Beyond 3 Neutrino Mixing

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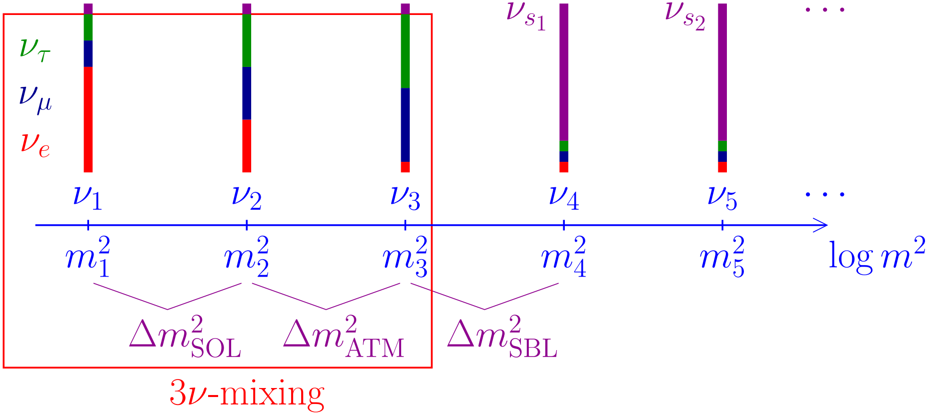
Beyond Three-Neutrino Mixing: Sterile Neutrinos



Sterile Neutrinos from Physics Beyond the SM

- Neutrinos are special in the Standard Model: the only neutral fermions
- In extensions of SM neutrinos can mix with non-SM fermions
- SM: $L_L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix}$ $\qquad \widetilde{\Phi} = i\sigma_2\,\Phi^* = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} \xrightarrow[\text{Breaking}]{\text{Symmetry}} \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix}$
- SM singlet $\overline{L_L}\widetilde{\Phi}$ can couple to new singlet chiral fermion field ν_R (right-handed neutrino) related to physics beyond the SM
- Known examples: SUSY, new symmetries, extra dimensions, mirror world, ... [see http://www.nu.to.infn.it/Sterile_Neutrinos/]
- Dirac mass term $\sim \overline{L_L}\widetilde{\Phi}\nu_R$ $\quad + \quad$ Majorana mass term $\sim \overline{\nu_R^c}\nu_R$
- Diagonalization of mass matrix $\Longrightarrow$ massive Majorana neutrinos

Light Sterile Neutrinos

- Light anti-ν_R are called sterile neutrinos

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

- Sterile means no standard model interactions
  [Pontecorvo, Sov. Phys. JETP 26 (1968) 984]
- Active neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$ can oscillate into light sterile neutrinos (ν_s)
- Observables:
  - Disappearance of active neutrinos (neutral current deficit)
  - Indirect evidence through combined fit of data (current indication)
- Short-baseline anomalies + 3ν-mixing:

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

$$\begin{array}{ccccc} \nu_1 & \nu_2 & \nu_3 & \nu_4 & \ldots \\ \nu_e & \nu_\mu & \nu_\tau & \nu_{s_1} & \ldots \end{array}$$

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

- Other possibilities (not incompatible):

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

    [Das, Pulido, Picariello, PRD 79 (2009) 073010]
    [de Holanda, Smirnov, PRD 83 (2011) 113011]

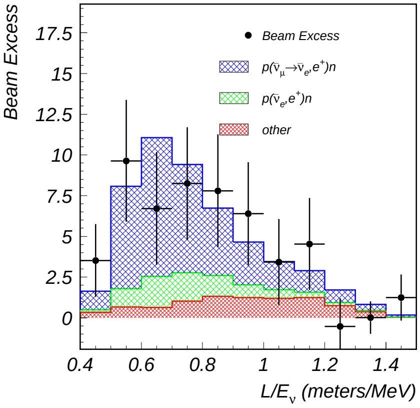
  - Heavy sterile neutrinos with mass scale $\gg 1\,\text{eV}$: could be Warm Dark Matter

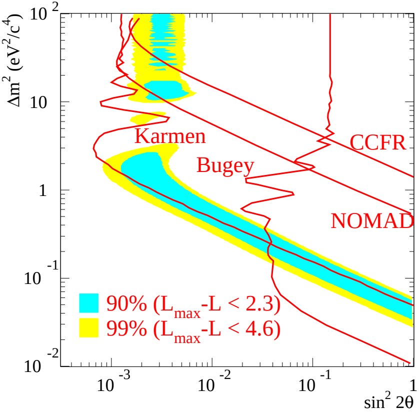
    [Kusenko, Phys. Rept. 481 (2009) 1]
    [Boyarsky, Ruchayskiy, Shaposhnikov, Ann. Rev. Nucl. Part. Sci. 59 (2009) 191]
    [Drewes, arXiv:1303.6912]

LSND

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

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\quad L \simeq 30\,\mathrm{m}$ $\quad 20\,\mathrm{MeV} \le E \le 200\,\mathrm{MeV}$



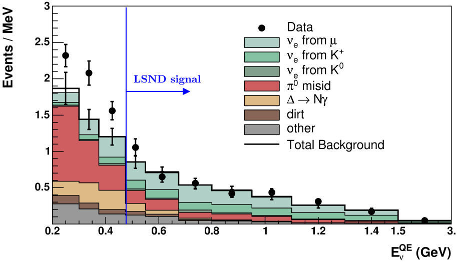


3.8σ excess $\quad \Delta m^2_{\mathrm{LSND}} \gtrsim 0.2\,\mathrm{eV}^2 \quad (\gg \Delta m^2_{\mathrm{A}} \gg \Delta m^2_{\mathrm{S}})$

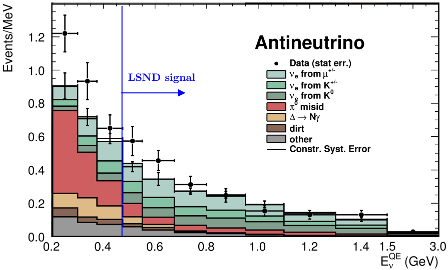
MiniBooNE

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

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



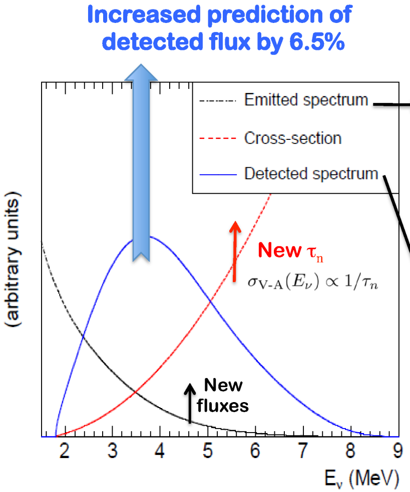
$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]



- Purpose: check LSND signal.
- Different L and E.
- Similar L/E (oscillations).
- LSND signal: $E > 475\,\text{MeV}$.
- Agreement with LSND signal?
- CP violation?
- Low-energy anomaly!
  Energy reconstruction problem?

[Martini et al, PRD 85 (2012) 093012; PRD 87 (2013) 013009]

New Reactor $\bar{\nu}_e$ Fluxes



i) **Neutrino Emission:**

- **Improved reactor neutrino spectra → <u>+3.5%</u>**
- **Accounting for long-lived isotopes in reactors → <u>+1%</u>**

ii) **Neutrino Detection:**

- **Reevaluation of σ_{IBD} → <u>+1.5%</u> (evolution of the neutron life time)**
- **Reanalysis of all SBL experiments**

[T. Lasserre, TAUP 2013]

Reactor Electron Antineutrino Anomaly

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

[update in White Paper, arXiv:1204.5379]

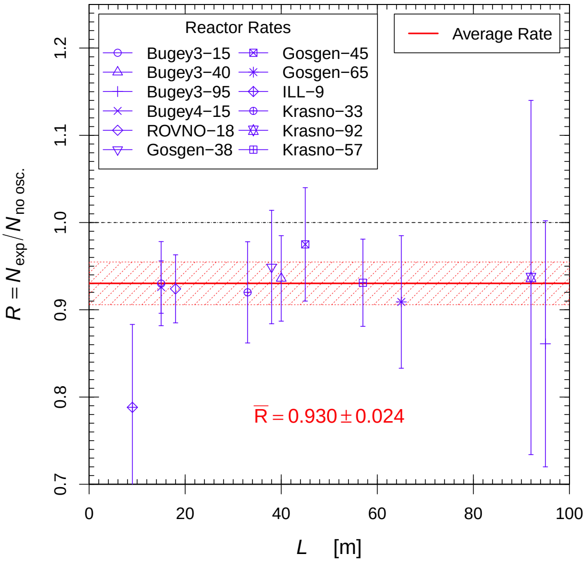
new reactor $\bar{\nu}_e$ fluxes

[Mueller et al, PRC 83 (2011) 054615]

[Huber, PRC 84 (2011) 024617]

$\sim 2.8\sigma$ anomaly

[see also:
Sinev, arXiv:1103.2452;
Ciuffoli, Evslin, Li, JHEP 12 (2012) 110;
Zhang, Qian, Vogel, PRD 87 (2013) 073018;
Ivanov et al, arXiv:1306.1995]



Gallium Anomaly

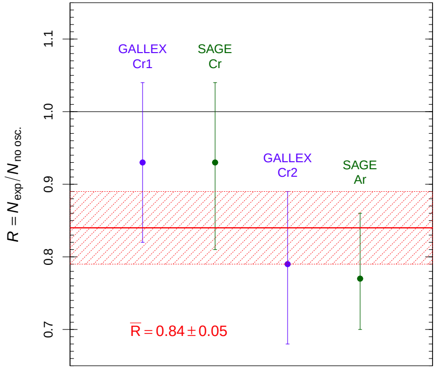
Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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

Anomaly supported by new ${}^{71}\text{Ga}({}^{3}\text{He}, {}^{3}\text{H}){}^{71}\text{Ge}$ cross section measurement

[Frekers et al., PLB 706 (2011) 134]



$E \sim 0.7\,\text{MeV}$

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

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

$\sim 2.9\sigma$ anomaly

[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; PRD 86 (2012) 113014]

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

Effective SBL Oscillation Probabilities in 3+1 Schemes

$$P_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} = \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

No CP Violation!

$$P_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} = 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

Perturbation of 3ν Mixing: $|U_{e4}|^2 \ll 1\,,\ |U_{\mu 4}|^2 \ll 1\,,\ |U_{\tau 4}|^2 \ll 1\,,\ |U_{s4}|^2 \simeq 1$

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

↑ SBL

$$\sin^2 2\vartheta_{\alpha\alpha} \ll 1$$

$$\Downarrow$$

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

[Okada, Yasuda, IJMPA 12 (1997) 3669-3694]

[Bilenky, Giunti, Grimus, EPJC 1 (1998) 247]

Effective SBL Oscillation Probabilities in 3+2 Schemes

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

$$\eta = \arg[U^*_{e4} U_{\mu4} U_{e5} U^*_{\mu5}]$$

$$P_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} = 4|U_{e4}|^2 |U_{\mu4}|^2 \sin^2\phi_{41} + 4|U_{e5}|^2 |U_{\mu5}|^2 \sin^2\phi_{51} + 8|U_{\mu4} U_{e4} U_{\mu5} U_{e5}| \sin\phi_{41} \sin\phi_{51} \cos(\phi_{54} \overset{(+)}{-} \eta)$$

$$P_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} = 1 - 4(1 - |U_{\alpha4}|^2 - |U_{\alpha5}|^2)(|U_{\alpha4}|^2 \sin^2\phi_{41} + |U_{\alpha5}|^2 \sin^2\phi_{51}) - 4|U_{\alpha4}|^2 |U_{\alpha5}|^2 \sin^2\phi_{54}$$

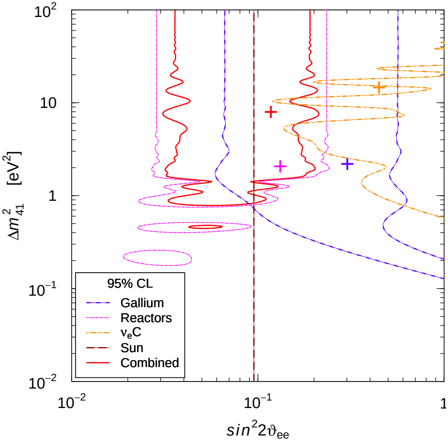
[Sorel, Conrad, Shaevitz, PRD 70 (2004) 073004; Maltoni, Schwetz, PRD 76 (2007) 093005; Karagiorgi et al, PRD 80 (2009) 073001; Kopp, Maltoni, Schwetz, PRL 107 (2011) 091801; Giunti, Laveder, PRD 84 (2011) 073008; Donini et al, JHEP 07 (2012) 161; Archidiacono et al, PRD 86 (2012) 065028; Conrad et al, 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, arXiv:1308.5288; Girardi, Meroni, Petcov, arXiv:1308.5802]

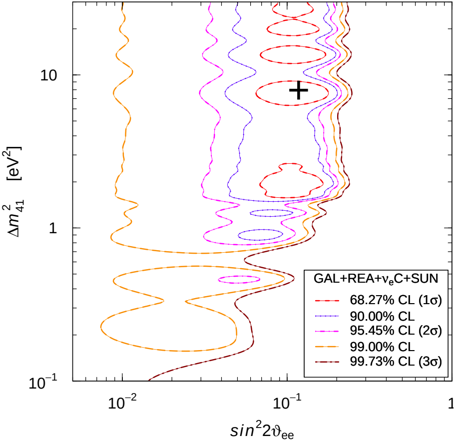
- Good: CP violation
- Bad: Two massive sterile neutrinos at the eV scale!

  4 more parameters: $\underbrace{\Delta m^2_{41}, |U_{e4}|^2, |U_{\mu4}|^2}_{3+1}, \Delta m^2_{51}, |U_{e5}|^2, |U_{\mu5}|^2, \eta$

Global ν_e and $\bar{\nu}_e$ Disappearance

[Giunti, Laveder, Y.F. Li, Q.Y. Liu, H.W. Long, PRD 86 (2012) 113014]





$\nu_e + {}^{12}\mathrm{C} \to {}^{12}\mathrm{N}_{\mathrm{g.s.}} + e^-$

KARMEN + LSND

[Conrad, Shaevitz, PRD 85 (2012) 013017]

[Giunti, Laveder, PLB 706 (2011) 200]

solar ν_e + KamLAND $\bar{\nu}_e$ + ϑ_{13}

[Giunti, Li, PRD 80 (2009) 113007]

[Palazzo, PRD 83 (2011) 113013; PRD 85 (2012) 077301]

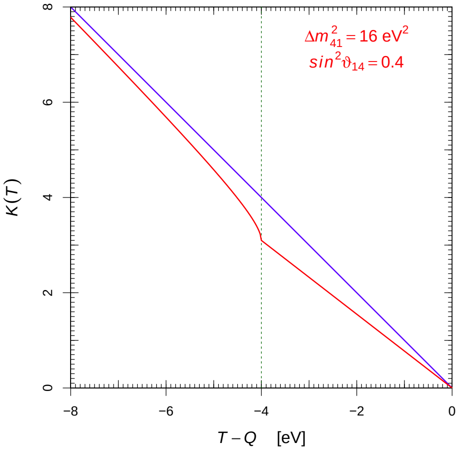
GoF = 62% PGoF = 4%

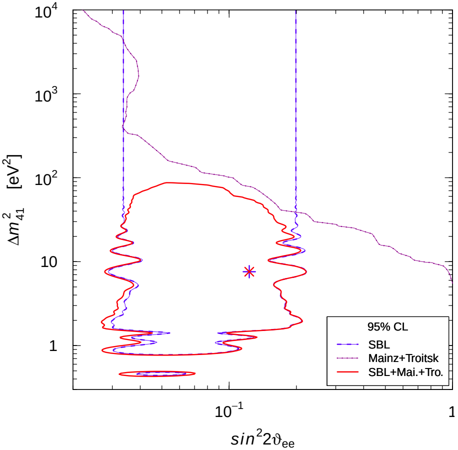
No Osc. excluded at 2.7σ

$\Delta\chi^2/\mathrm{NDF} = 10.1/2$

Mainz and Troitsk Limit on m_4^2

[Kraus, Singer, Valerius, Weinheimer, EPJC 73 (2013) 2323] [Belesev et al, JETP Lett. 97 (2013) 67; arXiv:1307.5687]



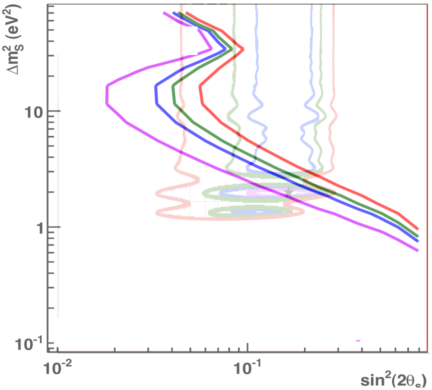


$$m_4 \gg m_1, m_2, m_3 \implies \Delta m^2_{41} \equiv m_4^2 - m_1^2 \simeq m_4^2$$

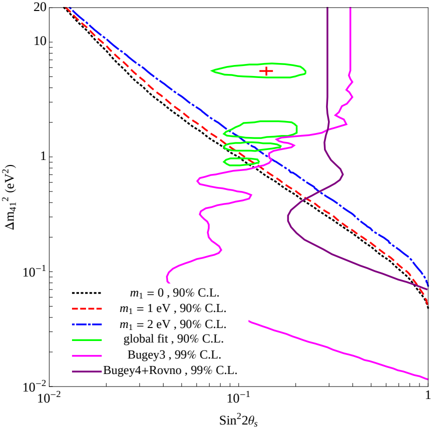
$$2\sigma: \quad 0.85 \lesssim \Delta m^2_{41} \lesssim 43\,\text{eV}^2 \implies 6\,\text{cm} \lesssim \frac{L^{\text{OSC}}_{41}}{E\,[\text{MeV}]} \lesssim 3\,\text{m}$$

[Giunti, Laveder, Y.F. Li, H.W. Long, PRD 87 (2013) 013004]

KATRIN Sensitivity



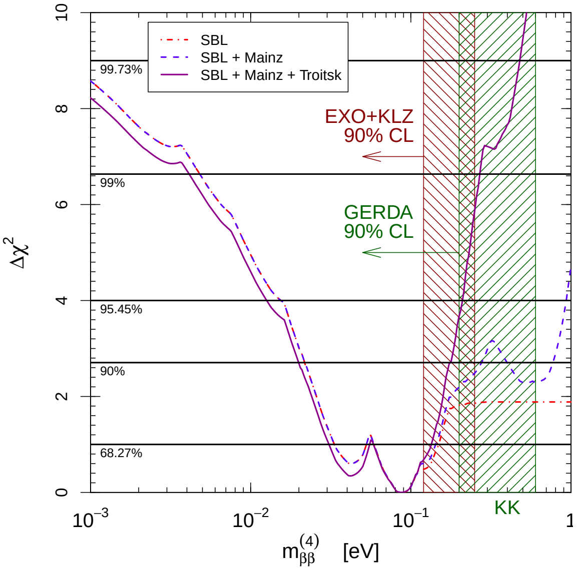
[Formaggio, Barrett, PLB 706 (2011) 68]



[Esmaili, Peres, PRD 85 (2012) 117301]

[see also: Sejersen Riis, Hannestad, JCAP (2011) 1475; Sejersen Riis, Hannestad, Weinheimer, PRC 84 (2011) 045503]

Neutrinoless Double-β Decay



$$|m_{\beta\beta}| = \left|\sum_{k=1}^{4} U_{ek}^2\, m_k\right|$$

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

caveat:

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

[Barry et al, JHEP 07 (2011) 091]

[Li, Liu, PLB 706 (2012) 406]

[Rodejohann, JPG 39 (2012) 124008]

[Girardi, Meroni, Petcov, arXiv:1308.5802]

3+1: Appearance vs Disappearance

- ν_e disappearance experiments:

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

- ν_μ disappearance experiments:

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

- $\nu_\mu \to \nu_e$ experiments:

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

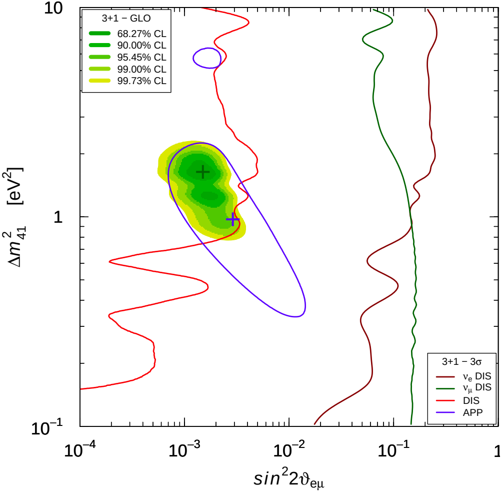
- Upper bounds on $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu} \Longrightarrow$ strong limit on $\sin^2 2\vartheta_{e\mu}$

[Okada, Yasuda, IJMPA 12 (1997) 3669-3694]

[Bilenky, Giunti, Grimus, EPJC 1 (1998) 247]

3+1 Global Fit

[Giunti, Laveder, Y.F. Li, H.W. Long, arXiv:1308.5288]



- APP $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$: LSND (Y), MiniBooNE (?), OPERA (N), ICARUS (N), KARMEN (N), NOMAD (N), BNL-E776 (N)
- DIS ν_e & $\bar{\nu}_e$: Reactors (Y), Gallium (Y), ν_eC (N), Solar (N)
- DIS ν_μ & $\bar{\nu}_\mu$: CDHSW (N), MINOS (N), Atmospheric (N), MiniBooNE/SciBooNE (N)

MiniBooNE $E > 475\,\text{MeV}$

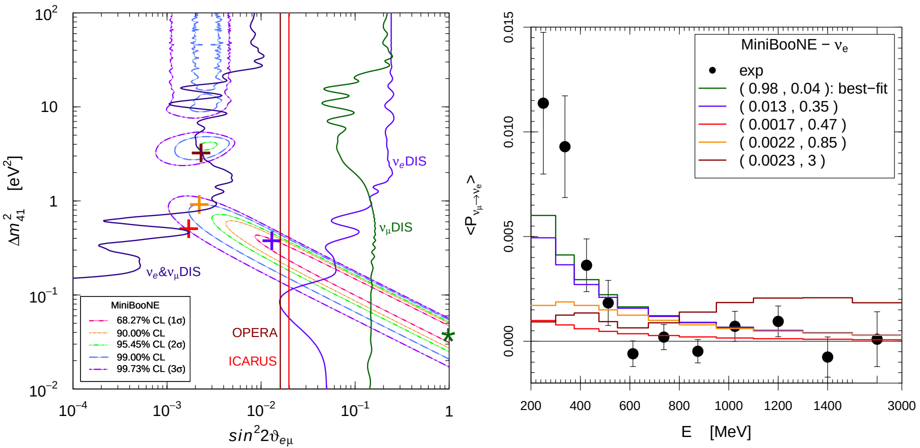
GoF = 29% PGoF = 9%

No Osc. excluded at 6.2σ

$\Delta\chi^2/\text{NDF} = 46.2/3$

[different approach and conclusions: Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]

MiniBooNE Low-Energy Excess?

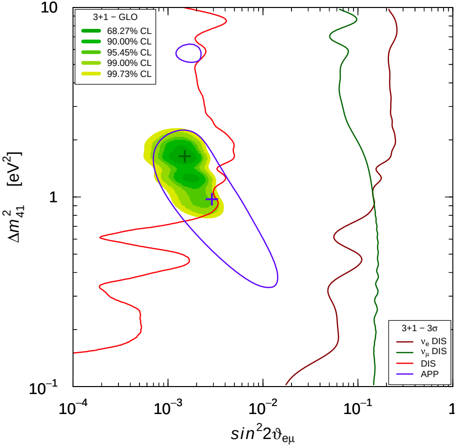


- No fit of low-energy excess for realistic
  $$\Delta m^2_{41} \gtrsim 0.8\,\text{eV}^2 \text{ and } \sin^2 2\vartheta_{e\mu} \lesssim 5 \times 10^{-3}$$
- APP-DIS PGoF $= 0.1\%$
- Neutrino energy reconstruction problem?

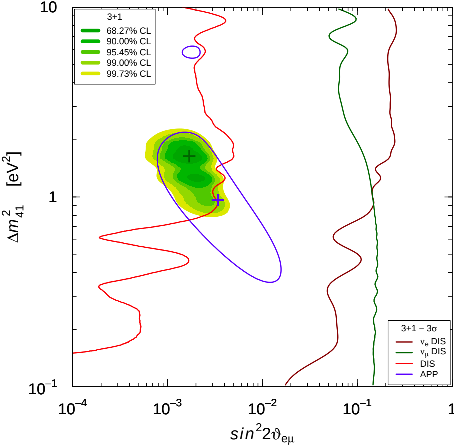
[Martini, Ericson, Chanfray, PRD 85 (2012) 093012; PRD 87 (2013) 013009]

MiniBooNE Impact on SBL Oscillations?

with MiniBooNE



without MiniBooNE



With MiniBooNE: GoF = 29% PGoF = 9%

No Osc. excluded at 6.2σ

$\Delta\chi^2/\mathrm{NDF} = 46.2/3$

Without MiniBooNE: GoF = 19% PGoF = 8%

No Osc. excluded at 6.3σ

$\Delta\chi^2/\mathrm{NDF} = 47.1/3$

Without LSND: No Osc. excluded only at 2.1σ ($\Delta\chi^2/\mathrm{NDF} = 8.3/3$)

3+2

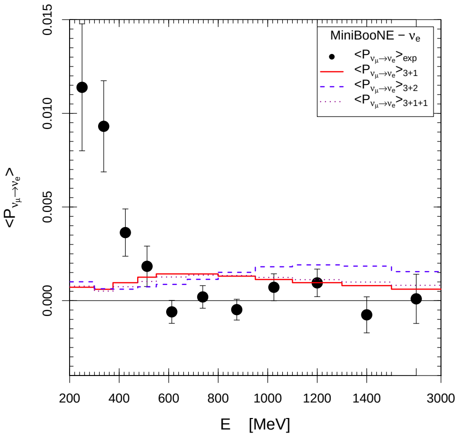
- 3+2 should be preferred to 3+1 only if
  - there is evidence of two peaks of the probability corresponding to two Δm^2's

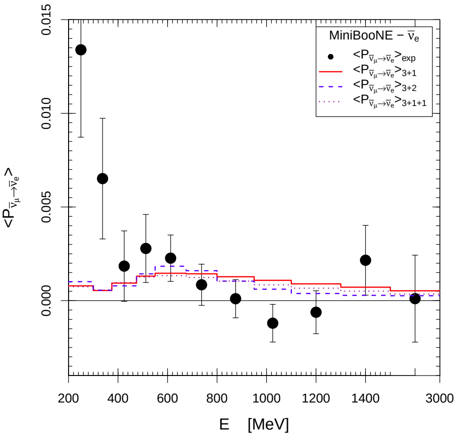
    or
  - there is CP-violating difference of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions
- 2008 ν + 2010 $\bar{\nu}$ MiniBooNE data indicated ν–$\bar{\nu}$ difference

  $\Downarrow$

  reasonable and useful to consider 3+2
- ν–$\bar{\nu}$ difference almost disappeared with 2012 $\bar{\nu}$ data
- Okkam razor: 3+1 is enough!
- Different approach and conclusions:
  - Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050:
    Use all MiniBooNE data. No 3+1 global fit. 3+2 slightly preferred? Small allowed region.
  - Conrad, Ignarra, Karagiorgi, Shaevitz, Spitz, AHEP 2013 (2013) 163897:
    Use all MiniBooNE data. 3+2 strongly preferred. Very small allowed regions.

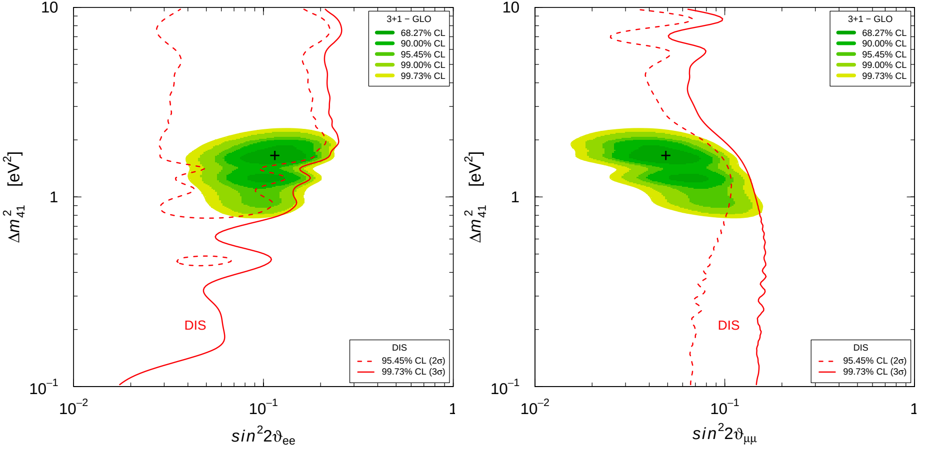
MiniBooNE Low-Energy Excess?





- 3+1: GoF = 6% PGoF = 0.2%
- 3+2: GoF = 8% PGoF = 0.1%
- 3+1+1: GoF = 6% PGoF = 0.2%

ν_e and ν_μ Disappearance



Many Exciting New Experiments and Projects

- Reactor $\bar{\nu}_e$ Disappearance:
  - Nucifer (OSIRIS, Saclay), Stereo (ILL, Grenoble) [arXiv:1204.5379]
  - DANSS (Kalinin Nuclear Power Plant, Russia) [arXiv:1304.3696], POSEIDON (PIK, Gatchina, Russia) [arXiv:1204.2449]
  - SCRAAM (San Onofre, California) [arXiv:1204.5379]
  - CARR (China Advanced Research Reactor) [arXiv:1303.0607]
  - Neutrino-4 (SM-3, Dimitrovgrad, Russia), SOLID (BR2, Belgium), Hanaro (Korea) [D. Lhuillier, EPSHEP 2013]
- Radioactive Source ν_e and $\bar{\nu}_e$ Disappearance:
  - SOX (Borexino, Gran Sasso, Italy) [arXiv:1304.7721]
  - CeLAND (^{144}Ce@KamLAND, Japan) [arXiv:1107.2335]
  - SAGE (Baksan, Russia) [arXiv:1006.2103]
  - IsoDAR (DAEδALUS, USA) [arXiv:1210.4454, arXiv:1307.2949]
  - SNO+, Daya Bay, RENO [T. Lasserre, Neutrino 2012]
- Accelerator $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ Appearance:
  - ICARUS/NESSIE (CERN) [arXiv:1304.2047, arXiv:1306.3455]
  - nuSTORM [arXiv:1308.0494]
  - OscSNS (Oak Ridge, USA) [arXiv:1305.4189, arXiv:1307.7097]

Effects of light sterile neutrinos can be also seen in:

- 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, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]

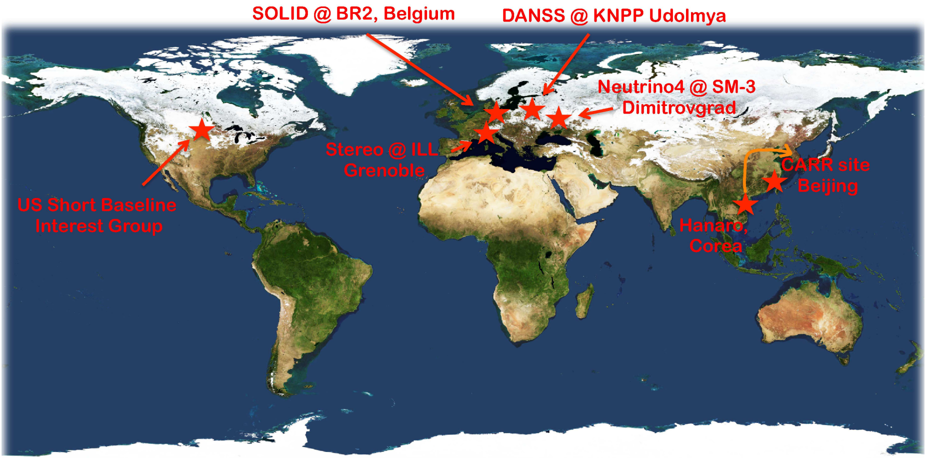
- Atmospheric neutrinos

  [Goswami, PRD 55 (1997) 2931;
  Bilenky, Giunti, Grimus, Schwetz, PRD 60 (1999) 073007;
  Maltoni, Schwetz, Tortola, Valle, NPB 643 (2002) 321, PRD 67 (2003) 013011;
  Choubey, JHEP 12 (2007) 014;
  Razzaque, Smirnov, JHEP 07 (2011) 084, PRD 85 (2012) 093010;
  Gandhi, Ghoshal, PRD 86 (2012) 037301;
  Esmaili, Halzen, Peres, JCAP 1211 (2012) 041;
  Esmaili, Smirnov, arXiv:1307.6824]

- Supernova neutrinos

  [Caldwell, Fuller, Qian, PRD 61 (2000) 123005;
  Peres, Smirnov, NPB 599 (2001);
  Sorel, Conrad, PRD 66 (2002) 033009;
  Tamborra, Raffelt, Huedepohl, Janka, JCAP 1201 (2012) 013;
  Wu, Fischer, Martinez-Pinedo, Qian, arXiv:1305.2382]

Experimental Prospects: Nuclear Reactors



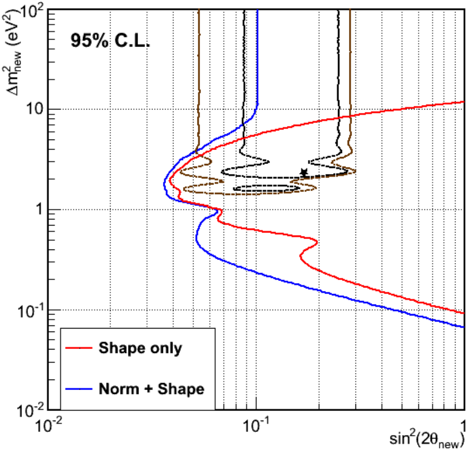
Test of both reactor & gallium anomalies

[T. Lasserre, TAUP 2013]

Experiment Type	Projects	P_{Th}	M_{det}	L	Depth
Mature Gd-doped LS detector Technology	Nucifer (FRA)	70 MW	0.7 tons	7 m	Few mwe
	Stéréo (FRA)	50 MW	2 tons	[8-11] m	10 mwe
	Neutrino 4 (RU)	100 MW	2 tons	[6-12] m	Surf.
Highly segmented detector for background reduction	DANSS (RU)	1 GW	1 ton	[10-12] m	50 mwe
	SoLid (UK)	45-80 MW	3 tons	8 m	10 m
Enhanced neutron Tagging					
	Hanaro (KO)	30 MW	0.5 t	6 m	Few mwe
2 detector complex or Moving detector	US project	20-120 MW	-	4m & 15m	Surf.
	China project	-			
	DANSS/Neutrino4	Movable detector			

[T. Lasserre, TAUP 2013]

Stereo Sensitivity



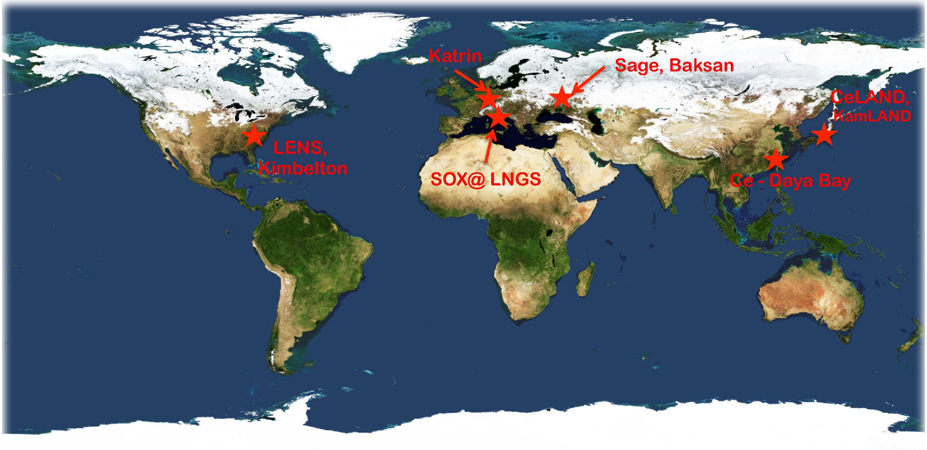
- 6 ILL cycles (1.5 year running)
- L_0 = 9.8 m
- S/B = 1.5
- E_{vis}>2 MeV, Neutron cut = 5 MeV
- Complete det response
- δL=20 cm, δE/E~10%@ 1MeV
- δEscale = 2%
- All syst. of ^{235}U spectrum
- 3.5% total norm error
- 480 ν/day expected

- Funded by ANR grant

- Time schedule:
  2013-2014: design and construction
  Mid-late 2014: installation
  2015-2016: data taking

[D. Lhuillier, Lomonosov 2013]

Experimental Prospects: Radioactive Sources



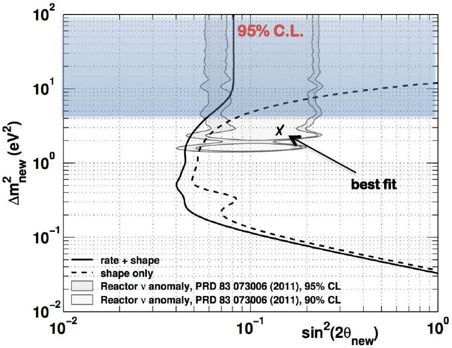
Test of both reactor & gallium anomalies

[T. Lasserre, TAUP 2013]

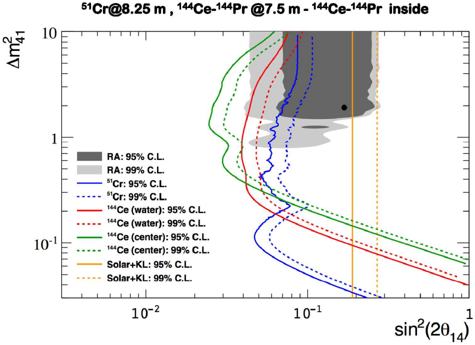
Type	Detection	Background	Isotope	Production	Activity	Projects
ν_e	$\nu_e e \to \nu_e e$ 5% E_{res} 15cm R_{res} or Radio-chemical	Detector Radioactivity Solar ν (irreducible) ν generator impurities	^{51}Cr 0.75 MeV $t_{1/2}$=26d	n_{th} irradiation in Reactor	>3 MCi	Sage LENS
					>10 MCi	SOX (SNO+)
			^{37}Ar 0.8 MeV $t_{1/2}$=35d	n_{fast} irradiation in Reactor (breeder)	>1 MCi	-
					5 MCi	Ricochet
$\bar{\nu}_e$	$\bar{\nu}_e p \to e^+ n$ E_{th}=1.8 MeV (e^+,n) 5% E_{res} 15cm R_{res}	reactor ν, geo ν, ν generator impurities	^{144}Ce E<3MeV $t_{1/2}$=285d	spent nuclear fuel reprocessing + REE extraction	75 kCi	CeLAND SOX
					500 kCi	Daya-Bay
			^{90}Sr ^{106}Rh		-	-
	$^3H \to He\ e^- \bar{\nu}_e$ EC/β-decay	Kink search	^{3}H E<18 keV	Irradiation in reactors	3 Ci	KATRIN (Mare/Echo)

[T. Lasserre, TAUP 2013]

CeLAND (KamLAND)



SOX (Borexino)



Data Taking Goals

^{144}Ce-^{144}Pr in 2015

^{51}Cr in 2015
^{144}Ce-^{144}Pr in 2016/7

[T. Lasserre, TAUP 2013]

Experimental Prospects: Accelerator Neutrinos

Test of LSND/MinibooNE/reactor/gallium anomalies
If positive signal, detailed study of sterile-ν phenomenology

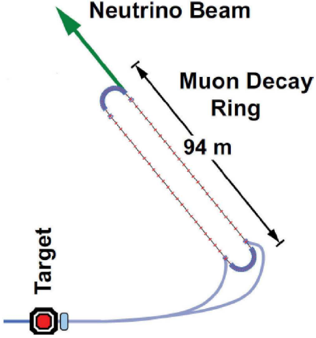
[T. Lasserre, TAUP 2013]

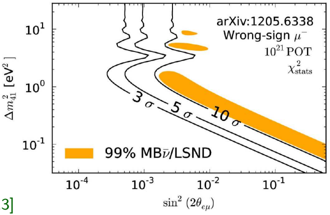
Type	Source	App. /Dis.	Oscillation Channels	Projects
Isotope Decay at Rest	$p + {}^{9}Be \to {}^{8}Li + 2p$ $n + {}^{7}Li \to {}^{8}Li$ ${}^{8}Li \to {}^{9}Be + e^{-} + \bar{\nu}_e$	Dis.	$\bar{\nu}_e \to \bar{\nu}_e$	IsoDAR
Pion (Kaon) Decay at Rest	$\pi^{+} \to \mu^{+} \nu_\mu$ $\hookrightarrow e^{+} \bar{\nu}_\mu \nu_e$	App. & Dis.	$\bar{\nu}_\mu \to \bar{\nu}_e$ $\nu_e \to \nu_e$	OscSNS, DAEδALUS, KDAR
Pion Decay in Flight	$\pi^{+} \to \mu^{+} \nu_\mu$ $\hookrightarrow e^{+} \bar{\nu}_\mu \nu_e$	App. & Dis.	$\nu_\mu \to \nu_e$ $\bar{\nu}_\mu \to \bar{\nu}_e$ $\nu_\mu \to \nu_\mu$ $\nu_e \to \nu_e$	MINOS+, MicroBooNE, LAr1kton Icarus/Nessie
Low-E Neutrino Factory	$\mu^{+} \to e^{+} \bar{\nu}_\mu \nu_e$ $\mu^{-} \to e^{-} \nu_\mu \bar{\nu}_e$	App. & Dis.	$\nu_e \to \nu_\mu$ $\bar{\nu}_e \to \bar{\nu}_\mu$ $\nu_\mu \to \nu_\mu$ $\bar{\nu}_e \to \bar{\nu}_e$	ν STORM

[T. Lasserre, TAUP 2013]

Muon Decay Rings: ν-STORM

- **Neutrino Factory Concept**
  - 60 GeV protons on solid target
  - Horn capture and π transfer
  - Muon Decay ring
- **APP and DIS channels with:**
  - $\overset{(-)}{\nu}_{\mu}$, $\overset{(-)}{\nu}_{e}$
- **kT-scale Minos-like**
  - 2 km baseline
- **Golden Mode**
  - $\overset{(-)}{\nu}_{\mu}$ APP in a $\overset{(-)}{\nu}_{e}$ beam
- Definitive sterile ν search





[T. Lasserre, TAUP 2013]

Conclusions

- Short-Baseline ν_e and $\bar{\nu}_e$ 3+1 Disappearance:
  - Reactor $\bar{\nu}_e$ anomaly is alive and exciting.
  - Gallium ν_e anomaly strengthened by new cross-section measurements.
  - Many promising projects to test short-baseline ν_e and $\bar{\nu}_e$ disappearance in a few years with reactors and radioactive sources.
  - Independent tests through effect of m_4 in β-decay and $(\beta\beta)_{0\nu}$-decay.
- Short-Baseline $\bar{\nu}_\mu \to \bar{\nu}_e$ LSND Signal:
  - MiniBooNE experiment has been inconclusive.
  - Better experiments are needed to check LSND signal!
  - If $|U_{e4}| > 0$ why not $|U_{\mu 4}| > 0$? $\Longrightarrow$ Maybe LSND luckily observed a fluctuation of a small $\bar{\nu}_\mu \to \bar{\nu}_e$ transition probability with amplitude $\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2$, which has not been seen by other appearance experiments.
- Cosmology:
  - Important effects of sterile neutrinos.
  - Implications depend on theoretical framework and considered data set.
  - Cosmological indications must be checked by laboratory experiments.