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Entropy production from decay of the GeV scale right-handed neutrinos and the primordial gravitational wave

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In preparation

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Outline

1. Introduction
2. Entropy production
3. Primordial gravitational wave
4. Summary

GeV scale right-handed neutrinos

- **Seesaw mechanism that can explain tiny neutrino masses**

  Minkowski '77 Yanagida '79 Gell-mann, Ramona, Slansky '79 Glashow '79

- **Baryogenesis via neutrino oscillation**

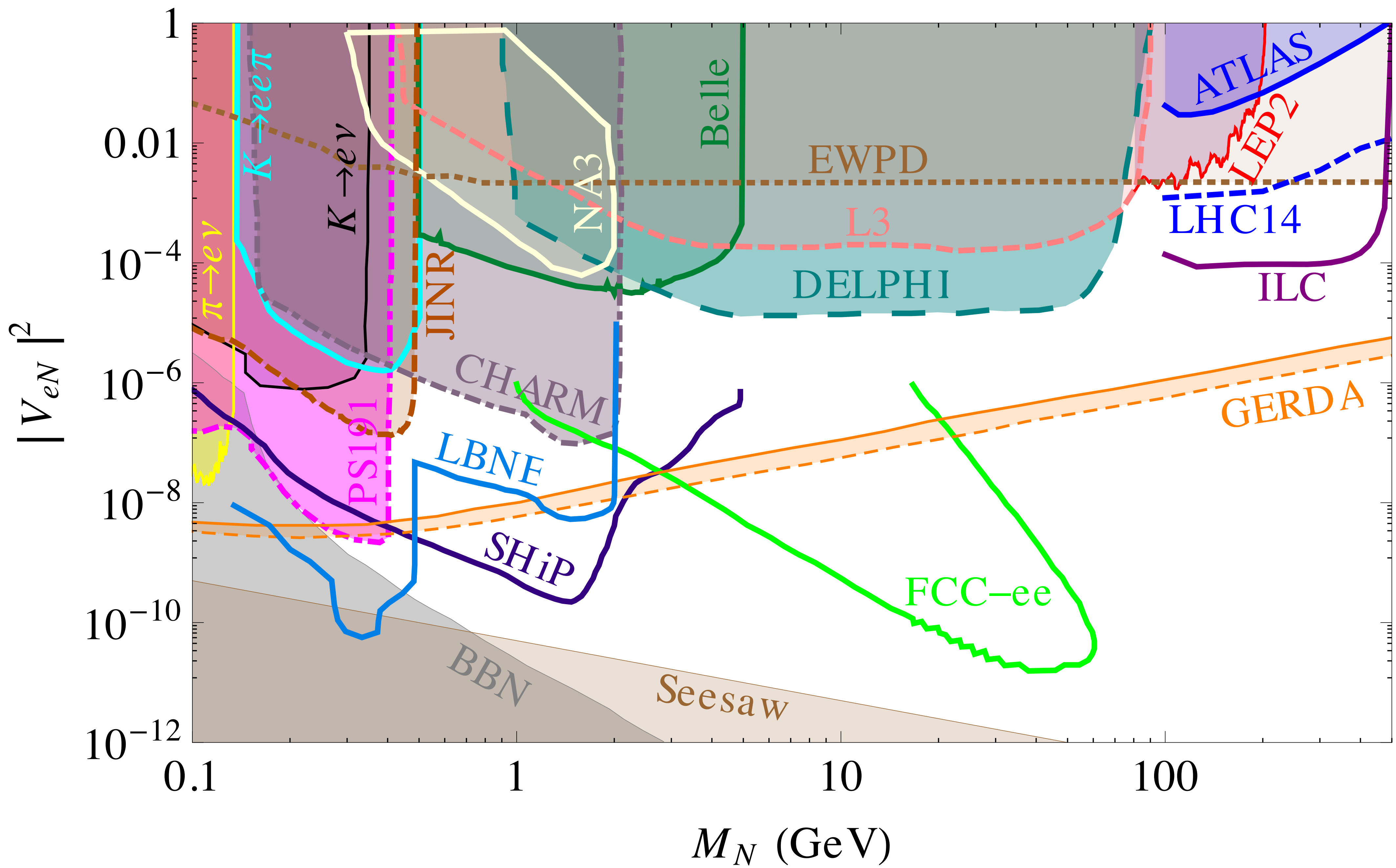
  Akhmedov, Rubakov, Smirnov '98 Asaka, Shaposhnikov '05

- **Testability**

  F.F.Deppisch, P.S.Bhupal Dev, A.Pilaftsis '15

HNL search

F.F.Deppisch, P.S.Bhupal Dev, A.Pilaftsis '15



Motivation

Are there any other methods for exploring RH neutrinos？

→ Entropy production due to decay of RHvs that modifies the gravitational wave spectrum.

Seesaw mechanism

Extension by right-handed neutrinos

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial_\mu \gamma^\mu \nu_R - F\bar{L}\nu_R \Phi - \frac{M_M}{2}\bar{\nu}_R \nu_R^c + h.c.$$

Seesaw mechanism (type I)

$$-\mathcal{L}_M = \frac{1}{2}\left(\bar{\nu}_L, \bar{\nu}_R^c\right)\begin{pmatrix} 0 & M_D \\ M_D^T & M_M \end{pmatrix}\begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + h.c. = \frac{1}{2}\left(\bar{\nu}, \bar{N}\right)\begin{pmatrix} M_\nu & 0 \\ 0 & M_M \end{pmatrix}\begin{pmatrix} \nu^c \\ N \end{pmatrix}$$

$$M_\nu = -M_D^T M_M^{-1} M_D \ \ (M_\nu \ll M_D)$$

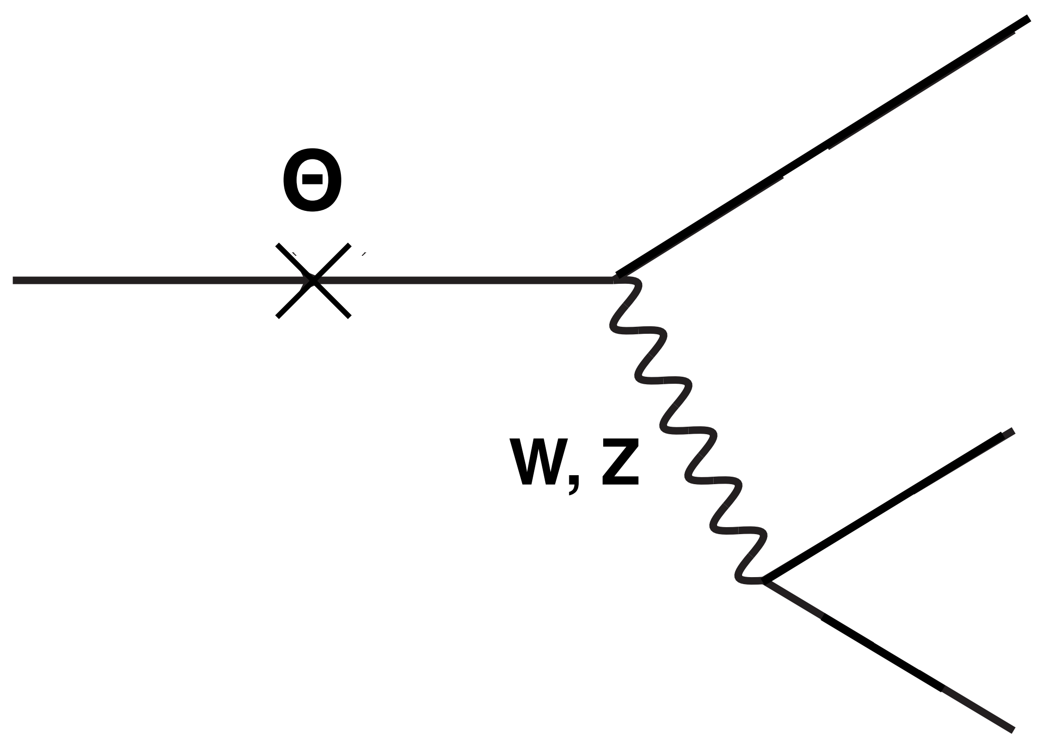
Mixing of light neutrinos and heavy neutrinos

$$\nu_L = U\nu + \Theta N^c$$

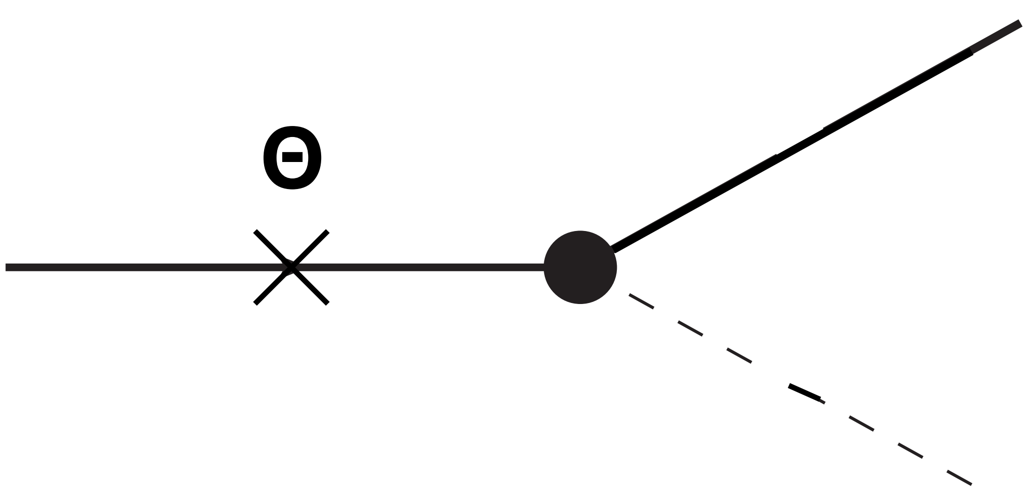
$$\Theta = \frac{M_D}{M_M} = \frac{F\langle\Phi\rangle}{M_M}$$

Decay of right-handed neutrinos

3 Body decay



2 Body decay



Lifetime can be
τ~ O(0.1) sec

@ M = 1 GeV

※ near BBN bound

Scenario

Temperature [GeV]

O(1) — ▶ $T = T_{dec}$

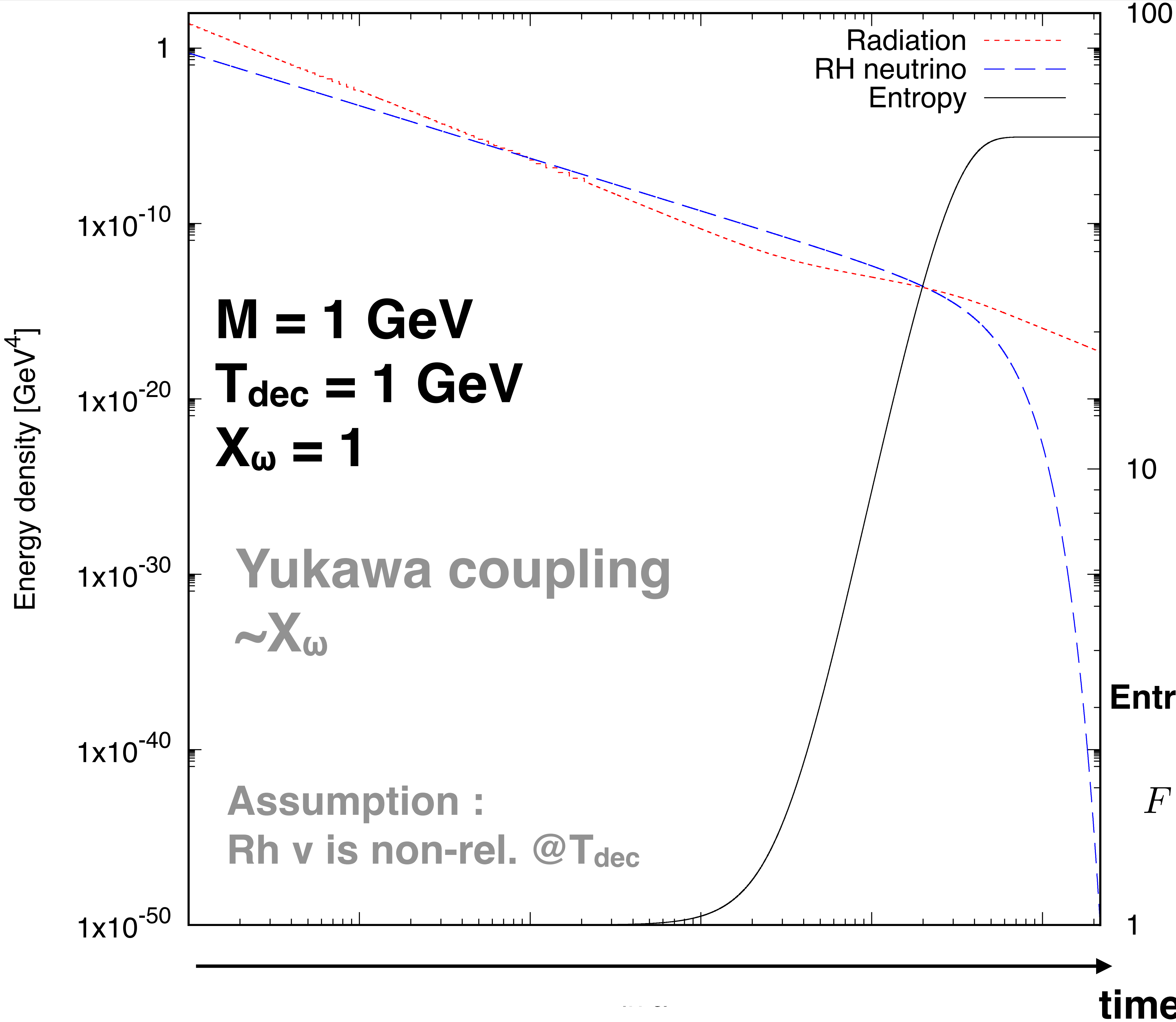
RHν decouples from thermal equilibrium ($\Gamma_N < H$).

The number of RHν will freeze out.

RHν will decay.

**If RHν is non-relativistic particles with sufficient lifetime and the energy density of RHν dominates the universe,
the entropy production occurs
and changes the thermal history of universe.**

Entropy production



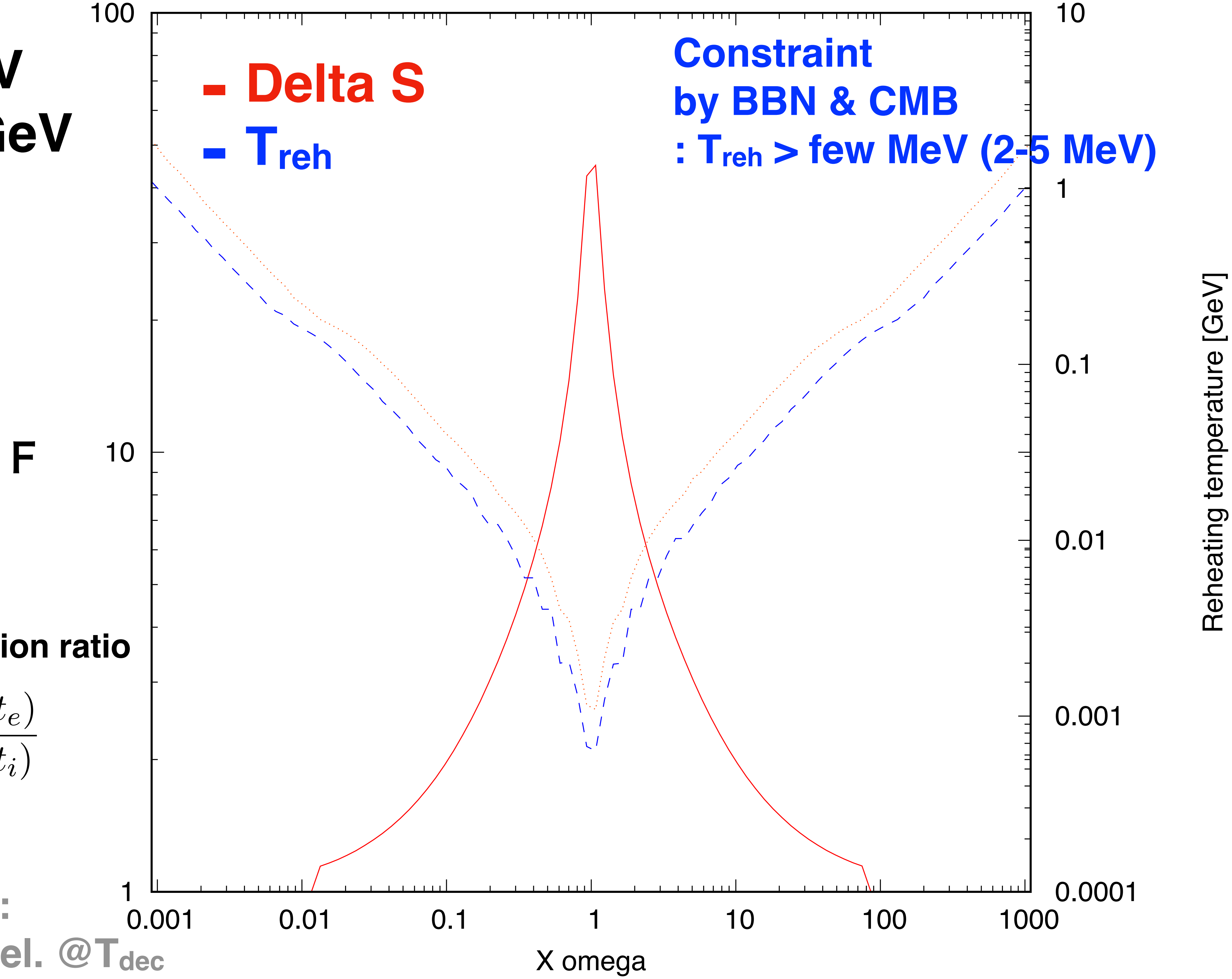
F

Entropy production ratio

$$F = \frac{s(t_e)a^3(t_e)}{s(t_i)a^3(t_i)}$$

Entropy production

M = 1 GeV
T_{dec} = 1 GeV



Entropy production ratio

$$F = \frac{s(t_e)a^3(t_e)}{s(t_i)a^3(t_i)}$$

Assumption :
Rh ν is non-rel. @T_{dec}

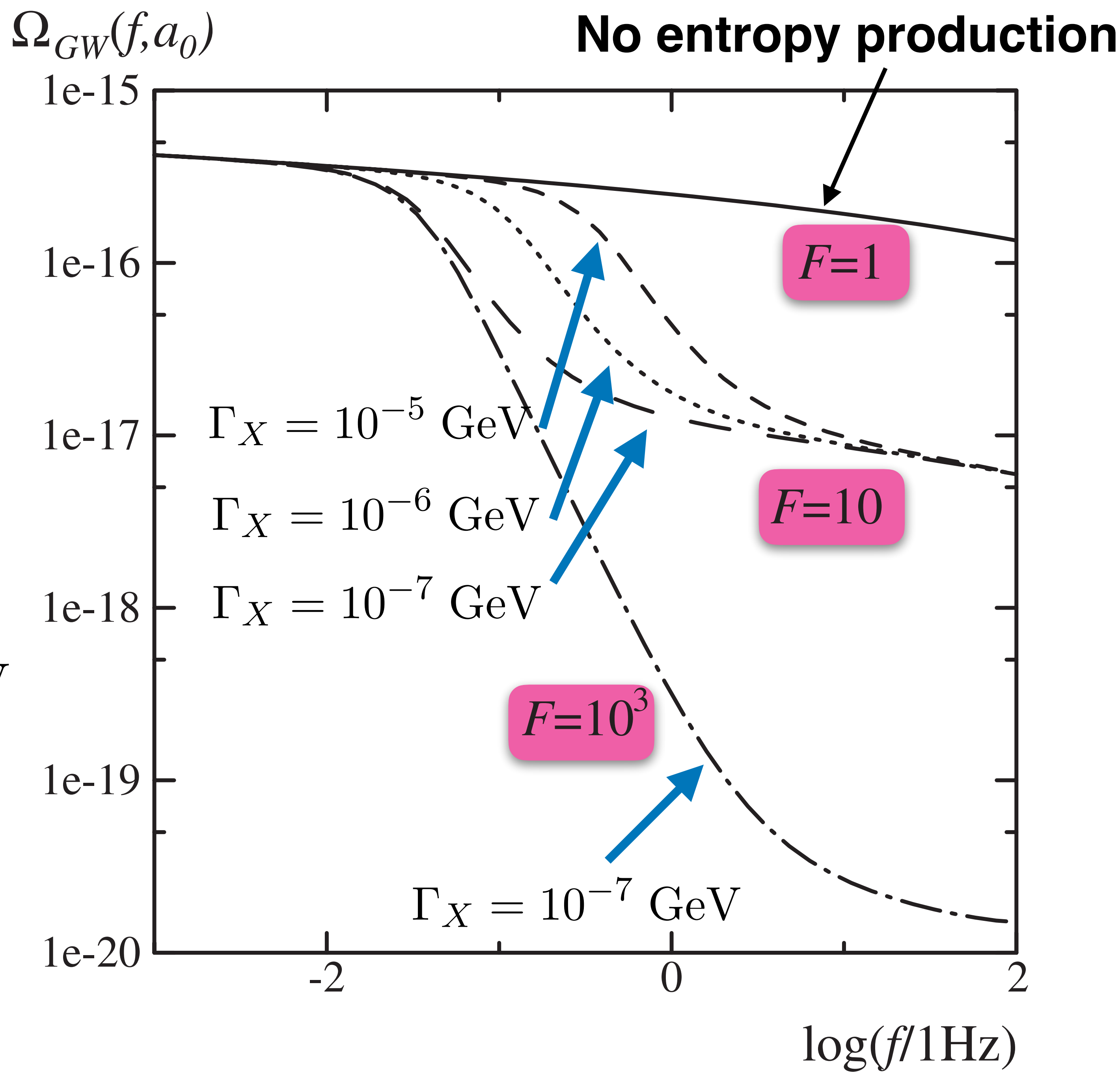
Primordial gravitational wave

$$\Omega_{GW} = \frac{1}{\rho_{cr}} \frac{d\rho_{GW}}{d\ln k}$$

$$\frac{\mathrm{d}\ln\Omega_{\mathrm{GW}}(f,a)}{\mathrm{d}\ln a} = 3w(a) - 1$$

w = p / ρ

$$T \sim 3 \times 10^6 \ \mathrm{GeV}$$
$$\Gamma_X = 10^{-7} \sim 10^{-5} \ \mathrm{GeV}$$
$$m_X \sim (0.8 \sim 4) \times 10^{10} \ \mathrm{GeV}$$



(Approximated) modified GW spectrum

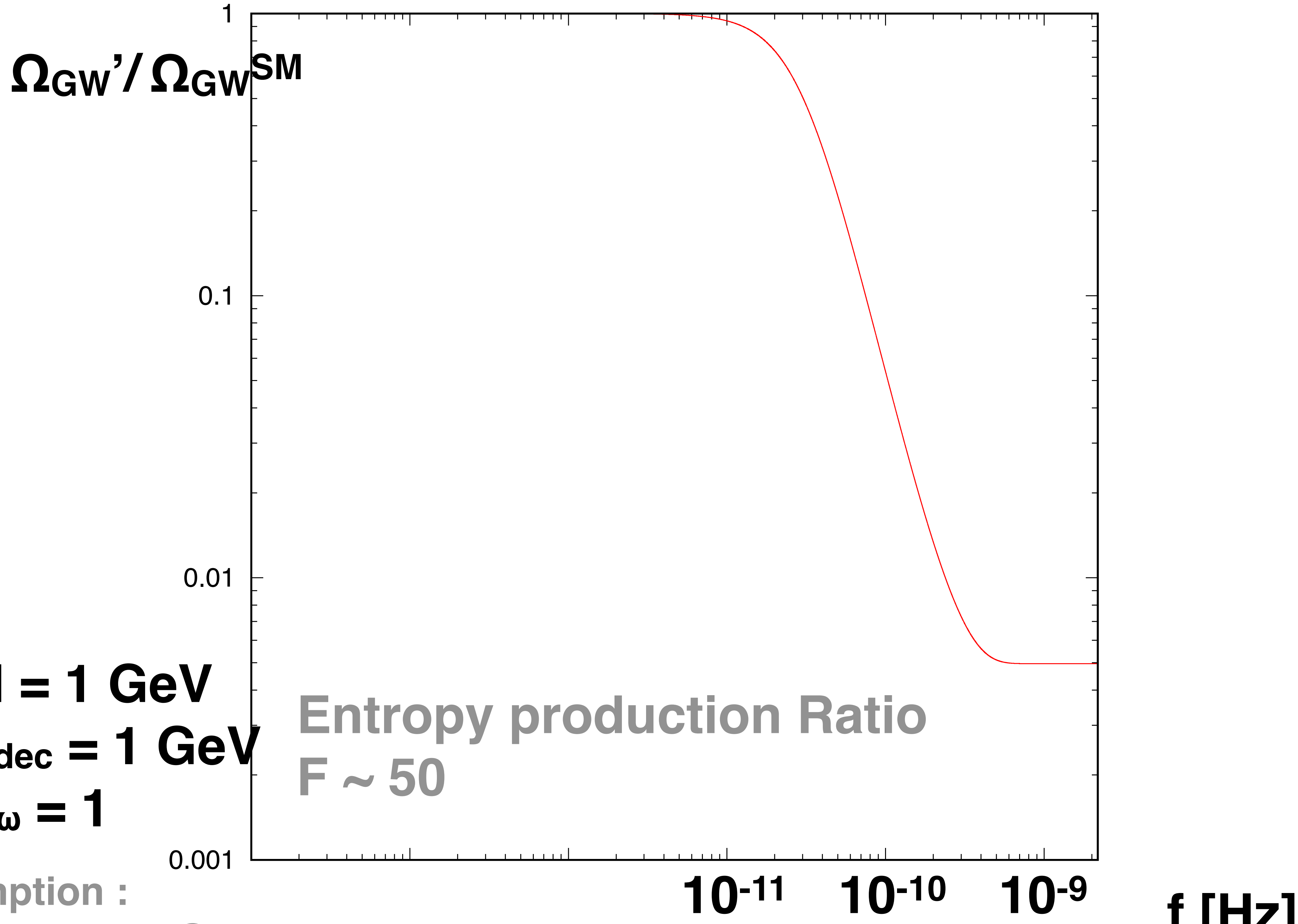
$$\Omega_{GW}^{SM'}(a_0) = F^{-\frac{4}{3}}\Omega_{GW}^{SM}(a_0)$$

Dilution factor

$$F = \frac{s(t_e)a^3(t_e)}{s(t_i)a^3(t_i)}$$

[Seto, Yokoyama, J.Phys.Soc.Jap. 72 (2003) 3082-3086]

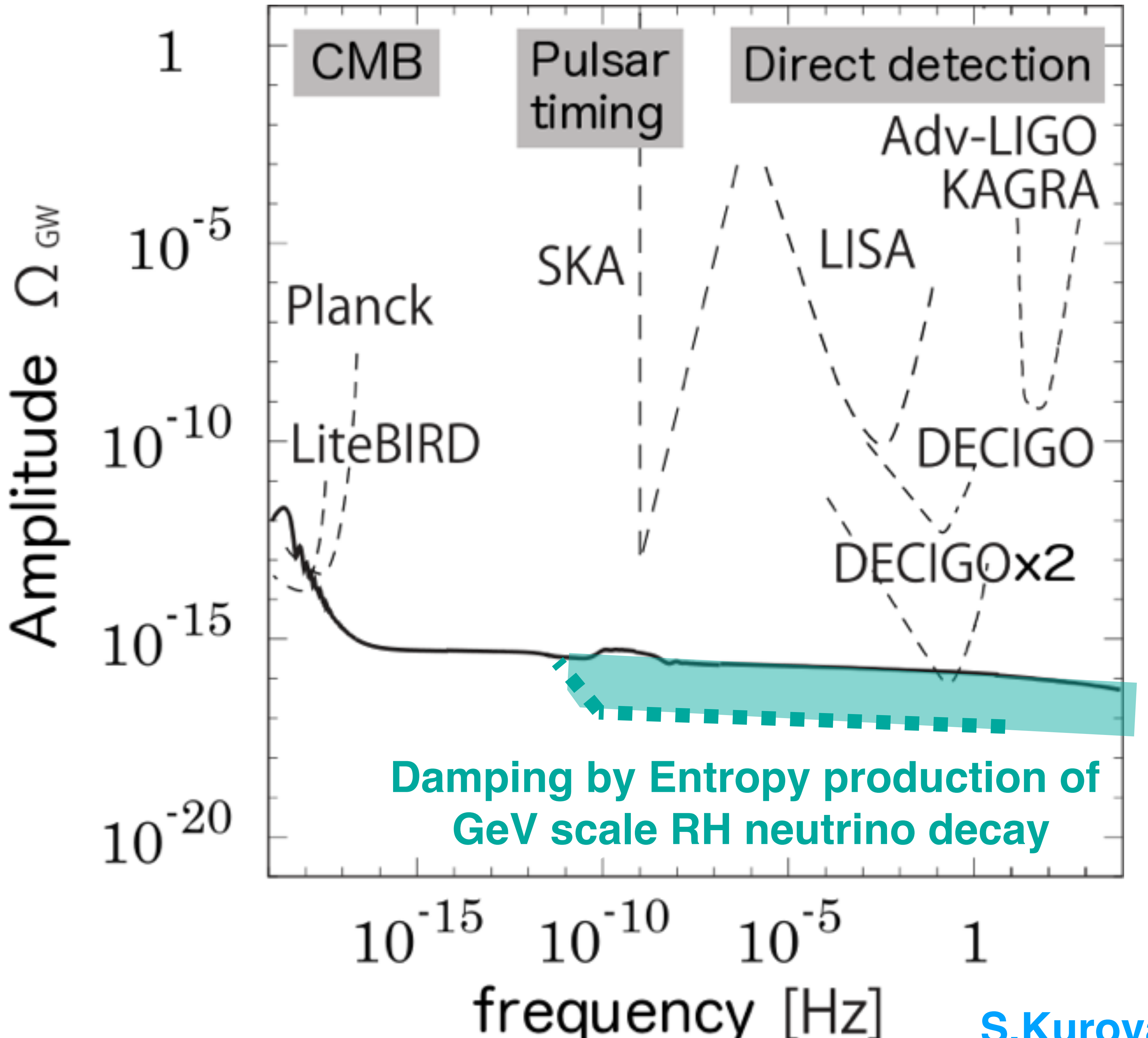
Modified spectrum by GeV scale RH neutrino



M = 1 GeV
T_{dec} = 1 GeV
X_{ω} = 1

Assumption :
Rh ν is non-rel. @T_{dec}

Primordial gravitational wave



S.Kuroyanagi, SI2017 slide

Summary

- If the lifetime of the right-handed neutrino is long enough, the right-handed neutrinos can realize the entropy production in the early universe.
- The entropy production changes the thermal history of the universe and affects the primordial gravitational spectrum.
- Dilution of primordial gravitational wave spectrum by entropy production of right-handed neutrinos starts to occur from about 10^{-11} - 10^{-8} Hz (SKA range).