Neutrino Reactions with Deuteron in Core-Collapse Supernova (重陽子形成を伴うニュートリノ生成反応)

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Contents

Introduction

Neutrino reactions in supernovae simulations

Electron captures	Elastic scattering	Pair creation and annihilation Nucleon Bremsstrahlung
$e^- + p \leftrightarrow \nu_e + n$	$\nu + N \leftrightarrow \nu + N$	$e^- + e^+ \leftrightarrow \nu + \bar{\nu}$
$e^+ + n \leftrightarrow \bar{\nu}_e + p$	$\nu + A \leftrightarrow \nu + A$	$N + N \leftrightarrow N + N + \nu + \bar{\nu}$
$e^- + A \leftrightarrow \nu_e + A'$	$\nu + e^\pm \leftrightarrow \nu + e^\pm$	

S. Bruenn (1985)

Reactions on nucleon(N) and heavy nucleus(A)

Neutrino production: cooling

(proto-neutron star to neutron star, source of neutrinos)

absorption: heating

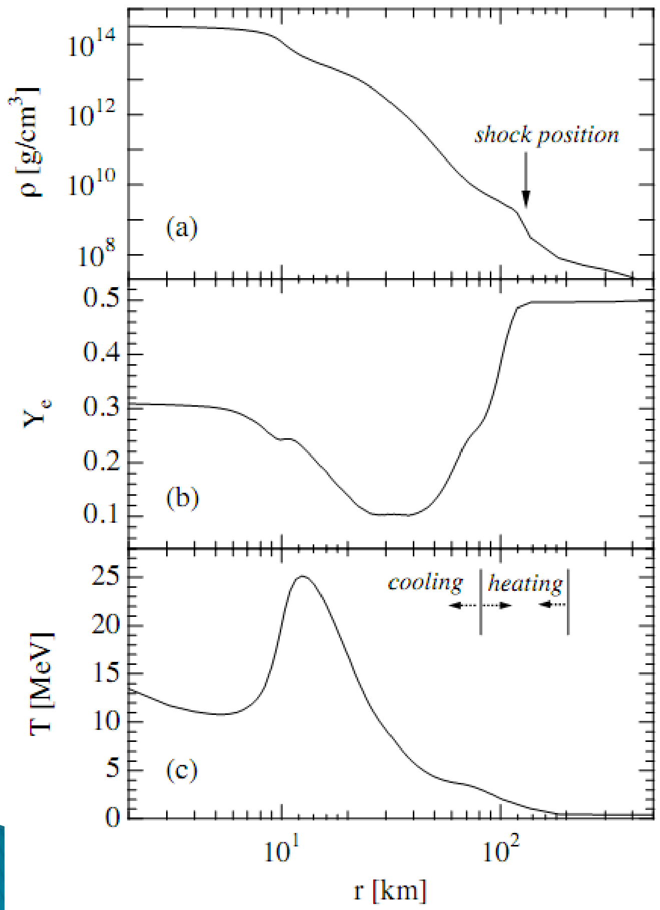
(shock wave revival -> delayed explosion)

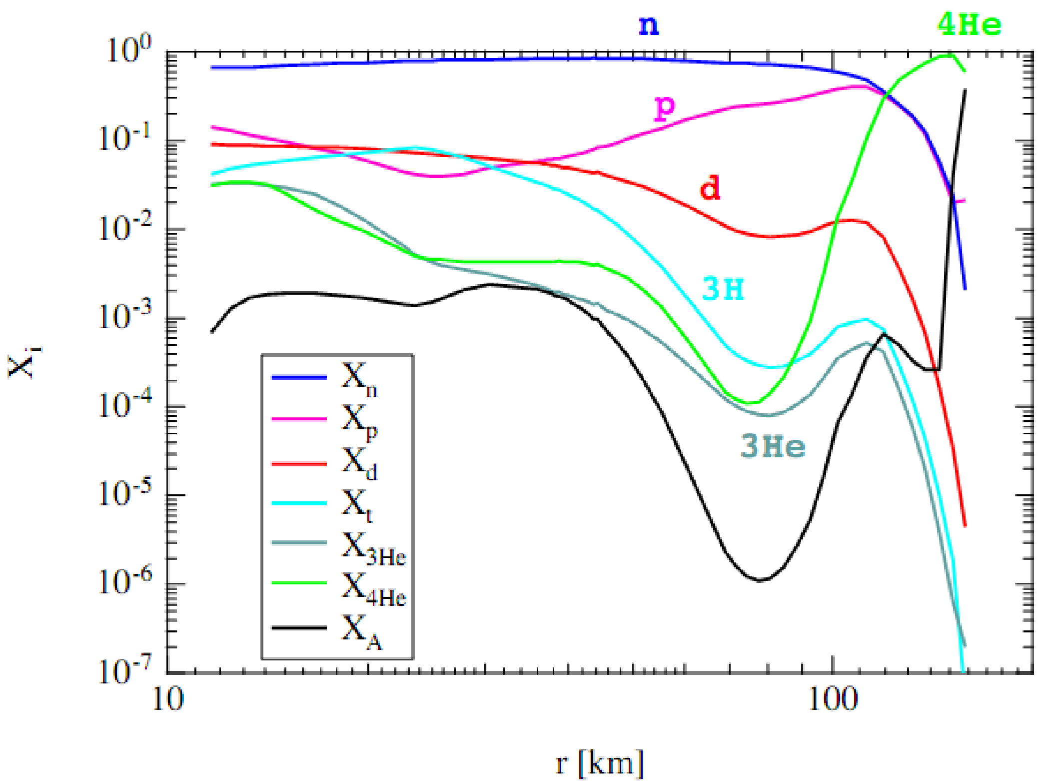
Existence of light elements

$\mathrm{d}, \mathrm{t}, {}^3\mathrm{He}, {}^4\mathrm{He}$ abundances

t = 0.15s after core bounce

K. Sumiyoshi and G. Röpke, (2008)





Analysis for neutrino absorption on light elements

$\nu - {}^4\mathrm{He}$: W. C. Haxton, (1988), D. Gazit and N. Barnea, (2007)

$\nu - {}^3\mathrm{He},\ \mathrm{t}$: E. O'Connor et al., (2007),A. Arcones et al., (2008)

$\nu/\bar{\nu} - d$: S. X. Nakamura et al.(2009)

Averaged energy transfer cross section per one nucleon : S. X. Nakamura et al.(2009)

$$\frac{<\sigma\omega>}{A} = \frac{1}{A}\int dE_\nu f(E_\nu)\sigma(E_\nu)\omega(E_\nu)$$

ω : initial neutrino energy loss

$$\nu/\bar{\nu} - d > \nu - {}^3\mathrm{He},\mathrm{t} > \nu - {}^4\mathrm{He}$$

Objective: Neutrino emission reactions with Deuteron in two-nucleon system

Electron/Positron capture on deuteron

$$e^- + d \rightarrow n + n + \nu_e$$

$$e^+ + d \rightarrow p + p + \bar{\nu}_e$$

Comparing to traditional reactions (A≤2)

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

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

Deuteron bound

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

$$p + p \rightarrow d + e^+ + \nu_e$$

$$n + p \rightarrow d + \nu + \bar{\nu}$$

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

(NC: neutrino bremsstrahlung)

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

$$\vdots$$

(CC: modified URCA)

We developed a model of Neutrino emissivity $Q(T, \mu_i)$ for deuteron reactions in **any supernova environment**

Today: Showing analysis example in one snapshot (t = 150ms after core bounce)

Model and Neutrino emissivity

Formalism

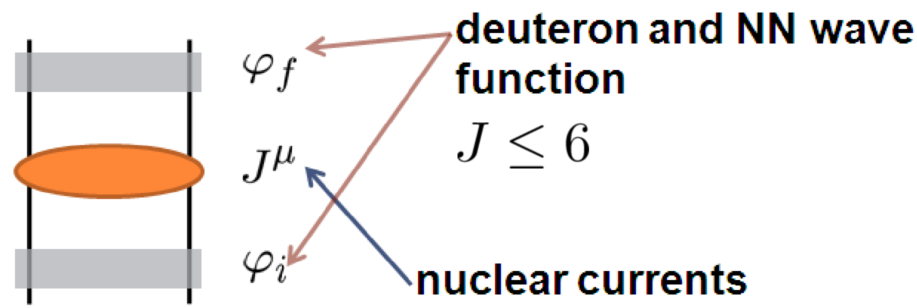
(S.Nakamura *et al.*, 2001)

Weak Hamiltonian: Current-Current Interaction

$$\mathcal{H}_W^{CC} = \frac{G_F V_{ud}}{\sqrt{2}} \int d\vec{x} J^{\mu}_{CC}(\vec{x}) L_{\mu}^{CC}(\vec{x}), \quad \mathcal{H}_W^{NC} = \frac{G_F}{\sqrt{2}} \int d\vec{x} J^{\mu}_{NC}(\vec{x}) L_{\mu}^{NC}(\vec{x})$$

Standard Nuclear Physics Approach (SNPA)

$$\langle f \mid \mathcal{H}_W \mid i \rangle \propto$$



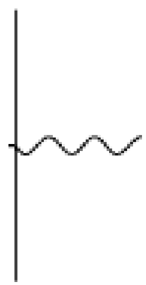
Nuclear currents: $J^\mu = J^\mu_{one-body} + J^\mu_{two-body}$

NN potential: AV18

Nuclear currents construction

$$J^{\mu} = J^{\mu}_{one-body} + J^{\mu}_{two-body}$$ Impulse current + Exchange current

Impulse current



Isovector currents

$$\langle N(p')|V^{\pm}_{\lambda}(0)|N(p)\rangle = \bar{u}(p')\left[f_V\gamma_\lambda + i\frac{f_M}{2M_N}\sigma_{\lambda\rho}q^{\rho}\right]\tau^{\pm}u(p)$$

$$\langle N(p')|A^{\pm}_{\lambda}(0)|N(p)\rangle = \bar{u}(p')\left[f_A\gamma_\lambda\gamma^5 + f_P\gamma^5 q_\lambda\right]\tau^{\pm}u(p)$$

Isoscalar current

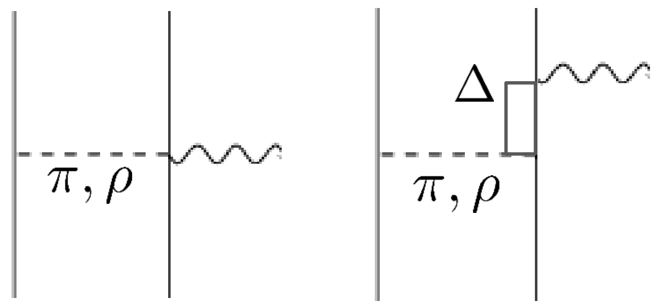
$$\langle N(p')|V^{s}_{\lambda}(0)|N(p)\rangle = \bar{u}(p')\left[f_V\gamma_\lambda + i\frac{f^s_M}{2M_N}\sigma_{\lambda\rho}q^{\rho}\right]\frac{1}{2}u(p)$$

$$q^{\mu} = p'^{\mu} - p^{\mu}$$ Momentum transfer for leptons

Exchange currents

NSGK formula (S.Nakamura *et.al.*, PRC **63** (2001) 034617)

$J^{\mu}_{two-body}$: π, ρ exchange currents + Δ excited π, ρ exchange currents



etc.

Axial $N\Delta$ **coupling :**

Adjust to the tritium β decay rate

Vector currents :

reproduce $np \to d\gamma$ experimental cross section

Neutrino emissivity (Q)

S.W.Bruenn(1985)
T.A.Thompson et al.(2000) etc.

Q: Value of Energy carried by neutrino per unit time and volume

$$Q = \prod_{i,f} \left[\int \frac{d\mathbf{p}_{i,f}}{(2\pi)^3} \right] (2\pi)^4 \delta^{(4)}(p_f - p_i) \sum_{spin} |\langle f \mid \mathcal{H}_W \mid i \rangle|^2$$

$$\times E_\nu \prod_i f_i \prod_{f,\mathrm{fermion}} (1 - f_f)$$

Transition amplitude

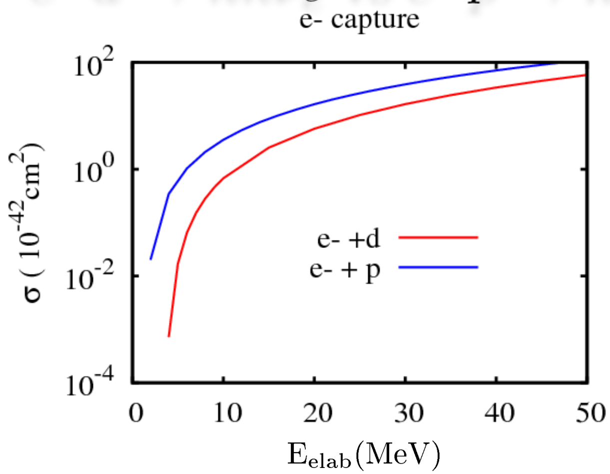
Initial distribution, Final fermion Pauli blocking

Emitted neutrino energy

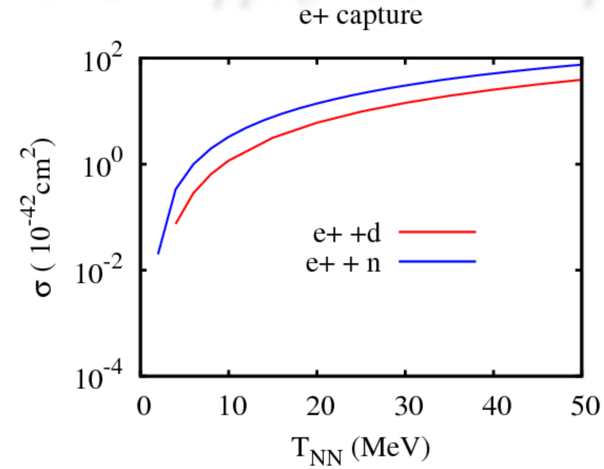
Results

Total Cross section

$$e^- d \to nn\nu_e \text{ vs } e^- p \to n\nu_e$$

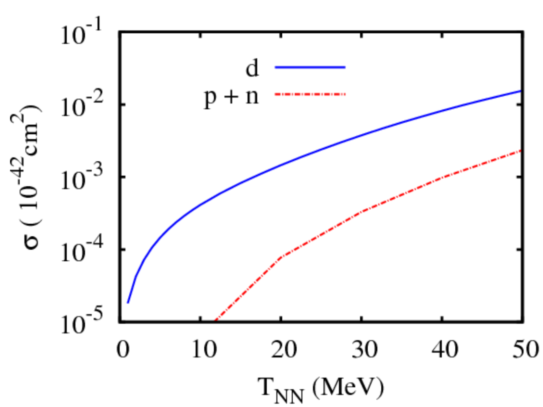


$$e^+ d \to pp\bar{\nu}_e \text{ vs } e^+ n \to p\bar{\nu}_e$$

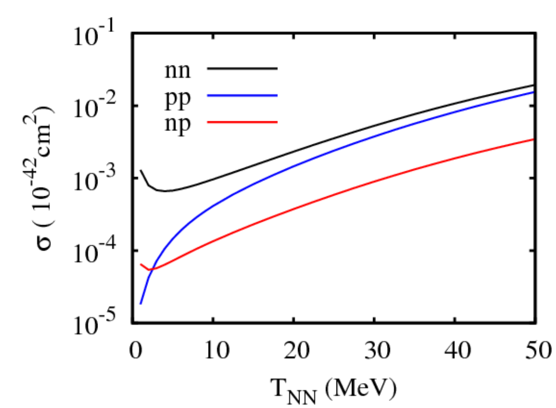


$$\sigma(ed)/\sigma(eN) \sim \left(\frac{1}{2} \sim \frac{1}{5}\right)$$

$$pp \to de^+\nu_e \qquad pp \to pne^+\nu_e$$



$$nn \to de^-\bar{\nu},\ pp \to de^+\nu,\ pn \to d\bar{\nu}\nu$$



$$\sigma(pp \to d)/\sigma(pp \to pn) \sim 10$$

$$\sigma^{CC}_{nn} > \sigma^{CC}_{pp} > \sigma^{NC}_{pn}$$

Emissivity(Q), r=10-100km

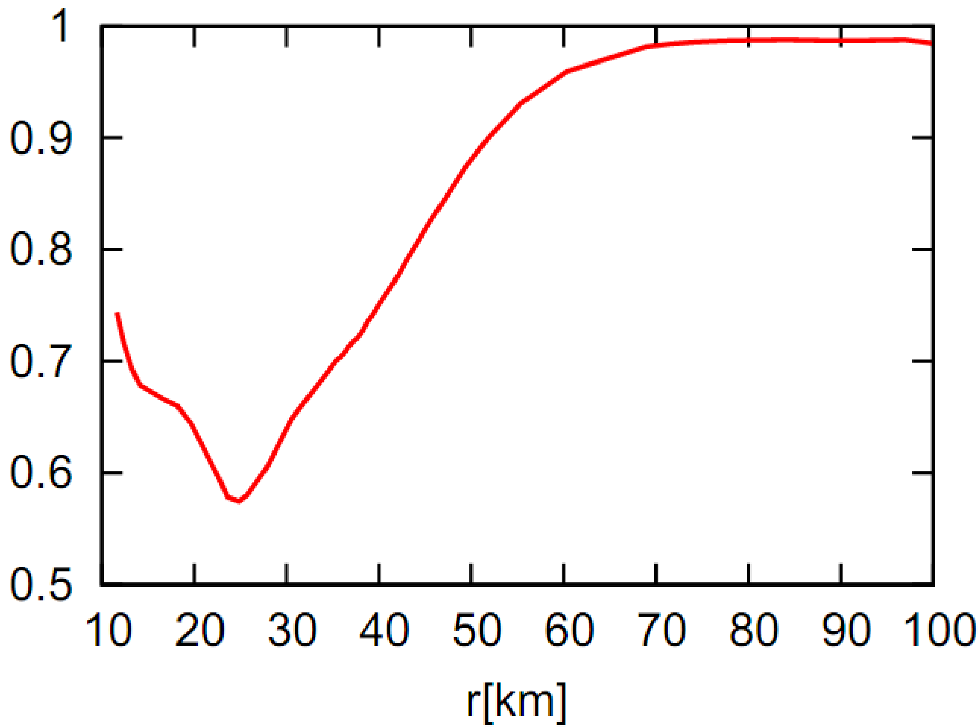
$t_{\text{after bounce}} = 0.15s,$ Sumiyoshi and Röpke(2008)

Electron capture

(A) Nucleon + Light nuclei (Baryon number conserved, Some of N -> d, t,…)

(B) No light nuclei

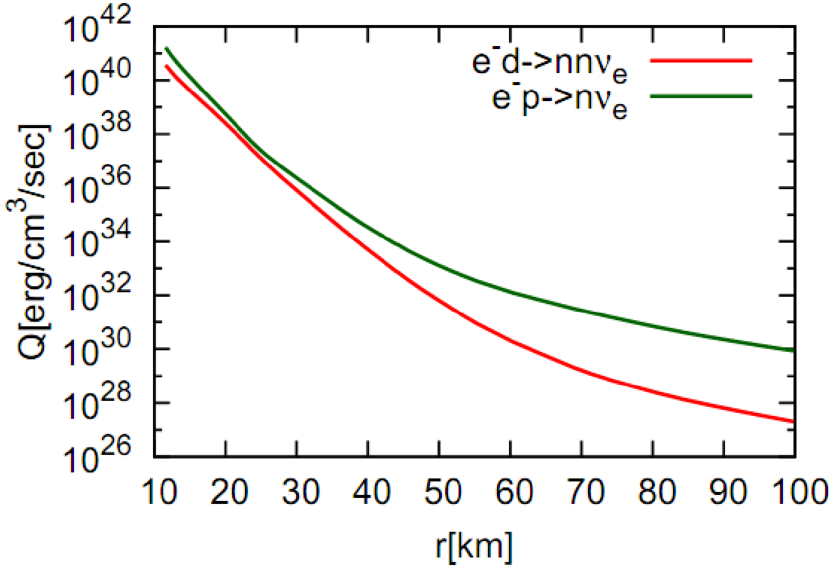
$$\frac{Q_{(A)}(e^- p \to n\nu_e) + Q_{(A)}(e^- d \to nn\nu_e)}{Q_{(B)}(e^- p \to n\nu_e)} < 1$$

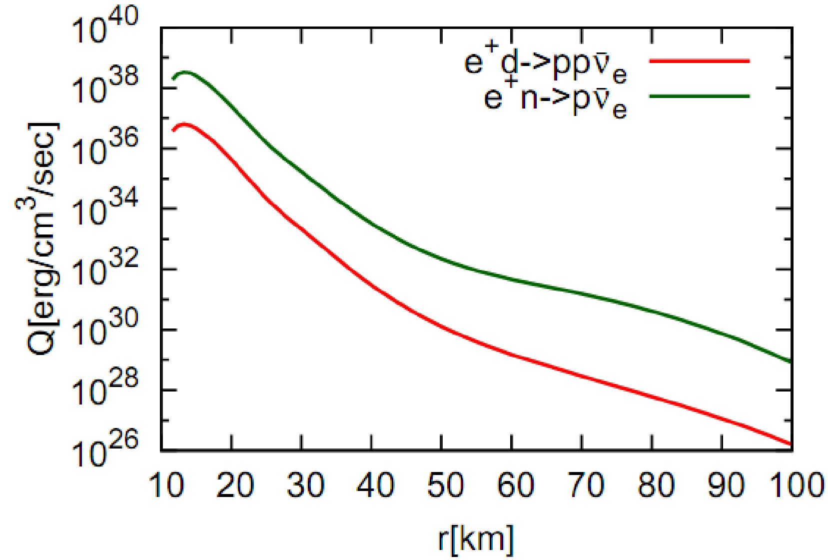


$Q(e^- p)$ is reduced by deuteron existence

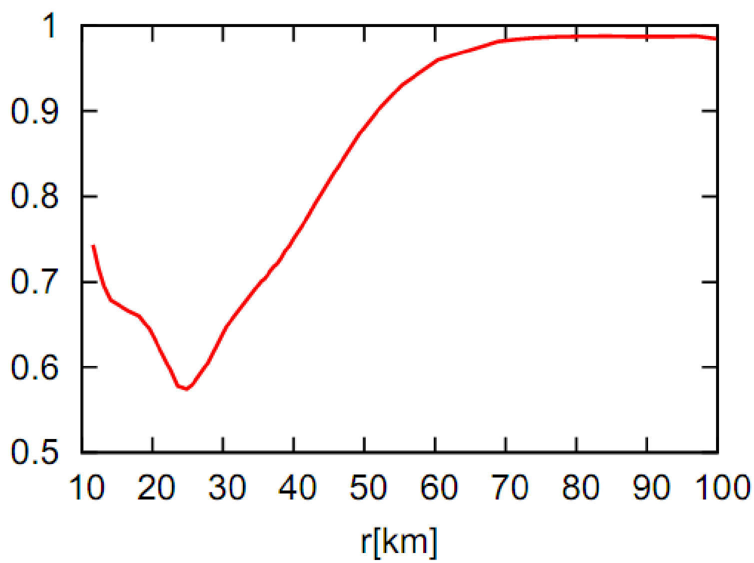
e^- capture $\qquad$ e^+ capture

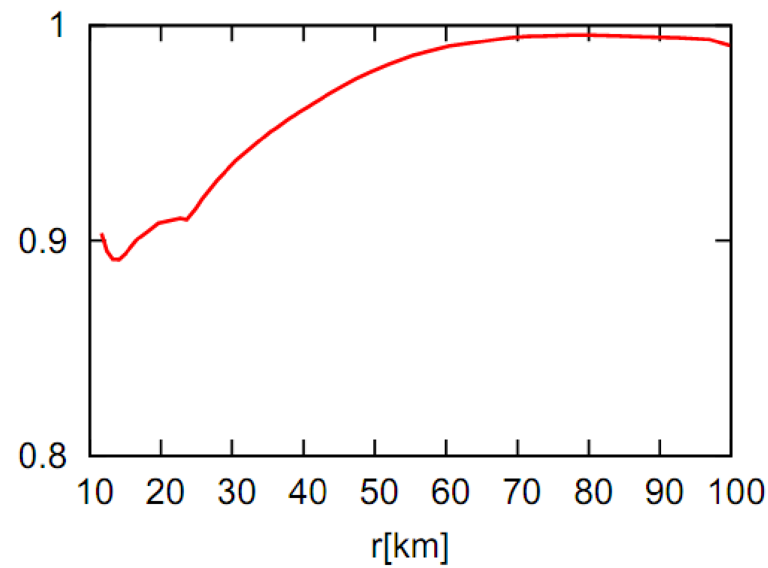
Emissivity using (A) (nucleon + light nuclei)



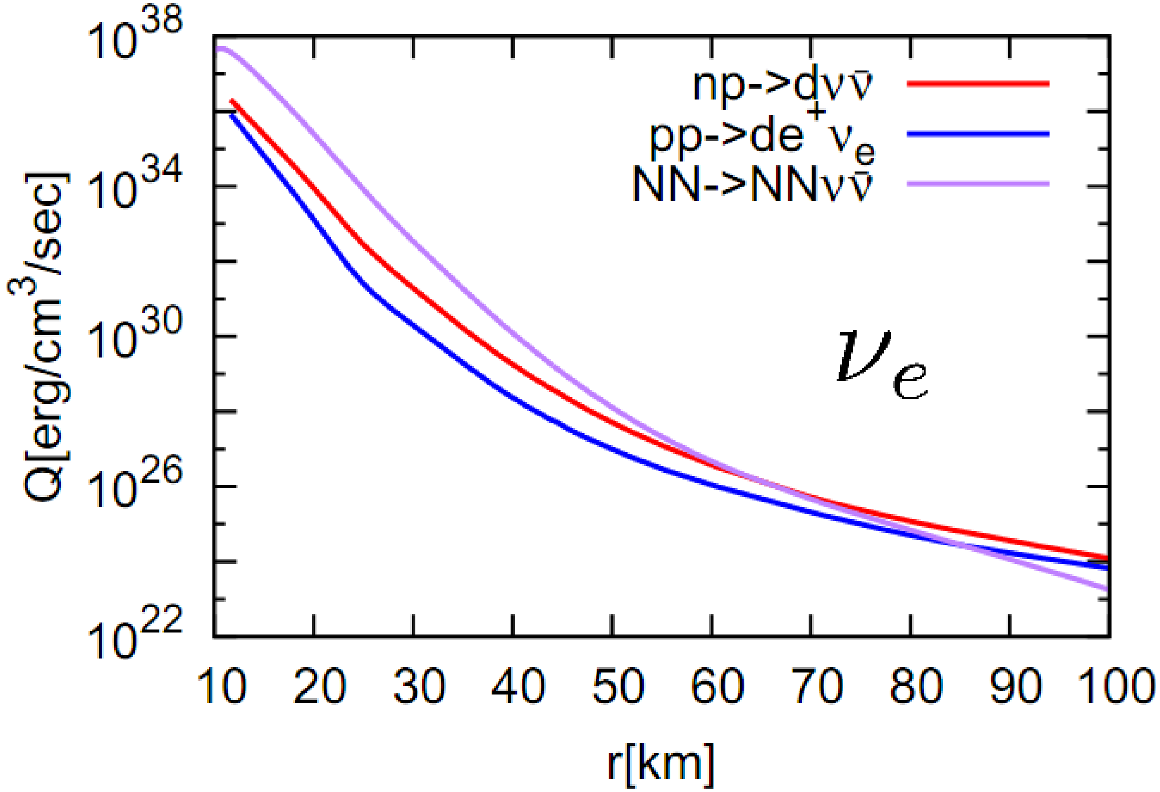


Ratio



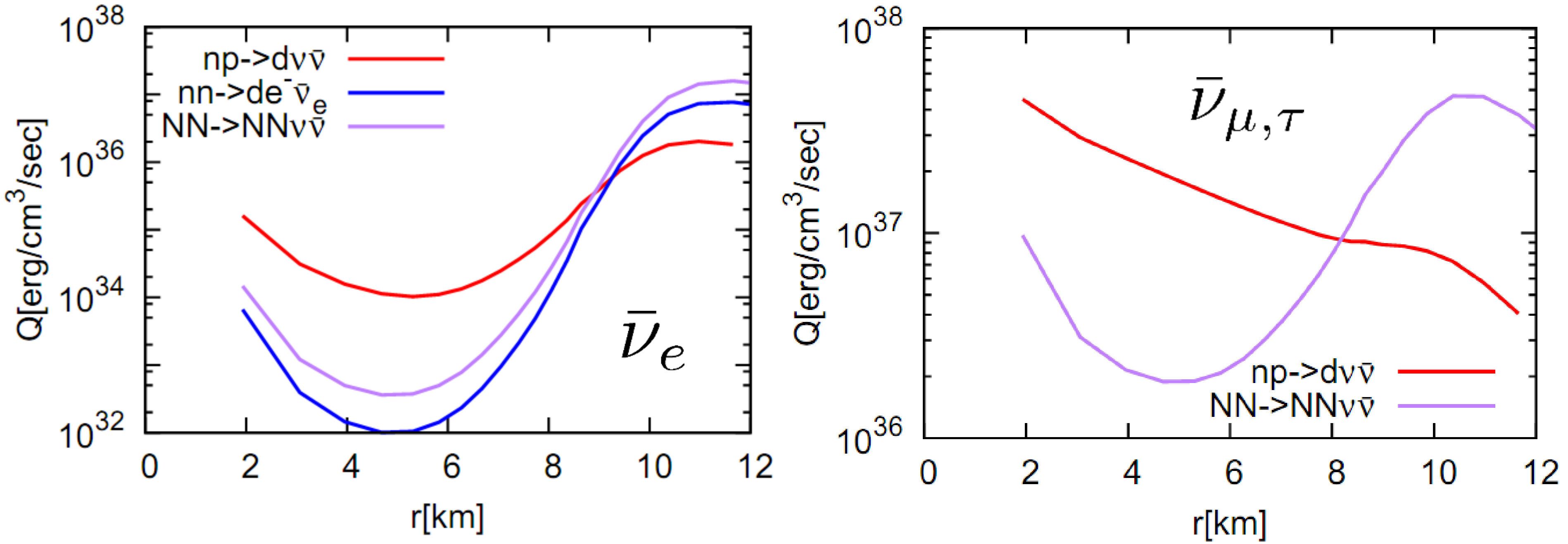


$np \to d\nu\bar{\nu}$
$pp \to de^{+}\nu_e$ vs $NN \to NN\nu\bar{\nu}$ emissivity



$$Q(np \to d) \sim Q(NN\ brems)$$

r=1-10km, NN->d



Inner region - high density$(\sim 10^{14} g/cm^3)$,

relatively low temperature $(\sim 10MeV)$:

$$np \to d\nu\bar{\nu} \;>\; \text{NN brems}$$

No nucleon Pauli blocking   nucleon Pauli blocking affect

This is the first step calculation!

(Need NN short range correlations, deuteron??)

Summary

We developed the **neutrino emissivity** $Q(T, \mu_i)$ for $ed \to NN, NN \to d$ reactions

Transition amplitude: impulse and exchange(π-,ρ-,Δ excited π-,ρ- exchange) currents

An example: t(after bounce) = 0.15s snapshot analysis

r=10-100km

$Q(e^- p)$ is reduced because of deuteron existence

$Q(np \to d) \sim Q(NN\ brems)$

r=1-8km

$Q(np \to d) > Q(brems)$

Future

- Provide a use-friendly form for supernova simulations
- Deuteron in high dense matter?
- NN->NN re-analysis on our model