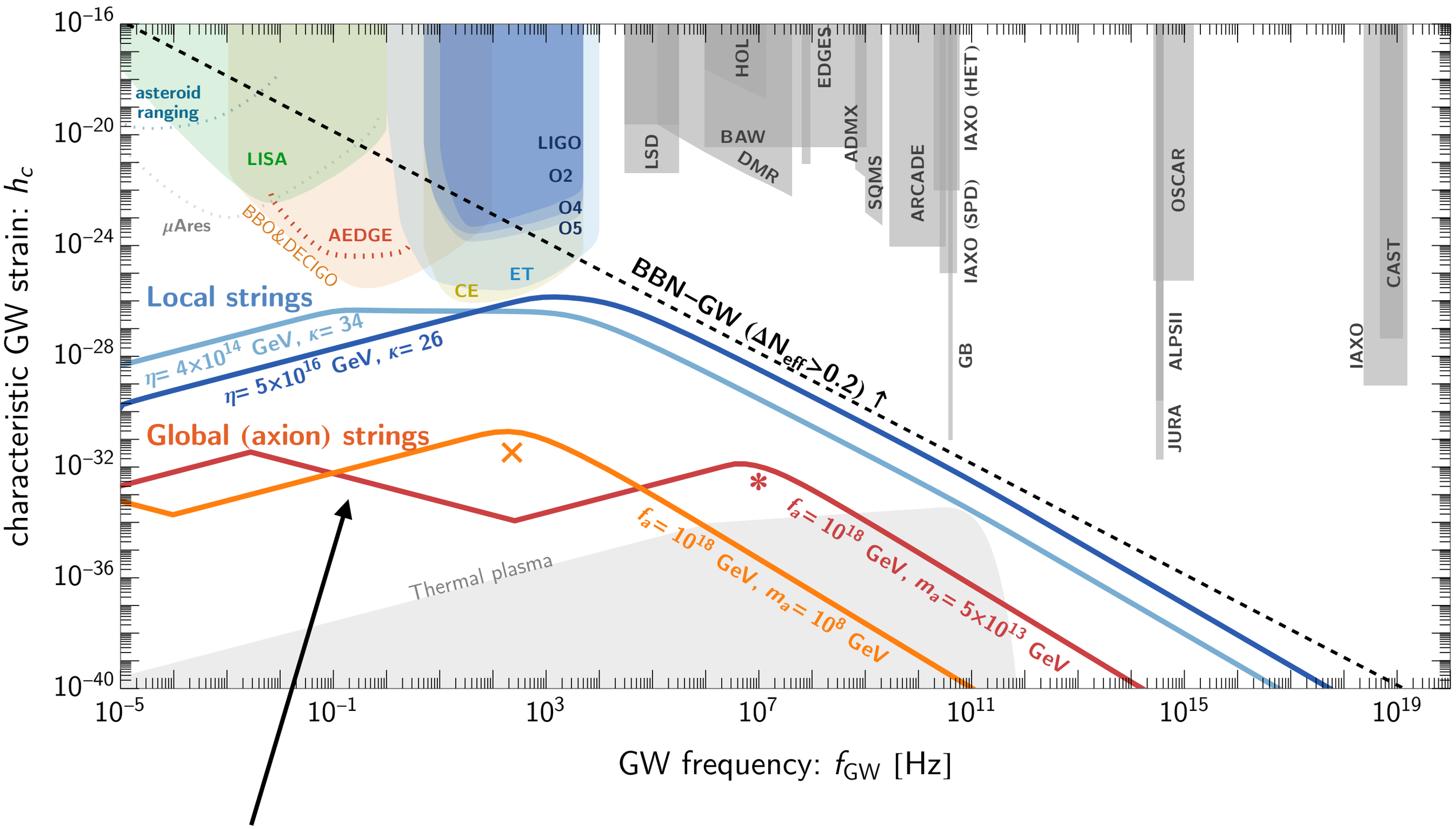
GW signal in UHF from axion strings is suppressed,
i.e., requiring at least sensitivity $h_c \simeq 10^{-31}$.

Thank You!

Back-up

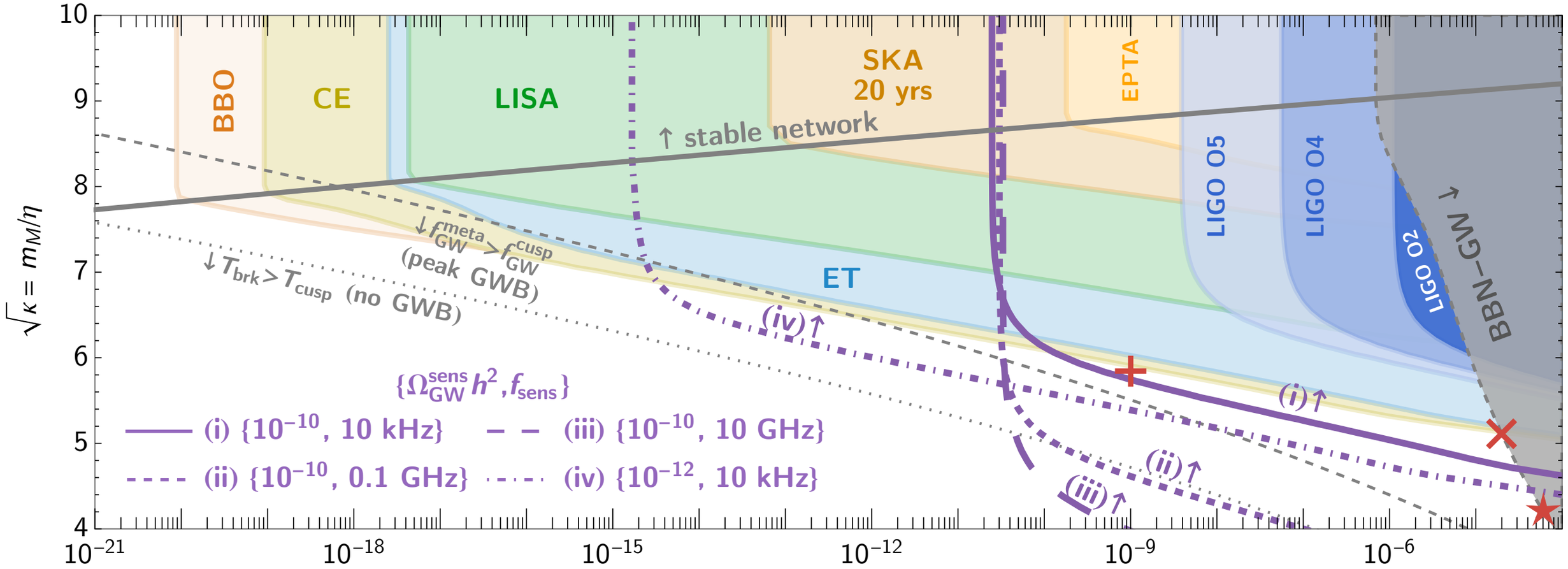
UHF GWB from local and global (axionic) strings (Best cases)

Servant, Simakachorn [2312.09281]

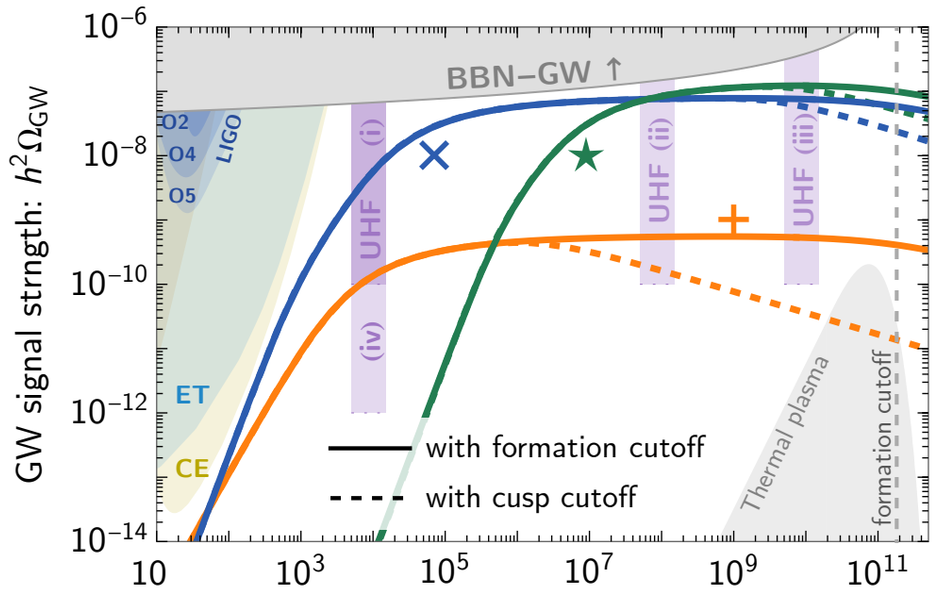


Low-frequency slope is changed by the modified causality tail during the axion matter domination.

Detectability of GWB from metastable local strings



Servant, Simakachorn [2312.09281]



UV cutoffs in cosmic–string GWB

Servant, Simakachorn [2312.09281]

$$f_{\rm GW}^{\rm form} \simeq 182\ {\rm GHz}\,\sqrt{\lambda}\left[\frac{g_*(T_{\rm form})}{106.75}\right]^{\frac{1}{4}}$$

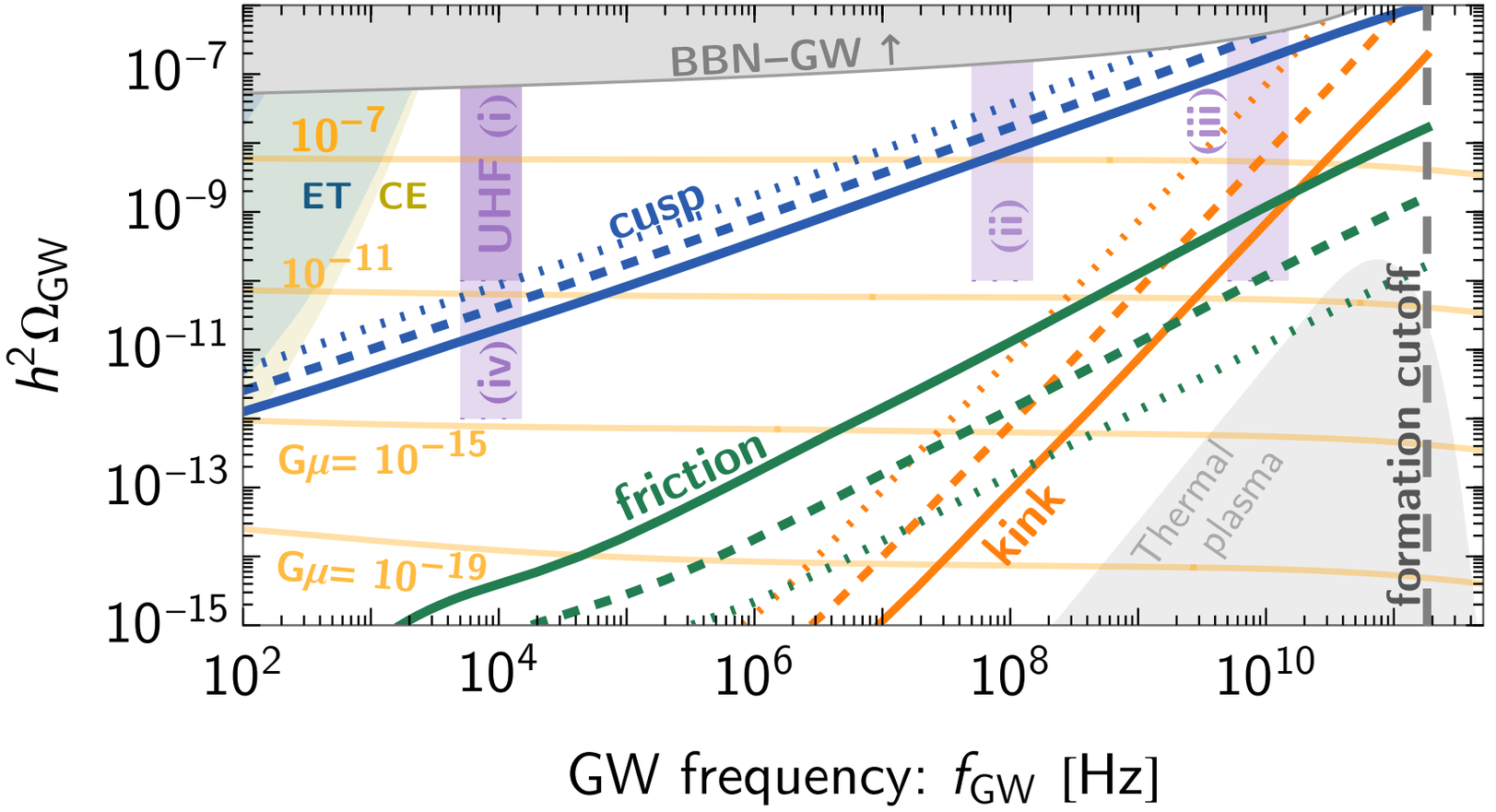
$$f_{\rm GW}^{\rm fric} \simeq 0.45\ {\rm GHz}\ \beta_{\rm fric}^{-1}\left(\frac{G\mu}{10^{-11}}\right)^{\frac{1}{2}}\left[\frac{g_*(T)}{106.75}\right]^{\frac{3}{4}}$$

$$f_{\rm GW}^{\rm cusp} \simeq 62.3\ {\rm kHz}\sqrt{\frac{1}{\beta_c}}\left(\frac{G\mu}{10^{-11}}\right)^{3/4}$$

$$f_{\rm GW}^{\rm kink} \simeq 2.79\ {\rm GHz}\sqrt{\frac{1}{\beta_k}}\left(\frac{G\mu}{10^{-11}}\right)^{1/4}$$

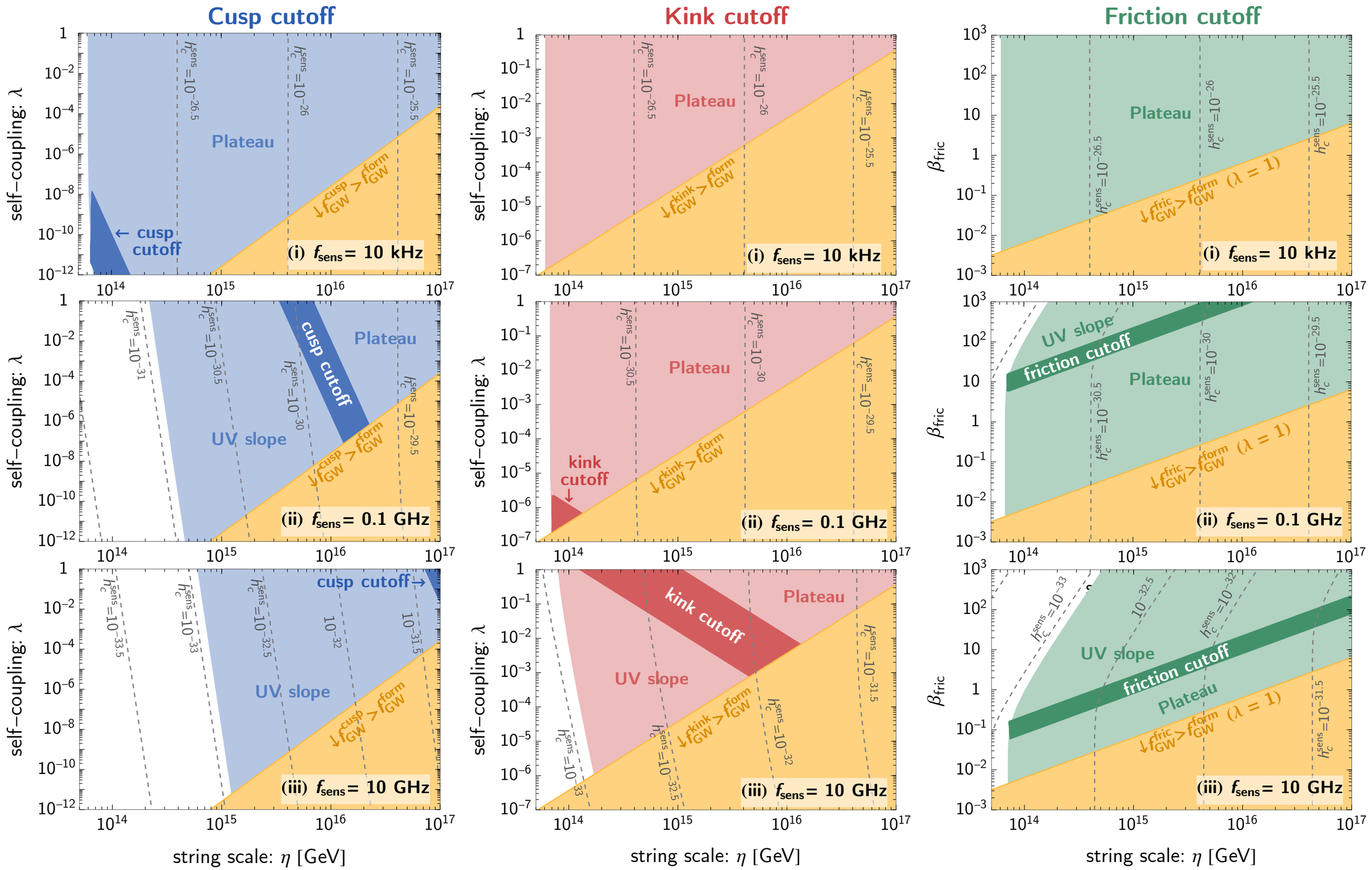
$$\beta_c \simeq N_c\lambda^{-1/4},\ \text{and}\ \beta_k \simeq N_{kk}\lambda^{-1/2}$$

Cutoff positions



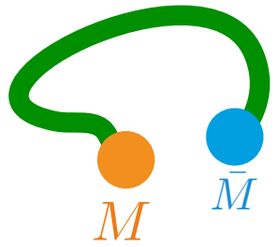
Reconstruction of scalar potential with UHF GWB

Servant, Simakachorn [2312.09281]

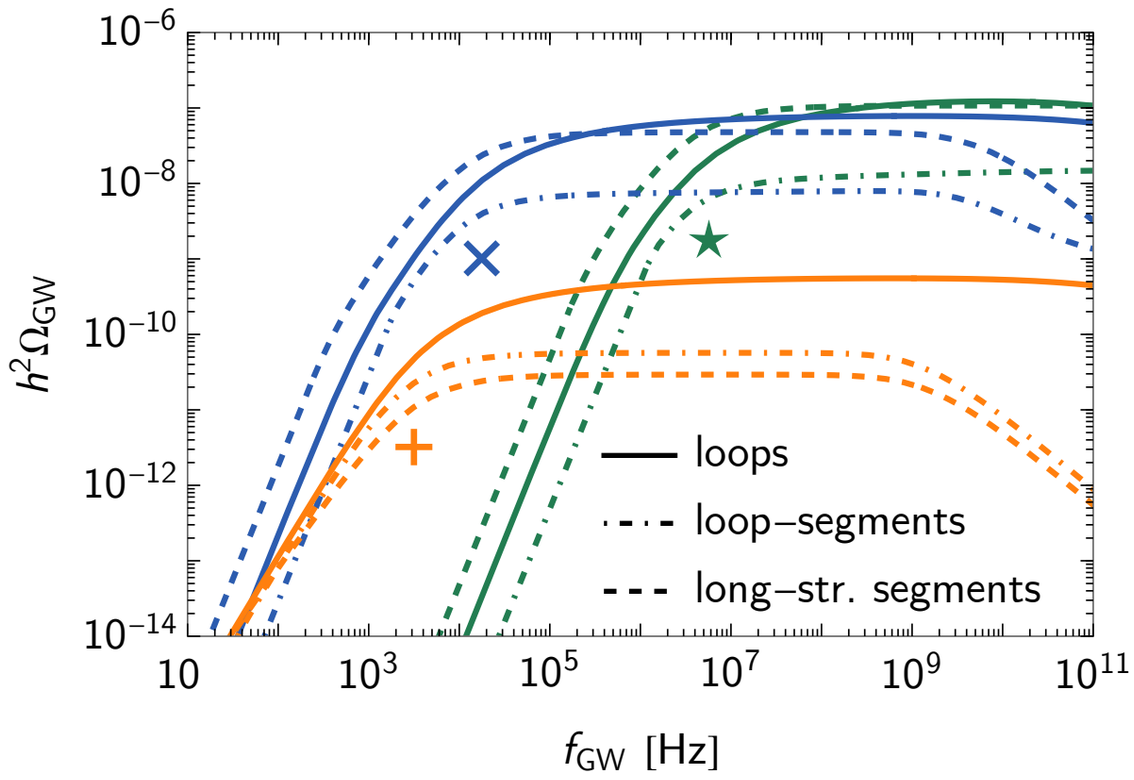


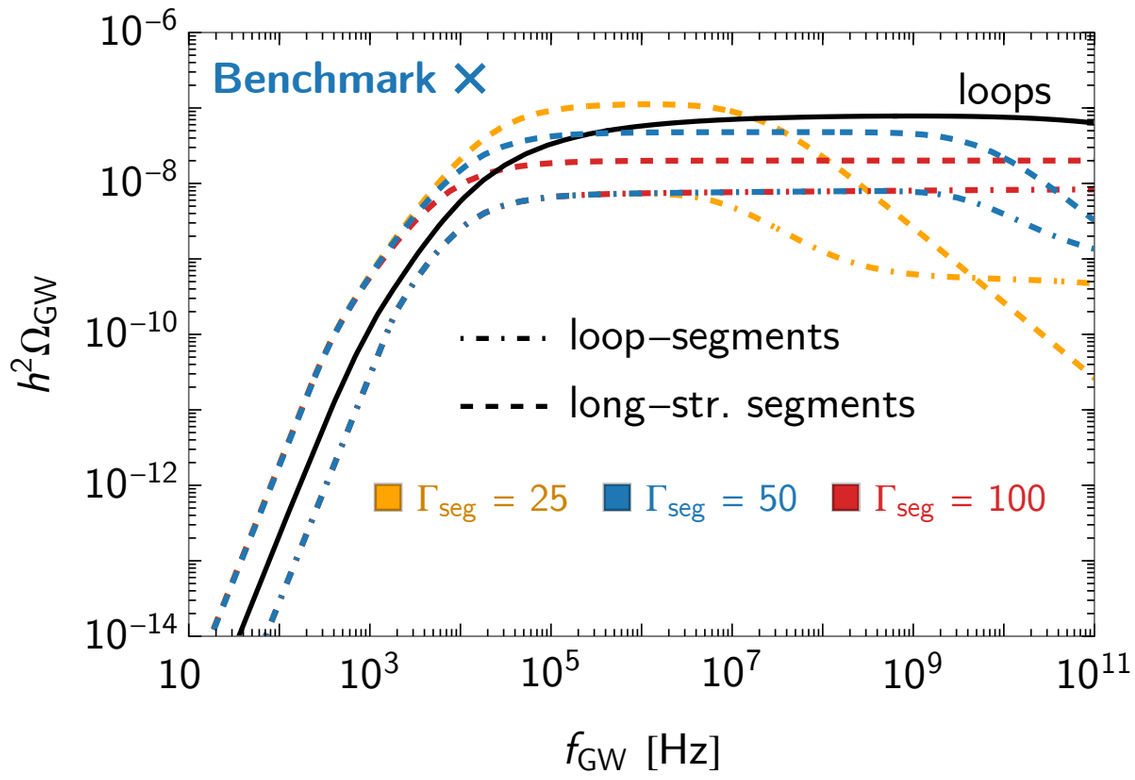
GWB from string segments

Servant, Simakachorn [2312.09281]



Currently, there are several uncertainties in calculating the GW from segments.





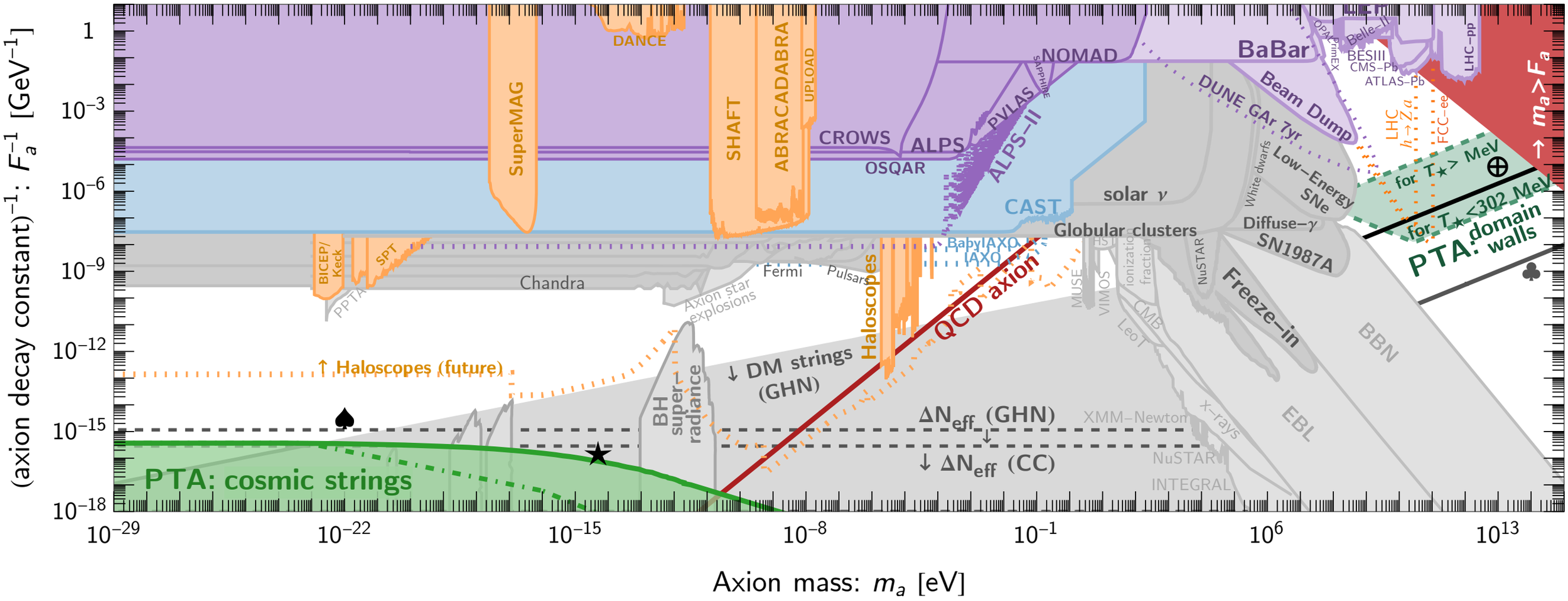
See more details also in Buchmüller, Domcke, Schmitz [2107.04578]

For going beyond the thin soliton approximation
see Dvali, Valbuena-Bermudez, Zantedeschi [2210.14947].

Pulsar timing array constraints on postinflationary axion

Servant, Simakachorn [2307.03121]

Using NANOGrav 15-year data



Axion matter domination from axionic string decay

Servant, Simakachorn [2312.09281]

Axion string–wall system decays.

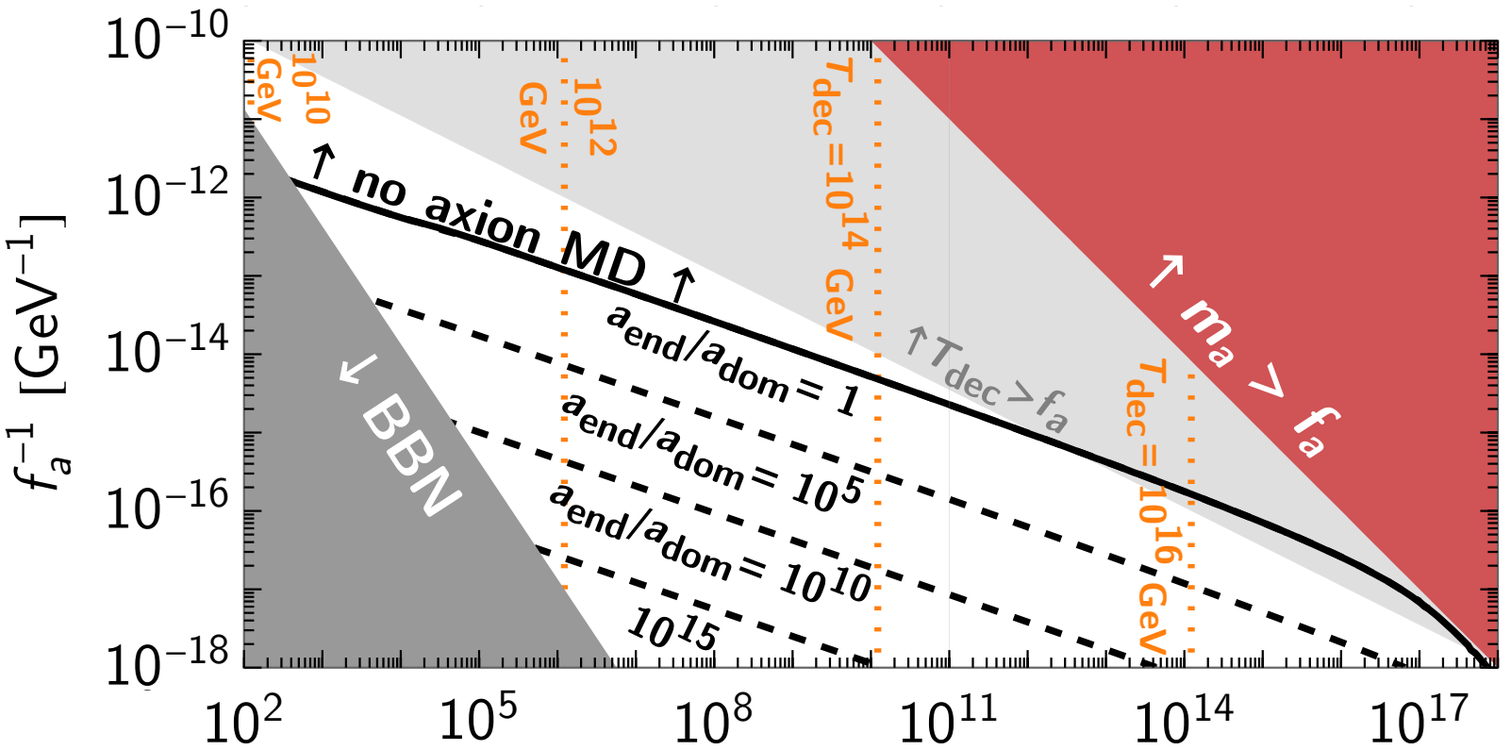
$$T_{\rm dec} \sim 10^9\ {\rm GeV}\sqrt{m_a/{\rm GeV}}$$

Axion–matter domination

$$T_{\rm dom} \simeq T_{\rm dec} G\mu(T_{\rm dec})$$

Axions decay into photons

$$T_{a\gamma} \simeq 4.2\ {\rm MeV}\left[\frac{106.75}{g_*(T_{a\gamma})}\right]^{\frac{1}{4}}\left(\frac{m_a}{\rm TeV}\right)^{\frac{3}{2}}\left[\frac{10^{12}\ {\rm GeV}}{f_a}\right]$$



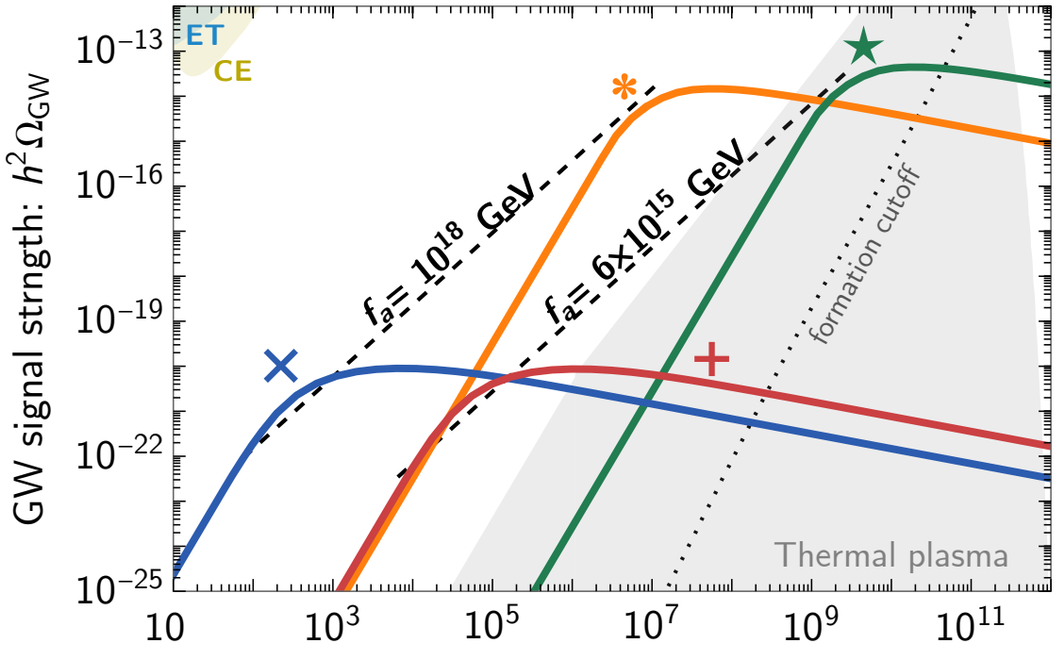
Duration of Axion matter domination

$$\mathcal{B} \equiv \frac{a_{\rm dom}}{a_{\rm end}} = \left[\left(\frac{3\sqrt{10}}{64\pi^2}\right)\frac{m_a^3 g_{a\gamma}^2 M_{\rm Pl}}{g_*^{1/2}(T_{\rm dom})T_{\rm dom}^2}\right]^{\frac{2}{3}} \leq 1,$$

$$g_{a\gamma} = 1.92\alpha_{\rm em}/(2\pi f_a)$$

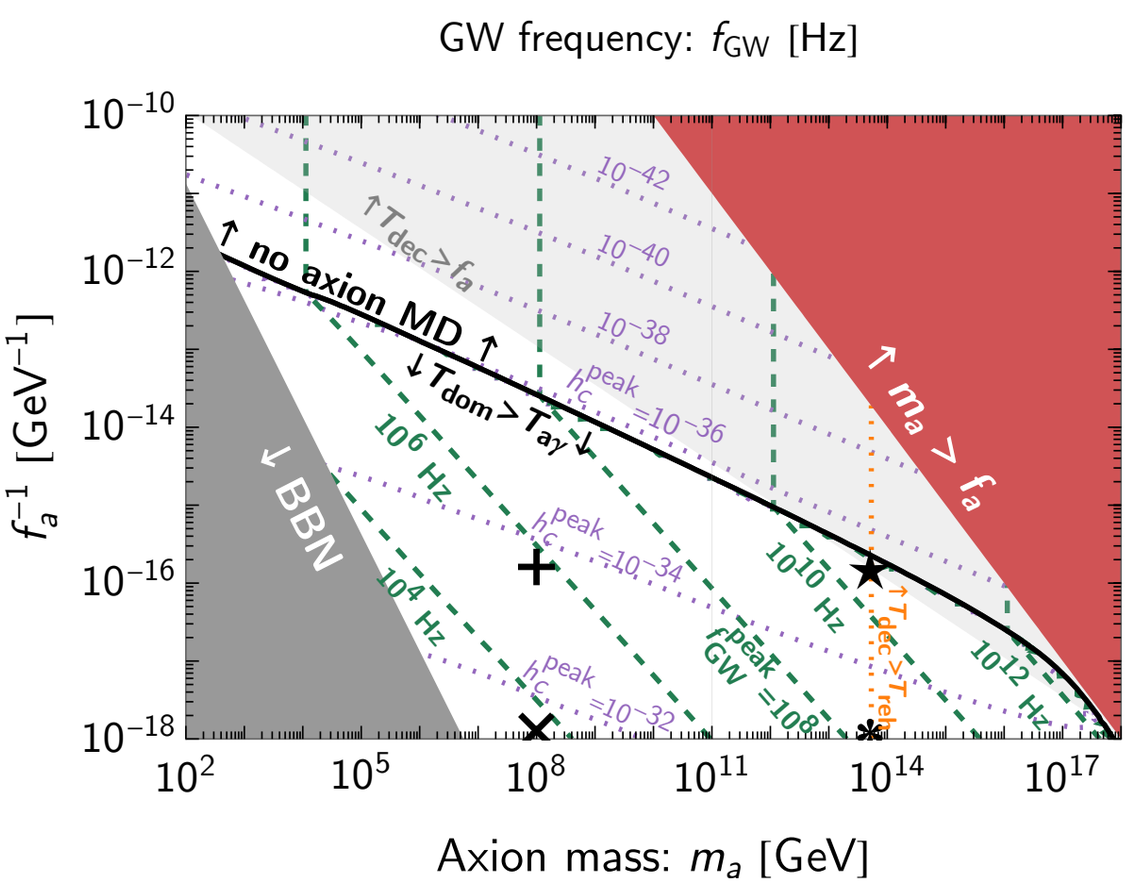
Suppressed UHF GWB from axion strings

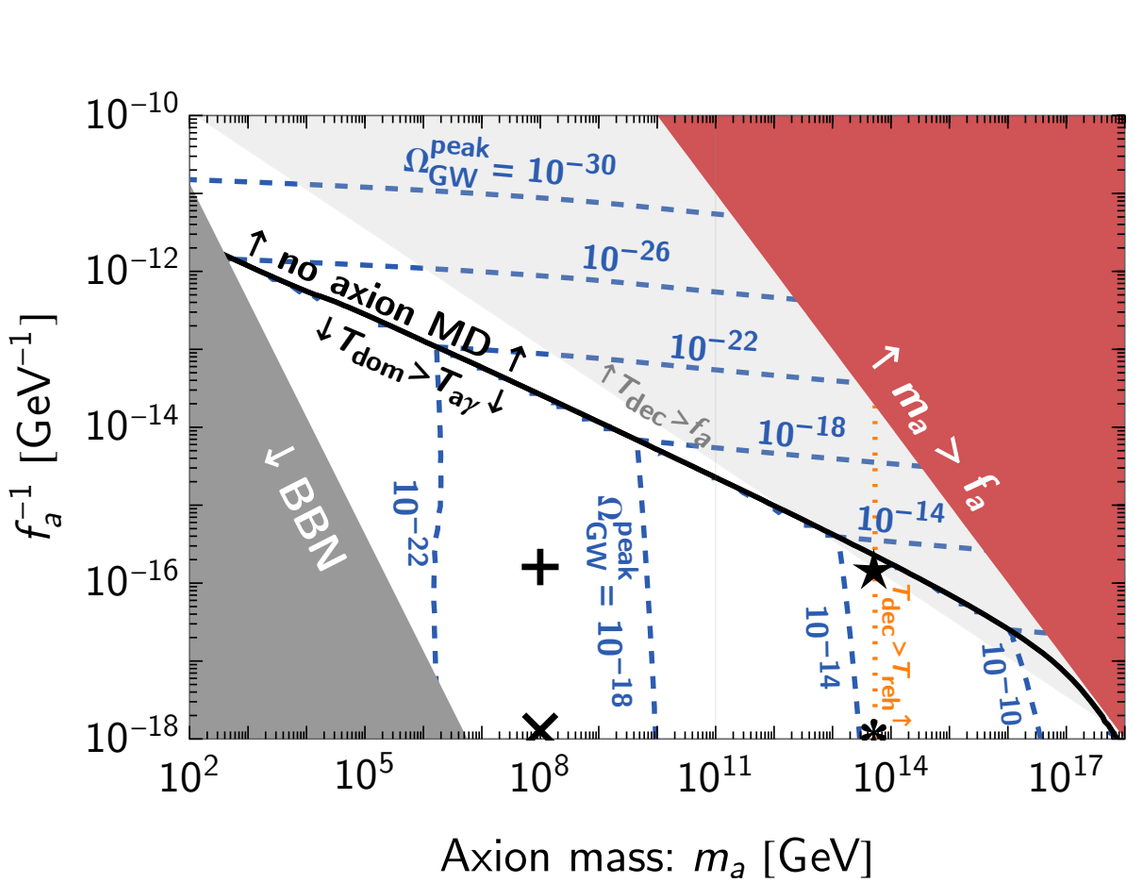
Servant, Simakachorn [2312.09281]



$$\Omega_{\rm GW}(f_{\rm GW}) = \Omega_{\rm GW}^{\rm RD}[f_{\rm GW}^{\rm RD}(f_{\rm GW})]\frac{\mathcal{G}(T_{\rm end})}{\mathcal{G}(T_{\rm dom})}\mathcal{B}.$$

$$f_{\rm GW} = f_{\rm GW}^{\rm RD}\left[\frac{\mathcal{G}(T_{\rm end})}{\mathcal{G}(T_{\rm dom})}\right]^{\frac{1}{4}}\mathcal{B}^{\frac{1}{4}}.$$





The scale-invariant local-string GWB during radiation-domination (simple argument)

Fraction of energy density in GW today

$$\Omega_{\mathrm{GW},0} = \left(\frac{\rho_{\mathrm{GW,prod}}}{\rho_{\mathrm{tot},0}}\right)\left(\frac{a_{\mathrm{prod}}}{a_0}\right)^4 = \left(\frac{\rho_{\mathrm{GW,prod}}}{\rho_{\mathrm{tot,prod}}}\right)\left(\frac{\rho_{\mathrm{tot,prod}}}{\rho_{\mathrm{tot},0}}\right)\left(\frac{a_{\mathrm{prod}}}{a_0}\right)^4$$

constant

Long-lasting

Inflationary GW

(scale-invariant) tensor perturbation: $\Delta_h^2 \simeq (H/M_{\mathrm{Pl}})^2$

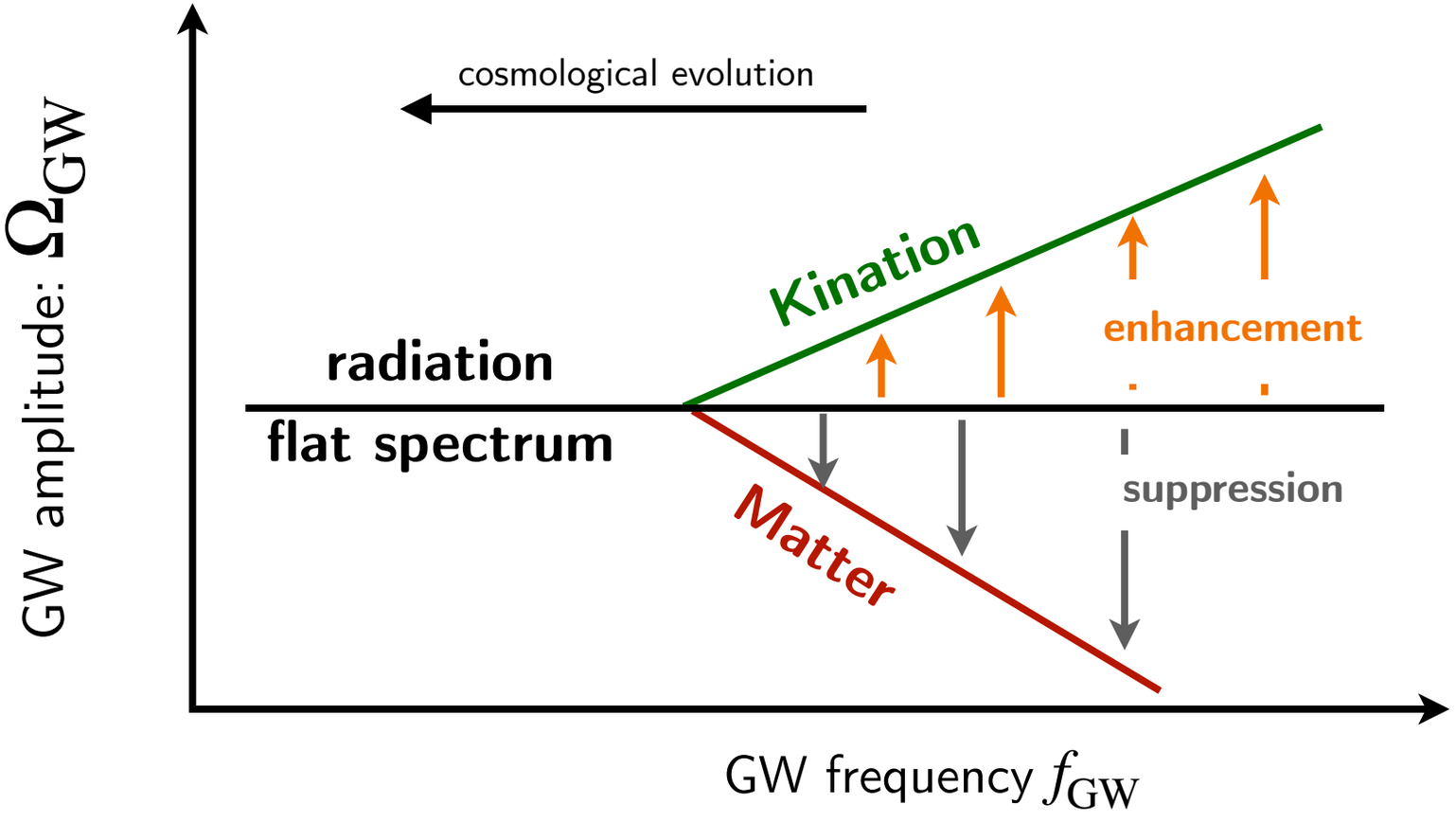
$(\rho_{\mathrm{GW}}/\rho_{\mathrm{tot}})_{\mathrm{prod}} = \mathrm{constant}$

Cosmic-string GW:

$\rho_{\mathrm{GW}} \propto \rho_{\mathrm{string-network}} \propto \rho_{\mathrm{tot}}$

in the so-called "scaling regime"

Gouttenoire, Servant, Simakachorn, 2111.01150

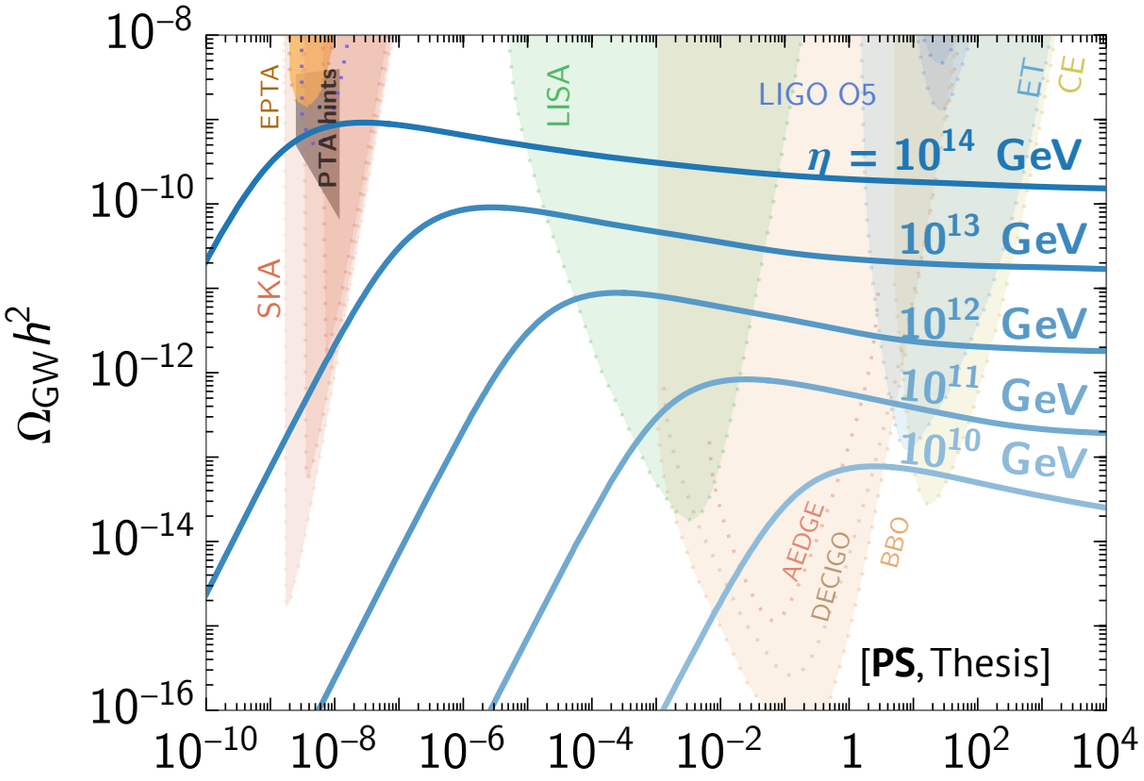


$$\rho_{\mathrm{tot}} \propto \begin{cases} a^{-3} \text{ for matter era,} \\ a^{-4} \text{ for radiation era,} \\ a^{-6} \text{ for kination era} \end{cases}$$

GW from cosmic strings

generated from spontaneous symmetry breaking at an energy scale η

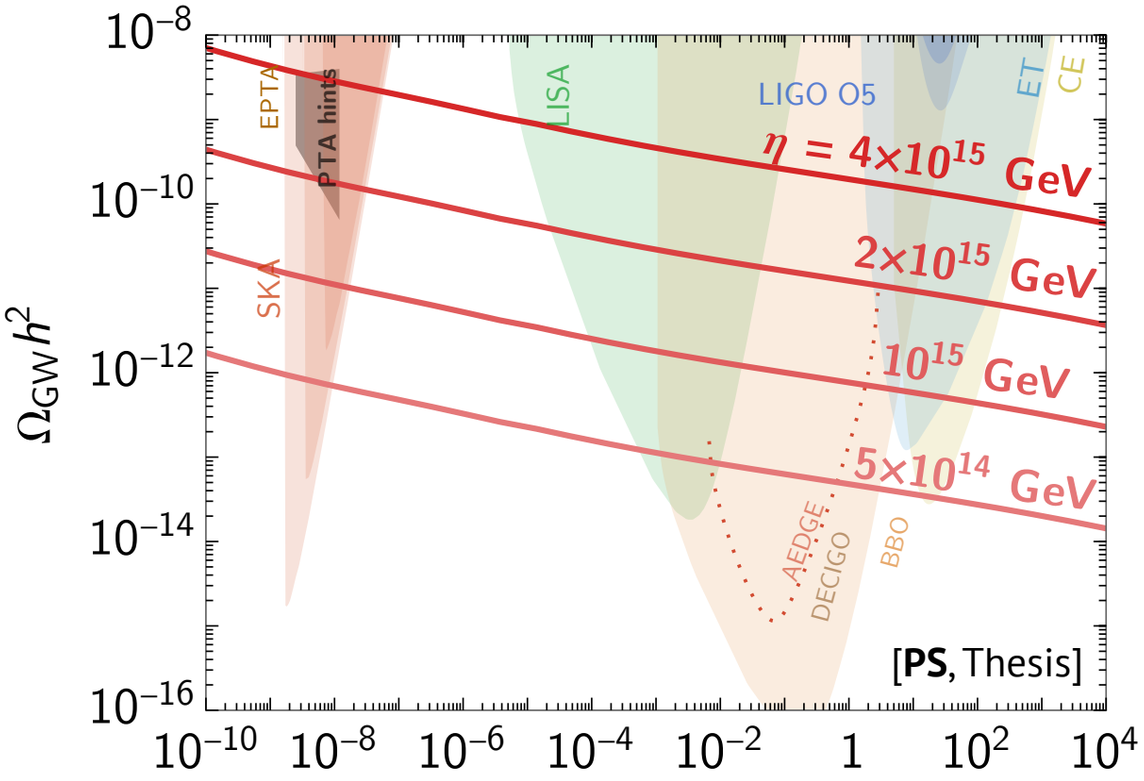
Local cosmic strings



frequency of GW $f_{\rm GW}$ [Hz]

$$\Omega_{\rm GW}^{\rm local} \propto \sqrt{G\mu} \propto \eta$$

Global cosmic strings



frequency of GW $f_{\rm GW}$ [Hz]

$$\Omega_{\rm GW}^{\rm global} \propto \eta^4$$

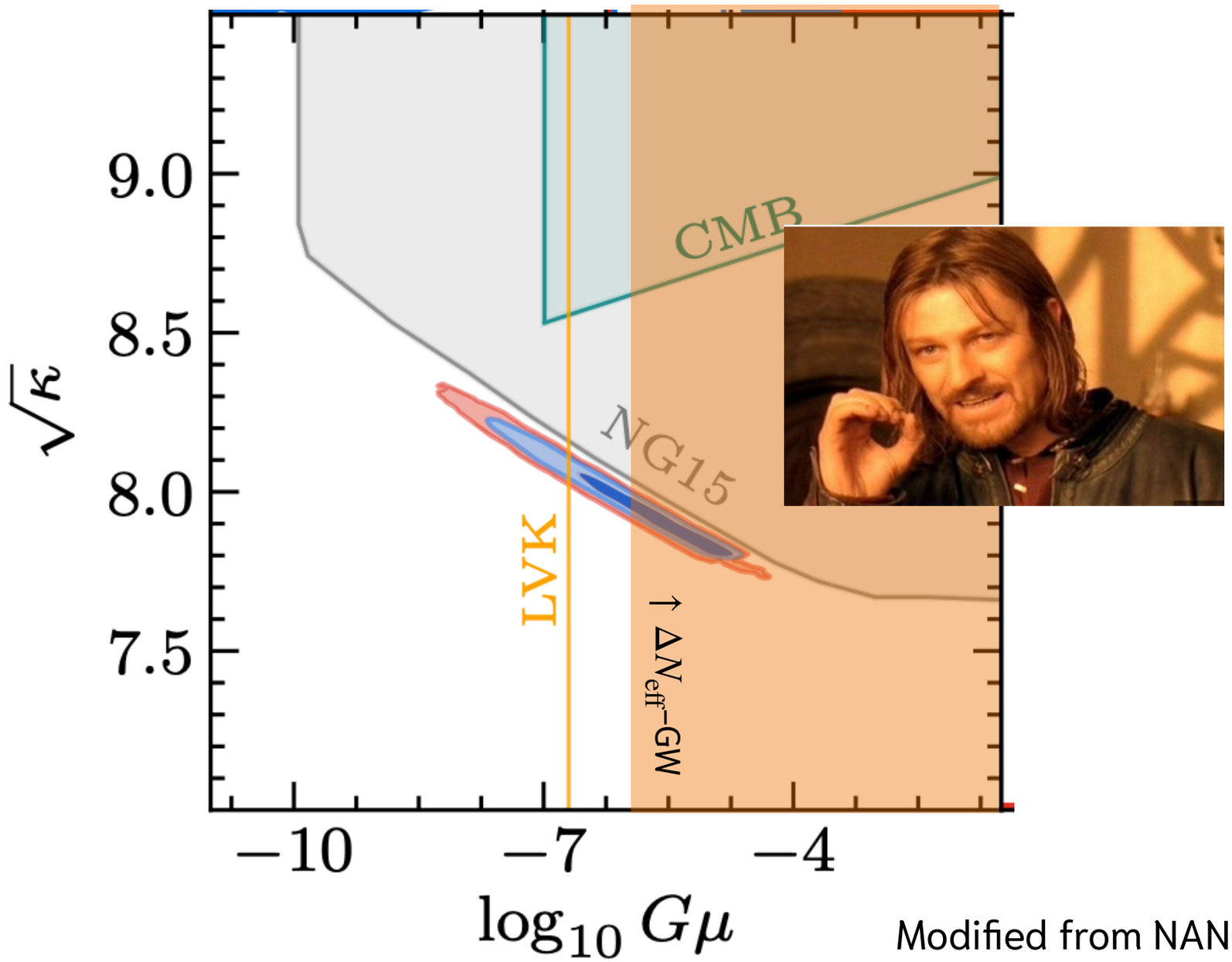
$$f_{\rm GW}(T) \simeq \begin{cases} (2\times10^{-3}\ {\rm Hz})\left(\frac{0.1\times50\times10^{-11}}{\alpha\times\Gamma G\mu}\right)^{1/2}\left(\frac{T}{\rm GeV}\right)\left[\frac{g_*(T)}{g_*(T_0)}\right]^{\frac{1}{4}} & \text{(local strings)}, \\ (4.7\times10^{-6}\ {\rm Hz})\left(\frac{0.1}{\alpha}\right)\left(\frac{T}{\rm GeV}\right)\left[\frac{g_*(T)}{g_*(T_0)}\right]^{\frac{1}{4}} & \text{(global strings)}, \end{cases}$$

↑ Temperature of the Universe

Local metastable strings can explain PTA data super well?

The best-fit region is excluded by LVK bound,
and on top of that the strings with $G\mu > 10^{-5}$ are in tension with $\Delta N_{\rm eff}$-GW bound

The Bayes factor for explaining the PTA data should be smaller than NG15 analysis.



Modified from NANOGrav [2306.16219]