Sterile Neutrinos in Particle Physics and Cosmology

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Outline

(1) A brief history of neutrinos

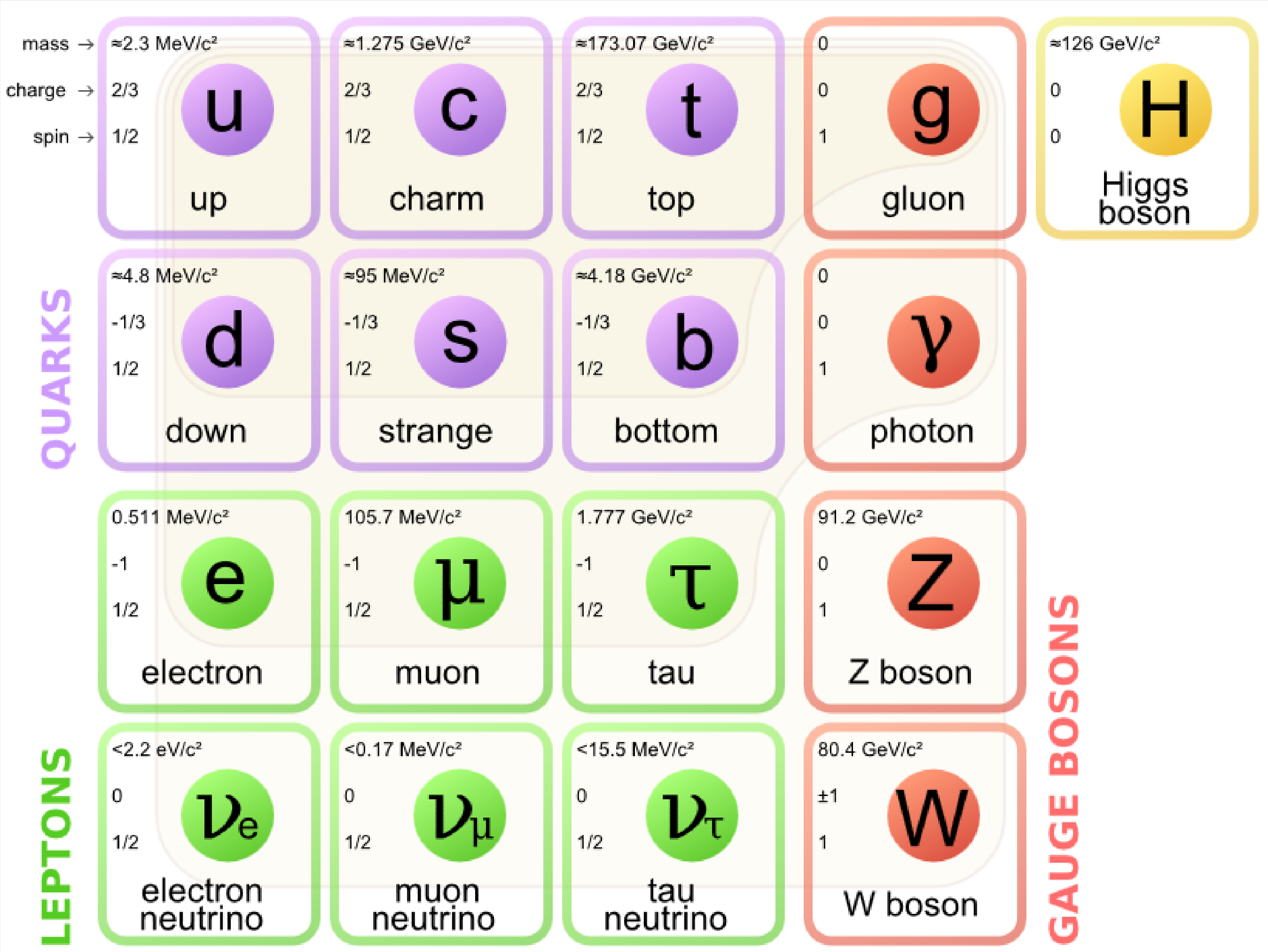
(2) Discovery and status of neutrino oscillations

(3) Sterile neutrinos from short baseline oscillations

(4) Sterile neutrinos as the cosmic neutrino background

(5) Sterile neutrinos as the candidate of warm DM

Standard Model



Standard Model of Elementary Particles:

a) Three generations of quarks and leptons

b) Gauge bosons as force carriers:

strong interaction (8 gluons)

Weak interaction (W & Z)

Electromagnetic interaction (γ)

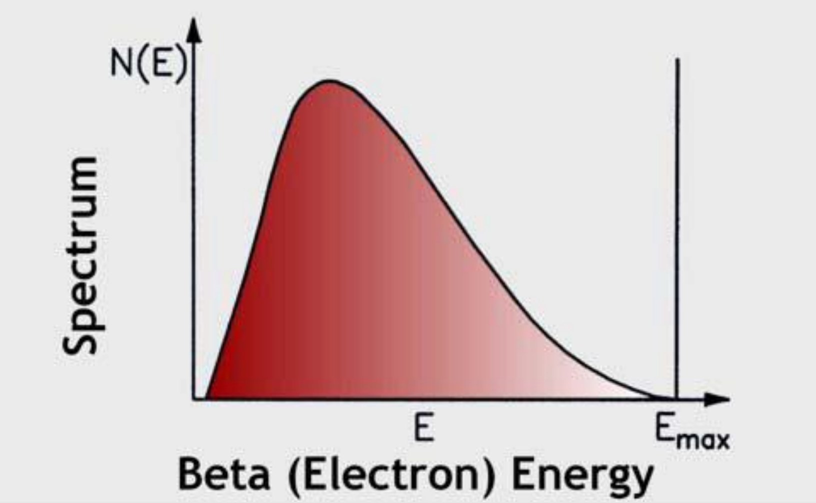
Gravitation (Graviton?)

Massive neutrinos are already the Physics beyond the Standard Model

Neutrino Prehistory: Nuclear Beta Decay

(1) In earlier of 1900s, radioactivity was observed in different nucleus, including α, β, γ rays.

(2) Chadwick discovers that electron energy spectrum in Nuclear Beta Decay is continuous.



$$^{210}_{83}\mathrm{Bi} \rightarrow ^{210}_{84}\mathrm{Po} + e^-$$

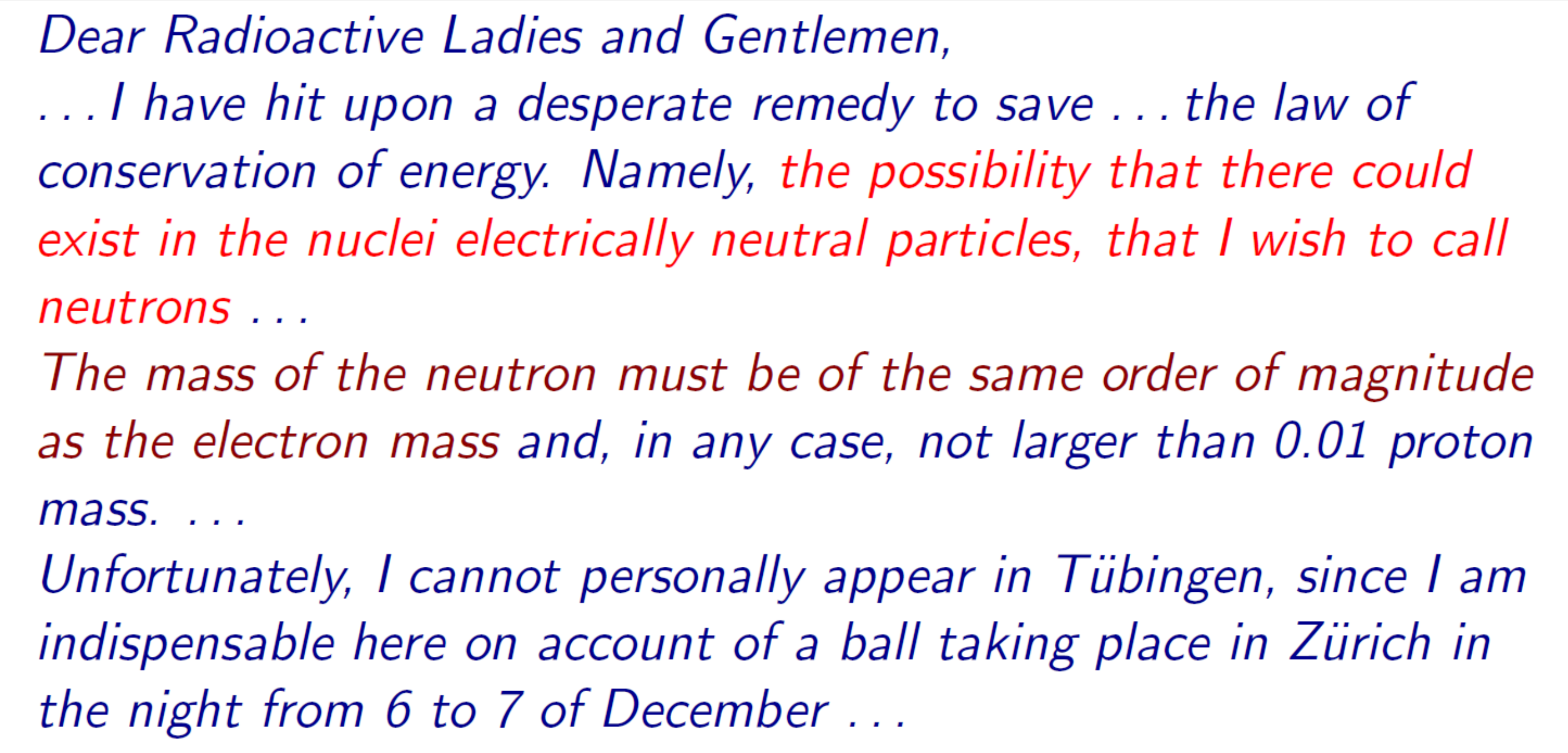
Two-body final state ⇒ Energy-Momentum conservation implies that electron has a unique energy value.

Niels Bohr proposed that energy may be conserved statistically, but energy conservation may be violated in individual decays.

However, Wolfgang Pauli had a different idea.

Neutrino Birth: Pauli - 4 December 1930

4 December 1930: Wolfgang Pauli sent a Public letter to the group of the Radioactive at the district society meeting in Tubingen:



Dear Radioactive Ladies and Gentlemen,

. . . I have hit upon a desperate remedy to save . . . the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons . . .

The mass of the neutron must be of the same order of magnitude as the electron mass and, in any case, not larger than 0.01 proton mass. . . .

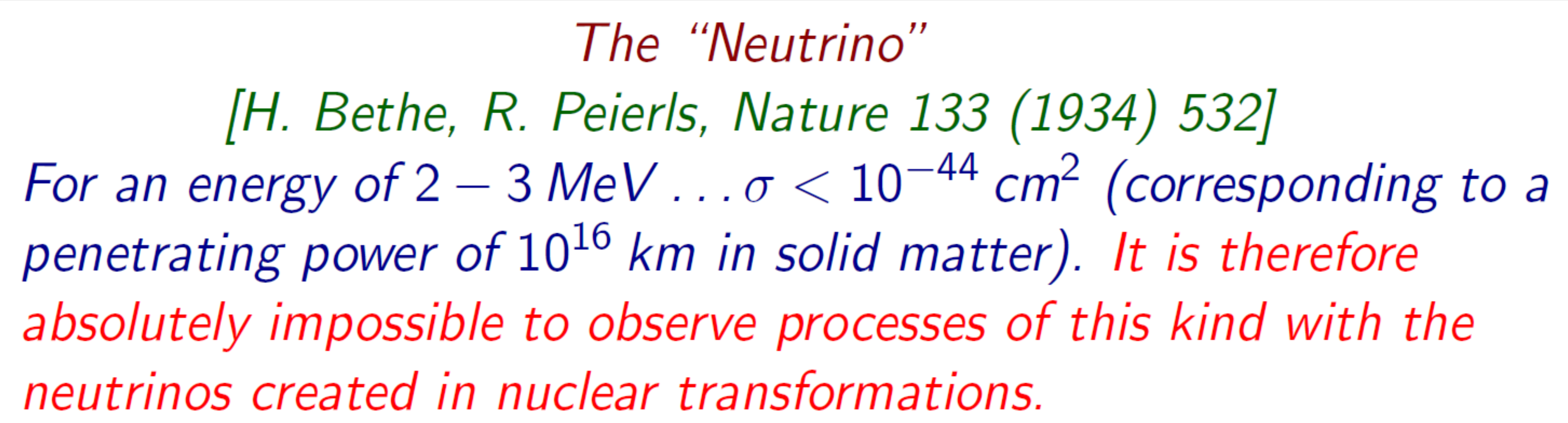
Unfortunately, I cannot personally appear in Tübingen, since I am indispensable here on account of a ball taking place in Zürich in the night from 6 to 7 of December . . .

$$ {}^{210}_{83}\mathrm{Bi} \longrightarrow {}^{210}_{84}\mathrm{Po} + e^{-} + \text{“neutron”} $$

Neutrino detection, impossible ?

The neutron was discovered by Chadwick in 1932.

1933: Enrico Fermi proposes the name neutrino and formulates the theory of Weak Interactions.



The "Neutrino"

[H. Bethe, R. Peierls, Nature 133 (1934) 532]

For an energy of $2-3$ *MeV* $\ldots \sigma < 10^{-44}$ *cm*^{2} *(corresponding to a penetrating power of* 10^{16} *km in solid matter). It is therefore absolutely impossible to observe processes of this kind with the neutrinos created in nuclear transformations.*

(1) 10^{16} **km ≈** 10^3 **light years ≈ 10 times the diameter of our galaxy.**

(2) We have this mysterious new particle and we cannot detect it?

How depressing!

Never Say Never

1951: Clyde Cowan and Frederick Reines start to plan to detect neutrinos with the reaction

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

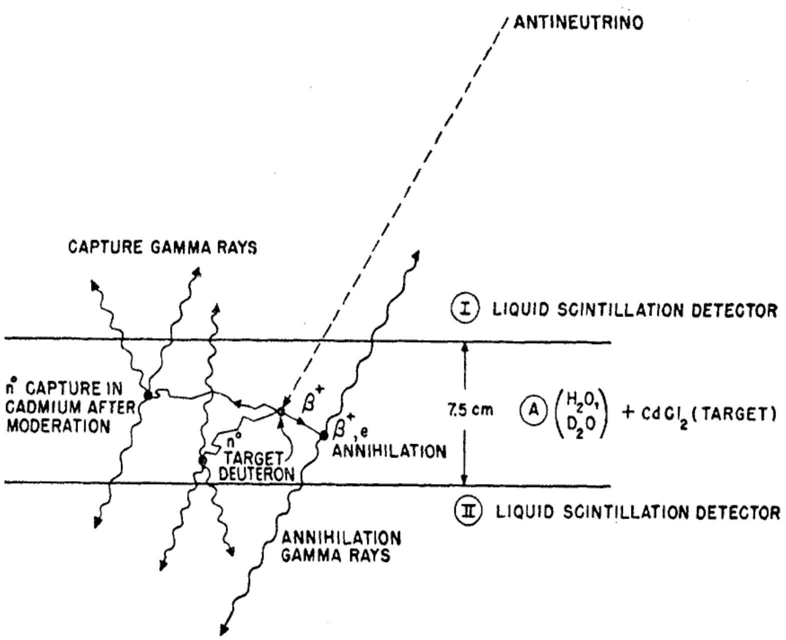
with a large detector (~ 1m^3) filled with liquid scintillator viewed by many photomultipliers.

(1) At that time the largest detectors had a volume of about a liter!

(2) But how to find an intense source of neutrinos?

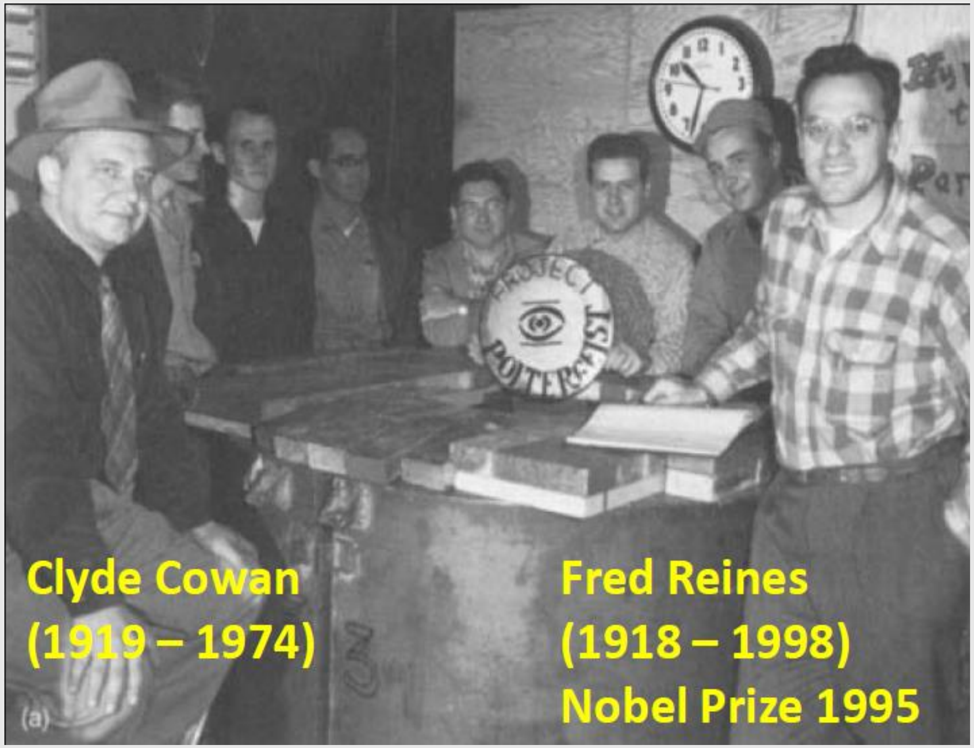
(3) 1951: Reines to Fermi: neutrino detector near an atomic bomb?

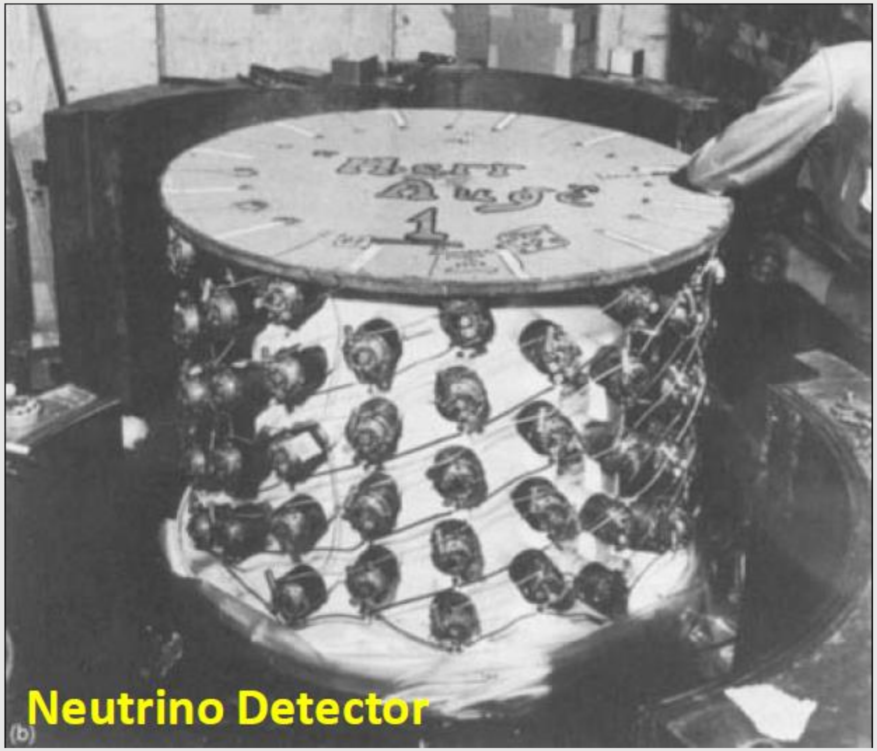
(4) Afterwards, neutrinos from nuclear reactors: more practical possibility!



[Cowan, Reines, Physical Review 107 (1957) 1609]

Discovery of neutrinos: 1956





I confronted Bethe with this pronouncement some 20 years later and with his characteristic good humor he said, "Well, you shouldn't believe everything you read in the papers".

[Reines, Nobel Lecture 1995]

Milestones of neutrino detection

1956: Cowan and Reines discovered the first neutrino: electron antineutrino (from nuclear reactors).

Nobel prize in 1995.

1962: L. Lederman, M. Schwartz and J. Steinberger discovered the second neutrino: muon neutrino (in accelerator neutrino beam).

Nobel prize in 1988.

1968: R. Davis discovered the solar neutrinos, and during 1968-1995, identified the solar neutrino problem.

1987: M. Koshiba observed the supernova neutrinos from SN1987A.

Nobel prize in 2002.

2000: The DONUT experiment at Fermi Lab discovered the third neutrino: tau neutrino (in accelerator neutrino beam).

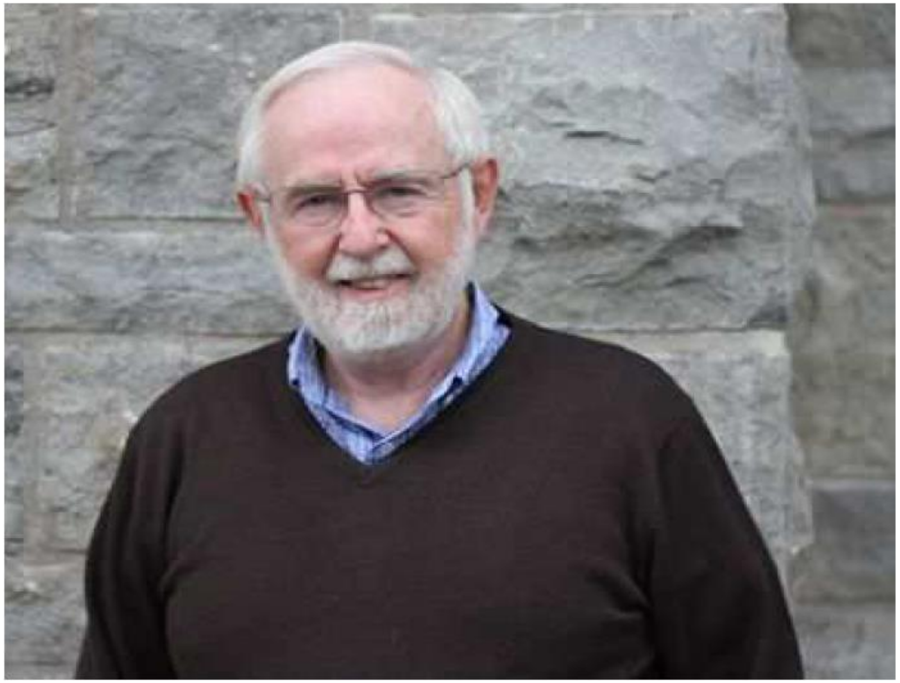
Discovery of Neutrino Oscillations

1998: Oscillations of atmospheric neutrinos observed by the Super-Kamiokande experiment

Takaaki Kajita
2015 Physics Nobel Prize

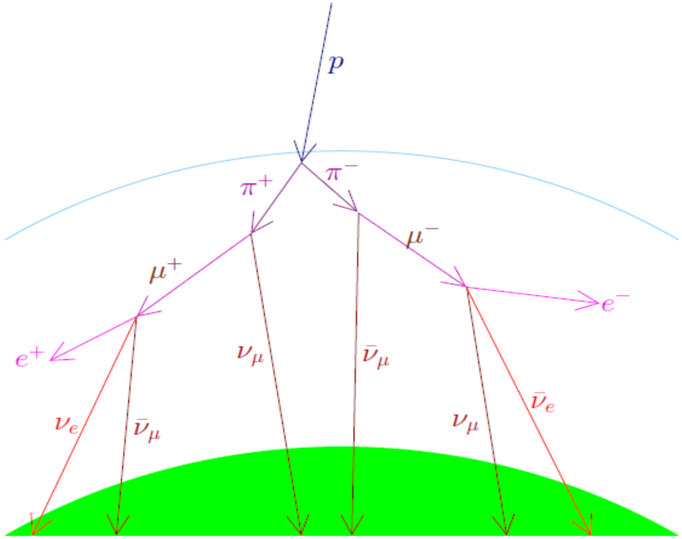
2002: Oscillations of solar neutrinos observed by the SNO experiment

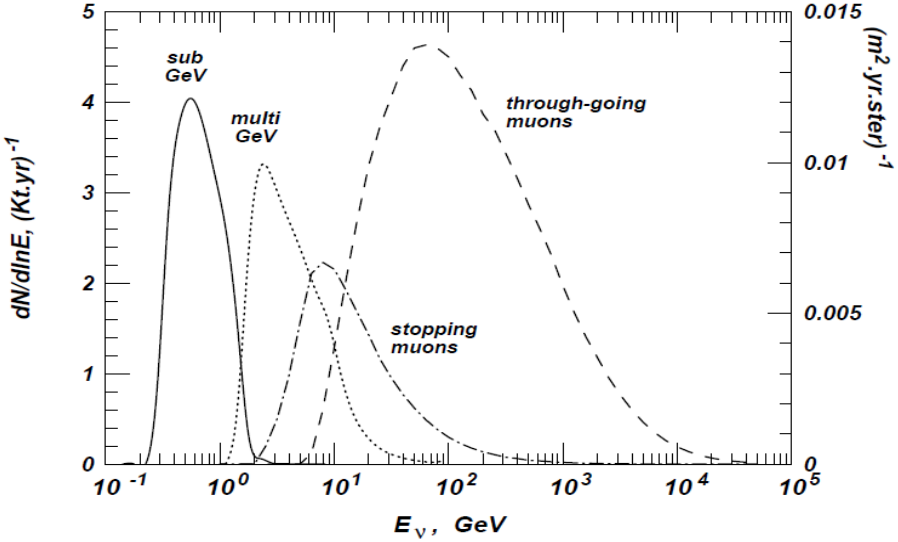
Arthur B. McDonald
2015 Physics Nobel Prize



"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Atmospheric neutrino anomaly





$$\frac{N(\nu_\mu + \bar{\nu}_\mu)}{N(\nu_e + \bar{\nu}_e)} \simeq 2 \qquad \text{at } E \lesssim 1\,\text{GeV}$$

uncertainty on ratios: $\sim 5\%$

uncertainty on fluxes: $\sim 30\%$

ratio of ratios

$$R \equiv \frac{[N(\nu_\mu + \bar{\nu}_\mu)/N(\nu_e + \bar{\nu}_e)]_{\text{data}}}{[N(\nu_\mu + \bar{\nu}_\mu)/N(\nu_e + \bar{\nu}_e)]_{\text{MC}}}$$

$$R^{\text{K}}_{\text{sub-GeV}} = 0.60 \pm 0.07 \pm 0.05$$

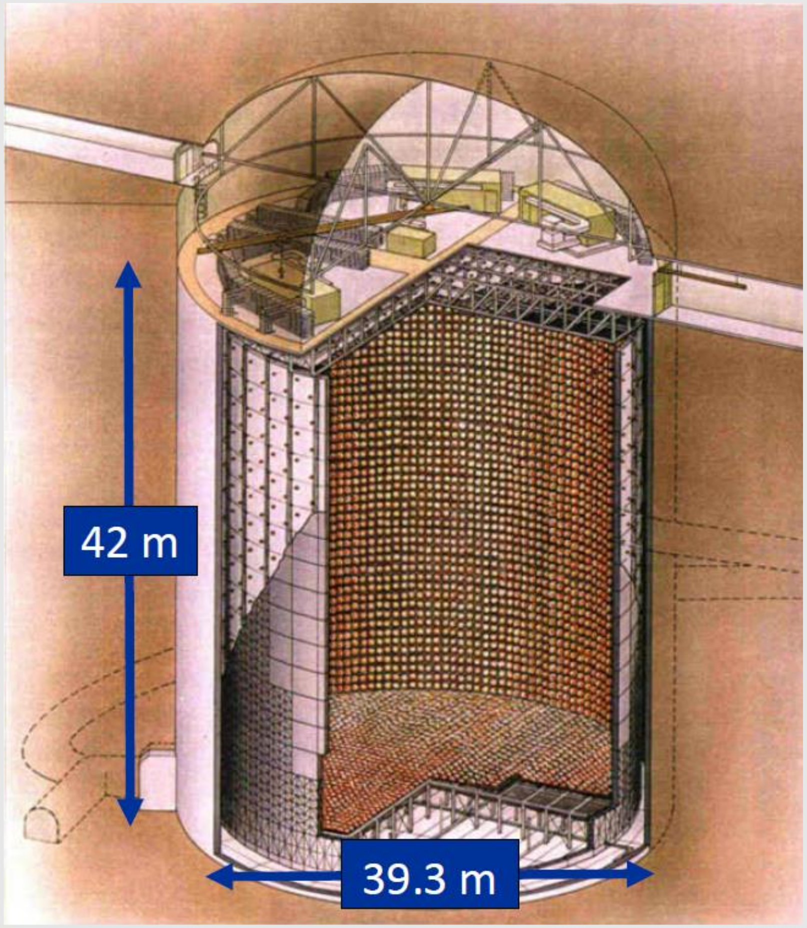
[Kamiokande, PLB 280 (1992) 146]

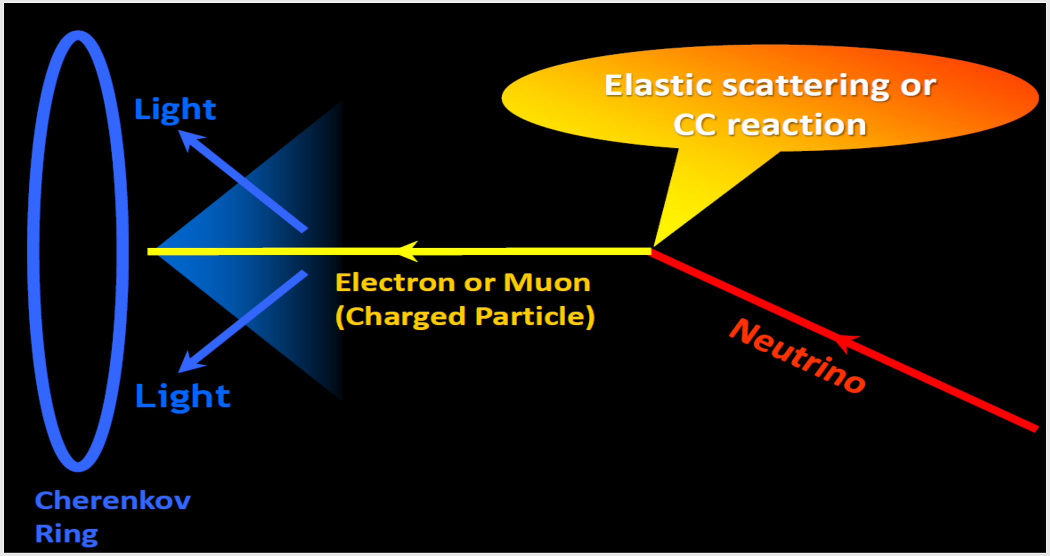
$$R^{\text{K}}_{\text{multi-GeV}} = 0.57 \pm 0.08 \pm 0.07$$

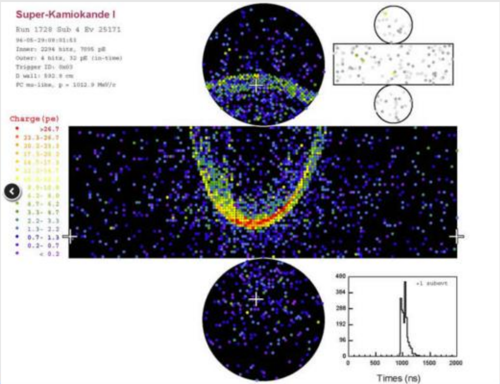
[Kamiokande, PLB 335 (1994) 237]

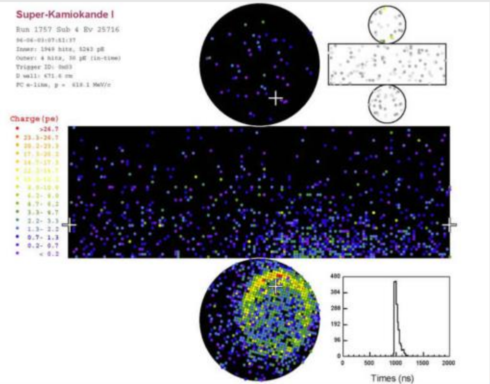
Super-Kamiokande (from 1996-now)

50 k-ton water Cherenkov detector with large-area photomultipliers, powerful discrimination of electrons and muons



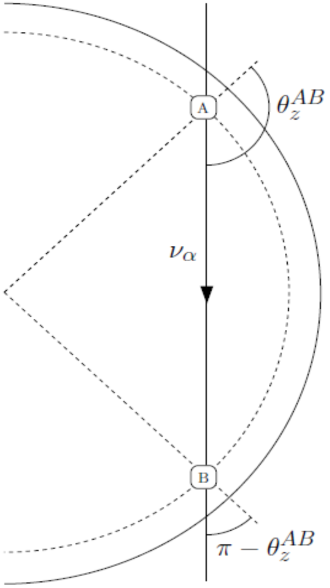






Super-Kamiokande: 1998 discovery

On June 4th, Takaaki Kajita presented at Neutrino 1998:



$E_\nu \gtrsim 1\,\text{GeV} \Rightarrow$ isotropic flux of cosmic rays

$$\phi_{\nu_\alpha}^{(A)}(\theta_z^{AB}) = \phi_{\nu_\alpha}^{(B)}(\pi - \theta_z^{AB}) \qquad \phi_{\nu_\alpha}^{(A)}(\theta_z^{AB}) = \phi_{\nu_\alpha}^{(B)}(\theta_z^{AB})$$

$$\Downarrow$$

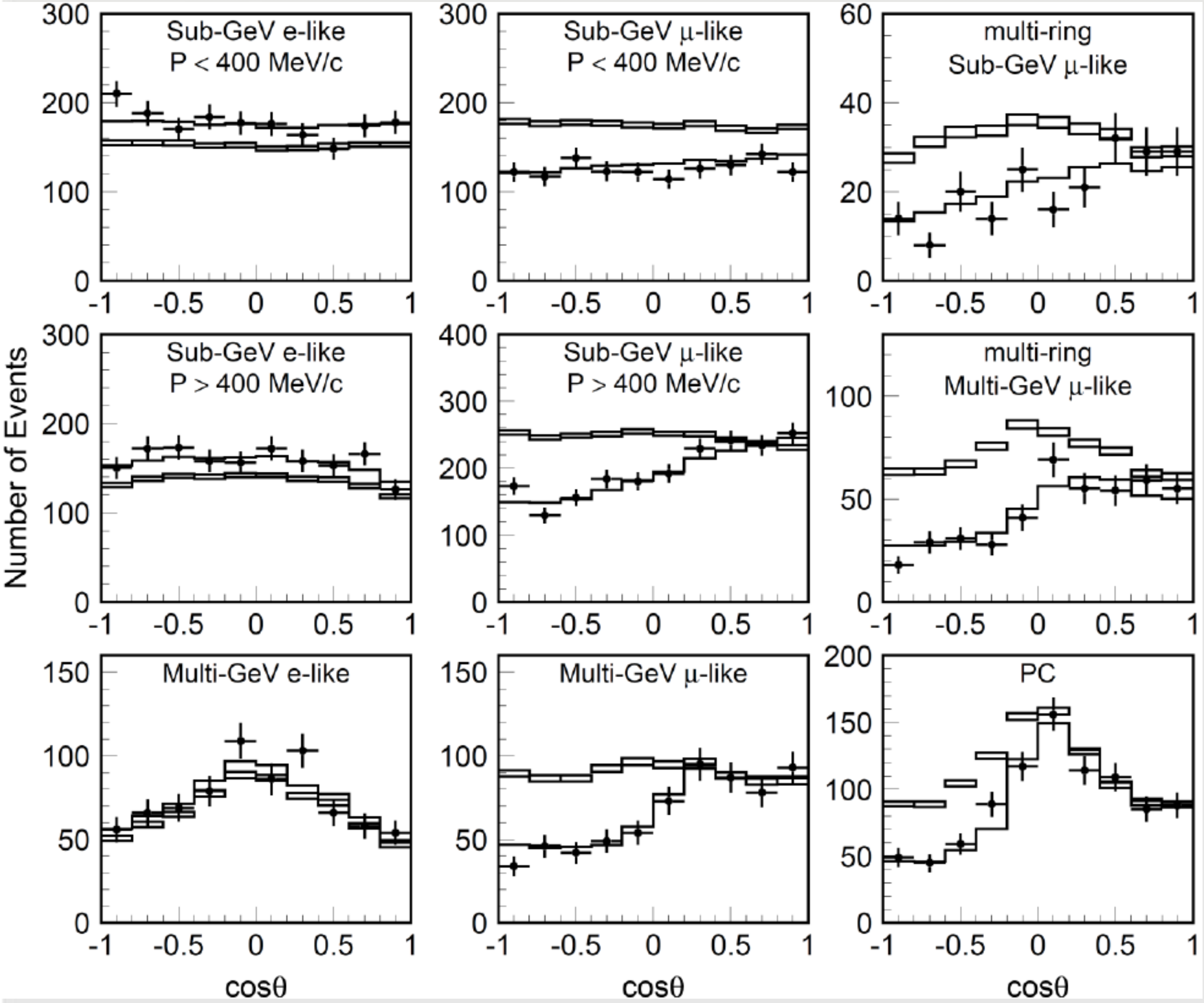
$$\phi_{\nu_\alpha}^{(A)}(\theta_z) = \phi_{\nu_\alpha}^{(A)}(\pi - \theta_z)$$

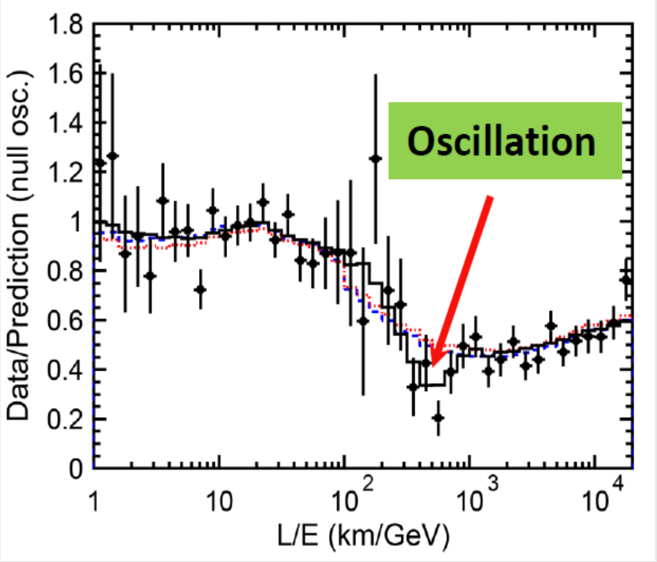
$$\boxed{A_{\nu_\mu}^{\text{up-down}}(\text{SK}) = \left(\frac{N_{\nu_\mu}^{\text{up}} - N_{\nu_\mu}^{\text{down}}}{N_{\nu_\mu}^{\text{up}} + N_{\nu_\mu}^{\text{down}}}\right) = -0.296 \pm 0.048 \pm 0.01}$$

[Super-Kamiokande, Phys. Rev. Lett. 81 (1998) 1562, hep-ex/9807003]

6σ model independent evidence of ν_μ disappearance due to oscillations!

Super-Kamiokande: oscillatory evidence





↑ ~13000 km

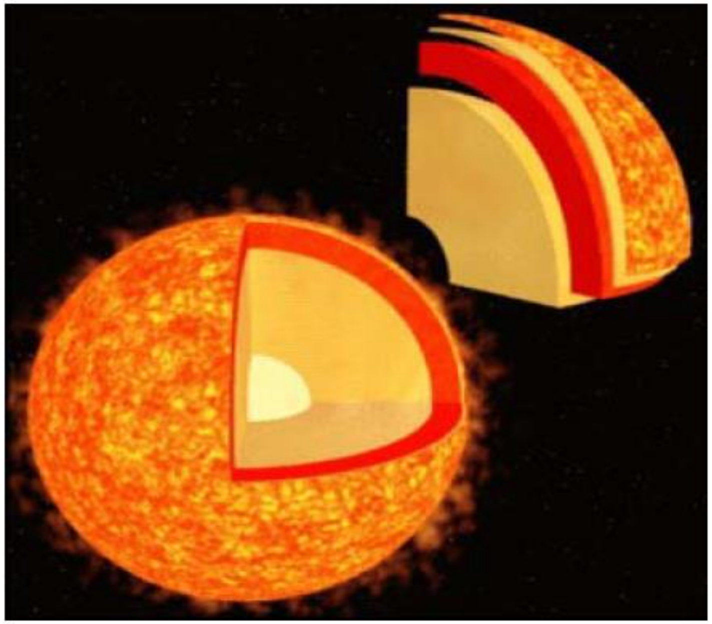
← ~500 km

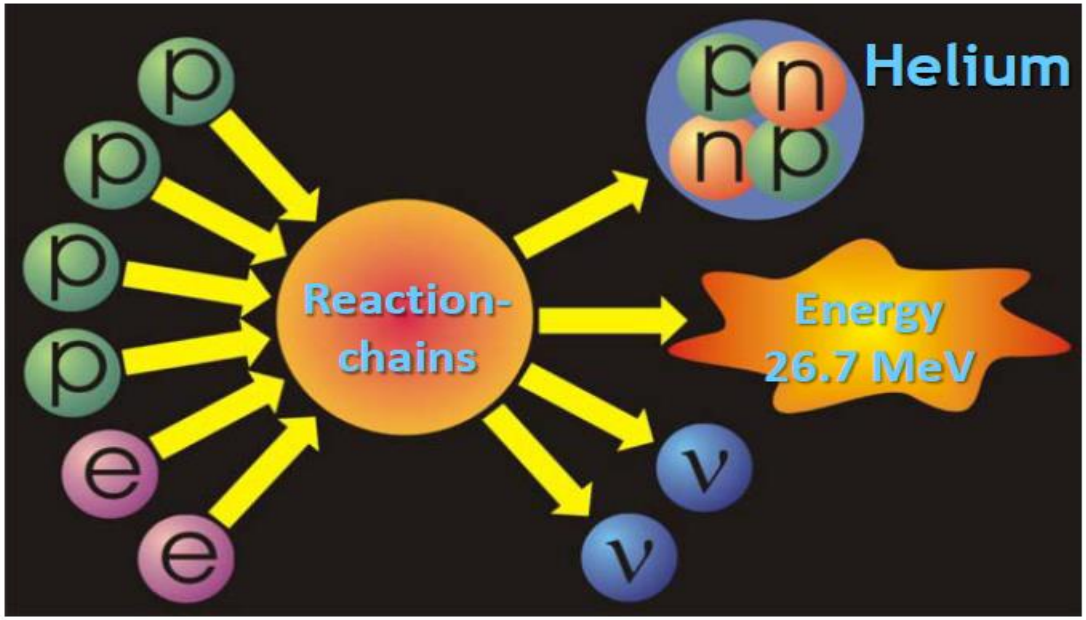
↓ ~15 km

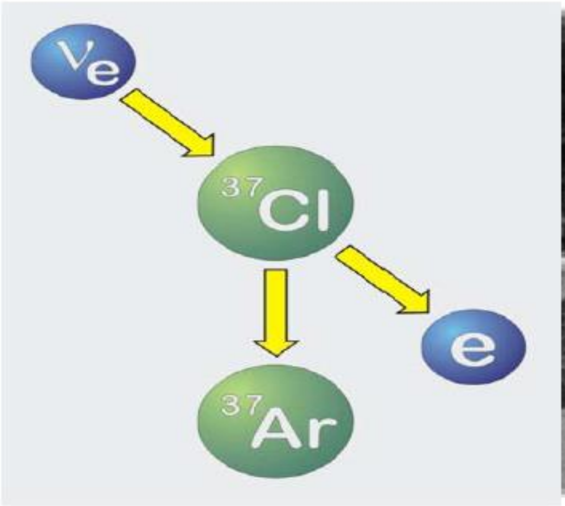
The energy and baseline depedence provides the oscillatory evidence.

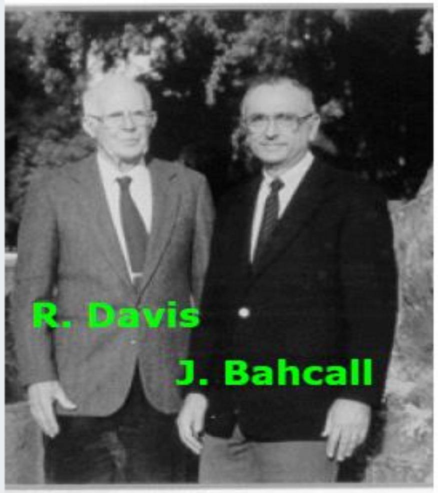
The L/E curve rules out neutrino decay and decoherence explanations.

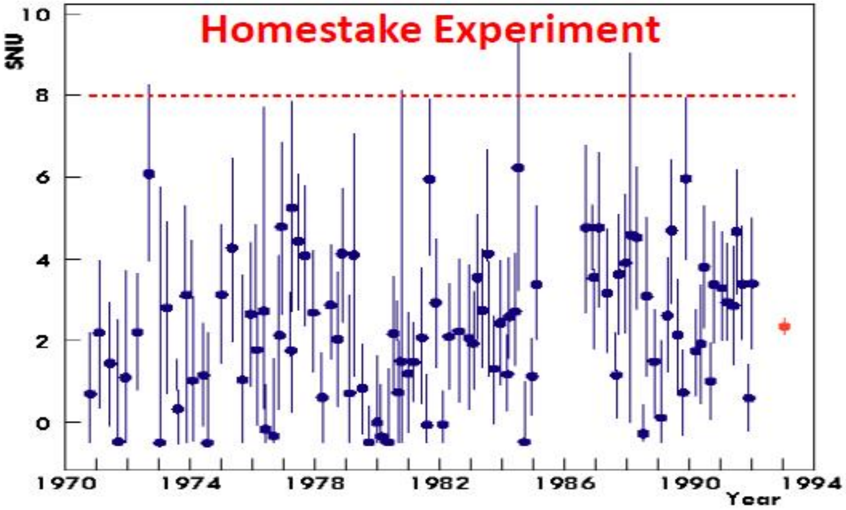
Discovery of solar neutrinos: 1968











Solar neutrino production

A Helium nucleus is produced by the fusion of 4 Hydrogen nuclei;

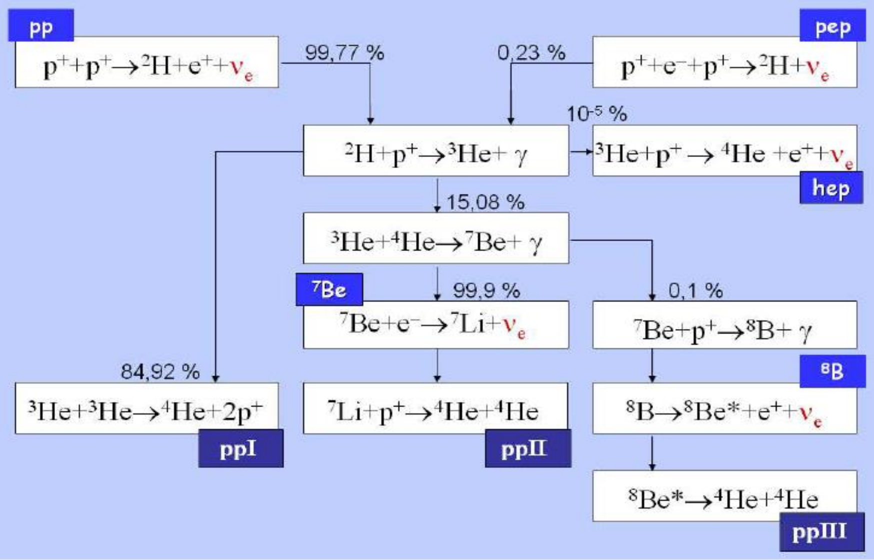
$$4p \rightarrow He + 2e^{+} + 2\nu_e$$

This reaction produces about 27 MeV energy.
Then, the total neutrino flux on the Earth is;

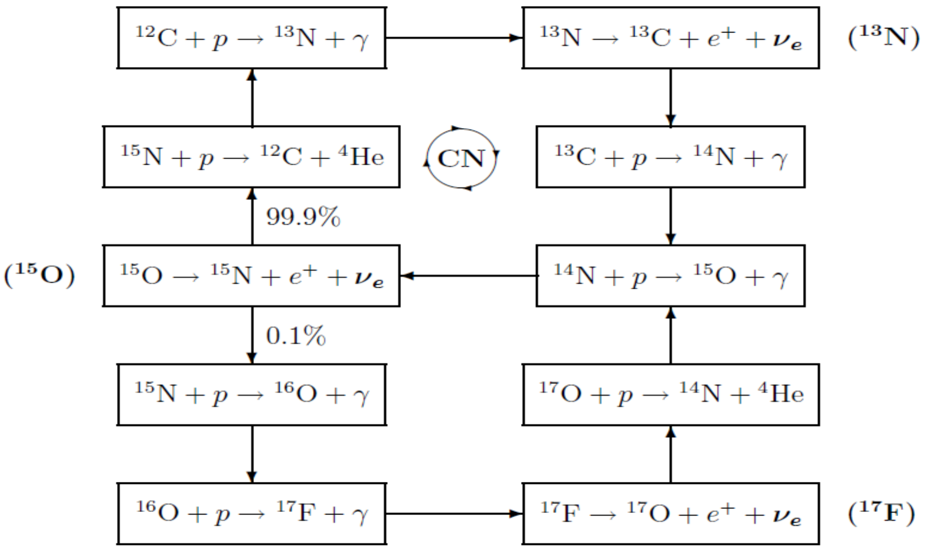
$$flux = \frac{1}{4\pi R^2} \times \frac{L_{sun}}{27MeV} \times 2\nu_e$$

$$(L_{sun} = 3.86 \times 10^{33} erg/\sec)$$

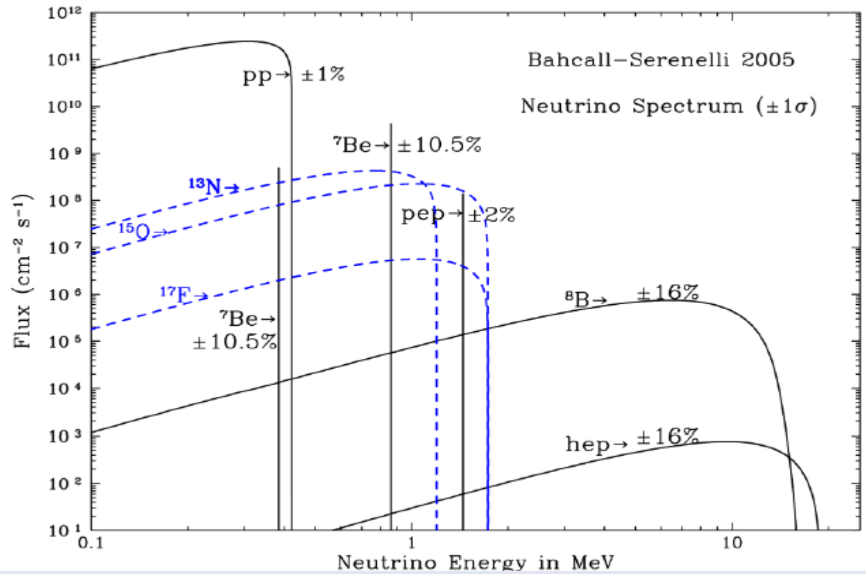
$$= 6 \times 10^{10} \nu_e / cm^2 / \sec$$



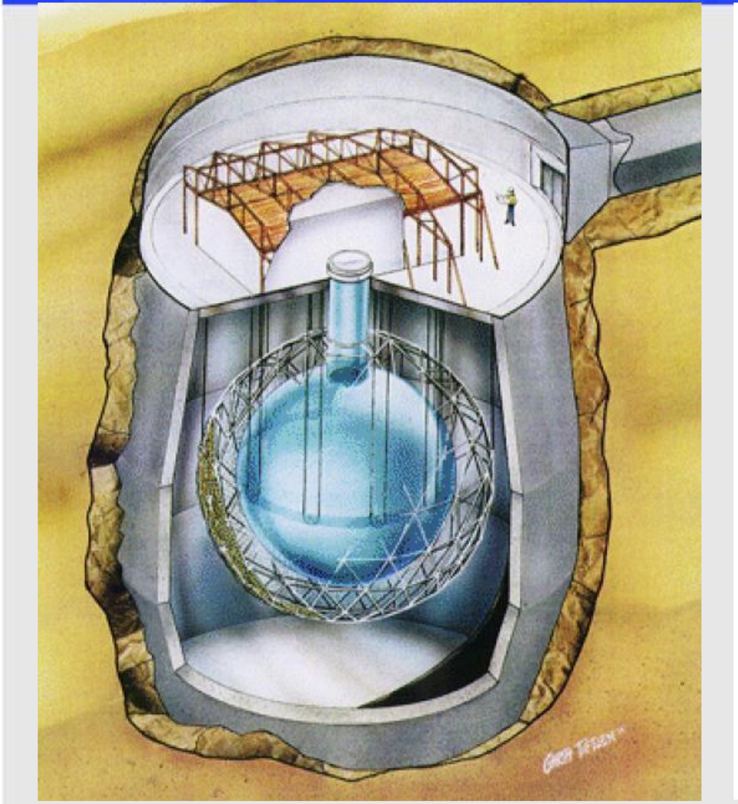
pp
$p^+ + p^+ \rightarrow {}^2H + e^+ + \nu_e$
99,77 %
0,23 %
pep
$p^+ + e^- + p^+ \rightarrow {}^2H + \nu_e$
10^{-5} %
${}^2H + p^+ \rightarrow {}^3He + \gamma$
${}^3He + p^+ \rightarrow {}^4He + e^+ + \nu_e$
hep
15,08 %
${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
7Be
99,9 %
${}^7Be + e^- \rightarrow {}^7Li + \nu_e$
0,1 %
${}^7Be + p^+ \rightarrow {}^8B + \gamma$
8B
84,92 %
${}^3He + {}^3He \rightarrow {}^4He + 2p^+$
ppI
${}^7Li + p^+ \rightarrow {}^4He + {}^4He$
ppII
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$
${}^8Be^* \rightarrow {}^4He + {}^4He$
ppIII

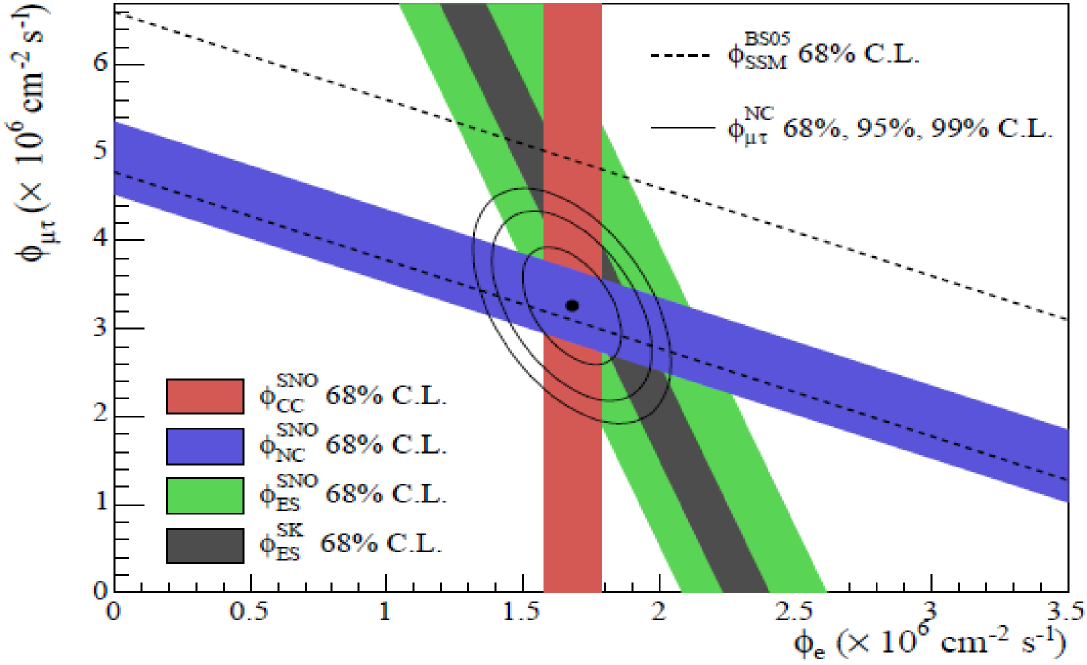


${}^{12}C + p \rightarrow {}^{13}N + \gamma$
${}^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$
$({}^{13}N)$
${}^{15}N + p \rightarrow {}^{12}C + {}^4He$
CN
${}^{13}C + p \rightarrow {}^{14}N + \gamma$
99.9%
$({}^{15}O)$
${}^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$
${}^{14}N + p \rightarrow {}^{15}O + \gamma$
0.1%
${}^{15}N + p \rightarrow {}^{16}O + \gamma$
${}^{17}O + p \rightarrow {}^{14}N + {}^4He$
${}^{16}O + p \rightarrow {}^{17}F + \gamma$
${}^{17}F \rightarrow {}^{17}O + e^+ + \nu_e$
$({}^{17}F)$



SNO: Sudbury Neutrino Observatory





[SNO, PRL 89 (2002) 011301, nucl-ex/0204008]

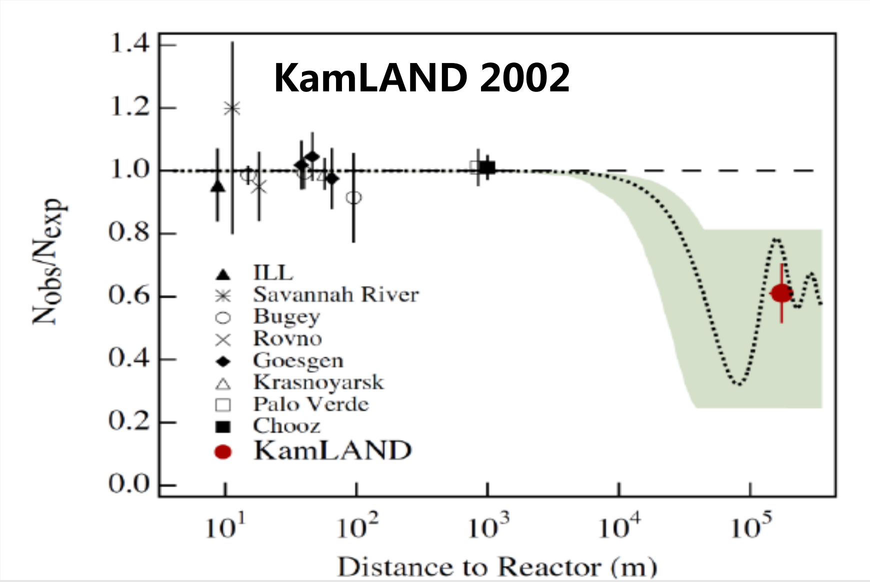
$$\begin{array}{ll} \text{CC}: & \nu_e + d \to p + p + e^- \\ \text{NC}: & \nu_\alpha + d \to p + n + \nu_\alpha \\ \text{ES}: & \nu_\alpha + e^- \to \nu_\alpha + e^- \end{array}$$

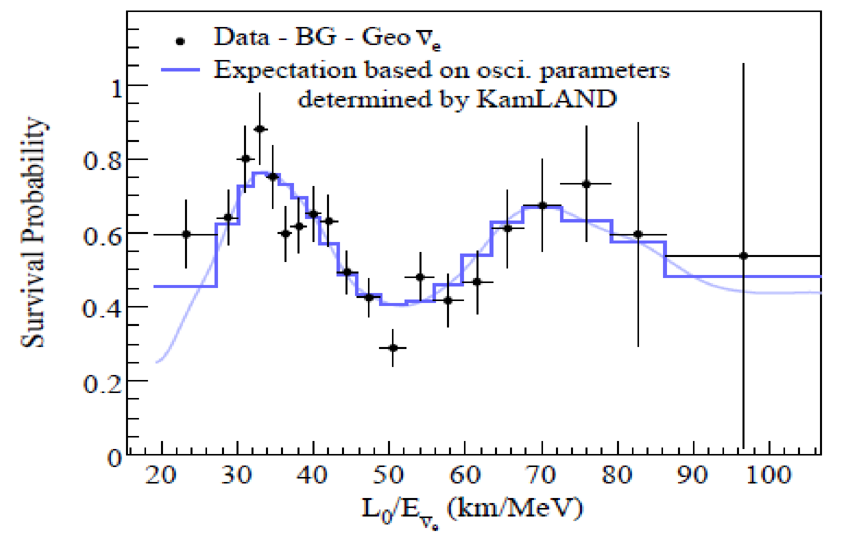
$$\Phi^{\text{SNO}}_{\nu_e} = 1.76 \pm 0.11 \times 10^6\,\text{cm}^{-2}\,\text{s}^{-1}$$

$$\Phi^{\text{SNO}}_{\nu_\mu,\nu_\tau} = 5.41 \pm 0.66 \times 10^6\,\text{cm}^{-2}\,\text{s}^{-1}$$

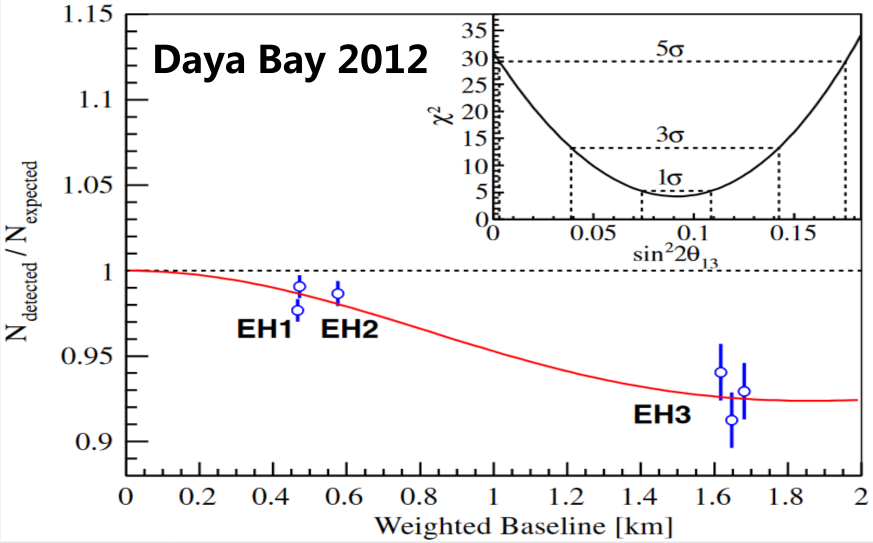
- SNO proved in a model independent way that the Solar Neutrino Problem is a manifestation of Neutrino Oscillations: $\nu_e \to \nu_\mu, \nu_\tau$

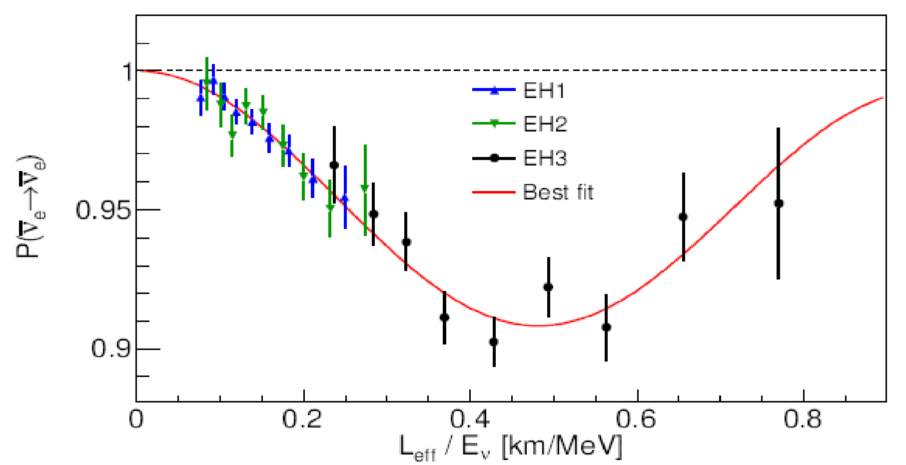
Confirmation


KamLAND 2002



[KamLAND, PRL 100 (2008) 221803, arXiv:0801.4589]


Daya Bay 2012



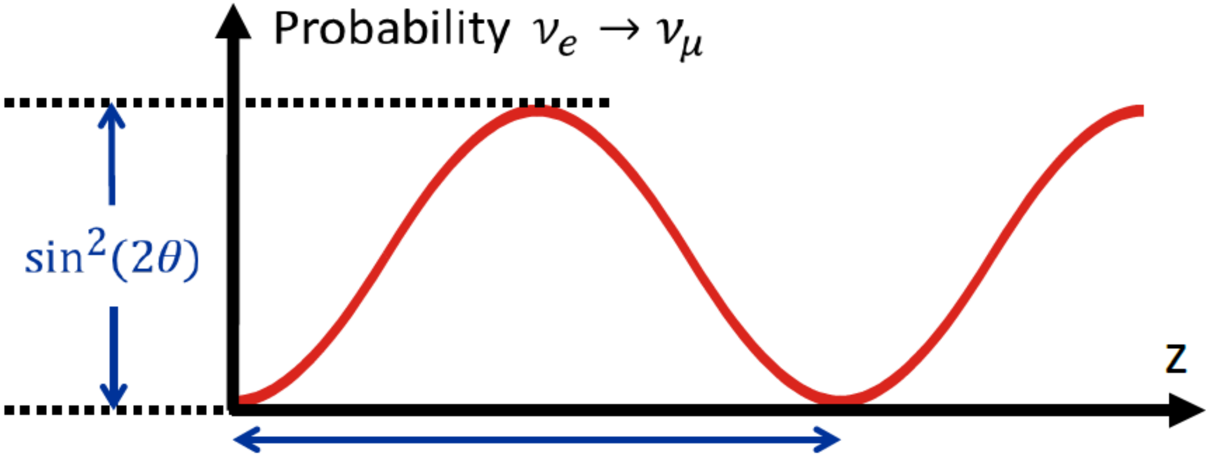
[Daya Bay, PRL, 112 (2014) 061801, arXiv:1310.6732]

Neutrino Oscillation Theory

Two-flavor mixing $\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$

Pontecorvo, 1957; Maki, Nakagawa, Sakata, 1962

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



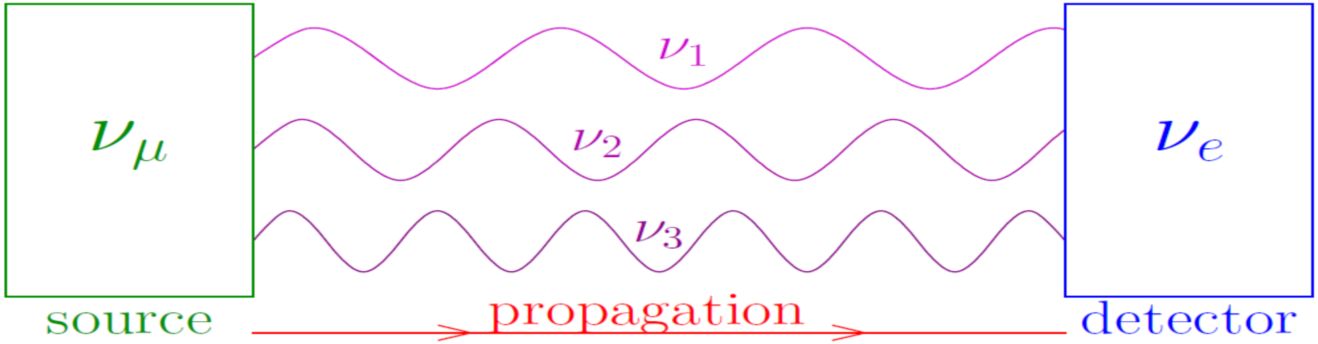
Oscillation Length $\dfrac{4\pi E}{\delta m^2} = 2.5\ \mathrm{m}\ \dfrac{E}{\mathrm{MeV}}\left(\dfrac{\mathrm{eV}^2}{\delta m}\right)$

Bruno Pontecorvo
(1913–1993)
Invented ν oscillations

Neutrino Oscillations: quantum phenomena of massive neutrinos at the macroscopic distances

ν oscillation in 3-flavor framework

$$|\nu(t=0)\rangle = |\nu_\mu\rangle = U_{\mu 1}\,|\nu_1\rangle + U_{\mu 2}\,|\nu_2\rangle + U_{\mu 3}\,|\nu_3\rangle$$



$$|\nu(t>0)\rangle = U_{\mu 1}\,e^{-iE_1 t}\,|\nu_1\rangle + U_{\mu 2}\,e^{-iE_2 t}\,|\nu_2\rangle + U_{\mu 3}\,e^{-iE_3 t}\,|\nu_3\rangle \neq |\nu_\mu\rangle$$

$$E_k^2 = p^2 + m_k^2$$

$$P_{\nu_\mu \to \nu_e}(t>0) = |\langle \nu_e | \nu(t>0)\rangle|^2 \sim \sum_{k>j} \mathrm{Re}\left[U_{ek}\,U^*_{\mu k}\,U^*_{ej}\,U_{\mu j}\right] \sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right)$$

transition probabilities depend on U and $\Delta m^2_{kj} \equiv m_k^2 - m_j^2$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

Experimental evidence of ν oscillations

Solar

$\nu_e \to \nu_\mu , \nu_\tau$

VLBL Reactor

$\bar{\nu}_e$ disappearance

$$\left(\begin{array}{c} \text{SNO, BOREXino} \\ \text{Super-Kamiokande} \\ \text{GALLEX/GNO, SAGE} \\ \text{Homestake, Kamiokande} \end{array} \right)$$

(KamLAND)

$$\to \left\{ \begin{array}{l} \Delta m^2_{\mathrm{S}} = \Delta m^2_{21} \simeq 7.6 \times 10^{-5}\ \mathrm{eV}^2 \\ \sin^2\vartheta_{\mathrm{S}} = \sin^2\vartheta_{12} \simeq 0.30 \end{array} \right.$$

Atmospheric

$\nu_\mu \to \nu_\tau$

LBL Accelerator

ν_μ disappearance

LBL Accelerator

$\nu_\mu \to \nu_\tau$

$$\left(\begin{array}{c} \text{Super-Kamiokande} \\ \text{Kamiokande, IMB} \\ \text{MACRO, Soudan-2} \end{array} \right)$$

$$\left(\begin{array}{c} \text{K2K, MINOS} \\ \text{T2K, NO}\nu\text{A} \end{array} \right)$$

(Opera)

$$\to \left\{ \begin{array}{l} \Delta m^2_{\mathrm{A}} = |\Delta m^2_{31}| \simeq 2.4 \times 10^{-3}\ \mathrm{eV}^2 \\ \sin^2\vartheta_{\mathrm{A}} = \sin^2\vartheta_{23} \simeq 0.50 \end{array} \right.$$

LBL Accelerator

$\nu_\mu \to \nu_e$

(T2K, MINOS, NOνA)

LBL Reactor

$\bar{\nu}_e$ disappearance

$$\left(\begin{array}{c} \text{Daya Bay, RENO} \\ \text{Double Chooz} \end{array} \right)$$

$$\to \left\{ \begin{array}{l} \Delta m^2_{\mathrm{A}} = |\Delta m^2_{31}| \\ \sin^2\vartheta_{13} \simeq 0.023 \end{array} \right.$$

Unknown issues

Neutrino mass ordering: reactor & atmospheric nus

Lepton CP violation: accelerator nus

Absolute neutrino masses: β decay & ν-less double β decay

Dirac vs. Majorana nature: ν-less double β decay

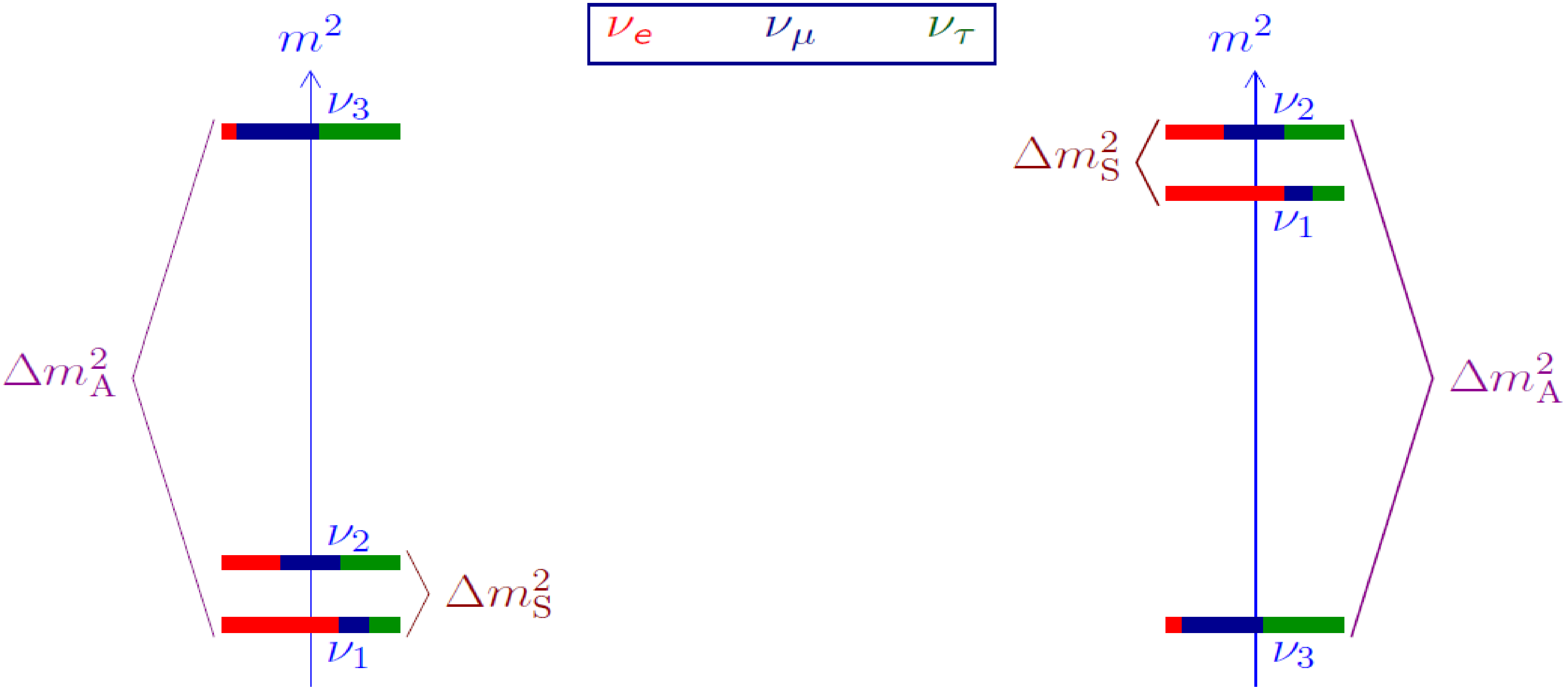
More Neutrino Species: sterile neutrinos

Origin of Neutrino Masses? seesaw?

Origin of Large Flavor Mixing? flavor symmetry?

Cosmological baryon asymmetry? leptogenesis?

Unknown mass ordering: JUNO



Normal Ordering

Inverted Ordering

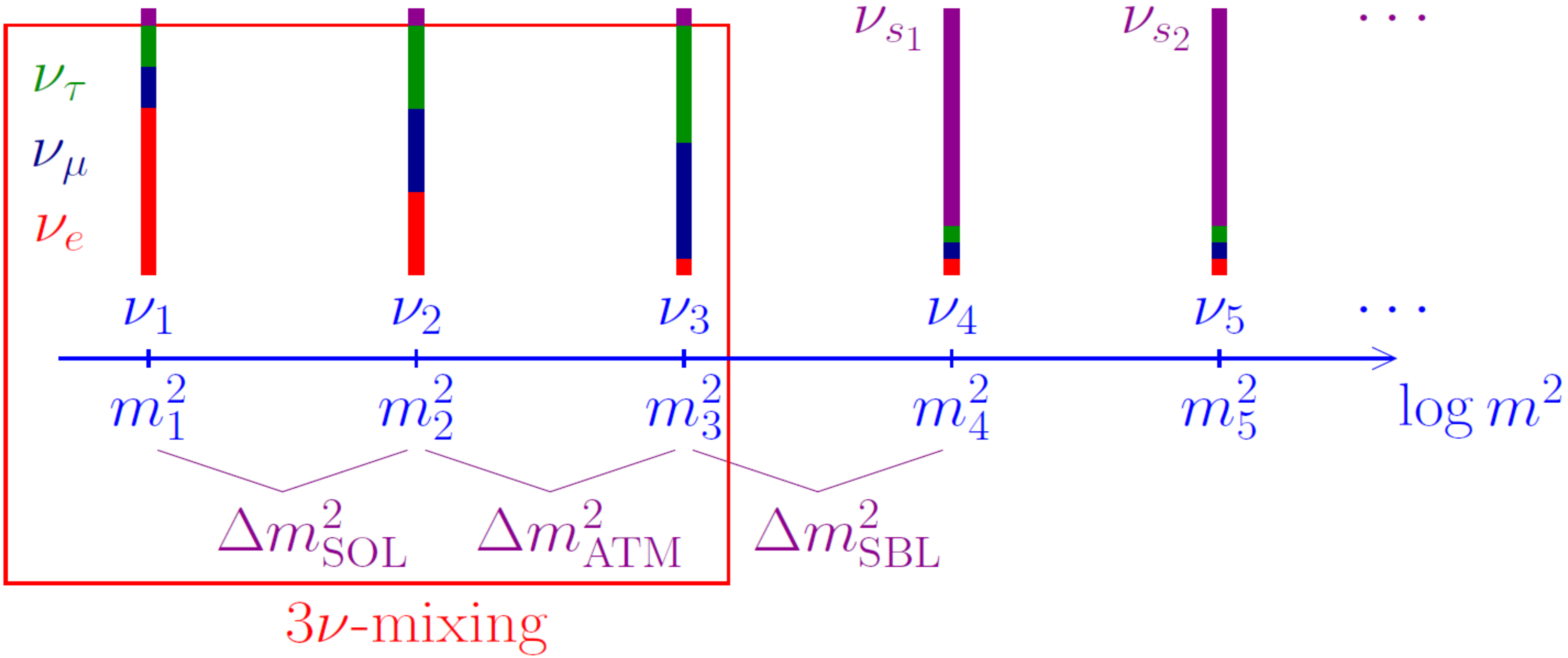
$\Delta m^2_{31} > \Delta m^2_{32} > 0$

$\Delta m^2_{32} < \Delta m^2_{31} < 0$

absolute scale is not determined by neutrino oscillation data

Sterile neutrinos in short baseline oscillations

Beyond 3-ν oscillations: Sterile neutrinos



sterile neutrinos: mass eigenstates of mostly sterile neutrinos

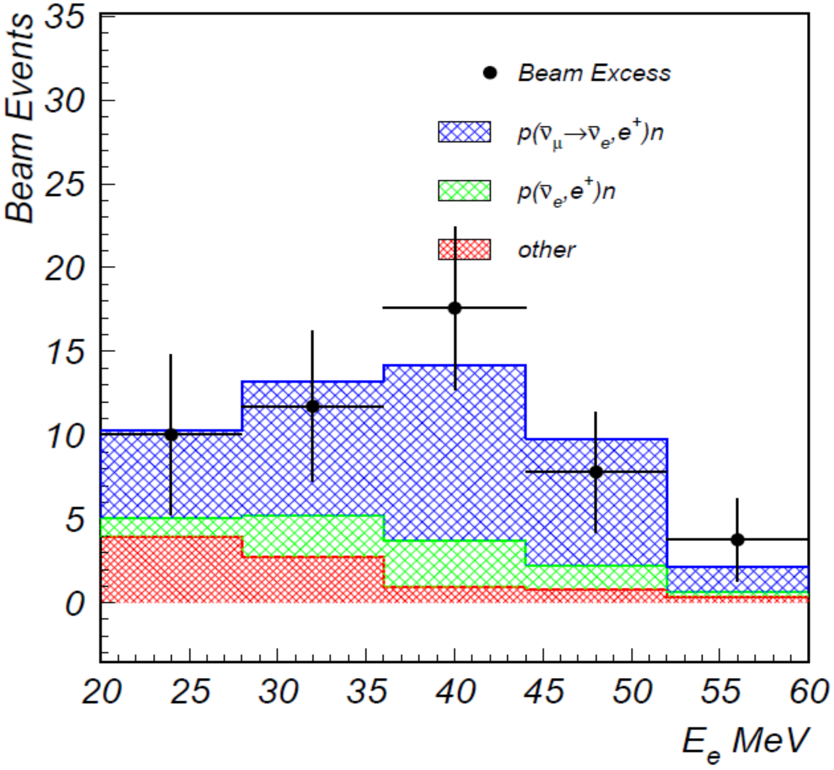
Explanation of short baseline oscillations: eV-scale sterile neutrinos

Topical Review: ***Gariazzo, Giunti, Laveder, Li, Zavanin, JPG 43 (2016) 033001***

LSND

[PRL 75 (1995) 2650; PRC 54 (1996) 2685; PRL 77 (1996) 3082; PRD 64 (2001) 112007]

$\bar{\nu}_\mu \to \bar{\nu}_e$ $L \simeq 30\,\text{m}$ $20\,\text{MeV} \leq E \leq 60\,\text{MeV}$



- Well known source of $\bar{\nu}_\mu$:

$$\mu^+ \text{ at rest} \to e^+ + \nu_e + \bar{\nu}_\mu$$

- $\bar{\nu}_\mu \xrightarrow[L \simeq 30\,\text{m}]{} \bar{\nu}_e$
- Well known detection process of $\bar{\nu}_e$:

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

- But signal not seen by KARMEN with same method at $L \simeq 18\,\text{m}$

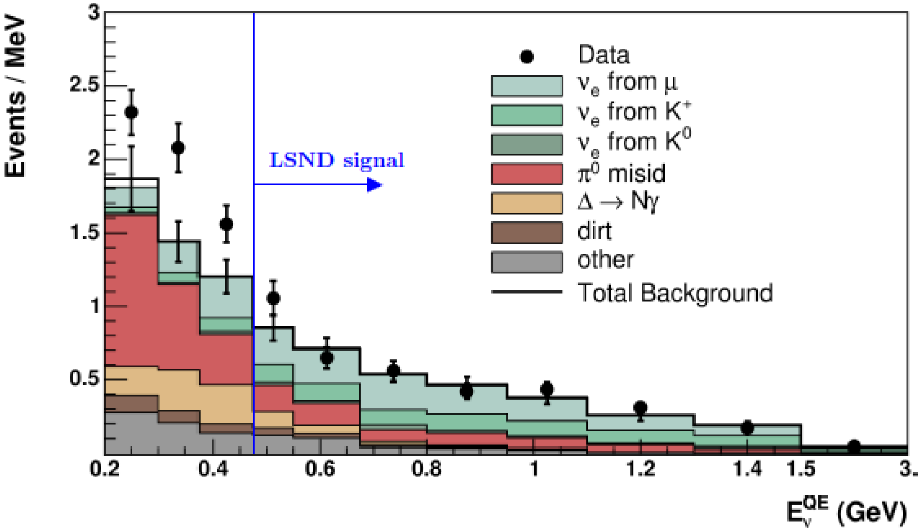
[PRD 65 (2002) 112001]

Nominal $\approx 3.8\sigma$ excess $\Delta m^2 \gtrsim 0.2\,\text{eV}^2$ $(\gg \Delta m^2_\text{A} \gg \Delta m^2_\text{S})$

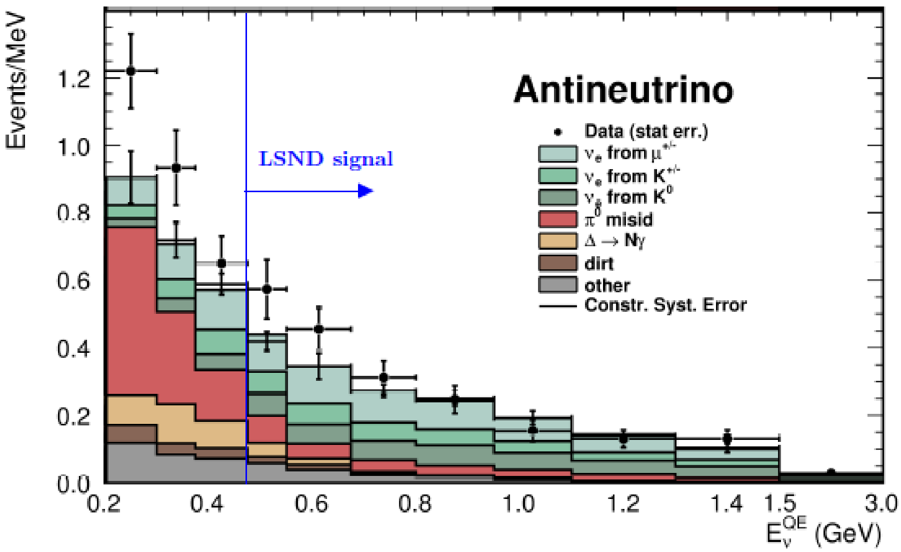
MiniBooNE

$L \simeq 541\,\mathrm{m}$ $\quad$ $200\,\mathrm{MeV} \leq E \lesssim 3\,\mathrm{GeV}$

$\nu_\mu \to \nu_e$ [PRL 102 (2009) 101802]



$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]



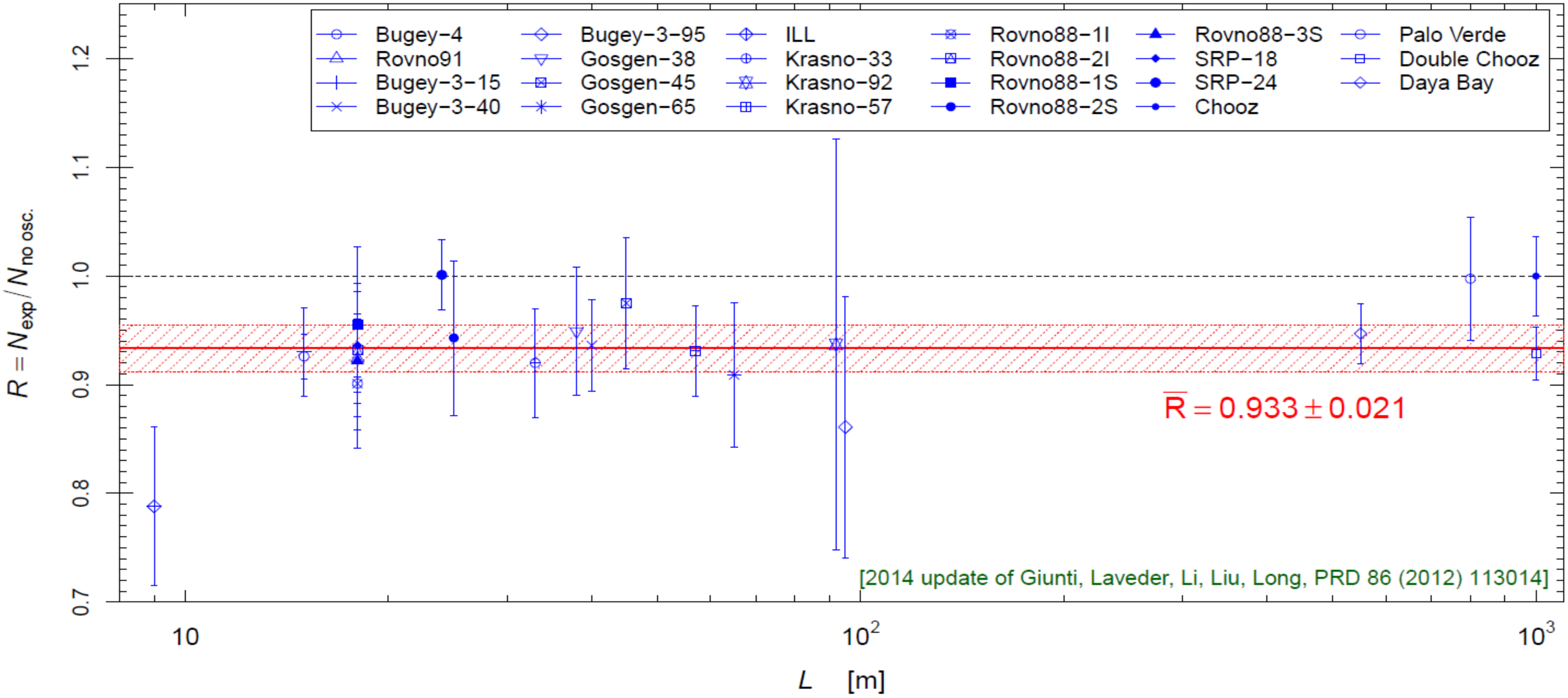
Purpose: check LSND signal with different L&E, but the same L/E

~3σ excess: Agreement with LSND or not?

Reactor antineutrino anomaly

[Mention et al, PRD 83 (2011) 073006; update in White Paper, arXiv:1204.5379]

New reactor $\bar{\nu}_e$ fluxes [Mueller et al, PRC 83 (2011) 054615; Huber, PRC 84 (2011) 024617]



[2014 update of Giunti, Laveder, Li, Liu, Long, PRD 86 (2012) 113014]

$\bar{\nu}_e \to \bar{\nu}_e$ $L \sim 10 - 100\,\text{m}$ $E \sim 4\,\text{MeV}$

Nominal $\approx 3.1\sigma$ deficit $\Delta m^2 \gtrsim 0.5\,\text{eV}^2$ $(\gg \Delta m^2_{\text{A}} \gg \Delta m^2_{\text{S}})$

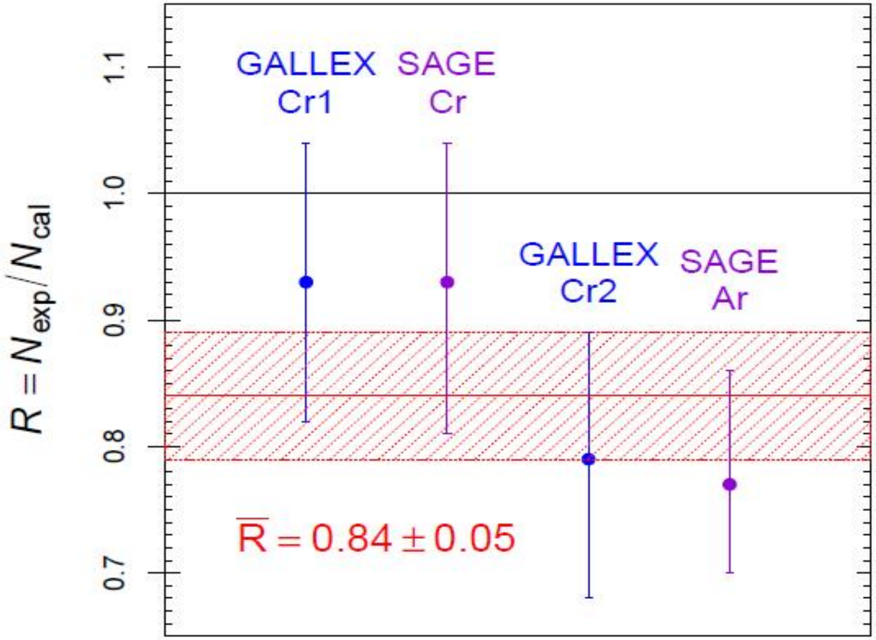
[see also: Sinev, arXiv:1103.2452; Ciuffoli, Evslin, Li, JHEP 12 (2012) 110; Zhang, Qian, Vogel, PRD 87 (2013) 073018; Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050; Ivanov et al, PRC 88 (2013) 055501]

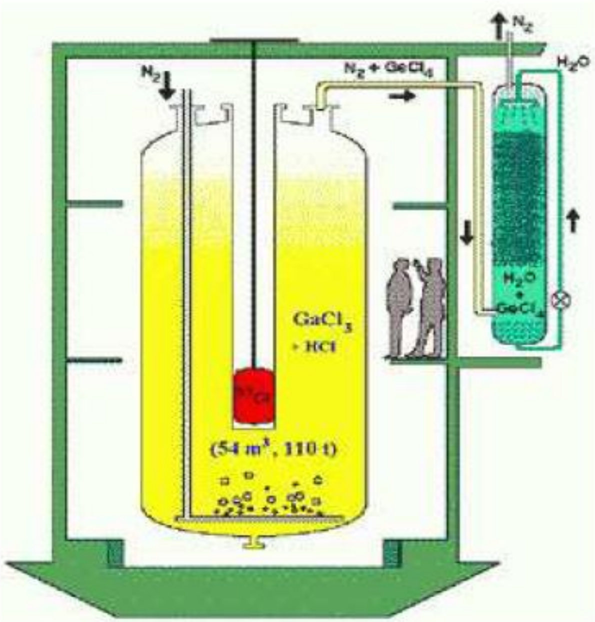
Gallium anomaly

Gallium Radioactive Source Experiments: GALLEX and SAGE

Detection Process: $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$

ν_e Sources: $e^- + {}^{51}\text{Cr} \to {}^{51}\text{V} + \nu_e$ $\quad e^- + {}^{37}\text{Ar} \to {}^{37}\text{Cl} + \nu_e$





$\langle L \rangle_{\text{GALLEX}} = 1.9\,\text{m}$ $\quad \langle L \rangle_{\text{SAGE}} = 0.6\,\text{m}$

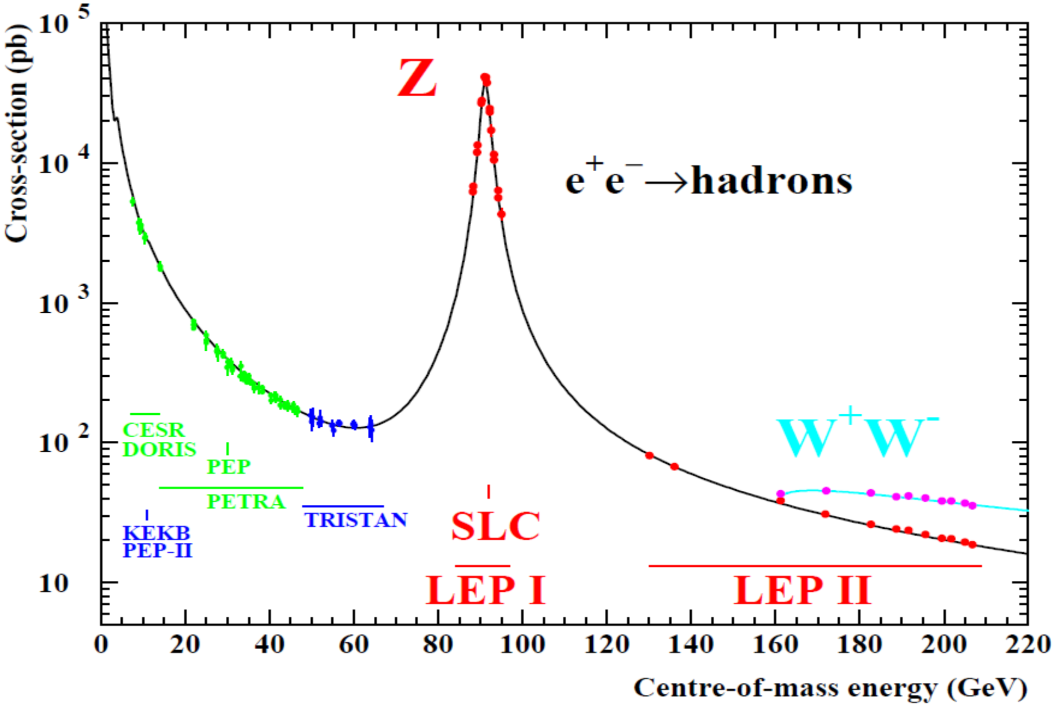
$\Delta m^2_{\text{SBL}} \gtrsim 1\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}}$

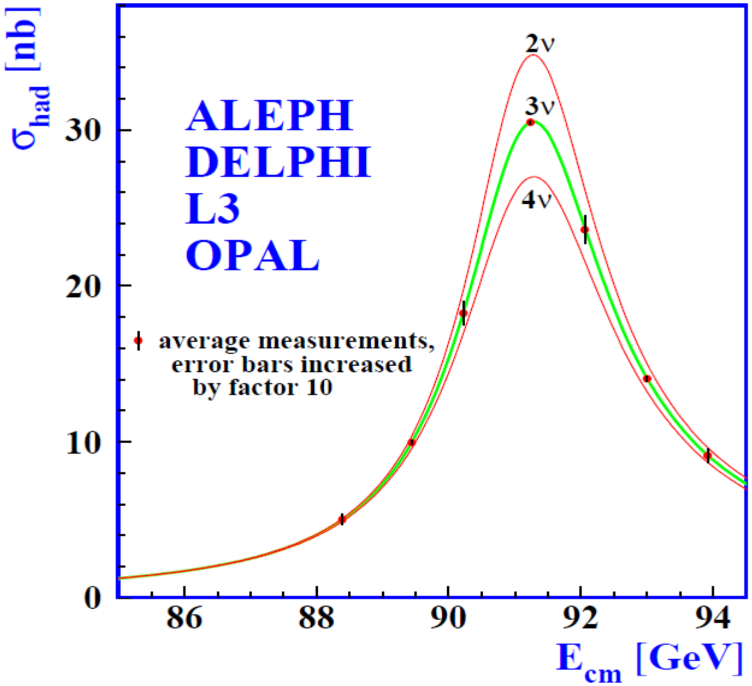
$\approx 2.9\sigma$ deficit

[SAGE, PRC 73 (2006) 045805; PRC 80 (2009) 015807]

[Laveder et al, Nucl.Phys.Proc.Suppl. 168 (2007) 344;
MPLA 22 (2007) 2499; PRD 78 (2008) 073009;
PRC 83 (2011) 065504]

Why sterile neutrinos?



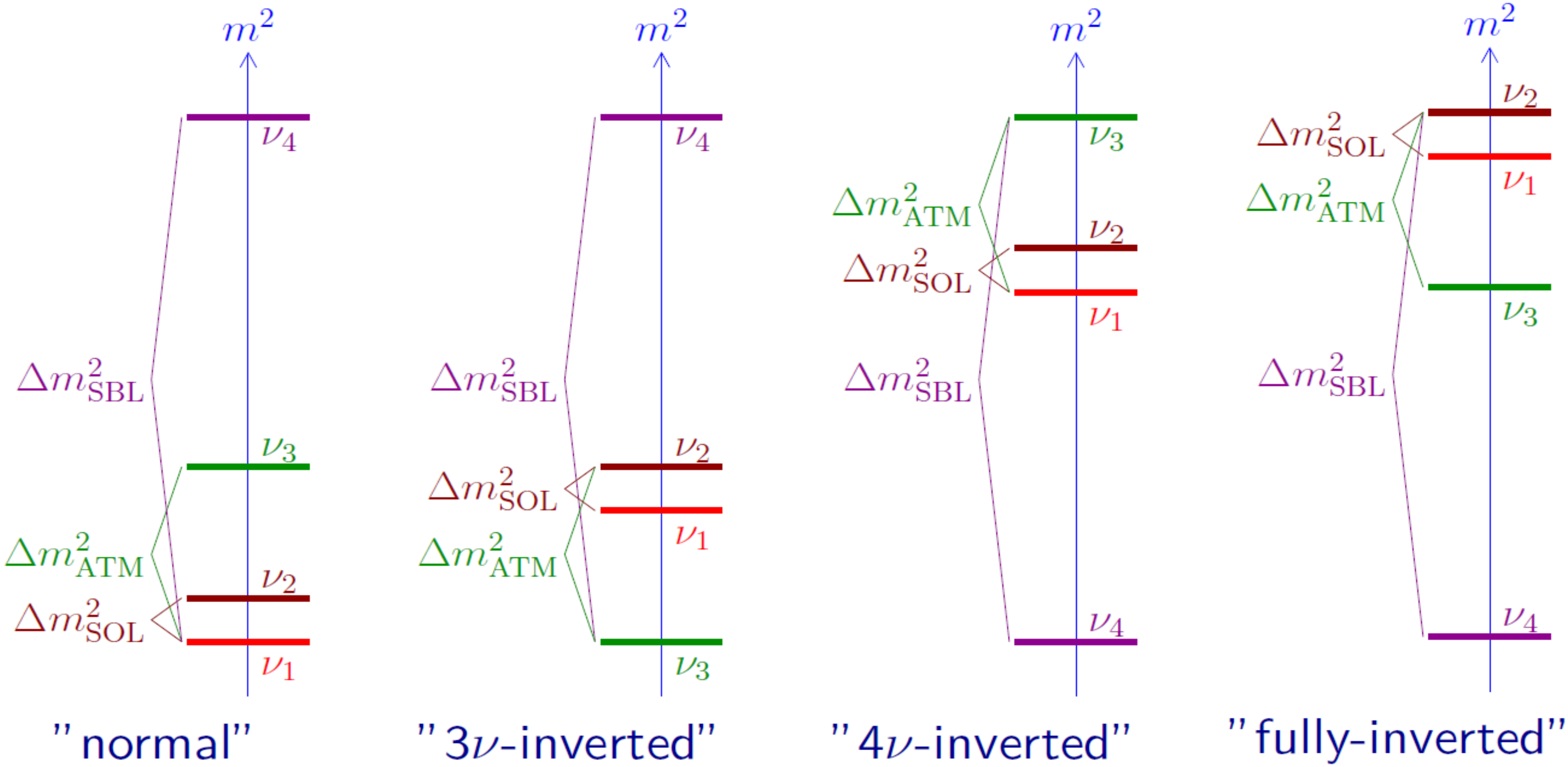


[LEP, Phys. Rept. 427 (2006) 257, arXiv:hep-ex/0509008]

$$\Gamma_Z = \sum_{\ell=e,\mu,\tau} \Gamma_{Z\to\ell\bar{\ell}} + \sum_{q\neq t} \Gamma_{Z\to q\bar{q}} + \Gamma_{\mathrm{inv}} \qquad \Gamma_{\mathrm{inv}} = N_\nu\, \Gamma_{Z\to\nu\bar{\nu}}$$

$$\boxed{N_\nu = 2.9840 \pm 0.0082}$$

3+1 schemes



Perturbation of 3-ν Mixing

$|U_{e4}|^2 \ll 1$ $|U_{\mu 4}|^2 \ll 1$ $|U_{\tau 4}|^2 \ll 1$ $|U_{s4}|^2 \simeq 1$

Effective SBL oscillations in 3+1 schemes

In SBL experiments $\Delta_{21} \ll \Delta_{31} \ll 1$.

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

- Amplitude of $\nu_\mu \to \nu_e$ transitions:

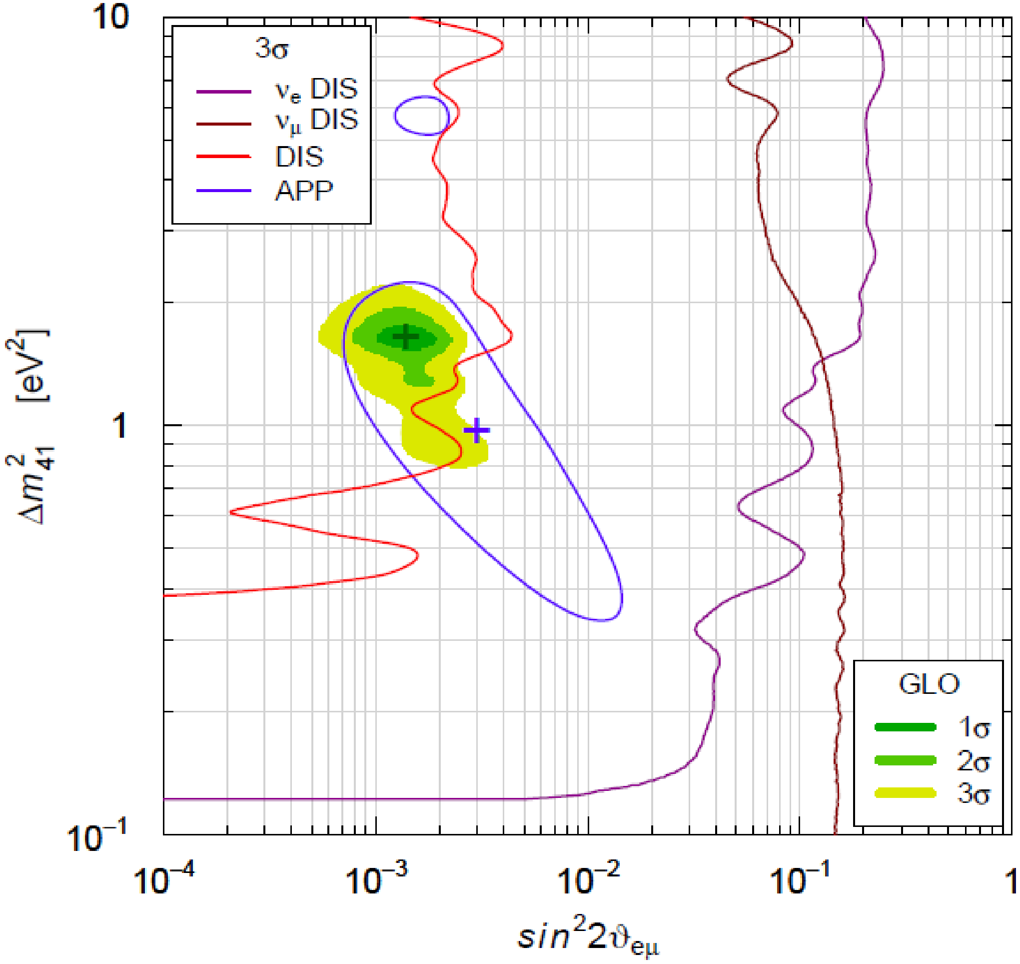
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2 |U_{\mu 4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

- Upper bounds on ν_e and ν_μ disappearance $\Rightarrow$ strong limit on $\nu_\mu \to \nu_e$

[Okada, Yasuda, IJMPA 12 (1997) 3669; Bilenky, Giunti, Grimus, EPJC 1 (1998) 247]

- Similar constraint in 3+2, 3+3, . . . , 3+N_s! [Giunti, Zavanin, MPLA 31 (2015) 1650003]

Global status of the 3+1 fit



MiniBooNE $E > 475$ MeV

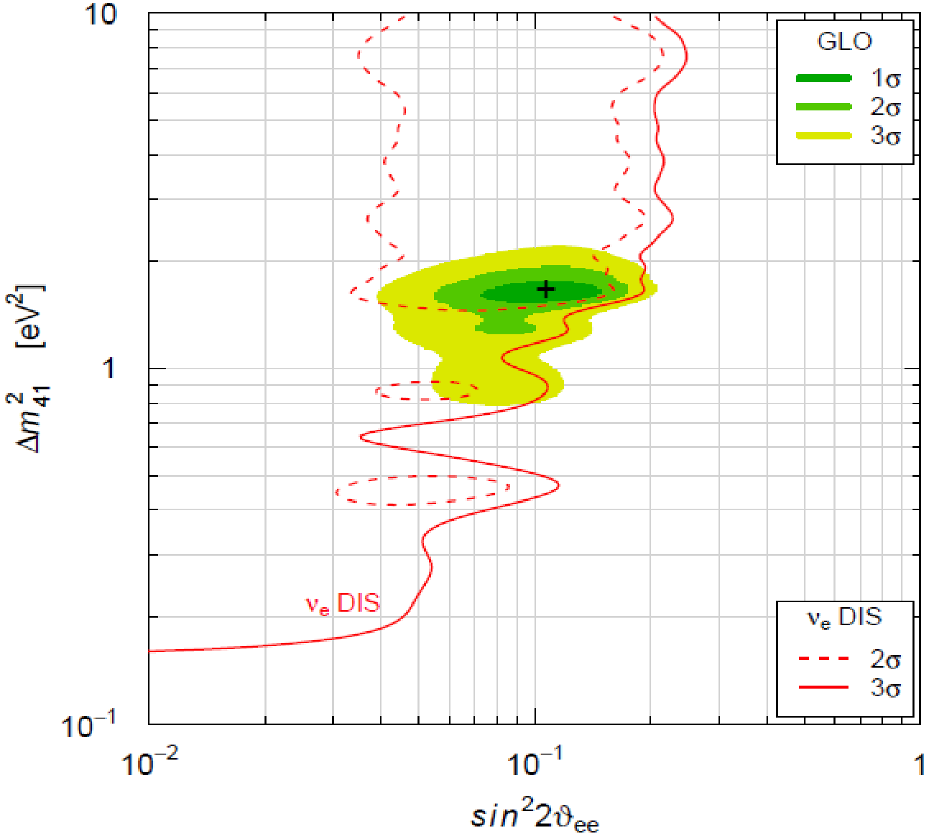
GoF = 26%   PGoF = 7%

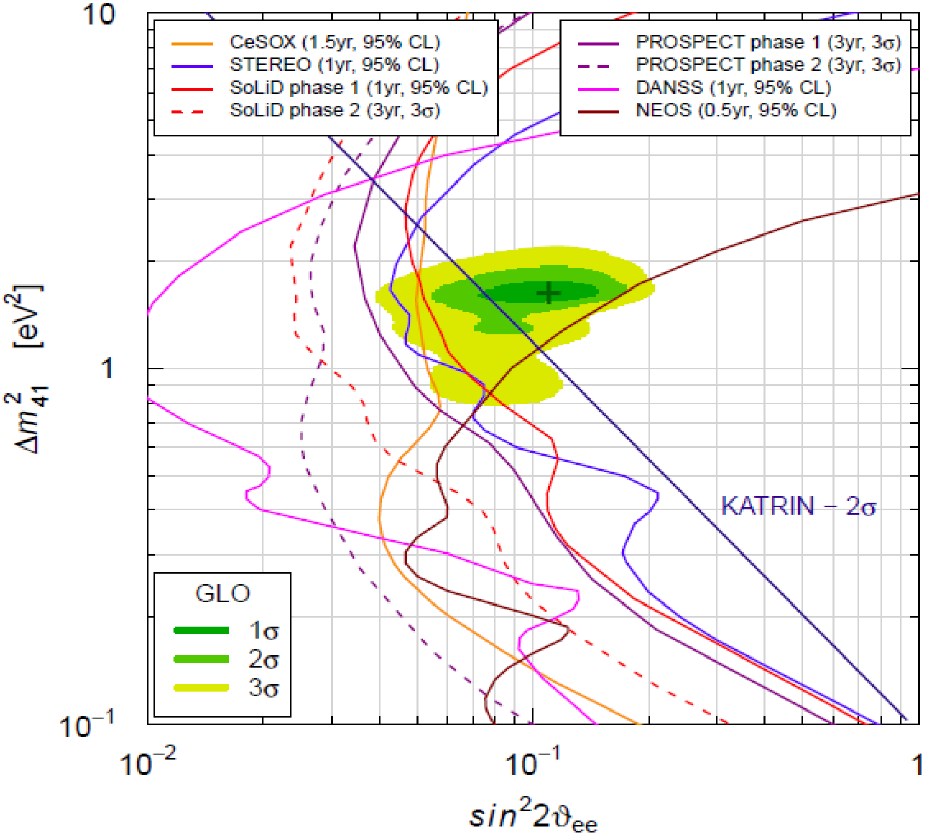
- APP $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$: LSND ($\nu_s$), MiniBooNE (?), OPERA ($\cancel{\nu_s}$), ICARUS ($\cancel{\nu_s}$), KARMEN ($\cancel{\nu_s}$), NOMAD ($\cancel{\nu_s}$), BNL-E776 ($\cancel{\nu_s}$)
- DIS ν_e & $\bar{\nu}_e$: Reactors (ν_s), Gallium (ν_s), ν_eC ($\cancel{\nu_s}$), Solar ($\cancel{\nu_s}$)
- DIS ν_μ & $\bar{\nu}_\mu$: CDHSW ($\cancel{\nu_s}$), MINOS ($\cancel{\nu_s}$), Atmospheric ($\cancel{\nu_s}$), MiniBooNE/SciBooNE ($\cancel{\nu_s}$)

No Osc. nominally disfavored at $\approx 6.3\sigma$

$\Delta\chi^2/\text{NDF} = 47.7/3$

Near future: νe disappearance

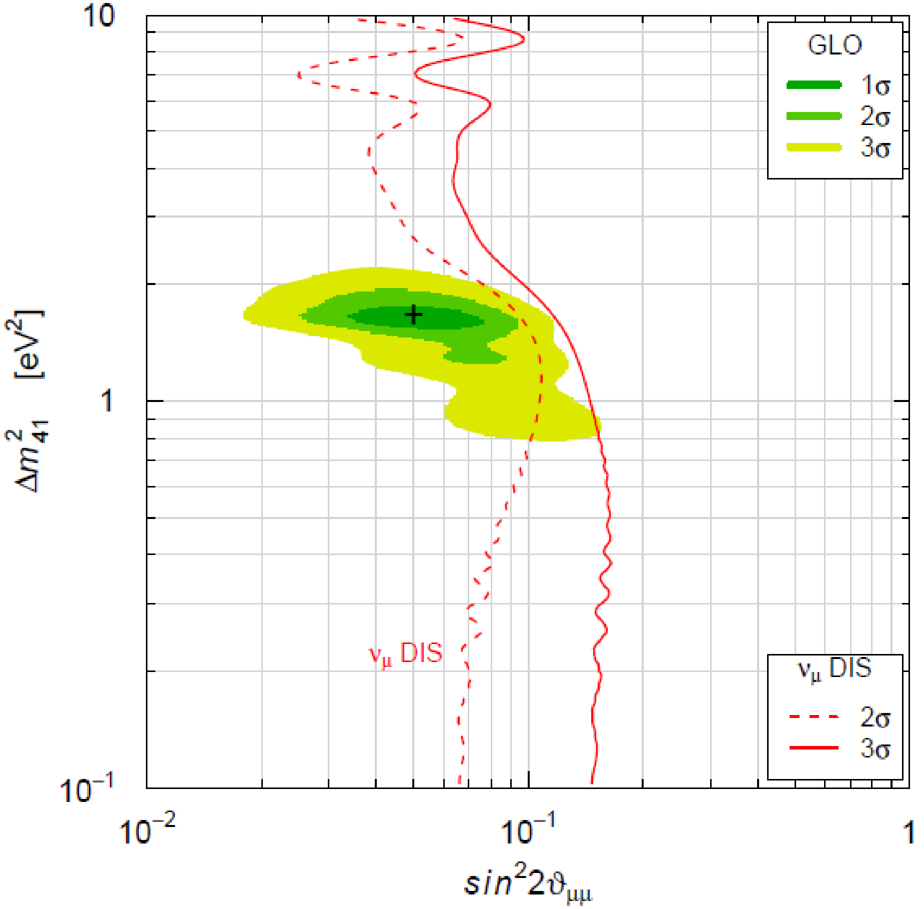




CeSOX (BOREXINO, Italy)
^{144}Ce — 100 kCi [Vivier@TAUP2015]
rate: 1% normalization uncertainty
8.5 m from detector center
KATRIN (Germany)
Tritium β decay [Mertens@TAUP2015]

STEREO (France) $L \simeq$ 8-12m [Sanchez@EPSHEP2015]
SoLid (Belgium) $L \simeq$ 5-8m [Yermia@TAUP2015]
PROSPECT (USA) $L \simeq$ 7-12m [Heeger@TAUP2015]
DANSS (Russia) $L \simeq$ 10-12m [arXiv:1412.0817]
NEOS (Korea) $L \simeq$ 25m [Oh@WIN2015]

Near future: νμ disappearance

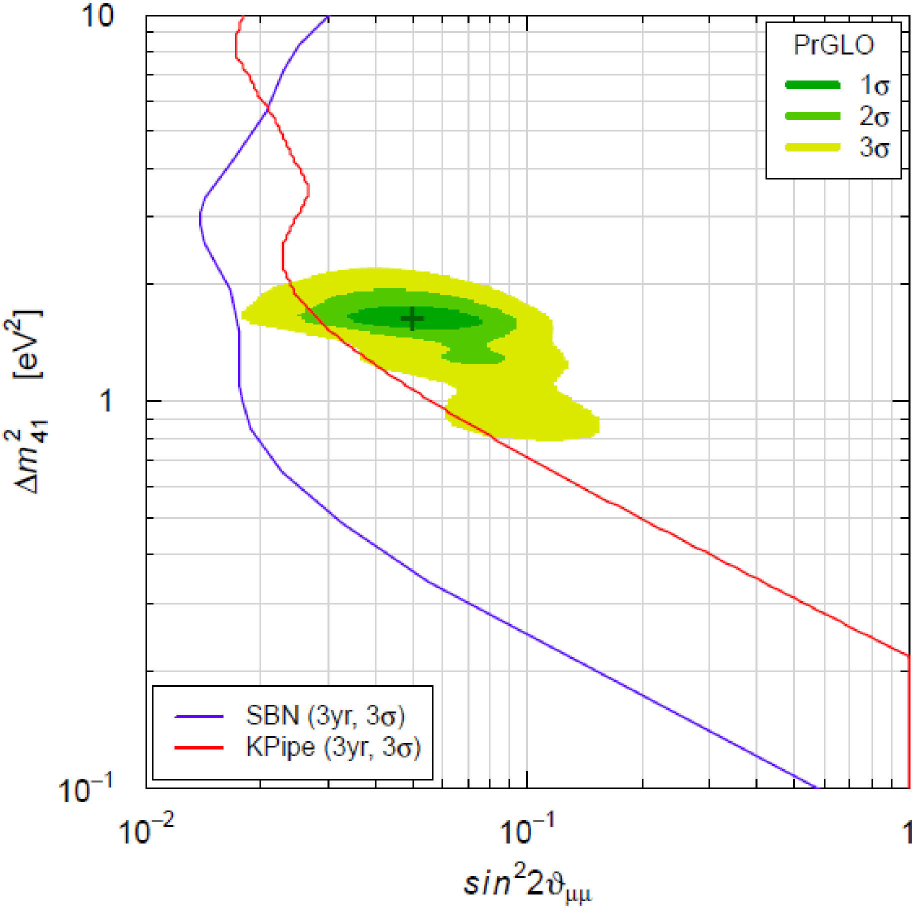


SBN (USA) [arXiv:1503.01520]

LAr1-ND $L \simeq 100$m

MicroBooNE $L \simeq 470$m

ICARUS T600 $L \simeq 600$m

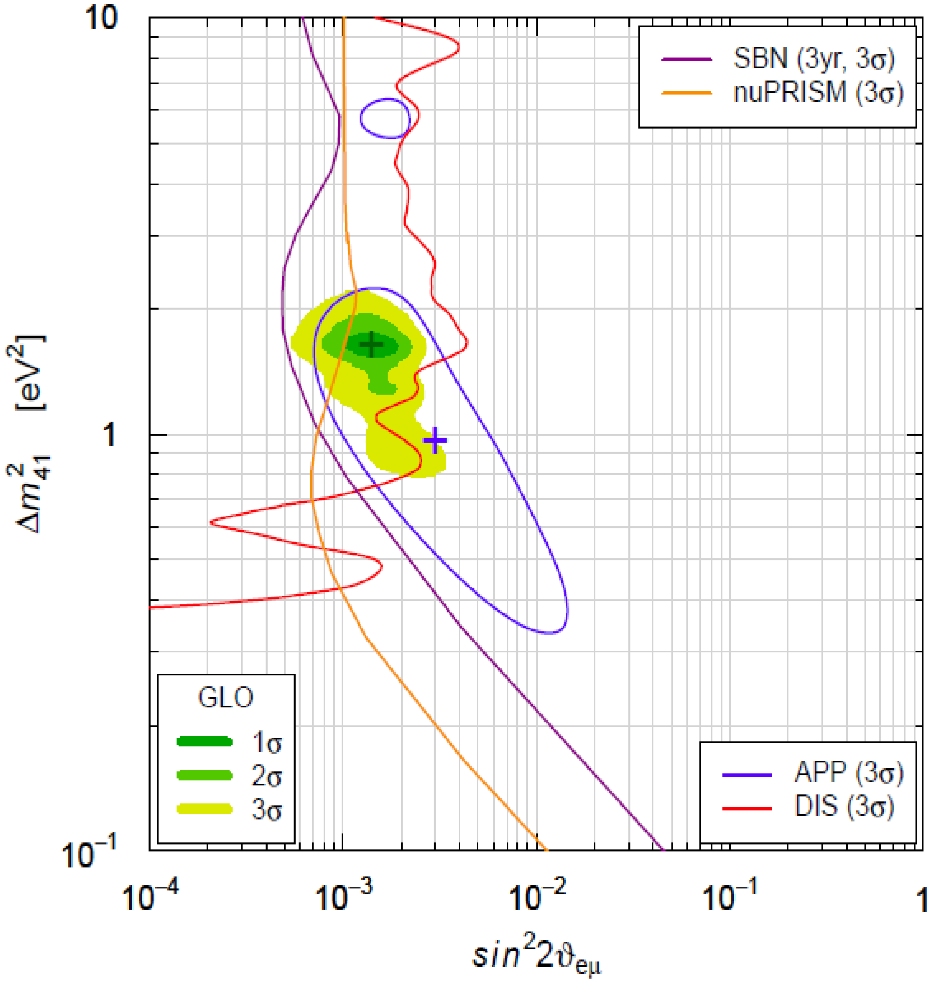


KPipe (Japan) [arXiv:1510.06994]

$L \simeq 30$-150m

120 m long detector!

Near future: νμ→νe appearance



SBN (FNAL, USA)

[arXiv:1503.01520]

3 Liquid Argon TPCs

LAr1-ND $L \simeq 100\,\text{m}$

MicroBooNE $L \simeq 470\,\text{m}$

ICARUS T600 $L \simeq 600\,\text{m}$

nuPRISM (J-PARC, Japan)

[Wilking@NNN2015]

$L \simeq 1\,\text{km}$

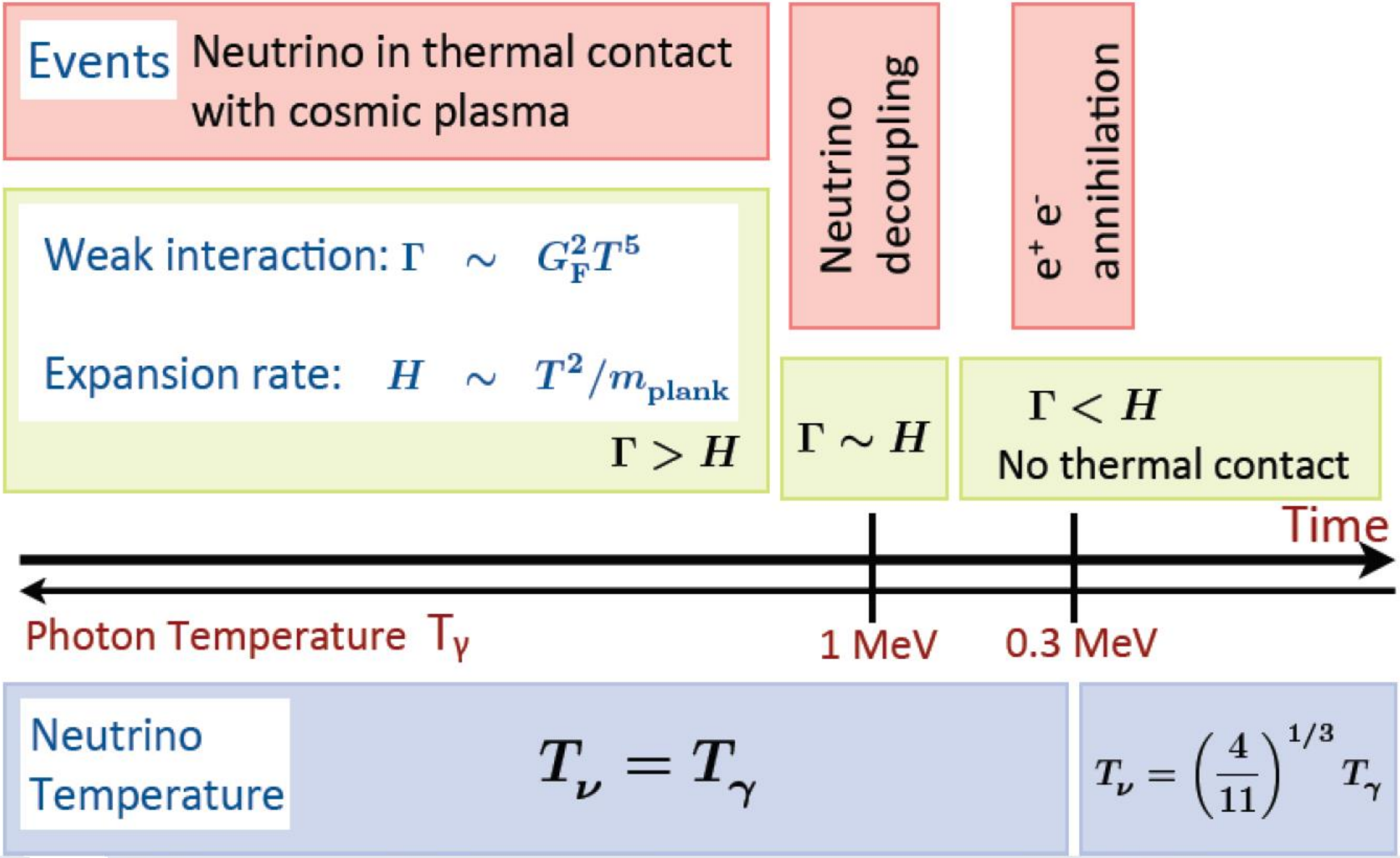
50 m tall water Cherenkov detector

1° – 4° off-axis

can be improved with T2K ND

eV Sterile neutrinos as the cosmic neutrino background

Cosmic neutrino background



Events Neutrino in thermal contact with cosmic plasma

Neutrino decoupling

$e^+ e^-$ annihilation

Weak interaction: $\Gamma \sim G_F^2 T^5$

Expansion rate: $H \sim T^2/m_{\text{plank}}$

$\Gamma > H$

$\Gamma \sim H$

$\Gamma < H$

No thermal contact

Time

Photon Temperature T_γ

1 MeV

0.3 MeV

Neutrino Temperature

$$T_\nu = T_\gamma$$

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma$$

Relativistic Neutrino: Effective Number $\mathrm{N}_{\mathrm{eff}}$

Radiation energy density ρ_r in the early Universe:

$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\mathrm{eff}}\right]\rho_\gamma = \left[1 + 0.2271 N_{\mathrm{eff}}\right]\rho_\gamma$$

ρ_γ photon energy density, 7/8 is for fermions, $(4/11)^{4/3}$ due to photon reheating after neutrino decoupling

- $N_{\mathrm{eff}} \rightarrow$ all the radiation contribution not given by photons
- $N_{\mathrm{eff}} \simeq 1$ correspond to a single family of active neutrino, in equilibrium in the early Universe
- Active neutrinos: $N_{\mathrm{eff}} = 3.046$ [Mangano et al., 2005] due to not instantaneous decoupling for the neutrinos
- additional LSν contributes with $\Delta N_{\mathrm{eff}} = N_{\mathrm{eff}} - 3.046$:

$$\Delta N_{\mathrm{eff}} = \frac{\rho_s^{\mathrm{rel}}}{\rho_\nu} = \left[\frac{7}{8}\frac{\pi^2}{15}{T_\nu}^4\right]^{-1} \frac{1}{\pi^2}\int dp\, p^3 f_s(p)$$

[Acero et al., 2009]

ρ_ν energy density for one active neutrino species, ρ_s^{rel} energy density of LSν when relativistic, p neutrino momentum, $f_s(p)$ momentum distribution, $T_\nu = (4/11)^{1/3}\, T_\gamma$

Non-Relativistic Neutrino: Effective Mass m_{eff}

$m_s \simeq 1$ eV $\to \nu_s$ is non-relativistic today ($T_\nu \propto 10^{-4}$ eV)

LSν density parameter today:

$$\omega_s = \Omega_s h^2 = \frac{\rho_s}{\rho_c} h^2 = \frac{h^2}{\rho_c} \frac{m_s}{\pi^2} \int dp\, p^2 f_s(p)$$

[Acero et al., 2009]

ρ_s energy density of non-relativistic LSν, ρ_c critical density and h reduced Hubble parameter

Alternatively:

$$m_s^{\mathrm{eff}} = 94.1\,\mathrm{eV}\,\omega_s$$

[Planck 2013 Results, XVI]

The factor ($94.1\,\mathrm{eV}$) is the same for the active neutrinos:

$$\omega_{\nu,\text{active}} = \sum_{\text{active}} m_\nu / (94.1\,\mathrm{eV})$$

If $f_s(p) = f_{\mathrm{active}}(p)$, $m_s^{\mathrm{eff}} \equiv m_s$

Momentum distribution

$\Delta N_{\rm eff}$, $m_s^{\rm eff}$ depend on the momentum distribution function $f_s(p)$.

LSν relativistic at decoupling $\Rightarrow$ $f_s(p)$ independent of m_s.
Active neutrinos decoupled at $T_\nu \simeq 1$ MeV. Is the same for LSν?

Oscillations + sterile $\Rightarrow$ LSν decouples not later than active neutrinos.

Production mechanism?

Thermal production (TH):
temperature $T_s = \alpha\, T_\nu$

$$f_s(p) = \frac{1}{e^{p/T_s} + 1}$$

$$\Downarrow$$

$$\Delta N_{\rm eff} = \alpha^4$$

$$\omega_s = \alpha^3\, m_s/(94.1\,{\rm eV})$$

$$\Downarrow$$

$$m_s^{\rm eff} = \alpha^3 m_s = \Delta N_{\rm eff}^{3/4} m_s$$

Non-thermal production:
[Dodelson, Widrow 1993] (DW) model

$$f_s(p) = \frac{\beta}{e^{p/T_\nu} + 1}$$

$$\Downarrow$$

$$\Delta N_{\rm eff} = \beta$$

$$\omega_s = \beta\, m_s/(94.1\,{\rm eV})$$

$$\Downarrow$$

$$m_s^{\rm eff} = \beta m_s = \Delta N_{\rm eff}\, m_s$$

Additional radiation

$\rho_r = [1 + 0.2271 N_{\text{eff}}]\, \rho_\gamma$

$H^2 = 8\pi G \rho_T / 3$

N_{eff} controls the expansion rate H in the early Universe, during radiation dominated phase

influence on

Big Bang Nucleosynthesis: production of light nuclei

matter-radiation equality

expansion rate at CMB decoupling

CMB+BBN+^4He, D abundances:

$\Delta N_{\text{eff}} \lesssim 0.2$ at 95% CL
[Cyburt et al., 2015]

Free-streaming(1)

Massive neutrino

$\Downarrow$

damping in the perturbations due to free-streaming length λ_{FS}

Relativistic neutrinos

- velocity $v_s \simeq c$
- $\boxed{\lambda_{FS}/a \propto (aH)^{-1} \propto t^{1/3} \text{ (MD)}}$

Non-relativistic neutrinos

- $\langle v_s \rangle = \dfrac{\int p^2 dp\, f(p)\, p/m_s}{\int p^2 dp\, f(p)} \propto \dfrac{\Delta N_{\rm eff}}{\omega_s}$
- $\boxed{\lambda_{FS}/a \propto (a^2H)^{-1} \propto t^{-1/3} \text{ (MD)}}$

$\Rightarrow$ Maximum λ_{FS}/a at the time of non-relativistic transition.

$\Downarrow$

Corresponds to $k_{\rm nr} \simeq 0.0178\, \Omega_m^{1/2} \left(\dfrac{T_\nu}{T_s}\right)^{1/2} \left(\dfrac{m_s}{1\,\mathrm{eV}}\right)^{1/2} h\,\mathrm{Mpc}^{-1}$

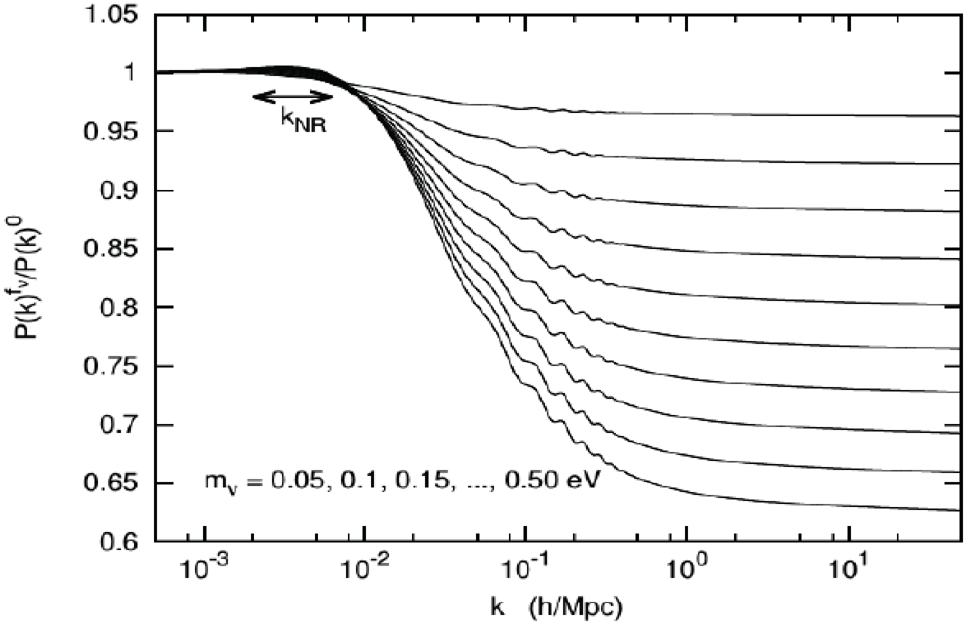
Free-streaming(2)

Damping occurs for all $k \gtrsim k_{\rm nr}$

Plot: $\dfrac{P_{m_\nu>0}(k)}{P_{m_\nu=0}(k)}$

- top to bottom: $m_\nu = 0.05$ eV to $m_\nu = 0.5$ eV
- $\Delta P/P \simeq -7(8)(m_\nu/1\ \mathrm{eV})$

[Neutrino Cosmology, Lesgourgues et al.]
(fixed h, ω_m, ω_b, ω_Λ)



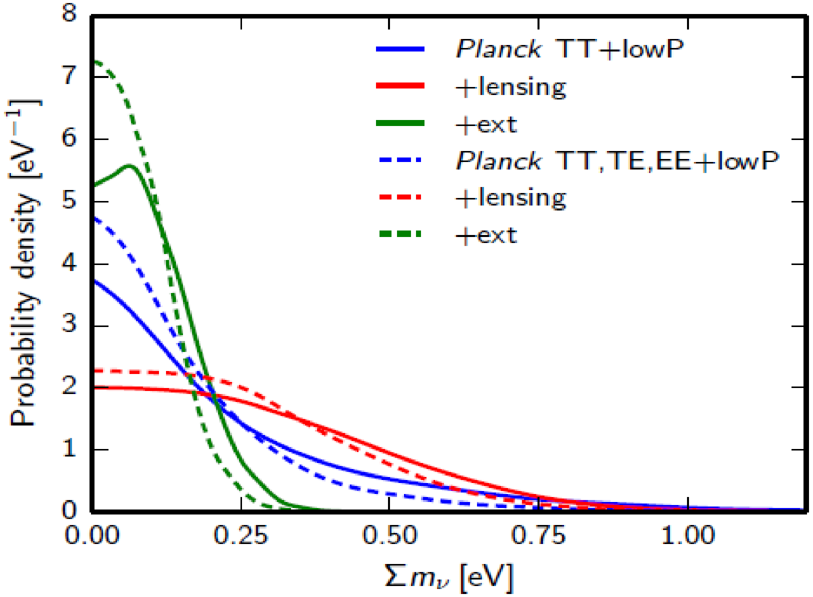
Expected constraints from future surveys:

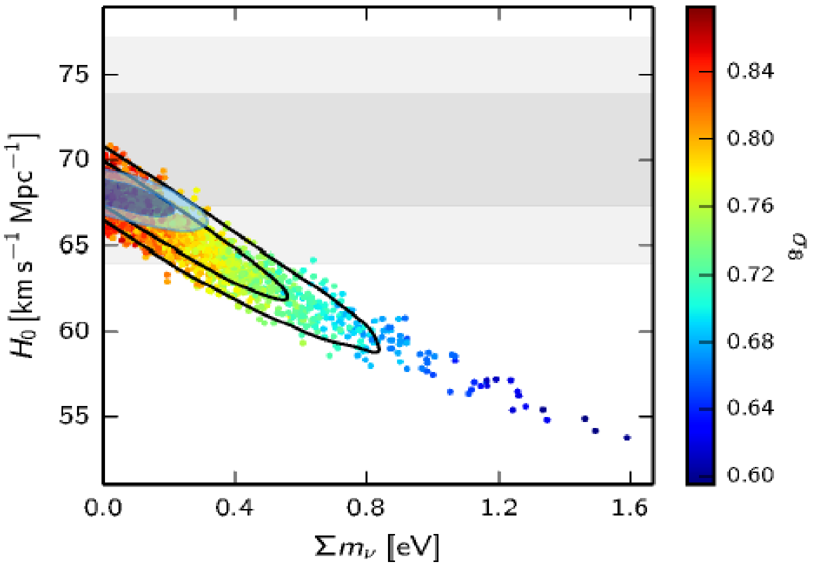
- Planck CMB + DES: $\sigma(m_\nu) \simeq 0.04$–$0.06$ eV [Font-Ribera et al., 2014]
- Planck CMB + Euclid: $\sigma(m_\nu) \simeq 0.03$ eV [Audren et al., 2013]

Limits on the three neutrino framework

[Planck, arXiv:1502.01589]

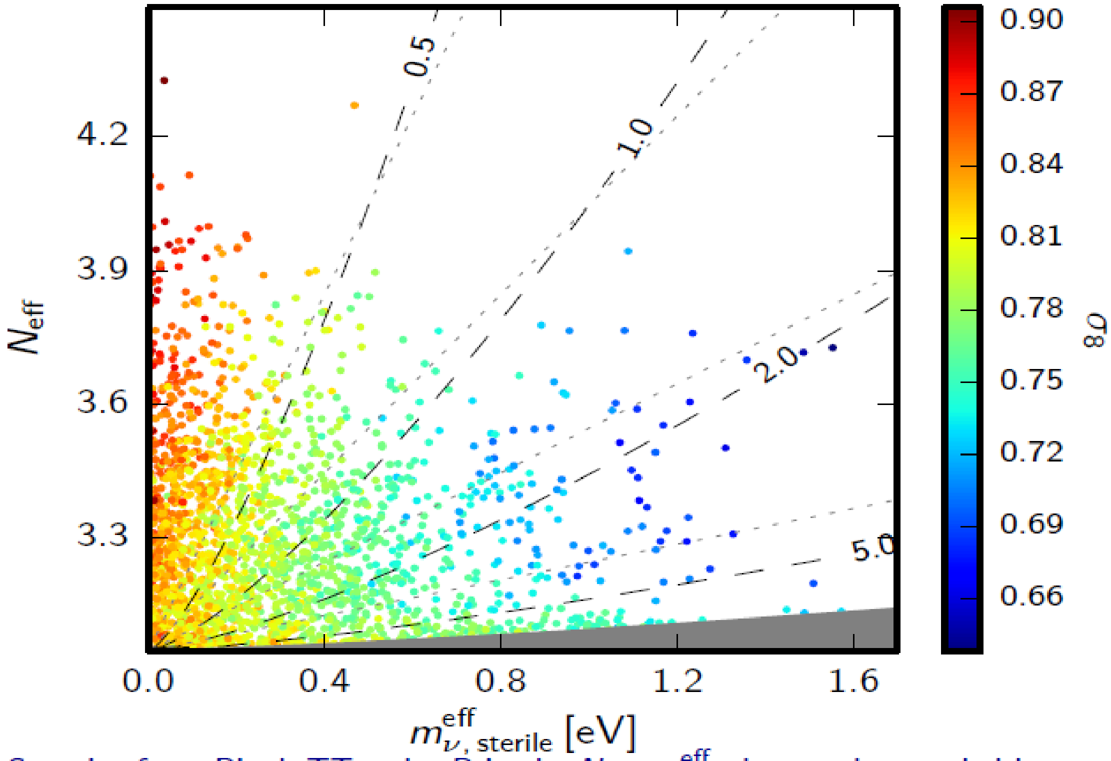
Cosmological data set	Σ (at 95% C.L.)
Plank TT + lowP	< 0.72 eV
Plank TT + lowP + BAO	< 0.21 eV
Plank TT,TE,EE + lowP	< 0.49 eV
Plank TT,TE,EE + lowP + BAO	< 0.17 eV
Plank TT + lowP + lensing	< 0.68 eV
Plank TT,TE,EE + lowP + lensing	< 0.59 eV
Plank TT + lowP + lensing + BAO + H_0	< 0.23 eV





Limits on Massive Sterile Neutrinos

$N_{\rm eff} < 3.7$ $m_s^{\rm eff} < 0.52$ (95%; Plank TT + lowP + lensing + BAO)



Samples from Plank TT + lowP in the $N_{\rm eff}$–$m_s^{\rm eff}$ plane, colour-coded by σ_8, in models with one massive sterile neutrino family, with effective mass $m_s^{\rm eff}$, and the three active neutrinos as in the base ΛCDM model. The physical mass of the sterile neutrino in the thermal scenario, $m_s^{\rm thermal}$, is constant along the grey dashed lines, with the indicated mass in eV; the grey region shows the region excluded by our prior $m_s^{\rm thermal} < 10\,\mathrm{eV}$, which excludes most of the area where the neutrinos behave nearly like dark matter. The physical mass in the Dodelson-Widrow scenario, $m_s^{\rm DW}$, is constant along the dotted lines (with the value indicated on the adjacent dashed lines).

[arXiv:1502.01589]

- $m_s^{\rm eff} \equiv 94.1\Omega_s h^2\ \mathrm{eV}$
- Thermally distributed:

$$f_s(E) = \frac{1}{e^{E/T_s}+1}$$

$$m_s^{\rm eff} = \left(\frac{T_s}{T_\nu}\right)^3 m_4 = (\Delta N_{\rm eff})^{3/4} m_4$$

- Dodelson-Widrow:

$$f_s(E) = \frac{\chi}{e^{E/T_\nu}+1}$$

$$m_s^{\rm eff} = \chi_s m_4$$

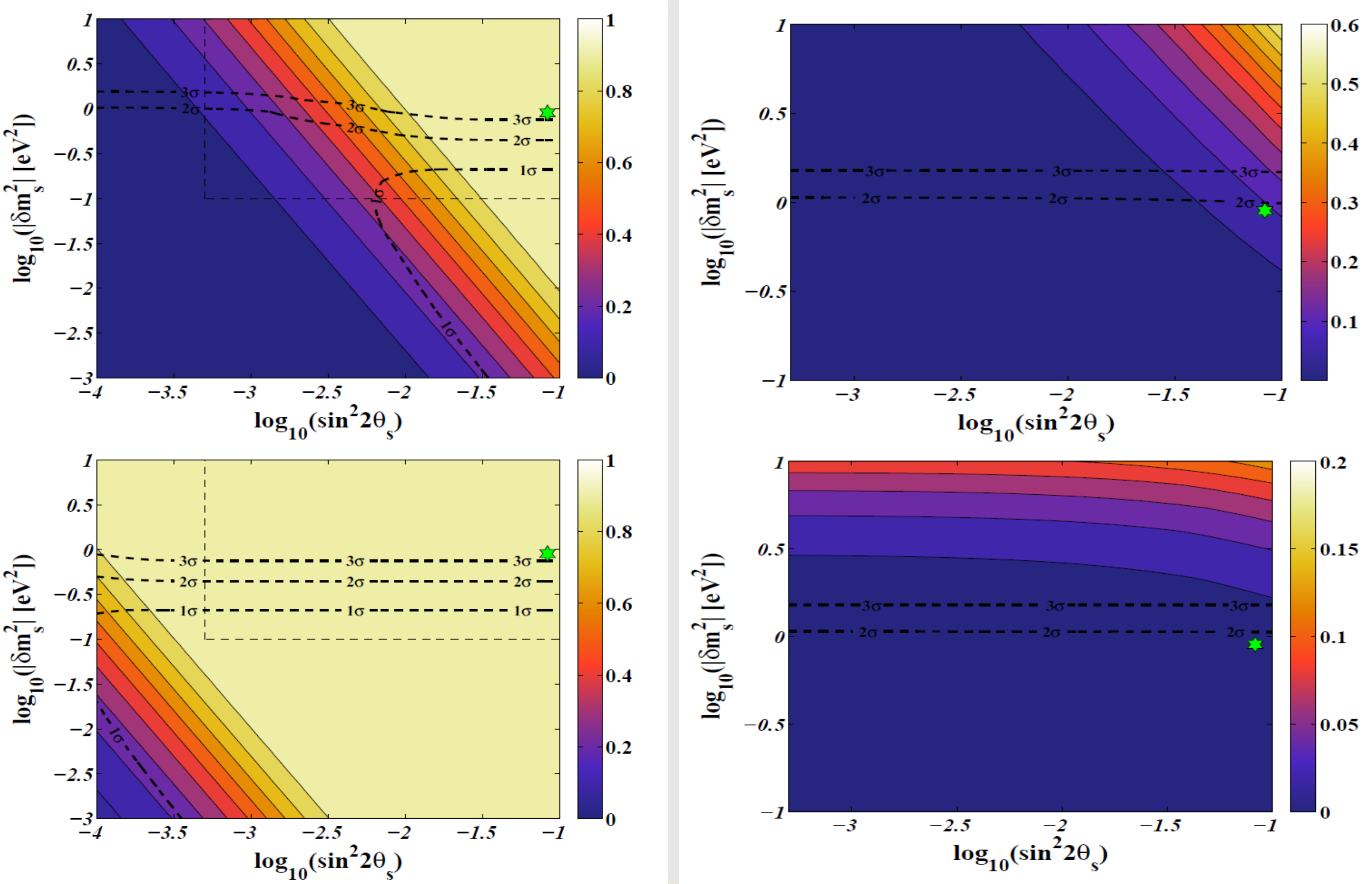
Tension between ΔN_{eff} = 1 and ms ≈ 1 eV

Sterile neutrinos are thermalized ($\Delta N_{\text{eff}} = 1$) by active-sterile oscillations before neutrino decoupling [Dolgov, Villante, NPB 679 (2004) 261]

Proposed mechanisms to avoid the tension:

- Large lepton asymmetry [Hannestad, Tamborra, Tram, JCAP 1207 (2012) 025; Mirizzi, Saviano, Miele, Serpico, PRD 86 (2012) 053009; Saviano et al., PRD 87 (2013) 073006; Hannestad, Hansen, Tram, JCAP 1304 (2013) 032]
- Enhanced background potential due to interactions in the sterile sector [Hannestad, Hansen, Tram, PRL 112 (2014) 031802; Dasgupta, Kopp, PRL 112 (2014) 031803; Bringmann, Hasenkamp, Kersten, JCAP 1407 (2014) 042; Ko, Tang, PLB 739 (2014) 62; Archidiacono, Hannestad, Hansen, Tram, PRD 91 (2015) 065021; Mirizzi, Mangano, Pisanti, Saviano, PRD 90 (2014) 113009, PRD 91 (2015) 025019; Tang, arXiv:1501.00059]
- A larger cosmic expansion rate at the time of sterile neutrino production [Rehagen, Gelmini JCAP 1406 (2014) 044]
- MeV dark matter annihilation [Ho, Scherrer, PRD 87 (2013) 065016]
- Invisible decay [Gariazzo, Giunti, Laveder, arXiv:1404.6160]
- Free primordial power spectrum of scalar fluctuations (Inflationary Freedom) [Gariazzo, Giunti, Laveder, JCAP 1504 (2015) 023]

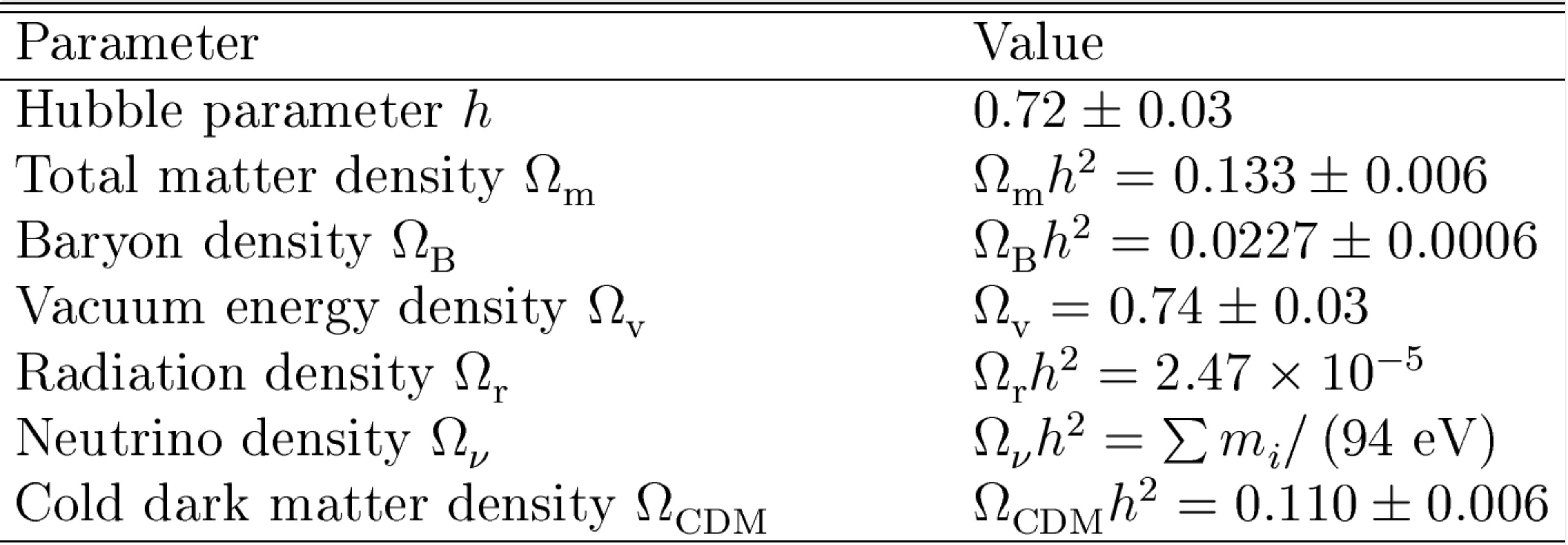
Large lepton asymmetry (0 vs. 10^{-2}) 1204.5861



keV Sterile neutrinos as Warm Dark Matter

How dark is the matter ?

All observations at the galactic, galaxy cluster, and cosmological scales show the existence of Dark matter.
Today's matter & energy densities in the Universe:



Parameter	Value
Hubble parameter h	0.72 ± 0.03
Total matter density $\Omega_{\rm m}$	$\Omega_{\rm m} h^2 = 0.133 \pm 0.006$
Baryon density $\Omega_{\rm B}$	$\Omega_{\rm B} h^2 = 0.0227 \pm 0.0006$
Vacuum energy density $\Omega_{\rm v}$	$\Omega_{\rm v} = 0.74 \pm 0.03$
Radiation density $\Omega_{\rm r}$	$\Omega_{\rm r} h^2 = 2.47 \times 10^{-5}$
Neutrino density Ω_ν	$\Omega_\nu h^2 = \sum m_i / \left(94 \text{ eV}\right)$
Cold dark matter density $\Omega_{\rm CDM}$	$\Omega_{\rm CDM} h^2 = 0.110 \pm 0.006$

Hot dark matter: CvB is guaranteed but not significant.
Cold dark matter: most likely? At present most popular.
Warm dark matter: suppress the small-scale structures.

keV sterile neutrino as Warm DM

Compared to Cold DM, warm DM can suppress the formation of small-scale structures.

Sterile neutrinos at the keV scale are excellent candidate of warm DM. (A white paper: 1602.04816)

(1) Lifetime (the Universe's age ~ 10^{17} s)

$$\tau_{\nu_4} \simeq \frac{2.88 \times 10^{27}}{C_\nu} \left(\frac{m_4}{1\ \mathrm{keV}}\right)^{-5} \left(\frac{s_{14}^2 + s_{24}^2 + s_{34}^2}{10^{-8}}\right)^{-1} \mathrm{s}$$

(2) Number density:

$$\rho_{\mathrm{DM}}^{\mathrm{local}} \simeq 0.3\ \mathrm{GeV\ cm}^{-3}$$

$$n_{\nu_4} \simeq 10^5\ (3\ \mathrm{keV}/m_4)\ \mathrm{cm}^{-3}$$

(3) Production:

Active-Sterile Oscillations in the early universe (non-resonant or resonant);

Decays of neutral scalars; etc.

X-ray observation

(1) Radiative decay:

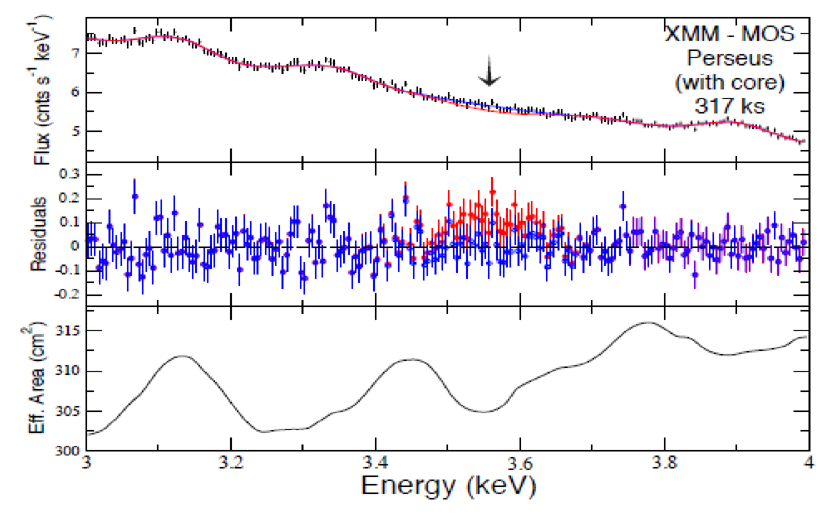
$$\sum_{i=1}^{3}\Gamma(\nu_4\to\nu_i+\gamma)\simeq\frac{9\alpha_{\rm em}C_\nu G_{\rm F}^2m_4^5}{512\pi^4}\sum_{i=1}^{3}\left|\sum_{\alpha=e}^{\tau}V_{\alpha 4}V_{\alpha i}^*\right|^2$$
$$=\frac{9\alpha_{\rm em}C_\nu G_{\rm F}^2m_4^5}{512\pi^4}\sum_{i=1}^{3}|V_{s4}V_{si}^*|^2$$
$$\simeq\frac{9\alpha_{\rm em}C_\nu G_{\rm F}^2m_4^5}{512\pi^4}\left(s_{14}^2+s_{24}^2+s_{34}^2\right)$$

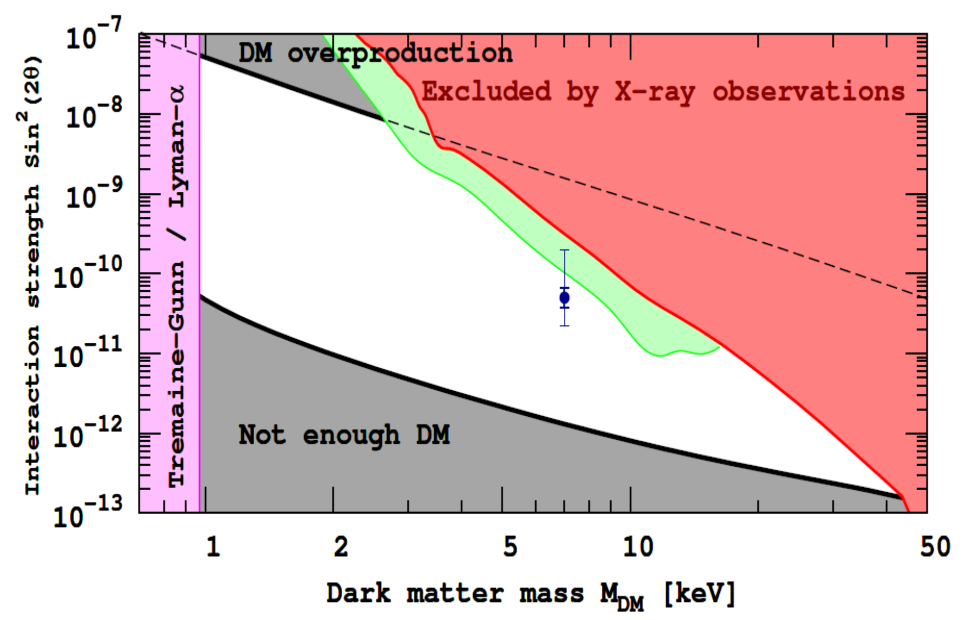
(2) Bound on the parameter space (Abazajian *et al*, 2007)

(3) Recent indications (1402.2301, 1402.4119)

XMM-Newton and Chandra observatory

X-ray line at ~3.5 keV (m_4 ~ 7.0 keV)

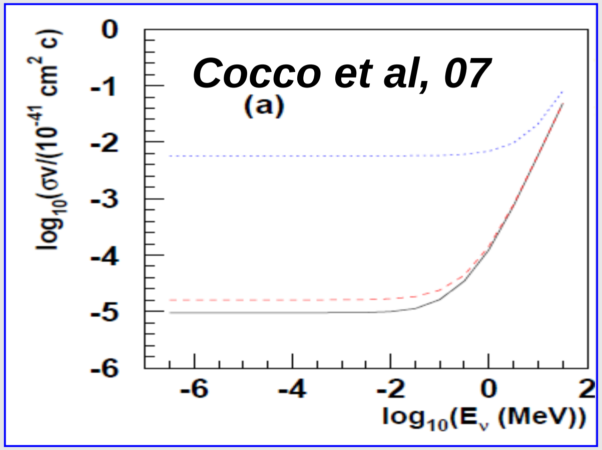




Direct detection method

Beta-decaying nuclei: targets of low energy neutrinos

(*Weinberg, 62, Irvine & Humphs, 83*)

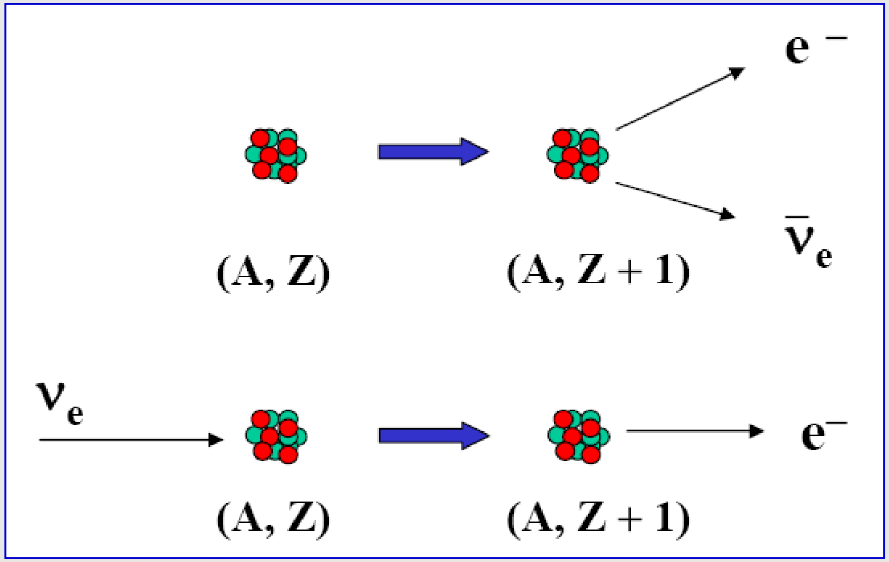


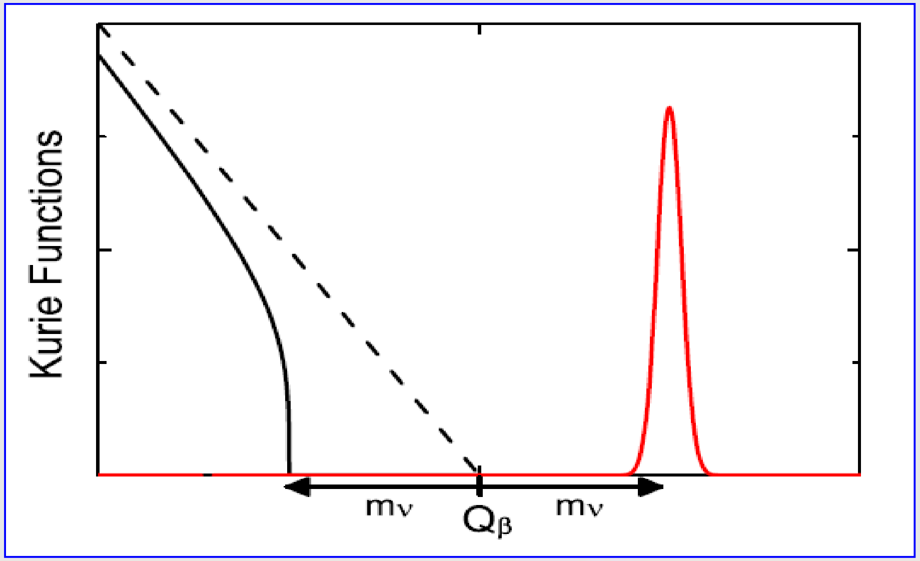
(1) no energy threshold on incident neutrinos

(2) mono-energetic outgoing electrons

(3) application to the keV neutrino detection

(Liao 10; Li & Xing 10, 11)

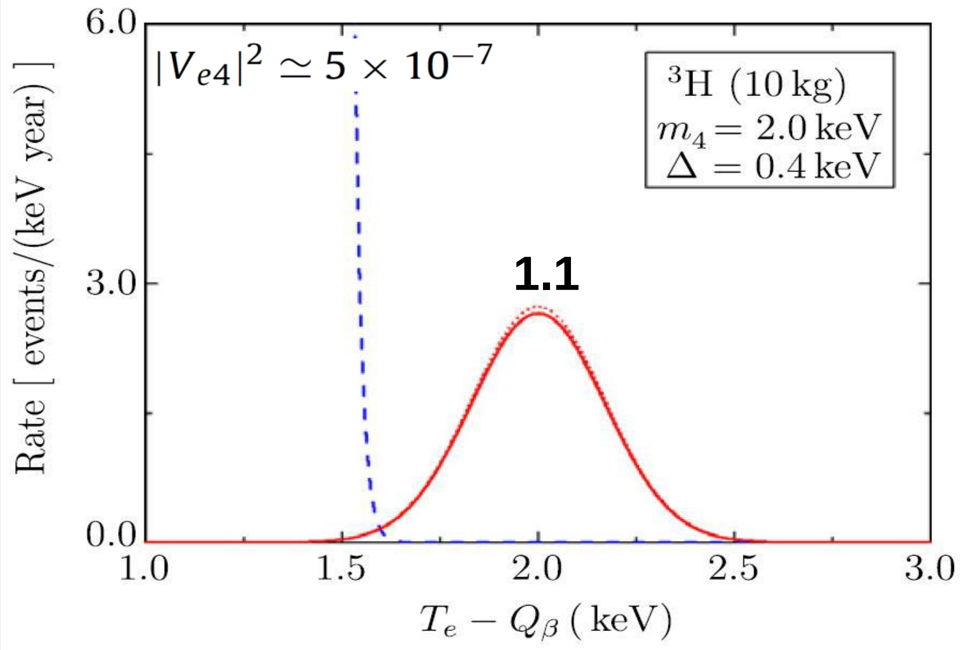




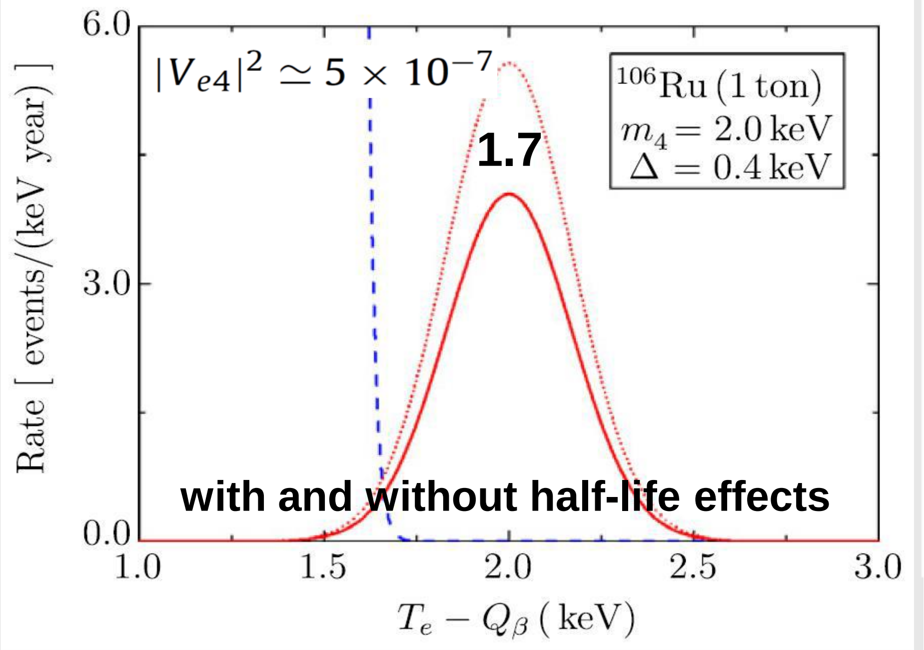
Capture on beta-decaying nuclei

Candidate nuclei: *(Liao 10; Li & Xing 10, 11)*

$$
\begin{aligned}
{}^{3}\mathrm{H} &: \quad Q_\beta = 18.6\ \mathrm{keV}\,, \quad t_{1/2} = 3.888\times 10^{8}\ \mathrm{s}\,, \quad \sigma_{\nu_i} v_{\nu_i}/c = 7.84\times 10^{-45}\ \mathrm{cm}^2 \\
{}^{106}\mathrm{Ru} &: \quad Q_\beta = 39.4\ \mathrm{keV}\,, \quad t_{1/2} = 3.228\times 10^{7}\ \mathrm{s}\,, \quad \sigma_{\nu_i} v_{\nu_i}/c = 5.88\times 10^{-45}\ \mathrm{cm}^2
\end{aligned}
$$



1.1



1.7

with and without half-life effects

tiny active-sterile neutrino mixing angles (main problem)

background from solar neutrinos and ES scattering. (Liao, 13)

Summary and Outlook

(1) Understanding intrinsic properties of neutrinos

Most of oscillation phenomena support the standard three neutrino framework.

New experiments designed for mass ordering and CP violation.

Problem: short baseline oscillations need light sterile neutrinos, future experiments are mandatory to test these anomalies.

(2) Cosmological roles of light sterile neutrinos

eV scale sterile neutrinos contribute to the cosmic neutrino background, but their thermal history could be different.

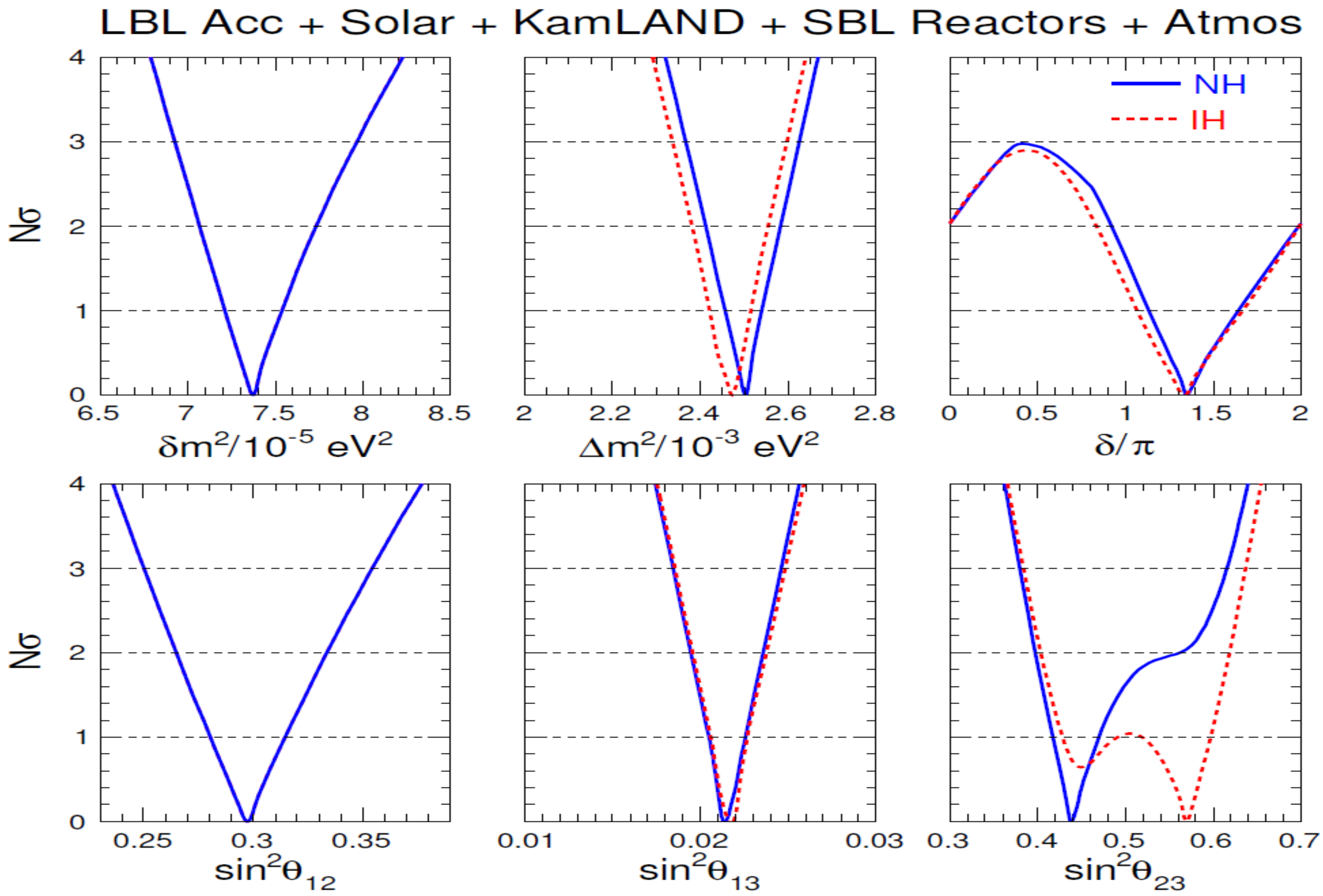
Tension between $\Delta N_{eff} = 1$ and ms ≈ 1 eV

keV scale sterile neutrinos are excellent candidates of warm dark matter. Promising prospects in X-ray observation and captures of beta-decaying nuclei.

Thank you

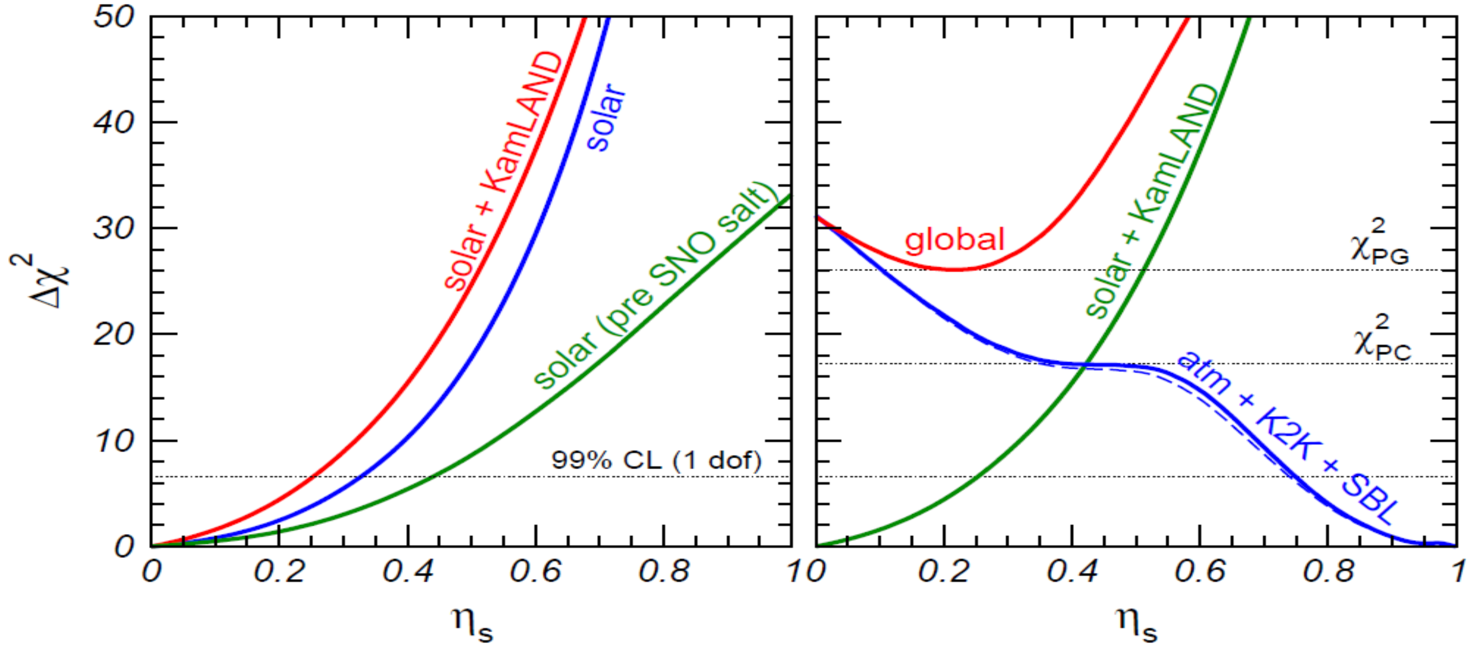
Backup

Status of 3-ν oscillations



[Capozzi, Lisi, Marrone, Montanino, Palazzo, arXiv:1601.07777]

2+2 schemes are disfavored



matter effects + SNO NC matter effects

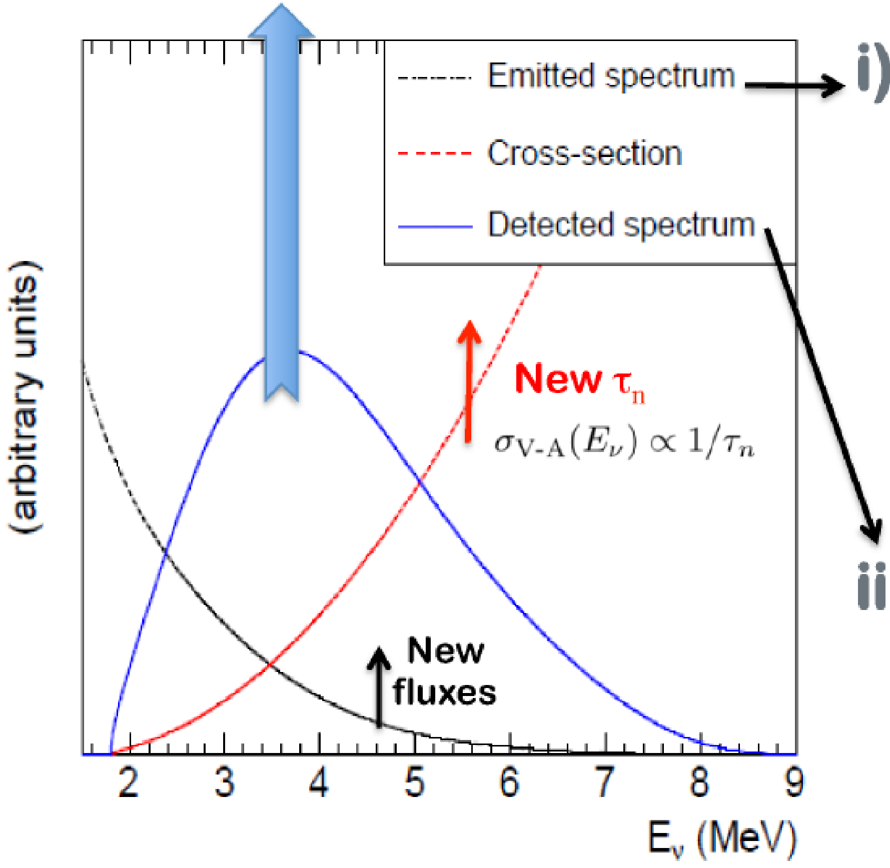
$$\eta_s = |U_{s1}|^2 + |U_{s2}|^2$$
$$1 - \eta_s = |U_{s3}|^2 + |U_{s4}|^2$$

$$99\%\ \text{CL:} \quad \begin{cases} \eta_s < 0.25 & \text{(solar + KamLAND)} \\ \eta_s > 0.75 & \text{(atmospheric + K2K)} \end{cases}$$

[Maltoni, Schwetz, Tortola, Valle, New J. Phys. 6 (2004) 122, arXiv:hep-ph/0405172]

New Reactor $\bar{\nu}_e$ Fluxes

Increased prediction of detected flux by 6.5%



i) **Neutrino Emission:**

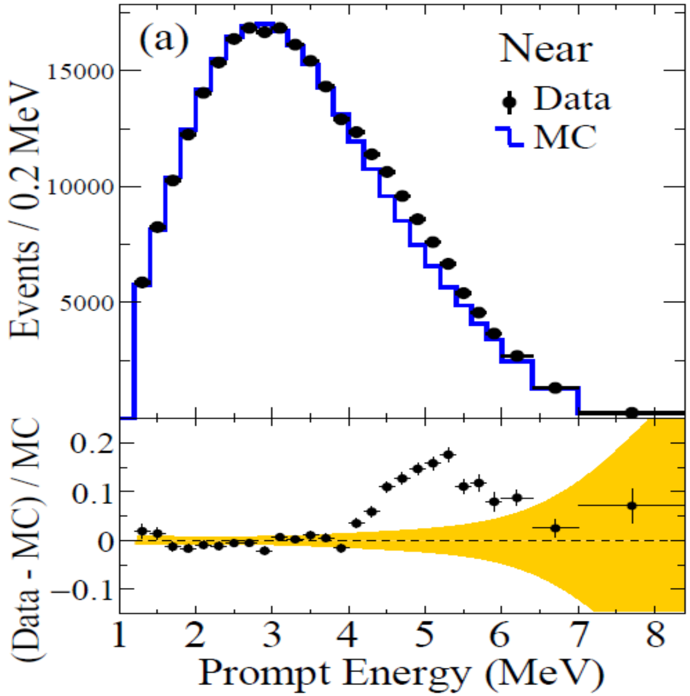
- **Improved reactor neutrino spectra → +3.5%**
- **Accounting for long-lived isotopes in reactors → +1%**

ii) **Neutrino Detection:**

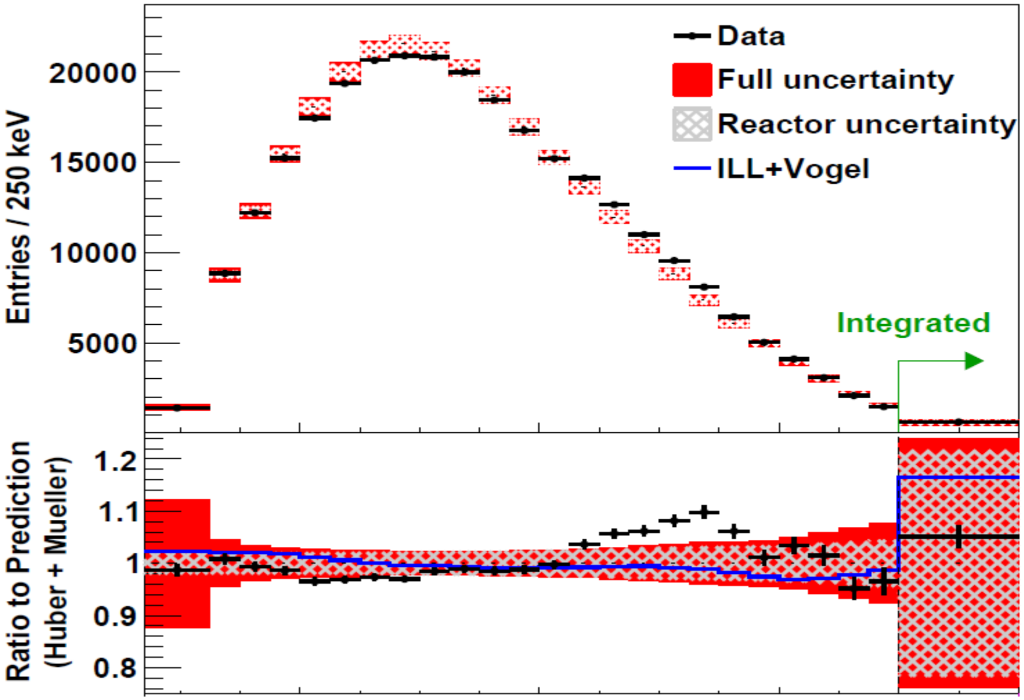
- **Reevaluation of σ_{IBD} → +1.5% (evolution of the neutron life time)**
- **Reanalysis of all SBL experiments**

[T. Lasserre, TAUP 2013]

New feature in reactors: 5 MeV bump

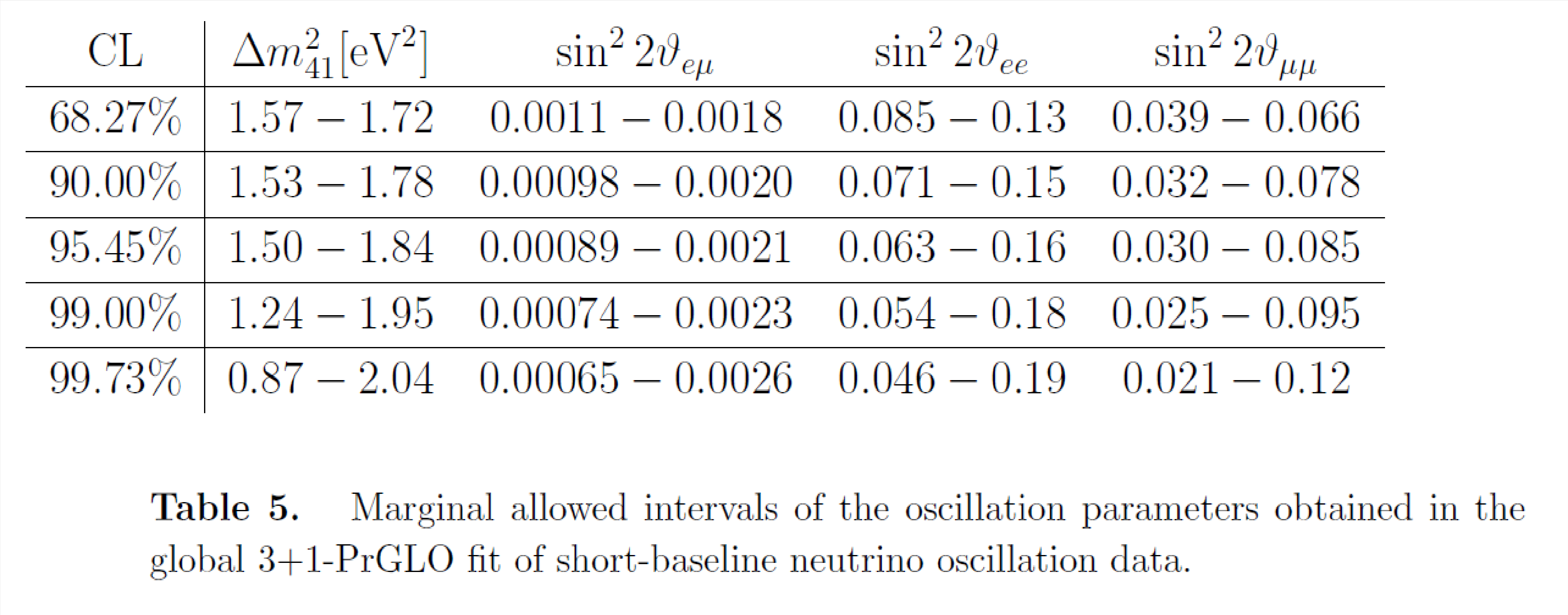


[RENO, arXiv:1511.05849]



[Daya Bay, arXiv:1508.04233]

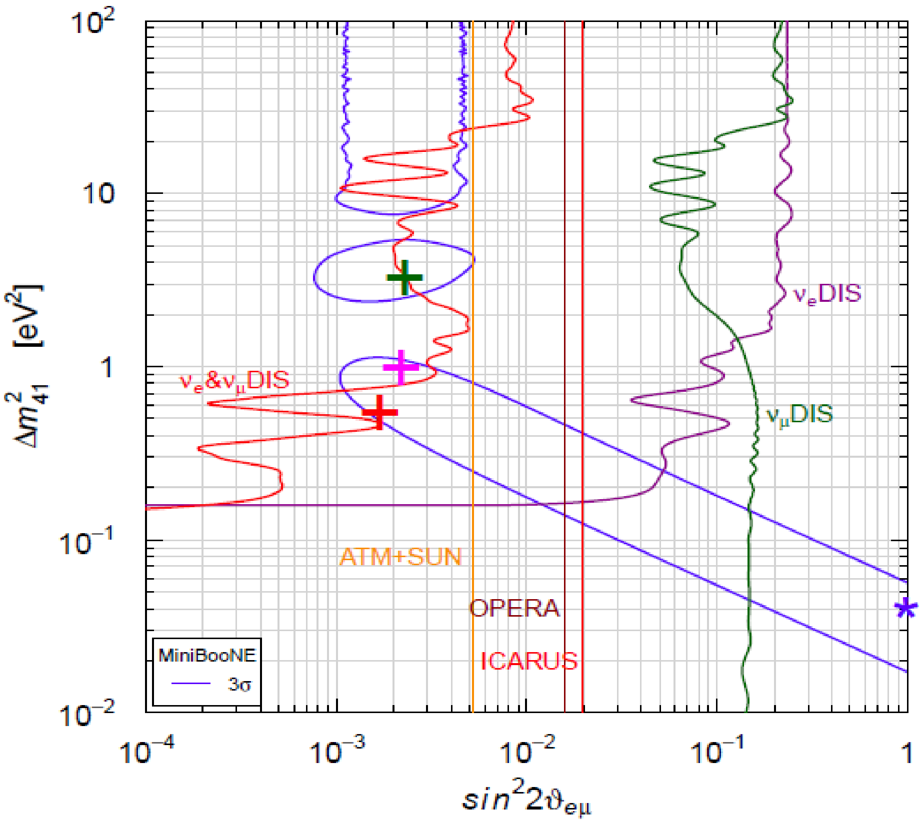
- Local problem with $\sim 3\%$ effect on total flux.
- It is an excess!
- It occurs both for the new high Muller-Huber fluxes and the old low Schreckenbach-Vogel fluxes.
- Real problem: apparent incompatibility of the bump with the β spectra from ^{235}U and ^{239}Pu measured by Schreckenbach et al. at ILL in 1982-1985.

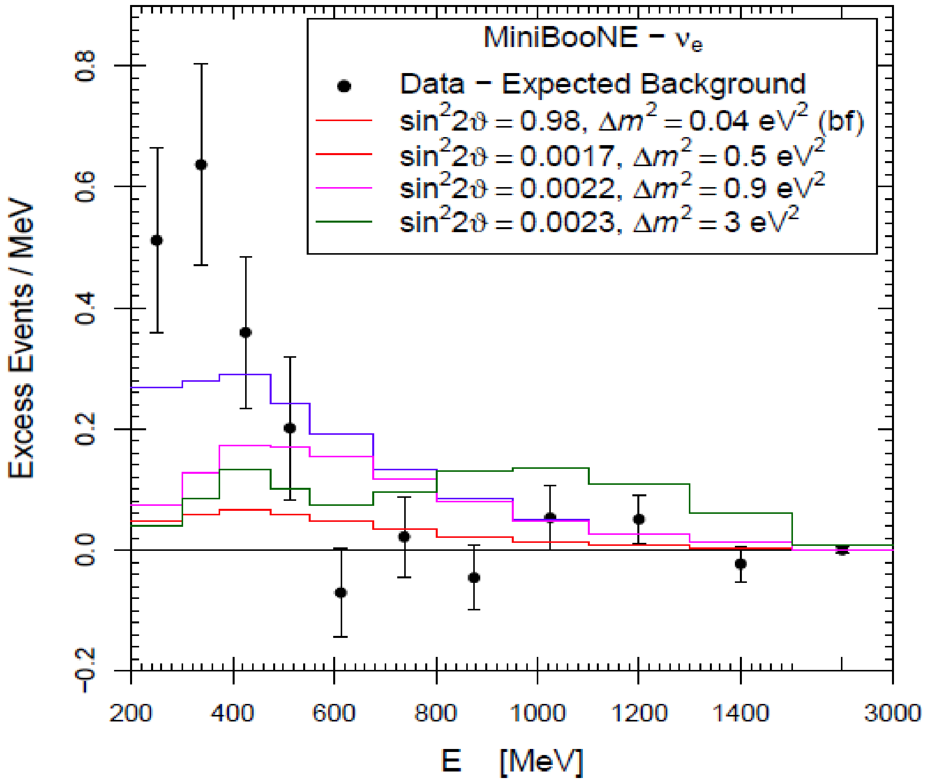


CL	Δm^2_{41}[eV^2]	$\sin^2 2\vartheta_{e\mu}$	$\sin^2 2\vartheta_{ee}$	$\sin^2 2\vartheta_{\mu\mu}$
68.27%	1.57 – 1.72	0.0011 – 0.0018	0.085 – 0.13	0.039 – 0.066
90.00%	1.53 – 1.78	0.00098 – 0.0020	0.071 – 0.15	0.032 – 0.078
95.45%	1.50 – 1.84	0.00089 – 0.0021	0.063 – 0.16	0.030 – 0.085
99.00%	1.24 – 1.95	0.00074 – 0.0023	0.054 – 0.18	0.025 – 0.095
99.73%	0.87 – 2.04	0.00065 – 0.0026	0.046 – 0.19	0.021 – 0.12

Table 5. Marginal allowed intervals of the oscillation parameters obtained in the global 3+1-PrGLO fit of short-baseline neutrino oscillation data.

MiniBooNE Low-Energy Excess?





- No fit of low-energy excess for realistic $\sin^2 2\vartheta_{e\mu} \lesssim 3 \times 10^{-3}$
- MB low-energy excess is the main cause of bad APP-DIS PGoF $= 0.1\%$
- Pragmatic Approach: discard the Low-Energy Excess because it is very likely not due to oscillations

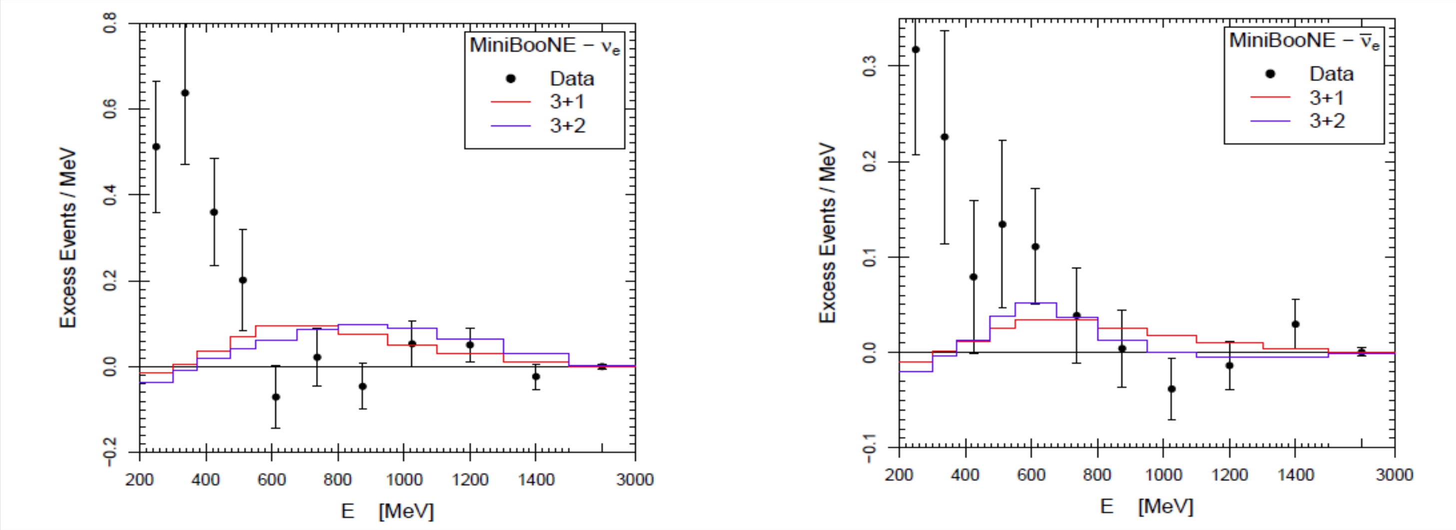
[Giunti, Laveder, Li, Long, PRD 88 (2013) 073008]

Status of 3+2 fit

Can we include two sterile neutrinos to improve the fit?

(1) It contains more mixing and mass parameters

(2) It allows CP violation between neutrino and antineutrino channels



- 3+2 can fit slightly better the small $\bar{\nu}_e$ excess at about 600 MeV
- 3+2 fit of low-energy excess as bad as 3+1
- Claims that 3+2 can fit low-energy excess do not take into account constraints from other data

secret interactions: hidden gauge boson 1310.5926

The effective 4-point self interaction

$$G_X \equiv \frac{g_X^2}{M_X^2}.$$

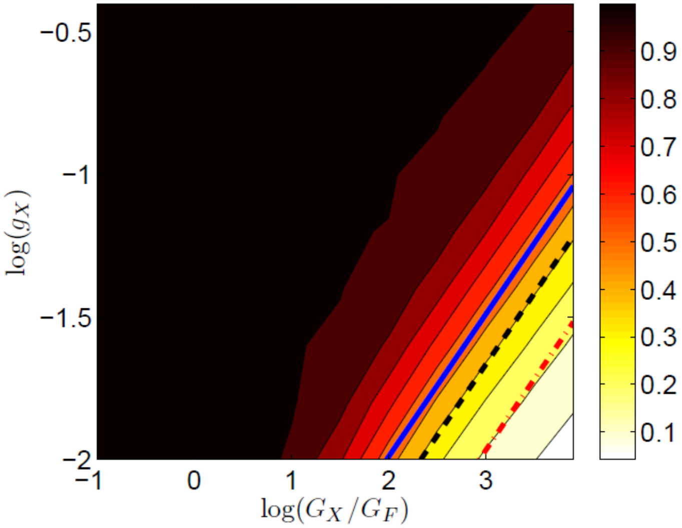


FIG. 2: Contours of equal thermalization. $\Delta N_{\rm eff}$ is given by the colors. The solid, dashed, and dot-dashed lines correspond to hidden bosons with masses $M_X = 300$ MeV, 200 MeV, and 100 MeV respectively.

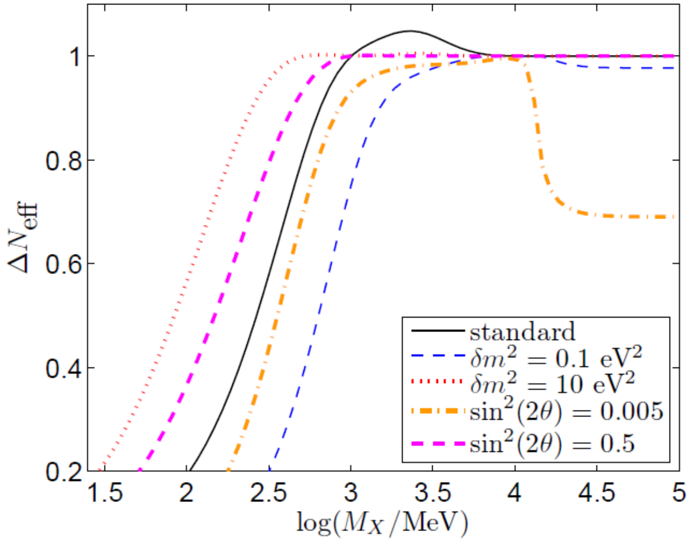
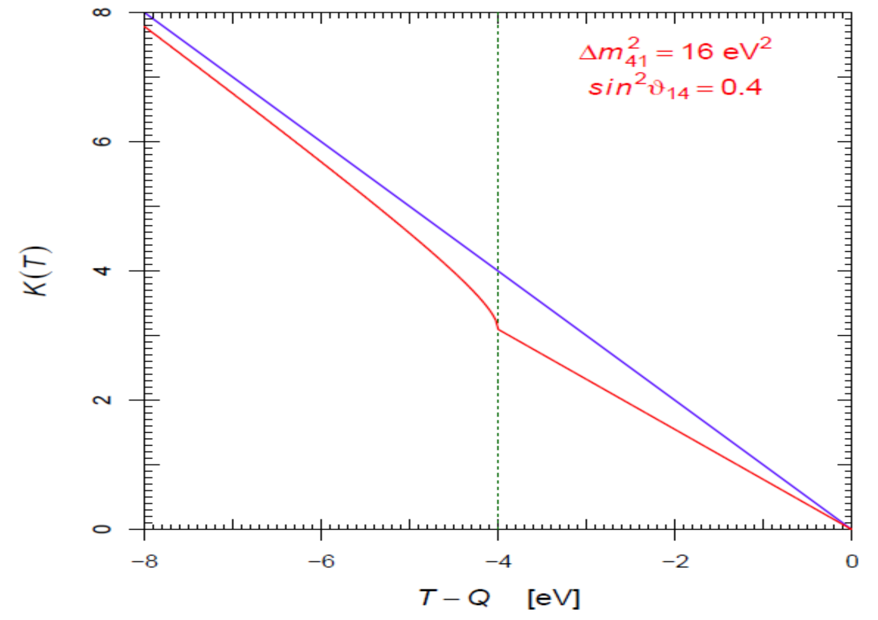
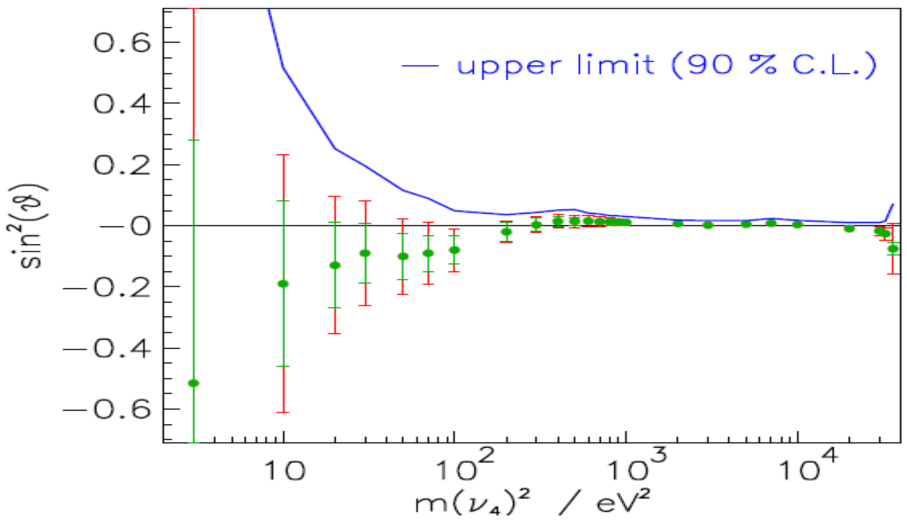


FIG. 3: Dependence of $\Delta N_{\rm eff}$ on the mixing parameters. $g_X = 0.01$ has been used for all the models while G_X has been changed to give the variation in mass.

Implications in non-oscillation probes

Beta decay: Mainz and Troitsk Limits



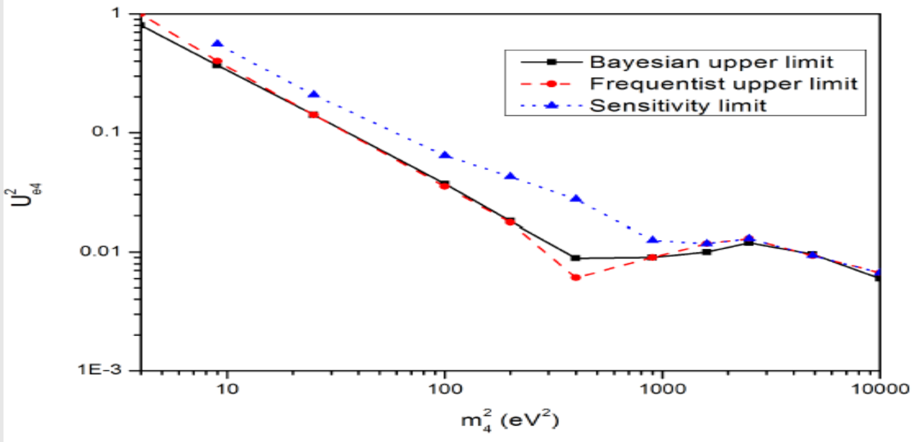


[Kraus, Singer, Valerius, Weinheimer, EPJC 73 (2013) 2323]

Search for spectra distortion can put limits on the heavy neutrino component.

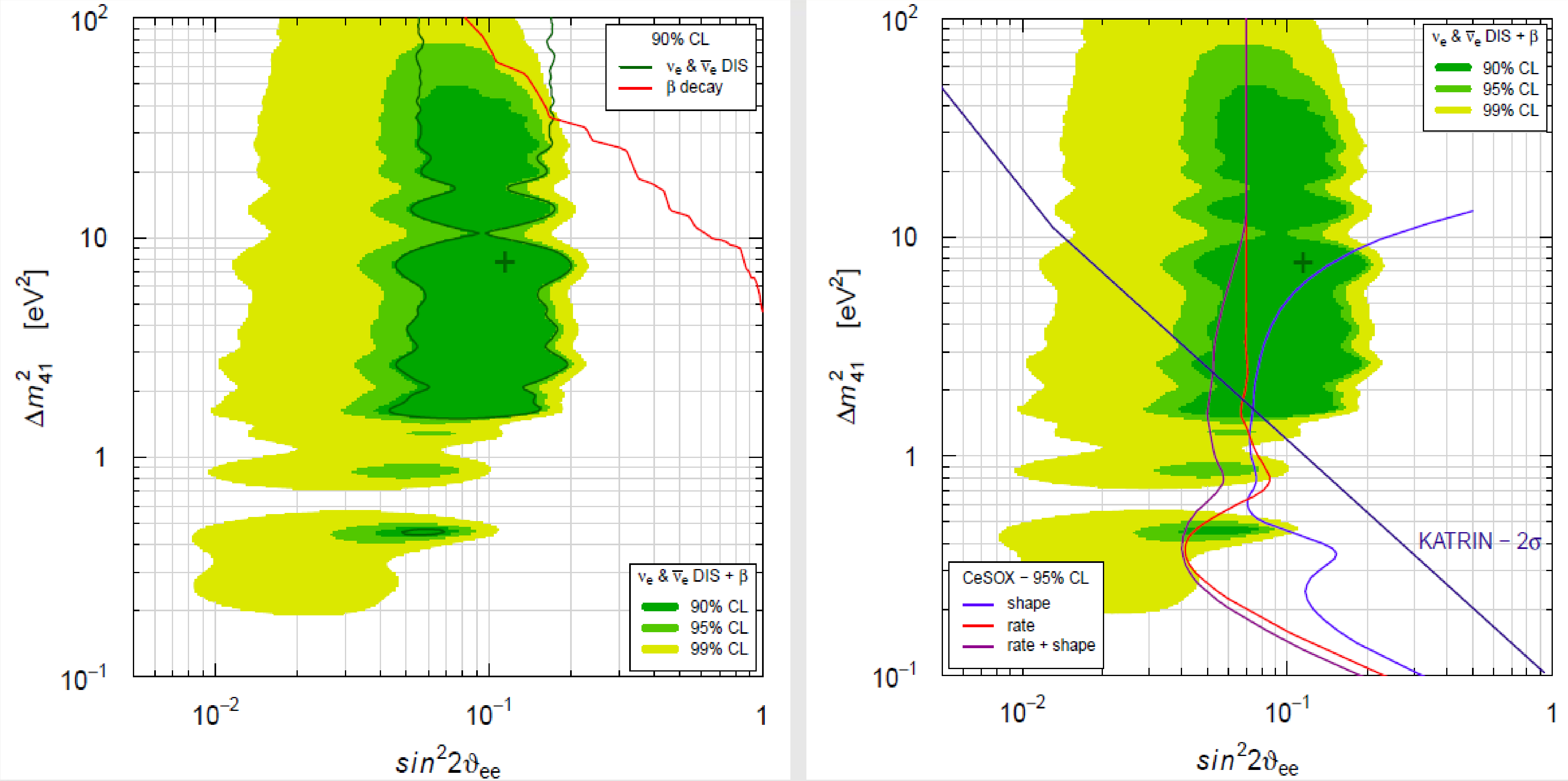
Current limits from Mainz and Troitsk are rather poor.

Future KATRIN is very competitive.



[Belesev et al, JPG 41 (2014) 015001]

Beta decay (2)

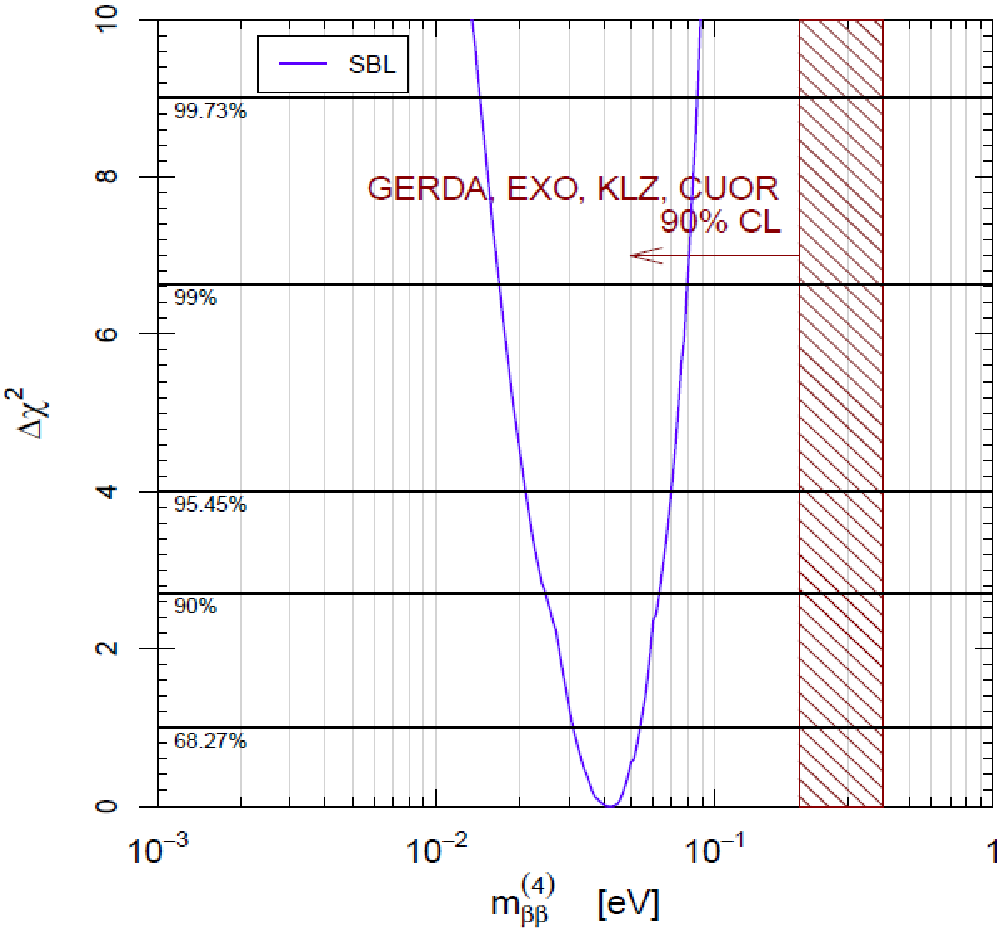


Mainz and Troitsk → lower limit:

$$7\,\text{cm} \lesssim \frac{L_{41}^{\text{osc}}}{E\,[\text{MeV}]} \lesssim 2\,\text{m} \qquad (2\sigma)$$

Double beta decay

$$m_{\beta\beta} = |U_{e1}|^2\, m_1 + |U_{e2}|^2\, e^{i\alpha_{21}}\, m_2 + |U_{e3}|^2\, e^{i\alpha_{31}}\, m_3 + |U_{e4}|^2\, e^{i\alpha_{41}}\, m_4$$



Pragmatic 3+1 Fit

$$m_{\beta\beta}^{(k)} = |U_{ek}|^2 m_k$$

$$m_1 \ll m_4$$

$$\Downarrow$$

$$m_{\beta\beta}^{(4)} \simeq |U_{e4}|^2 \sqrt{\Delta m_{41}^2}$$

surprise:

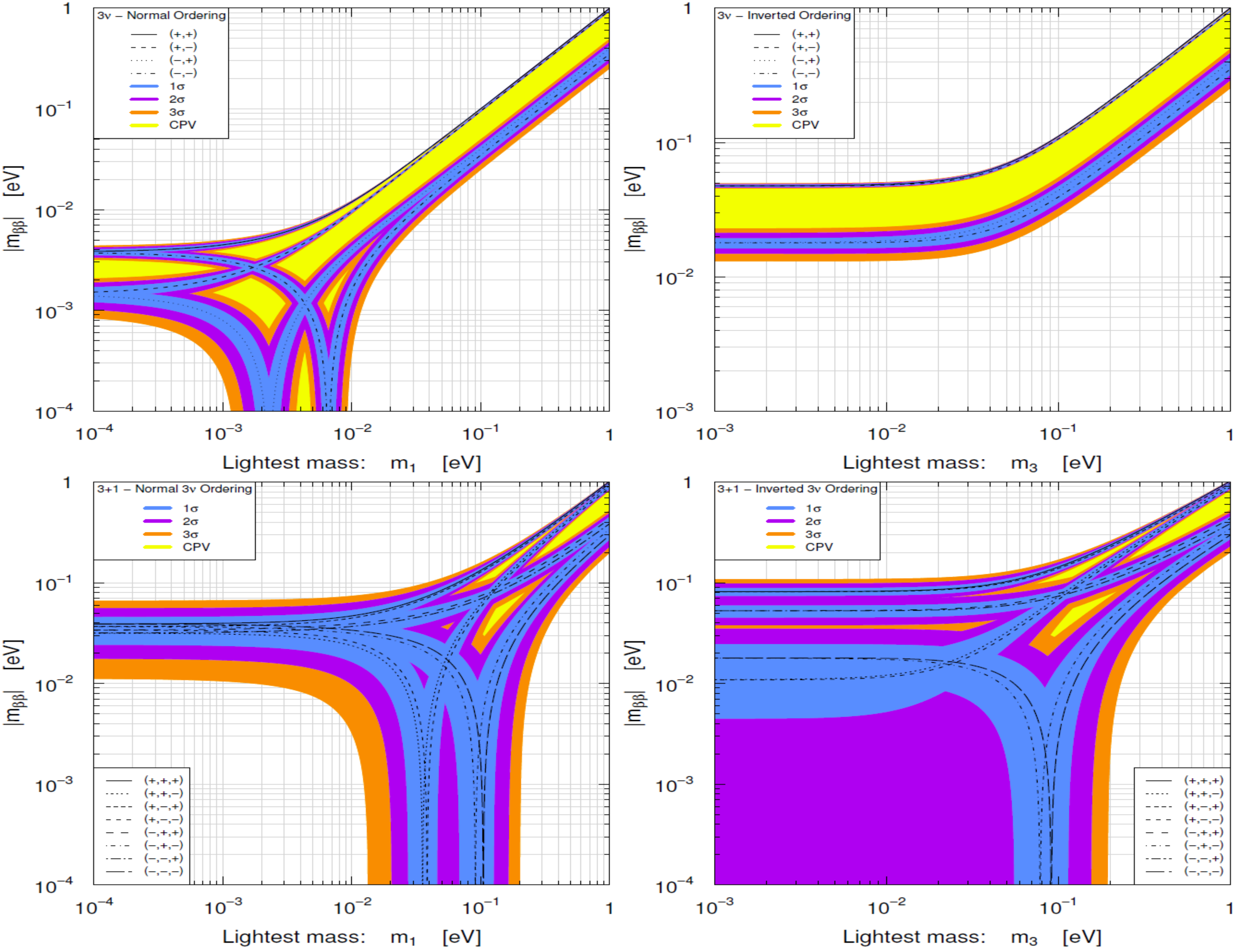
possible cancellation with $m_{\beta\beta}^{(3\nu)}$

[Barry et al, JHEP 07 (2011) 091]

[Li, Liu, PLB 706 (2012) 406]

[Rodejohann, JPG 39 (2012) 124008]

[Girardi, Meroni, Petcov, JHEP 1311 (2013) 146]


3ν – Normal Ordering
(+,+)
(+,−)
(−,+)
(−,−)
1σ
2σ
3σ
CPV
$|m_{\beta\beta}|$ [eV]
Lightest mass: m_1 [eV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
3ν – Inverted Ordering
(+,+)
(+,−)
(−,+)
(−,−)
1σ
2σ
3σ
CPV
$|m_{\beta\beta}|$ [eV]
Lightest mass: m_3 [eV]
3+1 – Normal 3ν Ordering
1σ
2σ
3σ
CPV
(+,+,+)
(+,+,−)
(+,−,+)
(+,−,−)
(−,+,+)
(−,+,−)
(−,−,+)
(−,−,−)
$|m_{\beta\beta}|$ [eV]
Lightest mass: m_1 [eV]
3+1 – Inverted 3ν Ordering
1σ
2σ
3σ
CPV
(+,+,+)
(+,+,−)
(+,−,+)
(+,−,−)
(−,+,+)
(−,+,−)
(−,−,+)
(−,−,−)
$|m_{\beta\beta}|$ [eV]
Lightest mass: m_3 [eV]