Neutrino Theory and Phenomenology

PART 5

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

NBIA PhD School
Neutrinos underground & in the heavens

The Niels Bohr International Academy, Copenhagen, Denmark

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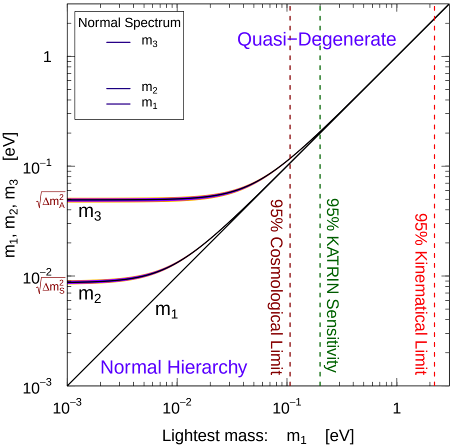
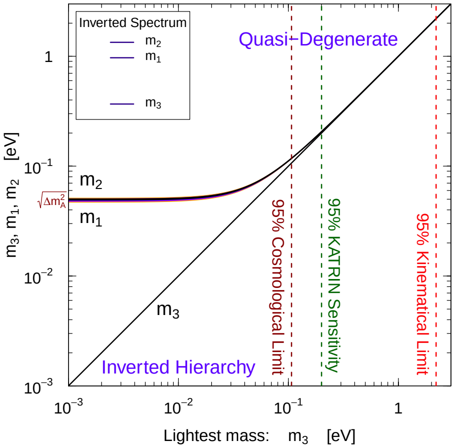
Neutrino Mixing Phenomenology

Open Problems

- $\vartheta_{23} \lesseqgtr 45^\circ$?
  - T2K (Japan), NOνA (USA), IceCube-PINGU, INO (India), ...
- Mass Hierarchy ?
  - NOνA (USA), JUNO (China), RENO-50 (Korea), IceCube-PINGU, INO (India), ...
- CP violation ?
  - NOνA (USA), LBNE (USA), LAGUNA-LBNO (EU), HyperK (Japan), ...
- Absolute Mass Scale ?
  - β Decay, Neutrinoless Double-β Decay, Cosmology, ...
- Dirac or Majorana ?
  - Neutrinoless Double-β Decay, ...
- Beyond Three-Neutrino Mixing ? Sterile Neutrinos ?

Absolute Scale of Neutrino Masses





$$m_2^2 = m_1^2 + \Delta m_{21}^2 = m_1^2 + \Delta m_S^2$$
$$m_3^2 = m_1^2 + \Delta m_{31}^2 = m_1^2 + \Delta m_A^2$$

$$m_1^2 = m_3^2 - \Delta m_{31}^2 = m_3^2 + \Delta m_A^2$$
$$m_2^2 = m_1^2 + \Delta m_{21}^2 \simeq m_3^2 + \Delta m_A^2$$

Quasi-Degenerate for $m_1 \simeq m_2 \simeq m_3 \simeq m_\nu \gtrsim \sqrt{\Delta m_A^2} \simeq 5 \times 10^{-2}\,\text{eV}$

95% Cosmological Limit: Planck + WMAP9 + highL + BAO [arXiv:1303.5076]

Tritium Beta-Decay

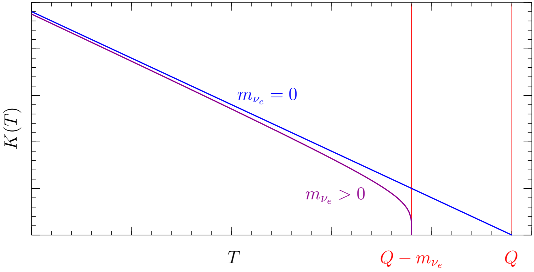
$^3\text{H} \to {}^3\text{He} + e^- + \bar{\nu}_e$

$$\frac{d\Gamma}{dT} = \frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E)\, pE\, (Q-T) \sqrt{(Q-T)^2 - m_{\nu_e}^2}$$

$$Q = M_{^3\text{H}} - M_{^3\text{He}} - m_e = 18.58\,\text{keV}$$

Kurie plot

$$K(T) = \sqrt{\frac{d\Gamma/dT}{\frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E)\, pE}} = \left[(Q-T)\sqrt{(Q-T)^2 - m_{\nu_e}^2}\right]^{1/2}$$



$\boxed{m_{\nu_e} < 2.2\,\text{eV} \quad (95\%\ \text{C.L.})}$

Mainz & Troitsk

[Weinheimer, hep-ex/0210050]

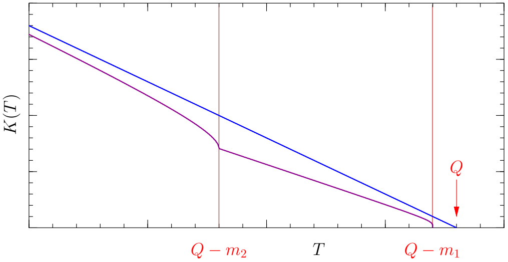
future: KATRIN

[www.katrin.kit.edu]

start data taking in 2015

sensitivity: $m_{\nu_e} \simeq 0.2\,\text{eV}$

Neutrino Mixing $\Longrightarrow K(T) = \left[(Q-T) \sum_k |U_{ek}|^2 \sqrt{(Q-T)^2 - m_k^2} \right]^{1/2}$



analysis of data is different from the no-mixing case: $2N-1$ parameters $\left(\sum_k |U_{ek}|^2 = 1 \right)$

if experiment is not sensitive to masses ($m_k \ll Q-T$)

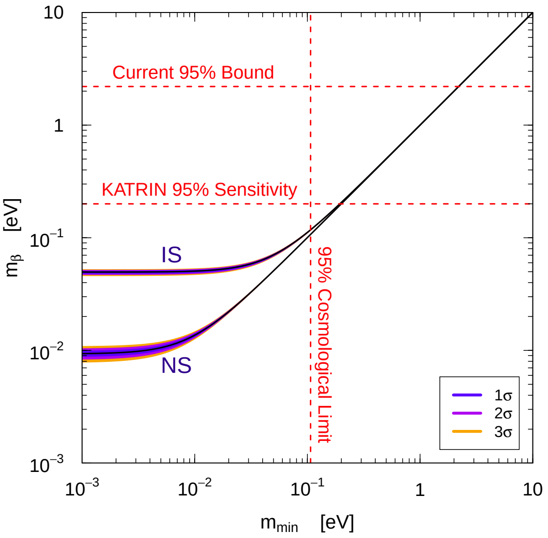
effective mass: $\boxed{m_\beta^2 = \sum_k |U_{ek}|^2 m_k^2}$

$$K^2 = (Q-T)^2 \sum_k |U_{ek}|^2 \sqrt{1 - \frac{m_k^2}{(Q-T)^2}} \simeq (Q-T)^2 \sum_k |U_{ek}|^2 \left[1 - \frac{1}{2} \frac{m_k^2}{(Q-T)^2} \right]$$

$$= (Q-T)^2 \left[1 - \frac{1}{2} \frac{m_\beta^2}{(Q-T)^2} \right] \simeq (Q-T) \sqrt{(Q-T)^2 - m_\beta^2}$$

Predictions of 3ν-Mixing Paradigm

$$m_\beta^2 = |U_{e1}|^2\, m_1^2 + |U_{e2}|^2\, m_2^2 + |U_{e3}|^2\, m_3^2$$



- Quasi-Degenerate:

  $$m_\beta^2 \simeq m_\nu^2 \sum_k |U_{ek}|^2 = m_\nu^2$$

- Inverted Hierarchy:

  $$m_\beta^2 \simeq (1 - s_{13}^2)\Delta m_{\rm A}^2 \simeq \Delta m_{\rm A}^2$$

- Normal Hierarchy:

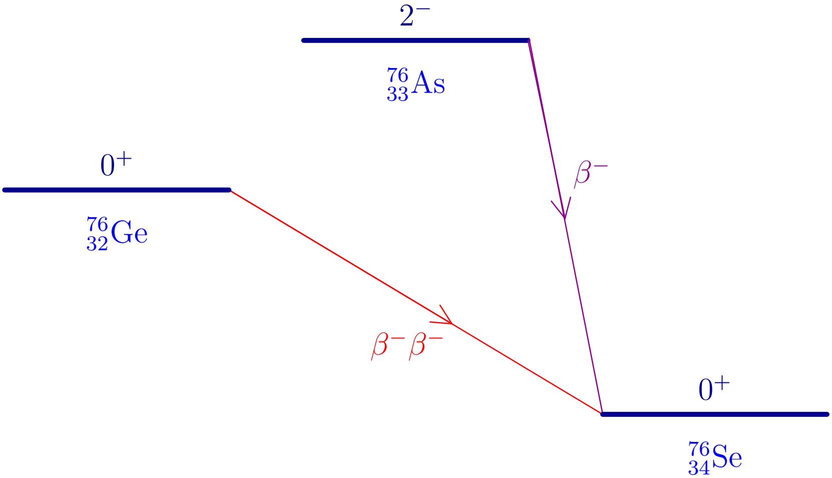
  $$m_\beta^2 \simeq s_{12}^2 c_{13}^2 \Delta m_{\rm S}^2 + s_{13}^2 \Delta m_{\rm A}^2$$
  $$\simeq 2 \times 10^{-5} + 6 \times 10^{-5}\, \mathrm{eV}^2$$

- $m_\beta \lesssim 4 \times 10^{-2}\, \mathrm{eV}$

  $\Downarrow$

  Normal Spectrum

Neutrinoless Double-Beta Decay



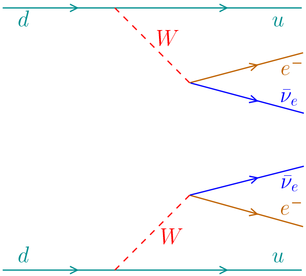
Effective Majorana Neutrino Mass: $$m_{\beta\beta} = \sum_k U_{ek}^2 \, m_k$$

Two-Neutrino Double-β Decay: $\Delta L = 0$

$$\mathcal{N}(A,Z) \to \mathcal{N}(A,Z+2) + e^- + e^- + \bar{\nu}_e + \bar{\nu}_e$$

$$(T^{2\nu}_{1/2})^{-1} = G_{2\nu}\,|\mathcal{M}_{2\nu}|^2$$

second order weak interaction process
in the Standard Model



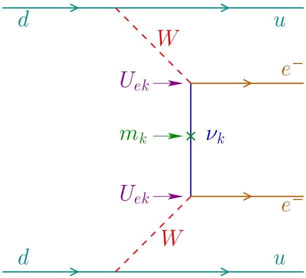
Neutrinoless Double-β Decay: $\Delta L = 2$

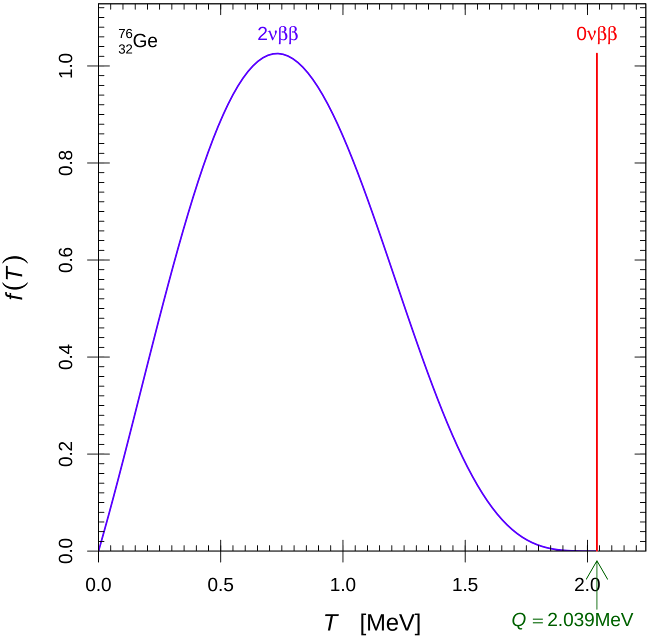
$$\mathcal{N}(A,Z) \to \mathcal{N}(A,Z+2) + e^- + e^-$$

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}\,|\mathcal{M}_{0\nu}|^2\,|m_{\beta\beta}|^2$$

effective
Majorana
mass

$$|m_{\beta\beta}| = \left|\sum_k U_{ek}^2\, m_k\right|$$





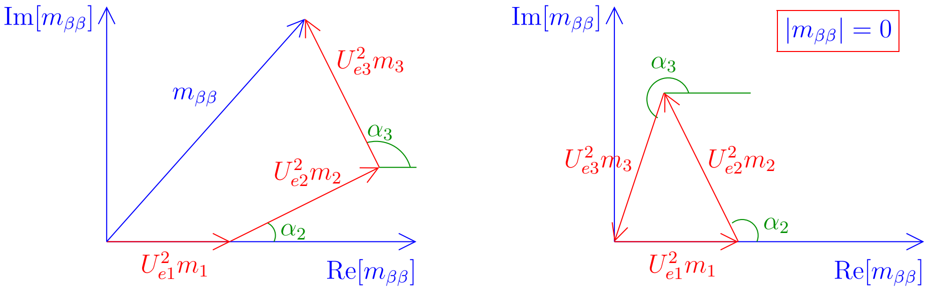
$^{76}_{32}$Ge
$2\nu\beta\beta$
$0\nu\beta\beta$
$f(T)$
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
2.0
T [MeV]
$Q = 2.039$MeV

Effective Majorana Neutrino Mass

$$m_{\beta\beta} = \sum_k U_{ek}^2 \, m_k \qquad \text{complex } U_{ek} \Rightarrow \text{possible cancellations}$$

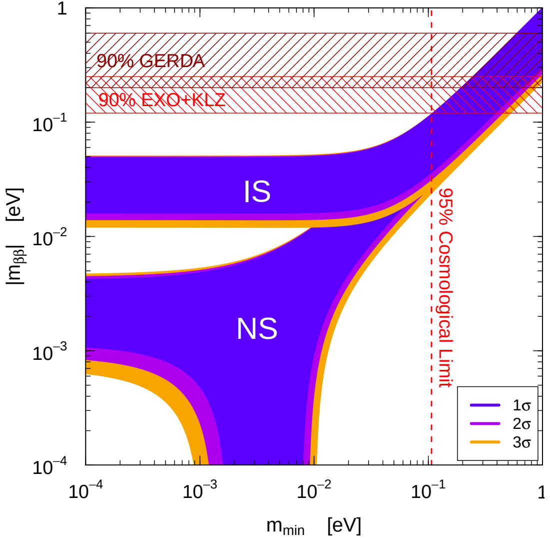
$$m_{\beta\beta} = |U_{e1}|^2 \, m_1 + |U_{e2}|^2 \, e^{i\alpha_2} \, m_2 + |U_{e3}|^2 \, e^{i\alpha_3} \, m_3$$

$$\alpha_2 = 2\lambda_2 \qquad \alpha_3 = 2\left(\lambda_3 - \delta_{13}\right)$$



Predictions of 3ν-Mixing Paradigm

$$m_{\beta\beta} = |U_{e1}|^2\, m_1 + |U_{e2}|^2\, e^{i\alpha_2}\, m_2 + |U_{e3}|^2\, e^{i\alpha_3}\, m_3$$



- Quasi-Degenerate:

$$|m_{\beta\beta}| \simeq m_\nu \sqrt{1 - s^2_{2\vartheta_{12}} s^2_{\alpha_2}}$$

- Inverted Hierarchy:

$$|m_{\beta\beta}| \simeq \sqrt{\Delta m^2_{\text{A}} (1 - s^2_{2\vartheta_{12}} s^2_{\alpha_2})}$$

- Normal Hierarchy:

$$|m_{\beta\beta}| \simeq |s^2_{12}\sqrt{\Delta m^2_{\text{S}}} + e^{i\alpha} s^2_{13}\sqrt{\Delta m^2_{\text{A}}}|$$

$$\simeq |2.7 + 1.2 e^{i\alpha}| \times 10^{-3}\,\text{eV}$$

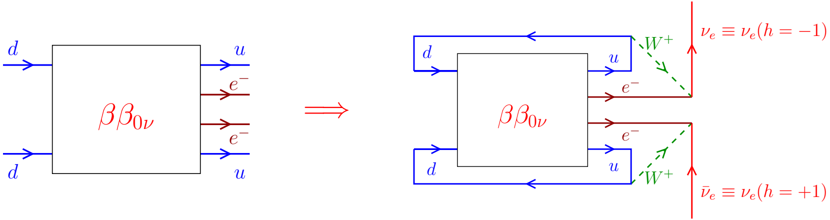
$m_1 \gtrsim 10^{-3}\,\text{eV} \Rightarrow$ cancellation?

$|m_{\beta\beta}| \lesssim 10^{-2}\,\text{eV} \Longrightarrow$ Normal Spectrum

$\beta\beta_{0\nu}$ Decay $\Leftrightarrow$ Majorana Neutrino Mass

$|m_{\beta\beta}|$ can vanish because of unfortunate cancellations among m_1, m_2, m_3 contributions or because neutrinos are Dirac

$\beta\beta_{0\nu}$ decay can be generated by another mechanism beyond SM



[Schechter, Valle, PRD 25 (1982) 2951] [Takasugi, PLB 149 (1984) 372]

Majorana Mass Term: $\boxed{\mathcal{L}_{eL}^{\mathrm{M}} = -\frac{1}{2}\, m_{ee} \left(\overline{\nu_{eL}^{c}}\, \nu_{eL} + \overline{\nu_{eL}}\, \nu_{eL}^{c} \right)}$

four-loop diagram calculation: $m_{ee} \sim 10^{-24}\,\mathrm{eV}$ [Duerr, Lindner, Merle, JHEP 06 (2011) 091]

- In any case finding $\beta\beta_{0\nu}$ decay is important information to solve the Dirac-Majorana question in favor of Majorana

- On the other hand, it is not possible to prove experimentally that neutrinos are Dirac.
  A Dirac neutrino is equivalent to 2 Majorana neutrinos with the same mass.
  Impossible to prove experimentally that mass splitting is exactly zero.

Sterile Neutrinos

- I consider sterile neutrinos with mass scale $\sim 1\,\mathrm{eV}$ in light of short-baseline Reactor Anomaly, Gallium Anomaly, LSND.
- Other possibilities (not incompatible):
  - Very light sterile neutrinos with mass scale $\ll 1\,\mathrm{eV}$: important for solar neutrino phenomenology

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

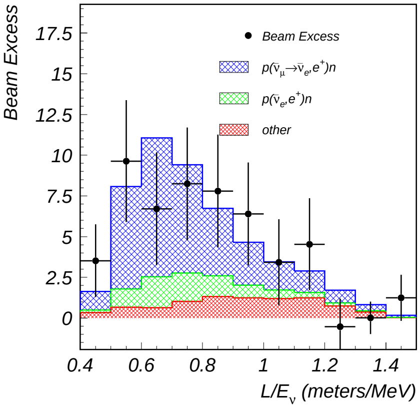
  - Heavy sterile neutrinos with mass scale $\gg 1\,\mathrm{eV}$: could be Warm Dark Matter

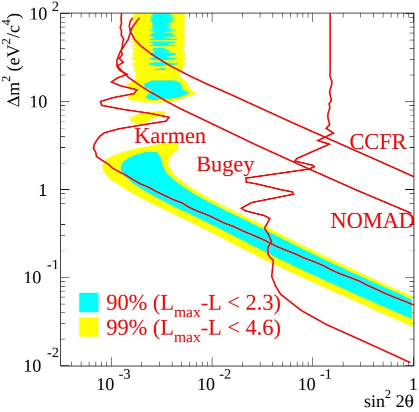
    [Kusenko, Phys. Rept. 481 (2009) 1]
    [Boyarsky, Ruchayskiy, Shaposhnikov, Ann. Rev. Nucl. Part. Sci. 59 (2009) 191]
    [Drewes, IJMPE, 22 (2013) 1330019]

LSND

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

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



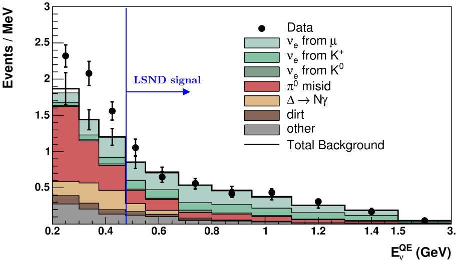


3.8σ excess $\qquad$ $\Delta m^2_{\mathrm{LSND}} \gtrsim 0.2\,\mathrm{eV}^2$ $\qquad$ $(\gg \Delta m^2_{\mathrm{A}} \gg \Delta m^2_{\mathrm{S}})$

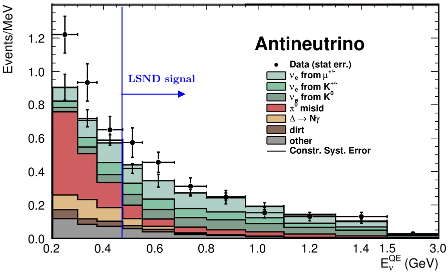
MiniBooNE

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

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



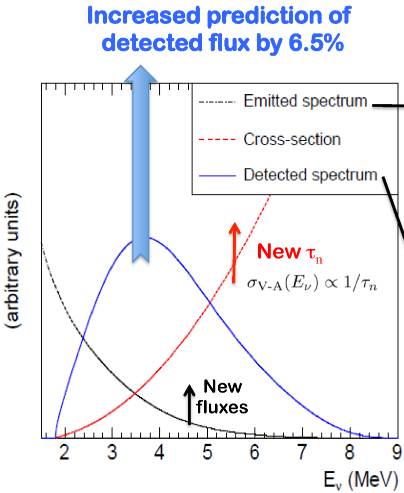
$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]



- 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!

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



i) **Neutrino Emission:**

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

ii) **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]

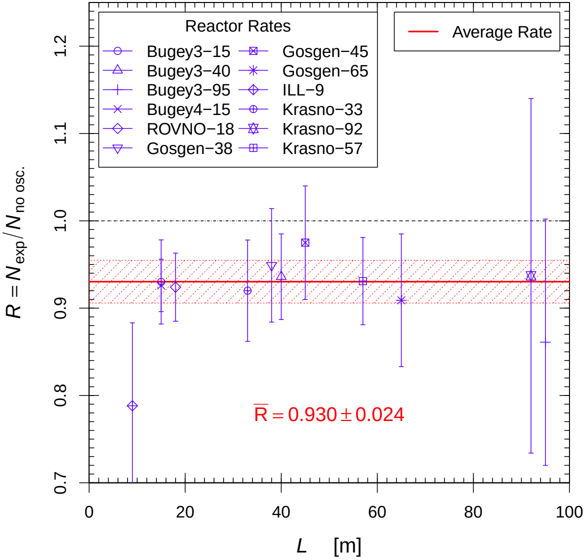
new reactor $\bar{\nu}_e$ fluxes

[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, PRC 88 (2013) 055501]



Gallium Anomaly

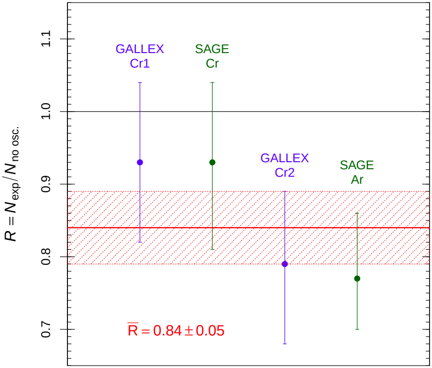
Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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

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

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



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

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

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

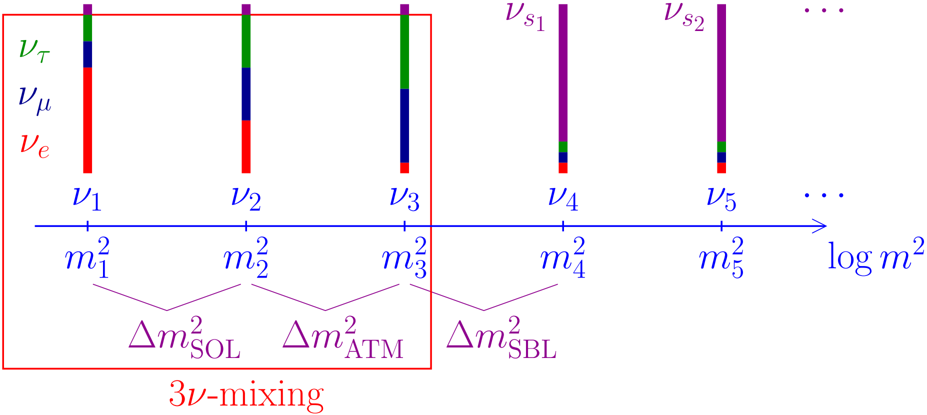
$\sim 2.9\sigma$ anomaly

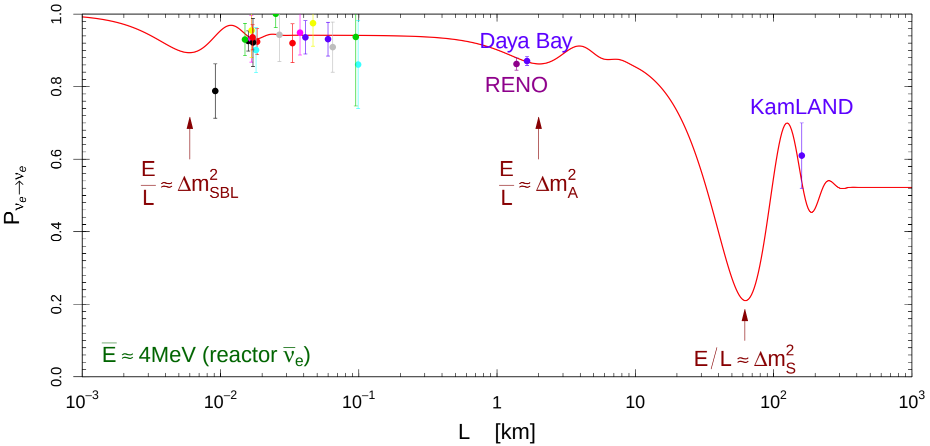
[SAGE, PRC 73 (2006) 045805; PRC 80 (2009) 015807]

[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]

Beyond Three-Neutrino Mixing: Sterile Neutrinos





$P_{\nu_e \to \nu_e}$
1.0
0.8
0.6
0.4
0.2
0.0
Daya Bay
RENO
KamLAND
$\frac{E}{L} \approx \Delta m^2_{SBL}$
$\frac{E}{L} \approx \Delta m^2_{A}$
$E/L \approx \Delta m^2_{S}$
$\overline{E} \approx$ 4MeV (reactor $\overline{\nu}_e$)
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
L [km]

Effective SBL Oscillation Probabilities in 3+1 Schemes

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

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

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

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

SBL

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

but CP violation is not observable in SBL experiments!

Effective SBL Oscillation Probabilities in 3+2 Schemes

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

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

$$P_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} = 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2 \phi_{41} + 4|U_{e5}|^2 |U_{\mu 5}|^2 \sin^2 \phi_{51}$$
$$+ 8|U_{\mu 4} U_{e4} U_{\mu 5} U_{e5}| \sin \phi_{41} \sin \phi_{51} \cos(\phi_{54} \overset{(+)}{-} \eta)$$

$$P_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} = 1 - 4(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2 \phi_{41} + |U_{\alpha 5}|^2 \sin^2 \phi_{51})$$
$$- 4|U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2 \phi_{54}$$

[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, PRD 88 (2013) 073008; Girardi, Meroni, Petcov, JHEP 1311 (2013) 146]

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

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

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:

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

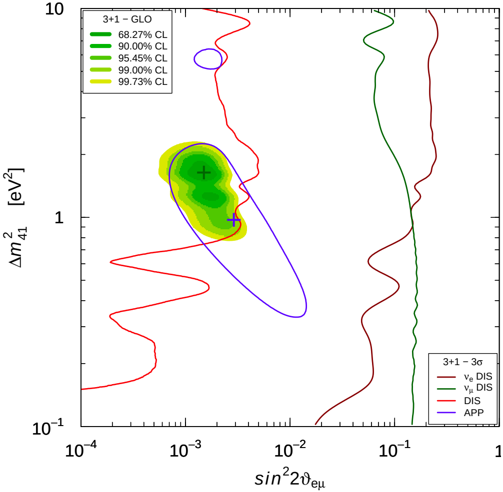
- Upper bounds on $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu}$ $\Longrightarrow$ strong limit on $\sin^2 2\vartheta_{e\mu}$

[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]

Goodness of Fit

- Assumption or approximation: Gaussian uncertainties and linear model
- $\chi^2_{\rm min}$ has χ^2 distribution with Number of Degrees of Freedom

$$\mathrm{NDF} = N_{\rm D} - N_{\rm P}$$

$N_{\rm D} =$ Number of Data $\qquad N_{\rm P} =$ Number of Fitted Parameters

- $\langle \chi^2_{\rm min} \rangle = \mathrm{NDF} \qquad \mathrm{Var}(\chi^2_{\rm min}) = 2\mathrm{NDF}$
- $\mathrm{GoF} = \int_{\chi^2_{\rm min}}^{\infty} p_{\chi^2}(z, \mathrm{NDF})\, dz \qquad p_{\chi^2}(z, n) = \dfrac{z^{n/2-1} e^{-z/2}}{2^{n/2}\Gamma(n/2)}$

Parameter Goodness of Fit

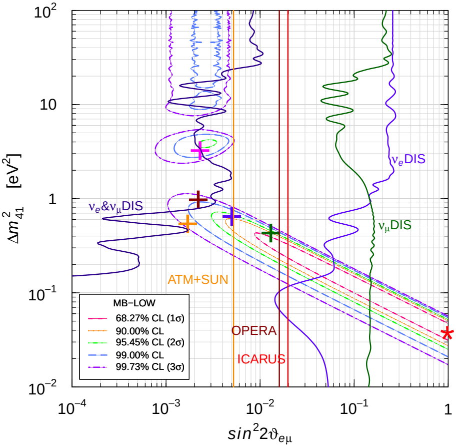
Maltoni, Schwetz, PRD 68 (2003) 033020, arXiv:hep-ph/0304176

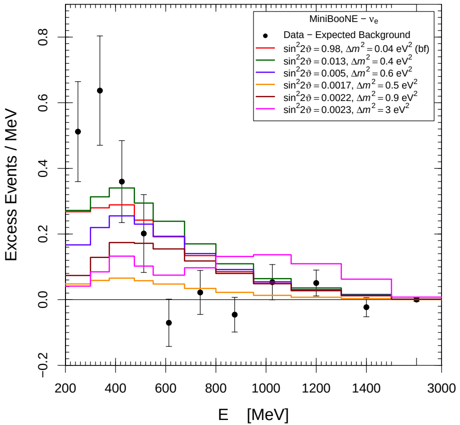
- Measure compatibility of two (or more) sets of data points A and B under fitting model
- $\chi^2_{\rm PGoF} = (\chi^2_{\rm min})_{\rm A+B} - [(\chi^2_{\rm min})_{\rm A} + (\chi^2_{\rm min})_{\rm B}]$
- $\chi^2_{\rm PGoF}$ has χ^2 distribution with Number of Degrees of Freedom

$$\mathrm{NDF}_{\rm PGoF} = N_{\rm P}^{\rm A} + N_{\rm P}^{\rm B} - N_{\rm P}^{\rm A+B}$$

- $\mathrm{PGoF} = \int_{\chi^2_{\rm PGoF}}^{\infty} p_{\chi^2}(z, \mathrm{NDF}_{\rm PGoF})\, dz$

MiniBooNE Low-Energy Excess?

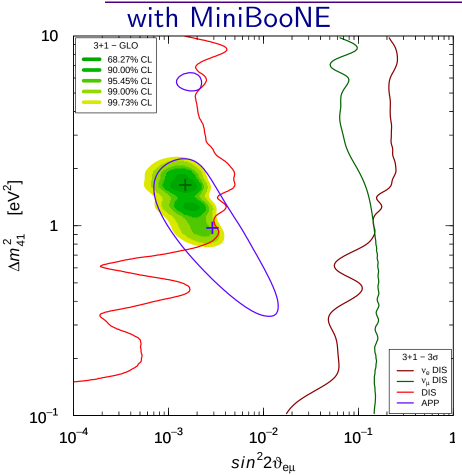


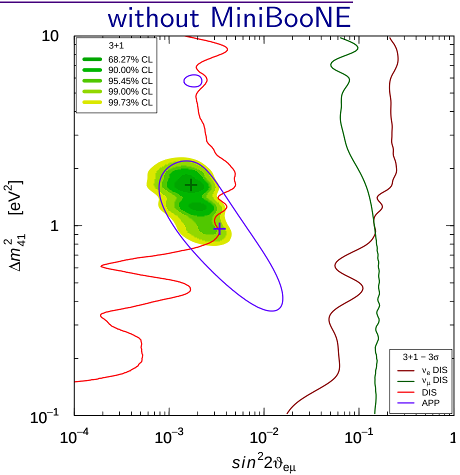


- No fit of low-energy excess for realistic $\sin^2 2\vartheta_{e\mu} \lesssim 5 \times 10^{-3}$
- APP-DIS PGoF $= 0.1\%$
- Neutrino energy reconstruction problem?

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

MiniBooNE Impact on SBL Oscillations?





with MiniBooNE	without MiniBooNE
GoF = 29% PGoF = 9%	GoF = 19% PGoF = 8%
No Osc. excluded at 6.2σ	No Osc. excluded at 6.3σ
$\Delta\chi^2/\text{NDF} = 46.2/3$	$\Delta\chi^2/\text{NDF} = 47.1/3$

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

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

- 2008 ν + 2010 $\bar{\nu}$ MiniBooNE data indicated ν–$\bar{\nu}$ difference

  $\Downarrow$

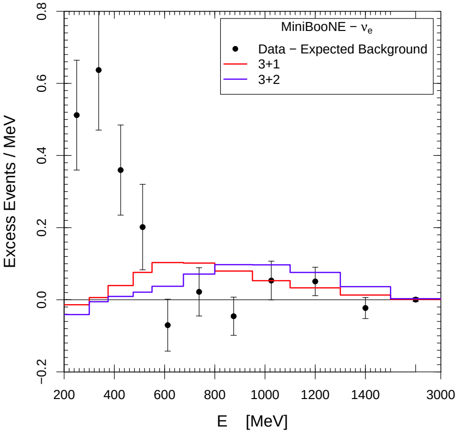
  reasonable and useful to consider 3+2

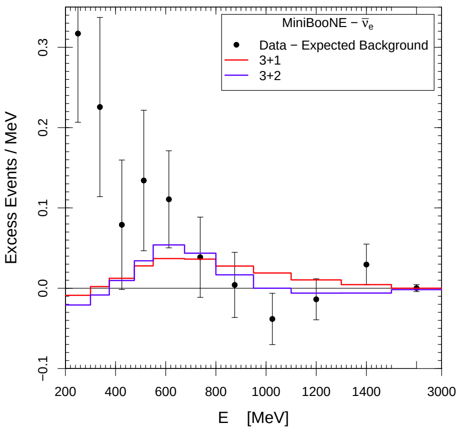
- ν–$\bar{\nu}$ difference almost disappeared with 2012 $\bar{\nu}$ data

- 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.

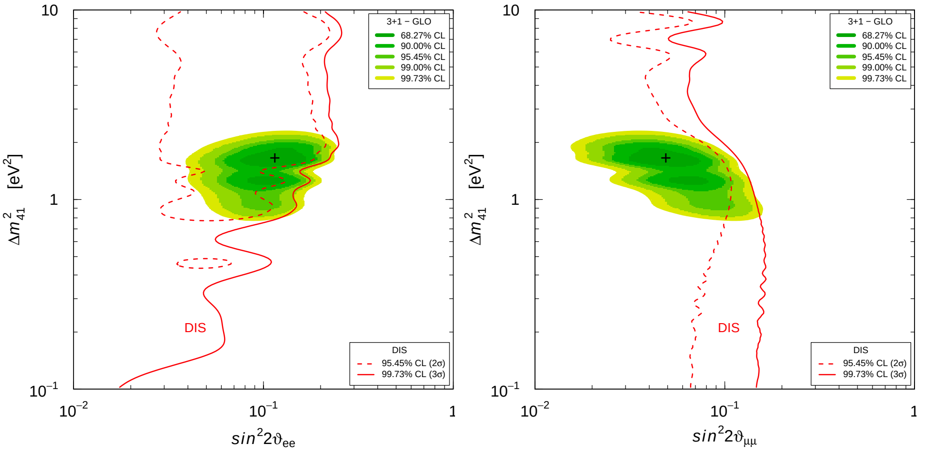
MiniBooNE Low-Energy Excess?





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

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]

Conclusions

- Robust Three-Neutrino Mixing Paradigm.
  Open problems: $\vartheta_{23} \lesseqgtr 45^\circ$?, Mass Hierarchy, CP Violation, Absolute Mass Scale, Dirac or Majorana?
- Very interesting indications of light sterile neutrinos with $m_s \approx 1\,\text{eV}$:
  - LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal.
  - Reactor $\bar{\nu}_e$ disappearance.
  - Gallium ν_e disappearance.
- Many promising projects to test in a few years short-baseline ν_e and $\bar{\nu}_e$ disappearance with reactors and radioactive sources.
- More difficult (expensive) projects to check the LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal are under discussion.
- Cosmology:
  - Important effects of sterile neutrinos.
  - Implications depend on theoretical framework and considered data set.
  - Cosmological indications must be checked by laboratory experiments.