Neutrino-Nucleus Reactions induced by Solar and Supernova Neutrinos

“nuclear structure, ν-process nucleosynthesis
neutrino properties (mass hierarchy)
ν-detection, cooling of stars”

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ν-nucleus reactions <-> spin-dependent excitations in nuclei

- New shell-model Hamiltonians which describes well spin modes in nuclei -> New ν-nucleus reaction cross sections

1. ν-^{12}C with SFO (p-shell)
   Light-element nucleosynthesis in supernova explosions
   ν-oscillation effects and ν-mass hierarchy
2. ν- ^{13}C and low-energy ν detection by ^{13}C
   Cross sections induced by solar ν
3. ν-^{56}Fe, ν-^{56}Ni and e-captures on Ni isotopes with GXPF1J
4. ν- ^{40}Ar with VMU (monopole-based universal interaction)

＊important roles of tensor force

- Detailed e-capture and beta-decay rates for URCA nuclear pairs in 8-10 solar-mass stars (A=23, 25, 27)
  USDB (sd-shell): Cooling of O-Ne-Mg core by URCA

Collaborators

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1. Neutrino-induced Reactions on ^{12}C and Light-Element Nucleosynthesis in Supernova Explosions

New shell-model Hamiltonian in p-shell

p-shell（p-sd） Cohen-Kurath+Millener-Kurath → SFO

[p: CK (8-16)2BME, p-sd: MK, sd, p2-(sd)2: Kuo’s G-matrix]

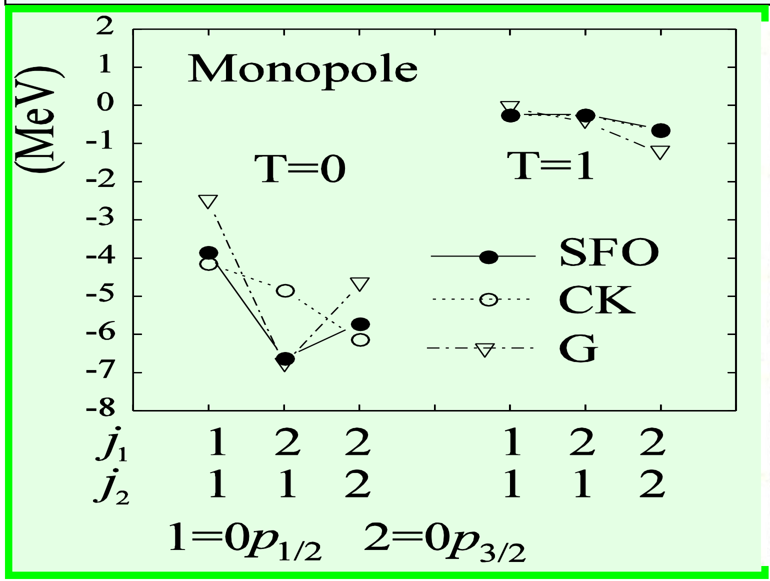
Monopole terms in p1/2-p3/2 , T=0 enhanced：ΔV = -1.9 MeV

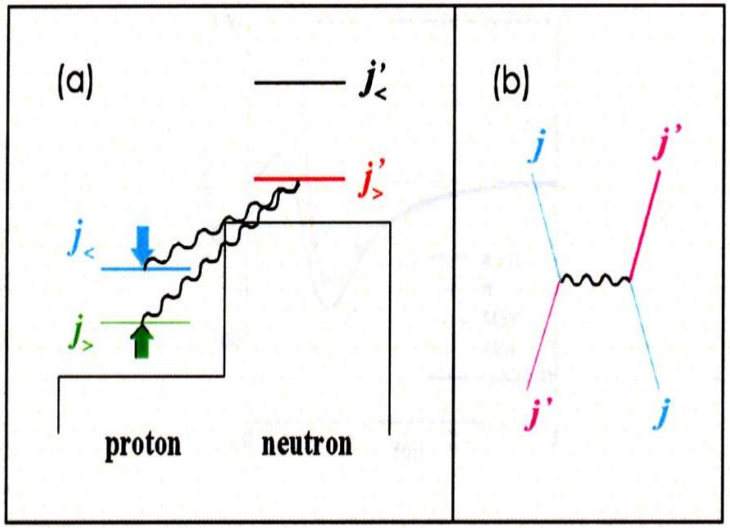
SFO: Suzuki, Fujimoto, Otsuka, PR C67, 044302 (2003)

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

Proper tensor components:

Attractive (repulsive) between p1/2-p3/2 (p1/2-p1/2, p3/2-p3/2)





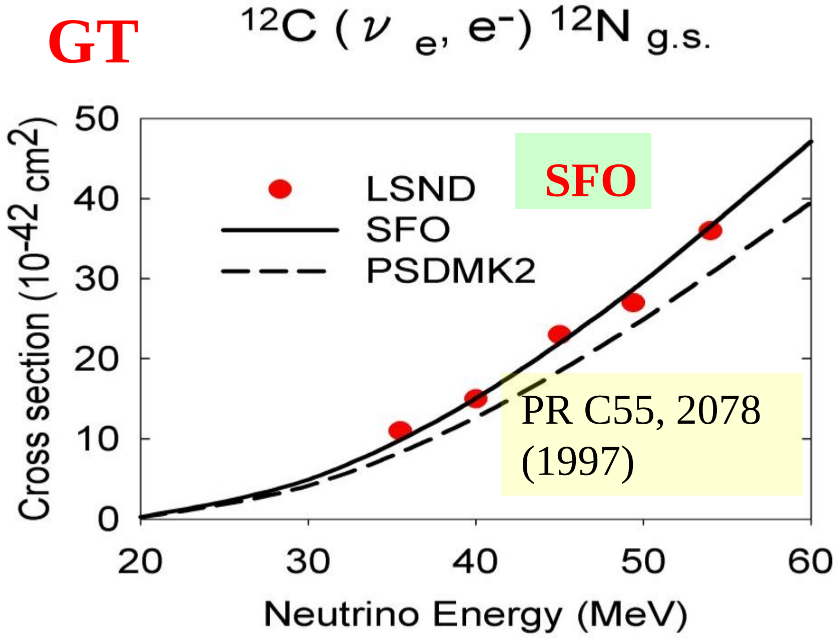
Change of magic number toward drip-lines:
e.g. 8 → 6

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

Systematic improvements in the magnetic moments and GT transitions in p-shell nuclei (^{12}C, ^{14}C) .

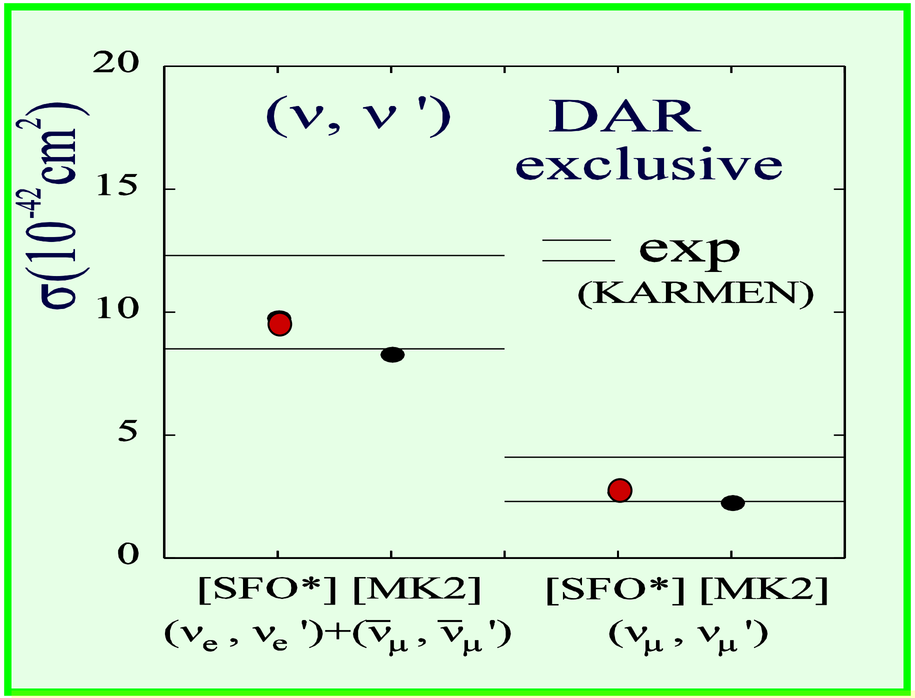
SFO*: g_A^{eff}/g_A=0.95
B(GT: 12C)_cal = experiment

GT

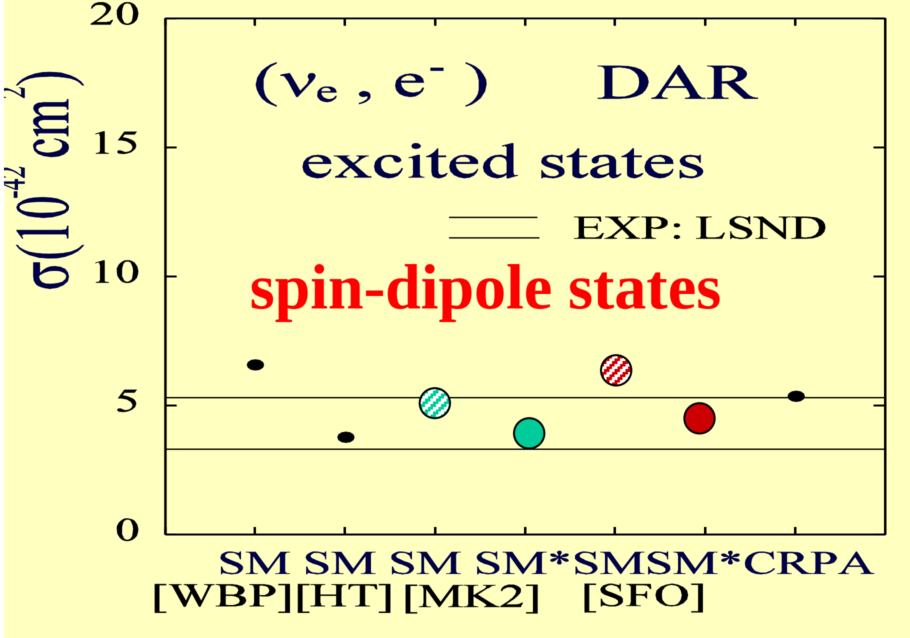


SFO

PR C55, 2078 (1997)



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



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

Nucleosynthesis processes of light elements

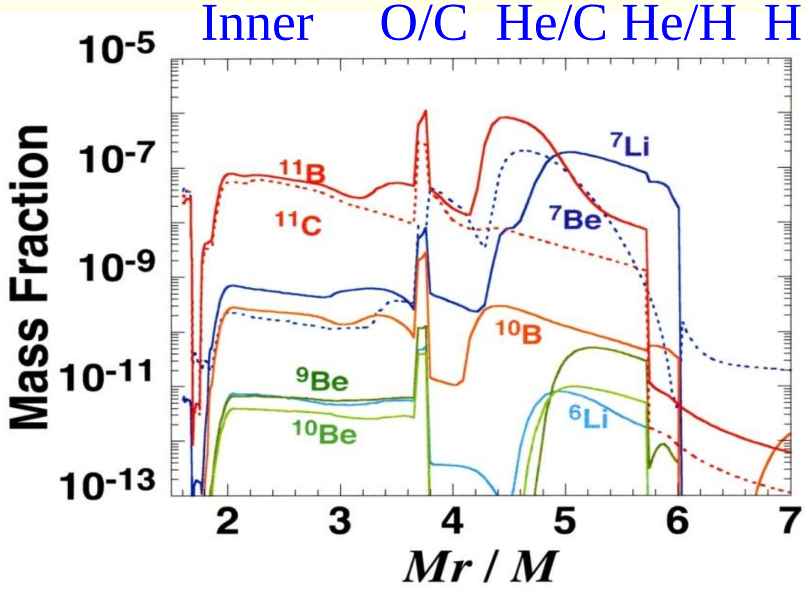
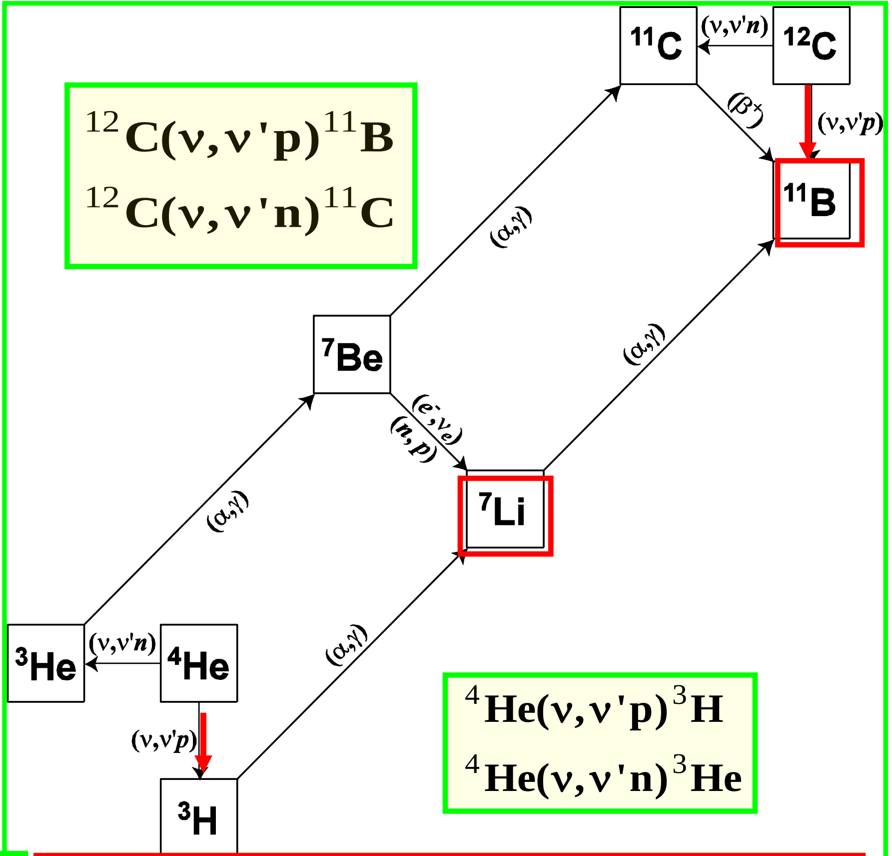


Fig. 4.— Mass fraction distribution of Model 1. The mass fractions of ^{7}Li and ^{7}Be, and ^{11}B and ^{11}C are separated.



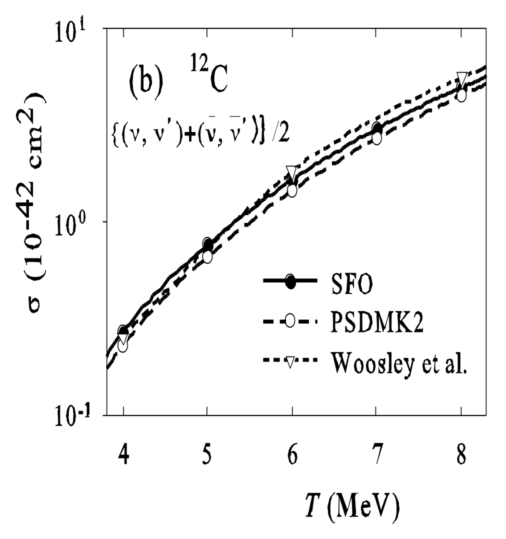
^{12}C(ν,ν'p)^{11}B

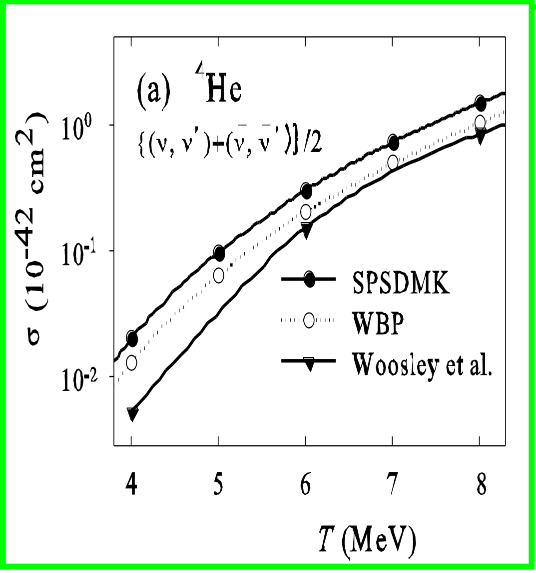
^{12}C(ν,ν'n)^{11}C

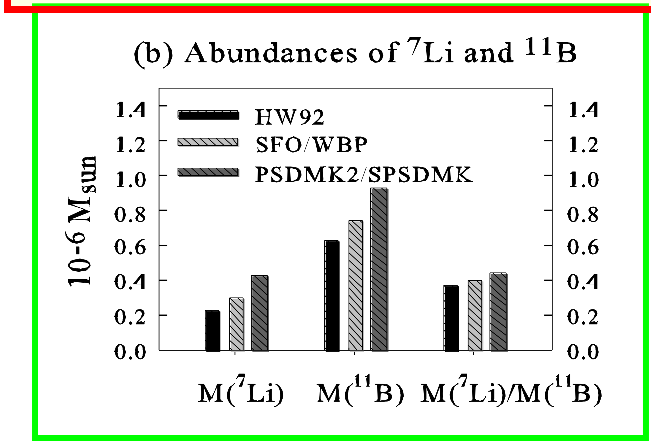
^{4}He(ν,ν'p)^{3}H

^{4}He(ν,ν'n)^{3}He

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





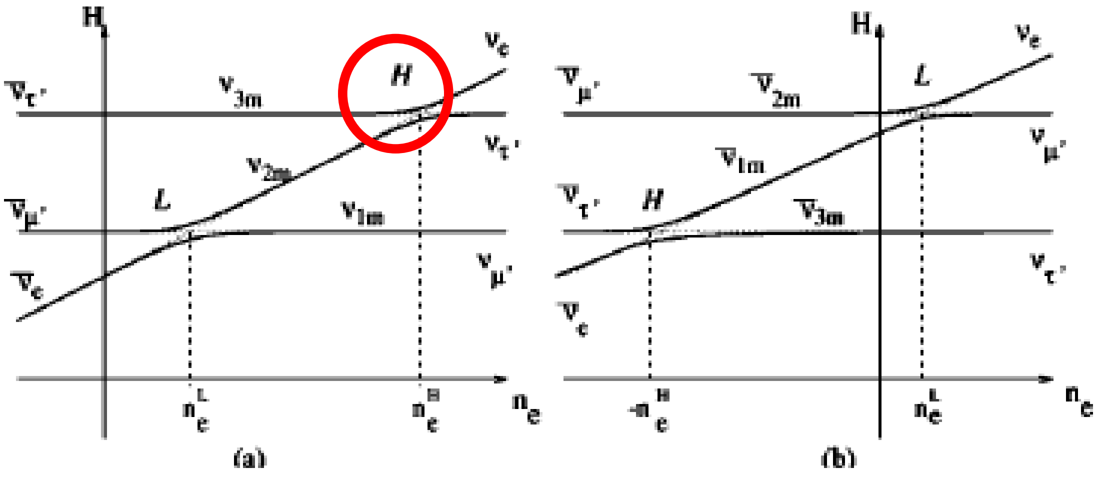


ν oscillations

MSW effects

Normal hierarchy

Inverted hierarchy



Normal – hierarchy

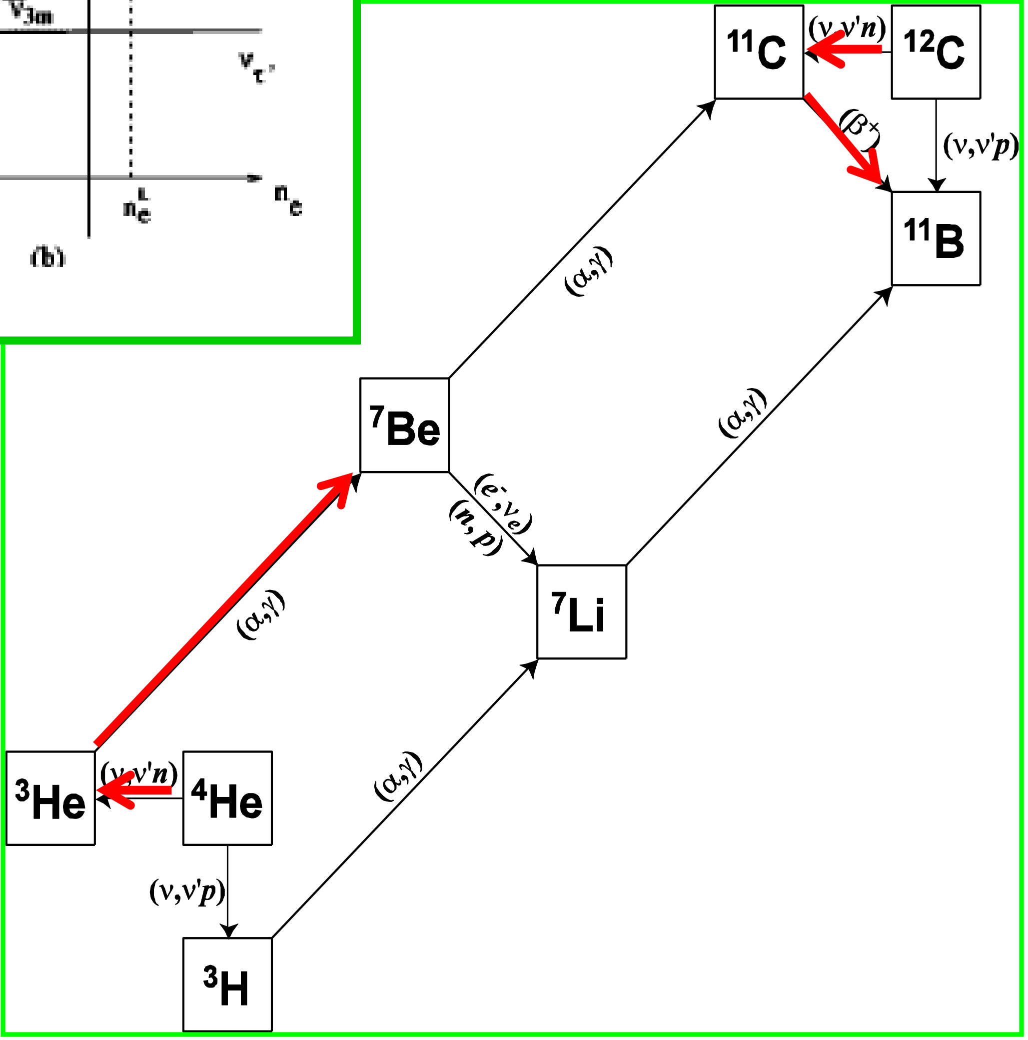
$$\nu_\mu, \nu_\tau \rightarrow \nu_e$$

Increase in the rates of charged-current reactions

4He$(\nu_e, e^- p)$**3He**

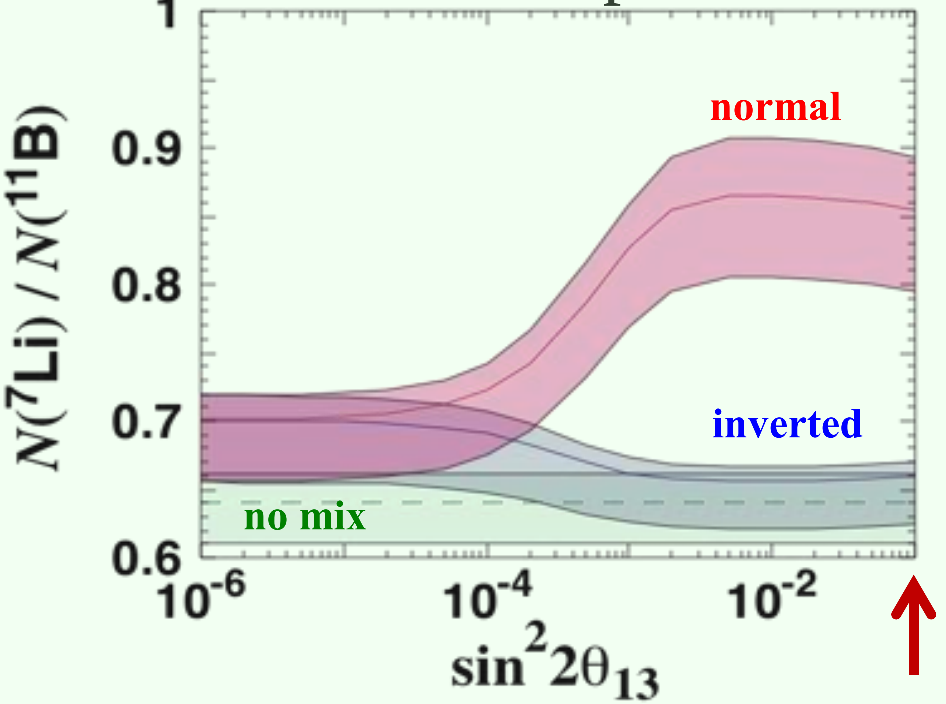
12C$(\nu_e, e^- p)$**11C**

in the He layer



^{7}Li/^{11}B Dependence on Mass Hierarchy and θ_{13}

- $N(^{7}\mathrm{Li})/N(^{11}\mathrm{B})$ ➡ Good indicator for neutrino oscillation parameters



Including uncertainties in neutrino temperatures

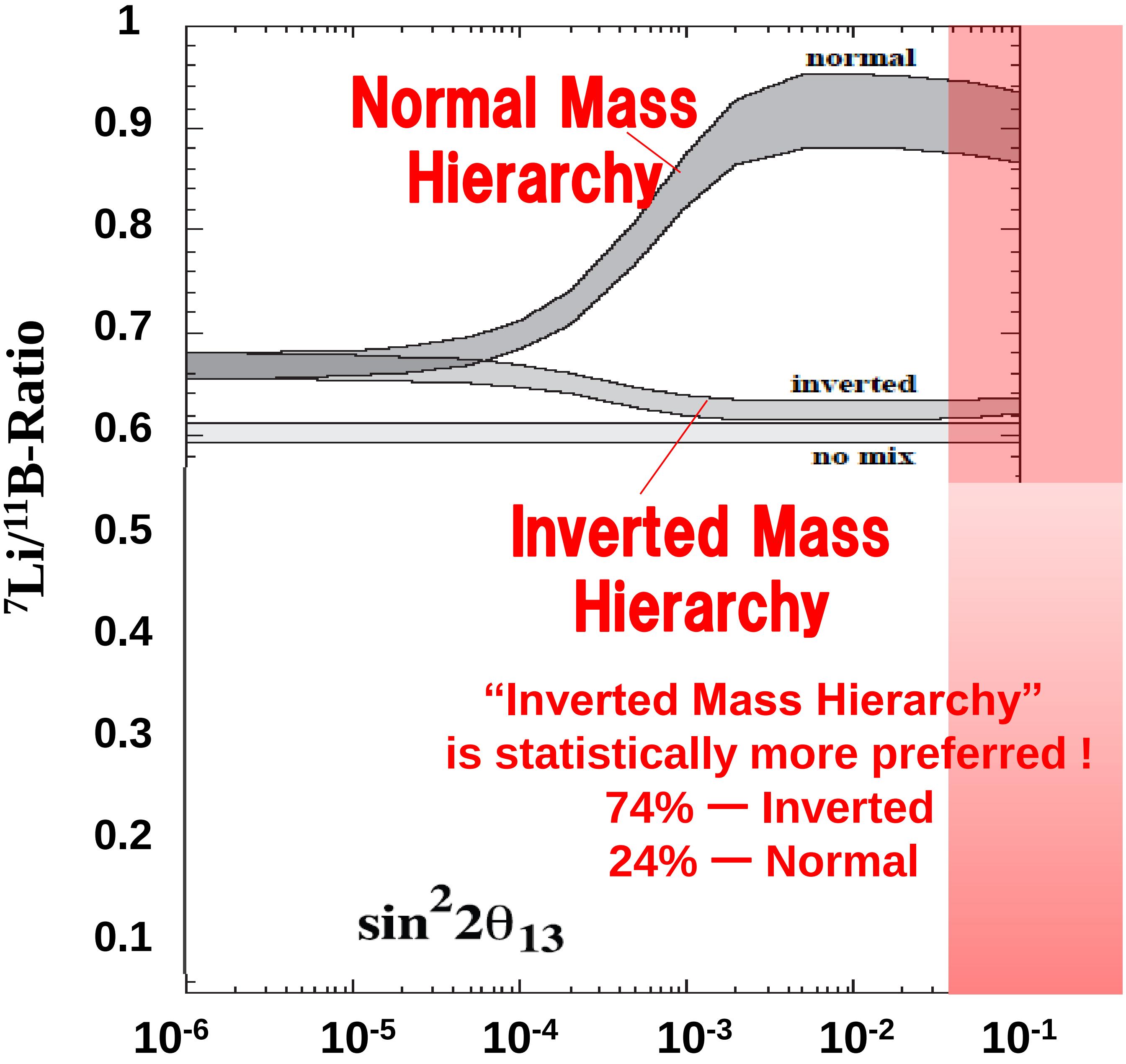
$(T_{\nu e}, T_{\bar{\nu} e}, T_{\nu\mu,\tau}, E_{\nu})$
= (3.2, 5.0, 6.0, 3.0)
, (3.2, 4.8, 5.8, 3.0)
, (3.2, 5.0, 6.4, 2.4)
, (3.2, 4.1, 5.0, 3.5)
, (4.0, 4.0, 6.0, 3.0)
, (4.0, 5.0, 6.0, 3.0)
(MeV, MeV, MeV, $\times 10^{53}$ ergs)

- **Normal** mass hierarchy and **$\sin^2 2\theta_{13} > 0.002$**
  ➡ **$N(7\mathrm{Li})/N(11\mathrm{B}) > 0.8$**
  Possibility for constraining ***mass hierarchy*** and *lower limit of the mixing angle θ_{13}*.

Yoshida et al.,
PRL 96 (2006)

Neutrino experiments ➡ Constraining ***upper limit*** *of θ_{13}*

Supernova X-Grain Coinstraint



Normal Mass Hierarchy

Inverted Mass Hierarchy

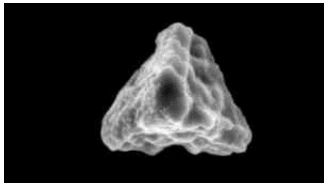
"Inverted Mass Hierarchy"
is statistically more preferred !
74% — Inverted
24% — Normal

Mathews, Kajino, Aoki And Fujiya, Phys. Rev. D85,105023 (2012).

- 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



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

2. ν-induced reactions on ^{13}C

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

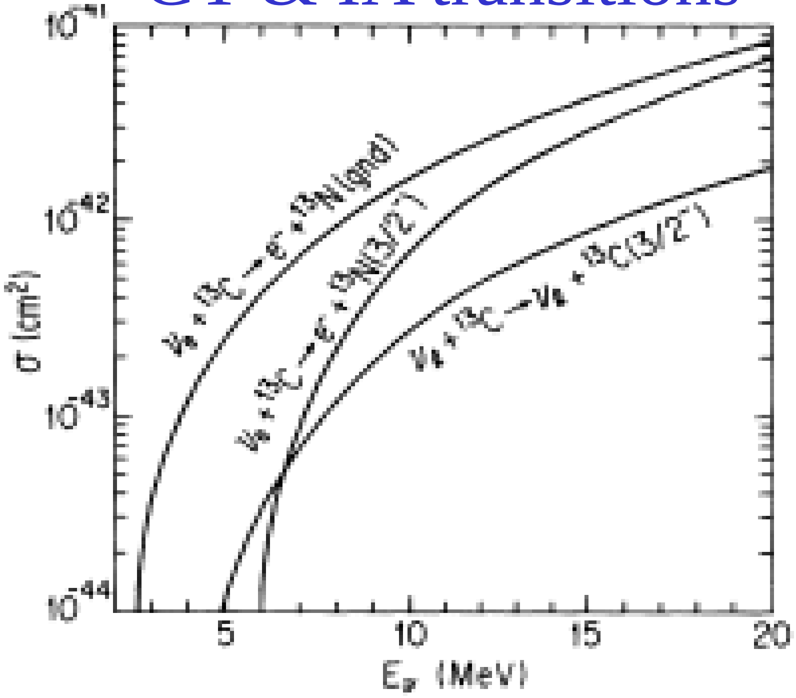
$E_\nu \le 10\,\mathrm{MeV} \quad E_\nu^{th}(^{12}\mathrm{C}) \approx 13\,\mathrm{MeV}$

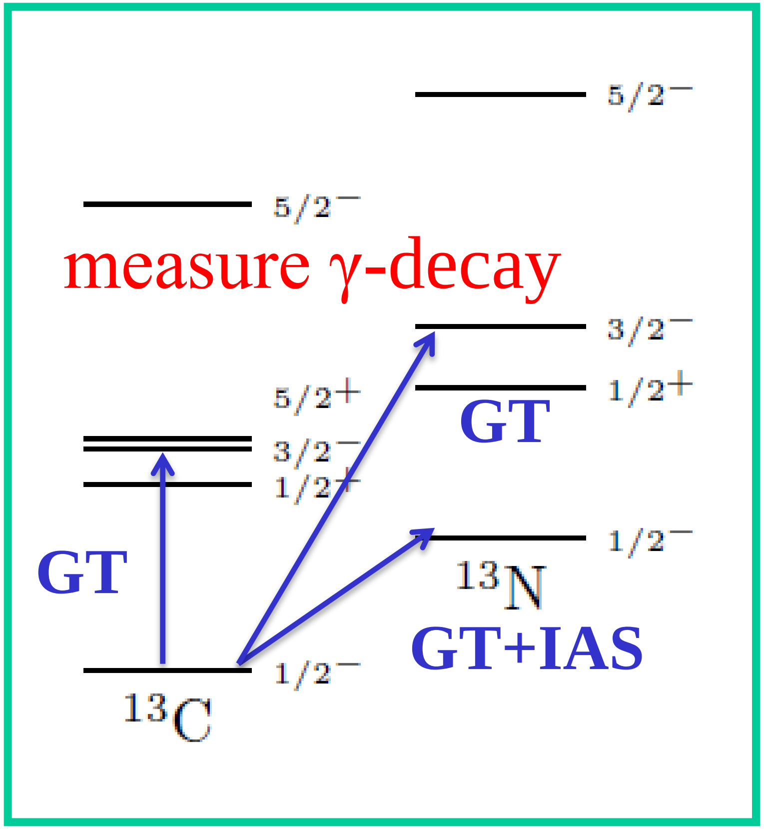
Natural isotope abundance = 1.07%

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

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

GT & IA transitions





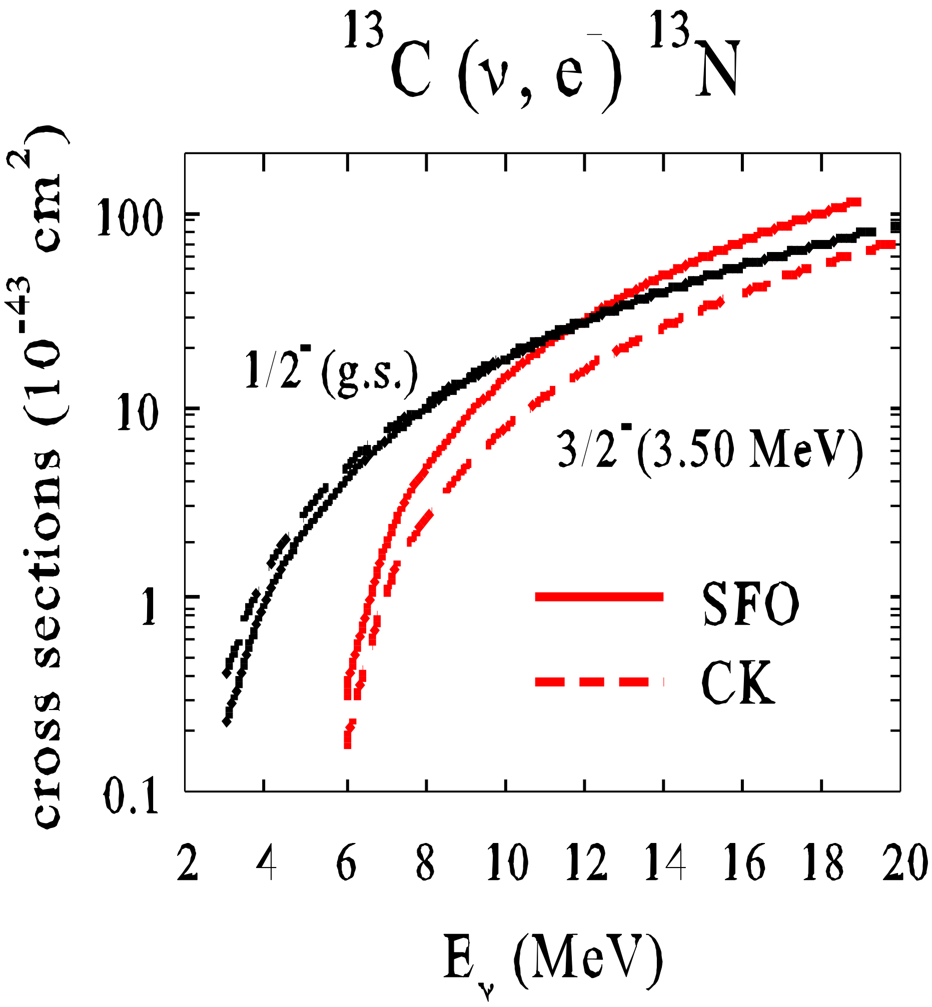
Fukugita et al., PR C41 (1990)

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

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

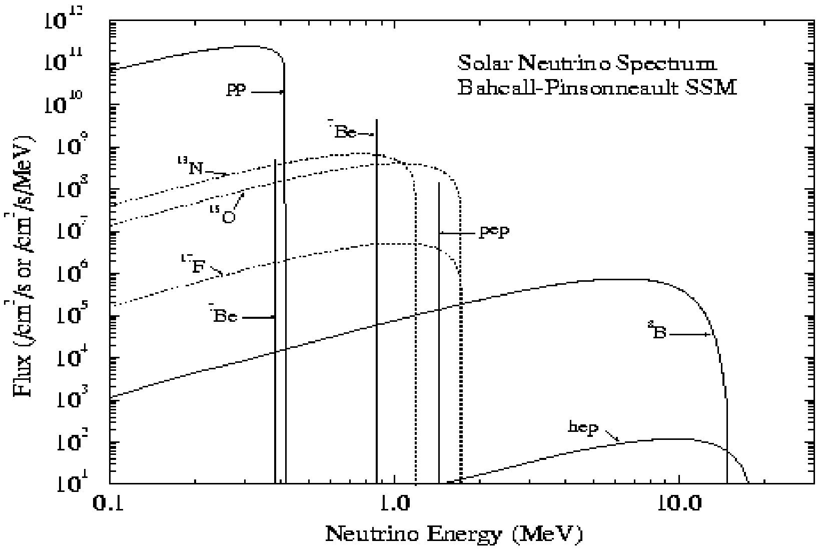
CK: $1.07\times10^{-42}\,\text{cm}^2$

SFO: $1.34\times10^{-42}\,\text{cm}^2$

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

CK: $1.16\times10^{-43}\,\text{cm}^2$

SFO: $2.23\times10^{-43}\,\text{cm}^2$



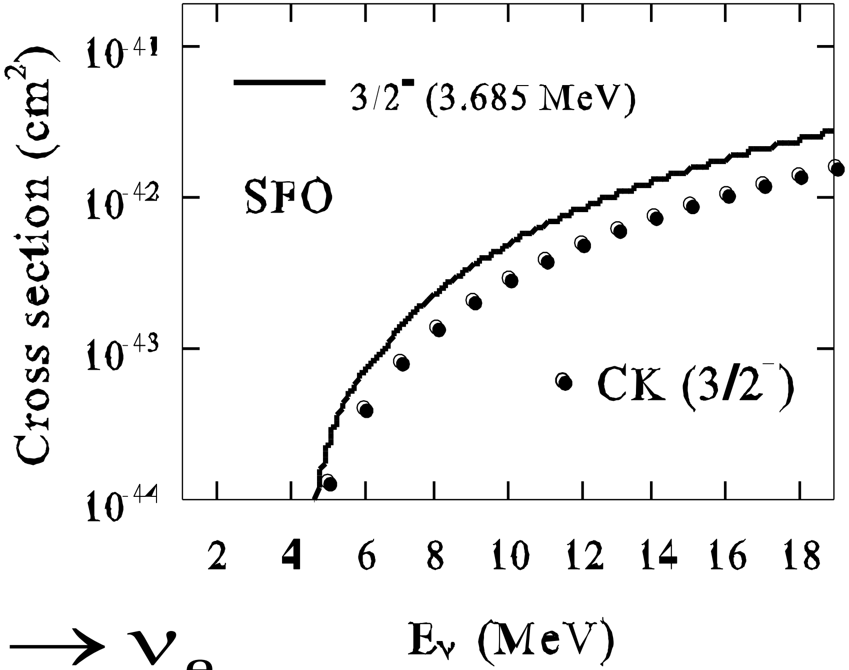
Reactor $\overline{\nu}_e$

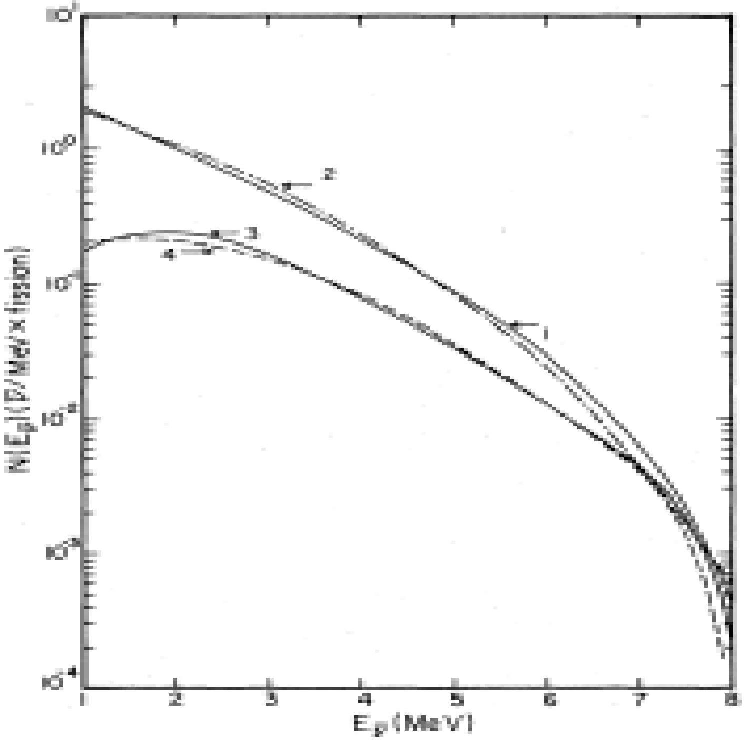
$(\overline{\nu}_e, \overline{\nu}_e) \rightarrow \overline{\nu}_e - \mathrm{flux}$

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

$E_{\overline{\nu}} \leq 8\mathrm{MeV}$

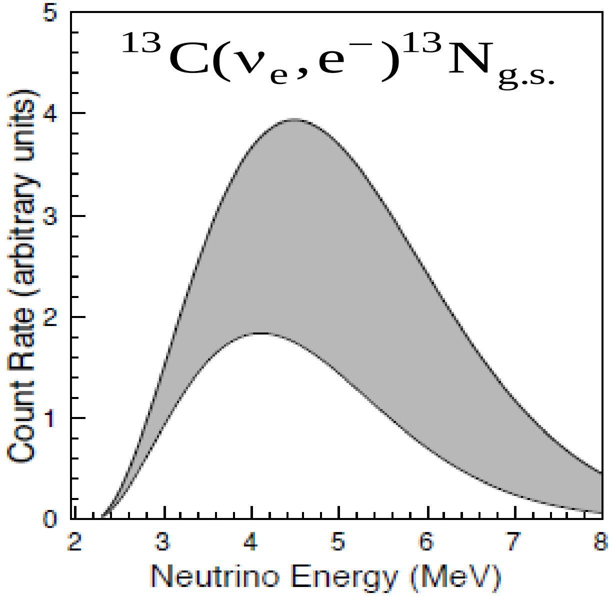
reactor $\overline{\nu}_e$ spectrum



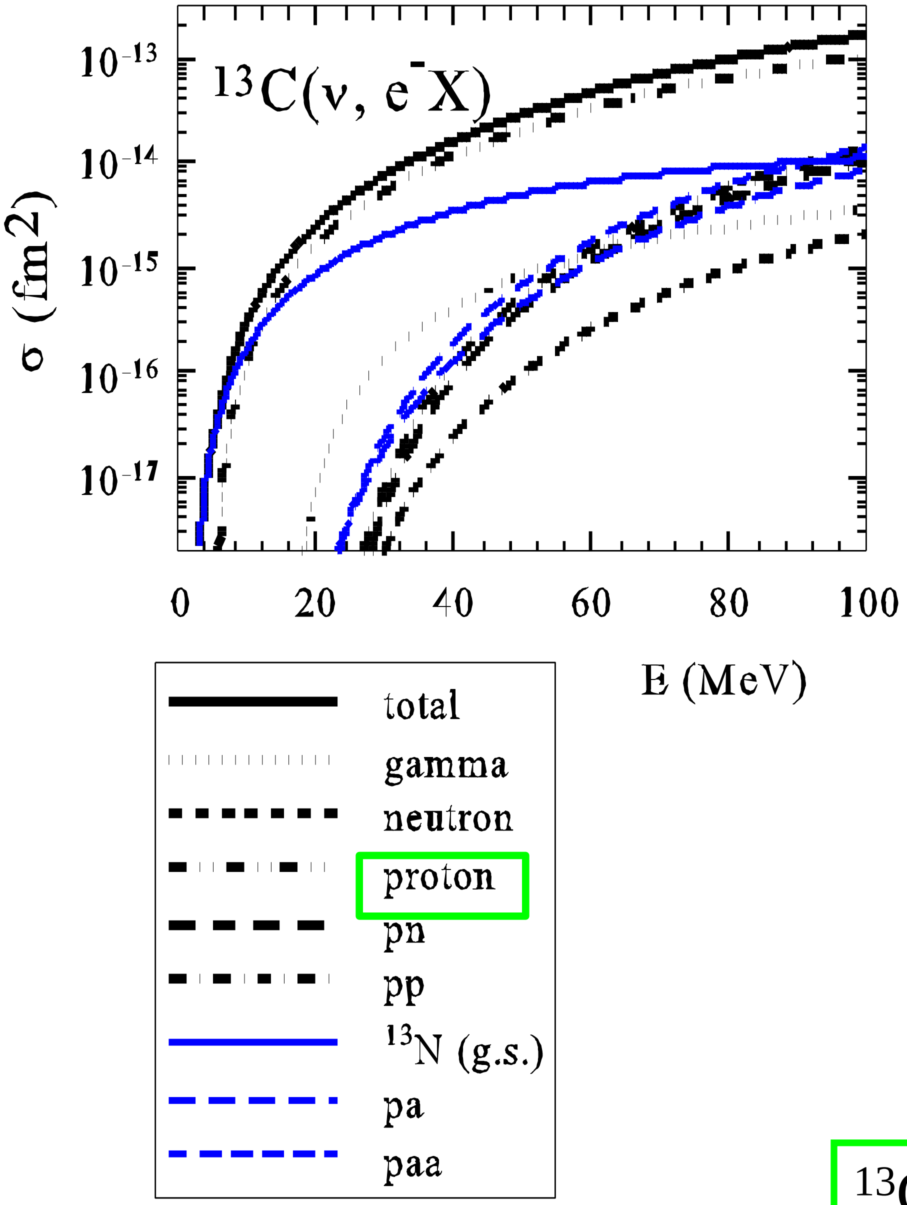


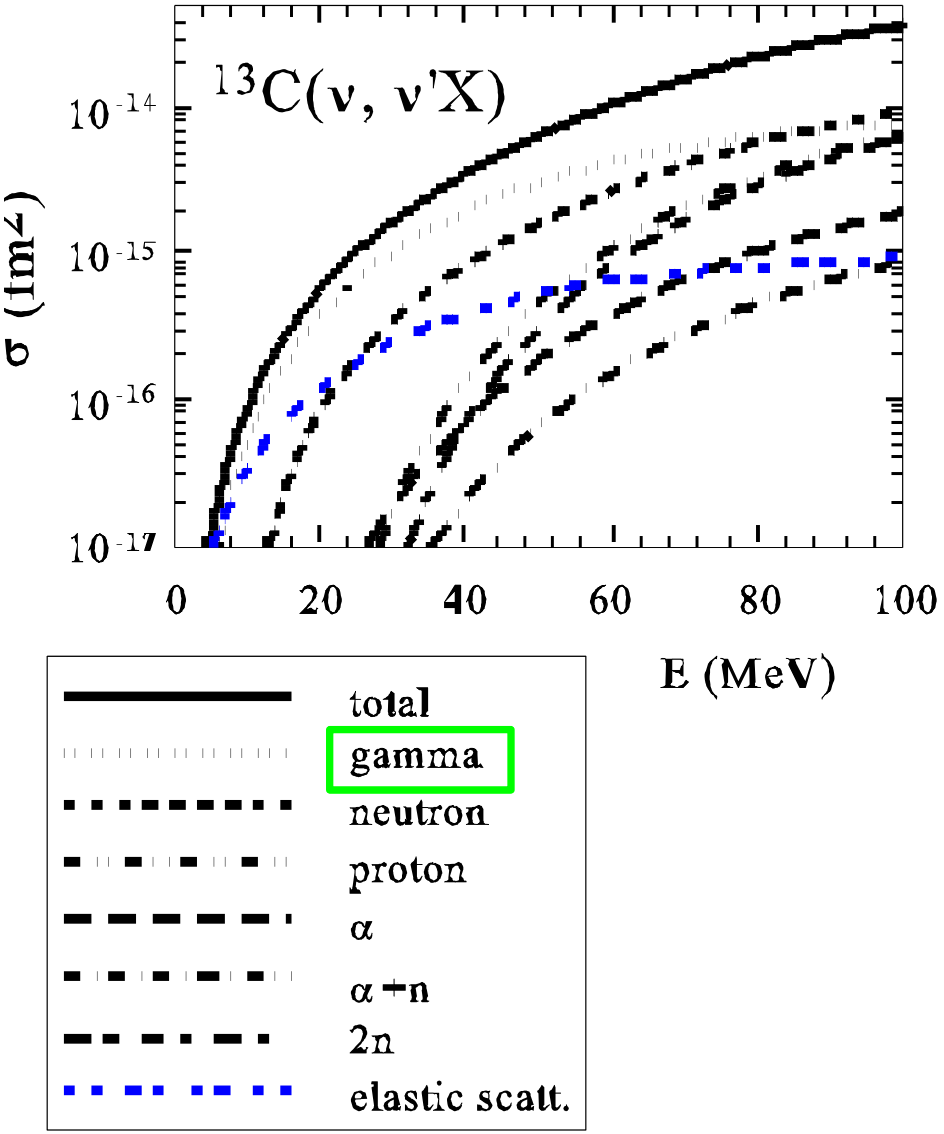
Vogel et al.

$\overline{\nu}_e \rightarrow \nu_e$



Partial cross sections of gamma and particle emissions





^{13}C* ->^{13}C +γ

^{13}C* -> ^{12}C *+ n, ^{12}C (2^+) -> ^{12}C +γ

3. ν- ^{56}Fe, ν- ^{56}Ni and ^{56}Ni (e^-, ν) ^{56}Co Reactions

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

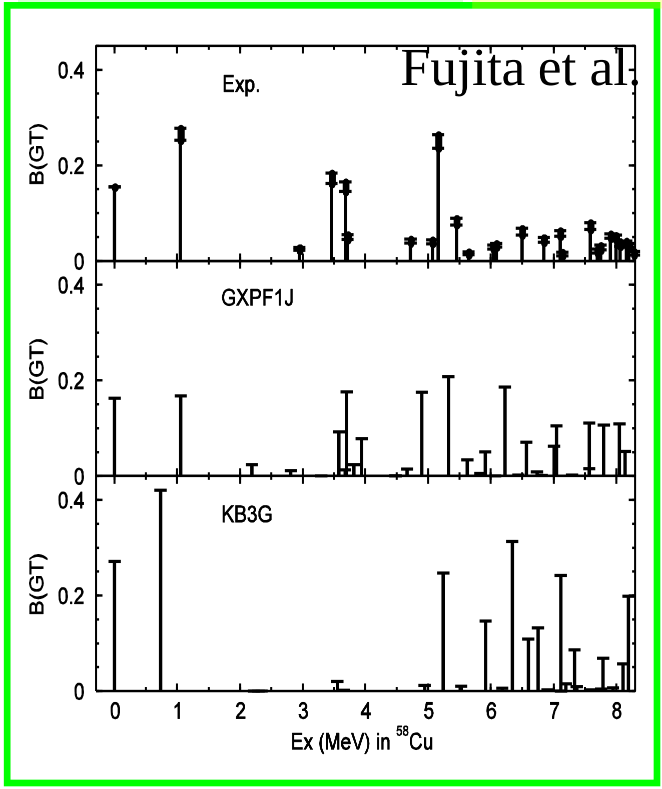
- **Spin properties of fp-shell nuclei are well described**

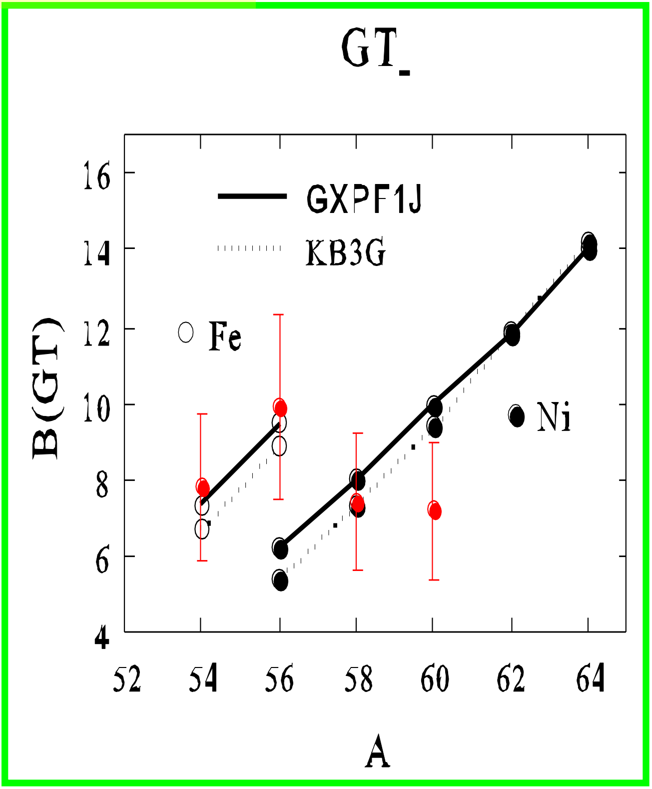
B(GT_-) for ^{58}Ni

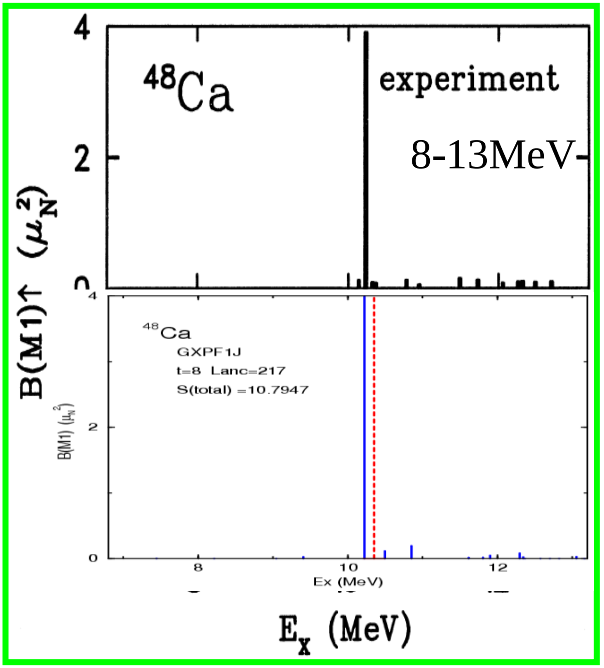
$g_A^{eff}/g_A^{free}=0.74$

M1 strength (GXPF1J)

$g_S^{eff}/g_S=0.75\pm0.2$

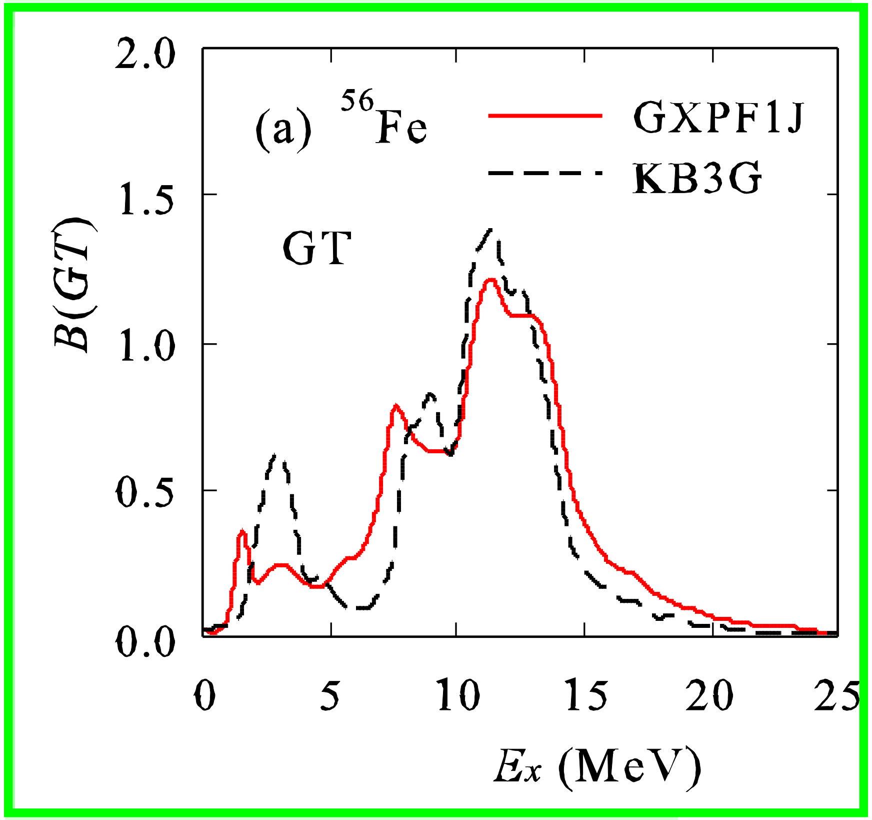


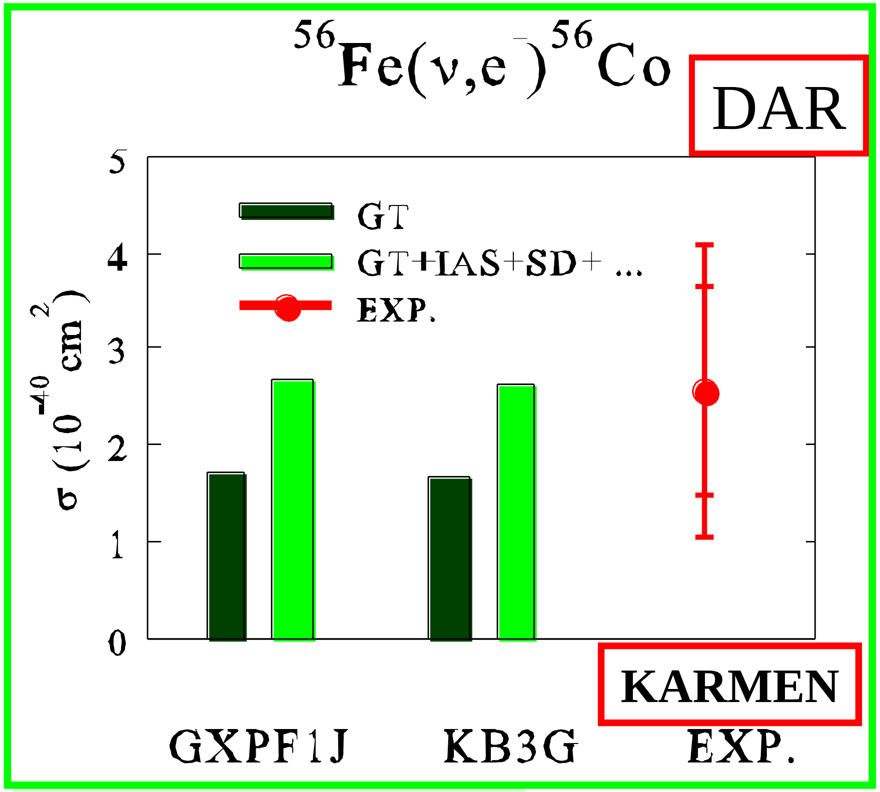




$^{56}\mathrm{Fe}(\nu_e, e^-)^{56}\mathrm{Co}$

GXPF1J Honma et al.
cf. KB3 Caurier et al.





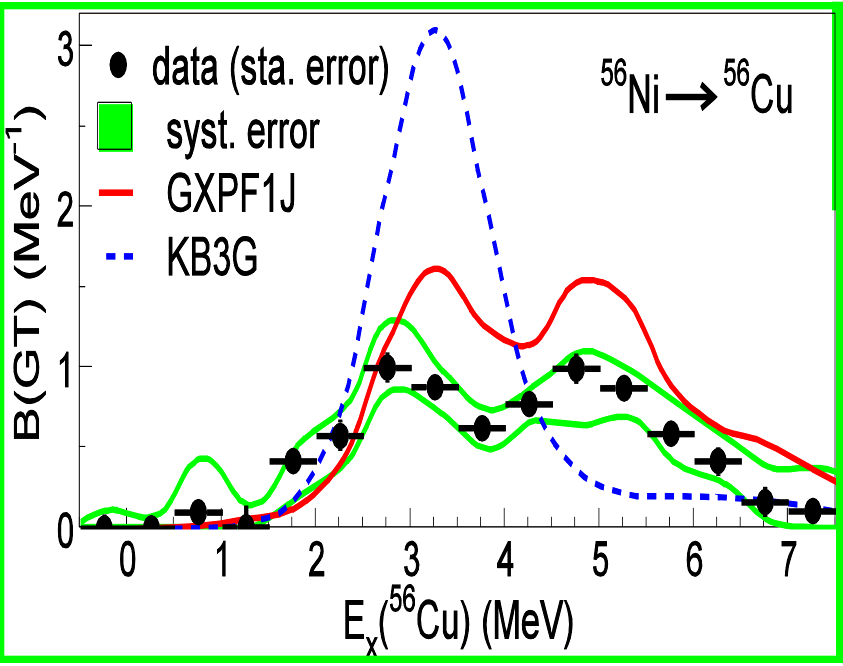
B(GT)=9.5
$B(GT)_{exp}=9.9\pm2.4$
$B(GT)_{KB3G}=9.0$

SD + … : RPA (SGII)

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

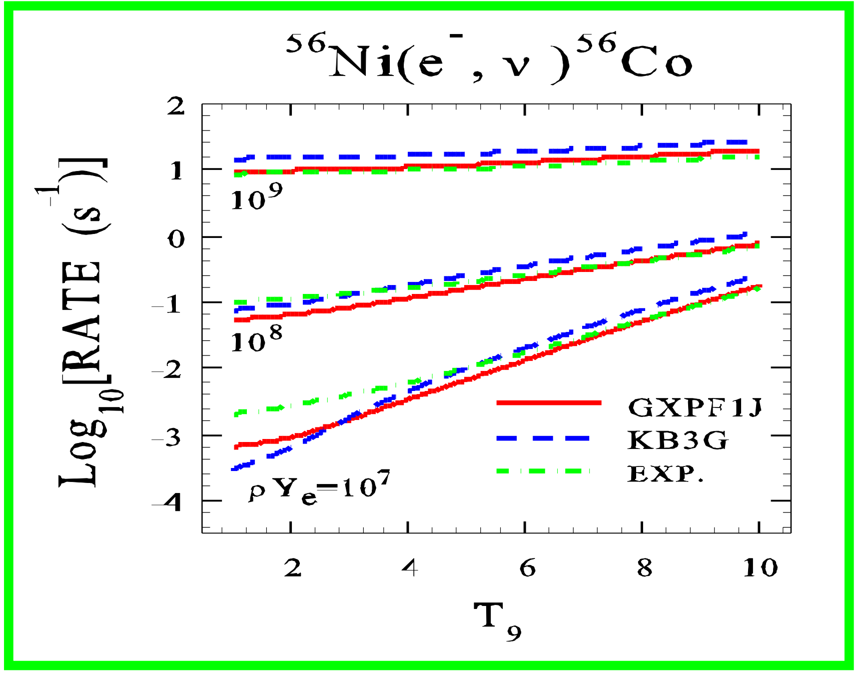
QRPA(SIII)	352
QRPA(G-matrix formalism)	174

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



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

e-capture rates in stellar environments: $\rho Y_e = 10^7 - 10^{10}\ \mathrm{g/cm^3}$



Suzuki, Honma, Mao, Otsuka, Kajino, PR C83, 044619 (2011)

Type-Ia supernova explosion

Accretion of matter to white-dwarf from binary star

→ supernova explosion when white-dwarf mass > Chandrasekhar limit

→ ^{56}Ni (N=Z)

→ ^{56}Ni (e$^-$, ν) ^{56}Co $Y_e = 0.5 \rightarrow Y_e < 0.5$ (neutron-rich)

→ production of neutron-rich isotopes; more ^{58}Ni

Decrease of e-capture rate on ^{56}Ni

→ less production of ^{58}Ni.

e-capture rates:

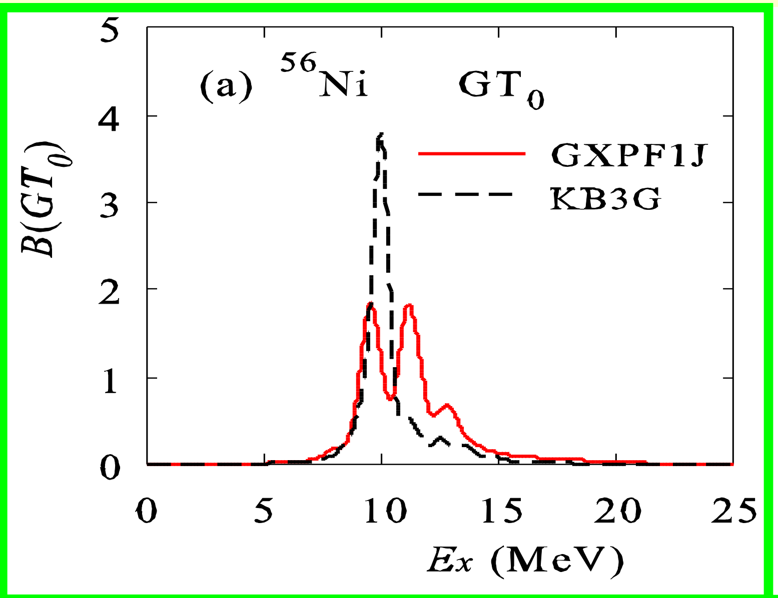
GXPF1J < KB3G

←→

Y_e (GXPF1J) > Y_e (KB3G)

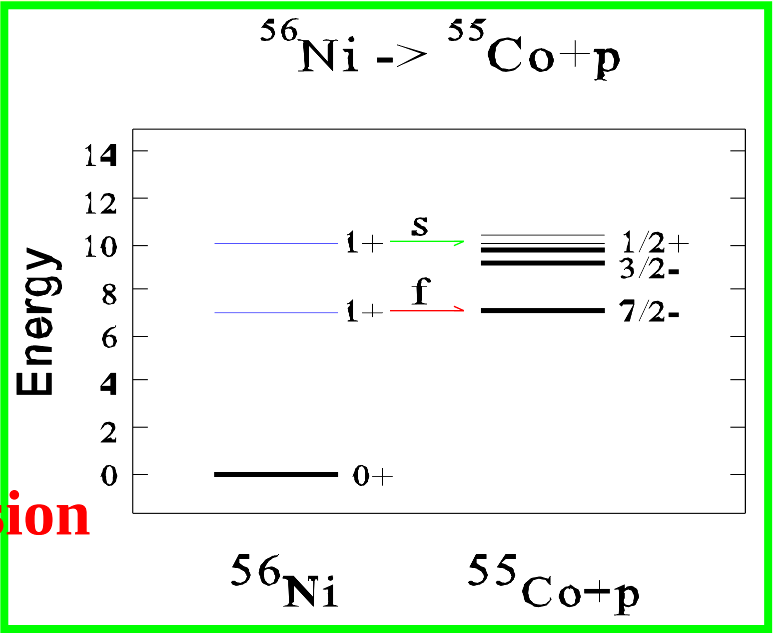
Problem of over-production of ^{58}Ni may be solved.

● ^{56}Ni (ν, ν') ^{56}Ni



B(GT)=6.2 (GXPF1J)

B(GT)=5.4 (KB3G)

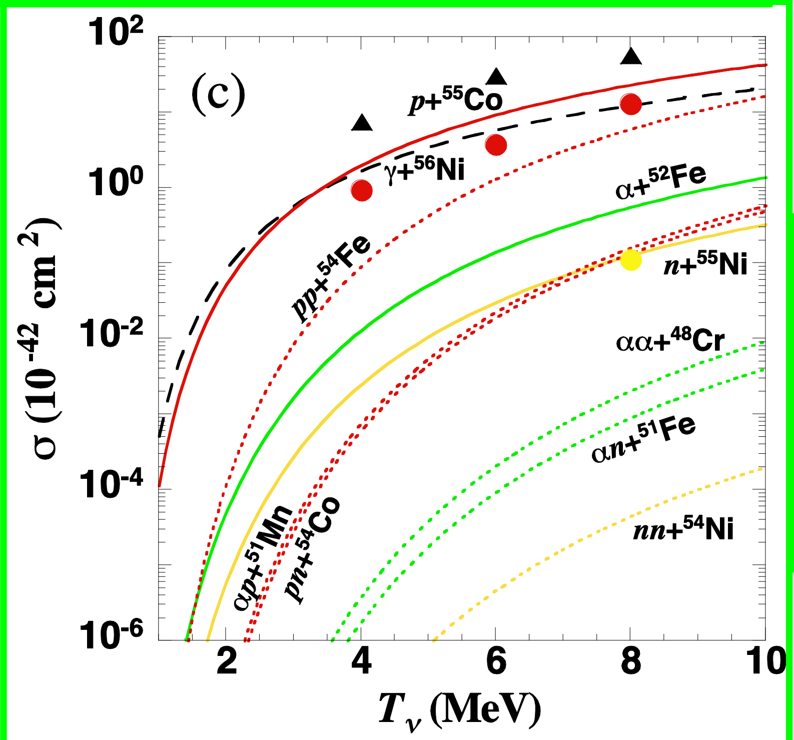


large p emission cross section

Synthesis of Mn in Population III Star

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

^{54}Fe(p, γ)^{55}Co



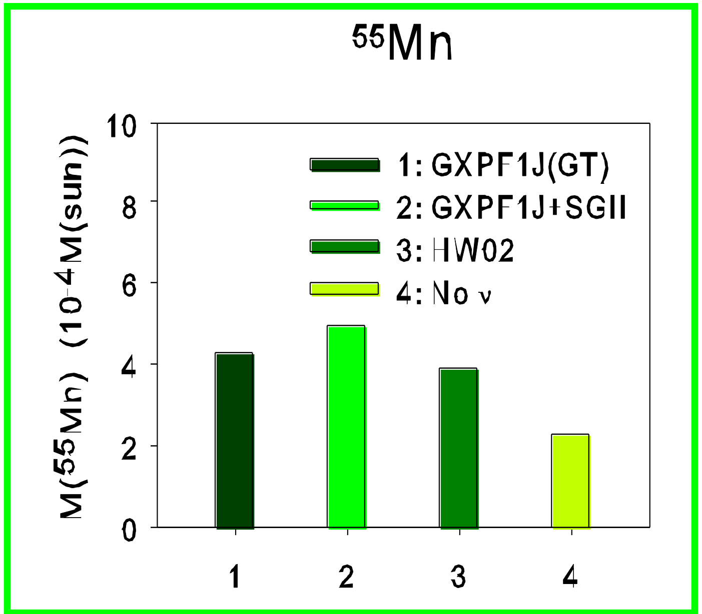
cf: HW02

▲ gamma

● p

● n

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



4. ν- ^{40}Ar Reactions

Liquid argon = powerful target for SNν detection

VMU= Monopole-based universal interaction

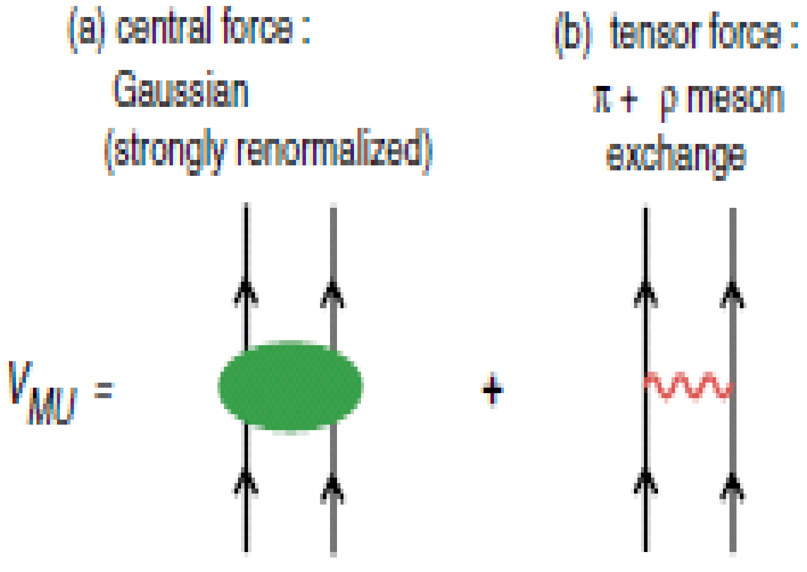


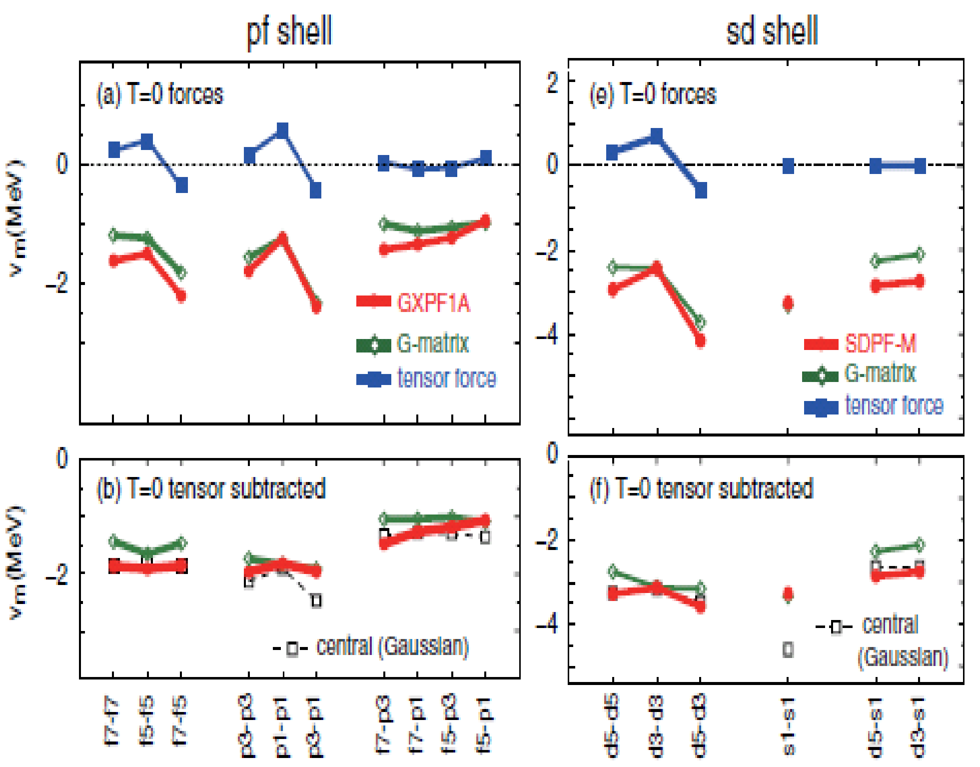
FIG. 2 (color online). Diagrams for the V_{MU} interaction.

Important roles of tensor force

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

Monopole terms in V_{nn}

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



tensor force: bare≈renormalized

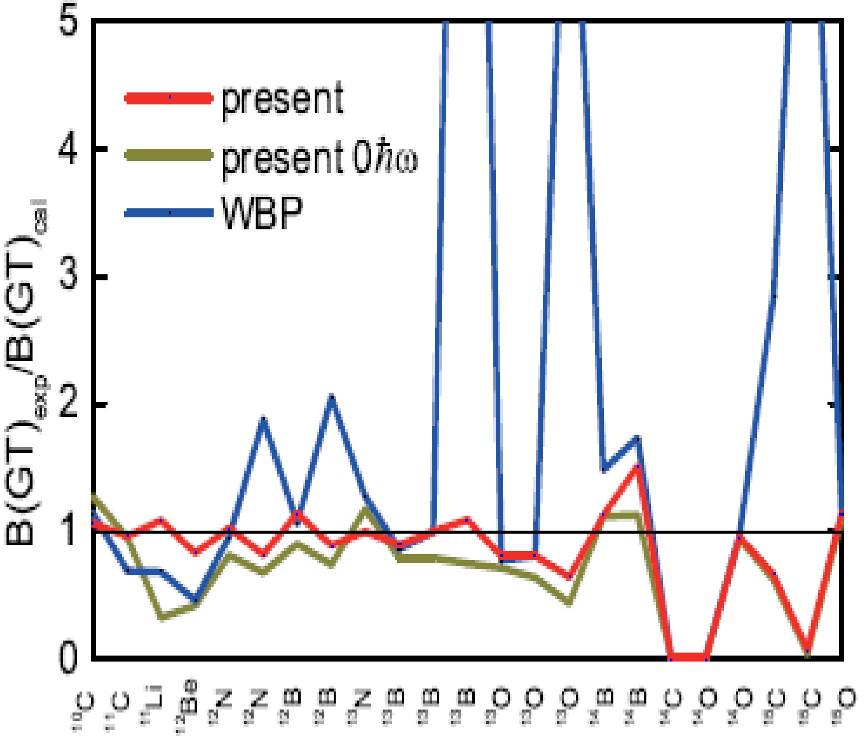
○ p-sd shell: VMU for p-sd,

Yuan, Suzuki, Otsuka, Xu, Tsunoda,
PR C85, 064324 (2012) .

p: SFO

sd: SDPF-M (Utsuno)

p-sd: VMU tensor = π+ρ,
2-body LS = σ+ρ+ω (M3Y)
central= renormalized VMU



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

SDPF-VMU-LS

sd: SDPF-M (Utsuno et al.)

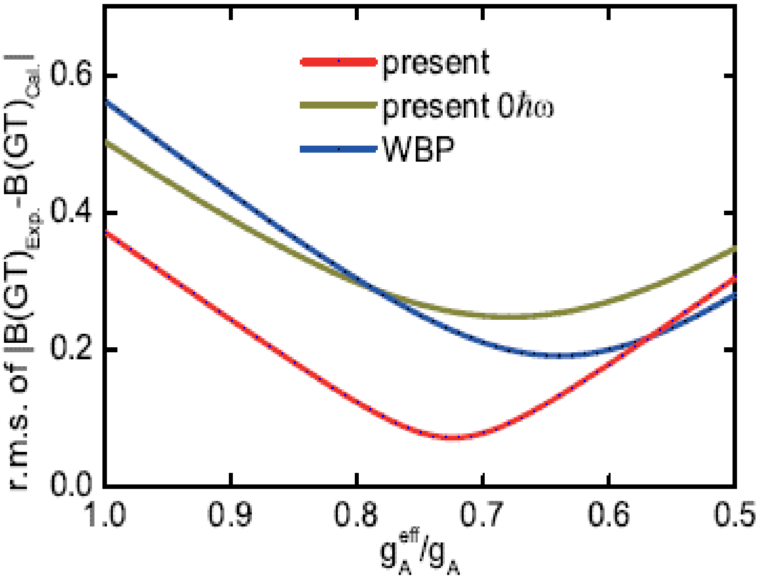
fp: GXPF1 (Honma et al.)

sd-pf: VMU + 2-bpdy LS

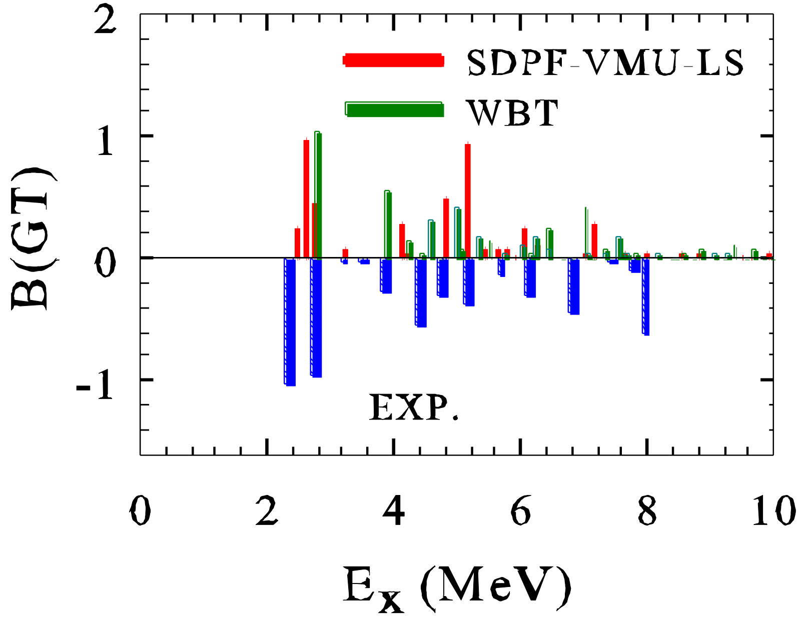
$(sd)^{-2}$ $(fp)^2$: 2hw

B(GT) & ν-^{40}Ar cross sections

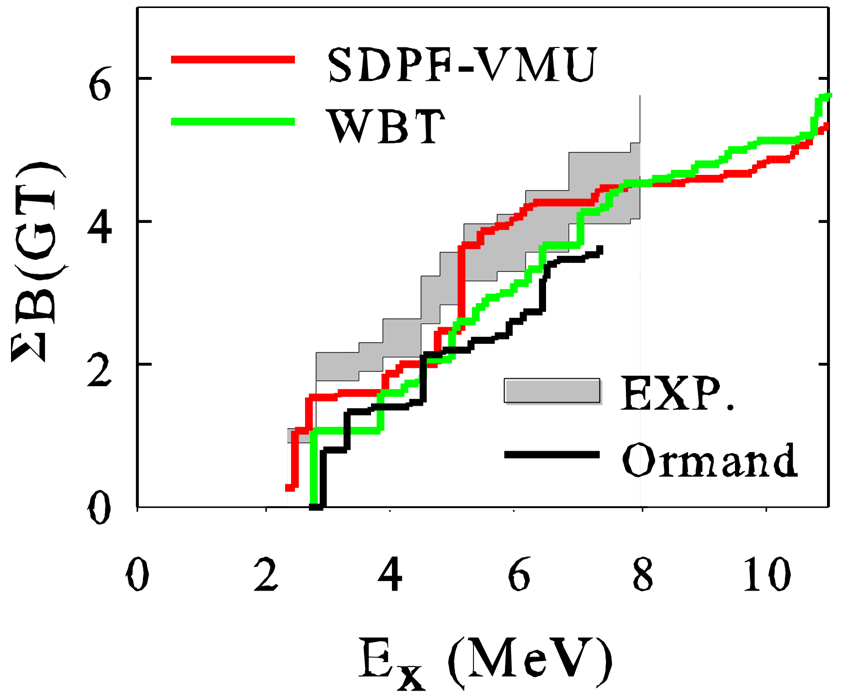
Solar ν cross sections folded over ^{8}B ν spectrum

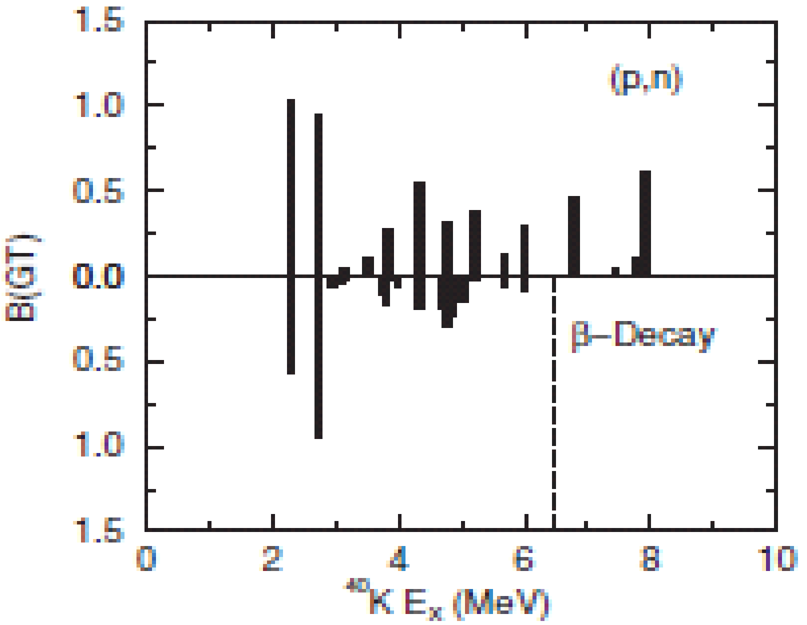


^{40}Ar -> ^{40}K

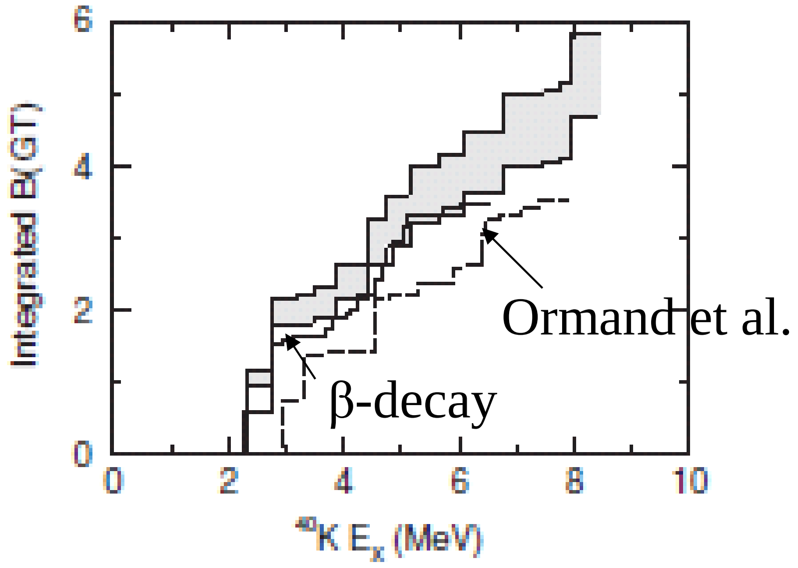


^{40}Ar -> ^{40}K

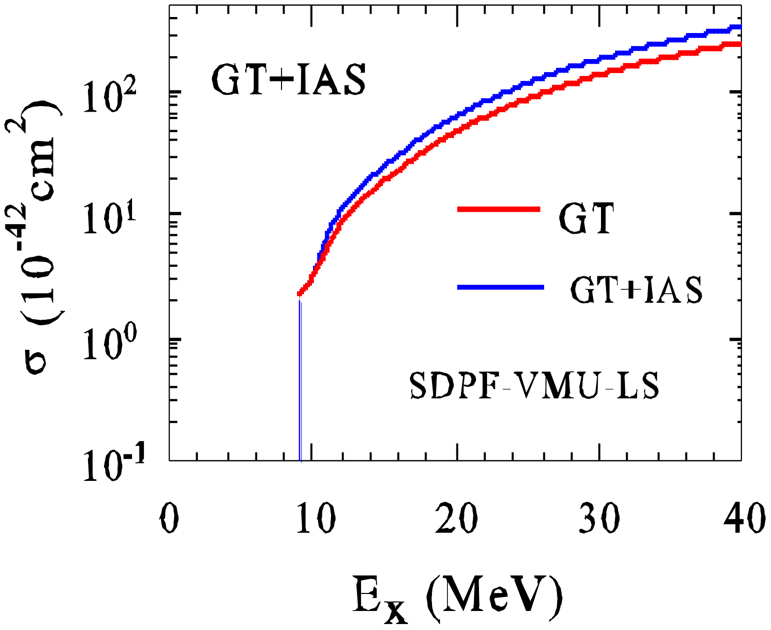




(p,n) Bhattacharya et al., PR C80 (2009)



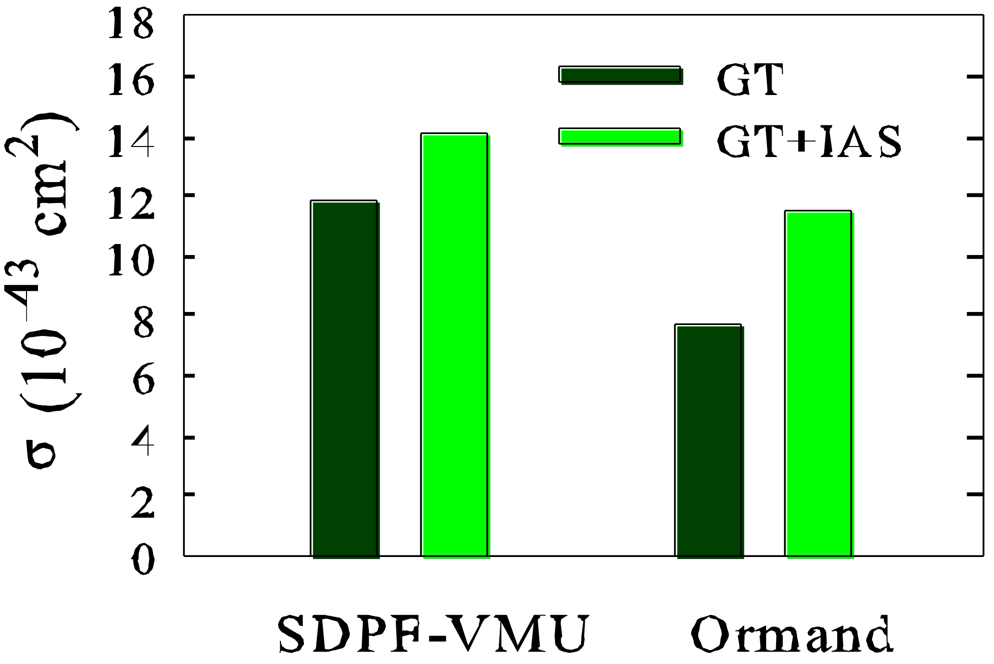
^{40}Ar -> ^{40}K



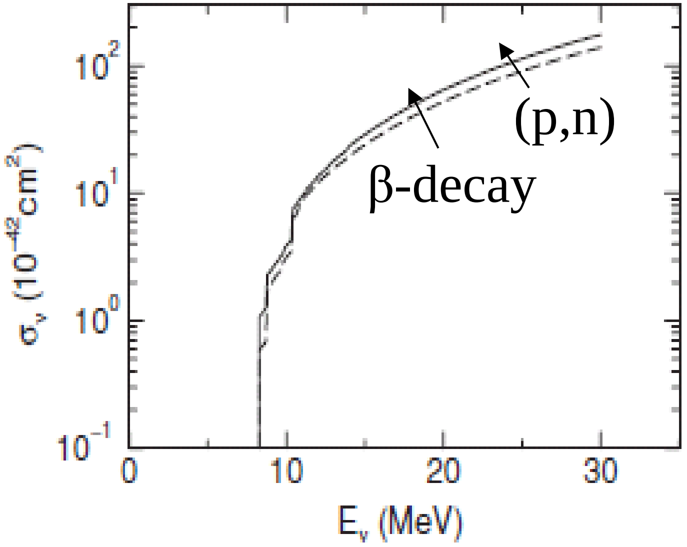
GT+IAS
$E_e > 5$ MeV : ICARUS

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

^{40}Ar (ν, e$^-$) ^{40}K



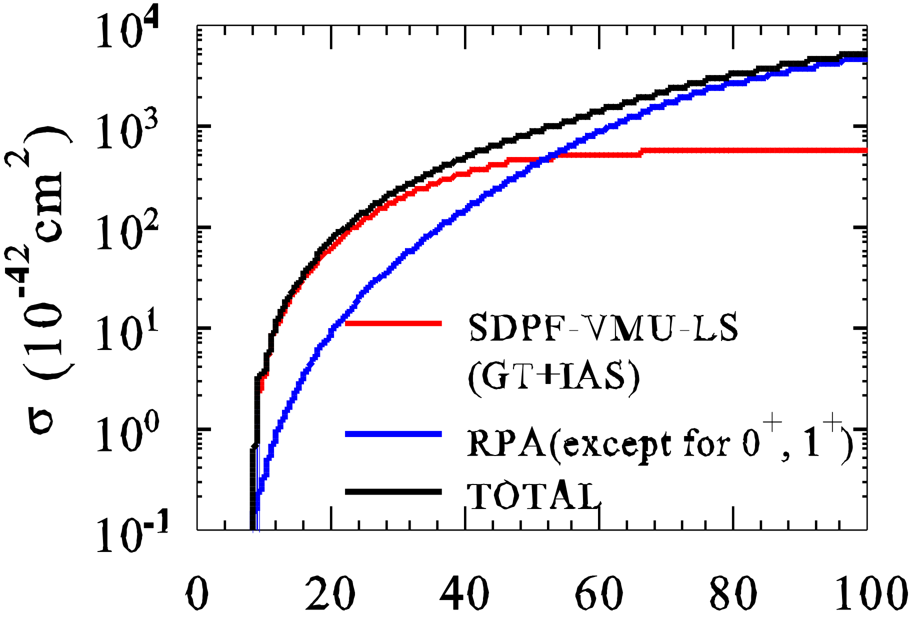
IAS: $C0+L0 \approx [(q^2-\omega^2)/q^2]^2 \times C$; $^+$ C0 only
GT: $E_1^5 + M1 + C_1^5 + L_1^5$; $^+$ E_1^5 only

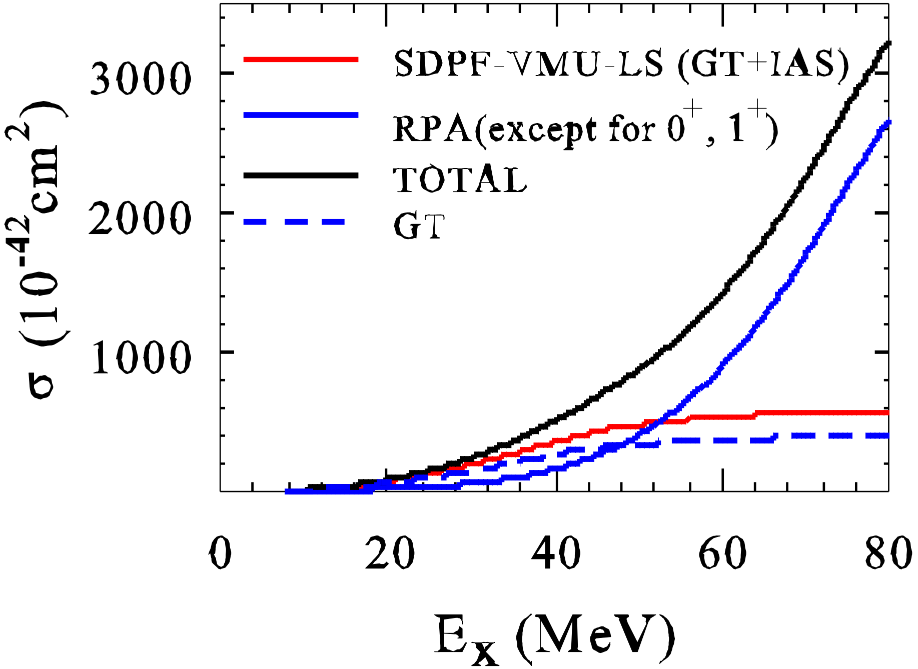


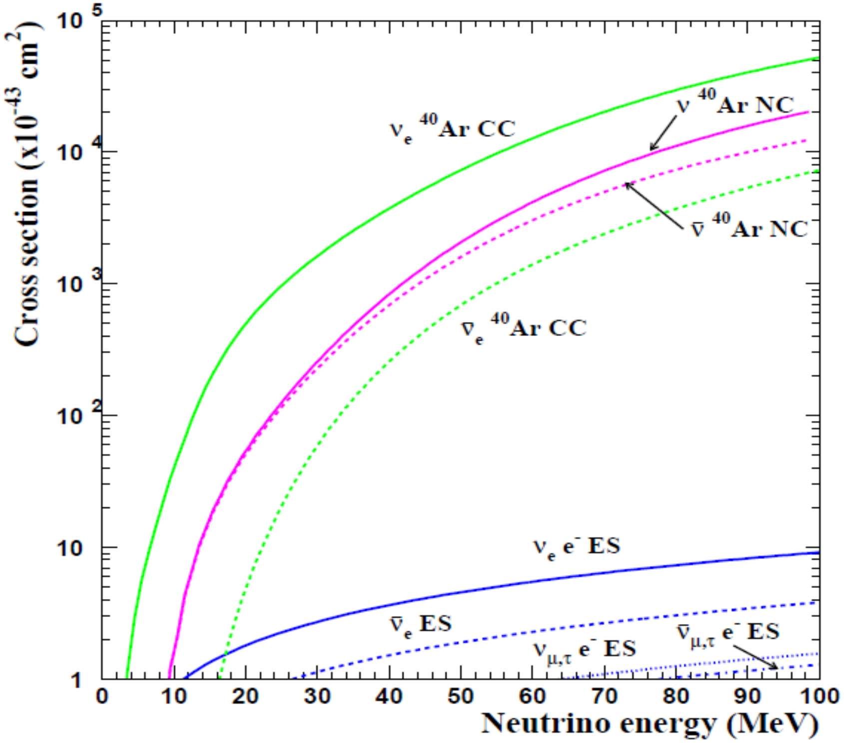
$^+$Ormand et al, PL B345, 343 (1995)

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

^{40}Ar -> ^{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).

5. Detailed e-capture and beta-decay rates for URCA nuclear pairs in 8-10 solar-mass stars

Nuclear URCA process

$$^{23}Na + e^{-} \longrightarrow {}^{23}Ne + \nu$$

$$^{23}Ne \longrightarrow {}^{23}Na + e^{-} + \overline{\nu}$$

Q=4.376 MeV

(^{24}Na → ^{24}Mg: Q=5.516 MeV)

$$^{25}Mg + e^{-} \longrightarrow {}^{25}Na + \nu$$

Q=3.835 MeV

$$^{25}Na \longrightarrow {}^{25}Mg + e^{-} + \overline{\nu}$$

(^{26}Na → ^{26}Mg: Q=9.354 MeV)

$$^{27}Al + e^{-} \longrightarrow {}^{27}Mg + \nu$$

Q=2.610 MeV

$$^{27}Mg \longrightarrow {}^{27}Al + e^{-} + \overline{\nu}$$

Cooling of O-Ne-Mg core of stars

sd-shell: USDB Brown and Richter

e-capture and beta-dccay rates evaluated at

$$8.0 < \log_{10}(\rho Y_e) < 9.2 \quad \text{in steps of } 0.02$$

$$8.0 < \log_{10} T < 9.2 \quad \text{in steps of } 0.05$$

cf: Oda et al.,

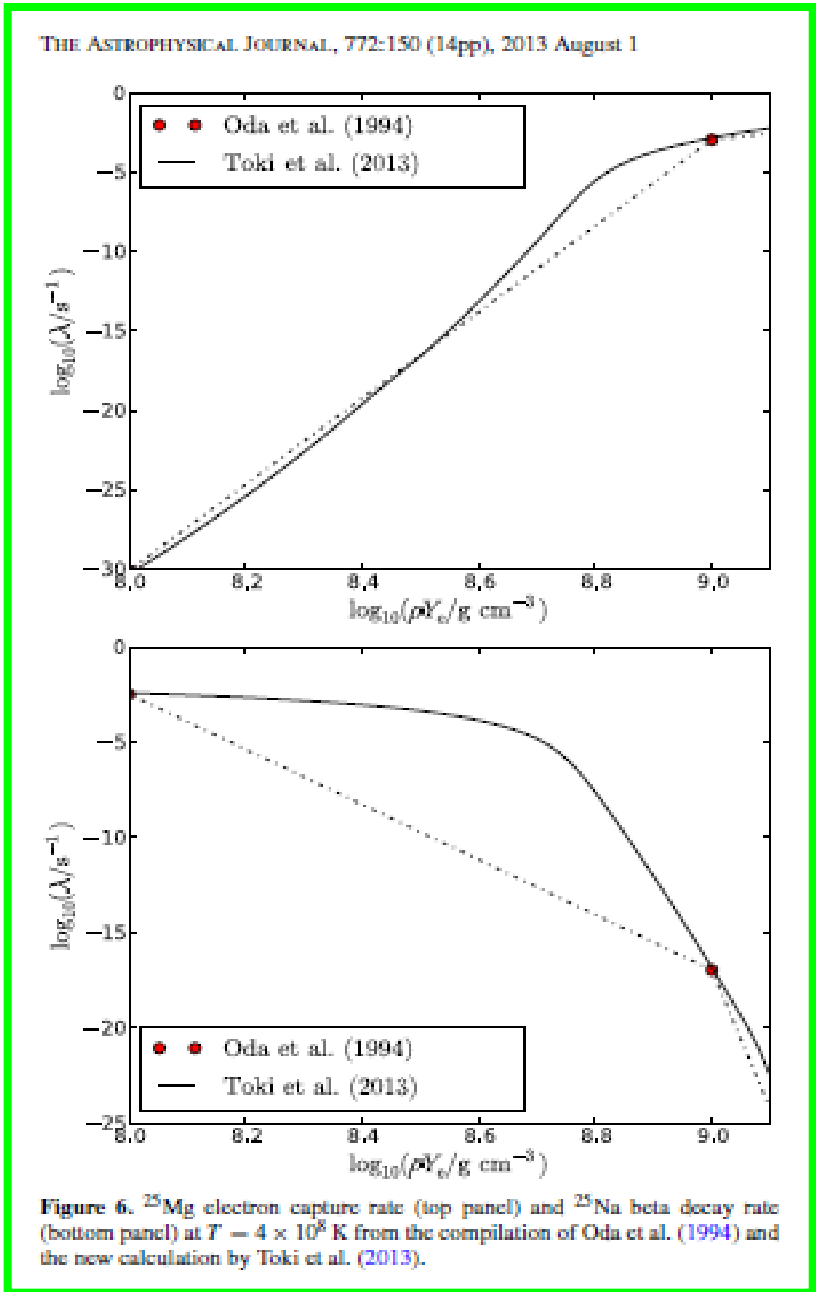
At. Data and Nucl. Data Tables 56, 231 (1994)

$$0.0 < \log_{10}(\rho Y_e) < 11.0 \quad \text{in steps of } 1.0$$

$$7.0 < \log_{10} T < 10.477$$

$$T_9 = 0.01,\ 0.10,\ 0.20,\ 0.40,\ 0.70,\ 1.0,$$

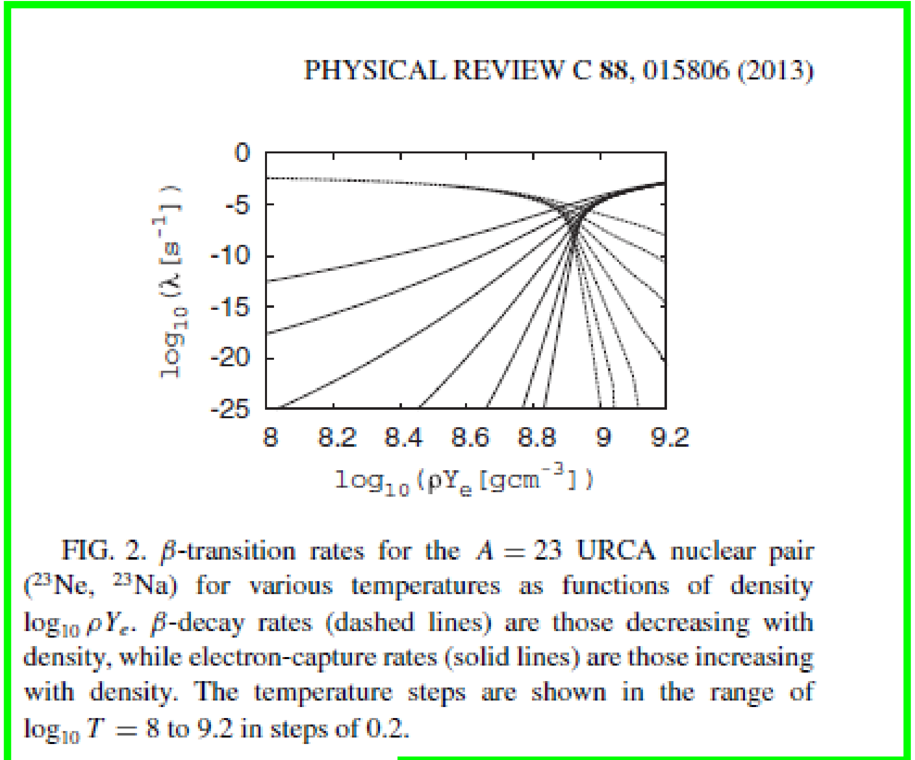
$$1.5,\ 2.0,\ 3.0,\ 5.0,\ 10.0,\ 30.0$$



THE ASTROPHYSICAL JOURNAL, 772:150 (14pp), 2013 August 1

Figure 6. ^{25}Mg electron capture rate (top panel) and ^{25}Na beta decay rate (bottom panel) at $T = 4 \times 10^8$ K from the compilation of Oda et al. (1994) and the new calculation by Toki et al. (2013).

(^{23}Ne, ^{23}Na)



PHYSICAL REVIEW C 88, 015806 (2013)

FIG. 2. β-transition rates for the $A = 23$ URCA nuclear pair (^{23}Ne, ^{23}Na) for various temperatures as functions of density $\log_{10}\rho Y_e$. β-decay rates (dashed lines) are those decreasing with density, while electron-capture rates (solid lines) are those increasing with density. The temperature steps are shown in the range of $\log_{10} T = 8$ to 9.2 in steps of 0.2.

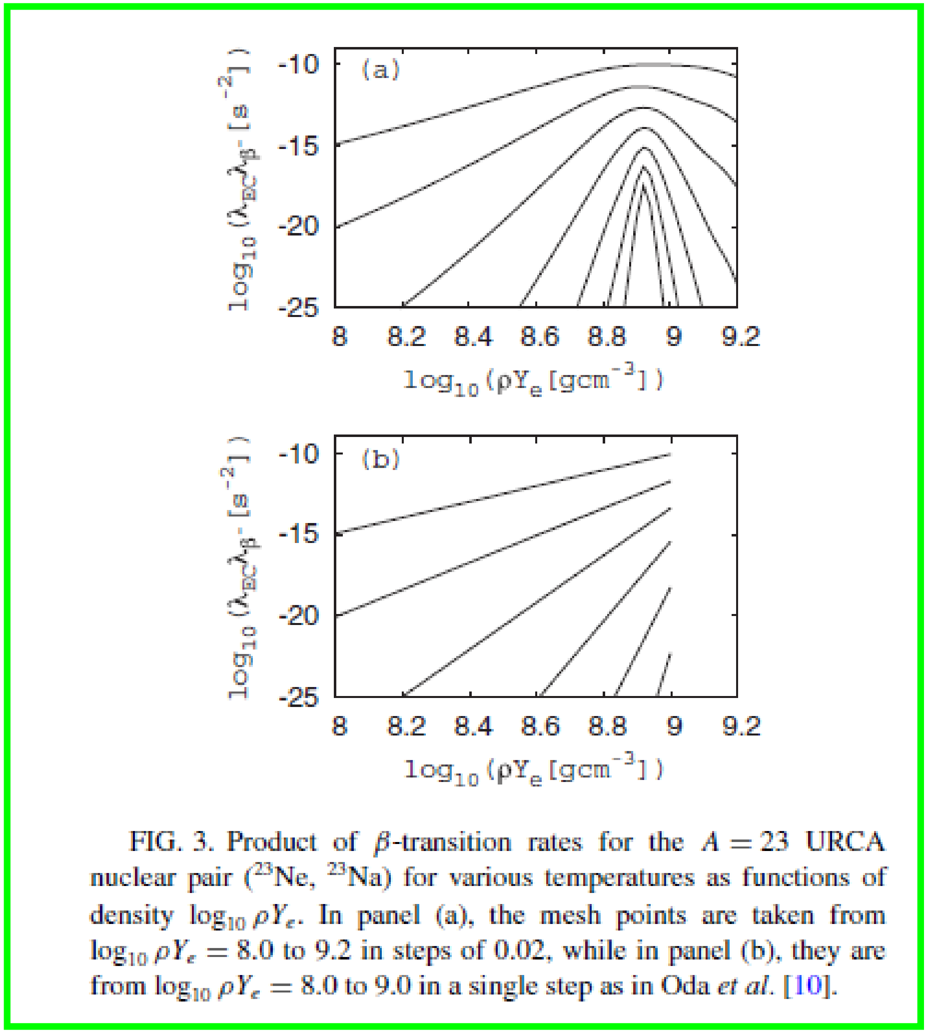
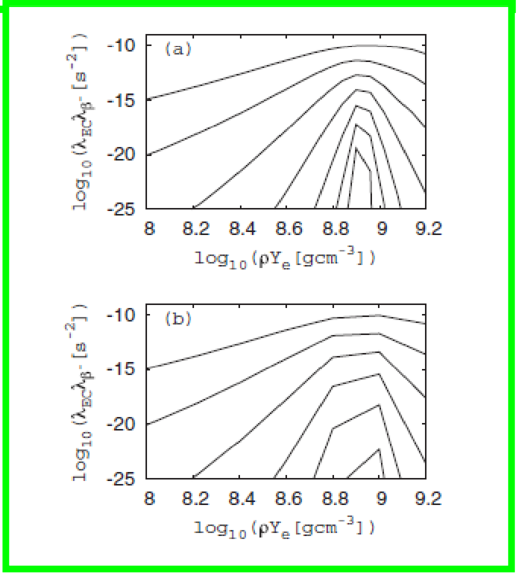


FIG. 3. Product of β-transition rates for the $A = 23$ URCA nuclear pair (^{23}Ne, ^{23}Na) for various temperatures as functions of density $\log_{10}\rho Y_e$. In panel (a), the mesh points are taken from $\log_{10}\rho Y_e = 8.0$ to 9.2 in steps of 0.02, while in panel (b), they are from $\log_{10}\rho Y_e = 8.0$ to 9.0 in a single step as in Oda *et al.* [10].

$$\Delta\log_{10}(\rho Y_e) = 0.06$$

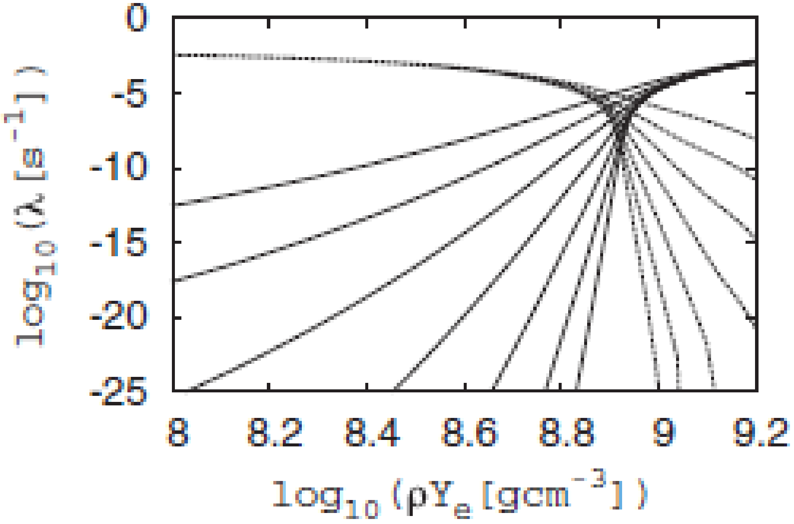
$$\Delta\log_{10}(\rho Y_e) = 0.2$$



URCA density at $\log_{10}\rho Y_e = 8.92$ for $A = 23$

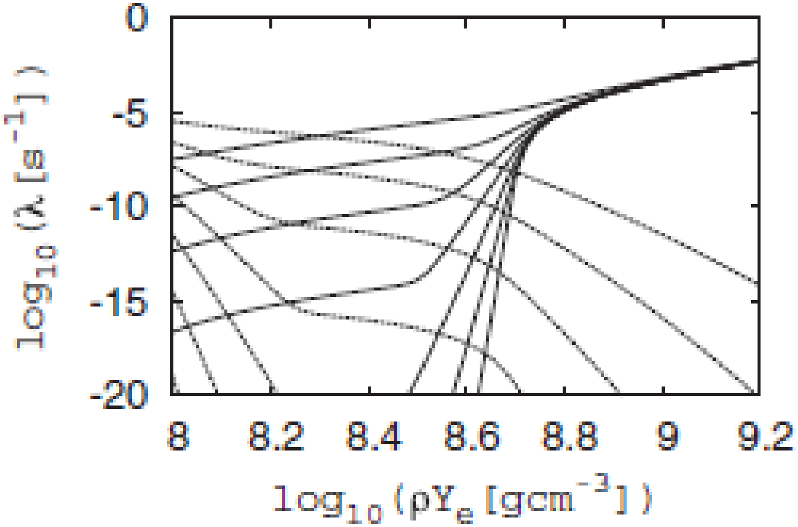
Cooling of O-Ne-Mg core by the nuclear URCA processes

(^{25}Na, ^{25}Mg)

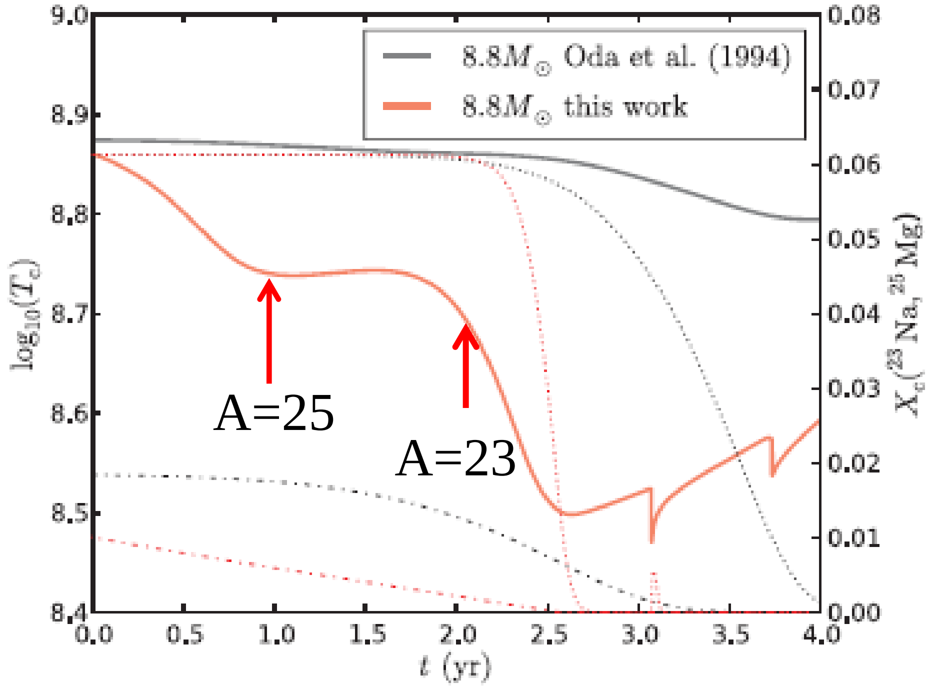


URCA density at $\log_{10}\rho Y_e = 8.81$

(^{27}Mg, ^{27}Al)

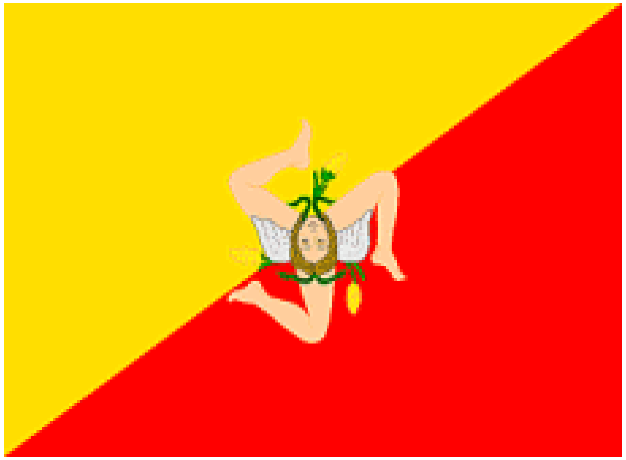


No clear URCA density for A=27

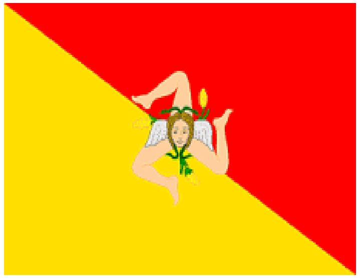


Summary

- **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 $^{12}C\ (\nu, e^-)\ ^{12}N$, $^{12}C\ (\nu, \nu')\ ^{12}C$ and $^{56}Fe\ (\nu, e^-)\ ^{56}Co$**
- **Effects of ν-oscillations in nucleosynthesis abundance ratio of $^{7}Li/^{11}B$ → ν mass hierarchy**



inverted hierarchy



normal hierarchy

- New ν capture cross sections on ^{13}C by SFO
  Enhanced solar ν cross sections compared to Cohen-Kurath (p shell)
  Detection of low-energy reactor anti-ν
- 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)

- **Detailed e-capture and beta-decay rates for URCA nuclear pairs in 8-10 solar-mass stars**

  → URCA density for A=25 and 23 with fine mesh of density and temperature

  → Cooling of O-Ne-Mg core by nuclear URCA processes

Toki, Suzuki, Nomoto, Jones and Hirschi, PR C 88, 015806 (2013)
Jones et al., Astrophys. J. 772, 150 (2013)

2006, Sept.