Neutrino-Nucleus Reactions and Nucleosynthesis
ニュートリノ-原子核反応と元素合成、

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New shell-model Hamiltonians which describes the spin modes such as GT strength in nuclei very well

-> New ν-nucleus reaction cross sections

ν-nucleus reactions: $E_\nu \leq 100$ MeV

1. ν-^{12}C, ν- ^{13}C
2. ν-^{16}O
3. ν-^{56}Fe, ν-^{56}Ni
4. ν- ^{40}Ar

- low-energy ν-detection
  Scintillator (CH, …), H_2O, Liquid-Ar, Fe
- nucleosynthesis of light elements in supernova explosion
- ν-oscillation effects

e-capture rates in stellar environments

- pf-shell: nucleosynthesis of iron-group elements in Type Ia SNe

Collaborators

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● ν-nucleus reactions

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

Suzuki, Fujimoto, Otsuka, PR C69, (2003) , Yuan, Suzuki, .. PRC85 (2012)
Honma, Otsuka, Mizusaki, Brown, PR C65 (2002); C69 (2004)
Suzuki, Honma et al., PR C79, (2009)
Otsuka, Suzuki, Honma, Utsuno et al., PRL 104 (2010) 012501
Suzuki and Honma, PR C87, 014607 (2013)
Yuan, Suzuki, Otsuka et al., PR C85, 064324 (2012)

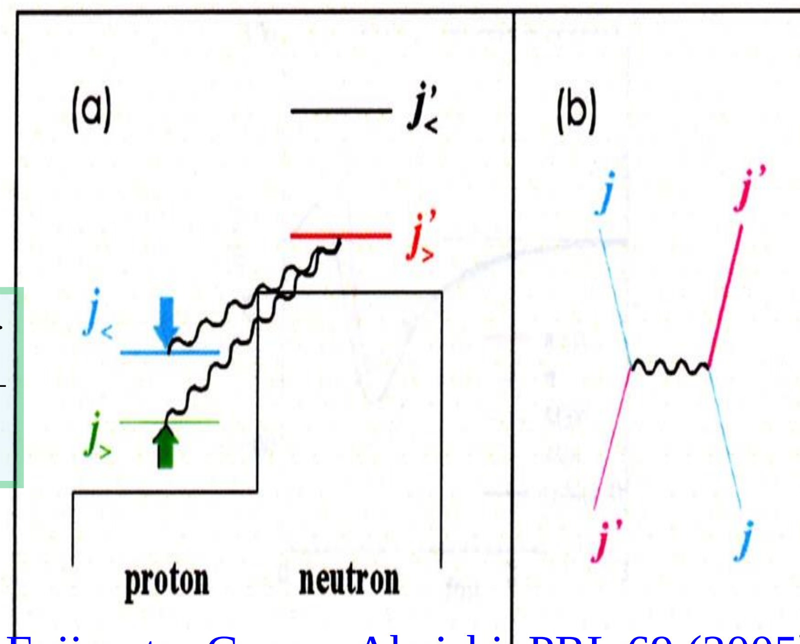
* important roles of tensor force

Monopole terms of V_{NN}

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

$j_> - j_<$:   attractive

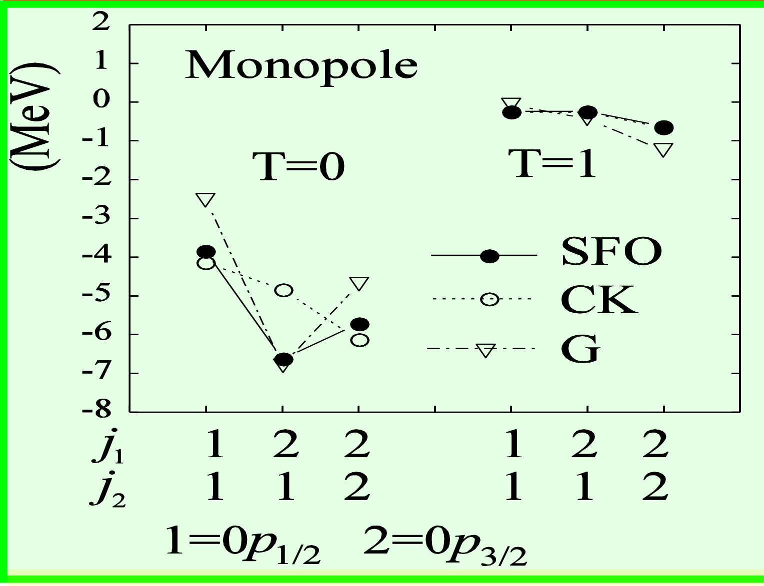
$j_> - j_>, j_< - j_<$: repulsive

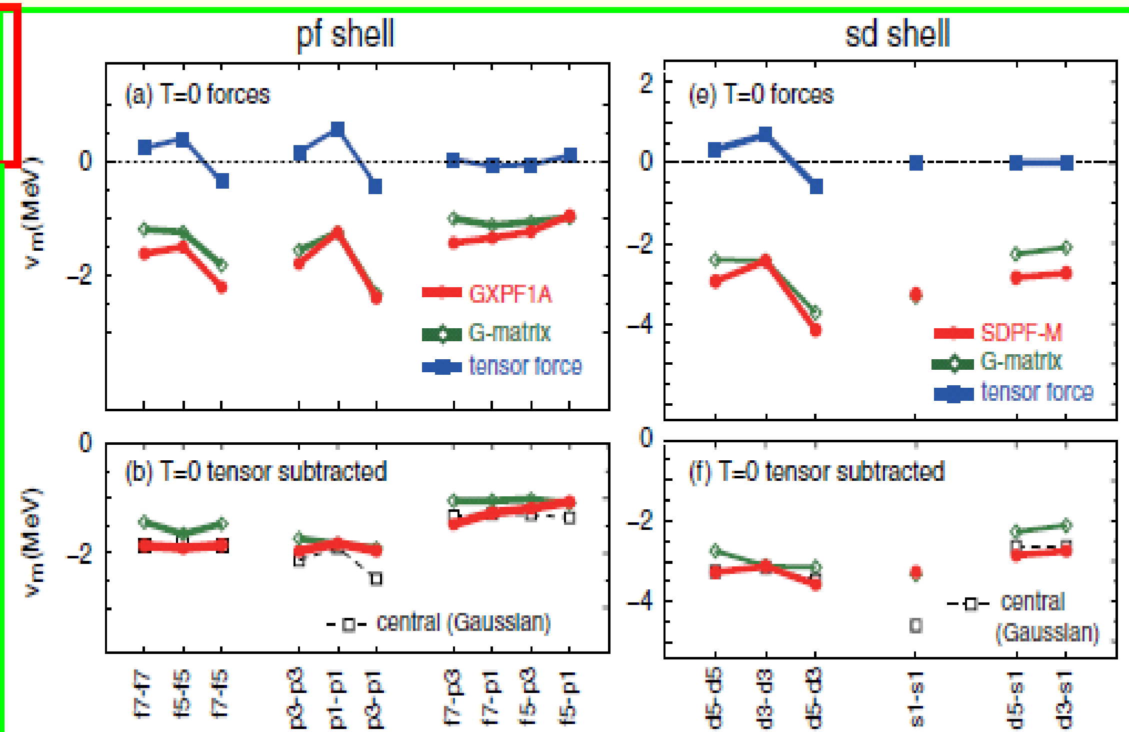


Otsuka, Suzuki, Fujimoto, Grawe, Akaishi, PRL 69 (2005)

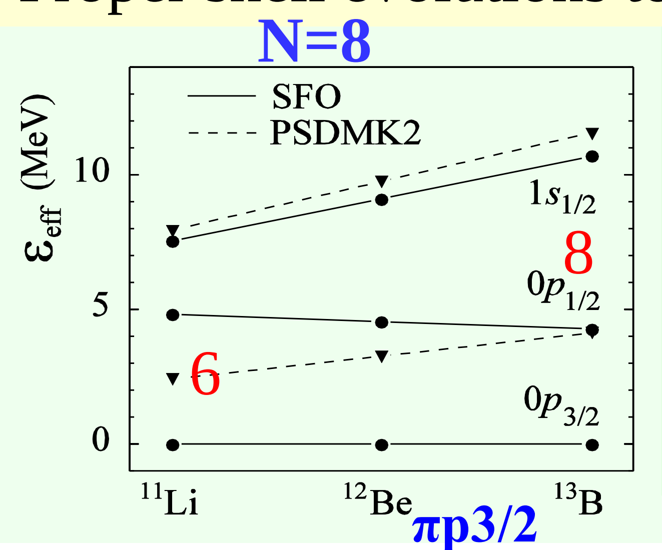
Monopole terms: New SM interactions vs. microscopic G matrix

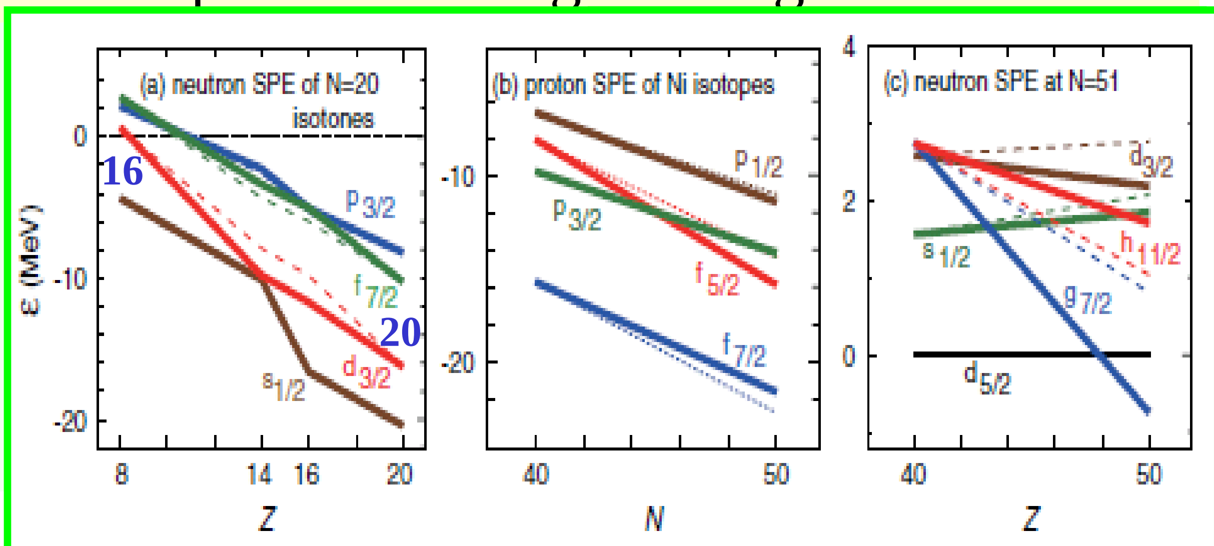
tensor force → characteristic orbit dependence: kink





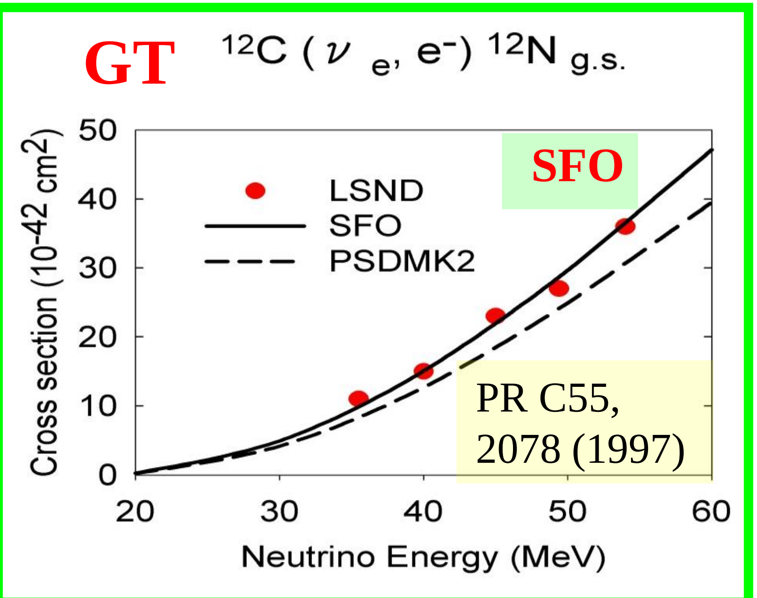
Proper shell evolutions toward drip-lines: Change of magic numbers





- **ν-nucleus reactions**

p-shell: SFO



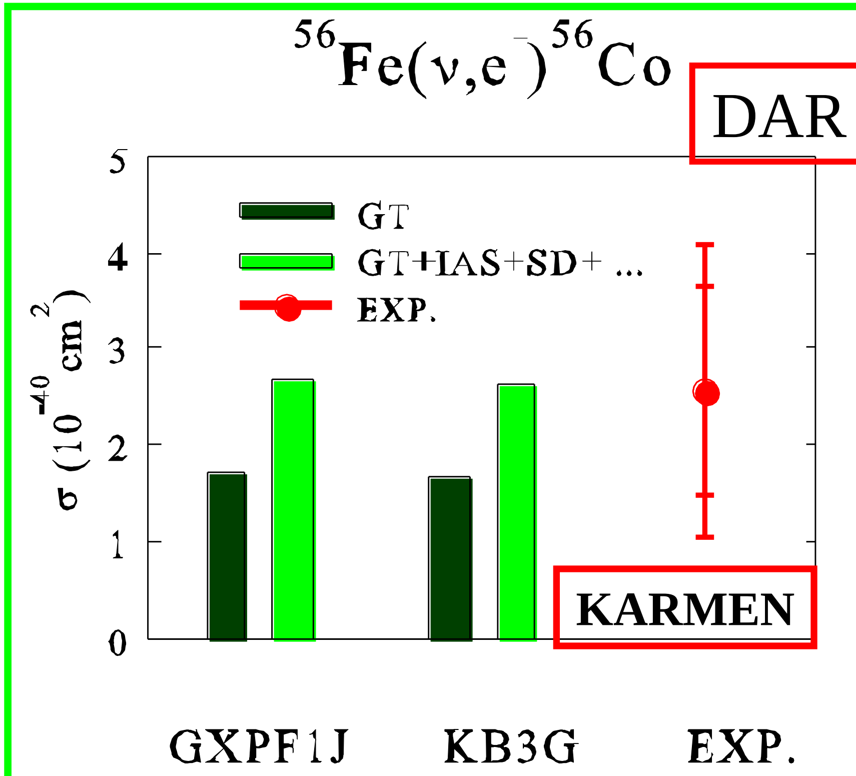
Suzuki, Chiba, Yoshida,Kajino, Otsuka, PR C74, 034307, (2006).

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

(ν, ν'), (ν_e, e^-) SD exc.
SFO reproduces DAR cross sections

pf-shell: GXPF1J (Honma et al.)

cf. KB3 Caurier et al.



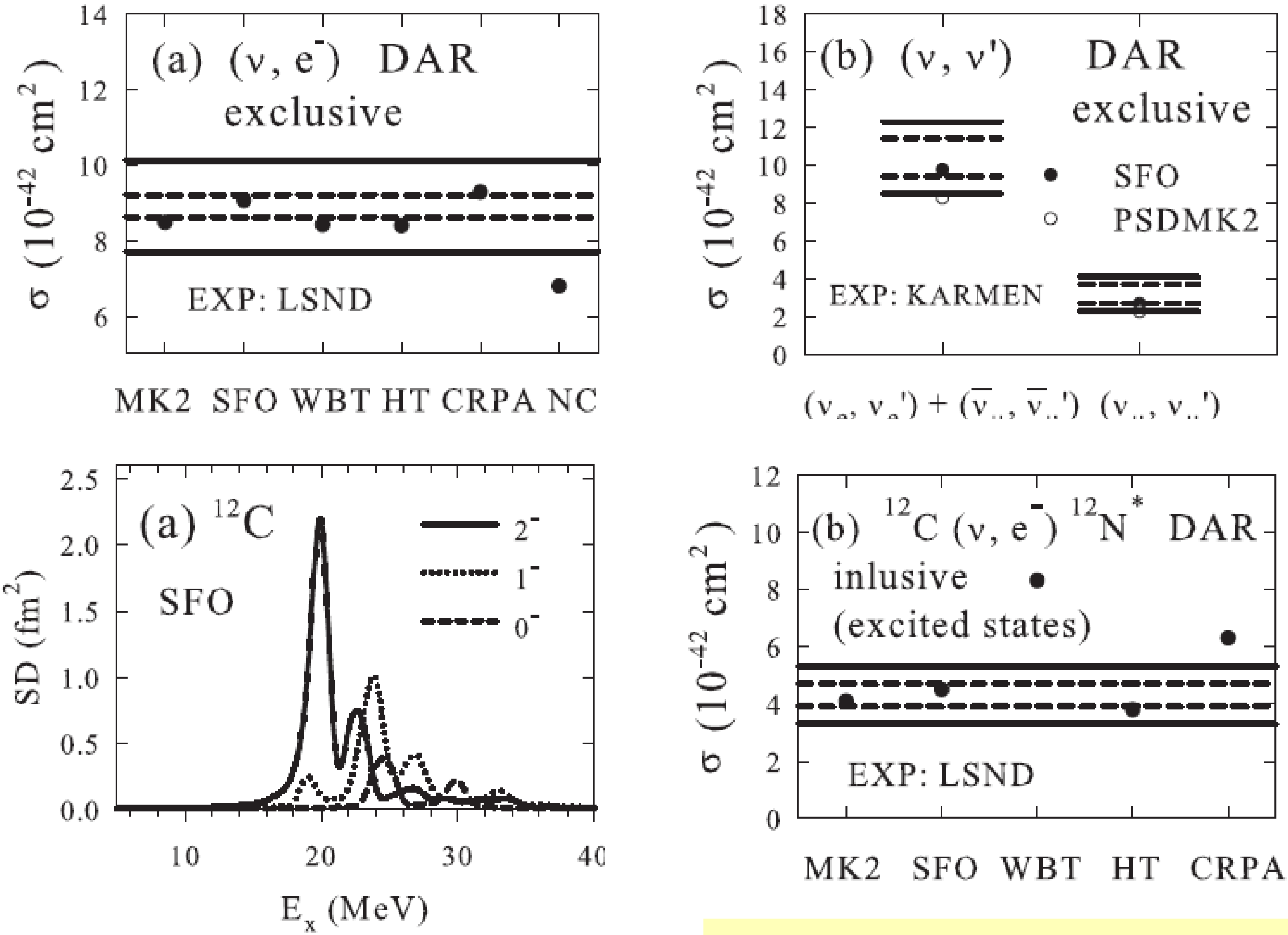
B(GT)=9.5 $B(GT)_{exp}$=9.9±2.4 $B(GT)_{KB3G}$=9.0

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

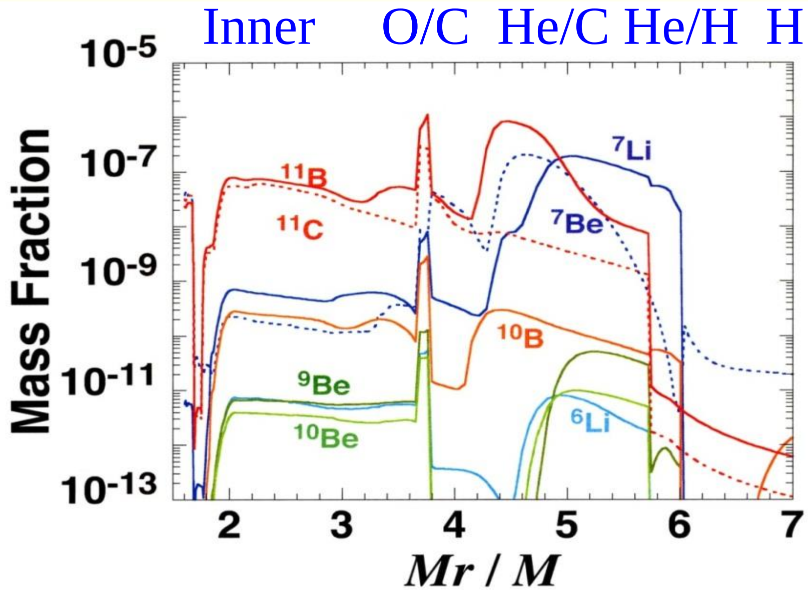
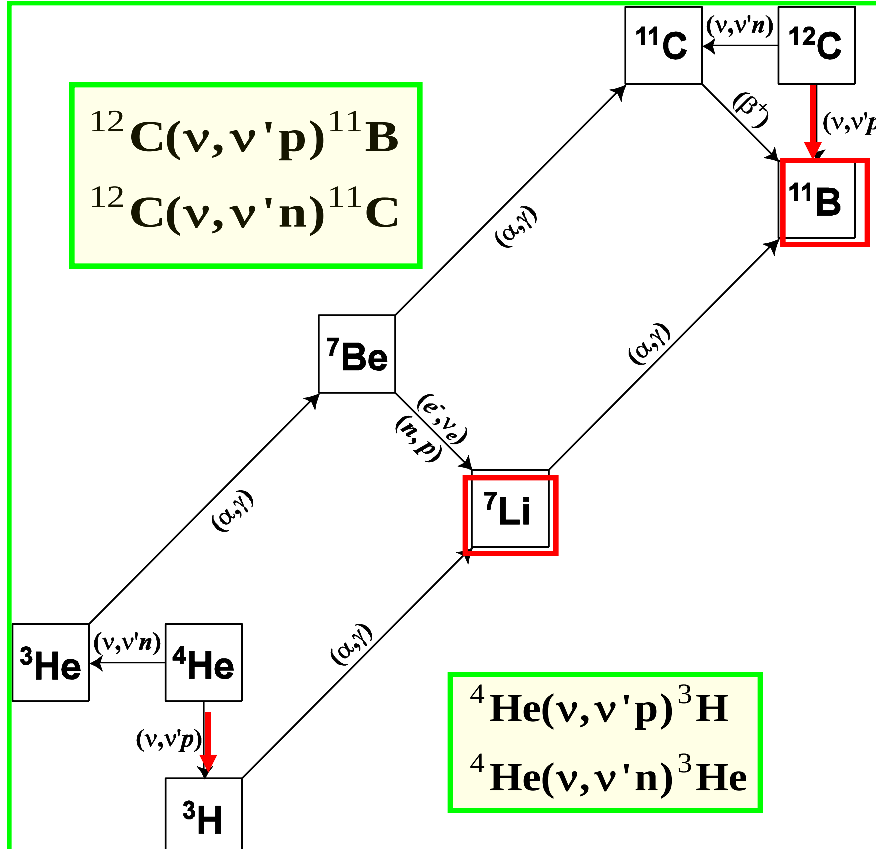
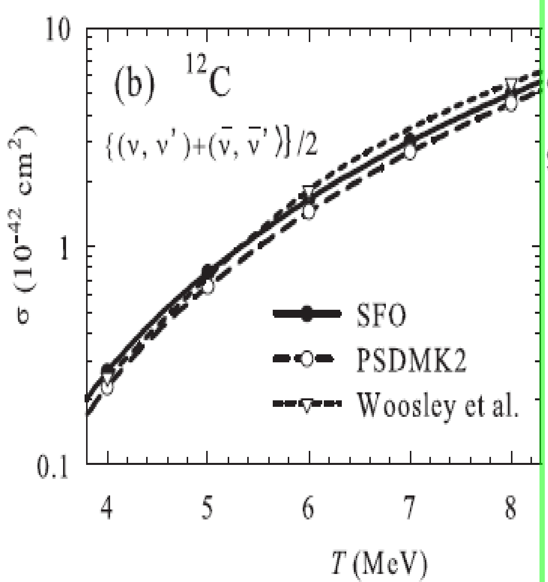
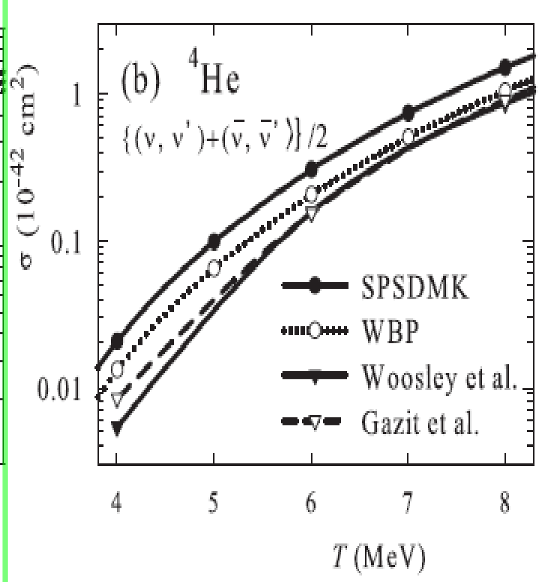


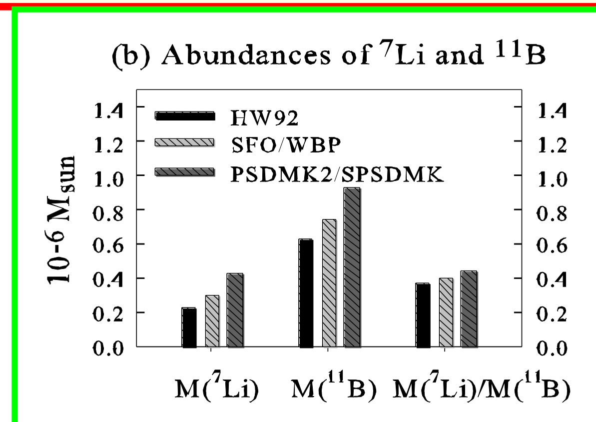
Fig. 4.— Mass fraction distribution of Model 1. The mass fractions of ^{7}Li and ^{7}Be, and ^{11}B and ^{11}C are separated.





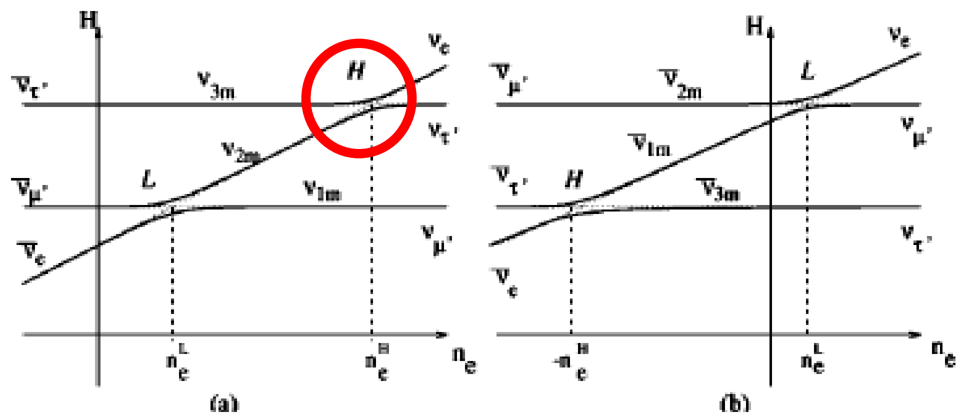


Enhancement of ^{11}B and ^{7}Li abundances in supernova explosions

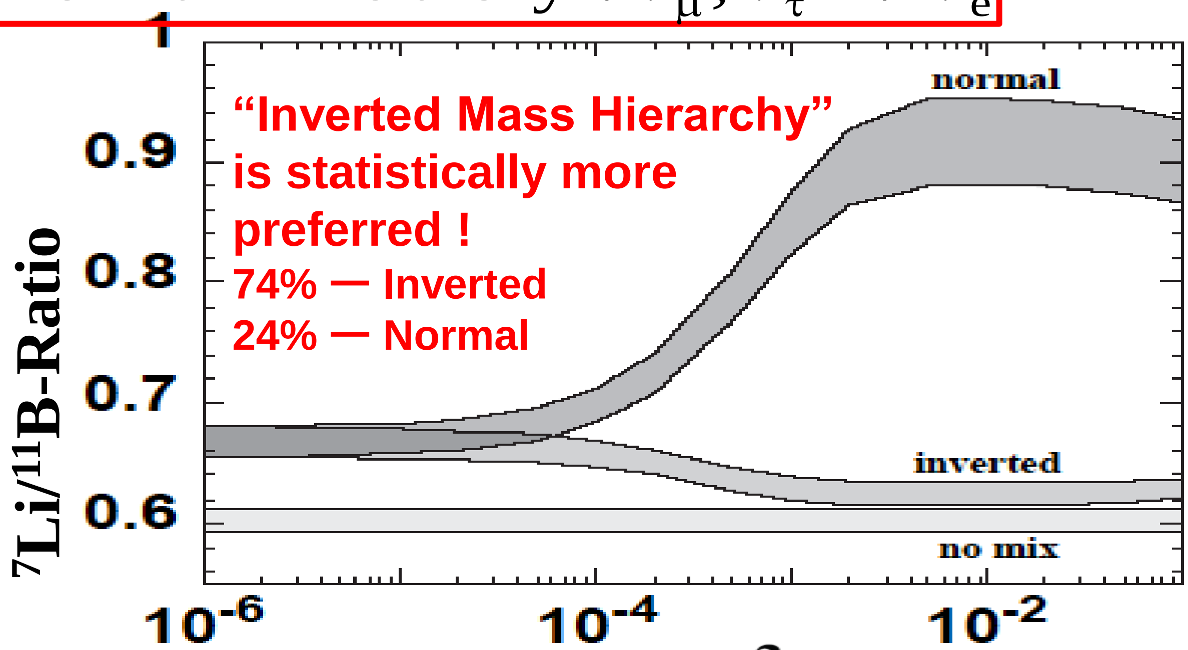


MSW ν oscillations

Normal hierarchy | Inverted hierarchy



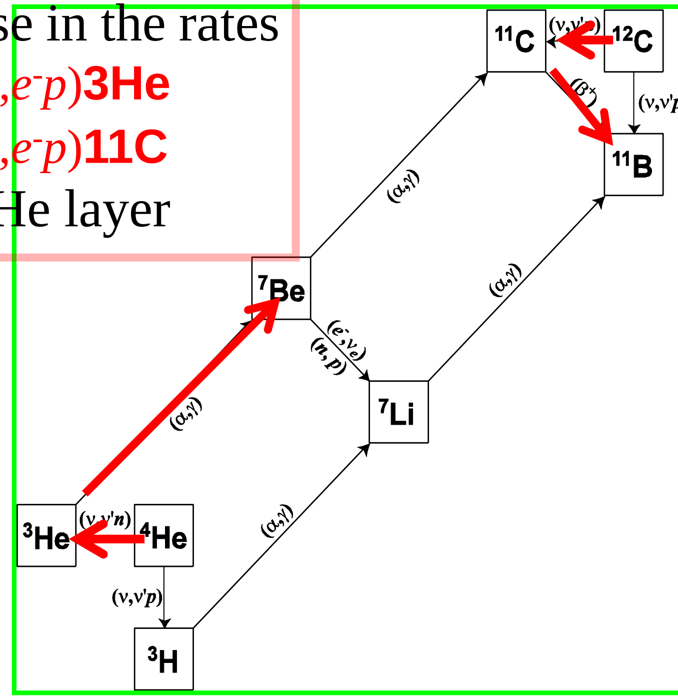
$$\text{Normal} - \text{hierarchy}: \nu_\mu, \nu_\tau \rightarrow \nu_e$$



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

Yoshida et al.,PRL 96 (2006)

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



- 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).

▪ ν-induced reactions on ^{13}C

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

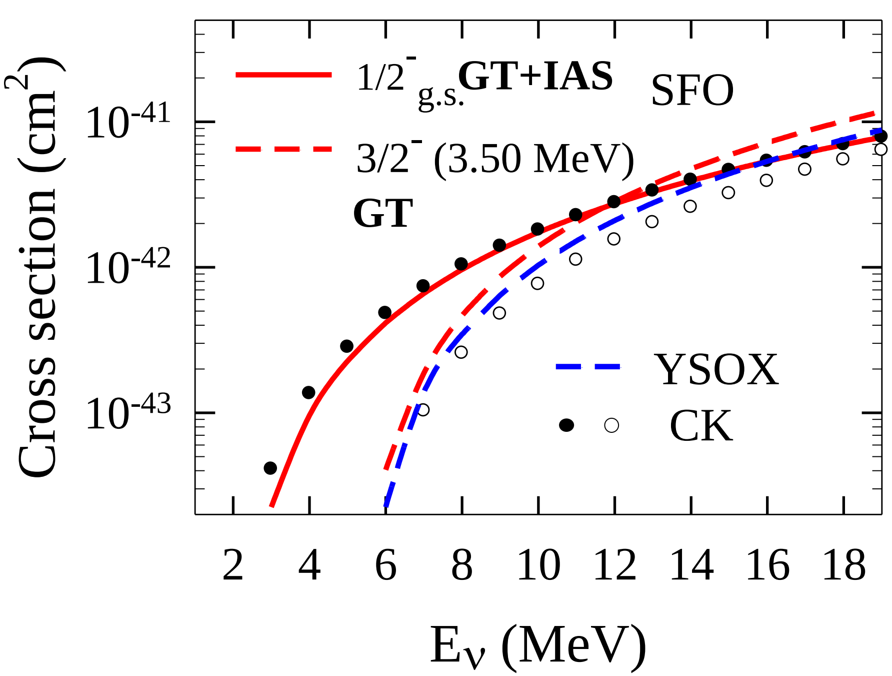
$E_\nu \le 10\,\mathrm{MeV} \quad E_\nu^{th}(^{12}C) \approx 13\,\mathrm{MeV}$

Natural isotope abundance = 1.07%

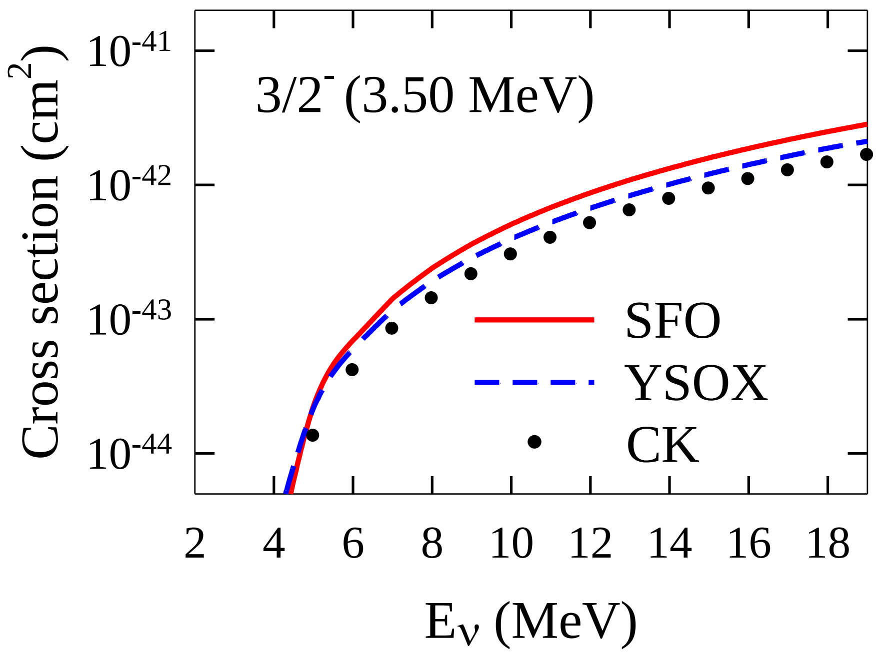
reactor anti-ν

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)

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

$$\frac{d\sigma}{dT}(E,T) = \frac{G_F^2}{2\pi} M\{2 - \frac{MT}{E^2}\} \frac{Q_W^2}{4} F^2(Q^2) \qquad \text{T=recoil energy}$$

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

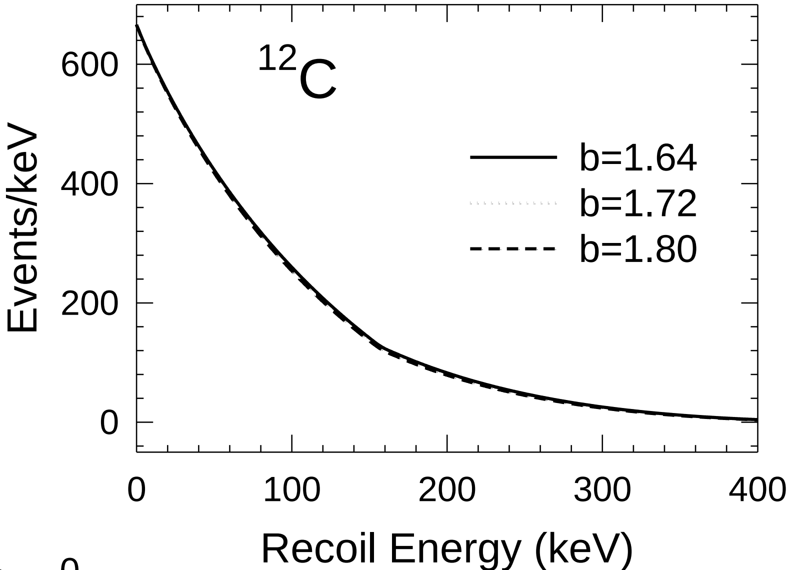
$$F(Q^2) = \{NF_n(Q^2) - (1 - 4\sin^2\theta_W)ZF_p(Q^2)\}/Q_W$$

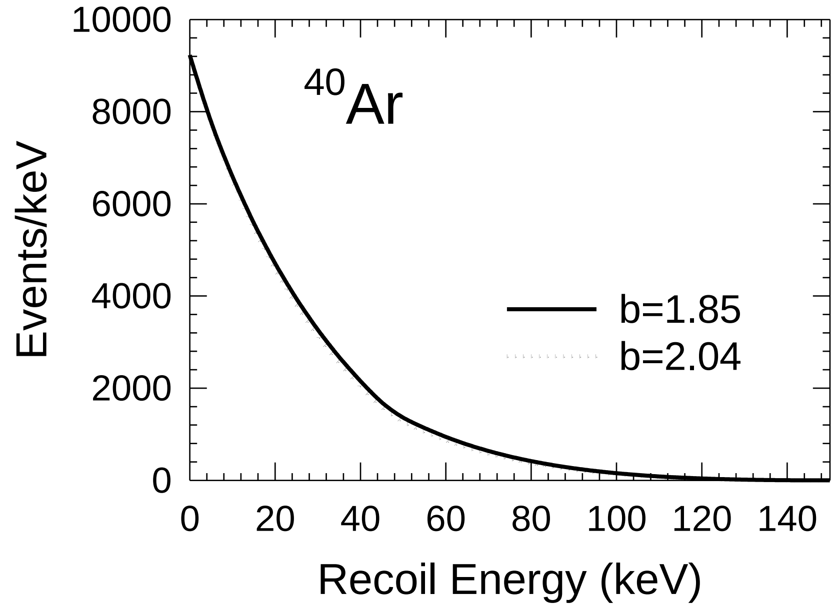
$$Q^2 = 2E^2TN/(E^2 - ET)$$

Events/keV - Recoil energy (keV)

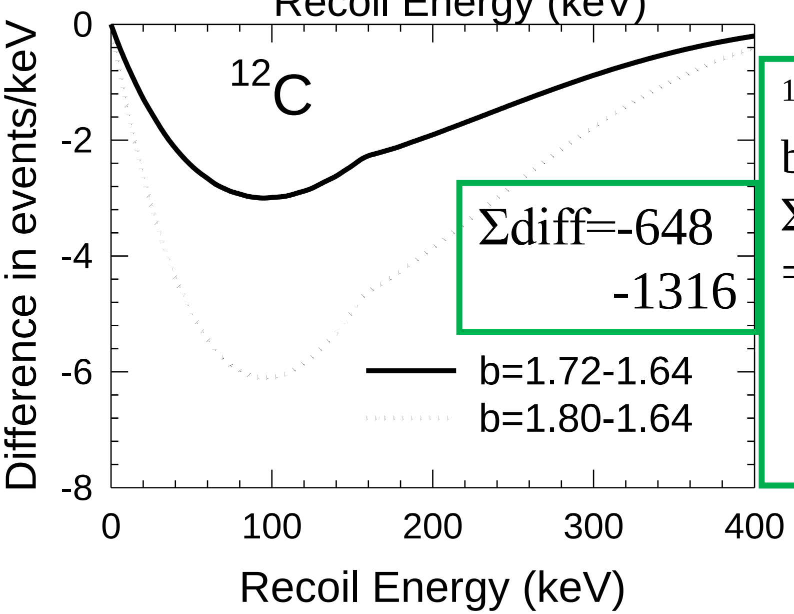
DAR ν (3-flavors)

$\Phi = 3\times10^{7}$ /cm²/s, 1year, target=1 ton



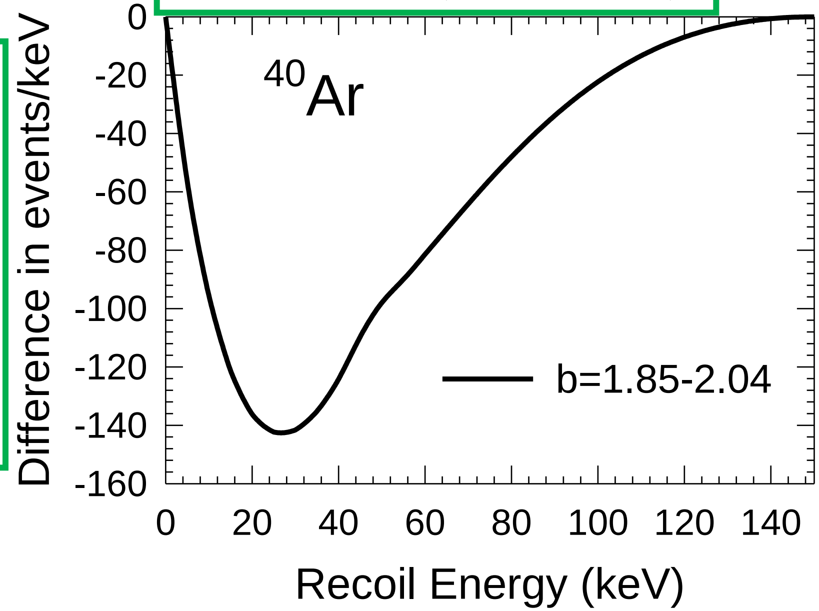


Σdiff=-8770
-2970 (T>50 keV)
-287 (T>100 keV)



Σdiff=-648
-1316

^{12}C:
b=1.80-1.64
Σdiff
=-1158
(T >50 keV)
-867
(T>100 keV)



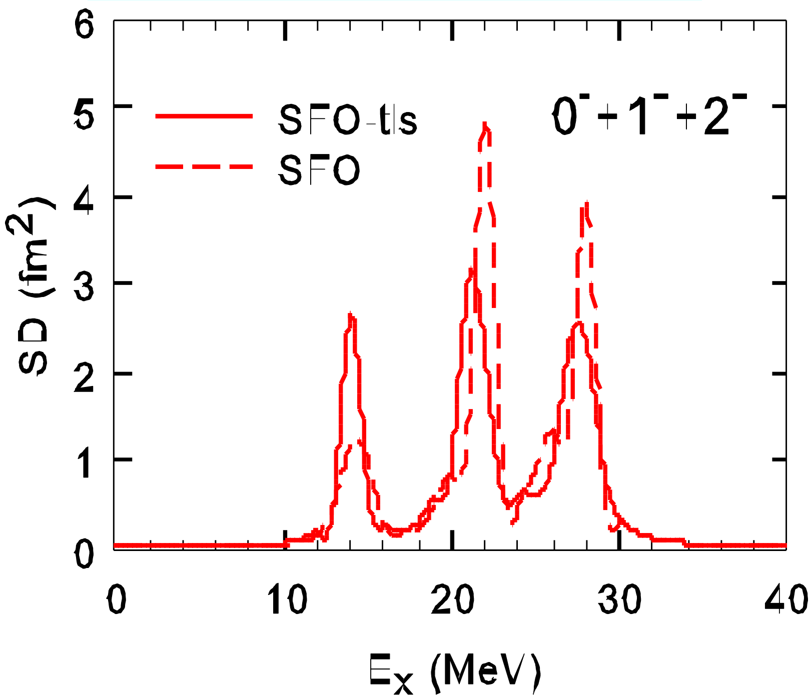
- ν-induced reactions on ^{16}O
- Modification of SFO → SFO-tls

  Full inclusion of tensor force

  - p-sd: tensor->π+ρ

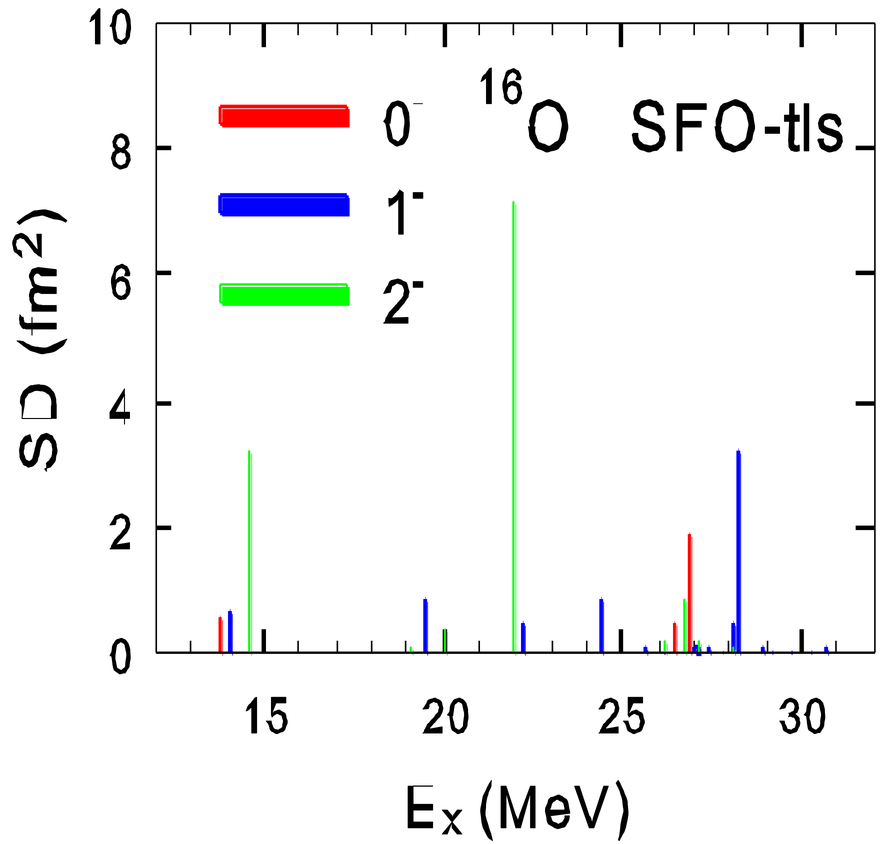
    LS -> σ+ρ+ω

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

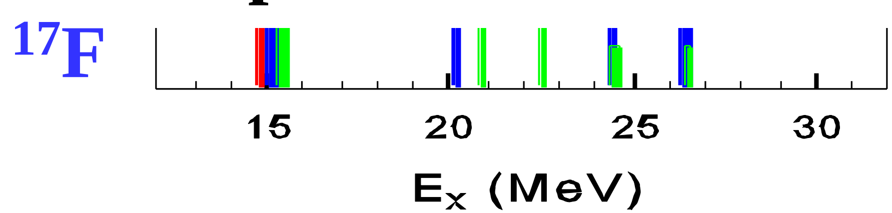


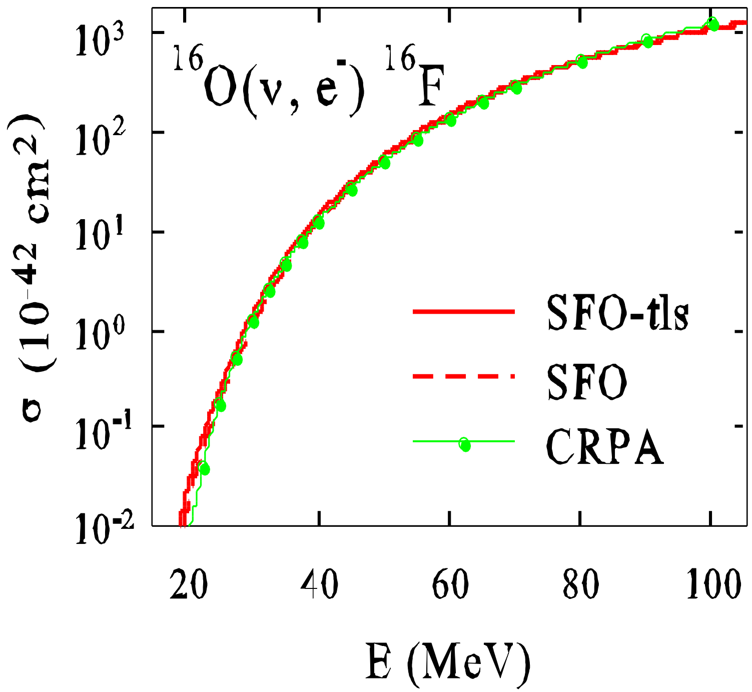
Spin-dipole strength in ^{16}O

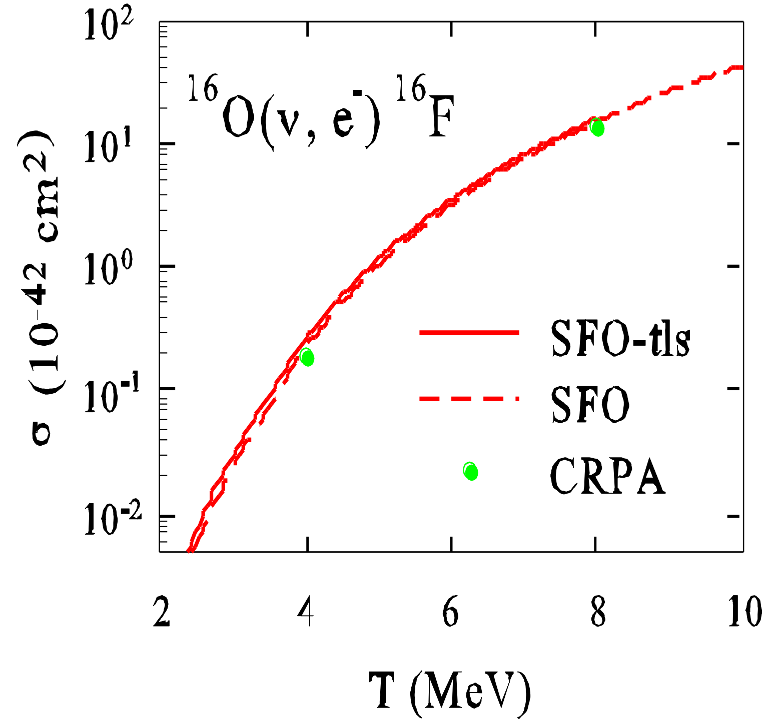
$$O(\lambda) = r[Y^1 \times \sigma]^\lambda t_-$$

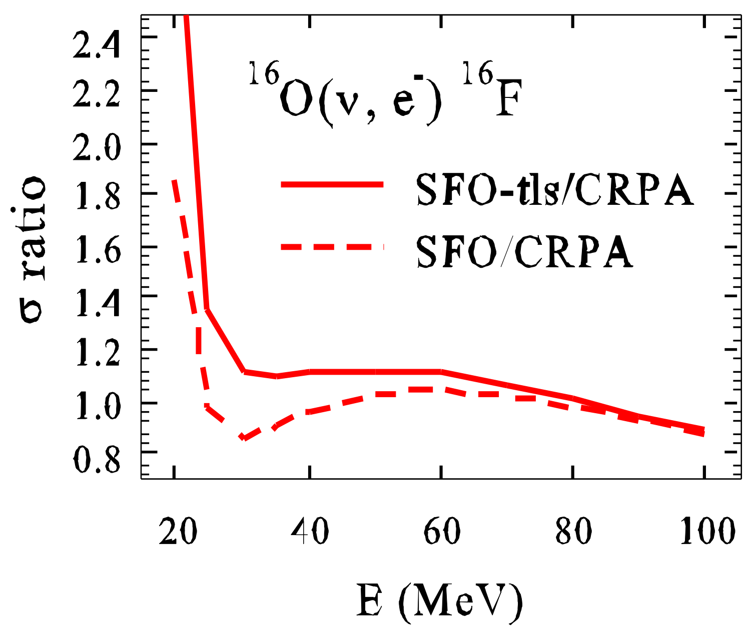


exp.









T= temperature of supernova ν

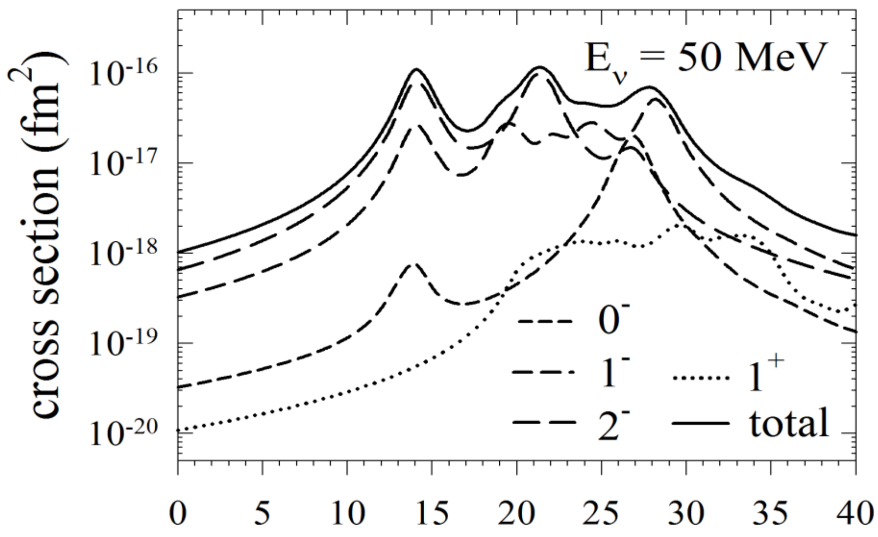
T	σ(SFO-tls)/σ(CRPA):
4	1.41
8	1.17

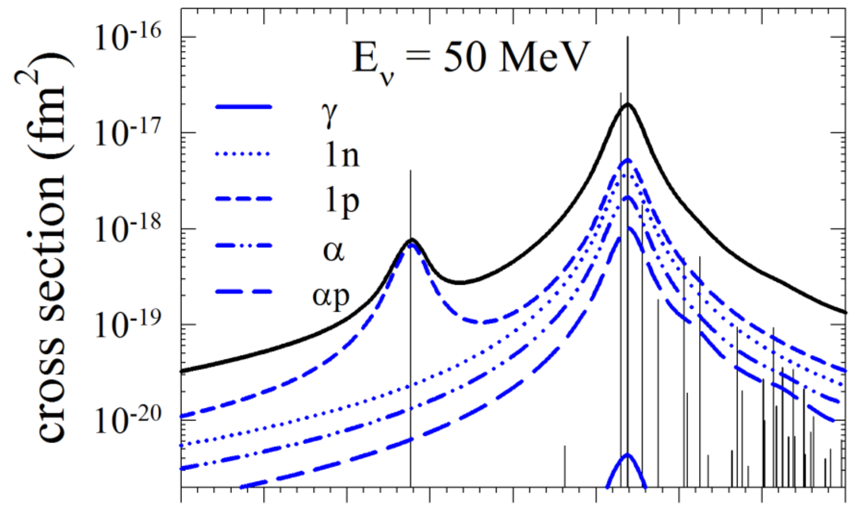
g_A^{eff}/g_A=0.95

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

^{16}O Neutral current reactions

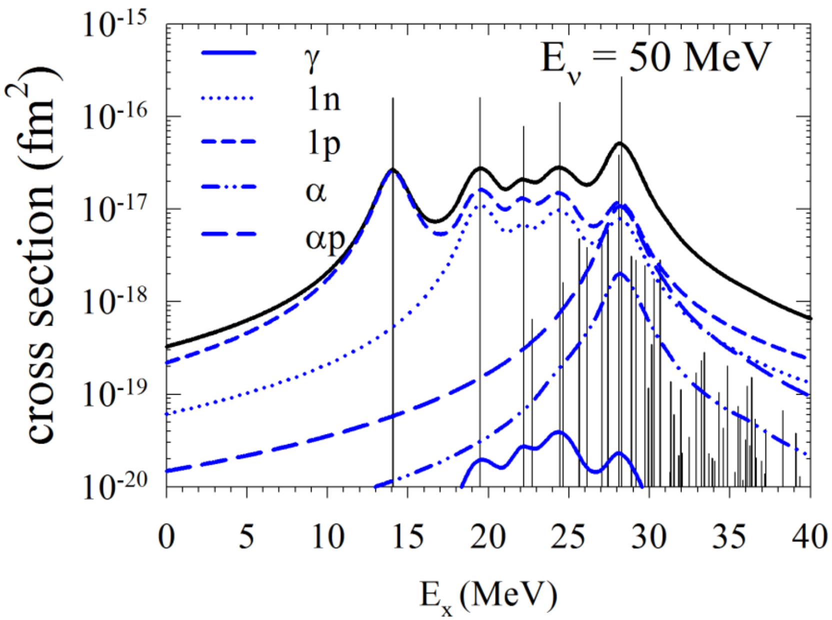
^{16}O 0^-

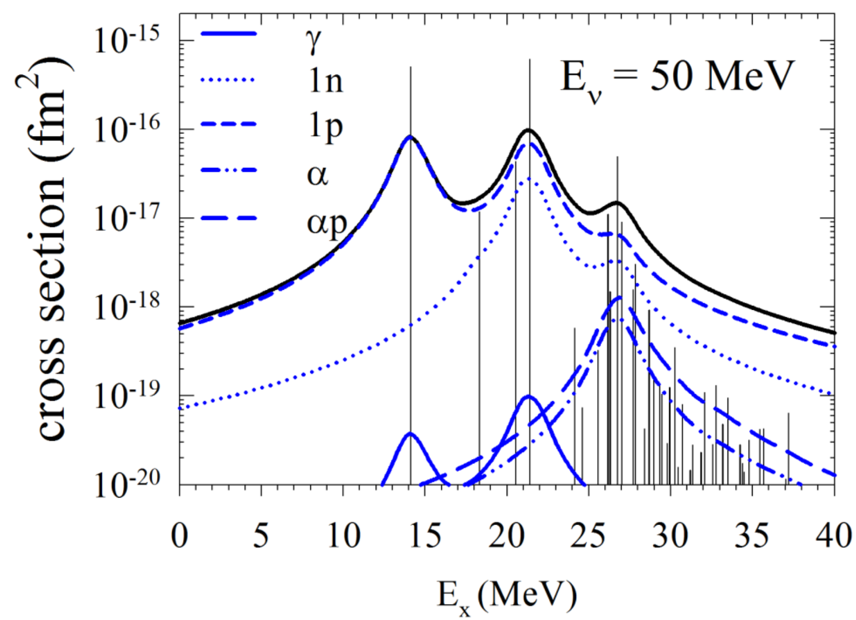


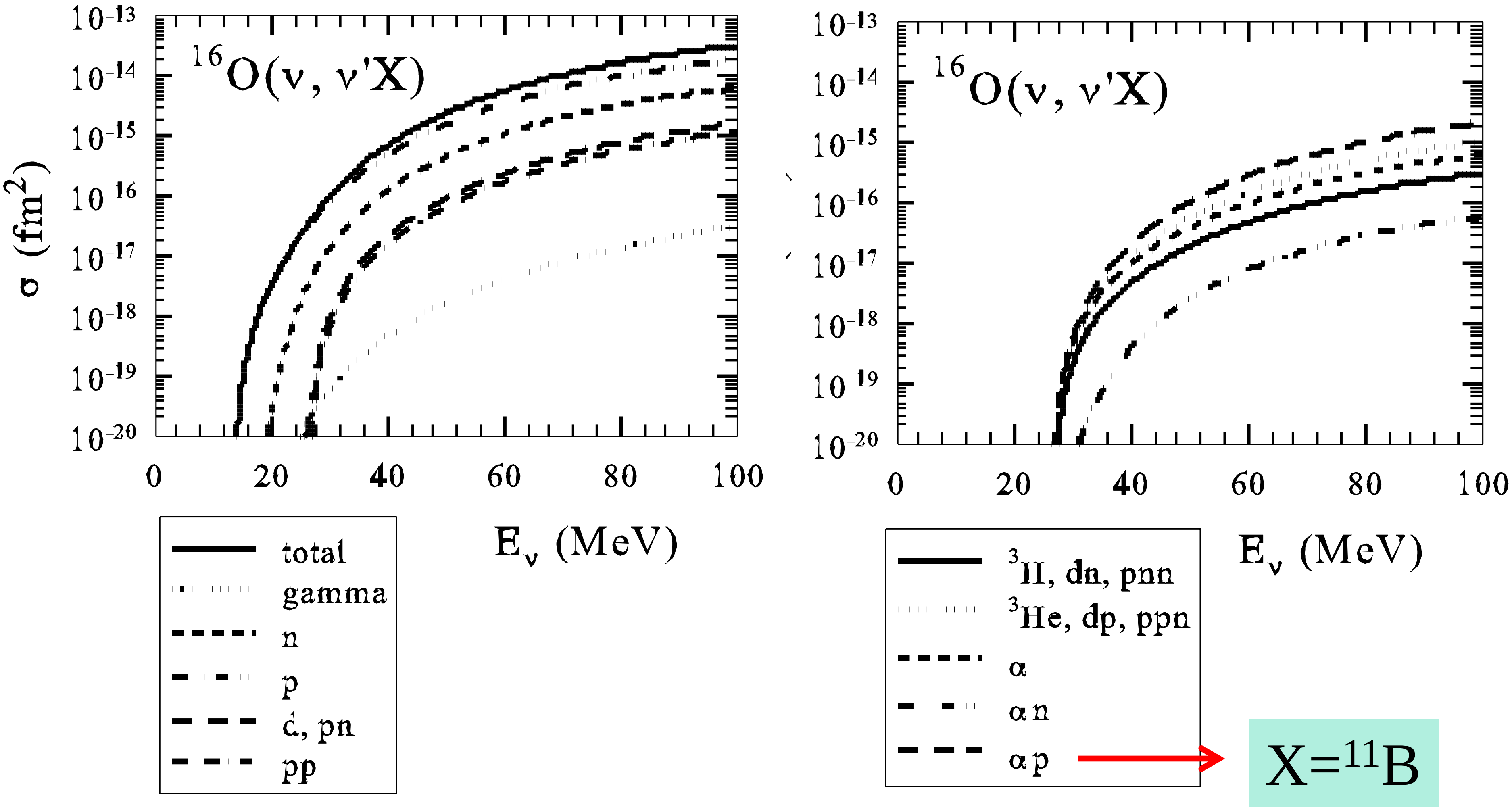


^{16}O 1^-

^{16}O 2^-







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

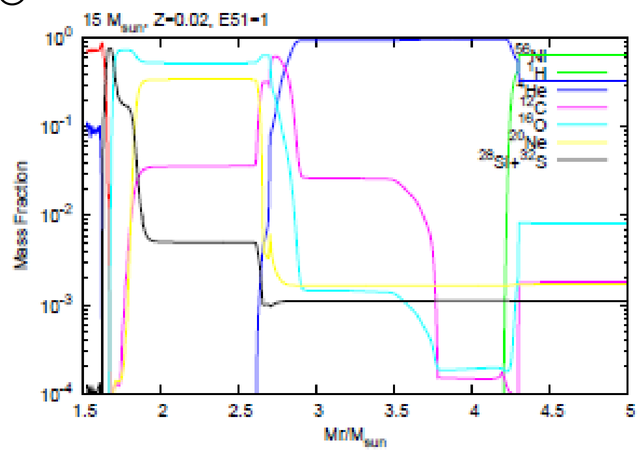
Production yields of ^{11}B and ^{11}C ($10^{-7}M_\odot$)

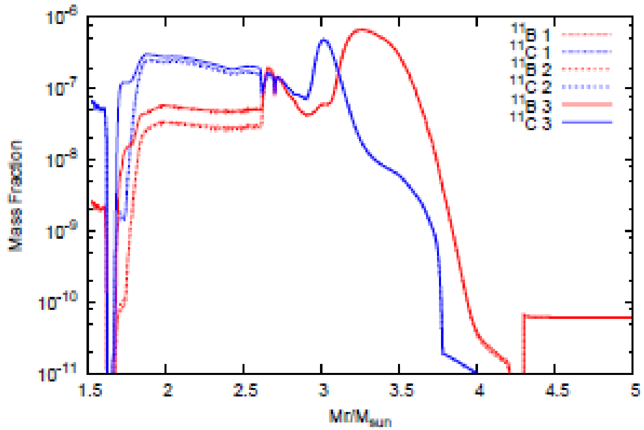
	$15M_\odot$ モデル			$20M_\odot$ モデル		
核種生成量	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
$M(^{11}\mathrm{B})$	2.94	2.92	3.13	6.77	6.58	7.66
$M(^{11}\mathrm{C})$	2.80	2.71	3.20	9.33	8.91	9.64
$M(^{11}\mathrm{B}+^{11}\mathrm{C})$	5.74	5.62	6.33	16.10	15.49	17.29

T. Yoshida

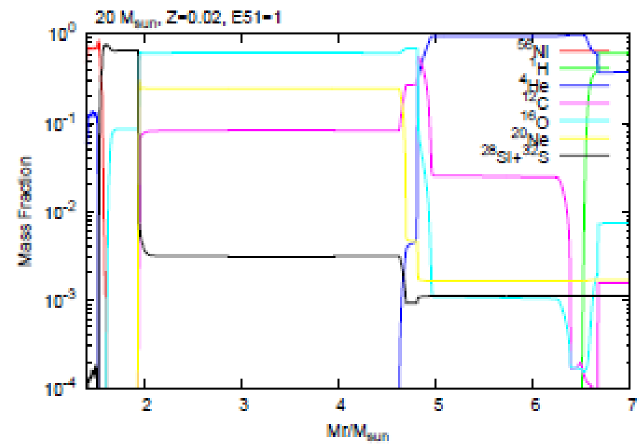
Case1: previous branches used in ^{16}O (γ, n, p, α-emissions) and HW92 cross sections
Case2: previous branches, and new cross sections
Case3: multi-particle branches and new cross sections

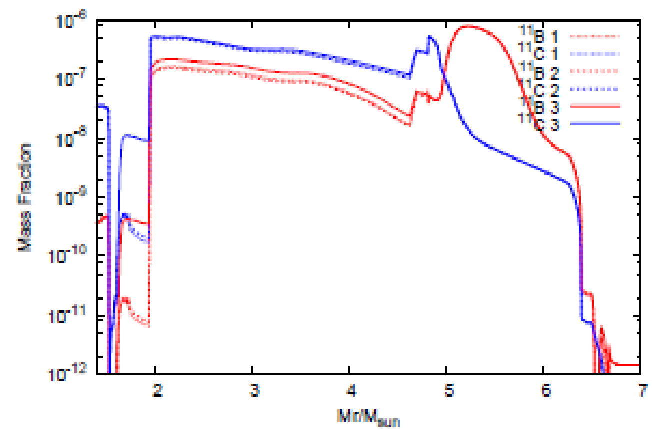
$15M_\odot$





$20M_\odot$





▪ 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)

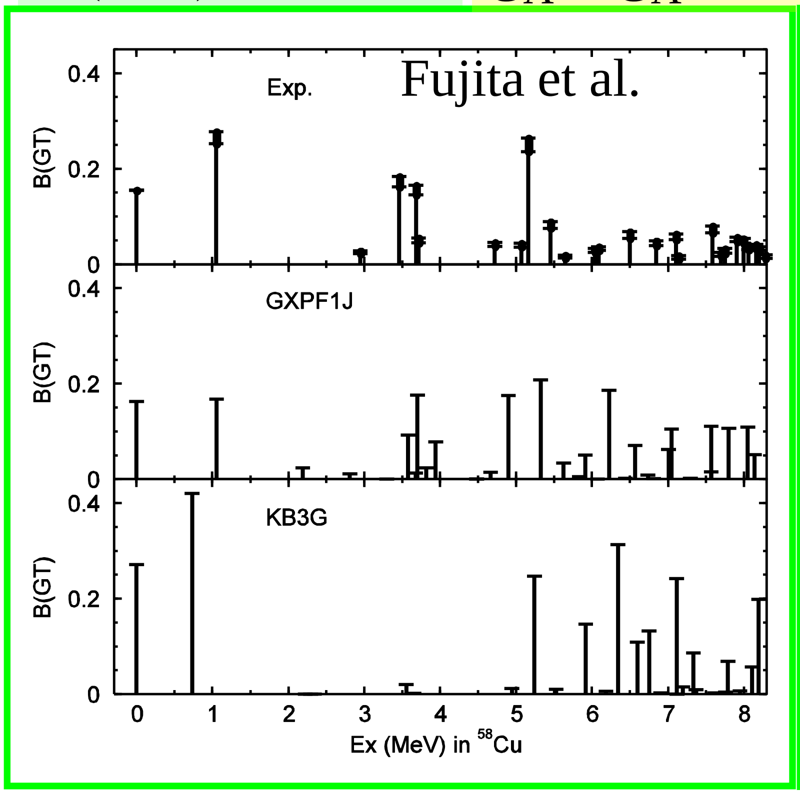
KB3: Caurier et al, Rev. Mod. Phys. 77, 427 (2005)

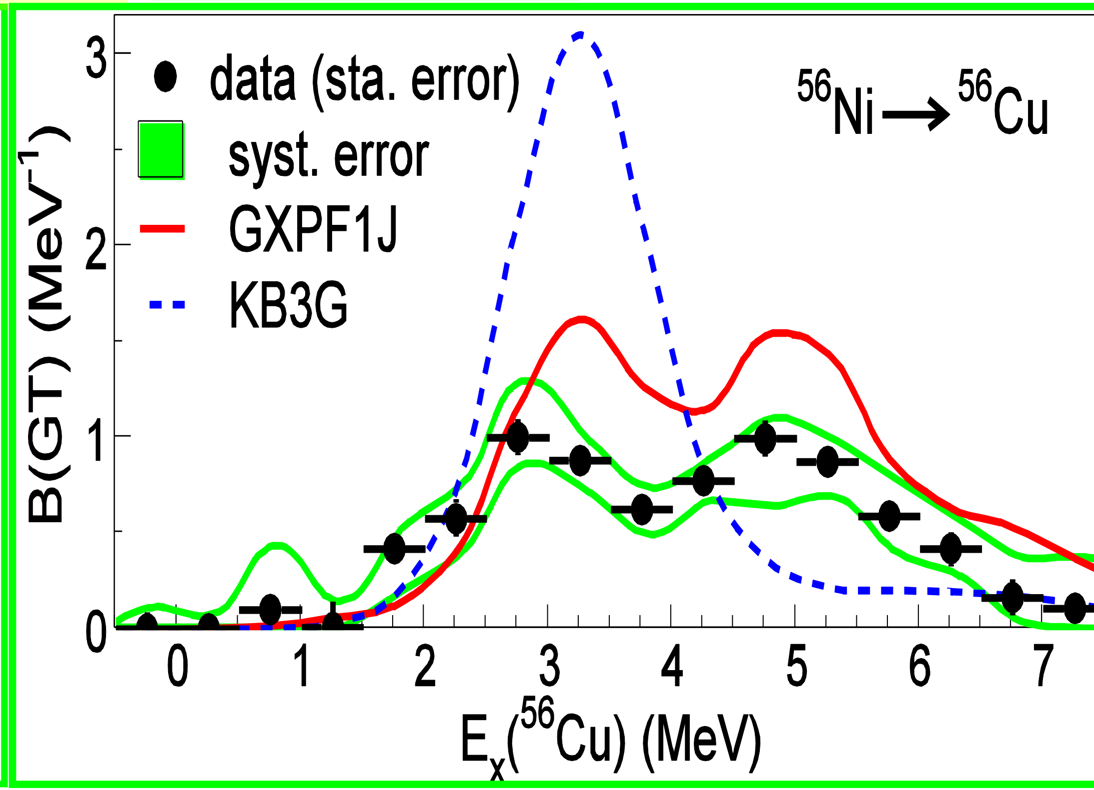
○ KB3G A = 47-52 KB + monopole corrections

○ GXPF1 A = 47-66

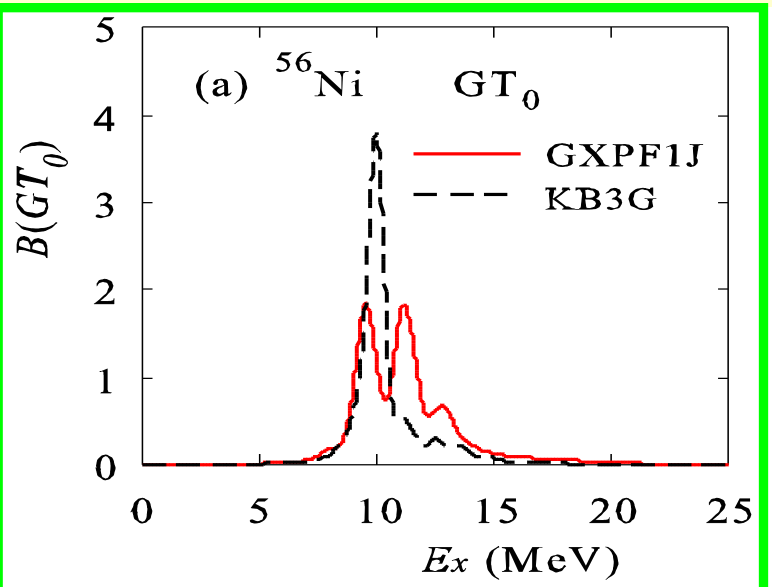
▪ **Spin properties of fp-shell nuclei are well described**

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)



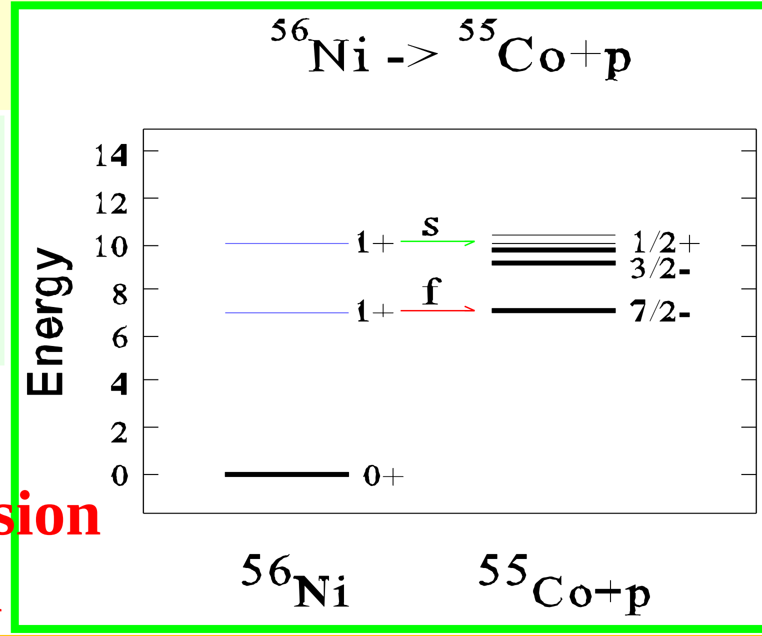


● ^{56}Ni (ν, ν') ^{56}Ni



B(GT)=6.2 (GXPF1J)
B(GT)=5.4 (KB3G)

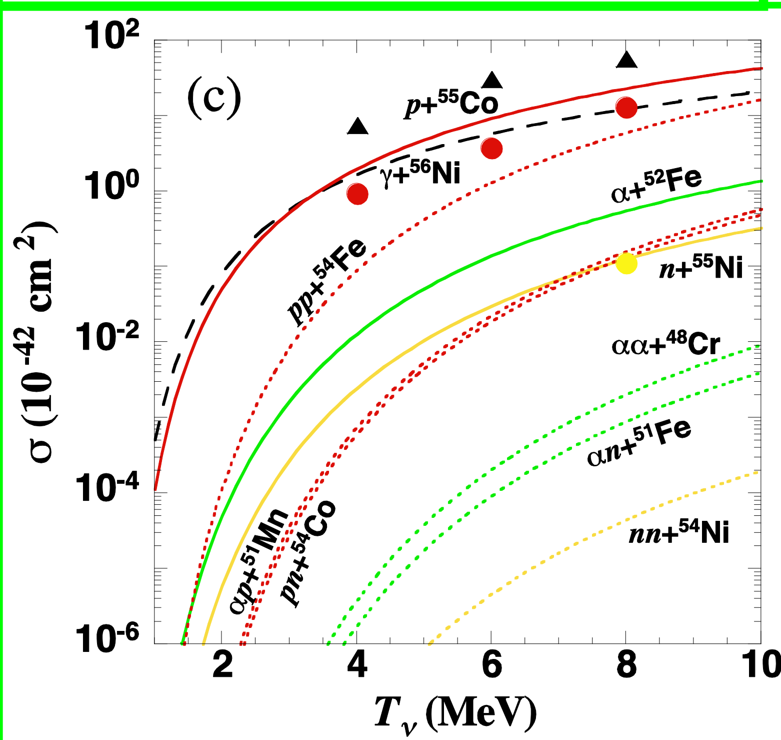
large p emission cross section



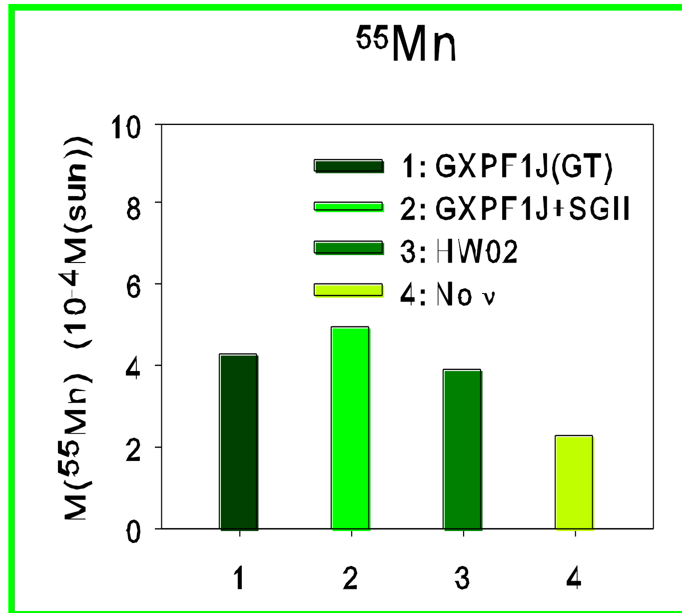
Synthesis of Mn in Population III Star

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

^{54}Fe(p, γ)^{55}Co

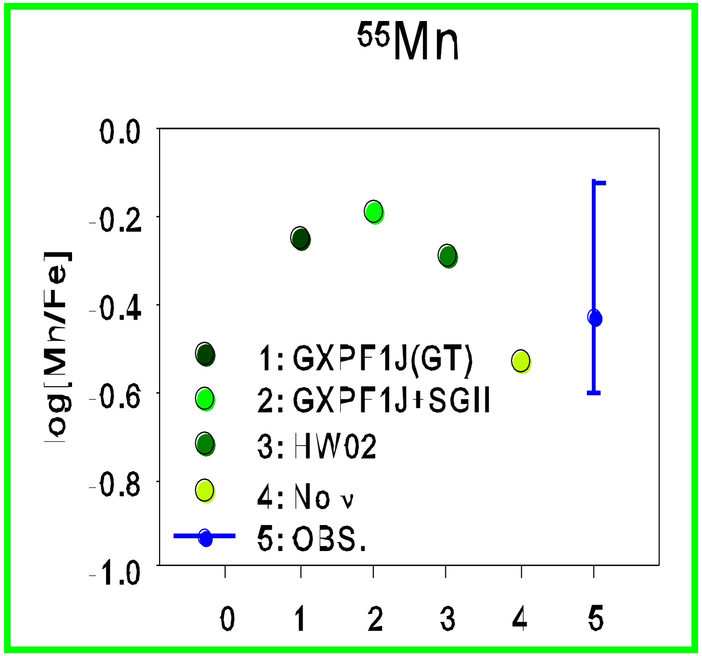


cf: HW02
▲ gamma
● p
● n



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

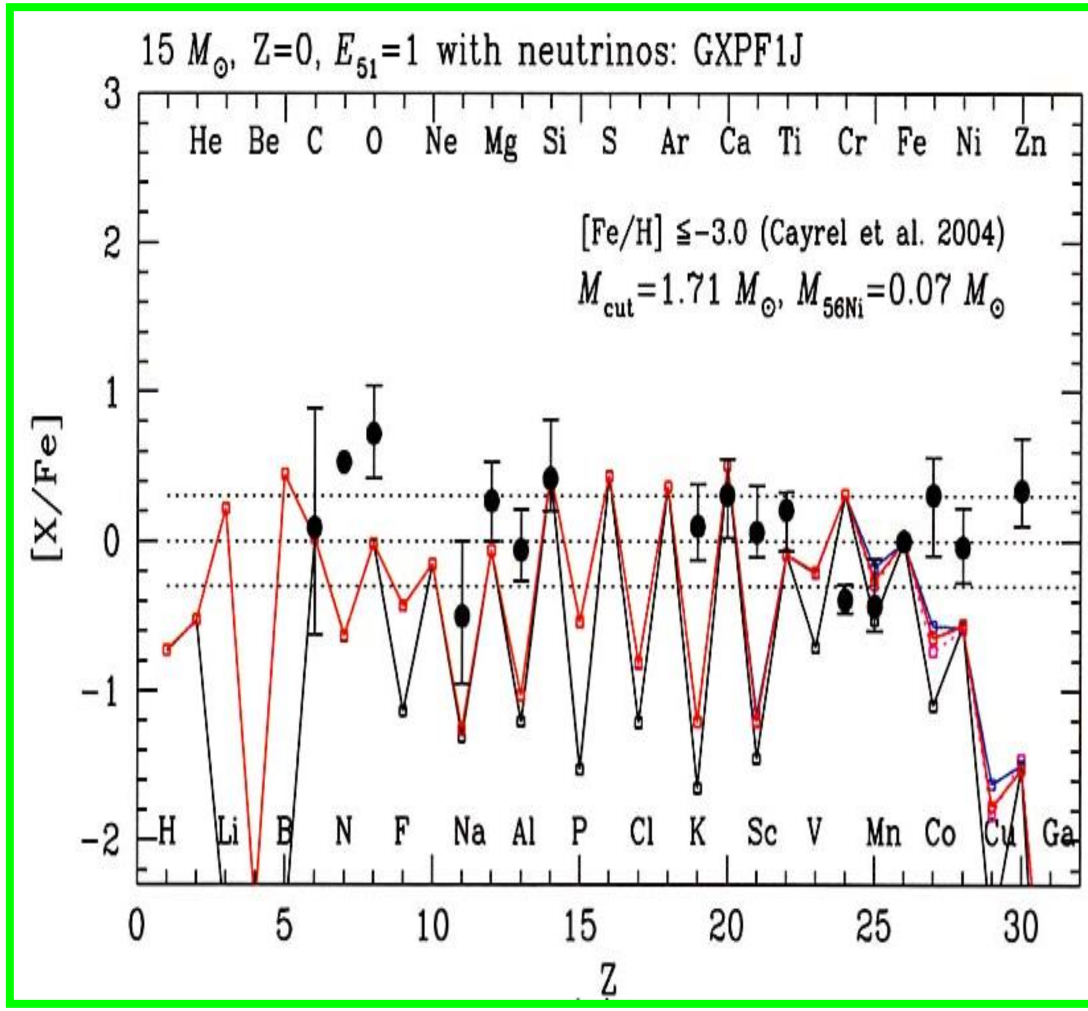
Yoshida, Umeda, Nomoto



Suzuki et al., PR C79 (2009)

OBS: Cayrel et al., Astron. Astrophys. 416 (2004)

	[Mn/Fe]
No ν	**-0.53**
HW02	**-0.29**
GXPF1J(GT)	**-0.25**
GXPF1J(all)	**-0.19**



No ν

With ν(GXPF1J)

With ν(Woosley)

$$^{58}\mathrm{Ni}(p,\gamma)^{59}\mathrm{Cu}(e^-,\nu)^{59}\mathrm{Ni}(e^-,\nu)^{59}\mathrm{Co}$$

▪ ν- ^{40}Ar reactions

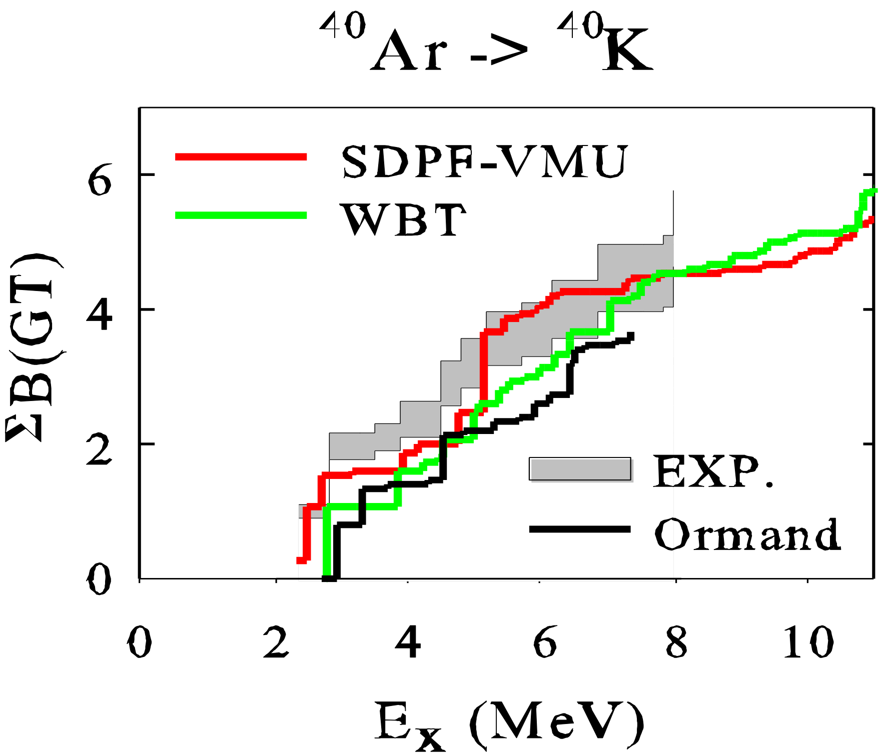
Liquid argon = powerful target for SNν detection

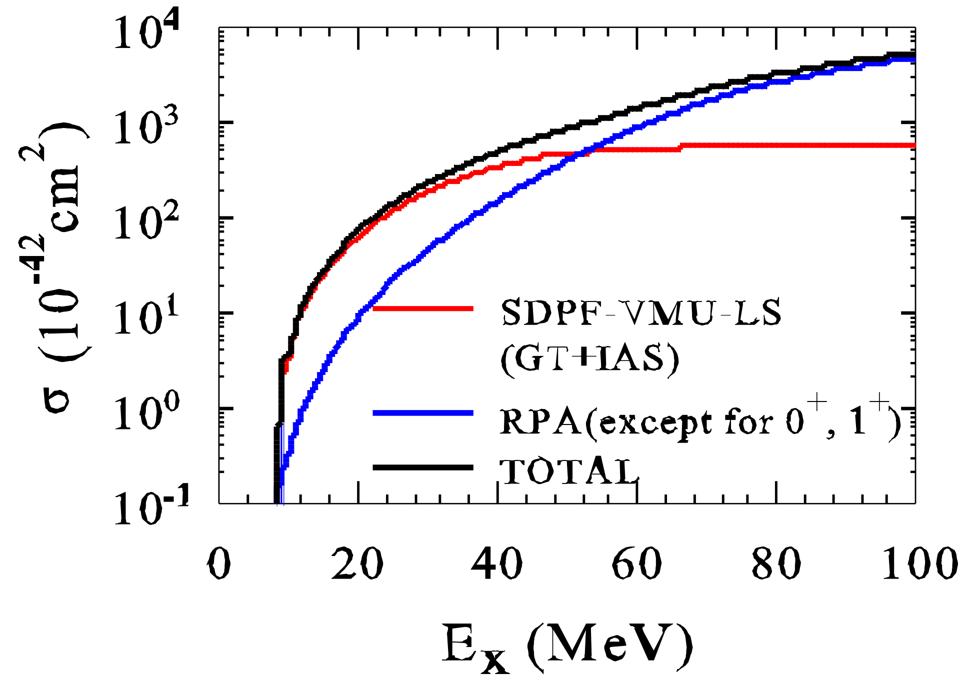
sd-pf shell: **^{40}Ar (ν, e$^-$) ^{40}K** (sd)$^{-2}$ (fp)^2 : 2hw

SDPF-VMU-LS

sd: SDPF-M (Utsuno et al.) fp: GXPF1 (Honma et al.)

sd-pf: VMU + 2-body LS





Suzuki and Honma, PR C87, 014607 (2013)

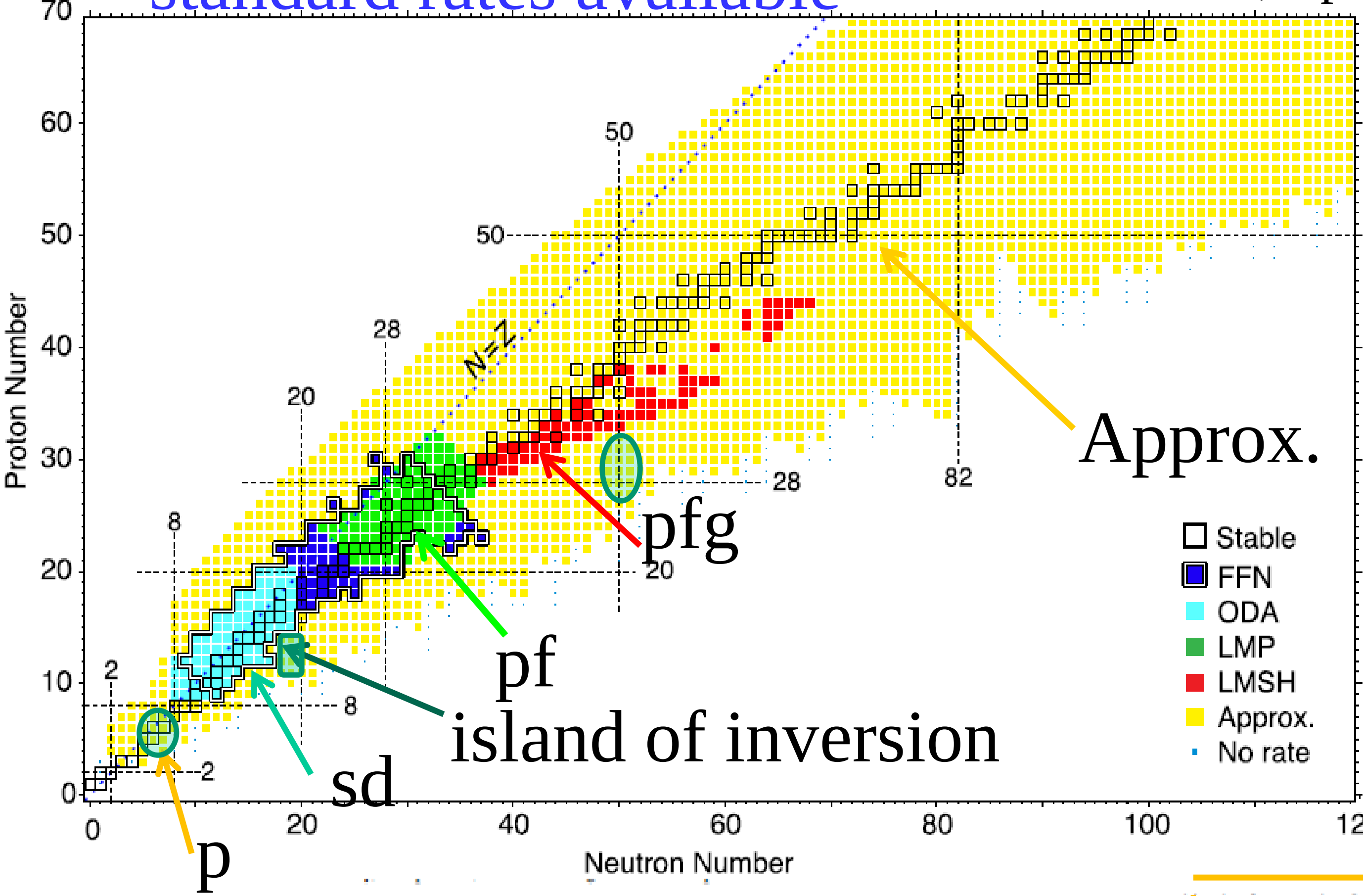
(p,n) Bhattacharya et al., PR C80, 055501 (2009)

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

Electron-capture (weak) rates in stellar environments

- standard rates available

Sullivan et al., ApJ. 816, 44 (2016)



Missing

- Island of inv. sd-pf
- ~^{78}Ni N=50 pf-gds
- p-shell

Table	Model Space s	p	sd	pf	pfg/sdg	T (GK)	$\mathrm{Log}_{10}(\rho Y_e$ g cm$^{-3})$	Reference
FFN	x	...	x	x	...	0.01–100	1.0–11	Fuller et al. (1982)
ODA	x	...	x	...	...	0.01–30	1.0–11	Oda et al. (1994)
LMP	x	...	...	x	...	0.01–100	1.0–11	Langanke et al. (2003), Langanke (2001a)
LMSH	...	...	...	...	x	8.12–39.1	9.22–12.4	Hix et al. (2003), Langanke et al. (2001a)
Approx.	x	x	x	x	x	...	...	Langanke et al. (2003)

Approx.

B (=4.6) and ΔE (=2.5 MeV)

$$\eta = \chi + \mu_e/T,$$

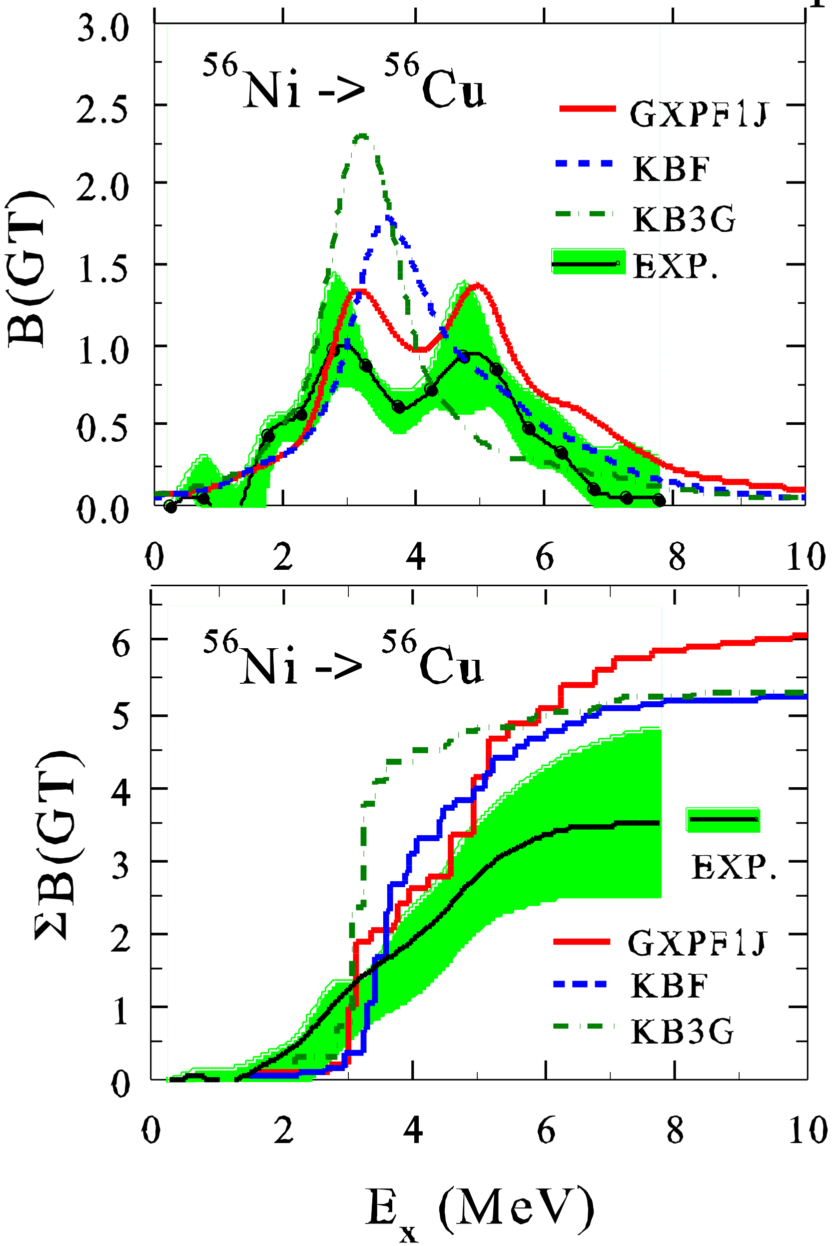
$$\chi = (Q - \Delta E)/T,$$

$$\lambda_{\mathrm{EC}} = \frac{\ln 2 \cdot B}{K}\left(\frac{T}{m_e c^2}\right)^5 [F_4(\eta) - 2\chi F_3(\eta) + \chi^2 F_2(\eta)]$$

$$F_k(\eta) = \int_0^\infty \frac{x^k}{\exp(x-\eta)+1} dx,$$

$$F_k(\eta) = -\Gamma(k+1)\mathrm{Li}_{k+1}(-e^\eta),$$

▪ pf-shell: GT strength in ^{56}Ni: GXPF1J vs KB3G vs KBF

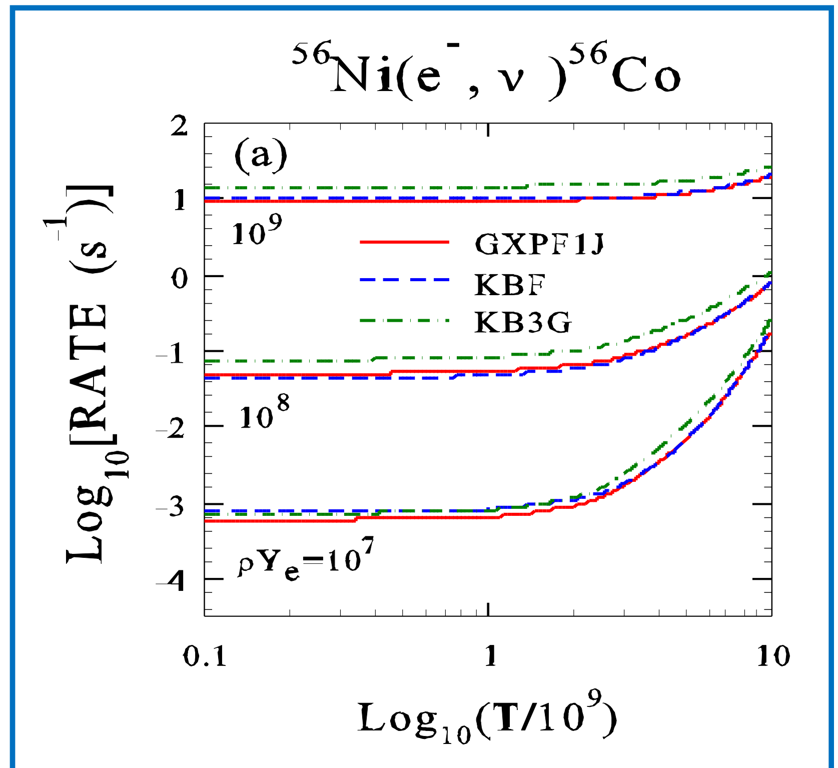


EXP: Sasano et al., PRL 107, 202501 (2011)

KBF: Table by Langanke and Martinez-Pinedo,

At. Data and Nucle. Data Tables 79, 1 (2001)

- fp-shell nuclei: KBF Caurier et al., NP A653, 439 (1999)
- Experimental data available are taken into account: Experimantal Q-values, energies and B(GT) values available
- Densities and temperatures at FFN (Fuller-Fowler-Newton) grids:



▪Type-Ia SNe and synthesis of iron-group nuclei

Accretion of matter to white-dwarf from binary star

→ supernova explosion when white-dwarf mass ≈ Chandrasekhar limit

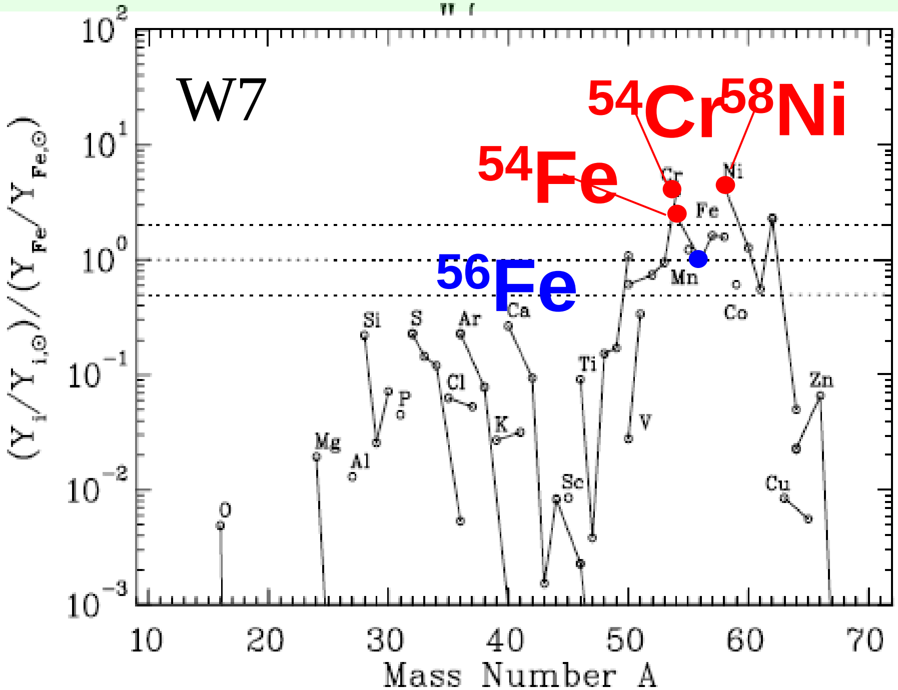
→ ^{56}Ni (N=Z)

→ ^{56}Ni (e^-, ν) ^{56}Co Y_e =0.5 → 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 and larger Y_e

Problem of over-production of neutron-excess iron-group isotopes such as ^{58}Ni, ^{54}Cr … compared with solar abundances



Iwamoto et al., ApJ. Suppl, 125, 439 (1999)

e-capture rates with FFN

(Fuller-Fowler-Newman)

Type-Ia SNe

W7 model : fast deflagration

WDD2: Slow deflagration

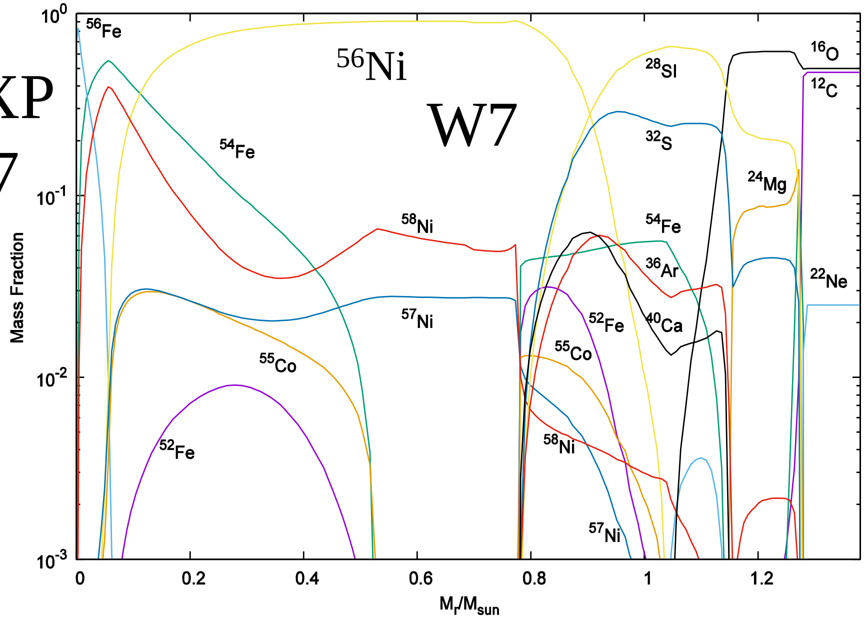
+ delayed detonation

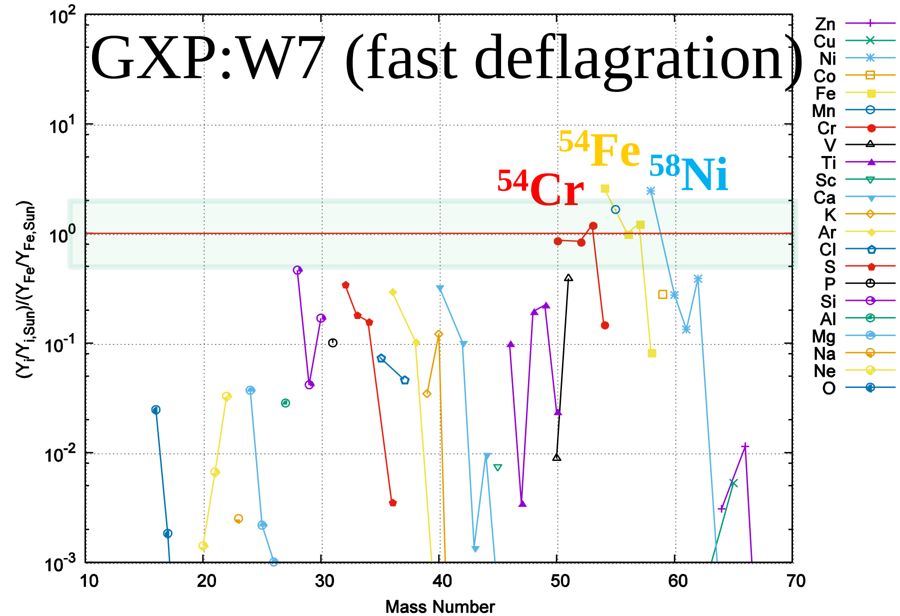
Initial: C-O white dwarf, $M=1.0M_\odot$

central; ρ_9=2.12, T_c=1x10^7K

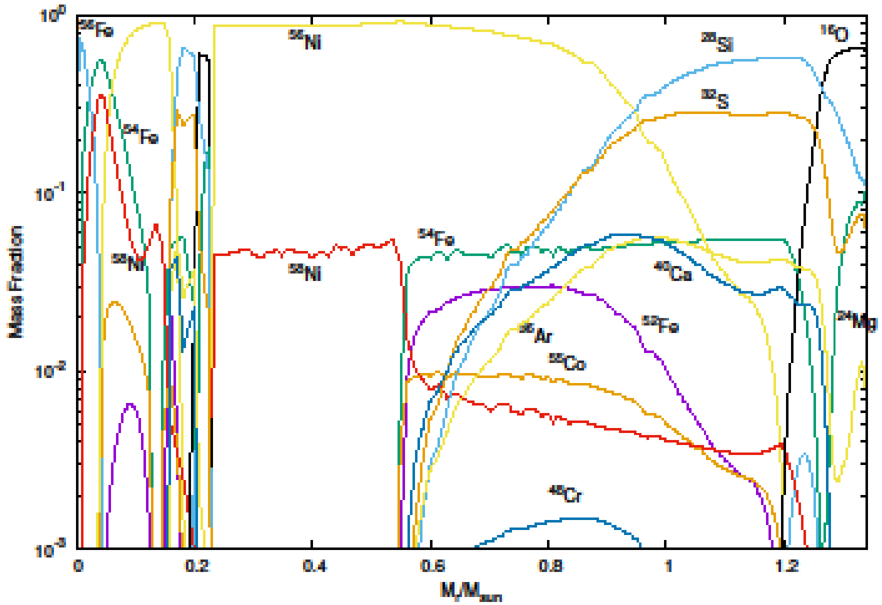
e-capture rates: GXP; GXPF1J (21≤Z≤32) and KBF (other Z)

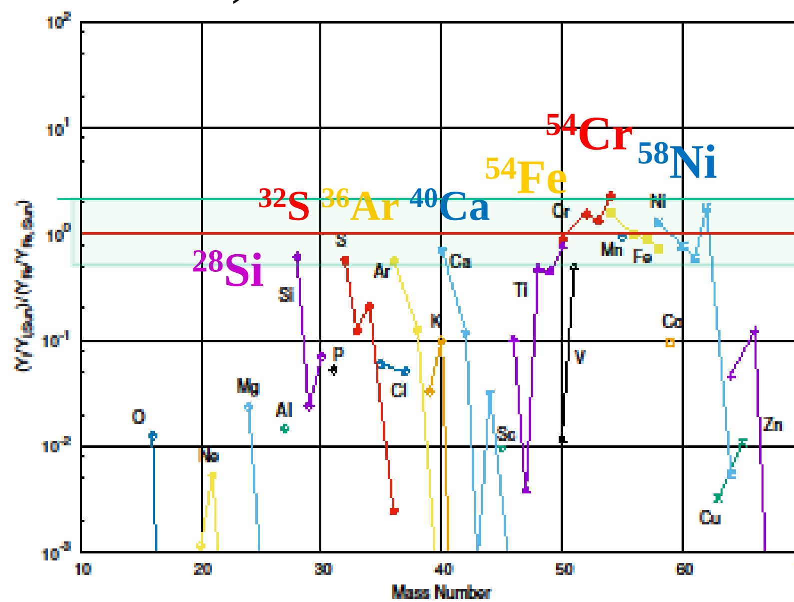
GXP
W7





GXP: WDD2 (slow deflagration + detonation)





Mori, Famiano, Kajino, Suzuki, Hidaka, Honma, Iwamoto, Nomoto, Otsuka, ApJ. 833, 179 (2016)

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)

○ New weak rates for pf-shell from GXPF1J

Nucleosynthesis of iron-group elements in Type Ia Sne: GXPF1J gives smaller e-capture rates (cf. KBF, KB3G, FFN), and leads to larger Y_e with less neutron-rich isotopes, thus can solve the over-production problem in iron-group nuclei.