# Oscillations Beyond Three-Neutrino Mixing (Light Sterile Neutrinos)

**Carlo Giunti**

INFN, Torino, Italy

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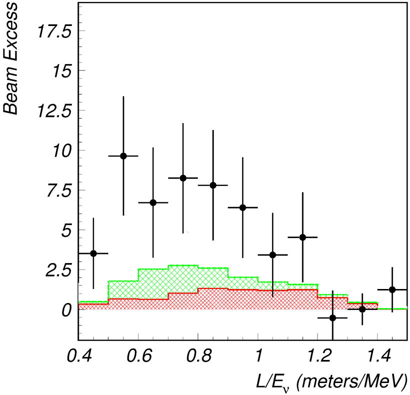
# Indications of SBL Oscillations Beyond $3\nu$

# LSND

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

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\quad$ $20\,\text{MeV} \le E \le 52.8\,\text{MeV}$




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

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

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

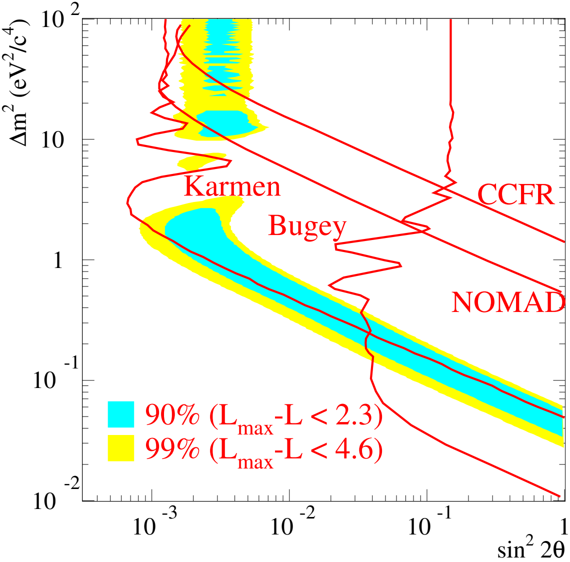
$L \simeq 30\,\text{m}$

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

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]

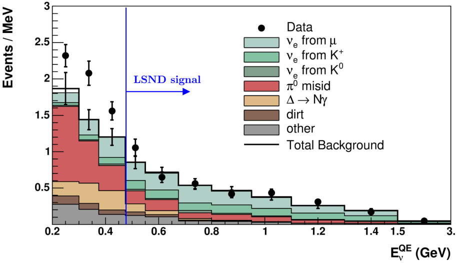



$$\Delta m^2_{\text{SBL}} \gtrsim 3 \times 10^{-2}\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \simeq 2.5 \times 10^{-3}\,\text{eV}^2 \gg \Delta m^2_{\text{SOL}}$$

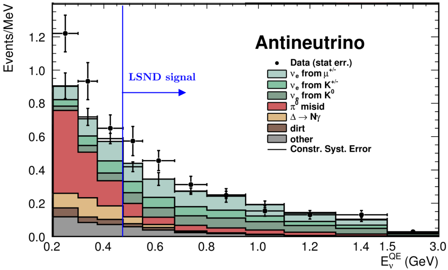
# MiniBooNE

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

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

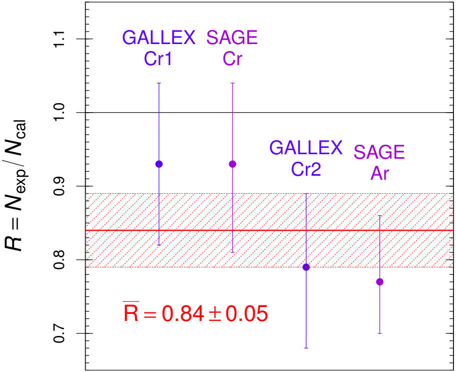
# Gallium Anomaly

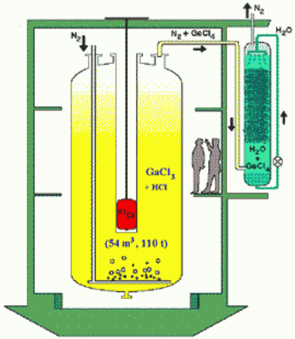
## Gallium Radioactive Source Experiments: GALLEX and SAGE

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




$\approx 2.9\sigma$ deficit

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

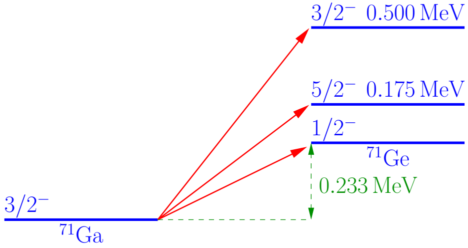
$\Delta m^2_{\text{SBL}} \gtrsim 1\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}}$

[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%!

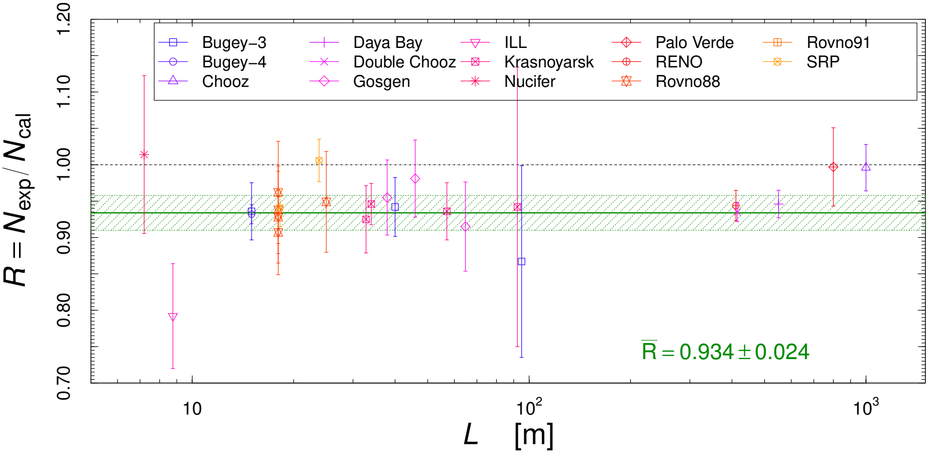
| | | $\frac{BGT_{175}}{BGT_{G.S.}}$ | $\frac{BGT_{500}}{BGT_{G.S.}}$ |
|---|---|---|---|
| Krofcheck et al. PRL 55 (1985) 1051 | $^{71}Ga(p,n)^{71}Ge$ | $< 0.056$ | $0.126 \pm 0.023$ |
| Haxton PLB 431 (1998) 110 | Shell Model | $0.19 \pm 0.18$ | |
| Frekers et al. PLB 706 (2011) 134 | $^{71}Ga(^{3}He,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

- The $^{71}Ga(^{3}He, ^{3}H)^{71}Ge$ 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.

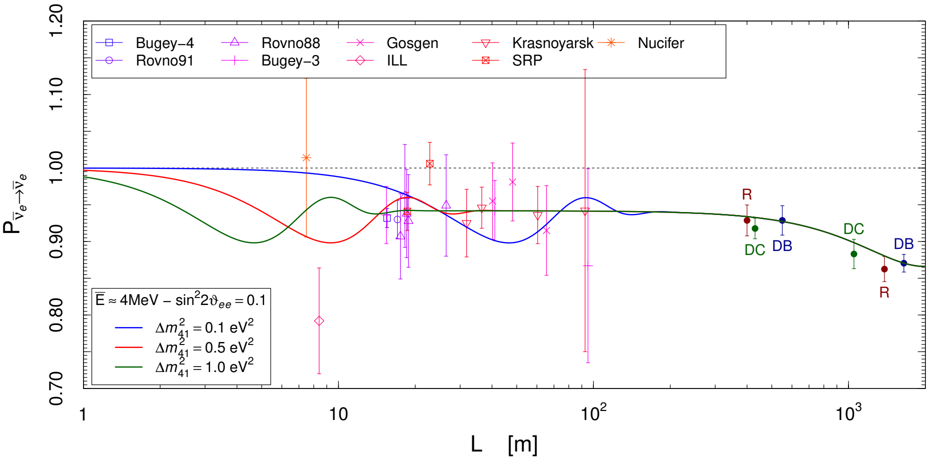
# Reactor Electron Antineutrino Anomaly

[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]



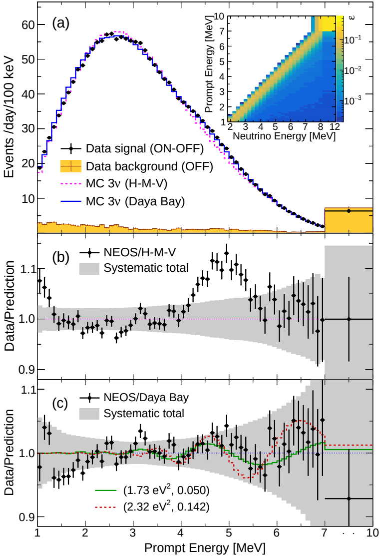

$\approx 2.8\sigma$ deficit



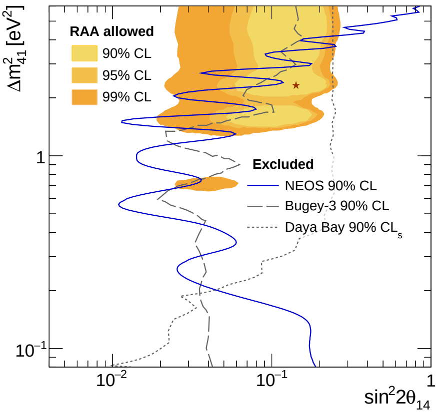

$$\Delta m^2_{\text{SBL}} \gtrsim 0.5\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}}$$

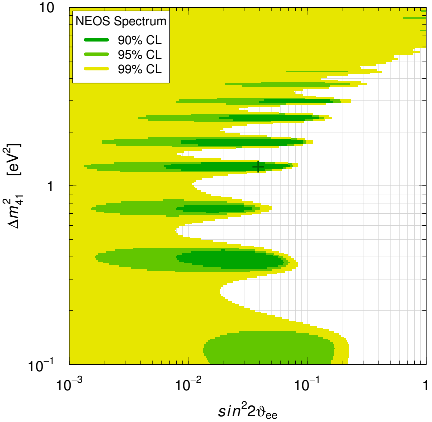
# NEOS

[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:

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

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

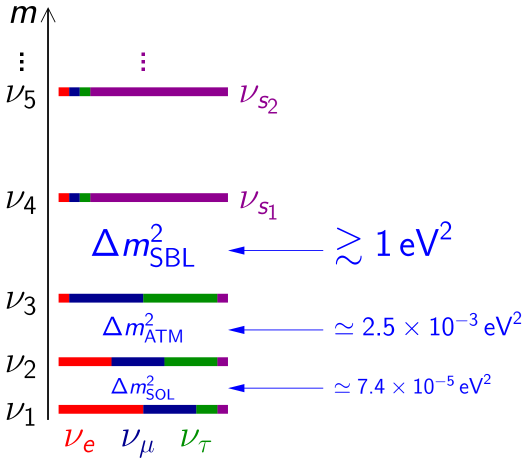
## 2-D $\chi^2$ Analysis

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

$\chi^2$ 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

# 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-$\nu_R$ 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 $(\nu_s)$
- Observables:
  - Disappearance of active neutrinos (neutral current deficit)
  - Indirect evidence through combined fit of data (current indication)
- Short-baseline anomalies + $3\nu$-mixing:

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

- Here I consider sterile neutrinos with mass scale $\sim 1\,\mathrm{eV}$ in light of short-baseline Reactor Anomaly, Gallium Anomaly, LSND.

- Other possibilities (not incompatible):

  - Very light sterile neutrinos with mass scale $\ll 1\,\mathrm{eV}$: important for solar neutrino phenomenology

    [de Holanda, Smirnov, PRD 69 (2004) 113002; PRD 83 (2011) 113011]

    [Das, Pulido, Picariello, PRD 79 (2009) 073010]

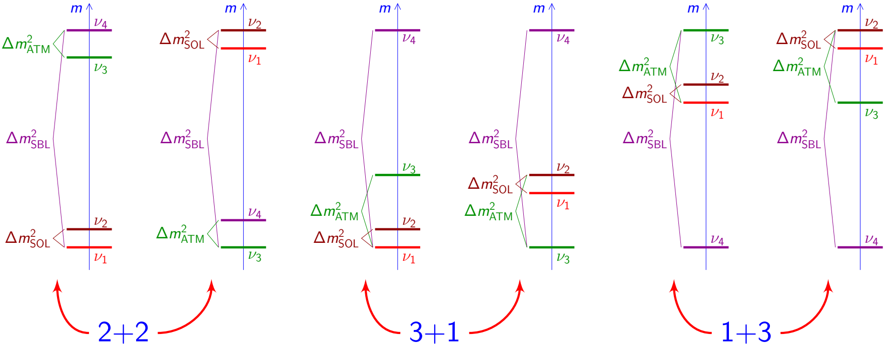
    Recent Daya Bay constraints for $10^{-3} \lesssim \Delta m^2 \lesssim 10^{-1}\,\mathrm{eV}^2$ [PRL 113 (2014) 141802]

  - Heavy sterile neutrinos with mass scale $\gg 1\,\mathrm{eV}$: could be Warm Dark Matter

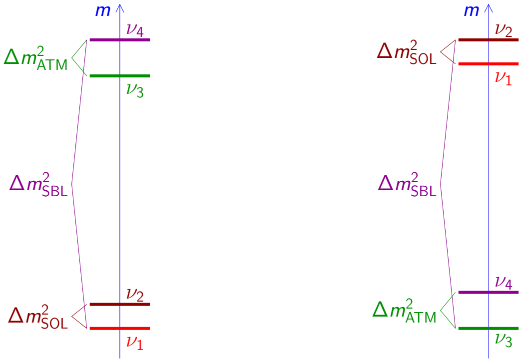
    [Asaka, Blanchet, Shaposhnikov, PLB 631 (2005) 151; Asaka, Shaposhnikov, PLB 620 (2005) 17; Asaka, Shaposhnikov, Kusenko, PLB 638 (2006) 401; Asaka, Laine, Shaposhnikov, JHEP 0606 (2006) 053, JHEP 0701 (2007) 091]

    [Reviews: Kusenko, Phys. Rept. 481 (2009) 1; Boyarsky, Ruchayskiy, Shaposhnikov, Ann. Rev. Nucl. Part. Sci. 59 (2009) 191; Boyarsky, Iakubovskyi, Ruchayskiy, Phys. Dark Univ. 1 (2012) 136; Drewes, IJMPE, 22 (2013) 1330019]

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



# 2+2 Four-Neutrino Schemes

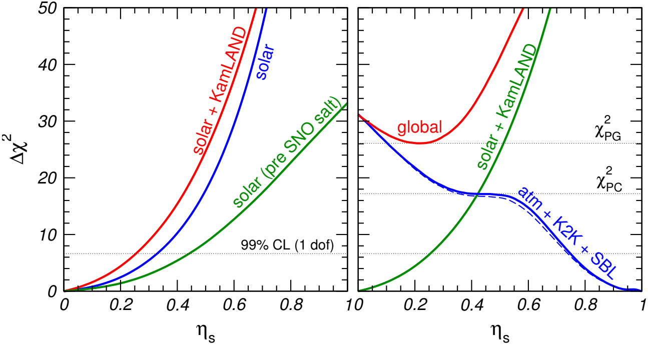



- After LSND (1995) 2+2 was preferred to 3+1, because of the 3+1 appearance-disappearance tension

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

- This is not a perturbation of 3-$\nu$ Mixing $\Longrightarrow$ Large active–sterile oscillations for solar or atmospheric neutrinos!

# 2+2 Schemes are Strongly Disfavored




Solar: Matter Effects + SNO NC

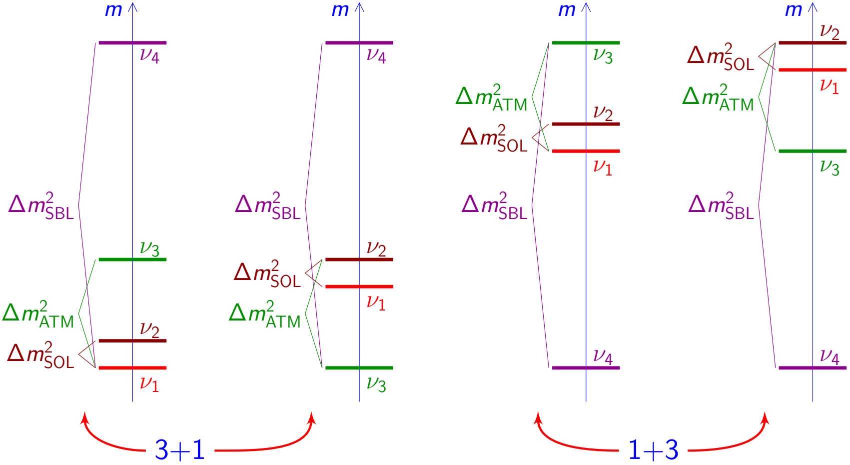
Atmospheric: Matter Effects

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

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

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

# 3+1 and 1+3 Four-Neutrino Schemes




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

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

[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

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

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

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

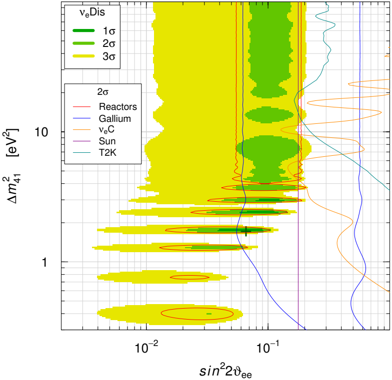
SBL

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

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

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



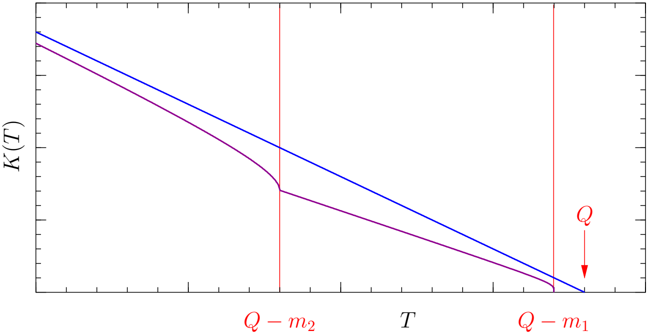

- KARMEN+LSND $\nu_e$–$^{12}$C
  [Conrad, Shaevitz, PRD 85 (2012) 013017]
  [CG, Laveder, PLB 706 (2011) 20]
- Solar $\nu_e$ + KamLAND $\bar{\nu}_e$
  [Li et al, PRD 80 (2009) 113007, PRD 86 (2012) 113014]
  [Palazzo, PRD 83 (2011) 113013, PRD 85 (2012) 077301]
- T2K Near Detector $\nu_e$ disappearance
  [T2K, PRD 91 (2015) 051102]
- $\Delta\chi^2_{\text{NO}}/\text{NDF}_{\text{NO}} = 14.1/2 \Rightarrow \approx 3.3\sigma$ anom.
- Best Fit: $\Delta m^2_{41} = 1.7\,\text{eV}^2$
  $\sin^2 2\vartheta_{ee} = 0.066 \quad \Leftrightarrow \quad |U_{e4}|^2 = 0.017$
- $\chi^2_{\text{min}}/\text{NDF} = 163.0/174 \Rightarrow \text{GoF} = 71\%$

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

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

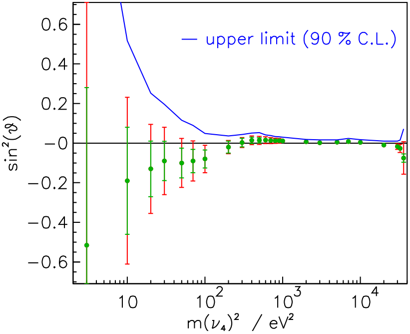
Kurie function: $$K(T) = \left[ (Q-T) \sum_k |U_{ek}|^2 \sqrt{(Q-T)^2 - m_k^2} \right]^{1/2}$$

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

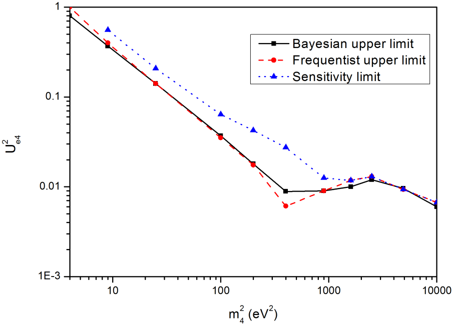


# Mainz and Troitsk Limit on $\Delta m^2_{41} \simeq m^2_4$

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



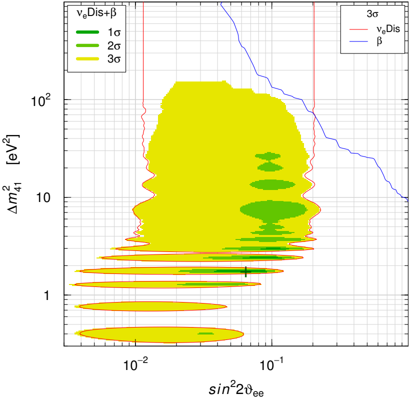

[Kraus, Singer, Valerius, Weinheimer, EPJC 73 (2013) 2323]




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

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

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

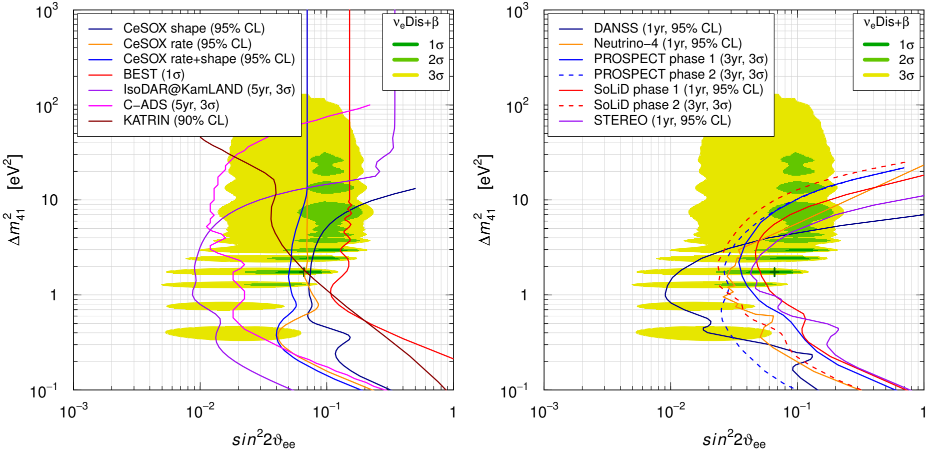



- Best Fit: $\Delta m^2_{41} = 1.7\,\text{eV}^2$
  $\sin^2 2\vartheta_{ee} = 0.066 \quad \Leftrightarrow \quad |U_{e4}|^2 = 0.017$

- $2\,\text{cm} \lesssim \dfrac{L^{\text{osc}}_{41}}{E\,[\text{MeV}]} \lesssim 7\,\text{m}$ 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) $^{144}\text{Ce} \to \bar{\nu}_e$
BOREXINO: $L \simeq$ 5-12m [Vivier@TAUP2015]

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

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

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

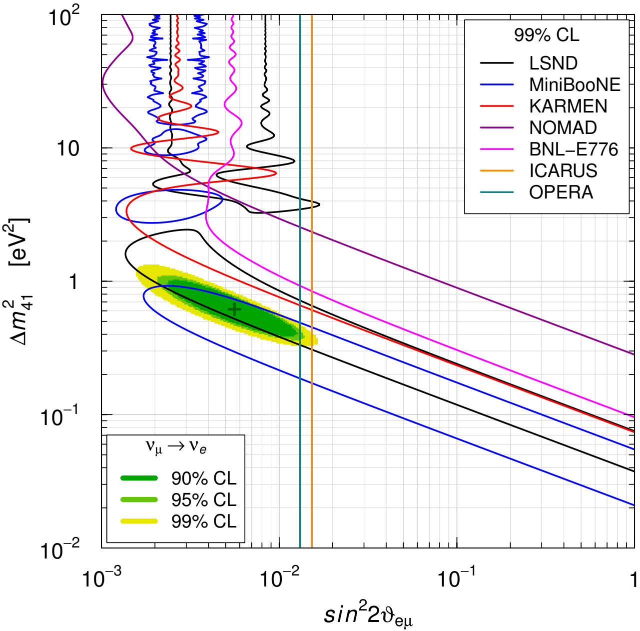
PROSPECT (ORNL, USA) $L \simeq$ 7-12m [arXiv:1512.02202]

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

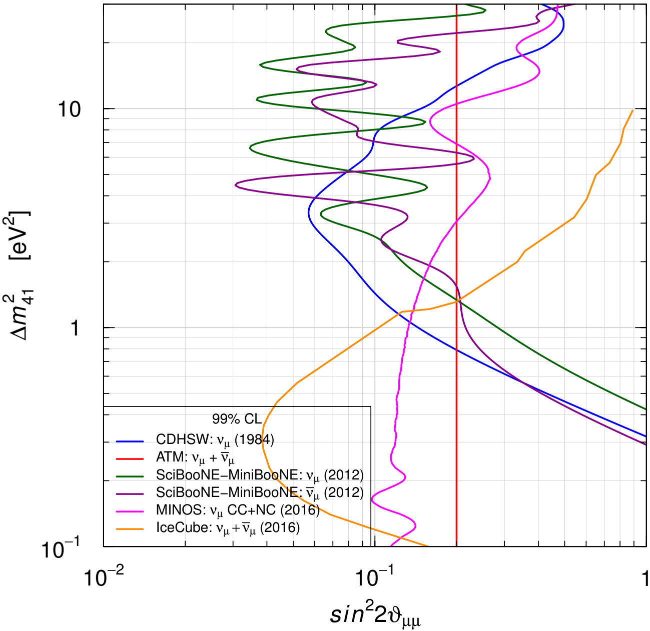
STEREO (ILL, France) $L \simeq$ 8-12m [arXiv:1602.00568]

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

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



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



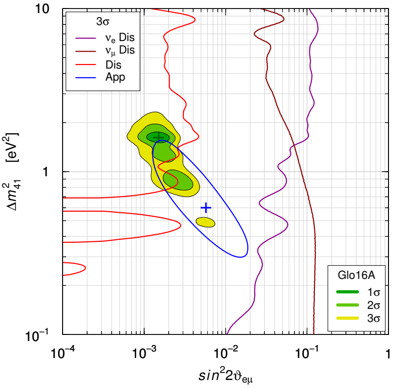
# 3+1 Appearance-Disappearance Tension

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

$\nu_\mu$ 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, JHEP 1706 (2017) 135]
- $\Delta\chi^2_{\rm NO}/{\rm NDF_{NO}} = 53.1/3 \Rightarrow \approx 6.7\sigma$ anom.
- Best Fit: $\Delta m^2_{41} = 1.6\,{\rm eV}^2$
  $|U_{e4}|^2 = 0.027 \quad |U_{m4}|^2 = 0.015$
- $\chi^2_{\rm min}/{\rm NDF} = 288.4/250 \Rightarrow {\rm GoF} = 4.8\%$
- $\chi^2_{\rm PG}/{\rm NDF_{PG}} = 13.4/2 \Rightarrow {\rm GoF_{PG}} = 0.13\%$
- Similar tension in 3+2, 3+3, ..., 3+$N_s$
  [CG, Zavanin, MPLA 31 (2015) 1650003]

# Goodness of Fit

- Assumption or approximation: Gaussian uncertainties and linear model
- $\chi^2_{\text{min}}$ has $\chi^2$ distribution with Number of Degrees of Freedom

$$\text{NDF} = N_{\text{D}} - N_{\text{P}}$$

$N_{\text{D}}$ = Number of Data $\qquad$ $N_{\text{P}}$ = Number of Fitted Parameters

- $\langle \chi^2_{\text{min}} \rangle = \text{NDF}$ $\qquad$ $\text{Var}(\chi^2_{\text{min}}) = 2\text{NDF}$
- $\text{GoF} = \displaystyle\int_{\chi^2_{\text{min}}}^{\infty} p_{\chi^2}(z, \text{NDF})\, \mathrm{d}z$ $\qquad$ $p_{\chi^2}(z, n) = \dfrac{z^{n/2-1} e^{-z/2}}{2^{n/2}\Gamma(n/2)}$

# Parameter Goodness of Fit

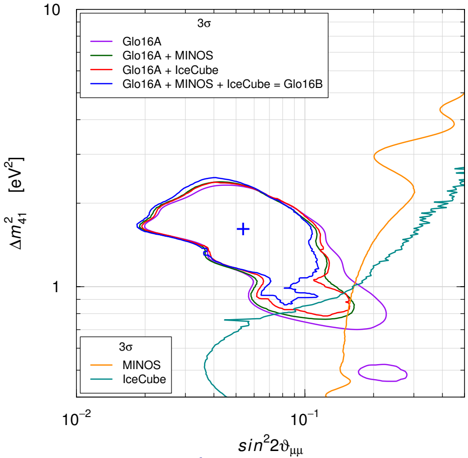
Maltoni, Schwetz, PRD 68 (2003) 033020 (arXiv:hep-ph/0304176)

- Measure compatibility of two (or more) sets of data points $A$ and $B$ under fitting model
- $\chi^2_{\text{PGoF}} = (\chi^2_{\text{min}})_{\text{A+B}} - [(\chi^2_{\text{min}})_{\text{A}} + (\chi^2_{\text{min}})_{\text{B}}]$
- $\chi^2_{\text{PGoF}}$ has $\chi^2$ distribution with Number of Degrees of Freedom

$$\text{NDF}_{\text{PGoF}} = N_{\text{P}}^{\text{A}} + N_{\text{P}}^{\text{B}} - N_{\text{P}}^{\text{A+B}}$$

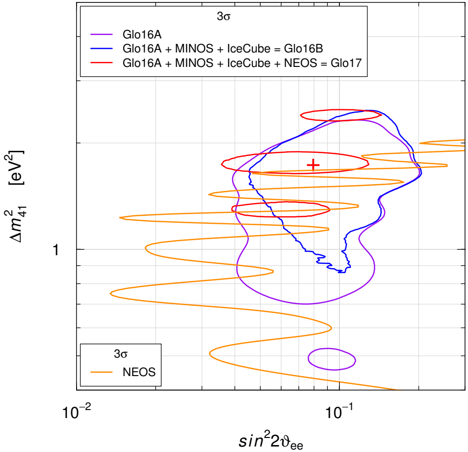
- $\text{PGoF} = \displaystyle\int_{\chi^2_{\text{PGoF}}}^{\infty} p_{\chi^2}(z, \text{NDF}_{\text{PGoF}})\, \mathrm{d}z$

# Effects of MINOS and IceCube



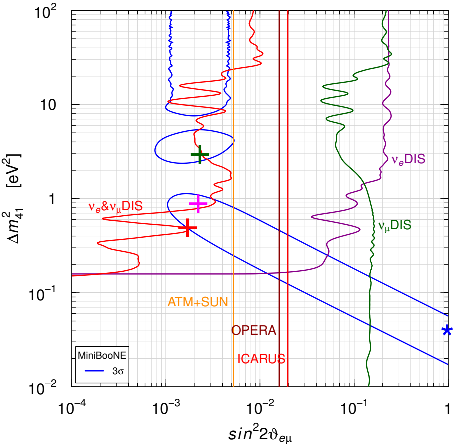

- IceCube effect in agreement with
  Collin, Arguelles, Conrad, Shaevitz, PRL 117 (2016) 221801
- Best Fit: $\Delta m^2_{41} = 1.6\,\text{eV}^2$ $\quad |U_{e4}|^2 = 0.028$ $\quad |U_{\mu 4}|^2 = 0.014$
- $\chi^2_{\text{min}}/\text{NDF} = 556.9/525 \Rightarrow \text{GoF} = 16\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 14.4/2 \Rightarrow \text{GoF}_{\text{PG}} = 0.075\%$ $\quad \leftarrow$ Strong tension!

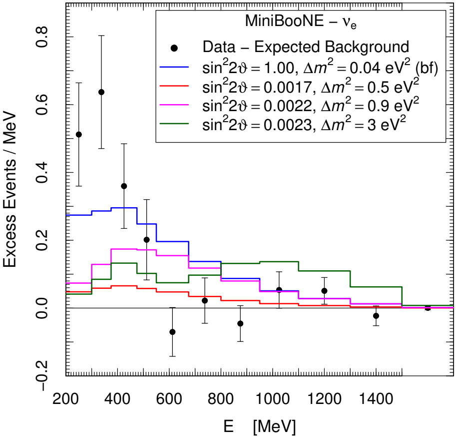
# Effects of NEOS




- Best Fit: $\Delta m^2_{41} = 1.7\,\text{eV}^2$ $|U_{e4}|^2 = 0.021$ $|U_{\mu 4}|^2 = 0.016$
- $\chi^2_{\text{min}}/\text{NDF} = 622.1/585 \Rightarrow \text{GoF} = 14\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 17.2/2 \Rightarrow \text{GoF}_{\text{PG}} = 0.019\%$ $\leftarrow$ Strong tension!

# MiniBooNE Low-Energy Anomaly




- Fit of MB low-energy excess requires small $\Delta m^2_{41}$ and large $\sin^2 2\vartheta_{e\mu}$, in contradiction with disappearance data.
- Multinucleon effects in neutrino energy reconstruction are not enough to solve the problem [Martini, Ericson, Chanfray, PRD 85 (2012) 093012; PRD 87 (2013) 013009; Ericson, Garzelli, CG, Martini, PRD 93 (2016) 073008]

# Neutrino energy reconstruction problem?

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

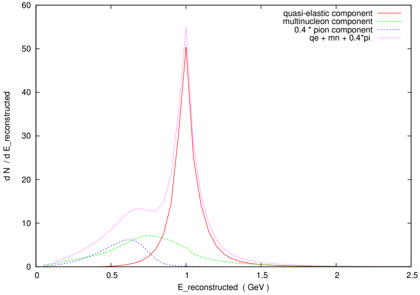
- Effect due to multinucleon interactions whose signal is indistinguishable from that due to quasielastic charged-current scattering

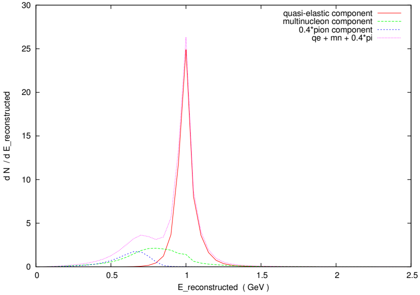
$$\nu_e + n \to p + e^- \qquad\qquad \bar{\nu}_e + p \to n + e^+$$

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

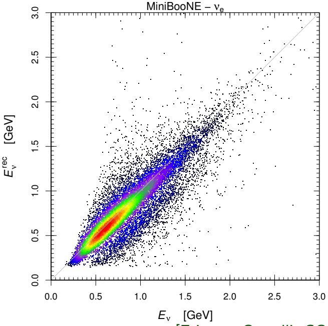
$$E_\nu^{\rm QE} = \frac{2\,(M_{\rm i} - E_{\rm B})\,E_e - \left(m_e^2 - 2M_{\rm i}E_{\rm B} + E_{\rm B}^2 + \Delta M_{\rm if}^2\right)}{2\,(M_{\rm i} - E_{\rm B} - E_e + p_e\cos\theta_e)}$$

- 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 $\pi^+$ absorbed by a nucleus)

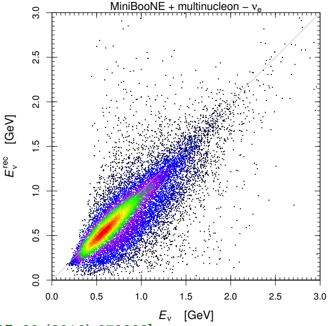


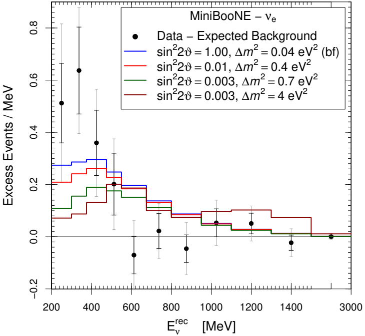

## MiniBooNE $\nu_\mu \to \nu_e$ full transmutation Monte Carlo events

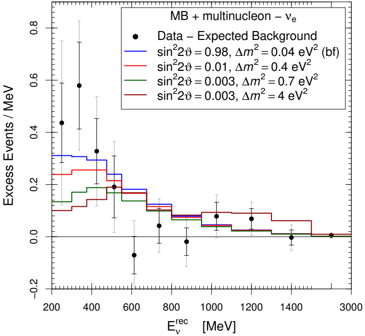


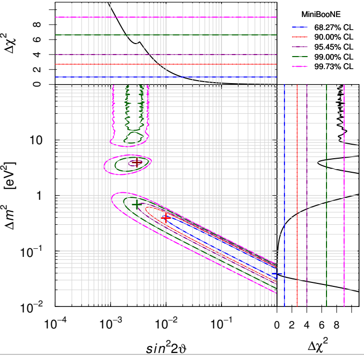

$\to$

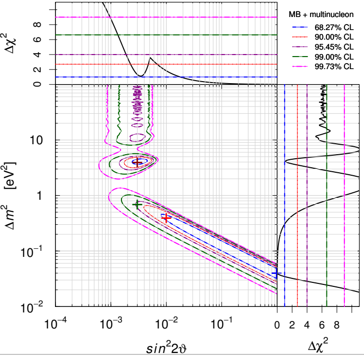


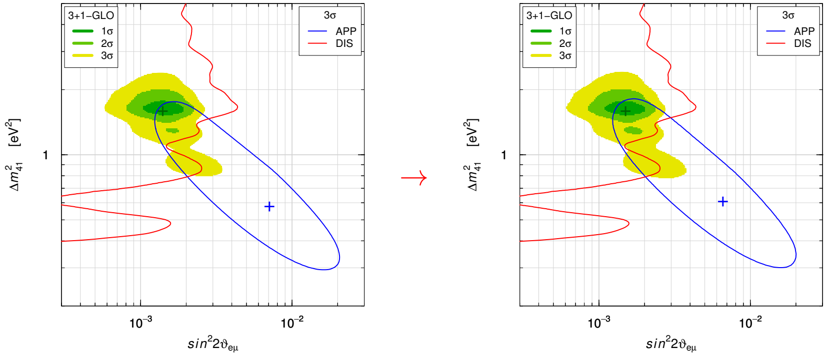

[Ericson, Garzelli, CG, Martini, PRD 93 (2016) 073008]


MiniBooNE – $\nu_e$
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
$E_\nu^{rec}$ [MeV]


MB + multinucleon – $\nu_e$
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
$E_\nu^{rec}$ [MeV]


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


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

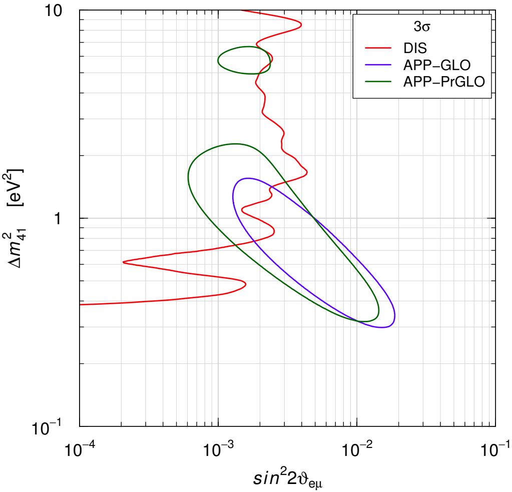



GoF = 7% PGoF = 0.2% GoF = 7% PGoF = 0.2%

- 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 $\rightarrow$ Pragmatic

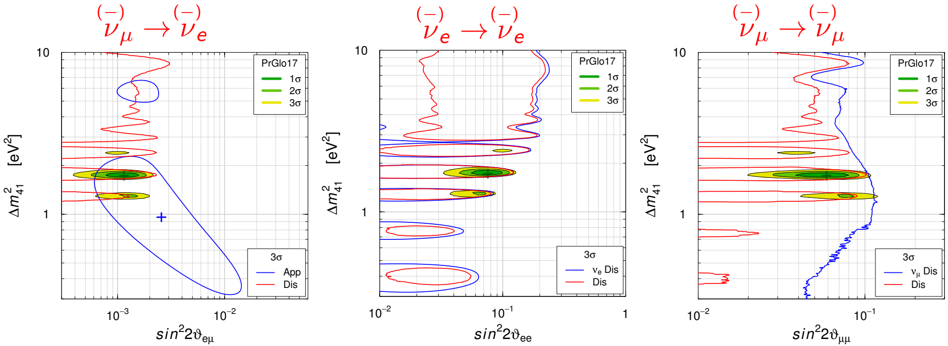
[CG, Laveder, Li, Long, PRD 88 (2013) 073008]



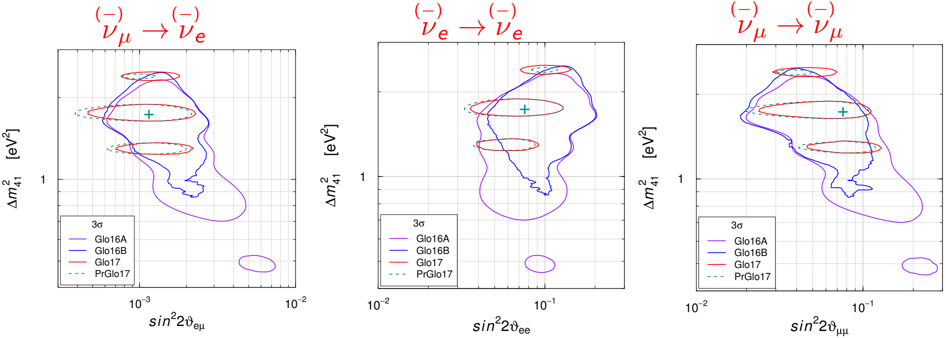

- APP-GLO: all MiniBooNE data
- APP-PrGLO: only MiniBooNE $E > 475\,\text{MeV}$ data (Pragmatic)

# Pragmatic Global 3+1 Fit

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

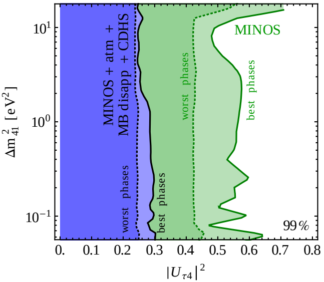



- $\Delta\chi^2_{\text{NO}}/\text{NDF}_{\text{NO}} = 47.4/4 \Rightarrow \approx 6.1\sigma$ anomaly
- Best Fit: $\Delta m^2_{41} = 1.7\,\text{eV}^2$ $|U_{e4}|^2 = 0.020$ $|U_{\mu4}|^2 = 0.015$
- $\chi^2_{\text{min}}/\text{NDF} = 595.1/579 \Rightarrow \text{GoF} = 31\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 7.2/2 \Rightarrow \text{GoF}_{\text{PG}} = 2.7\%$ $\leftarrow$ Mild tolerable tension!

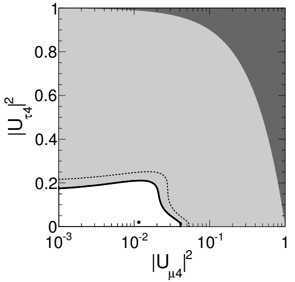


$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$
$\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$
$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$
$\Delta m^2_{41}$ [eV$^2$]
1
3σ
Glo16A
Glo16B
Glo17
PrGlo17
$10^{-3}$
$10^{-2}$
$10^{-1}$
$sin^2 2\vartheta_{e\mu}$
$sin^2 2\vartheta_{ee}$
$sin^2 2\vartheta_{\mu\mu}$

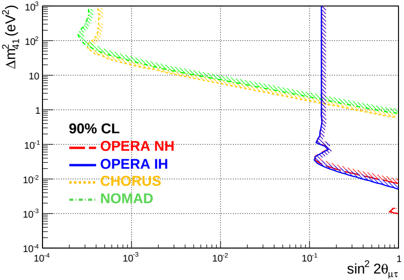
# Bounds on $|U_{\tau 4}|^2$



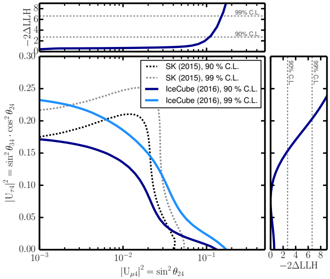

[Kopp et al, JHEP 1305 (2013) 050]




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



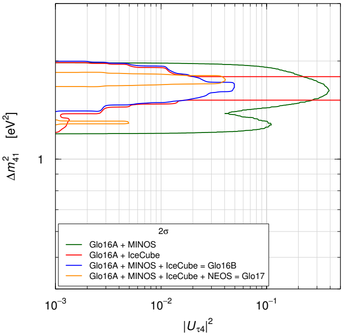

$\nu_\mu \to \nu_\tau$ [OPERA, JHEP 1506 (2015) 069]

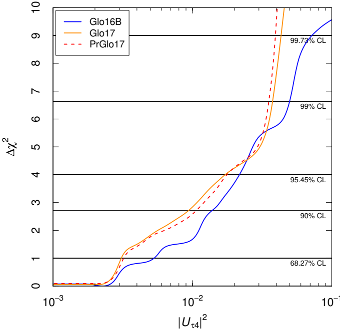



[IceCube DeepCore, arXiv:1702.05160]

MINOS and IceCube data give information on $|U_{\tau 4}|^2$:

- MINOS: neutral-current event sample
- IceCube: matter effects for high-energy neutrinos propagating in the Earth.



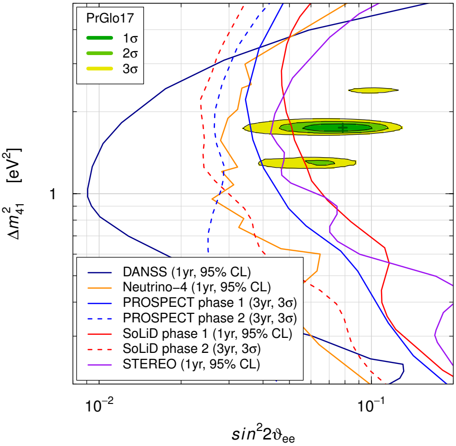

90% CL:

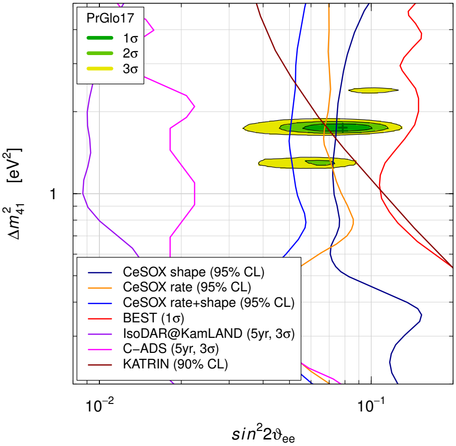
| | |
|---|---|
| Glo16A + MINOS: | $\vartheta_{34} < 27^\circ$ |
| Glo16A + IceCube: | $\vartheta_{34} < 7.4^\circ$ |
| Glo16B: | $\vartheta_{34} < 7.4^\circ$ |
| Glo17: | $\vartheta_{34} < 5.6^\circ$ |
| PrGlo17: | $\vartheta_{34} < 6^\circ$ |

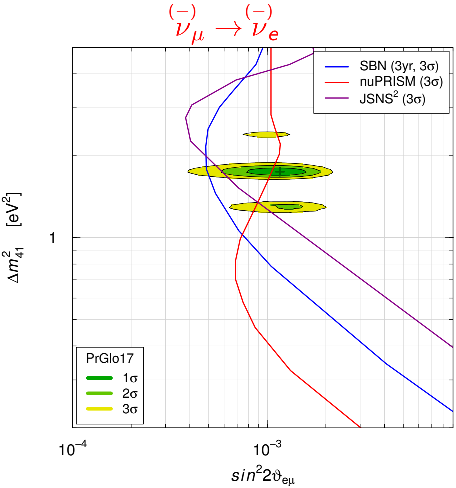
[Gariazzo, CG, Laveder, Li, JHEP 1706 (2017) 135]

# The Race for the Light Sterile

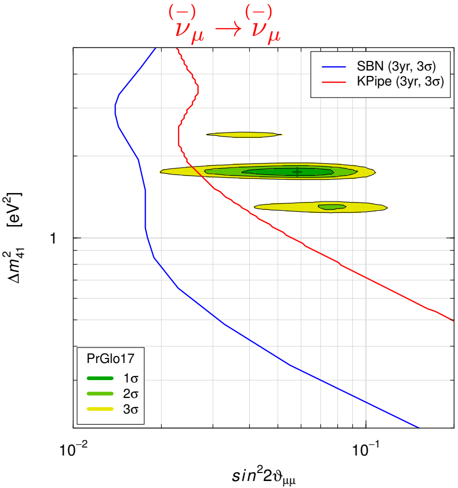
$$\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$$



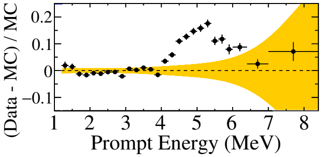


$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$
SBN (3yr, 3σ)
nuPRISM (3σ)
JSNS$^2$ (3σ)
PrGlo17
1σ
2σ
3σ
$\Delta m^2_{41}$ [eV$^2$]
1
$10^{-4}$
$10^{-3}$
$sin^2 2\vartheta_{e\mu}$

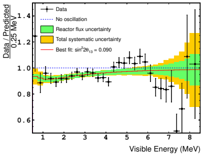



$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$
SBN (3yr, 3σ)
KPipe (3yr, 3σ)
PrGlo17
1σ
2σ
3σ
$\Delta m^2_{41}$ [eV$^2$]
1
$10^{-2}$
$10^{-1}$
$sin^2 2\vartheta_{\mu\mu}$

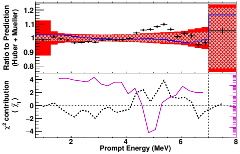
# Reactor Antineutrino 5 MeV Bump




[RENO, arXiv:1511.05849]

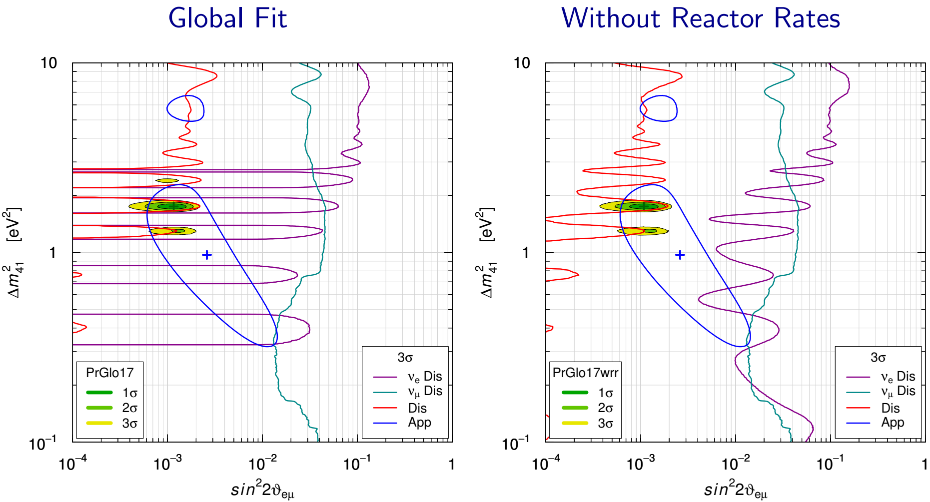



[Double Chooz, arXiv:1406.7763]




[Daya Bay, arXiv:1508.04233]

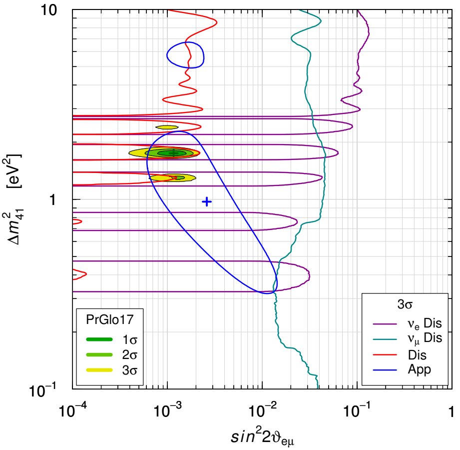
- Cannot be explained by neutrino oscillations (SBL oscillations are averaged in Double Chooz, Daya Bay, RENO).
- Very likely due to theoretical miscalculation of the spectrum.
- $\sim 3\%$ effect on total flux, but if it is an excess it increases the anomaly!
- No post-bump complete calculation of the 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]

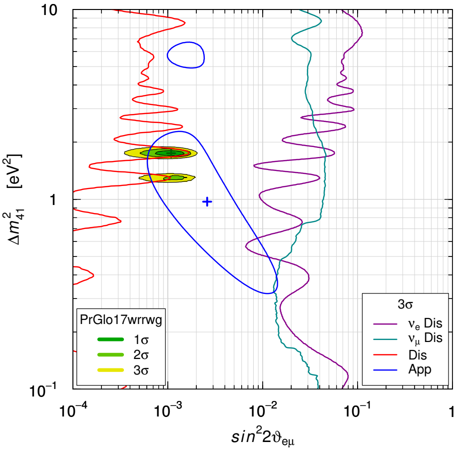



The Reactor Antineutrino Anomaly has small impact on the global fit.

# Global Fit

# Without Reactor Rates and Gallium Data

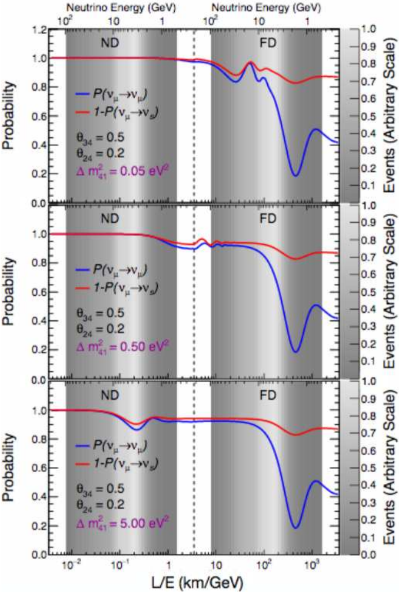


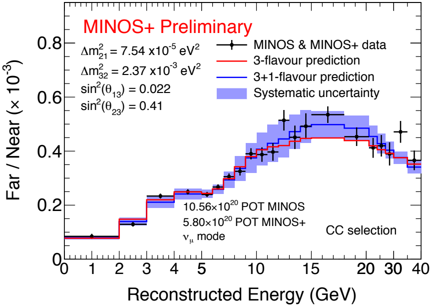



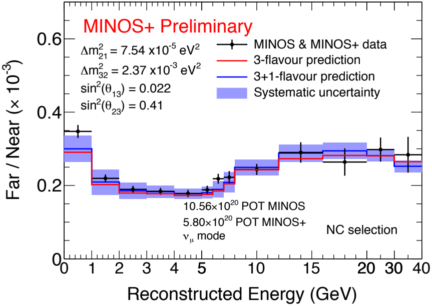

Given the current constraints, only the LSND signal is crucial for a positive indication in favor of active-sterile SBL oscillations.

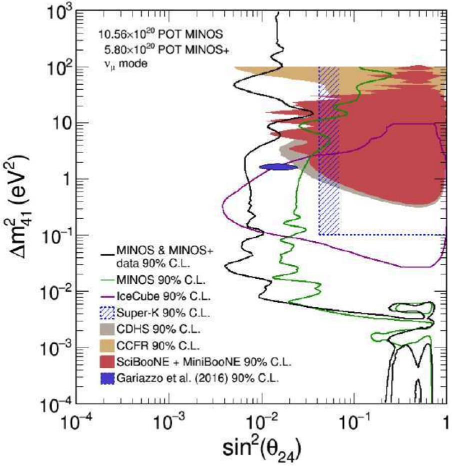
# Preliminary Bound from MINOS & MINOS+

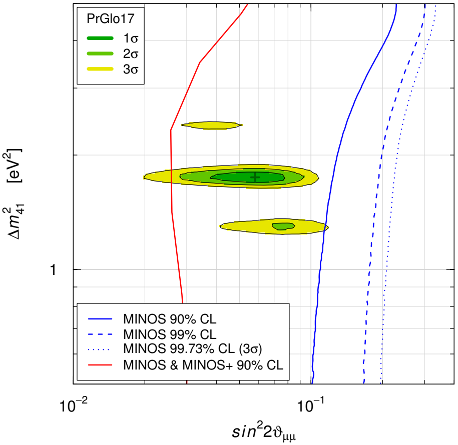
[Flanagan @ PPC2017]



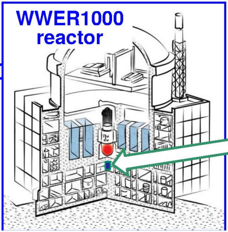

10.56×10^20 POT MINOS
5.80×10^20 POT MINOS+
νμ mode
MINOS & MINOS+ data 90% C.L.
MINOS 90% C.L.
IceCube 90% C.L.
Super-K 90% C.L.
CDHS 90% C.L.
CCFR 90% C.L.
SciBooNE + MiniBooNE 90% C.L.
Gariazzo et al. (2016) 90% C.L.
$\Delta m^2_{41}$ (eV$^2$)
$\sin^2(\theta_{24})$

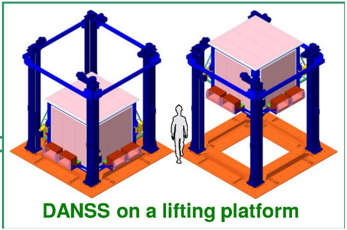

PrGlo17
1σ
2σ
3σ
MINOS 90% CL
MINOS 99% CL
MINOS 99.73% CL (3σ)
MINOS & MINOS+ 90% CL
$\Delta m^2_{41}$ [eV$^2$]
$sin^2 2\vartheta_{\mu\mu}$

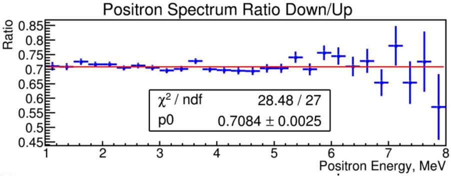
# Preliminary Bound from DANSS

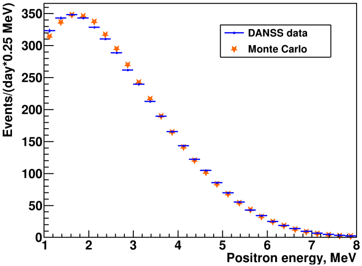
[Danilov @ Moriond EW 2017, Svirida @ WIN2017, Danilov @ EPS-HEP 2017]

**Detector of reactor AntiNeutrino based on Solid Scintillator**

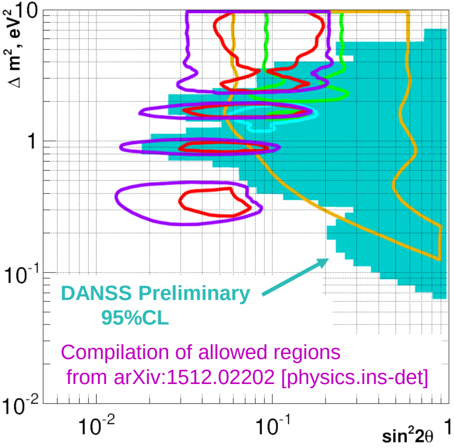



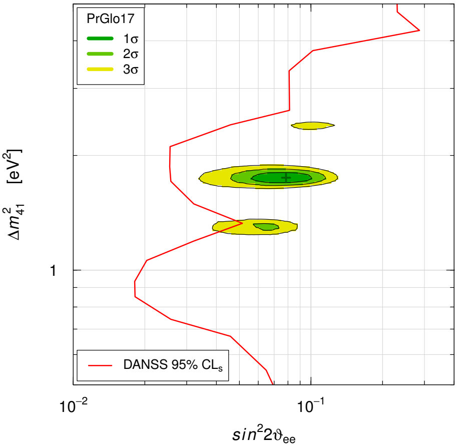




Up = 10.7 m    Down = 12.7 m

No 5 MeV bump!

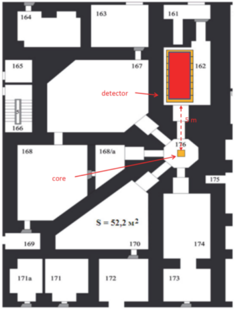

Δ m², eV²
10
1
10⁻¹
10⁻²
10⁻²
10⁻¹
1
sin²2θ
DANSS Preliminary
95%CL
Compilation of allowed regions
from arXiv:1512.02202 [physics.ins-det]

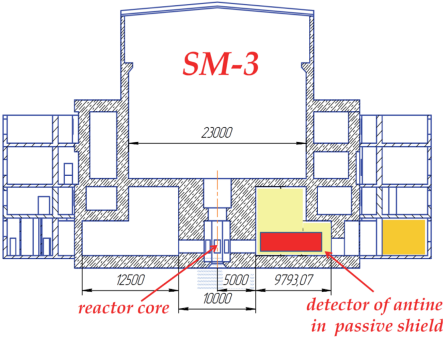

PrGlo17
1σ
2σ
3σ
DANSS 95% CLs
Δm²₄₁ [eV²]
1
10⁻²
10⁻¹
sin²2ϑee

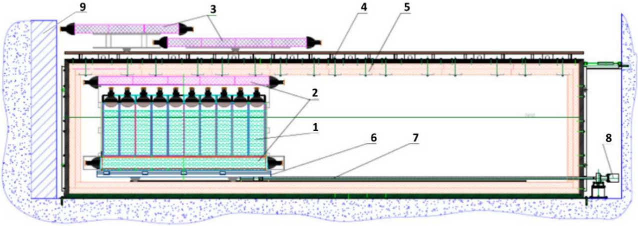
# Results of Neutrino-4

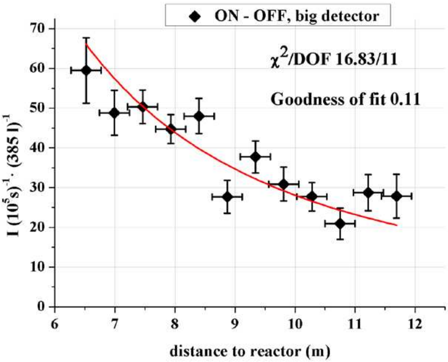
[arXiv:1708.00421]

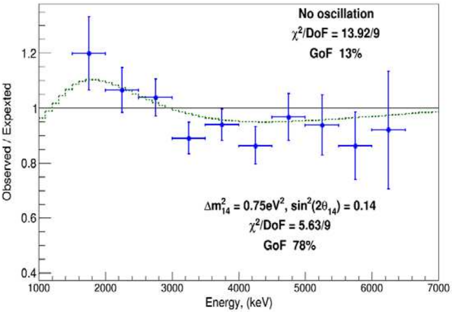
**Reactor:** SM-3 reactor in Dimitrovgrad (Russia): 100 MW compact core 35x42x42 cm$^3$





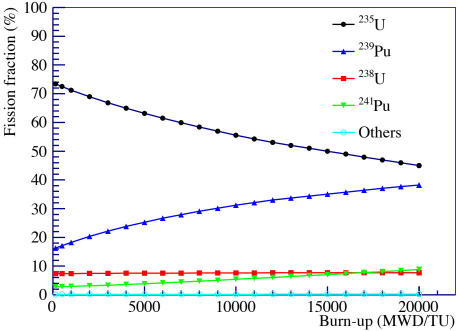




- If the green curve corresponds to oscillations it seems wrong.
- No 5 MeV bump! Covered by oscillations? I think unlikely because it would need a too large oscillation amplitude.
- Maybe the 5 MeV bump is not due to $^{235}$U?
  - 5 MeV bump seen in power reactors with effective fuel fractions $F(^{235}\text{U}) \approx 0.55 \qquad F(^{238}\text{U}) \approx 0.08 \qquad F(^{239}\text{Pu}) \approx 0.31 \qquad F(^{241}\text{Pu}) \approx 0.06$
  - SM-3 is a research reactor with highly enriched $^{235}$U fuel:
  $$F(^{235}\text{U}) \approx 1 \qquad F(^{238}\text{U}) \approx F(^{239}\text{Pu}) \approx F(^{241}\text{Pu}) \approx 0$$

# 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 $^{235}$U, $^{238}$U, $^{239}$Pu, $^{241}$Pu.

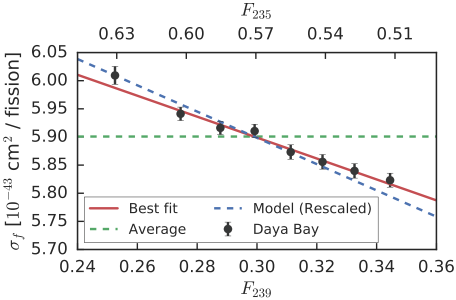


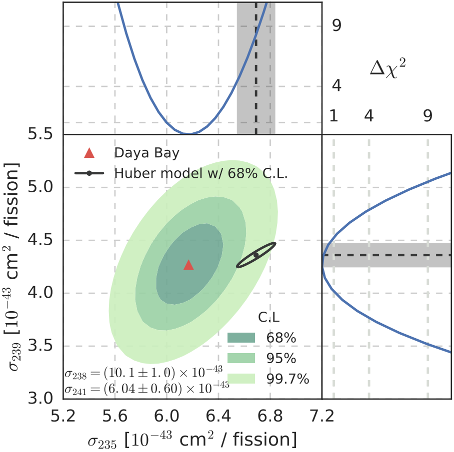

- Cross section per fission:

$$\sigma_f = \sum_{i=235,238,239,241} F_i \, \sigma_{f,i}$$

- Effective fission fractions:

$$F_{235}, \; F_{238}, \; F_{239}, \; F_{241}.$$






- Best fit: suppression of $\sigma_{f,235}$.

- Equal fluxes suppression:
$$\Delta\chi^2/\mathrm{NDF} = 7.9/1$$
disfavored at $2.8\sigma$.

- Equal fluxes suppression corresponds to SBL oscillations, but theoretical flux uncertainties must be taken into account.

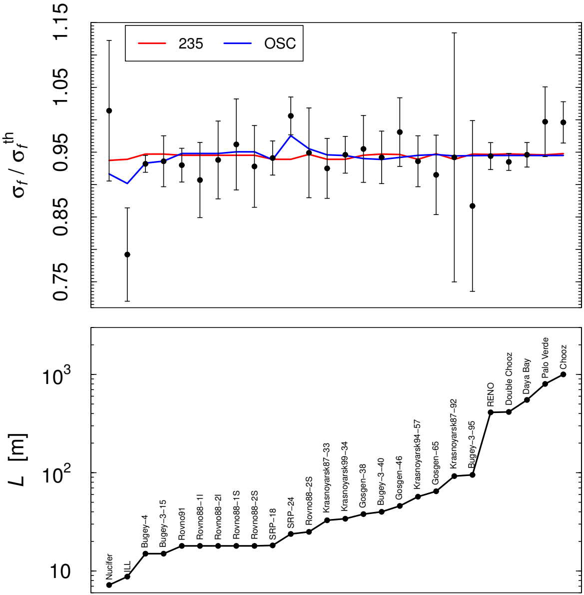
With theoretical flux uncertainties:

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

MC: OSC disfavored at $2.6\sigma$

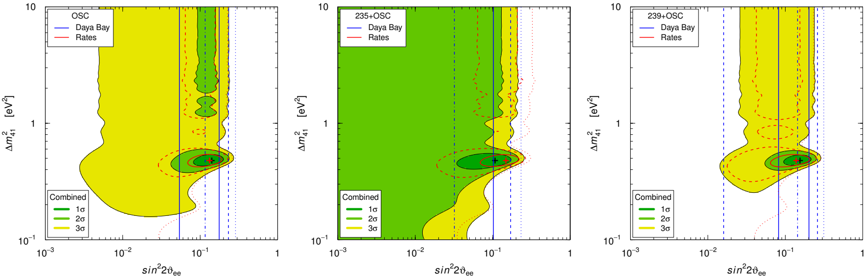
| All Reactors | $^{235}$U | OSC |
|---|---|---|
| $\chi^2_{\rm min}$ | 25.3 | 23.0 |
| NDF | 32 | 31 |
| GoF | 79% | 85% |

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




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

| | $^{235}$U | $^{235}$U + $^{239}$U | OSC | $^{235}$U+OSC | $^{239}$U+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% |
| $\Delta m^2_{41}$ | — | — | 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 |




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

# Effective SBL Oscillation Probabilities in 3+2 Schemes

$$\Delta_{kj} = \Delta m^2_{kj} L / 4E$$

$$\eta = \arg[U^*_{e4} U_{\mu 4} U_{e5} U^*_{\mu 5}]$$

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\Delta_{41} + 4|U_{e5}|^2|U_{\mu 5}|^2 \sin^2\Delta_{51} + 8|U_{\mu 4} U_{e4} U_{\mu 5} U_{e5}| \sin\Delta_{41} \sin\Delta_{51} \cos(\Delta_{54} \overset{(+)}{-} \eta)$$

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} = 1 - 4(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2\Delta_{41} + |U_{\alpha 5}|^2 \sin^2\Delta_{51}) - 4|U_{\alpha 4}|^2|U_{\alpha 5}|^2 \sin^2\Delta_{54}$$

[Sorel, Conrad, Shaevitz, PRD 70 (2004) 073004; Maltoni, Schwetz, PRD 76 (2007) 093005; Karagiorgi et al, PRD 80 (2009) 073001; Kopp, Maltoni, Schwetz, PRL 107 (2011) 091801; Giunti, Laveder, PRD 84 (2011) 073008; Donini et al, JHEP 07 (2012) 161; Archidiacono et al, PRD 86 (2012) 065028; Jacques, Krauss, Lunardini, PRD 87 (2013) 083515; Conrad et al, AHEP 2013 (2013) 163897; Archidiacono et al, PRD 87 (2013) 125034; Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050; Giunti, Laveder, Y.F. Li, H.W. Long, PRD 88 (2013) 073008; Girardi, Meroni, Petcov, JHEP 1311 (2013) 146]

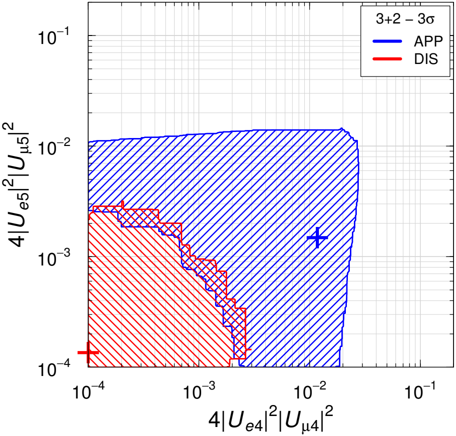
- Good: CP violation
- Bad: Two massive sterile neutrinos at the eV scale!

  4 more parameters: $\underbrace{\Delta m^2_{41}, |U_{e4}|^2, |U_{\mu 4}|^2}_{3+1}, \Delta m^2_{51}, |U_{e5}|^2, |U_{\mu 5}|^2, \eta$

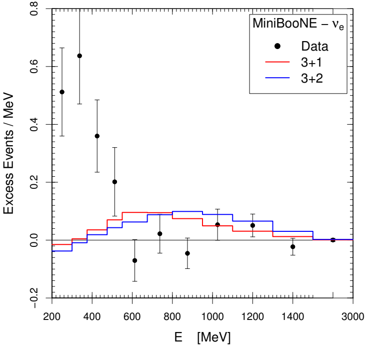
| Global Fits | Our Fit | | KMMS | |
|---|---|---|---|---|
| | 3+1 | 3+2 | 3+1 | 3+2 |
| GoF | 6% | 10% | 19% | 23% |
| PGoF | 0.06% | 0.3% | 0.01% | 0.003% |

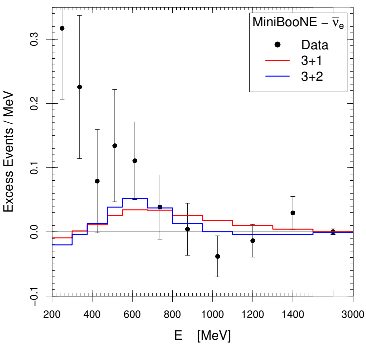
- Our Fit: Gariazzo, CG, Laveder, Li, Zavanin, JPG 43 (2016) 033001
- KMMS: Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050

APP-DIS 3+2 Tension:



# 3+2 cannot fit MiniBooNE Low-Energy Excess




- Note difference between 3+2 $\nu_e$ and $\bar{\nu}_e$ histograms due to CP violation
- 3+2 can fit slightly better the small $\bar{\nu}_e$ excess at about 600 MeV
- 3+2 fit of low-energy excess as bad as 3+1
- Claims that 3+2 can fit low-energy excess do not take into account constraints from other data
- Conclusion: 3+2 is not needed

# Appearance vs Disappearance in $N = 3 + N_s$ Mixing

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

$$\frac{\Delta m^2_{21} L}{4E} \ll \frac{\Delta m^2_{31} L}{4E} \ll 1$$

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \delta_{\alpha\beta} - 4 \sum_{k=4}^{N} |U_{\alpha k}|^2 \left( \delta_{\alpha\beta} - |U_{\beta k}|^2 \right) \sin^2 \Delta_{k1}$$
$$+8 \sum_{k=4}^{N} \sum_{j=k+1}^{N} |U_{\alpha j} U_{\beta j} U_{\alpha k} U_{\beta k}| \sin \Delta_{k1} \sin \Delta_{j1} \cos(\Delta_{jk} \overset{(+)}{-} \eta_{\alpha\beta jk})$$

$$\Delta_{jk} = \frac{\Delta m^2_{jk} L}{4E} \qquad \eta_{\alpha\beta jk} = \arg\left[ U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \right]$$

## Survival Probabilities

$$P^{\mathrm{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - 4 \sum_{k=4}^{N} |U_{\alpha k}|^2 \left(1 - |U_{\alpha k}|^2\right) \sin^2 \Delta_{k1}$$
$$+ 8 \sum_{k=4}^{N} \sum_{j=k+1}^{N} |U_{\alpha j}|^2 |U_{\alpha k}|^2 \sin \Delta_{j1} \sin \Delta_{k1} \cos \Delta_{jk}$$

Effective amplitude of $\overset{(-)}{\nu}_\alpha$ disappearance due to $\nu_\alpha - \nu_k$ mixing:

$$\sin^2 2\vartheta^{(k)}_{\alpha\alpha} = 4|U_{\alpha k}|^2 \left(1 - |U_{\alpha k}|^2\right) \simeq 4|U_{\alpha k}|^2$$

$$|U_{\alpha k}|^2 \ll 1 \qquad (\alpha = e, \mu, \tau; \quad k = 4, \ldots, N)$$

$$P^{\mathrm{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sum_{k=4}^{N} \sin^2 2\vartheta^{(k)}_{\alpha\alpha} \sin^2 \Delta_{k1}$$

## Appearance Probabilities ($\alpha \neq \beta$)

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq 4 \sum_{k=4}^{N} |U_{\alpha k}|^2 |U_{\beta k}|^2 \sin^2 \Delta_{k1} + 8 \sum_{k=4}^{N} \sum_{j=k+1}^{N} |U_{\alpha j} U_{\beta j} U_{\alpha k} U_{\beta k}| \sin \Delta_{k1} \sin \Delta_{j1} \cos(\Delta_{jk} \overset{(+)}{-} \eta_{\alpha\beta jk})$$

Effective amplitude of $\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta$ transitions due to $\nu_\alpha - \nu_k$ mixing:

$$\sin^2 2\vartheta^{(k)}_{\alpha\beta} = 4 |U_{\alpha k}|^2 |U_{\beta k}|^2$$

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sum_{k=4}^{N} \sin^2 2\vartheta^{(k)}_{\alpha\beta} \sin^2 \Delta_{k1} + 2 \sum_{k=4}^{N} \sum_{j=k+1}^{N} \sin 2\vartheta^{(k)}_{\alpha\beta} \sin 2\vartheta^{(j)}_{\alpha\beta} \sin \Delta_{k1} \sin \Delta_{j1} \cos(\Delta_{jk} \overset{(+)}{-} \eta_{\alpha\beta jk})$$

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

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

$$\boxed{\sin^2 2\vartheta_{\alpha\beta}^{(k)} \simeq \frac{1}{4} \sin^2 2\vartheta_{\alpha\alpha}^{(k)} \sin^2 2\vartheta_{\beta\beta}^{(k)}}$$

$$\left.\begin{array}{l} \sin^2 2\vartheta_{ee}^{(k)} \ll 1 \\ \sin^2 2\vartheta_{\mu\mu}^{(k)} \ll 1 \end{array}\right\} \Rightarrow \quad \sin^2 2\vartheta_{e\mu}^{(k)} \quad \text{is quadratically suppressed}$$

on the other hand, observation of $\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta$ transitions due to $\Delta m^2_{k1}$ imply that the corresponding $\overset{(-)}{\nu}_\alpha$ and $\overset{(-)}{\nu}_\beta$ disappearances must be observed

Effects of light sterile neutrinos should also be seen in:

- $\beta$ 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-$\beta$ 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, PRL 118 (2017) 031804; Kayser et al, JHEP 1511 (2015) 039, JHEP 1611 (2016) 122; 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]

# Effective 3+1 LBL Oscillation Probabilities

[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, PRL 118 (2017) 031804; Kayser et al, JHEP 1511 (2015) 039, JHEP 1611 (2016) 122]

$$|U_{e3}| \simeq \sin\vartheta_{13} \simeq 0.15 \sim \varepsilon \quad \Longrightarrow \quad \varepsilon^2 \sim 0.03$$

$$|U_{e4}| \simeq \sin\vartheta_{14} \simeq 0.17 \sim \varepsilon$$

$$|U_{\mu4}| \simeq \sin\vartheta_{24} \simeq 0.11 \sim \varepsilon$$

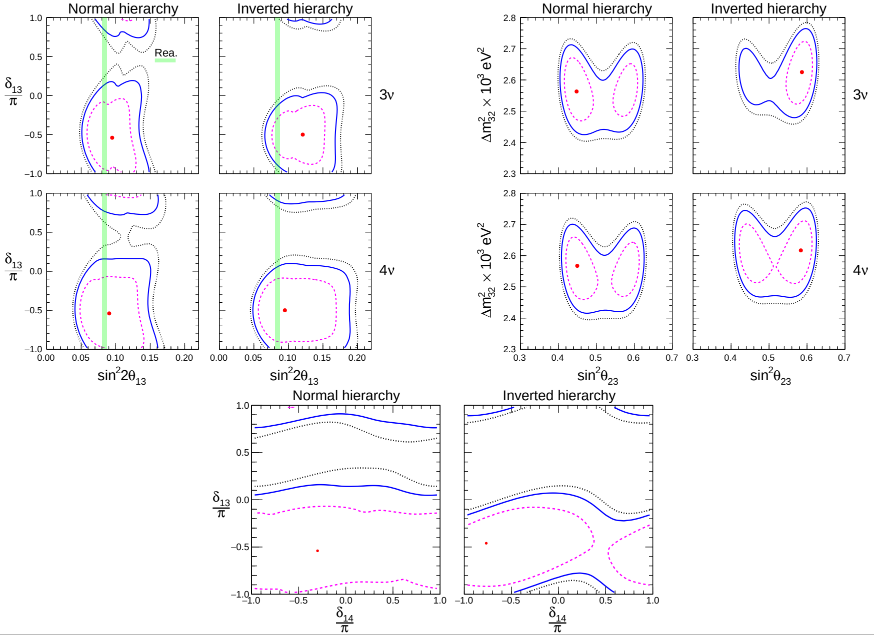
$$\alpha \equiv \frac{\Delta m^2_{21}}{|\Delta m^2_{31}|} \simeq \frac{7 \times 10^{-5}}{2.4 \times 10^{-3}} \simeq 0.031 \sim \varepsilon^2$$

At order $\varepsilon^3$: [Klop, Palazzo, PRD 91 (2015) 073017] $\Delta_{kj} \equiv \Delta m^2_{kj} L/4E$

$$\begin{aligned} P^{\text{LBL}}_{\nu_\mu\to\nu_e} \simeq\ & 4\sin^2\vartheta_{13}\sin^2\vartheta_{23}\sin^2\Delta_{31} && \sim \varepsilon^2 \\ & +2\sin\vartheta_{13}\sin 2\vartheta_{12}\sin 2\vartheta_{23}(\alpha\Delta_{31})\sin\Delta_{31}\cos(\Delta_{32}+\delta_{13}) && \sim \varepsilon^3 \\ & +4\sin\vartheta_{13}\sin\vartheta_{14}\sin\vartheta_{24}\sin\vartheta_{23}\sin\Delta_{31}\sin(\Delta_{31}+\delta_{13}-\delta_{14}) && \sim \varepsilon^3 \end{aligned}$$

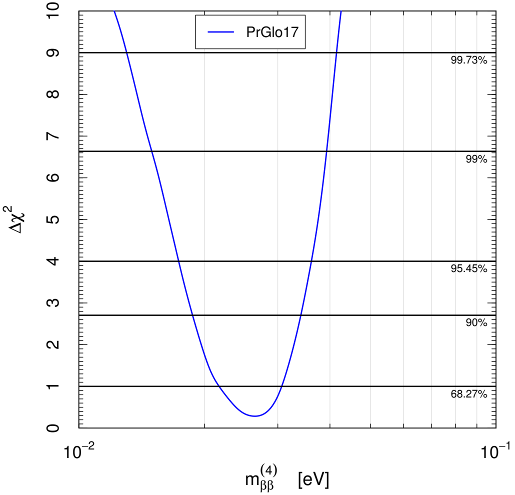
# CP Violation in T2K and NO$\nu$A

[Capozzi, CG, Laveder, Palazzo, PRD 95 (2017) 033006 (arXiv:1612.07764)]



# Neutrinoless Double-Beta Decay

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




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

$$m_1 \ll m_4$$

$$\Downarrow$$

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

warning:

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

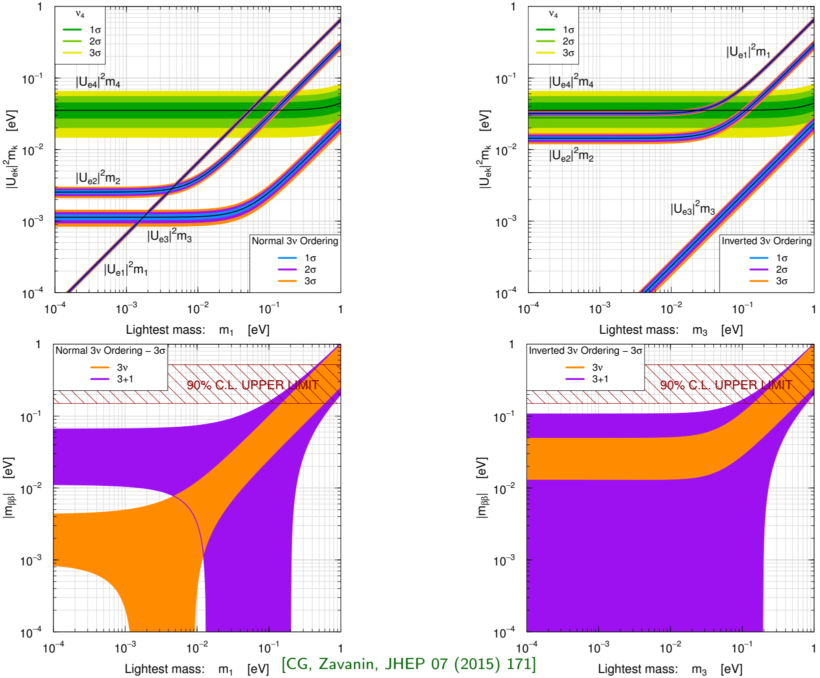

[Barry, Rodejohann, Zhang, JHEP 07 (2011) 091]

[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 sterile neutrinos (new physics!) at the eV scale:
  - LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ 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.
  - $\nu_\mu \to \nu_e$ 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 $m_4 \approx 1\,\text{eV}$. 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).