Cosmic Archeology with Primordial GW Backgrounds

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Fundamental Physics and Gravitational Wave Detectors Workshop, Pollica 2024
16.09.2024

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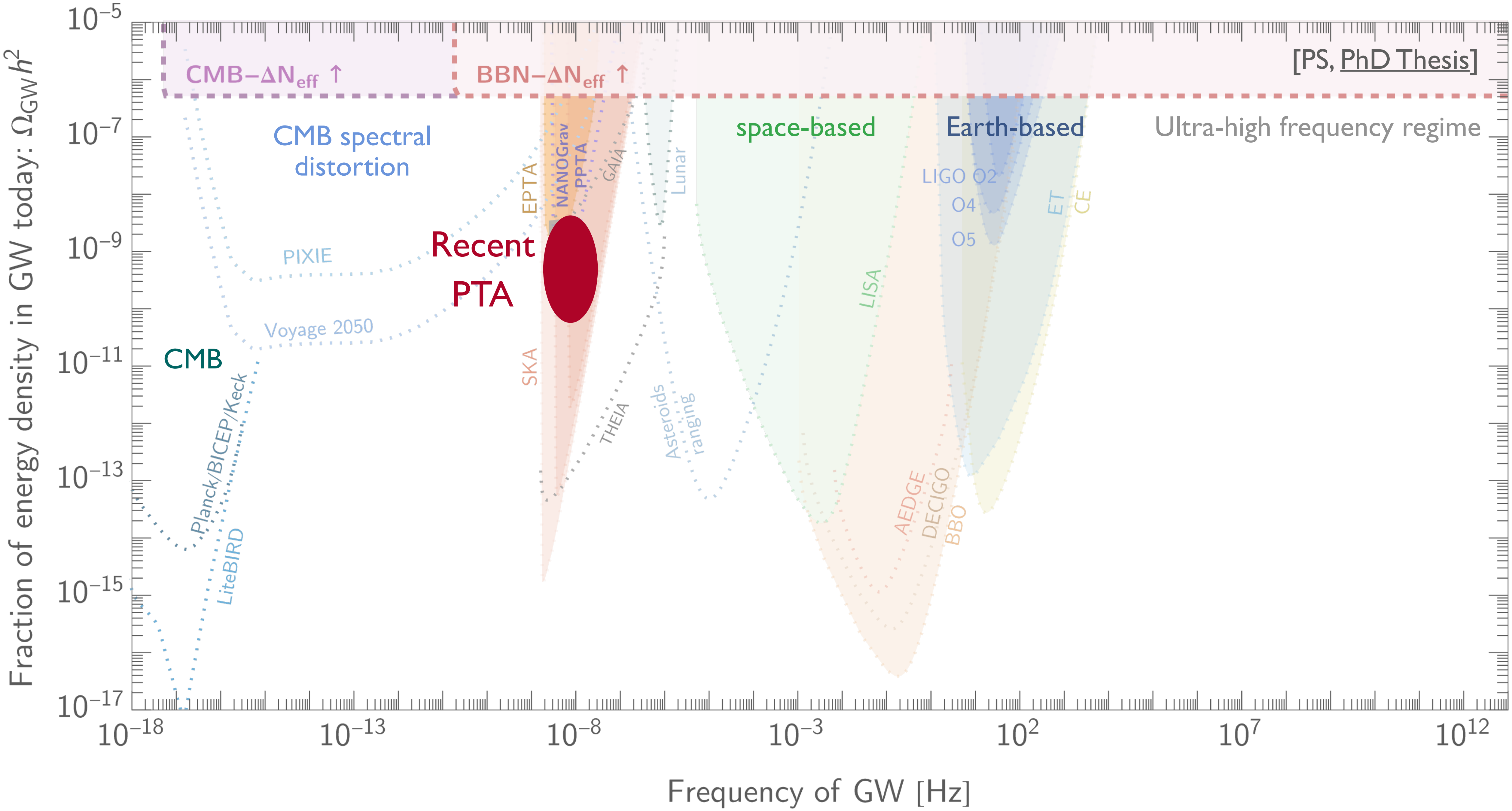
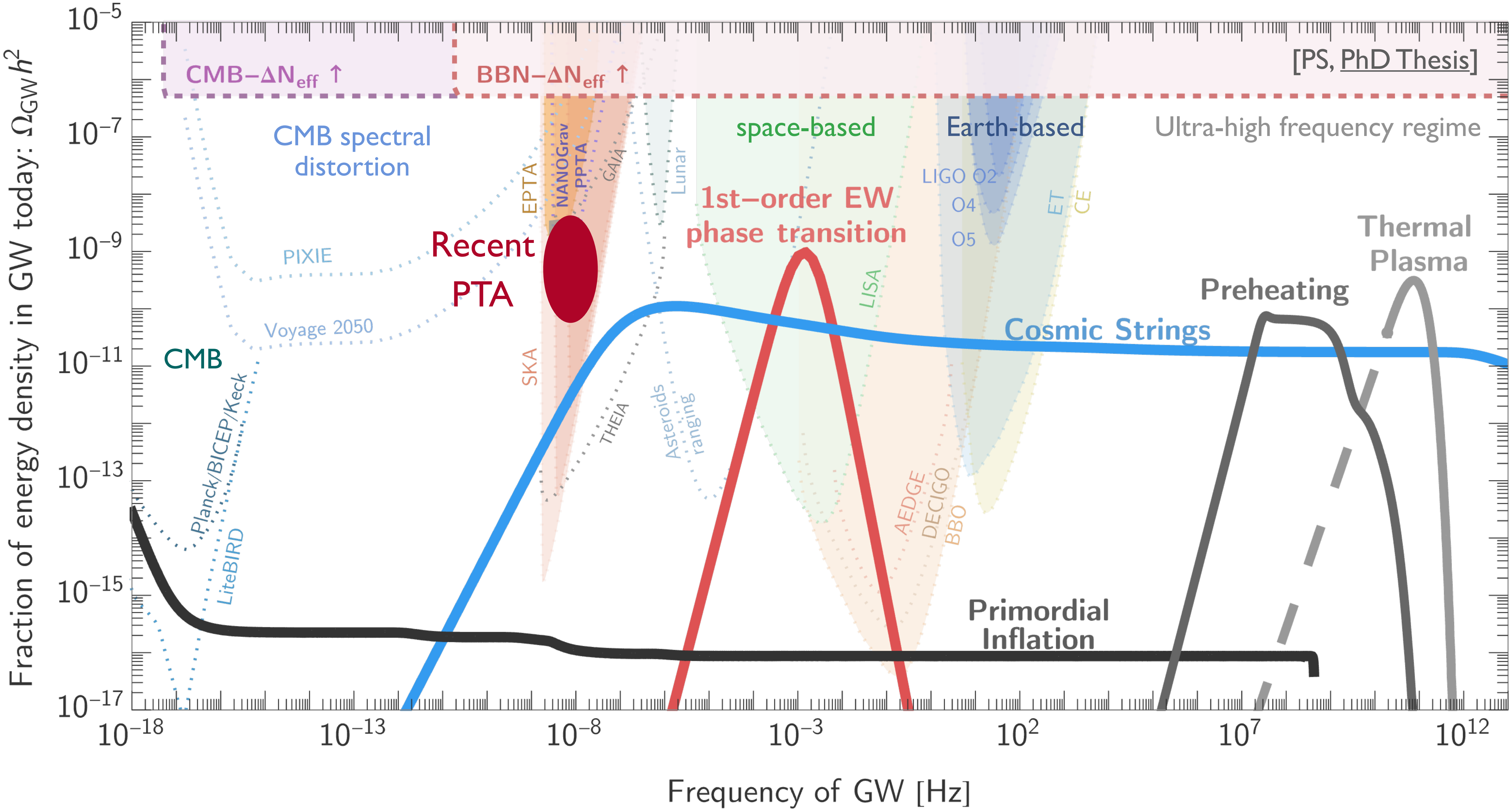
Landscape of Primordial Gravitational-Wave Background (GWB)



Landscape of Primordial Gravitational–Wave Background (GWB)

$$\rho^{\rm GW}_{\rm today} = \rho^{\rm GW}_{\rm prod}\left(\frac{a_{\rm prod}}{a_{\rm today}}\right)^4$$

Most cosmological GWB ⇔ BSM of particle physics



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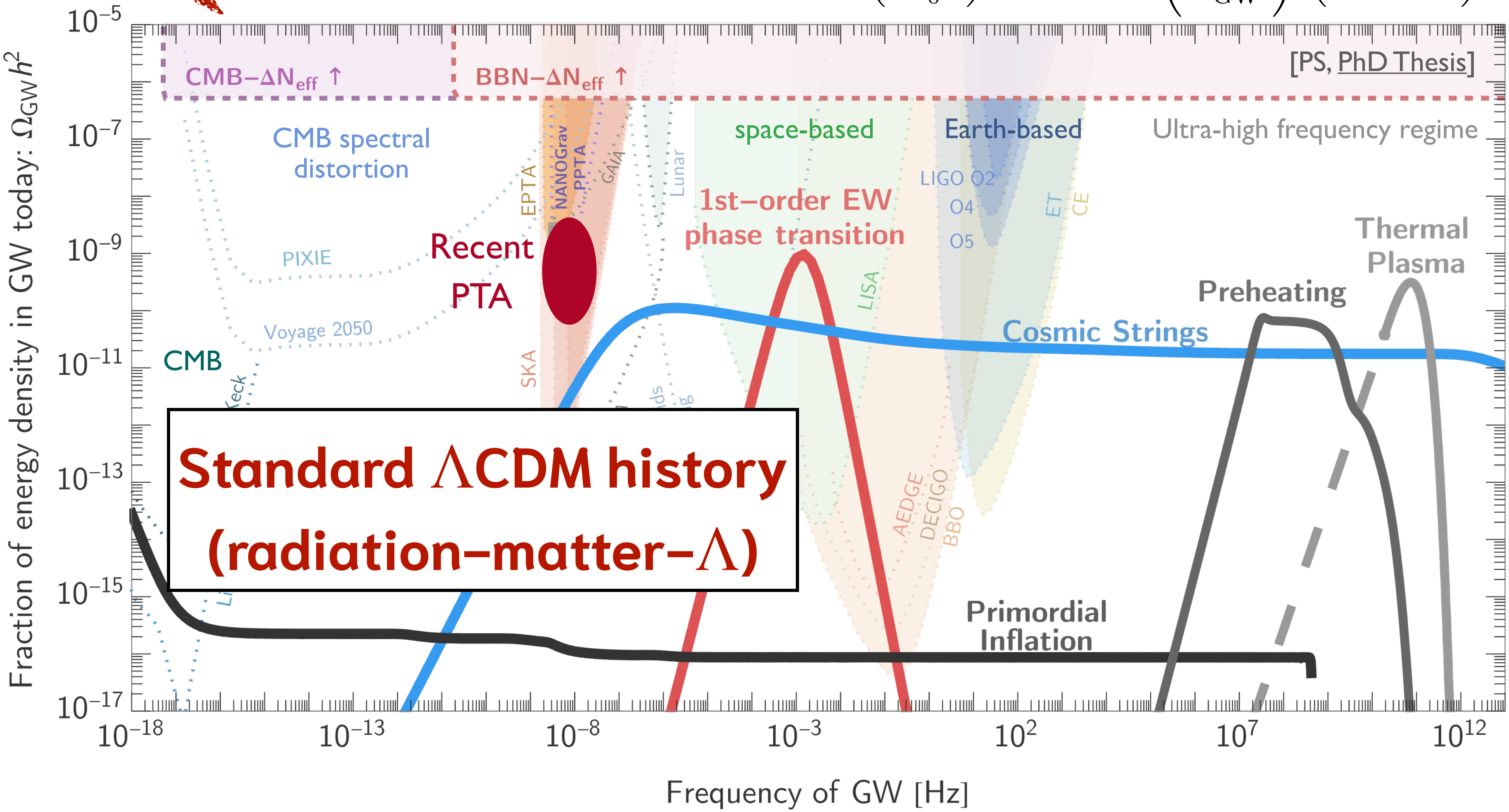
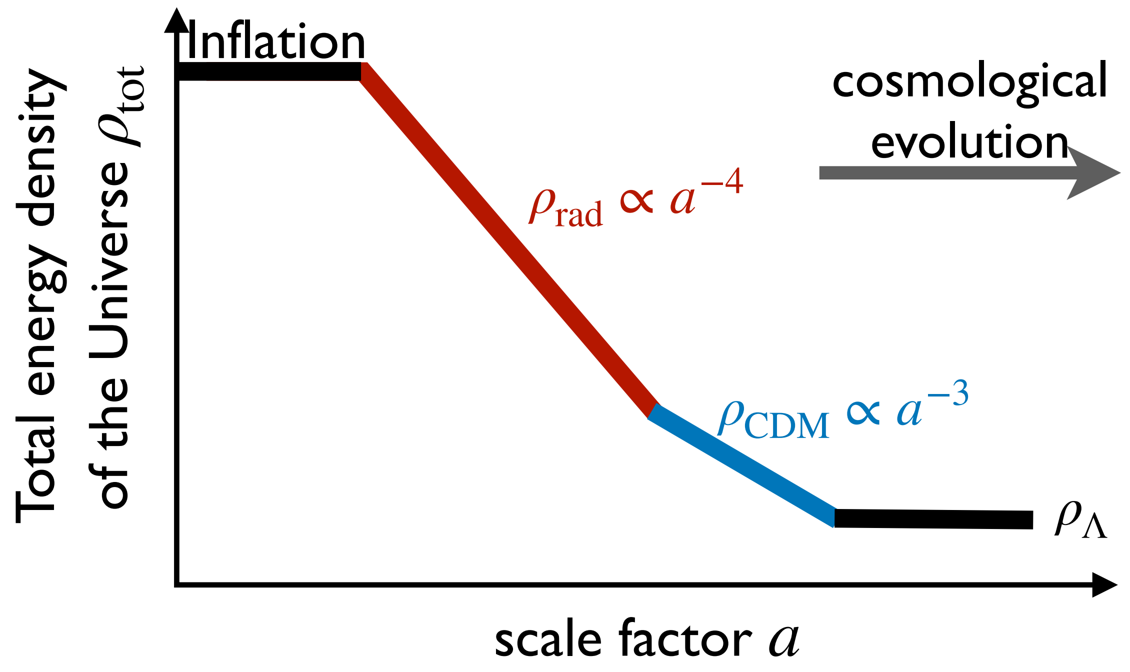
cosmic evolution

$$f_{\rm GW,0} = \lambda^{-1}_{\rm GW}\left(\frac{a_{\rm prod}}{a_0}\right) \simeq 10^{-6}\ {\rm Hz}\left(\frac{H^{-1}_{\rm prod}}{\lambda_{\rm GW}}\right)\left(\frac{T_{\rm prod}}{100\ {\rm GeV}}\right)$$



The Standard ΛCDM universe



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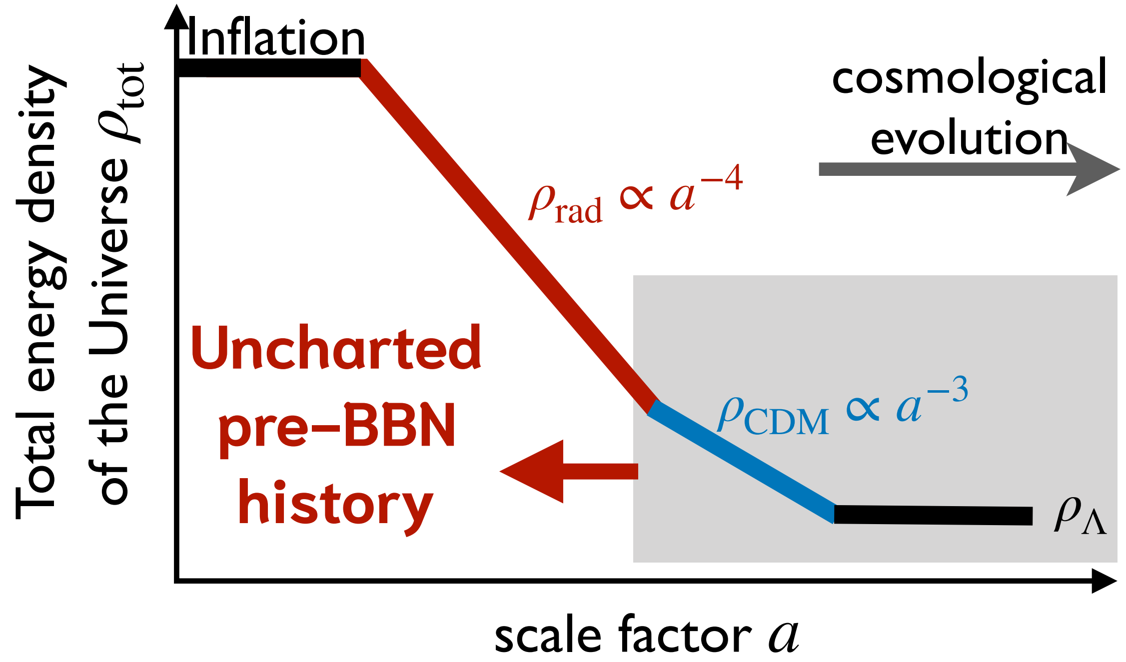

Post–BBN history is well constrained. ($T \lesssim$ MeV, $t \gtrsim 1$ s)

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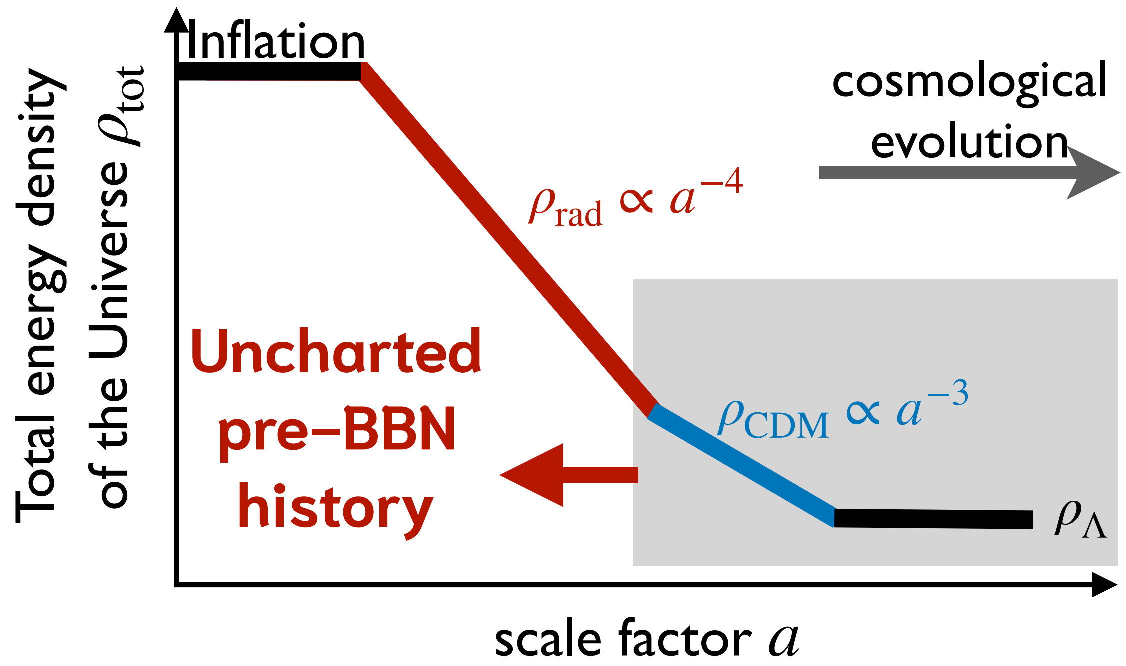

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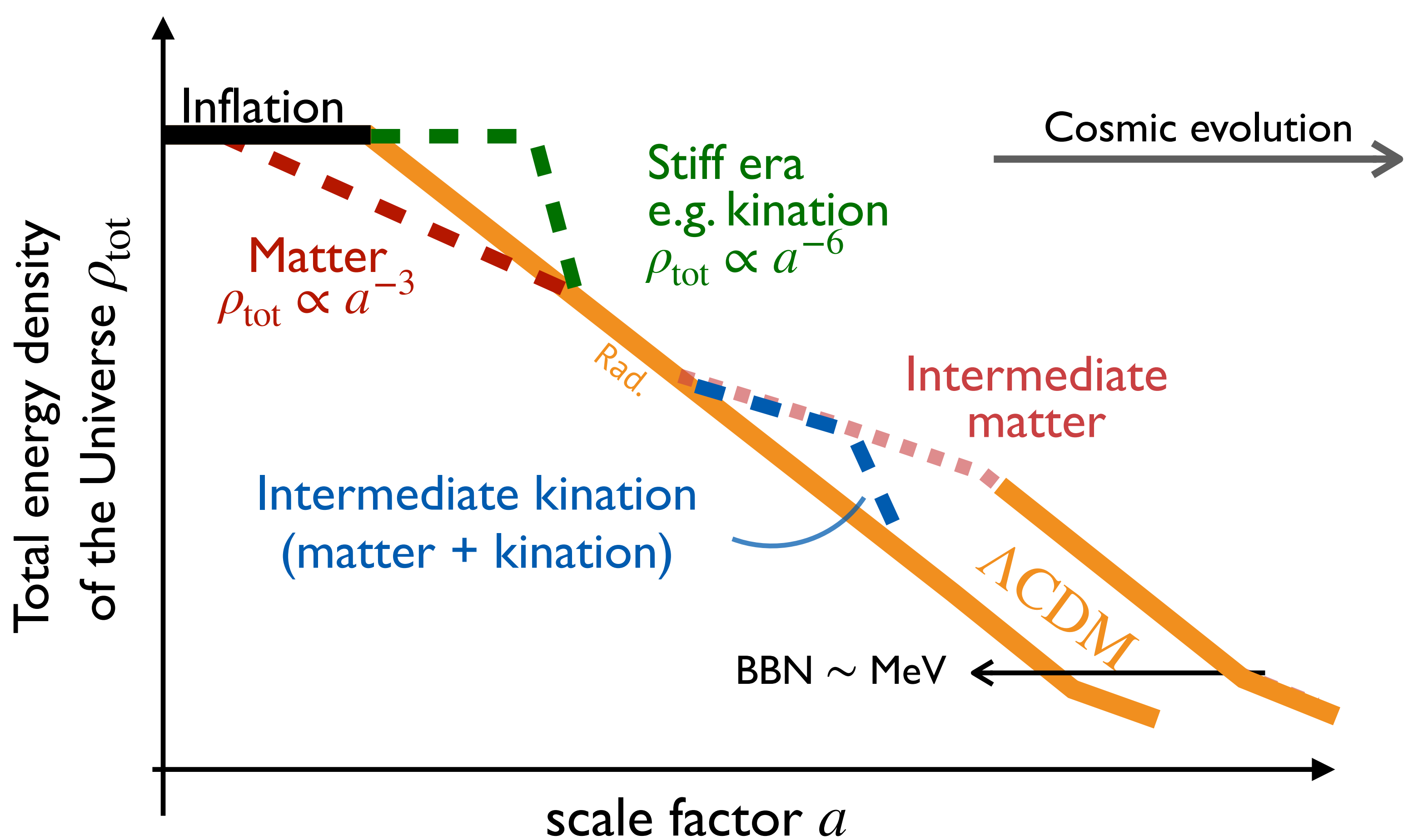
Cosmic histories beyond the standard (ΛCDM) picture.



Charting cosmic history with primordial GWB

Non–standard cosmic history affects

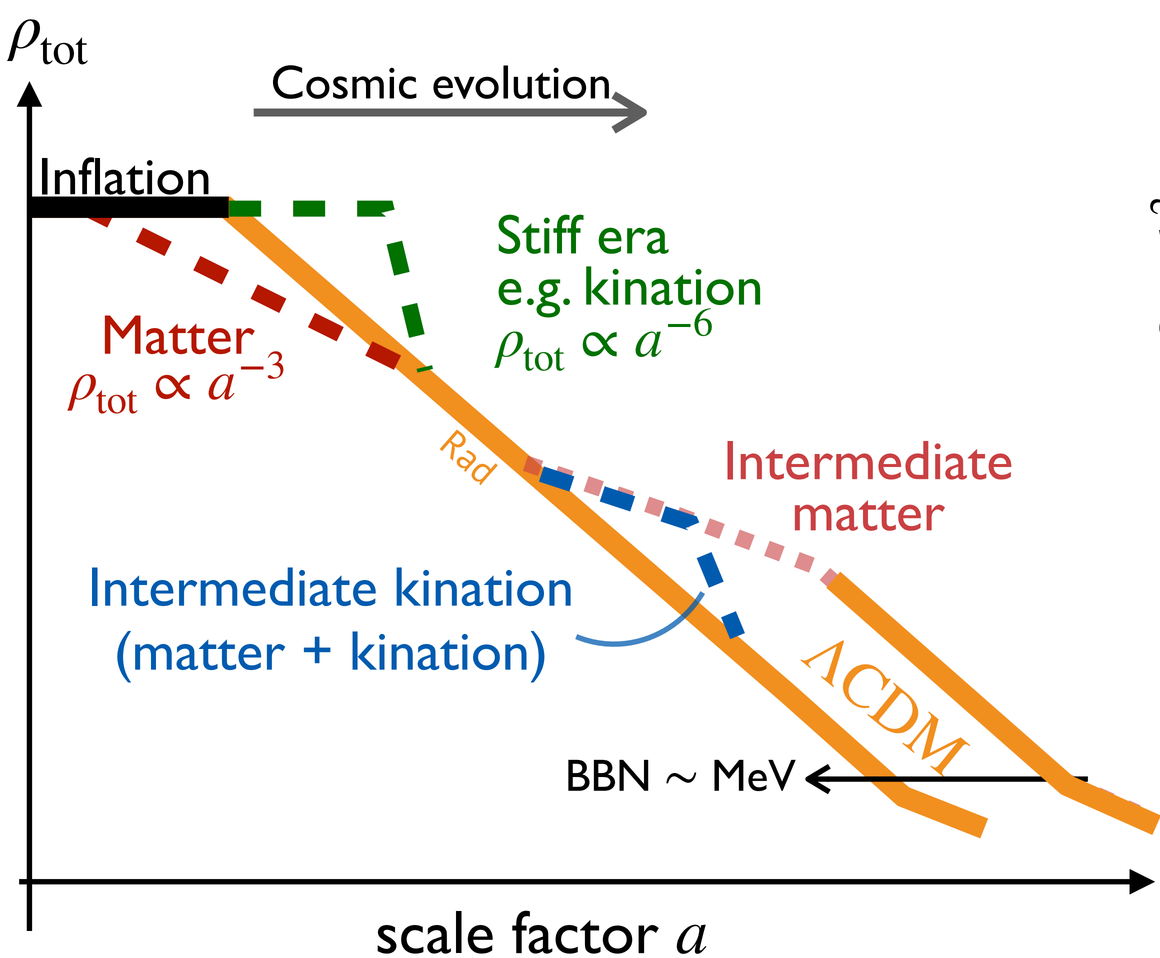
– The GW sources

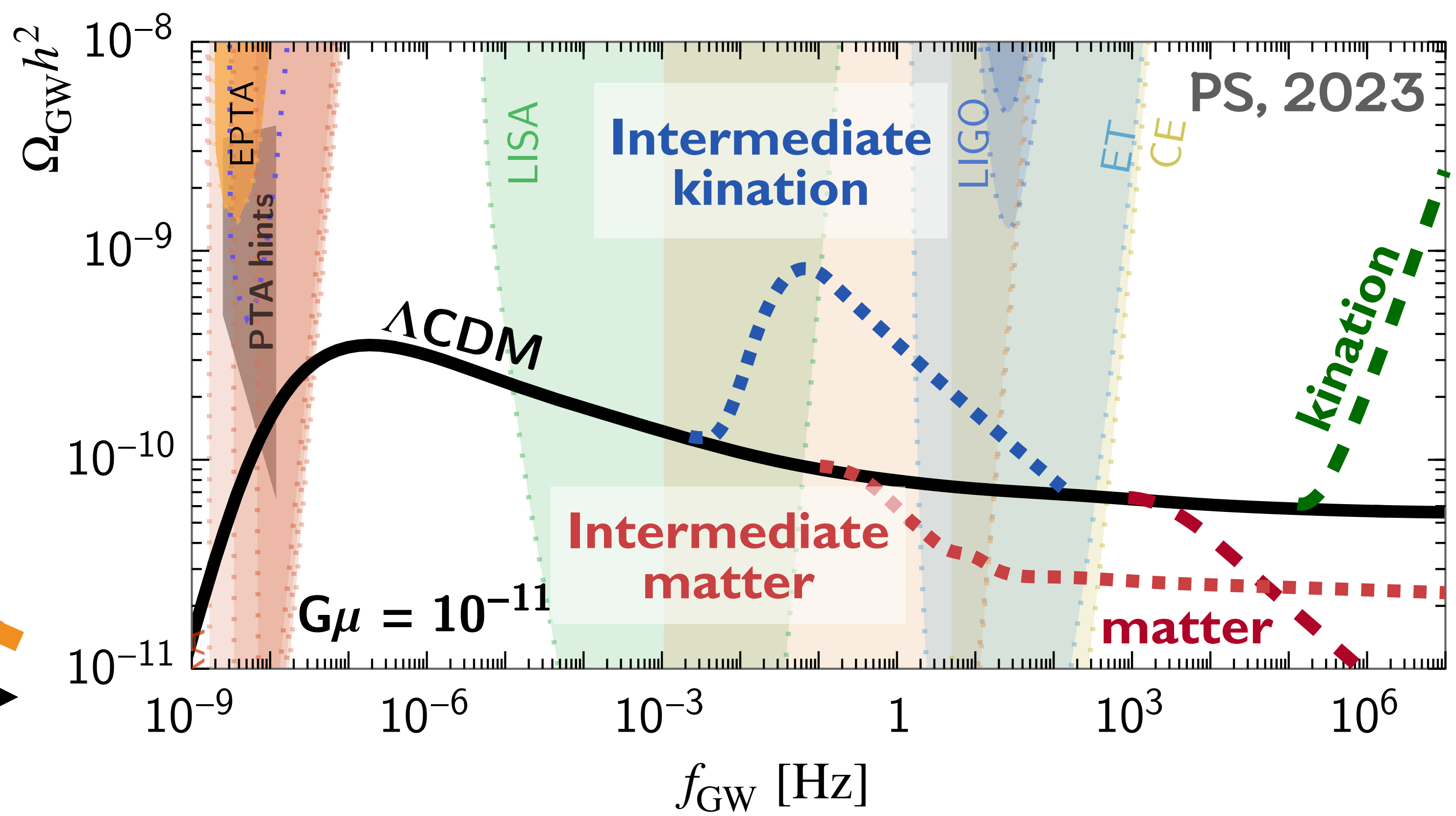
– The dilution from cosmic expansion

$$\rho^{\rm GW}_{\rm today} = \rho^{\rm GW}_{\rm prod} \left(\frac{a_{\rm prod}}{a_{\rm today}} \right)^4$$

"Non–standard" history beyond SM radiation era

⇒ "Features" in GW spectrum.





For long–lasting sources,
e.g., cosmic strings and inflation.

Several works...

- UV completions for non-standard cosmic histories
- how to probe with GWB from local & global cosmic strings, inflation, etc.

Matter/Stiff

e.g., reheating after inflation

⇒ Suppressed/enhanced

(Using cosmic-string GWB)

Cui, Lewicki, Wells, 1711.03104, 1808.08968

Servant, Gouttenoire, **PS** 1912.02569

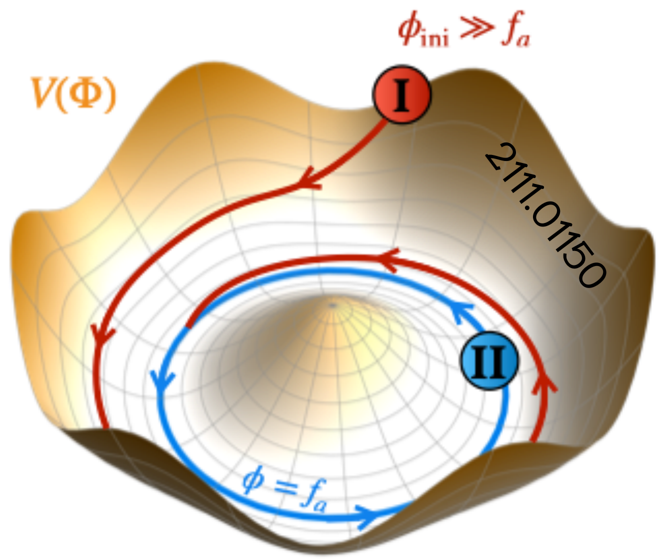
Intermediate Kination

e.g., "Rotating Axion"

⇒ "Peak" Signature

Co, Dunsky, Fernandez, et al. 2108.09299

Servant, Gouttenoire, **PS** 2108.10328, 2111.01150



Intermediate Matter

e.g., oscillating moduli, dark photons, primordial black holes,

Servant, Gouttenoire, **PS** 1912.03245

Blasi, Brdar, Schmitz, 2004.02889

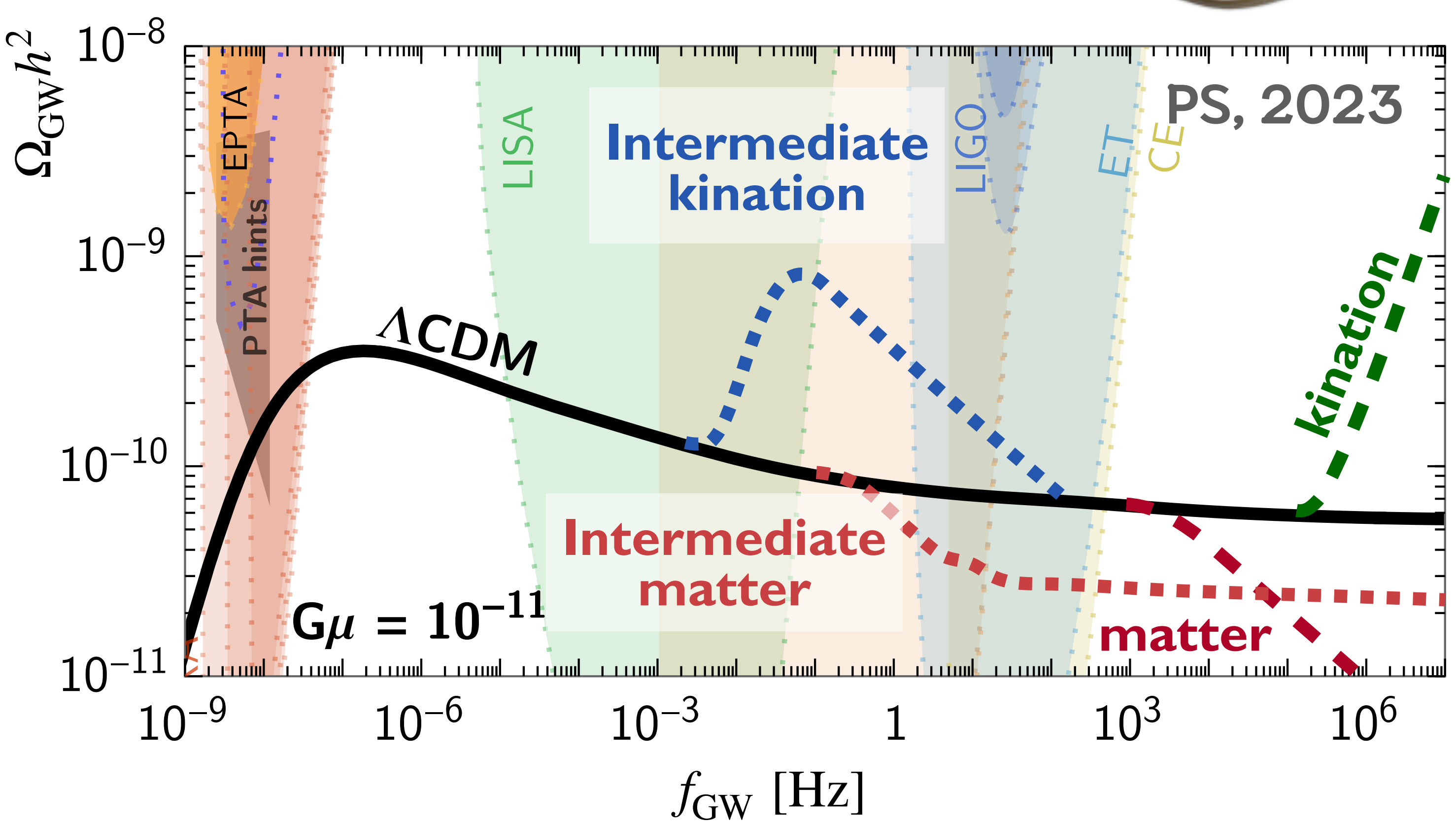
Ghoshal, Gouttenoire, Heurtier, **PS**, 2304.04793

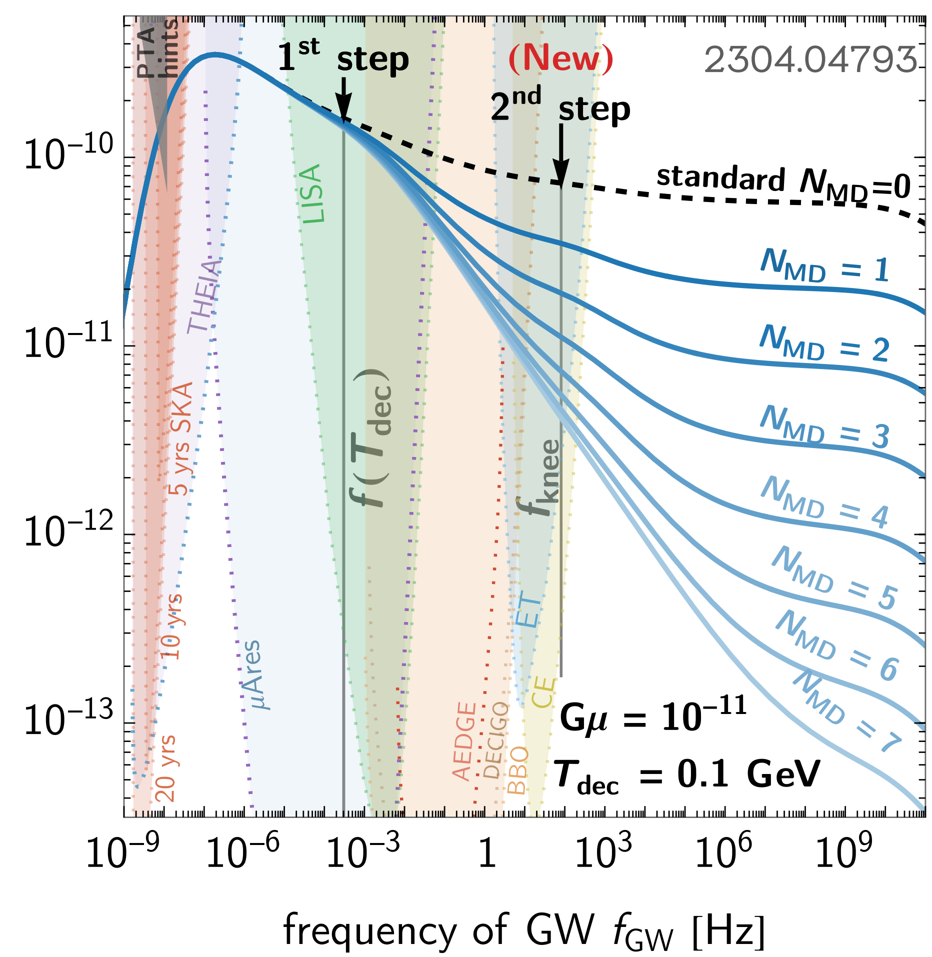
& Extra relativistic DOFs

Cui, Lewicki, Wells, 1808.08968,

Servant, **PS,** To appear

⇒ (multi)-step signature





Other directions

PTA observations

GWB Interpretation

Many sources
including scalar-induced GWB
with non-Gaussianity.

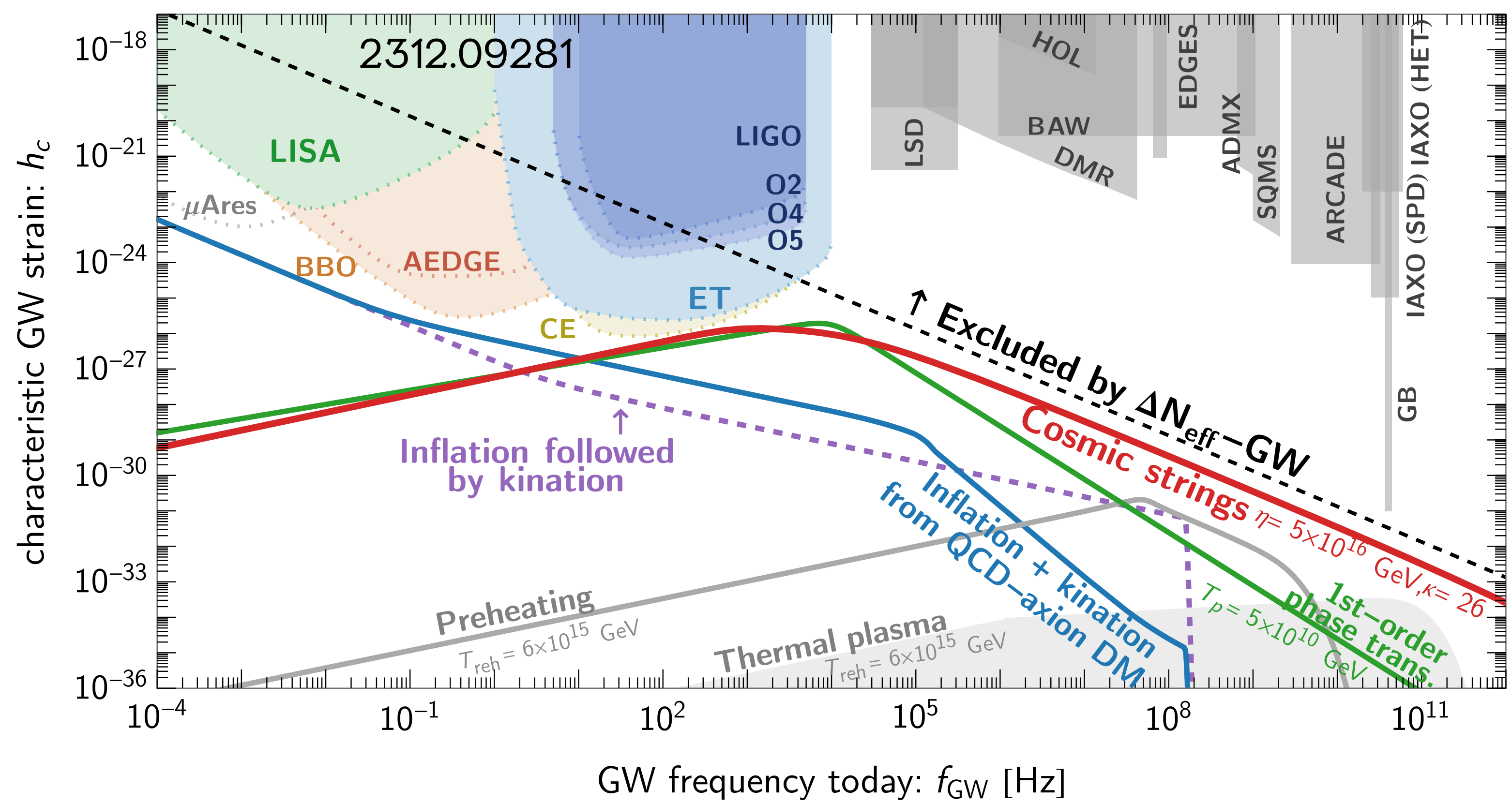
Figueroa, Pieroni, Ricciardone, **PS**
2307.02399

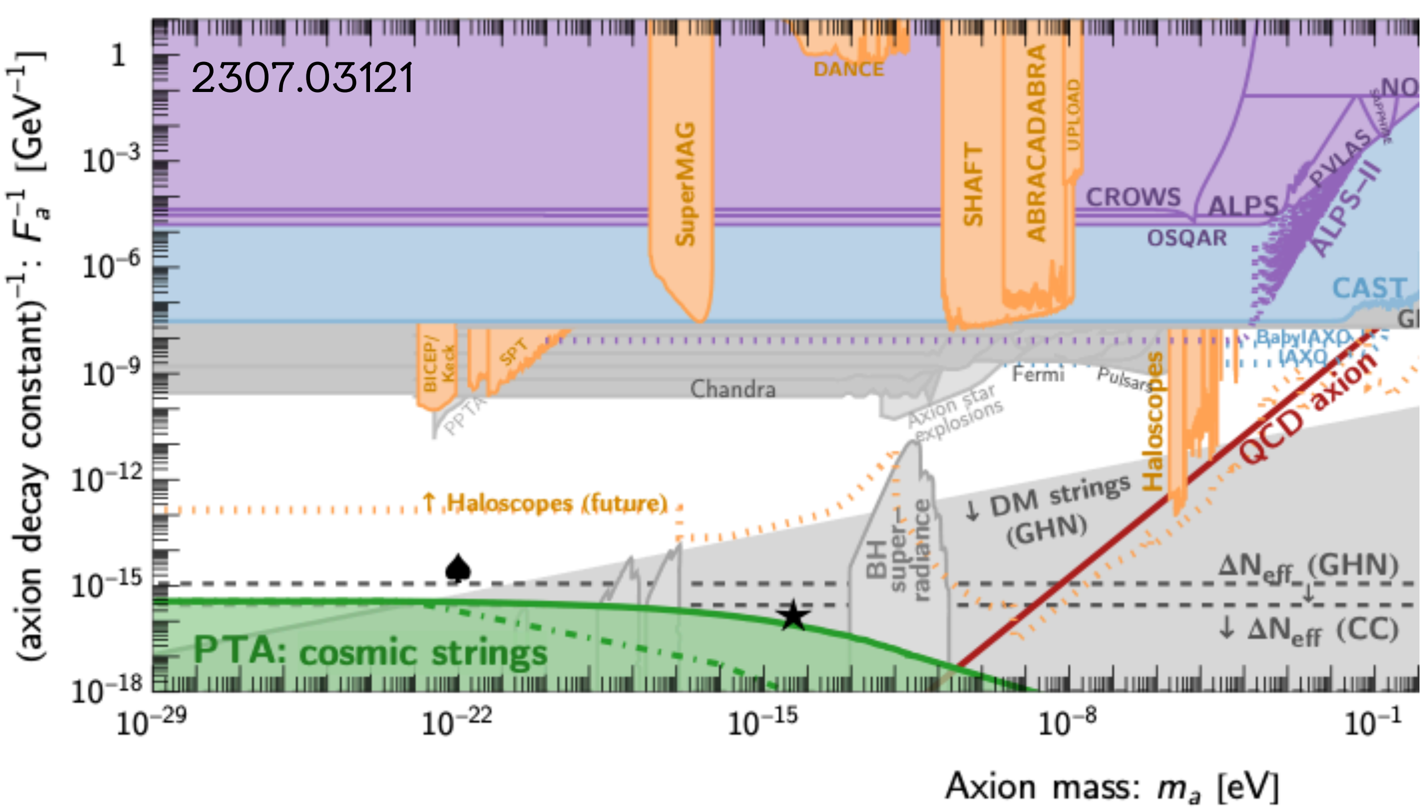
Constraints on postinflationary axion (from strings/domain-wall GWB)

Servant, **PS** 2307.03121

Ultra-high frequency (> kHz) GWB: the case of cosmic strings

Servant, PS
2312.09281





The signal from metastable local strings
can be as high as $\Delta N_{\rm eff}$ bound,
allowing the scalar potential reconstruction.

Signals from global (axionic) strings
are suppressed by heavy axions.

We really need UHF experiments that probe below $\Delta N_{\rm eff}$ bound.

A Shameless Advertisement

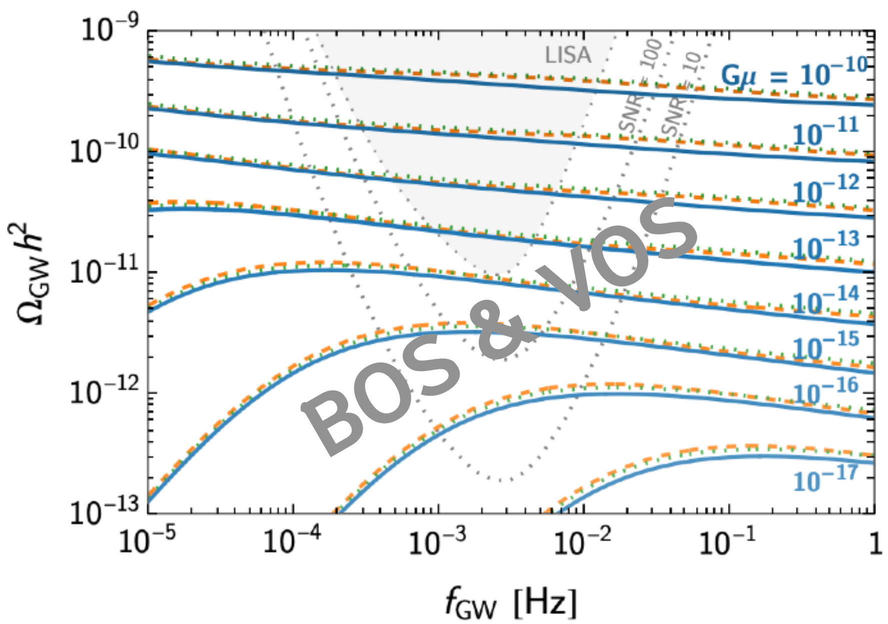
peerasima / cosmic-strings-GWB

Templates' Catalogue for cosmic-string GWB

Publicly available soon with ***Simulation-based reconstruction of cosmic-string GWB***

Ongoing work [Figueroa, Dimitriou, PS, Zaldivar]

Faster inference!
Larger parameter-space exploration!



Extensive lists of models
and non-standard scenarios.

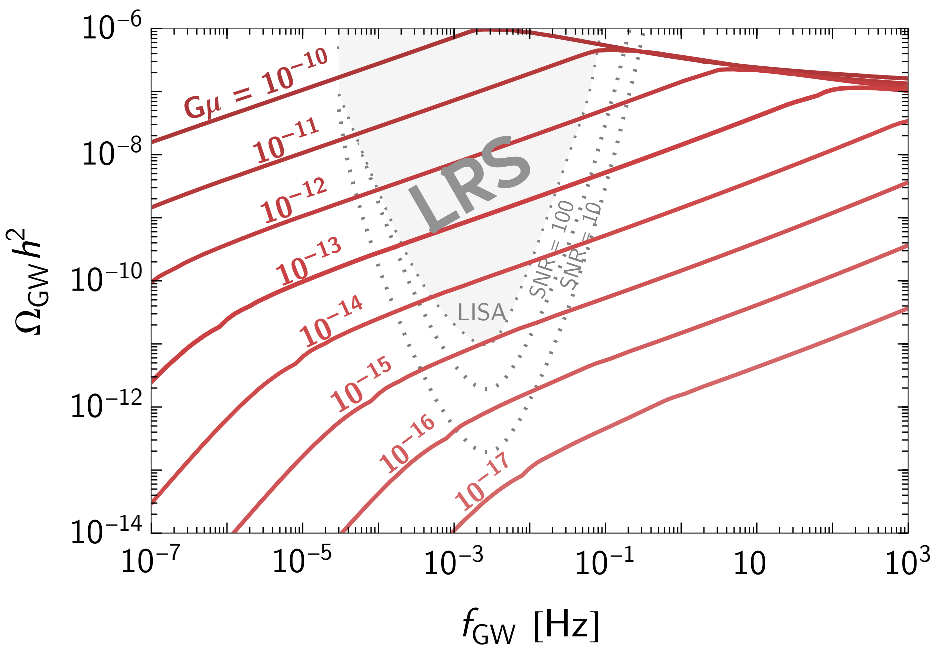
Conventional

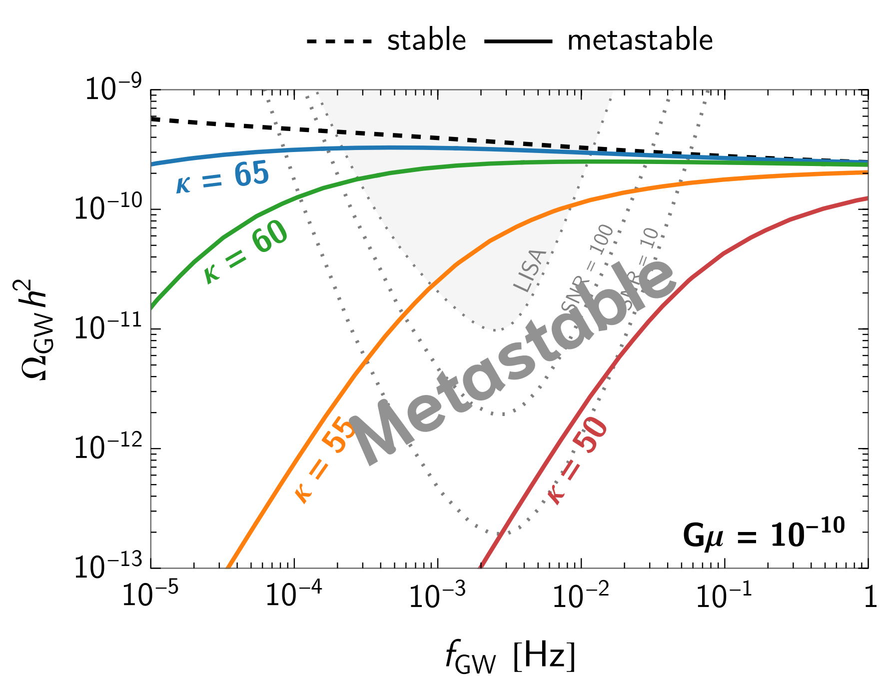
Semi-analytic (VOS)

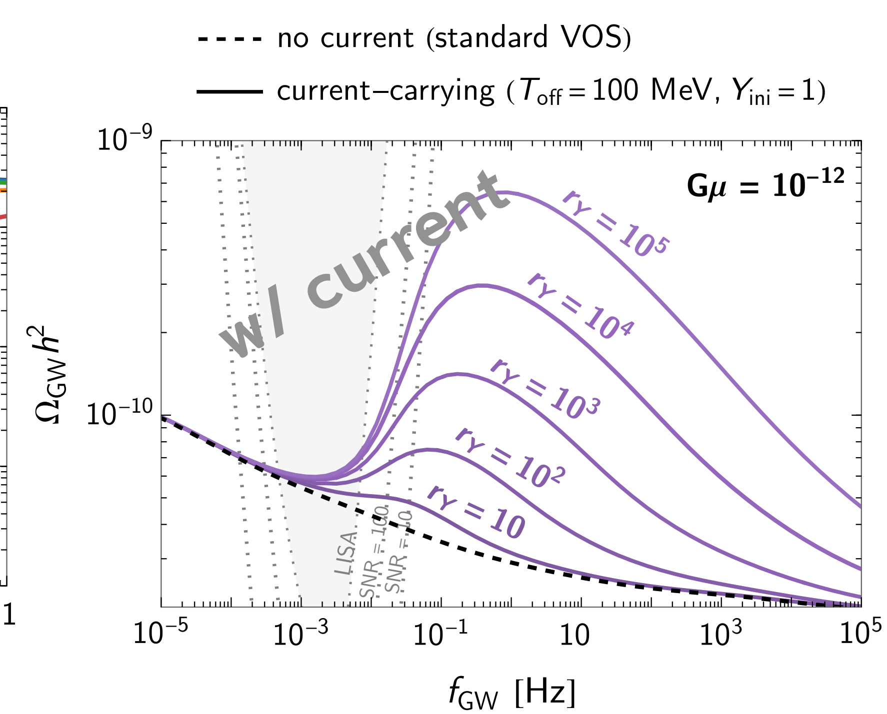
Numerical (BOS & LRS)

Non-conventional

Non-standard GW emission (α, q),
Extra rela. DOFs., UV cutoffs, Non-ST cosmo
Metastable strings, Current-carrying strings







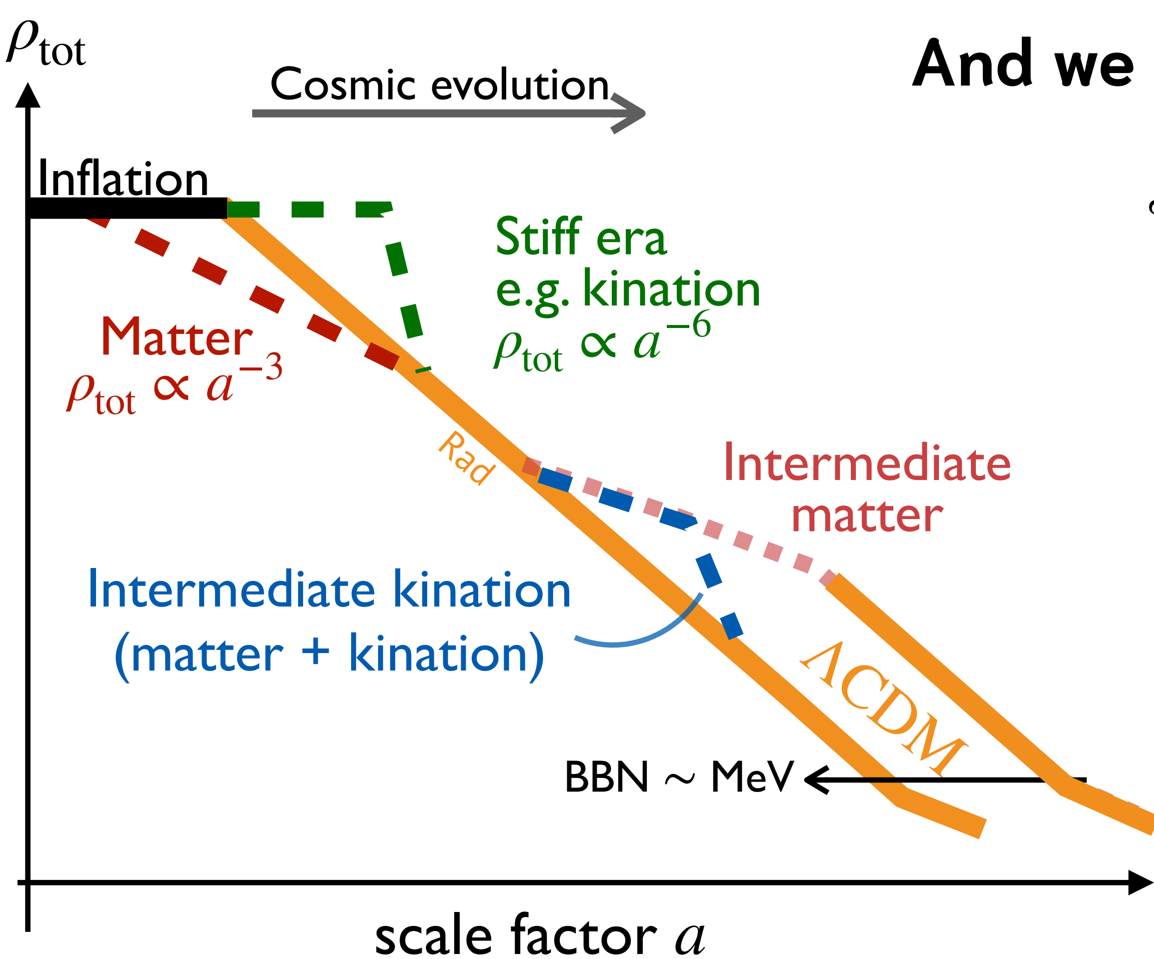
SUMMARY

A new era for exploiting primordial GW as unique tools

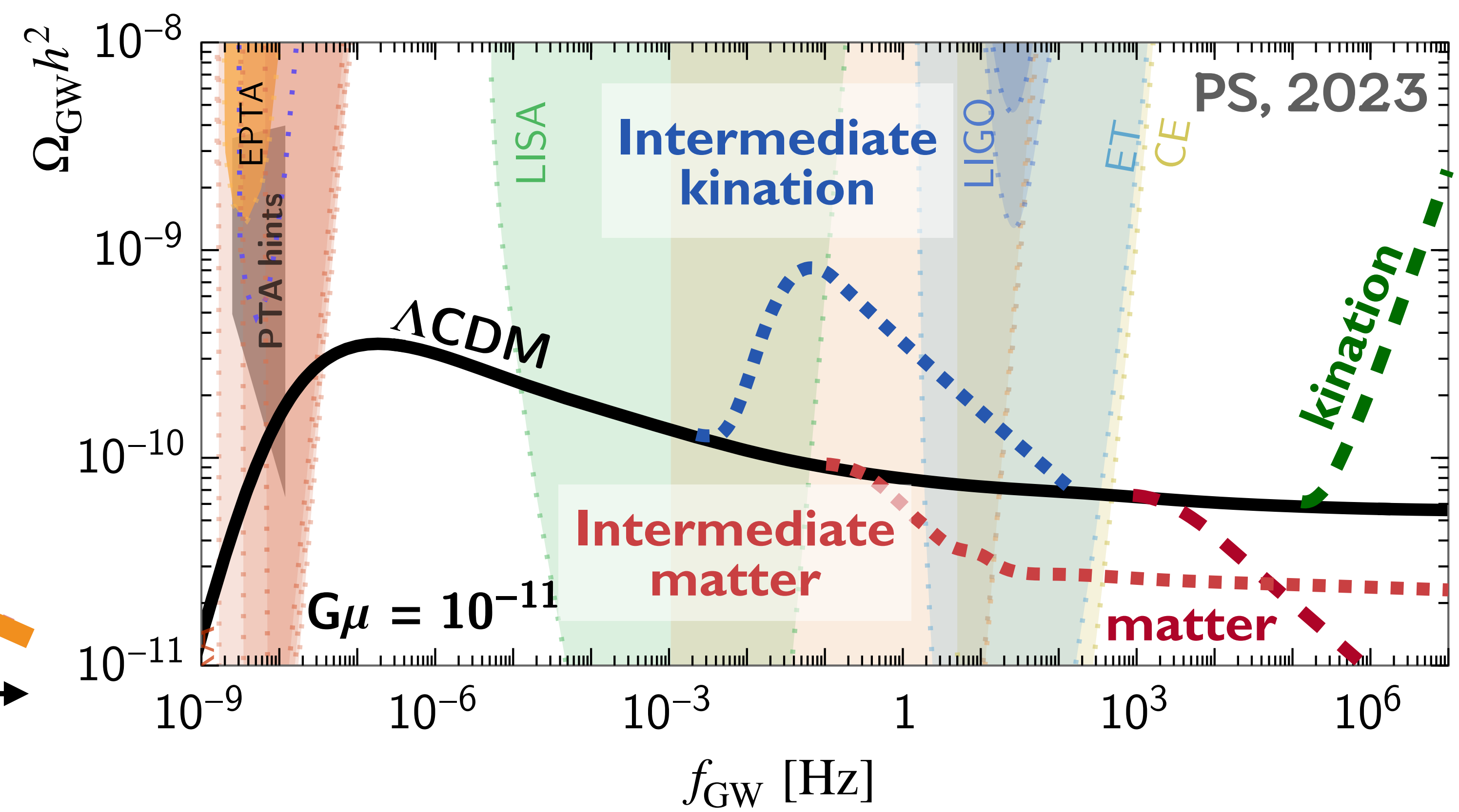
for charting the early–Universe cosmology and high–energy particle physics.

- Physics beyond the SM induces non–standard cosmological histories (beyond the radiation era)
- Smoking–gun spectral distortions of primordial GW exist, detectable by future GW experiments.

(I.e., matter era, extra DOFs ⇒ suppression, kination era ⇒ enhancement)



And we need UHF experiments to probe primordial GWs.



MORE STUFFS...

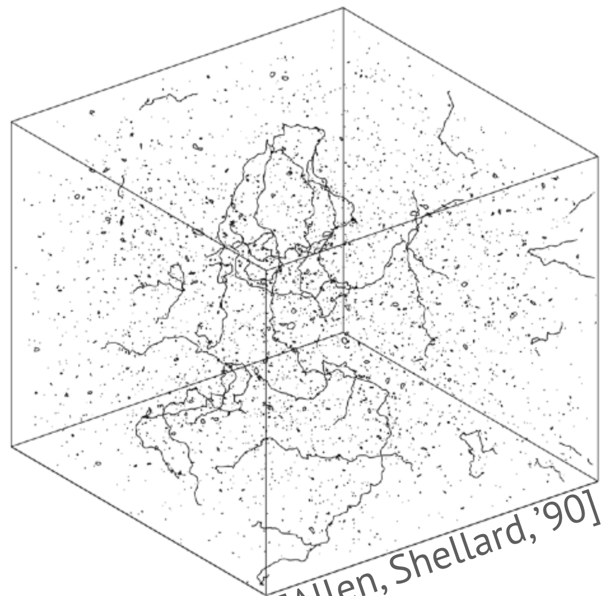
Cosmic Strings & their GW

Reviews e.g., [LISA Cosmo, 1909.00819] and [Servant, Gouttenoire, PS, 1912.02569]

A topological defect from spontaneous symmetry breaking at the energy scale η

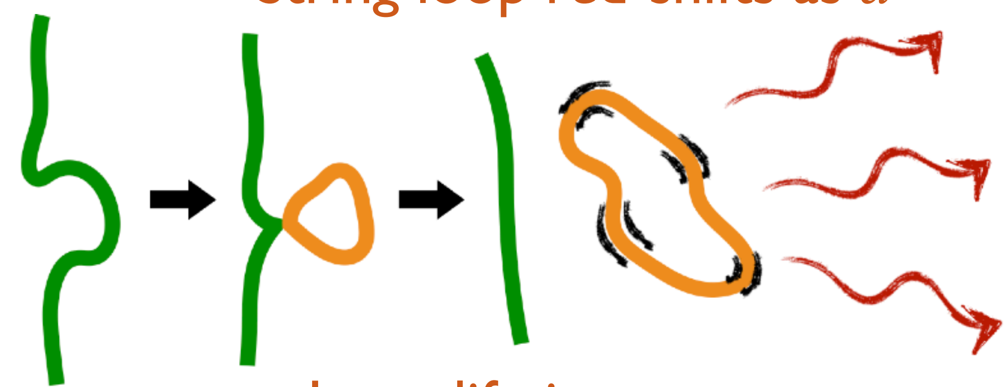
[Kibble,'76]

String tension: $G\mu = \left(\dfrac{\eta}{m_{\rm Pl}}\right)^2$



[Allen, Shellard,'90]

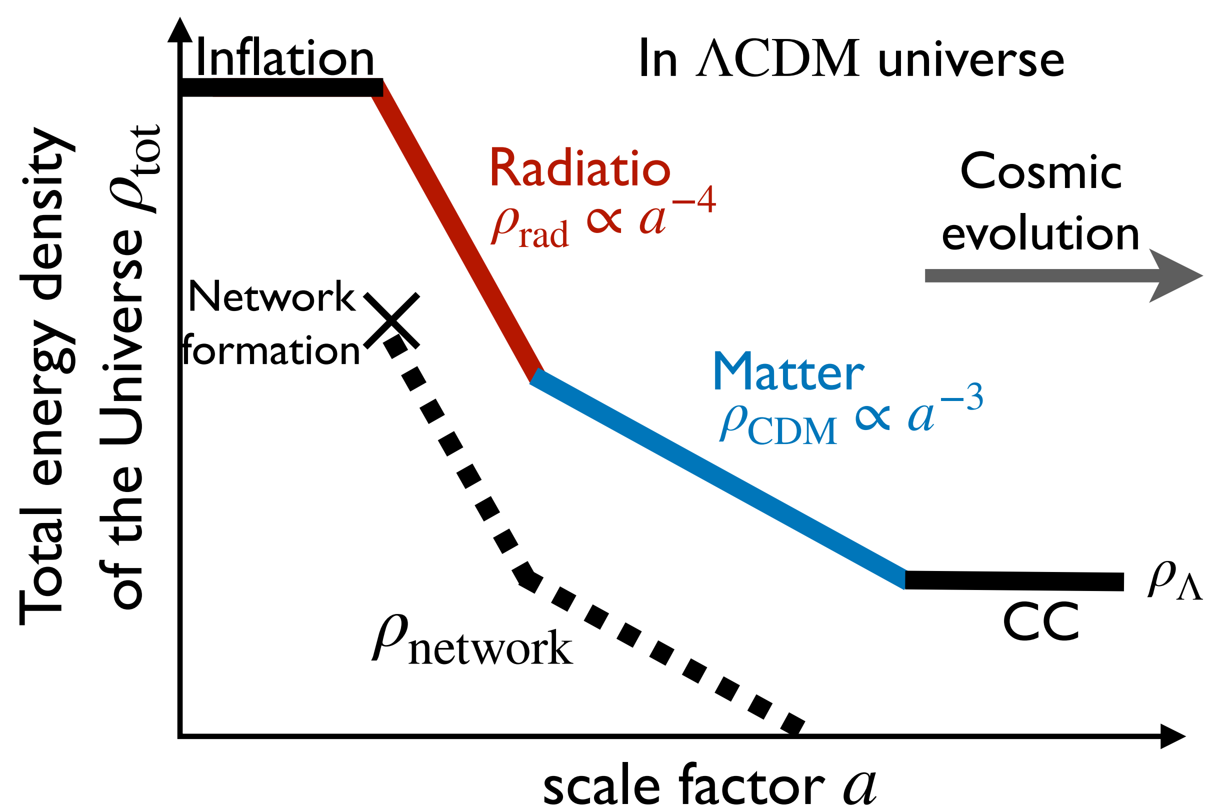
String loop red-shifts as a^{-3}



Loop lifetime $\dfrac{\mathcal{O}(10^{-3})}{G\mu} t_{\rm prod}$

(Local string)

Decay to GW (or particles)



In the "scaling" regime:

$$\rho_{\rm network} \simeq \mu/t^2 \sim G\mu\rho_{\rm tot}$$

Total energy density of the universe

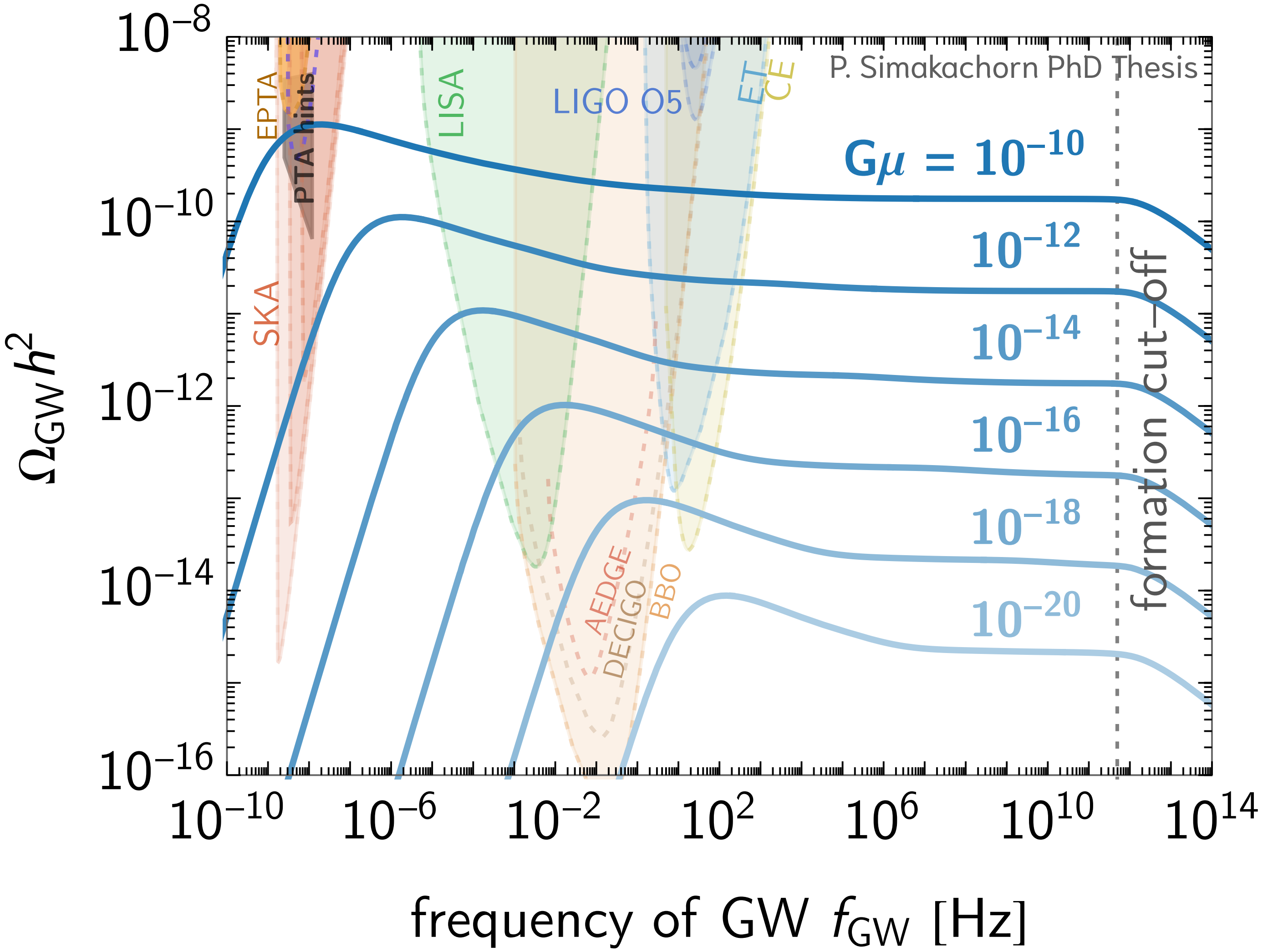
Local strings! and their GWB

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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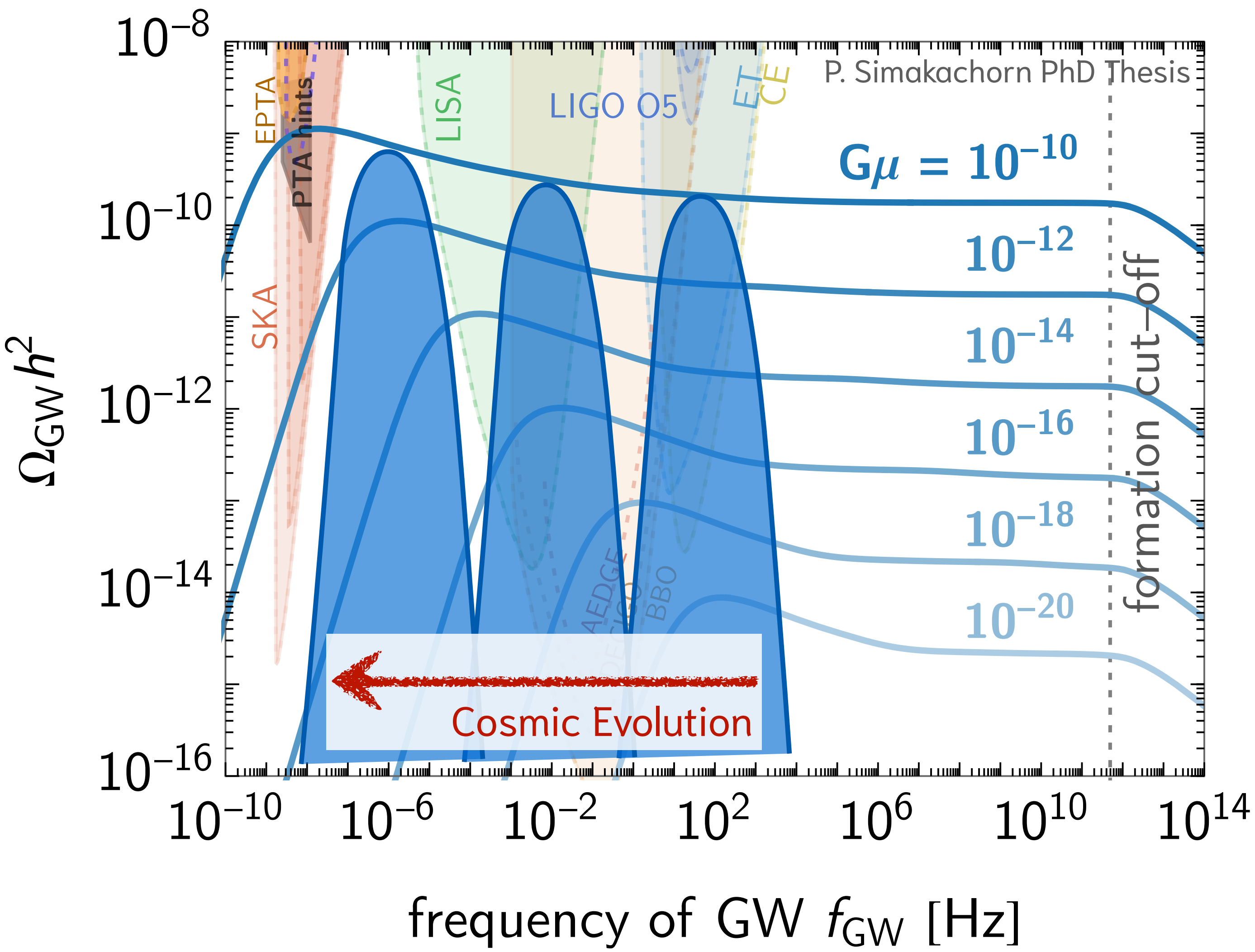

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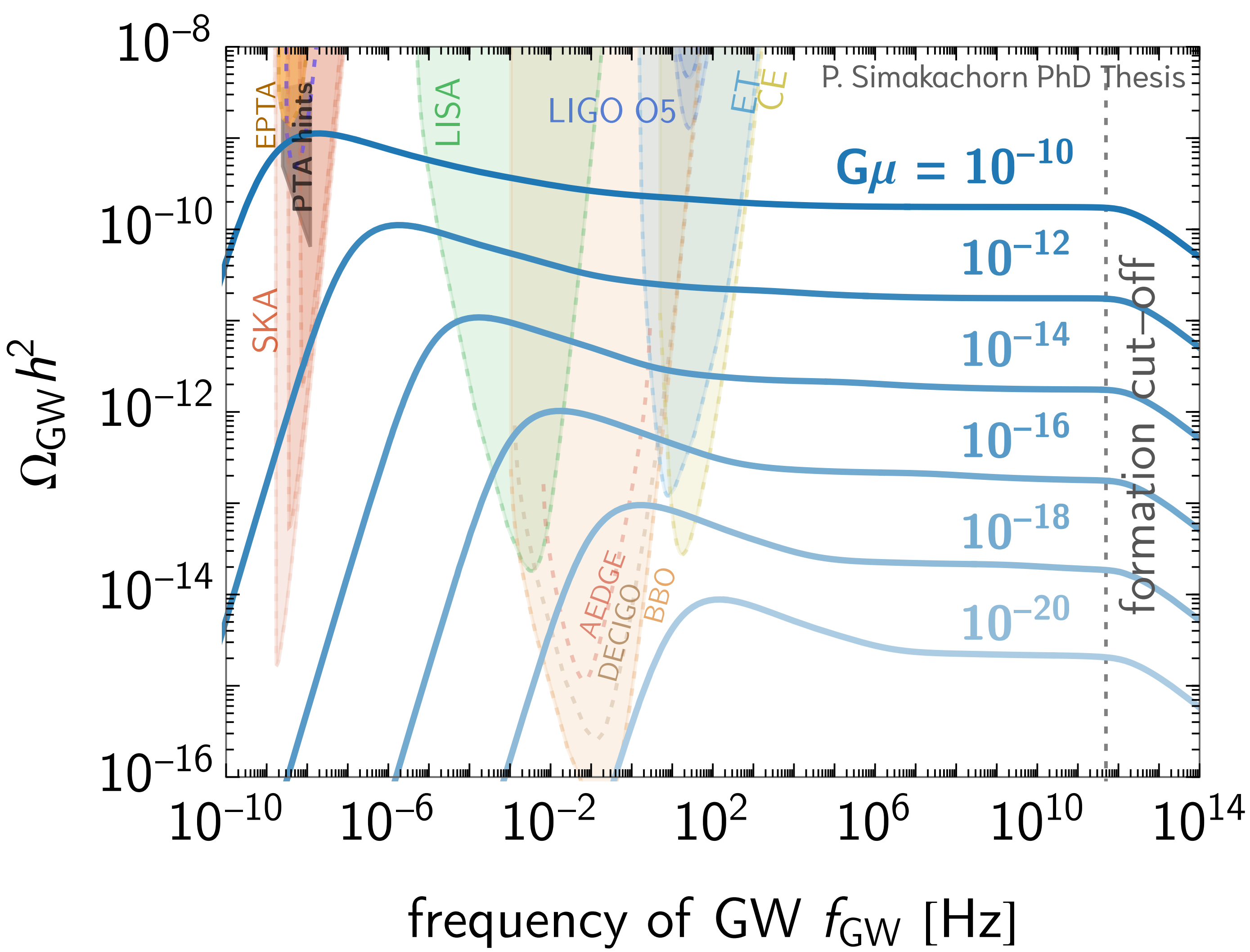

Not so large UHF signals due to observations @ low-frequency.

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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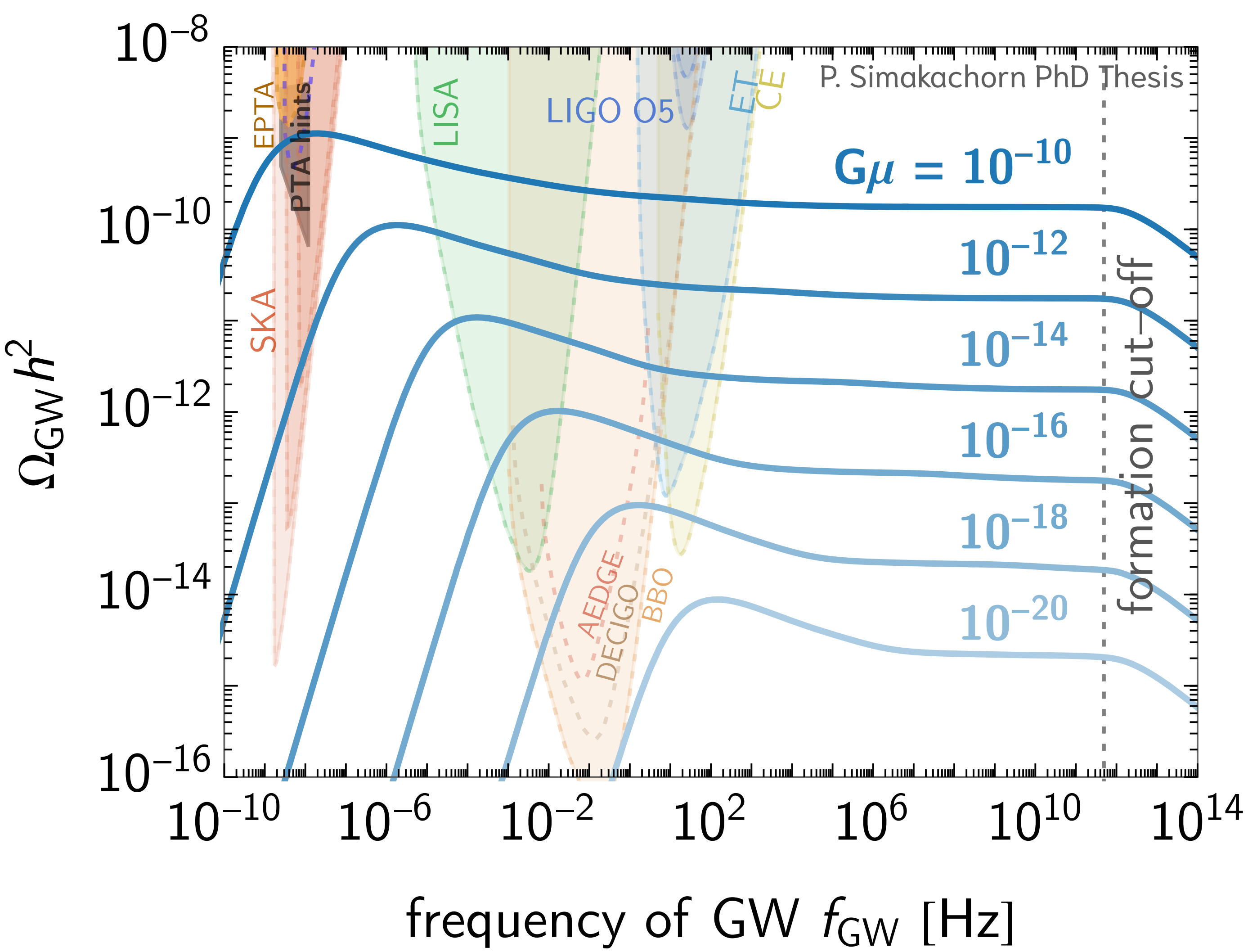

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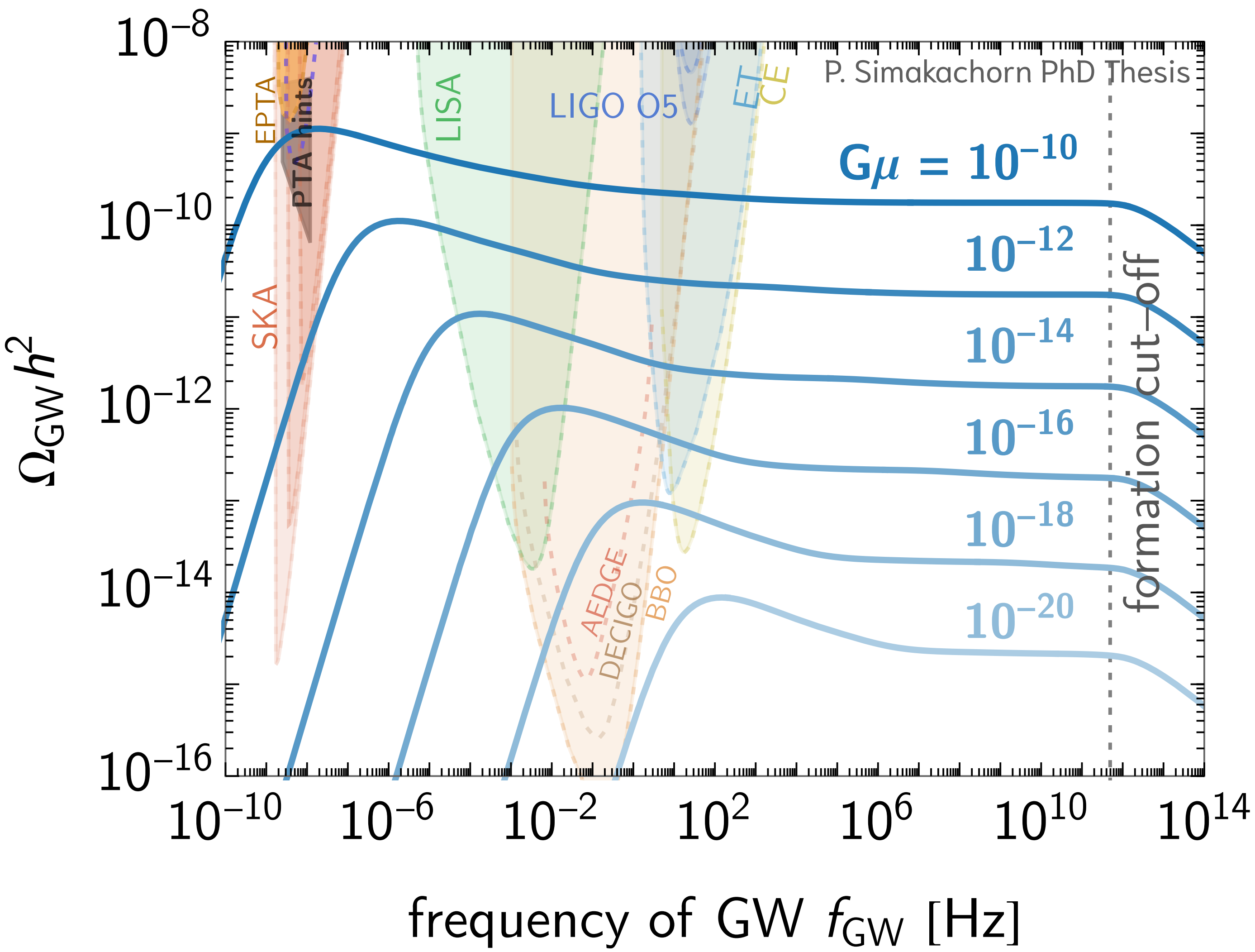

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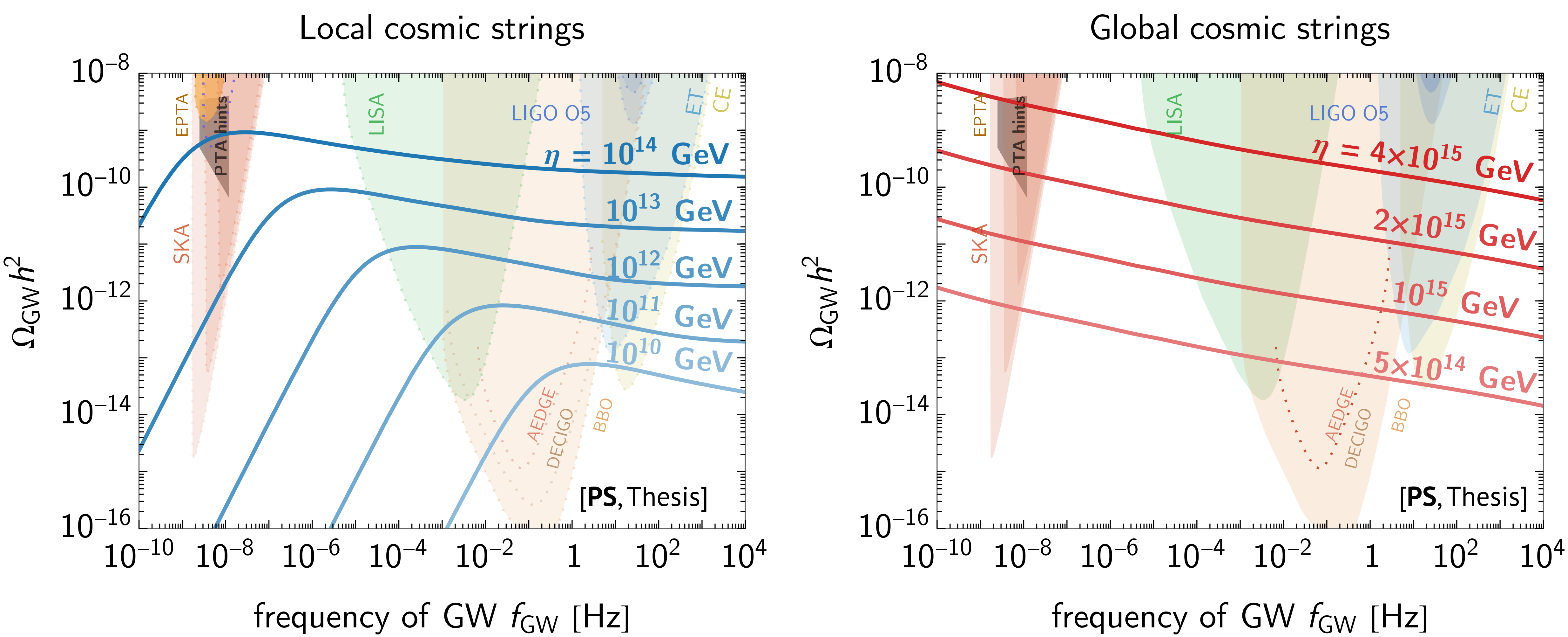
String network decays!

GW from cosmic strings

generated from spontaneous symmetry breaking at an energy scale η



$$\Omega_{\rm GW}^{\rm local} \propto \sqrt{G\mu} \propto \eta \qquad\qquad \Omega_{\rm GW}^{\rm global} \propto \eta^4$$

$$f_{\rm GW}(T) \simeq \begin{cases} (2\times 10^{-3}\ \text{Hz}) \left(\frac{0.1\times 50\times 10^{-11}}{\alpha\times\Gamma G\mu}\right)^{1/2} \left(\frac{T}{\rm GeV}\right) \left[\frac{g_*(T)}{g_*(T_0)}\right]^{\frac{1}{4}} & \text{(local strings)}, \\ (4.7\times 10^{-6}\ \text{Hz}) \left(\frac{0.1}{\alpha}\right) \left(\frac{T}{\rm GeV}\right) \left[\frac{g_*(T)}{g_*(T_0)}\right]^{\frac{1}{4}} & \text{(global strings)}, \end{cases}$$

↑ Temperature of the Universe

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

Fraction of energy density in GW today

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

constant

Long-lasting **Inflationary GW**

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

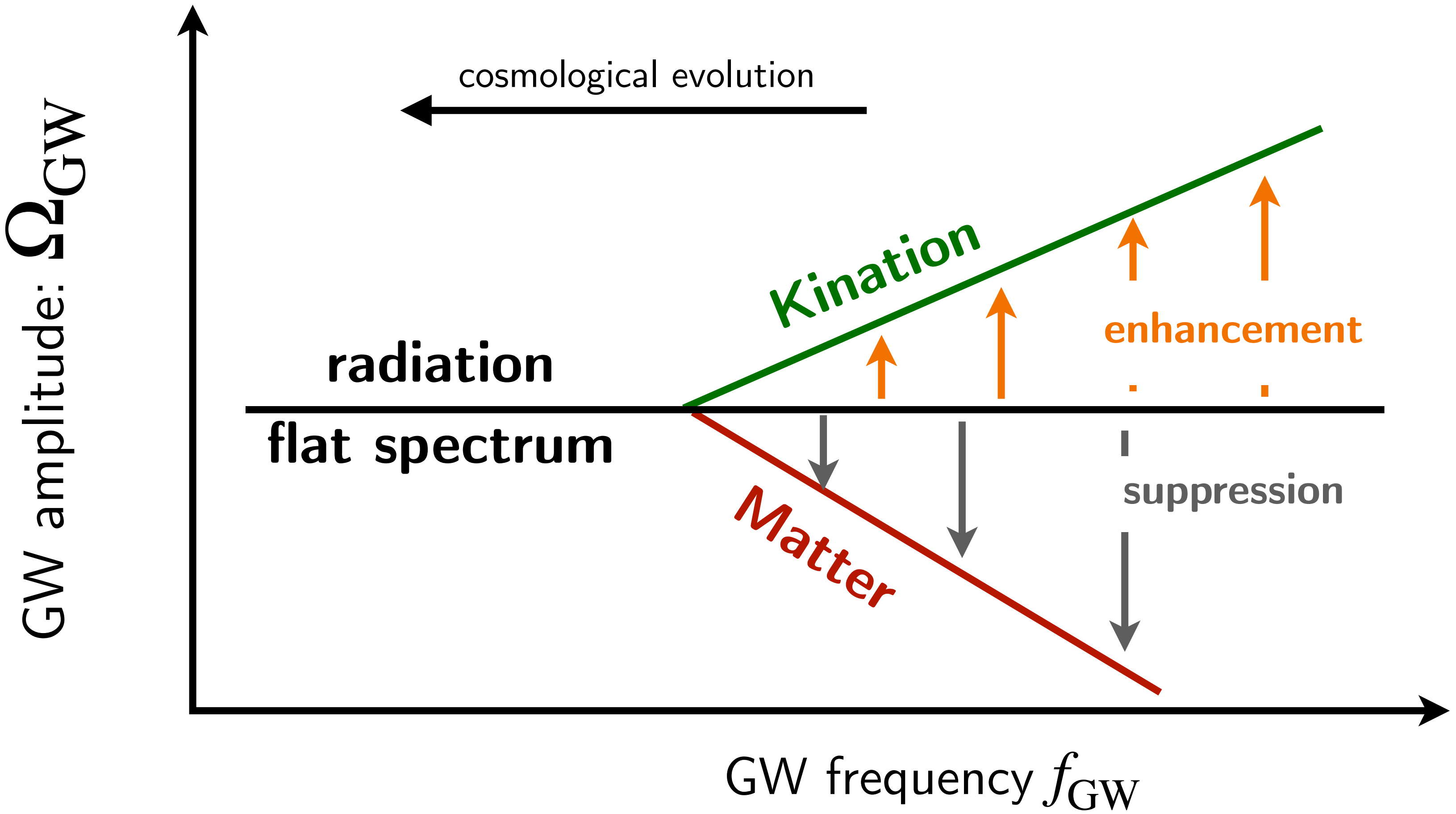
$$(\rho_{\rm GW}/\rho_{\rm tot})_{\rm prod} = \text{constant}$$

Cosmic-string GW:

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

in the so-called "scaling regime"

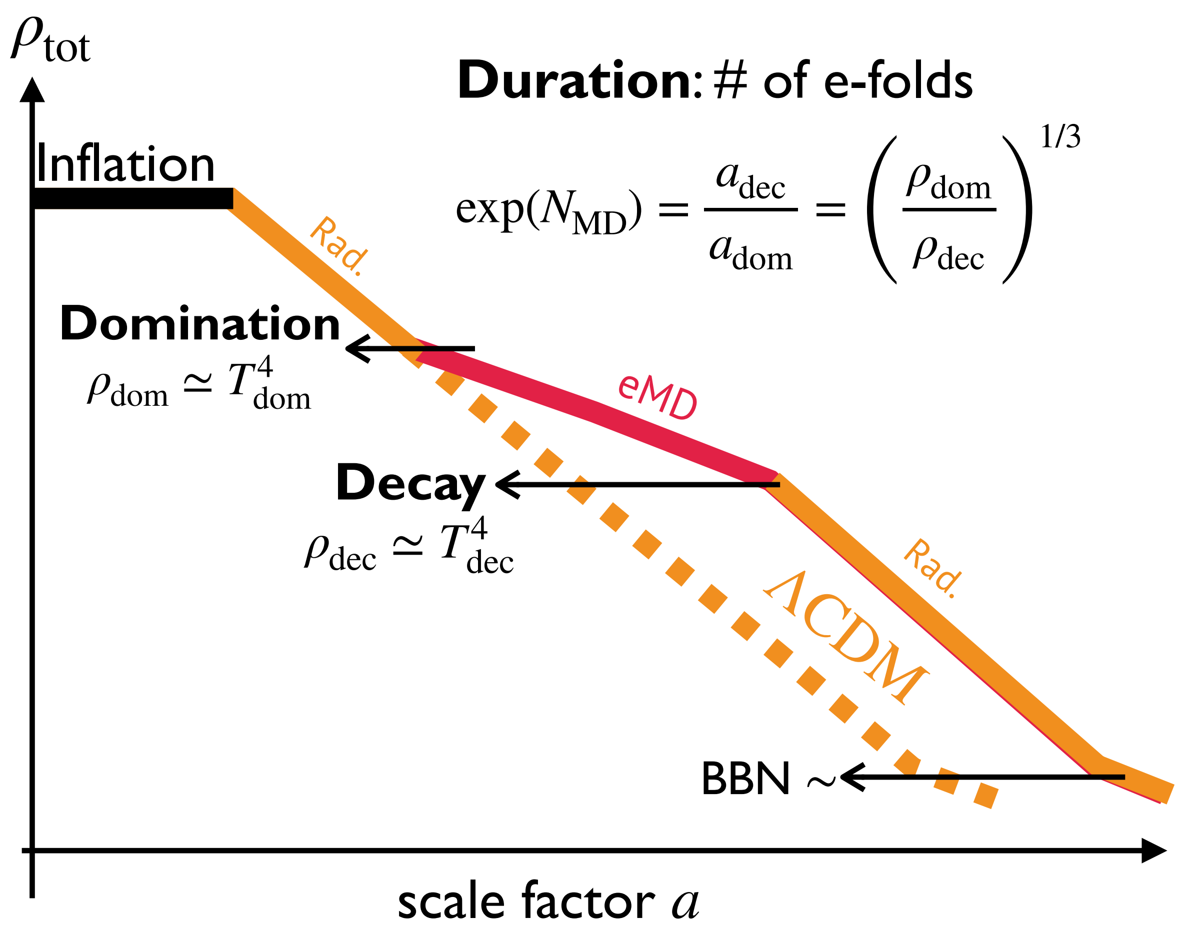
Gouttenoire, Servant, Simakachorn, 2111.01150

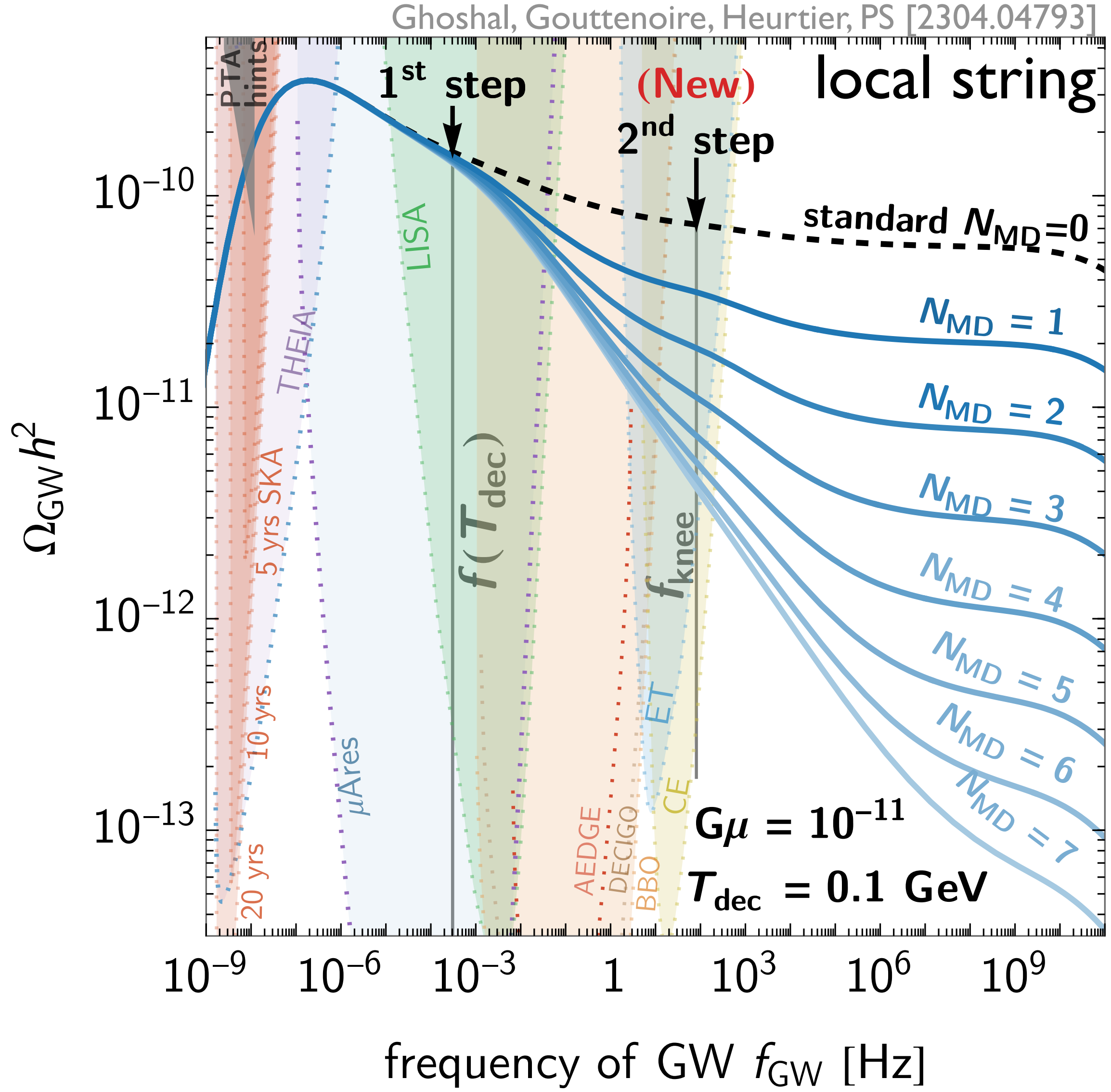


$$\rho_{\rm tot} \propto \begin{cases} a^{-3} & \text{for matter era,} \\ a^{-4} & \text{for radiation era,} \\ a^{-6} & \text{for kination era} \end{cases}$$

Intermediate early matter-domination era (eMD)

dominates at temp. $T_{\rm dom}$, later decays and reheats the radiation to $T_{\rm dec}$.





Previously eMD associated to a step feature,

Servant, Gouttenoire, PS 1912.03245   Blasi, Brdar, Schmitz 2004.02889

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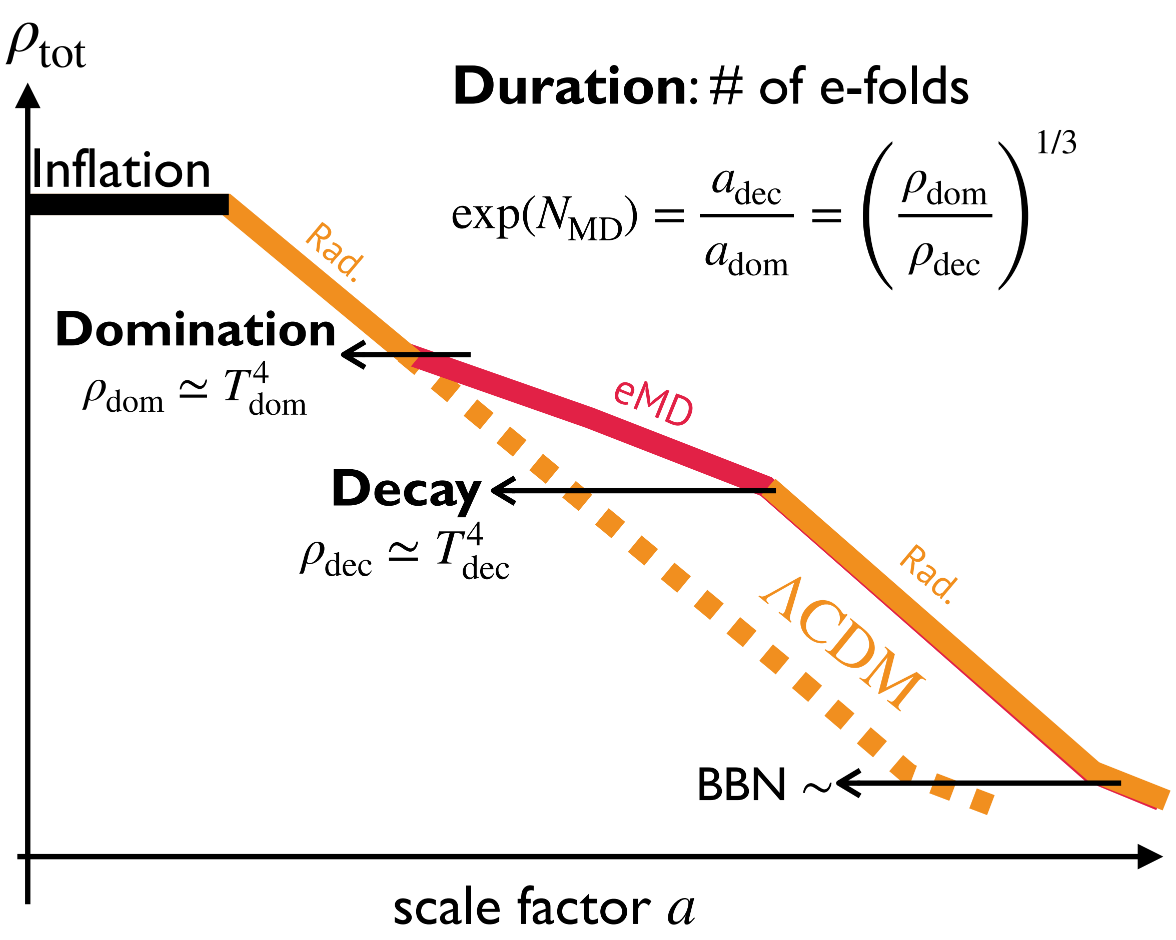
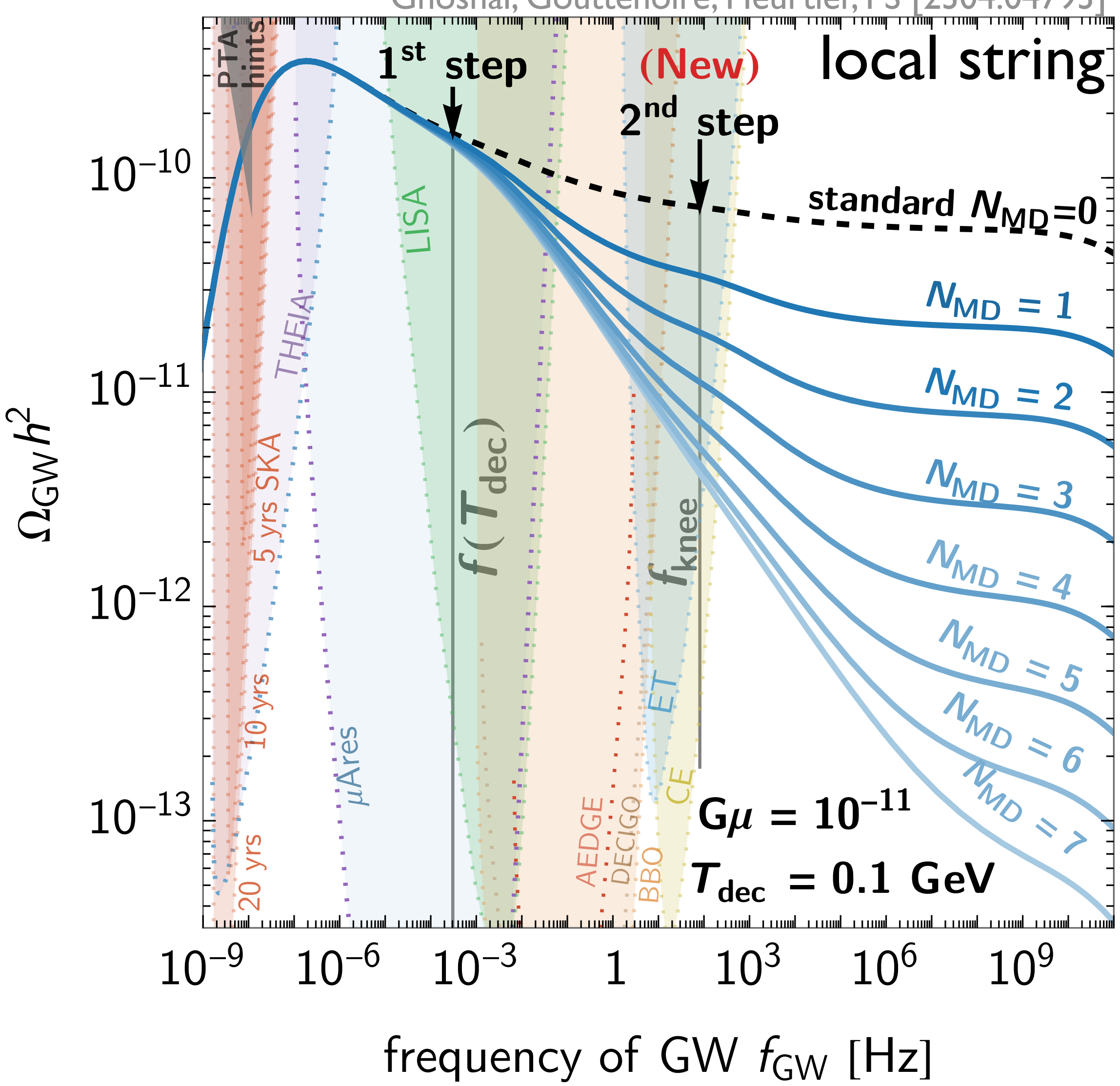


Ghoshal, Gouttenoire, Heurtier, PS [2304.04793]



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Recently, eMD ⇒ "double-step" with a "knee"

associated with loop populations "produced before" and "decay after" eMD.

I.e., $\rho_{\rm loop} \propto a^{-3}$ and $\rho_{\rm loop}/\rho_{\rm tot}$ does not dilute during eMD, unlike loops decaying before eMD.

Ghoshal, Gouttenoire, Heurtier, PS 2304.04793

Local strings! and their GWB

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

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GW from a loop

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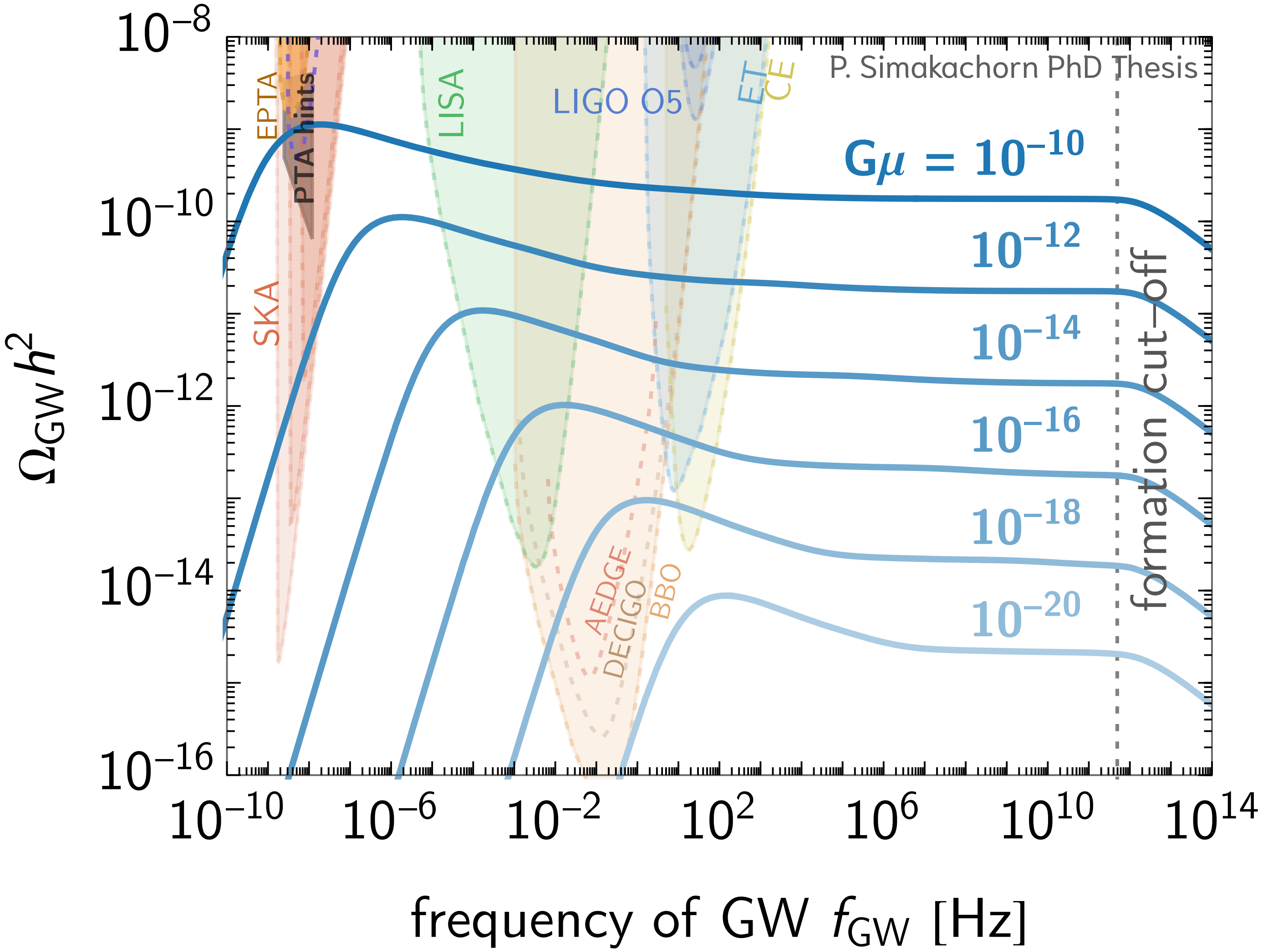

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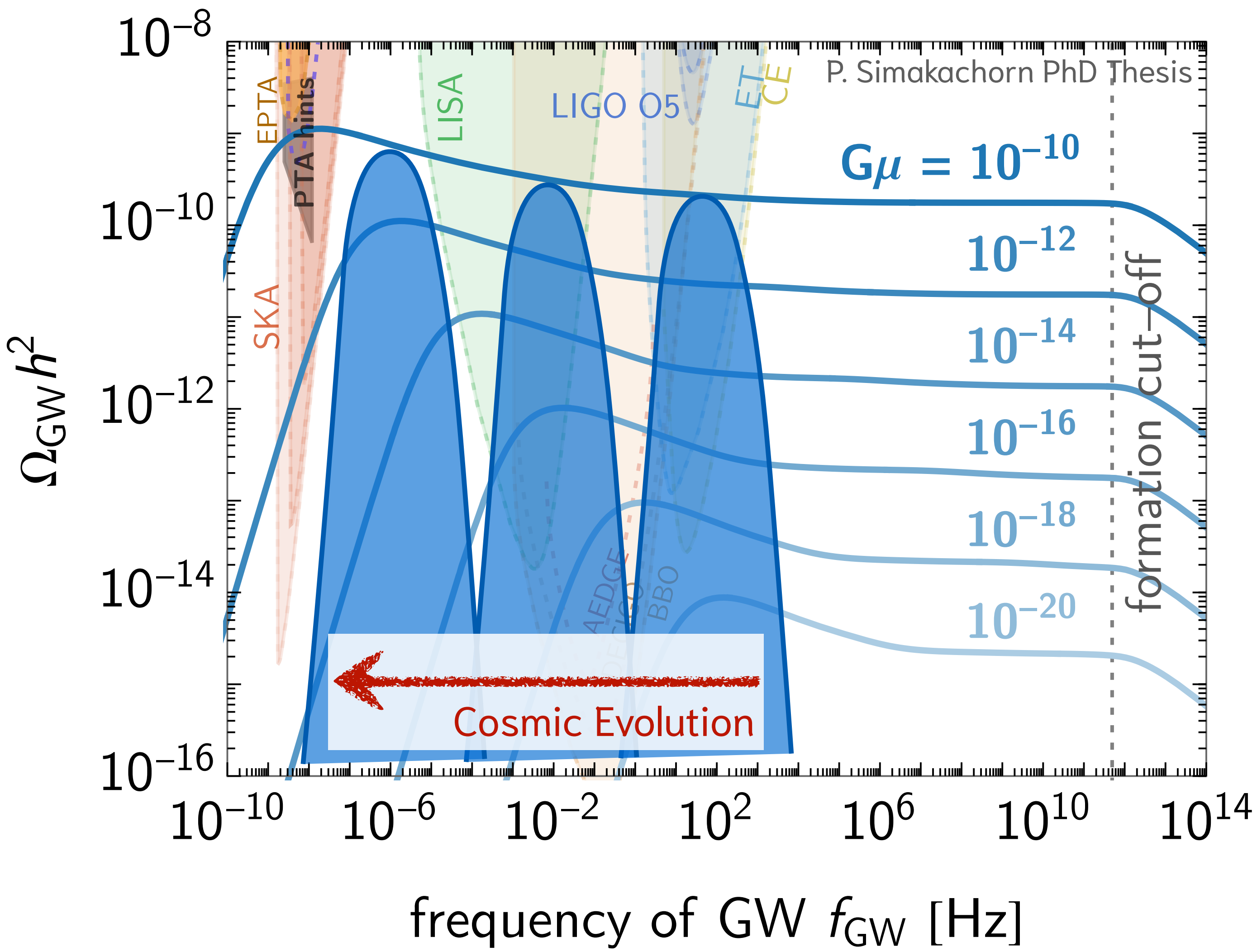

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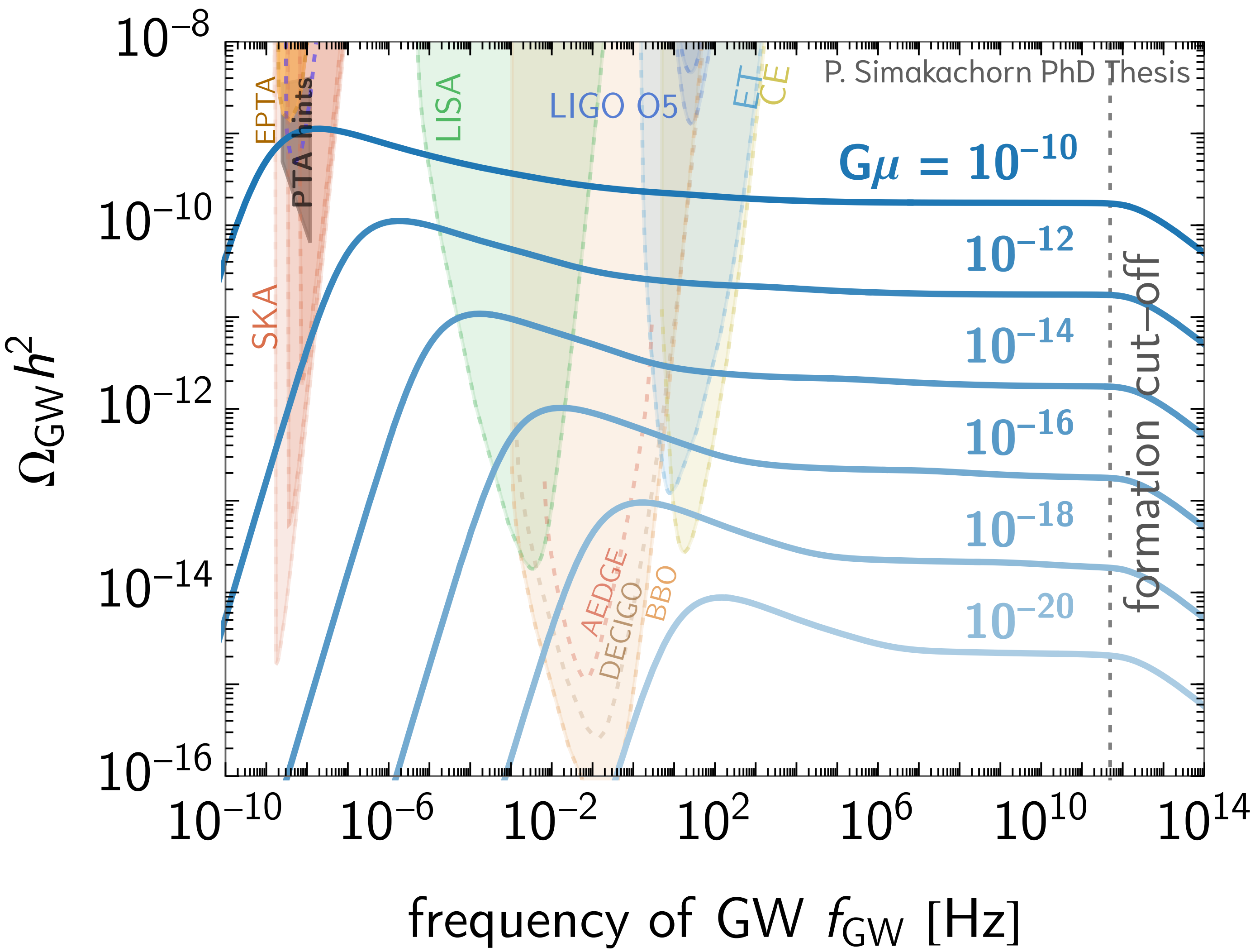

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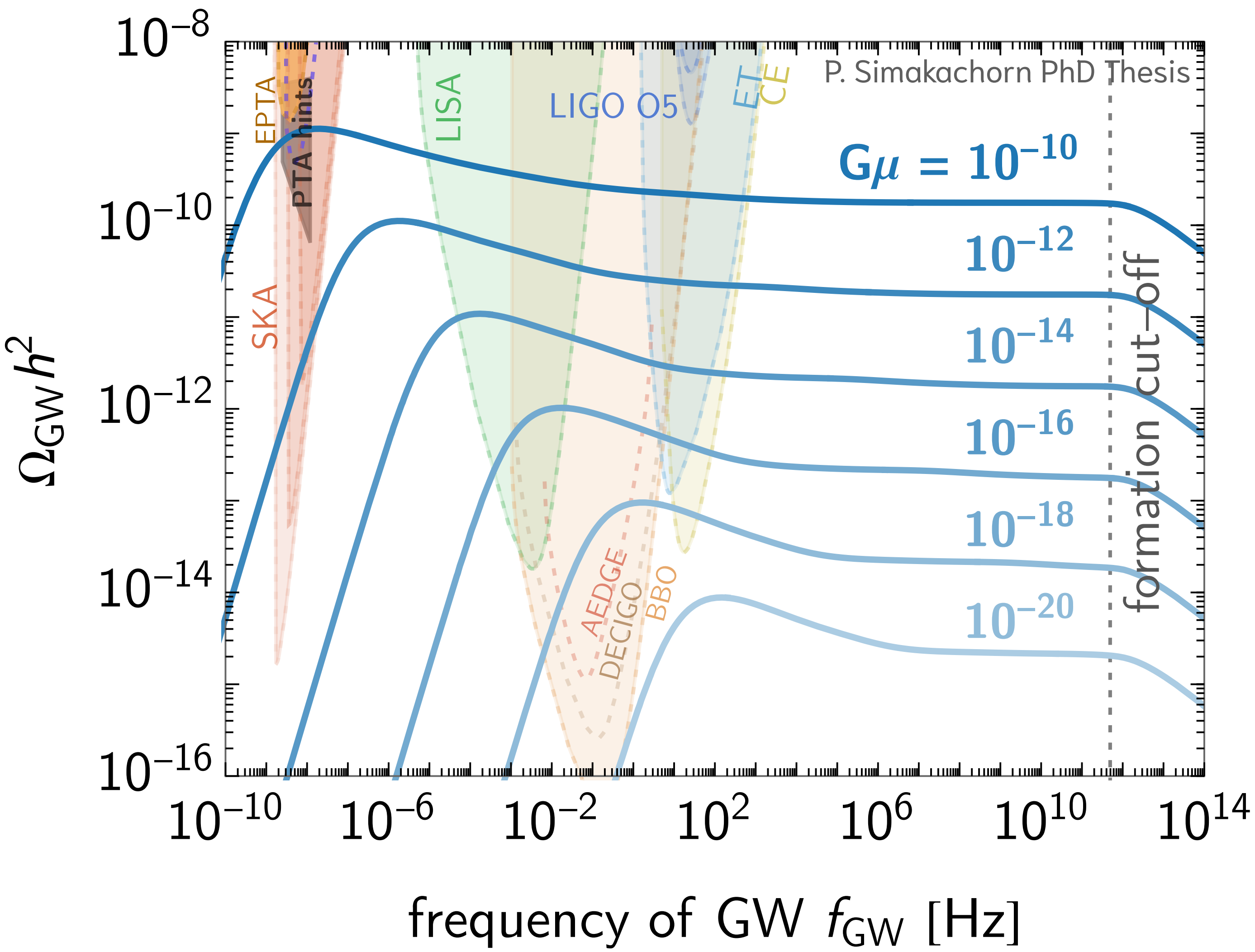
Local strings! and their GWB

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)



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

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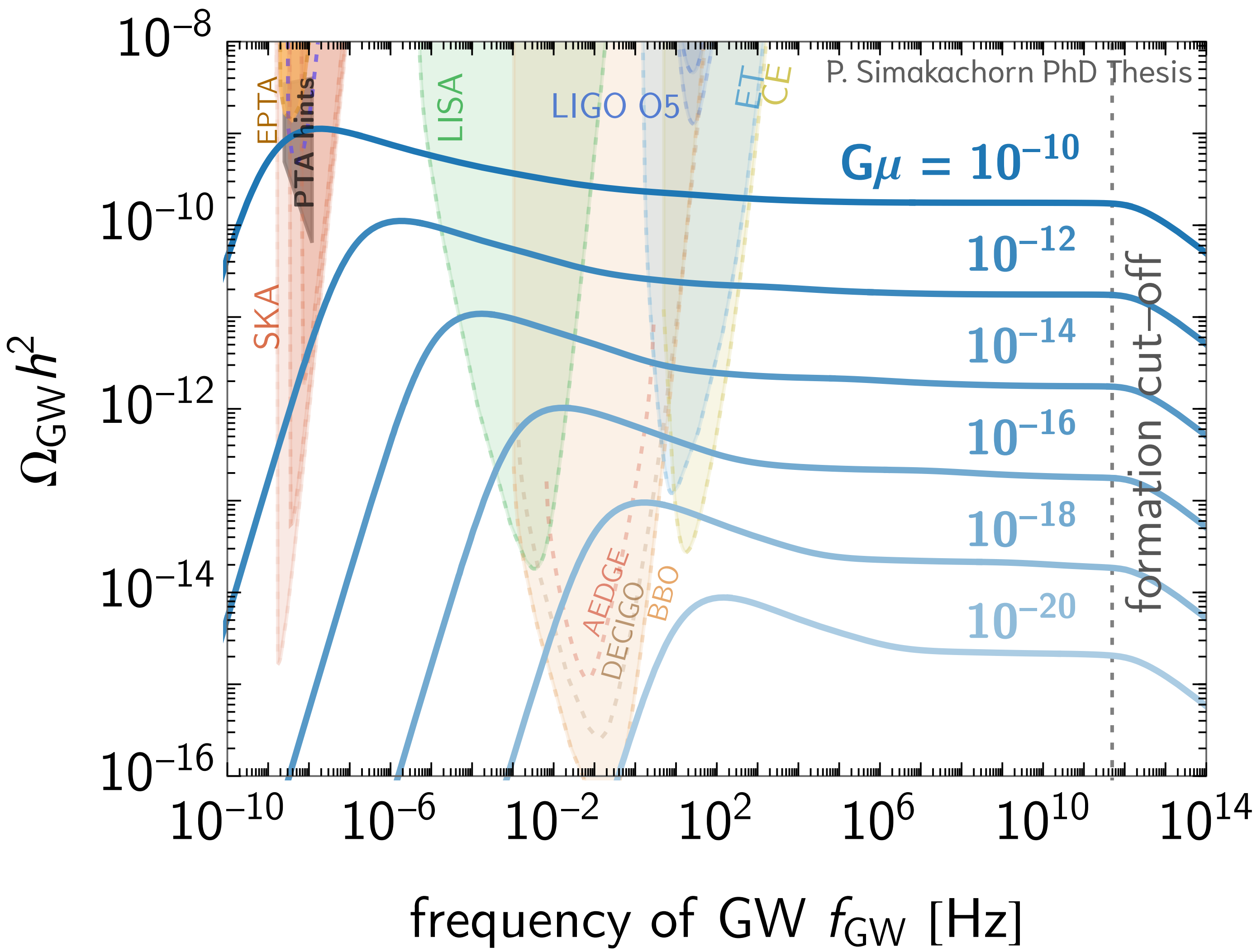

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String network decays!

Reconstruction of the scalar potential via GW

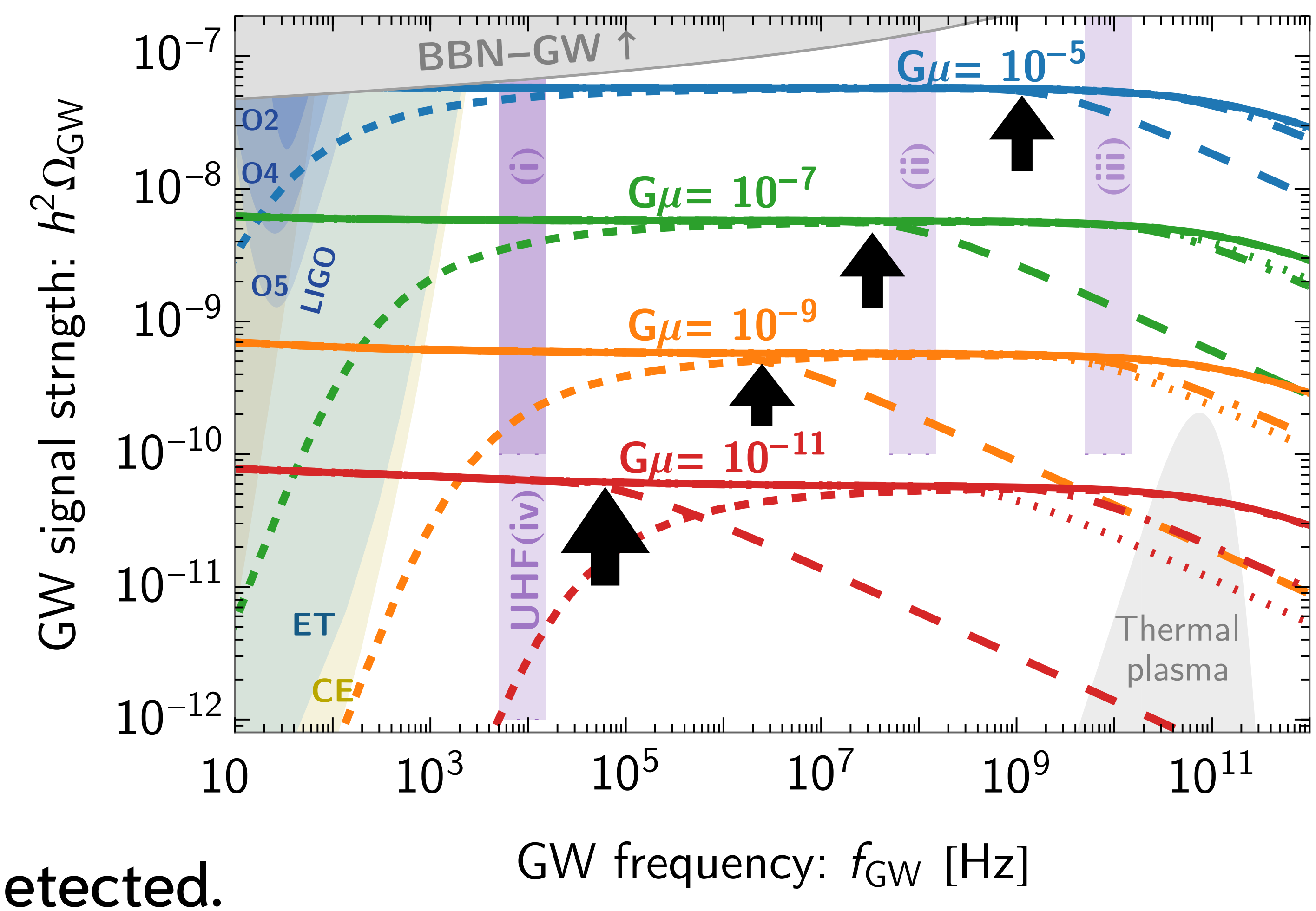
Servant, Simakachorn [2312.09281]

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

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

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

$$V(\Phi) \simeq \lambda(|\Phi|^2 - \eta^2)^2$$

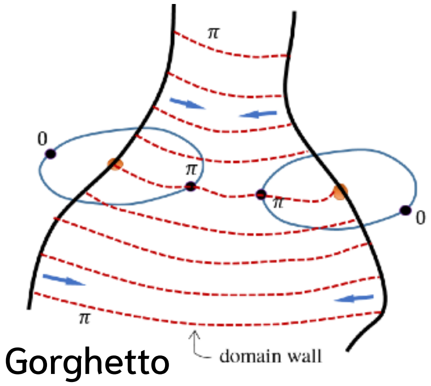


How to extract the UV cutoff if GWB is detected.

- 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)

Axionic (or global) strings

String–domain wall



M. Gorghetto

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

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

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

- Pulsar–timing arrays

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

Servant, Simakachorn [2307.03121]

Axionic (or global) strings

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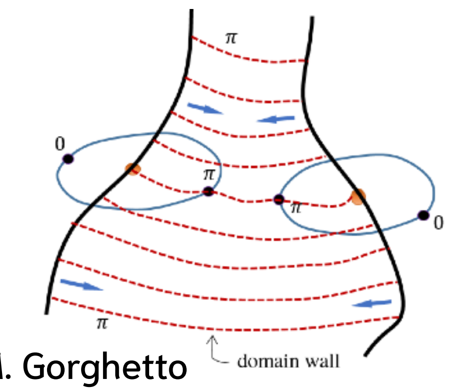

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Servant, Simakachorn [2307.03121]

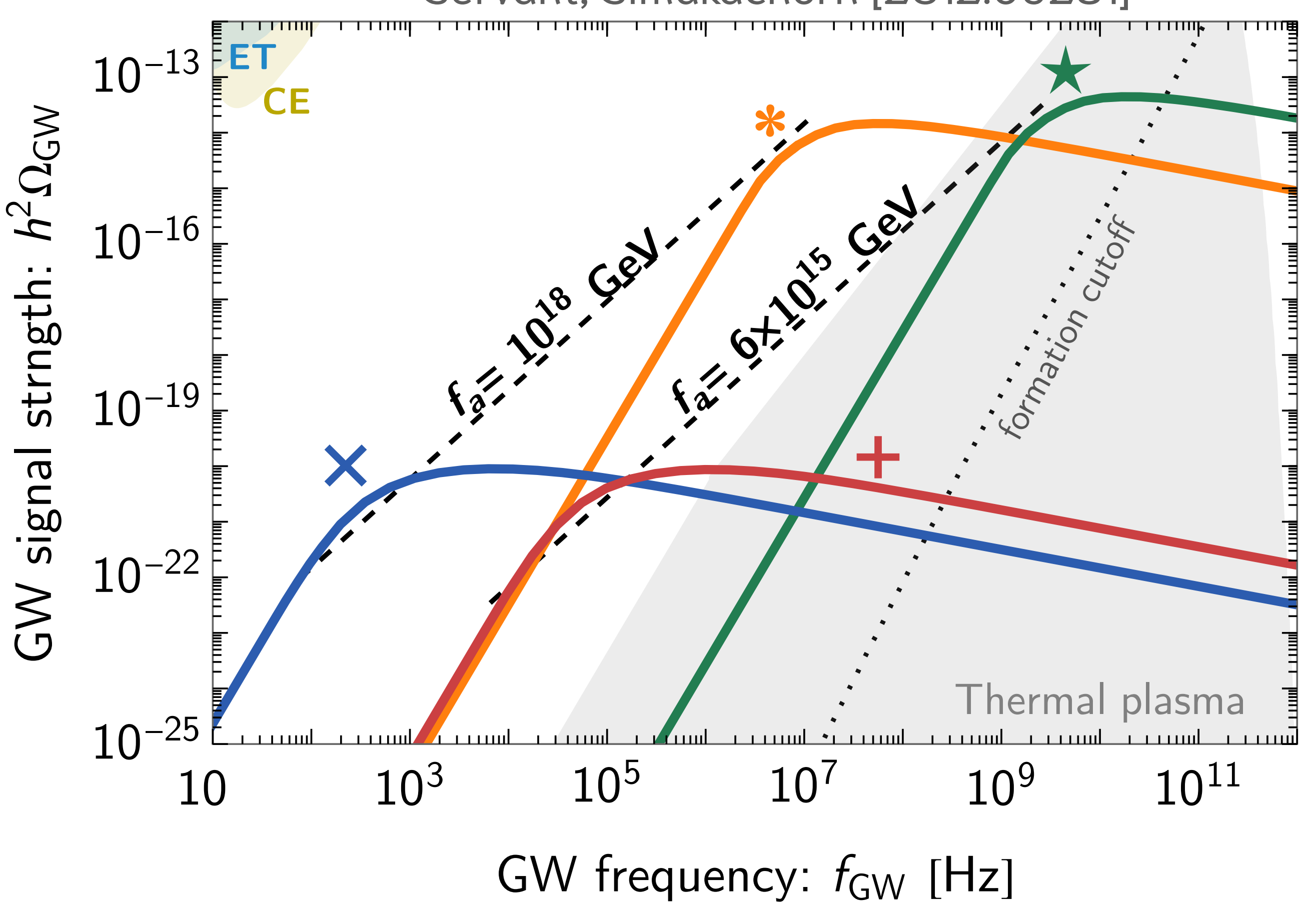
Heavy axion ($m_a \gtrsim$ GeV)

⇒ IR cutoff in UHF

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

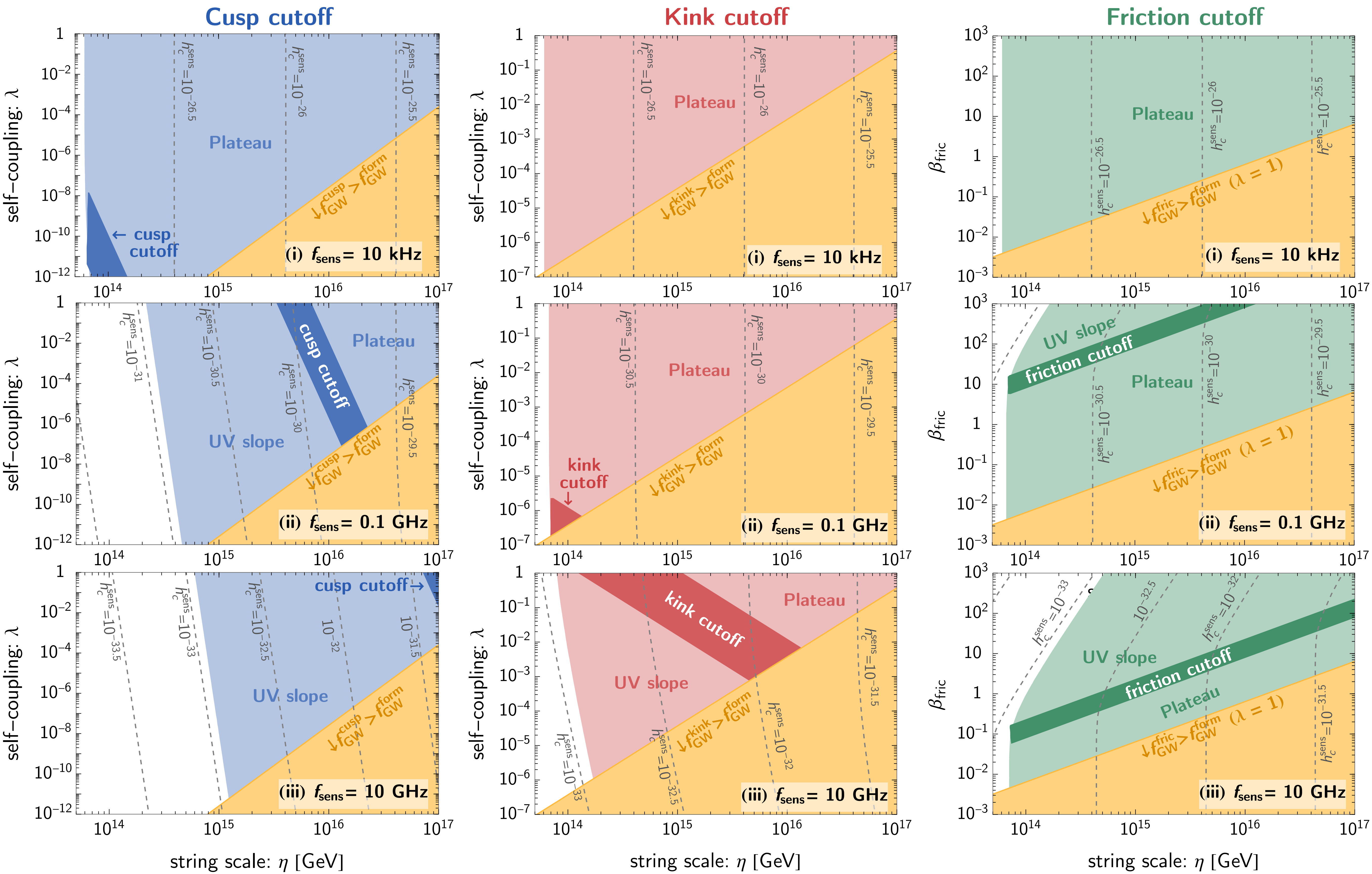
GWB is diluted by matter domination from axions produced from string collapse.

Servant, Simakachorn [2312.09281]



Reconstruction of scalar potential with UHF GWB

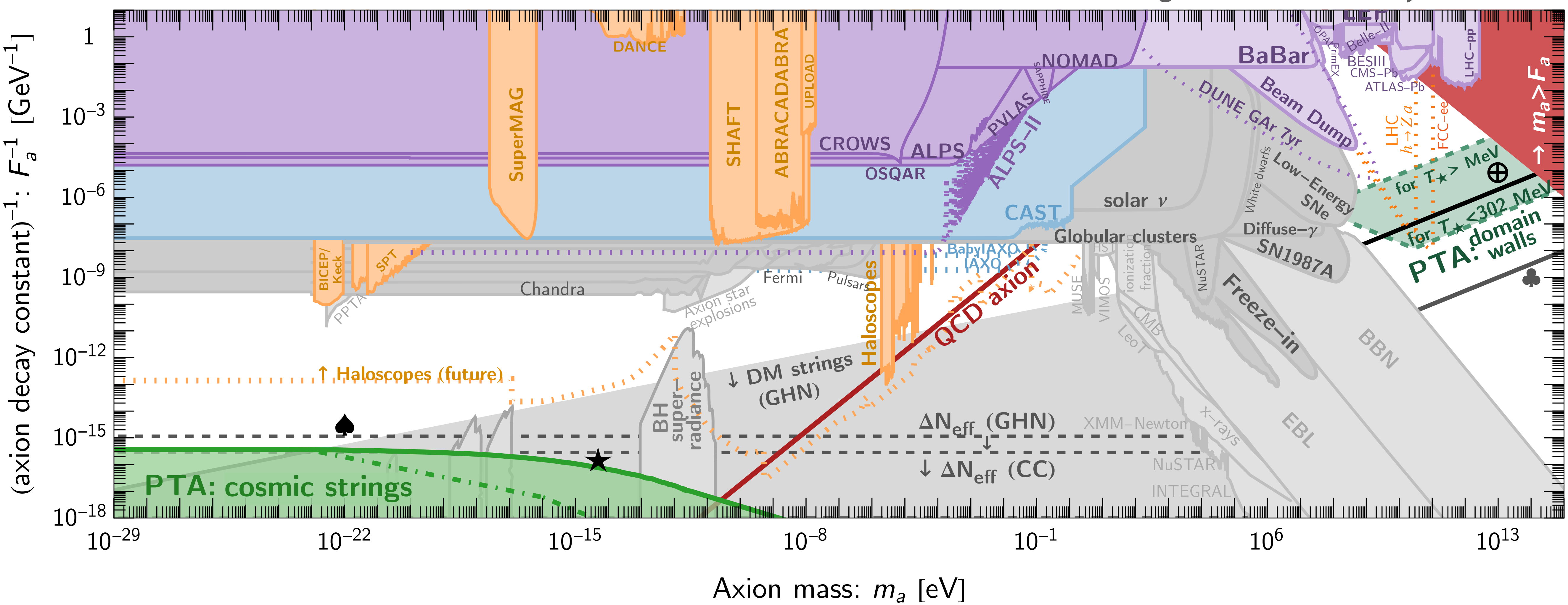
Servant, Simakachorn [2312.09281]



Pulsar timing array constraints on postinflationary axion

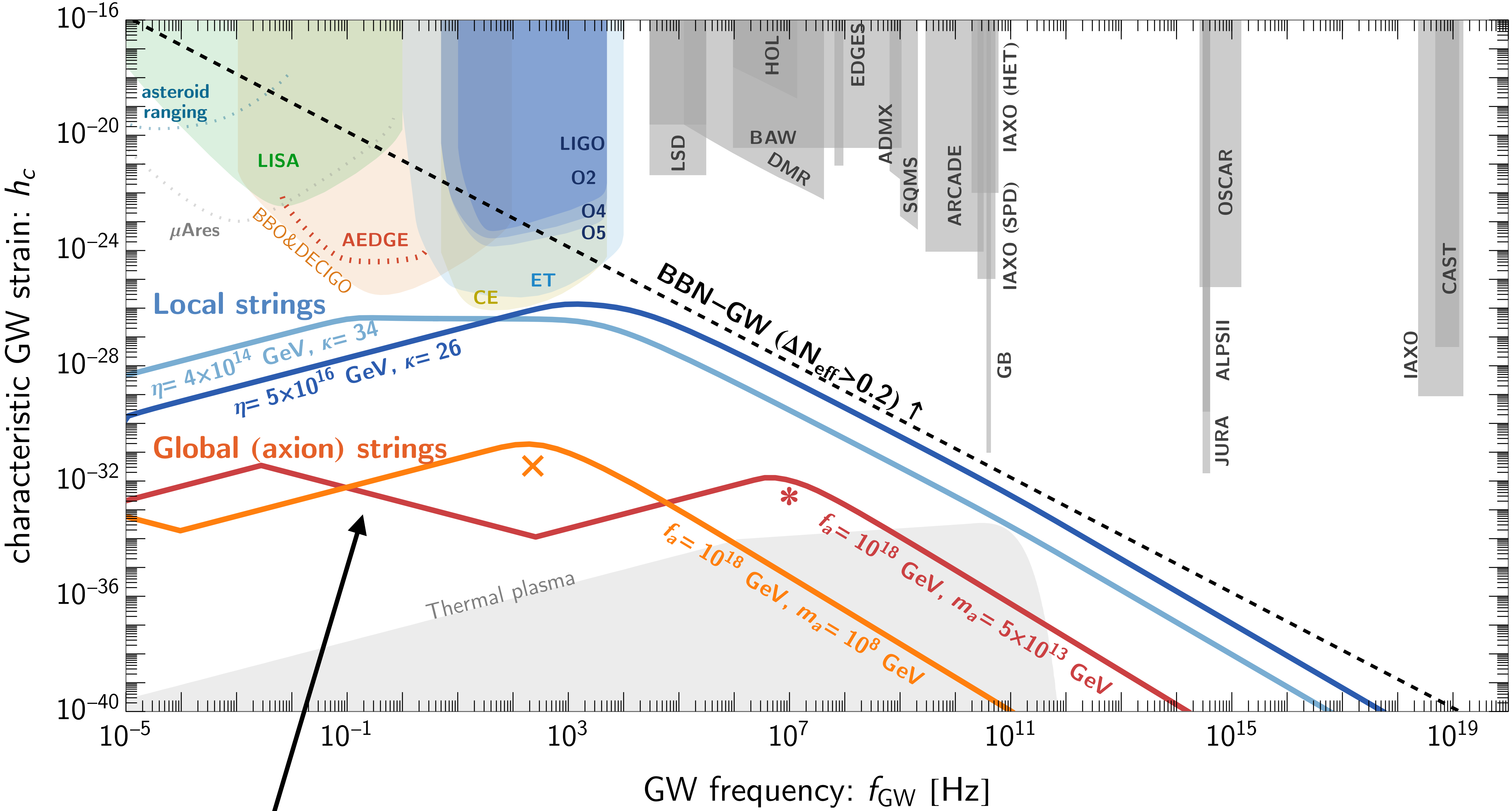
Servant, Simakachorn [2307.03121]

Using NANOGrav 15-year data



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.

Axion matter domination from axionic string decay

Servant, Simakachorn [2312.09281]

Axion string–wall system decays.

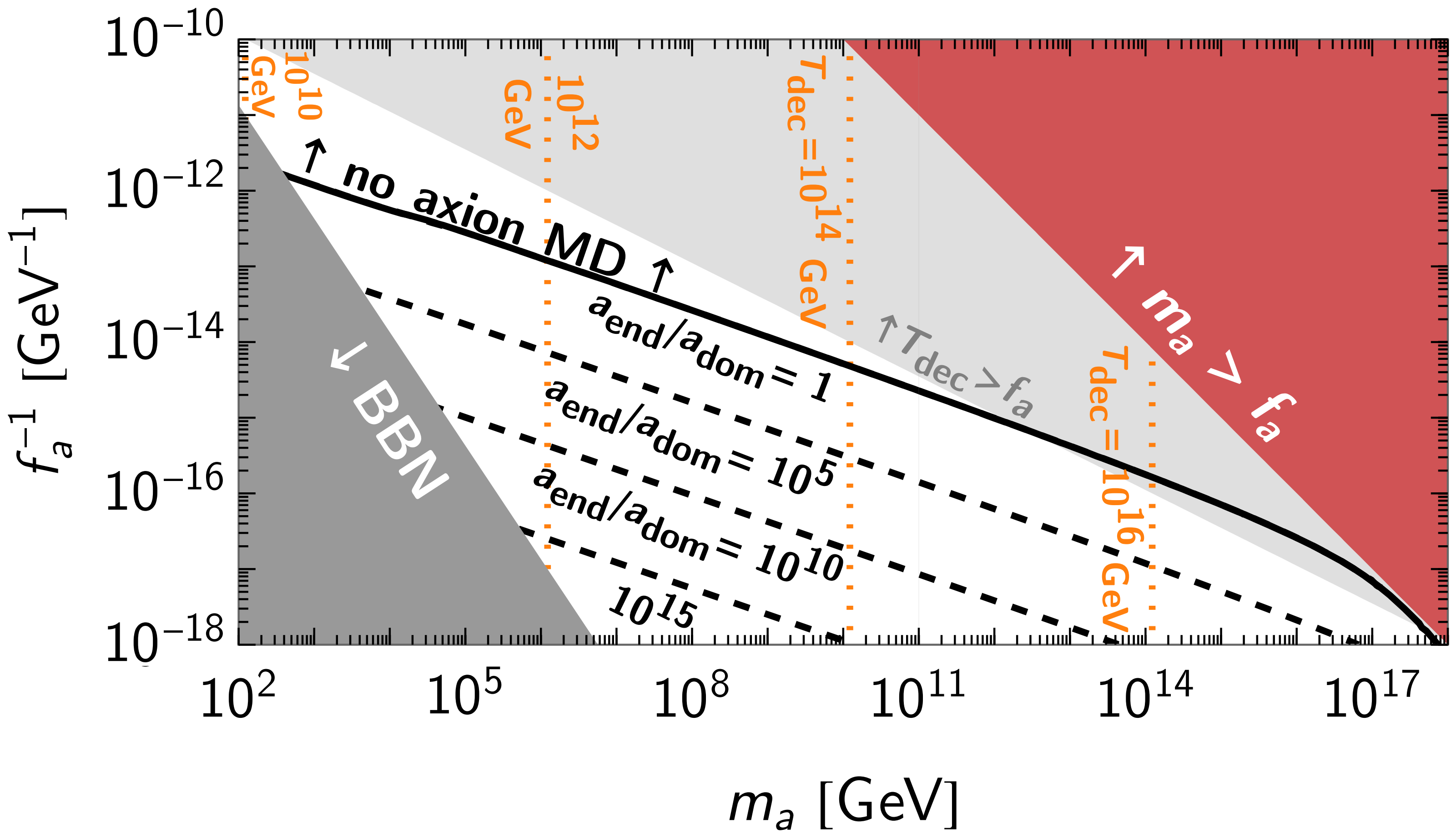
$$T_{\rm dec} \sim 10^9 \ {\rm GeV}\sqrt{m_a/{\rm GeV}}$$

Axion–matter domination

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

Axions decay into photons

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



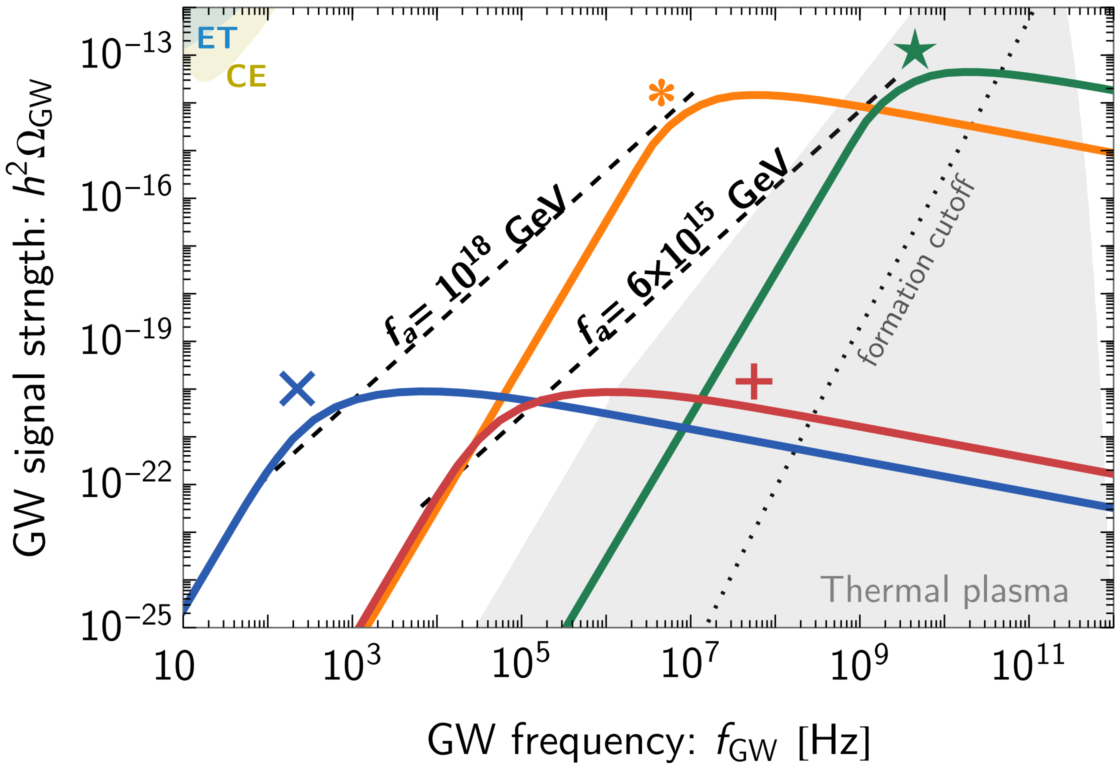
Duration of Axion matter domination

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

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

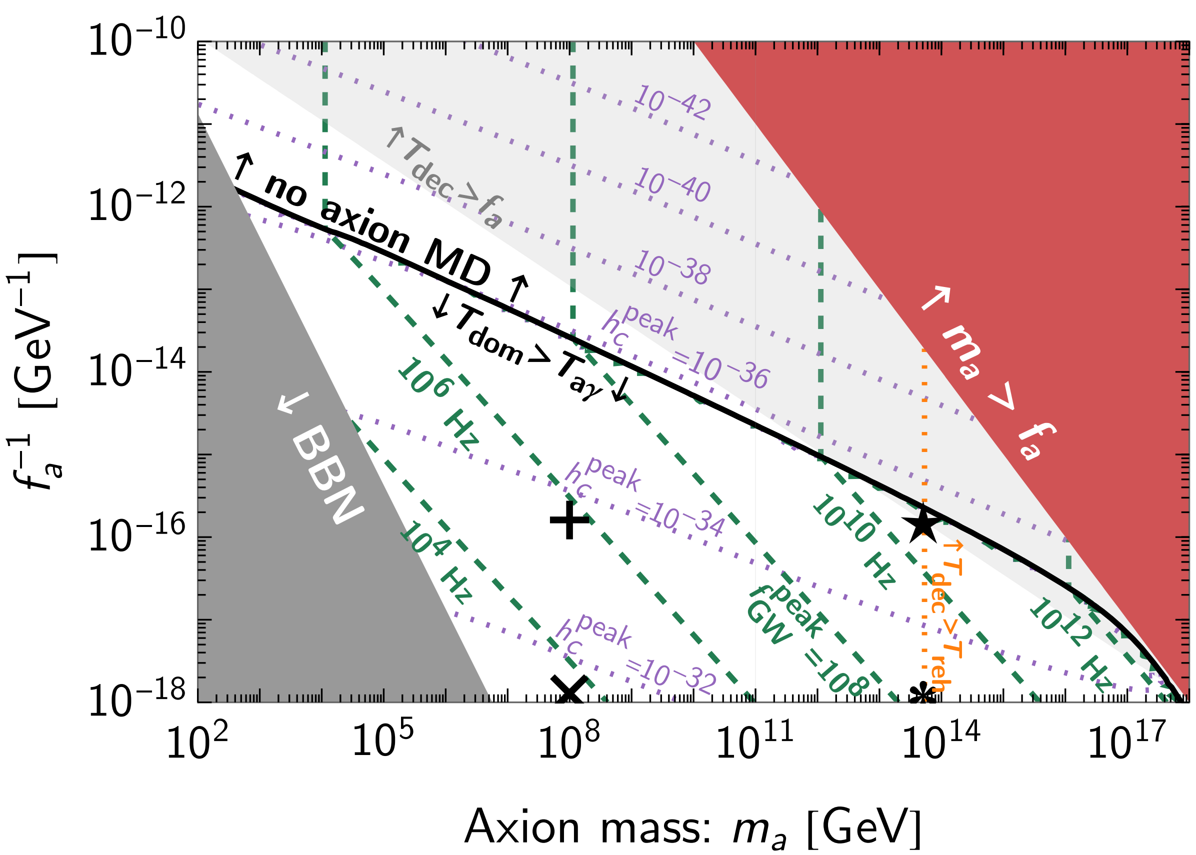
Suppressed UHF GWB from axion strings

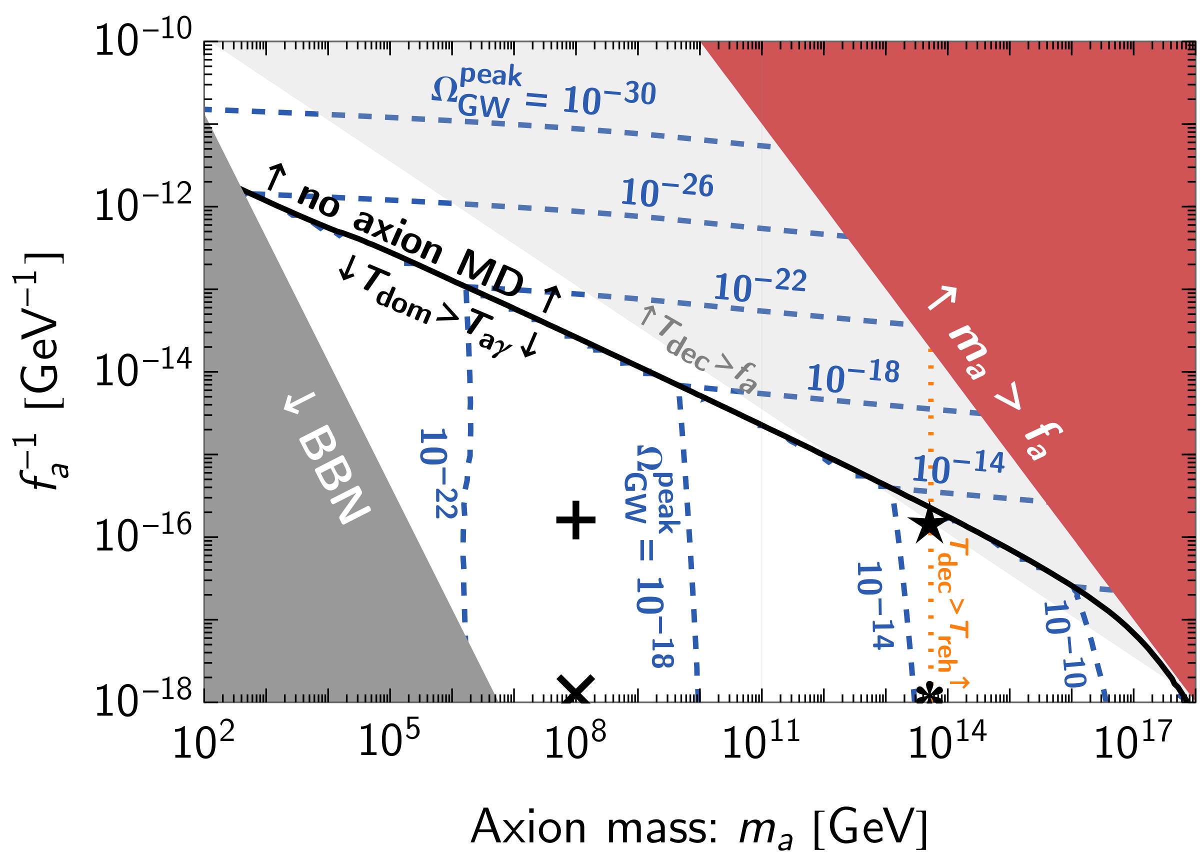
Servant, Simakachorn [2312.09281]



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

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

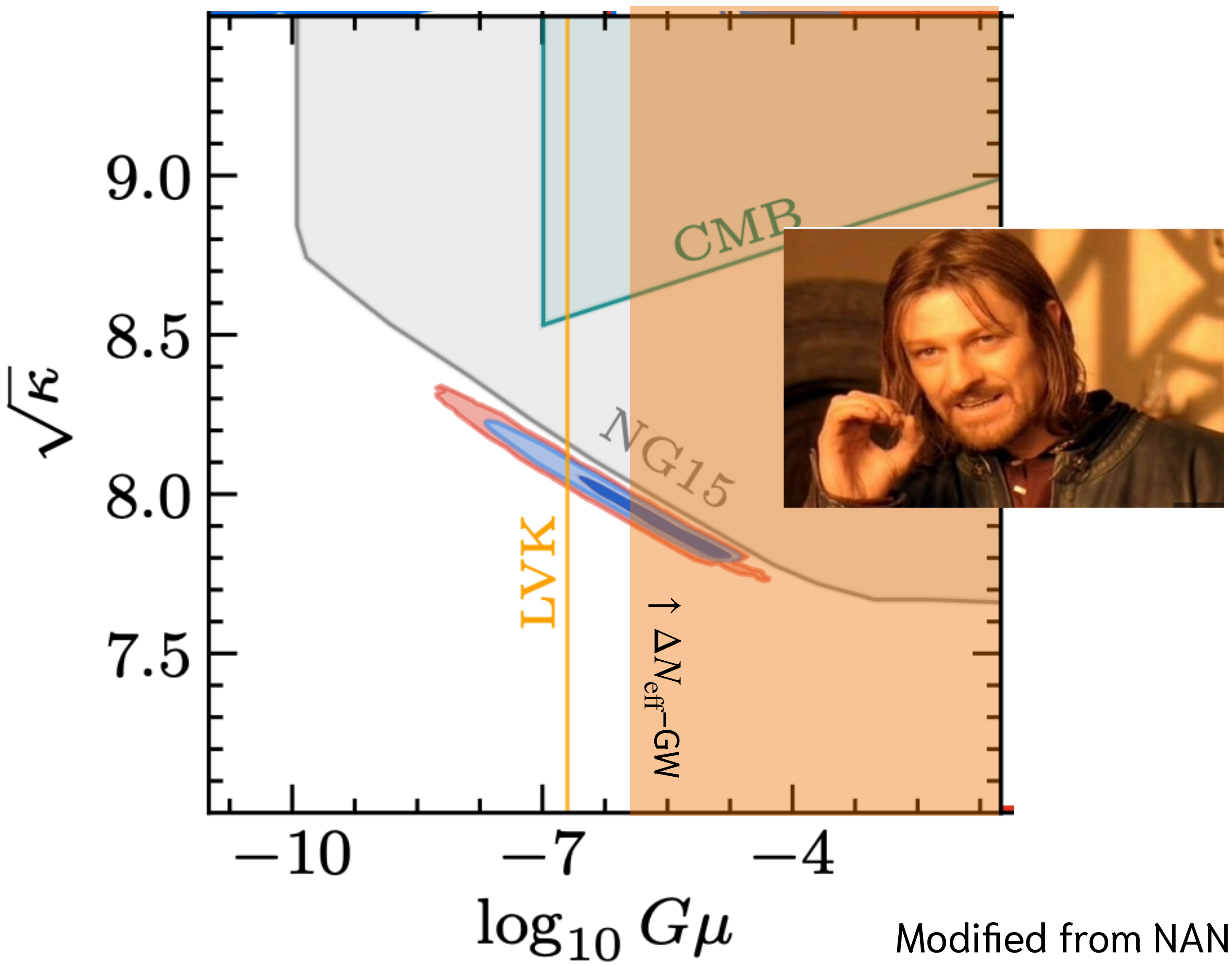




Local metastable strings can explain PTA data super well?

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]