

# Short-Baseline Neutrino Oscillation Anomalies and Light Sterile Neutrinos

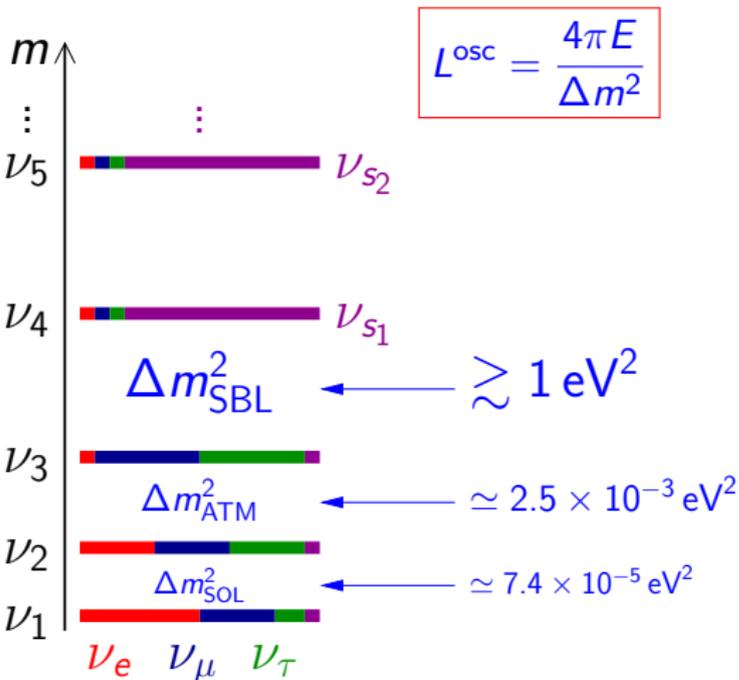
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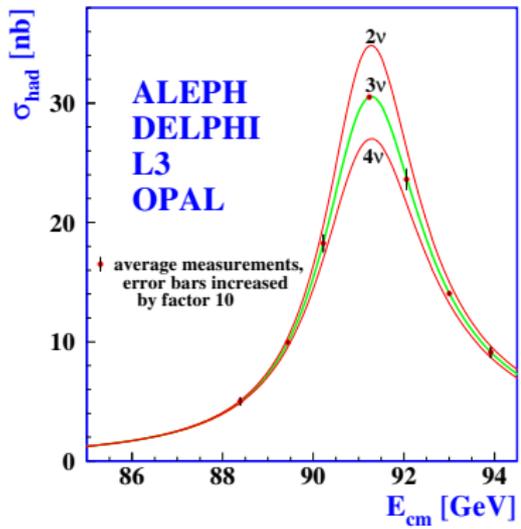
13th Vienna Central European Seminar

30 November - 1 December 2017

# Beyond Three-Neutrino Mixing: Sterile Neutrinos



$$L^{\text{osc}} = \frac{4\pi E}{\Delta m^2}$$



$$N_{\nu_{\text{active}}}^{\text{LEP}} = 2.9840 \pm 0.0082$$

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**
- ▶ Light left-handed anti- $\nu_R$  are **light sterile neutrinos**

$$\nu_R^c \rightarrow \nu_{sL} \quad (\text{left-handed})$$

- ▶ Sterile means **no standard model interactions**

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

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

$$\Delta m_{21}^2 \ll |\Delta m_{31}^2| \ll |\Delta m_{41}^2| \leq \dots$$

$\nu_1$	$\nu_2$	$\nu_3$	$\nu_4$	...
$\nu_e$	$\nu_\mu$	$\nu_\tau$	$\nu_{s1}$	...

# Effective 3+1 SBL Oscillation Probabilities

Appearance ( $\alpha \neq \beta$ )

$$P_{\nu_\alpha \rightarrow \nu_\beta}^{\text{SBL}(-)(-)} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right)$$

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

Disappearance

$$P_{\nu_\alpha \rightarrow \nu_\alpha}^{\text{SBL}(-)(-)} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right)$$

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

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

SBL

▶ CP violation is not observable in SBL experiments!

▶ Observable in LBL accelerator exp. sensitive to  $\Delta m_{\text{ATM}}^2$  [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; Kayser et al, JHEP 1511 (2015) 039, JHEP 1611 (2016) 122] and solar exp. sensitive to  $\Delta m_{\text{SOL}}^2$  [Long, Li, CG, PRD 87, 113004 (2013) 113004]

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

## 3+1: Appearance vs Disappearance

- ▶ Amplitude of  $\nu_e$  disappearance:

$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 (1 - |U_{e4}|^2) \simeq 4|U_{e4}|^2$$

- ▶ Amplitude of  $\nu_\mu$  disappearance:

$$\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu4}|^2 (1 - |U_{\mu4}|^2) \simeq 4|U_{\mu4}|^2$$

- ▶ Amplitude of  $\nu_\mu \rightarrow \nu_e$  transitions:

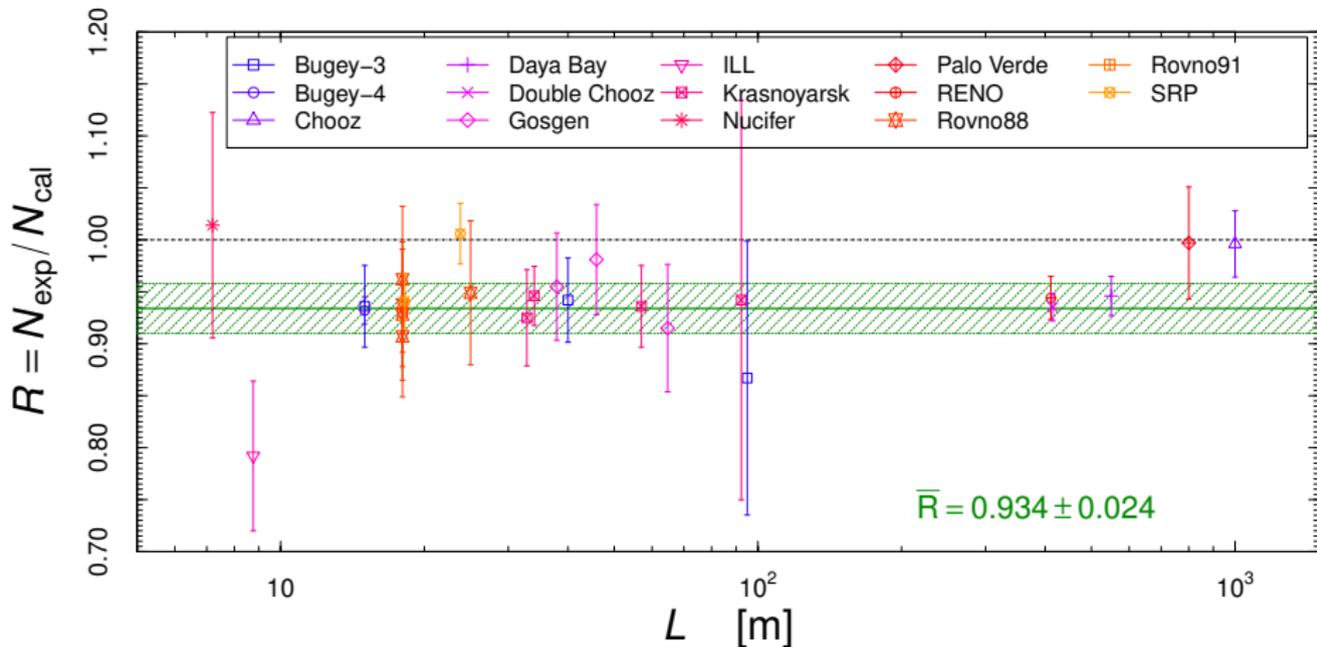
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2 |U_{\mu4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

# Reactor Electron Antineutrino Anomaly

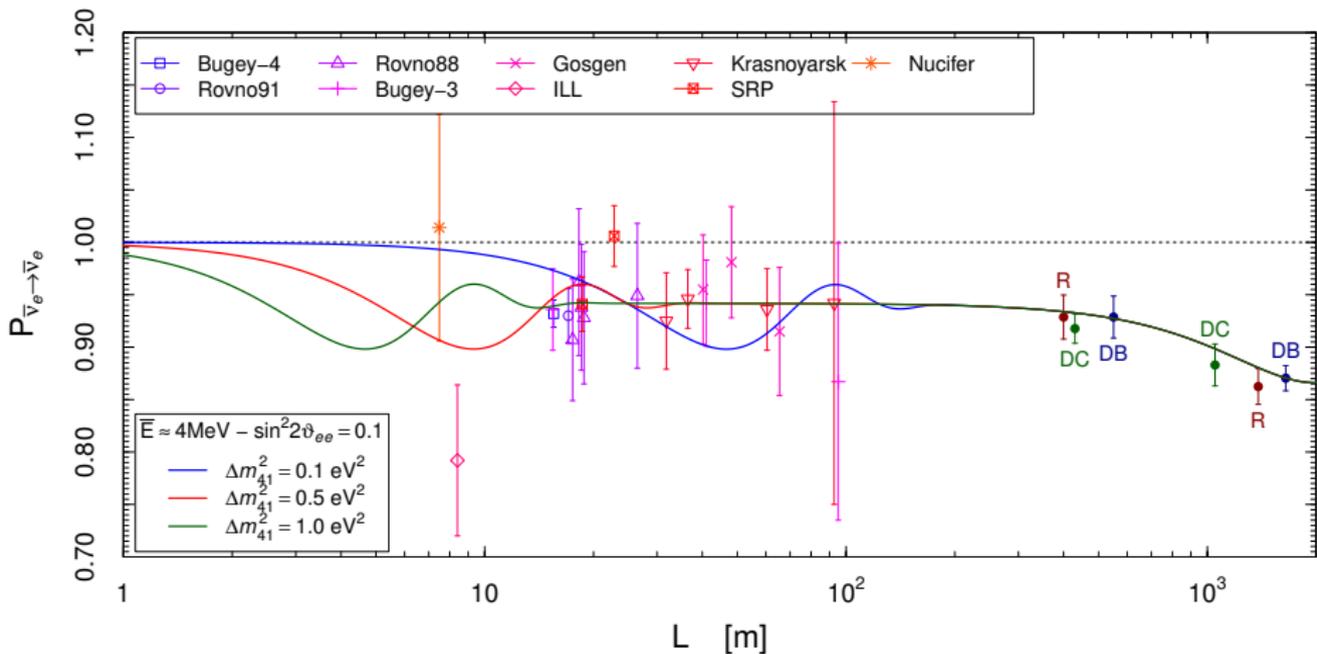
[Mention et al, PRD 83 (2011) 073006]

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

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



$\approx 2.8\sigma$  deficit

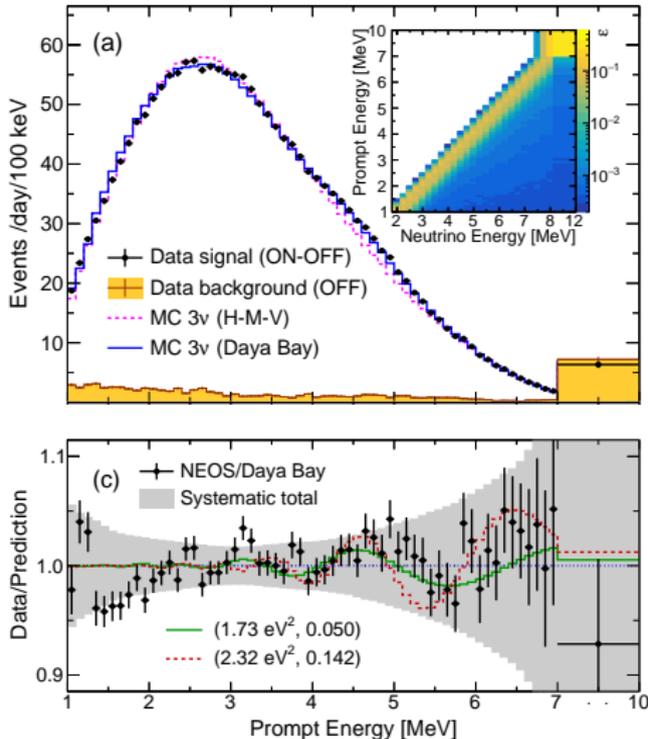


$$\Delta m_{\text{SBL}}^2 \gtrsim 0.5 \text{ eV}^2 \gg \Delta m_{\text{ATM}}^2$$

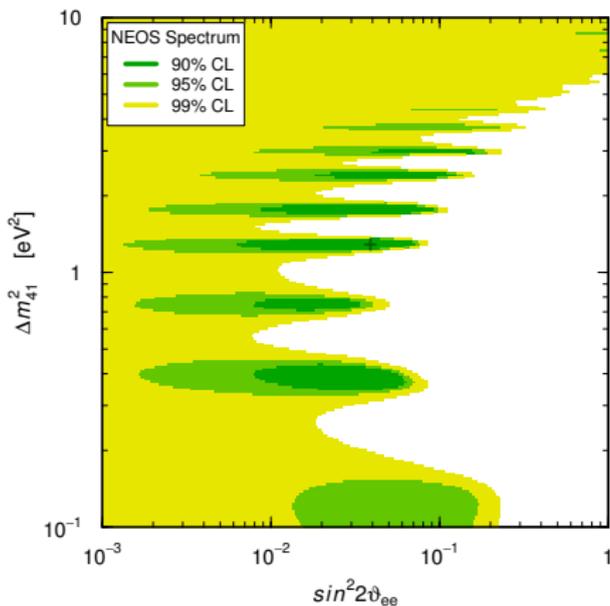
- ▶ SBL oscillations are averaged at the Daya Bay, RENO, and Double Chooz near detectors  $\implies$  no spectral distortion

# NEOS

[PRL 118 (2017) 121802 (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.



Best Fits:

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

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

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

$\chi^2$  distribution:  $\approx 2.1\sigma$  anomaly

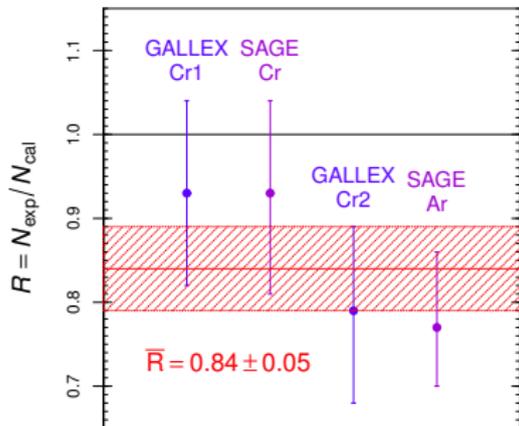
NEOS Monte Carlo:  $\approx 1.2\sigma$  anomaly

# Gallium Anomaly

Gallium Radioactive Source Experiments: GALLEX and SAGE

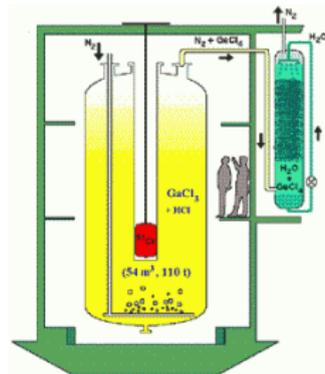


Test of Solar  $\nu_e$  Detection:



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

$\Delta m_{\text{SBL}}^2 \gtrsim 1 \text{ eV}^2 \gg \Delta m_{\text{ATM}}^2$

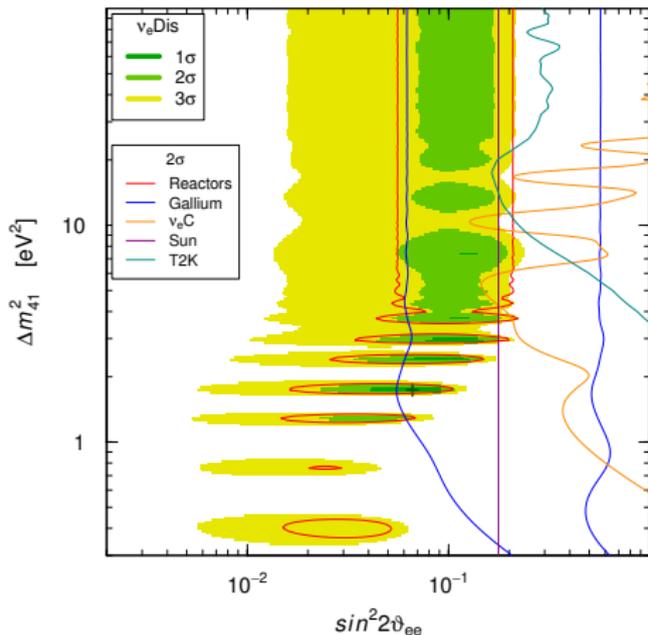


$\approx 2.9\sigma$  deficit

[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]

▶  ${}^3\text{He} + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + {}^3\text{H}$  cross section measurement [Frekers et al., PLB 706 (2011) 134]

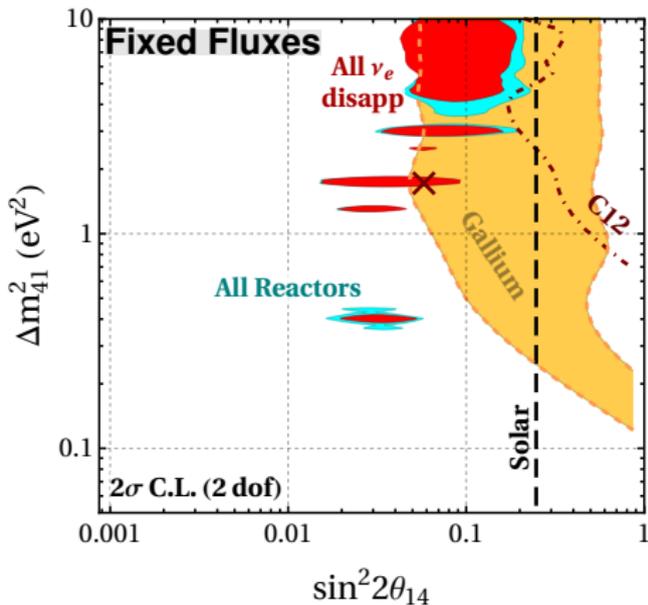
# Global $\nu_e$ and $\bar{\nu}_e$ Disappearance



[Gariazzo, CG, Laveder, Li, JHEP 1706 (2017) 135]

▶  $\approx 3.3\sigma$  anomaly

▶ Best Fit: 
$$\begin{cases} \Delta m_{41}^2 \simeq 1.7 \text{ eV}^2 \\ \sin^2 2\vartheta_{ee} \simeq 0.07 \end{cases}$$



[Dentler, Hernandez-Cabezudo, Kopp, Maltoni, Schwetz, JHEP 1711 (2017) 099]

▶  $\approx 3.0\sigma$  anomaly

▶ Best Fit: 
$$\begin{cases} \Delta m_{41}^2 \simeq 1.7 \text{ eV}^2 \\ \sin^2 2\vartheta_{ee} \simeq 0.06 \end{cases}$$

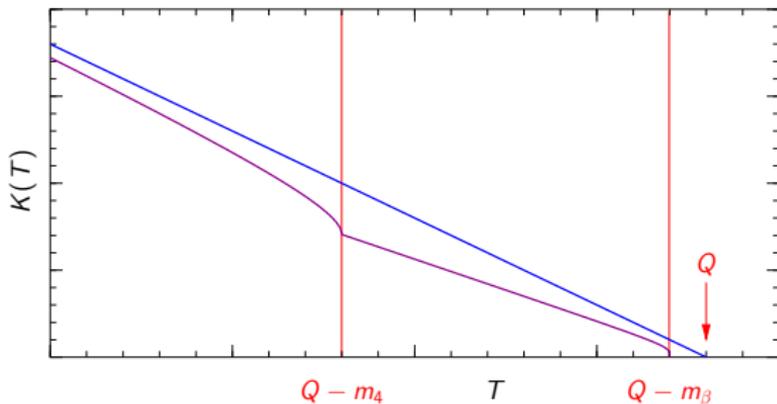
# Tritium Beta-Decay: ${}^3\text{H} \rightarrow {}^3\text{He} + e^- + \bar{\nu}_e$

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

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

$$\frac{K^2(T)}{Q-T} = \sum_k |U_{ek}|^2 \sqrt{(Q-T)^2 - m_k^2} \theta(Q-T-m_k)$$

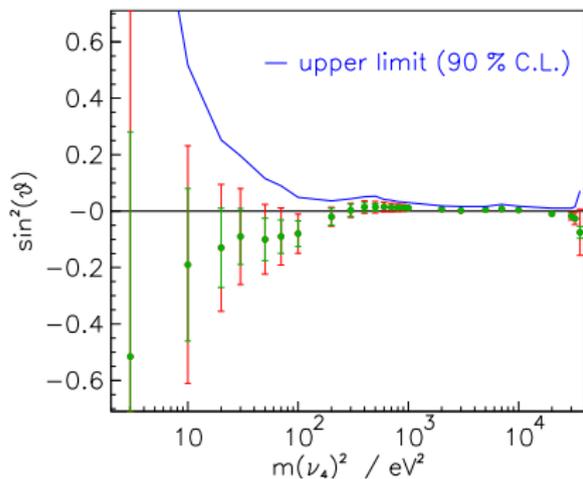
$$m_4 \gg m_{1,2,3} \Rightarrow \simeq (1 - |U_{e4}|^2) \sqrt{(Q-T)^2 - m_\beta^2} \theta(Q-T-m_\beta) \\ + |U_{e4}|^2 \sqrt{(Q-T)^2 - m_4^2} \theta(Q-T-m_4)$$



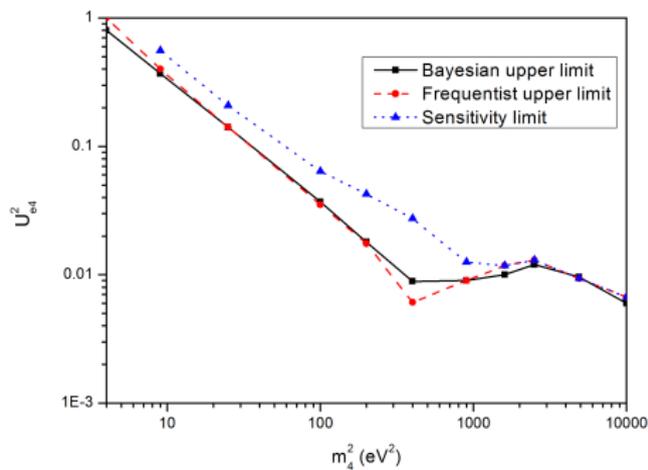
$$m_\beta^2 = \sum_{k=1}^3 |U_{ek}|^2 m_k^2$$

# Mainz and Troitsk Limit on $\Delta m_{41}^2 \simeq m_4^2$

$$m_4 \gg m_{1,2,3} \implies \Delta m_{41}^2 \equiv m_4^2 - m_1^2 \simeq m_4^2$$



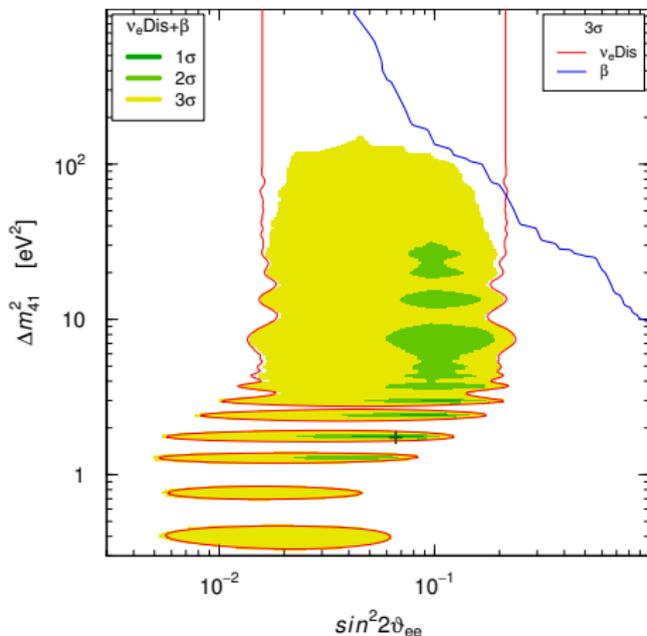
[Kraus, Singer, Valerius, Weinheimer, EPJC 73 (2013) 2323]



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

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

[Gariazzo, CG, Laveder, Li, JHEP 1706 (2017) 135 (arXiv:1703.00860)]

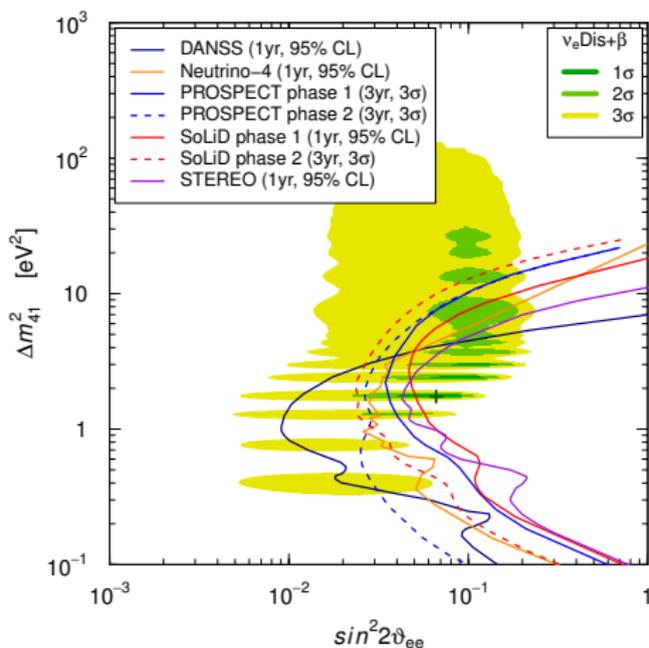
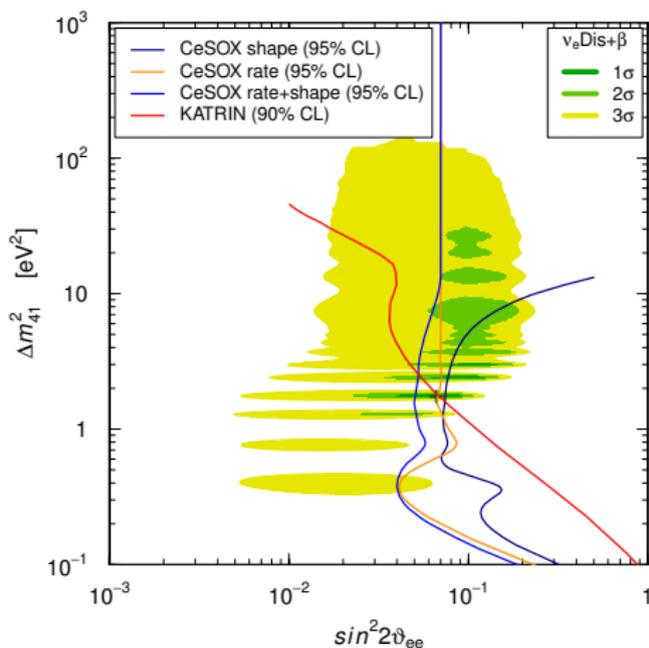


$$\blacktriangleright L_{41}^{\text{osc}} = \frac{4\pi E}{\Delta m_{41}^2}$$

$$\blacktriangleright 2 \text{ cm} \lesssim \frac{L_{41}^{\text{osc}}}{E [\text{MeV}]} \lesssim 7 \text{ m} \quad (3\sigma)$$

$$\blacktriangleright 0.0050 \lesssim \sin^2 2\vartheta_{ee} \lesssim 0.23 \quad (3\sigma)$$

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



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

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

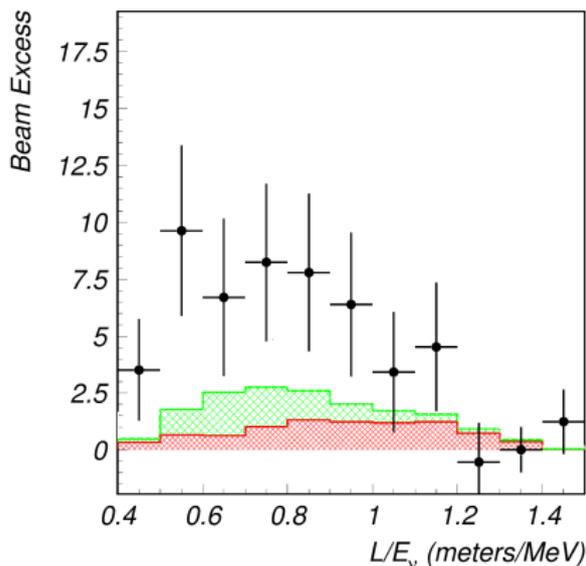
DANSS (Kalinin, Russia)  $L \simeq 10\text{-}12\text{m}$  [arXiv:1606.02896]  
 Neutrino-4 (RIAR, Russia)  $L \simeq 6\text{-}11\text{m}$  [JETP 121 (2015) 578]  
 PROSPECT (ORNL, USA)  $L \simeq 7\text{-}12\text{m}$  [arXiv:1512.02202]  
 SoLiD (SCK-CEN, Belgium)  $L \simeq 5\text{-}8\text{m}$  [arXiv:1510.07835]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

# LSND

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

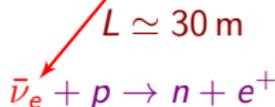
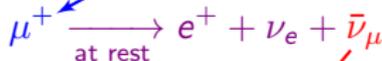
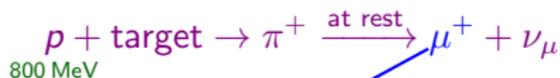
$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

$$20 \text{ MeV} \leq E \leq 52.8 \text{ MeV}$$



$$\Delta m_{\text{SBL}}^2 \gtrsim 0.1 \text{ eV}^2 \gg \Delta m_{\text{ATM}}^2$$

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



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]

# MiniBooNE

$L \simeq 541 \text{ m}$

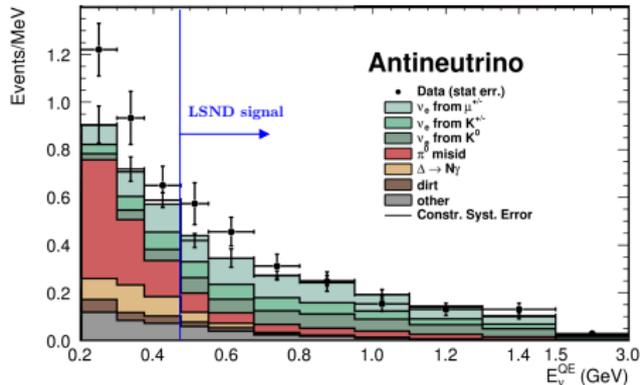
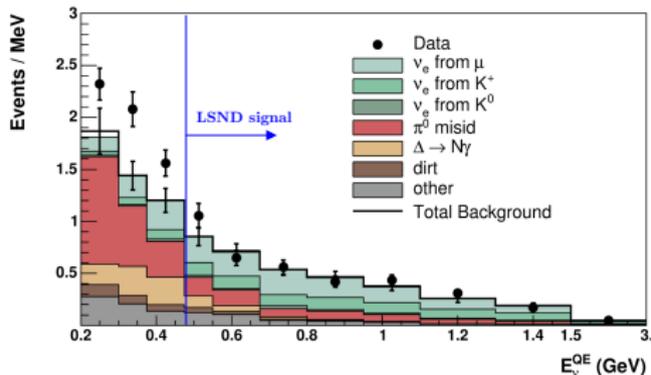
$200 \text{ MeV} \leq E \lesssim 3 \text{ GeV}$

$\nu_\mu \rightarrow \nu_e$

[PRL 102 (2009) 101802]

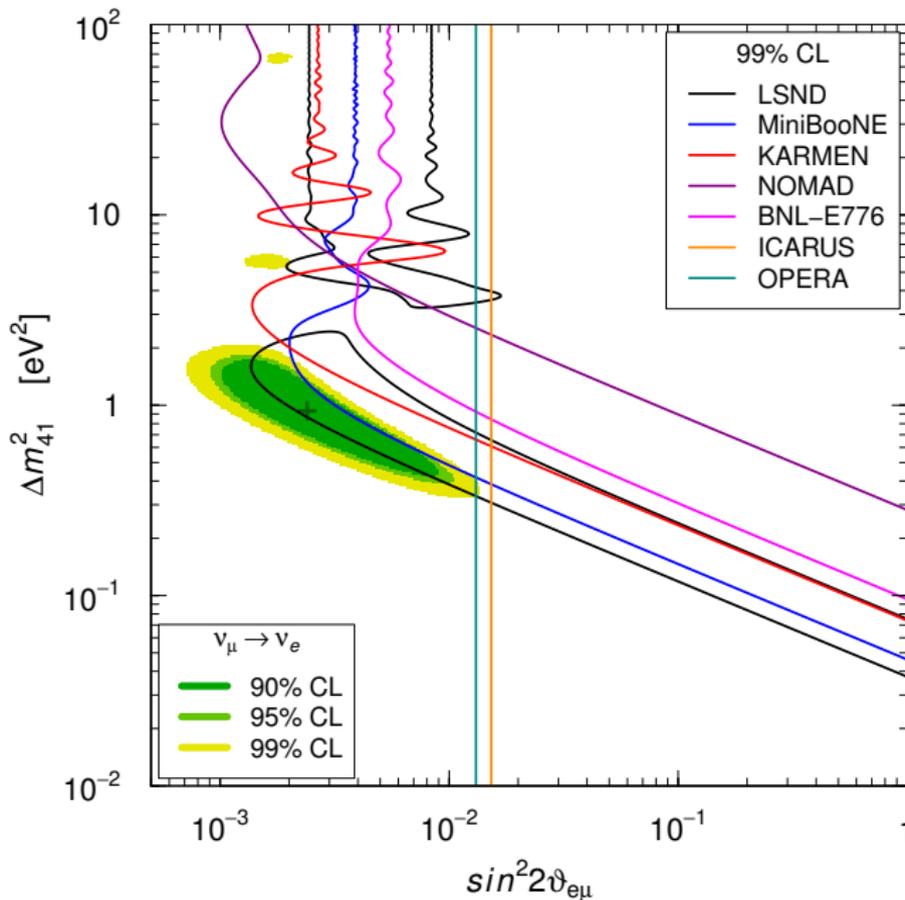
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

[PRL 110 (2013) 161801]

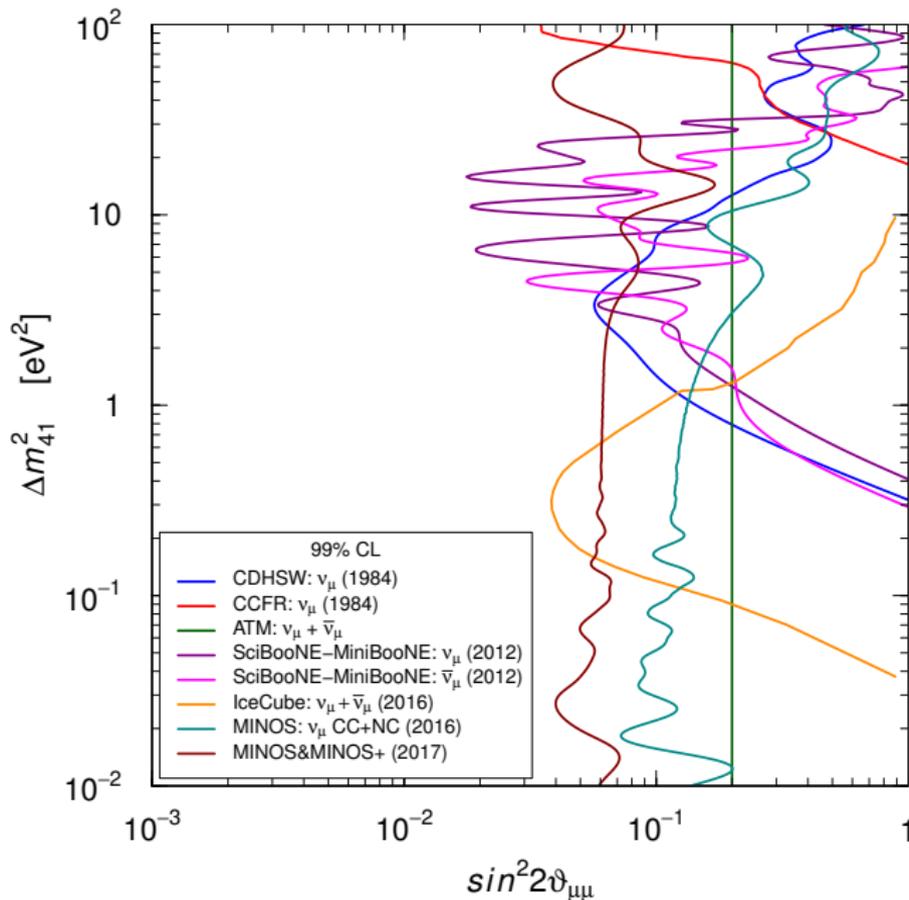


- ▶ Purpose: check LSND signal.
- ▶ Different  $L$  and  $E$ .
- ▶ Similar  $L/E$  (oscillations).
- ▶ No money, no Near Detector.
- ▶ LSND signal:  $E > 475 \text{ MeV}$ .
- ▶ Agreement with LSND signal?
- ▶ Low-energy anomaly  $\Rightarrow$  MicroBooNE
- ▶ Pragmatic Approach:  $E > 475 \text{ MeV}$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

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



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



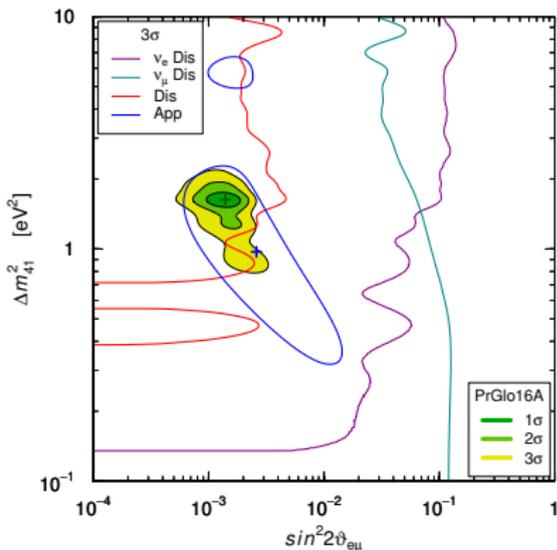
# 3+1 Appearance-Disappearance Tension

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

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

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

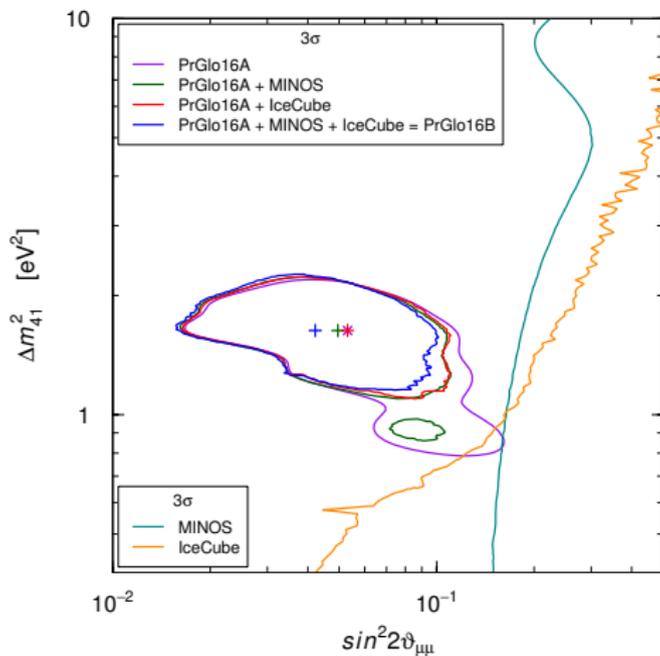
[Okada, Yasuda, IJMPA 12 (1997) 3669; Bilenky, CG, Grimus, EPJC 1 (1998) 247]



- ▶  $\nu_\mu \rightarrow \nu_e$  is quadratically suppressed!
- ▶ PrGlo16A = 2016 data except MINOS and IceCube [Gariazzo, CG, Laveder, Li, JHEP 1706 (2017) 135]
- ▶  $\Delta\chi^2_{\text{NO}}/\text{NDF}_{\text{NO}} = 48.3/3 \Rightarrow \approx 6.4\sigma$  anom.
- ▶ Best Fit:  $\Delta m_{41}^2 = 1.6 \text{ eV}^2$   
 $|U_{e4}|^2 = 0.026 \quad |U_{\mu4}|^2 = 0.013$
- ▶  $\chi^2_{\text{min}}/\text{NDF} = 262.0/244 \Rightarrow \text{GoF} = 20\%$
- ▶  $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 3.8/2 \Rightarrow \text{GoF}_{\text{PG}} = 15\%$
- ▶ Similar tension in 3+2, 3+3, ..., 3+N<sub>s</sub>

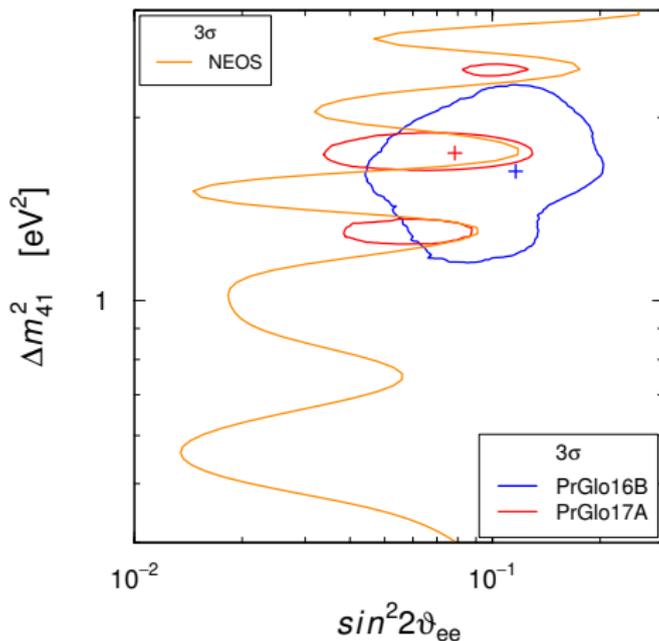
[CG, Zavanin, MPLA 31 (2015) 1650003]

# Effects of MINOS and IceCube



- ▶ IceCube effect in agreement with Collin, Arguelles, Conrad, Shaevitz, PRL 117 (2016) 221801
- ▶ Best Fit:  $\Delta m_{41}^2 = 1.6 \text{ eV}^2$   $|U_{e4}|^2 = 0.030$   $|U_{\mu 4}|^2 = 0.011$
- ▶  $\chi_{\text{min}}^2/\text{NDF} = 530.3/519 \Rightarrow \text{GoF} = 36\%$
- ▶  $\chi_{\text{PG}}^2/\text{NDF}_{\text{PG}} = 4.7/2 \Rightarrow \text{GoF}_{\text{PG}} = 9.7\%$  ← More tension!

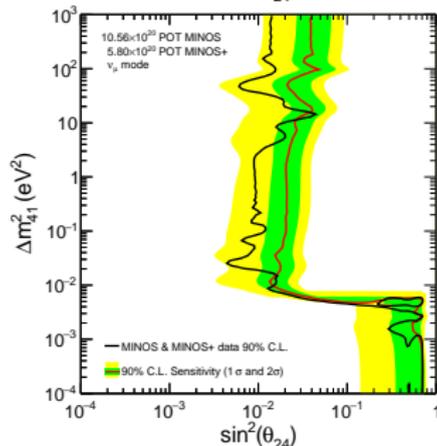
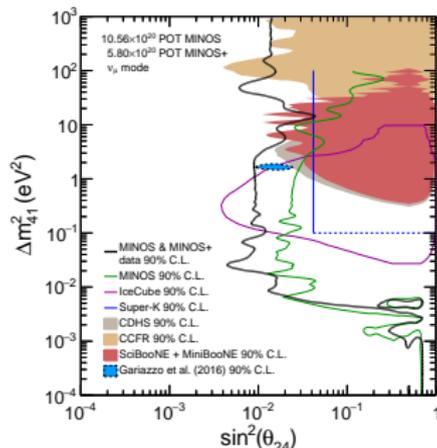
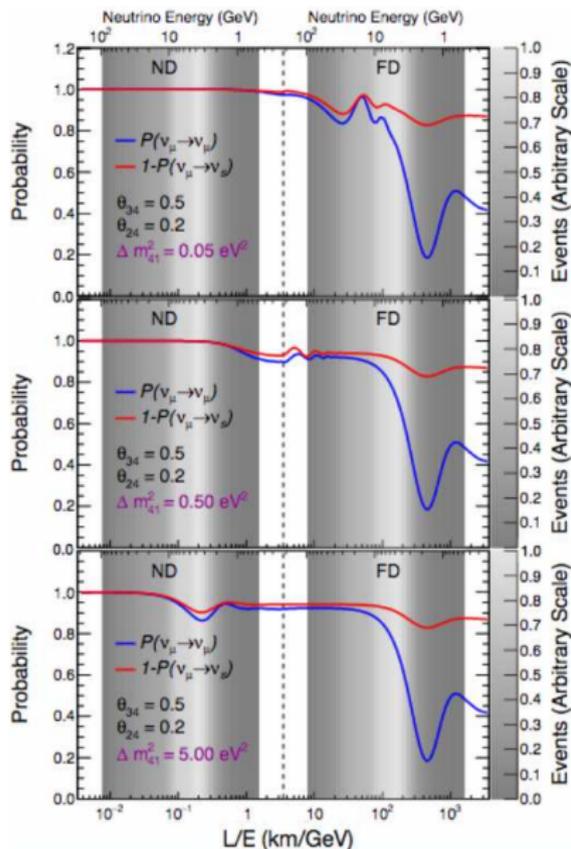
# Effects of NEOS



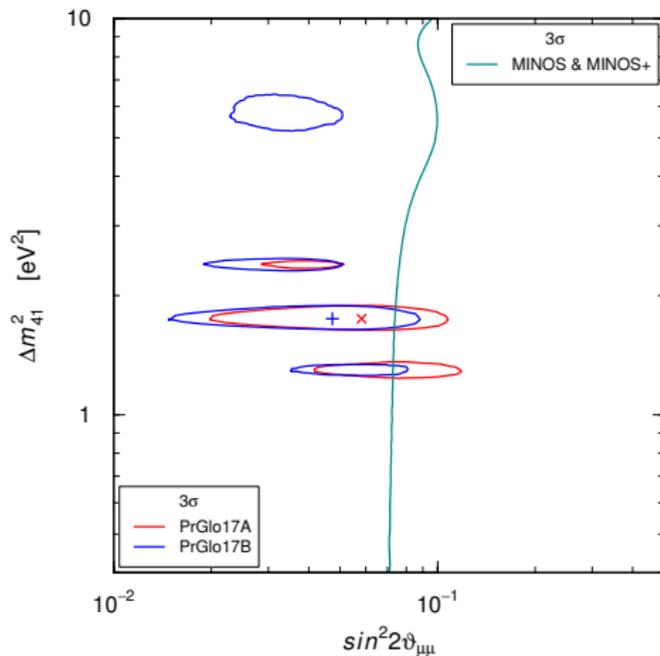
- ▶ Best Fit:  $\Delta m_{41}^2 = 1.7 \text{ eV}^2$   $|U_{e4}|^2 = 0.020$   $|U_{\mu 4}|^2 = 0.015$
- ▶  $\chi_{\text{min}}^2/\text{NDF} = 595.1/579 \Rightarrow \text{GoF} = 31\%$
- ▶  $\chi_{\text{PG}}^2/\text{NDF}_{\text{PG}} = 7.2/2 \Rightarrow \text{GoF}_{\text{PG}} = 2.7\% \leftarrow \text{More tension!}$

# New Bound from MINOS & MINOS+

[arXiv:1710.06488]

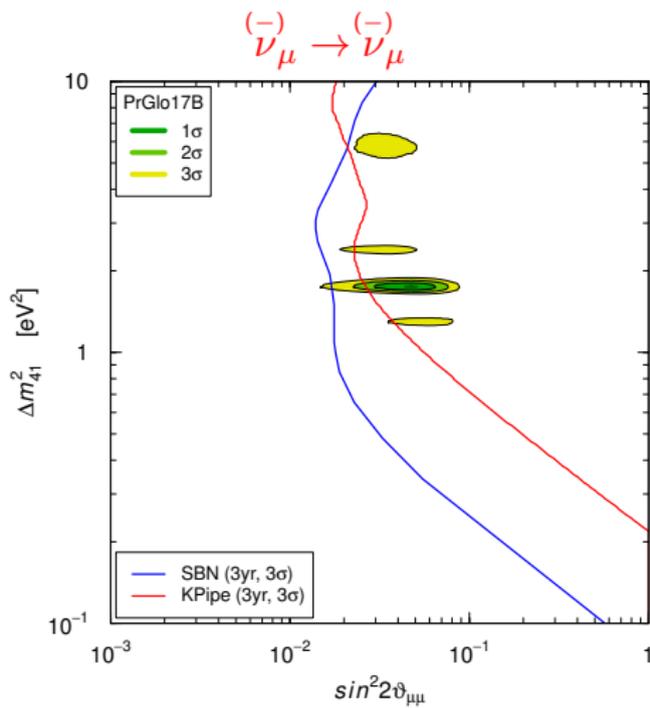
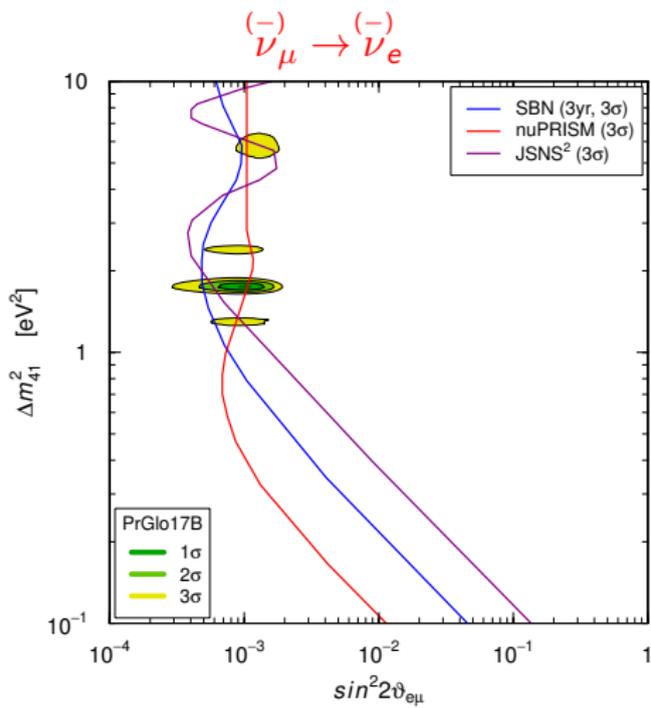


# Effects of MINOS & MINOS+

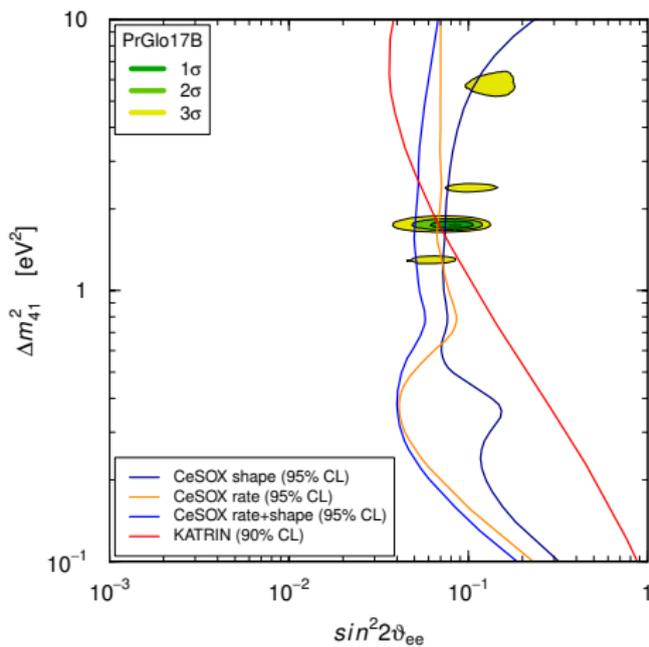
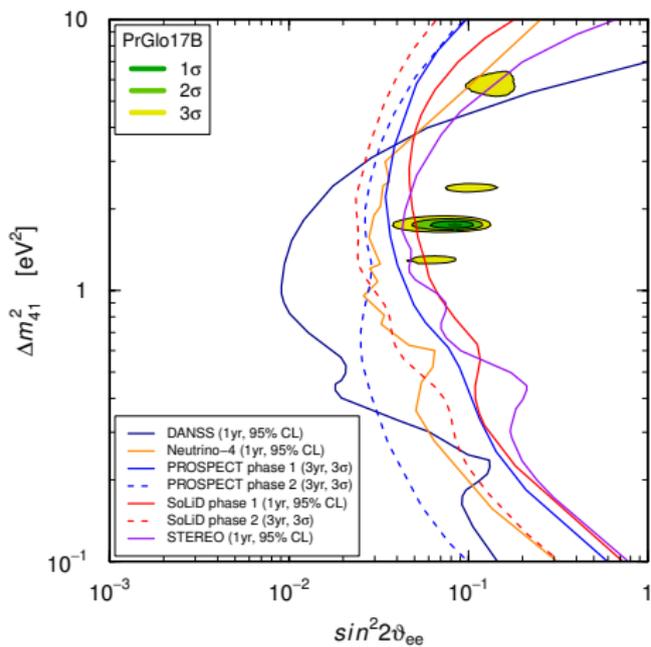


- ▶ Best Fit:  $\Delta m_{41}^2 = 1.7 \text{ eV}^2$   $|U_{e4}|^2 = 0.021$   $|U_{\mu 4}|^2 = 0.012$
- ▶  $\chi_{\text{min}}^2/\text{NDF} = 608.9/615 \Rightarrow \text{GoF} = 56\%$
- ▶  $\chi_{\text{PG}}^2/\text{NDF}_{\text{PG}} = 10.9/2 \Rightarrow \text{GoF}_{\text{PG}} = 0.43\% \leftarrow \text{More tension!}$
- ▶ The MINOS & MINOS+ bound disfavors the LSND  $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e$  signal.

# New Dedicated Experiments



$$\bar{\nu}_e \rightarrow \bar{\nu}_e$$



# Conclusions

- ▶ Exciting indications of sterile neutrinos (new physics!) at the eV scale:
  - ▶ LSND  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  signal (caveat: single experimental signal).
  - ▶ Gallium  $\nu_e$  disappearance (caveat: overestimated detector efficiency?).
  - ▶ Reactor  $\bar{\nu}_e$  disappearance (caveat: flux calculation dependence).
- ▶ Independent tests through effect of  $m_4$  in  $\beta$ -decay and  $\beta\beta_{0\nu}$ -decay.
- ▶ The MINOS & MINOS+ bound disfavors the LSND  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  signal.
- ▶ Unclear prelim. results from the reactor exp. DANSS and Neutrino-4.
- ▶ **Cosmology**: strong tension with  $\Delta N_{\text{eff}} = 1$  and  $m_4 \approx 1$  eV. It may be solved by a non-standard cosmological mechanism.
- ▶ Vigorous experimental program to check **conclusively** in a few years:
  - ▶  $\nu_e$  and  $\bar{\nu}_e$  disappearance with reactors and radioactive sources.
  - ▶  $\nu_\mu \rightarrow \nu_e$  transitions with accelerator neutrinos.
  - ▶  $\nu_\mu$  disappearance with accelerator neutrinos.
- ▶ Possible timeline:
  - ▶ **2018**: Results from the reactor exp. STEREO, SoLid, and PROSPECT.
  - ▶ **2019**: Results from the source exp. SOX.
  - ▶ **2021**: Results from the accelerator exp. SBN and JSNS<sup>2</sup>.