Phenomenology of Light Sterile Neutrinos

Carlo Giunti

INFN, Sezione di Torino, and Dipartimento di Fisica Teorica, Università di Torino

carlo.giunti@to.infn.it

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

HigPlk 2014

2nd International Workshop on Particle Physics and Cosmology after Higgs and Planck

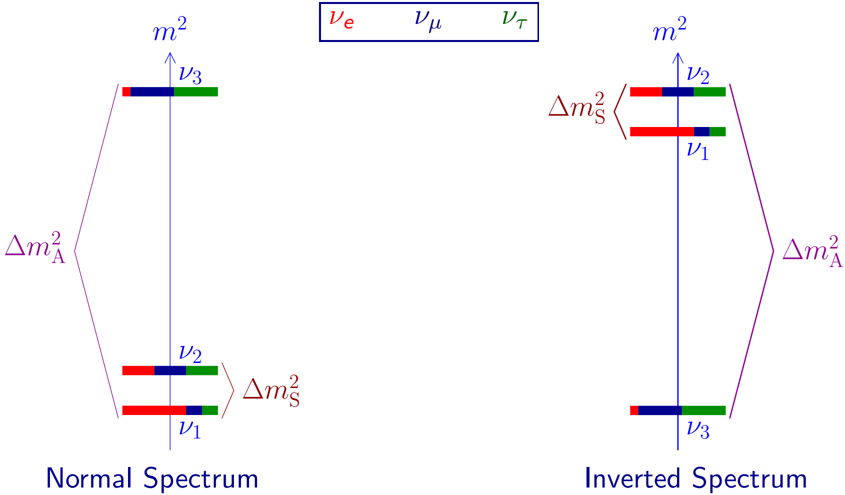
Taiwan

8-11 October 2014

Experimental Evidences of Neutrino Oscillations

Solar $\nu_e \to \nu_\mu, \nu_\tau$	SNO, BOREXino; Super-Kamiokande; GALLEX/GNO, SAGE; Homestake, Kamiokande	$\to$	$\Delta m^2_{\mathrm{S}} \simeq 7.6 \times 10^{-5}\,\mathrm{eV}^2$, $\sin^2\vartheta_{\mathrm{S}} \simeq 0.30$
VLBL Reactor $\bar{\nu}_e$ disappearance	(KamLAND)		
Atmospheric $\nu_\mu \to \nu_\tau$	Super-Kamiokande; Kamiokande, IMB; MACRO, Soudan-2	$\to$	$\Delta m^2_{\mathrm{A}} \simeq 2.4 \times 10^{-3}\,\mathrm{eV}^2$, $\sin^2\vartheta_{\mathrm{A}} \simeq 0.50$
LBL Accelerator ν_μ disappearance	(K2K, MINOS, T2K)		
LBL Accelerator $\nu_\mu \to \nu_\tau$	(Opera)		
LBL Accelerator $\nu_\mu \to \nu_e$	(T2K, MINOS)	$\to$	Δm^2_{A}, $\sin^2\vartheta_{13} \simeq 0.023$
LBL Reactor $\bar{\nu}_e$ disappearance	Daya Bay, RENO; Double Chooz		

Three-Neutrino Mixing Paradigm



absolute mass scale is not determined by neutrino oscillation data

Indications of SBL Oscillations Beyond 3ν Mixing

- Reactor Electron Antineutrino Anomaly: $\bar{\nu}_e \to \bar{\nu}_e$

$$L \simeq 10 - 100\,\text{m} \qquad E \simeq 4\,\text{MeV}$$

$$\sim 3.1\sigma \text{ deficit} \qquad \Delta m^2 \gtrsim 0.5\,\text{eV}^2 \qquad (\gg \Delta m^2_{\text{A}} \gg \Delta m^2_{\text{S}})$$

- Gallium Anomaly: $\nu_e \to \nu_e$

$$L \simeq 1\,\text{m} \qquad E \simeq 1\,\text{MeV}$$

$$\sim 2.9\sigma \text{ deficit} \qquad \Delta m^2 \gtrsim 1\,\text{eV}^2 \qquad (\gg \Delta m^2_{\text{A}} \gg \Delta m^2_{\text{S}})$$

- LSND: Accelerator $\bar{\nu}_\mu \to \bar{\nu}_e$

$$L \simeq 30\,\text{m} \qquad E \simeq 50\,\text{MeV}$$

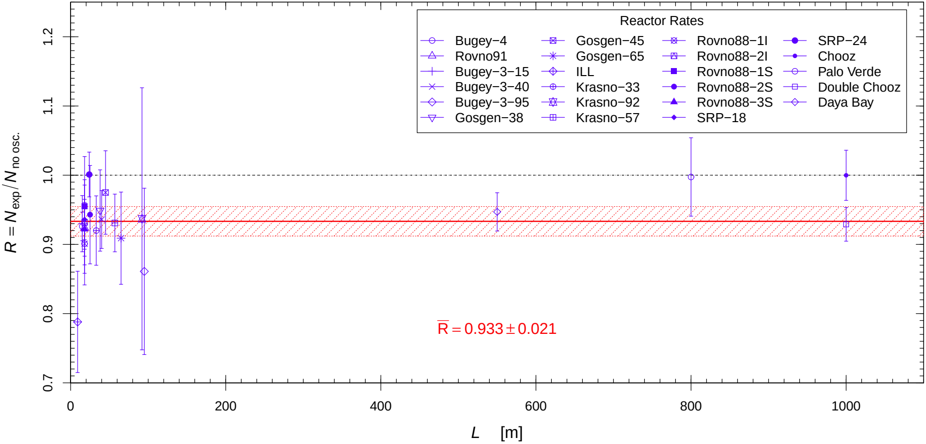
$$\sim 3.8\sigma \text{ excess} \qquad \Delta m^2 \gtrsim 0.2\,\text{eV}^2 \qquad (\gg \Delta m^2_{\text{A}} \gg \Delta m^2_{\text{S}})$$

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]



[see also: Sinev, arXiv:1103.2452; Giunti, Laveder, Li, Liu, Long, PRD 86 (2012) 113014;
Ciuffoli, Evslin, Li, JHEP 12 (2012) 110; Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050;
Zhang, Qian, Vogel, PRD 87 (2013) 073018; Ivanov et al, PRC 88 (2013) 055501]

Gallium Anomaly

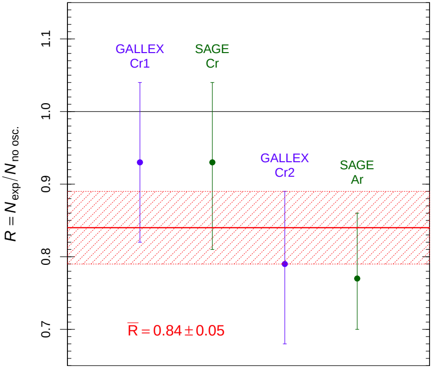
Gallium Radioactive Source Experiments: GALLEX and SAGE

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]

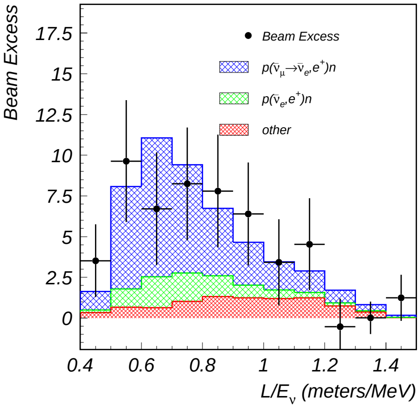
[Laveder et al, Nucl.Phys.Proc.Suppl. 168 (2007) 344; MPLA 22 (2007) 2499; PRD 78 (2008) 073009; PRC 83 (2011) 065504; PRD 86 (2012) 113014]

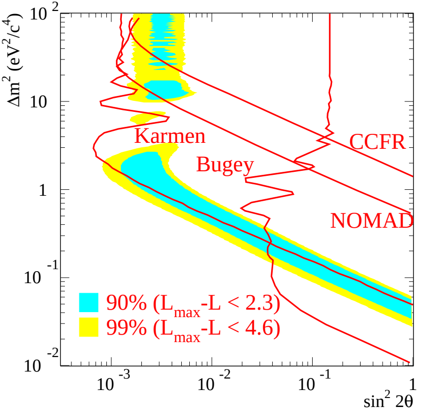
[Mention et al, PRD 83 (2011) 073006]

LSND

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

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



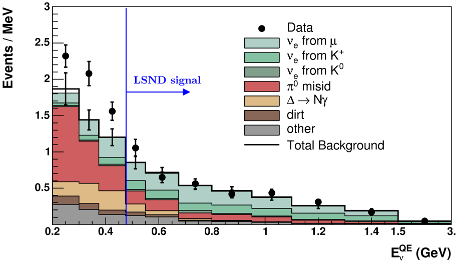


3.8σ excess $\quad \Delta m^2_{\text{LSND}} \gtrsim 0.2\,\text{eV}^2 \quad (\gg \Delta m^2_{\text{A}} \gg \Delta m^2_{\text{S}})$

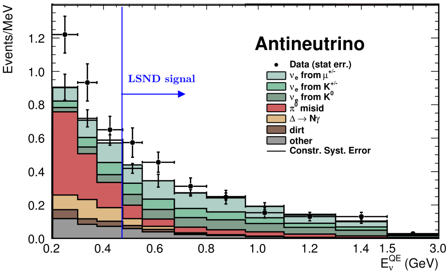
MiniBooNE

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

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



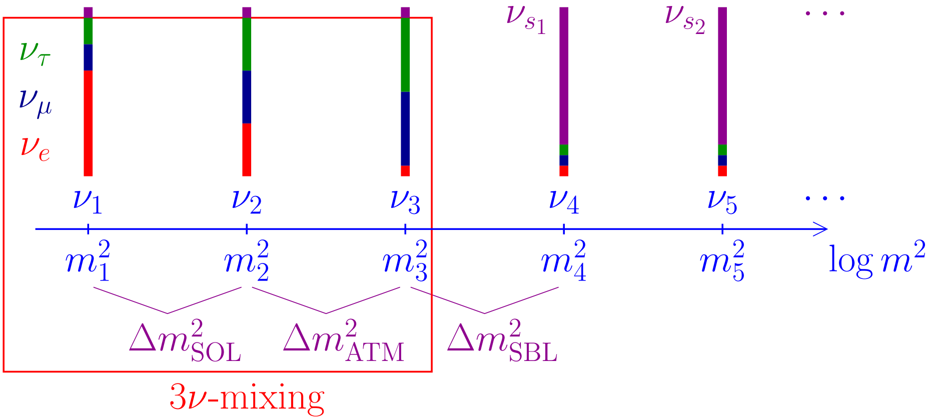
$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]



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

- Agreement with LSND signal?
- CP violation?
- Low-energy anomaly!

Beyond Three-Neutrino Mixing: Sterile Neutrinos



Light Sterile Neutrinos

- Physics Beyond the SM $\Longrightarrow$ right-handed sterile neutrinos
- 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:

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

Effective SBL Oscillation Probabilities in 3+1 Schemes

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

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

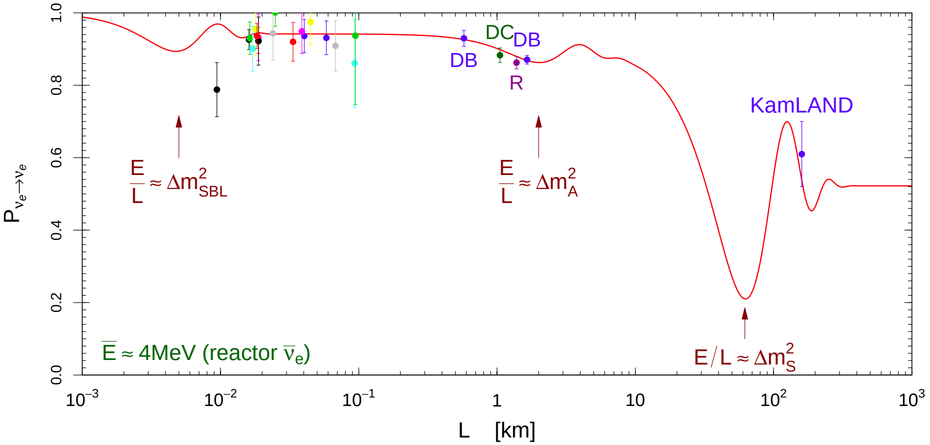
Perturbation of 3ν Mixing: $|U_{e4}|^2 \ll 1\,,\ |U_{\mu 4}|^2 \ll 1\,,\ |U_{\tau 4}|^2 \ll 1\,,\ |U_{s4}|^2 \simeq 1$

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

↑ SBL

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

but CP violation is not observable in SBL experiments!



$$P^{\mathrm{LBL}}_{\overset{(-)}{\nu_e} \to \overset{(-)}{\nu_e}} \simeq 1 - \frac{1}{2} \sin^2 2\vartheta_{14} - \cos^4 \vartheta_{14} \sin^2 2\vartheta_{13} \sin^2 \left(\frac{\Delta m^2_{31} L}{4E} \right)$$

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:

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

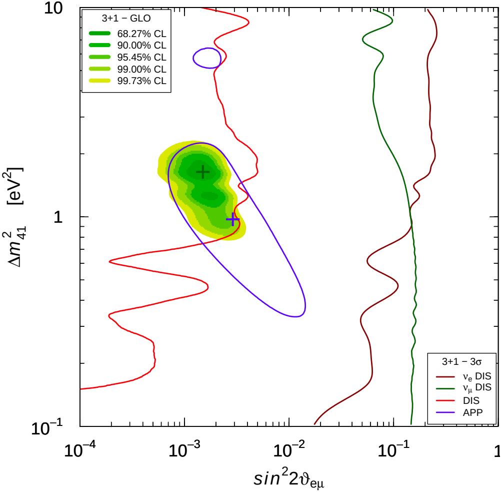
- Upper bounds on $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu}$ $\Longrightarrow$ strong limit on $\sin^2 2\vartheta_{e\mu}$

[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, PRD 88 (2013) 073008]



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

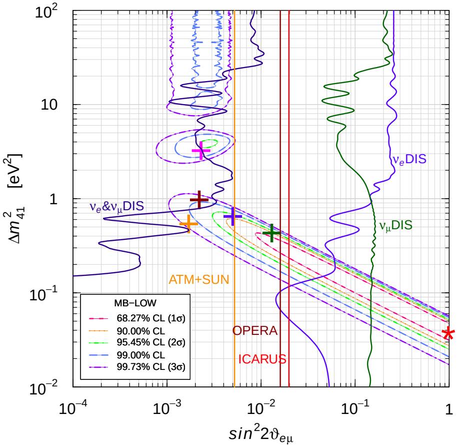
GoF = 29% PGoF = 9%

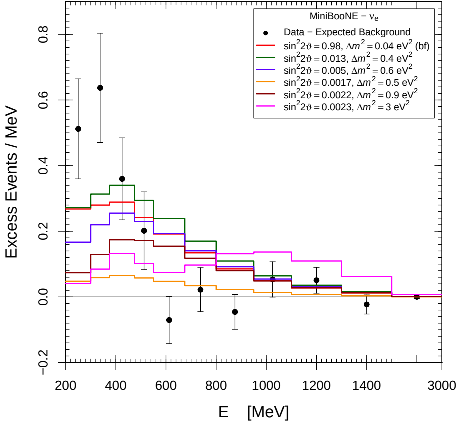
No Osc. excluded at 6.2σ

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

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

MiniBooNE Low-Energy Excess?

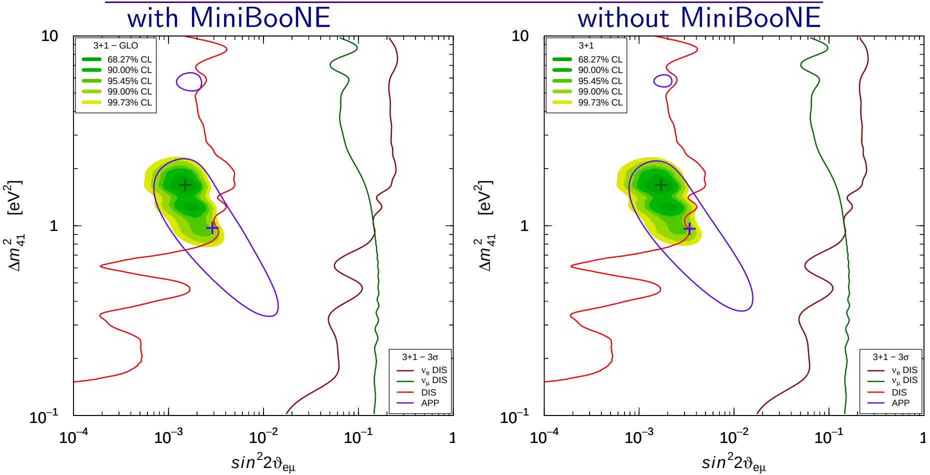




- No fit of low-energy excess for realistic $\sin^2 2\vartheta_{e\mu} \lesssim 5 \times 10^{-3}$
- APP-DIS PGoF $= 0.1\%$
- Neutrino energy reconstruction problem?

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

MiniBooNE Impact on SBL Oscillations?



GoF = 29% PGoF = 9%

No Osc. excluded at 6.2σ

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

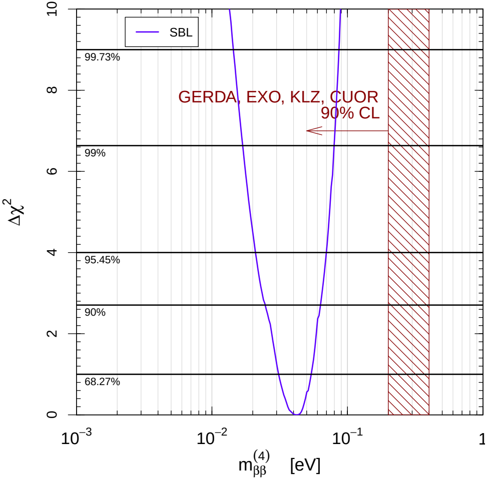
GoF = 19% PGoF = 8%

No Osc. excluded at 6.3σ

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

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

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

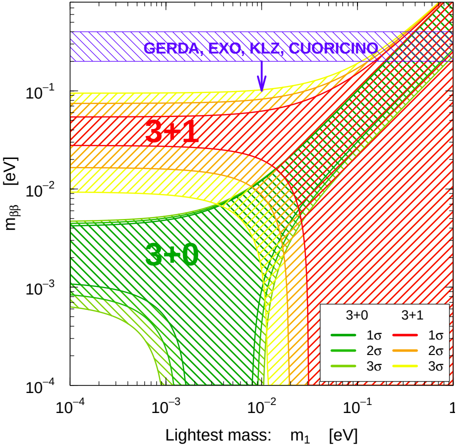
[Barry et al, JHEP 07 (2011) 091]

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

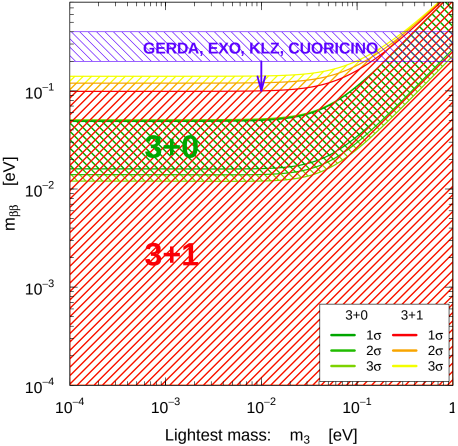
[Rodejohann, JPG 39 (2012) 124008]

[Girardi, Meroni, Petcov, JHEP 1311 (2013) 146]

Normal 3ν Spectrum



Inverted 3ν Spectrum



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:
  - Cosmological data allow $\Delta N_{\text{eff}} \approx 1$.
  - Tension between $\Delta N_{\text{eff}} = 1$ and $m_s \approx 1\,\text{eV}$.