Neutrino magnetic moment, sterile neutrinos and Big Bang Nucleosynthesis

Baha Balantekin
University of Wisconsin

INT
July 11, 2017

At lower energies, beyond Standard Model physics is described by local operators

$$L = L_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_i \frac{C_i^{(7)}}{\Lambda^3} O_i^{(7)} + \ldots$$

Majorana neutrino mass (unique)

Includes Majorana neutrino magnetic moment

$$\mu_\nu \propto \frac{m_\nu}{\Lambda^2}$$

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

Example: Neutrino-electron scattering via magnetic moment

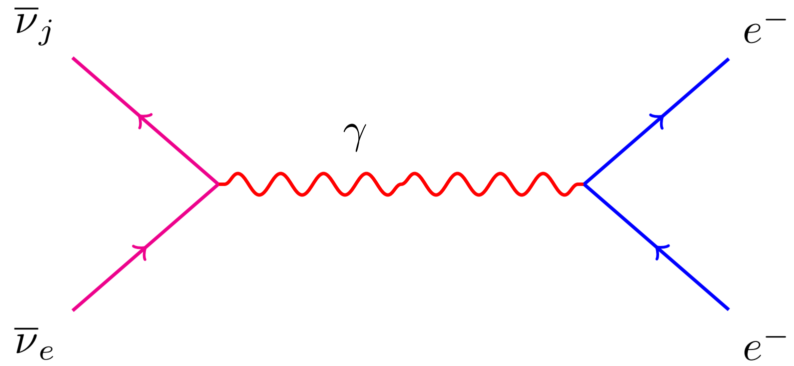
$$\sigma \propto \sum_i \left| \langle \nu_i | \hat{\mu} | \nu_e \rangle \right|^2 = \langle \nu_e | \hat{\mu}^\dagger \hat{\mu} | \nu_e \rangle$$

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

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

The matrix representation of this operator is best given in the mass basis

Neutrino-electron scattering at reactors



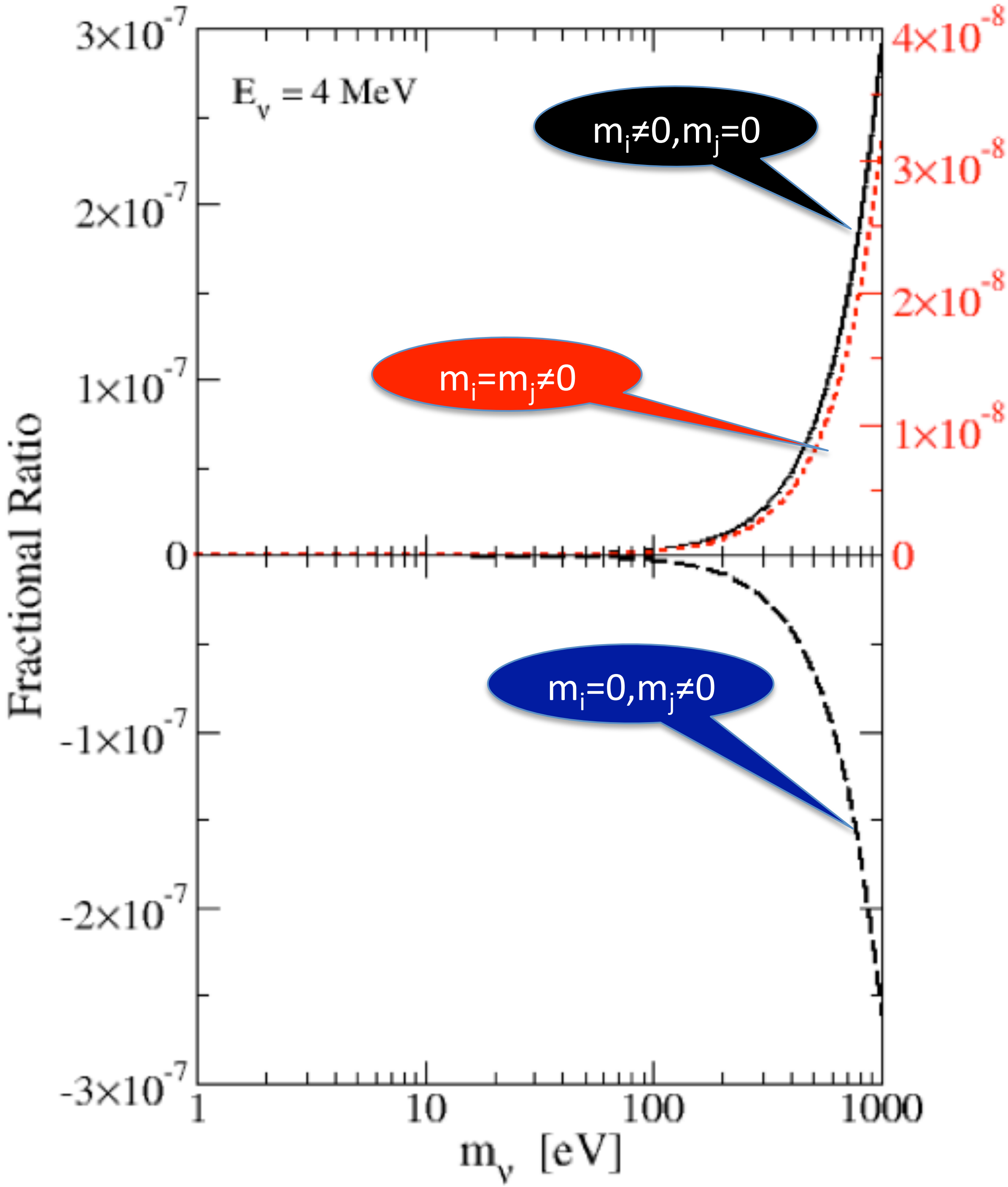
$$\frac{d\sigma_{ij}}{dt} = \frac{\alpha^2 \pi \mu_{ij}^2}{2m_e^2 \lambda}\left[\frac{1}{t}\left(2\lambda + 4m_e^2 m_i^2 + 2A\,\delta m^2 + 2m_e^2\,\delta m^2 + \left[\delta m^2\right]^2\right) + \left(2A + \delta m^2\right) + \frac{2m_e^2\left(\delta m^2\right)^2}{t^2}\right]$$

$$\delta m^2 = m_i^2 - m_j^2$$

$$A = s - m_e^2 - m_i^2$$

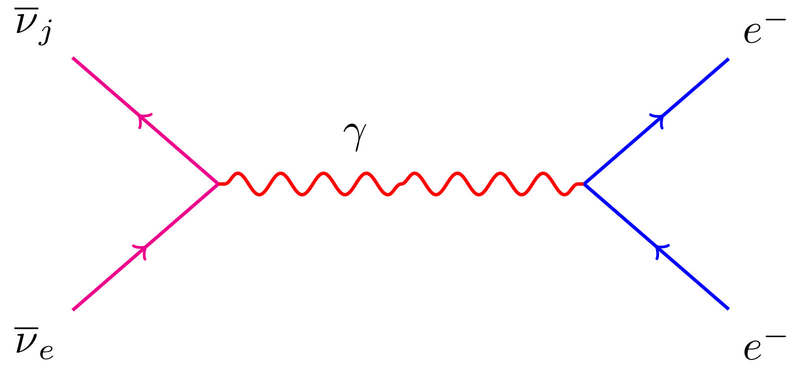
$$\lambda = A^2 - 4m_e^2\, m_i^2$$

$$\frac{\left\langle \frac{d\sigma}{dt} \right\rangle_{m\neq 0} - \left\langle \frac{d\sigma}{dt} \right\rangle_{m=0}}{\left\langle \frac{d\sigma}{dt} \right\rangle_{m=0}}$$



A.B.B. & Vassh

Neutrino-electron scattering at reactors



$$\frac{d\sigma_{ij}}{dt} = \frac{\alpha^2 \pi \mu_{ij}^2}{2m_e^2\lambda}\left[\frac{1}{t}\left(2\lambda + 4m_e^2 m_i^2 + 2A\,\delta m^2 + 2m_e^2\,\delta m^2 + \left[\delta m^2\right]^2\right) + \left(2A + \delta m^2\right) + \frac{2m_e^2\left(\delta m^2\right)^2}{t^2}\right]$$

$$\delta m^2 = m_i^2 - m_j^2$$

$$A = s - m_e^2 - m_i^2$$

$$\lambda = A^2 - 4m_e^2 m_i^2$$

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

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

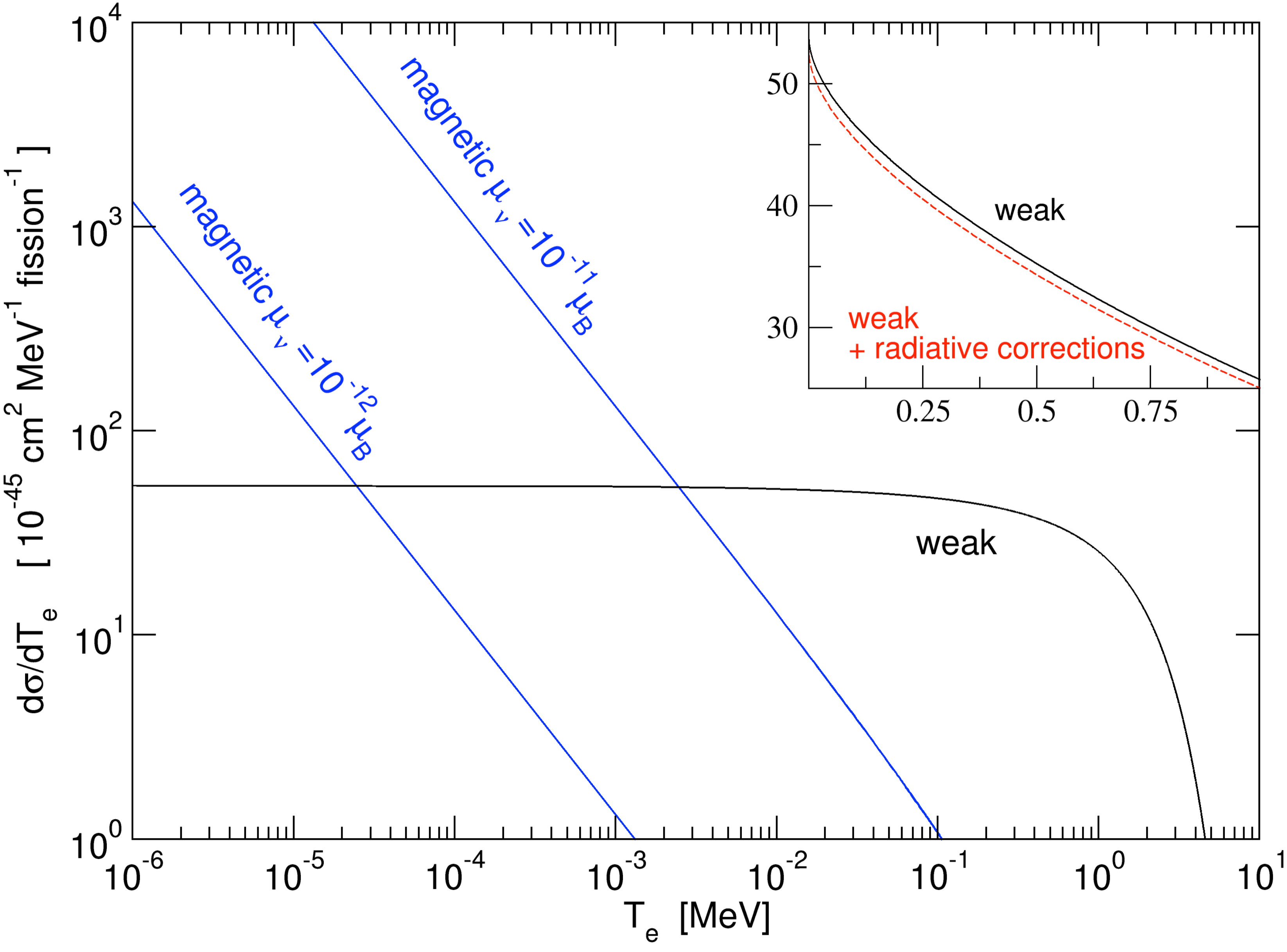
$$\mu_{\text{eff}}^2 = \sum_i \left|\sum_j U_{ej} e^{-iE_jL}\mu_{ji}\right|^2$$

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

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

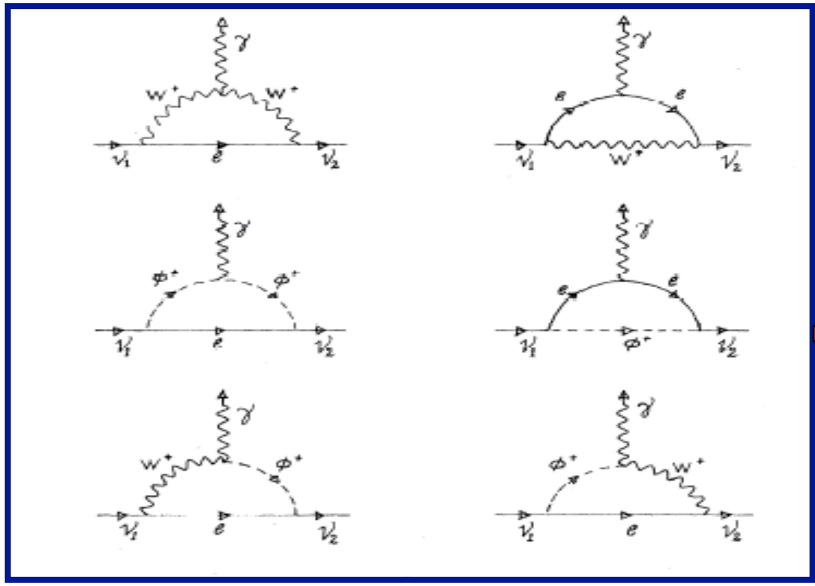
$g_V = 2\sin^2\theta_W + 1/2$

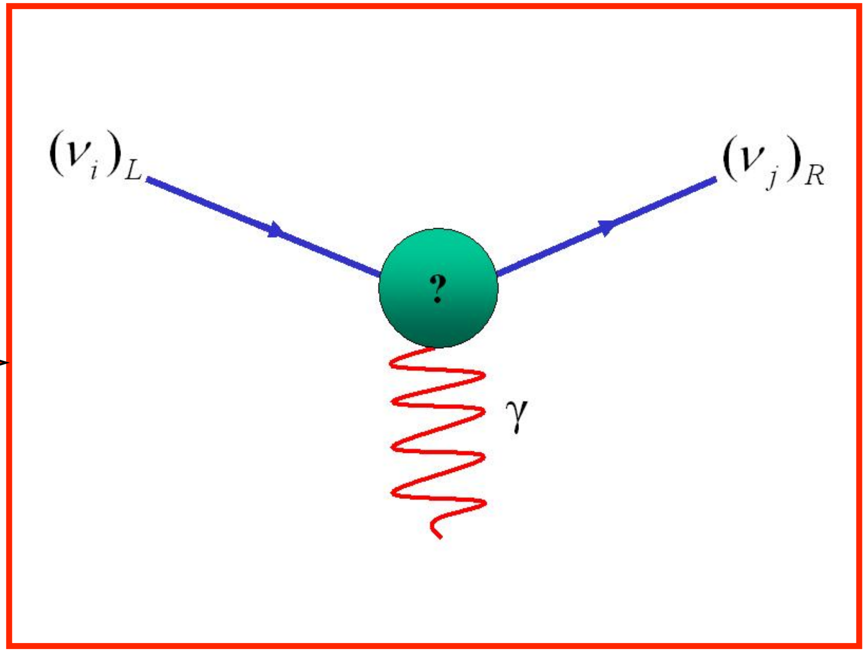
$g_A = \begin{cases} +1/2 \text{ for electron neutrinos} \\ -1/2 \text{ for electron antineutrinos} \end{cases}$



magnetic $\mu_\nu = 10^{-11} \mu_B$
magnetic $\mu_\nu = 10^{-12} \mu_B$
weak
weak
weak
+ radiative corrections
50
40
30
0.25
0.5
0.75
$d\sigma/dT_e$ [10^{-45} cm^2 MeV^{-1} fission^{-1}]
T_e [MeV]
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}

Neutrino Magnetic Moment in the Standard Model





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

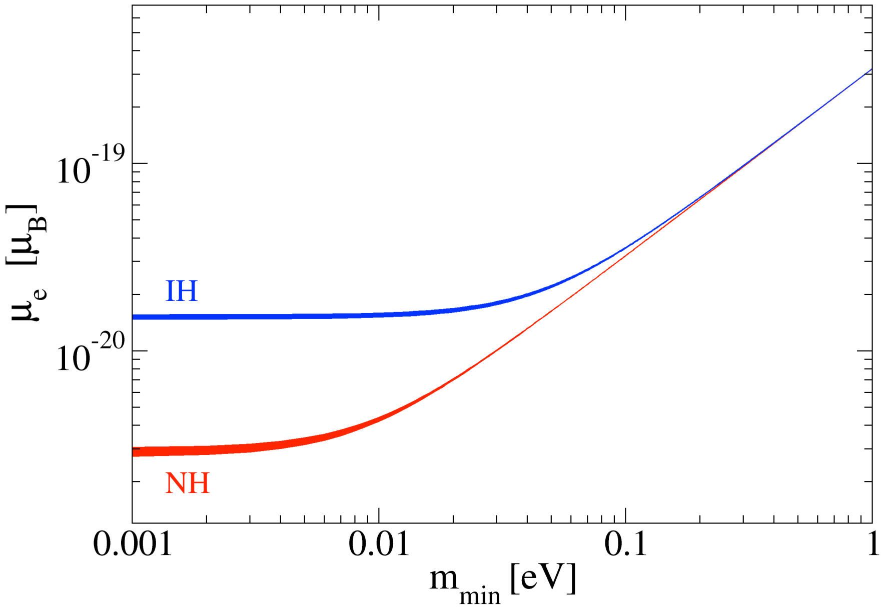
$$f(r_\ell) \approx -\frac{3}{2} + \frac{3}{4} r_\ell + \ldots, \quad r_\ell = \left(\frac{m_\ell}{M_W}\right)^2$$

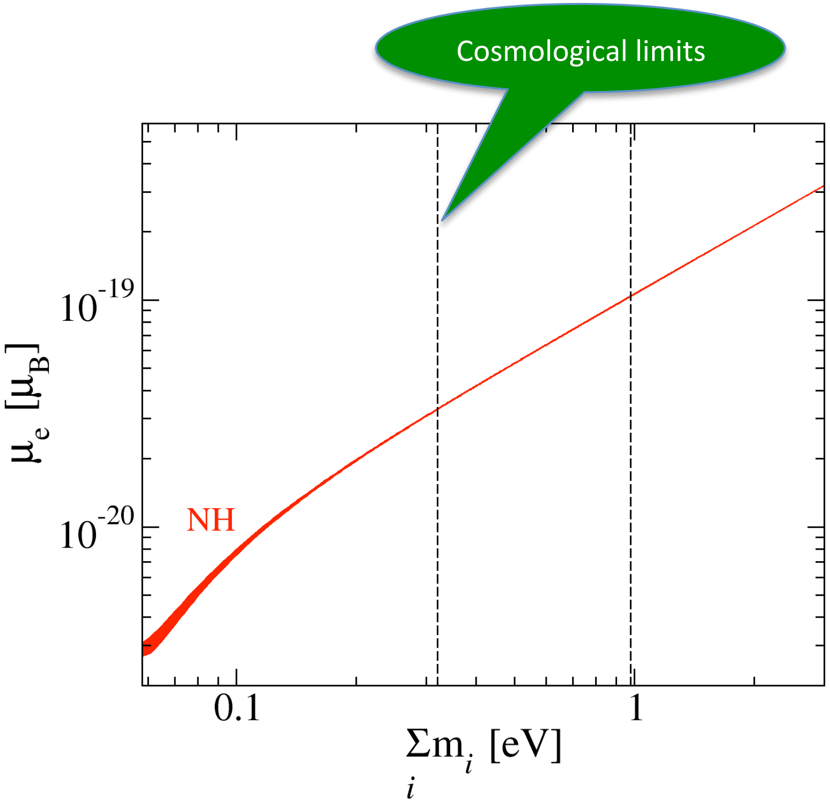
Symmetry principles: $\mu_\nu \to 0$ as $m_\nu \to 0$

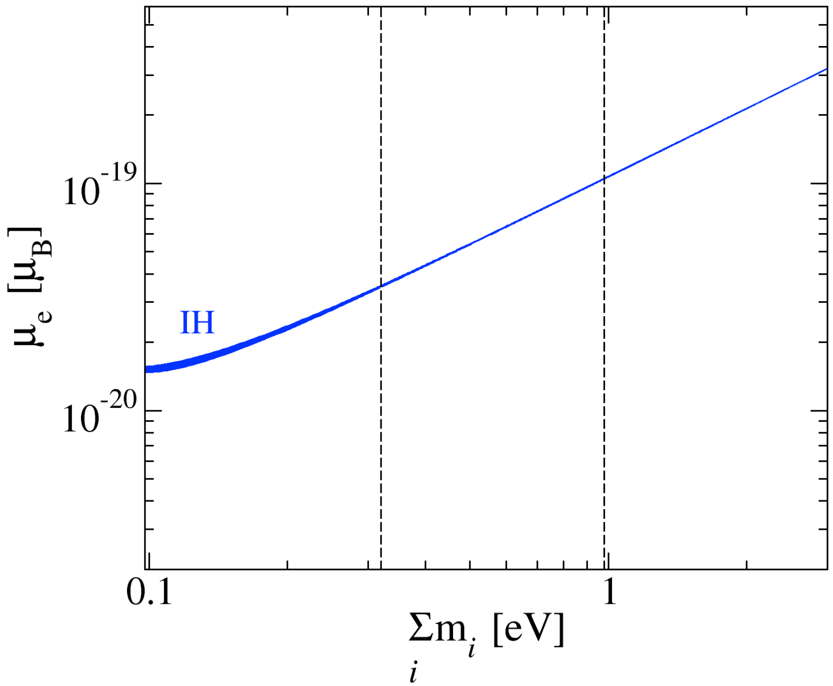
Standard Model (Dirac)

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

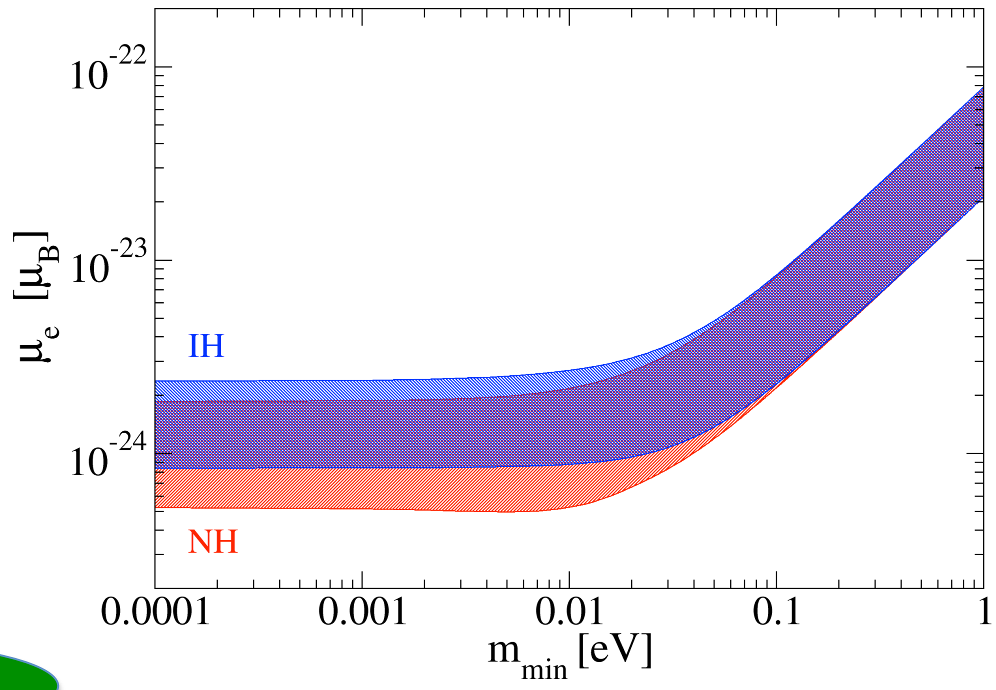
A.B.B., N. Vassh, PRD **89** (2014) 073013

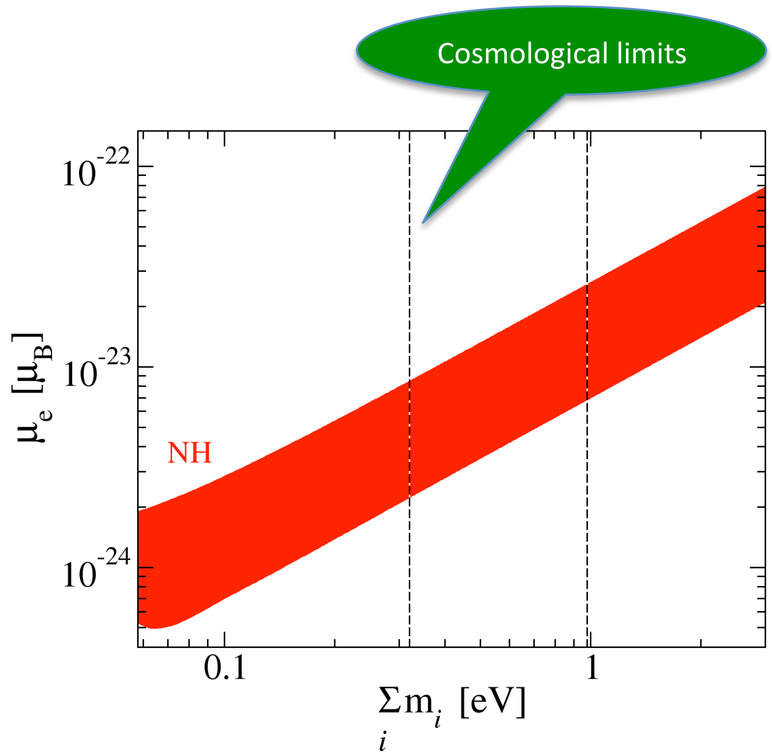


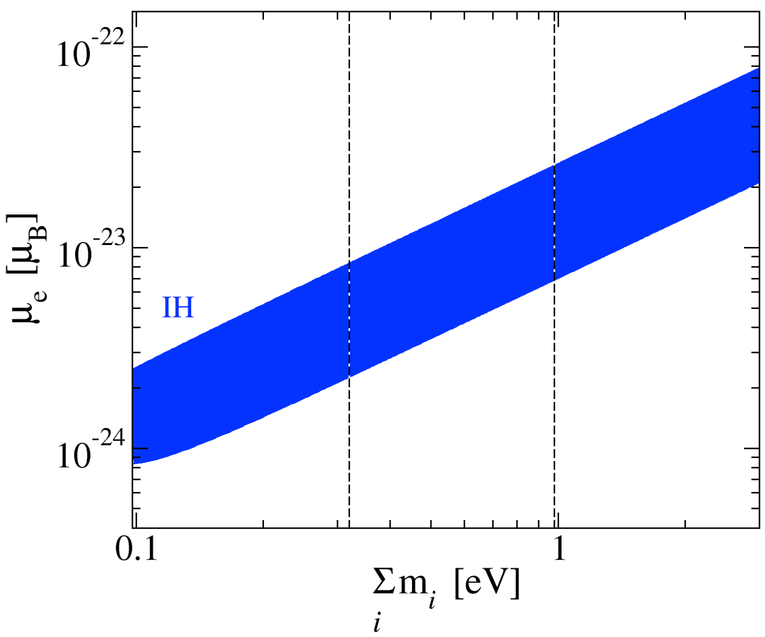




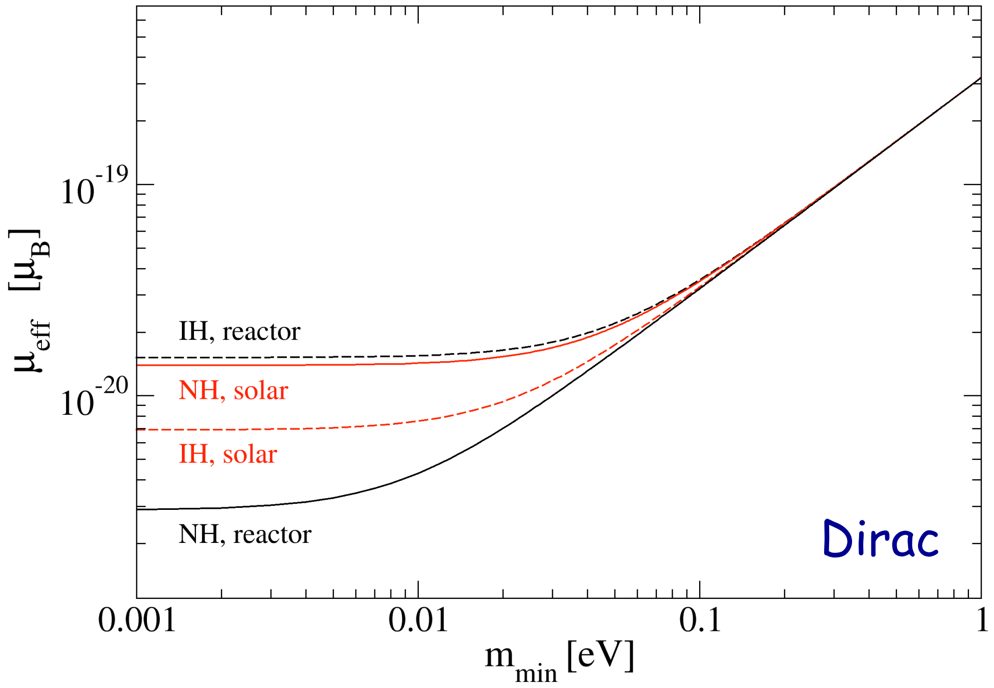
Standard Model (only) contribution to the Majorana neutrino magnetic moment measured at reactors



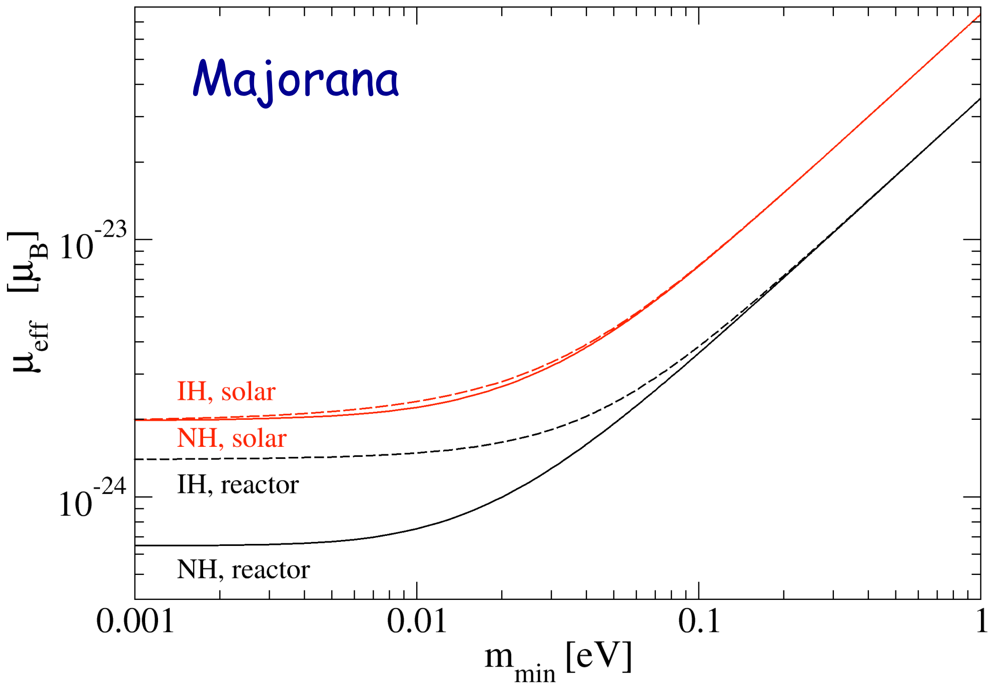


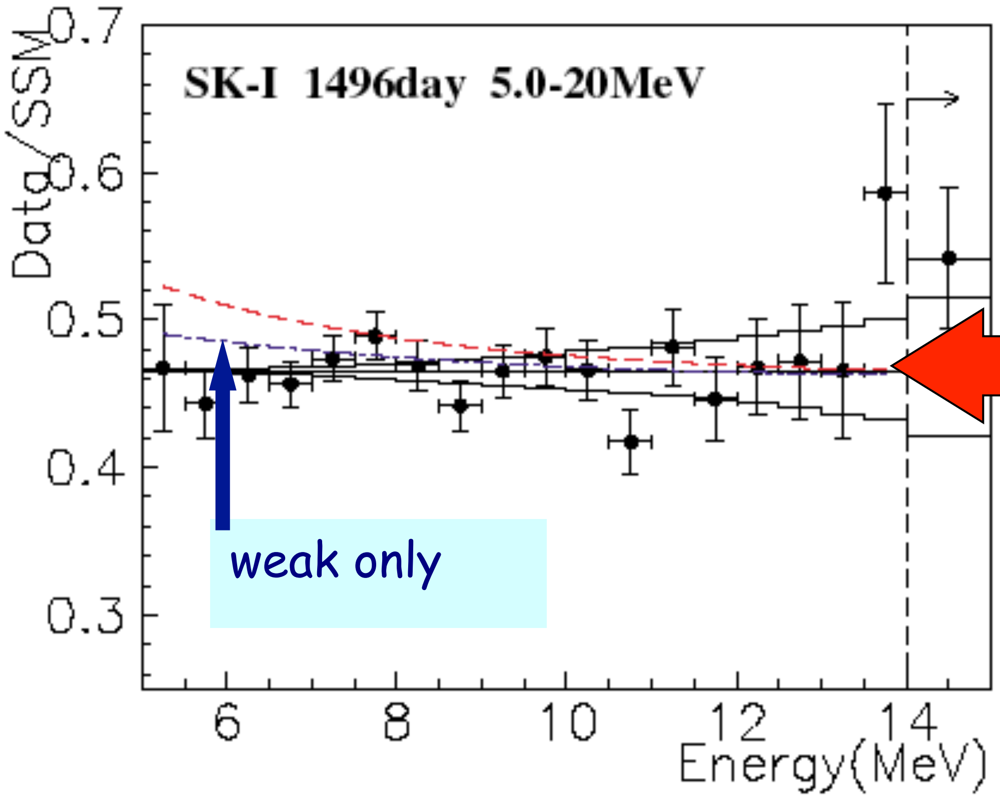


Reactors vs. solar Cerenkov detectors



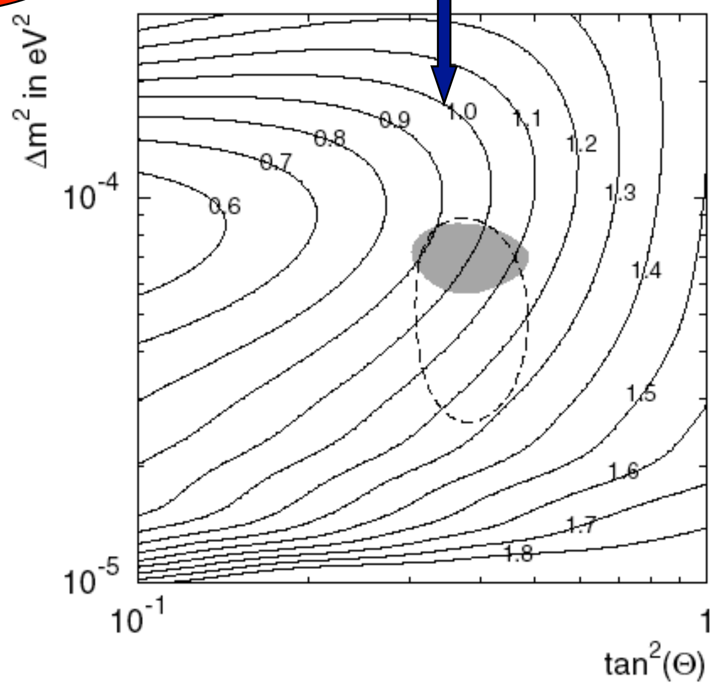
A.B.B. & N. Vassh
AIP Conf.Proc. **1604** (2014) 150
arXiv:1404.1393





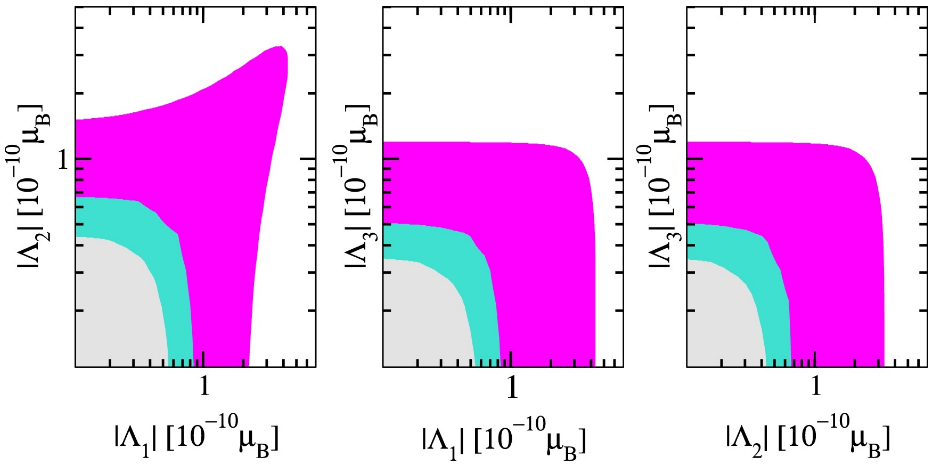
additional $\mu_\nu < 10^{-10} \mu_B$

$\mu_\nu = 10^{-10} \mu_B$



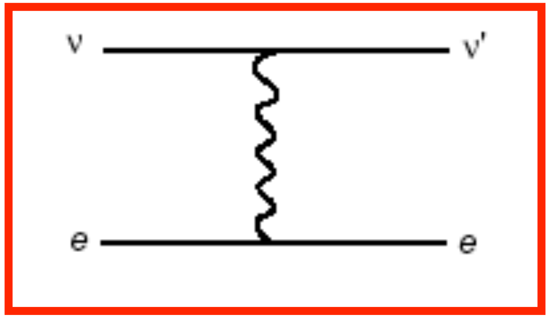
SuperK: $\mu_\nu \leq (3.6 \times 10^{-10})\mu_B$ at 90%C.L.

SuperK + KamLAND: $\mu_\nu \leq (1.1 \times 10^{-10})\mu_B$ at 90%C.L.

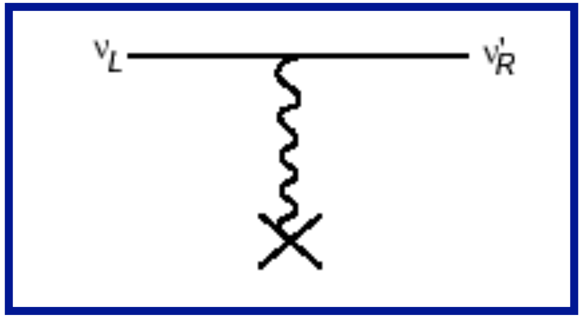


Canas, et al analysis of the Borexino Data

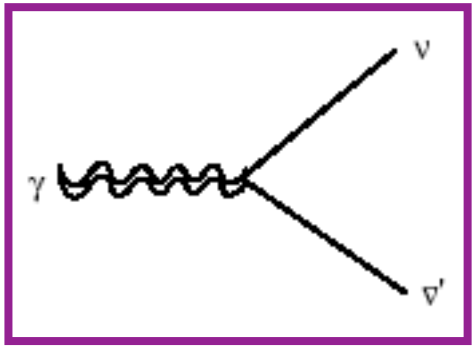
Physical Processes with a Neutrino Magnetic Moment



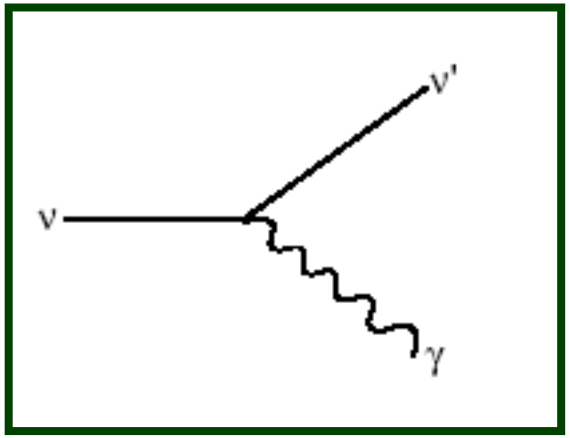
ν-e scattering



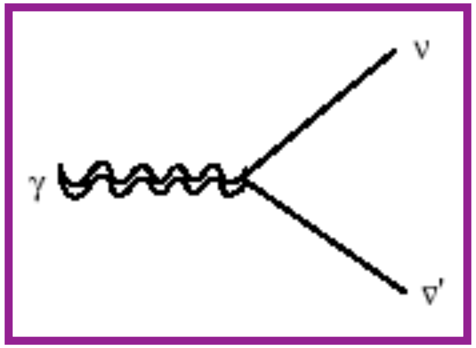
Spin-flavor precession



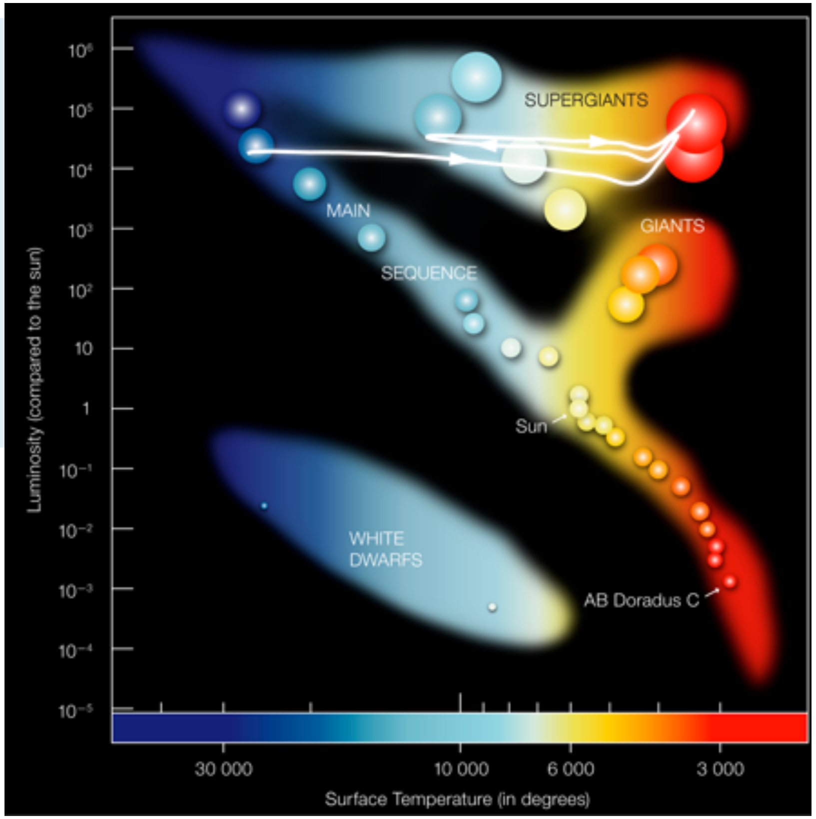
Plasmon decay

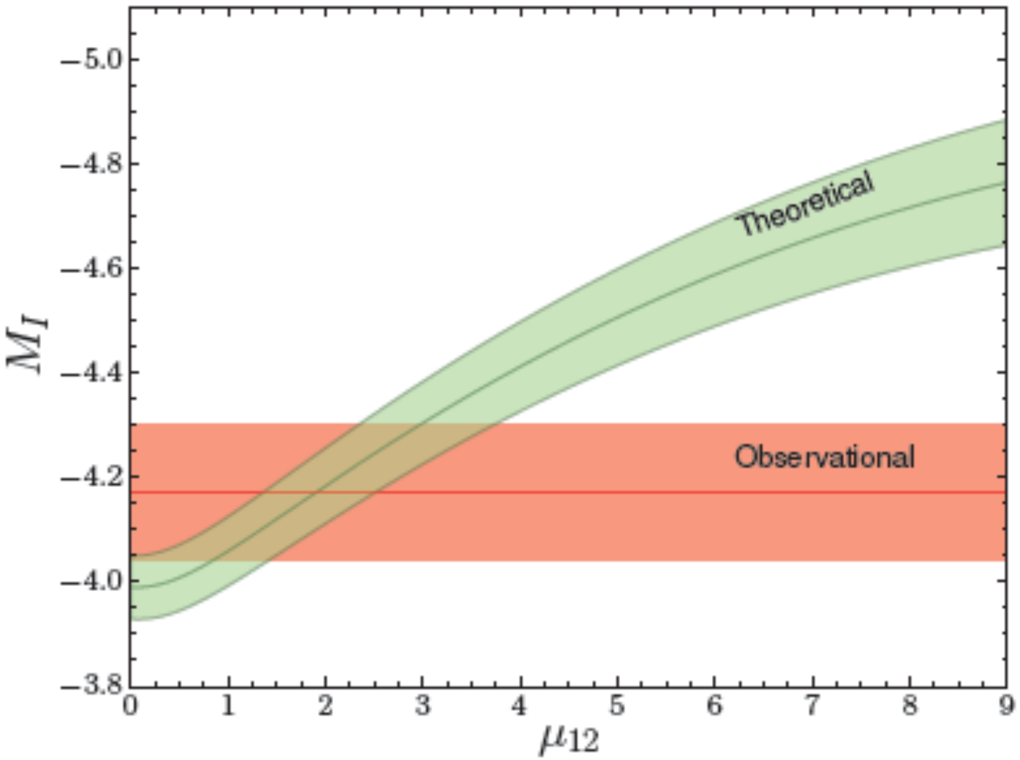


Neutrino decay



A large enough neutrino magnetic moment implies enhanced plasmon decay rate: $\gamma \rightarrow \nu\nu$. Since the neutrinos freely escape the star, this is turn cools a red giant star faster delaying helium ignition.

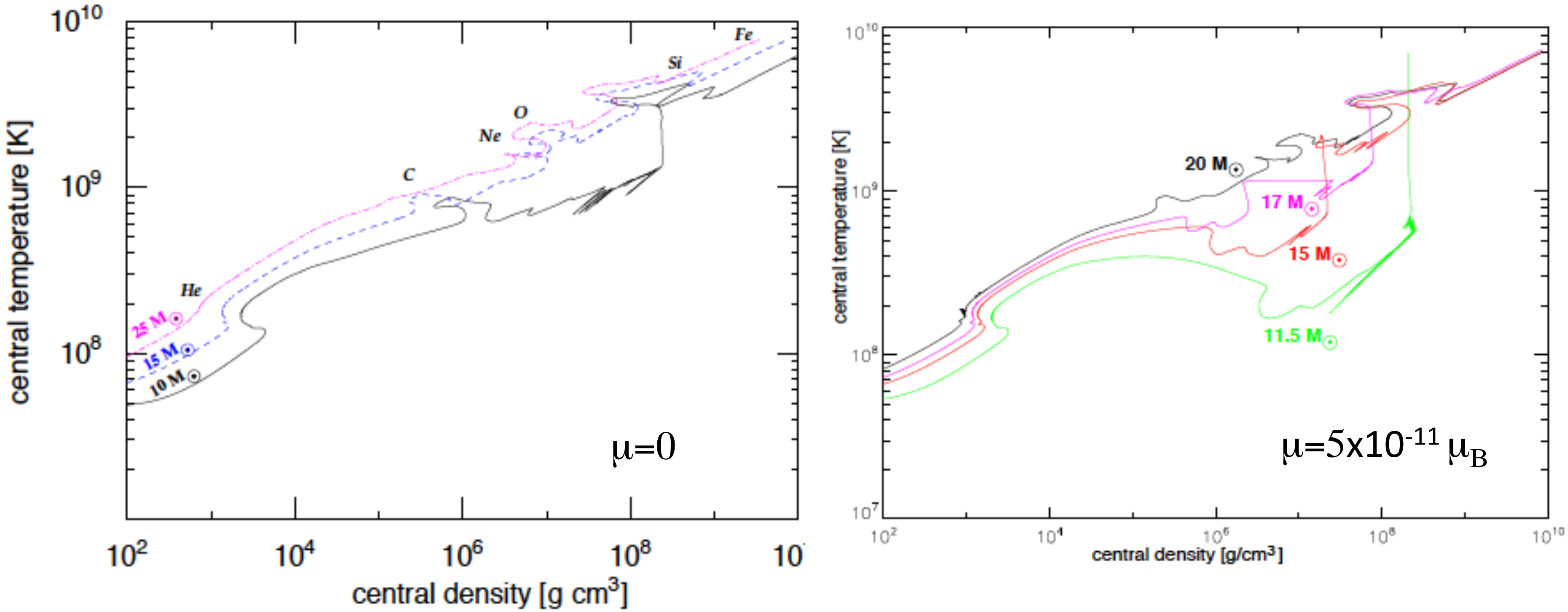




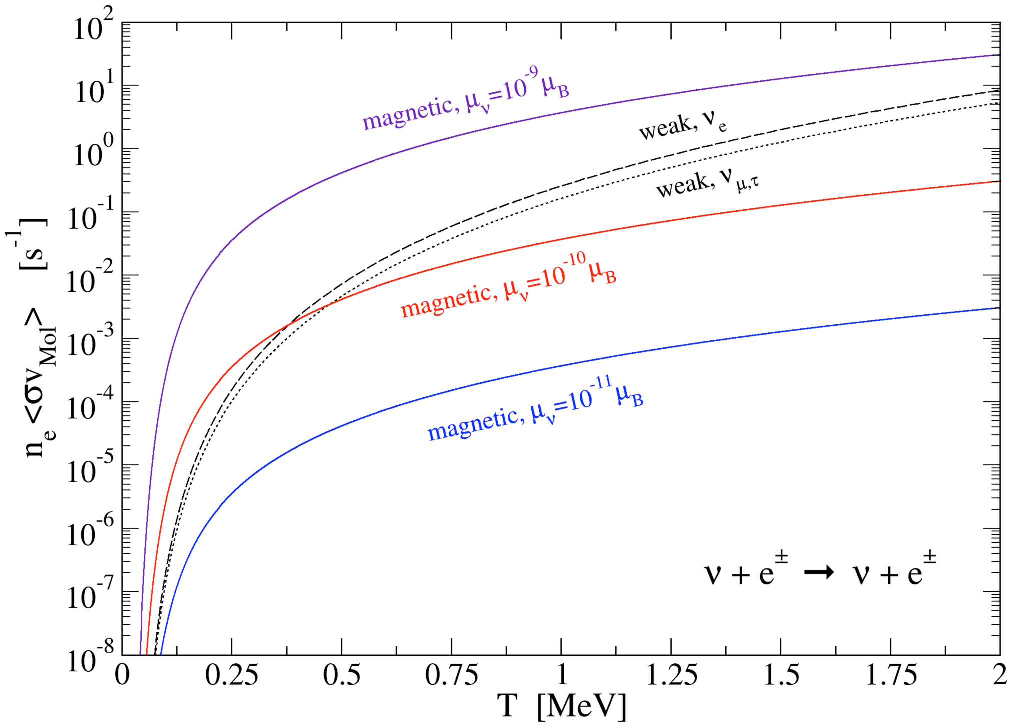
Globular cluster M5
➔ $\mu_\nu < 4.5 \times 10^{-12}\ \mu_B$
(95% C.L.)

arXiv:1308.4627

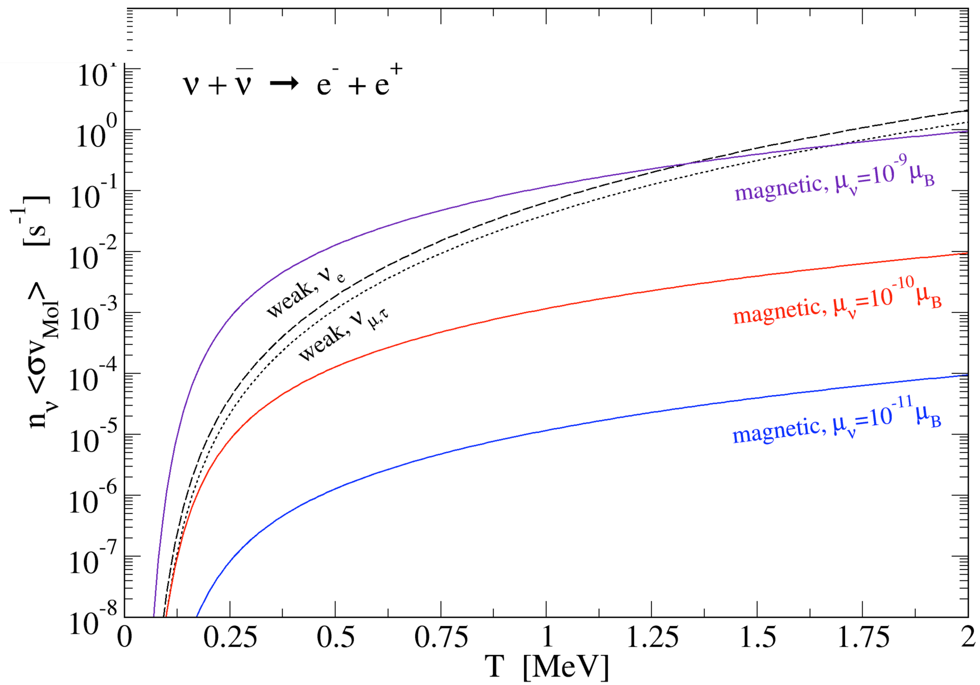
Neutrino magnetic moment may impact stellar evolution



Heger, Friedland, Giannotti and Cirigliano, Astrophys.J. **696**, 608 (2009)

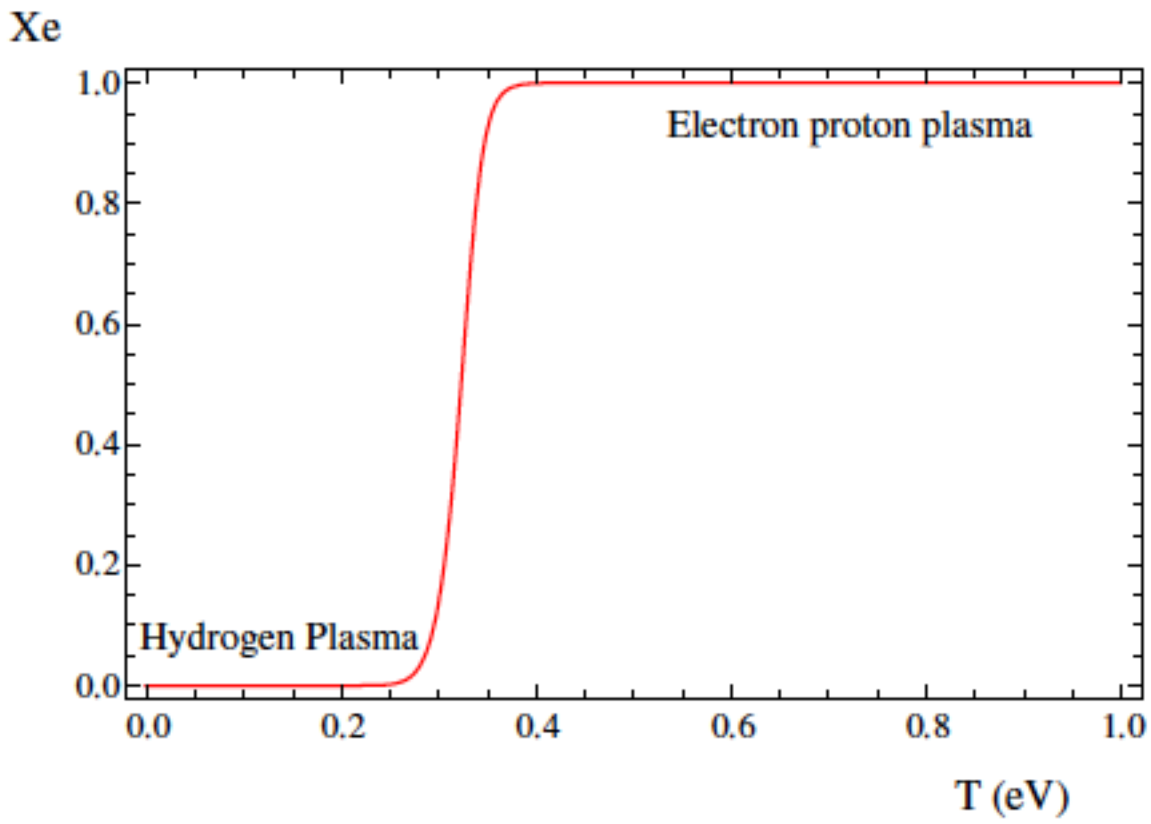


The effect of the neutrino magnetic moment on neutrino decoupling in the BBN epoch

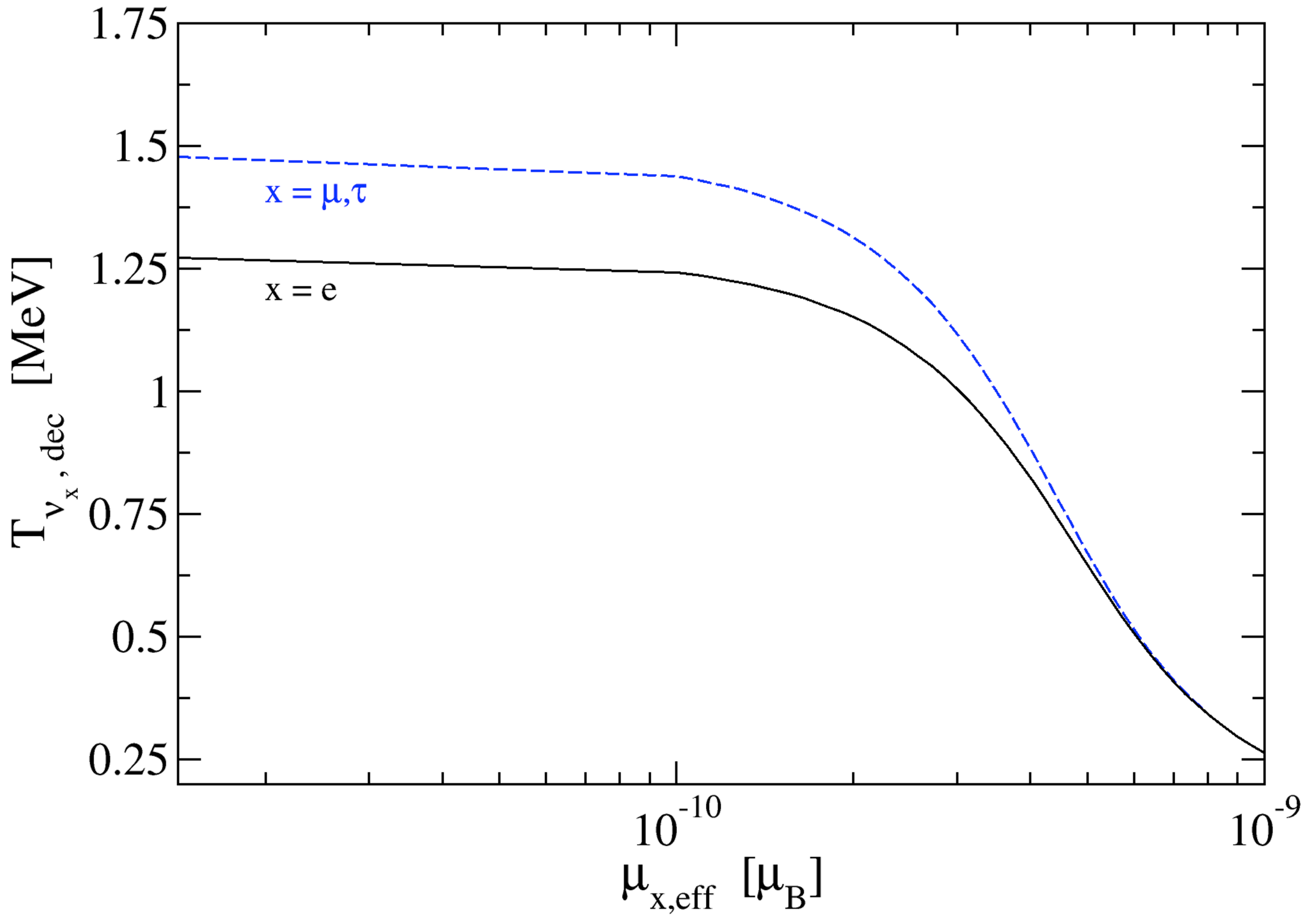


Vassh, Grohs, Balantekin, Fuller, Phys. Rev. D 92, 125020 (2015)

Ionization rate

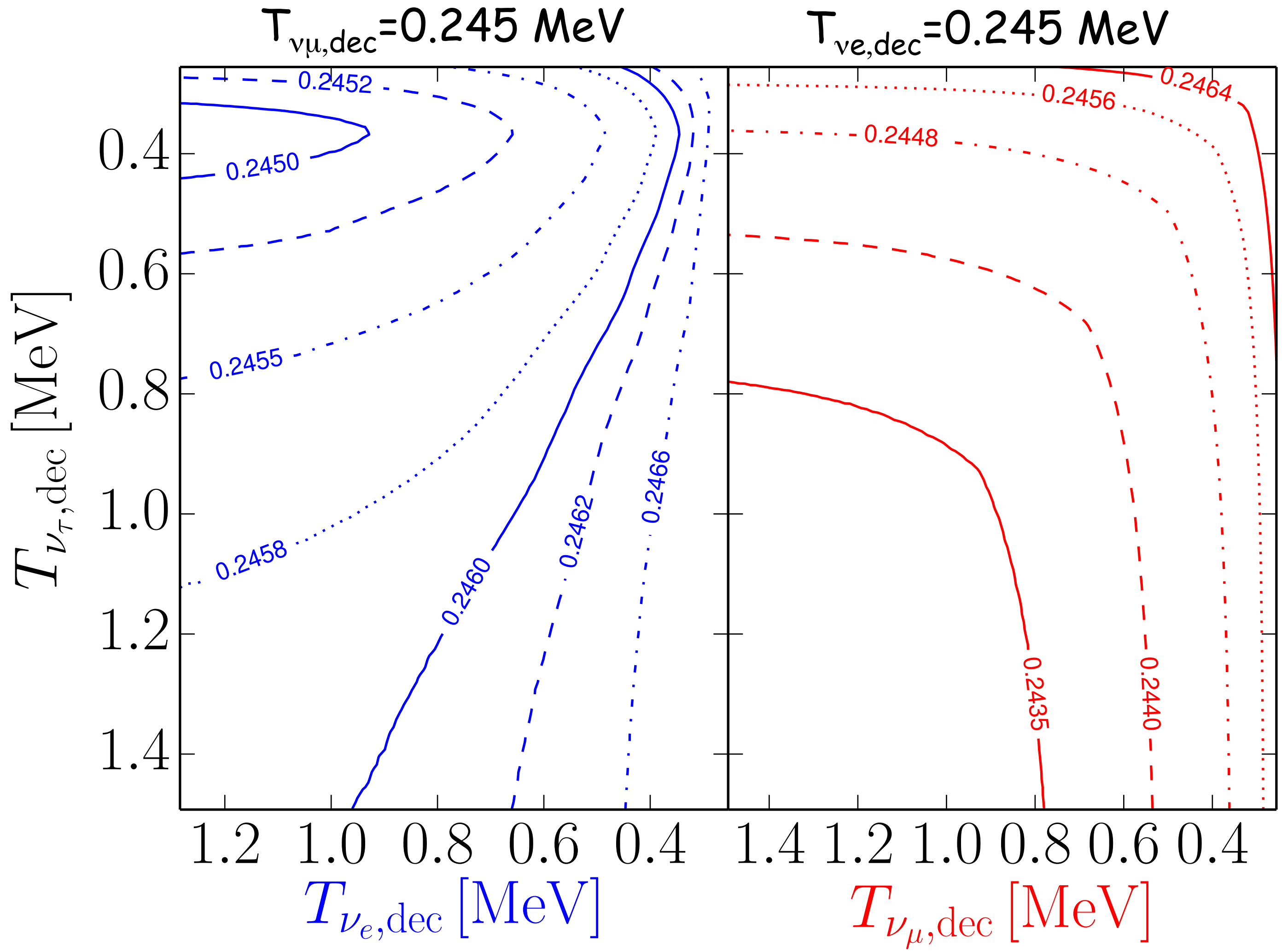


Decoupling temperature of three flavors

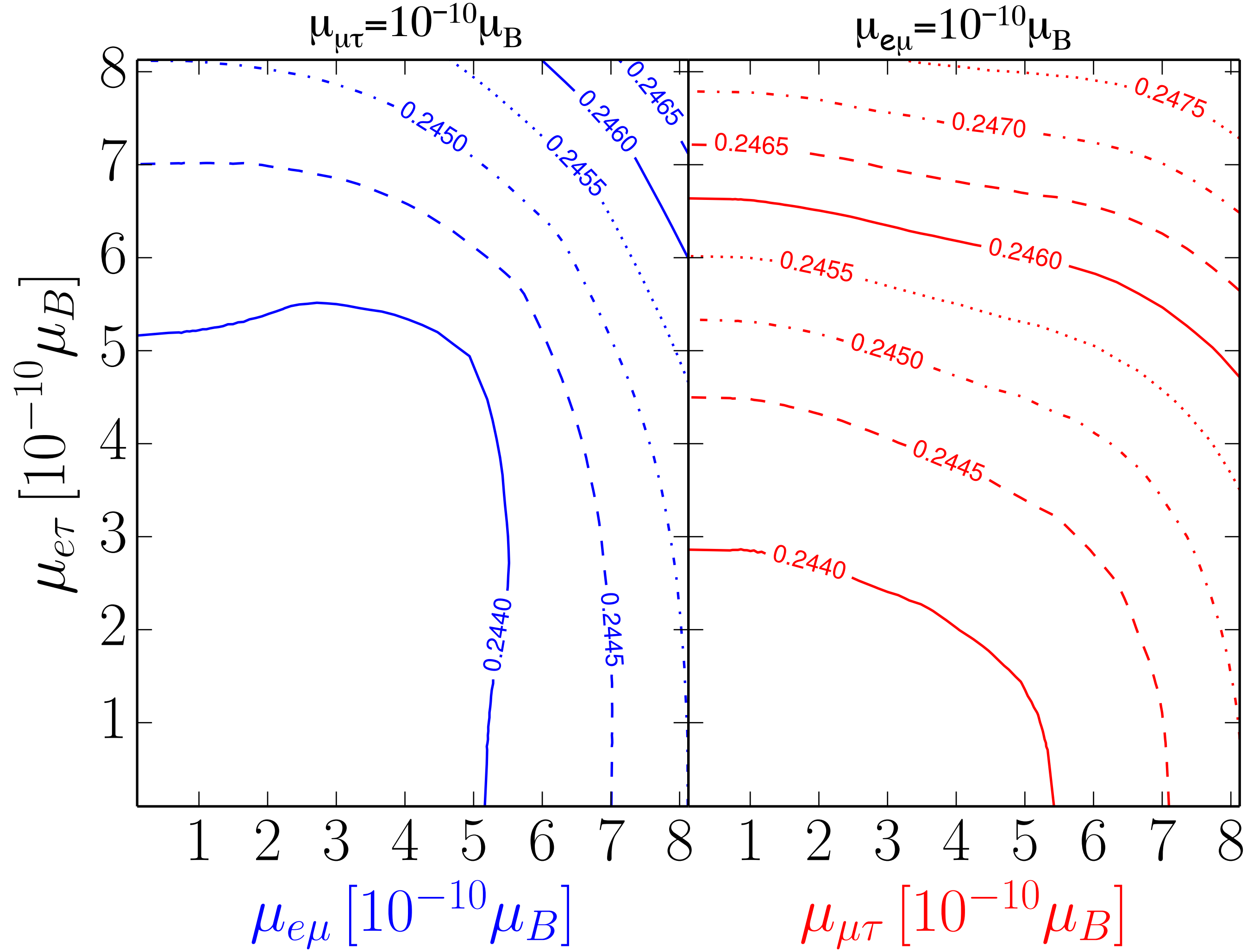


Contours of constant Y_P

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



Contours of constant Y_p



The change in the BBN abundances due to the neutrino magnetic moment

Solid lines: $\mu_{e\tau} = 10^{-11} \mu_B$

black: $\mu_{\mu\tau} = 10^{-11} \mu_B$

red: $\mu_{\mu\tau} = 4 \times 10^{-10} \mu_B$

blue: $\mu_{\mu\tau} = 6 \times 10^{-10} \mu_B$

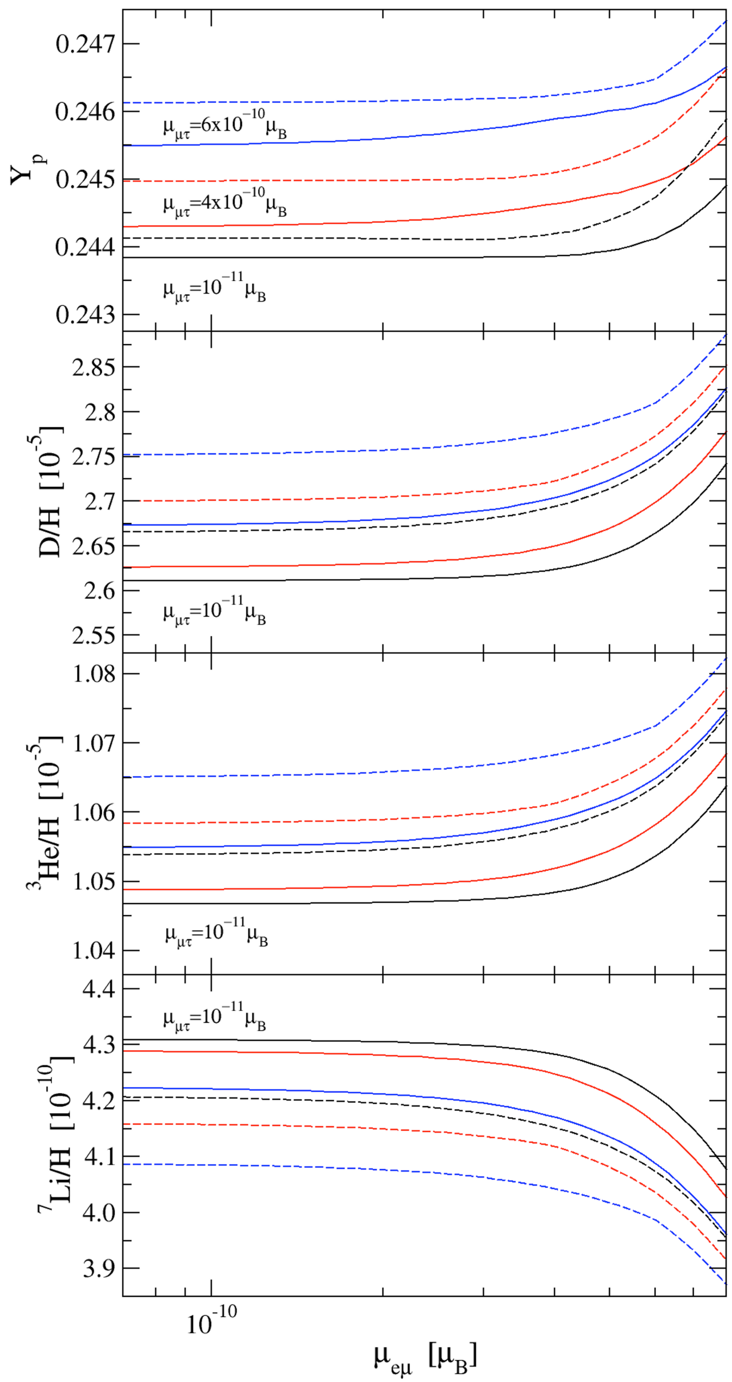
Dashed lines: $\mu_{e\tau} = 6 \times 10^{-10} \mu_B$

black: $\mu_{\mu\tau} = 10^{-11} \mu_B$

red: $\mu_{\mu\tau} = 4 \times 10^{-10} \mu_B$

blue: $\mu_{\mu\tau} = 6 \times 10^{-10} \mu_B$

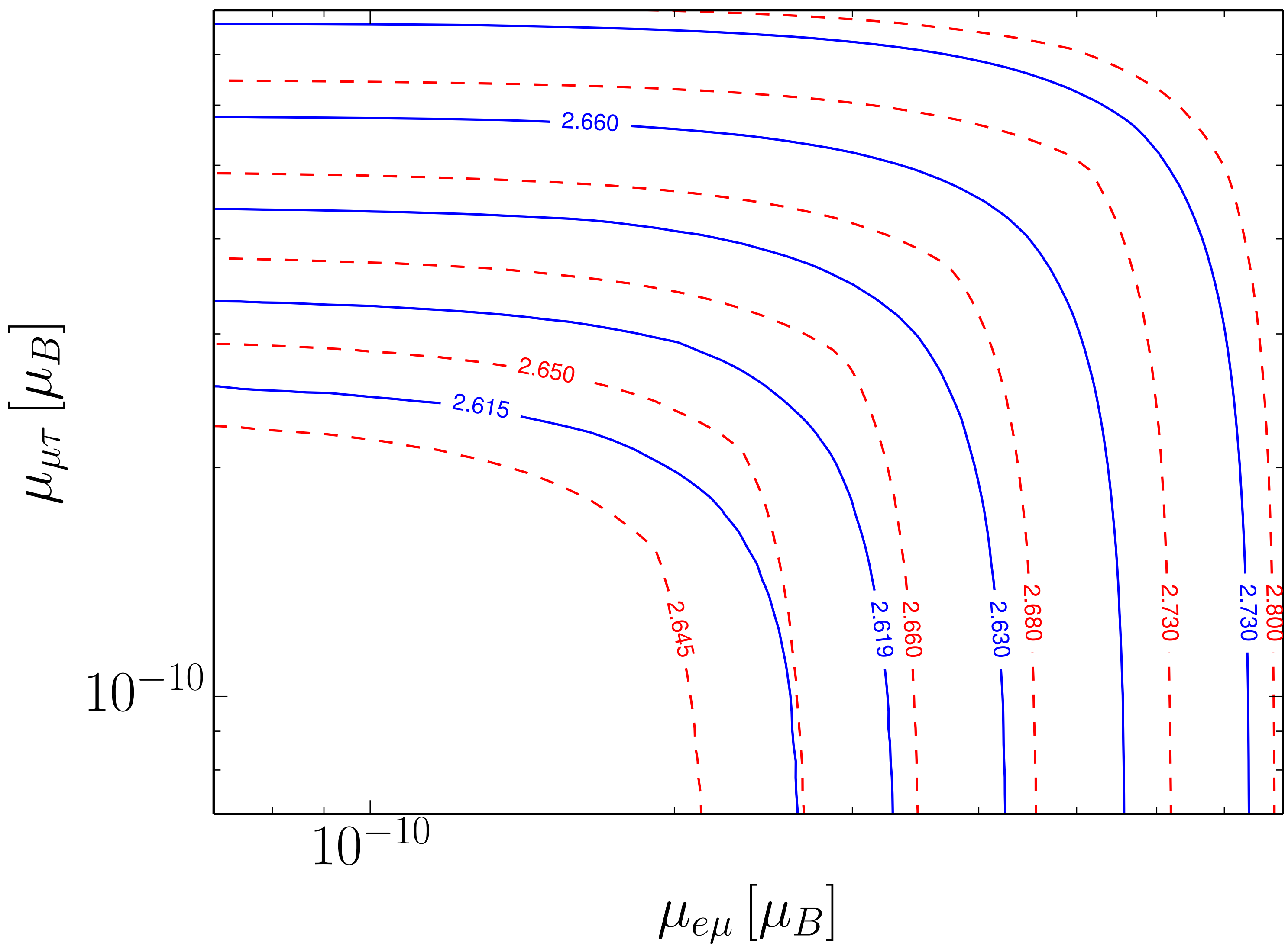
Vassh, Grohs, Balantekin, Fuller, arXiv:1510.0042



Contours of constant $10^5 \times (D/H)$

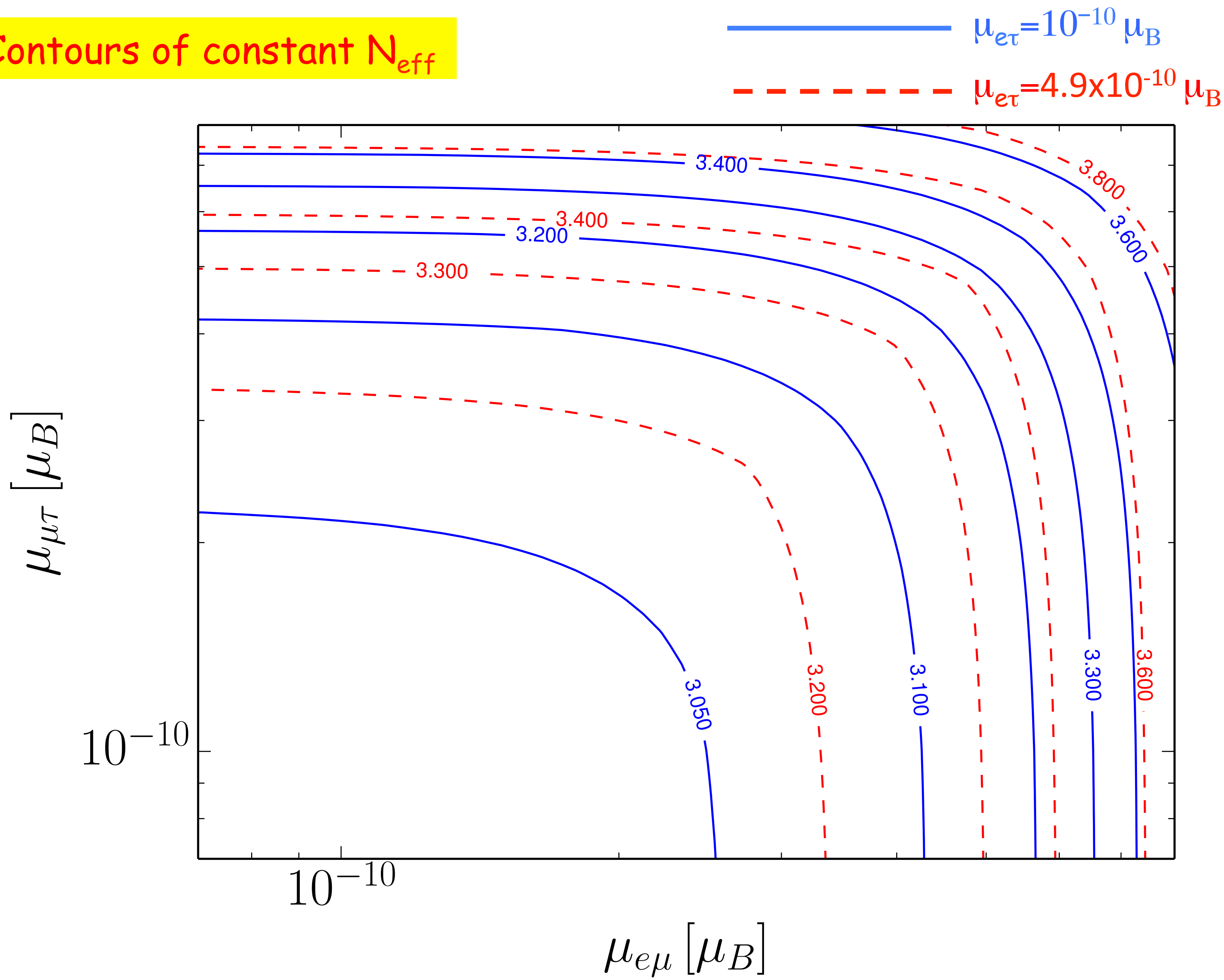
$\mu_{e\tau}=10^{-10}\,\mu_B$

$\mu_{e\tau}=4.9\times10^{-10}\,\mu_B$



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

Contours of constant N_{eff}



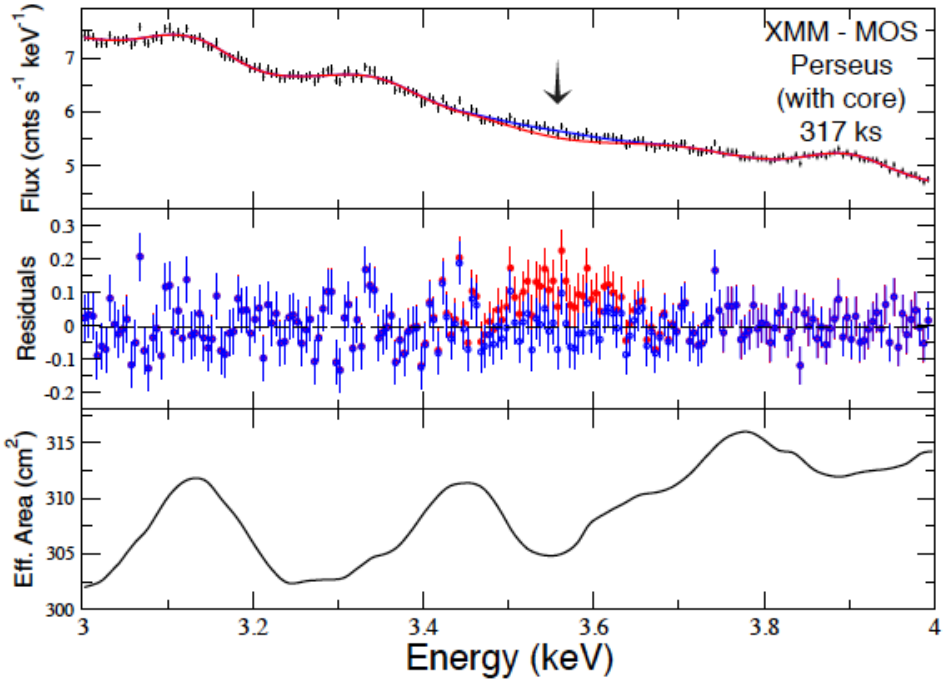
Planck: $N_{eff} = 3.30 \pm 0.27 \quad \Rightarrow \quad \mu \leq 6\times10^{-10}\,\mu_B$

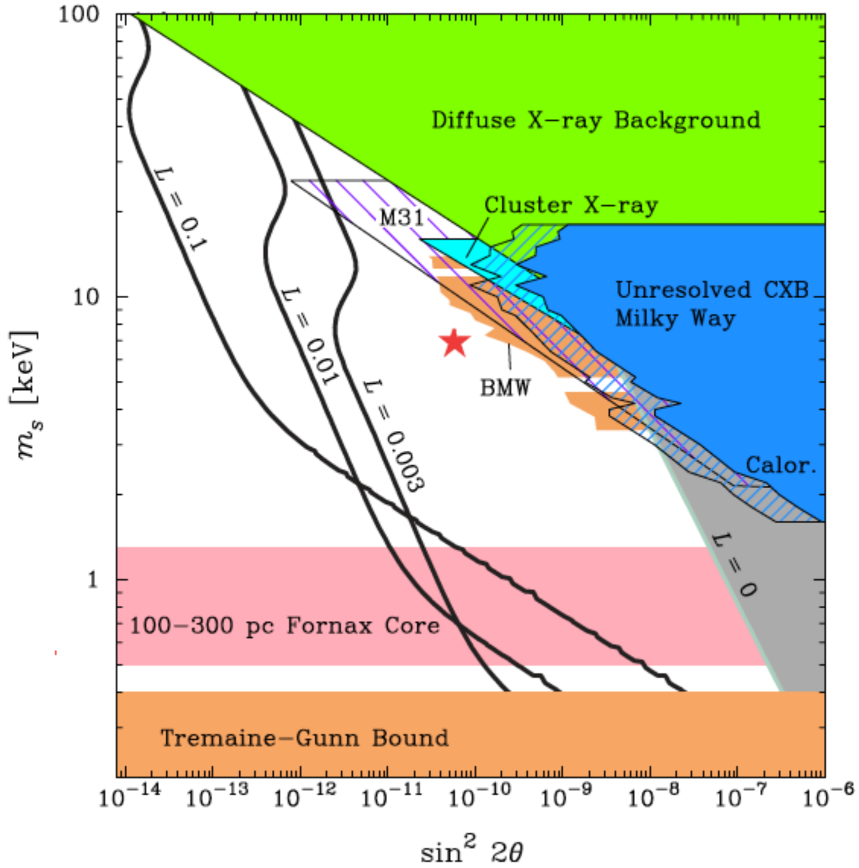
SUBMITTED TO ApJ, 2014 FEBRUARY 10
Preprint typeset using LATEX style emulateapj v. 04/17/13

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

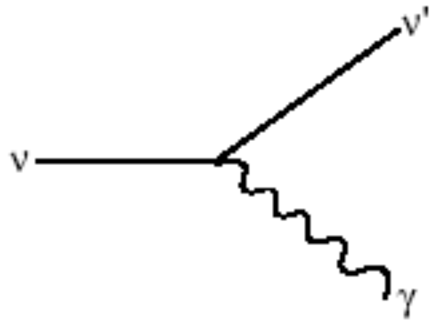
ESRA BULBUL[1,2], MAXIM MARKEVITCH[2], ADAM FOSTER[1], RANDALL K. SMITH[1] MICHAEL LOEWENSTEIN[2], AND SCOTT W. RANDALL[1]
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[2] NASA Goddard Space Flight Center, Greenbelt, MD, USA.

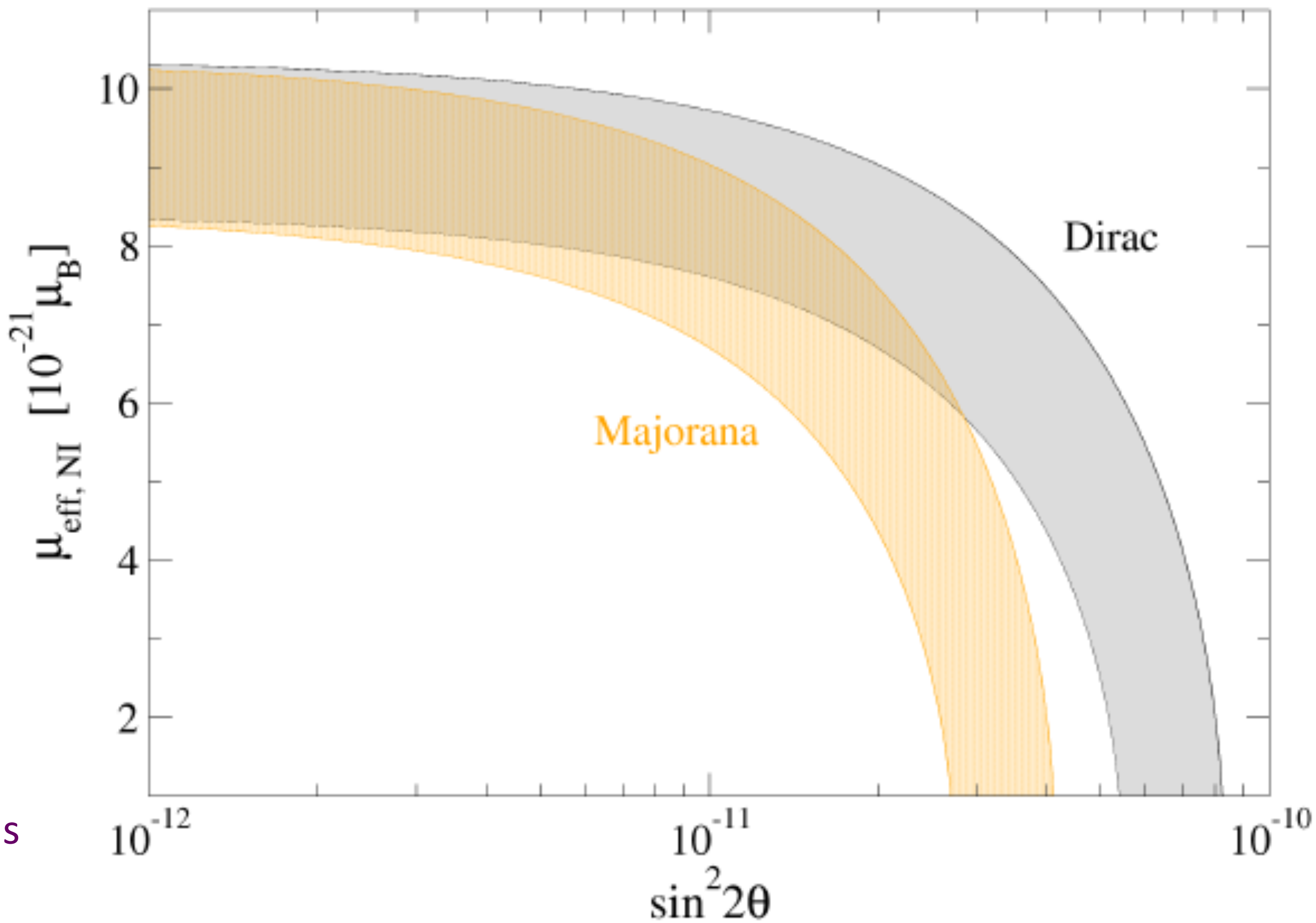
Submitted to ApJ, 2014 February 10





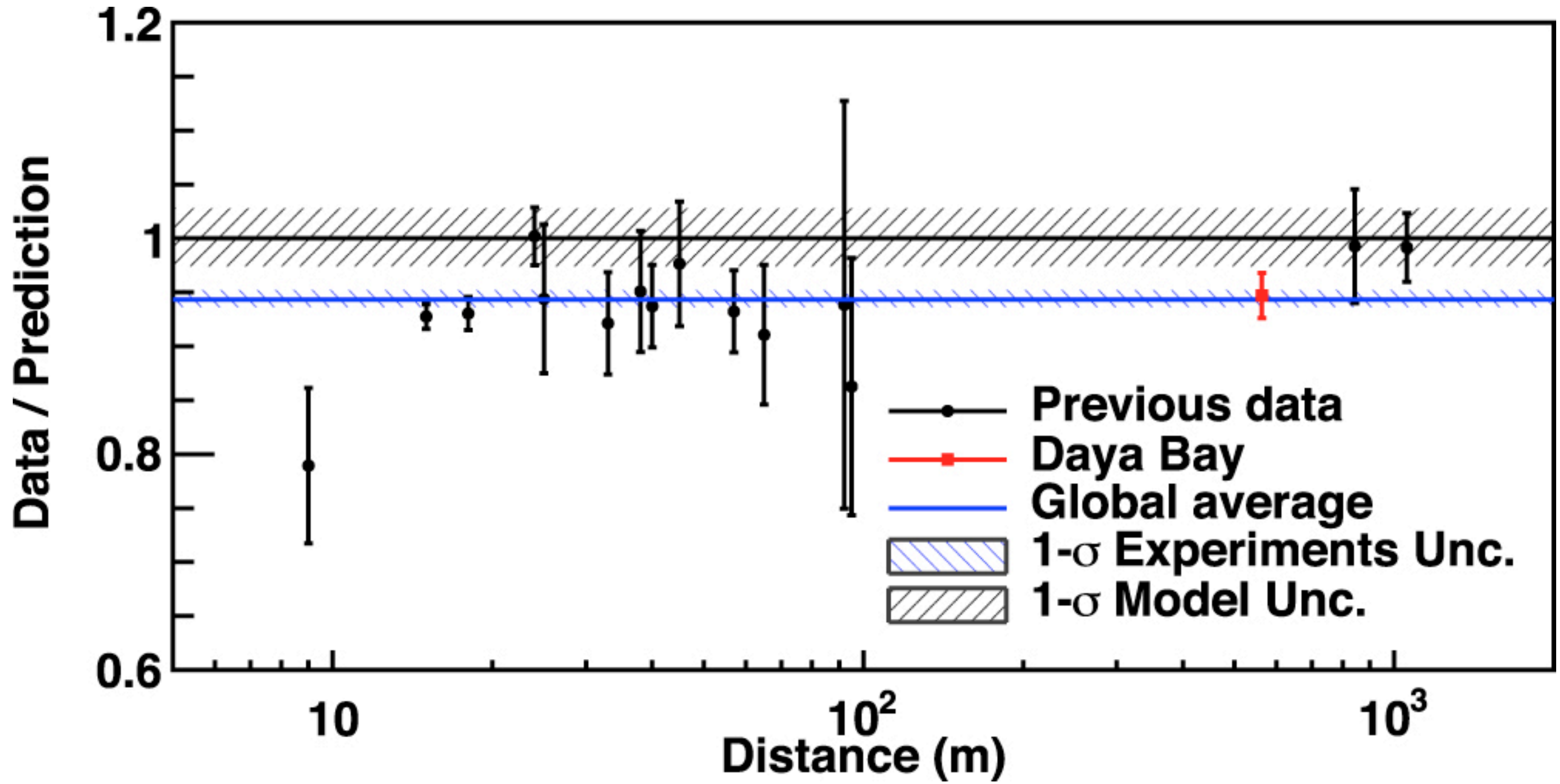
See also : arXiv:1204.5477 [hep-ph],
F. Bezrukov, A. Kartavtsev, M. Lindner



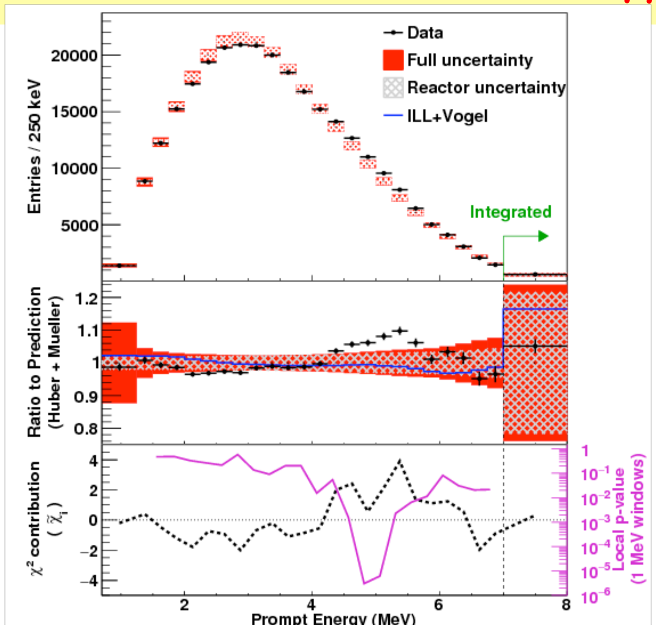


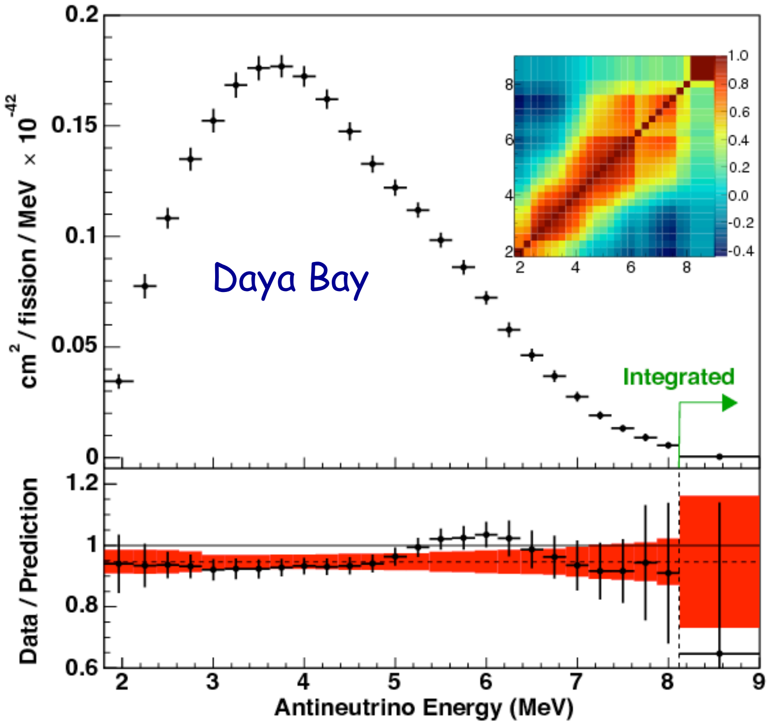
Vassh Ph.D. thesis

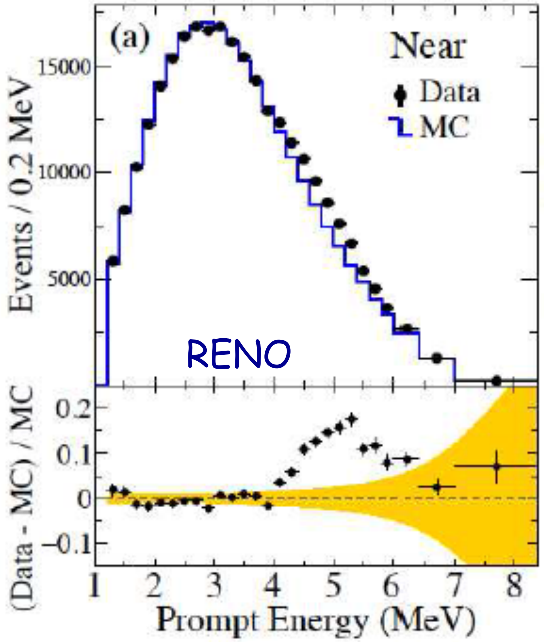
"The reactor anomaly"

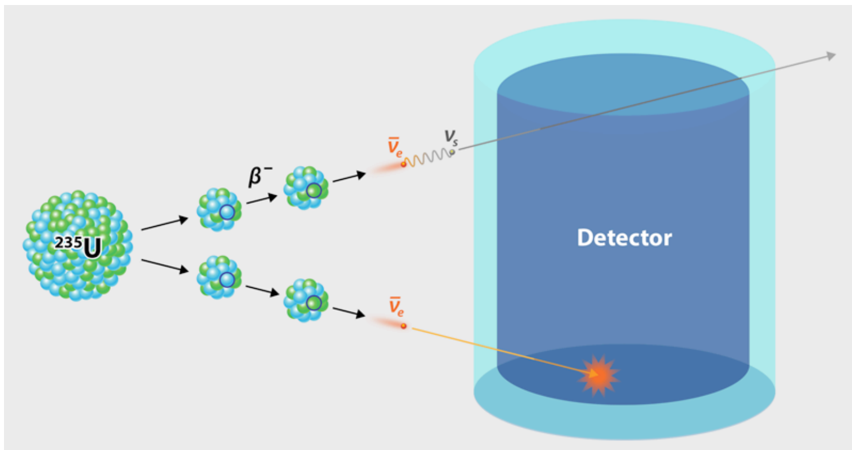


Then comes the bump!



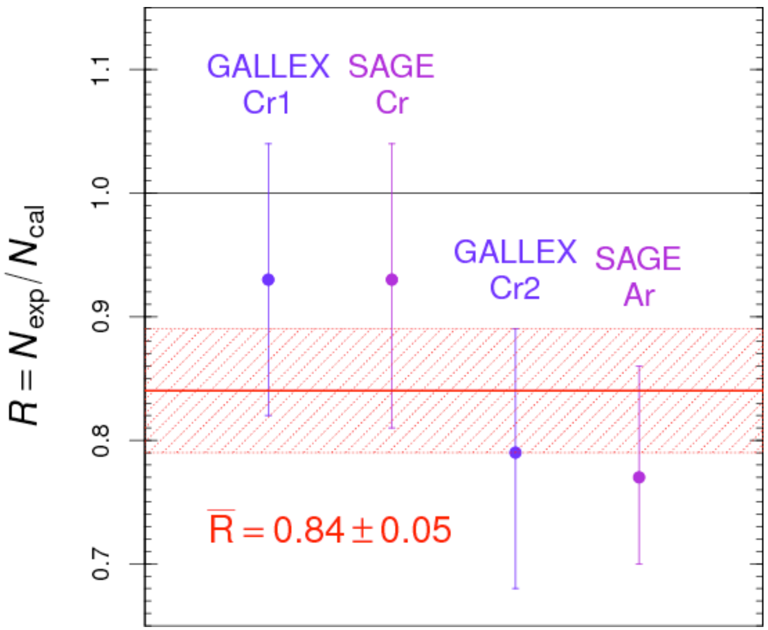


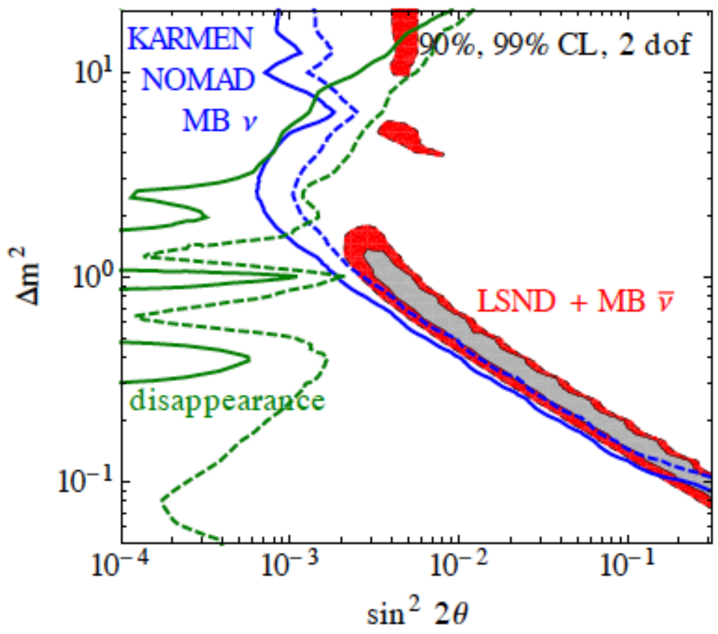


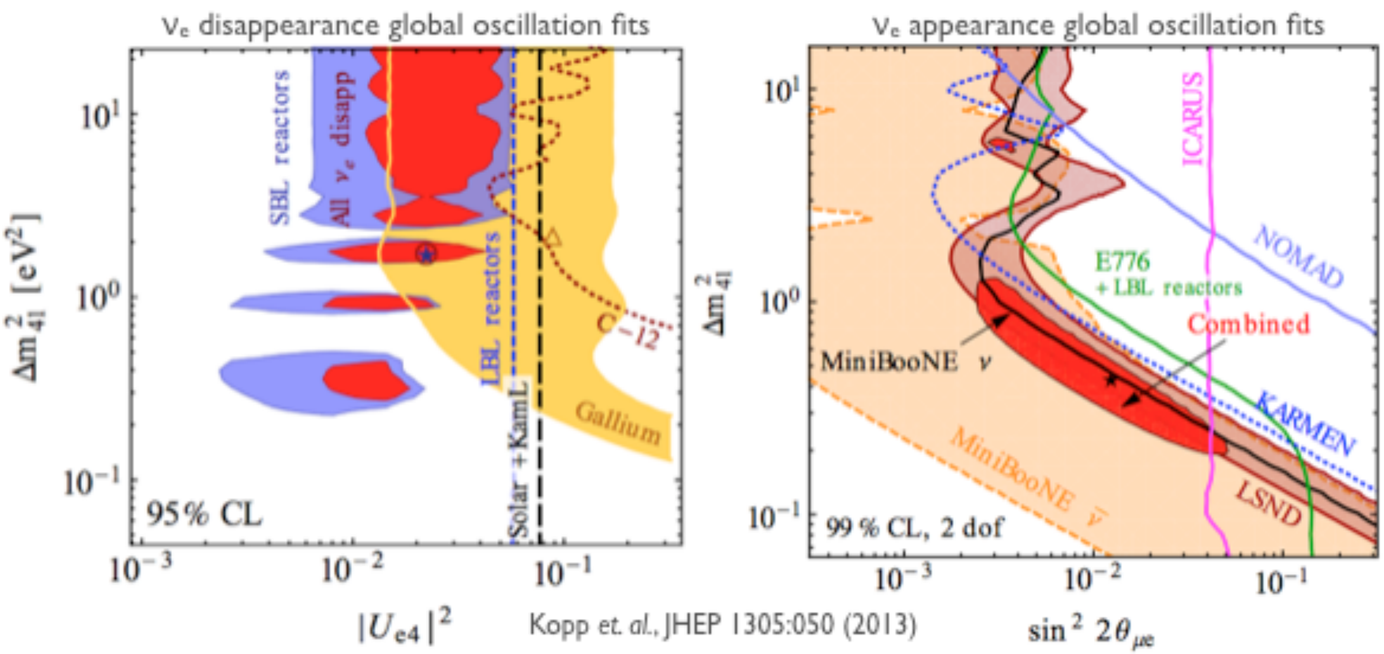


Source: APS

Does the reactor-flux anomaly imply active-sterile neutrino mixing?

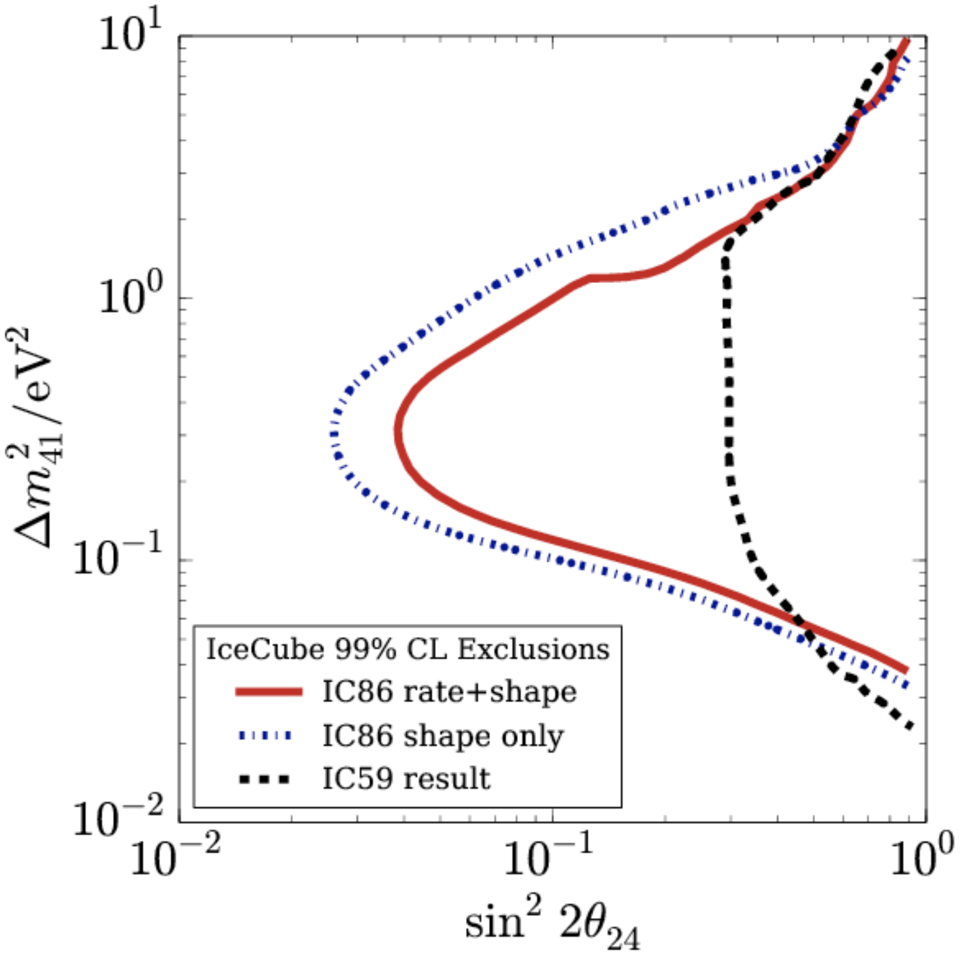


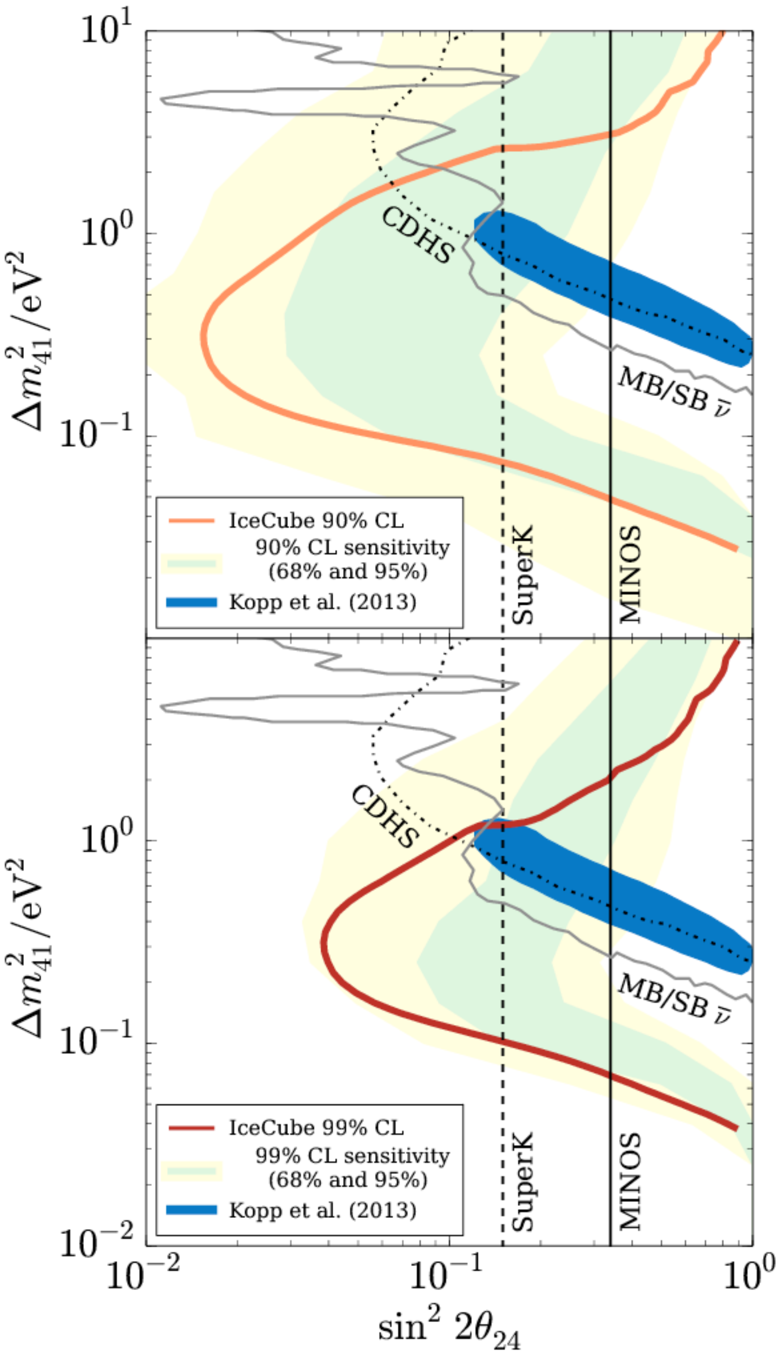




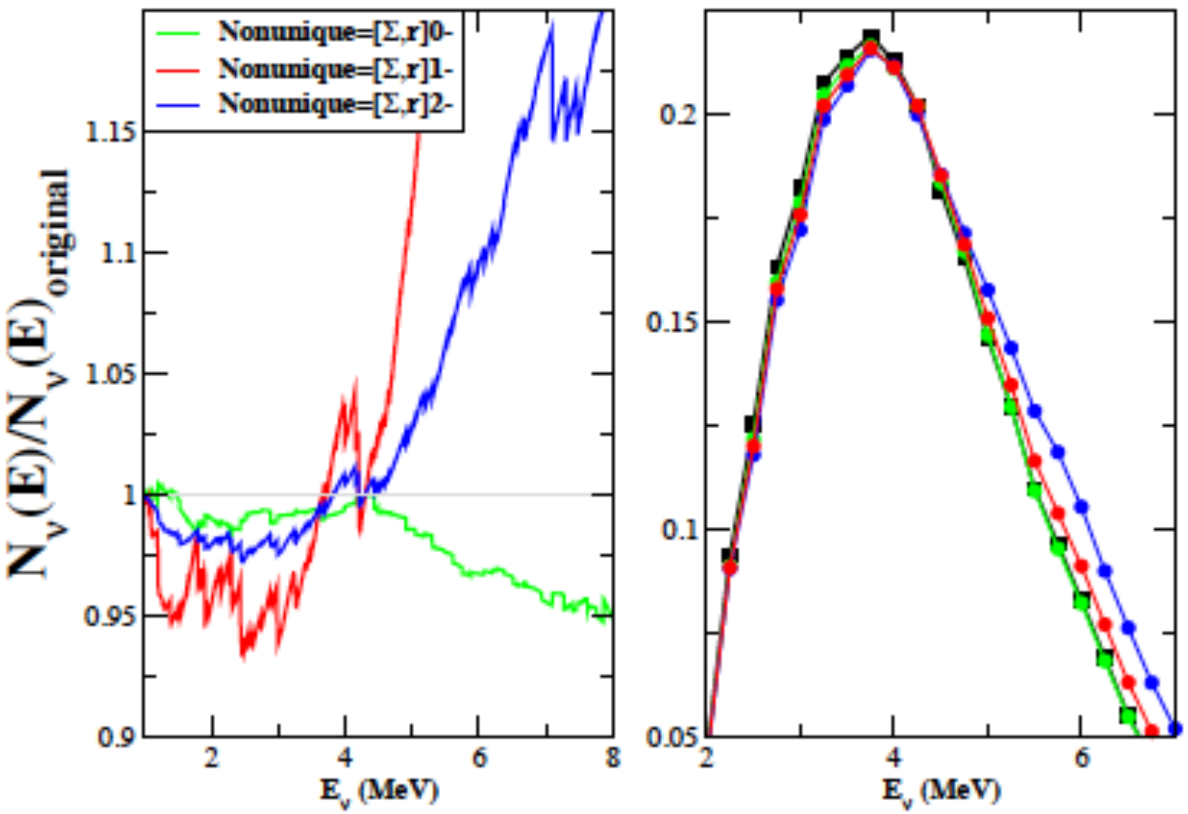
Kopp et. al., JHEP 1305:050 (2013)

Sterile Neutrino Limits from ICECUBE – θ_{24}





Does the reactor-flux anomaly imply active-sterile neutrino mixing?

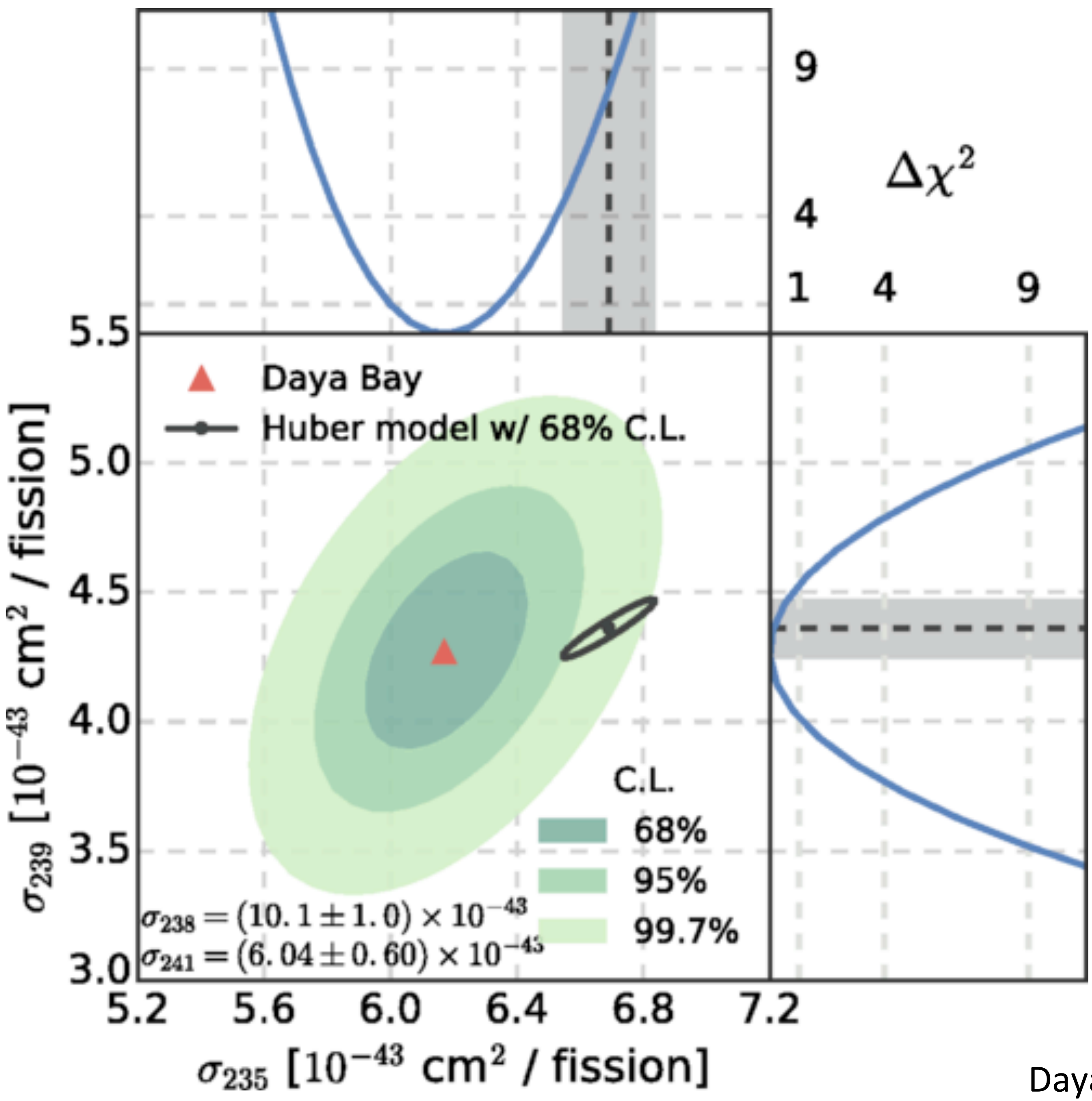


Hayes, et al., arXiv: 1309.4146 [nucl-th]

β−decays of many isotopes in a reactor are more complicated than we assumed:

Neutrino wave function:

$$e^{ikx} = \underbrace{1}_{\text{allowed app.}} + \underbrace{ikx}_{\text{first forbidden}} + \frac{1}{2}\underbrace{(ikx)^2}_{\text{second forbidden}} + \dots$$



Daya Bay 2017

Questions about sterile neutrinos in no specific order

- Is there any $\bar{\nu}_\mu$ disapperance?
- Do both reactor and non-reactor $\bar{\nu}_e$'s disappear?
- Is there visible oscillatory behavior?
- Can the sterile nature of the new flavors be established without recourse to the Z width?
- Is there any associated CP violation?

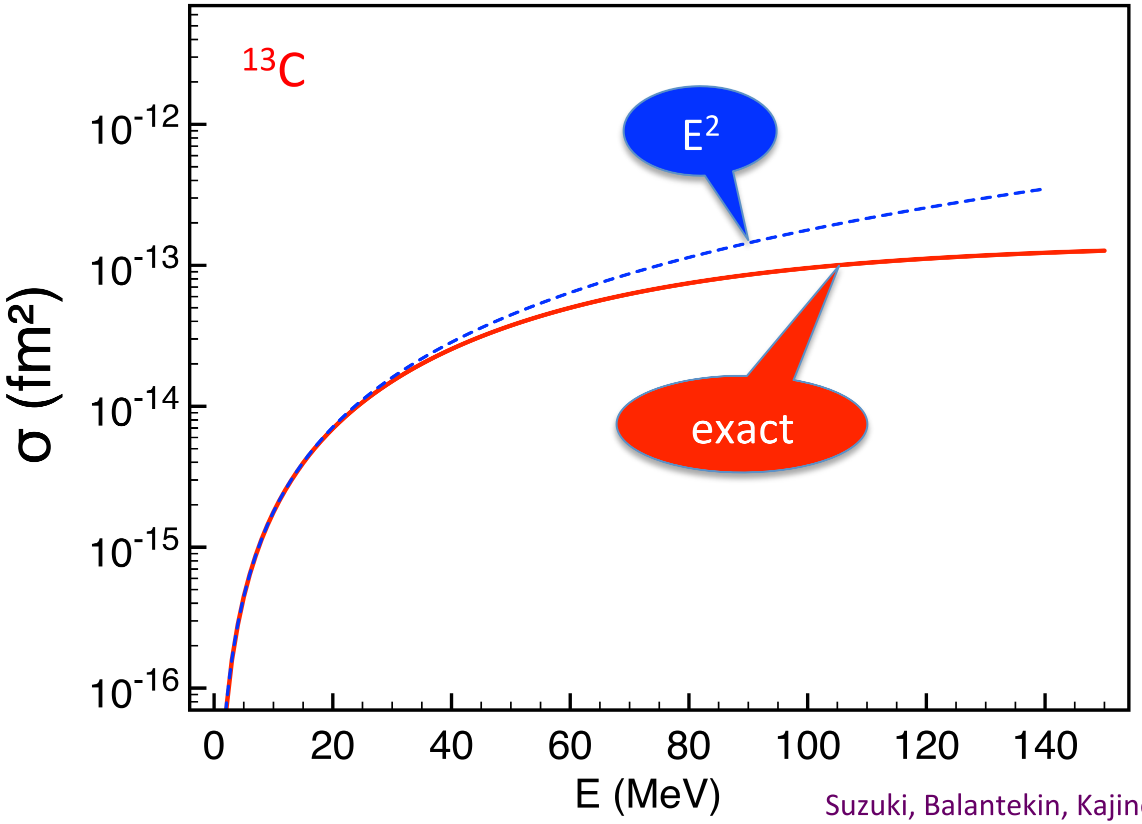
Oscillatory behavior of the neutral-current event rate, would establish, without recourse to the Z-width, oscillation into sterile flavor(s).

Neutrino Coherent Scattering

$$\nu + A \to \nu + A$$

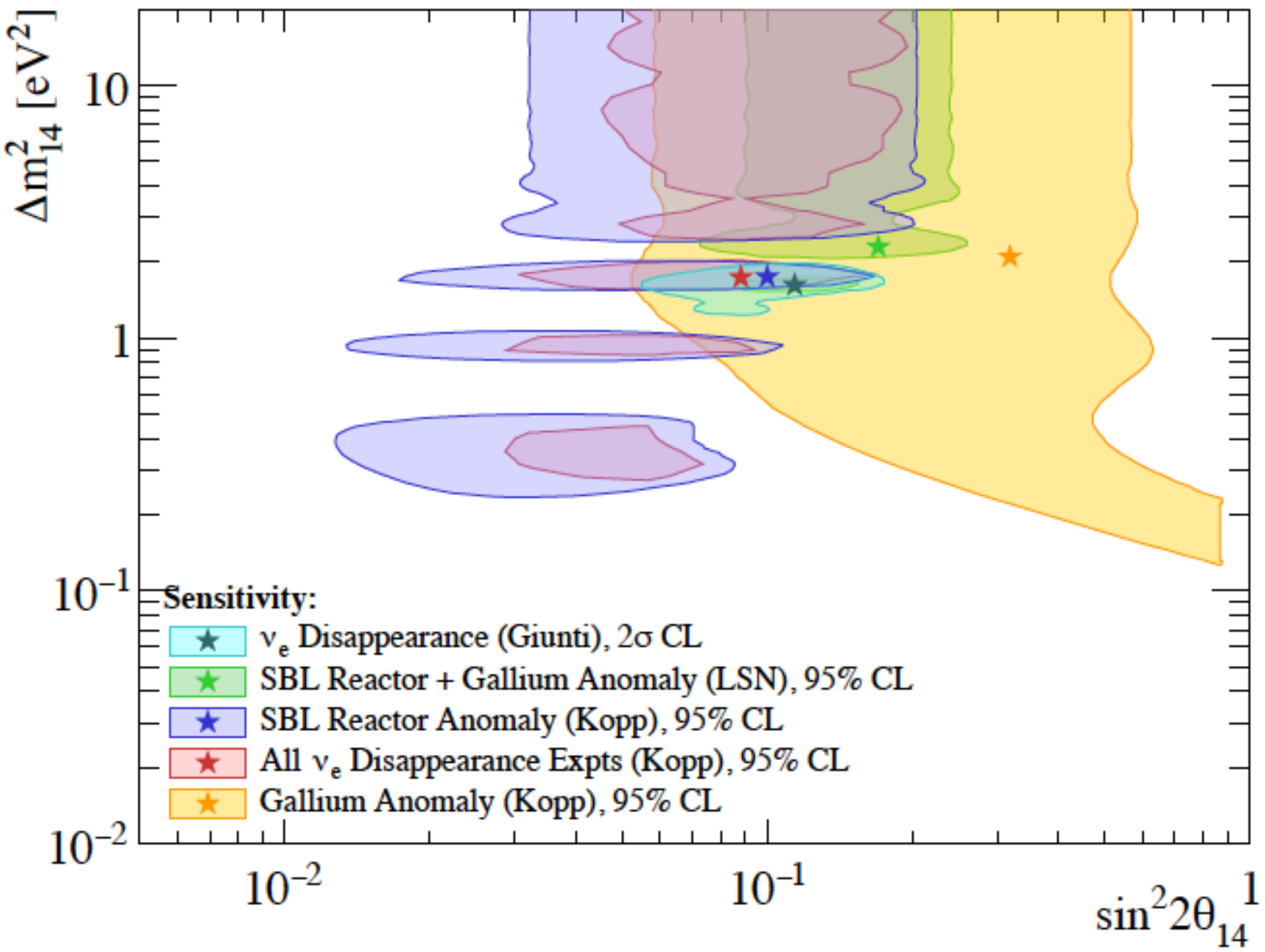
$$\frac{d\sigma}{d\cos\theta} = \frac{G_F^2}{8\pi}\left\{Z^2\left(4\sin^2\theta_W - 1\right) + N\right\}^2 E_\nu^2 (1+\cos\theta)$$

$$T_{\rm av.\,recoil} = \frac{2}{3A}\left(\frac{E_\nu}{\rm MeV}\right)\,{\rm keV}$$

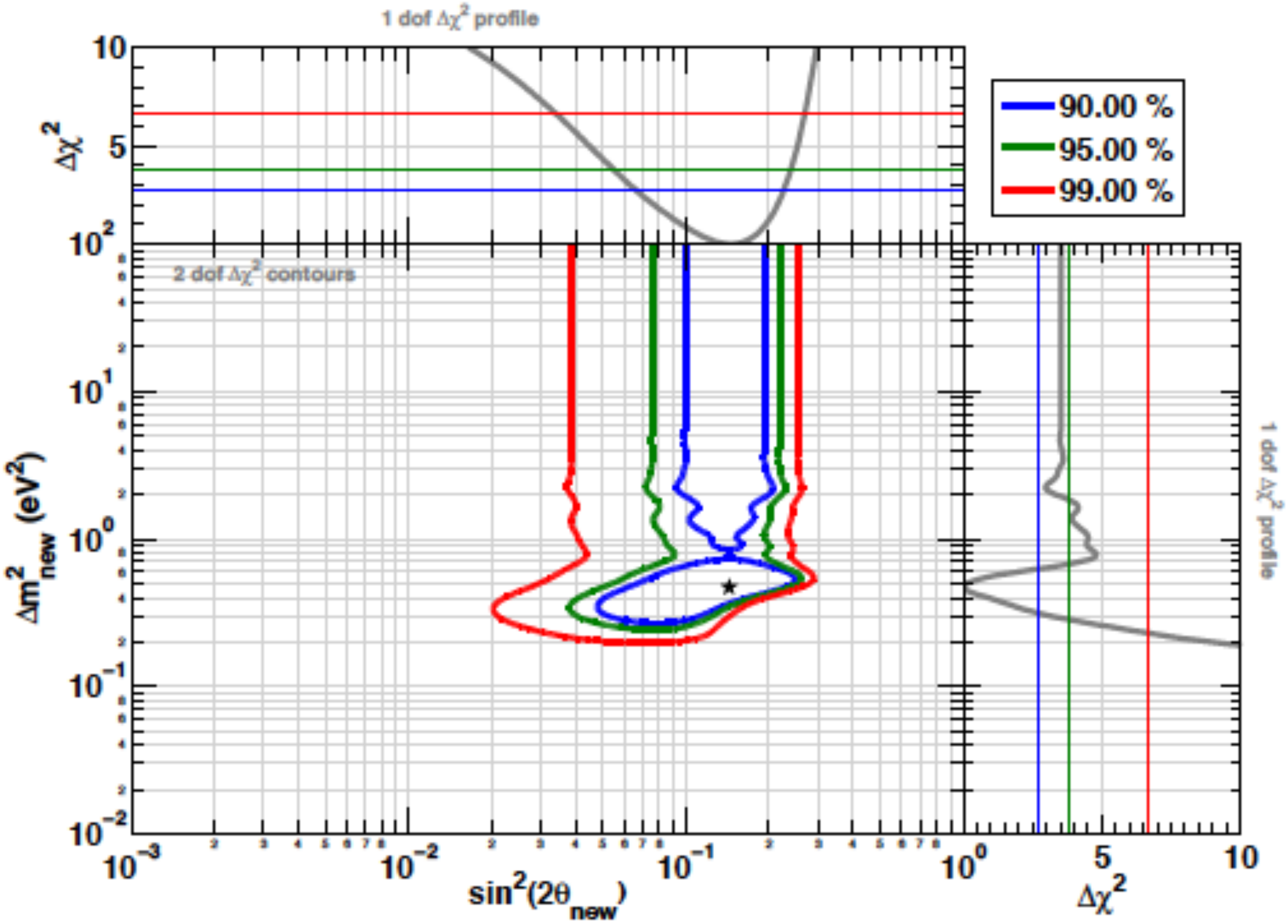


Suzuki, Balantekin, Kajino, Chiba

- First calculated by Freedman.
- This reaction is background to the dark matter searches with nuclear targets.
- Nuclear form factors need to be included. McLaughlin, Engel.
- A calculation for scintillators with the state-of-the-art nuclear interactions is shown on the left.



PROSPECT Collaboration, arXiv:1512.02202



Kopp

At very close distances to the reactor

and for $m_4^2 \geq 1\ \mathrm{eV}^2$

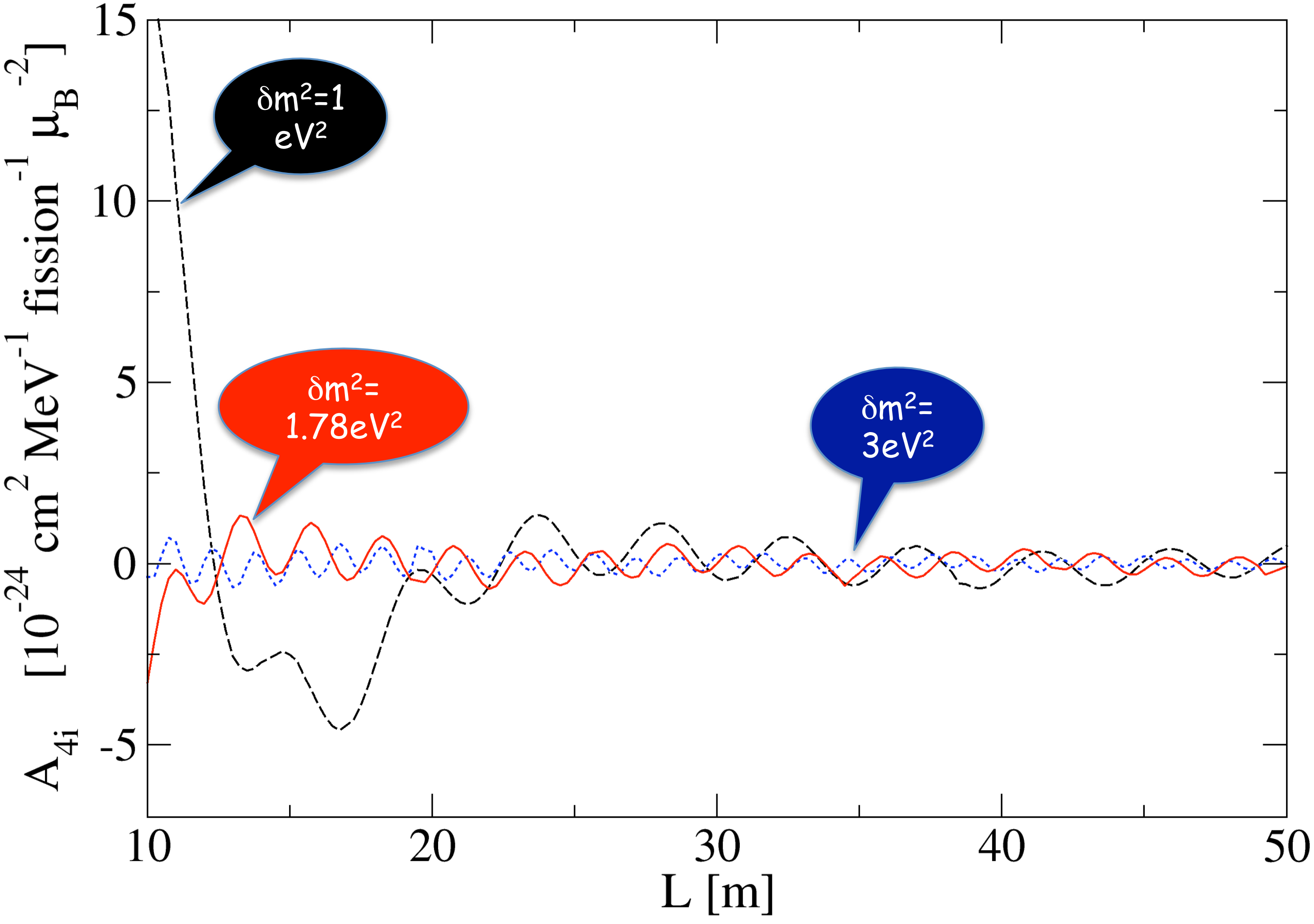
$$P\left(\bar{\nu}_e \to \bar{\nu}_e\right) = 1 - 2\left|U_{e4}\right|^2 + 2\left|U_{e4}\right|^4$$

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

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

For a sufficiently heavy sterile neutrino the phases with $(E_4 - E_i)L$ average to zero

$$\mu_{eff}^2 = \sum_{i,j=1}^{3} \left[U_{ei} \left(\mu \mu^+ \right)_{ij} U_{je}^+ \right] + U_{e4} \left(\mu \mu^+ \right)_{44} U_{4e}^+$$



$$A_{4i} = \int_{E_\nu,\min}^{\infty} \frac{2\alpha^2\pi}{m_e^2}\left[\frac{1}{T_e} - \frac{1}{E_\nu}\right]\left[\cos\left(\frac{\delta m_{4i}^2 L}{2E_\nu}\right)\right]\left(\frac{dN}{dE_\nu}\right) dE_\nu$$

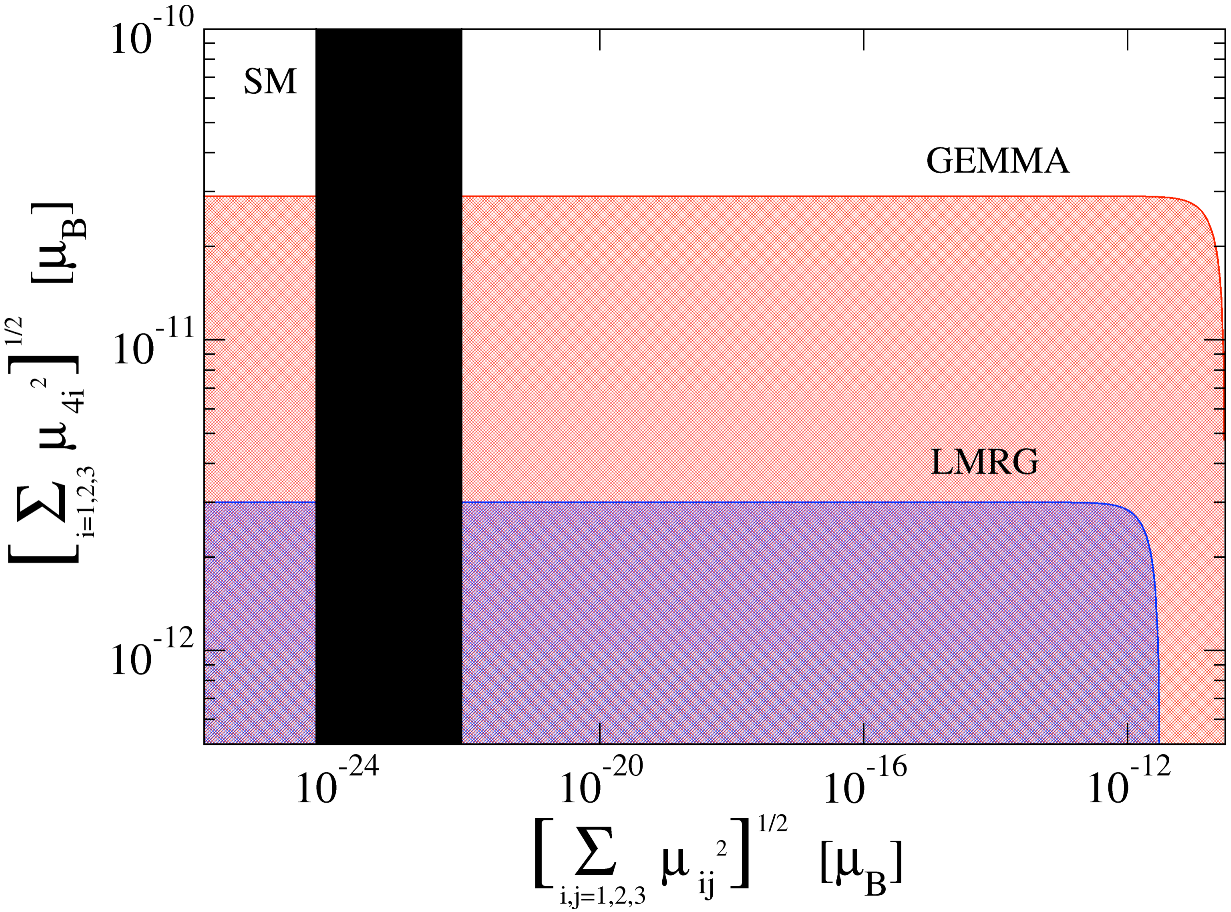
For a sufficiently heavy sterile neutrino the phases with $(E_4 - E_i)L$ average to zero

$$\mu_{eff}^2 = \sum_{i,j=1}^{3}\left[U_{ei}\left(\mu\mu^+\right)_{ij}U_{je}^+\right] + U_{e4}\left(\mu\mu^+\right)_{44}U_{4e}^+$$

$$\Rightarrow \mu_{eff}^2 \le \sum_{i=1}^{3}\mu_{i4}^2 + \left(1-\left|U_{e4}\right|^2\right)\sum_{i,j=1}^{3}\mu_{ij}^2$$

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

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



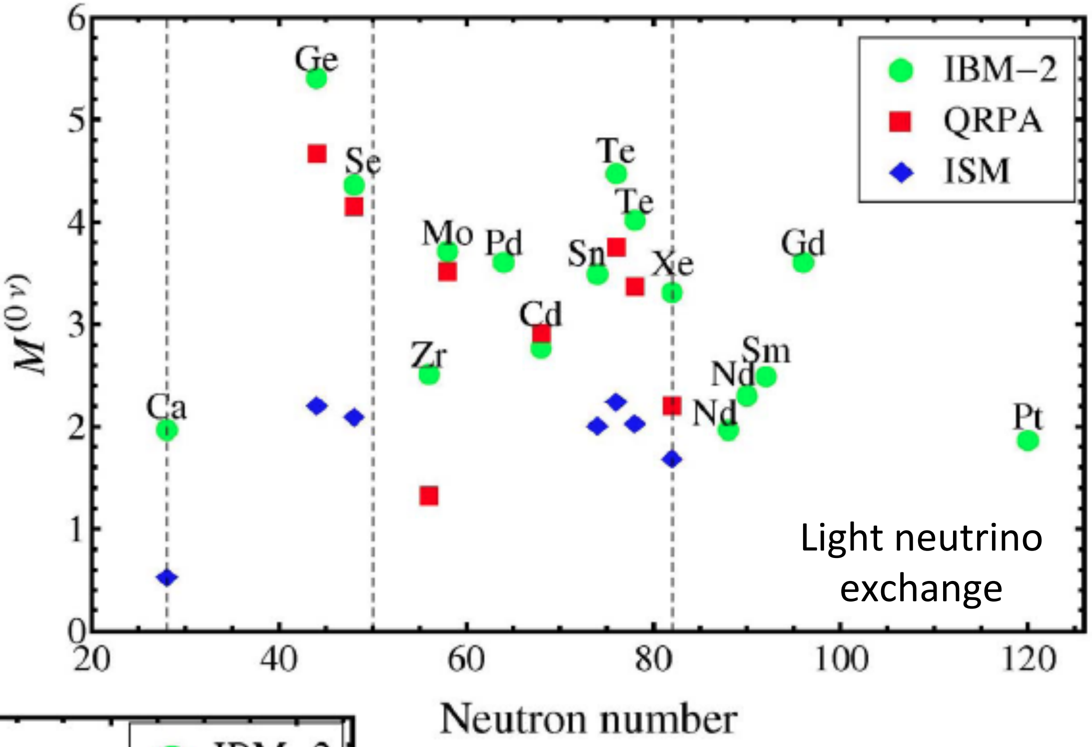
0ν double beta decay

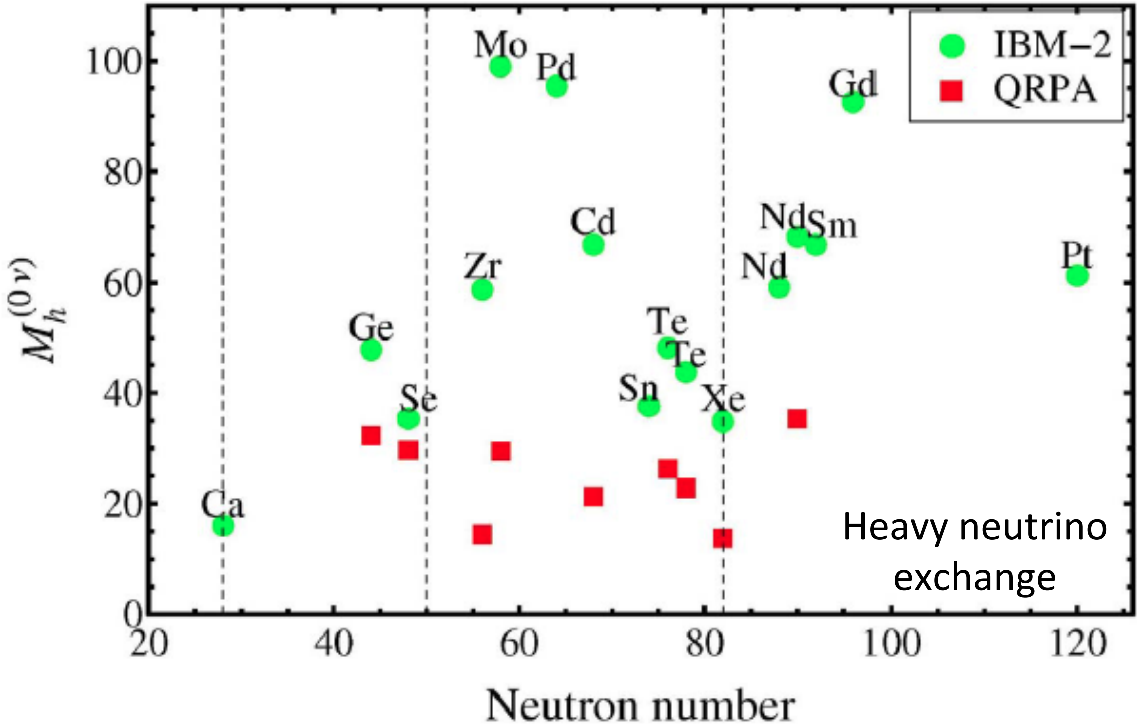
$$(1/T_{1/2}) = G(E,Z)\, M^2\, \langle m_{\beta\beta}\rangle^2$$

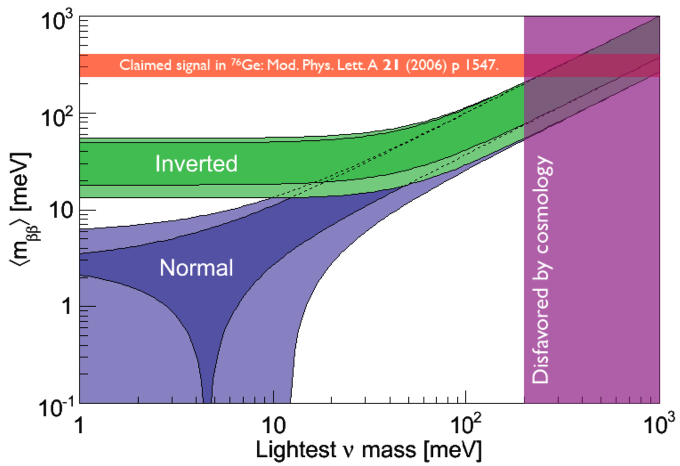
$G(E,Z)$: phase space

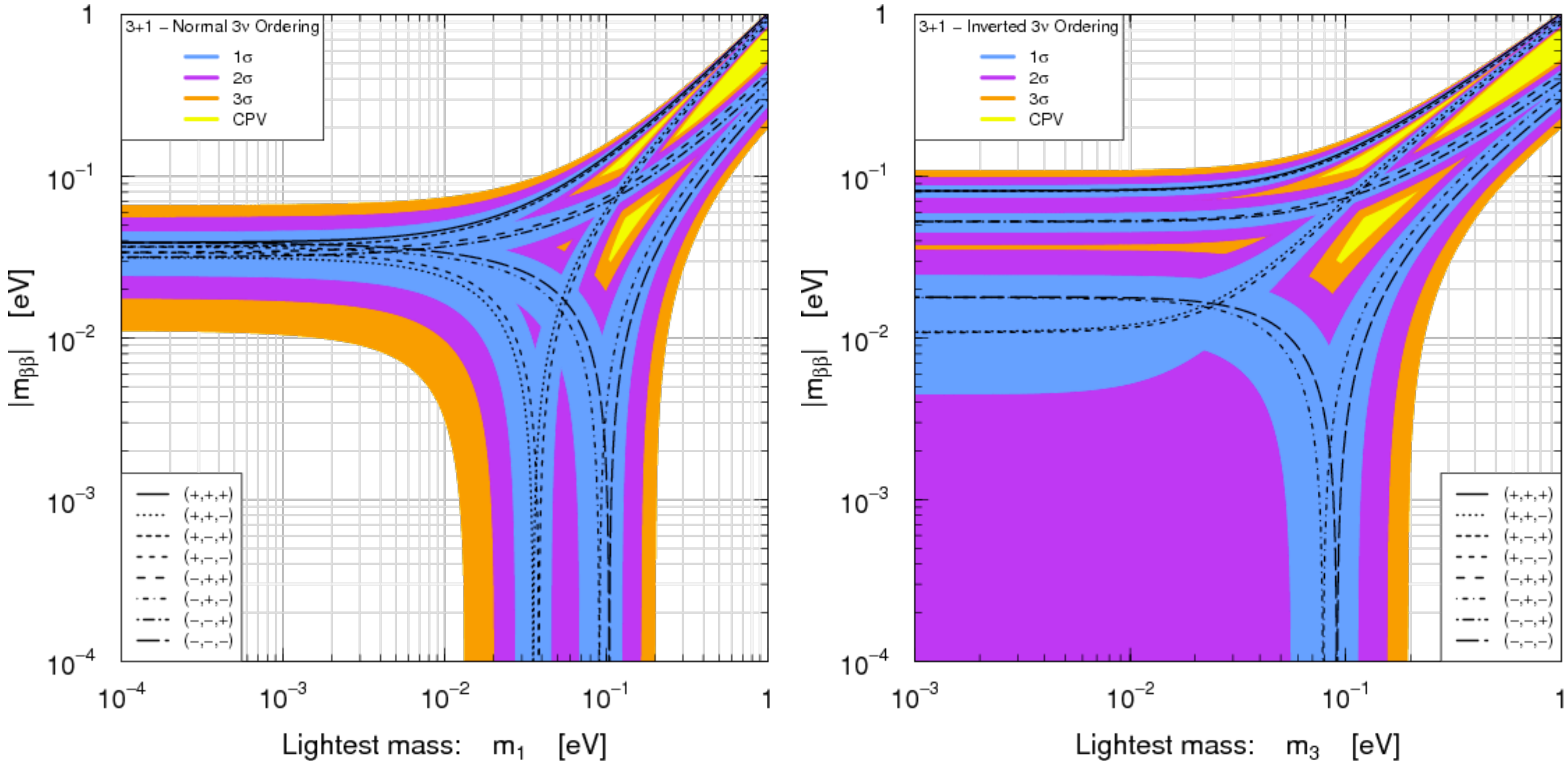
M : nuclear matrix element

$$\langle m_{\beta\beta}\rangle = |\Sigma_j\, |U_{ej}|^2\, m_j\, e^{i\delta(j)}|$$



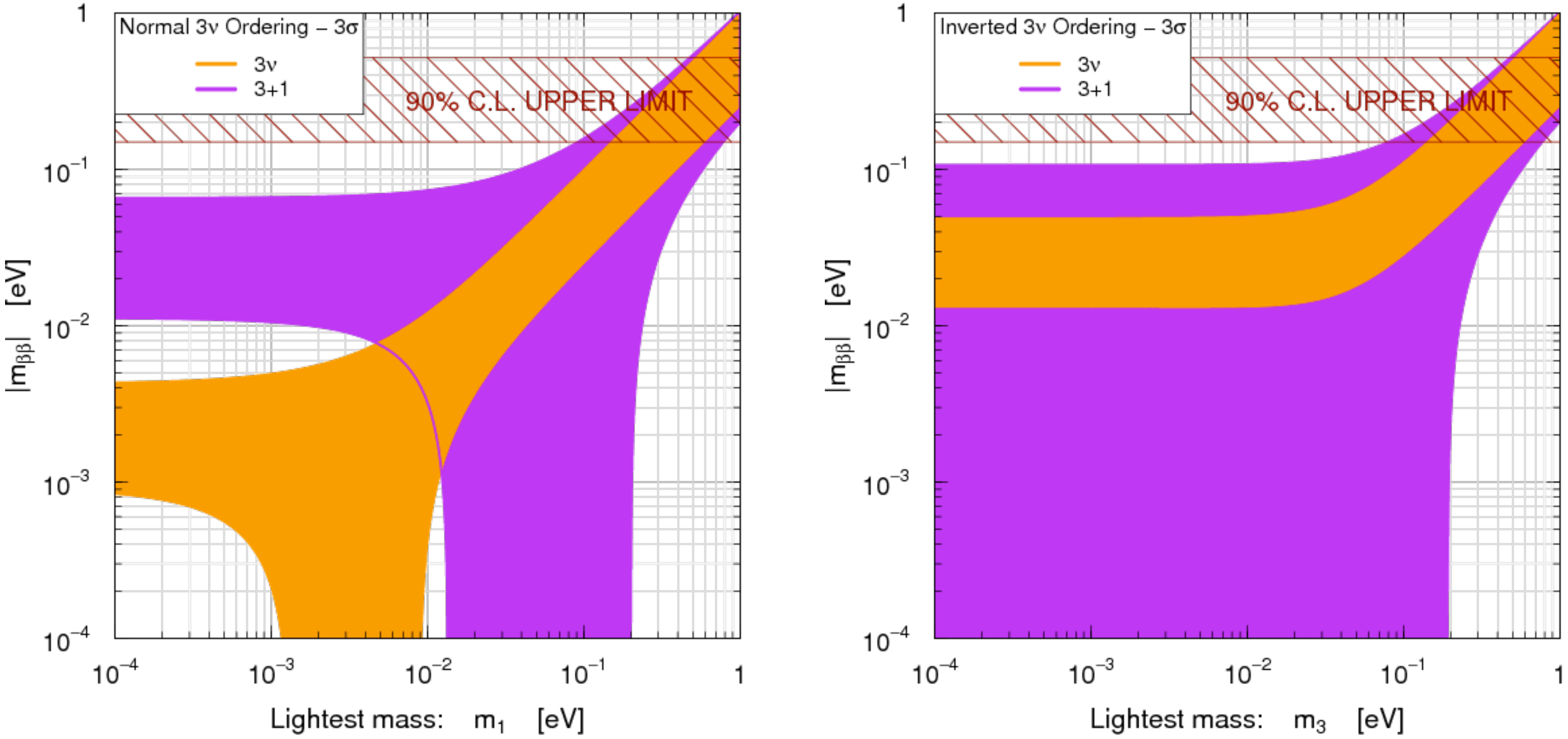






Giunti and Zavanin

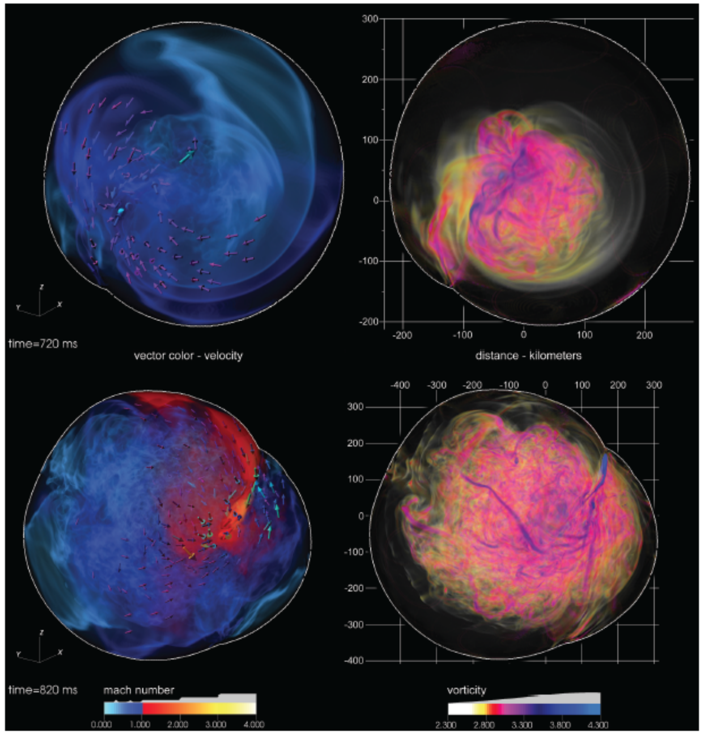
A positive result would be consistent with 3+1 light active neutrinos and NH, IH, and quasi-degenerate scenario, but not definitive as to mechanism



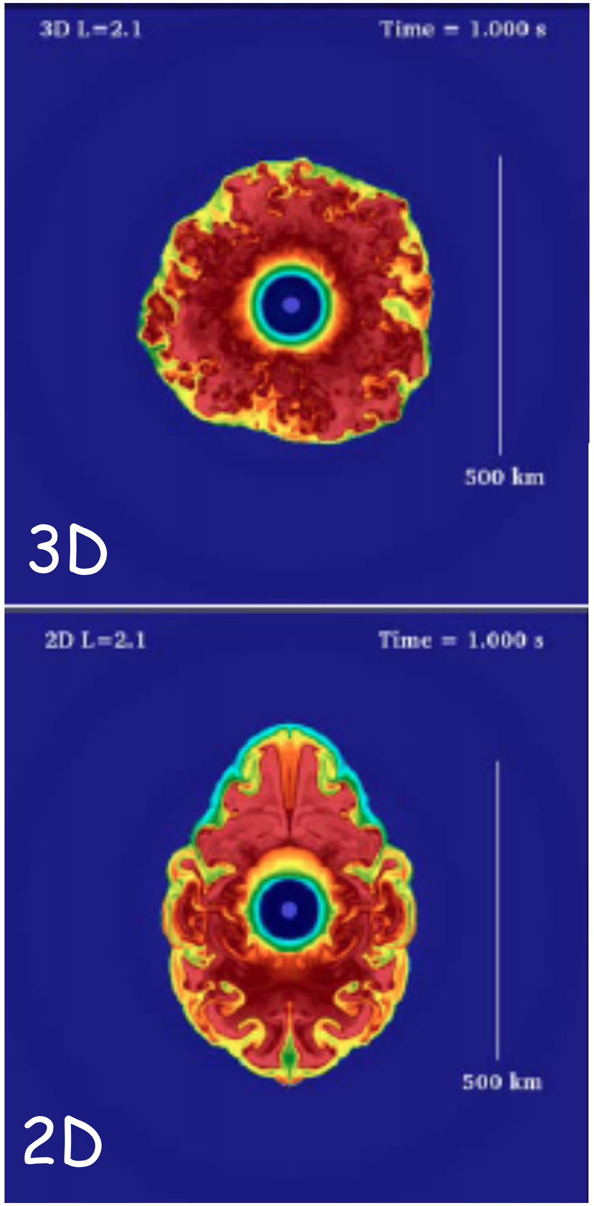
Giunti

$$|m_{\beta\beta}| = \left| |U_{e1}|^2 m_1 + \left| |U_{e2}|^2 e^{i\alpha_2} m_2 \right| + \left| |U_{e3}|^2 e^{i\alpha_3} m_3 \right| + \left| |U_{e4}|^2 e^{i\alpha_4} m_4 \right| \right|$$

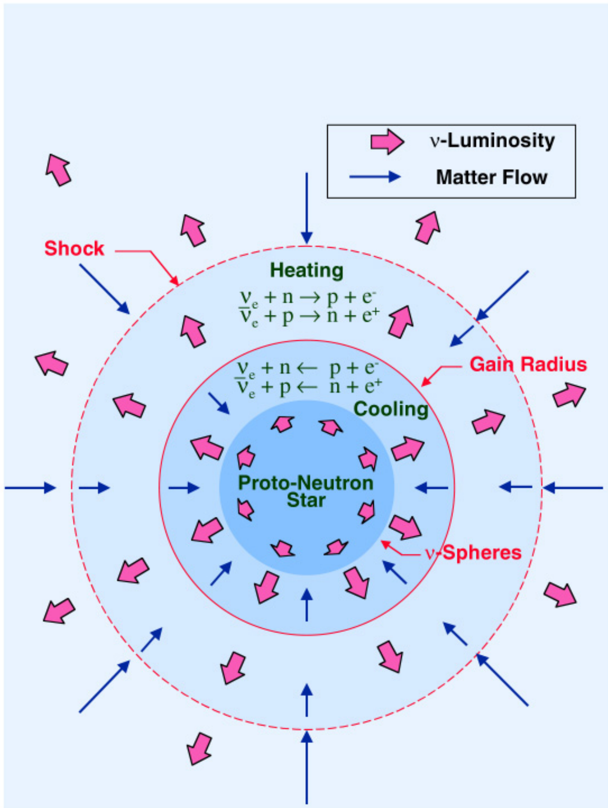
ORNL/UT

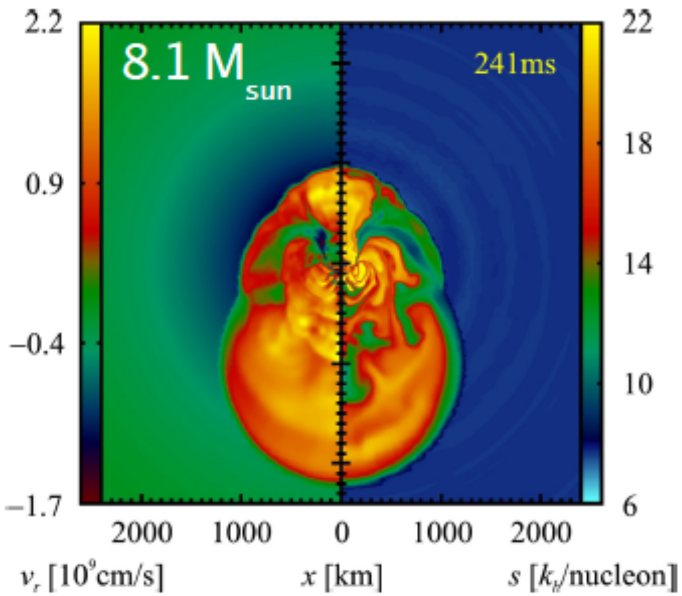


Development of 2D and 3D models for core-collapse supernovae: Complex interplay between turbulence, neutrino physics and thermonuclear reactions.



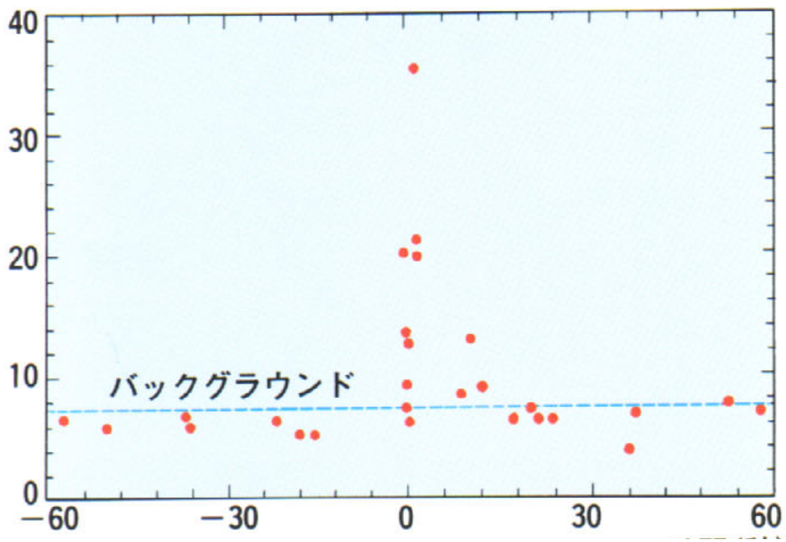
Princeton

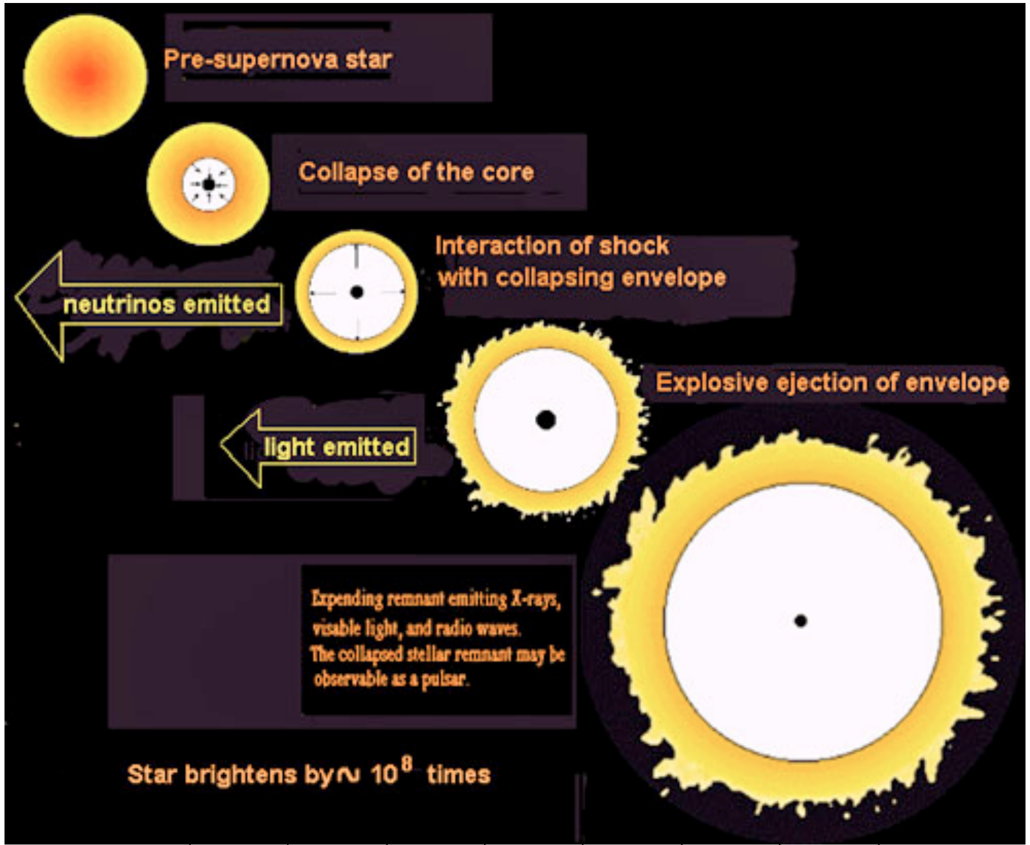




Munich

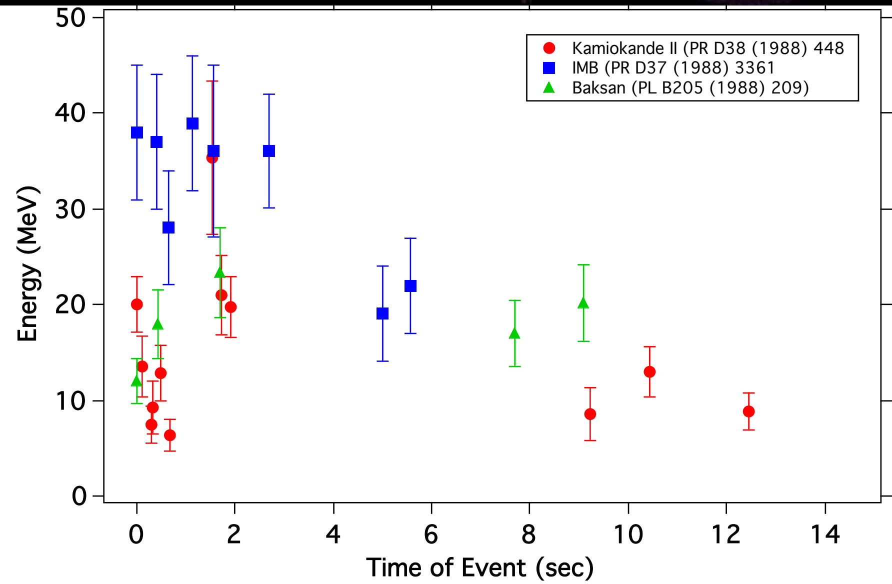
Neutrinos from core-collapse supernovae





•$M_{prog} \geq$ 8 $M_{sun} \Rightarrow \Delta E \approx 10^{53}$ ergs $\approx 10^{59}$ MeV

•99% of the energy is carried away by neutrinos and antineutrinos with $10 \leq E_\nu \leq 30$ MeV $\Rightarrow 10^{58}$ neutrinos



CP-violation

$$T_{23}T_{13}T_{12} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$c_{ij} = \cos\theta_{ij} \qquad s_{ij} = \sin\theta_{ij}$$

$$i\frac{\partial}{\partial t}\begin{pmatrix} \psi_e \\ \tilde{\psi}_\mu \\ \tilde{\psi}_\tau \end{pmatrix} = \left[T_{13}T_{12}\begin{pmatrix} E_1 & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & E_3 \end{pmatrix} T_{12}^\dagger T_{13}^\dagger + \begin{pmatrix} V_{e\mu} & 0 & 0 \\ 0 & s_{23}^2 V_{\tau\mu} & -c_{23}s_{23}V_{\tau\mu} \\ 0 & -c_{23}s_{23}V_{\tau\mu} & c_{23}^2 V_{\tau\mu} \end{pmatrix} \right] \begin{pmatrix} \psi_e \\ \tilde{\psi}_\mu \\ \tilde{\psi}_\tau \end{pmatrix}$$

$$\tilde{\psi}_\mu = \cos\theta_{23}\psi_\mu - \sin\theta_{23}\psi_\tau$$

$$\tilde{\psi}_\tau = \sin\theta_{23}\psi_\mu + \cos\theta_{23}\psi_\tau$$

$$V_{e\mu} = 2\sqrt{2}G_F N_e \left[1 + O\left(\alpha \frac{m_\mu}{m_W}\right)^2 \right]$$

$$V_{\tau\mu} = -\frac{3\sqrt{2}\alpha G_F}{\pi \sin^2\theta_W}\left(\frac{m_\tau}{m_W}\right)^2 \left[\left(N_p + N_n\right)\log\frac{m_\tau}{m_W} + \left(\frac{N_p}{2} + \frac{N_n}{3}\right) \right]$$

We need to solve an evolution equation

$$i\frac{\partial}{\partial t}U = HU$$

If we ignore $V_{\tau\mu}$ it is easy to show that the CP-violating phase factorizes:

$$U(\delta) = SU(\delta = 0)S^{\dagger} \qquad S = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\delta} \end{pmatrix}$$

This factorization still holds when collective oscillations are include, but breaks down if there is spin-flavor precession

This factorization implies that neither

$$P\left(\nu_e \rightarrow \nu_e\right)$$

nor

$$P\left(\nu_\mu \rightarrow \nu_e\right) + P\left(\nu_\tau \rightarrow \nu_e\right)$$

depend on the CP-violating phase δ.

If the ν_μ and ν_τ luminosities are the same at the neutrinosphere of a core-collapse supernova, this factorization implies that ν_e and ν_e fluxes observed at terrestrial detectors will not be sensitive to the CP-violating phase! To see its effects you need to measure ν_μ and ν_τ luminosities separately!

If you see the effects of δ in either charged- or neutral current scattering that may mean any of the following:

- There are new neutrino interactions beyond the standard model operating either within the neutron star or during propagation.
- Standard Model loop corrections (very easy to quantify) are seen.
- There are sterile neutrino states.

Factorization of the CP-violating phase if there are no sterile neutrinos

$$H(\delta) = H_{\nu} + H_{\nu\nu} = \mathbf{S} H(\delta = 0) \mathbf{S}^{\dagger}$$

$$\mathbf{S} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\delta} \end{pmatrix}$$

Holds if neutrino magnetic moment is ignored.

- MSW Hamiltonian: Balantekin, Gava, Volpe, Phys. Lett B662, 396 (2008).
- Collective Hamiltonian in the mean-field approximation: Gava, Volpe, Phys. Rev. D78, 083007 (2008).
- Exact collective Hamiltonian: Pehlivan, Balantekin, Kajino, Phys. Rev. D90, 065011 (2014).

Collective oscillations of three flavors with magnetic moment

Neutrinos: $$T_{ij}(|\mathbf{p}|,\mathbf{p}) = a_i^\dagger(\mathbf{p})a_j(\mathbf{p})$$

Antineutrinos: $$T_{ij}(-|\mathbf{p}|,\mathbf{p}) = -b_j^\dagger(\mathbf{p})b_i(\mathbf{p})$$

$$H_{\nu\nu} = \frac{G_F}{\sqrt{2}V}\sum_{i,j=1}^{3}\sum_{E,\mathbf{p}}\sum_{E',\mathbf{p}'}\left(1-\cos\theta_{\mathbf{pp}'}\right)T_{ij}(E,\mathbf{p})T_{ji}(E',\mathbf{p}')$$

$$\underbrace{H_\nu + H_{\nu\nu}}_{\text{with } \delta\neq 0} = S_\tau^\dagger \underbrace{(H_\nu + H_{\nu\nu})}_{\text{with } \delta=0} S_\tau$$

$$\underbrace{H_\nu + H_{\nu\nu} + H_{\mathsf{SFP}}(\mu)}_{\text{with } \delta\neq 0} = S_\tau^\dagger \left(\underbrace{H_\nu + H_{\nu\nu} + H_{\mathsf{SFP}}(\mu_{\mathsf{eff}})}_{\text{with } \delta=0} \right) S_\tau$$

$$\mu_{\mathsf{eff}} = S_\tau^\dagger \mu S_\tau = \begin{pmatrix} 0 & \mu_{12} & \mu_{13} e^{i\delta} \\ -\mu_{12} & 0 & \mu_{23} e^{i\delta} \\ -\mu_{13} e^{i\delta} & -\mu_{23} e^{i\delta} & 0 \end{pmatrix}$$

Pehlivan *et al.*, Phys. Rev.D 90, 065011 (2014)


Thank you!