

International Workshop XLI on Gross Properties of Nuclei and Nuclear Excitations,
“Astrophysics and Nuclear Structure”, Jan 26 – Feb 1, 2013, Hirschegg, Austria

*Self-consistent description of supernova electron capture
and neutrino-nucleus processes*



N. Paar

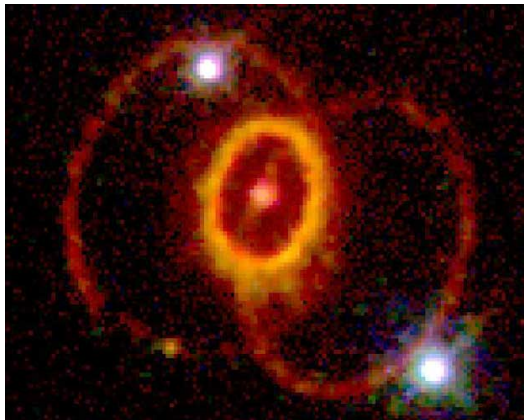
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Croatia*



OUTLINE

The goal is self-consistent microscopic description inspired by EDFs, of nuclear structure, excitations, weak interaction processes, and nuclear equation of state of relevance for astrophysics and nucleosynthesis

1. Inelastic neutrino-nucleus reactions involving supernova neutrinos. Large-scale calculations for charge-exchange reactions
2. Electron capture on nuclei at finite temperature in stellar environment
3. Nuclear equation of state – constraints on the symmetry energy from theory of collective nuclear motion and experimental data



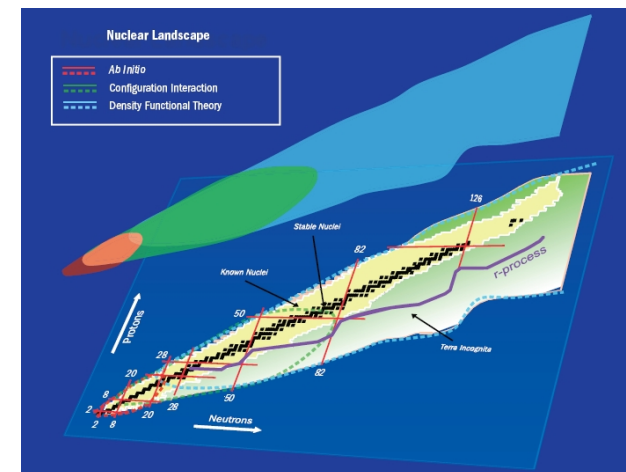
Periodic Table of Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18														
1 H Hydrogen																	2 He Helium														
3 Li Lithium	4 Be Beryllium											10 Ne Neon	11 Na Sodium	12 Mg Magnesium	13 Al Aluminum	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon											
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton														
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon														
55 Cs Cesium	56 Ba Barium	57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 Fr Francium	88 Ra Radium	89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium	103 Lr Lawrencium	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111 Rg Roentgenium	112 Uu Ununbium	113 Uub Ununbium	114 Uuq Ununquadium	115 Uup Ununpentium	116 Uuq Ununquadium	117 Uuh Ununheptium	118 Uuo Ununoctium

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

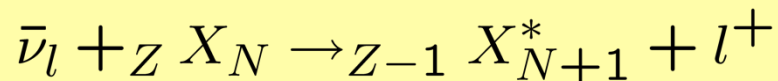
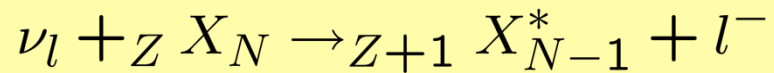
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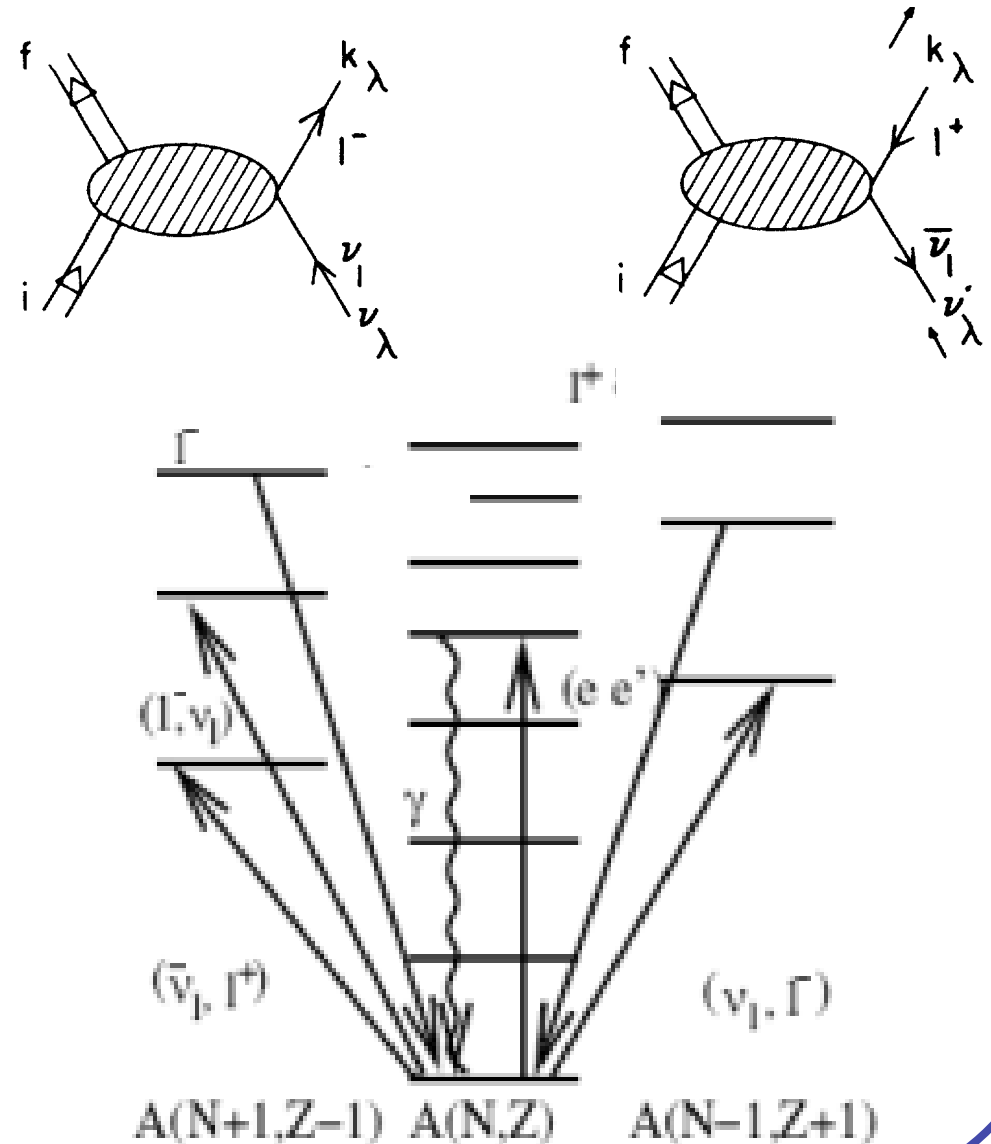


LOW-ENERGY NEUTRINO-NUCLEUS PROCESSES

Charged-current neutrino-nucleus reactions



The properties of nuclei and their excitations govern the neutrino-nucleus cross sections. Nuclear transitions induced by neutrinos involve operators with finite momentum transfer.



NEUTRINO-NUCLEUS CROSS SECTIONS

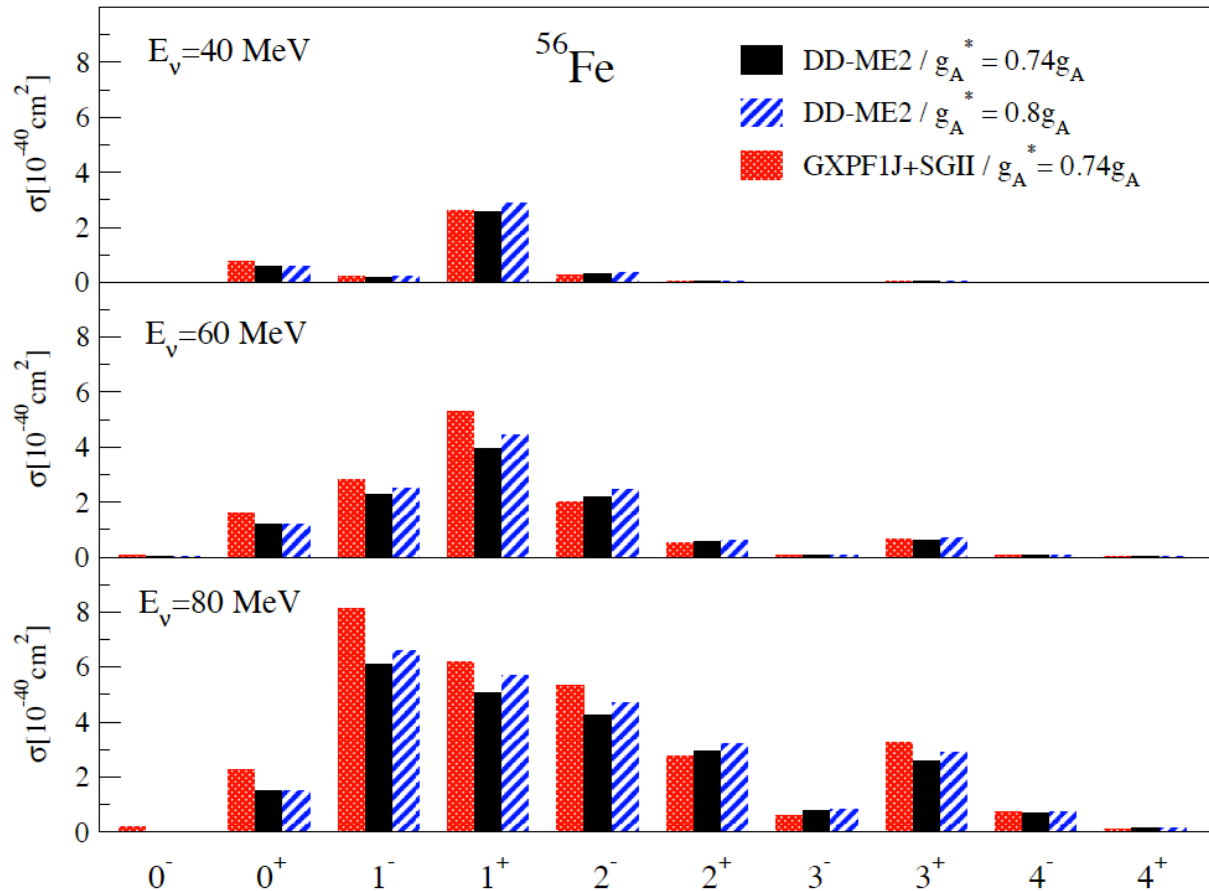
$$\begin{aligned}
 \frac{d\sigma_\nu}{d\Omega} &= \frac{2G_F^2 \cos^2 \theta_c}{\pi} \frac{E_l^2}{2J_i + 1} \\
 &\times \left\{ \sum_{J \geq 1} \left\{ [1 - (\hat{\nu} \cdot \hat{q})(\hat{q} \cdot \beta)] \left[|\langle J_f || \hat{T}_J^{MAG} || J_i \rangle|^2 + |\langle J_f || \hat{T}_J^{EL} || J_i \rangle|^2 \right] \right. \right. \\
 &\quad \left. \left. + [\hat{q}(\hat{\nu} - \beta)] 2 \operatorname{Re} \langle J_f || \hat{T}_J^{MAG} || J_i \rangle \langle J_f || \hat{T}_J^{EL} || J_i \rangle^* \right\} \right. \\
 &\quad \left. + \sum_{J \geq 0} \left\{ (1 + \hat{\nu} \cdot \beta) |\langle J_f || \hat{M}_J || J_i \rangle|^2 \right. \right. \\
 &\quad \left. \left. + (1 - \hat{\nu} \cdot \beta + 2(\hat{\nu} \cdot \hat{q})(\hat{q} \cdot \beta)) |\langle J_f || \hat{L}_J || J_i \rangle|^2 \right. \right. \\
 &\quad \left. \left. - [\hat{q}(\hat{\nu} + \beta)] 2 \operatorname{Re} \langle J_f || \hat{L}_J || J_i \rangle \langle J_f || \hat{M}_J || J_i \rangle^* \right\} \right\} \quad k = E_l \beta
 \end{aligned}$$

Transition matrix elements are described in a self-consistent way using relativistic Hartree-Bogoliubov model for the initial (ground) state and relativistic quasiparticle random phase approximation for excited states (RHB+RQRPA)

DD-ME2 density-dependent effective interaction + Gogny pairing

CHARGED-CURRENT NEUTRINO-NUCLEUS CROSS SECTIONS

Multipole composition of the neutrino-nucleus cross sections:
RNEDF (DD-ME2) vs. shell model + RPA (SGII)



In addition to GT, at larger neutrino energies excitations of higher multiplicities (forbidden transitions) contribute.

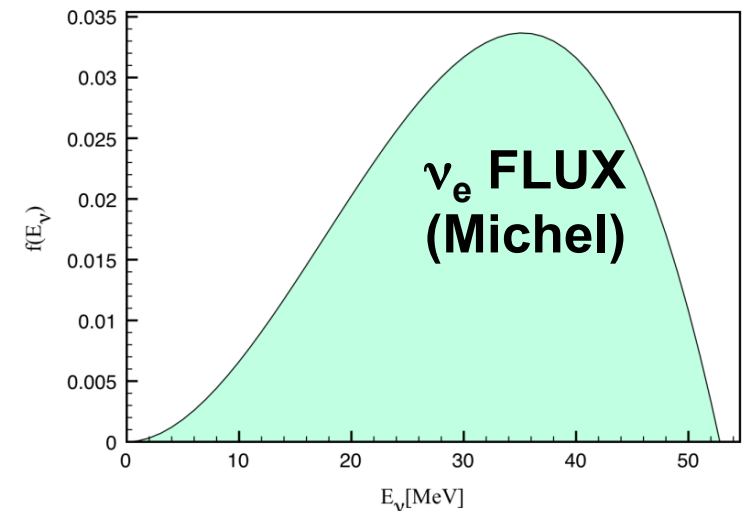
Remarkable agreement between models based on completely different foundations and effective interactions !

UNCERTAINTIES IN MODELING ν -NUCLEUS CROSS SECTIONS

Neutrino-nucleus cross sections for ^{56}Fe target, averaged over the electron neutrino from μ^+ decay at rest (DAR)

$^{56}\text{Fe}(\nu_e, e^-) ^{56}\text{Co}$	$\langle\sigma\rangle(10^{-42}\text{cm}^2)$
QRPA(SII) (Lazauskas et al.)	352
Shell model (GXPF1J) + RPA (SGII) (T. Suzuki et al.)	259
RPA (Kolbe, Langanke)	240
QRPA (Cheoun et al.)	173
RNEDF (DD-ME2)	263
EXP. (KARMEN)	256\pm108\pm43

$$\langle\sigma_\nu\rangle = \frac{\int dE_\nu \sigma_\nu(E_\nu) f(E_\nu)}{\int dE'_\nu f(E'_\nu)}$$

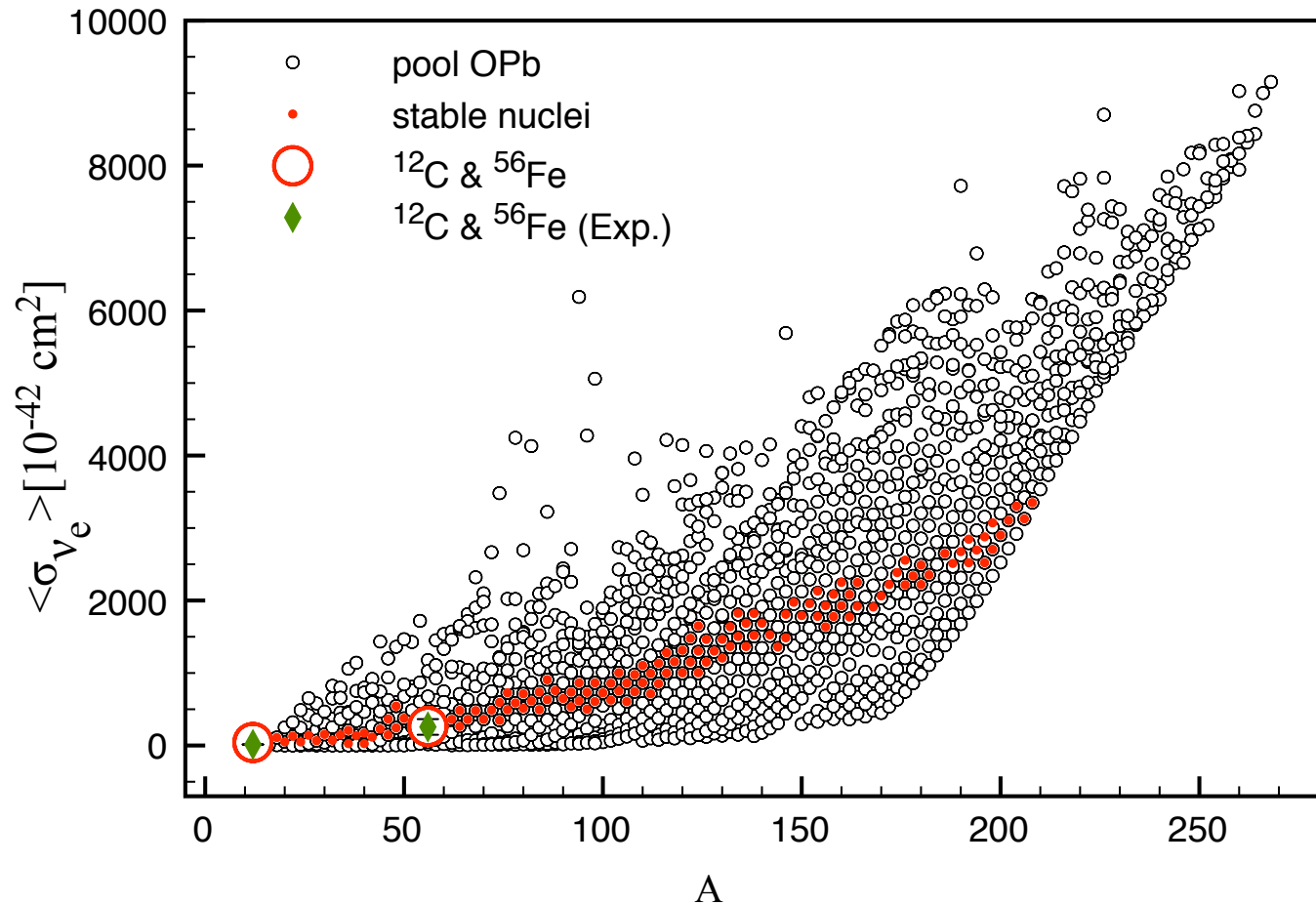


$$\langle\sigma\rangle_{th} = (258 \pm 57) \times 10^{-42} \text{cm}^2$$

Present theoretical uncertainty from all models appear considerably smaller than the experimental one.

LARGE-SCALE CALCULATIONS OF ν_e -NUCLEUS CROSS SECTIONS

The cross sections are averaged over the neutrino spectrum from muon DAR.

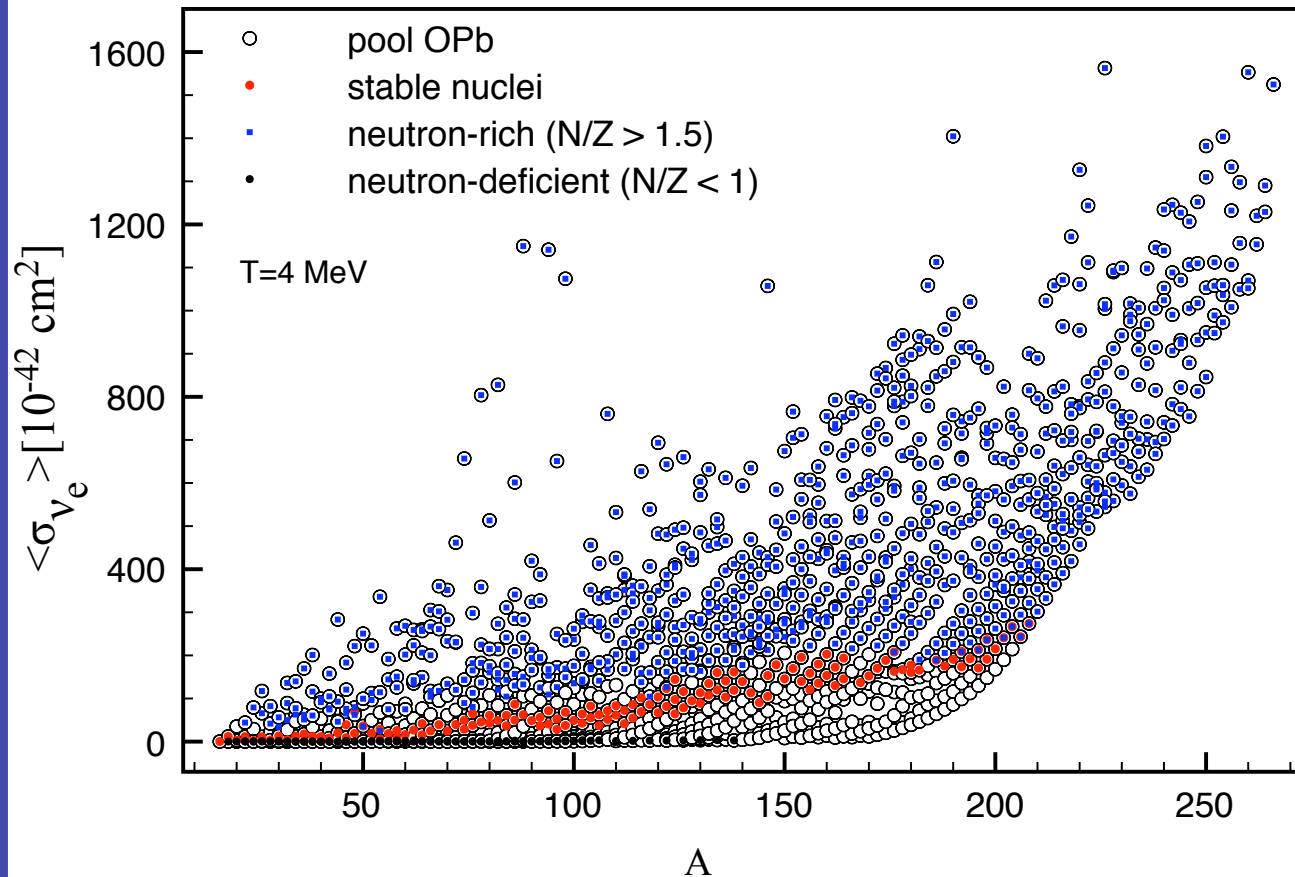


Model calculations include all multipoles (both parities) up to $J=5$.

The model calculations reasonably reproduce the only two experimental cases, ^{12}C and ^{56}Fe .

LARGE-SCALE CALCULATIONS OF ν -NUCLEUS CROSS SECTIONS

The cross sections averaged over supernova neutrino spectrum.



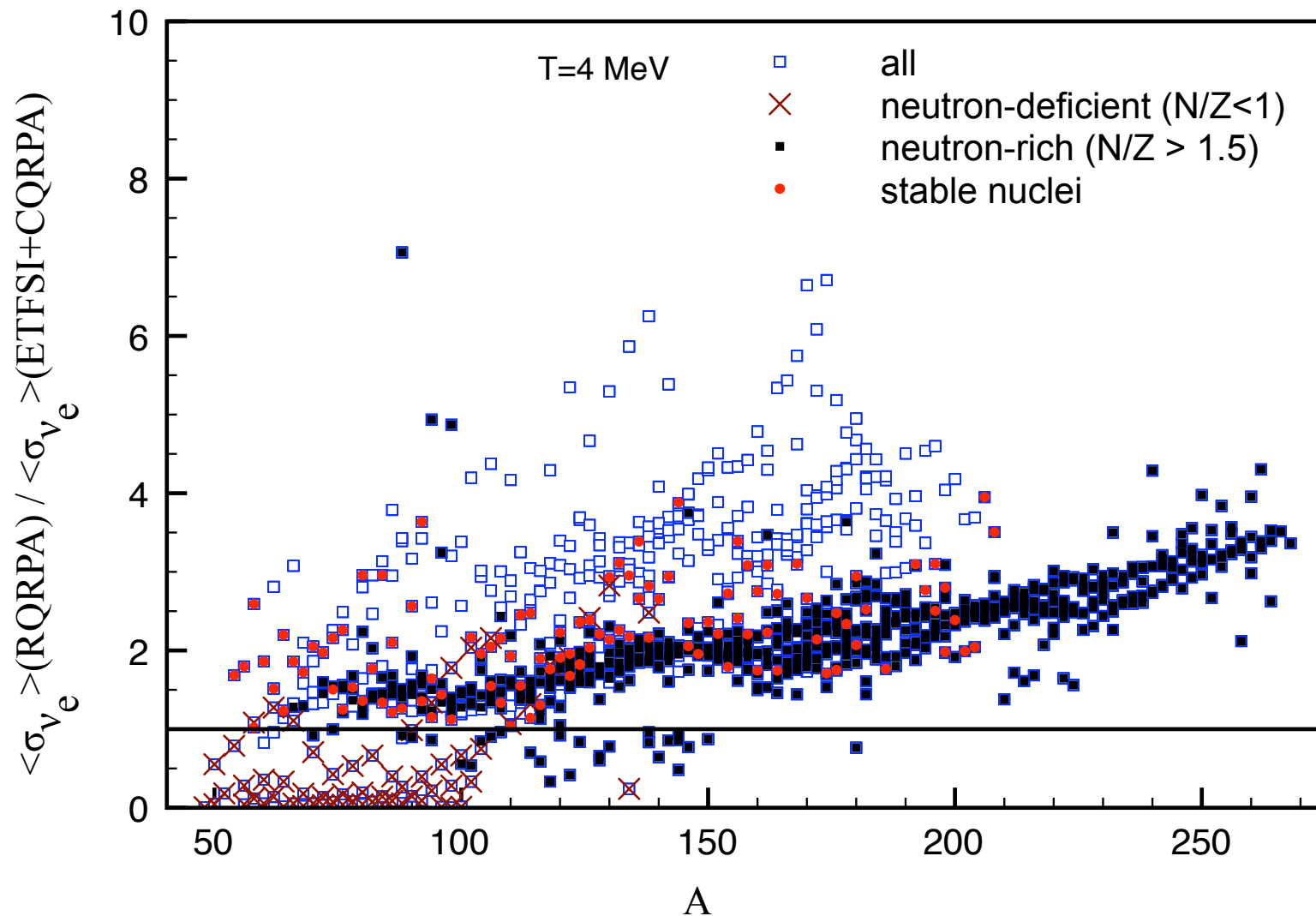
ADVANTAGES:

- 1) self-consistent parameter-free microscopic description of the cross sections (apart from the effective interactions that are fixed)
- 2) Complete calculations including all transition operators at finite momentum transfer and transitions up to $J=5$ (both parities)

The cross sections become considerably enhanced in neutron-rich nuclei, while those in neutron-deficient and proton-rich nuclei are small (blocking).

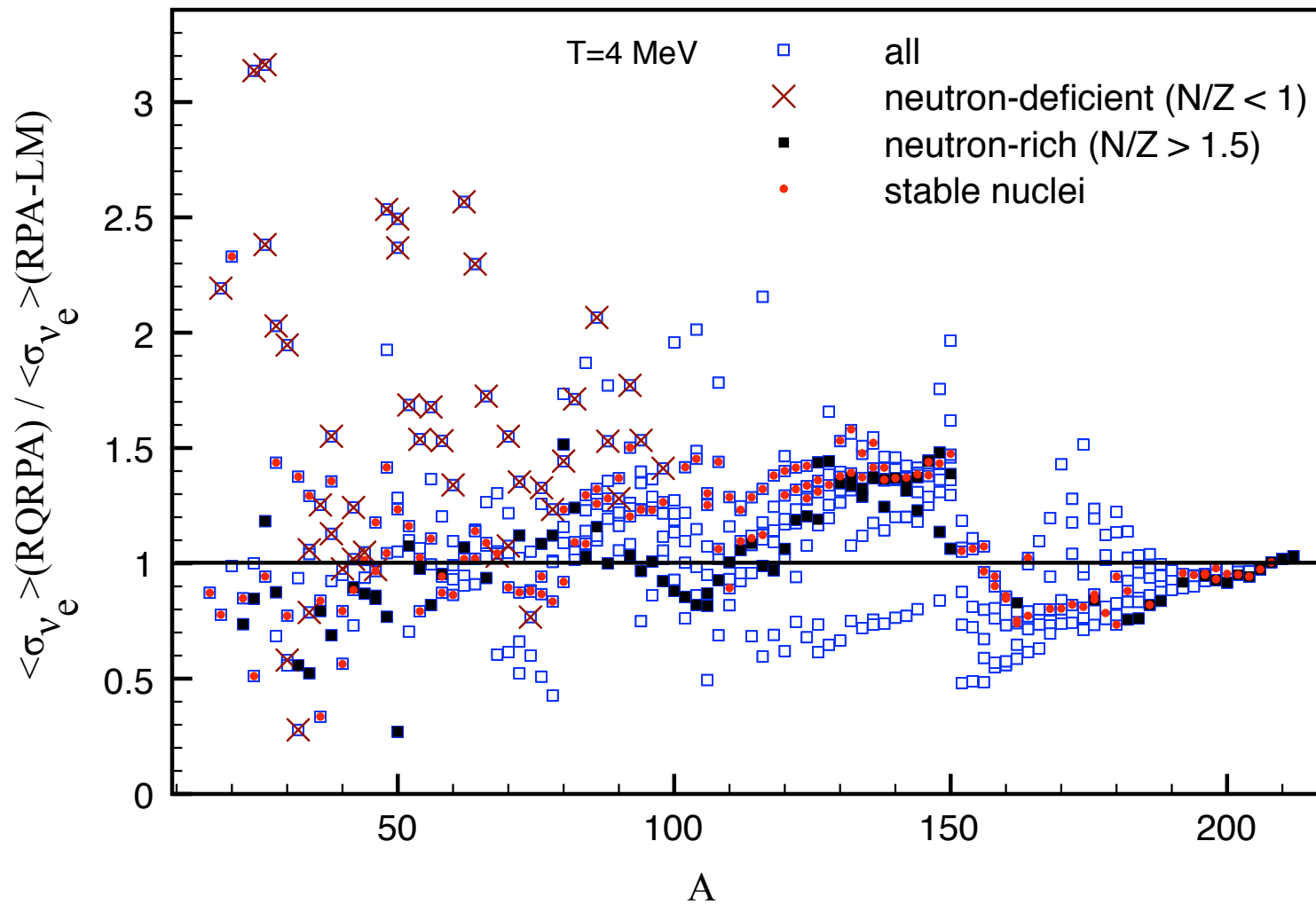
LARGE-SCALE CALCULATIONS OF ν -NUCLEUS CROSS SECTIONS

How the RNEDF results (up to $J=5$) compare to ETFSI+CQRPA (only IAS & GT transitions; Borzov, Goriely) ?



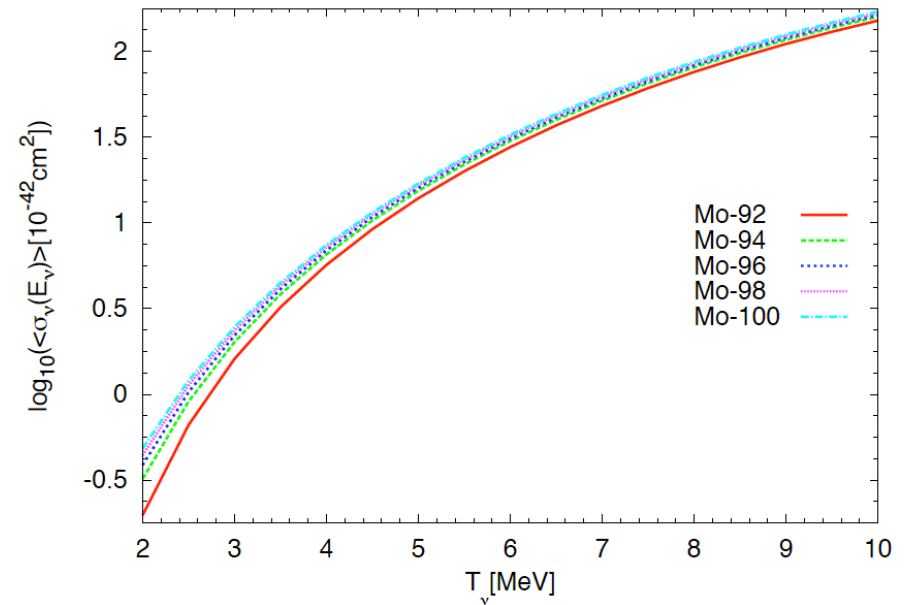
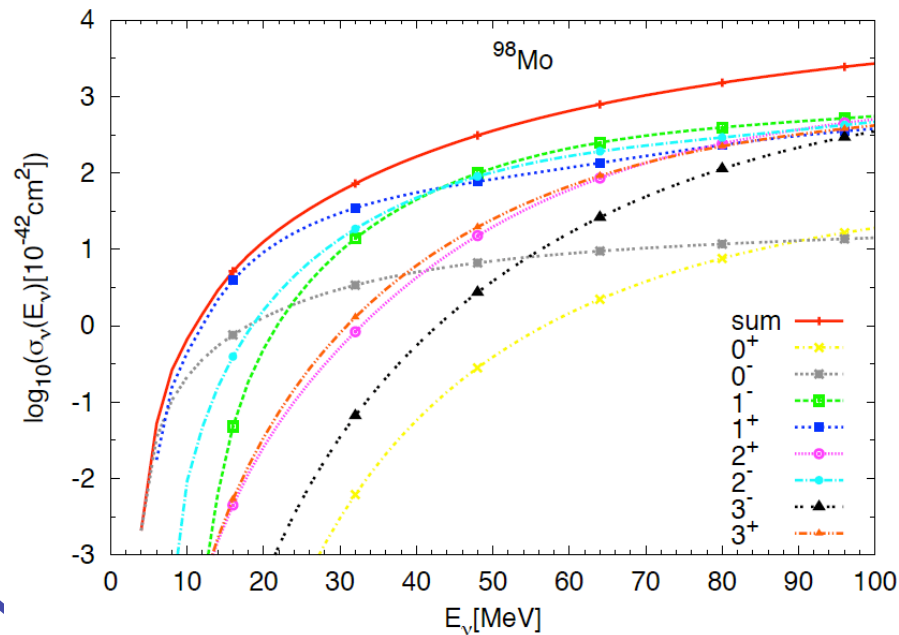
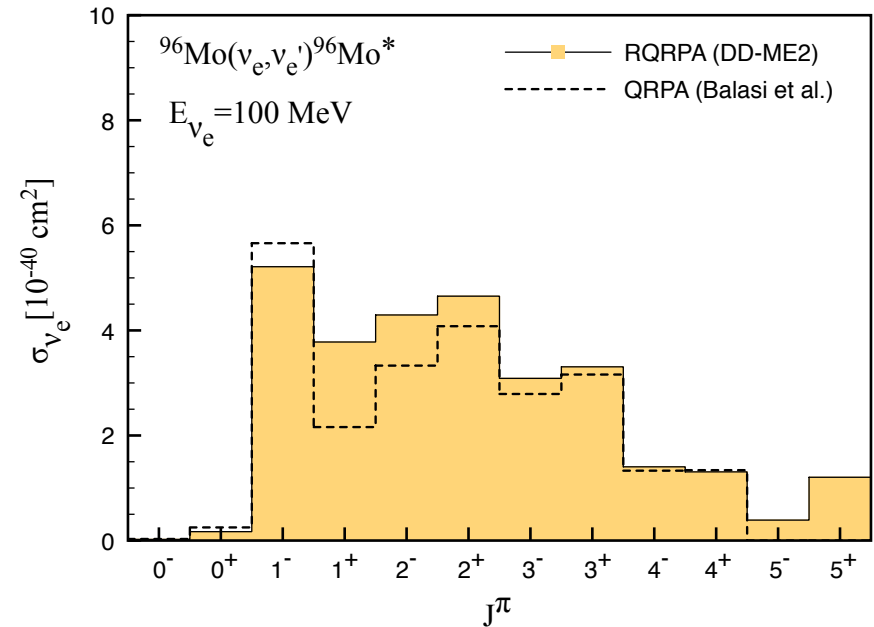
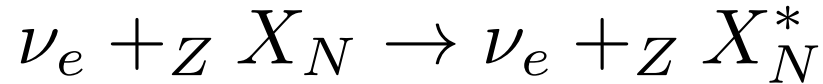
LARGE-SCALE CALCULATIONS OF ν -NUCLEUS CROSS SECTIONS

How the RNEDF results compare to RPA (Woods-Saxon + Landau-Migdal Force) by Kolbe, Langanke et al. ?



NEUTRAL-CURRENT NEUTRINO-NUCLEUS CROSS SECTIONS

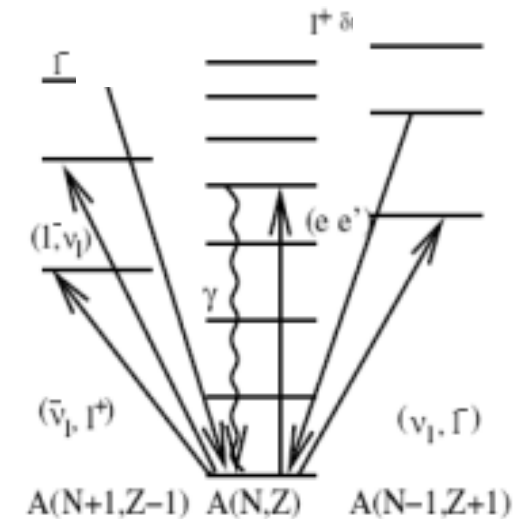
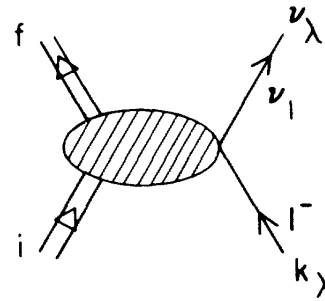
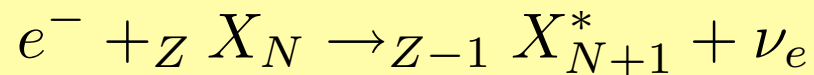
- Inelastic neutrino-nucleus scattering through the weak neutral-current plays important role in neutrino transport in stellar environment



STELLAR ELECTRON CAPTURE

- The core of a massive star at the end of hydrostatic burning is stabilized by electron degeneracy pressure (as long as its mass does not exceed the Chandrasekhar limit)
- Electron capture reduces the number of electrons available for pressure support (in opposition to nuclear beta decay)

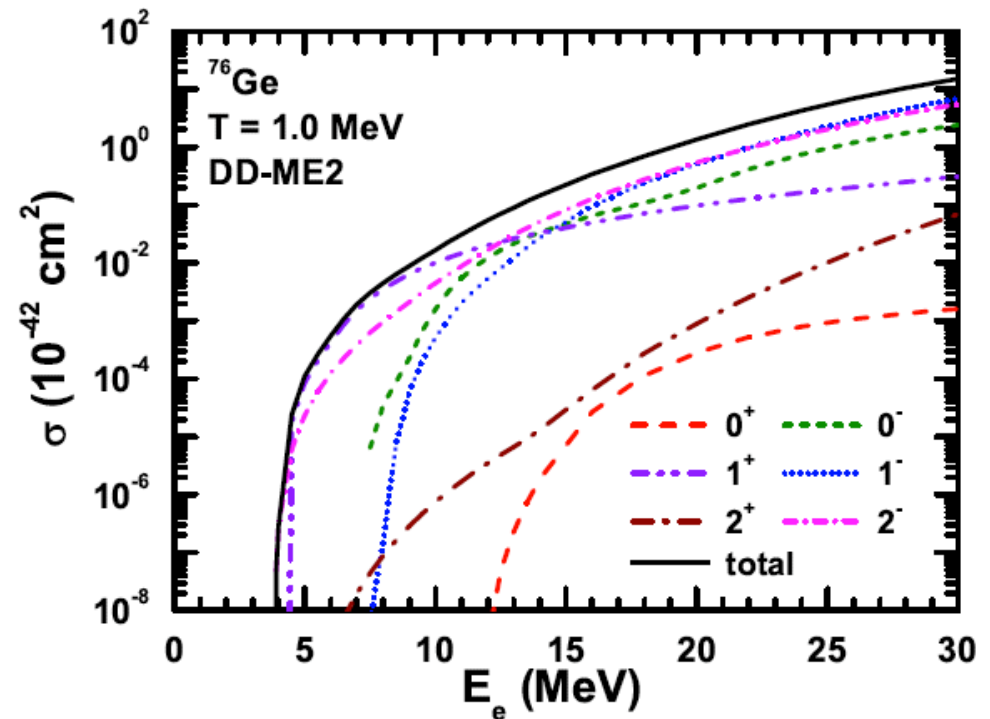
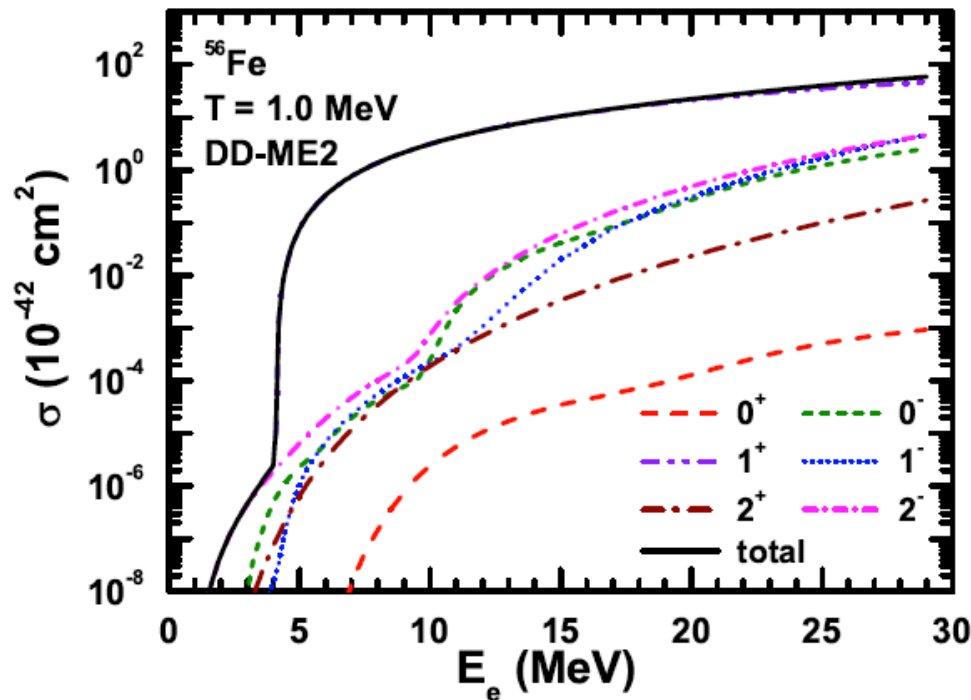
Electron capture



- Electron capture initiates the gravitational collapse of the core of a massive star, triggering a supernova explosion

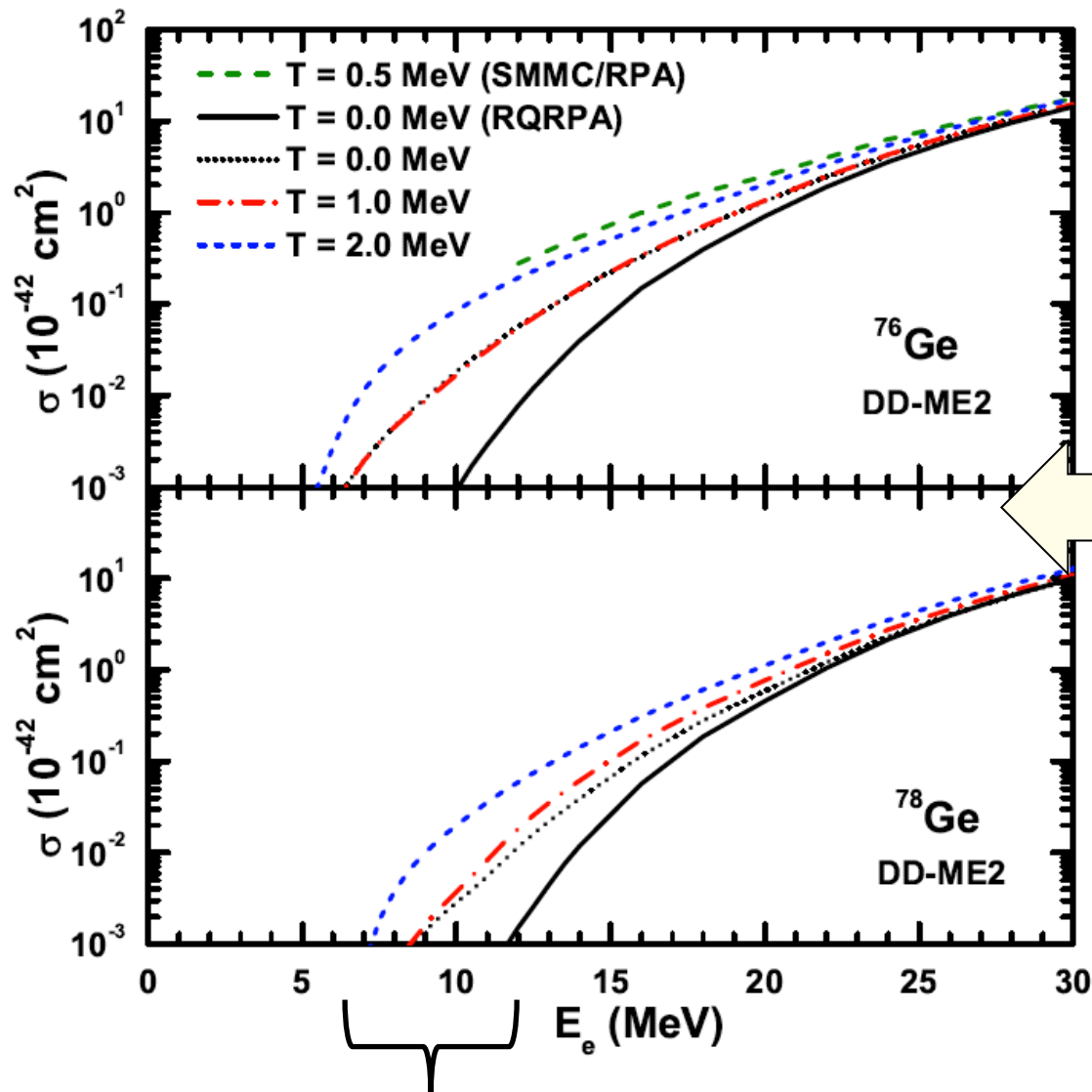
ELECTRON CAPTURE (EC) CROSS SECTIONS

- Model based on finite temperature (RMF + RPA)
- Finite temperature effects are described by Fermi-Dirac occupation factors for each single-nucleon state at the level of RMF, the same occupation factors are transferred to the RPA



For ^{56}Fe the electron capture is dominated by the GT+ transitions, while for neutron-rich nuclei (^{76}Ge) forbidden transitions play more prominent role)

STELLAR ELECTRON CAPTURE ON NEUTRON RICH Ge ISOTOPEs

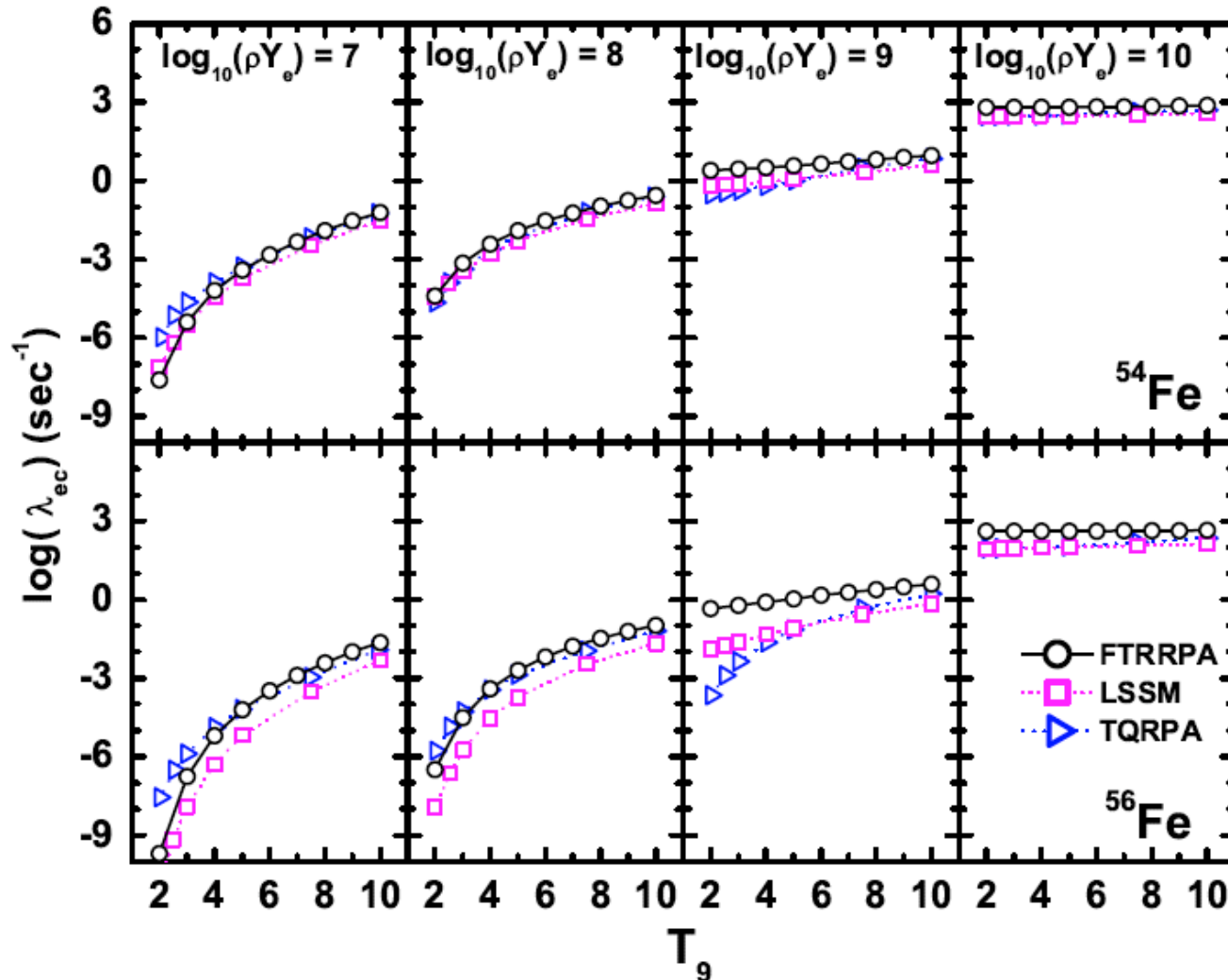


DEPENDENCE OF THE ELECTRON CAPTURE CROSS SECTIONS ON TEMPERATURE

Unblocking effect: electron-capture threshold energy decreases with temperature.

STELLAR ELECTRON CAPTURE RATES ON Fe ISOTOPES

$$\lambda_{ec} = \frac{1}{\pi^2 \hbar^3} \int_{E_e^0}^{\infty} p_e E_e \sigma_{ec}(E_e) f(E_e, \mu_e, T) dE_e$$



FTRRPA - present

LSSM – large scale
shell model

K. Langanke and
G. Martinez-Pinedo,
At. Data Nucl. Data
Tables 79, 1 (2001).

TQRPA

A.A. Dzhiyev et al.,
PRC 81, 015804 (2010)

NUCLEAR EOS - CONSTRAINING THE SYMMETRY ENERGY

In order to explore the evolution of the excitation spectra as a function of the density dependence of the symmetry energy, a set of interactions is used, that span a broad range of values for the symmetry energy at saturation density (J) and the slope parameter (L).

Nuclear matter energy per part.:

$$E(\rho, \alpha) = E(\rho, 0) + S_2(\rho)\alpha^2 + \dots$$

$$\alpha = (N - Z)/A$$

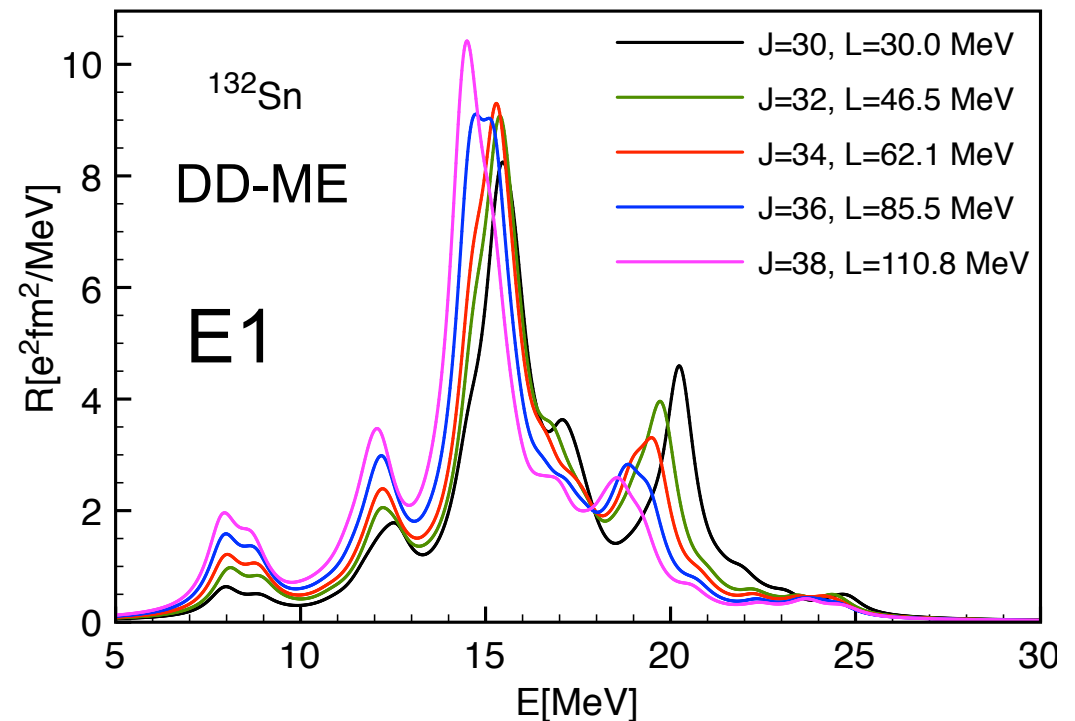
Symmetry energy term:

$$S_2(\rho) = J - L\epsilon + \dots$$

$$\epsilon = (\rho_0 - \rho)/(3\rho_0)$$

$$L = 3\rho_0 \left. \frac{dS_2(\rho)}{d\rho} \right|_{\rho_0}$$

Neutron skin thickness (ΔR_{pn}) in nuclei is strongly correlated with symmetry energy at saturation density (J) & slope of the symmetry energy (L)

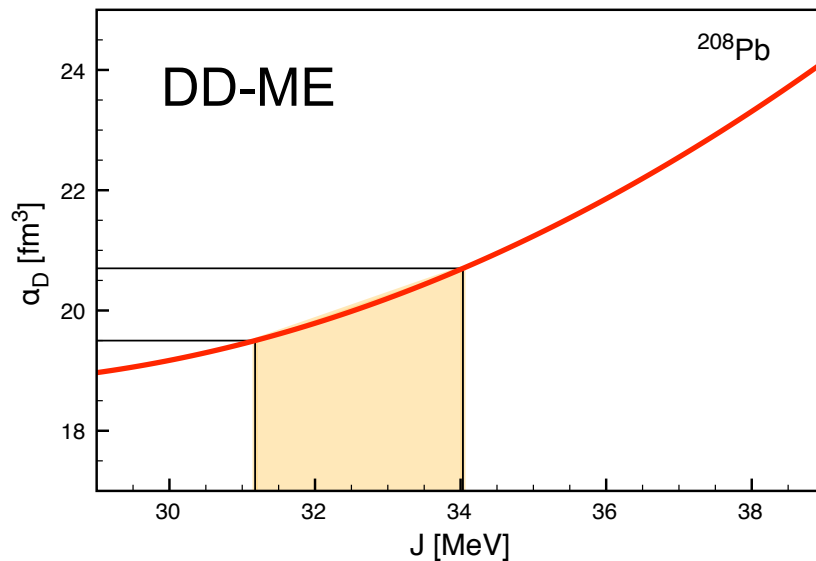
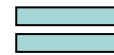


CONSTRAINING THE SYMMETRY ENERGY

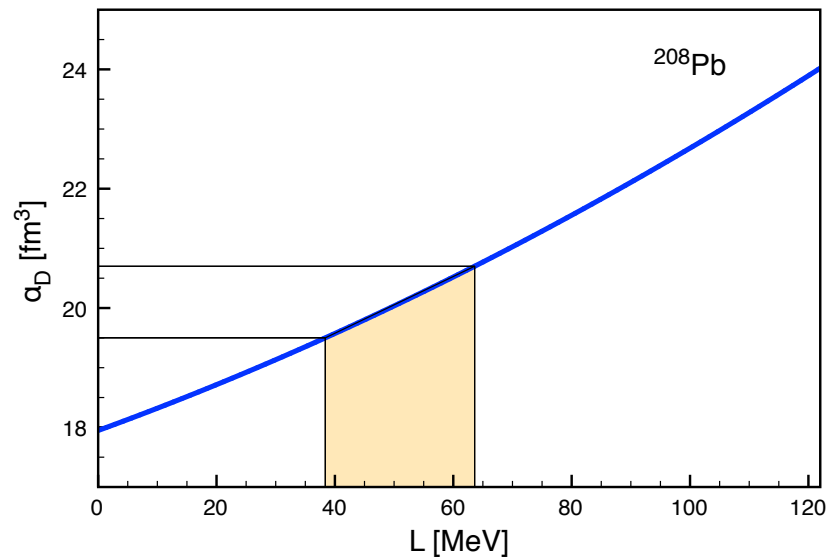
- Theoretical constraints on the symmetry energy at saturation density [J] and slope of the symmetry energy [L] from dipole polarizability [$\alpha_D = (8\pi/9)e^2 m_{-1}$] using relativistic nuclear energy density functionals



- Exp. data from polarized proton inelastic scattering, $\alpha_D = 18.9(13) \text{ fm}^3/e^2$
A. Tamii et al., PRL. 107, 062502 (2011)



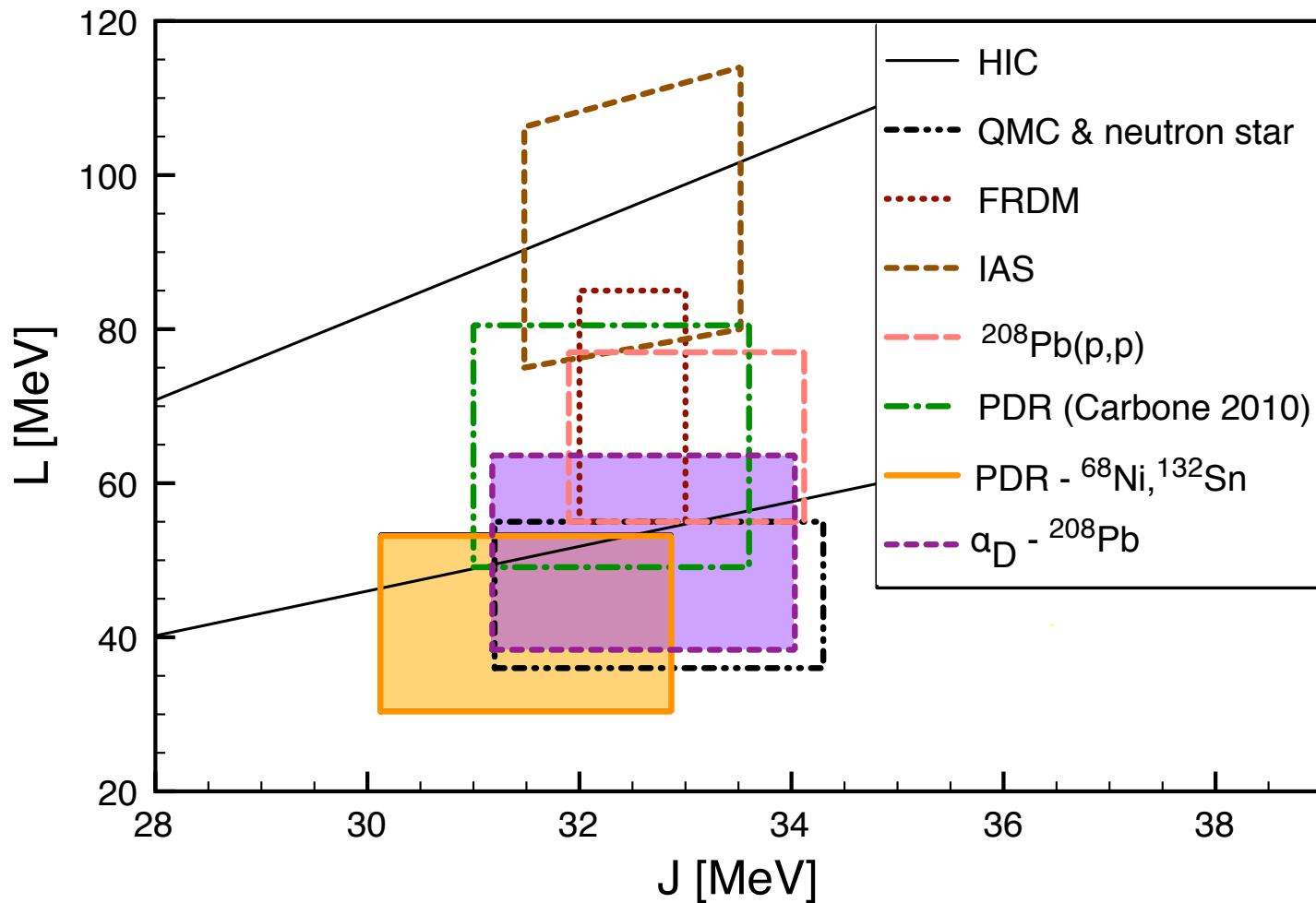
$$J = (32.6 \pm 1.4) \text{ MeV}$$



$$L = (50.9 \pm 12.6) \text{ MeV}$$

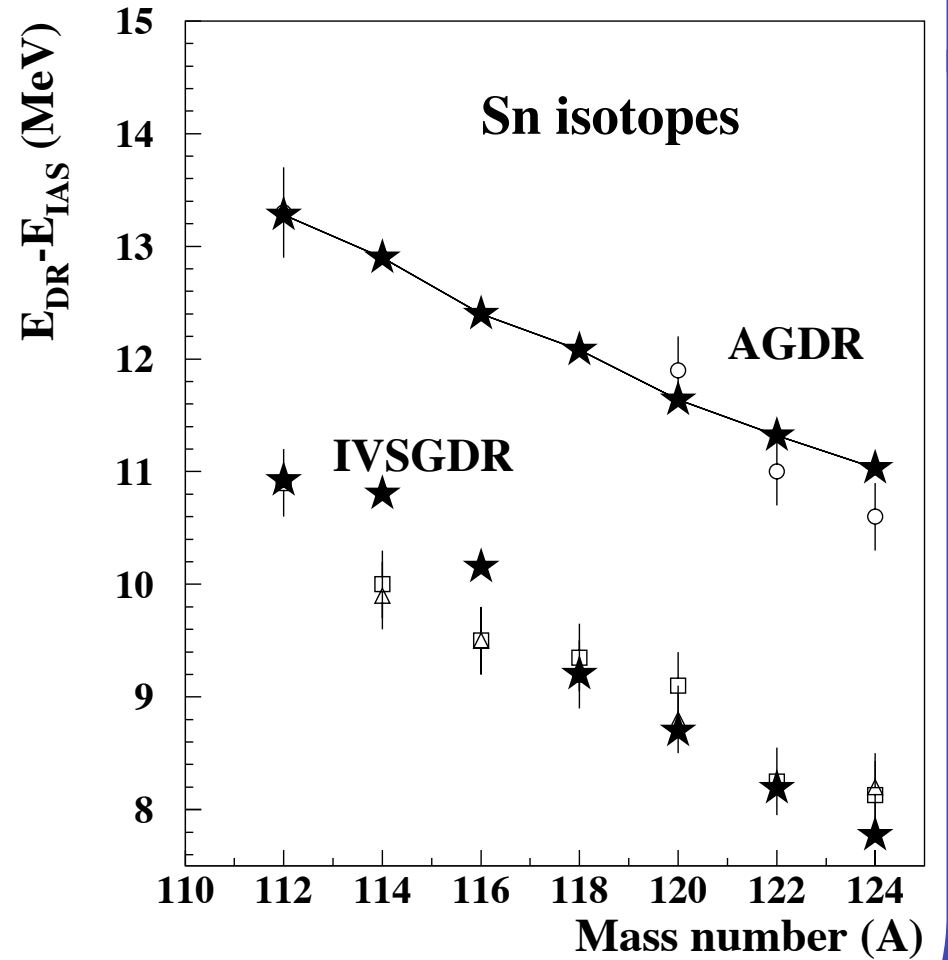
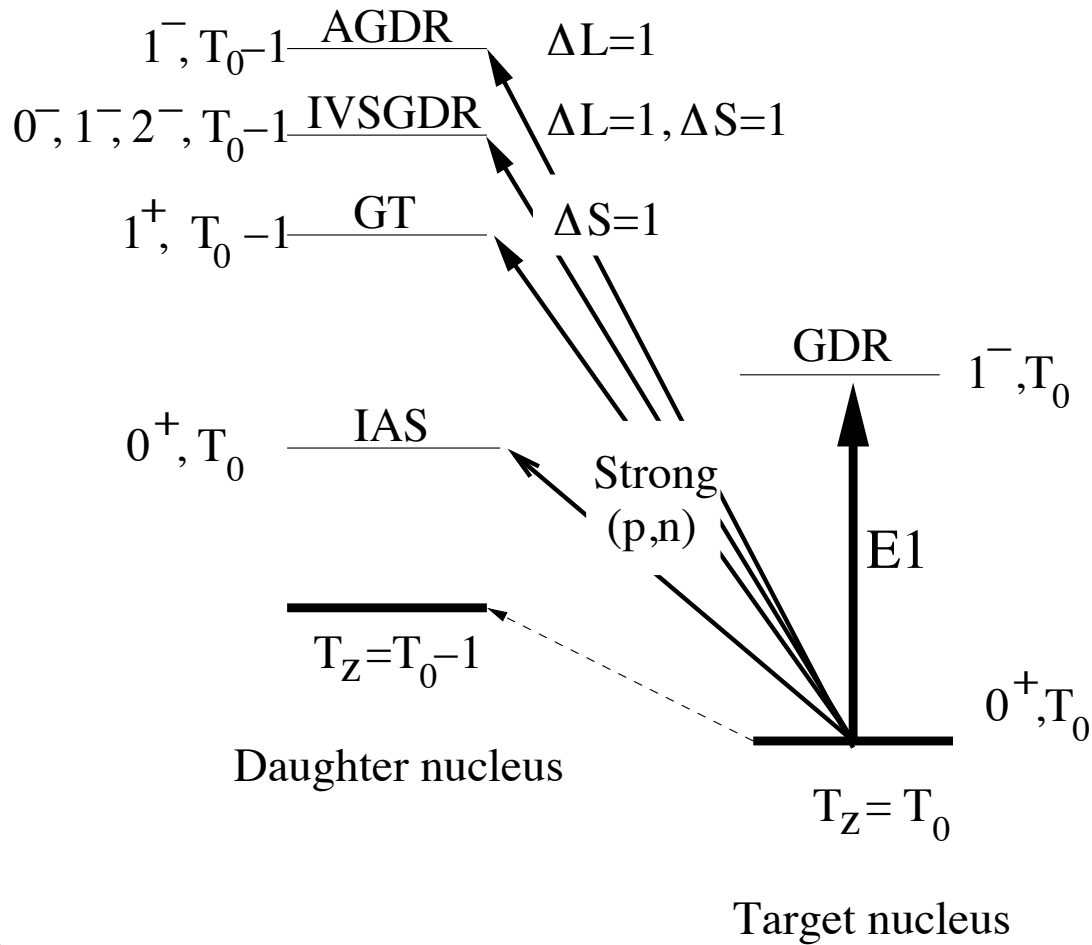
CONSTRAINING THE SYMMETRY ENERGY

- Constraining the symmetry energy at saturation density (J) and slope of the symmetry energy (L) from various approaches:



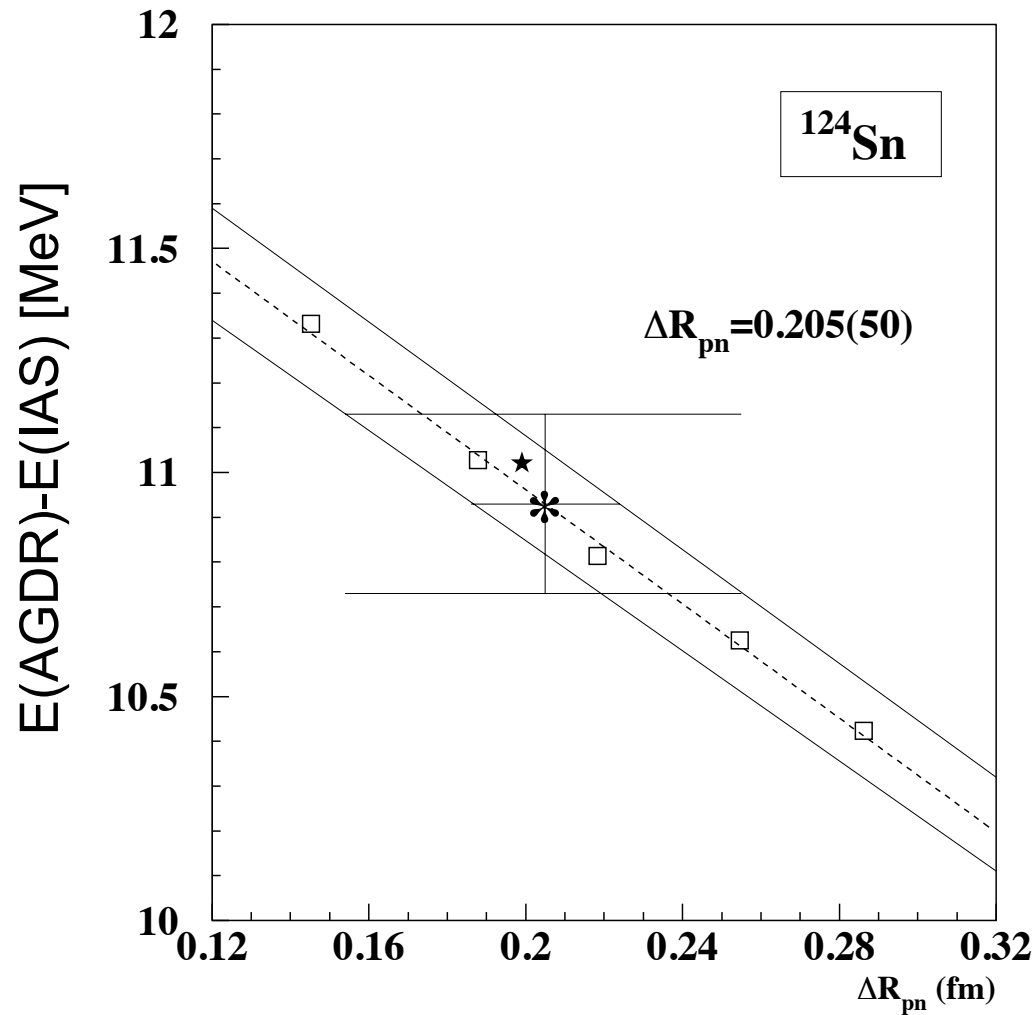
Also see M. B. Tsang et al., PRC 86, 015803 (2012)

ANTI-ANALOG GDR AND NEUTRON-SKIN THICKNESS



ANTI-ANALOG GDR AND NEUTRON-SKIN THICKNESS

TEST CASE: ^{124}Sn



neutron skin thickness

METHOD	ΔR_{pn} (fm)
(p,p) 0.8 GeV	0.25 ± 0.05
(α, α') IVGDR 120 MeV	0.21 ± 0.11
Antiproton absorption	0.19 ± 0.09
($^3\text{He}, t$) IVSGDR	0.27 ± 0.07
Pygmy dipole resonance	0.19 ± 0.05
(p,p) 295 MeV	0.185 ± 0.05
AGDR - present result	0.21 ± 0.05

CONCLUDING REMARKS

- ✓ We have established self-consistent framework based on the relativistic nuclear energy density functional to describe
 - neutrino-nucleus cross sections, both for neutral-current and charged current reactions
 - electron capture rates at finite temperature
- Includes complete set of transition operators and transitions of all relevant multipoles (forbidden transitions)
- This framework allows universal modeling of neutrino-nucleus cross sections (OPb pool completed), electron capture rates, and beta decays
- ✓ Studies (both theoretical and experimental) of dipole polarizability and AGDR provide useful constraints on the nuclear symmetry energy and neutron skin thickness

ACKNOWLEDGEMENTS & PUBLICATIONS

NEUTRINO-NUCLEUS REACTIONS:

- N. Paar, T. Suzuki, M. Honma, T. Marketin, and D. Vretenar, PRC 84, 047305 (2011).
- A. R. Samana, F. Krmpotic, N. Paar, C. A. Bertulani, PRC 83, 045807 (2011).
- H. Đapo, N. Paar, PRC 86, 035804 (2012).
- N. Paar, H. Tutman, T. Marketin, T. Fischer, submitted to PRC (2012).

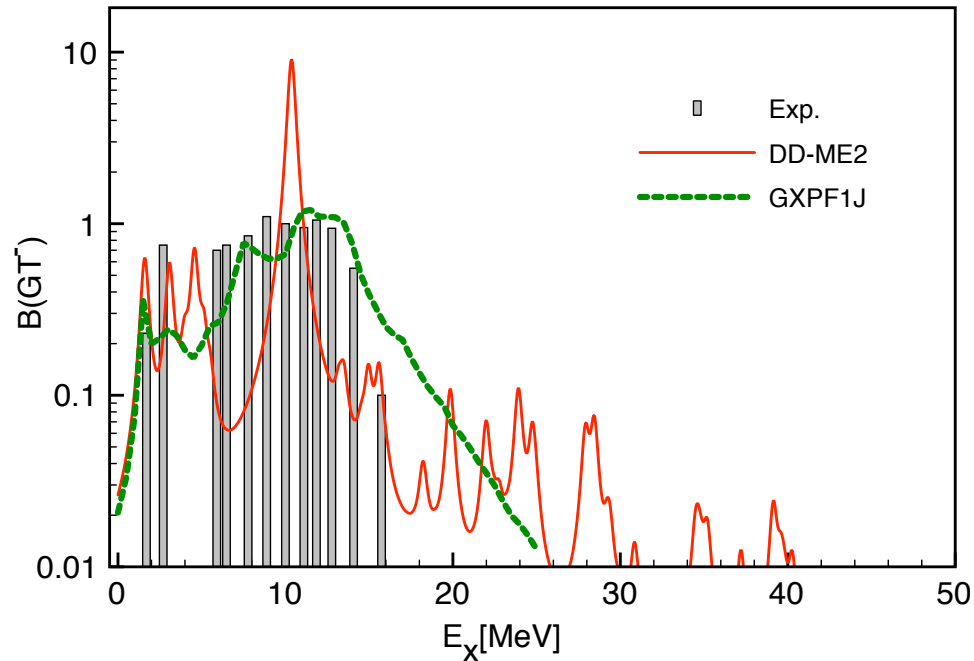
ELECTRON CAPTURE:

- Y. F. Niu, N. Paar, D. Vretenar, and J. Meng, PRC 83, 045807 (2011).
- A. F. Fantina, E. Khan, G. Colo, N. Paar, and D. Vretenar, PRC 86, 035805 (2012).

NEUTRON-SKIN THICKNESS & SYMMETRY ENERGY:

- J. Piekarewicz et al., PRC 85, 041302(R) (2012).
- A. Krasznahorkay, N. Paar, D. Vretenar, M. Harakeh, submitted to PLB (2012).

GAMOW-TELLER TRANSITION STRENGTH FOR ^{56}Fe



Gamow-Teller (GT) transitions calculated in two models:

- RQRPA (DD-ME2)

- Shell model (GXPF1J)
T. Suzuki et al.

Shell model includes important correlations among nuclei, accurately reproduces the experimental GT strength. However, already in medium mass nuclei the model spaces become large, many nuclei and forbidden transitions remain beyond reach.

RQRPA reproduces total GT strength and global properties of transition strength. Allows systematic calculations of high multipole excitations (forbidden transitions), enables extrapolations toward nuclei away from the valley of stability.