Critical Review on Neutrino Anomalies

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Neutrinos: the Quest for a New Physics Scale

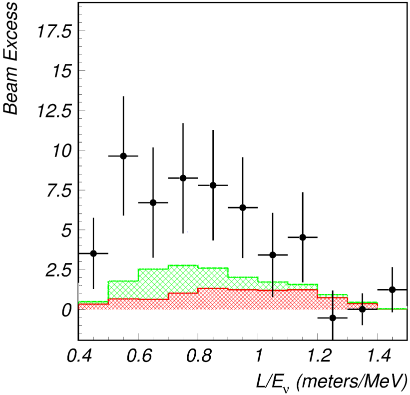
CERN, 27-31 March 2017

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 $\bar{\nu}_\mu$

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

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

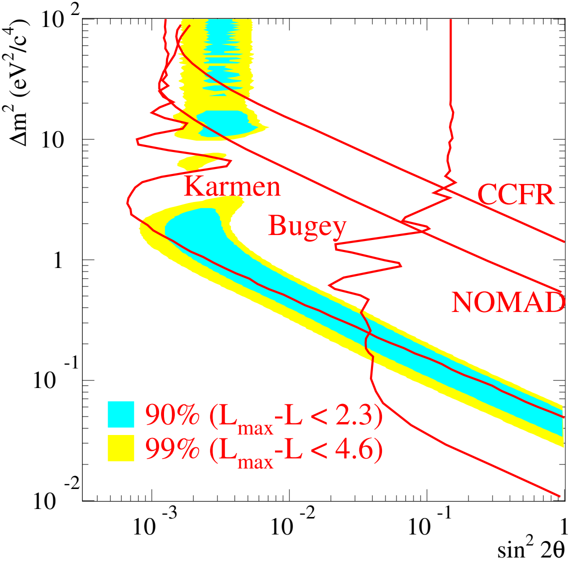
$$L \simeq 30\,\text{m}$$

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

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]

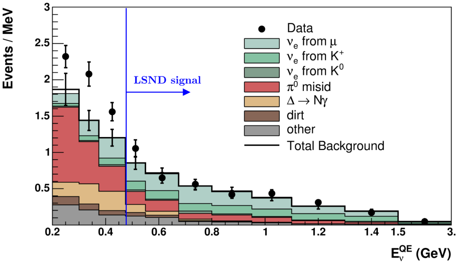


$$\Delta m^2_{\text{SBL}} \gtrsim 3 \times 10^{-2}\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \simeq 2.5 \times 10^{-3}\,\text{eV}^2 \gg \Delta m^2_{\text{SOL}}$$

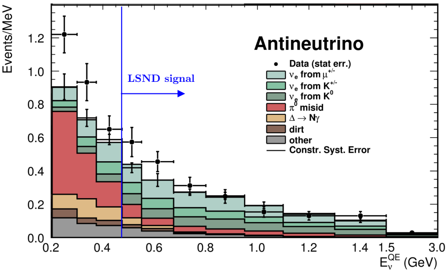
MiniBooNE

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

$\nu_\mu \to \nu_e$ [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!

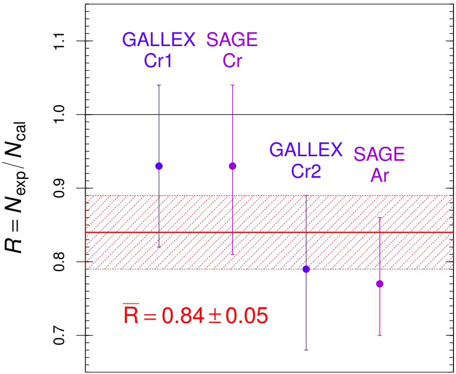
Gallium Anomaly

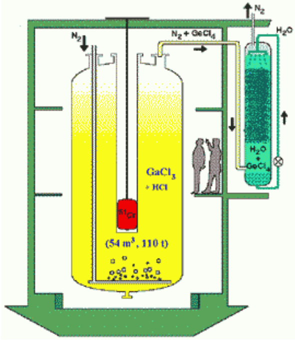
Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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

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





$\approx 2.9\sigma$ deficit

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

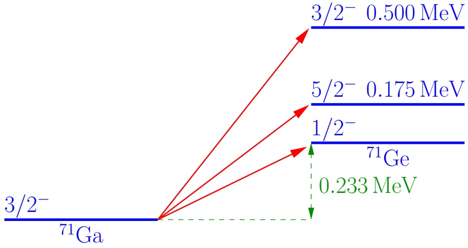
$\Delta m^2_{\text{SBL}} \gtrsim 1\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}}$

[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

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

- Calculation: Bahcall, PRC 56 (1997) 3391



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

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

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

- Contribution of excited states only 5%!

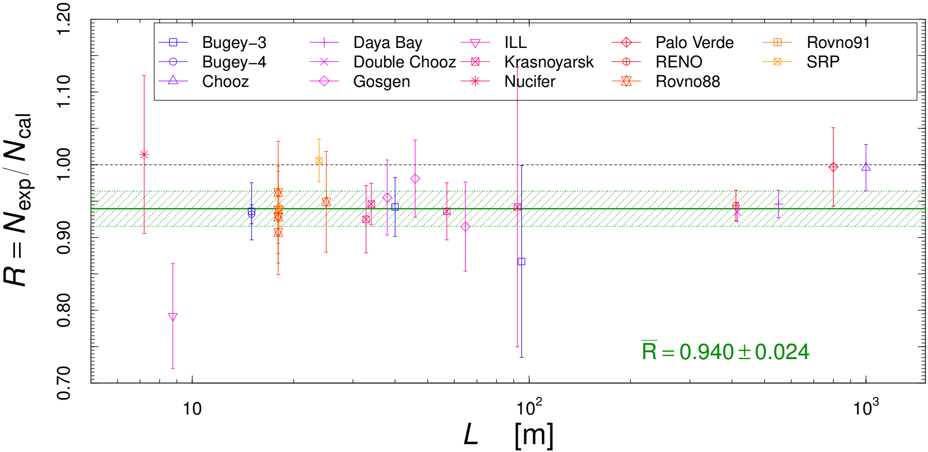
		$\frac{\mathrm{BGT}_{175}}{\mathrm{BGT}_{\mathrm{G.S.}}}$	$\frac{\mathrm{BGT}_{500}}{\mathrm{BGT}_{\mathrm{G.S.}}}$
Krofcheck et al. PRL 55 (1985) 1051	$^{71}\mathrm{Ga}(p,n)^{71}\mathrm{Ge}$	< 0.056	0.126 ± 0.023
Haxton PLB 431 (1998) 110	Shell Model	0.19 ± 0.18	
Frekers et al. PLB 706 (2011) 134	$^{71}\mathrm{Ga}(^{3}\mathrm{He},{}^{3}\mathrm{H})^{71}\mathrm{G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

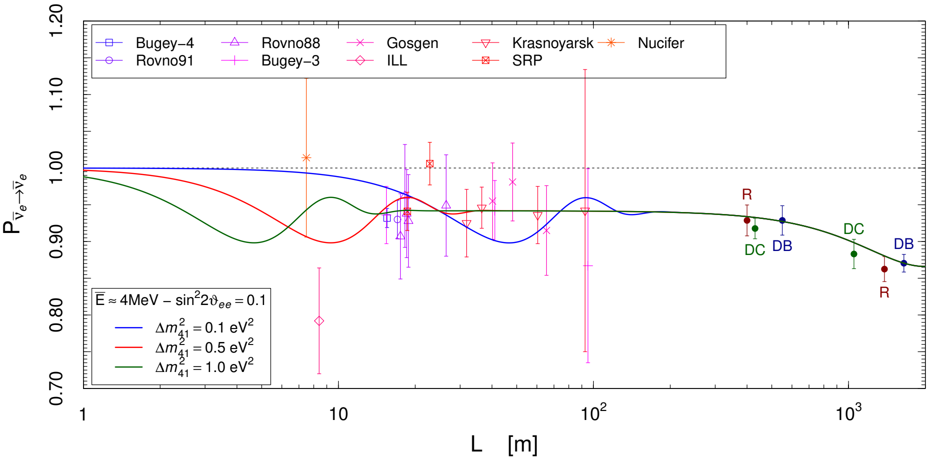
Reactor Electron Antineutrino Anomaly

[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]

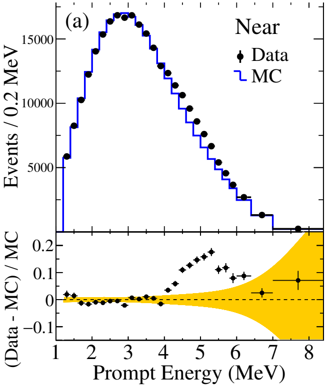


$\approx 2.5\sigma$ deficit

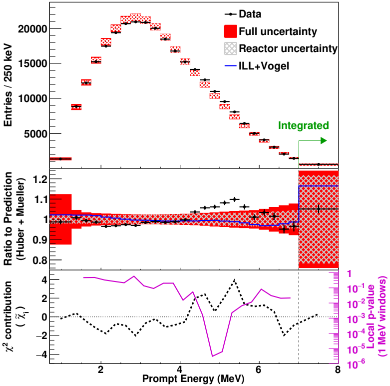


$$\Delta m^2_{\text{SBL}} \gtrsim 0.5\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}}$$

5 MeV Bump



[RENO, arXiv:1511.05849]

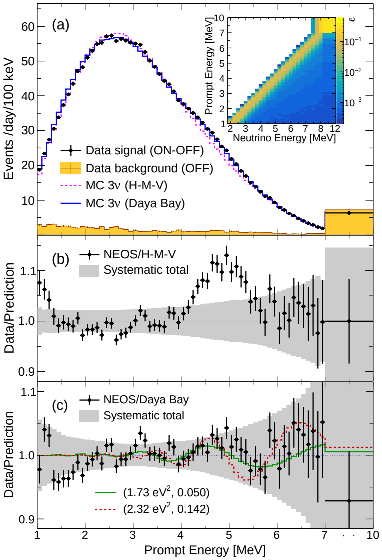


[Daya Bay, arXiv:1508.04233]

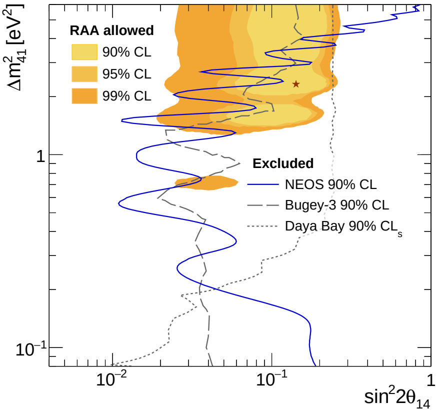
- It is correlated with the reactor activity.
- Cannot be explained by neutrino oscillations.
- Very likely due to theoretical miscalculation of the spectrum.
- $\sim 3\%$ effect on total flux.
- It seems to be an excess!

NEOS

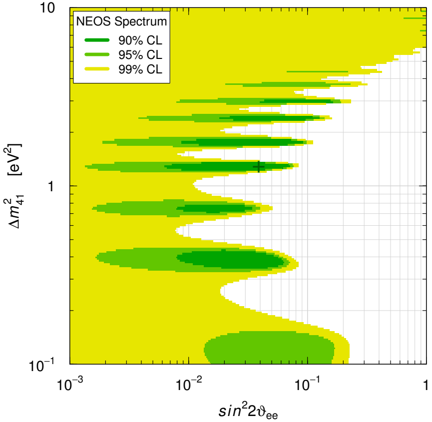
[arXiv:1610.05134]



- 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]



2-D χ^2 Analysis

Best Fits:

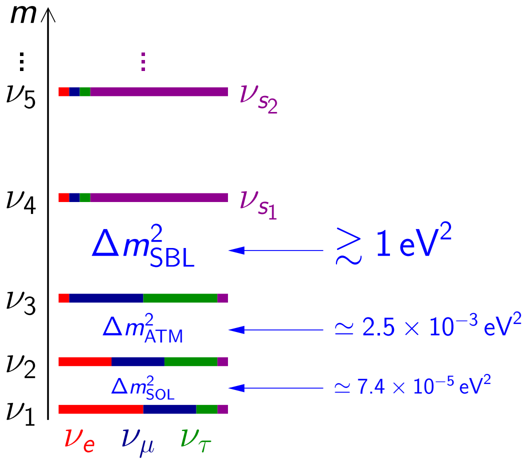
$$\Delta m^2_{41} = 1.7\,\text{eV}^2 \qquad \sin^2 2\theta_{14} = 0.05$$

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

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

$$\approx 2.1\sigma \text{ anomaly}$$

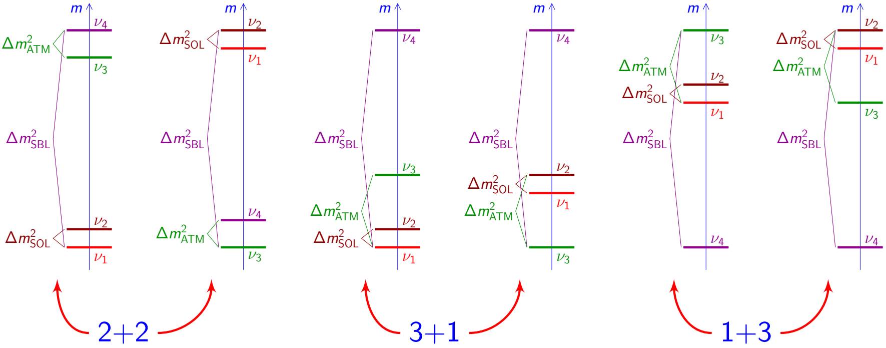
Beyond Three-Neutrino Mixing: Sterile Neutrinos



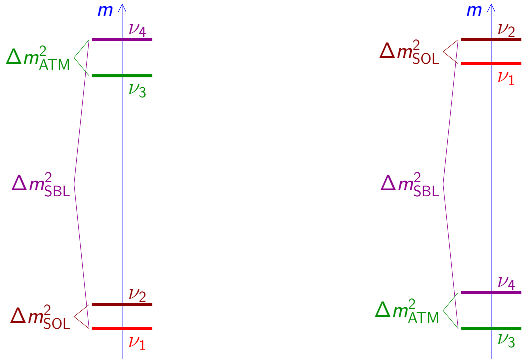
Terminology: a eV-scale sterile neutrino

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

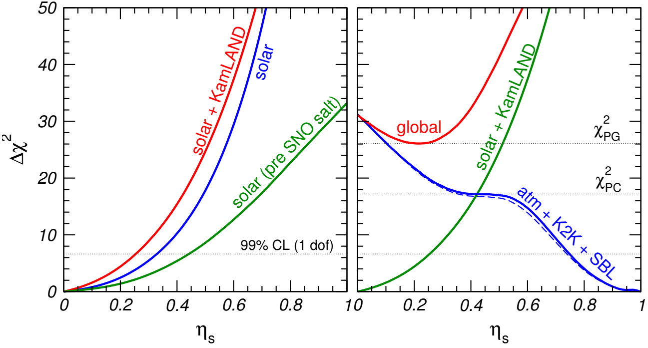


- After LSND (1995) 2+2 was preferred to 3+1, because of the 3+1 appearance-disappearance tension

[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

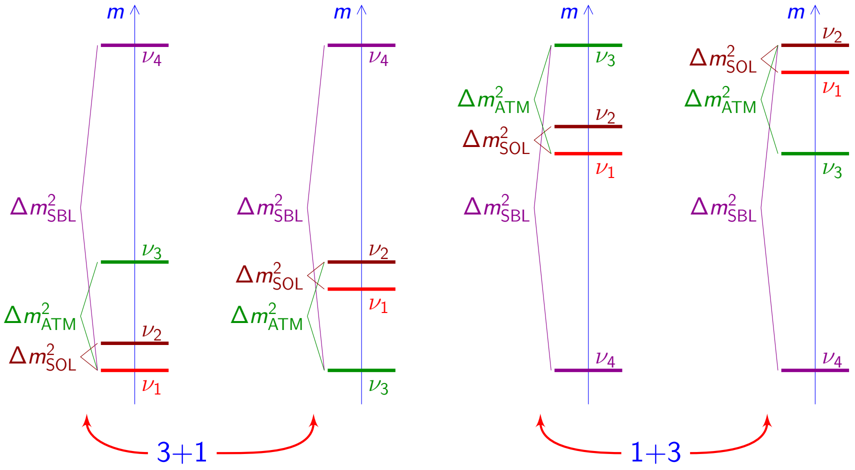
Atmospheric: Matter Effects

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

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

[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):

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

[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

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

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

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

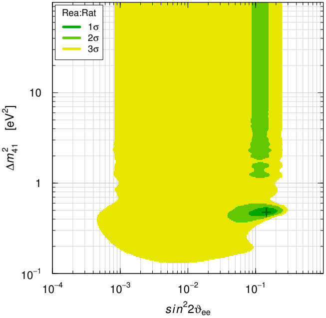
SBL

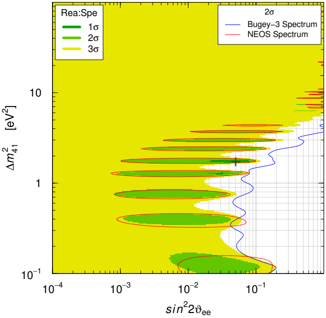
- 6 mixing angles
- 3 Dirac CP phases
- 3 Majorana CP phases

- 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]

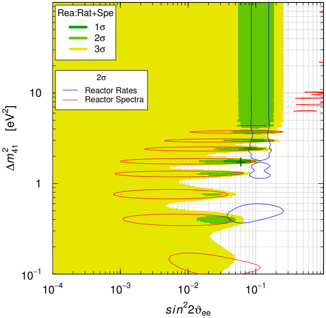
Reactor $\bar{\nu}_e$ Disappearance

Reactor Rates





Reactor Spectra



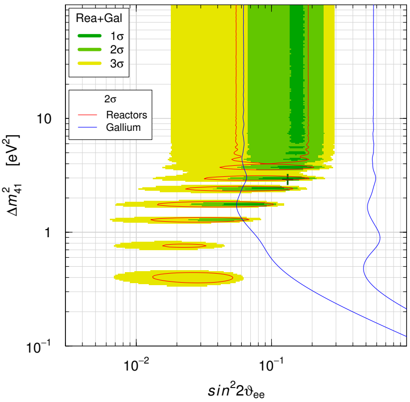
[Gariazzo, CG, Laveder, Li, arXiv:1703.00860]

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

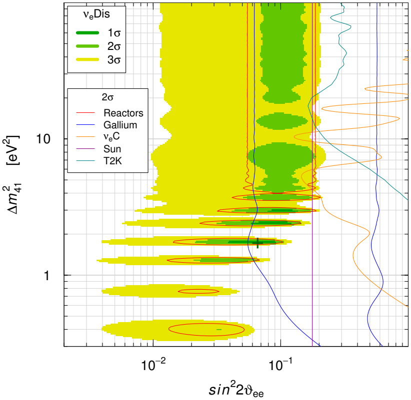
[Gariazzo, CG, Laveder, Li, arXiv:1703.00860]



- $\Delta\chi^2_{\text{NO}} = 14.6 \Rightarrow \approx 3.4\sigma$ 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]

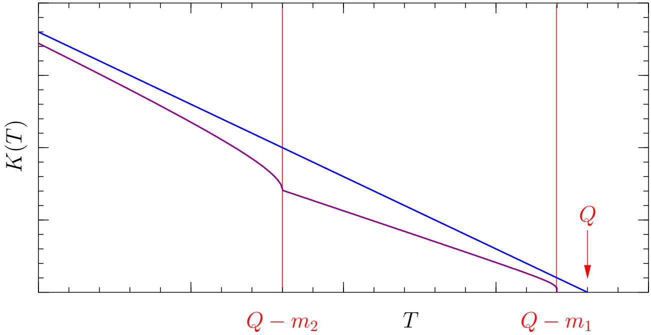
- $\Delta\chi^2_{\text{NO}} = 13.3 \Rightarrow \approx 3.2\sigma$ anomaly
- Best Fit: $\Delta m^2_{41} = 1.7\,\text{eV}^2$
  $\sin^2 2\vartheta_{ee} = 0.066 \quad \Leftrightarrow \quad |U_{e4}|^2 = 0.017$
- $\chi^2_{\text{min}}/\text{NDF} = 162.5/174 \Rightarrow \text{GoF} = 72\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}}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

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

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

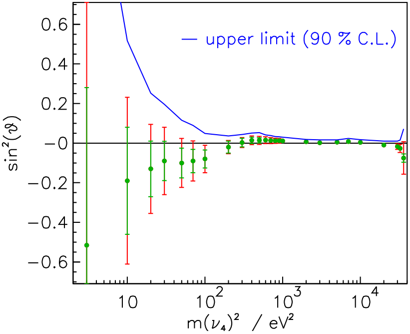
Kurie function: $$K(T) = \left[(Q - T) \sum_k |U_{ek}|^2 \sqrt{(Q-T)^2 - m_k^2} \right]^{1/2}$$

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

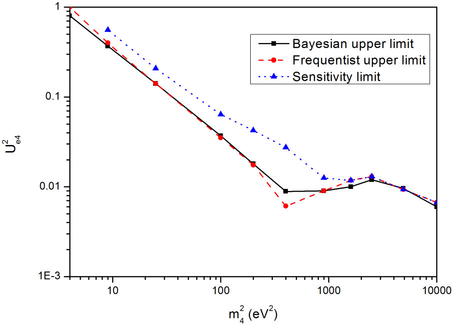


Mainz and Troitsk Limit on $\Delta m^2_{41} \simeq m^2_4$

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



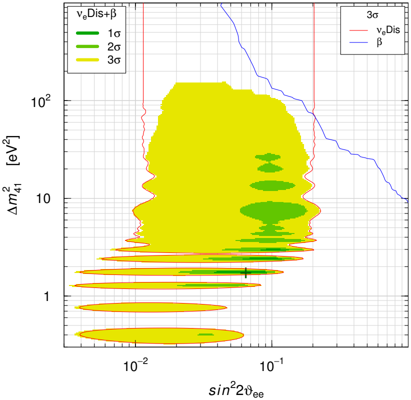
[Kraus, Singer, Valerius, Weinheimer, EPJC 73 (2013) 2323]



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

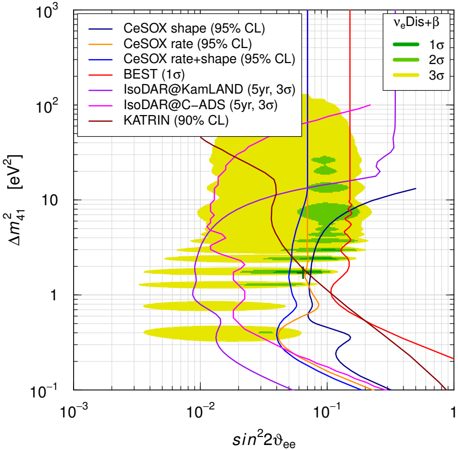
Global ν_e and $\bar{\nu}_e$ Disappearance + β Decay

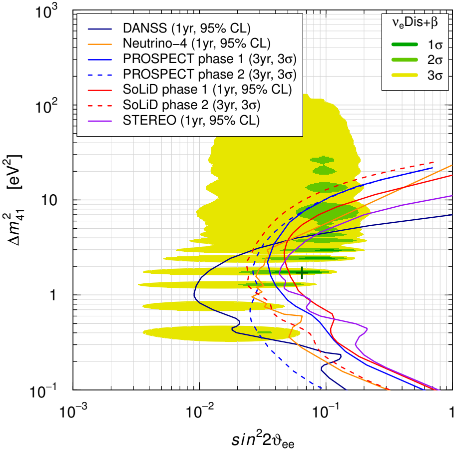
[Gariazzo, CG, Laveder, Li, arXiv:1703.00860]



- 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 $\to \bar{\nu}_e$
BOREXINO: $L \simeq$ 5-12m [Vivier@TAUP2015]

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

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

IsoDAR@C-ADS (Guangdong, China)
^{8}Li $\to \bar{\nu}_e$ $L \simeq$ 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]

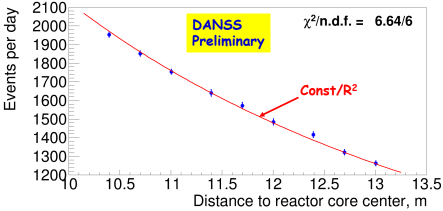
SoLid (SCK-CEN, Belgium) $L \simeq$ 5-8m [arXiv:1510.07835]

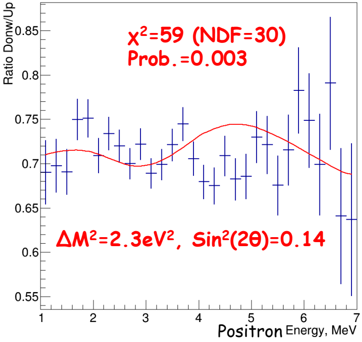
STEREO (ILL, France) $L \simeq$ 8-12m [arXiv:1602.00568]

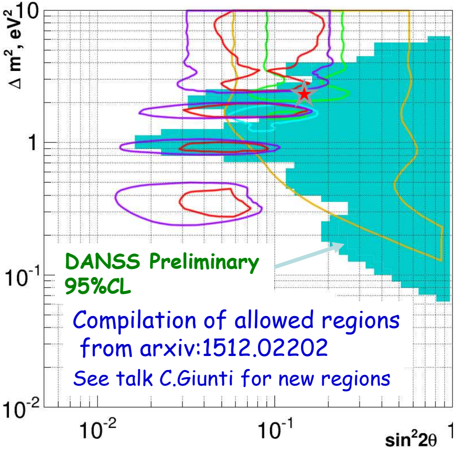
KATRIN (Karlsruhe, Germany) ^{3}H $\to \bar{\nu}_e$ [Drexlin@NOW2016]

DANSS

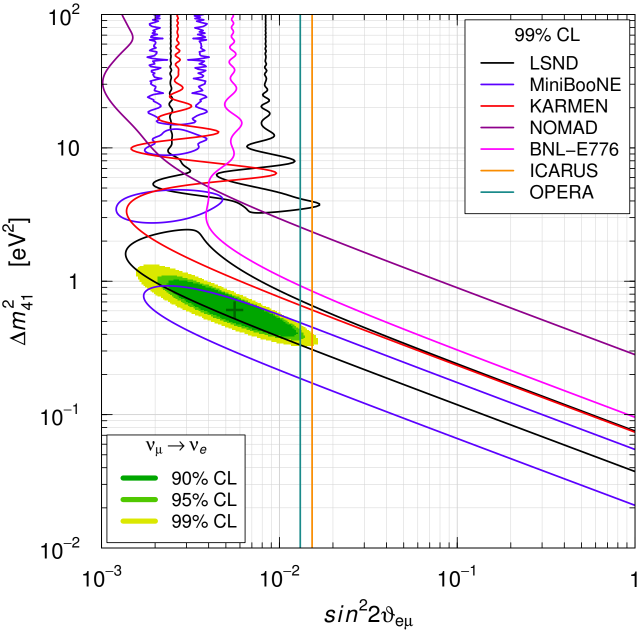
[Danilov, Moriond EW 2017]



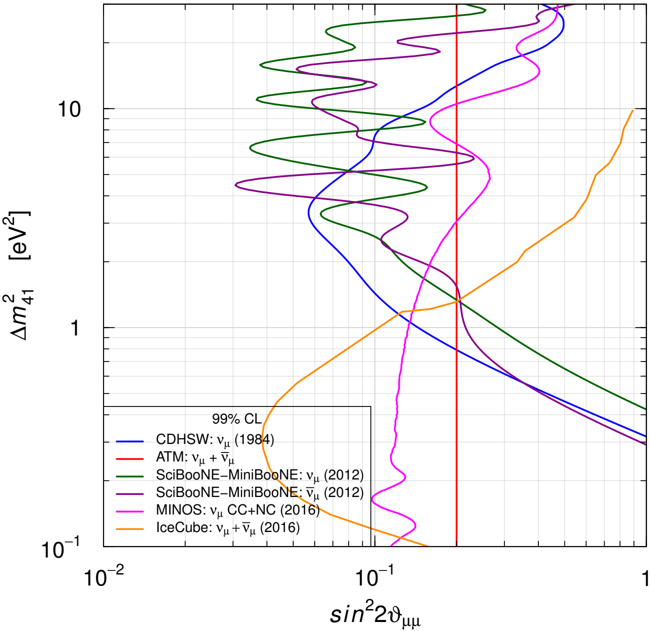




$\bar{\nu}_\mu \to \bar{\nu}_e$ and $\nu_\mu \to \nu_e$ Appearance



ν_μ and $\bar{\nu}_\mu$ Disappearance



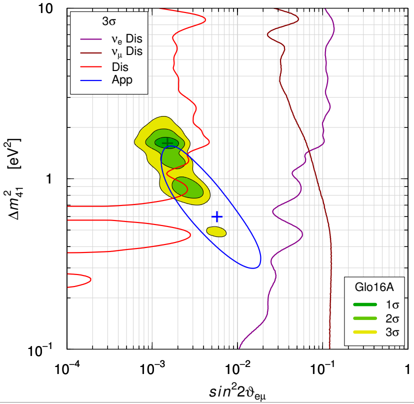
3+1 Appearance-Disappearance Tension

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

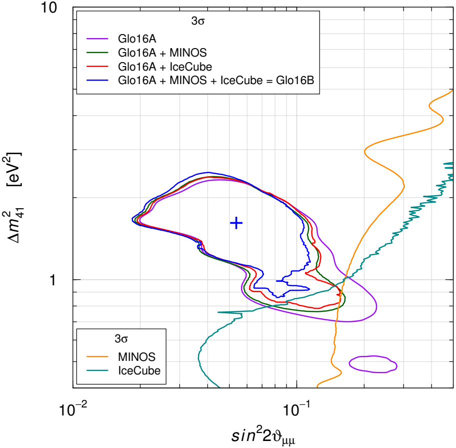
[Okada, Yasuda, IJMPA 12 (1997) 3669; Bilenky, CG, Grimus, EPJC 1 (1998) 247]

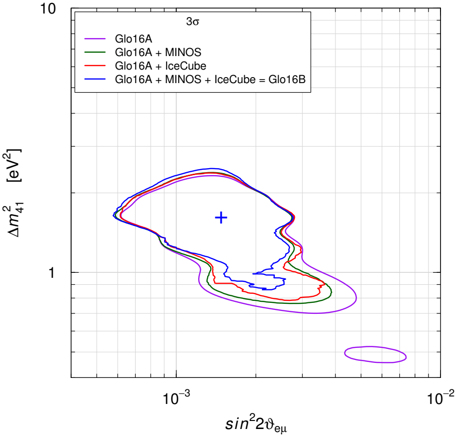


- $\nu_\mu \to \nu_e$ is quadratically suppressed!
- Glo16A = 2016 data except MINOS and IceCube
  [Gariazzo, CG, Laveder, Li, arXiv:1703.00860]
- $\Delta\chi^2_{\text{NO}} = 51.9 \Rightarrow \approx 6.4\sigma$ anomaly
- Best Fit: $\Delta m^2_{41} = 1.6\,\text{eV}^2$
  $|U_{e4}|^2 = 0.025 \quad |U_{m4}|^2 = 0.015$
- $\chi^2_{\text{min}}/\text{NDF} = 288.3/249 \Rightarrow \text{GoF} = 4\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 13.4/2 \Rightarrow \text{GoF}_{\text{PG}} = 0.1\%$
- 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]



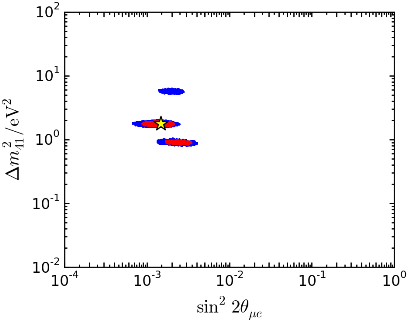


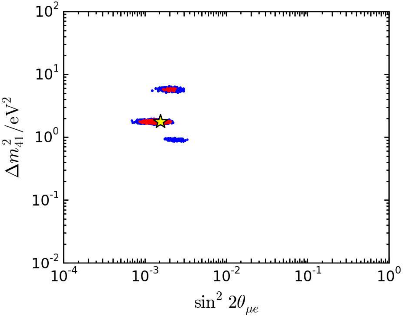
- Glo16B = Glo16A + MINOS + IceCube $\Delta\chi^2_{\text{NO}} = 50.7 \Rightarrow \approx 6.3\sigma$ anomaly
- Best Fit: $\Delta m^2_{41} = 1.6\,\text{eV}^2$ $|U_{e4}|^2 = 0.027$ $|U_{\mu 4}|^2 = 0.014$
- $\chi^2_{\text{min}}/\text{NDF} = 556.9/525 \Rightarrow \text{GoF} = 16\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}}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

Another Analysis of SBL + IceCube

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

SBL → SBL + IceCube



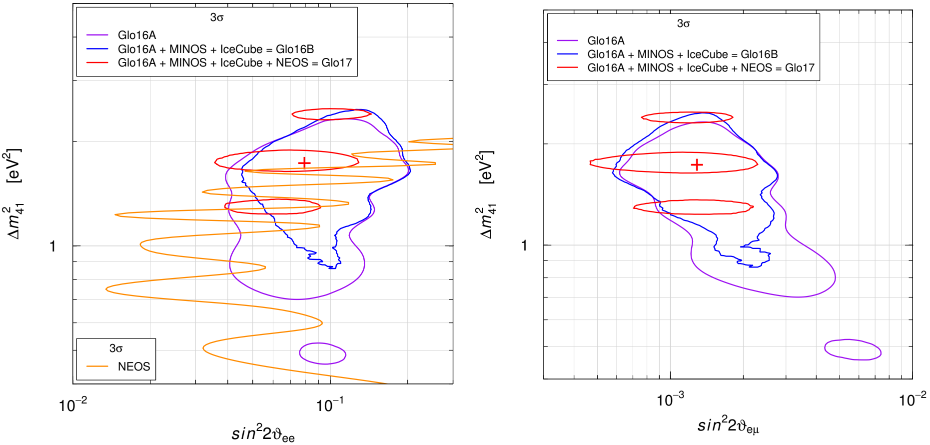


Red: 90% CL   Blue: 99% CL

3+1	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	$\lvert U_{\tau 4}\rvert$	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

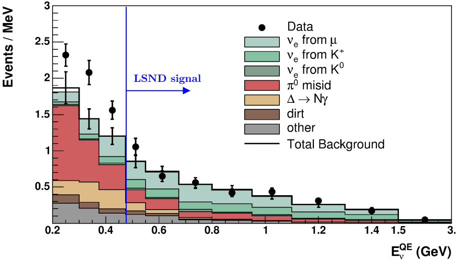
[Gariazzo, CG, Laveder, Li, arXiv:1703.00860]



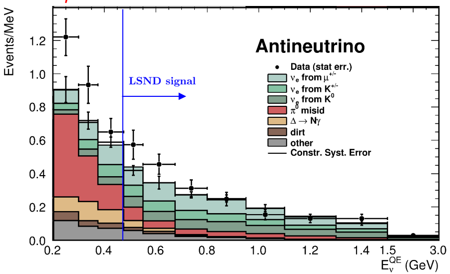
- Glo17 = GLO16B + NEOS $\qquad \Delta\chi^2_{\text{NO}} = 50.8 \Rightarrow \approx 6.3\sigma$ anomaly
- Best Fit: $\Delta m^2_{41} = 1.7\,\text{eV}^2 \quad |U_{e4}|^2 = 0.020 \quad |U_{\mu 4}|^2 = 0.016$
- $\chi^2_{\text{min}}/\text{NDF} = 621.7/585 \Rightarrow \text{GoF} = 14\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}}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

MiniBooNE Low-Energy Anomaly

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



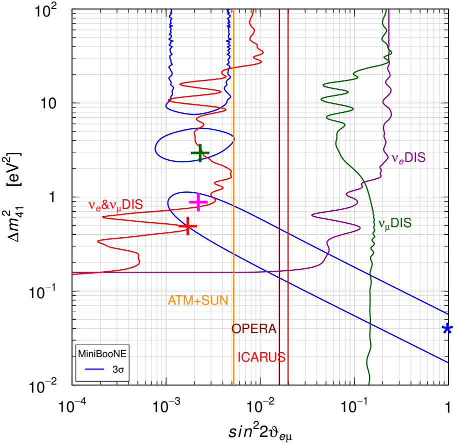
$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]

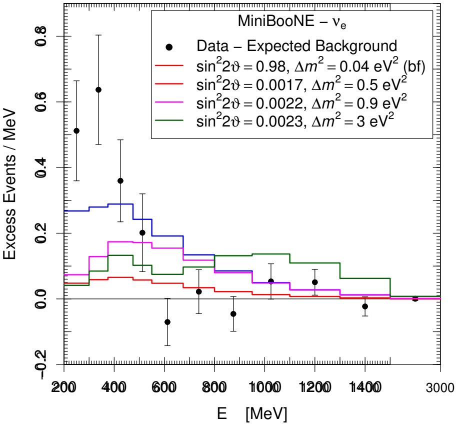


- Fit of MB Low-Energy Excess requires small Δm^2_{41} and large $\sin^2 2\vartheta_{e\mu}$, in contradiction with disappearance data

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

- 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 $\sin^2 2\vartheta_{e\mu} \lesssim 3 \times 10^{-3}$

Neutrino energy reconstruction problem?

[Martini, Ericson, Chanfray, PRD 85 (2012) 093012; PRD 87 (2013) 013009]

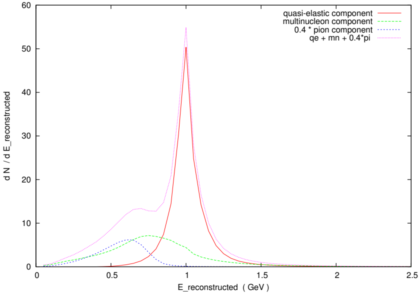
- Effect due to multinucleon interactions whose signal is indistinguishable from that due to quasielastic charged-current scattering

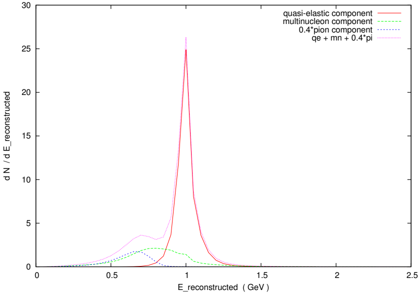
$$\nu_e + n \to p + e^- \qquad \bar{\nu}_e + p \to n + e^+$$

- In the MiniBooNE analysis the reconstructed neutrino energy is ($E_{\rm B} \simeq 25\,{\rm MeV}$)

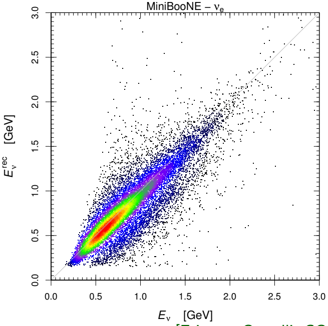
$$E_\nu^{\rm QE} = \frac{2\,(M_{\rm i} - E_{\rm B})\,E_e - \left(m_e^2 - 2M_{\rm i}E_{\rm B} + E_{\rm B}^2 + \Delta M_{\rm if}^2\right)}{2\,(M_{\rm i} - E_{\rm B} - E_e + p_e\cos\theta_e)}$$

- The MiniBooNE collaboration took into account:
  - Fermi motion of the initial nucleon
  - Charged-current single charged pion production events in which the pion is not observed
    (e.g. $\nu_e + n \to \Delta^+ + e^- \to n + \pi^+ + e^-$ with π^+ absorbed by a nucleus)

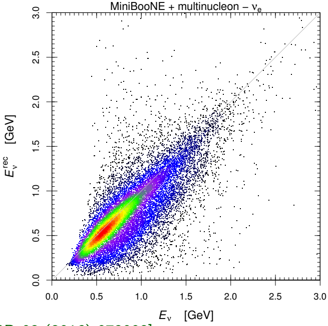




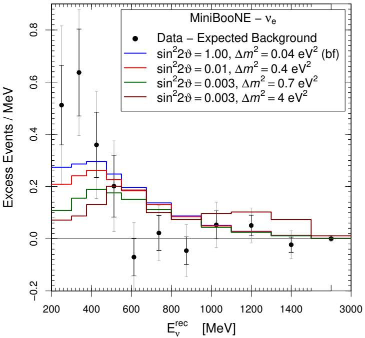
MiniBooNE $\nu_\mu \to \nu_e$ full transmutation Monte Carlo events



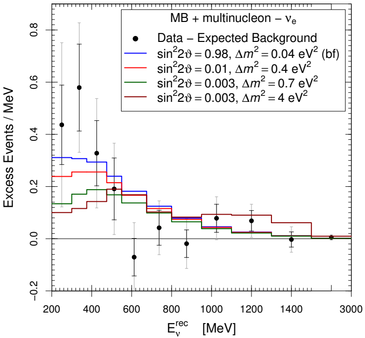
$\rightarrow$

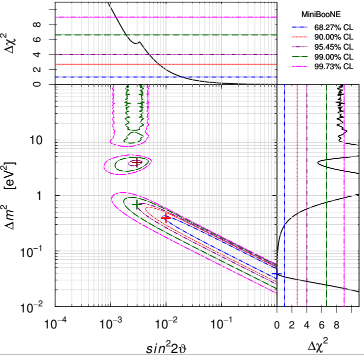


[Ericson, Garzelli, CG, Martini, PRD 93 (2016) 073008]

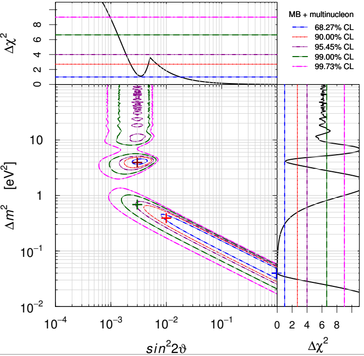

MiniBooNE – ν_e
Data – Expected Background
$\sin^2 2\vartheta = 1.00$, $\Delta m^2 = 0.04$ eV^2 (bf)
$\sin^2 2\vartheta = 0.01$, $\Delta m^2 = 0.4$ eV^2
$\sin^2 2\vartheta = 0.003$, $\Delta m^2 = 0.7$ eV^2
$\sin^2 2\vartheta = 0.003$, $\Delta m^2 = 4$ eV^2
Excess Events / MeV
E_ν^{rec} [MeV]

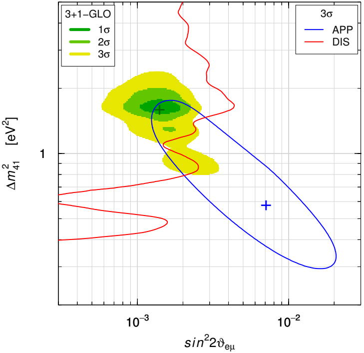
→


MB + multinucleon – ν_e
Data – Expected Background
$\sin^2 2\vartheta = 0.98$, $\Delta m^2 = 0.04$ eV^2 (bf)
$\sin^2 2\vartheta = 0.01$, $\Delta m^2 = 0.4$ eV^2
$\sin^2 2\vartheta = 0.003$, $\Delta m^2 = 0.7$ eV^2
$\sin^2 2\vartheta = 0.003$, $\Delta m^2 = 4$ eV^2
Excess Events / MeV
E_ν^{rec} [MeV]

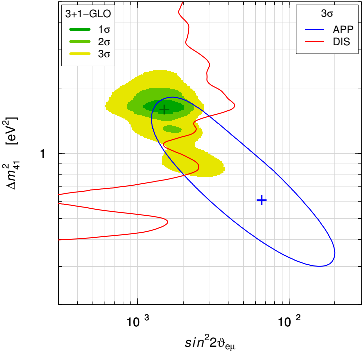

MiniBooNE
68.27% CL
90.00% CL
95.45% CL
99.00% CL
99.73% CL
$\Delta\chi^2$
Δm^2 [eV^2]
$sin^2 2\vartheta$

→


MB + multinucleon
68.27% CL
90.00% CL
95.45% CL
99.00% CL
99.73% CL
$\Delta\chi^2$
Δm^2 [eV^2]
$sin^2 2\vartheta$



→

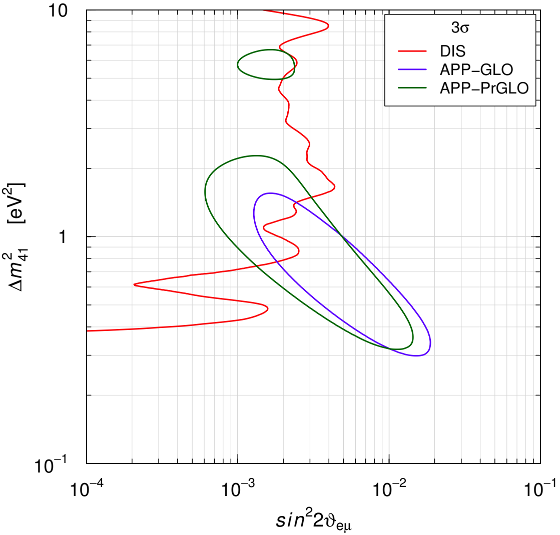


GoF = 7% PGoF = 0.2% GoF = 7% PGoF = 0.2%

- Multinucleon interactions can decrease slightly the MiniBooNE low-energy anomaly
- Multinucleon interactions cannot solve the APP-DIS tension
- MicroBooNE is crucial for checking the MiniBooNE low-energy anomaly
- If confirmed it is a real problem

Global → Pragmatic

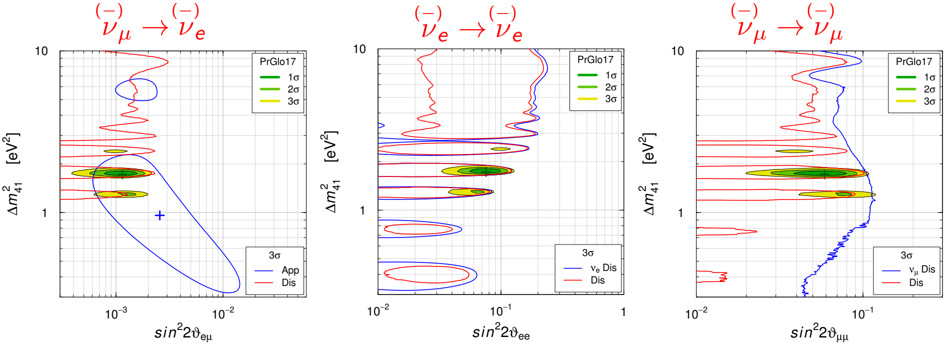
[CG, arXiv:1609.04688]



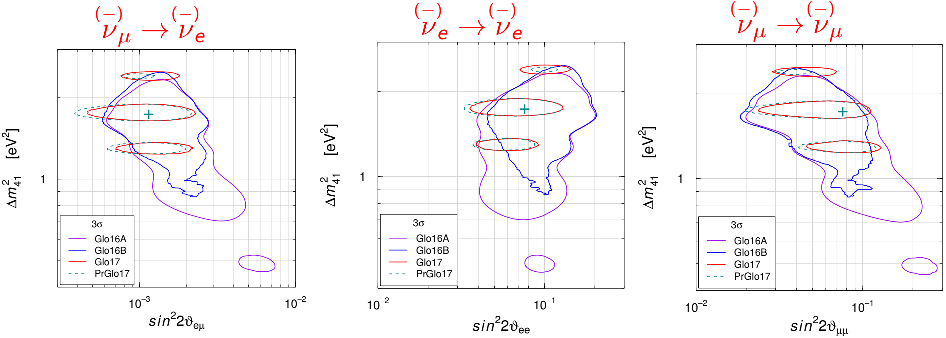
- APP-GLO: all MiniBooNE data
- APP-PrGLO: only MiniBooNE $E > 475\,\mathrm{MeV}$ data (Pragmatic)

Pragmatic Global 3+1 Fit

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

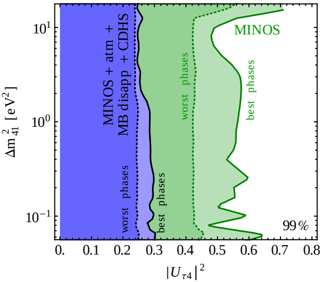


- $\Delta\chi^2_{\text{NO}} = 46.5 \Rightarrow \approx 6.0\sigma$ anomaly
- Best Fit: $\Delta m^2_{41} = 1.7\,\text{eV}^2$ $|U_{e4}|^2 = 0.019$ $|U_{\mu4}|^2 = 0.015$
- $\chi^2_{\text{min}}/\text{NDF} = 594.8/579 \Rightarrow \text{GoF} = 32\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 7.4/2 \Rightarrow \text{GoF}_{\text{PG}} = 3\%$ $\leftarrow$ Mild tolerable tension!

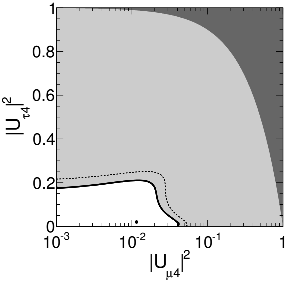


$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$
$\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$
$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$
Δm^2_{41} [eV^2]
1
3σ
Glo16A
Glo16B
Glo17
PrGlo17
10^{-3}
10^{-2}
10^{-1}
$sin^2 2\vartheta_{e\mu}$
$sin^2 2\vartheta_{ee}$
$sin^2 2\vartheta_{\mu\mu}$

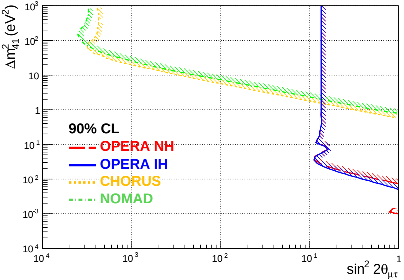
Bounds on $|U_{\tau 4}|^2$



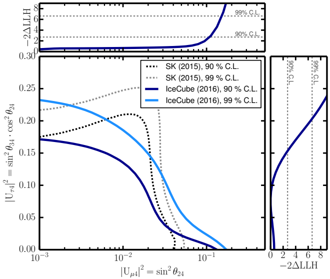
[Kopp et al, JHEP 1305 (2013) 050]



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

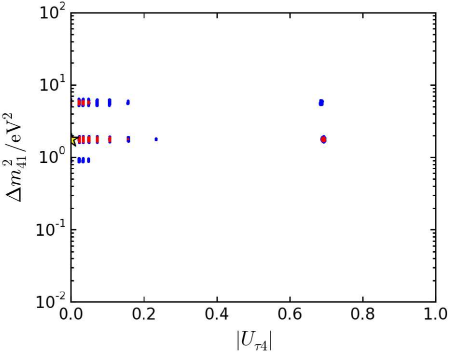


$\nu_\mu \to \nu_\tau$ [OPERA, JHEP 1506 (2015) 069]



[IceCube DeepCore, arXiv:1702.05160]

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

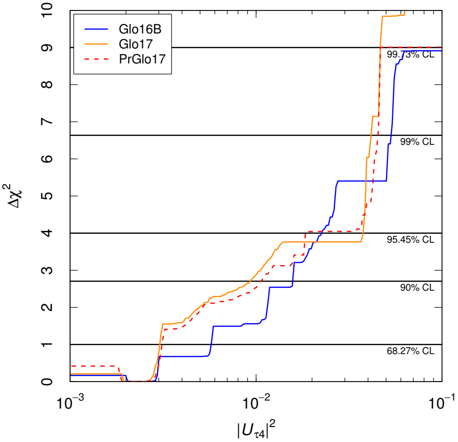


90% CL

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

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

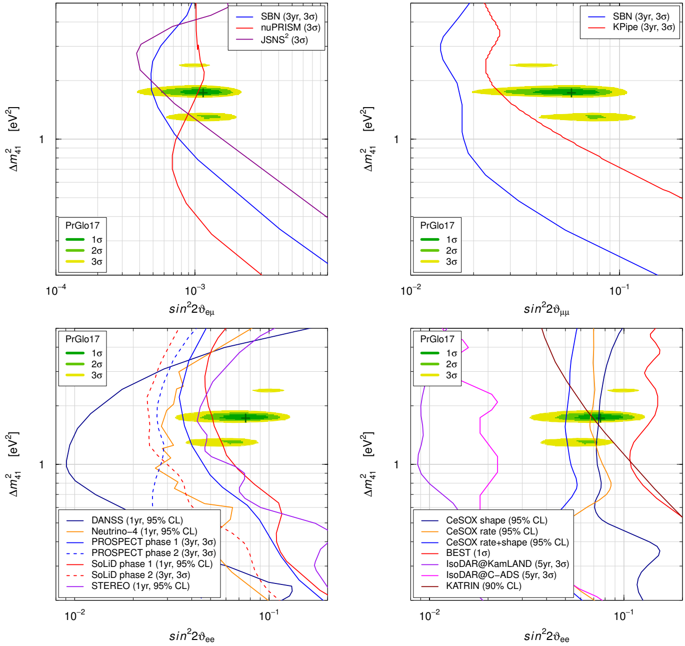
[Gariazzo, CG, Laveder, Li, arXiv:1703.00860]



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

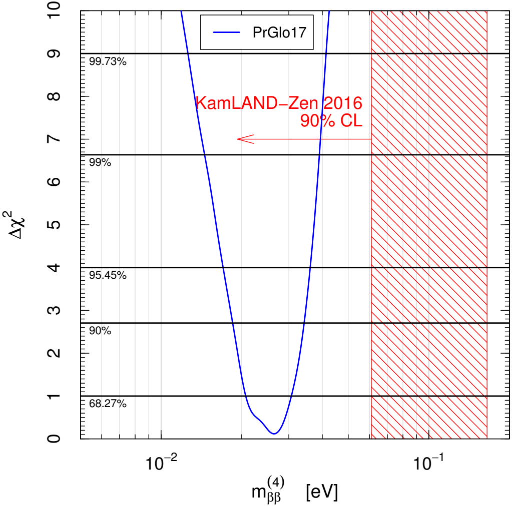


Effects of light sterile neutrinos should also be seen in:

- 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]

Neutrinoless Double-Beta Decay

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



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

$$m_1 \ll m_4$$

$$\Downarrow$$

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

surprise:

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

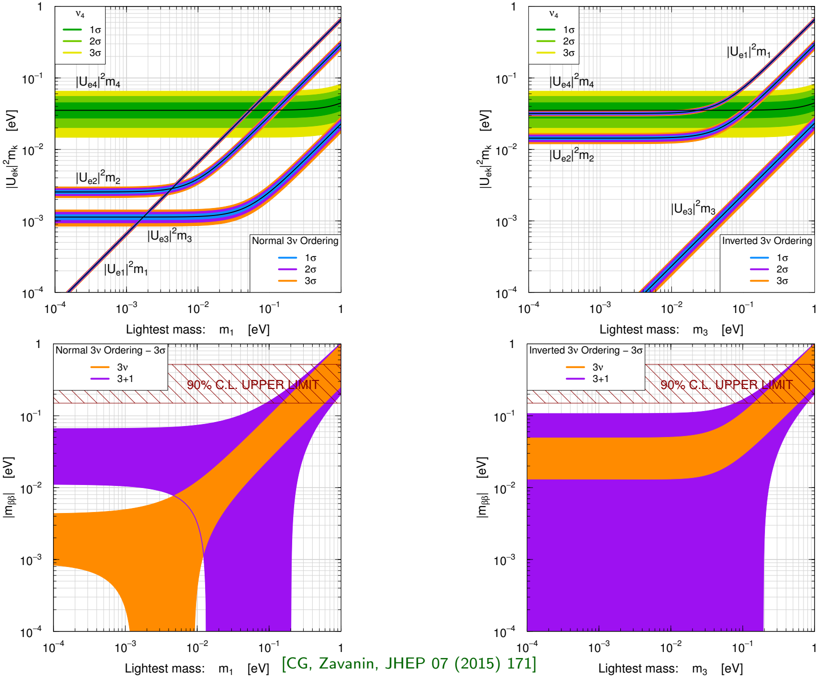
[Barry et al, JHEP 07 (2011) 091]

[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.
  - 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: strong tension with $\Delta N_{\text{eff}} = 1$ and $m_4 \approx 1\,\text{eV}$. It may be solved by 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).