Relic neutrino/sterile neutrino DM search in neutron stars

based on arXiv: 2408.01484

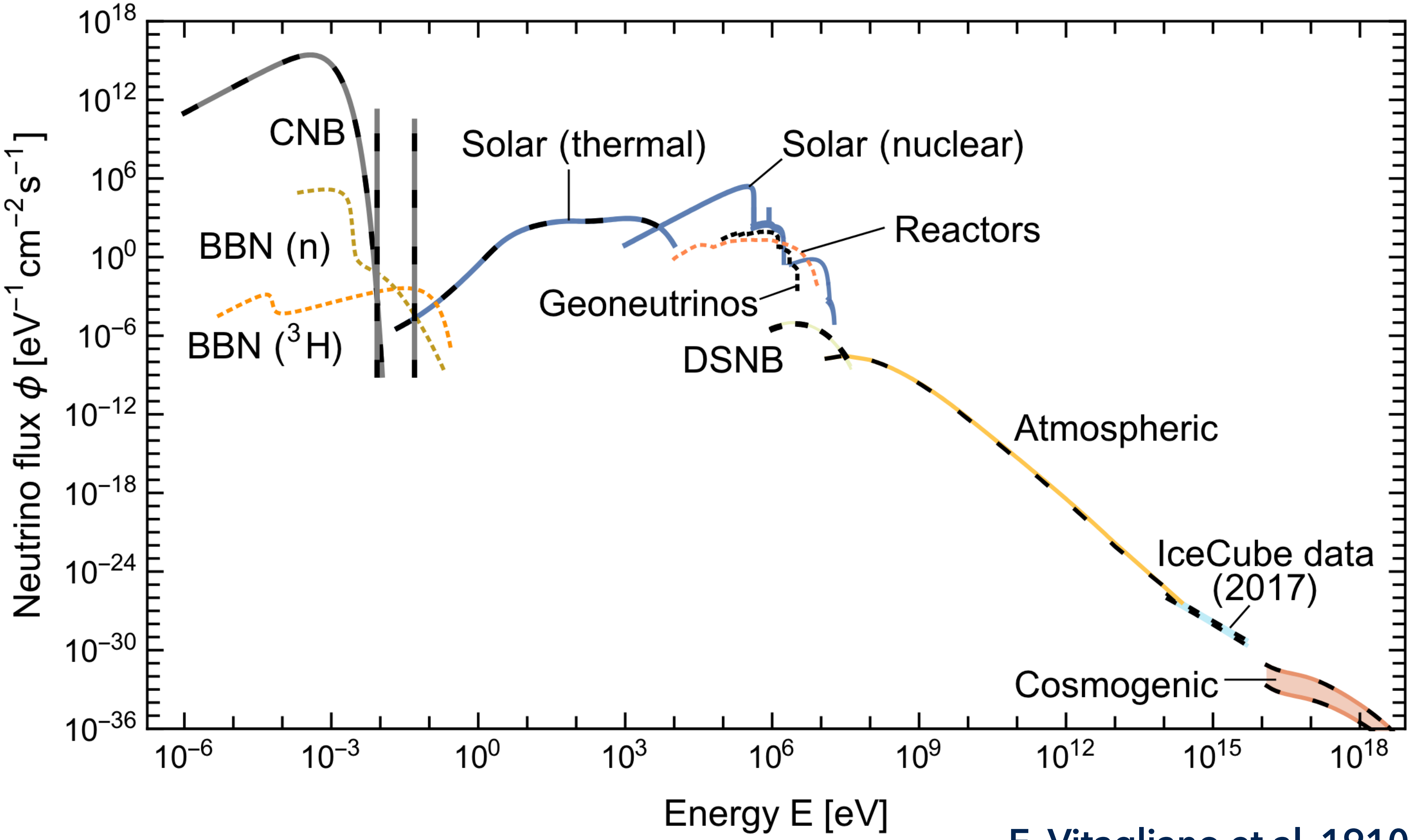
with Saurav Das, Bhupal Dev, and Amarjit Soni

TeVPA 2024

email: o.takuya@wustl.edu

Cosmic neutrino background

- temperature: $T_\nu = (4/11)^{1/3} T_{\mathrm{CMB}} \simeq 1.945\ \mathrm{K}$
- number density: $n_\nu \simeq 56\ \mathrm{cm}^{-3}$ per flavor
- expected to have the largest flux
- detected only indirectly (BBN, CMB, large-scale structure…)

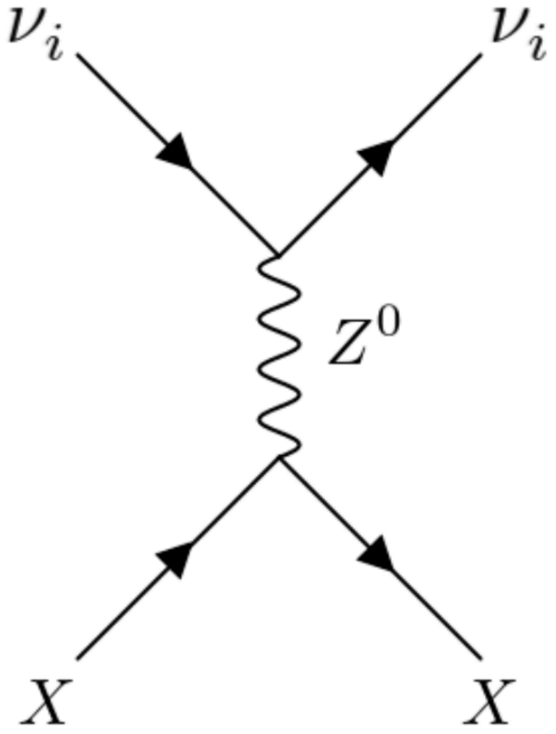


E. Vitagliano et al. 1910.11878

Coherent Enhancement

- neutrino-neutron elastic scattering cross section:

$$\sigma_{\nu n} = \frac{G_F^2}{4\pi} E_\nu^2 \simeq \left(4 \times 10^{-65}\ \mathrm{cm}^2\right) \left(\frac{E_\nu}{10^{-4}\ \mathrm{eV}}\right)^2$$



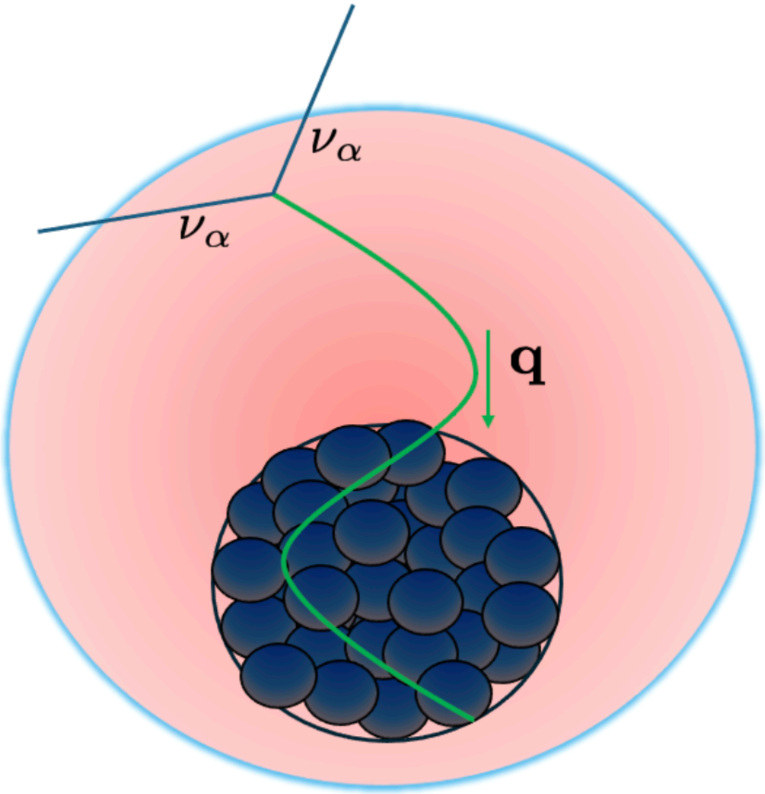
- neutrinos interact with more than one particles collectively; $\sigma \propto \left| F\left(\vec{q}^2\right) \right|^2 \propto N_C^2$

- N_C: a number of particles in the sphere with a radius

$$\lambda_\nu = 2\pi / |\,\mathbf{q}\,|$$

e.g.) neutron star

$$N_C \simeq \frac{4}{3}\pi\lambda_\nu^3 n_n \simeq 3 \times 10^{30} \left(\frac{0.1\ \mathrm{eV}}{|\,\mathbf{q}\,|}\right)^3 \left(\frac{n_n}{4 \times 10^{38}\ \mathrm{cm}^{-3}}\right)$$

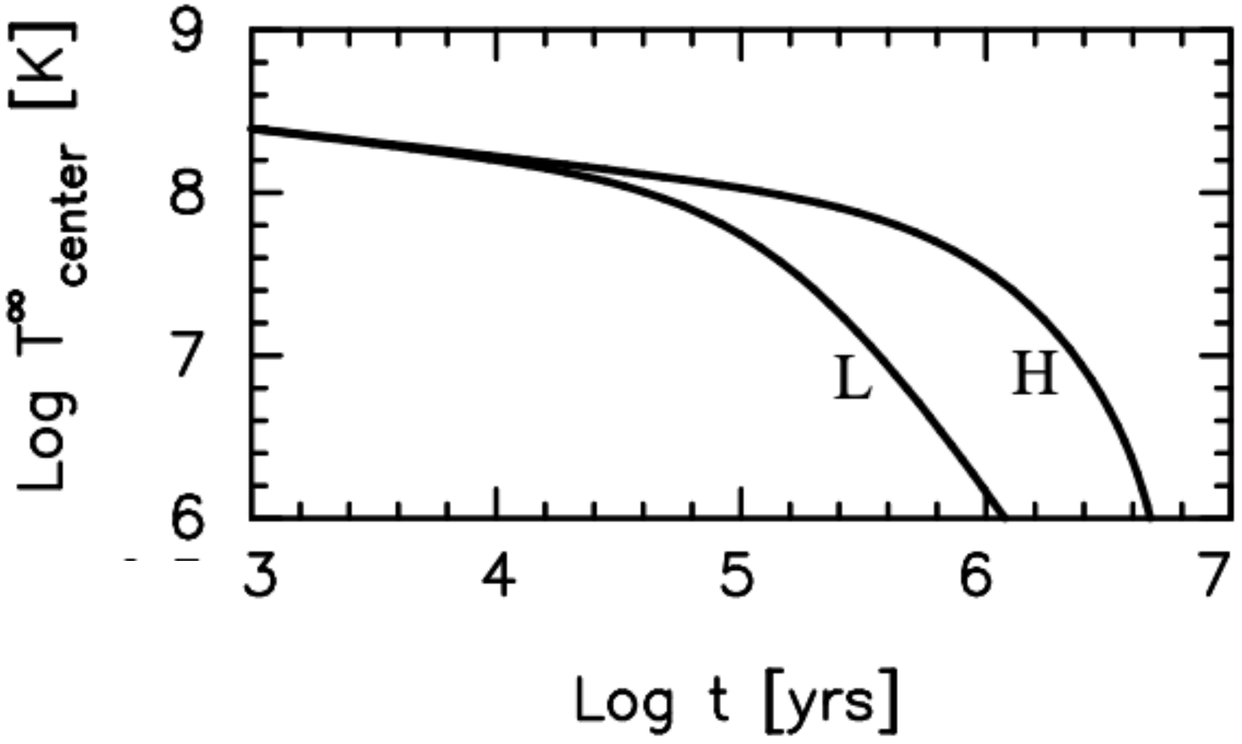


Neutron stars

- a star consists mostly of degenerate neutrons
  ($\rho_{\rm core} \sim 10^{14-15}$ g/cm^3, $R_{\rm NS} \simeq 10$ km, $M_{\rm NS} \simeq 1.5 M_\odot$, $p_{f,n} \simeq 400$ MeV, $p_{f,e} \simeq 150$ MeV)

- keep losing energy by photon and neutrino emissions

- the standard cooling scenario predicts a cold $\mathcal{O}(100)$ K NS at $t_{\rm age} = 10^9$ yr



D. Page et al. 0403657

- JWST can possibly detect a $T_{\rm NS} \sim 1000$ K NS located near ($d \lesssim 10$ pc) earth

Particle capture by a NS

- relic neutrinos/sterile neutrino DM are first gravitationally attracted by a NS

- capture rate: $\dot{N} = \pi b_{\max}^2 v_{\rm rel} n_\nu$

where $$b_{\max} = \left(\frac{2GM_{\rm NS}R_{\rm NS}}{v_{\rm rel}^2}\right)^{1/2} \left(1 - \frac{2GM_{\rm NS}}{R_{\rm NS}}\right)^{-1/2}$$

- on the surface of a NS, $E_\nu \simeq \left(1 - 2GM_{\rm NS}/R_{\rm NS}\right)^{-1/2} \simeq 1.3 m_\nu$

- Heavy particles have kinetic energy K_ν higher than $\simeq 3T_{\rm NS} \rightarrow$ NS heating
- Light particles have kinetic energy K_ν lower than $\simeq 3T_{\rm NS} \rightarrow$ NS cooling

NS cooling due to CνB scatterings

- Energy loss rate of a NS:

$$L_{\mathrm{C}\nu\mathrm{B}} = \dot{N} \times (3T_{\mathrm{NS}} - K_\nu) \min\left(1, \frac{\langle\sigma\rangle}{\sigma_{\mathrm{th}}}\right)$$

- σ_{th}: the cross section required for a neutrino to acquire energy equal to $3T_{\mathrm{NS}} - K_\nu$

$$\sigma_{\mathrm{th}} \simeq \frac{\pi R_{\mathrm{NS}}^2 m_n}{M_{\mathrm{NS}}}\left(\frac{3T_{\mathrm{NS}} - K_\nu}{\langle\Delta E\rangle}\right) \simeq 1.8\times 10^{-45}\ \mathrm{cm}^2 \left(\frac{R_{\mathrm{NS}}}{10\ \mathrm{km}}\right)^2 \left(\frac{1.5 M_\odot}{M_{\mathrm{NS}}}\right)\left(\frac{3T_{\mathrm{NS}} - K_\nu}{\langle\Delta E\rangle}\right)$$

- neutrinos are subject to an effective matter potential

$$U = \mp\, 13.2\ \mathrm{eV}\left(\frac{\rho_n}{7\times 10^{14}\ \mathrm{g/cm^3}}\right) \quad (-\cdots\nu, +\cdots\bar{\nu})$$

anti-neutrinos unlikely to overcome the potential barrier

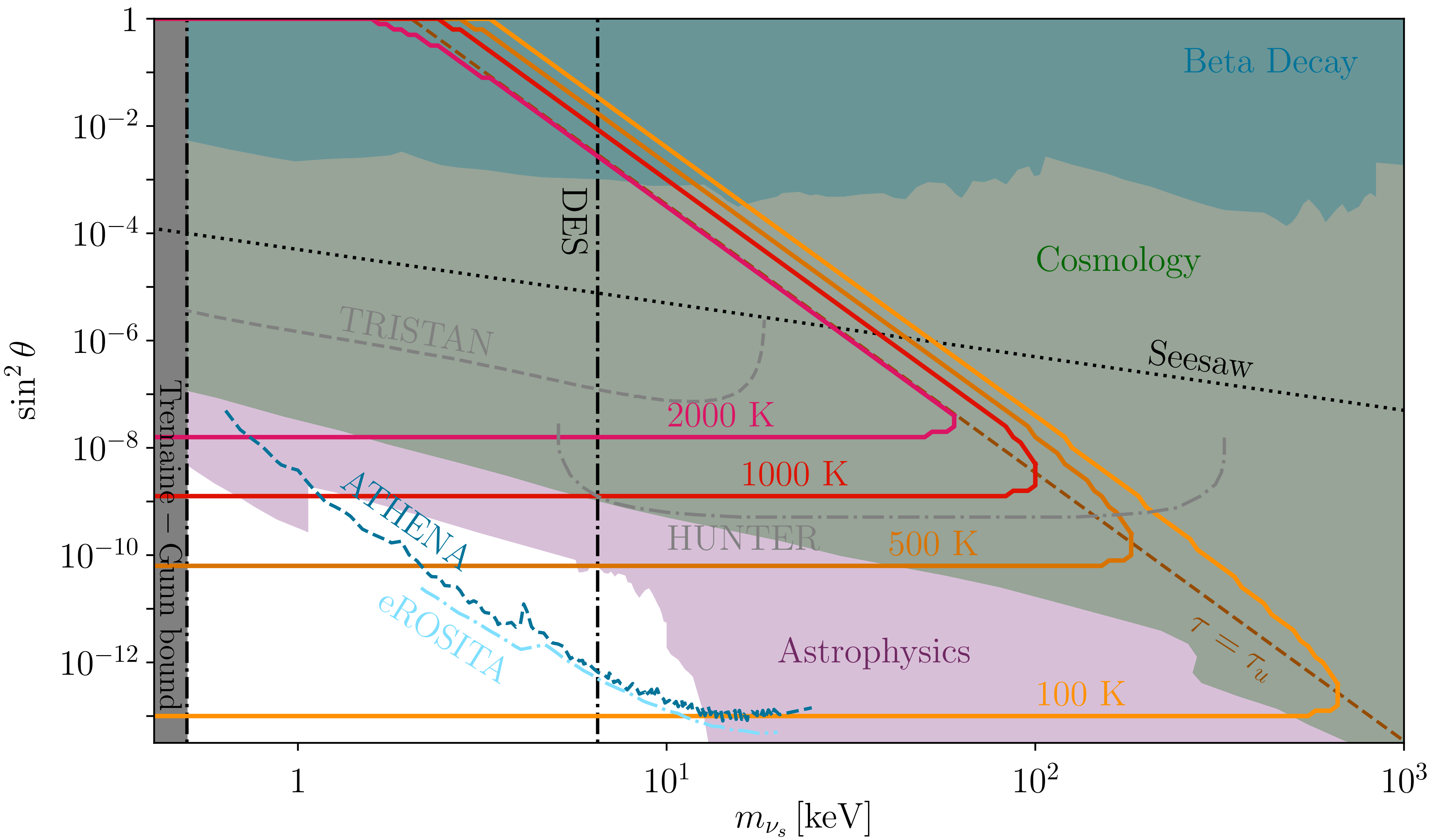
- Energy loss turns out to be quite small compared to that due to photon emission

$$\frac{L_{\mathrm{C}\nu\mathrm{B}}}{L_\gamma} \simeq 1.4\times 10^{-14}\left(\frac{10^5\ \mathrm{K}}{T_{\mathrm{NS}}}\right)^3 \quad \text{for } T_{\mathrm{NS}} = 10^5\ \mathrm{K},\ m_\nu = 0.1\ \mathrm{eV}$$

NS heating due to ν_s scatterings

- Energy loss rate of a NS: $L_{\nu_s} = \dot{N}(E_{\nu_s,\mathrm{surface}} - 3T_{\mathrm{NS}}) \min\left(1, \langle\sigma\rangle/\sigma_{\mathrm{th}}\right)$
- T_{NS}^{∞}: a surface temperature of a NS observed at infinity

$$4\pi R^2 \sigma_{\mathrm{SB}} (T_{\mathrm{NS}}^{\infty})^4 = (L_{\nu_s} + 4\pi R_{\mathrm{NS}}^2 \sigma_{\mathrm{SB}} T_{\mathrm{NS}}^4)\left(1 - \frac{2GM_{\mathrm{NS}}}{R_{\mathrm{NS}}}\right)$$



Summary

- a direct detection of CνB is notoriously hard due to the small cross section

- one of possible ways to overcome this difficulty is making use of a coherent scattering where the cross section is amplified by a factor of N_C

- a NS is cooled down by capturing relic neutrinos

$$\frac{L_{\mathrm{C}\nu\mathrm{B}}}{L_\gamma} \simeq 1.4 \times 10^{-14} \left(\frac{10^5 \ \mathrm{K}}{T_{\mathrm{NS}}} \right)^3 \text{ for } T_{\mathrm{NS}} = 10^5 \ \mathrm{K},\ m_\nu = 0.1 \ \mathrm{eV}$$

- a NS is heated up by capturing sterile neutrino DM

  $\rightarrow T_{\mathrm{NS}} = 1000 \ \mathrm{K}$ for sterile neutrinos with $\sin\theta^2 \gtrsim 10^{-9}$

Backup slides

NS cooling curve

- In the minimal cooling scenario, $\dfrac{dT}{dt} = \dfrac{-\epsilon_\nu - \epsilon_\gamma + \epsilon_{\mathrm{C}\nu\mathrm{B}}}{c_V}$
- $\epsilon_\nu = 7.5 \times 10^{-3} \left(\dfrac{n}{n_0}\right)^{2/3} \left(\dfrac{T}{10^4\ \mathrm{K}}\right)^{8}\ \mathrm{eV\ m^{-3}\ s^{-1}}$
- $\epsilon_\gamma = \dfrac{L_\gamma}{(4/3)\pi R^3} \simeq 1.5 \times 10^{23} \left(\dfrac{T}{10^4\ \mathrm{K}}\right)^{2.2}\ \mathrm{eV\ m^{-3}\ s^{-1}}$
- Energy injection from sterile neutrino DM balances with energy loss due to a photon emission

$T_{\mathrm{NS,init}} = 10^{10}$ K,
$m_{\nu_s} = 10$ keV