Neutrino Coherent Scattering, neutrino dipole moments, and connection to cosmology

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ACFI Workshop on
Neutrino-Electron Scattering at
Low Energies
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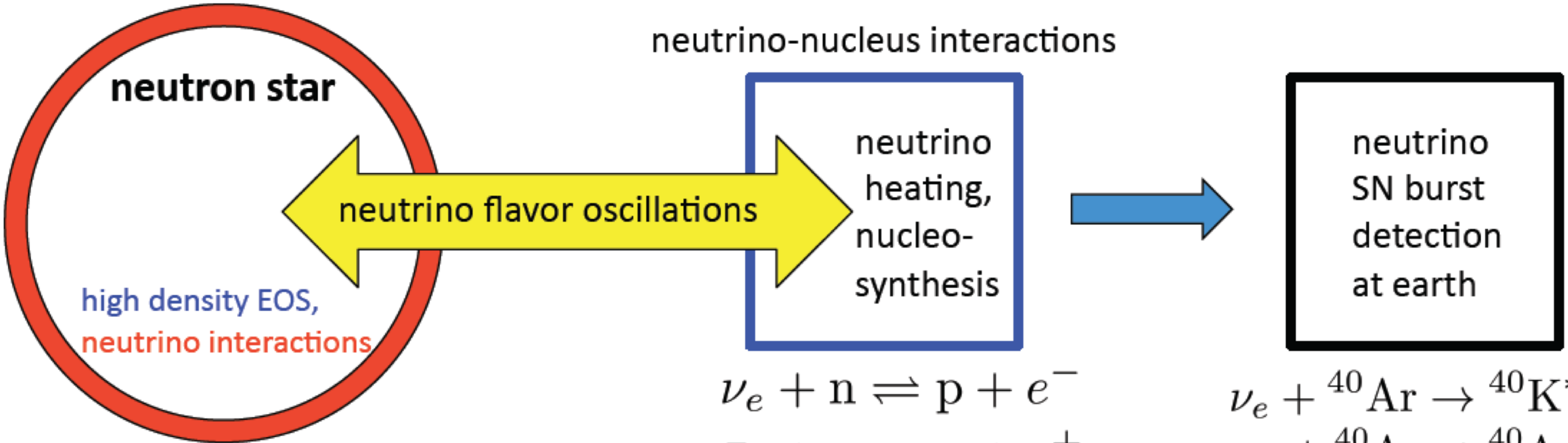
Understanding neutrino-nucleus interactions are essential to neutrino physics: for example consider a core-collapse supernova.

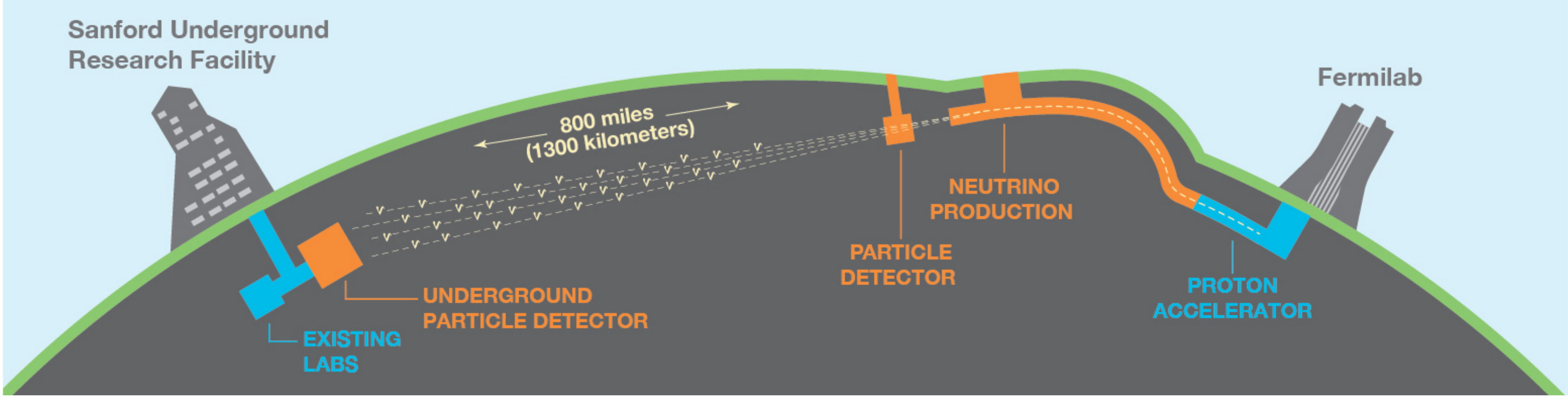
Balantekin and Fuller, Prog. Part. Nucl. Phys. **71** 162 (2013)



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

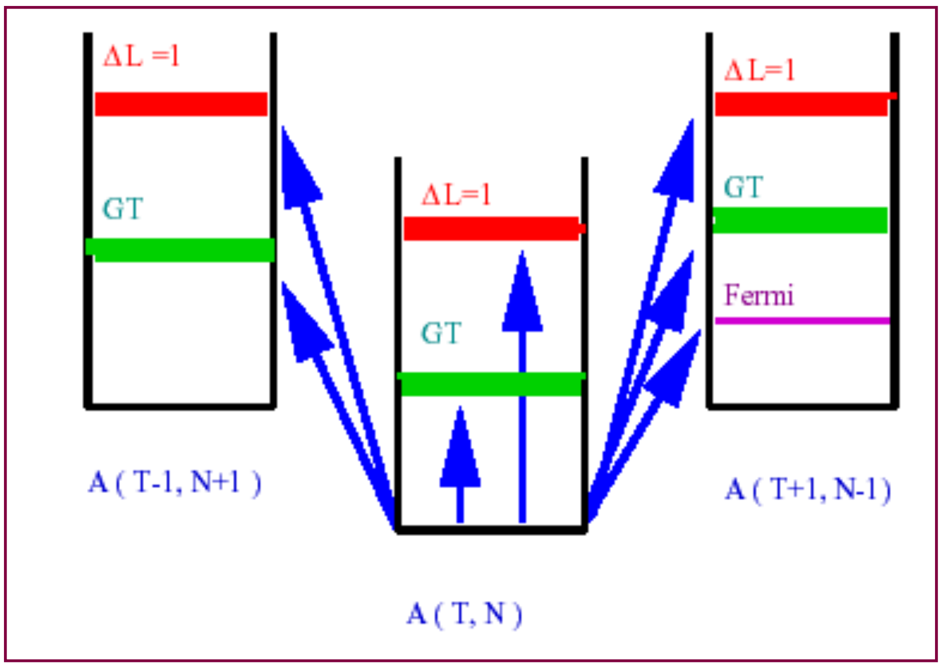
$$\nu_e + {}^{40}\mathrm{Ar} \to {}^{40}\mathrm{K}^* + e^-$$
$$\nu_x + {}^{40}\mathrm{Ar} \to {}^{40}\mathrm{Ar}^* + \nu_x$$

or a long-baseline experiment



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

For many aspects of SN physics we need to know what happens when a 10-40 MeV neutrino 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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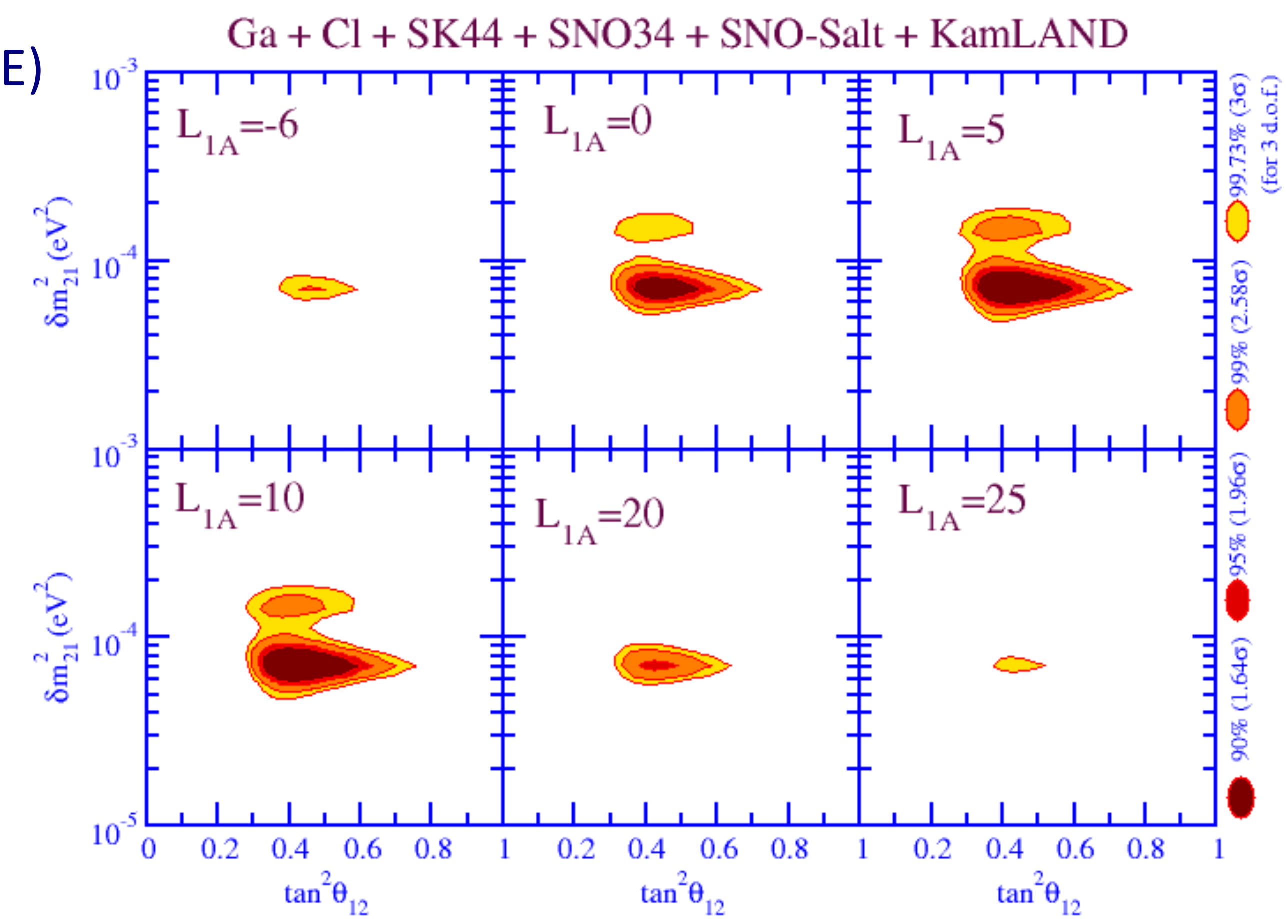

A.B. Balantekin and H. Yuksel, PRC **68** 055801 (2003)

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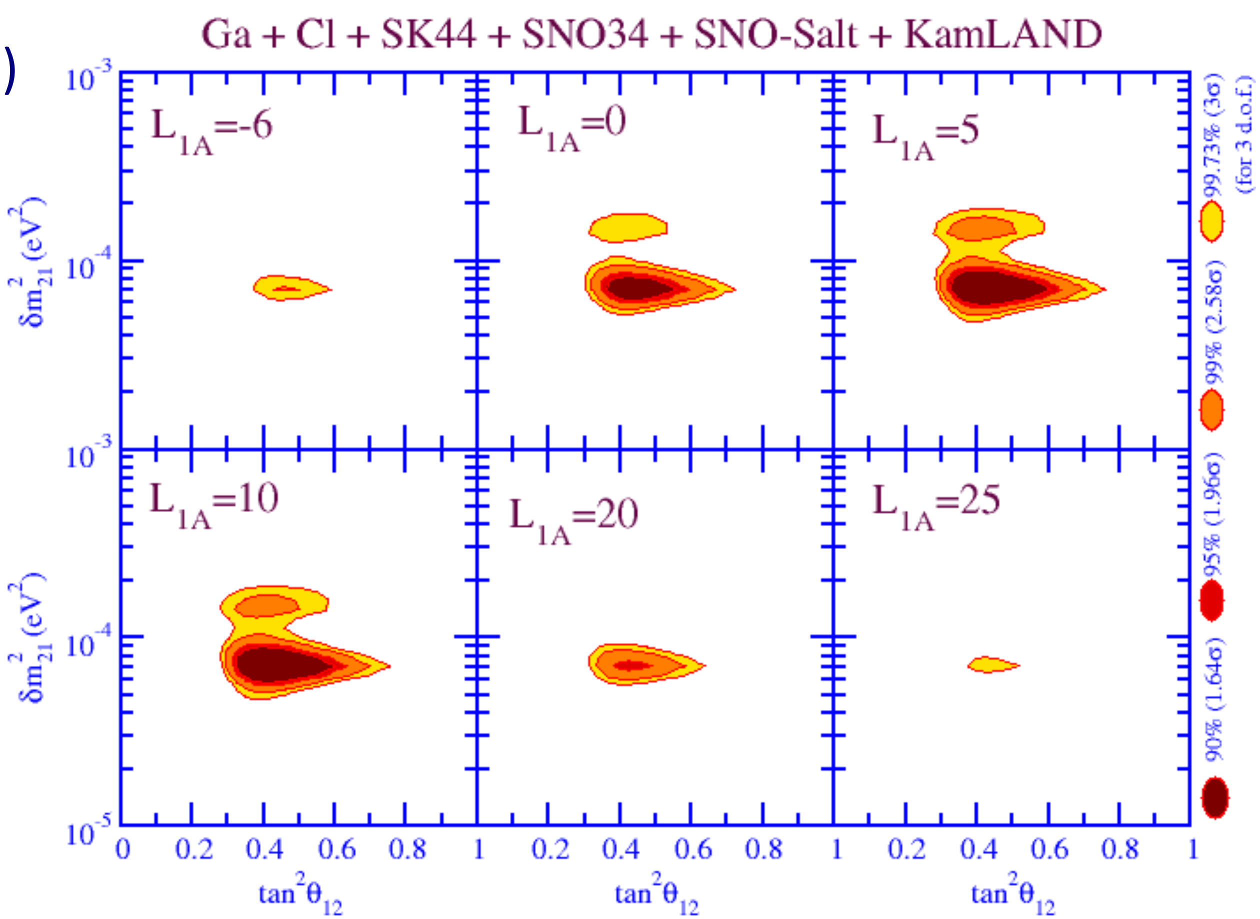
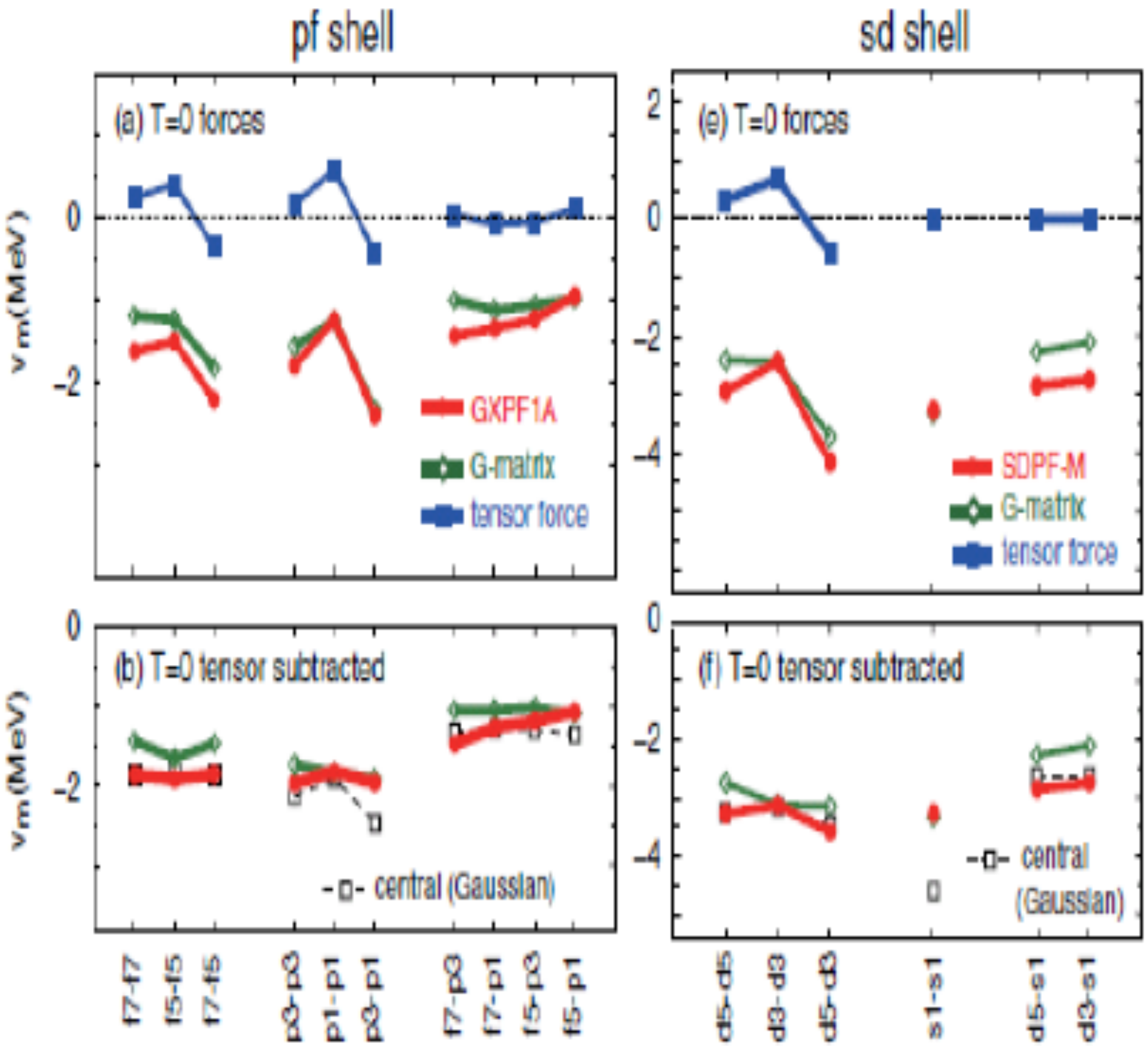
L_{1A}=3.9(0.1)(1.0)(0.3)(0.9) fm^3 at a renormalization scale set by the physical pion mass
Savage et al., PRL 119, 062002 (2017)



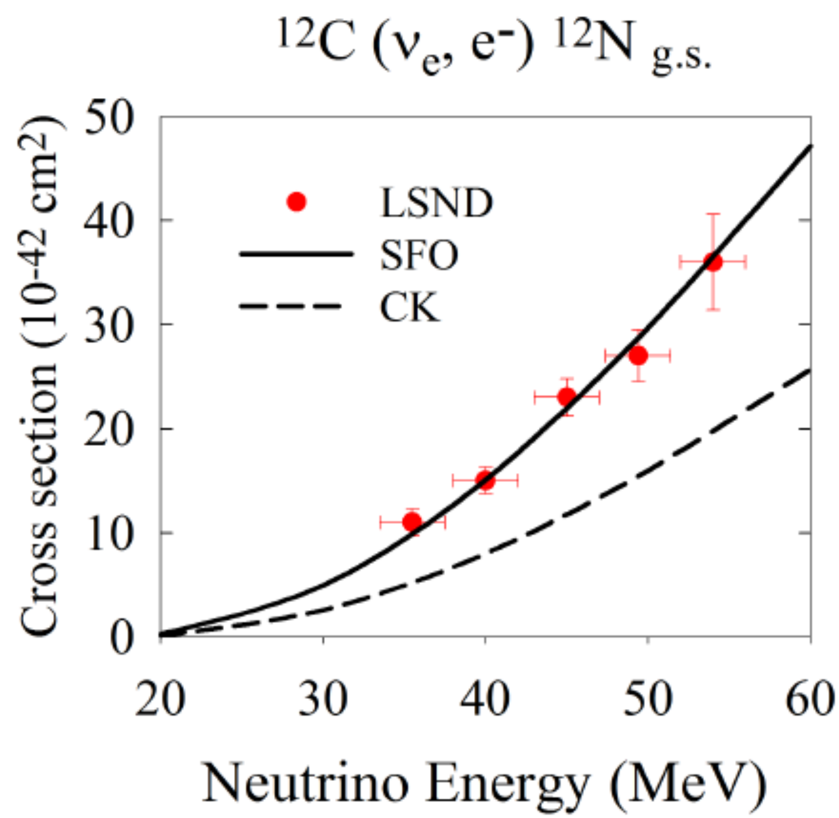
A.B. Balantekin and H. Yuksel, PRC **68** 055801 (2003)

Difficult to go beyond two-body systems!

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

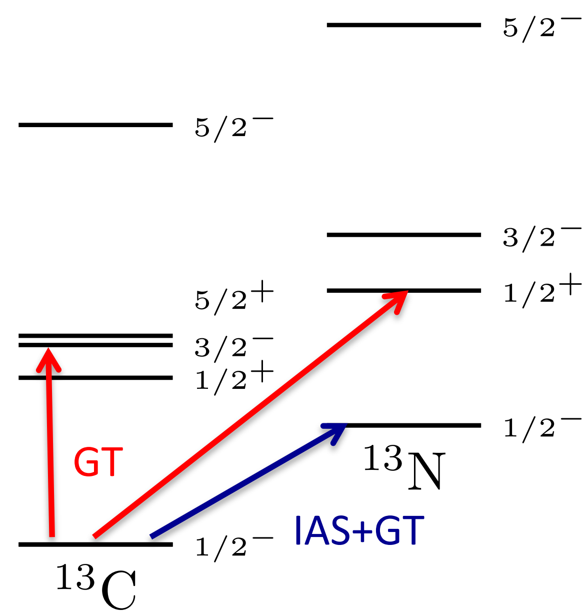


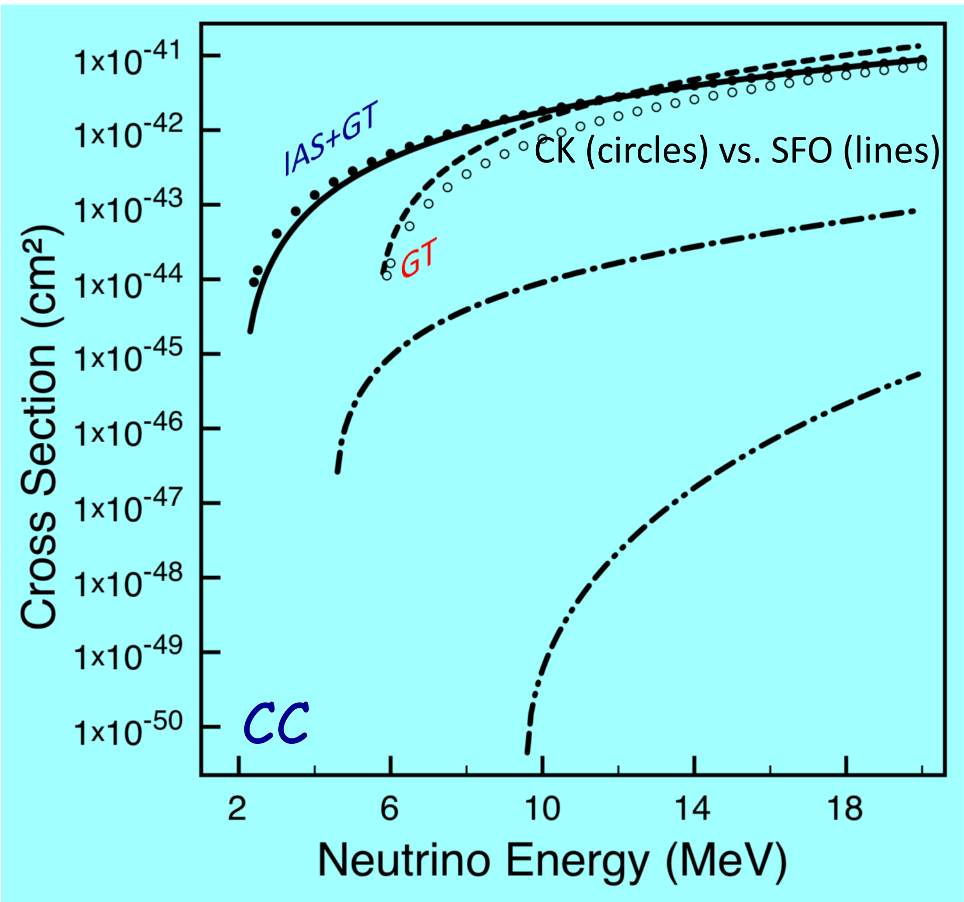
Suzuki, Fujimoto, Otsuka

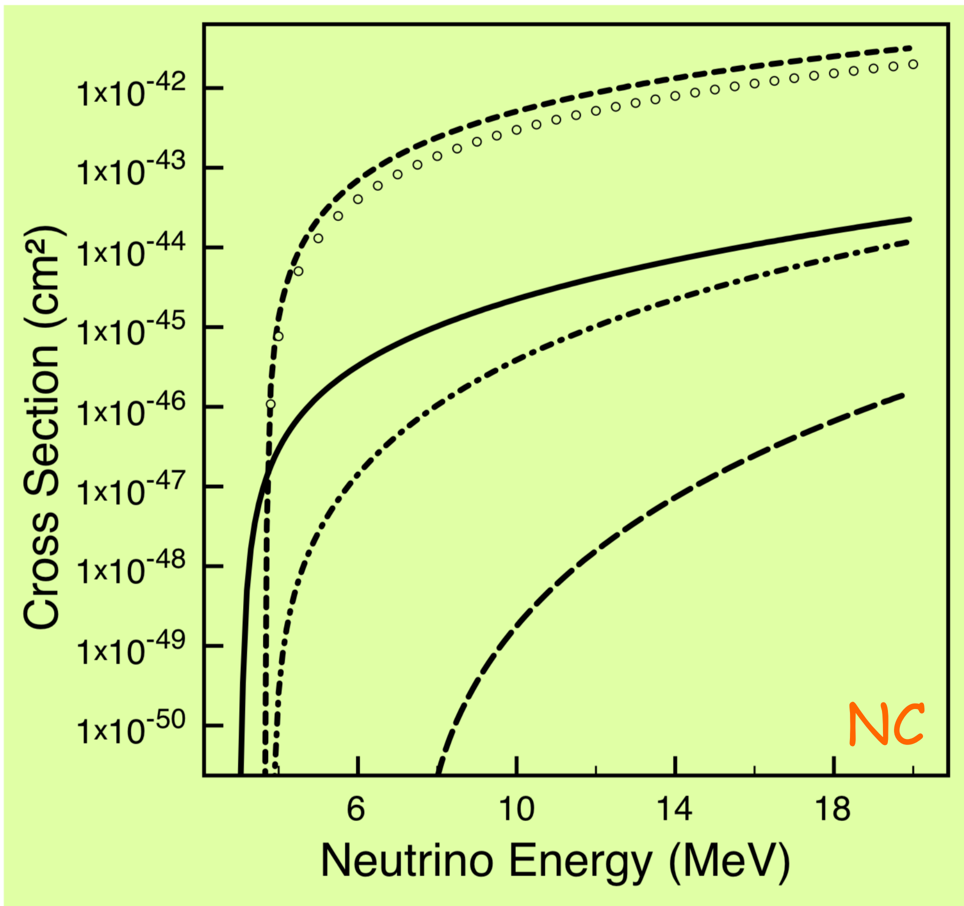


An example: $\nu_e + ^{13}C$

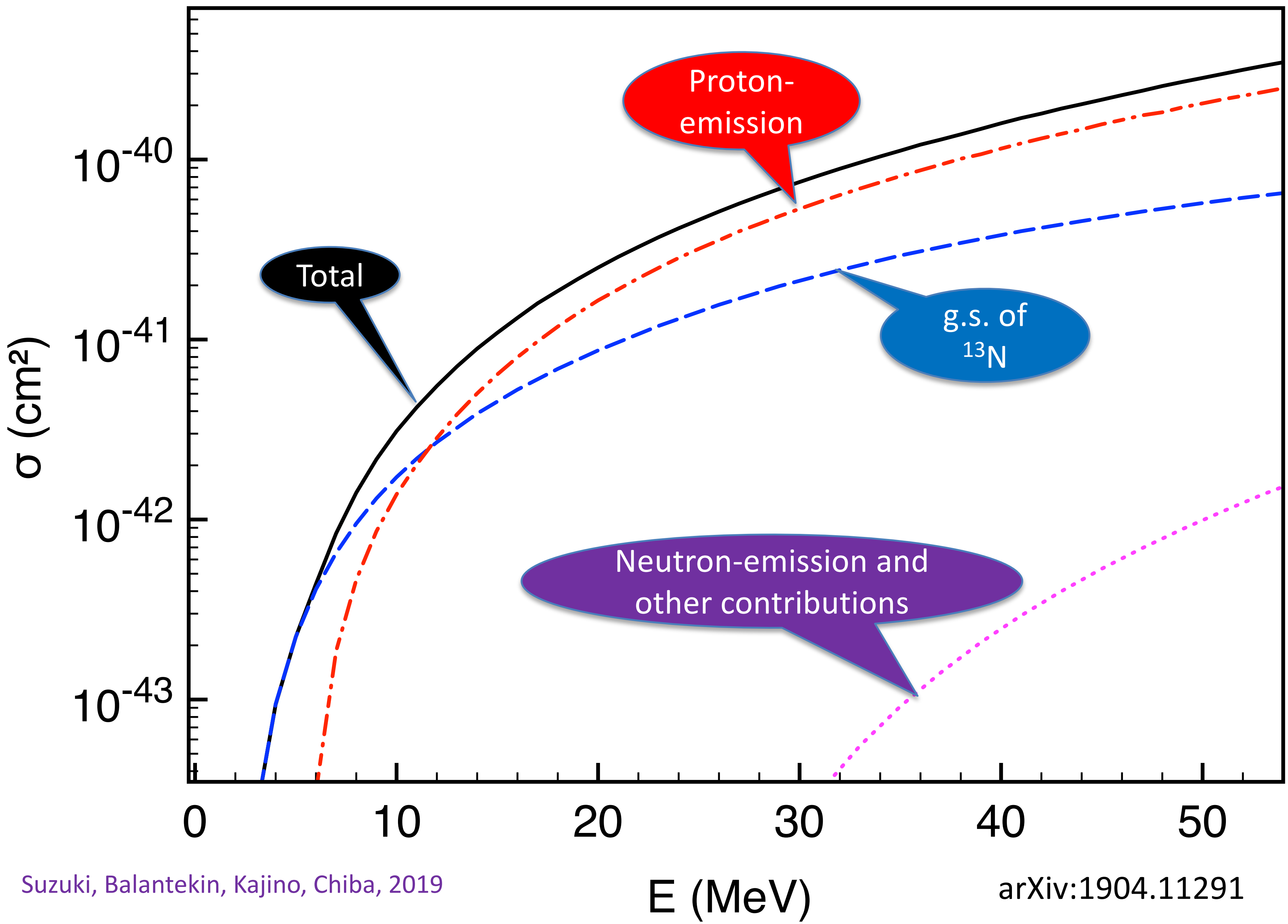
Suzuki, Balantekin, Kajino,
Phys. Rev. C **86**, 015502 (2012)







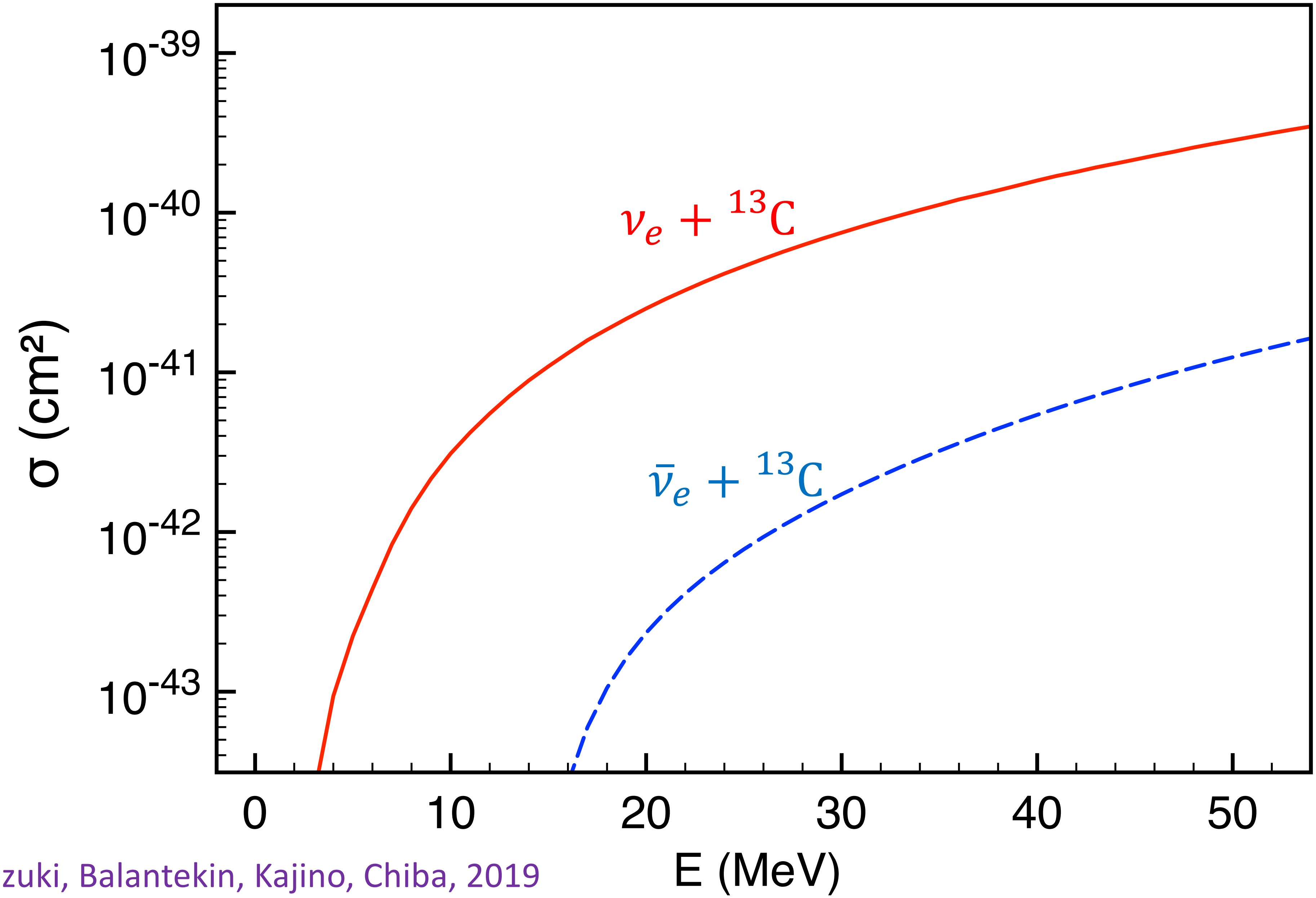
$\nu_e + {}^{13}C$ charged-current scattering



Suzuki, Balantekin, Kajino, Chiba, 2019

arXiv:1904.11291

Comparison of charged-current cross sections



Suzuki, Balantekin, Kajino, Chiba, 2019

Neutrino Coherent Scattering

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

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

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

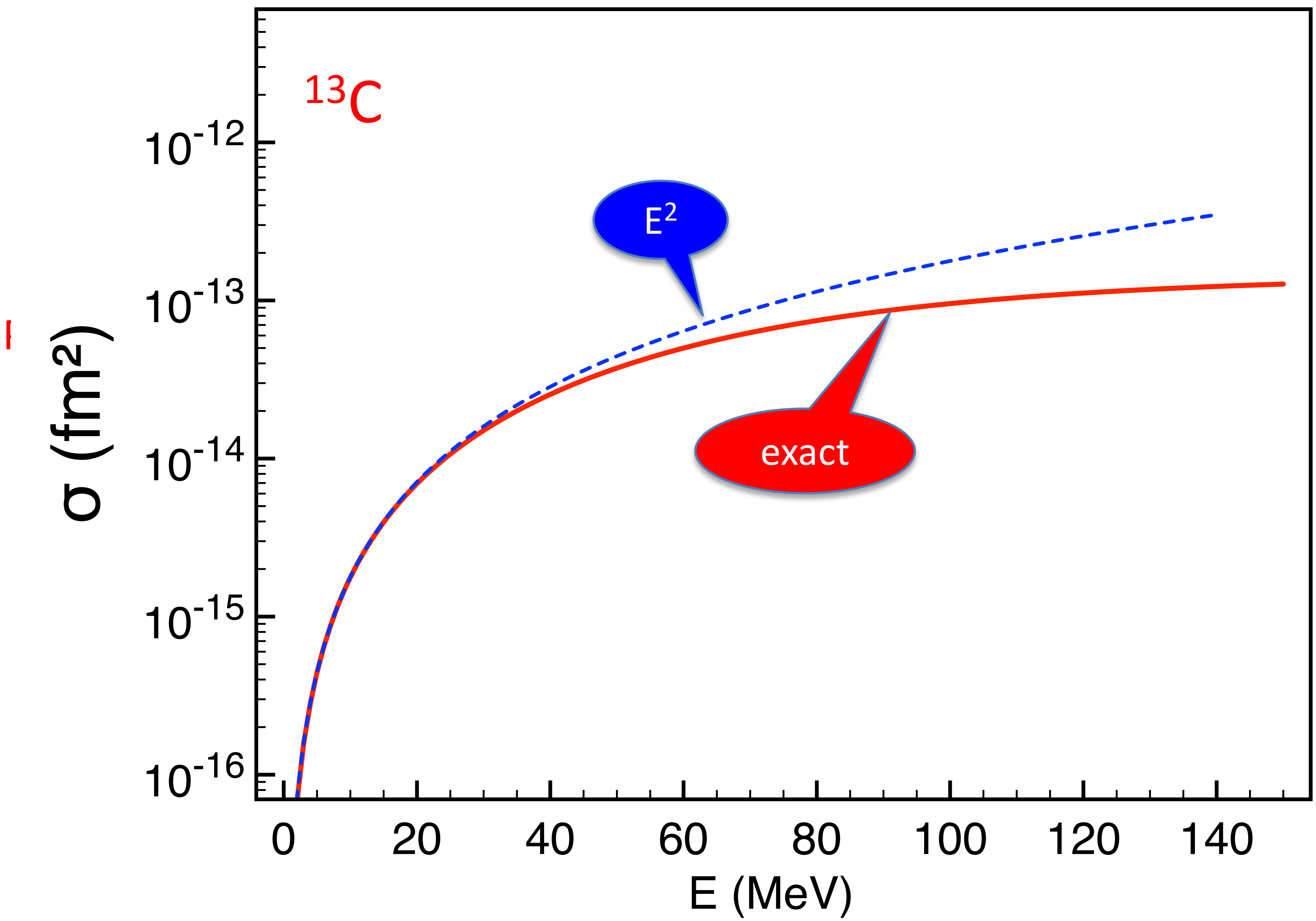
$$Q^2 = 2MT$$

For nearly spherical systems

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

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

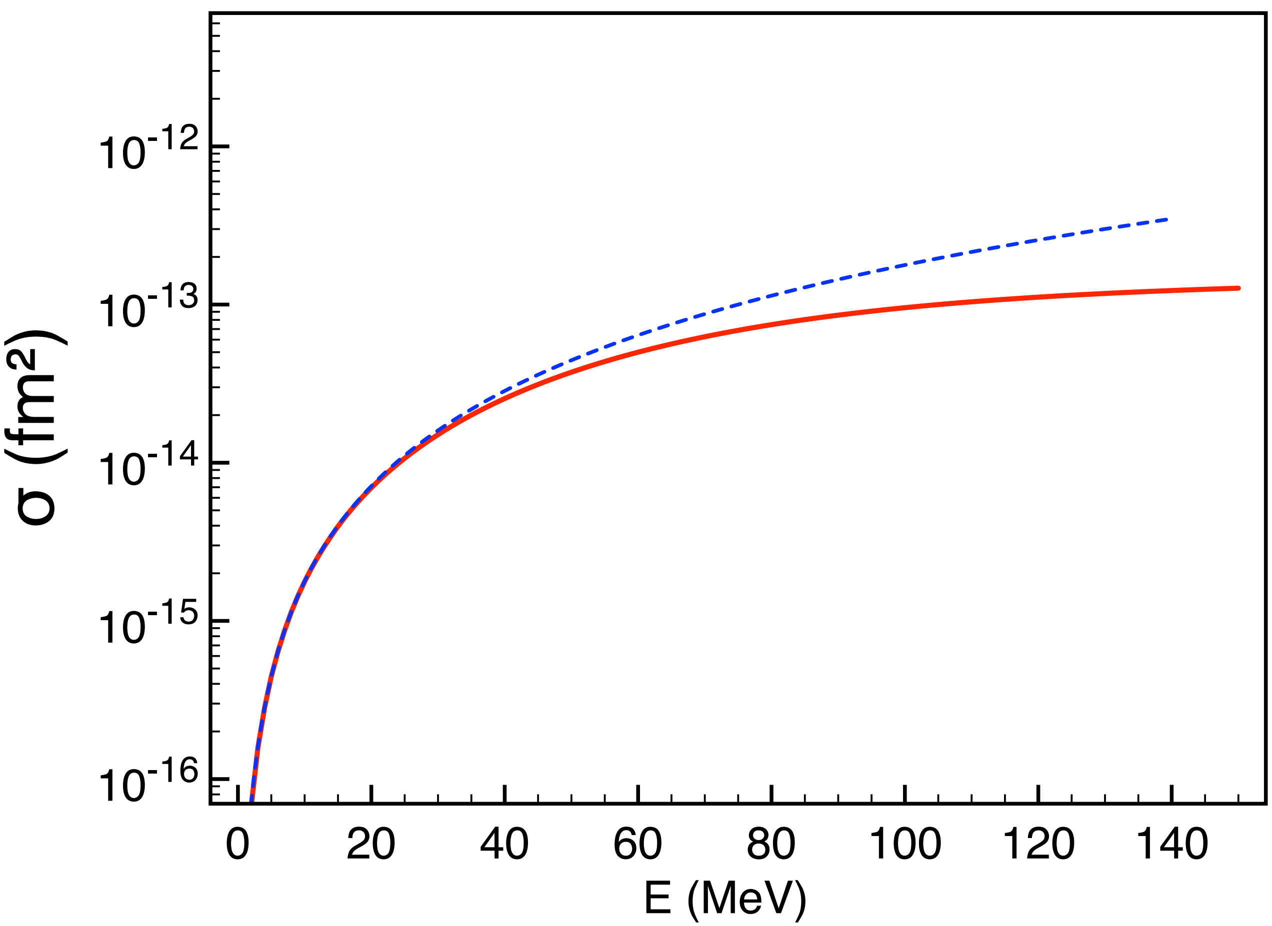
$$\sigma(E) \propto E^2 + \text{ nuclear corrections}$$



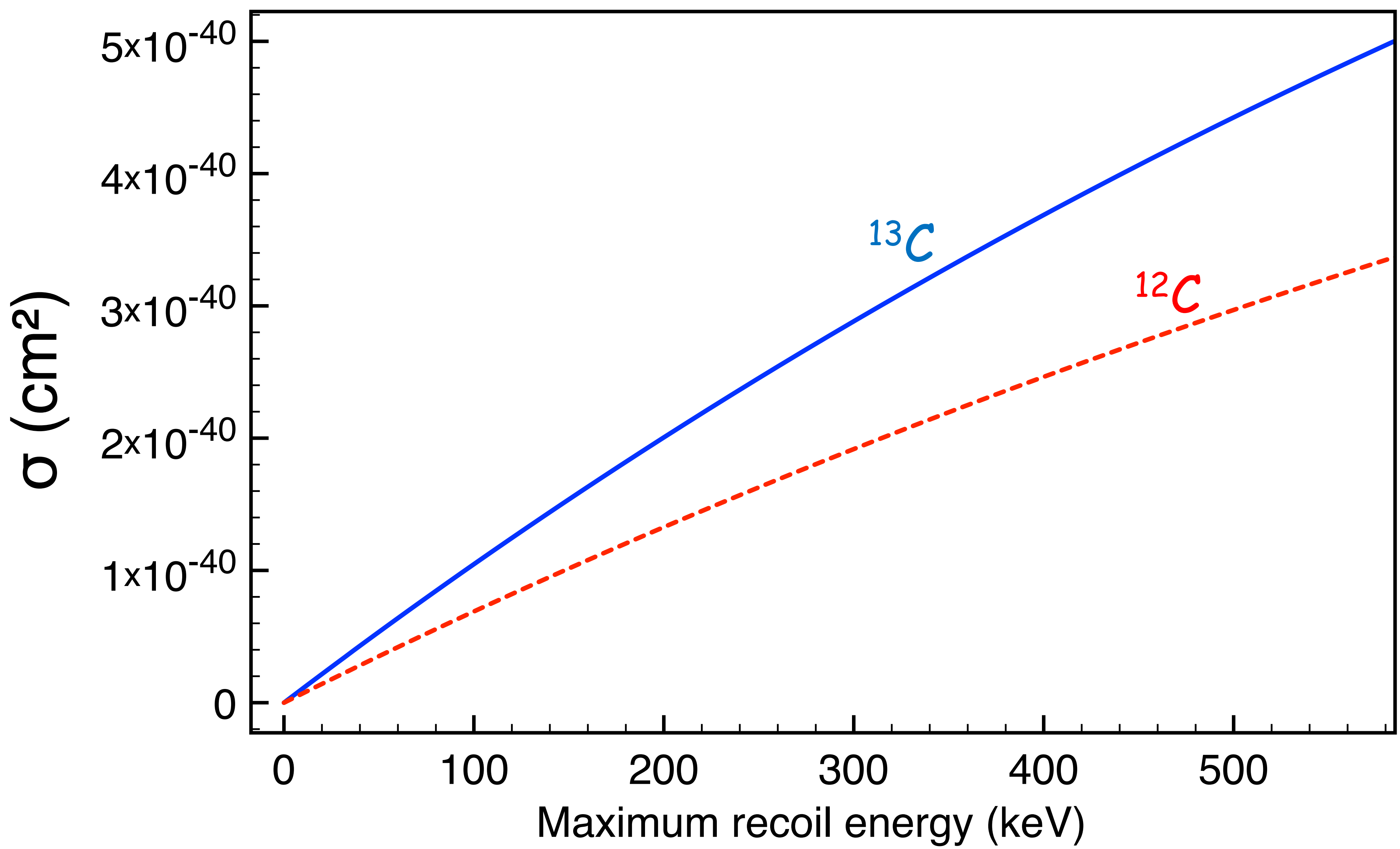
Suzuki, Balantekin, Kajino, Chiba, 2019

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

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



Coherent elastic neutrino cross sections



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

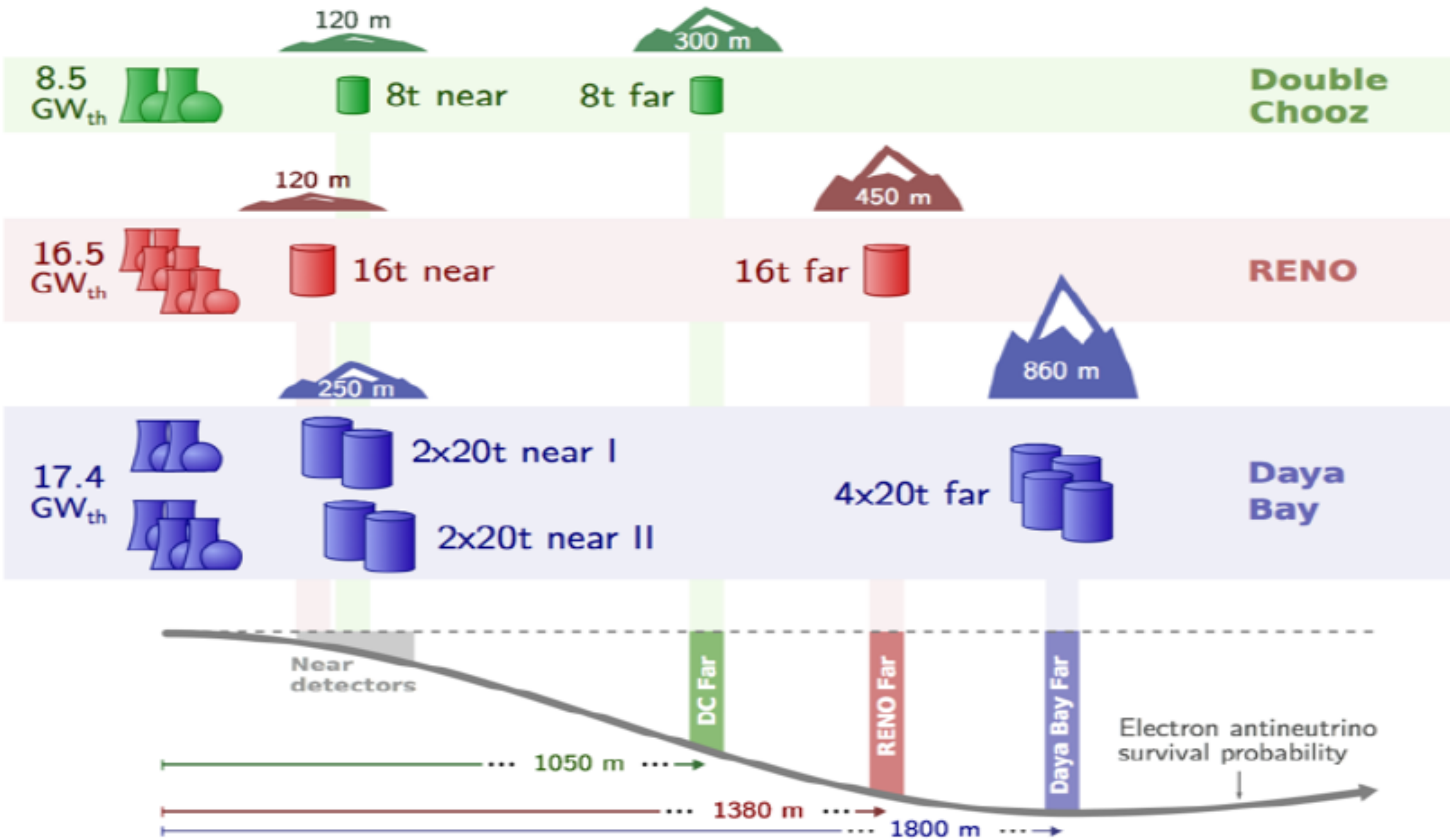
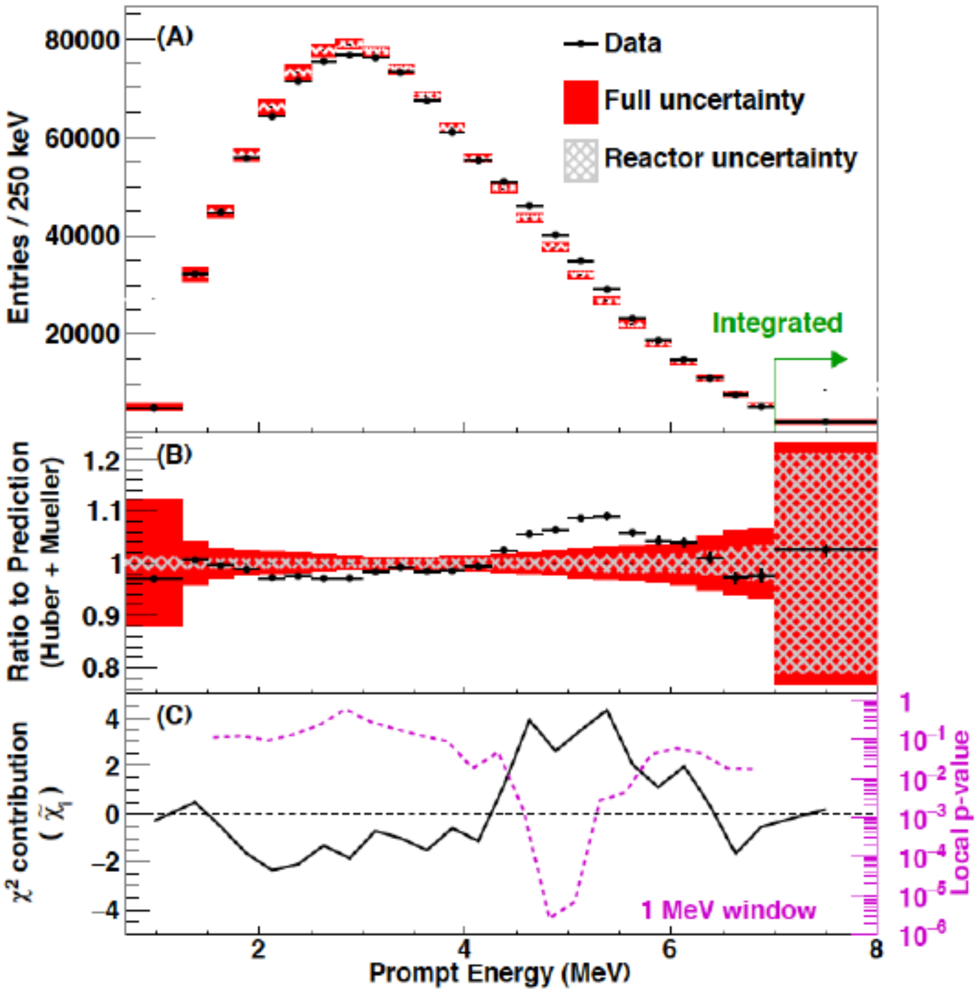
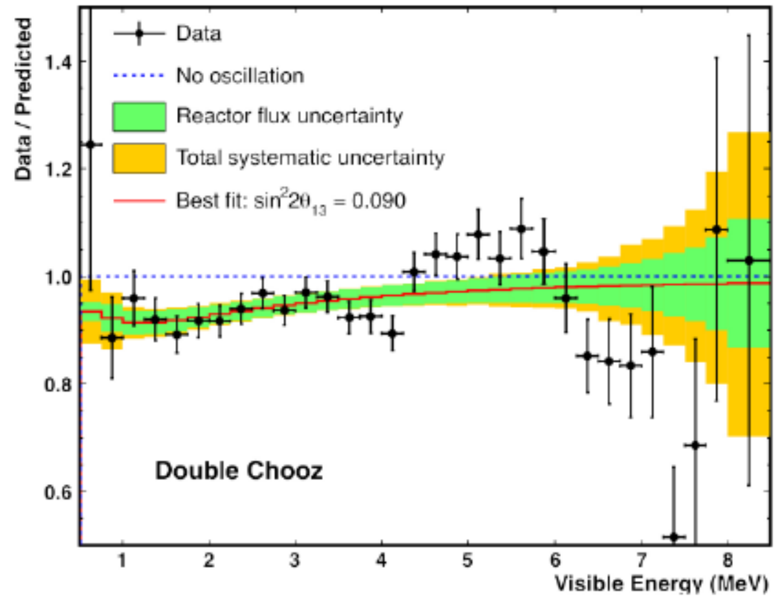
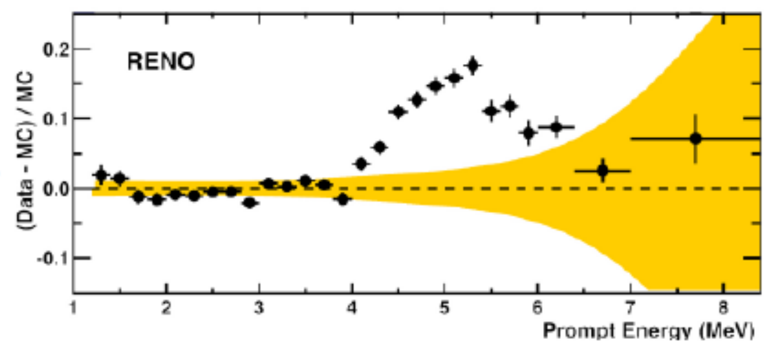
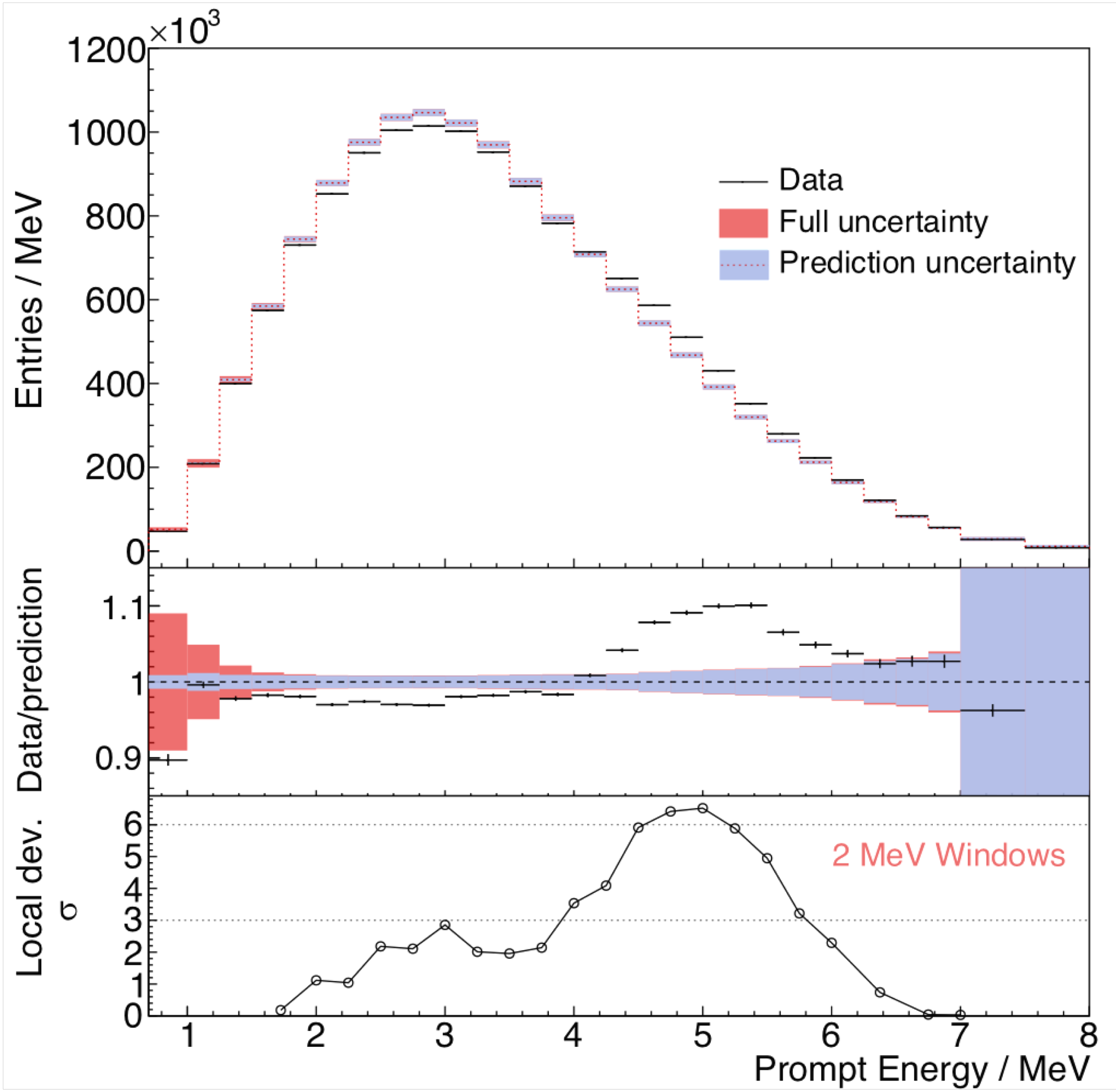


Fig: S. Jetter

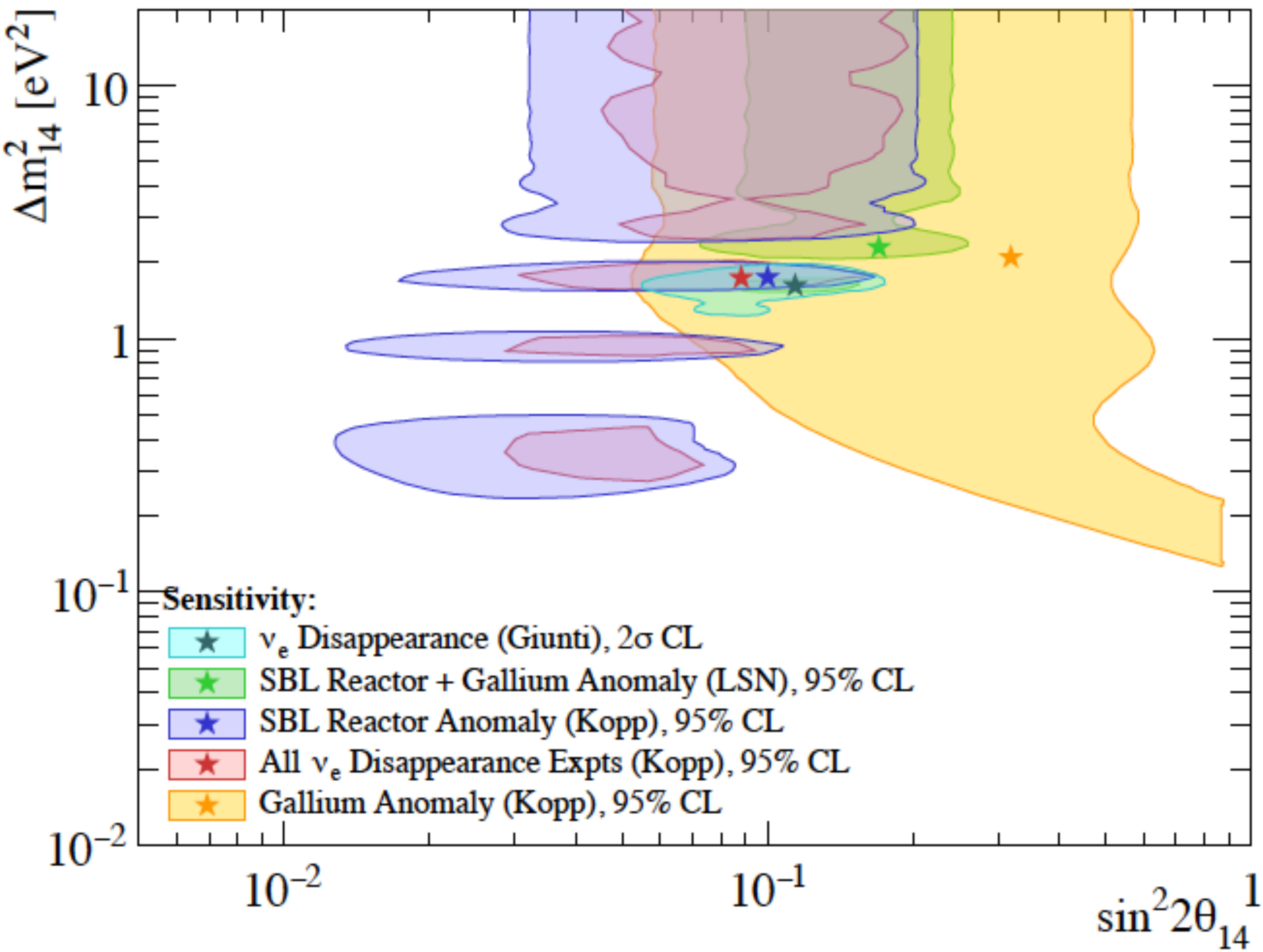

(A)
Data
Full uncertainty
Reactor uncertainty
Integrated
Entries / 250 keV
80000
60000
40000
20000
(B)
Ratio to Prediction
(Huber + Mueller)
1.2
1.1
1
0.9
0.8
(C)
χ^2 contribution
$(\tilde{\chi}_i)$
4
2
0
−2
−4
1 MeV window
Local p-value
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
2
4
6
8
Prompt Energy (MeV)


Data
No oscillation
Reactor flux uncertainty
Total systematic uncertainty
Best fit: $\sin^2 2\theta_{13}$ = 0.090
Data / Predicted
1.4
1.2
1.0
0.8
0.6
Double Chooz
1
2
3
4
5
6
7
8
Visible Energy (MeV)


RENO
(Data - MC) / MC
0.2
0.1
0.0
-0.1
1
2
3
4
5
6
7
8
Prompt Energy (MeV)



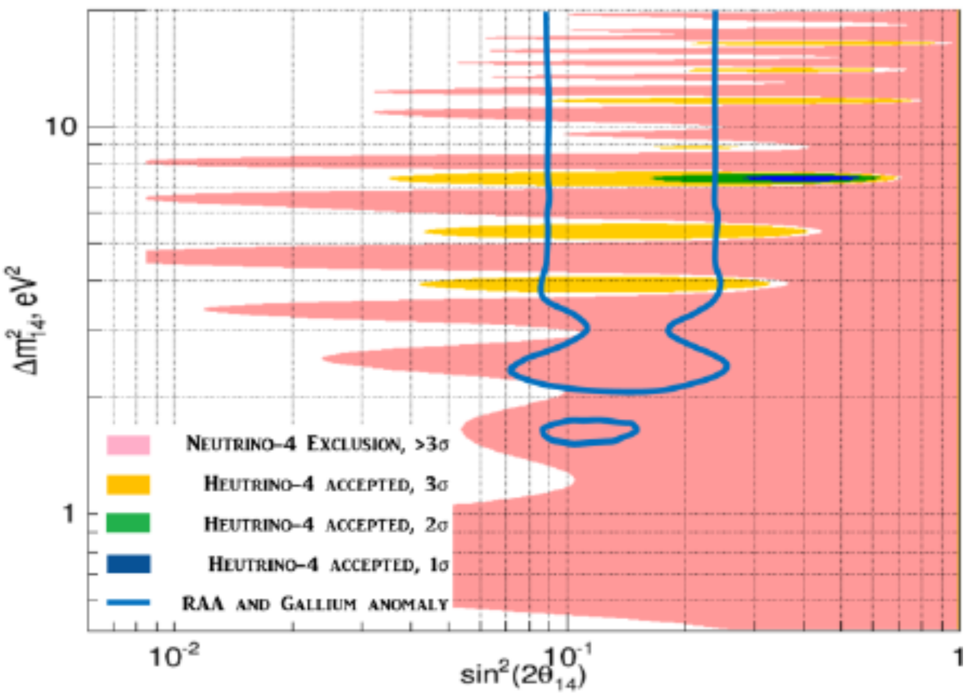
Daya Bay,
arXiv:1904.07812

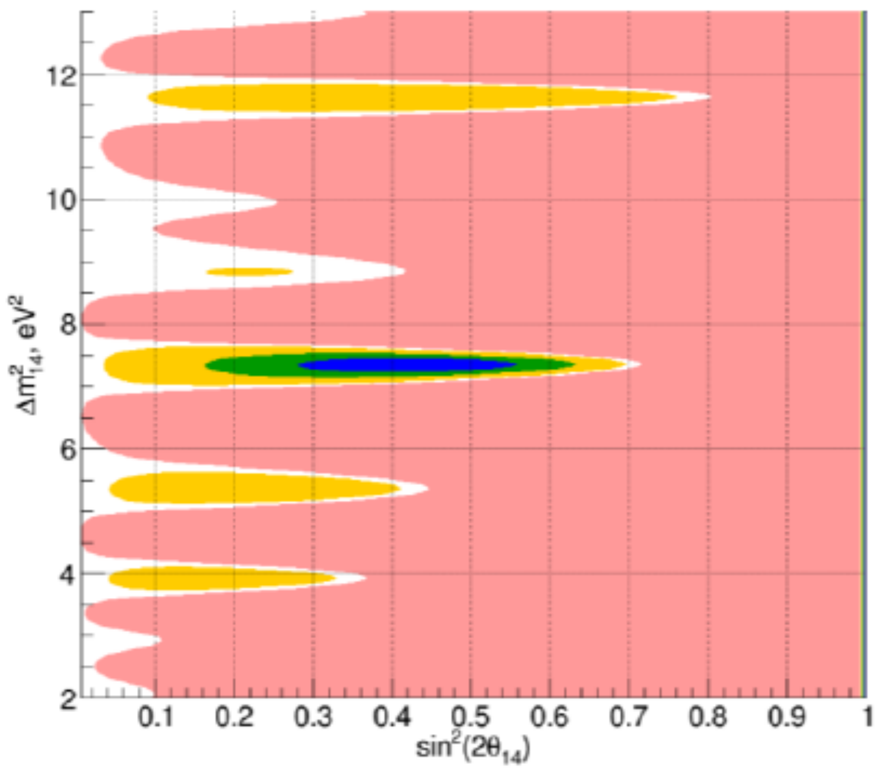


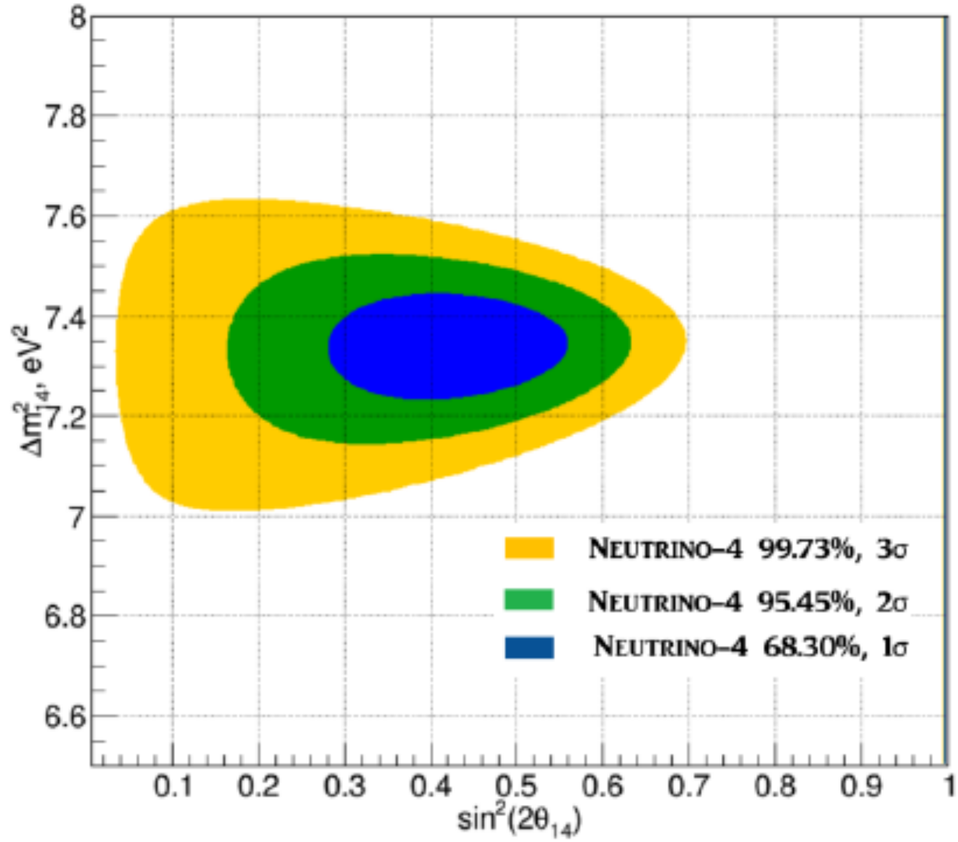
PROSPECT Collaboration, J. Phys. G **43**, 113001 (2016)

NEUTRINO-4 claim

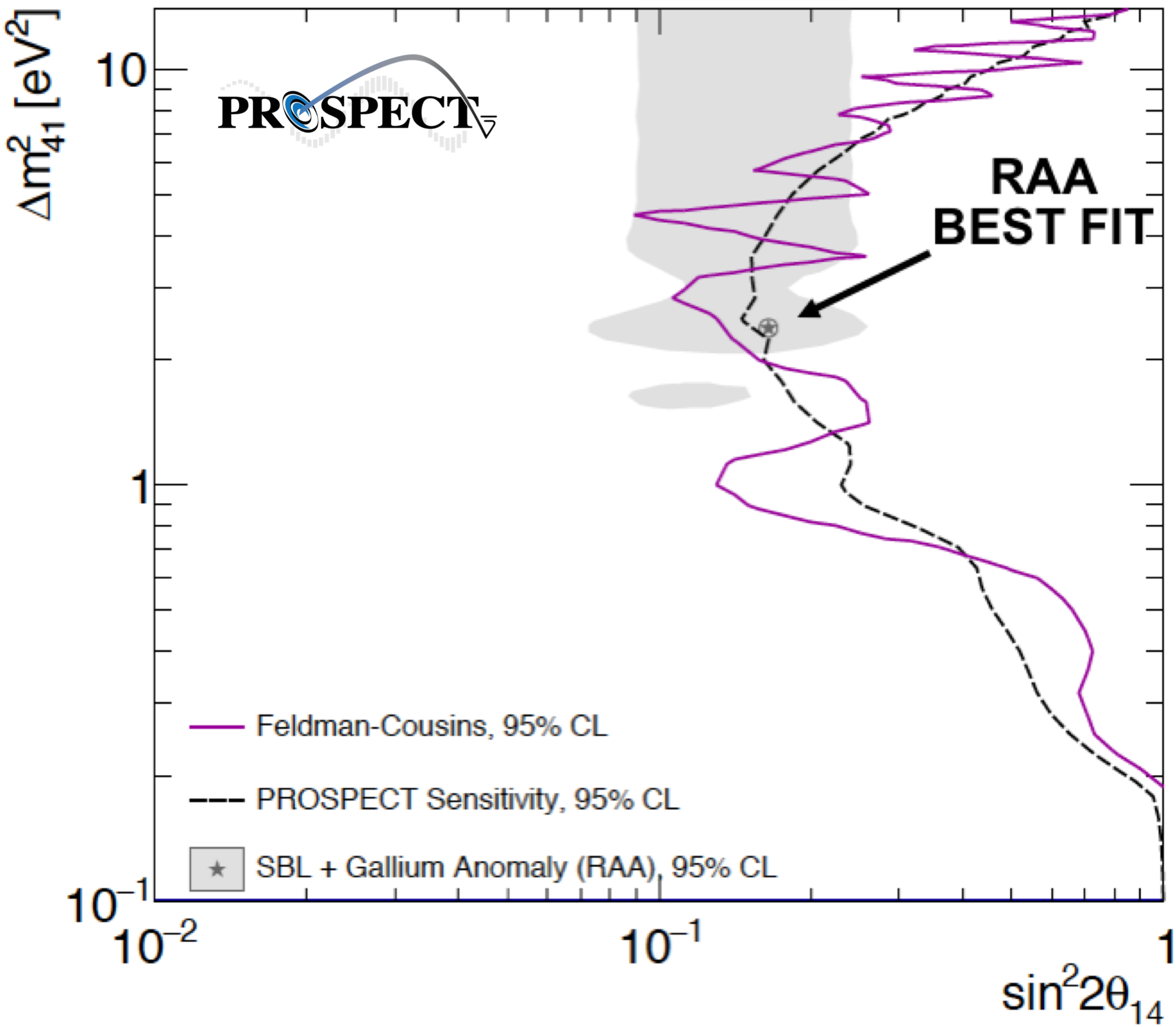
arXiv: 1809.10561







Oscillation Exclusion



PROSPECT - arXiv:1806.02784

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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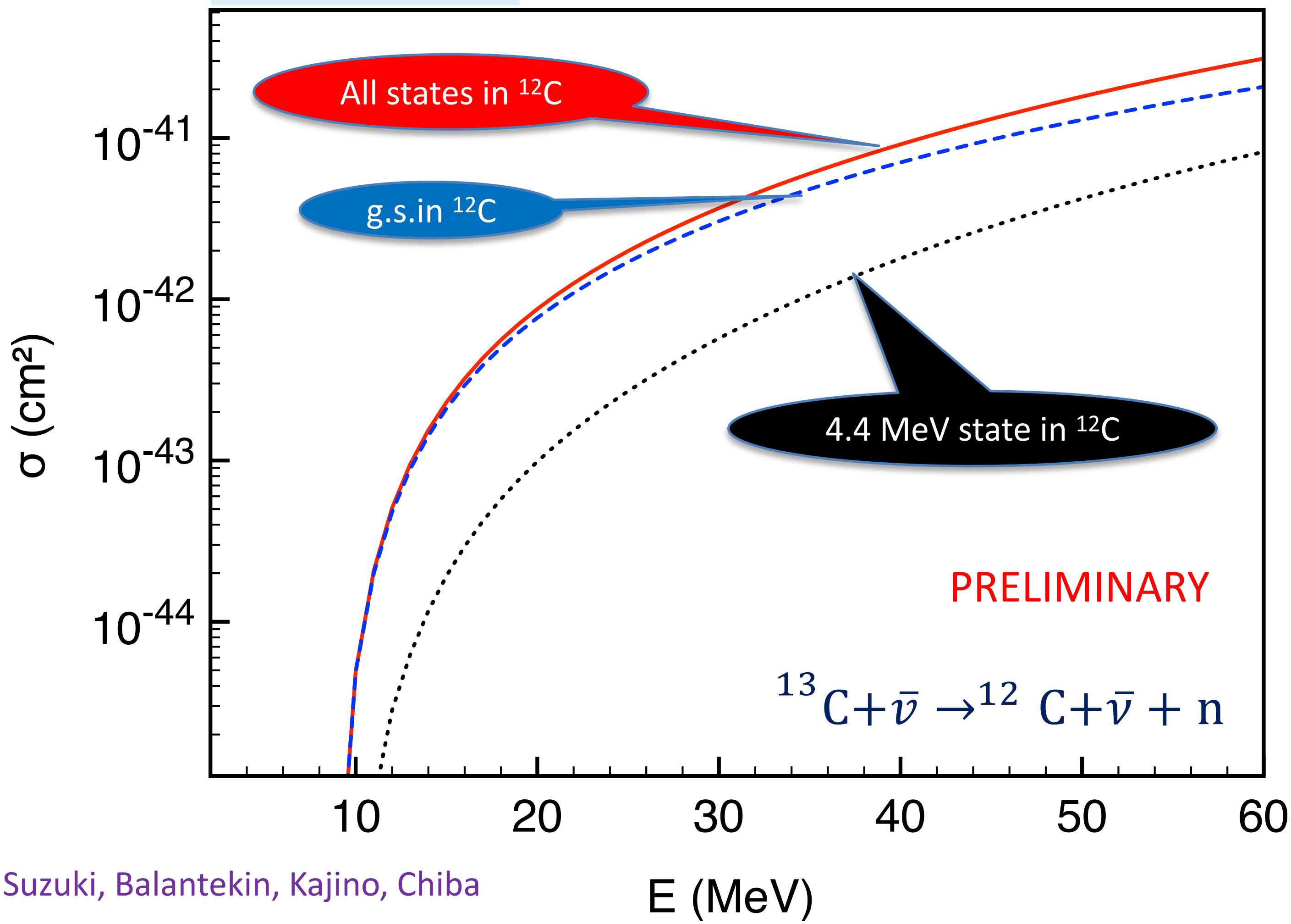
HOWEVER



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.

Introduce a magnetic moment operator, $\hat{\mu}$

Example: Neutrino-electron scattering via magnetic moment

$$\sigma \propto \sum_i \left| \langle \nu_i | \hat{\mu} | \nu_e \rangle \right|^2 = \langle \nu_e | \hat{\mu}^\dagger \hat{\mu} | \nu_e \rangle$$

Dirac magnetic moment $\hat{\mu}^\dagger = \hat{\mu}$

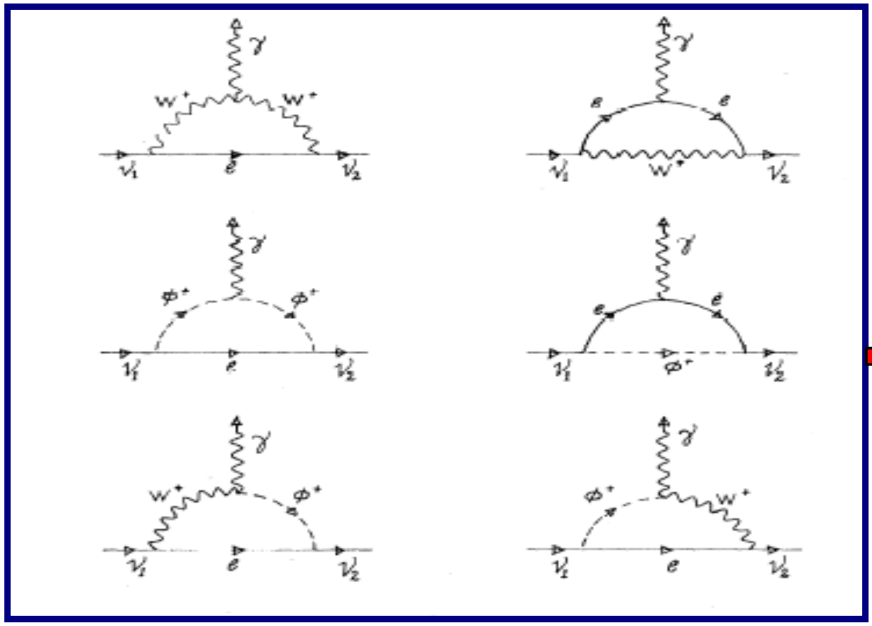
Majorana magnetic moment $\hat{\mu}^T = -\hat{\mu}$

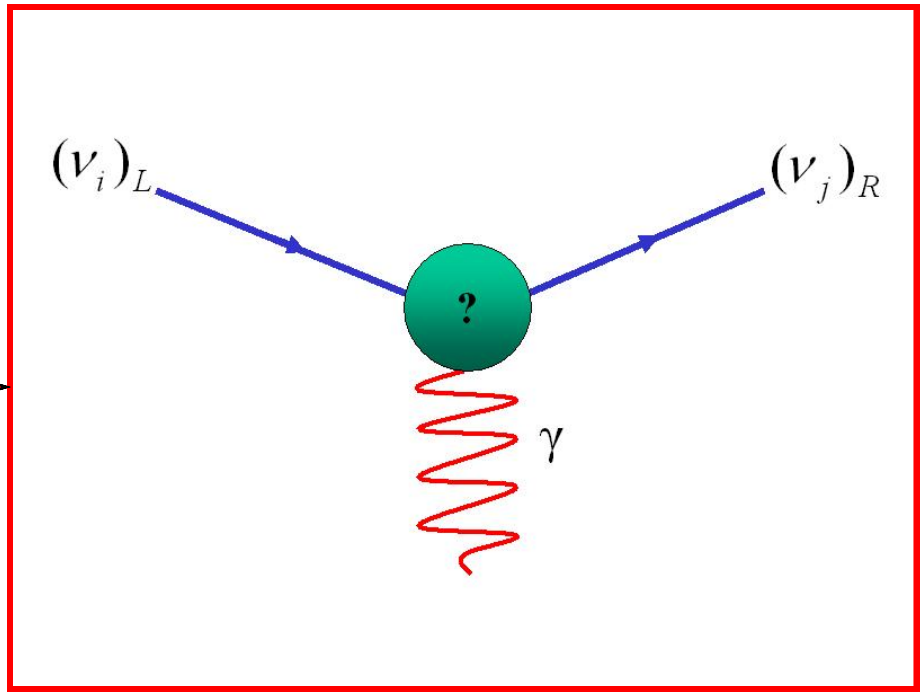
A reactor experiment measuring electron antineutrino magnetic moment is an inclusive one, i.e. it sums over all the neutrino final states

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

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

Neutrino Magnetic Moment in the Standard Model





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

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

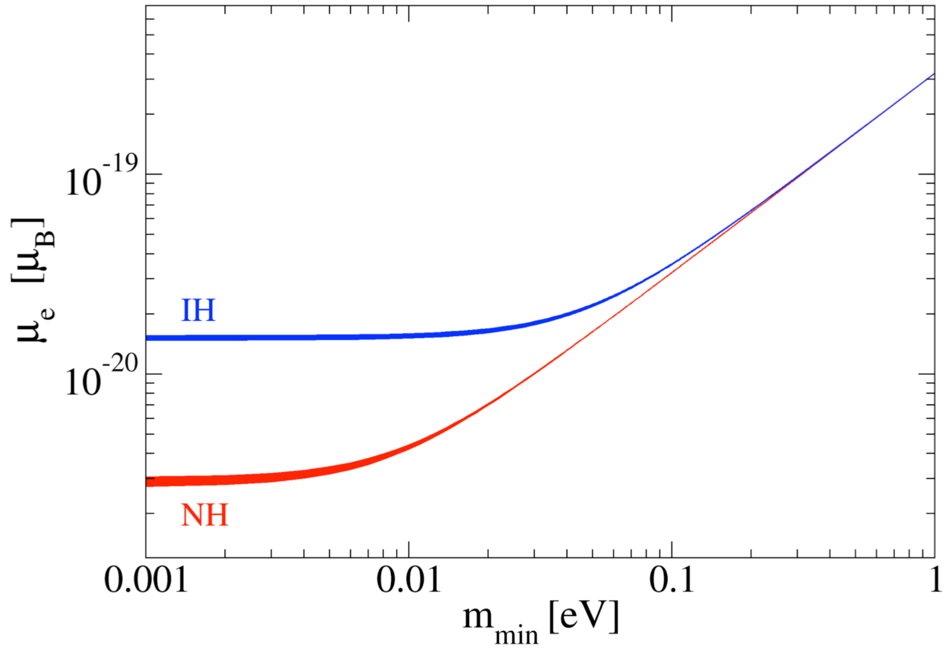
Standard Model (Dirac)

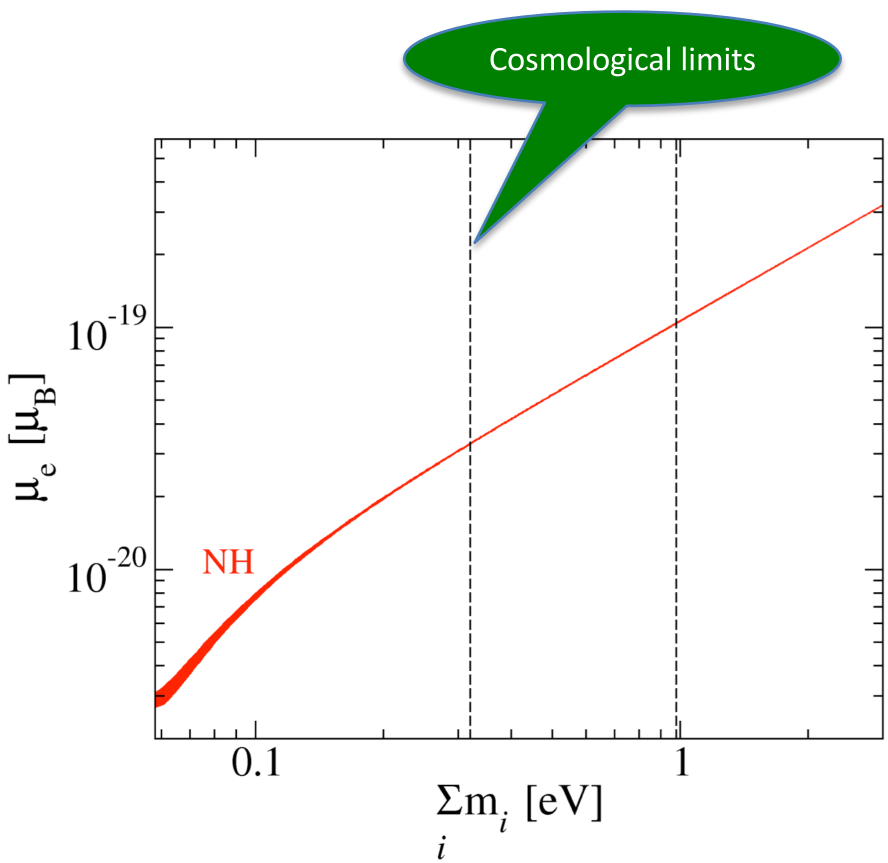
Symmetry Principles

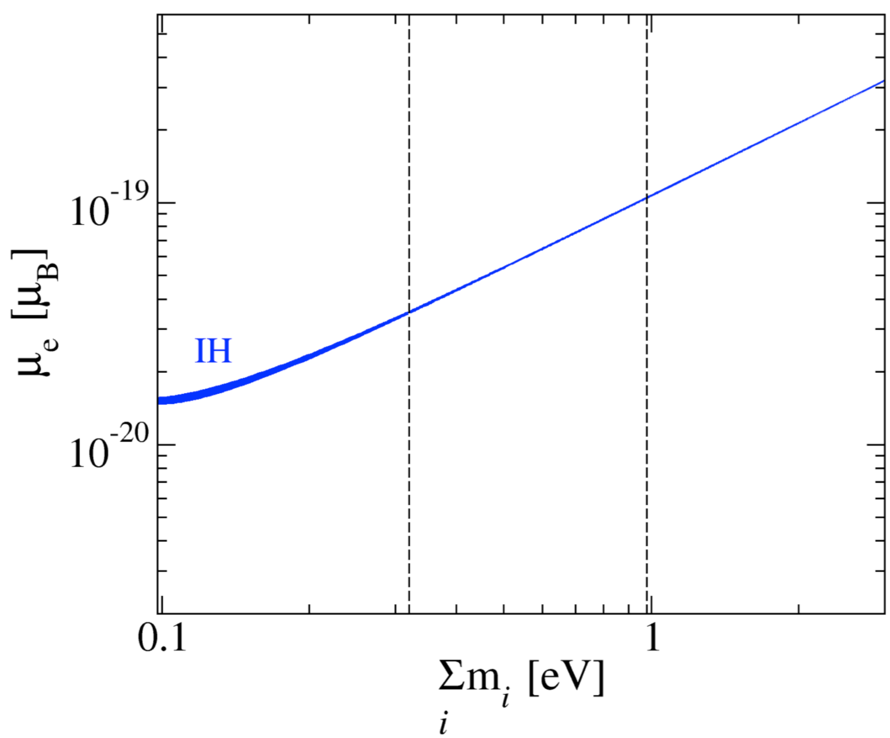
$\Rightarrow \mu_\nu \to 0$ as $m_\nu \to 0$

Standard Model (only) contribution to the Dirac neutrino magnetic moment measured at reactors

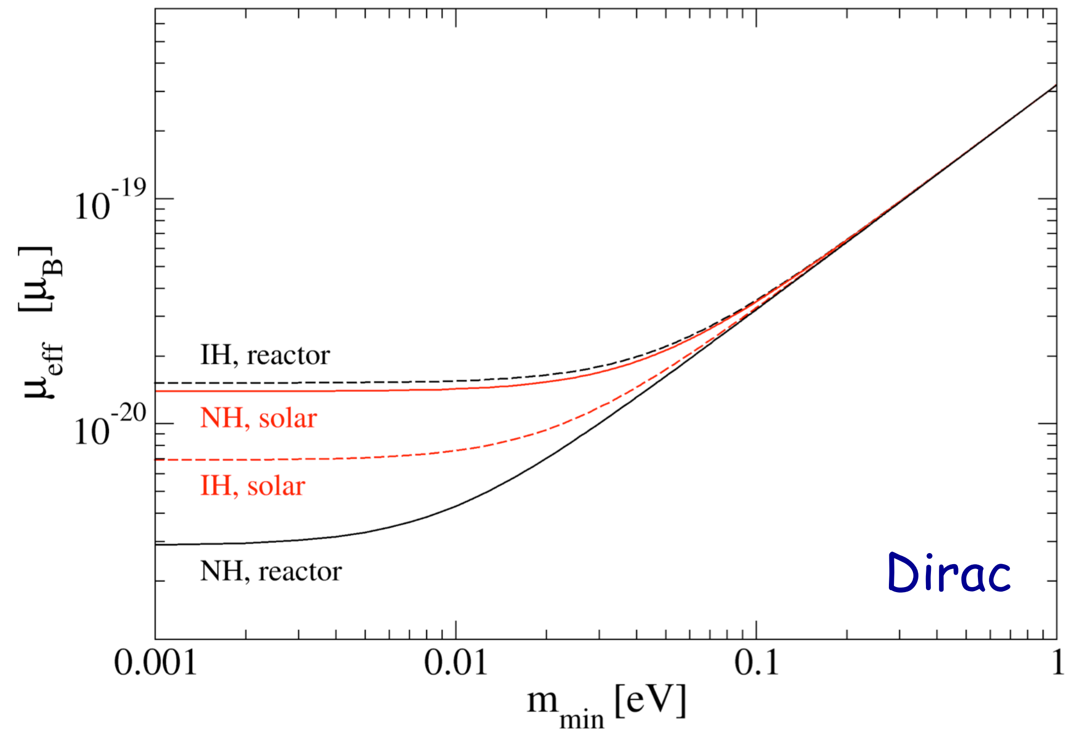
A.B.B., N. Vassh, PRD **89** (2014) 073013



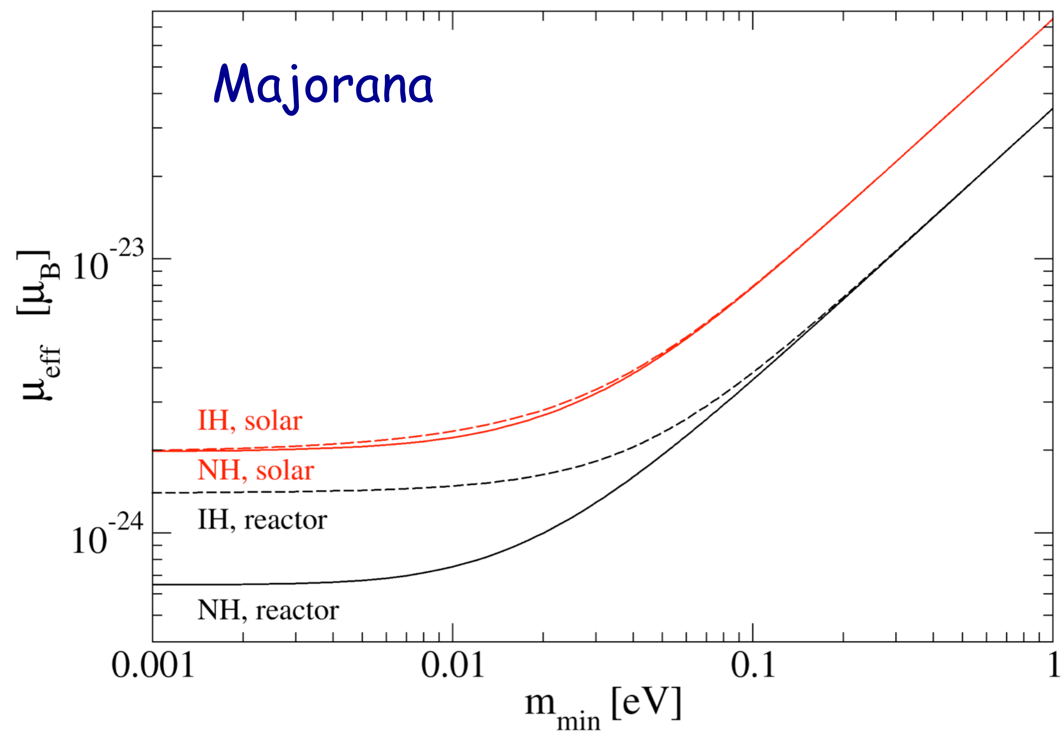




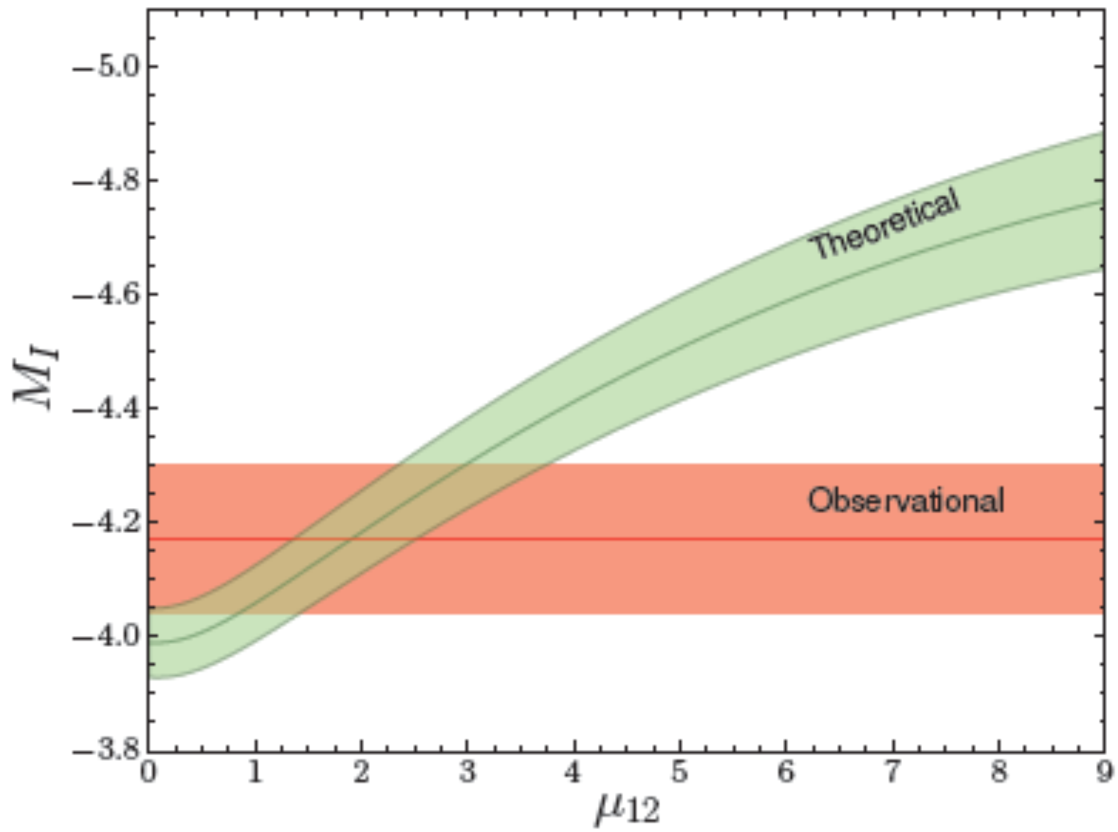
Reactors vs. solar Cerenkov detectors



A.B.B. & N. Vassh
AIP Conf.Proc. **1604** (2014) 150
arXiv:1404.1393

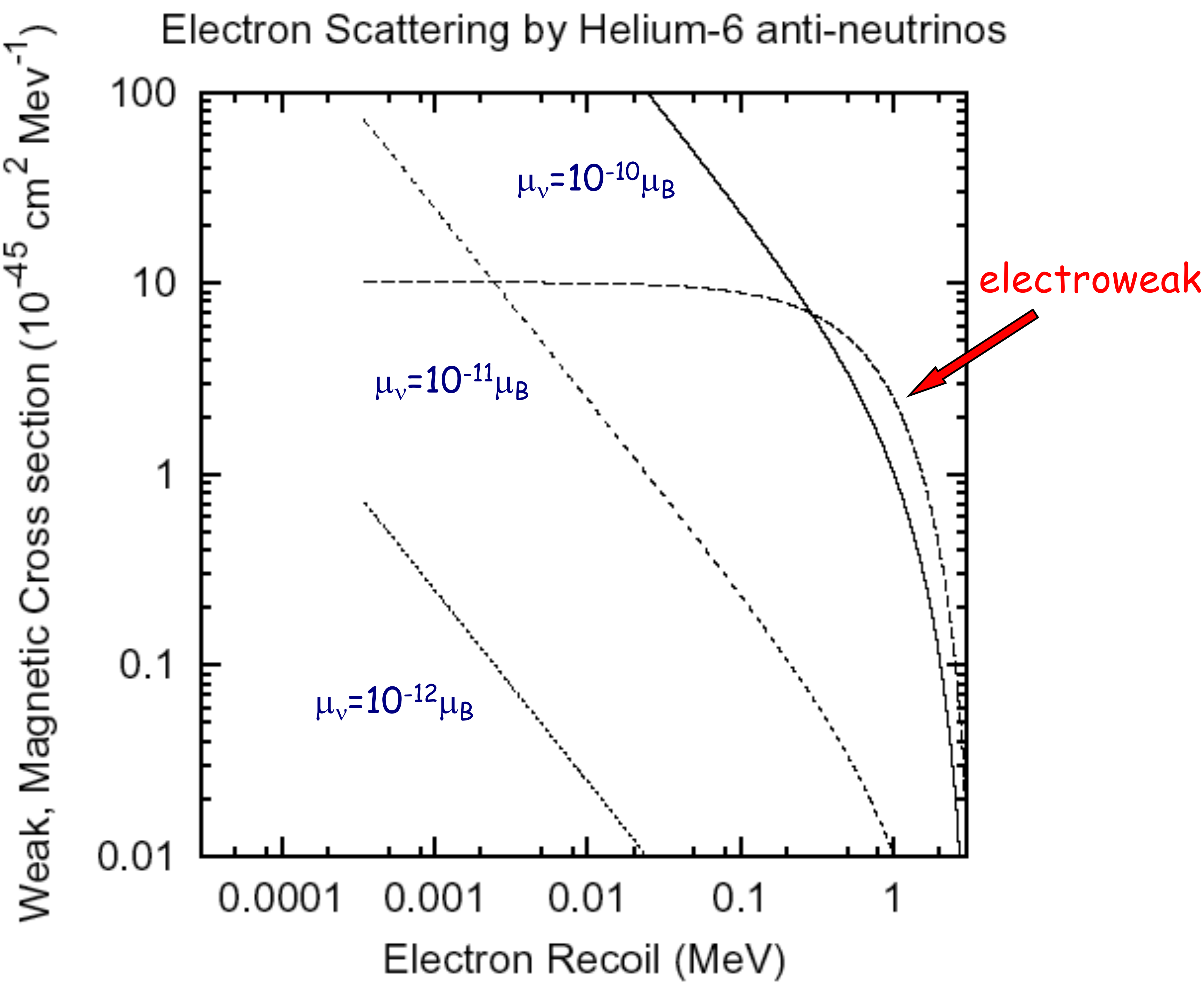


Extension of the red giant branch in globular clusters



Globular cluster M5 ➔ $\mu_\nu < 4.5 \times 10^{-12}\ \mu_B$ (95% C.L.)

arXiv:1308.4627

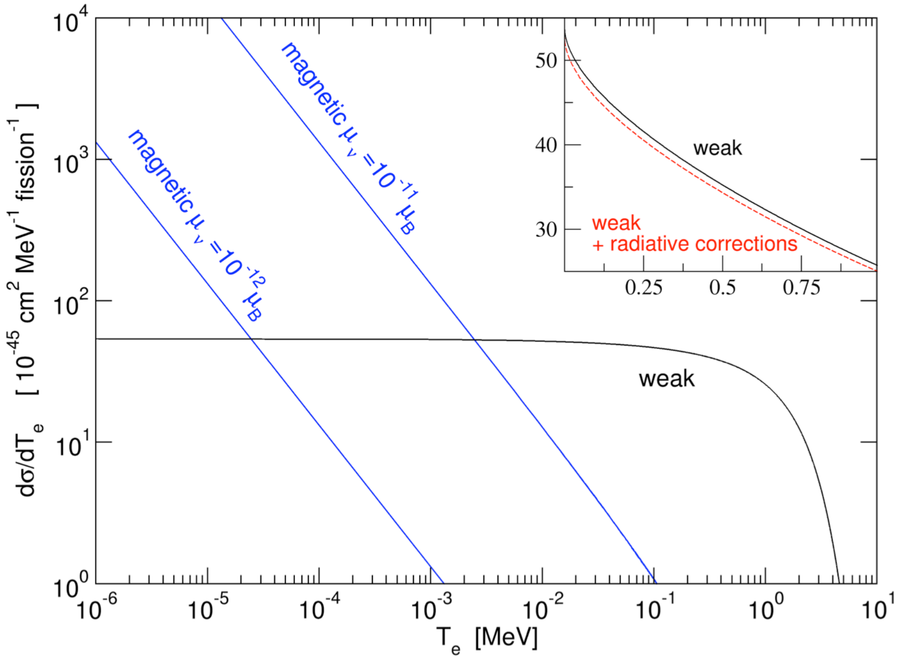

Electron Scattering by Helium-6 anti-neutrinos
Weak, Magnetic Cross section (10^{-45} cm^2 Mev^{-1})
100
10
1
0.1
0.01
0.0001
0.001
0.01
0.1
1
Electron Recoil (MeV)
$\mu_\nu=10^{-10}\mu_B$
$\mu_\nu=10^{-11}\mu_B$
$\mu_\nu=10^{-12}\mu_B$
electroweak

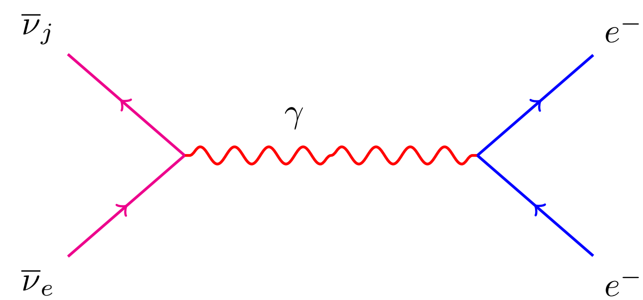
$$\frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi}\left[(g_V + g_A)^2 + (g_V - g_A)^2\left(1 - \frac{T}{E_\nu}\right)^2 + (g_A^2 - g_V^2)\frac{m_e T}{E_\nu^2}\right]$$ ← weak

$$+\frac{\pi\alpha^2\mu^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right)$$ ← magnetic

$$g_v = 2\sin^2\theta_W + 1/2$$

$$g_A = \begin{cases} +1/2 & \text{for electron neutrinos} \\ -1/2 & \text{for electron antineutrinos} \end{cases}$$





Classical screening in an electron-positron plasma

$$n_{\pm} = \frac{g}{(2\pi)^3}\int d^3\mathbf{p}\,\frac{1}{e^{(E\pm\mu)/T}+1} \Rightarrow \rho_b = -e\left(n_- - n_+\right)$$

Introducing a charge Ze at $r=0$ will create a potential ϕ

$$\rho_a = \frac{-e}{\pi^2}\int d^3\mathbf{p}\left[\frac{1}{e^{(E-e\phi-\mu)/T}+1} - \frac{1}{e^{(E+e\phi+\mu)/T}+1}\right]$$

$$\nabla^2\phi = -4\pi\left[\rho_a - \rho_b + Ze\,\delta^3(\mathbf{r})\right]$$

$$\nabla^2\phi = -\left[-\frac{1}{\lambda_D^2}\phi + 2\pi\left(\frac{\partial^2}{\partial\mu^2}\rho_b\right)(e\phi)^2 + 4\pi Ze\,\delta^3(\mathbf{r})\right] + O\left((e\phi)^3\right)$$

$$\frac{1}{4\pi\lambda_D^2} = e^2\frac{\partial}{\partial\mu}\left[n_- - n_+\right] \Rightarrow \phi(r) = \frac{Ze}{r}\exp\left(-r/\lambda_D\right)$$

Explicitly verified in Q.E.D. only up to third order.

Quantum derivation in finite-temperature Q.E.D.

$$\frac{1}{\lambda_D^2} = -\Pi^{00}\left(k_0 = 0, \mathbf{k} \to 0\right)$$

$$= -e^2 T \sum_{n_p} \int \frac{d^3\mathbf{p}}{(2\pi)^3} \ \mathrm{Tr}\left(\gamma^0 G(p) \Gamma^0(p,p) G(p)\right)$$

$$= -e^2 T \sum_{n_p} \int \frac{d^3\mathbf{p}}{(2\pi)^3} \ \mathrm{Tr}\left(\gamma^0 G(p) \frac{\partial G^{-1}}{\partial \mu}(p) G(p)\right)$$

$$= e^2 \frac{\partial}{\partial \mu} T \sum_{n_p} \int \frac{d^3\mathbf{p}}{(2\pi)^3} \ \mathrm{Tr}\left(\gamma^0 G(p)\right)$$

$$= e^2 \left(\frac{\partial n}{\partial \mu}\right)_T = e^2 \frac{\partial^2}{\partial \mu^2} P(\mu, T)$$

Note that the pressure is so far calculated only to order e^3 at finite temperature

Magnetic scattering of neutrinos and electrons

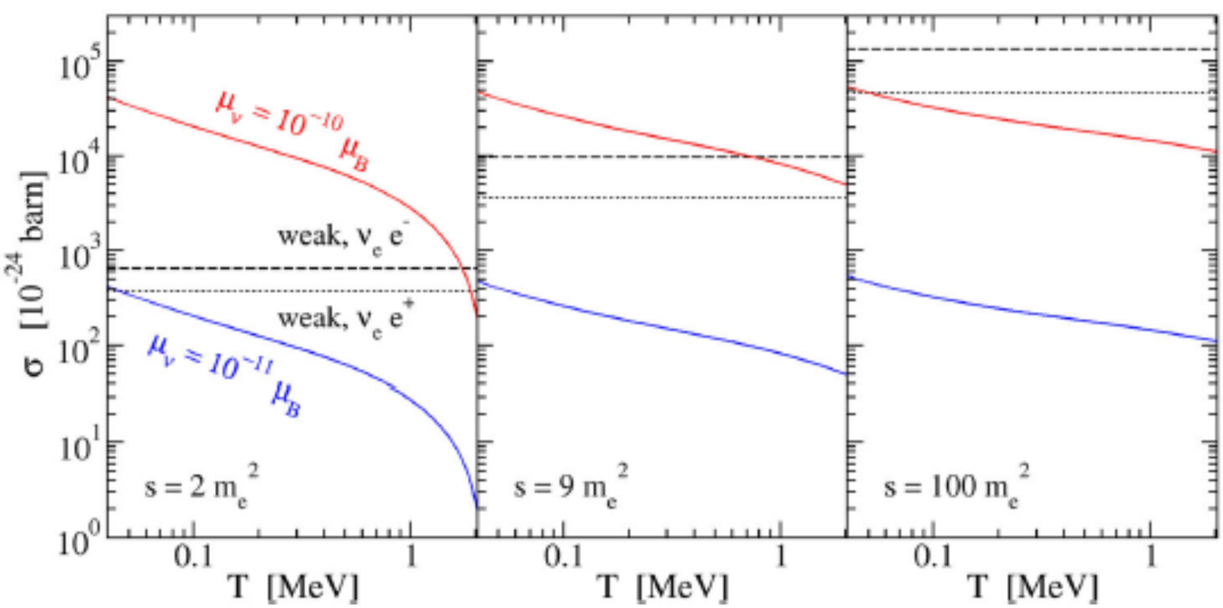
In the laboratory

$$\frac{d\sigma}{dT_e} = \frac{\alpha^2 \pi}{m_e^2}\left(\sum_i \left|\sum_j U_{ej} e^{-iE_j L}\mu_{ji}\right|^2\right)\left[\frac{1}{T_e} - \frac{1}{E_\nu}\right]$$

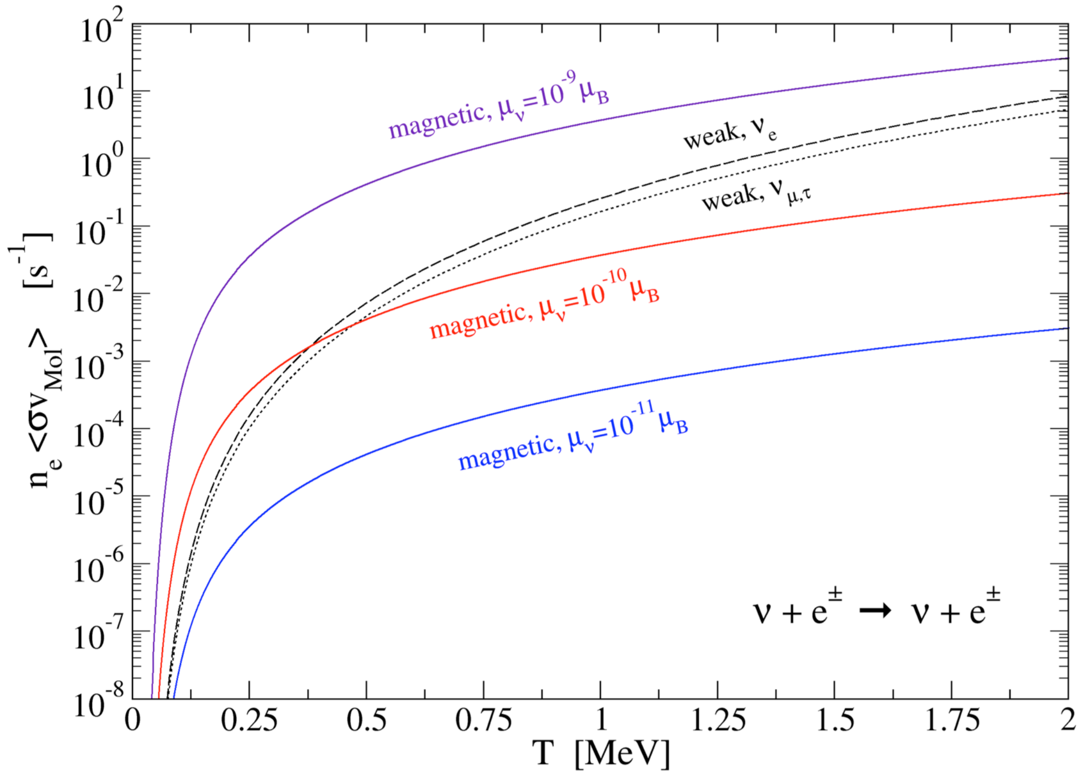
In relativistic e^+e^- plasma

$$\sigma(s) = \frac{\pi^2 \alpha^2 \mu_\nu^2}{m_e^2}\left[\frac{|t_{\text{max}}|}{s - m_e^2} - \frac{s - m_e^2}{s} + \log\frac{(s - m_e^2)^2}{s|t_{\text{max}}|}\right]$$

$$t_{\text{max}} = -2m_e\left(\sqrt{m_e^2 + \frac{1}{\lambda_D^2}} - m_e\right)$$

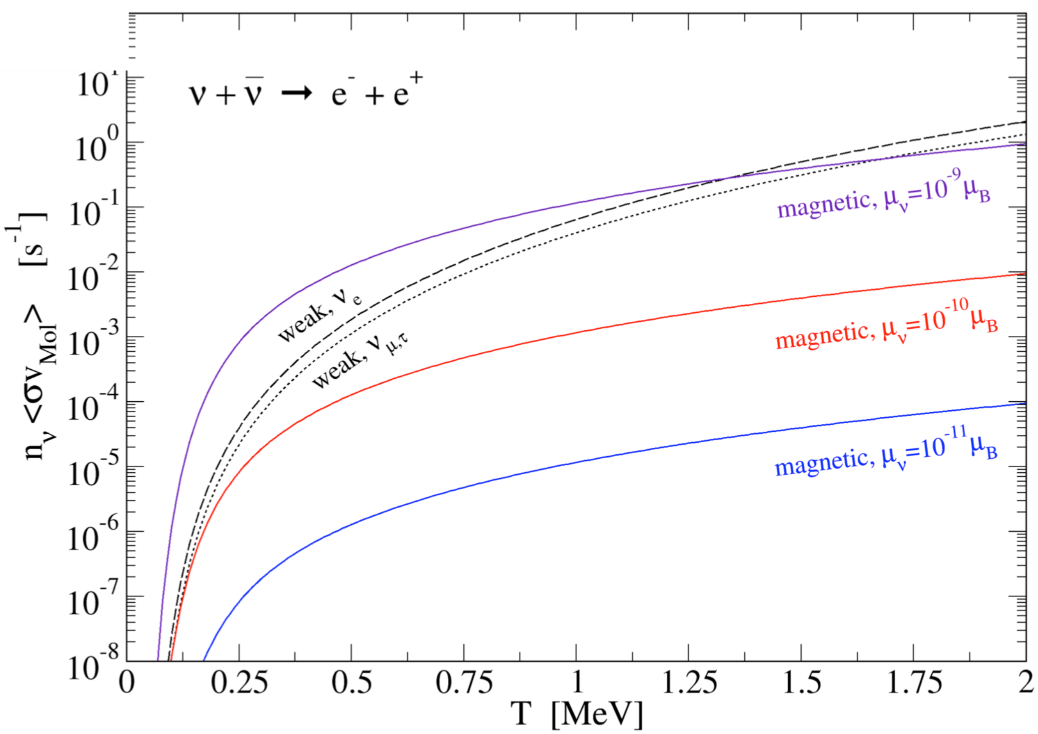


Vassh, Grohs, Balantekin, Fuller, Phys. Rev. **D 92,** 125020 (2015)



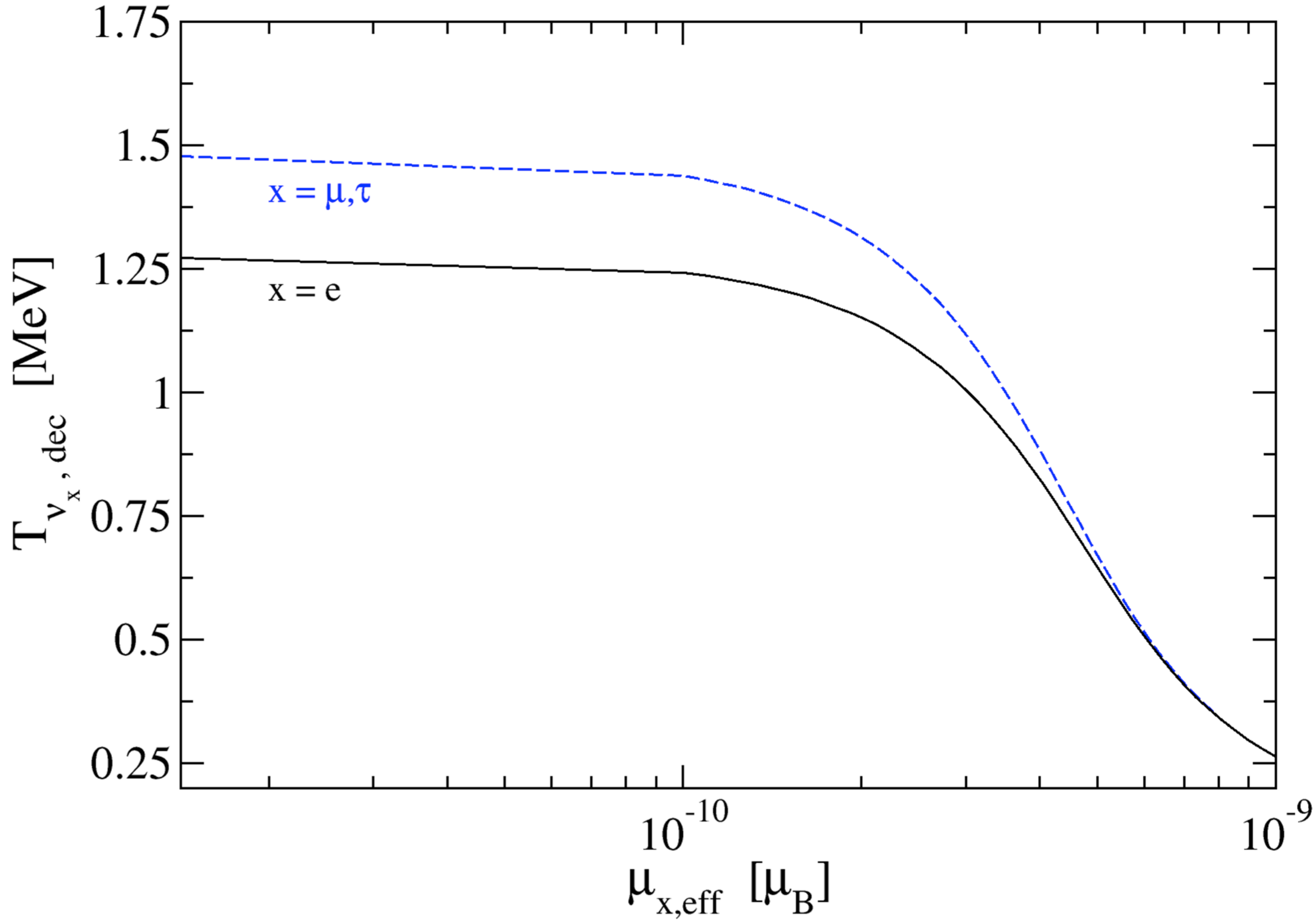
The effect of the neutrino magnetic moment on neutrino decoupling in the BBN epoch

$$\frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi}\left[(g_V+g_A)^2 + (g_V-g_A)^2\left(1-\frac{T}{E_\nu}\right)^2 + \left(g_A^2-g_V^2\right)\frac{m_e T}{E_\nu^2}\right] + \frac{\pi\alpha^2\mu^2}{m_e^2}\left(\frac{1}{T}-\frac{1}{E_\nu}\right)$$



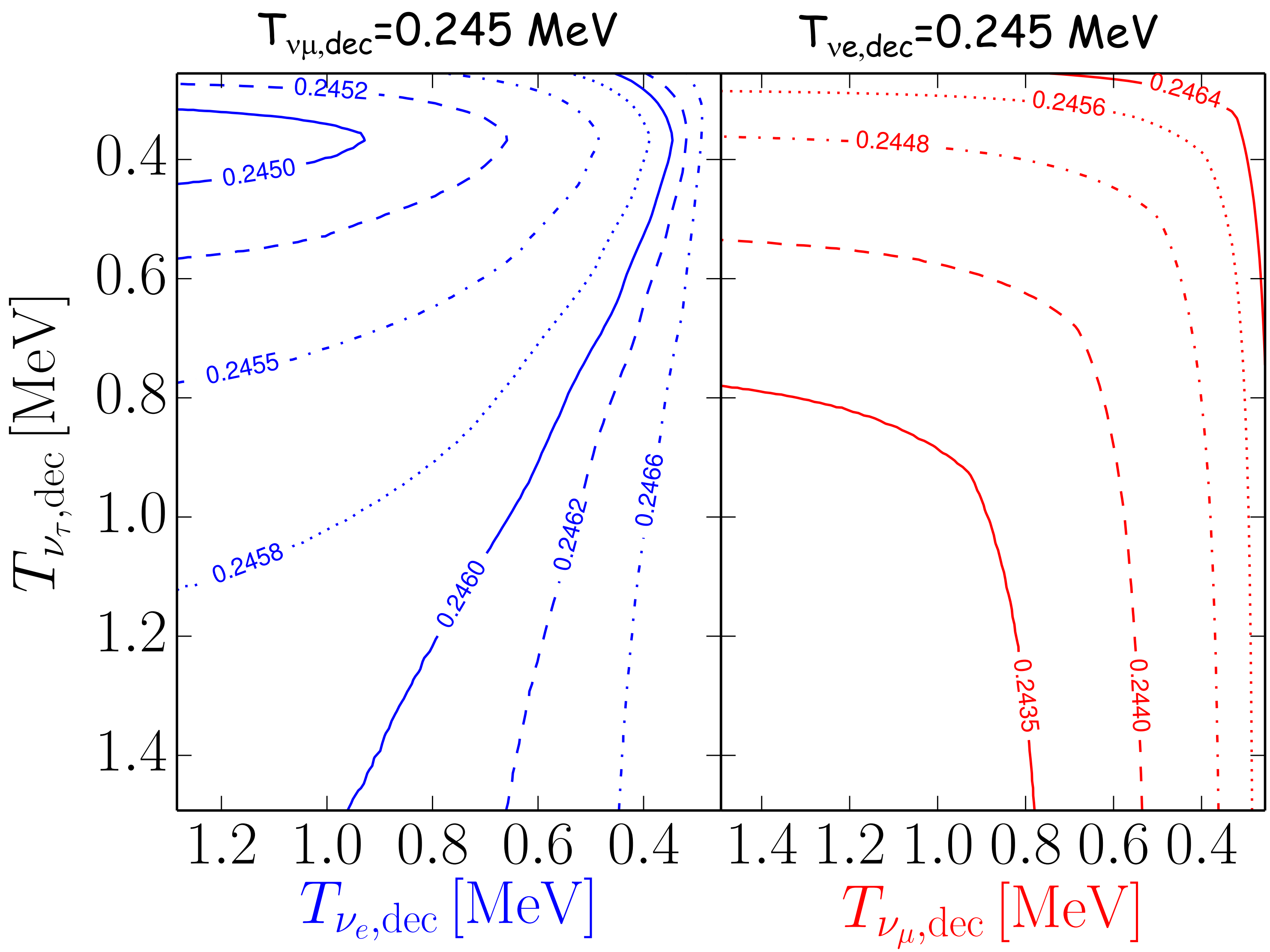
Vassh, Grohs, Balantekin, Fuller, Phys. Rev. D 92, 125020 (2015)

Decoupling temperature of three flavors

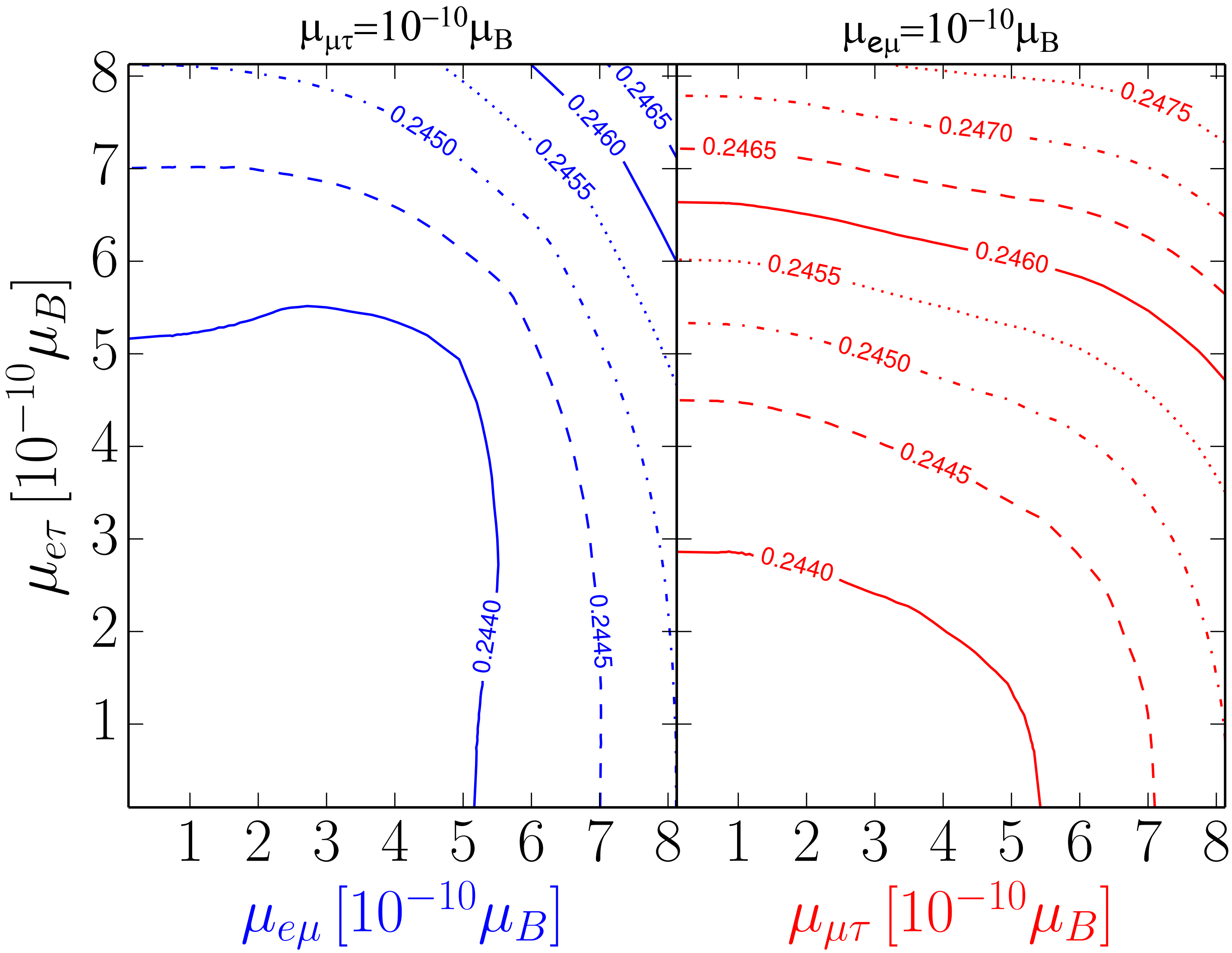


Contours of constant Y_P

$$Y_P \equiv \frac{4n_{He}}{n_p + n_n}$$



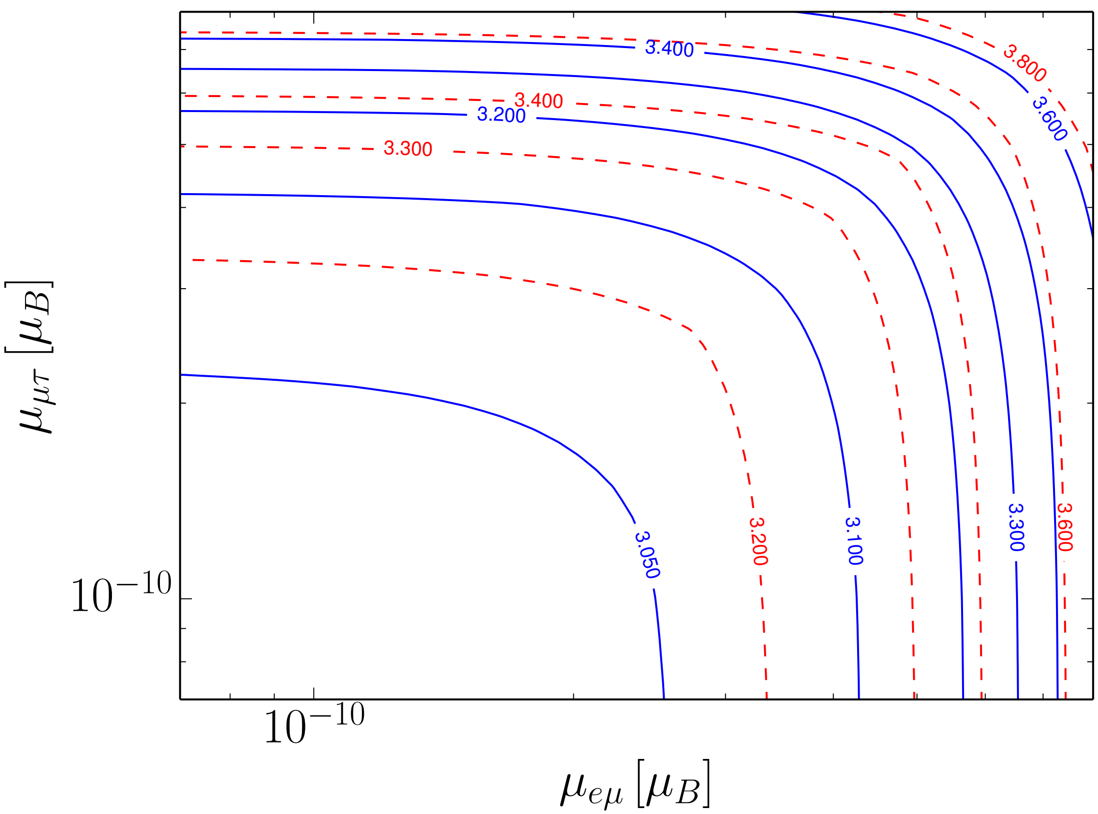
Contours of constant Y_P



Contours of constant N_{eff}

$\mu_{e\tau}=10^{-10}\,\mu_B$

$\mu_{e\tau}=4.9\text{x}10^{-10}\,\mu_B$



$$\rho_{\text{relativistic}} = \frac{\pi^2}{15}T_\gamma^4\left[1+\frac{7}{8}N_{\text{effective}}\left(\frac{4}{11}\right)^{4/3}\right]$$

Planck: $N_{\text{eff}} = 3.30 \pm 0.27 \quad \Rightarrow \quad \mu \le 6\times10^{-10}\,\mu_B$

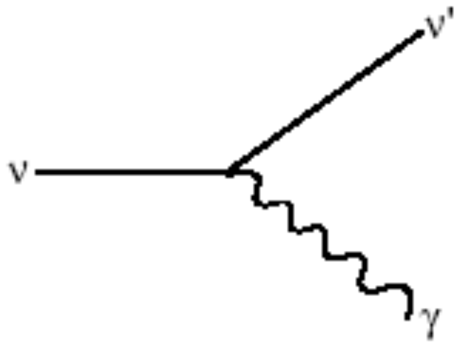
Including magnetic moment in coherent neutrino scattering

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

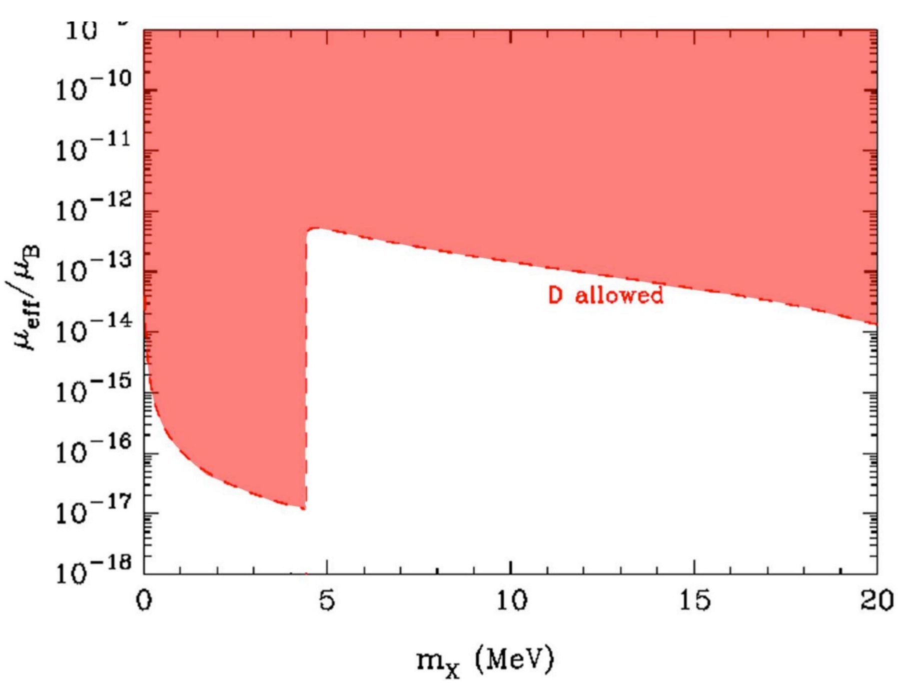
$$\mu_{\text{eff}}^2 = \sum_i \left|\sum_j U_{(e \text{ or } \mu)j} \; e^{-iE_jL}\mu_{ji}\right|^2$$

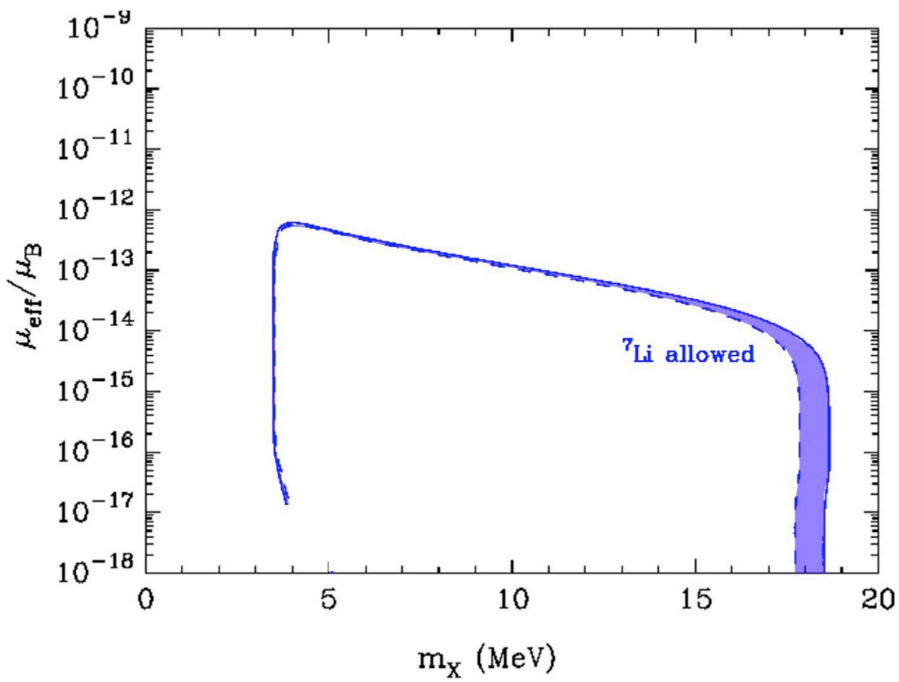
Note that this is a different combination than what is measured at reactors or solar neutrino experiments!

Sterile neutrino decay and Big Bang Nucleosynthesis



$$\Gamma_{i\to j} = \frac{|\mu|^2}{8\pi}\left(\frac{m_i^2 - m_j^2}{m_i}\right)^3 = 5.308\, s^{-1}\left(\frac{\mu_{eff}}{\mu_B}\right)^2\left(\frac{m_i^2 - m_j^2}{m_i^2}\right)^3\left(\frac{m_i}{eV}\right)^3$$





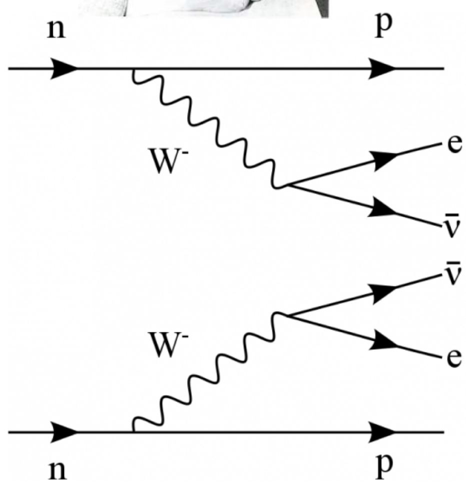
Kusakabe, A.B.B., Kajino, and Pehlivan, Phys. Rev. D 87, 085045 (2013)

How can we tell if the neutrinos are Dirac or Majorana particles?

- Neutrinoless double beta decay –only possible for Majorana neutrinos

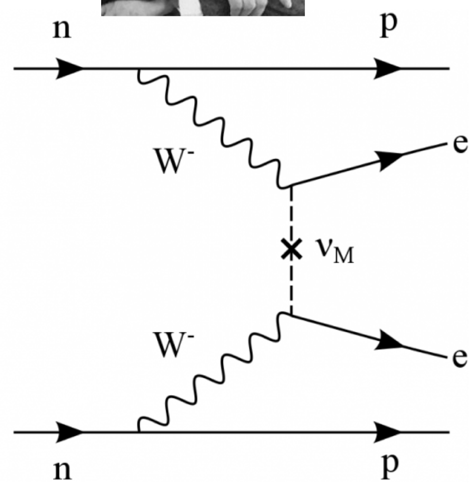
2νββ

Meyer

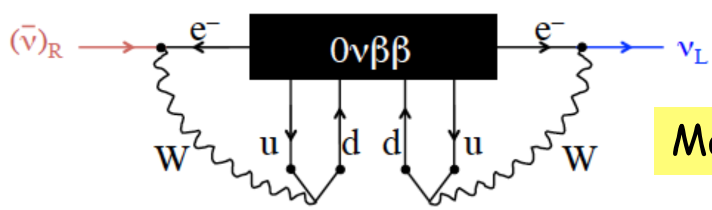


0νββ

Racah



0νββ decay



Majorana mass

How can we tell if the neutrinos are Dirac or Majorana particles?

- Neutrinoless double beta decay –only possible for Majorana neutrinos

- Capturing cosmic background neutrinos. At least two of them are non-relativistic where what kind of mass you have matters. Very difficult experiments with significant uncertainties due to the lack of knowledge of the local neutrino density.

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- Measure angular distribution in decays.

How can we tell if the neutrinos are Dirac or Majorana particles?

- Measure angular distribution in decays.

The decay angular distribution is isotropic in the Majorana case, and not isotropic in the Dirac case. Next speaker, B. Kayser, will show how this conclusion follows from general symmetry arguments.