Sterile neutrinos at the eV-scale?

LAL, Paris, 5 Feb. 2013

Thomas Schwetz

Max-Planck-Institut für Kernphysik
Heidelberg, Germany

Kopp, Machado, Maltoni, TS, 13 (in preparation)

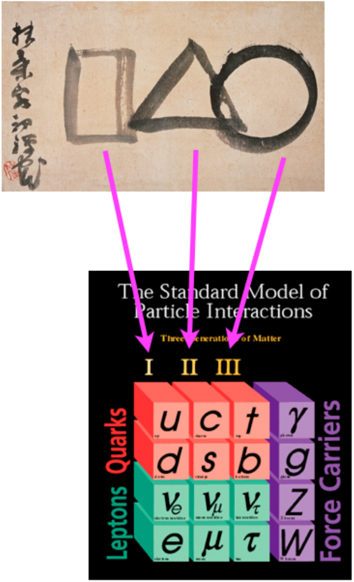
Kennin-ji temple, Kyoto

Sengai Gibon, 1750-1837

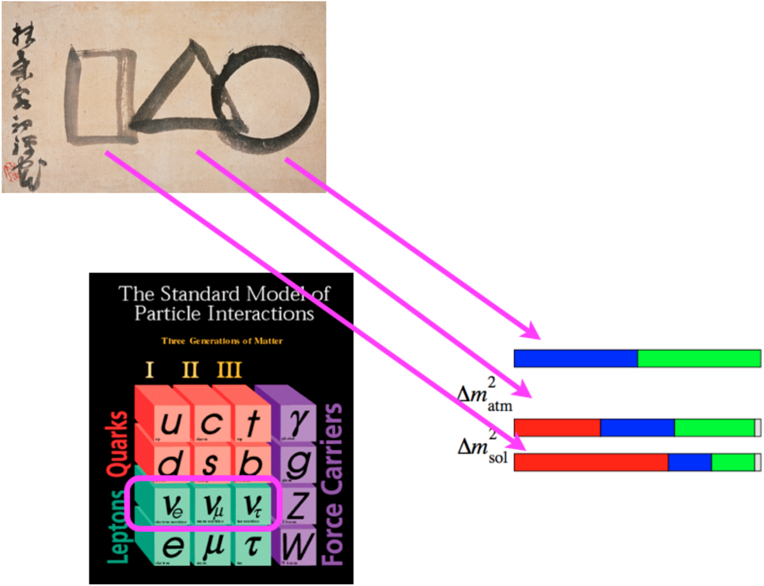
Kennin-ji temple, Kyoto

Sengai Gibon, 1750-1837

> "The idea behind the □△○ is that all things in this universe are represented by these forms."



The Standard Model of
Particle Interactions
Three Generations of Matter
I II III
u c t γ
d s b g
ν_e ν_μ ν_τ Z
e μ τ W
Quarks
Leptons
Force Carriers

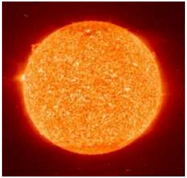


The Standard Model of Particle Interactions
Three Generations of Matter
I II III
Quarks
Leptons
Force Carriers
u c t γ
d s b g
ν_e ν_μ ν_τ Z
e μ τ W
$\Delta m^2_{\rm atm}$
$\Delta m^2_{\rm sol}$

Global data on neutrino oscillations

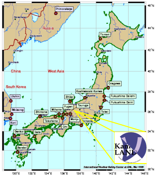
from various neutrino sources and
vastly different energy and distance scales:

sun



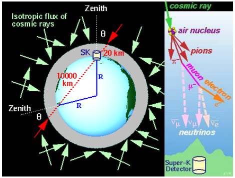
Homestake,SAGE,GALLEX
SuperK, SNO, Borexino

reactors



KamLAND, CHOOZ
D-Chooz, DayaBay, RENO

atmosphere



SuperKamiokande

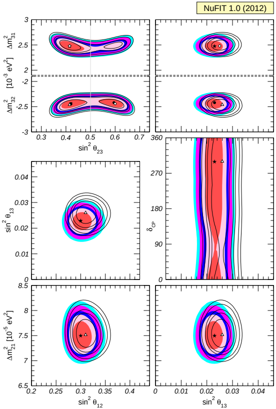
accelerators

K2K, MINOS, T2K

- global data nicely fitted with the 3 neutrinos from the SM!

Three-flavour global fit

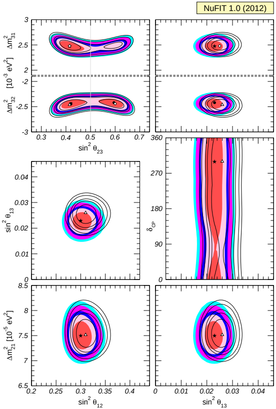
	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.302^{+0.013}_{-0.012}$	$0.267 \to 0.344$
$\theta_{12}/^\circ$	$33.36^{+0.81}_{-0.78}$	$31.09 \to 35.89$
$\sin^2\theta_{23}$	$0.413^{+0.037}_{-0.025} \oplus 0.594^{+0.021}_{-0.022}$	$0.342 \to 0.667$
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.3}_{-1.3}$	$35.8 \to 54.8$
$\sin^2\theta_{13}$	$0.0227^{+0.0023}_{-0.0024}$	$0.0156 \to 0.0299$
$\theta_{13}/^\circ$	$8.66^{+0.44}_{-0.46}$	$7.19 \to 9.96$
$\delta_{\mathrm{CP}}/^\circ$	300^{+66}_{-138}	$0 \to 360$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.18}_{-0.19}$	$7.00 \to 8.09$
$\dfrac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$+2.473^{+0.070}_{-0.067}$	$+2.276 \to +2.695$
$\dfrac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.427^{+0.042}_{-0.065}$	$-2.649 \to -2.242$



Gonzalez-Garcia, Maltoni, Salvado, TS, 1209.3023; www.nu-fit.org

Three-flavour global fit

	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.302^{+0.013}_{-0.012}$	$0.267 \to 0.344$
$\theta_{12}/^\circ$	$33.36^{+0.81}_{-0.78}$	$31.09 \to 35.89$
$\sin^2\theta_{23}$	$0.413^{+0.037}_{-0.025} \oplus 0.594^{+0.021}_{-0.022}$	$0.342 \to 0.667$
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.3}_{-1.3}$	$35.8 \to 54.8$
$\sin^2\theta_{13}$	$0.0227^{+0.0023}_{-0.0024}$	$0.0156 \to 0.0299$
$\theta_{13}/^\circ$	$8.66^{+0.44}_{-0.46}$	$7.19 \to 9.96$
$\delta_{\mathrm{CP}}/^\circ$	300^{+66}_{-138}	$0 \to 360$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.18}_{-0.19}$	$7.00 \to 8.09$
$\dfrac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$+2.473^{+0.070}_{-0.067}$	$+2.276 \to +2.695$
$\dfrac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.427^{+0.042}_{-0.065}$	$-2.649 \to -2.242$

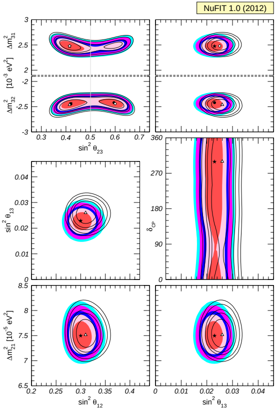


Gonzalez-Garcia, Maltoni, Salvado, TS, 1209.3023; www.nu-fit.org

Job completed?

Three-flavour global fit

	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.302^{+0.013}_{-0.012}$	$0.267 \to 0.344$
$\theta_{12}/^\circ$	$33.36^{+0.81}_{-0.78}$	$31.09 \to 35.89$
$\sin^2\theta_{23}$	$0.413^{+0.037}_{-0.025} \oplus 0.594^{+0.021}_{-0.022}$	$0.342 \to 0.667$
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.3}_{-1.3}$	$35.8 \to 54.8$
$\sin^2\theta_{13}$	$0.0227^{+0.0023}_{-0.0024}$	$0.0156 \to 0.0299$
$\theta_{13}/^\circ$	$8.66^{+0.44}_{-0.46}$	$7.19 \to 9.96$
$\delta_{\rm CP}/^\circ$	300^{+66}_{-138}	$0 \to 360$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.18}_{-0.19}$	$7.00 \to 8.09$
$\dfrac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$+2.473^{+0.070}_{-0.067}$	$+2.276 \to +2.695$
$\dfrac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.427^{+0.042}_{-0.065}$	$-2.649 \to -2.242$



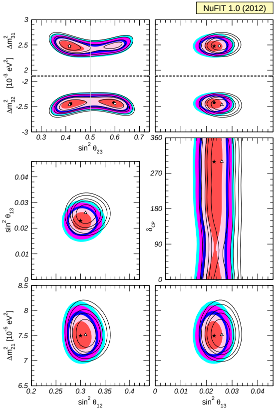
Gonzalez-Garcia, Maltoni, Salvado, TS, 1209.3023; www.nu-fit.org

Job completed? NO!

- mass ordering, CP violation, absolute neutrino mass, Majorana nature

Three-flavour global fit

	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.302^{+0.013}_{-0.012}$	$0.267 \to 0.344$
$\theta_{12}/^\circ$	$33.36^{+0.81}_{-0.78}$	$31.09 \to 35.89$
$\sin^2\theta_{23}$	$0.413^{+0.037}_{-0.025} \oplus 0.594^{+0.021}_{-0.022}$	$0.342 \to 0.667$
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.3}_{-1.3}$	$35.8 \to 54.8$
$\sin^2\theta_{13}$	$0.0227^{+0.0023}_{-0.0024}$	$0.0156 \to 0.0299$
$\theta_{13}/^\circ$	$8.66^{+0.44}_{-0.46}$	$7.19 \to 9.96$
$\delta_{CP}/^\circ$	300^{+66}_{-138}	$0 \to 360$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.18}_{-0.19}$	$7.00 \to 8.09$
$\dfrac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$+2.473^{+0.070}_{-0.067}$	$+2.276 \to +2.695$
$\dfrac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.427^{+0.042}_{-0.065}$	$-2.649 \to -2.242$



Gonzalez-Garcia, Maltoni, Salvado, TS, 1209.3023; www.nu-fit.org

Job completed? NO!

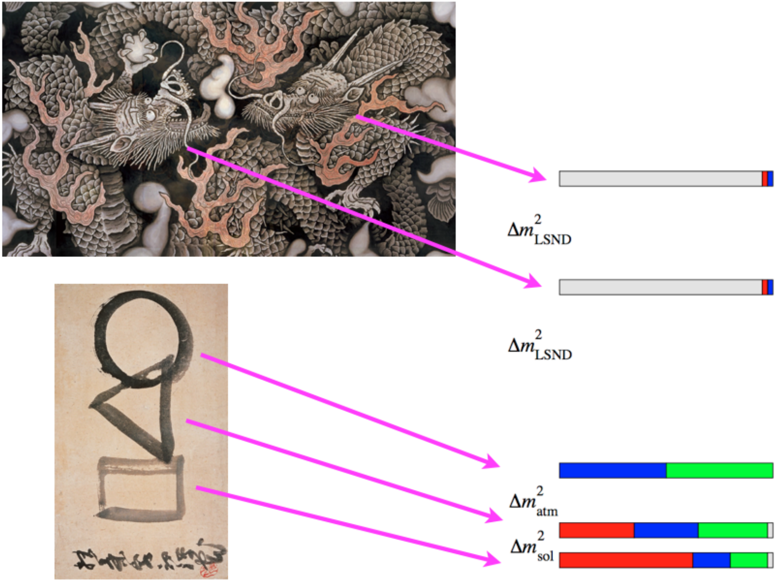
- mass ordering, CP violation, absolute neutrino mass, Majorana nature
- several anomalies at the $\sim 3\sigma$ level do not fit into this picture

Anomalies

- LSND hint for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations with $E/L \sim 1$ eV^2
- MiniBooNE search for $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ at similar E/L
- Reactor anomaly: new evaluation of reactor neutrino flux suggests $\bar{\nu}_e$ disappearance at very short distance
- Gallium anomaly: radio active source measurments in Gallium solar neutrino experiments

Maybe Sengai Gibon was wrong, and there are beasts, which cannot be represented by  ?

Twin Dragons, Kennin-ji Temple, Kyoto


$\Delta m^2_{\mathrm{LSND}}$
$\Delta m^2_{\mathrm{LSND}}$
$\Delta m^2_{\mathrm{atm}}$
$\Delta m^2_{\mathrm{sol}}$

Sterile neutrinos - a very simple extension of the SM

"sterile neutrinos": fermionic gauge singlets or right-handed neutrinos

Yukawa term:

$$\mathcal{L}_Y = -y \bar{L}_L \tilde{\phi} N_R + \mathrm{h.c.}$$

bare Majorana mass term:

$$\frac{1}{2} N_R^T C^{-1} M_R^* N_R + \mathrm{h.c.}$$

- can have any number of them
  (no requirement from anomaly cancellation for true singlets)
- we have no (very little) guidance about their mass (y and M_R)
  M_R is not related to the Higgs VEV (unlike for charged fermions)
  $\Rightarrow$ new scale in the theory

Sterile neutrinos at which scale?

- a comon prejustice is that they should be heavy:
  10^{15} GeV (GUT-motivation?) $\rightarrow$ seesaw
  10^{10} GeV (Leptogenesis)
- maybe sterile neutrinos are related to new physics at the TeV scale? (TeV scale L-R models, RPV SUSY, radiative neutrino mass, ...)
- maybe they have mass in the GeV range (Leptogenesis by oscillations) Shaposhnikov et al
- maybe they have mass in the keV range (warm dark matter)
- maybe they have mass in the eV range (SBL neutrino oscillations)
- maybe they have a mass highly degenerate with the active neutrinos (10^{-5} eV^2) $\rightarrow$ missing upturn of P_{ee} in solar neutrinos deHolanda, Smirnov

Sterile neutrinos at which scale?

- a comon prejustice is that they should be heavy:
  10^{15} GeV (GUT-motivation?) $\rightarrow$ seesaw
  10^{10} GeV (Leptogenesis)
- maybe sterile neutrinos are related to new physics at the TeV scale?
  (TeV scale L-R models, RPV SUSY, radiative neutrino mass, ...)
- maybe they have mass in the GeV range
  (Leptogenesis by oscillations) Shaposhnikov et al
- maybe they have mass in the keV range (warm dark matter)
- maybe they have mass in the eV range (SBL neutrino oscillations)
- maybe they have a mass highly degenerate with the active neutrinos (10^{-5} eV^2) $\rightarrow$ missing upturn of P_{ee} in solar neutrinos deHolanda, Smirnov

Sterile neutrinos at which scale?

- a comon prejustice is that they should be heavy:
  10^{15} GeV (GUT-motivation?) $\rightarrow$ seesaw
  10^{10} GeV (Leptogenesis)

- maybe sterile neutrinos are related to new physics at the TeV scale?
  (TeV scale L-R models, RPV SUSY, radiative neutrino mass, ...)

- maybe they have mass in the GeV range
  (Leptogenesis by oscillations) Shaposhnikov et al

- maybe they have mass in the keV range (warm dark matter)

- maybe they have mass in the eV range (SBL neutrino oscillations)

- maybe they have a mass highly degenerate with the active neutrinos (10^{-5} eV^2) $\rightarrow$ missing upturn of P_{ee} in solar neutrinos deHolanda, Smirnov

Sterile neutrinos at which scale?

- a comon prejustice is that they should be heavy:
  10^{15} GeV (GUT-motivation?) $\rightarrow$ seesaw
  10^{10} GeV (Leptogenesis)
- maybe sterile neutrinos are related to new physics at the TeV scale?
  (TeV scale L-R models, RPV SUSY, radiative neutrino mass, ...)
- maybe they have mass in the GeV range
  (Leptogenesis by oscillations) Shaposhnikov et al
- maybe they have mass in the keV range (warm dark matter)
- maybe they have mass in the eV range (SBL neutrino oscillations)
- maybe they have a mass highly degenerate with the active neutrinos (10^{-5} eV^2) $\rightarrow$ missing upturn of P_{ee} in solar neutrinos deHolanda, Smirnov

Sterile neutrinos at which scale?

- a comon prejustice is that they should be heavy:
  10^{15} GeV (GUT-motivation?) $\rightarrow$ seesaw
  10^{10} GeV (Leptogenesis)

- maybe sterile neutrinos are related to new physics at the TeV scale?
  (TeV scale L-R models, RPV SUSY, radiative neutrino mass, ...)

- maybe they have mass in the GeV range
  (Leptogenesis by oscillations) Shaposhnikov et al

- maybe they have mass in the keV range (warm dark matter)

- maybe they have mass in the eV range (SBL neutrino oscillations)

- maybe they have a mass highly degenerate with the active neutrinos
  (10^{-5} eV^2) $\rightarrow$ missing upturn of P_{ee} in solar neutrinos deHolanda, Smirnov

Sterile neutrinos at which scale?

- a comon prejustice is that they should be heavy:
  10^{15} GeV (GUT-motivation?) $\to$ seesaw
  10^{10} GeV (Leptogenesis)
- maybe sterile neutrinos are related to new physics at the TeV scale?
  (TeV scale L-R models, RPV SUSY, radiative neutrino mass, ...)
- maybe they have mass in the GeV range
  (Leptogenesis by oscillations) Shaposhnikov et al
- maybe they have mass in the keV range (warm dark matter)
- maybe they have mass in the eV range (SBL neutrino oscillations)
- maybe they have a mass highly degenerate with the active neutrinos (10^{-5} eV^2) $\to$ missing upturn of P_{ee} in solar neutrinos deHolanda, Smirnov

Sterile neutrinos at which scale?

- a comon prejustice is that they should be heavy:
  10^{15} GeV (GUT-motivation?) $\rightarrow$ seesaw
  10^{10} GeV (Leptogenesis)

- maybe sterile neutrinos are related to new physics at the TeV scale?
  (TeV scale L-R models, RPV SUSY, radiative neutrino mass, ...)

- maybe they have mass in the GeV range
  (Leptogenesis by oscillations) Shaposhnikov et al

- maybe they have mass in the keV range (warm dark matter)

- maybe they have mass in the eV range (SBL neutrino oscillations)

- maybe they have a mass highly degenerate with the active neutrinos (10^{-5} eV^2) $\rightarrow$ missing upturn of P_{ee} in solar neutrinos deHolanda, Smirnov

Sterile neutrinos at which scale?

- a comon prejustice is that they should be heavy:
  10^{15} GeV (GUT-motivation?) $\longrightarrow$ seesaw
  10^{10} GeV (Leptogenesis)

- maybe sterile neutrinos are related to new physics at the TeV scale?
  (TeV scale L-R models, RPV SUSY, radiative neutrino mass, ...)

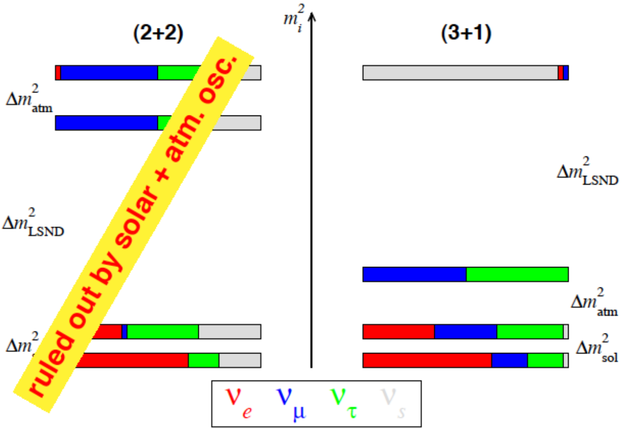
- maybe they have mass in the GeV range
  (Leptogenesis by oscillations) Shaposhnikov et al

- maybe they have mass in the keV range (warm dark matter)

- maybe they have mass in the eV range (SBL neutrino oscillations)

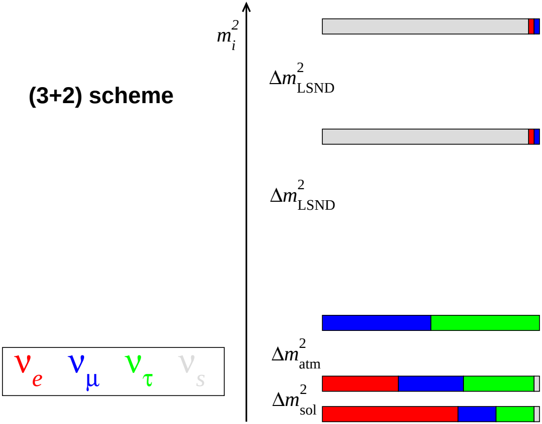
- maybe they have a mass highly degenerate with the active neutrinos (10^{-5} eV^2) $\longrightarrow$ missing upturn of P_{ee} in solar neutrinos deHolanda, Smirnov

4-neutrino schemes



3+1: small perturbation to 3-active case

5-neutrino schemes



Peres, Smirnov, hep-ph/0011054; Sorel, Conrad, Shaevitz, hep-ph/0305255

- In the following I will treat neutrino masses m_i and mixings $U_{\alpha i}$ to be independent $\rightarrow$ arbitrary $n \times n$ neutrino mass matrix $(n = 3 + s)$ "phenomenological model" (PM)

- to be contrasted to "minimal models" (MM), where m_i and $U_{\alpha i}$ emerge from the diagonalization of the seesaw mass matrix

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \qquad \begin{array}{ll} m_D : & 3 \times s\,(\text{complex}) \\ M_R : & s \times s\,(\text{symmetric}) \end{array}$$

Blennow, Fernandez-Martinez, 1107.3992; Fan, Langacker, 1201.6662;

Donini, Hernandez, Lopez-Pavon, Maltoni, TS 1205.5230

	# Δm^2	# angles	# phases
3+2 PM	4	9	5
3+2 MM	4	4	3

Outline

Hints for ν_e disappearance

- The reactor anomaly
- Gallium anomaly
- Global ν_e disappearance data

Hints for $\nu_\mu \to \nu_e$ appearance

- LSND and MiniBooNE

Can we explain all the hints together?

- 3+1
- 3+2

More exotic proposals

Cosmology

Sterile neutrino projects

Conclusions

Outline

Hints for ν_e disappearance
- The reactor anomaly
- Gallium anomaly
- Global ν_e disappearance data

Hints for $\nu_\mu \to \nu_e$ appearance
- LSND and MiniBooNE

Can we explain all the hints together?
- 3+1
- 3+2

More exotic proposals

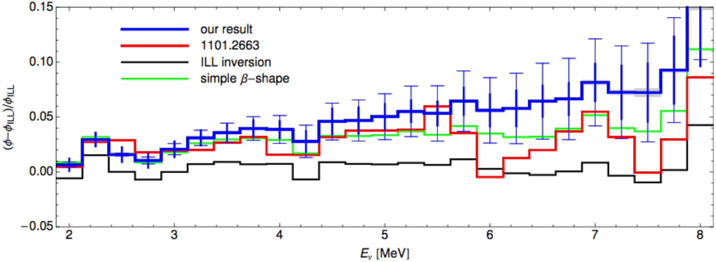
Cosmology

Sterile neutrino projects

Conclusions

New reactor flux calculations

- to predict the $\bar{\nu}_e$ flux from nuclear reactors one has to convert the measured e^- spectra from ^{235}U, ^{239}Pu, ^{241}Pu into neutrino spectra
  Schreckenbach et al., 82, 85, 89
- recent improved calculation Mueller et al., 1101.2663 $\sim$ 3% higher fluxes (ab initio calculations + virtual branches for missing part)
- confirmed by independent calculation P. Huber, 1106.0687 (virtual branches)



New reactor flux calculations

- to predict the $\bar{\nu}_e$ flux from nuclear reactors one has to convert the measured e^- spectra from ^{235}U, ^{239}Pu, ^{241}Pu into neutrino spectra
  Schreckenbach et al., 82, 85, 89
- recent improved calculation Mueller et al., 1101.2663 $\sim$ 3% higher fluxes (ab initio calculations + virtual branches for missing part)
- confirmed by independent calculation P. Huber, 1106.0687 (virtual branches)
- increase of predicted number of neutrino-induced events compared to old flux calculations:

^{235}U	^{239}Pu	^{241}Pu	^{238}U
3.7%	4.2%	4.7%	9.8%

New reactor flux calculations and data at $L \lesssim 100$ m

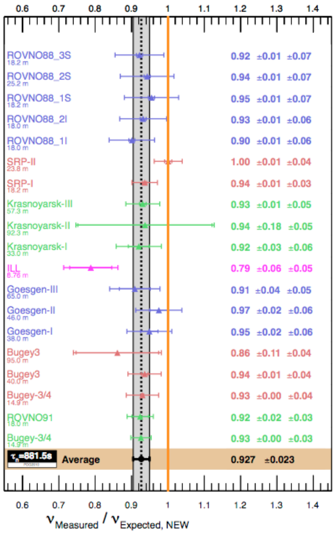
- fitting the data with a free normalization factor f
- taking into account correlations
- flux uncertainties from P. Huber, 1106.0687 (bin-to-bin uncor.: 2nd order polynomial fit + energy dep. fully correlated errors)

$$f = 0.935 \pm 0.024$$

$$\chi^2_{\min} = 15.7/18 \quad (P = 61\%)$$

$$\chi^2_{f=1} = 23.0/19 \quad (P = 2.4\%)$$

$$\Delta\chi^2_{f=1} = 7.25 \quad (2.7\sigma)$$



Mention et al, 1101.2755 (2012 upd)

New reactor flux calculations and data at $L \lesssim 100$ m

- fitting the data with a free normalization factor f
- taking into account correlations
- flux uncertainties from P. Huber, 1106.0687 (bin-to-bin uncor.: 2nd order polynomial fit + energy dep. fully correlated errors)

$$f = 0.935 \pm 0.024$$

$$\chi^2_{\rm min} = 15.7/18 \quad (P = 61\%)$$

$$\chi^2_{f=1} = 23.0/19 \quad (P = 2.4\%)$$

$$\Delta\chi^2_{f=1} = 7.25 \quad (2.7\sigma)$$

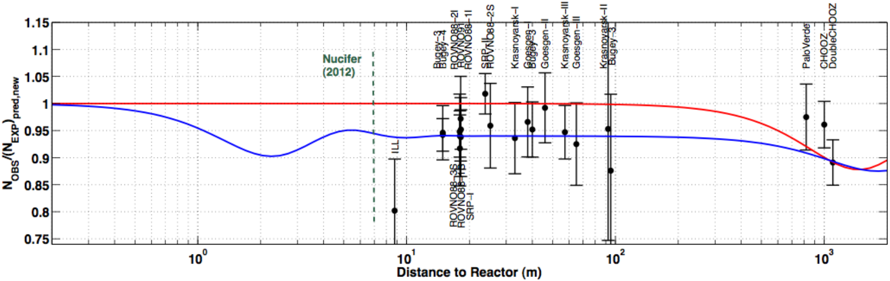
all depends on

- neutron life time
- original ILL electron spectrum normalization

adding an adhoc additional 2% (3%) error reduces the significance to 2.1σ (1.7σ)

New reactor fluxes and global reactor data

Mention et al., 1101.2755



- θ_{13} can reduce flux at $L \gtrsim 1$ km but not at shorter baselines
- sterile neutrino with $\Delta m^2 \sim 1\,\text{eV}^2$ can account for rate reduction at $L \gtrsim 10 - 100$ m

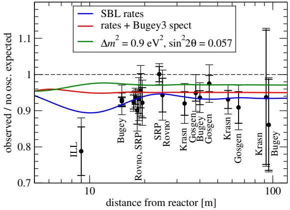
Reactor data and sterile neutrinos

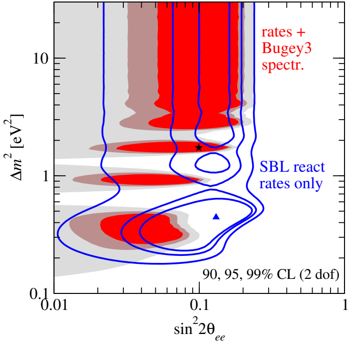
- SBL reactor data (rates only)

$$\sin^2 2\theta = 0.13,\ \Delta m^2 = 0.44\,\mathrm{eV}^2$$
$$\chi^2_{\mathrm{min}} = 11.5/17 \quad (P = 83\%)$$
$$\Delta\chi^2_{\text{no-osc}} = 11.4/2 \quad (99.7\%\mathrm{CL}, 2.9\sigma)$$

- SBL reactor data (incl. Bugey3 spectral data)

$$\sin^2 2\theta = 0.099,\ \Delta m^2 = 1.75\,\mathrm{eV}^2$$
$$\chi^2_{\mathrm{min}} = 58.3/74 \quad (P = 91\%)$$
$$\Delta\chi^2_{\text{no-osc}} = 9.0/2 \quad (98.9\%\mathrm{CL}, 2.5\sigma)$$





The Gallium anomaly Acero,Giunti,Laveder,0711.4222; Giunti,Laveder,1006.3244

radioactive sources in gallium solar neutrino exps.: $\nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + e^-$

^{51}Cr:	747 keV (81.6%)	427 keV (9.0%)	752 keV (8.5%)	432 keV (0.9%)
^{37}Ar:	811 keV (90.2%)	813 keV (9.8%)		

compare observed rate to expected rate according to cross section calculations

the reaction $\nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + e^-$
can proceed to the ground state or
through excited states of ^{71}Ge

previous calculations based on Bahcall hep-ph/9710491, Haxton nucl-th/9804011
recent measurement of $^{71}\text{Ga}(^3\text{He}, t)^{71}\text{Ge}$ D. Frekers et al., PLB 706, 134 (2011):

- contribution of $7.2 \pm 2.0\%$ from excited states (for ^{51}Cr)
- correction of ratios relative to Bahcall expectation
  by factor 0.982 (0.977) for Cr (Ar) sources

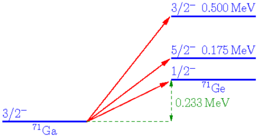
The Gallium anomaly Acero,Giunti,Laveder,0711.4222; Giunti,Laveder,1006.3244

radioactive sources in gallium solar neutrino exps.: $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$

^{51}Cr:	747 keV (81.6%)	427 keV (9.0%)	752 keV (8.5%)	432 keV (0.9%)
^{37}Ar:	811 keV (90.2%)	813 keV (9.8%)		

compare observed rate to expected rate according to cross section calculations

the reaction $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$ can proceed to the ground state or through excited states of ^{71}Ge



previous calculations based on Bahcall hep-ph/9710491, Haxton nucl-th/9804011

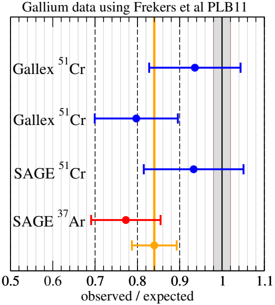
recent measurement of $^{71}\text{Ga}(^3\text{He}, t)^{71}\text{Ge}$ D. Frekers et al., PLB 706, 134 (2011):

- contribution of $7.2 \pm 2.0\%$ from excited states (for ^{51}Cr)
- correction of ratios relative to Bahcall expectation by factor 0.982 (0.977) for Cr (Ar) sources

The Gallium anomaly

combined fit:

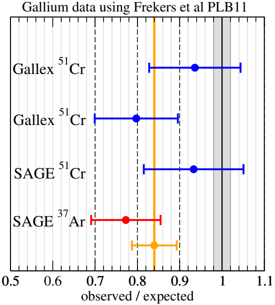
$$\chi^2_{\rm min} = 2.3/3\,{\rm dof}$$
$$r = 0.84^{+0.054}_{-0.051}$$
$$\Delta\chi^2_{r=1} = 8.7\,(2.9\sigma)$$



The Gallium anomaly

combined fit:

$$\chi^2_{\min} = 2.3/3\,\mathrm{dof}$$
$$r = 0.84^{+0.054}_{-0.051}$$
$$\Delta\chi^2_{r=1} = 8.7\,(2.9\sigma)$$



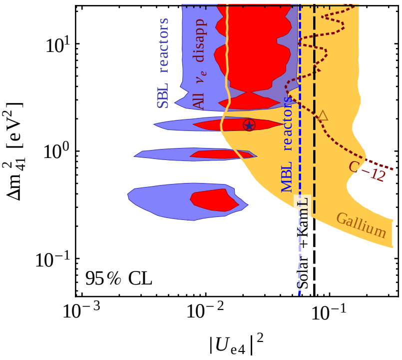
oscillations with $\Delta m^2 \sim 1$ eV^2 can lead to reduction of the ν_e flux within the detector volume: see e.g., Acero,Giunti,Laveder,0711.4222

$$R = \frac{\sum_{i,\mathrm{lines}} \mathrm{Br}_i \sigma_i \int_V d^3x\, P(L/E_i)/L^2}{\sum_{i,\mathrm{lines}} \mathrm{Br}_i \sigma_i \int_V d^3x\, 1/L^2}$$

similar oscillation parameters as needed for reactor anomaly

Global ν_e disappearance data

- reactor and gallium anomalies
- reactors at larger baselines (Chooz, Palo Verde, DoubleChooz, DayaBay, RENO, KamLAND)
- ν_e disappearance constraints from LSND and KARMEN from $\nu_e + ^{12}\mathrm{C} \to ^{12}\mathrm{N} + e^-$
  J. Reichenbacher, PhD U.Karlsruhe 05;
  Conrad, Shaevitz, 1106.5552
- solar neutrinos: degeneracy between θ_{13} and θ_{14} e.g.Palazzo 11
  determination of θ_{13} by reactors leads to a non-trivial bound on ν_e mixing with eV-scale states from solar + KamLAND

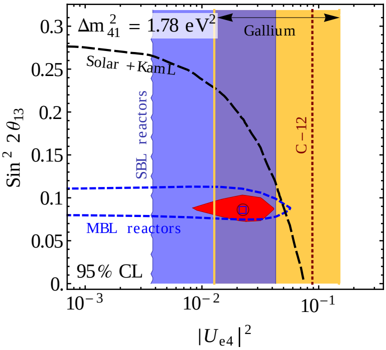


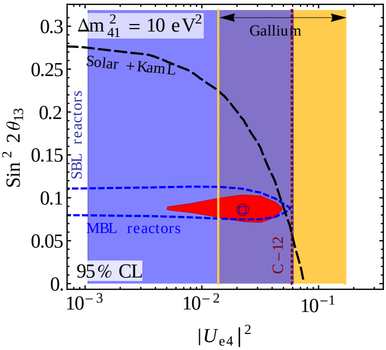
$\sin^2 2\theta = 0.09\,, \quad \Delta m^2 = 1.78\,\mathrm{eV}^2$

$\chi^2_{\text{min}} = 296.8/328\,(64\%)$

$\Delta\chi^2_{\text{no-osc}} = 12.9/2 \quad (99.8\%\mathrm{CL}, 3.1\sigma)$

Is the θ_{13} measurement affected by sterile neutrinos?





robust θ_{13} determination from near/far comparison at Daya Bay, RENO

Outline

Hints for ν_e disappearance
- The reactor anomaly
- Gallium anomaly
- Global ν_e disappearance data

Hints for $\nu_\mu \to \nu_e$ appearance
- LSND and MiniBooNE

Can we explain all the hints together?
- 3+1
- 3+2

More exotic proposals

Cosmology

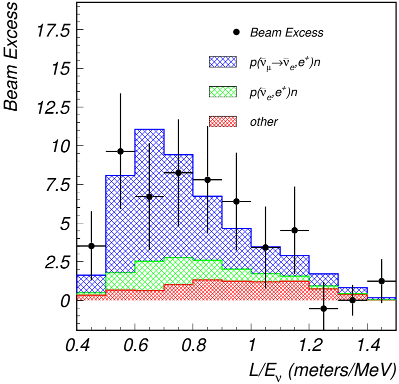
Sterile neutrino projects

Conclusions

LSND

signal for $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions at the $E/L \sim 1$ eV^2 scale (3.8σ)

A. Aguilar et al., Phys. Rev. D64, 112007 (2001)



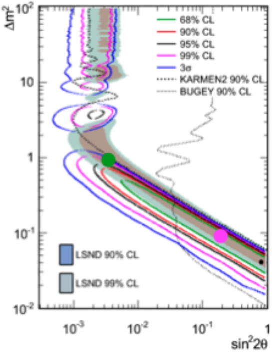
[critique from HARP-CDP 1110.4265, 1112.3852; reply in 1112.2181]

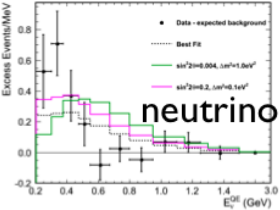
MiniBooNE C. Polly Neutrino2012

Simultaneous 3+1 fit to ν and anti-ν data

- WS accounted for properly
- Construction of correlated systematic error matrix (Z. Pavlovic)
- E>200 MeV BF preferred at 3.8σ over null

Total Excess: 240.3 +/- 34.5 +/- 52.6

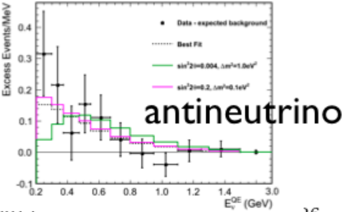




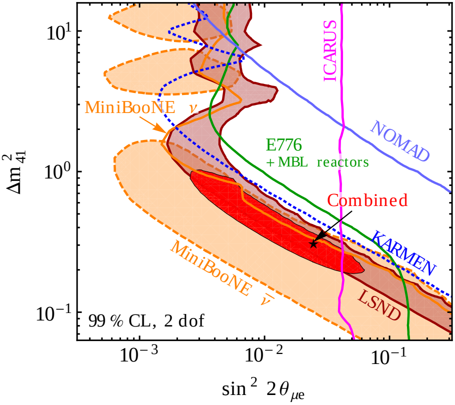
LSND: 3.8σ

* Simultaneous fit (E>200 MeV) with fully-correlated systematic to entire MB neutrino and anti-neutrino data

combined	E > 200 MeV	E > 475 MeV
χ^2(null)	42.53	12.87
Prob(null)	0.1%	35.8%
χ^2(bf)	24.72	10.67
Prob(bf)	6.7%	35.8%



Global data on SBL $\nu_\mu \to \nu_e$ appearance



Outline

Hints for ν_e disappearance
- The reactor anomaly
- Gallium anomaly
- Global ν_e disappearance data

Hints for $\nu_\mu \to \nu_e$ appearance
- LSND and MiniBooNE

Can we explain all the hints together?
- 3+1
- 3+2

More exotic proposals

Cosmology

Sterile neutrino projects

Conclusions

3+1 SBL oscillations

appearance

$$P_{\mu e} = \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

disappearance ($\alpha = e, \mu$)

$$P_{\alpha\alpha} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\alpha\alpha} = 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)$$

- effective 2-flavour oscillations
- no CP violation $\longrightarrow$ same results for $\bar{\nu}$ (LSND, MB) and ν (MB) data

3+1 SBL oscillations

appearance

$$P_{\mu e} = \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\mu e} = 4|U_{e4}|^2 |U_{\mu 4}|^2$$

disappearance ($\alpha = e, \mu$)

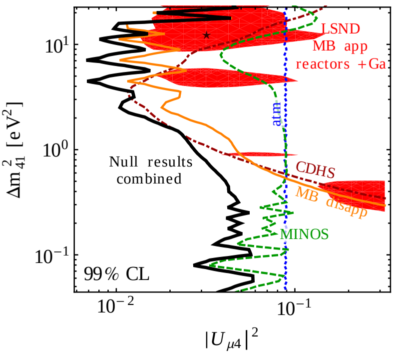
$$P_{\alpha\alpha} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2)$$

$$\boxed{\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}}$$

$\nu_\mu \to \nu_e$ app. signal requires also signal in both, ν_e and ν_μ disappearance (appearance mixing angle quadratically suppressed)

Limits on ν_μ disappearance

- CDHS PLB 1984
- SuperK atmospherics Bilenky, Giunti, Grimus, TS 99; Maltoni, TS, Valle 01
- MINOS 1001.0336, 1104.3922 (CC data most important)
- MiniBooNE $\nu_\mu(\bar{\nu}_\mu)$ disappearance 1106.5685



additional constraints not included in following analysis from atmospheric data in IceCube Nunokawa, Peres, Zukanovich 03; Choubey 07;Razzaque, Smirnov 11, 12; Barger, Gao, Marfatia 11; Esmaili, Halzen, Peres 12

Fitting all together?

there are three classes of data:

$\nu_e \to \nu_e$ disappearance	$\sin^2 2\theta_{ee}$
$\nu_\mu \to \nu_\mu$ disappearance	$\sin^2 2\theta_{\mu\mu}$
$\nu_\mu \to \nu_e$ appearance	$\sin^2 2\theta_{\mu e}$

$$\boxed{\sin^2 2\theta_{\mu e} \approx \frac{1}{4}\sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}}$$

- each combination of two sets is consistent (they depend on different mixing parameters)
- BUT: strong tension if all three of them are combined

Fitting all together?

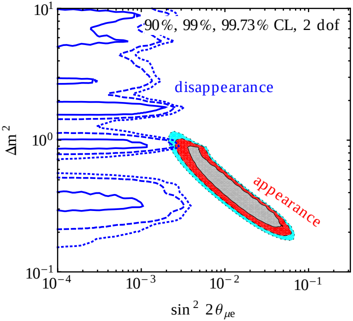
there are three classes of data:

$\nu_e \to \nu_e$ disappearance $\sin^2 2\theta_{ee}$

$\nu_\mu \to \nu_\mu$ disappearance $\sin^2 2\theta_{\mu\mu}$

$\nu_\mu \to \nu_e$ appearance $\sin^2 2\theta_{\mu e}$

$$\boxed{\sin^2 2\theta_{\mu e} \approx \frac{1}{4}\sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}}$$



consistency of appearance vs disappearance $\chi^2_{\rm PG} = 18.8/2,\ P = 8 \times 10^{-5}$

Add more sterile neutrinos?

3+2 SBL oscillations:

appearance:

$$\begin{aligned} P_{\nu_\mu \to \nu_e} &= 4\,|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2\phi_{41} + 4\,|U_{e5}|^2 |U_{\mu 5}|^2 \sin^2\phi_{51} \\ &+ 8\,|U_{e4} U_{\mu 4} U_{e5} U_{\mu 5}| \sin\phi_{41} \sin\phi_{51} \cos(\phi_{54} - \delta) \end{aligned}$$

disappearance:

$$P_{\nu_\alpha \to \nu_\alpha} \approx 1 - 4 \sum_{i=4,5} |U_{\alpha i}|^2 \sin^2\phi_{i1} - 4\,|U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2\phi_{54}$$

$$[\phi_{ij} \equiv \Delta m_{ij}^2 L / 4E]$$

- phase $\delta \equiv \arg\left(U_{e4}^* U_{\mu 4} U_{e5} U_{\mu 5}^*\right) \to$ CP violation
  Karagiorgi et al. 06; Maltoni, TS 07

Add more sterile neutrinos?

3+2 SBL oscillations:

appearance:

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

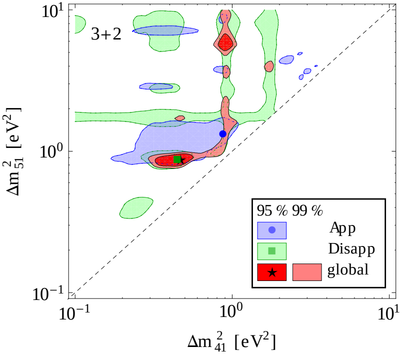
disappearance:

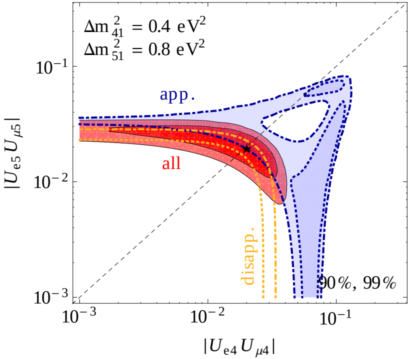
$$P_{\nu_\alpha \to \nu_\alpha} \approx 1 - 4\sum_{i=4,5}|U_{\alpha i}|^2 \sin^2\phi_{i1} - 4\,|U_{\alpha 4}|^2|U_{\alpha 5}|^2 \sin^2\phi_{54}$$

$$\left[\phi_{ij} \equiv \Delta m^2_{ij} L/4E\right]$$

- BUT: constrain $|U_{ei}|$ and $|U_{\mu i}|$ $(i = 4, 5)$ from disappearance to be reconciled with appearance amplitudes $|U_{ei}U_{\mu i}|$

Severe tension also in the 3+2 fit





consistency of appearance vs disappearance $\chi^2_{\rm PG} = 22.5/4,\ P = 1.6 \times 10^{-4}$

$\chi^2_{3+1} - \chi^2_{3+2} = 11.4/4$ (97.8%)

Outline

- Hints for ν_e disappearance
  - The reactor anomaly
  - Gallium anomaly
  - Global ν_e disappearance data
- Hints for $\nu_\mu \to \nu_e$ appearance
  - LSND and MiniBooNE
- Can we explain all the hints together?
  - 3+1
  - 3+2
- More exotic proposals
- Cosmology
- Sterile neutrino projects
- Conclusions

More exotic proposals

- 3-neutrinos and CPT violation Murayama, Yanagida 01; Barenboim, Borissov, Lykken 02; Gonzalez-Garcia, Maltoni, TS 03
- 4-neutrinos and CPT violation Barger, Marfatia, Whisnant 03
- Exotic muon-decay Babu, Pakvasa 02
- CPT viol. quantum decoherence Barenboim, Mavromatos 04
- Lorentz violation Kostelecky et al., 04, 06; Gouvea, Grossman 06
- mass varying ν Kaplan,Nelson,Weiner 04; Zurek 04; Barger,Marfatia,Whisnant 05
- shortcuts of sterile νs in extra dim Paes, Pakvasa, Weiler 05
- decaying sterile neutrino Palomares-Riuz, Pascoli, TS 05; Gninenko 10
- 2 decaying sterile neutrinos with CPV Palomares-Riuz, Pascoli, TS 05
- energy dependent quantum decoherence Farzan, TS, Smirnov 07
- sterile neutrinos and new gauge boson Nelson, Walsh 07
- sterile ν with energy dep. mass or mixing TS 07
- sterile ν with nonstandard interactions Akhmedov, TS 10; Conrad, Karagiorgi, Shaevitz, 12

More exotic proposals

- 3-neutrinos and CPT violation Murayama, Yanagida 01; Barenboim, Borissov, Lykken 02; Gonzalez-Garcia, Maltoni, TS 03
- 4-neutrinos and CPT violation Barger, Marfatia, Whisnant 03
- Exotic muon-decay Babu, Pakvasa 02
- CPT viol. quantum decoherence Barenboim, Mavromatos 04
- Lorentz violation Kostelecky et al., 04, 06; Gouvea, Grossman 06
- mass varying ν Kaplan,Nelson,Weiner 04; Zurek 04; Barger,Marfatia,Whisnant 05
- shortcuts of sterile νs in extra dim Paes, Pakvasa, Weiler 05
- decaying sterile neutrino Palomares-Riuz, Pascoli, TS 05; Gninenko 10
- 2 decaying sterile neutrinos with CPV Palomares-Riuz, Pascoli, TS 05
- energy dependent quantum decoherence Farzan, TS, Smirnov 07
- sterile neutrinos and new gauge boson Nelson, Walsh 07
- sterile ν with energy dep. mass or mixing TS 07
- sterile ν with nonstandard interactions Akhmedov, TS 10; Conrad, Karagiorgi, Shaevitz, 12

most of these proposals involve sterile neutrinos

More exotic proposals

- 3-neutrinos and CPT violation Murayama, Yanagida 01; Barenboim, Borissov, Lykken 02; Gonzalez-Garcia, Maltoni, TS 03
- 4-neutrinos and CPT violation Barger, Marfatia, Whisnant 03
- Exotic muon-decay Babu, Pakvasa 02
- CPT viol. quantum decoherence Barenboim, Mavromatos 04
- Lorentz violation Kostelecky et al., 04, 06; Gouvea, Grossman 06
- mass varying ν Kaplan,Nelson,Weiner 04; Zurek 04; Barger,Marfatia,Whisnant 05
- shortcuts of sterile νs in extra dim Paes, Pakvasa, Weiler 05
- decaying sterile neutrino Palomares-Riuz, Pascoli, TS 05; Gninenko 10
- 2 decaying sterile neutrinos with CPV Palomares-Riuz, Pascoli, TS 05
- energy dependent quantum decoherence Farzan, TS, Smirnov 07
- sterile neutrinos and new gauge boson Nelson, Walsh 07
- sterile ν with energy dep. mass or mixing TS 07
- sterile ν with nonstandard interactions Akhmedov, TS 10; Conrad, Karagiorgi, Shaevitz, 12

most of these proposals have problems with some data

Two examples

Energy dependent quantum decoherence Farzan, TS, Smirnov 07

- no sterile neutrino needed
- LSND signal controlled by the 1-3 mixing: $0.0014 < \sin^2\theta_{13} < 0.034$, reconciled with MB$\nu$ and other null-result exps. by energy dependence
- consistent with solar, KamL, atm, MINOS, and reactor anomaly positive signal for θ_{13} in long-baseline accelerator experiments

Two examples

Energy dependent quantum decoherence Farzan, TS, Smirnov 07

- no sterile neutrino needed
- LSND signal controlled by the 1-3 mixing: $0.0014 < \sin^2\theta_{13} < 0.034$, reconciled with MB$\nu$ and other null-result exps. by energy dependence
- consistent with solar, KamL, atm, MINOS, and reactor anomaly positive signal for θ_{13} in long-baseline accelerator experiments
- BUT: near/far at reactors: null-result $\longrightarrow$ Excluded by Daya Bay/RENO!

Two examples

Energy dependent quantum decoherence Farzan, TS, Smirnov 07

- no sterile neutrino needed
- LSND signal controlled by the 1-3 mixing: $0.0014 < \sin^2\theta_{13} < 0.034$, reconciled with MB$\nu$ and other null-result exps. by energy dependence
- consistent with solar, KamL, atm, MINOS, and reactor anomaly positive signal for θ_{13} in long-baseline accelerator experiments
- BUT: near/far at reactors: null-result $\longrightarrow$ Excluded by Daya Bay/RENO!

Sterile neutrino + non-standard interactions Akhmedov, TS 10

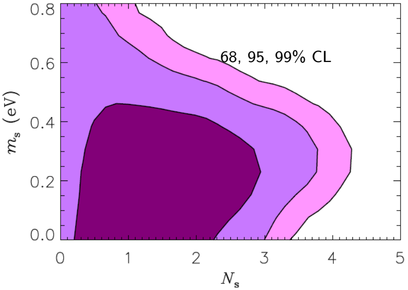
- 4th neutrino with $\Delta m^2_{41} \sim 1$ eV^2
- new type of CC-like interaction, different for LSND and other exps
- required NSI strength of few % is consistent with direct bounds, but gauge invariant UV completion difficult (LFV, collider constraints)

  Biggio, Blennow, Fernandez-Martinez, 0907.0097; Gavela, Hernandez, Ota, Winter, 0809.3451; Antusch, Baumann, Fernandez, 0807.1003; Davidson, Sanz, 1108.5320

Outline

eV sterile neutrinos and cosmology

Hamann et al., 1006.5276

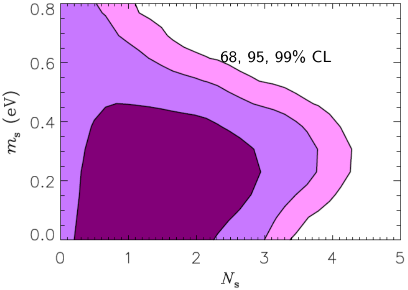


- CMB, SDSS, HST: prefer some extra radiation, but limit on HDM excludes two eV-scale neutrinos
- BBN: $N_s < 1.2$ (95% CL)
  Mangano, Serpico, 1103.1261

		$N_{\rm eff}$	$\sum m_\nu$
WMAP 9y 1212.5226	+ACT+SPT+BAO+H_0	3.84 ± 0.40	< 0.44 eV (95%)
SPT 1212.6267	+WMAP 7y+BAO+H_0	3.71 ± 0.35	0.32 ± 0.11 eV (68%)
ATC 1301.0824	+WMAP 7yr+BAO+H_0	3.52 ± 0.39	< 0.39 eV (95%)

eV sterile neutrinos and cosmology

Hamann et al., 1006.5276



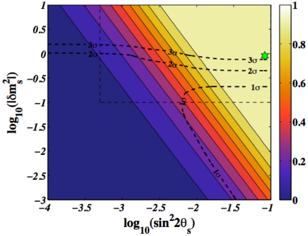
- CMB, SDSS, HST: prefer some extra radiation, but limit on HDM excludes two eV-scale neutrinos
- BBN: $N_s < 1.2$ (95% CL)
  Mangano, Serpico, 1103.1261

		$N_{\rm eff}$	$\sum m_\nu$
WMAP 9y 1212.5226	+ACT+SPT+BAO+H_0	3.84 ± 0.40	< 0.44 eV (95%)
SPT 1212.6267	+WMAP 7y+BAO+H_0	3.71 ± 0.35	0.32 ± 0.11 eV (68%)
ATC 1301.0824	+WMAP 7yr+BAO+H_0	3.52 ± 0.39	< 0.39 eV (95%)

PLANCK: obtain $\delta N_s \approx 0.2$ very soon

eV sterile neutrinos and cosmology

bounds assume full equilibration of sterile neutrinos



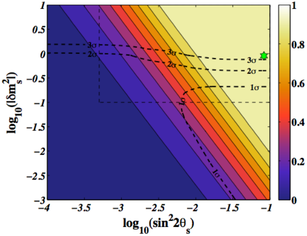
Hannestad, Tamborra, Tram, 1204.5861

... typically fulfilled for LSND or RAA-like mass/mixing

Enqvist, Kainulainen, Thomson, 92; Shi, Schramm, Fields, 93; Okada, Yasuda, 96; Bilenky, Giunti, Grimus, TS, 98; DiBari, 01;...

eV sterile neutrinos and cosmology

bounds assume full equilibration of sterile neutrinos



Hannestad, Tamborra, Tram, 1204.5861

... typically fulfilled for LSND or RAA-like mass/mixing

Enqvist, Kainulainen, Thomson, 92; Shi, Schramm, Fields, 93; Okada, Yasuda, 96; Bilenky, Giunti, Grimus, TS, 98; DiBari, 01;...

invent a mechanism to avoid thermalization

- large chemical potential: $L_\mu = 10^{-2}$
  Foot, Volkas, 95; Chu, Cirelli, 06; Smith, Fuller, Kishimoto, Abazajian, 06; Hannestad, Tamborra, Tram, 12
- assume very low re-heating temperature (dangerously close to BBN)
  Gelmini, Palomares-Ruiz, Pascoli, astro-ph/0403323
- extra radiation + chemical potential for ν_e Hamann, Hannestad, Raffelt, Wong, 1108.4136
- DE equation of state $w < -1$ Elgaroy, Kristiansen, 1104.0704
- assume that we live in a large void, and a modified spectrum of primordial density perturbations (non-scale free) Hunt, Sarkar, 07, 08; Nadathur, Sarkar, 10

Outline

Subjective selection of proposed sterile ν searches

searches for ν_e disappearance:

- reactor experiments (Nucifer, SCRAAM, STEREO,...)
- radio-active source experiments in large detectors
  Ce-LAND (KamLAND), Borexino, SNO+, DayaBay,...

accelerator based searches for eV-scale oscillations

- MiniBooNE extensions (e.g., MicroBooNE)
- LAr-TPC/muon spectrometer at CERN SPS 1208.0862
- stored muon beam (nuSTORM) 1206.0294

other experiments

- MINOS+, atmospheric neutrinos in IceCube

See "Light Sterile Neutrinos: A White Paper" Abazajian et al., 1204.5379

Outline

Conclusions

- There are a couple of "hints" for sterile neutrinos at the eV scale (at the level of $\sim 3\sigma$)
- Hints from ν_e disappearance from reactor and gallium anomalies: consistent with each other, not in disagreement with any other data
- Hints from $\nu_\mu \to \nu_e$ appearance experiments (LSND, MiniB) in strong tension with other data:
  - non-observation of ν_μ disappearance (CDHS, MINOS, SK, MiniB)
- more sterile neutrinos (3+2): more freedom in fit (CPV) tension between appearance and disappearance remains severe

Establishing the existence of sterile neutrinos (at any scale) would be a great discovery of physics beyond the Standard Model!

Merci beaucoup