# Neutrino-Nucleus Reaction Cross Sections for Neutrino Detection and Nucleosynthesis in Supernova Explosions

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Nihon University

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Sept. 15, 2016

- New shell-model Hamiltonians which describes the spin modes in nuclei very well
  → New ν-nucleus reaction cross sections
  $E_\nu \leq 100$ MeV

1. ν-$^{12}$C, ν- $^{13}$C: SFO (p-shell)
2. ν-$^{16}$O: SFO-tls (p +p-sd shell)
4. ν-$^{56}$Fe, ν-$^{56}$Ni: GXPF1J (pf-shell)
5. ν-$^{40}$Ar: VMU (monopole-based universal interaction) +SDPF-M +GXPF1J

- Nucleosynthesis in supernova explosion
  low-energy ν-detection
  ν-oscillation effects

# Collaborators

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- New shell-model Hamiltonians and successful description of Gamow-Teller (GT) strengths and M1 transitions & moments
  - SFO (p-shell, p-sd shell): GT in $^{12}C$, $^{14}C$, M1 moments
    - Suzuki, Fujimoto, Otsuka, PR C69, (2003)
  - GXPF1J (fp-shell): GT in Fe and Ni isotopes, M1 strengths
    - Honma, Otsuka, Mizusaki, Brown, PR C65 (2002); C69 (2004)
    - Suzuki, Honma et al., PR C79, (2009)
  - VMU (monopole-based universal interaction)
    - Otsuka, Suzuki, Honma, Utsuno et al., PRL 104 (2010) 012501

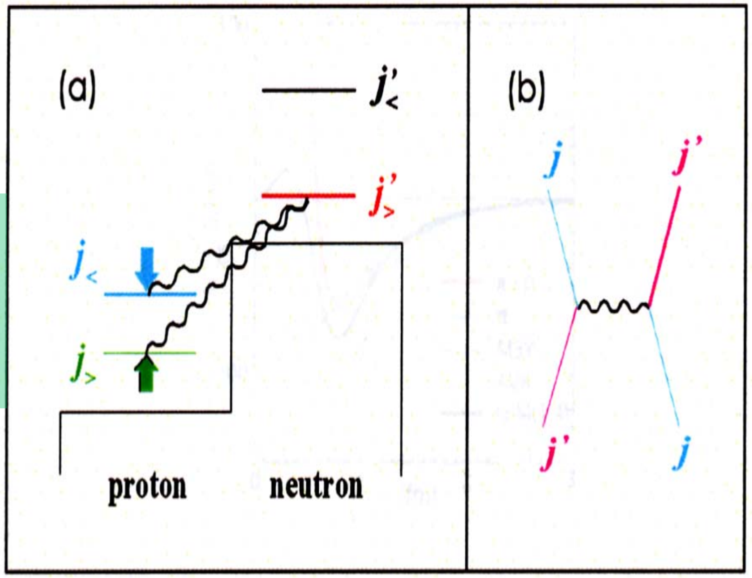
* important roles of tensor force

Monopole terms of $V_{NN}$

$$V_M^T(j_1 j_2) = \frac{\sum_J (2J+1) < j_1 j_2; JT | V | j_1 j_2; JT >}{\sum_J (2J+1)}$$

$j_> - j_<$ : attractive

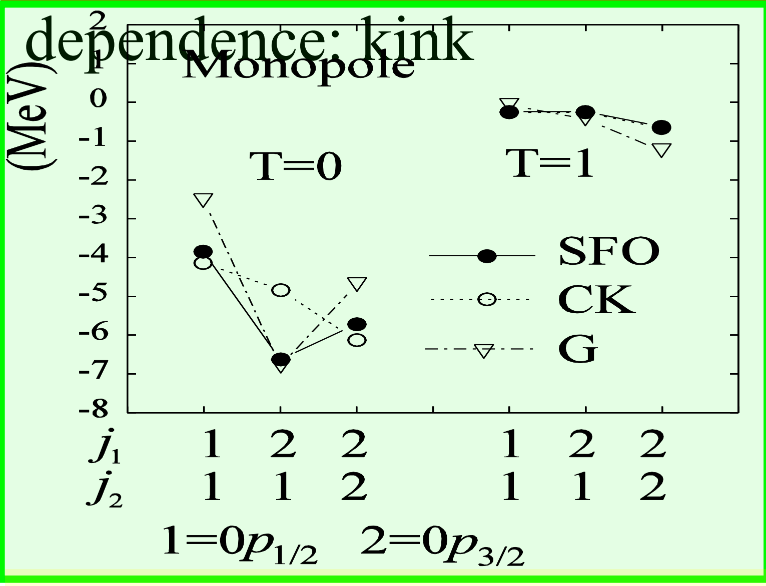
$j_> - j_>, j_< - j_<$ : repulsive

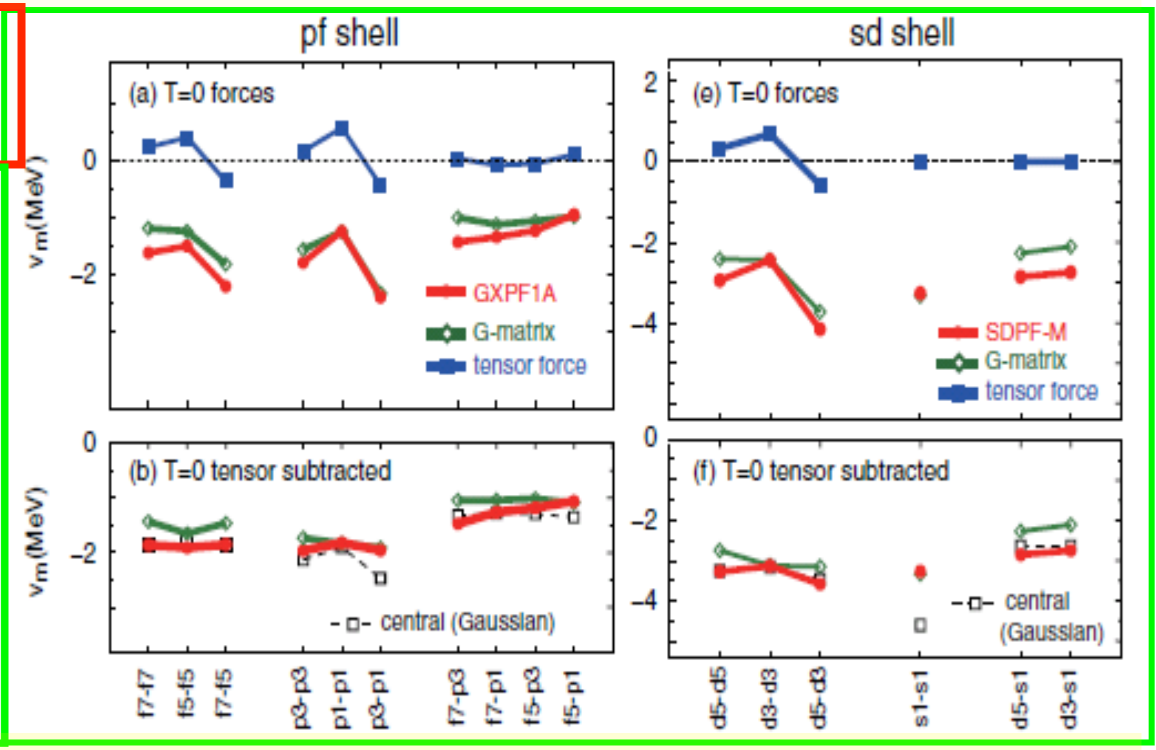



Otsuka, Suzuki, Fujimoto, Grawe, Akaishi, PRL 69 (2005)

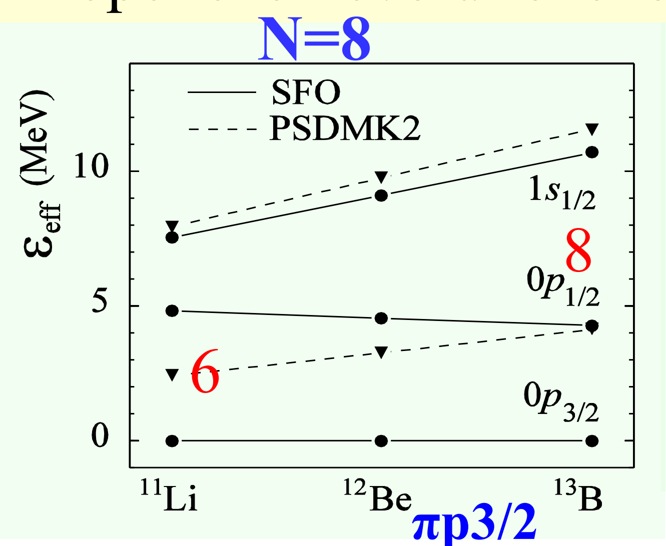
# Monopole terms: New SM interactions vs. microscopic G matrix

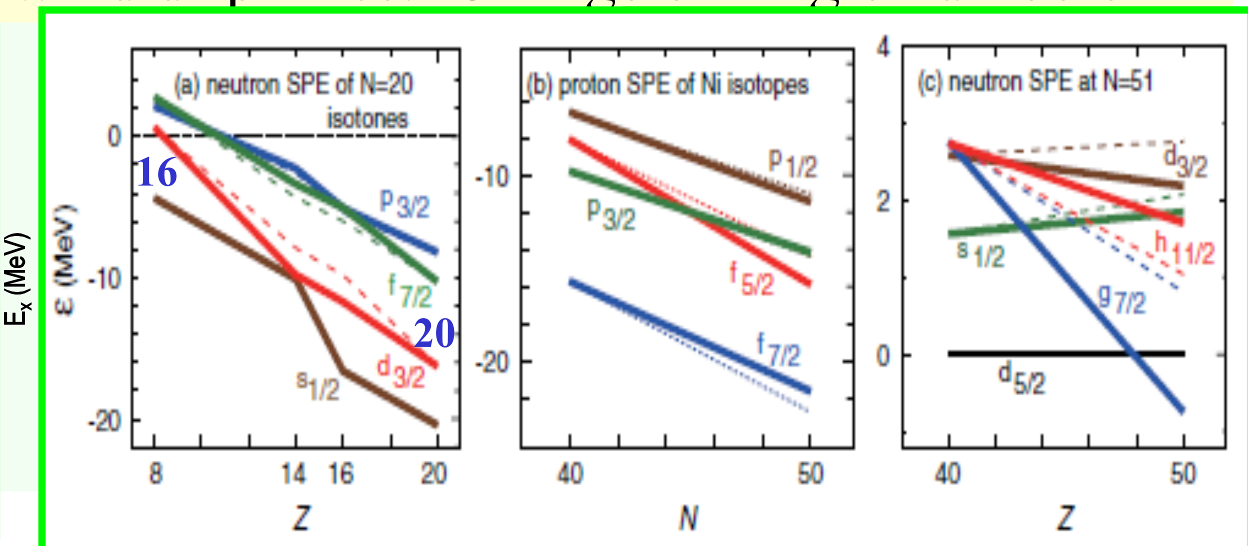
tensor force → characteristic orbit dependence: kink




## Proper shell evolutions toward drip-lines: Change of magic numbers



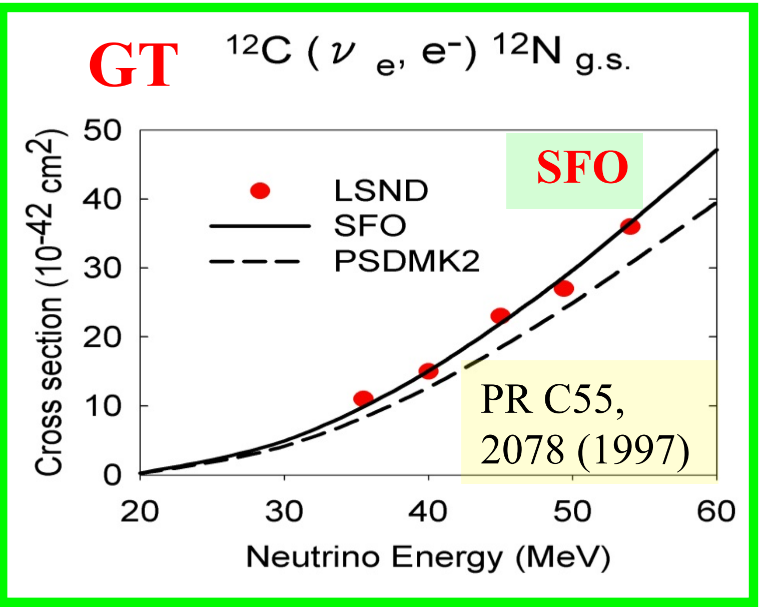



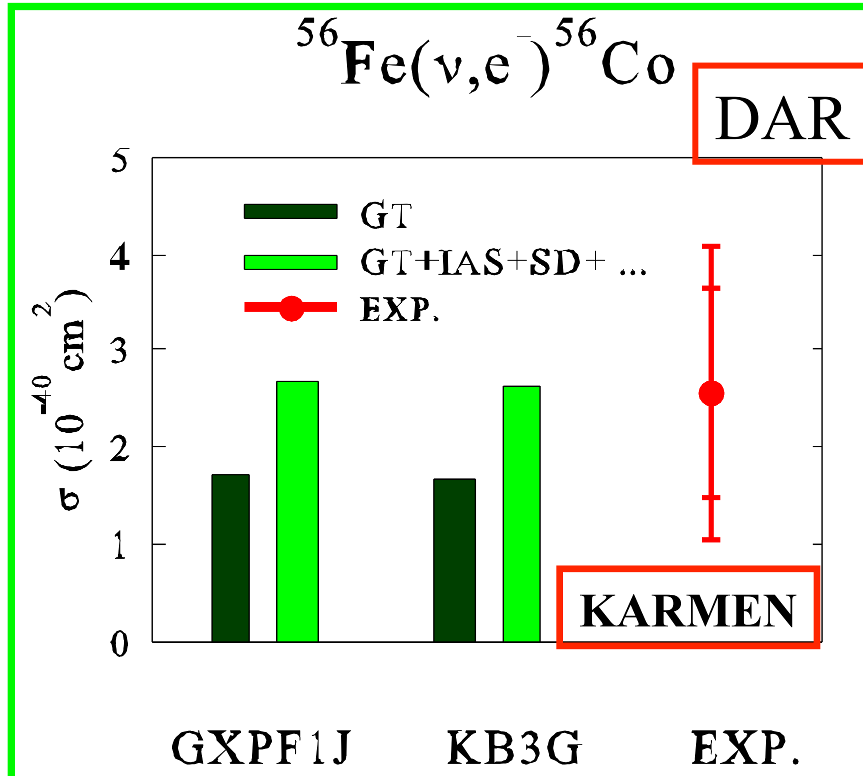
## ･ν-nucleus reactions

**p-shell: SFO**

**pf-shell: GXPF1J** (Honma et al.)

**cf. KB3** Caurier et al.




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

**SFO: $g_A^{eff}/g_A$=0.95**

**B(GT: 12C)_cal = experiment**

$(\nu, \nu')$, $(\nu_e, e^-)$ SD exc.

SFO reproduces DAR cross sections

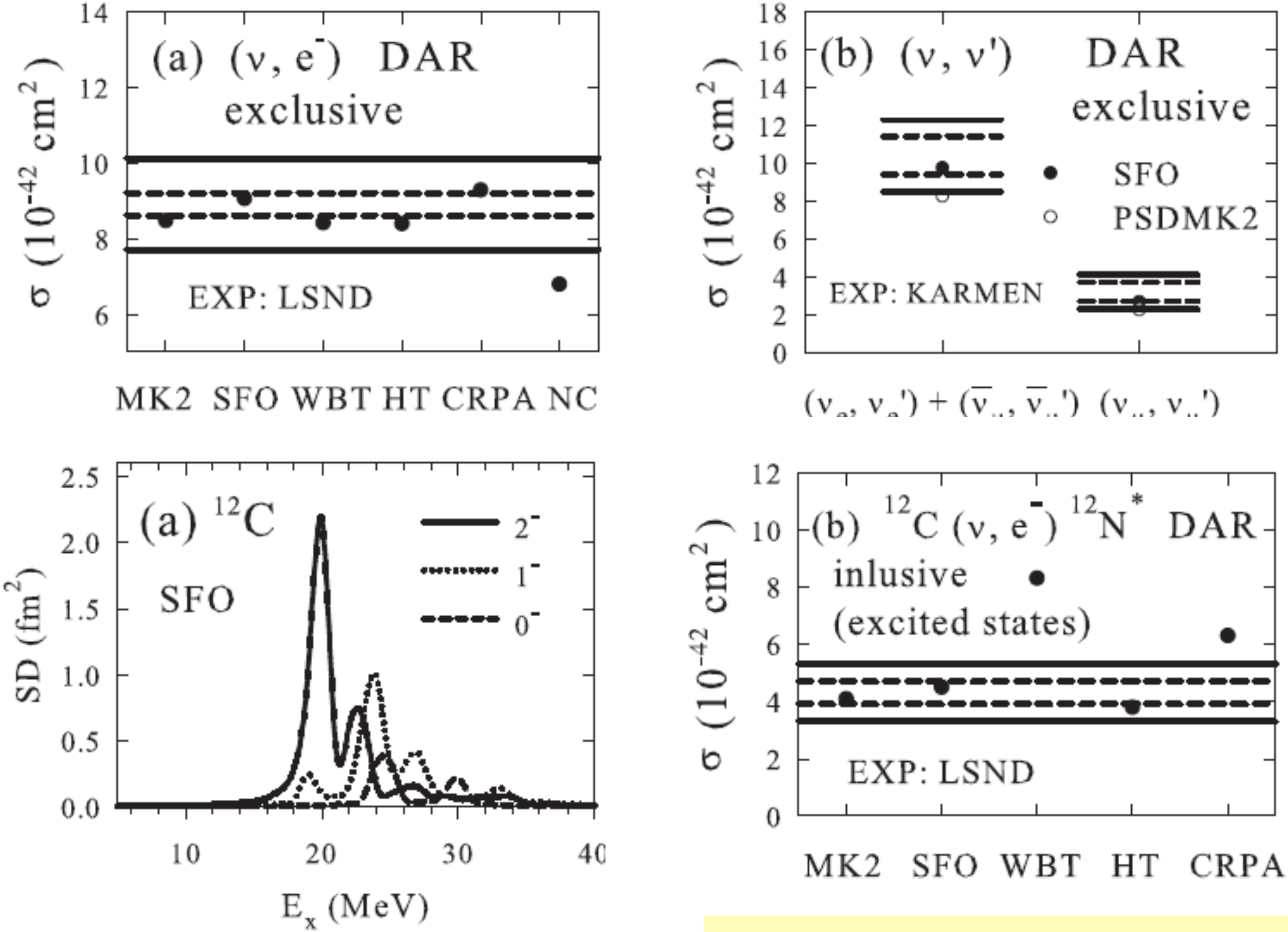
$B(GT)=9.5$  $B(GT)_{exp}=9.9\pm2.4$  $B(GT)_{KB3G}=9.0$

SD + … : RPA (SGII)

$$\langle\sigma\rangle_{exp} = (256 \pm 108 \pm 43) \times 10^{-42} \text{ cm}^2.$$
$$\langle\sigma\rangle_{th} = (258 \pm 57) \times 10^{-42} \text{ cm}^2.$$

| | |
|---|---|
| SM(GXPF1J)+RPA(SGII) | 259 x10 $^{-42}$cm$^2$ |
| RHB+RQRPA(DD-ME2) | 263 |
| RPA(Landau-Migdal force) | 240 |

# $^{12}C$




HT: Hayes-Towner, PR C62, 015501 (2000)
CRPA: Kolb-Langanke-Vogel, NP A652, 91 (1999)

# ▪Nucleosynthesis processes of light elements

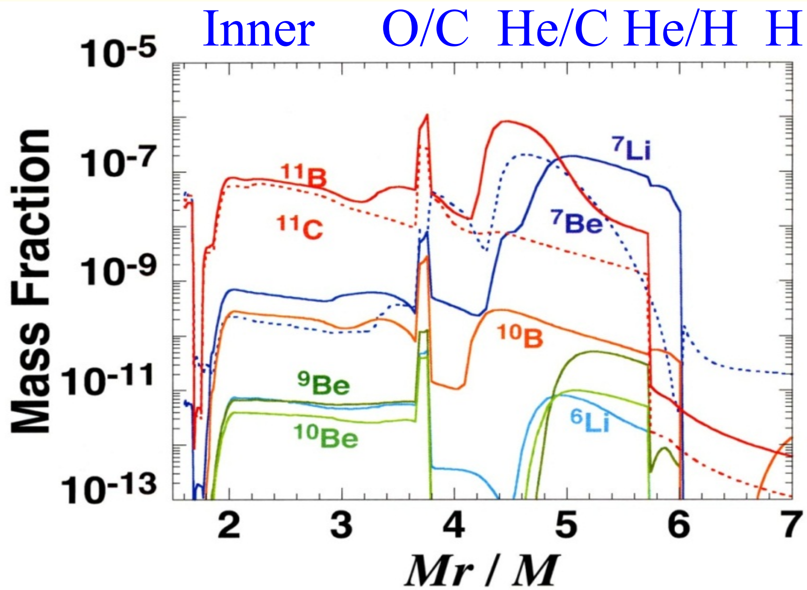
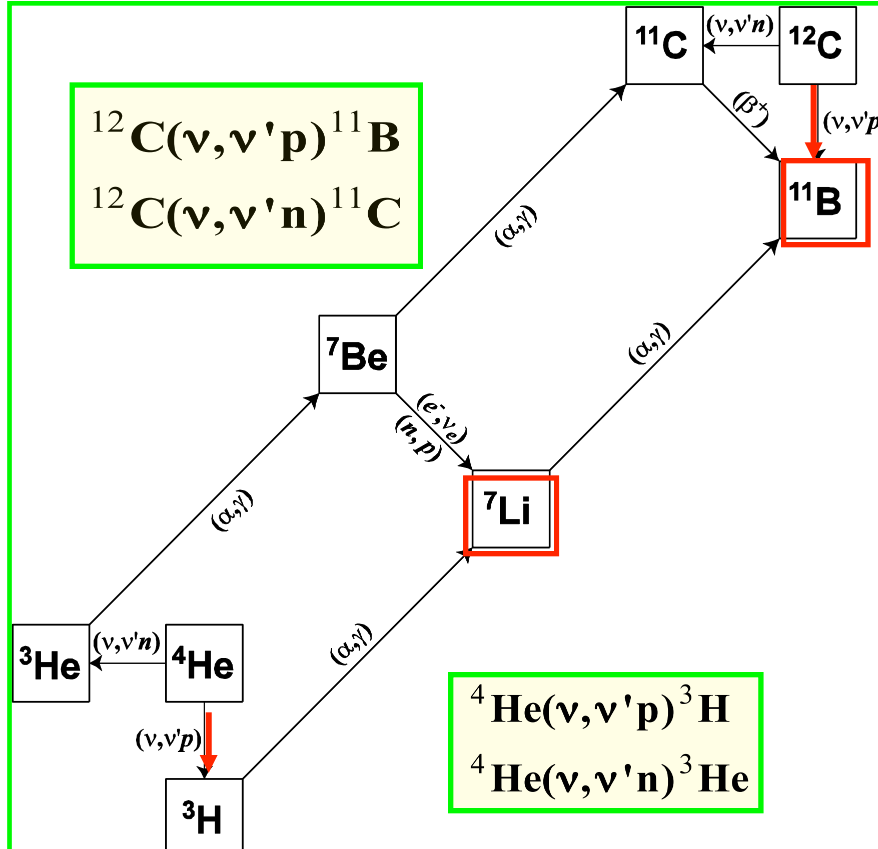
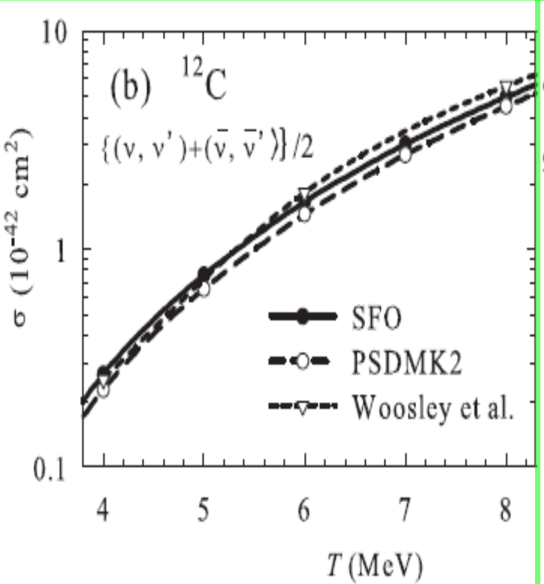
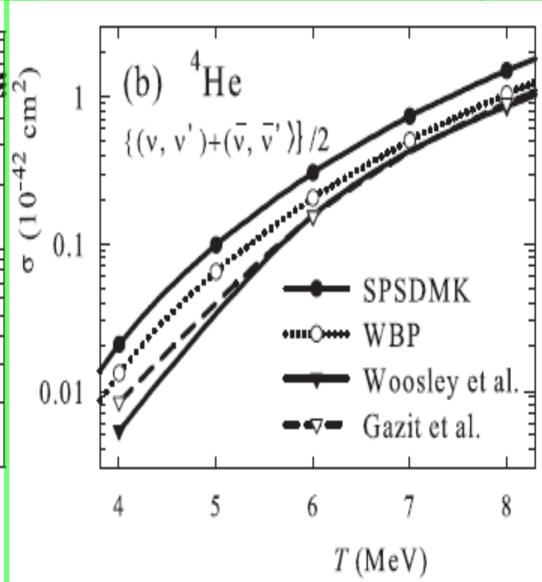


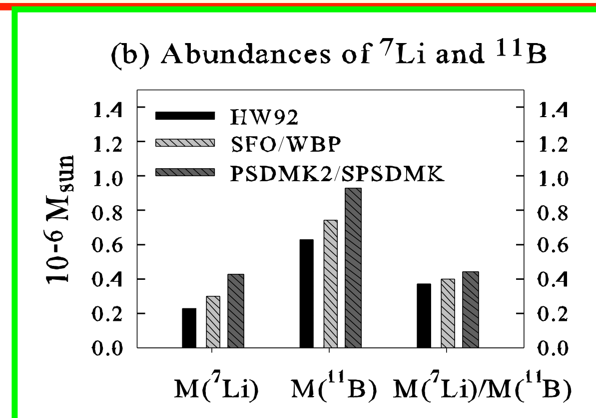

Fig. 4.— Mass fraction distribution of Model 1. The mass fractions of $^{7}$Li and $^{7}$Be, and $^{11}$B and $^{11}$C are separated.



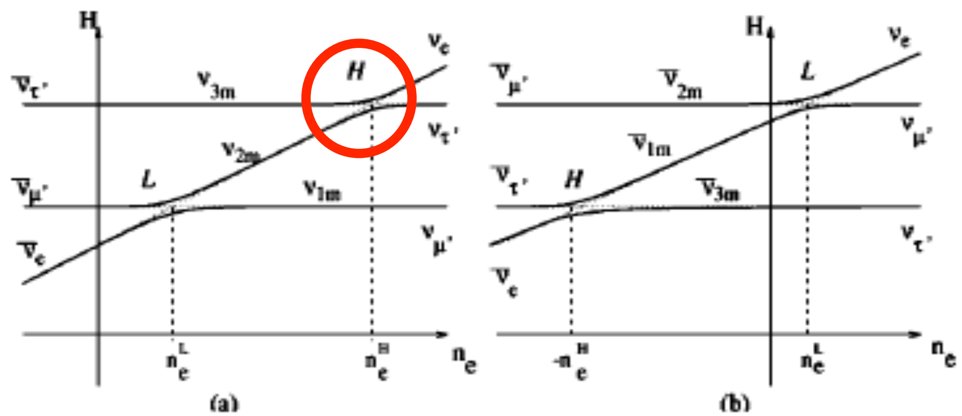




Enhancement of $^{11}$B and $^{7}$Li abundances in supernova explosions



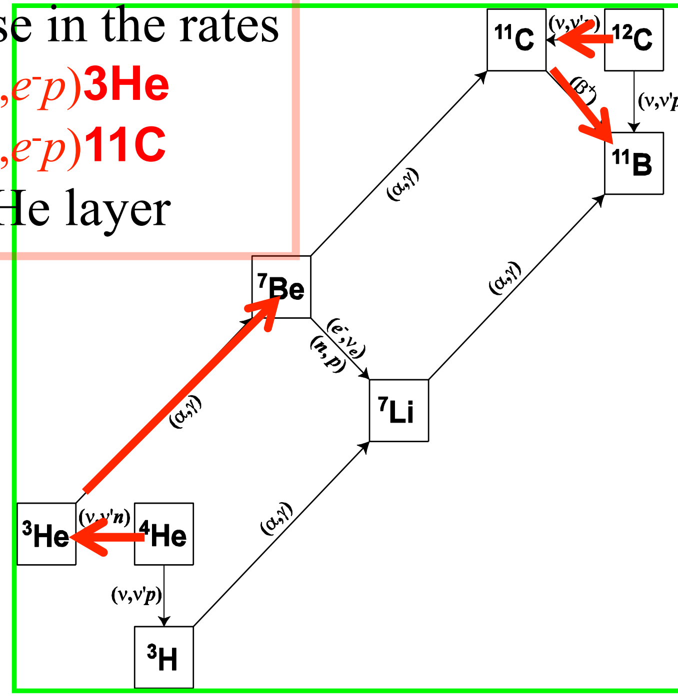
# MSW ν oscillations

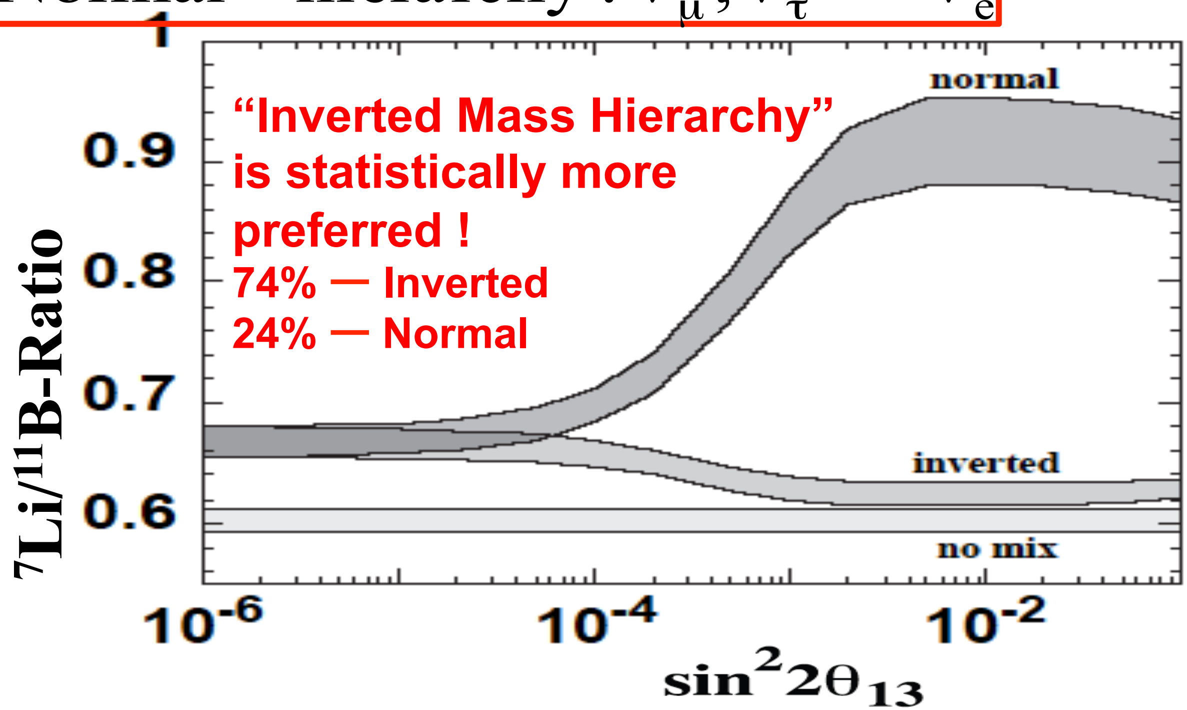
Normal hierarchy | Inverted hierarchy




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

Increase in the rates
$^4He(\nu_e, e^- p)^3He$
$^{12}C(\nu_e, e^- p)^{11}C$
in the He layer




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

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

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

First Detection of $^7Li/^{11}B$ 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).

## ▪ ν-induced reactions on $^{13}$C

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

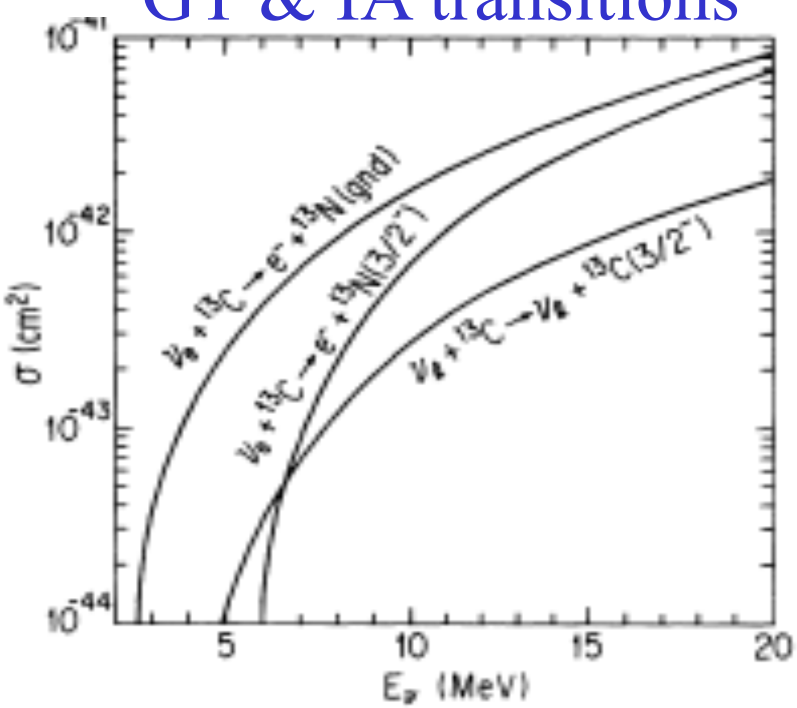
$E_\nu \leq 10\text{MeV} \quad E_\nu^{th}(^{12}C) \approx 13\text{MeV}$

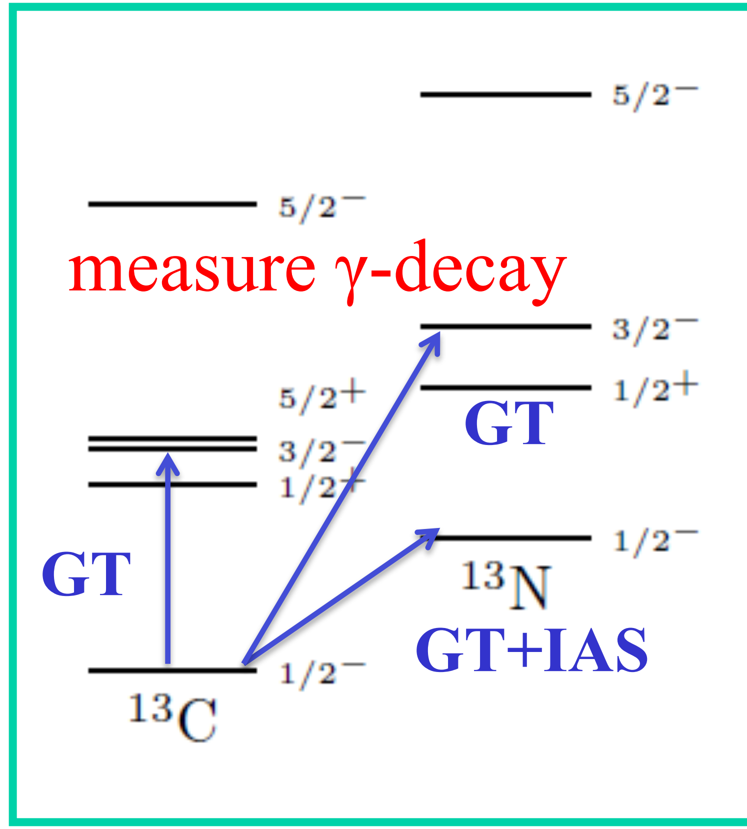
Natural isotope abundance = 1.07%

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

$^{13}C(\nu_e, \nu_e')^{13}C$

GT & IA transitions

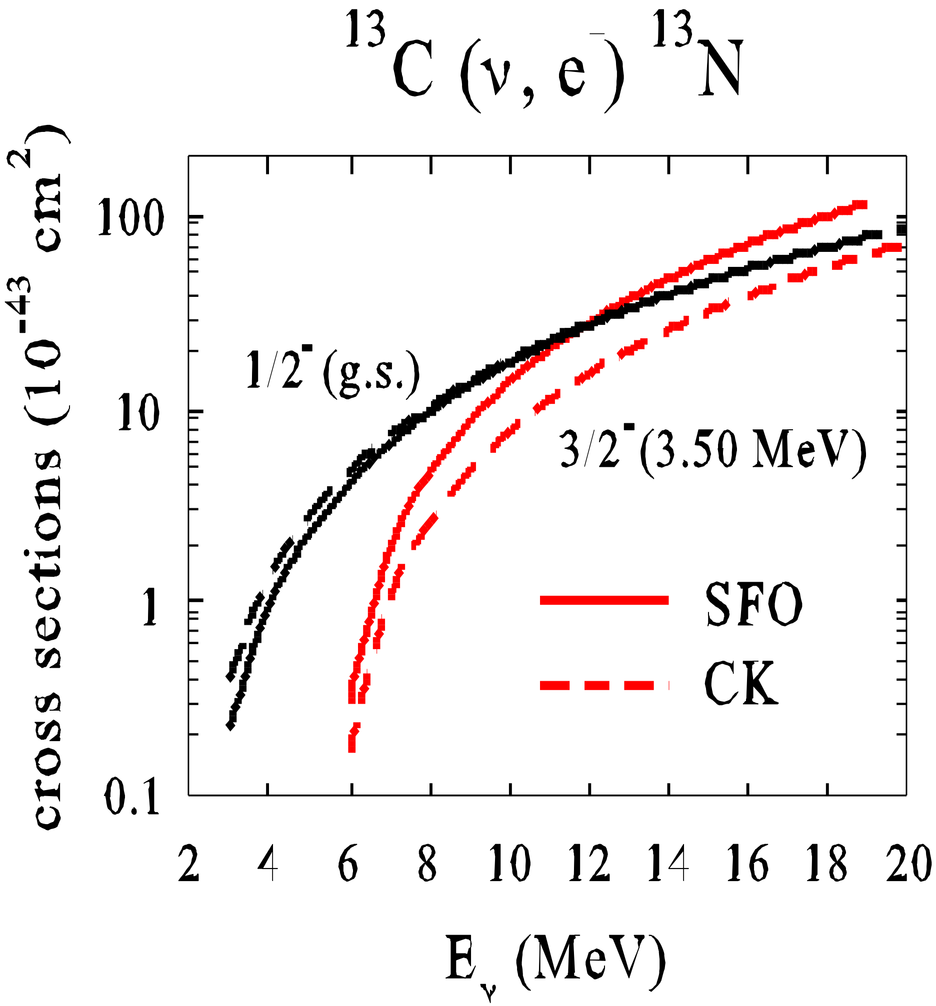



Fukugita et al., PR C41 (1990)
p-shell: Cohen-Kurath
$g_A^{eff}/g_A = 0.69$

**Detector for solar ν**

# p-sd shell:  SFO




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

## Solar ν cross sections folded over $^8$B ν spectrum

$(\nu_e, e^-)\ [\frac{1}{2}^-\ (g.s.) + \frac{3}{2}^-\ (3.50\,\text{MeV})]$

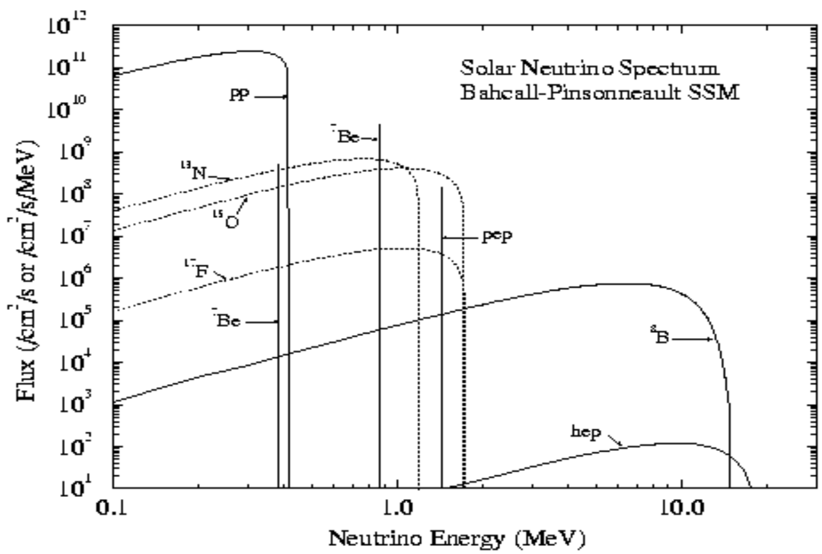
CK: $1.07 \times 10^{-42}\,\text{cm}^2$

SFO: $1.34 \times 10^{-42}\,\text{cm}^2$

$(\nu, \nu')\quad \frac{3}{2}^-\ (3.69\,\text{MeV})$

CK: $1.16 \times 10^{-43}\,\text{cm}^2$

SFO: $2.23 \times 10^{-43}\,\text{cm}^2$



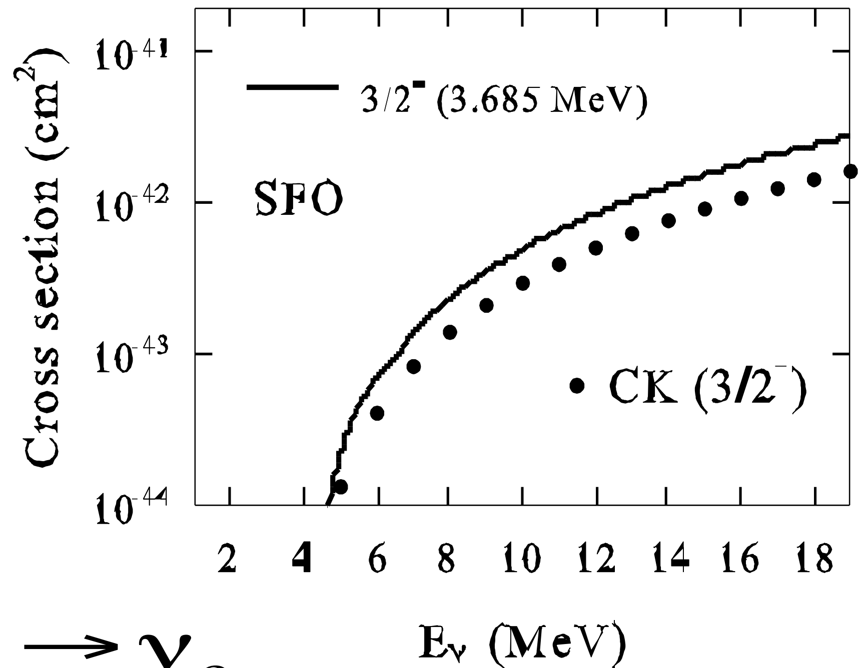
Reactor $\bar{\nu}_e$

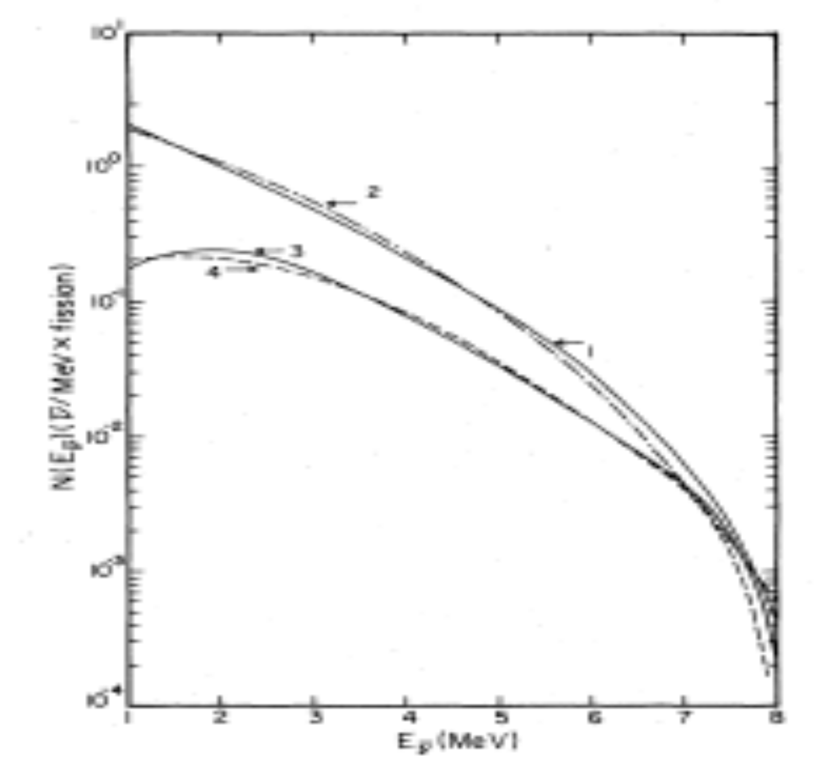
$(\bar{\nu}_e, \bar{\nu}_e) \rightarrow \bar{\nu}_e - \text{flux}$

$E_{\bar{\nu}} \leq 8\text{MeV}$

reactor $\bar{\nu}_e$ spectrum

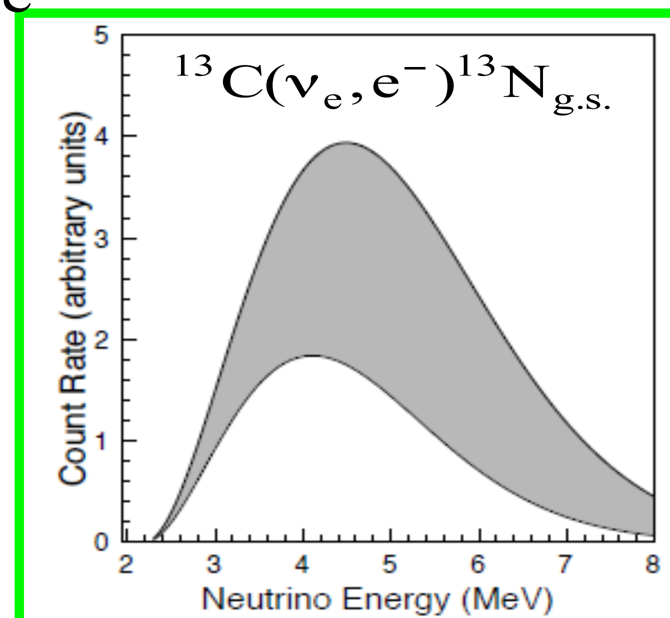
$^{13}C\,(\bar{\nu}_e, \bar{\nu}_e')\,^{13}C$



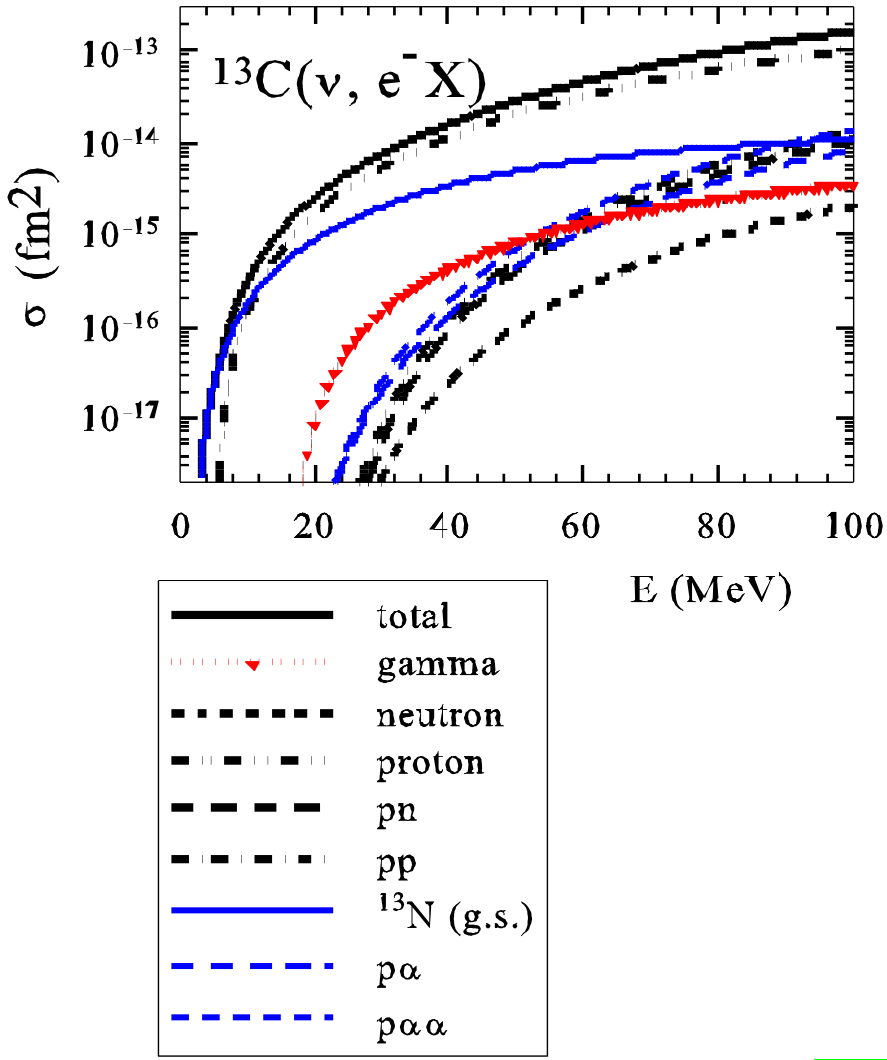



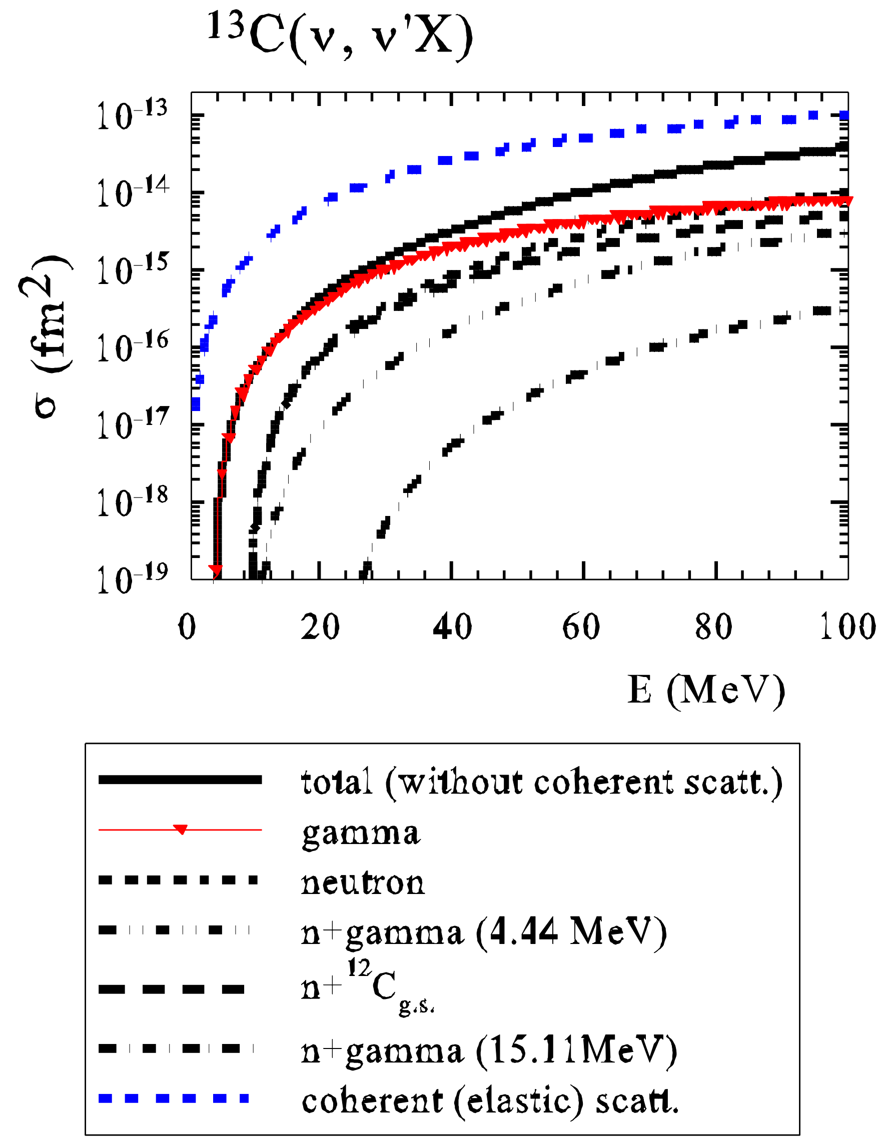

Vogel et al.

$\bar{\nu}_e \longrightarrow \nu_e$



# Partial cross sections of gamma and particle emissions




$^{13}C^* \rightarrow {}^{13}C + \gamma$

$^{13}C^* \rightarrow {}^{12}C^* + n, \quad {}^{12}C\,(2^+) \rightarrow {}^{12}C + \gamma$

Coherent (elastic) scattering on $^{12}$C and $^{13}$C

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

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

**Full inclusion of tensor force**

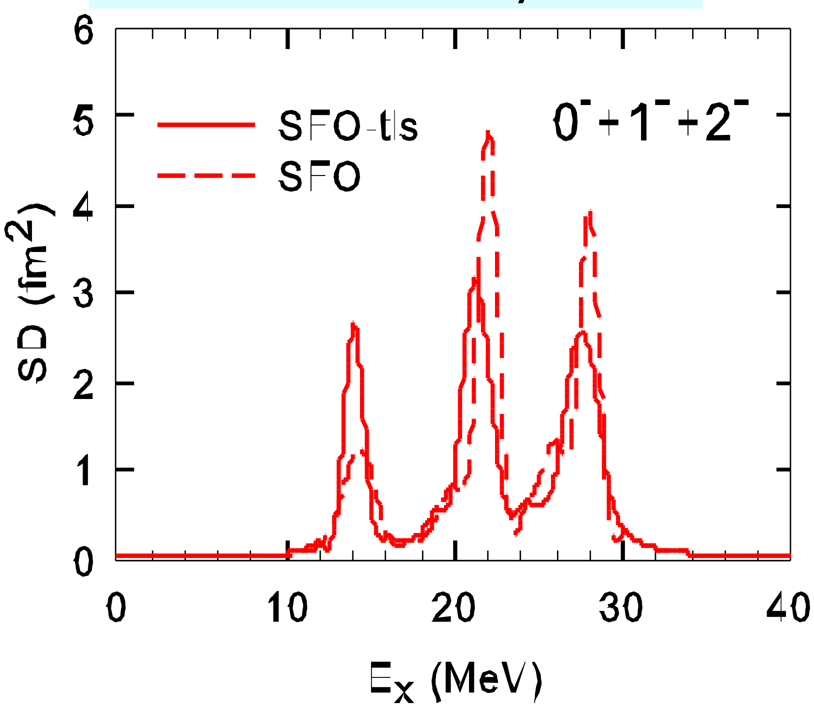
- **p-sd: tensor->π+ρ**

**LS -> σ+ρ+ω**

$$V = V_C + V_T + V_{LS}$$

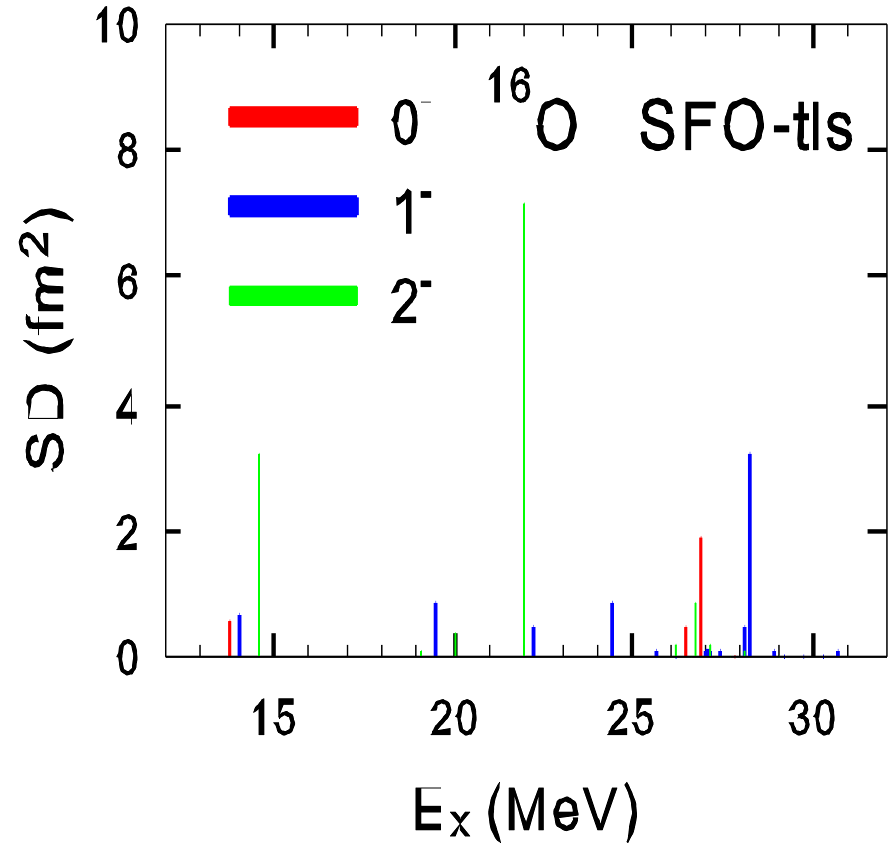
$$V_T = V_\pi + V_\rho$$

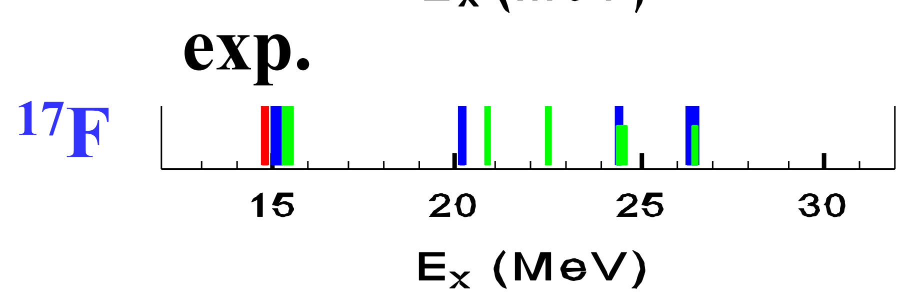
$$V_{LS} = V_{\sigma+\omega+\rho}$$

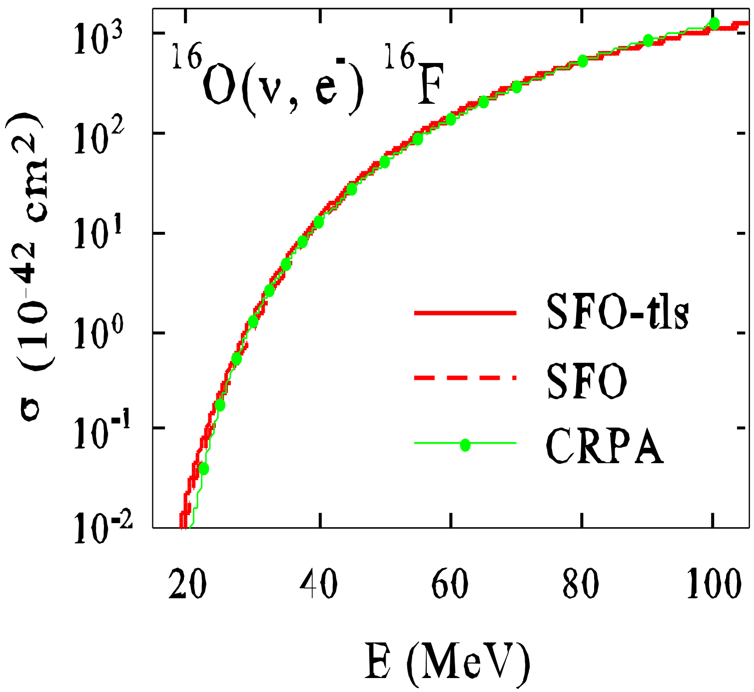


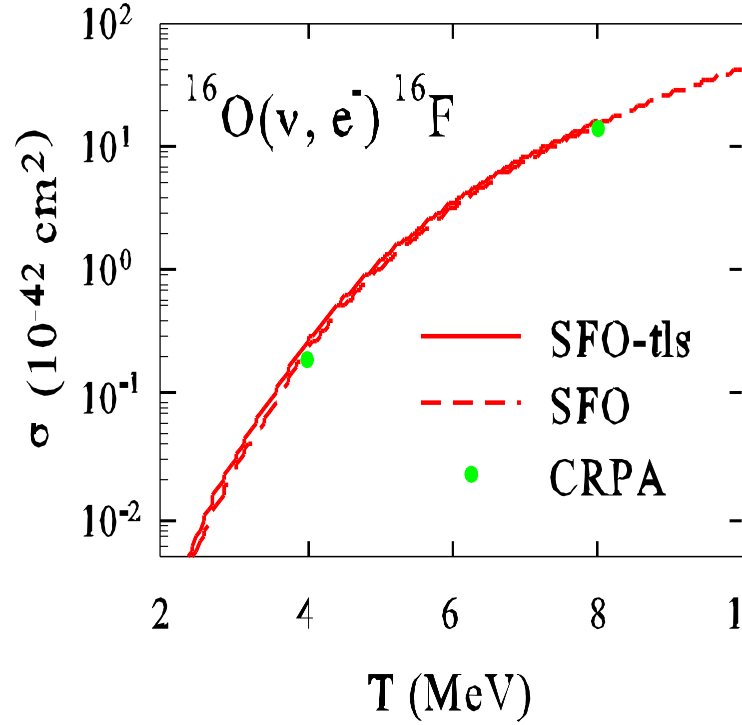

# Spin-dipole strength in $^{16}O$

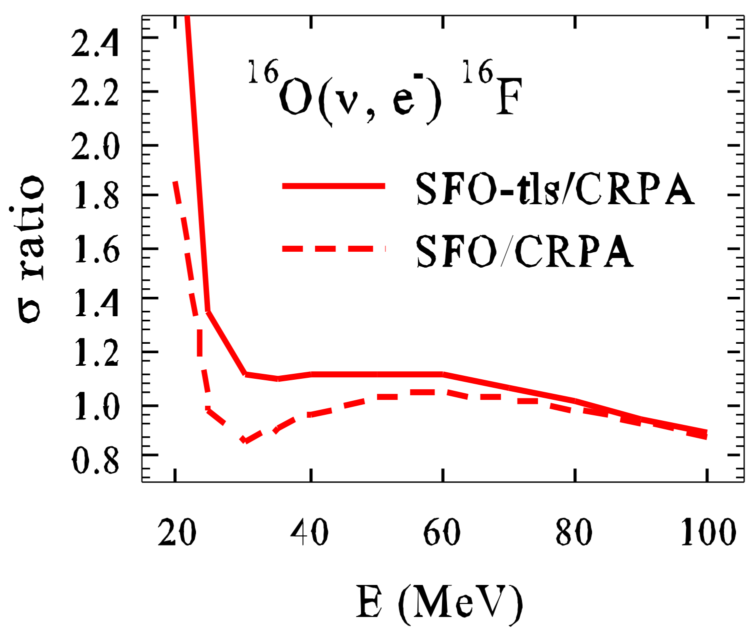
$$O(\lambda) = r[Y^1 \times \sigma]^\lambda t_-$$





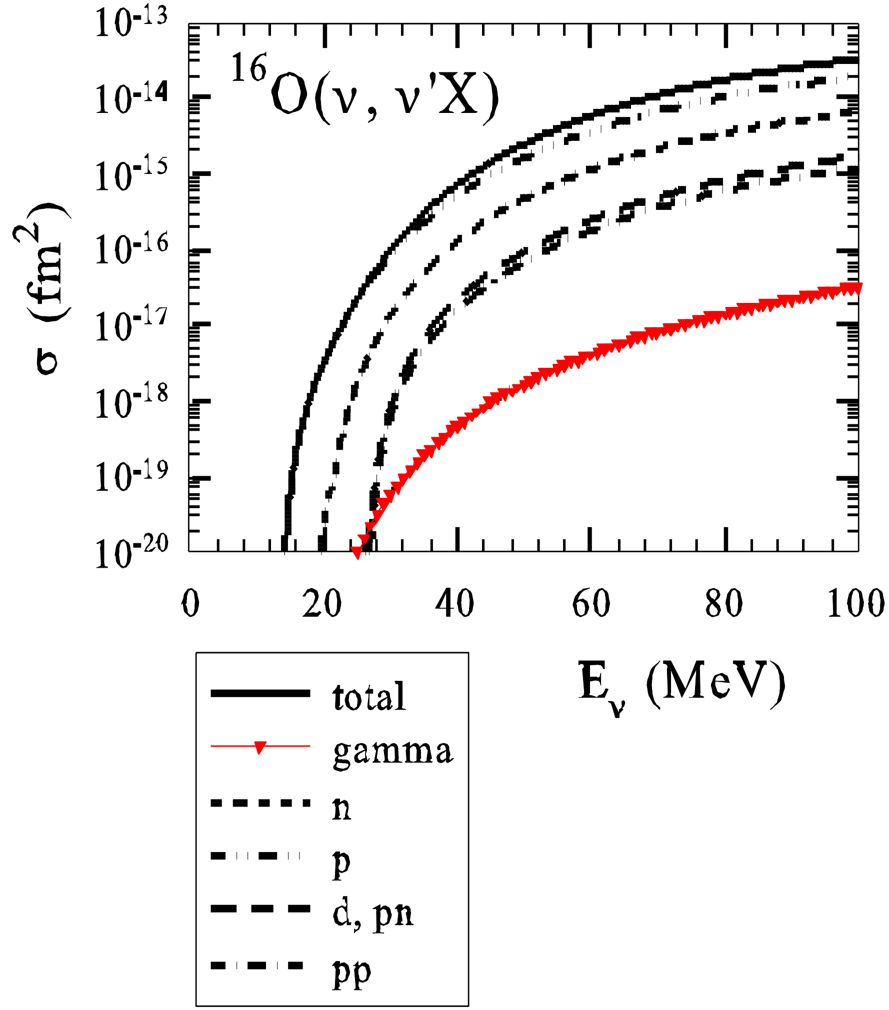



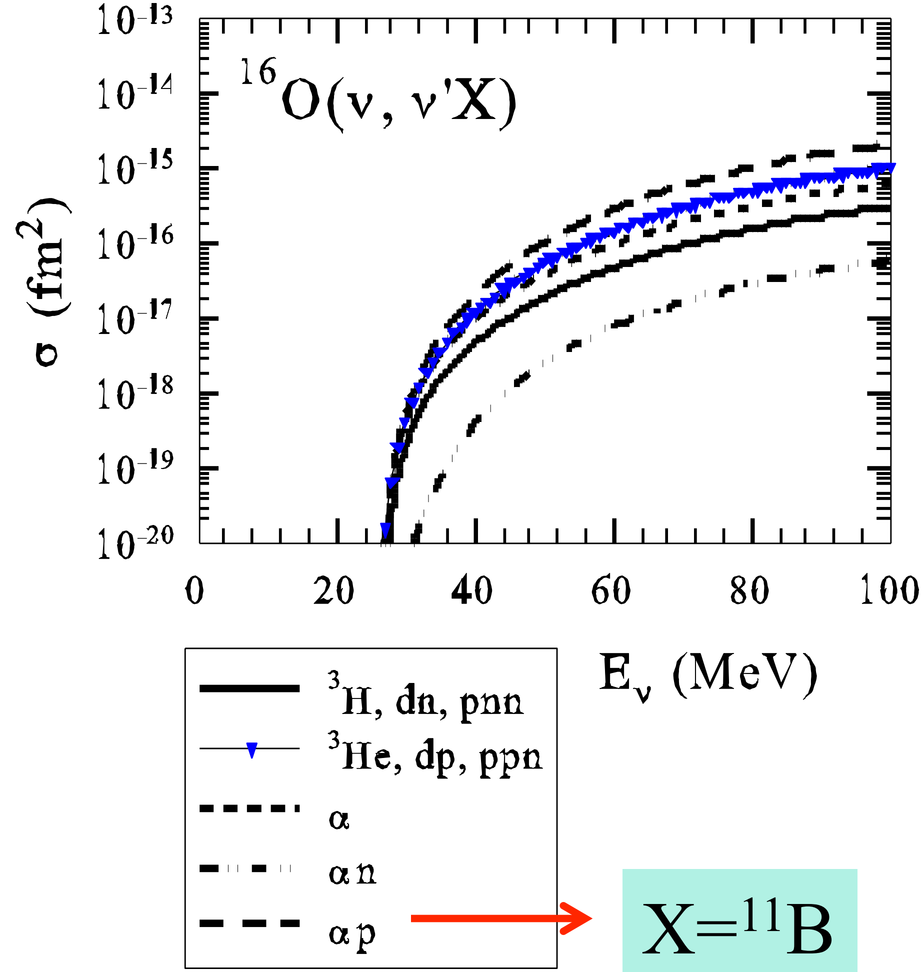

T= temperature of supernova ν

| T | σ(SFO-tls)/σ(CRPA): |
|---|---|
| 4 | 1.41 |
| 8 | 1.17 |

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

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




X=$^{11}$B

$$\frac{\sigma(^{16}O(\nu,\nu'\alpha p)^{11}B)}{\sigma(^{12}C(\nu,\nu'p)^{11}B)} \approx 20\%$$

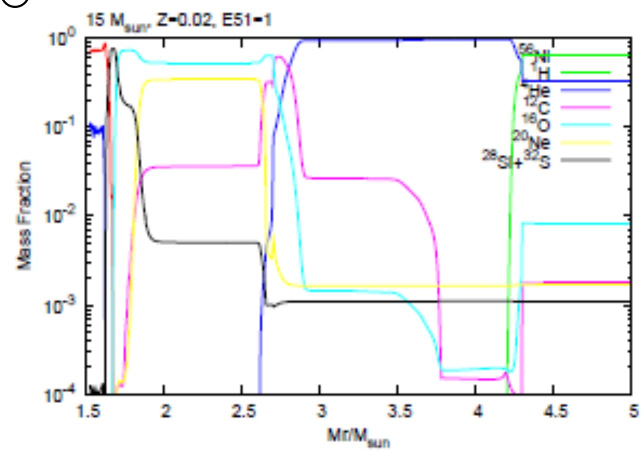
# Production yields of $^{11}$B and $^{11}$C ($10^{-7}M_\odot$)

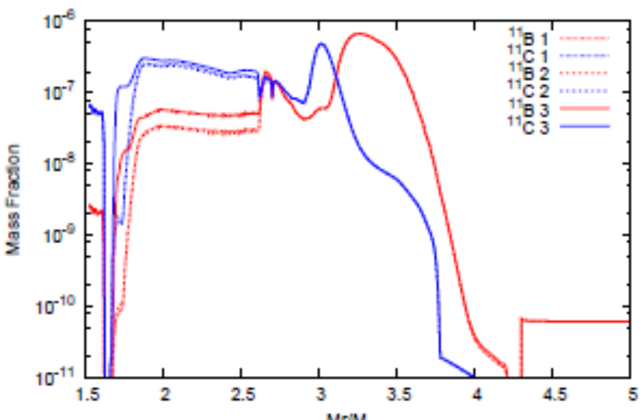
| | $15M_\odot$ モデル | | | $20M_\odot$ モデル | | |
|---|---|---|---|---|---|---|
| 核種生成量 | Case 1 | Case 2 | Case 3 | Case 1 | Case 2 | Case 3 |
| $M(^{11}\mathrm{B})$ | 2.94 | 2.92 | 3.13 | 6.77 | 6.58 | 7.66 |
| $M(^{11}\mathrm{C})$ | 2.80 | 2.71 | 3.20 | 9.33 | 8.91 | 9.64 |
| $M(^{11}\mathrm{B}+^{11}\mathrm{C})$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

T. Yoshida

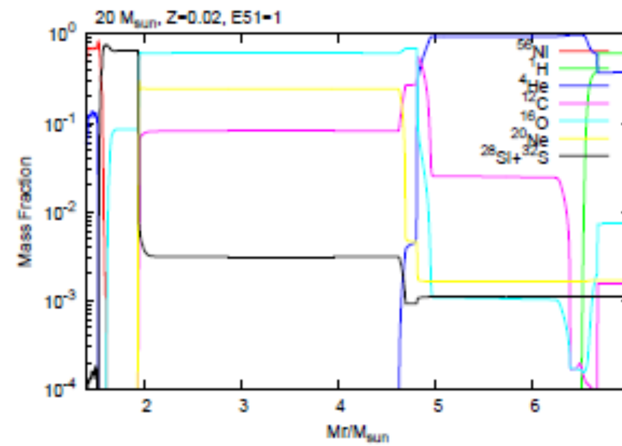
Case1: previous branches used in $^{16}$O ($\gamma$, n, p, $\alpha$-emissions) and HW92 cross sections
Case2: previous branches, and new cross sections
Case3: multi-particle branches and new cross sections

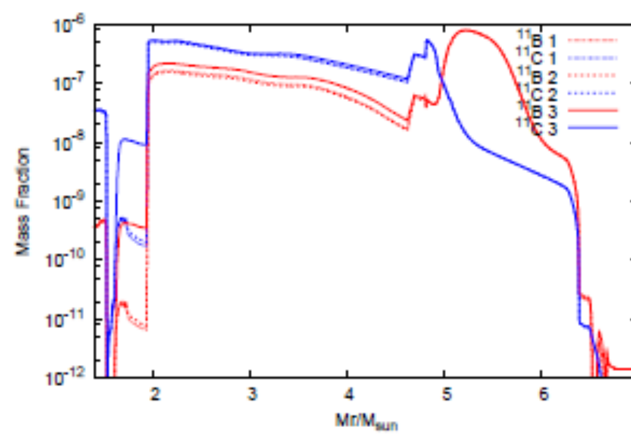
$15M_\odot$




$20M_\odot$



## ▪ ν- $^{40}$Ar reactions

Liquid argon = powerful target for SNν detection

VMU= Monopole-based universal interaction

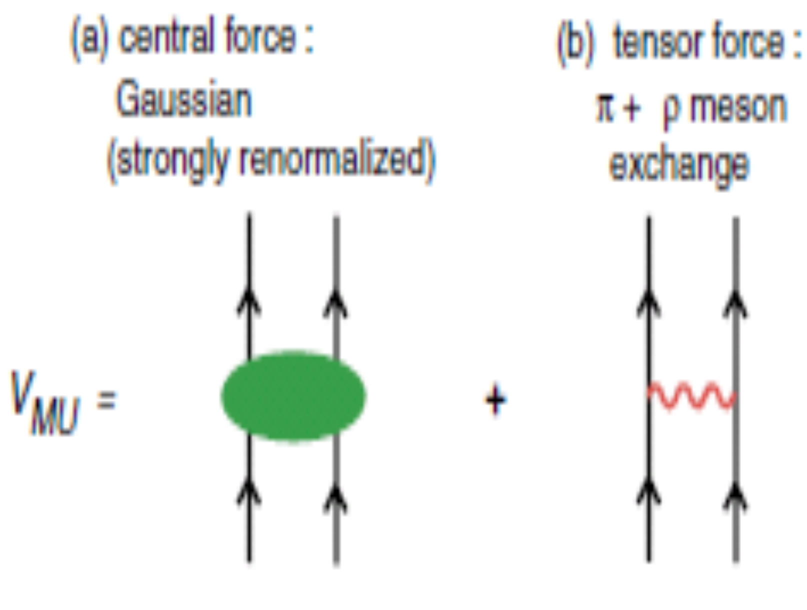



FIG. 2 (color online). Diagrams for the $V_{MU}$ interaction.

**Important roles of tensor force**

Otsuka, Suzuki, Honma, Utsuno, Tsunoda, Tsukiyama, Hjorth-Jensen PRL 104 (2010) 012501

tensor force: bare≈renormalized

○ sd-pf shell: **$^{40}$Ar (ν, e$^-$) $^{40}$K**

SDPF-VMU-LS

sd: SDPF-M (Utsuno et al.)

fp: GXPF1 (Honma et al.)

sd-pf: VMU + 2-body LS

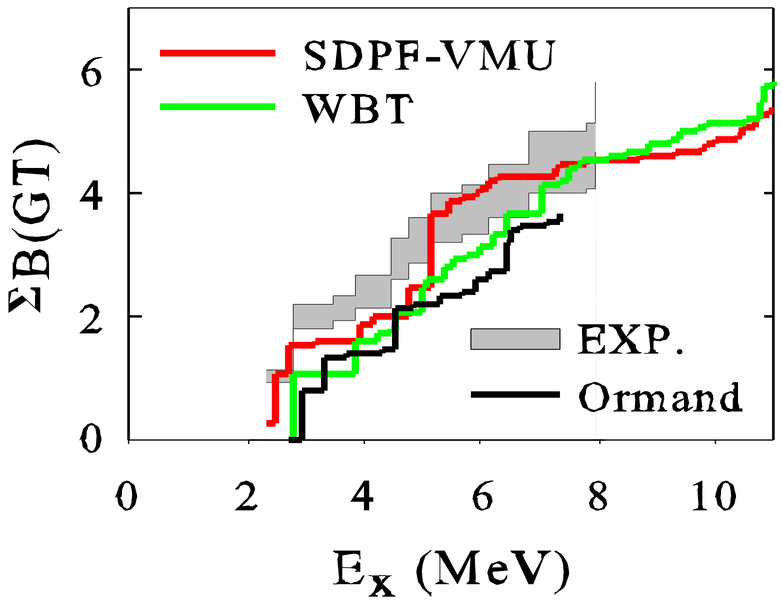
$(sd)^{-2}\ (fp)^{2}$ : 2hw

B(GT) & ν-$^{40}$Ar cross sections

Solar ν cross sections folded over $^{8}$B ν spectrum

Suzuki and Honma, PR C87, 014607 (2013)

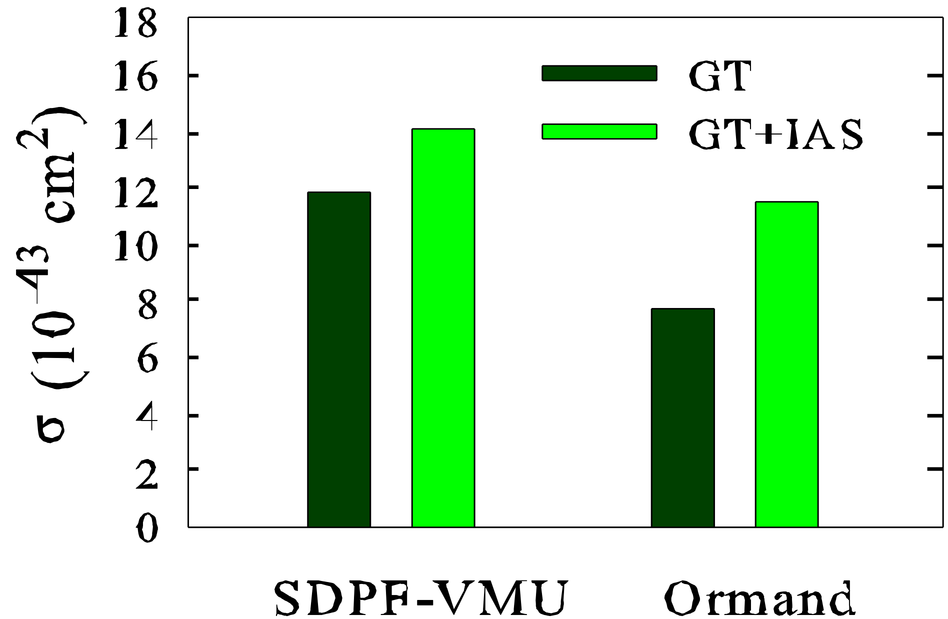
$^{40}$Ar -> $^{40}$K



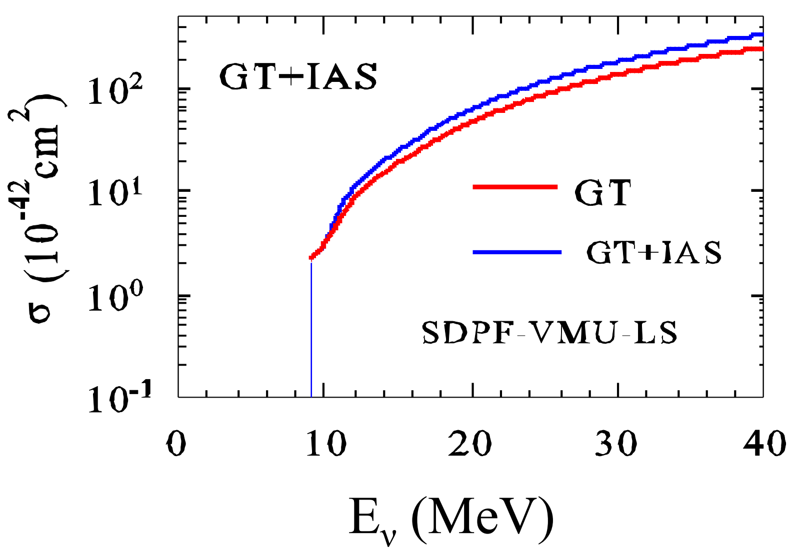

GT+IAS
$E_e$ > 5 MeV : ICARUS

Solar ν cross sections folded over $^8$B ν spectrum

$^{40}$Ar (ν, e$^-$) $^{40}$K




$^{40}$Ar -> $^{40}$K

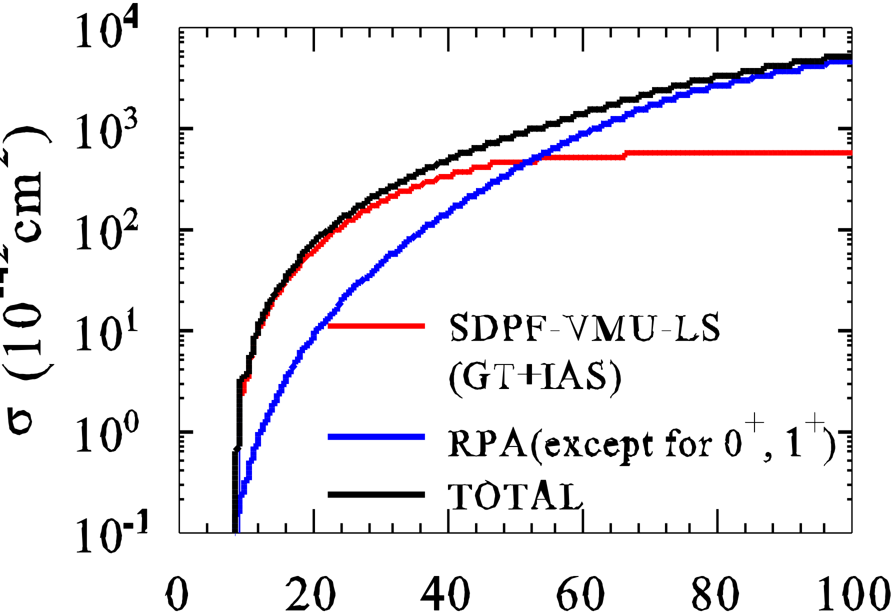


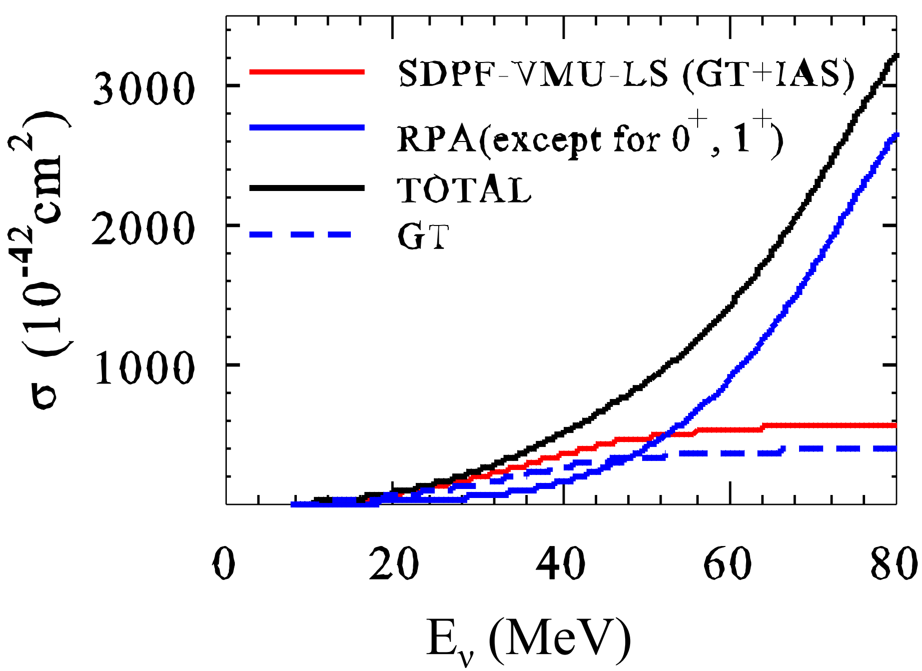

IAS: C0+L0 $\approx [(q^2-\omega^2)/q^2]^2 \times C$ ; $^+$ C0 only
GT: $E_1^5 + M1 + C_1^5 + L_1^5$ ; $^+$ $E_1^5$ only

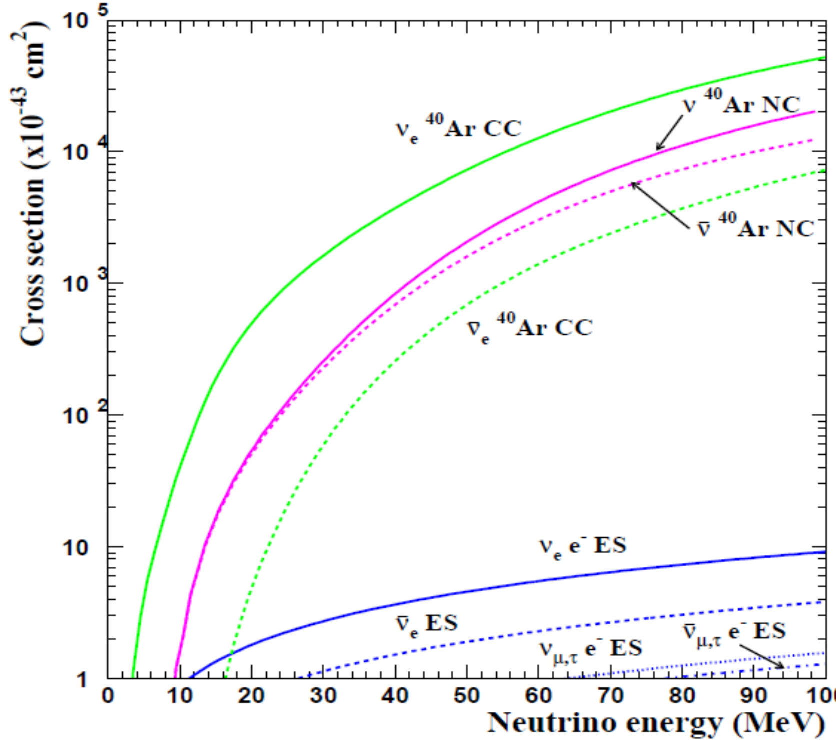
$^+$Ormand et al, PL B345, 343 (1995)

(p,n) Bhattacharya et al., PR C80, 055501 (2009)

# $^{40}Ar \rightarrow {}^{40}K$



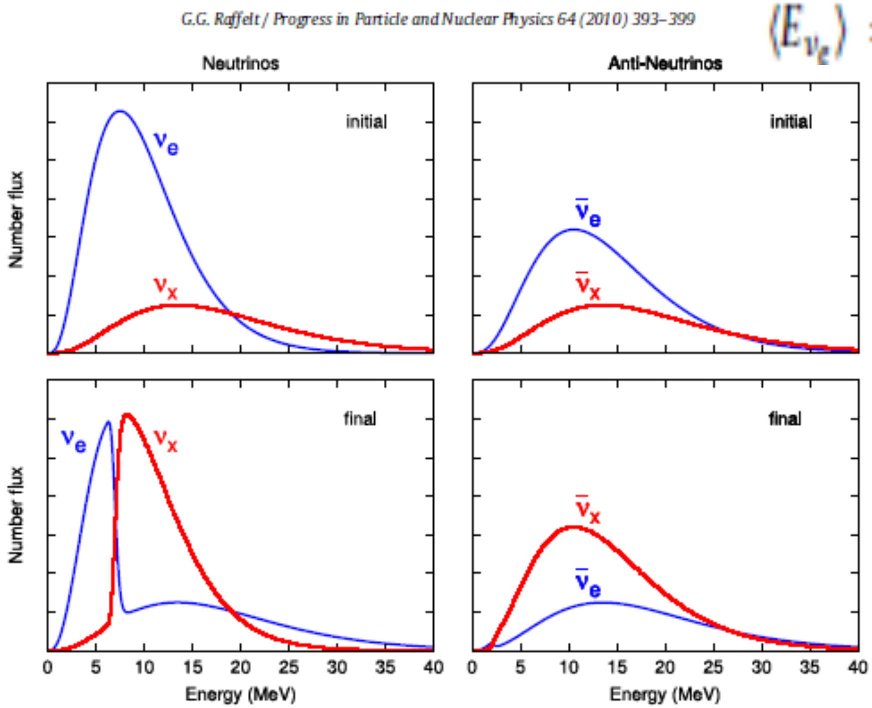




E. Kolbe, K. Langanke, G. Mart´ınez-Pinedo, and P. Vogel, J. Phys. G **29**, 2569 (2003);
I. Gil-Botella and A. Rubbia, JCAP **10**, 9 (2003).

# Spectrum with $\nu$-oscillations

- With collective oscillation effects




$\langle E_{\nu_e}\rangle = 10$, $\langle E_{\bar{\nu}_e}\rangle = 14$ and $\langle E_{\nu_x}\rangle = 18$ MeV.

A: $F_{\nu_e}(E) = F_{\nu_x}(E)$

B:

$F_{\nu_e}(E) = \sin^2\theta_{12}F_{\nu_e}(E)$

$+\cos^2\theta_{12}F_{\nu_x}(E) \quad (E < E_{split})$

$F_{\nu_e}(E) = F_{\nu_x}(E) \quad (E > E_{split})$

- With collective and MSW effects

$$F_{\nu_e}(E) = p(E)F^0_{\nu_e}(E) + [1 - p(E)]F^0_{\nu_x}(E),$$

Survival probabilities including collective effects for the scenario described in the text.

| Scenario | Hierarchy | $\sin^2\Theta_{13}$ | $p(E < E_{split})$ | $p(E > E_{split})$ | $\bar{p}(E)$ | Earth effects |
|---|---|---|---|---|---|---|
| A | Normal | $\gtrsim 10^{-3}$ | 0 | 0 | $\cos^2\Theta_\odot$ | $\bar{\nu}_e$ |
| B | Inverted | $\gtrsim 10^{-3}$ | $\sin^2\Theta_\odot$ | 0 | $\cos^2\Theta_\odot$ | $\bar{\nu}_e$ |
| C | Normal | $\lesssim 10^{-5}$ | $\sin^2\Theta_\odot$ | $\sin^2\Theta_\odot$ | $\cos^2\Theta_\odot$ | $\nu_e$ and $\bar{\nu}_e$ |
| D | Inverted | $\lesssim 10^{-5}$ | $\sin^2\Theta_\odot$ | 0 | 0 | – |

# Cross sections folded over the spectra

- Target = $^{13}C$ $\langle E_{\nu_e} \rangle = 10$, $\langle E_{\bar{\nu}_e} \rangle = 14$ and $\langle E_{\nu_x} \rangle = 18$ MeV.

| | A (normal) | B (inverted) |
|---|---|---|
| no oscillation | 8.01 | 8.01 ($10^{-42}cm^2$) |
| collective osc. | 8.01 | 39.44 |
| collective +MSW | 39.31 | 39.35 |

- Target = $^{48}Ca$ Q($^{48}Ca$-$^{48}Sc$)=2.8 MeV E($1^+$; $^{48}Sc$) = 2.5 MeV

| | A (normal) | B (inverted) |
|---|---|---|
| no oscillation | 73.56 | 73.56 ($10^{-42}cm^2$) |
| collective osc. | 73.56 | 303.4 |
| collective +MSW | 302.6 | 302.8 |

$E_{split}$ is too small to distinguish the ν-mass hierarchy in case of Collect.+MSW oscillations

# Summary

- **New ν –induced cross sections based on new shell-model Hamiltonians with proper tensor forces (SFO for p-shell, GXPF1 for pf-shell, VMU)**

- **Good reproduction of experimental data for $^{12}$C (ν, e$^-$) $^{12}$N, $^{12}$C (ν, ν’) $^{12}$C and $^{56}$Fe (ν, e$^-$) $^{56}$Co**

- **Effects of ν-oscillations in nucleosynthesis**
  **abundance ratio of $^{7}$Li/$^{11}$B → ν mass hierarchy**
  **inverted hierarchy vs. normal hierarchy**

- **New ν capture cross sections on $^{13}$C by SFO**
  **Enhanced solar ν cross sections compared to CK**
  **Detection of low-energy reactor anti-ν**

- **New ν capture cross sections on $^{16}$O by SFO-tls**
  **Production of $^{11}$B by $^{16}$O(ν, ν’αp)$^{11}$B**

- **GXPF1J well describes the GT strengths in Ni isotopes :**
  **$^{56}$Ni two-peak structure confirmed by recent exp.**

**→ 1. Accurate evaluation of e-capture rates at stellar environments**

**2. Large p-emission cross section for $^{56}$Ni and production of more $^{55}$Mn in Pop. III stars**

- **VMU for sd-pf-shell:**
  **GT strength consistent with (p, n) reaction**

**→ new cross section for $^{40}$Ar (ν,e$^{-}$) $^{40}$K induced by solar ν**

**Suzuki and Honma, PR C87, 014607 (2013)**

- **Identification of ν-spectrum with oscillations (collective + MSW) by low-energy ν scattering is not easy as $E_{split}$ is not large enough.**

# ▪ ν- $^{56}$Ni reactions and synthesis of $^{55}$Mn

New shell-model Hamiltonains in pf-shell

**GXPF1**: Honma, Otsuka, Mizusaki, Brown, PR C65 (2002); C69 (2004)

**KB3:** Caurier et al, Rev. Mod. Phys. 77, 427 (2005)

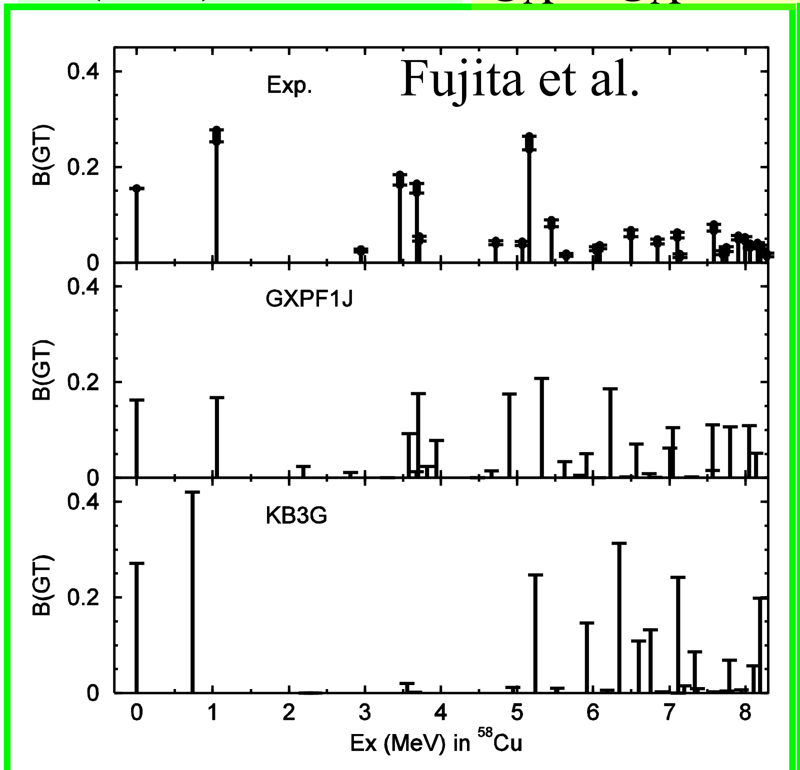
○ KB3G A = 47-52 KB + monopole corrections

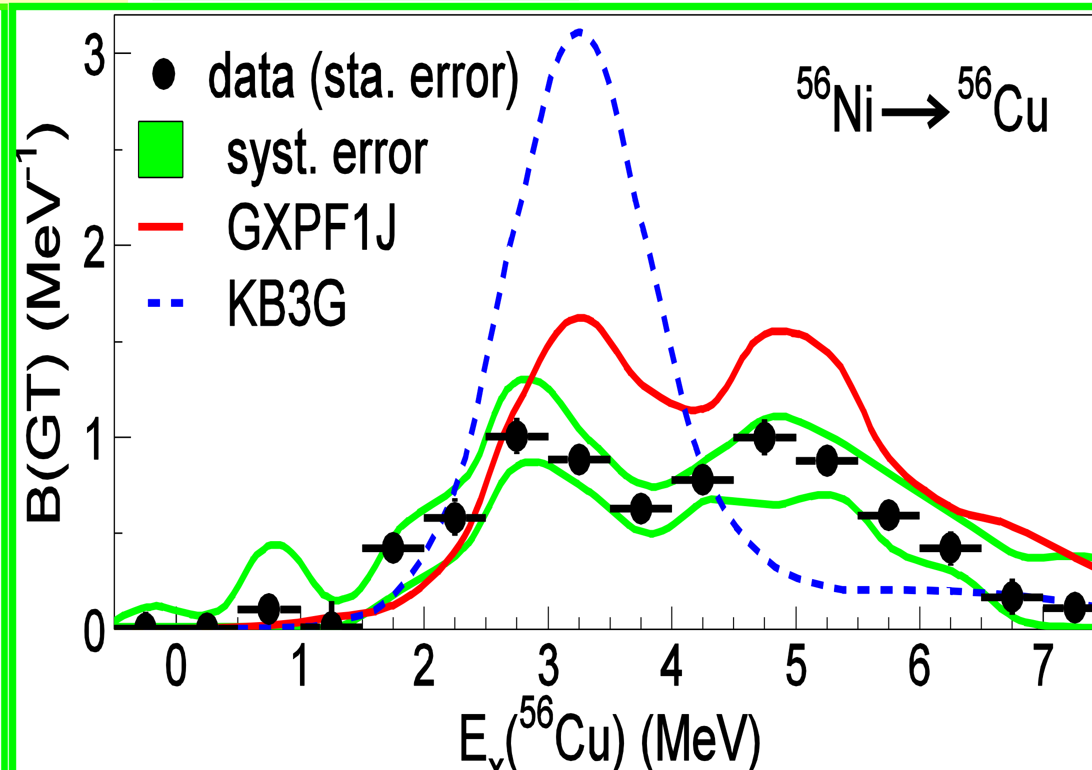
○ GXPF1 A = 47-66

▪ **Spin properties of fp-shell nuclei are well described**

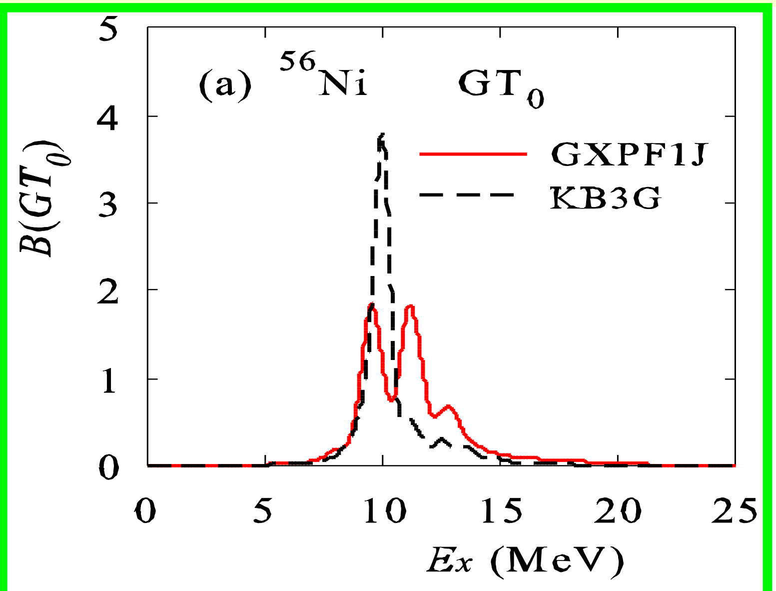
B(GT_) for $^{58}$Ni $g_A^{eff}/g_A^{free}$=0.74 B(GT) for $^{56}$Ni

Sasano et al., PRL 107, 202501 (2011)



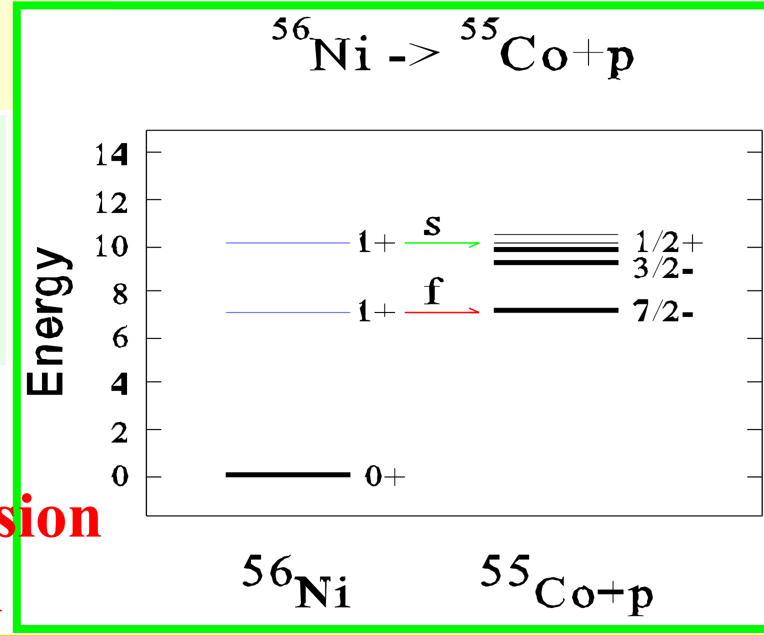



# • $^{56}$Ni (ν, ν') $^{56}$Ni




B(GT)=6.2 (GXPF1J)

B(GT)=5.4 (KB3G)

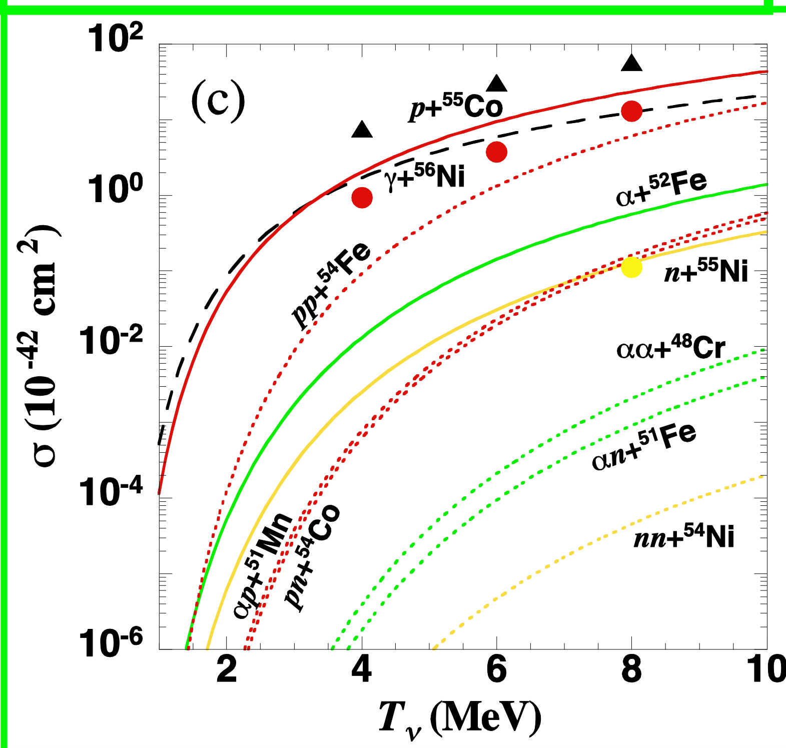



**large p emission cross section**

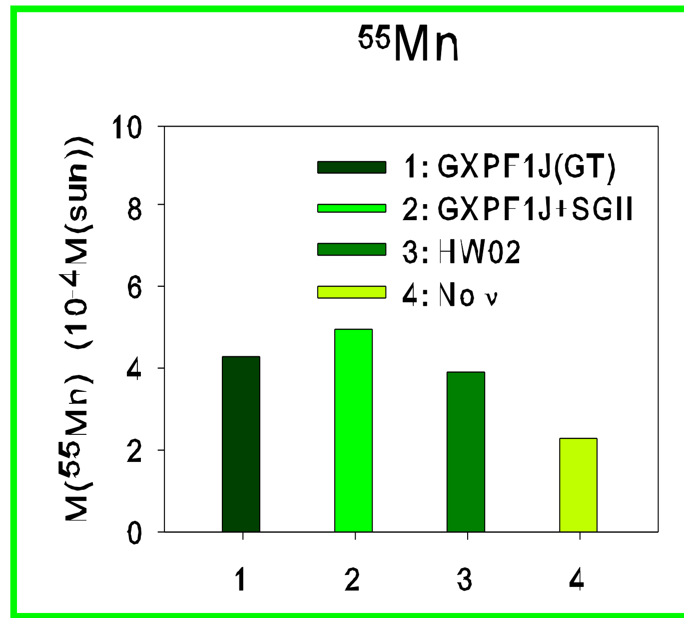
## Synthesis of Mn in Population III Star

$^{56}\mathrm{Ni}(\nu,\nu' p)^{55}\mathrm{Co}$, $^{55}\mathrm{Co}(e^-,\nu)^{55}\mathrm{Fe}(e^-,\nu)^{55}\mathrm{Mn}$

$^{54}\mathrm{Fe}(p,\gamma)^{55}\mathrm{Co}$




cf:
HW02
▲ gamma
● p
○ n




**Suzuki, Honma et al., PR C79, 061603(R) (2009)**