CPNR workshop 2025: Neutrinos and Physics beyond the Standard Model

Probing seesaw and Leptogenesis with high frequency gravitational waves

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2410.01900

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Standard Model of particle physics → Massless Neutrinos

Massive Neutrinos

NuFIT 6.0 (2024)

		Normal Ordering ($\Delta\chi^2 = 0.6$)		Inverted Ordering (best fit)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
IC19 without SK atmospheric data	$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.345$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$
	$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$
	$\sin^2\theta_{23}$	$0.561^{+0.012}_{-0.015}$	$0.430 \to 0.596$	$0.562^{+0.012}_{-0.015}$	$0.437 \to 0.597$
	$\theta_{23}/^\circ$	$48.5^{+0.7}_{-0.9}$	$41.0 \to 50.5$	$48.6^{+0.7}_{-0.9}$	$41.4 \to 50.6$
	$\sin^2\theta_{13}$	$0.02195^{+0.00054}_{-0.00058}$	$0.02023 \to 0.02376$	$0.02224^{+0.00056}_{-0.00057}$	$0.02053 \to 0.02397$
	$\theta_{13}/^\circ$	$8.52^{+0.11}_{-0.11}$	$8.18 \to 8.87$	$8.58^{+0.11}_{-0.11}$	$8.24 \to 8.91$
	$\delta_{CP}/^\circ$	177^{+19}_{-20}	$96 \to 422$	285^{+25}_{-28}	$201 \to 348$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.534^{+0.025}_{-0.023}$	$+2.463 \to +2.606$	$-2.510^{+0.024}_{-0.025}$	$-2.584 \to -2.438$
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
IC24 with SK atmospheric data	$\sin^2\theta_{12}$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$
	$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$
	$\sin^2\theta_{23}$	$0.470^{+0.017}_{-0.013}$	$0.435 \to 0.585$	$0.550^{+0.012}_{-0.015}$	$0.440 \to 0.584$
	$\theta_{23}/^\circ$	$43.3^{+1.0}_{-0.8}$	$41.3 \to 49.9$	$47.9^{+0.7}_{-0.9}$	$41.5 \to 49.8$
	$\sin^2\theta_{13}$	$0.02215^{+0.00056}_{-0.00058}$	$0.02030 \to 0.02388$	$0.02231^{+0.00056}_{-0.00056}$	$0.02060 \to 0.02409$
	$\theta_{13}/^\circ$	$8.56^{+0.11}_{-0.11}$	$8.19 \to 8.89$	$8.59^{+0.11}_{-0.11}$	$8.25 \to 8.93$
	$\delta_{CP}/^\circ$	212^{+26}_{-41}	$124 \to 364$	274^{+22}_{-25}	$201 \to 335$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.513^{+0.021}_{-0.019}$	$+2.451 \to +2.578$	$-2.484^{+0.020}_{-0.020}$	$-2.547 \to -2.421$

Need to introduce BSM physics

[I. Esteban et al, JHEP 12 (2024) 216]

Type I seesaw and neutrino mass

Type-I seesaw: **SM + 3 Right handed neutrinos**

[Minkowsky, 1977; Yanagida, 1979; Gell-Mann,Ramond,Slansky,1979; Mohapatra,Senjanovic,1980]

$$\mathscr{L}_{BSM} = Y^{\nu}_{\alpha i}\bar{\ell}_{L_\alpha}\tilde{H}N_i + \frac{1}{2}M_N\bar{N}^c N + \mathrm{h.c.}$$

$$\begin{tikzcd}
 & m_\nu = -m_D M_N^{-1} m_D^T \\
\begin{pmatrix} \bar{\nu}_L & \overline{(N_R)^c} \end{pmatrix} \underbrace{\begin{pmatrix} 0_{3\times3} & m^D_{3\times3} \\ m^{D^T}_{3\times3} & M_{N_{3\times3}} \end{pmatrix}}_{m_{\mathrm{seesaw}}} \begin{pmatrix} (\nu_L)^c \\ N_R \end{pmatrix} \arrow[r, "\mathbb{L}^\dagger m_{seesaw}\mathbb{L}^* = m^{block}_{diag}"] & \begin{pmatrix} m_{\nu_{3\times3}} & 0_{3\times3} \\ 0_{3\times3} & M_{N_{3\times3}} \end{pmatrix} \arrow[u] \arrow[d, "U^\dagger m_\nu U^* = D_m"'] \\
 & \begin{pmatrix} D_{m_{3\times3}} & 0_{3\times3} \\ 0_{3\times3} & D_{M_{3\times3}} \end{pmatrix} \arrow[dl] \arrow[d] \\
D_m = \mathrm{diag}(m_1, m_2, m_3) & D_M = \mathrm{diag}(M_1, M_2, M_3)
\end{tikzcd}$$

[see Prof. Xing's slide]

Type I seesaw and Baryogenesis via Leptogenesis

Observed Baryon asymmetry $Y_B = 8.7 \times 10^{-11}$ [Planck, 2018] $Y_B = \dfrac{n_B - n_{\bar{B}}}{s}$

Dynamically generate baryon asymmetry

- C and CP violation
- baryon number violation
- Out of equilibrium dynamics

[Sakharov,1965]

Type-I seesaw: **SM + 3 Right handed neutrinos**

$$\mathscr{L}_{BSM} = Y^{\nu}_{\alpha i} \bar{\ell}_{L_\alpha} \tilde{H} N_i + \frac{1}{2} M_N \bar{N}^c N + \mathrm{h.c.}$$

CP Violation

Lepton number violation

Out of equilibrium dynamics → **Decay of RHN below T<M**

$[N \to \ell + H]$

$[N \to \bar{\ell} + H^\dagger]$

$\boxed{\Delta L \neq 0}$

Sphaleron Transition

$\boxed{\Delta B \neq 0}$

[Fukugita, Yangida, 1986; Luty 1992; Covi, Roulet, Vissani 1996]

Type I seesaw, Leptogenesis and neutrino mass

Note:

Neutrino mass

$$m_\nu \sim \frac{(Y_\nu v)^2}{2M_N} \longrightarrow m_\nu \sim 0.05 \text{ eV} \longrightarrow M_N \sim 10^{14} Y_\nu^2 \text{ GeV}$$

[crude estimation]

Large RHNS

Leptogenesis (thermal)

$$M_1 < M_2 < M_3 \quad +$$ RHNs are in thermal bath before decay

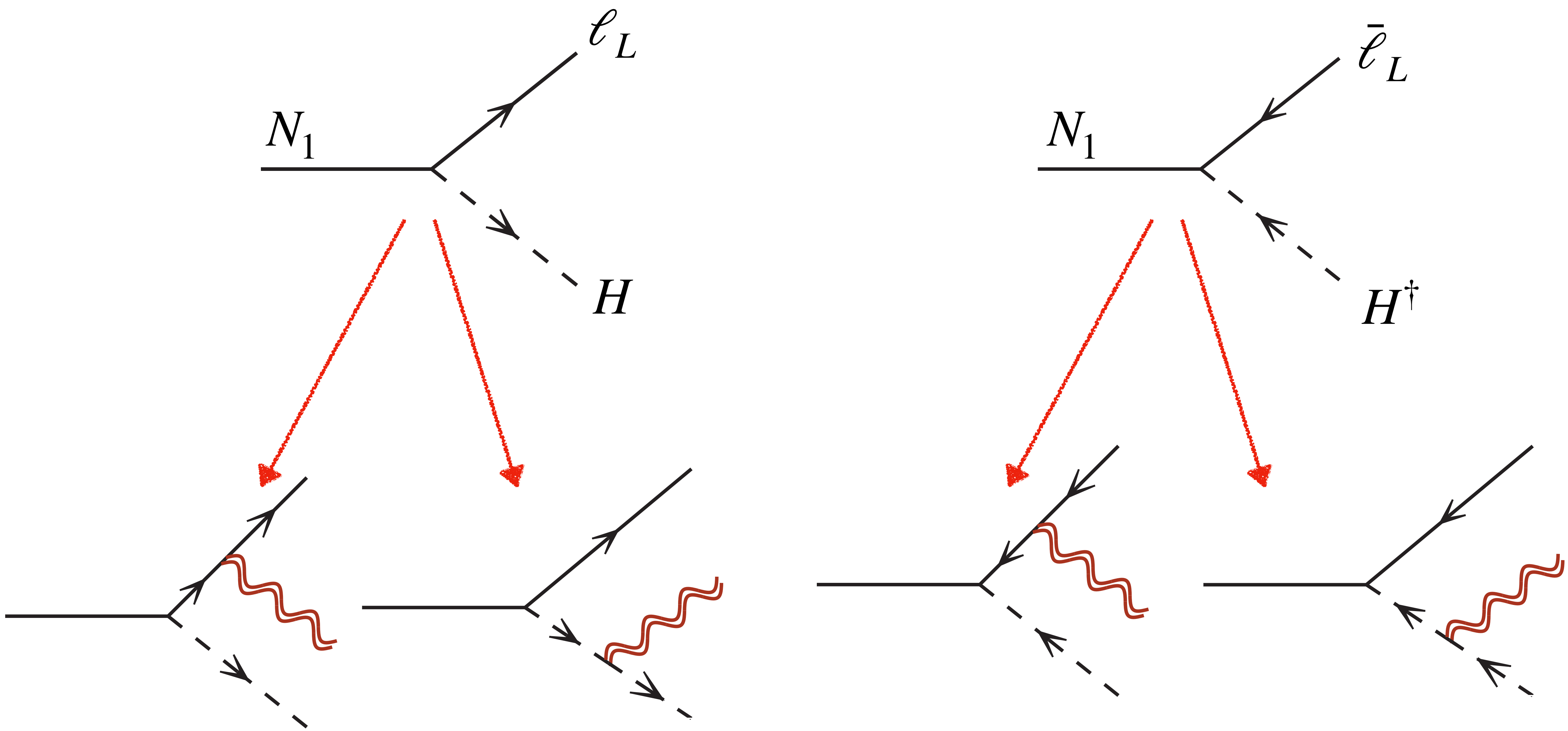
$$|\epsilon_1| \lesssim \frac{3}{8\pi} M_1 (m_3 - m_1) \longrightarrow M_1 \gtrsim 10^8 \text{ GeV}$$

Direct experimental test is impossible

[see Prof. Yang's Talk]

Type I seesaw, Leptogenesis and neutrino mass, Gravitational waves

Gravitational Waves can help probing the Seesaw/Leptogenesis scale



How do we get the diagrams?

$$S = \int d^4x \sqrt{-g}\, \left[2\kappa^{-2}\mathscr{R} + \mathscr{L}_{\mathrm{SM}} + \mathscr{L}_{\mathrm{N}}\right]$$

$$\mathscr{L}_\phi = g^{\mu\nu}(D_\mu \phi)^*(D^\mu \phi) - m^2 \phi^* \phi + \ldots$$

$$\mathscr{L}_\psi = \frac{i}{2}\left(\bar{\psi}\gamma^\mu(\overrightarrow{\nabla}_\mu - ieA_\mu)\psi) - \bar{\psi}(\overleftarrow{\nabla}_\mu + ieA_\mu)\gamma^\mu\psi - m\bar{\psi}\psi\right)$$

$$g_{\mu\nu} = \eta_{\mu\nu} + \kappa h_{\mu\nu} + \kappa^2 h^{\mu\lambda} h_{\nu\lambda} + \ldots$$

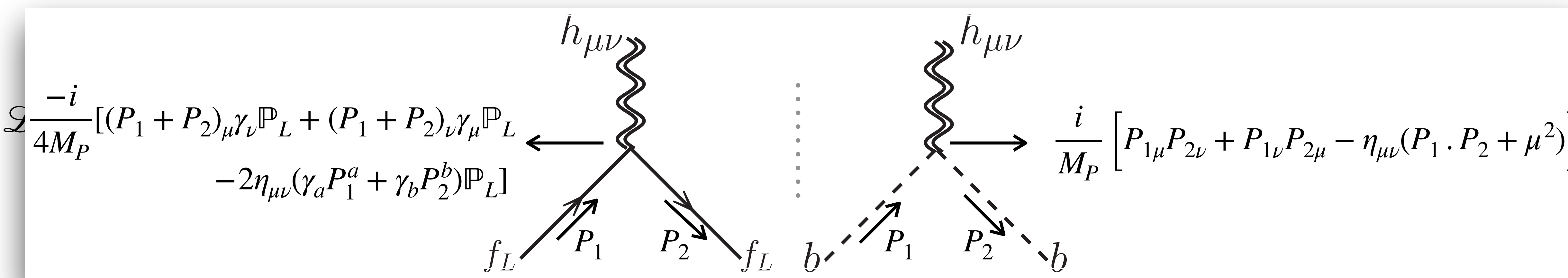
$$\mathscr{L}^g_{\mathrm{int}} = -\frac{\kappa}{2} h_{\mu\nu} T^{\mu\nu}_X$$

$$T^{\mu\nu}_\psi = \frac{i}{4}\left[\bar{\psi}\gamma^\mu\partial^\nu\psi + \bar{\psi}\gamma^\nu\partial^\nu\psi\right] - \eta^{\mu\nu}\left[\frac{i}{2}\bar{\psi}\gamma^\alpha\partial_\alpha\psi - m_\psi\bar{\psi}\psi\right]$$

$$T^{\mu\nu}_s = \partial^\mu s \partial^\nu s - \eta^{\mu\nu}\left[\frac{1}{2}\partial^\alpha s \partial_\alpha s - V(s)\right]$$

How do we get the diagrams?

$$S = \int d^4x \sqrt{-g}\left[2\kappa^{-2}\mathscr{R} + \mathscr{L}_{\mathrm{SM}} + \mathscr{L}_{\mathrm{N}}\right]$$



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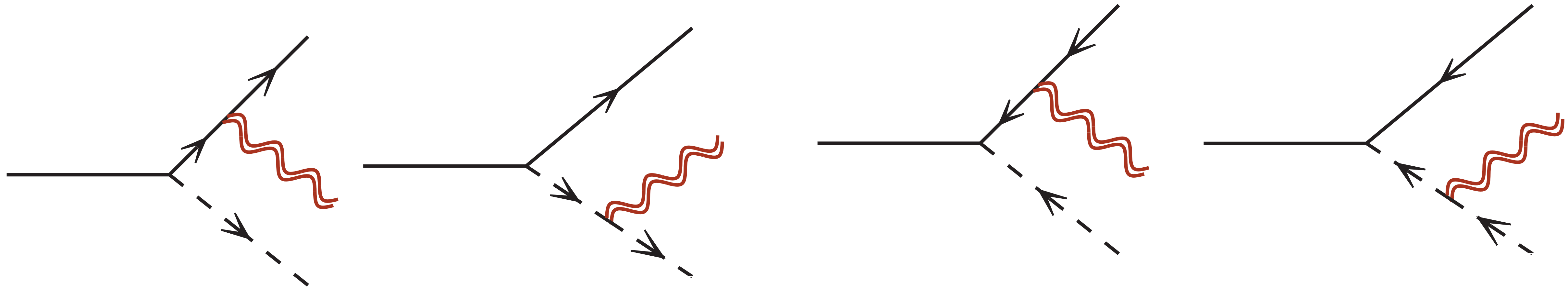
$$\mathscr{L}^g_{\mathrm{int}} = -\frac{\kappa}{2}h_{\mu\nu}T^{\mu\nu}_X$$

Decay rates



$$\frac{d\Gamma^{1\to 3}}{dE_k} = \frac{(Y_\nu^\dagger Y_\nu)_{11}}{128\pi^3}\frac{M_1^2}{M_p^2}\mathcal{G}(x)$$

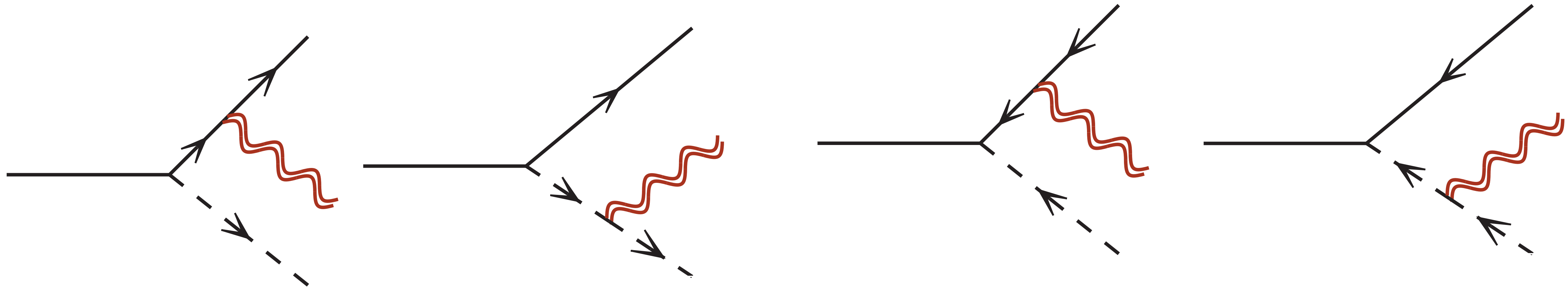
$$(1-x)^2(1-2x)/x \qquad x = E_k/M_1$$

Note:

For small E_k :

IR divergence

Decay rates



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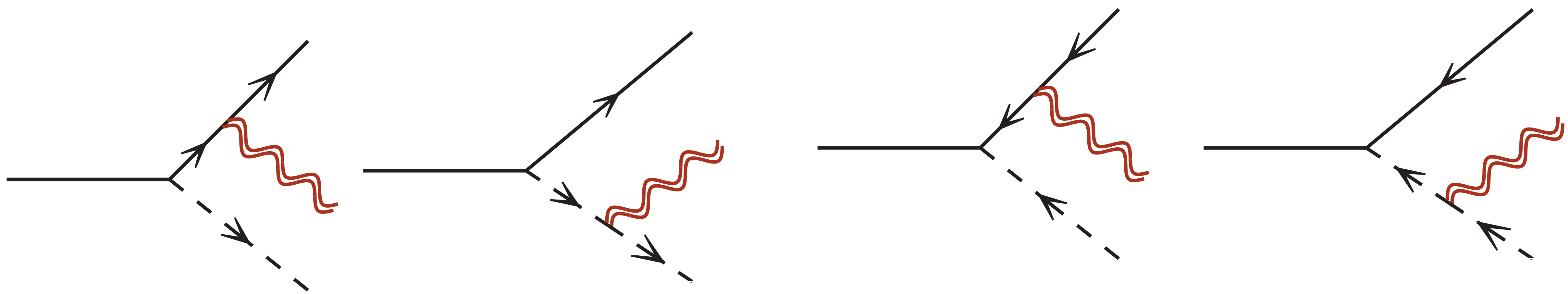
[S. Weinberg, 1965]

Decay rates



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$$(1-x)^2(1-2x)/x \qquad x = E_k/M_1$$

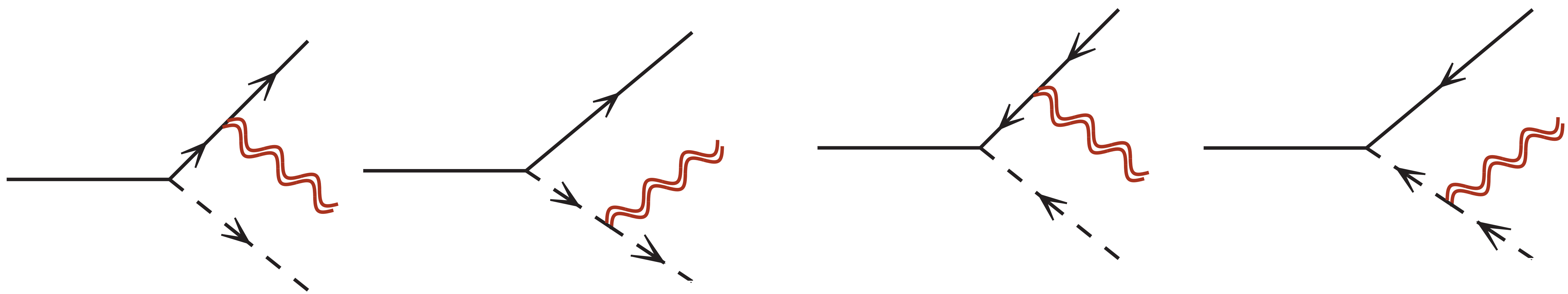
Note:

For large E_k :

$$\frac{d\Gamma^{1\to3}}{dE_k} = 0$$

[kinematic contraint]

Gravitational wave relic



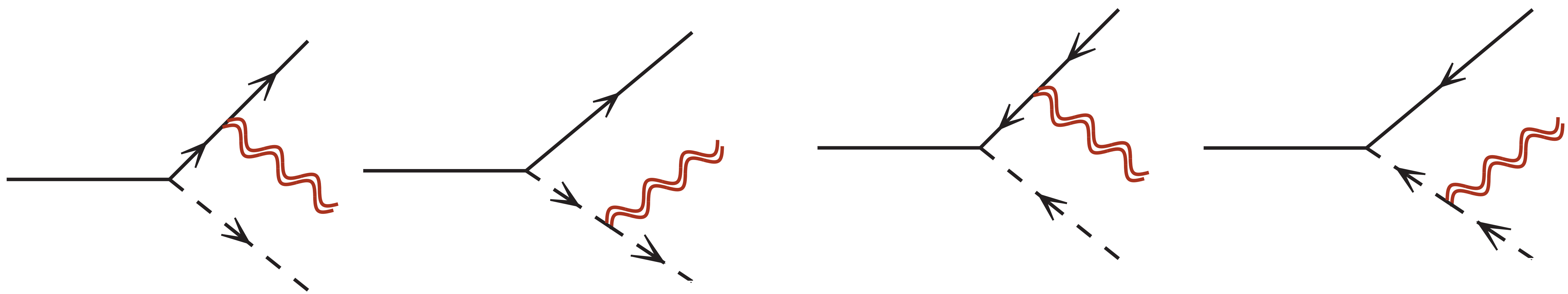
$$(1-x)^2(1-2x)/x$$

$$\frac{d\Gamma^{1\to 3}}{dE_k} = \frac{(Y_\nu^\dagger Y_\nu)_{11}}{128\pi^3}\frac{M_1^2}{M_p^2}\mathscr{G}(x) \qquad x = E_k/M_1$$

$$\frac{d}{dt}\left(\frac{d\rho_{\rm GW}}{dE_k}\right) + 4\mathscr{H}\frac{d\rho_{\rm GW}}{dE_k} = \frac{E_k}{M_1}\frac{d\Gamma^{1\to 3}}{dE_k} n_{N_1} E_{N_1}$$

$$\Omega^0_{\rm GW} h^2 = \left[\frac{h^2}{\rho_c^0} E_k \frac{d\rho_{GW}}{dE_k}\right]_0 = h^2\left(\frac{\Omega_\gamma^0}{\rho_R^*}\right) E_{k_*}\left[\frac{d\rho_{GW}}{dE_k}\right]_*$$

Gravitational wave relic



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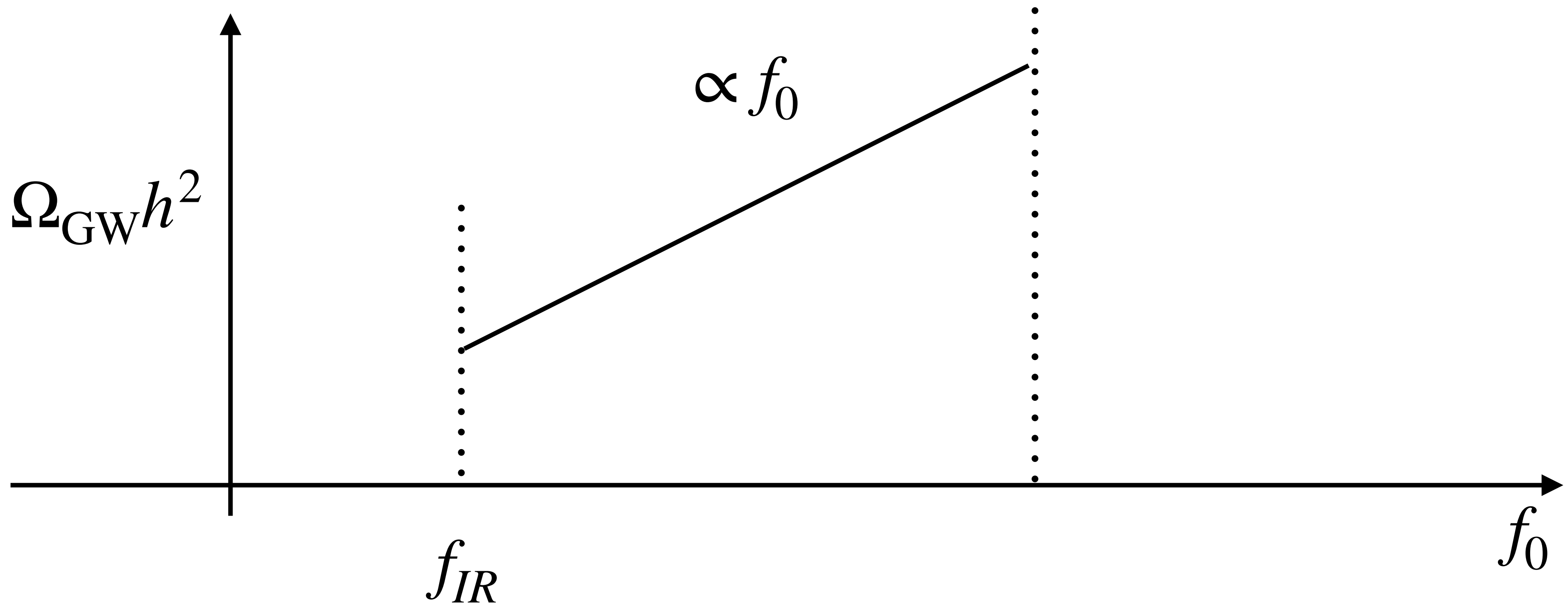
$$\Omega^0_{\rm GW}h^2 \propto f^0$$

$$\Omega^0_{\rm GW}h^2 = \left[\frac{h^2}{\rho_c^0}E_k\frac{d\rho_{GW}}{dE_k}\right]_0 = h^2\left(\frac{\Omega_\gamma^0}{\rho_R^*}\right)E_{k_*}\left[\frac{d\rho_{GW}}{dE_k}\right]_*$$

Gravitational wave relic



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Actual scenario: with Leptogenesis

$$\frac{dn_{N_1}}{dt} + 3\mathscr{H} n_{N_1} = -\,(n_{N_1} - n_{N_1}^{\mathrm{eq}})\langle \Gamma_{N_1} \rangle - n_{N_1}\Gamma^{1\to 3}$$

$$\frac{dn_{B-L}}{dt} + 3\mathscr{H} n_{B-L} = -\,\left[(n_{N_1} - n_{N_1}^{\mathrm{eq}})\varepsilon_\ell + n_{B-L}\frac{n_{N_1}^{\mathrm{eq}}}{n_l^{\mathrm{eq}}}\right]\langle \Gamma_{N_1} \rangle$$

$$\frac{d}{dt}\left(\frac{d\rho_{\mathrm{GW}}}{dE_k}\right) + 4\mathscr{H}\frac{d\rho_{\mathrm{GW}}}{dE_k} = \frac{E_k}{M_1}\frac{d\Gamma^{1\to 3}}{dE_k} n_{N_1} E_{N_1}$$

Assumption: Initially, lightest RHN is in thermal equilibrium

$M_1 = 10^{10}$ GeV

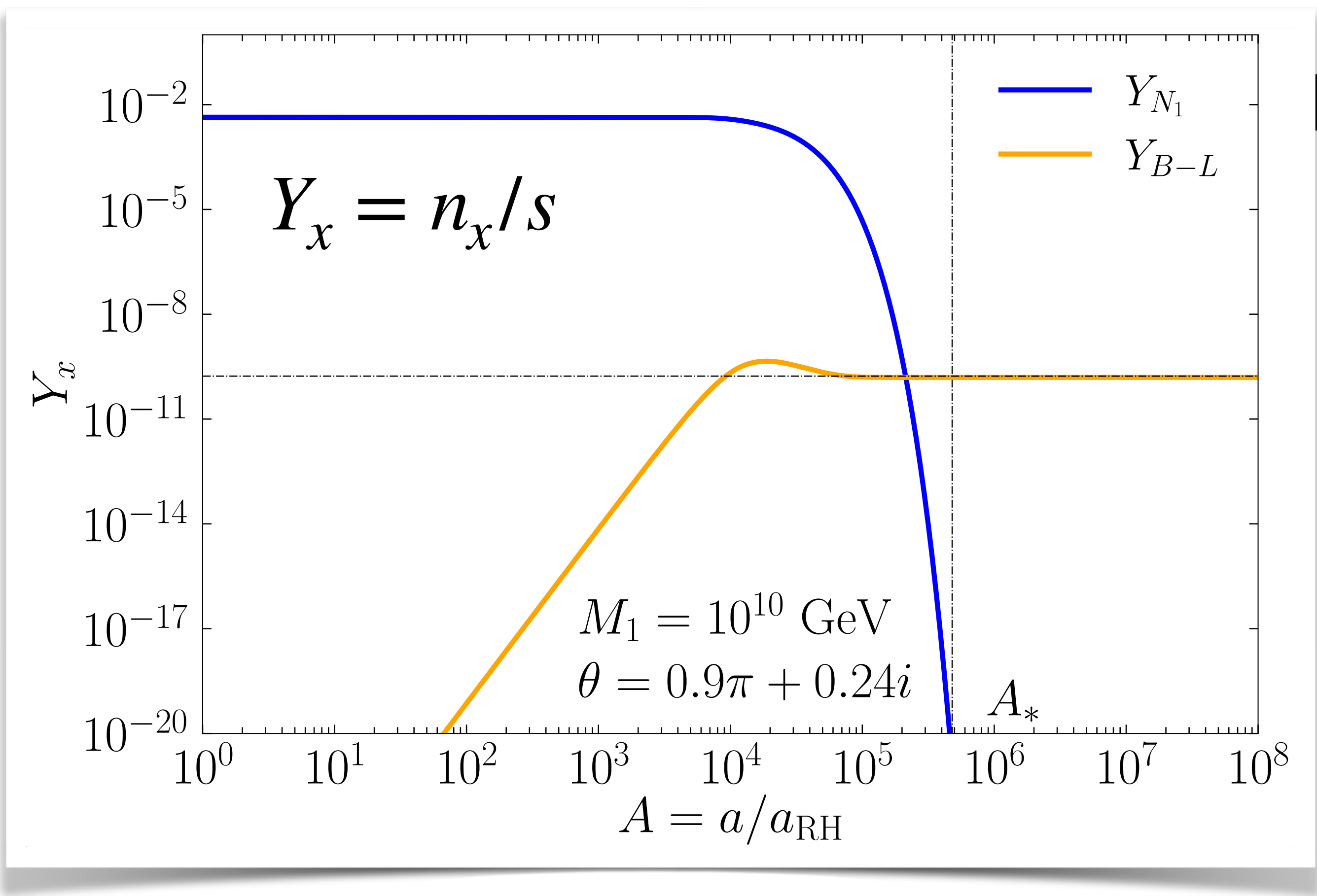
Thermal Leptogenesis

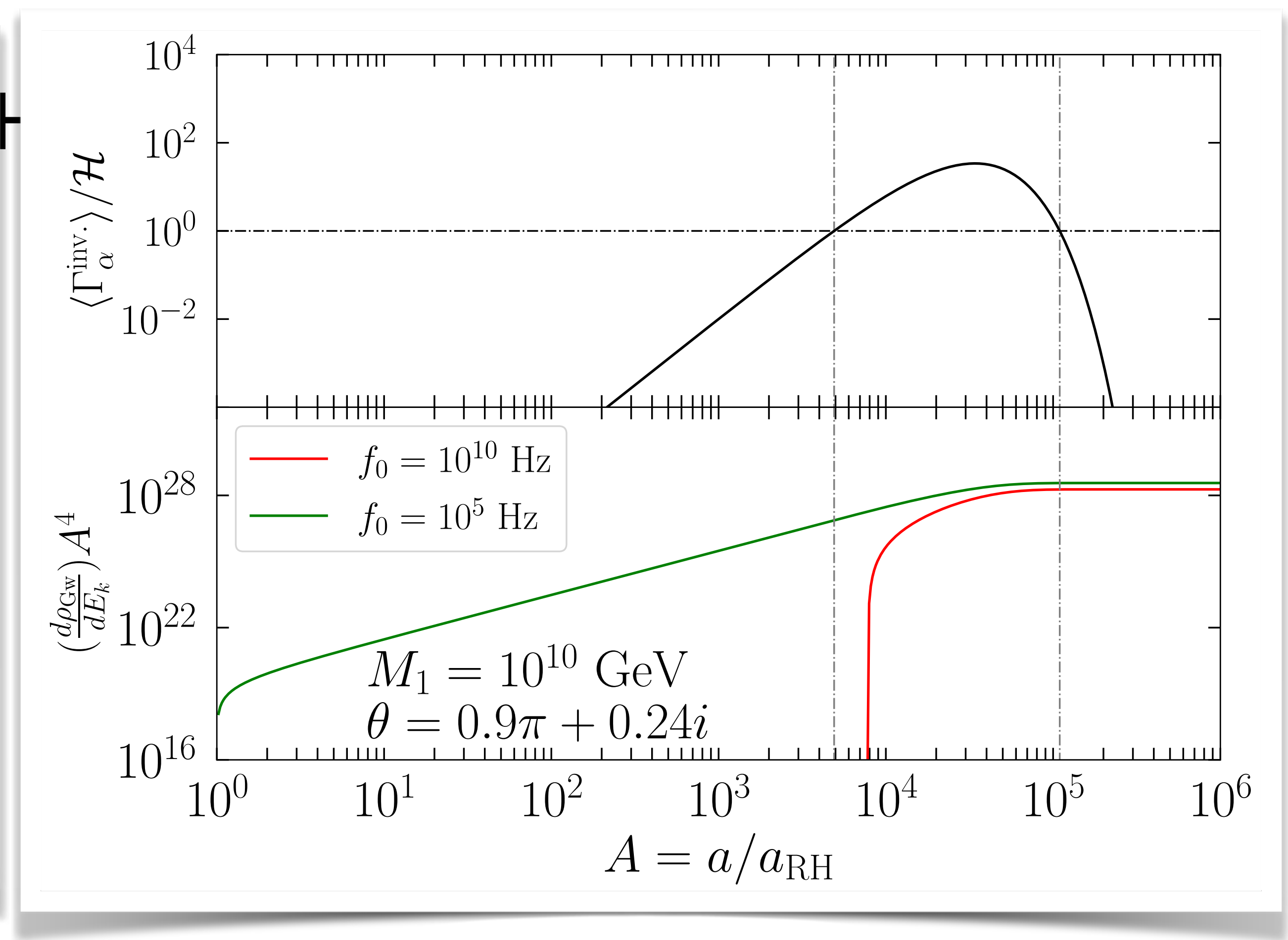
Actual scenario: with Leptogenesis

$$\frac{dn_{N_1}}{dt} + 3\mathscr{H}n_{N_1} = -(n_{N_1} - n_{N_1}^{\text{eq}})\langle\Gamma_{N_1}\rangle - n_{N_1}\Gamma^{1\to3}$$

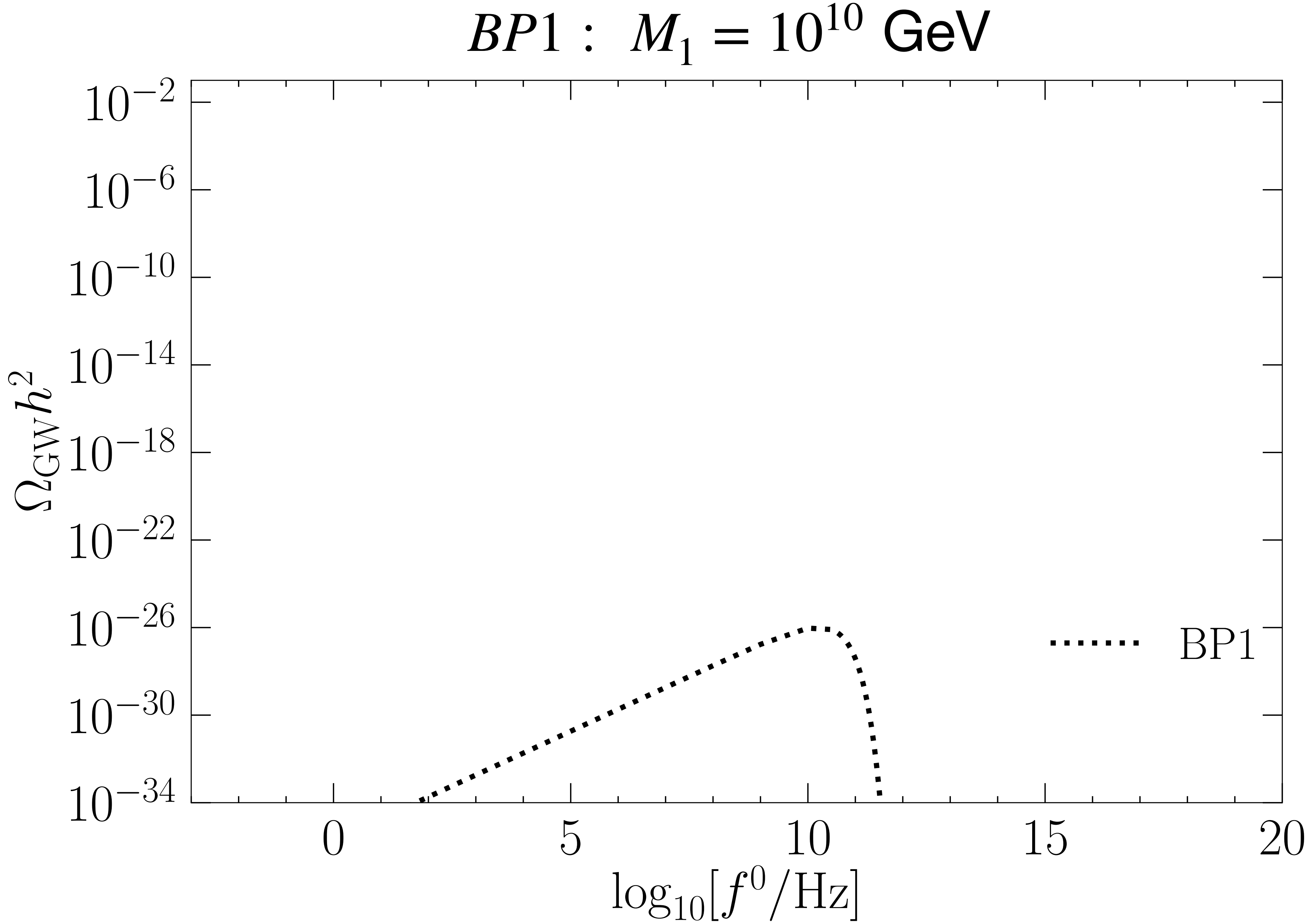
$$\frac{dn_{B-L}}{dt} + 3\mathscr{H}n_{B-L} = -\left[(n_{N_1} - n_{N_1}^{\text{eq}})\varepsilon_\ell + n_{B-L}\frac{n_{N_1}^{\text{eq}}}{n_l^{\text{eq}}}\right]\langle\Gamma_{N_1}\rangle$$

$$\frac{d}{dt}\left(\frac{d\rho_{\text{GW}}}{dE_k}\right) + 4\mathscr{H}\frac{d\rho_{\text{GW}}}{dE_k} = \frac{E_k}{M_1}\frac{d\Gamma^{1\to3}}{dE_k}n_{N_1}E_{N_1}$$





Actual scenario: with Leptogenesis



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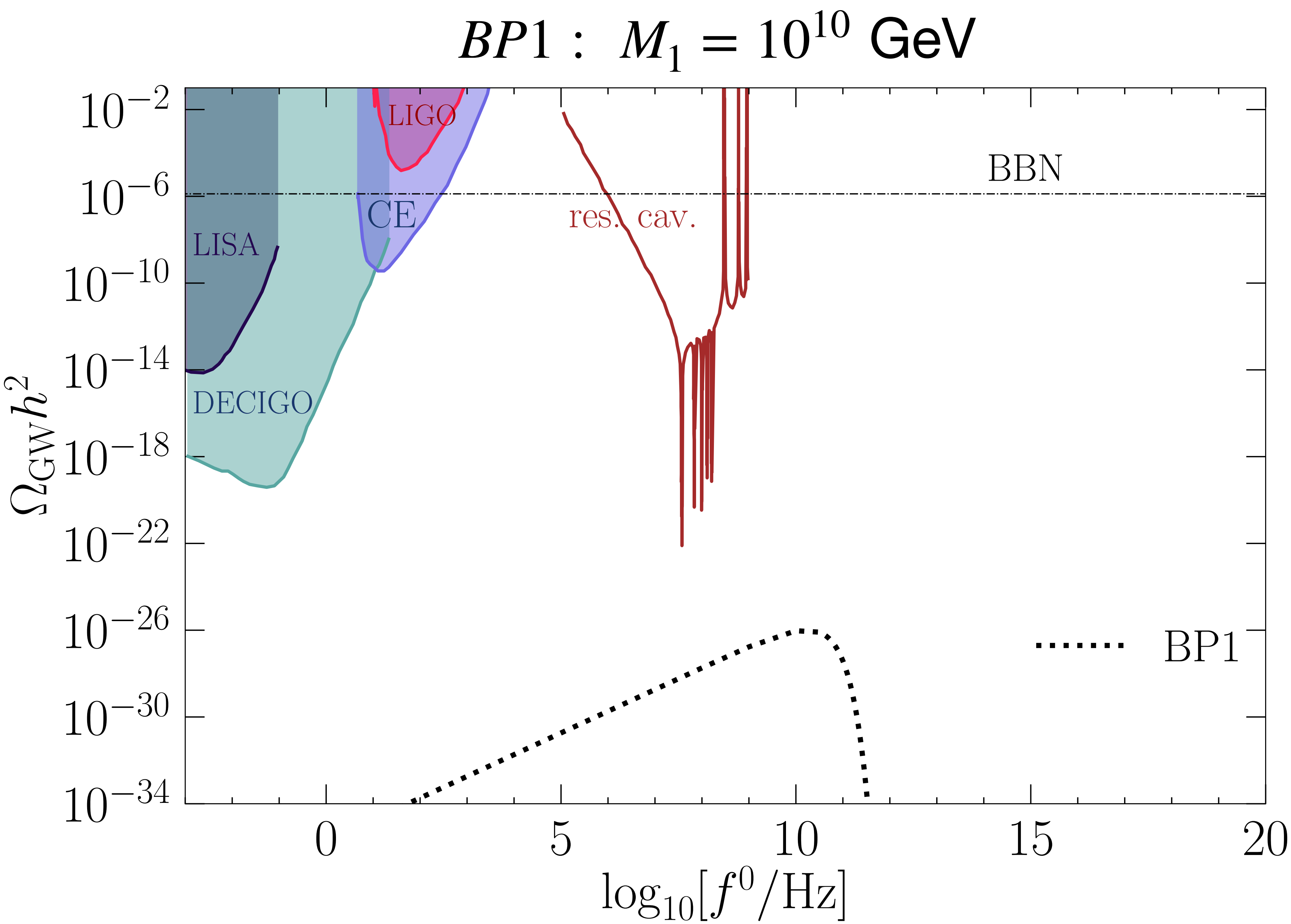

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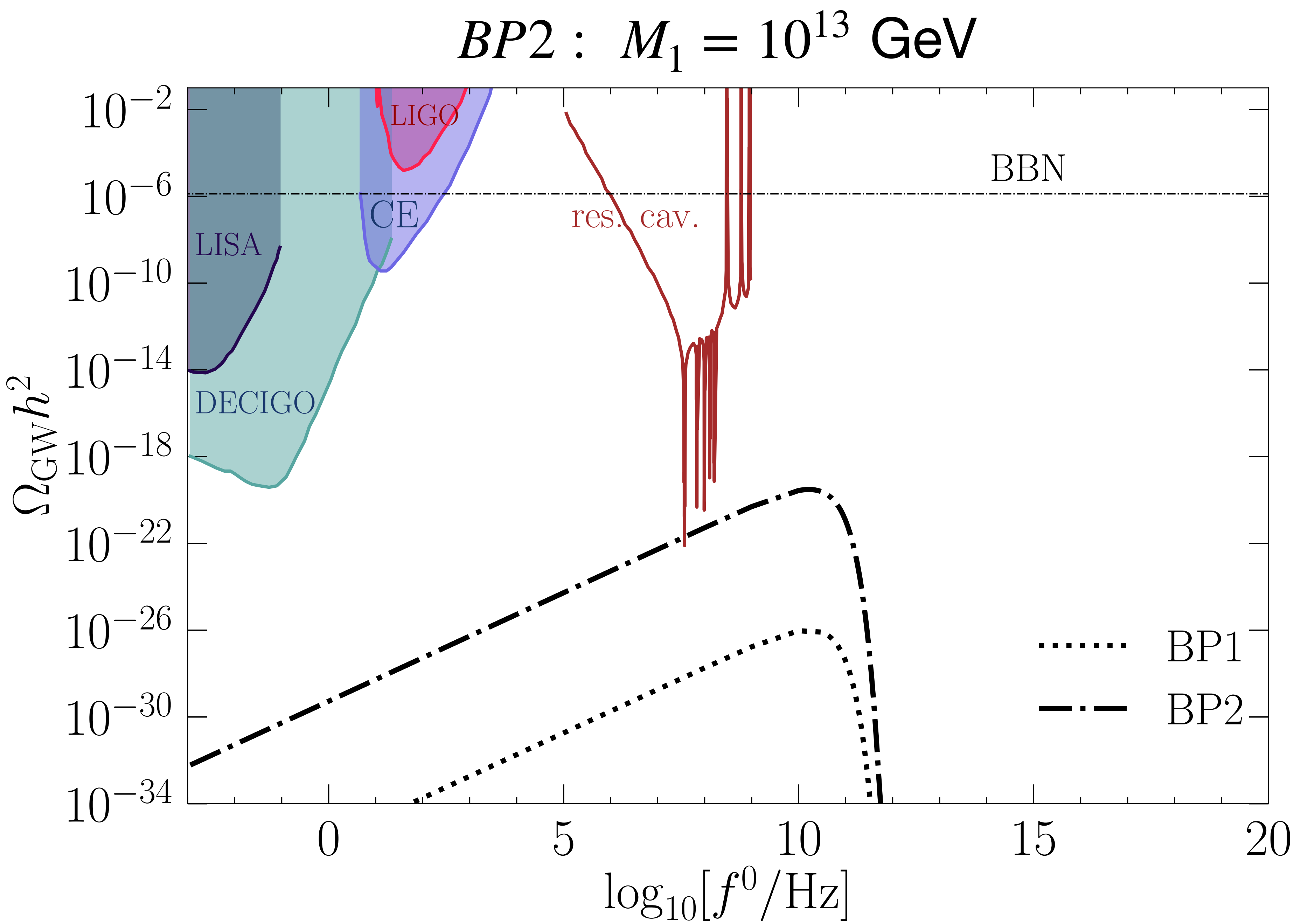

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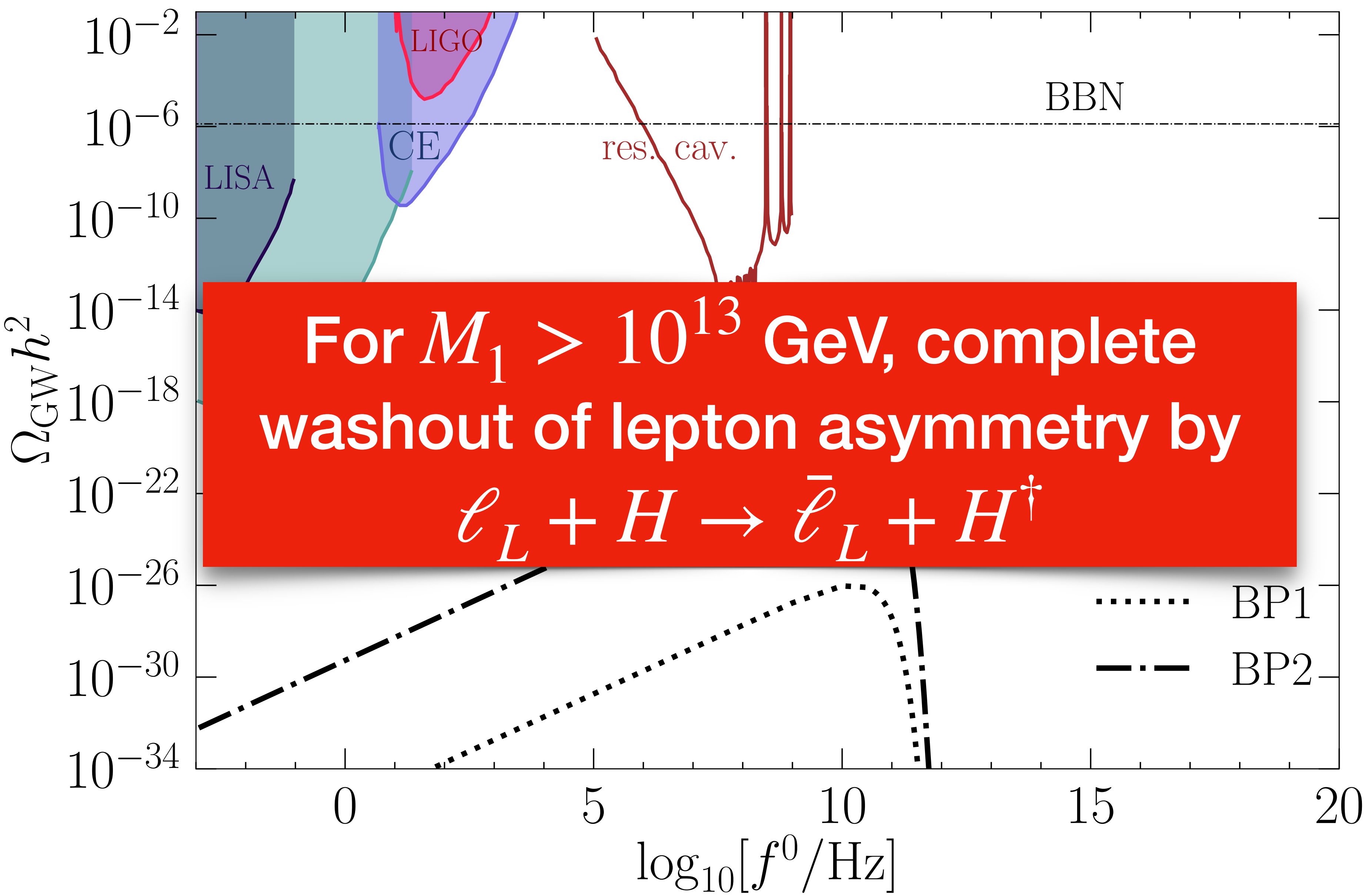
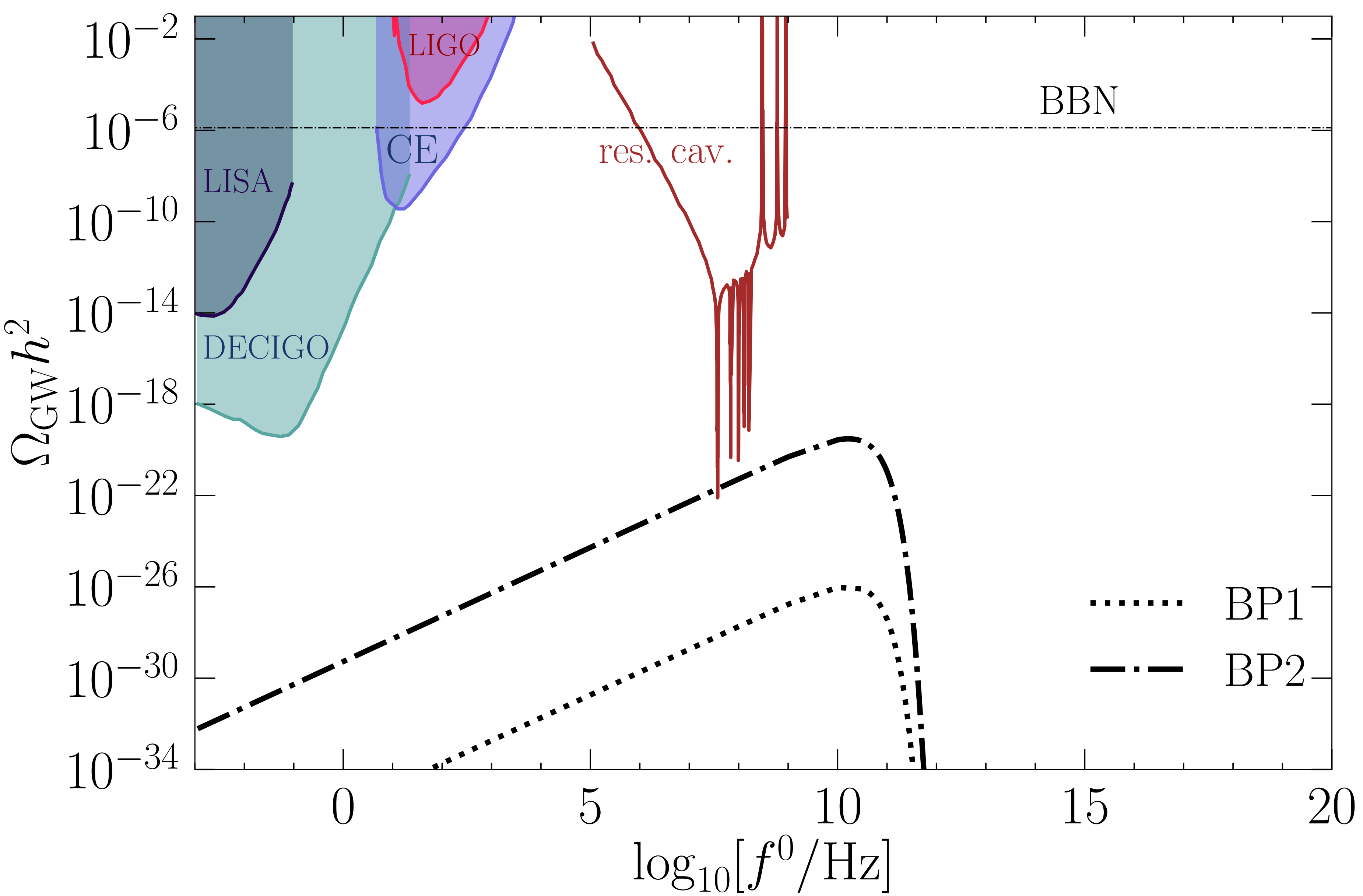


For $M_1 > 10^{13}$ GeV, complete washout of lepton asymmetry by $\ell_L + H \to \bar{\ell}_L + H^\dagger$

Actual scenario: with Leptogenesis



Actual scenario: with nonthermal Leptogenesis

$$\frac{M_N}{2}\overline{N^c}N \longrightarrow \phi\overline{N^c}N$$

$$\downarrow$$

$T_* = 10^{12}$ GeV : ϕ gets large vev and RHN gets huge mass

$$\downarrow$$

$M_1 = 10^{15}$ GeV

$$\downarrow$$

No inverse decay

$$\downarrow$$

“Non thermal” Leptogenesis

Actual scenario: with nonthermal Leptogenesis

$$\frac{M_N}{2}\overline{N^c}N \longrightarrow \phi\overline{N^c}N$$

$\downarrow$

$T_* = 10^{12}$ GeV : ϕ gets large vev and RHN gets huge mass

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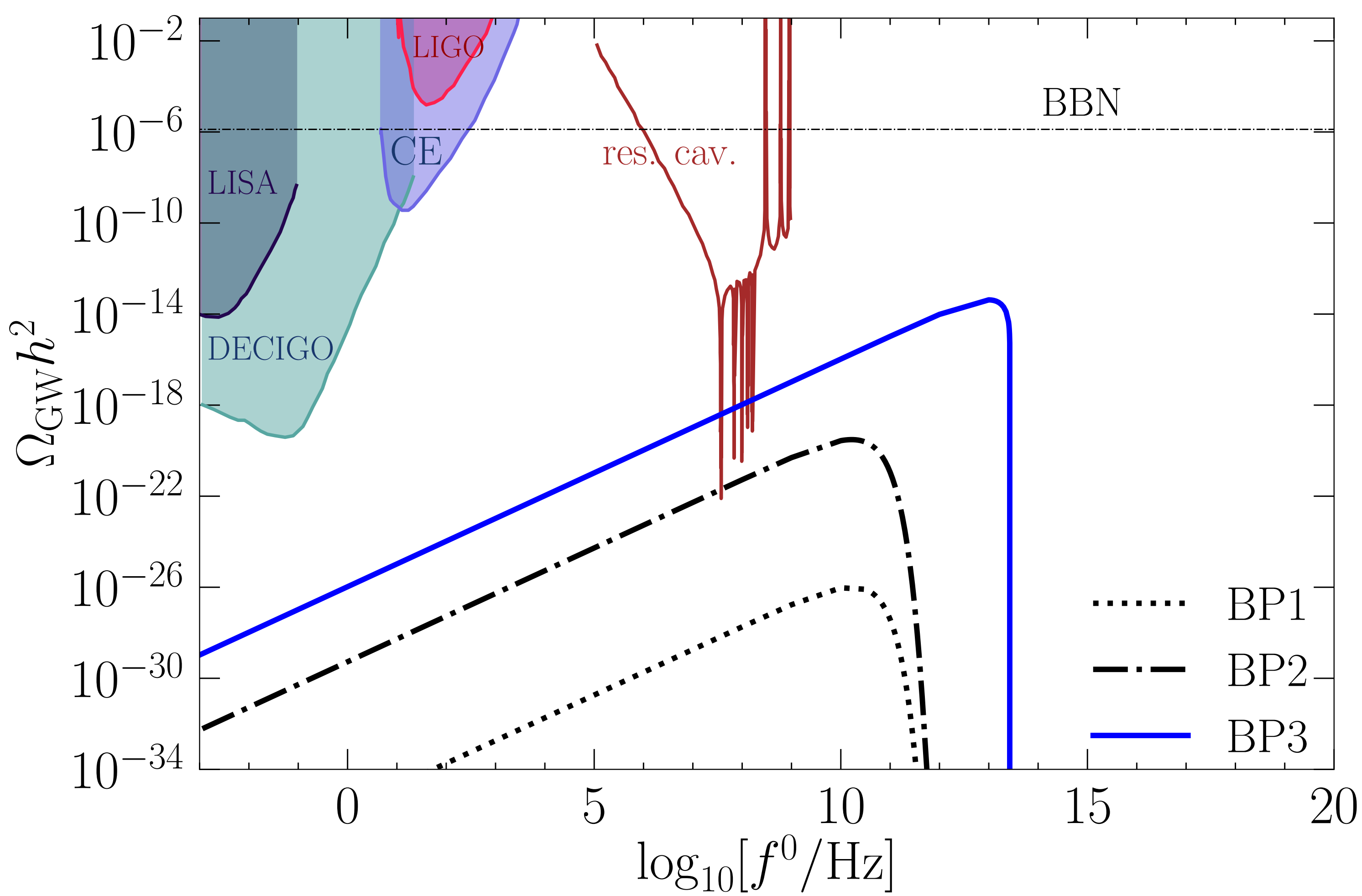
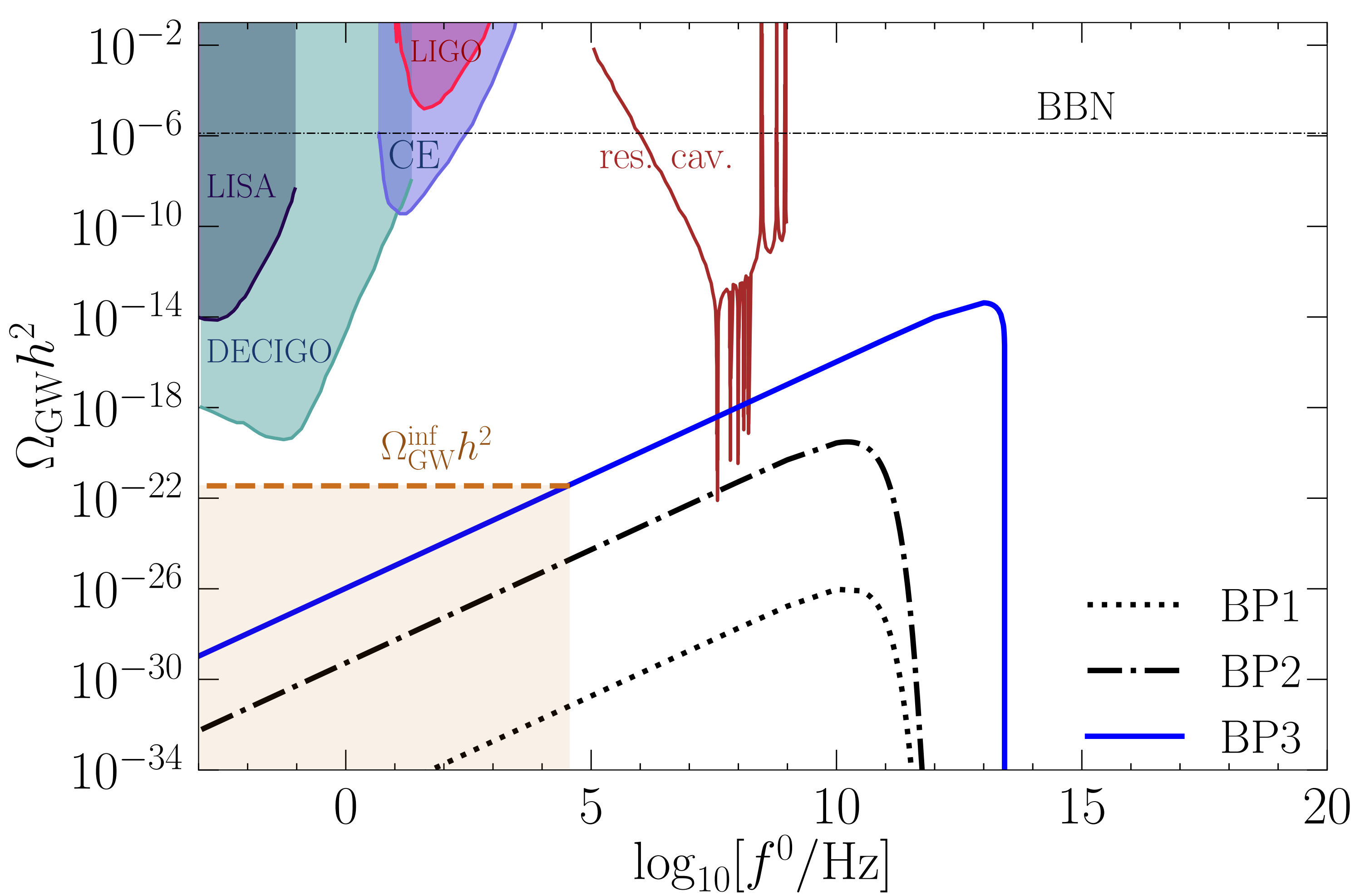


Other sources: inflationary tensor modes

$$h^2\Omega_{\rm GW}^{\rm inf} \simeq 3.5\times10^{-22}\left(\frac{g_*^{RH}}{106.75}\right)^{-1/2}\left(\frac{H_{end}}{1.43\times10^{10}\ \text{GeV}}\right)^2$$

$$f \leq f_{RH} = 4\times10^4\ \text{Hz}\left(\frac{g_*^{RH}}{106.75}\right)^{-\frac{1}{12}}\left(\frac{H_{end}}{1.43\times10^{10}\ \text{GeV}}\right)$$



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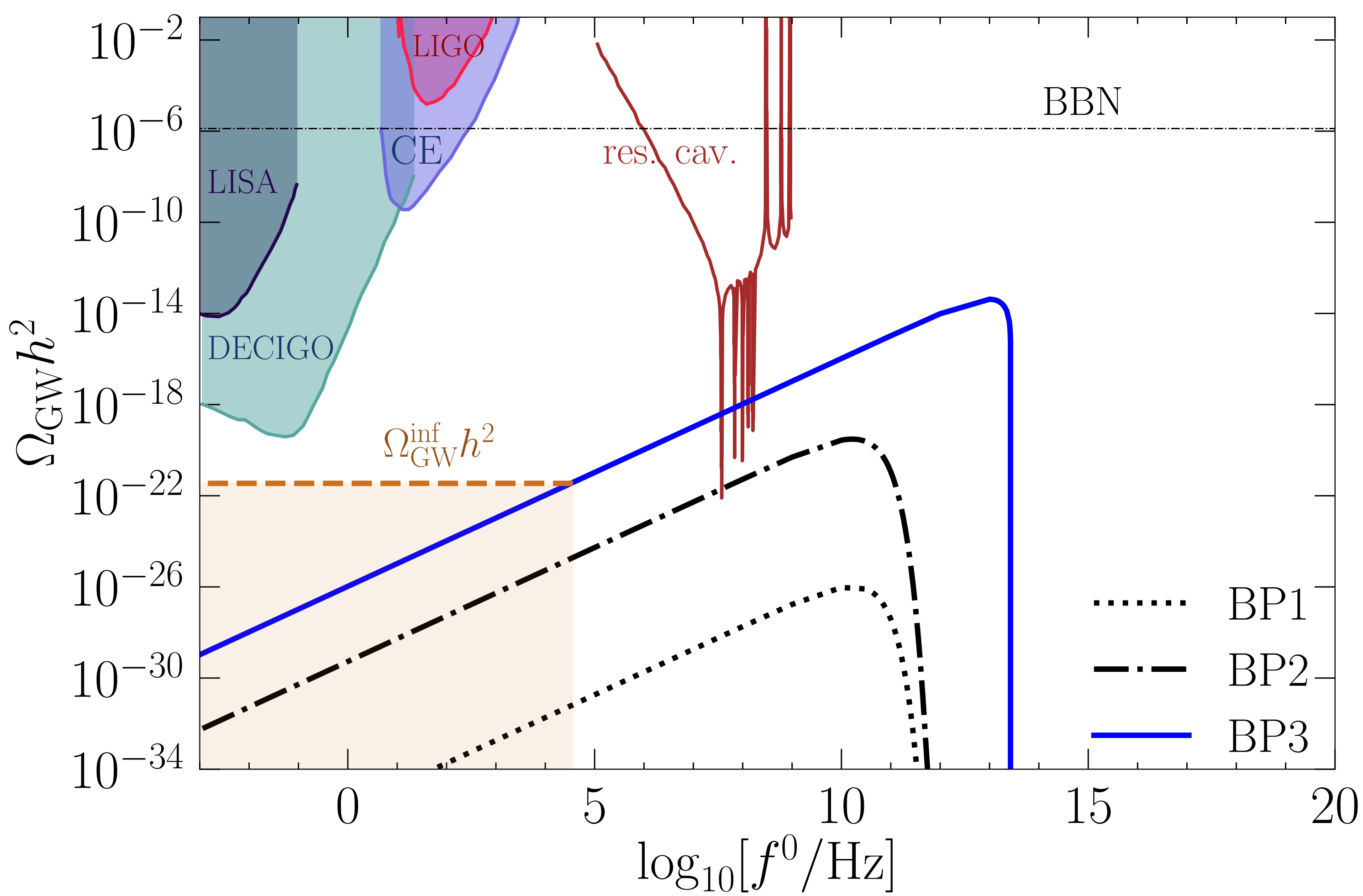

Very high frequency

No contamination

detectable in future experiments

Conclusion:

- High scale seesaw mechanism can generate baryon asymmetry via Leptogenesis mechanism.
- We **cannot** probe **high scale** seesaw mechanism in **colliders**.
- **Gravitational bremsstrahlung** from this heavy seesaw state decay provides a new source of stochastic high frequency gravitational waves.
- Although strength is **suppressed** due to the **presence of Planck mass**, the signal is **not contaminated** by other gravitational wave sources.
- Though **undetectable** with **current experiments**, such spectra encode early-Universe particle physics at extremely high scales.
- **Future cavity experiments** may have the **ability to detect** such signal and probe the **High scale seesaw** along with **Leptogenesis** mechanism.

Thank you!!