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Cosmic Gravitational Waves as Tracers of Leptogenesis

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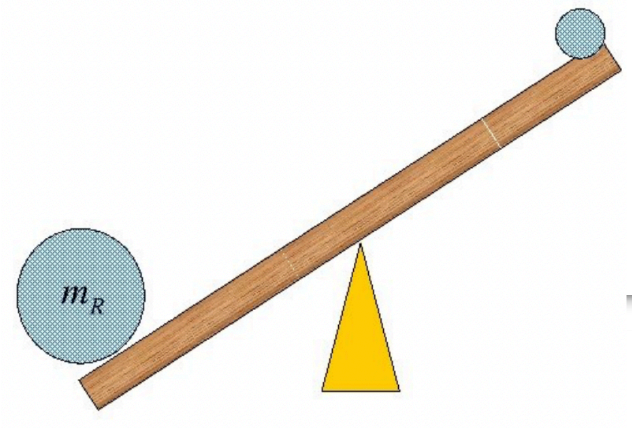
Based on

Chianese, Datta, Miele, Samanta, **Saviano** PRDL 2025
Chianese, Dom`enech, Papanikolaou, Samanta and **Saviano,** [arXiv:2504.20135 [hep-ph]].

Baryogenesis via Leptogenesis

Simple and elegant explanation of the cosmological matter-antimatter asymmetry

$$\mathcal{L} \supset -y_D \overline{L}\tilde{H} N_R - \frac{1}{2} M_N \overline{N_R^C} N_R + \text{h.c.}$$



Right Handed Neutrinos (RHNs)

- ***Naturally satisfies the Sakharov conditions***

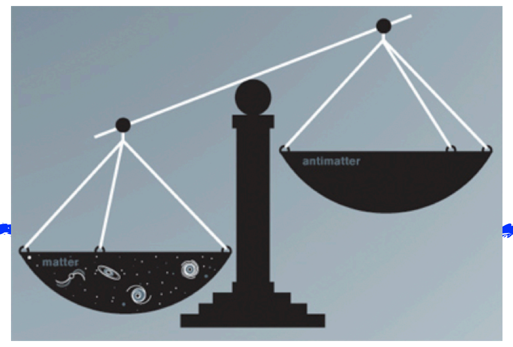
☑ L violation due to the Majorana nature of heavy RHNs
L → B through sphaleron interactions.

☑ New source of CP violation in the leptonic sector
due to Dirac Yukawa couplings.

☑ Departure from thermal equilibrium when $\Gamma_N < H$.

Present in the SM but not sufficient…

⟷



Baryon asymmetry of the Universe

$$\eta \equiv \left.\frac{n_B - n_{\bar{B}}}{n_\gamma}\right|_0 = (6.21 \pm 0.16) 10^{-10}$$

Planck Collaboration

$$Y_{\Delta B} \equiv \left.\frac{n_B - n_{\bar{B}}}{s}\right|_0 = (8.75 \pm 0.23) \times 10^{-11}$$

Inferred independently by BBN and CMB data

- ***Provides a common link between ν mass and baryon asymmetry***

[Fukugita, Yanagida PLB'86] *[**Reviews:** Buchmüller+ 2005; Davidson+ 2008; Sheng Fong+ 2012]*

Distinct flavor regimes of High-scale Leptogenesis

10^9 GeV $\qquad$ 10^{12} GeV $\qquad$ M_N

Three-flavor (3FL) $\qquad$ **Two-flavor (2FL)**

The rates of processes mediated by the τ and μ Yukawa coupling are non negligible…

↓

Lepton flavors effects must be taken into account

↓

Low-energy neutrino phenomenology

One-flavor (1FL)

vanilla leptogenesis

no charged lepton flavour effects

↓

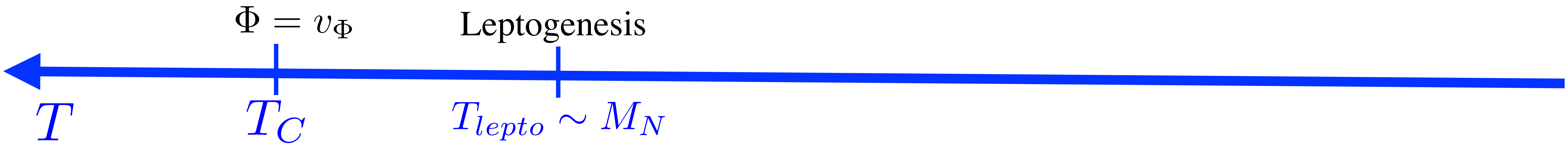
No sensitivity to low-scale neutrino mixing matrix

Abada, Davidson, Josse-Michaux, Losada, Riotto '06 ; Nardi, Nir, Roulet, Racker '06; Abada et al. '06; Blanchet, Di Bari, Raffelt '06; De Simone, Riotto '06 ; Barbieri, Creminelli, Strumia,Tetradis '99; Pilaftsis '05,;Pilaftsis, Underwood '05…

cannot be tested by terrestrial experiments

It is therefore necessary to find other evidence to test the neutrino sector → ***Stochastic GW background***

The $U(1)_{B\text{-}L}$ model



Ultraviolet realization of seesaw models based on the gauge $U(1)_{B\text{-}L}$ symmetry with coupling g', naturally embedded in many Grand Unified Theories (GUTs)

$$-\Delta\mathcal{L} \supset \frac{1}{2} y_N \overline{N_R} \Phi N_R^C + y_D \overline{N_R} \tilde{H}^\dagger L + \frac{1}{4}\lambda_{H\Phi} H^2 \Phi^2 + V(\Phi, T)$$

	$U(1)_{B-L}$
L	-1
H	0
N_R	-1
Φ	2

Davidson PRD 1979; Marshak+ PLB 1980;
Buchmüller+ JCAP 2013; Buchmüller+ PLB 2020; Buchmüller+ JCAP 2023

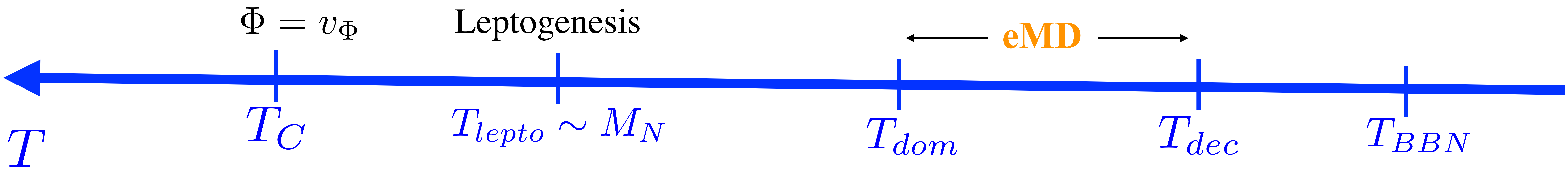
- ***$U(1)_{B-L}$ phase transition at T_c (critical T):*** Φ gets its vev and RHNs become massive

$$\boxed{V(\Phi, T) \to V(\Phi, 0) = -\mu^2\Phi^2/2 + \lambda\Phi^4/4} \qquad v_\Phi = \frac{\mu}{\sqrt{\lambda}}, \quad m_\Phi = \sqrt{2\lambda}\, v_\Phi, \quad M_N = y_N v_\Phi$$

- Second-order Phase Transition (PT): the Φ oscillations around v v_Φ behave as a matter field

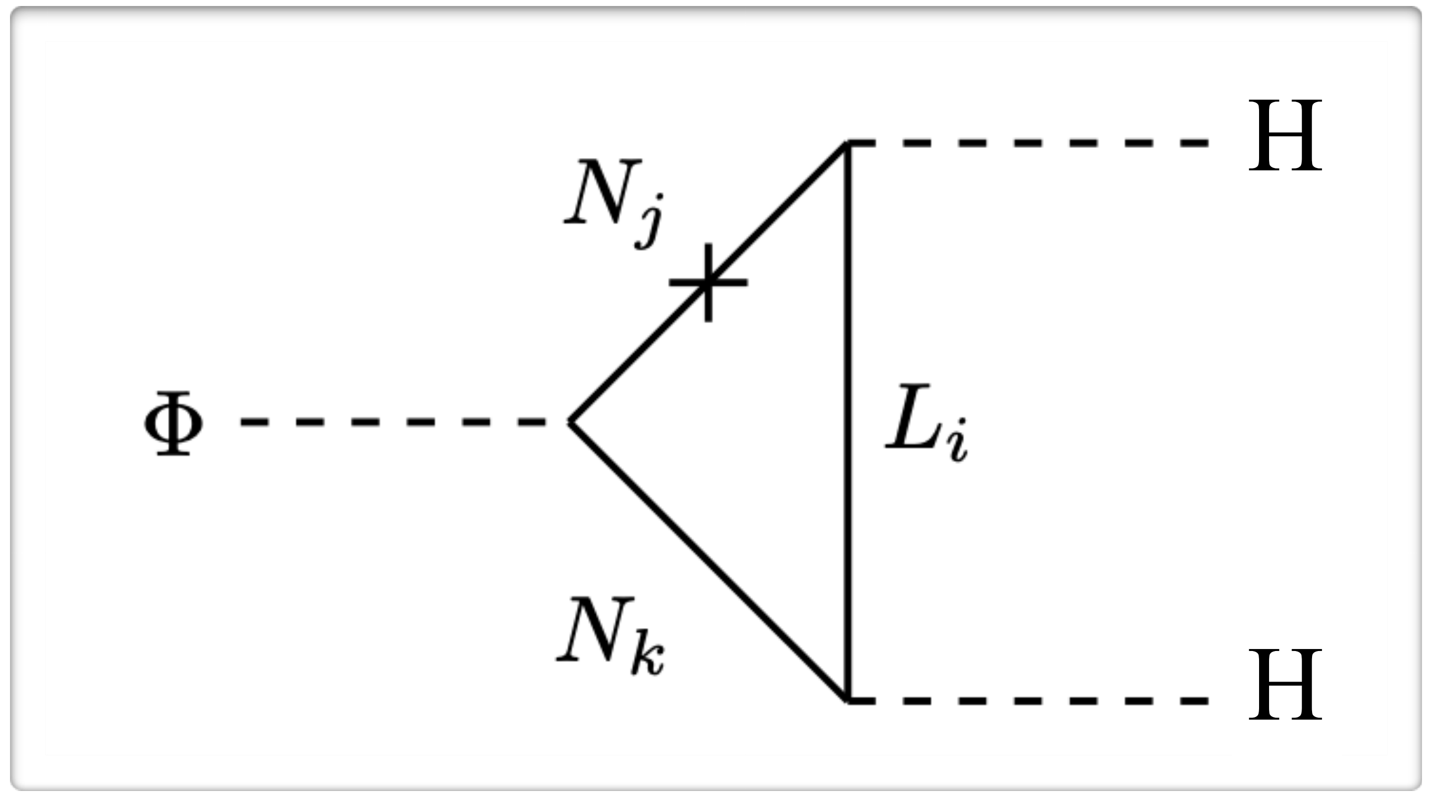
order parameter $\quad \dfrac{\Phi(T_c)}{T_c} \lesssim 0.08 \implies \lambda \sim g'^3$

M_N-dependent matter domination



Φ long-lived to induce a **early Matter-Domination (eMD)** epoch starting at $T_{dom} = \dfrac{\rho_\Phi(T_c)}{\rho_R(T_c)}$

The eMD ends when Φ decays at $T_{\rm dec}$, main decay: radiative decay **$\Phi \to HH$**



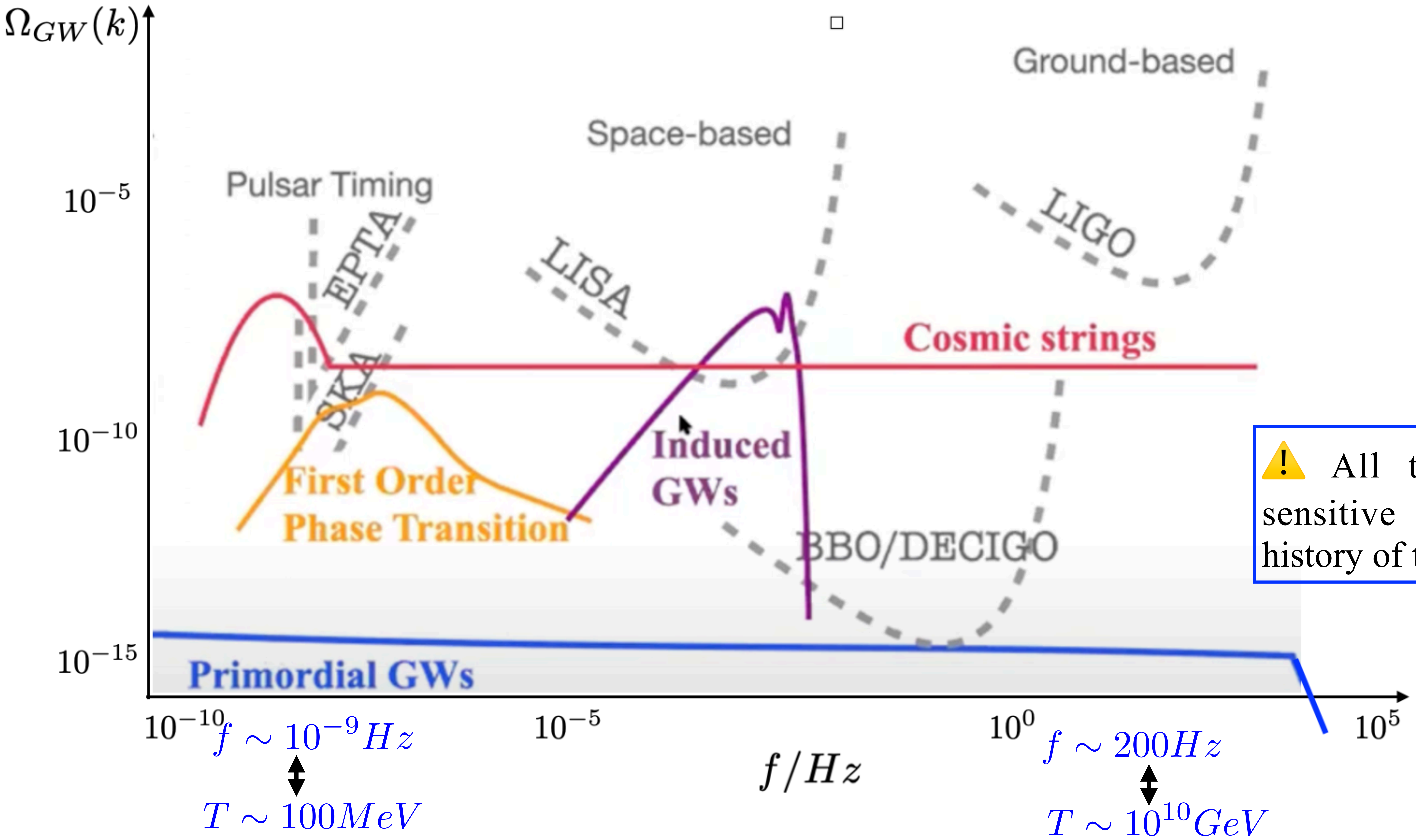
$$\lambda_{H\Phi}^{\text{1-loop}} > \lambda_{H\Phi}^{\text{tree}}$$

mediated by the neutrino Dirac Yukawa y_D and the coupling y_N → connection between the ν param and the lifetime of Φ → **GW spectrum sensitive to M_N**

The eMD depends on the RHN mass scale!

*Chianese, Datta, Samanta, **Saviano**, JCAP 2024;Chianese, Datta, Miele, Samanta, **Saviano** PRDL 2025*

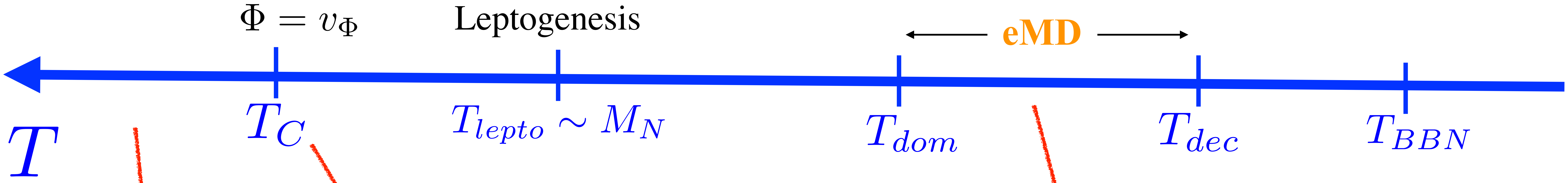
Cosmological Stochastic GW background



⚠ All these spectra are sensitive to the expansion history of the early universe

Cosmologically generated GW backgrounds provide a unique opportunity to study the state of the very early universe at $T > T_{BBN}$ and represent an important new physics target for a number of upcoming and proposed observatories

Leptogenesis with Gravitational Waves



GWs from $U(1)_{B\text{-}L}$ cosmic strings

Chianese, Datta, Miele, Samanta, ***Saviano***

PRD Letters 111 (2025)

GWs induced by the primordial fluctuations

Chianese, Domènech, Papanikolaou, Samanta, ***Saviano***

arXiv:2504.20135

Primordial GWs from inflation

Chianese, Datta, Samanta, Saviano JCAP 11 (2024)

Direct possible signature of leptogenesis with primordial stochastic GW background by focusing on the RHN sector.

⚠ A gauged *U(1)$_{B\text{-}L}$* breaking can be also responsible of radiation of ***gravitational waves***

GW Spectrum from cosmic string

Cosmic strings are topological defects that may have been formed at phase transitions in the very early Universe. They create loops that radiate GWs and particles.

The GW energy density is given by:

$$\boxed{\Omega_{\rm GW} = \sum_{k=1}^{k_{\rm max}} \frac{2k\mathcal{F}_\alpha G\mu^2\Gamma_k}{f\rho_c}\int_{t_i}^{t_0}\left[\frac{a(t)}{a(t_0)}\right]^5 n_\omega(t,l_k)\mathrm{d}t} \sim \begin{cases} f^{3/2} & f \ll f_{\rm peak} \\ \Omega_{\rm GW}^{\rm plt} & f_{\rm peak} \ll f \lesssim f_{\rm dec} \\ f^{-1/3} & f \gtrsim f_{\rm dec} \end{cases}$$

Leptogenesis-modified cosmology

string tension

loop number density

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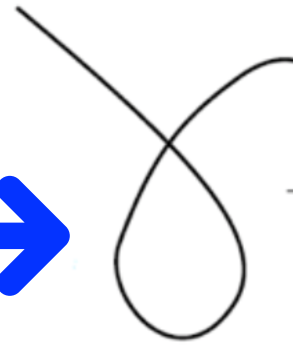
string tension

loop number density

Basic scheme

$\mathcal{L} \subset \frac{1}{2} y_N \overline{N_R} \Phi N_R^C$ → $\cancel{U(1)_{B-L}}$ → $M_N = y_N v_\phi$ →  → $\Omega_{\rm GW}$ **(almost) scale-invariant plateau**

J. A. Dror, T. Hiramatsu, K. Kohri, H. Murayama, and G. White, (2020); S. Blasi, V. Brdar, and K. Schmitz, (2020); R. Samanta and S. Datta, (2021); S. Datta, A. Ghosal, and R. Samanta, (2021), Vilenkin PLB 1981; Vachaspati & Vilenkin PRD 1985; Damour & Vilenkin PRD 2001; Sousa & Avelino PRD 2013; Blanco-Pillado+ PRD 2014; Blanco-Pillado & Olum PRD 2017; Auclair+ JCAP 2020; Sousa+ PRD 2020; Schmitz & Schröder PRD 2024; Baeza-Ballesteros+ arXiv:2408.02364; Schmitz & Schröder arXiv:2412.20907; Schmitz & Schröder arXiv:2505.04537 , W. Buchmüller, V. Domcke, K. Kamada, and K. Schmitz, (2013),(2020), A. Davidson, (1979); R. E. Marshak and R. N. Mohapatra, (1980).

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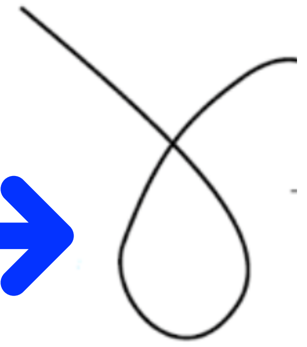
$\mathcal{L} \subset \frac{1}{2} y_N \overline{N_R} \Phi N_R^C$ → $\cancel{U(1)_{B-L}}$ → $M_N = y_N v_\phi$ →  → $\Omega_{\rm GW}$ **(almost) scale-invariant plateau**

More Involved scheme: this talk

*Chianese, Datta, Miele, Samanta, **Saviano** PRDL 2025*

M_N-dependent matter domination → M_N-dependent GW spectrum → **the plateau breaks at high frequencies**

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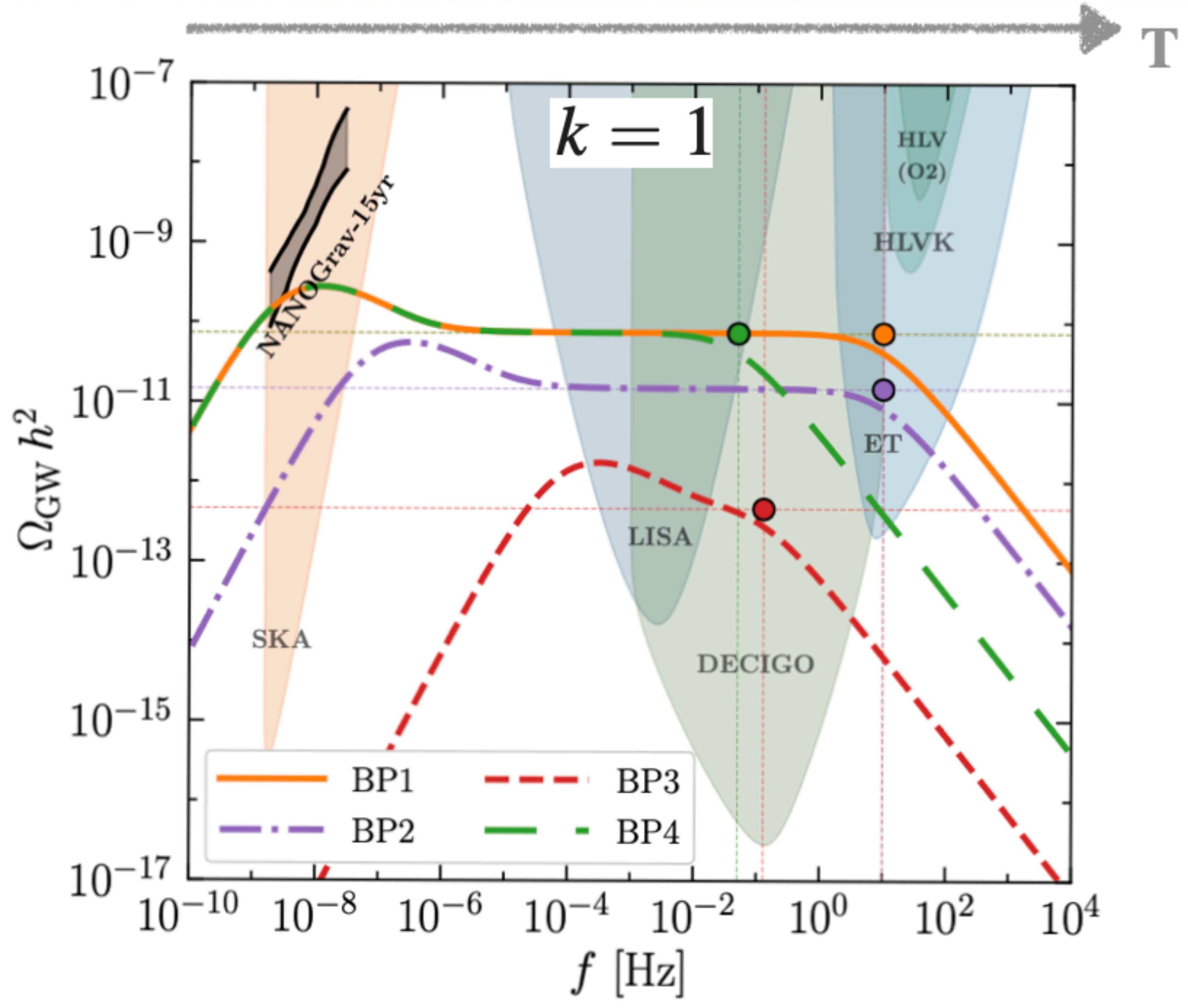

BP1 (2FL) $M_N = 1.6\times10^9$ GeV, $y_N = 1.4\times10^{-5}$

BP2 (3FL) $M_N = 4.2\times10^8$ GeV, $y_N = 1.8\times10^{-5}$

BP3 (3FL) $M_N = 5.2\times10^6$ GeV, $y_N = 6.8\times10^{-6}$

BP4 (3FL) $M_N = 2.7\times10^8$ GeV, $y_N = 2.2\times10^{-6}$

$g' = 10^{-4}$

*Chianese, Datta, Miele, Samanta, **Saviano** PRDL 2025*

GW Spectrum from cosmic string

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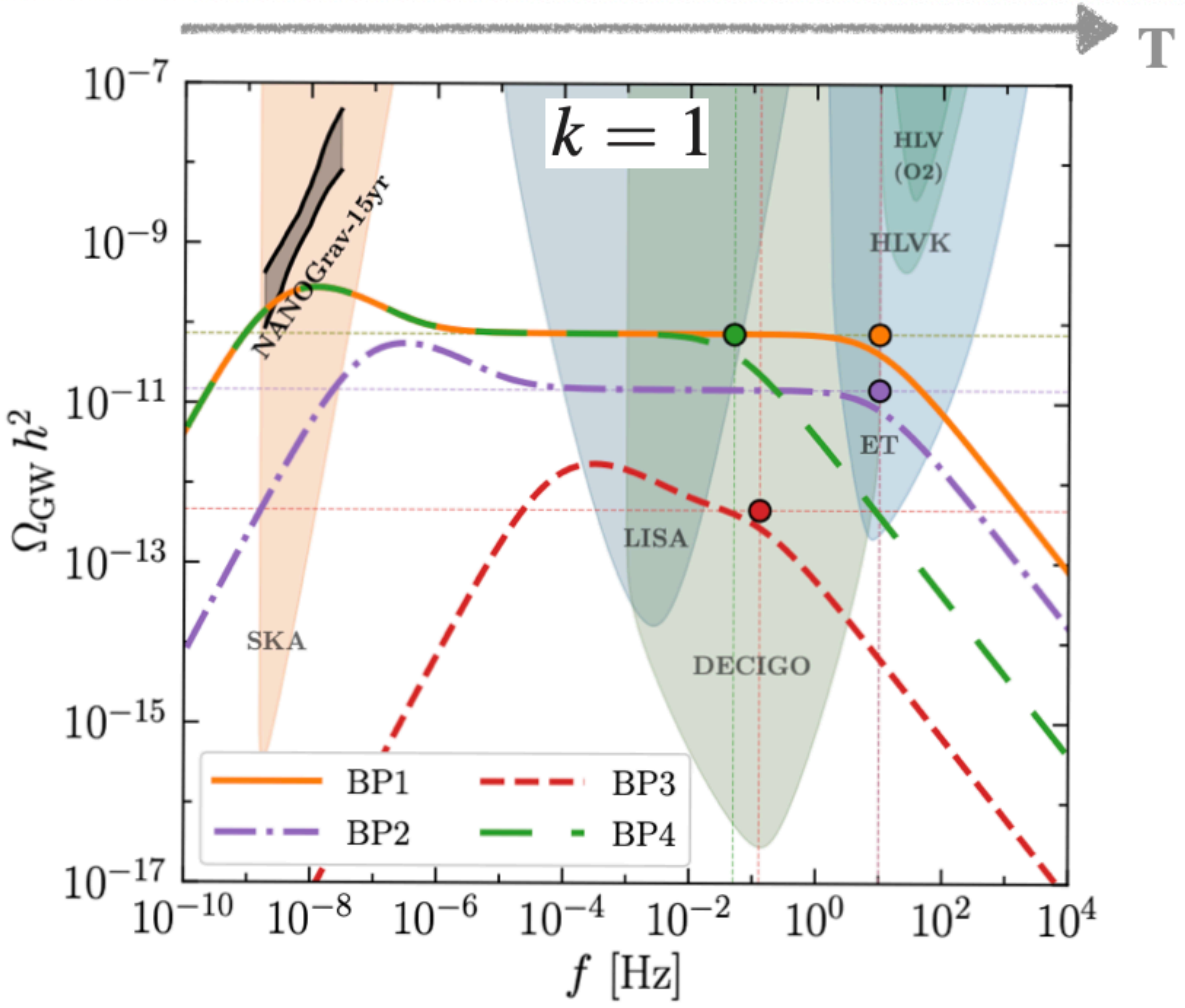

Measuring both the plateau and the break frequency will pinpoint the leptogenesis mass scale!

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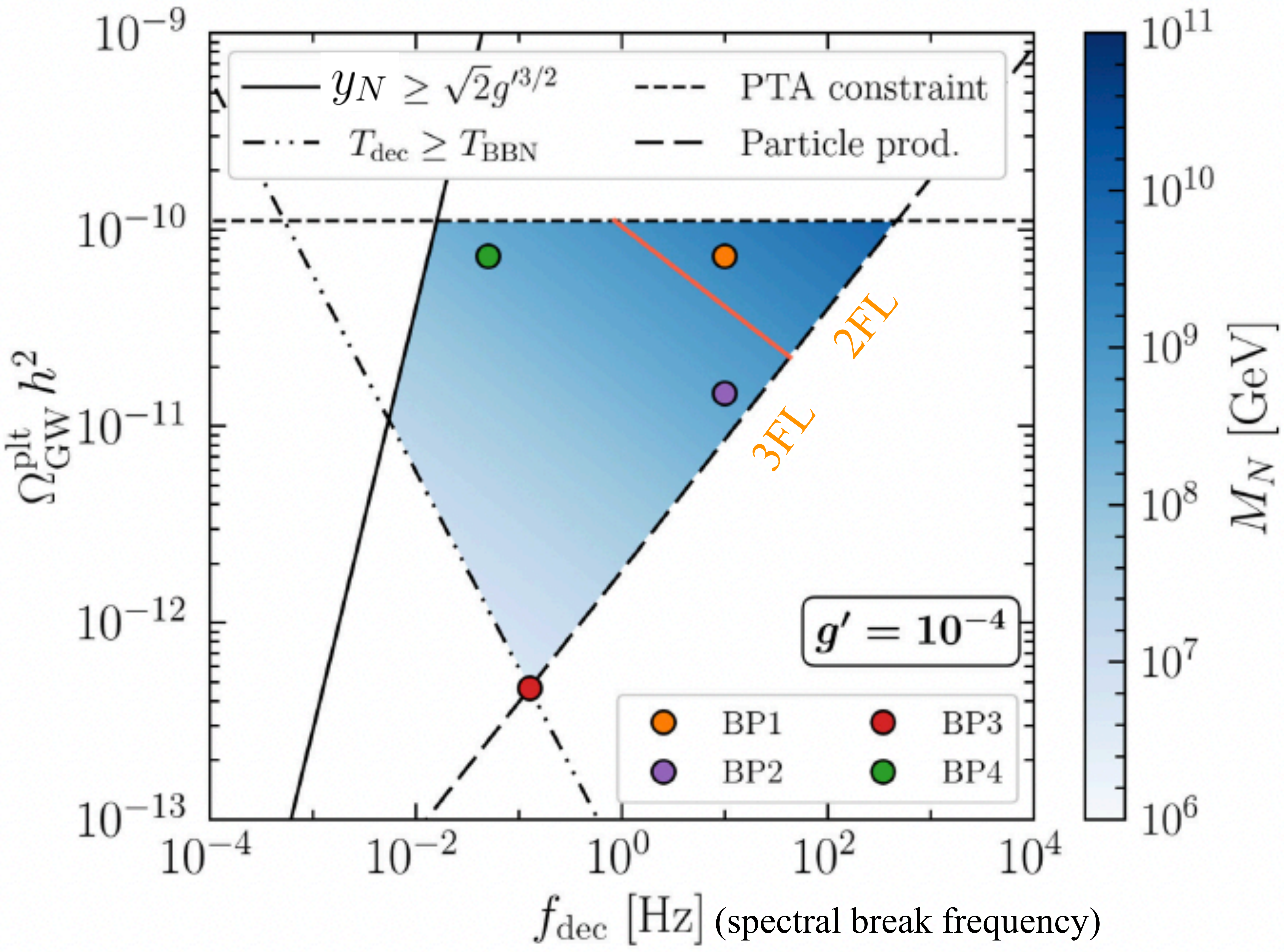
Parameter Space (GWFRL window)



(spectral break frequency)

Relevant constraints:

i) the bound from the recent observations of nHz GWs by PTA;

ii) GWs radiation dominant over particle emission;

iii) $T_{\rm dec} \gtrsim T_{\rm BBN}$

iv) scalar field Φ is long-lived.

The orange solid line marks the transition between 3FL and 2FL leptogenesis regimes.

Each flavored regime, sensitive to low-energy neutrino experiments, leaves a marked imprint on the GWs spectrum

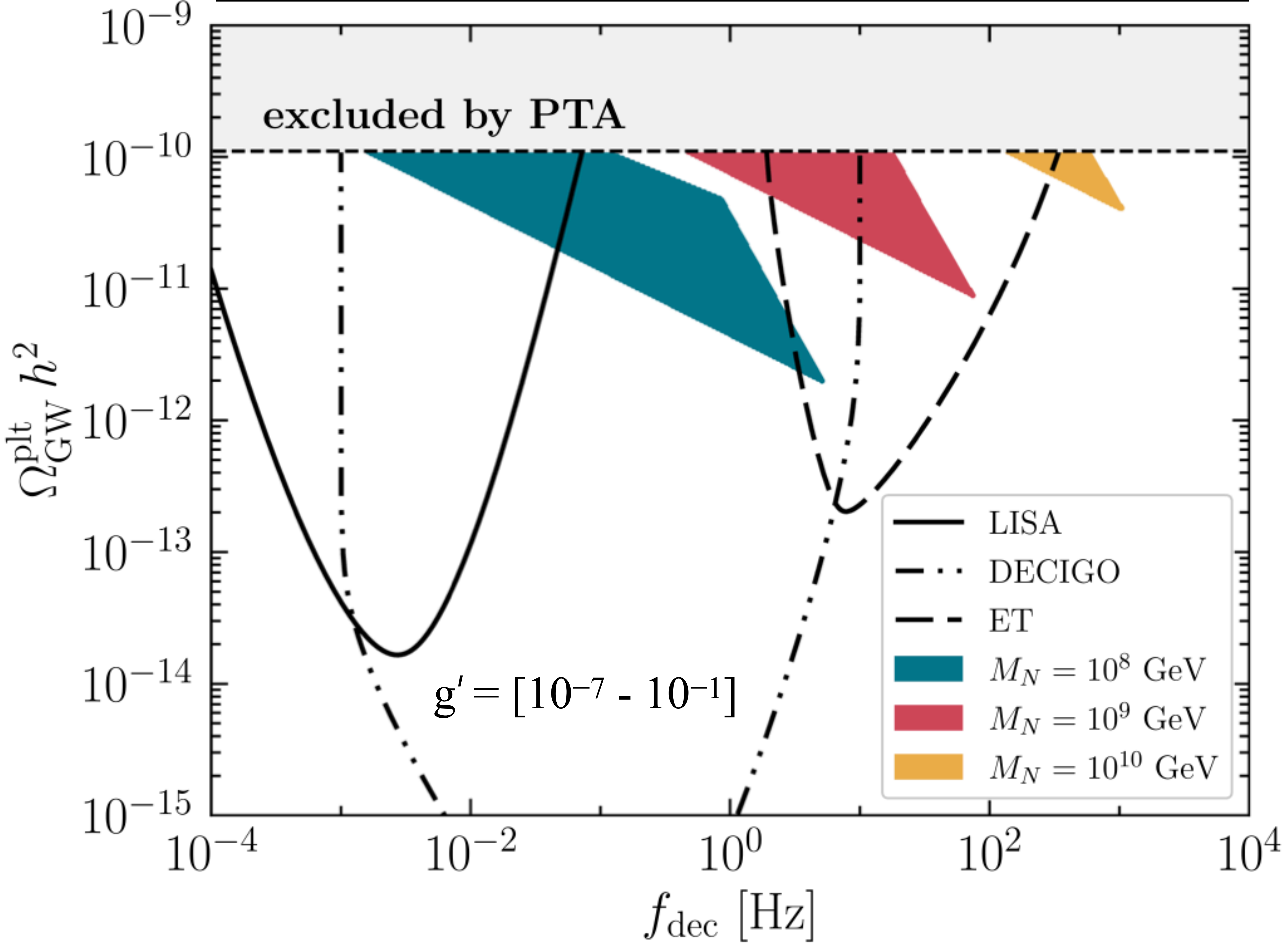
*Chianese, Datta, Miele, Samanta, **Saviano** PRDL 2025*

GW windows for flavored regimes of leptogenesis GWFRL

Different flavor regimes of HS leptogenesis could produce GW signature with spectral features depending on the MN

- The 3FL regime implies a spectral break in the LISA/DECIGO frequency band
- The 2FL regime (for $g' \geq 10^{-3}$) is highly disfavored due to higher GW amplitudes
- The 1FL regime is excluded by PTA

Allowed regions for f_{dec} and Ω_{plt}, once we fix the value of the leptogenesis scale M_N (region with different colors)



Chianese, Datta, Miele, Samanta, ***Saviano*** *PRDL 2025*

Induced GWs (IGWs)

They are sourced by primordial fluctuations in the early Universe due to second-order gravitational interactions.

Bulk velocities in the Universe lead to anisotropic stresses which source GWs: $T_{ij} \sim \rho v_i v_j$

- We need at least the largest possible non-linear scale enters the Hubble radius during the eMD

$$k(\tau_{\rm dec}) < \mathcal{H}_{\rm dec} \quad \Longrightarrow \quad A_{\rm s}^{\rm min} \equiv \alpha^4 \left(\frac{a_{\rm dom}}{a_{\rm dec}}\right)^2 \approx 9 \left(\frac{T_{\rm dec}}{T_{\rm dom}}\right)^2$$

Minimum amplitude of the primordial spectrum of density fluctuations

- For the IGW spectrum, **numerical simulations on non—linear scales ($k > k_{\rm NL}$) give**

$$\Omega_{\rm GW,0}h^2 = 4.2 \times 10^{-5}\, A_s^{11/8} \left(\frac{f}{f_{\rm high}}\right)^{3/2} \quad \text{for} \quad f_{\rm low} \leq f \leq f_{\rm high}$$

End to eMD (scalar decay)

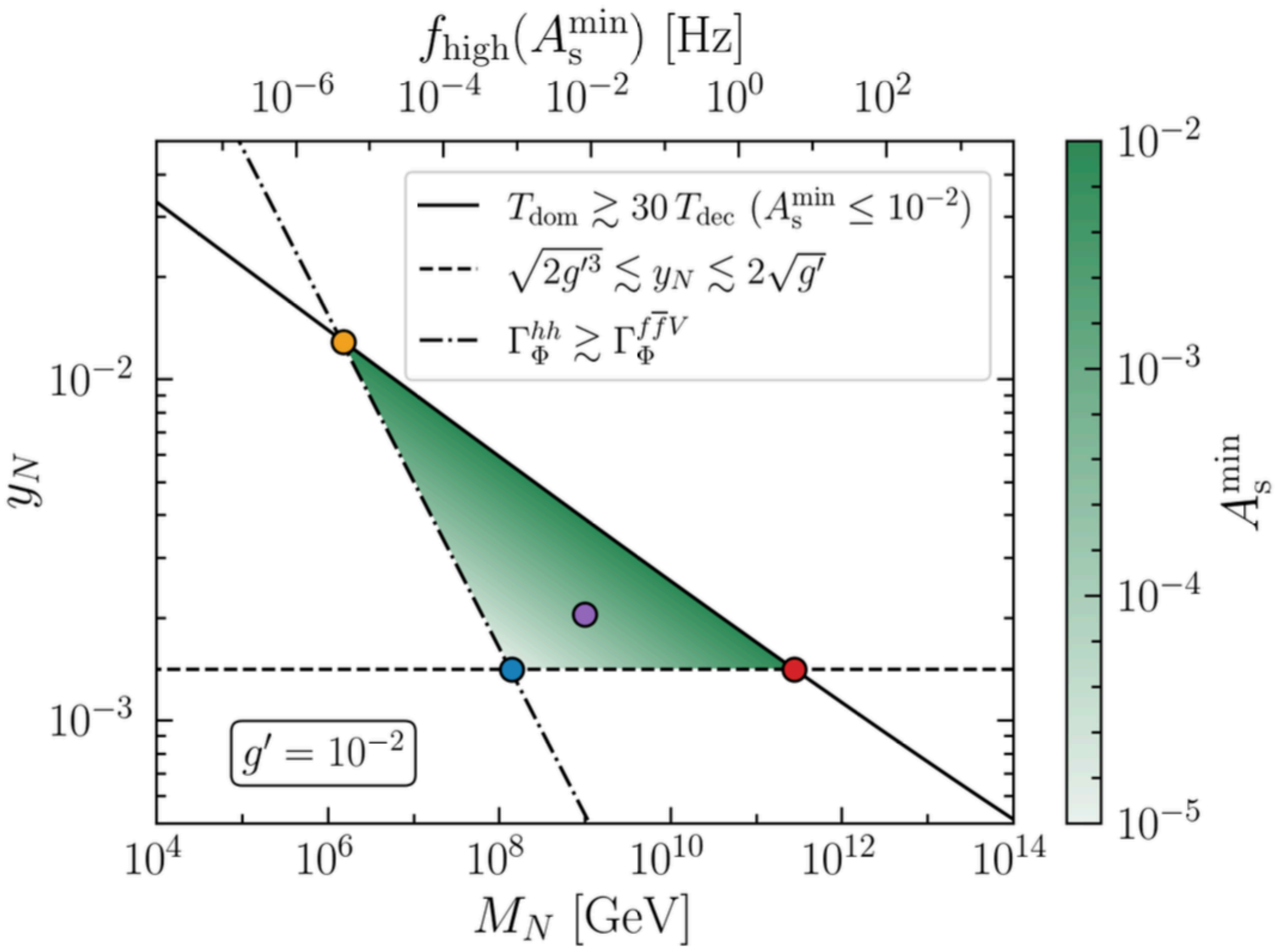
Numerical resolution

$$f_{\rm low} \simeq 3.8 \times 10^{-6}\ {\rm Hz} \left(\frac{T_{\rm dec}}{10\,{\rm GeV}}\right)$$

$$f_{\rm high} \simeq 6.4 \times 10^{-5}\ {\rm Hz} \left(\frac{A_{\rm s}}{10^{-5}}\right)^{-1/4} \left(\frac{T_{\rm dec}}{10\,{\rm GeV}}\right)$$

Review: Domènech Universe'21
Numerical simulations: Eggemeier+ PRD'23; Fernandez+ PRL'24; Dalianis & Kouvaris JCAP'24

IGWs from leptogenesis eMD



Parameter space achieving an eMD era uniquely determined by the two remaining model parameters M_N and the coupling y_N.

The scalar field must dominate the Universe for long enough before decaying in order to develop nonlinear structures.

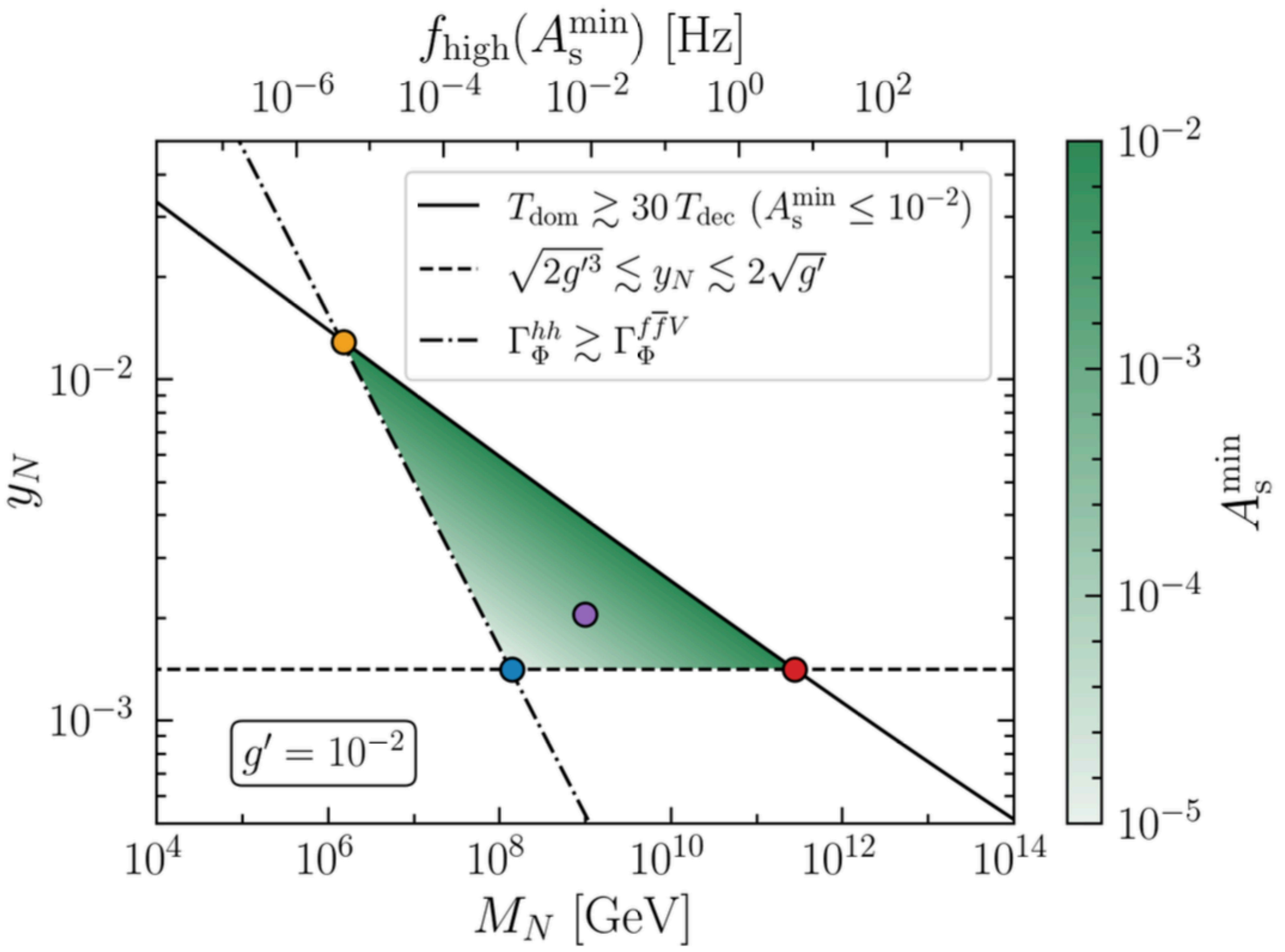
This requirement is related to the amplitude of the primordial spectrum of density fluctuations, As.

We set a minimum value for As

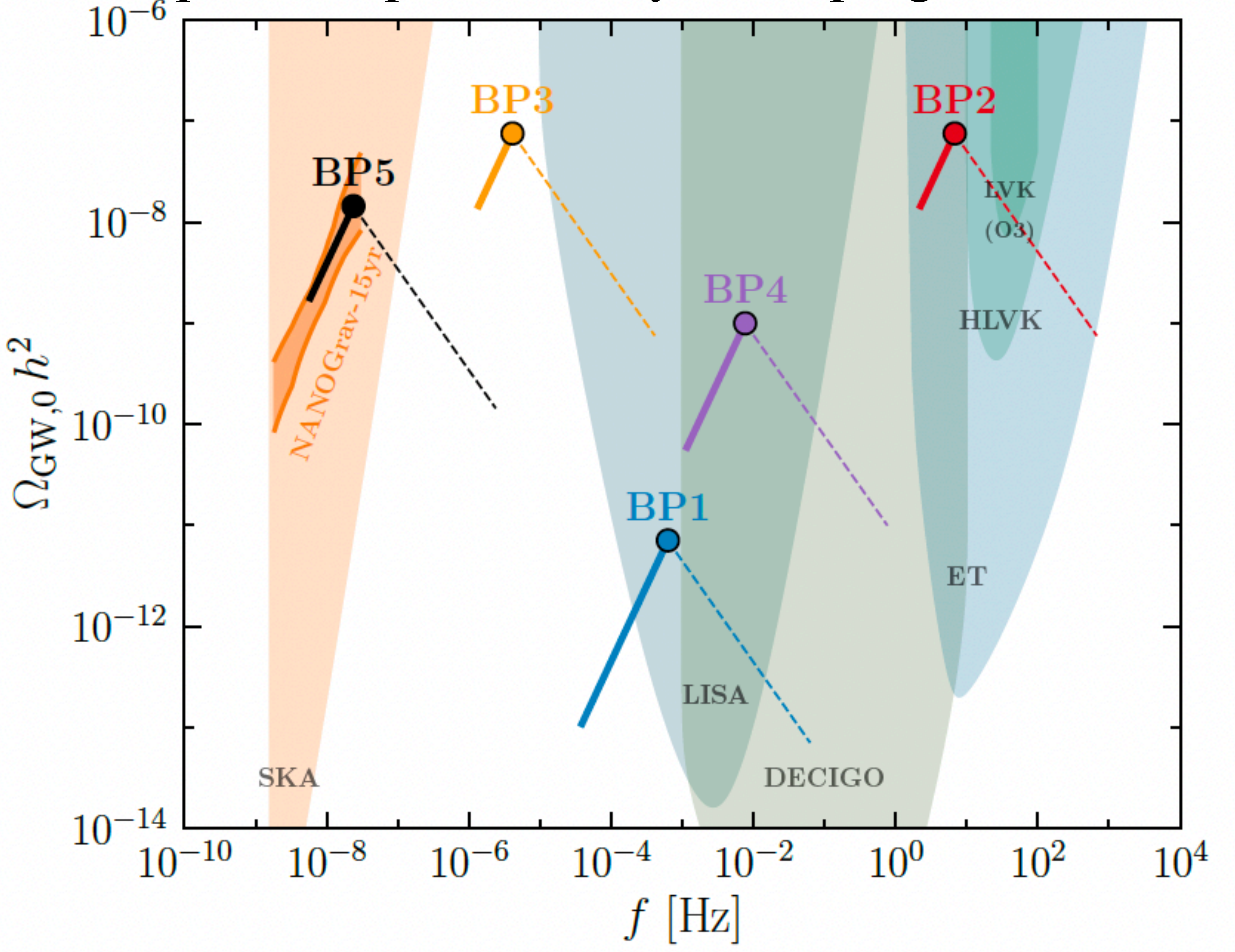
Direct link between the frequency and amplitude of these IGWs and the thermal leptogenesis scale!

*Chianese, Dom`enech, Papanikolaou, Samanta and **Saviano**, [arXiv:2504.20135 [hep-ph]].*

IGWs from leptogenesis eMD



GW spectrum predicted by our leptogenesis model.

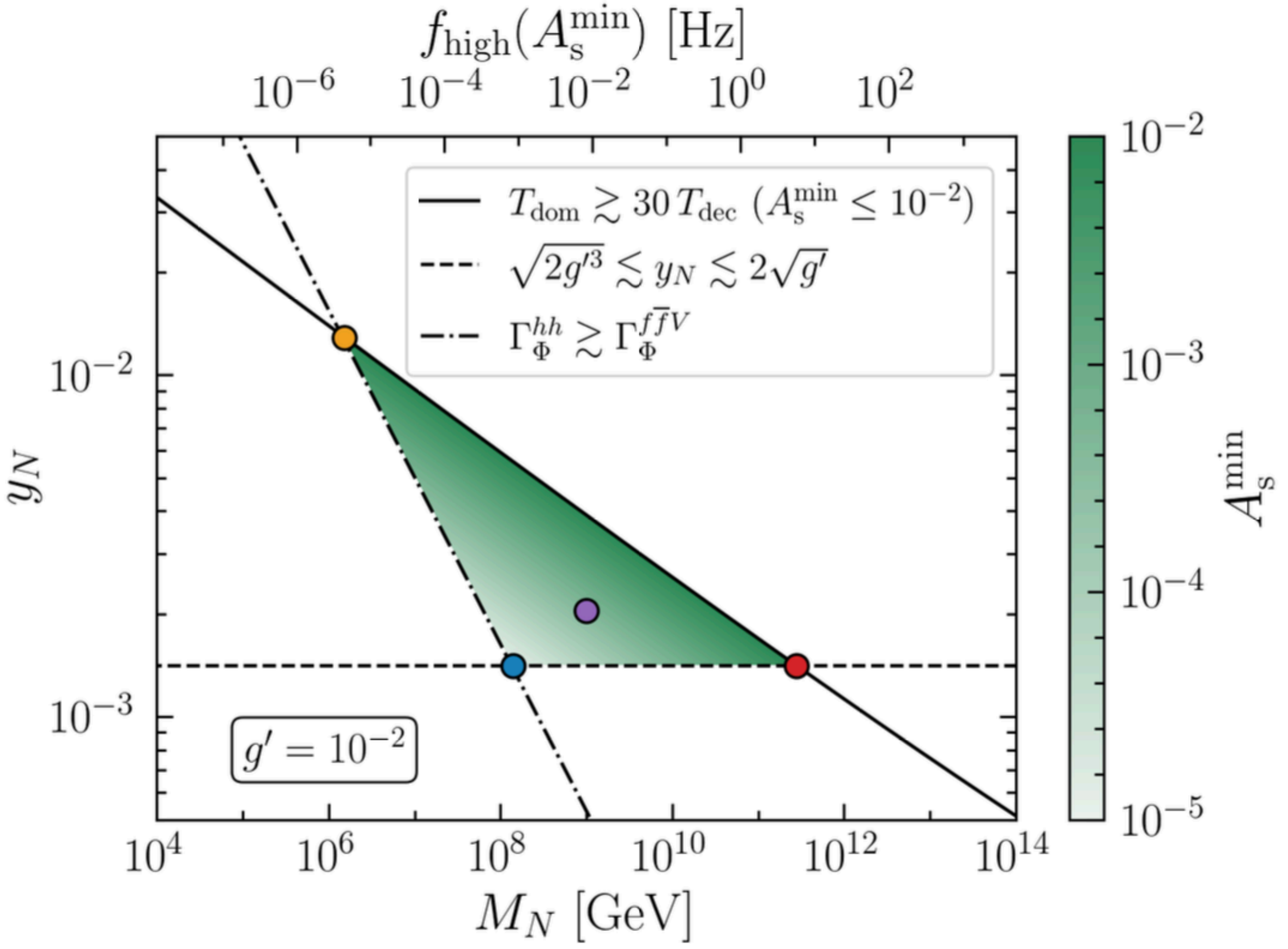


The dashed lines display the extrapolation of the GW spectrum as f^{-1}.

	g'	M_N [GeV]	y_N	A_s
BP1	10^{-2}	1.4×10^8	1.4×10^{-3}	1.18×10^{-5}
BP2	10^{-2}	2.8×10^{11}	1.4×10^{-3}	9.96×10^{-3}
BP3	10^{-2}	1.5×10^6	1.8×10^{-2}	1.00×10^{-2}
BP4	10^{-2}	1.0×10^9	2.0×10^{-3}	4.30×10^{-4}
BP5	10^{-3}	1.0×10^6	1.5×10^{-4}	3.00×10^{-3}

*Chianese, Dom`enech, Papanikolaou, Samanta and **Saviano**, [arXiv:2504.20135 [hep-ph]]*

IGWs from leptogenesis eMD



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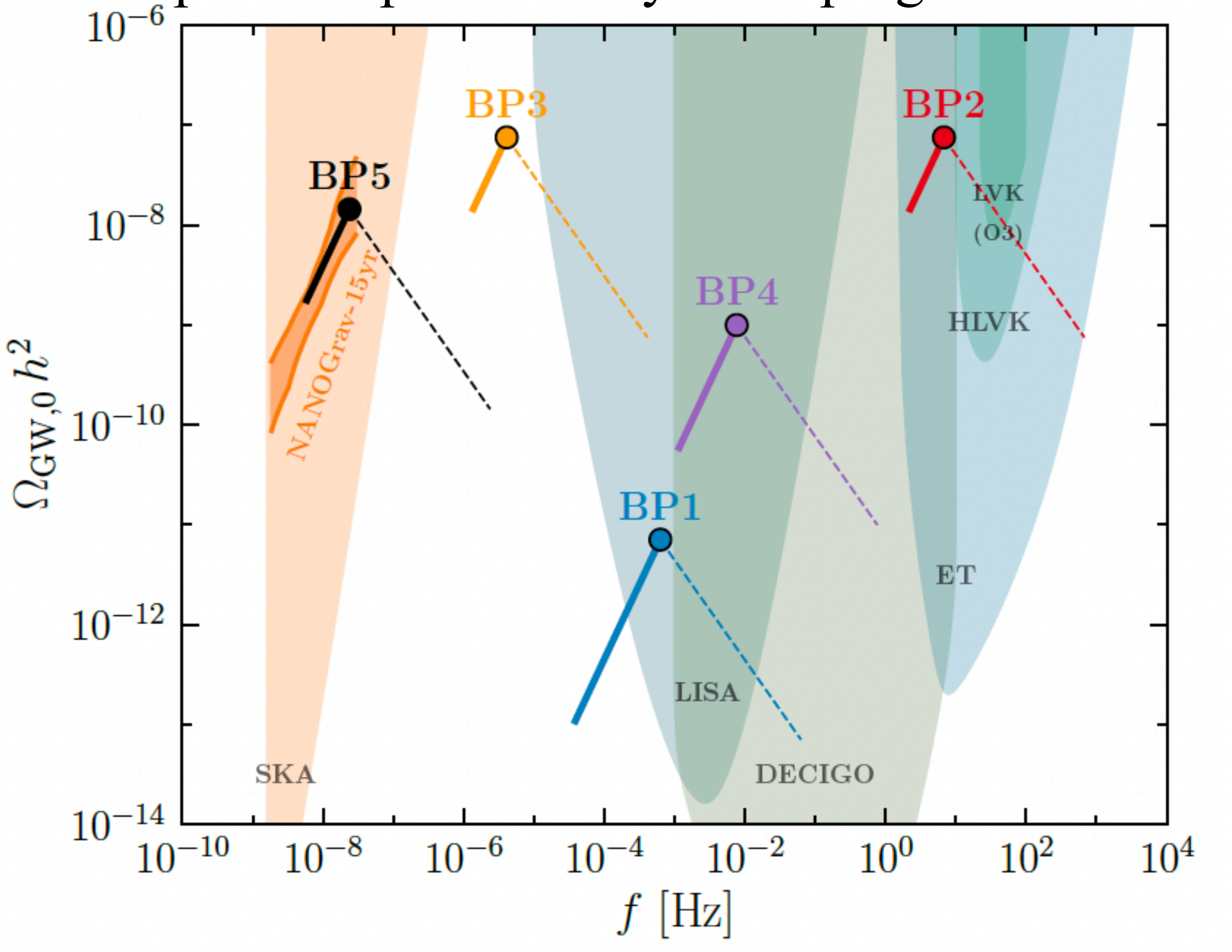
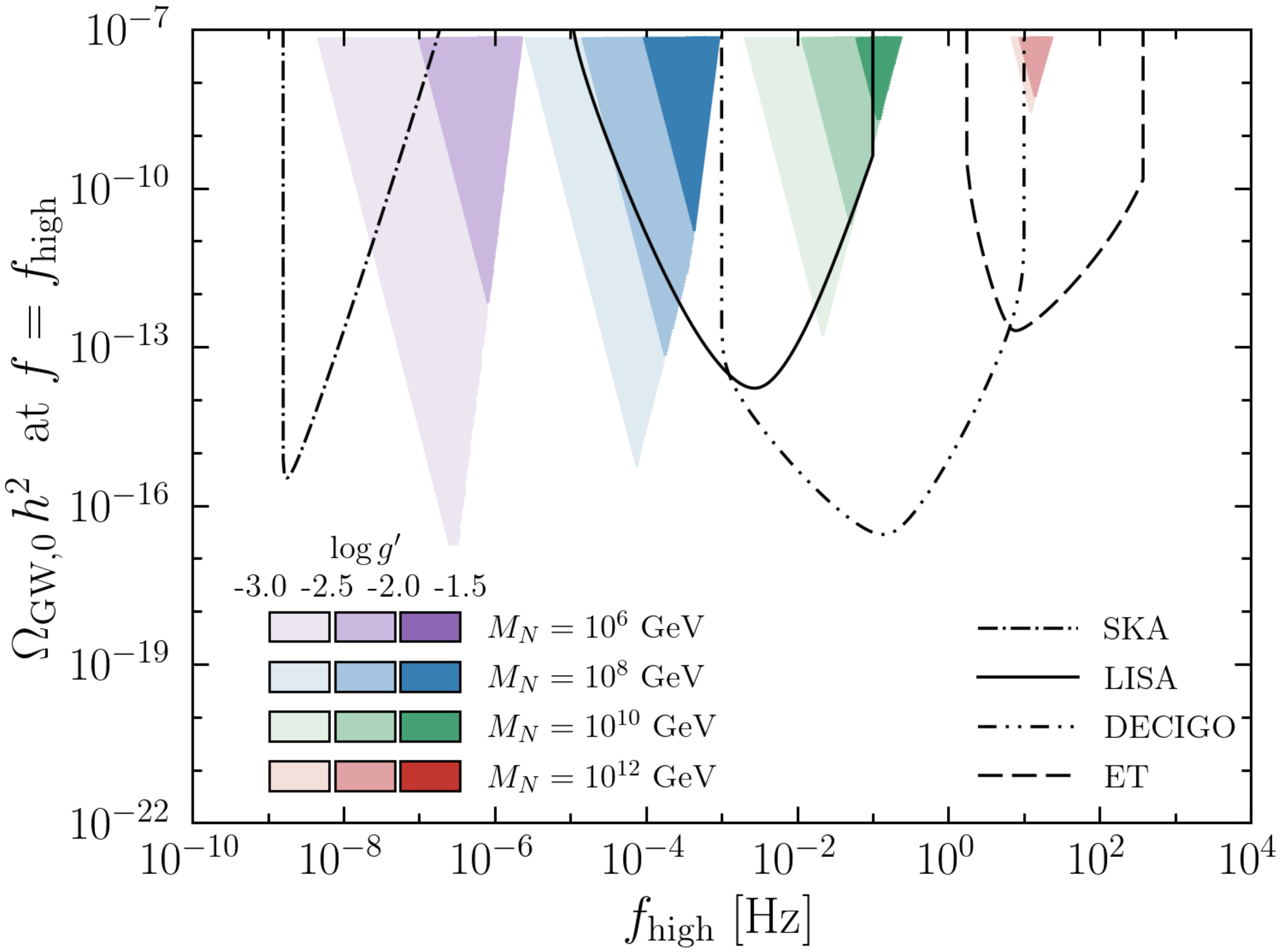


The dashed lines display the extrapolation of the GW spectrum as f^{-1}.

By observing the peak of the IGW spectrum, we can deduce $T_{\rm dec}$ from the peak frequency and so M_N.

*Chianese, Dom`enech, Papanikolaou, Samanta and **Saviano**, [arXiv:2504.20135 [hep-ph]].*

Experimental reach



MAIN RESULTS

- Smaller g' imply longer duration of the eMD and smaller decay temperatures T_{dec}
- Leptogenesis scales M_N <10^{12} GeV have less discovery potential with IGWs owing to the constraint $v_\Phi \leq \Lambda_{GUT}$ and $A_s \leq 10^{-2}$
- Link between leptogenesis models with M_N (10^6 GeV) and the PTA excess

A detection of an IGW background would hint at a particular leptogenesis scale.

*Chianese, Domènech, Papanikolaou, Samanta and **Saviano**, [arXiv:2504.20135 [hep-ph]].*

Conclusions

- **High-scale leptogenesis offers low-energy neutrino phenomenology, which however is not unique, unless the flavor structure of the theory is constrained by invoking symmetries.**

- **In the $U(1)_{B-L}$ leptogenesis model, a feeble Higgs-portal coupling implies a matter-dominated epoch intimately linked to the leptogenesis scale M_N, leading to interesting cosmological consequences.**

- **GWs are produced both by the cosmic strings and by the amplification of primordial density fluctuations during the early matter-dominated era .**

- **Current and future GW experiments provide a robust probe of the flavor regimes of high-scale leptogenesis, with strong complementarity to low-scale neutrino experiments.**

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The $U(1)_{B\text{-}L}$ model

Ultraviolet realization of seesaw models based on the gauge $U(1)_{B\text{-}L}$ symmetry with coupling g', naturally embedded in many Grand Unified Theories (GUTs)

	$U(1)_{B-L}$
L	-1
H	0
N_R	-1
Φ	2

$$-\Delta\mathcal{L} \supset \frac{1}{2} y_N \overline{N_R} \Phi N_R^C + y_D \overline{N_R} \tilde{H}^\dagger L + \frac{1}{4}\lambda_{H\Phi} H^2 \Phi^2 + V(\Phi, T)$$

1. ***$U(1)_{B-L}$ phase transition:*** Φ gets its vev and RHNs become massive

$$\boxed{V(\Phi,T) \to V(\Phi,0) = -\mu^2\Phi^2/2 + \lambda\Phi^4/4} \qquad v_\Phi = \frac{\mu}{\sqrt{\lambda}}, \quad m_\Phi = \sqrt{2\lambda} v_\Phi, \quad M_N = y_N v_\Phi$$

2. ***CP-asymmetrically N_R decay:*** $\boxed{N_R \to LH}$ around $T_{\rm lepto} \sim M_N$

3. ***Electroweak phase transition:*** the SM Higgs get its vev and ν mass generates

$$\boxed{m_\nu = \frac{y_D\, v_H^2}{M_N} \quad \text{(type-I seesaw)}}$$

Davidson PRD 1979; Marshak+ PLB 1980;
Buchmüller+ JCAP 2013; Buchmüller+ PLB 2020; Buchmüller+ JCAP 2023

The U(1)$_{B\text{-}L}$ model

$\Phi = v_\Phi$ Leptogenesis

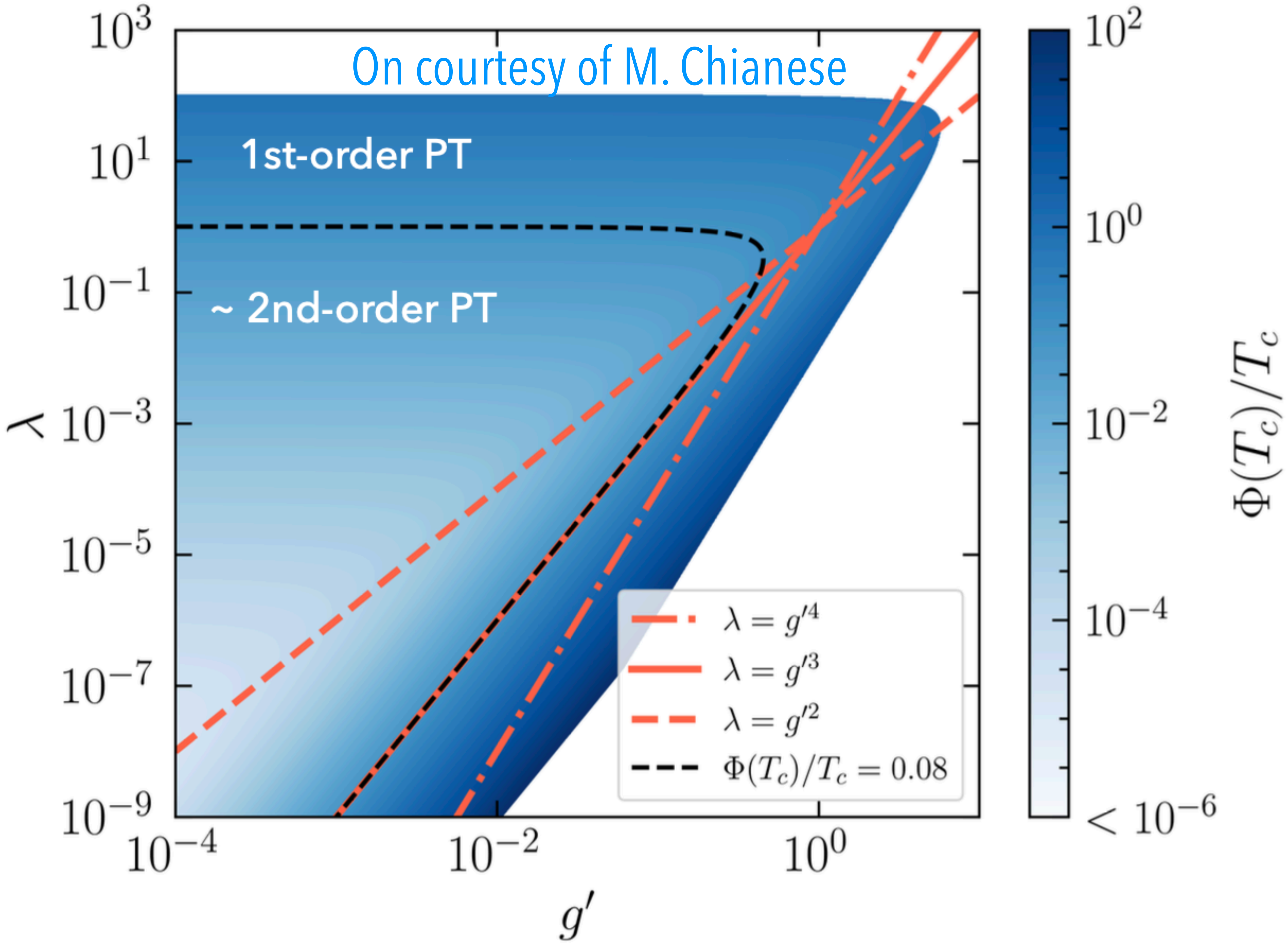
T T_C $T_{lepto} \sim M_N$

- Second-order Phase Transition (PT): the Φ oscillations around v v_Φ behave as a matter field

order parameter $$\frac{\Phi(T_c)}{T_c} \lesssim 0.08 \implies \lambda \sim g'^3$$

- Successful Leptogenesis implies

$$T_{\text{lepto}} \lesssim T_c \implies y_N \lesssim 2\sqrt{g'}$$



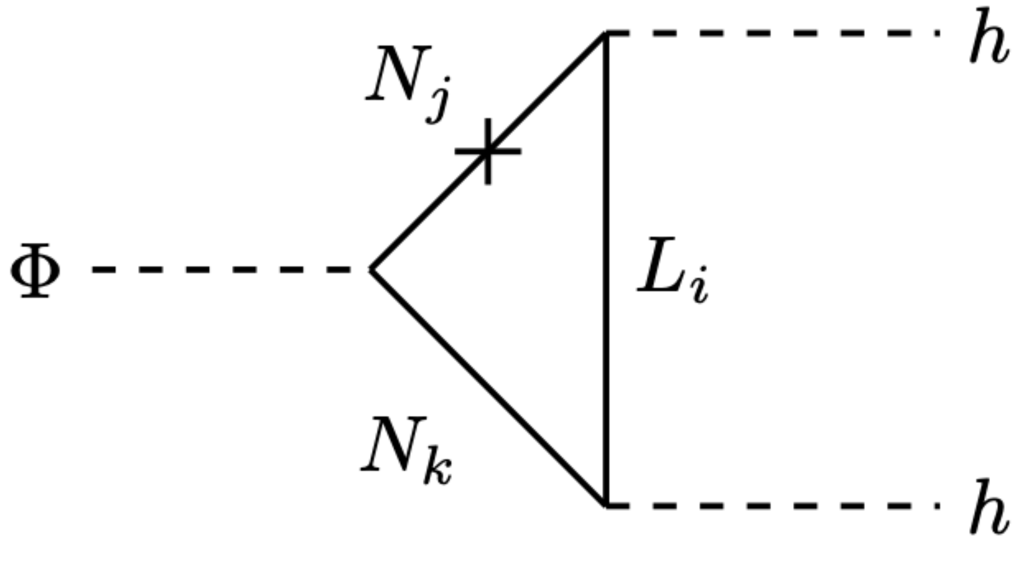
Quiros hep-ph/9901312; Megevand & Ramirez Nucl. Phys. B (2017); Datta & Samanta JHEP (2022

Model constraints

- The scale of leptogenesis is bounded form above as $T_{\rm lepto} \sim M_N \lesssim T_c \simeq 2\sqrt{g'}v_\Phi$

- Φ long-lived to induce a matter- domination epoch: $M_N > m_\Phi = \sqrt{2\lambda}v_\Phi$ (To prevent $(\Phi \to NN)$)

So we identify the following range $m_\Phi < M_N \lesssim T_c \Longrightarrow \sqrt{2g'}g' < y_N \lesssim 2\sqrt{g'}$ with $\lambda = g'^3$



$$\lambda_{\Phi H}^{\text{1-loop}} \sim \frac{y_D^2\, y_N^2}{2\pi^2} \ln\left(\frac{\Lambda_{\rm GUT}}{\Lambda}\right)$$

with $y_D = \sqrt{\frac{m_\nu\, y_N\, v_\Phi}{v_h^2}}$

Model constraints (other decay channels)

$\Phi \to HH \Longrightarrow \lambda_{H\Phi}^{\text{1-loop}} > \lambda_{H\Phi}^{\text{tree}}$

$\Phi \to NN$

$\Longrightarrow$ forbidden if $y_N \gtrsim \sqrt{2g'}$

$\Phi \to Z'Z'$

$\Phi \to f\bar{f}V \Longrightarrow \Gamma_\Phi^{hh} \gtrsim \Gamma_\Phi^{ffV}$

$\lambda \simeq g'^3$ to obtain an insignificant barrier height so that the field rolls smoothly to its minimum.
A smooth transition can be only obtained for $\lambda \sim g'^n$ with $n \lesssim 3$, while higher powers $n > 3$ would increase the barrier height.
For $n < 3$, the parameter space becomes more restricted by the following constraints:
i) to avoid a second period of inflation,
ii) to forbid $\Phi \to Z'Z'$ and $\Phi \to f\bar{f}V$

GW Spectrum from cosmic string

Total energy loss from a loop decomposed into a set of normal-mode oscillations with frequencies

$$f_k = 2k/l_k = a(t_0)/a(t)f$$

k=1,2,3..k_{max}, $f=f(t_0)$, l = size of the radiating loop

Total GW energy density is computed by summing all the k modes:

emitted power in the k-th mode

$$\boxed{\Omega_{\mathrm{GW}} = \sum_{k=1}^{k_{\max}} \frac{2k\mathcal{F}_\alpha G\mu^2\Gamma_k}{f\rho_c} \int_{t_i}^{t_0} \left[\frac{a(t)}{a(t_0)}\right]^5 n_\omega(t, l_k)\mathrm{d}t}$$

string tension

loop number density

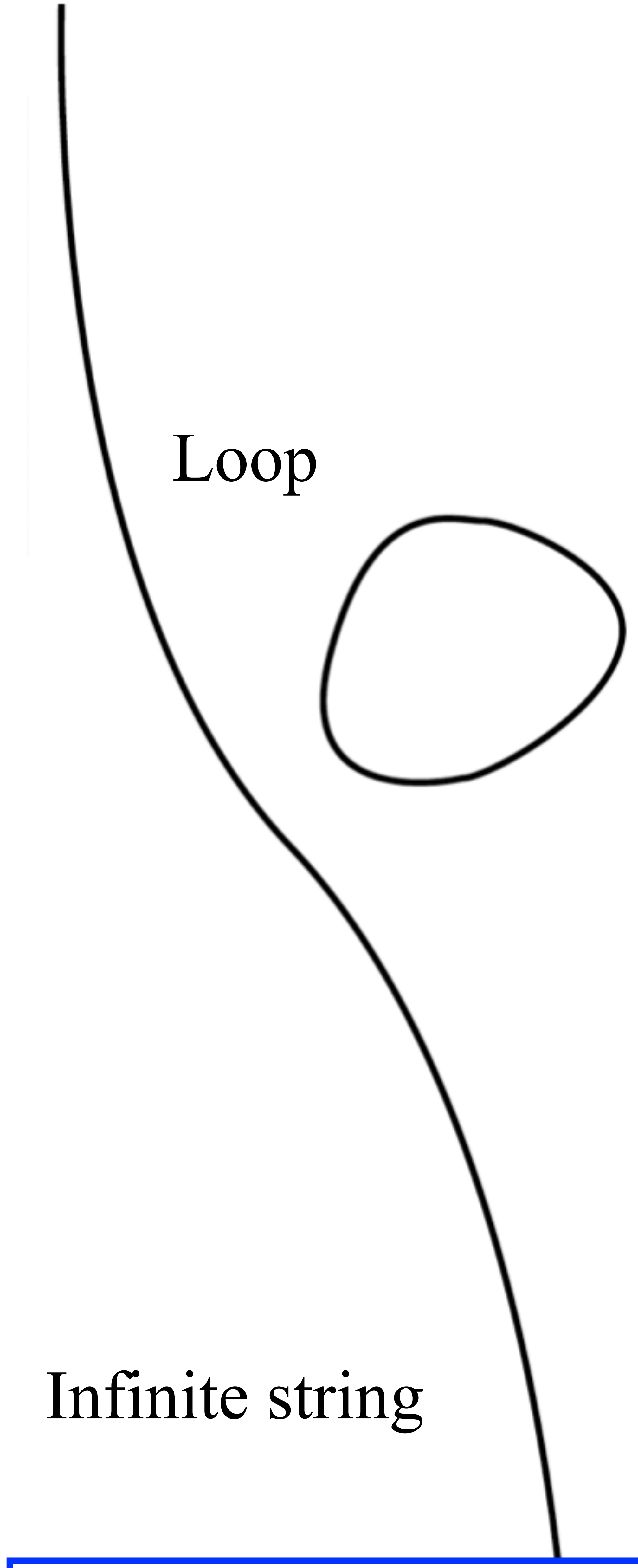
Scale-invariant plateau

$$\Omega^{\mathrm{plt}}_{\mathrm{GW}} \propto \sqrt{\mu} = \sqrt{\frac{\pi v_\Phi^2}{\ln(2g'^2/\lambda)}}$$

$$f_{\mathrm{dec}} \simeq 0.45\,\mathrm{Hz}\left(\frac{10^{-12}}{G\mu}\right)^{1/2}\left(\frac{T_{\mathrm{dec}}}{\mathrm{GeV}}\right)$$

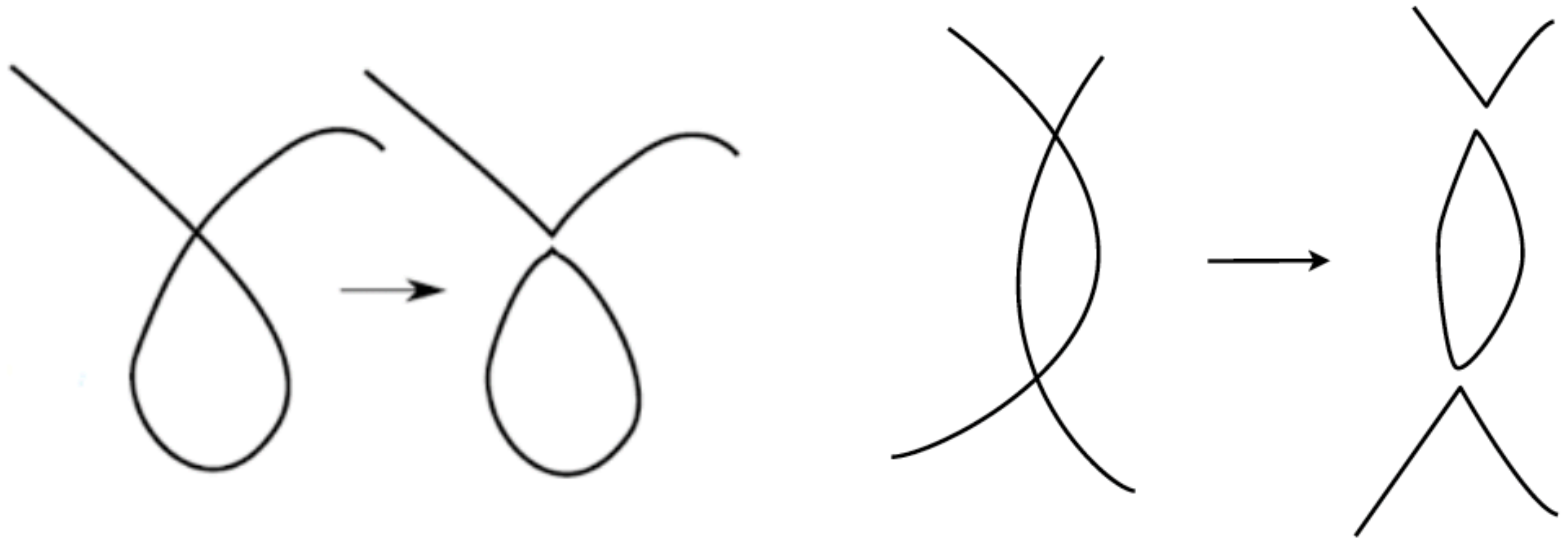
Decay of the scalar field

Evolution of Cosmic Strings



- ***"Stretching " by cosmological expansion***

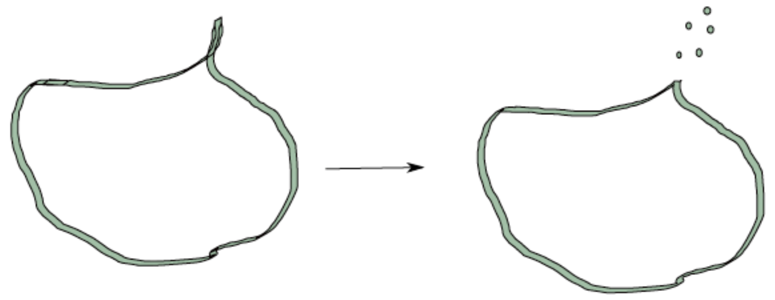
•Intercommute and create loops:



•Wiggle and emit radiation

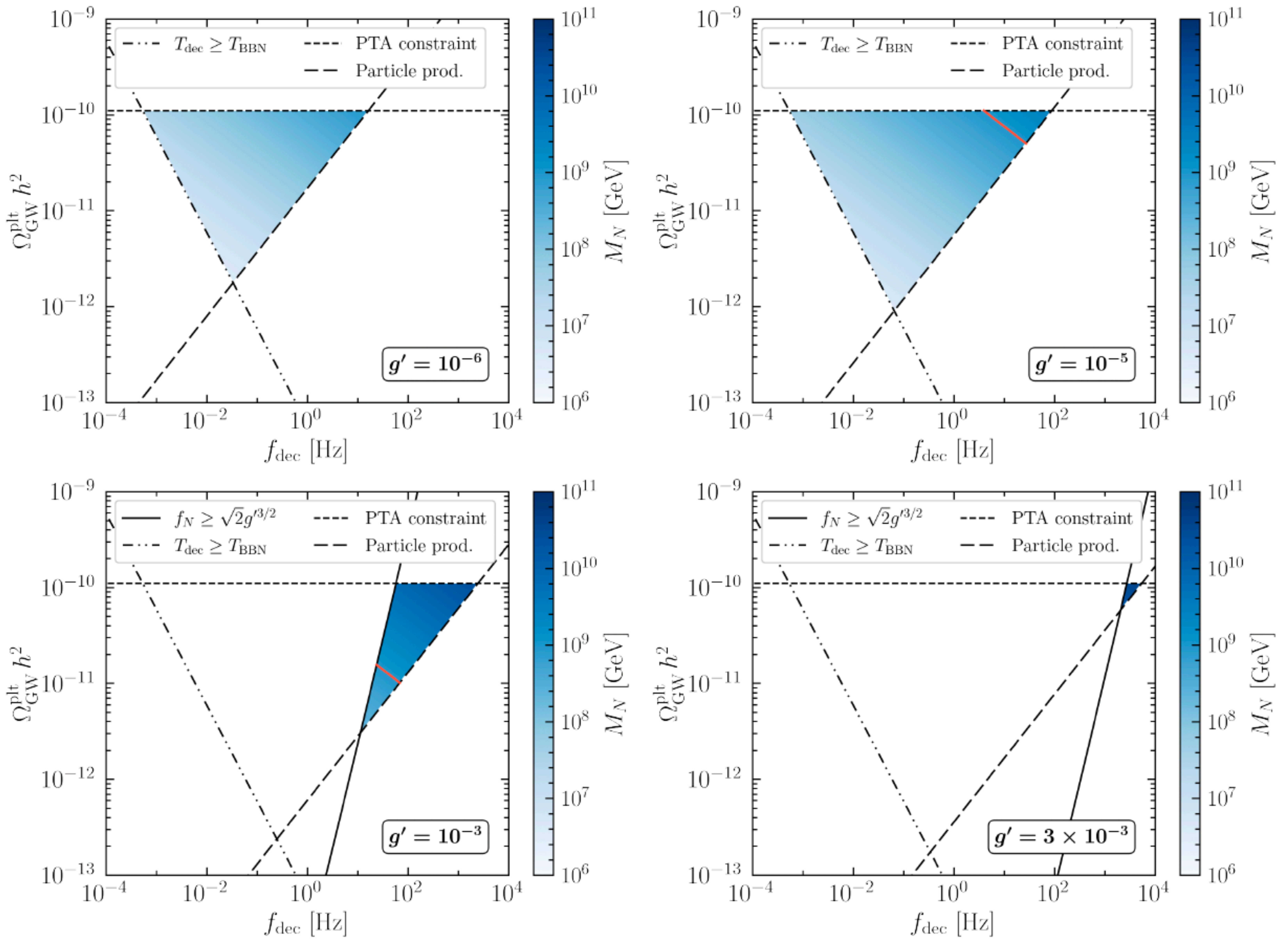
GWs:

Particles:



We focus on GW radiated from cosmic string loops cut from the long strings produced by the spontaneous $U(1)_{B-L}$

IMPACT OF THE g′ ON THE GWFRL WINDOW (Cosmic string)



We find that the largest allowed ranges of the spectral break frequency and the GW plateau amplitude are robust against different choices of g’

This justifies our definition of the GWFRL window as:

$$10^{-3} \lesssim f_{\rm dec}/{\rm Hz} \lesssim 10^{3}$$

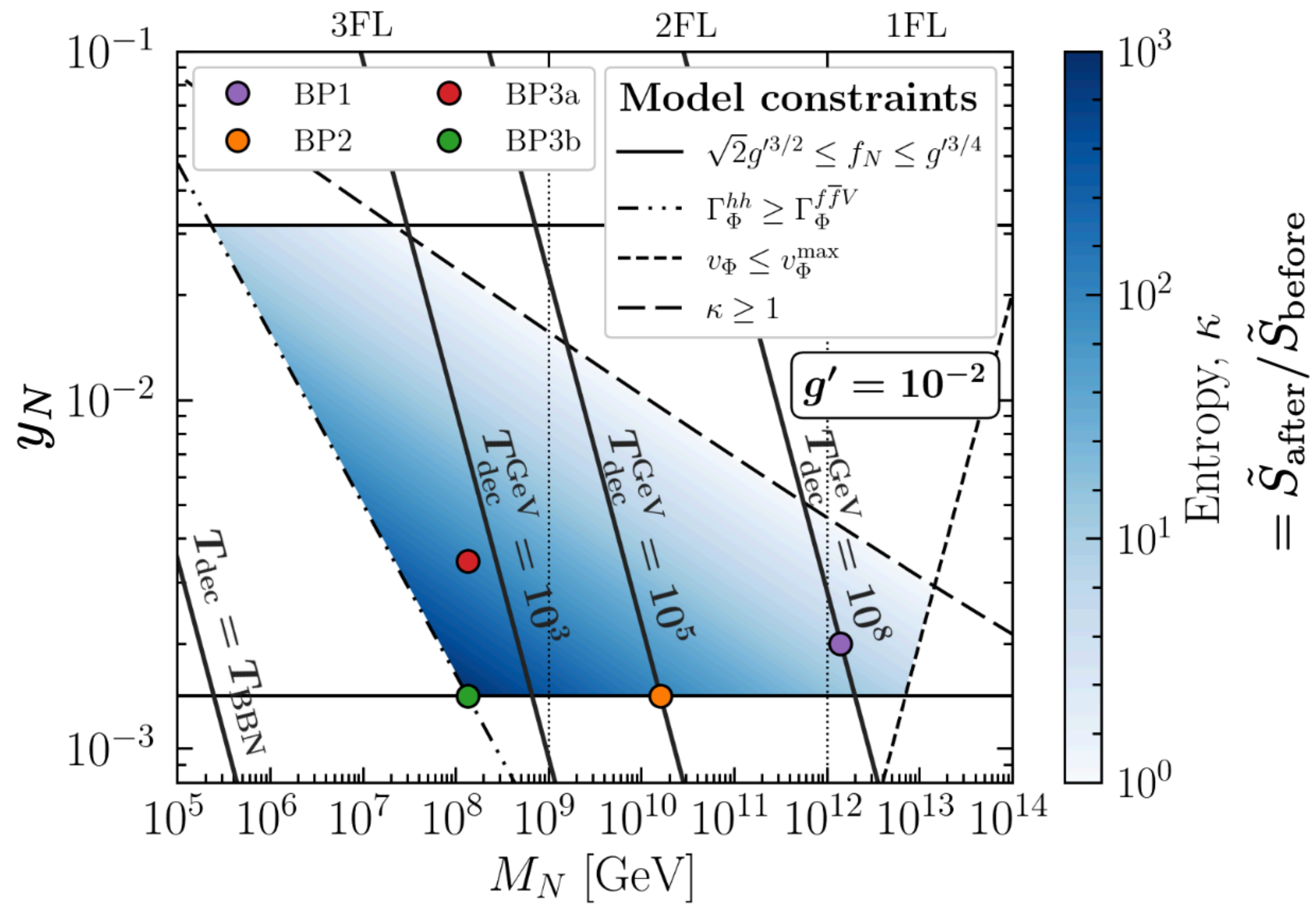
$$10^{-13} \lesssim \Omega_{\rm GW}^{\rm plt} h^2 \lesssim 10^{-10}$$

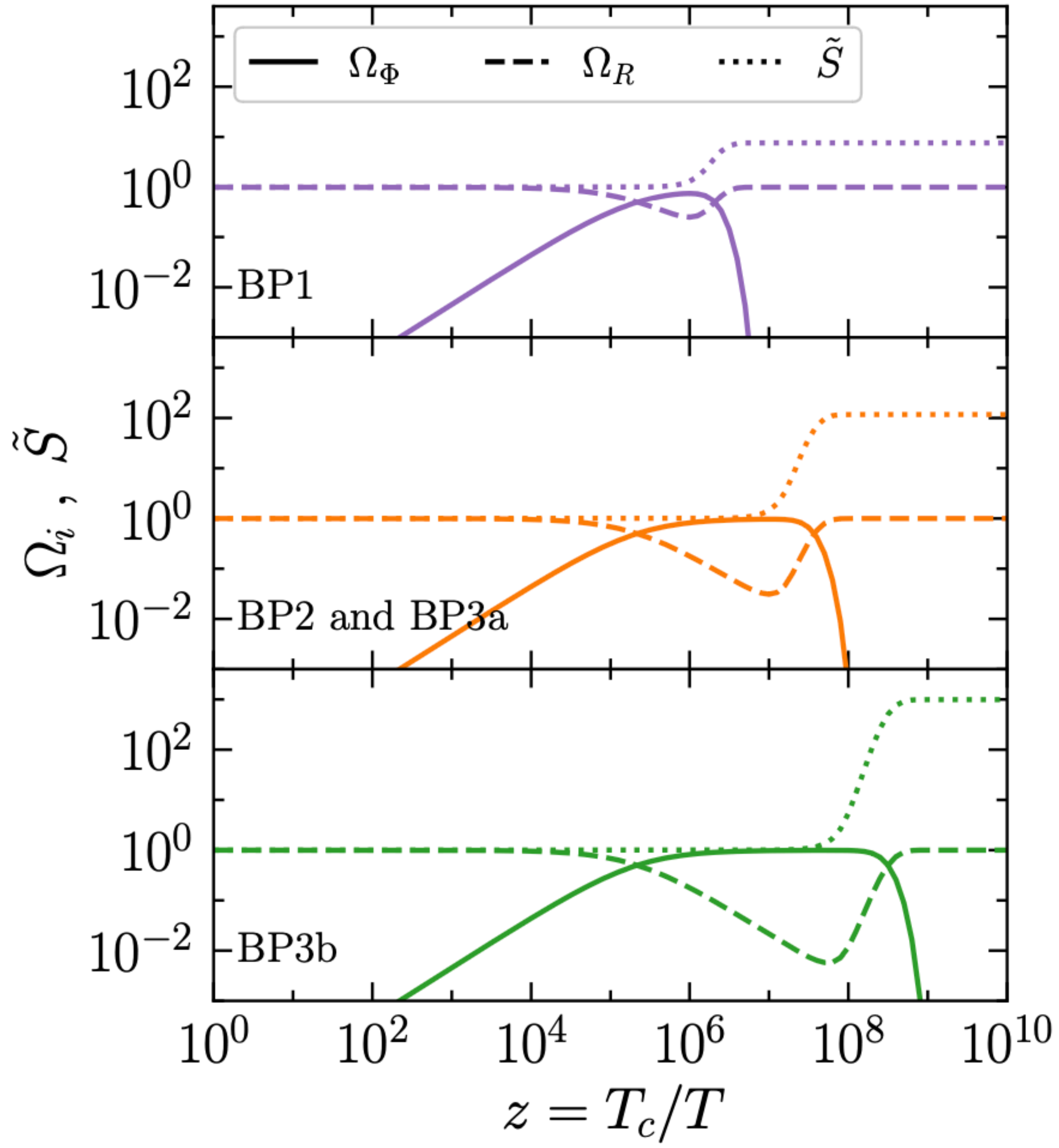
3D parameter space and entropy production

The scalar field Φ with initial vacuum energy $\rho_\Phi\,(T_c) \simeq \lambda v_\Phi^4/4$ dominates the energy density for a period, and injects entropy as it decays.

We account for this effect by solving the Friedmann equations

The model is determined by the three parameters $\{g',\, M_N,\, y_N\}$





$$\Omega_i = \rho_i/\rho_{\rm tot}$$

Entropy dilution of BAU by a factor of $\kappa \sim T_{\rm dec}/T_{\rm dom}$

The length of the eMD phase must be long enough for non-linearities to develop ➡️ the lower the As, the longer the eMD must be, and the smaller the allowed parameter space is. The parameter space closes at As = Amin

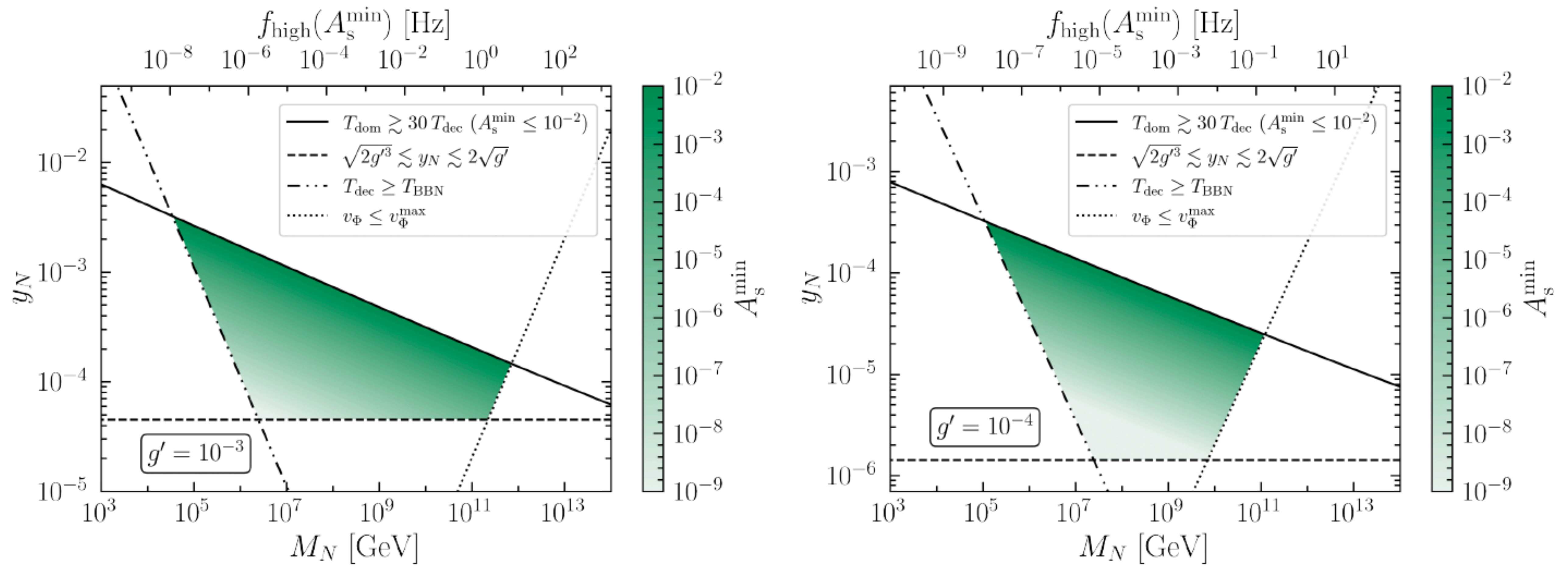


FIG. S1. Allowed parameter space for smaller g' values, specifically $g' = 10^{-3}$ (left) $g' = 10^{-4}$ (right). The rest of the description remains the same as in Fig. 1, barring the appearance of $T_{\rm dec} \gtrsim T_{\rm BBN}$ and $v_\Phi \lesssim v_\Phi^{\rm max}$ constraints in both the plots. In both panels of Fig. S1, the minimum values of $A_s^{\rm min}$ appear similar due to the constraint imposed in the parameter scan, namely $A_s \in [\max(10^{-9}, A_s^{\rm min}), 10^{-2}]$.

Decreasing g′ opens the allowed parameter space to lower values of y_N and M_N. It also extends the compatible parameter space to lower values of f_{high} and $A_{min}s$.

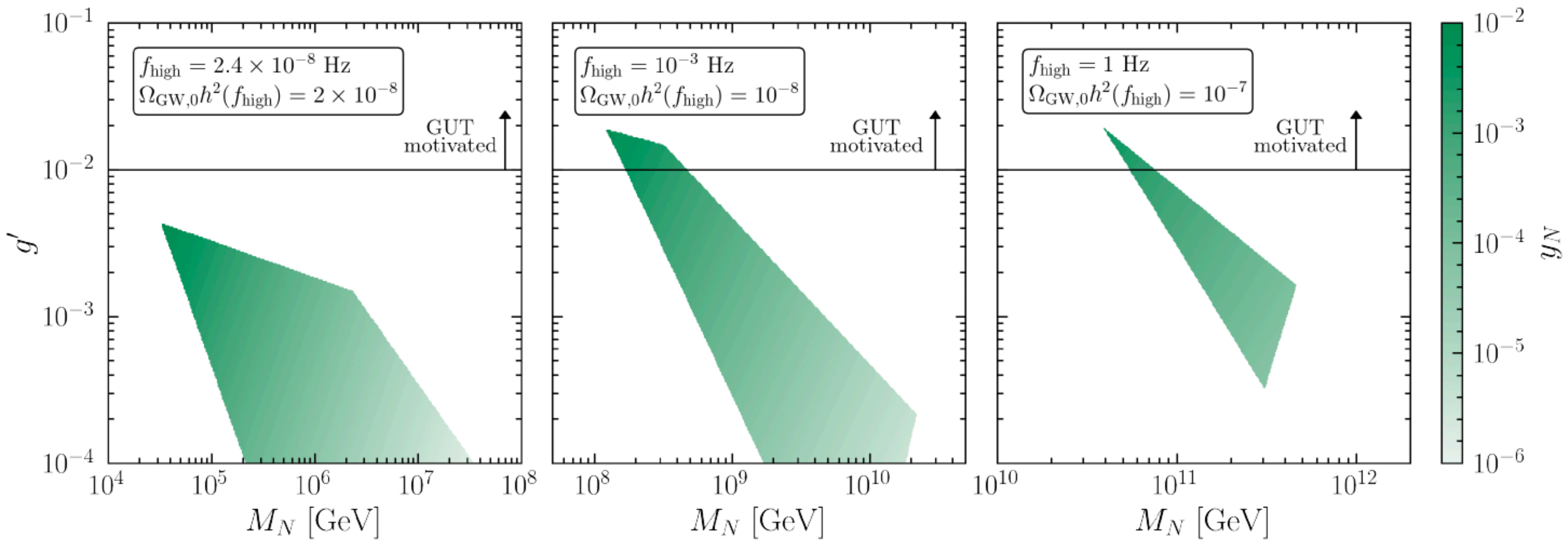


FIG. S2. Allowed parameter space in g'–M_N plane with a color gradient representing y_N, for three benchmark pairs of $(\Omega_{\rm GW}, f_{\rm high})$ across different frequency bands. These plots illustrate that, as g' increases, the mapping of the leptogenesis scale onto the peak GW frequency becomes increasingly sharp.

For larger g′ and for higher f_{high}, the mapping of M_N onto f_{high} becomes tighter →

- For sufficiently large g′, well-separated leptogenesis scales can be resolved through features in the GW frequency spectrum.

- In the opposite case, the parameter space becomes more degenerate for smaller values of g′ and lower f_{high}

Formation of PBHs

A sufficiently large spectrum of primordial fluctuations could trigger formation of PBHs.

- The mass of the resulting PBHs is given by the mass inside a Hubble volume when a given fluctuation with wavenumber k enters the Hubble radius

$$\boxed{M_{\rm PBH} = \gamma M_{\rm dec} \left(\frac{k}{k_{\rm dec}}\right)^{-3}}$$

$$k_{\rm dec} = a(T_{\rm dec}) H(T_{\rm dec})$$

$$M_{\rm dec} = 5 \times 10^{-10} M_\odot \left(\frac{g_\rho}{106.75}\right)^{-1/2} \left(\frac{T_{\rm dec}}{10^4 {\rm GeV}}\right)^{-2}$$

For a scale-invariant spectrum, we expect PBH formation from k = kdom to k = kdec

We focus on the maximum PBH mass generated: $M_{\rm PBH}^{\rm Max} = M_{\rm dec}$ where $10\,{\rm MeV} < T_{\rm dec} < 10^7\,{\rm GeV}$

PBHs are always relatively light if they form, except for the lowest decay temperatures

$$M_{\rm PBH}^{\rm Max}(T_{\rm dec} = 10^7\,{\rm GeV}) = 10^{-16}\,M_\odot \qquad M_{\rm PBH}^{\rm Max}(T_{\rm dec} = 10\,{\rm MeV}) = 300\,M_\odot$$

- We estimate the fraction of PBHs as dark matter today to be $\boxed{f_{\rm PBH} \approx 2 \times 10^{13}\,\beta \left(\frac{g_\rho}{g_s}\right) \left(\frac{T_{\rm dec}}{10^4 {\rm GeV}}\right),}$

where $\beta \approx 5.7 \times 10^{-4}\,A_s^{5/2}$ for $10^{-4} < A_s < 0.25.$

For As < 10−4, angular momentum during collapse becomes important and can prevent collapse