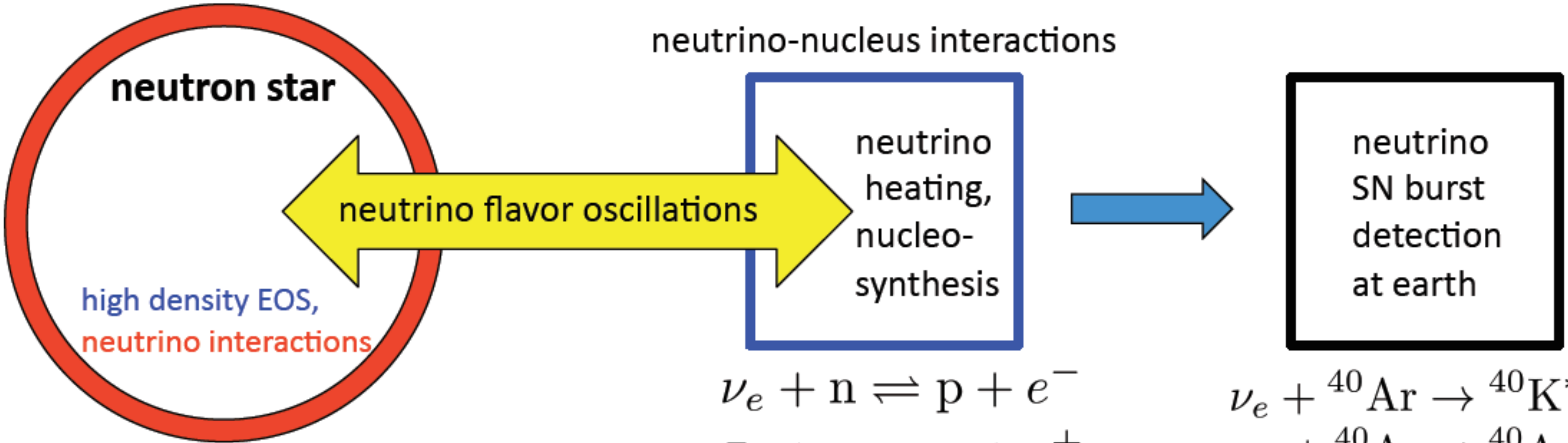
Theoretical Perspectives on Coherent Elastic Neutrino-Nucleus Scattering

MITP Virtual Workshop on Parity Violation and Related Topics
July 2020

A.B. Balantekin

Understanding neutrino-nucleus interactions are essential to neutrino physics: for example consider a core-collapse supernova.

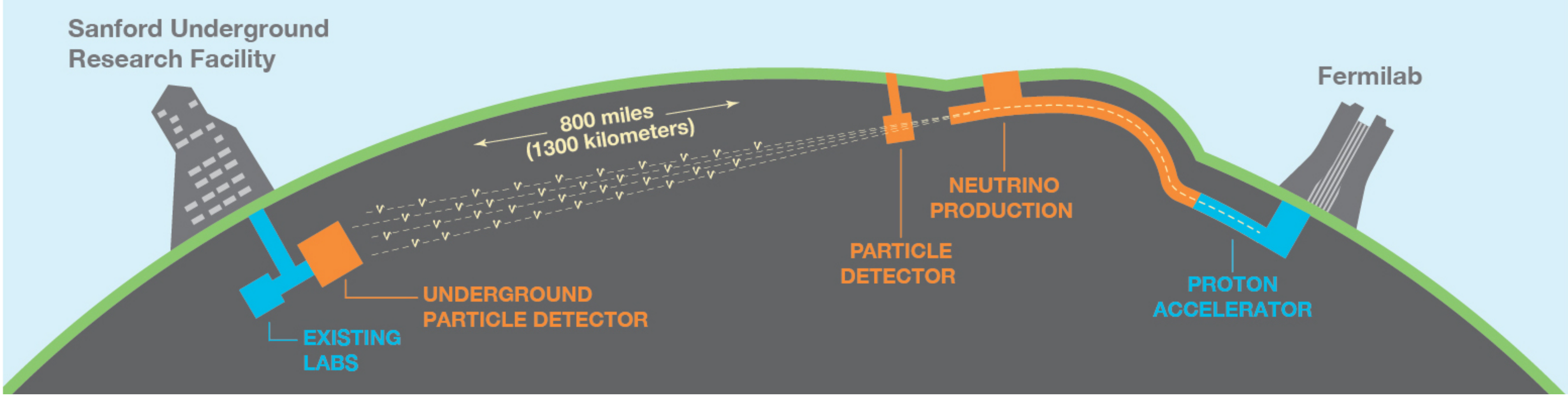
Balantekin and Fuller, Prog. Part. Nucl. Phys. **71** 162 (2013)



$$\nu_e + \mathrm{n} \rightleftharpoons \mathrm{p} + e^-$$
$$\bar{\nu}_e + \mathrm{p} \rightleftharpoons \mathrm{n} + e^+$$

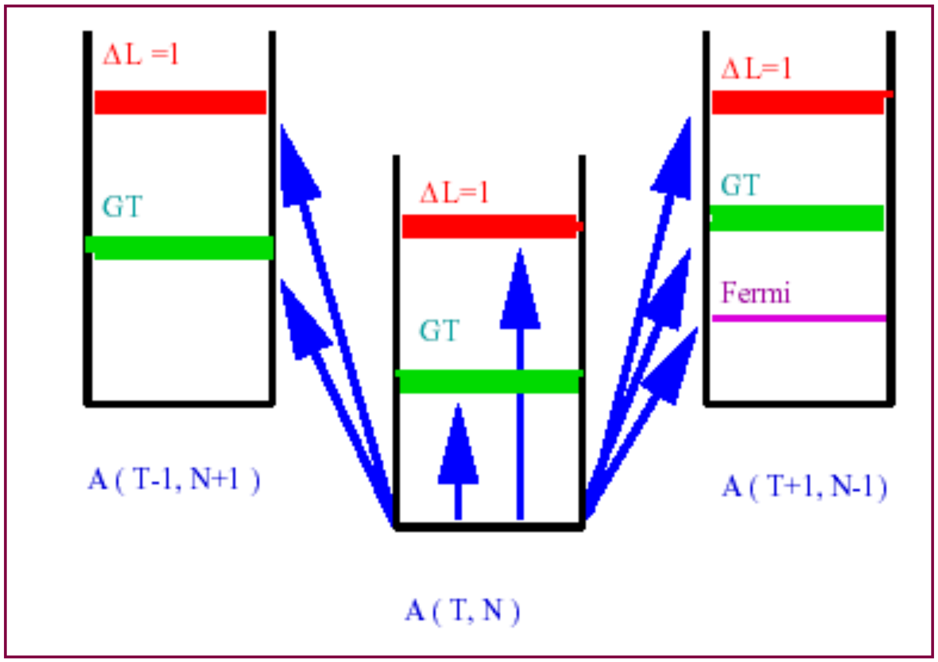
$$\nu_e + {}^{40}\mathrm{Ar} \to {}^{40}\mathrm{K}^* + e^-$$
$$\nu_x + {}^{40}\mathrm{Ar} \to {}^{40}\mathrm{Ar}^* + \nu_x$$

or a long-baseline experiment



How can we accurately calculate neutrino-nucleus cross sections and beta decay rates?

We need to know what happens when a neutrino with energies up to 50 - 100 MeV hits a nucleus? Where does the strength lie? What is g_A/g_V?



Neutrino wave function

$$e^{ikr} \approx 1 + ikr - \frac{1}{2}(kr)^2 + \cdots$$

allowed

First-forbidden

Second-forbidden

As the incoming neutrino energy increases, the contribution of the states which are not well-known increase, including first- and even second-forbidden transitions.

Example of an approach from the first principles: Using effective field theory for low-energy neutrino-deuteron scattering

Below the pion threshold $^3S_1 \rightarrow {}^1S_0$ transition dominates and one only needs the coefficient of the two-body counter term, L_{1A} (isovector two-body axial current)

L_{1A} can be obtained by comparing the cross section $\sigma(E) = \sigma_0(E) + L_{1A}\, \sigma_1(E)$ with cross-section calculated using other approaches or measured experimentally (e.g. use solar neutrinos as a source).

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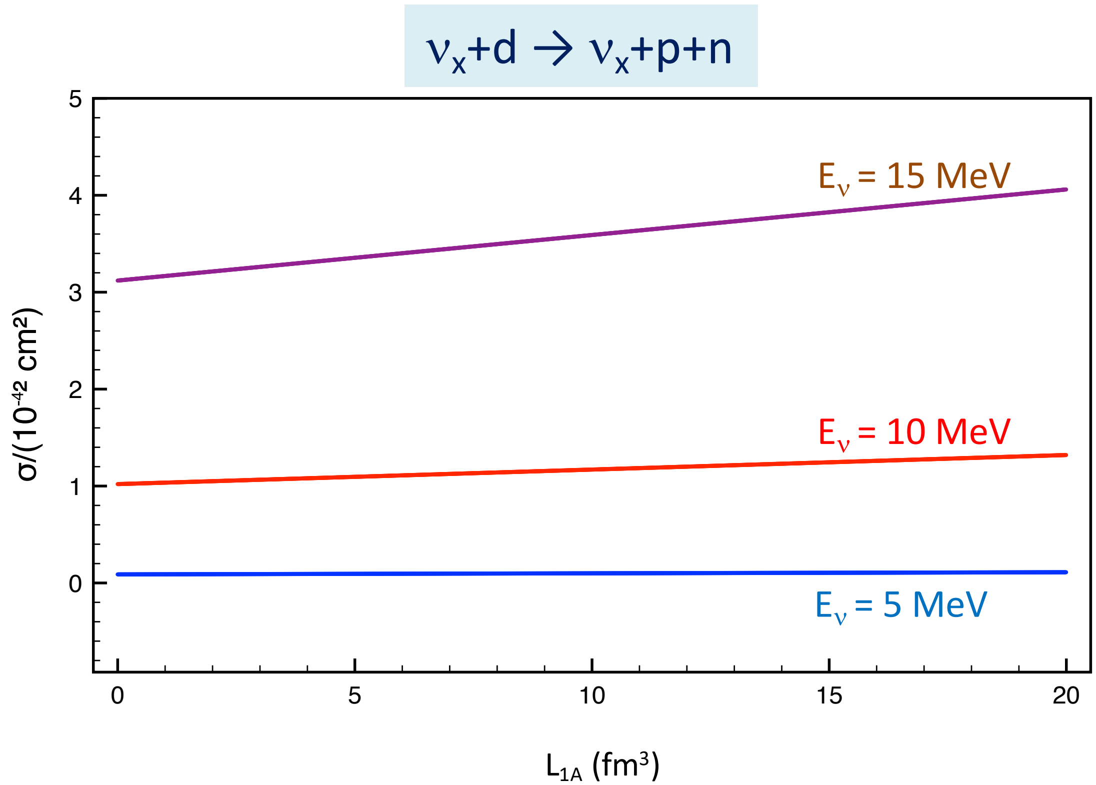

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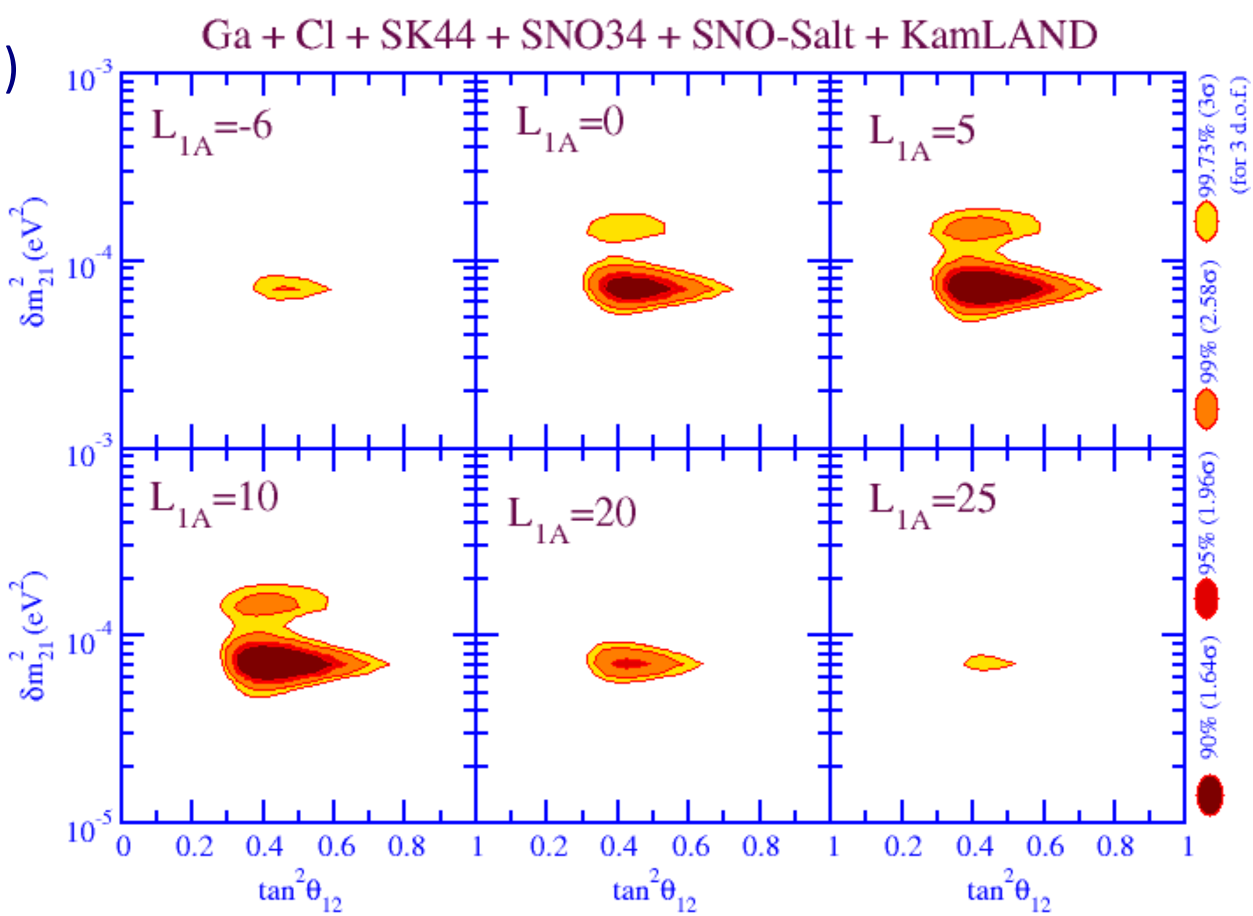
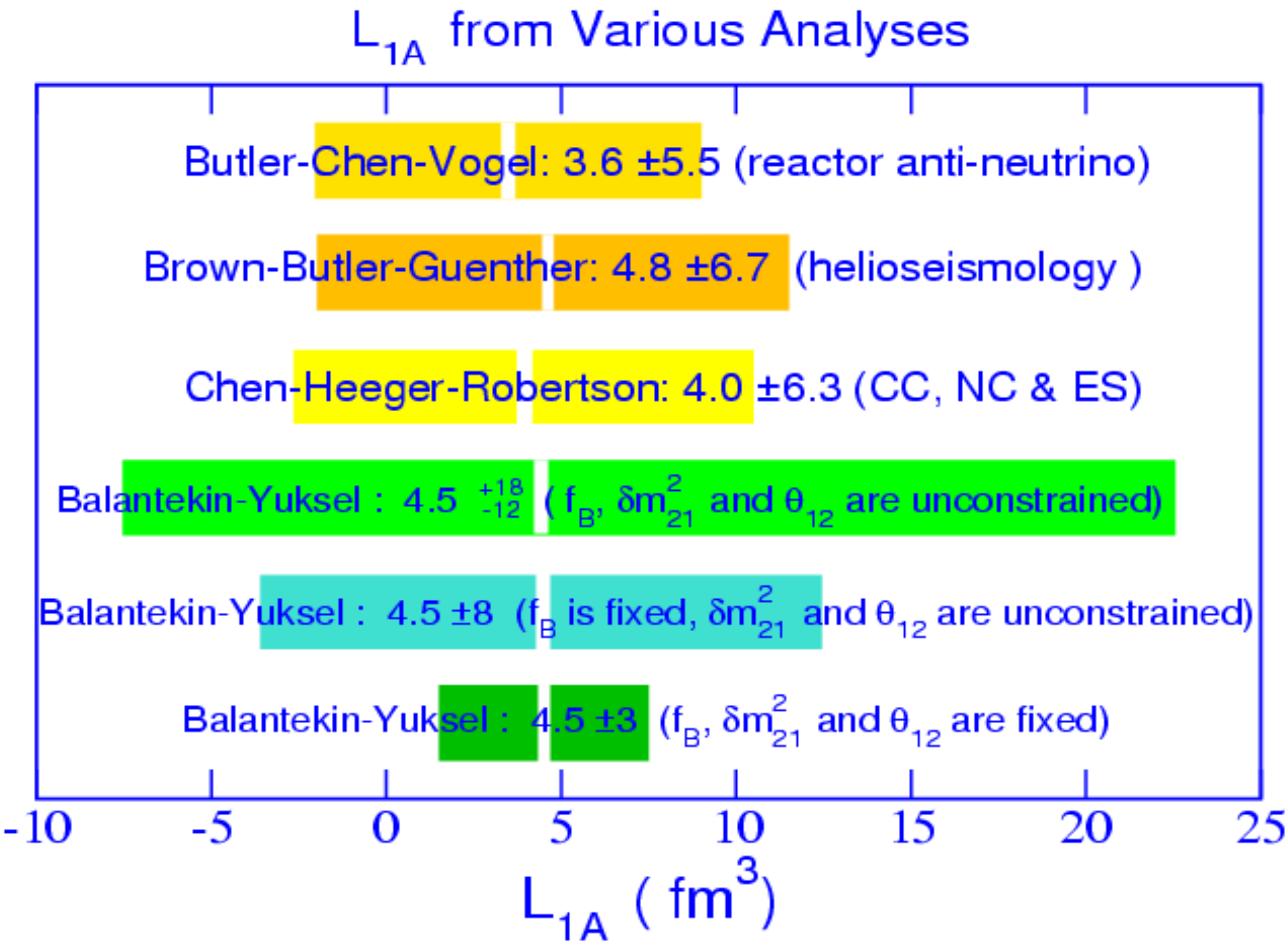


A.B. Balantekin and H. Yuksel, PRC **68** 055801 (2003)



L1A from Various Analyses
Butler-Chen-Vogel: 3.6 ±5.5 (reactor anti-neutrino)
Brown-Butler-Guenther: 4.8 ±6.7 (helioseismology)
Chen-Heeger-Robertson: 4.0 ±6.3 (CC, NC & ES)
Balantekin-Yuksel : 4.5 +18 -12 (fB, δm2 21 and θ12 are unconstrained)
Balantekin-Yuksel : 4.5 ±8 (fB is fixed, δm2 21 and θ12 are unconstrained)
Balantekin-Yuksel : 4.5 ±3 (fB, δm2 21 and θ12 are fixed)
-10
-5
0
5
10
15
20
25
L1A (fm3)

Example of an approach from the first principles: Using effective field theory for low-energy neutrino-deuteron scattering

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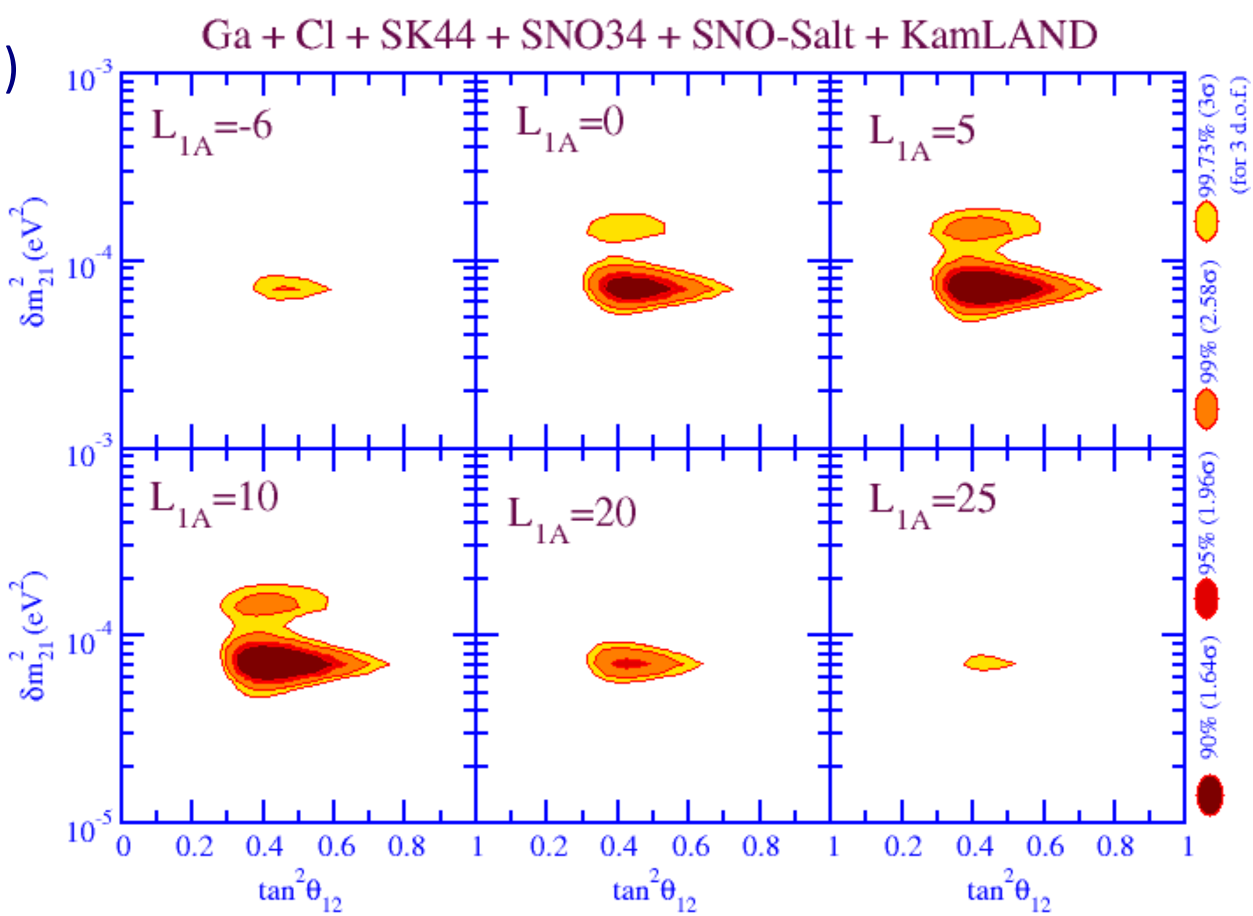
L_{1A} can be obtained by comparing the cross section $\sigma(E) = \sigma_0(E) + L_{1A}\,\sigma_1(E)$ with cross-section calculated using other approaches or measured experimentally (e.g. use solar neutrinos as a source).

L_{1A}=3.9(0.1)(1.0)(0.3)(0.9) fm^3 at a renormalization scale set by the physical pion mass
Savage et al., PRL 119, 062002 (2017)



A.B. Balantekin and H. Yuksel, PRC **68** 055801 (2003)

Difficult to go beyond two-body systems!

One can use neutrinos to probe strangeness in nuclei with weak neutral current:

$$\left\langle N\middle|A_\mu^Z\middle|N\right\rangle \approx \frac{1}{2}\left\langle N\middle|\underbrace{\bar{u}\gamma_\mu\gamma_5 u-\bar{d}\gamma_\mu\gamma_5 d}_{\text{isovector}}-\underbrace{\bar{s}\gamma_\mu\gamma_5 s}_{isoscalar}\middle|N\right\rangle$$

Goes to Δs at $Q^2=0$

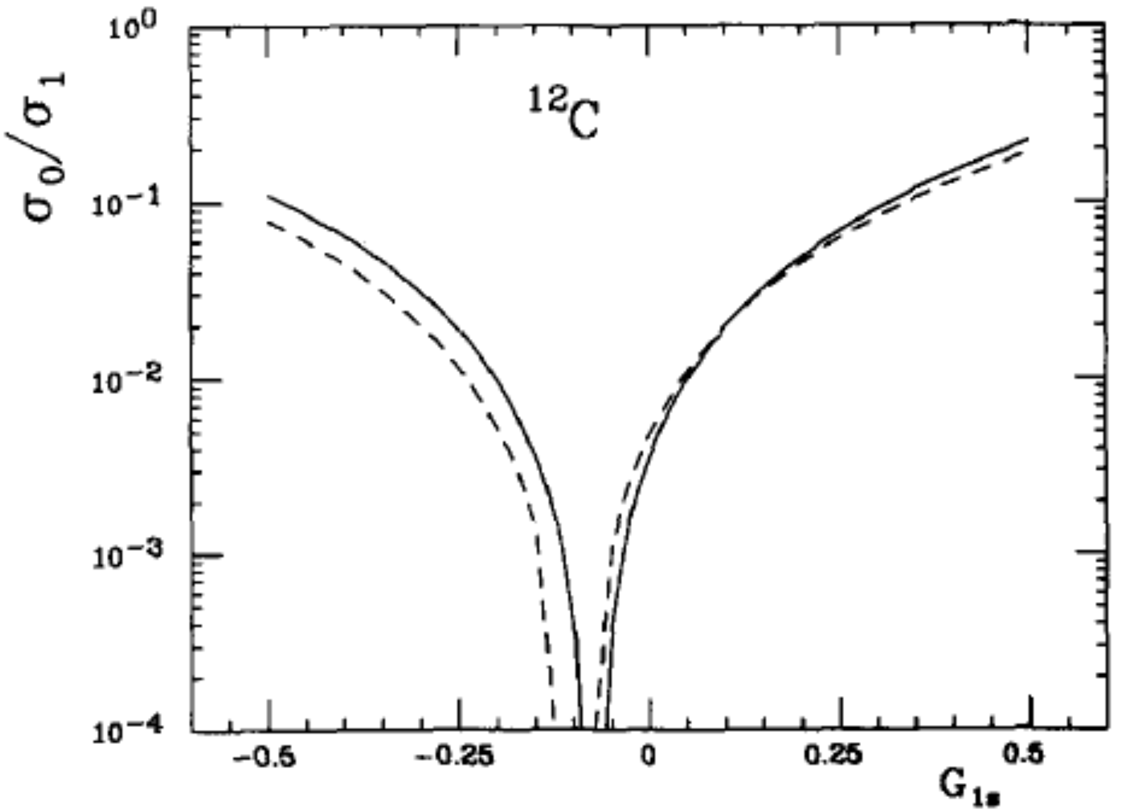
$$\frac{\sigma\left(\nu+A\rightarrow p+X\right)}{\sigma\left(\nu+A\rightarrow n+X'\right)}\approx 1+\frac{16}{5}\Delta s$$

Would be one if the weak neutral current was only isovector

Another possibility is to look for isoscalar excitations:

$$\nu + {}^{12}C \rightarrow {}^{12}C^*\left(12.7\ \mathrm{MeV},\, 1^+, T=0\right) + \nu$$

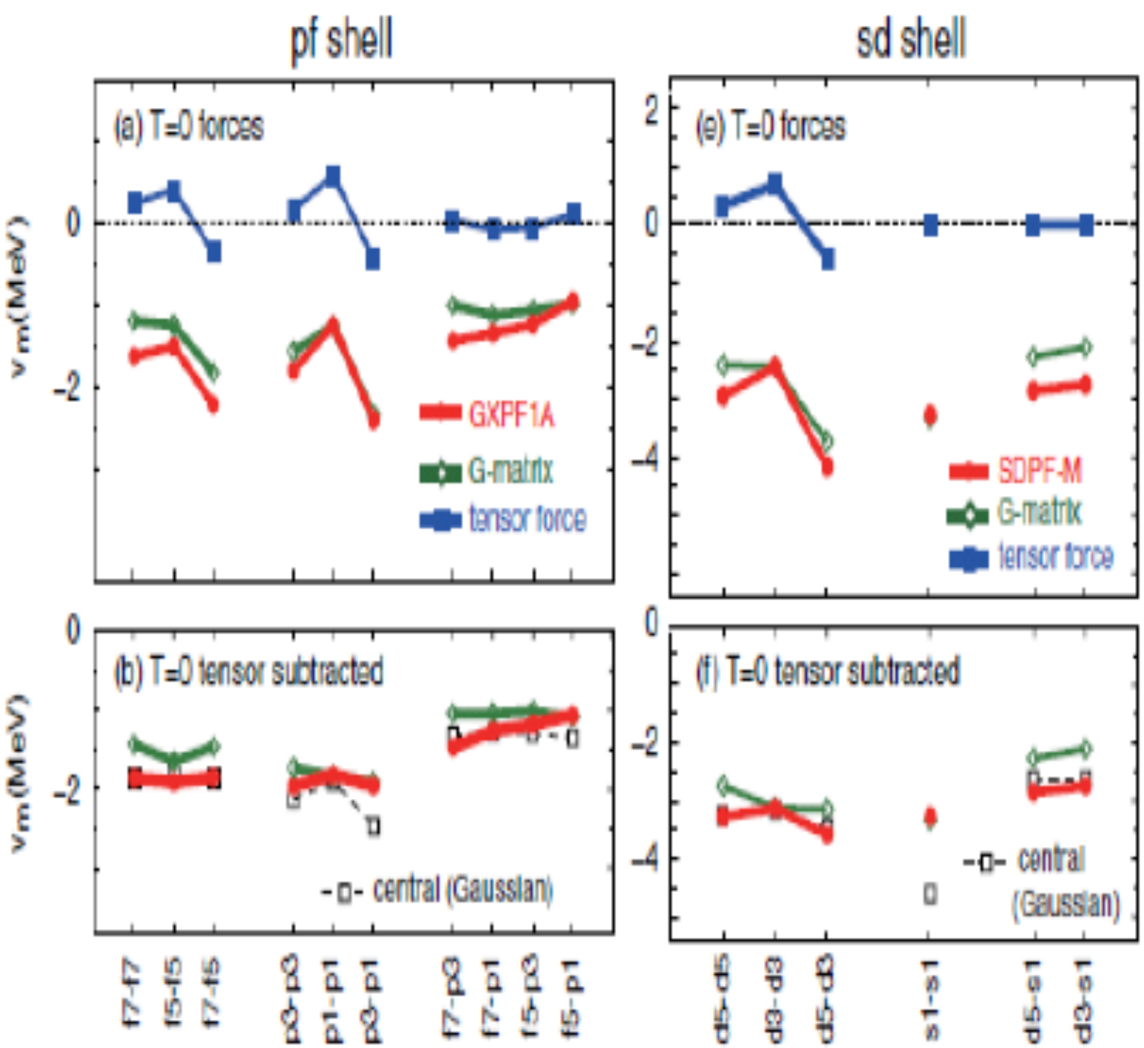
$$\frac{\nu + {}^{12}C \rightarrow {}^{12}C^*\left(12.7\ \mathrm{MeV}\right) + \nu}{\nu + {}^{12}C \rightarrow {}^{12}C^*\left(15.11\ \mathrm{MeV}\right) + \nu}$$



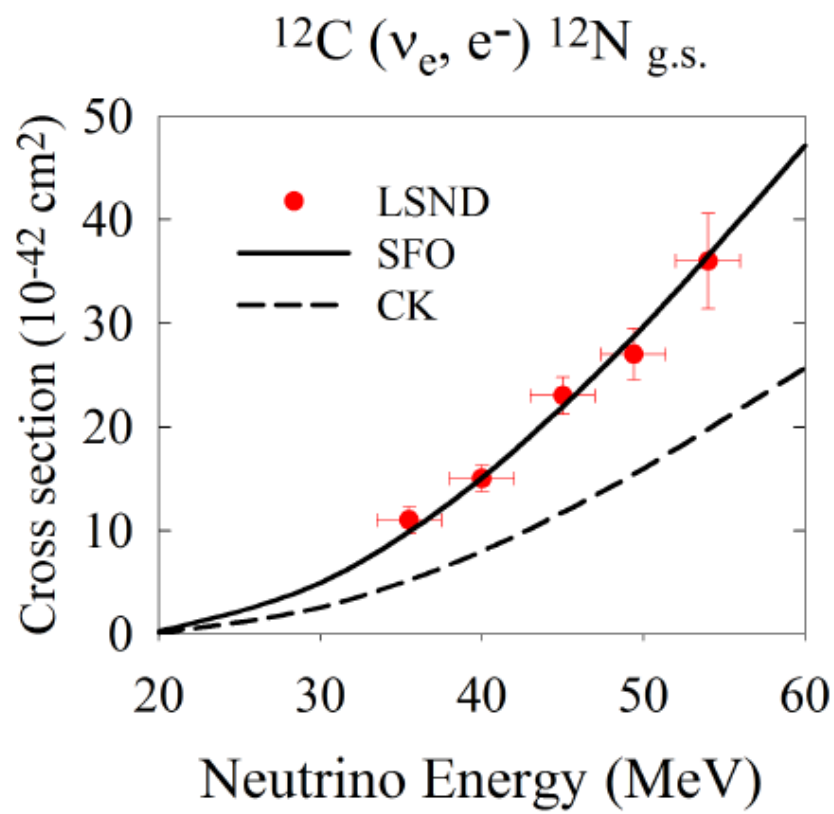
Caution: isospin mixing!

Suzuki *et al.*, Phys. Lett. B **252**, 323 (1990)

A new p-sd shell model (SFO) including up to 2-3 hΩ excitations which can describe well the magnetic moments and Gamow-Teller (GT) transitions in p-shell nuclei with a small quenching for spin g-factor and axial-vector coupling constant

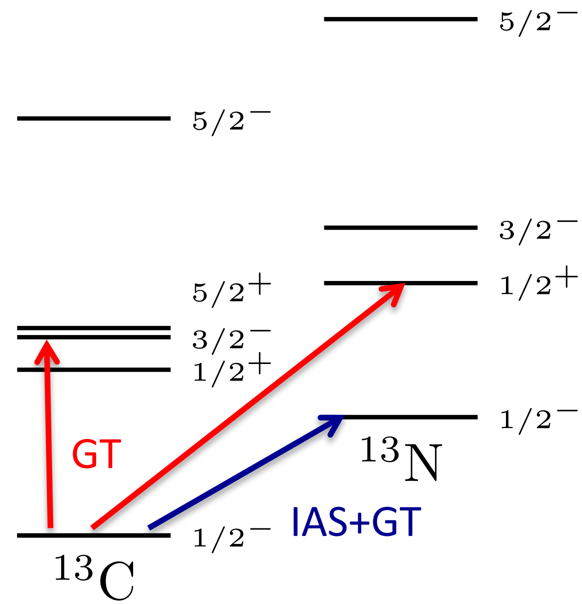


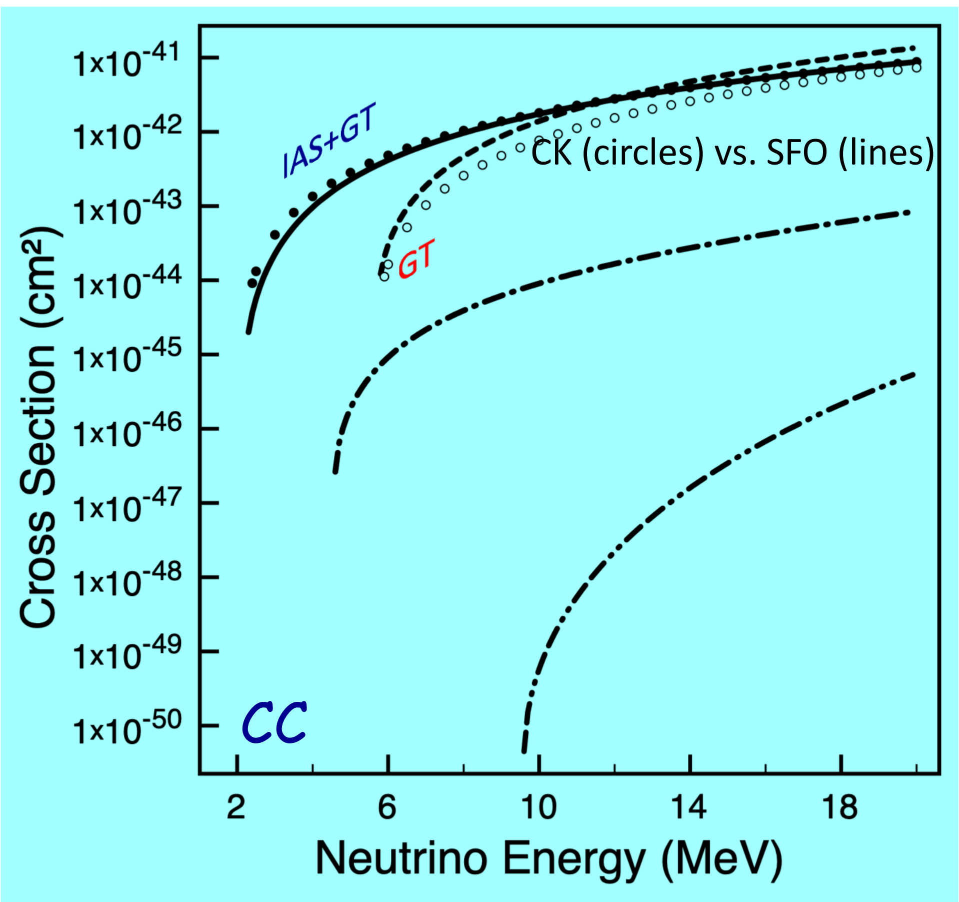
Suzuki, Fujimoto, Otsuka

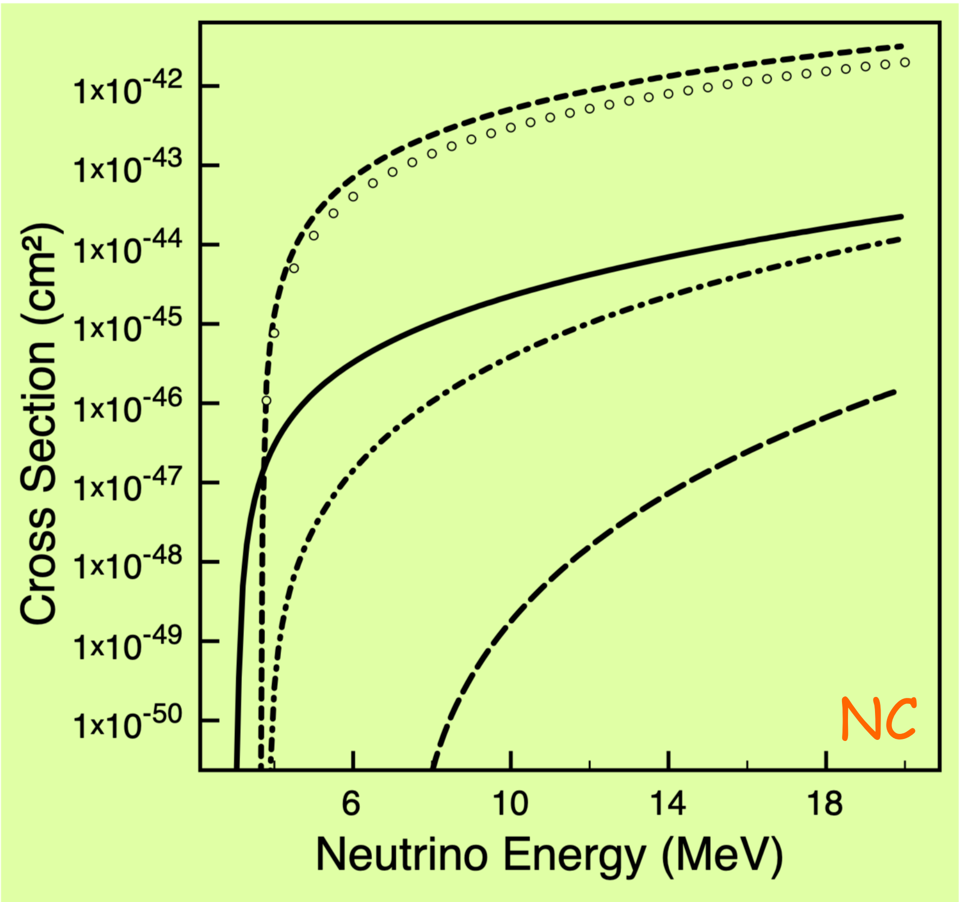


An example: $\nu_e + {}^{13}C$

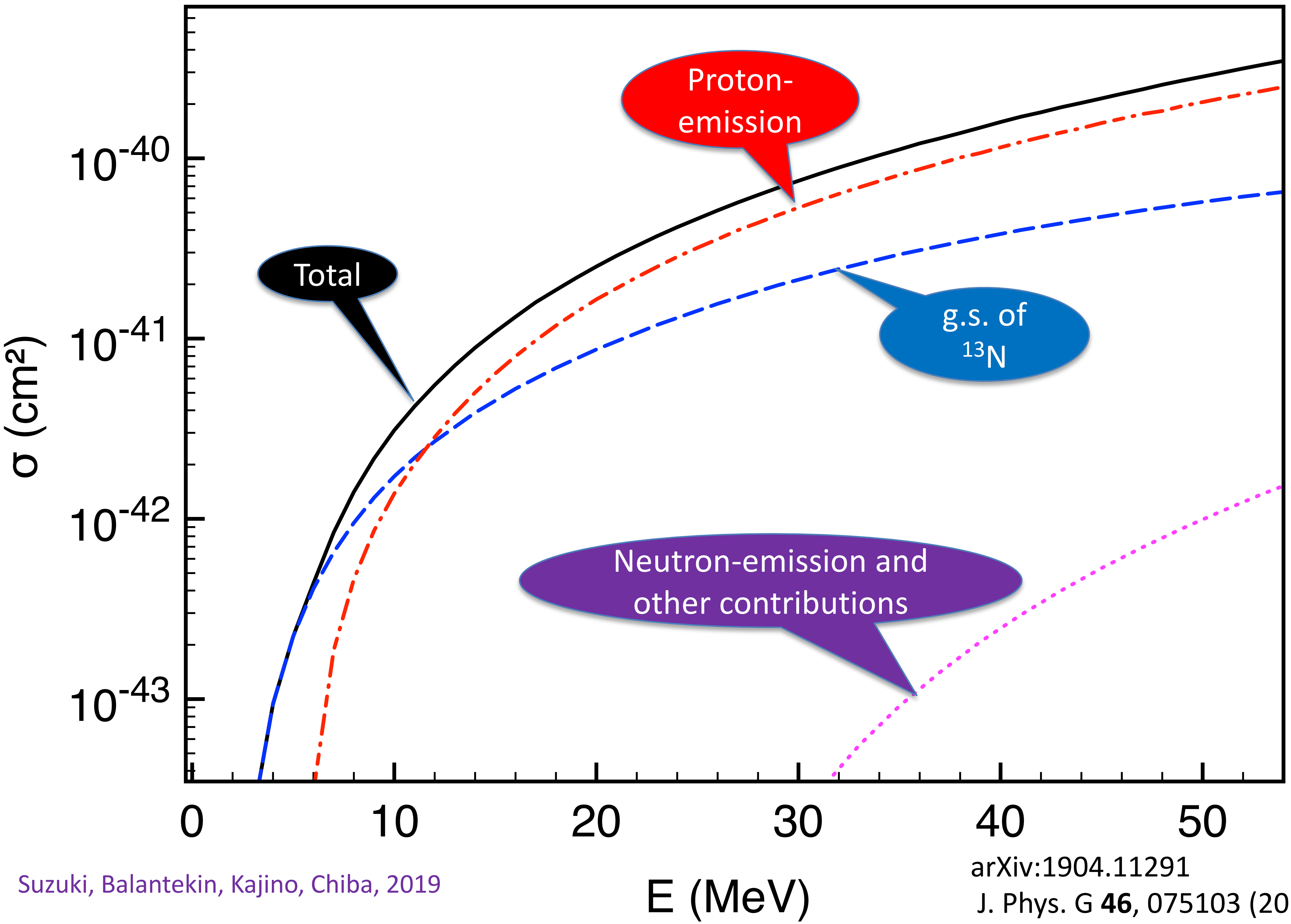
Suzuki, Balantekin, Kajino,
Phys. Rev. C **86**, 015502 (2012)







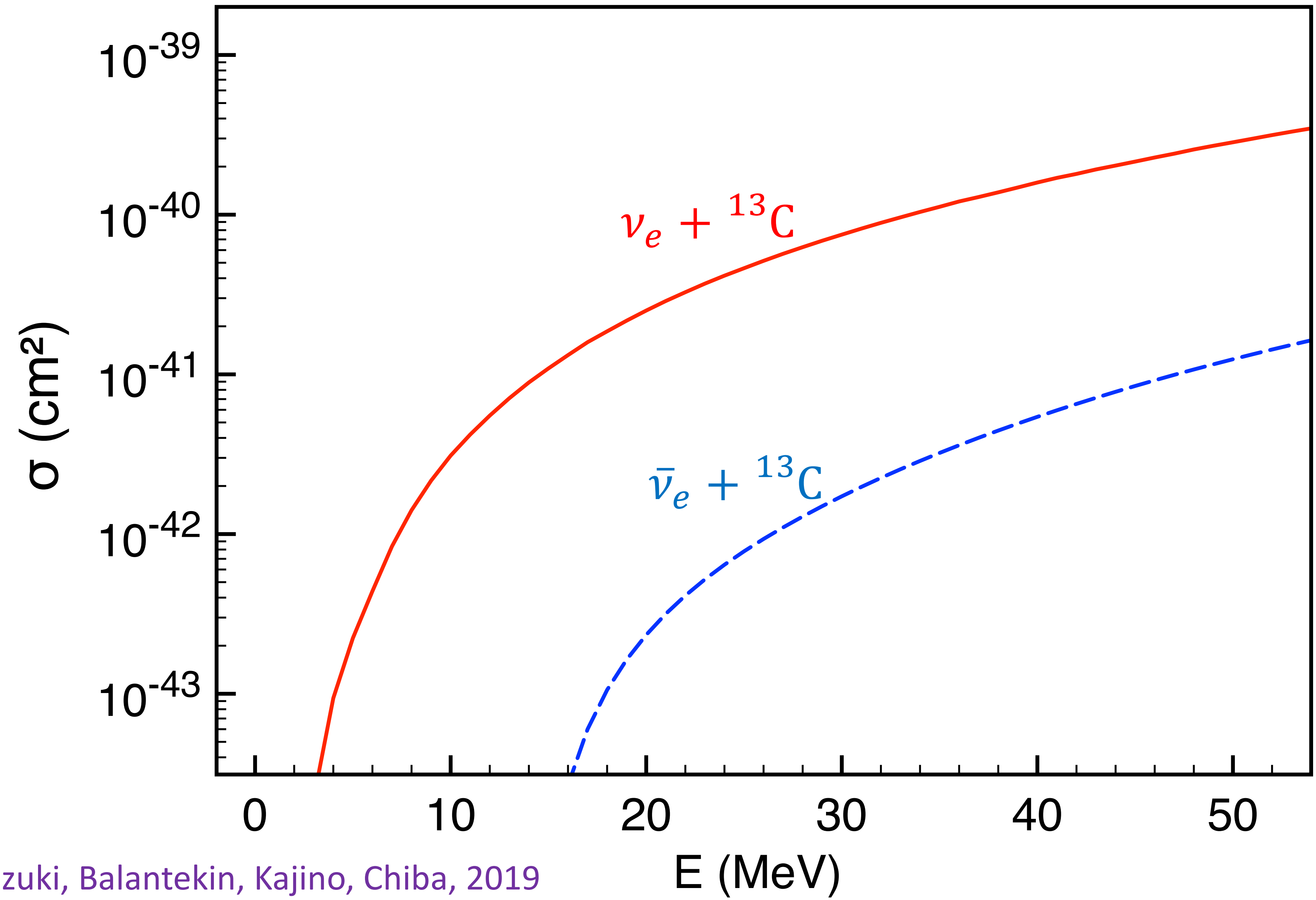
$\nu_e + {}^{13}C$ charged-current scattering



Suzuki, Balantekin, Kajino, Chiba, 2019

arXiv:1904.11291
J. Phys. G **46**, 075103 (2019)

Comparison of charged-current cross sections



Suzuki, Balantekin, Kajino, Chiba, 2019

Neutrino Coherent Scattering

$$\frac{d\sigma}{dT}(E,T) = \frac{G_F^2}{8\pi} M \left[2 - \frac{2T}{T_{max}} + \left(\frac{T}{E}\right)^2\right] Q_W^2 [F(Q^2)]^2$$

$$T_{max} = \frac{2E^2}{2E+M}$$

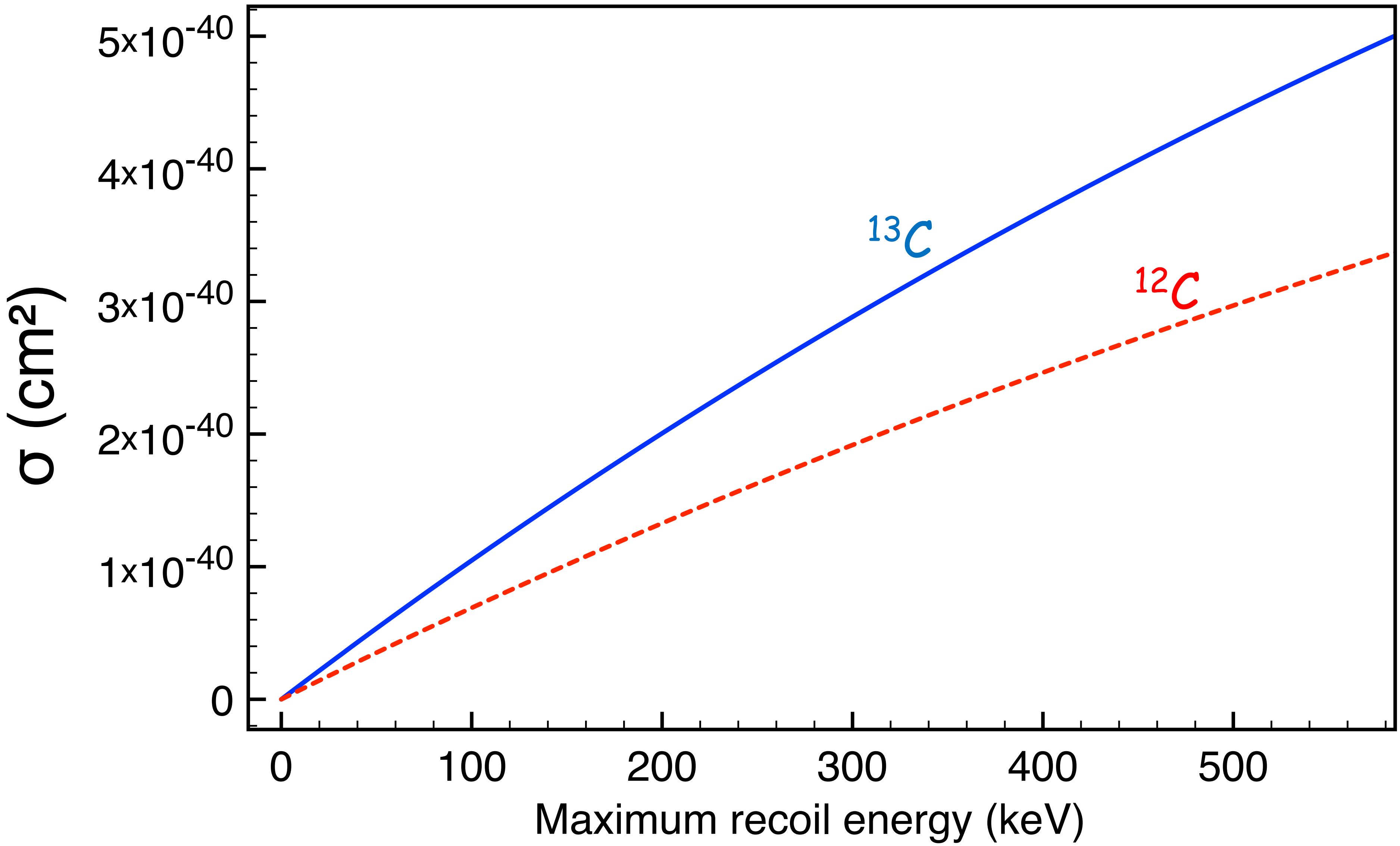
$$Q_W = N - (1 - 4\sin^2\theta_W)\, Z$$

$$Q^2 = 2MT$$

For nearly spherical systems

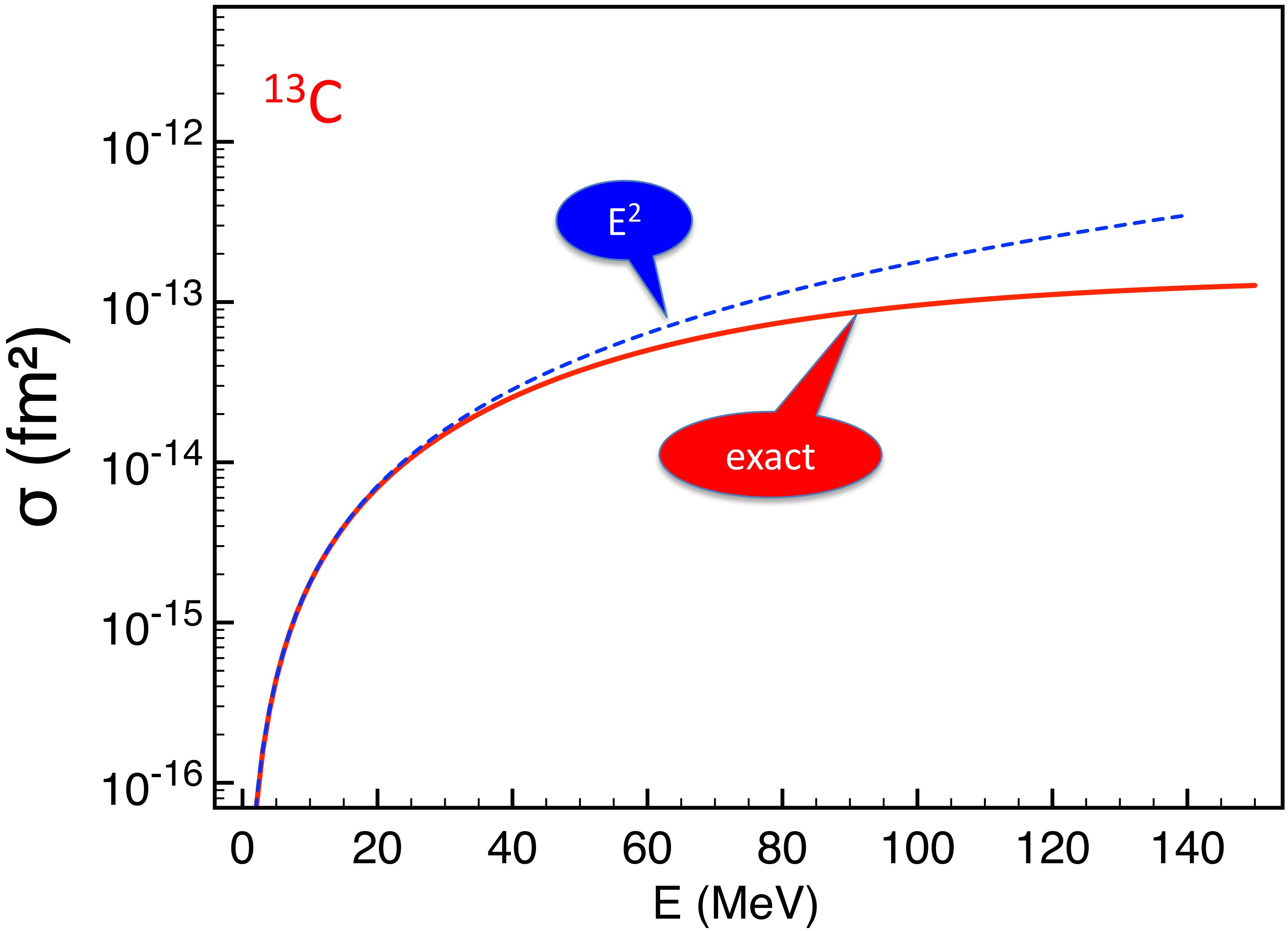
$$F(Q^2) = \frac{1}{Q_W} \int dr\, r^2 \frac{\sin^2(Qr)}{Qr} \left[\rho_n(r) - (1 - 4\sin^2\theta_W)\,\rho_p(r)\right]$$

Coherent elastic neutrino cross sections



$$\frac{d\sigma}{dT}(E,T) = \frac{G_F^2}{8\pi} M \left[2 - \frac{2T}{T_{max}} + \left(\frac{T}{E}\right)^2\right] Q_W^2 [F(Q^2)]^2$$

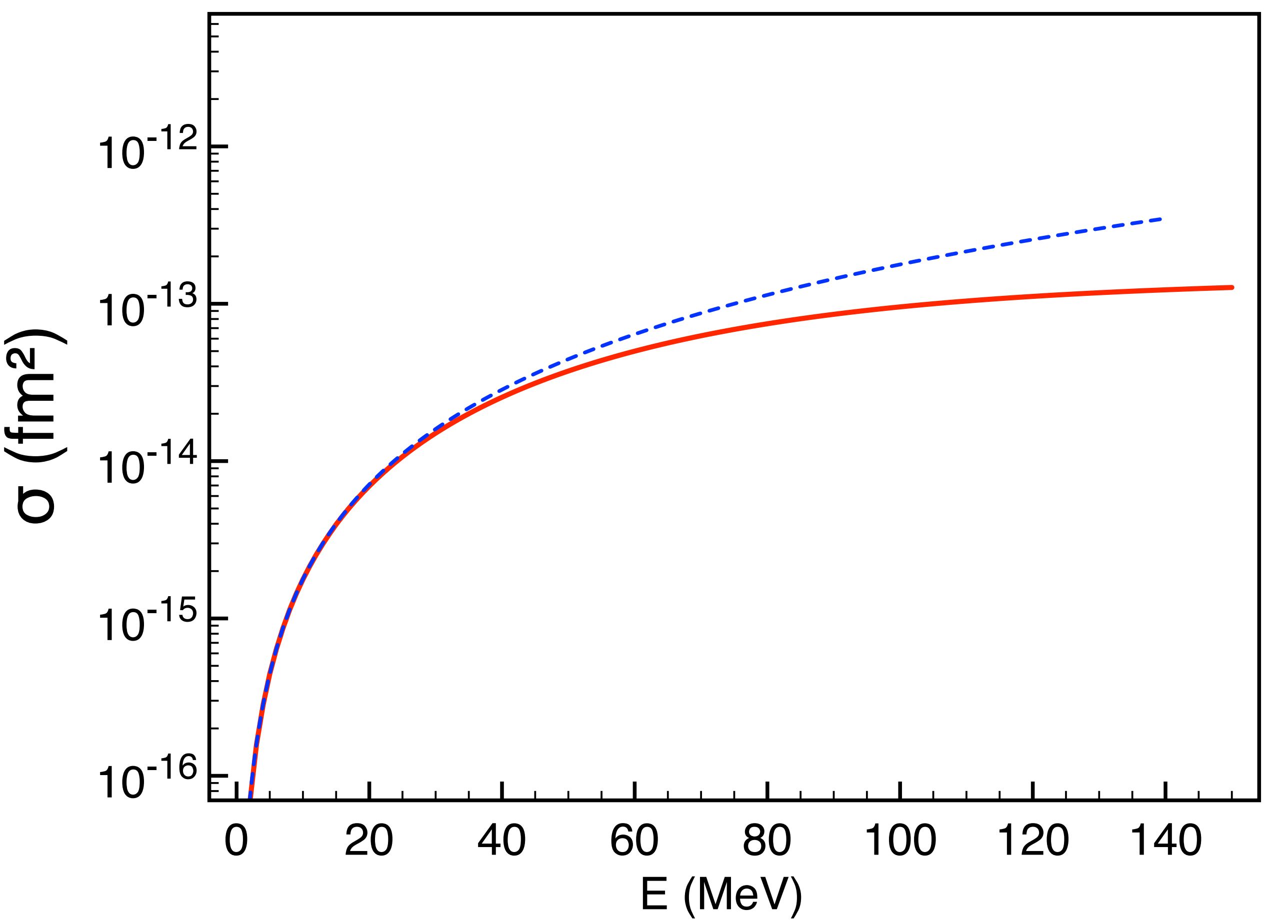
$$\sigma(E) \propto E^2 + \text{ nuclear corrections}$$



Suzuki, Balantekin, Kajino, Chiba, 2019

$$F(Q^2) = 1 + \eta_2 Q^2 + \eta_4 Q^4 + \cdots ,$$

$$\sigma(E) = \frac{G_F^2}{4\pi} Q_W^2 E^2 \left[\left(1 + \frac{8}{3}\eta_2 E^2 + \frac{8}{3}(\eta_2^2 + 2\eta_4) E^4 + \cdots \right) \right.$$
$$\left. - \frac{2}{M} \left(E + \frac{16}{3}\eta_2 E^3 + \frac{24}{3}(\eta_2^2 + 2\eta_4) E^5 + \cdots \right) + \cdots \right]$$

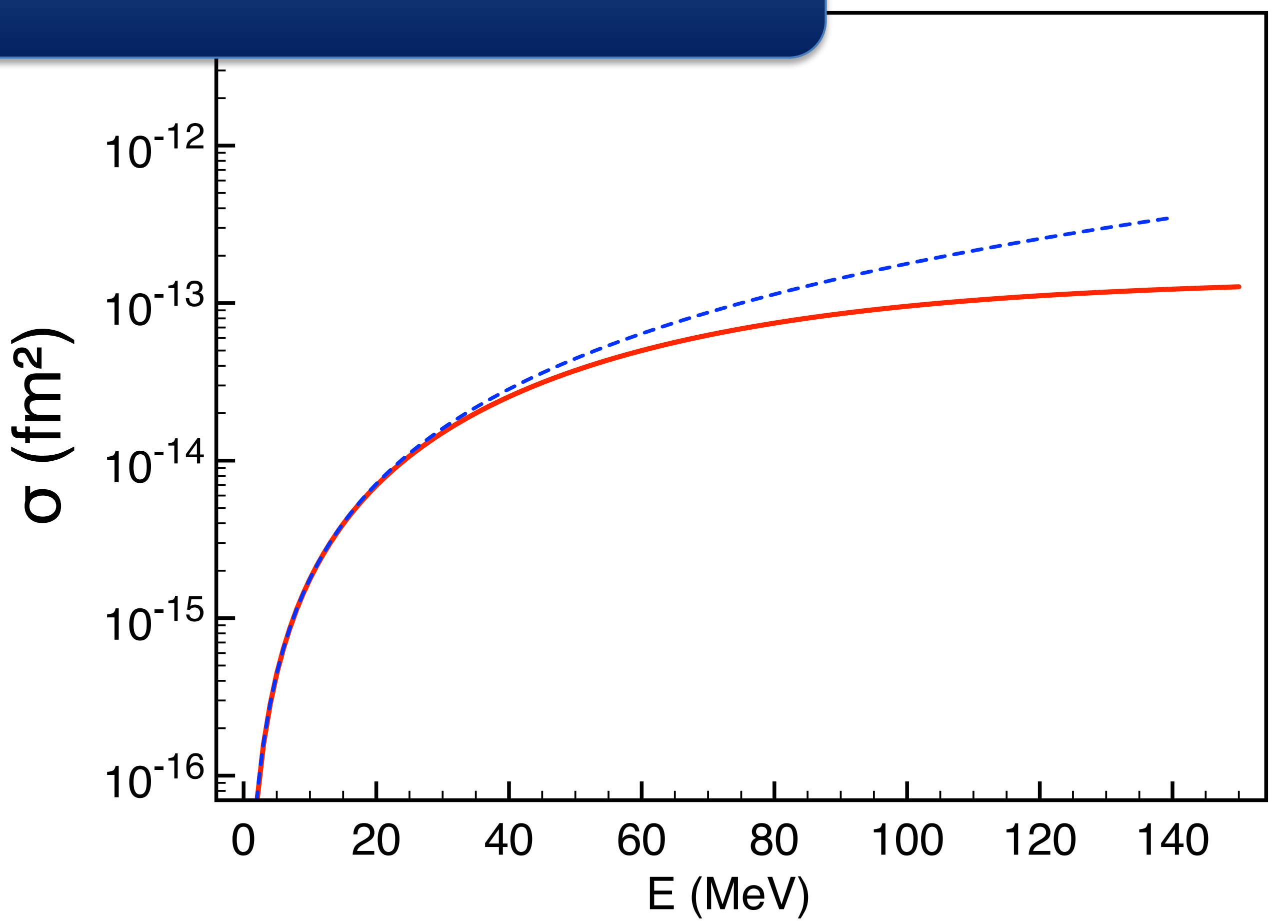


$$\ldots Q^4 + \cdots ,$$

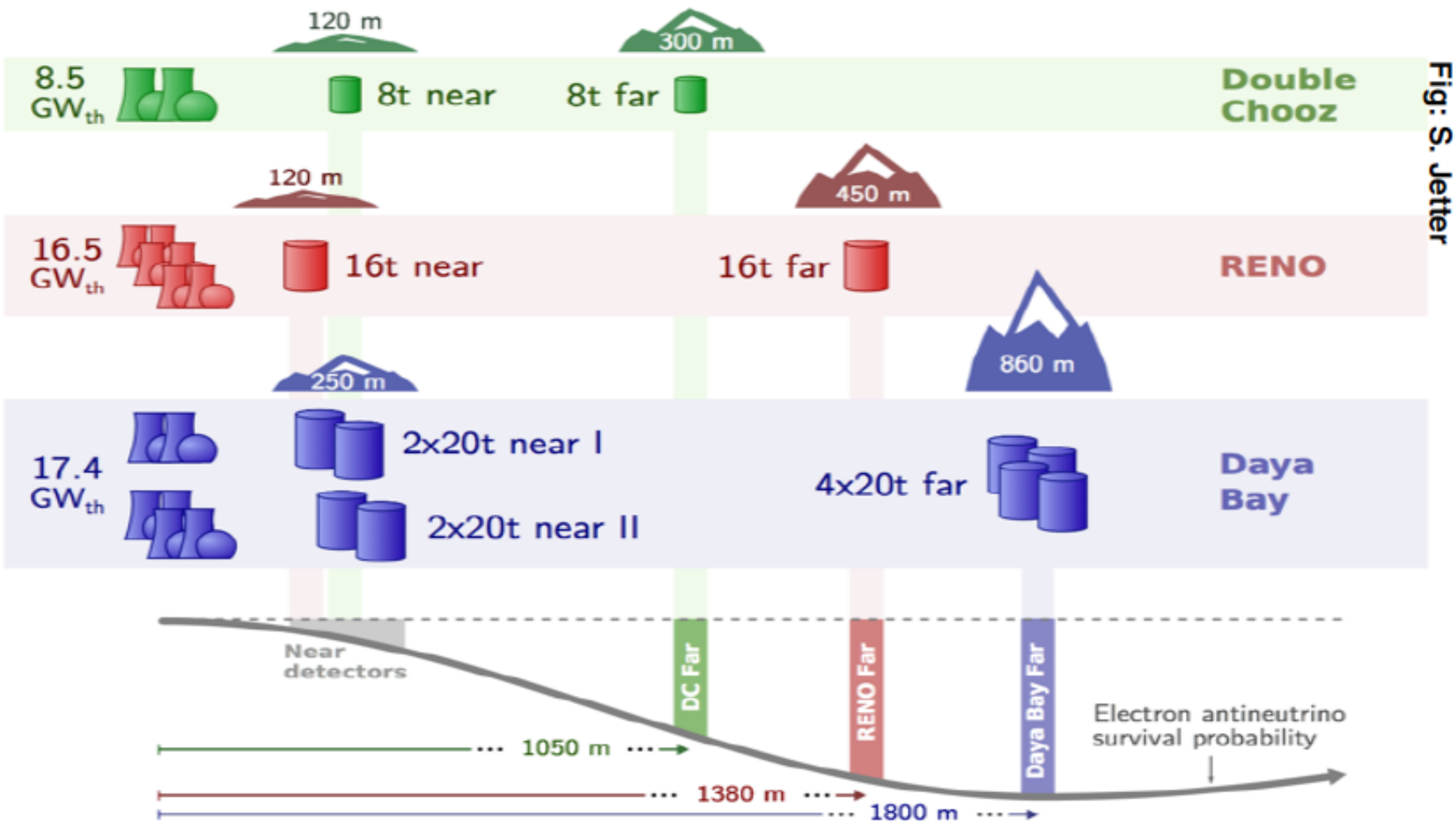
Simply a loss of the cross section can be due to the unaccounted nuclear effects, not to the presence of sterile neutrinos! Observing sterile neutrinos require observing oscillations

$$\ldots (\eta_2^2 + 2\eta_4)E^4 + \cdots \Big)$$

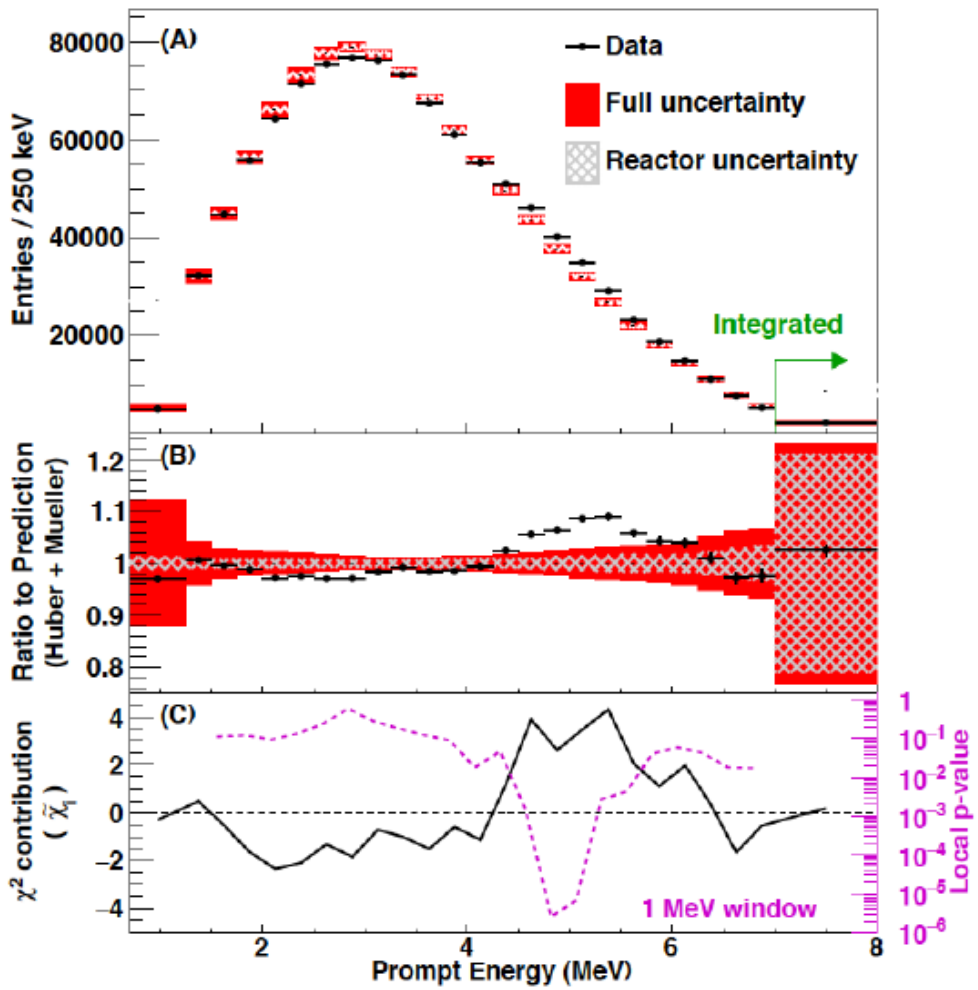
$$\ldots 2\eta_4)E^5 + \cdots \Big) + \cdots \Big]$$

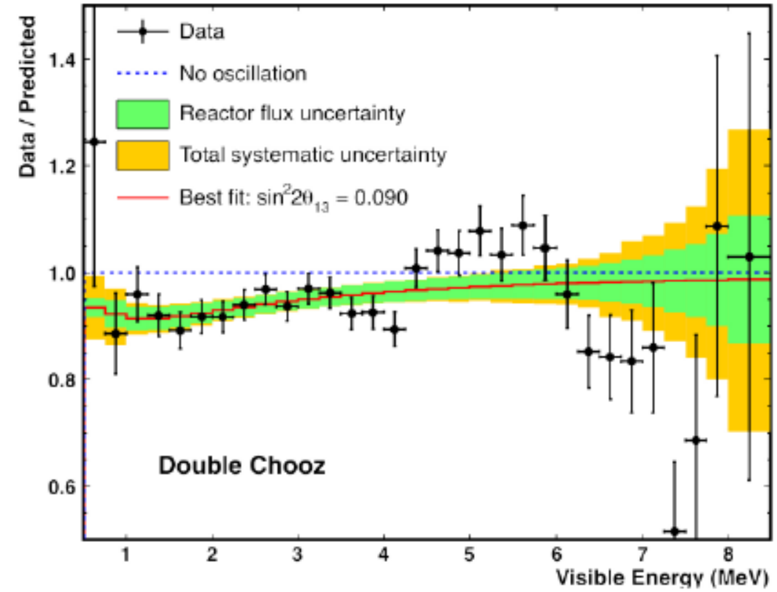


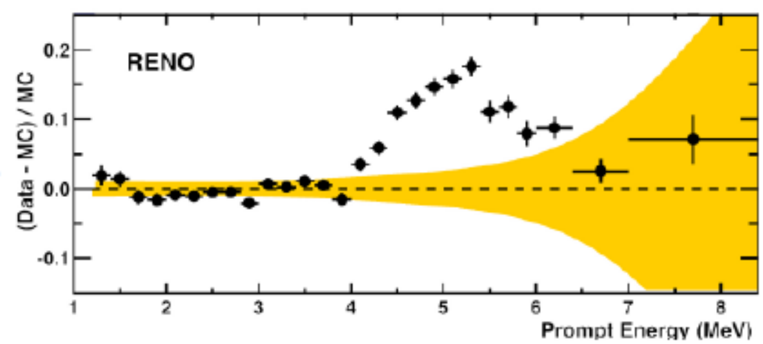
Reactor neutrino experiments to measure the remaining mixing angle also measure the reactor neutrino flux



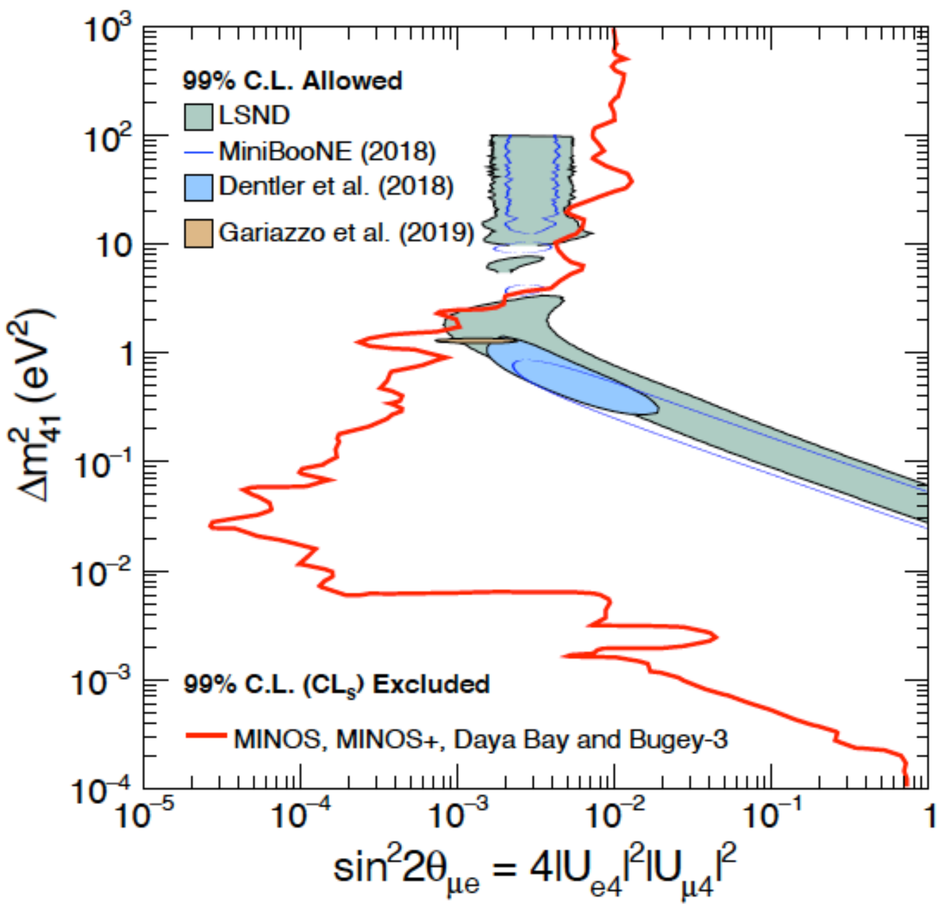
The reactor anomaly



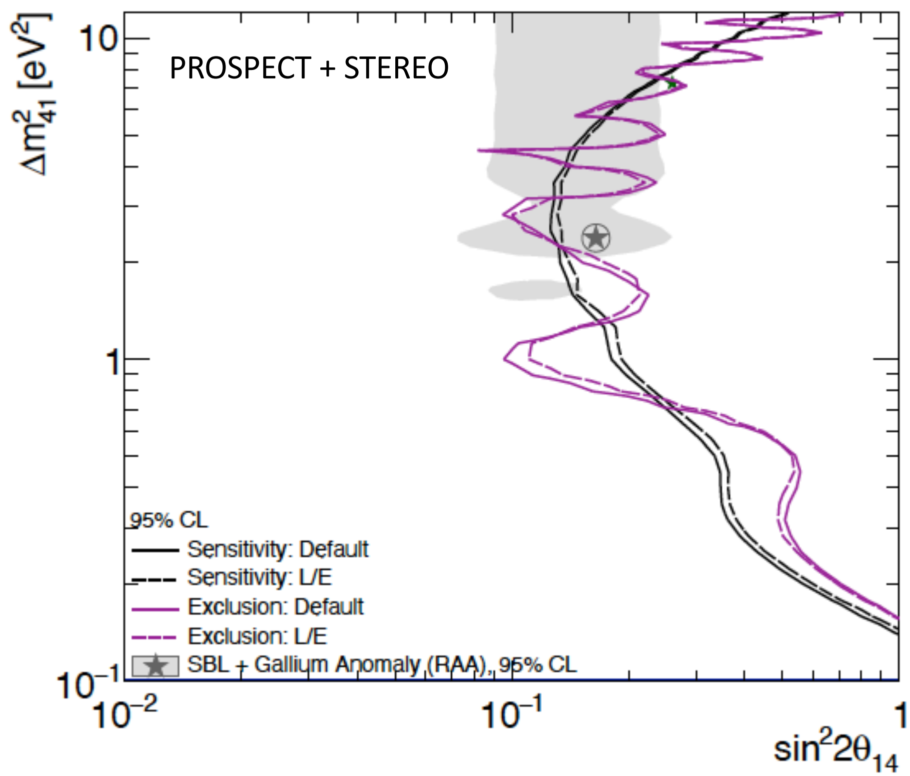




A sterile neutrino solution is not yet settled:



arXiv:2002.00301[hep-ex]



arXiv:2006.13147[hep-ex]

Are we missing a nuclear physics explanation?

An alternative solution:

$^{13}\mathrm{C}(\bar{\nu}, \bar{\nu}' n)^{12}\mathrm{C}^{*}(4.4\ MeV) \rightarrow {}^{12}\mathrm{C}(\mathrm{g.s.}) + \gamma$

Berryman, Bradar, Huber, arXiv: 1803.08506

4.4 MeV prompt photon and proton recoils from thermalized neutron can mimic neutrinos around 5 MeV

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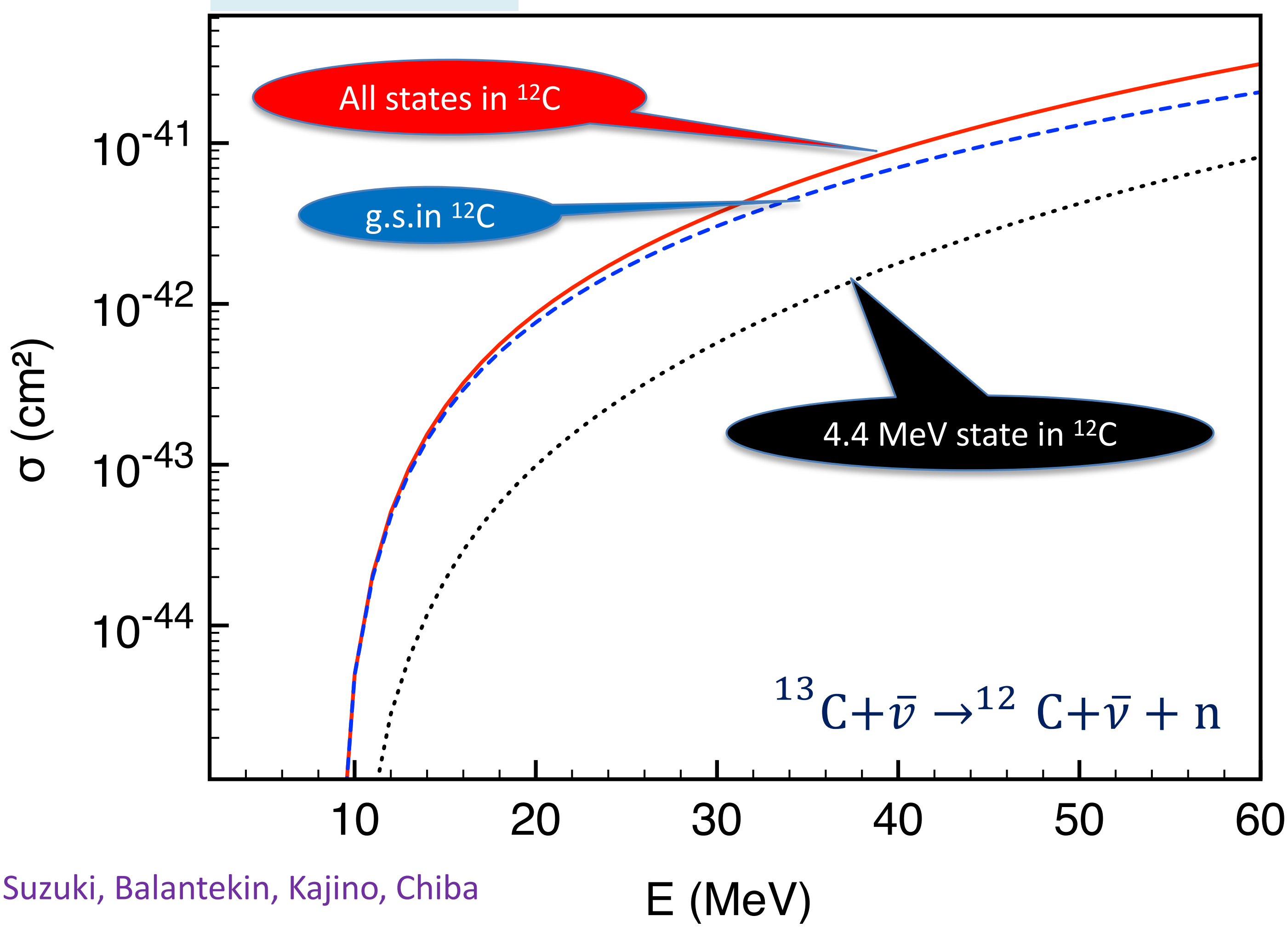
HOWEVER

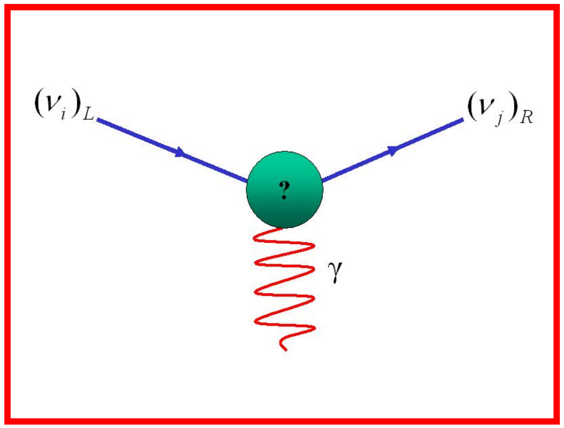


Suzuki, Balantekin, Kajino, Chiba

State of the art SM calculation using SFO Hamiltonian which includes tensor and enhanced monopole interactions is too small.

→This solution requires BSM physics.

Neutrino magnetic moment



- Defined in the mass basis
- Non-zero in the Standard Model:

$$\mu_{ij} = -\frac{eG_F}{8\sqrt{2}\pi^2}(m_i + m_j)\sum_{\ell} U_{\ell i} U^*_{\ell j} f(r_\ell)$$

$$f(r_\ell) \approx -\frac{3}{2} + \frac{3}{4} r_\ell + \ldots, \quad r_\ell = \left(\frac{m_\ell}{M_W}\right)^2$$

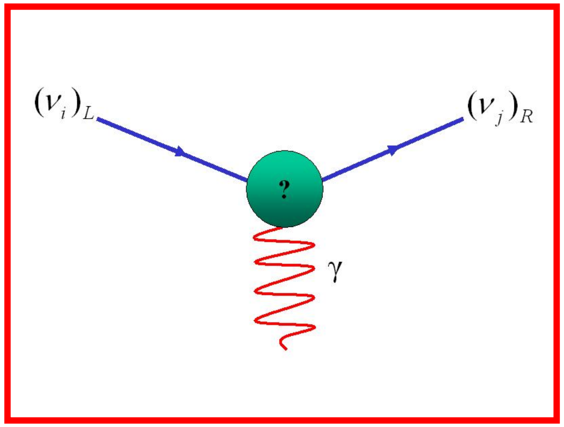
Dirac ν

A reactor experiment measuring electron antineutrino magnetic moment is an inclusive one, i.e. it sums over all the neutrino final states

$$\frac{d\sigma}{dT_e} = \frac{\alpha^2 \pi}{m_e^2} \mu_{\text{eff}}^2 \left[\frac{1}{T_e} - \frac{1}{E_\nu}\right]$$

$$\mu_{\text{eff}}^2 = \sum_i \left|\sum_j U_{ej} e^{-iE_j L} \mu_{ji}\right|^2$$

Neutrino magnetic moment



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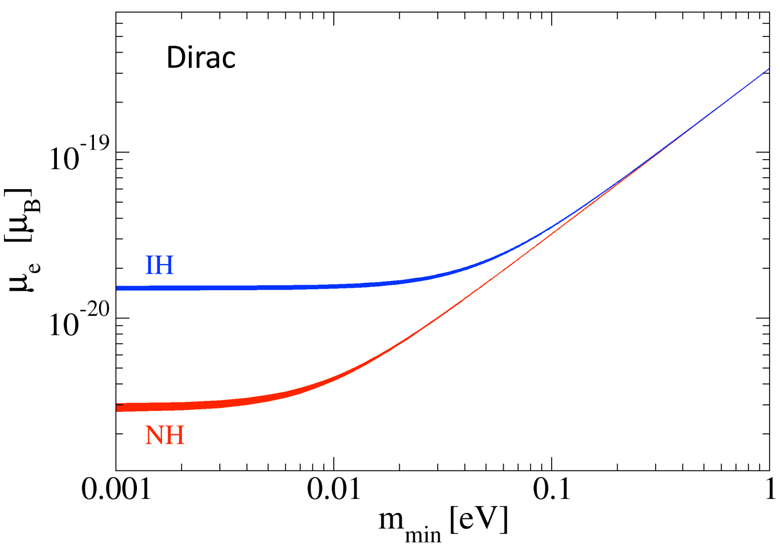

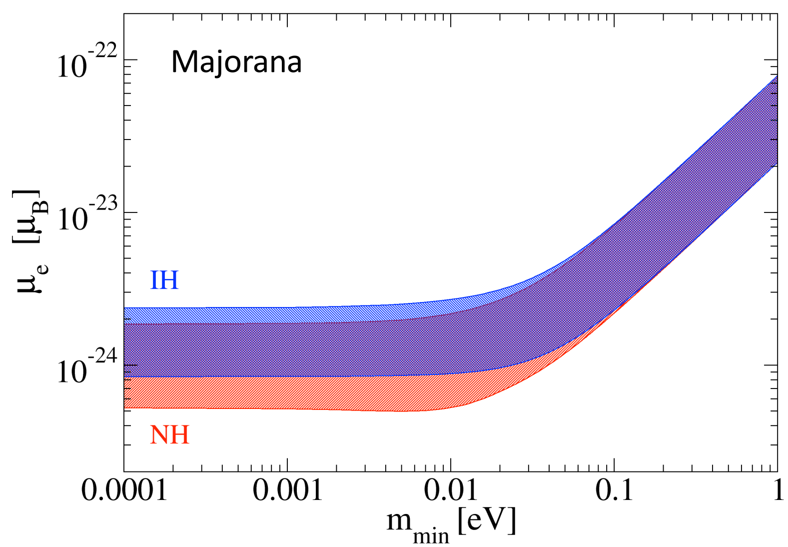

A.B.B., N. Vassh, PRD **89** (2014) 073013

Including magnetic moment in coherent neutrino scattering

$$\frac{d\sigma}{dT} = \frac{G_F^2}{8\pi} M \left[2 - \frac{2T}{T_{max}} + \left(\frac{T}{E}\right)^2\right] Q_W^2 [F_Z(Q^2)]^2 + \frac{\pi \alpha^2 \mu_{\mathrm{eff}}^2 Z^2}{m_e^2} \left[\frac{1}{T} - \frac{1}{E}\right] \left[F_\gamma(Q^2)\right]^2$$

$$\mu_{\mathrm{eff}}^2 = \sum_i \left| \sum_j U_{(e \text{ or } \mu)j} \; e^{-iE_j L} \mu_{ji} \right|^2$$

Note that this is a different combination than what is measured at reactors or solar neutrino experiments!

Thank You

Snowmass 2021: U.S. Strategic Planning Process for Particle Physics

NF06: Neutrino Interaction Cross-Sections Working Group

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We are contacting experimental collaborations, nuclear and astrophysicists.
We want to hear from all stakeholders.
Letters of interest are due to August 31, 2020:
https://snowmass21.org/loi

An online workshop is tentatively planned on September 3 and 4, 2020.