Inflationary Gravitational Wave Spectral Shapes as test for Low-Scale Leptogenesis

Based on arXiv : 2405.06603

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Baryon asymmetry of the universe (BAU)

$$\eta_B^{\text{CMB}} = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.21 \pm 0.16) \times 10^{-10}$$

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Inflationary epoch: Dilutes any pre-existing asymmetry

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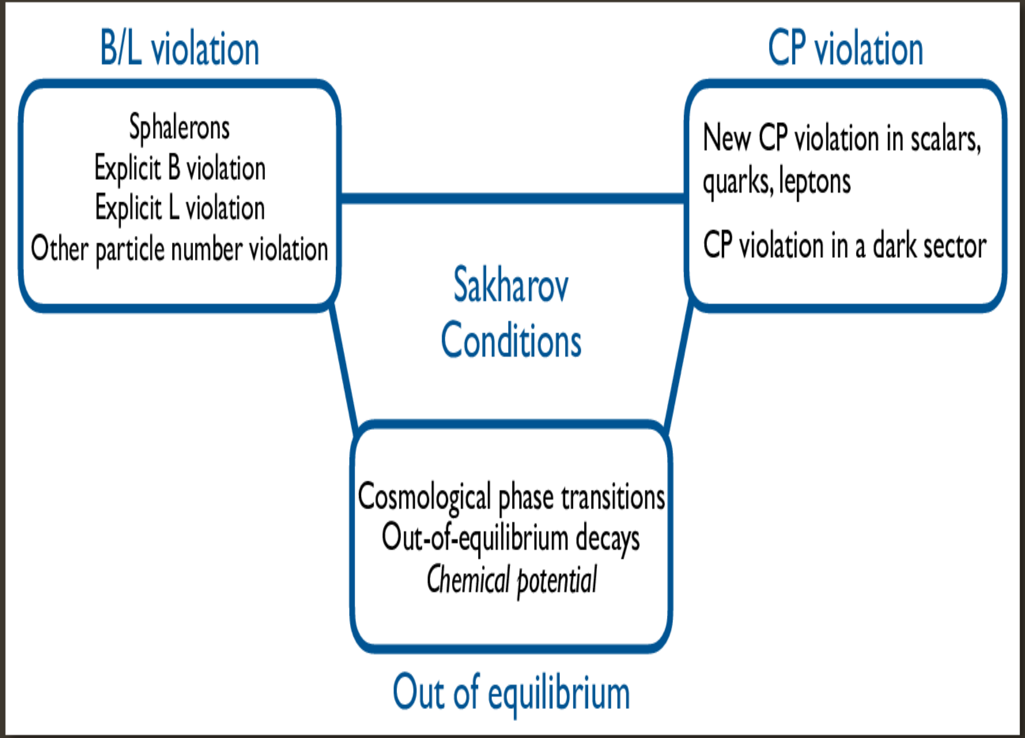

arXiv: 2203.05010

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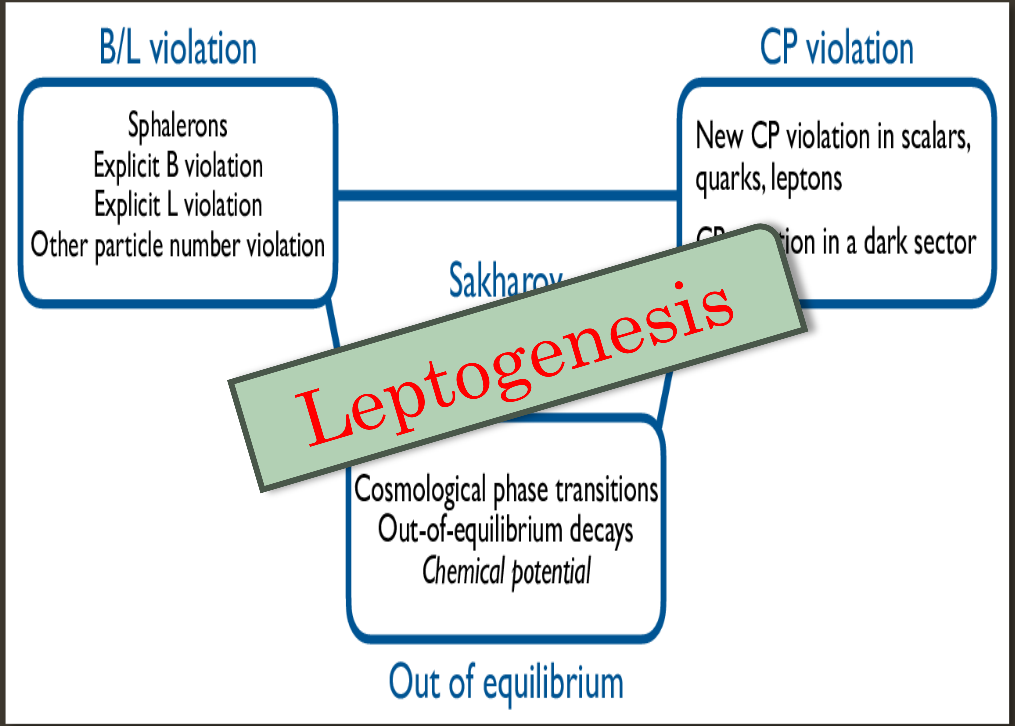

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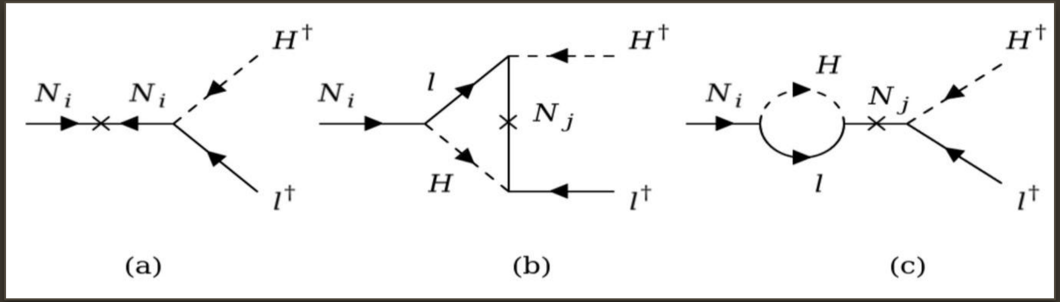
Leptogensis:



Thermal Leptogenesis	• Leptogenesis Scale : Very high (Difficult to test) • Davidson Ibara bound : $M_1 \gtrsim 10^9$ GeV
Non-thermal Leptogenesis	• Leptogenesis Scale : $M_1 \gtrsim 10^6$ GeV (Difficult to test)
Resonant Leptogenesis	• Leptogenesis Scale : $M_1 \sim 100$ GeV (Testable)

Leptogenesis via scalar decay

Model setup: →

$$\mathcal{L}_{thermal} = \mathcal{L}_{\rm SM} + i\overline{N}\not{\partial}N - \left(\lambda\overline{L}\tilde{H}N + \frac{M_N}{2}\overline{N^C}N + \text{h.c}\right)$$

$$\mathcal{L}_{\rm nonthermal} = \mathcal{L}_{\rm thermal} - \left(\frac{y_N}{2}\phi\overline{N^C}N + \frac{y_R}{2}\phi\bar{f}f + \text{h.c}\right)$$

We have considered resonant leptogenesis for this work!

$$T_\phi = \left(\frac{90}{8\pi^3 g_*(T_\phi)}\right)^{\frac{1}{4}}\sqrt{\Gamma_\phi M_{\rm pl}}\,, \quad T_{N_1} \approx M_1\sqrt{K}$$

$$\Gamma_\phi = \Gamma_{\phi\to N_1N_1} + \Gamma_{\phi\to N_2N_2} + \Gamma_{\phi\to R}$$

$$\Gamma_{\phi\to N_iN_i} = \frac{|y_{N_i}|^2}{16\pi}M_\phi\left(1 - \frac{4M_i^2}{M_\phi^2}\right)^{3/2}, \quad \Gamma_{\phi\to R} = \frac{|y_R|^2}{8\pi}M_\phi$$

- $y_R = 0 \to$ For non-thermal case
- $y_R \gtrsim \frac{1}{y_{N_1}}\sqrt{\frac{T_\phi}{M_{\rm pl}}} \to$ For thermal case

Boltzmann equations

$$\dot{\rho}_\phi = -3H\rho_\phi - \Gamma_\phi\, \rho_\phi$$

$$\dot{\rho}_{N_1} = -3H\rho_{N_1} + \Gamma_{\phi\to N_1 N_1}\, \rho_\phi - \Gamma_{N_1}(\rho_{N_1} - \rho^{eq}_{N_1})$$

$$\dot{\rho}_{N_2} = -3H\rho_{N_2} + \Gamma_{\phi\to N_2 N_2}\, \rho_\phi - \Gamma_{N_2}(\rho_{N_2} - \rho^{eq}_{N_2})$$

$$\dot{n}_{B-L} = -3Hn_{B-L} - \epsilon \sum_{i=1}^{2} \Gamma_{N_i}(n_{N_i} - n^{eq}_{N_i}) - \Gamma_{ID}\, n_{B-L}$$

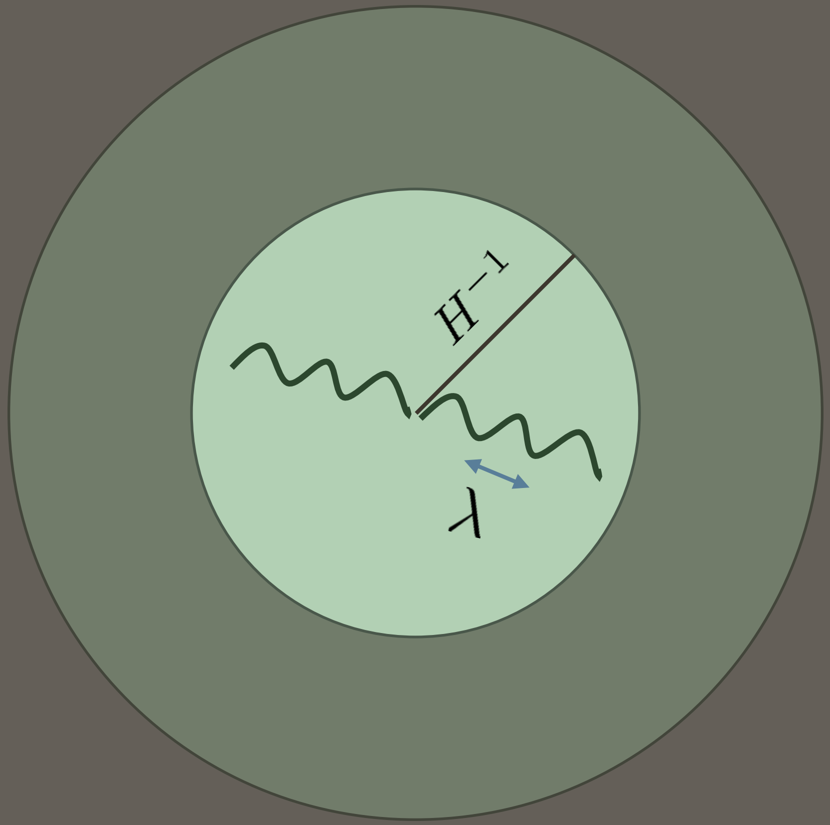
$$\dot{\rho}_R = -4H\rho_R + \Gamma_{\phi\to R}\, \rho_\phi + \sum_{i=1}^{2} \Gamma_{N_i}(\rho_{N_i} - \rho^{eq}_{N_i})$$

$$\kappa_f = -\tfrac{4}{3}\epsilon^{-1} R^{-3/4} \tilde{N}_{\text{B-L}} \left[\frac{\pi^4 g_*^{3/4}}{30^3 \zeta(3)^4}\right]$$

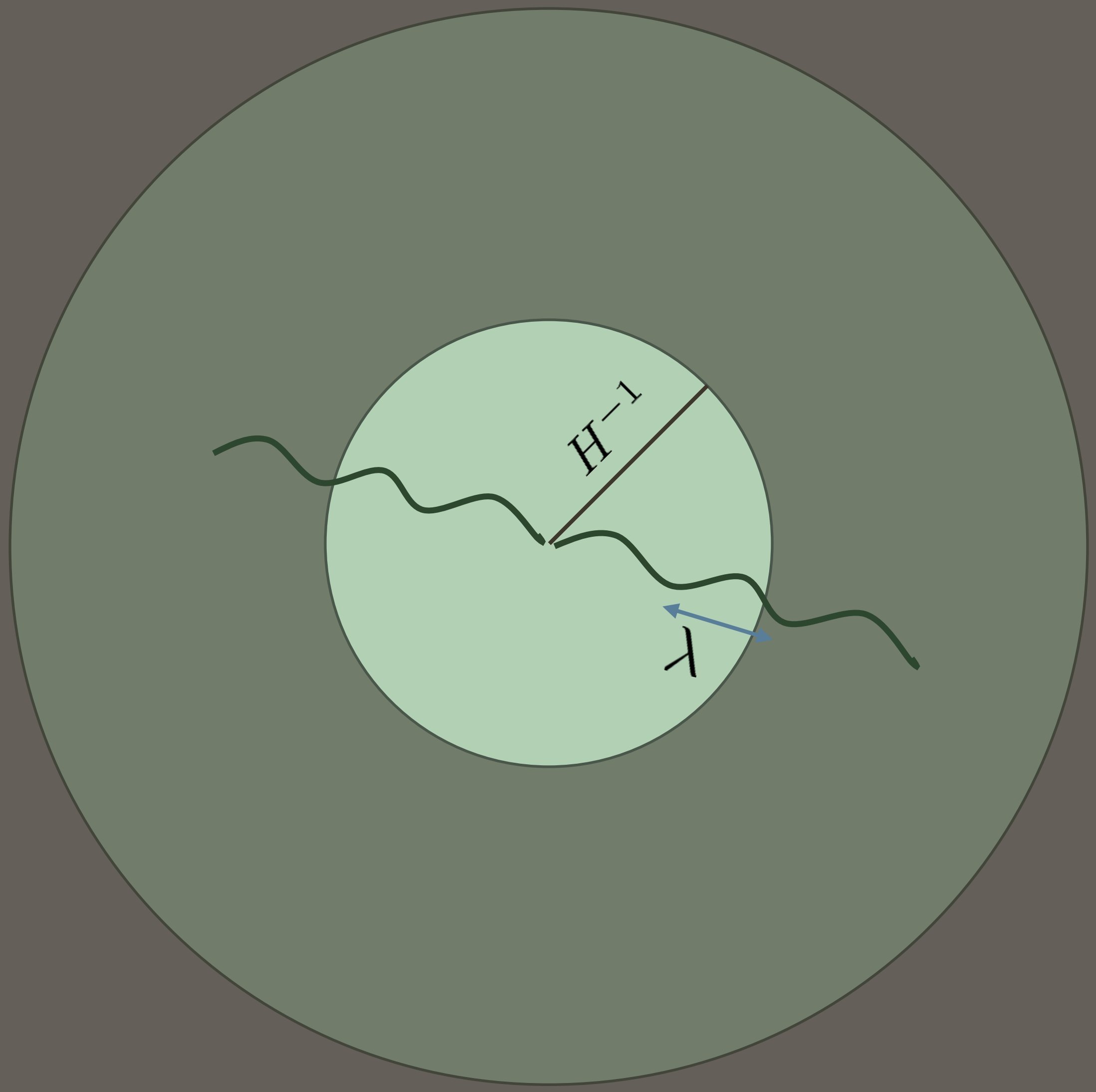
Woernle et al 0801.3972

Inflationary Gravitational wave (GW)

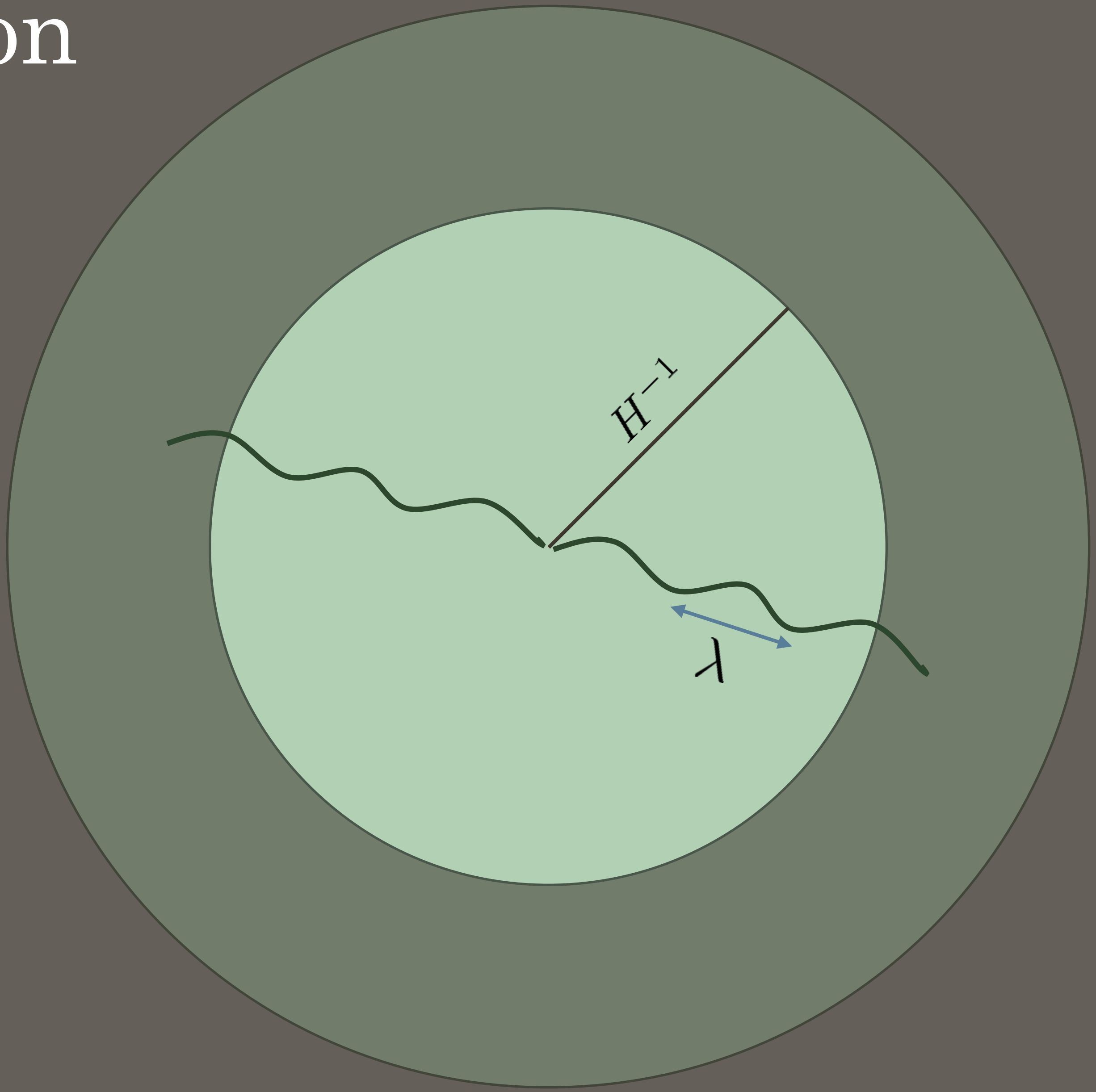
Inflation



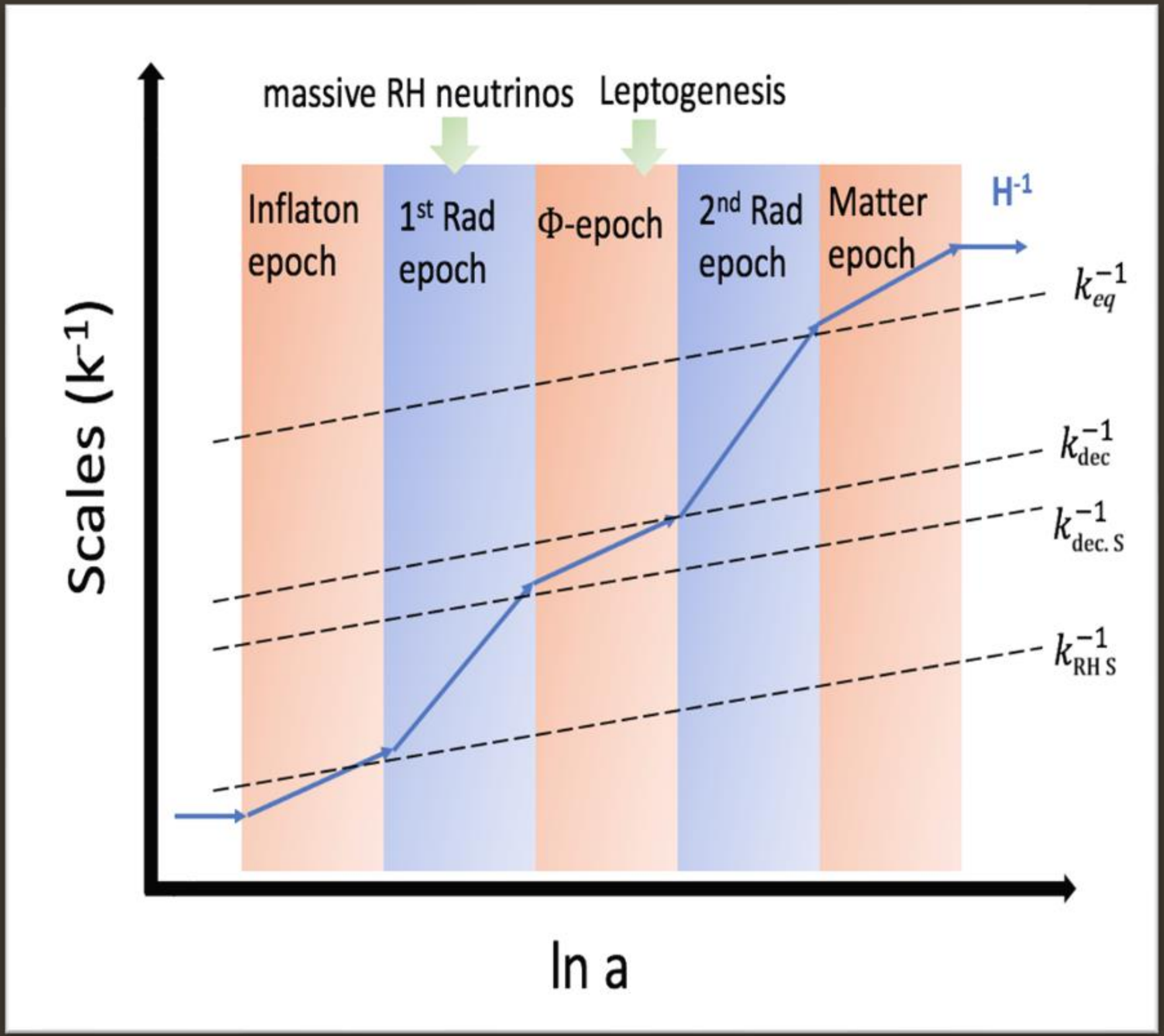
Inflation



Post-inflation



Intermediate matter domination



S. Dutta et. al., JHEP (2022).

Inflationary Gravitational wave (GW)

$$F(k)_{\text{standard}} = T_1^2\left(\frac{k}{k_{\text{eq.}}}\right) T_2^2\left(\frac{k}{k_{\text{RH}}}\right)$$

$$\Omega_{GW}(k) = \frac{1}{12}\left(\frac{k}{a_0 H_0}\right)^2 T_T^2(k) P_T^{\text{prim.}}(k)$$

$$T_1^2(x) = 1 + 1.57x + 3.42x^2$$

$$T_2^2(x) = \left(1 - 0.22x^{3/2} + 0.65x^2\right)^{-1}$$

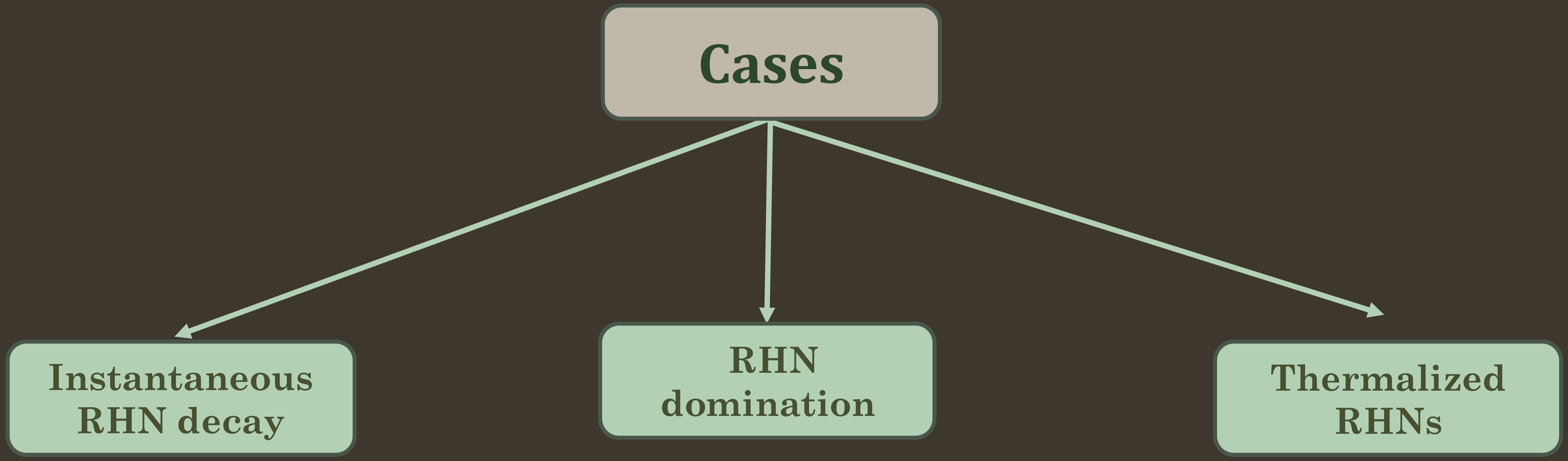
$$T_3^2(x) = 1 + 0.59x + 0.65x^2$$

$$F(k)_{\text{IMD}} = T_1^2\left(\frac{k}{k_{\text{eq.}}}\right) T_2^2\left(\frac{k}{k_{\text{dec.}}}\right) T_3^2\left(\frac{k}{k_{\text{dec. S}}}\right) T_2^2\left(\frac{k}{k_{\text{RH S}}}\right)$$

Thermal Leptogensis

$$F(k)_{\text{IMD}}^{\text{2-step}} = T_1^2\left(\frac{k}{k_{\text{eq.}}}\right) T_2^2\left(\frac{k}{k_{\text{dec.}}^{\phi}}\right) T_3^2\left(\frac{k}{k_{\text{dec.S}}^{\phi}}\right) T_2^2\left(\frac{k}{k_{\text{dec.}}^{N}}\right) T_3^2\left(\frac{k}{k_{\text{dec.S}}^{N}}\right) T_2^2\left(\frac{k}{k_{\text{RH S}}^{\text{2-step}}}\right)$$

Classification of scenarios



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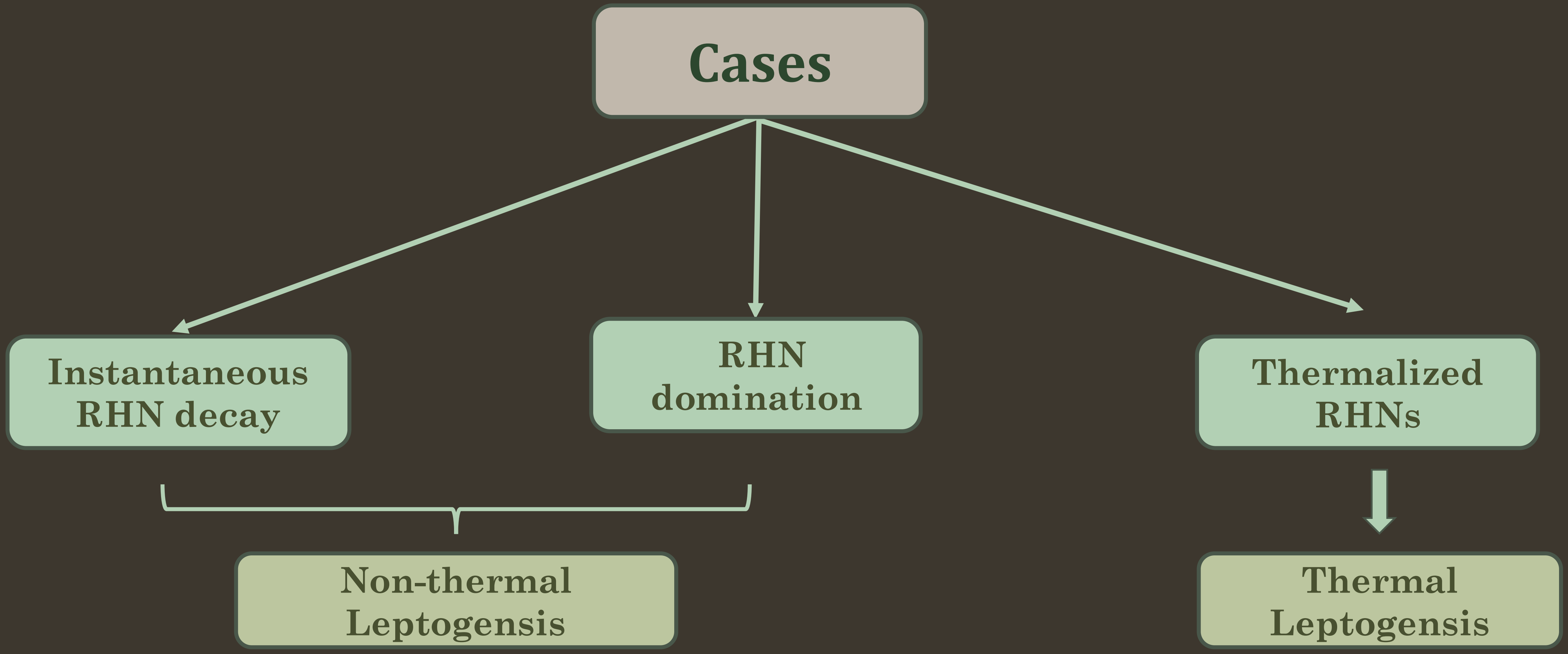


Classification of scenarios : Case (a)

Case (a)

Instantaneous RHN decay

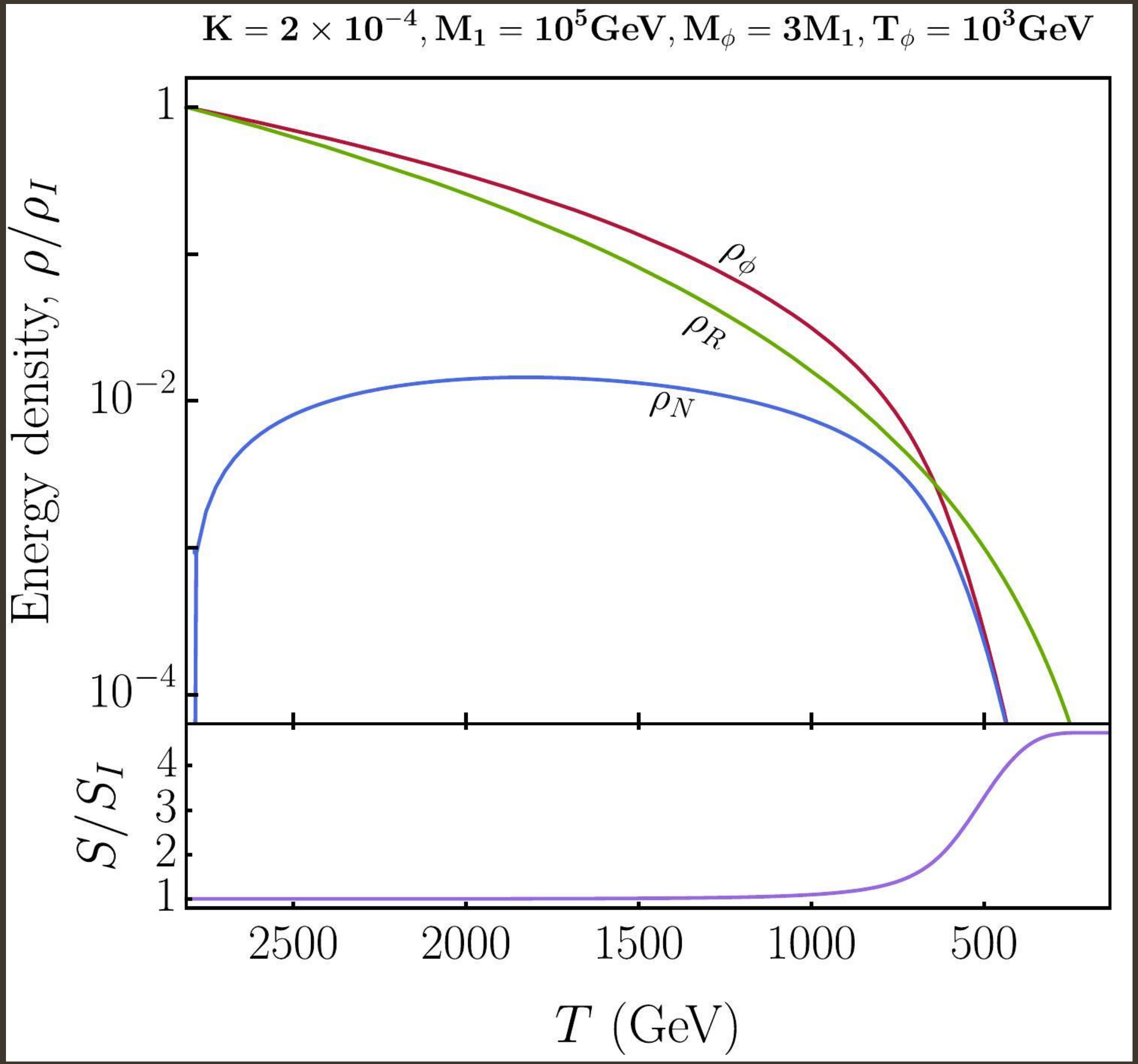
$\Gamma_N \gg \Gamma_\phi$

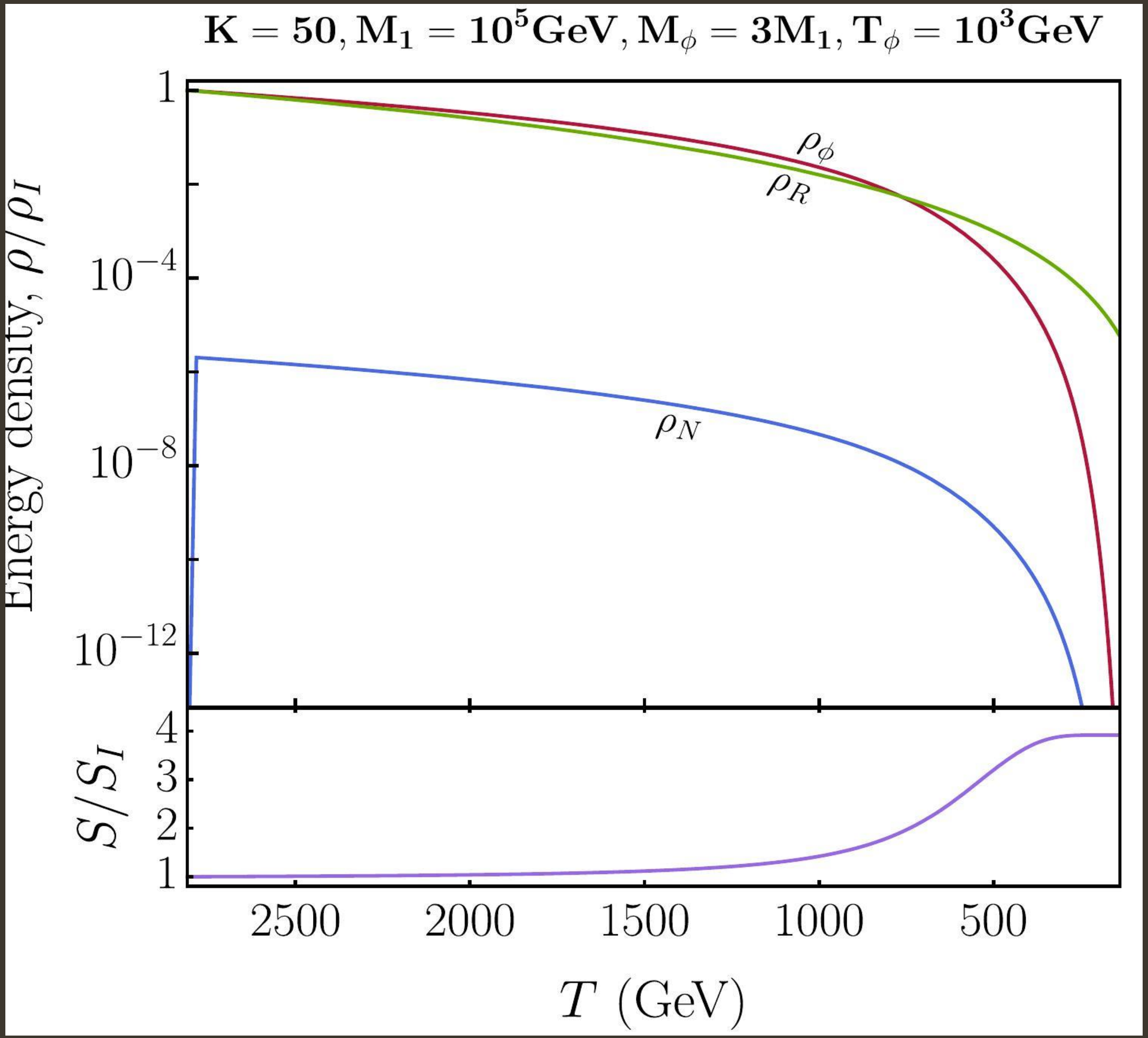
$T_{\mathrm{N}_1} > T_\phi$

RHN domination

Thermalized RHNs

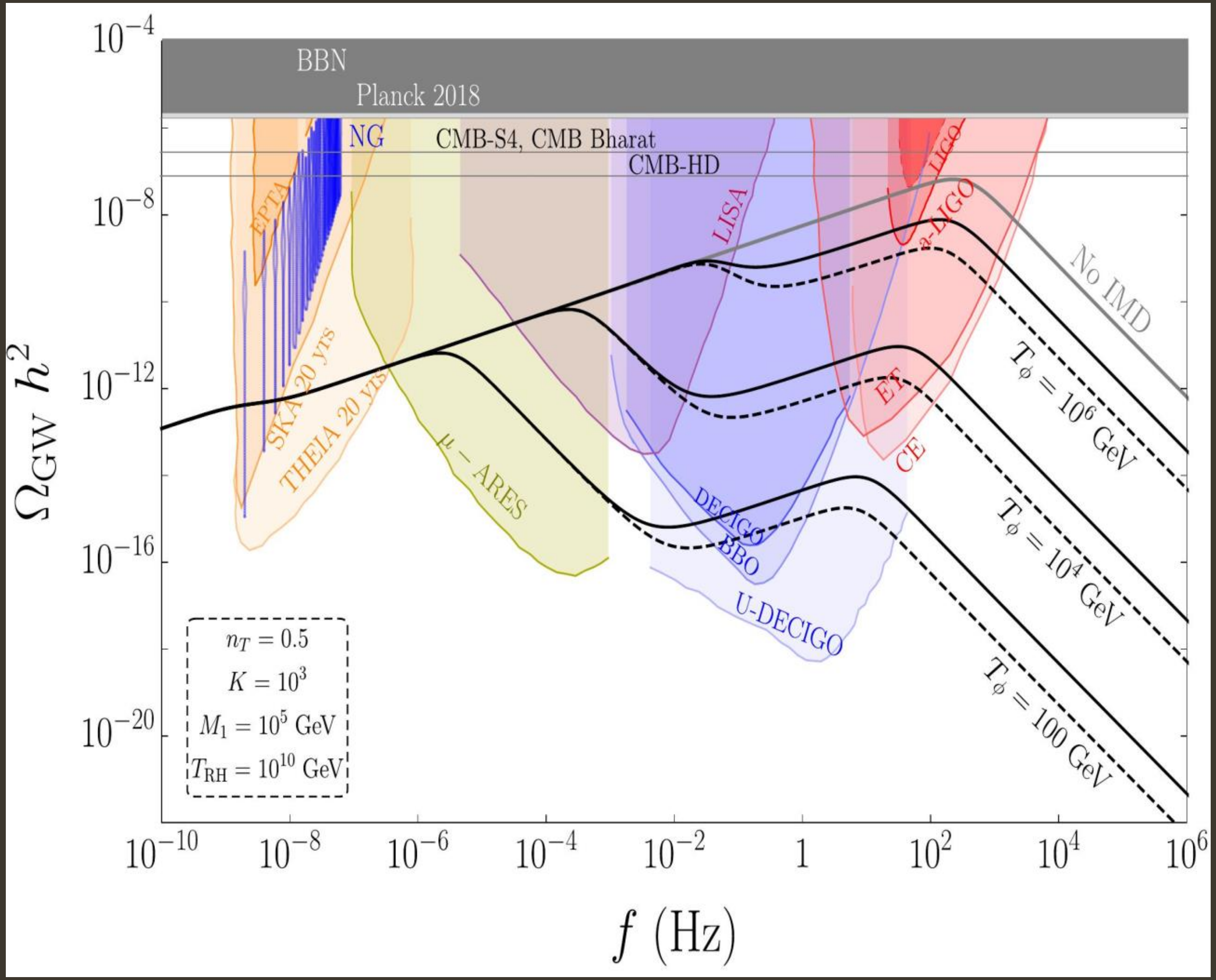
Case (a) : Instantaneous RHN decay





K<1 **K>1**

Case (a) : Gravitational wave spectrum



Case (a) : Gravitational wave spectrum

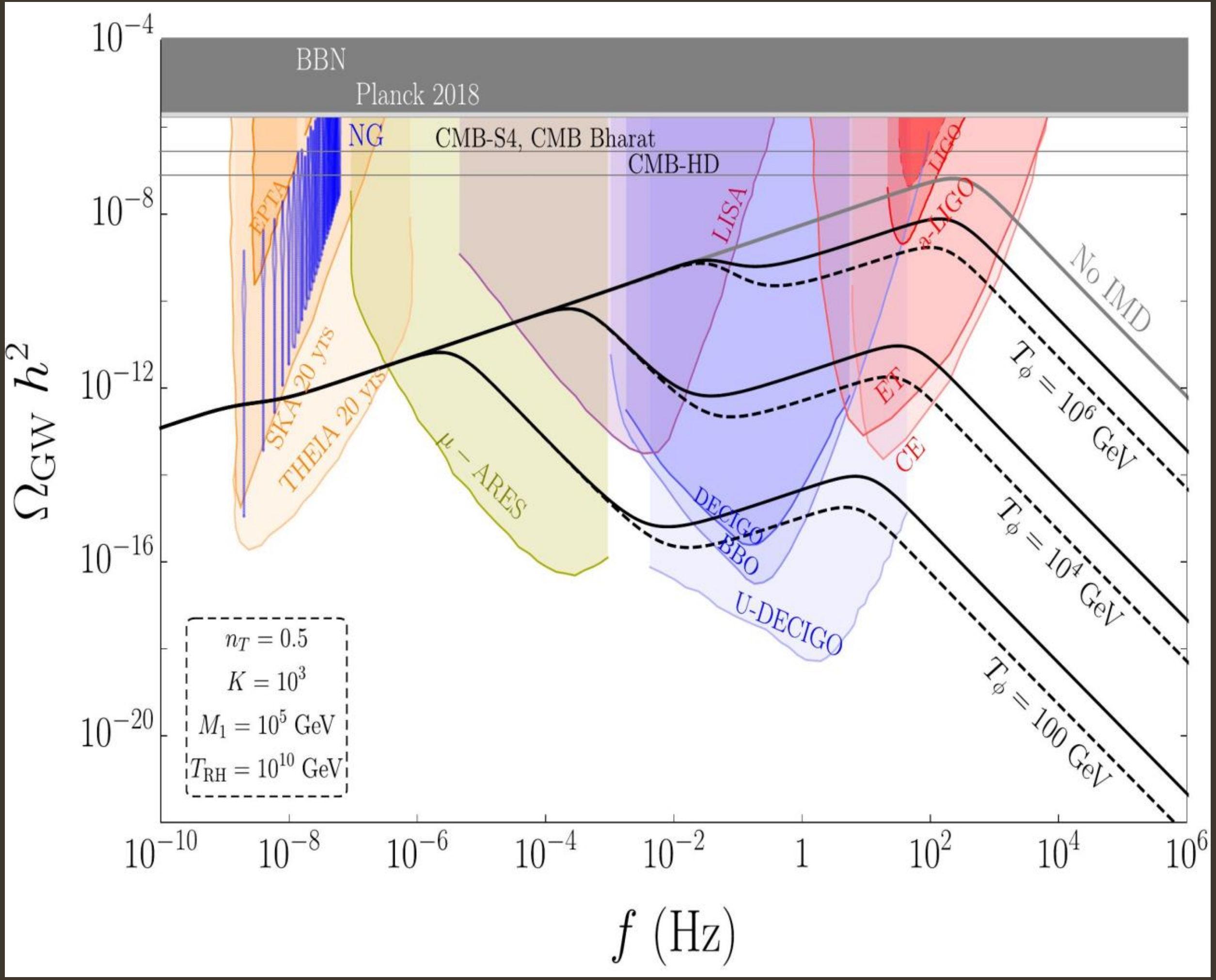
Dilution Factor from Entropy injection

$$\Delta = \frac{s(T_{\text{after}})a^3(T_{\text{after}})}{s(T_{\text{before}})a^3(T_{\text{before}})}$$

$$= \left(1 + 2.95\left(\frac{2\pi^2\langle g_*(T)\rangle}{45}\right)^{\frac{1}{3}} \frac{(\frac{n_\chi}{s}M_\chi)^{\frac{4}{3}}}{(M_{\text{pl}}\Gamma_\chi)^{\frac{2}{3}}}\right)^{\frac{3}{4}}$$

$$\left.\frac{n_\phi}{s}\right|_f = \frac{45\,\zeta(3)}{2\pi^4\, g_{*S}}$$

$$\Delta_\phi \simeq 3.7\times 10^9 \left(\frac{M_\phi}{10^{15}\ \text{GeV}}\right)\left(\frac{\text{TeV}}{T_\phi}\right)$$



Classification of scenarios :

Case (b)

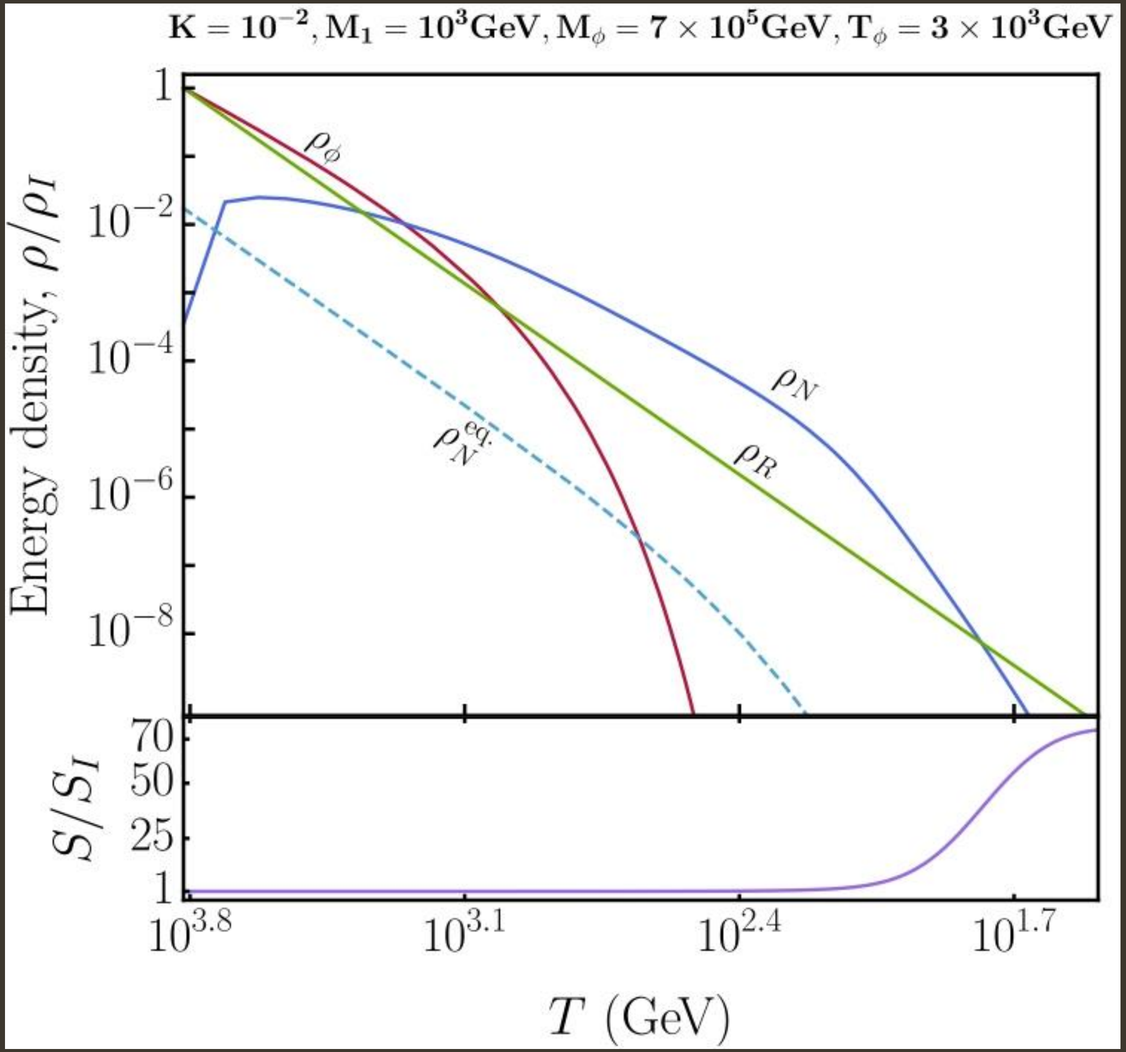
Instantaneous RHN decay

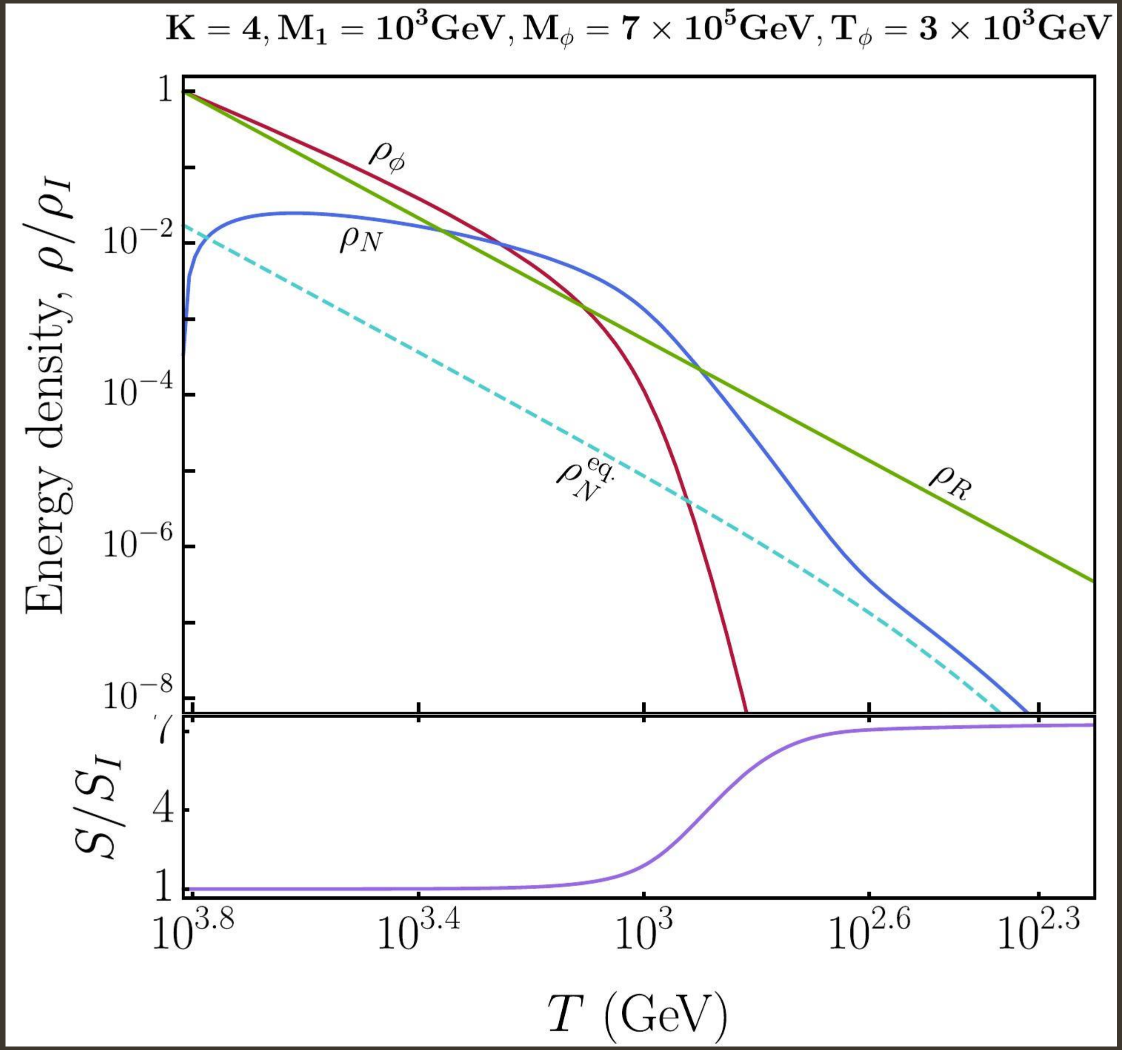
RHN domination

$$\Gamma_N \ll \Gamma_\phi$$
$$T_{N_1} < T_\phi$$

Thermalized RHNs

Case (b) : RHN domination

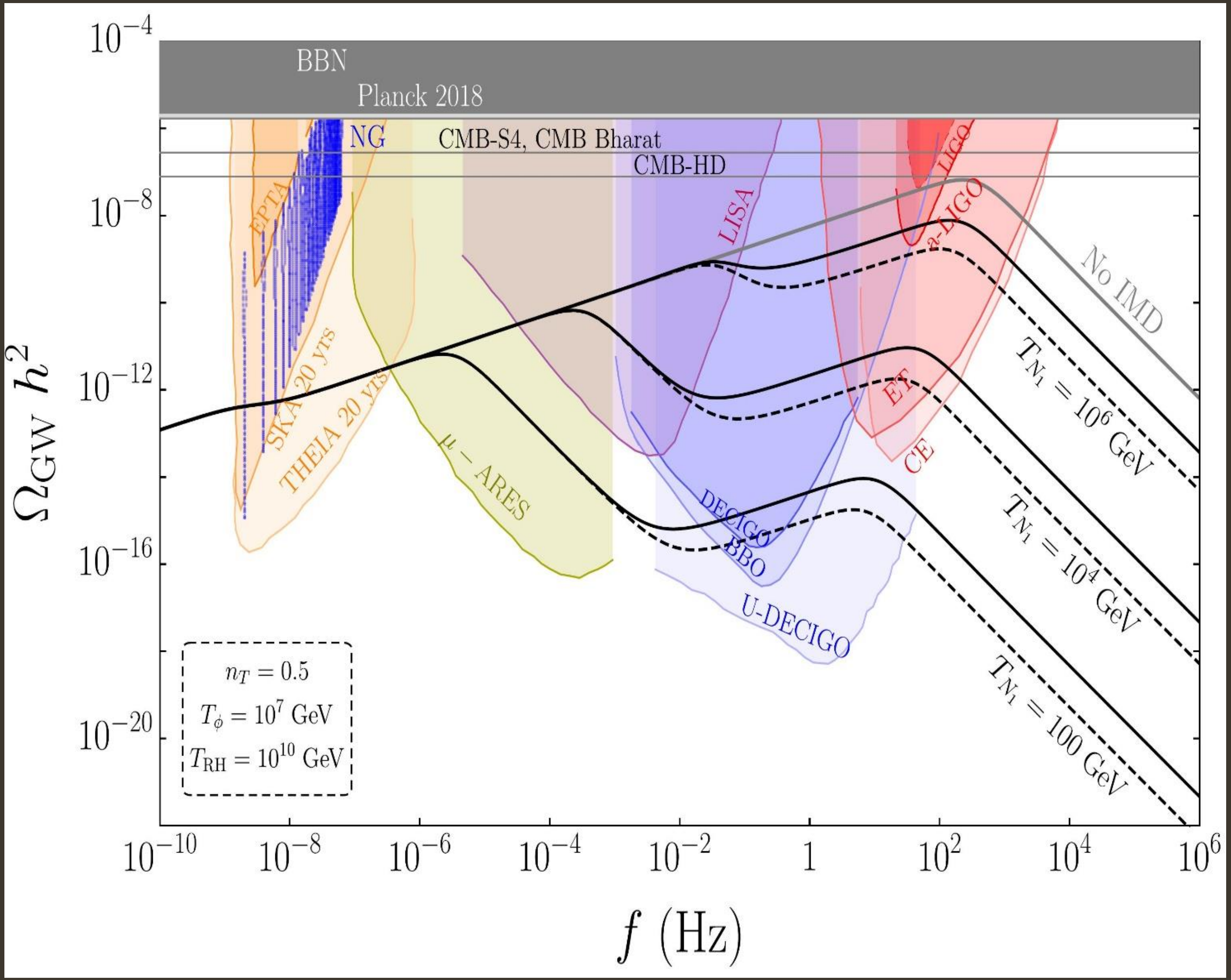




K<1

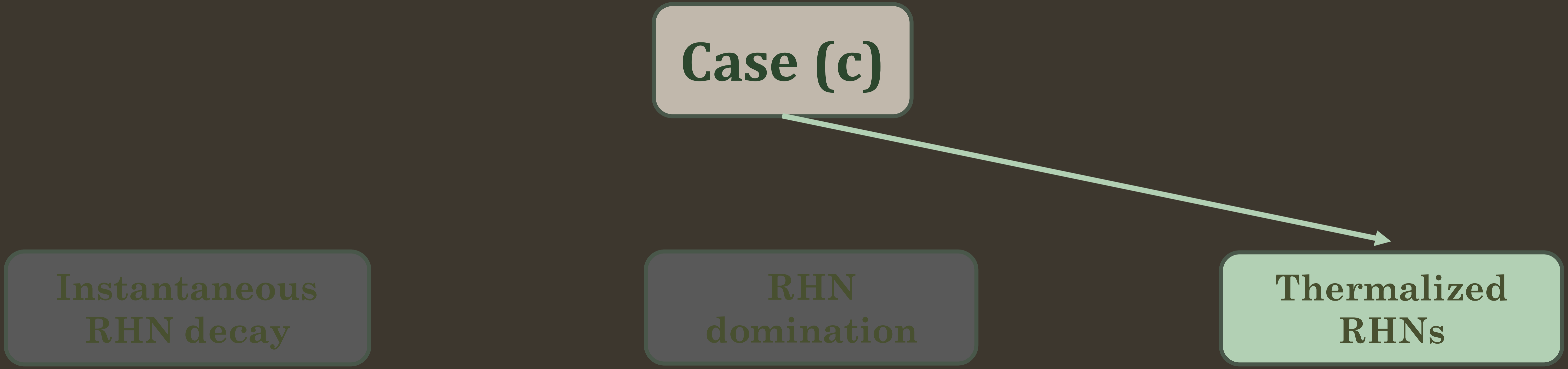
K>1

Case (b) : GW spectrum



$$\Delta \simeq 3.7 \times 10^9 \left(\frac{M_\phi}{10^{15}\ \text{GeV}}\right)\left(\frac{10^5\ \text{GeV}}{M_1}\right)\sqrt{\frac{10^{-4}}{K}}$$

Classification of scenarios : Case (c)



$$T_{N_1} \ll T_\phi$$

$$T_\phi \gg T_{dom}^{N_1}$$

$$T_{N_1} < T_{dom}^{N_1} \sim 2\% M_1$$

Classification of scenarios : Case (c)

Case (c)

Instantaneous RHN decay

RHN domination

Thermalized RHNs

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Two step entropy injection

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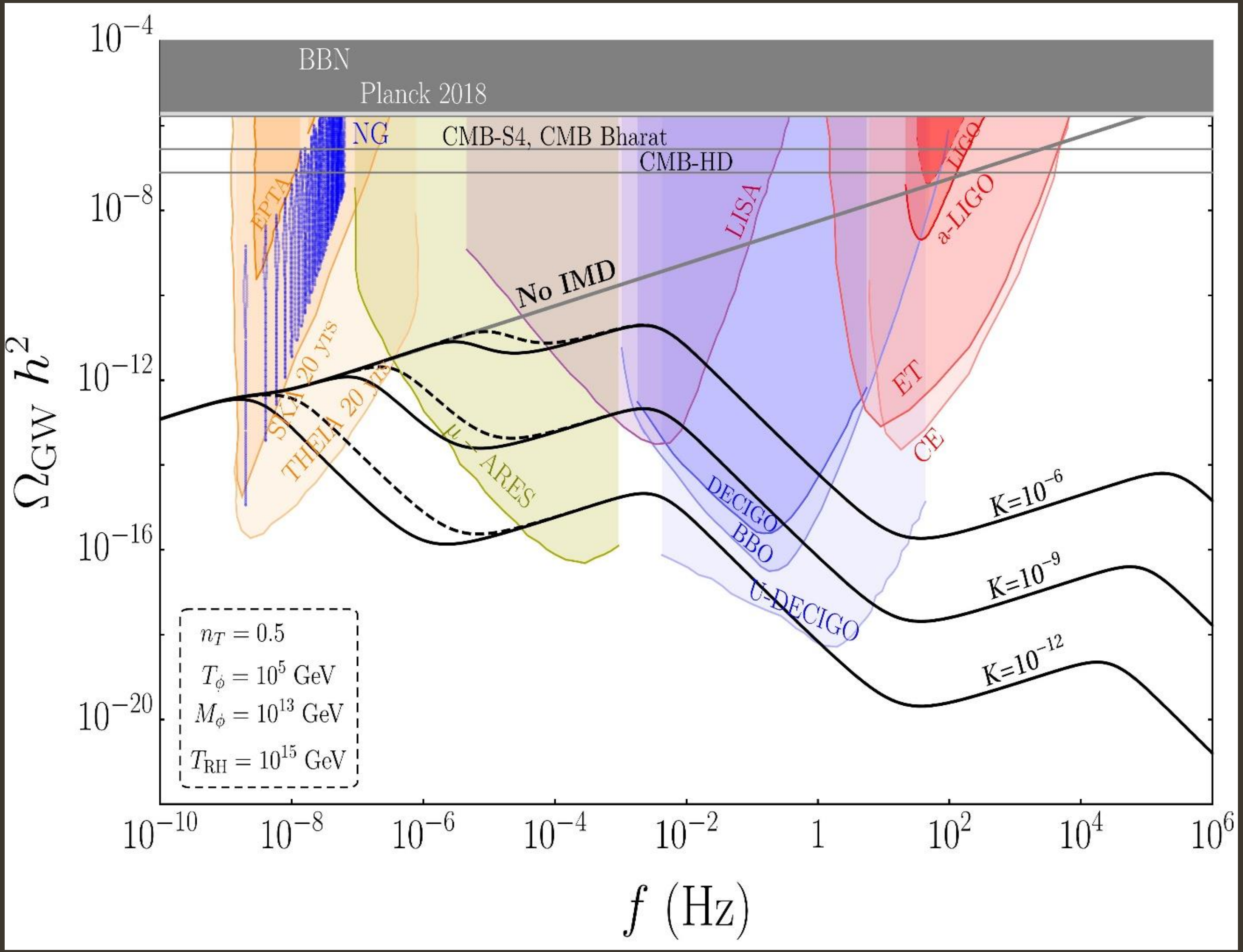
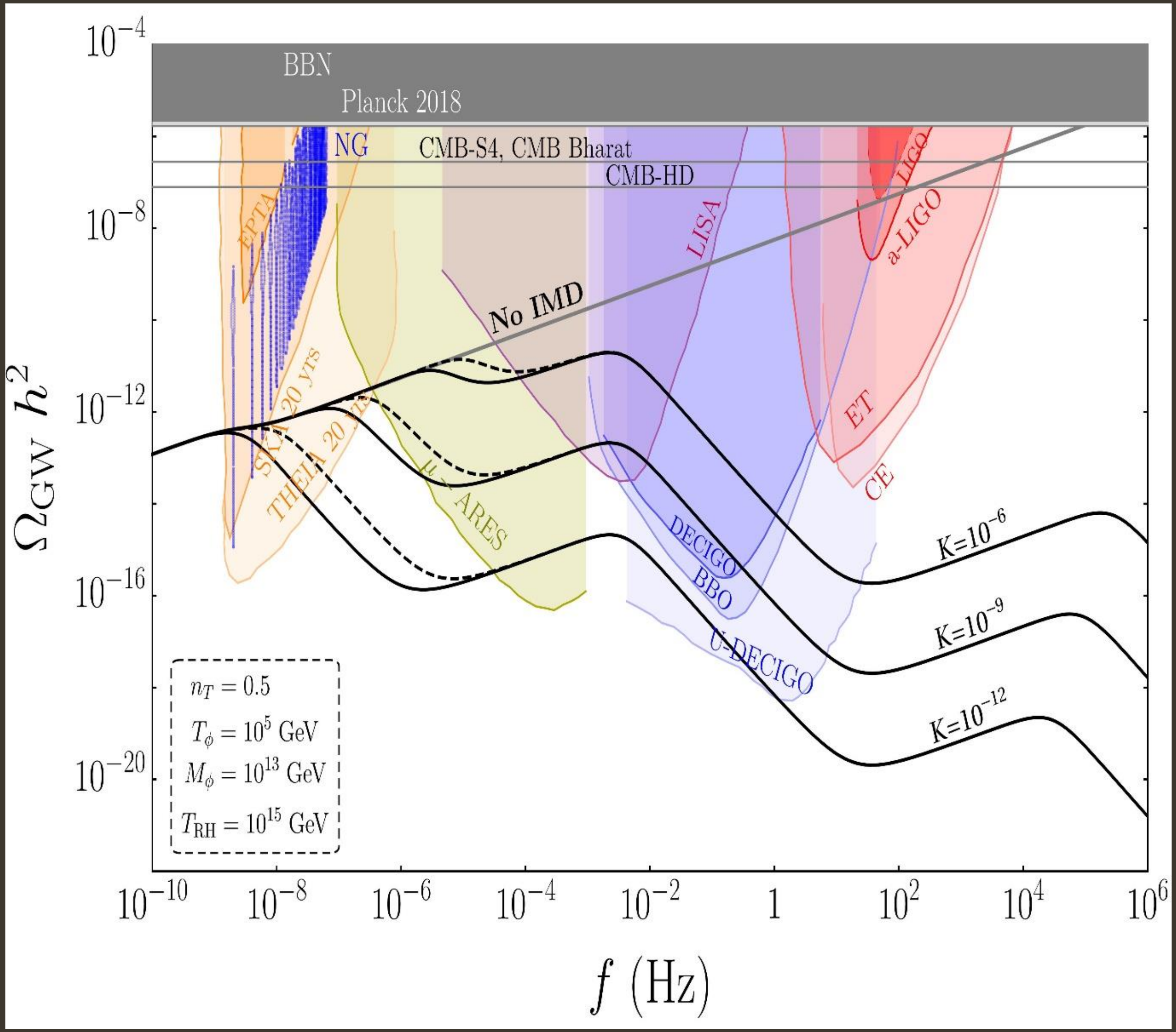
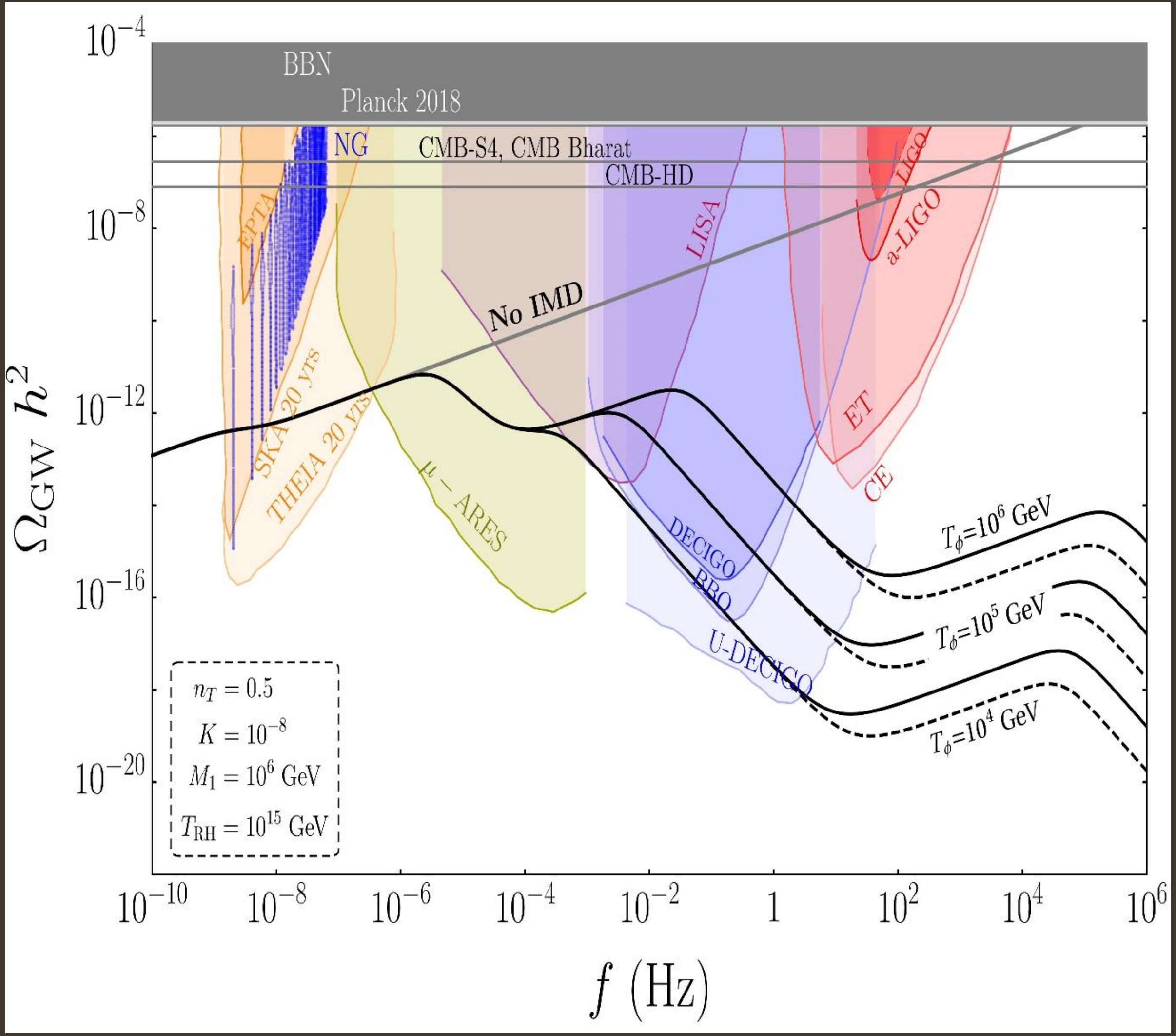


$$\Delta_N \simeq 1109 \sqrt{\frac{10^{-10}}{K}}$$

$$\Delta_\phi \simeq 3.7 \times 10^9 \left(\frac{M_\phi}{10^{15}\ \text{GeV}}\right)\left(\frac{\text{TeV}}{T_\phi}\right)$$

Two step entropy injection





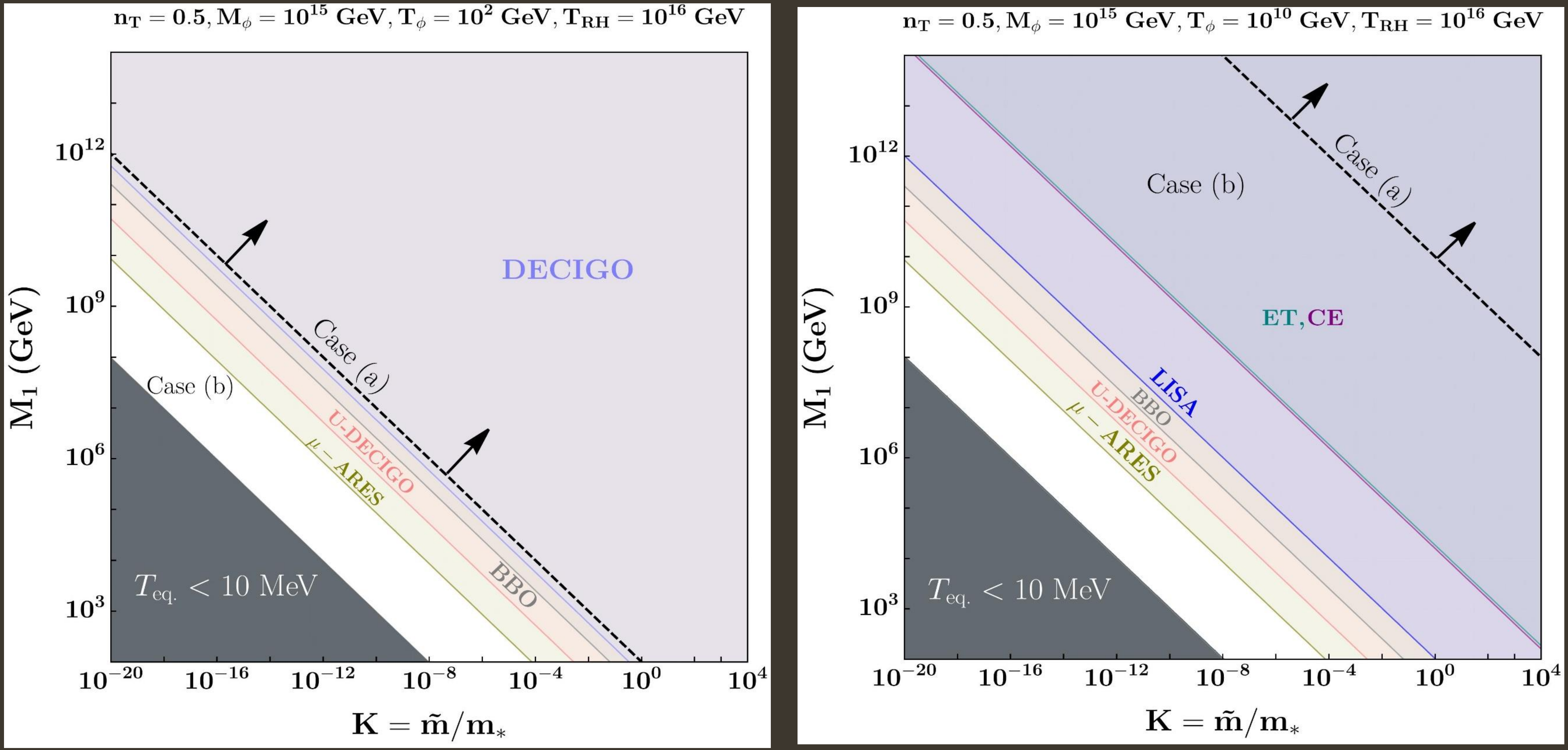
Signal to Noise ratio (SNR)

$$SNR = \frac{P_{signal}}{P_{noise}}$$

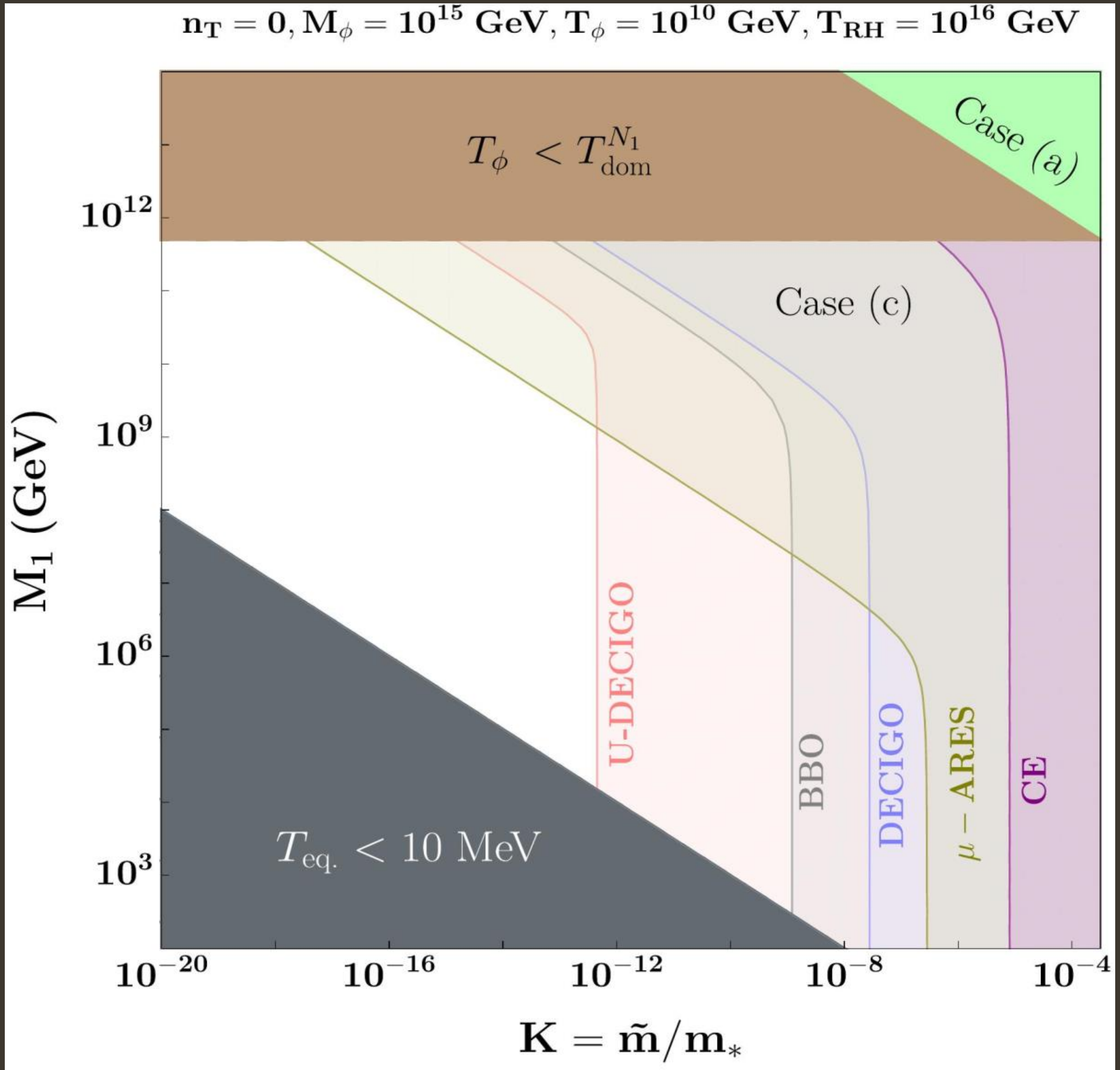
P_{signal}: Wanted component

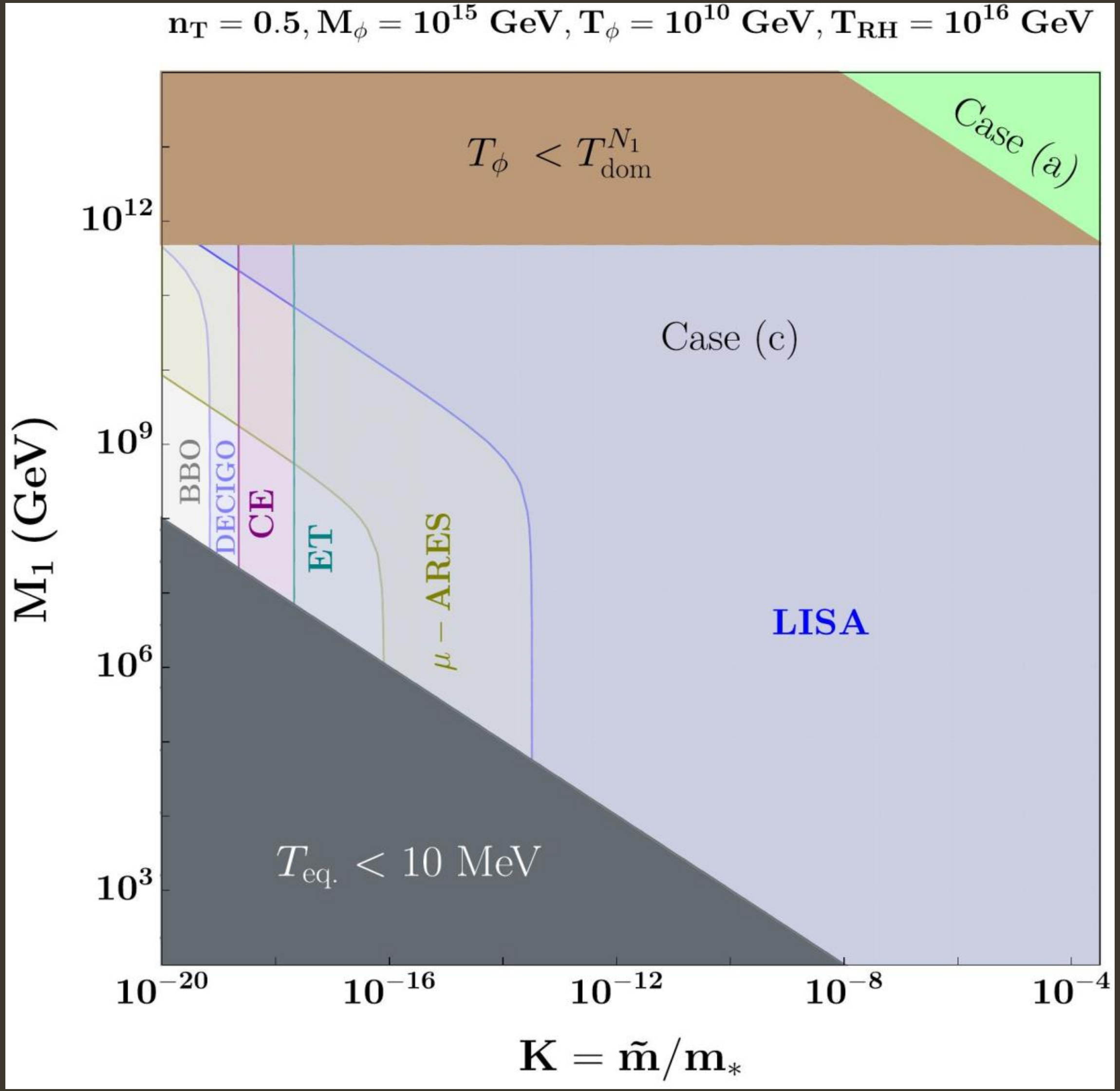
P_{noise}: Unwanted component

Non-Thermal Leptogenesis:



Thermal Leptogenesis:





Result :

$n_T = 0$

M_ϕ (GeV)	T_ϕ (GeV)	U-DECIGO	BBO	μ–ARES	LISA	ET	CE
10^{15}	10^{10}	Non-Th, Th	Non-Th, Th	Non-Th, Th	-	-	Non-Th, Th
	10^{6}	Non-Th, Th	Non-Th, Th	Non-Th, Th	-	-	-
	10^{2}	-	-	-	-	-	-
10^{10}	10^{6}	Non-Th	Non-Th	Non-Th	-	-	-
	10^{2}	-	-	-	-	-	-
10^{5}	10^{2}	Non-Th	Non-Th	Non-Th	-	-	-

$n_T = 0.5$

M_ϕ (GeV)	T_ϕ (GeV)	U-DECIGO	BBO	μ–ARES	LISA	ET	CE
10^{15}	10^{10}	Non-Th, Th	Non-Th, Th	Non-Th, Th	Non-Th, Th	Non-Th, Th	Non-Th, Th
	10^{6}	Non-Th, Th	Non-Th, Th	Non-Th, Th	Non-Th, Th	Non-Th, Th	Non-Th, Th
	10^{2}	Non-Th	Non-Th	Non-Th	-	-	-
10^{10}	10^{6}	Non-Th	Non-Th	Non-Th	Non-Th	Non-Th	Non-Th
	10^{2}	Non-Th	Non-Th	Non-Th	Non-Th	Non-Th	Non-Th
10^{5}	10^{2}	Non-Th	Non-Th	Non-Th	Non-Th	Non-Th	Non-Th

Conclusion

- The overall SNR is larger for a larger spectral index n_T.
- For vanishing Yukawa coupling y_R, we obtain non-thermal leptogenesis which can be probed in future GW experiments such as U-DECIGO, BBO etc.
- Thermal leptogenesis with two-step entropy injection is possible with a non-zero y_R. We propose the two-step entropy injection transfer function. Such two step will be detected in U-DECIGO, BBO, $\mu-$ARES etc. for $n_T = 0$ and LISA, ET and CE as well for $n_T = 0.5$.
- If $T_{N_1} < T_\phi$, then lower values of M_1 and K reduce SNR and therefore challenging to test for all experiments.
- If $T_\phi < T_{N_1}$ in the non-thermal scenario, a lower T_ϕ value decreases the SNR and frequency of suppression $f_{\rm sup}$ making it more difficult to observe.
- A higher M_ϕ means larger entropy injection which decreases the overall SNR values for all experiments
- In Case (a), where RHNs decay instantaneously after production from ϕ decay, the leptogenesis scale is $\sim T_\phi$ which means GW experiments can probe leptogenesis even for strong washout $K > 1$ where RHNs do not dominate the energy budget of the Universe. This is unlike thermal leptogenesis where the RHN domination criterion $K \lesssim 10^{-4}$ must be satisfied for GW sensitivity.

Thank you