Muon creation in proto-neutron stars and its implication for neutrino signal in cooling phase

Ken’ichi Sugiura
(PhD student, Waseda University)

Collaborators: Shoichi Yamada (Waseda Univ.)
Ken’ichiro Nakazato (Kyushu Univ.)
Hideyuki Suzuki (Tokyo University of Sci.)

Table of contents

1. Introduction: Evolution scenario from SN to NS

2. Standard model of proto-neutron star (PNS) cooling

3. Neutrino reactions relating with muon and implication for neutrino signal

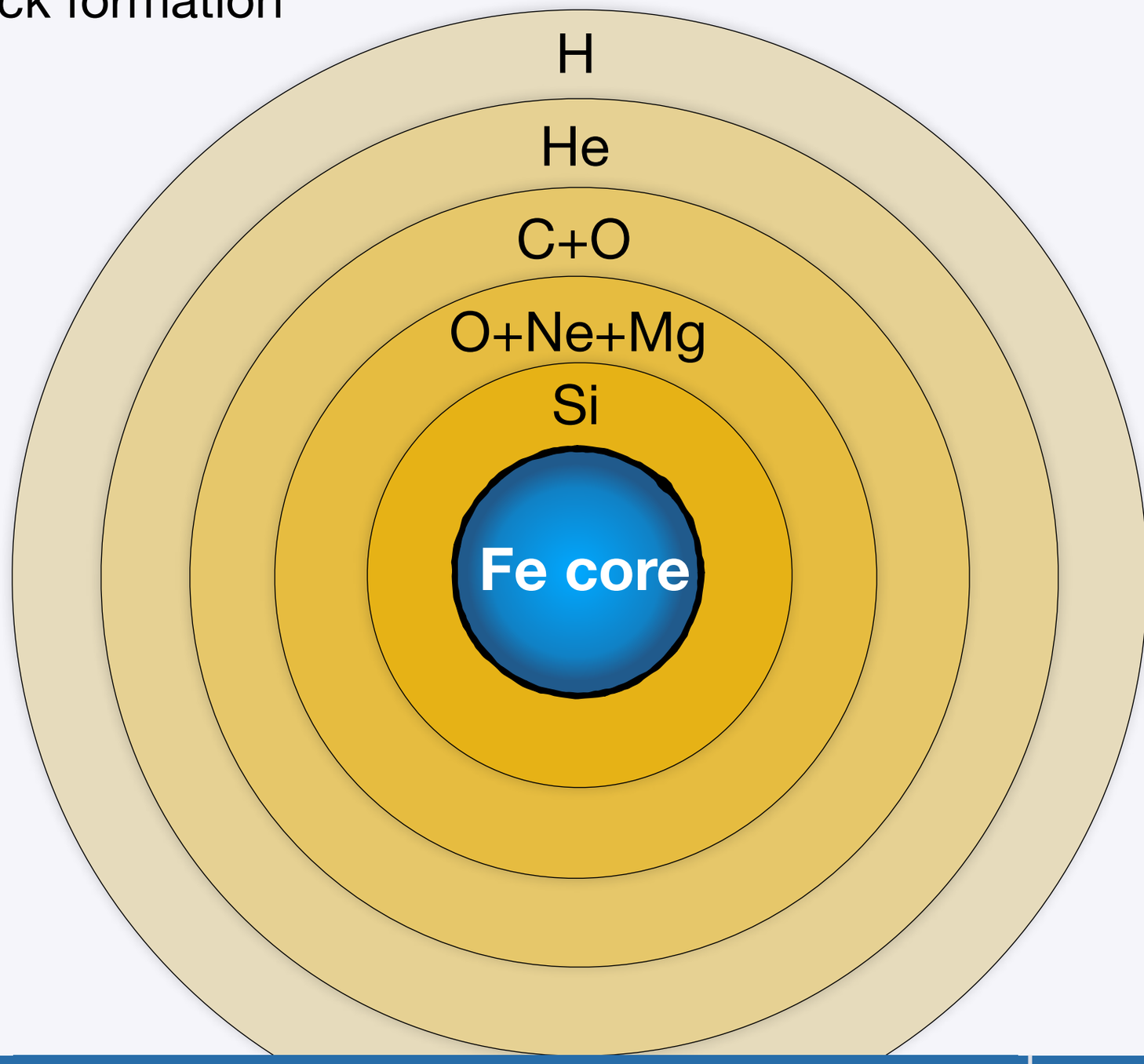
4. Summary

From Supernova to Neutron Star

~1s

Supernova

Core collapse of massive star
→Core bounce + shock formation
→Shock propagation

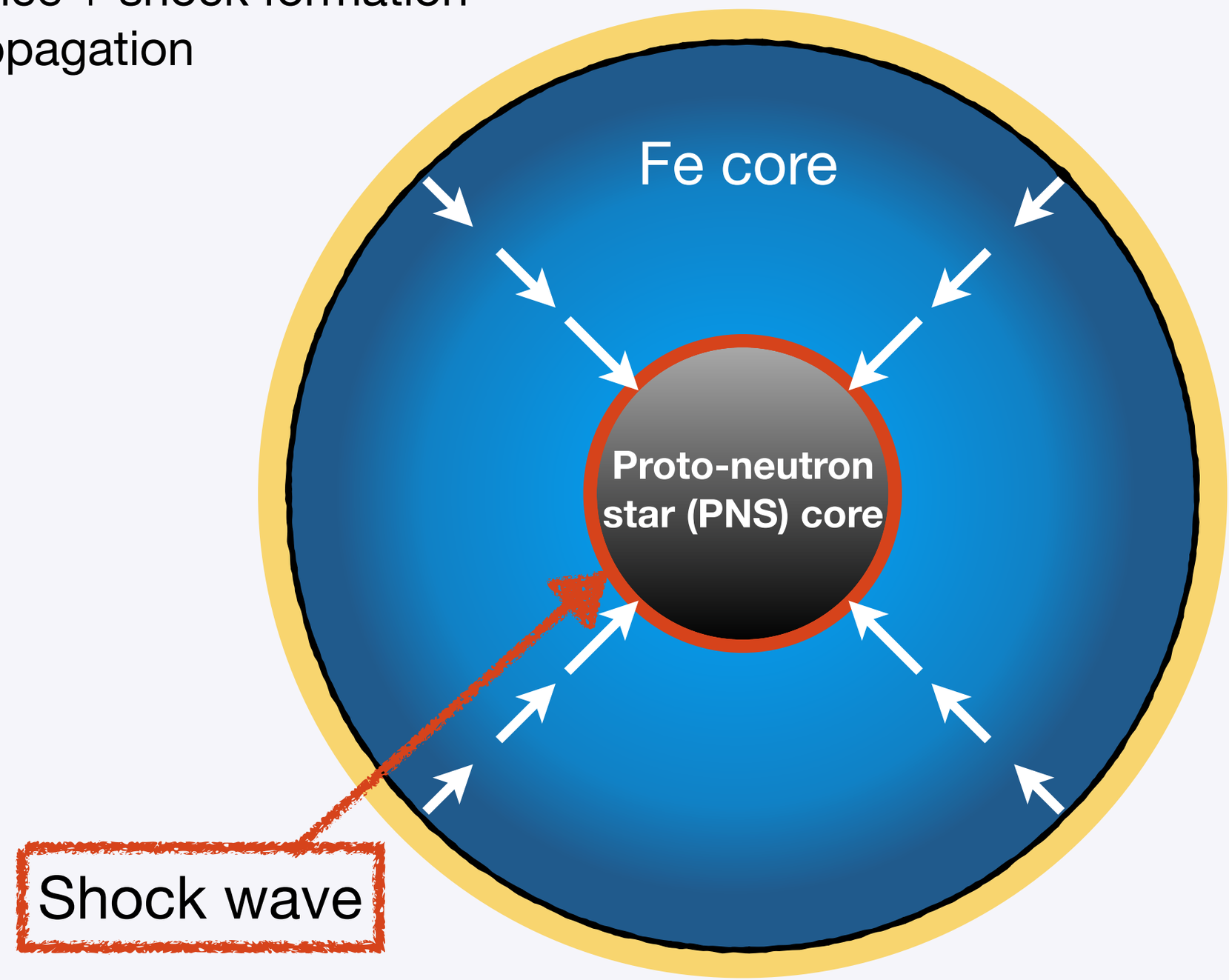


From Supernova to Neutron Star

~1s

Supernova

Core collapse of massive star
→Core bounce + shock formation
→Shock propagation



From Supernova to Neutron Star

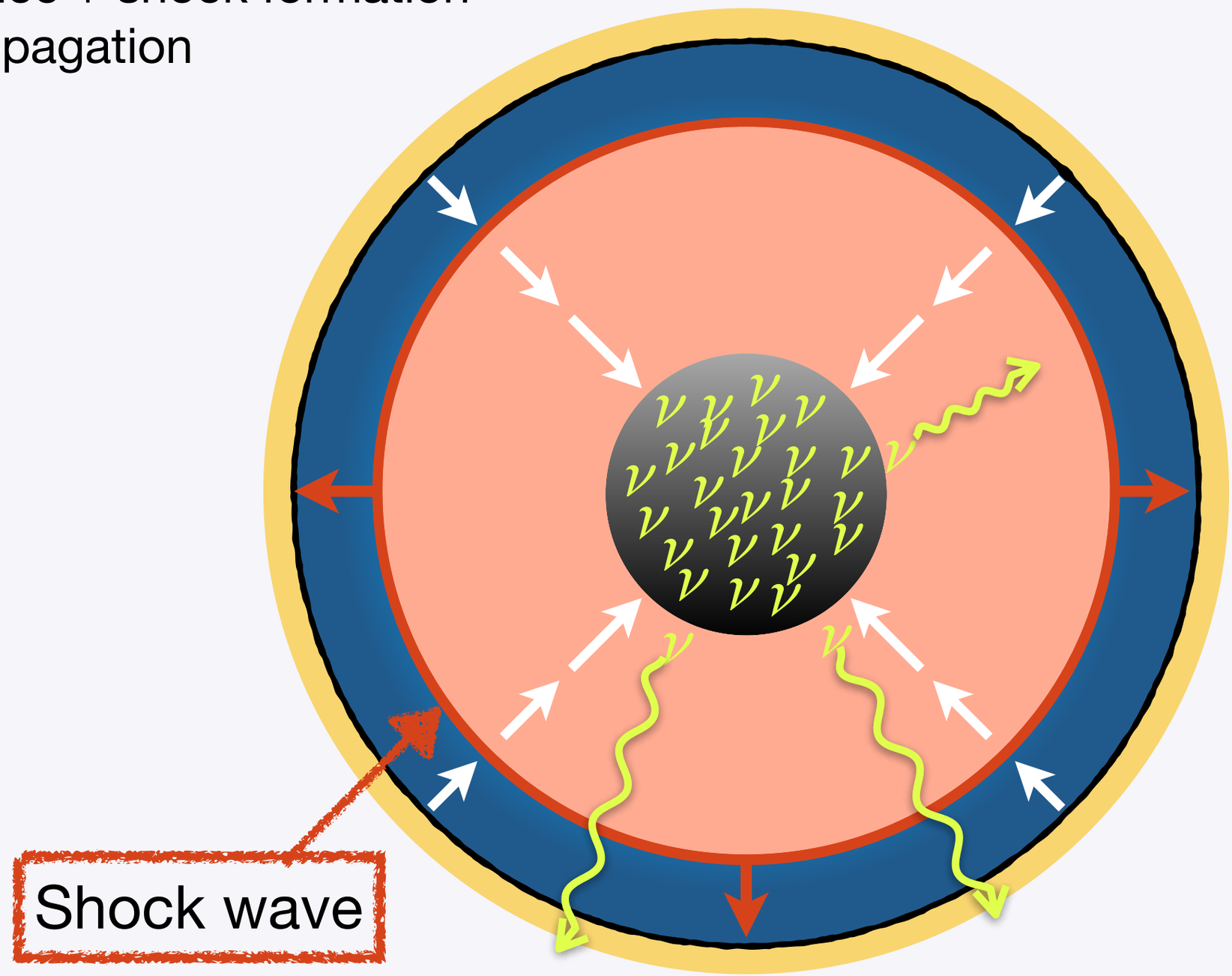
~1s

Supernova

Core collapse of massive star

→Core bounce + shock formation

→Shock propagation



From Supernova to Neutron Star

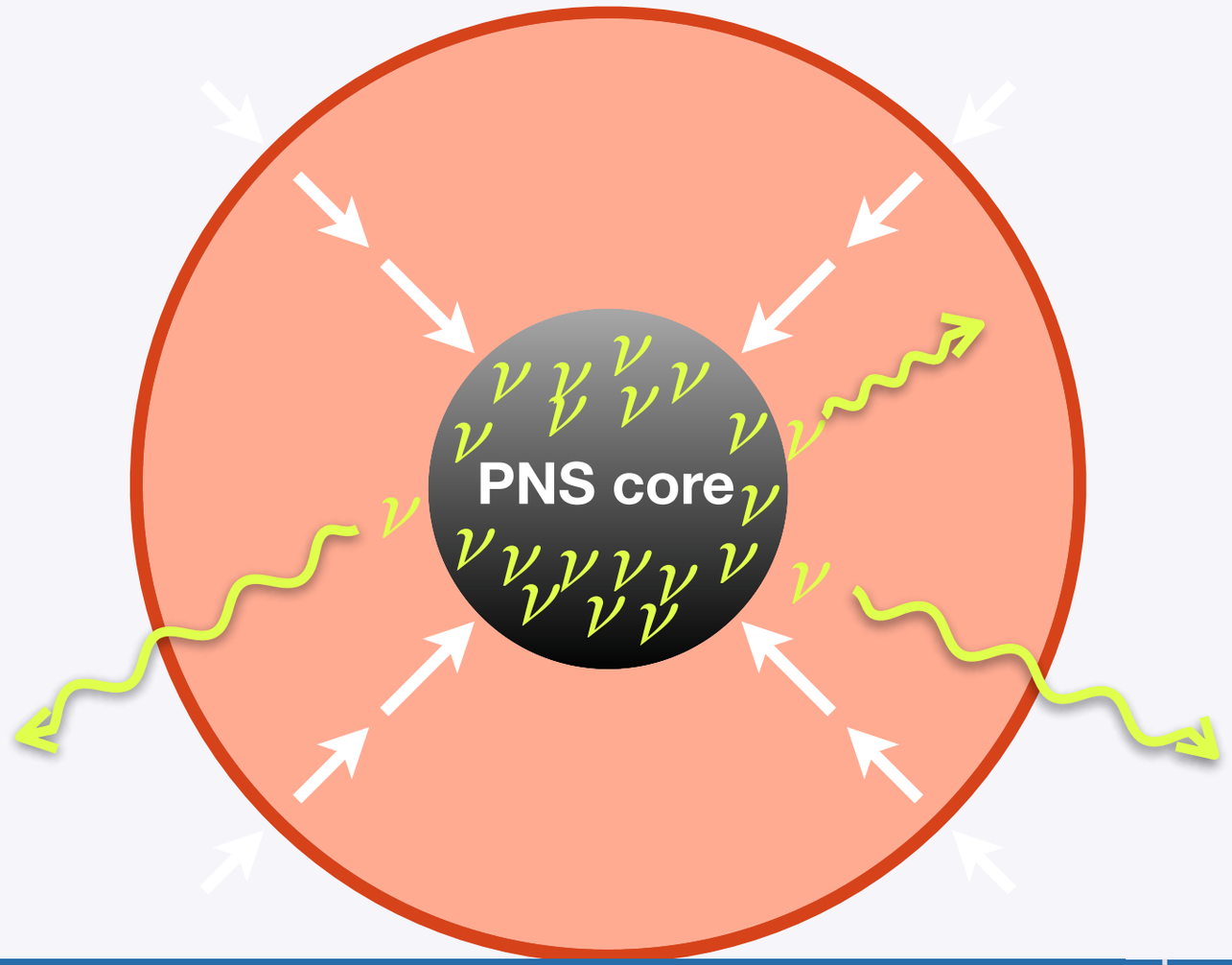
~1s

Supernova

~a few sec.

Mantle contraction (T ~ a few 10MeV)

Accretion of shock heated matter onto PNS core.
Contraction to the size of final neutron star.



From Supernova to Neutron Star

~1s

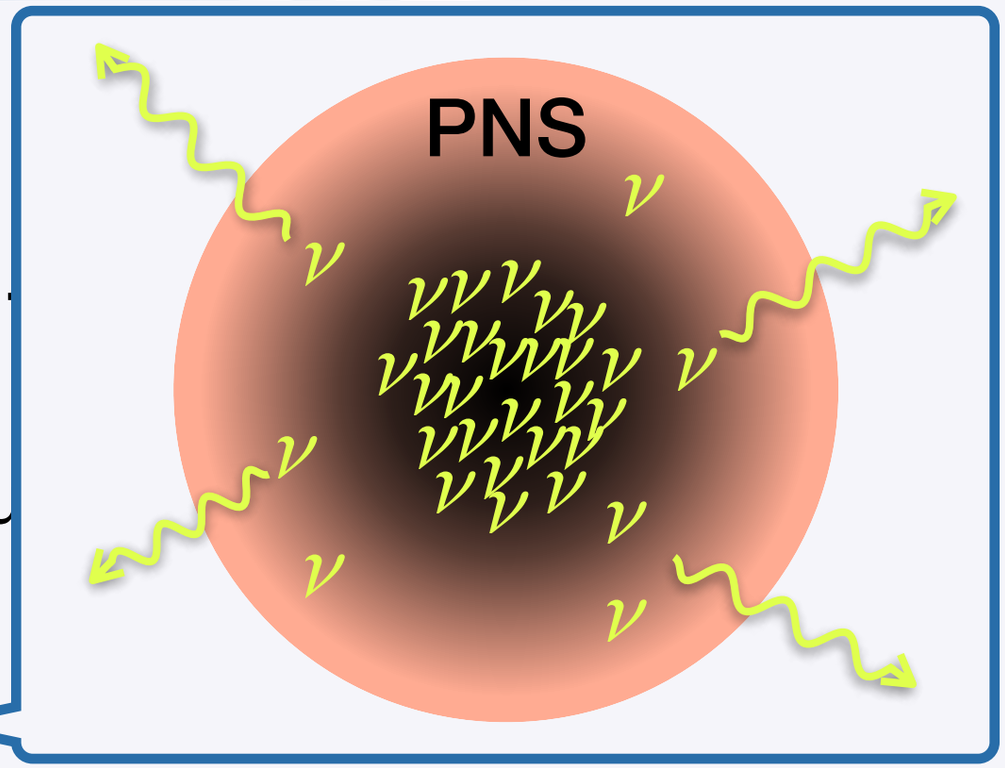
Supernova

~a few sec.

Mantle contraction (T ~ a few

Accretion of shock heated matter
Contraction to the size of final neu

Deleptonization (T ~ 10MeV)



~20 s

Neutrinos are emitted diffusively.
Deleptonization progresses due to neutrino emission.
Thermal energy of accreted matter conducts to the center.

From Supernova to Neutron Star

~1s

~a few sec.

~20 s

To NS

Supernova

Mantle contractio

Accretion of shock
Contraction to the

Deleptonization (T

Neutrinos are emitt
Deleptonization pro
Thermal energy of accreted matter conducts to the center.

Thermal cooling (T ~ a few MeV)

Neutrinos are decoupled.
PNS cooling due to thermal pair neutrino process
and modified Urca process.

PNS

Thermal pair process

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

$$N + N \leftrightarrows N + N + \nu + \bar{\nu}$$

Modified Urca process

$$N + n \rightarrow N + p + e^- + \bar{\nu}_e$$

$$N + p + e^- \rightarrow N + n + \nu_e$$

From Supernova to Neutron Star

~1s

Supernova

~a few sec.

Mantle contraction (T ~ a few 10MeV)

Accretion of shock heated matter onto PNS core
Contraction to the size of final neutron star

~20 s

Deleptonization (T ~ 10MeV)

Neutrinos are emitted diffusively.
Deleptonization progresses due to neutrino emission.
Thermal energy of accreted matter conducts to the center.

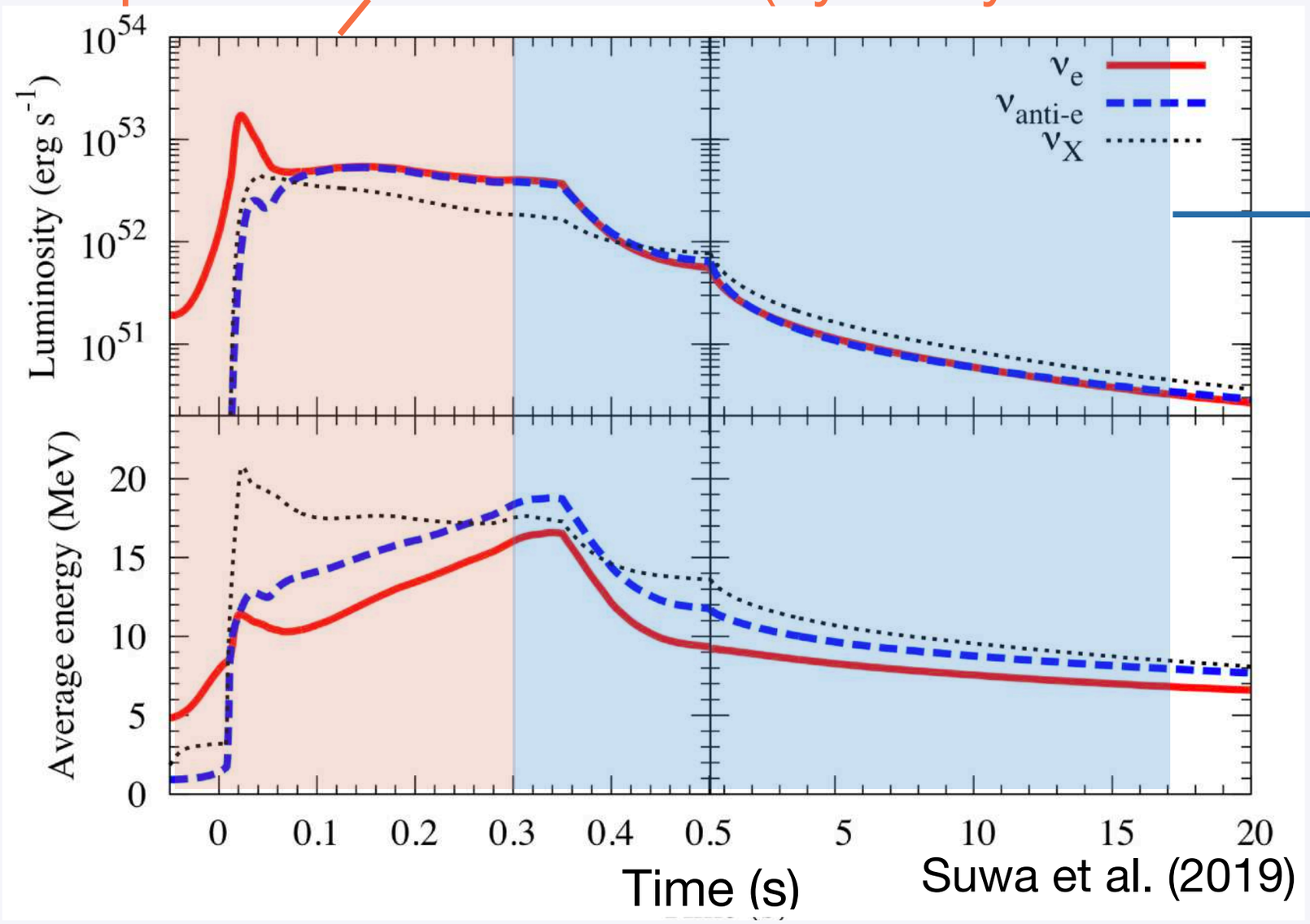
Thermal cooling (T ~ a few MeV)

Neutrinos are decoupled.
PNS cooling due to thermal pair neutrino process
and modified Urca process.

To NS

Standard Neutrino Signals from PNS

explosion & contraction (hydrodynamical caluculation)



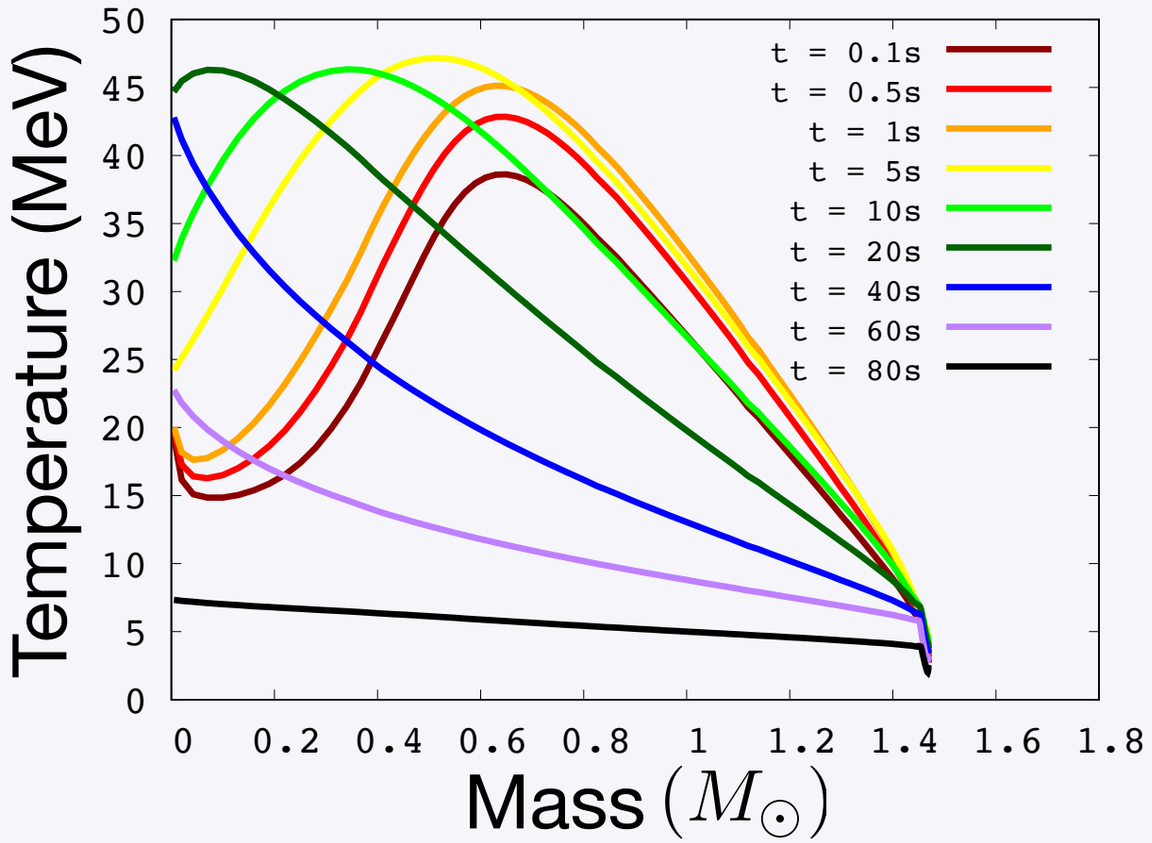
Suwa et al. (2019)

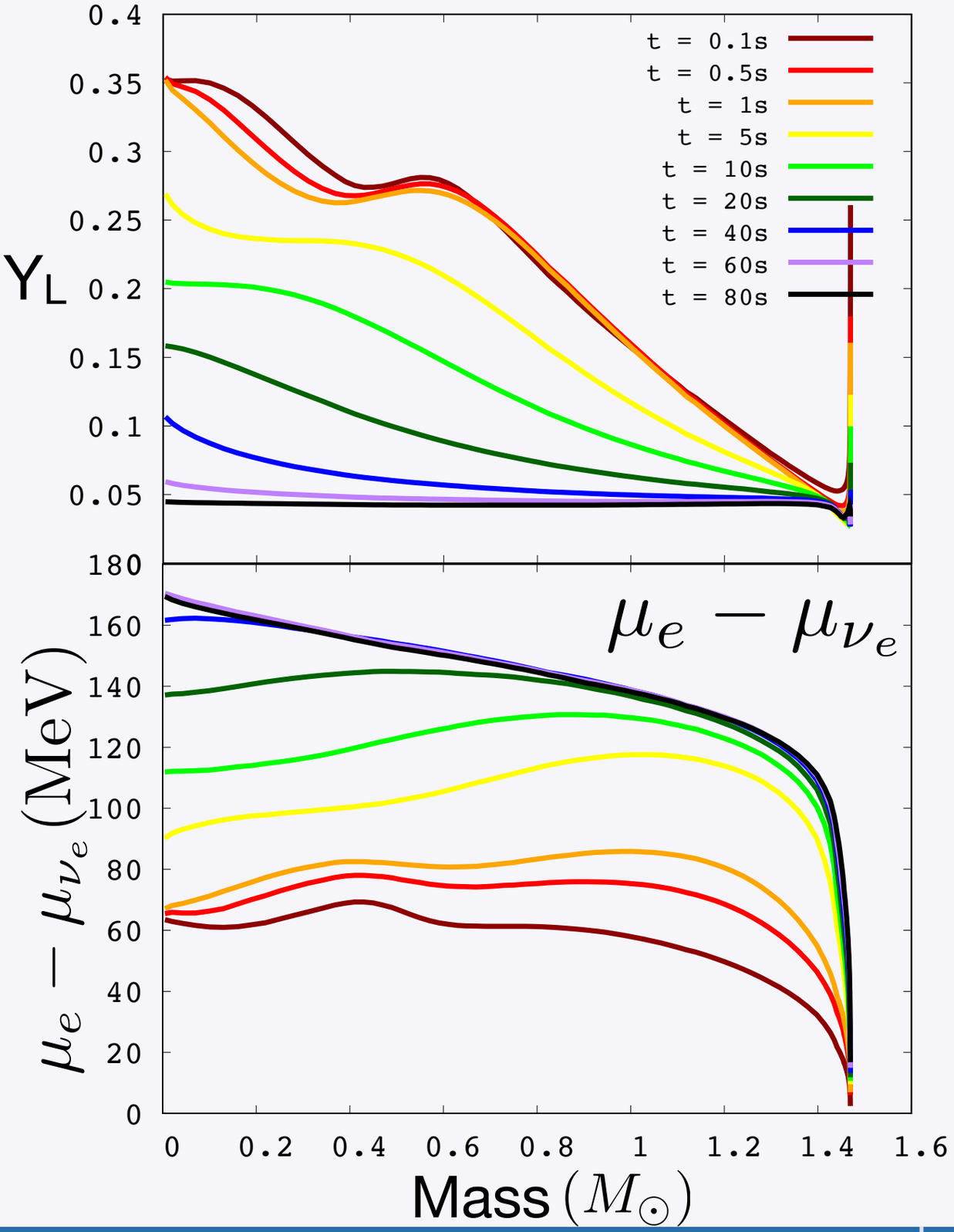
Delaptonization

(quasi-static evolution)

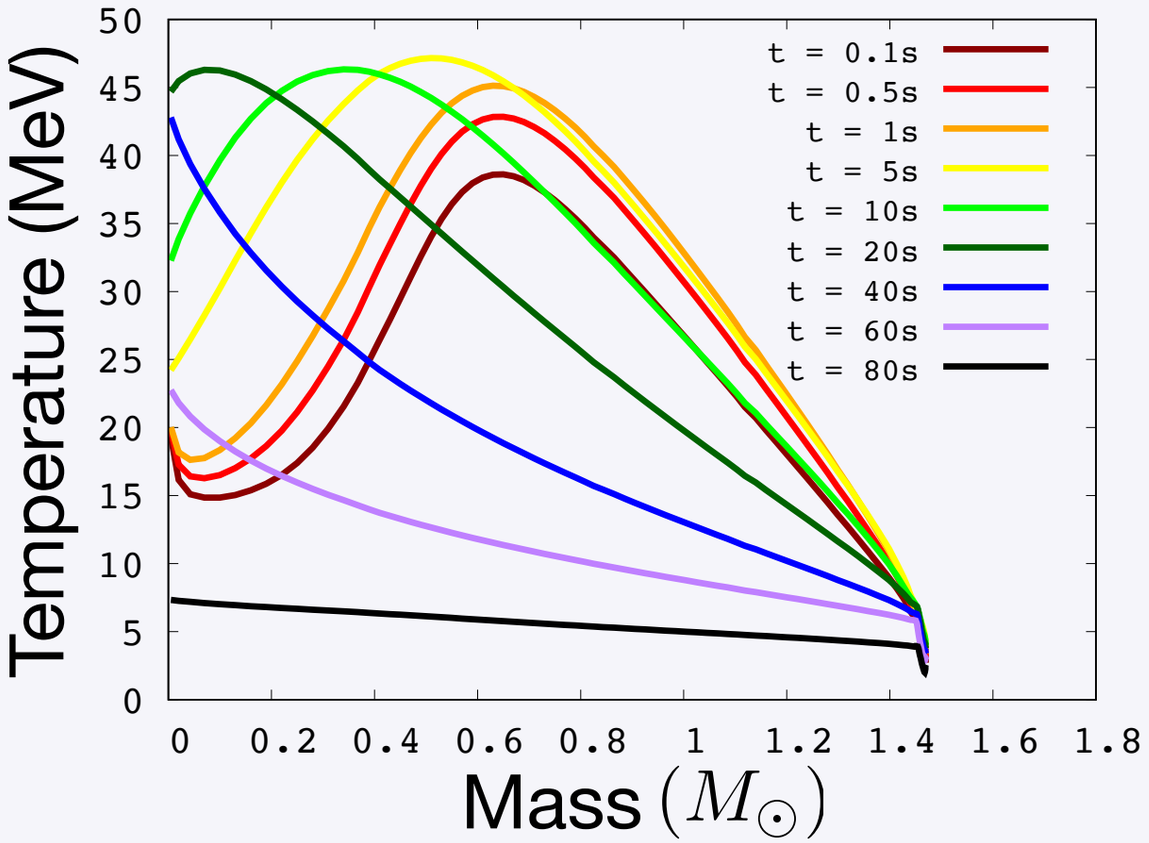
- We can observe neutrino signals for ~100s for the galactic SN in Super-Kamiokande (Suwa et al. 2019)
- Cooling timescale of PNS gives the constraint on M-R relation of PNS (See Nakazato's poster (P11))

Evolution of interior of standard PNS





Evolution of interior of standard PNS

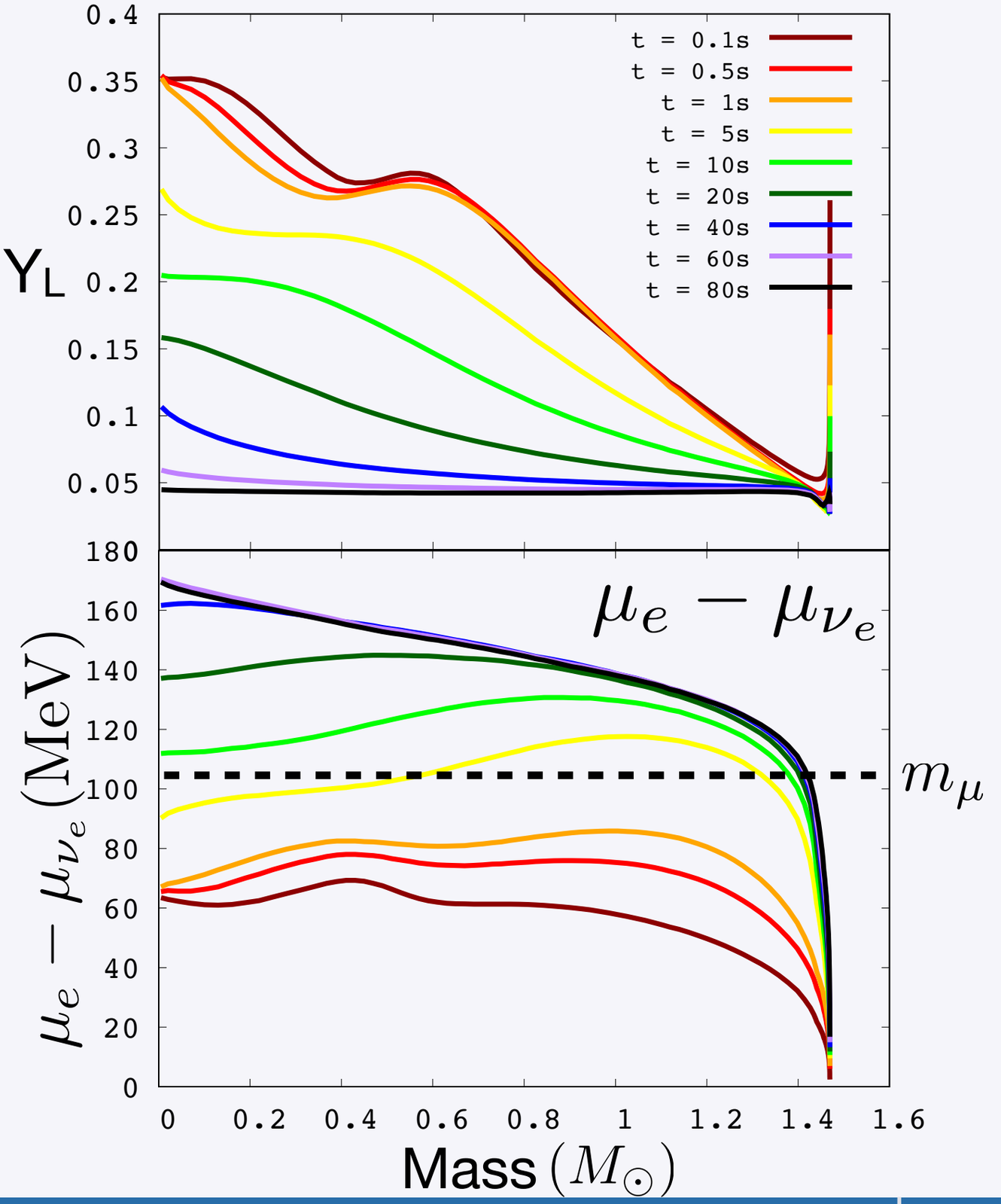


e.g. $\mu^- \leftrightarrows e^- + \bar{\nu}_e + \nu_\mu$

chemical equilibrium condition

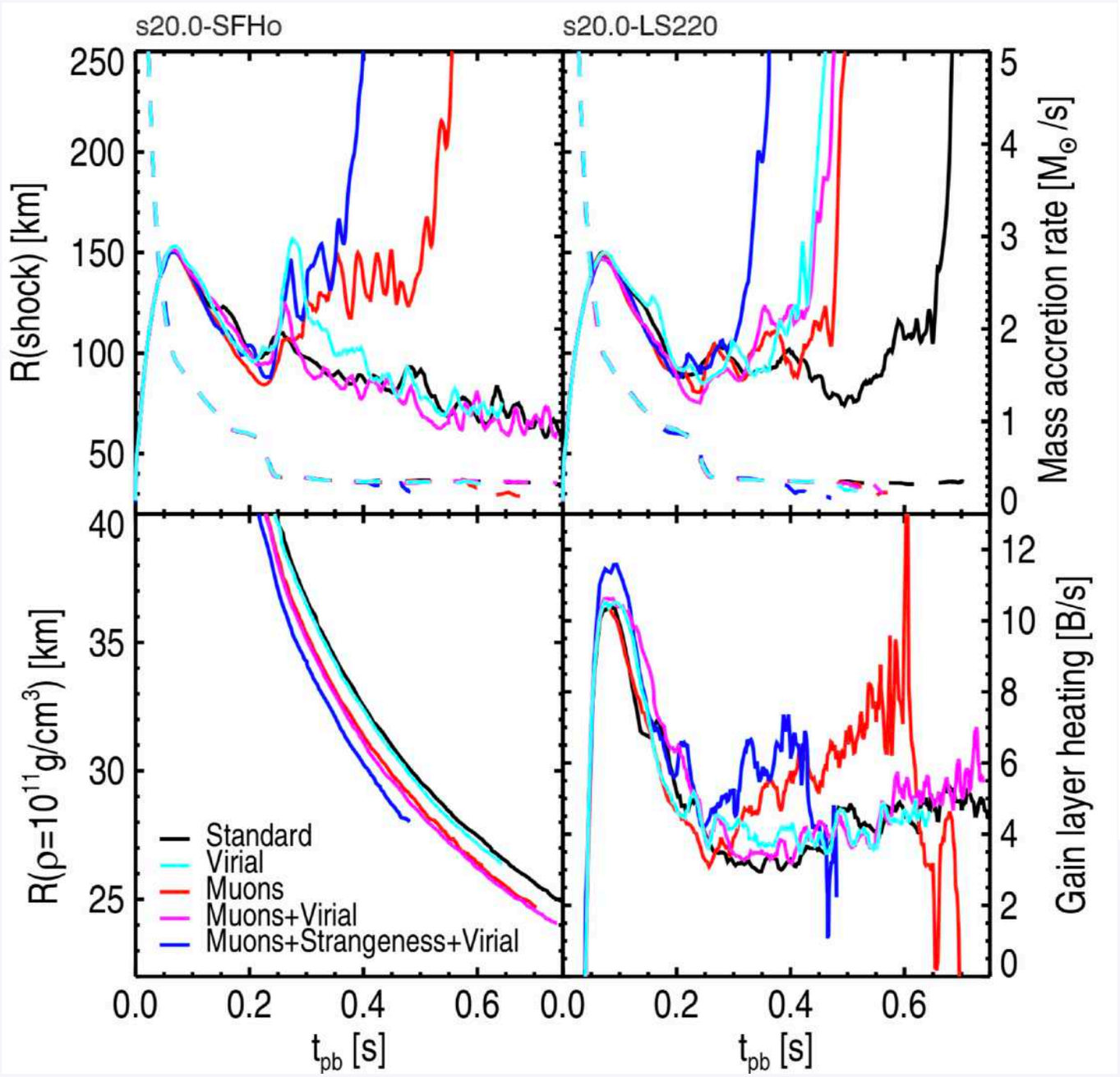
$$\mu_\mu = \mu_e - \mu_{\nu_e} + \mu_{\nu_\mu}$$

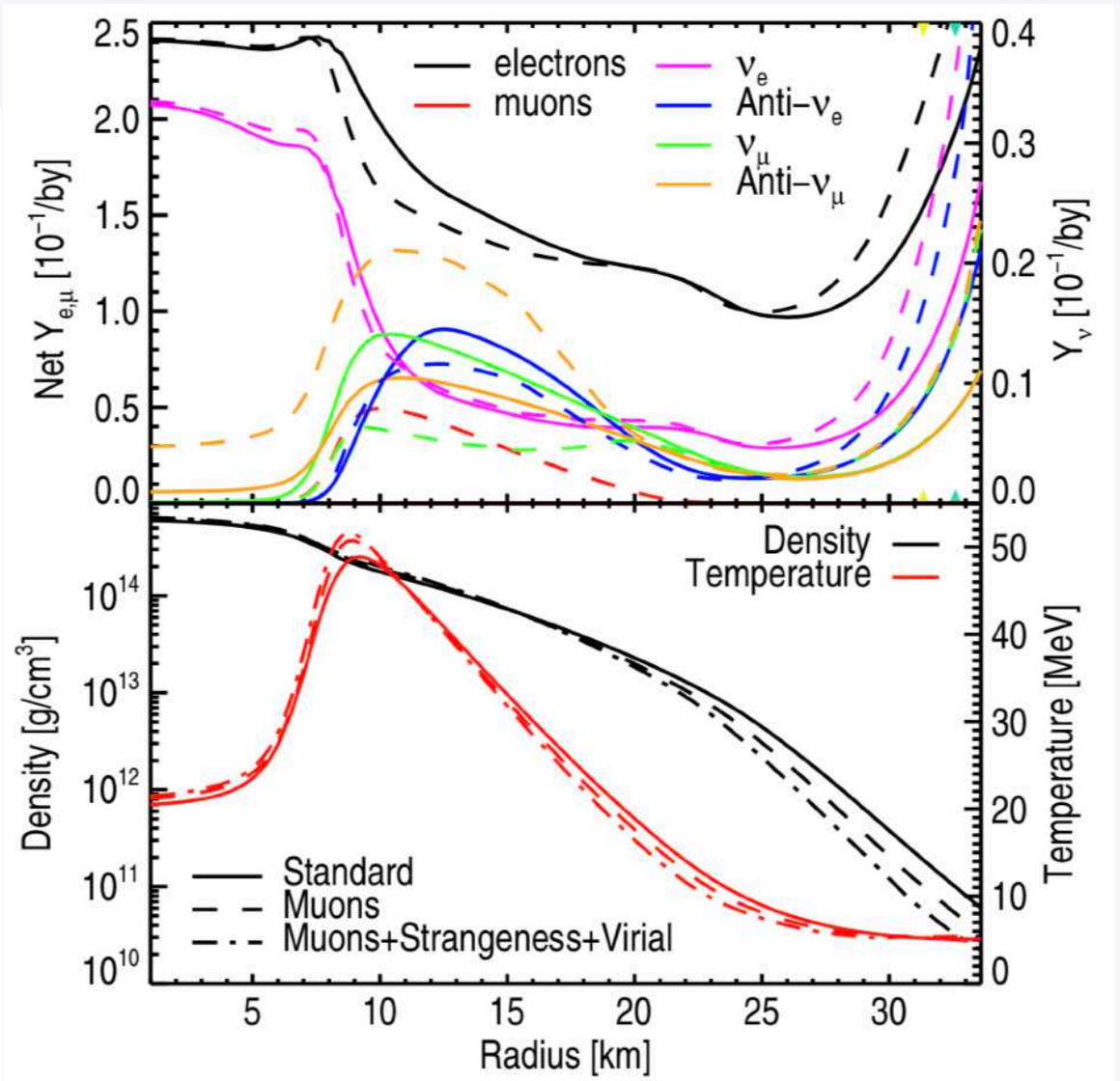
Muon can be appeared in PNS cooling phase



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

Neutrino reactions related to muon

Muon decay

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

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

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 scattering

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

Reaction rate related with muon

Neutrino transport equation

$$\frac{1}{c}\frac{df_\nu}{d\tau} = \underbrace{\eta_\nu}_{\text{emissivity}}(1-f_\nu) - \underbrace{\frac{1}{\lambda_\nu}}_{\text{mean free path}} f_\nu$$

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

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

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

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

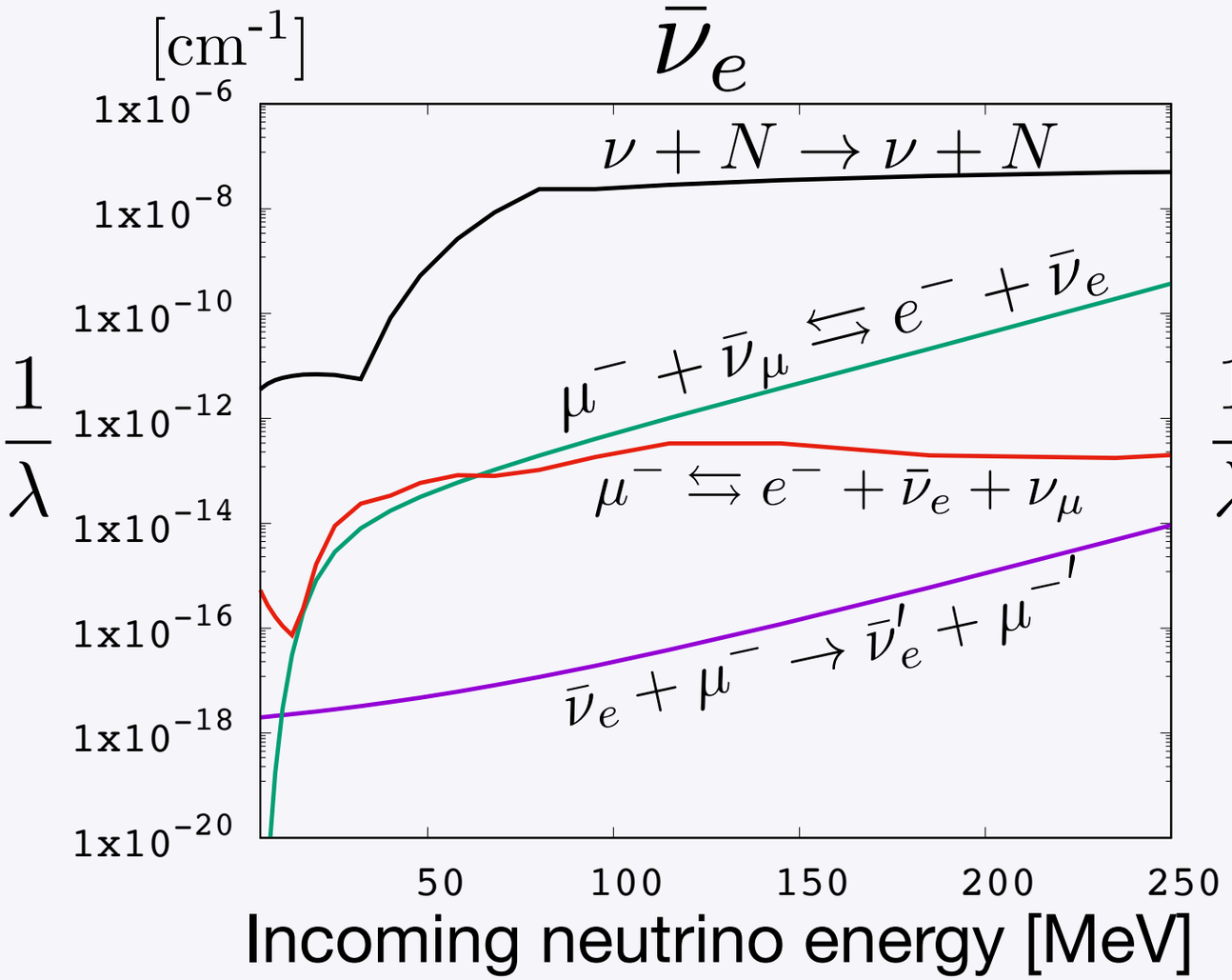
Fidutial model of deleptonization phase

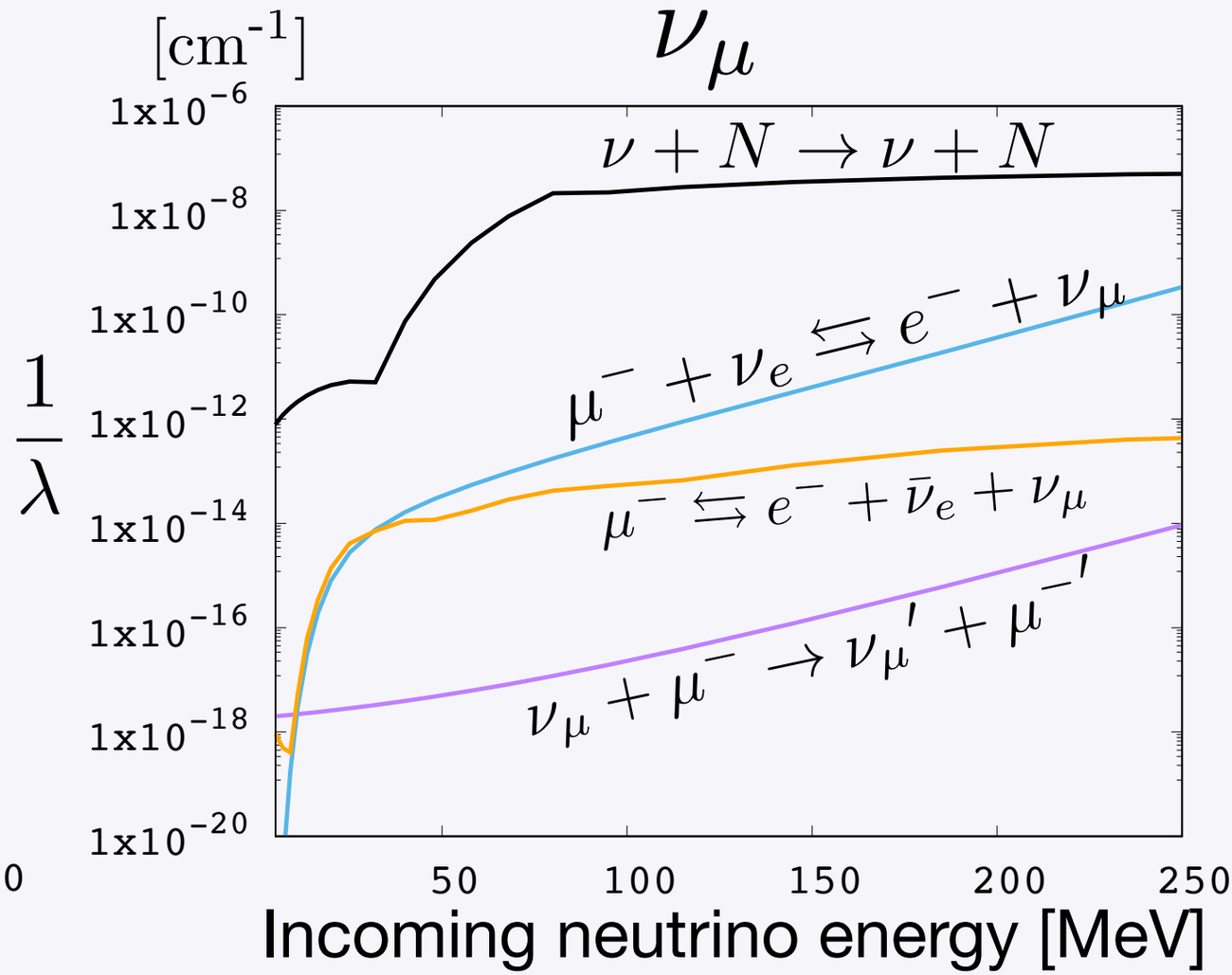
- t ~ 10s (deleptonization phase), R ~ 10 km

$$\rho = 3.24 \times 10^{14}\,\mathrm{gcm}^{-3}, T = 20\,\mathrm{MeV}, Y_e = 0.10 \qquad Y_\mu = 0.04$$

$$\mu_n = 962.5\,\mathrm{MeV},\ \ \mu_p = 862.5\,\mathrm{MeV}, \mu_e = 156.2\,\mathrm{MeV}, \mu_\mu = 148.7\,\mathrm{MeV},$$

(determined from Furusawa-Togashi EoS + muon)





Implication for neutrino signal

Neutrino transport equation

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

↓ 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

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

Implication for neutrino signal

Neutrino transport equation

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

↓ 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

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

- Cooling timescale become longer (up to a few %)

Summary and Future work

Summary

- We are studying on effects of existence of **muon** in PNS**.**
  - ☑ We calculated reaction rates related with muons
  - ☑ Mean free paths of electron anti-neutrino and muon neutrino are affected by the muon existence.
  - ☑ **Flavor exchange** and **muon decay** can affect to the PNS cooling
  - ☑ **Cooling timescale** in deleptonization phase become **longer**.

Future work

- PNS cooling calculation with $npe\mu$-matter including muon related reactions
- Evaluation of Direct Urca process reaction threshold
- Pion effect (Fore & Reddy (2019))