# ニュートリノ重陽子反応と超新星爆発への影響

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- Phys. Rev. C80 (2009), 035802
- ApJ 801 (2015), 78

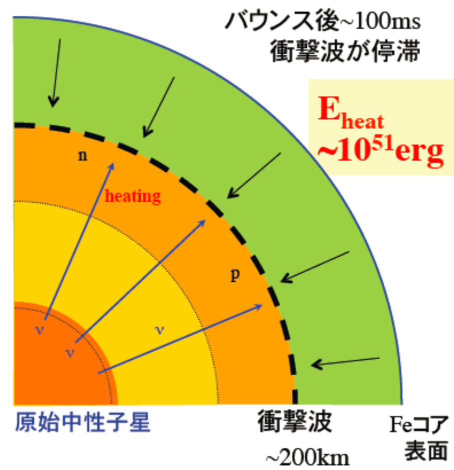
Semi-leptonic process for two nucleon system
micro-physics

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

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

Supernova explosion: cooling ニュートリノ生成
heating ニュートリノ吸収

neutrino transport eq.




住吉Lecture@理研　2014

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- 物質中の重陽子

## 軽元素のニュートリノ反応

従来考慮されてきたニュートリノ反応

核子＋代表的な原子核

核子

$$\nu_e + n \leftrightarrow e^- + p \qquad \nu + N \leftrightarrow \nu + N$$

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

原子核

$$\nu_e + A \leftrightarrow e^- + A' \qquad \nu + A \leftrightarrow \nu + A$$

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

neutrino-brems

電子

$$e^- + e^+ \leftrightarrow \nu + \bar{\nu} \qquad \nu_e + e \leftrightarrow \nu_e + e^-$$

S. W. Bruennm Astro. J. Suppl 58 (1985)771
A. Burrows,S. Reddy, T. Thompson, NPA777(2006),356.

# 軽元素のセミレプトニック過程

Heating due to nuclear excitation from NC reactions (4He, 12C,16O,56Fe)

W.C. Haxton PRL60(1988)1999

[ Role of Neutrino-4He on shock revival ]

N. Ohnishi,K.Kotake,S. Yamada Astrophys. J 667 (2007)375

Study of neutrino reaction rate on a few nucleon system

4He D. Gazit, N. Barnea PRL 98(2007)192591,PRC 70 (2004) 04880
t,3He E. O'Connor, D. Gazit, C.J.Horowiz, A.Schwenk,N.Barnea PRC75(2007)055803

T. Suzuki et al. PRC74 (2006) 034307, T. Yoshida et al. apj 686 (2008) 448, 4He, 12C (shell model)

What about Deuteron?

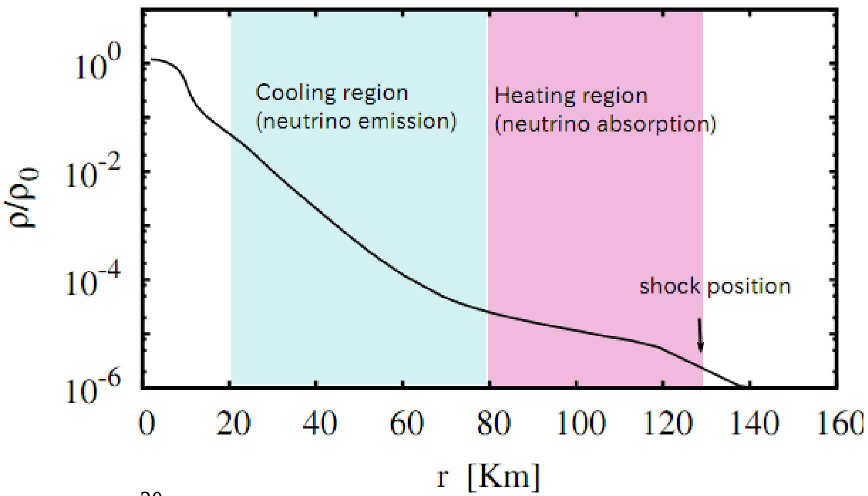
# 軽元素の存在

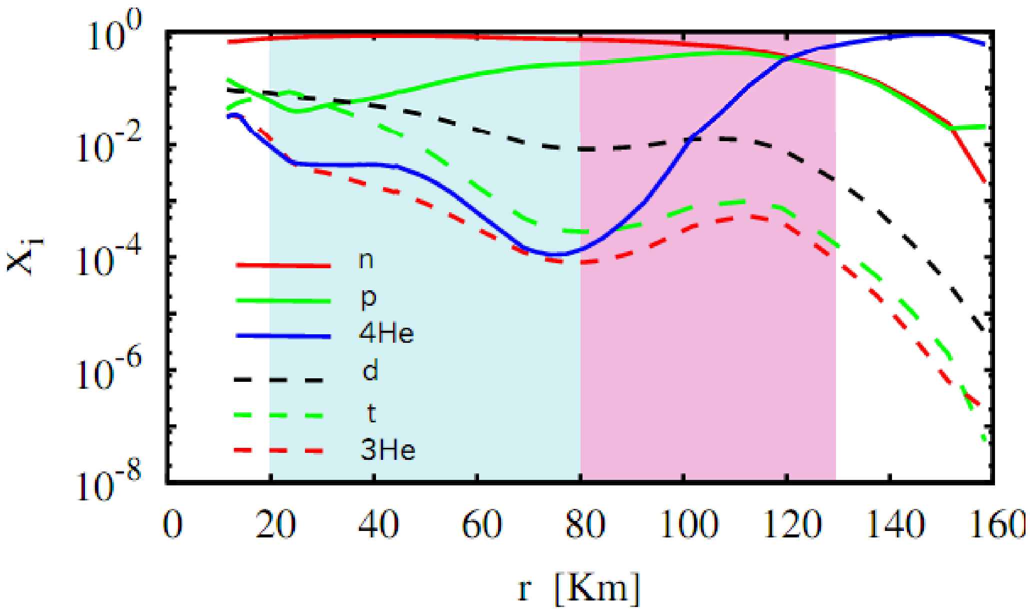
Sumiyoshi, Röpke, PRC 77, 055804 (2008)

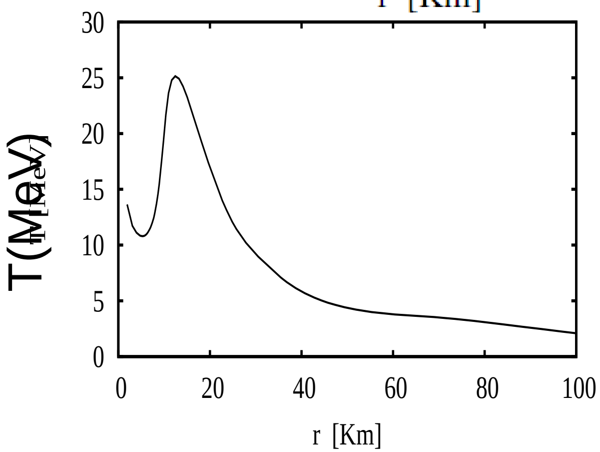
15 $M_\odot$ , 150 ms after core bounce

Nuclear statistical equilibrium assumed

cf. Arcones et al. PRC 78, 015806 (2008)




abundant appearance of d, triton, 3He, 4He

## I Neutrino absorption ( heating region)

S. Nakamura, K. Sumiyoshi, T. Sato (PRC80)

$$\nu + d \rightarrow N + N + l$$

Energy transfer cross section $< \sigma\omega >$

## II Neutrino production (cooling region)

S. Nasu, S. Nakamura, K. Sumiyoshi, F. Myhrer, K. Kubodera T. Sato(APJ 801)

$$e + d \rightarrow N + N + \nu \qquad N + N \rightarrow d + e + \nu$$

Neutrino emissivity $Q$

Important relevance to neutrino physics, astrophysics

- Supernova ($\nu$–heating, $\nu$–emission)
- $\nu$–oscillation experiment @ SNO
- Solar fusion (*pp*-chain)

# セミレプトニック過程の反応理論

$$< f(A_f, l_f)|H_W|i(A_i, l_i) >$$

Well established method for electroweak process in a few nucleon system

1) ‘exact’ nuclear state vector (A_f, A_i) from solution of Schrodinger eq.
with realistic NN interaction (ANLV18, Bonn, Nijmegen).

2) Low energy effective interaction.

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

Nuclear current tested by
photo-, electron-reactions, muon capture, beta decay

# 原子核弱電流

Vector and Axial vector current

$$J_\mu^x = V_\mu^x - A_\mu^x \quad (x = CC, NC)$$

Nuclear current consists of one-nucleon(IA) and many-body(MEC) current (effective current due to truncation of Fock-Space)

$$J_\mu^x = J_\mu^x(IA) + J_\mu^x(MEC)$$

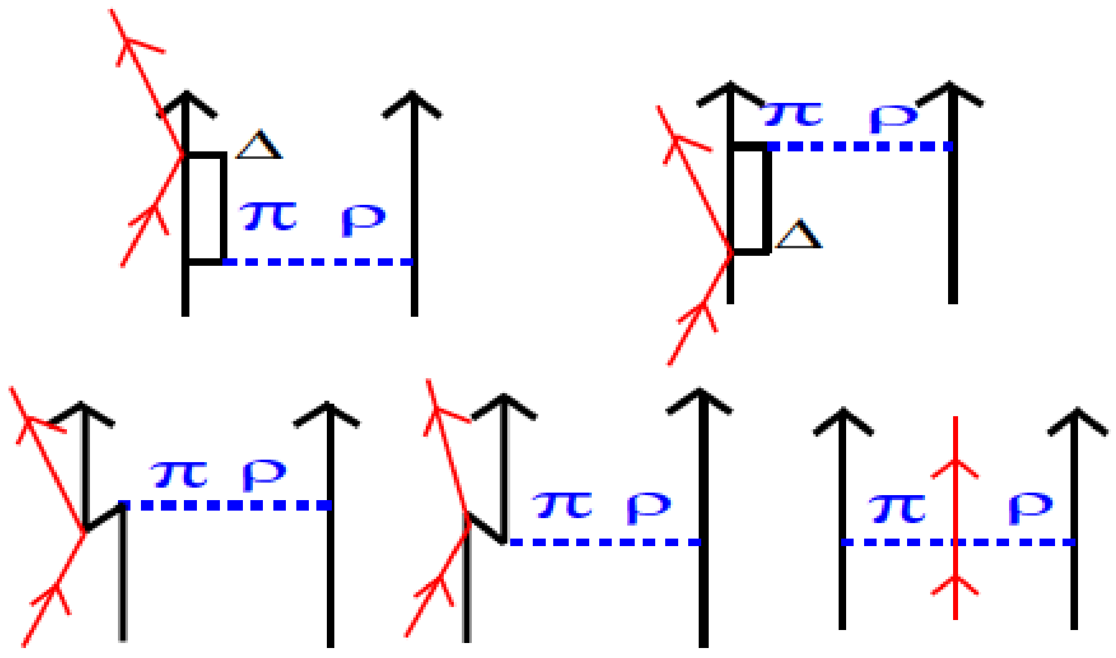
IA CC Current

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

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

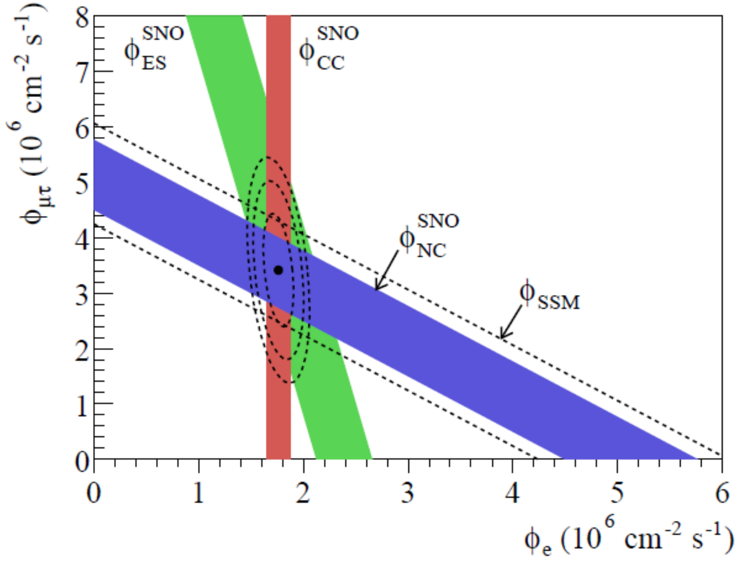
# Exchange axial-vector current

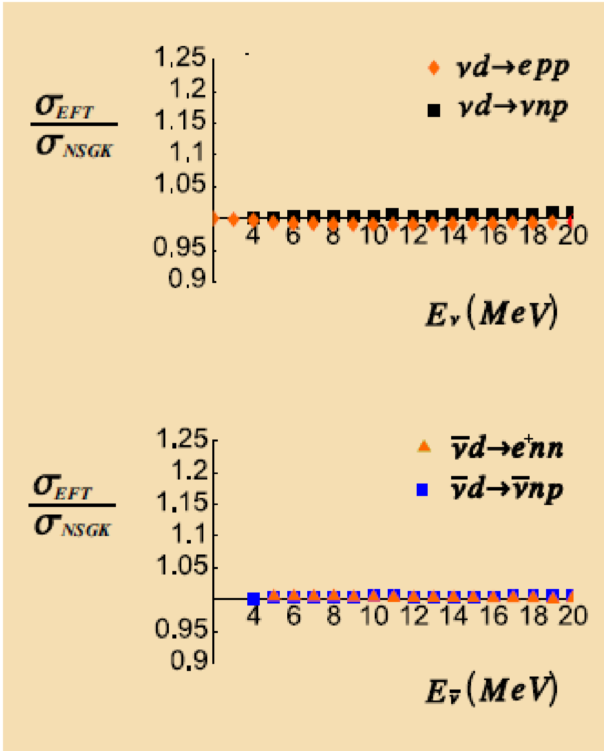
R. Schiavilla et al. PRC **58**, 1263 (1998)

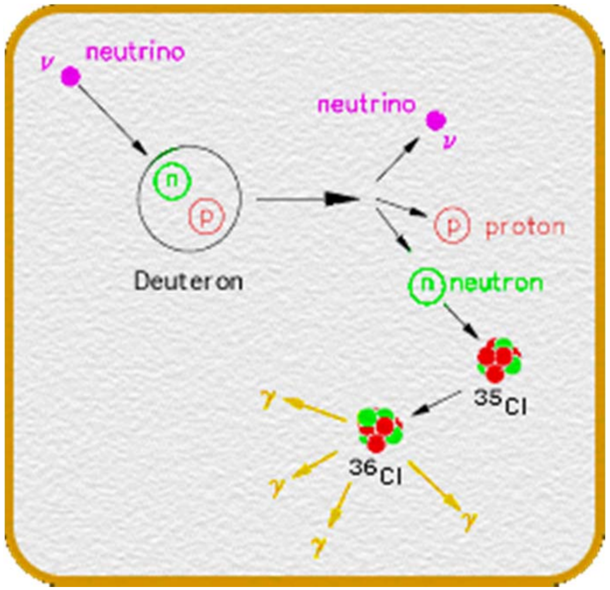


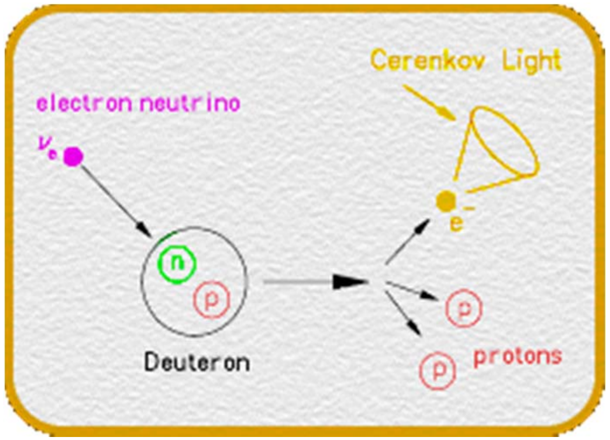

- Fit $AN\Delta$ coupling to tritium $\beta$-decay rate
- Rigorous three-body calculation

PRL 87(2001)071301, PRL 89(2002)011301,011302



# 加熱過程

CC

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

NC

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

## Contact of micro-physics with hydrodynamics, transport equation

Average energy transfer cross section

$$< \sigma^{CC} E_\nu > \; = \; \int dE_\nu \frac{N}{T_\nu^2} \frac{E_\nu^2}{e^{E_\nu/T_\nu}+1} \frac{d\sigma^{CC}}{dE_\nu} E_\nu$$

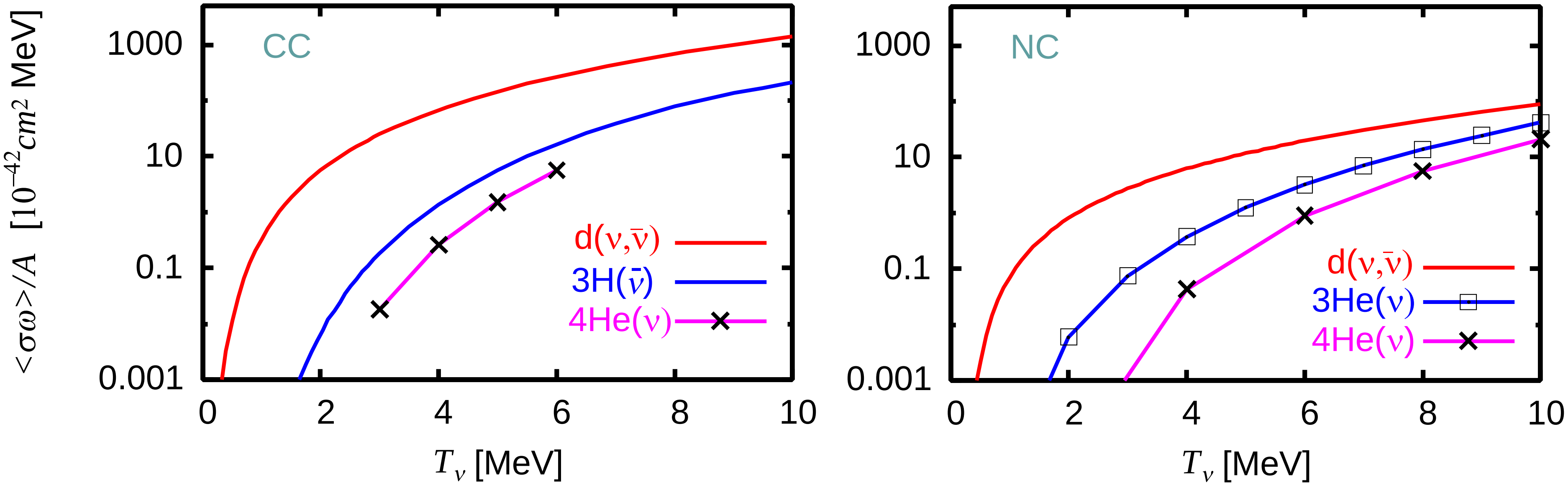
$$< \sigma^{NC} \omega > \; = \; < \sigma^{NC} \omega >_\nu + < \sigma^{NC} \omega >_{\bar{\nu}}$$

ニュートリノ加熱率

$$Q_\nu^A = \frac{\rho X_i}{m_u} \frac{L_\nu}{4\pi R^2} \frac{< \sigma^i E_\nu > / A}{< E_\nu >}$$

H. Bethe RMP 62 (1990)801, W. C. Haxton PRL 60(1988) 1999

# Thermal average of energy transfer cross sections




$*$ <  $\sigma\omega$ > for the deuteron is much larger than those of $^3$H, $^3$He, $^4$He

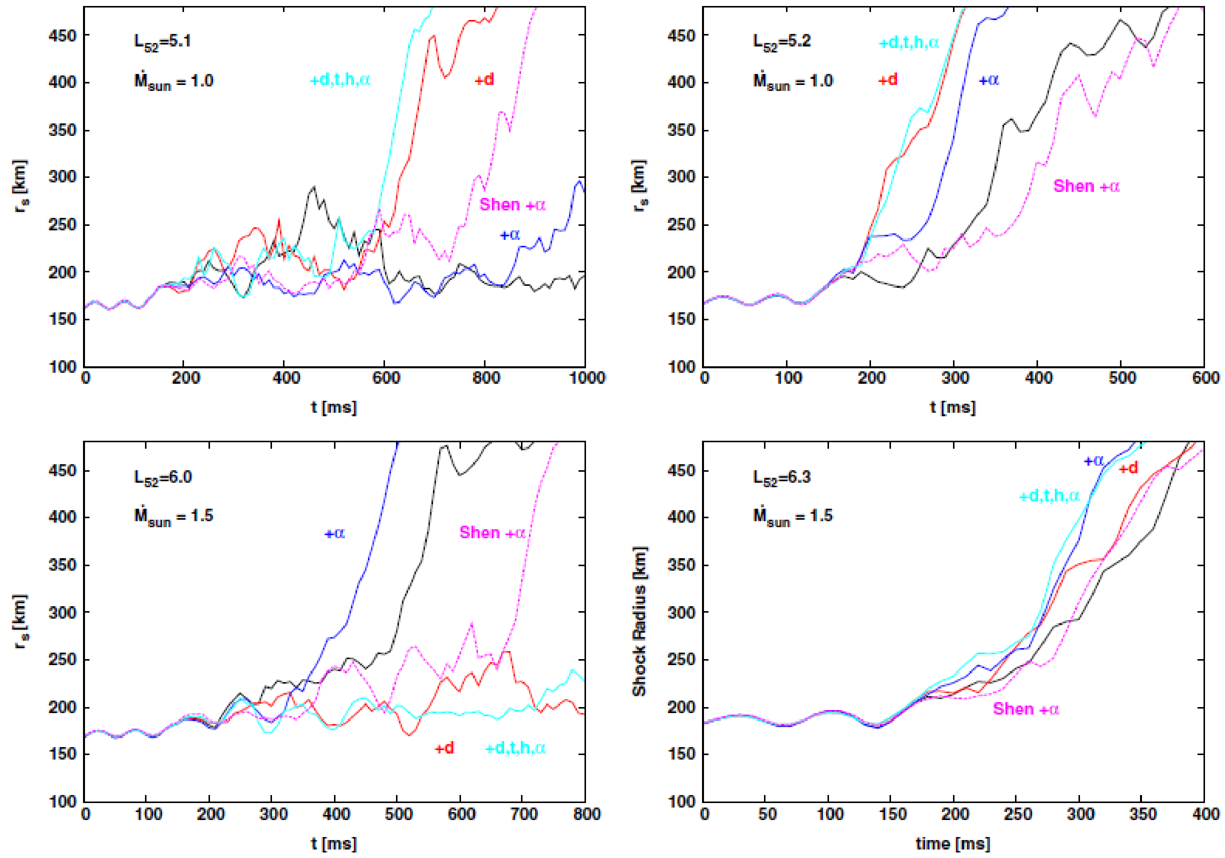
$*$ Small binding energy $\Rightarrow$ rapid increase of $<\sigma\omega>$ at low $T_\nu$

$*$ $<\sigma\omega>_{\nu_e d} \,/\, <\sigma\omega>_{\nu_e N} \sim$ 0.44 at $T_{\nu_e}$ = 5MeV

$*$ $<\sigma\omega>_{\nu_\mu d} \,/\, <\sigma\omega>_{\nu_e N} \sim$ 0.25 at $T_{\nu_e}$ = 5MeV and $T_{\nu_\mu}$ = 10MeV

# Influence of inelastic neutrino reactions with light nuclei

S. Furusawa, H. Nagakura, K. Sumiyoshi, S. Yamada, APJ774 (2013)81




Light nuclei affect favorably/unfavorably for shock revival
Non-negligible, but not dominant mechanism

# ニュートリノ冷却(生成反応)

Previous(A<_2)

$\ast$ $p + e^- \longrightarrow n + \nu_e$

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

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

$\ast$ $p + p \longrightarrow p + n + e^+ + \nu_e$

$\ast$ $N + N \longrightarrow N + N + \nu + \bar{\nu}$

New

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

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

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

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

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

emissivity Q

$$Q = \prod_{i,f}\left[\int \frac{d\mathbf{p}_{i,f}}{(2\pi)^3}\right](2\pi)^4\delta^{(4)}(p_f - p_i)\sum_{spin}|\langle f \mid \mathcal{H}_W \mid i\rangle|^2$$
$$\times E_\nu \prod_i f_i \prod_{f,\mathrm{fermion}} (1 - f_f)$$

Note: detailed balance can be used to relate emission and absorption

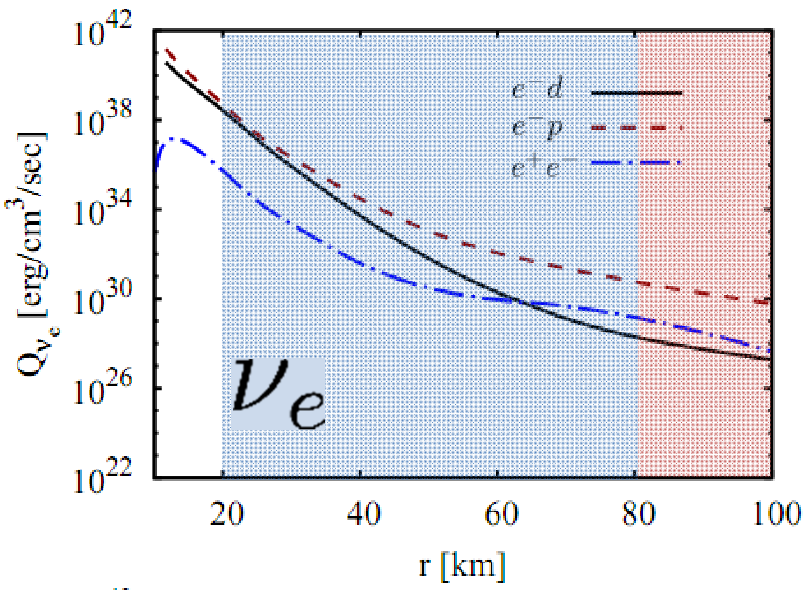
$$\nu_e + n \to e^- + p \qquad\Longleftrightarrow\qquad e^- + p \to \nu_e + n$$
$$\nu_e + d \to e^- + p + p \qquad\qquad e^- + p + p \to \nu_e + d$$

not

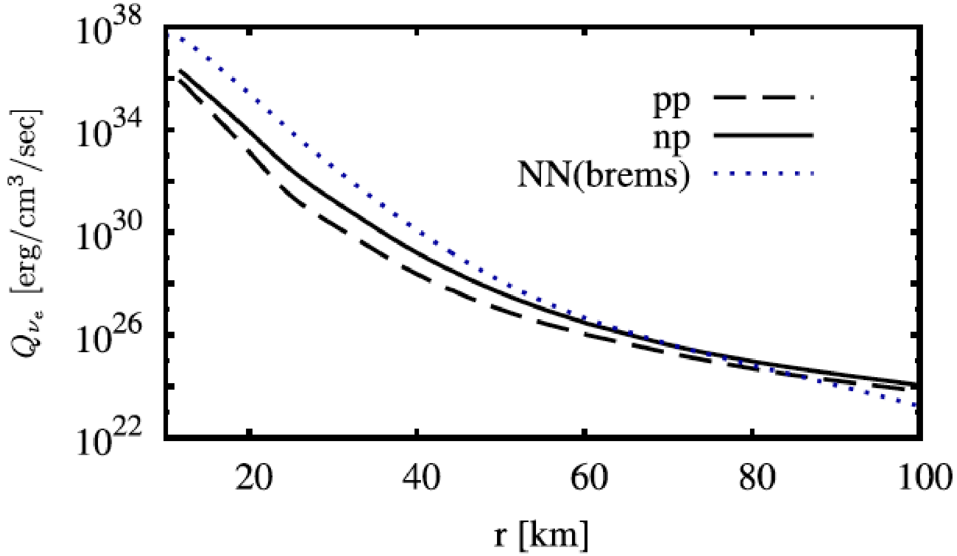
$$e^- + d \to \nu_e + n + n$$

# Neutrino emissivity

$e^-$ capture



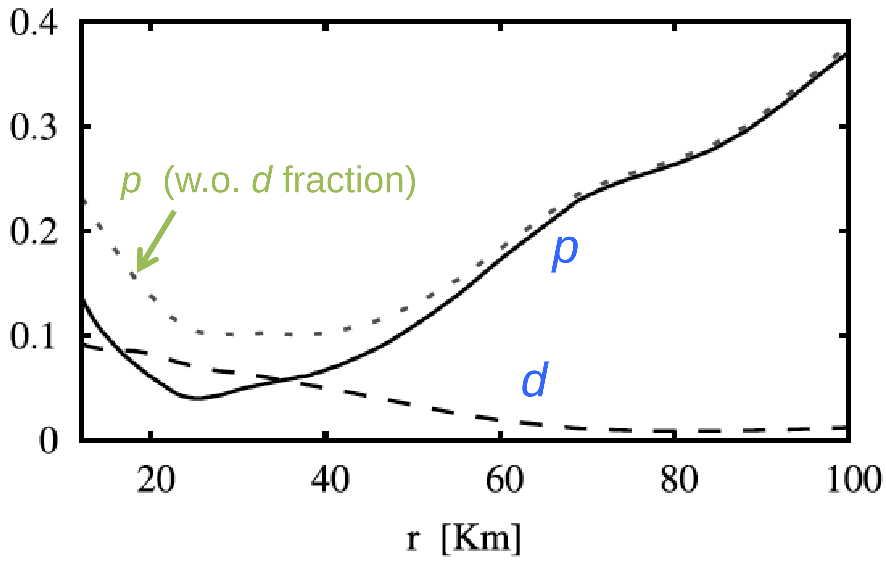

NN fusion



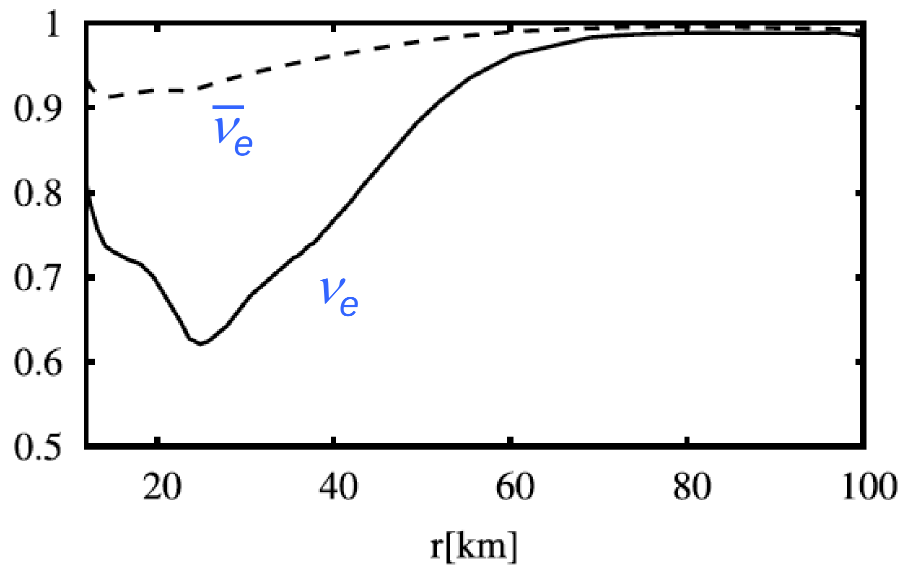

- Use profile (T,X_i, rho) of Sumiyoshi-Ropke at 150ms
- Electron capture on deuteron ~ proton
- NN-fusion can be comparable role as NN-brems

# Change of $\nu_e$ emissivity due to deuteron

Mass fraction



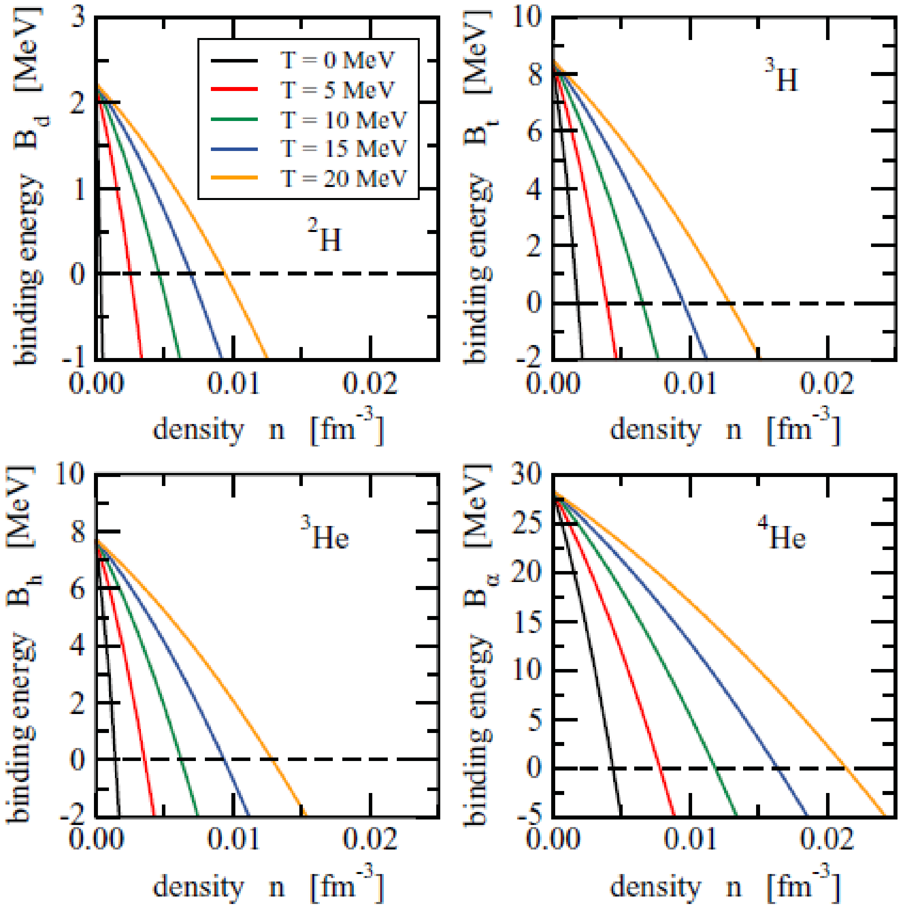

Q(N+d) / Q(N)




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

Effectively reduced $\nu_e$ emissivity

# 物質中の束縛状態




Binding energy of light cluster
in symmetric nuclear medium

S. Typel et al. PRC81 015803(2010)

In medium effective Lippmann-Schwinger Equation

$$T(\boldsymbol{p},\boldsymbol{p}',\boldsymbol{P},\omega+i\eta)=V(\boldsymbol{p},\boldsymbol{p}')+\int d^3q V(\boldsymbol{p},\boldsymbol{q})\mathcal{G}_2^0(\boldsymbol{q},\boldsymbol{P},\omega+i\eta)T(\boldsymbol{q},\boldsymbol{p}',\boldsymbol{P},\omega+i\eta).$$

$$\mathcal{G}_2^0(z)=\int_{-\infty}^{\infty}\frac{d\omega}{2\pi}\frac{d\omega'}{2\pi}\frac{1-f(\omega)-f(\omega')}{z-\omega-\omega'}A(\omega)A(\omega')$$

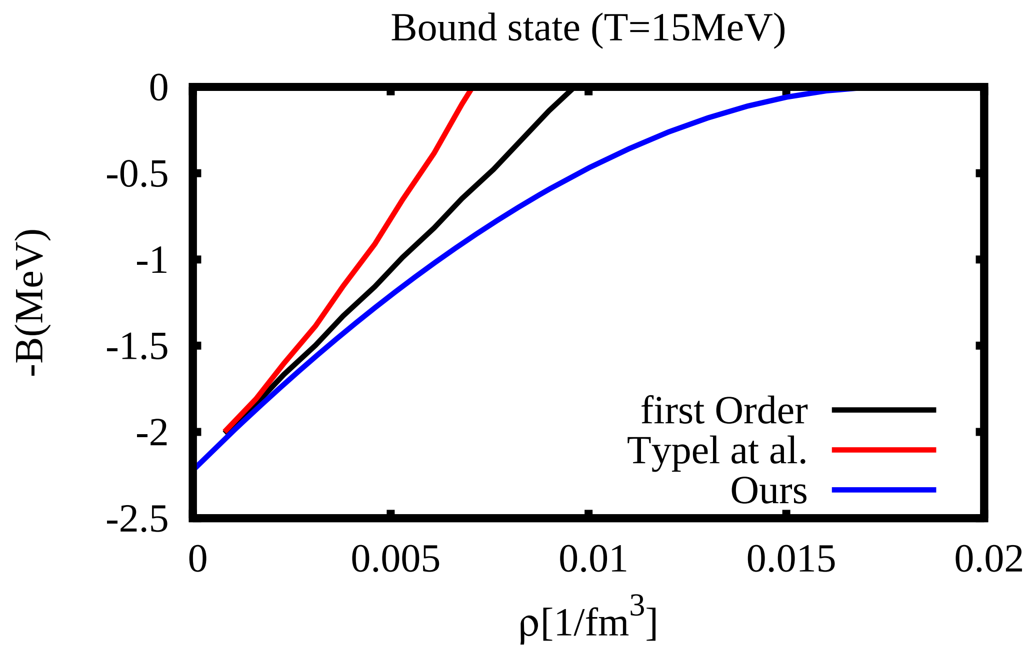
$$A(\boldsymbol{p}_1,\omega)=\frac{-2\mathrm{Im}\Sigma(\boldsymbol{p}_1,\omega+i\eta)}{\left[\omega-\frac{p_1^2}{2m}-\mathrm{Re}\Sigma(\boldsymbol{p}_1,\omega)\right]^2+[\mathrm{Im}\Sigma(\boldsymbol{p}_1,\omega+i\eta)]^2}$$

- Single particle spectrum in medium : quasi-particle approx.

$$Im\Sigma \rightarrow 0 \qquad A(p,\omega)\rightarrow 2\pi\delta(\omega-\frac{p^2}{2m}-Re\Sigma(p,E(p))$$

- Pauli on intermediate particles.
- Modification of NN interaction itself. (X)

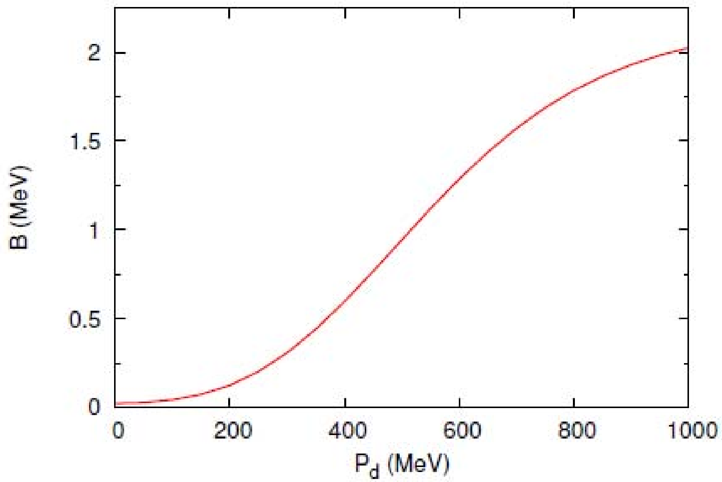
Density dependence of Bound state energy (P=0)



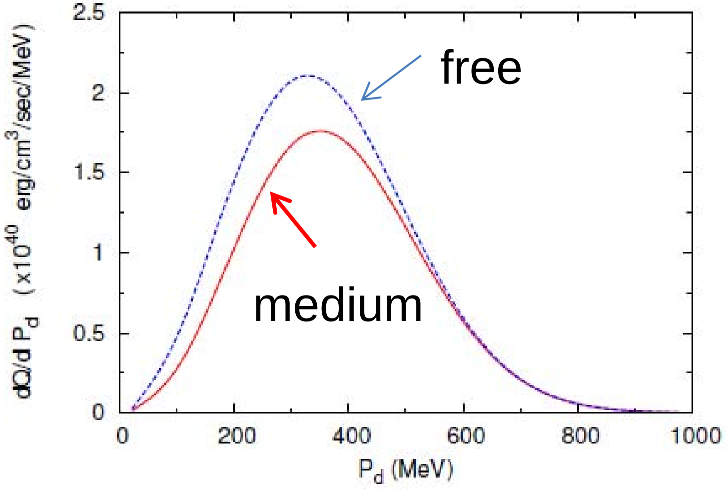

[核物質/10] 程度の密度で静止した重陽子は束縛しなくなる

Effects of medium on emissivity

Binding energy




emissivity




ANLV18 potential, including Pauli effect,
profile of S-R, at r=11.7km

# まとめ

- 重陽子が関与するニュートリノ生成、吸収率を微視的な電弱反応模型を用いて解析した。
- $< \sigma\omega >$ 重陽子＞＞4He, 3He,t、 核子の25-44%
- $Q$ 重陽子のニュートリノは核子の吸収率と同程度の大きさを持つ。Effectiveにニュートリノ放出率を減らす可能性もある。
- 重陽子の関与する反応率の「データ」を提供したい。

- 比較的物質密度が大きくなると、核物質におけるニュートリノ反応を再検討する必要がある。さらに一粒子過程、散乱状態への遷移の統一的な解析をしたい。
- 現在4Heにおけるニュートリノ吸収、生成率の解析はW. Horiuchi, M. Murata氏との共同で進行中である。

# 10th International Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region(NuInt15)

**日時：11月16日（月）～21日（土） (2015)**
**場所：大阪大学　吹田地区　銀杏会館**

ニュートリノ原子核相互作用に関する第10回国際会議、今回は低エネルギーニュートリノ原子核相互作用をテーマの一つに加える。

Long base line and atmospheric neutrino experiments and oscillation parameters
Confronting theory and experiment
Electron-nucleus reaction
CC and NC quasi-elastic neutrino-nucleus reaction
Pion production and other inelastic reactions
DIS and shallow inelastic reaction
Low energy neutrino-nucleus reaction
Future experiments
Path forward and future prospects

共催：新学術研究「ニュートリノフロンティアの融合と進化」
　　　Kavli Instiutute for Physics and Mathematics of the Universe

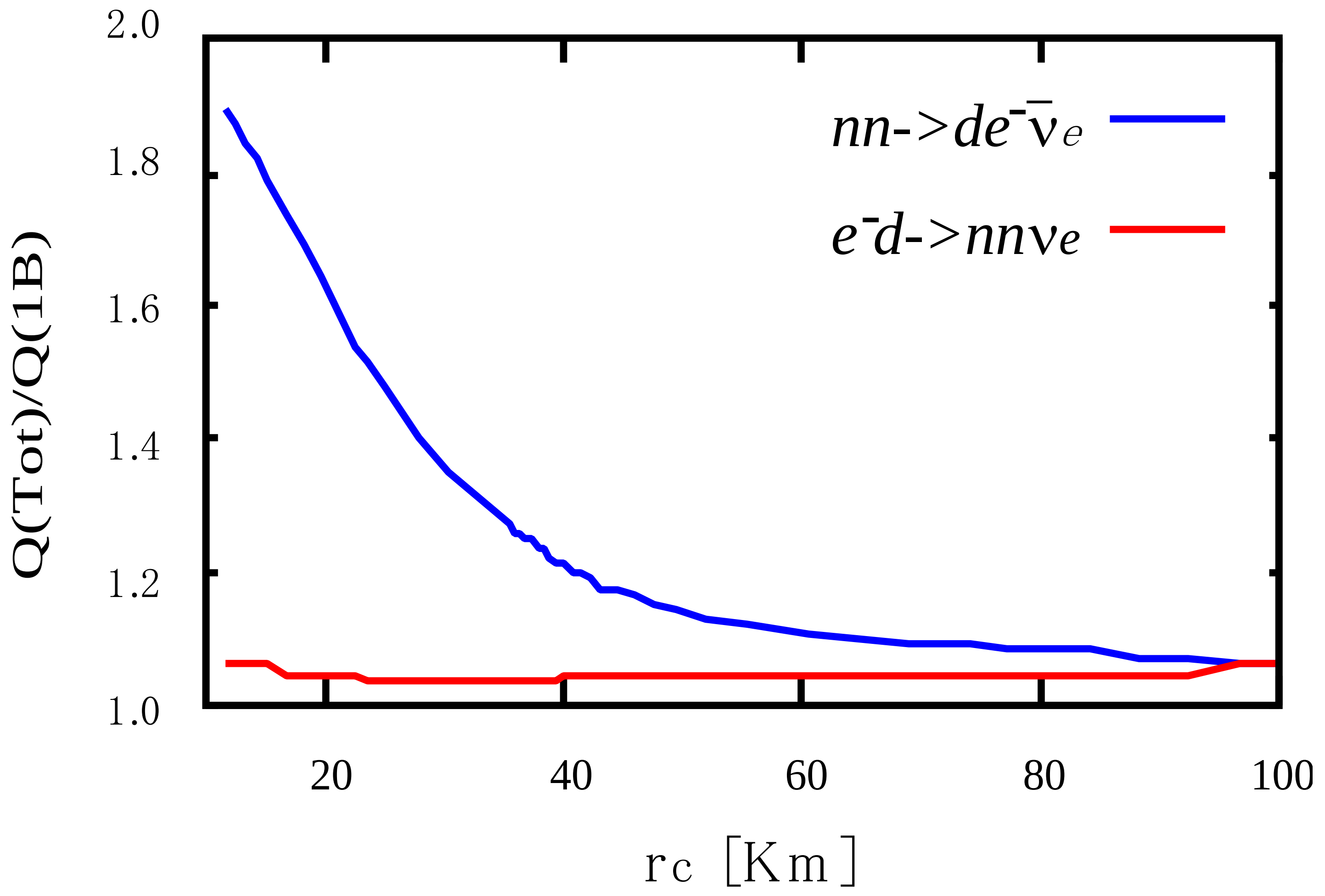
http://bit.ly/nuint15

# 第2回ニュートリノ反応国際スクールNuSTEC @岡山大学開催(11月8日—14日, 2015)

- 第1回NuSTEC (Neutrino Nucleus Scattering Theory and Experiment Collaboration)@FNAL ----- 90名の学生を集めた(右写真)。
  - ニュートリノ物理(ニュートリノ振動、宇宙物理)の発展にニュートリノ原子核反応開発は必須。
  - 博士修士学生、博士研究者対象にニュートリノ原子核反応の基礎を講義。
- 第2回目2015年11月16-21日NuInt15 (阪大)の前の週に、岡山大学で開催することはNuSTEC委員会で承認された。(主催:作田・小汐)
  - 低エネルギー原子核反応(超新星、2重ベータ崩壊)を加えたい。
- 協賛:新学術研究「地下素核研究」、岡山大学
- 学生さんへ参加よろしくお願いします。

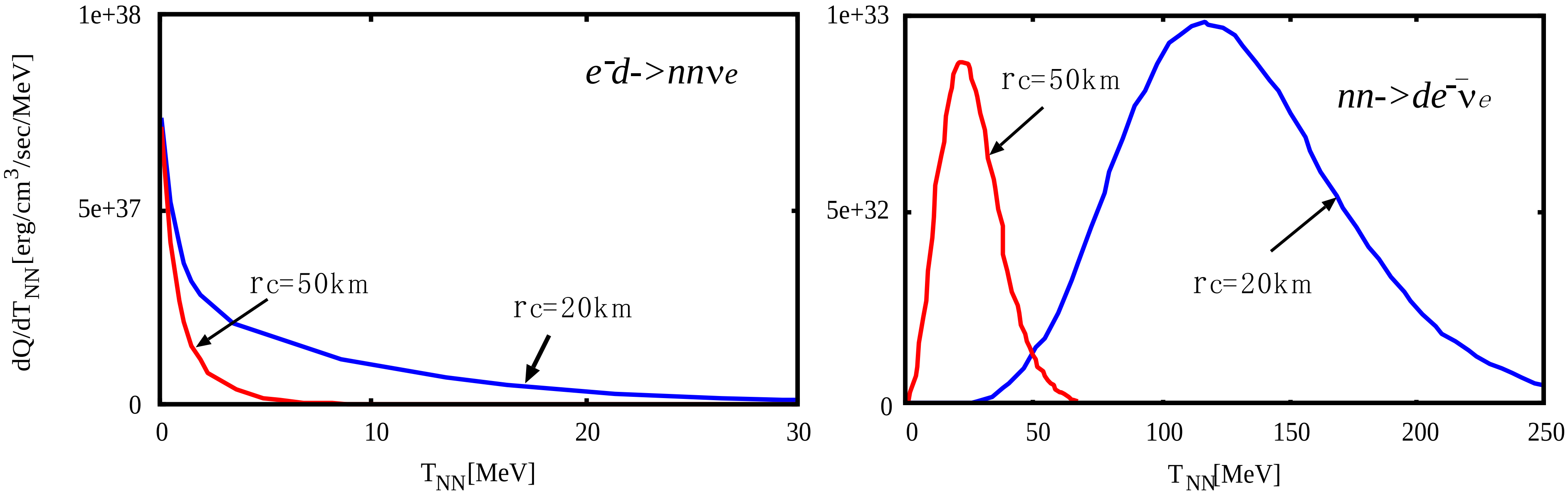
# Backups

# Meson exchange current effect on $Q$




Large effect on NN fusion !

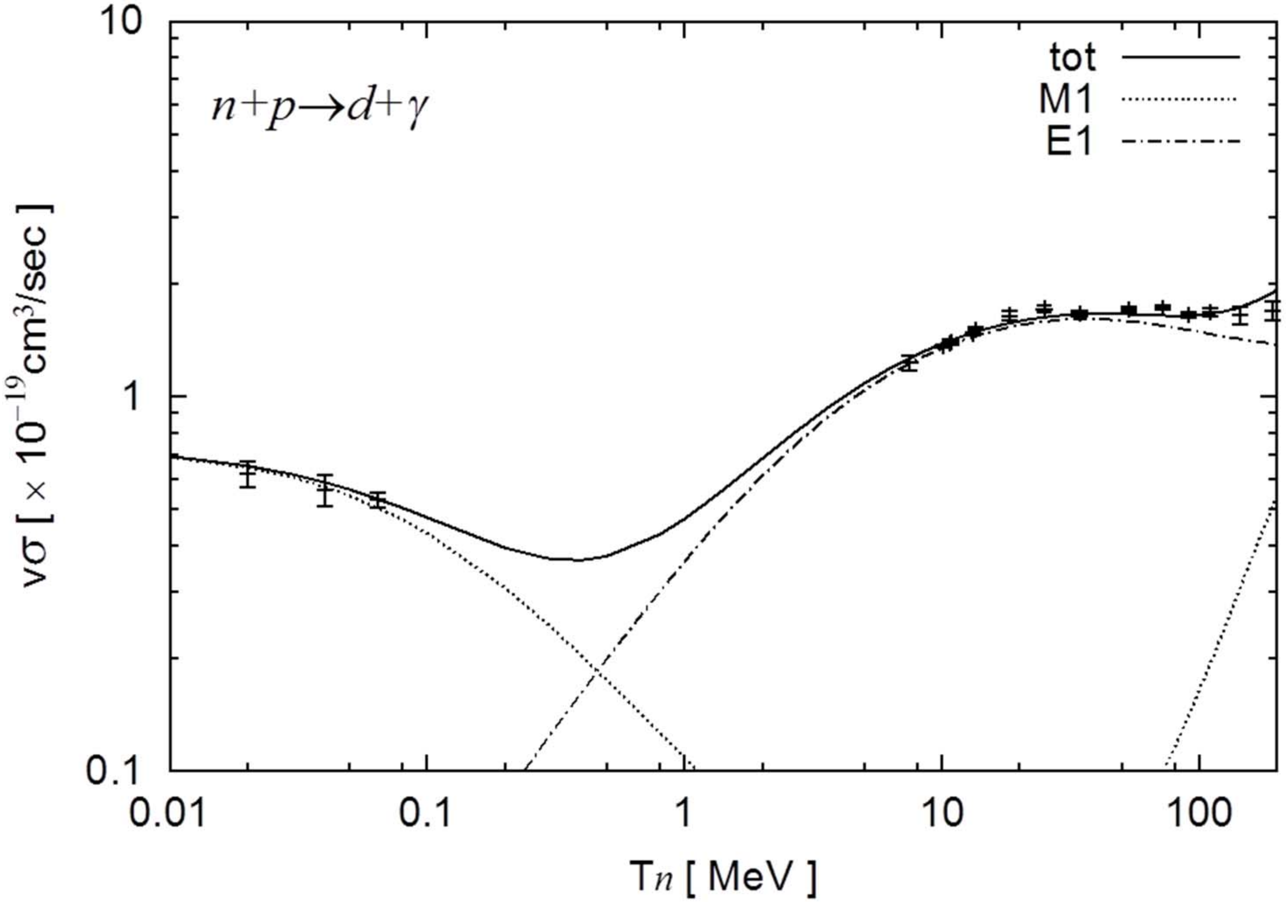
# Why so large meson exchange current effect ?




★ Higher NN kinetic energy causes large exchange current effect

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

# Comparison with $np \rightarrow d\gamma$ data



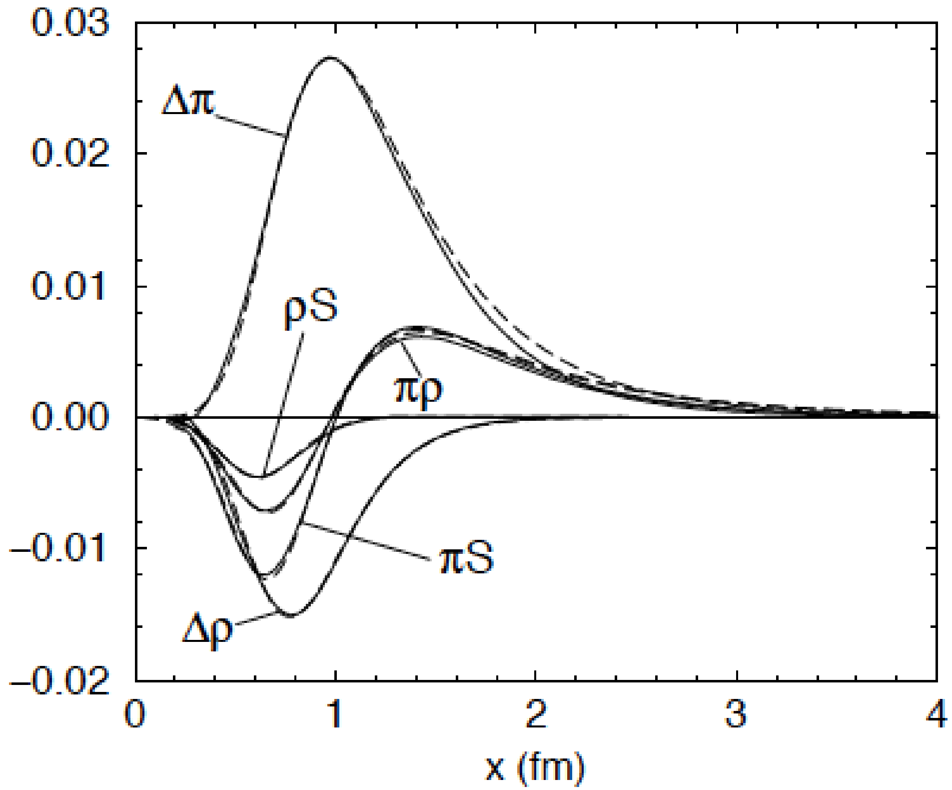

Exchange currents contribute about 10 %

## Why tritium $\beta$ decay?

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

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

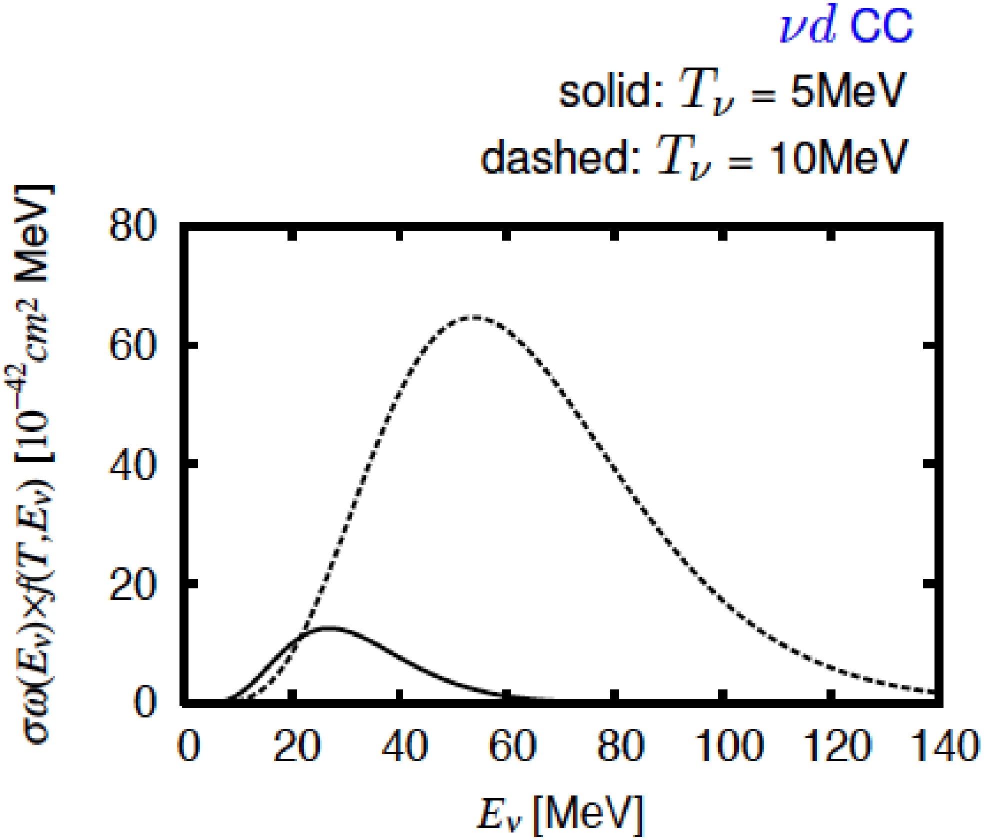
ρ(*x*) [fm$^{-1}$]




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

Schiavilla et al., PRC58,1263(1998)

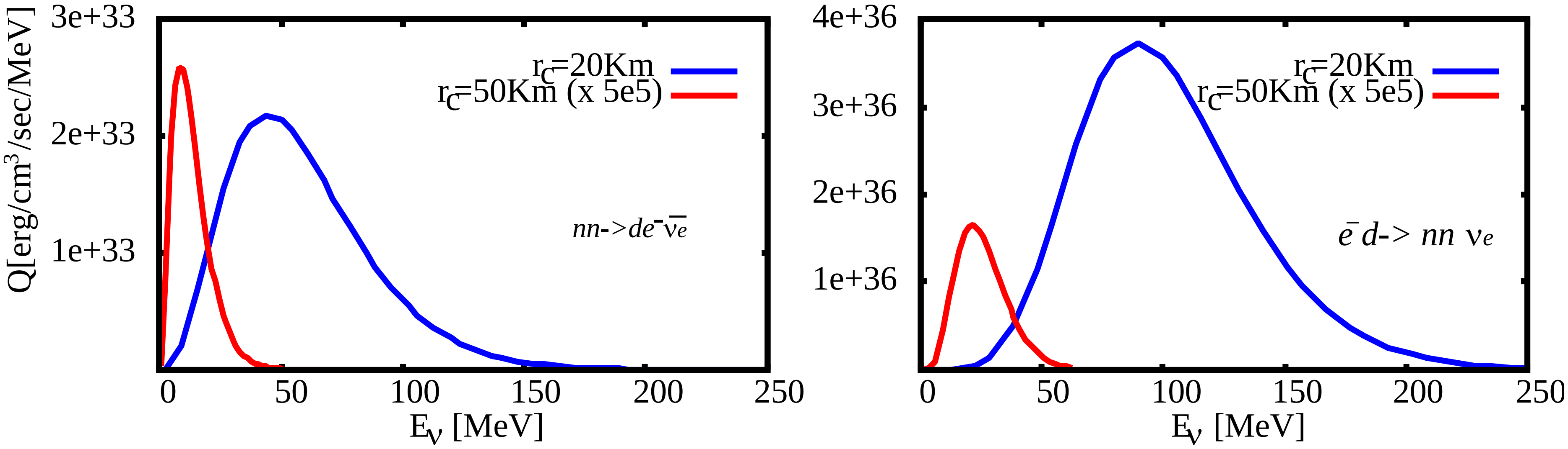
## $E_\nu$-dependence of energy transfer cross section




$*$ Main contribution is from $E_\nu$ = 20 (60) MeV for $T_\nu$ = 5 (10) MeV

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

# Neutrino spectrum



# 重力崩壊型超新星爆発

住吉Lecture＠理研　2014