The 4th International Symposium on Neutrinos and Dark Matter in Nuclear Physics
June 11-15th, 2012, Nara, Japan

# Neutrino-nucleus reactions based on relativistic nuclear energy density functional

*N. Paar*

*Physics Department*
*Faculty of Science*
*University of Zagreb*
*Croatia*

# NEUTRINO-NUCLEUS REACTIONS BASED ON RNEDF

**OBJECTIVES:**

- description of low-energy neutrino-nucleus interaction using self-consistent theory of nuclear structure and excitations of target nuclei based on relativistic nuclear energy density functional (RNEDF).

- neutrino-nucleus cross sections for supernova neutrinos, neutrino detectors, neutrino nucleosynthesis, etc.



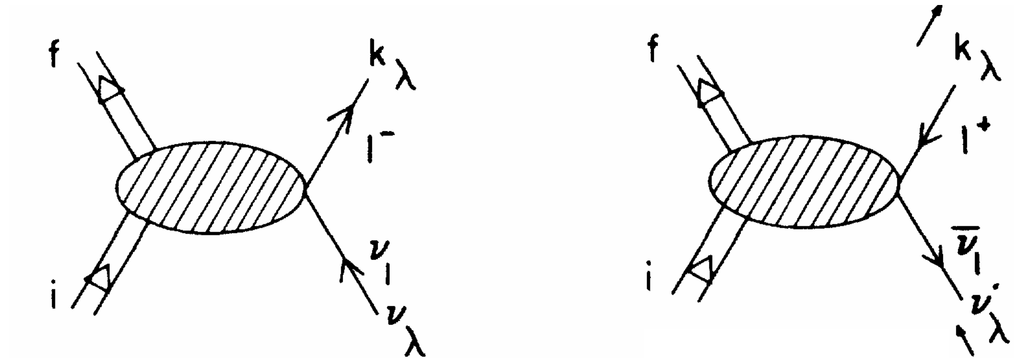
- **N. Paar, T. Suzuki, M. Honma, T. Marketin, and D. Vretenar, PRC 84, 047305 (2011).**
- **H. Đapo, N. Paar, nucl-th/arXiv:1203.5224 (2012).**
- **A. R. Samana, F. Krmpotic, N. Paar, C. A. Bertulani, PRC 83, 045807 (2011).**
- **Y. F. Niu, N. Paar, D. Vretenar, and J. Meng, Phys. Lett. B 681, 315 (2009).**
- **N. Paar, D. Vretenar, T. Marketin, and P. Ring, PRC 77, 024608 (2008).**
- **N. Paar, H. Tutman, T. Marketin, in preparation (2012).**

# LOW-ENERGY NEUTRINO-NUCLEUS PROCESSES

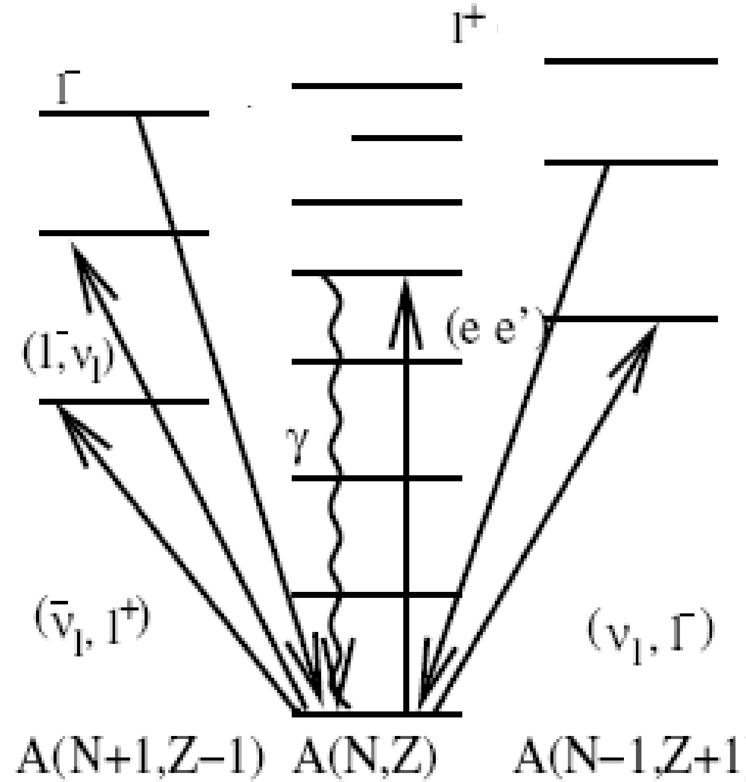
## Neutrino-induced processes

$$\nu_l +_Z X_N \rightarrow_{Z+1} X^*_{N-1} + l^-$$

$$\bar{\nu}_l +_Z X_N \rightarrow_{Z-1} X^*_{N+1} + l^+$$




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



# NEUTRINO-NUCLEUS CROSS SECTIONS

$$\widehat{H}_W = -\frac{G}{\sqrt{2}}\int d\boldsymbol{x}\mathcal{J}^{\lambda}(\boldsymbol{x})j_{\lambda}(\boldsymbol{x})$$ Hamiltonian for the weak interaction

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

$$\boldsymbol{k} = E_l\boldsymbol{\beta}$$

Transverse magnetic & Transverse electric multipole operators

Coulomb & longitudinal multipole operators

Transition matrix elements $\langle J_f||\widehat{\mathcal{O}}||J_i\rangle$ include the structure properties of target nuclei

# NEUTRINO-NUCLEUS CROSS SECTIONS

Neutrino-nucleus cross sections based on relativistic nuclear energy density functional (RNEDF)

RELATIVISTIC HARTREE-BOGOLIUBOV MODEL (RHB)
+ RELATIVISTIC QUASIPARTICLE RPA (RQRPA)

BOTH THE GROUND STATE EQUATIONS & RESIDUAL QRPA INTERACTION <u>ARE DERIVED FROM THE SAME ENERGY DENSITY FUNCTIONAL</u>

$\sigma_\nu$

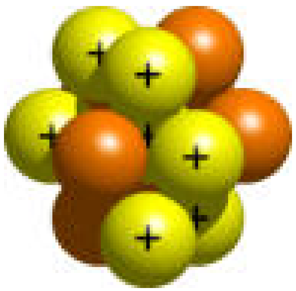
reduced matrix elements for the neutrino-nucleus cross section

$$\langle J_f||\hat{\mathcal{O}}^J||J_i\rangle = \sum_{pn}\langle p||\hat{\mathcal{O}}^J||n\rangle(X_{pn}^{fJ}u_pv_n + (-1)^J Y_{pn}^{fJ}v_pu_n)$$

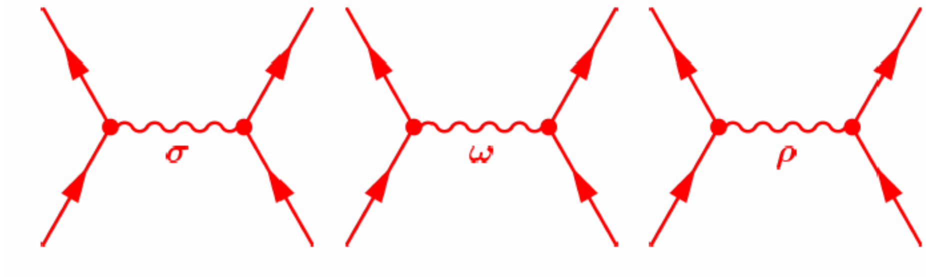
RQRPA amplitudes

RHB occupation probabilities

# NUCLEI IN THE RELATIVISTIC MEAN FIELD THEORY



system of Dirac nucleons coupled to the exchange mesons and the photon field through an effective Lagrangian.




Lagrangian density

$$\mathcal{L} = \mathcal{L}_N + \mathcal{L}_m + \mathcal{L}_{int}$$

$$\mathcal{L}_N = \bar{\psi}\left(i\gamma^\mu \partial_\mu - m\right)\psi$$

$$\begin{aligned}\mathcal{L}_m \;=\;& \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu \\ & -\frac{1}{4}\vec{R}_{\mu\nu}\vec{R}^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\vec{\rho}^\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}\end{aligned}$$

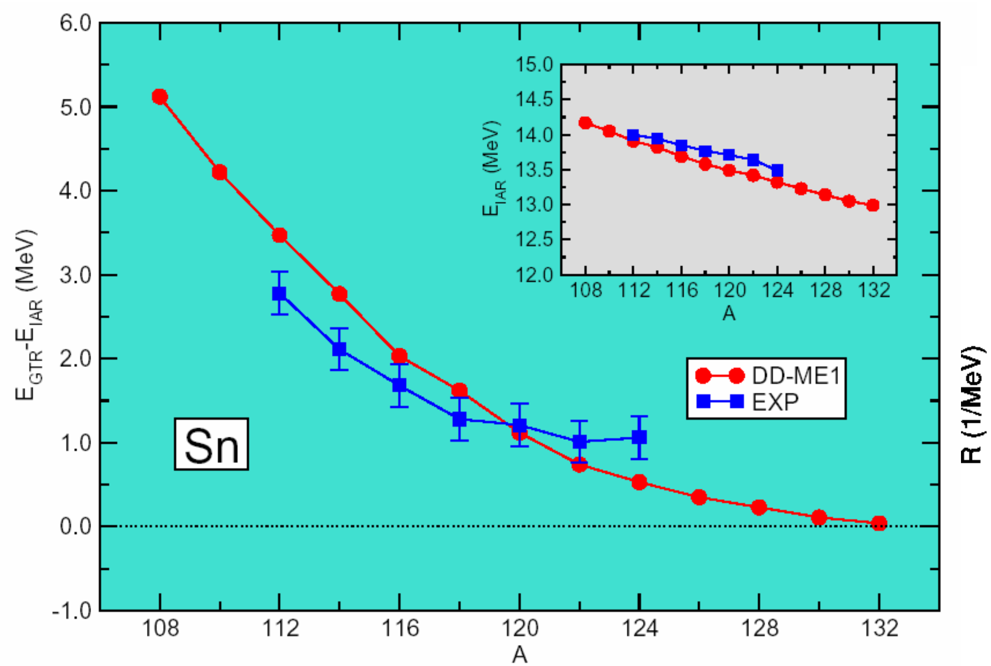
$$\mathcal{L}_{int} = -\bar{\psi}\Gamma_\sigma\sigma\psi - \bar{\psi}\Gamma_\omega^\mu\omega_\mu\psi - \bar{\psi}\vec{\Gamma}_\rho^\mu\vec{\rho}_\mu\psi - \bar{\psi}\Gamma_e^\mu A_\mu\psi.$$

DD-ME2 density-dependent effective interaction + Gogny pairing

# CHARGE-EXCHANGE EXCITATIONS FROM RQRPA

ISOSPIN-FLIP EXCITATIONS (Isobaric analogue)

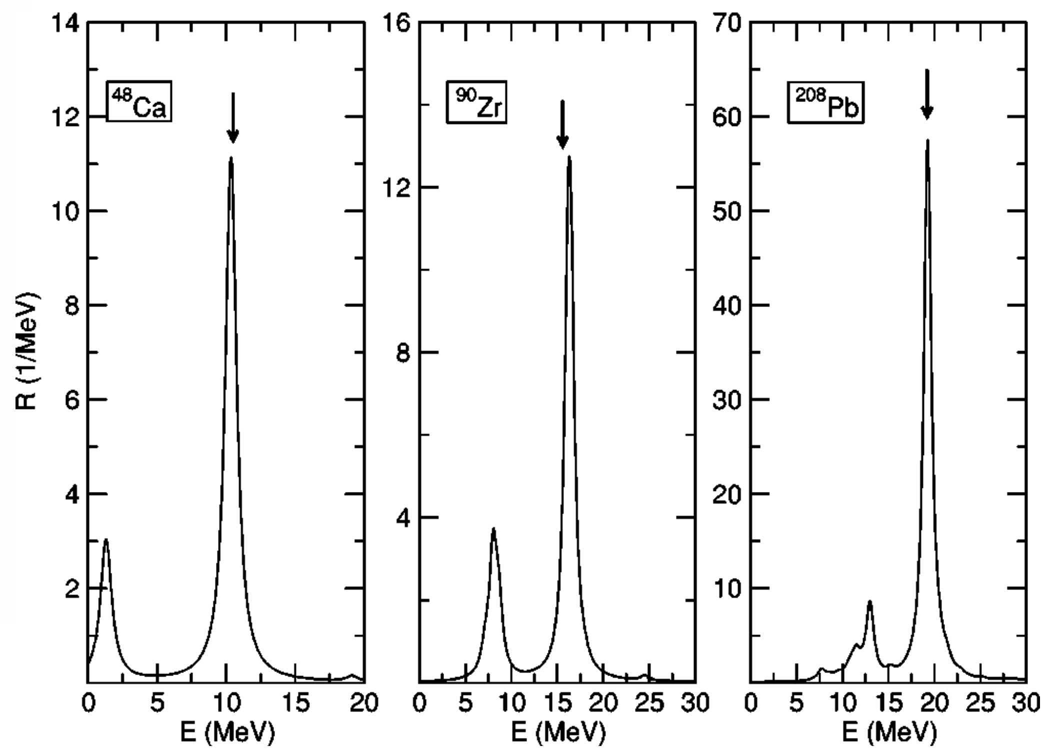
$$T^{F}_{\beta^{\pm}} = \sum_{i=1}^{A} \tau_{\pm}$$



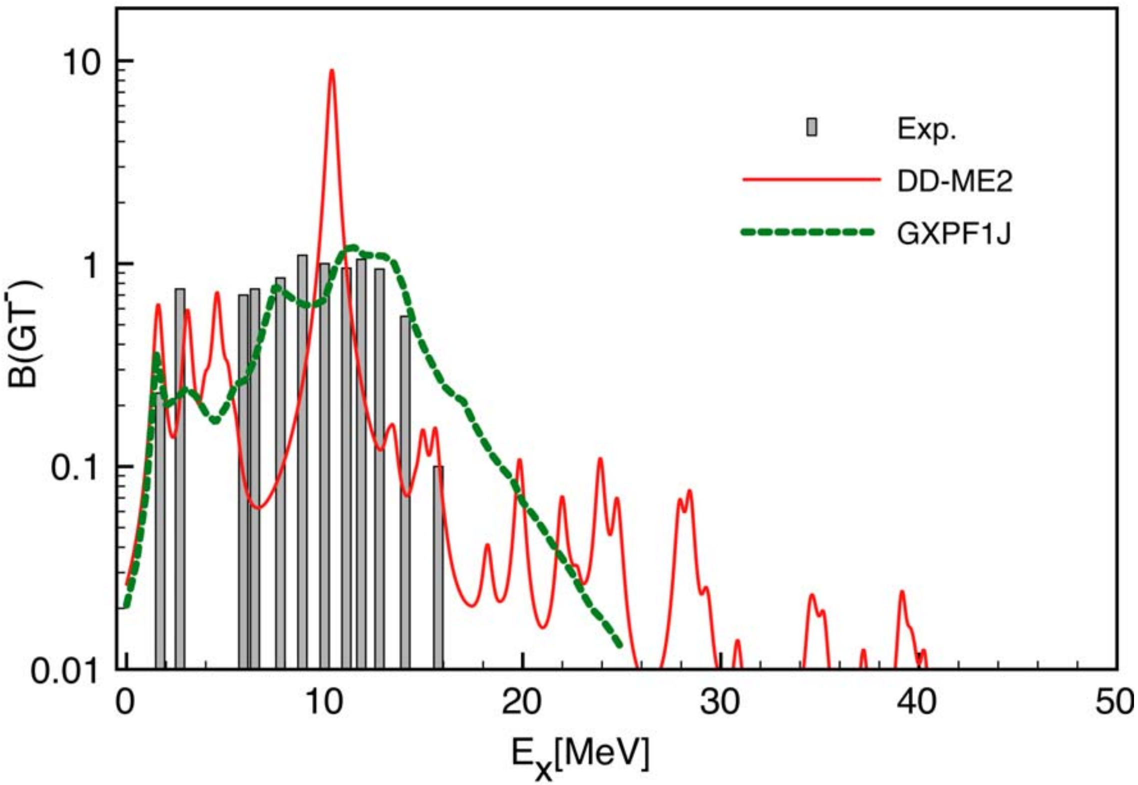

The isotopic dependence of the energy spacings between the Gamow-Teller resonance and isobaric analogue state

SPIN-FLIP & ISOSPIN-FLIP EXCITATIONS (Gamow-Teller)

$$T^{GT}_{\beta^{\pm}} = \sum_{i=1}^{A} \Sigma\tau_{\pm}$$



# 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.

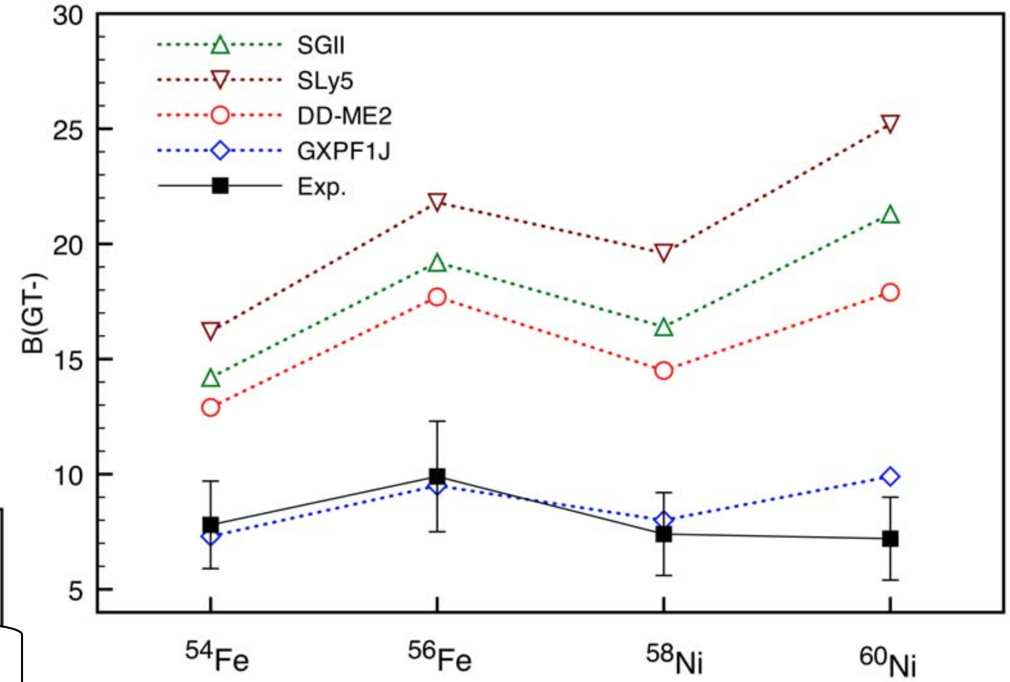
Shell model includes important correlations among nuclei, accurately reproduces the experimental GT strength. However, already in medium mass nuclei the model spaces become large, many nuclei and forbidden transitions remain beyond reach.

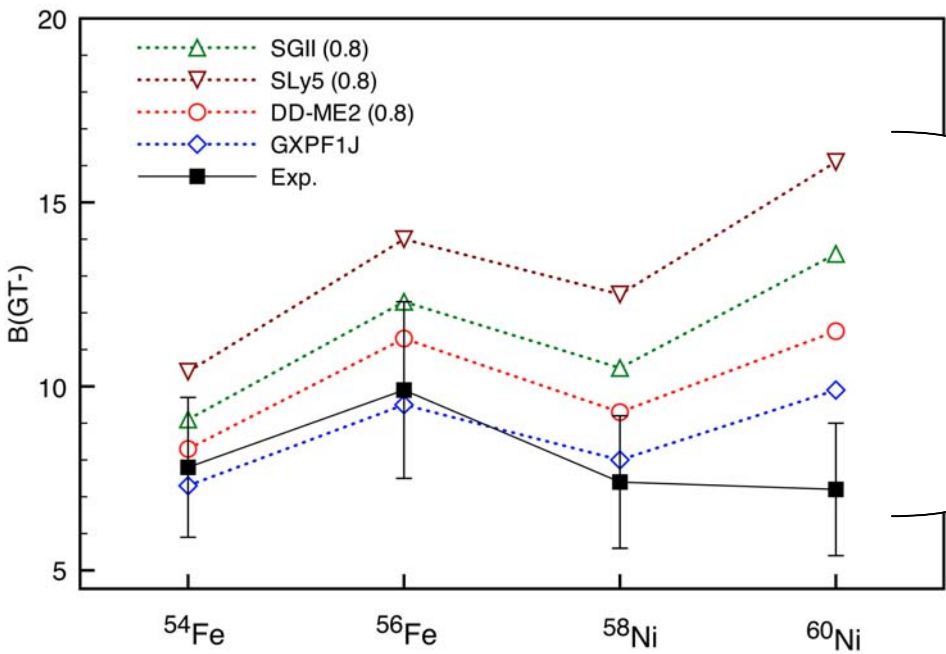
RQRPA reproduces total GT strength and global properties of transition strength. Allows systematic calculations of high multipole excitations (forbidden transitions), enables extrapolations toward nuclei away from the valley of stability.

# GT$^-$ TRANSITION STRENGTH IN IRON GROUP NUCLEI

Overall GT$^-$ transition strength obtained using:

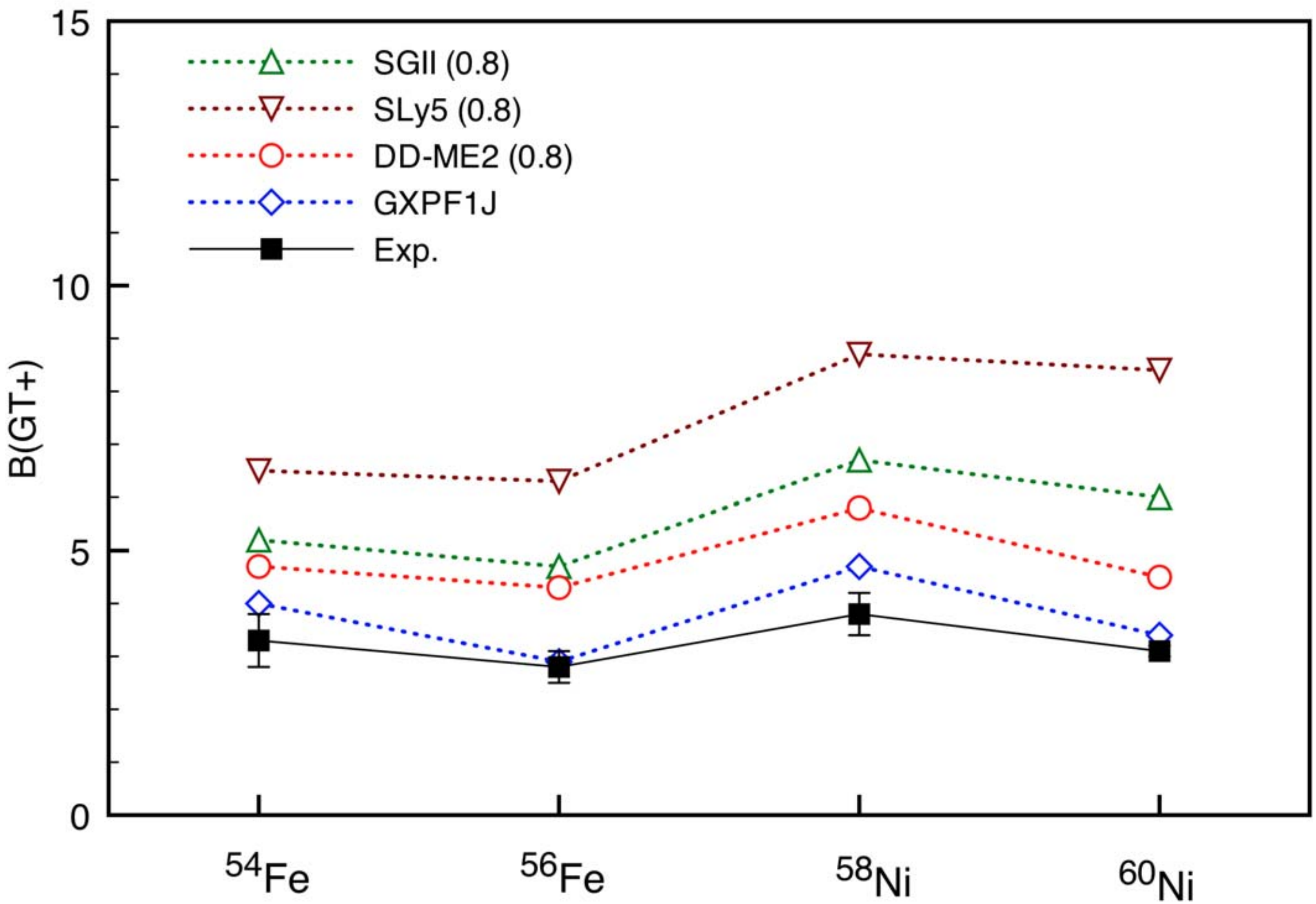
1) Skyrme functional (SGII,SLy5)
2) Relativistic functional (DD-ME2)
3) Shell model (GXPF1J)
   T. Suzuki et al.




With quenching in $g_A$, quenching factor 0.8 in (R)QRPA, 0.74 in the shell model

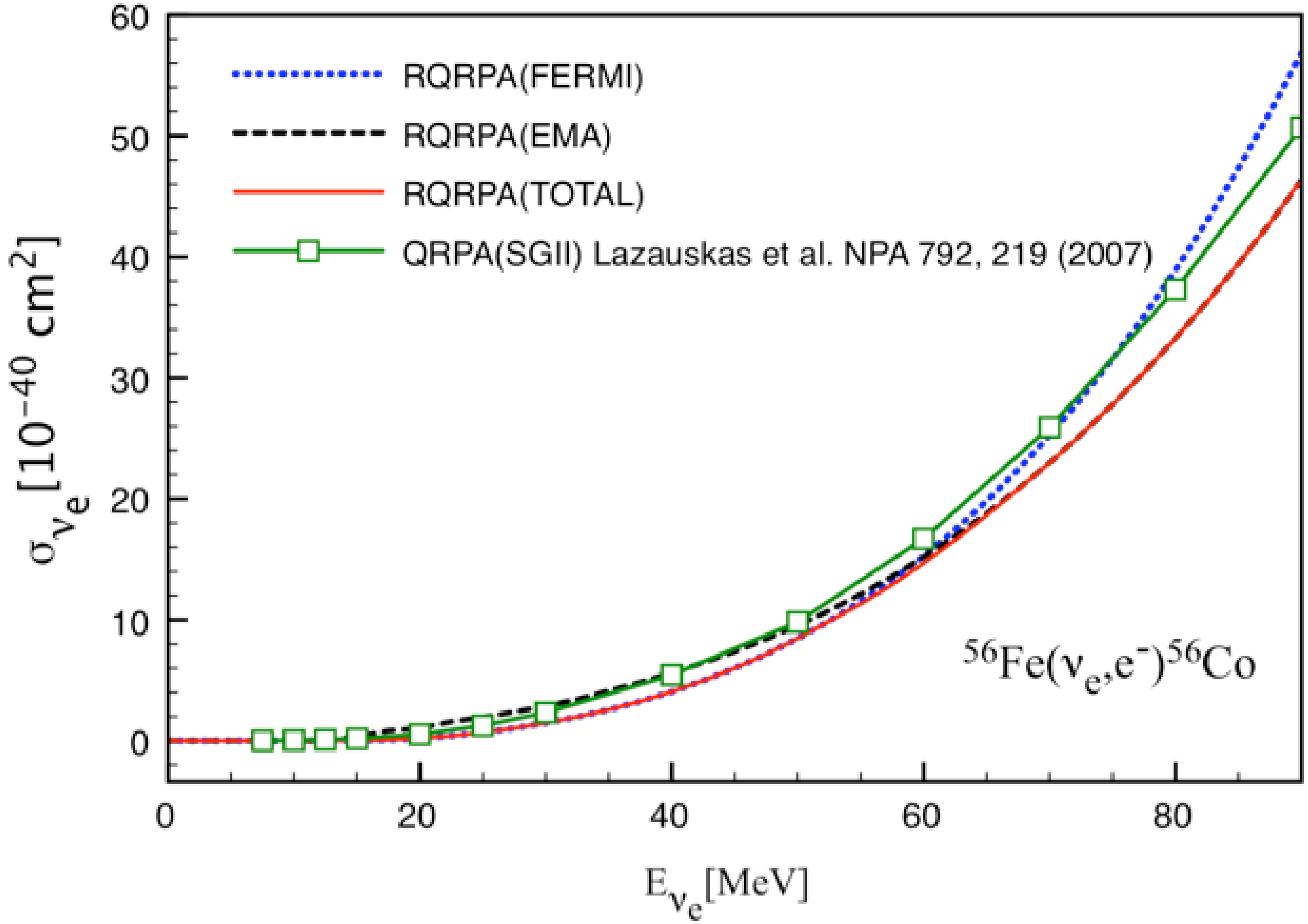
# $GT^+$ TRANSITION STRENGTH IN IRON GROUP NUCLEI




Overall $GT^+$ transition strength obtained using:

1)Skyrme functional
(SGII,SLy5)
2) Relativistic functional
(DD-ME2)
3) Shell model
(GXPF1J)
T. Suzuki et al.

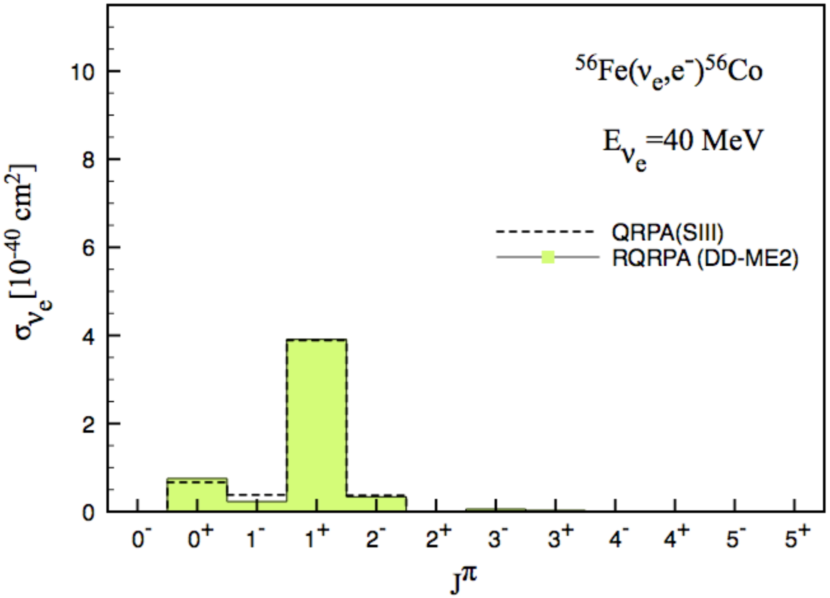
# CHARGED-CURRENT NEUTRINO-NUCLEUS CROSS SECTIONS FOR $^{56}Fe$

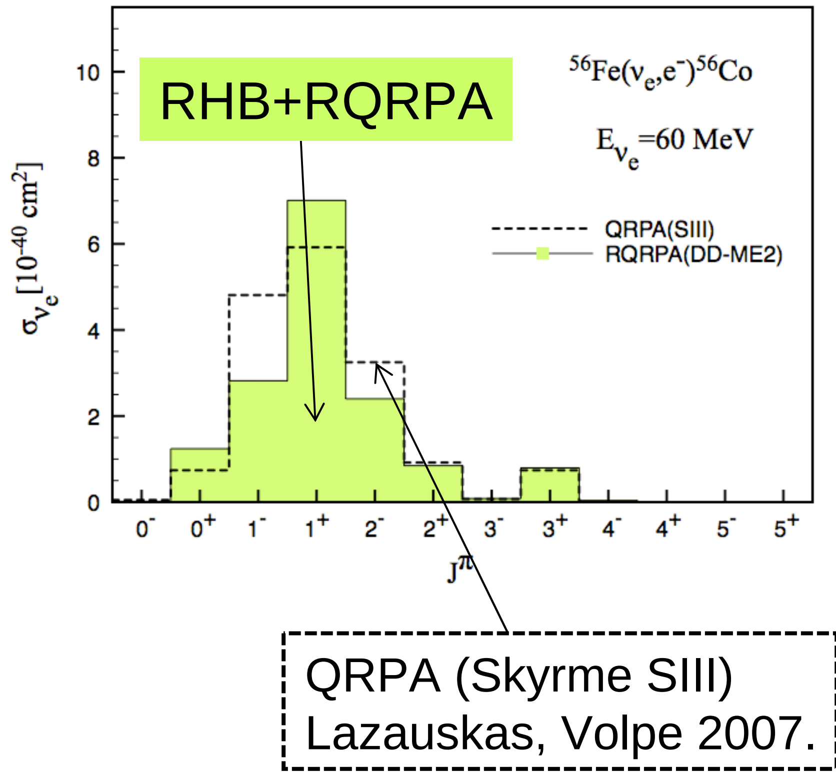


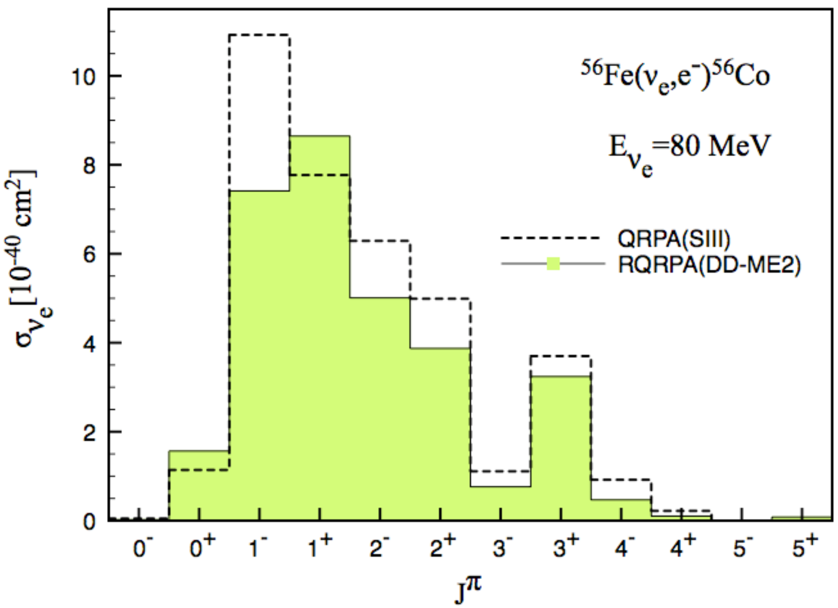

Model calculations include all multipoles (both parities) up to J=5. Coulomb interaction between outgoing electron and residual nucleus is taken into account.

Partly due to enhanced $GT^-$ transition strength, Skyrme functional results in larger cross sections than relativistic EDF.

# DISTRIBUTION OF CROSS SECTIONS OVER MULTIPOLARITIES



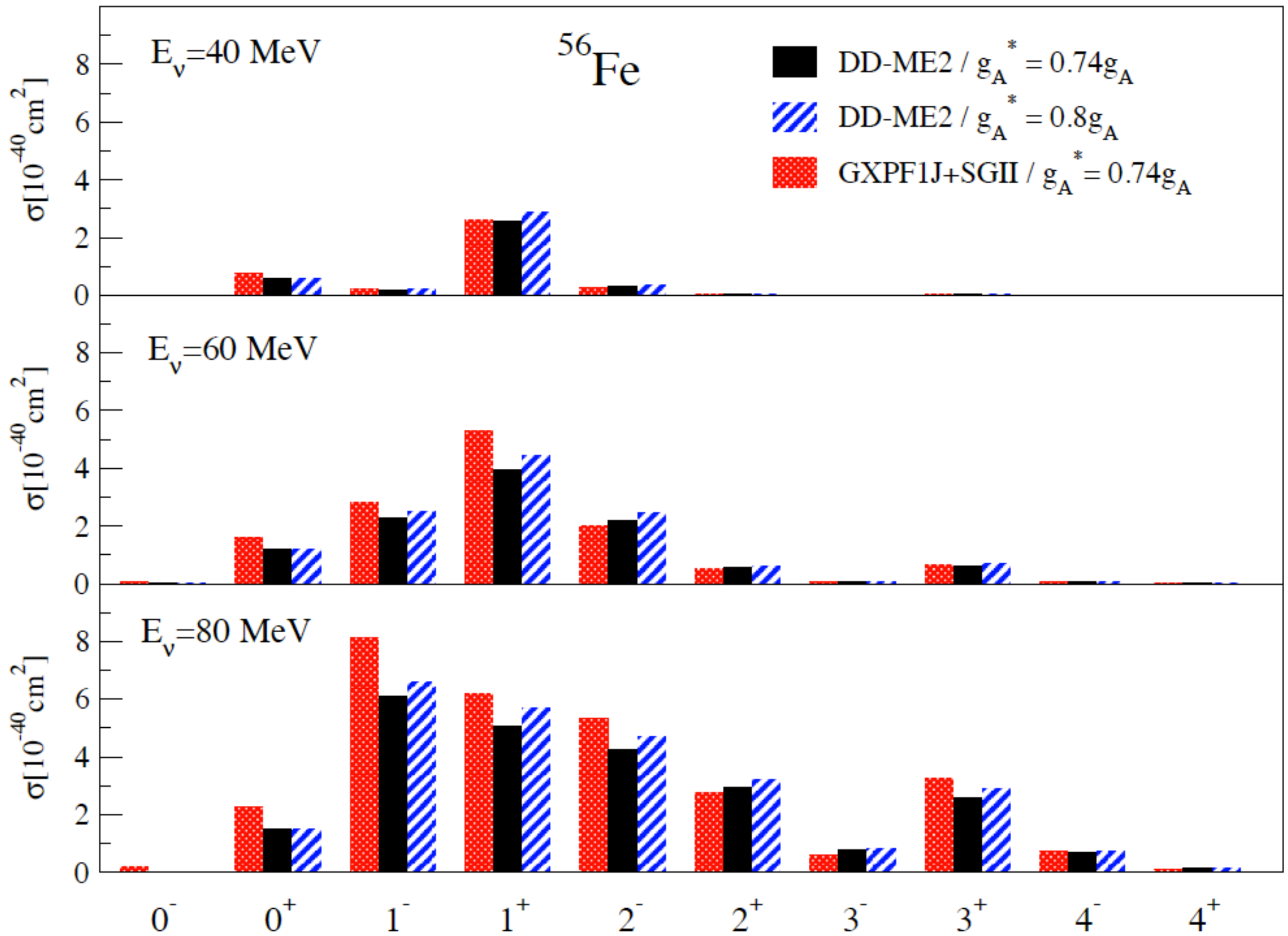




GT, spin-dipole, and excitations of higher multipolarities contribute to neutrino-nucleus cross sections.

# CHARGED-CURRENT NEUTRINO-NUCLEUS CROSS SECTIONS

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

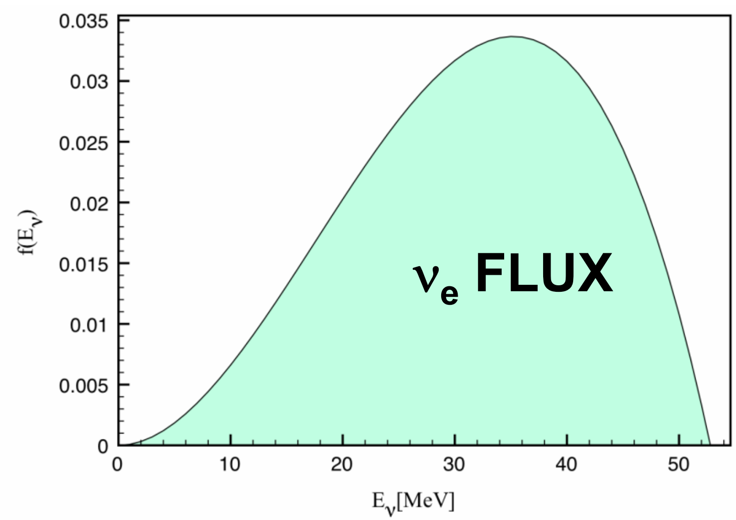



Remarkable agreement between two models based on completely different foundations and effective interactions!

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

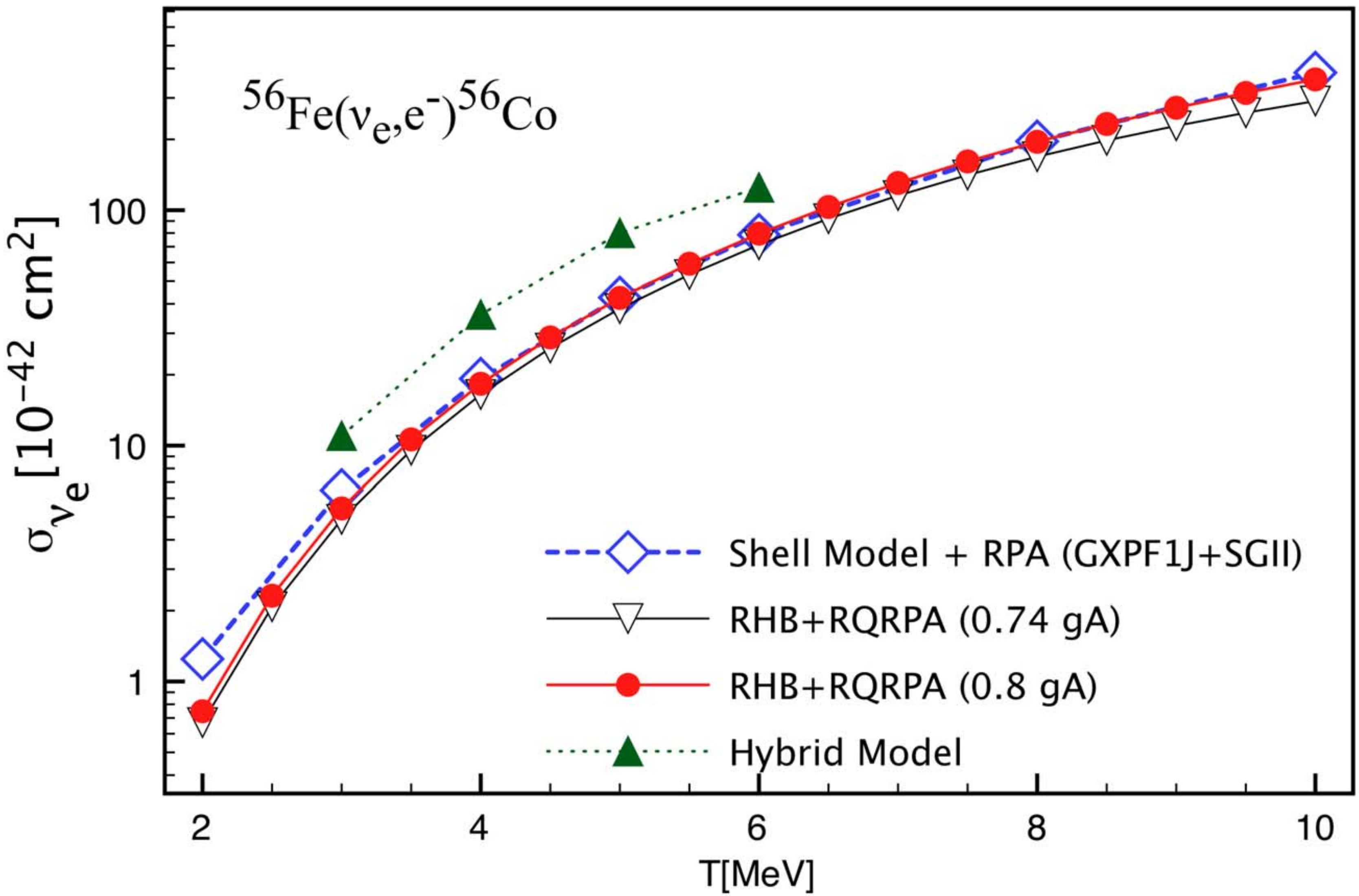
$$\langle \sigma_\nu \rangle = \frac{\int dE_\nu \sigma_\nu(E_\nu) f(E_\nu)}{\int dE'_\nu f(E'_\nu)}$$

| $^{56}Fe(\nu_e,e^-)\,^{56}Co$ | $<\sigma>(10^{-42}cm^2)$ |
|---|---|
| QRPA(SIII) (Lazauskas et al.) | 352 |
| Shell model (GXPF1J) + RPA (SGII) (T. Suzuki et al.) | 259 |
| RPA (Kolbe, Langanke) | 240 |
| QRPA (Cheoun et al.) | 173 |
| PN-RQRPA | 263 |
| EXP. (KARMEN) | 256±108±43 |



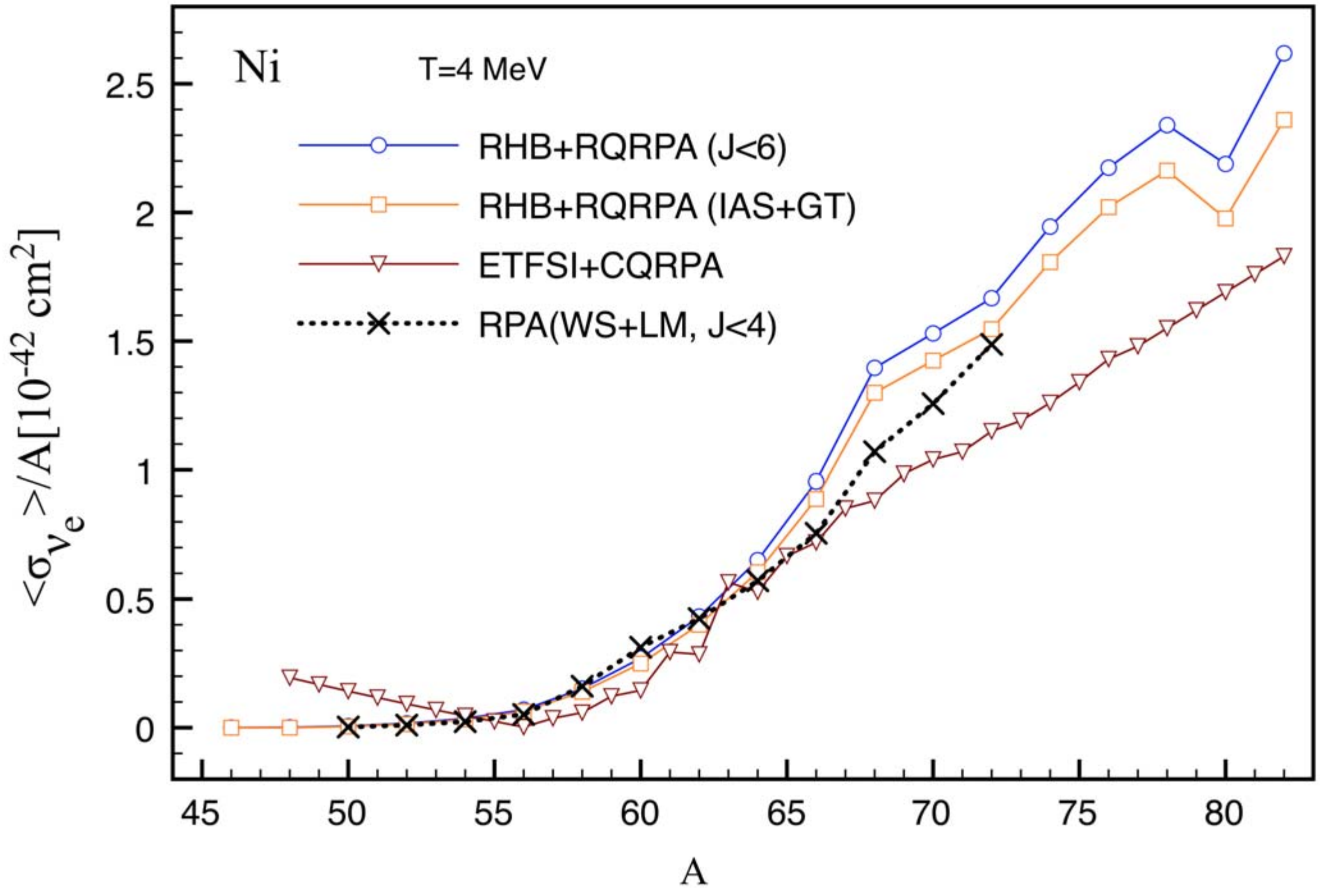

$$\langle \sigma \rangle_{th} = (258 \pm 57) \times 10^{-42} cm^2$$

# CROSS SECTIONS AVERAGED OVER SUPERNOVA NEUTRINO FLUX



# ISOTOPIC DEPENDENCE OF NEUTRINO-NUCLEUS CROSS SECTIONS

Cross sections averaged over supernova neutrino flux for Ni isotope chain. Various models and effective interactions result in deviations at low mass and neutron-rich isotopes.

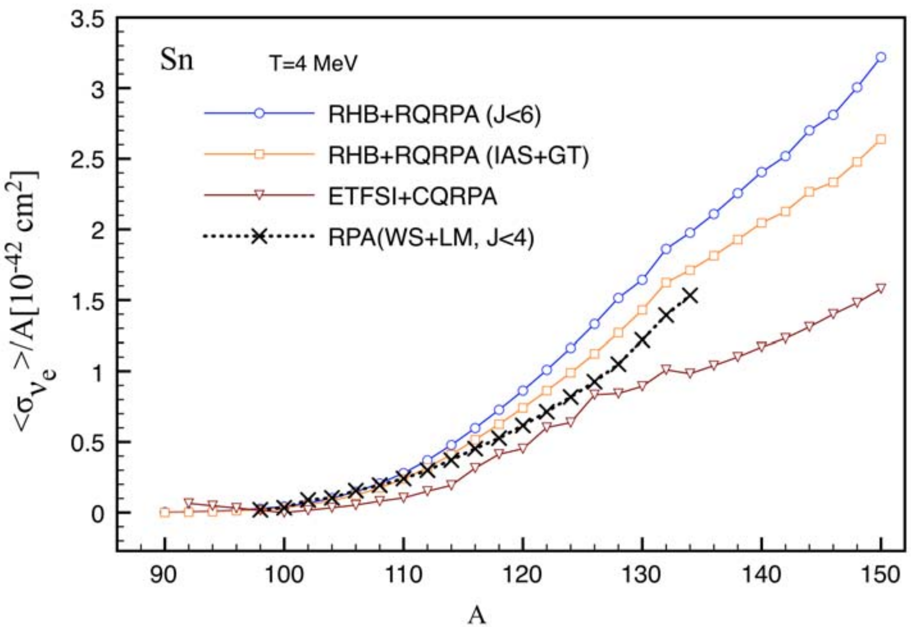



Major improvements of the new approach:

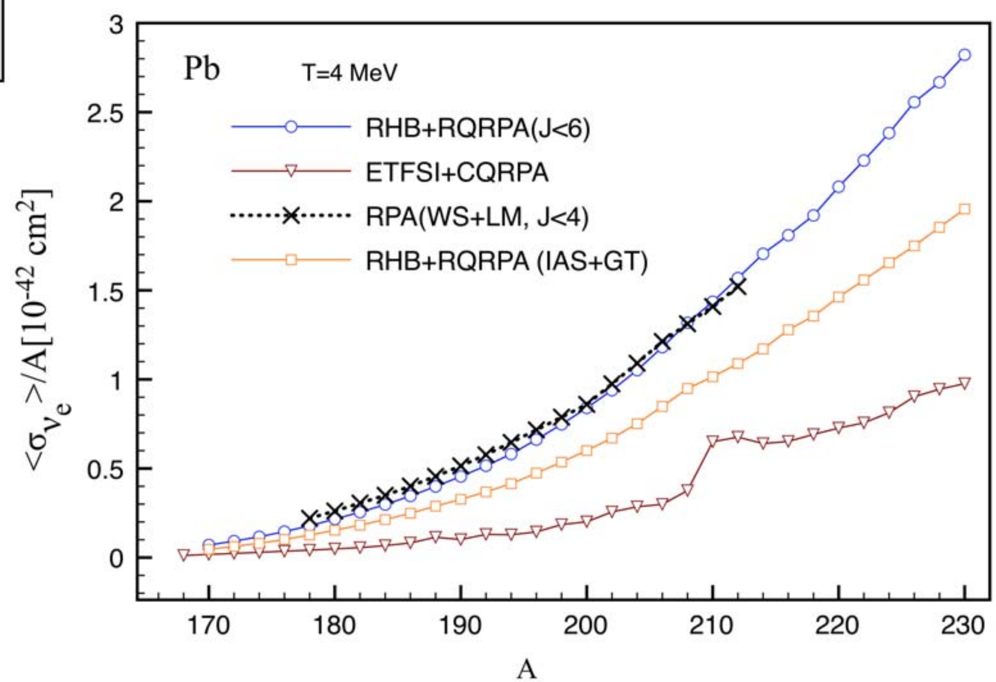
1)self-consistent parameter-free microscopic description of the cross sections (apart from the effective interactions that are fixed)

2) Systematic calculations including all transitions up to J=5

# ISOTOPIC DEPENDENCE OF NEUTRINO-NUCLEUS CROSS SECTIONS

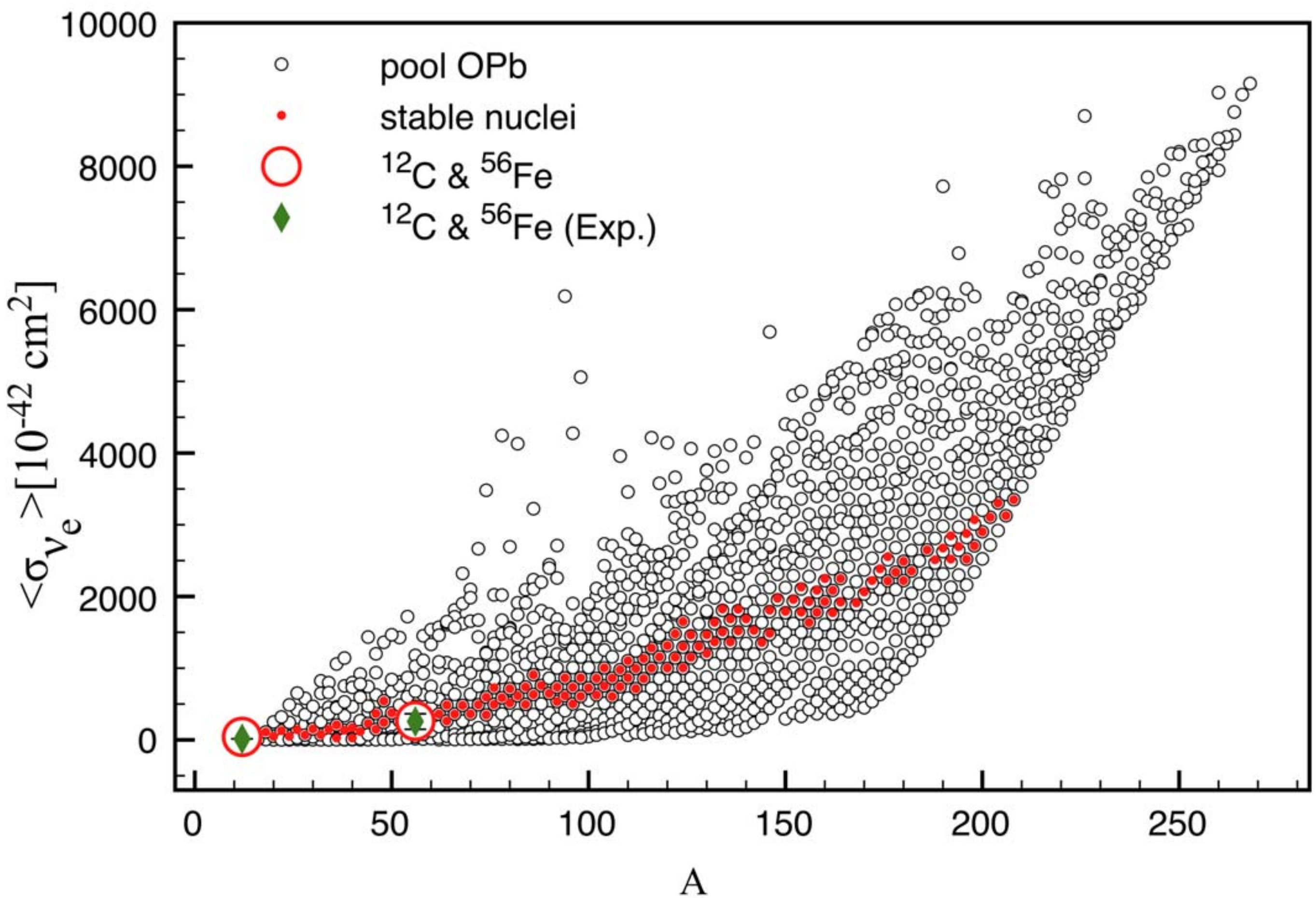



RHB+RQRPA – present results
ETFSI+CQRPA – Borzov, Goriely
RPA (Woods-Saxon + Landau-Migdal force) – Kolbe, Langanke



# LARGE-SCALE CALCULATIONS OF $\nu$-NUCLEUS CROSS SECTIONS

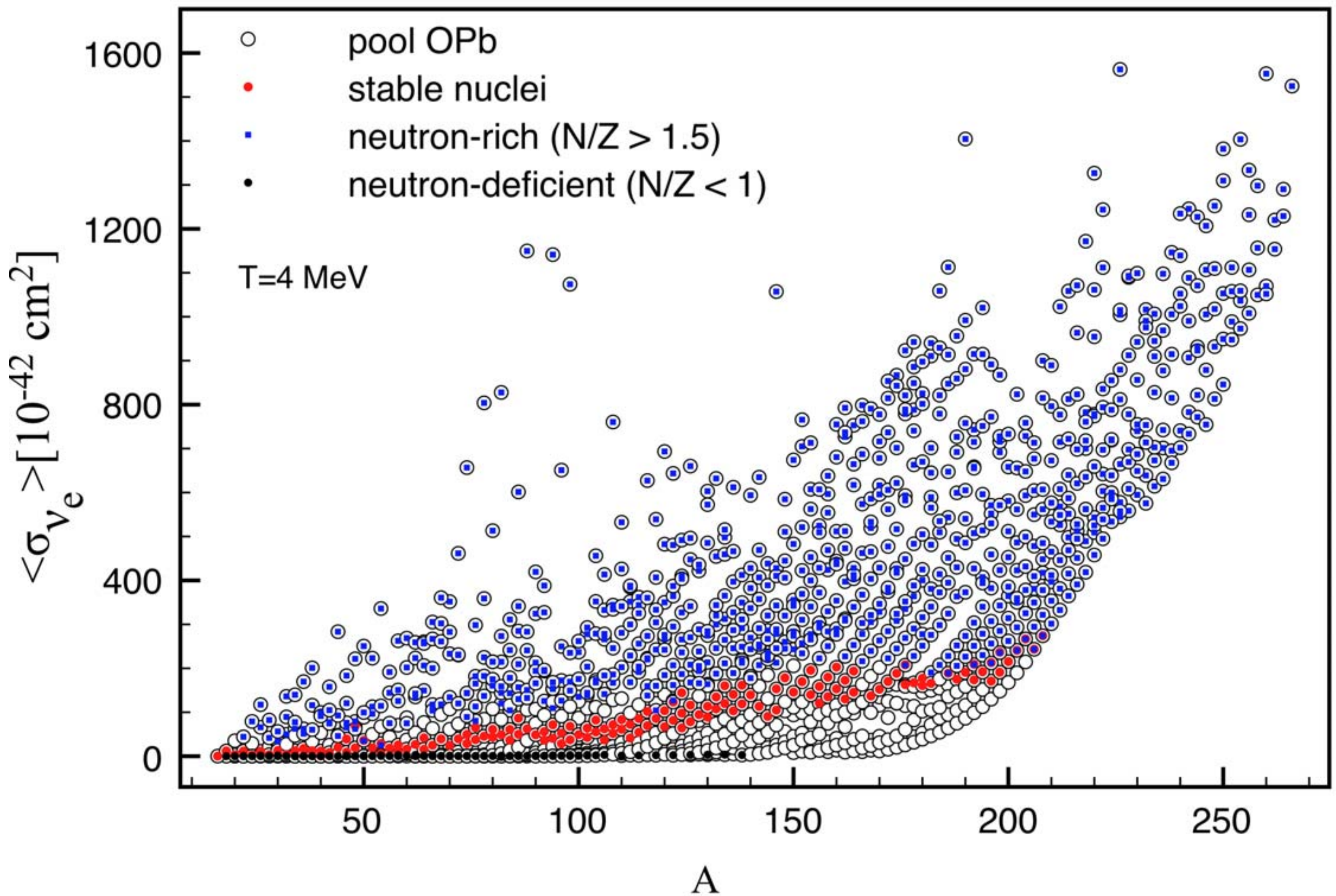
The cross sections are averaged over the neutrino spectrum from muon DAR.




Systematic calculations based on the RNEDF without any adjustments to nuclei under consideration. The model calculations reasonably reproduce the only two experimental cases, for $^{12}$C and $^{56}$Fe.

# LARGE-SCALE CALCULATIONS OF $\nu$-NUCLEUS CROSS SECTIONS

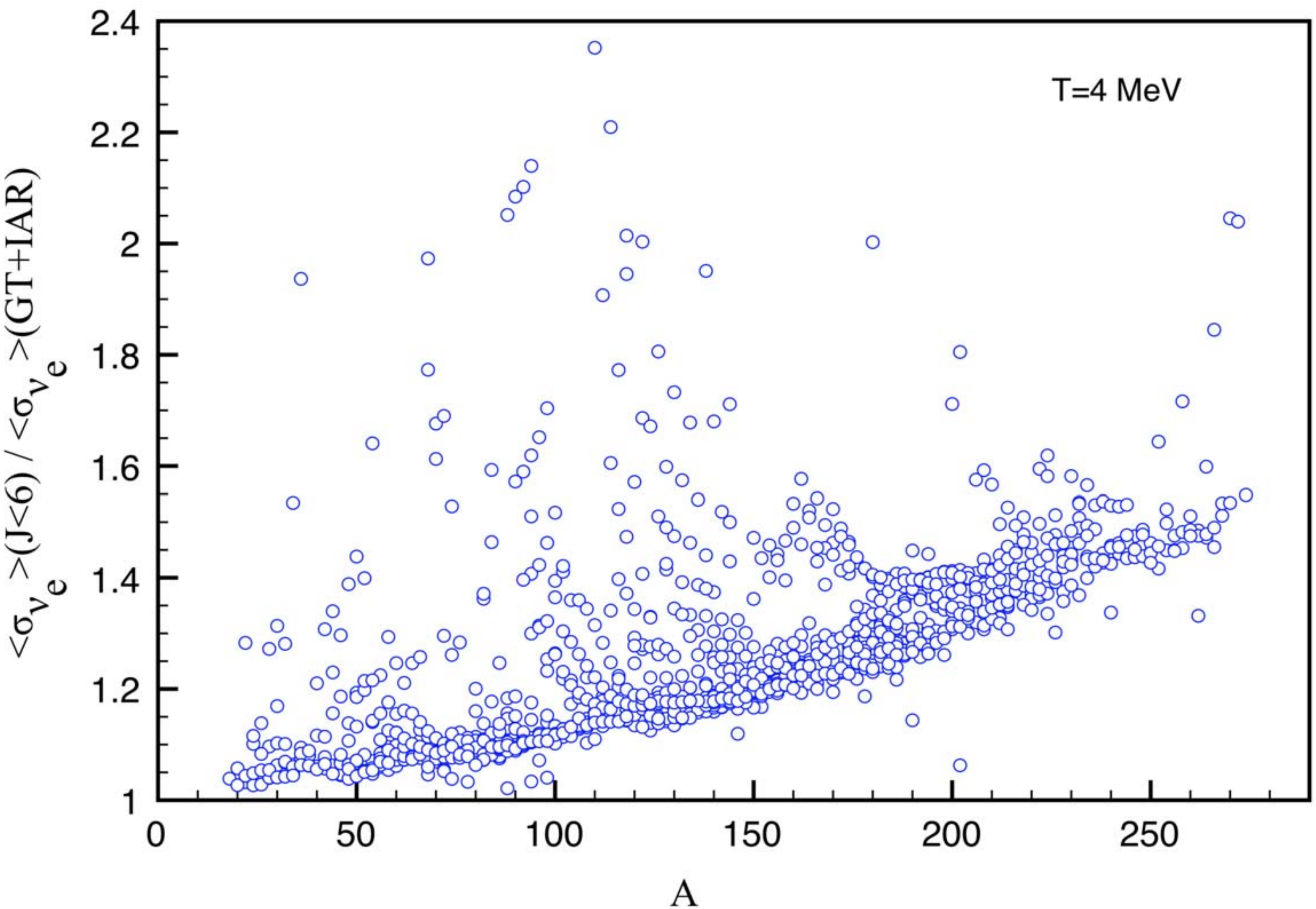
The cross sections are averaged over supernova neutrino spectrum.




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 $\nu$-NUCLEUS CROSS SECTIONS

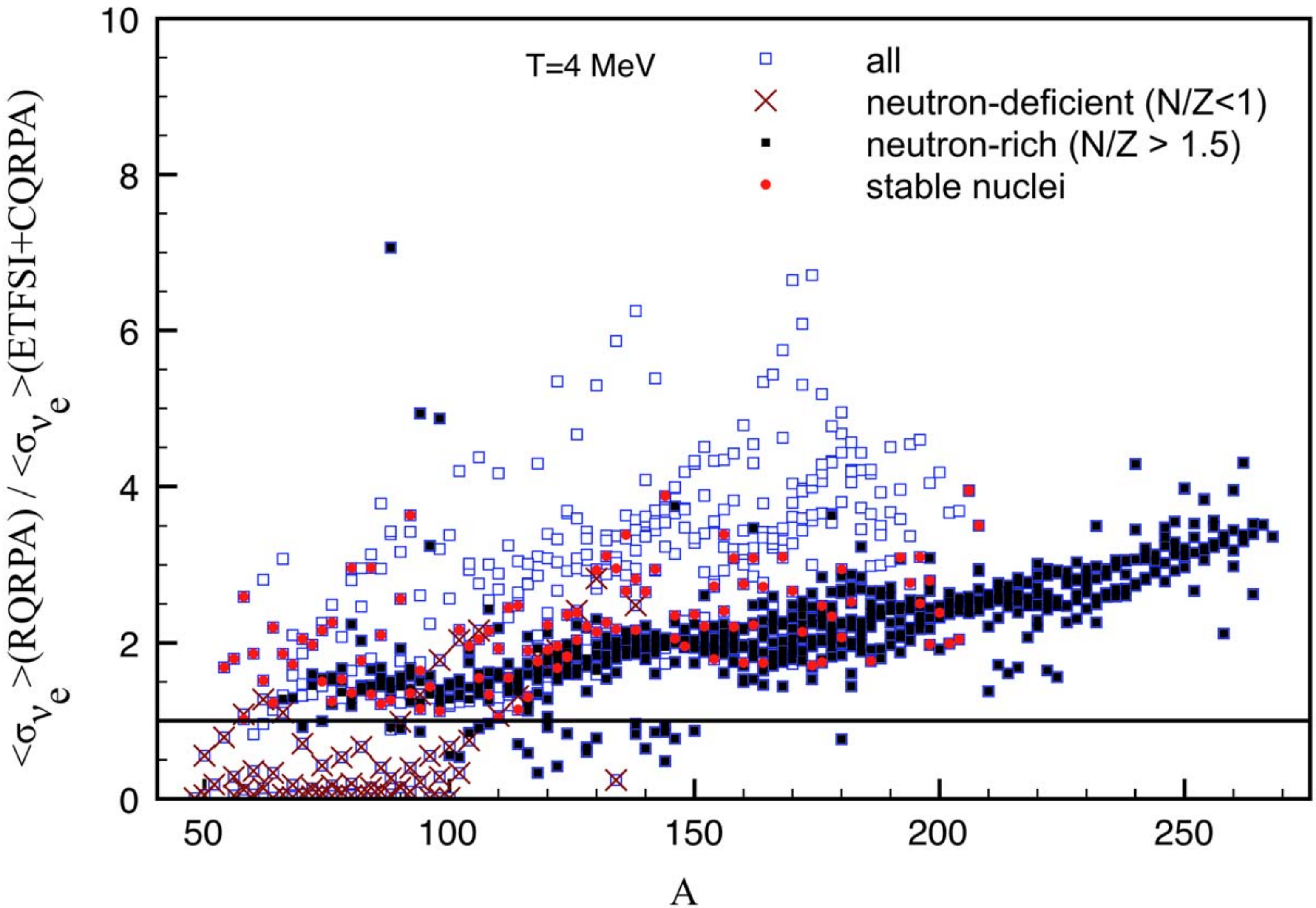
The role of forbidden transitions along the OPb pool of target nuclei




Ratio of the overall cross sections (up to J=5) vs. GT+IAR cross sections

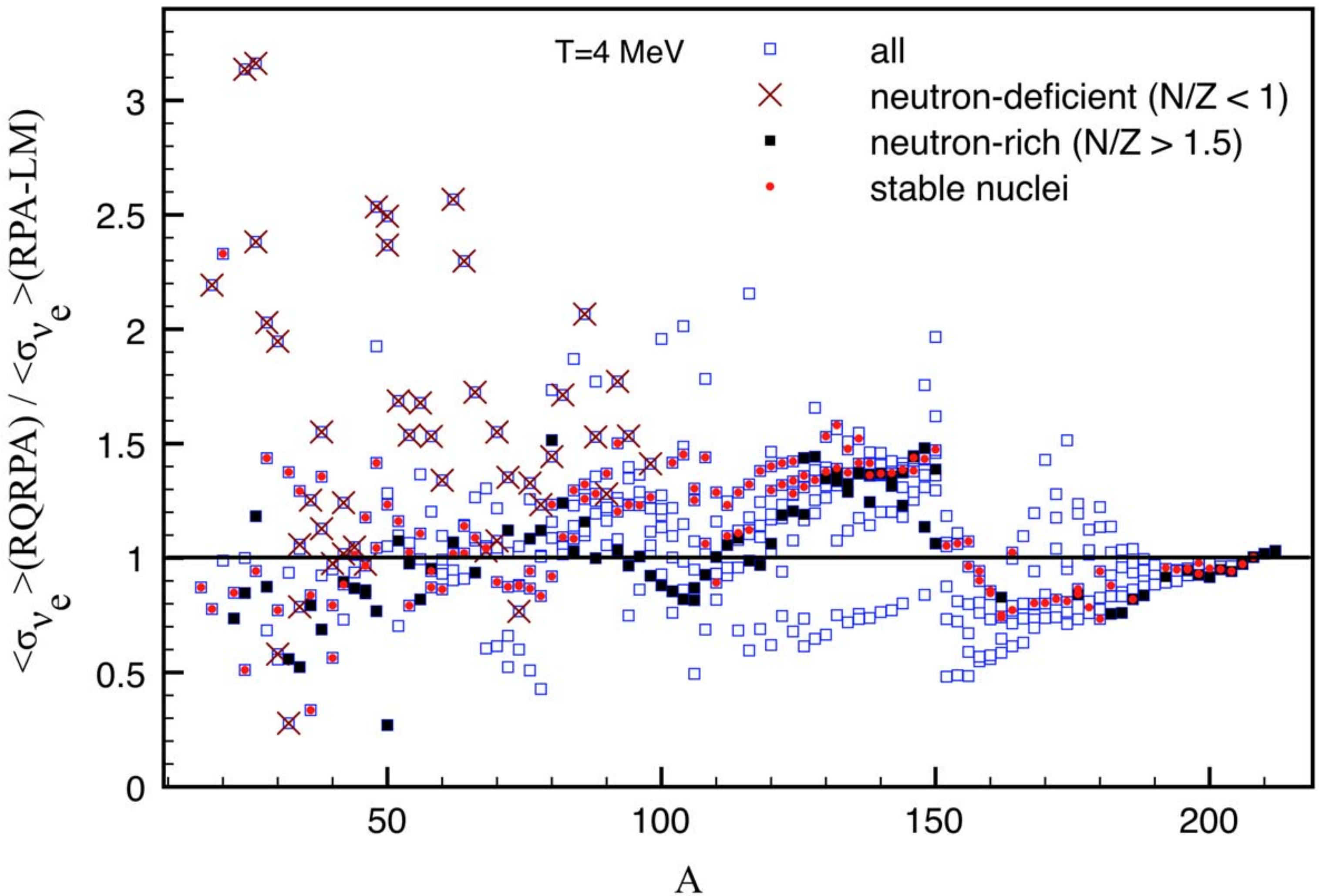
# LARGE-SCALE CALCULATIONS OF $\nu$ -NUCLEUS CROSS SECTIONS

How the RNEDF results compare to ETFSI+CQRPA (Borzov, Goriely) ?

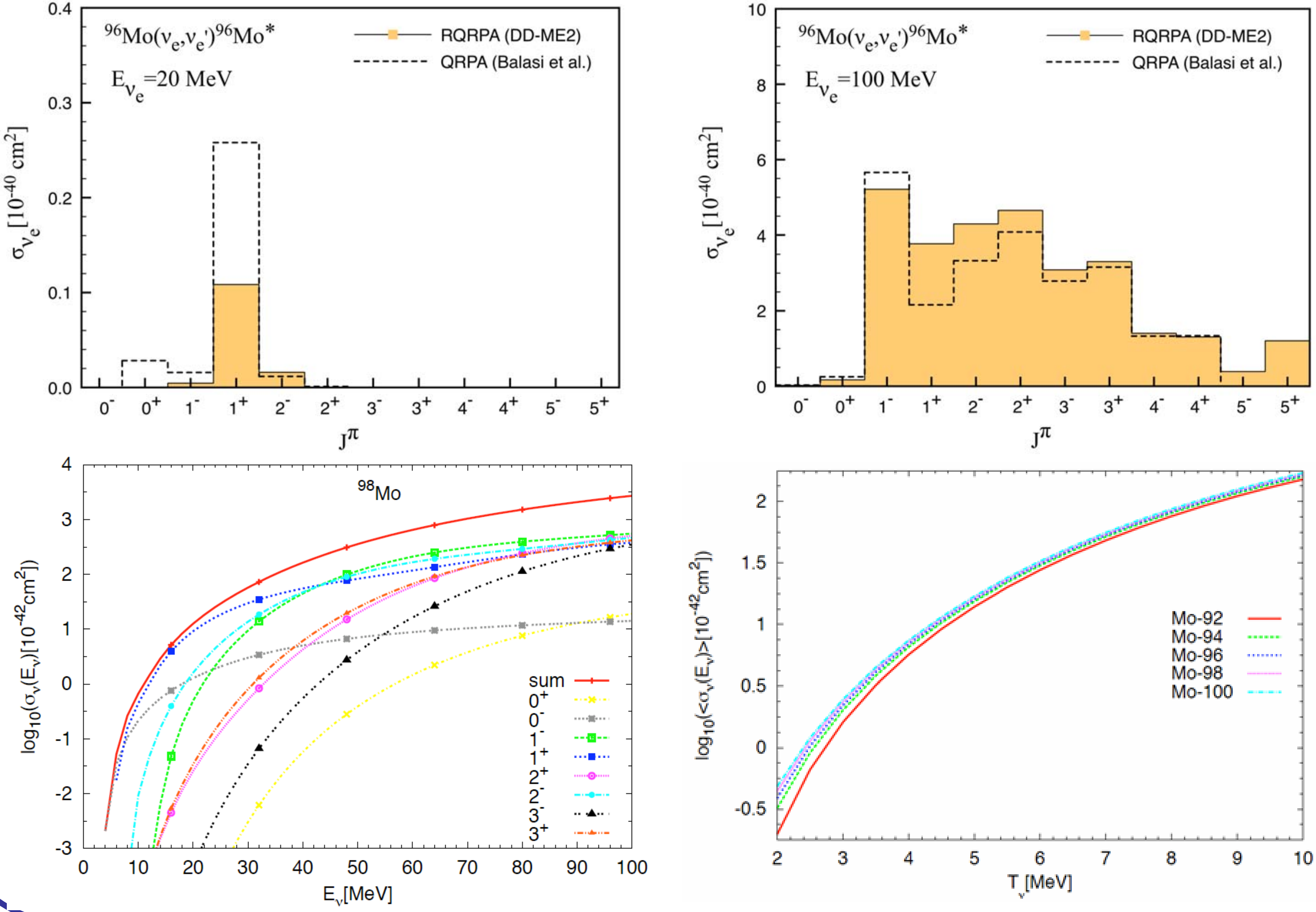


# LARGE-SCALE CALCULATIONS OF $\nu$-NUCLEUS CROSS SECTIONS

How the RNEDF results compare to RPA by Kolbe, Langanke et al. ?



# NEUTRAL-CURRENT NEUTRINO-NUCLEUS CROSS SECTIONS



# CONCLUDING REMARKS

We have established self-consistent framework to describe neutrino-nucleus cross sections, both for neutral-current and charged current reactions.

Implementation of the relativistic nuclear energy density functional, with parameters adjusted to global nuclear properties, allows parameter free modeling of the neutrino-nucleus cross sections.

Multipole composition of the cross sections from various models and effective interactions appear in agreement on several test cases. However, there are variations in the overall cross sections.

In the case of iron group nuclei, reasonable theoretical error estimate of neutrino-nucleus cross section is obtained.

The model can be extended to regions of nuclei away from the valley of stability, including those on the path of the r-process. Large scale calculations have been conduced for OPb pool of even nuclei.

Open questions: deformations, finite temperature, odd nuclei, etc…