

Sterile Neutrinos

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Neutrino Unbound: <http://www.nu.to.infn.it>

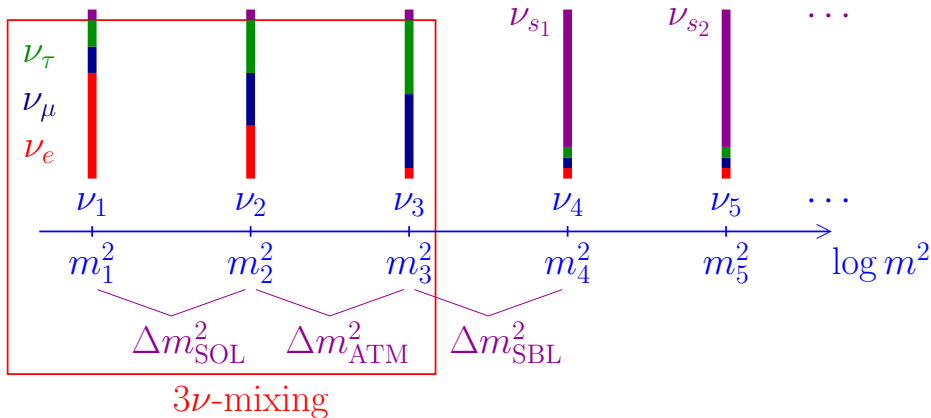
Pontecorvo100

Symposium in honour of Bruno Pontecorvo
for the centennial of the birth

Pisa, Italy

18-20 September 2013

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: $L_L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix} \quad \tilde{\Phi} = i\sigma_2 \Phi^* = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} \xrightarrow[\text{Breaking}]{\text{Symmetry}} \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix}$

- ▶ SM singlet $\overline{L}_L \tilde{\Phi}$ 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** $\sim \overline{L}_L \tilde{\Phi} \nu_R$ + **Majorana mass term** $\sim \overline{\nu_R^c} \nu_R$
- ▶ Diagonalization of mass matrix \implies massive Majorana neutrinos

Light Sterile Neutrinos

- ▶ Light anti- ν_R are called **sterile neutrinos**

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

- ▶ Sterile means **no standard model interactions**
[Pontecorvo, Sov. Phys. JETP 26 (1968) 984]
- ▶ Active neutrinos (ν_e, ν_μ, ν_τ) 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:

$$\begin{array}{cccccc} \Delta m_{21}^2 & \ll & |\Delta m_{31}^2| & \ll & |\Delta m_{41}^2| & \leq \dots \\ \nu_1 & & \nu_2 & & \nu_3 & \dots \\ \nu_e & & \nu_\mu & & \nu_\tau & \dots \\ & & & & \nu_{s1} & \dots \end{array}$$

- ▶ 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]

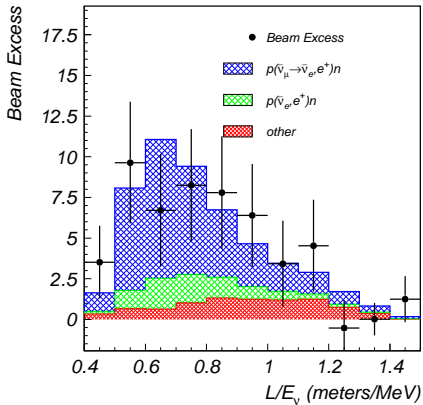
LSND

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

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

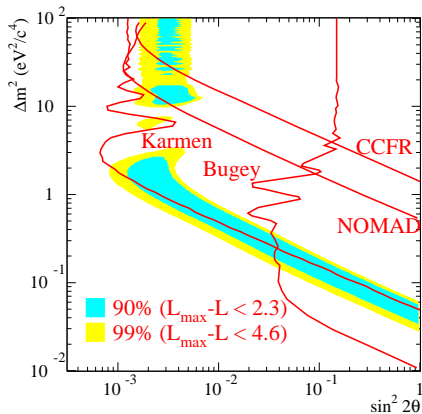
$$L \simeq 30 \text{ m}$$

$$20 \text{ MeV} \leq E \leq 200 \text{ MeV}$$



3.8 σ excess

$$\Delta m_{\text{LSND}}^2 \gtrsim 0.2 \text{ eV}^2 \quad (\gg \Delta m_{\text{A}}^2 \gg \Delta m_{\text{S}}^2)$$



MiniBooNE

$L \simeq 541 \text{ m}$

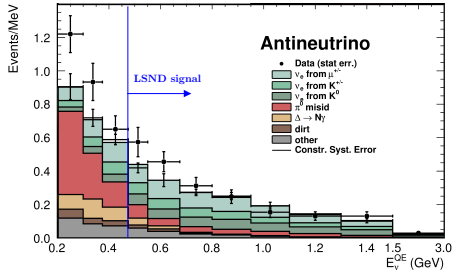
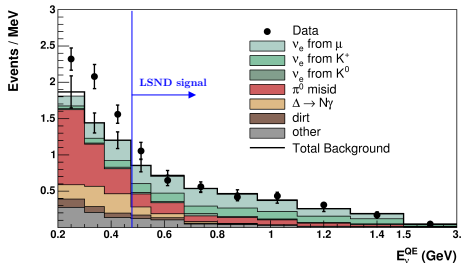
$200 \text{ MeV} \leq E \lesssim 3 \text{ GeV}$

$\nu_\mu \rightarrow \nu_e$

[PRL 102 (2009) 101802]

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

[PRL 110 (2013) 161801]



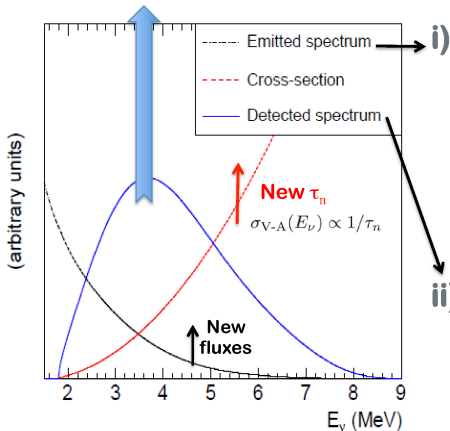
- ▶ Purpose: check LSND signal.
- ▶ Different L and E .
- ▶ Similar L/E (oscillations).
- ▶ LSND signal: $E > 475 \text{ MeV}$.

- ▶ 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

Increased prediction of
detected flux by 6.5%



Neutrino Emission:

- Improved reactor neutrino spectra → +3.5%
- Accounting for long-lived isotopes in reactors → +1%

Neutrino Detection:

- Reevaluation of σ_{IBD} → +1.5%
(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

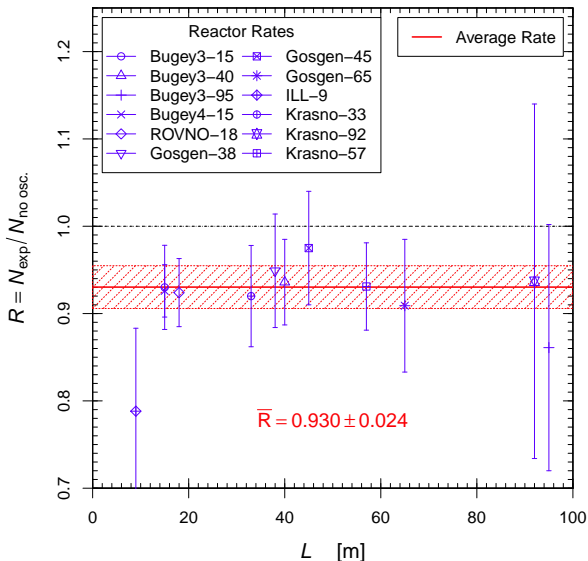
[see also:

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

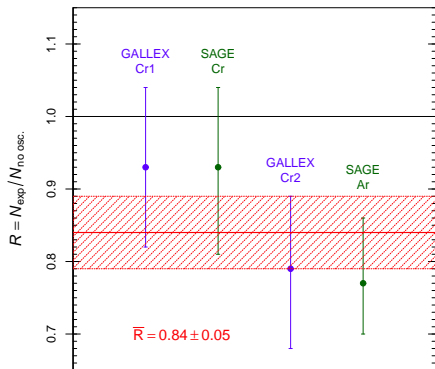
Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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

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

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

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

No CP Violation!

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

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

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

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

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



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

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

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

↑
SBL

Effective SBL Oscillation Probabilities in 3+2 Schemes

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

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

$$P_{\nu_{\mu} \rightarrow \nu_e}^{(-) \quad (-)} = 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2 \phi_{41} + 4|U_{e5}|^2 |U_{\mu 5}|^2 \sin^2 \phi_{51} + 8|U_{\mu 4} U_{e4} U_{\mu 5} U_{e5}| \sin \phi_{41} \sin \phi_{51} \cos(\phi_{54} \overset{(+)}{-} \eta)$$

$$P_{\nu_{\alpha} \rightarrow \nu_{\alpha}}^{(-) \quad (-)} = 1 - 4(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2 \phi_{41} + |U_{\alpha 5}|^2 \sin^2 \phi_{51}) - 4|U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2 \phi_{54}$$

[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]

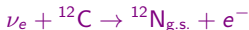
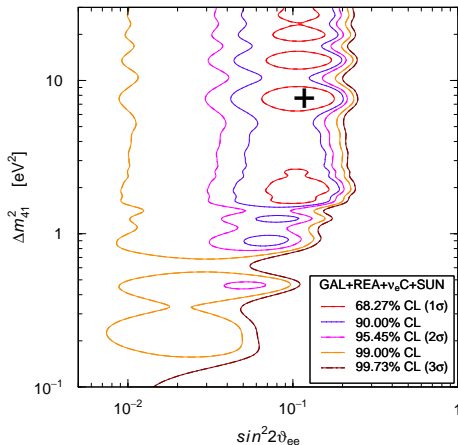
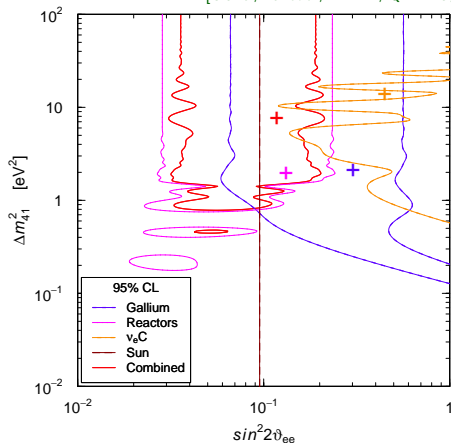
▶ Good: CP violation

▶ Bad: Two massive sterile neutrinos at the eV scale!

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

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

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



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]

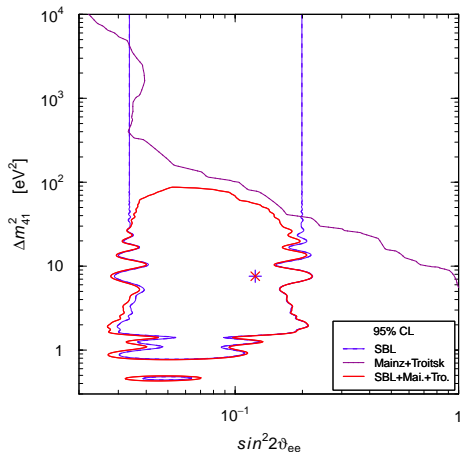
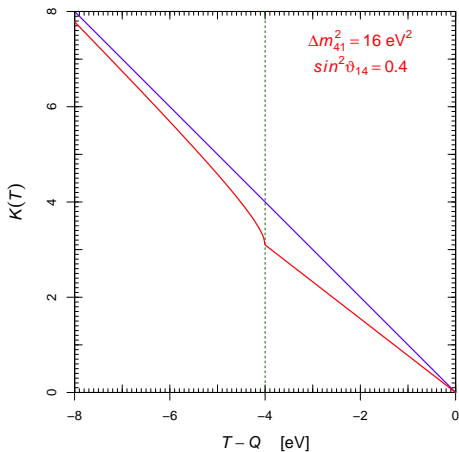
GoF = 62% PGoF = 4%

No Osc. excluded at 2.7σ

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

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]

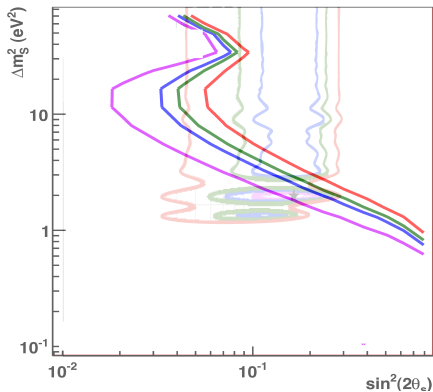


$$m_4 \gg m_1, m_2, m_3 \implies \Delta m_{41}^2 \equiv m_4^2 - m_1^2 \simeq m_4^2$$

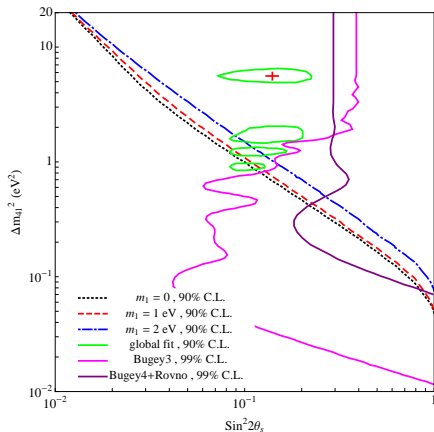
$$2\sigma : 0.85 \lesssim \Delta m_{41}^2 \lesssim 43 \text{ eV}^2 \implies 6 \text{ cm} \lesssim \frac{L_{41}^{\text{osc}}}{E [\text{MeV}]} \lesssim 3 \text{ m}$$

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

KATRIN Sensitivity



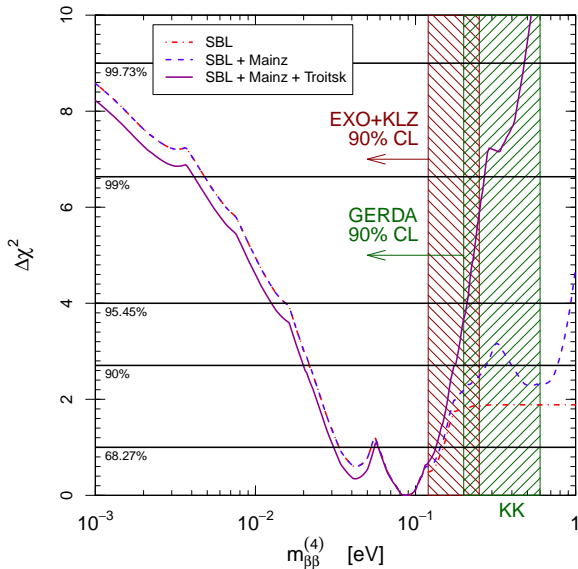
[Formaggio, Barrett, PLB 706 (2011) 68]



[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:

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

- ▶ ν_μ disappearance experiments:

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

- ▶ $\nu_\mu \rightarrow \nu_e$ experiments:

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

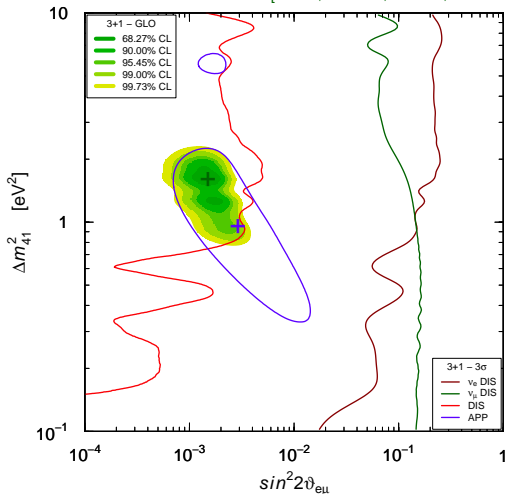
- ▶ Upper bounds on $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu} \implies$ strong limit on $\sin^2 2\vartheta_{e\mu}$

[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]



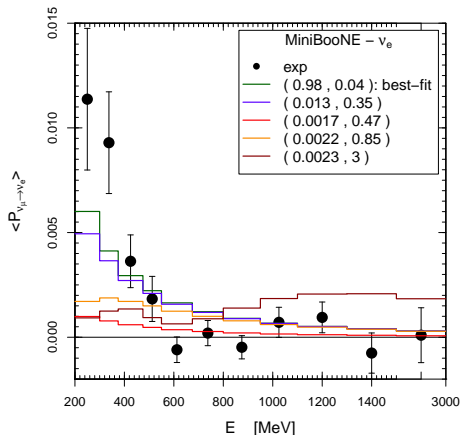
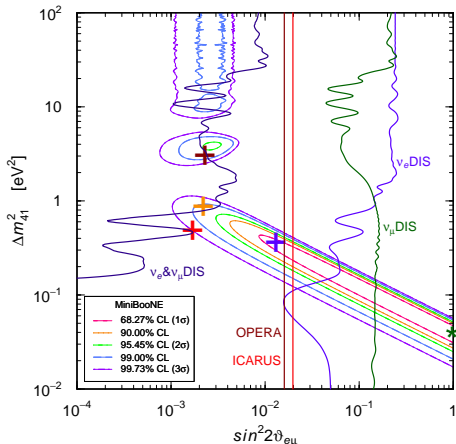
MiniBooNE $E > 475$ MeV
GoF = 29% PGoF = 9%

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

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?

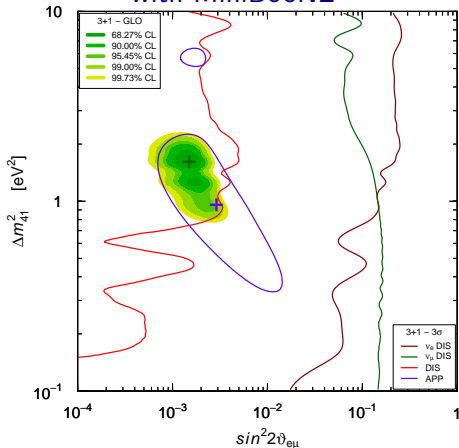


- ▶ No fit of low-energy excess for realistic $\Delta m_{41}^2 \gtrsim 0.8 \text{ eV}^2$ and $\sin^2 2\theta_{e\mu} \lesssim 5 \times 10^{-3}$
- ▶ APP-DIS PGoF = 0.1%
- ▶ Neutrino energy reconstruction problem?

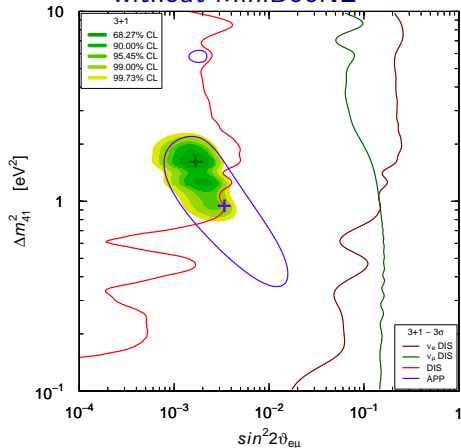
[Martini, Ericson, Chanfray, PRD 85 (2012) 093012; PRD 87 (2013) 013009]

MiniBooNE Impact on SBL Oscillations?

with MiniBooNE



without MiniBooNE



GoF = 29% PGoF = 9%

No Osc. excluded at 6.2 σ

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

GoF = 19% PGoF = 8%

No Osc. excluded at 6.3 σ

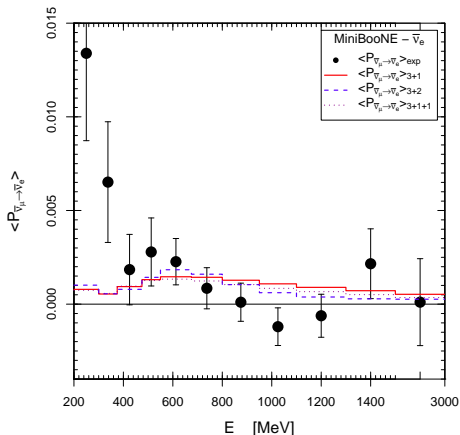
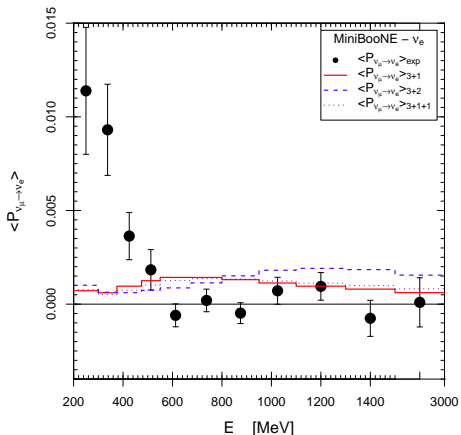
$\Delta\chi^2/\text{NDF} = 47.1/3$

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

3+2

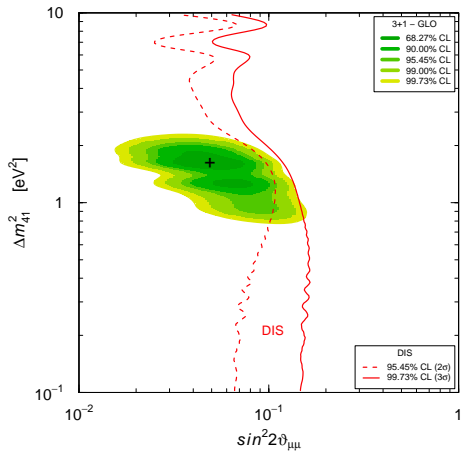
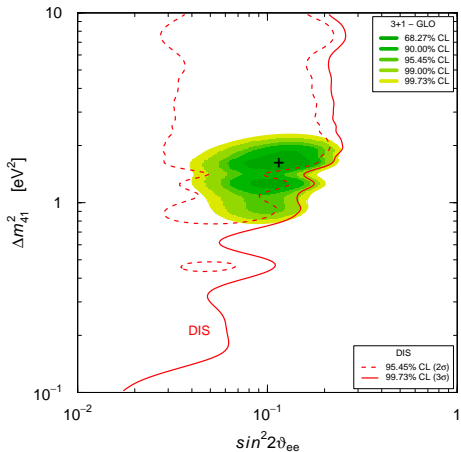
- ▶ $3+2$ should be preferred to $3+1$ only if
 - ▶ there is evidence of two peaks of the probability corresponding to two Δm^2 's
 - or
 - ▶ there is CP-violating difference of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions
- ▶ 2008 ν + 2010 $\bar{\nu}$ MiniBooNE data indicated $\nu-\bar{\nu}$ difference
 - ⇓
 - reasonable and useful to consider $3+2$
- ▶ $\nu-\bar{\nu}$ 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 (DAE δ ALUS, USA) [arXiv:1210.4454, arXiv:1307.2949]
 - ▶ SNO+, Daya Bay, RENO [T. Lasserre, Neutrino 2012]
- ▶ Accelerator $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ 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]

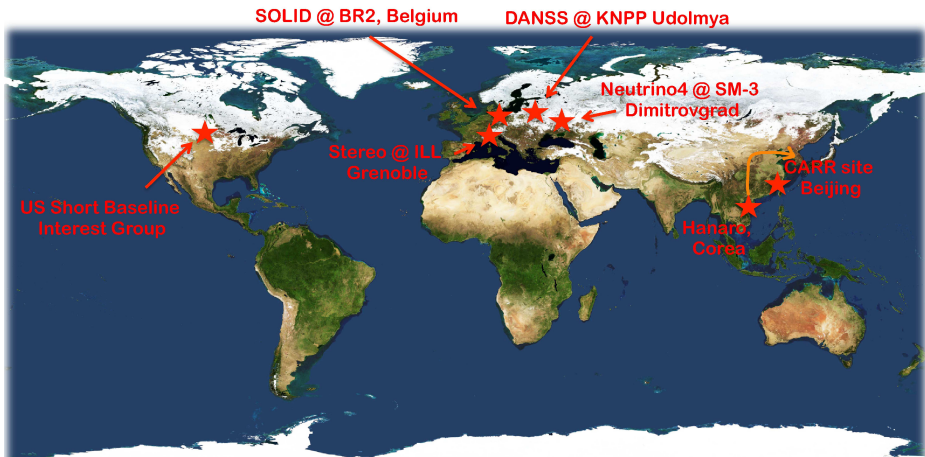
▶ Atmospheric neutrinos

[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



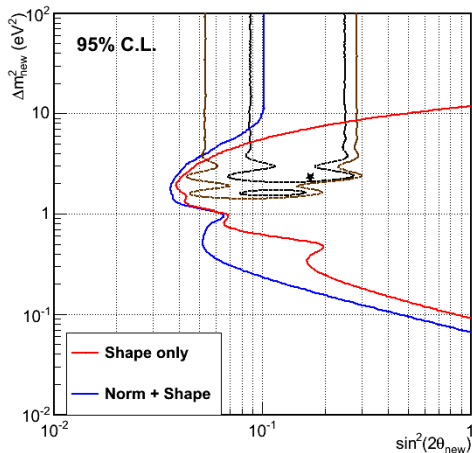
Test of both reactor & gallium anomalies

[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
	St�r�eo (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
 - $\delta L = 20$ cm, $\delta E/E \sim 10\%$ @ 1 MeV
 - $\delta E_{scale} = 2\%$
 - All syst. of ^{235}U spectrum
 - 3.5% total norm error
 - 480 v/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



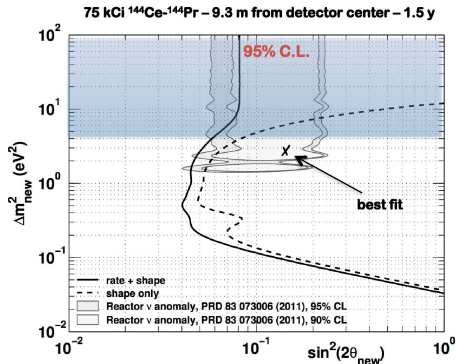
Test of both reactor & gallium anomalies

[T. Lasserre, TAUP 2013]

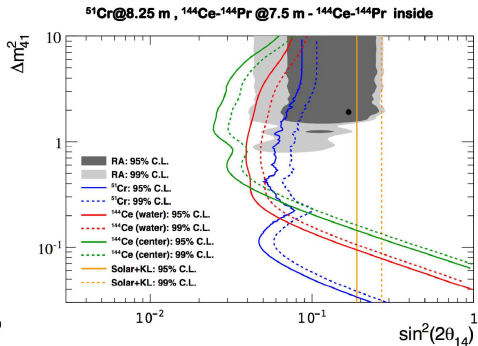
Type	Detection	Background	Isotope	Production	Activity	Projects
ν_e	$\nu_e e \rightarrow \nu_e e$ 5% E_{res} 15cm R_{res}	Detector Radioactivity Solar ν (irreducible)	^{51}Cr 0.75 MeV $t_{1/2}=26\text{d}$	n_{th} irradiation in Reactor	>3 MCi	Sage LENS
			>10 MCi		SOX (SNO+)	
	or Radio-chemical	ν generator impurities	^{37}Ar 0.8 MeV $t_{1/2}=35\text{d}$	n_{fast} irradiation in Reactor (breeder)	>1 MCi	-
			5 MCi		Ricochet	
$\bar{\nu}_e$	$\bar{\nu}_e p \rightarrow e^+ n$ $E_{th}=1.8\text{ MeV}$ (e^+, n)	reactor ν , geo ν , ν generator impurities	^{144}Ce $E < 3\text{MeV}$ $t_{1/2}=285\text{d}$	spent nuclear fuel reprocessing + REE extraction	75 kCi	CeLAND SOX
			500 kCi		Daya-Bay	
	5% E_{res} 15cm R_{res}	^{90}Sr ^{106}Rh	-	-		
	$^3\text{H} \rightarrow \text{He } e^- \bar{\nu}_e$ EC/ β -decay	Kink search	^3H $E < 18\text{ keV}$	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	$p + {}^9\text{Be} \rightarrow {}^8\text{Li} + 2p$ $n + {}^7\text{Li} \rightarrow {}^8\text{Li}$ ${}^8\text{Li} \rightarrow {}^9\text{Be} + e^- + \bar{\nu}_e$	Dis.	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	IsoDAR
Pion (Kaon) Decay at Rest	$\pi^+ \rightarrow \mu^+ \nu_\mu$ $\quad \quad \quad \searrow$ $\quad \quad \quad e^+ \bar{\nu}_\mu \nu_e$	App. & Dis.	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_e \rightarrow \nu_e$	OscSNS, DAE δ ALUS, KDAR
Pion Decay in Flight	$\pi^+ \rightarrow \mu^+ \nu_\mu$ $\quad \quad \quad \searrow$ $\quad \quad \quad e^+ \bar{\nu}_\mu \nu_e$	App. & Dis.	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_\mu \rightarrow \nu_e$ $\nu_\mu \rightarrow \nu_\mu$ $\nu_e \rightarrow \nu_e$	MINOS+, MicroBooNE, LAR1kton Icarus/Nessie
Low-E Neutrino Factory	$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$ $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$	App. & Dis.	$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ $\nu_e \rightarrow \nu_\mu$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ $\nu_\mu \rightarrow \nu_e$	ν STORM

[T. Lasserre, TAUP 2013]

Muon Decay Rings: ν -STORM

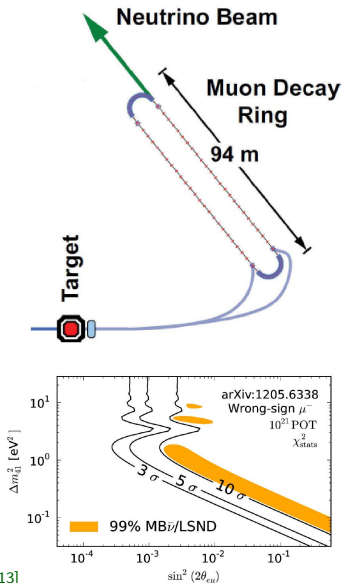
- **Neutrino Factory Concept**
 - 60 GeV protons on solid target
 - Horn capture and π transfer
 - Muon Decay ring

- **APP and DIS channels with:**
 - $(\bar{\nu})_{\mu}, (\bar{\nu})_e$

- **kT-scale Minos-like**
 - 2 km baseline

- **Golden Mode**
 - $(\bar{\nu})_{\mu}$ APP in a $(\bar{\nu})_e$ 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 $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ LSND Signal:
 - ▶ MiniBooNE experiment has been inconclusive.
 - ▶ Better experiments are needed to check LSND signal!
 - ▶ If $|U_{e4}| > 0$ why not $|U_{\mu 4}| > 0$? \implies Maybe LSND luckily observed a fluctuation of a small $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ 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: (see talk by Steen Hannestad)
 - ▶ Important effects of sterile neutrinos.
 - ▶ Implications depend on theoretical framework and considered data set.
 - ▶ Cosmological indications must be checked by laboratory experiments.