Oscillations Beyond Three-Neutrino Mixing (Status of Light Sterile Neutrinos)

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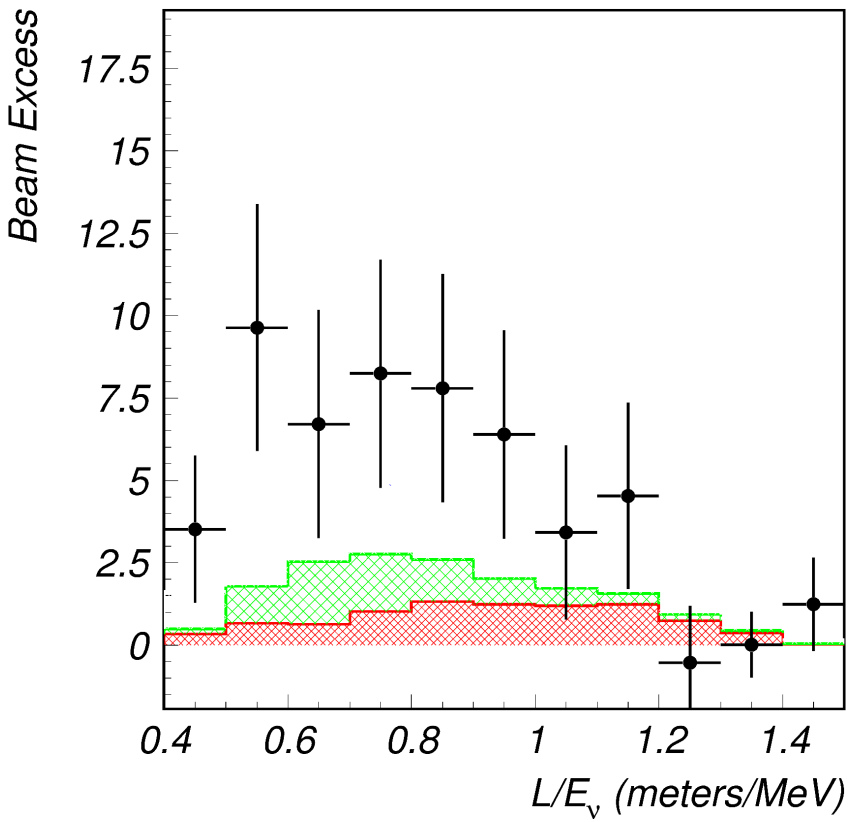
Indications of SBL Oscillations Beyond 3ν

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 $\bar{\nu}_\mu$

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

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

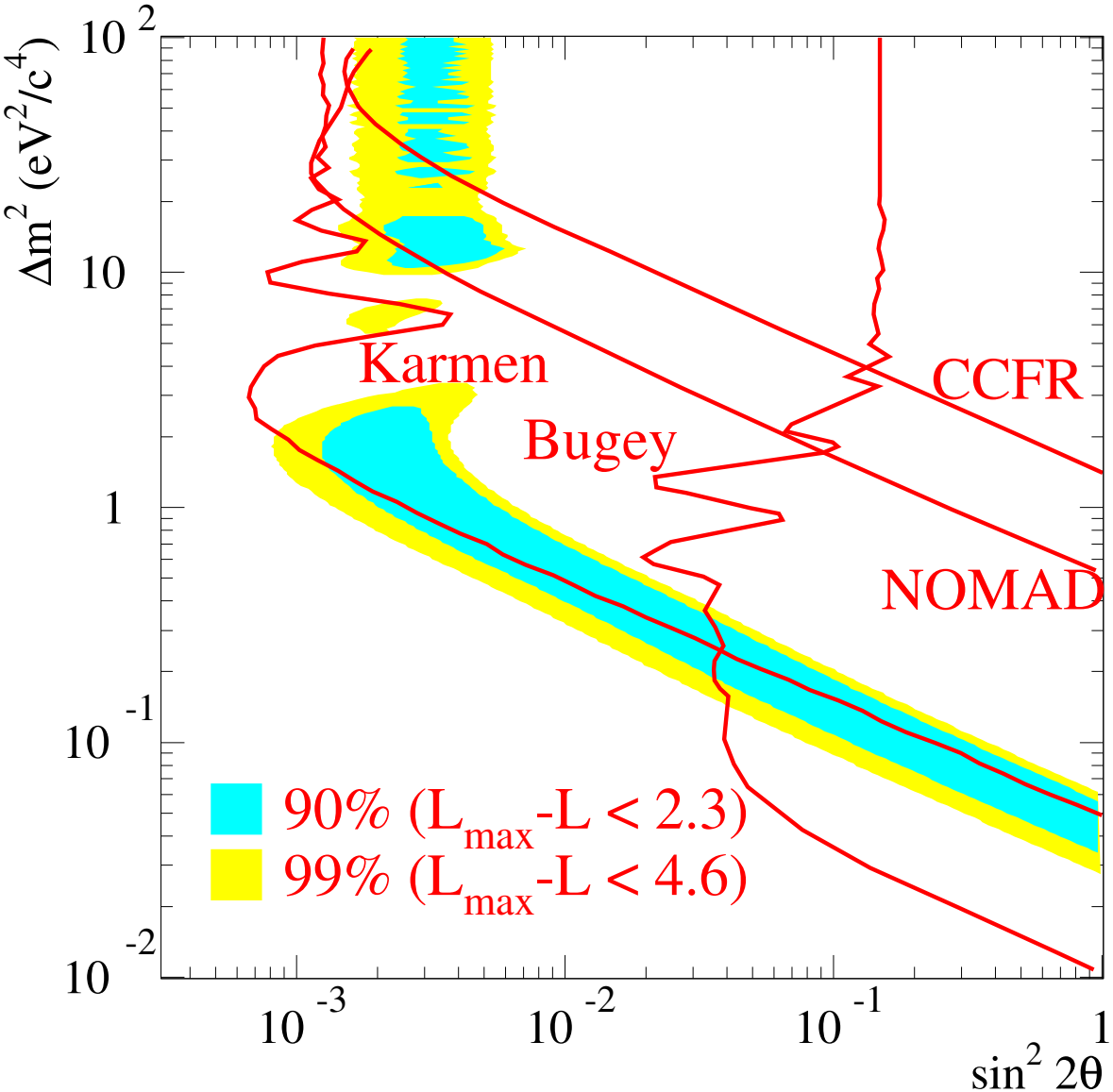
$$L \simeq 30\,\text{m}$$

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

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]

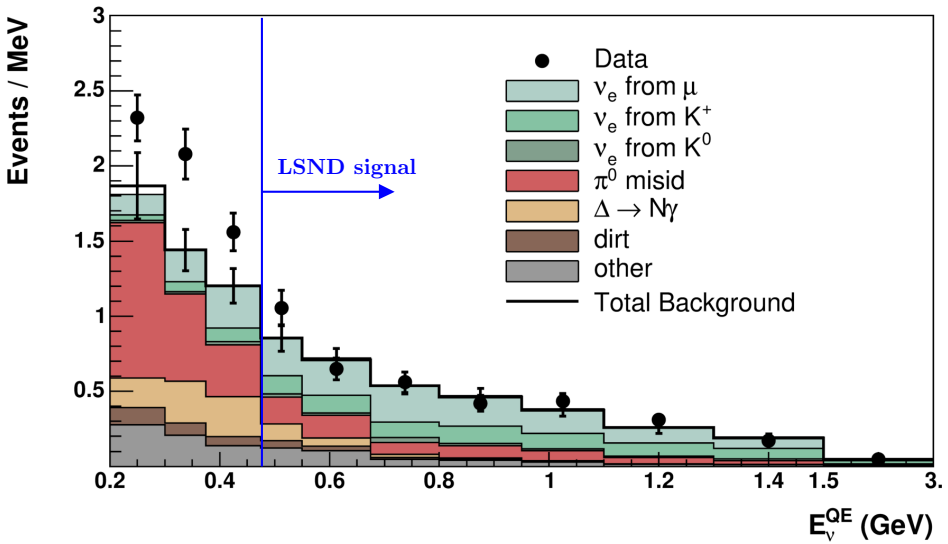


$$\Delta m^2_{\text{SBL}} \gtrsim 3 \times 10^{-2}\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \simeq 2.5 \times 10^{-3}\,\text{eV}^2 \gg \Delta m^2_{\text{SOL}}$$

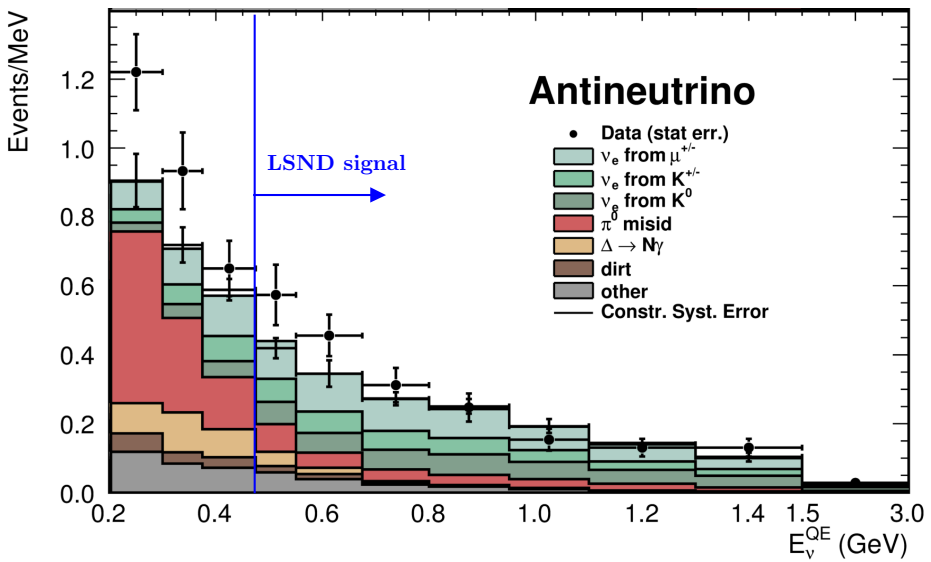
MiniBooNE

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

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

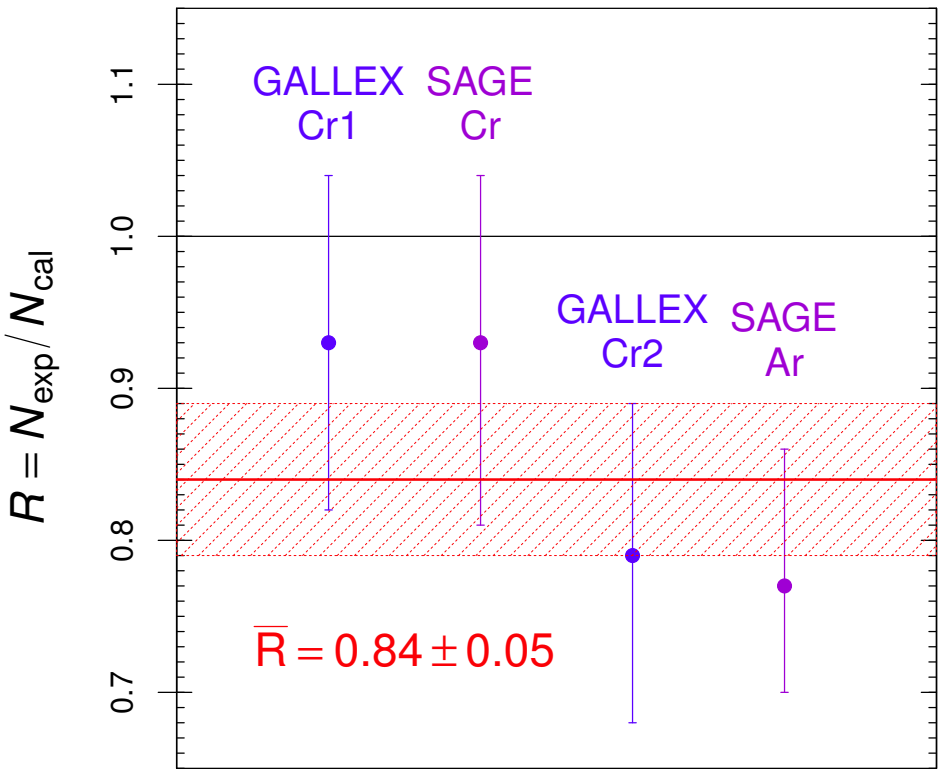
Gallium Anomaly

Gallium Radioactive Source Experiments: GALLEX and SAGE

ν_e Sources: $e^- + {}^{51}\mathrm{Cr} \to {}^{51}\mathrm{V} + \nu_e$ $E \simeq 0.75\,\mathrm{MeV}$ $\quad$ $e^- + {}^{37}\mathrm{Ar} \to {}^{37}\mathrm{Cl} + \nu_e$ $E \simeq 0.81\,\mathrm{MeV}$

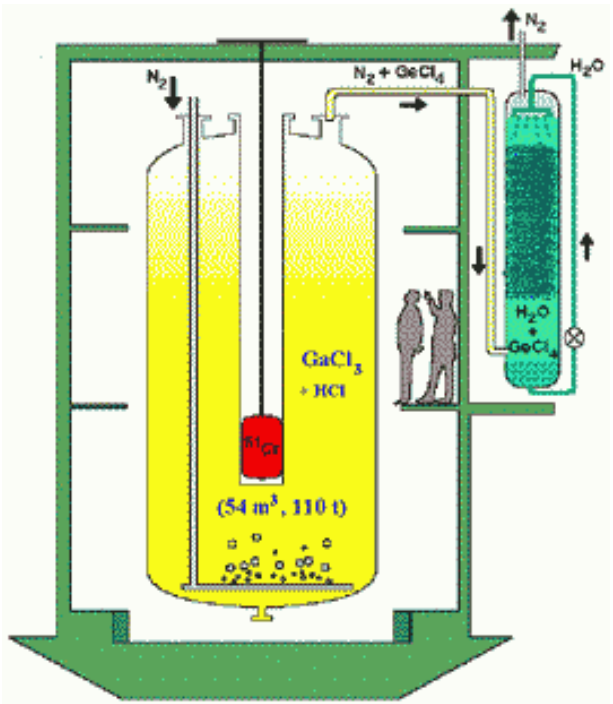
$\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$

Test of Solar ν_e Detection:



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

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



$\approx 2.9\sigma$ deficit

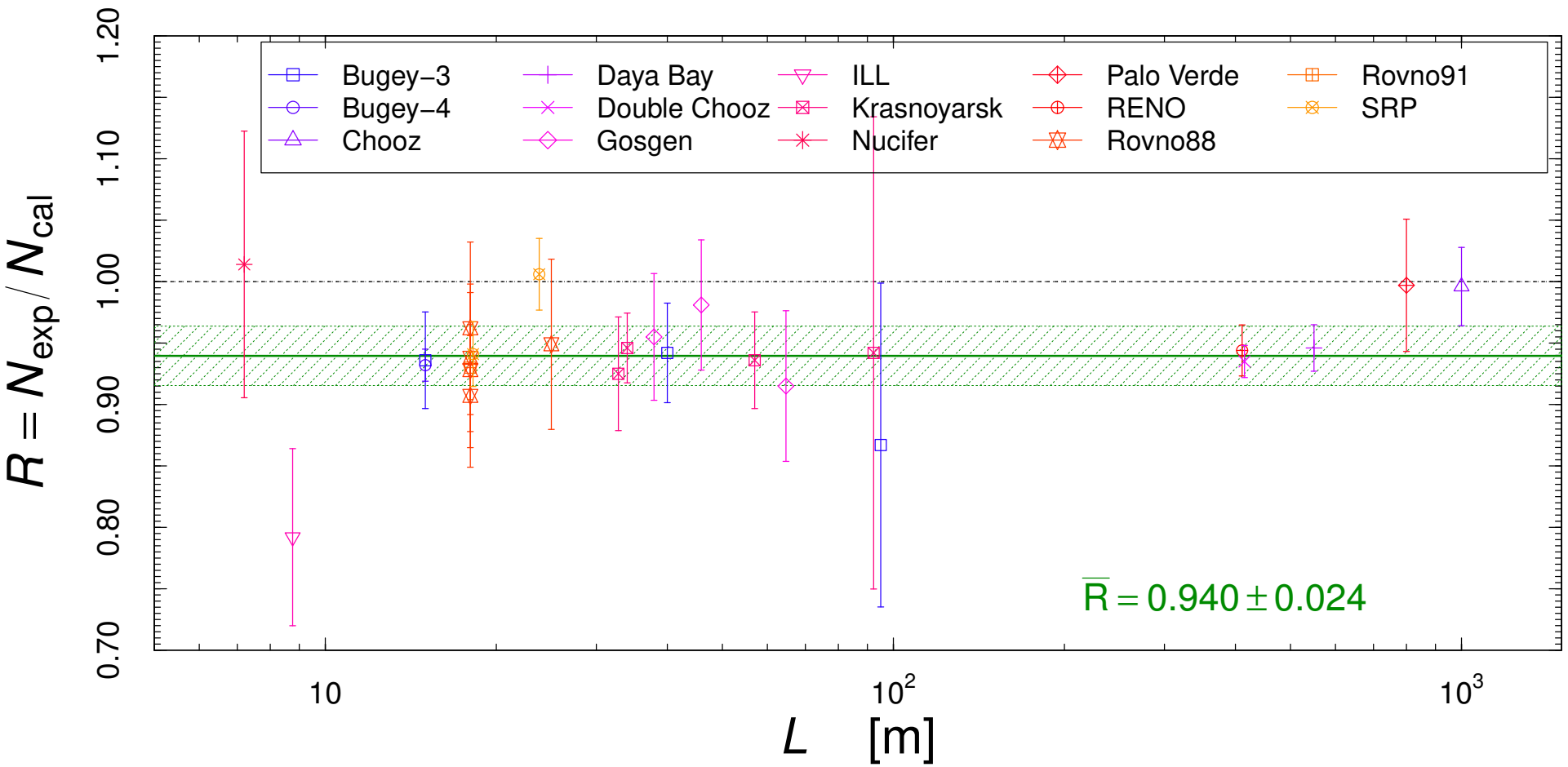
[SAGE, PRC 73 (2006) 045805; PRC 80 (2009) 015807; Laveder et al, Nucl.Phys.Proc.Suppl. 168 (2007) 344, MPLA 22 (2007) 2499, PRD 78 (2008) 073009, PRC 83 (2011) 065504]

Reactor Electron Antineutrino Anomaly

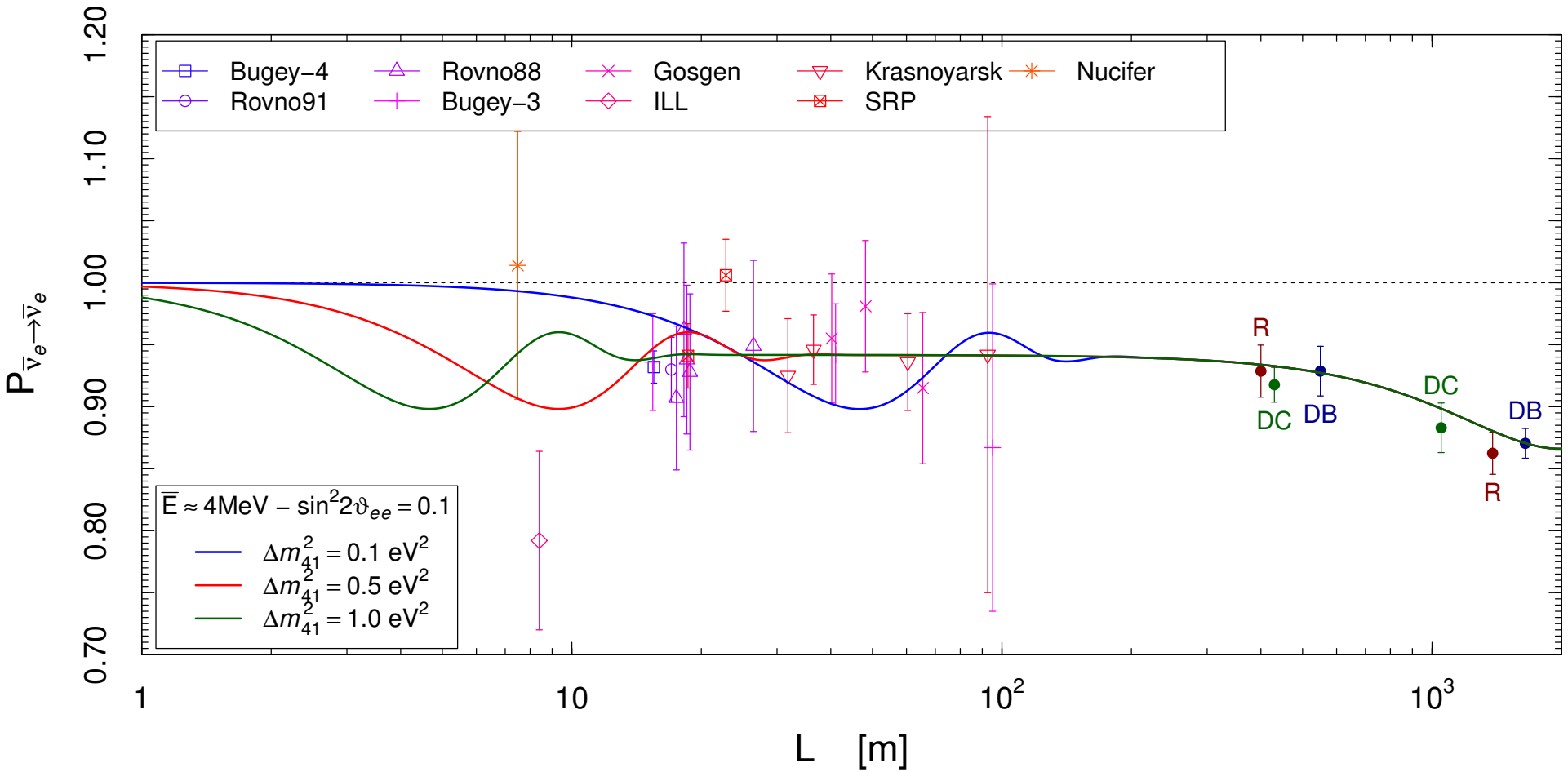
[Mention et al, PRD 83 (2011) 073006]

New reactor $\bar{\nu}_e$ fluxes

[Mueller et al, PRC 83 (2011) 054615; Huber, PRC 84 (2011) 024617]



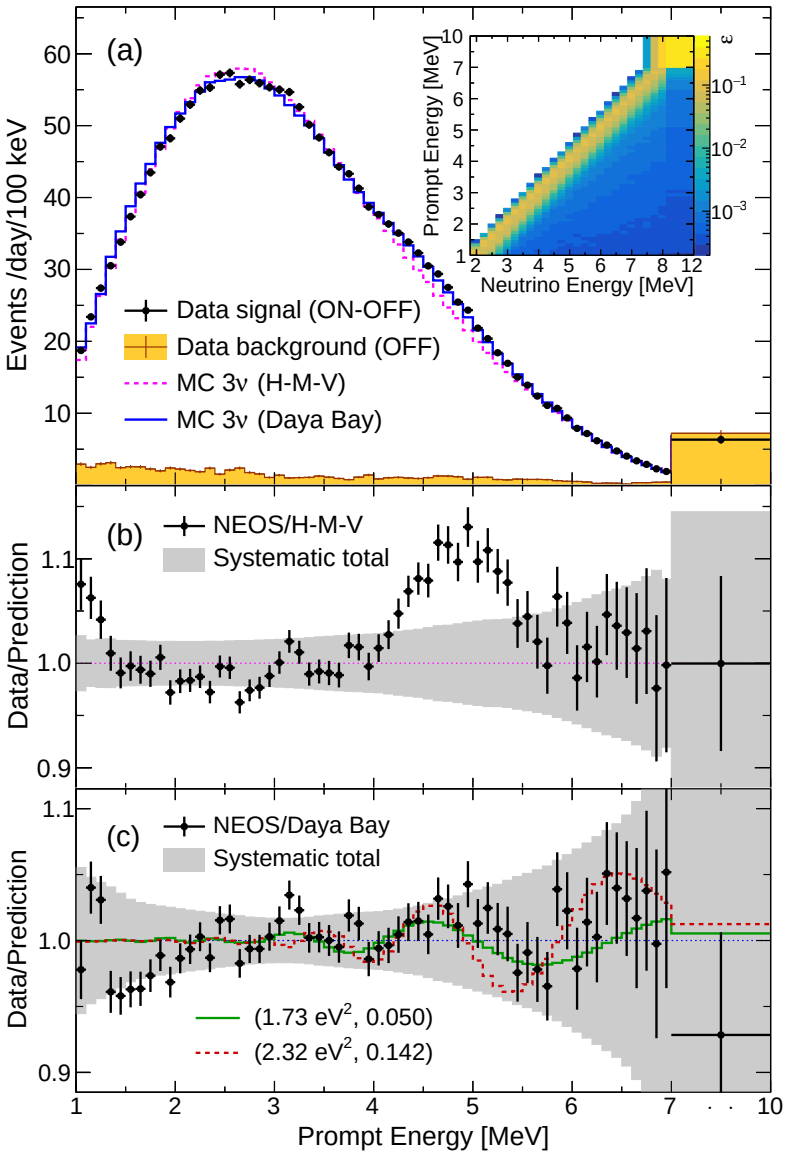
$\approx 2.5\sigma$ deficit



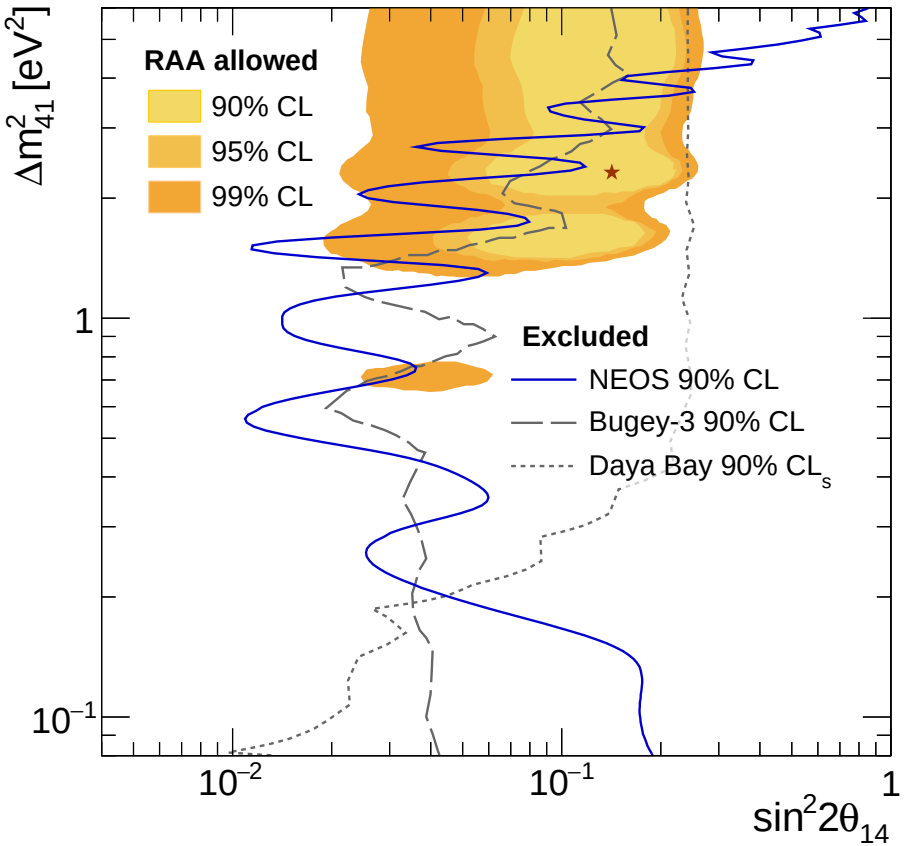
$$\Delta m^2_{\text{SBL}} \gtrsim 0.5\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}}$$

NEOS

[arXiv:1610.05134]



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

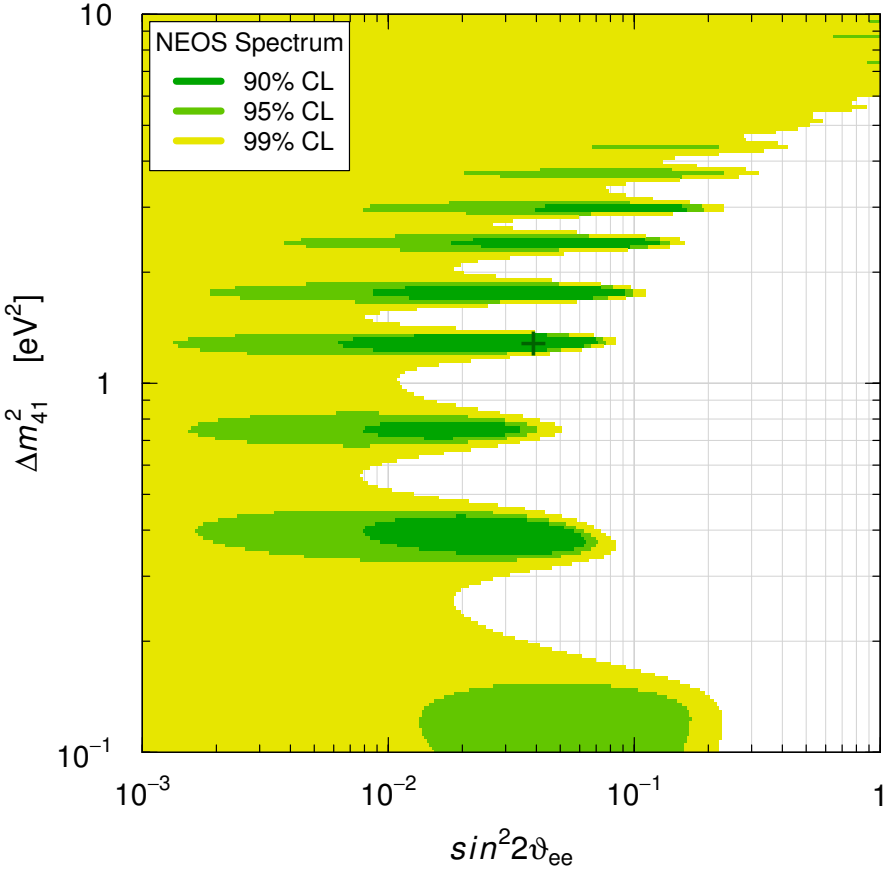


Raster Scan [NEOS, arXiv:1610.05134]

Best Fits:

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

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

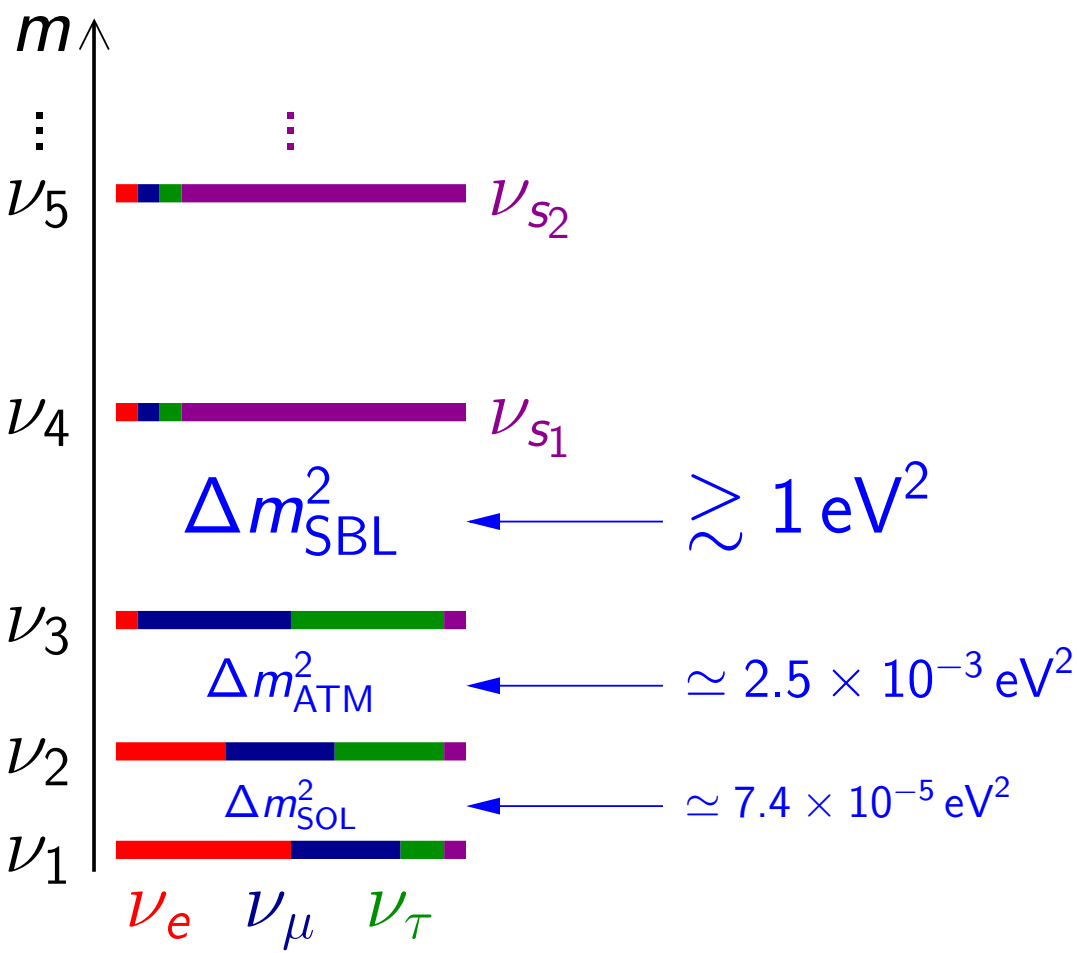


2-D χ^2 Analysis

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

$\approx 2.1\sigma$ anomaly

Beyond Three-Neutrino Mixing: Sterile Neutrinos



Terminology: a eV-scale sterile neutrino

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

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:

$$\Delta m^2_{21} \ll |\Delta m^2_{31}| \ll |\Delta m^2_{41}| \leq \ldots$$

ν_1	ν_2	ν_3	ν_4	$\ldots$
ν_e	ν_μ	ν_τ	ν_{s_1}	$\ldots$

Effective 3+1 SBL Oscillation Probabilities

Appearance ($\alpha \neq \beta$)

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

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

Disappearance

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

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

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

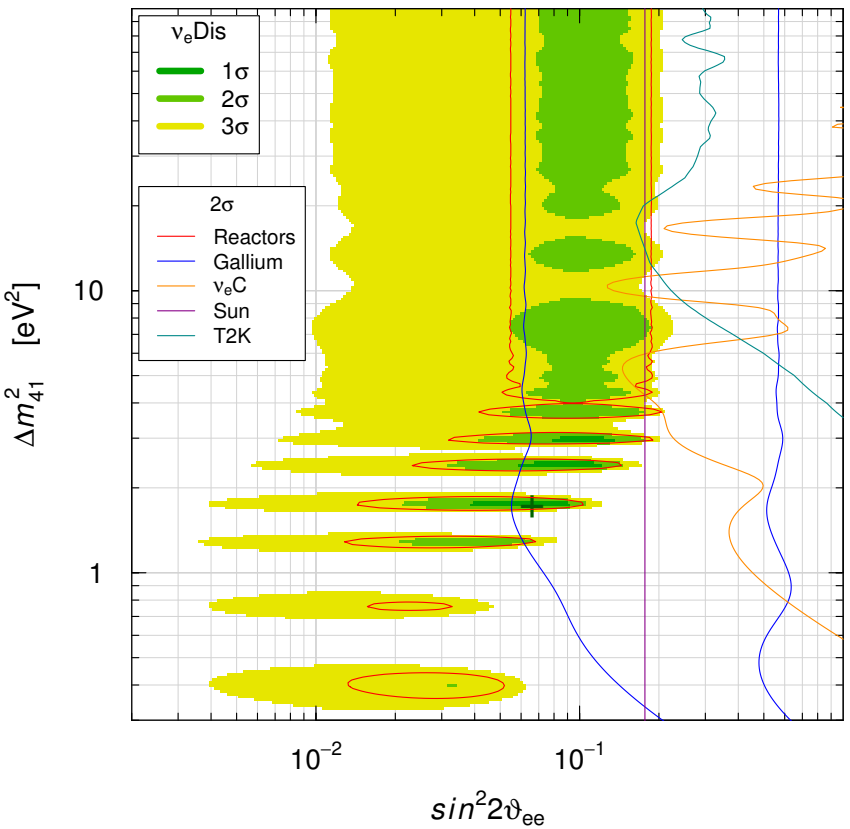
SBL

- 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

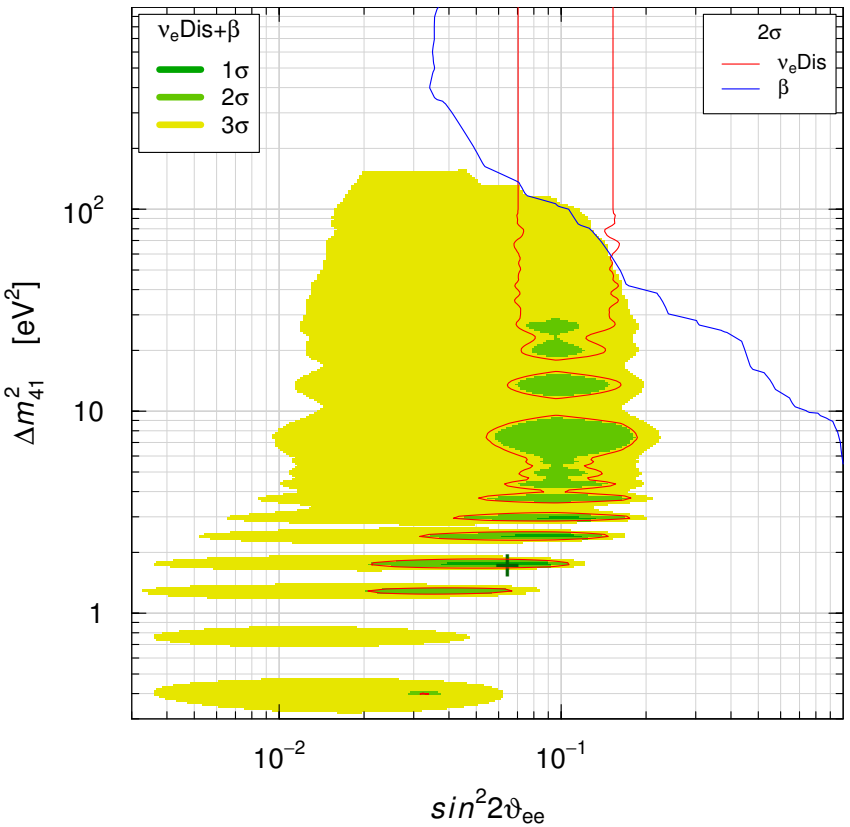
[Gariazzo, CG, Laveder, Li, arXiv:1703.00860]



- 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: $\Delta m^2_{41} = 1.7\,\text{eV}^2$
  $\sin^2 2\vartheta_{ee} = 0.066 \quad \Leftrightarrow \quad |U_{e4}|^2 = 0.017$
- $\chi^2_{\text{min}}/\text{NDF} = 162.5/174 \Rightarrow \text{GoF} = 72\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 13.8/7 \Rightarrow \text{GoF}_{\text{PG}} = 6\%$

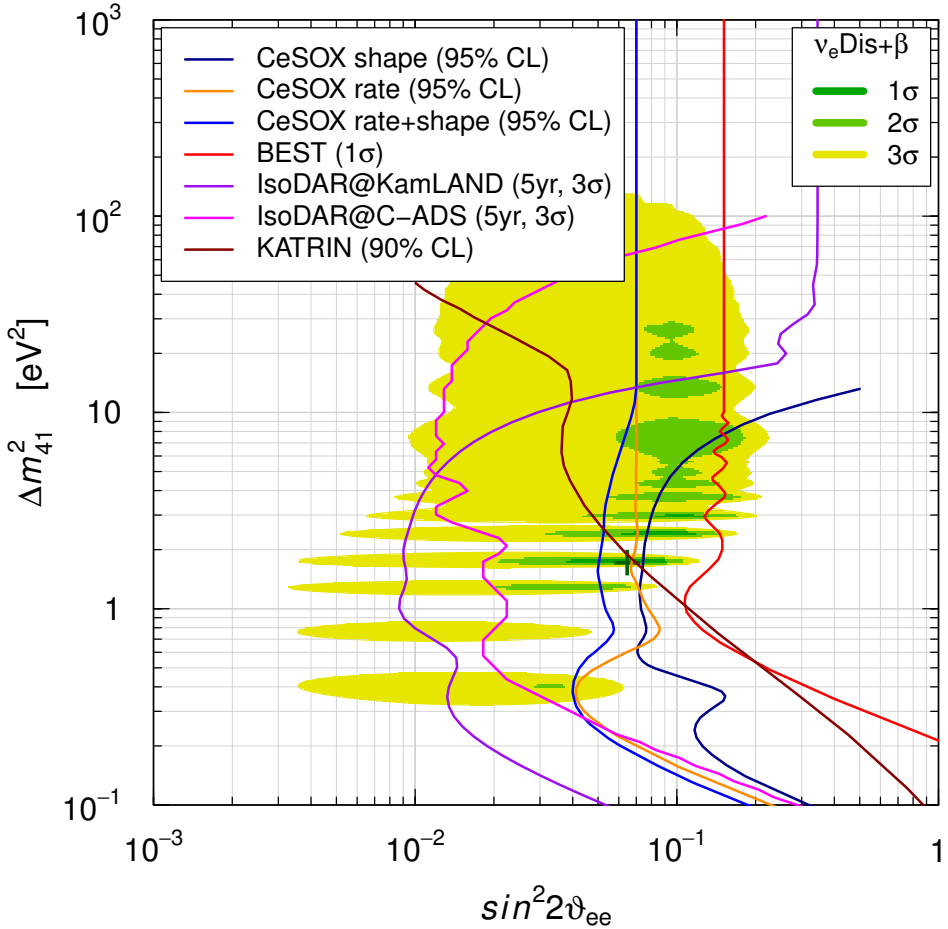
Global ν_e and $\bar{\nu}_e$ Disappearance + β Decay

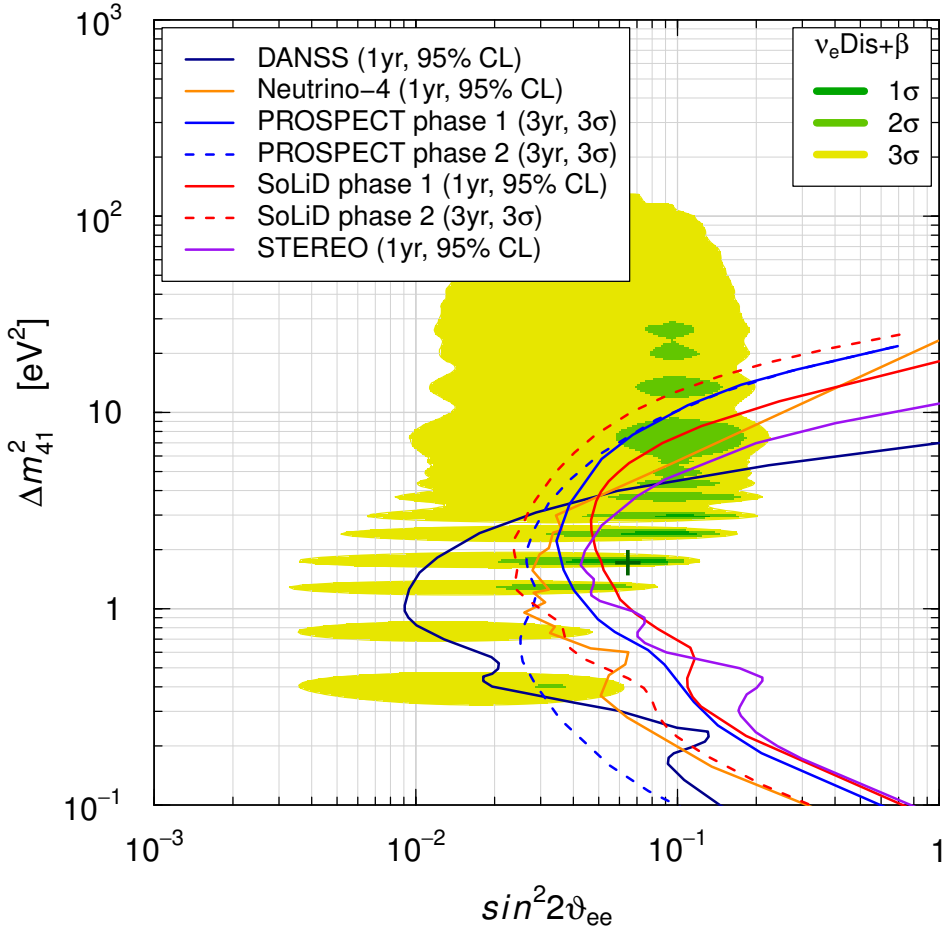
[Gariazzo, CG, Laveder, Li, arXiv:1703.00860]



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

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]

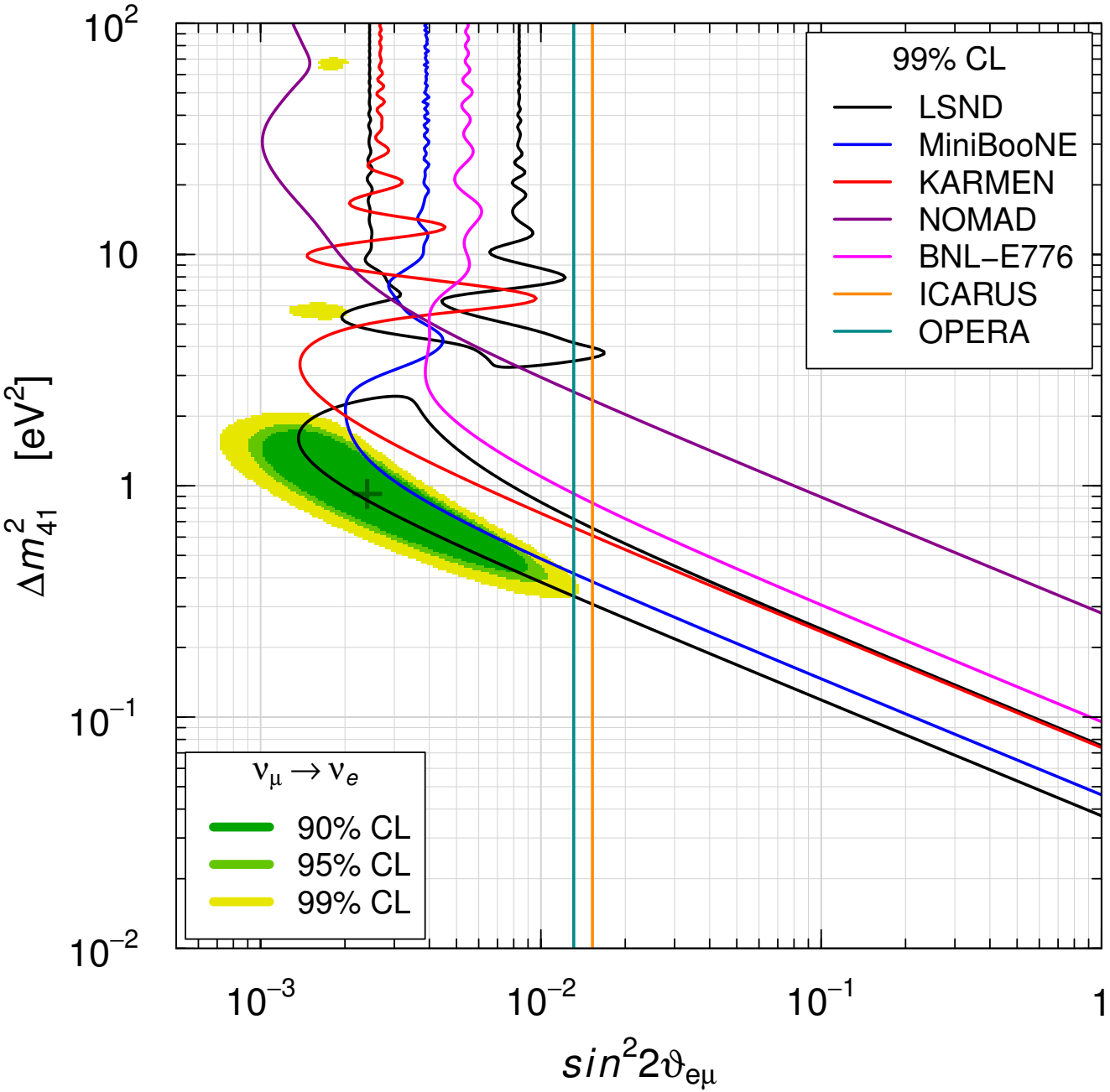
PROSPECT (ORNL, USA) $L \simeq$ 7-12m [arXiv:1512.02202]

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

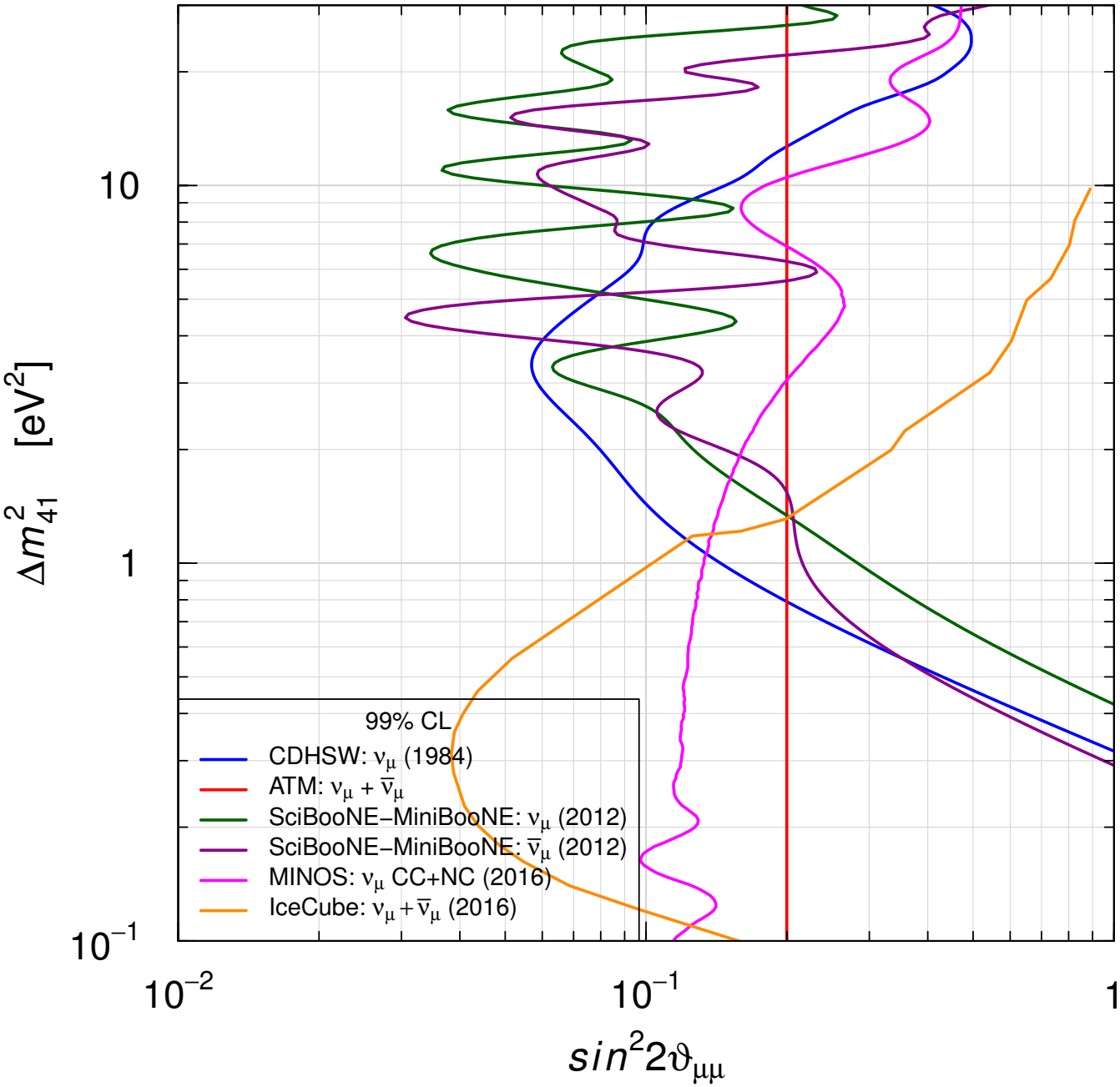
STEREO (ILL, France) $L \simeq$ 8-12m [arXiv:1602.00568]

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

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



ν_μ and $\bar{\nu}_\mu$ Disappearance



3+1 Appearance-Disappearance Tension

ν_e DIS

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

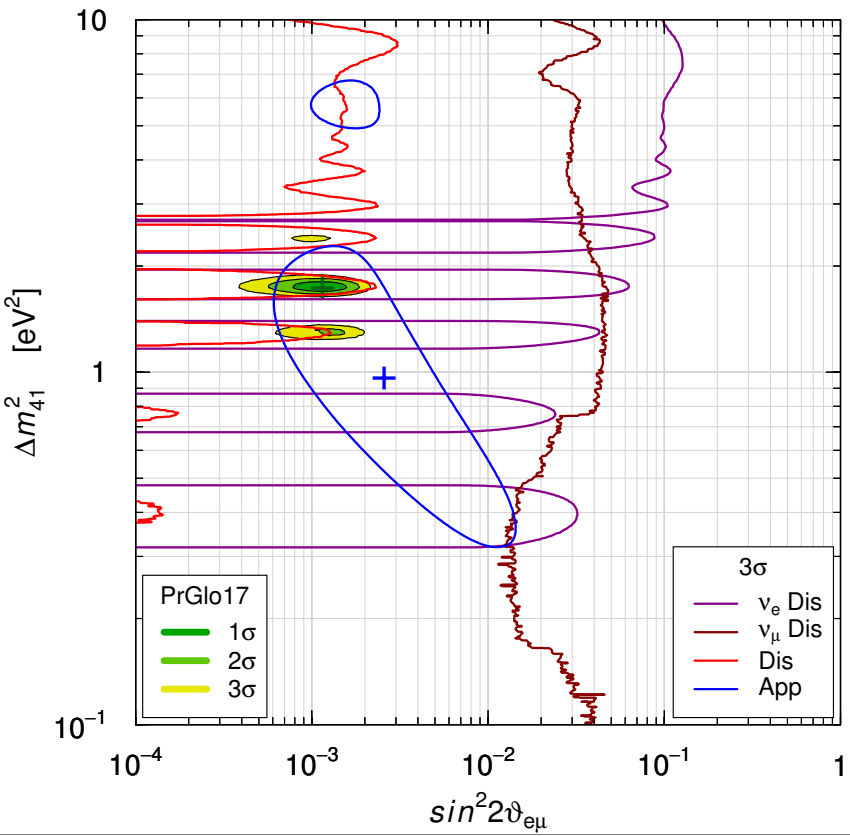
ν_μ DIS

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

$\nu_\mu \to \nu_e$ APP

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

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



- $\nu_\mu \to \nu_e$ is quadratically suppressed!
- PrGlo17 = Pragmatic Global Fit 2017

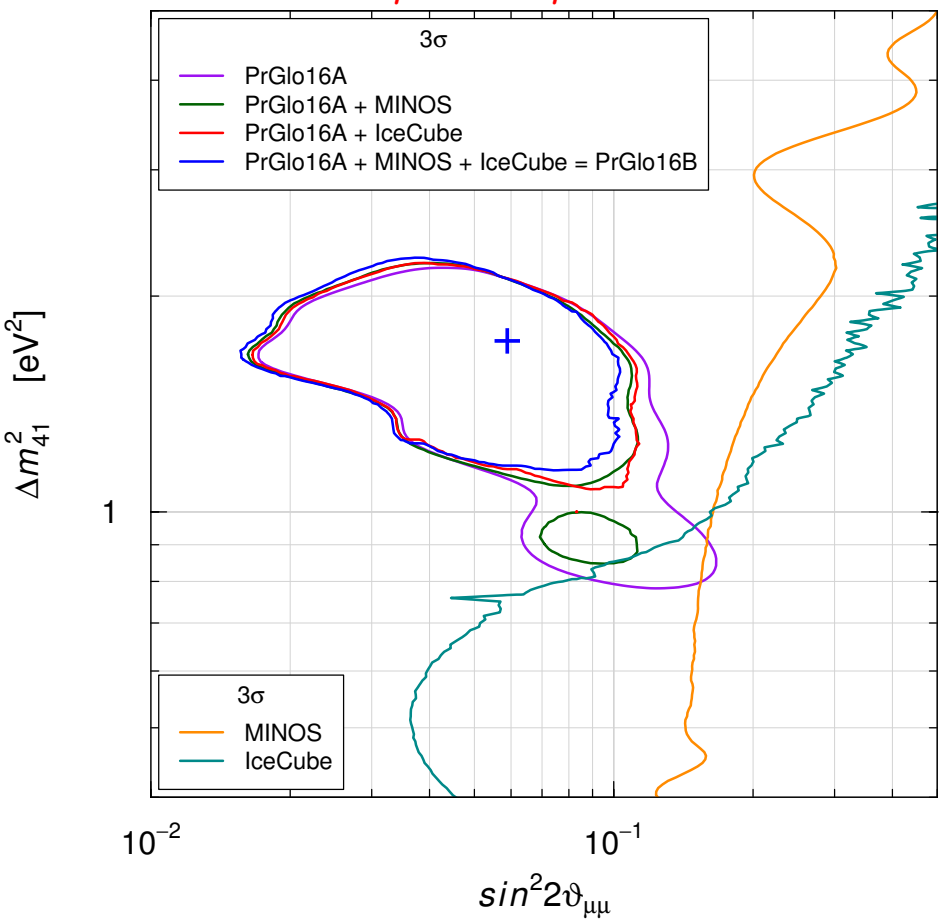
  [Gariazzo, CG, Laveder, Li, arXiv:1703.00860]
- $\Delta\chi^2_{\rm NO} = 46.5 \Rightarrow \approx 6.0\sigma$ anomaly
- Best Fit: $\Delta m^2_{41} = 1.7\,{\rm eV}^2$

  $|U_{e4}|^2 = 0.019 \quad |U_{\mu 4}|^2 = 0.015$
- $\chi^2_{\rm min}/{\rm NDF} = 594.8/579 \Rightarrow {\rm GoF} = 32\%$
- $\chi^2_{\rm PG}/{\rm NDF}_{\rm PG} = 7.4/2 \Rightarrow {\rm GoF}_{\rm PG} = 3\%$
- Similar tension in 3+2, 3+3, ..., 3+N_s

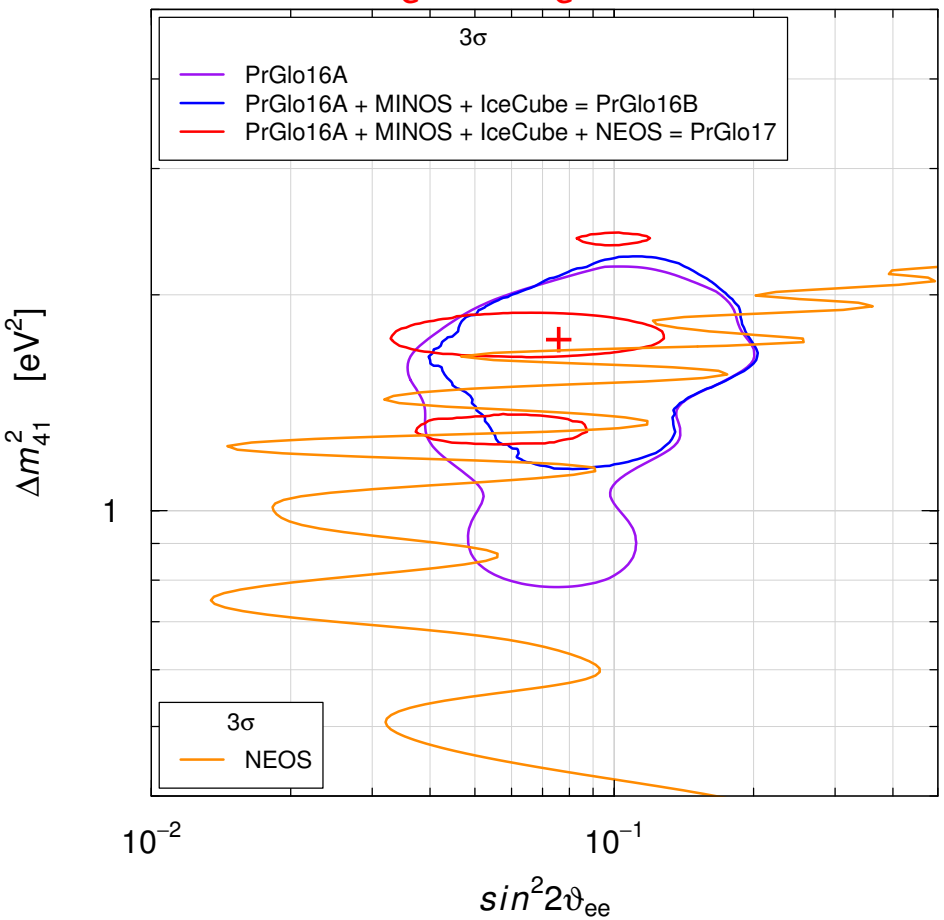
  [CG, Zavanin, MPLA 31 (2015) 1650003]

Effects of MINOS, IceCube and NEOS

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

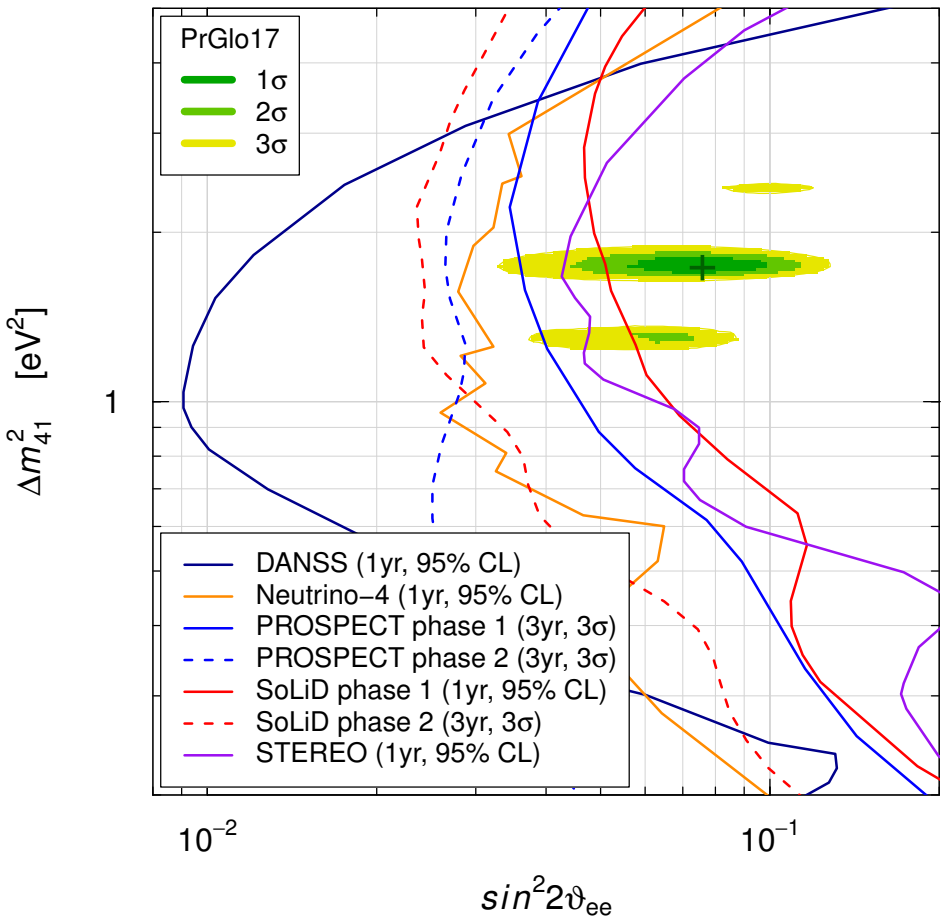


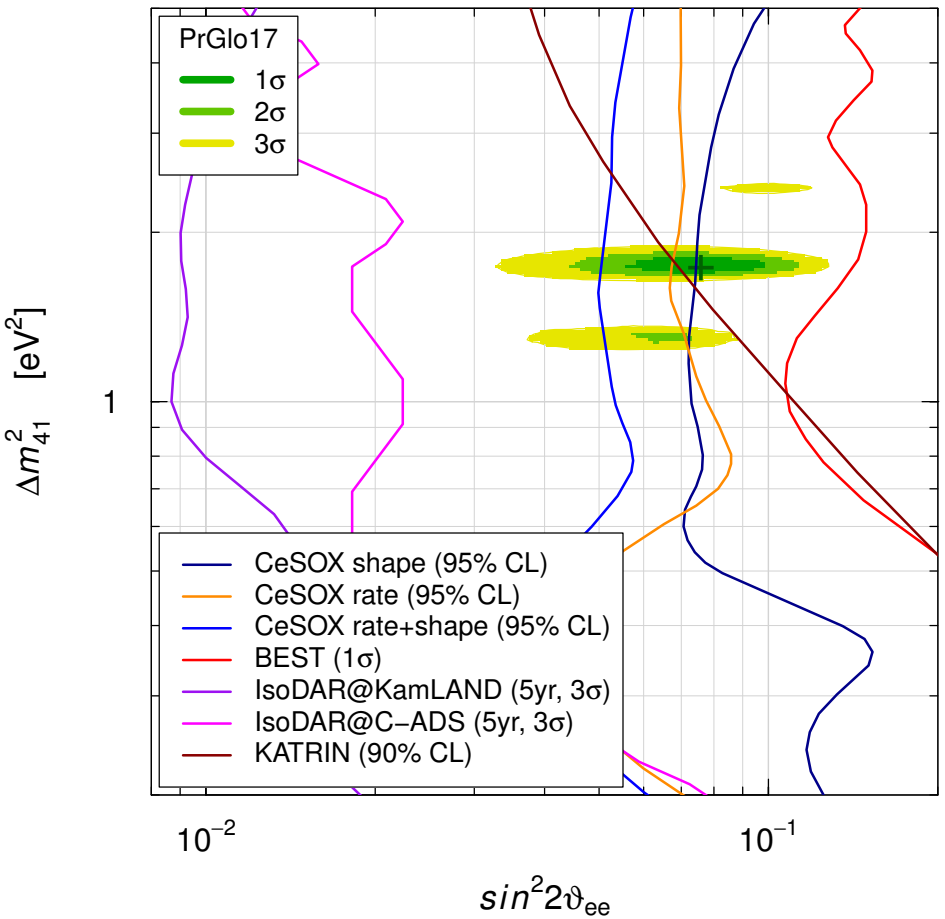
$\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$

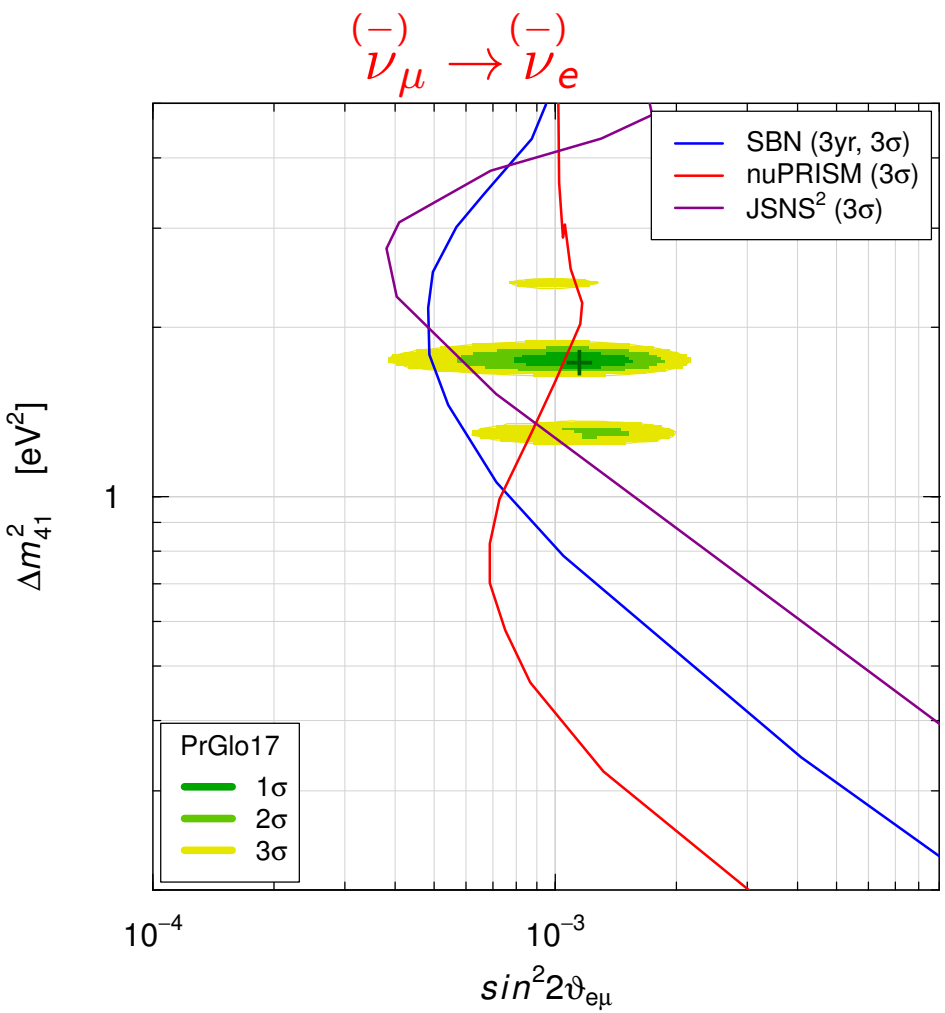


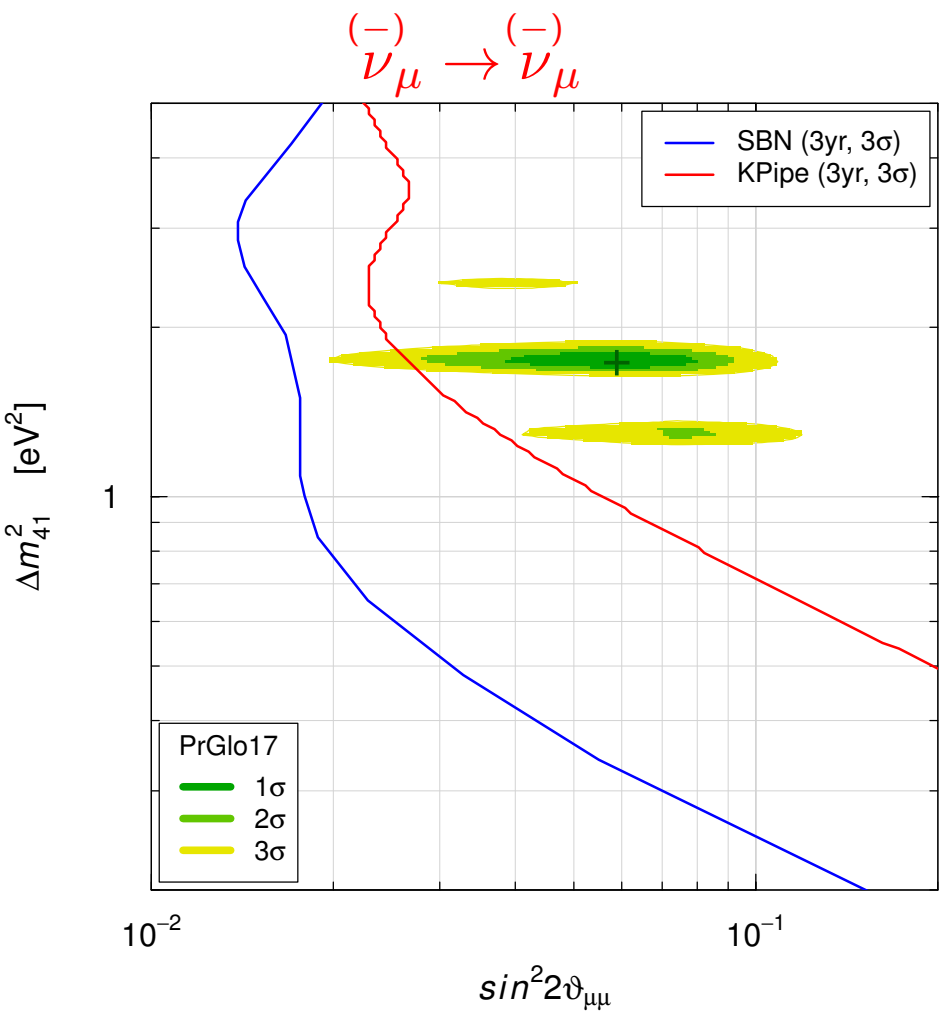
The Race for the Light Sterile

$$\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$$






$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$
SBN (3yr, 3σ)
nuPRISM (3σ)
JSNS^2 (3σ)
PrGlo17
1σ
2σ
3σ
Δm^2_{41} [eV^2]
1
10^{-4}
10^{-3}
$sin^2 2\vartheta_{e\mu}$

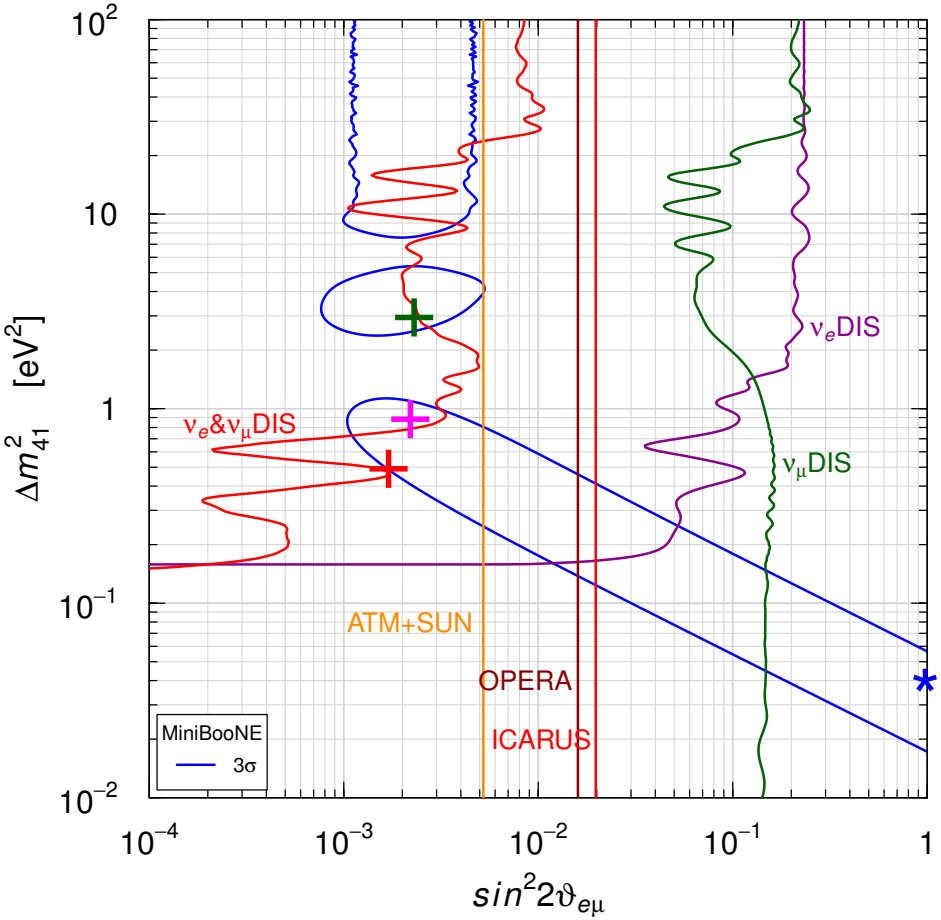

$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$
SBN (3yr, 3σ)
KPipe (3yr, 3σ)
PrGlo17
1σ
2σ
3σ
Δm^2_{41} [eV^2]
1
10^{-2}
10^{-1}
$sin^2 2\vartheta_{\mu\mu}$

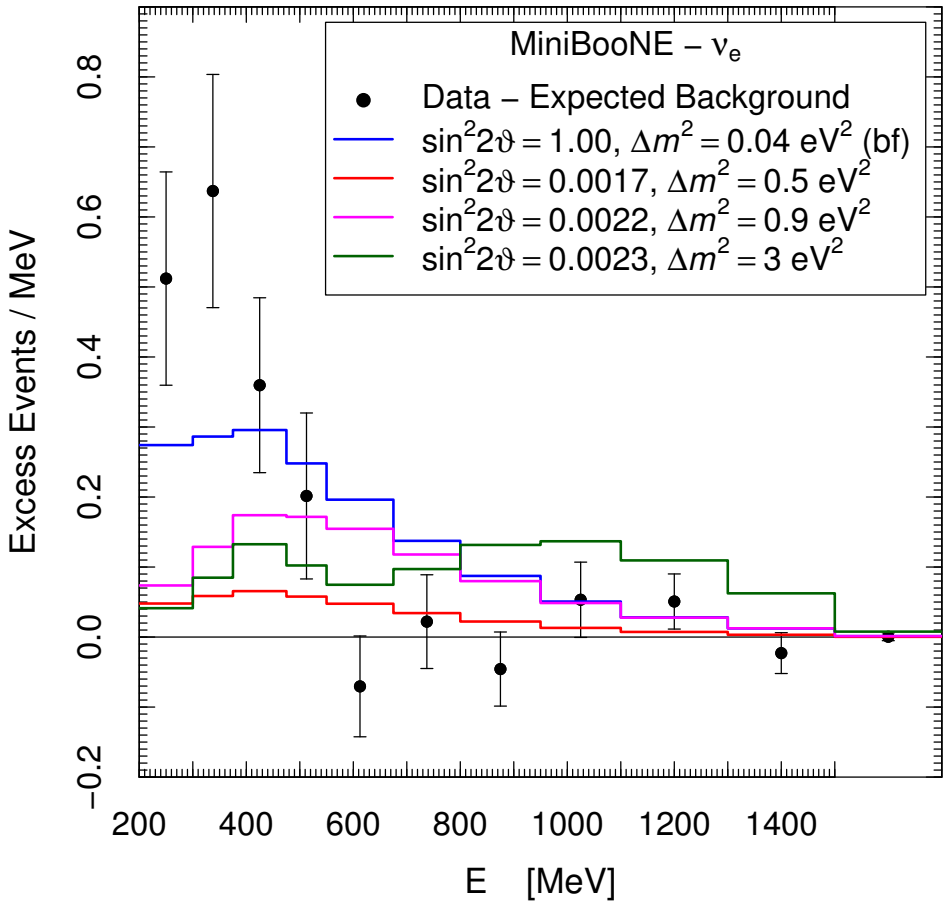
Conclusions

- 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 $\Delta N_{\rm eff} = 1$ 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).

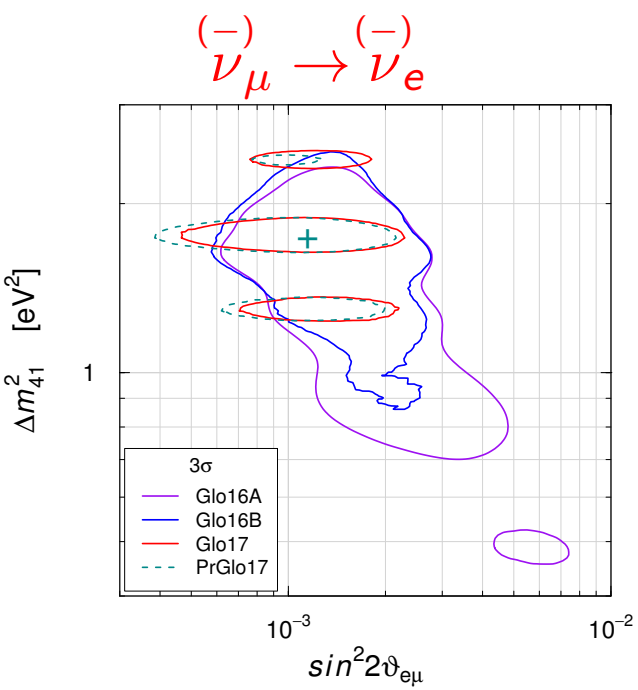
Backup Slides

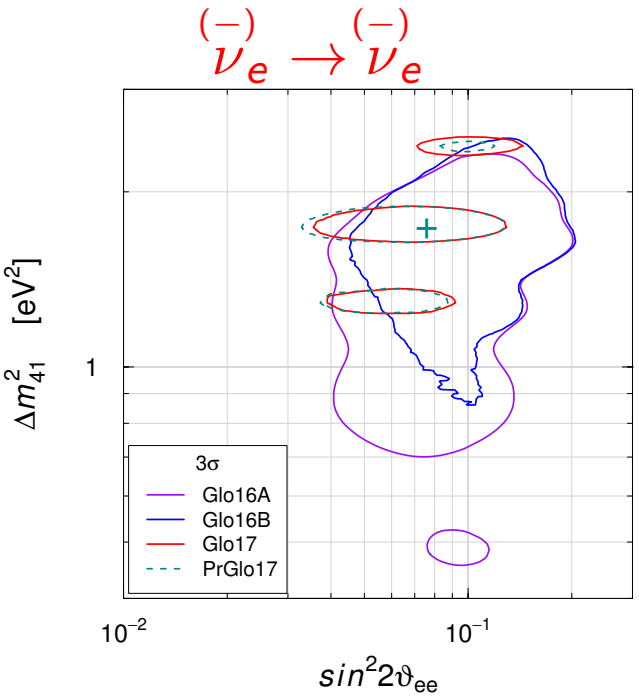
MiniBooNE Low-Energy Anomaly

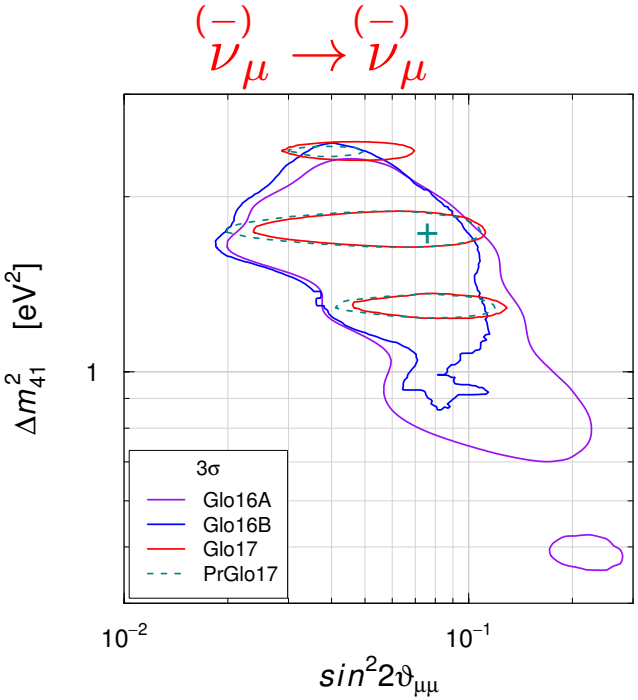




No fit of low-energy excess for realistic $\sin^2 2\vartheta_{e\mu} \lesssim 3 \times 10^{-3}$


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

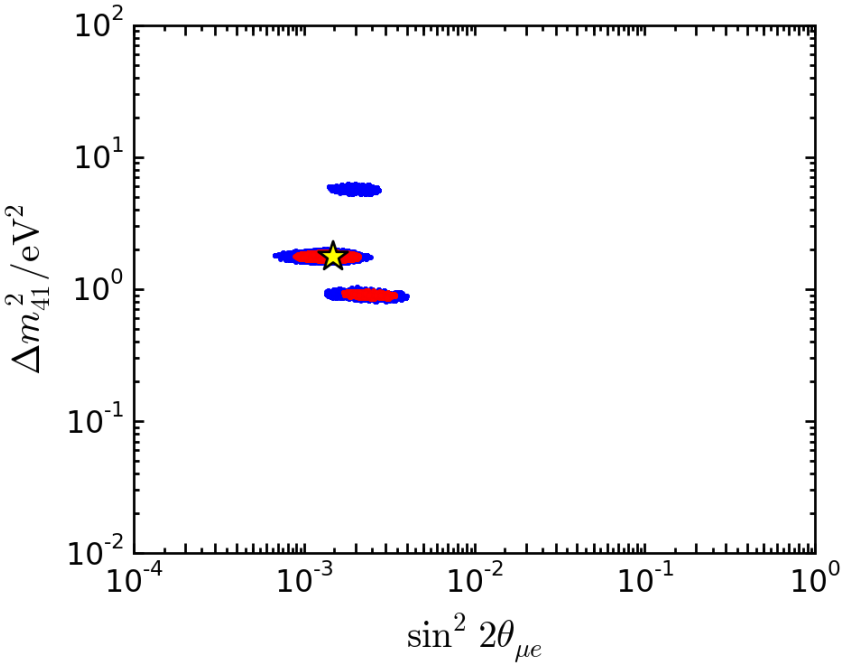

$\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$
Δm^2_{41} [eV^2]
1
10^{-2}
10^{-1}
$sin^2 2\vartheta_{ee}$
3σ
Glo16A
Glo16B
Glo17
PrGlo17


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

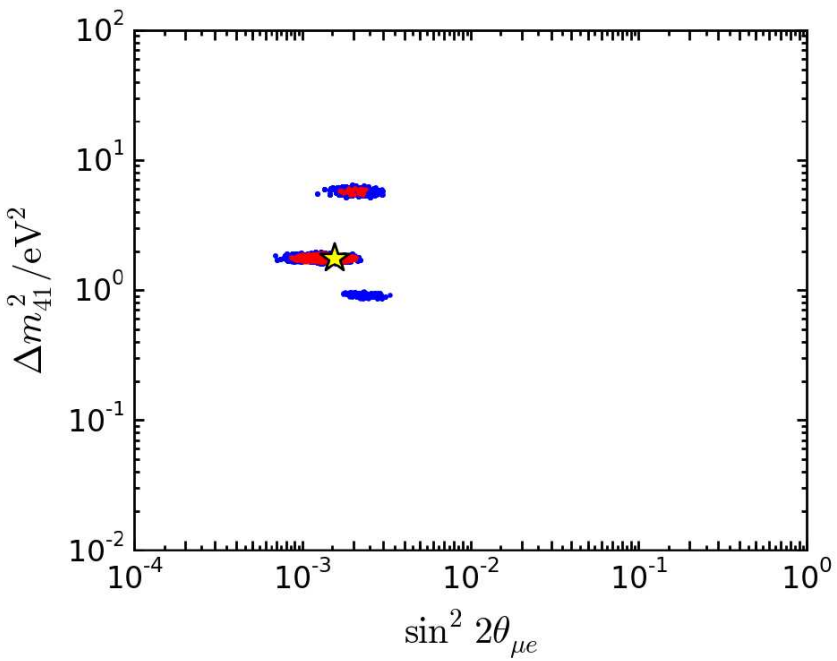
Another Analysis of SBL + IceCube

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

SBL



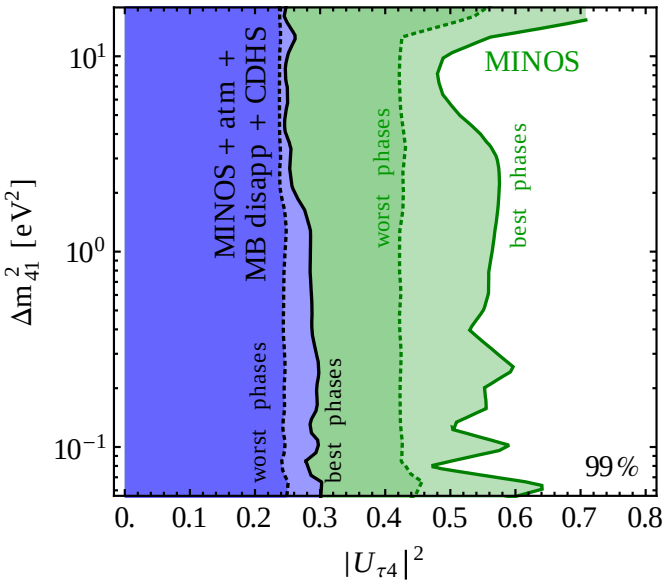
SBL + IceCube



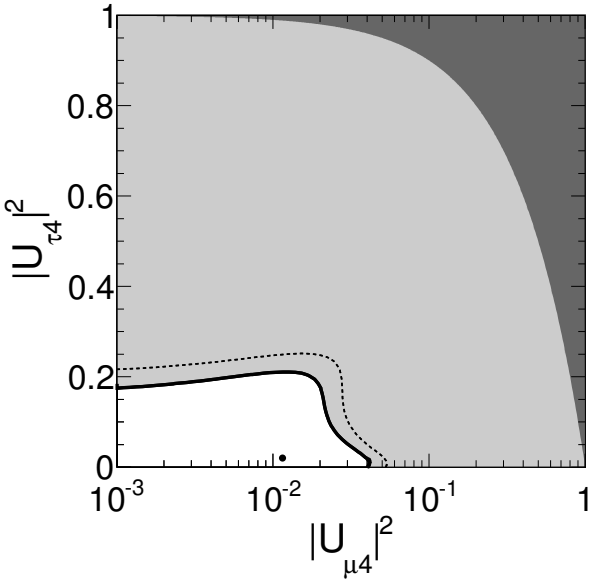
Red: 90% CL Blue: 99% CL

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)

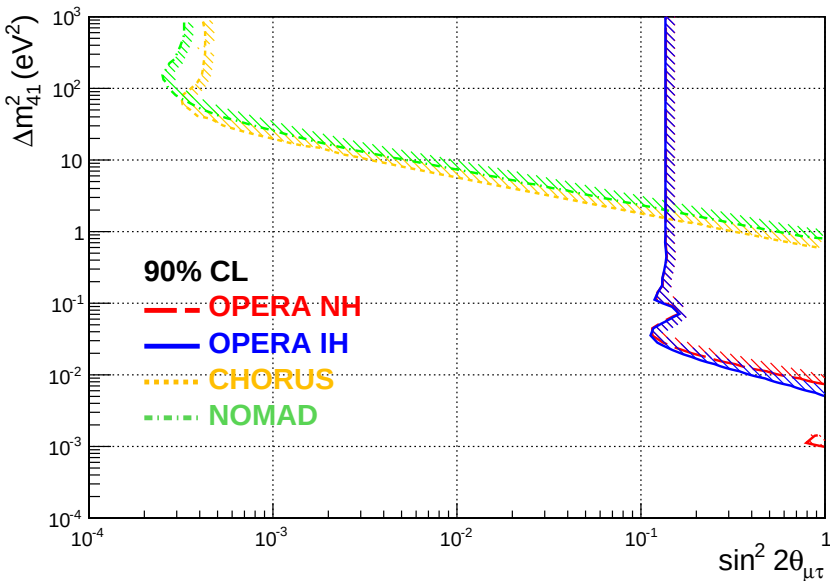
Bounds on $|U_{\tau 4}|^2$



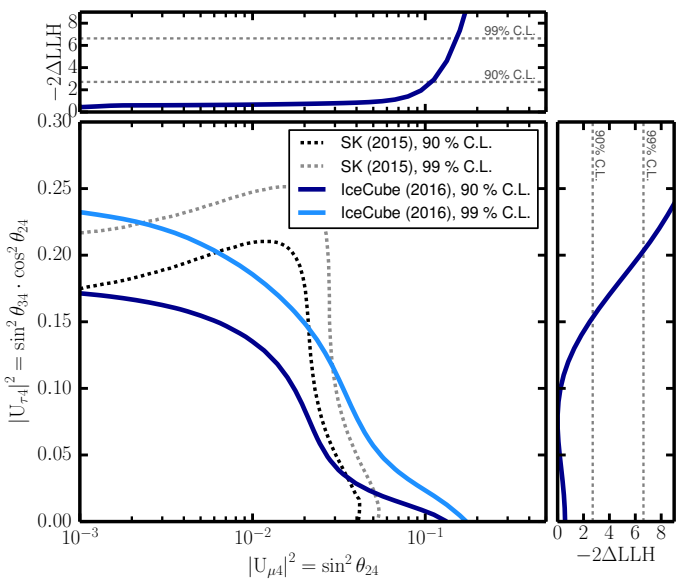
[Kopp et al, JHEP 1305 (2013) 050]



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

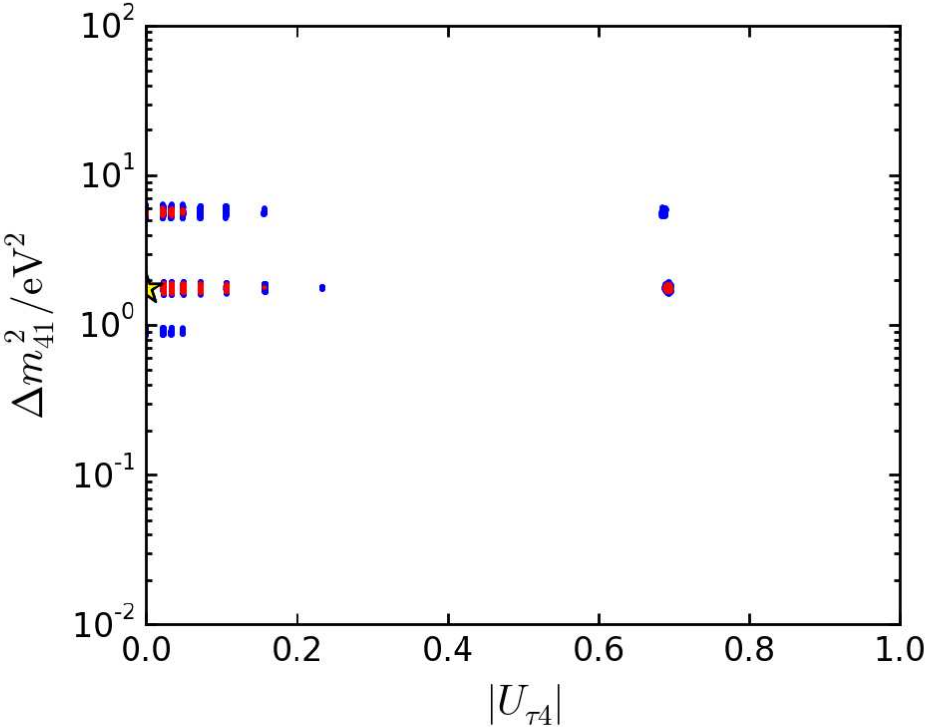


$\nu_\mu \longrightarrow \nu_\tau$ [OPERA, JHEP 1506 (2015) 069]



[IceCube DeepCore, arXiv:1702.05160]

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

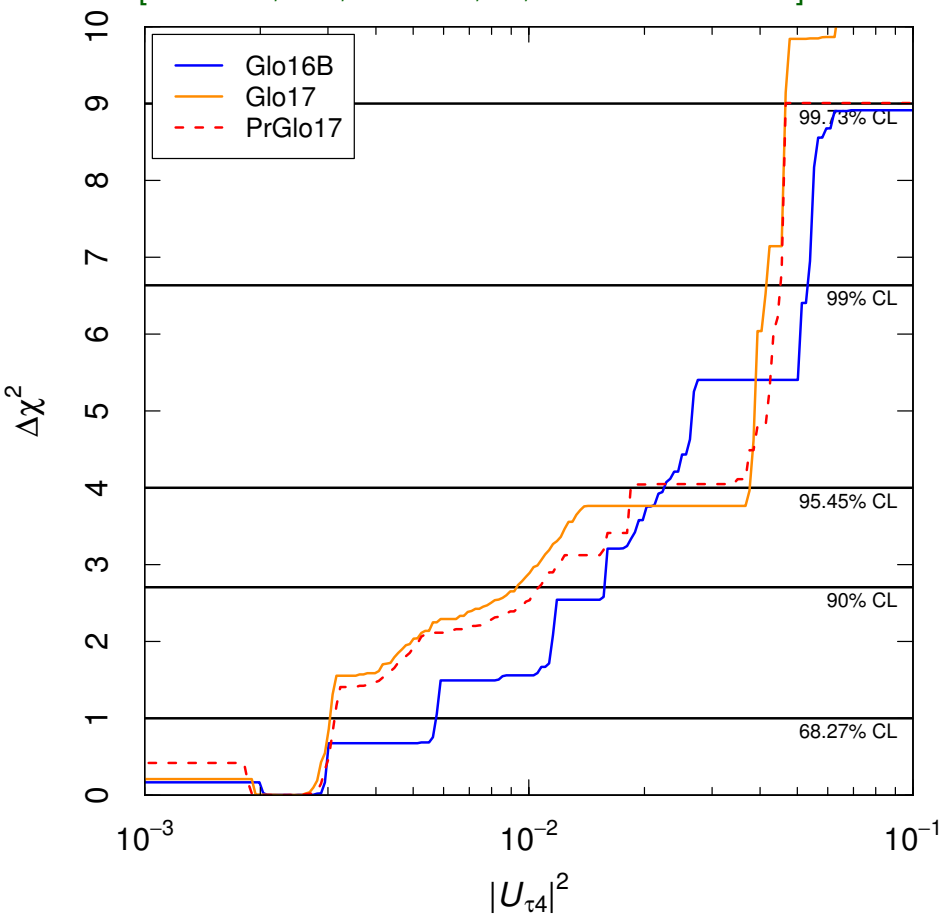


90% CL

$\vartheta_{34} < 6^\circ$ 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:	$\vartheta_{34} < 6.0^\circ$