ν-nucleus reactions on ^{13}C and ^{16}O at supernova energies

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ν-detection

Scintillator (CH, …), H_2O, Liquid-Ar, Fe

ν-^{12}C, ν- ^{13}C, ν-^{16}O, ν-^{56}Fe, ν- ^{40}Ar

Cross sections for various γ and particle emission channels

Detection of SNν and nucleosynthesis

ν-oscillation effects (MSW oscillations in SNe): dependence of charged-current reaction cross sections on ν mass hierarchy

ν- ^{13}C reactions
Suzuki, Balantekin, Kajino, and Chiba
J. Phys. G 46, 075103 (2019)

ν- ^{16}O reactions
Suzuki, Chiba, Yoshida, Takahashi, and Umeda,
Phys. Rev. C98, 034613 (2018)

Neutrino oscillations in ν- ^{16}O reactions
Nakazato, Suzuki, and Sakuda, PTEP 2018, 123E02 (2018)

● ν-nucleus reactions with new shell-model Hamiltonians

ν-^{12}C, ν- ^{13}C: **SFO** (p-shell; space p-sd)

Suzuki, Fujimoto, Otsuka, PR C69, (2003),

＊ important roles of tensor force → proper shell evolutions and change of magic numbers toward drip-lines

Otsuka, Suzuki, Fujimoto, Grawe, Akaishi, PRL 69 (2005)

- Spin responses of nuclei are quite well described.

GT strength in ^{12}C, ^{14}C; $O = g_A \sigma t_-$

Mag. mom. of p-shell nuclei; $\mu = g_s s + g_\ell \ell$

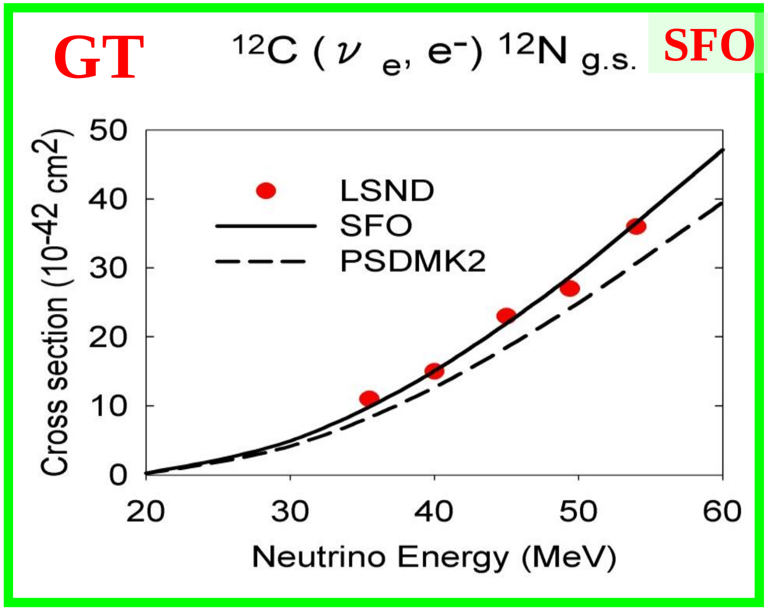
- **ν-nucleus reactions**

SFO: g_A^{eff}/g_A=0.95
B(GT: 12C)_cal = experiment

(ν, ν'), (ν_e, e^-) exclusive & inclusive
SFO reproduces DAR cross sections

Suzuki, Chiba, Yoshida, Kajino, Otsuka, PR C74, 034307, (2006).

LSND: PR C55, 2078 (1997)



▪ ν-induced reactions on ^{13}C

^{13}C: attractive target for very low energy ν

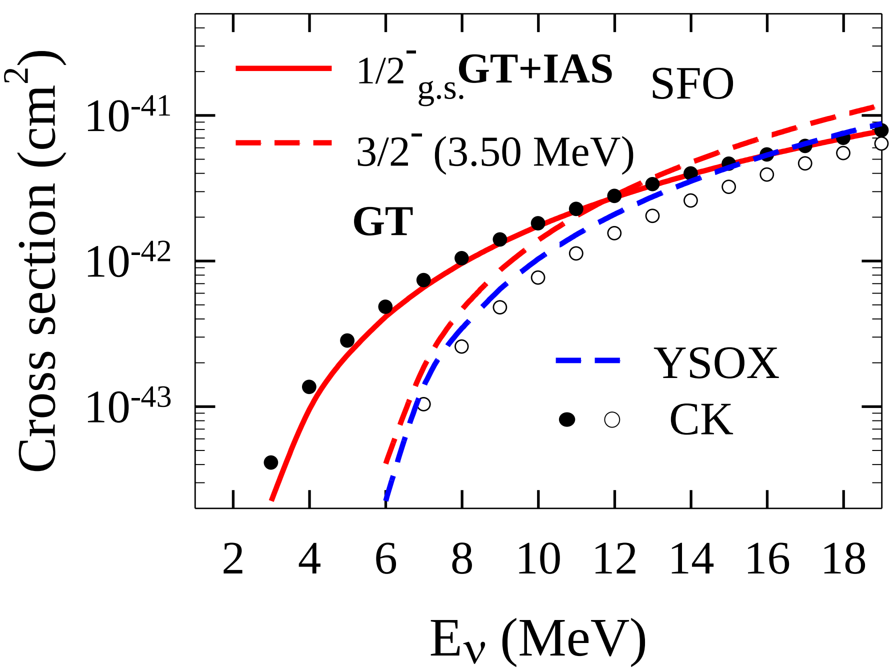
$E_\nu \leq 10\,\text{MeV} \quad E_\nu^{th}(^{12}C) \approx 13\,\text{MeV}$

reactor anti-ν

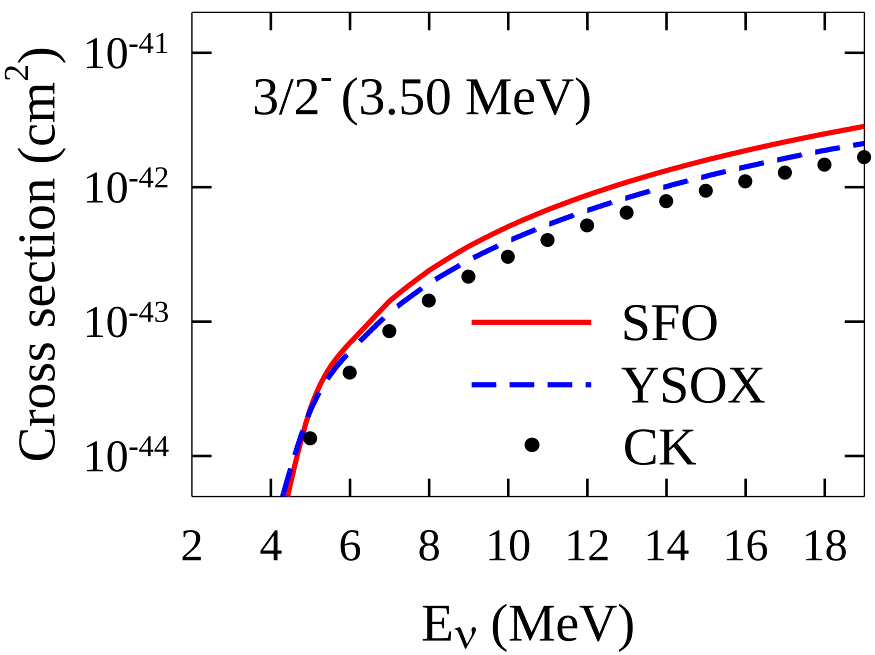
$\text{Natural isotope abundance} = 1.07\%$

Detector for solar ν (E<15MeV)
and reactor anti-ν (E< 8 MeV)

$^{13}C\ (\nu_e, e^-)\ ^{13}N$



$^{13}C\ (\bar{\nu}_e, \bar{\nu}_e')\ ^{13}C$



g_A^{eff}/g_A=0.95(SFO),0.85(YSOX)
0.69 (CK)

YSOX: Yuan, Suzuki, Otsuka et al., PR C85, 064324 (2012)

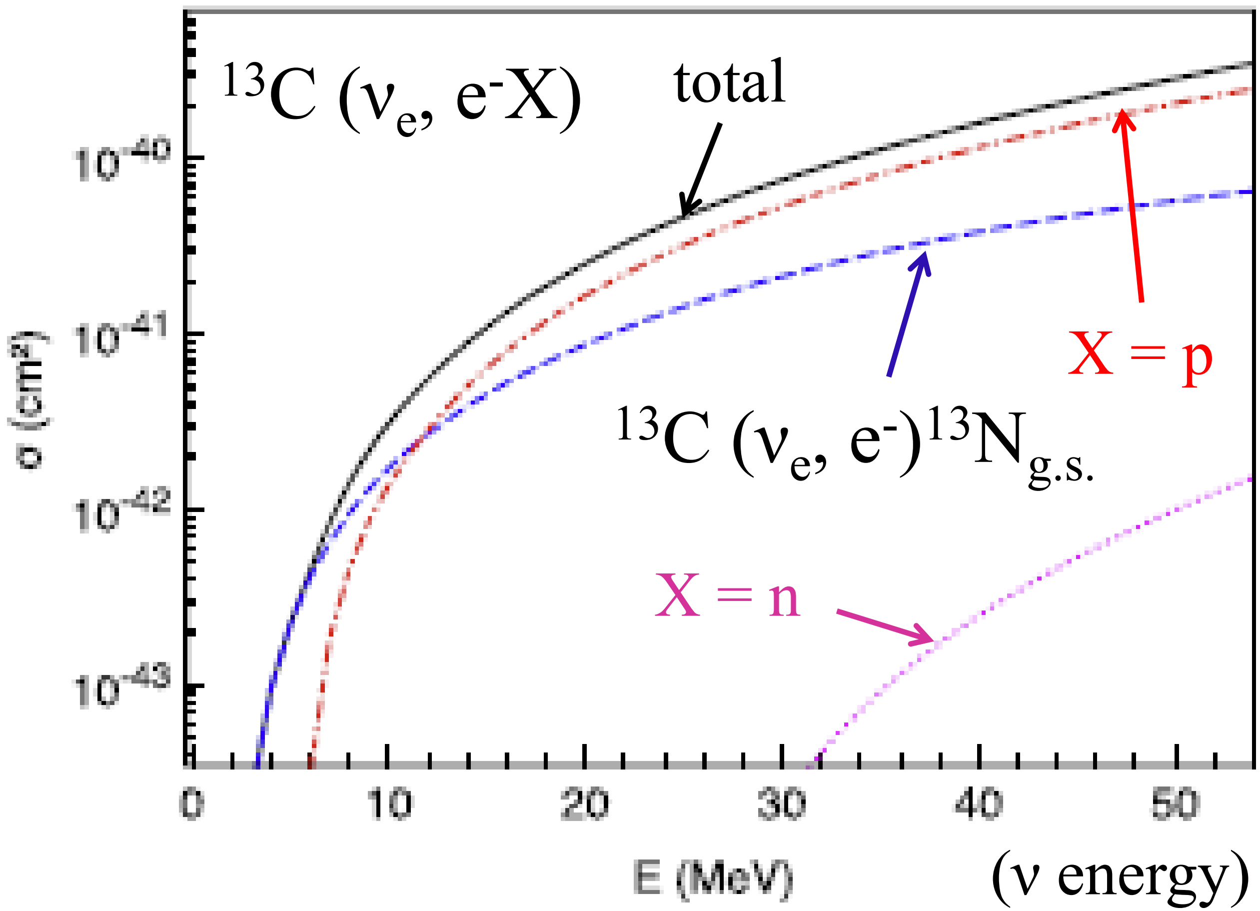
Suzuki, Balantekin, Kajino, PR C86, 015502 (2012)

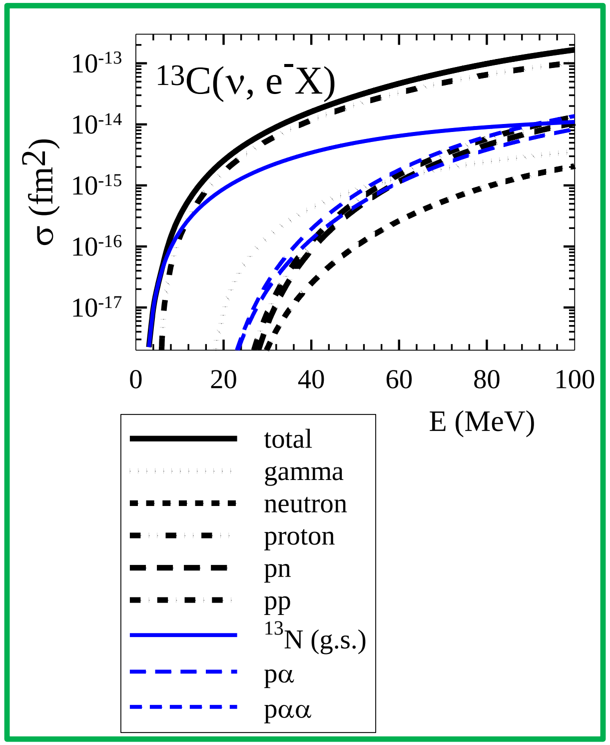
Charged-current cross sections at SN ν energies

Hauser-Feshbach statistical model

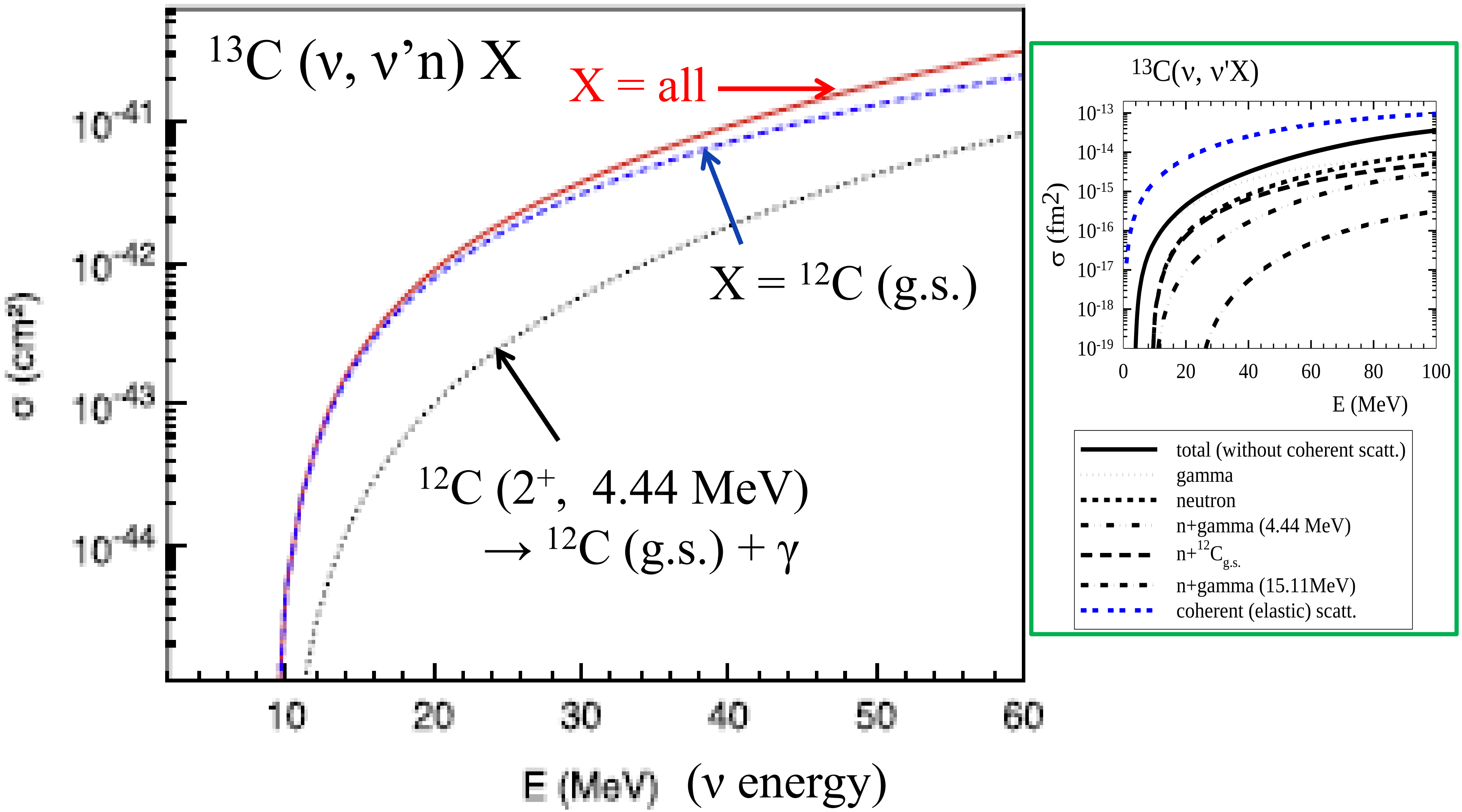
Branching ratios for γ and particle emission channels (with multi-particle emission channels): γ, n, p, np (d), nn, pp, ^{3}H (nnp), ^{3}He (npp), α, αp, αn, αnn, αnp, αpp, ...

Isospin conservation is taken into account (S. Chiba)





Neutral-current neutron-emission cross sections



Particle physics origin of the 5 MeV bump in the reactor antineutrino spectrum?

PHYSICAL REVIEW D **99,** 055045 (2019)

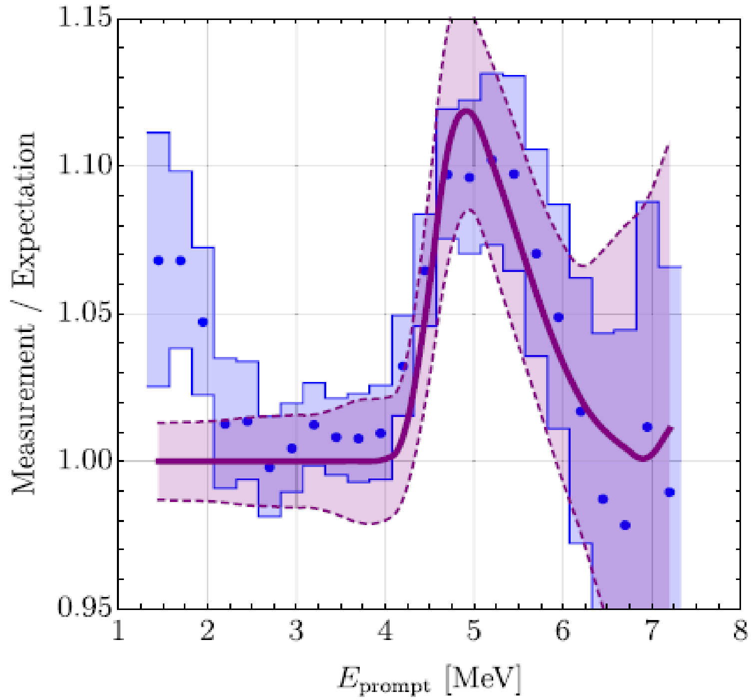


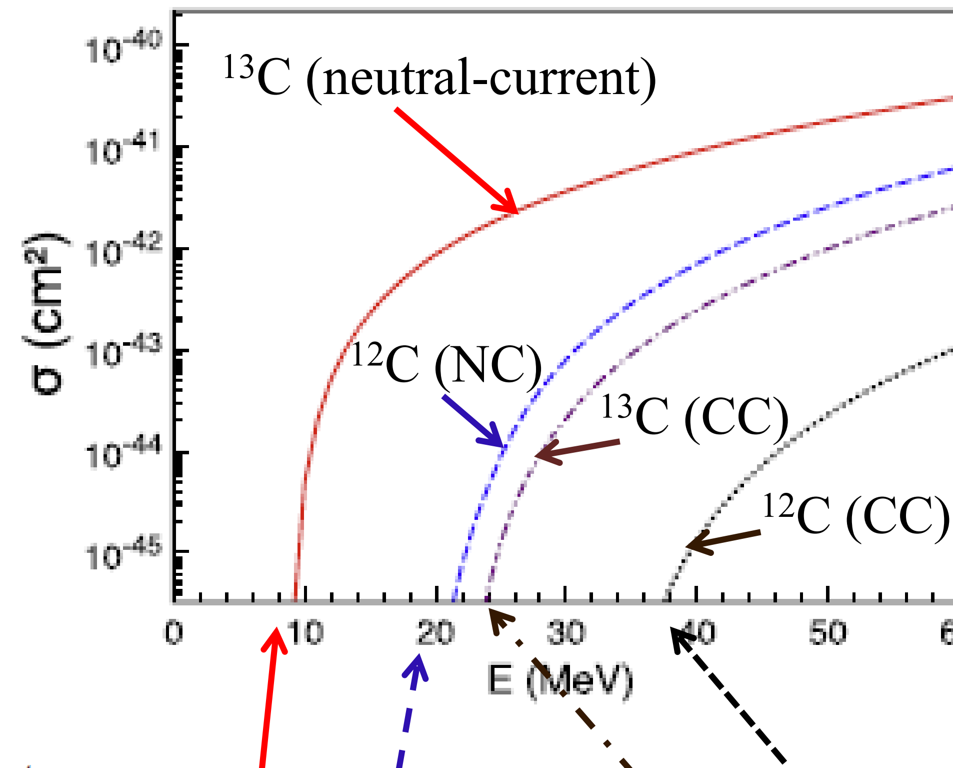
FIG. 1. The prompt energy spectrum corresponding to the best-fit point in Eq. (8). Only transitions to the first excited state of ^{12}C have been included. See text for details.

$^{13}C\ (\bar{\nu}, \bar{\nu}'n)\ ^{12}C\ (2^+, 4.44\ \text{MeV})$

$\rightarrow\ ^{12}C\ (\text{g.s.}) + \gamma$

E_{th} =9.4 MeV Reactor $\bar{\nu}$ with E ～ 16 MeV

Neutron-emission cross sections for $\nu_e - {}^{12}C$, ^{13}C reactions



E_{th} = 4.95, 18.72 MeV, 22.28, 32.38 MeV

The cross section for n emission with γ in the standard model is so small to make a bump in the reactor $\bar{\nu}$ spectrum.

Fallot et al, PRL 109 (2012)

Coherent (elastic) scattering on light target

Neutral current $A_\mu^s = V_\mu^s = 0$

$$J_\mu^{(0)} = A_\mu^3 + V_\mu^3 - 2\sin^2\theta_W J_\mu^\gamma$$

Vector part: $V_\mu^{(0)} = V_\mu^3 - 2\sin^2\theta_W J_\mu^\gamma$

C0: $(G_E^{IV} - 2\sin^2\theta_W G_E) < g.s. | j_0(qr) Y^{(0)} | g.s. >$

$$<=> \frac{1}{2} G_E^p (1 - 4\sin^2\theta_W)\rho_p(r) - \frac{1}{2} G_E^p \rho_n(r) \qquad (G_E^n \approx 0)$$

$$= -\frac{1}{2} G_E^p \{\rho_n(r) - 0.08\rho_p(r)\} \quad (\sin^2\theta_W = 0.23)$$

Probe of neutron density distribution

Patton, Engel, MacLaghlin, Schunck, PRC 86, 024612 (2012)

$$\frac{d\sigma}{dT}(E,T) = \frac{G_F^2}{2\pi} M \{2 - \frac{2T}{T_{max}} + \frac{T^2}{E^2}\} \frac{Q_W^2}{4} F^2(Q^2), \quad T_{max} = 2E^2/(2E+M)$$

$T = recoil\ energy$

$$Q_W = N - (1 - 4\sin^2\theta_W) Z$$

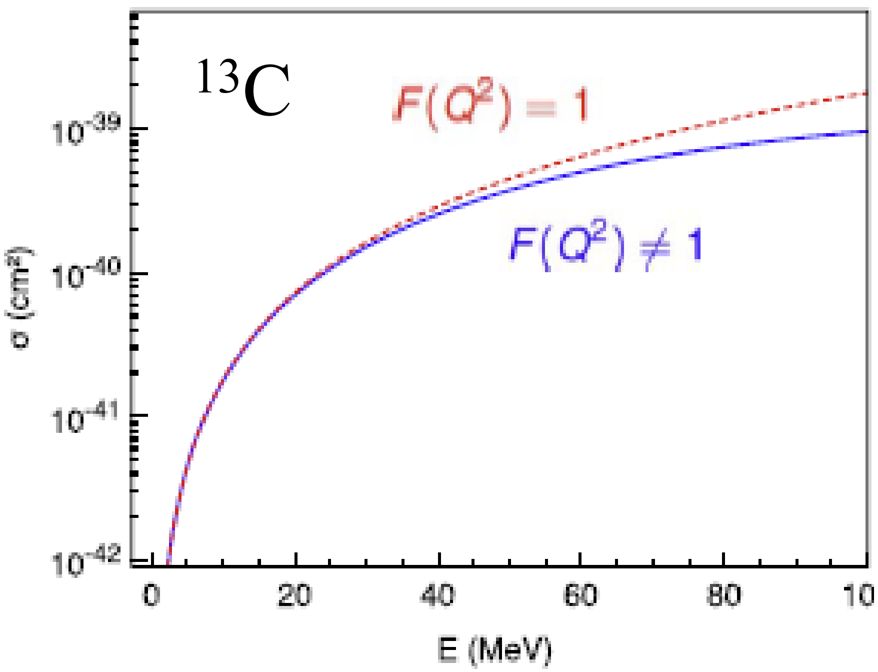
$$F(Q^2) = \{N F_n(Q^2) - (1 - 4\sin^2\theta_W) Z F_p(Q^2)\} / Q_W$$

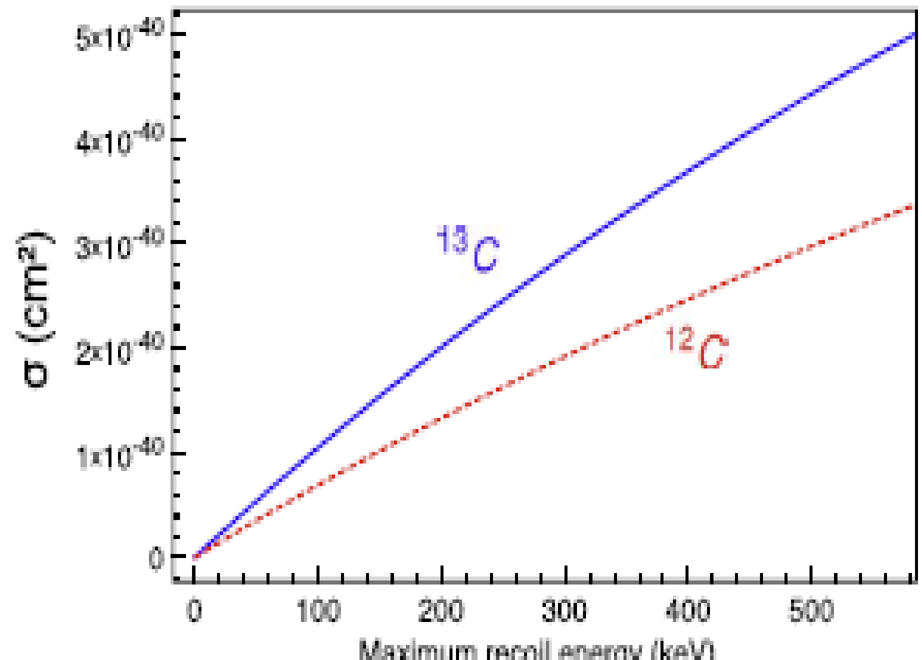
$$Q^2 = 2MT + T^2$$

$$F_{n,p}(Q^2) = \int r^2 j_0(Qr)\rho_{n,p}(r)dr$$

$$\sigma(E) = \int_0^{T_{\max}} dT \frac{d\sigma}{dT}(E,T)$$

Nuclear effects and Isotope dependence in coherent scattering

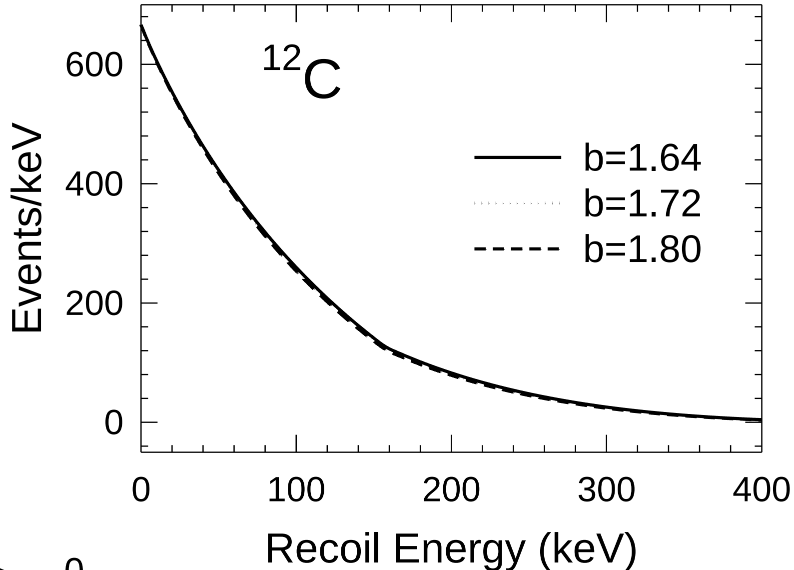


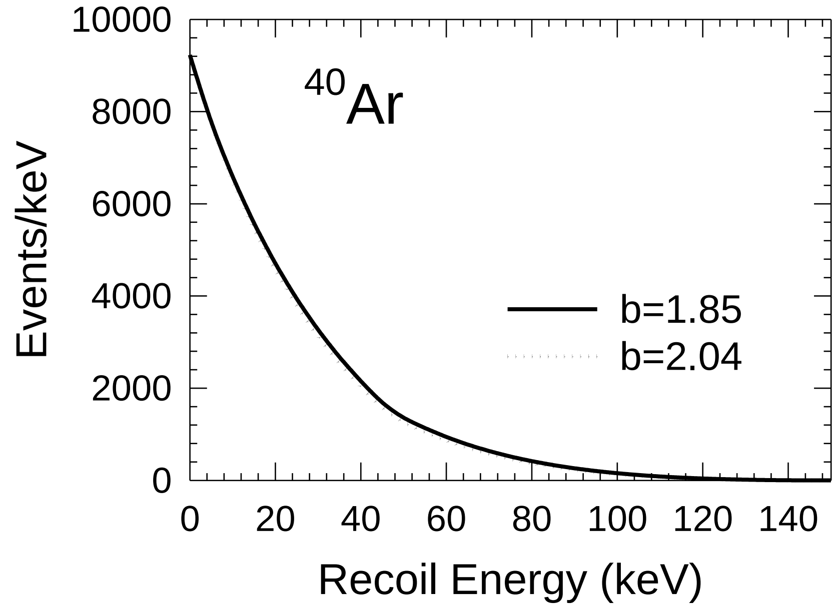


Events/keV - Recoil energy (keV)

DAR ν (3-flavors)

Φ= 3x10^7 /cm^2/s, 1year, target=1 ton

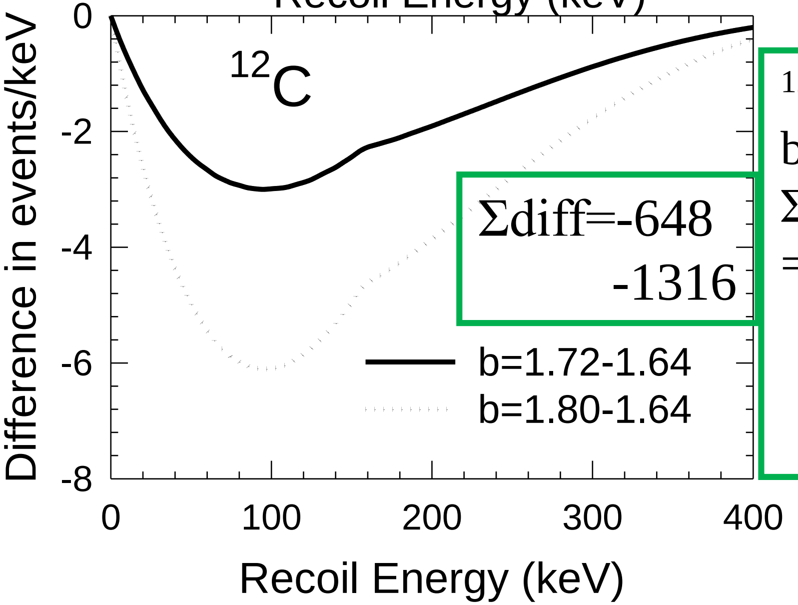




Σdiff=-8770

-2970 (T>50 keV)

-287 (T>100 keV)



^{12}C:

b=1.80-1.64

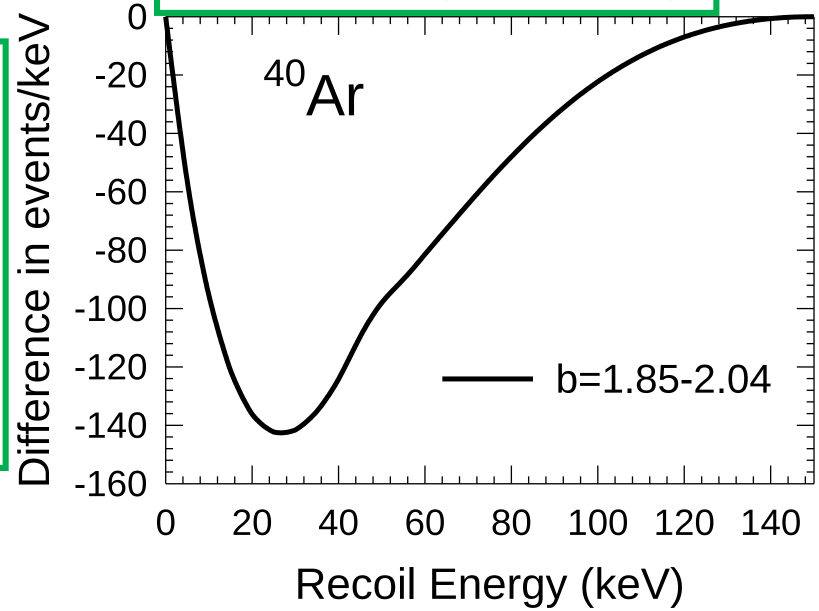
Σdiff

=-1158

(T >50 keV)

-867

(T>100 keV)



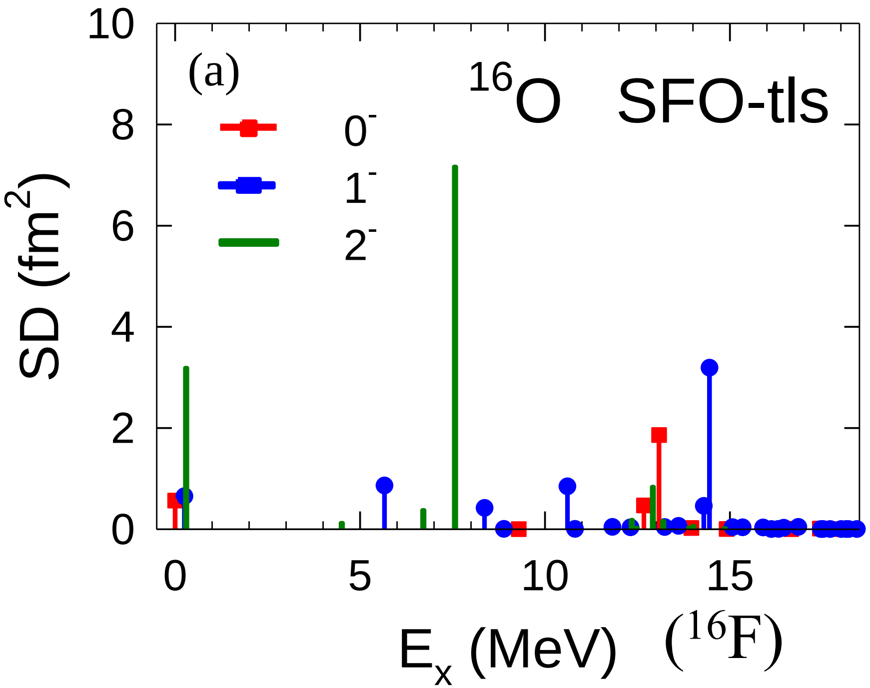
- **ν-induced reactions on ^{16}O**
- **Modification of SFO → SFO-tls**

  Full inclusion of tensor force

  - **p-sd: tensor-> π+ρ**

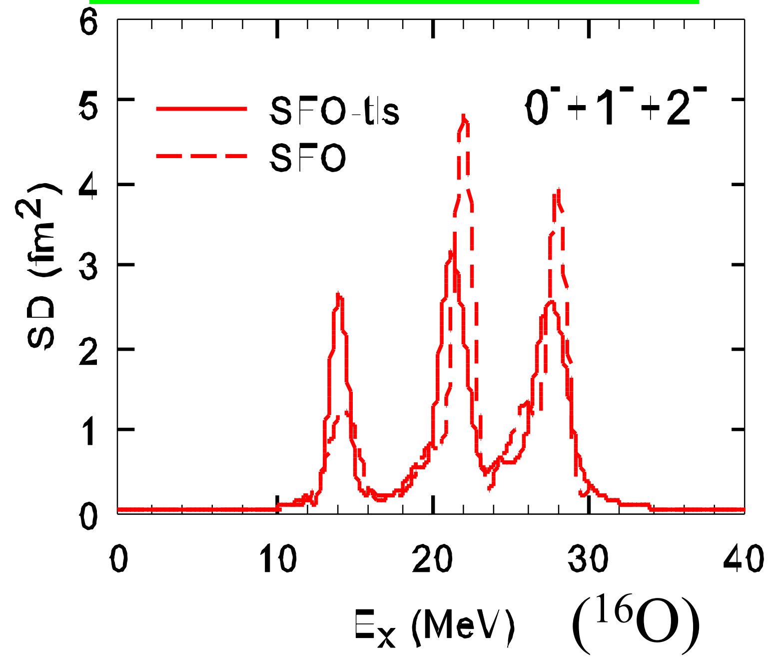
    LS -> σ+ρ+ω

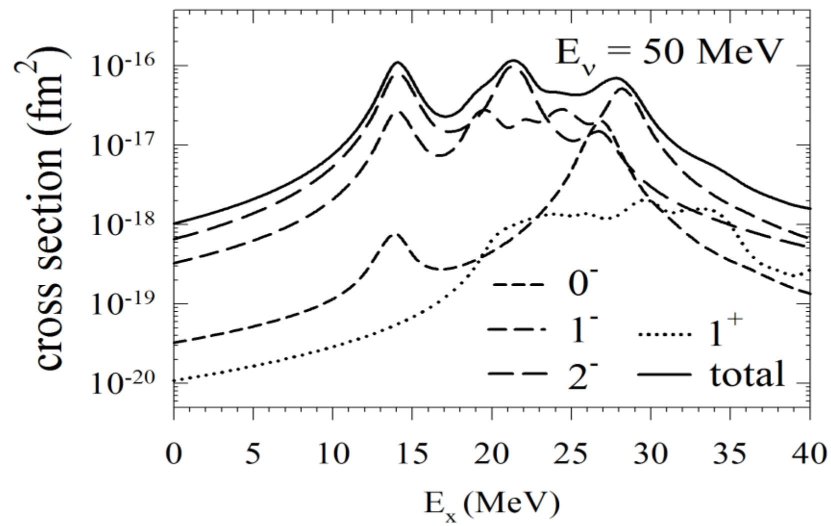
$$V = V_C + V_T + V_{LS}$$
$$V_T = V_\pi + V_\rho$$
$$V_{LS} = V_{\sigma+\omega+\rho}$$



Spin-dipole strength in ^{16}O

$$O(\lambda) = r[Y^1 \times \sigma]^\lambda t_-$$





Spin-dipole sum

$$B(SD\lambda)_{\mp} = \frac{1}{2J_i+1}\sum_f |< f \parallel S^{\lambda}_{\mp} \parallel i >|^2 \qquad S^{\lambda}_{\mp\mu} = r[Y^1 \times \vec{\sigma}]^{\lambda}_{\mu} t_{\mp}$$

NEWS-rule: $S^{\lambda}_{-} - S^{\lambda}_{+} = \langle 0 \mid [\hat{S}^{\lambda}_{-}, \hat{S}^{\lambda}_{+}] \mid 0 \rangle = \frac{2\lambda+1}{4\pi}(N\langle r^2\rangle_n - Z\langle r^2\rangle_p)$

Energy-weighted sum

$$EWS^{\lambda}_{\pm} = \sum_{\mu} |< \lambda, \mu \mid S^{\lambda}_{\pm\mu} \mid 0 >|^2 (E_{\lambda} - E_0),$$

$$EWS^{\lambda} = EWS^{\lambda}_{-} + EWS^{\lambda}_{+} = \frac{1}{2} < 0 \mid [S^{\lambda\dagger}_{-}, [H, S^{\lambda}_{-}]] + [[S^{\lambda\dagger}_{+}, H], S^{\lambda}_{+}] \mid 0 >$$

kinetic energy term (K) for $H = \frac{p^2}{2m}$

$$EWS^{\lambda}_{K} = \frac{3}{4\pi}(2\lambda+1)\frac{\hbar^2}{2m}A[1 + \frac{f_{\lambda}}{3A} < 0 \mid \sum_i \vec{\sigma}_i \cdot \vec{\ell}_i \mid 0 >]$$

= 0 for LS-closed core

$f_{\lambda} = 2$, 1 and -1 for $\lambda^{\pi} = 0^-$, 1^- and 2^-, respectively.

One-body spin-orbit potential term $\quad V_{LS} = -\xi \sum_i \vec{\ell}_i \cdot \vec{\sigma}_i,$

$$EWS^{\lambda}_{LS} = \frac{3}{4\pi}(2\lambda+1)\frac{f_{\lambda}}{3}\xi < 0 \mid \sum_i (r_i^2 + g_{\lambda} r_i^2 \vec{\ell}_i \cdot \vec{\sigma}_i) \mid 0 >$$

$g_{\lambda} = 1$ for $\lambda^{\pi} = 0^-$, 1^- and $g_{\lambda} = -7/5$ for $\lambda^{\pi} = 2^-$.

For N=Z, $EWS^{\lambda}_{-} = EWS^{\lambda}_{+}$, and $EWS^{2}_{-}/5 < EWS^{1}_{-}/3 < EWS^{0}_{-}$

Spin-dipole sum

$$S_\lambda(SD) = \sum_\mu |< \lambda,\mu \mid S^\lambda_{-,\mu} \mid 0 >|^2 = \begin{cases} \frac{3}{4\pi}4b^2 = 2.99\text{fm}^2 & \lambda^\pi = 0^- \\ \frac{3}{4\pi}12b^2 = 8.98\text{fm}^2 & \lambda^\pi = 1^- \\ \frac{3}{4\pi}20b^2 = 14.96\text{fm}^2 & \lambda^\pi = 2^- \end{cases}$$

$p \rightarrow sd$

$\propto 2\lambda+1$

EWS^λ_-	0^-	1^-	2^-	
K+LS	56.4	144.1	155.9	MeV·fm^2
SFO-tls (/(K+LS)	73.0 (1.29)	173.2 (1.20)	246.5 (1.58)	
SFO (/(K+LS)	76.1 (1.35)	175.0 (1.21)	258.2 (1.66)	

$\bar{E}_\lambda = EWS^\lambda_- / NEWS^\lambda_-$,	0^-	1^-	2^-	
SFO-tls	24.5	25.1	20.1	MeV
SFO	25.8	25.2	21.0	

Splitting of the strength comes from one-body LS term and two-body tensor interaction

Tensor interaction: attractive for 0^-, 2^-, & repulsive for 1^-

$$V_T(r) = F(r)\{[\sigma_1 \times \sigma_2]^{(2)} \times [r^2 Y_2(\hat{r})]^{(2)}\}^{(0)},$$

$$V_T(r) = F(r)\sum_\lambda \frac{\sqrt{4\pi}}{6}\left(\frac{10}{3}\right)^{1/2} \begin{Bmatrix} -2\sqrt{5} \\ \sqrt{15} \\ -1 \end{Bmatrix} \times \{r_1[\sigma_1 \times Y_1(\hat{r}_1)]^{(\lambda)}$$

$$\times r_2[\sigma_2 \times Y_1(\hat{r}_2)]^{(\lambda)}\}^{(0)}, \qquad \text{for } \lambda = \begin{Bmatrix} 0^- \\ 1^- \\ 2^- \end{Bmatrix}.$$

● μ-capture rate on ^{16}O and the quenching factor

The muon capture rate for $^{16}O\ (\mu, \nu_\mu)\ ^{16}N$ from the 1s Bohr atomic orbit

$$\omega_\mu = \frac{2G^2}{1+\nu/M_T} \mid \phi_{1s} \mid^2 \frac{1}{2J_i+1}\left(\sum_{J=0}^{\infty} \mid < J_f \parallel M_J - L_J \parallel J_i > \mid^2 + \mid < J_f \parallel T_J^{el} - T_J^{mag} \parallel J_i > \mid^2\right),$$

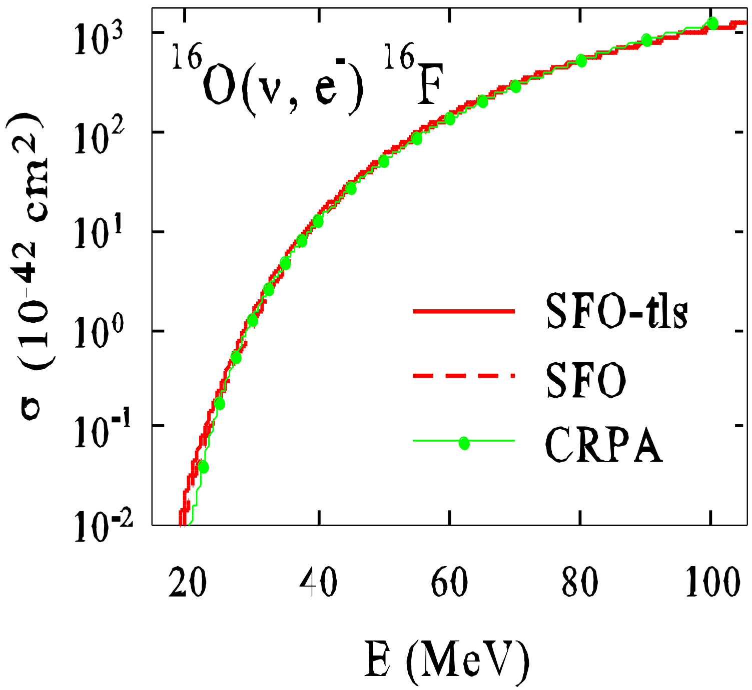
$$\mid \phi_{1s} \mid^2 = \frac{R}{\pi}\left(\frac{m_\mu M_T}{m_\mu + M_T} Z\alpha\right)^3 \qquad R = 0.79$$

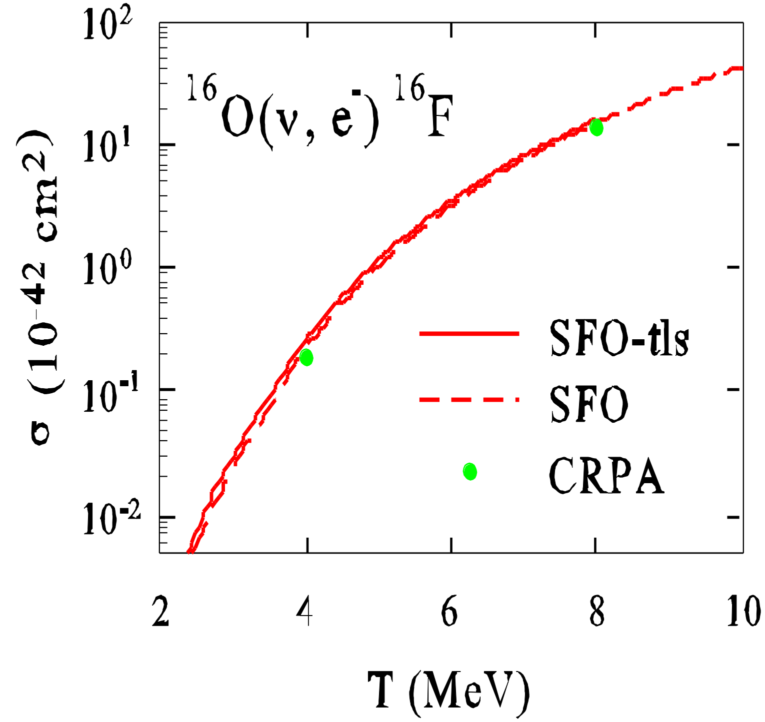
Induced pseudo-scalar current $F_P(q_\mu^2) = \frac{2M_N}{q_\mu^2 + m_\pi^2} F_A(q_\mu^2)$ Goldberger-Treiman

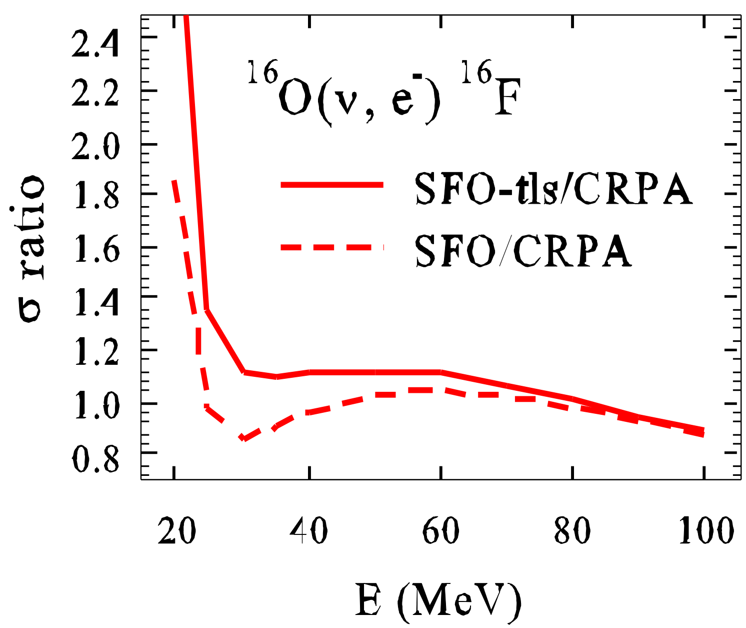
$$-2M_N F_A = \sqrt{2} g_\pi F_\pi$$

f $= g_A^{eff}/g_A = 0.95$

SFO	$10.21\times10^4\ s^{-1}$	(SFO/exp =0.995)
SFO-tls	$11.20\times10^4\ s^{-1}$	(SFO-tls/exp=1.092)
Exp.	$10.26\times10^4\ s^{-1}$	







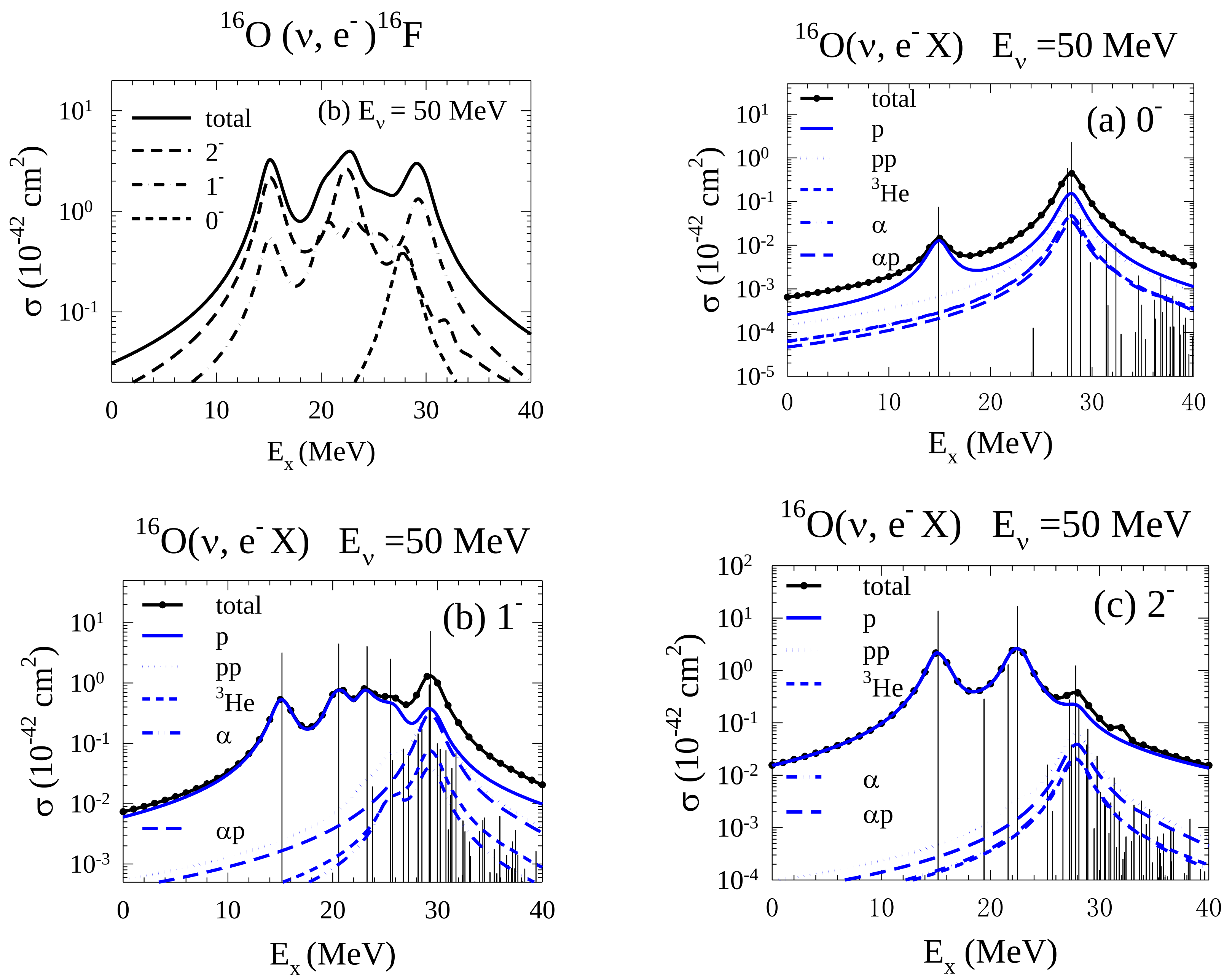
T= temperature of supernova ν

T	σ(SFO-tls)/σ(CRPA):
4	1.41
8	1.17

$\mathbf{g_A^{eff}/g_A=0.95}$

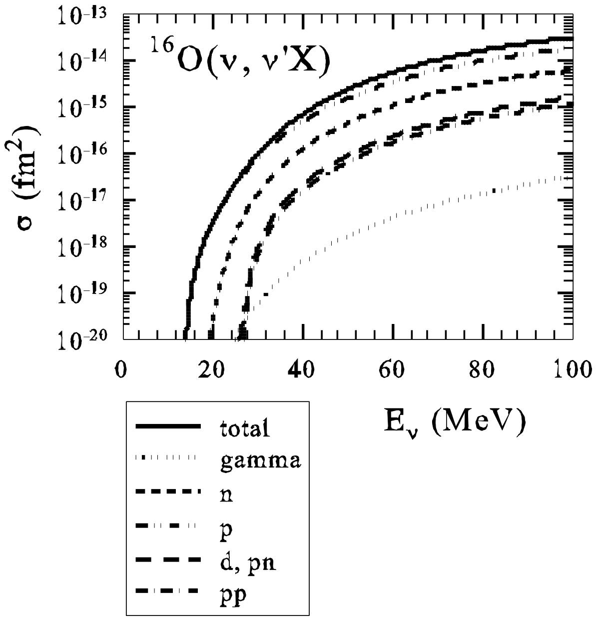
CRPA: Kolbe, Langanke & Vogel, PR D66 (2002)

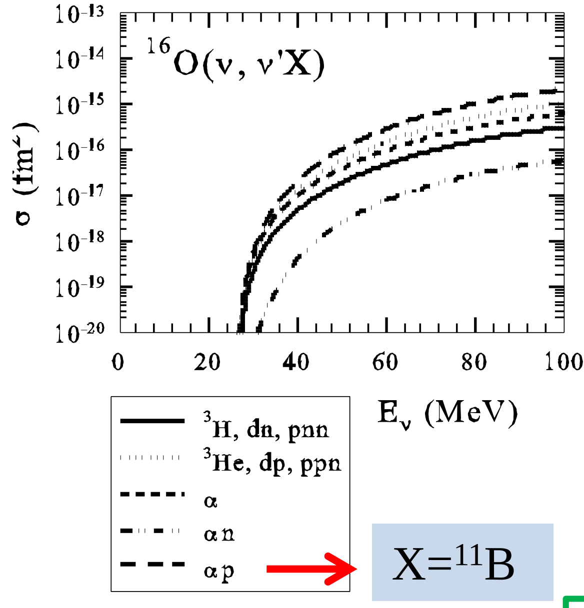
cf. CRPA: Jachowicz et al., PR C65 (2002)
RPA/QRPA: Lazauskas and Volpe, NP A792 (2007)

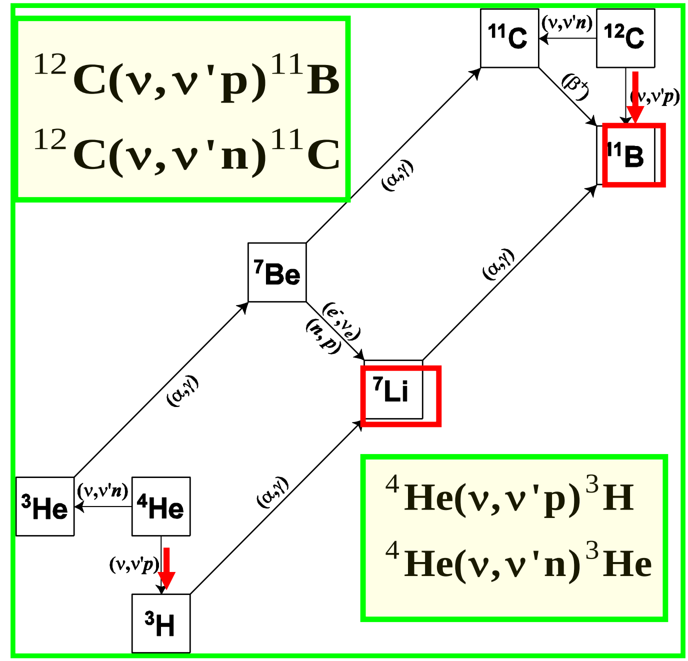


16O (ν, e-)16F
(b) Eν = 50 MeV
total
2-
1-
0-
σ (10-42 cm2)
Ex (MeV)
16O(ν, e- X) Eν =50 MeV
(a) 0-
total
p
pp
3He
α
αp
σ (10-42 cm2)
Ex (MeV)
16O(ν, e- X) Eν =50 MeV
(b) 1-
total
p
pp
3He
α
αp
σ (10-42 cm2)
Ex (MeV)
16O(ν, e- X) Eν =50 MeV
(c) 2-
total
p
pp
3He
α
αp
σ (10-42 cm2)
Ex (MeV)

Synthesis of ^{11}B and ^{11}C in SNe







$$\frac{\sigma(^{16}\mathrm{O}(\nu,\nu'\alpha p)^{11}\mathrm{B})}{\sigma(^{12}\mathrm{C}(\nu,\nu'p)^{11}\mathrm{B})} \approx 10\%$$

Case1: previous branches used in ^{16}O (γ, n, p, α-emissions) and HW92 cross sections
Case2: previous branches, and new cross sections
Case3: multi-particle branches and new cross sections

Production yields of ^{11}B and ^{11}C ($10^{-7}M_\odot$)

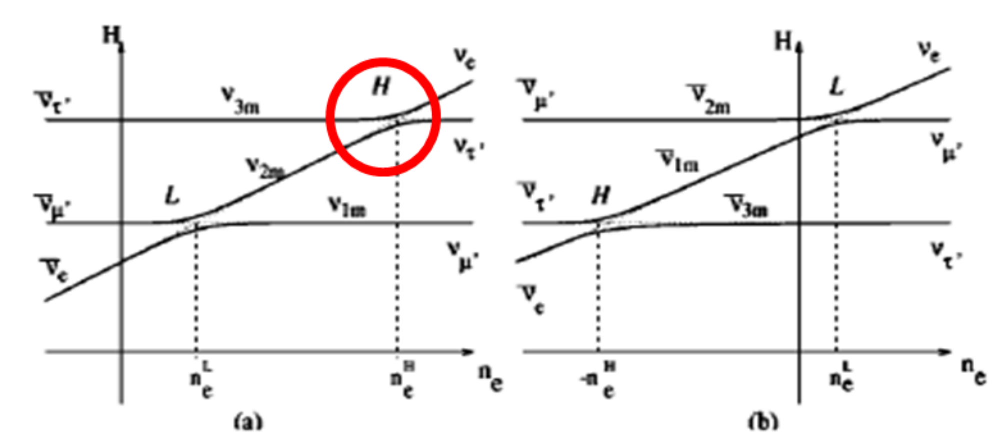
yields	$15M_\odot$			$20M_\odot$		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
$M(^{11}\mathrm{B})$	2.94	2.92	3.13	6.77	6.58	7.66
$M(^{11}\mathrm{C})$	2.80	2.71	3.20	9.33	8.91	9.64
$M(^{11}\mathrm{B}+^{11}\mathrm{C})$	5.74	5.62	6.33	16.10	15.49	17.29

T. Yoshida

ν oscillation effects → ν mass hierarchy

MSW ν oscillations

Normal hierarchy	Inverted hierarchy



$$\text{Normal} - \text{hierarchy}: \nu_\mu, \nu_\tau \rightarrow \nu_e$$

$$\text{Inverted} - \text{hierarchy}: \bar{\nu}_\mu, \bar{\nu}_\tau \rightarrow \bar{\nu}_e$$

$N(\nu_e) = P{*}N^0(\nu_e) + (1\text{-}P){*}N^0(\nu_x)$

$N(\text{anti-}\nu_e) = P'{*}N^0(\text{anti-}\nu_e) + (1\text{-}P'){*}N^0(\nu_x)$

Normal hierarchy: (P, P') = (0, 0.68)

Inverted hierarchy: (P, P') = (0.32, 0); $\sin^2\theta_{12}=0.32$

Dighe and Smirnov, PR D62, 033007 (2000)

Resonance condition

$$\rho Y_e = N_e = \frac{\Delta}{2\sqrt{2}EG_F}\cos 2\theta$$

$$= 6.55\times 10^6 \left(\frac{\Delta m_{ij}^2}{1\text{eV}^2}\right)\left(\frac{1\text{MeV}}{E_\nu}\right)\cos 2\theta_{ij} \quad \text{g}\cdot\text{cm}^{-3}$$

H – resonance: θ_{13}

$$\rho Y_e = 300 - 3000 \ \text{g}\cdot\text{cm}^{-3}$$

He/C layer

L – resonance: θ_{12}

$$\rho Y_e = 4 - 40 \ \text{g}\cdot\text{cm}^{-3}$$

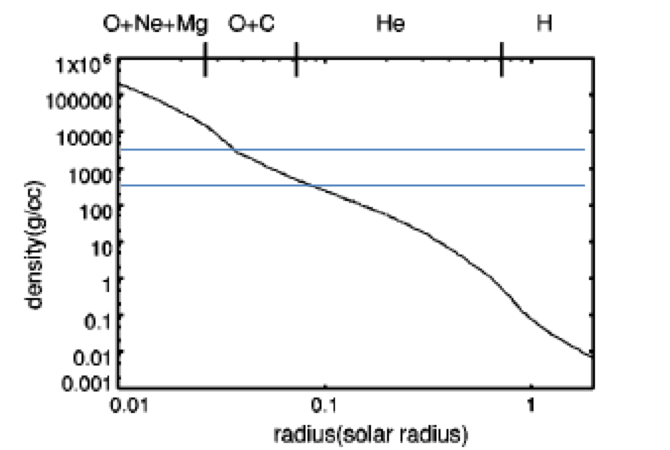
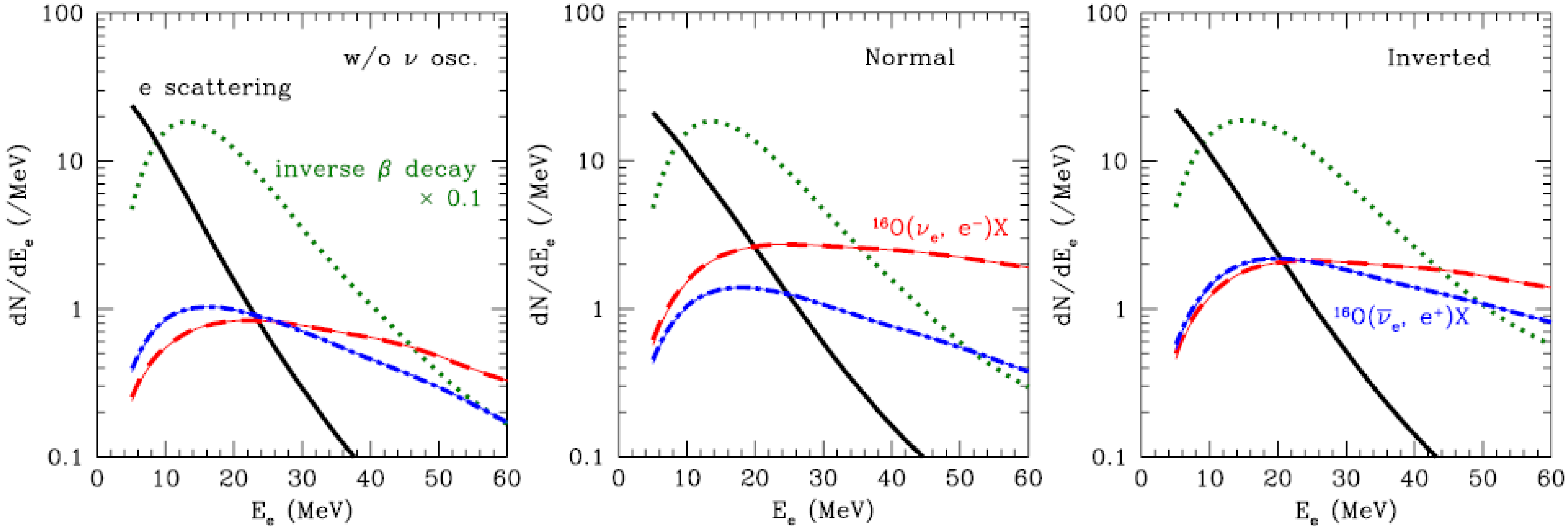


FIG. 3. Density profile of the presupernova star model used in the paper [20]. The progenitor mass is set to be $15M_\odot$.

Charged current scattering off ^{16}O nucleus as a detection channel of supernova neutrinos

Ken'ichiro Nakazato[1], Toshio Suzuki[2], and Makoto Sakuda[3]

PTEP 2018, 123E02 82018)



(M, Z) =(20M$_\odot$, 0.02) Z = metalicity

<E_ν_e> = 9.32 MeV, <E_$\bar{\nu}_e$> = 11.1 MeV, <E_ν_x> =11.9 MeV

Nakazato et al., ApJ. Suppl. 205, 2 (2013)

Expected event numbers

	ordinary supernova		
reaction	no osc.	normal	inverted
$^{16}O(\nu_e, e^-)X$	41	178	134
$^{16}O(\bar{\nu}_e, e^+)X$	36	58	103
electron scattering	140	157	156
inverse β-decay	3199	3534	4242
total	3416	3927	4635

10 kpc, Super-K (32.8 kton)

Table 6 Expected event numbers with a threshold energy of $E_e = 5$ MeV for the models in Table 5.

	black hole formation		
reaction	no osc.	normal	inverted
$^{16}O(\nu_e, e^-)X$	2482	2352	2393
$^{16}O(\bar{\nu}_e, e^+)X$	1349	1255	1055
electron scattering	514	320	351
inverse β-decay	17525	14879	9255
total	21870	18806	13054

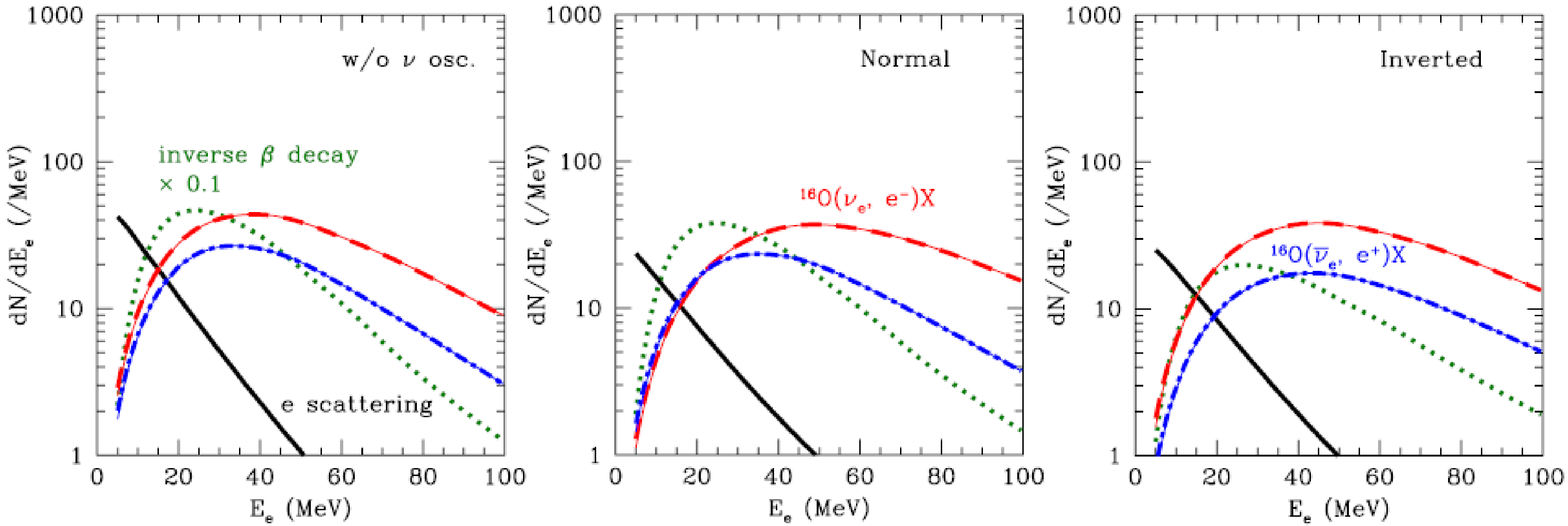


Fig. 5 Same as Fig. 4 but for the model with $(M, Z) = (30M_\odot, 0.004)$, which corresponds to a black-hole-forming collapse.

Summary

1. ・ ν-^{12}C GT + SD shell-model with SFO
   Coherent scattering
   ・ ν-^{13}C GT + SD, n-emission channel, coherent scatt.
   ・ ν-^{16}O SD shell-model with SFO-tls
   ・ Partial cross sections for particle and γ emission channels with Hauser-Feshbach statistical model
   ・ Synthesis of ^{11}B: $^{12}C\,(\nu, \nu' p)\,^{11}B$, $^{16}O\,(\nu, \nu' \alpha p)\,^{11}B$
   ^{11}C: $^{12}C(\nu, e^{-}p)\,^{11}C$, $^{16}O\,(\nu, e^{-}\alpha p)\,^{11}C$

2. MSW ν oscillation effects
   Mass hierarchy dependence:
   Cross sections of $^{16}O\,(\nu, e^{-})\,X$ and $^{16}O\,(\bar{\nu}, e^{+})\,X$ induced by SN ν

Collaborators

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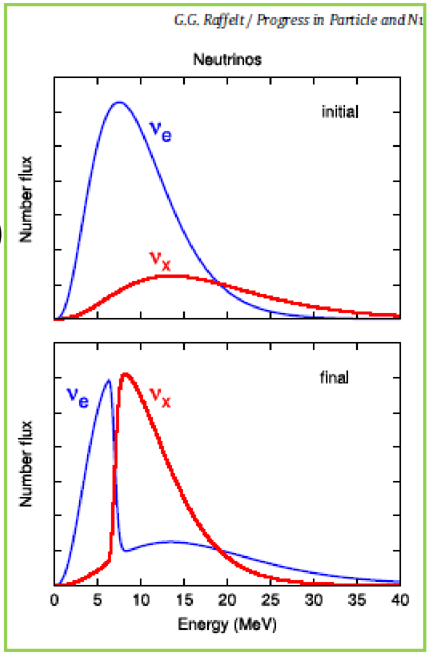
Backups

Effects of collective ν oscillation

・Splitting (swapping) of ν spectrum occurs for inverted (normal) hierarchy for ν, and for normal (inverted) hierarchy for anti-ν.

Bimodial instability: Raffelt et al., PPNP 64 (2010)



ν:	Collective	MSW	Collect.+MSW
normal	×	○	○
inverted	○	×	○

・MAA: Multi-azimuthal-angle instability

Splitting also occurs for normal (inverted) hierarchy for ν (anti-ν); N(ν_e) > N(ν_e)

Raffelt et al., PRL111, 091101 (2011)

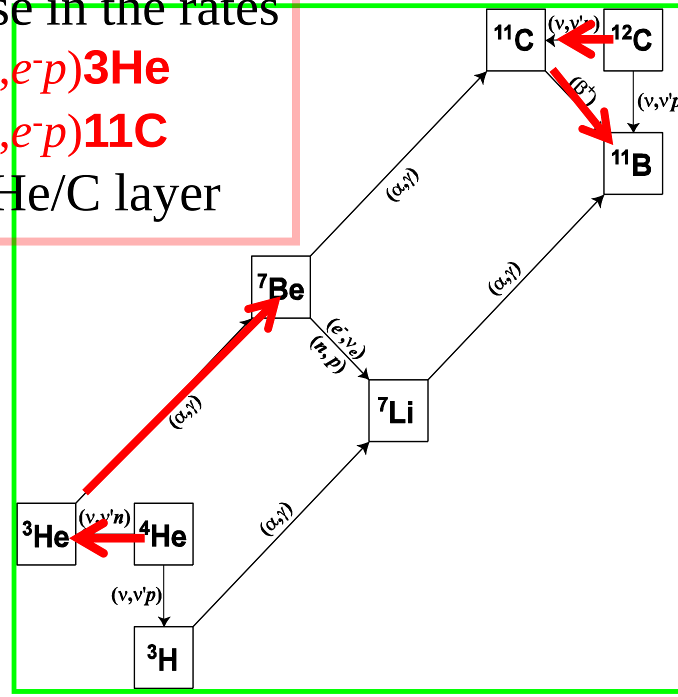
Chakraborty and Mirizzi, PRD 90, 033004 (2014)

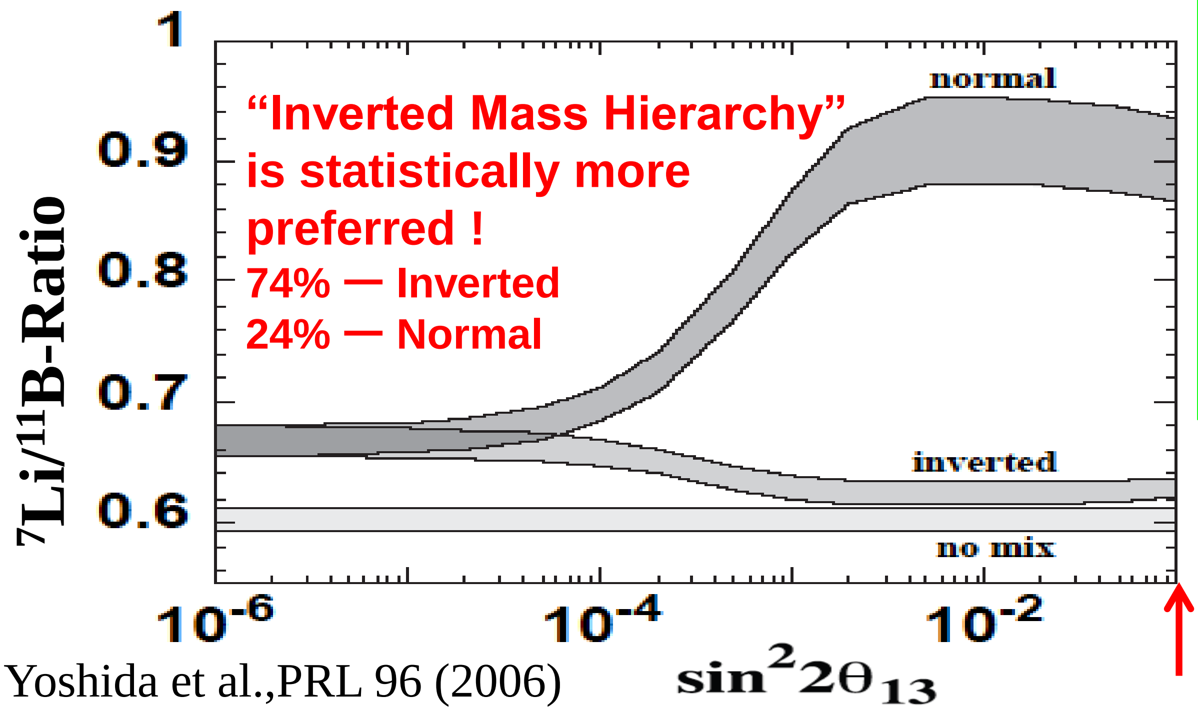
ν:	Collective	MSW	Collect.+MSW
normal	○	○	×
inverted	○	×	○

MSW ν oscillations

$\text{Normal-hierarchy}: \nu_\mu, \nu_\tau \rightarrow \nu_e$

Increase in the rates
4He(ν_e,e^-p)3He
12C(ν_e,e^-p)11C
in the He/C layer





"Inverted Mass Hierarchy" is statistically more preferred !
74% — Inverted
24% — Normal

Yoshida et al.,PRL 96 (2006)

- T2K, MINOS (2011)
- Double CHOOZ, Daya Bay, RENO (2012)

$\sin^2 2\theta_{13} = 0.1$

First Detection of ^{7}Li/^{11}B in SN-grains in Murchison Meteorite

- W. Fujiya, P. Hoppe, & U. Ott, ApJ 730, L7 (2011).

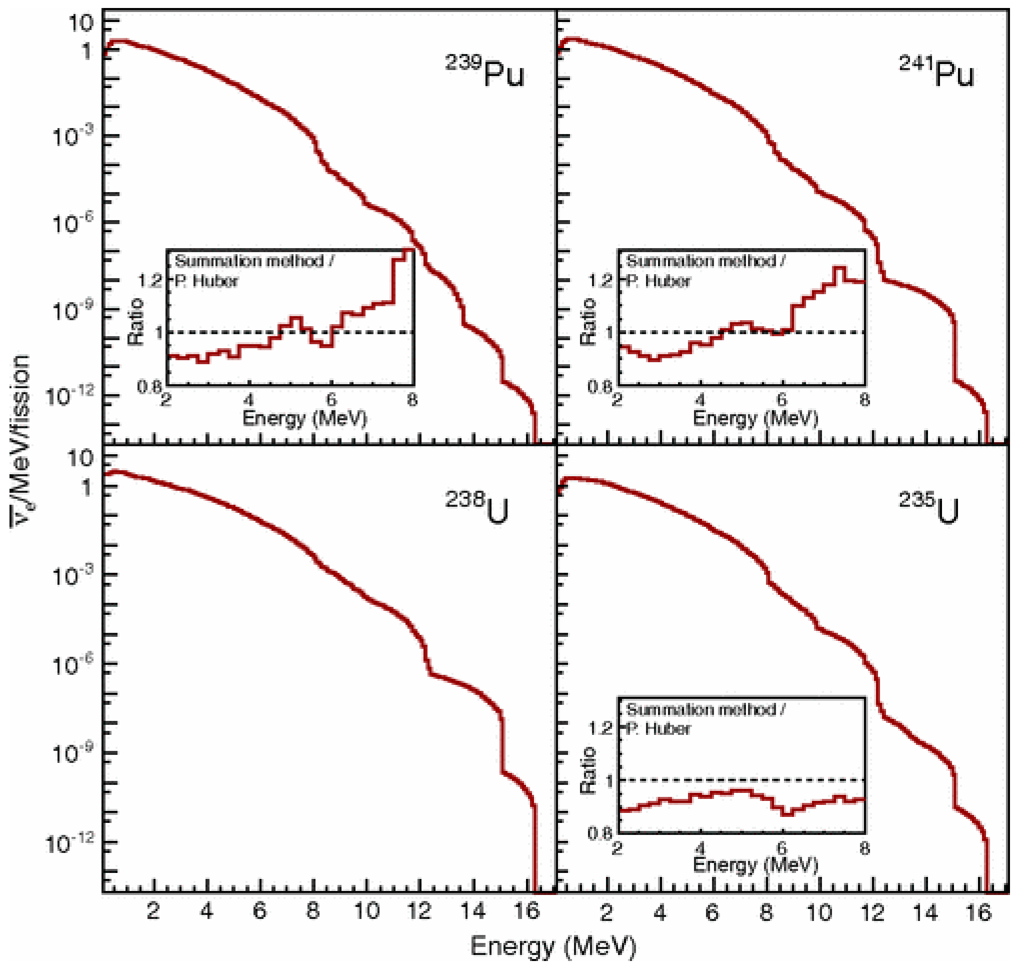
Bayesian analysis:
Mathews, Kajino, Aoki and Fujiya, Phys. Rev. D85,105023 (2012).

For MAA instability case:
^{7}Li/^{11}B → normal hierarchy (?)

New Antineutrino Energy Spectra Predictions from the Summation of Beta Decay Branches of the Fission Products

M. Fallot, S. Cormon, M. Estienne, A. Algora, V. M. Bui, A. Cucoanes, M. Elnimr, L. Giot, D. Jordan, J. Martino, A. Onillon, A. Porta, G. Pronost, A. Remoto, J. L. Taín, F. Yermia, and A.-A. Zakari-Issoufou

Phys. Rev. Lett. 109, 202504 – Published 13 November 2012



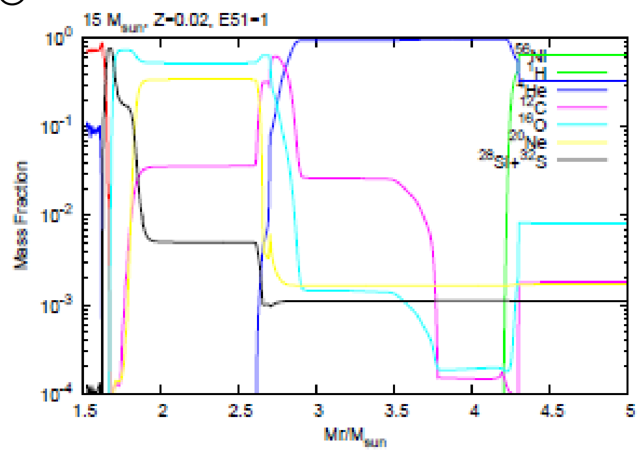
Production yields of ^{11}B and ^{11}C ($10^{-7}M_\odot$)

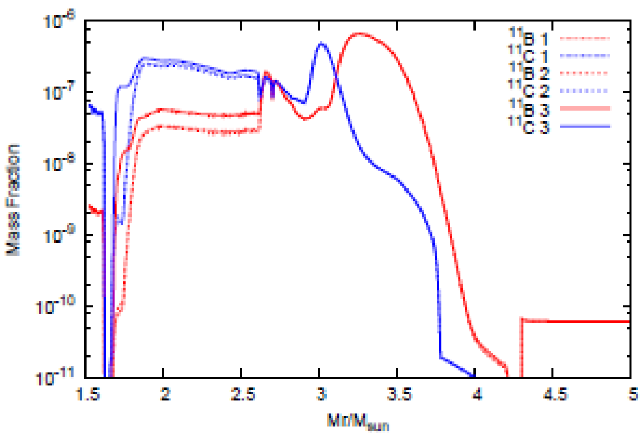
核種生成量	$15M_\odot$ モデル Case 1	Case 2	Case 3	$20M_\odot$ モデル Case 1	Case 2	Case 3
$M(^{11}\mathrm{B})$	2.94	2.92	3.13	6.77	6.58	7.66
$M(^{11}\mathrm{C})$	2.80	2.71	3.20	9.33	8.91	9.64
$M(^{11}\mathrm{B}+^{11}\mathrm{C})$	5.74	5.62	6.33	16.10	15.49	17.29

T. Yoshida

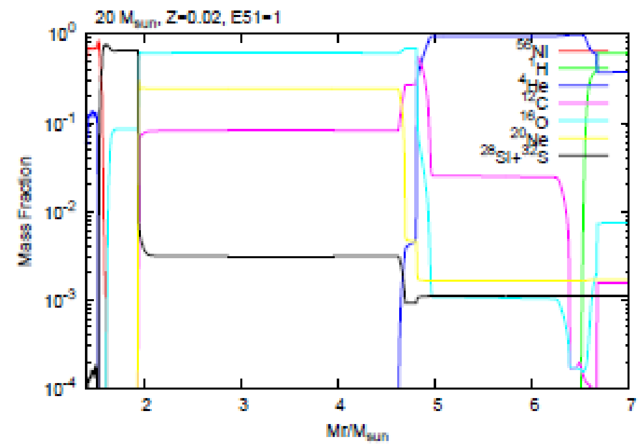
Case1: previous branches used in ^{16}O (γ, n, p, α-emissions) and HW92 cross sections
Case2: previous branches, and new cross sections
Case3: multi-particle branches and new cross sections

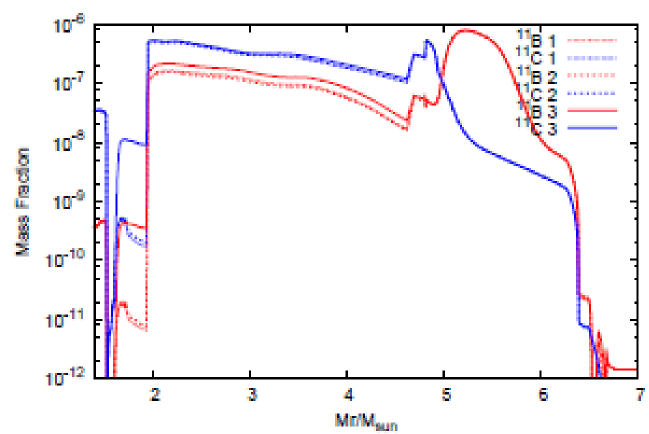
$15M_\odot$

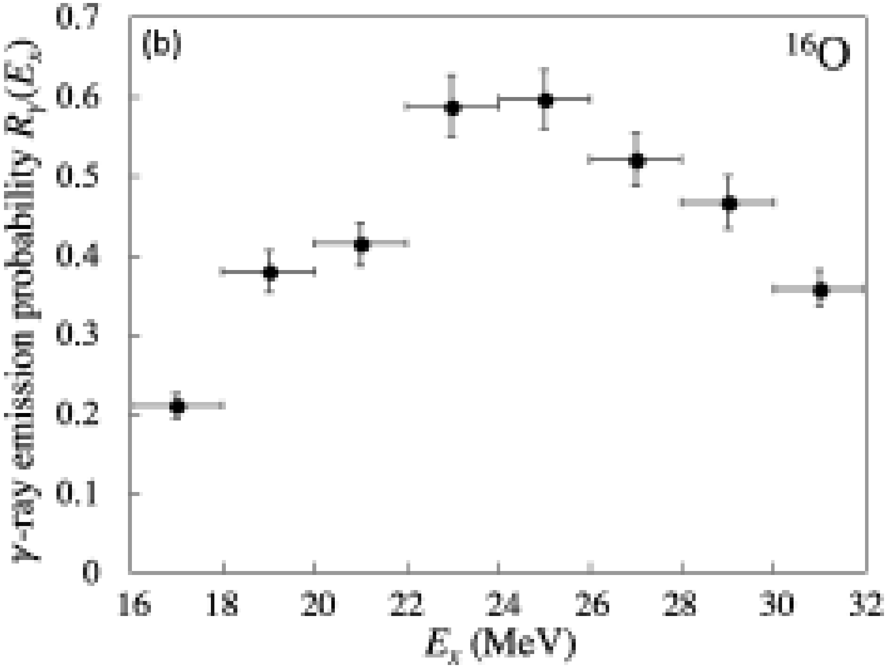




$20M_\odot$







Sakuda et al.,
Proc. OMEG15 Conference

Reaction	Present work FD	mMB	NK1	NK2	Beacom-Vogel [8] FD
$p(\bar{\nu}_e, e^+)n$	6000	6000	3260	17300	8300
NC $^{16}O(\nu,\nu')^{16}O^*(E_\gamma>5$ MeV)	456	9	57	940	710
Cf. CC $^{16}O(\nu_e, e^-) + ^{16}O(\bar{\nu}_e, e^+)(E_e > 5$ MeV) [26]	-	-	77	3831	-
νe elastic scattering [26]	-	-	140	514	-

Table III. Expected number of neutrino events from a core-collapse supernova at 10 kpc to be detected at Super-K (32.8kton).