# Short-Baseline Neutrino Oscillation Anomalies and Light Sterile Neutrinos


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Cagliari High Energy Physics Colloquium

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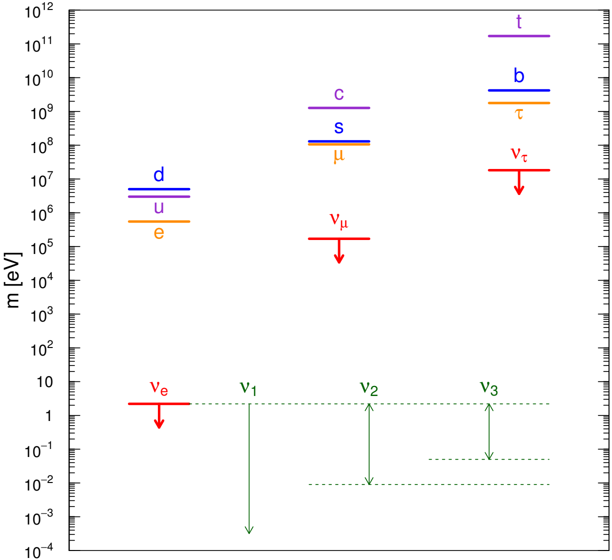
# Fermion Mass Spectrum



# Neutrino Mixing

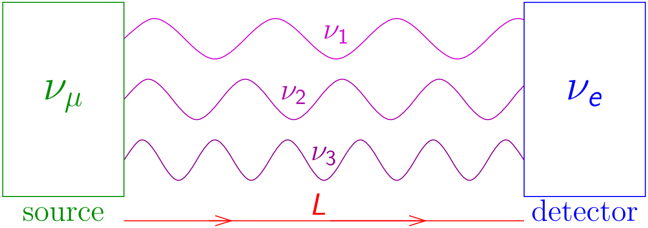
- Flavor Neutrinos: $\nu_e$, $\nu_\mu$, $\nu_\tau$ produced in Weak Interactions
- Massive Neutrinos: $\nu_1$, $\nu_2$, $\nu_3$ propagate from Source to Detector
- Neutrino Mixing: a Flavor Neutrino is a superposition of Massive Neutrinos

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

- $U$ is the $3 \times 3$ unitary Neutrino Mixing Matrix

# Neutrino Oscillations

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




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

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

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

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

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

| | | | |
|---|---|---|---|
| $\nu_e \to \nu_\mu$ | $\nu_e \to \nu_\tau$ | $\nu_\mu \to \nu_e$ | $\nu_\mu \to \nu_\tau$ |
| $\bar{\nu}_e \to \bar{\nu}_\mu$ | $\bar{\nu}_e \to \bar{\nu}_\tau$ | $\bar{\nu}_\mu \to \bar{\nu}_e$ | $\bar{\nu}_\mu \to \bar{\nu}_\tau$ |

# A Brief History of Neutrino Oscillations

- 1957: Pontecorvo proposed Neutrino Oscillations in analogy with $K^0 \leftrightarrows \bar{K}^0$ oscillations (Gell-Mann and Pais, 1955) $\Longrightarrow$ $\nu \leftrightarrows \bar{\nu}$
- In 1957 only one neutrino type $\nu = \nu_e$ was known! The possible existence of $\nu_\mu$ was discussed by several authors. Maybe the first have been Sakata and Inoue in 1946 and Konopinski and Mahmoud in 1953. Maybe Pontecorvo did not know. He discussed the possibility to distinguish $\nu_\mu$ from $\nu_e$ in 1959.
- 1962: Maki, Nakagava, Sakata proposed a model with $\nu_e$ and $\nu_\mu$ and Neutrino Mixing:

  *"weak neutrinos are not stable due to the occurrence of a virtual transmutation $\nu_e \leftrightarrows \nu_\mu$"*
- 1962: Lederman, Schwartz and Steinberger discover $\nu_\mu$
- 1967: Pontecorvo: intuitive $\nu_e \leftrightarrows \nu_\mu$ oscillations with maximal mixing. Applications to reactor and solar neutrinos ("prediction" of the solar neutrino problem).
- 1969: Gribov and Pontecorvo: $\nu_e - \nu_\mu$ mixing and oscillations. But no clear derivation of oscillations with a factor of 2 mistake in the phase (misprint?).

- 1975-76: Start of the "Modern Era" of Neutrino Oscillations with a general theory of neutrino mixing and a rigorous derivation of the oscillation probability by Eliezer and Swift, Fritzsch and Minkowski, and Bilenky and Pontecorvo. [Bilenky, Pontecorvo, Phys. Rep. (1978) 225]
- 1978: Wolfenstein discovers the effect on neutrino oscillations of the matter potential ("Matter Effect")
- 1985: Mikheev and Smirnov discover the resonant amplification of solar $\nu_e \to \nu_\mu$ oscillations due to the Matter Effect ("MSW Effect")
- 1998: the Super-Kamiokande experiment observed in a model-independent way the Vacuum Oscillations of atmospheric neutrinos ($\nu_\mu \to \nu_\tau$).
- 2002: the SNO experiment observed in a model-independent way the flavor transitions of solar neutrinos ($\nu_e \to \nu_\mu, \nu_\tau$), mainly due to adiabatic MSW transitions. [see: Smirnov, arXiv:1609.02386]
- 2015: Takaaki Kajita (Super-Kamiokande) and Arthur B. McDonald (SNO) received the Physics Nobel Prize "for the discovery of neutrino oscillations, which shows that neutrinos have mass"

# Three-Neutrino Mixing Paradigm

Standard Parameterization of Mixing Matrix

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

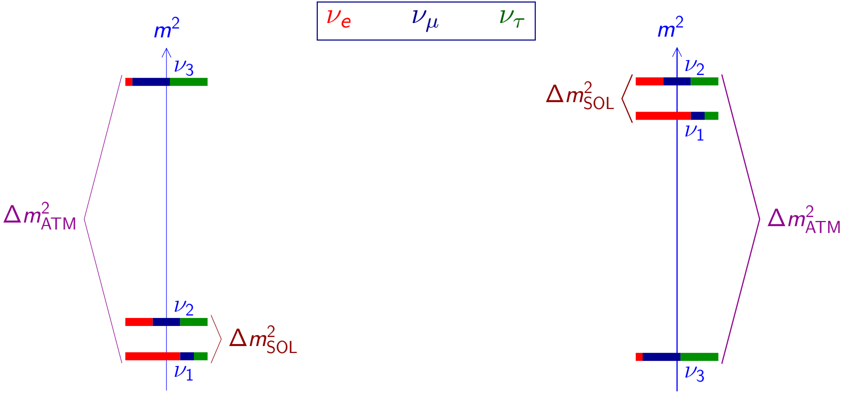
$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13}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

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

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

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

# Mass Ordering




Normal Ordering

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

Inverted Ordering

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

absolute scale is not determined by neutrino oscillation data

# Experimental Evidences of Neutrino Oscillations

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

VLBL Reactor
$\bar{\nu}_e$ disappearance

$\begin{pmatrix} \text{SNO, BOREXino} \\ \text{Super-Kamiokande} \\ \text{GALLEX/GNO, SAGE} \\ \text{Homestake, Kamiokande} \end{pmatrix}$

(KamLAND)

$$\to \begin{cases} \Delta m^2_{\text{SOL}} = \Delta m^2_{21} \simeq 7.6 \times 10^{-5}\,\text{eV}^2 \\ \sin^2\vartheta_{\text{SOL}} = \sin^2\vartheta_{12} \simeq 0.30 \end{cases}$$

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

LBL Accelerator
$\nu_\mu$ disappearance

LBL Accelerator
$\nu_\mu \to \nu_\tau$

$\begin{pmatrix} \text{Super-Kamiokande} \\ \text{Kamiokande, IMB} \\ \text{MACRO, Soudan-2} \end{pmatrix}$

$\begin{pmatrix} \text{K2K, MINOS} \\ \text{T2K, NO}\nu\text{A} \end{pmatrix}$

(Opera)

$$\to \begin{cases} \Delta m^2_{\text{ATM}} = |\Delta m^2_{31}| \simeq 2.4 \times 10^{-3}\,\text{eV}^2 \\ \sin^2\vartheta_{\text{ATM}} = \sin^2\vartheta_{23} \simeq 0.50 \end{cases}$$

LBL Accelerator
$\nu_\mu \to \nu_e$

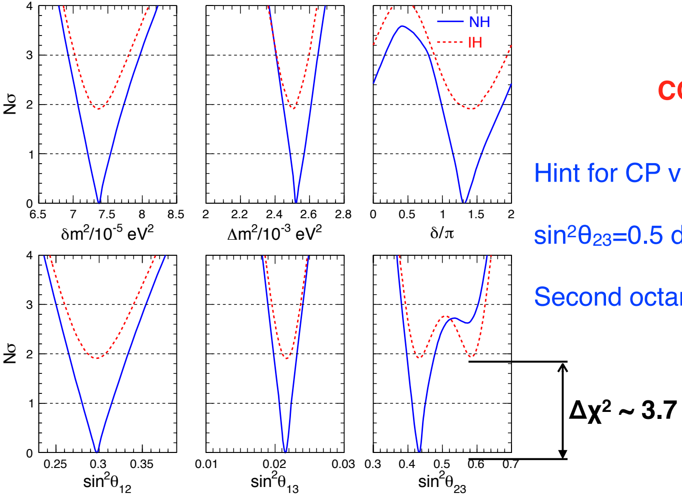
(T2K, MINOS, NO$\nu$A)

LBL Reactor
$\bar{\nu}_e$ disappearance

$\begin{pmatrix} \text{Daya Bay, RENO} \\ \text{Double Chooz} \end{pmatrix}$

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

# September 2016 Global Fit




**COMMENTS**

Hint for CP violation at ~2σ

$\sin^2\theta_{23}=0.5$ disfavoured at ~2.8σ

Second octant disfavoured at ~2σ

[Capozzi, Lisi, Marrone, Montanino, Palazzo @ NOW2016, September 2016]

[See also: Esteban, Gonzalez-Garcia, Maltoni, Martinez-Soler, Schwetz, arXiv:1611.01514]

# Open Problems

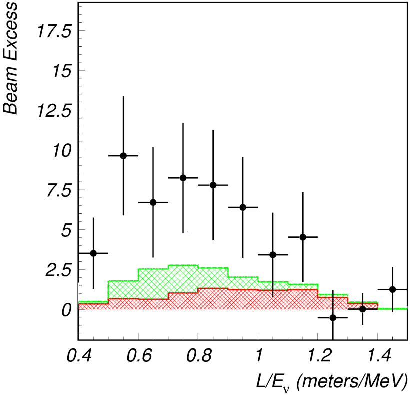
- $\vartheta_{23} \lesseqgtr 45^\circ$ ?
  - T2K (Japan), NO$\nu$A (USA), ...
- CP violation ? $\delta_{13} \approx 3\pi/2$ ?
  - T2K (Japan), NO$\nu$A (USA), DUNE (USA), HyperK (Japan), ...
- Mass Ordering ?
  - JUNO (China), RENO-50 (Korea), PINGU (Antarctica), ORCA (EU), INO (India), ...
- Absolute Mass Scale ?
  - $\beta$ Decay, Neutrinoless Double-$\beta$ Decay, Cosmology, ...
- Dirac or Majorana ?
  - Neutrinoless Double-$\beta$ Decay, ...
- Beyond Three-Neutrino Mixing ? Sterile Neutrinos ?

# Indications of SBL Oscillations Beyond $3\nu$

# LSND

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

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\quad$ $20\,\text{MeV} \leq E \leq 60\,\text{MeV}$




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

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

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

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

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

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

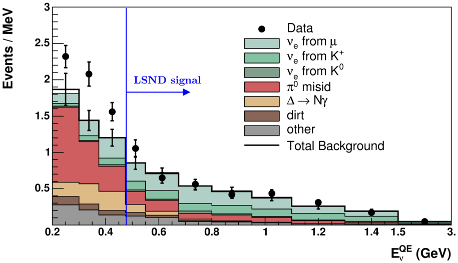
[PRD 65 (2002) 112001]

$\approx 3.8\sigma$ excess $\qquad$ $\Delta m^2_{\text{SBL}} \gtrsim 0.2\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}}$

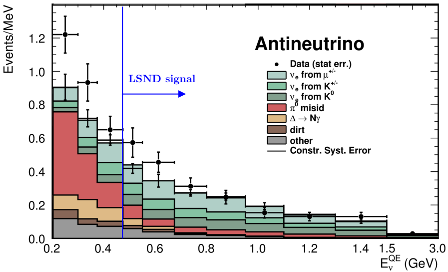
# MiniBooNE

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

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




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

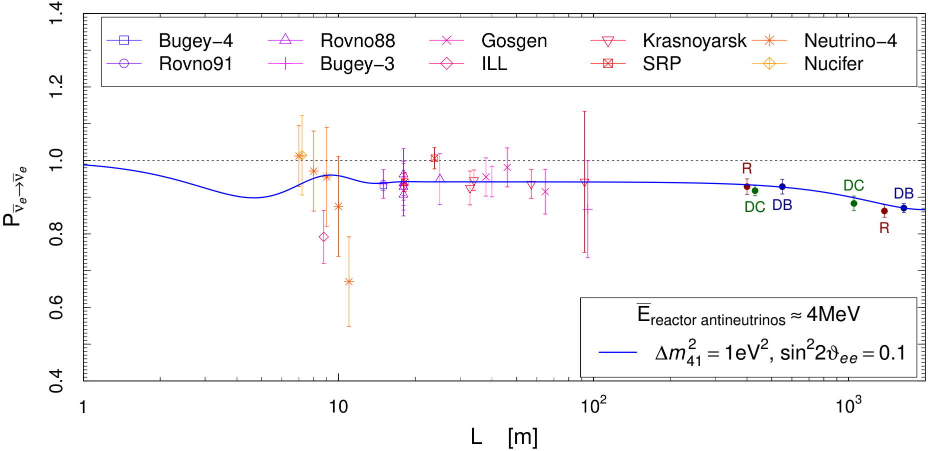



- Purpose: check LSND signal.
- Different $L$ and $E$.
- Similar $L/E$ (oscillations).
- No money, no Near Detector.
- LSND signal: $E > 475\,\mathrm{MeV}$.
- Agreement with LSND signal?
- CP violation?
- Low-energy anomaly!

# 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]




$\approx 2.9\sigma$ deficit $\quad \Delta m^2_{\text{SBL}} \gtrsim 1\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}}$

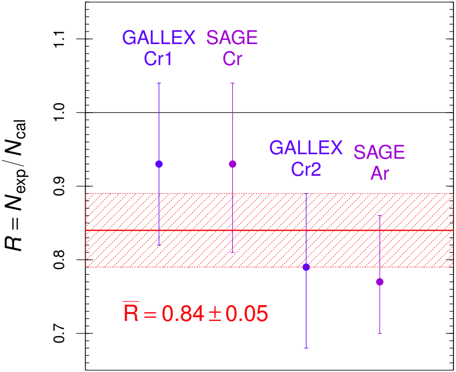
# Gallium Anomaly

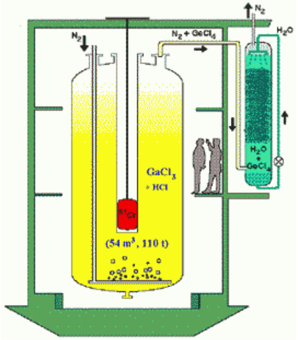
Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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

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



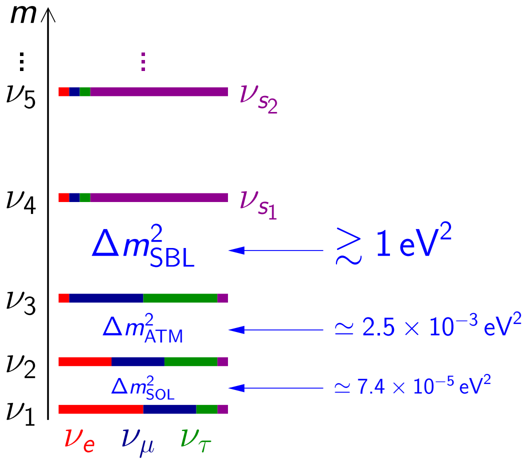

$\approx 2.9\sigma$ deficit

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

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

[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]

# Beyond Three-Neutrino Mixing: Sterile Neutrinos




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

# Sterile Neutrinos from Physics Beyond the SM

- Neutrinos are special in the Standard Model: the only neutral fermions
- Active left-handed neutrinos can mix with non-SM singlet fermions often called right-handed neutrinos Neutrino Portal [A. Smirnov, arXiv:1502.04530]
- Light left-handed anti-$\nu_R$ are light sterile neutrinos

$$\nu_R^c \to \nu_{sL} \qquad \text{(left-handed)}$$

- Sterile means no standard model interactions

[Pontecorvo, Sov. Phys. JETP 26 (1968) 984]

- Active neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$ can oscillate into light sterile neutrinos $(\nu_s)$
- Observables:
  - Disappearance of active neutrinos (neutral current deficit)
  - Indirect evidence through combined fit of data (current indication)
- Short-baseline anomalies + $3\nu$-mixing:

$$\begin{array}{ccccccccc} & \Delta m^2_{21} & \ll & |\Delta m^2_{31}| & \ll & |\Delta m^2_{41}| & \leq & \ldots \\ \nu_1 & & \nu_2 & & \nu_3 & & \nu_4 & & \ldots \\ \nu_e & & \nu_\mu & & \nu_\tau & & \nu_{s_1} & & \ldots \end{array}$$

# 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

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

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

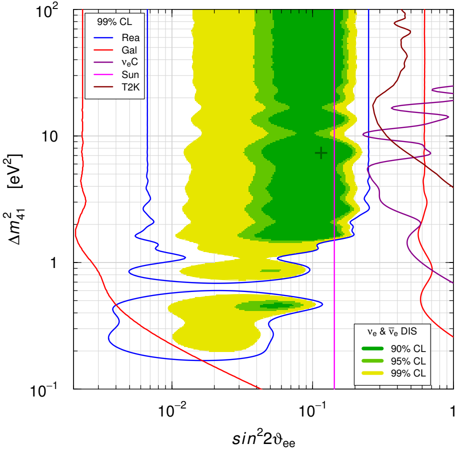
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

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 $\Delta m^2_{\text{ATM}}$ [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 $\Delta m^2_{\text{SOL}}$ [Long, Li, CG, PRD 87, 113004 (2013) 113004]

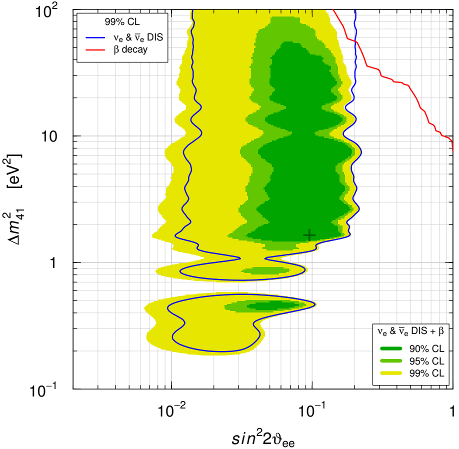
# Global $\nu_e$ and $\bar{\nu}_e$ Disappearance




KARMEN + LSND $\nu_e + {}^{12}\mathrm{C} \to {}^{12}\mathrm{N}_{\mathrm{g.s.}} + e^-$
[Conrad, Shaevitz, PRD 85 (2012) 013017]
[CG, Laveder, PLB 706 (2011) 200]

solar $\nu_e$ + KamLAND $\bar{\nu}_e$ + $\vartheta_{13}$
[CG, Li, PRD 80 (2009) 113007]
[Palazzo, PRD 83 (2011) 113013; PRD 85 (2012) 077301]
[CG, Laveder, Li, Liu, Long, PRD 86 (2012) 113014]

T2K Near Detector $\nu_e$ disappearance
[T2K, PRD 91 (2015) 051102]

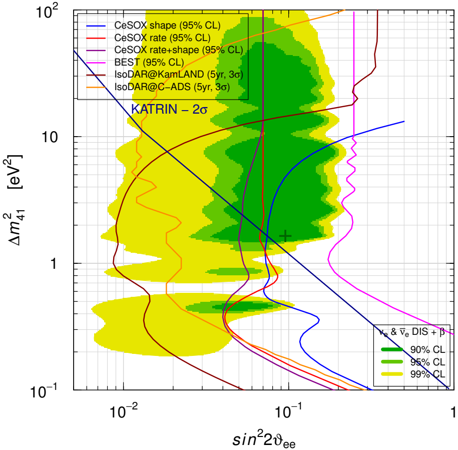


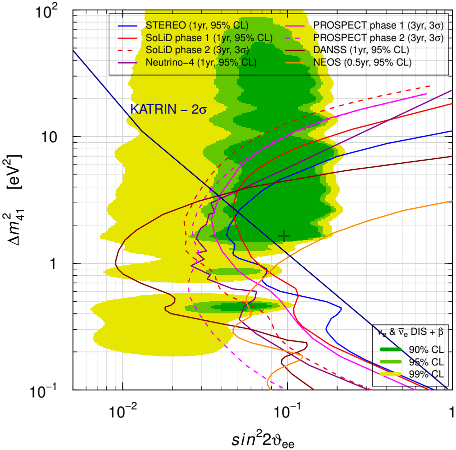

Mainz + Troitsk Tritium $\beta$ decay
[Mainz, EPJC 73 (2013) 2323]
[Troitsk, JETPL 97 (2013) 67; JPG 41 (2014) 015001]

No Osc. excluded at $2.8\sigma$
$(\Delta\chi^2/\mathrm{NDF} = 10.8/2)$

$$6\,\mathrm{cm} \lesssim \frac{L_{41}^{\mathrm{osc}}}{E\,[\mathrm{MeV}]} \lesssim 6\,\mathrm{m} \qquad (2\sigma)$$

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




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

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

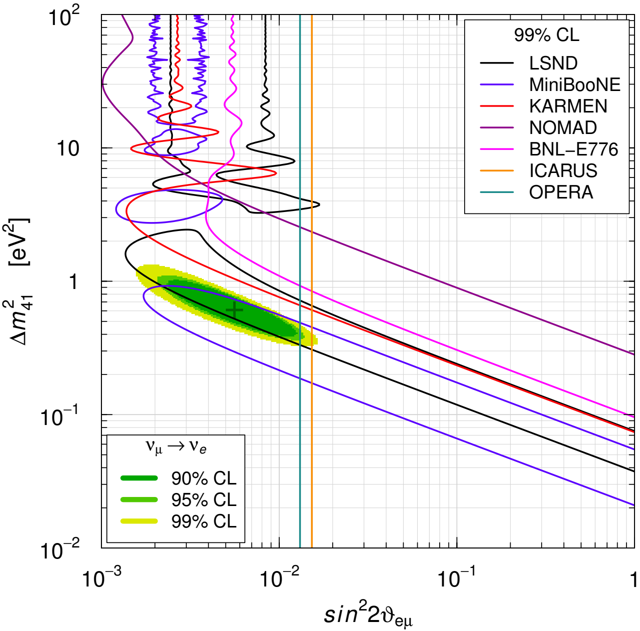
IsoDAR@KamLAND (Kamioka, Japan)
$^{8}\text{Li} \to \bar{\nu}_e$ $L \simeq$ 16m [arXiv:1511.05130]

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

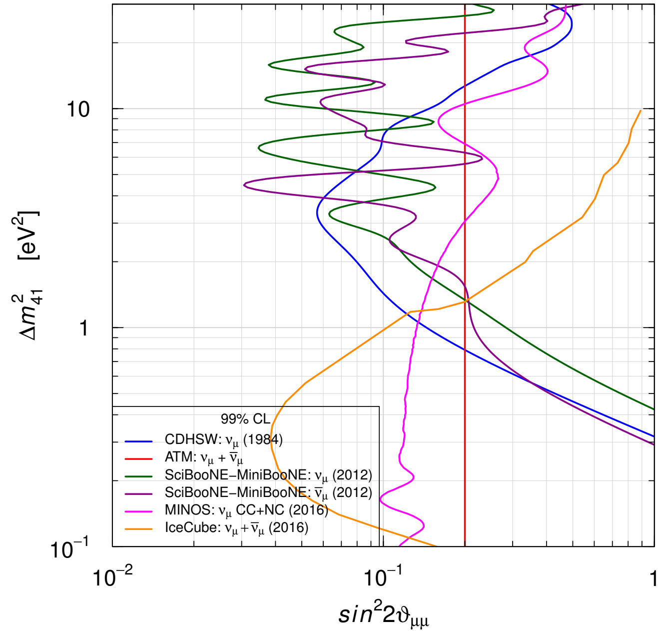
STEREO (ILL, France) $L \simeq$ 8-12m [arXiv:1602.00568]
SoLid (SCK-CEN, Belgium) $L \simeq$ 5-8m [arXiv:1510.07835]
Neutrino-4 (RIAR, Russia) $L \simeq$ 6-11m [JETP 121 (2015) 578]
PROSPECT (ORNL, USA) $L \simeq$ 7-12m [arXiv:1512.02202]
DANSS (Kalinin, Russia) $L \simeq$ 10-12m [arXiv:1606.02896]
NEOS (Hanbit, Korea) $L \simeq$ 24m [Oh@WIN2015]

KATRIN (Karlsruhe, Germany) $^{3}\text{H} \to \bar{\nu}_e$ [Mertens@TAUP2015]

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



# $\nu_\mu$ and $\bar{\nu}_\mu$ Disappearance



# 3+1 Appearance-Disappearance Tension

$\nu_e$ DIS

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

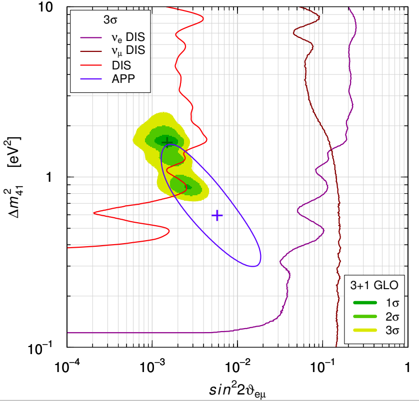
$\nu_\mu$ DIS

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

$\nu_\mu \to \nu_e$ 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!
- Similar constraint in

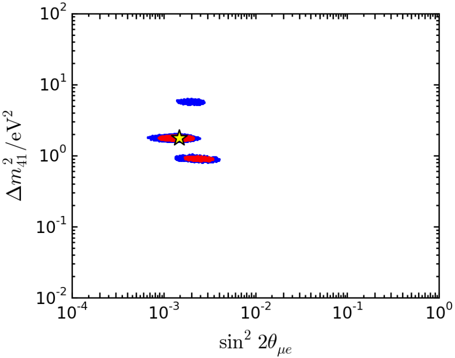
  3+2, 3+3, . . . , 3+$N_s$

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

Update of [Gariazzo, CG, Laveder, Li, Zavanin, JPG 43 (2016) 033001] with improved treatment of the MiniBooNE background disappearance due to neutrino oscillations according to information from Bill Louis (thanks!)

Collin, Arguelles, Conrad, Shaevitz

[NPB 908 (2016) 354]




Best Fit: $\Delta m^2_{41} = 1.75\,\text{eV}^2$

$|U_{e4}|^2 = 0.027 \qquad |U_{\mu 4}|^2 = 0.014$

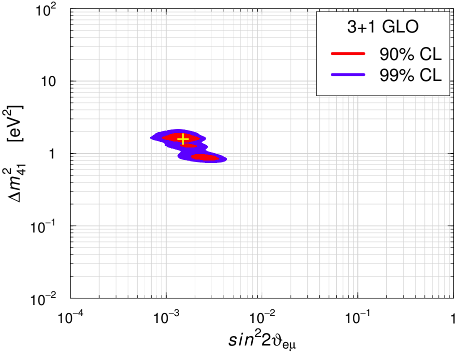
$\text{GoF} = 57\%\,(\chi^2_{\text{min}}/\text{NDF} = 306.8/312)$

$\text{GoF}_{\text{null}} = 4.4\%\,(\chi^2/\text{NDF} = 359.2/315)$

$\Delta\chi^2/\text{NDF} = 52.3/3\ (\approx 6.7\sigma)$

Our Fit

Update of [Gariazzo, CG, Laveder, Li, Zavanin, JPG 43 (2016) 033001]




Best Fit: $\Delta m^2_{41} = 1.6\,\text{eV}^2$

$|U_{e4}|^2 = 0.028 \qquad |U_{\mu 4}|^2 = 0.014$

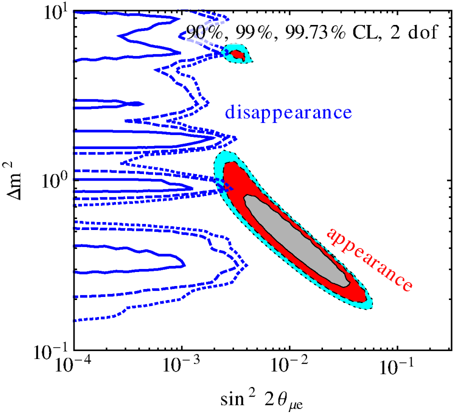
$\text{GoF} = 6\%\,(\chi^2_{\text{min}}/\text{NDF} = 304.0/268)$

$\text{GoF}_{\text{null}} = 0.04\%\,(\chi^2/\text{NDF} = 355.2/271)$

$\Delta\chi^2/\text{NDF} = 51.2/3\ (\approx 6.6\sigma)$

## Kopp, Machado, Maltoni, Schwetz

[JHEP 1305 (2013) 050]




Best Fit: $\Delta m^2_{41} = 0.93\,\mathrm{eV}^2$

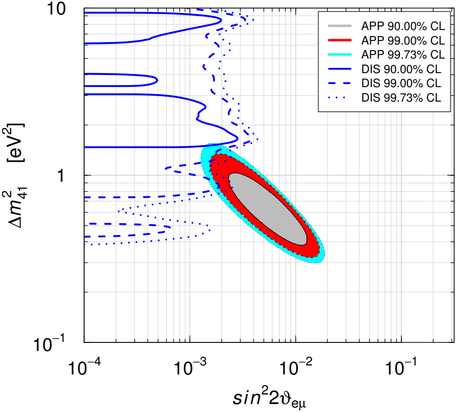
$|U_{e4}|^2 = 0.023$ $|U_{\mu4}|^2 = 0.029$

$\mathrm{GoF} = 19\%\,(\chi^2_{\mathrm{min}}/\mathrm{NDF} = 712/680)$

$\mathrm{GoF_{PG}} = 0.01\%\,(\chi^2_{\mathrm{PG}}/\mathrm{NDF} = 18.0/2)$

## Our Fit

Update of [Gariazzo, CG, Laveder, Li, Zavanin, JPG 43 (2016) 033001]




Best Fit: $\Delta m^2_{41} = 1.6\,\mathrm{eV}^2$

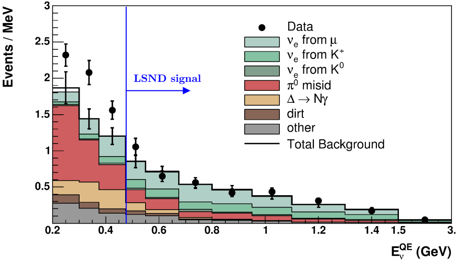
$|U_{e4}|^2 = 0.028$ $|U_{\mu4}|^2 = 0.014$

$\mathrm{GoF} = 6\%\,(\chi^2_{\mathrm{min}}/\mathrm{NDF} = 304.0/268)$

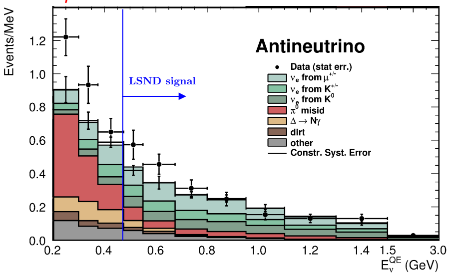
$\mathrm{GoF_{PG}} = 0.06\%\,(\chi^2/\mathrm{NDF} = 15.0/2)$

# MiniBooNE Low-Energy Anomaly

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




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

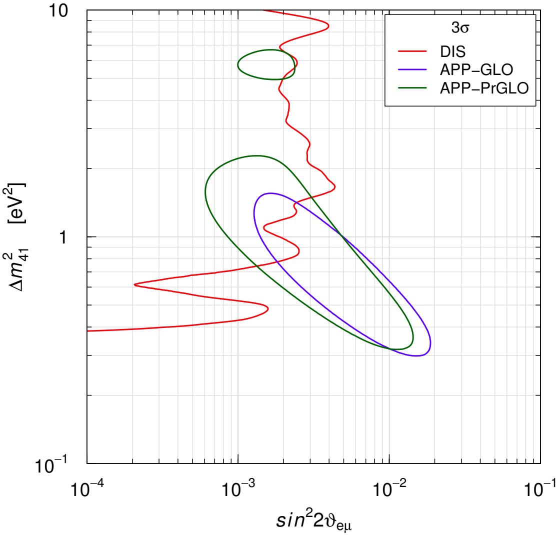



- Fit of MB Low-Energy Excess requires small $\Delta m^2_{41}$ and large $\sin^2 2\vartheta_{e\mu}$, in contradiction with disappearance data

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

- MB low-energy excess is the main cause of bad APP-DIS $\mathrm{GoF}_{\mathrm{PG}} = 0.06\%$
- 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

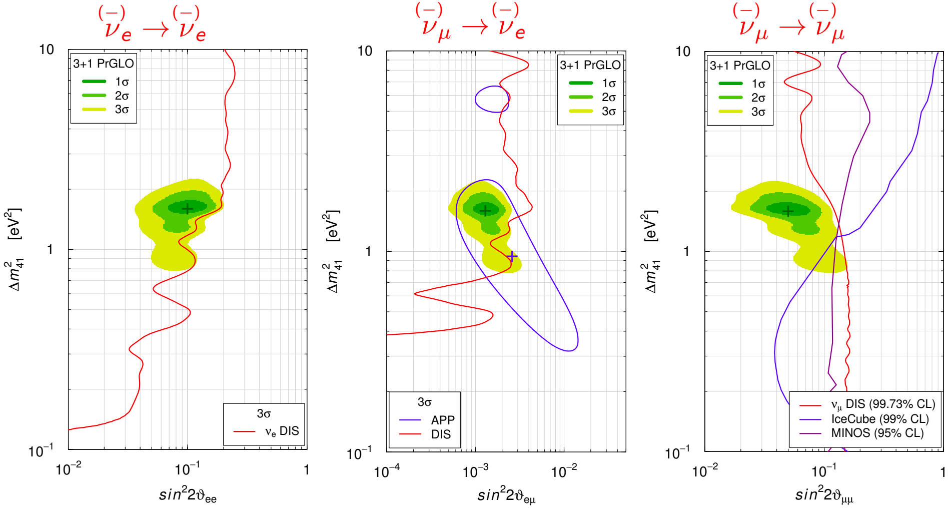
# Global → Pragmatic




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

# Pragmatic Global 3+1 Fit

Update of [Gariazzo, CG, Laveder, Li, Zavanin, JPG 43 (2016) 033001]




GoF = 24%    PGoF = 7%

No Osc. disfavored at $\approx 6.2\sigma$

$\Delta\chi^2/\text{NDF} = 46.6/3$

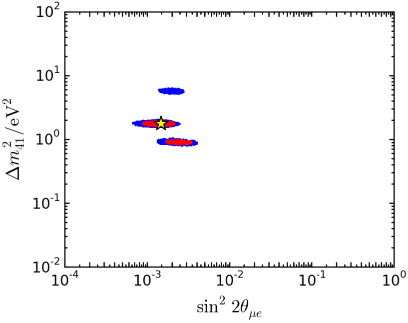
Not yet included:

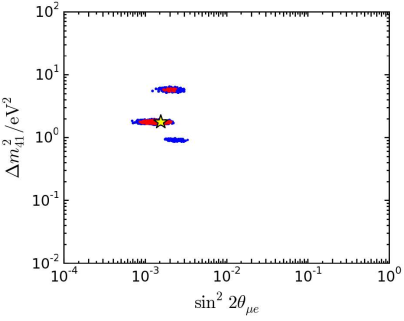
- IceCube, arXiv:1605.01990
- MINOS, arXiv:1607.01176

# SBL + IceCube

[Collin, Arguelles, Conrad, Shaevitz, arXiv:1607.00011]

SBL → SBL + IceCube

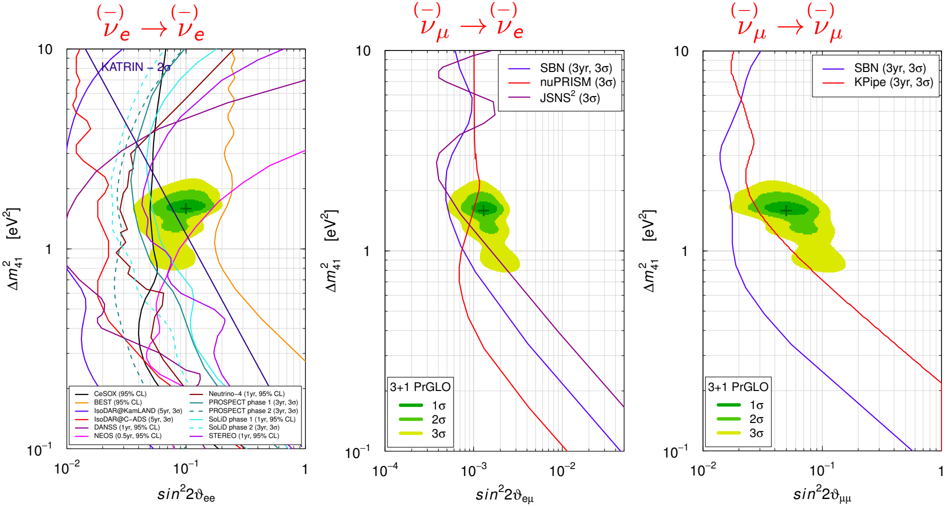



Red: 90% CL Blue: 99% CL

| 3+1 | $\Delta m^2_{41}$ | $\lvert U_{e4}\rvert$ | $\lvert U_{\mu 4}\rvert$ | $\lvert U_{\tau 4}\rvert$ | $N_{bins}$ | $\chi^2_{\min}$ | $\chi^2_{\text{null}}$ | $\Delta\chi^2$ (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) |

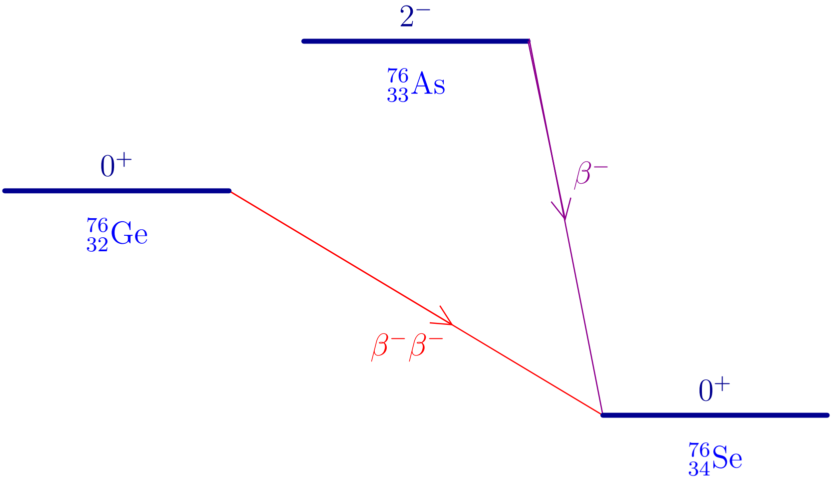
# The Race for the Light Sterile



## Effects of light sterile neutrinos should also be seen in:

- $\beta$ 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-$\beta$ 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, arXiv:1601.05995, arXiv:1603.03759, arXiv:1605.04299; Gandhi et al, JHEP 1511 (2015) 039; Pant et al, arXiv:1509.04096, Choubey, Pramanik, arXiv:1604.04731]
- 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]

# Neutrinoless Double-Beta Decay



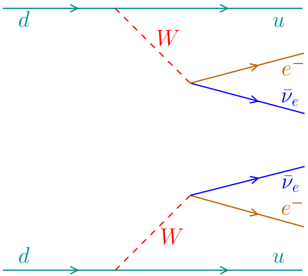

Effective Majorana Neutrino Mass: $m_{\beta\beta} = \sum_k U_{ek}^2 \, m_k$

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

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

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

second order weak interaction process
in the Standard Model

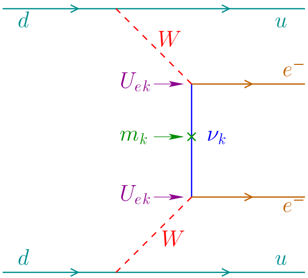


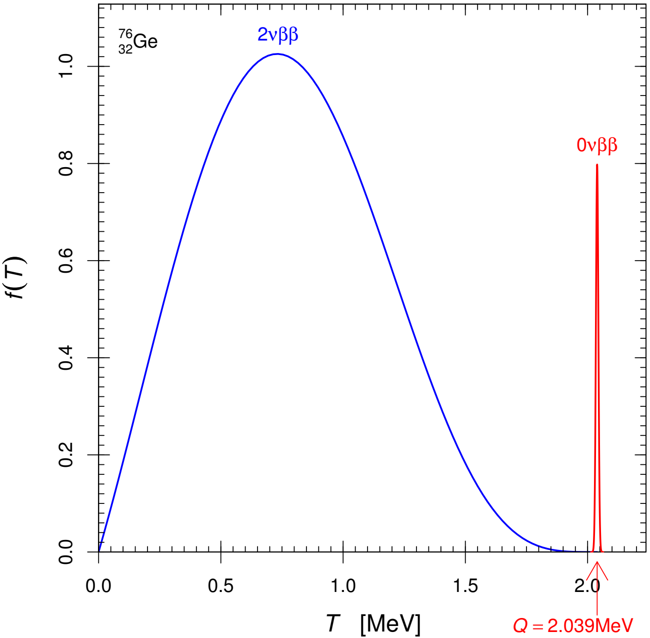

## Neutrinoless Double-$\beta$ Decay: $\Delta L = 2$

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

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

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





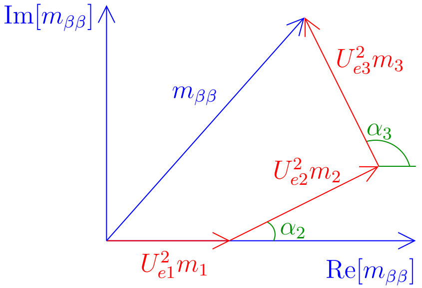
$^{76}_{32}$Ge
2νββ
0νββ
f(T)
T [MeV]
Q = 2.039MeV
0.0
0.2
0.4
0.6
0.8
1.0
0.5
1.5
2.0

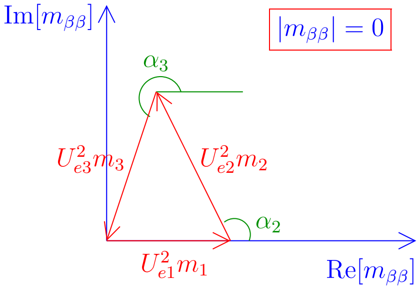
# Effective Majorana Neutrino Mass

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

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

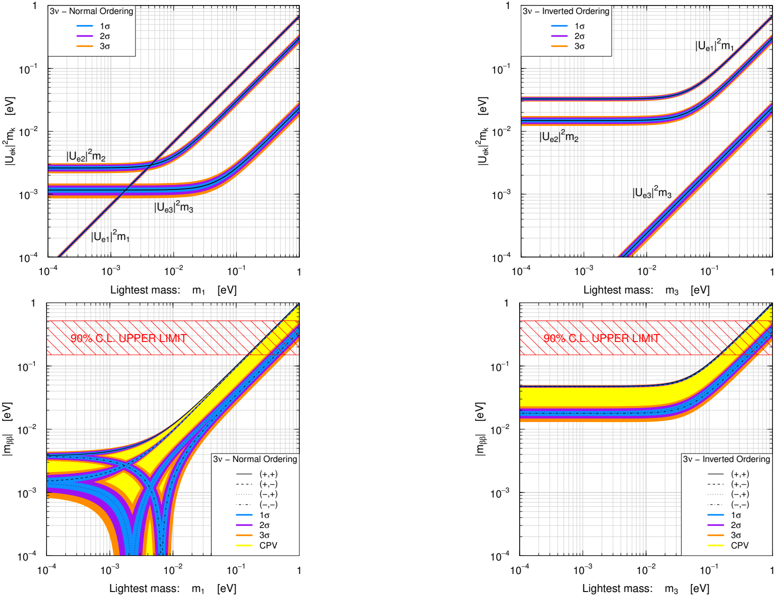
$$\alpha_2 = 2\lambda_2 \qquad \alpha_3 = 2\left(\lambda_3 - \delta_{13}\right)$$



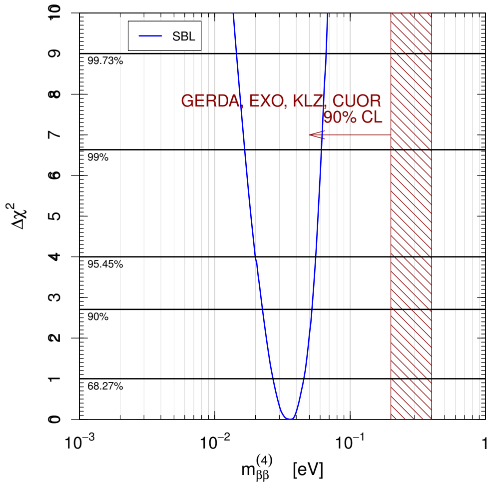
# Predictions of $3\nu$-Mixing Paradigm

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



# 3+1 Mixing

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




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 $m_{\beta\beta}^{(3\nu)}$

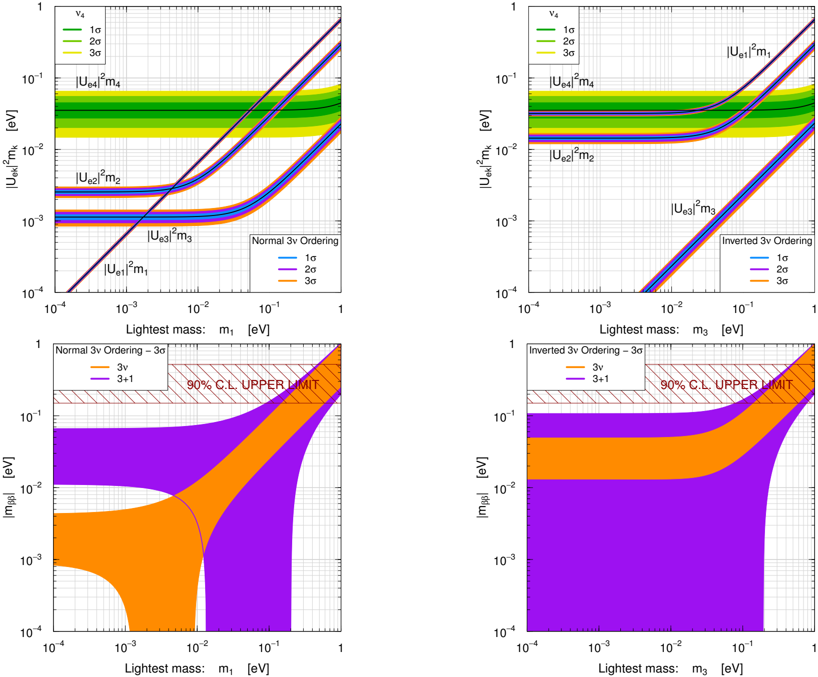
[Barry et al, JHEP 07 (2011) 091]

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

[Rodejohann, JPG 39 (2012) 124008]

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

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



ν4
1σ
2σ
3σ
$|U_{e4}|^2 m_4$
$|U_{e2}|^2 m_2$
$|U_{e3}|^2 m_3$
$|U_{e1}|^2 m_1$
Normal 3ν Ordering
Inverted 3ν Ordering
$|U_{ek}|^2 m_k$ [eV]
Lightest mass: $m_1$ [eV]
Lightest mass: $m_3$ [eV]
Normal 3ν Ordering – 3σ
Inverted 3ν Ordering – 3σ
3ν
3+1
90% C.L. UPPER LIMIT
$|m_{\beta\beta}|$ [eV]

# Conclusions

- Exciting indications of light sterile neutrinos at the eV scale:
  - LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal.
  - Gallium $\nu_e$ disappearance.
  - Reactor $\bar{\nu}_e$ disappearance.
- Vigorous experimental program to check conclusively in a few years:
  - $\nu_e$ and $\bar{\nu}_e$ disappearance with reactors and radioactive sources.
  - $\nu_\mu \to \nu_e$ transitions with accelerator neutrinos.
  - $\nu_\mu$ disappearance with accelerator neutrinos.
- Possibilities for the next years:
  - Reactor and source experiments $\nu_e$ and $\bar{\nu}_e$ observe SBL oscillations: big excitement and explosion of the field.
  - Because of 5 MeV bump we know that the calculated spectrum must be corrected: oscillations must be observed as a function of distance!
  - 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).
  - Sterile neutrinos will always be allowed at all mass scales below the existing mixing bounds.