The Gravitational Wave Background as a Particle Detector

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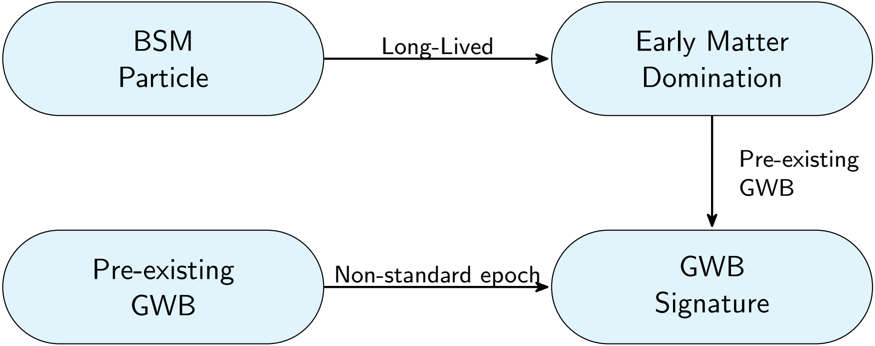
June 11 2026

Based on 2511.01779, 2604.20792 and 2605.28804

The General Idea



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Tracking Particles in the Early Universe

- The evolution of particle abundances and the background cosmology is described by Boltzmann equations.
- For a BSM particle X with decay rate Γ_X,

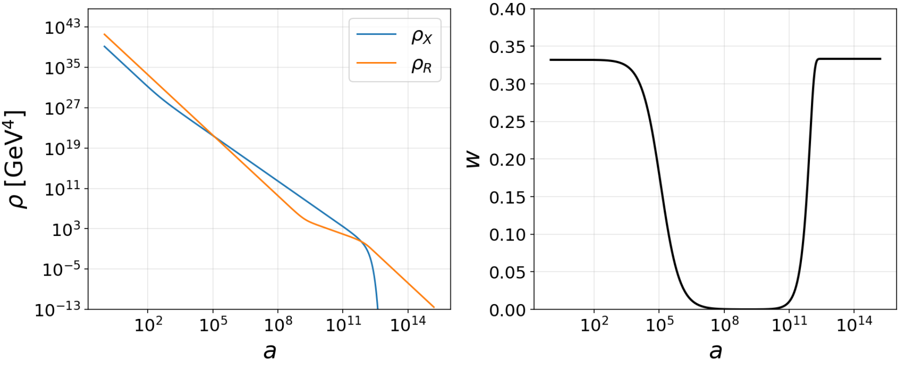
$$\begin{aligned}\dot{\rho}_X + (3+w)H\rho_X &= -\Gamma_X\rho_X \\ \dot{\rho}_R + 4H\rho_R &= \Gamma_X\rho_X\end{aligned} \tag{1}$$

- The Hubble rate is determined by the total energy density

$$H^2 = \frac{8\pi}{3M_{\mathrm{Pl}}^2}(\rho_R + \rho_X) \tag{2}$$

- These equations track the transition between radiation domination and matter domination.

Benchmark



10^{43}
10^{35}
10^{27}
10^{19}
10^{11}
10^{3}
10^{-5}
10^{-13}
ρ [GeV^4]
ρ_X
ρ_R
10^2
10^5
10^8
10^{11}
10^{14}
a
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
w
10^2
10^5
10^8
10^{11}
10^{14}
a

Onset and End of Early Matter Domination

- Consider a long-lived particle species X with mass M and initial yield $Y_i \equiv n_X/s$. When X becomes non-relativistic the energy densities are

$$\rho_R = \frac{\pi^2}{30} g_* T^4, \quad \rho_X = M Y_i s, \quad s = \frac{2\pi^2}{45} g_{*s} T^3 \tag{3}$$

- Their ratio evolves as

$$\frac{\rho_X}{\rho_R} = \frac{4}{3} Y_i \frac{M}{T}. \tag{4}$$

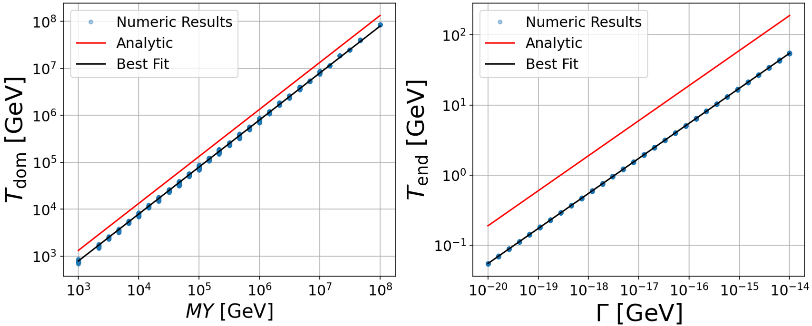
- Matter domination begins when $\rho_X = \rho_R$:

$$T_{\rm dom} \simeq \frac{4}{3} Y_i M. \tag{5}$$

- The matter dominated era ends when the particle decays

$$\Gamma = H(T_{\rm end}) \Rightarrow T_{\rm end} = \left(\frac{90}{\pi^2 g_*}\right)^{1/4} \sqrt{\Gamma M_{\rm Pl}}\ . \tag{6}$$

Onset and End of Early Matter Domination



The best–fit relations extracted from the numerical scan are

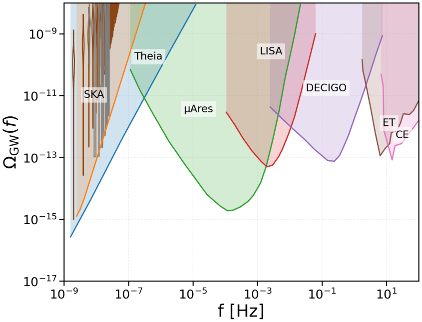
$$T_{\rm dom} = 0.793\,(Y_i M), \quad T_{\rm end} = 0.16\,\sqrt{\Gamma M_{\rm Pl}} \tag{7}$$

The condition for matter domination is then,

$$\boxed{\frac{\Gamma M_{pl}}{Y_i^2 M^2} < \; 24.6} \tag{8}$$

Gravitational-Wave Backgrounds

- A stochastic gravitational-wave background (GWB) is a golden ticket to the early universe.
- A wide range of experiments will come online over the next decade, probing for a GWB across many orders of magnitude in frequency.

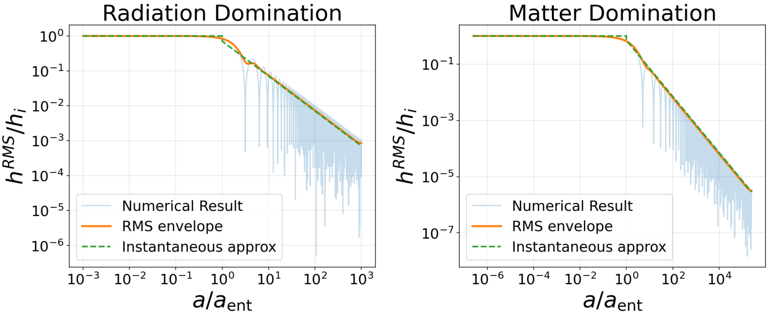


- Importantly for us, any deviation from standard radiation domination leaves a characteristic imprint on the gravitational-wave spectrum.

Horizon Entry and the Evolution of $\Omega_{\rm GW}$

The tensor mode equation in Fourier space is

$$\ddot{h}_k + 3H\dot{h}_k + \frac{k^2}{a^2}h_k = 0 \tag{9}$$



Key point: Evolution of $\Omega_{\rm GW}$ begins at horizon entry ($k \sim aH$)

Effect on Gravitational Waves

- The two key quantities ρ_{total} and ρ_{GW}.The fluid equations for each of the species is,

$$\dot{\rho}_{GW} - 4H\rho_{GW} = 0, \quad \dot{\rho}_{tot} - 3H(w(a)+1)\rho_{tot} = 0 \tag{10}$$

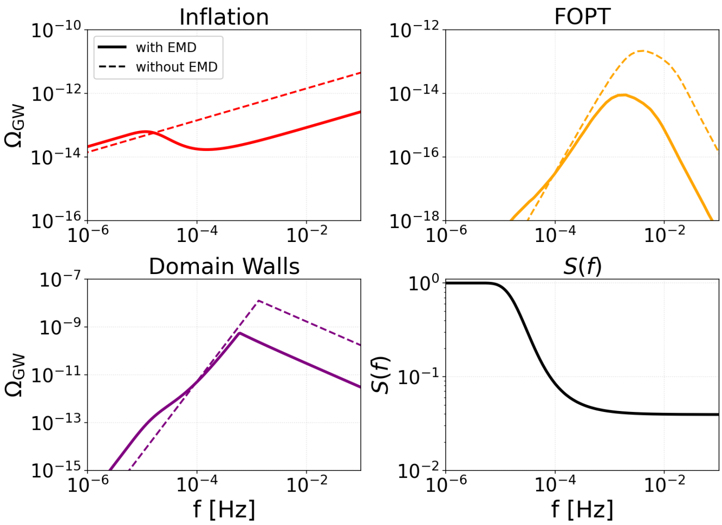
- The gravitational-wave energy density evolves according to

$$\Omega_{\rm GW}(a,f) = \Omega^{i}_{\rm GW}(f')C \exp\left[\int_{a_{ent}(f)}^{a_f} (3w(a)-1)\, d\ln a\right] \tag{11}$$

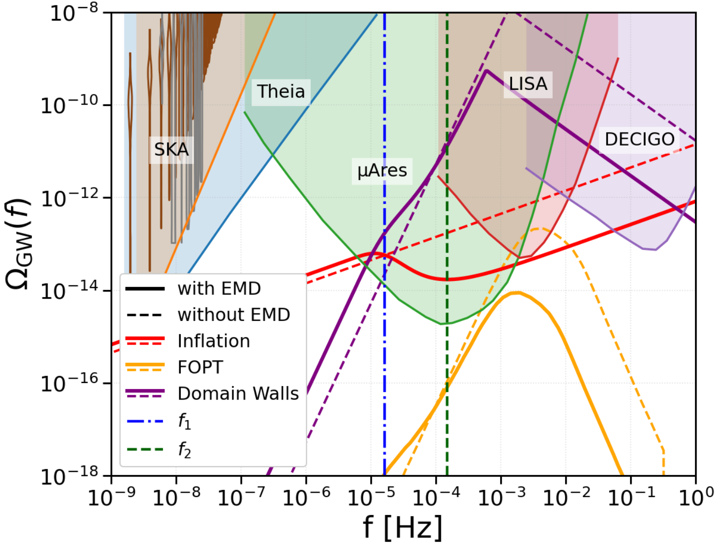
- During radiation domination ($w = 1/3$) the spectrum remains unchanged.
- During matter domination ($w = 0$) the spectrum is suppressed.
- We look to find the change which we

$$S(f) = \exp\left[\int_{a_{ent}(f)}^{a_f} (3w(a)-1)\, d\ln a\right] \tag{12}$$

Benchmark

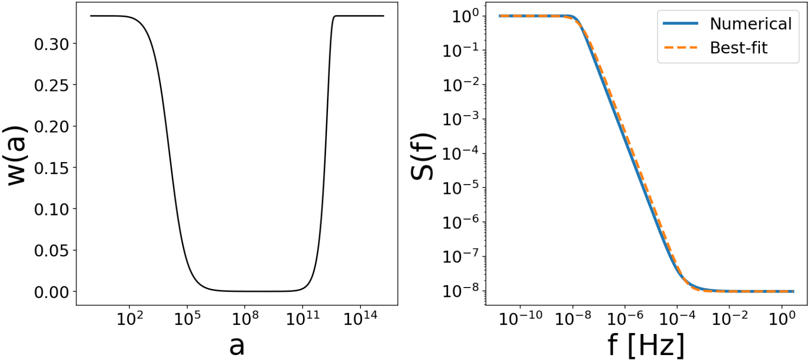

Inflation
with EMD
without EMD
10^{-10}
10^{-12}
10^{-14}
10^{-16}
Ω_{GW}
10^{-6}
10^{-4}
10^{-2}
FOPT
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-6}
10^{-4}
10^{-2}
Domain Walls
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
Ω_{GW}
10^{-6}
10^{-4}
10^{-2}
f [Hz]
$S(f)$
10^{0}
10^{-1}
10^{-2}
$S(f)$
10^{-6}
10^{-4}
10^{-2}
f [Hz]

Benchmark



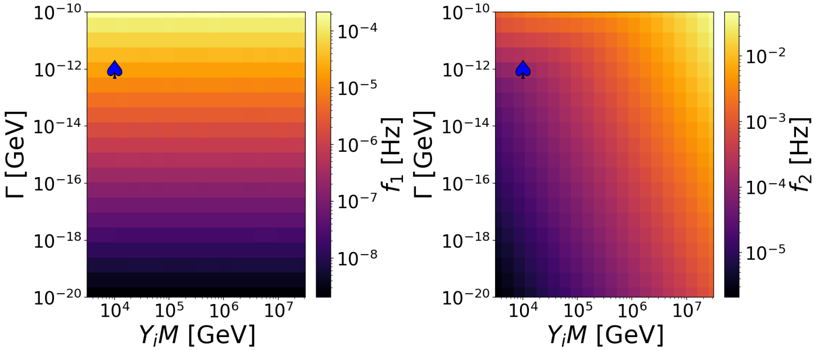
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
$\Omega_{GW}(f)$
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}
f [Hz]
SKA
Theia
µAres
LISA
DECIGO
with EMD
without EMD
Inflation
FOPT
Domain Walls
f_1
f_2

Benchmark



Best fit described by,

$$S(f, f_1, f_2) = \frac{1 + (f/f_1)^2}{1 + (f/f_2)^2}, \tag{13}$$

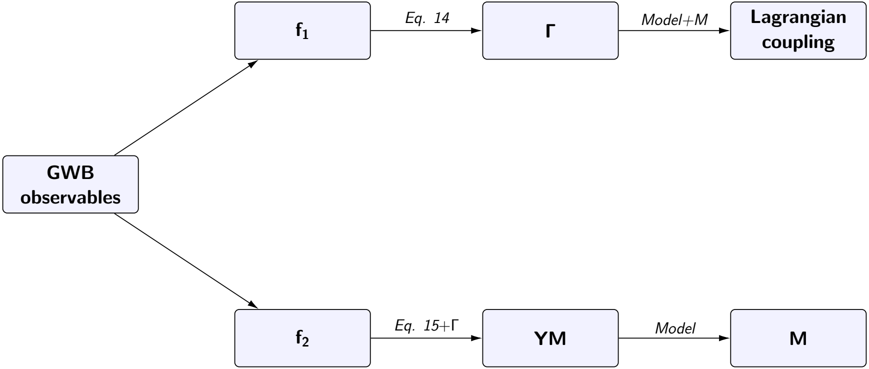


these results have best fits,

$$f_1 = 20.6 \left(\frac{\Gamma}{\mathrm{GeV}}\right)^{1/2} \mathrm{Hz} \tag{14}$$

$$f_2 = 2.10 \times 10^{-5} \left(\frac{Y_i M}{\mathrm{GeV}}\right)^{2/3} \left(\frac{\Gamma}{\mathrm{GeV}}\right)^{1/6} \mathrm{Hz}, \tag{15}$$

Overview



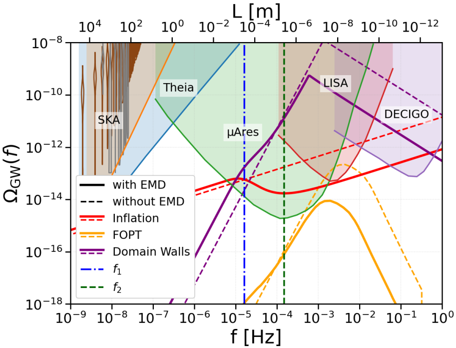
f1
Eq. 14
Γ
Model+M
Lagrangian coupling
GWB observables
f2
Eq. 15+Γ
YM
Model
M

LLP Searches at Colliders

- Many upcoming laboratory experiments are designed to probe LLPs.
- To make the complementarity with collider searches for LLPs more transparent, we rewrite the characteristic frequency f_1 in terms of the proper decay length, $L = 1/\Gamma$

$$f_1 = 2.9 \times 10^{-7} \left(\frac{1\ \mathrm{m}}{L}\right)^{1/2} \ \mathrm{Hz}\ . \tag{16}$$

- Remarkably, the Decay lengths probed $\mathcal{O}(100m)$ corresponds to a feature in the signal detected!



Right-Handed Neutrinos

- In the Standard Model, neutrinos are massless since only left-handed neutrinos are included.
- Neutrino oscillations imply non-zero neutrino masses.
- Introduce gauge-singlet right-handed neutrinos $N_R \sim (1, 1, 0)$.
- They allow a Dirac Yukawa coupling

$$\mathcal{L}_Y \supset -y_\nu \bar{L}\tilde{H}N_R,$$

generating neutrino masses after EWSB $m_D = y_\nu v$.

- Since N_R is neutral under the SM gauge group, a Majorana mass term is also allowed:

$$\mathcal{L}_M \supset -\frac{1}{2}M_R\overline{N_R^c}N_R.$$

- This leads naturally to the Type-I seesaw mechanism

$$m_\nu \sim \frac{m_D^2}{M_R},$$

explaining tiny neutrino masses.

Right-Handed Neutrinos

- For RHN decays,

$$\Gamma_N = \frac{\tilde{m} M^2}{8\pi v^2}, \quad \frac{\Gamma_N M_{\rm Pl}}{Y_i^2 M^2} < 24.6. \tag{17}$$

so the explicit dependence on the RH neutrino mass cancels in the condition

$$\frac{\tilde{m}\, M_{\rm Pl}}{8\pi v^2\, Y_i^2} < 24.6. \tag{18}$$

- Using $v = 174\,{\rm GeV}$ and expressing $\tilde{m}$ in eV,

$$\tilde{m}({\rm eV}) < 7.7 \times 10^{-3}\, Y_i^2. \tag{19}$$

- In the minimal Type-I seesaw with vanishing initial abundance, this condition cannot be satisfied.
- Non-thermal production mechanisms can evade this relation, allowing Y_i to be treated as a free parameter.

Right-Handed Neutrinos

- Using the frequency relations we already have in generality,

$$f_1 = 20.6 \left(\frac{\Gamma}{\mathrm{GeV}}\right)^{1/2} \ \mathrm{Hz} \tag{20}$$

$$f_2 = 2.10 \times 10^{-5} \left(\frac{Y_i M}{\mathrm{GeV}}\right)^{2/3} \left(\frac{\Gamma}{\mathrm{GeV}}\right)^{1/6} \ \mathrm{Hz}, \tag{21}$$

- We apply the initial abundance, Mass and effective neutrino mass

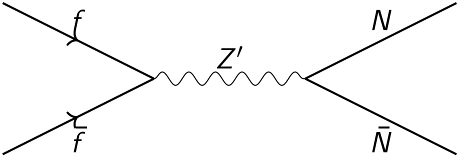
$$f_1 = 2.36 \times 10^{-6} \left(\frac{\tilde{m}}{\mathrm{eV}}\right)^{1/2} \left(\frac{M}{\mathrm{GeV}}\right) \ \mathrm{Hz} \tag{22}$$

$$f_2 = 1.01 \times 10^{-7} \, Y_i^{2/3} \left(\frac{\tilde{m}}{\mathrm{eV}}\right)^{1/6} \left(\frac{M}{\mathrm{GeV}}\right) \ \mathrm{Hz} \tag{23}$$

- So if a production mechanism is imposed, say thermal initial conditions from freeze-out. The Mass and effective neutrino mass of the dominating RHN can be determined.

$U(1)_{B-L}$ Model

- One nice mechanism is the $U(1)_{B-L}$ model that enforces RHNs and occurs in many GUT models.
- The RHNs can be produced thermally and then frozen out. Studied in 2511.01779



(a)

Figure: *Thermal Production of right-handed neutrinos via a Z' mediator.*

- Naturally get the early-matter domination from right-handed neutrinos and the GWB from Cosmic Strings.

$U(1)_{B-L}$ Model

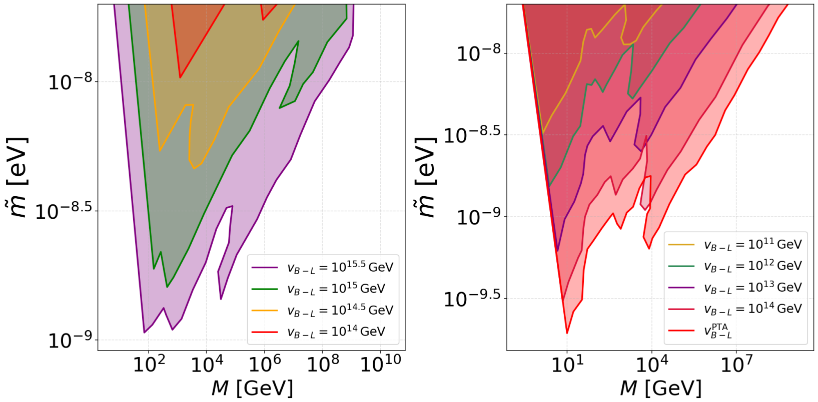


Figure: The panels show the detectable parameter space for global (left) and local (right) strings cases shown in the massm effective neutrino mass plane.

Gravitinos

- In supergravity, the graviton has a spin-$\frac{3}{2}$ superpartner: the gravitino $\psi_{3/2}$. Gravitinos decay gravitationally,

$$\Gamma_{3/2} \simeq m_{3/2}^3 / M_{pl}^2 \tag{24}$$

- Due to its long-lived nature and abundance in early universe there is a "***Gravitino Problem***" whereby it causes a period of EMD ruining BBN
- Simplest solution to this problem to have the gravitino decay before BBN,

$$\Gamma_{3/2} > H(T_{BBN}) \Rightarrow m_{3/2} > \mathcal{O}(100)\ \mathrm{TeV} \tag{25}$$

  putting it beyond the reach of colliders
- This makes it an ideal candidate for us!

Gravitinos

- Applying the gravitino decay rate $\Gamma \simeq m_{3/2}^3/M_{pl}^2$ one can see the dependence on this condition being,

$$\frac{\Gamma_{3/2} M_{pl}}{Y_i^2 m_{3/2}^2} < 24.6 \Rightarrow \frac{m_{3/2}}{Y_i^2 M_{pl}} < 24.6 \tag{26}$$

and one can immediately see how natural this is for gravitinos whose mass is expected to be well below the Planck scale. The exact condition on the initial abundance can now be written as

$$Y_i \gtrsim 3.35 \times 10^{-8} \sqrt{\frac{m_{3/2}}{100\,\text{TeV}}} \,. \tag{27}$$

For representative values,

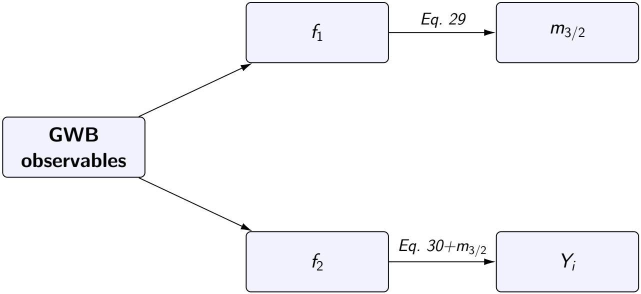
$$\begin{aligned} m_{3/2} &= 100\,\text{TeV} \;\Rightarrow\; Y_i \gtrsim 3.35 \times 10^{-8}, \\ m_{3/2} &= 10^9\,\text{TeV} \;\Rightarrow\; Y_i \gtrsim 1.1 \times 10^{-4} \,. \end{aligned} \tag{28}$$

Gravitinos

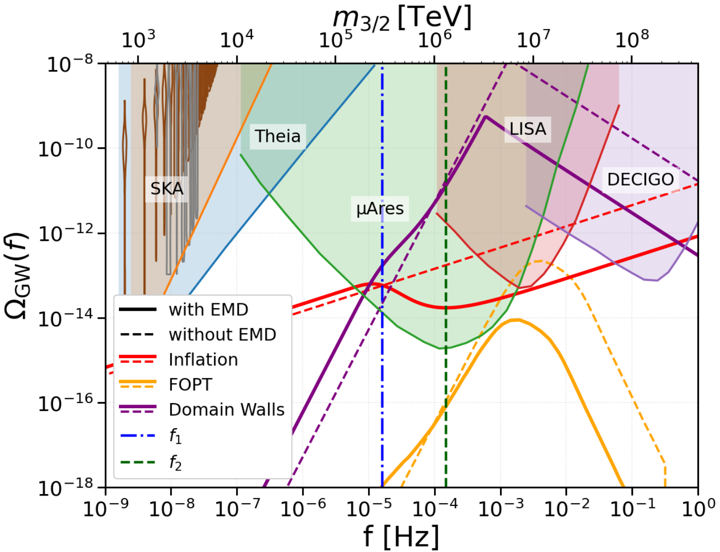
The scan for f_1 and f_2 yields the best-fit relation

$$f_1 = 9.77 \times 10^{-11} \left(\frac{m_{3/2}}{100\,\text{TeV}}\right)^{3/2} \text{Hz}, \tag{29}$$

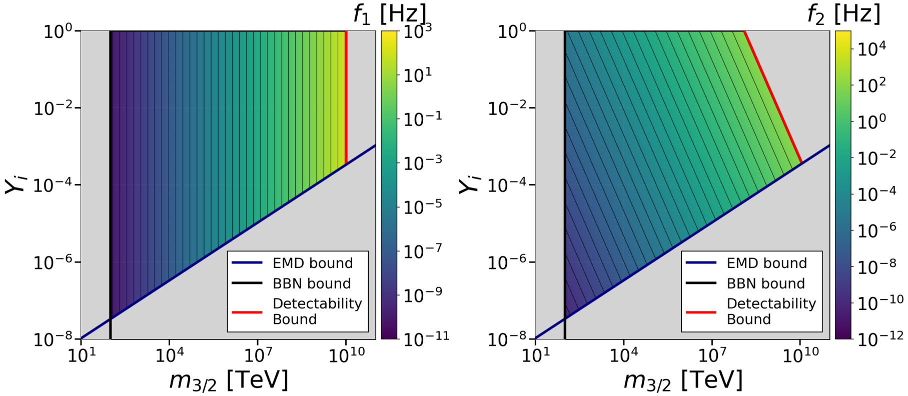
$$f_2 = 7.60 \times 10^{-6}\, Y_i^{2/3} \left(\frac{m_{3/2}}{100\,\text{TeV}}\right)^{7/6} \text{Hz}. \tag{30}$$



Benchmark


$m_{3/2}$ [TeV]
10^3
10^4
10^5
10^6
10^7
10^8
$\Omega_{GW}(f)$
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
Theia
LISA
SKA
DECIGO
μAres
with EMD
without EMD
Inflation
FOPT
Domain Walls
f_1
f_2
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
f [Hz]

Gravitinos



f_1 [Hz]
Y_i
$m_{3/2}$ [TeV]
EMD bound
BBN bound
Detectability Bound
f_2 [Hz]
Y_i
$m_{3/2}$ [TeV]
EMD bound
BBN bound
Detectability Bound

Extra-Dimensions

- Compactifying extra-dimensions imply the existence of scalar fields called Moduli.
- Moduli decay gravitationally,

$$\Gamma_\phi \simeq m_\phi^3 / M_{pl}^2 \tag{31}$$

- Due to its long-lived nature and abundance in early universe there is a ***"Moduli Problem"*** whereby it causes a period of EMD ruining BBN
- Simplest solution to this problem to have the moduli decay before BBN,

$$\Gamma_\phi > H(T_{BBN}) \Rightarrow m_\phi > \mathcal{O}(100)\ \mathrm{TeV} \tag{32}$$

  putting it beyond the reach of colliders
- This makes it an ideal candidate for us!

Extra Dimensions

- Misalignment mechanism produces an abundance of moduli. When the Hubble rate drops below the modulus mass,

$$H \simeq m_\phi,$$

  the modulus field begins coherent oscillations about its minimum and redshifts as matter.

- The characteristic frequencies become

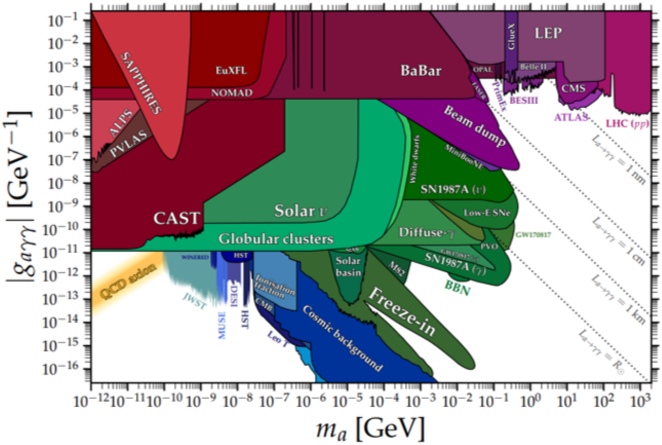
$$f_1 \propto m_\phi^{3/2} \tag{33}$$

$$f_2 = ?? \tag{34}$$

- The probed mass range coincides with that of gravitinos because gravitational decays lead to the same $f_1 \leftrightarrow m$ correspondence.
- Results coming in the next few months hopefully!

Axion-Like Particles (ALPs)

- ALPs are light pseudo-scalar particles appearing generically in string compactifications.
- They arise from the breaking of approximate global symmetries. Huge area of research looking for them,



Conclusions

- Long-lived particles generically induce a period of early matter domination.
- This non-standard expansion history leaves a universal imprint on primordial gravitational-wave backgrounds.
- The resulting spectral distortion is well described by two characteristic frequencies, f_1 and f_2, corresponding to the onset and termination of the matter-dominated era.
- These frequencies are directly determined by microscopic parameters, with $f_1 \propto \Gamma^{1/2}$ and $f_2 \propto (YM)^{2/3}\Gamma^{1/6}$, establishing a direct map between observables and particle physics.
- Gravitational-wave measurements therefore provide a model-independent probe of long-lived particles.
- LLP decay lengths probed by upcoming experiments map directly onto the frequency range of the observed signal.