Short-Baseline Neutrino Anomalies

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Selected Puzzles in Particle Physics

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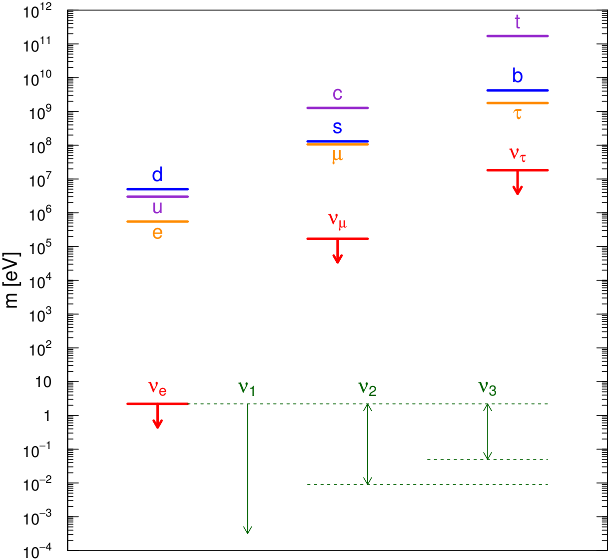
Fermion Mass Spectrum



Neutrino Mixing

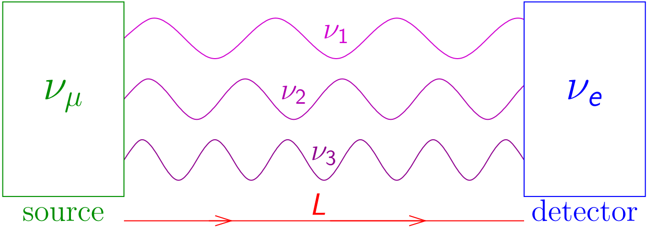
- Flavor Neutrinos: ν_e, ν_μ, ν_τ produced in Weak Interactions
- Massive Neutrinos: ν_1, ν_2, ν_3 propagate from Source to Detector
- Neutrino Mixing: a Flavor Neutrino is a superposition of Massive Neutrinos

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

- U is the 3×3 unitary Neutrino Mixing Matrix

Neutrino Oscillations

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



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

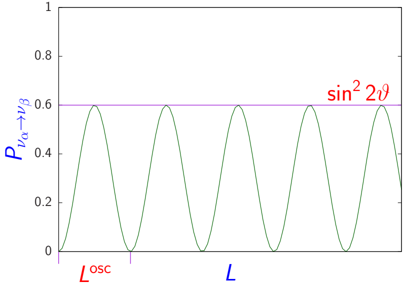
$$E_k^2 = p^2 + m_k^2$$

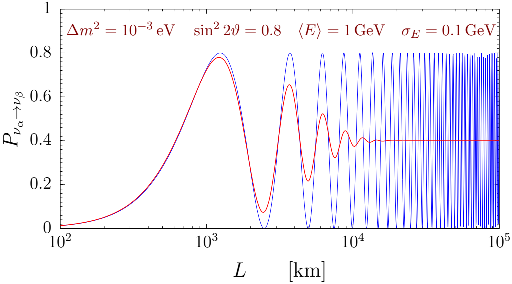
$$P_{\nu_\mu\to\nu_e}(t>0) = |\langle\nu_e|\nu(t>0)\rangle|^2 \sim \sum_{k>j} \mathrm{Re}\left[U_{ek}\,U_{\mu k}^*\,U_{ej}^*\,U_{\mu j}\right]\sin^2\left(\frac{\Delta m_{kj}^2 L}{4E}\right)$$

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

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

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





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 Paradigm

Standard Parameterization of Mixing Matrix

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

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

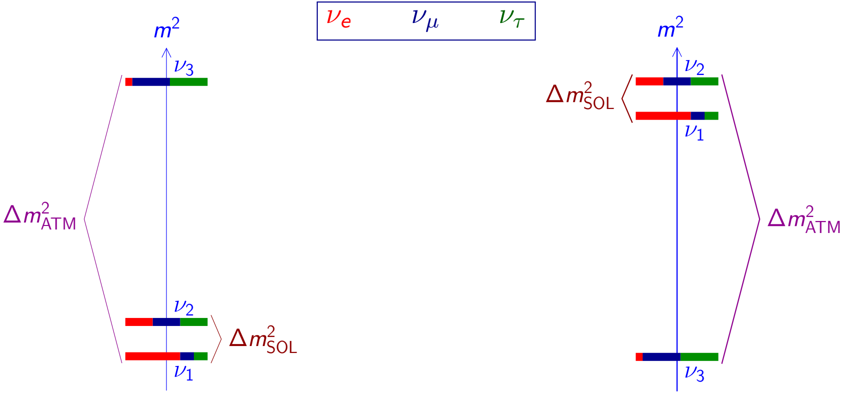
$c_{ab} \equiv \cos\vartheta_{ab}$ $\quad s_{ab} \equiv \sin\vartheta_{ab}$ $\quad 0 \leq \vartheta_{ab} \leq \frac{\pi}{2}$ $\quad 0 \leq \delta_{13}, \lambda_{21}, \lambda_{31} < 2\pi$

OSCILLATION PARAMETERS

- 3 Mixing Angles: 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

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

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

(KamLAND)

$$\rightarrow \left\{ \begin{array}{c} \Delta m^2_{\text{SOL}} = \Delta m^2_{21} \simeq 7.5 \times 10^{-5}\,\text{eV}^2 \\ \sin^2\vartheta_{\text{SOL}} = \sin^2\vartheta_{12} \simeq 0.30 \end{array} \right.$$

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

LBL Accelerator
ν_μ disappearance

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

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

(K2K, MINOS
T2K, NOνA)

(Opera)

$$\rightarrow \left\{ \begin{array}{c} \Delta m^2_{\text{ATM}} = |\Delta m^2_{31}| \simeq 2.5 \times 10^{-3}\,\text{eV}^2 \\ \sin^2\vartheta_{\text{ATM}} = \sin^2\vartheta_{23} \simeq 0.50 \end{array} \right.$$

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

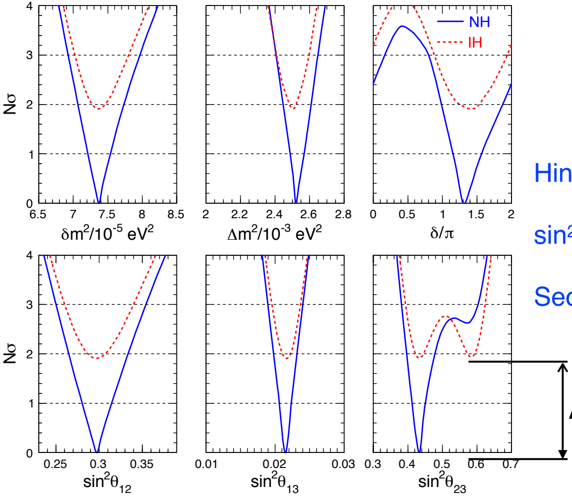
LBL Reactor
$\bar{\nu}_e$ disappearance

(T2K, MINOS, NOνA)

(Daya Bay, RENO
Double Chooz)

$$\rightarrow \left\{ \begin{array}{c} \Delta m^2_{\text{ATM}} = |\Delta m^2_{31}| \\ \sin^2\vartheta_{13} \simeq 0.023 \end{array} \right.$$

September 2016 Global Fit



$\Delta\chi^2 \sim 3.7$

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

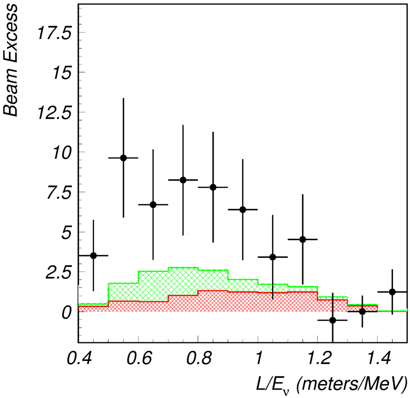
- $\vartheta_{23} \lesseqgtr 45^\circ$?
  - T2K (Japan), NOνA (USA), ...
- CP violation ? $\delta_{13} \approx 3\pi/2$?
  - T2K (Japan), NOνA (USA), DUNE (USA), HyperK (Japan), ...
- Mass Ordering ?
  - JUNO (China), RENO-50 (Korea), PINGU (Antarctica), ORCA (EU), INO (India), ...
- Absolute Mass Scale ?
  - β Decay, Neutrinoless Double-β Decay, Cosmology, ...
- Dirac or Majorana ?
  - Neutrinoless Double-β Decay, ...
- Beyond Three-Neutrino Mixing ? Sterile Neutrinos ?

Indications of SBL Oscillations Beyond 3ν

LSND

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

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



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

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

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

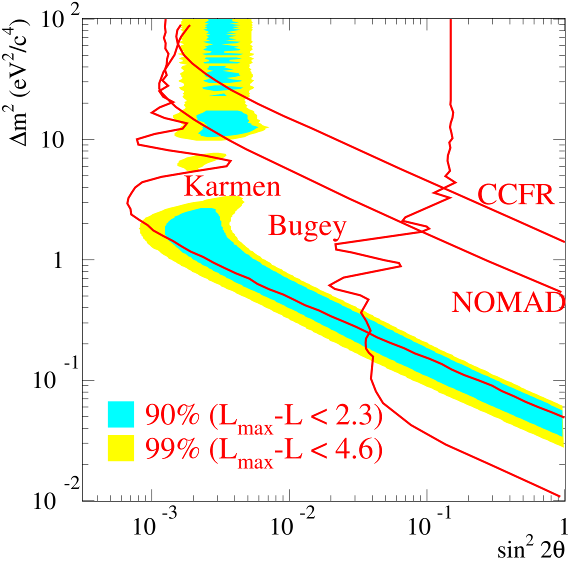
  $\bar{\nu}_e + p \to n + e^+$

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

- $\approx 3.8\sigma$ excess

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

  [PRD 65 (2002) 112001]

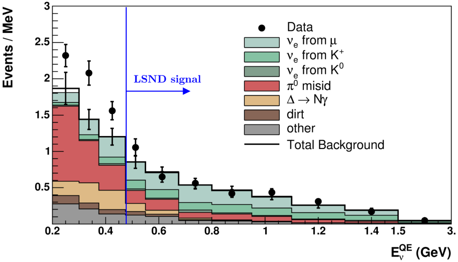


$$\Delta m^2_{\text{SBL}} \gtrsim 3 \times 10^{-2}\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \simeq 2.5 \times 10^{-3}\,\text{eV}^2 \gg \Delta m^2_{\text{SOL}}$$

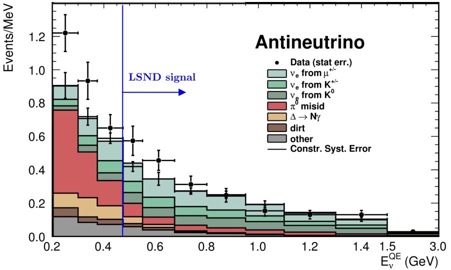
MiniBooNE

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

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



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

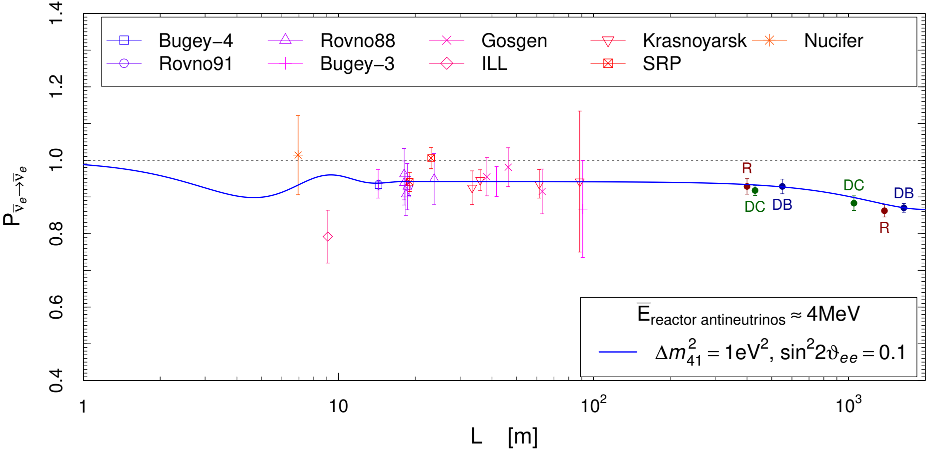


- Purpose: check LSND signal.
- Different L and E.
- Similar L/E (oscillations).
- No money, no Near Detector.
- LSND signal: $E > 475\,\text{MeV}$.
- Agreement with LSND signal?
- CP violation?
- Low-energy anomaly!

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

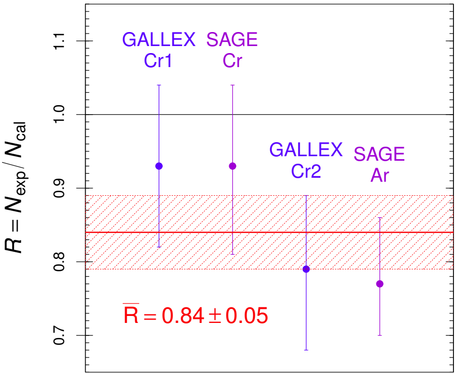
Gallium Anomaly

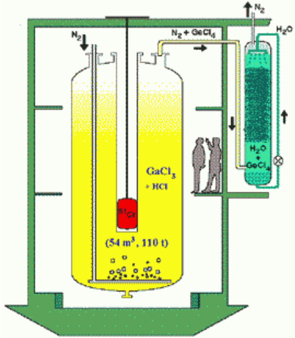
Gallium Radioactive Source Experiments: GALLEX and SAGE

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

$E \simeq 0.75\,\text{MeV}$ $\qquad$ $E \simeq 0.81\,\text{MeV}$

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





$\approx 2.9\sigma$ deficit

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

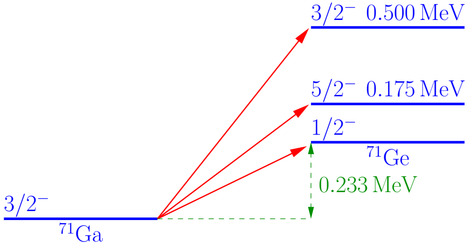
$\Delta m^2_{\text{SBL}} \gtrsim 1\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}}$

[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]

- Deficit could be due to overestimate of

$$\sigma(\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-)$$

- Calculation: Bahcall, PRC 56 (1997) 3391



- $\sigma_{\mathrm{G.S.}}$ from $T_{1/2}({}^{71}\mathrm{Ge}) = 11.43 \pm 0.03\,\mathrm{days}$ [Hampel, Remsberg, PRC 31 (1985) 666]

$$\sigma_{\mathrm{G.S.}}({}^{51}\mathrm{Cr}) = 55.3 \times 10^{-46}\,\mathrm{cm}^2\,(1 \pm 0.004)_{3\sigma}$$

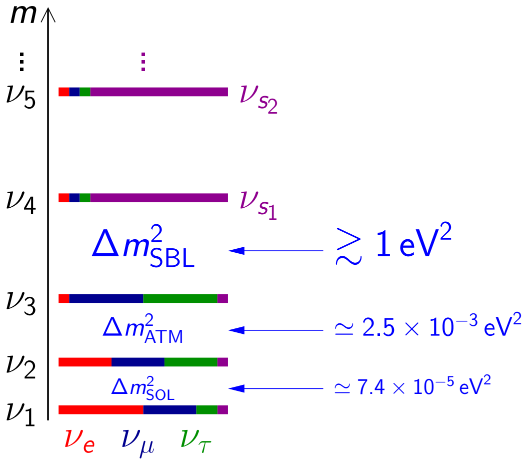
- $\sigma({}^{51}\mathrm{Cr}) = \sigma_{\mathrm{G.S.}}({}^{51}\mathrm{Cr}) \left(1 + 0.669\,\dfrac{\mathrm{BGT}_{175}}{\mathrm{BGT}_{\mathrm{G.S.}}} + 0.220\,\dfrac{\mathrm{BGT}_{500}}{\mathrm{BGT}_{\mathrm{G.S.}}}\right)$

- Contribution of excited states only 5%!

		$\frac{\mathrm{BGT}_{175}}{\mathrm{BGT}_{\mathrm{G.S.}}}$	$\frac{\mathrm{BGT}_{500}}{\mathrm{BGT}_{\mathrm{G.S.}}}$
Krofcheck et al. PRL 55 (1985) 1051	$^{71}\mathrm{Ga}(p,n)^{71}\mathrm{Ge}$	< 0.056	0.126 ± 0.023
Haxton PLB 431 (1998) 110	Shell Model	0.19 ± 0.18	
Frekers et al. PLB 706 (2011) 134	$^{71}\mathrm{Ga}(^{3}\mathrm{He},{}^{3}\mathrm{H})^{71}\mathrm{Ge}$	0.039 ± 0.030	0.202 ± 0.016

- The $^{71}\mathrm{Ga}(^{3}\mathrm{He},{}^{3}\mathrm{H})^{71}\mathrm{Ge}$ data confirm the contribution of the two excited states.
- Haxton: “The calculation predicts destructive interference between the (p,n) spin and spin-tensor matrix elements”
- It is unlikely that the deficit is caused by an overestimate of the cross section.
- Possible explanations:
  - Statistical fluctuations.
  - Experimental faults.
  - Short-baseline oscillations.

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-ν_R are light sterile neutrinos

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

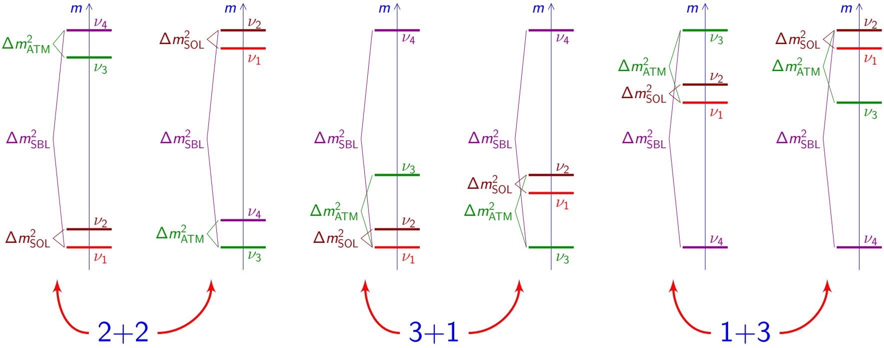
- Sterile means no standard model interactions

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

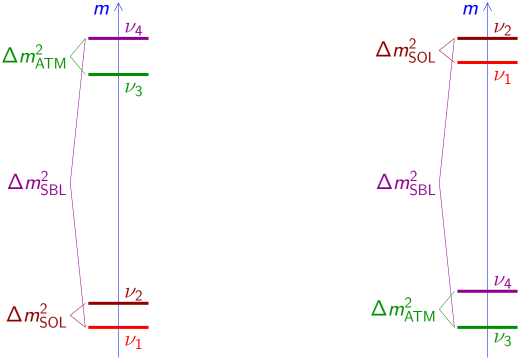
- Active neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$ can oscillate into light sterile neutrinos (ν_s)
- Observables:
  - Disappearance of active neutrinos (neutral current deficit)
  - Indirect evidence through combined fit of data (current indication)
- Short-baseline anomalies + 3ν-mixing:

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

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



2+2 Four-Neutrino Schemes

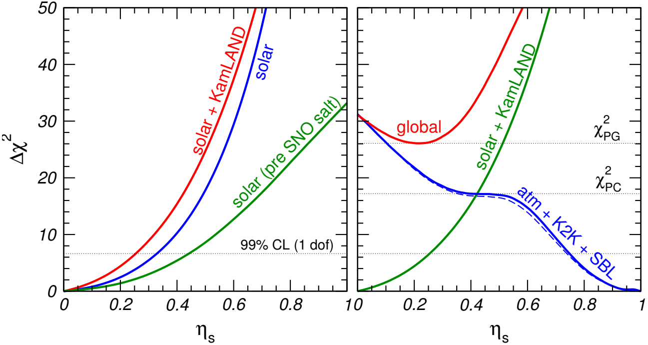


- After LSND (1995) 2+2 was preferred to 3+1, because of the 3+1 appearance-disappearance tension

[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

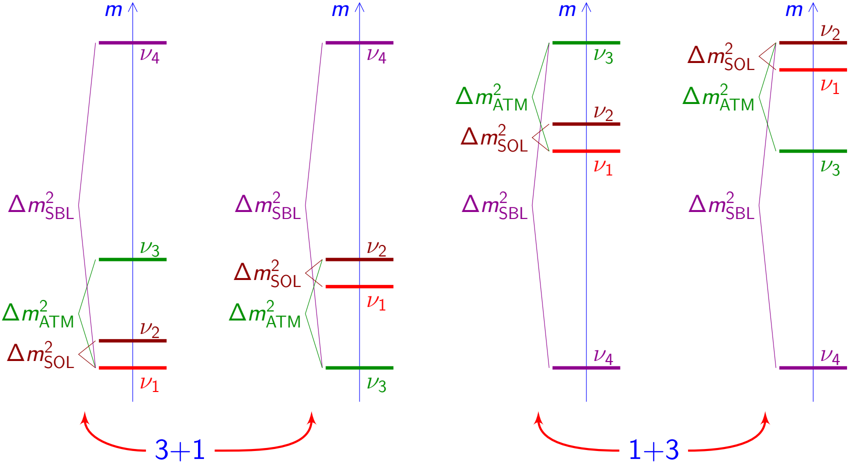
Atmospheric: Matter Effects

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

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

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

3+1 and 1+3 Four-Neutrino Schemes

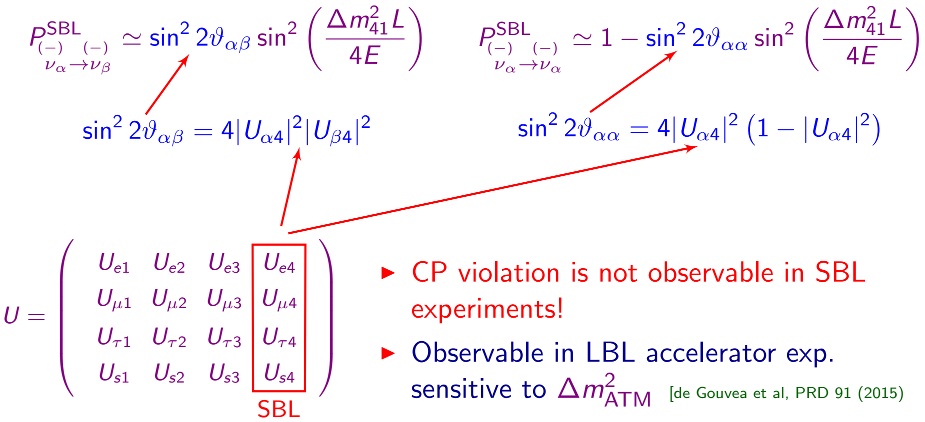


- Perturbation of 3-ν Mixing: $|U_{e4}|^2, |U_{\mu 4}|^2, |U_{\tau 4}|^2 \ll 1 \quad |U_{s4}|^2 \simeq 1$
- 1+3 schemes are disfavored by cosmology (ΛCDM):

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

[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

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

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

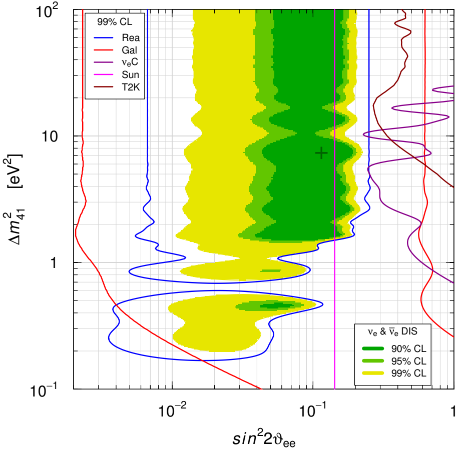
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

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 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]

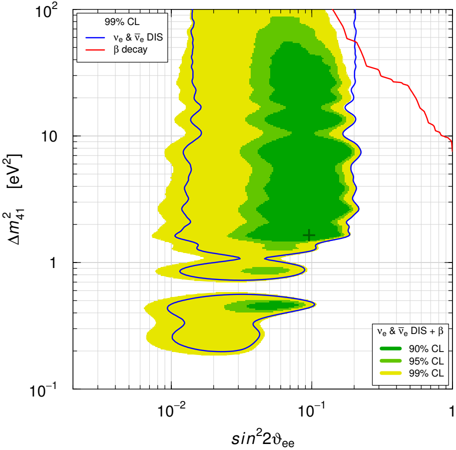
Global ν_e and $\bar{\nu}_e$ Disappearance



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

solar ν_e + KamLAND $\bar{\nu}_e$ + ϑ_{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 ν_e disappearance
[T2K, PRD 91 (2015) 051102]



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

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

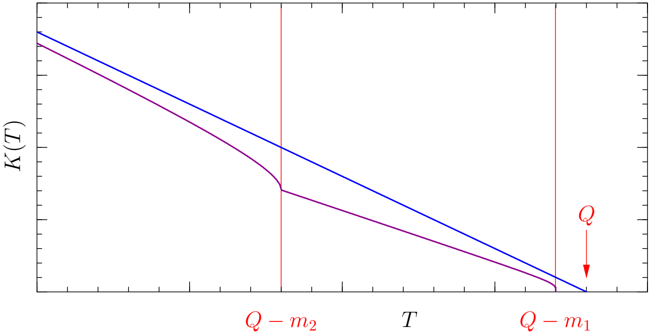
$$6\,\text{cm} \lesssim \frac{L^{\text{osc}}_{41}}{E\,[\text{MeV}]} \lesssim 6\,\text{m} \qquad (2\sigma)$$

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

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

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

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

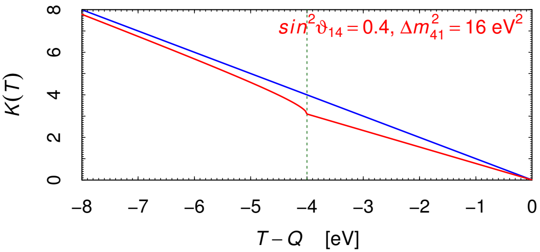


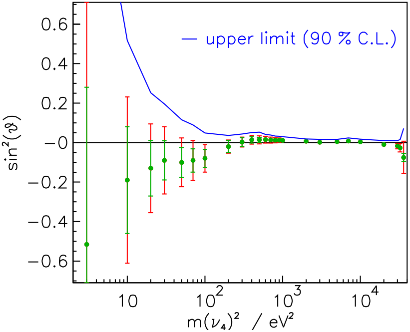
Mainz and Troitsk Limit on $\Delta m^2_{41} \simeq m^2_4$

$$m_4 \gg m_1, m_2, m_3$$

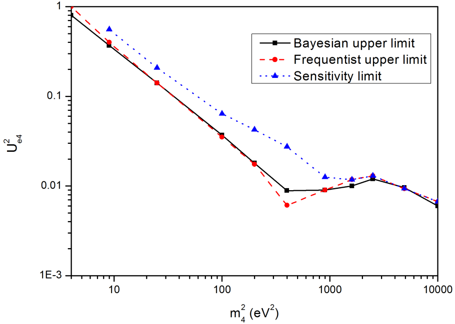
$$\Downarrow$$

$$\Delta m^2_{41} \equiv m^2_4 - m^2_1 \simeq m^2_4$$



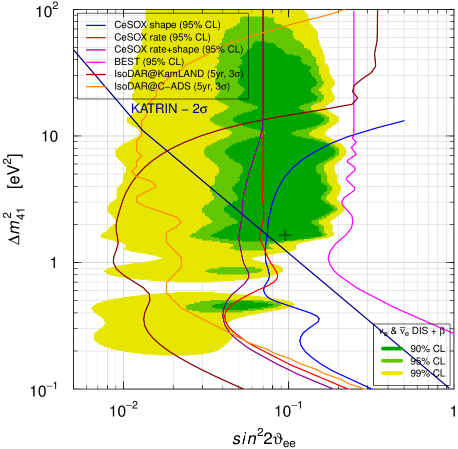


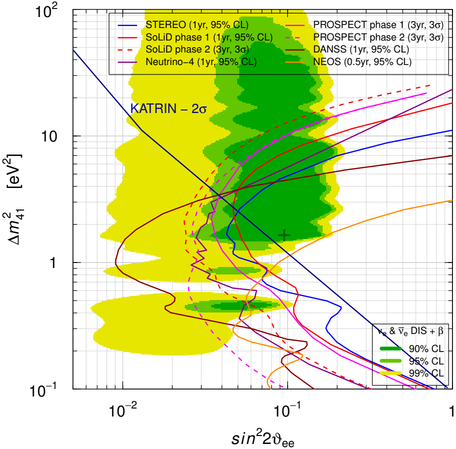
[Kraus, Singer, Valerius, Weinheimer, EPJC 73 (2013) 2323]



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

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





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

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

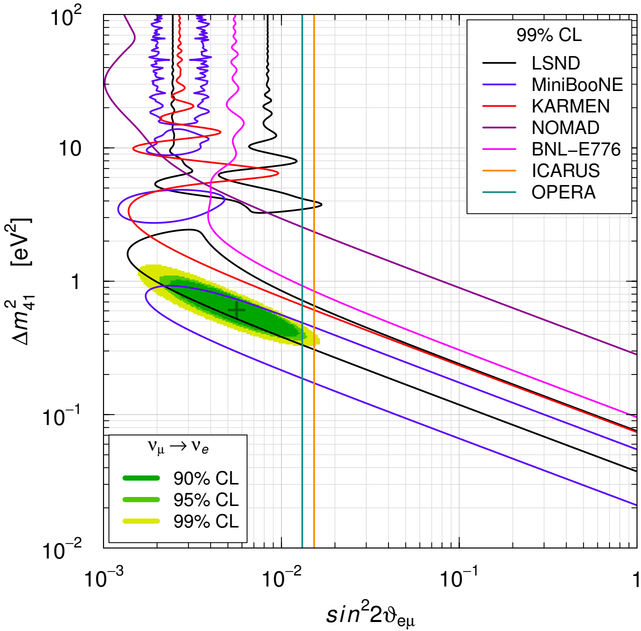
IsoDAR@KamLAND (Kamioka, Japan)
$^{8}\mathrm{Li} \to \bar{\nu}_e$ $L \simeq$ 16m [arXiv:1511.05130]

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

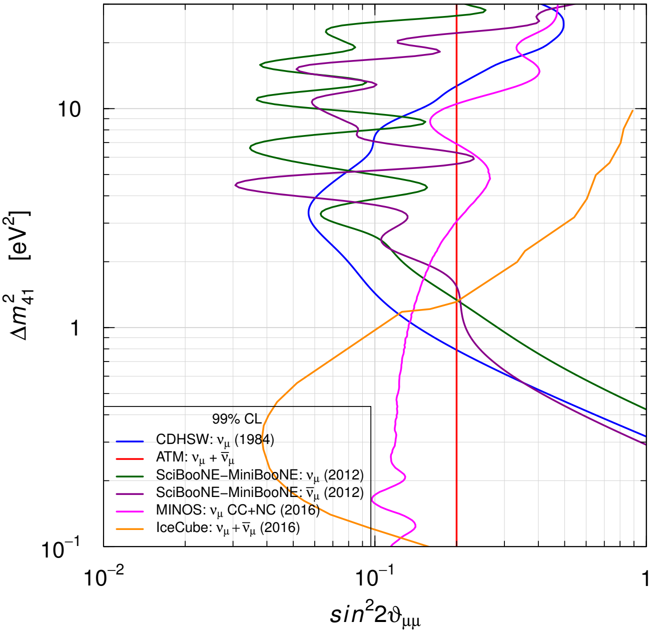
STEREO (ILL, France) $L \simeq$ 8-12m [arXiv:1602.00568]
SoLid (SCK-CEN, Belgium) $L \simeq$ 5-8m [arXiv:1510.07835]
Neutrino-4 (RIAR, Russia) $L \simeq$ 6-11m [JETP 121 (2015) 578]
PROSPECT (ORNL, USA) $L \simeq$ 7-12m [arXiv:1512.02202]
DANSS (Kalinin, Russia) $L \simeq$ 10-12m [arXiv:1606.02896]
NEOS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

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

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



ν_μ and $\bar{\nu}_\mu$ Disappearance



3+1 Appearance-Disappearance Tension

ν_e DIS

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

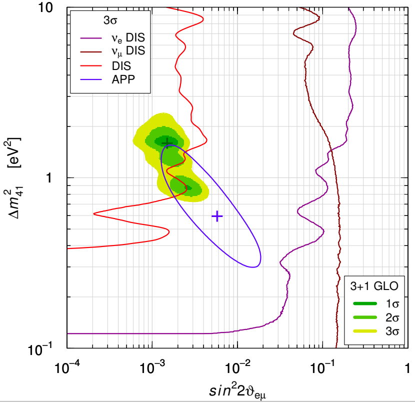
ν_μ DIS

$$\sin^2 2\vartheta_{\mu\mu} \simeq 4|U_{\mu4}|^2$$

$\nu_\mu \to \nu_e$ APP

$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4}\sin^2 2\vartheta_{ee}\sin^2 2\vartheta_{\mu\mu}$$

[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

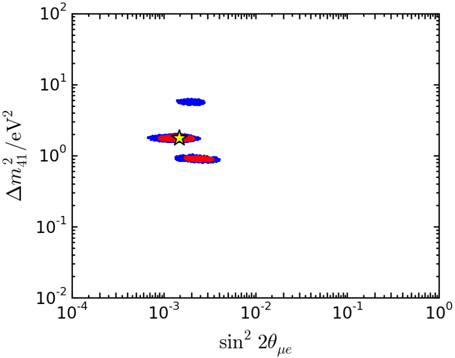
  [CG, Zavanin, MPLA 31 (2015) 1650003]

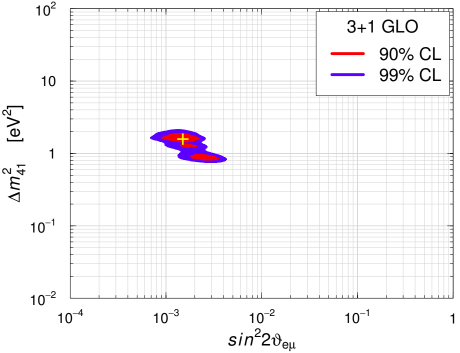
Collin, Arguelles, Conrad, Shaevitz

[NPB 908 (2016) 354]

Our Fit

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





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

$|U_{e4}|^2 = 0.027$ $|U_{\mu4}|^2 = 0.014$

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

$\mathrm{GoF_{null}} = 4.4\%\,(\chi^2/\mathrm{NDF} = 359.2/315)$

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

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

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

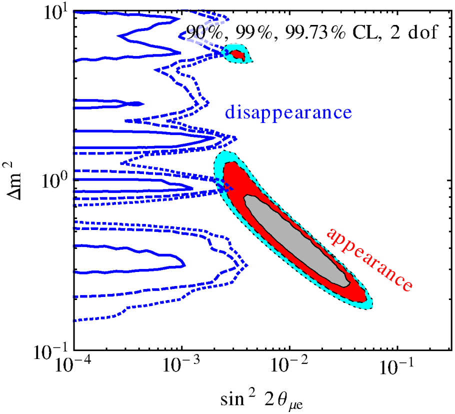
$\mathrm{GoF} = 6\%\,(\chi^2_{\mathrm{min}}/\mathrm{NDF} = 304.0/268)$

$\mathrm{GoF_{null}} = 0.04\%\,(\chi^2/\mathrm{NDF} = 355.2/271)$

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

Kopp, Machado, Maltoni, Schwetz

[JHEP 1305 (2013) 050]



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

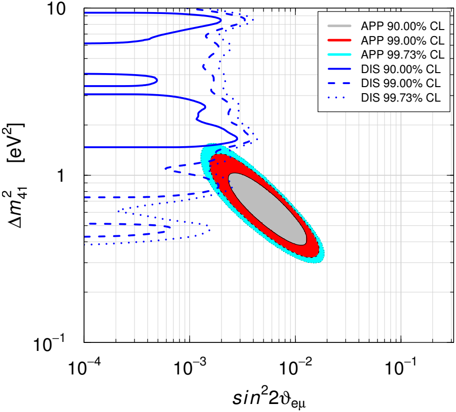
$|U_{e4}|^2 = 0.023 \qquad |U_{\mu 4}|^2 = 0.029$

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

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

Our Fit

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



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

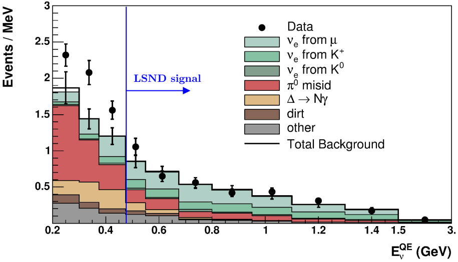
$|U_{e4}|^2 = 0.028 \qquad |U_{\mu 4}|^2 = 0.014$

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

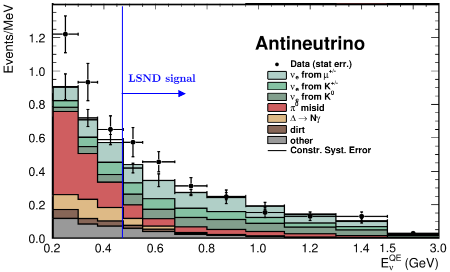
$\text{GoF}_{\text{PG}} = 0.06\%\,(\chi^2/\text{NDF} = 15.0/2)$

MiniBooNE Low-Energy Anomaly

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



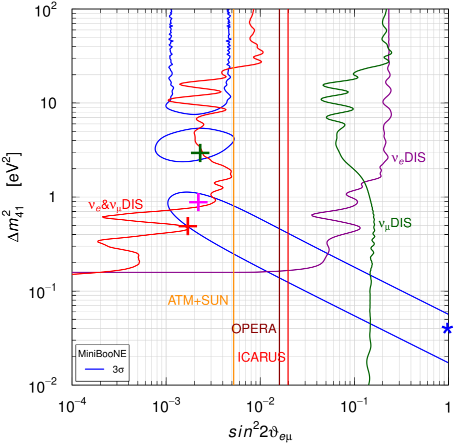
$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]

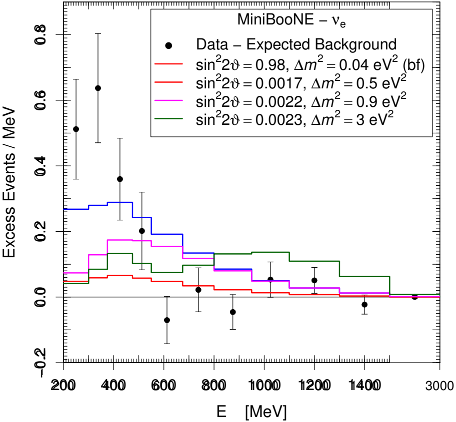


- Fit of MB Low-Energy Excess requires small Δm^2_{41} and large $\sin^2 2\vartheta_{e\mu}$, in contradiction with disappearance data

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

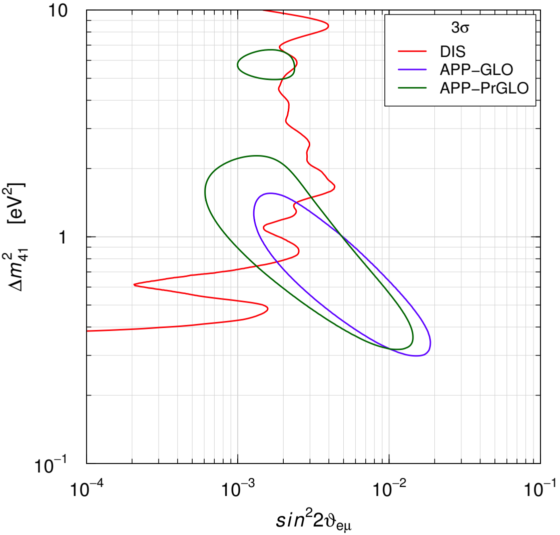
- MB low-energy excess is the main cause of bad APP-DIS $\text{GoF}_{\text{PG}} = 0.06\%$
- Pragmatic Approach: discard the Low-Energy Excess because it is likely not due to oscillations [CG, Laveder, Li, Long, PRD 88 (2013) 073008]
- MicroBooNE is crucial for checking the MiniBooNE Low-Energy Anomaly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





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

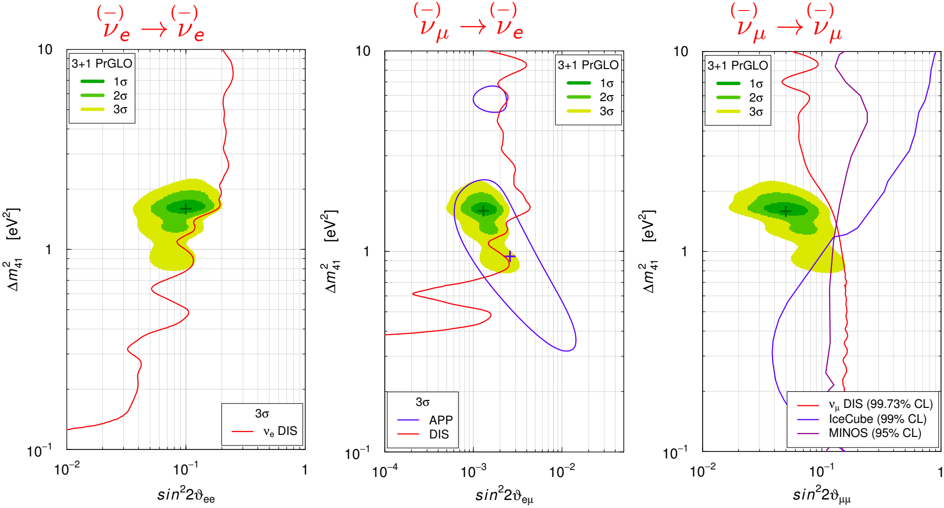
Global → Pragmatic



- APP-GLO: all MiniBooNE data
- APP-PrGLO: only MiniBooNE $E > 475\,\text{MeV}$ 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 $\approx 6.2\sigma$

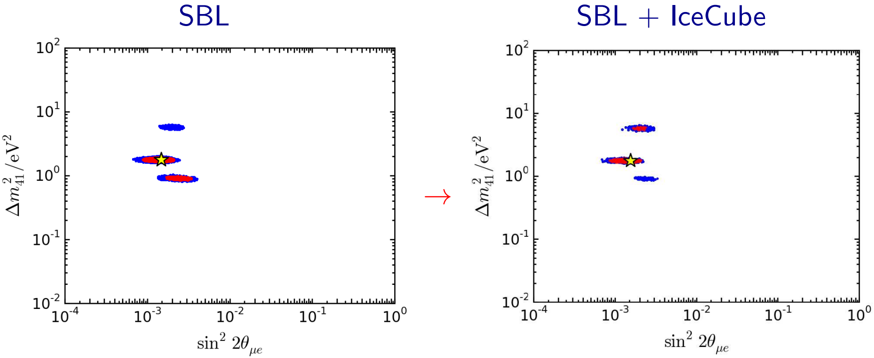
$\Delta\chi^2/\text{NDF} = 46.6/3$

Not yet included:

- IceCube [PRL 117 (2016) 071801 (arXiv:1605.01990)]
- MINOS [PRL 117 (2016) 151803 (arXiv:1607.01176)]

SBL + IceCube

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

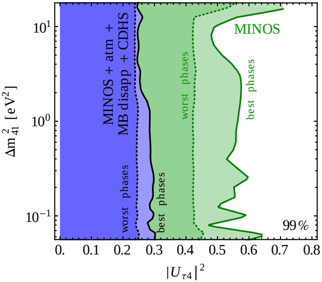

SBL

SBL + IceCube

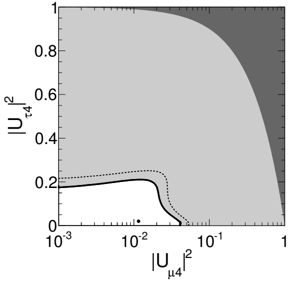
Red: 90% CL Blue: 99% CL

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)

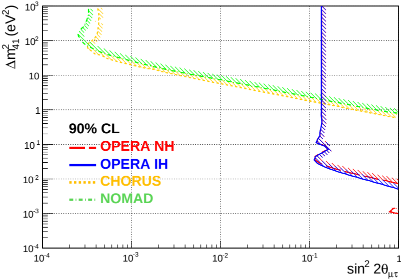
Bounds on $|U_{\tau 4}|$



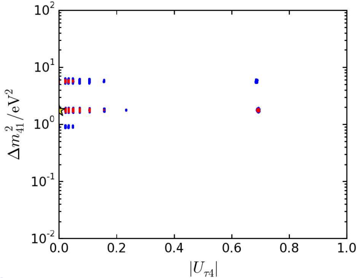
[Kopp et al, JHEP 1305 (2013) 050]



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

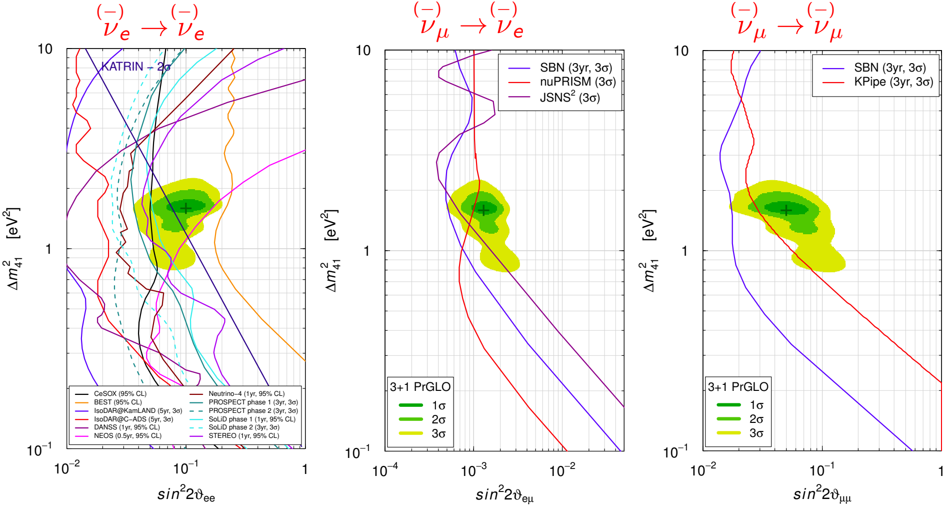


$\nu_\mu \to \nu_\tau$ [OPERA, JHEP 1506 (2015) 069]



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

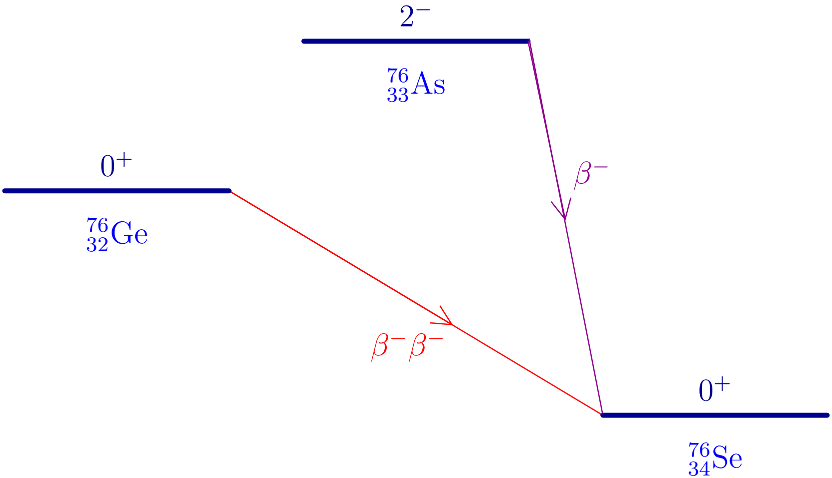
The Race for the Light Sterile



Effects of light sterile neutrinos should also be seen in:

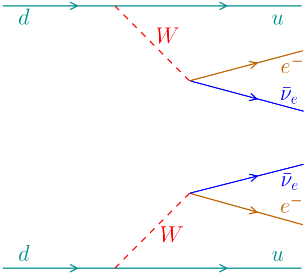
- β Decay Experiments
  [Hannestad et al, JCAP 1102 (2011) 011, PRC 84 (2011) 045503; Formaggio, Barrett, PLB 706 (2011) 68; Esmaili, Peres, PRD 85 (2012) 117301; Gastaldo et al, JHEP 1606 (2016) 061]
- Neutrinoless Double-β Decay Experiments
  [Rodejohann et al, JHEP 1107 (2011) 091; Li, Liu, PLB 706 (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]

Neutrinoless Double-Beta Decay



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

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

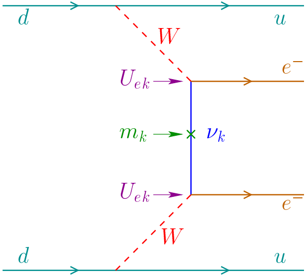


$$\mathcal{N}(A,Z) \to \mathcal{N}(A,Z+2) + e^- + e^- + \bar{\nu}_e + \bar{\nu}_e$$

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

second order weak interaction process
in the Standard Model

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

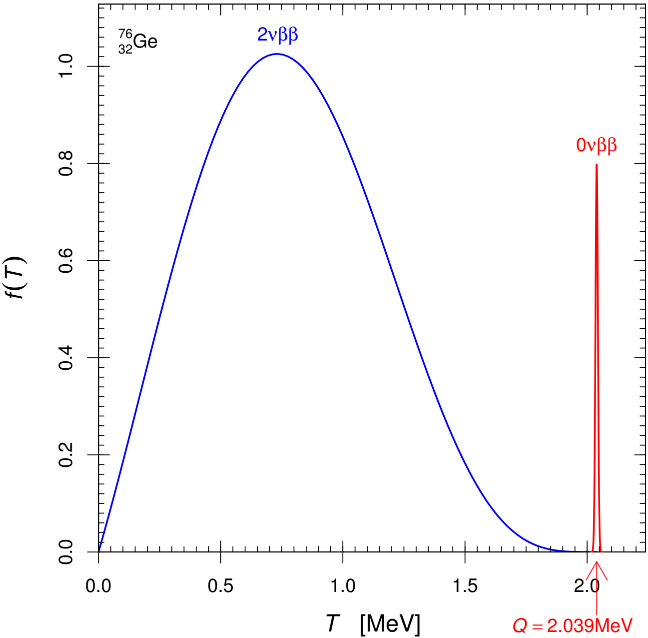


$$\mathcal{N}(A,Z) \to \mathcal{N}(A,Z+2) + e^- + e^-$$

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

effective
Majorana
mass

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



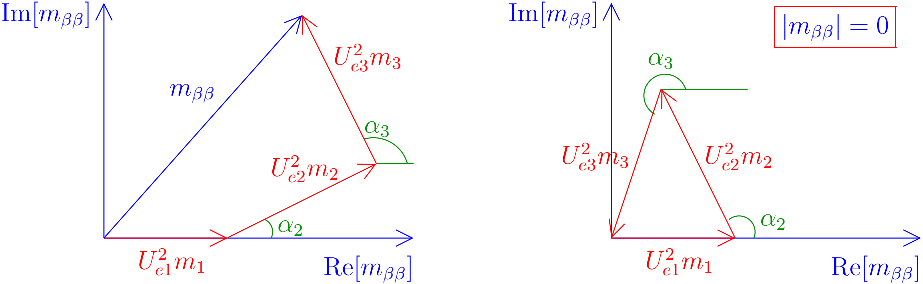
$^{76}_{32}$Ge
2νββ
0νββ
1.0
0.8
0.6
0.4
0.2
0.0
$f(T)$
0.0
0.5
1.0
1.5
2.0
T [MeV]
$Q = 2.039$MeV

Effective Majorana Neutrino Mass

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

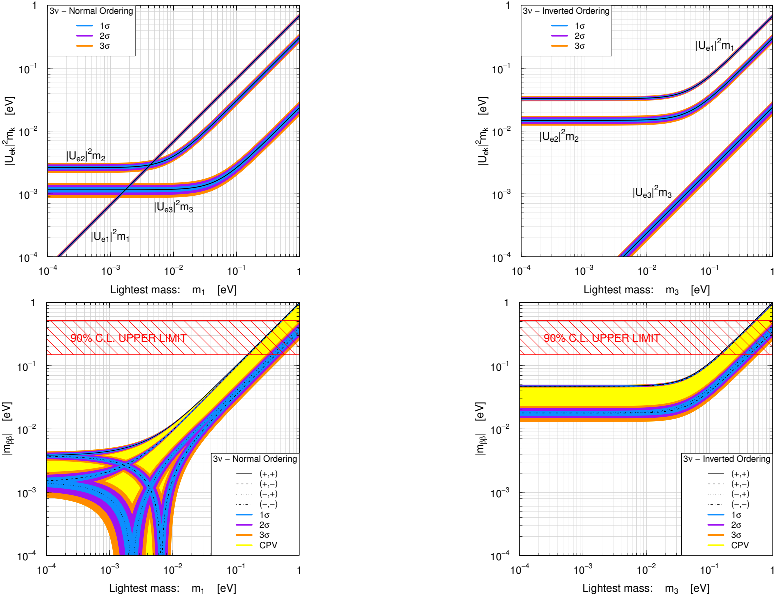
$$m_{\beta\beta} = |U_{e1}|^2 \, m_1 + |U_{e2}|^2 \, e^{i\alpha_2} \, m_2 + |U_{e3}|^2 \, e^{i\alpha_3} \, m_3$$

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



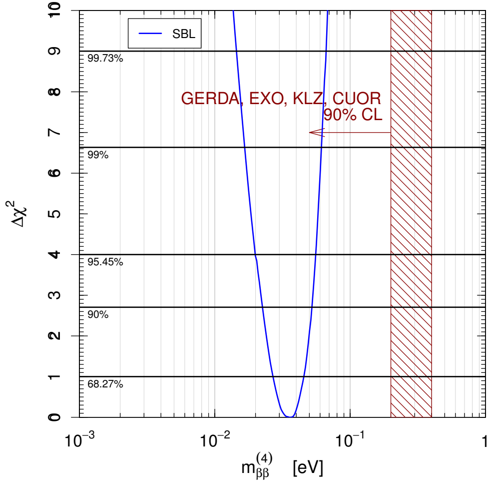
Predictions of 3ν-Mixing Paradigm

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



3+1 Mixing

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



Pragmatic 3+1 Fit

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

$$m_1 \ll m_4$$

$$\Downarrow$$

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

surprise:

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

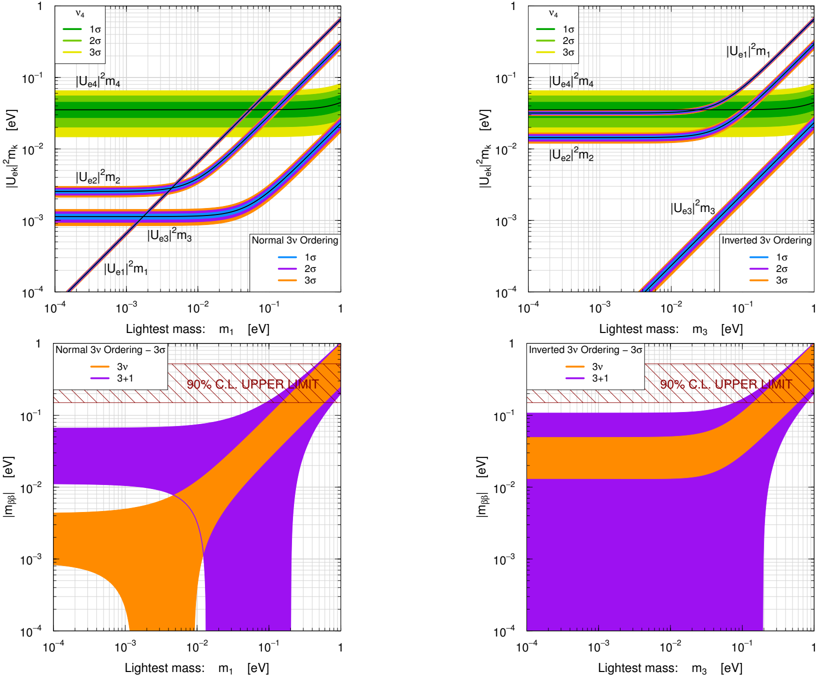
[Barry et al, JHEP 07 (2011) 091]

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

[Rodejohann, JPG 39 (2012) 124008]

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

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


ν_4
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
1σ
2σ
3σ
$|U_{ek}|^2 m_k$ [eV]
Lightest mass: m_1 [eV]
$|U_{e1}|^2 m_1$
Inverted 3ν Ordering
Lightest mass: m_3 [eV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Normal 3ν Ordering – 3σ
3ν
3+1
90% C.L. UPPER LIMIT
$|m_{\beta\beta}|$ [eV]
Inverted 3ν Ordering – 3σ

Cosmology

- neutrinos in equilibrium in early Universe through weak interactions:

$$\nu\bar{\nu} \leftrightarrows e^+e^- \qquad \overset{(-)}{\nu} e \leftrightarrows \overset{(-)}{\nu} e \qquad \overset{(-)}{\nu} N \leftrightarrows \overset{(-)}{\nu} N$$

$$\nu_e n \leftrightarrows p e^- \qquad \bar{\nu}_e p \leftrightarrows n e^+ \qquad n \leftrightarrows p e^- \bar{\nu}_e$$

- weak interactions freeze out $\Longrightarrow$ active $(\nu_e, \nu_\mu, \nu_\tau)$ neutrino decoupling

$$\Gamma_{\text{weak}} = N\sigma v \sim G_F^2 T^5 \sim T^2/M_P \sim \sqrt{G_N T^4} \sim \sqrt{G_N \rho} \sim H$$

$$T_{\nu\text{-dec}} \sim 1\,\text{MeV} \qquad t_{\nu\text{-dec}} \sim 1\,\text{s}$$

- relic neutrinos: $T_\nu = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_\gamma \simeq 1.945\,\text{K} \Longrightarrow k\, T_\nu \underset{(T_\gamma = 2.725 \pm 0.001\,\text{K})}{\simeq} 1.676 \times 10^{-4}\,\text{eV}$

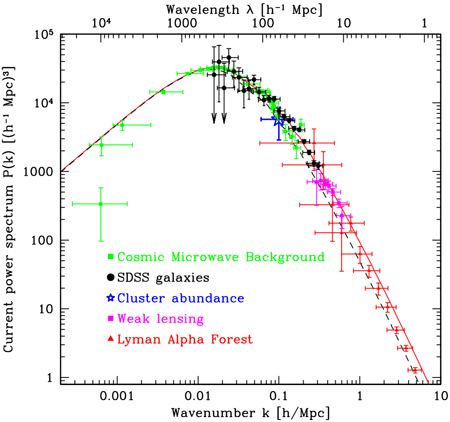
- number density: $n_f = \frac{3}{4}\frac{\zeta(3)}{\pi^2} g_f T_f^3 \Longrightarrow n_{\nu_k,\bar{\nu}_k} \simeq 0.1827\, T_\nu^3 \simeq 112\,\text{cm}^{-3}$

- density contribution: $\Omega_k = \frac{n_{\nu_k,\bar{\nu}_k}\, m_k}{\rho_c} \simeq \frac{1}{h^2}\frac{m_k}{94.1\,\text{eV}} \Rightarrow \boxed{\Omega_\nu\, h^2 = \frac{\sum_k m_k}{94.1\,\text{eV}}}$

$\left(\rho_c = \frac{3H^2}{8\pi G_N}\right)$

[Gershtein, Zeldovich, JETP Lett. 4 (1966) 120; Cowsik, McClelland, PRL 29 (1972) 669]

Power Spectrum of Density Fluctuations



[Tegmark, hep-ph/0503257]

Solid Curve: flat ΛCDM model

$(\Omega_{\mathrm{M}}^{0} = 0.28\,,\ h = 0.72\,,\ \Omega_{\mathrm{B}}^{0}/\Omega_{\mathrm{M}}^{0} = 0.16)$

Dashed Curve: $\sum_{k=1}^{3} m_k = 1\,\mathrm{eV}$

hot dark matter
prevents early galaxy formation

$$\delta(\vec{x}) \equiv \frac{\rho(\vec{x}) - \overline{\rho}}{\overline{\rho}}$$

$$\langle \delta(\vec{x}_1)\delta(\vec{x}_2) \rangle = \int \frac{d^3k}{(2\pi)^3}\, e^{i\vec{k}\cdot\vec{x}}\, P(\vec{k})$$

small scale suppression

$$\begin{aligned} \frac{\Delta P(k)}{P(k)} &\approx -8\,\frac{\Omega_\nu}{\Omega_m} \\ &\approx -0.8 \left(\frac{\sum_k m_k}{1\,\mathrm{eV}}\right) \left(\frac{0.1}{\Omega_m\, h^2}\right) \end{aligned}$$

for

$$k \gtrsim k_{\mathrm{nr}} \approx 0.026 \sqrt{\frac{m_\nu}{1\,\mathrm{eV}}}\, \sqrt{\Omega_m}\, h\,\mathrm{Mpc}^{-1}$$

[Hu, Eisenstein, Tegmark, PRL 80 (1998) 5255]

WMAP (First Year) [AJ SS 148 (2003) 175 (astro-ph/0302209)]

CMB (WMAP, ...) + LSS (2dFGRS) + HST + SN-Ia $\Longrightarrow$ Flat ΛCDM

$$T_0 = 13.7 \pm 0.2\,\text{Gyr} \qquad h = 0.71^{+0.04}_{-0.03}$$

$$\Omega_0 = 1.02 \pm 0.02 \qquad \Omega_b = 0.044 \pm 0.004 \qquad \Omega_m = 0.27 \pm 0.04$$

$$\Omega_\nu h^2 < 0.0076 \quad \text{(95\% conf.)} \quad \Longrightarrow \quad \sum_{k=1}^{3} m_k < 0.71\,\text{eV}$$

WMAP (Five Years) [AJS 180 (2009) 330 (astro-ph/0803.0547)]

CMB + HST + SN-Ia + BAO

$$T_0 = 13.72 \pm 0.12\,\text{Gyr} \qquad h = 0.705 \pm 0.013$$

$$-0.0179 < \Omega_0 - 1 < 0.0081 \quad \text{(95\% C.L.)}$$

$$\Omega_b = 0.0456 \pm 0.0015 \qquad \Omega_m = 0.274 \pm 0.013$$

$$\sum_{k=1}^{3} m_k < 0.67\,\text{eV} \quad \text{(95\% C.L.)} \qquad N_{\text{eff}} = 4.4 \pm 1.5$$

Fogli, Lisi, Marrone, Melchiorri, Palazzo, Rotunno, Serra, Silk, Slosar

[PRD 78 (2008) 033010 (hep-ph/0805.2517)]

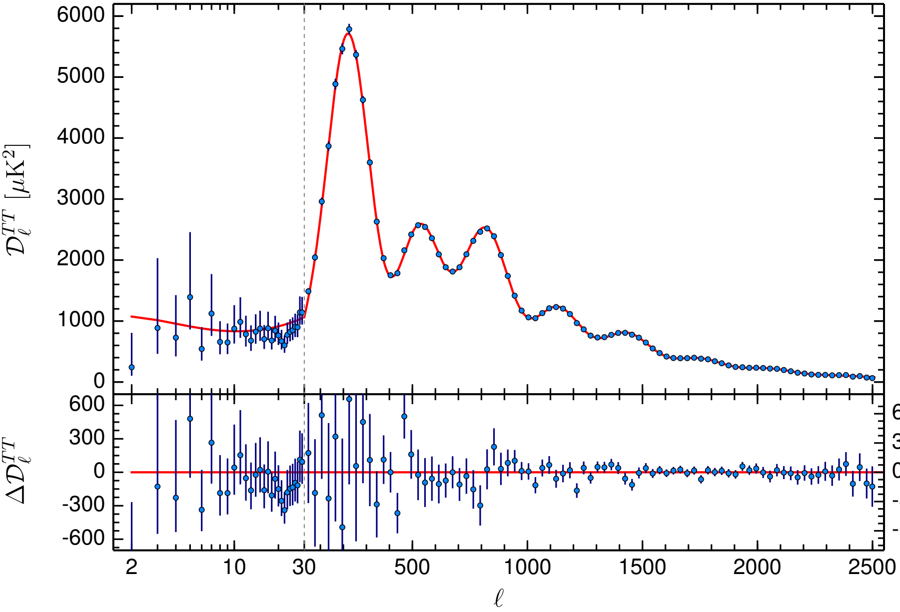
Flat ΛCDM

Case	Cosmological data set	Σ (at 2σ)
1	CMB	< 1.19 eV
2	CMB + LSS	< 0.71 eV
3	CMB + HST + SN-Ia	< 0.75 eV
4	CMB + HST + SN-Ia + BAO	< 0.60 eV
5	CMB + HST + SN-Ia + BAO + Lyα	< 0.19 eV

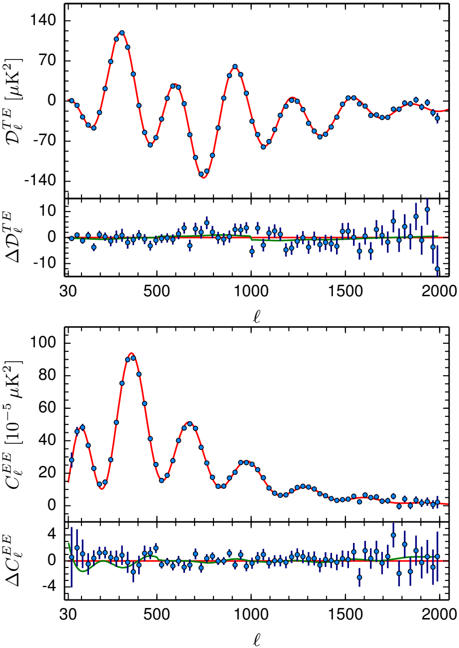
2σ (95% C.L.) constraints on the sum of ν masses Σ.

Planck

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

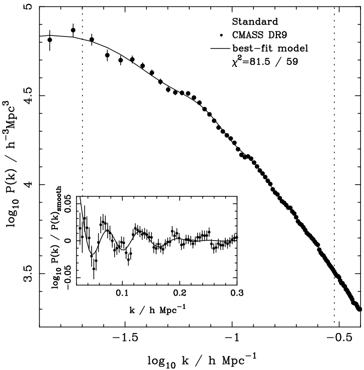


Planck Polarization Data



Planck Terminology

- TT denotes the Planck TT data (low-ℓ for $\ell < 30$ and high-ℓ for $\ell \geq 30$).
- lowP denotes the Planck polarization data at multipoles $\ell < 30$ (low-ℓ).
- TE denotes the Planck TE data at $\ell \geq 30$.
- EE denotes the Planck EE data at $\ell \geq 30$.
- Lensing denotes the Planck weak lensing data.
- BAO denotes the Baryon Acoustic Oscillation data.



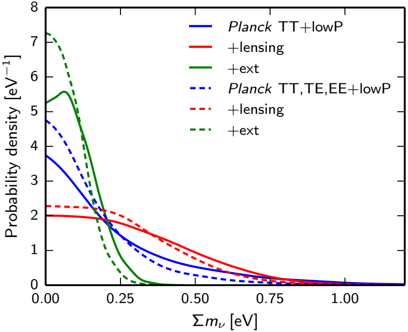
Baryon Oscillation Spectroscopic Survey (BOSS)
part of the Sloan Digital Sky Survey III (SDSS-III)
Data Release 9 (DR9) CMASS sample

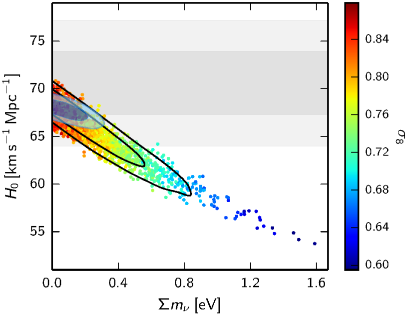
[MNRAS, 427 (2013) 3435 (arXiv:1203.6594)]

Sum of Standard Light Neutrino Masses

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

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





Light Sterile Neutrinos in Cosmology

- sterile neutrinos are produced by $\nu_{e,\mu,\tau} \to \nu_s$ oscillations before active neutrino decoupling ($t_{\nu\text{-dec}} \sim 1\,\text{s}$) [Dolgov, Villante, NPB 679 (2004) 261]
- energy density of radiation before matter-radiation equality:

$$\rho_R = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\text{eff}}\right]\rho_\gamma \qquad (t < t_{\text{eq}} \sim 6 \times 10^4\,\text{y})$$

$N_{\text{eff}}^{\text{SM}} = 3.046$ [Mangano et al, NPB 729 (2005) 221] $\qquad \Delta N_{\text{eff}} = N_{\text{eff}} - N_{\text{eff}}^{\text{SM}}$

- sterile neutrino contribution:

$$\rho_s = (T_s/T_\nu)^4 \rho_\nu \quad \Longrightarrow \quad \Delta N_{\text{eff}} = (T_s/T_\nu)^4$$

- sterile neutrino $\nu_s \simeq \nu_4$ with mass $m_s = m_4 \simeq \sqrt{\Delta m^2_{41}} \sim 1\,\text{eV}$ becomes non-relativistic at $T_\nu \sim m_s/3$, that is at $t_{\nu_s\text{-nr}} \sim 2.0 \times 10^5\,\text{y}$, before recombination at $t_{\text{rec}} \sim 3.8 \times 10^5\,\text{y}$
- current energy density of sterile neutrinos:

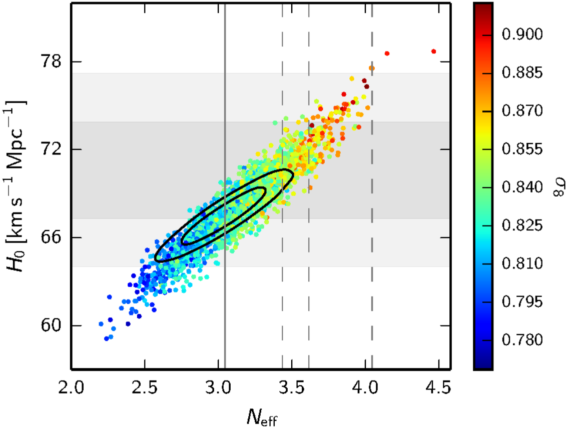
$$\Omega_s = \frac{n_s m_s}{\rho_c} \simeq \frac{1}{h^2}\,\frac{(T_s/T_\nu)^3 m_s}{94.1\,\text{eV}} = \frac{1}{h^2}\,\frac{\Delta N_{\text{eff}}^{3/4} m_s}{94.1\,\text{eV}} = \frac{1}{h^2}\,\frac{m_s^{\text{eff}}}{94.1\,\text{eV}}$$

$$m_s^{\text{eff}} = \Delta N_{\text{eff}}^{3/4} m_s = (T_s/T_\nu)^3 m_s$$

Limits on Dark Radiation

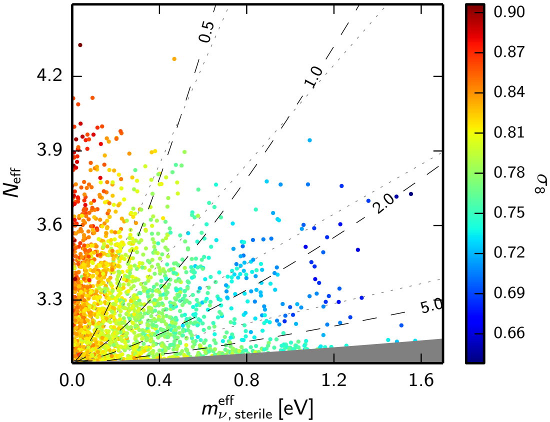
[Planck, Astron. Astrophys. 594 (2016) A13 (arXiv:1502.01589)]

Cosmological data set	N_{eff}
Planck TT + lowP	3.13 ± 0.32
Planck TT + lowP + BAO	3.15 ± 0.23
Planck TT,TE,EE + lowP	2.99 ± 0.20
Planck TT,TE,EE + lowP + BAO	3.04 ± 0.18



Limits on Light Sterile Neutrinos

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



m_4 is constant along the gray dashed (dotted) lines in the thermal (Dodelson-Widrow) scenario. The gray region is excluded by the prior $m_4^{\rm thermal} < 10\,\rm eV$, which excludes most of the area where the neutrinos behave nearly like dark matter.

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

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

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

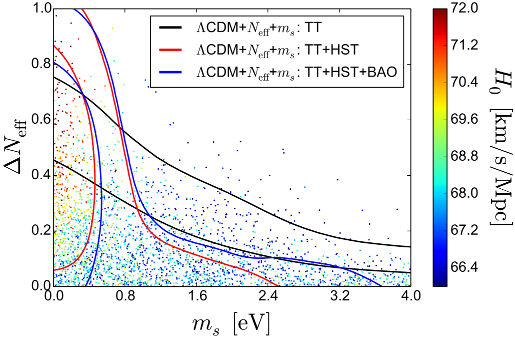
- Dodelson-Widrow:

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

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

Parameter	TT	TT+HST	TT+BAO	TT+HST+BAO	TTTEEE
H_0 [km/s/Mpc]	$68.0^{+1.0}_{-1.5}$	$70.7^{+1.7}_{-2.0}$	$68.3^{+0.6}_{-1.0}$	$69.8^{+1.2}_{-1.5}$	$67.0^{+0.7}_{-0.8}$
$N_{\rm eff}$	< 3.53	< 3.88	< 3.49	< 3.84	< 3.36

Marginalised constraints are given at 1σ, while upper bounds are given at 2σ.

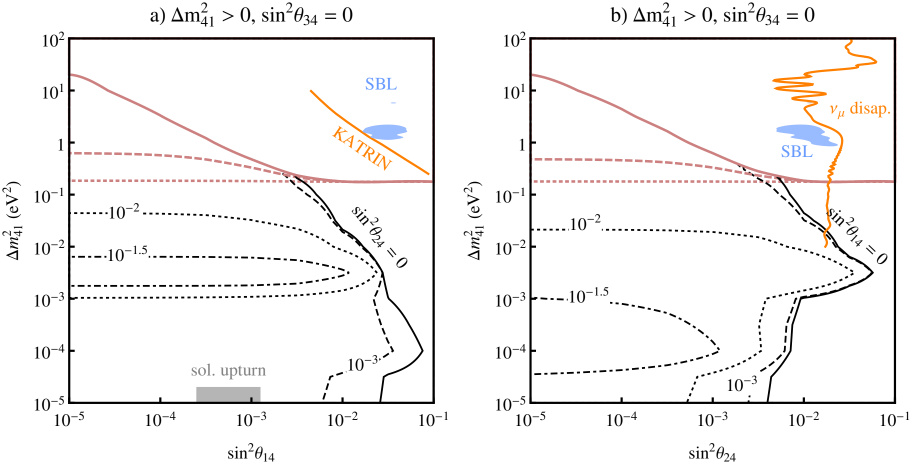


The excluded regions are on the right of each line, at 1σ and 2σ confidence level.

[Archidiacono, Gariazzo, CG, Hannestad, Hansen, Laveder, Tram, JCAP 1608 (2016) 067]

Standard Cosmological Scenario Mixing Bounds

[Mirizzi, Mangano, Saviano, Borriello, CG, Miele, Pisanti, PLB 726 (2013) 8 (arXiv:1303.5368)]



Non-standard mechanism for partial thermalization of ν_s is needed

Tension between $\Delta N_{\text{eff}} = 1$ and $m_s \approx 1\,\text{eV}$

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]
- Interactions in the sterile sector [Hannestad, Hansen, Tram, PRL 112 (2014) 031802; Dasgupta, Kopp et al, PRL 112 (2014) 031803, JCAP 1510 (2015) 011; Bringmann, Hasenkamp, Kersten, JCAP 1407 (2014) 042; Ko, Tang, PLB 739 (2014) 62; Archidiacono, Hannestad et al, PRD 91 (2015) 065021, PRD 93 (2016) 045004, JCAP 1608 (2016) 067; Mirizzi, Mangano, Pisanti, Saviano, PRD 90 (2014) 113009, PRD 91 (2015) 025019; Tang, PLB 750 (2015) 201; Cherry, Friedland, Shoemaker, arXiv:1411.1071, arXiv:1605.06506]
- 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, CG, Laveder, arXiv:1404.6160]
- Free primordial power spectrum of scalar fluctuations (Inflationary Freedom) [Gariazzo, CG, Laveder, JCAP 1504 (2015) 023]

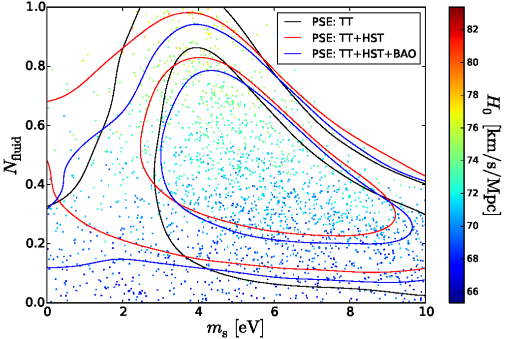
Pseudoscalar–Sterile Neutrino Interactions

[Archidiacono, Gariazzo, CG, Hannestad, Hansen, Laveder, Tram, JCAP 1608 (2016) 067]

$$\mathcal{L} \sim g_s \phi \bar{\nu}_4 \gamma_5 \nu_4 \qquad 10^{-6} \lesssim g_s \lesssim 10^{-5}$$

Parameter	TT	TT+HST	TT+BAO	TT+HST+BAO	TTTEEE
H_0 [km/s/Mpc]	$71.4^{+1.8}_{-3.0}$	72.4 ± 2.5	69.8 ± 1.4	71.1 ± 1.2	70.9 ± 1.8
N_{eff}	< 3.94	3.53 ± 0.18	< 3.67	3.49 ± 0.18	< 3.69

Marginalised constraints are given at 1σ, while upper bounds are given at 2σ.

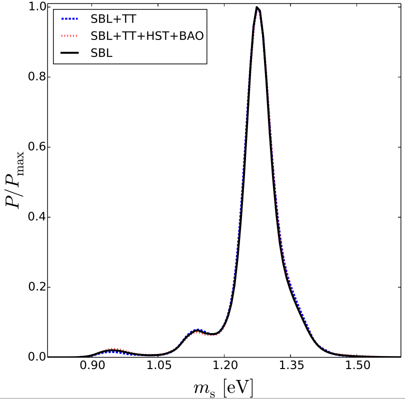


The excluded regions are on the right of each line, at 1σ and 2σ confidence level.

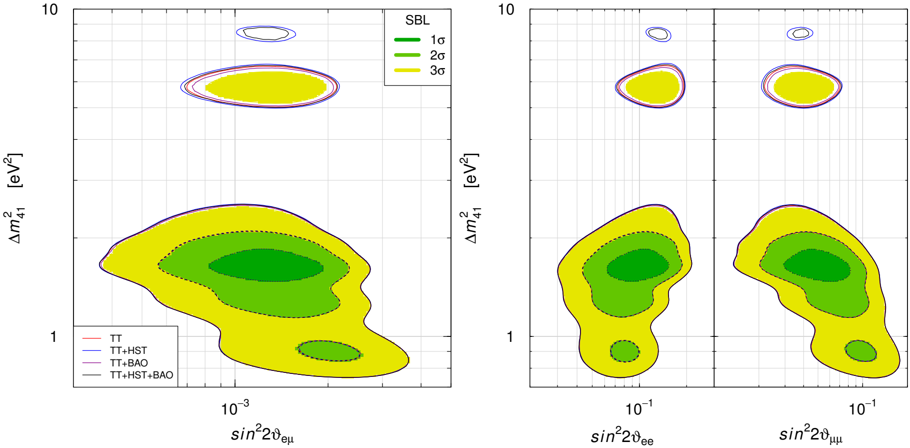
Analysis of Cosmological Data with SBL Prior

Parameter	SBL+TT	SBL+TT+HST	SBL+TT+BAO	SBL+TT+HST+BAO
H_0 [km/s/Mpc]	$70.9^{+1.6}_{-3.3}$	72.2 ± 1.7	$69.19^{+0.83}_{-1.4}$	$70.6^{+1.1}_{-1.4}$
N_{eff}	< 3.97	3.51 ± 0.20	< 3.57	$3.43^{+0.18}_{-0.22}$
m_s[eV]	$1.272^{+0.052}_{-0.038}$	$1.274^{+0.050}_{-0.038}$	$1.270^{+0.055}_{-0.035}$	$1.270^{+0.055}_{-0.035}$

Marginalised constraints are given at 1σ, while upper bounds are given at 2σ.



Analysis of SBL Data with Cosmological Prior



Conclusions

- Exciting indications of light sterile neutrinos at the eV scale:
  - LSND $\bar{\nu}_{\mu} \to \bar{\nu}_{e}$ signal.
  - Gallium ν_{e} disappearance.
  - Reactor $\bar{\nu}_{e}$ disappearance.
- 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).