Sterile Neutrinos and Neutrino Magnetic Moments

ACFI Workshop: Neutrino
Mass: From the Terrestrial
Laboratory to the Cosmos

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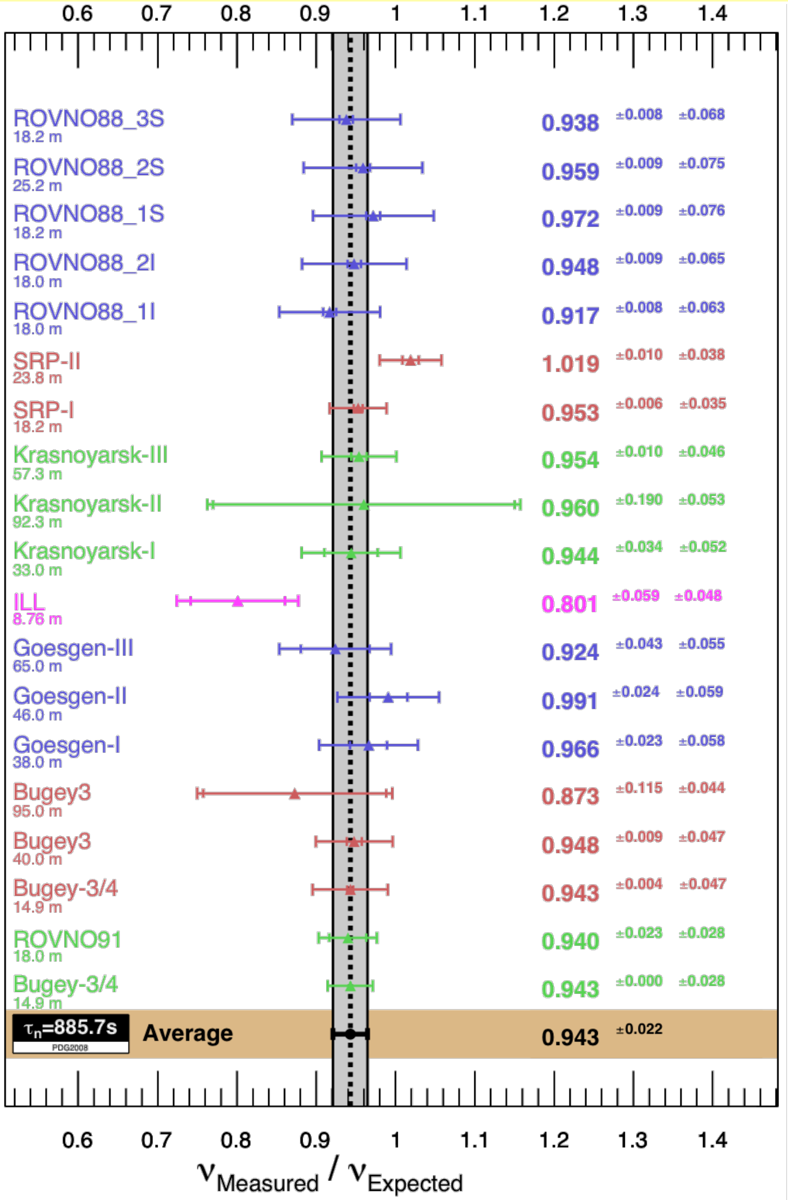
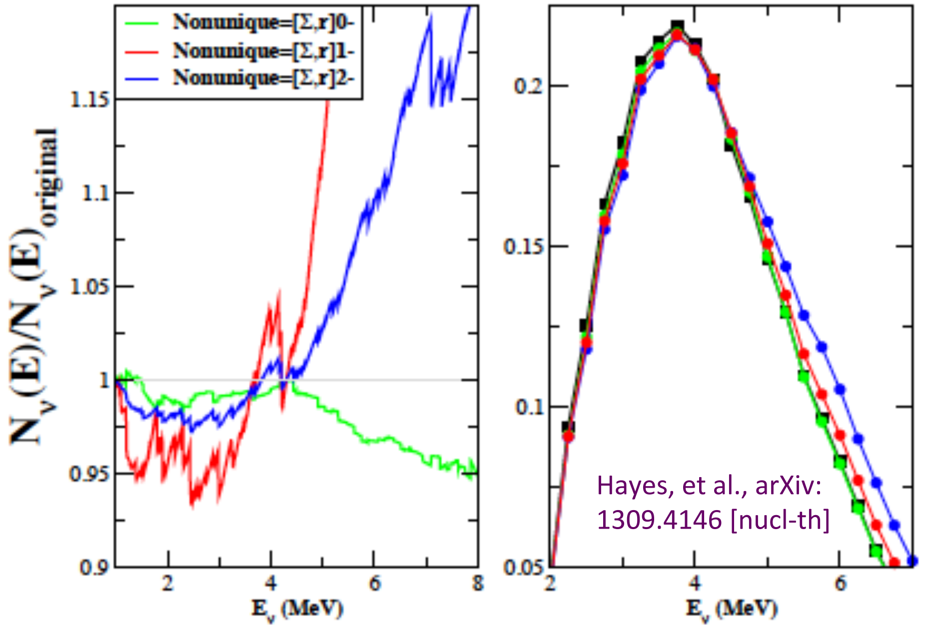
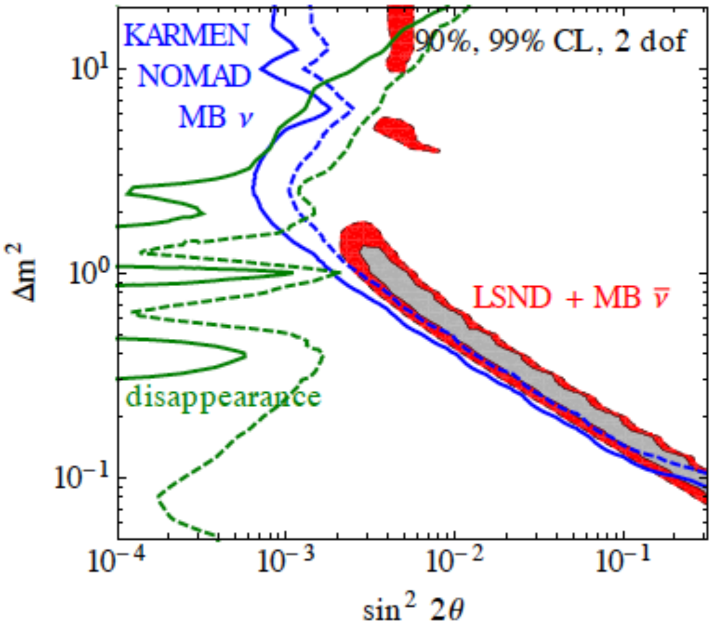
Does the reactor-flux anomaly imply active-sterile neutrino mixing?



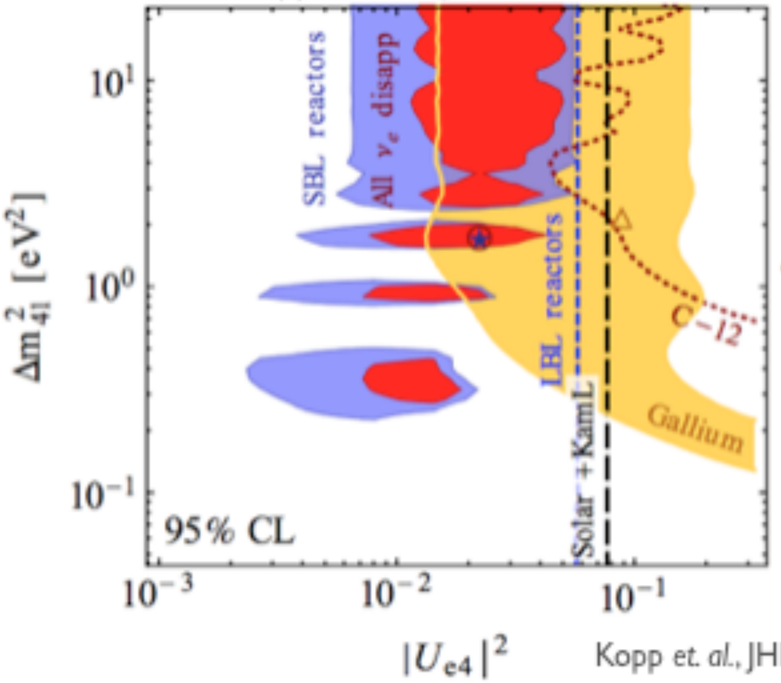


Hayes, et al., arXiv: 1309.4146 [nucl-th]

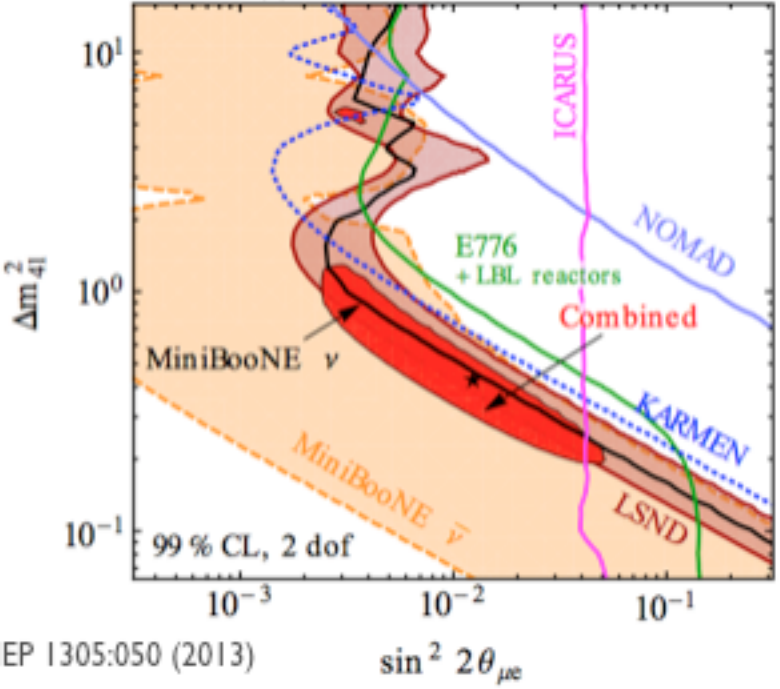


Can we know the reactor neutrino flux ever as well as we need?

νe disappearance global oscillation fits



νe appearance global oscillation fits



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

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?

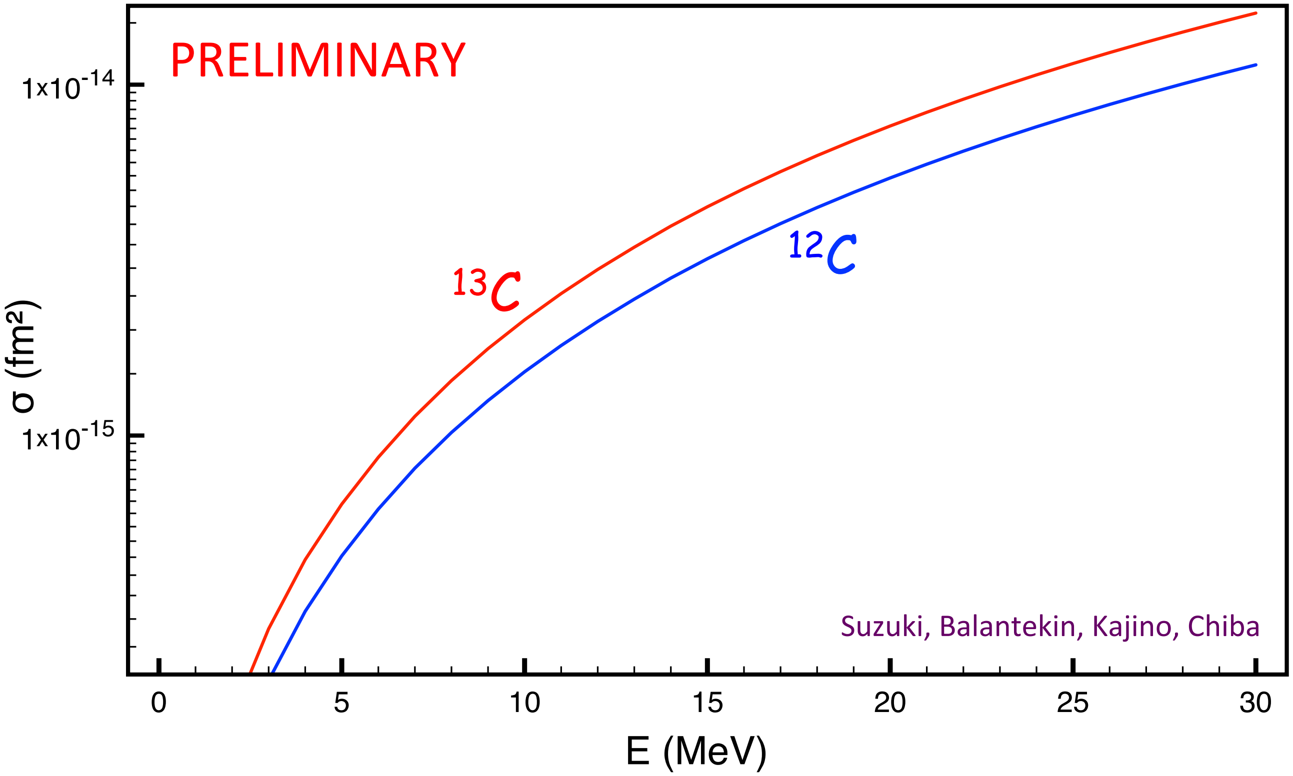
Oscillatory behavior of the neutral-current event rate, would establish, without recourse to the Z-width, oscillation into sterile flavor(s).

Neutrino Coherent Scattering

$$\nu + A \rightarrow \nu + A$$

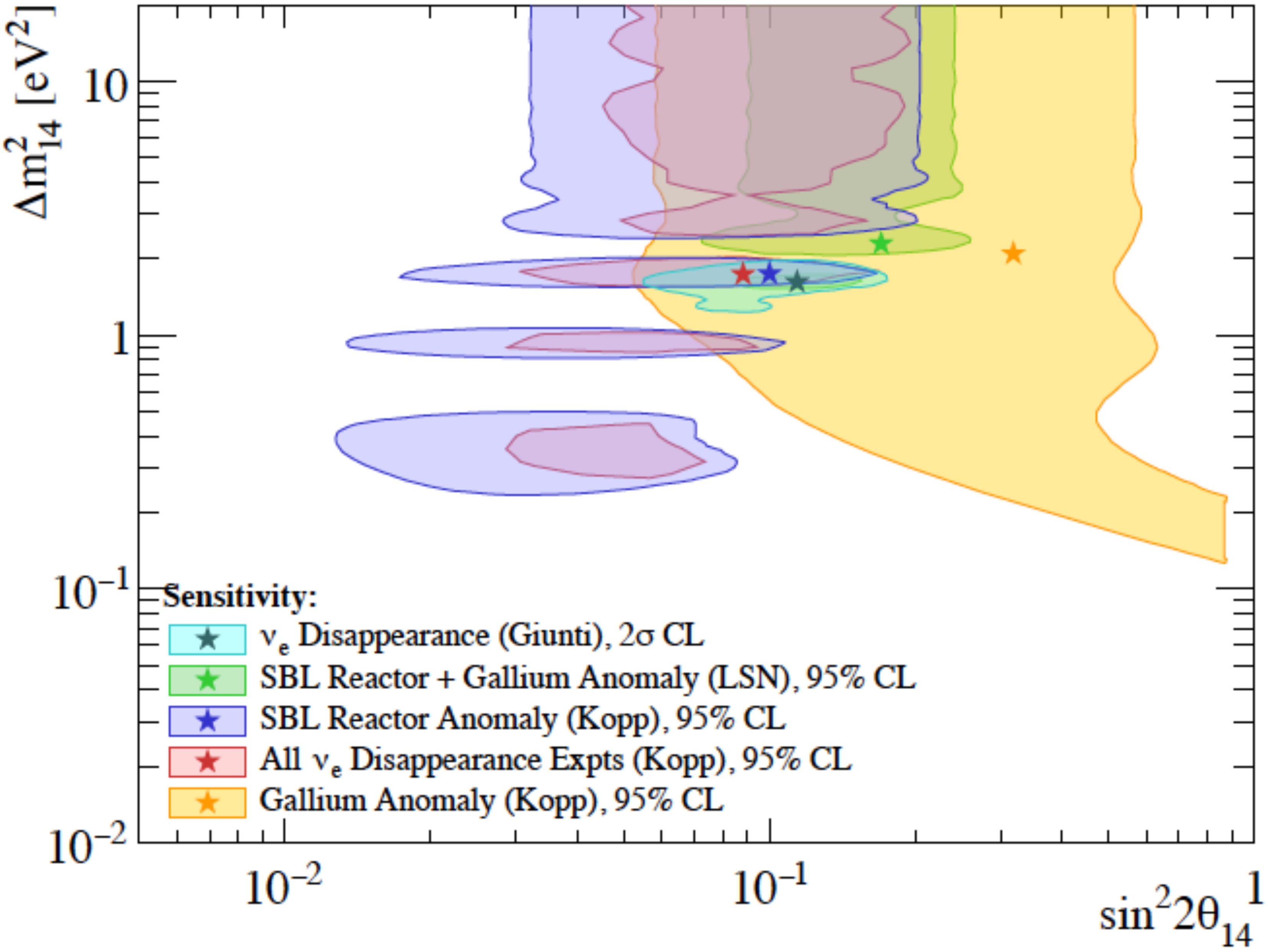
$$\frac{d\sigma}{d\cos\theta} = \frac{G_F^2}{8\pi}\left\{Z^2\left(4\sin^2\theta_W - 1\right) + N\right\}^2 E_\nu^2 (1+\cos\theta)$$

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



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

In effective field theories at lower energies, beyond Standard Model physics is described by local operators

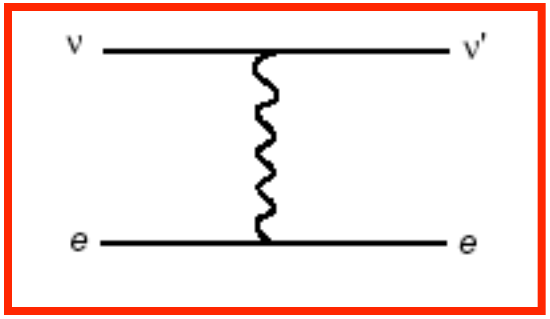
$$\boxed{L = L_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_i \frac{C_i^{(7)}}{\Lambda^3} O_i^{(7)} + \ldots}$$

Majorana neutrino mass (unique)

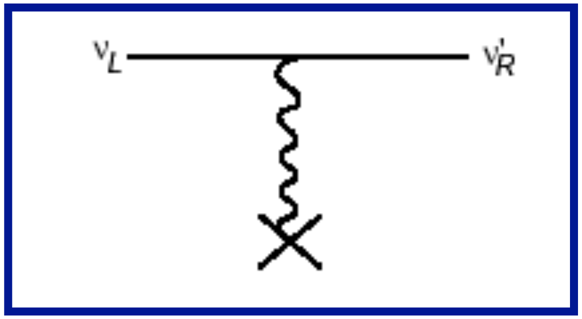
Includes Majorana neutrino magnetic moment

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

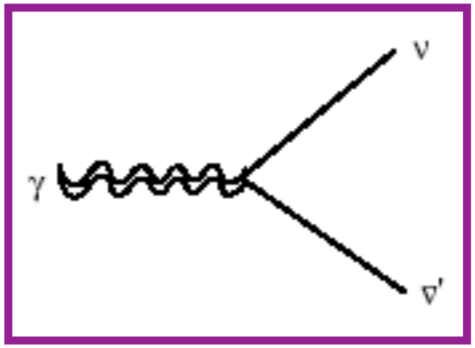
Physical Processes with a Neutrino Magnetic Moment



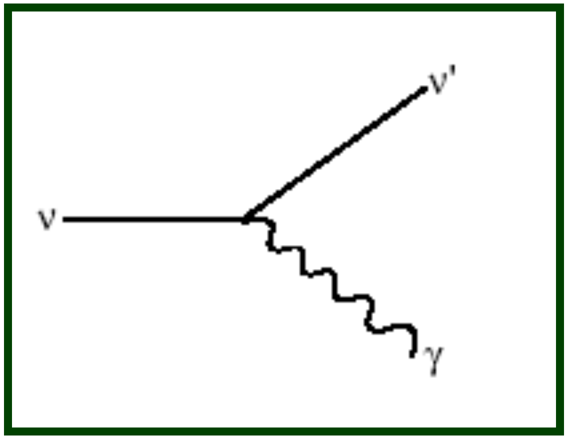
ν-e scattering



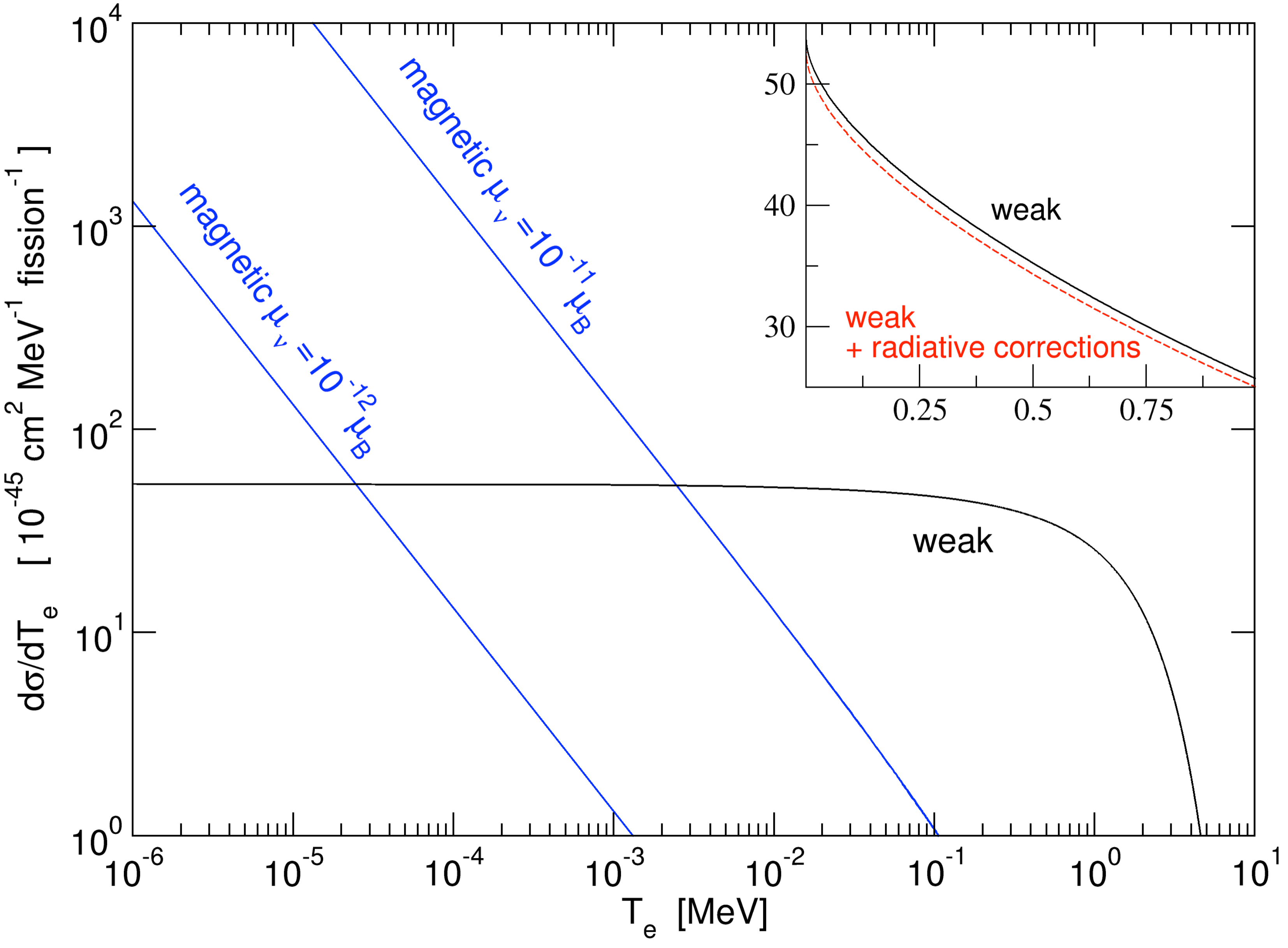
Spin-flavor precession



Plasmon decay

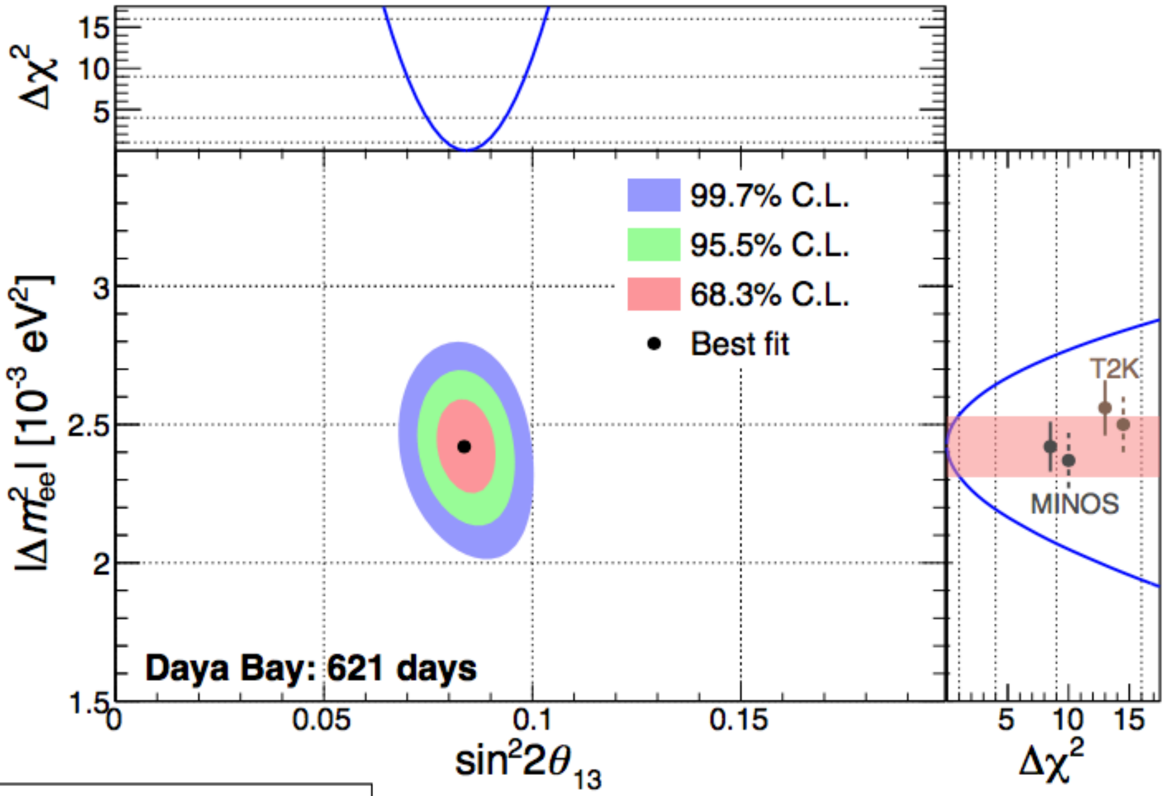


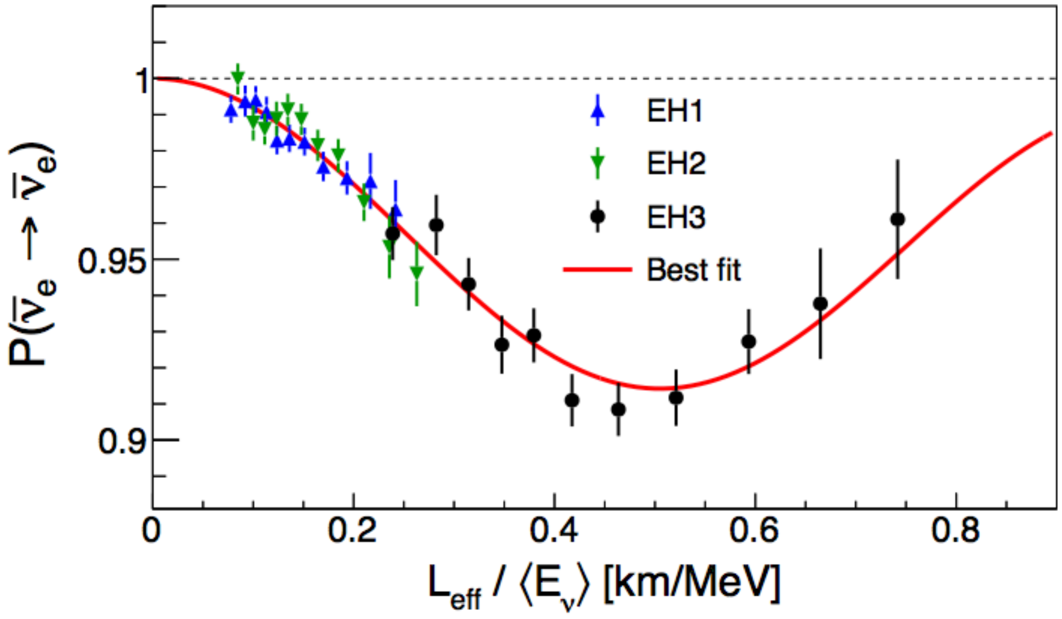
Neutrino decay



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
10^4
10^3
10^2
10^1
10^0
$d\sigma/dT_e$ [10^{-45} cm^2 MeV^{-1} fission^{-1}]
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
T_e [MeV]

Recent neutrino experiments such as the Daya Bay experiment well pinned the neutrino parameters.





$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

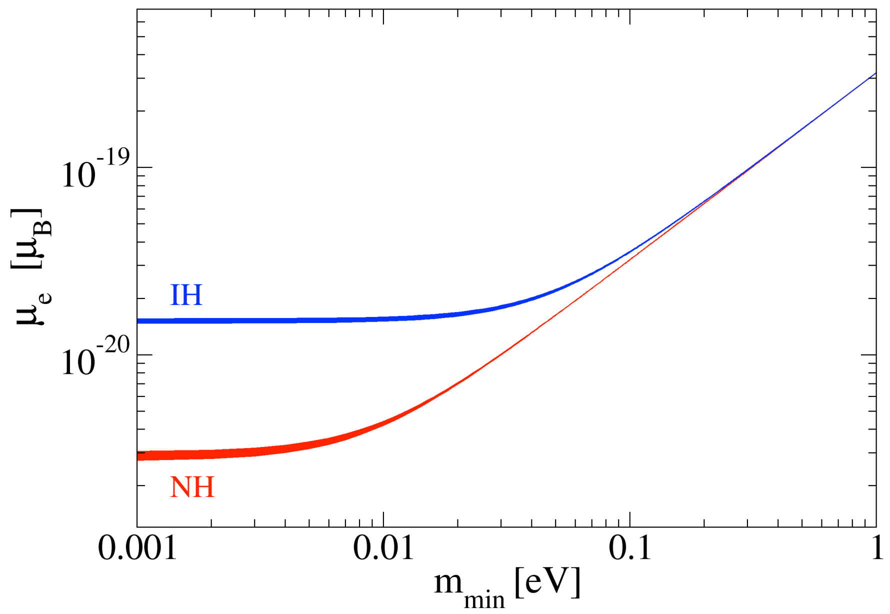
$$\left|\delta m^2_{ee}\right| = \left(2.42 \pm 0.11\right) \times 10^{-3} \mathrm{eV}^2$$

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

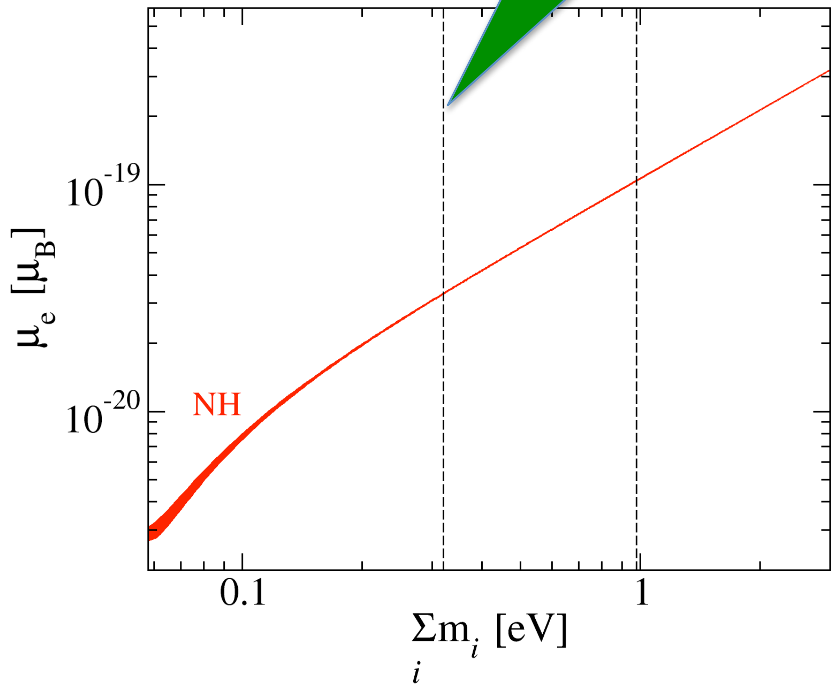
$$\mu_{\mathrm{eff}}^2 = \sum_i \left| \sum_j U_{ej} e^{-iE_j L} \mu_{ji} \right|^2$$

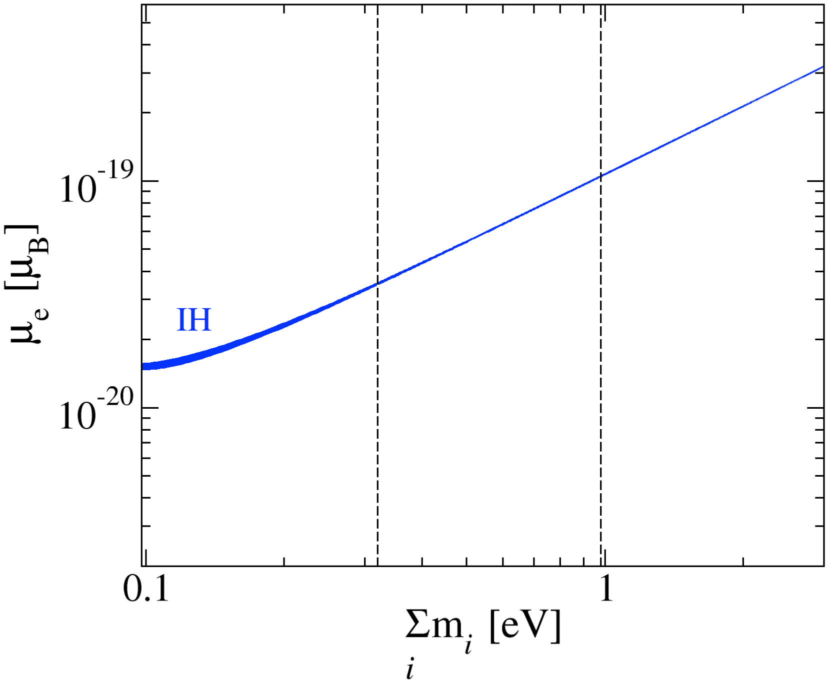
Standard Model (only) contribution to the Dirac neutrino magnetic moment measured at reactors

A.B.B., N. Vassh, arXiv:1312.6858
PRD **89** (2014) 073013

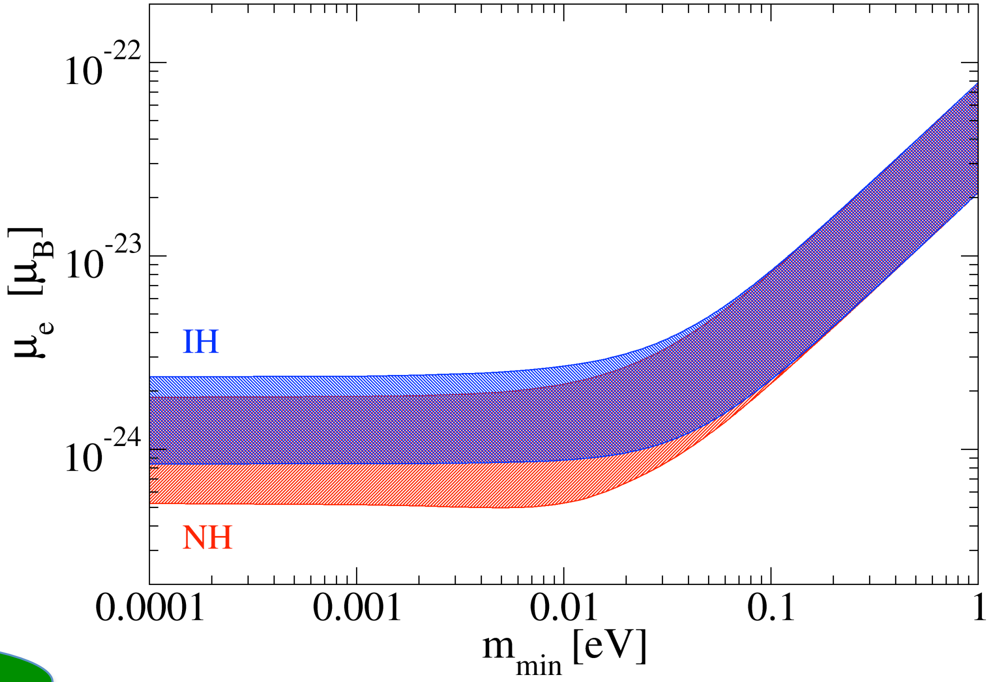


Cosmological limits

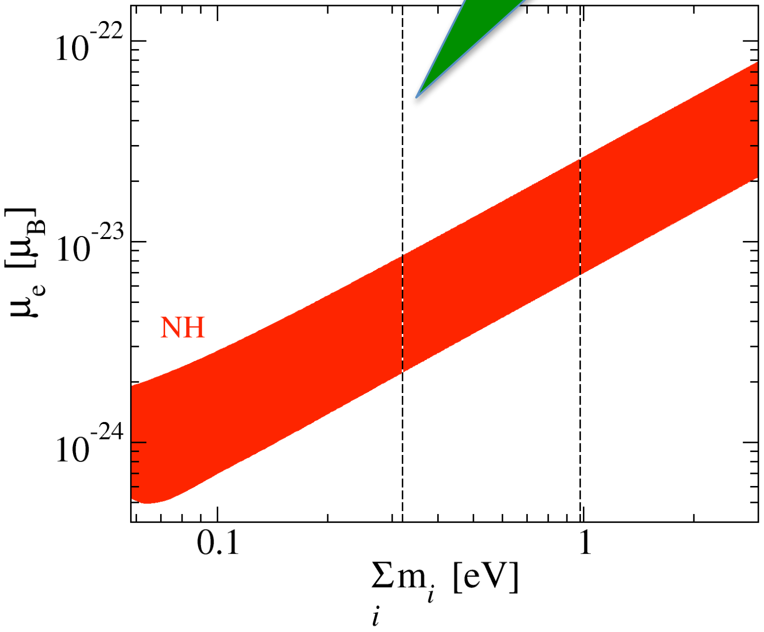


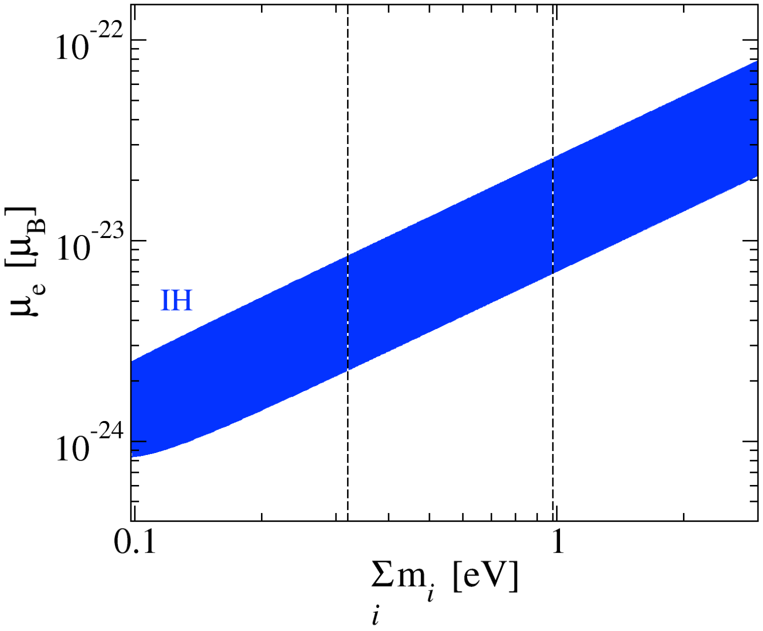


Standard Model (only) contribution to the Majorana neutrino magnetic moment measured at reactors

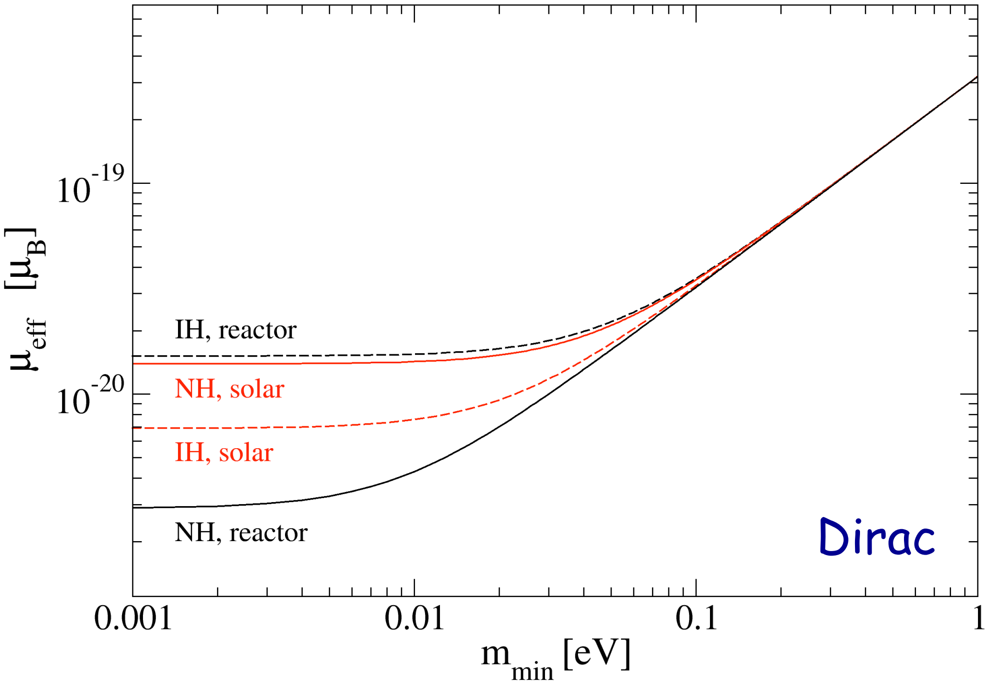


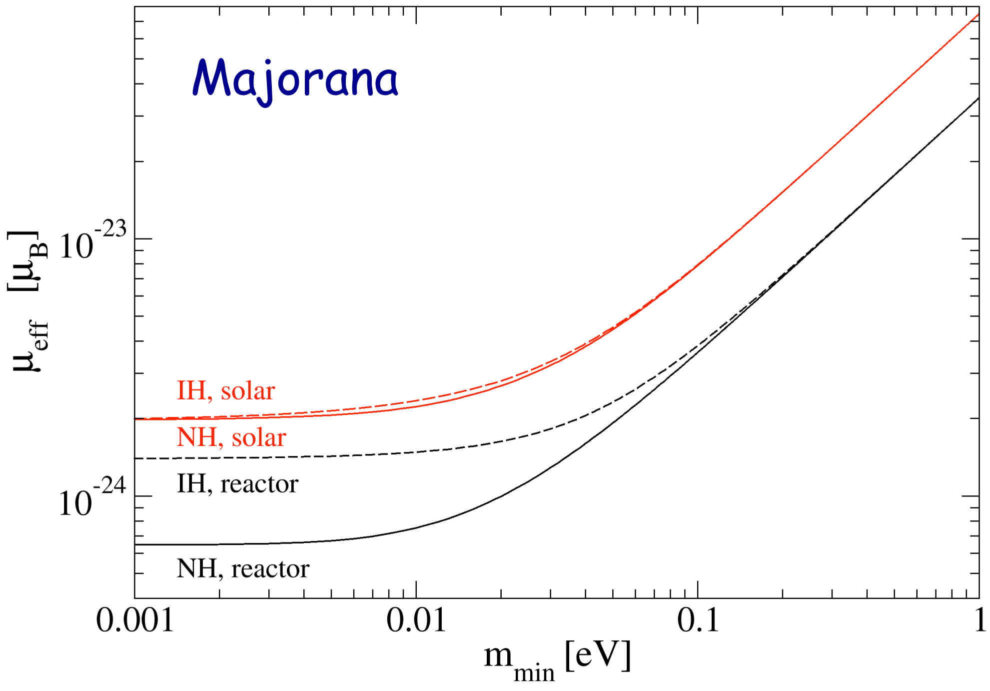
Cosmological limits



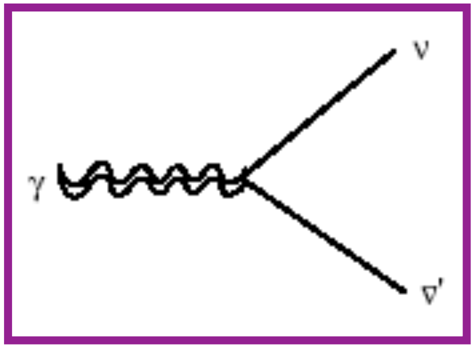


Reactor vs. solar neutrinos

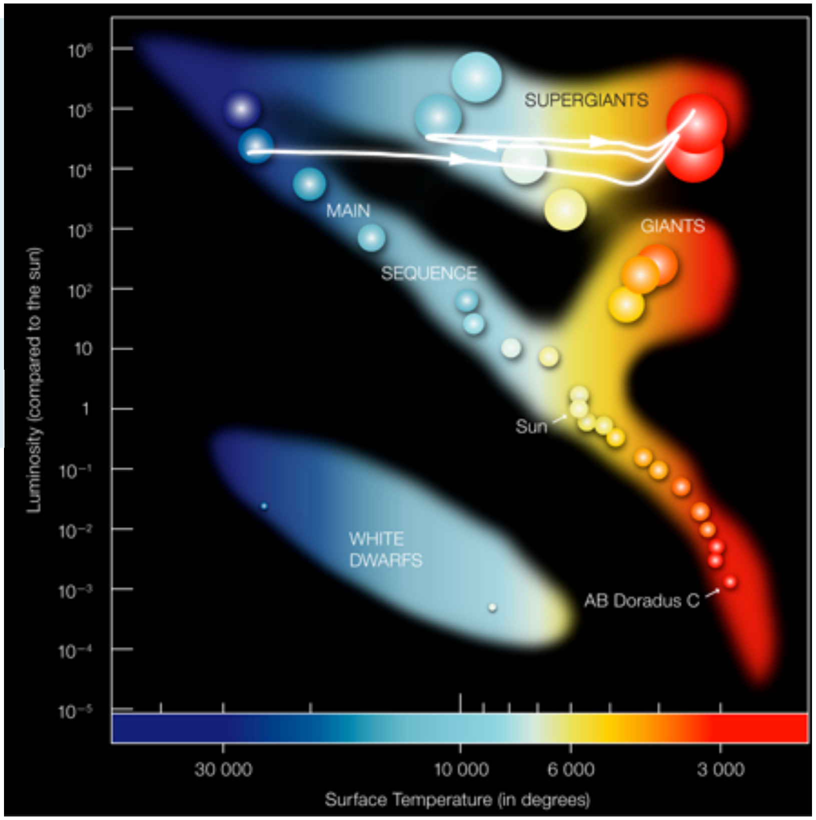


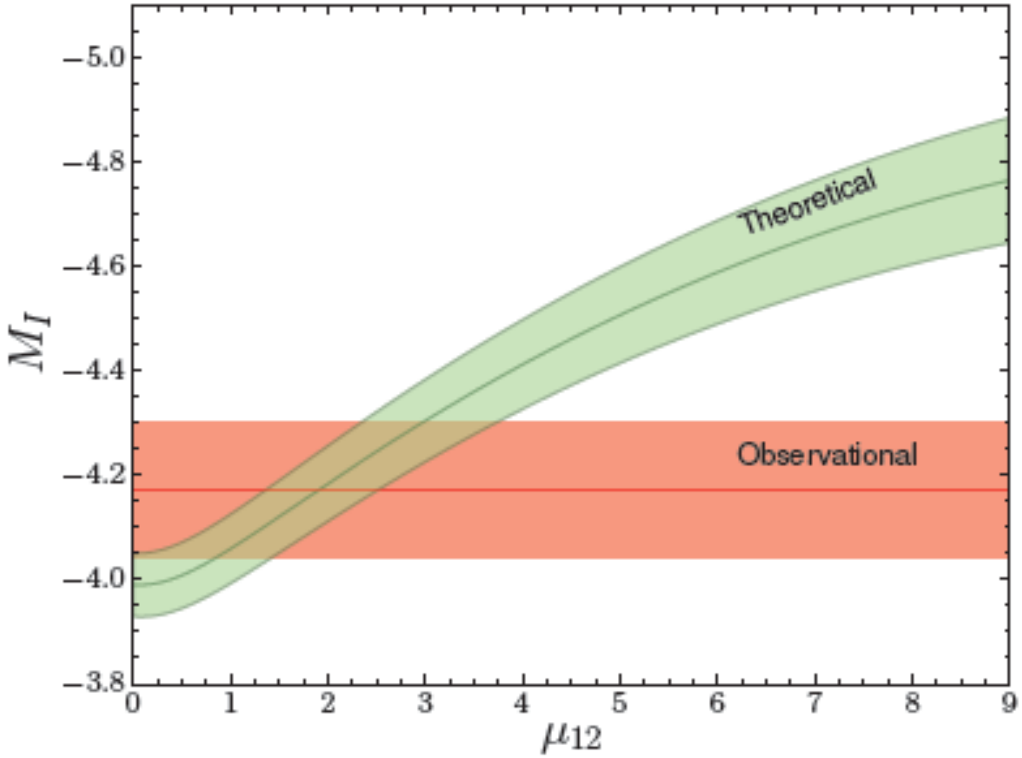


A.B.B. & N. Vassh
AIP Conf.Proc. **1604** (2014) 150
arXiv:1404.1393



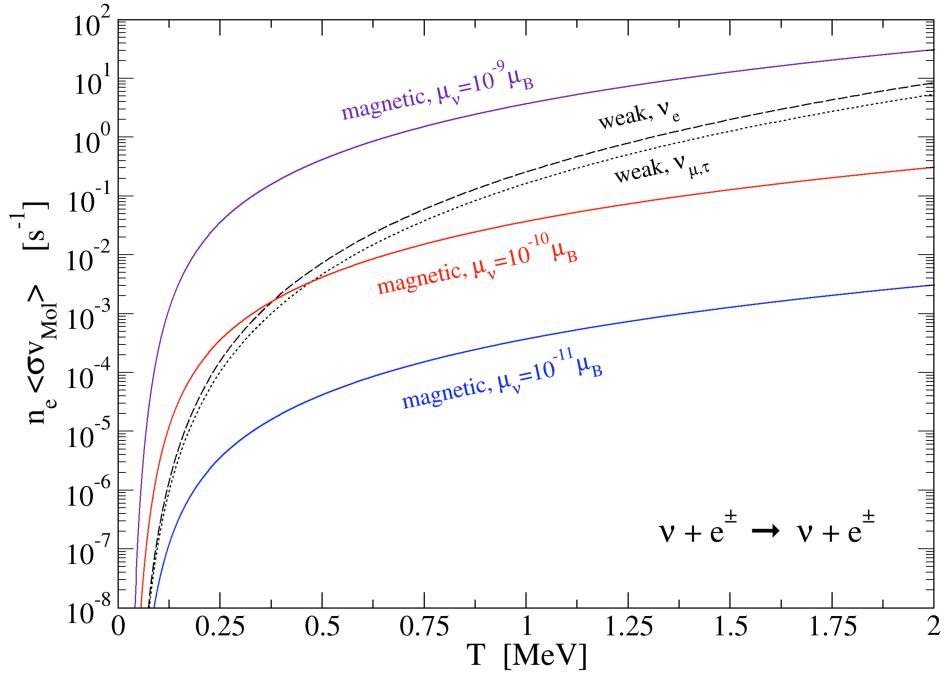
A large enough neutrino magnetic moment implies enhanced plasmon decay rate: γ→νν. Since the neutrinos freely escape the star, this is turn cools a red giant star faster delaying helium ignition.

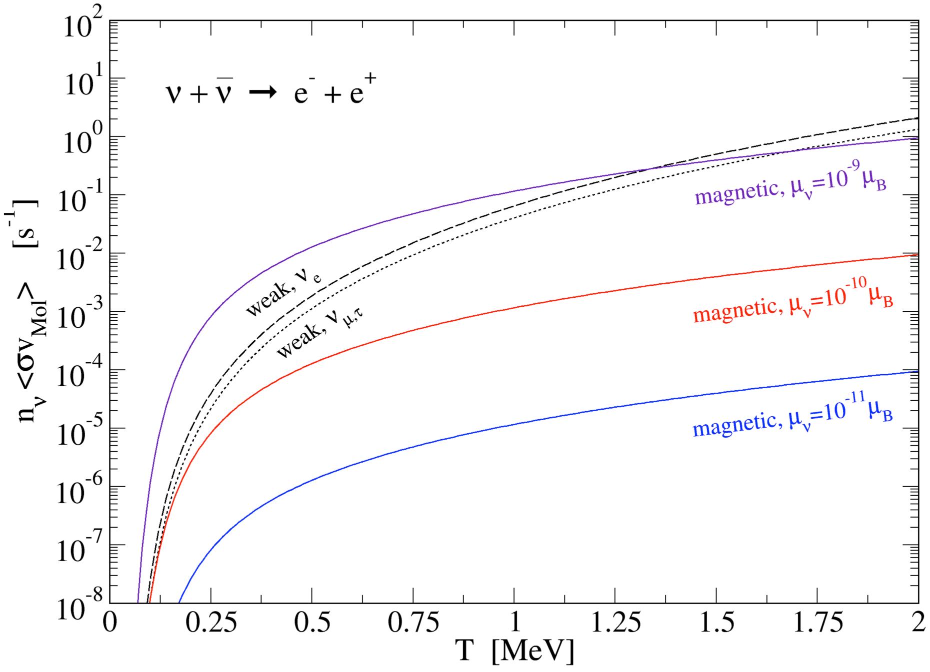




Globular cluster M5
➔ $\mu_\nu < 4.5 \times 10^{-12}\ \mu_B$
(95% C.L.)

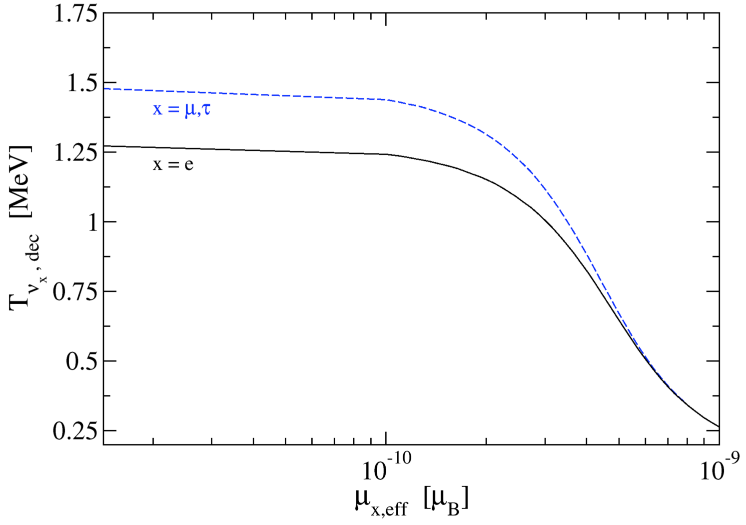
arXiv:1308.4627





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

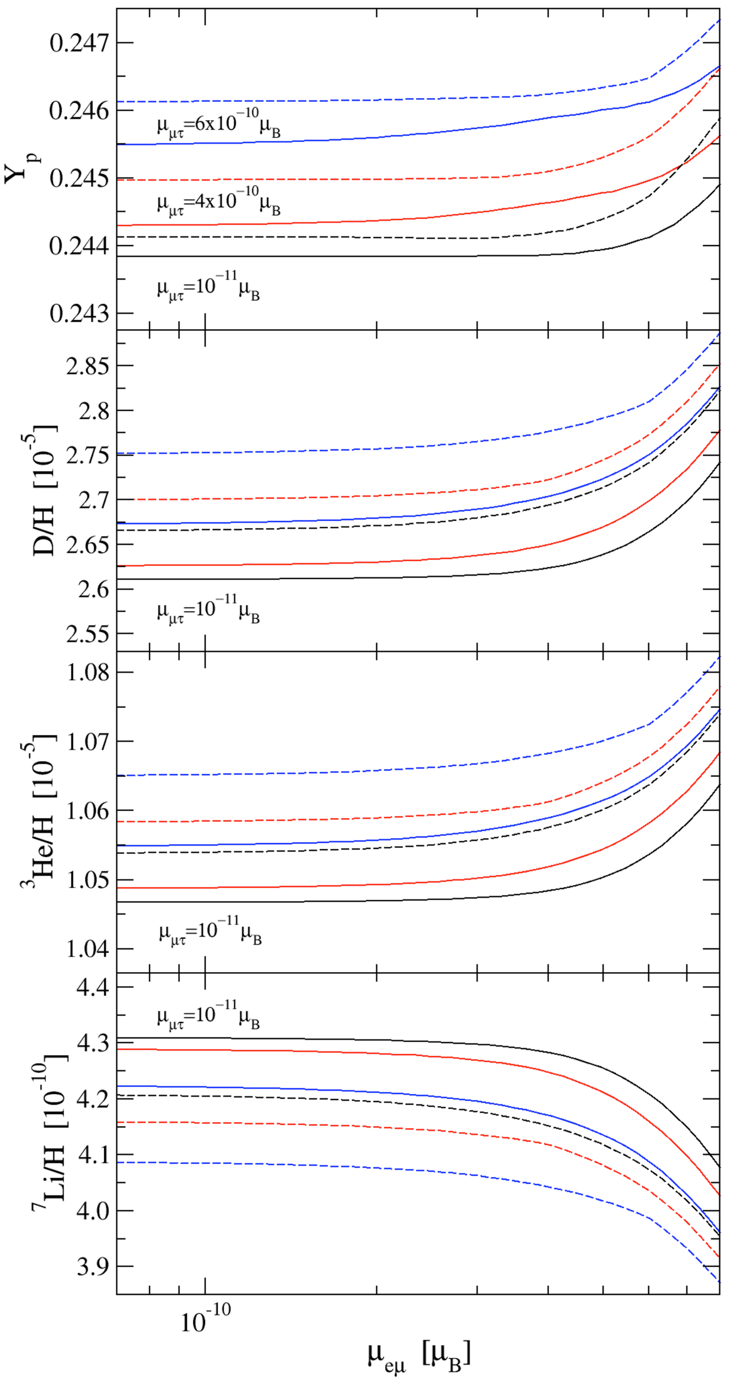
Vassh, Grohs, Balantekin, Fuller, arXiv:1510.0042



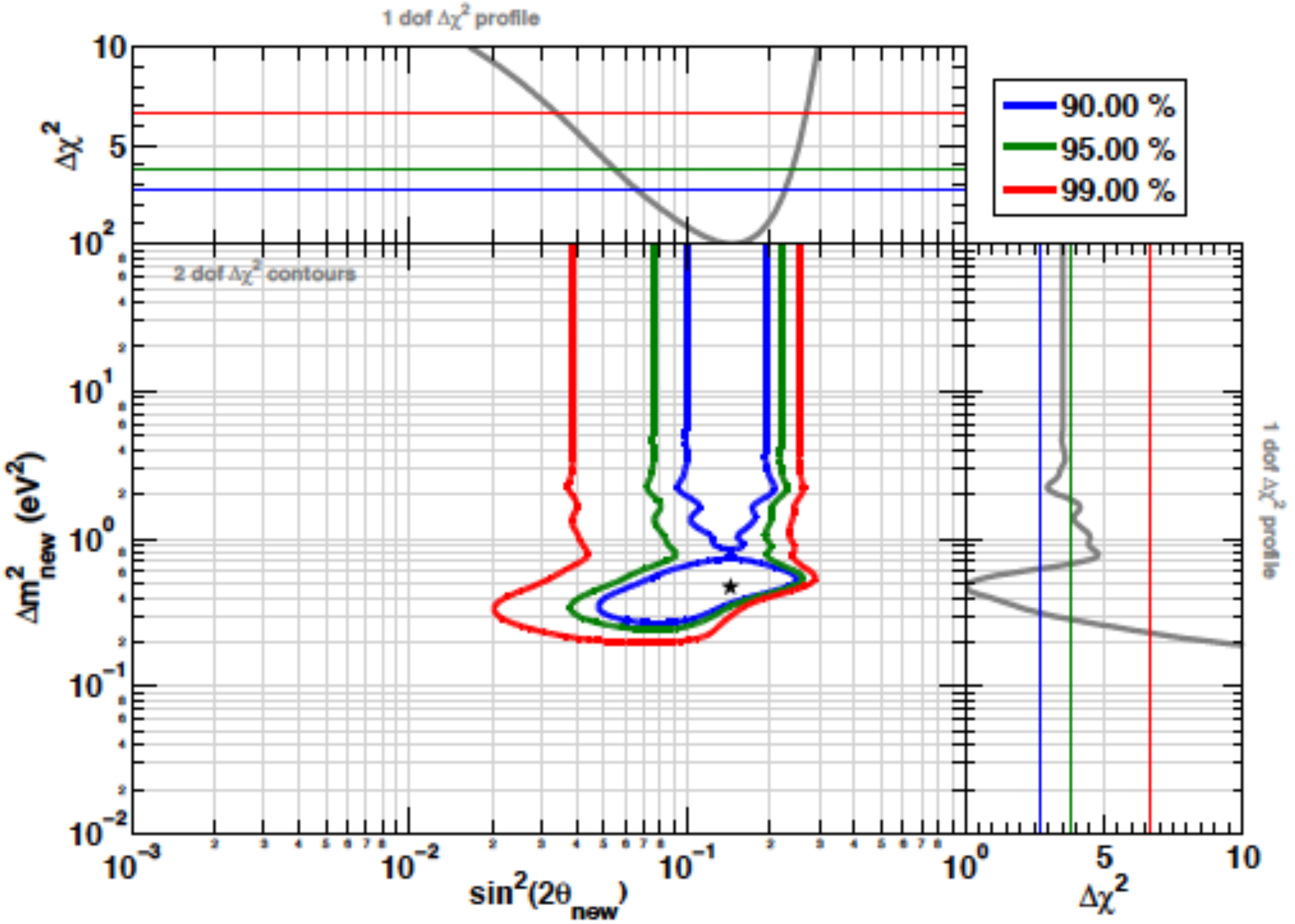
The change in the BBN abundances due to the neutrino magnetic moment

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



Kopp

At very close distances to the reactor and for $m_4^2 \geq 1\ \text{eV}^2$

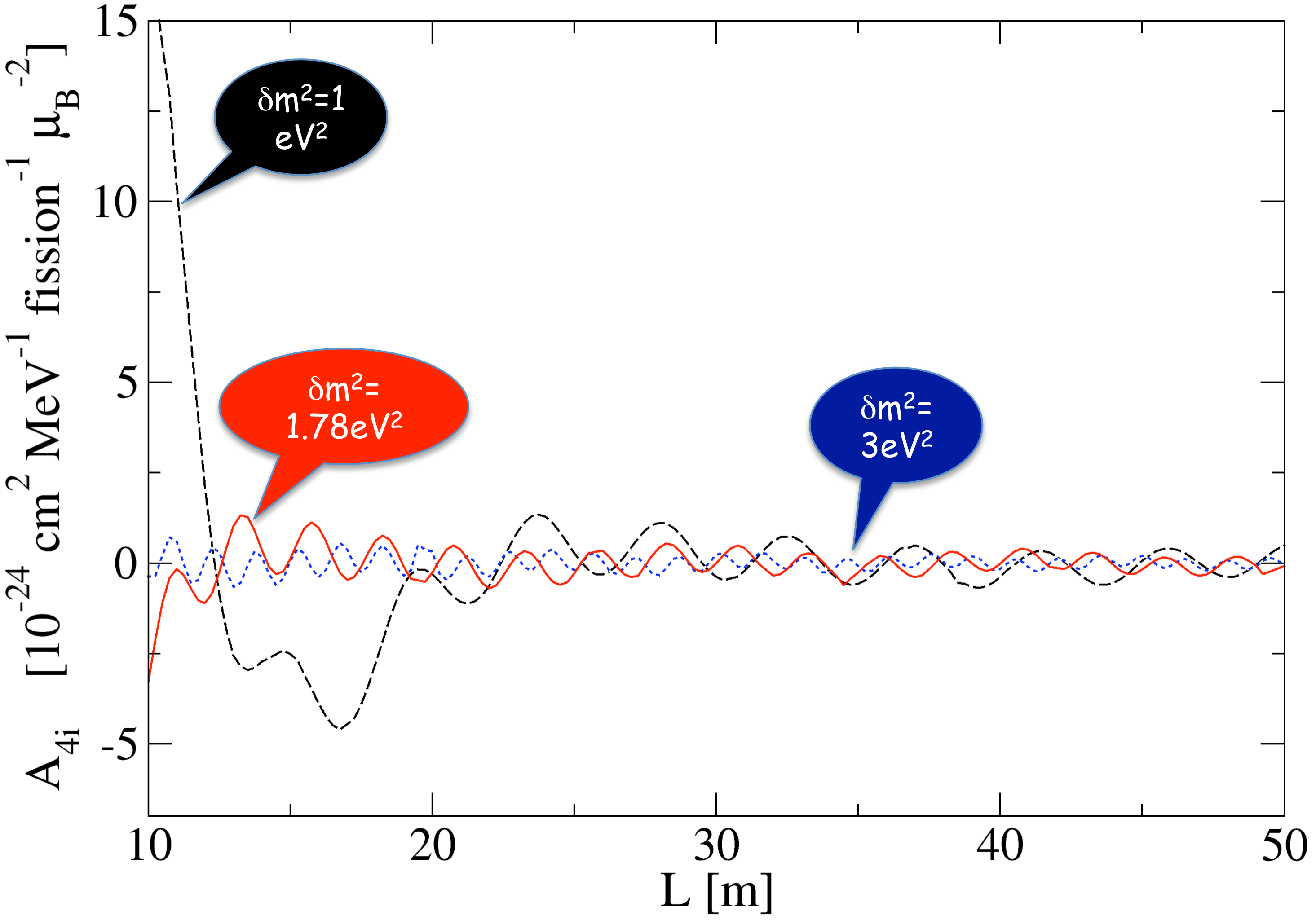
$$P\left(\bar{\nu}_e \rightarrow \bar{\nu}_e\right) = 1 - 2\left|U_{e4}\right|^2 + 2\left|U_{e4}\right|^4$$

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

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

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

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

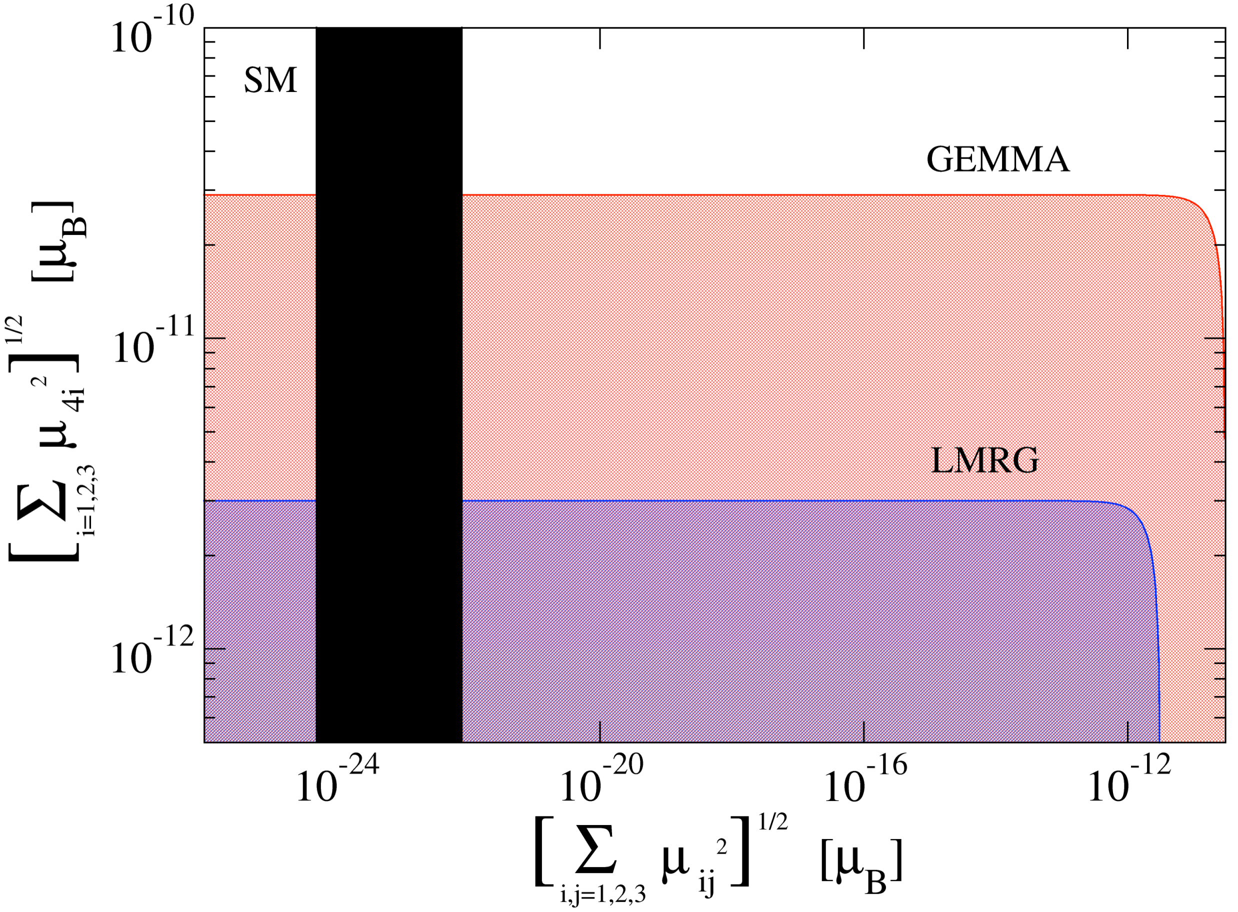


$$A_{4i} = \int_{E_\nu,\min}^{\infty} \frac{2\alpha^2\pi}{m_e^2}\left[\frac{1}{T_e}-\frac{1}{E_\nu}\right]\left[\cos\left(\frac{\delta m_{4i}^2 L}{2E_\nu}\right)\right]\left(\frac{dN}{dE_\nu}\right)dE_\nu$$

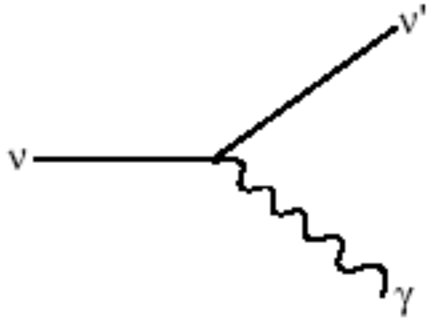
For a sufficiently heavy sterile neutrino the phases with $(E_4 - E_i)L$ average to zero

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

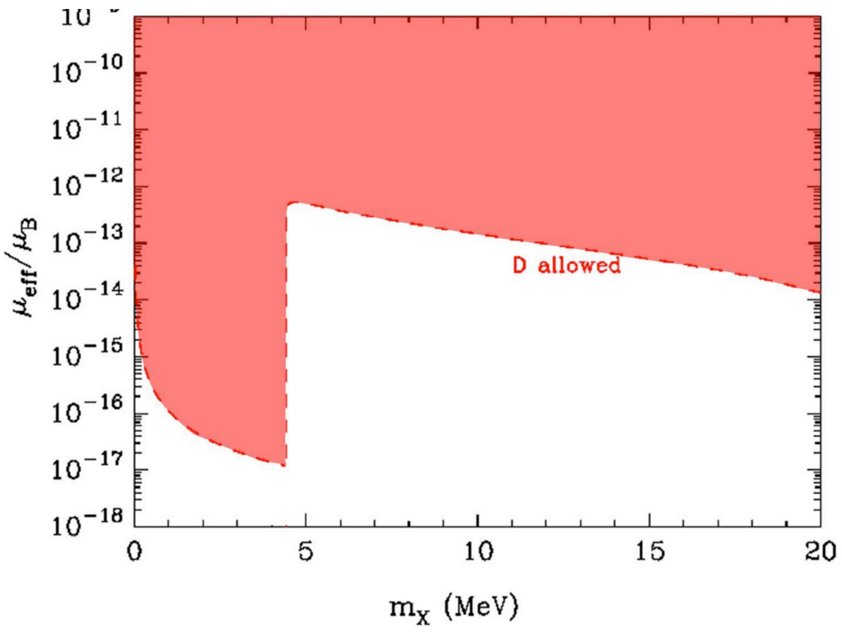
$$\Rightarrow \mu_{eff}^2 \le \sum_{i=1}^{3}\mu_{i4}^2 + \left(1-\left|U_{e4}\right|^2\right)\sum_{i,j=1}^{3}\mu_{ij}^2$$

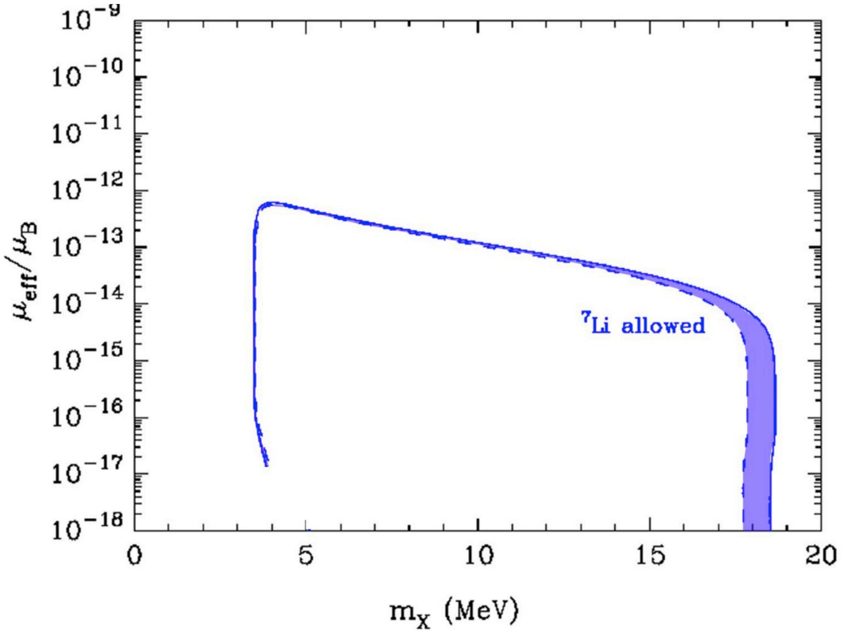


Sterile neutrino decay and Big Bang Nucleosynthesis



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





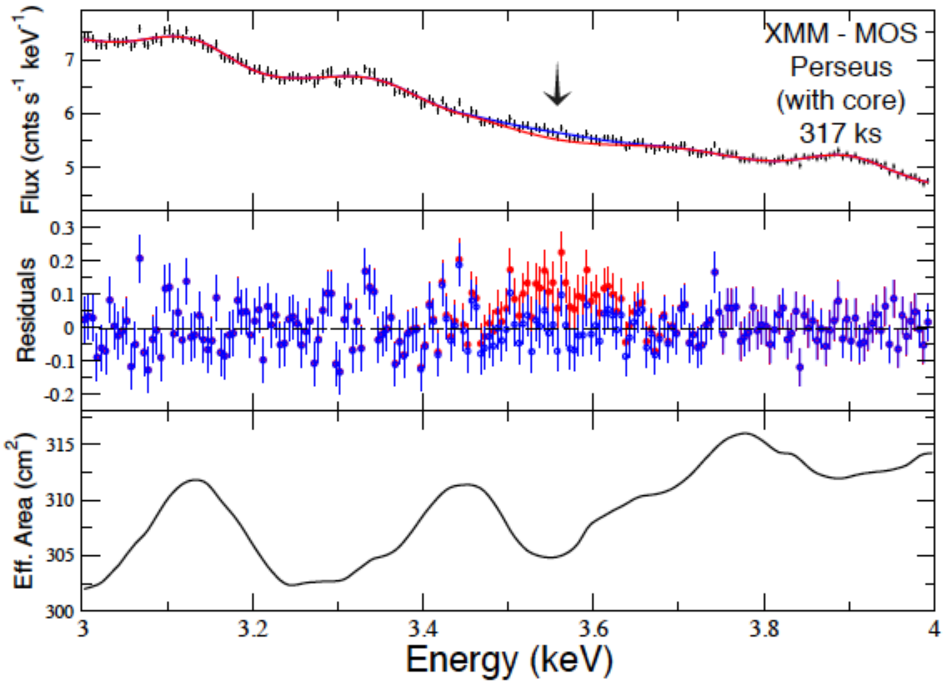
Kusakabe, A.B.B., Kajino, and Pehlivan, Phys. Rev. D 87, 085045 (2013)

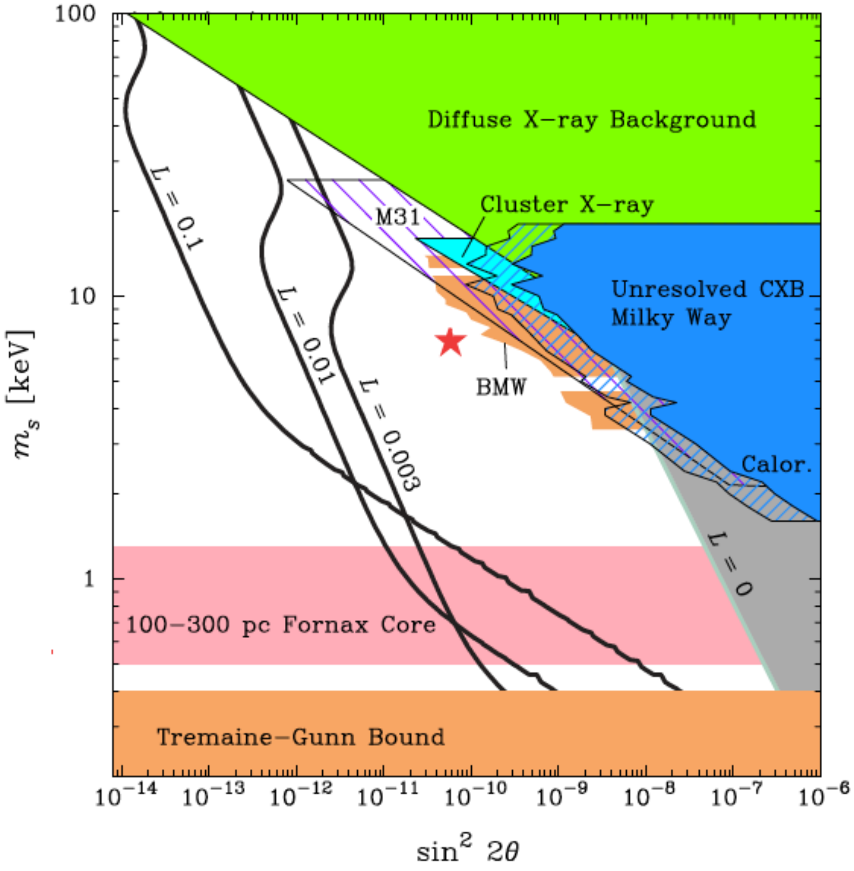
Submitted to ApJ, 2014 February 10
Preprint typeset using LaTeX style emulateapj v. 04/17/13

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

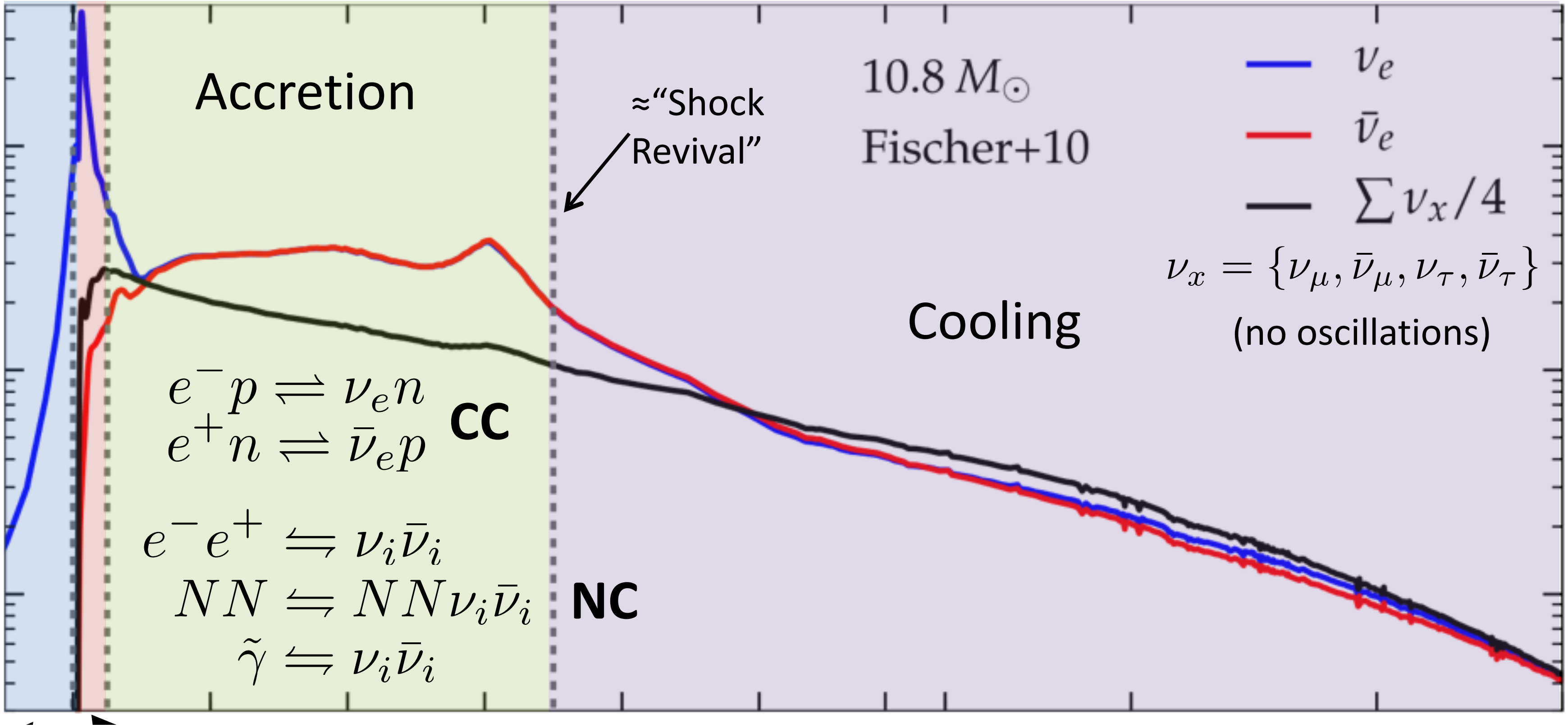




Sterile neutrino mass	How it asserts itself	What does it solve?
~ 1 eV	Mixing with active flavors	Reactor anomaly, IceCube data
~ 7 keV	Electromagnetic decay	Gammas rays from the galactic centers
~ 4-5 MeV	Electromagnetic decay	^{7}Li problem in BBN

Are we cooking up a separate magic potion for each malady?
I certainly hope not!

SN Neutrino Flavor Content



Adopted from Messer

Symmetry magazine

If we want to catch a supernova with neutrinos we'd better know what neutrinos do inside a supernova. What can sterile neutrinos do in a core-collapse supernova?

λ_p: proton weak loss rate (rate for $\bar{\nu}_e + p \rightarrow e^+ + n$ and $e^- + p \rightarrow \nu_e + n$ reactions)

λ_n: neutron weak loss rate (rate for $\nu_e + n \rightarrow e^- + p$ and $e^+ + n \rightarrow \bar{\nu}_e + p$ reactions)

$$\frac{dN_p}{dt} = -\lambda_p N_p + \lambda_n N_n$$

Electron fraction: $Y_e \equiv \dfrac{\text{Net number of electrons}}{\text{Number of baryons}}$

Neutral medium, only protons and neutrons: $Y_e = \dfrac{N_p}{N_p + N_n}$

Neutral medium, with protons, neutrons and alphas: $Y_e = \dfrac{N_p + 2N_\alpha}{N_p + N_n + 4N_\alpha}$

Mass fraction of alphas: $X_\alpha = \dfrac{4N_\alpha}{N_p + N_n + 4N_\alpha}$

$$\frac{d}{dt}\left[Y_e - \boxed{\frac{1}{2}X_\alpha}\right] = \lambda_n - \left(\lambda_p + \lambda_n\right)Y_e + \frac{1}{2}\left(\lambda_p - \lambda_n\right)X_\alpha$$

Vanishes if weak interactions of alphas are ignored

$dY_e/dt = 0$

$$Y_e = \frac{\lambda_n}{\lambda_p + \lambda_n} + \frac{1}{2}\frac{\lambda_p - \lambda_n}{\lambda_p + \lambda_n} X_\alpha$$

If alpha particles are present

$$Y_e^{(0)} = \frac{1}{1 + \lambda_p / \lambda_n}$$

If alpha particles are absent

$$Y_e = Y_e^{(0)} + \left(\frac{1}{2} - Y_e^{(0)}\right) X_\alpha$$

If $Y_e^{(0)} < 1/2$, non-zero X_α increases Y_e. If $Y_e^{(0)} >$ 1/2, non-zero X_α decreases Y_e.

Non-zero X_α pushes Y_e to 1/2

Alpha effect

Matter-enhanced oscillations with active-sterile mixing

$$i\frac{\partial}{\partial r}\begin{pmatrix}\Psi_{e,x}(r)\\ \Psi_{s}(r)\end{pmatrix}=\begin{pmatrix}\varphi_{e,x}(r) & \Lambda_{e,x}\\ \Lambda_{e,x} & -\varphi_{e,x}(r)\end{pmatrix}\begin{pmatrix}\Psi_{e,x}(r)\\ \Psi_{s}(r)\end{pmatrix}$$

$$\Lambda_{e,x}=\frac{\delta m^2}{4E}\sin 2\theta_{es,ex}$$

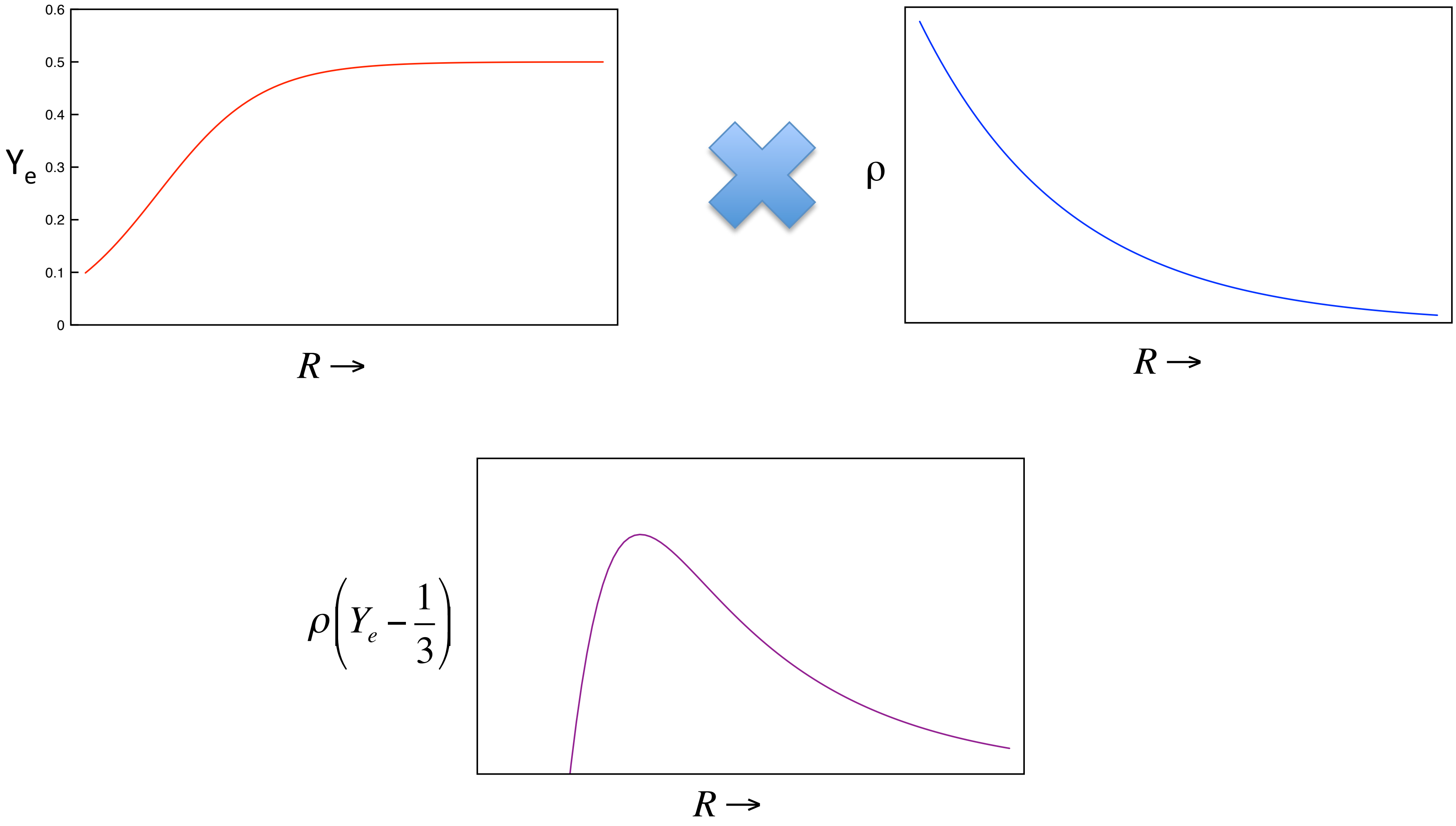
$$\varphi_e(r)=\frac{1}{4E}\left(\pm 2\sqrt{2}G_F\left[N_e^-(r)-N_e^+(r)-\frac{N_n(r)}{2}\right]E-\delta m^2\cos 2\theta_s\right)$$

$$\varphi_e(r)=\pm\frac{3G_F\rho(r)}{2\sqrt{2}m_N}\left(Y_e-\frac{1}{3}\right)-\frac{\delta m^2}{4E}\cos 2\theta_{es}$$

$$\varphi_{\mu,\tau}(r)=\pm\frac{G_F\rho(r)}{2\sqrt{2}m_N}\left(Y_e-1\right)-\frac{\delta m^2}{4E}\cos 2\theta_{\mu s,\tau x}$$

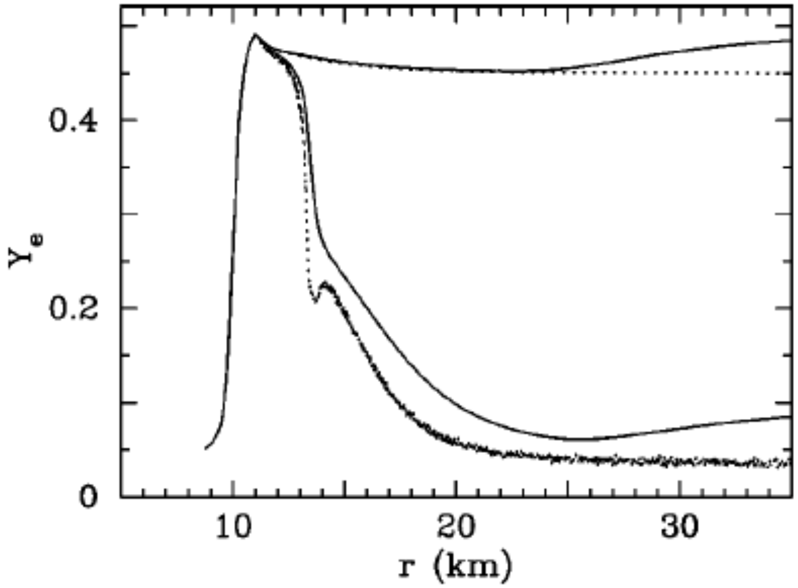
Neutrinos: + sign

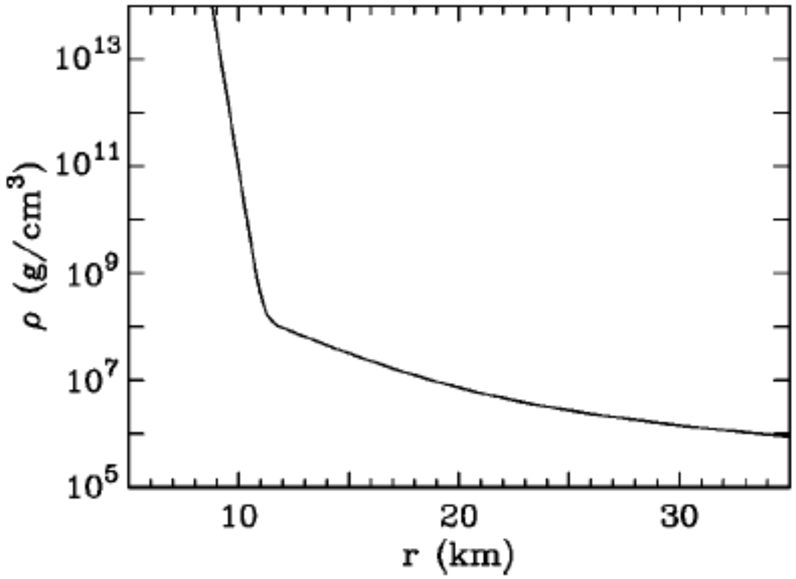
Antineutrinos: - sign

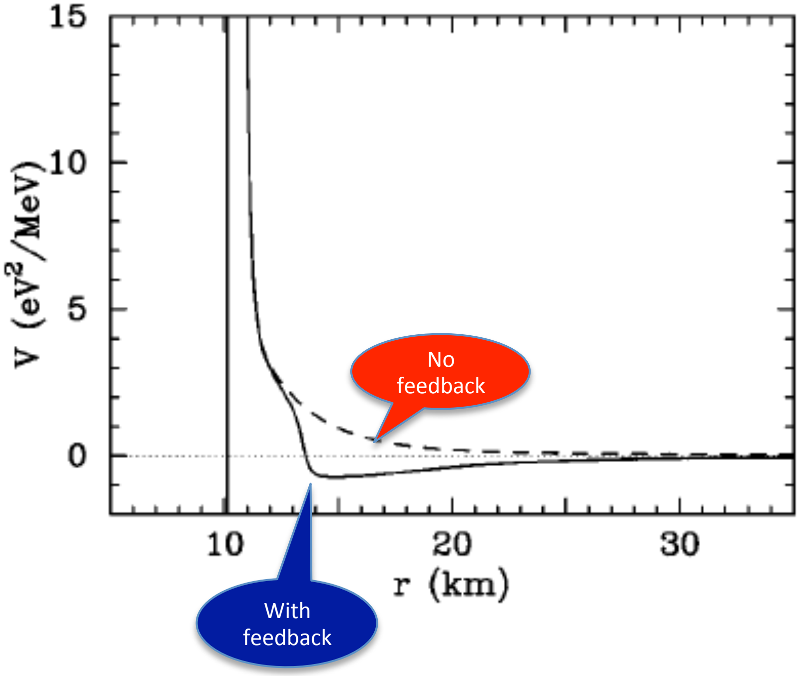


MSW Resonance Condition:

$$\varphi_e(r) = \pm \frac{3G_F\rho(r)}{2\sqrt{2}m_N}\left(Y_e - \frac{1}{3}\right) - \frac{\delta m^2}{4E}\cos 2\theta_{es} = 0$$

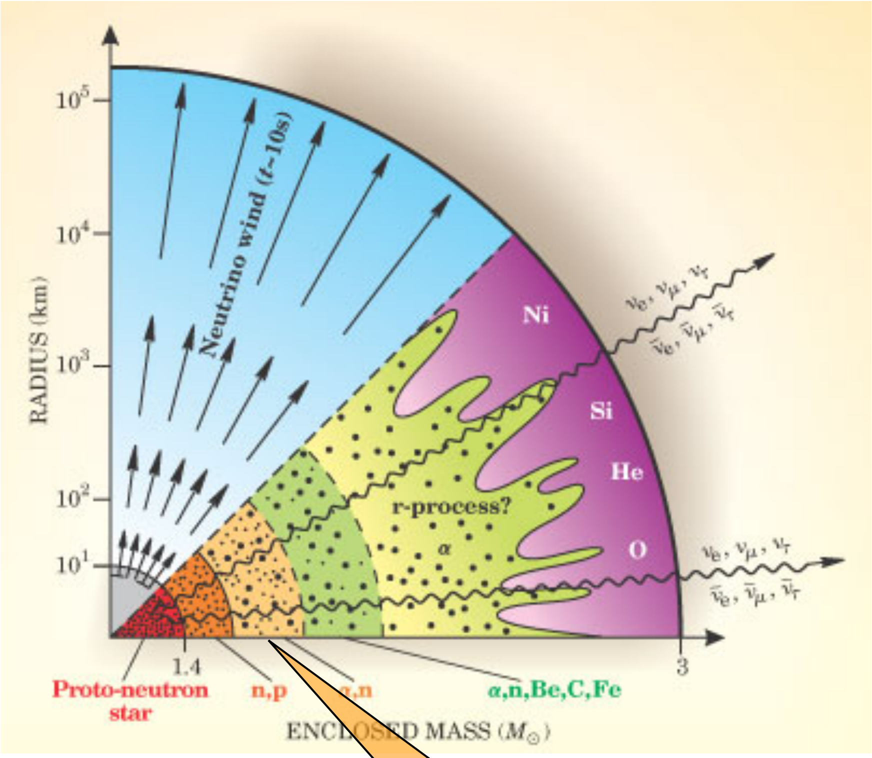


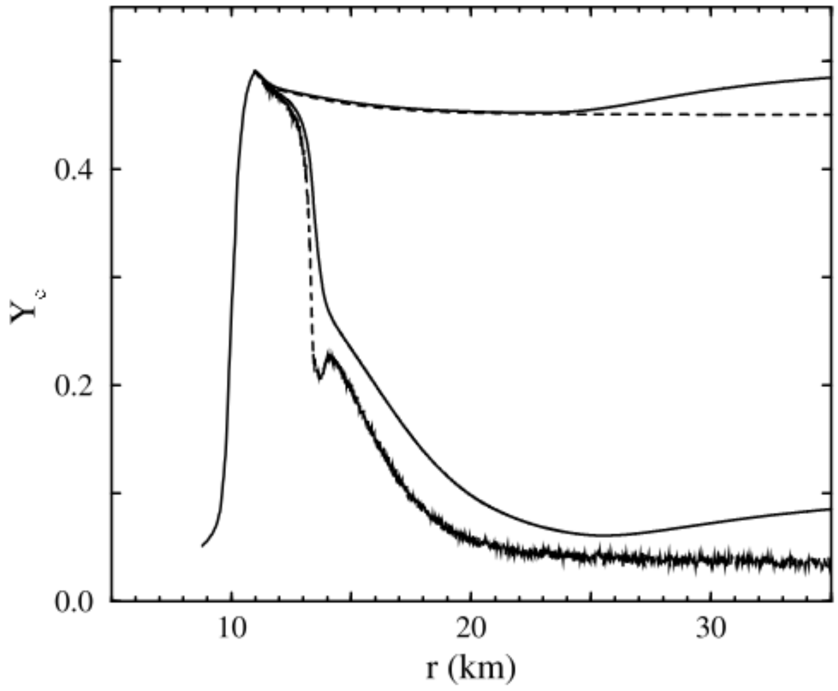




Note that this discussion ignores collective neutrino oscillations!

Fetter, McLaughlin, Balantekin, Fuller, 1999

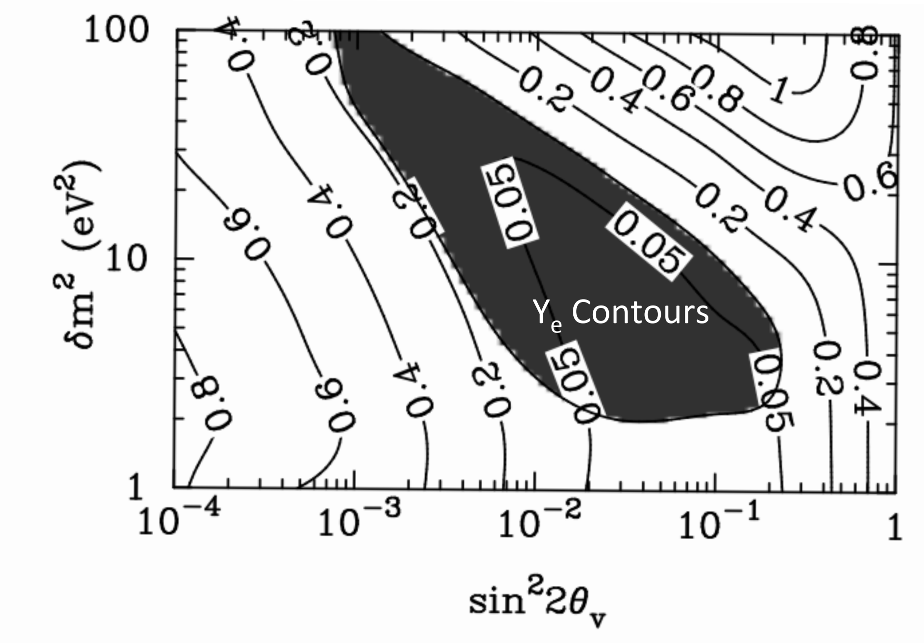


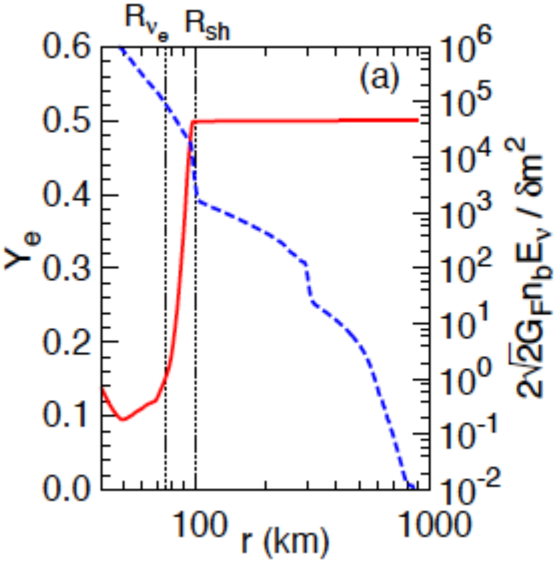


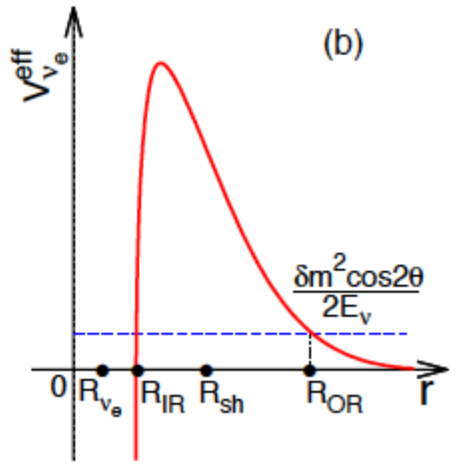
Alpha effect

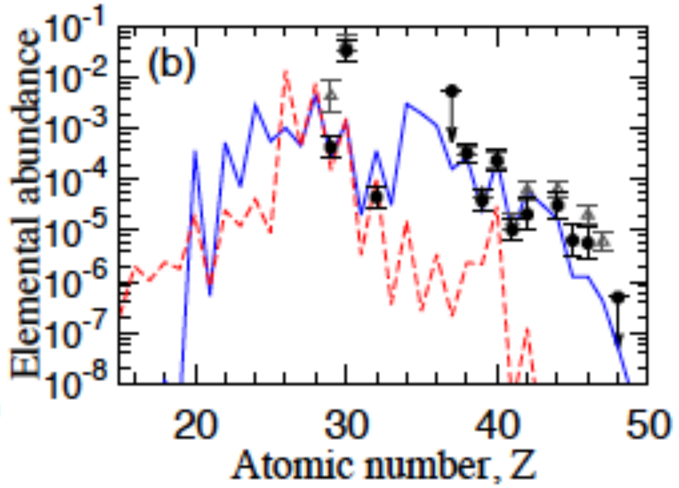
Active-sterile mixing could yield very low values of Y_e, which is crucial for r-process nucleosynthesis

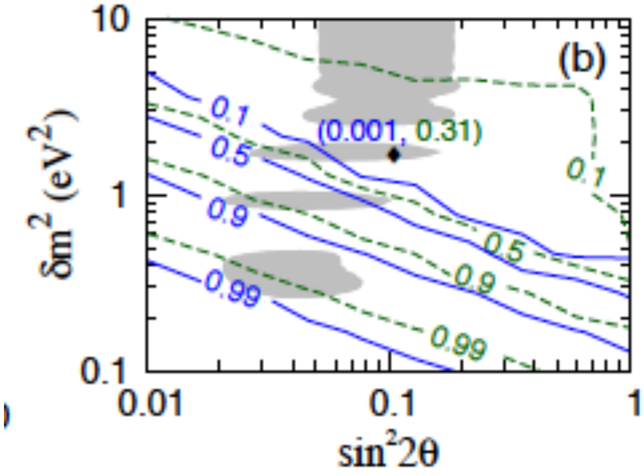
McLaughlin, Fetter, Balantekin, Fuller, Astropart. Phys., 18, 433 (2003)





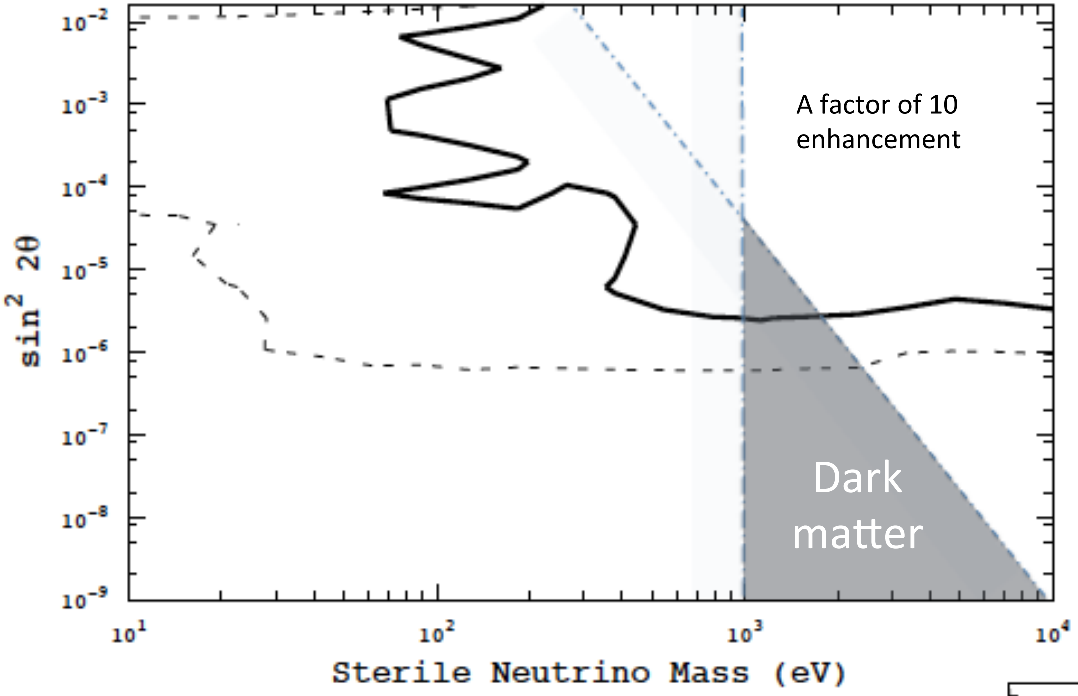






Active-sterile mixing with the parameters inferred from reactor anomaly enables nucleosynthesis, but seems to suppress shock reheating by neutrinos.

Wu, Fischer, Martinez-Pinedo, Qian, 2013

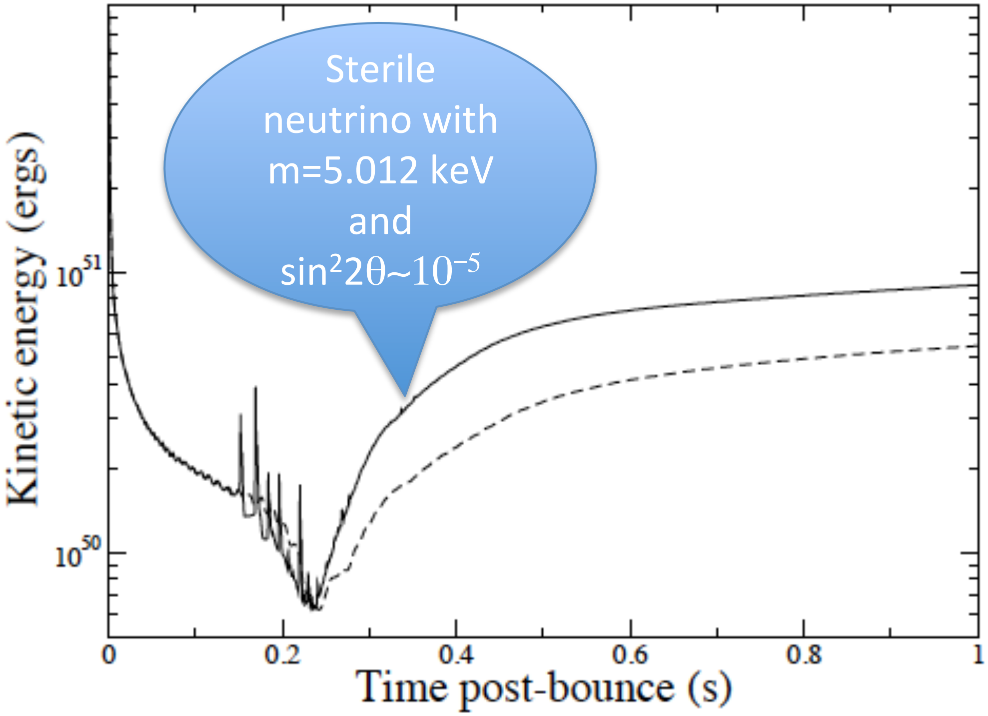


A factor of 10 enhancement

Dark matter

Enhancement due to active-sterile mixing

Warren,Meixner, Matthews. Hidaka, Kajino, 2014



Sterile neutrino with m=5.012 keV and $\sin^2 2\theta \sim 10^{-5}$

Thank you very much!