超新星爆発におけるミューオン生成とニュートリノシグナルへの影響

杉浦 健一 (早稲田大学)

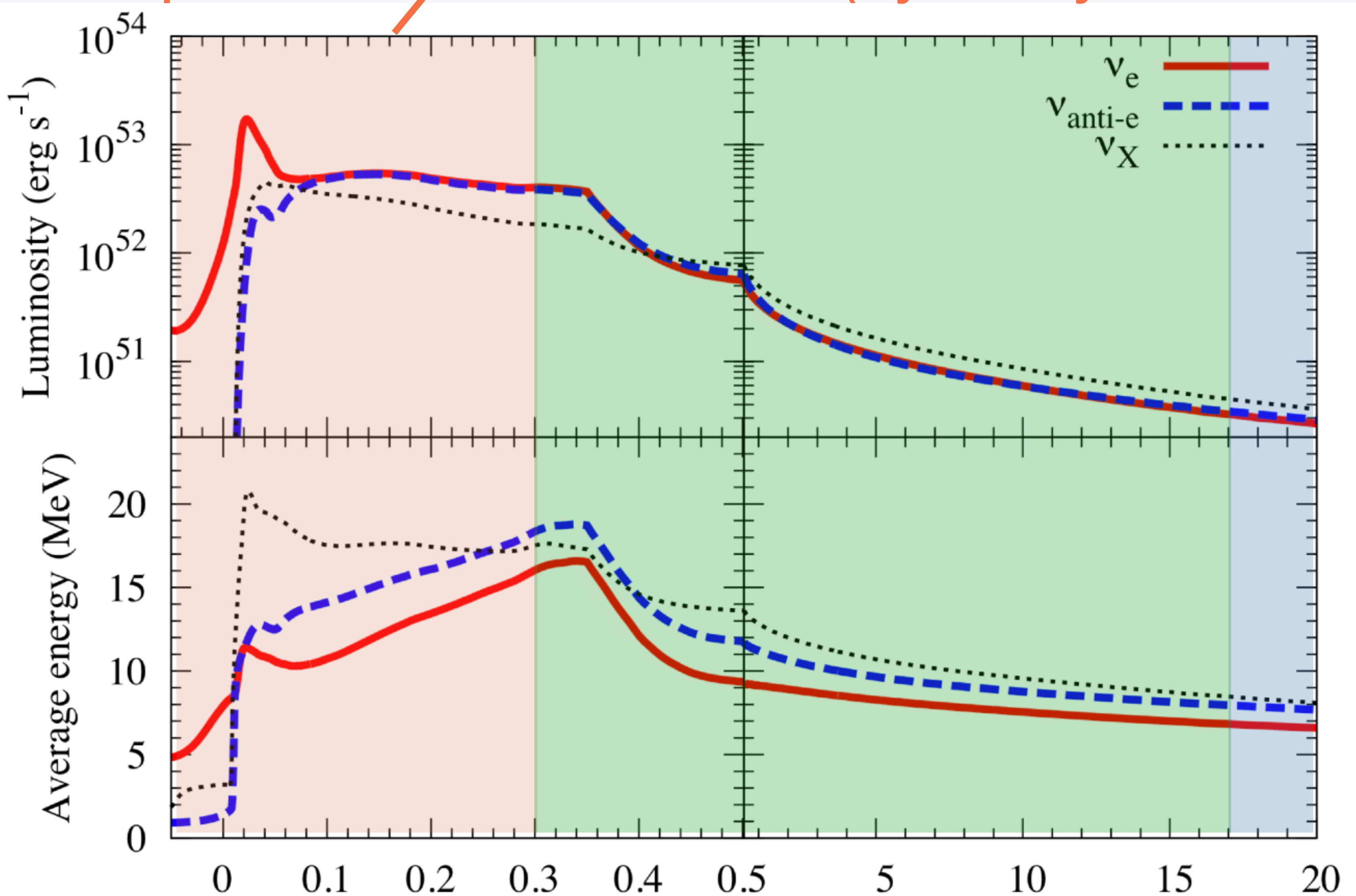
第7回超新星ニュートリノ研究会

Collaborators: 山田 章一 (早稲田大学), 古澤 峻 (東京理科大学)
中里 健一郎 (九州大学), 鈴木 英之 (東京理科大学)

Table of contents

Standard Neutrino Signals from PNS

explosion & contraction (hydrodynamical caluculation)

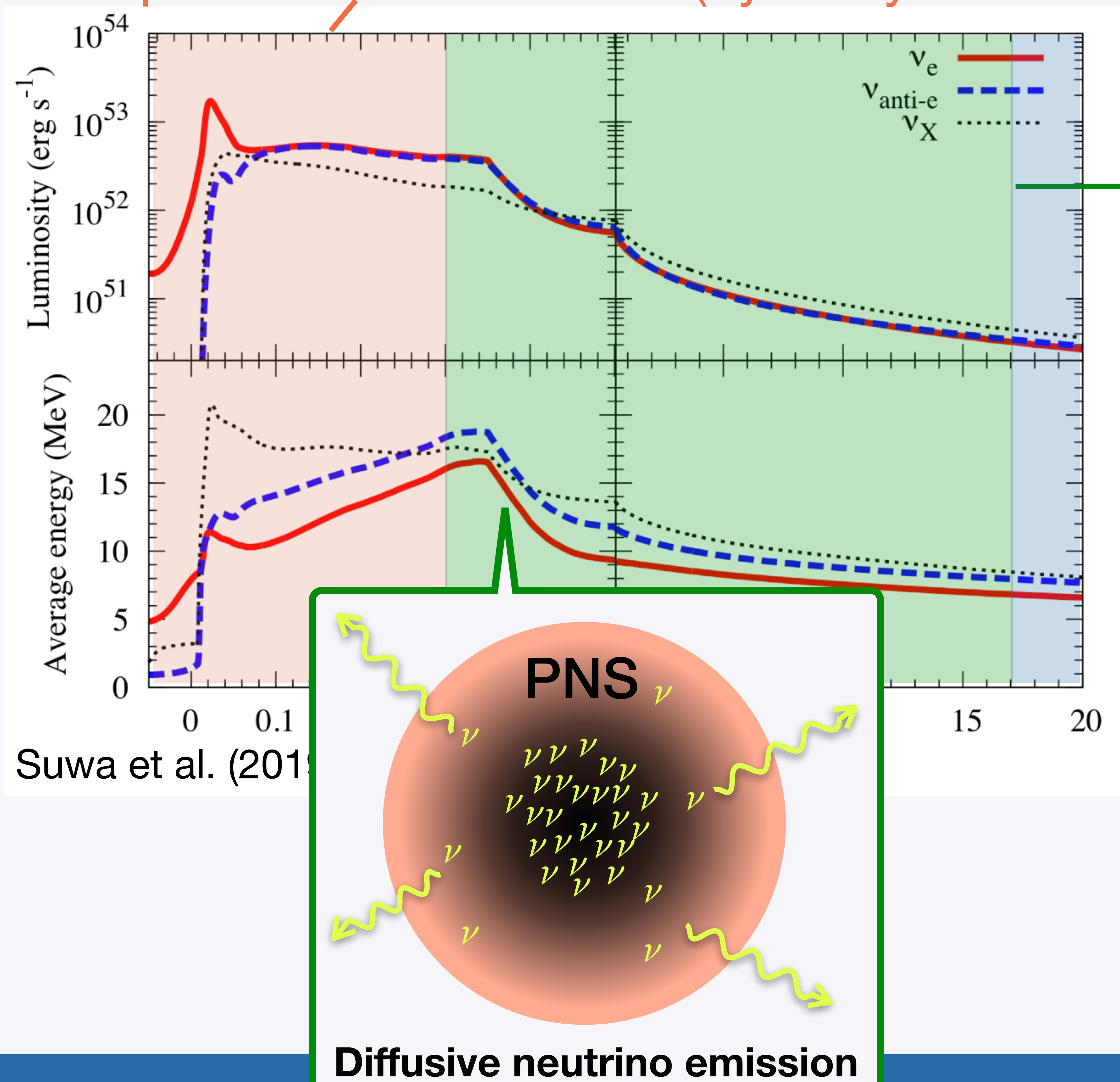


Suwa et al. (2019)

Time (s)

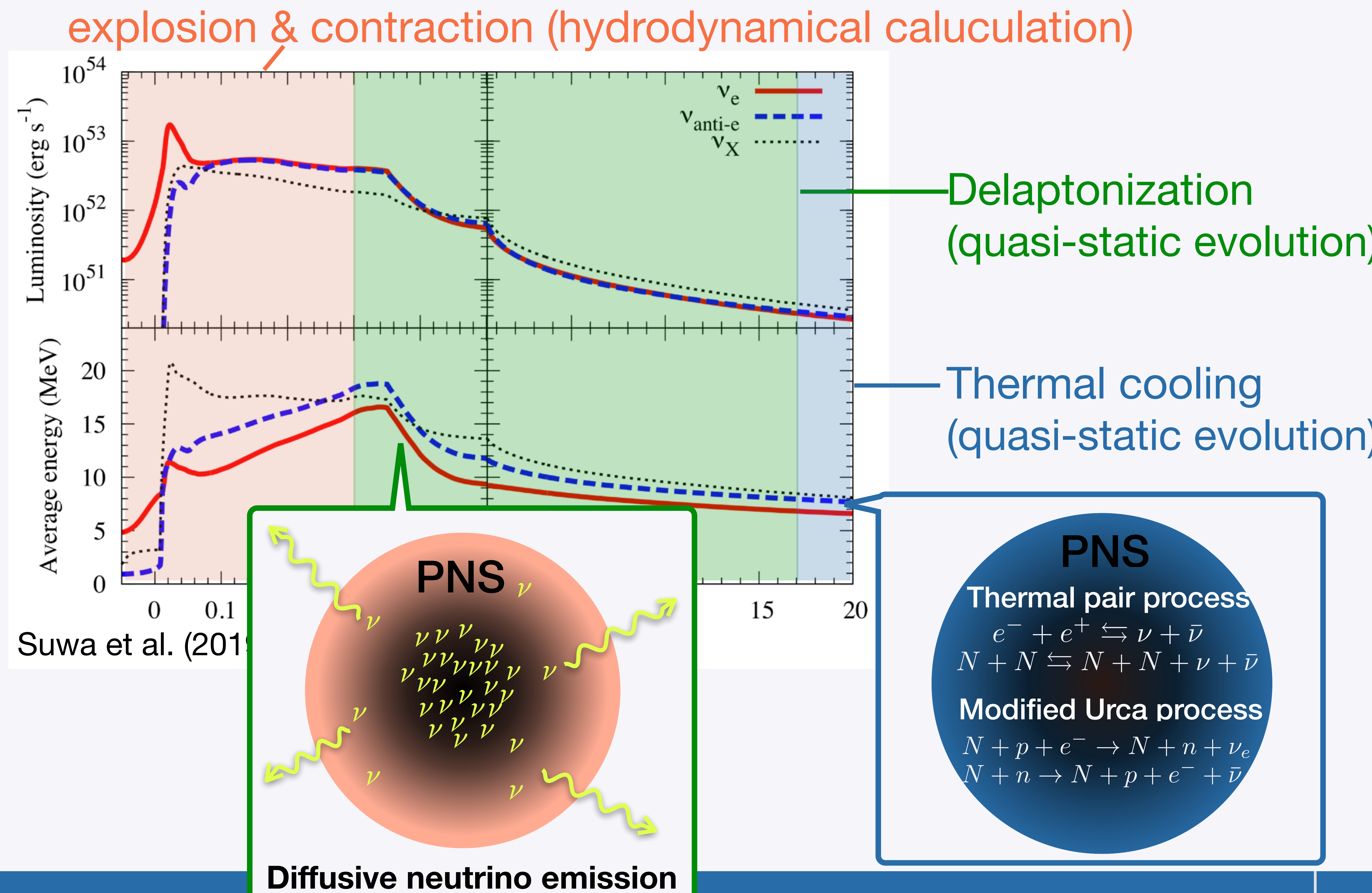
Standard Neutrino Signals from PNS

explosion & contraction (hydrodynamical caluculation)



Delaptonization
(quasi-static evolution)

Standard Neutrino Signals from PNS

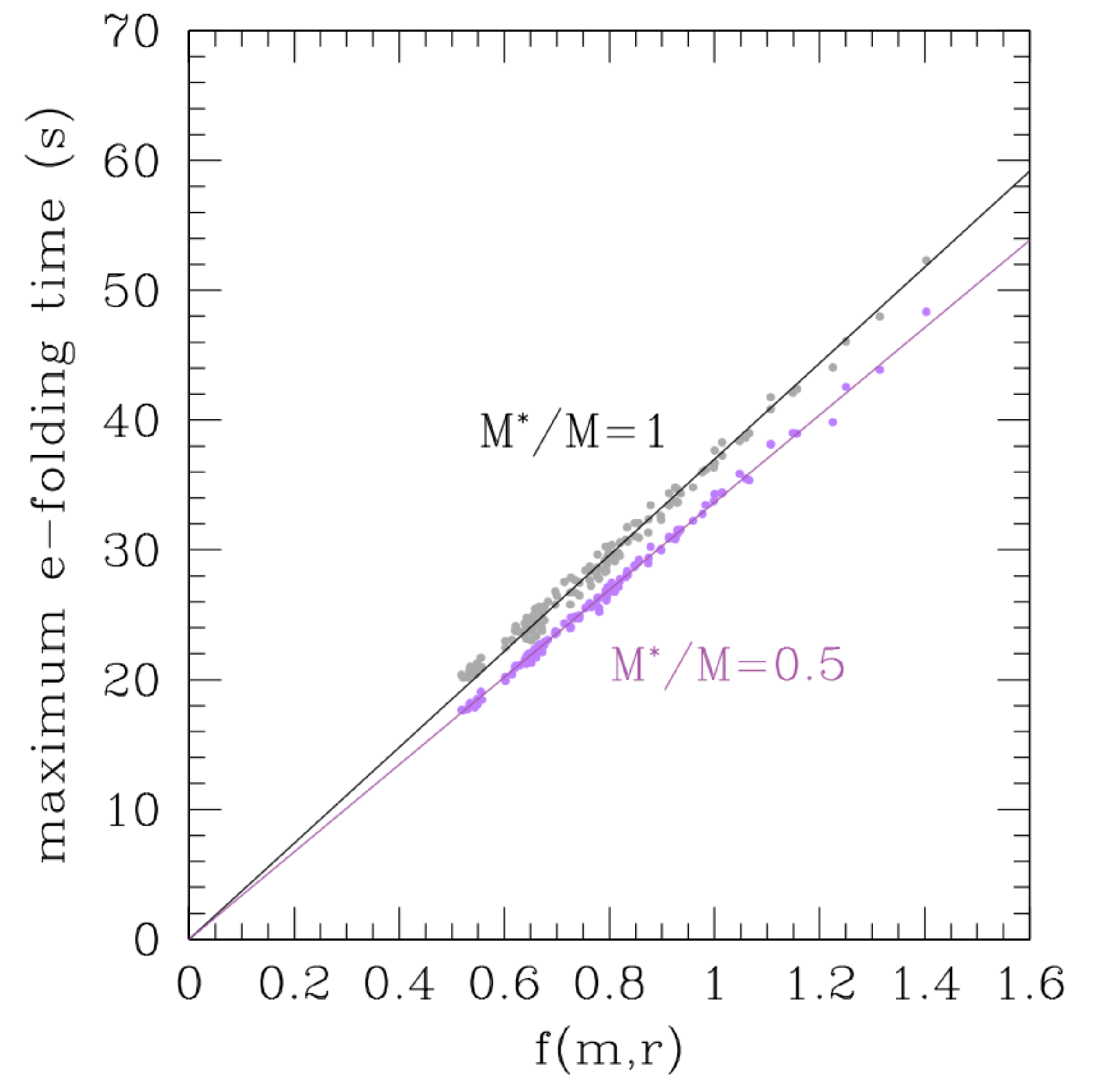


Cooling timescale of proto-neutron star

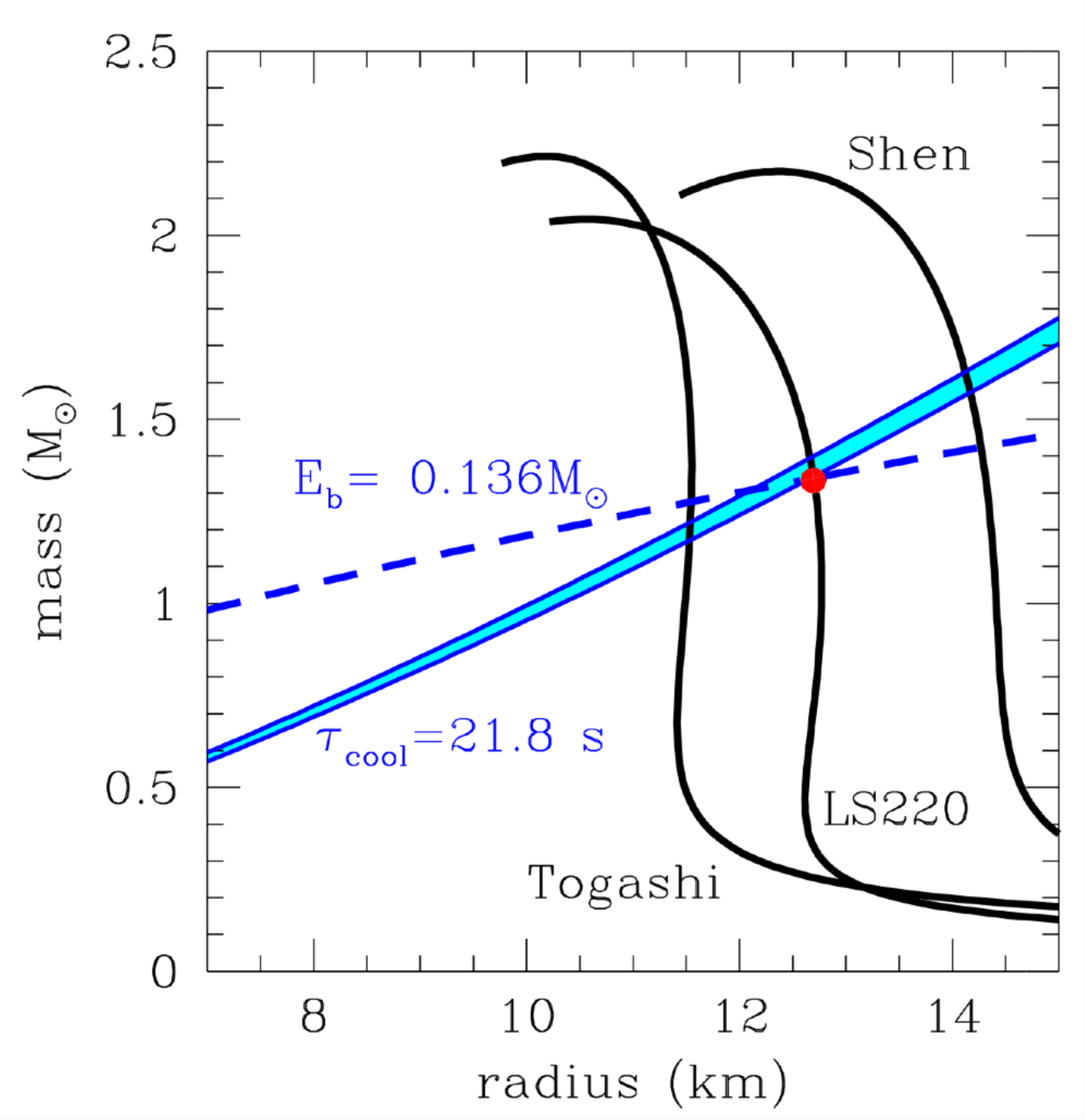
$$\tau_{\rm cool} := \max_t \tau_{\bar{\nu}_e}(t)$$

$$\tau_{\rm cool} = \tau^* \left(\frac{m}{1.4\,\mathrm{M}_\odot}\right)^2 \left(\frac{r}{10\,\mathrm{km}}\right)^{-3} \frac{1}{(1-0.5\beta)\sqrt{1-2\beta}}$$

$$\beta = Gm/rc^2$$

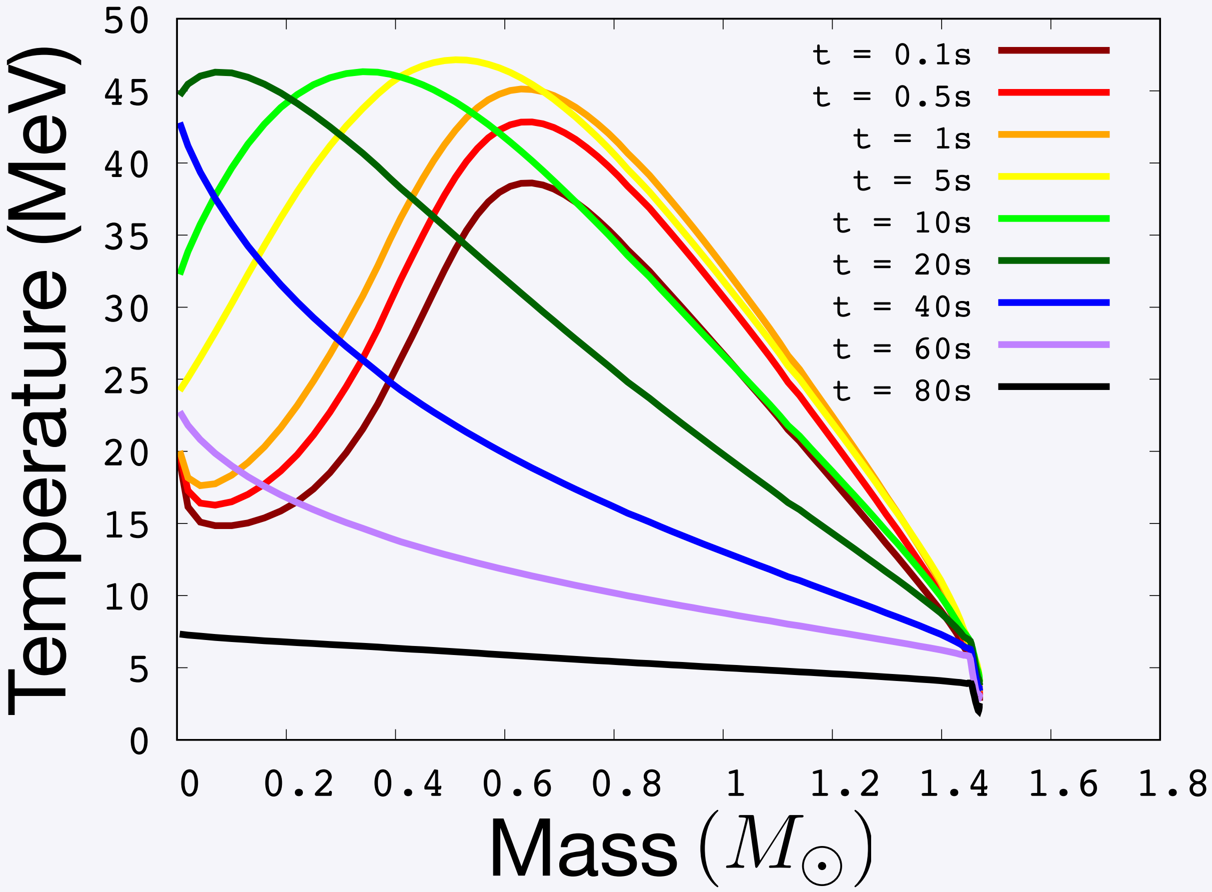


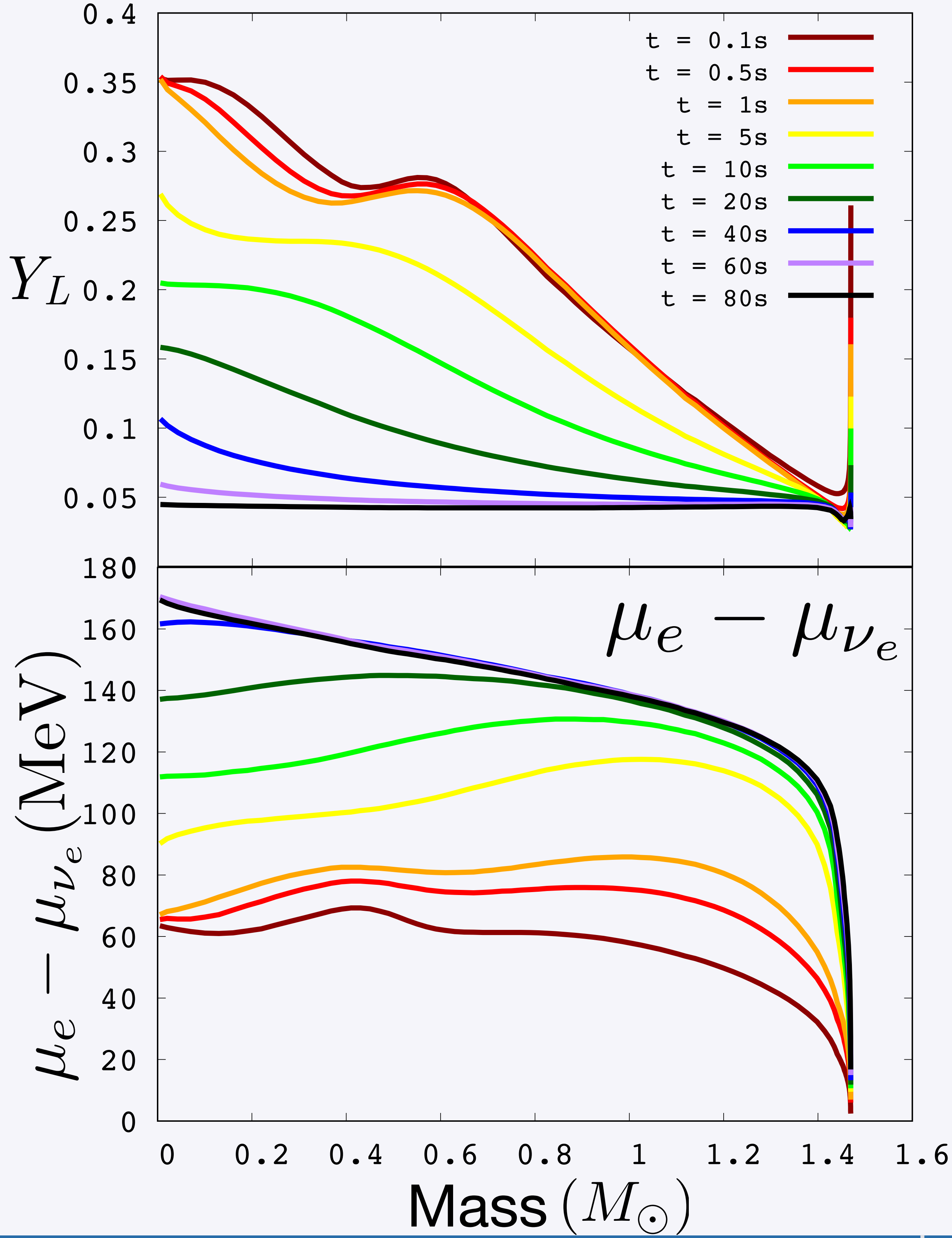
Constraint on M-R relation



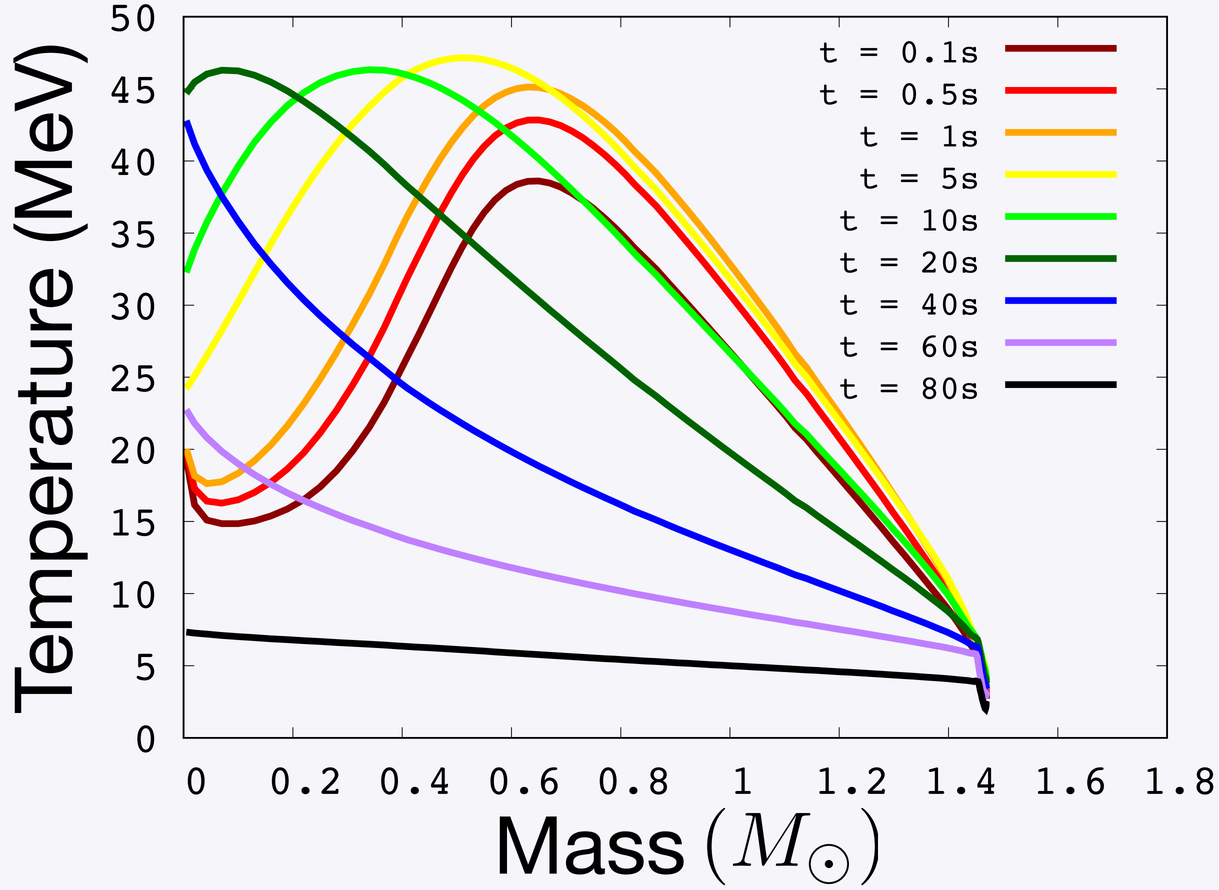
Nakazato & Suzuki (2020)

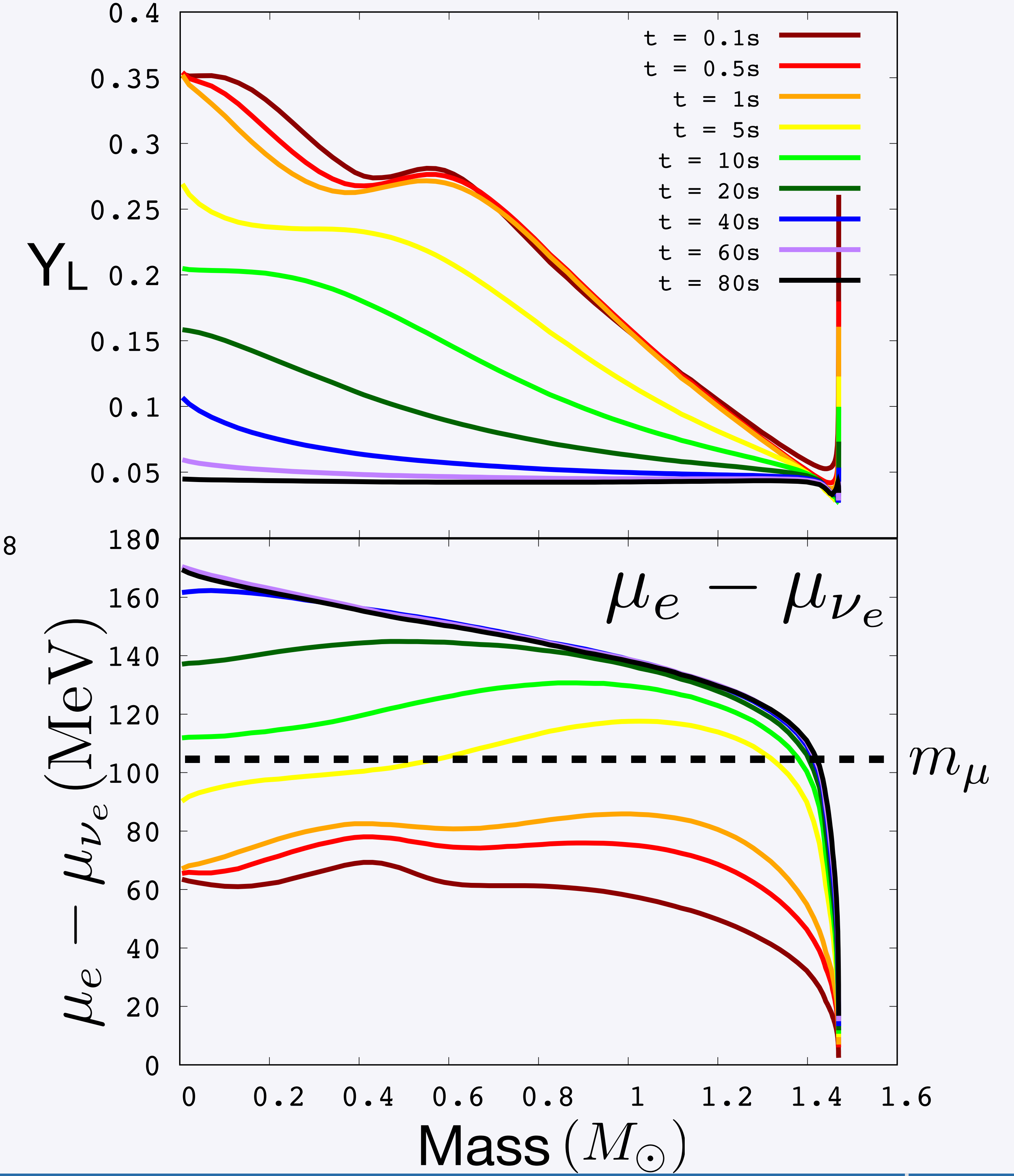
Evolution of interior of standard PNS





Evolution of interior of standard PNS





e.g. $\mu^- \leftrightarrows e^- + \bar{\nu}_e + \nu_\mu$

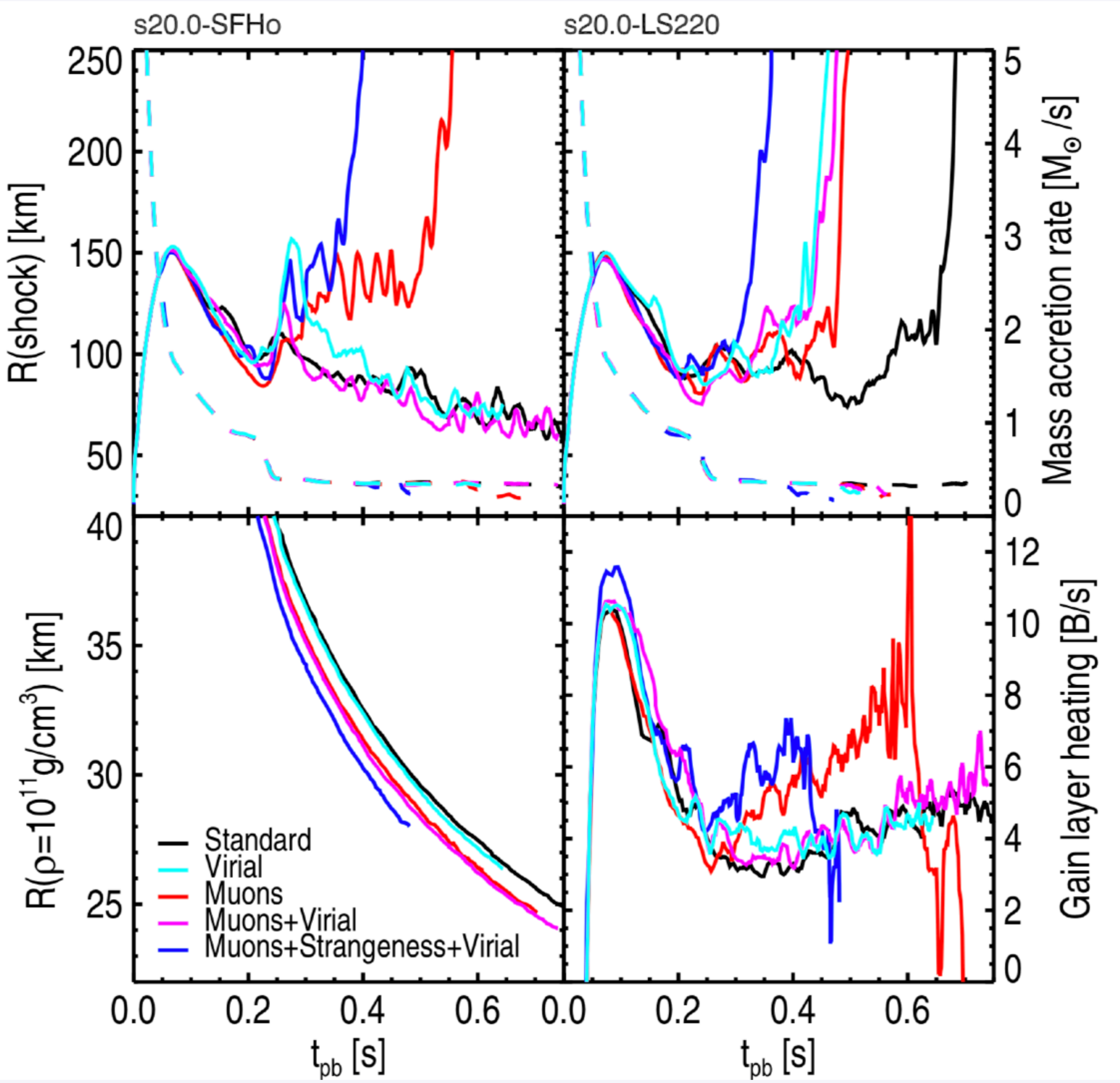
chemical equilibrium condition

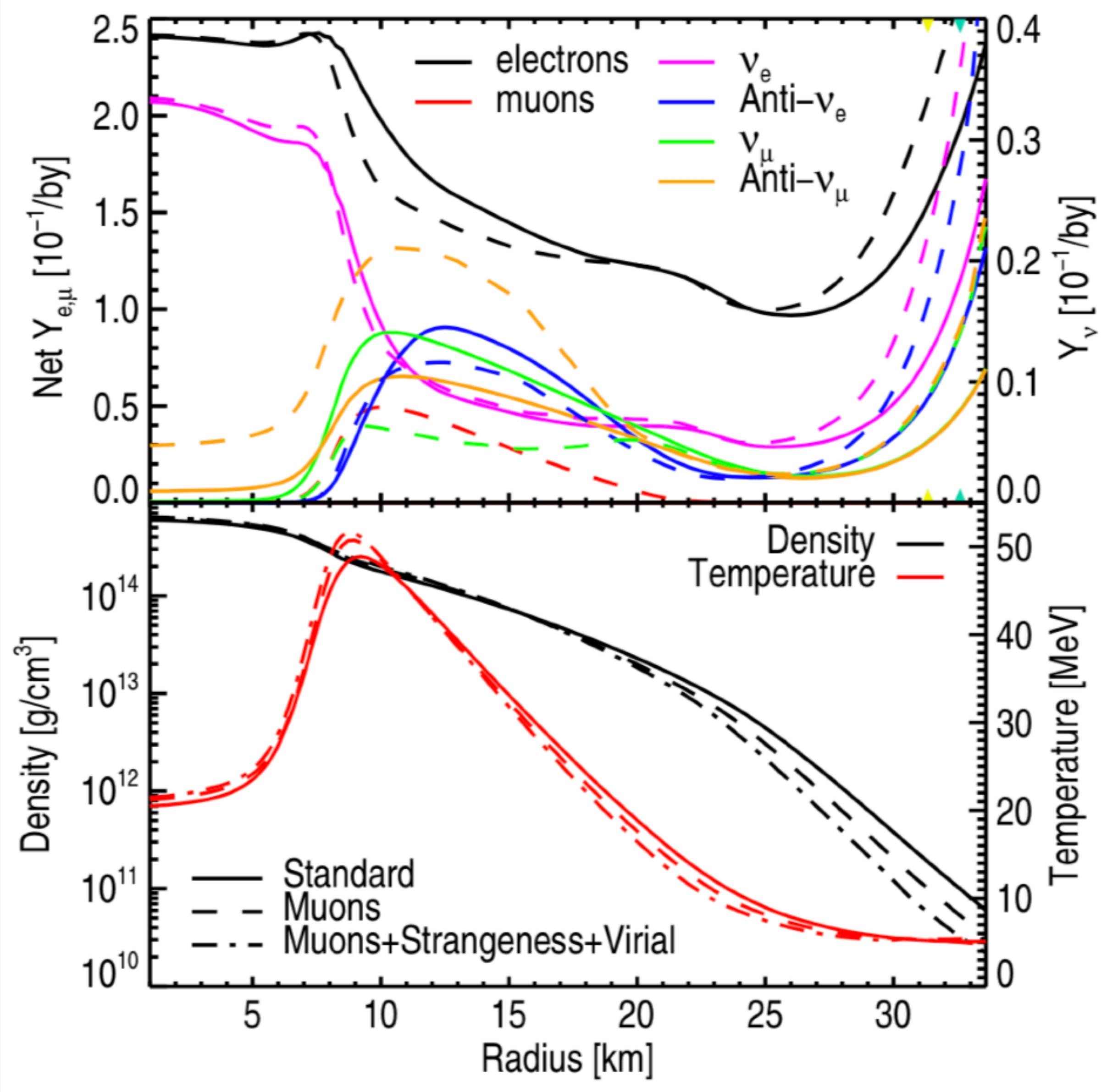
$$\mu_\mu = \mu_e - \mu_{\nu_e} + \mu_{\nu_\mu}$$

Muon can be appeared in PNS cooling phase

Importance of muon creation in SN explosion

- “Muon creation in SN matter facilitates neutrino-driven explosions” (Bollig et al. 2017)





Thermal energy of electron

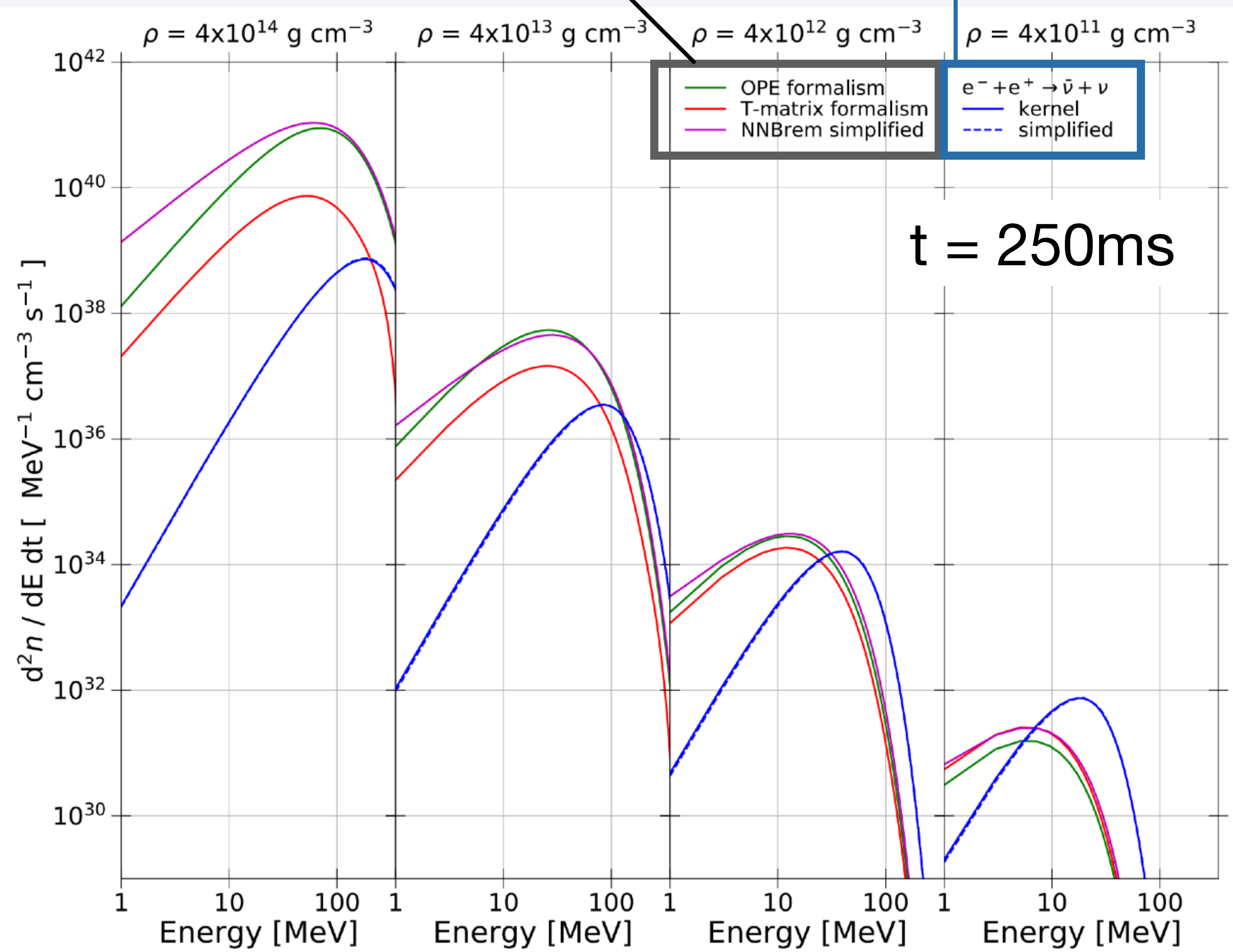
→Rest mass energy of muon

→Rapid contraction of PNS

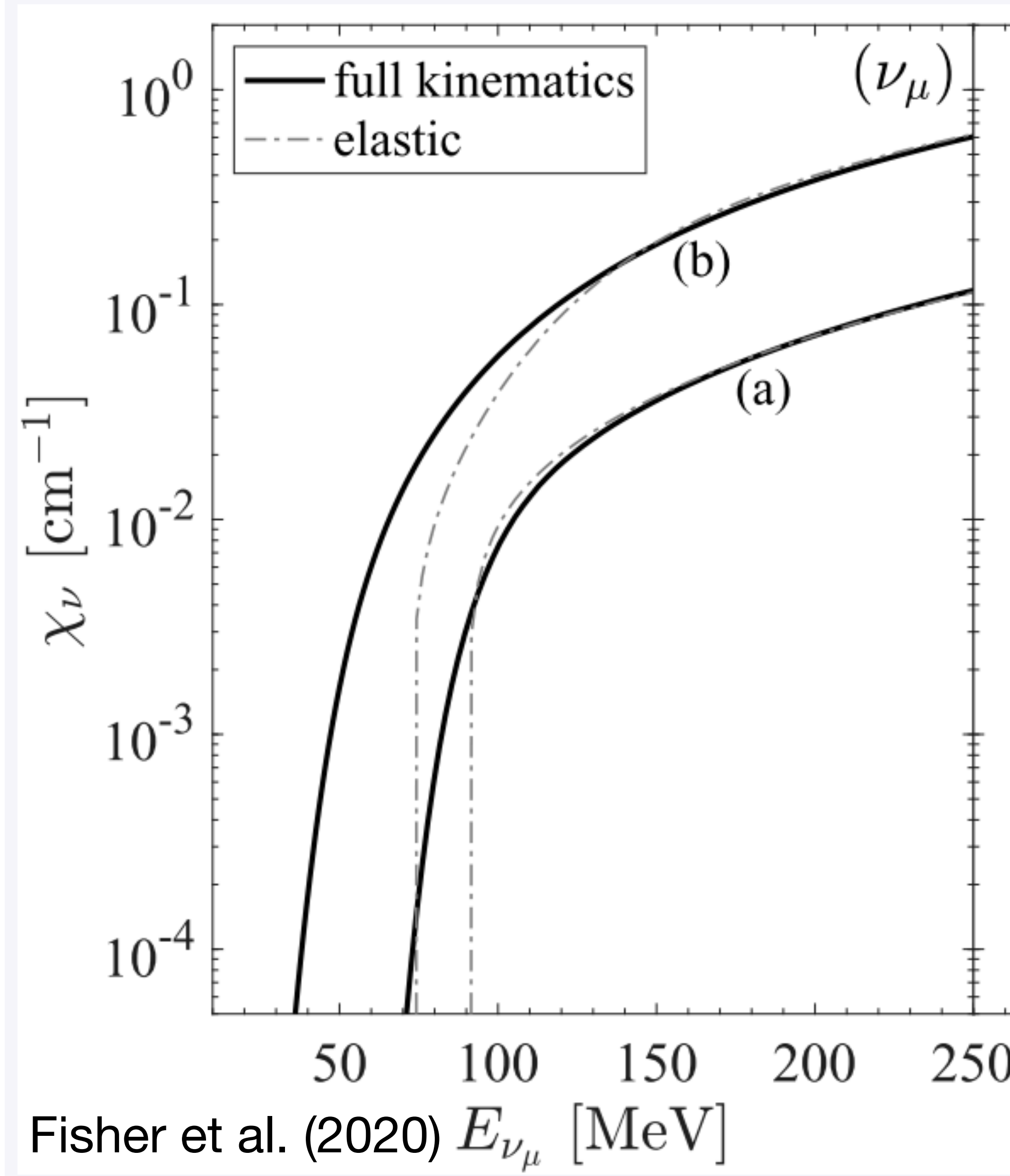
Muonization process

$N + N \leftrightarrows N + N + \nu + \bar{\nu}$ $e^- + e^+ \leftrightarrows \nu + \bar{\nu}$

(a) $\nu_\mu + n \leftrightarrows \mu^- + p$
(b) $\bar{\nu}_\mu + p \leftrightarrows \mu^+ + n$



Betranhandy & O'Connor (2020)



Fisher et al. (2020)

	T [MeV]	ρ [g cm^{-3}]	Y_e	Y_μ	μ_e [MeV]	μ_μ [MeV]	$U_n - U_p$[a] [MeV]
(a)	10	5×10^{13}	0.2	10^{-4}	108.1	51.7	13.9

Neutrino reactions related to muon

Muon scattering

$$\nu + \mu^{\pm} \leftrightarrows \nu' + \mu^{\pm\prime}$$

Muon capture

$$\mu^- + p \leftrightarrows n + \nu_\mu$$

$$\mu^+ + n \leftrightarrows p + \bar{\nu}_\mu$$

Flavor exchange reaction

$$\mu^- + \bar{\nu}_\mu \leftrightarrows e^- + \bar{\nu}_e$$

$$\mu^+ + \nu_\mu \leftrightarrows e^+ + \nu_e$$

$$\mu^- + \nu_e \leftrightarrows e^- + \nu_\mu$$

$$\mu^+ + \bar{\nu}_e \leftrightarrows e^+ + \bar{\nu}_\mu$$

Annihilation reaction

$$\mu^- + \mu^+ \leftrightarrows \nu + \bar{\nu}$$

$$\mu^- + e^+ \leftrightarrows \bar{\nu}_e + \nu_\mu$$

$$\mu^+ + e^- \leftrightarrows \nu_e + \bar{\nu}_\mu$$

Muon decay

$$\mu^- \leftrightarrows e^- + \bar{\nu}_e + \nu_\mu$$

$$\mu^+ \leftrightarrows e^+ + \nu_e + \bar{\nu}_\mu$$

Neutrino reactions related to muon

Muon scattering

$$\nu + \mu^{\pm} \leftrightarrows \nu' + \mu^{\pm\prime}$$

Muon capture

$$\mu^- + p \leftrightarrows n + \nu_\mu$$

$$\mu^+ + n \leftrightarrows p + \bar{\nu}_\mu$$

Flavor exchange reaction

$$\mu^- + \bar{\nu}_\mu \leftrightarrows e^- + \bar{\nu}_e$$

$$\mu^+ + \nu_\mu \leftrightarrows e^+ + \nu_e$$

$$\mu^- + \nu_e \leftrightarrows e^- + \nu_\mu$$

$$\mu^+ + \bar{\nu}_e \leftrightarrows e^+ + \bar{\nu}_\mu$$

Annihilation reaction

$$\mu^- + \mu^+ \leftrightarrows \nu + \bar{\nu}$$

$$\mu^- + e^+ \leftrightarrows \bar{\nu}_e + \nu_\mu$$

$$\mu^+ + e^- \leftrightarrows \nu_e + \bar{\nu}_\mu$$

Muon decay

$$\mu^- \leftrightarrows e^- + \bar{\nu}_e + \nu_\mu$$

$$\mu^+ \leftrightarrows e^+ + \nu_e + \bar{\nu}_\mu$$

Reaction rate related with muon

Neutrino transport equation

$$\frac{1}{c}\frac{df_\nu}{d\tau} = \underline{\eta_\nu}(1-f_\nu) - \frac{1}{\underline{\lambda_\nu}} f_\nu$$

emissivity   mean free path

- For example: $\mu^- + \bar{\nu}_\mu \leftrightarrows e^- + \bar{\nu}_e$

$$\frac{1}{\lambda_{\bar{\nu}_e}} = \frac{1}{2\epsilon_{\bar{\nu}_\mu}} \int \frac{2f_\mu(\epsilon_\mu)d^3\boldsymbol{p}_\mu}{(2\pi)^3 2\epsilon_\mu} \frac{(1-f_e(\epsilon_e))d^3\boldsymbol{p}_e}{(2\pi)^3 2\epsilon_e} \frac{(1-f_{\bar{\nu}_e}(\epsilon_{\bar{\nu}_e}))d^3\boldsymbol{p}_{\bar{\nu}_e}}{(2\pi)^3 2\epsilon_{\bar{\nu}_e}}$$
$$\times (2\pi)^4 \delta^4(p_e + p_{\bar{\nu}_e} - p_\mu + p_{\bar{\nu}_\mu})|\mathcal{M}|^2$$

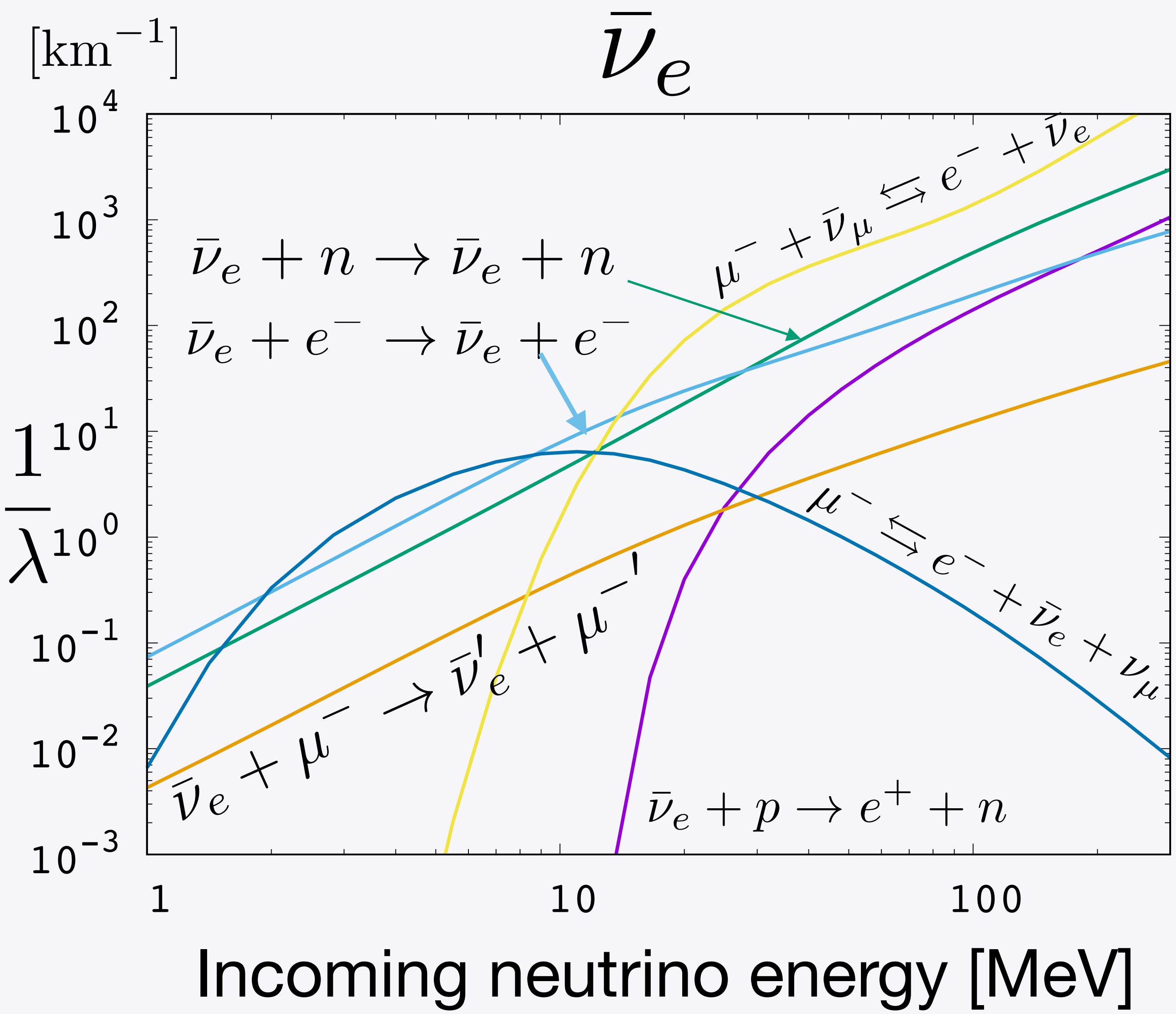
$$|\mathcal{M}|^2 = 64 G_F^2 (p_e \cdot p_{\bar{\nu}_\mu})(p_\mu \cdot p_{\bar{\nu}_e})$$

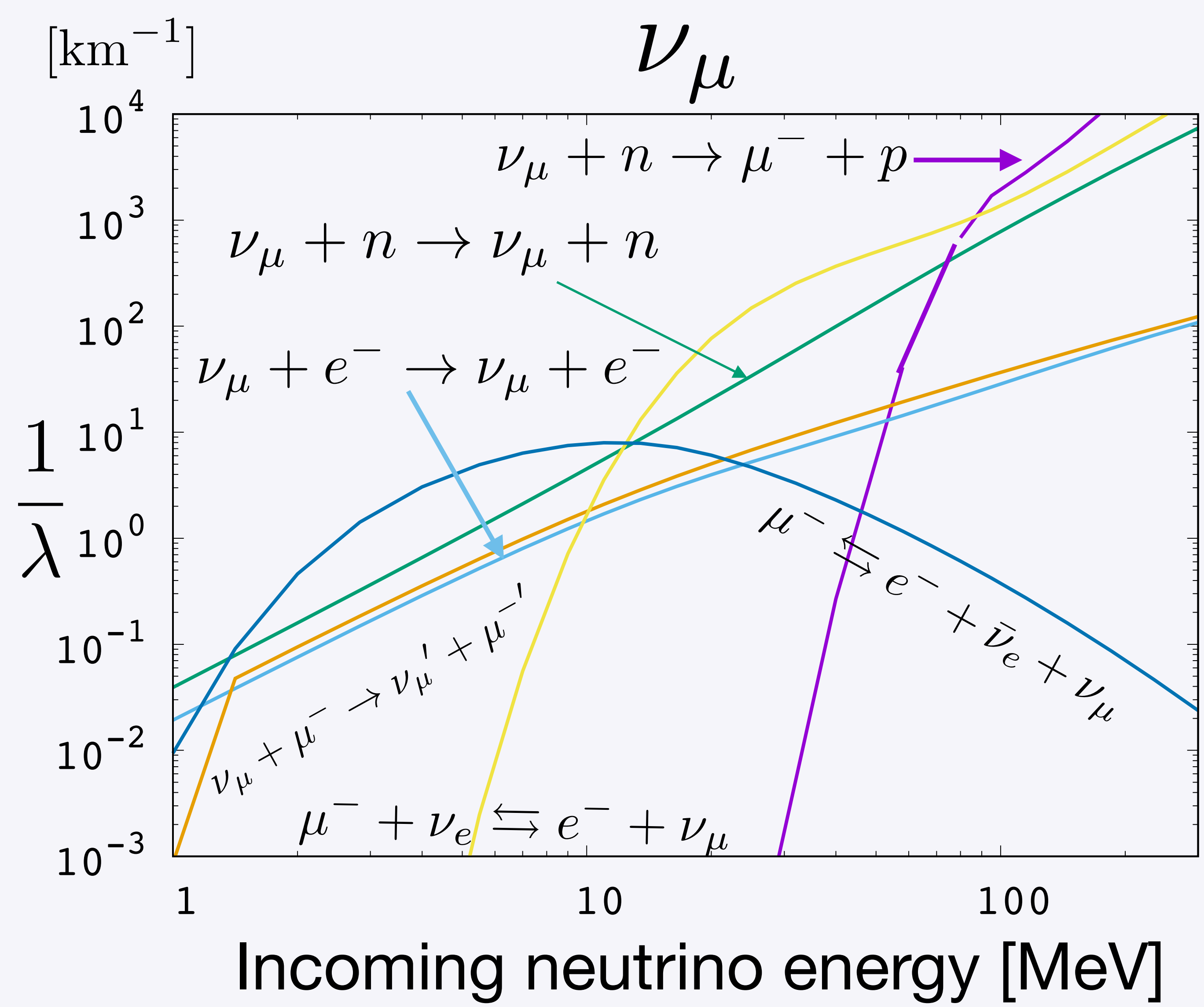
- For simplicity, neutrino distributions are assumed to be Fermi-Dirac distributions with chemical equilibrium chemical potential.

Early phase (t ~ 0.4s)

ϱ [g/cc]	T [MeV]	Y_e	Y_μ	μ_n [MeV]	μ_p [MeV]	μ_e [MeV]	μ_μ [MeV]
1*10[14]	38.3	0.13	0.04	886	801	83.3	64.1

Typically, r ~ 15 km



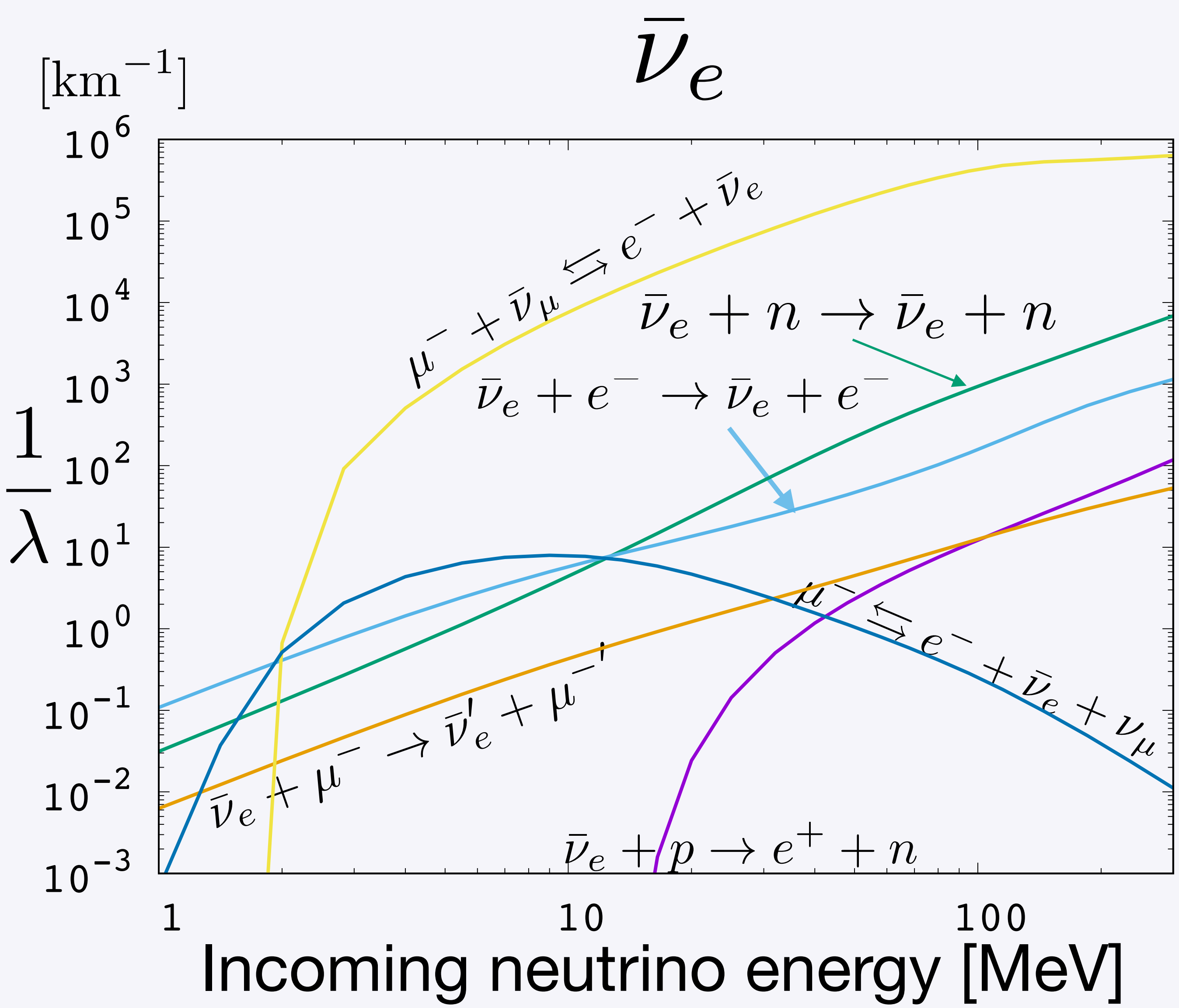


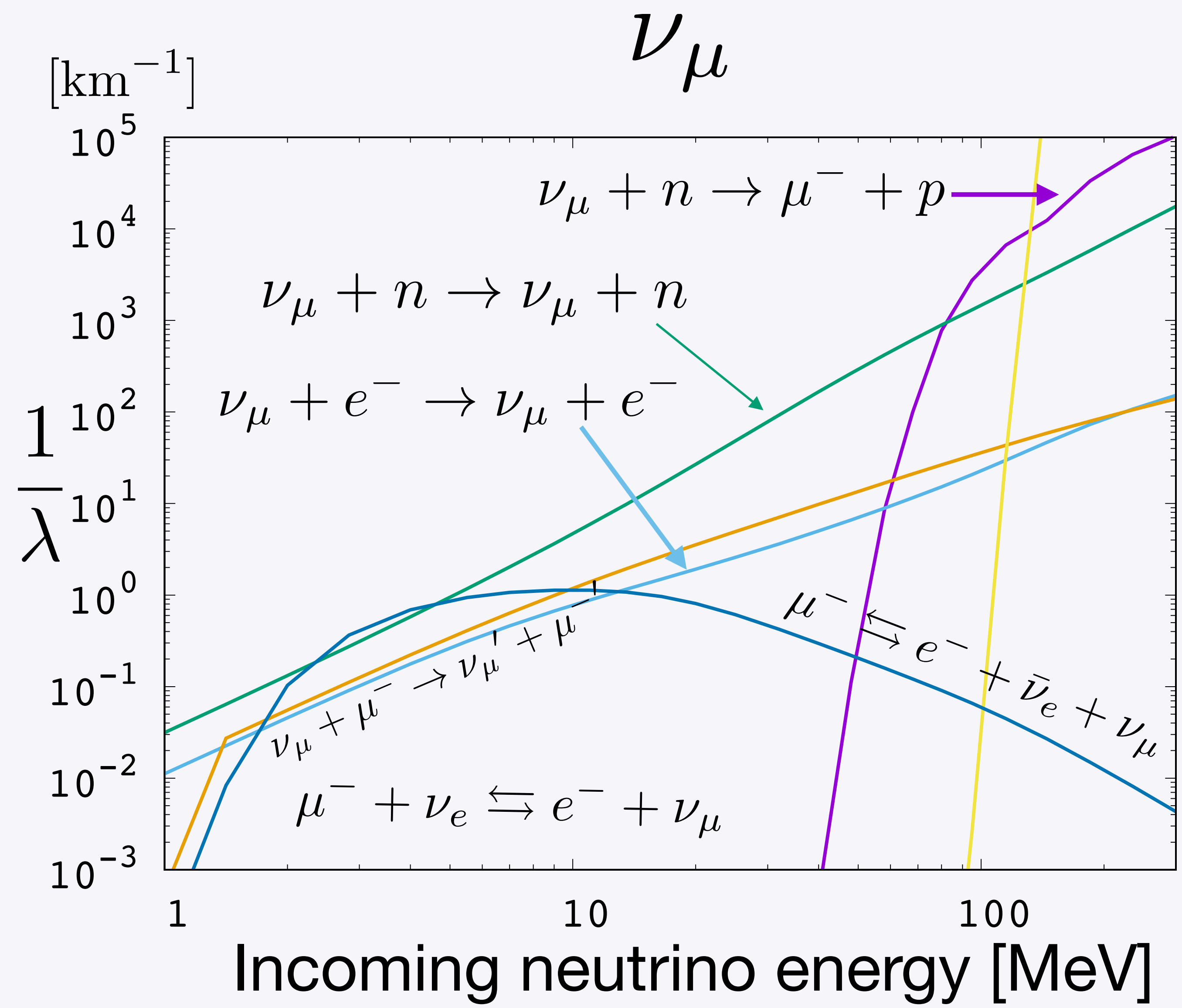
Deleptonization phase (t ~ 10s)

ϱ [g/cc]	T [MeV]	Y_e	Y_μ	μ_n [MeV]	μ_p [MeV]	μ_e [MeV]	μ_μ [MeV]
3.24×10^{14}	20	0.08	0.02	965	851	143	127

Typically, r ~ 10 km

(determined from Furusawa-Togashi EoS + muon)





Implication for neutrino signal

Neutrino transport equation

$$\frac{1}{c}\frac{df_\nu}{d\tau} = \eta_\nu \left(1 - f_\nu\right) - \frac{1}{\lambda_\nu} f_\nu$$

In diffusion limit

$$F_\nu^E = -\frac{\Gamma T^3}{\alpha 6\pi^2}\left[D_4 \frac{\partial(\alpha T)}{\partial r} + D_{3,e}\alpha T \frac{\partial(\mu_{\nu_e}/T)}{\partial r} + D_{3,\mu}\alpha T \frac{\partial(\mu_{\nu_\mu}/T)}{\partial r}\right]$$

$$D_4 = \sum_i D_4^i = \sum_i \int_0^\infty d\epsilon \frac{\epsilon^4 f_{i,\mathrm{FD}}\left(1 - f_{i,\mathrm{FD}}\right)}{T^5}\lambda_{\nu_i}$$

- Cooling timescale in deleptonization phase
  → Kelvin-Helmholtz timescale

$$\tau_{\mathrm{KH}} \sim \frac{E^{\mathrm{th}}}{F_\nu^E} \propto \frac{1}{D_4}$$

- D_4 ratio with/without muon: $D_4^{\mathrm{muon}}/D_4^{\mathrm{w/o\ muon}} \sim 1.1$

Implication for neutrino signal

Neutrino transport equation

$$\frac{1}{c}\frac{df_\nu}{d\tau} = \eta_\nu\left(1 - f_\nu\right) - \frac{1}{\lambda_\nu} f_\nu$$

In diffusion limit

$$F_\nu^E = -\frac{\Gamma T^3}{\alpha 6\pi^2}\left[D_4 \frac{\partial(\alpha T)}{\partial r} + D_{3,e}\alpha T \frac{\partial(\mu_{\nu_e}/T)}{\partial r} + D_{3,\mu}\alpha T \frac{\partial(\mu_{\nu_\mu}/T)}{\partial r}\right]$$

$$D_4 = \sum_i D_4^i = \sum_i \int_0^\infty d\epsilon \frac{\epsilon^4 f_{i,\mathrm{FD}}\left(1 - f_{i,\mathrm{FD}}\right)}{T^5} \lambda_{\nu_i}$$

- Cooling timescale in deleptonization phase
  → Kelvin-Helmholtz timescale

$$\tau_{\mathrm{KH}} \sim \frac{E^{\mathrm{th}}}{F_\nu^E} \propto \frac{1}{D_4}$$

- D_4 ratio with/without muon: $D_4^{\mathrm{w/o\ muon}}/D_4^{\mathrm{muon}} \sim 1.06$

Summary and Future work

Summary

- ミューオンの関係するニュートリノ反応の計算
  - 電子型反ニュートリノとミューオンニュートリノの平均自由行程は(特に高エネルギー側で) 影響を受ける.
  - 冷却タイムスケールはミューオンの存在によって長くなることが予想される (数%程度になるか？)
  - ニュートリノスペクトルの形が変わることが予想される.

Future work

- $npe\mu$-物質を仮定した PNS 冷却計算を用いた定量的な評価
- 核子の多体相互作用をきちんと組み込んだニュートリノ反応
- ミューオン型 (反) ニュートリノの非対称な反応に起因するニュートリノ振動？