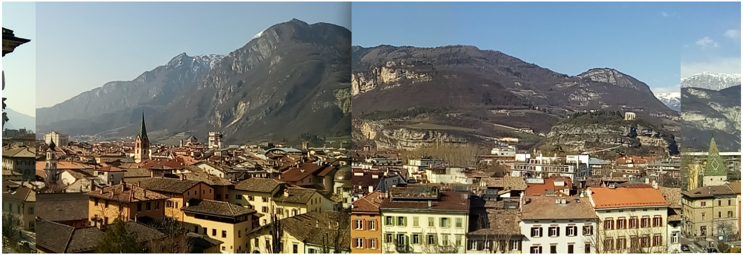
Short-Baseline Neutrino Oscillation Anomalies and Reactor Antineutrino Fluxes

Carlo Giunti

INFN, Torino, Italy

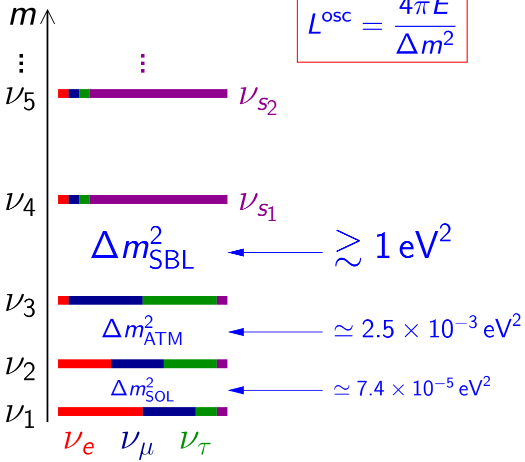
Determination of the Absolute Electron (Anti)-Neutrino Mass

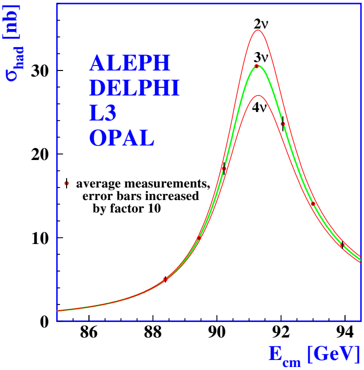
26-30 March 2018, ECT*, Trento, Italy



Beyond Three-Neutrino Mixing: Sterile Neutrinos

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





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

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-ν_R are light sterile neutrinos

$$\nu_R^c \to \nu_{sL} \qquad \text{(left-handed)}$$

- Sterile means no standard model interactions

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

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

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

Effective 3+1 SBL Oscillation Probabilities

Appearance ($\alpha \neq \beta$)

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

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

Disappearance

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

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

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

SBL

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

- CP violation is not observable in SBL experiments!
- Observable in LBL accelerator exp. sensitive to Δm^2_{ATM} [de Gouvea et al, PRD 91 (2015) 053005, PRD 92 (2015) 073012, arXiv:1605.09376; Palazzo et al, PRD 91 (2015) 073017, PLB 757 (2016) 142; Kayser et al, JHEP 1511 (2015) 039, JHEP 1611 (2016) 122] and solar exp. sensitive to Δm^2_{SOL} [Long, Li, CG, PRD 87, 113004 (2013) 113004]

3+1: Appearance vs Disappearance

- Amplitude of ν_e disappearance:

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

- Amplitude of ν_μ disappearance:

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

- Amplitude of $\nu_\mu \to \nu_e$ transitions:

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

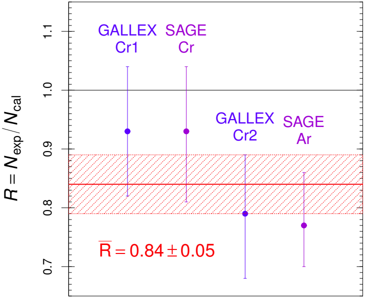
Gallium Anomaly

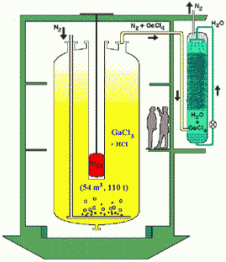
Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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

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





$\approx 2.9\sigma$ deficit

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

[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]

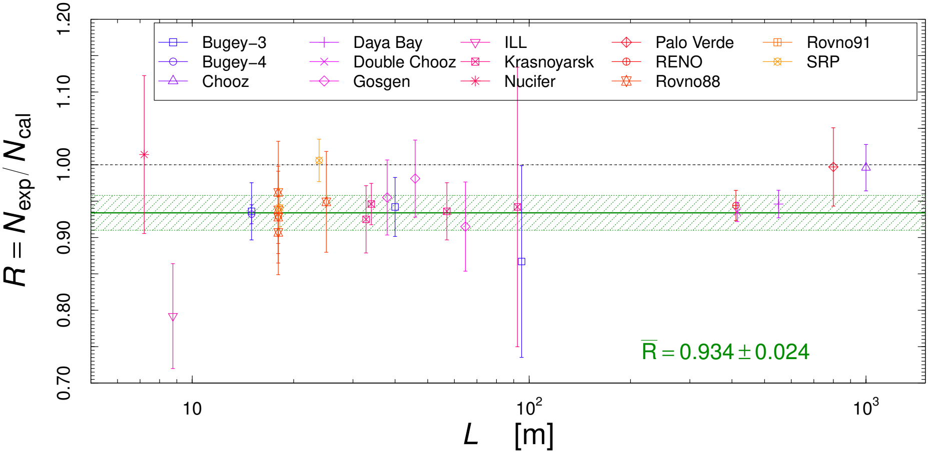
$$\Delta m^2_{\mathrm{SBL}} \gtrsim 1\,\mathrm{eV}^2 \gg \Delta m^2_{\mathrm{ATM}}$$

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

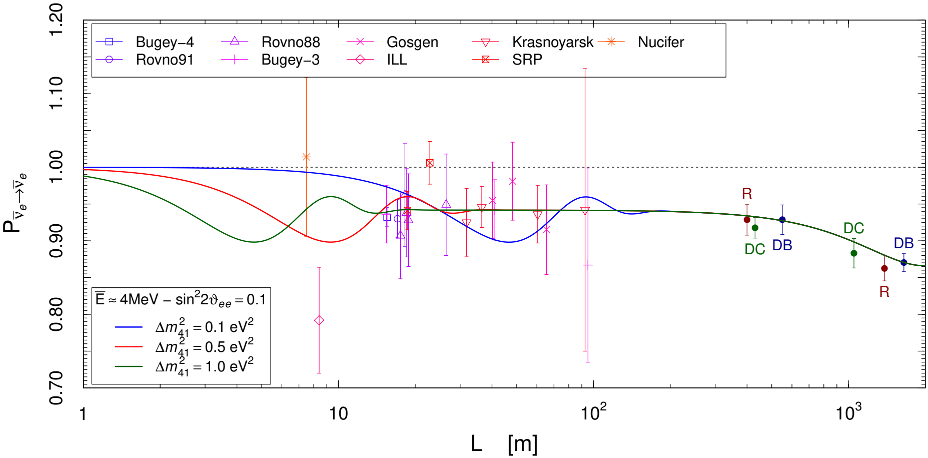
Reactor Electron Antineutrino Anomaly

[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]



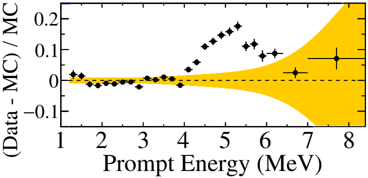
$\approx 2.8\sigma$ deficit



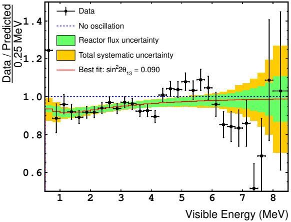
$$\Delta m^2_{\text{SBL}} \gtrsim 0.5\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}}$$

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

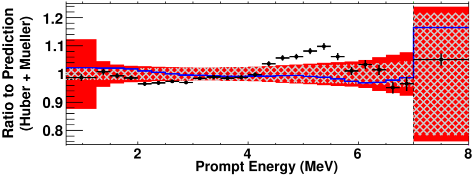
Reactor Antineutrino 5 MeV Bump



[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 RENO, DC, DB).
- It is likely due to a theoretical miscalculation of the spectrum. (Or to detector energy nonlinearity [Mention et al, PLB 773 (2017) 307]).
- $\sim 3\%$ effect on total flux, but if it is an excess it increases the anomaly!
- No post-bump complete calculation of the neutrino fluxes.
- Nominal Saclay-Huber flux calculation uncertainty: $\sim 2.5\%$.
- Increasing the flux uncertainty is a game that one can play, but there are only guesses, e.g.$\sim 5\%$ [Hayes and Vogel, ARNPS 66 (2016) 219].
- Bottom line: the status of the reactor anomaly is controversial.

Reactor $\bar{\nu}_e$ Flux

- Reactor $\bar{\nu}_e$ flux produced by the β decays of the fission products of

$$^{235}\text{U} \qquad ^{238}\text{U} \qquad ^{239}\text{Pu} \qquad ^{241}\text{Pu}$$

- For each allowed β decay the electron spectrum is

$$S_\beta(E_e) = K p_e E_e \left(E_e - E_0\right)^2 F(Z, E_e) \qquad (E_\nu = E_0 - E_e)$$

From the measurement of the β spectrum $S_\beta(E_e)$ one can determine K and E_0, which determine the neutrino spectrum

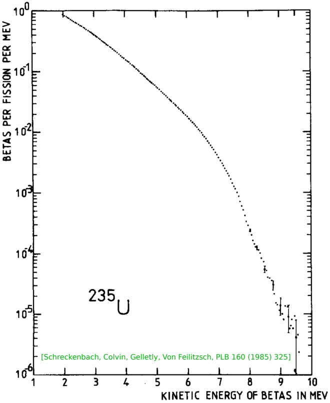
$$S_\nu(E_\nu) = K \sqrt{(E_0 - E_e)^2 - m_e^2}\,(E_0 - E_e)\, E_\nu^2 F(Z, E_e)$$

- Aggregate reactor spectrum (electron or neutrino):

$$S_{\text{tot}}(E, t) = \sum_k \underset{\substack{\uparrow \\ \text{fission fractions}}}{f_k(t)}\, S_k(E) \qquad (k = 235, 238, 239, 241)$$

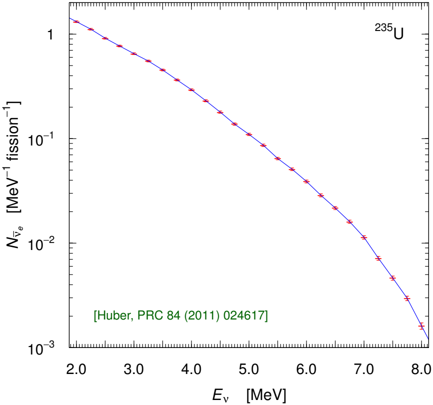
$$S_k(E) = \sum_n \underset{\substack{\uparrow \\ \text{cumulative} \\ \text{fission yield}}}{Y_n^k} \sum_b \text{BR}_n^b\, S_n^b(E)$$

- The *ab initio* calculation of each $S_k^{\nu}(E_\nu)$ requires knowledge of about 1000 spectra and branching ratios $(k = 235, 238, 239, 241)$.
- Nuclear data tables are incomplete and sometimes inexact.
- Semi-empirical method: inversion with ~ 30 virtual β branches of the aggregate β spectra $S_k^{\beta}(E_e)$ measured at ILL in the 80's.



[Schreckenbach, Colvin, Gelletly, Von Feilitzsch, PLB 160 (1985) 325]

$\Longrightarrow$



[Huber, PRC 84 (2011) 024617]

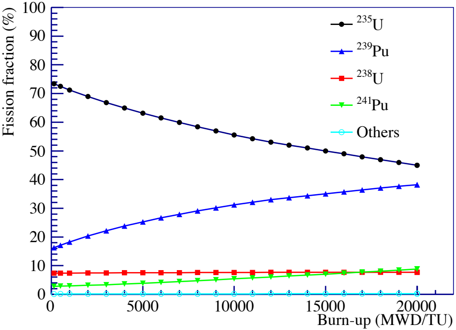
Unsolved problem: no bump in the aggregate β spectra

Daya Bay Reactor Fuel Evolution

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

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

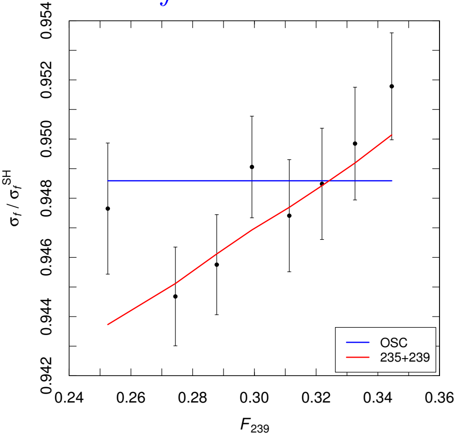
$$F_{235},\ F_{238},\ F_{239},\ F_{241}.$$

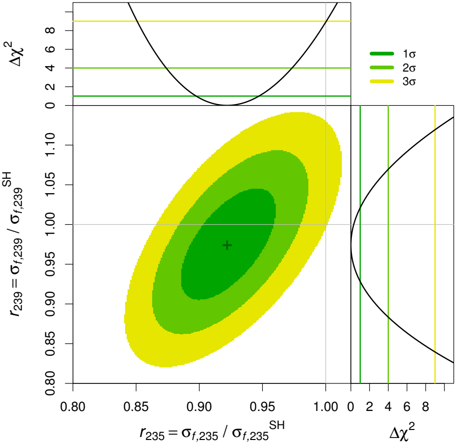


- Cross section per fission:

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

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





- Fits of Daya Bay data:
  - $r_k = \sigma_{f,k}/\sigma_{f,k}^{\text{SH}}$

$$\sigma_f^{\text{th}} = \sum_k F_k \, r_k \, \sigma_{f,k}^{\text{SH}}$$

$$k = 235, 238, 239, 241$$

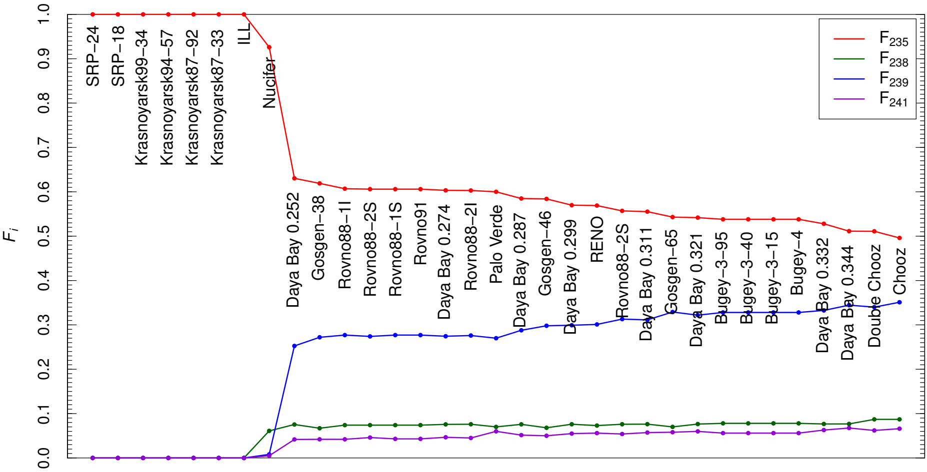
  - OSC: $\sigma_f^{\text{th}} = P_{\nu_e \to \nu_e} \sum_k F_k \, \sigma_{f,k}^{\text{SH}}$

	r_{235}	$r_{235} + r_{239}$	OSC
χ^2_{min}	3.8	3.6	9.5
NDF	7	6	7
GoF	80%	73%	22%

- Best fit: mainly suppression of $\sigma_{f,235}$ ($r_{235} < 1$)
- r_{235} and OSC are not nested models
- MC: OSC disfavored at 2.6σ

[CG, X.P. Ji, M. Laveder, Y.F. Li, B.R. Littlejohn, JHEP 1710 (2017) 143 (arXiv:1708.01133)]

Fuel Fractions of All Reactor Experiments

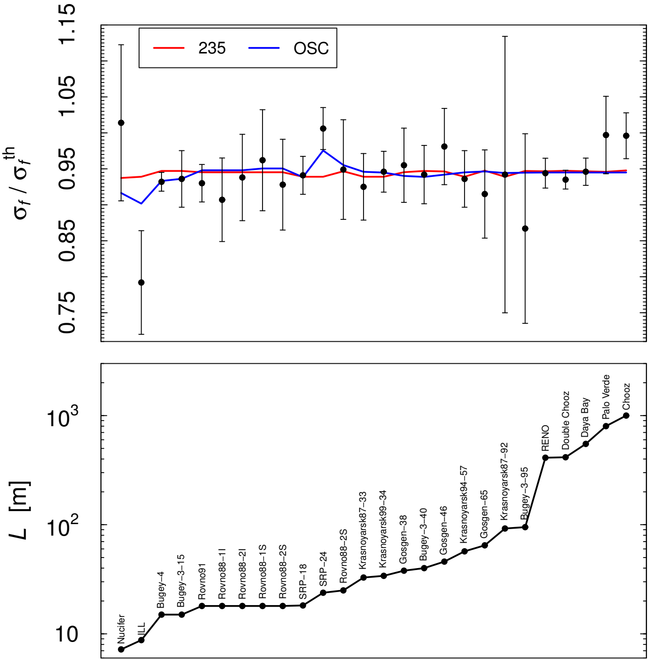


All Reactors

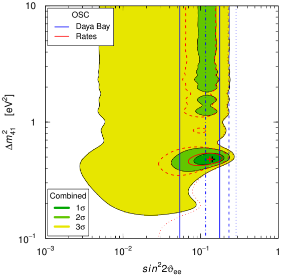
	r_{235}	OSC
χ^2_{min}	25.3	23.0
NDF	32	31
GoF	79%	85%

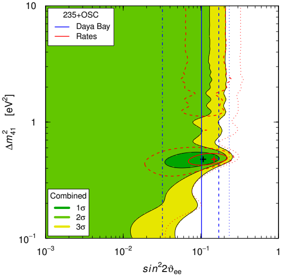
Best fit: OSC

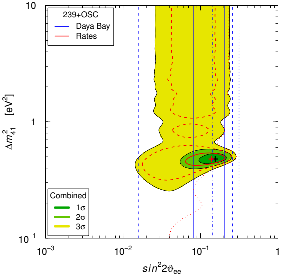
MC: r_{235} disfavored at 1.7σ



	r_{235}	$r_{235} + r_{239}$	OSC	r_{235}+OSC	r_{239}+OSC
χ^2_{min}	25.3	24.8	23.0	20.2	17.5
NDF	32	31	31	30	30
GoF	79%	78%	85%	91%	100%
Δm^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

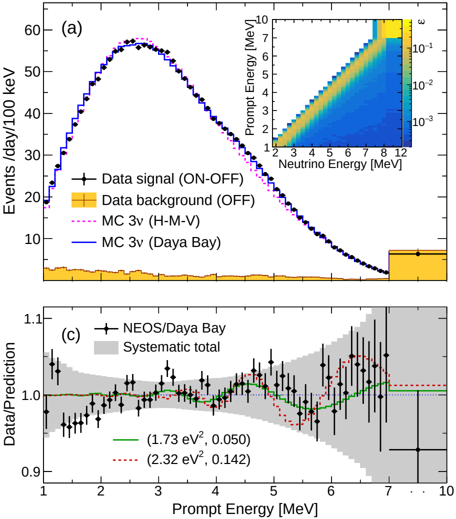






NEOS

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

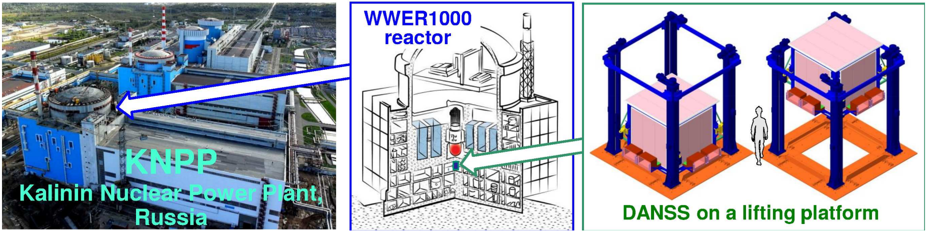


- Hanbit Nuclear Power Complex in Yeong-gwang, Korea.
- Thermal power of 2.8 GW.
- Detector: a ton of Gd-loaded liquid scintillator in a gallery approximately 24 m from the reactor core.
- The measured antineutrino event rate is 1976 per day with a signal to background ratio of about 22.

DANSS

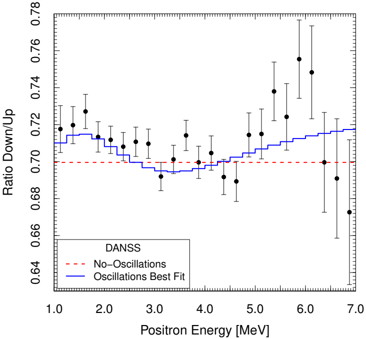
[Danilov @ Solvay Workshop, 1 December 2017, and La Thuile 2018, 3 March 2018]

Detector of reactor AntiNeutrino based on Solid Scintillator



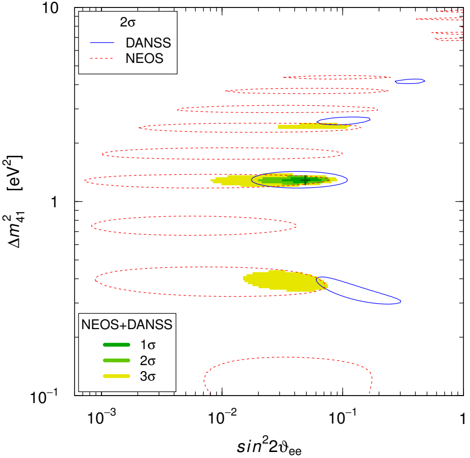
- Installed on a movable platform under a 3 GW reactor.
- Large neutrino flux.
- Reactor shielding of cosmic rays.
- Variable source-detector distance with the same detector!

$$\begin{aligned} \text{Down} &= 12.7\,\text{m} \\ \text{Up} &= 10.7\,\text{m} \end{aligned}$$



Model-Independent $\bar{\nu}_e$ SBL Oscillations

[Gariazzo, CG, Laveder, Li, arXiv:1801.06467]



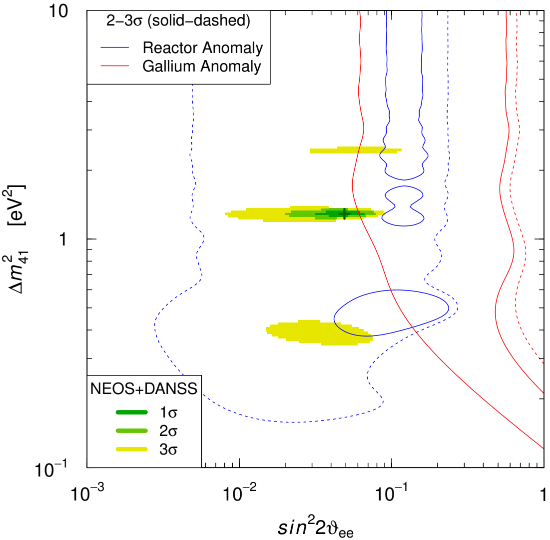
$$\sim 3.7\sigma$$

$$\Delta m^2_{41} = 1.29 \pm 0.03$$

$$\sin^2 2\vartheta_{ee} = 0.049 \pm 0.011$$

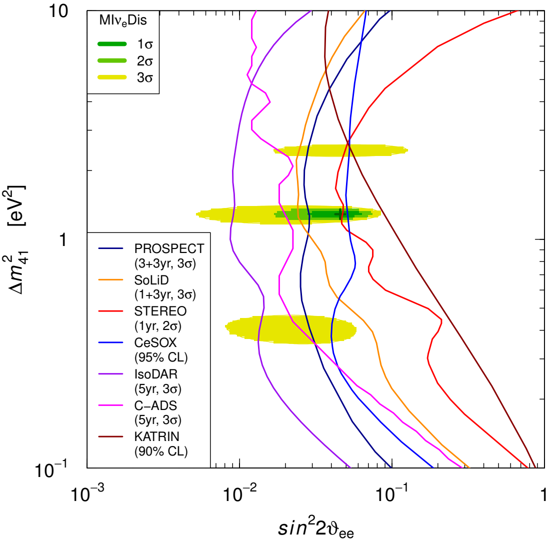
$$|U_{e4}|^2 = 0.012 \pm 0.003$$

Comparison with the Reactor and Gallium Anomalies

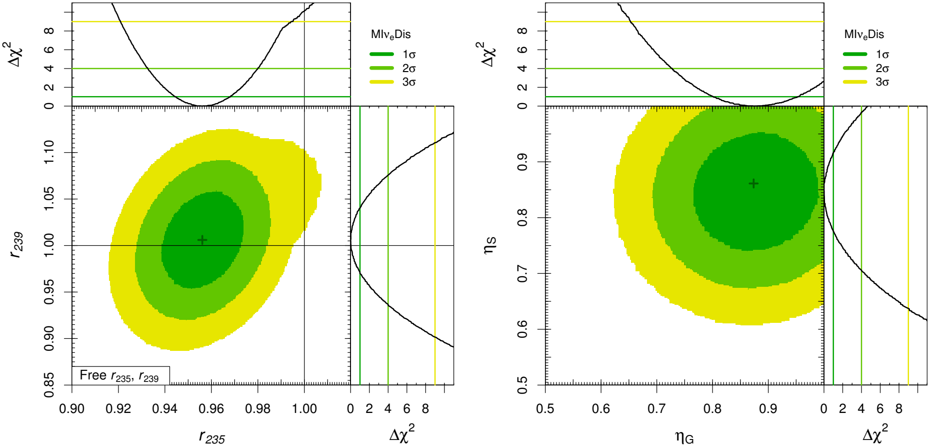


- 3σ agreement.
- 2σ tension.
- Overestimate of the reactor fluxes.
- Overestimate of the GALLEX and SAGE efficiencies.

Global Model-Independent ν_e and $\bar{\nu}_e$ Disappearance

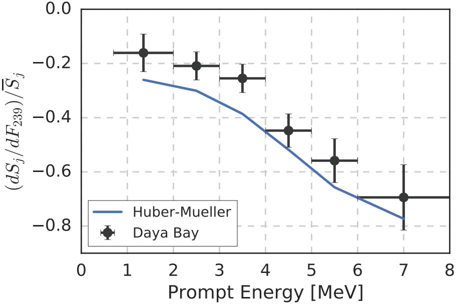


- NEOS and DANSS.
- Reactor rates with free ^{235}U and ^{239}Pu fluxes: r_{235} and r_{239}.
- Gallium data with free GALLEX and SAGE efficiencies: η_G and η_S.
- Ratio of the spectra measured at 40 m and 15 m from the source in the Bugey-3 experiment.
- Ratio of the KARMEN and LSND $\nu_e + {}^{12}\text{C} \to {}^{12}\text{N}_{\text{g.s.}} + e^-$ scattering data at 18 m and 30 m from the source.



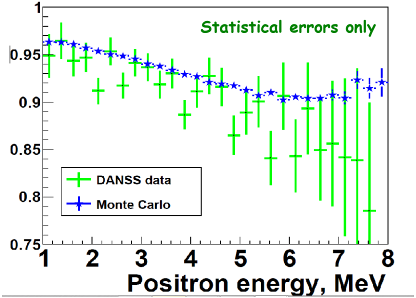
- Confirmed indication of $r_{235} < 1$ (Daya Bay evolution).
- Likely small overestimate of the GALLEX and SAGE efficiencies.

Different Daya Bay and DANSS Evolutions



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

Ratio of positron spectra
at the end and beginning of campaign



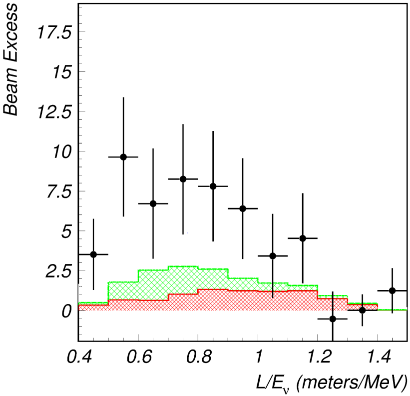
Clear evidence for spectrum evolution
Spectrum evolution is consistent with MC
contrary to Daya Bay measurements

[Danilov @ La Thuile 2018, 3 March 2018]

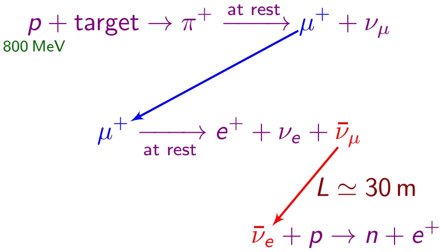
LSND

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

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



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



$$\underset{800\,\text{MeV}}{p} + \text{target} \to \pi^+ \xrightarrow{\text{at rest}} \mu^+ + \nu_\mu$$

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

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

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

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

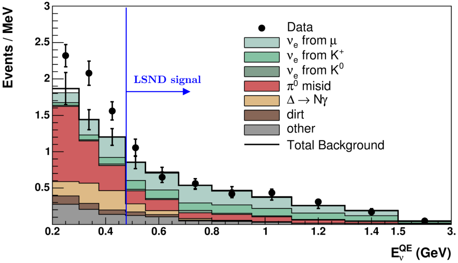
[PRD 65 (2002) 112001]

$\Delta m^2_{\text{SBL}} \gtrsim 0.1\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}}$

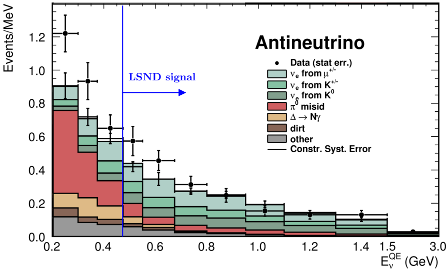
MiniBooNE

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

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

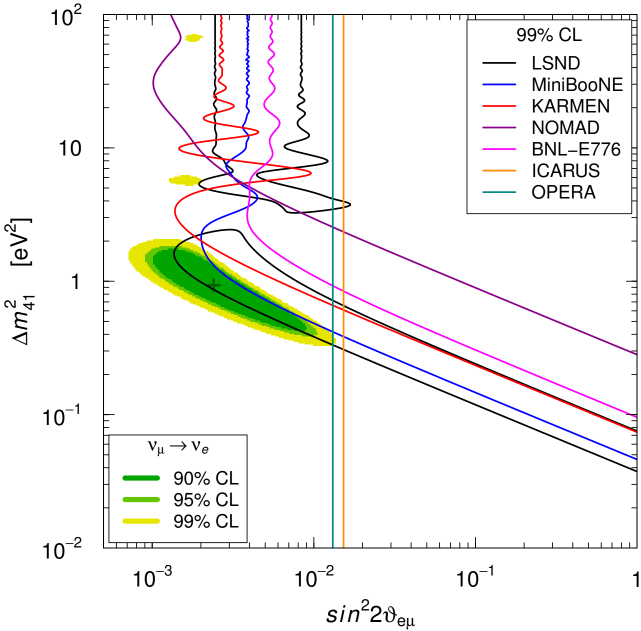


$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]

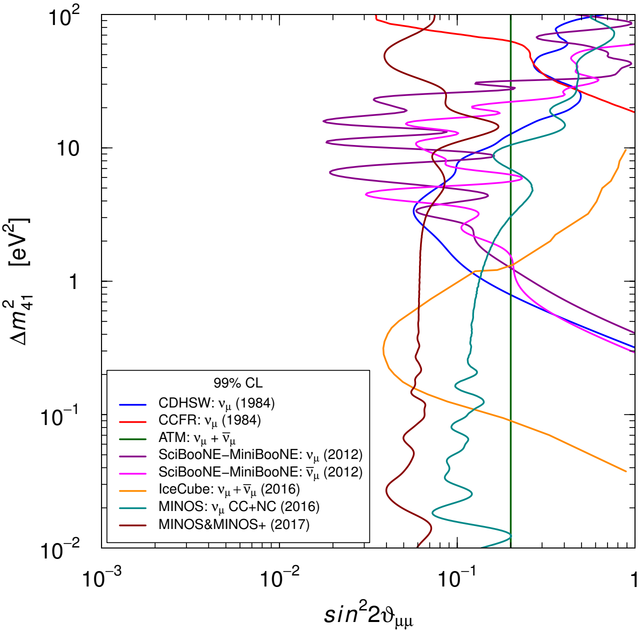


- Purpose: check LSND signal.
- Different L and E.
- Similar L/E (oscillations).
- No money, no Near Detector.
- LSND signal: $E > 475\,\text{MeV}$.
- Agreement with LSND signal?
- Low-energy anomaly $\Rightarrow$ MicroBooNE
- Pragmatic Approach: $E > 475\,\text{MeV}$.

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



ν_μ and $\bar{\nu}_\mu$ Disappearance



3+1 Appearance-Disappearance Tension

ν_e DIS

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

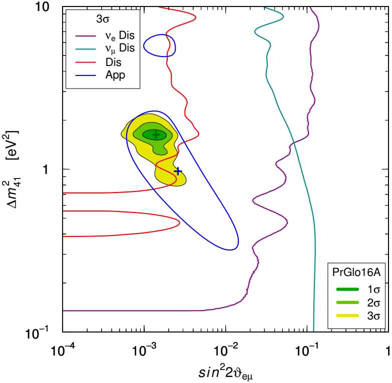
ν_μ DIS

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

$\nu_\mu \to \nu_e$ APP

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

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



- $\nu_\mu \to \nu_e$ is quadratically suppressed!
- PrGlo16A = early 2016 data

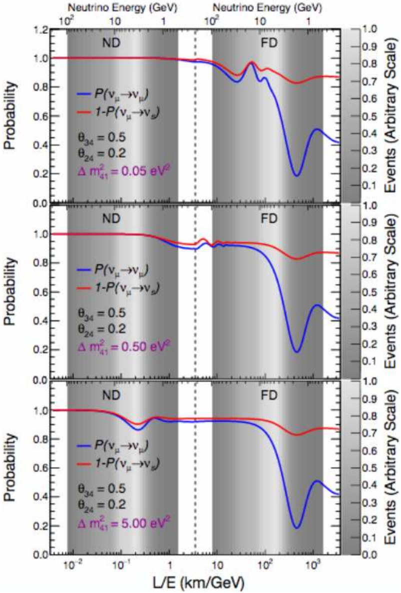
  [Gariazzo, CG, Laveder, Li, JHEP 1706 (2017) 135]

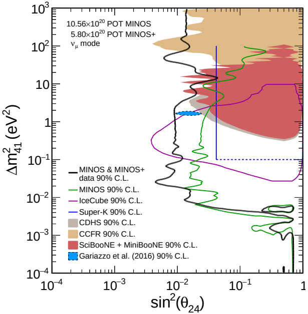
  $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 3.8/2 \Rightarrow \text{GoF}_{\text{PG}} = 15\%$
- Similar tension in 3+2, 3+3, . . . , 3+N_s

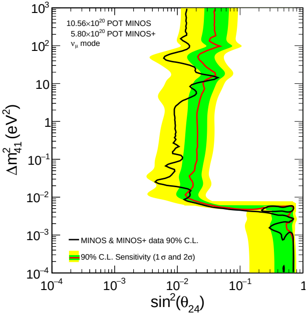
  [CG, Zavanin, MPLA 31 (2015) 1650003]

New Bound from MINOS+

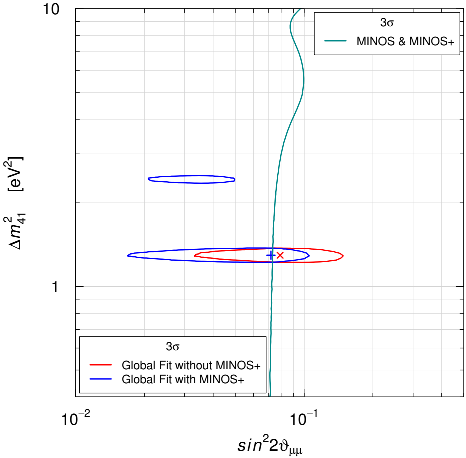
[arXiv:1710.06488]







Effects of MINOS+



- Best Fit: $\Delta m^2_{41} = 1.3\,\text{eV}^2$ $|U_{e4}|^2 = 0.017$ $|U_{\mu4}|^2 = 0.018$
- $\chi^2_{\text{min}}/\text{NDF} = 638.6/638 \Rightarrow \text{GoF} = 49\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 14.6/2 \Rightarrow \text{GoF}_{\text{PG}} = 0.07\%$ ← Intolerable tension!
- The MINOS+ bound disfavors the LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal.

Conclusions

- Exciting model-independent indication of light sterile neutrinos at the eV scale from the NEOS and DANSS experiments $\Longrightarrow$ New Physics beyond the Standard Model!
- Agreement with the Reactor and Gallium Anomalies $\Longrightarrow$ Needed revision of the ^{235}U calculation and small decrease of the GALLEX and SAGE efficiencies.
- Can be checked in the near future by the reactor experiments STEREO, SoLid, and PROSPECT.
- Independent tests through effect of m_4 in β-decay (KATRIN, Holmium) and $\beta\beta_{0\nu}$-decay.
- The MINOS+ bound (if correct) disfavors the LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal.