Neutrino Emissivities from Deuteron-Breakup and Formation in Supernovae

ApJ 801, 78 (2015)

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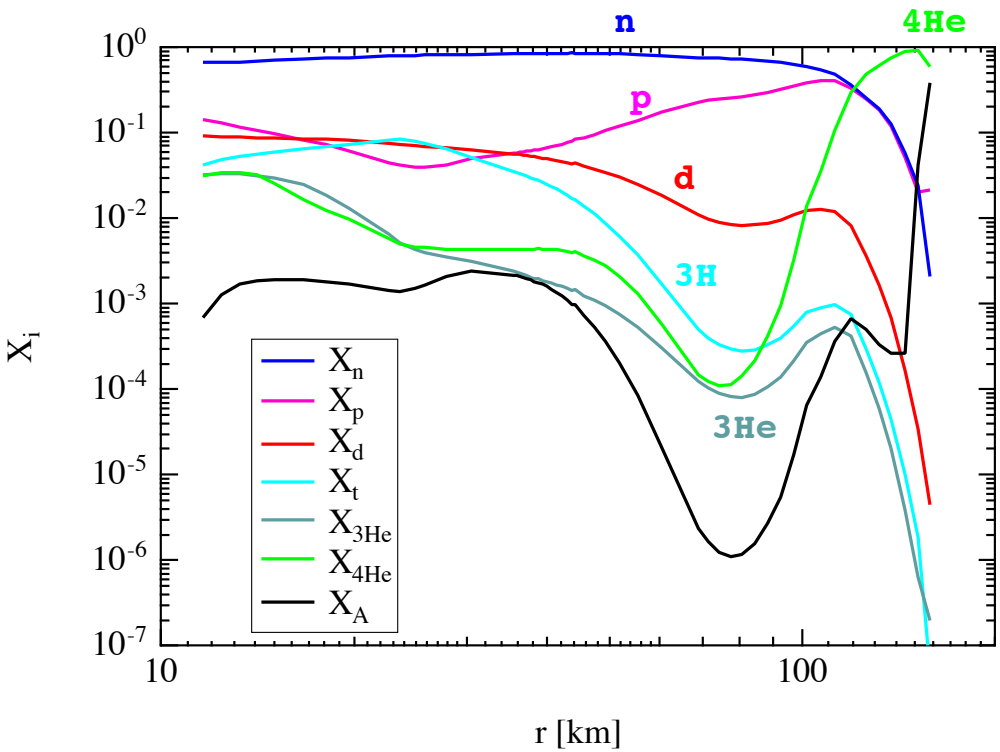
Introduction

Light elements in supernova (SN) ^{2}H, ^{3}H, ^{3}He … etc.

Snapshot of supernova profile (150 ms after core bounce)

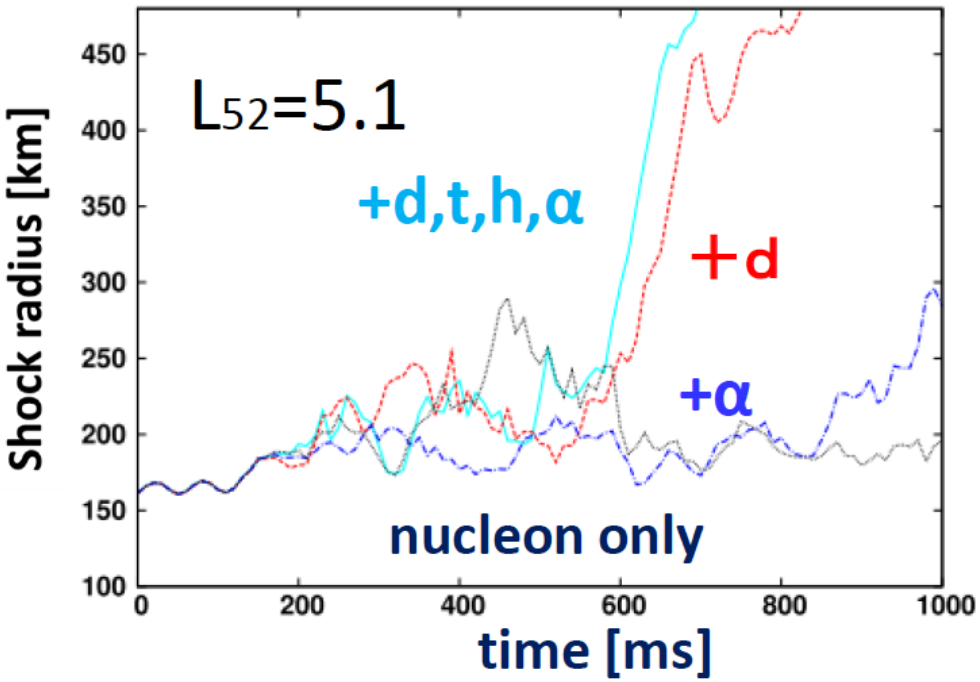


Mass fraction abundance of light elements based on nuclear statistical equilibrium

Sumiyoshi, Röpke, PRC 77, 055804 (2008)

Q : Can light elements in SN influence SN evolution ?

Yes, it does !



2D supernova simulation in

Furusawa et al, ApJ 774, 78 (2013)

ν–absorption by

: nucleon only

: nucleon + α

: nucleon + *d*

: nucleon + *d, t, h,* α

Neutrino absorption by deuteron can boost shockwave drastically in some cases

Neutrino emission from light elements in SN

ν-emission previously considered (A≤2)

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

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* $p + p \rightarrow p + n + e^+ + \nu_e$
* $N + N \rightarrow N + N + \nu + \bar{\nu}$

New agents considered here

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

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

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

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

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

Neutrino emission from light elements in SN

ν-emission previously considered (A≤2)	New agents considered here
* $p + e^- \rightarrow n + \nu_e$	$d + e^- \rightarrow n + n + \nu_e$
* $n + e^+ \rightarrow p + \bar{\nu}_e$	$d + e^+ \rightarrow p + p + \bar{\nu}_e$
* $n + n \rightarrow p + n + e^- + \bar{\nu}_e$	$n + n \rightarrow d + e^- + \bar{\nu}_e$
* $p + p \rightarrow p + n + e^+ + \nu_e$	$p + p \rightarrow d + e^+ + \nu_e$
* $N + N \rightarrow N + N + \nu + \bar{\nu}$	$p + n \rightarrow d + \nu + \bar{\nu}$

Questions to be addressed :

- How much ν are emitted by deuteron processes compared with the conventional ones ?
- Regarding SN evolution, what is implied by the new ν-emission from light elements ?

Contents of this talk : description of model ➔ numerical results ➔ conclusion

MODEL

Calculational method

Well-established method for electroweak processes in few-nucleon systems

$$\langle \psi_f | H_{\rm ew} | \psi_i \rangle$$

$|\psi\rangle$: solution of Schröding eq. with high-precision NN (+ NNN) potential

AV18, Nijmegen, Bonn, chiral etc.

Weak Interaction Hamiltonian

$$H_W^{CC} = \frac{G'_F V_{ud}}{\sqrt{2}} \int d\boldsymbol{x} [J_\lambda^{CC}(\boldsymbol{x}) L^\lambda(\boldsymbol{x}) + \text{h. c.}] \qquad \text{for CC}$$

$$H_W^{NC} = \frac{G'_F}{\sqrt{2}} \int d\boldsymbol{x} [J_\lambda^{NC}(\boldsymbol{x}) L^\lambda(\boldsymbol{x}) + \text{h. c.}] \qquad \text{for NC}$$

$$L^\lambda(\boldsymbol{x}) = \bar{\psi}_l(\boldsymbol{x}) \gamma^\lambda (1 - \gamma^5) \psi_\nu(\boldsymbol{x})$$

Nuclear current

$$J_\lambda^{CC}(\boldsymbol{x}) = V_\lambda^{\pm}(\boldsymbol{x}) + A_\lambda^{\pm}(\boldsymbol{x})$$

$$J_\lambda^{NC}(\boldsymbol{x}) = V_\lambda^{3} - 2\sin^2\theta_W (V_\lambda^{3} + V_\lambda^{s}) + A_\lambda^{3}$$

$V(A)$: Vector (Axial) current

V^s : Isoscalar vector current

θ_W : Weinberg Angle $\sin^2\theta_W = 0.23$

J_λ = (one-body current) + (two-body exchange current)

Impulse approximation (IA) current

$$< p' \,|V_\lambda(0)|\, p > \;=\; \bar{u}(p')\left[f_V\gamma_\lambda + i\frac{f_M}{2M_N}\sigma_{\lambda\rho}q^\rho\right]u(p)$$

$$< p' \,|A_\lambda(0)|\, p > \;=\; \bar{u}(p')\left[f_A\gamma_\lambda\gamma^5 + f_P\gamma^5 q_\lambda\right]u(p)$$

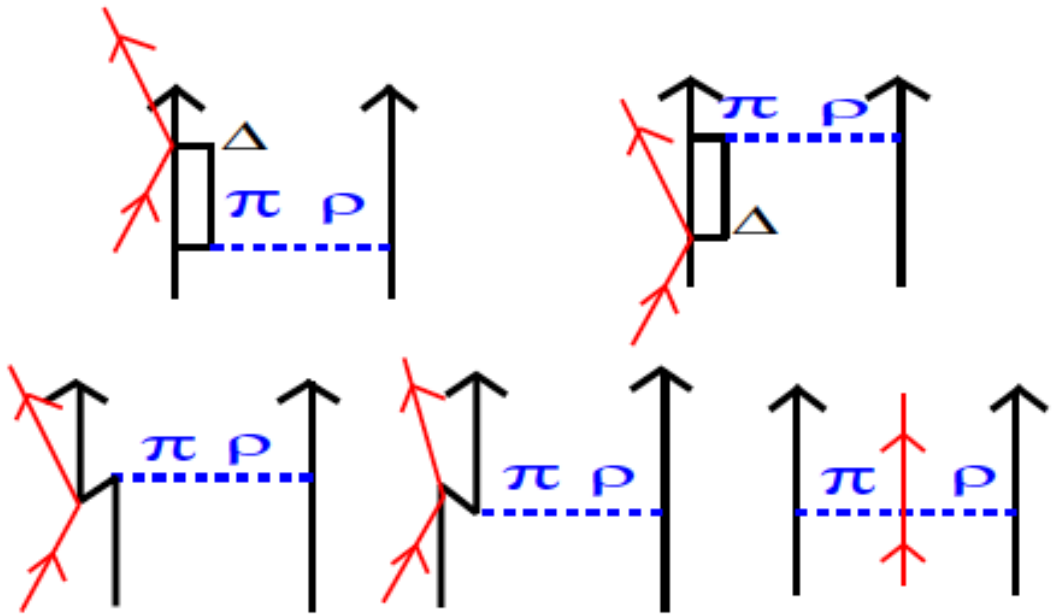
$$q_\lambda \;\equiv\; p'_\lambda - p_\lambda$$

$$f_M \;:\; \text{CVC} \qquad f_P : \text{PCAC}$$

$$f_A(q_\mu^2) \;=\; -g_A\left(1 - \frac{q_\mu^2}{1.04\,[\text{GeV}^2]}\right)^{-2}, \quad g_A = 1.2670 \pm 0.0030 \;\; (\text{PDG})$$

Exchange axial-vector current

Schiavilla et al., PRC 58, 1263 (1998)



Fit $AN\Delta$ coupling to tritium β-decay rate with rigorous three-body calculation

Predicted rates for muon captures on deuteron and ^{3}He are consistent with data

Marcucci et al., PRC 83 (2011)

$\nu_e + d \rightarrow e^- + p + p$, $\nu + d \rightarrow \nu + p + n$ for SNO expt. SN et al. PRC 63 (2000) ; NPA707 (2002)

Emissivity (Q)

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

$$Q = \frac{(2\pi)^4}{\mathcal{S}} \int \frac{d\boldsymbol{p}_{N_1}}{(2\pi)^3} \frac{d\boldsymbol{p}_{N_2}}{(2\pi)^3} \frac{d\boldsymbol{p}_d}{(2\pi)^3} \frac{d\boldsymbol{p}_\nu}{(2\pi)^3} \frac{d\boldsymbol{p}_{e^-}}{(2\pi)^3} \delta^{(4)}(p_f - p_i)$$

$$\times E_\nu \sum_{spin} |\langle \psi_f | H_{\rm ew} | \psi_i \rangle|^2 \quad f_d\, f_e (1 - f_{N_1})(1 - f_{N_2})$$

$$f_k(p_k) = \frac{1}{\exp((e_k(p_k) - \mu_k)/k_B T) \pm 1}$$

+ : fermion

− : boson

$\mathcal{S}$: symmetry factor for identical particles

Numerical results

Emissivities presented are for :

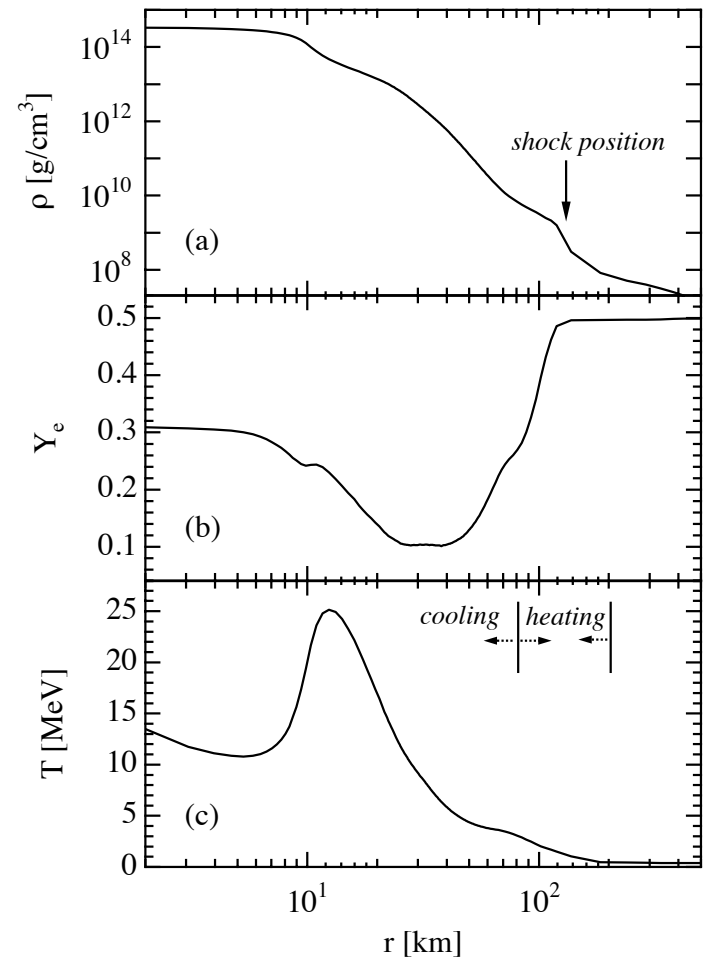
- Surface region of proto-neutron star (r > 10 km)

- Inner region of proto-neutron star (r < 10 km)

Deuteron can be largely modified,

or even doesn't exist

➔ "deuteron" as two-nucleon correlation in matter



supernova profile (150 ms after core bounce)

Sumiyoshi, Röpke, PRC 77, 055804 (2008)

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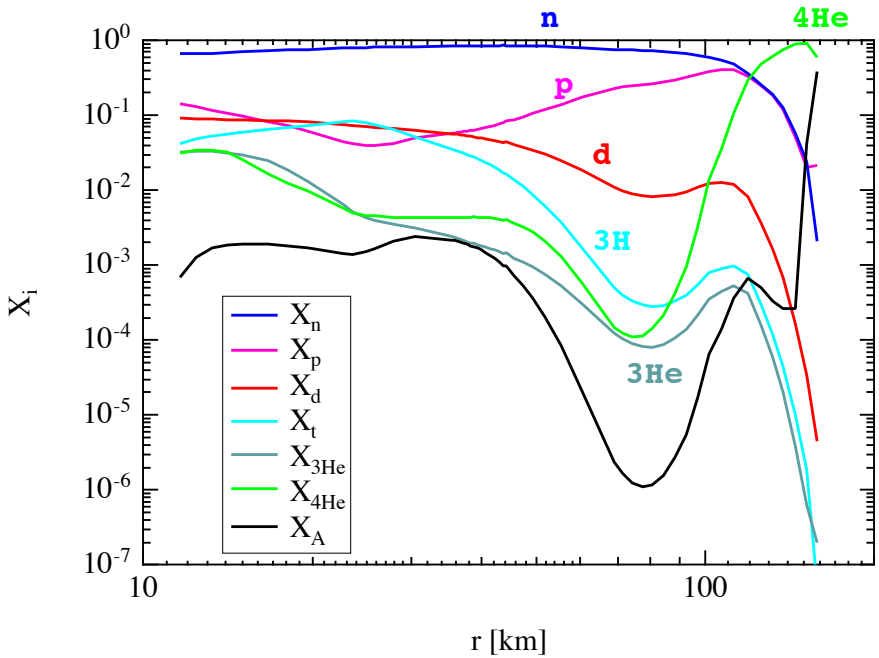
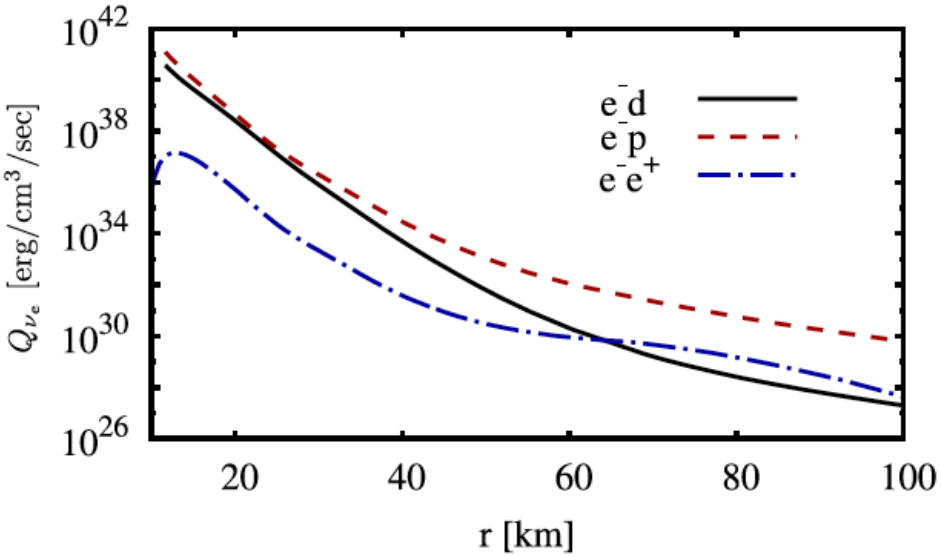


supernova profile (150 ms after core bounce)

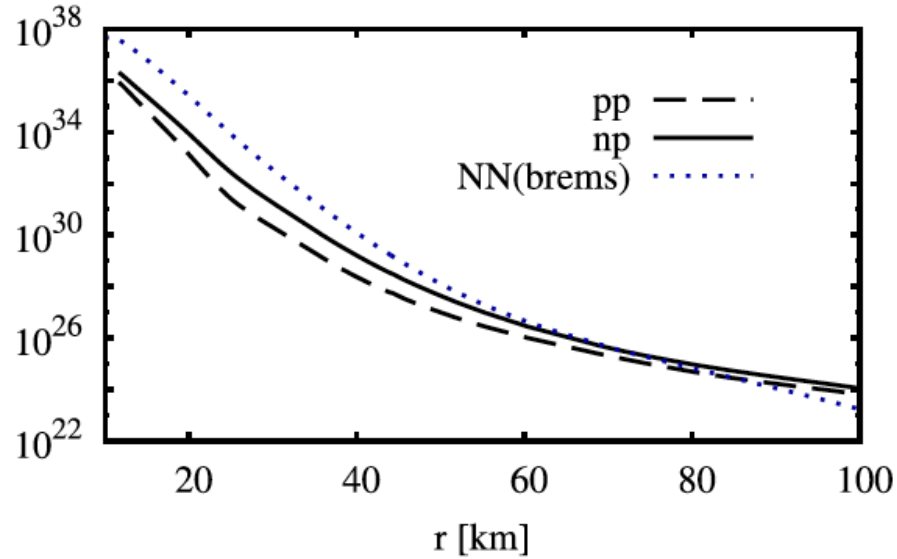
Sumiyoshi, Röpke, PRC 77, 055804 (2008)

ν_e-emissivity (r > 10 km)

electron capture



NN fusion

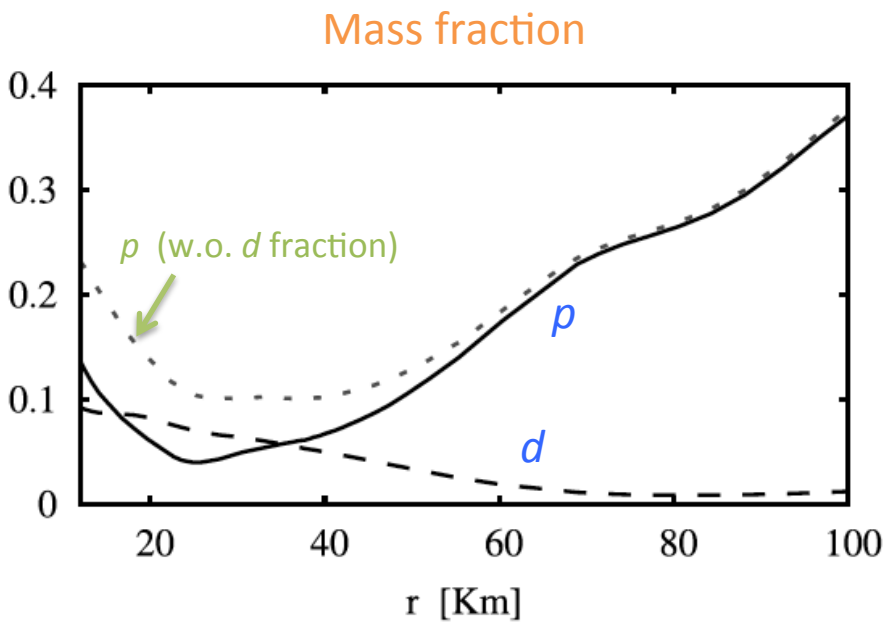


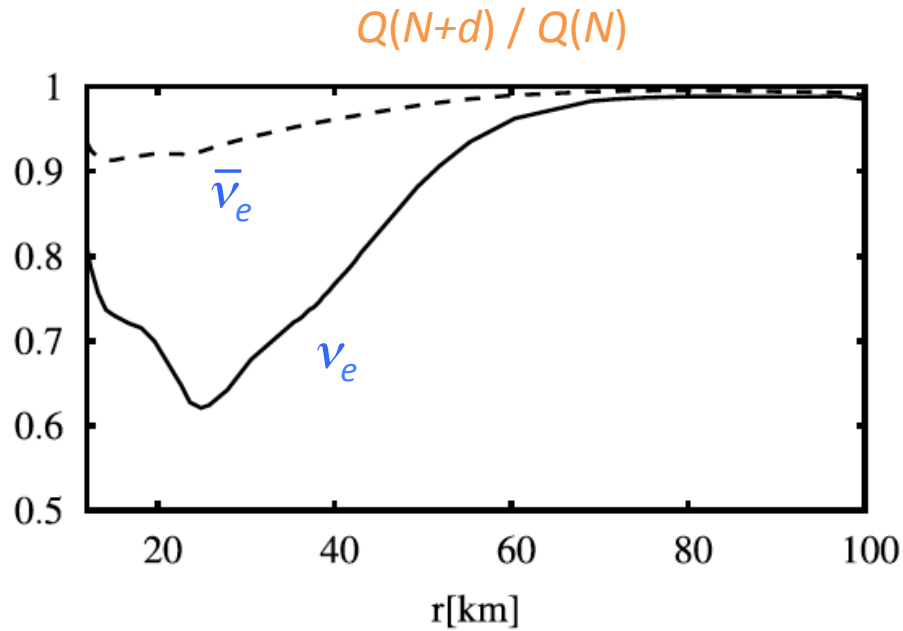
e^-p, e^+e^- : Bruenn, ApJS 58 (1985)

NN brem: Friman et al, ApJ 232 (1979)

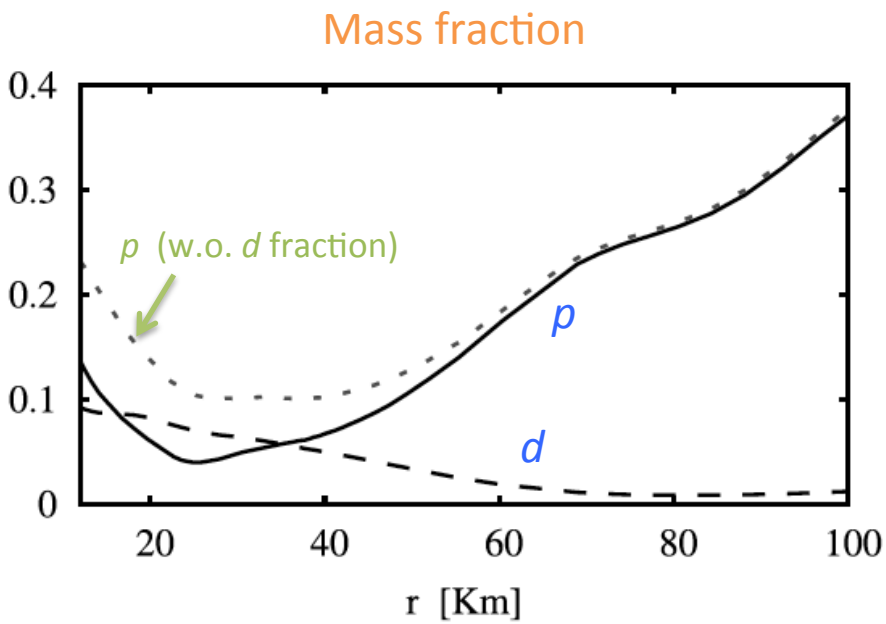
$Q\,(e^-p) > Q(e^-d) > Q\,(NN \rightarrow d)$

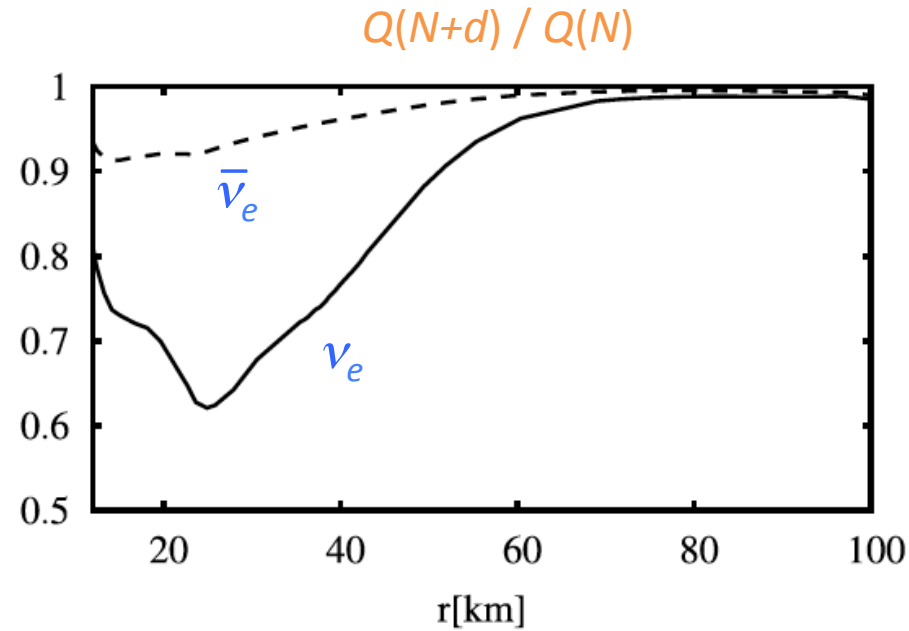
Change of ν_e emissivity due to deuteron





Change of ν_e emissivity due to deuteron





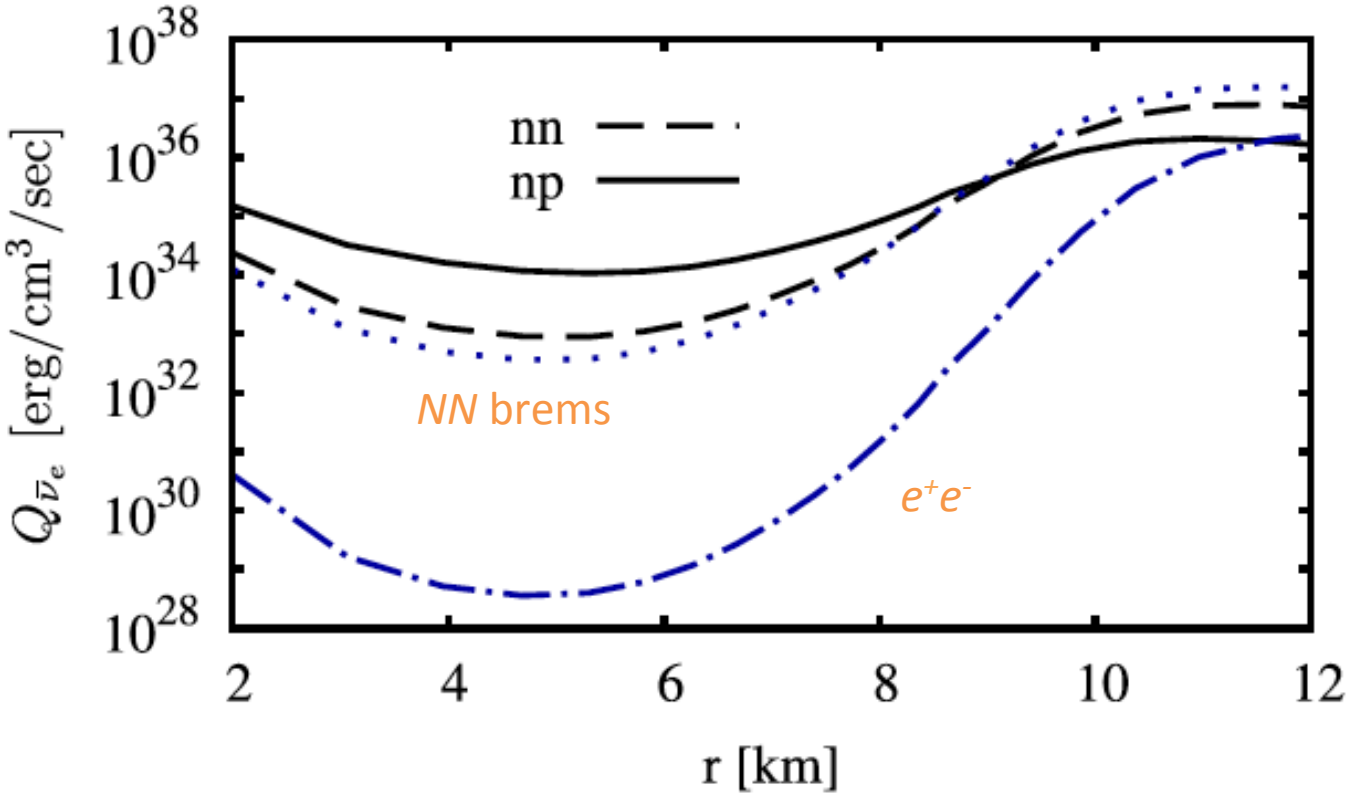
Deuterons exit at the cost of the proton abundance + $\sigma(e^- p) > \sigma(e^- d)$

↓

Effectively reduced ν_e emissivity → less ν-flux, ν-heating

Careful estimate of light element abundance & emissivity needed

$\bar{\nu}_e$-emissivity (inner region proto-neutron star)



Q (NN brem) ≈ Q (NN→d)

Whenever *NN* brem is important, *NN→ d* (correlation) can be also important

→ Possible important role in proto-neutron star cooling

Conclusion

ν-emission in SN: $e^{\pm} + d \rightarrow \nu_e(\bar{\nu}_e) + N + N$ $\quad N + N \rightarrow d + l + \bar{l}$

New agents other than direct & modified Urca, *NN* bremsstrahlung

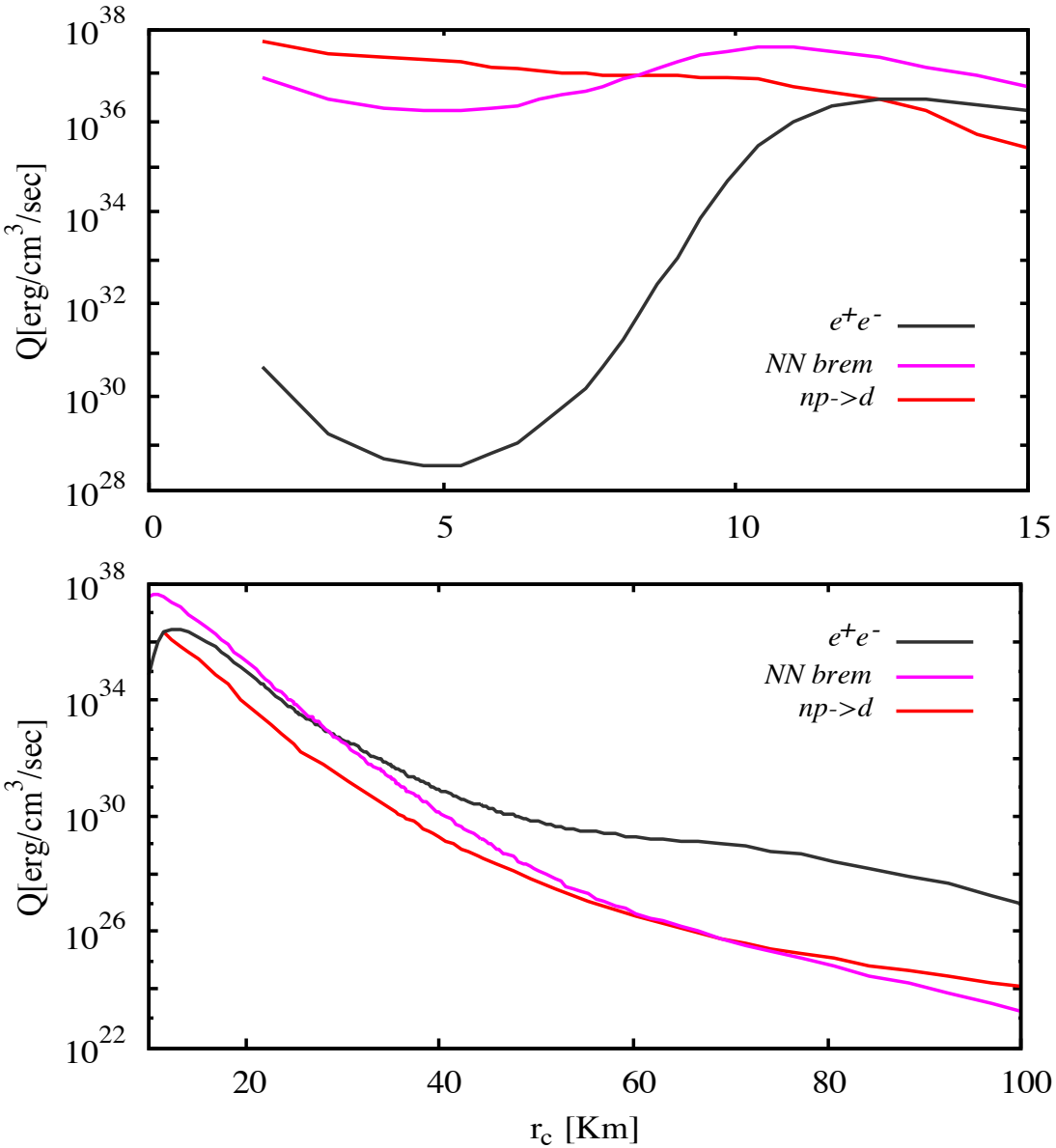
Emissivities ← *NN* wave functions based on high-precision *NN* potential
+ 1 & 2-body nuclear weak currents (tested by data)

Electron captures → effectively reduced ν_e emissivity
→ light element abundance & emissivity are important

NN fusions → play a role comparable to *NN* bremsstrahlung & modified Urca
→ *np* → $d\nu\bar{\nu}$ can be important for ν_μ emissivity

Backups

ν_μ-emissivity



Q (NN brem) ≈ Q (np➔d)

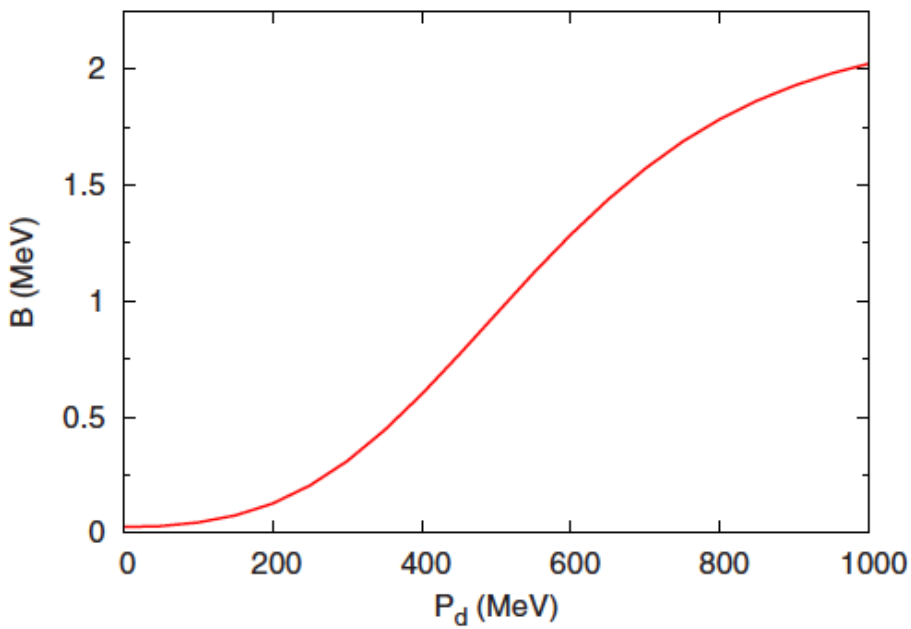
Whenever *NN* brem is important, *np➔d* can be also important

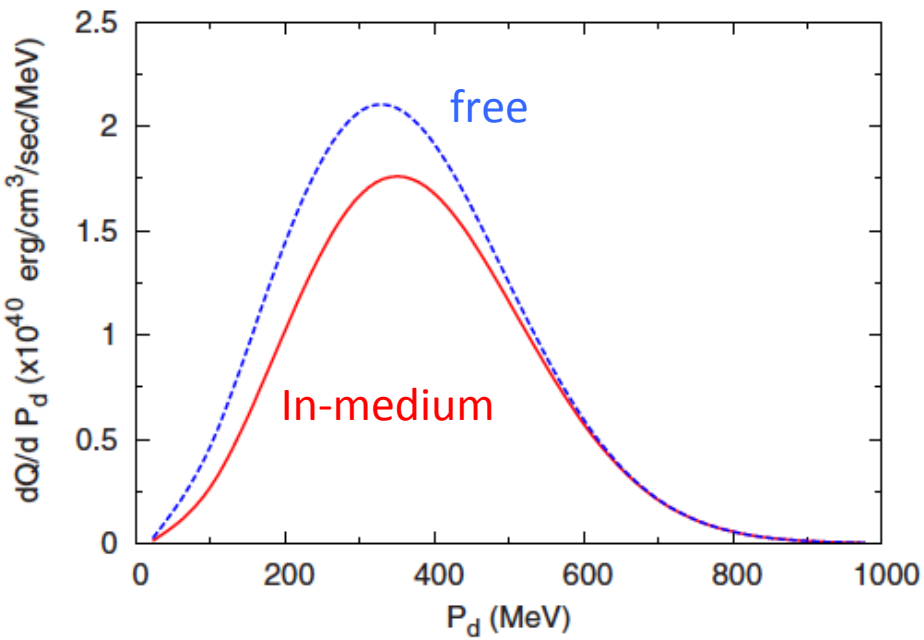
↓

Possible important role in proto-neutron star cooling

Medium effect on deuteron

Deuteron wave function with Pauli-blocking at $r = 11.7$ km, $\rho = 6\times10^{13}$g/cm^3, T=25 MeV





- Significant decrease of B.E. at P_d=0
- B.E. recovered free B.E. at P_d=1 GeV

Reduction rate : $1 - Q$(in-medium)/Q(free)

r (km)	11.7	19.7	40.6
Reduction rate (%)	15	5	1

Most recent applications of the model to weak processes

★ *pp*-fusion ($p + p \rightarrow d + e^{+} + \nu_e$) for solar model , Schiavilla et al. PRC 58 (1998)

★ Muon capture ($\mu^- + d \rightarrow n + n + \nu_\mu$, $\mu^- + {}^3He \rightarrow {}^3H + \nu_\mu$) , Marcucci et al., PRC 83 (2011)

	[1]	[2]	Theory	MuSun@PSI
$\Gamma(\mu^- + d)[s^{-1}]$	409 ± 40	470 ± 29	393	???

	[3]	Theory
$\Gamma(\mu^- + {}^3He)[s^{-1}]$	1496 ± 4	1496

[1] Cargnelli et al. (1998)
[2] Bardin et al. NPA 453 (1986)
[3] Ackerbauer et al. PLB 417 (1998)

★ *νd*-reactions ($\nu_e + d \rightarrow e^- + p + p$, $\nu + d \rightarrow \nu + p + n$) for SNO experiment

SN et al. PRC 63 (2000) ; NPA707 (2002)

➔ evidence of ν-oscillation, solar ν problem resolved

Emissivity (Q)

$$N_1 + N_2 \rightarrow N_1' + N_2' + \nu + \bar{\nu}$$

$$\begin{aligned} Q &= \frac{(2\pi)^4}{\mathcal{S}} \int \frac{d\boldsymbol{p}_{N_1}}{(2\pi)^3} \frac{d\boldsymbol{p}_{N_2}}{(2\pi)^3} \frac{d\boldsymbol{p}_{N_1'}}{(2\pi)^3} \frac{d\boldsymbol{p}_{N_2'}}{(2\pi)^3} \frac{d\boldsymbol{p}_{\nu}}{(2\pi)^3} \frac{d\boldsymbol{p}_{\bar{\nu}}}{(2\pi)^3} \delta^{(4)}(p_f - p_i) \\ &\times (E_\nu + E_{\bar{\nu}}) \sum_{spin} |\langle \psi_f | H_{\mathrm{ew}} | \psi_i \rangle|^2 F_{N_1} F_{N_2} (1 - F_{N_1'})(1 - F_{N_2'}) \end{aligned}$$

$$F_N = \frac{1}{1 + \exp[(\varepsilon_N - \mu_N)/kT]}$$

Emissivity (Q)

$$N_1 + N_2 \to d + \nu + \bar{\nu}$$

$$\begin{aligned} Q &= \frac{(2\pi)^4}{\mathcal{S}} \int \frac{d\boldsymbol{p}_{N_1}}{(2\pi)^3} \frac{d\boldsymbol{p}_{N_2}}{(2\pi)^3} \frac{d\boldsymbol{p}_d}{(2\pi)^3} \frac{d\boldsymbol{p}_\nu}{(2\pi)^3} \frac{d\boldsymbol{p}_{\bar{\nu}}}{(2\pi)^3} \delta^{(4)}(p_f - p_i) \\ &\times (E_\nu + E_{\bar{\nu}}) \sum_{spin} |\langle \psi_f | H_{\rm ew} | \psi_i \rangle|^2 F_{N_1} F_{N_2} \end{aligned}$$

11 dimensional integral !!

Approximation necessary to evaluate Q

Emissivity (Q)

$$Q \propto \int \underbrace{d\boldsymbol{p}_{N_1} d\boldsymbol{p}_{N_2} \cancel{d\boldsymbol{p}_d}}_{p^2 \cancel{dp}\, d\Omega_{\boldsymbol{p}}\, d\boldsymbol{P}} d\boldsymbol{p}_\nu d\boldsymbol{p}_{\bar{\nu}}\, \omega\, \underbrace{\delta(E_f - E_i)}_{\cancel{\delta\left[\left(B + \frac{p_d^2}{2M_d} + \omega\right) - \left(\frac{P^2}{4M_N} + \frac{p^2}{M_N}\right)\right]}} \cancel{\delta^{(3)}(\vec{p}_f - \vec{p}_i)} |M|^2 F_{N_1}(\vec{p}_1) F_{N_2}(\vec{p}_2)$$

Approximation !

$$Q \propto \int \underbrace{d\boldsymbol{p}_\nu d\boldsymbol{p}_{\bar{\nu}}}_{8\pi^2\, p_\nu^2 p_{\bar{\nu}}^2\, dp_\nu dp_{\bar{\nu}}\, d\cos\theta_{\nu\bar{\nu}}} \omega p^2 \left[\int d\Omega_{\boldsymbol{p}} |M|^2\right] \left[\int d\boldsymbol{P} F_{N_1}(\vec{P}/2 + \vec{p}) F_{N_2}(\vec{P}/2 - \vec{p})\right]$$

3 dimensional integral

Previous common approximation to evaluate $Q_{\text{NN-brem}}$

- One-pion-exchange potential, Born approximation

  Low-energy theorem

- Nuclear matrix element ➔ long wave length limit

  ➔ constant

Neither of them are adopted in this work

Previous common approximation to evaluate $Q_{\text{NN-brem}}$

- One-pion-exchange potential, Born approximation

  Low-energy theorem

- Neglect momentum transfer ($\vec{p}_\nu + \vec{p}_{\bar{\nu}}$)

  ➔ also angular correlation between ν and $\bar{\nu}$

- Nuclear matrix element ➔ long wave length limit

  ➔ constant

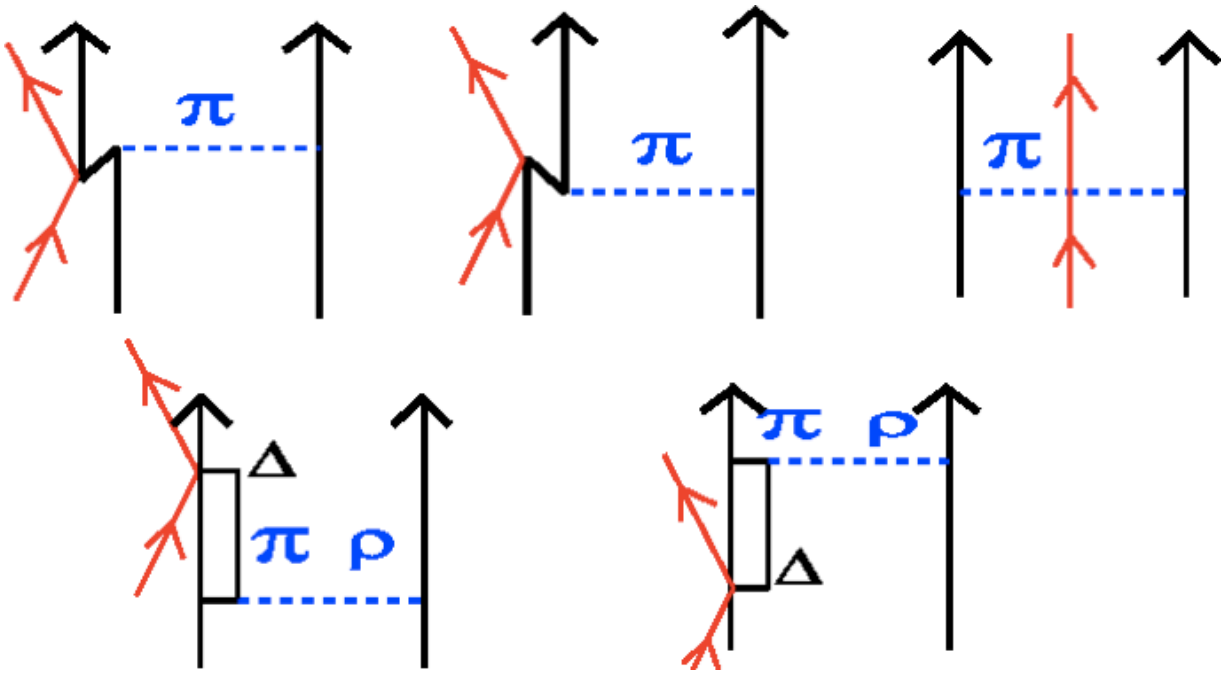
Emissivites from direct Urca, e^+e^- annihilation, *NN* brems ← compilation I

Emissivites from election captures on *d* & *NN* fusion ← compilation II

- Compilation I : Shen EoS, *N,* ^{4}He, a heavy nucleus
- Compilation II : light elements abundance from Sumiyoshi & Röpke (2008)

Both have the same density, temperature, electron fraction

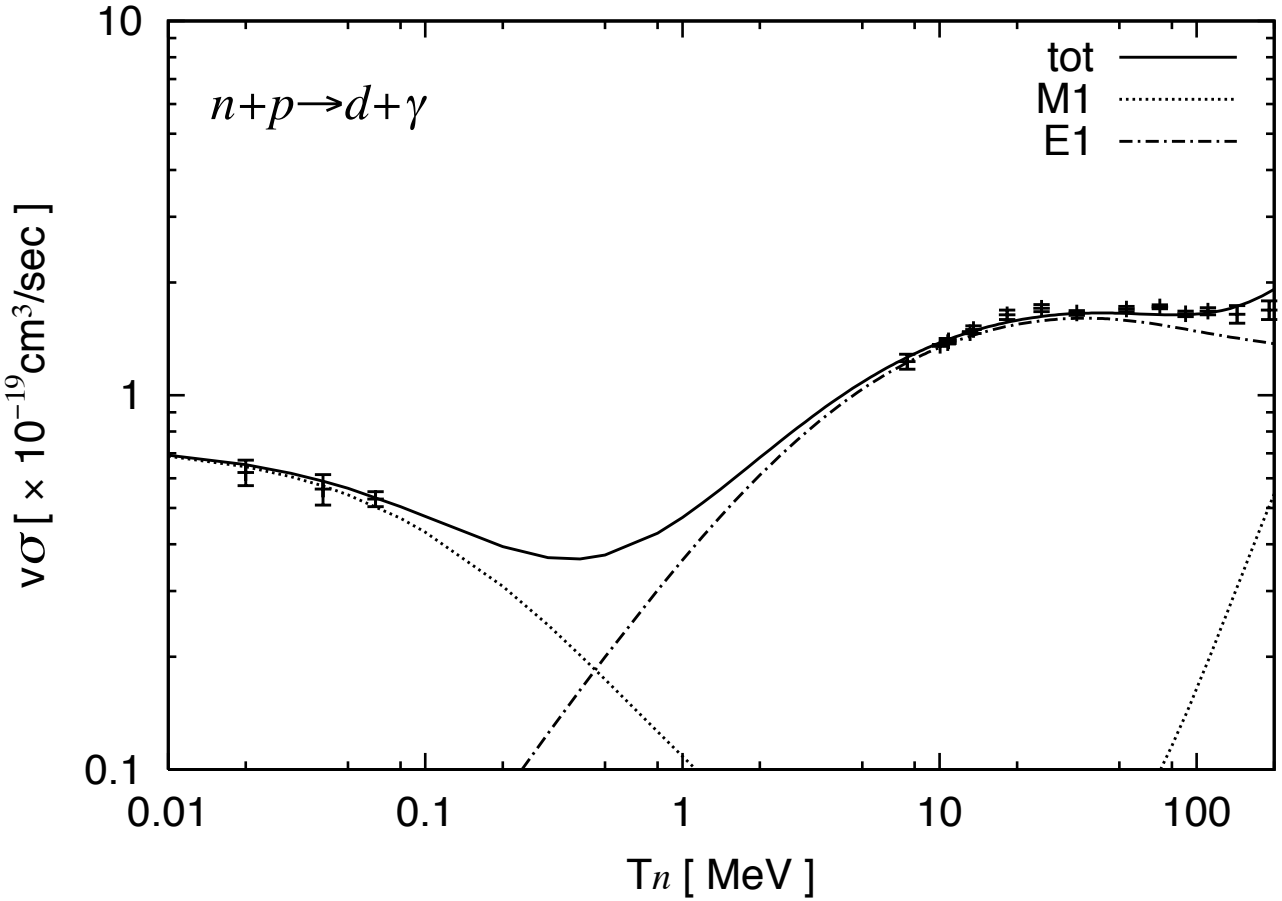
Exchange vector current



★ Current conservation for one-pion-exchange potential

★ $VN\Delta$ coupling is fitted to $np \rightarrow d\gamma$ data

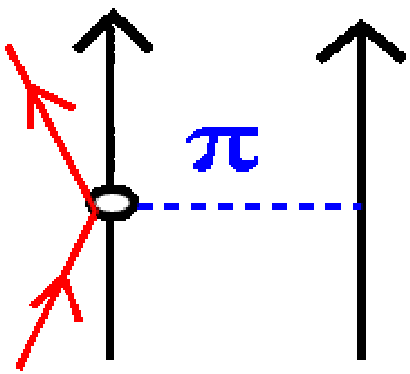
Comparison with $np \rightarrow d\gamma$ data



Exchange currents contribute about 10 %

Exchange axial charge

Kubodera, Delorme, Rho, PRL 40 (1978)



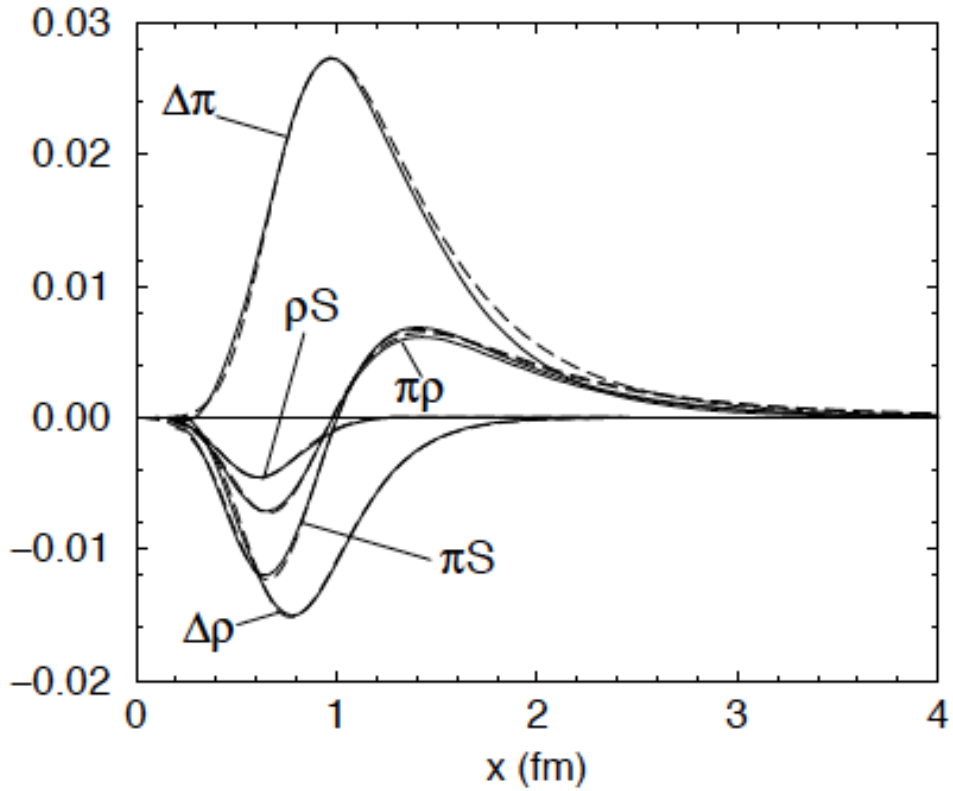
Soft pion theorem + PCAC

Why tritium β decay?

νd : Gamow-Teller ($^3S_1 \rightarrow {}^1S_0$) $\Rightarrow$ $\mathbf{A}_{EXC}$ is main correction

^{3}H : Fermi ($^1S_0 \rightarrow {}^1S_0$) & Gamow-Teller

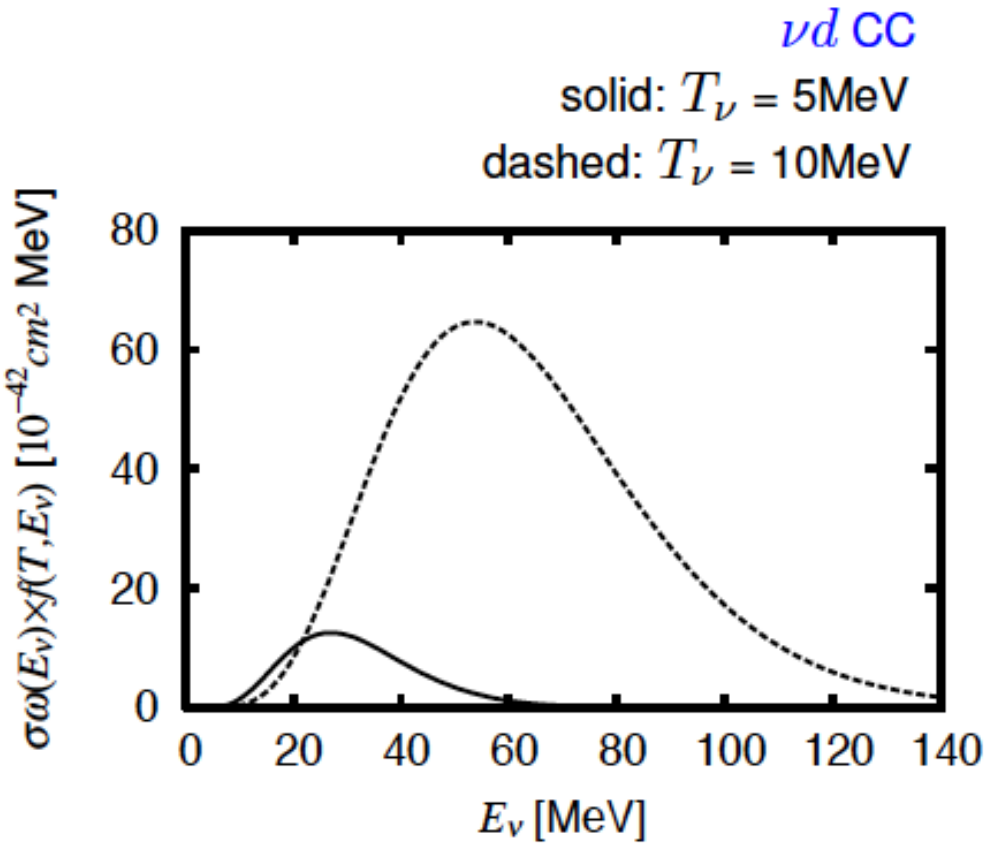
$\rho(x)$ [fm^{-1}]



$$\frac{\rho_{\nu d}}{\rho_{^3H}} \approx \text{const.}$$

Schiavilla et al., PRC**58**,1263(1998)

E_ν-dependence of energy transfer cross section

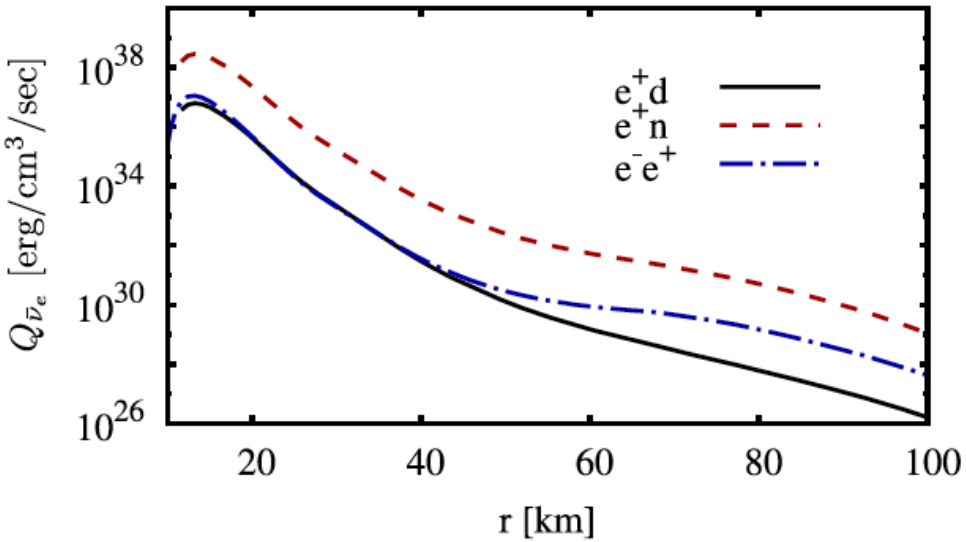


∗ Main contribution is from E_ν = 20 (60) MeV for T_ν = 5 (10) MeV

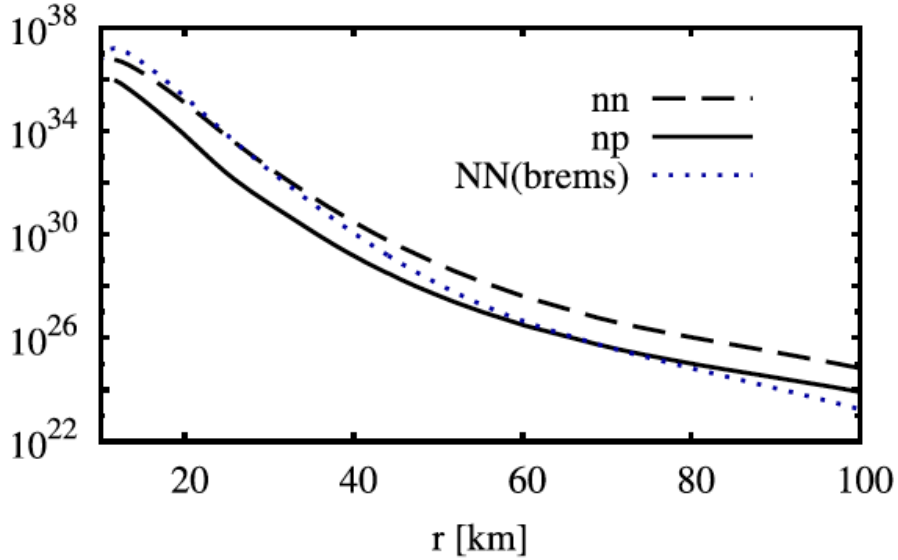
∗ High energy tail of $\sigma\omega \times f$ is appreciable

$\bar{\nu}_e$-emissivity

positron capture

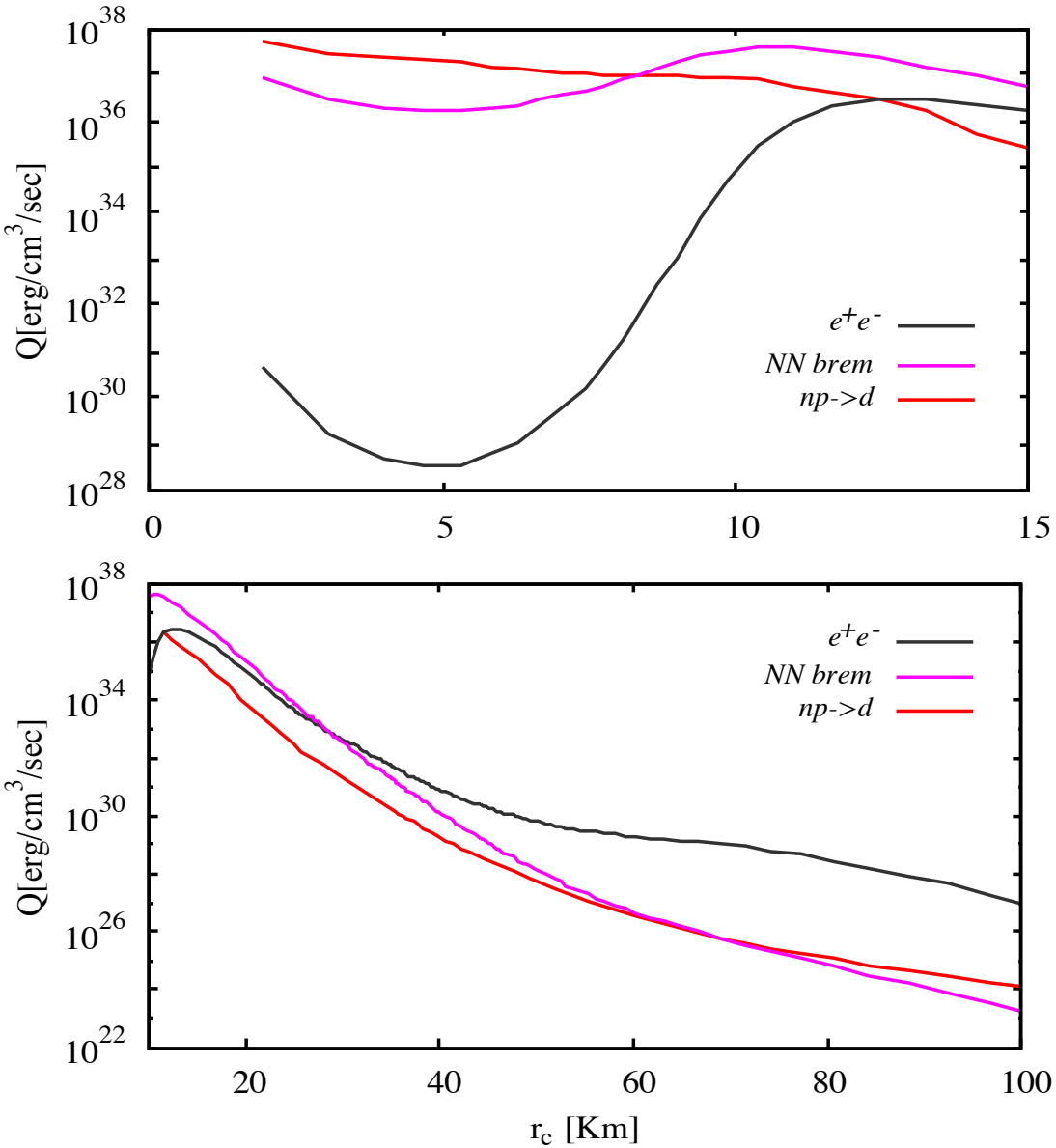


NN fusion



$Q\,(e^+ n) > Q(e^+ d) > Q\,(NN \rightarrow d)$

ν_μ-emissivity



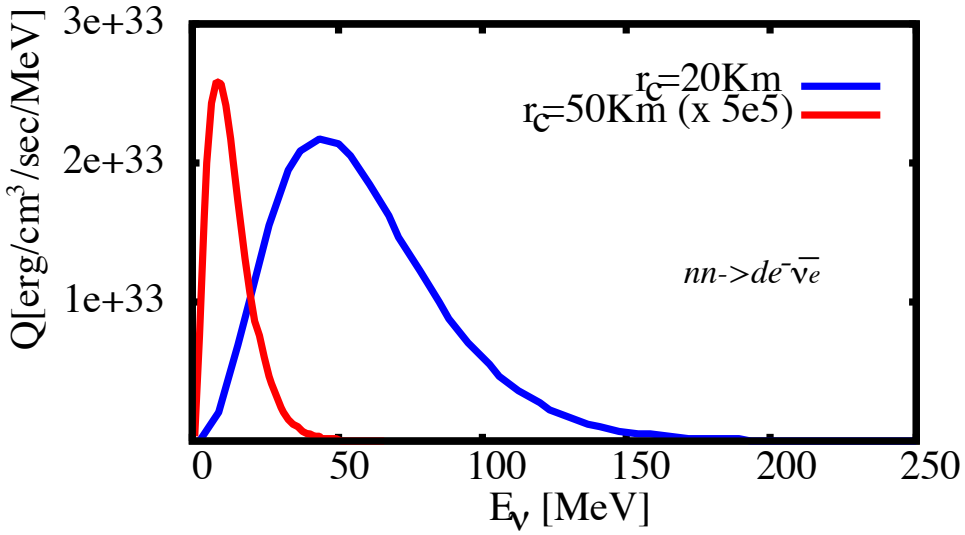
Q (NN brem) ≈ Q (np➔d)

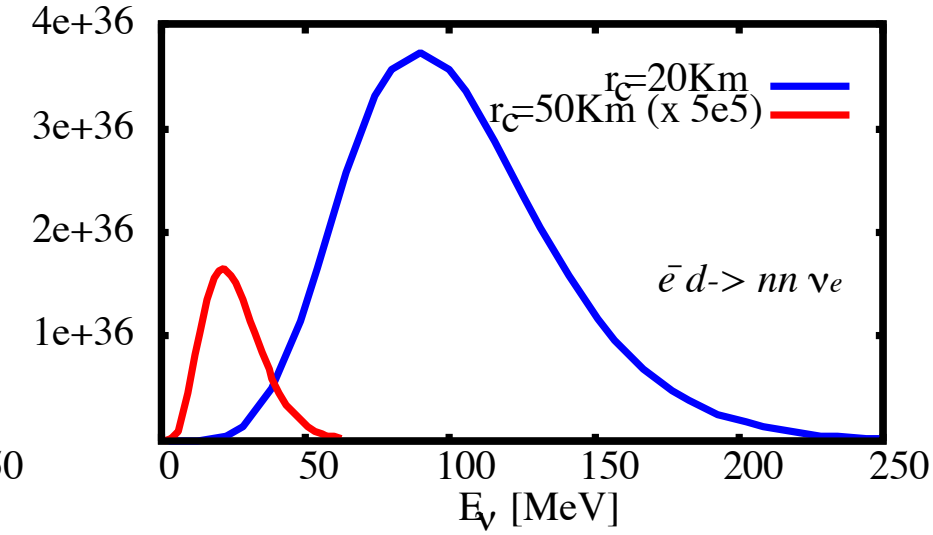
Whenever *NN* brem is important, *np➔d* can be also important

↓

Possible important role in proto-neutron star cooling

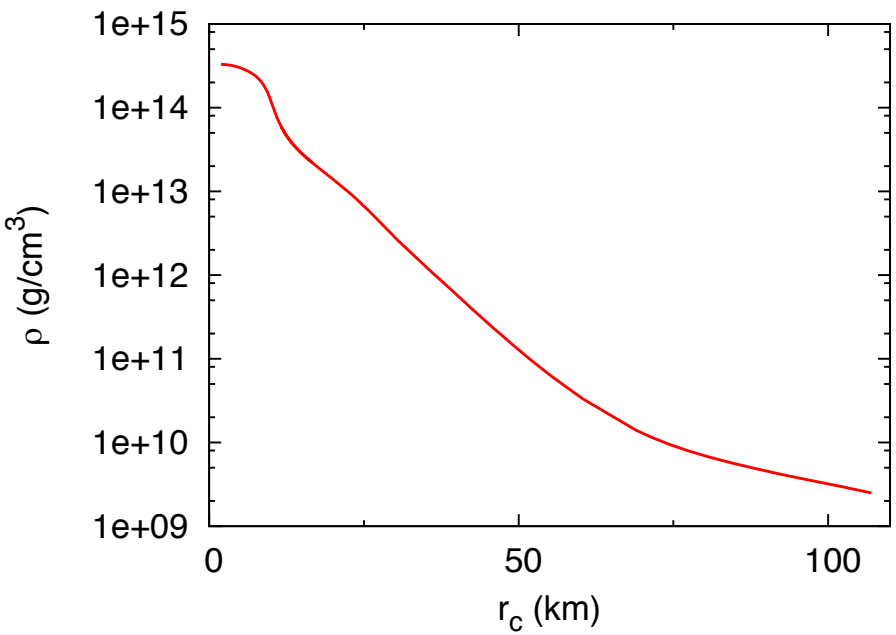
Neutrino spectrum



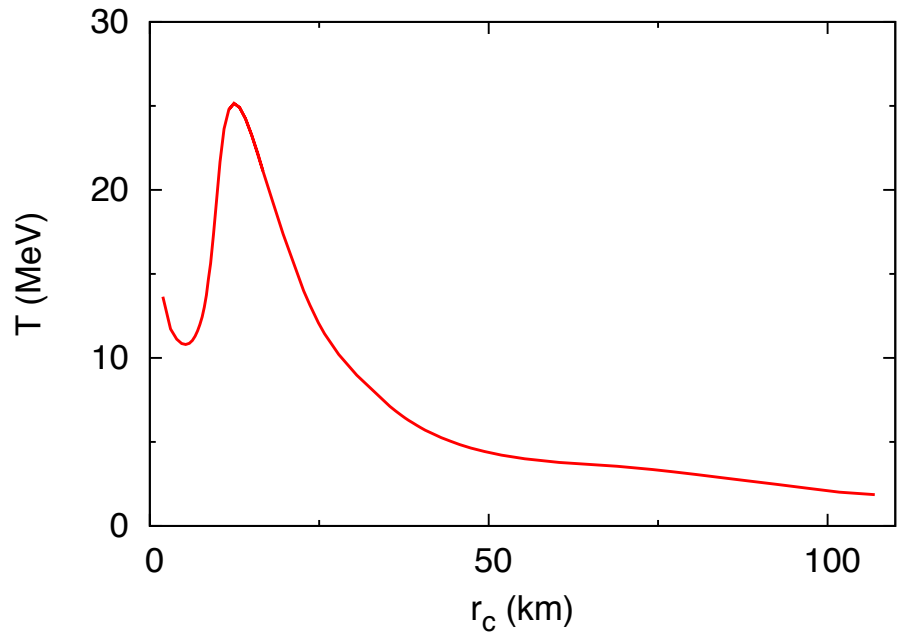


Supernova profile

density

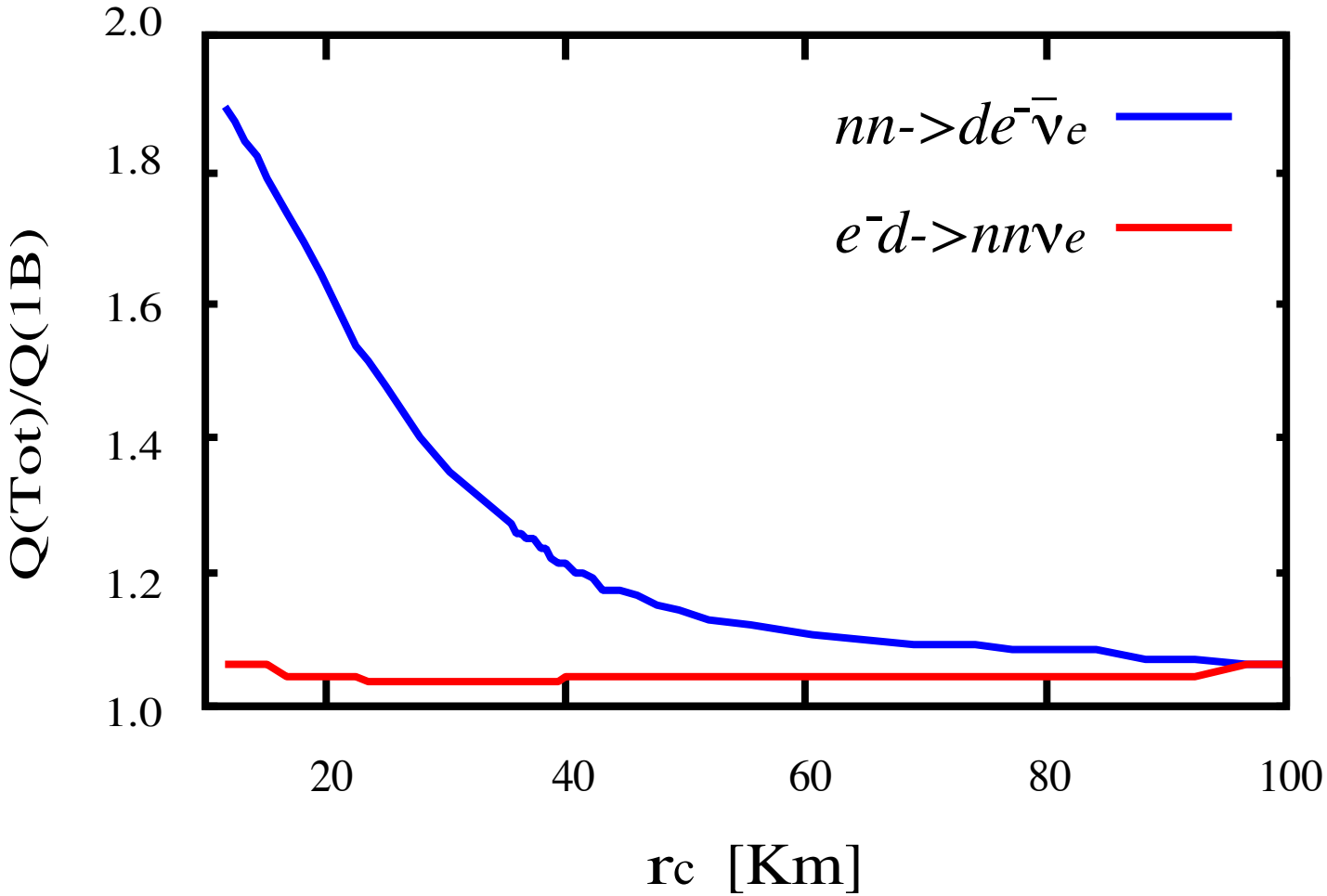


temperature



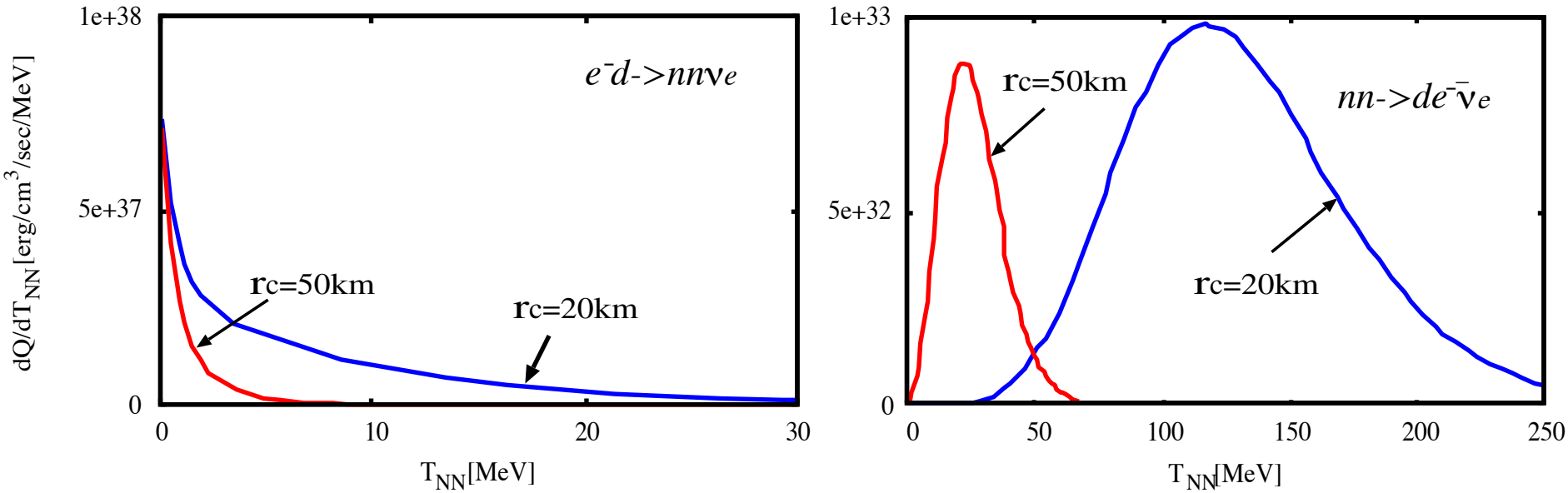
Sumiyoshi, Röpke, PRC 77, 055804 (2008)

Meson exchange current effect on *Q*



Large effect on NN fusion !

Why so large meson exchange current effect ?



★ Higher NN kinetic energy causes large exchange current effect

★ Axial exchange current & higher partial waves are important ; uncertainty