Induced gravitational waves as cosmic tracers of leptogenesis

2504.20135 - M. Chianese, G. Domenech, **T. Papanikolaou**, S. Rome, N. Saviano

Theodoros Papanikolaou

Gravitational Wave Probes of Physics Beyond Standard Model 4,
Faculty of Physics, University of Warsaw, 25/06/2025

SSM Scuola Superiore Meridionale

Leptogenesis

- Leptogenesis is a 2-step process [M. Fukugita & T. Yanagida - 1986]

Leptogenesis

- Leptogenesis is a 2-step process [M. Fukugita & T. Yanagida - 1986]

Lepton asymmetry $\Rightarrow$ **Sphalerons** $\Rightarrow$ Baryon Asymmetry

[V. A. Kuzmin et al. - 1986]

Leptogenesis

- Leptogenesis is a 2-step process [M. Fukugita & T. Yanagida - 1986]

Lepton asymmetry ⇒ **Sphalerons** ⇒ Baryon Asymmetry

[V. A. Kuzmin et al. - 1986]

- Lepton Asymmetry through the **Seesaw Mechanism**

[Yanagida - 1979, Glashow - 1979, Gell-Mann et al. - 1980, Mohapatra & Senjanovic - 1980]

Leptogenesis

- Leptogenesis is a 2-step process [M. Fukugita & T. Yanagida - 1986]

Lepton asymmetry $\Rightarrow$ **Sphalerons** $\Rightarrow$ Baryon Asymmetry

[V. A. Kuzmin et al. - 1986]

- Lepton Asymmetry through the **Seesaw Mechanism**

[Yanagida - 1979, Glashow - 1979, Gell-Mann et al. - 1980, Mohapatra & Senjanovic - 1980]

- Lepton asymmetry is produced at $T \sim M_N$, where $M_N \in [\mathrm{MeV}, 10^{15}\mathrm{GeV}]$.

Leptogenesis

- Leptogenesis is a 2-step process [M. Fukugita & T. Yanagida - 1986]

Lepton asymmetry $\Rightarrow$ **Sphalerons** $\Rightarrow$ Baryon Asymmetry

[V. A. Kuzmin et al. - 1986]

- Lepton Asymmetry through the **Seesaw Mechanism**

[Yanagida - 1979, Glashow - 1979, Gell-Mann et al. - 1980, Mohapatra & Senjanovic - 1980]

- Lepton asymmetry is produced at $T \sim M_N$, where $M_N \in [\mathrm{MeV}, 10^{15}\mathrm{GeV}]$.

- **Scales** $M_N > \mathcal{O}(\mathrm{TeV})$ are **not reachable by colliders.**

Distinct Flavor Regimes of High-Scale Leptonesis: $|L_i> = A_{i\alpha}|L_\alpha>$, where $\alpha = e, \mu, \tau$

$M_N<10^9$ GeV	$10^9 < M_N<10^{12}$ GeV	$>10^{12}$ GeV
Three-flavor (3FL)	**Two-flavor (2FL)**	**One-flavor (1FL) /vanilla regime**

M_N

the rates of processes mediated by the τ and μ Yukawa coupling are non negligible—> effects of lepton flavors must be taken into account

no charged lepton flavour effects—> no sensitivity to the neutrino mixing matrix: mixing angles and low-energy CP phases.

While the 1FL regime is not sensitive to neutrino mixing parameters, the 2FL and 3FL regimes can offer low-energy neutrino phenomenology, which however may not be unequivocal, unless the flavor structure of the theory is constrained by invoking symmetries.

cannot be tested by terrestrial experiments !!

It is therefore necessary to find other evidence to test the neutrino sector.

[Credits to N. Saviano]

Our leptogenesis scenario

Our leptogenesis scenario

- UV realisation of Type I seesaw mechanism based on $U(1)_{B-L}$ symmetry with gauge coupling g', naturally embedded to GUTs.

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

Our leptogenesis scenario

- UV realisation of Type I seesaw mechanism based on $U(1)_{B-L}$ symmetry with coupling g', naturally embedded to GUTs.

$$-\Delta\mathscr{L} \subset \frac{1}{2}y_N\overline{N_R}\underbrace{\Phi N_R^C + y_D\overline{N_R}}_{M_N,\, m_{\nu_i}}\tilde{H}^\dagger L + \frac{1}{4}\lambda_{H\Phi}H^2\Phi^2 + V(\Phi, T)$$

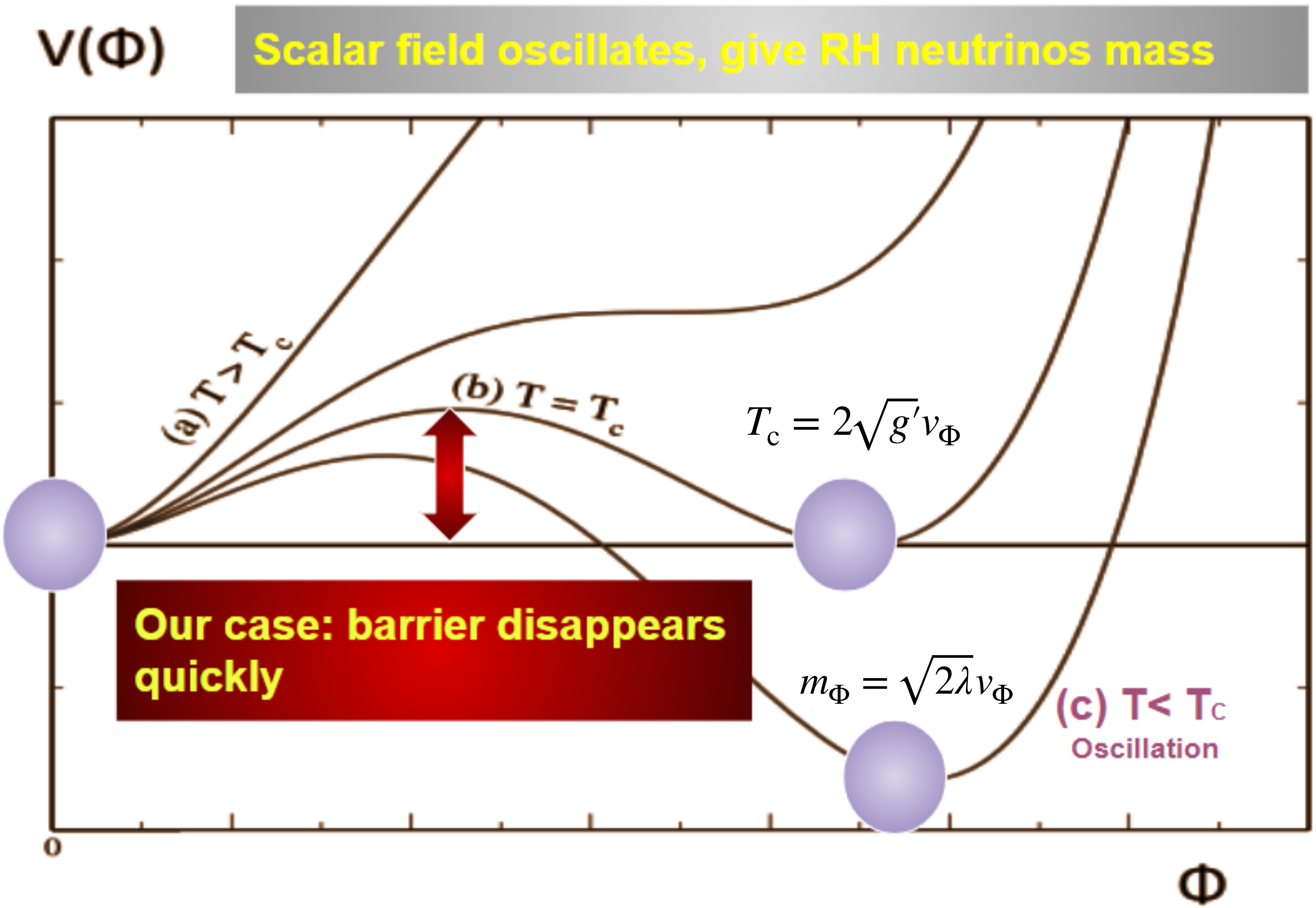
Our leptogenesis scenario

- UV realisation of Type I seesaw mechanism based on $U(1)_{B-L}$ symmetry with gauge coupling g', naturally embedded to GUTs.

$$-\Delta\mathscr{L} \subset \frac{1}{2} y_N \underbrace{\overline{N_R}\Phi N_R^C + y_D \overline{N_R}}_{M_N,\, m_{\nu_i}} \tilde{H}^\dagger L + \frac{1}{4} \underbrace{\lambda_{H\Phi}}_{\text{Decay of } \Phi} H^2 \Phi^2 + V(\Phi, T)$$

Our leptogenesis scenario

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

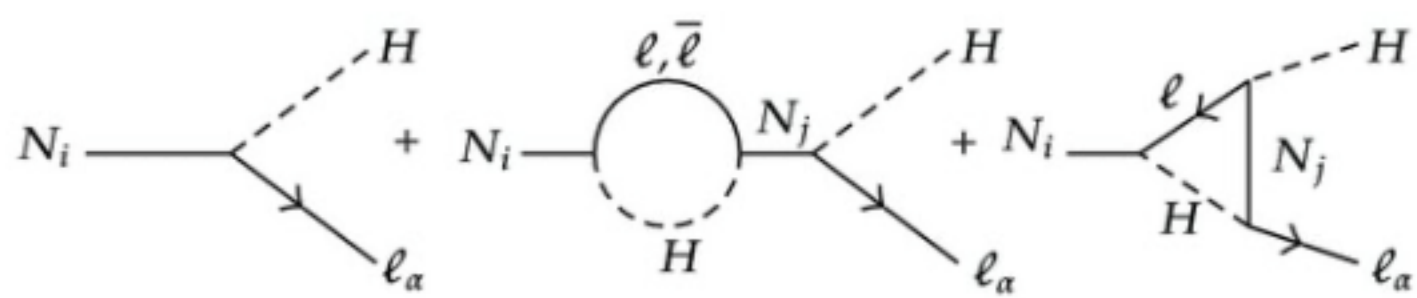


Our leptogenesis scenario

- UV realisation of Type-I seesaw mechanism based on $U(1)_{B-L}$ symmetry with coupling g', naturally embedded to GUTs.

$$-\Delta\mathscr{L} \subset \frac{1}{2} y_N \underbrace{\overline{N_R}\Phi N_R^C + y_D \overline{N_R}}_{M_N,\, m_{\nu_i}} \tilde{H}^\dagger L + \frac{1}{4} \underbrace{\lambda_{H\Phi}}_{\text{Decay of }\Phi} H^2 \Phi^2 + V(\Phi, T)$$

- At that time, **right-handed neutrinos (RHNs) become massive** with $M_N = y_N v_\Phi$, decaying **later CP-asymmetrically into lepton doublets and Higgs bosons** and producing the **lepton asymmetry around $T_{\rm lepto} \sim M_N$.**



Our leptogenesis scenario

- UV realisation of Type-I seesaw mechanism based on $U(1)_{B-L}$ symmetry with coupling g', naturally embedded to GUTs.

$$-\Delta\mathscr{L} \subset \frac{1}{2} y_N \underbrace{\overline{N_R}\Phi N_R^C + y_D \overline{N_R}}_{M_N,\, m_{\nu_i}} \tilde{H}^\dagger L + \frac{1}{4} \underbrace{\lambda_{H\Phi}}_{\text{Decay of } \Phi} H^2 \Phi^2 + V(\Phi, T)$$

- Later at $T_{\rm dom} < M_N$, Φ **dominates triggering an early matter-dominated (eMD) era.**

Our leptogenesis scenario

- UV realisation of Type-I seesaw mechanism based on $U(1)_{B-L}$ symmetry with coupling g', naturally embedded to GUTs.

$$-\Delta\mathscr{L} \subset \frac{1}{2}y_N\underbrace{\overline{N_R}\Phi N_R^C + y_D\overline{N_R}}_{M_N,\, m_{\nu_i}}\tilde{H}^\dagger L + \frac{1}{4}\underbrace{\lambda_{H\Phi}}_{\text{Decay of }\Phi}H^2\Phi^2 + V(\Phi, T)$$

- Later at $T_{\rm dom} < M_N$, Φ **dominates triggering an early matter-dominated (eMD) era.**

- **Once the SM Higgs takes its vev** $v_h = 174\mathrm{GeV}$ at the electroweak (EW) phase transition, **light neutrinos become massive** $m_{\nu_i} \sim y_D^2 v_h^2/M_N$ via the Type-I seesaw mechanism.

Our leptogenesis scenario

- UV realisation of Type-I seesaw mechanism based on $U(1)_{B-L}$ symmetry with coupling g', naturally embedded to GUTs.

$$-\Delta\mathscr{L} \subset \frac{1}{2}y_N\underbrace{\overline{N_R}\Phi N_R^C + y_D\overline{N_R}}_{M_N,\, m_{\nu_i}}\tilde{H}^\dagger L + \frac{1}{4}\underbrace{\lambda_{H\Phi}}_{\text{Decay of }\Phi}H^2\Phi^2 + V(\Phi, T)$$

- Later at $T_{\mathrm{dom}} < M_N$, Φ **dominates triggering an early matter-dominated (eMD) era.**

- **Once the SM Higgs takes its vev** $v_h = 174\mathrm{GeV}$ at the electroweak (EW) phase transition, **light neutrinos become massive** $m_{\nu_i} \sim y_D^2 v_h^2 / M_N$ via the Type-I seesaw mechanism.

- Finally, the early matter-dominated **(eMD) era triggered by Φ ends through the decay channel $\Phi \to hh$.**

Long lived Φ

The parameter space (M_N, y_N, g')

- In order to make Φ long lived one should require that $\Phi \to Z'Z'$ and $\Phi \to NN$ are kinematically forbidden leading to

The parameter space (M_N, y_N, g')

- In order to make Φ long lived one should require that $\Phi \to Z'Z'$ and $\Phi \to NN$ are kinematically forbidden leading to

$$M_{Z'} = \sqrt{2}g'v_\Phi > m_\Phi \Rightarrow \boxed{g' < 1} \quad \text{and} \quad M_N = y_N v_\Phi > m_\Phi = \sqrt{2\lambda}v_\Phi \Rightarrow \boxed{y_N > \sqrt{2g'^3}\,.}$$

The parameter space (M_N, y_N, g')

- In order to make Φ long lived one should require that $\Phi \to Z'Z'$ and $\Phi \to NN$ are kinematically forbidden leading to

$$M_{Z'} = \sqrt{2}g'v_\Phi > m_\Phi \Rightarrow \boxed{g' < 1} \quad \text{and} \quad M_N = y_N v_\Phi > m_\Phi = \sqrt{2\lambda}v_\Phi \Rightarrow \boxed{y_N > \sqrt{2g'^3}}.$$

- One should also account for the competitive channel $\Phi \to f\bar{f}V$ requiring that $\boxed{\Gamma_\Phi^{hh}(M_N, y_N, g') \geq \Gamma_\Phi^{f\bar{f}V}(M_N, y_N, g').}$

The parameter space (M_N, y_N, g')

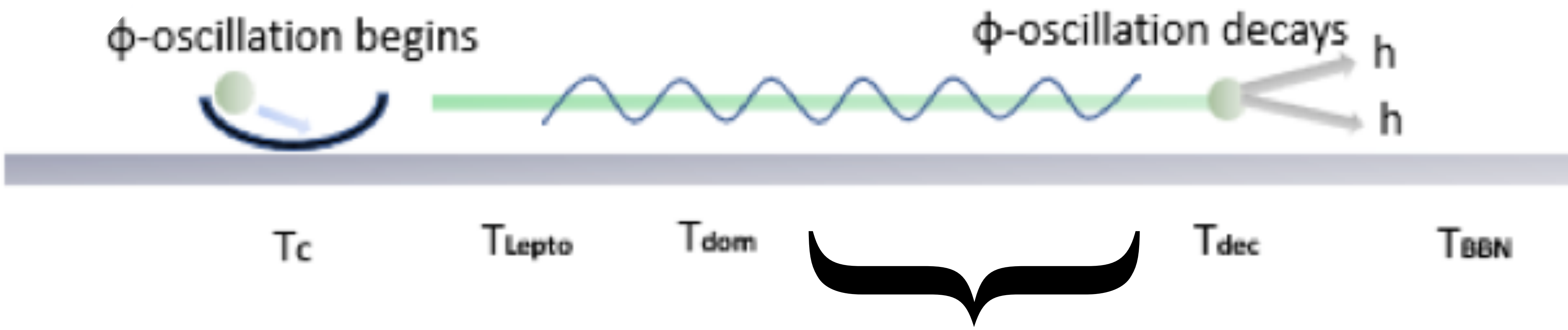
- In order to make Φ long lived one should require that $\Phi \to Z'Z'$ and $\Phi \to NN$ are kinematically forbidden leading to

$$M_{Z'} = \sqrt{2}g'v_\Phi > m_\Phi \Rightarrow \boxed{g' < 1} \quad \text{and} \quad M_N = y_N v_\Phi > m_\Phi = \sqrt{2\lambda}v_\Phi \Rightarrow \boxed{y_N > \sqrt{2g'^3}\,.}$$

- One should also account for the competitive channel $\Phi \to f\bar{f}V$ requiring that $\boxed{\Gamma_\Phi^{hh}(M_N, y_N, g') \geq \Gamma_\Phi^{f\bar{f}V}(M_N, y_N, g')\,.}$

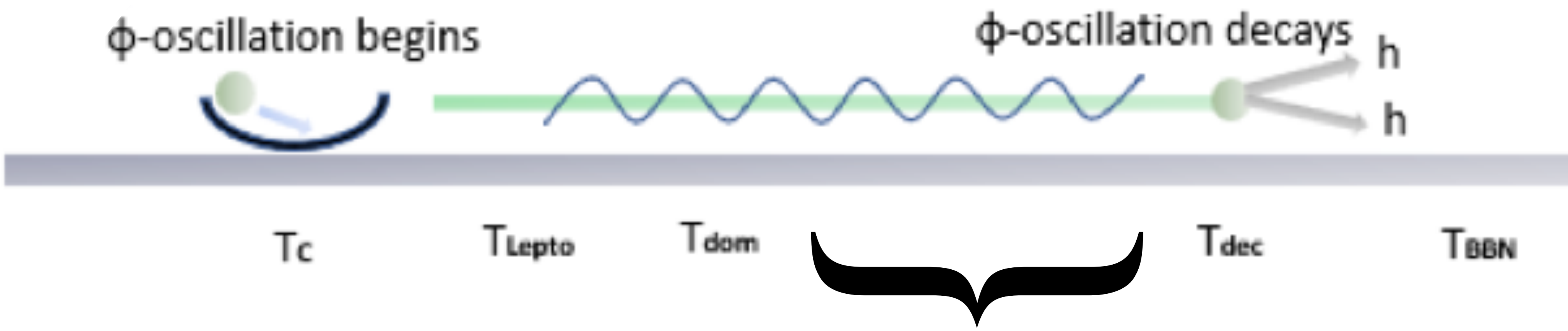
- Finally, one should require the lepton asymmetry takes place at $T_{\rm lepto} \sim M_N < T_c = 2\sqrt{g'}v_\Phi \;\; \Rightarrow \boxed{y_N < 2\sqrt{g'}\,.}$

The overall picture



Φ-driven eMD era

The overall picture



Φ-driven eMD era

What is the GW phenomenology of such an eMD era?

Induced GWs

Induced GWs

- **Primordial induced GWs** are generated through second order gravitational effects: $\mathscr{L}^{(3)}_{\Psi,h} \ni h\Psi^2$ [S. Matarrese et al. - 1993, 1994, 1998, G. Domenech - 2021].

Induced GWs

- **Primordial induced GWs** are generated through second order gravitational effects: $\mathscr{L}^{(3)}_{\Psi,h} \ni h\Psi^2$ [S. Matarrese et al. - 1993, 1994, 1998, G. Domenech - 2021].

$$\mathscr{R} = \frac{5+3w}{3(1+w)}\Psi, \text{ for } k \ll aH$$

$$\mathscr{P}_h(\eta, k) \propto \int \mathrm{d}v \int \mathrm{d}u \left(\int f(v, u, k, \eta) \mathrm{d}\eta \right)^2 \mathscr{P}_{\mathscr{R}}(kv) \mathscr{P}_{\mathscr{R}}(ku) \,.$$

Induced GWs

- **Primordial induced GWs** are generated through second order gravitational effects: $\mathscr{L}^{(3)}_{\Psi,h} \ni h\Psi^2$ [S. Matarrese et al. - 1993, 1994, 1998, G. Domenech - 2021].

$$\downarrow \qquad \mathscr{R} = \frac{5+3w}{3(1+w)}\Psi, \text{ for } k \ll aH$$

$$\mathscr{P}_h(\eta, k) \propto \int \mathrm{d}v \int \mathrm{d}u \left(\int f(v,u,k,\eta)\mathrm{d}\eta \right)^2 \mathscr{P}_{\mathscr{R}}(kv)\mathscr{P}_{\mathscr{R}}(ku)\,.$$

$$\downarrow$$

$$\Omega_{\rm GW}(\eta,k) \equiv \frac{1}{\rho_{\rm tot}}\frac{\mathrm{d}\rho_{\rm GW}}{\mathrm{d}\ln k} = \frac{1}{24}\left(\frac{k}{a(\eta)H(\eta)}\right)^2 \mathscr{P}_h(\eta,k),$$

Induced GWs

- **Primordial induced GWs** are generated through second order gravitational effects: $\mathscr{L}^{(3)}_{\Psi,h} \ni h\Psi^2$ [S. Matarrese et al. - 1993, 1994, 1998, G. Domenech - 2021].

$$\mathscr{R} = \frac{5+3w}{3(1+w)}\Psi, \text{ for } k \ll aH$$

$$\mathscr{P}_h(\eta,k) \propto \int \mathrm{d}v \int \mathrm{d}u \left(\int f(v,u,k,\eta)\mathrm{d}\eta \right)^2 \mathscr{P}_{\mathscr{R}}(kv)\mathscr{P}_{\mathscr{R}}(ku)\,.$$

$$\Omega_{\mathrm{GW}}(\eta,k) \equiv \frac{1}{\rho_{\mathrm{tot}}}\frac{\mathrm{d}\rho_{\mathrm{GW}}}{\mathrm{d}\ln k} = \frac{1}{24}\left(\frac{k}{a(\eta)H(\eta)}\right)^2 \mathscr{P}_h(\eta,k),$$

- We will focus in our scenario on **GWs induced** during the **Φ-driven eMD era.**

IGWs from an eMD era

IGWs from an eMD era

- During an eMD phase, **sub-horizon density perturbations grow, i.e.** $\delta_k \propto a$**,** as well as velocity flows. One then expects **structure (Φ halo) formation** in the **non-linear regime** [Barenboim & Rasero - 2013].

IGWs from an eMD era

- During an eMD phase, **sub-horizon density perturbations grow, i.e.** $\delta_k \propto a$**,** as well as velocity flows. One then expects **structure (Φ halo) formation** in the **non-linear regime** [Barenboim & Rasero - 2013].

- **The scale of non-linearities** at a given conformal time η is estimated as [Assadullahi & Wands - 2009, Kohri & Terada - 2018]

$$k_{\rm NL}(\eta) \sim \alpha A_{\rm s}^{-1/4} \mathscr{H}(\eta)\,.$$

where we assumed a scale-invariant curvature power spectrum with amplitude $A_{\rm s}$, and $\alpha \simeq 1.7$. **Modes with** $k > k_{\rm NL}$ **are in the non-linear regime, i.e.** $\mathscr{P}_\delta(k > k_{\rm NL}) > 1$.

IGWs from an eMD era

- During an eMD phase, **sub-horizon density perturbations grow, i.e. $\delta_k \propto a$,** as well as velocity flows. One then expects **structure (Φ halo) formation** in the **non-linear regime** [Barenboim & Rasero - 2013].

- **The scale of non-linearities** at a given conformal time η is estimated as [Assadullahi & Wands - 2009, Kohri & Terada - 2018]

$$k_{\mathrm{NL}}(\eta) \sim \alpha A_{\mathrm{s}}^{-1/4} \mathscr{H}(\eta)\,.$$

where we assumed a scale-invariant curvature power spectrum with amplitude A_{s} and $\alpha \simeq 1.7$. **Modes with $k > k_{\mathrm{NL}}$ are in the non-linear regime, i.e. $\mathscr{P}_{\delta}(k > k_{\mathrm{NL}}) > 1$.**

- **IGWs on linear scales $k < k_{\mathrm{NL}}$ are negligible. IGW generation** is abundant on non-linear scales and **is dominated by the largest structures that form at the end of the eMD era** [Fernandez et al. - 2024].

IGWs from an eMD era

- We need thus to require that at least **the largest possible non-linear scale enters the Hubble radius during the eMD**, i.e. $k_{\rm NL}(\eta_{\rm dec}) < \mathscr{H}_{\rm dom}$.

IGWs from an eMD era

- We need thus to require that at least the **largest possible non-linear scale enters the Hubble radius during the eMD**, i.e. $k_{\rm NL}(\eta_{\rm dec}) < \mathscr{H}_{\rm dom}$.

$$\boxed{A_{\rm s} \geq A_{\rm s,min} = \alpha^4 \left(\frac{a_{\rm dom}}{a_{\rm dec}}\right)^2 \simeq 9 \left(\frac{T_{\rm dec}}{T_{\rm dom}}\right)^2,}$$

IGWs from an eMD era

- We need thus to require that at least **the largest possible non-linear scale enters the Hubble radius during the eMD**, i.e. $k_{\rm NL}(\eta_{\rm dec}) < \mathcal{H}_{\rm dom}$.

$$\downarrow$$

$$\boxed{A_{\rm s} \geq A_{\rm s,min} = \alpha^4 \left(\frac{a_{\rm dom}}{a_{\rm dec}}\right)^2 \simeq 9 \left(\frac{T_{\rm dec}}{T_{\rm dom}}\right)^2,}$$

$$\text{with} \quad T_{\rm dom} = \frac{\rho_\Phi(T_c)}{\rho_{\rm r}(T_c)} T_c \quad \text{and} \quad T_{\rm dec} = \tilde{T}_{\rm dec} \ln\left(\frac{\Lambda_{\rm GUT}}{\mu}\right),$$

$$\text{where} \quad \tilde{T}_{\rm dec} = \left(\frac{72}{5\pi^2 g_*}\right)^{1/4} 10^{-2} \left[M_{\rm Pl}\Gamma_0 \frac{y_N^3}{\sqrt{g'^3}} \left(\frac{M_N}{10^{13}{\rm GeV}}\right)^3\right]^{1/2}.$$

[Chianese et al. - 2024]

The non-linear IGW spectrum

- Borrowing results of numerical simulations [Eggemeier et al. - 2023, Fernandez et al. - 2024, Dalianis & Kouvaris - 2024], the GW signal can be fitted on non-linear scales quite well as

$$\boxed{\begin{gathered}\Omega_{\rm GW}(k) \simeq 0.05 A_{\rm s}^{7/4} \left(\frac{k}{\mathscr{H}_{\rm dec}} \right)^{3/2} \quad \text{for} \quad k_{\rm low} \leq k \leq k_{\rm high}, \\ \text{where} \quad k_{\rm low} = 15 \mathscr{H}_{\rm dec} \quad \text{and} \quad k_{\rm high} = 9 k_{\rm NL} = 14 \mathscr{H}_{\rm dec} / A_{\rm s}^{1/4}.\end{gathered}}$$

The non-linear IGW spectrum

- Borrowing results of numerical simulations [Eggemeier et al. - 2023, Fernandez et al. - 2024, Dalianis & Kouvaris - 2024], the GW signal can be fitted on non-linear scales quite well as

$$\boxed{\begin{gathered}\Omega_{\rm GW}(k) \simeq 0.05 A_{\rm s}^{7/4}\left(\frac{k}{\mathscr{H}_{\rm dec}}\right)^{3/2} \quad \text{for} \quad k_{\rm low} \leq k \leq k_{\rm high}, \\ \text{where} \quad k_{\rm low} = 15\mathscr{H}_{\rm dec} \quad \text{and} \quad k_{\rm high} = 9k_{\rm NL} = 14\mathscr{H}_{\rm dec}/A_{\rm s}^{1/4}.\end{gathered}}$$

- Analytical studies considering GW induced by early structure pancake gravitational collapse [Dalianis & Kouvaris - 2021, Flores et al. - 2023] suggest that for $k > k_{\rm high}$, $\Omega_{\rm GW} \propto 1/k^n$ with $n \geq 1$.

The non-linear IGW spectrum

- Borrowing results of numerical simulations [Eggemeier et al. - 2023, Fernandez et al. - 2024, Dalianis & Kouvaris - 2024], the GW signal can be fitted on non-linear scales quite well as

$$\boxed{\begin{gathered}\Omega_{\rm GW}(k) \simeq 0.05 A_{\rm s}^{7/4}\left(\frac{k}{\mathscr{H}_{\rm dec}}\right)^{3/2} \quad \text{for} \quad k_{\rm low} \leq k \leq k_{\rm high}, \\ \text{where} \quad k_{\rm low} = 15\mathscr{H}_{\rm dec} \quad \text{and} \quad k_{\rm high} = 9k_{\rm NL} = 14\mathscr{H}_{\rm dec}/A_{\rm s}^{1/4}.\end{gathered}}$$

- Analytical studies considering GW induced by early structure pancake gravitational collapse [Dalianis & Kouvaris - 2021, Flores et al. - 2023] suggest that for $k > k_{\rm high}$, $\Omega_{\rm GW} \propto 1/k^n$ with $n \geq 1$.

$$\boxed{f_{\rm high} \equiv \frac{k_{\rm high}}{2\pi} = \frac{14\mathscr{H}_{\rm dec}A_{\rm s}^{-1/4}}{2\pi} \propto \frac{M_N^3 y_N^3}{\sqrt{g'^3}} A_s^{-1/4}}$$

- One can establish **a remarkable connection between leptogenesis and IGWs** since $\Gamma_{\Phi}^{hh}(y_N, M_N, g') = \mathscr{H}_{\rm dec}/a_{\rm dec}$.

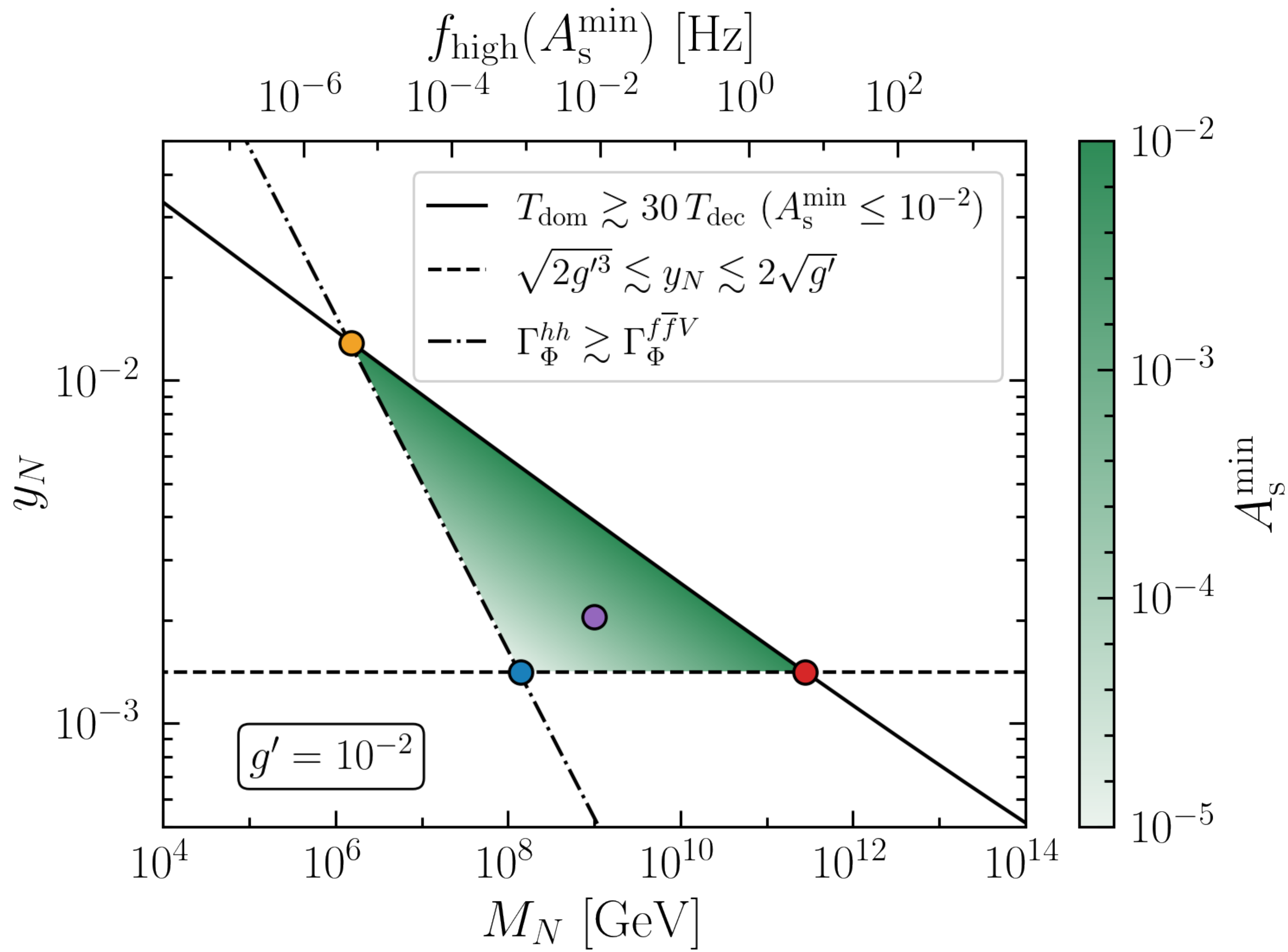
The non-linear IGW spectrum

- Working with frequencies f instead of wavenumbers k, one can recast $\Omega_{\rm GW}(k)$ as

$$\boxed{\begin{gathered}\Omega_{\rm GW,0}h^2 = 4.2\times 10^{-5}\, A_s^{11/8}\left(\frac{f}{f_{\rm high}}\right)^{3/2},\\ \text{where}\quad f_{\rm high}\simeq 6.4\times 10^{-5}{\rm Hz}\left(\frac{A_{\rm s}}{10^{-5}}\right)^{-1/4}\left(\frac{T_{\rm dec}}{10\,{\rm GeV}}\right)\quad\text{and}\\ f_{\rm low}\simeq 3.8\times 10^{-6}{\rm Hz}\left(\frac{T_{\rm dec}}{10{\rm GeV}}\right)\end{gathered}}$$

Results

The parameter space (M_N, y_N, g')



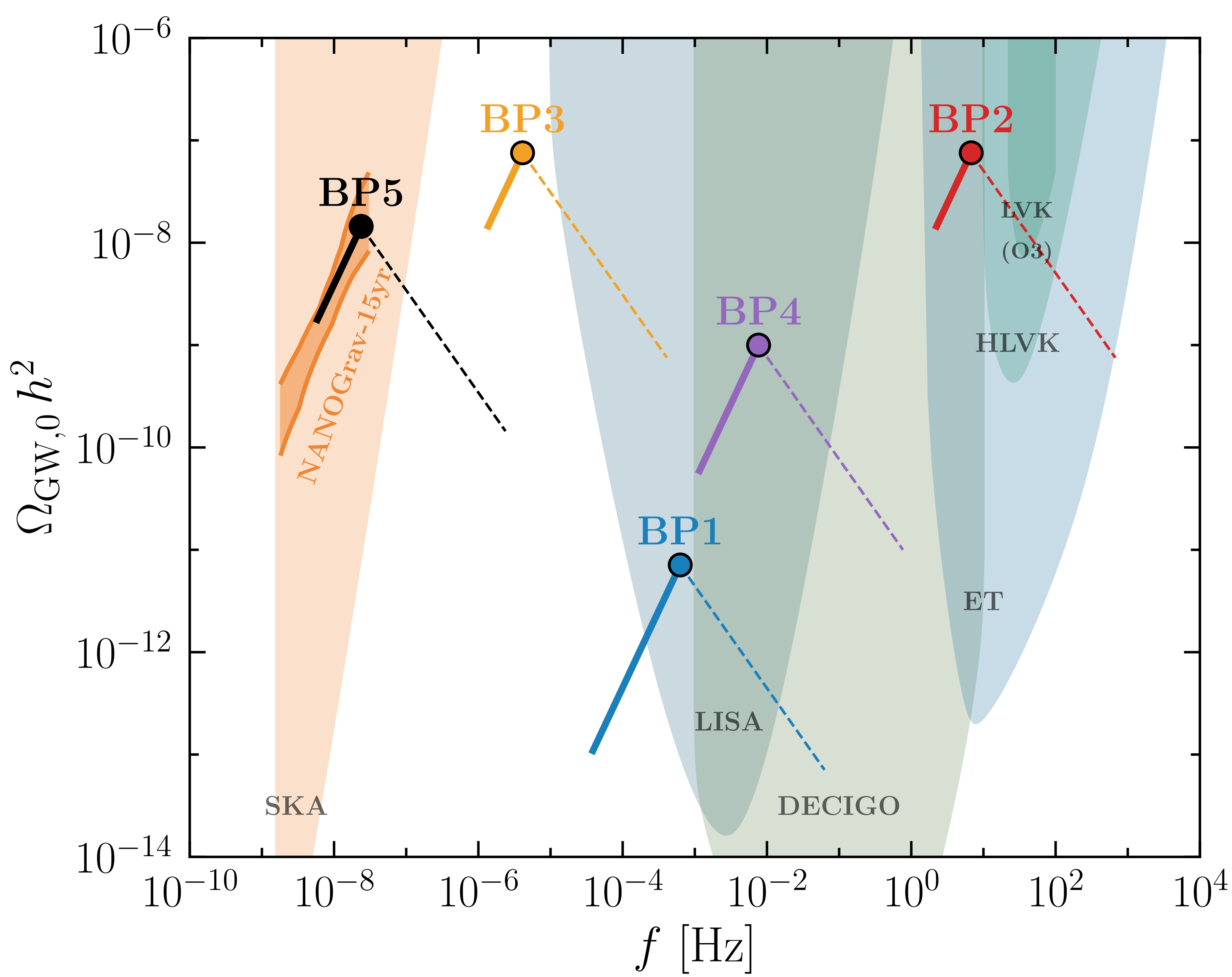
Benchmark parameter values

	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}

Benchmark parameter values

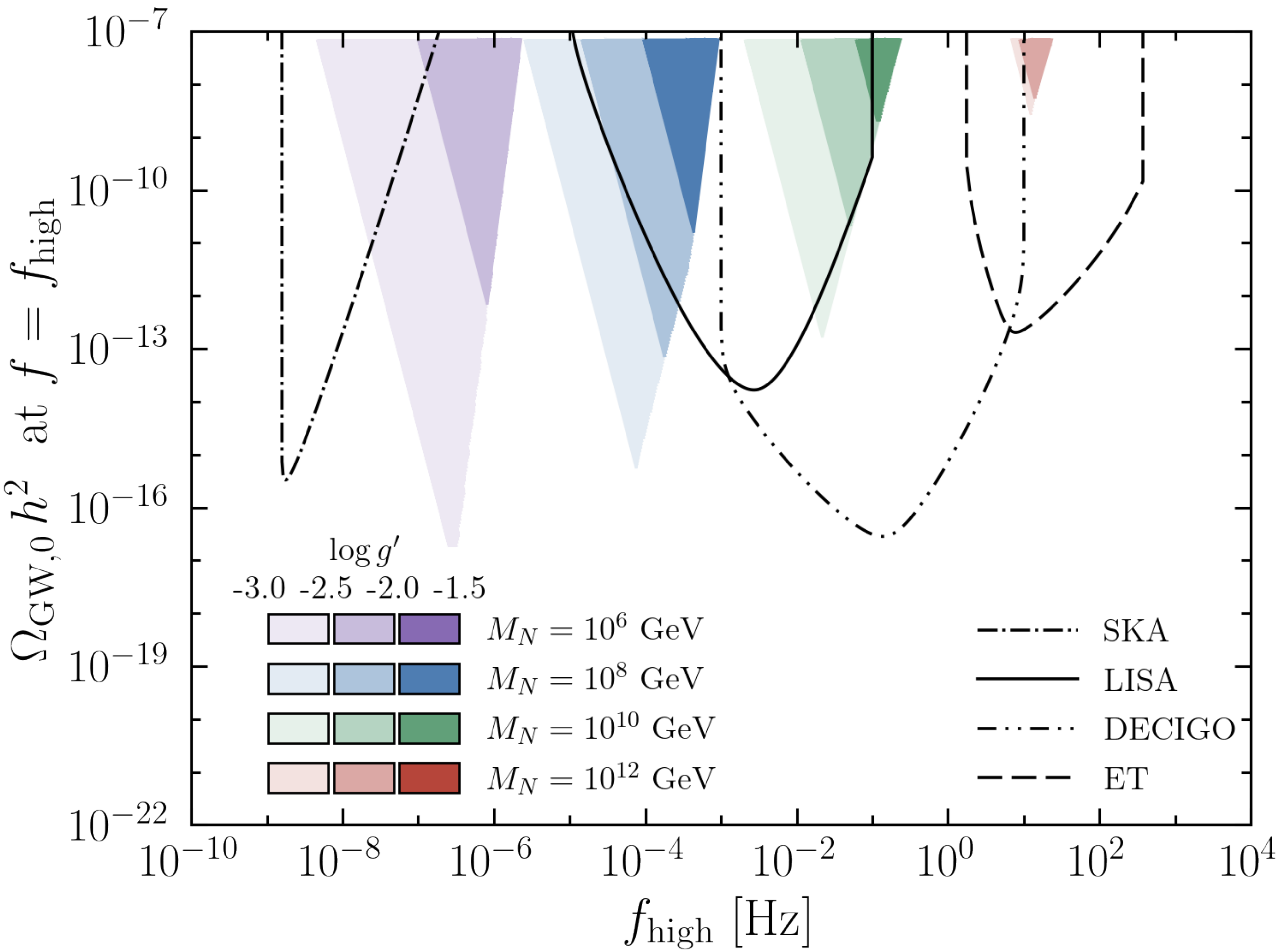
	g'	M_N [GeV]	y_N	A_s
BP1	10^{-2}	1.4×10^8	1.4×10^{-3}	1.18×10^{-5}
BP2	10^{-2}	2.8×10^{11}	1.4×10^{-3}	9.96×10^{-3}
BP3	10^{-2}	1.5×10^6	1.8×10^{-2}	1.00×10^{-2}
BP4	10^{-2}	1.0×10^9	2.0×10^{-3}	4.30×10^{-4}
BP5	10^{-3}	1.0×10^6	1.5×10^{-4}	3.00×10^{-3}

$$\Omega_{\rm GW} \propto \begin{cases} f^{3/2} & \text{for} \quad f_{\rm low} \leq f \leq f_{\rm high} \\ 1/f & \text{for} \quad f > f_{\rm high} \end{cases}$$



Detectability by GW observatories

$$y_N \in [\sqrt{2g'^3}, 2\sqrt{g'}], \quad A_s \in [\max(10^{-9}, A_s^{\min}), 10^{-2}]$$



Conclusions

Conclusions

- There is a **direct link between leptogenesis and the IGW spectrum**. In particular, f_{high} is directly related to M_N.

Conclusions

- There is a **direct link between leptogenesis and the IGW spectrum**. In particular, $f_{\rm high}$ is directly related to M_N.

- **Different flavor regimes**, characterized by different M_N values produce **GWs at varying frequencies.**

Conclusions

- There is a **direct link between leptogenesis and the IGW spectrum**. In particular, $f_{\rm high}$ is directly related to M_N.

- **Different flavor regimes**, characterized by different M_N values produce **GWs at varying frequencies.**

Future Perspectives

Conclusions

- There is a **direct link between leptogenesis and the IGW spectrum**. In particular, f_{high} is directly related to M_N.

- **Different flavor regimes**, characterized by different M_N values produce **GWs at varying frequencies.**

Future Perspectives

- **eMD eras favor** the formation of PBHs. Even with $A_{\mathrm{s}} \sim 10^{-4}$, one can produce **substantial PBH abundances** [Harada et al - 2016, Ballesteros et al. - 2019].

Conclusions

- There is a **direct link between leptogenesis and the IGW spectrum.** In particular, $f_{\rm high}$ is directly related to M_N.

- **Different flavor regimes**, characterized by different M_N values produce **GWs at varying frequencies.**

Future Perspectives

- **eMD eras favor** the formation of PBHs. Even with $A_{\rm s} \sim 10^{-4}$, one can produce **substantial PBH abundances** [Harada et al - 2016, Ballesteros et al. - 2019].

- **Any BSM physics framework** involving an **eMD epoch triggered by long lived particles** can be readily explored through **IGWs.**

Thanks for your attention

Appendix

Quasi-Degeneracy of RHNs

$$M_N > T_{\rm dom} \Rightarrow \Delta \simeq T_{\rm dec}/T_{\rm dom} \Rightarrow \eta_{\rm B} \simeq 10^{-3}\left(\frac{3m_\nu M_{N_i}}{8\pi v_h^2 \delta}\right)\Delta$$

$$\text{where } \delta = \frac{\mathrm{M_{N_i} - M_{N_j}}}{\mathrm{M_{N_i}}} \text{ is the quasi} - \text{degenarcy among RHNs}\,.$$

$$\eta_B \simeq 6.3\times 10^{-10} \Rightarrow \delta \simeq 0.2\left(\frac{M_{N_i}}{10^9 \mathrm{GeV}}\right)\sqrt{A_{\rm s}^{\rm min}}\,.$$

- Strong (weak) amplitude GWs are associated with weakly (strongly) quasi-degenerate RHNs.

Basics of Scalar Induced Gravitational Waves

- Choosing as the gauge for the GW frame the Newtonian gauge, the metric is written as

$$\mathrm{d}s^2 = a^2(\eta)\left\{-(1+2\Phi)\mathrm{d}\eta^2 + \left[(1-2\Phi)\delta_{ij} + \frac{h_{ij}}{2}\right]\mathrm{d}x^i\mathrm{d}x^j\right\}.$$

- The equation of motion for the Fourier modes, $h_{\vec{k}}$, read as:

$$h^{s,''}_{\vec{k}} + 2\mathscr{H}h^{s,'}_{\vec{k}} + k^2 h^s_{\vec{k}} = 4S^s_{\vec{k}}\,.$$

- The source term, $S_{\vec{k}}$ can be recast as:

$$S^s_{\vec{k}} = \int \frac{\mathrm{d}^3\vec{q}}{(2\pi)^{3/2}} e^s_{ij}(\vec{k}) q_i q_j \left[2\Phi_{\vec{q}}\Phi_{\vec{k}-\vec{q}} + \frac{4}{3(1+w)}(\mathscr{H}^{-1}\Phi'_{\vec{q}} + \Phi_{\vec{q}})(\mathscr{H}^{-1}\Phi'_{\vec{k}-\vec{q}} + \Phi_{\vec{k}-\vec{q}})\right].$$

- The GW spectral abundance can be written as

$$\Omega_{\mathrm{GW}}(\eta,k) \equiv \frac{1}{\rho_{\mathrm{tot}}}\frac{\mathrm{d}\rho_{\mathrm{GW}}}{\mathrm{d}\ln k} = \frac{1}{24}\left(\frac{k}{a(\eta)H(\eta)}\right)^2 \mathscr{P}_h(\eta,k)$$

$$\text{with}\quad \mathscr{P}_h(\eta,k) \equiv \frac{k^3|h_k|^2}{2\pi^2} \propto \int \mathrm{d}v \int \mathrm{d}u \left(\int f(v,u,k,\eta)\mathrm{d}\eta\right)^2 \mathscr{P}_\Phi(kv)\mathscr{P}_\Phi(ku)\,.$$