Study of neutrino-nucleus reactions and neutrino-emissions for neutrino detection, nucleosynthesis and cooling of stars

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

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

- 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

- sd-shell: cooling of O-Ne-Mg core in stars by nuclear URCA processes
- pf-shell: Type-Ia SNe and nucleosynthesis of iron-group elements
- sd-pf shell nuclei in the island of inversion
  EKK (extended Kuo-Krenciglowa method)

● ν-nucleus reactions

1. ν-^{12}C, ν- ^{13}C: SFO (p-shell)
2. ν-^{16}O, . ν-^{18}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)

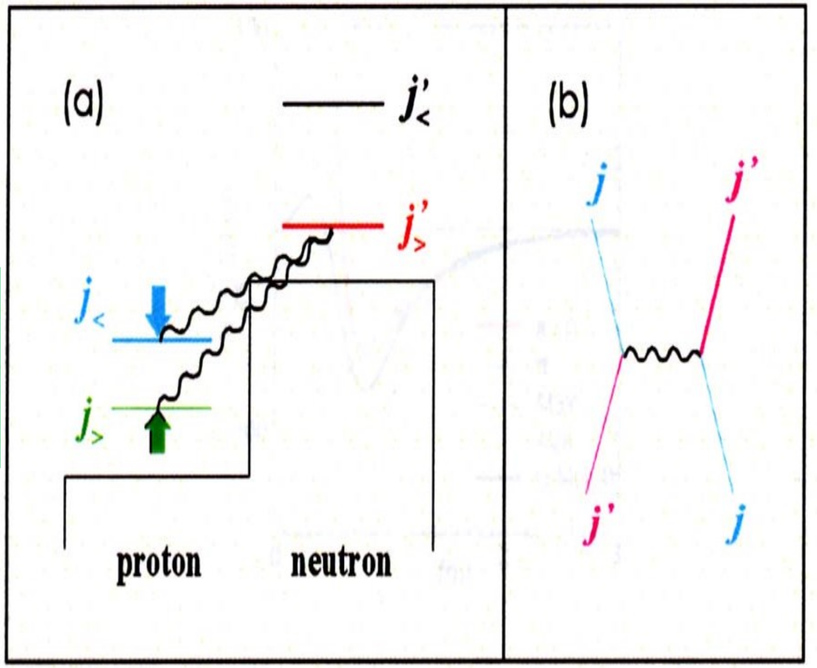
* important roles of tensor force

Monopole terms of V_{NN}

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

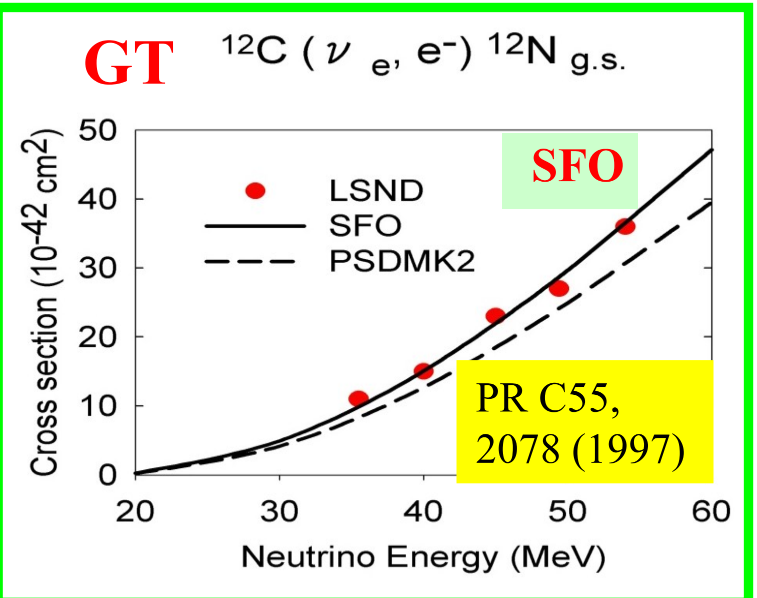
$j_> - j_<$: attractive

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



▪ν-nucleus reactions

p-shell: SFO



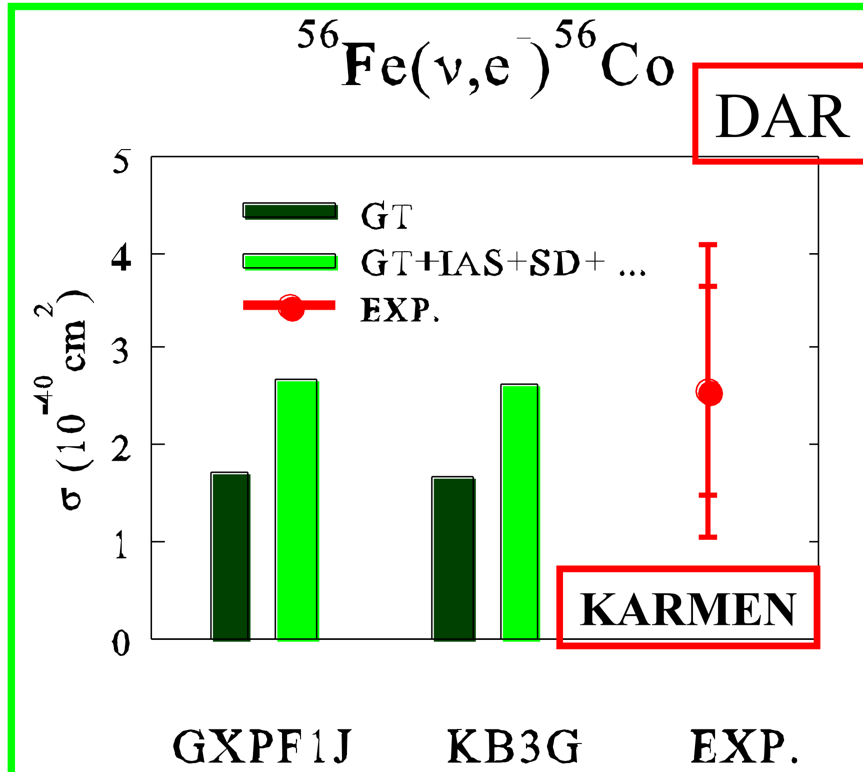
Suzuki, Chiba, Yoshida, Kajino, Otsuka, PR C74, 034307, (2006).

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.



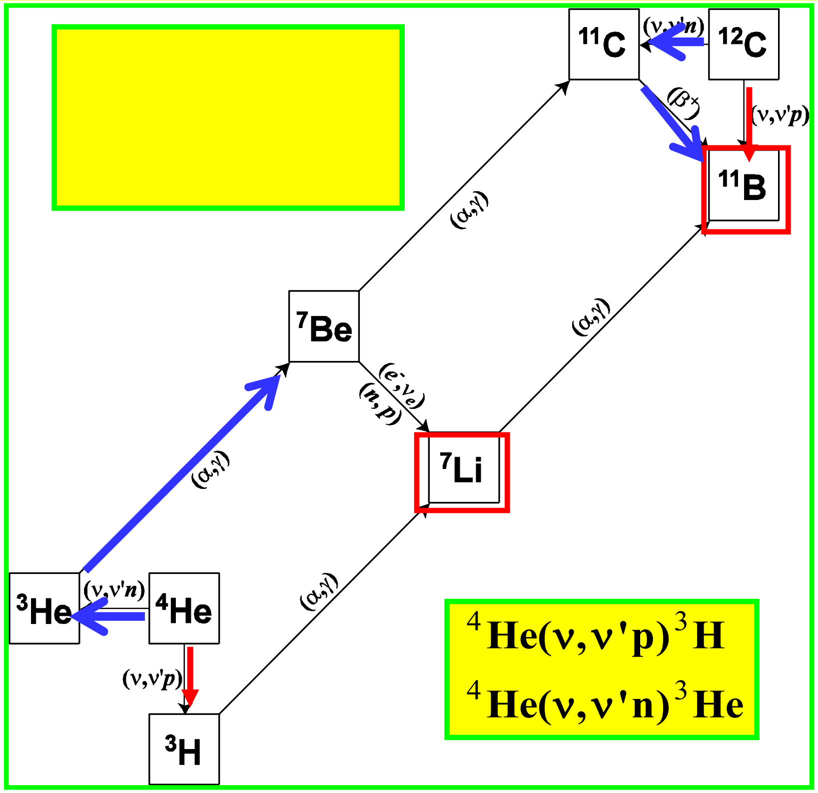
$B(GT)$=9.5 $B(GT)_{exp}$=9.9±2.4 $B(GT)_{KB3G}$=9.0

SD + … : RPA (SGII)

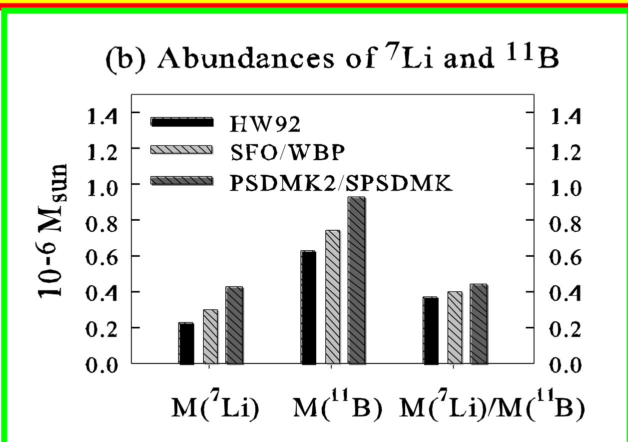
$$\langle\sigma\rangle_{exp} = (256 \pm 108 \pm 43) \times 10^{-42}\ \text{cm}^2.$$
$$\langle\sigma\rangle_{th} = (258 \pm 57) \times 10^{-42}\ \text{cm}^2.$$

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

▪Nucleosynthesis processes of light elements in SNe



Enhancement of ^{11}B and ^{7}Li abund.



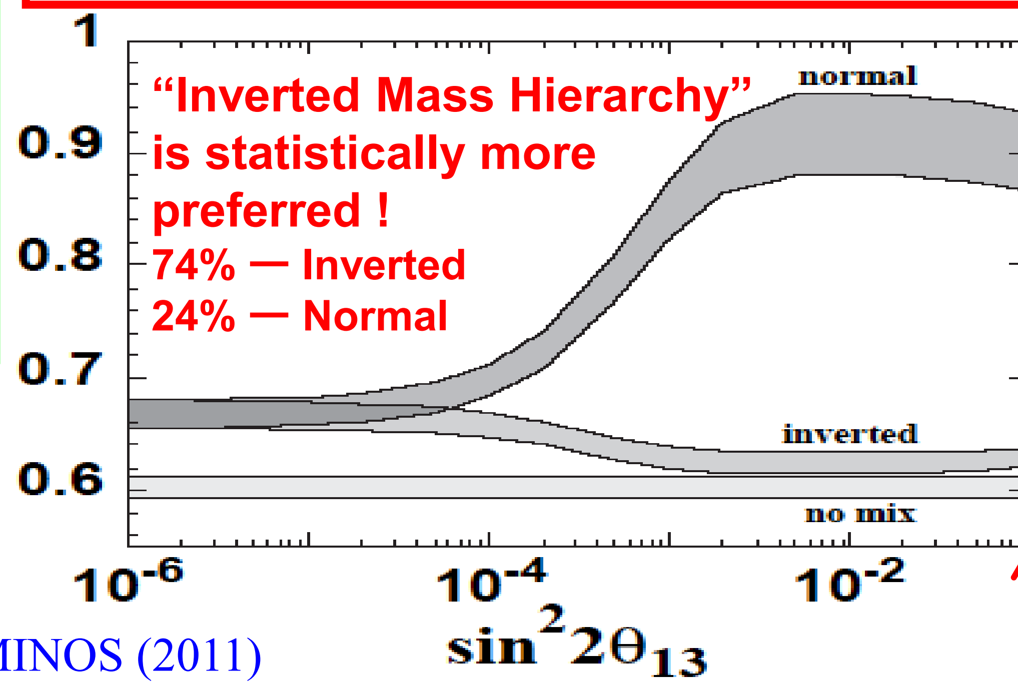
Effects of MSW ν oscillations

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

Increase in the rates in the He layer:

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

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



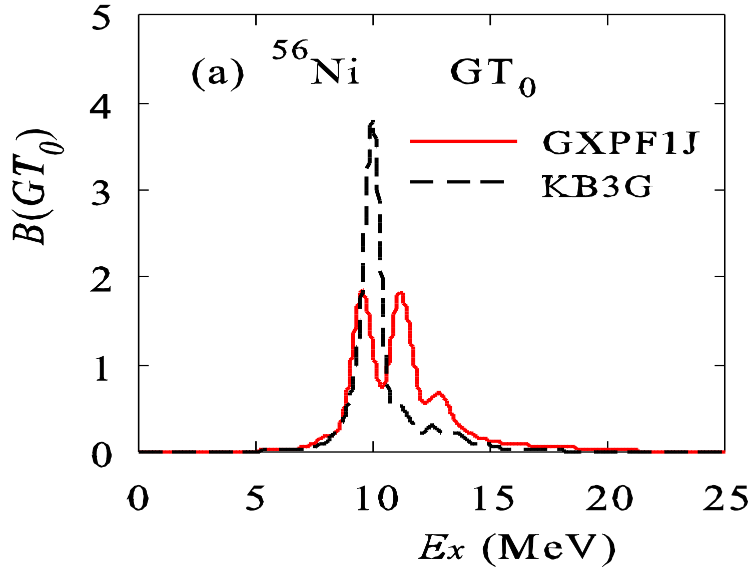
- T2K, MINOS (2011)
- Double CHOOZ, Daya Bay, RENO (2012)

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

Bayesian analysis:
Mathews, Kajino, Aoki and Fujiya, Phys. Rev. D85,105023 (2012).1

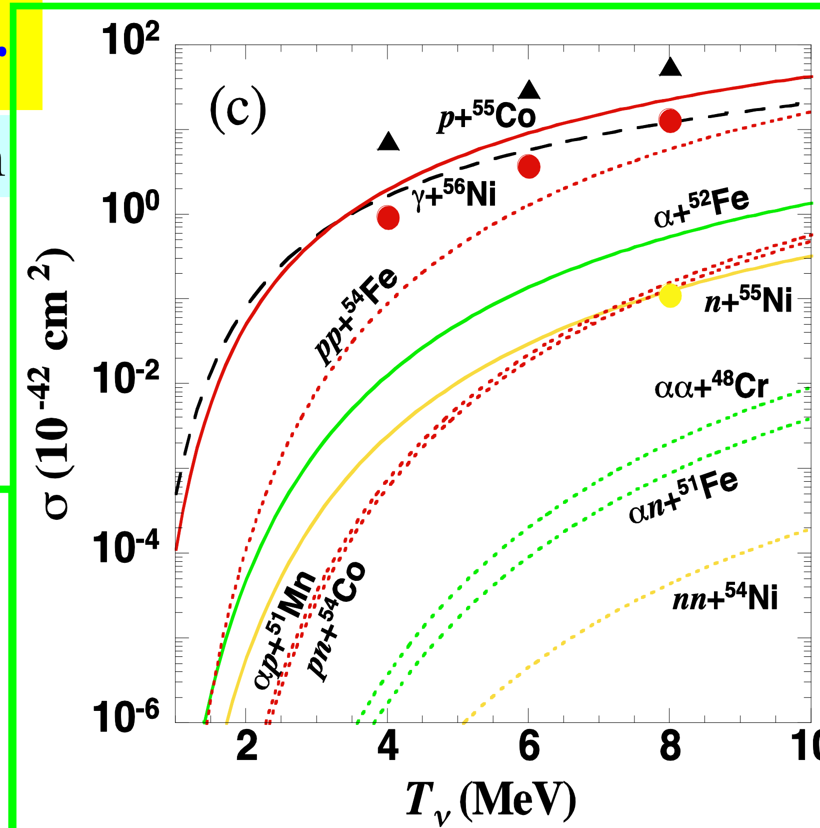
Synthesis of ^{55}Mn in Pop.III Star

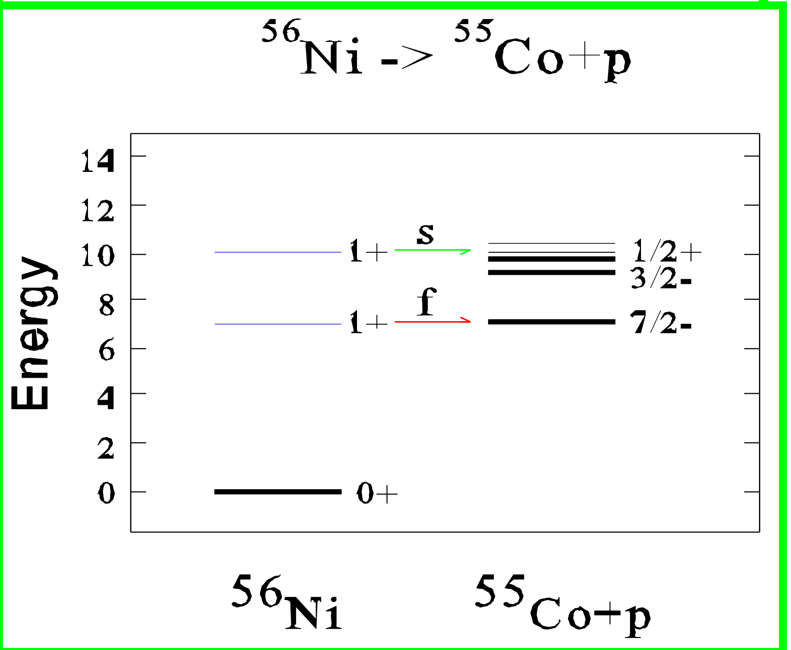
$^{56}Ni(\nu,\nu' p)^{55}Co$, $^{55}Co(e^-,\nu)^{55}Fe(e^-,\nu)^{55}Mn$



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

cf: HW02
▲ gamma
● p
● n

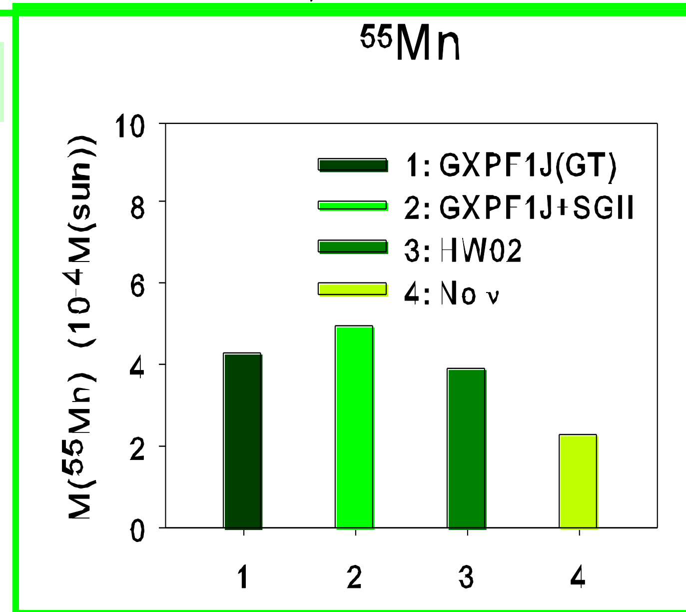




$^{54}Fe(p,\gamma)^{55}Co$

large proton emission cross section

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



▪ ν-induced reactions on ^{13}C

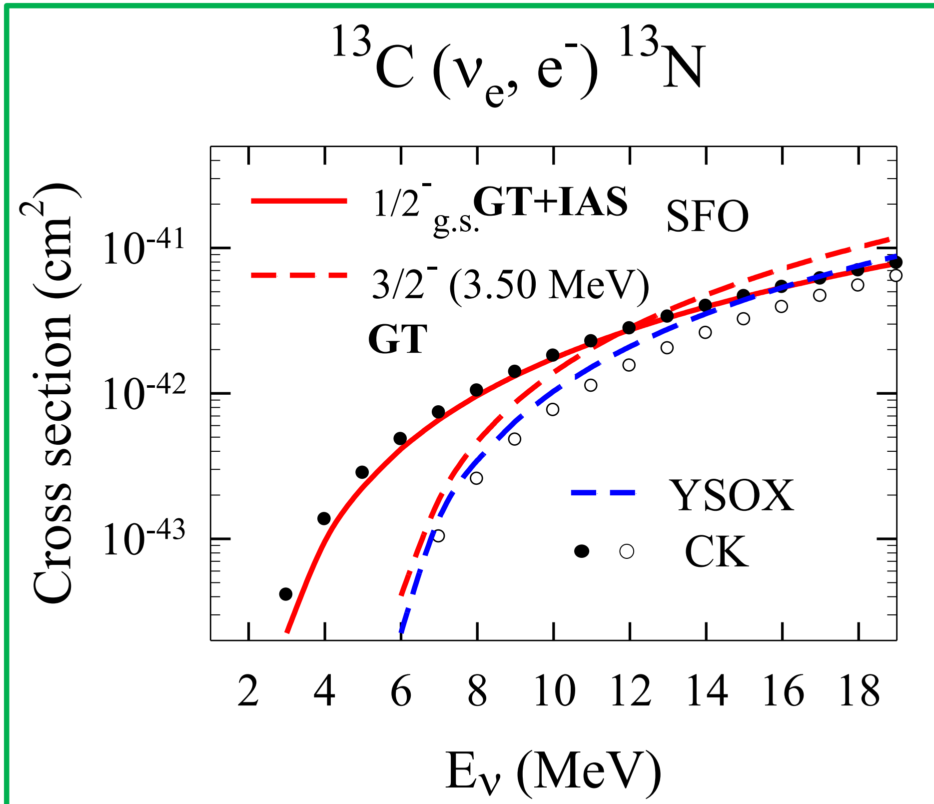
^{13}C: attractive target for very low energy ν

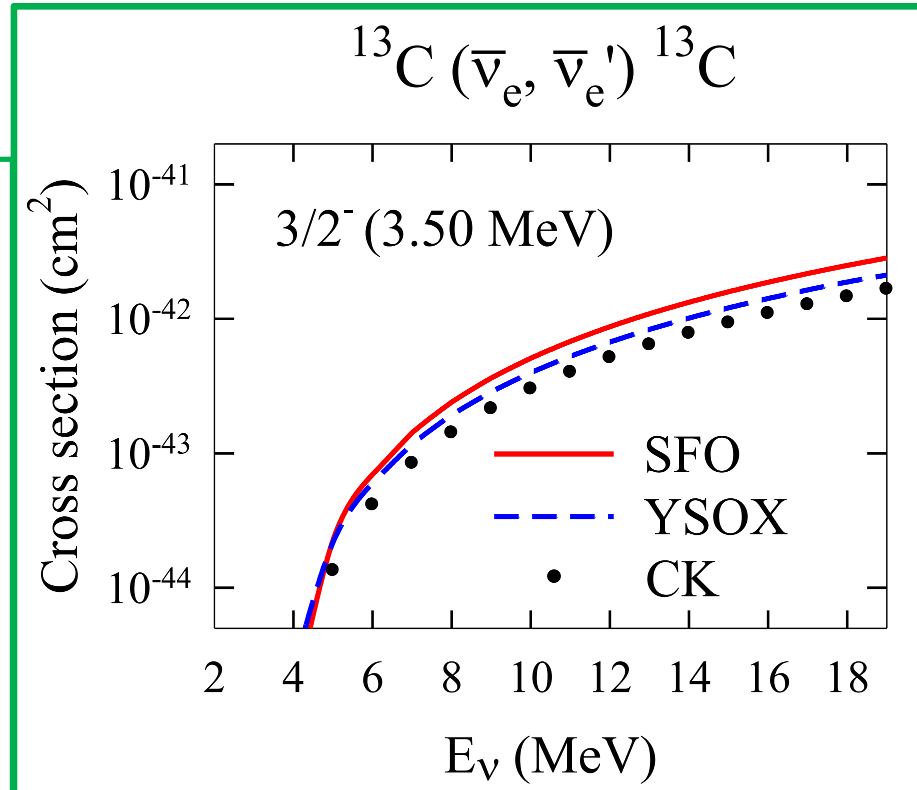
$E_\nu \leq 10\,\mathrm{MeV} \quad E_\nu^{th}(^{12}C) \approx 13\,\mathrm{MeV}$

Natural isotope abundance = 1.07%

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

reactor anti-ν





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)

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

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

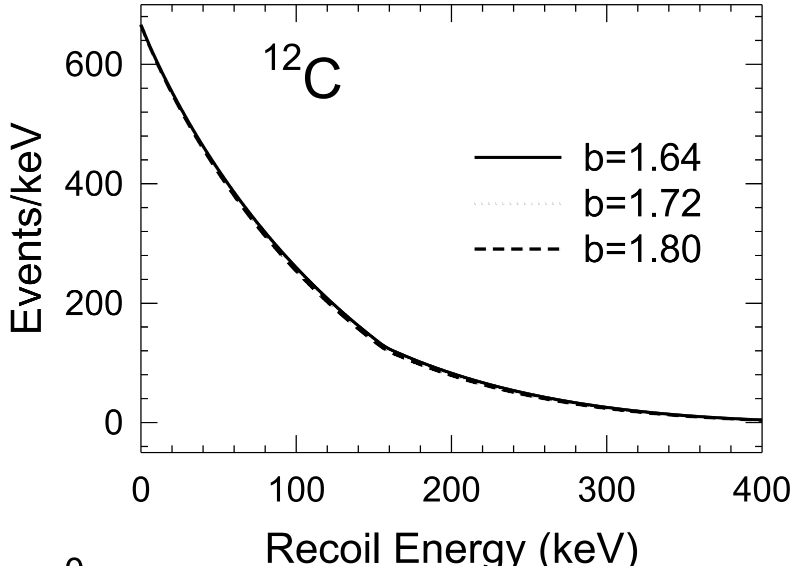
$$F(Q^2) = \{N F_n(Q^2) - (1 - 4\sin^2\theta_W) Z F_p(Q^2)\} / Q_W$$

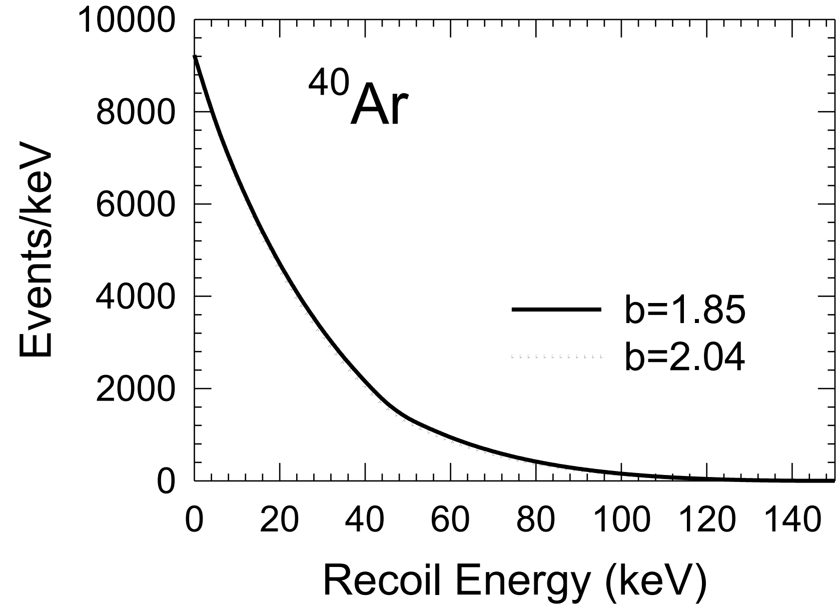
$$Q^2 = 2E^2 TN / (E^2 - ET)$$

Events/keV - Recoil energy (keV)

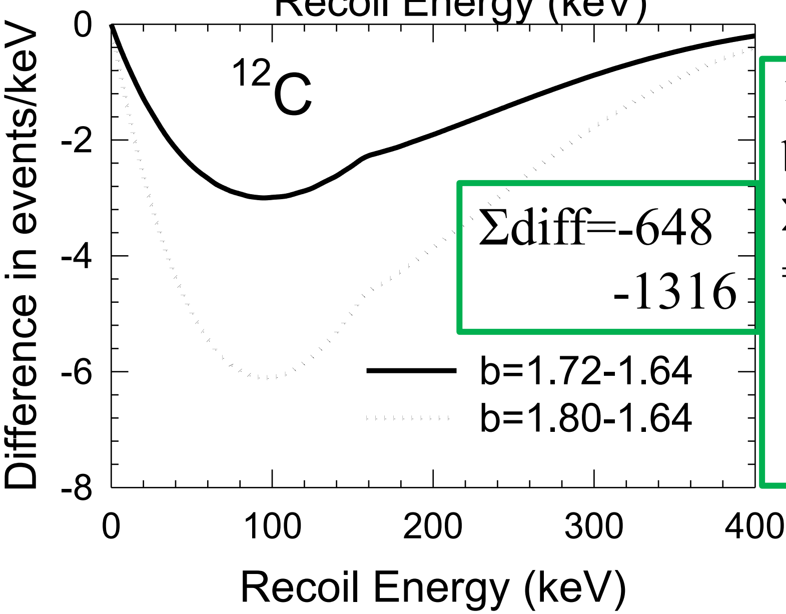
DAR ν (3-flavors)

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

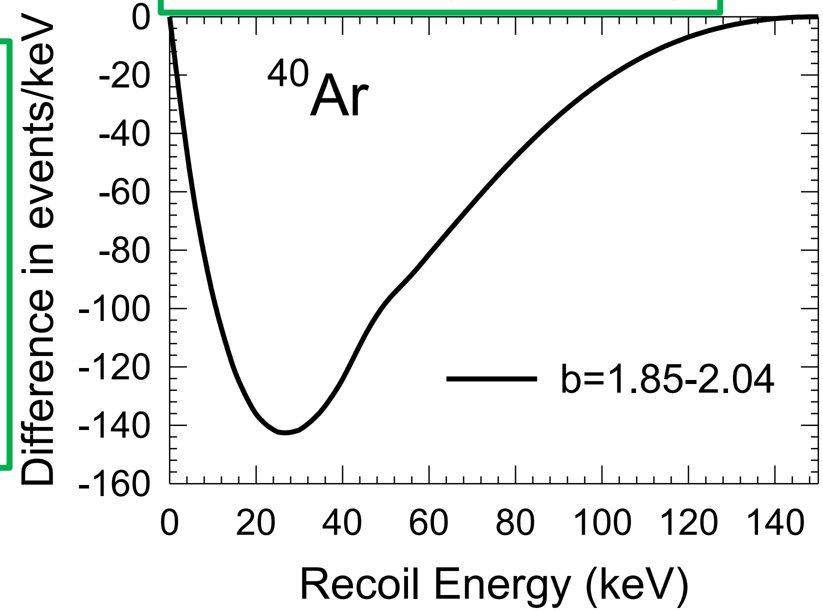




Σdiff=-8770
-2970 (T>50 keV)
-287 (T>100 keV)



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



▪ν-induced reactions on ^{16}O

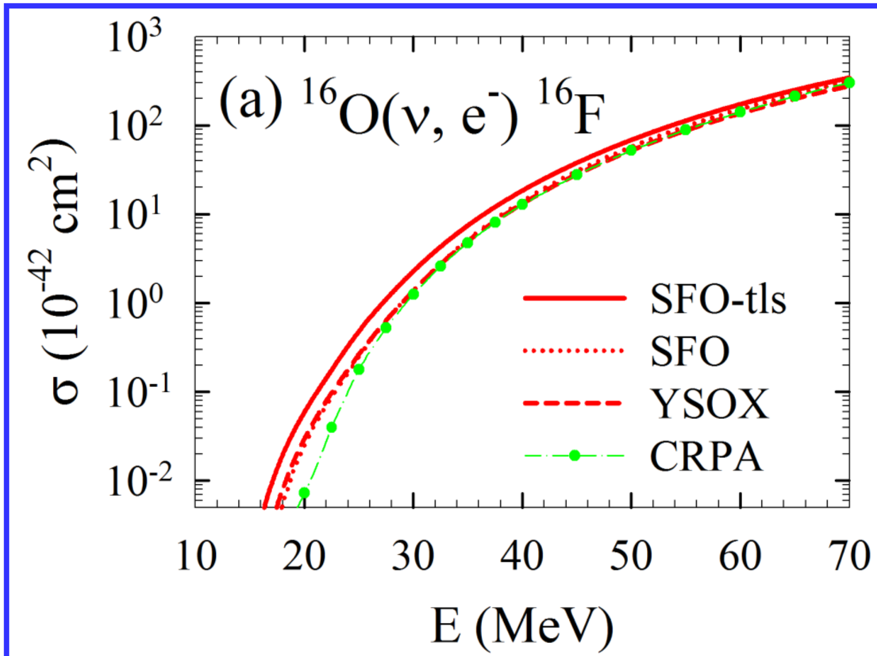
▪Modification of SFO → SFO-tls

Full inclusion of tensor force

▪p-sd: tensor->π+ρ , LS -> σ+ρ+ω

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

V_c=VMU → YSOX

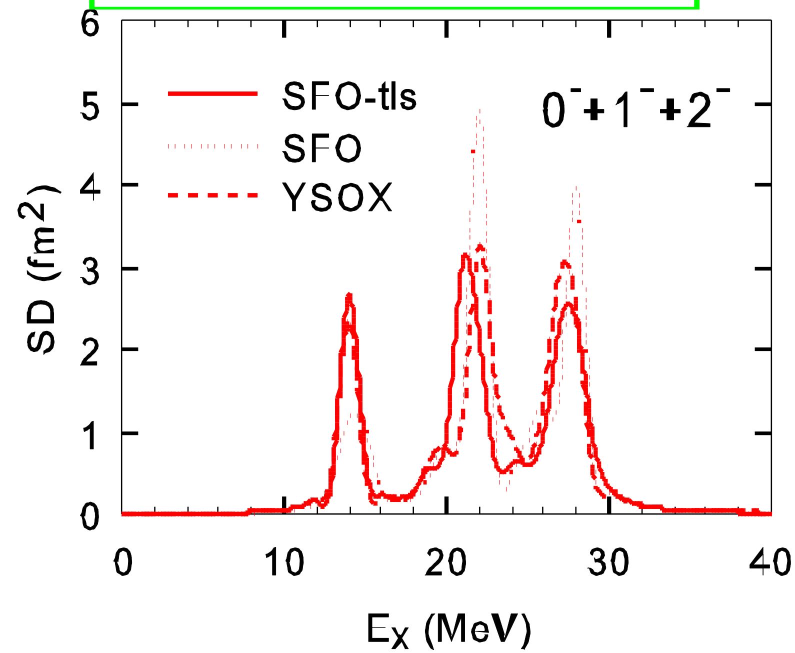


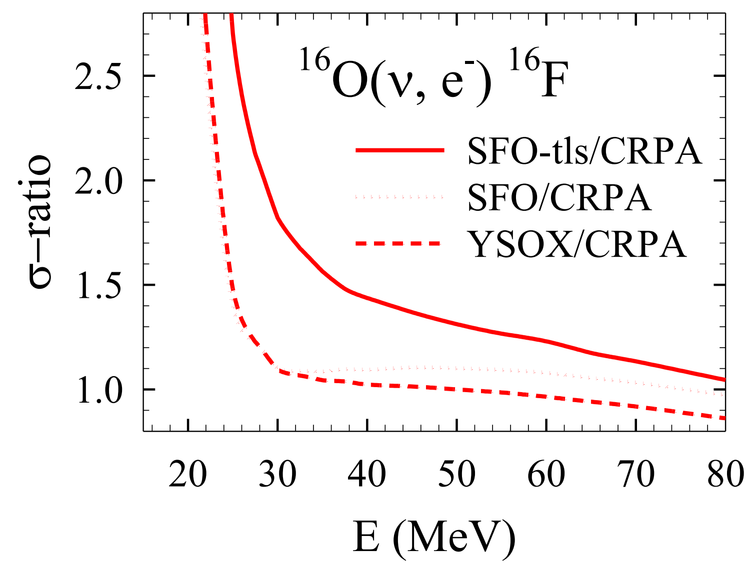
g_A^{eff}/g_A=0.95(SFO)
=0.85(YSOX)

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

Spin-dipole strength in ^{16}O

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





▪ ν- ^{40}Ar reactions

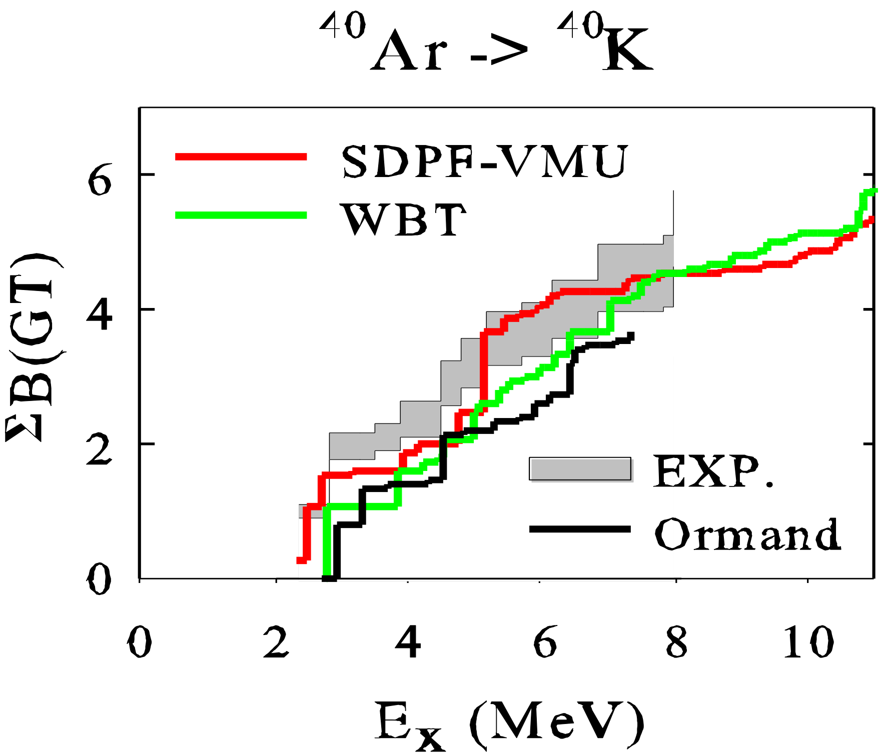
Liquid argon = powerful target for SNν detection

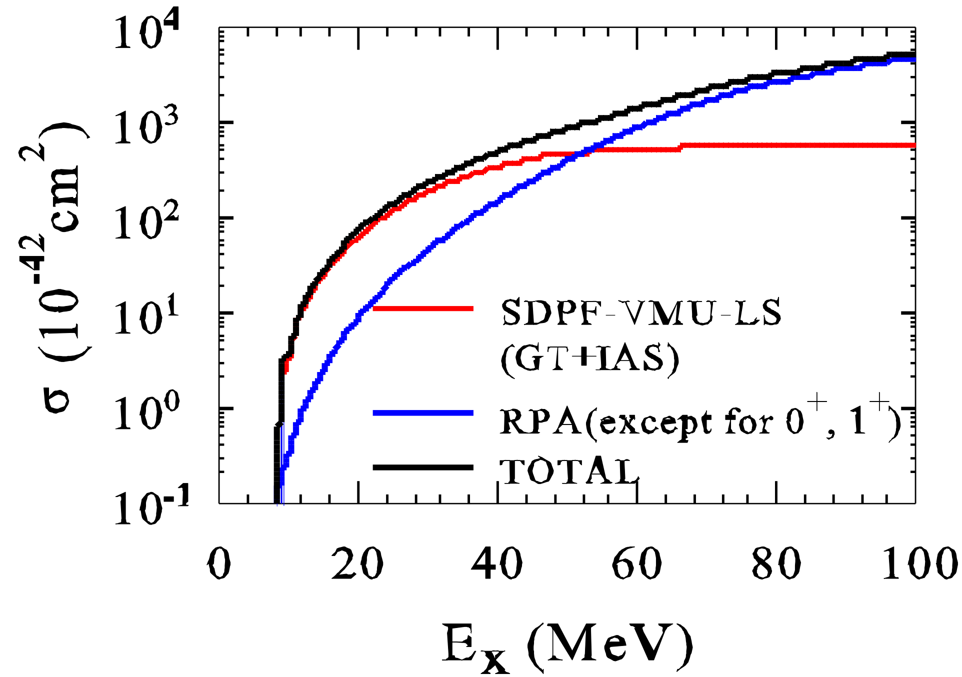
sd-pf shell: **^{40}Ar (ν, e$^-$) ^{40}K** (sd)$^{-2}$ (fp)^2 : 2hw

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).

Spectrum with ν-oscillations

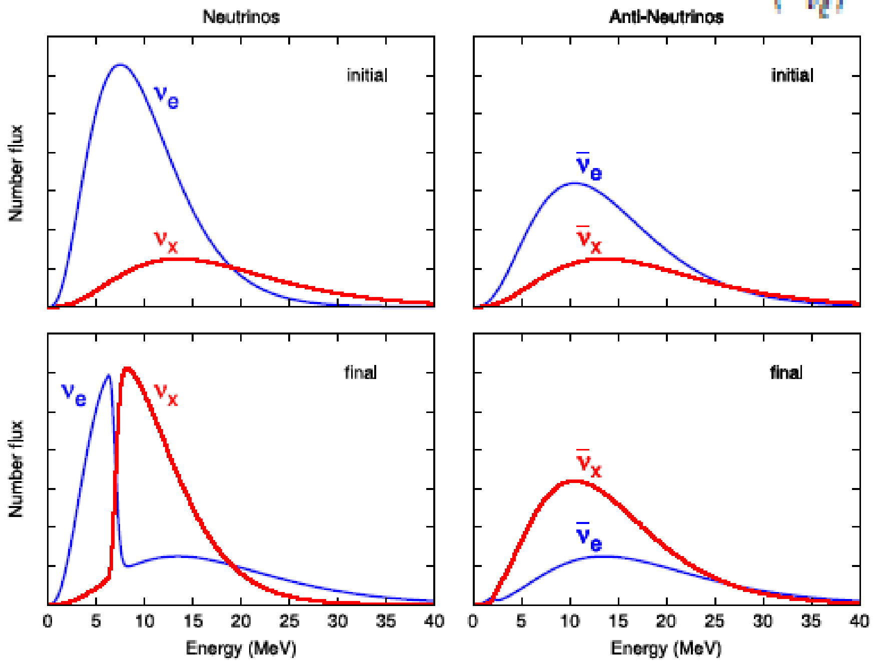
- With collective oscillation effects

G.G. Raffelt / Progress in Particle and Nuclear Physics 64 (2010) 393–399

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

Normal

Inverted



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	$\lesssim 10^{-5}$	$\sin^2\Theta_\odot$	$\sin^2\Theta_\odot$	$\cos^2\Theta_\odot$	ν_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 M(^{48}Ca)-M(^{48}Sc)=-0.79 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

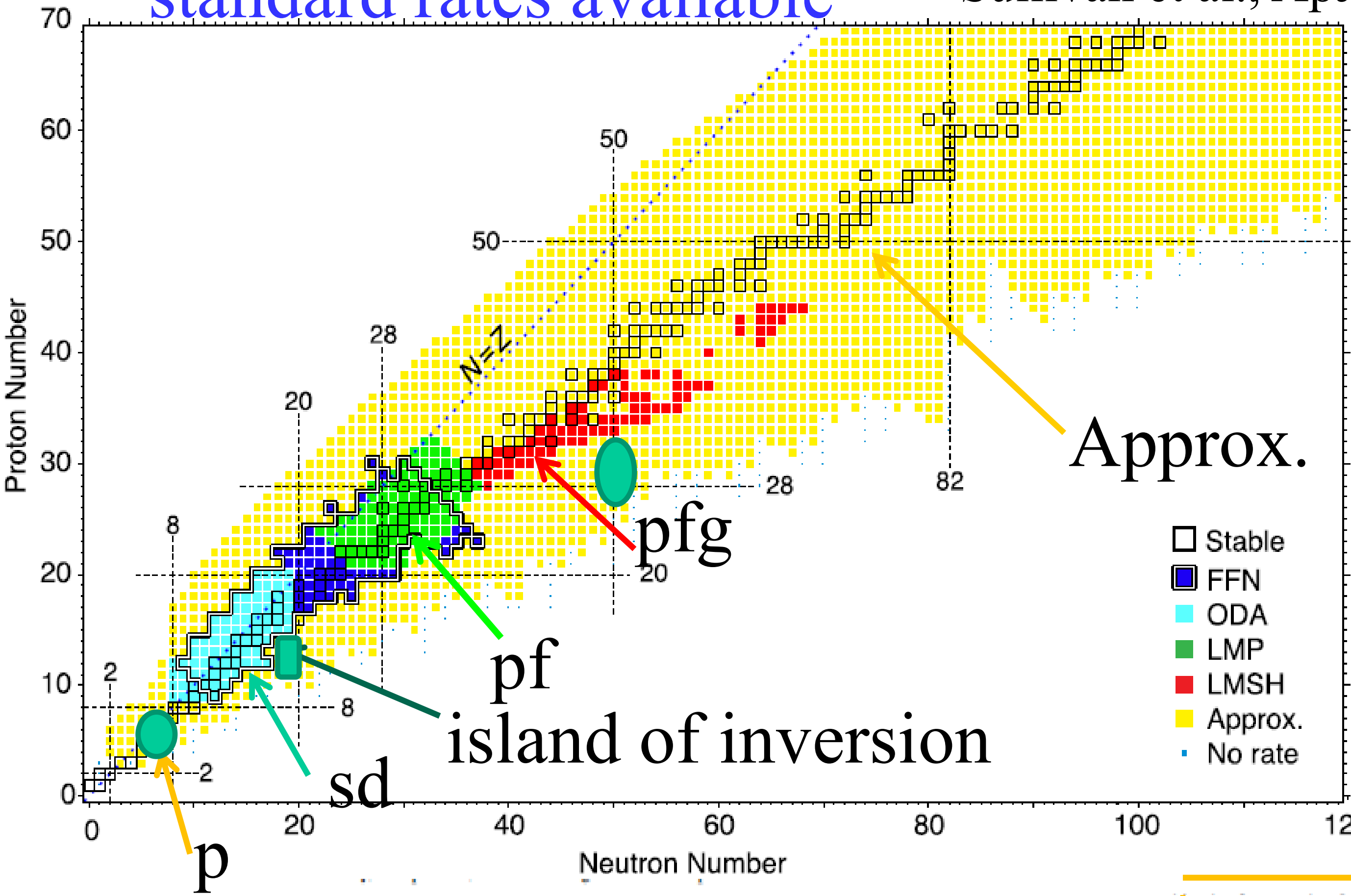
Summary

- **New ν –induced cross sections based on new shell-model Hamiltonians with proper tensor forces**
  ^{12}C, ^{13}C, ^{16}O, ^{18}O, ^{40}Ar, ^{56}Fe, ^{56}Ni
- **Detection of low-energy reactor, solar ν [^{13}C] and SNν [^{12}C, ^{16}O, ^{18}O, ^{40}Ar, ^{56}Fe]**
- **Coherent scattering on light nucleus with smaller recoil energy can be a good probe for neutron distribution in nucleus**
- **Nucleosynthesis elements by ν-processes**
  ν-^{12}C, ν-^{4}He → ^{7}Li, ^{11}B in CCSNe
  ν-^{56}Ni → ^{55}Mn in Pop. III stars
- **Effects of ν-oscillations (MSW) in nucleosynthesis**
  abundance ratio of ^{7}Li/^{11}B → ν mass hierarchy
- **Identification of ν-spectrum with oscillations by low-energy ν scattering is possible for MSW osc., but for collective osc. it is not easy as E_{split} is not large enough.**
  Collective ← nucleosynthesis of p-nuclei (Sasaki)
  MSW ← ν_e from neutronization (Scholberg)

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

Approx.

B (=4.6) and ΔE (=2.5 MeV)

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

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

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

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

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

Table	Model Space					T (GK)	$\mathrm{Log}_{10}(\rho Y_e\ \mathrm{g\ cm}^{-3})$	Reference
	s	p	sd	pf	pfg/sdg			
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)

▪URCA processes in sd-shell nuclei (USDB)

→ Cooling of O-Ne-Mg core in 8-10 $M_\odot$ stars

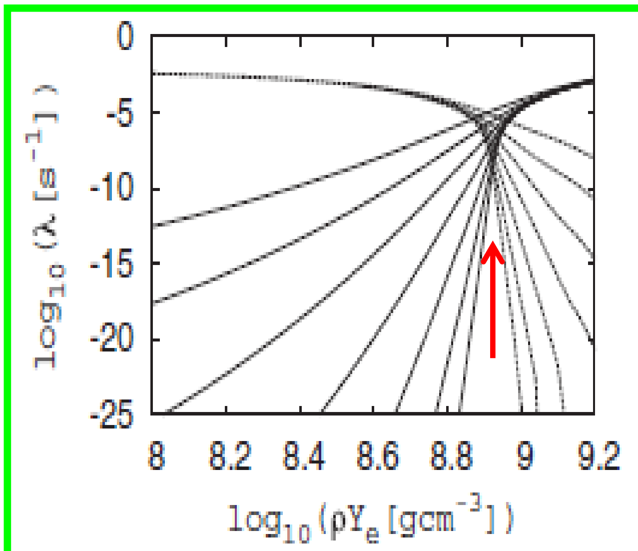
e-capture: ${}^{A}_{Z}X + e^{-} \rightarrow {}^{A}_{Z-1}Y + \nu$

β-decay: ${}^{A}_{Z-1}Y \rightarrow {}^{A}_{Z}X + e^{-} + \bar{\nu}$

They occur simultaneously at certain stellar conditions and energy is lost from stars by emissions of ν and → Cooling of stars

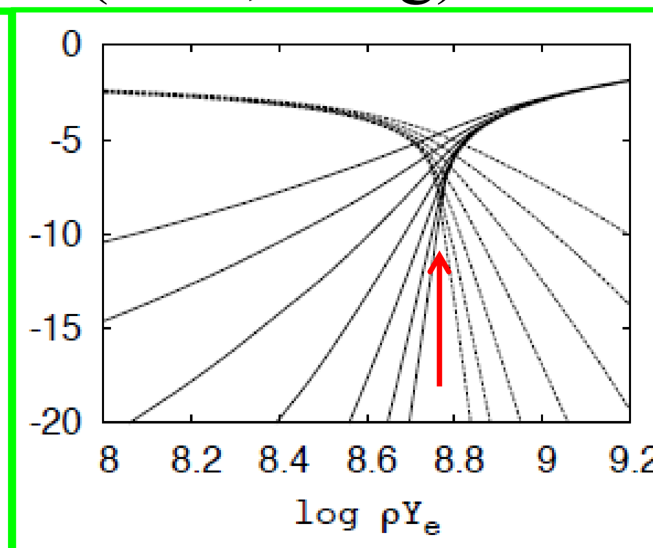
How much star is cooled → fate of the star after neon flash:

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



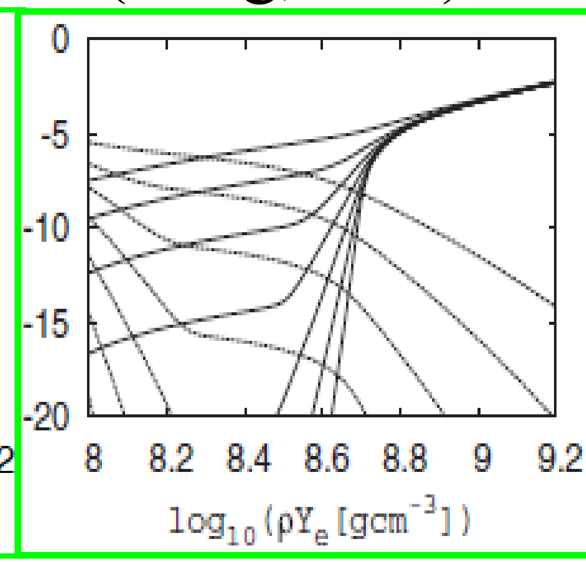
URCA density at $\log_{10}\rho Y_e = 8.92$

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



URCA density at $\log_{10}\rho Y_e = 8.78$

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

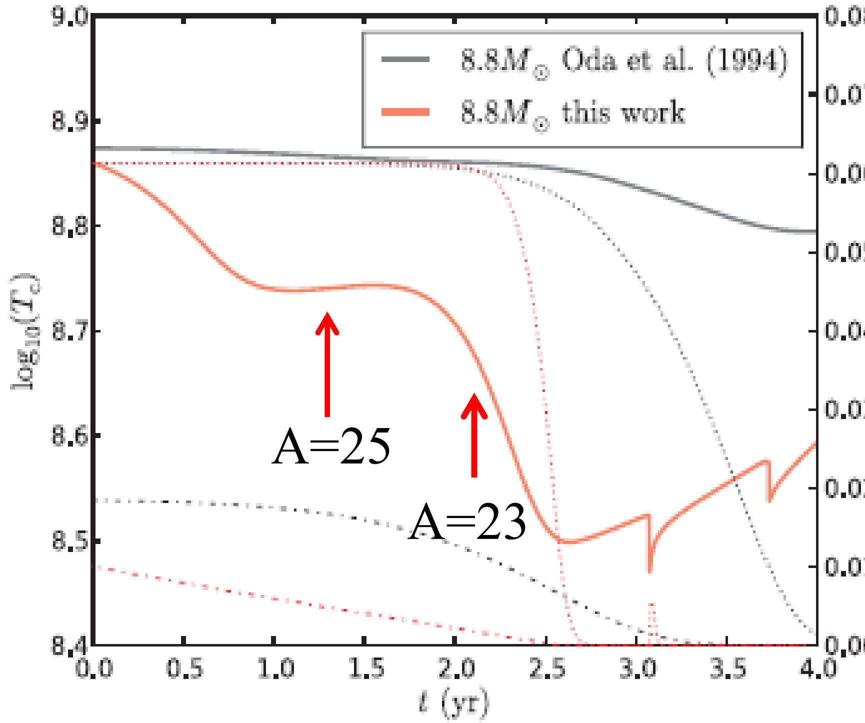


g.s. $1/2^{+} \longleftrightarrow 5/2^{+}$ forbidden

No clear URCA density for A=27 pair

Suzuki, Toki and Nomoto, ApJ. 817, 163 (2016)

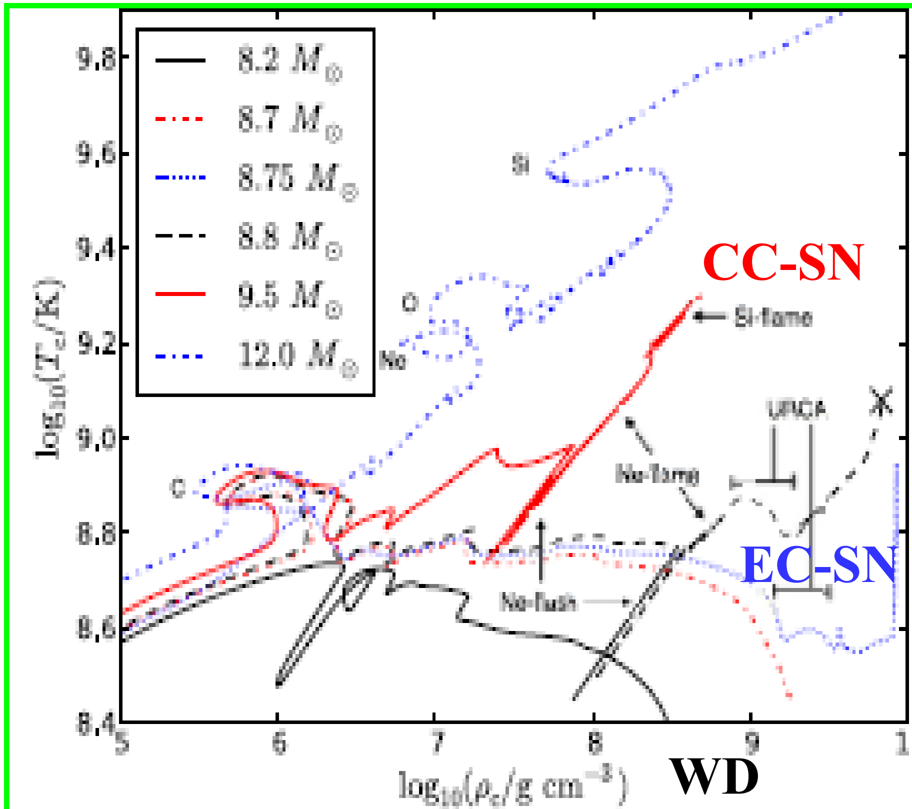
Cooling of O-Ne-Mg core by the nuclear URCA processes



8.8$M_\odot$ star collapses triggered by subsequent e-capture on ^{24}Mg and ^{20}Ne (e-capture supernova explosion)

Toki, Suzuki, Nomoto, Jones and Hirschi, PR C 88, 015806 (2013)

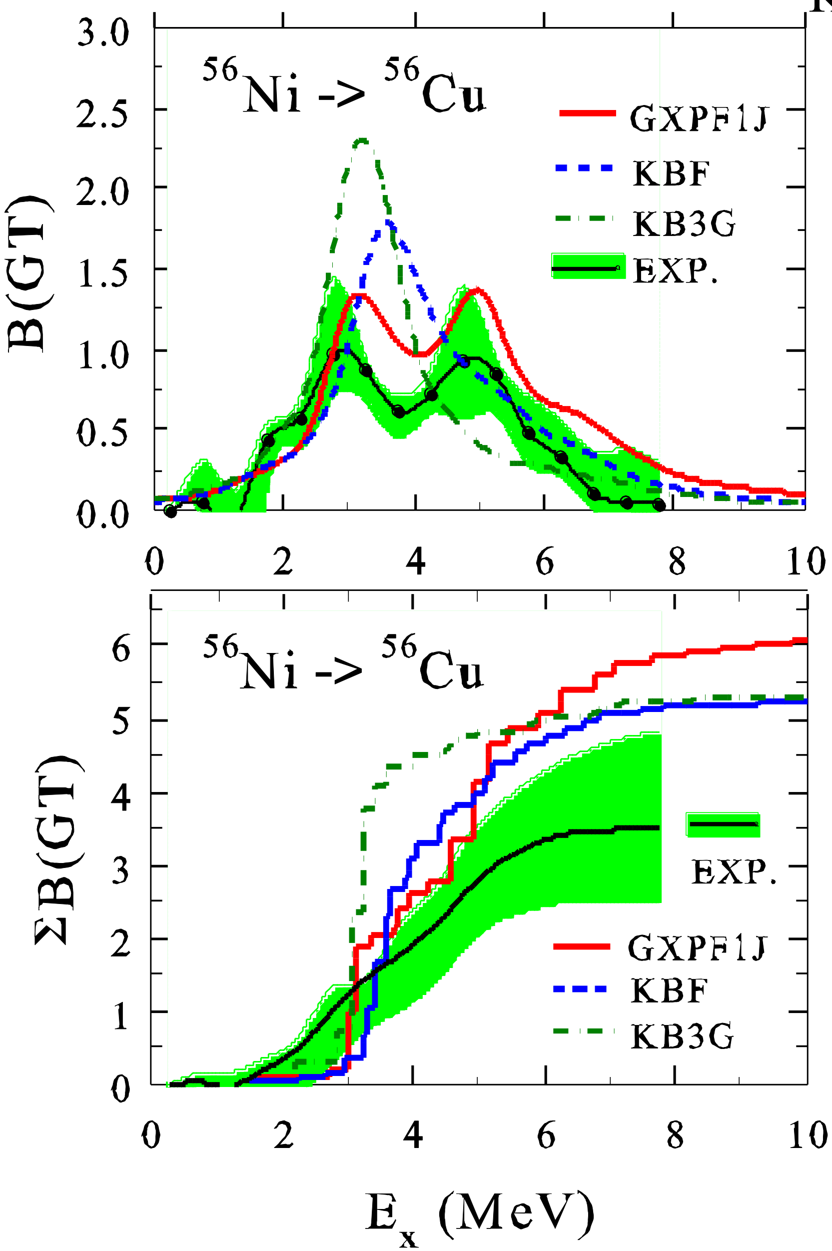
Fate of 8-10$M_\odot$ stars



Border of CC-SN or EC-SN is at M～9$M_\odot$, which is quite sensitive to nuclear weak rates

Jones et al., Astrophys. J. 772, 150 (2013)

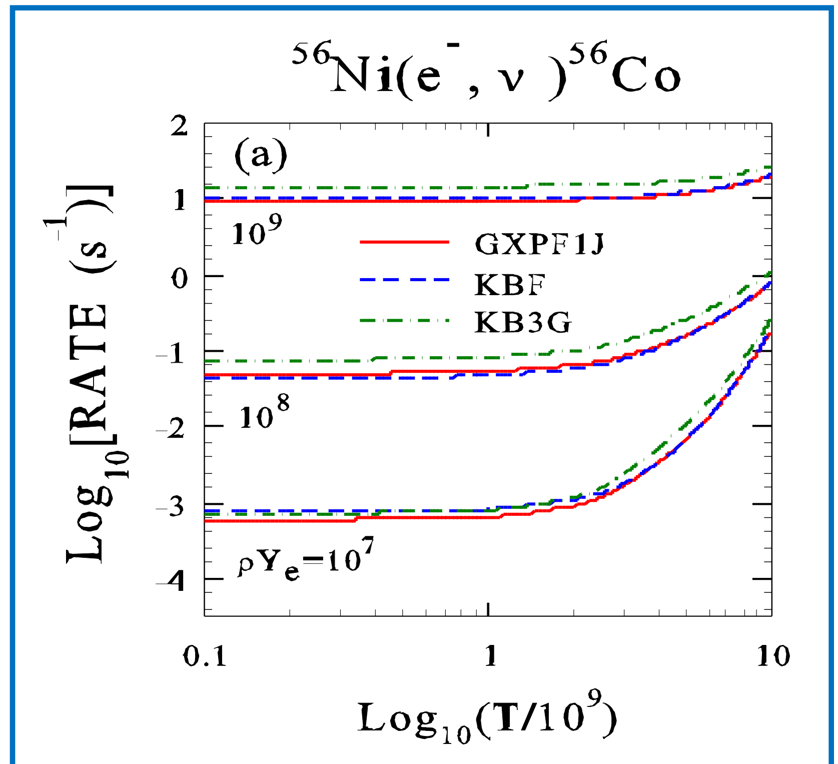
▪pf-shell: GT strength in ^{56}Ni: GXPF1J vs KB3G vs KBF



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

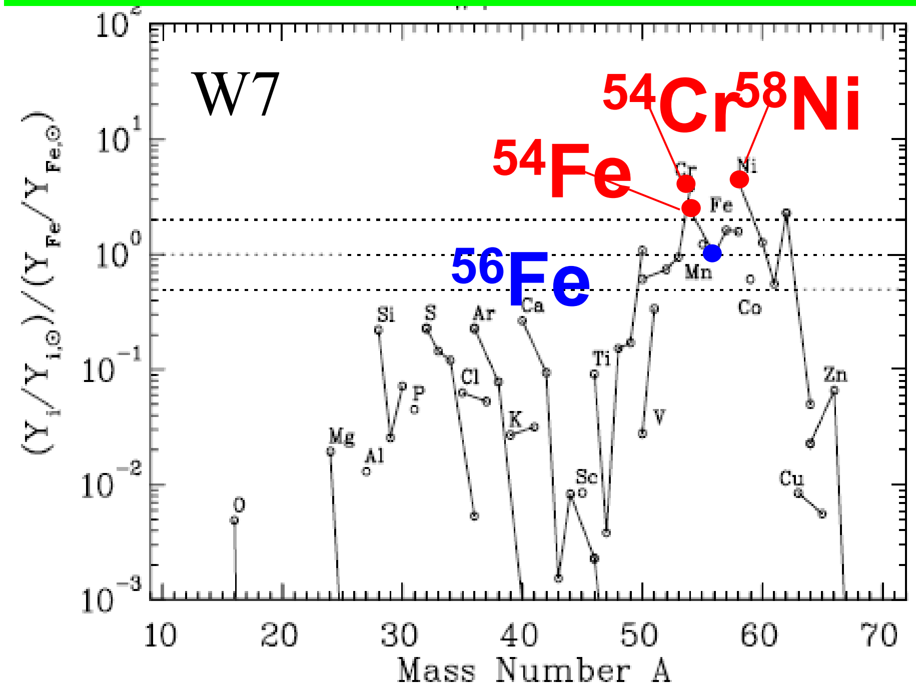
→ ^{56}Ni (N=Z)

→ ^{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

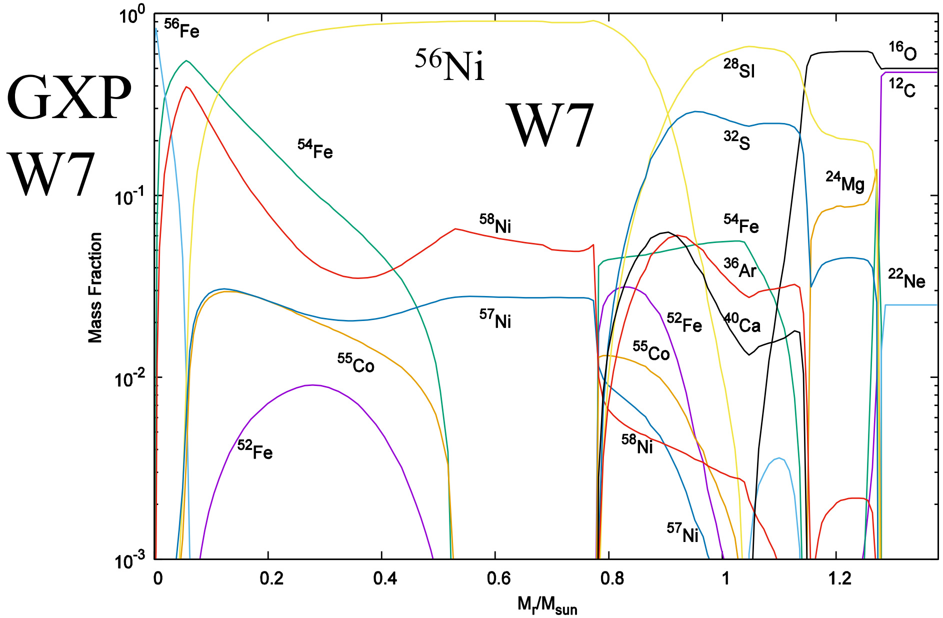
W7 model: fast deflagration

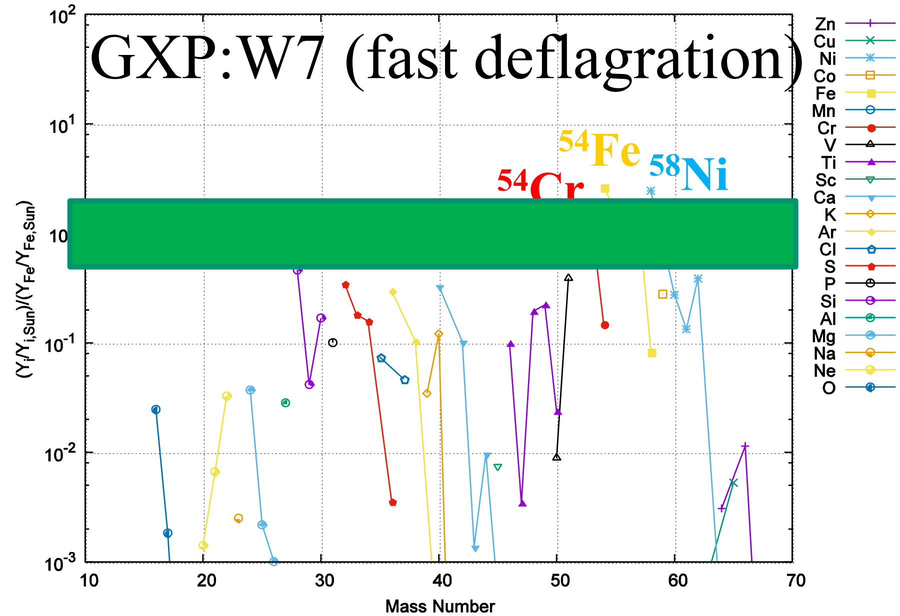
WDD2: Slow deflagration + delayed detonation

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

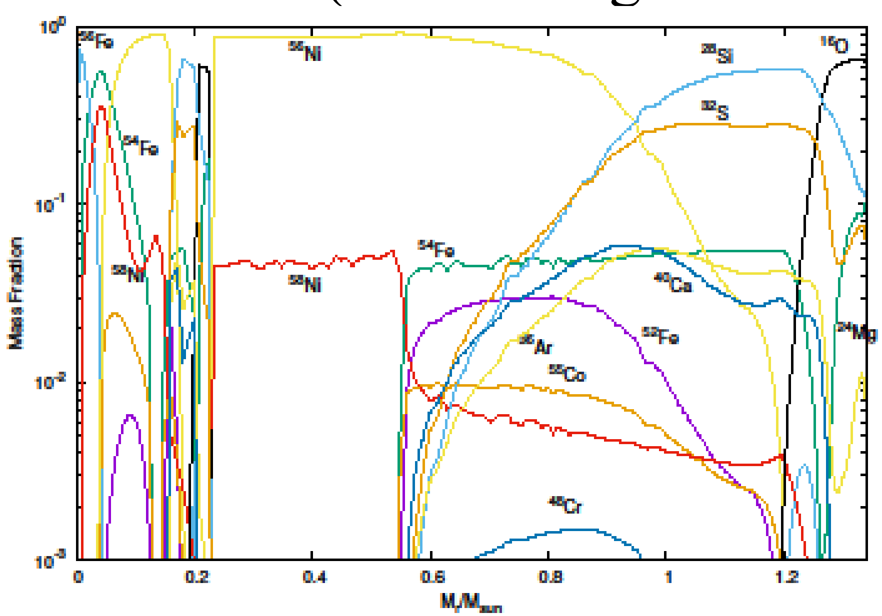
central; $\rho_9=2.12$, $T_c=1\mathrm{x}10^7$K

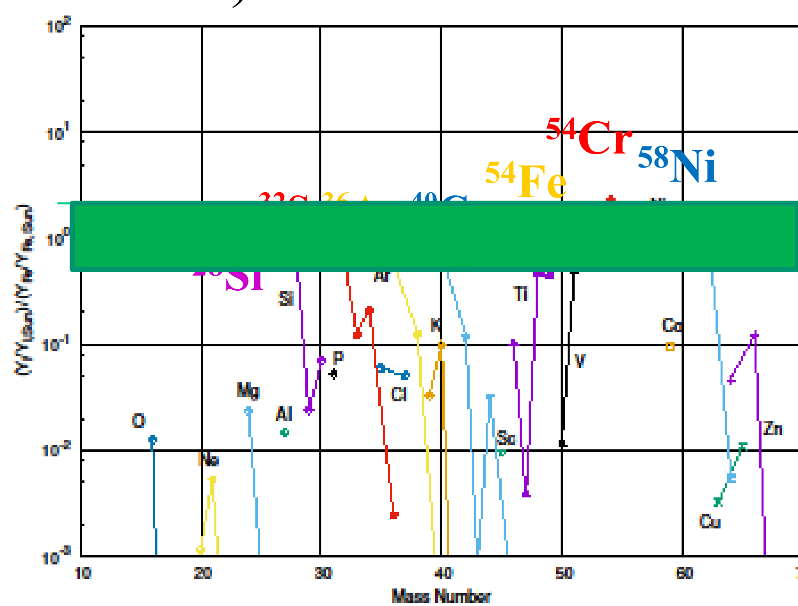
e-capture rates: GXP; GXPF1J (21≤Z≤32) and KBF (other Z)





GXP: WDD2 (slow deflagration + detonation)





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

Weak rates for nuclei in the island of inversion

Nature 505, 65 (2014)
doi:10.1038/nature12757

Strong neutrino cooling by cycles of electron capture and β^- decay in neutron star crusts

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Table 1 | Electron-capture/β^--decay pairs with highest cooling rates

Electron-capture/β^--decay pair: Parent	Daughter*	Density† (10^{10} g cm^{-3})	Chemical potential† (MeV)	Luminosity‡ (10^{36} erg s^{-1})
^{29}Mg	^{29}Na	4.79	13.3	24
^{55}Ti	^{55}Sc, ^{55}Ca	3.73	12.1	11
[illegible]	[illegible]	3.39	11.8	8.8
[illegible]	[illegible]	5.19	13.4	8.3
56Ti	56Sc	5.57	13.8	3.5
^{57}Cr	^{57}V	1.22	8.3	1.6
^{57}V	^{57}Ti, ^{57}Sc	2.56	10.7	1.6
^{63}Cr	^{63}V	6.82	14.7	0.97
^{105}Zr	^{105}Y	3.12	11.2	0.92
^{59}Mn	^{59}Cr	0.945	7.6	0.88
^{103}Sr	^{103}Rb	5.30	13.3	0.65
^{96}Kr	^{96}Br	6.40	14.3	0.65
^{65}Fe	^{65}Mn	2.34	10.3	0.60
^{65}Mn	^{65}Cr	3.55	11.7	0.46

Rates evaluated by QRPA
Shell-model evaluations are missing.

Island of inversion
Z=10-12, N = 20-22

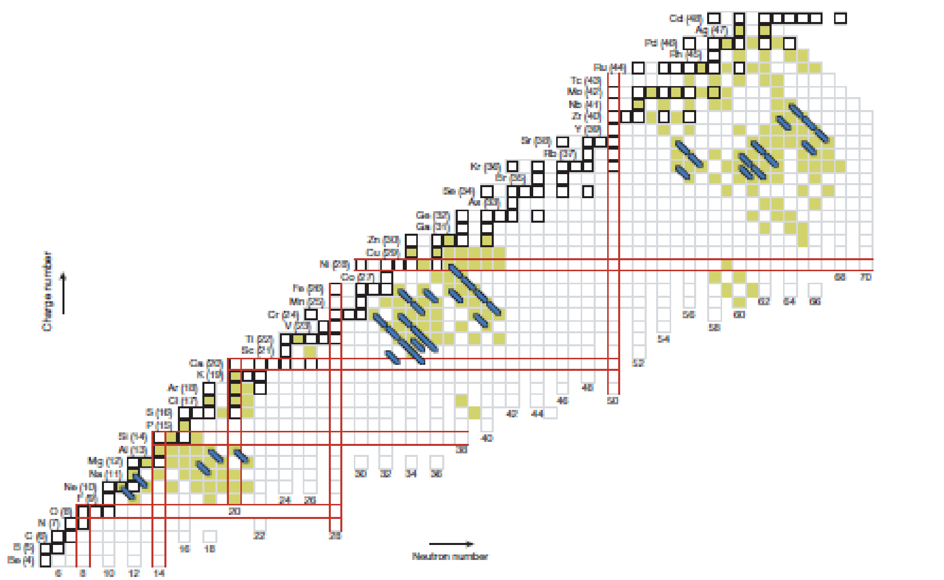
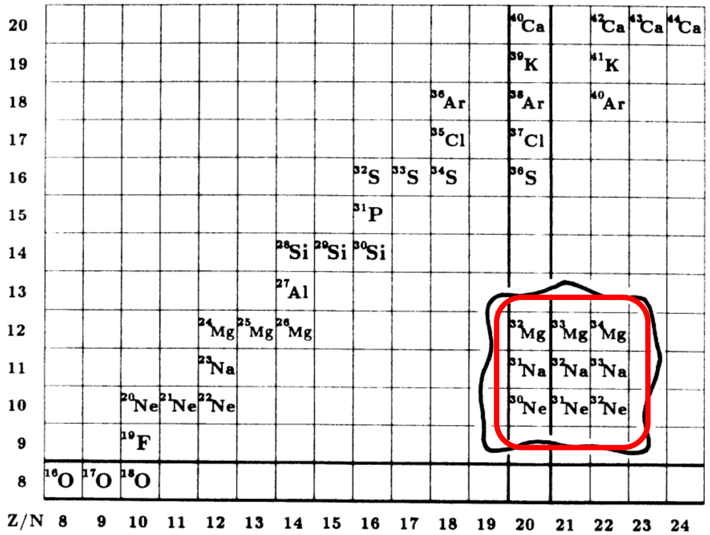


Figure 2 | Electron-capture/β^--decay pairs on a chart of the nuclides. The thick blue lines denote electron-capture/β^--decay pairs that would generate a strong neutrino luminosity in excess of 5×10^{34} erg s^{-1} at $T = 0.51$ GK for a composition consisting entirely of the respective electron-capture/β^--decay pair. They largely coincide with regions where allowed electron-capture and β^--decay transitions are predicted to populate low-lying states and subsequent electron capture is blocked (shaded squares, see also the discussion in ref. 3). These are mostly regions between the closed neutron and proton shells (pairs of horizontal and vertical red lines), where nuclei are significantly deformed (see Supplementary Information section 4). Nuclides that are β^--stable under terrestrial conditions are shown as squares bordered by thicker lines. Nuclear charge numbers are indicated in parentheses next to element symbols.

Island of inversion: sd<->pf

- Small shell-gap: $f_{7/2}$-$d_{3/2}$
- Small $E_x(2^+)$
- Large B(E2)

→ Large sd-pf admixture

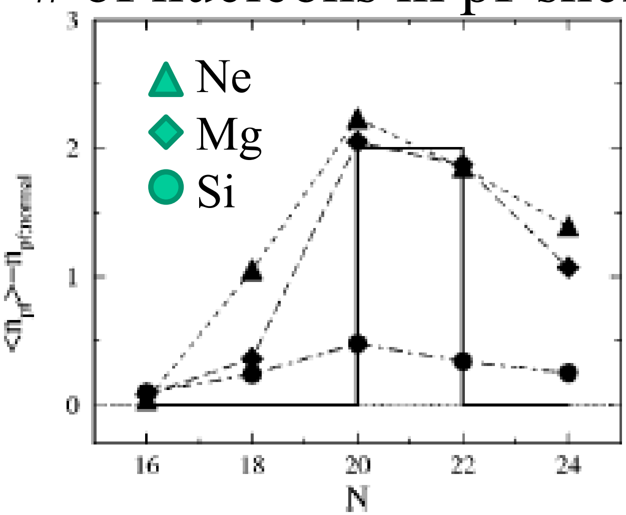


Warburton, Becker, Brown, PR C41, 1147 (1990)

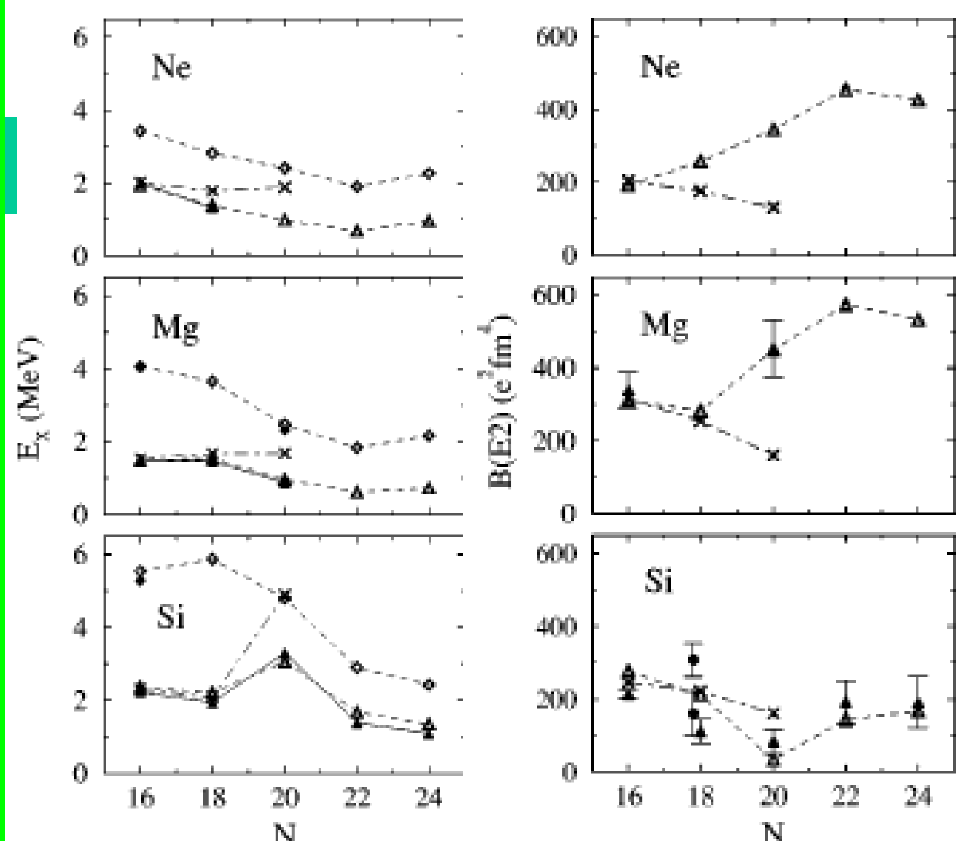
Neutron-rich Ne, Na, Mg isotopes

SDPF-M: Utsuno et al., PR C60, 054315 (1999)

# of nucleons in pf-shell

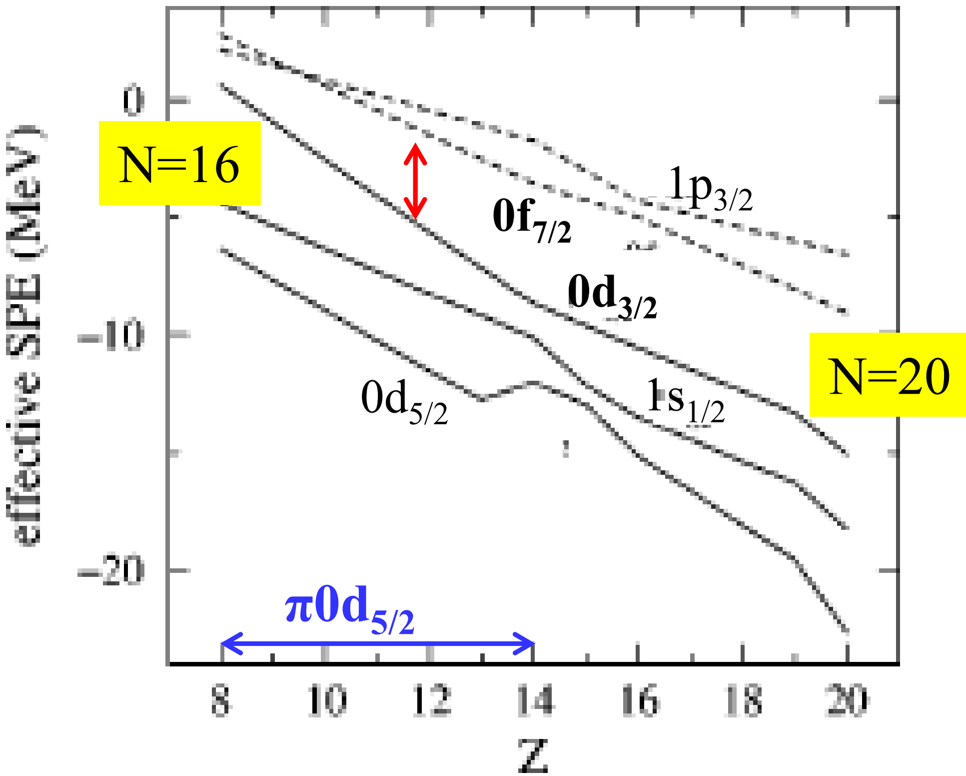


E_x: 2^+, 4^+ B(E2)



filled =exp. × = sd only

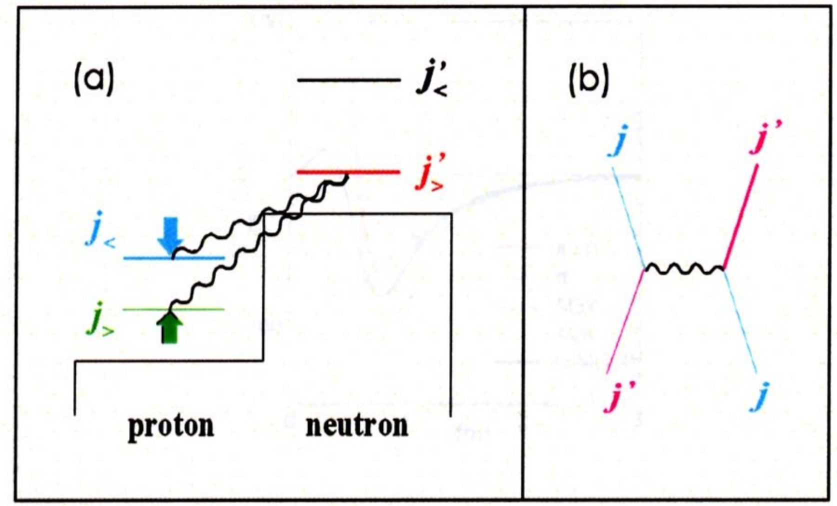
Neutron ESP for N=20 isotones



SDPF-M: Utsuno et al., PR C60, 054315 (1999)

Shell-gap ($\nu d_{3/2}$-$\nu f_{7/2}$) decreases for less protons in $d_{5/2}$-shell → Magic number changes from N=20 to N=16

Effects of Tensor Force on Shell Evolution



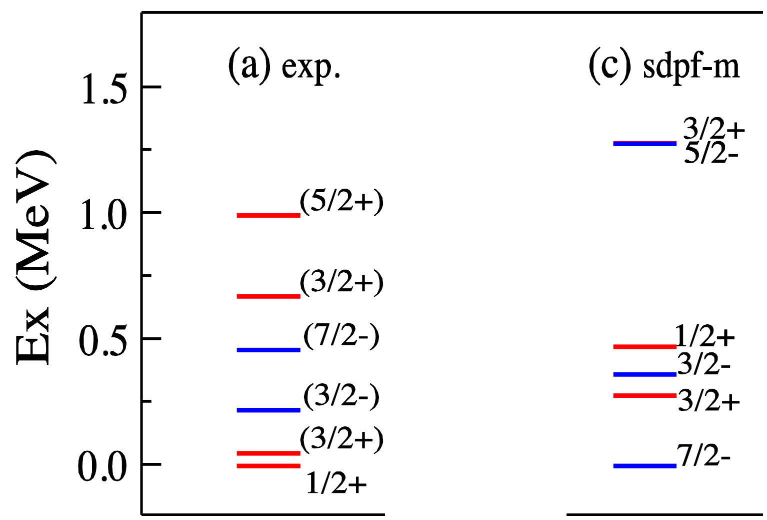
$\pi d_{5/2}$-$\nu d_{3/2}$: attraction
$\pi d_{5/2}$-$\nu f_{7/2}$: repulsion

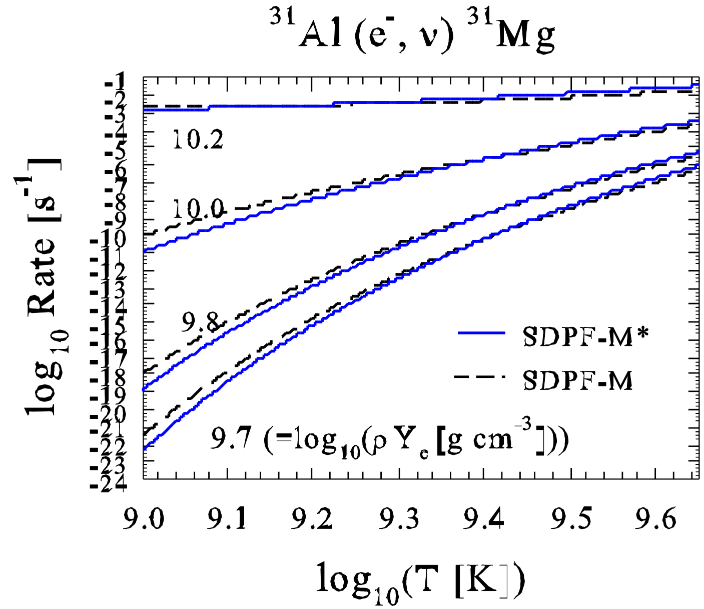
Monopole terms

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

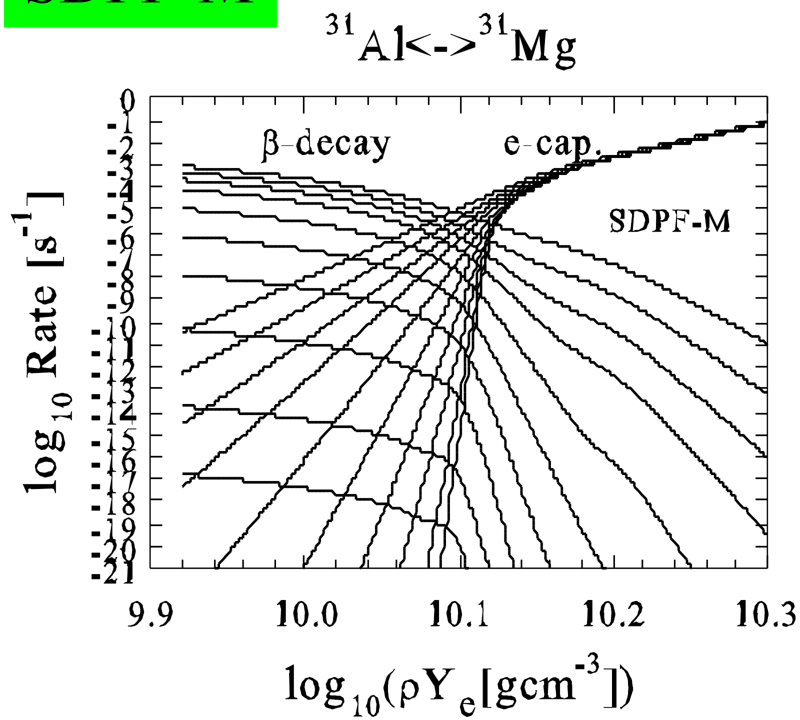
Otsuka, Suzuki, Fujimoto, Grawe, Akaishi, PRL 69 (2005)

^{31}Mg

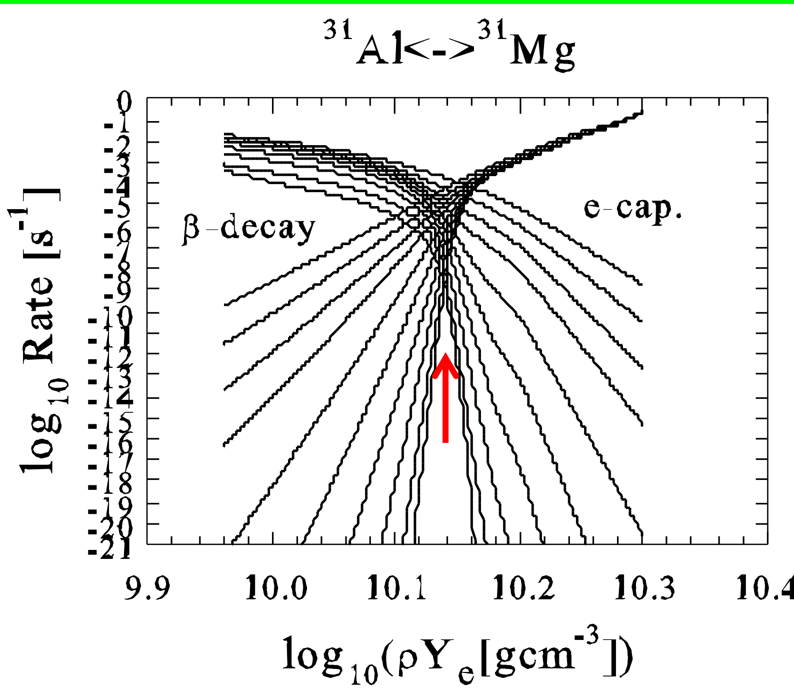




SDPF-M



SDPF-M*: E_x & B(GT) = exp.

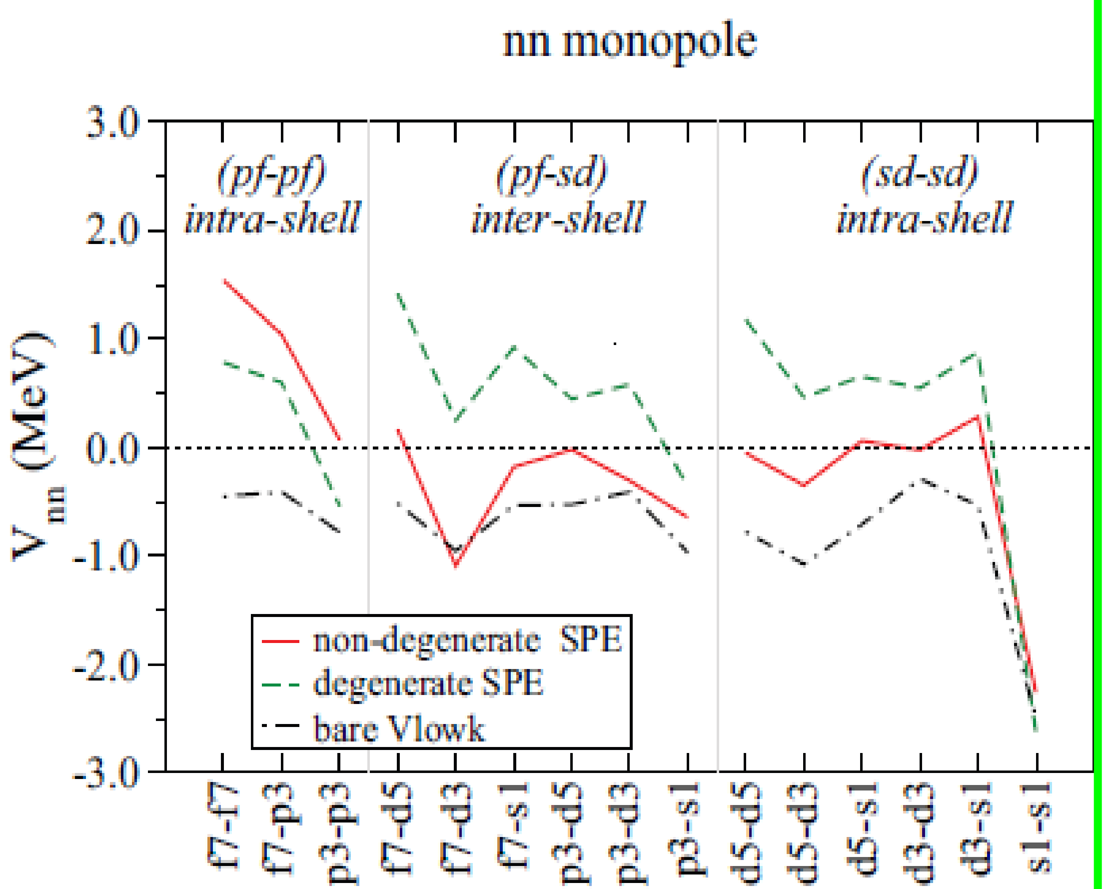


sd-pf shell

Non-degenerate treatment of sd and pf shells by
EKK (extended Kuo-Krenciglowa) method

Tsunoda, Takayanagi, Hjorth-Jensen and Otsuka, Phys. Rev. C 89, 024313 (2014)

Cf: monopoles with non-degenerate vs degenerate method



Kuo-Krenciglowa method

$$V_{\rm eff}^{(n)} = \hat{Q}(\epsilon_0) + \sum_{k=1}^{\infty} \hat{Q}_k(\epsilon_0)\{V_{\rm eff}^{(n-1)}\}^k,$$

$$PH_0P = \epsilon_0 P.$$

$$\hat{Q}(E) = PVP + PVQ\frac{1}{E - QHQ}QVP,$$

$$\hat{Q}_k(E) = \frac{1}{k!}\frac{d^k \hat{Q}(E)}{dE^k}.$$

Extended Kuo-Krenciglowa method

$$\tilde{H} = H - E$$

$$\tilde{H}_{\rm eff}^{(n)} = \tilde{H}_{\rm BH}(E) + \sum \hat{Q}_k(E)\{\tilde{H}_{\rm eff}^{(n-1)}\}^k,$$

$$\tilde{H}_{\rm eff} = H_{\rm eff} - E, \quad \tilde{H}_{\rm BH}(E) = H_{\rm BH}(E) - E,$$

$$H_{\rm BH}(E) = PHP - PVQ\frac{1}{E - QHQ}QVP.$$

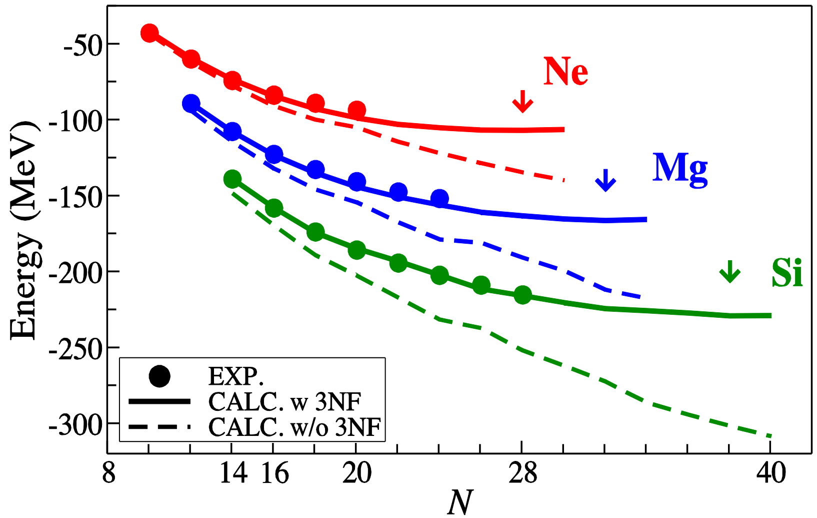
$$V_{\rm eff} = H_{\rm eff} - PH_0P.$$

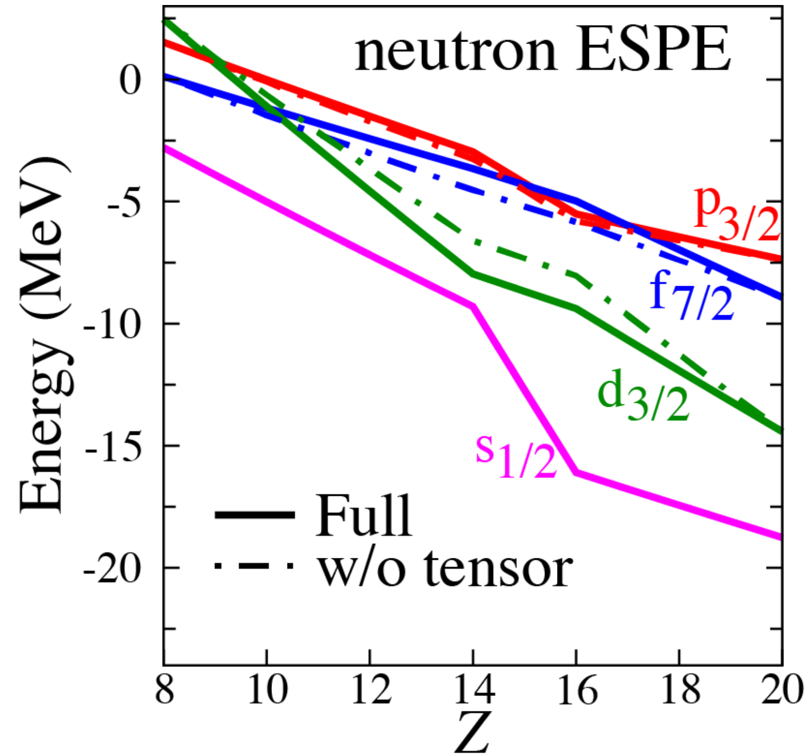
energy indpendent

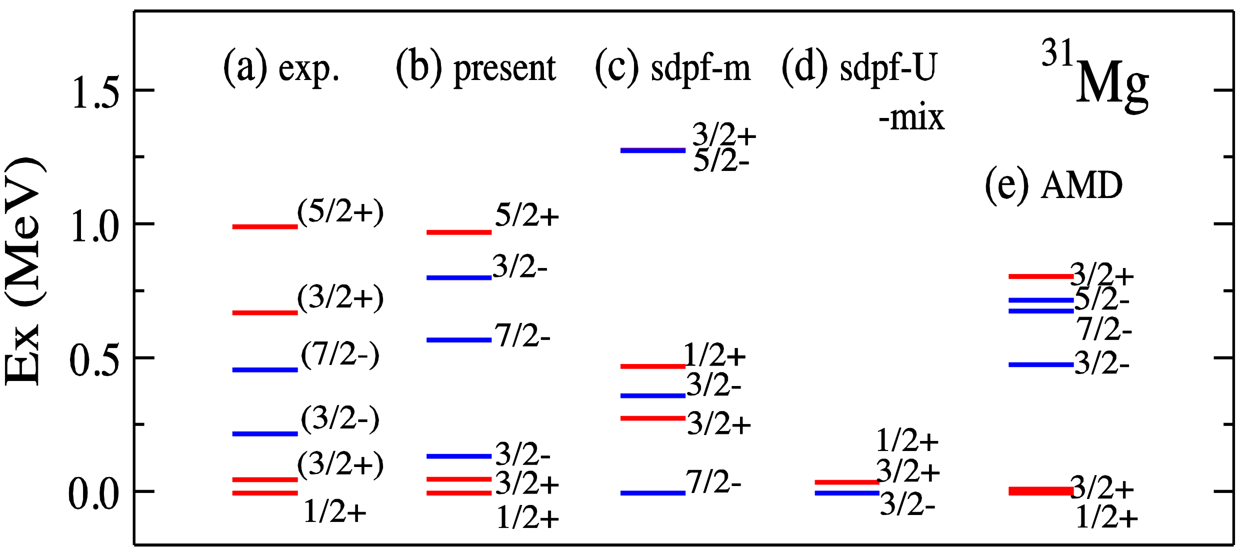
K. Takayanagi, Nucl. Phys. A 852, 61 (2011).
K. Takayanagi, Nucl. Phys. A 864, 91 (2011).

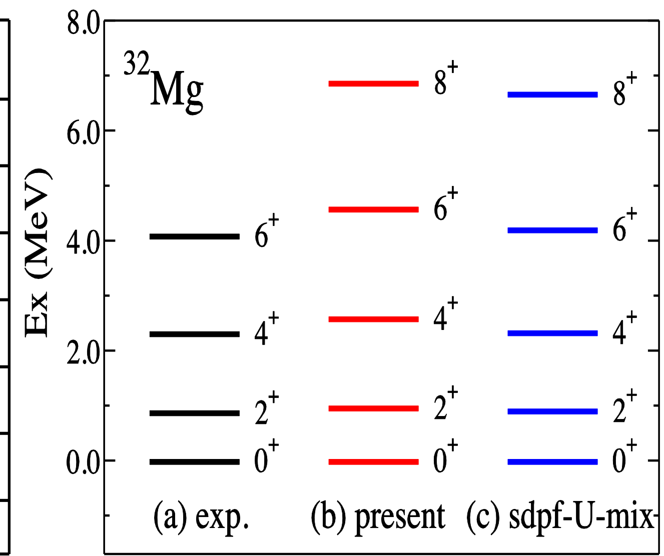
Neutron-rich isotopes in the island of inversion by EKK-method starting from chiral EFT interaction N^3LO+3N (FM)

Tsunoda, Otsuka, Shimizu, Hjorth-Jensen, Takayanagi and Suzuki, PRC 95, 021304(R) (2017)

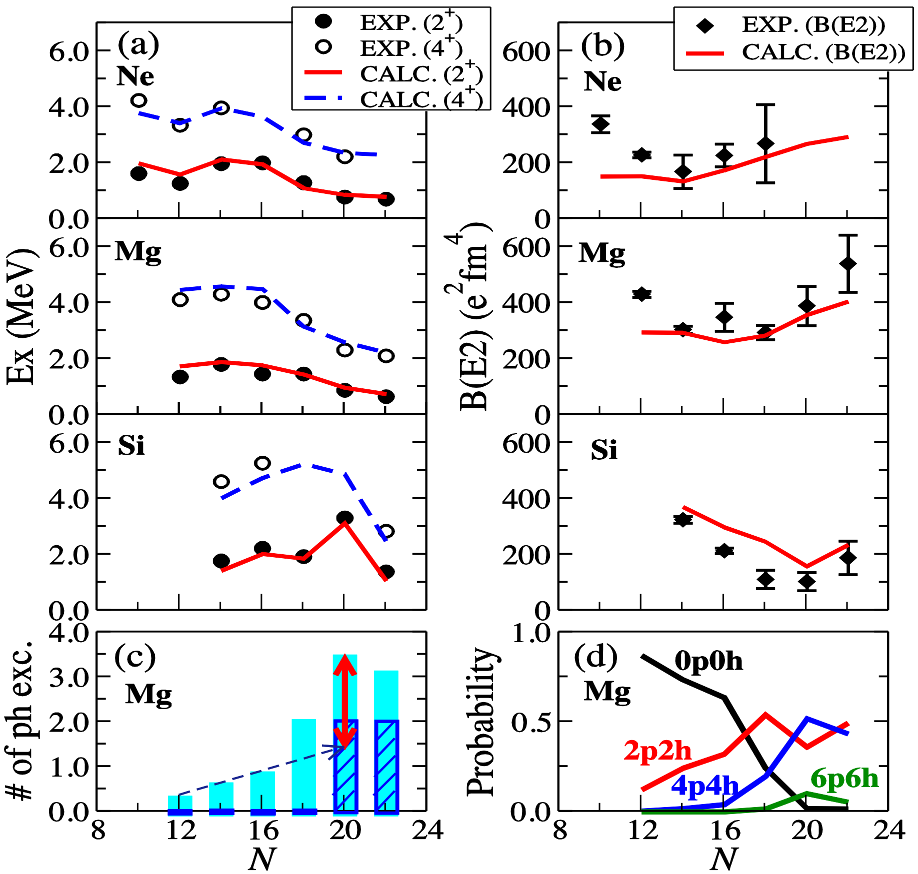




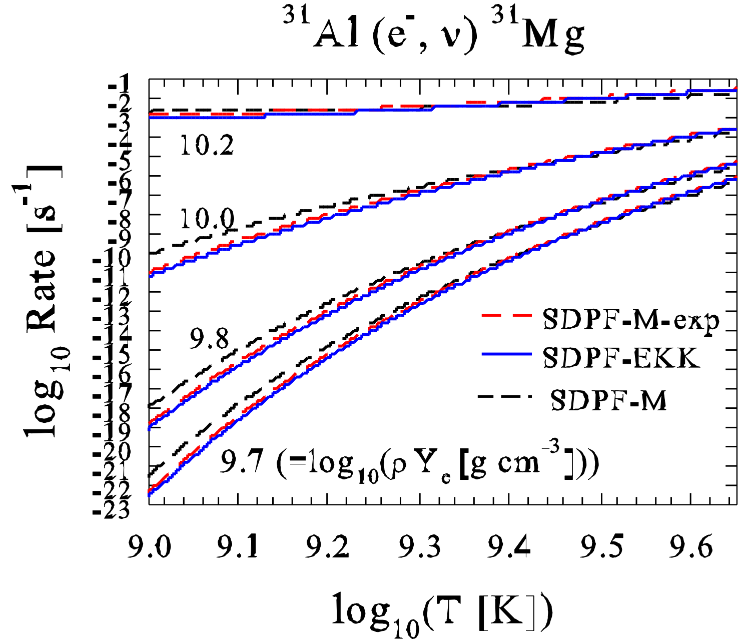


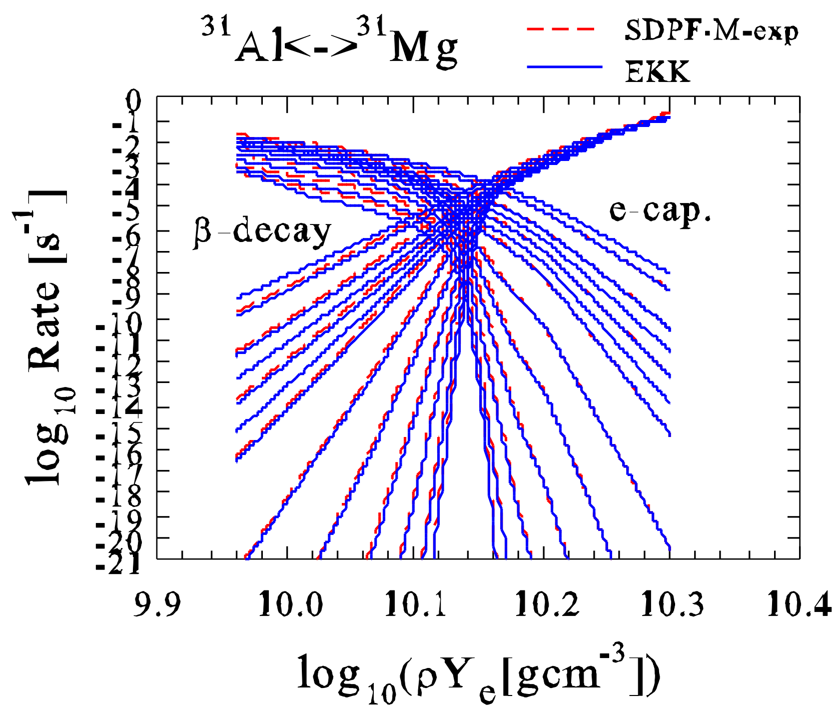


EKK vs EXP



2p-2h+4p-4h





Summary

1. Weak rates for one-major shell nuclei

○New weak rates for sd-shell from USDB

Nuclear URCA processes for A=23 and 25 nuclear pairs are important for the cooling of O-Ne-Mg core of 8-10 solar-mass stars and determines fate of stars with ∼$9M_\odot$ whether they end up with e-capture SNe or core-collapse SNe.

○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.

.2. Weak rates for two-major shell nuclei

○sd-pf shell nuclei in the island of inversion, important for URCA processes in neutron star crusts, are evaluated with EKK method starting from chiral EFT interaction N3LO +3N (FM).

e.g. ^{31}Al (e^-, ν)^{31}Mg, ^{31}Mg(,e^- ν)^{31}Al

Collaborators

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