Short-Baseline Neutrino Anomalies

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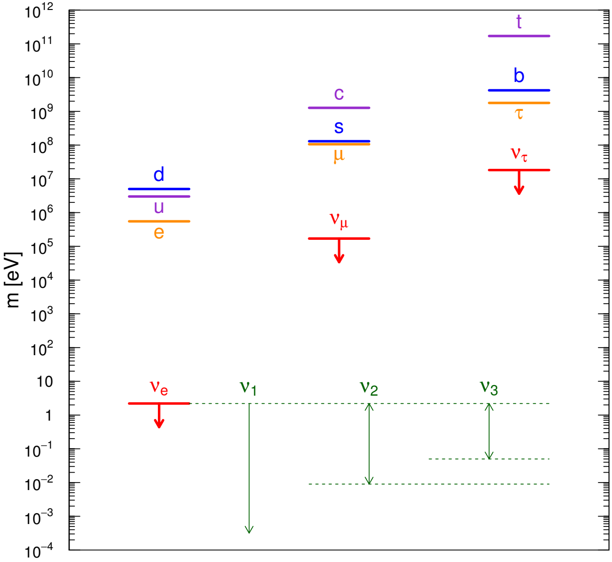
Fermion Mass Spectrum



Neutrino Mixing

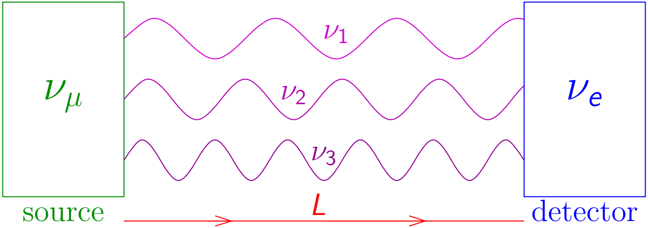
- Flavor Neutrinos: ν_e, ν_μ, ν_τ produced in Weak Interactions
- Massive Neutrinos: ν_1, ν_2, ν_3 propagate from Source to Detector
- Neutrino Mixing: a Flavor Neutrino is a superposition of Massive Neutrinos

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

- U is the 3×3 unitary Neutrino Mixing Matrix

Neutrino Oscillations

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



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

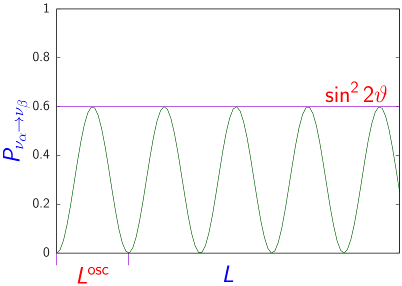
$$E_k^2 = p^2 + m_k^2 \qquad\qquad t = L$$

$$P_{\nu_\mu\to\nu_e}(L) = |\langle\nu_e|\nu(L)\rangle|^2 = \sum_{k,j} U_{ek}\,U_{\mu k}^{*}\,U_{ej}^{*}\,U_{\mu j}\,\exp\left(-i\frac{\Delta m_{kj}^2 L}{2E}\right)$$

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

$$\begin{array}{cccc} \nu_e \to \nu_\mu & \nu_e \to \nu_\tau & \nu_\mu \to \nu_e & \nu_\mu \to \nu_\tau \\ \bar\nu_e \to \bar\nu_\mu & \bar\nu_e \to \bar\nu_\tau & \bar\nu_\mu \to \bar\nu_e & \bar\nu_\mu \to \bar\nu_\tau \end{array}$$

2ν-mixing: $$P_{\nu_\alpha\to\nu_\beta} = \sin^2 2\vartheta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \quad \Longrightarrow \quad \boxed{L^{\text{osc}} = \frac{4\pi E}{\Delta m^2}}$$



Tiny neutrino masses lead to observable macroscopic oscillation distances!

$$\frac{L}{E} \lesssim \begin{cases} 10\,\frac{\text{m}}{\text{MeV}}\ \left(\frac{\text{km}}{\text{GeV}}\right) & \text{short-baseline experiments} & \Delta m^2 \gtrsim 10^{-1}\,\text{eV}^2 \\ 10^3\,\frac{\text{m}}{\text{MeV}}\ \left(\frac{\text{km}}{\text{GeV}}\right) & \text{long-baseline experiments} & \Delta m^2 \gtrsim 10^{-3}\,\text{eV}^2 \\ 10^4\,\frac{\text{km}}{\text{GeV}} & \text{atmospheric neutrino experiments} & \Delta m^2 \gtrsim 10^{-4}\,\text{eV}^2 \\ 10^{11}\,\frac{\text{m}}{\text{MeV}} & \text{solar neutrino experiments} & \Delta m^2 \gtrsim 10^{-11}\,\text{eV}^2 \end{cases}$$

Neutrino oscillations are the optimal tool to reveal tiny neutrino masses!

Three-Neutrino Mixing

Standard Parameterization of Mixing Matrix

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

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

$c_{ab} \equiv \cos\vartheta_{ab}$ $s_{ab} \equiv \sin\vartheta_{ab}$ $0 \leq \vartheta_{ab} \leq \frac{\pi}{2}$ $0 \leq \delta_{13}, \lambda_{21}, \lambda_{31} < 2\pi$

OSCILLATION PARAMETERS
- 3 Mixing Angles: ϑ_{12}, ϑ_{23}, ϑ_{13}
- 1 CPV Dirac Phase: δ_{13}
- 2 independent $\Delta m^2_{kj} \equiv m^2_k - m^2_j$: Δm^2_{21}, Δm^2_{31}

2 CPV Majorana Phases: λ_{21}, λ_{31} $\Longleftrightarrow$ $|\Delta L| = 2$ processes

Experimental Evidences of Neutrino Oscillations

Solar

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

(SNO, BOREXino
Super-Kamiokande
GALLEX/GNO, SAGE
Homestake, Kamiokande)

VLBL Reactor

$\bar{\nu}_e$ disappearance

(KamLAND)

$$\to \begin{cases} \Delta m^2_{\text{S}} = \Delta m^2_{21} \simeq 7.5 \times 10^{-5}\,\text{eV}^2 \\ \sin^2\vartheta_{\text{S}} = \sin^2\vartheta_{12} \simeq 0.30 \end{cases}$$

Atmospheric

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

(Super-Kamiokande
Kamiokande, IMB
MACRO, Soudan-2)

LBL Accelerator

ν_μ disappearance

(K2K, MINOS
T2K, NOνA)

LBL Accelerator

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

(Opera)

$$\to \begin{cases} \Delta m^2_{\text{A}} = |\Delta m^2_{31}| \simeq 2.5 \times 10^{-3}\,\text{eV}^2 \\ \sin^2\vartheta_{\text{A}} = \sin^2\vartheta_{23} \simeq 0.50 \end{cases}$$

LBL Accelerator

$\nu_\mu \to \nu_e$

(T2K, MINOS, NOνA)

LBL Reactor

$\bar{\nu}_e$ disappearance

(Daya Bay, RENO
Double Chooz)

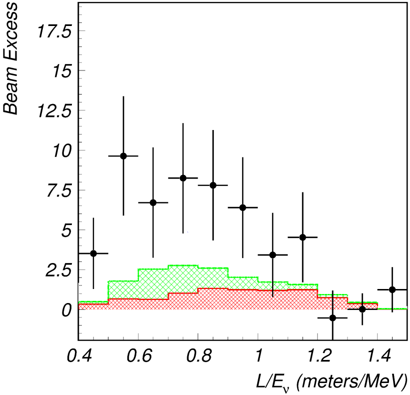
$$\to \begin{cases} \Delta m^2_{\text{A}} = |\Delta m^2_{31}| \\ \sin^2\vartheta_{13} \simeq 0.023 \end{cases}$$

Indications of SBL Oscillations Beyond 3ν

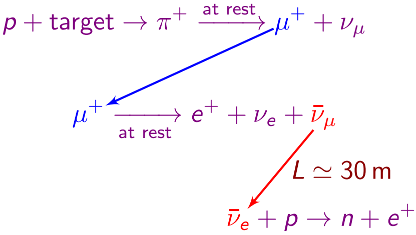
LSND

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

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\quad$ $20\,\text{MeV} \leq E \leq 52.8\,\text{MeV}$



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



$$p + \text{target} \to \pi^+ \xrightarrow{\text{at rest}} \mu^+ + \nu_\mu$$

$$\mu^+ \xrightarrow[\text{at rest}]{} e^+ + \nu_e + \bar{\nu}_\mu$$

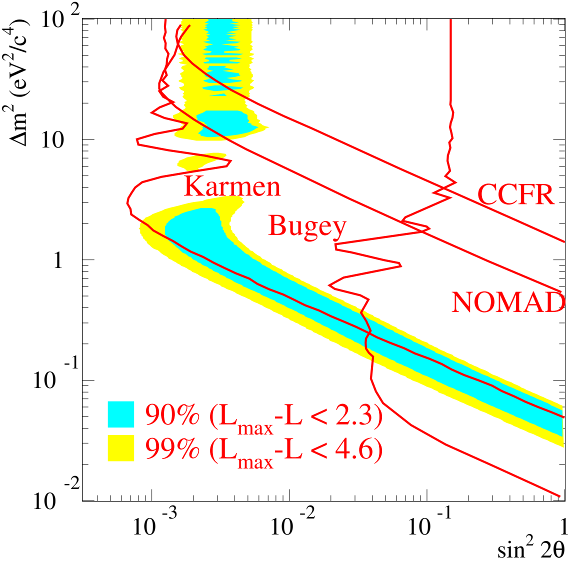
$L \simeq 30\,\text{m}$

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

Well-known detection process of $\bar{\nu}_e$

- $\approx 3.8\sigma$ excess
- But signal not seen by KARMEN at $L \simeq 18\,\text{m}$ with the same method

[PRD 65 (2002) 112001]

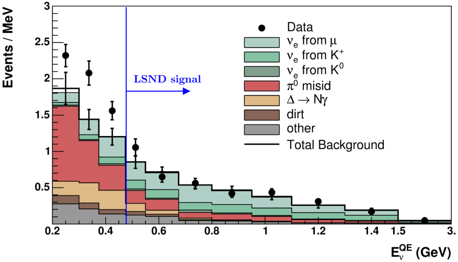


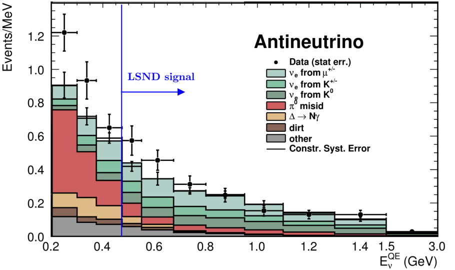
$$\Delta m^2_{\mathrm{SBL}} \gtrsim 3 \times 10^{-2}\,\mathrm{eV}^2 \gg \Delta m^2_{\mathrm{ATM}} \simeq 2.5 \times 10^{-3}\,\mathrm{eV}^2 \gg \Delta m^2_{\mathrm{SOL}}$$

MiniBooNE

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

$\nu_\mu \to \nu_e$ [PRL 102 (2009) 101802] $\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]





- Purpose: check LSND signal.
- Different L and E.
- Similar L/E (oscillations).
- No money, no Near Detector.

- LSND signal: $E > 475\,\mathrm{MeV}$.
- Agreement with LSND signal?
- CP violation?
- Low-energy anomaly!

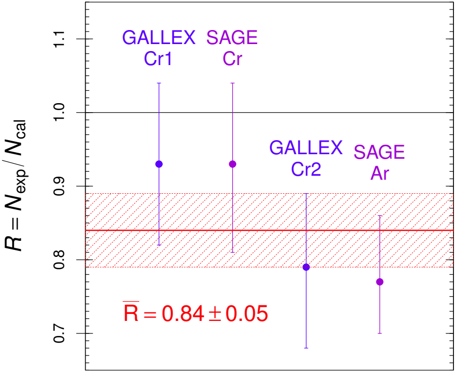
Gallium Anomaly

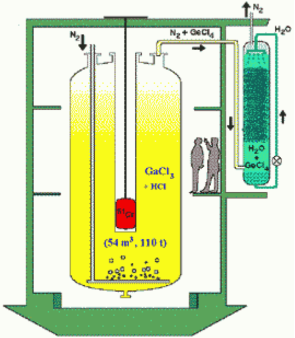
Gallium Radioactive Source Experiments: GALLEX and SAGE

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

$E \simeq 0.75\,\mathrm{MeV}$ $E \simeq 0.81\,\mathrm{MeV}$

Test of Solar ν_e Detection: $\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$





$\approx 2.9\sigma$ deficit

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

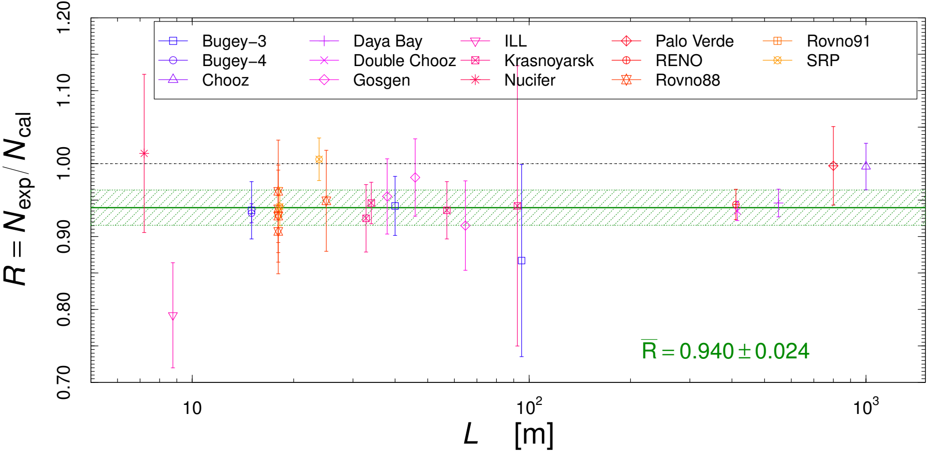
$\Delta m^2_{\mathrm{SBL}} \gtrsim 1\,\mathrm{eV}^2 \gg \Delta m^2_{\mathrm{ATM}} \gg \Delta m^2_{\mathrm{SOL}}$

[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]

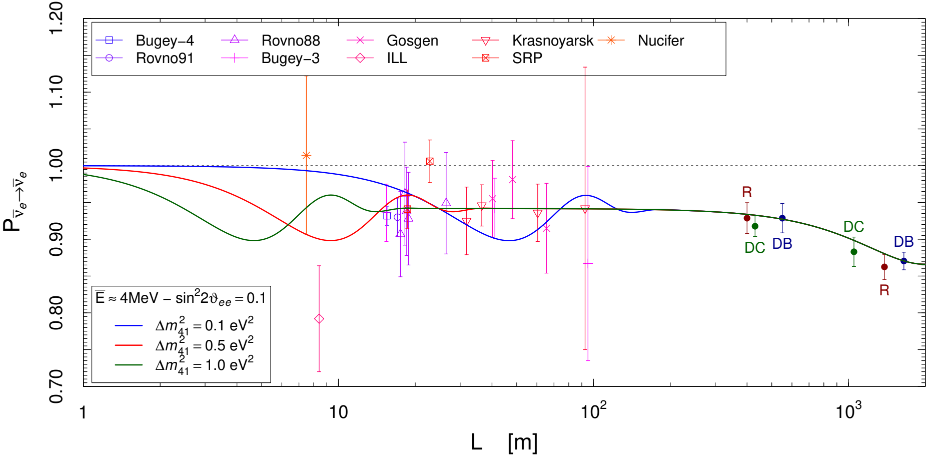
Reactor Electron Antineutrino Anomaly

[Mention et al, PRD 83 (2011) 073006]

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

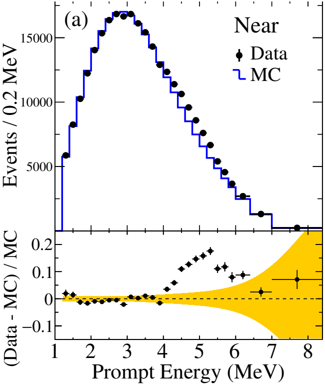


$\approx 2.5\sigma$ deficit

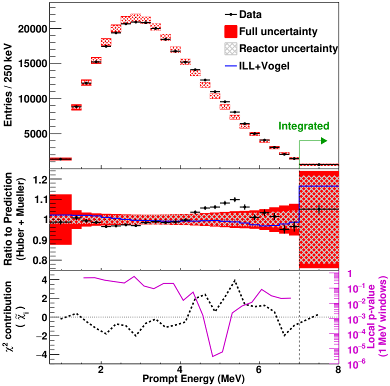


$$\Delta m^2_{\text{SBL}} \gtrsim 0.5\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}}$$

5 MeV Bump



[RENO, arXiv:1511.05849]

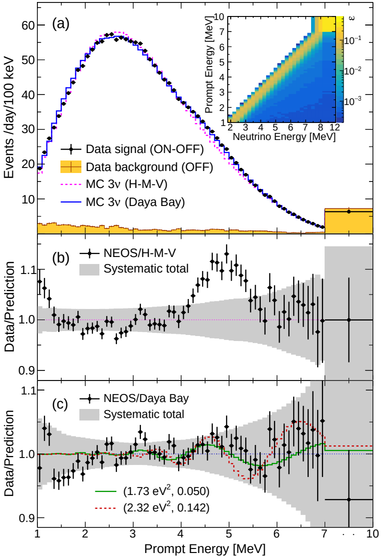


[Daya Bay, arXiv:1508.04233]

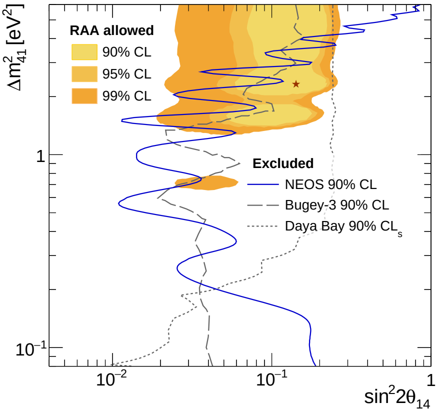
- Local problem with $\sim 3\%$ effect on total flux.
- It is an excess!
- It is correlated with the reactor activity.
- Cannot be explained by neutrino oscillations.
- Very likely due to theoretical miscalculation of the spectrum.

NEOS

[arXiv:1610.05134]



- Hanbit Nuclear Power Complex in Yeong-gwang, Korea.
- Thermal power of 2.8 GW.
- Detector: a ton of Gd-loaded liquid scintillator in a gallery approximately 24 m from the reactor core.
- The measured antineutrino event rate is 1976 per day with a signal to background ratio of about 22.

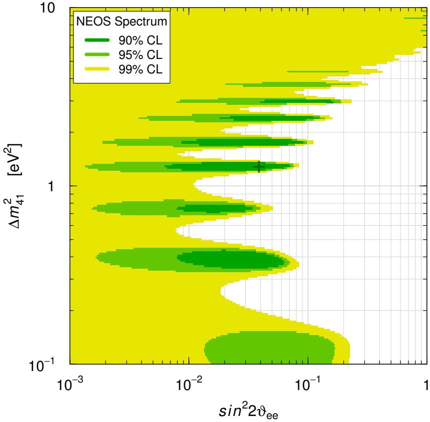


Raster Scan [NEOS, arXiv:1610.05134]

Best Fits:

$$\Delta m^2_{41} = 1.7\,\text{eV}^2 \qquad \sin^2 2\theta_{14} = 0.05$$

$$\Delta m^2_{41} = 1.3\,\text{eV}^2 \qquad \sin^2 2\theta_{14} = 0.04$$

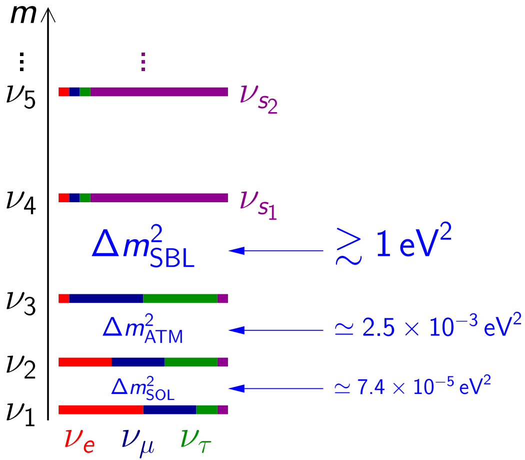


2-D χ^2 Analysis

$$\chi^2_{\text{no osc.}} - \chi^2_{\text{min}} = 6.5$$

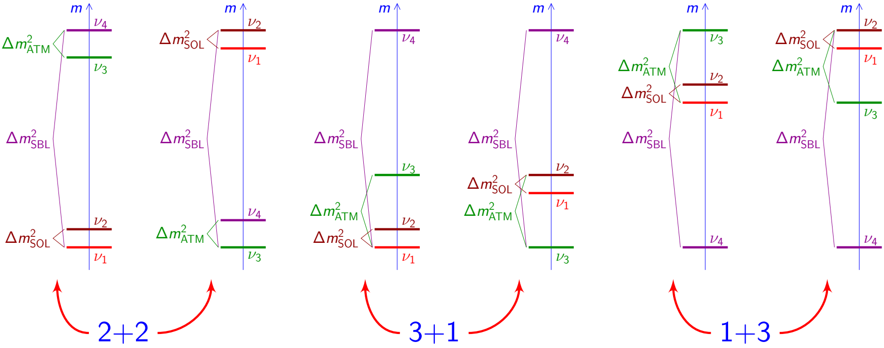
$\approx 2.1\sigma$ anomaly

Beyond Three-Neutrino Mixing: Sterile Neutrinos

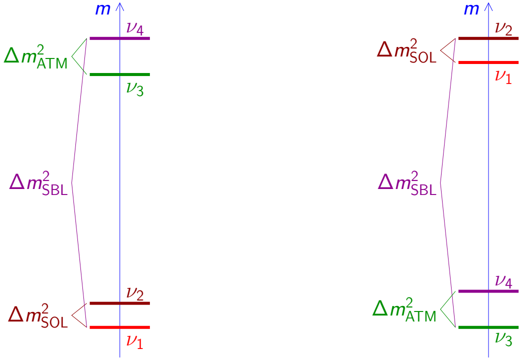


Terminology: a eV-scale sterile neutrino
means: a eV-scale massive neutrino which is mainly sterile

Four-Neutrino Schemes: 2+2, 3+1 and 1+3



2+2 Four-Neutrino Schemes

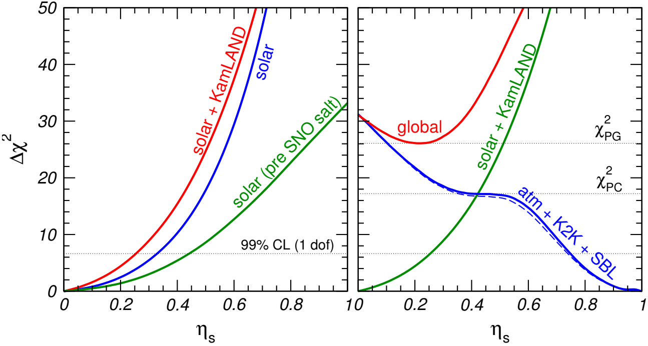


- After LSND (1995) 2+2 was preferred to 3+1, because of the 3+1 appearance-disappearance tension

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

- This is not a perturbation of 3-ν Mixing $\Longrightarrow$ Large active–sterile oscillations for solar or atmospheric neutrinos!

2+2 Schemes are Strongly Disfavored



Solar: Matter Effects + SNO NC

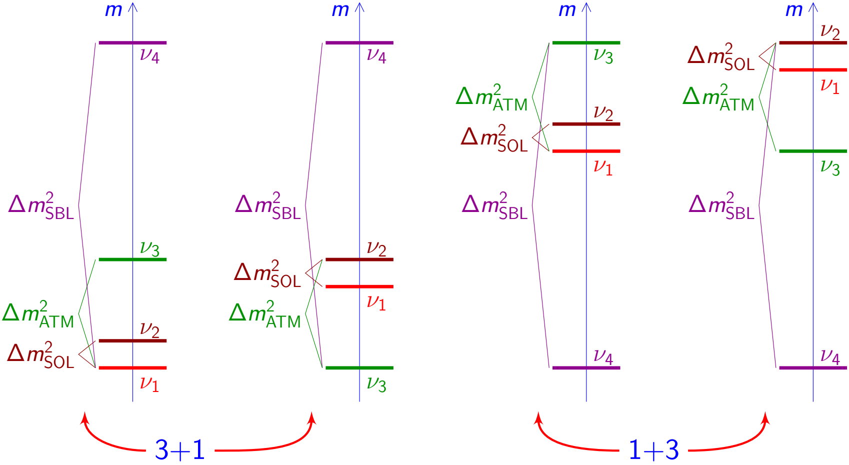
Atmospheric: Matter Effects

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

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

[Maltoni, Schwetz, Tortola, Valle, New J. Phys. 6 (2004) 122]

3+1 and 1+3 Four-Neutrino Schemes



- Perturbation of 3-ν Mixing: $|U_{e4}|^2, |U_{\mu4}|^2, |U_{\tau4}|^2 \ll 1 \quad |U_{s4}|^2 \simeq 1$
- 1+3 schemes are disfavored by cosmology (ΛCDM):

$$\sum_{k=1}^{3} m_k \lesssim 0.2\,\mathrm{eV}$$

[Planck, Astron. Astrophys. 594 (2016) A13 (arXiv:1502.01589)]

Effective 3+1 SBL Oscillation Probabilities

Appearance ($\alpha \neq \beta$)

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

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

Disappearance

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

$$\sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

$$U = \left(\begin{array}{ccc|c|} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{array}\right)$$

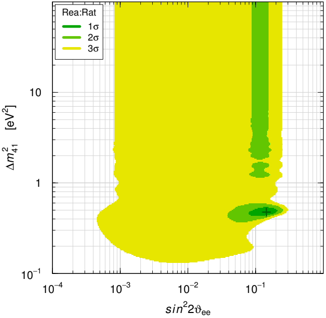
SBL

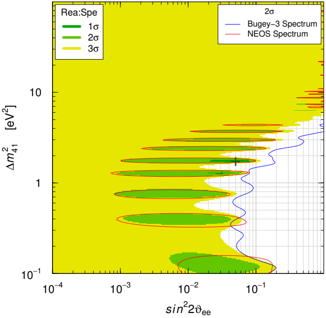
- 6 mixing angles
- 3 Dirac CP phases
- 3 Majorana CP phases

- CP violation is not observable in SBL experiments!
- Observable in LBL accelerator exp. sensitive to Δm^2_{ATM} [de Gouvea et al, PRD 91 (2015) 053005, PRD 92 (2015) 073012, arXiv:1605.09376; Palazzo et al, PRD 91 (2015) 073017, PLB 757 (2016) 142; Gandhi et al, JHEP 1511 (2015) 039] and solar exp. sensitive to Δm^2_{SOL} [Long, Li, CG, PRD 87, 113004 (2013) 113004]

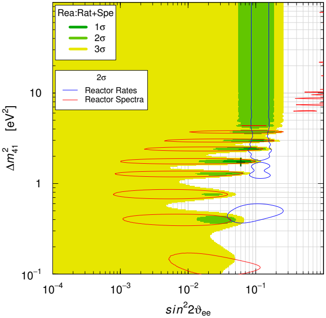
Reactor $\bar{\nu}_e$ Disappearance

Reactor Rates





Reactor Spectra



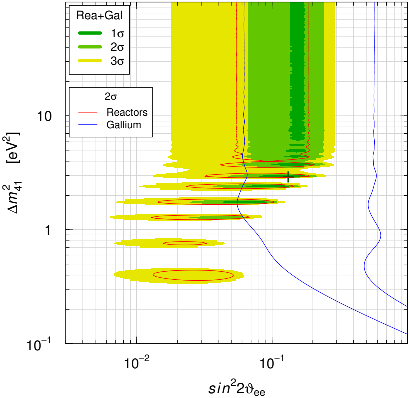
[Gariazzo, CG, Laveder, Li, arXiv:1703.00860]

Reactor Rates + Spectra

- $\Delta\chi^2_{\text{NO}} = 10.6 \Rightarrow \approx 2.8\sigma$ anomaly
- Best Fit: $\Delta m^2_{41} = 1.7\,\text{eV}^2$
  $\sin^2 2\vartheta_{ee} = 0.060 \quad \Leftrightarrow \quad |U_{e4}|^2 = 0.015$
- $\chi^2_{\text{min}}/\text{NDF} = 94.1/108 \Rightarrow \text{GoF} = 83\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 7.8/2 \Rightarrow \text{GoF}_{\text{PG}} = 2\%$

Reactor $\bar{\nu}_e$ + Gallium ν_e Disappearance

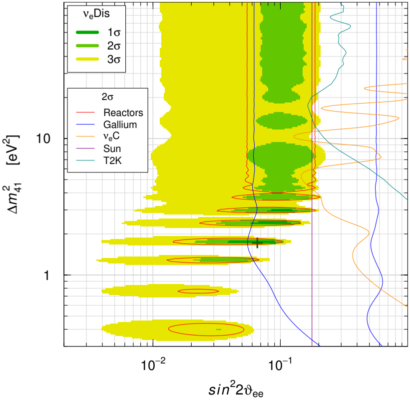
[Gariazzo, CG, Laveder, Li, arXiv:1703.00860]



- $\Delta\chi^2_{\text{NO}} = 14.6 \Rightarrow \approx 3.4\sigma$ anomaly
- Best Fit: $\Delta m^2_{41} = 3.0\,\text{eV}^2$
  $\sin^2 2\vartheta_{ee} = 0.13 \quad \Leftrightarrow \quad |U_{e4}|^2 = 0.034$
- $\chi^2_{\text{min}}/\text{NDF} = 107.3/112 \Rightarrow \text{GoF} = 61\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 5.4/2 \Rightarrow \text{GoF}_{\text{PG}} = 7\%$

Global ν_e and $\bar{\nu}_e$ Disappearance

[Gariazzo, CG, Laveder, Li, arXiv:1703.00860]



- KARMEN+LSND ν_e–^{12}C
  [Conrad, Shaevitz, PRD 85 (2012) 013017]
  [CG, Laveder, PLB 706 (2011) 20]
- Solar ν_e + KamLAND $\bar{\nu}_e$
  [Li et al, PRD 80 (2009) 113007, PRD 86 (2012) 113014]
  [Palazzo, PRD 83 (2011) 113013, PRD 85 (2012) 077301]
- T2K Near Detector ν_e disappearance
  [T2K, PRD 91 (2015) 051102]

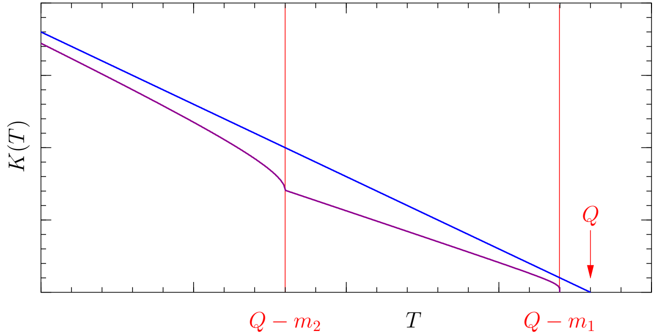
- $\Delta\chi^2_{\text{NO}} = 13.3 \Rightarrow \approx 3.2\sigma$ anomaly
- Best Fit: $\Delta m^2_{41} = 1.7\,\text{eV}^2$
  $\sin^2 2\vartheta_{ee} = 0.066 \quad \Leftrightarrow \quad |U_{e4}|^2 = 0.017$
- $\chi^2_{\text{min}}/\text{NDF} = 162.5/174 \Rightarrow \text{GoF} = 72\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 13.8/7 \Rightarrow \text{GoF}_{\text{PG}} = 6\%$

Tritium Beta-Decay: $^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_e$

$$\frac{d\Gamma}{dT} = \frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E)\, p\, E\, K^2(T)$$

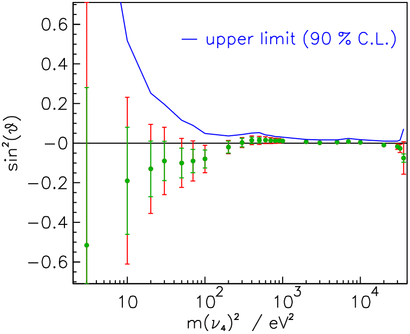
Kurie function: $$K(T) = \left[(Q - T) \sum_k |U_{ek}|^2 \sqrt{(Q-T)^2 - m_k^2} \right]^{1/2}$$

$$Q = M_{^3\mathrm{H}} - M_{^3\mathrm{He}} - m_e = 18.58\,\mathrm{keV}$$

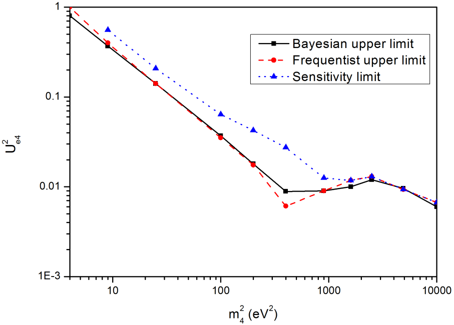


Mainz and Troitsk Limit on $\Delta m^2_{41} \simeq m^2_4$

$$m_4 \gg m_1, m_2, m_3 \quad \Longrightarrow \quad \Delta m^2_{41} \equiv m^2_4 - m^2_1 \simeq m^2_4$$



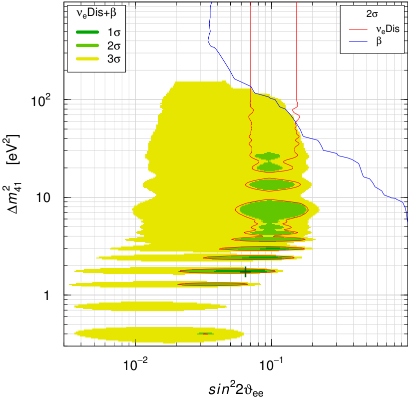
[Kraus, Singer, Valerius, Weinheimer, EPJC 73 (2013) 2323]



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

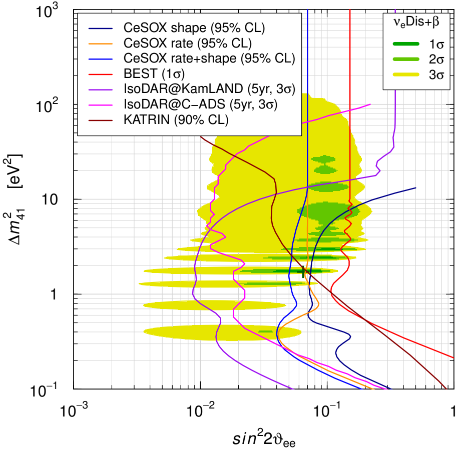
Global ν_e and $\bar{\nu}_e$ Disappearance + β Decay

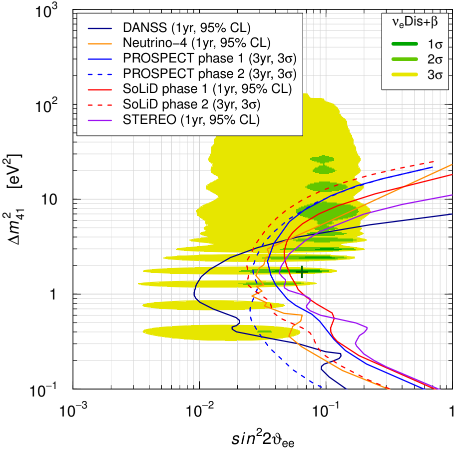
[Gariazzo, CG, Laveder, Li, arXiv:1703.00860]



- Best Fit: $\Delta m^2_{41} = 1.7\,\text{eV}^2$
  $\sin^2 2\vartheta_{ee} = 0.065 \quad \Leftrightarrow \quad |U_{e4}|^2 = 0.016$
- $2\,\text{cm} \lesssim \dfrac{L^{\text{osc}}_{41}}{E\,[\text{MeV}]} \lesssim 8\,\text{m}$ at 3σ
- $0.0033 \lesssim \sin^2 2\vartheta_{ee} \lesssim 0.22$ at 3σ

The Race for ν_e and $\bar{\nu}_e$ Disappearance





CeSOX (Gran Sasso, Italy) ^{144}Ce $\rightarrow \bar{\nu}_e$
BOREXINO: $L \simeq$ 5-12m [Vivier@TAUP2015]

BEST (Baksan, Russia) ^{51}Cr $\rightarrow \nu_e$
$L \simeq$ 5-12m [PRD 93 (2016) 073002]

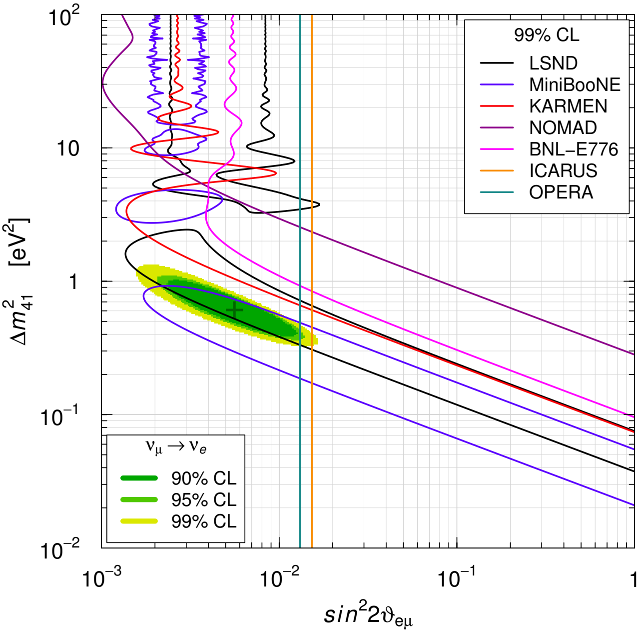
IsoDAR@KamLAND (Kamioka, Japan)
^{8}Li $\rightarrow \bar{\nu}_e$ $L \simeq$ 16m [arXiv:1511.05130]

IsoDAR@C-ADS (Guangdong, China)
^{8}Li $\rightarrow \bar{\nu}_e$ $L \simeq$ 15m [JHEP 1601 (2016) 004]

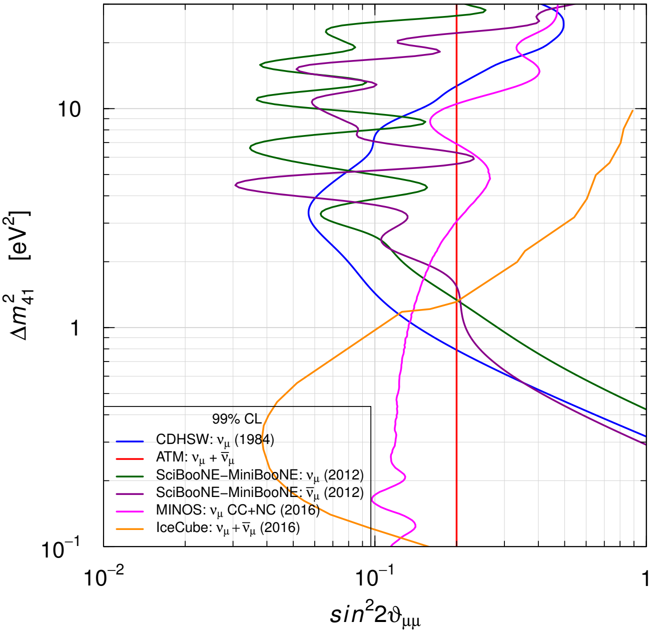
DANSS (Kalinin, Russia) $L \simeq$ 10-12m [arXiv:1606.02896]
Neutrino-4 (RIAR, Russia) $L \simeq$ 6-11m [JETP 121 (2015) 578]
PROSPECT (ORNL, USA) $L \simeq$ 7-12m [arXiv:1512.02202]
SoLid (SCK-CEN, Belgium) $L \simeq$ 5-8m [arXiv:1510.07835]
STEREO (ILL, France) $L \simeq$ 8-12m [arXiv:1602.00568]

KATRIN (Karlsruhe, Germany) ^{3}H $\rightarrow \bar{\nu}_e$ [Drexlin@NOW2016]

$\bar{\nu}_\mu \to \bar{\nu}_e$ and $\nu_\mu \to \nu_e$ Appearance



ν_μ and $\bar{\nu}_\mu$ Disappearance



3+1 Appearance-Disappearance Tension

ν_e DIS

$$\sin^2 2\vartheta_{ee} \simeq 4|U_{e4}|^2$$

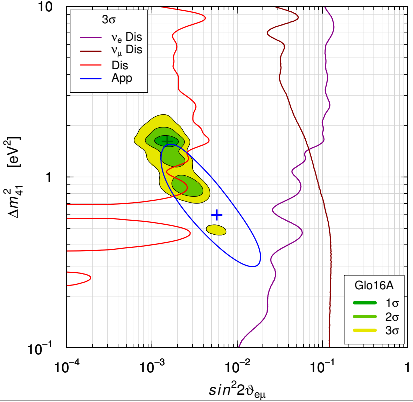
ν_μ DIS

$$\sin^2 2\vartheta_{\mu\mu} \simeq 4|U_{\mu 4}|^2$$

$\nu_\mu \to \nu_e$ APP

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

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



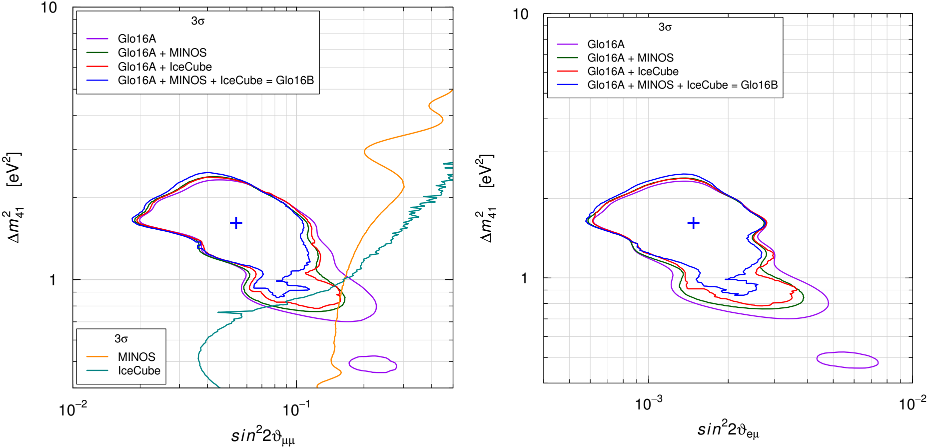
- $\nu_\mu \to \nu_e$ is quadratically suppressed!
- Glo16A = 2016 data except MINOS and IceCube [Gariazzo, CG, Laveder, Li, arXiv:1703.00860]
- $\Delta\chi^2_{\text{NO}} = 51.9 \Rightarrow \approx 6.4\sigma$ anomaly
- Best Fit: $\Delta m^2_{41} = 1.6\,\text{eV}^2$

  $|U_{e4}|^2 = 0.025 \quad |U_{m4}|^2 = 0.015$
- $\chi^2_{\text{min}}/\text{NDF} = 288.3/249 \Rightarrow \text{GoF} = 4\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 13.4/2 \Rightarrow \text{GoF}_{\text{PG}} = 0.1\%$
- Similar tension in 3+2, 3+3, ..., $3+N_s$

[CG, Zavanin, MPLA 31 (2015) 1650003]

Effects of MINOS and IceCube

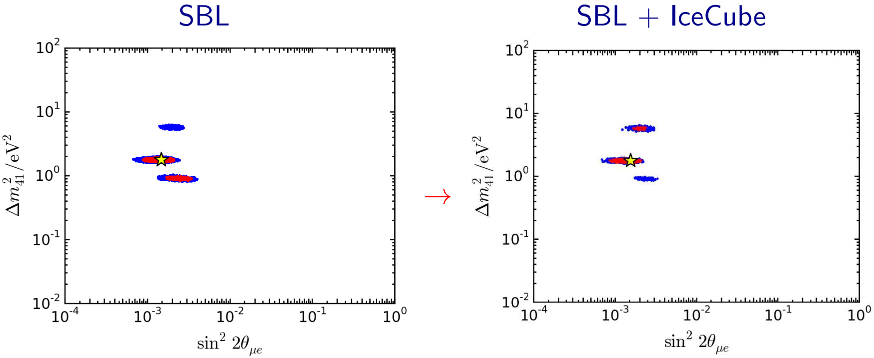
[Gariazzo, CG, Laveder, Li, arXiv:1703.00860]



- Glo16B = Glo16A + MINOS + IceCube $\Delta\chi^2_{\text{NO}} = 50.7 \Rightarrow \approx 6.3\sigma$ anomaly
- Best Fit: $\Delta m^2_{41} = 1.6\,\text{eV}^2$ $|U_{e4}|^2 = 0.027$ $|U_{\mu 4}|^2 = 0.014$
- $\chi^2_{\text{min}}/\text{NDF} = 556.9/525 \Rightarrow \text{GoF} = 16\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 14.5/2 \Rightarrow \text{GoF}_{\text{PG}} = 0.07\%$ ← Strong tension!

Another Analysis of SBL + IceCube

[Collin, Arguelles, Conrad, Shaevitz, PRL 117 (2016) 221801 (arXiv:1607.00011)]

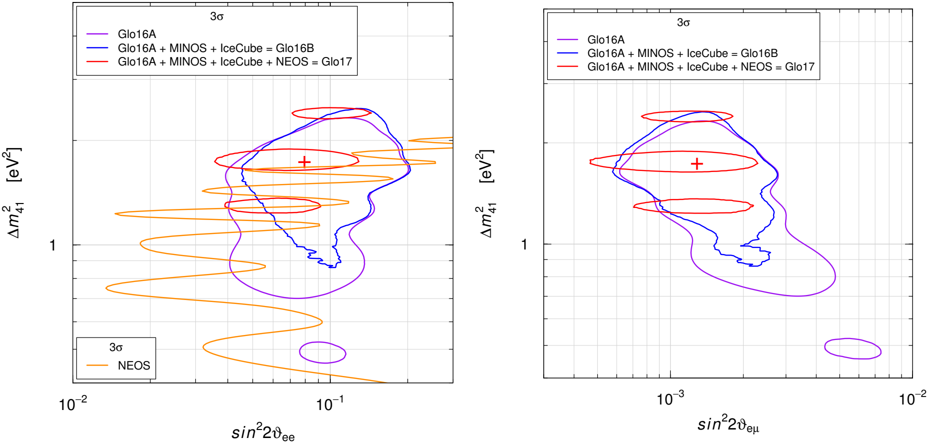


Red: 90% CL Blue: 99% CL

3+1	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu4}\rvert$	$\lvert U_{\tau4}\rvert$	N_{bins}	χ^2_{min}	χ^2_{null}	$\Delta\chi^2$ (dof)
SBL	1.75	0.163	0.117	-	315	306.81	359.15	52.34 (3)
SBL+IC	1.75	0.164	0.119	0.00	524	518.59	568.84	50.26 (4)
IC	5.62	-	0.314	-	209	207.11	209.69	2.58 (2)

Effects of NEOS

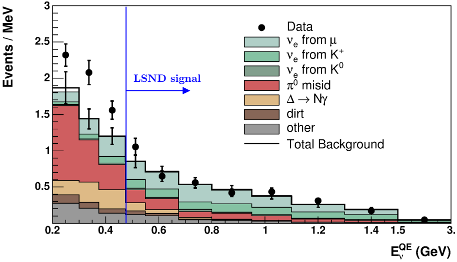
[Gariazzo, CG, Laveder, Li, arXiv:1703.00860]



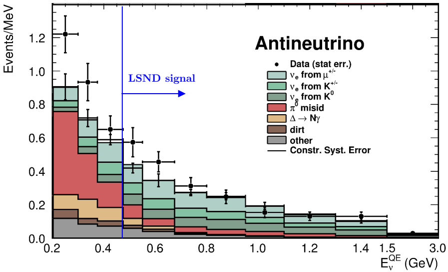
- Glo17 = GLO16B + NEOS $\Delta\chi^2_{\text{NO}} = 50.8 \Rightarrow \approx 6.3\sigma$ anomaly
- Best Fit: $\Delta m^2_{41} = 1.7\,\text{eV}^2$ $|U_{e4}|^2 = 0.020$ $|U_{\mu 4}|^2 = 0.016$
- $\chi^2_{\text{min}}/\text{NDF} = 621.7/585 \Rightarrow \text{GoF} = 14\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 17.3/2 \Rightarrow \text{GoF}_{\text{PG}} = 0.02\%$ $\leftarrow$ Strong tension!

MiniBooNE Low-Energy Anomaly

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



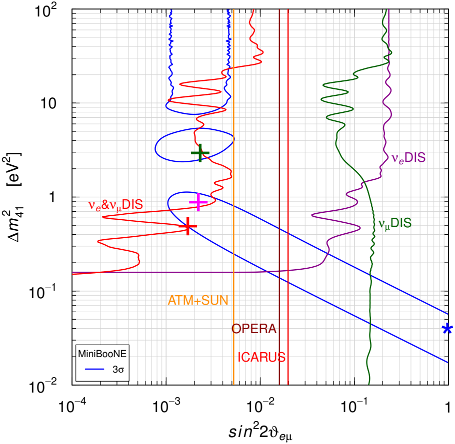
$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]

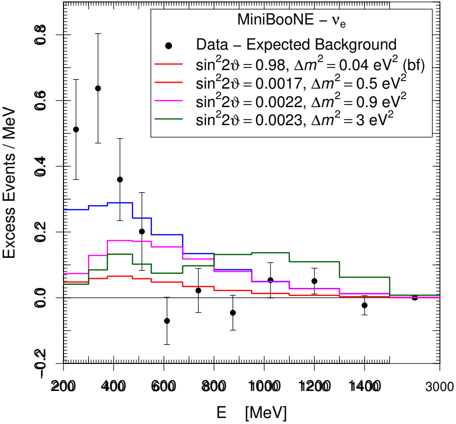


- Fit of MB Low-Energy Excess requires small Δm^2_{41} and large $\sin^2 2\vartheta_{e\mu}$, in contradiction with disappearance data

$$\boxed{P^{\text{SBL}}_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} = \sin^2 2\vartheta_{e\mu} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)}$$

- MB low-energy excess is the main cause of bad APP-DIS $\text{GoF}_{\text{PG}} = 0.06\%$
- Pragmatic Approach: discard the Low-Energy Excess because it is likely not due to oscillations [CG, Laveder, Li, Long, PRD 88 (2013) 073008]
- MicroBooNE is crucial for checking the MiniBooNE Low-Energy Anomaly and the consistency of different short-baseline data

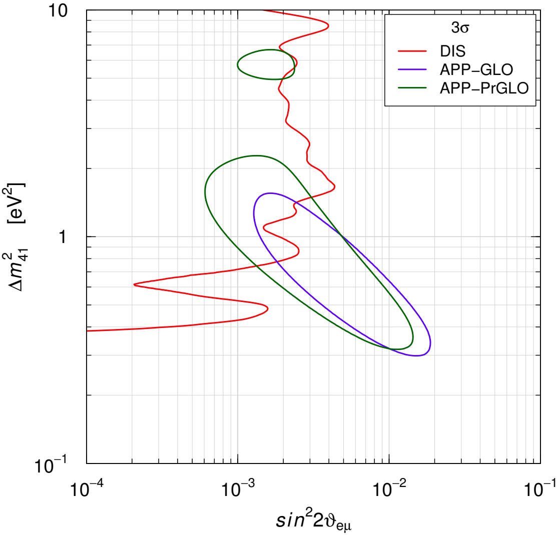




No fit of low-energy excess for realistic $\sin^2 2\vartheta_{e\mu} \lesssim 3 \times 10^{-3}$

Global → Pragmatic

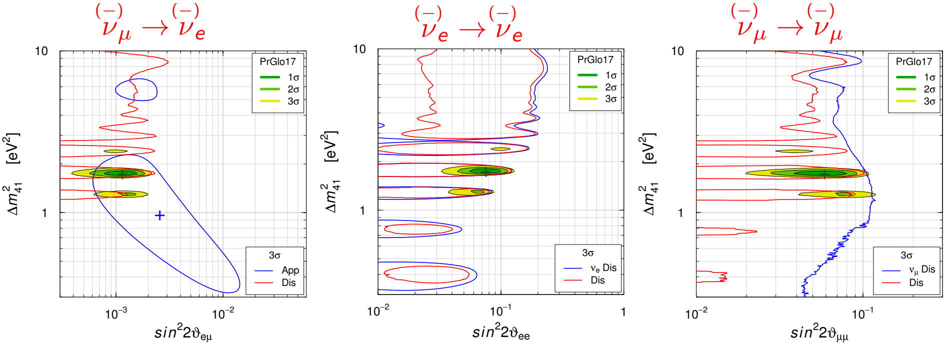
[CG, arXiv:1609.04688]



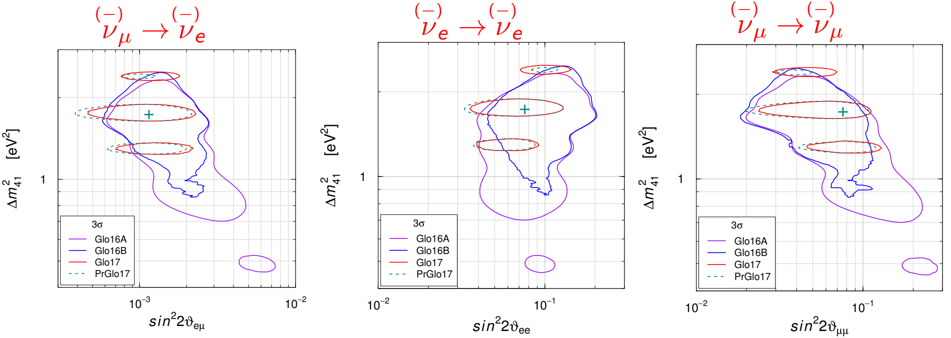
- APP-GLO: all MiniBooNE data
- APP-PrGLO: only MiniBooNE $E > 475\,\text{MeV}$ data (Pragmatic)

Pragmatic Global 3+1 Fit

[Gariazzo, CG, Laveder, Li, arXiv:1703.00860]



- $\Delta\chi^2_{\text{NO}} = 46.5 \Rightarrow \approx 6.0\sigma$ anomaly
- Best Fit: $\Delta m^2_{41} = 1.7\,\text{eV}^2$ $|U_{e4}|^2 = 0.019$ $|U_{\mu 4}|^2 = 0.015$
- $\chi^2_{\text{min}}/\text{NDF} = 594.8/579 \Rightarrow \text{GoF} = 32\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 7.4/2 \Rightarrow \text{GoF}_{\text{PG}} = 3\%$ ← Mild tolerable tension!

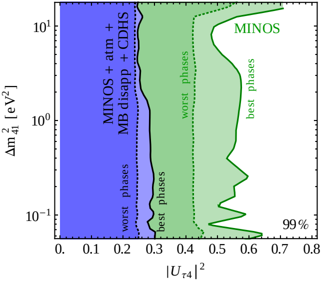


$\overset{(-)}{\nu}_{\mu} \to \overset{(-)}{\nu}_{e}$

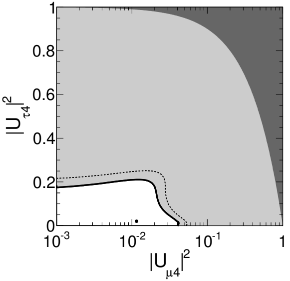
$\overset{(-)}{\nu}_{e} \to \overset{(-)}{\nu}_{e}$

$\overset{(-)}{\nu}_{\mu} \to \overset{(-)}{\nu}_{\mu}$

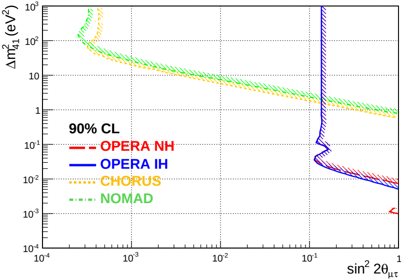
Bounds on $|U_{\tau 4}|^2$



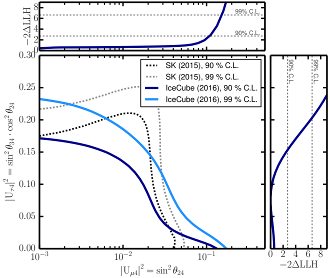
[Kopp et al, JHEP 1305 (2013) 050]



[Super-Kamiokande, PRD 91 (2015) 052019]

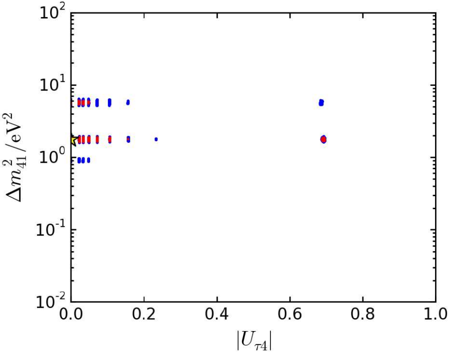


$\nu_\mu \to \nu_\tau$ [OPERA, JHEP 1506 (2015) 069]



[IceCube DeepCore, arXiv:1702.05160]

[Collin et al, PRL 117 (2016) 221801]

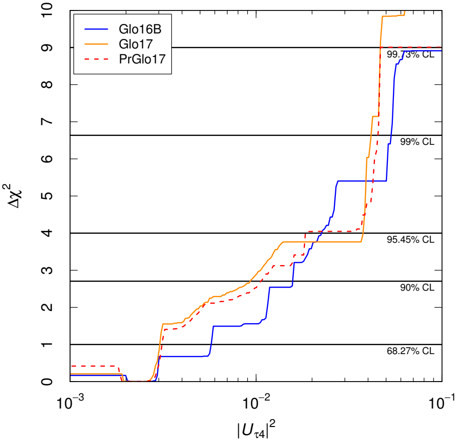


90% CL

$\vartheta_{34} < 6^\circ$ for $\Delta m^2_{41} \approx 6\,\mathrm{eV}^2$

$\vartheta_{34} < 80^\circ$ for $\Delta m^2_{41} \approx 2\,\mathrm{eV}^2$

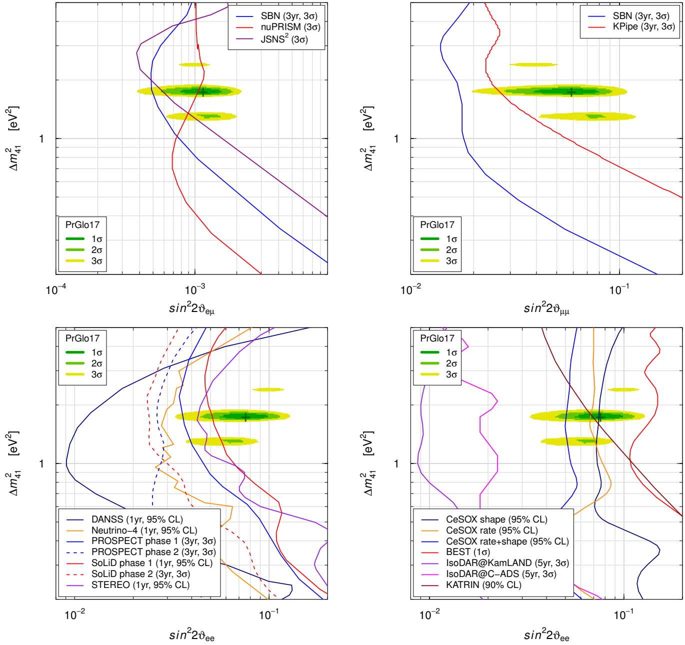
[Gariazzo, CG, Laveder, Li, arXiv:1703.00860]



90% CL

Glo16A + MINOS: $\vartheta_{34} < 27^\circ$
Glo16A + IceCube: $\vartheta_{34} < 7.3^\circ$
Glo16B: $\vartheta_{34} < 7.3^\circ$
Glo17: $\vartheta_{34} < 5.6^\circ$
PrGlo17: $\vartheta_{34} < 6.0^\circ$

The Race for the Light Sterile



Effects of light sterile neutrinos should also be seen in:

- β Decay Experiments
  [Hannestad et al, JCAP 1102 (2011) 011, PRC 84 (2011) 045503; Formaggio, Barrett, PLB 706 (2011) 68; Esmaili, Peres, PRD 85 (2012) 117301; Gastaldo et al, JHEP 1606 (2016) 061]
- Neutrinoless Double-β Decay Experiments
  [Rodejohann et al, JHEP 1107 (2011) 091; Li, Liu, PLB 706 (2012) 406; Meroni et al, JHEP 1311 (2013) 146, PRD 90 (2014) 053002; Pascoli et al, PRD 90 (2014) 093005; CG, Zavanin, JHEP 1507 (2015) 171; Guzowski et al, PRD 92 (2015) 012002]
- Long-baseline Neutrino Oscillation Experiments
  [de Gouvea et al, PRD 91 (2015) 053005, PRD 92 (2015) 073012, arXiv:1605.09376; Palazzo et al, PRD 91 (2015) 073017, PLB 757 (2016) 142, JHEP 1602 (2016) 111, JHEP 1609 (2016) 016, arXiv:1605.04299; Gandhi et al, JHEP 1511 (2015) 039; Pant et al, NPB 909 (2016) 1079, Choubey, Pramanik, PLB 764 (2017) 135]
- Solar neutrinos
  [Dooling et al, PRD 61 (2000) 073011, Gonzalez-Garcia et al, PRD 62 (2000) 013005; Palazzo, PRD 83 (2011) 113013, PRD 85 (2012) 077301; Li et al, PRD 80 (2009) 113007, PRD 87, 113004 (2013), JHEP 1308 (2013) 056; Kopp et al, JHEP 1305 (2013) 050]
- Atmospheric neutrinos
  [Goswami, PRD 55 (1997) 2931; Bilenky et al, PRD 60 (1999) 073007; Maltoni et al, NPB 643 (2002) 321, PRD 67 (2003) 013011; Choubey, JHEP 0712 (2007) 014; Razzaque, Smirnov, JHEP 1107 (2011) 084, PRD 85 (2012) 093010; Gandhi, Ghoshal, PRD 86 (2012) 037301; Barger et al, PRD 85 (2012) 011302; Esmaili et al, JCAP 1211 (2012) 041, JCAP 1307 (2013) 048, JHEP 1312 (2013) 014; Rajpoot et al, EPJC 74 (2014) 2936; Lindner et al, JHEP 1601 (2016) 124; Behera et al, arXiv:1605.08607]
- Supernova neutrinos
  [Caldwell, Fuller, Qian, PRD 61 (2000) 123005; Peres, Smirnov, NPB 599 (2001); Sorel, Conrad, PRD 66 (2002) 033009; Tamborra et al, JCAP 1201 (2012) 013; Wu et al, PRD 89 (2014) 061303; Esmaili et al, PRD 90 (2014) 033013]
- Cosmic neutrinos
  [Cirelli et al, NPB 708 (2005) 215; Donini, Yasuda, arXiv:0806.3029; Barry et al, PRD 83 (2011) 113012]
- Indirect dark matter detection [Esmaili, Peres, JCAP 1205 (2012) 002]
- Cosmology [see: Wong, ARNPS 61 (2011) 69; Archidiacono et al, AHEP 2013 (2013) 191047]

Effective 3+1 LBL Oscillation Probabilities

[de Gouvea et al, PRD 91 (2015) 053005, PRD 92 (2015) 073012, arXiv:1605.09376; Palazzo et al, PRD 91 (2015) 073017, PLB 757 (2016) 142, arXiv:1601.05995, arXiv:1603.03759, arXiv:1605.04299; Gandhi et al, JHEP 1511 (2015) 039]

$$|U_{e3}| \simeq \sin\vartheta_{13} \simeq 0.15 \sim \varepsilon \quad \Longrightarrow \quad \varepsilon^2 \sim 0.03$$

$$|U_{e4}| \simeq \sin\vartheta_{14} \simeq 0.17 \sim \varepsilon$$

$$|U_{\mu4}| \simeq \sin\vartheta_{24} \simeq 0.11 \sim \varepsilon$$

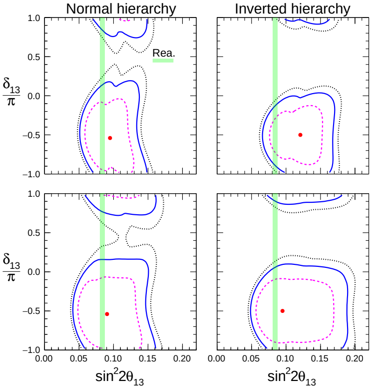
$$\alpha \equiv \frac{\Delta m^2_{21}}{|\Delta m^2_{31}|} \simeq \frac{7 \times 10^{-5}}{2.4 \times 10^{-3}} \simeq 0.031 \sim \varepsilon^2$$

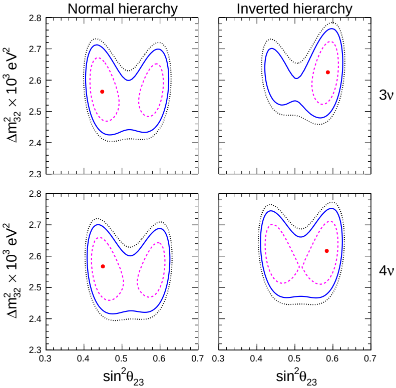
At order ε^3: [Klop, Palazzo, PRD 91 (2015) 073017] $\Delta_{kj} \equiv \Delta m^2_{kj} L/4E$

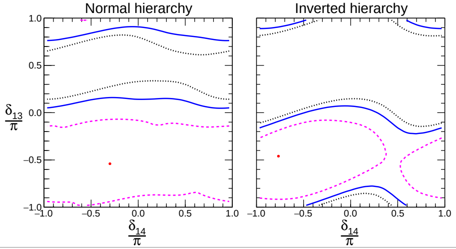
$$\begin{aligned} P^{\text{LBL}}_{\nu_\mu\to\nu_e} \simeq\ & 4\sin^2\vartheta_{13}\sin^2\vartheta_{23}\sin^2\Delta_{31} & \sim \varepsilon^2 \\ & +2\sin\vartheta_{13}\sin 2\vartheta_{12}\sin 2\vartheta_{23}(\alpha\Delta_{31})\sin\Delta_{31}\cos(\Delta_{32}+\delta_{13}) & \sim \varepsilon^3 \\ & +4\sin\vartheta_{13}\sin\vartheta_{14}\sin\vartheta_{24}\sin\vartheta_{23}\sin\Delta_{31}\sin(\Delta_{31}+\delta_{13}-\delta_{14}) & \sim \varepsilon^3 \end{aligned}$$

CP Violation in T2K and NOνA

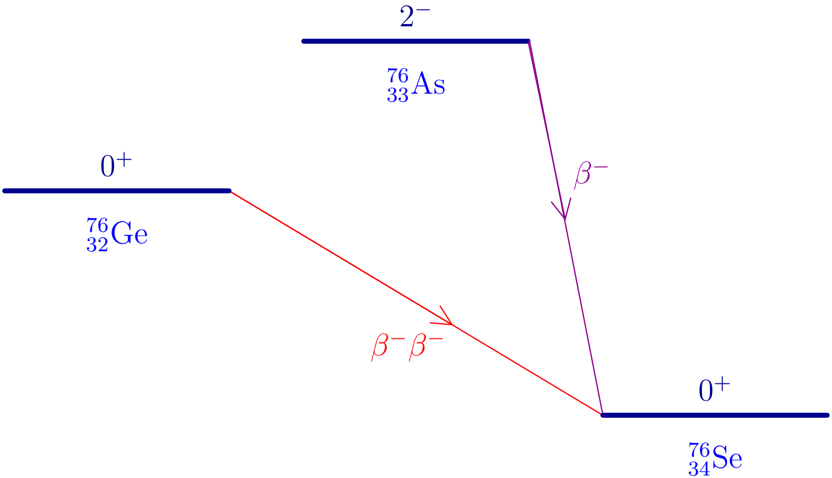
[Capozzi, CG, Laveder, Palazzo, PRD 95 (2017) 033006 (arXiv:1612.07764)]





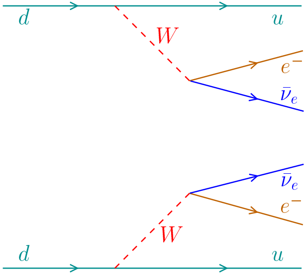


Neutrinoless Double-Beta Decay



Effective Majorana Neutrino Mass: $m_{\beta\beta} = \sum_k U_{ek}^2 \, m_k$

Two-Neutrino Double-β Decay: $\Delta L = 0$

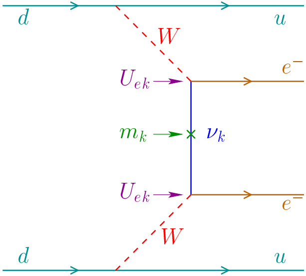


$$\mathcal{N}(A,Z) \to \mathcal{N}(A,Z+2) + e^- + e^- + \bar{\nu}_e + \bar{\nu}_e$$

$$(T_{1/2}^{2\nu})^{-1} = G_{2\nu}\,|\mathcal{M}_{2\nu}|^2$$

second order weak interaction process
in the Standard Model

Neutrinoless Double-β Decay: $\Delta L = 2$

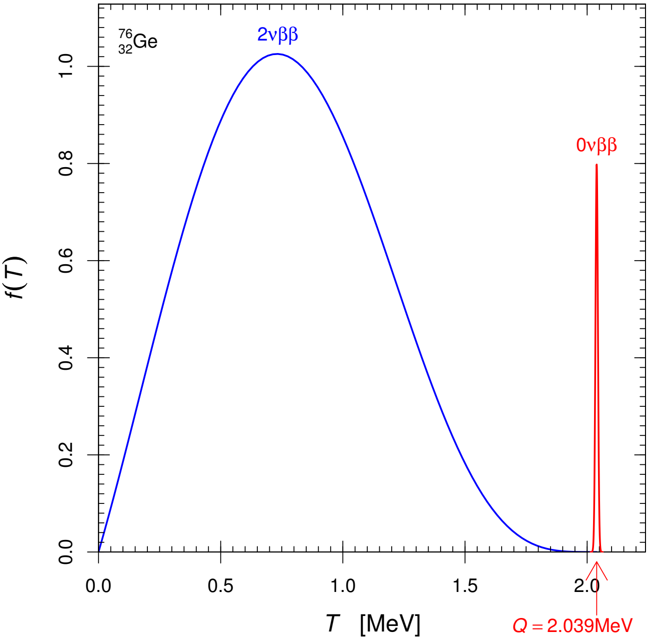


$$\mathcal{N}(A,Z) \to \mathcal{N}(A,Z+2) + e^- + e^-$$

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu}\,|\mathcal{M}_{0\nu}|^2\,|m_{\beta\beta}|^2$$

effective
Majorana
mass

$$|m_{\beta\beta}| = \left|\sum_k U_{ek}^2\, m_k\right|$$

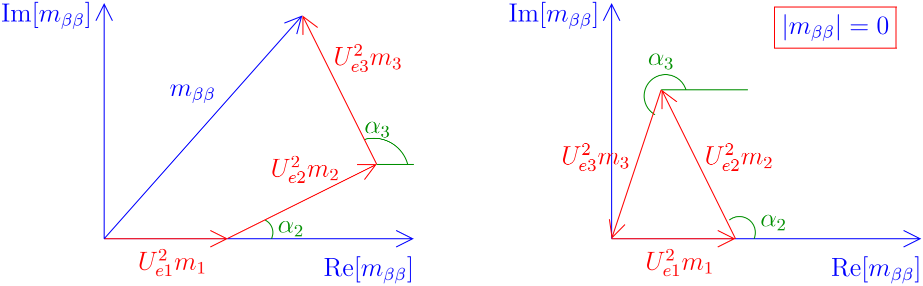

$^{76}_{32}$Ge
2νββ
0νββ
$f(T)$
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.5
1.0
1.5
2.0
T [MeV]
$Q = 2.039$MeV

Effective Majorana Neutrino Mass

$m_{\beta\beta} = \sum_k U_{ek}^2 \, m_k$ complex U_{ek} ⇒ possible cancellations

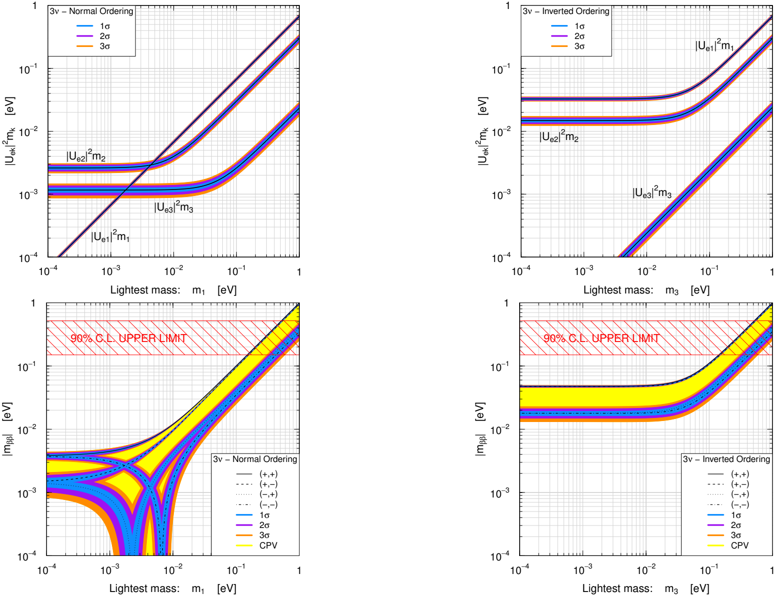
$$m_{\beta\beta} = |U_{e1}|^2 \, m_1 + |U_{e2}|^2 \, e^{i\alpha_2} \, m_2 + |U_{e3}|^2 \, e^{i\alpha_3} \, m_3$$

$$\alpha_2 = 2\lambda_2 \qquad \alpha_3 = 2\left(\lambda_3 - \delta_{13}\right)$$



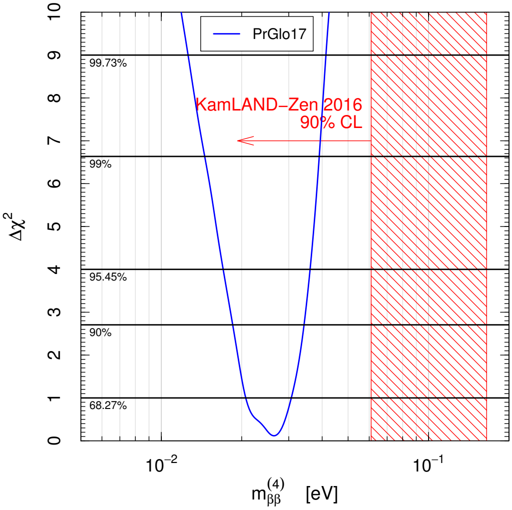
Predictions of 3ν-Mixing Paradigm

$$m_{\beta\beta} = |U_{e1}|^2\, m_1 + |U_{e2}|^2\, e^{i\alpha_2}\, m_2 + |U_{e3}|^2\, e^{i\alpha_3}\, m_3$$



3+1 Mixing

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



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

$$m_1 \ll m_4$$

$$\Downarrow$$

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

surprise:

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

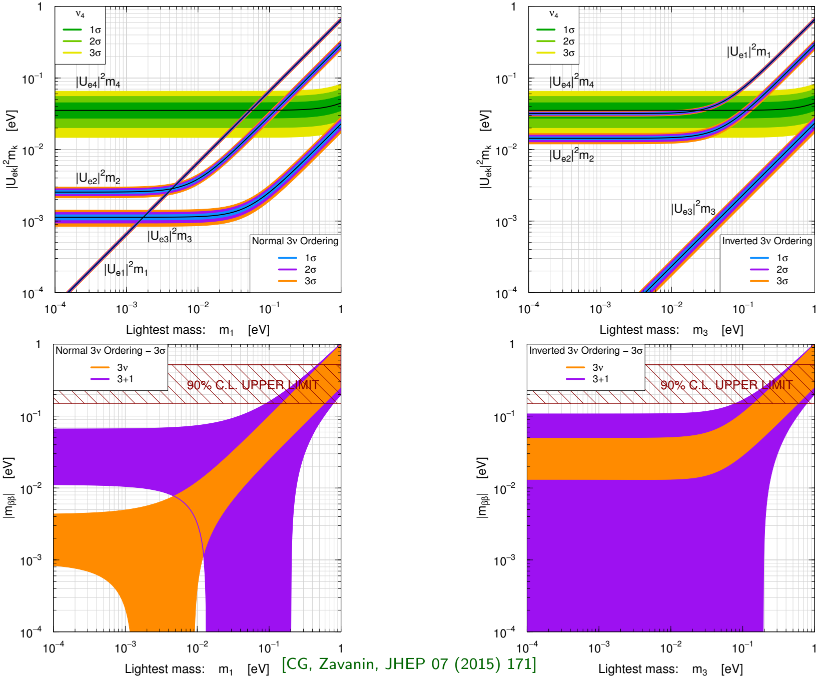
[Barry et al, JHEP 07 (2011) 091]

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

[Rodejohann, JPG 39 (2012) 124008]

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

[CG, Zavanin, JHEP 07 (2015) 171]



[CG, Zavanin, JHEP 07 (2015) 171]

Conclusions

- Exciting indications of light sterile neutrinos at the eV scale:
  - LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal (+ MiniBooNE?).
  - Gallium ν_e disappearance.
  - Reactor $\bar{\nu}_e$ disappearance (+ NEOS spectrum?).
- Vigorous experimental program to check conclusively in a few years:
  - ν_e and $\bar{\nu}_e$ disappearance with reactors and radioactive sources.
  - $\nu_\mu \to \nu_e$ transitions with accelerator neutrinos.
  - ν_μ disappearance with accelerator neutrinos.
- Independent tests through effect of m_4 in β-decay and $\beta\beta_{0\nu}$-decay.
- Cosmology: tension between $\Delta N_{\text{eff}} = 1$ and $m_s \approx 1\,\text{eV}$. It may be due to a non-standard cosmological mechanism.
- Possibilities for the next years:
  - Reactor and source experiments ν_e and $\bar{\nu}_e$ observe SBL oscillations: big excitement and explosion of the field.
  - Otherwise: still marginal interest to check the LSND appearance signal.
  - In any case the possibility of the existence of sterile neutrinos related to New Physics beyond the Standard Model will continue to be studied (e.g keV sterile neutrinos).