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)

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

[Astron.Astrophys. 641 (2020)]

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Inflationary epoch: Dilutes any pre-existing asymmetry

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After reheating : Generation of more baryon over anti-baryons?

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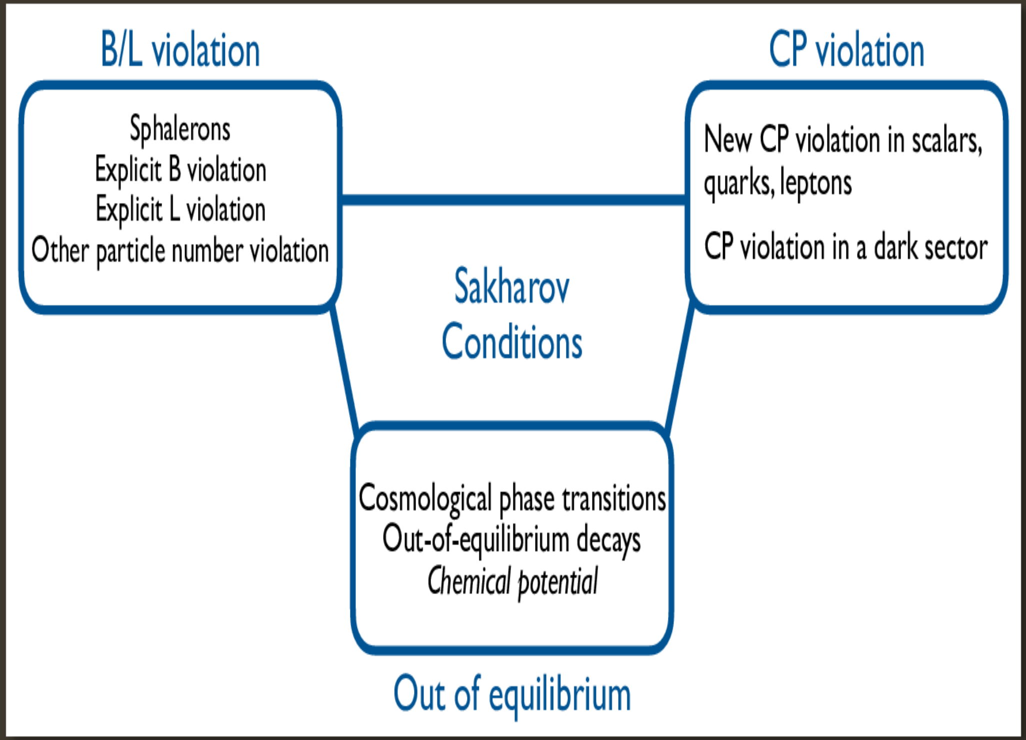

arXiv: 2203.05010

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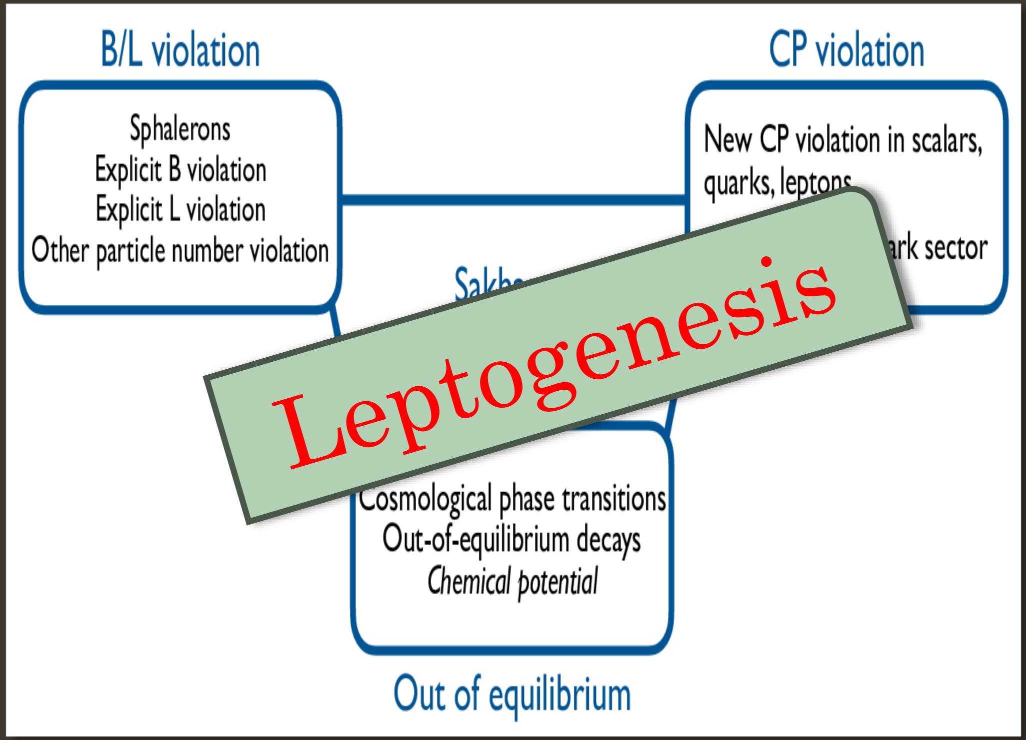

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Leptogenesis: A phenomenon which explains the baryon asymmetry through the generation of a lepton asymmetry, which is later converted into baryon asymmetry via sphaleron processes.

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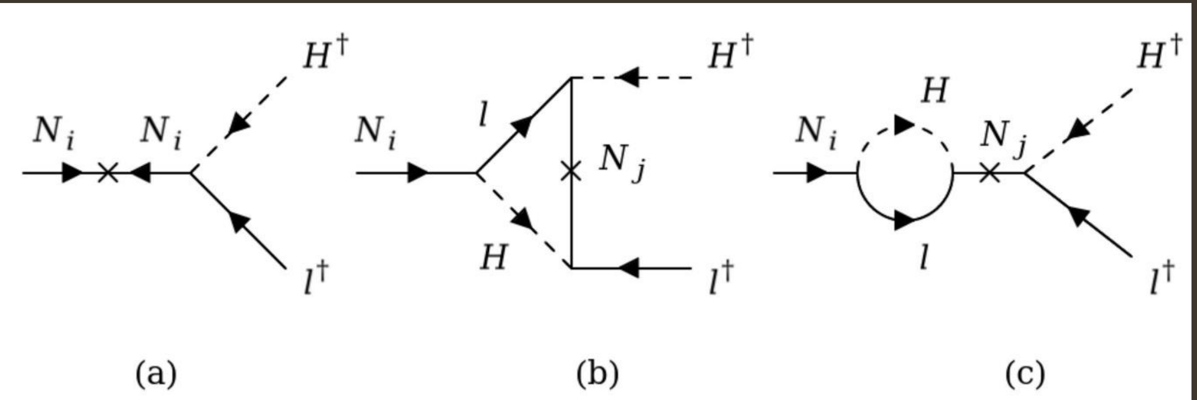
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + i\overline{N}\partial\!\!\!/ N - \left(\lambda \overline{L}\tilde{H}N + \frac{M_N}{2}\overline{N^C}N + \text{h.c}\right)$$



Tree level Diagram

Vertex Diagram

Self-energy Diagram

Testability of Leptogenesis :

Thermal Leptogenesis

$(M_1 \ll M_2 \ll M_3)$

[Phys. Lett. B 174 (1986)]

- RHNs are in Thermal equilibrium at production.
- Leptogenesis Scale : Very high (***Difficult to test***)
- Davidson Ibara bound : $M_1 \gtrsim 10^9$ GeV [Phys. Lett. B 535 (2002)]

Non-thermal Leptogenesis

[Phys. Lett. B 464 (1999)]

- RHNs were never in thermal equilibrium (scalar decay)
- Leptogenesis Scale : $M_1 \gtrsim 10^6$ GeV (***Difficult to test***)

[Nucl. Phys. B 806 (2009)]

Resonant Leptogenesis

$(M_1 \simeq M_2 \ll M_3)$

[Nucl. Phys. B 504 (1997)]

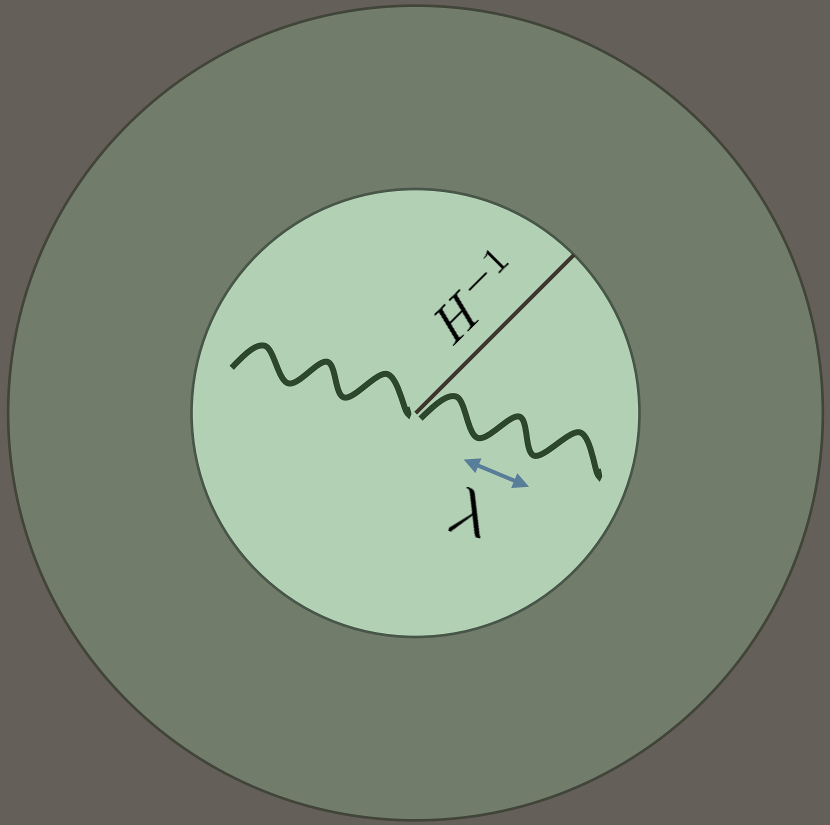
- Self energy diagrams enhance the CP asymmetry
- Leptogenesis Scale : $M_1 \sim 100$ GeV (***Testable***)

[Phys. Rev. D72 (2005)]

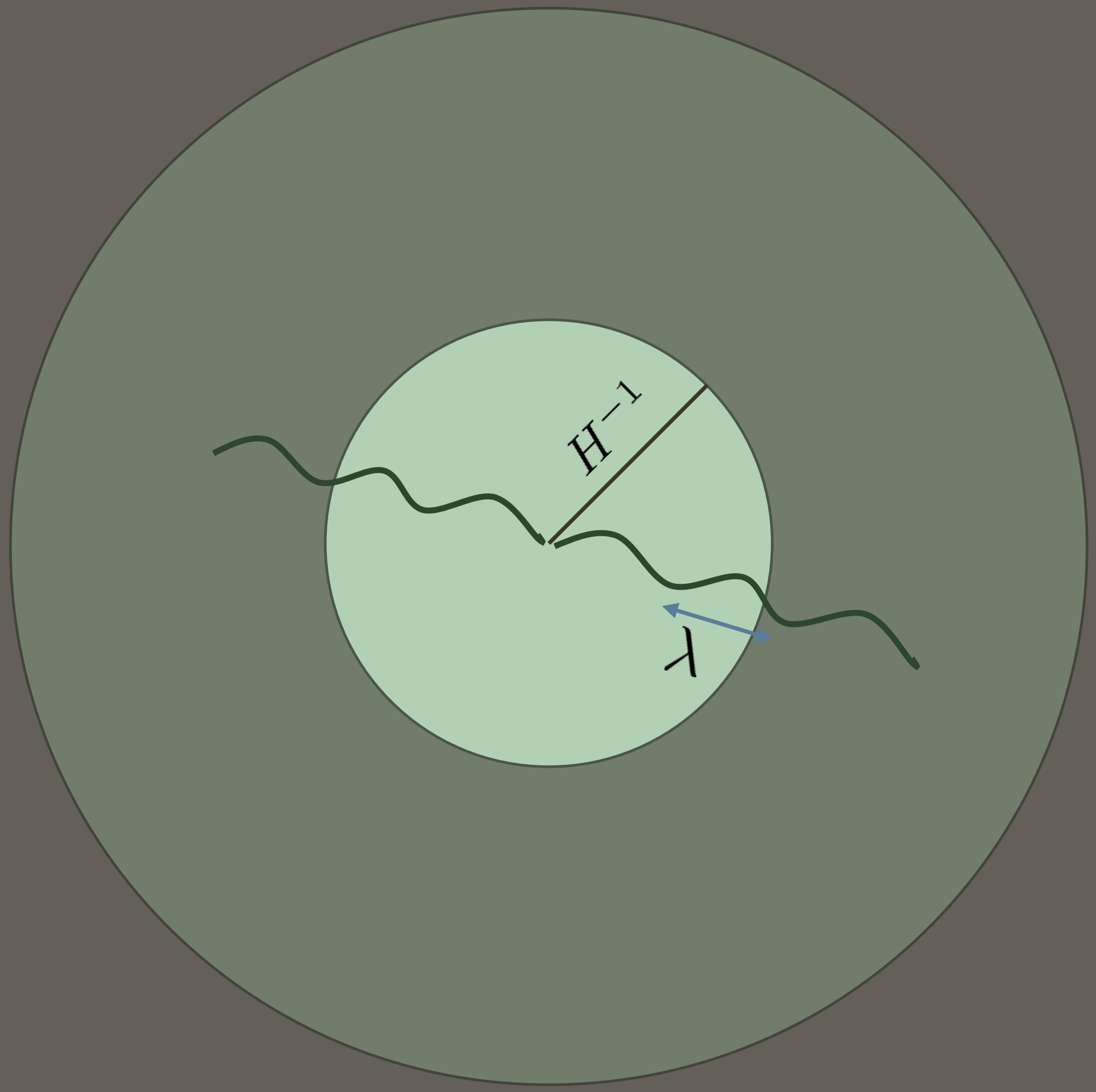
Inflationary Gravitational wave (GW)

Phys. Rev. D 85 (2012)[1109.0022]
JCAP 08 (2014) 036 [1405.0346],
JCAP 02 (2015) 003 [1407.4785],
JHEP 05 (2023) 172 [2301.05672]

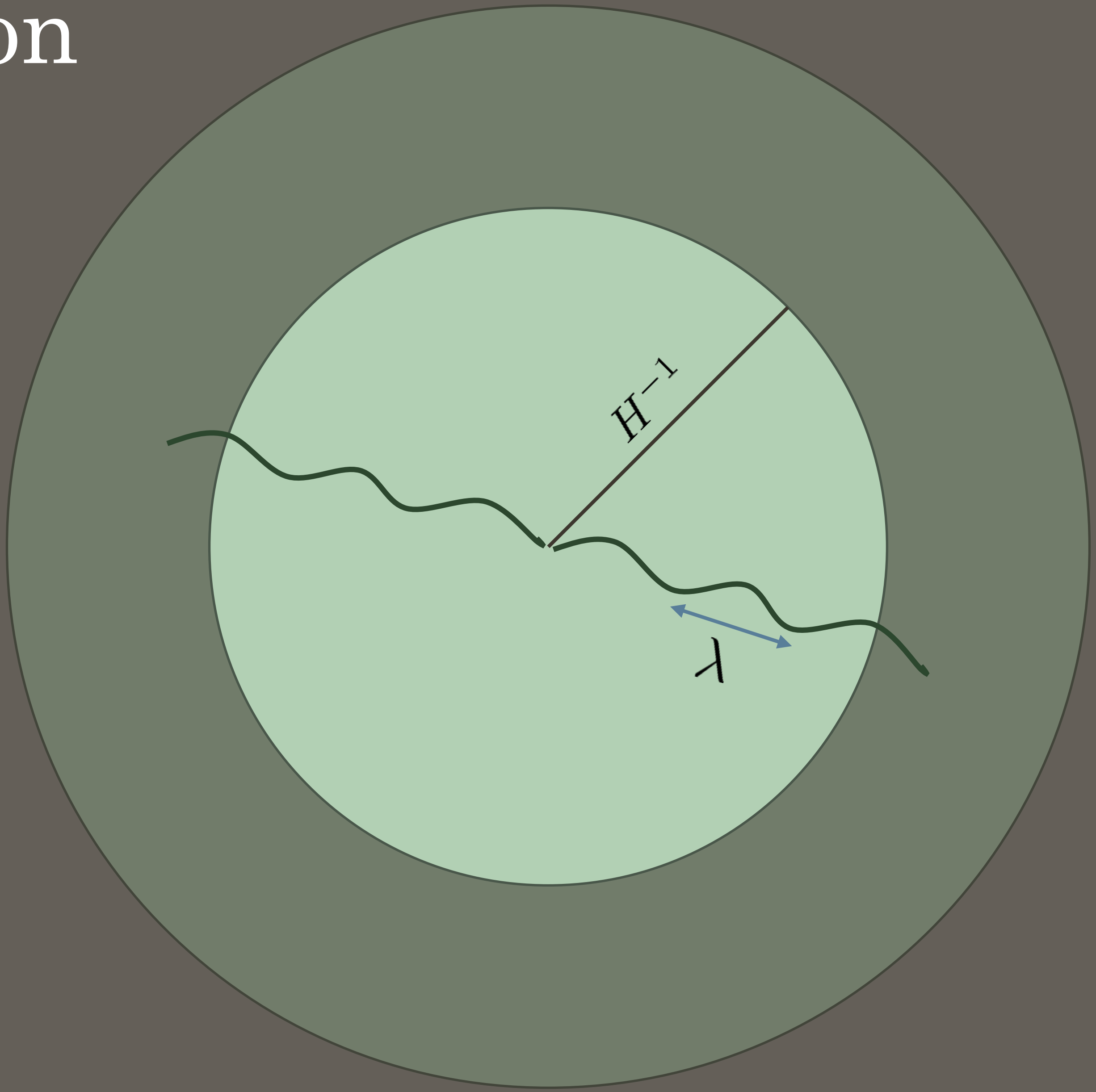
Inflation



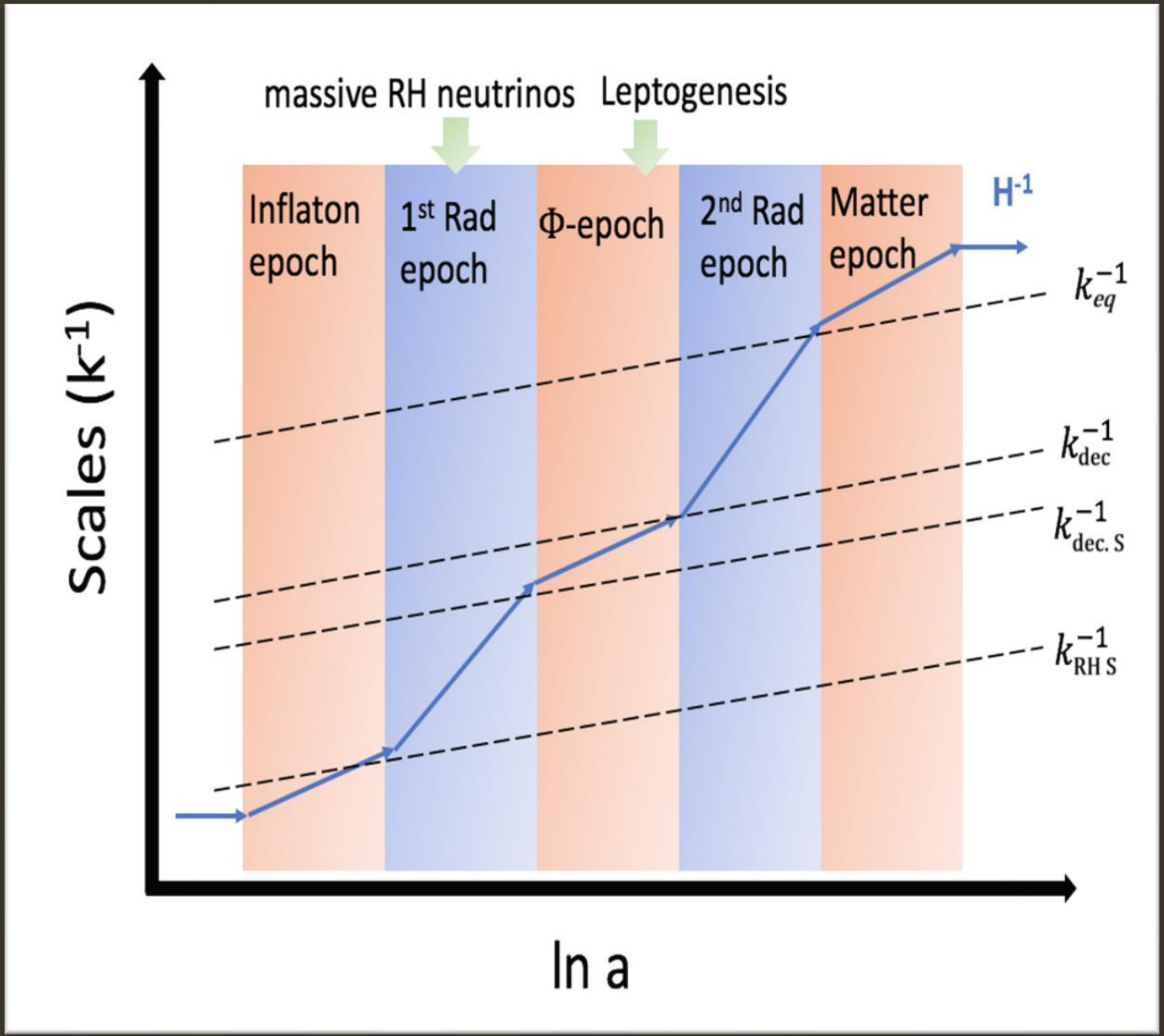
Inflation



Post-inflation



Intermediate matter domination



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

Inflationary Gravitational wave (GW)

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

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

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

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

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

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

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

Leptogenesis via scalar decay :

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

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

We have considered resonant non-thermal leptogenesis for this work!

$M_\phi \simeq 2M_{1,2} \implies$ Non-relativistic RHNs

$M_\phi \gg 2M_{1,2} \implies$ Relativistic RHNs

$$E_N(z) \sim \begin{cases} \frac{M_\phi}{2} & \text{for } T > T_\phi \\ \frac{M_\phi}{2\,T_\phi}\frac{M_1}{z} & \text{for } T_\phi \geq T > T_{\rm NR} \\ M_1 & \text{for } T \leq T_{\rm NR} \end{cases}$$

Scalar → Relativistic RHNs → Non-relativistic RHNs → Leptogenesis

$T_{\rm dom} \sim \frac{M_\phi}{g_*} \approx 0.01 M_\phi$

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

$T_{\rm NR} \sim T_\phi \frac{2M_1}{M_\phi}$

$T_{N_1} \approx M_1\sqrt{K}$

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

$$\Gamma_{N_i} = \Gamma^{rf}_{N_i}\,\frac{M_1}{E_N(z)} \sim \mathcal{H}(M_i)\,K\,\frac{M_1}{E_N(z)}$$

Lorentz boost: $\gamma_N = E_N(z)/M_1$

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

- $y_R = 0 \to$ 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

$$\dot{\rho}_\phi = -3\mathcal{H}\rho_\phi - \Gamma_\phi\left(\rho_\phi - \rho_\phi^{\rm eq}\right)$$

$$\dot{\rho}_{N_1} = -3\mathcal{H}\left(\rho_{N_1} + p_{N_1}\right) + \Gamma_{\phi\to N_1N_1}\left(\rho_\phi - \rho_\phi^{\rm eq}\right) - \Gamma_{N_1}\left(\rho_{N_1} - \rho_{N_1}^{eq}\right)$$

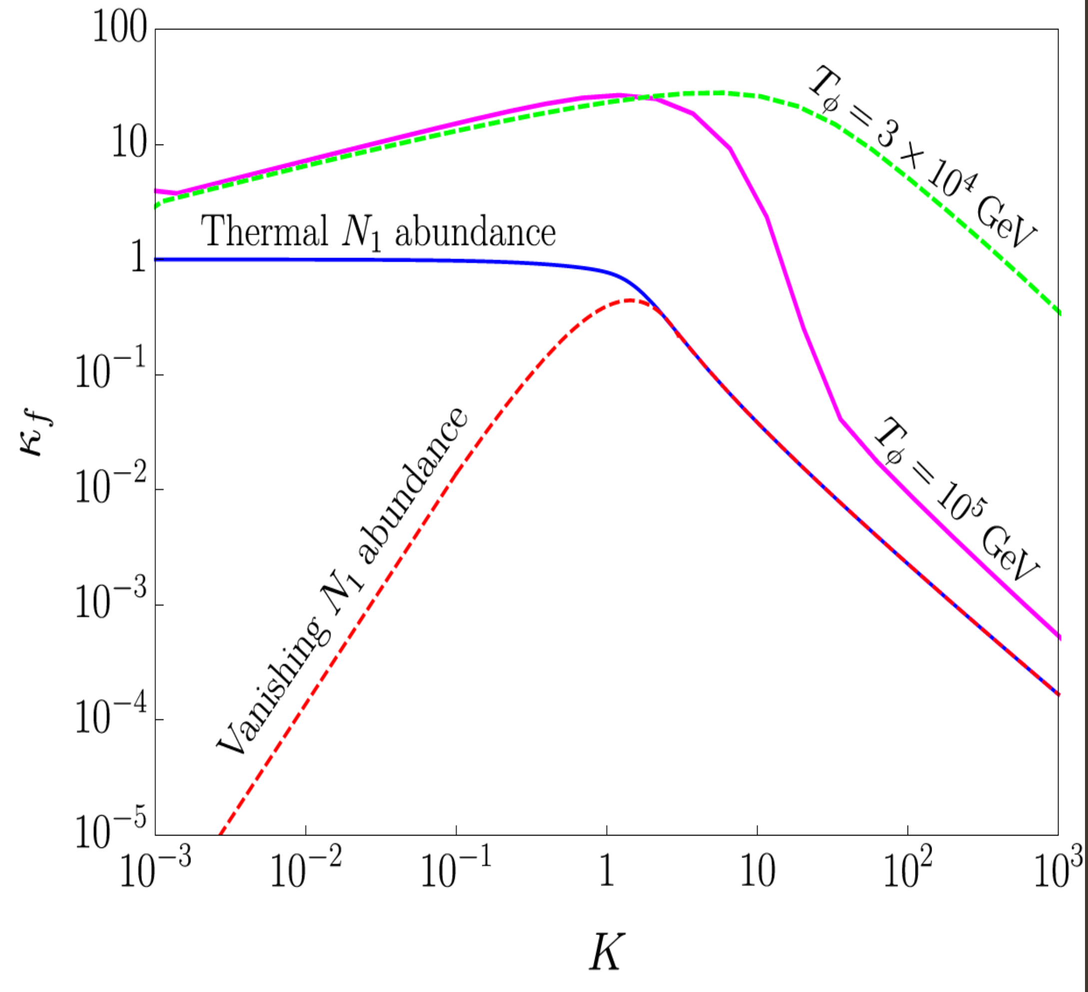
$$\dot{\rho}_{N_2} = -3\mathcal{H}\left(\rho_{N_2} + p_{N_2}\right) + \Gamma_{\phi\to N_2N_2}\left(\rho_\phi - \rho_\phi^{\rm eq}\right) - \Gamma_{N_2}\left(\rho_{N_2} - \rho_{N_2}^{eq}\right)$$

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

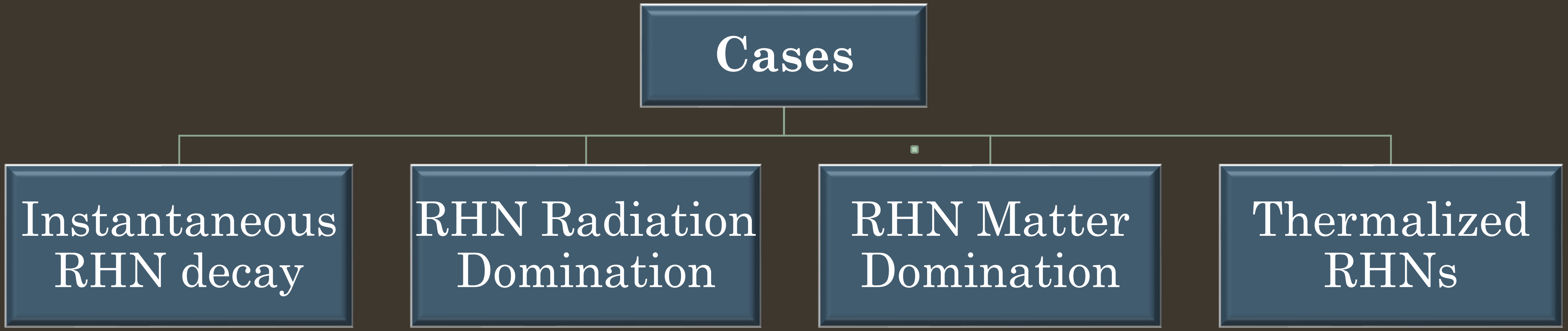
$$\dot{\rho}_R = -4\mathcal{H}\rho_R + \Gamma_{\phi\to R}\left(\rho_\phi - \rho_\phi^{\rm eq}\right) + \sum_{i=1}^{2}\Gamma_{N_i}\left(\rho_{N_i} - \rho_{N_i}^{eq}\right)$$

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

$$\eta_B \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma} = \frac{3}{4}\frac{a_{\rm sph}}{f}\,\epsilon_1\kappa_f \simeq 0.96\times 10^{-2}\,\epsilon_1\kappa_f$$



Classification of scenarios



Classification of scenarios

Cases

- Instantaneous RHN decay
- RHN Radiation Domination
- RHN Matter Domination
- Thermalized RHNs

Instantaneous RHN decay, RHN Radiation Domination, RHN Matter Domination → **Non-thermal Leptogensis**

$$(y_R = 0)$$

Thermalized RHNs → **Thermal Leptogensis**

$$(y_R \neq 0)$$

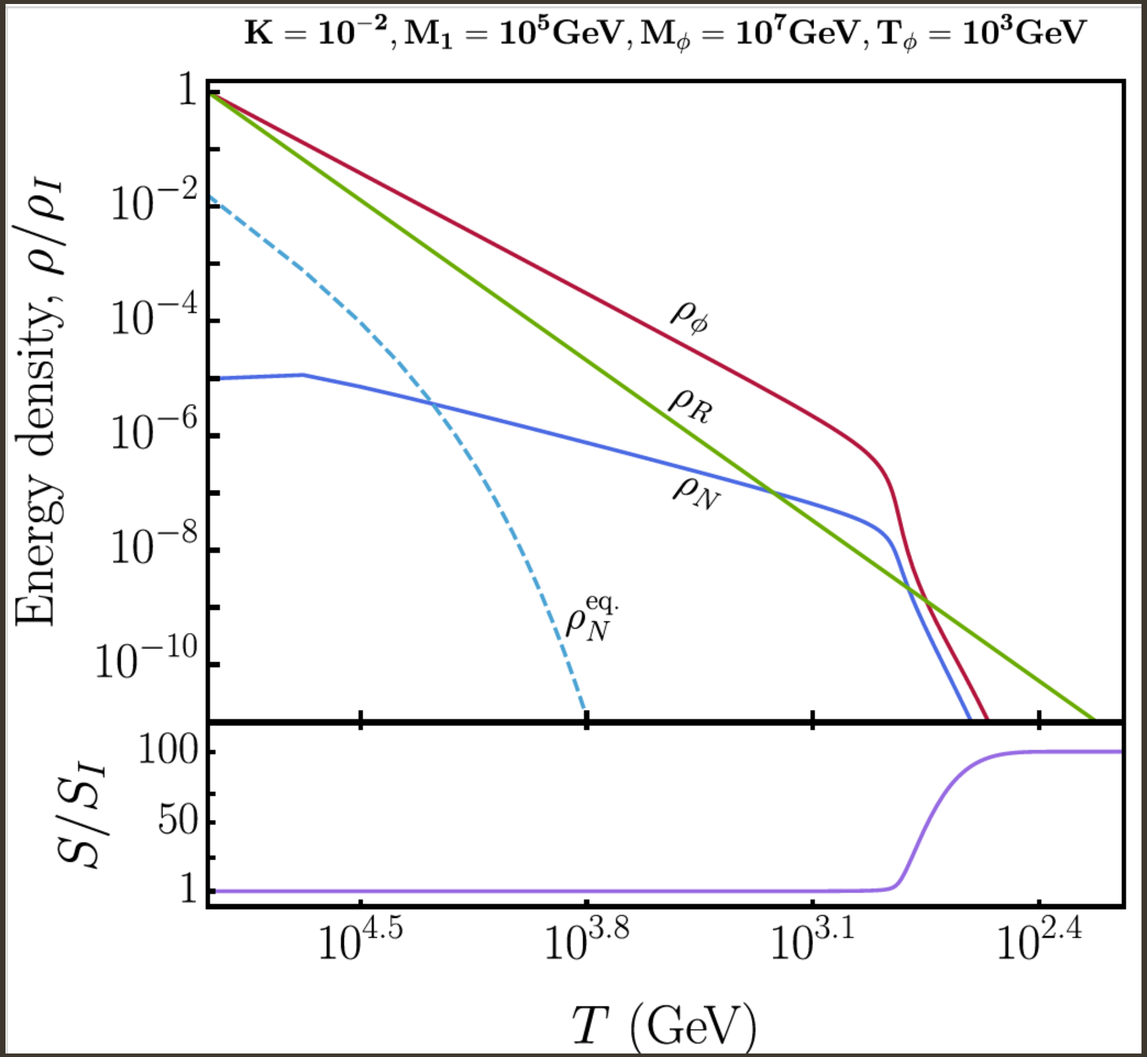
Classification of scenarios : Case (a)

- **Case (a)**
  - Instantaneous RHN decay
  - RHN Radiation Domination
  - RHN Matter Domination
  - Thermalized RHNs

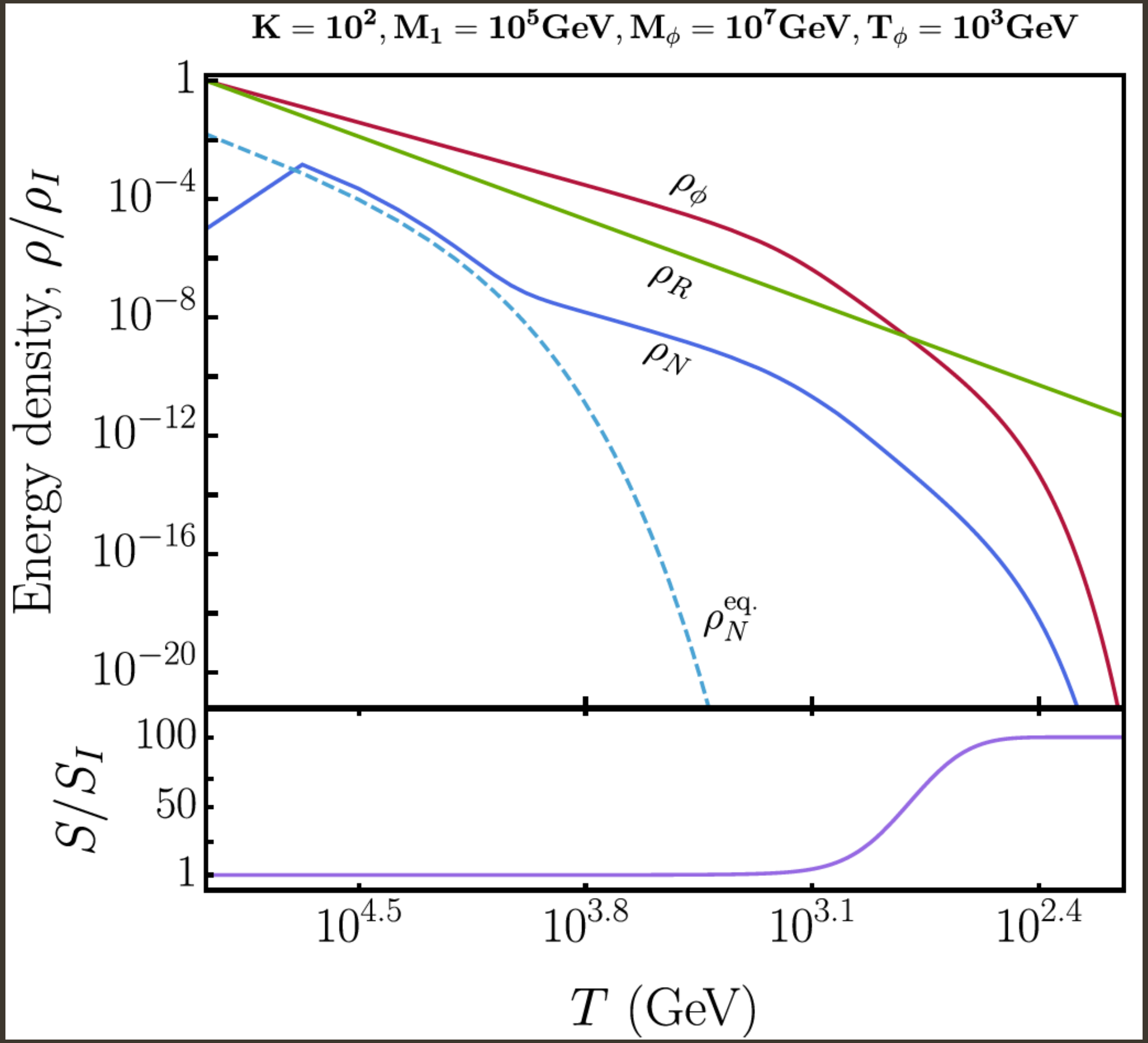
$$\Gamma_N \gg \Gamma_\phi$$

$$T_{\mathrm{N}_1}\sqrt{\frac{2M_1}{M_\phi}} \gg T_\phi$$

Case (a) : Instantaneous RHN decay

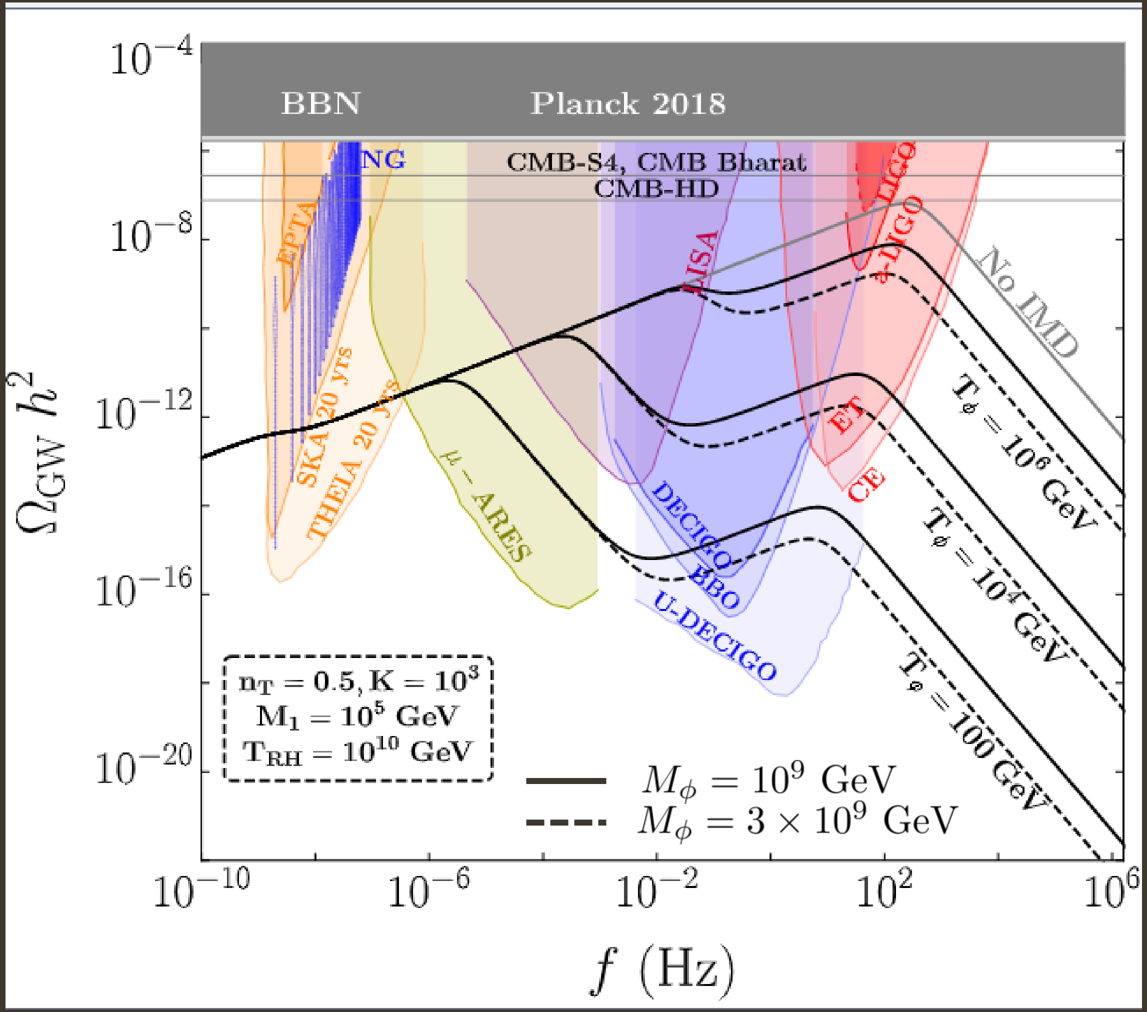


K<1



K>1

Case (a) : Gravitational wave spectrum



Case (a) : Gravitational wave spectrum

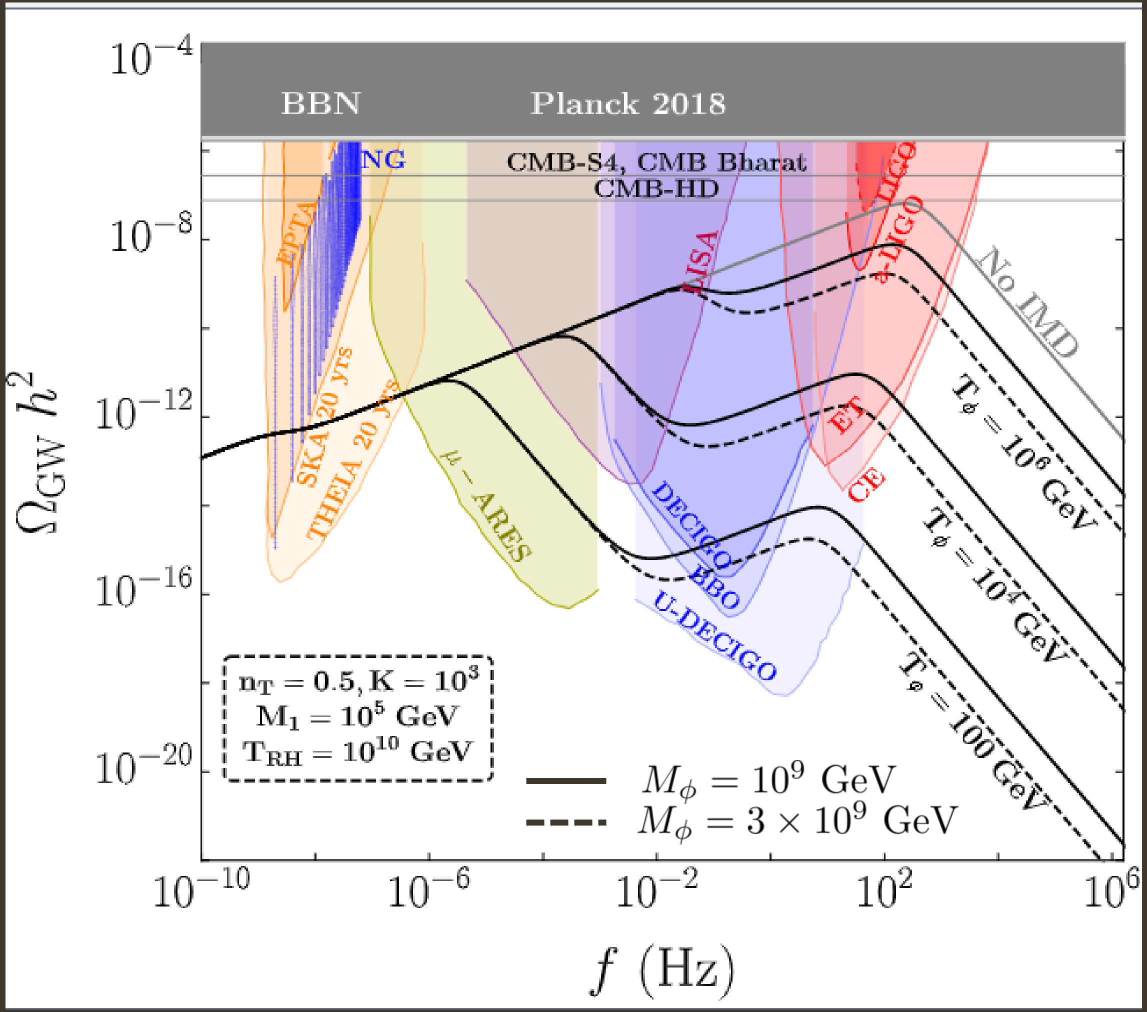
Dilution Factor from Entropy injection

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

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

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

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



Classification of scenarios : Case (b)

Case (b)

- Instantaneous RHN decay
- RHN Radiation Domination
- RHN Matter Domination
- Thermalized RHNs

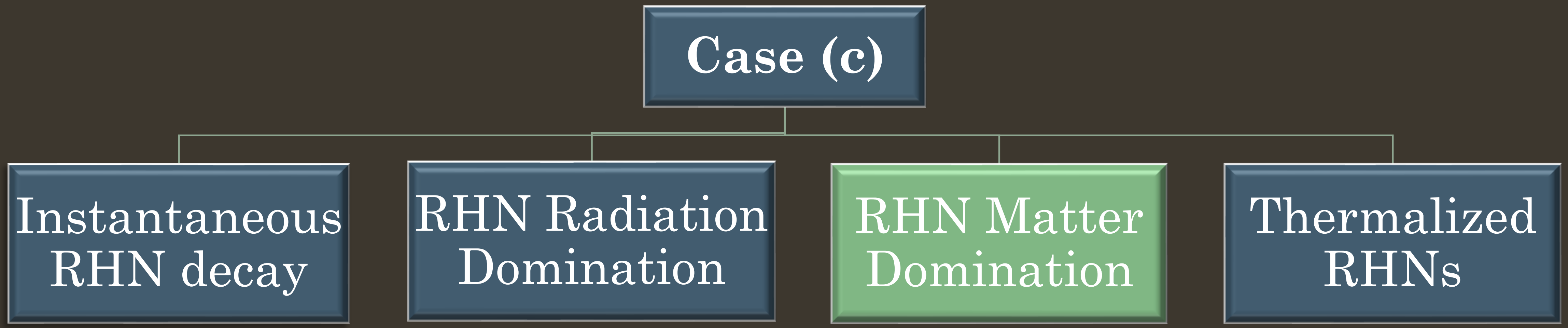
$$\Gamma_N \ll \Gamma_\phi$$

$$T_{N_1}\sqrt{\frac{2M_1}{M_\phi}} \ll T_\phi$$

$$T_N^{\rm rel} \sim \left(T_{N_1}^2\, T_{\rm NR}\right)^{1/3}, \text{ when } \Gamma_N(T_N^{\rm rel}) \sim \mathcal{H}(T_N^{\rm rel})$$

No entropy injection due to RHN decay implies no change in spectral shapes.

Classification of scenarios : Case (c)



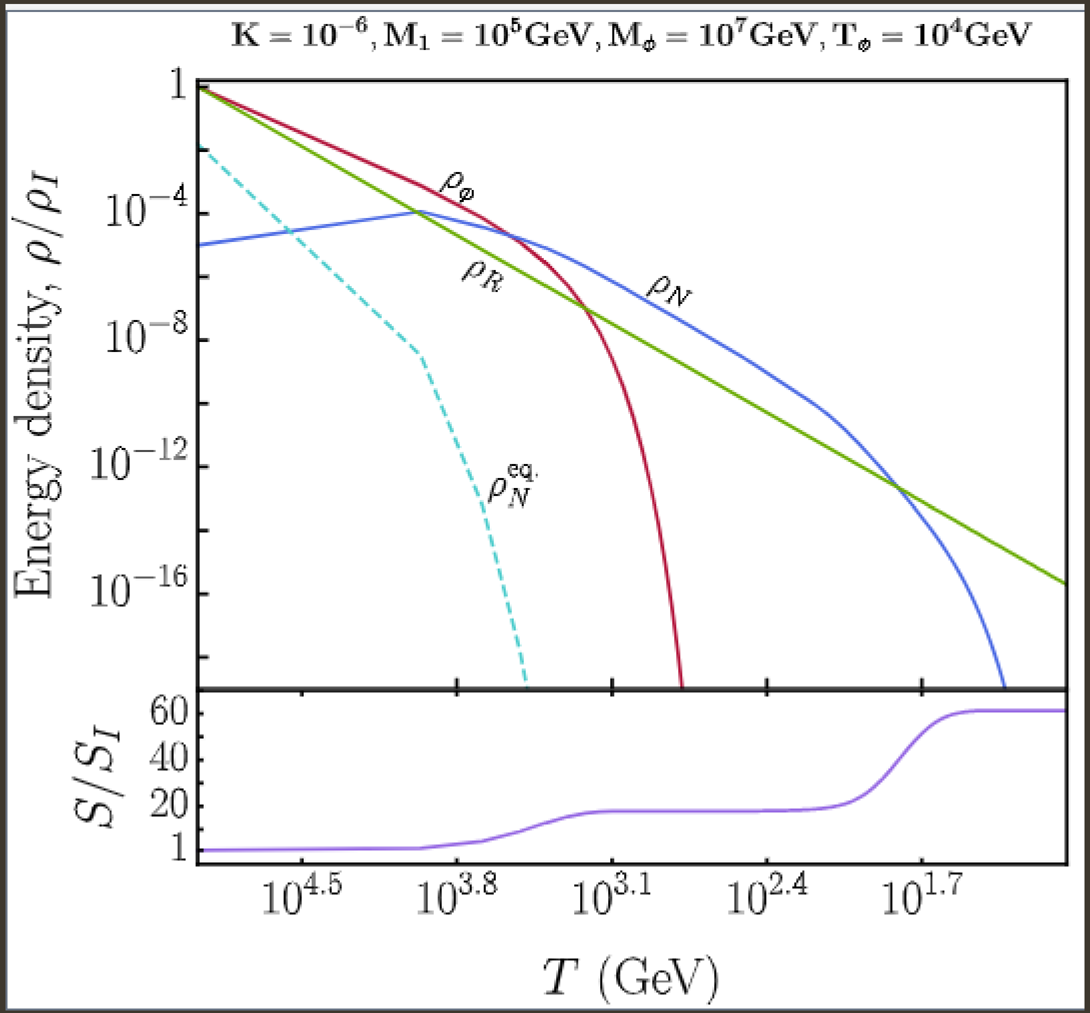
$$\Gamma_N \ll \Gamma_\phi$$

$$T_{N_1} < T_{\rm NR} < T_\phi$$

$$\Longrightarrow \quad \sqrt{K} < 2T_\phi / M_\phi$$

K >1 not possible!!

Case (c) : RHN Matter domination



Scalar decays to relativistic RHNs and injects entropy to the universe.

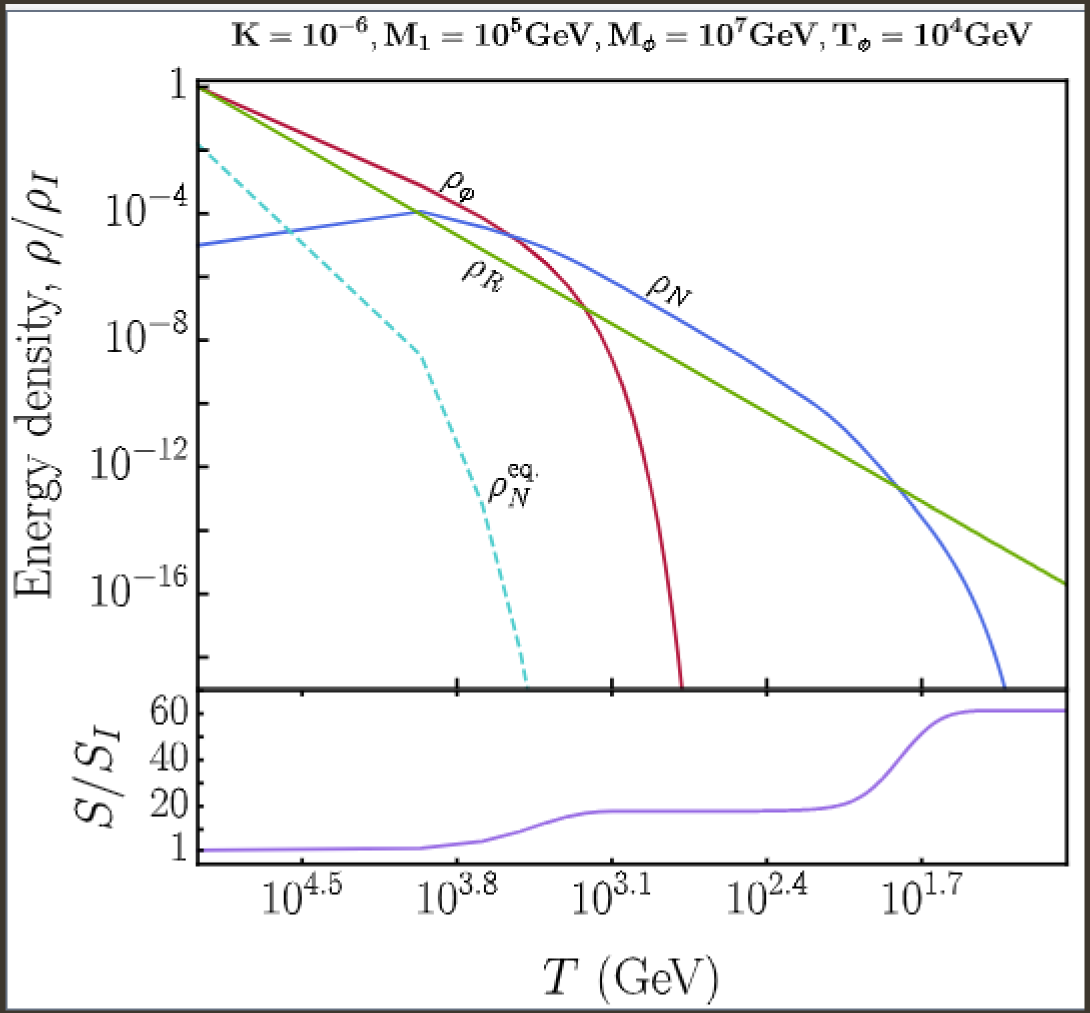
↓

RHNs becomes non-relativistic at $T_{NR.}$

↓

Non-relativistic RHNs decay to SM particles at T_{N_1} and injects entropy again.

Case (c) : RHN Matter domination



Scalar decays to relativistic RHNs and injects entropy to the universe.

RHNs becomes non-relativistic at T_{NR}.

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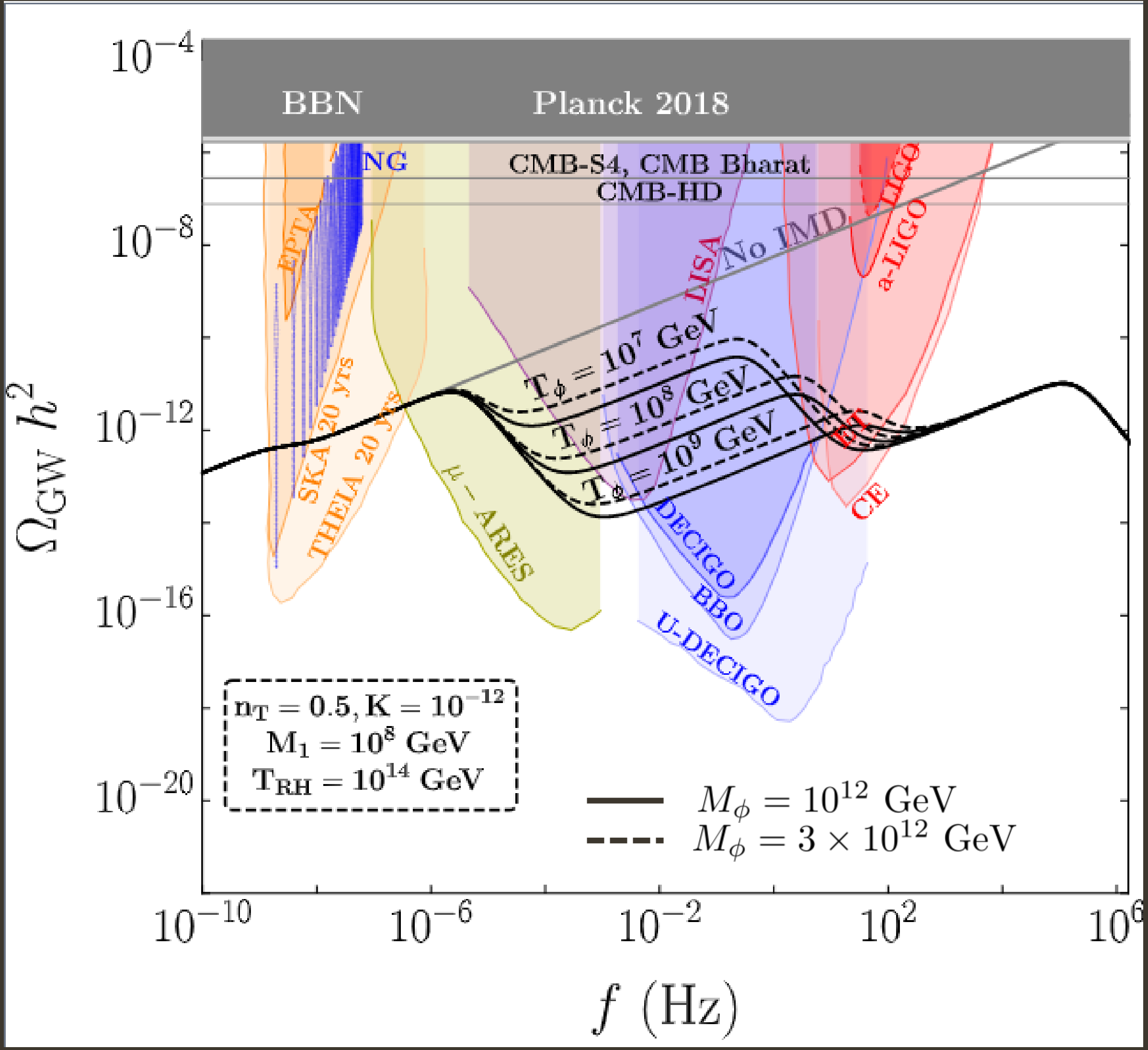
Two step Entropy injection

Case (c) : GW spectrum (Two step Entropy injection)



$$\frac{n_N}{s_{\rm tot}^{\rm after}} = \frac{2\, n_\phi}{\Delta_\phi\, s_{\rm tot}^{\rm before}} = \frac{2}{\Delta_\phi}\frac{n_\phi}{s} = \frac{45}{\pi^4}\frac{\zeta(3)}{g_{*S}}\frac{1}{\Delta_\phi}$$

$$\Delta_N \simeq 2000 \left(\frac{10^{-12}}{K}\right)^{1/2} \left(\frac{10^8\ {\rm GeV}}{M_\phi}\right) \left(\frac{T_\phi}{100\ {\rm TeV}}\right)$$

Classification of scenarios : Case (d)

Case (d)

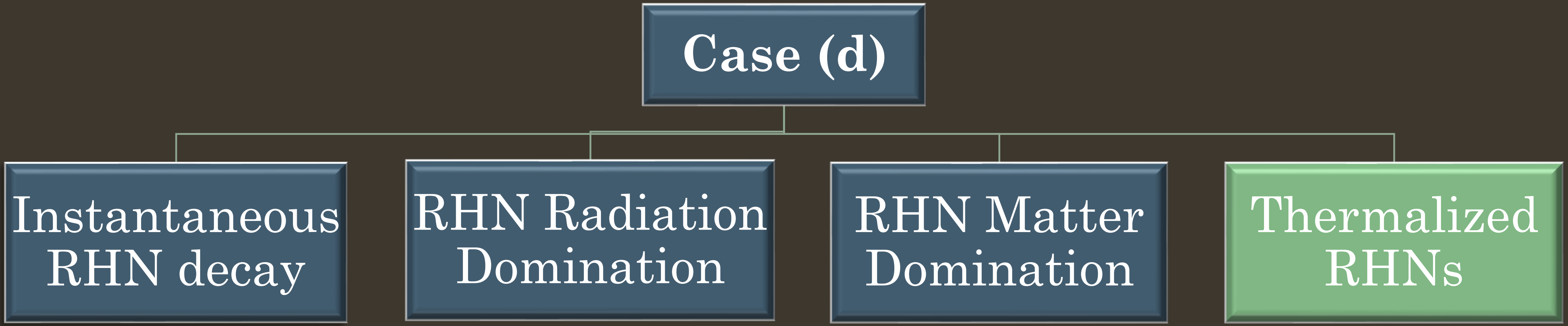
- Instantaneous RHN decay
- RHN Radiation Domination
- RHN Matter Domination
- **Thermalized RHNs**

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

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

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

Classification of scenarios : Case (d)

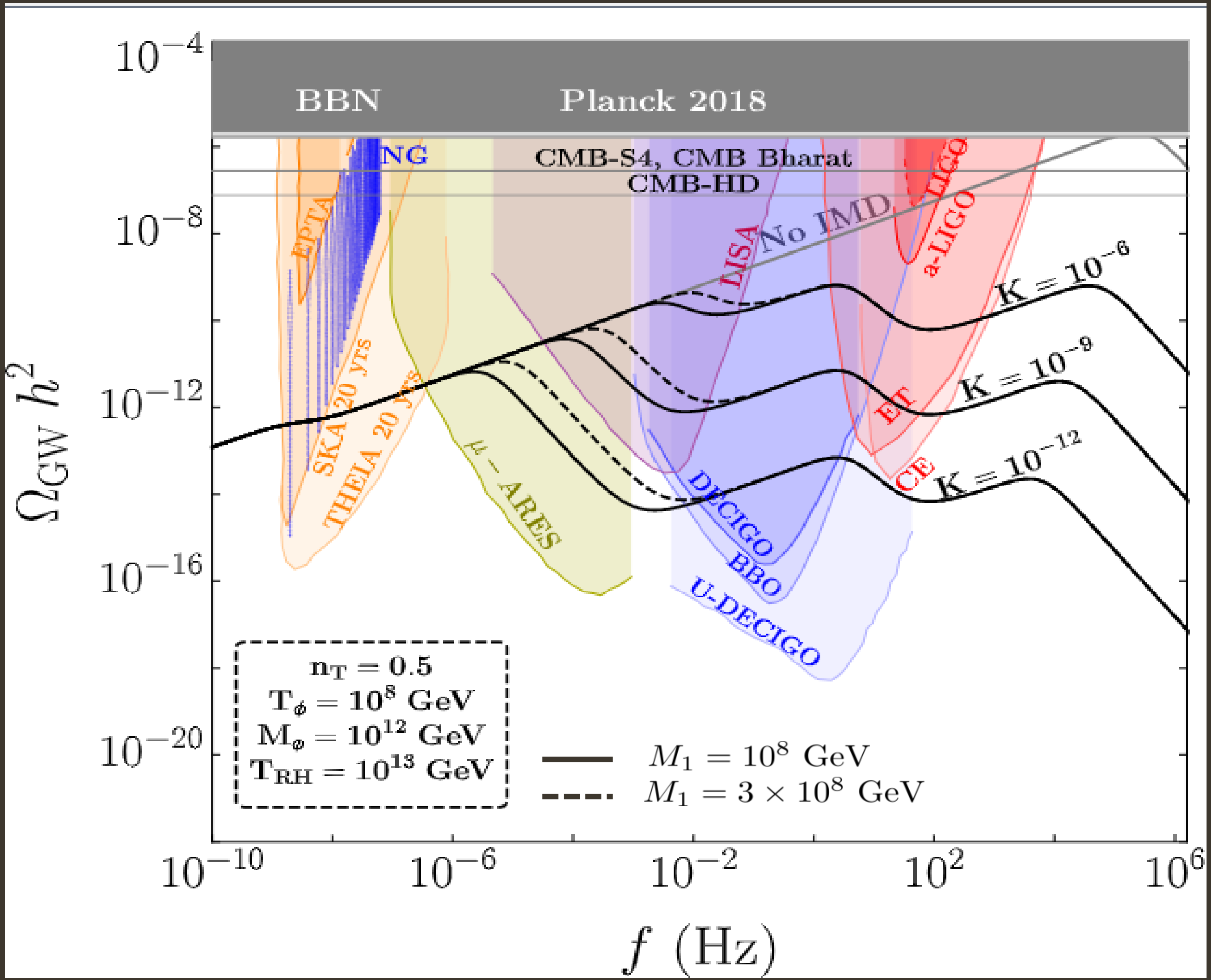


$$T_{N_1} \ll T_\phi$$

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

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

Case (d) Thermalised RHNs $(y_R \neq 0)$

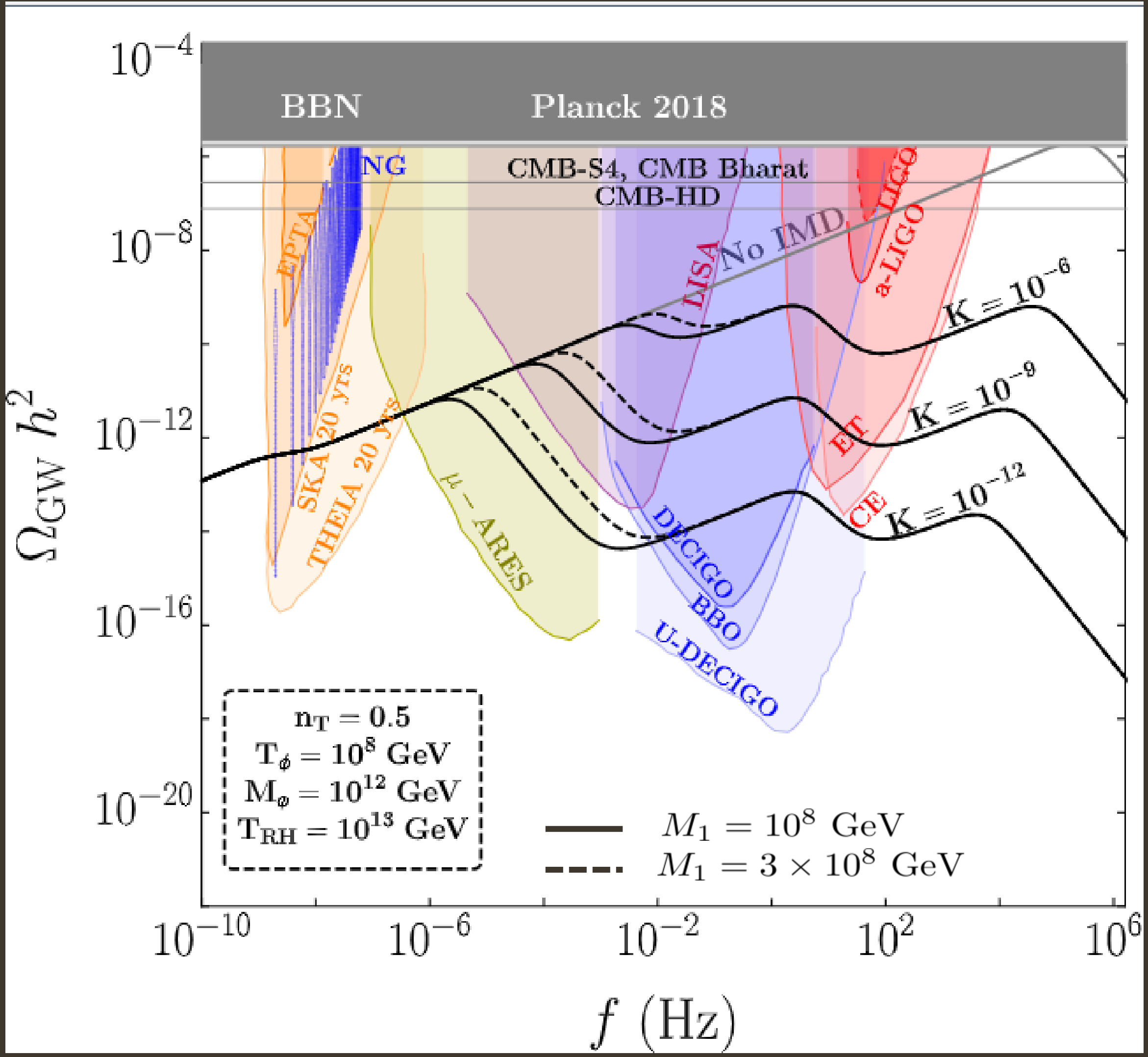


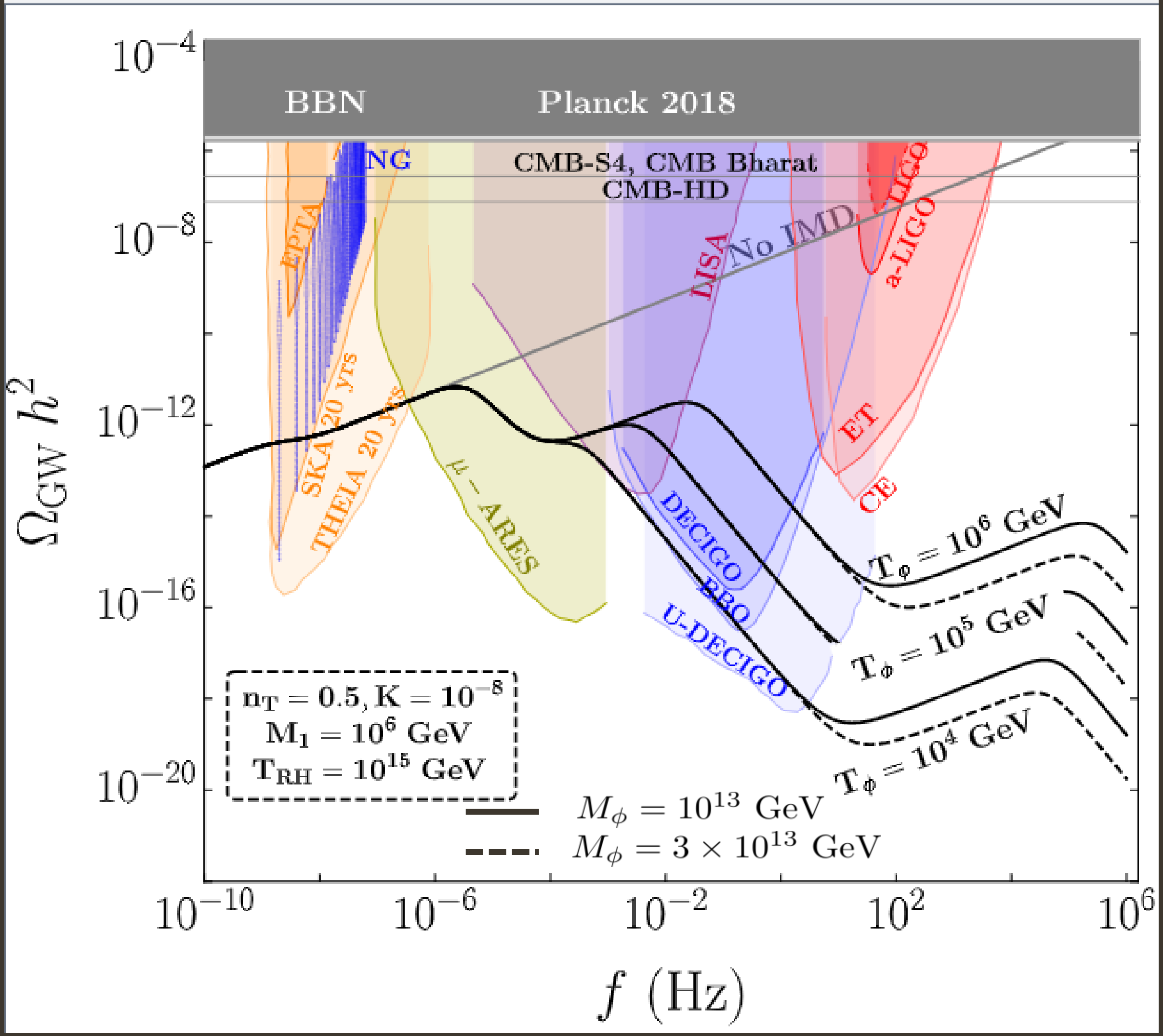
Two step entropy injection

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

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

Two step entropy injection





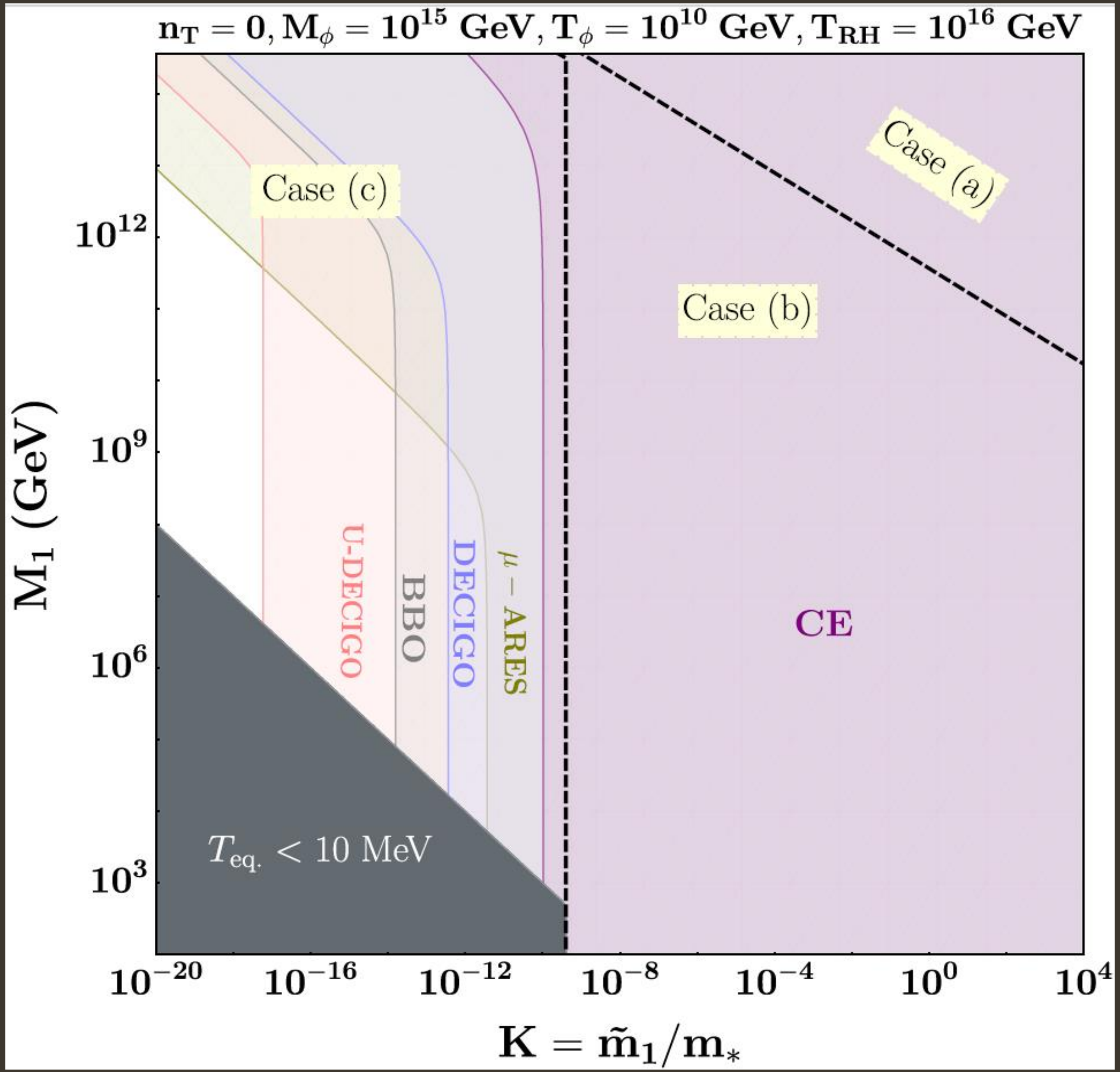
Signal to Noise ratio (SNR)

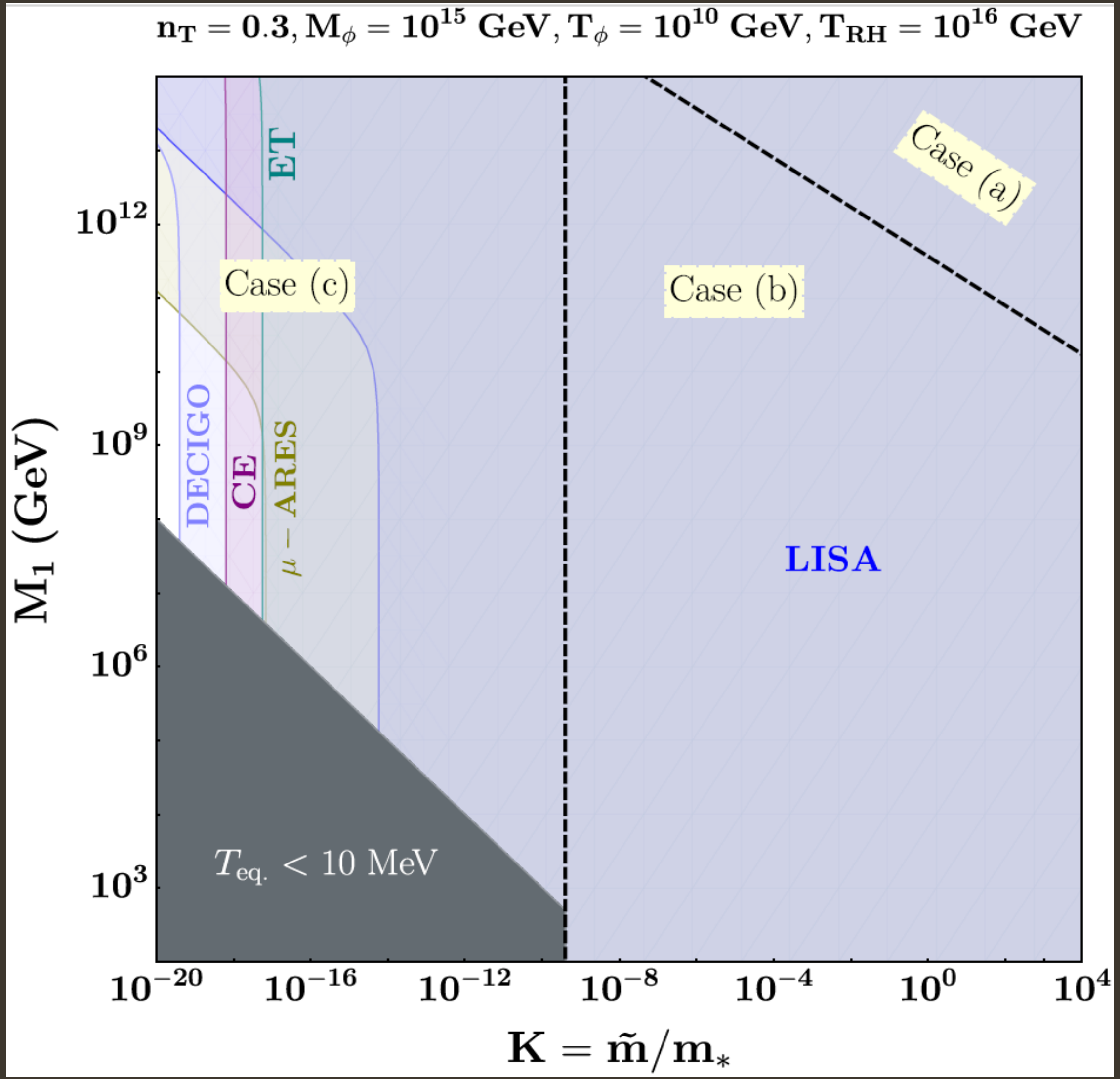
$$SNR = \frac{P_{signal}}{P_{noise}}$$

Wanted component

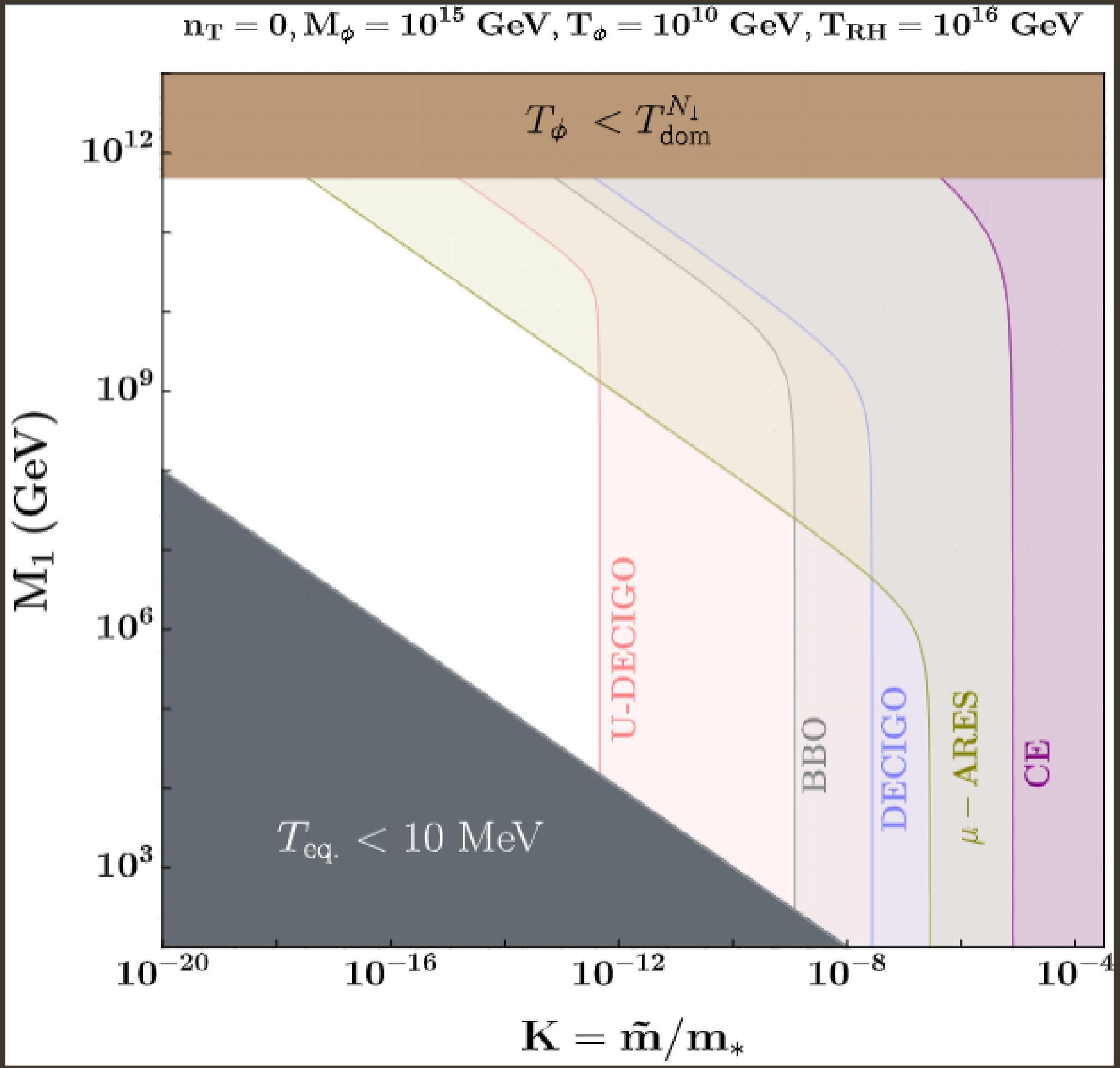
Unwanted component

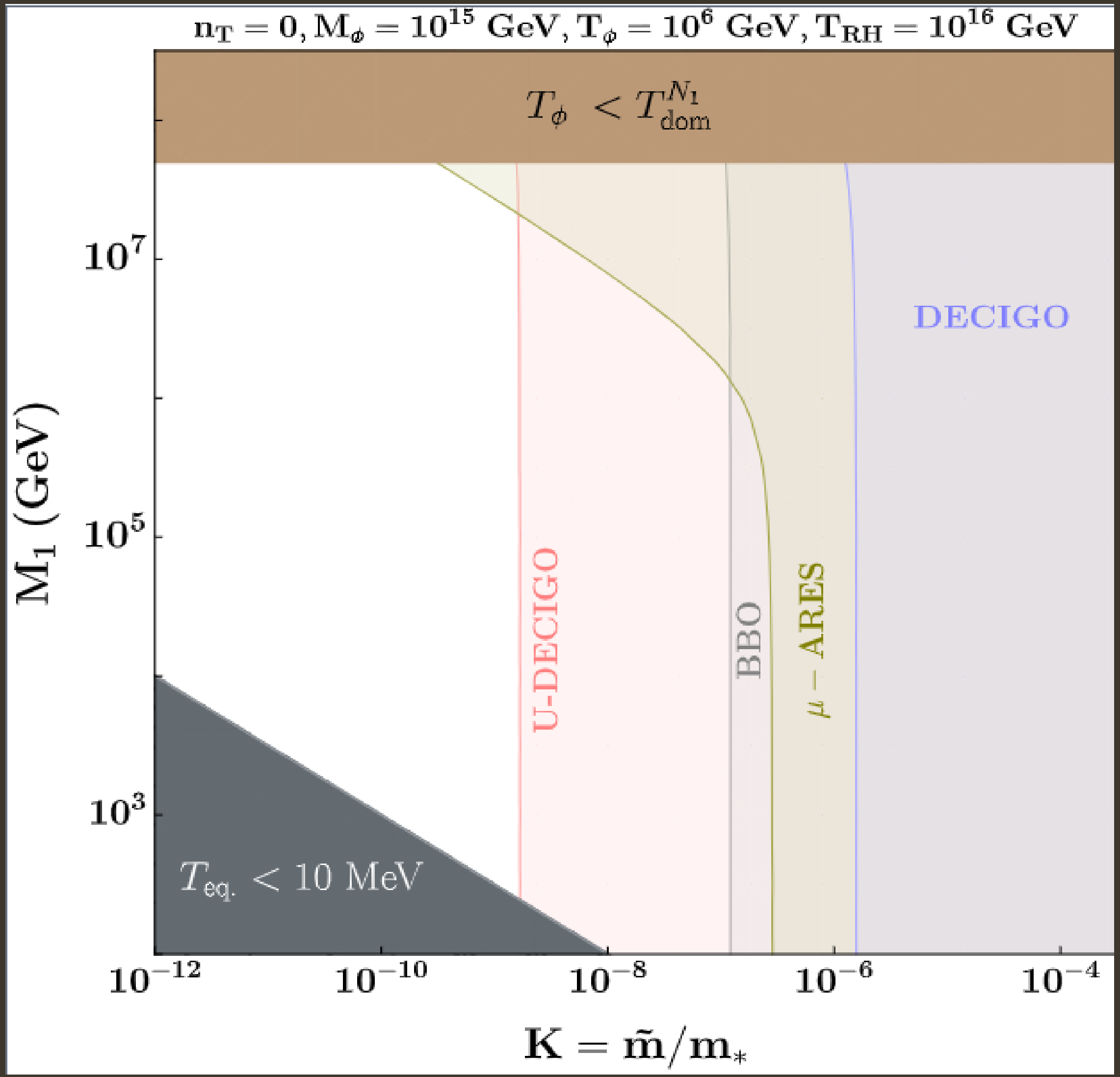
Non-Thermal Leptogenesis:





Thermal Leptogenesis:





Result :

$\mathbf{n_T = 0}$

M_ϕ (GeV)	T_ϕ (GeV)	U-DECIGO	BBO	$\mu-$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	-	-	-

$\mathbf{n_T = 0.3}$

M_ϕ (GeV)	T_ϕ (GeV)	U-DECIGO	BBO	$\mu-$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	-	-	-
10^{10}	10^{6}	Non-Th	Non-Th	Non-Th	Non-Th	Non-Th	Non-Th
	10^{2}	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 $n_T = 0.3$.
- If $T_{N_1} < T_\phi$, then lower values of M_1 and K reduce SNR and therefore challenging to test for all experiments.
- A higher M_ϕ in general means larger entropy injection which decreases the overall SNR values for all experiments. However, for Case (c), higher M_ϕ increases the SNR.
- M_ϕ also sets the upper bound on M_1 in our model, i.e. $M_1 \leq M_\phi/2$. We are interested in the parameter space where ϕ is long-lived to dominate the energy Budget of the Universe
- In Case (a) and Case (b),the leptogenesis scale is $\sim T_\phi$ which means GW experiments can probe leptogenesis even for strong washout $K > 1$ where RHNs might eventually thermalize with the radiation bath. Also a lower T_ϕ value decreases the SNR, making it more difficult to observe.

Thank you