

# Status of the Sterile Neutrino(s)

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Recent Developments in Neutrino Physics and Astrophysics  
10th Anniversary of Borexino

LNGS and GSSI, Assergi and L'Aquila, Italy, 4-7 September 2017

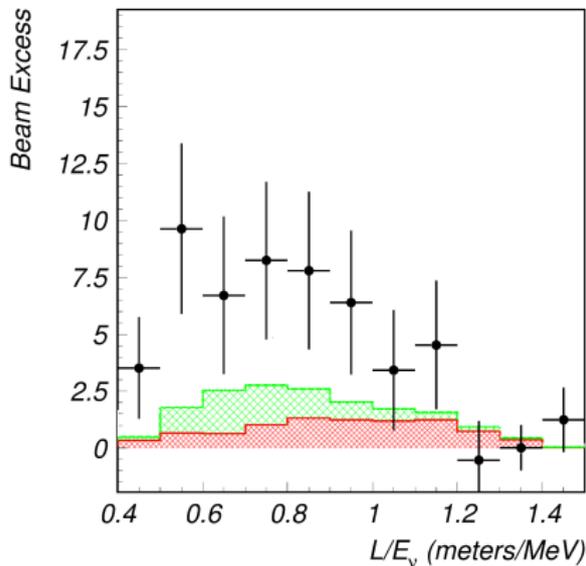


# LSND

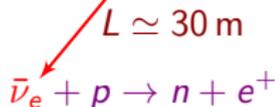
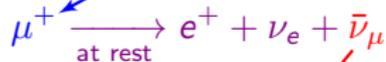
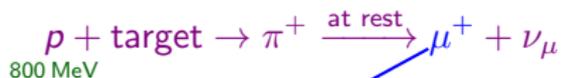
[PRL 75 (1995) 2650; PRC 54 (1996) 2685; PRL 77 (1996) 3082; PRD 64 (2001) 112007]

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

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



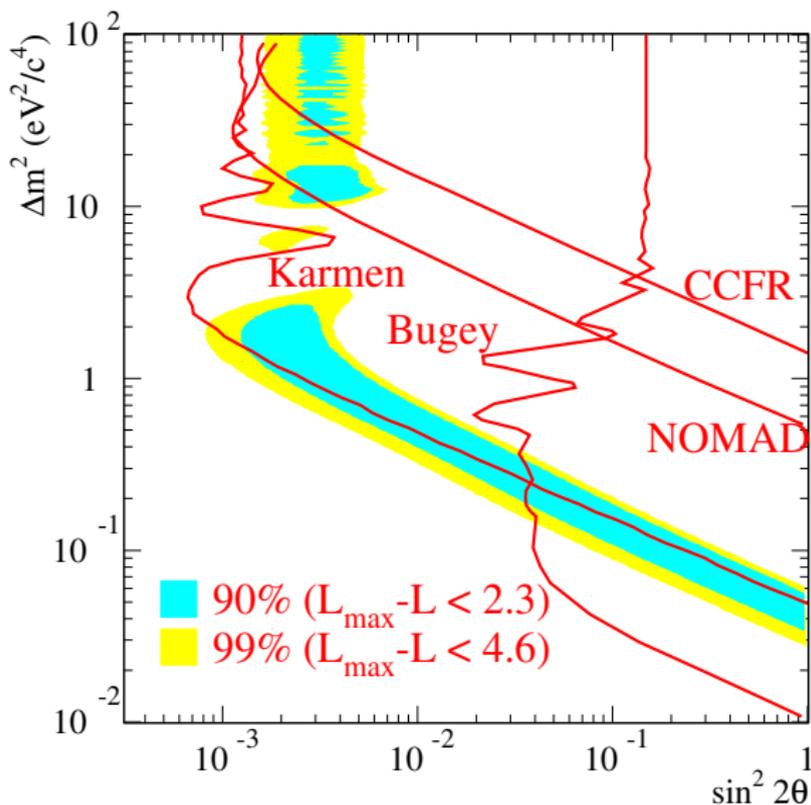
- ▶ Well-known and pure source of  $\bar{\nu}_\mu$



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]



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

# MiniBooNE

$L \simeq 541 \text{ m}$

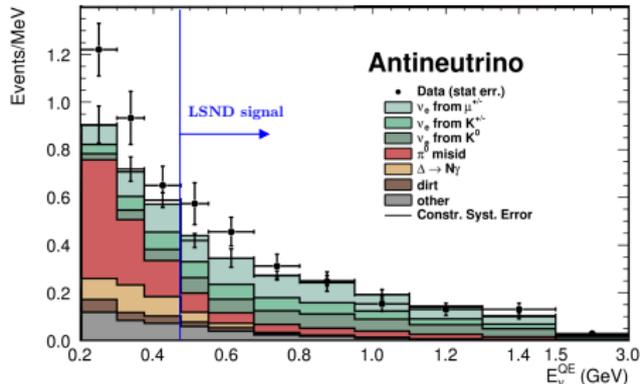
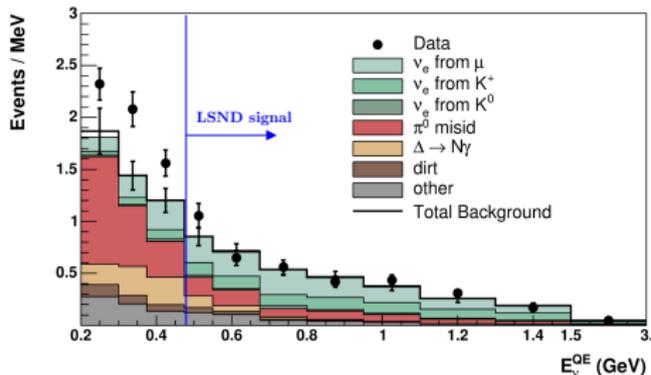
$200 \text{ MeV} \leq E \lesssim 3 \text{ GeV}$

$\nu_\mu \rightarrow \nu_e$

[PRL 102 (2009) 101802]

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

[PRL 110 (2013) 161801]



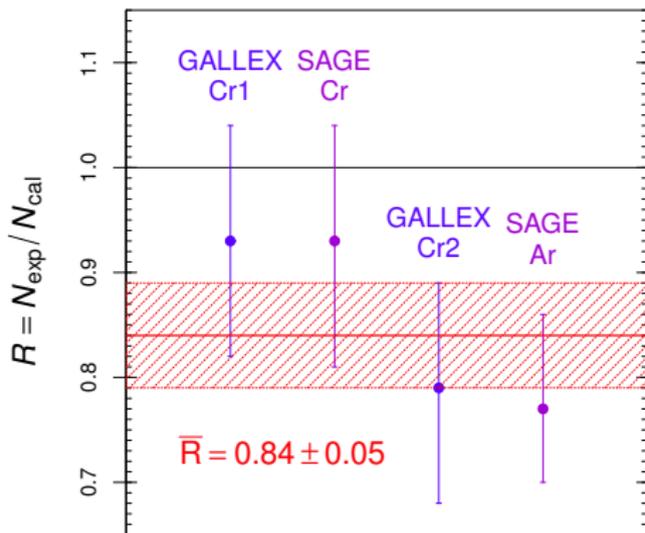
- ▶ Purpose: check LSND signal.
- ▶ Different  $L$  and  $E$ .
- ▶ Similar  $L/E$  (oscillations).
- ▶ No money, no Near Detector.
- ▶ LSND signal:  $E > 475 \text{ MeV}$ .
- ▶ Agreement with LSND signal?
- ▶ CP violation?
- ▶ Low-energy anomaly!  $\Rightarrow$  MicroBooNE

# Gallium Anomaly

Gallium Radioactive Source Experiments: GALLEX and SAGE

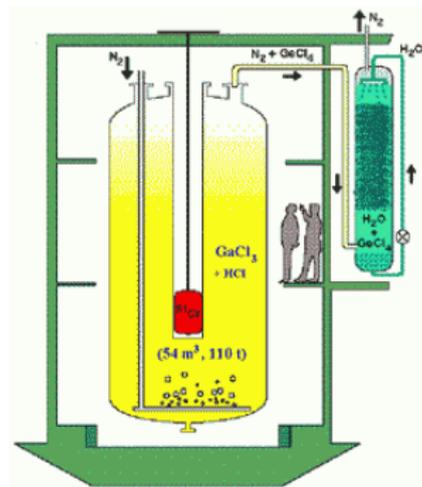


Test of Solar  $\nu_e$  Detection:



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

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



$\approx 2.9\sigma$  deficit

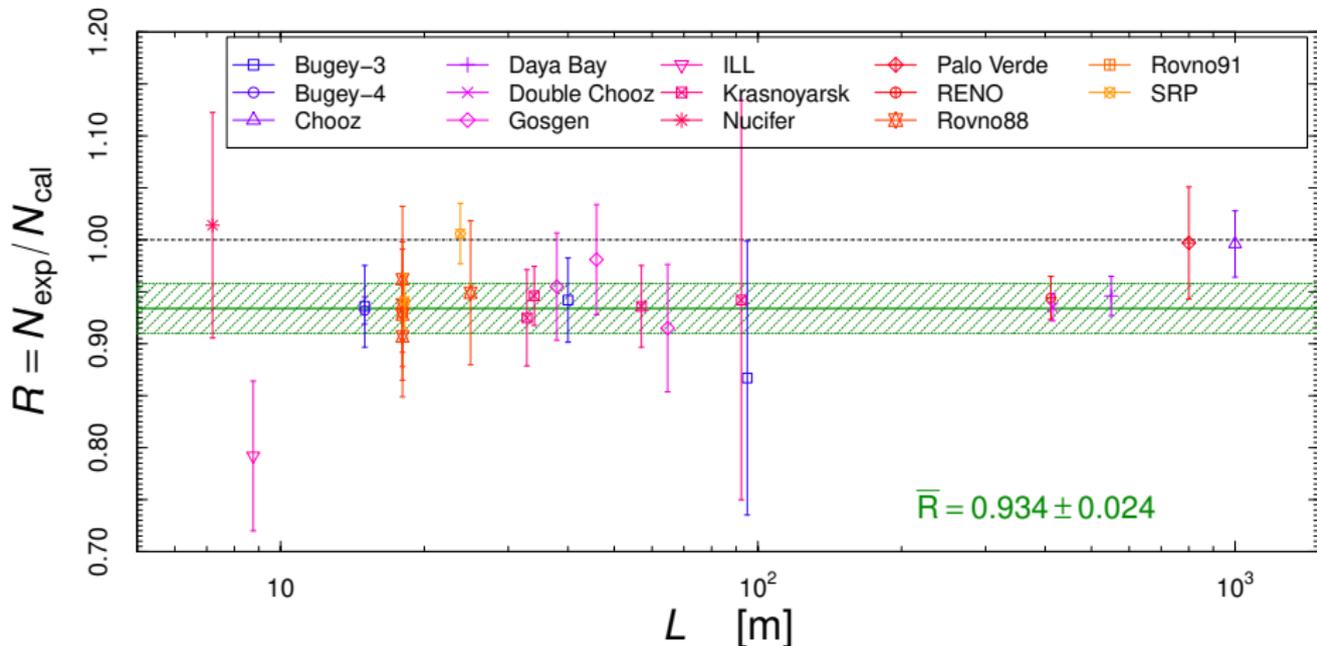
[SAGE, PRC 73 (2006) 045805; PRC 80 (2009) 015807;  
Laveder et al, Nucl.Phys.Proc.Suppl. 168 (2007) 344,  
MPLA 22 (2007) 2499, PRD 78 (2008) 073009,  
PRC 83 (2011) 065504]

# Reactor Electron Antineutrino Anomaly

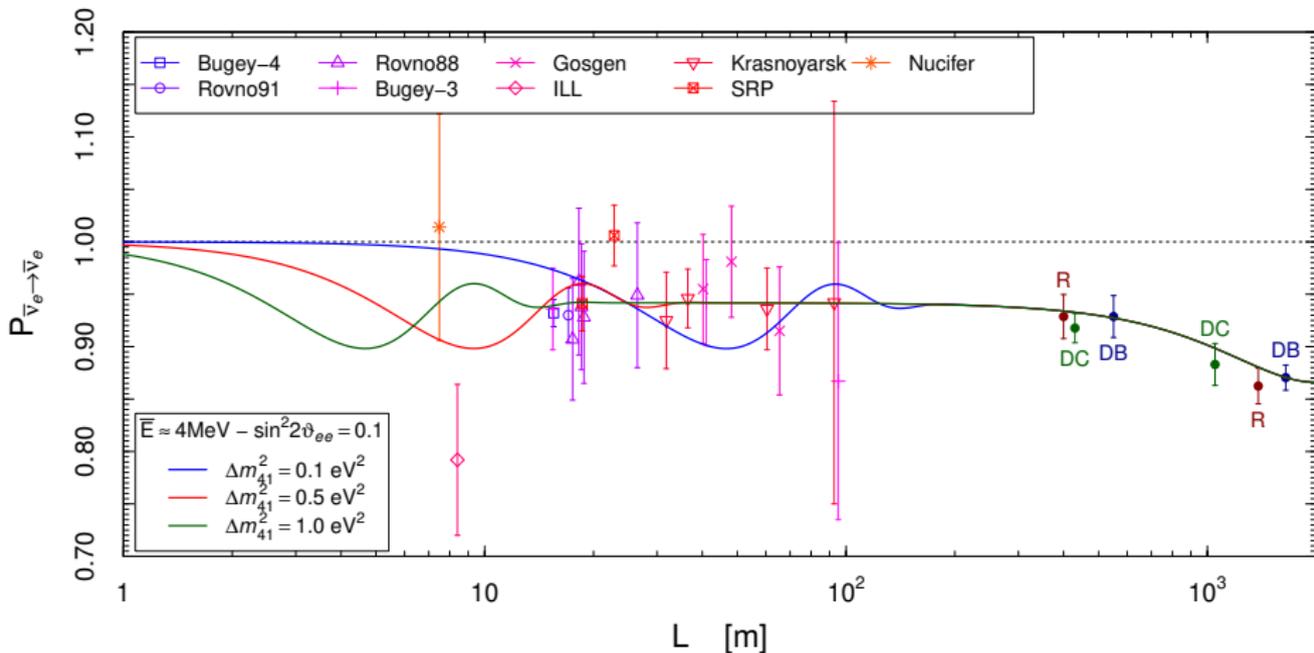
[Mention et al, PRD 83 (2011) 073006]

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

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



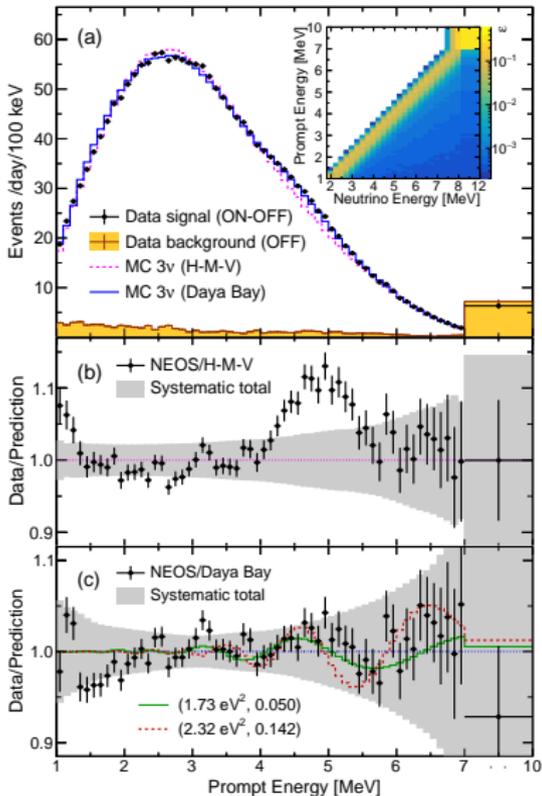
$\approx 2.8\sigma$  deficit



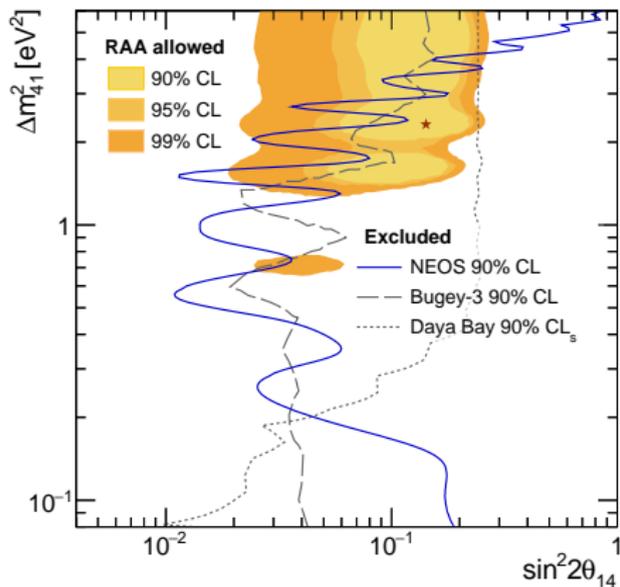
$$\Delta m_{\text{SBL}}^2 \gtrsim 0.5 \text{ eV}^2 \gg \Delta m_{\text{ATM}}^2 \gg \Delta m_{\text{SOL}}^2$$

# 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.



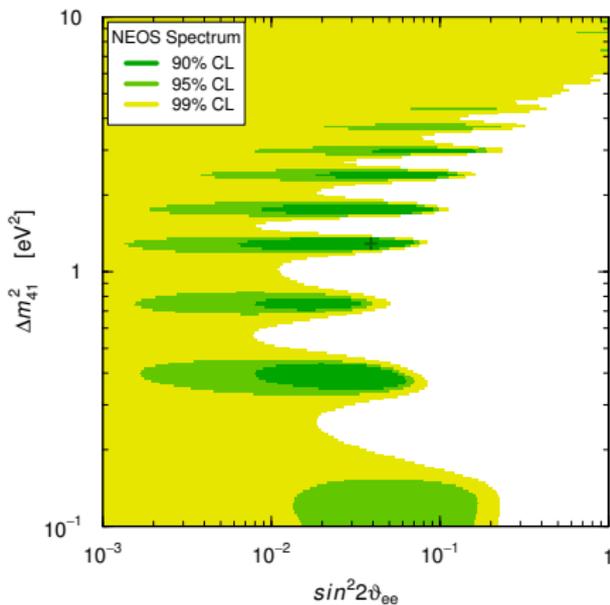
Raster Scan

[NEOS, PRL 118 (2017) 121802 (arXiv:1610.05134)]

Best Fits:

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

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



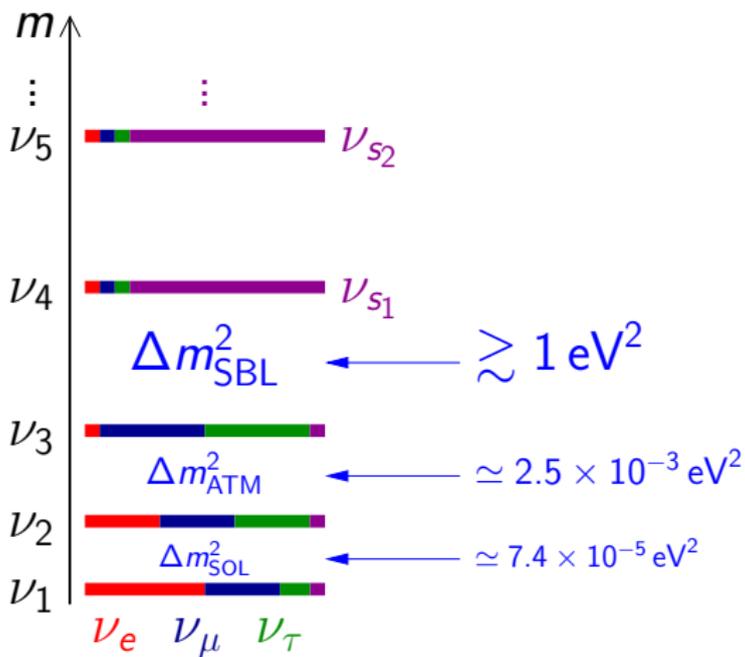
2-D  $\chi^2$  Analysis

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

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

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

# Beyond Three-Neutrino Mixing: Sterile Neutrinos



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

# 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

## Common Parameterization of $4 \times 4$ Mixing Matrix

$$U = [W^{34} R^{24} W^{14} R^{23} W^{13} R^{12}] \text{diag}\left(1, e^{i\lambda_{21}}, e^{i\lambda_{31}}, e^{i\lambda_{41}}\right)$$

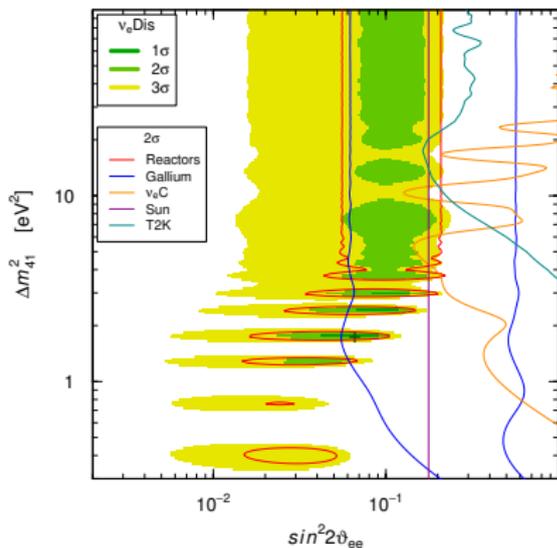
$$= \begin{pmatrix} c_{12}c_{13}c_{14} & s_{12}c_{13}c_{14} & c_{14}s_{13}e^{-i\delta_{13}} & s_{14}e^{-i\delta_{14}} \\ \dots & \dots & \dots & c_{14}s_{24} \\ \dots & \dots & \dots & c_{14}c_{24}s_{34}e^{-i\delta_{34}} \\ \dots & \dots & \dots & c_{14}c_{24}c_{34} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 & 0 \\ 0 & 0 & e^{i\lambda_{31}} & 0 \\ 0 & 0 & 0 & e^{i\lambda_{41}} \end{pmatrix}$$

$$|U_{e4}|^2 = \sin^2 \vartheta_{14} \Rightarrow \sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 (1 - |U_{e4}|^2) = \sin^2 2\vartheta_{14}$$

$$|U_{\mu 4}|^2 = \cos^2 \vartheta_{14} \sin^2 \vartheta_{24} \simeq \sin^2 \vartheta_{24} \Rightarrow \sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu 4}|^2 (1 - |U_{\mu 4}|^2) \simeq \sin^2 2\vartheta_{24}$$

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

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



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

- ▶ KARMEN+LSND  $\nu_e$ - $^{12}\text{C}$   
[Conrad, Shaevitz, PRD 85 (2012) 013017]  
[CG, Laveder, PLB 706 (2011) 20]
- ▶ Solar  $\nu_e$  + 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  $\nu_e$  disappearance  
[T2K, PRD 91 (2015) 051102]
- ▶  $\Delta\chi_{\text{NO}}^2/\text{NDF}_{\text{NO}} = 14.1/2 \Rightarrow \approx 3.3\sigma$  anom.
- ▶ Best Fit:  $\Delta m_{41}^2 = 1.7 \text{ eV}^2$   
 $\sin^2 2\vartheta_{ee} = 0.066 \Leftrightarrow |U_{e4}|^2 = 0.017$
- ▶  $\chi_{\text{min}}^2/\text{NDF} = 163.0/174 \Rightarrow \text{GoF} = 71\%$

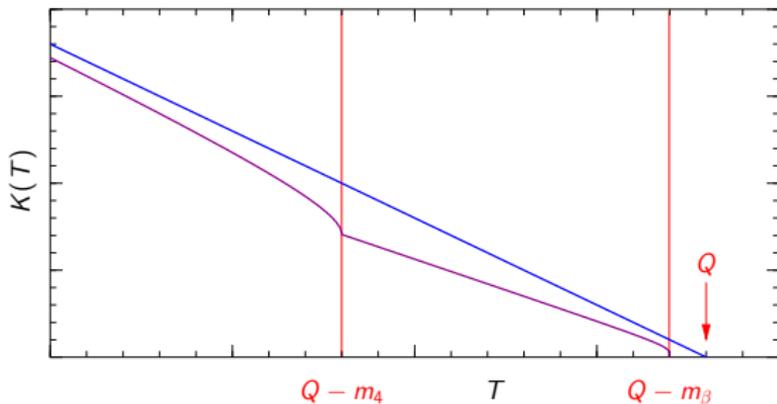
# Tritium Beta-Decay: ${}^3\text{H} \rightarrow {}^3\text{He} + e^- + \bar{\nu}_e$

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

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

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

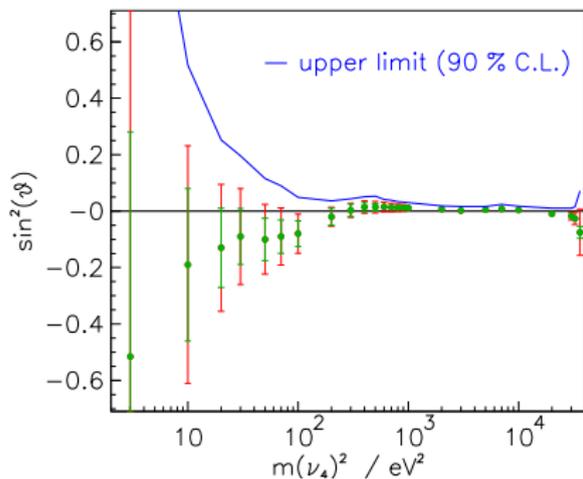
$$m_4 \gg m_{1,2,3} \Rightarrow \simeq (1 - |U_{e4}|^2) \sqrt{(Q - T)^2 - m_\beta^2} \theta(Q - T - m_\beta) \\ + |U_{e4}|^2 \sqrt{(Q - T)^2 - m_4^2} \theta(Q - T - m_4)$$



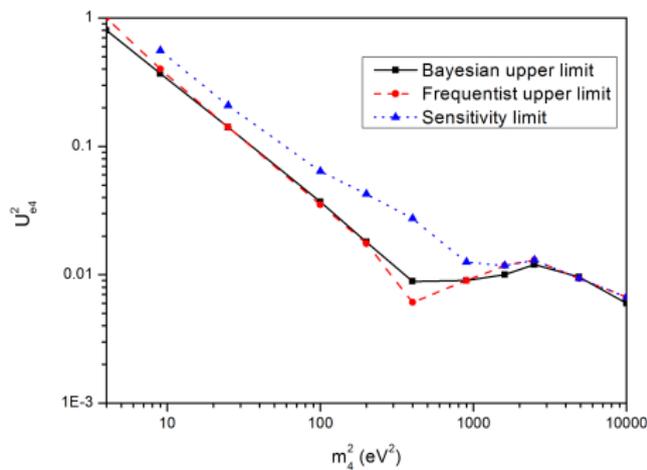
$$m_\beta^2 = \sum_{k=1}^3 |U_{ek}|^2 m_k^2$$

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

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



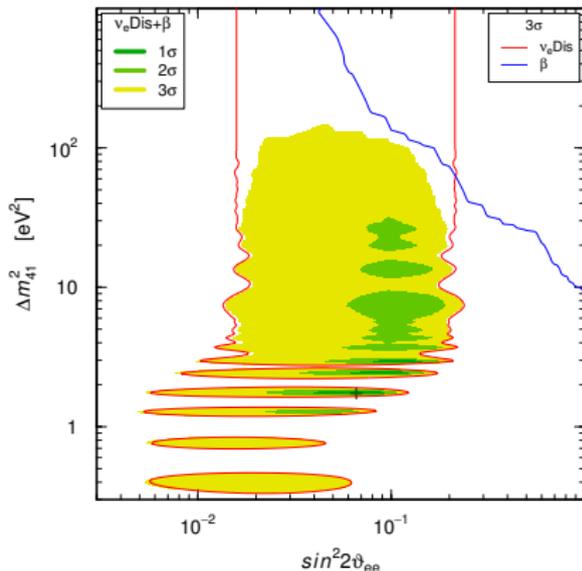
[Kraus, Singer, Valerius, Weinheimer, EPJC 73 (2013) 2323]



[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)]

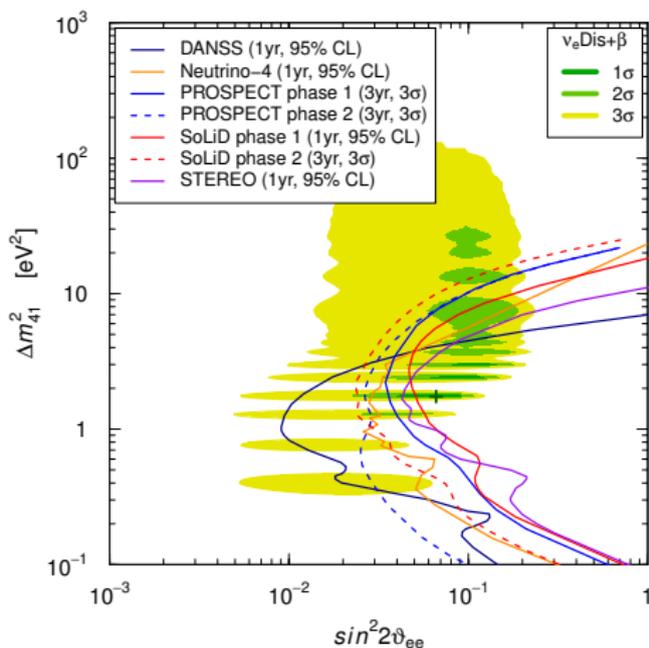
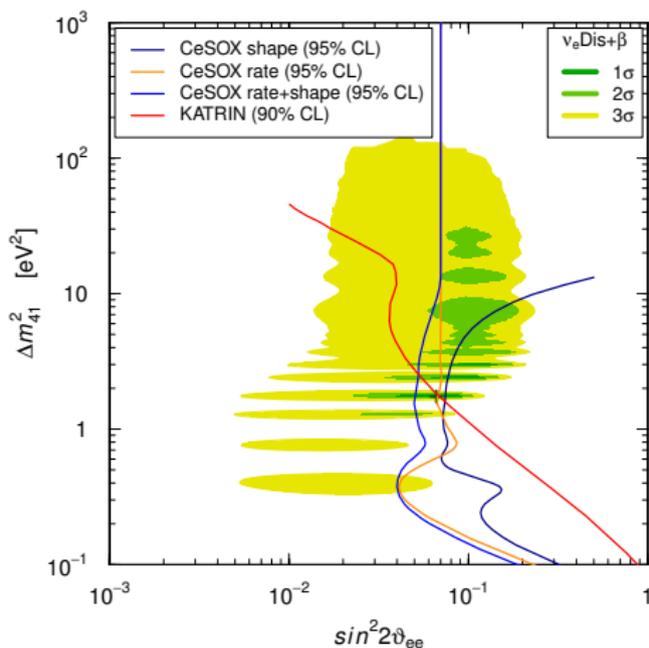


▶ Best Fit:  $\Delta m_{41}^2 = 1.7 \text{ eV}^2$   
 $\sin^2 2\vartheta_{ee} = 0.066 \Leftrightarrow |U_{e4}|^2 = 0.017$

▶  $2 \text{ cm} \lesssim \frac{L_{41}^{\text{osc}}}{E [\text{MeV}]} \lesssim 7 \text{ m}$  at  $3\sigma$

▶  $0.0050 \lesssim \sin^2 2\vartheta_{ee} \lesssim 0.23$  at  $3\sigma$

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

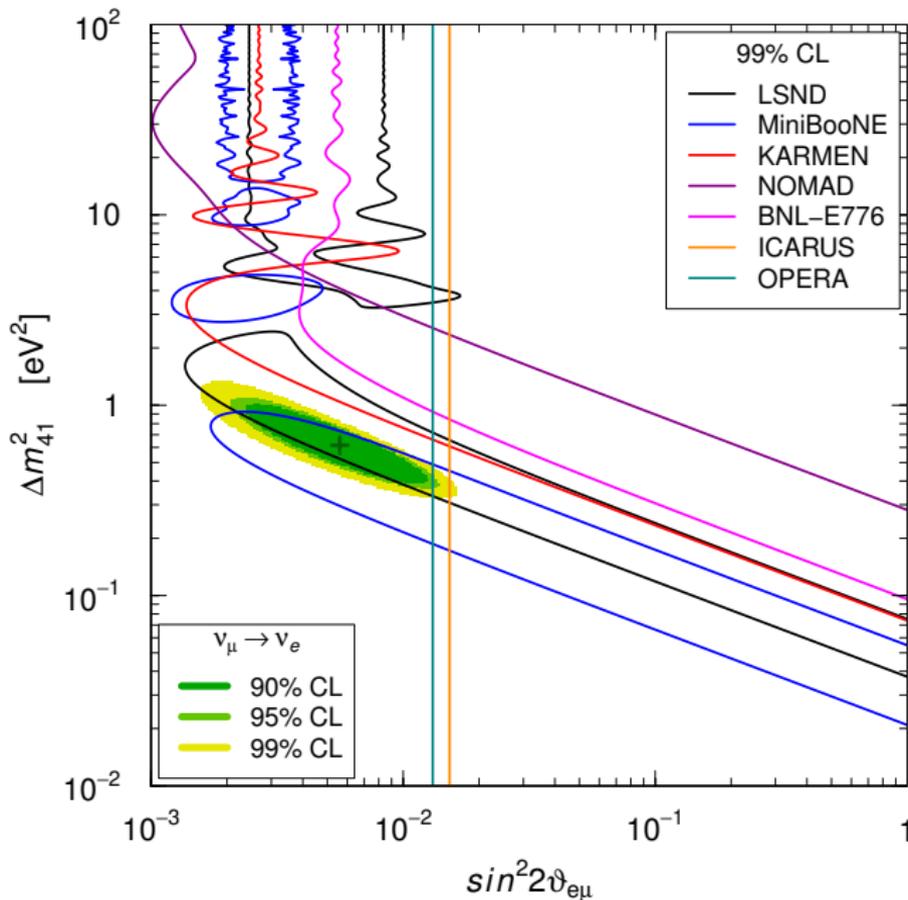


CeSOX (Gran Sasso, Italy)  $^{144}\text{Ce} \rightarrow \bar{\nu}_e$   
 BOREXINO:  $L \simeq 5\text{-}12\text{m}$  [Vivier@TAUP2015]

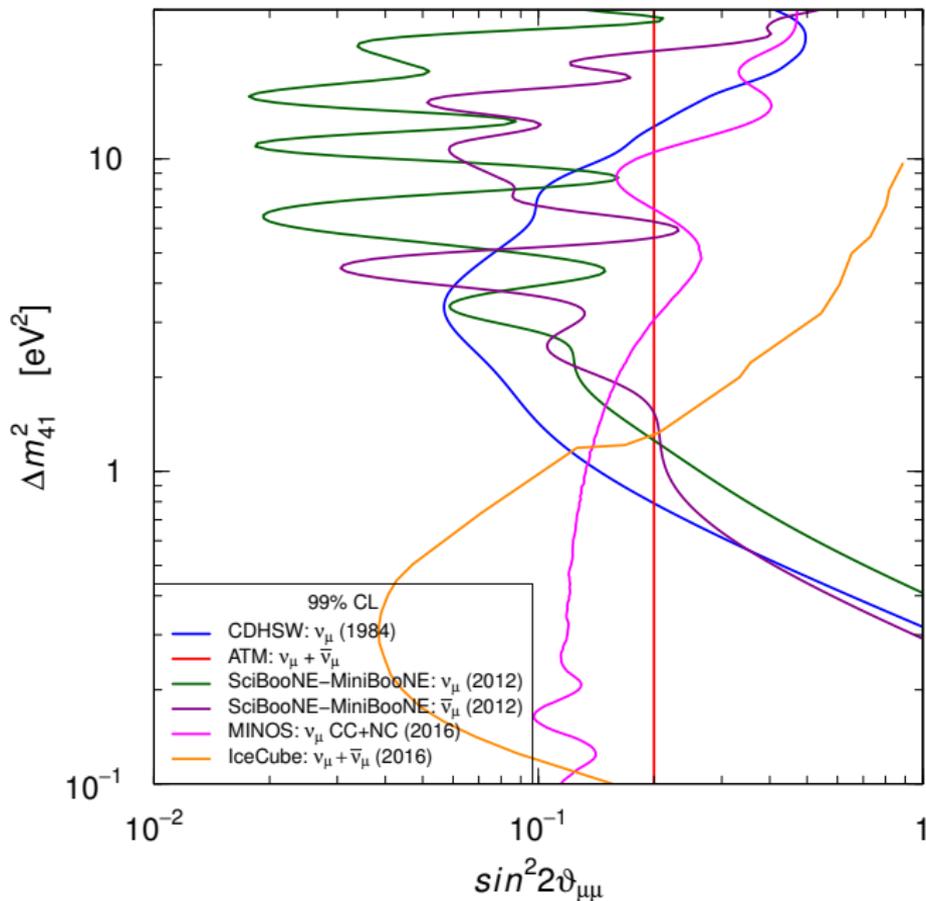
KATRIN (Karlsruhe, Germany)  $^3\text{H} \rightarrow \bar{\nu}_e$   
 [Drexlin@NOW2016]

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]

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



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



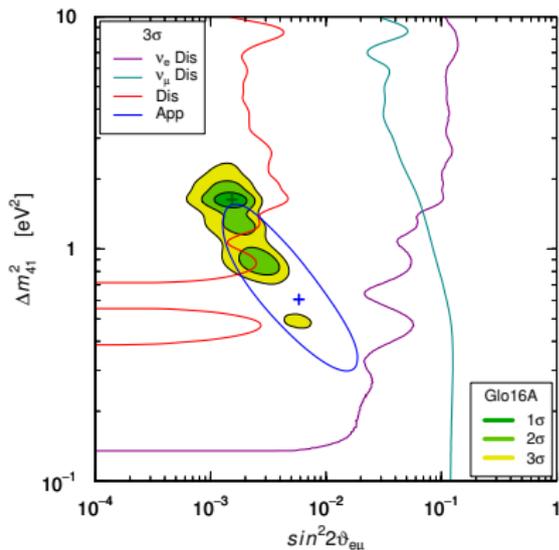
# 3+1 Appearance-Disappearance Tension

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

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

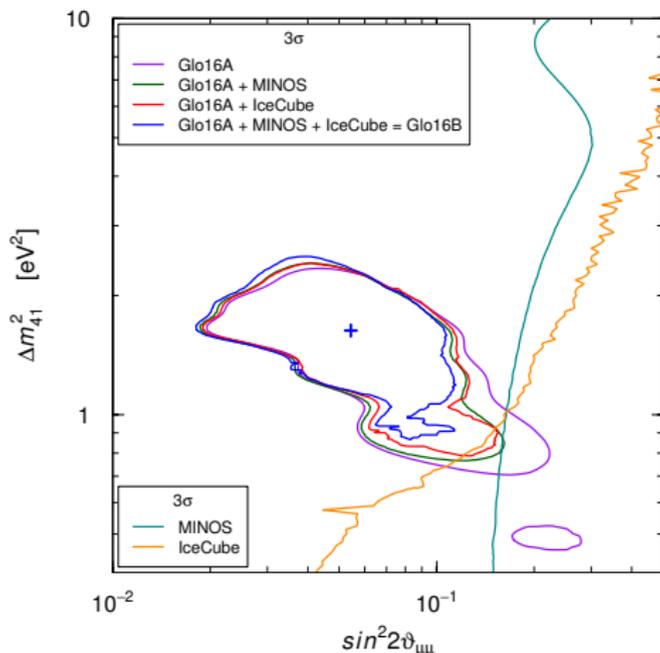
$$\nu_\mu \rightarrow \nu_e \text{ APP} \\ \sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

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



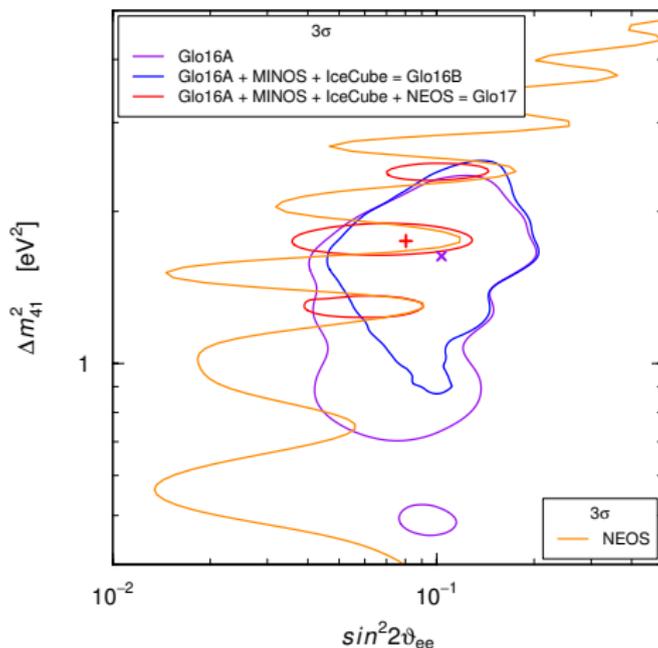
- ▶  $\nu_\mu \rightarrow \nu_e$  is quadratically suppressed!
- ▶ Glo16A = 2016 data except MINOS and IceCube [Gariazzo, CG, Laveder, Li, JHEP 1706 (2017) 135]
- ▶  $\Delta\chi^2_{\text{NO}}/\text{NDF}_{\text{NO}} = 53.1/3 \Rightarrow \approx 6.7\sigma$  anom.
- ▶ Best Fit:  $\Delta m_{41}^2 = 1.6 \text{ eV}^2$   
 $|U_{e4}|^2 = 0.027 \quad |U_{\mu4}|^2 = 0.015$
- ▶  $\chi^2_{\text{min}}/\text{NDF} = 288.4/250 \Rightarrow \text{GoF} = 4.8\%$
- ▶  $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 13.4/2 \Rightarrow \text{GoF}_{\text{PG}} = 0.13\%$
- ▶ 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:  $\Delta m_{41}^2 = 1.6 \text{ eV}^2$   $|U_{e4}|^2 = 0.028$   $|U_{\mu4}|^2 = 0.014$
- ▶  $\chi_{\text{min}}^2/\text{NDF} = 556.9/525 \Rightarrow \text{GoF} = 16\%$
- ▶  $\chi_{\text{PG}}^2/\text{NDF}_{\text{PG}} = 14.4/2 \Rightarrow \text{GoF}_{\text{PG}} = 0.075\% \leftarrow \text{Strong tension!}$

# Effects of NEOS

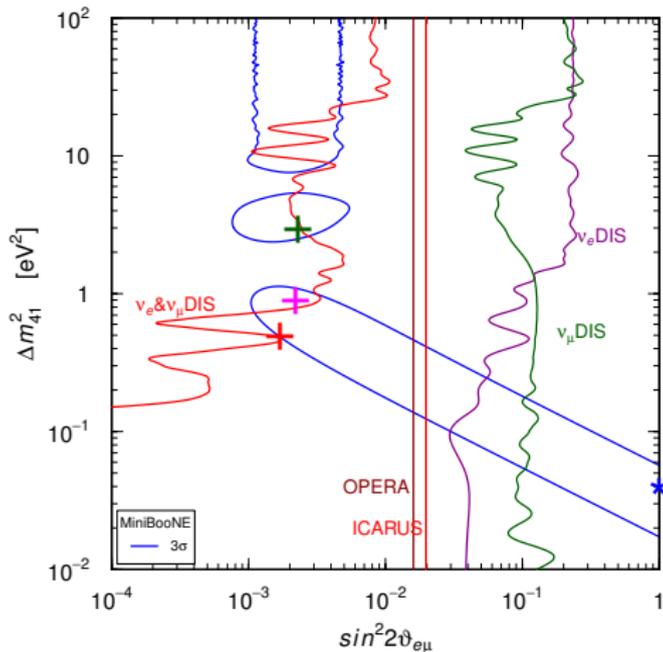
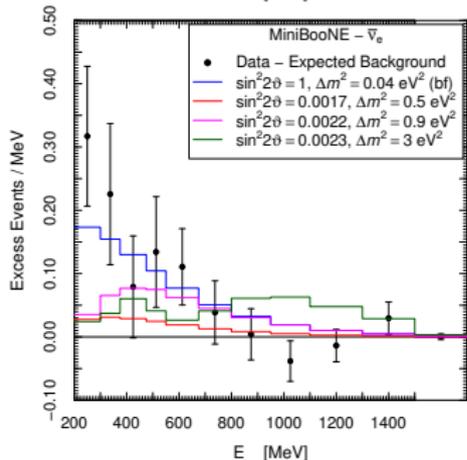
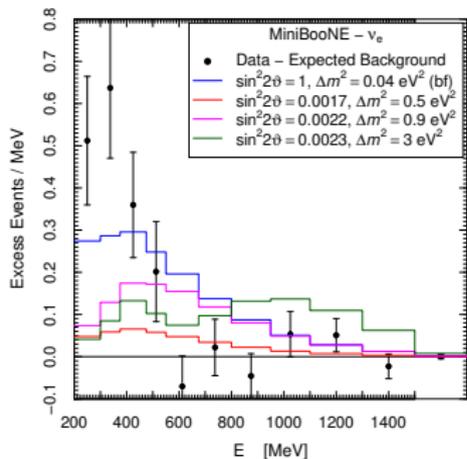


▶ Best Fit:  $\Delta m_{41}^2 = 1.7 \text{ eV}^2$   $|U_{e4}|^2 = 0.021$   $|U_{\mu 4}|^2 = 0.016$

▶  $\chi^2_{\min}/\text{NDF} = 622.1/585 \Rightarrow \text{GoF} = 14\%$

▶  $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 17.2/2 \Rightarrow \text{GoF}_{\text{PG}} = 0.019\% \leftarrow \text{Strong tension!}$

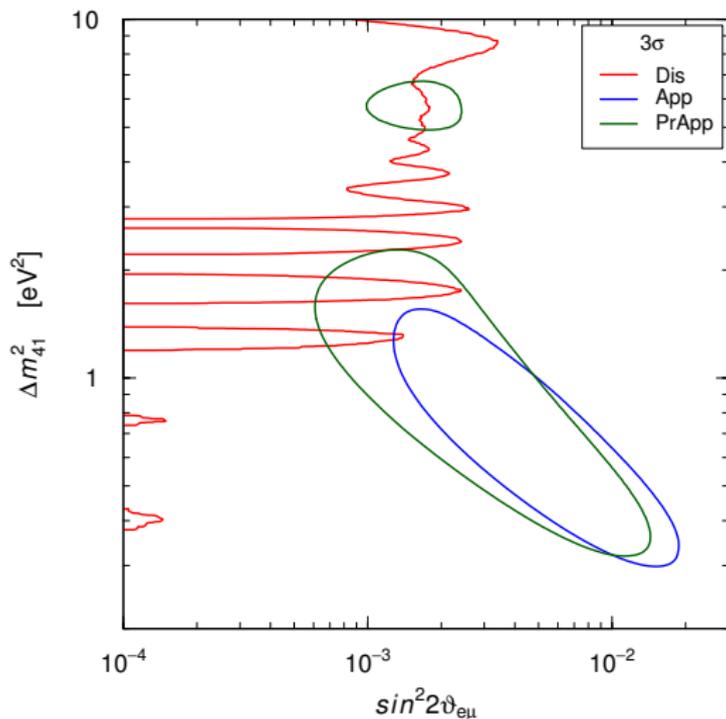
# MiniBooNE Low-Energy Anomaly



- ▶ Fit of MB low-energy excess requires small  $\Delta m^2_{41}$  and large  $\sin^2 2\theta_{e\mu}$ , in contradiction with disappearance data.
- ▶ Parameter goodness of fit of MB low-energy excess vs all other data:  $6 \times 10^{-6}$

# Global $\rightarrow$ Pragmatic

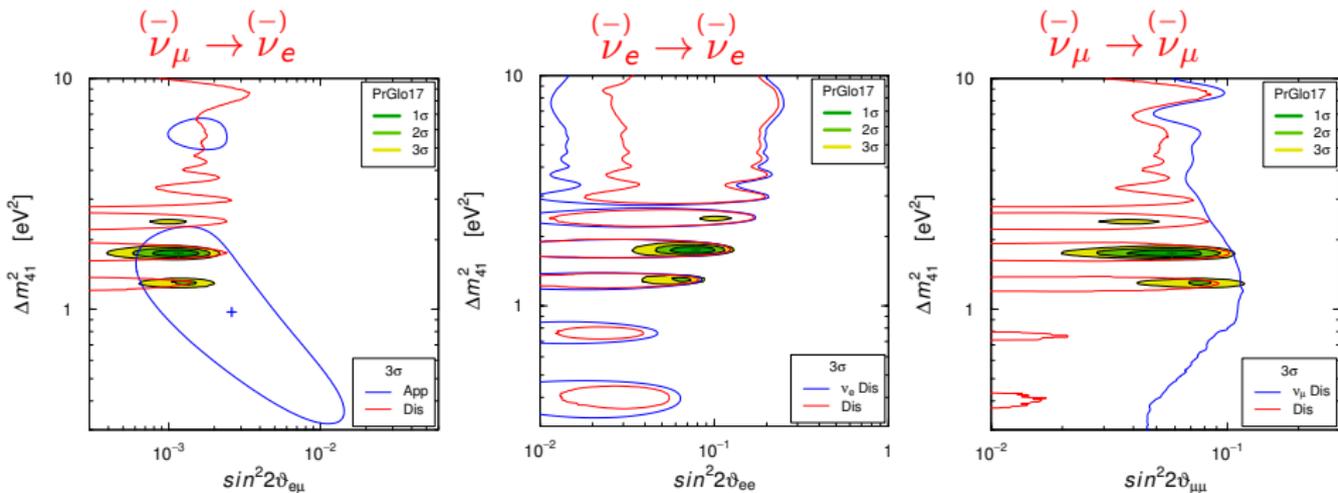
[CG, Laveder, Li, Long, PRD 88 (2013) 073008]



- ▶ App: all Appearance data
- ▶ PrApp: all Appearance data, except MiniBooNE low-energy bins

# Pragmatic Global 3+1 Fit

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



▶  $\Delta\chi_{\text{NO}}^2/\text{NDF}_{\text{NO}} = 47.4/4 \Rightarrow \approx 6.1\sigma$  anomaly

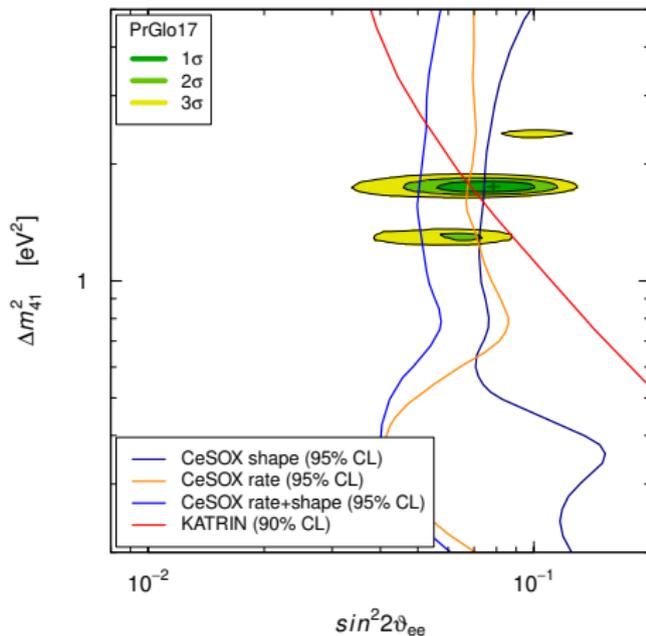
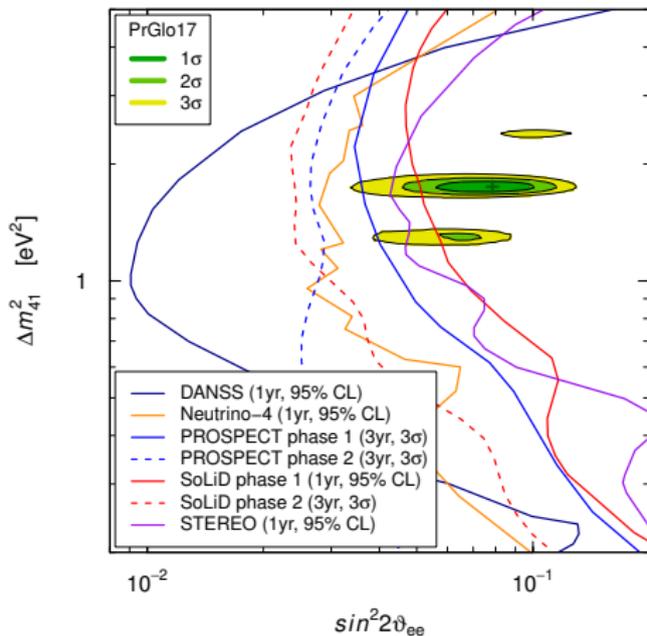
▶ Best Fit:  $\Delta m_{41}^2 = 1.7 \text{ eV}^2$   $|U_{e4}|^2 = 0.020$   $|U_{\mu 4}|^2 = 0.015$

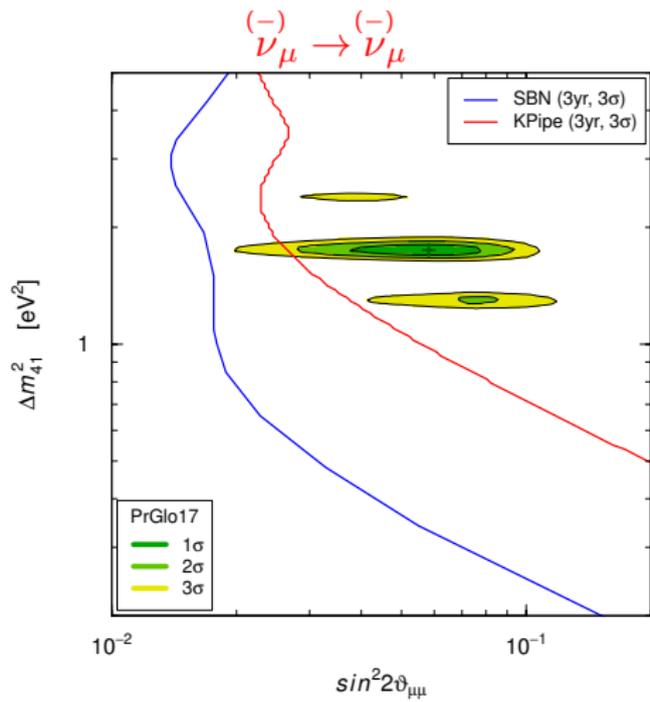
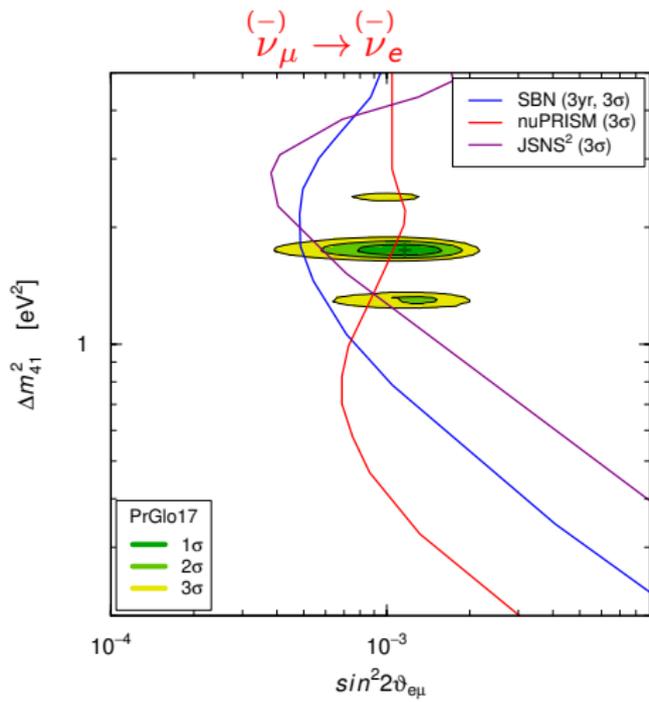
▶  $\chi_{\text{min}}^2/\text{NDF} = 595.1/579 \Rightarrow \text{GoF} = 31\%$

▶  $\chi_{\text{PG}}^2/\text{NDF}_{\text{PG}} = 7.2/2 \Rightarrow \text{GoF}_{\text{PG}} = 2.7\%$  ← Mild tolerable tension!

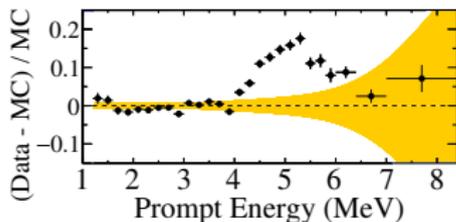
# The Race for the Light Sterile

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

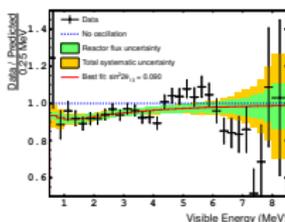




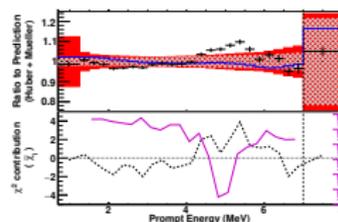
# Reactor Antineutrino 5 MeV Bump



[RENO, arXiv:1511.05849]



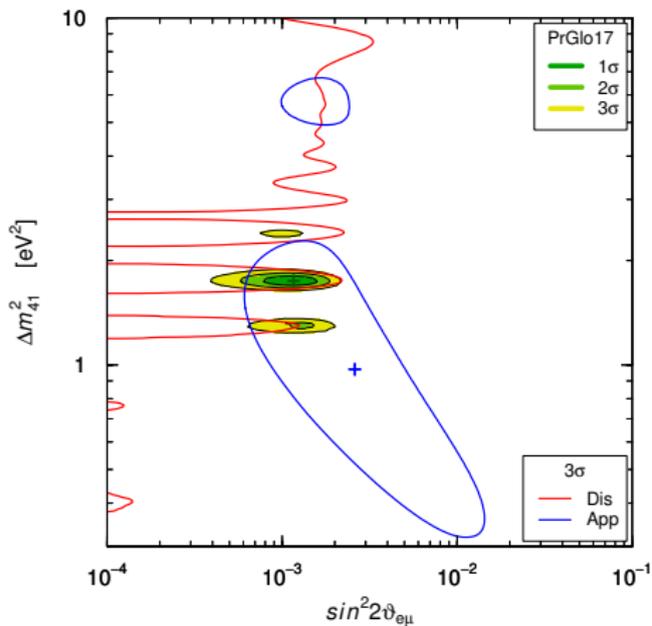
[Double Chooz, arXiv:1406.7763]



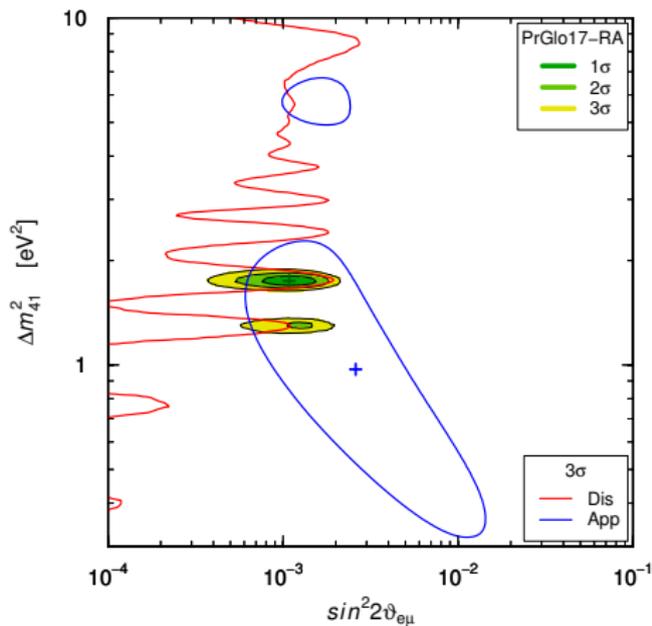
[Daya Bay, arXiv:1508.04233]

- ▶ Cannot be explained by neutrino oscillations (SBL oscillations are averaged in Double Chooz, Daya Bay, RENO).
- ▶ Very likely due to theoretical miscalculation of the spectrum.
- ▶  $\sim 3\%$  effect on total flux, but if it is an excess it increases the anomaly!
- ▶ No post-bump complete calculation of the neutrino fluxes.
- ▶ Saclay-Huber flux calculation uncertainty is about 2.5%.
- ▶ Increasing the flux uncertainty is a game that one can play, but there are only guesses, e.g. about 5%. [Hayes and Vogel, 2016]
- ▶ Better to exclude the reactor rates from the global fit. [suggestion of Pedro Machado at WIN 2017]

Global Fit

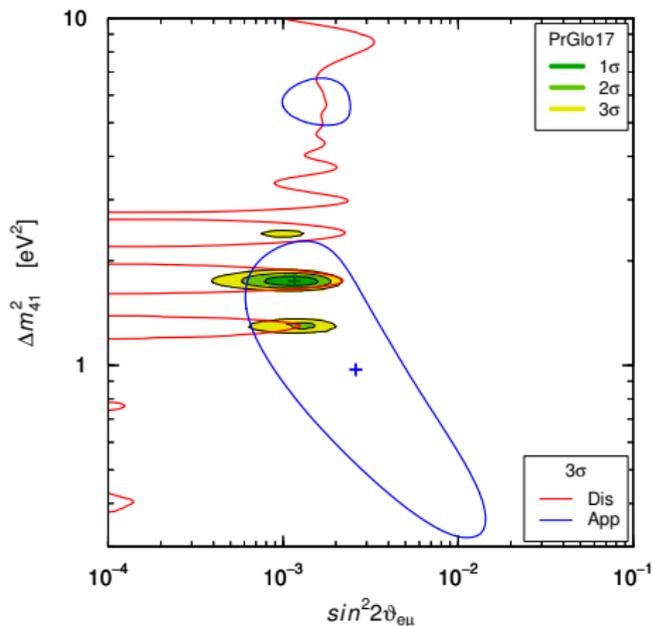


Without Reactor Rates

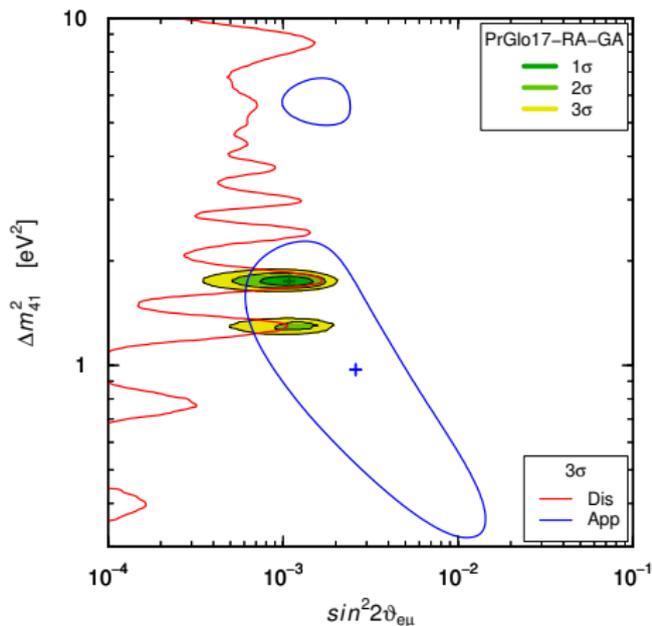


The Reactor Antineutrino Anomaly has small impact on the global fit.

## Global Fit

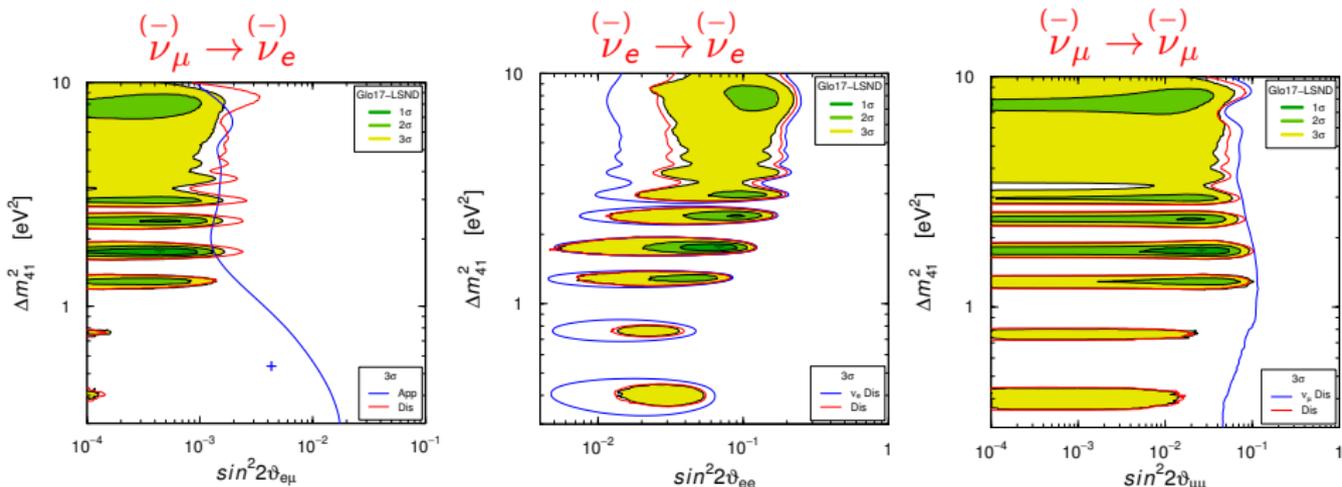


## Without Reactor Rates and Gallium Data



Given the current constraints, only the LSND signal is crucial for a positive indication in favor of active-sterile SBL oscillations.

# Global Analysis without LSND

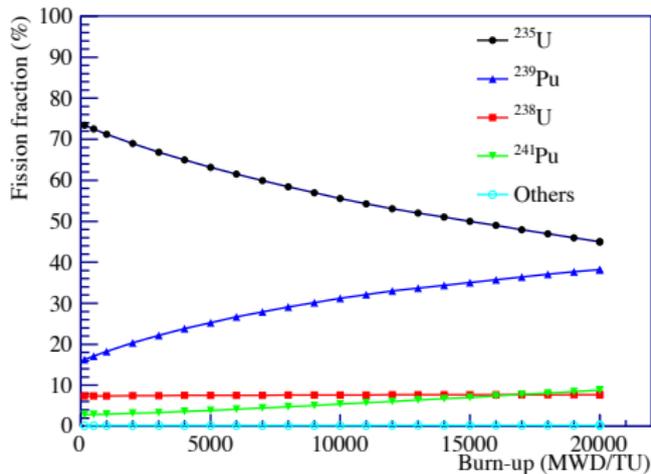


- ▶ All MiniBooNE data, including the low-energy bins
- ▶  $\Delta\chi^2_{\text{NO}}/\text{NDF}_{\text{NO}} = 17.1/4 \Rightarrow \approx 3.1\sigma$  anomaly
- ▶ Best Fit:  $\Delta m^2_{41} = 1.8 \text{ eV}^2$   $|U_{e4}|^2 = 0.017$   $|U_{\mu 4}|^2 = 0.0065$
- ▶  $\chi^2_{\text{min}}/\text{NDF} = 604.1/581 \Rightarrow \text{GoF} = 25\%$
- ▶  $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 9.3/2 \Rightarrow \text{GoF}_{\text{PG}} = 0.96\% \leftarrow \text{Tension!}$

# Daya Bay Reactor Fuel Evolution

[Daya Bay, PRL 118 (2017) 251801 (arXiv:1704.01082)]

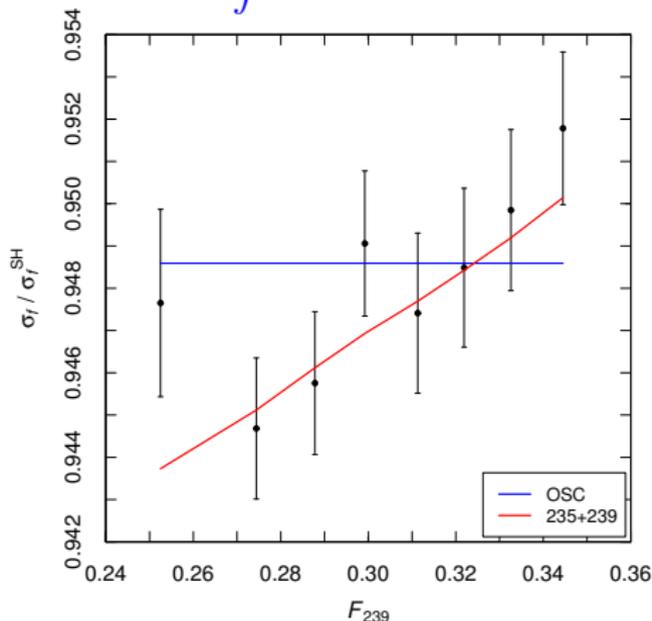
- ▶ Reactor  $\bar{\nu}_e$  flux produced by the  $\beta$  decays of the fission products of  $^{235}\text{U}$ ,  $^{238}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{241}\text{Pu}$ .
- ▶ Effective fission fractions:  
 $F_{235}$ ,  $F_{238}$ ,  $F_{239}$ ,  $F_{241}$ .

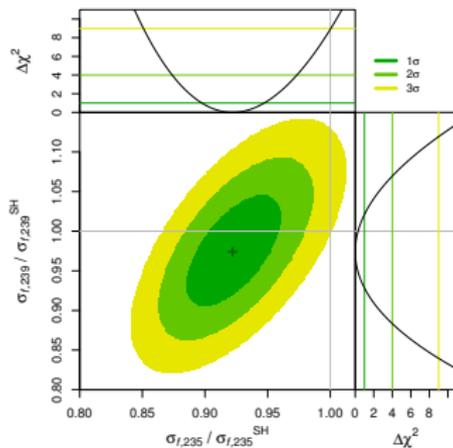
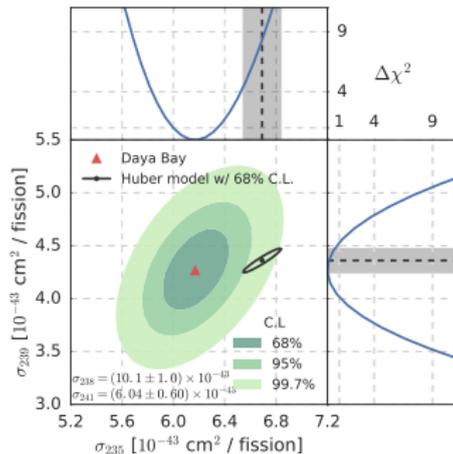


- ▶ Cross section per fission:

$$\sigma_f = \sum_{k=235,238,239,241} F_k \sigma_{f,k}$$

$$\sigma_{f,k} = \int dE_\nu \phi_k(E_\nu) \sigma(E_\nu)$$





- ▶ Best fit: mainly suppression of  $\sigma_{f,235}$
- ▶ Equal fluxes suppression:  
 $\Delta\chi^2/\text{NDF} = 7.9/1$   
disfavored at  $2.8\sigma$
- ▶ Equal fluxes suppression corresponds to SBL oscillations, but theoretical flux uncertainties must be taken into account

- ▶ With theoretical flux uncertainties:

Daya Bay	$^{235}\text{U}$	OSC
$\chi^2_{\min}$	3.8	9.5
NDF	7	7
GoF	80%	22%

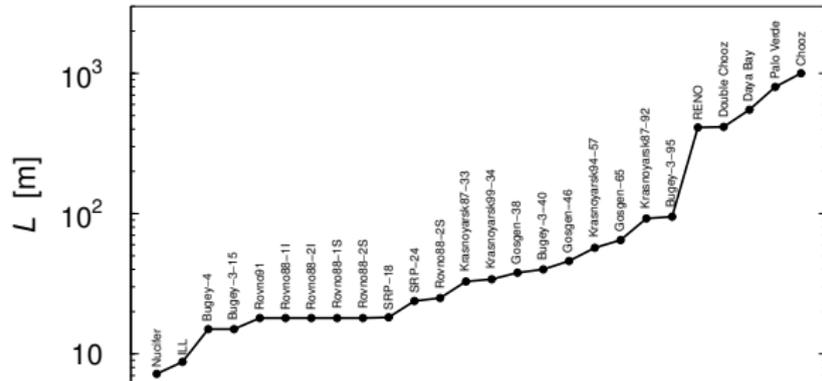
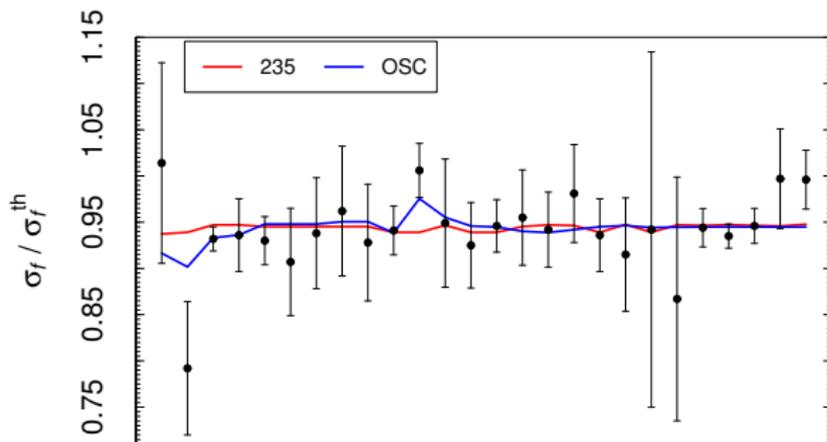
- ▶ MC: OSC disfavored at  $2.6\sigma$

[CG, X.P. Ji, M. Laveder, Y.F. Li, B.R. Littlejohn, arXiv:1708.01133]

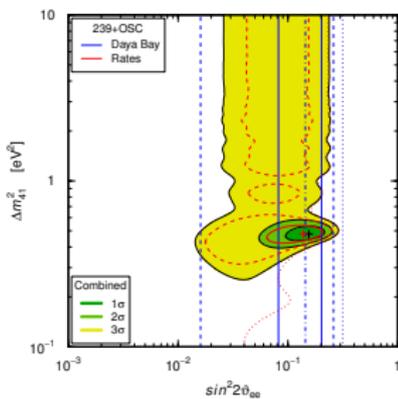
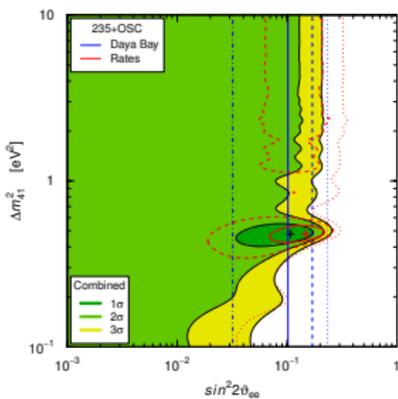
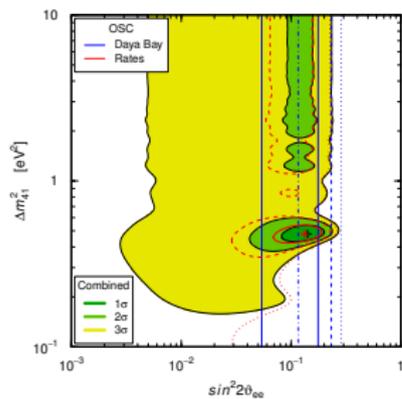
# Fuel Fractions of All Reactor Experiments

All Reactors	$^{235}\text{U}$	OSC
$\chi^2_{\min}$	25.3	23.0
NDF	32	31
GoF	79%	85%

MC:  $^{235}\text{U}$  disfavored at  $1.7\sigma$

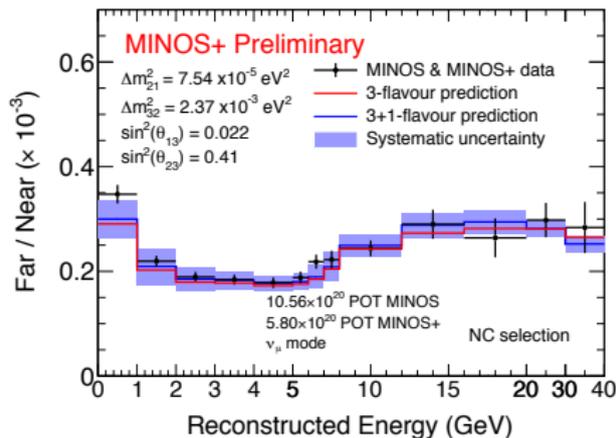
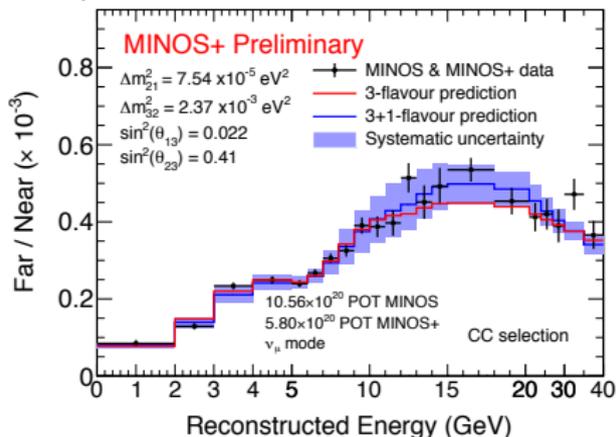
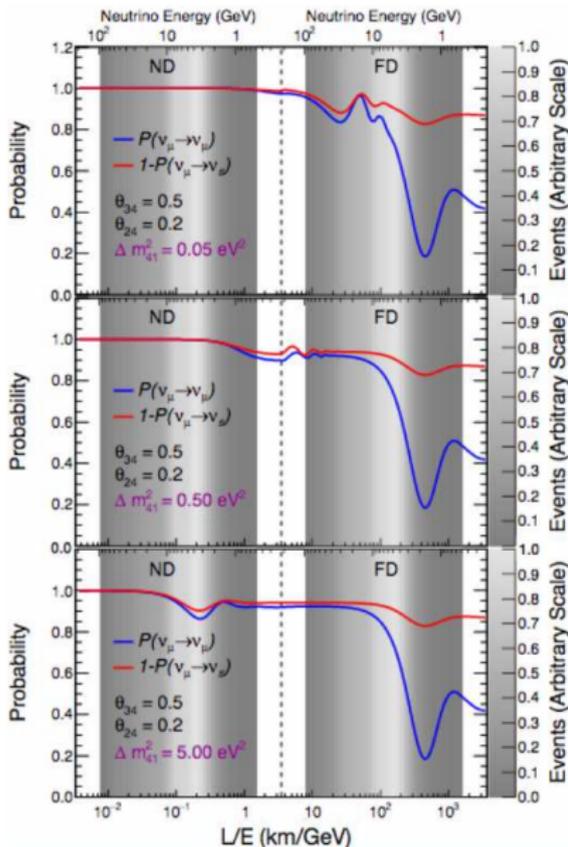


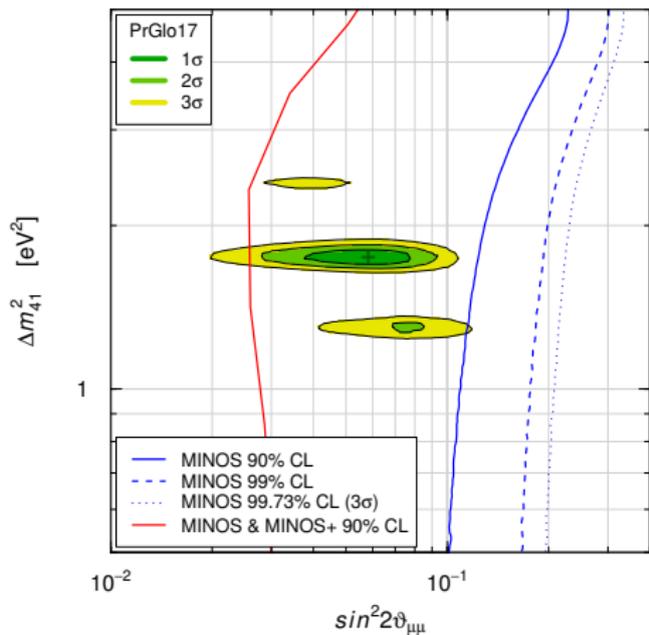
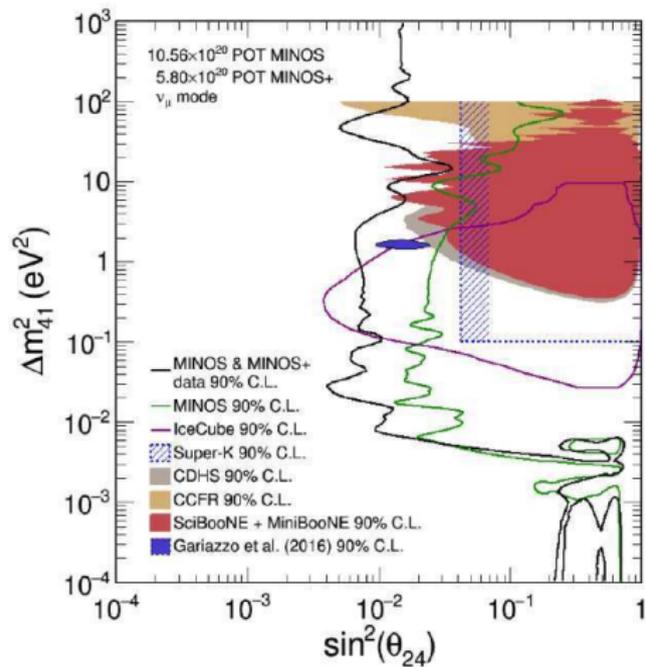
	$^{235}\text{U}$	$^{235}\text{U} + ^{239}\text{U}$	OSC	$^{235}\text{U} + \text{OSC}$	$^{239}\text{U} + \text{OSC}$
$\chi^2_{\min}$	25.3	24.8	23.0	20.2	17.5
NDF	32	31	31	30	30
GoF	79%	78%	85%	91%	100%
$\Delta m_{41}^2$	—	—	0.48	0.48	0.48
$\sin^2 2\vartheta_{ee}$	—	—	0.14	0.11	0.15
$r_{235}$	0.934	0.934	—	0.987	—
$r_{239}$	—	0.970	—	—	1.099



# Preliminary Bound from MINOS & MINOS+

[Flanagan @ PPC2017]

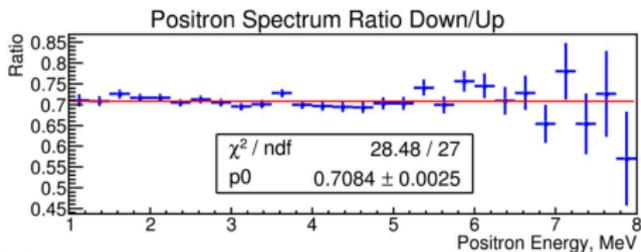
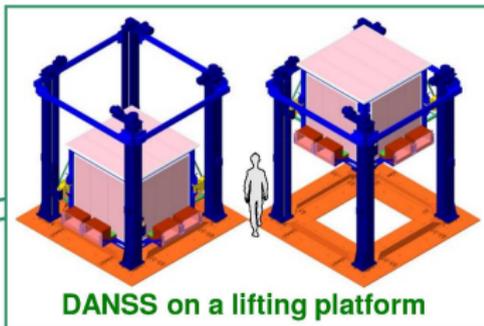
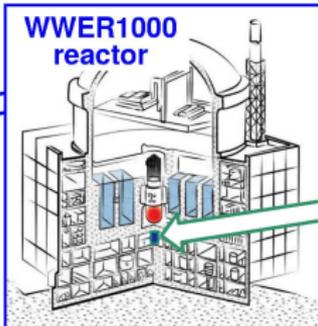




# Preliminary Bound from DANSS

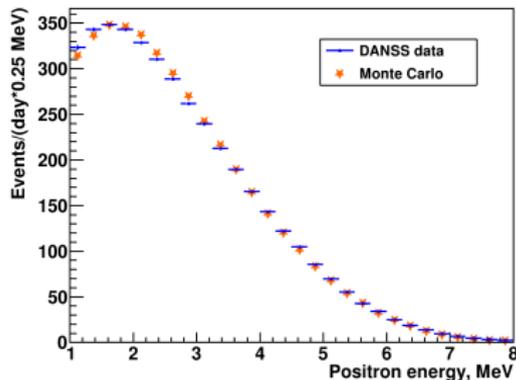
[Danilov @ Moriond EW 2017, Svirida @ WIN2017, Danilov @ EPS-HEP 2017]

## Detector of reactor AntiNeutrino based on Solid Scintillator

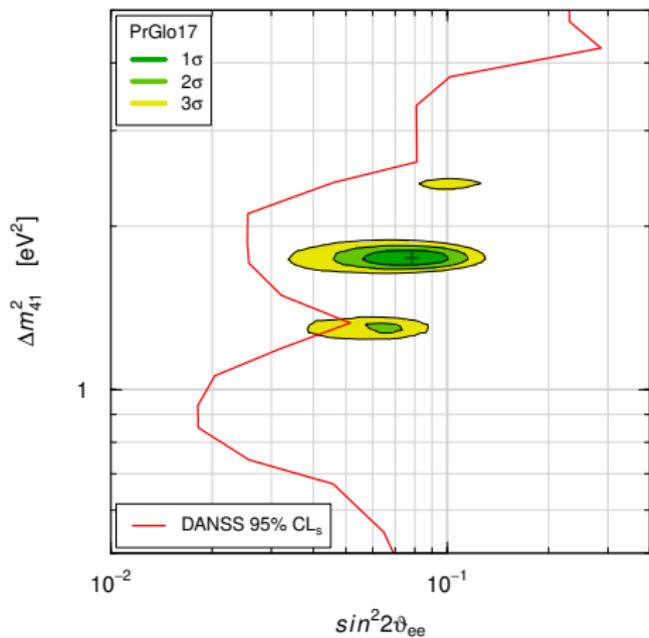
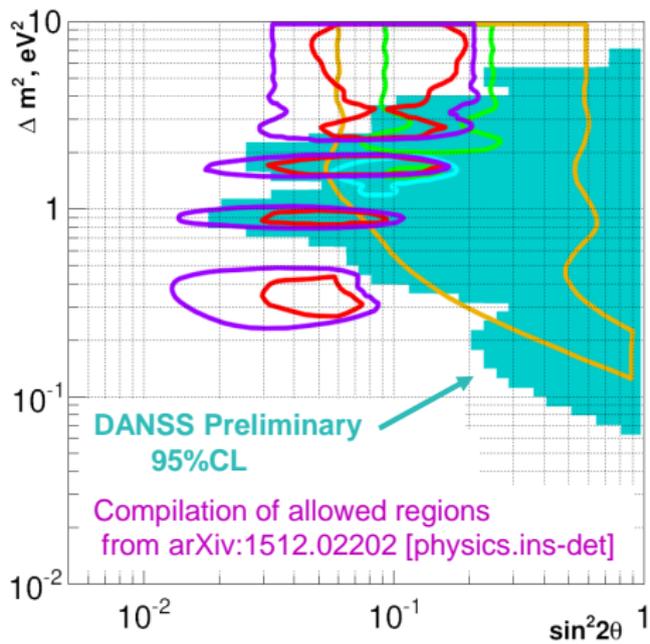


Up = 10.7 m

Down = 12.7 m



**No 5 MeV bump!**



# 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).
- ▶ 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.
- ▶ Independent tests through effect of  $m_4$  in  $\beta$ -decay and  $\beta\beta_{0\nu}$ -decay.
- ▶ **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.
- ▶ Possibilities for the next years:
  - ▶ **Reactor and source experiments**  $\nu_e$  and  $\bar{\nu}_e$  observe **SBL oscillations**: big excitement and explosion of the field.
  - ▶ **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).