Fine tuning QRPA calculations for ν_e-^{40}Ar cross section

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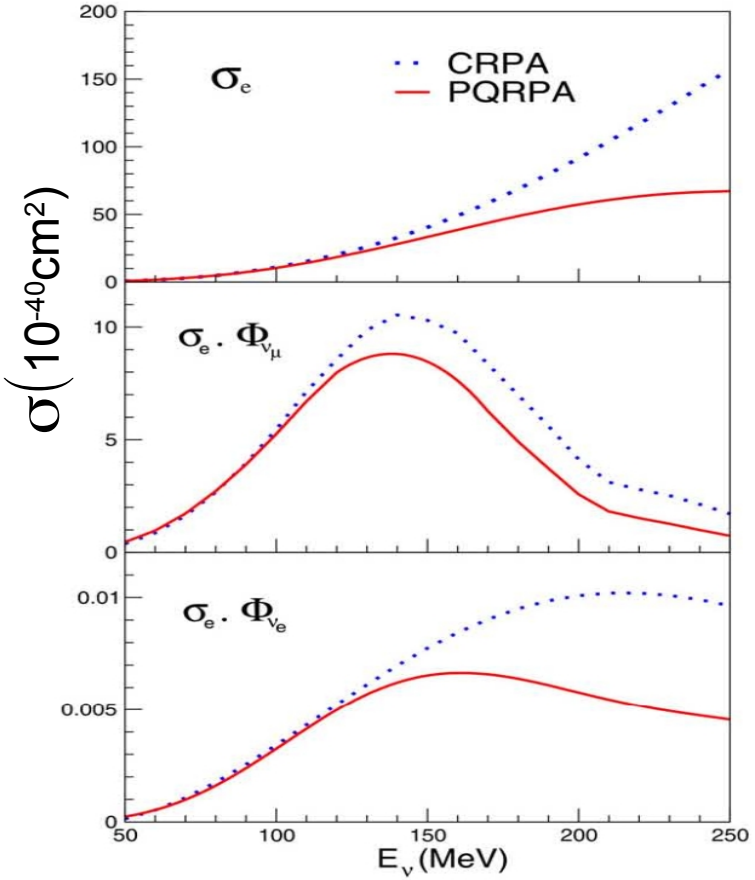
Outline

- Motivation
- On neutrino physics and nuclear structure.
- Detection of supernovae neutrinos
- Weak-Nuclear interaction formalism
- Nuclear Models

  QRPA and PQRPA
- Some numerical results

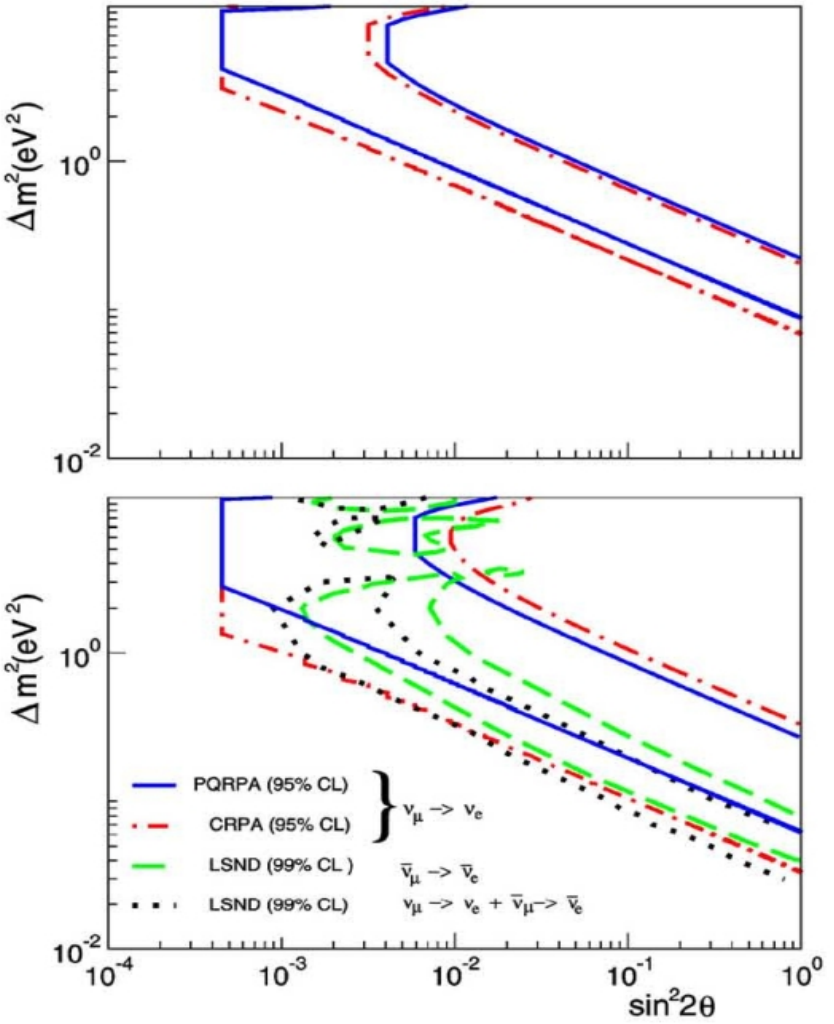
  $\nu_e / \bar{\nu}_e$ 40Ar cross section
- Summary

Motivation



ν-nucleus cross section are important to constrain parameters in neutrino oscillations.

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e \qquad \nu_\mu \rightarrow \nu_e$



* Increase probability oscillations.
* Confidence level region is diminished by difference in σ_e between PQRPA and CRPA, PLB (2005) 100

Supernovae Neutrinos – Signal Detection

Number of target nuclei

Neutrino flux

Interaction cross section

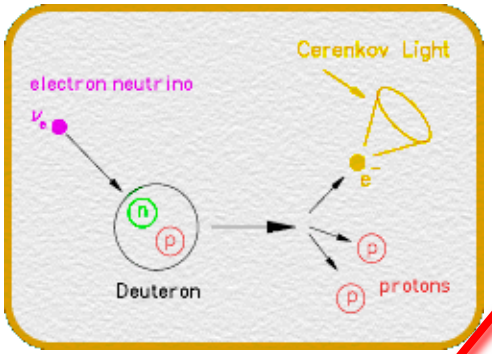
Efficiency

$$N_{ev} = N_t \int_0^{\infty} F(E_\nu) \cdot \sigma(E_\nu) \cdot \varepsilon(E_\nu) dE_\nu$$

SNO

$$\nu_e + d \rightarrow p + p + e^-$$

$$\bar{\nu}_e + p \rightarrow n + e^+$$



$$\sigma(E_\nu) \Leftrightarrow F(E_\nu)$$

LVD

Super-K

$$\nu_e + {}^{16}O \rightarrow {}^{16}F + e^-$$

$$\bar{\nu}_e + {}^{16}O \rightarrow {}^{16}N + e^+$$

$$\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-$$

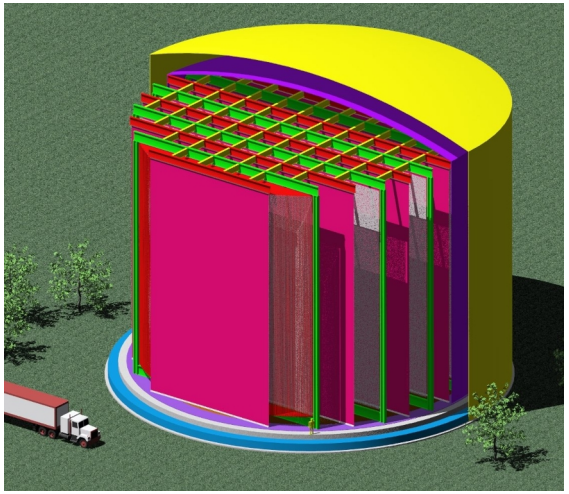
$$\bar{\nu}_e + {}^{12}C \rightarrow {}^{12}B + e^+$$

$$\nu_e + {}^{56}Fe \rightarrow {}^{56}Co + e^-$$

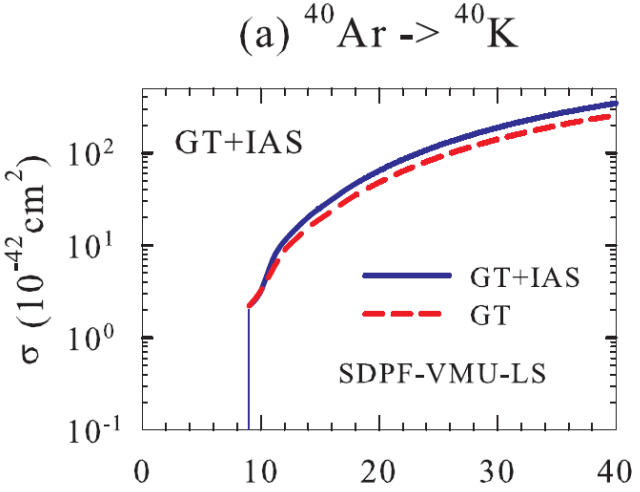
$$\bar{\nu}_e + {}^{56}Fe \rightarrow {}^{56}Mn + e^+$$

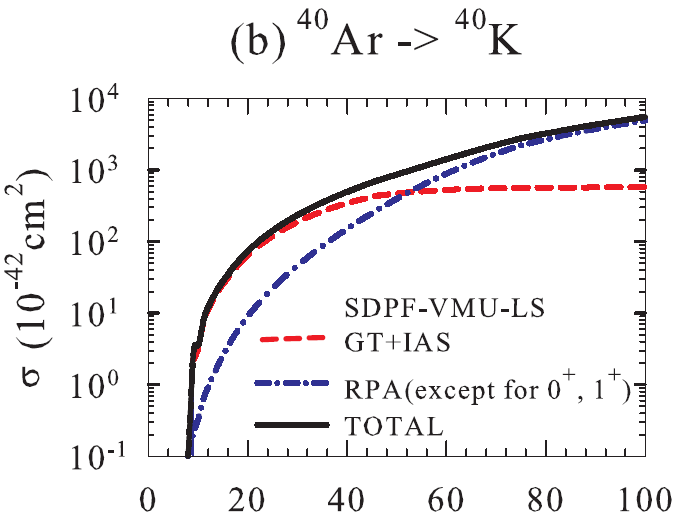
Supernovae Neutrinos – Signal Detection

LArTPC - Liquid Argon Time Projection Chambers: ν_e-^{40}Ar



http://www-lartpc.fnal.gov/

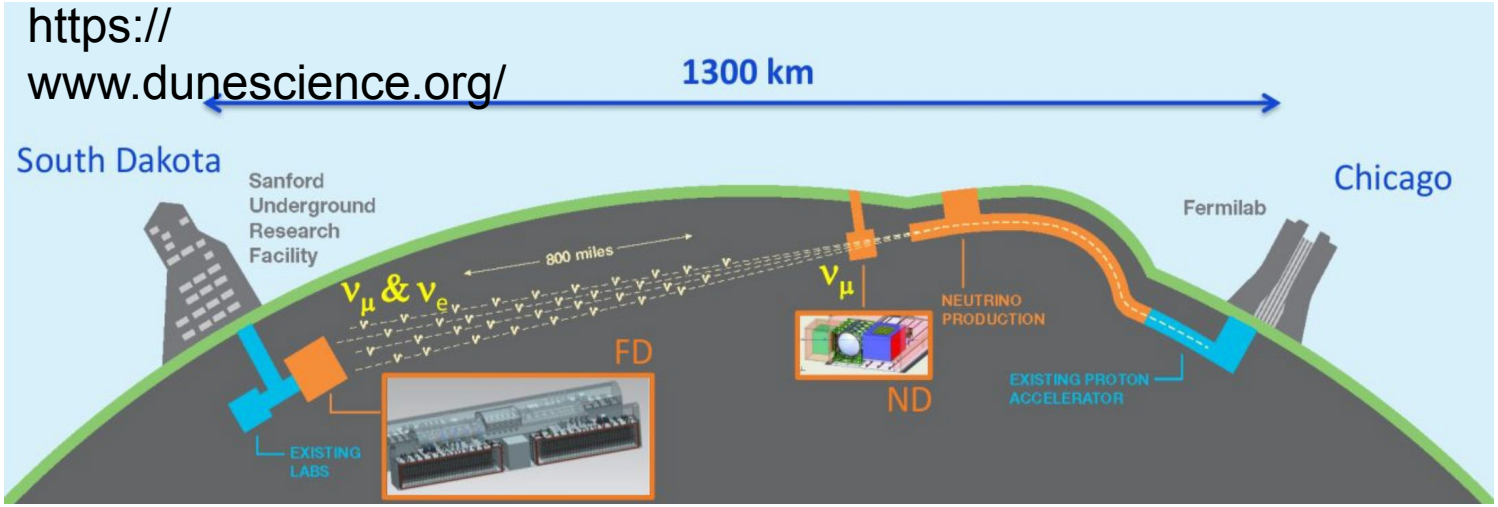




RPA: Ormand,Pizzochero, Bortignon, Broglia, PLB 345(343)1995
RPA: Martinez-Pinedo, Kolbe & Langanke K, priv. comm. Gil-Botella & Rubbia, JCAP10 (2003) 009
SM : T. Suzuki & M. Honma, arXiv:1211.4078v1 [nucl-th] 17 Nov 2012
QRPA : M. Cheoun etal , PRC **83,** 028801 (2011)

Supernovae Neutrinos – Signal Detection

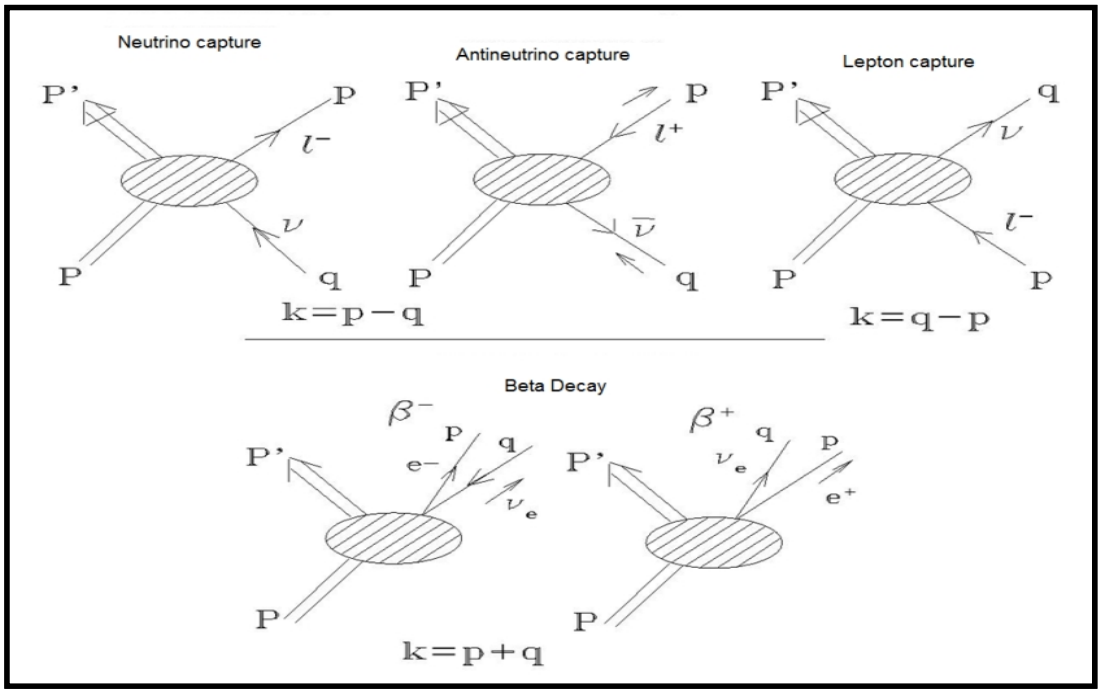
DUNE - Deep Underground Neutrino Experiment: ν_e - ^{40}Ar



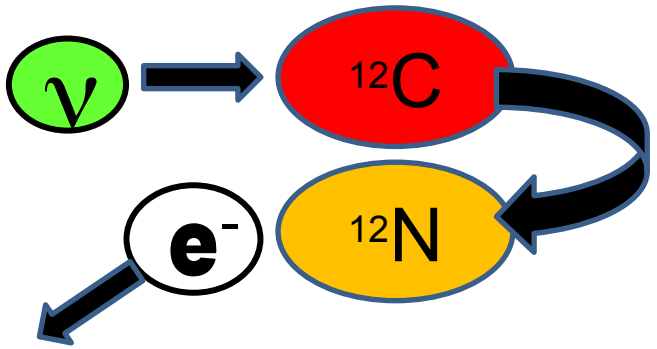
One of the primary physics goals for DUNE is to obtain a high-statistics measurement of core-collapse supernova.

B. Abi et al. (DUNE Collaboration), Eur. Phys. J. C 81, 423 (2021), 982

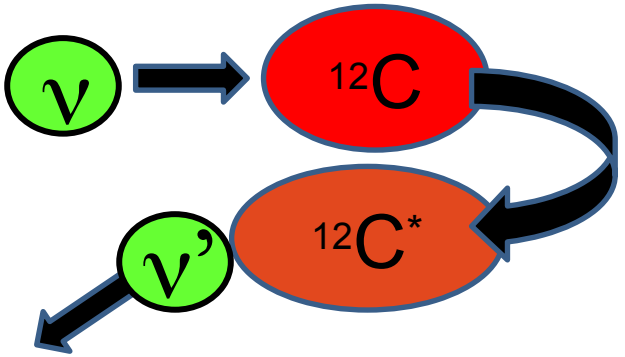
Weak–nuclear interaction



Charged Current



Neutral Current



$$\nu_e + A(Z,N) \Rightarrow A^*(Z+1,N-1) + e^-$$

$$\bar{\nu}_e + A(Z,N) \Rightarrow A^*(Z-1,N+1) + e^+$$

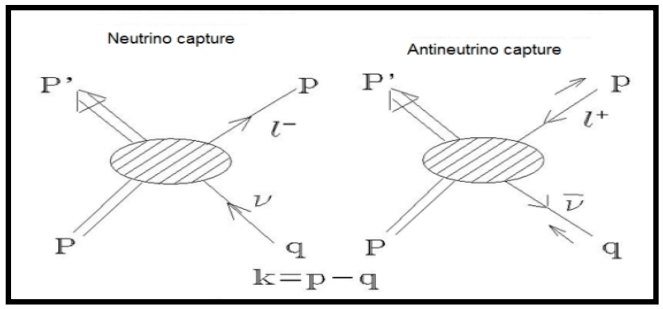
(i)O'Connell, Donelly & Walecka, PR6,719 (1972)
(ii) Kuramoto et al. NPA 512, 711 (1990)
(iii) Luyten et al. NP41,236 (1963)
(iv) Krmpotic et al. PRC71, 044319(2005).

ALL ARE EQUIVALENTS.

Weak–nuclear interaction

Reaction:

$$\nu_l + (Z, A) \rightarrow (Z+1, A) + l^-$$



Weak hamiltonian:

$$H_w(\mathbf{r}) = \frac{G}{\sqrt{2}} J_\alpha l^\alpha e^{-ik\cdot r},$$

$$J_\alpha = i\gamma_4 \left[g_V \gamma_\alpha - \frac{g_M}{2M}\sigma_{\alpha\beta}k_\beta + g_A\gamma_\alpha\gamma_5 + i\frac{g_P}{m_\ell}k_\alpha\gamma_5 \right]$$

$$l_\alpha = -i\bar{u}_{s_\ell}(\mathbf{p}, E_\ell)\gamma_\alpha(1+\gamma_5)u_{s_\nu}(\mathbf{q}, E_\nu)$$

Neutrino-nucleus cross section (Fermi's Golden Rule):

$$\sigma(E_\nu, J_n^\pi) = \frac{E_e|\mathbf{p_e}|}{2\pi} F(Z+S, E_e) \int_{-1}^{+1} d(cos\theta)\tau(\kappa, J_n^\pi),$$

p_l :Lepton momentum, E_l : Lepton energy, *F(Z+S,E):* Fermi function, S=1 or -1

Transition amplitude

$$\tau_\sigma(\kappa, \mathrm{J}) = \frac{G^2}{2J_i+1}\left[\sum_J \mathcal{L}_\emptyset |\langle \mathrm{J}||O_\emptyset(J)||J_i\rangle|^2 + \sum_{M=0\pm1} \mathcal{L}_M |\langle \mathrm{J}\|O_M(J)\|J_i\rangle|^2 \right.$$

$$\left. -2Re\left[\langle \mathrm{J}||O_\emptyset(J)||J_i\rangle^* \langle \mathrm{J}||O_0(J)||J_i\rangle\right]\mathcal{L}_{\emptyset 0} \right].$$

Neutrino/antineutrino cross sections ^{40}Ar

LArTPC - Liquid Argon Time Projection Chambers: ν_e-^{40}Ar

DUNE - Deep Underground Neutrino Experiment: ν_e - ^{40}Ar

- Some years ago G. McLaughlin talk me about to make a “gross averaged” of the CS for several nuclear models in ^{56}Fe. I disagree in that moment, nevertheless I change of idea due the difficult to obtain an error in the several theoretical nuclear models.
- In 40Ar, several work shown that:
  - Gamow -Teller Strengths of Beta decay : low energy – GT resonances & IAS;
  - Inclusive – exclusive muon capture rates: high energy - 100 MeV muon mass

RPA: Ormand,Pizzochero, Bortignon, Broglia, PLB 345(343)1995
RPA: Martinez-Pinedo, Kolbe & Langanke K, priv. comm. Gil-Botella & Rubbia, JCAP10 009 (2003)
SM : T. Suzuki & M. Honma, arXiv:1211.4078v1 [nucl-th] 17 Nov 2012
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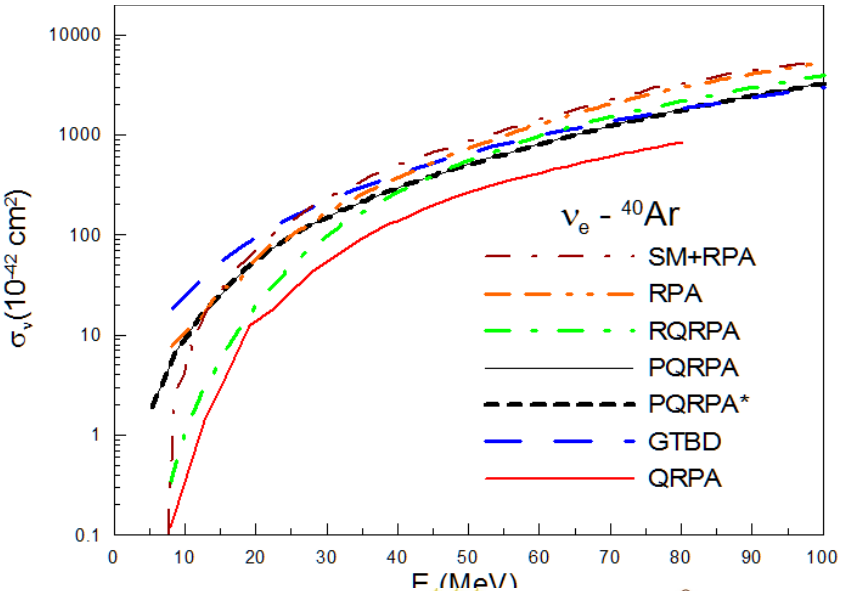
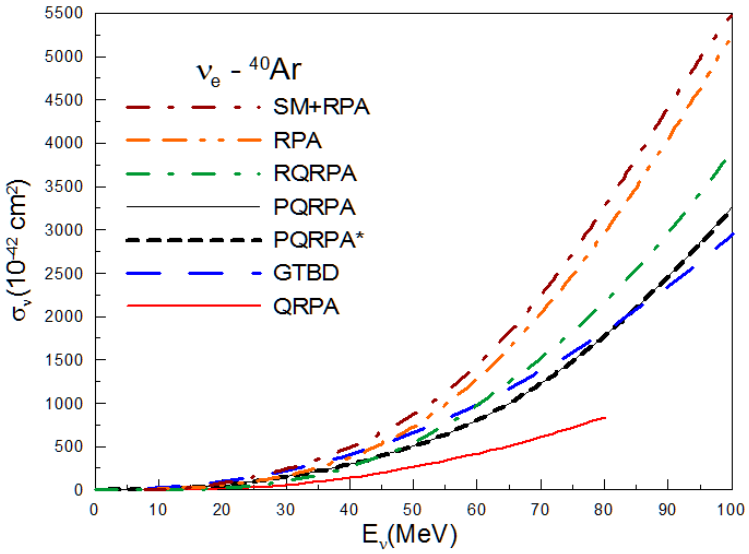
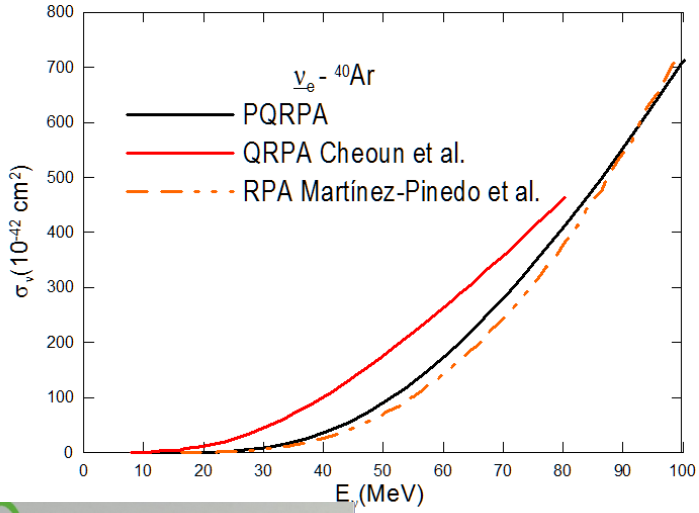
QRPA & PQRPA: Samana et al. (2016).

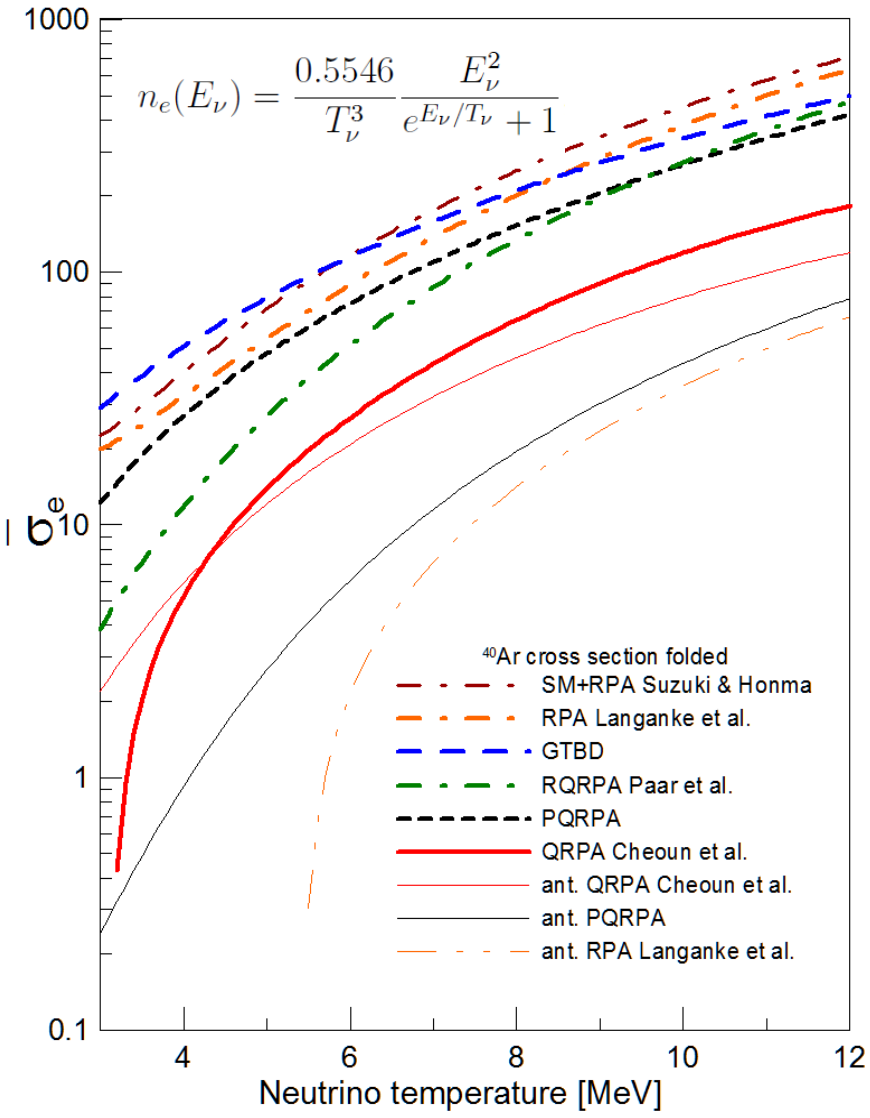


Neutrino/antineutrino cross sections ^{40}Ar

Folded cross section with SN fluxes







Fine tuning QRPA calculations for ν_e-^{40}Ar cross section – V Simpósio INCT– UFFl- RJ - Brazil- 2025

INCT-FNA INSTITUTO NACIONAL DE CIÊNCIA E TECNOLOGIA FÍSICA NUCLEAR E APLICAÇÕES

UESC Universidade Estadual de Santa Cruz

PROFÍSICA Mestrado Acadêmico em Física Universidade Estadual de Santa Cruz - UESC

Neutrino/antineutrino cross sections ^{40}Ar

PHYSICAL REVIEW D **107.** 112012 (2023)

Impact of cross-section uncertainties on supernova neutrino spectral parameter fitting in the Deep Underground Neutrino Experiment

- A key requirement for a correct interpretation of these measurements is a good understanding of the energy-dependent total cross section for charged-current neutrino electron absorption on argon.
- Using a toy model to neutrino spectra varying the cross section was found that large theoretical uncertainties on the cross section must be reduced before to extract the neutrino flux parameters.
- The neutrino spectral shape parameters can be known to better than 10% for a 20% uncertainty on the cross-section scale, although they will be sensitive to uncertainties on the shape of the CS,
- It is necessary to measure low- energy neutrino-Ar to improve theoretical precision,
- 12 cross section model were employed.

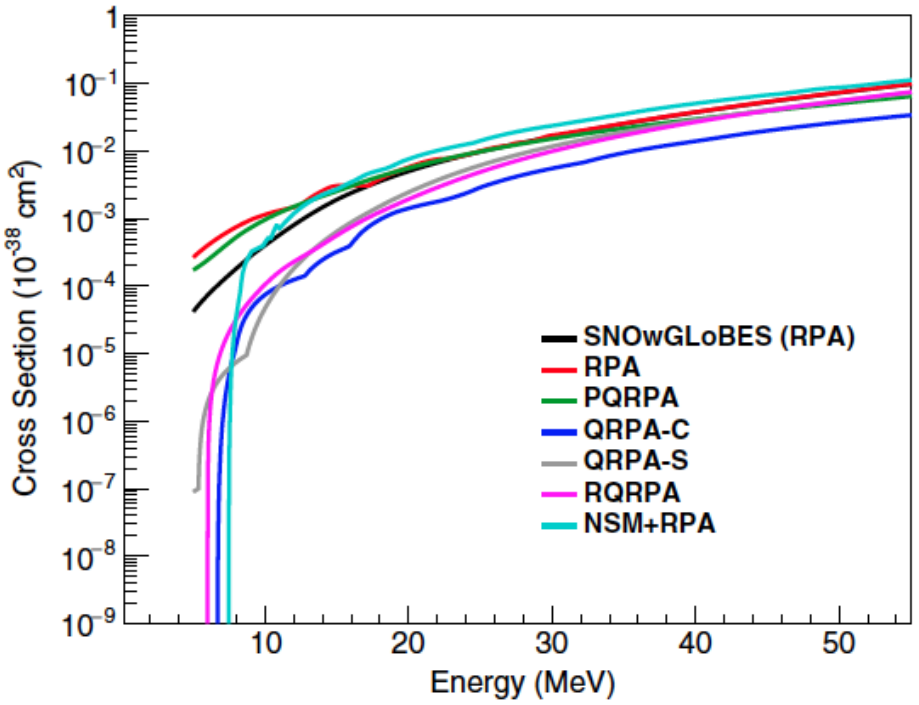


FIG. 6. Cross-section calculations for the $\nu_e - {}^{40}$Ar interaction from Refs. [29,38–44]. The labels are explained in Table I. Note the log scale on the y-axis.

Neutrino/antineutrino cross sections ^{40}Ar

(I) A ll of the microscopic models used here employ different residual interactions:
RPA - Skyrme interaction (including a spin-orbit term)
QRPA- Bonn CD potential
PQRPA- δ-interaction in PQRPA,
RQRPA- DDME2 relativistic nuclear energy density functional
SM - monopole based- universal interaction (VMU) in NSM + RPA.
The choice of was motivated by a successful description of: Gamow-Teller (GT) strengths, β-decay rates, muon capture rates.

$$\begin{pmatrix} \mathcal{A} & \mathcal{B} \\ \mathcal{B} & \mathcal{A} \end{pmatrix} \begin{pmatrix} X \\ Y \end{pmatrix} = \omega \begin{pmatrix} X \\ -Y \end{pmatrix}, \tag{3.24}$$

where

$$\begin{aligned} \mathcal{A}(pnp'n';J) &= (E_p + E_n)\delta_{pp'}\delta_{nn'} \\ &\quad + (u_p v_n u_{p'} v_{n'} + v_p u_n v_{p'} u_{n'}) F(pnp'n';J) \\ &\quad + (u_p u_n u_{p'} u_{n'} + v_p v_n v_{p'} v_{n'}) G(pnp'n';J), \\ \mathcal{B}(pnp'n';J) &= (v_p u_n u_{p'} v_{n'} + u_p v_n v_{p'} u_{n'}) F(pnp'n';J) \\ &\quad + (u_p u_n v_{p'} v_{n'} + v_p v_n u_{p'} u_{n'}) G(pnp'n';J). \end{aligned} \tag{3.25}$$

$$\begin{aligned} &\langle J_f, Z+\mu, N-\mu || \mathrm{O}_J || 0^+ \rangle \\ &= \sum_{pn} \left[\Lambda_\mu(pnJ) X^*(pnJ_f) + \Lambda_{-\mu}(pnJ) Y^*(pnJ_f) \right], \end{aligned}$$

$$\Lambda_\mu(pnJ) = -\frac{\langle p||\mathrm{O}_J||n\rangle}{\sqrt{2J+1}} \begin{cases} u_p v_n, & \text{for } \mu = +1, \\ u_n v_p, & \text{for } \mu = -1, \end{cases}$$

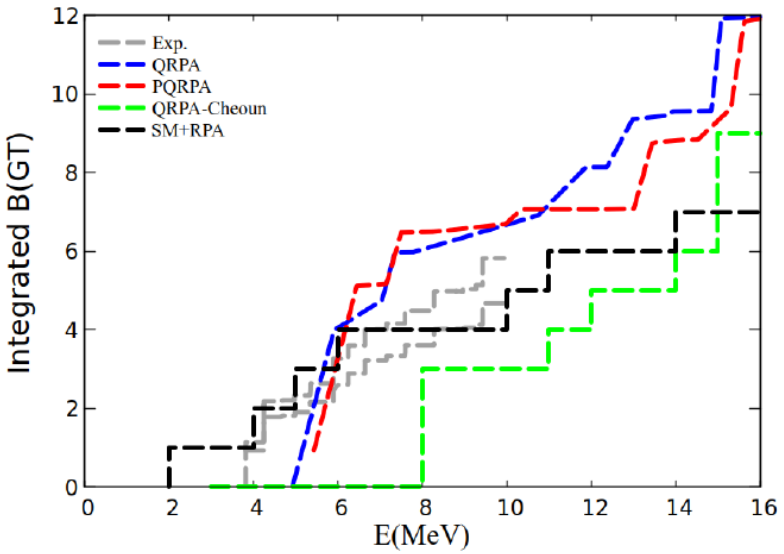


Fig. 5: Comparison of cumulative sum of the Gamow-Teller Strength B(GT) for QRPA (blue) and PQRPA (red), with experimental data (gray) [38], QRPA using Bonn-potential (green) [6] and Shell model+RPA (black) [2].

Samana et al,
CPC 181 (2010) 1123

$$\frac{|g_A \langle J_f||\sigma||J_i\rangle|^2}{2J_i+1} \equiv B(\mathrm{GT}) = \frac{6146}{ft}\ \mathrm{s}.$$

Neutrino/antineutrino cross sections ^{40}Ar

(II) Second, using a sufficiently large configuration space of nucleon states is important to prevent underestimation of the energy-dependent total cross section $\sigma(E_\nu)$ as the neutrino energy rises.

$$\sigma(E_\nu) = \sigma(E_\nu, 0^+) + \sigma(E_\nu, 1^+) + \sigma(E_\nu, 0^-) + \sigma(E_\nu, 1^-) + \sum_{J^\pi \geq 2^\pm}^{8^\pm} \sigma(E_\nu, J^\pi)\,.$$

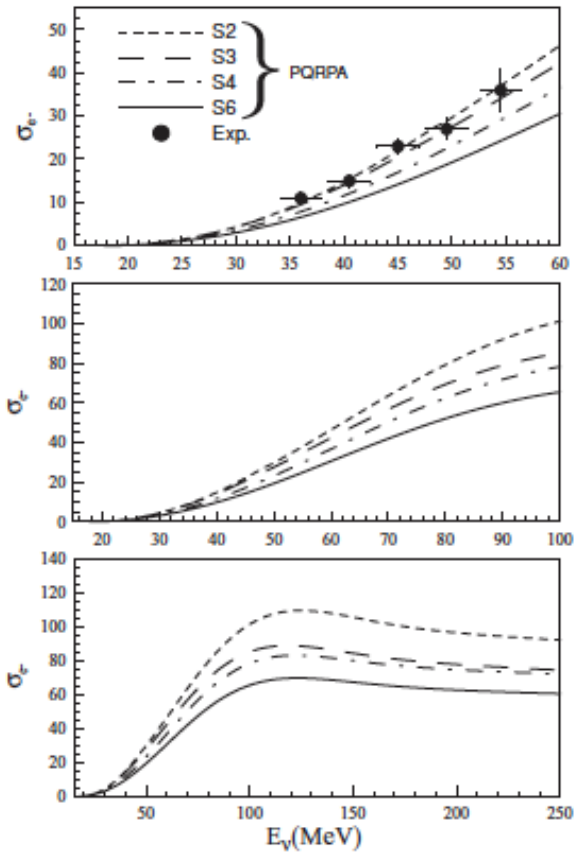
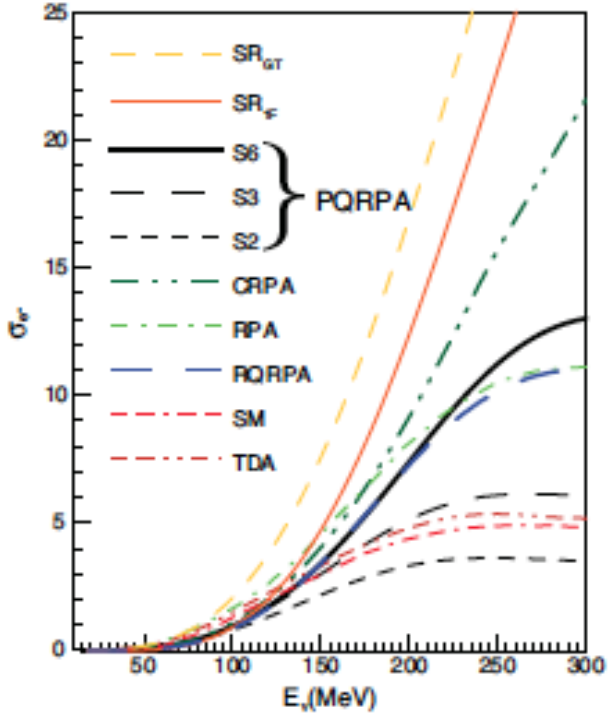


FIG. 2. Exclusive ^{12}C(ν, e^-)^{12}N cross section $\sigma_e(E_\nu, 1^+_1)$ (in units of 10^{-42} cm^2), plotted as a function of the incident neutrino energy



Samana, Krmpotic, Paar, Bertula
PRC 83, 024303 (2011)

FIG. 6. (Color online) Inclusive ^{12}C(ν, e^-)^{12}N cross section $\sigma_{e^-}(E_\nu)$ (in units of 10^{-39} cm^2) plotted as a function of the incident neutrino energy E_ν. PQRPA

Neutrino/antineutrino cross sections ^{40}Ar

(II) Second, using a sufficiently large configuration space of nucleon states is important to prevent underestimation of the energy-dependent total cross section $\sigma(E_\nu)$ as the neutrino energy rises.

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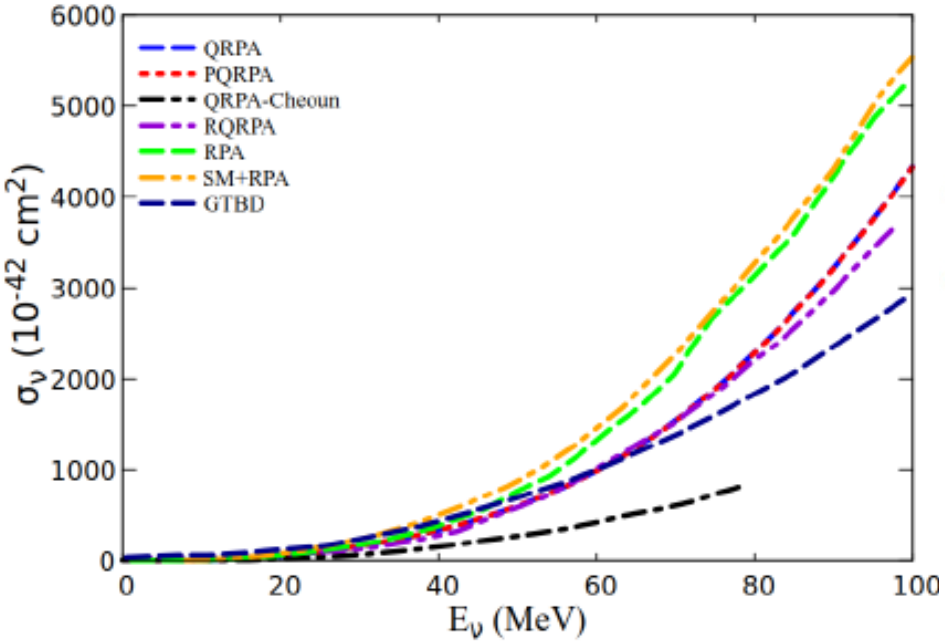
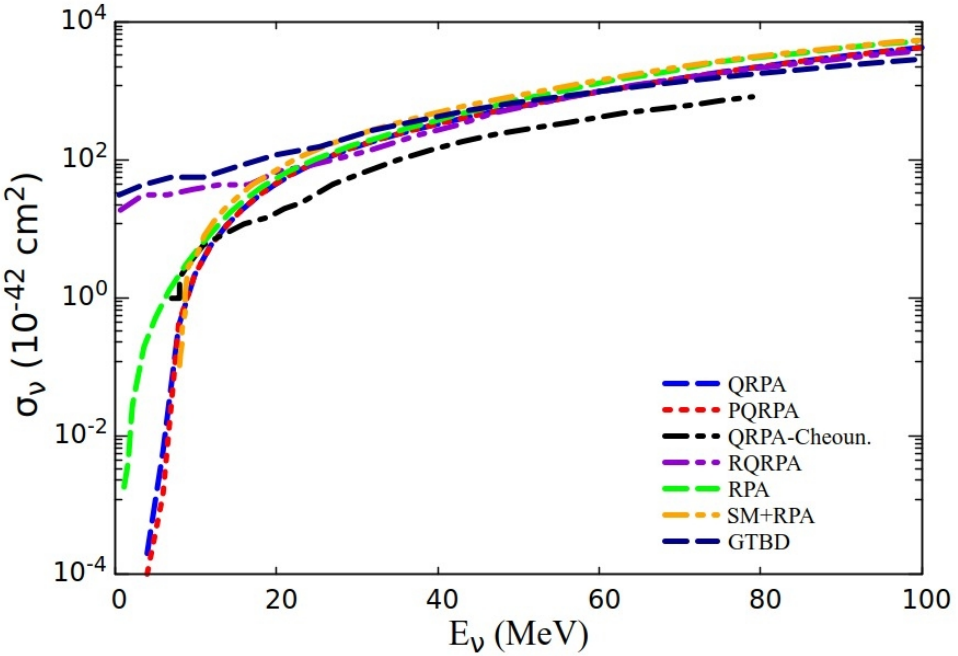




PQRPA and QRPA, RPA [Gil-Botella & Rubia, 2003], SM+RPA[Suzuki & Honma, 2013], GTBD [Samana et al, 2022], RQRPA [Paar et al., 20] and QRPA with Bonn potencial [Cheon et. al, 2011].

Neutrino/antineutrino cross sections ^{40}Ar

(III) some calculations use an effective (or quenched) value of the nucleon axial-vector coupling constant for which its bare value g_A=1.2756 from the experimental data is multiplied by a factor of around 0.8. There is still a lack of consensus in the nuclear physics community about whether this quenching is needed: $fq=g_{A,eff}/g_A$

PQRPA and QRPA ……..$g_{A,eff}$=1.0 fq=0.784

RPA [Gil-Botella & Rubia, 2003] ……$g_{A,eff}$=1.27 fq=1.0

RPA [Kolbe, 2003]…… ……$g_{A,eff}$=1.27 fq=1.0

SM+RPA[Suzuki & Honma, 2013]……..$g_{A,eff}$=0.98 fq=0.775

GTBD [Samana et al, 2022] ……$g_{A,eff}$=1.0 fq=0.784

RQRPA [Paar et al., 20] ……..$g_{A,eff}$=1.0 fq=0.784

QRPA with Bonn potencial [Cheon et. al, 2011]…….$g_{A,eff}$=0.94 fq=0.74

Most of these model adopt $g_{A,eff}$ to reproduce GT strength or cumulative sum of the GT strength.

Neutrino/antineutrino cross sections ^{40}Ar

PRD107, 112012 (2023)

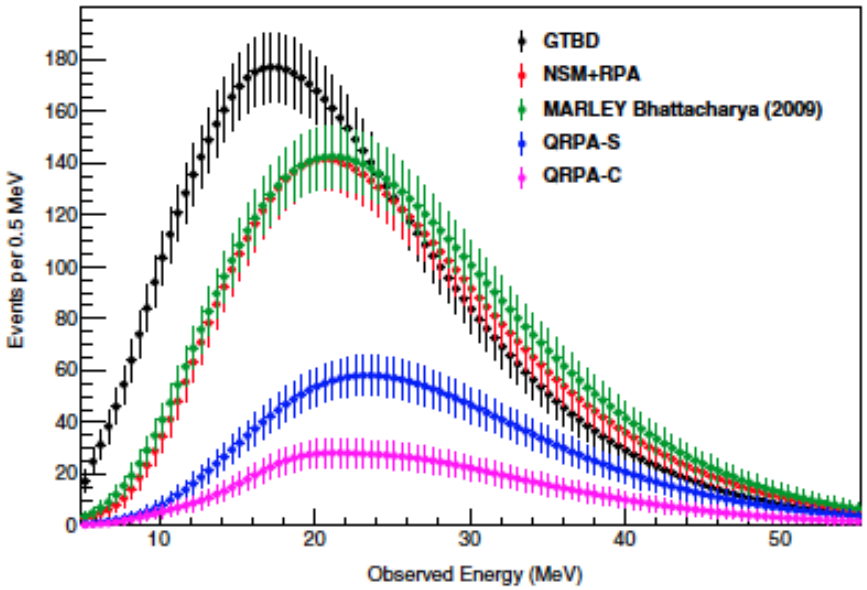


FIG. 8. SNOWGLOBES event rates for select cross-section calculations from Refs. [31,41,43–46]. The initial fluence parameter values for ν_e are $(\alpha^0, \langle E_\nu \rangle^0, \varepsilon^0) = (2.5, 9.5\ \text{MeV}, 5 \times 10^{52}\ \text{ergs})$, for $\bar{\nu}_e$ are $(\alpha^0, \langle E_\nu \rangle^0, \varepsilon^0) = (2.5, 12.0\ \text{MeV}, 5 \times 10^{52}\ \text{ergs})$, and for ν_x are $(\alpha^0, \langle E_\nu \rangle^0, \varepsilon^0) = (2.5, 15.6\ \text{MeV}, 5 \times 10^{52}\ \text{ergs})$. Normal mass ordering and MSW resonance were assumed. Note that "QRPA-C" and "QRPA-S" contain the same type of calculation performed by different groups, with the former by Cheoun *et al.* [43] and the latter by Samana and dos Santos [44]. More details about the various models are provided in Table I. The error bars are statistical.

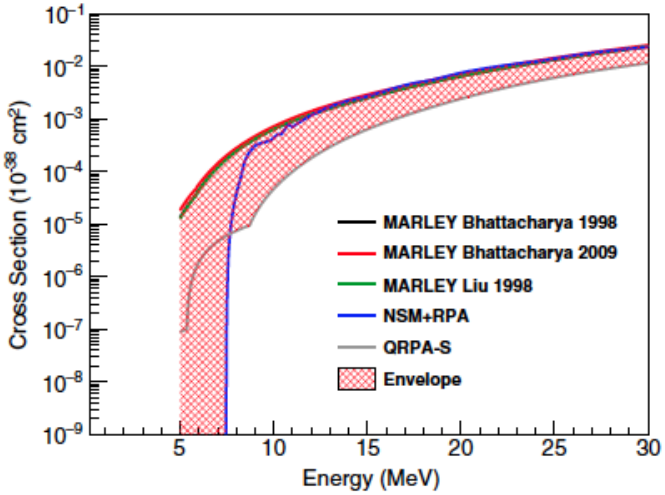


FIG. 15. Total cross section predictions for the $\nu_e - {}^{40}$Ar interaction from the selected subset of models discussed in Sec. III D. The shaded region represents the adopted uncertainty envelope based on the spread of these models.

TABLE IV. SNOWGLOBES estimated number of ν_eCC events in the DUNE far detectors for pinched-thermal flux parameters $(\alpha, \langle E_\nu \rangle, \varepsilon) = (2.5, 9.5, 5 \times 10^{52})$ for the ν_e flavor, a 10 kpc supernova, and assuming NMO and MSW oscillations via Eq. (5).

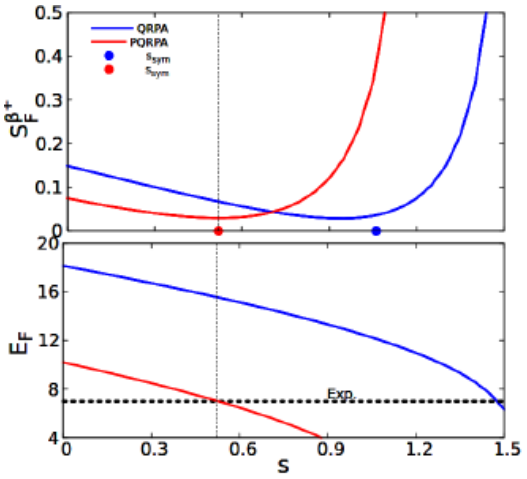
Cross-section model	Number of ν_eCC events	Number of ν_eCC events between [5, 15] MeV
QRPA-C [43]	1383	134
RQRPA [40]	2243	220
QRPA-S [44]	2791	243
SNOWGLOBES [29]	4486	624
B 1998 [32]	6307	874
L 1998 [32]	6390	883
NSM + RPA [41]	6391	897
B 2009 [32]	6852	988
PQRPA [42]	4562	909
RPA [38,39]	5064	998
GTBD [45,46]		

Neutrino/antineutrino cross sections ^{40}Ar

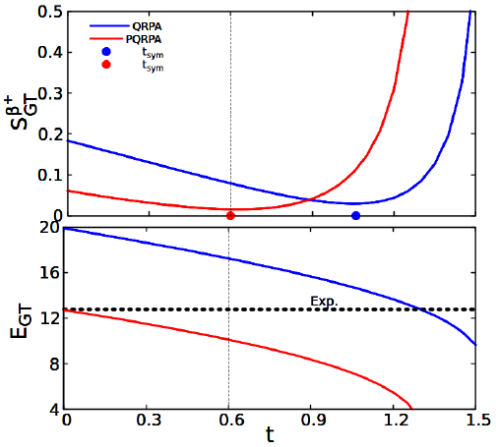
QRPA/PQRPA in ^{40}Ar – Weak observables constrains

- Gamow -Teller Strengths of Beta decay : low energy – GT resonances & IAS
- Inclusive – exclusive muon capture rates: high energy - 100 MeV muon mass

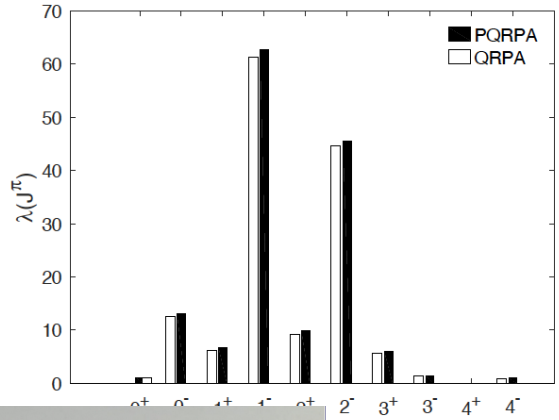
Fermi strength and energy to fix ‘s’ isovector pp.



GT strength and energy to fix ‘t’ isovector pp.



Muon capture rate distribution.



Experimental
Muon caoture rate

120 x 10^3 /s

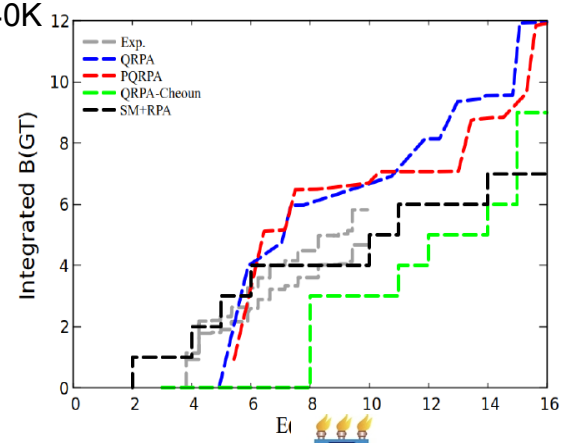
PQRPA

147.3 x 10^3 /s

QRPA

142.7 x 10^3 /s

Cumulative sum of the GT strength for 40Ar → 40K



Fine tuning QRPA calculations for ν_e-^{40}Ar cross section – V Simpósio INCT– UFFl- RJ - Brazil- 2025

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Neutrino/antineutrino cross sections ^{40}Ar

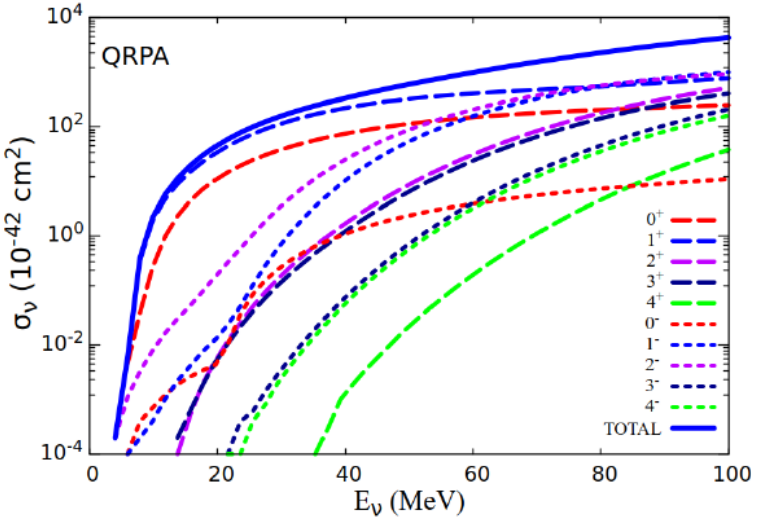


Fig. 10: Partial cross section for the reaction (ν_e,^{40}Ar) for the main multipole states contribution $J^\pi = 0^\pm - 4^\pm$, obtained using QRPA model.

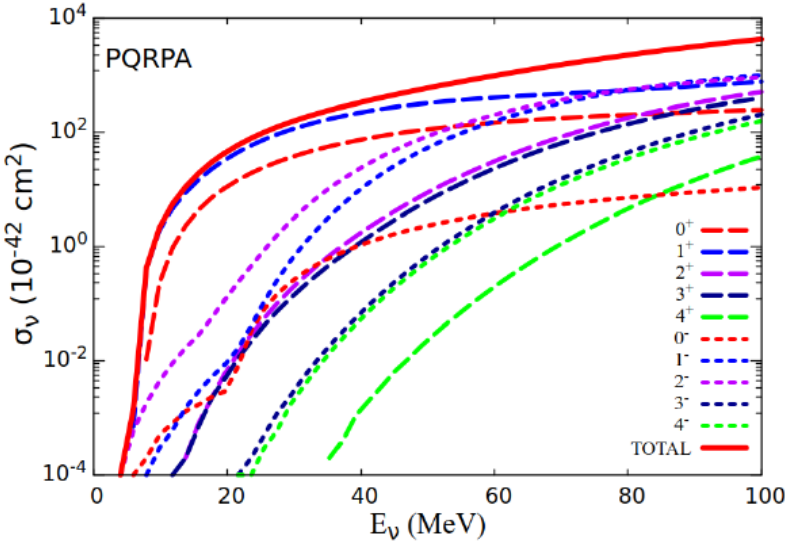
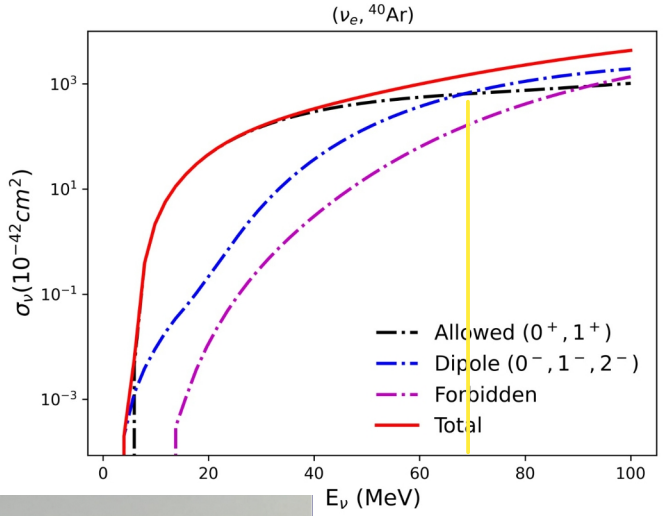
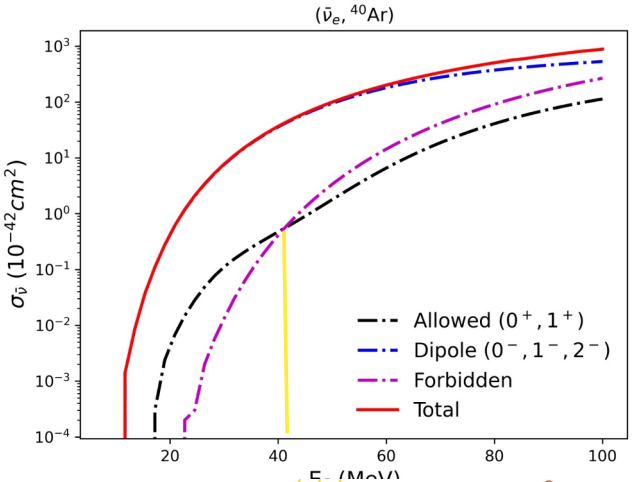


Fig. 11: Partial cross section for the reaction (ν_e,^{40}Ar) for the main multipole states contribution $J^\pi = 0^\pm - 4^\pm$, obtained using PQRPA model.

Allowed and forbidden contribution for PQRPA.





Fine tuning QRPA calculations for ν_e-^{40}Ar cross section – V Simpósio INCT– UFFl- RJ - Brazil- 2025

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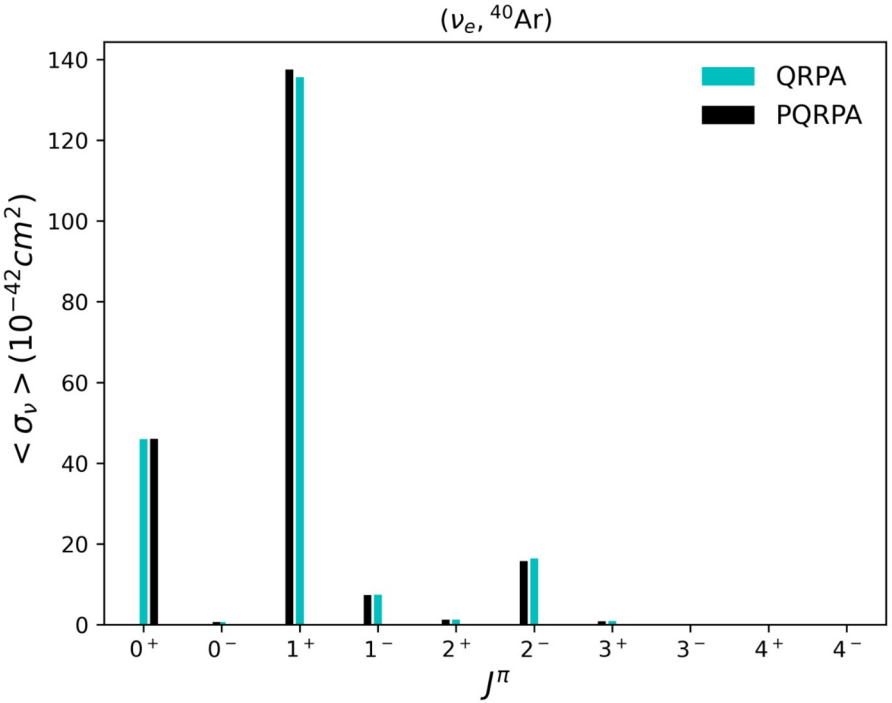
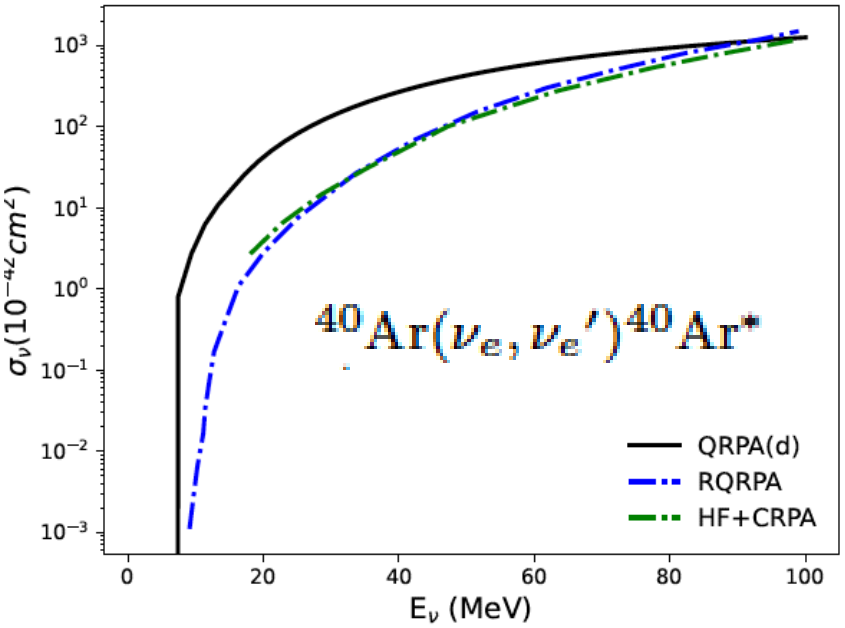
Neutrino/antineutrino cross sections ^{40}Ar

Averaged ν_ε –40Ar cross section with Michel spectrum, neutrinos from muon decay.



Neutral ν_e -40Ar cross section as function of neutrino energy.



Main contributions come from allowed transitions.

$$\langle\sigma\rangle \equiv \frac{\int_0^{m_\mu/2} \sigma(E_\nu)\phi(E_\nu)dE_\nu}{\int_0^{m_\mu/2} \phi(E_\nu)dE_\nu}, \qquad \phi(E_\nu) \propto E_\nu^2 m_\mu^{-4}(m_\mu - 2E_\nu).$$

Summary

- Due the universality of the weak hamiltonian, the nuclear models must be describe reasonably good the weak processes: GT strengths for β+ and β- (low energy region up to 40 MeV) and the inclusive muon capture rates (up to 100 MeV).

- A fine tuning could be require an agreement with exclusive reactions, as such as exclusive muon capture rates to first lowest states. Scarce available data for 40Ar or 18O (only inclusive λ) .

- There are several parameters in the nuclear model, one of the most more important is $\mathbf{g_A}$ that goes from 1 to 1.27. Improve the theoretical calculations.

- In LArTPC detectors the most relevant cross is CC 40Ar(ν_e,e-)40K that has never been measured experimentally. Recommendations of DUNE work (PRD107,112021 (2023)) can solve this issue.

Acknowlegments

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CAPES

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