Phenomenology of Light Sterile Neutrinos

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Experimental Evidences of Neutrino Oscillations

Solar $\nu_e \to \nu_\mu, \nu_\tau$

VLBL Reactor $\bar{\nu}_e$ **disappearance**

(SNO, BOREXino; Super-Kamiokande; GALLEX/GNO, SAGE; Homestake, Kamiokande) + (KamLAND)

$$\to \begin{cases} \Delta m^2_{\text{S}} \simeq 7.6 \times 10^{-5}\,\text{eV}^2 \\ \sin^2\vartheta_{\text{S}} \simeq 0.30 \end{cases}$$

Atmospheric $\nu_\mu \to \nu_\tau$

LBL Accelerator ν_μ **disappearance**

LBL Accelerator $\nu_\mu \to \nu_\tau$

(Super-Kamiokande; Kamiokande, IMB; MACRO, Soudan-2) + (K2K, MINOS, T2K) + (Opera)

$$\to \begin{cases} \Delta m^2_{\text{A}} \simeq 2.4 \times 10^{-3}\,\text{eV}^2 \\ \sin^2\vartheta_{\text{A}} \simeq 0.50 \end{cases}$$

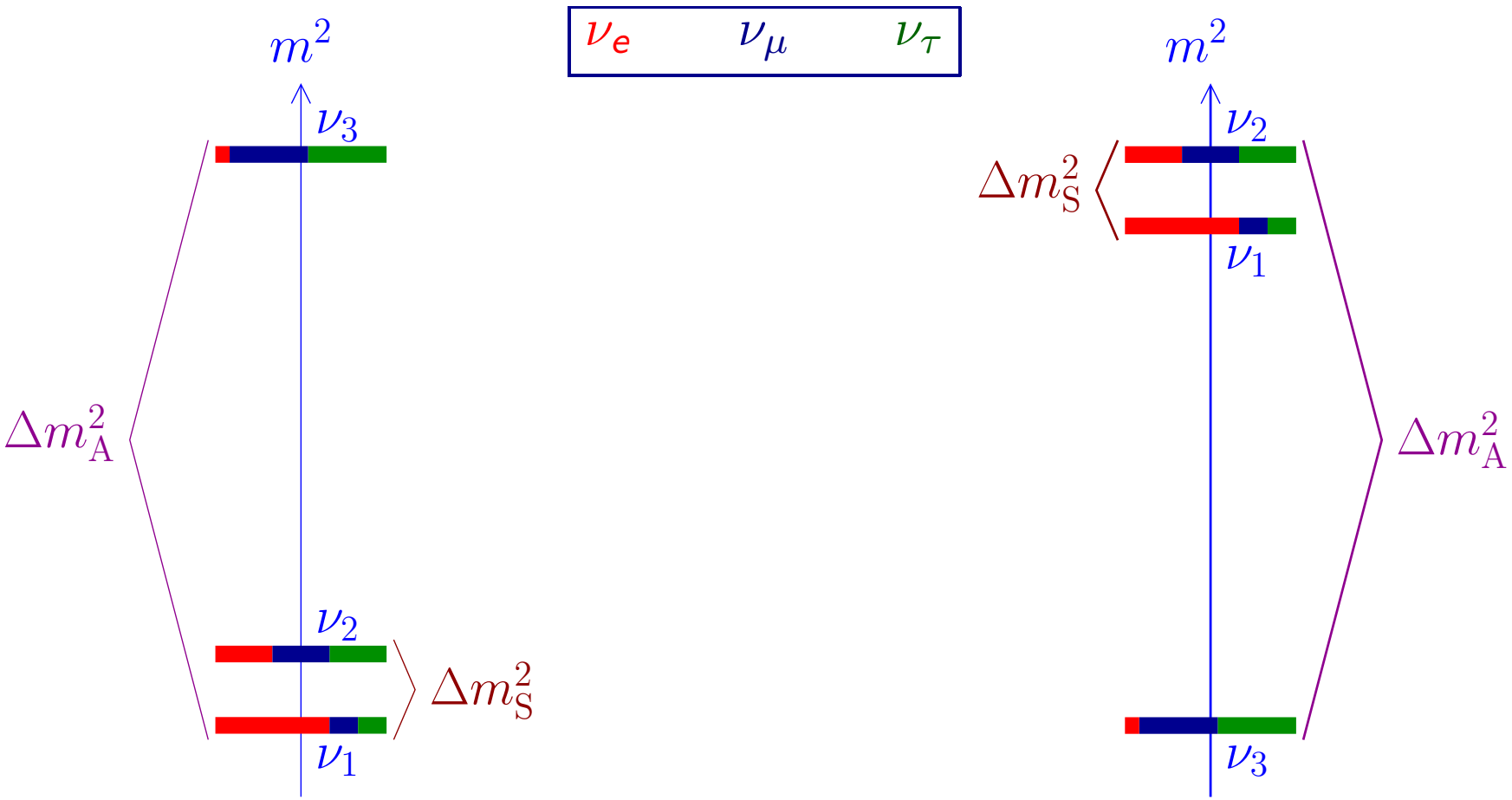
LBL Accelerator $\nu_\mu \to \nu_e$

LBL Reactor $\bar{\nu}_e$ **disappearance**

(T2K, MINOS) + (Daya Bay, RENO; Double Chooz)

$$\to \begin{cases} \Delta m^2_{\text{A}} \\ \sin^2\vartheta_{13} \simeq 0.023 \end{cases}$$

Three-Neutrino Mixing Paradigm



Normal Ordering

$\Delta m^2_{31} > \Delta m^2_{32} > 0$

Inverted Ordering

$\Delta m^2_{32} < \Delta m^2_{31} < 0$

absolute scale is not determined by neutrino oscillation data

$$\Delta m^2_{\rm S} = \Delta m^2_{21} \simeq 7.5^{+0.3}_{-0.2} \times 10^{-5}\,{\rm eV}^2 \qquad \text{uncertainty} \simeq 3\%$$

$$\Delta m^2_{\rm A} = |\Delta m^2_{31}| \simeq |\Delta m^2_{32}| \simeq 2.4^{+0.1}_{-0.1} \times 10^{-3}\,{\rm eV}^2 \qquad \text{uncertainty} \simeq 4\%$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix}$$

$\vartheta_{23} = \vartheta_{\rm A}$

$\sin^2\vartheta_{23} \simeq 0.4 - 0.6$

$P_{\rm osc} \propto \sin^2 2\vartheta_{23}$

maximal and flat

at $\vartheta_{23} = 45^\circ$

Daya Bay, RENO

Double Chooz

T2K, MINOS

$\sin^2\vartheta_{13} \simeq 0.023 \pm 0.002$

$\vartheta_{12} = \vartheta_{\rm S}$

$\sin^2\vartheta_{12} \simeq 0.30 \pm 0.01$

$\beta\beta_{0\nu}$

$$\frac{\delta \sin^2\vartheta_{23}}{\sin^2\vartheta_{23}} \simeq 40\% \qquad \frac{\delta \sin^2\vartheta_{13}}{\sin^2\vartheta_{13}} \simeq 10\% \qquad \frac{\delta \sin^2\vartheta_{12}}{\sin^2\vartheta_{12}} \simeq 5\%$$

Open Problems

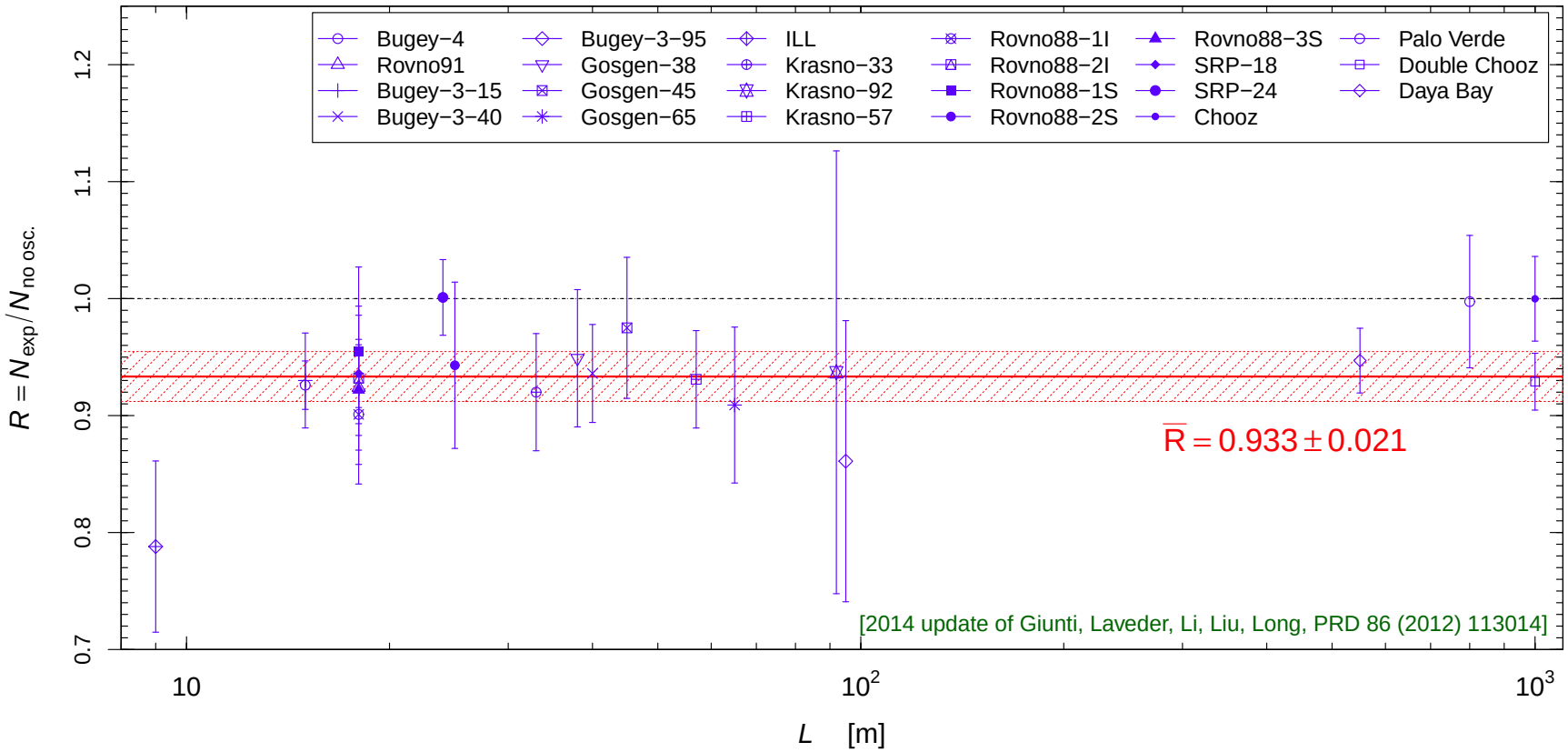
- $\vartheta_{23} \lessgtr 45^\circ$?
  - T2K (Japan), NOνA (USA), PINGU (Antarctica), ORCA (EU), INO (India), ...
- Mass Ordering (Hierarchy) ?
  - NOνA (USA), JUNO (China), RENO-50 (Korea), PINGU (Antarctica), ORCA (EU), INO (India), ...
- CP violation ?
  - T2K (Japan), NOνA (USA), LBNF (USA), HyperK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

Indications of SBL Oscillations Beyond 3ν

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]



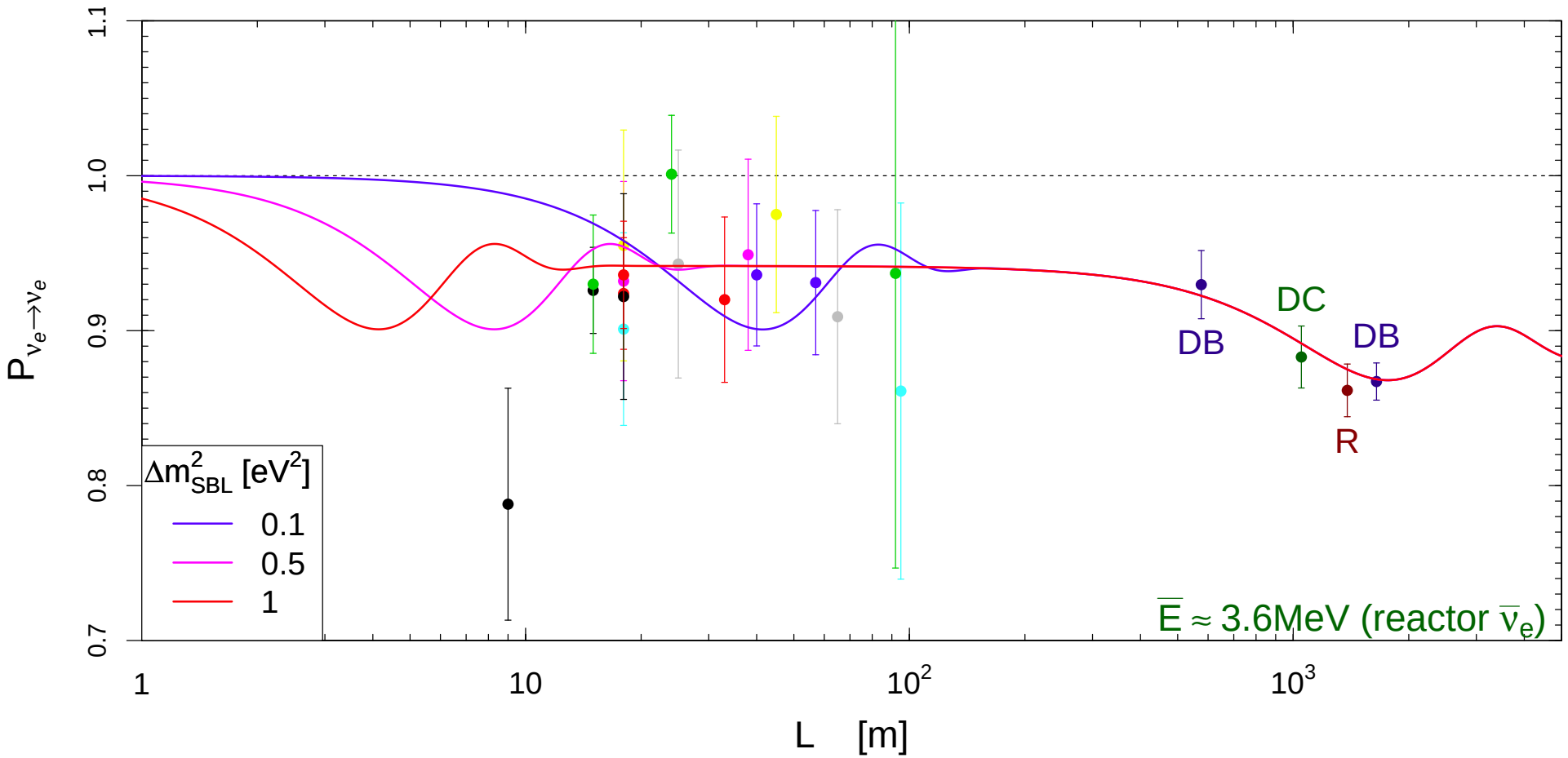
$\bar{\nu}_e \to \bar{\nu}_e$ $L \sim 10 - 100\,\text{m}$ $E \sim 4\,\text{MeV}$

Nominal $\approx 3.1\sigma$ deficit $\Delta m^2 \gtrsim 0.5\,\text{eV}^2$ $(\gg \Delta m^2_A \gg \Delta m^2_S)$

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

Problem: unknown $\bar{\nu}_e$ flux uncertainties?

[Hayes, Friar, Garvey, Jonkmans, PRL 112 (2014) 202501; Dwyer, Langford, PRL 114 (2015) 012502]

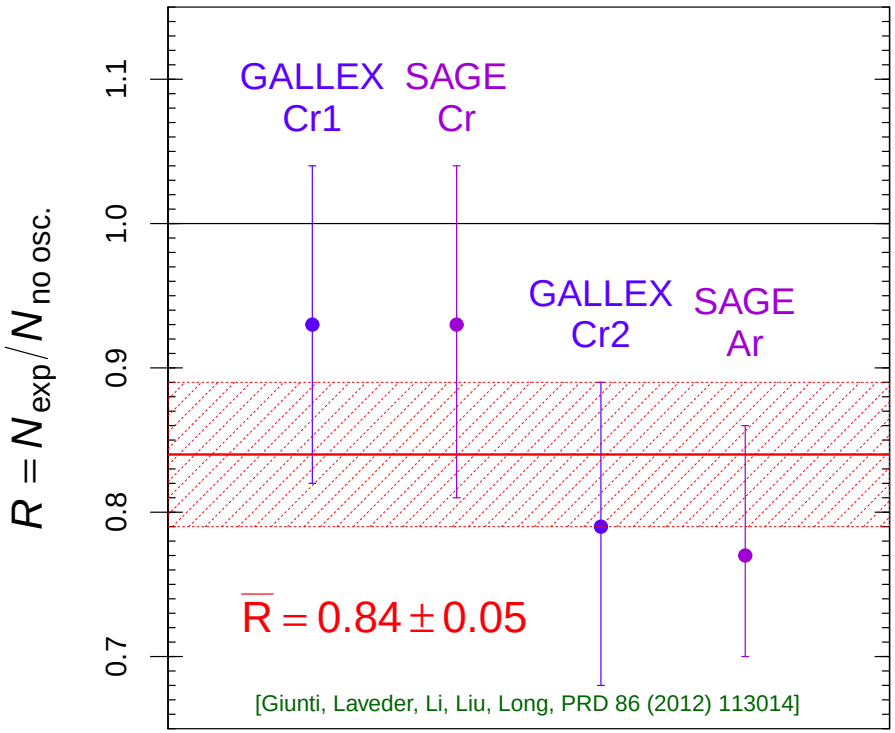

$P_{\nu_e \to \nu_e}$
1.1
1.0
0.9
0.8
0.7
1
10
10^2
10^3
L [m]
Δm^2_{SBL} [eV^2]
0.1
0.5
1
DB
DC
DB
R
$\overline{E} \approx 3.6$MeV (reactor $\overline{\nu}_e$)

Gallium Anomaly

Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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



$\bar{\nu}_e \to \bar{\nu}_e$ $E \sim 0.7\,\mathrm{MeV}$

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

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

Nominal $\approx 2.9\sigma$ anomaly

$\Delta m^2 \gtrsim 1\,\mathrm{eV}^2$ $(\gg \Delta m^2_{\mathrm{A}} \gg \Delta m^2_{\mathrm{S}})$

[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]

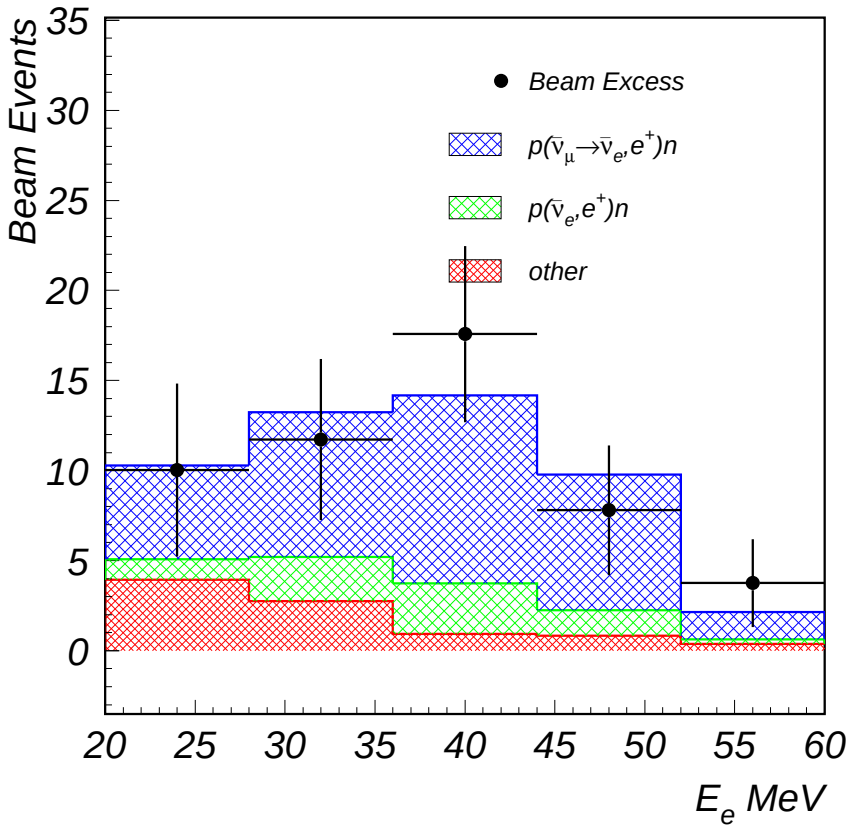
[Mention et al, PRD 83 (2011) 073006]

- ${}^3\mathrm{He} + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + {}^3\mathrm{H}$ cross section measurement [Frekers et al., PLB 706 (2011) 134]
- $E_{\mathrm{th}}(\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-) = 233.5 \pm 1.2\,\mathrm{keV}$ [Frekers et al., PLB 722 (2013) 233]

LSND

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

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\quad L \simeq 30\,\text{m}$ $\quad 20\,\text{MeV} \leq E \leq 60\,\text{MeV}$



- Well known source of $\bar{\nu}_\mu$:

$$\mu^+ \text{ at rest} \to e^+ + \nu_e + \bar{\nu}_\mu$$

- $\bar{\nu}_\mu \xrightarrow[L \simeq 30\,\text{m}]{} \bar{\nu}_e$
- Well known detection process of $\bar{\nu}_e$:

$$\bar{\nu}_e + p \to n + e^+$$

- But signal not seen by KARMEN with same method at $L \simeq 18\,\text{m}$

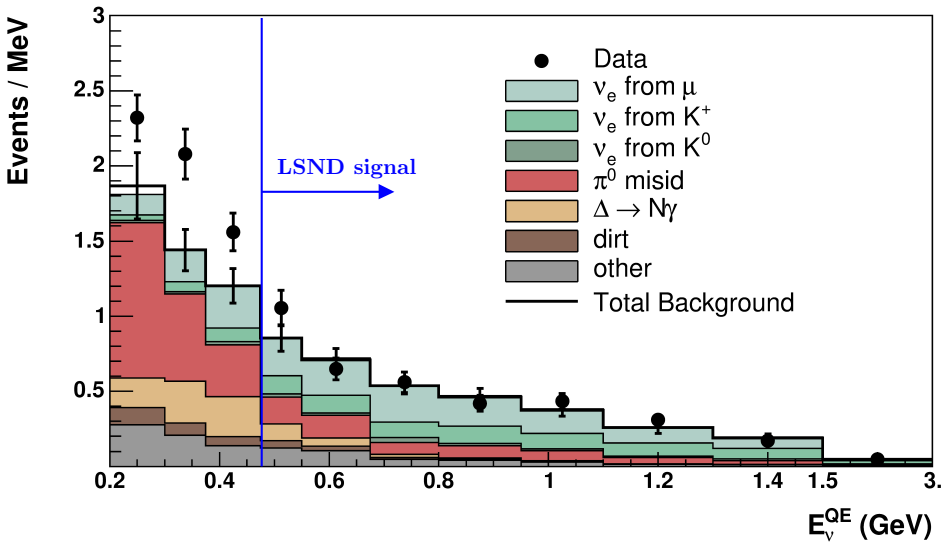
[PRD 65 (2002) 112001]

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

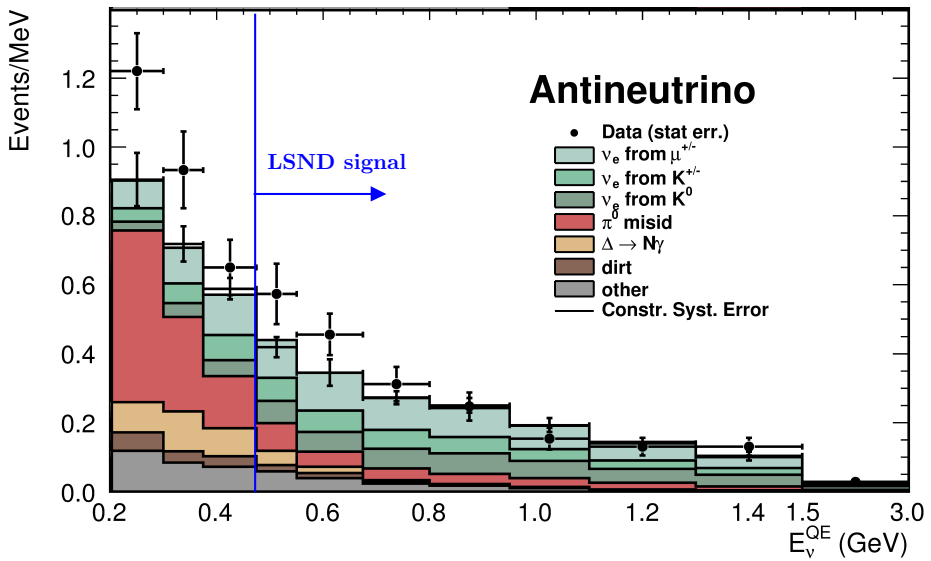
MiniBooNE

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

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



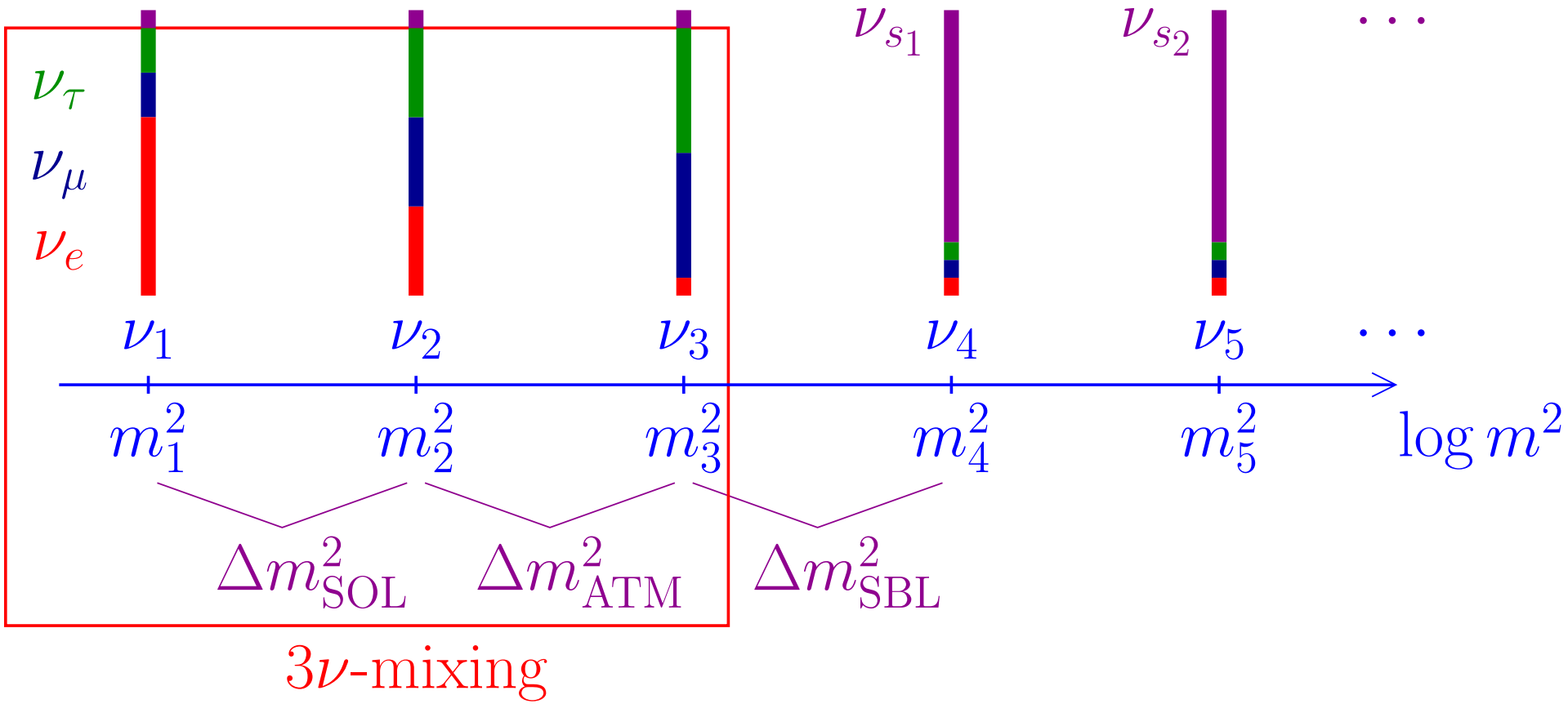
$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]



- Purpose: check LSND signal.
- Different L and E.
- Similar L/E (oscillations).
- No money, no Near Detector.

- LSND signal: $E > 475\,\text{MeV}$.
- Agreement with LSND signal?
- CP violation?
- Low-energy anomaly!

Beyond Three-Neutrino Mixing: Sterile Neutrinos



Terminology: a eV-scale sterile neutrino

means: a eV-scale massive neutrino which is mainly sterile

Sterile Neutrinos from Physics Beyond the SM

- Neutrinos are special in the Standard Model: the only neutral fermions
- Active left-handed neutrinos can mix with non-SM singlet fermions often called right-handed neutrinos Neutrino Portal [A. Smirnov, arXiv:1502.04530]
- Light anti-ν_R are light sterile neutrinos

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

- Sterile means no standard model interactions

[Pontecorvo, Sov. Phys. JETP 26 (1968) 984]

- Active neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$ can oscillate into light sterile neutrinos (ν_s)
- Observables:
  - Disappearance of active neutrinos (neutral current deficit)
  - Indirect evidence through combined fit of data (current indication)
- Short-baseline anomalies + 3ν-mixing:

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

ν_1	ν_2	ν_3	ν_4	$\ldots$
ν_e	ν_μ	ν_τ	ν_{s_1}	$\ldots$

- 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

    [de Holanda, Smirnov, PRD 69 (2004) 113002; PRD 83 (2011) 113011]

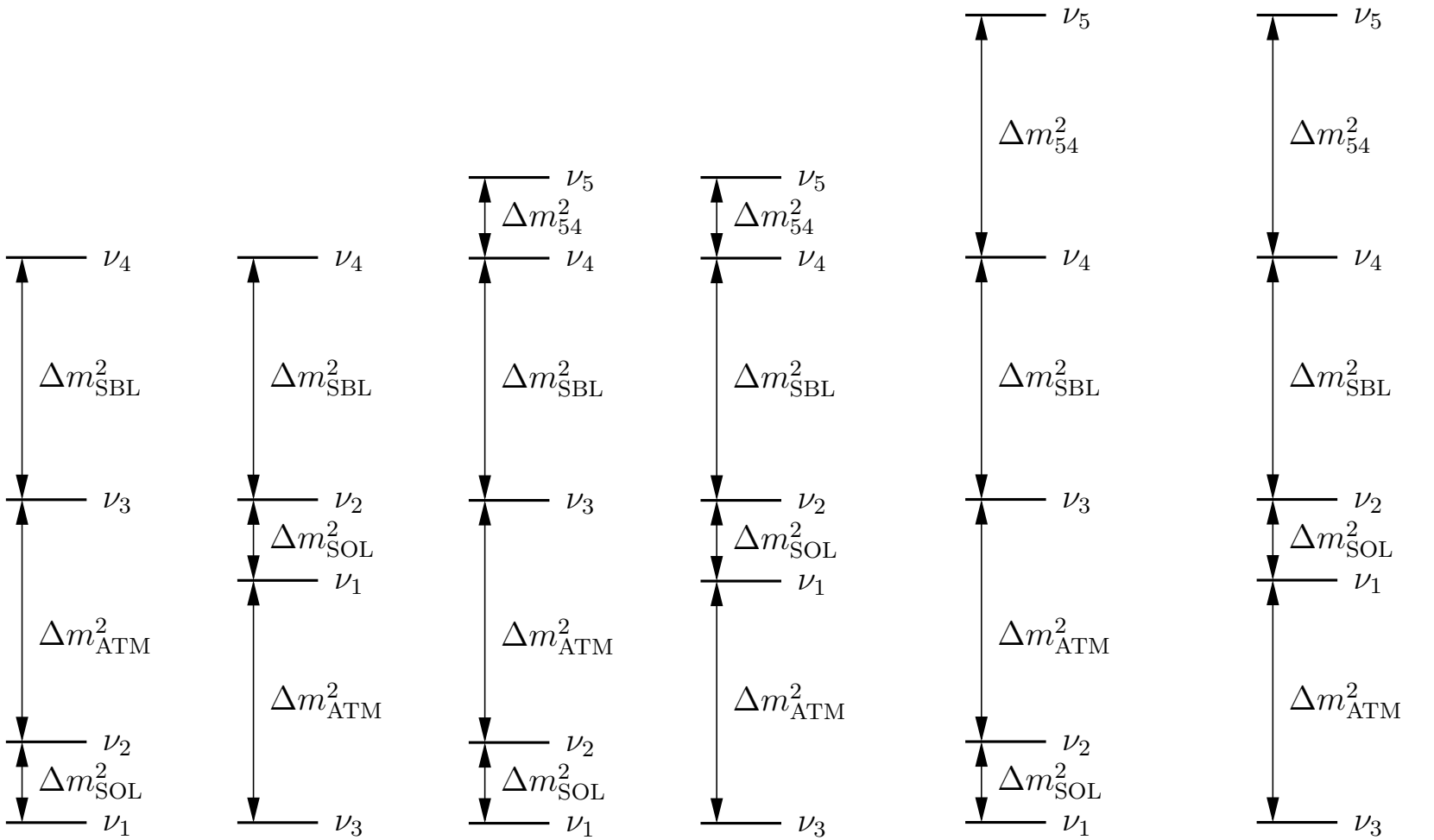
    [Das, Pulido, Picariello, PRD 79 (2009) 073010]

    Recent Daya Bay constraints for $10^{-3} \lesssim \Delta m^2 \lesssim 10^{-1}\,\text{eV}^2$ [PRL 113 (2014) 141802]

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

    [Asaka, Blanchet, Shaposhnikov, PLB 631 (2005) 151; Asaka, Shaposhnikov, PLB 620 (2005) 17; Asaka, Shaposhnikov, Kusenko, PLB 638 (2006) 401; Asaka, Laine, Shaposhnikov, JHEP 0606 (2006) 053, JHEP 0701 (2007) 091]

    [Reviews: Kusenko, Phys. Rept. 481 (2009) 1; Boyarsky, Ruchayskiy, Shaposhnikov, Ann. Rev. Nucl. Part. Sci. 59 (2009) 191; Boyarsky, Iakubovskyi, Ruchayskiy, Phys. Dark Univ. 1 (2012) 136; Drewes, IJMPE, 22 (2013) 1330019]


ν_4
$\Delta m^2_{\rm SBL}$
ν_3
$\Delta m^2_{\rm ATM}$
ν_2
$\Delta m^2_{\rm SOL}$
ν_1
$3_{\rm NO}+1$
ν_4
$\Delta m^2_{\rm SBL}$
ν_2
$\Delta m^2_{\rm SOL}$
ν_1
$\Delta m^2_{\rm ATM}$
ν_3
$3_{\rm IO}+1$
ν_5
Δm^2_{54}
ν_4
$\Delta m^2_{\rm SBL}$
ν_3
$\Delta m^2_{\rm ATM}$
ν_2
$\Delta m^2_{\rm SOL}$
ν_1
$3_{\rm NO}+2$
ν_5
Δm^2_{54}
ν_4
$\Delta m^2_{\rm SBL}$
ν_2
$\Delta m^2_{\rm SOL}$
ν_1
$\Delta m^2_{\rm ATM}$
ν_3
$3_{\rm IO}+2$
ν_5
Δm^2_{54}
ν_4
$\Delta m^2_{\rm SBL}$
ν_3
$\Delta m^2_{\rm ATM}$
ν_2
$\Delta m^2_{\rm SOL}$
ν_1
$3_{\rm NO}+1+1$
ν_5
Δm^2_{54}
ν_4
$\Delta m^2_{\rm SBL}$
ν_2
$\Delta m^2_{\rm SOL}$
ν_1
$\Delta m^2_{\rm ATM}$
ν_3
$3_{\rm IO}+1+1$

Effective SBL Oscillation Probabilities in 3+1 Schemes

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

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

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

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

- 6 mixing angles
- 3 Dirac CP phases
- 3 Majorana CP phases
- But CP violation is not observable in current SBL experiments!
- Observable in LBL accelerator exp. sensitive to $\Delta m^2_{\rm ATM}$ [de Gouvea, Kelly, Kobach, PRD 91 (2015) 053005; Klop, Palazzo, arXiv:1412.7524] and solar exp. sensitive to $\Delta m^2_{\rm SOL}$ [Long, Li, Giunti, PRD 87, 113004 (2013) 113004]

3+1: Appearance vs Disappearance

- Amplitude of ν_e disappearance:

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

- Amplitude of ν_μ disappearance:

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

- Amplitude of $\nu_\mu \to \nu_e$ transitions:

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

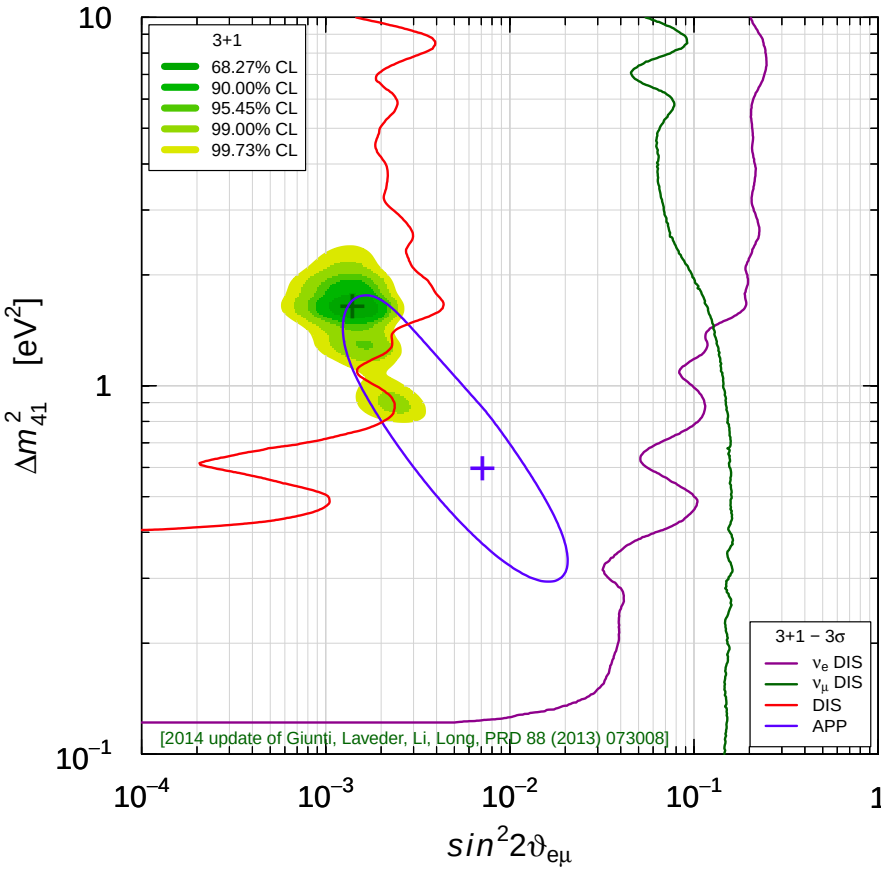
- Upper bounds on ν_e and ν_μ disappearance $\Rightarrow$ strong limit on $\nu_\mu \to \nu_e$

[Okada, Yasuda, IJMPA 12 (1997) 3669; Bilenky, Giunti, Grimus, EPJC 1 (1998) 247]

- Similar constraint in 3+2, 3+3, ..., 3+N_s !

Global 3+1 Fit

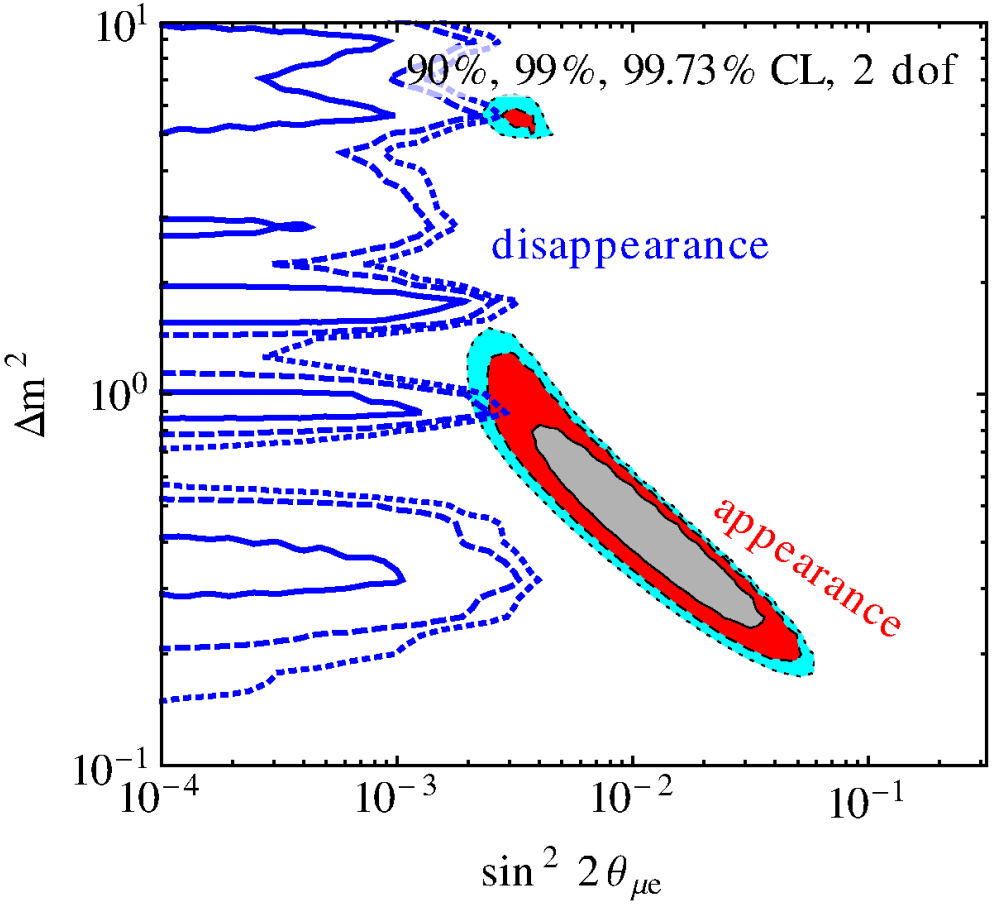
Our Fit



GoF = 5%

PGoF = 0.1%

Kopp, Machado, Maltoni, Schwetz



GoF = 19%

PGoF = 0.01%

[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

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

Parameter Goodness of Fit

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

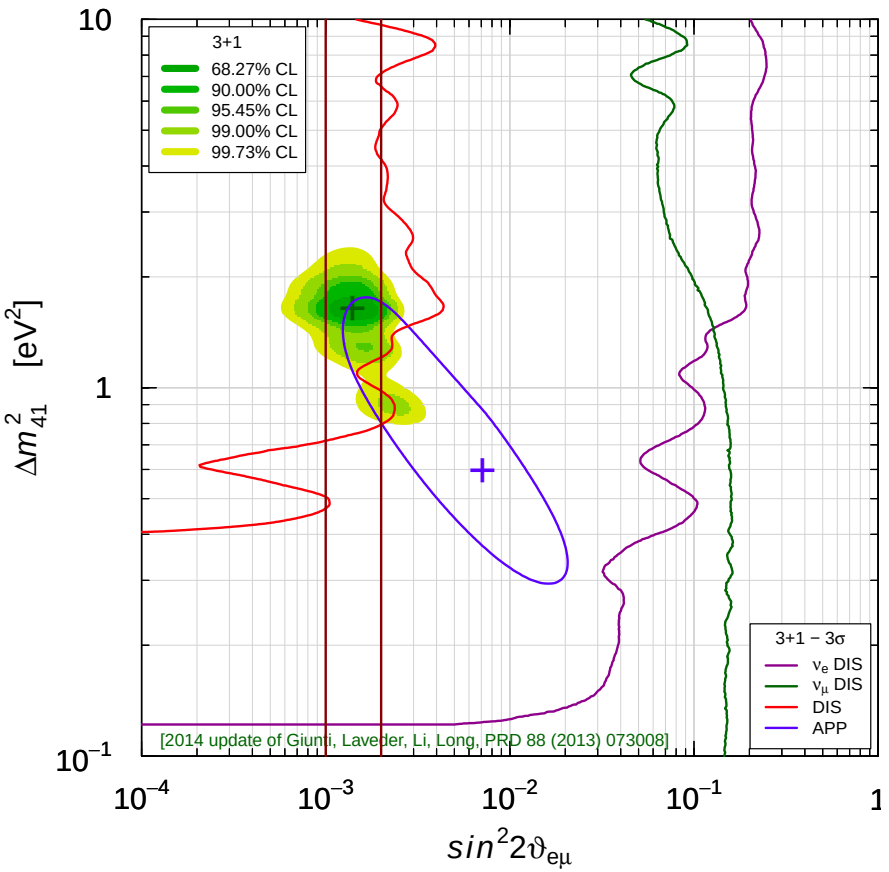
- Measure compatibility of two (or more) sets of data points A and B under fitting model
- $\chi^2_{\rm PGoF} = (\chi^2_{\rm min})_{\rm A+B} - [(\chi^2_{\rm min})_{\rm A} + (\chi^2_{\rm min})_{\rm B}]$
- $\chi^2_{\rm PGoF}$ has χ^2 distribution with Number of Degrees of Freedom

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

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

Global 3+1 Fit

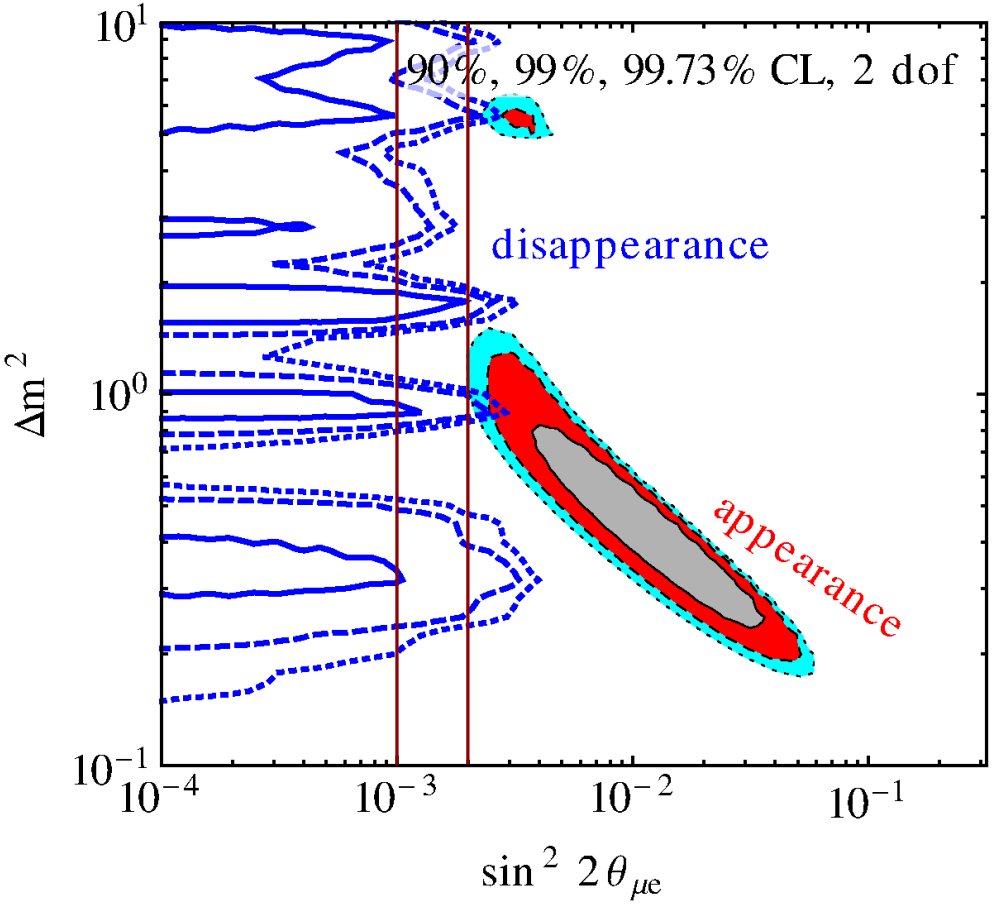
Our Fit



GoF = 5%

PGoF = 0.1%

Kopp, Machado, Maltoni, Schwetz



GoF = 19%

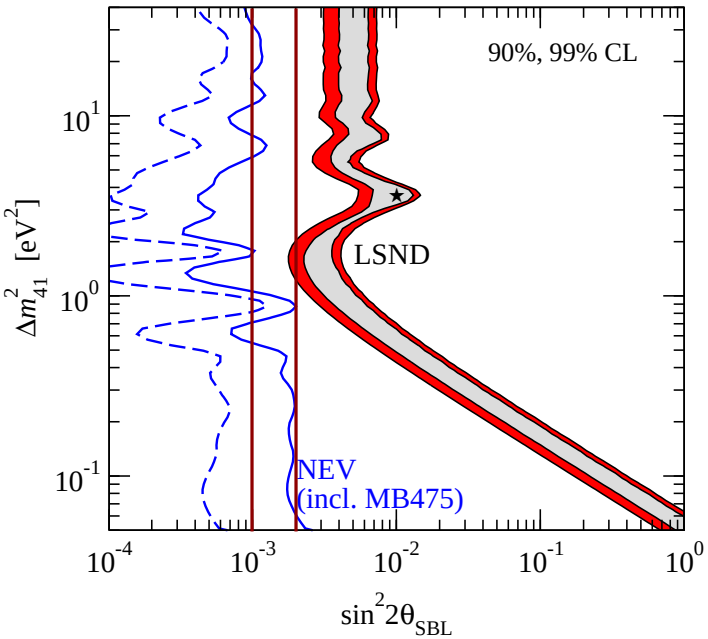
PGoF = 0.01%

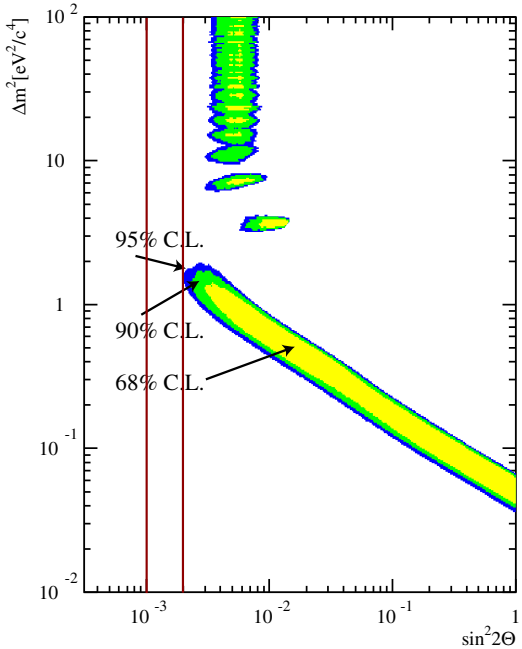
[Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]

Different LSND Treatments

only LSND data from $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ decay at rest

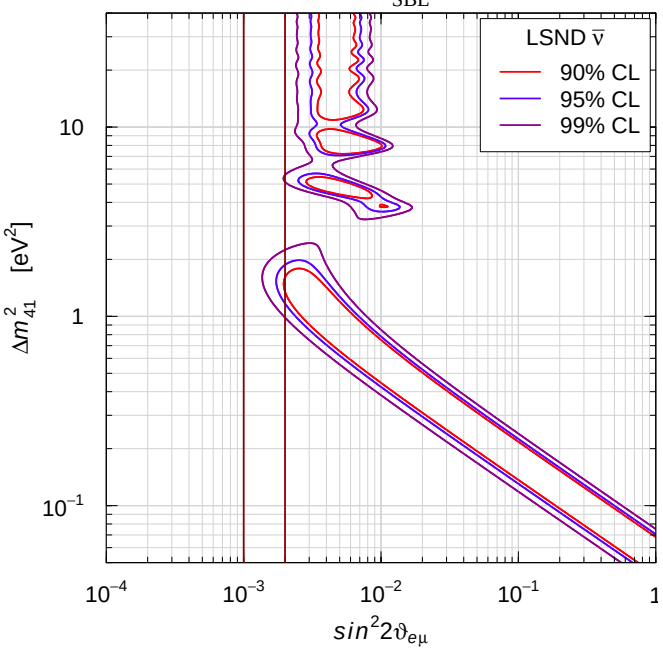
[Kopp, Machado, Maltoni, Schwetz]
[Maltoni, Schwetz, PRD 76 (2007) 093005]

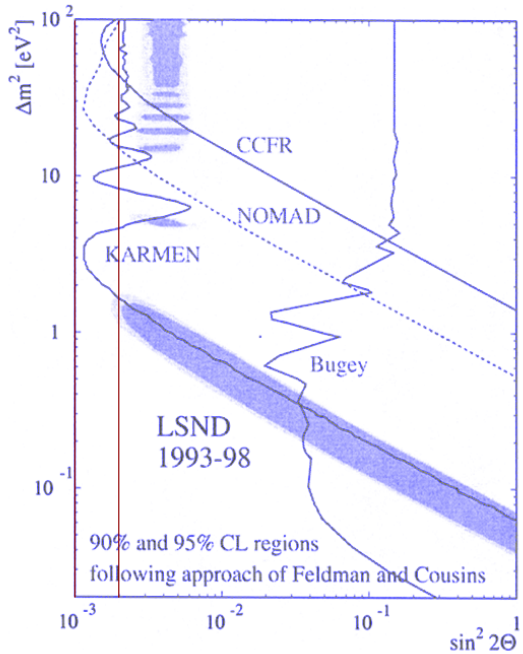




[Church, Eitel, Mills, Steidl, PRD 66 (2002) 013001]

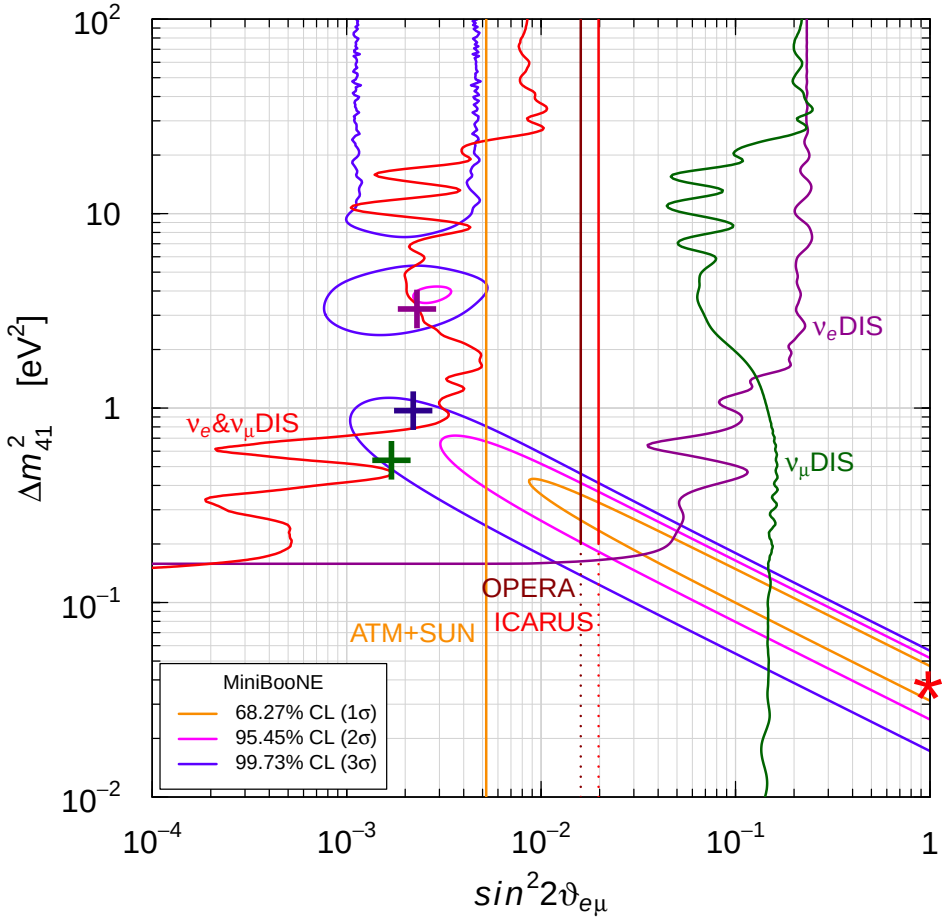
[Our Fit]
[improvement of Giunti, Laveder, PRD 82 (2010) 093016]

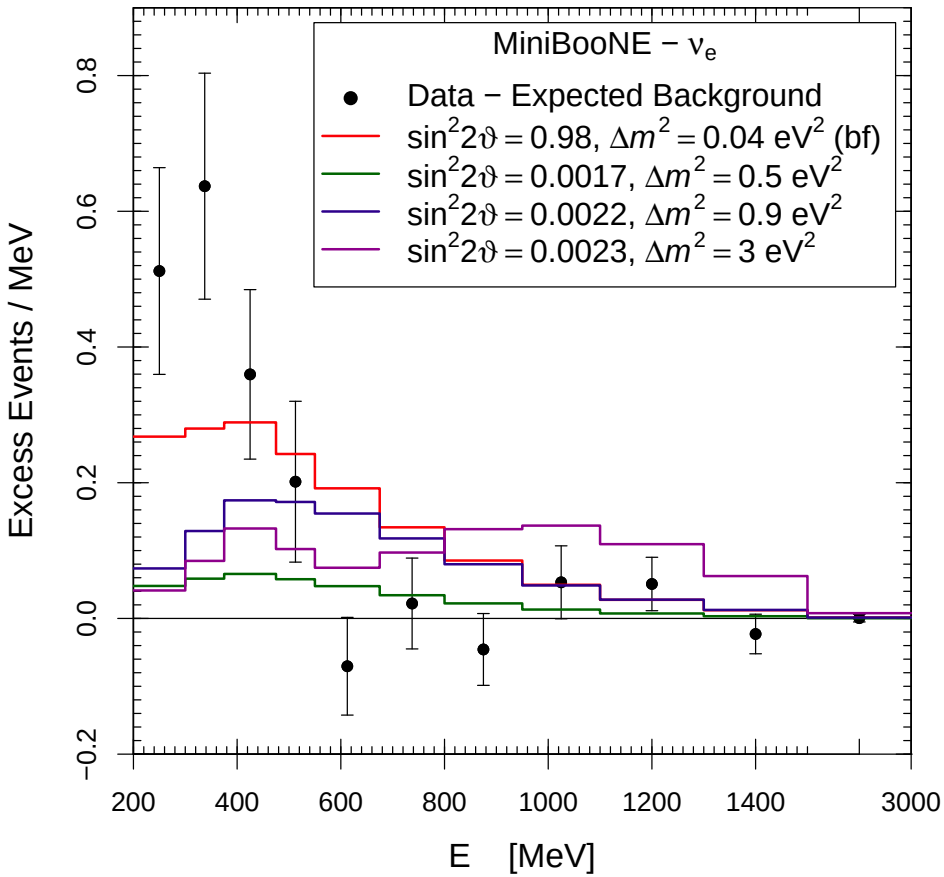




[Church (LSND), NPA 663 (2000) 799]

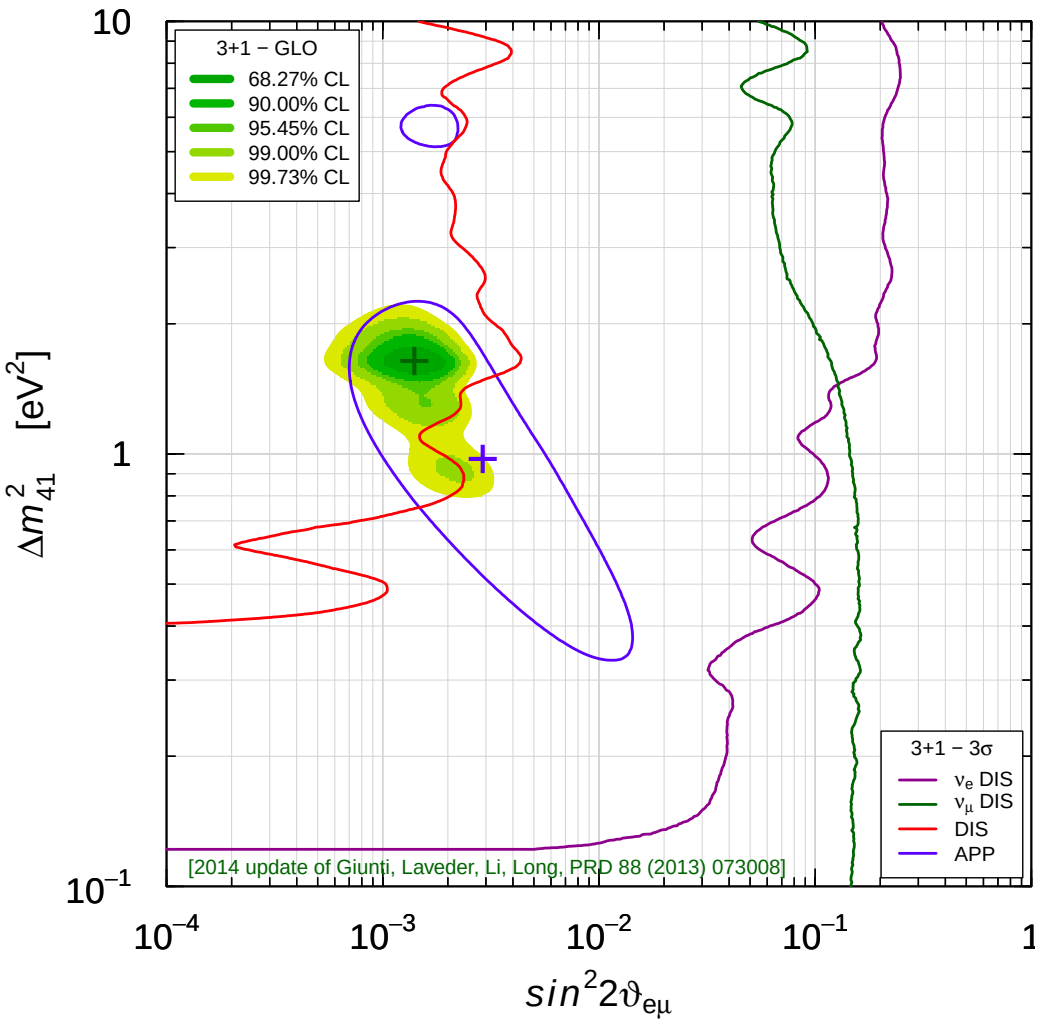
MiniBooNE Low-Energy Excess?





- No fit of low-energy excess for realistic $\sin^2 2\vartheta_{e\mu} \lesssim 3 \times 10^{-3}$
- Neutrino energy reconstruction problem? [Martini, Ericson, Chanfray, PRD 87 (2013) 013009]
- MB low-energy excess is the main cause of bad APP-DIS PGoF $= 0.1\%$
- Pragmatic Approach: discard the Low-Energy Excess because it is very likely not due to oscillations

Pragmatic 3+1 Fit



- APP $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$: LSND ($\nu_s$), MiniBooNE (?), OPERA ($\not{\nu_s}$), ICARUS ($\not{\nu_s}$), KARMEN ($\not{\nu_s}$), NOMAD ($\not{\nu_s}$), BNL-E776 ($\not{\nu_s}$)
- DIS ν_e & $\bar{\nu}_e$: Reactors (ν_s), Gallium (ν_s), ν_eC ($\not{\nu_s}$), Solar ($\not{\nu_s}$)
- DIS ν_μ & $\bar{\nu}_\mu$: CDHSW ($\not{\nu_s}$), MINOS ($\not{\nu_s}$), Atmospheric ($\not{\nu_s}$), MiniBooNE/SciBooNE ($\not{\nu_s}$)

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

GoF $= 26\%$ PGoF $= 7\%$

No Osc. nominally disfavored at $\approx 6.3\sigma$

$\Delta\chi^2/\text{NDF} = 47.7/3$

Effective SBL Oscillation Probabilities in 3+2 Schemes

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

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

$$P^{\rm SBL}_{\substack{(-)\\ \nu_\mu \to \nu_e}\ \substack{(-)\\ }} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\phi_{41} + 4|U_{e5}|^2|U_{\mu 5}|^2 \sin^2\phi_{51} + 8|U_{\mu 4}U_{e4}U_{\mu 5}U_{e5}|\sin\phi_{41}\sin\phi_{51}\cos(\phi_{54} \overset{(+)}{-} \eta)$$

$$P^{\rm SBL}_{\substack{(-)\\ \nu_\alpha \to \nu_\alpha}\ \substack{(-)\\ }} = 1 - 4(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2\phi_{41} + |U_{\alpha 5}|^2 \sin^2\phi_{51}) - 4|U_{\alpha 4}|^2|U_{\alpha 5}|^2 \sin^2\phi_{54}$$

[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; Jacques, Krauss, Lunardini, PRD 87 (2013) 083515; 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]

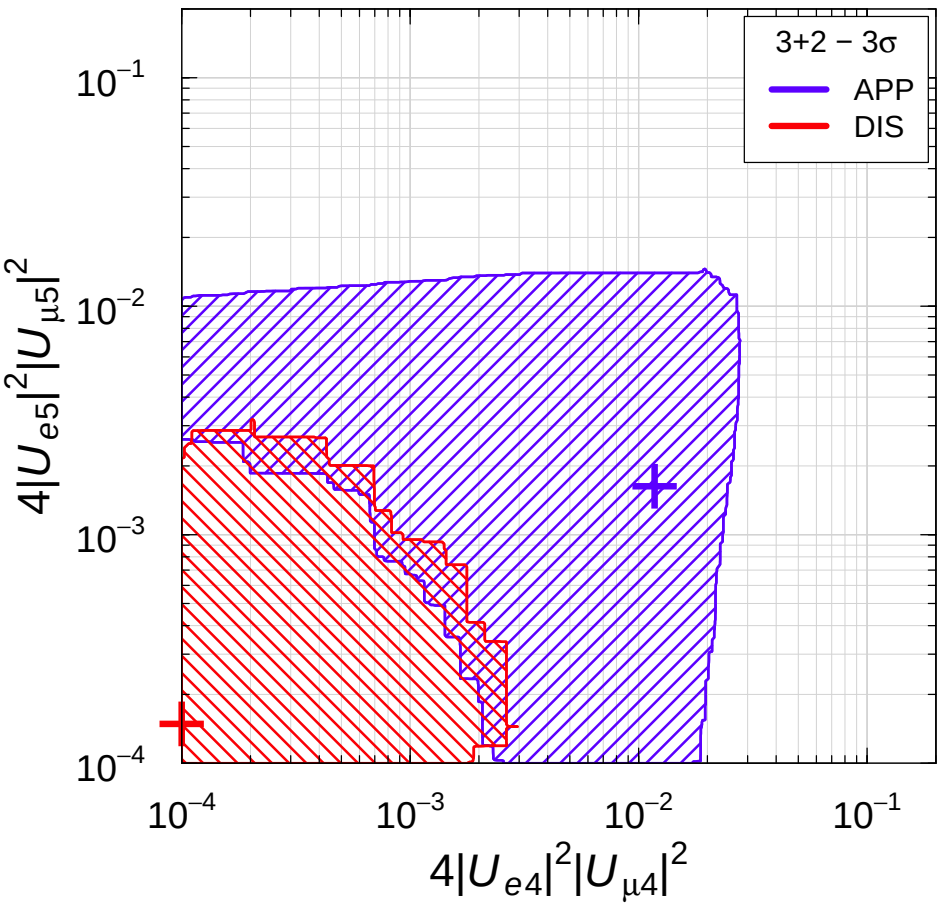
- Good: CP violation
- Bad: Two massive sterile neutrinos at the eV scale!

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

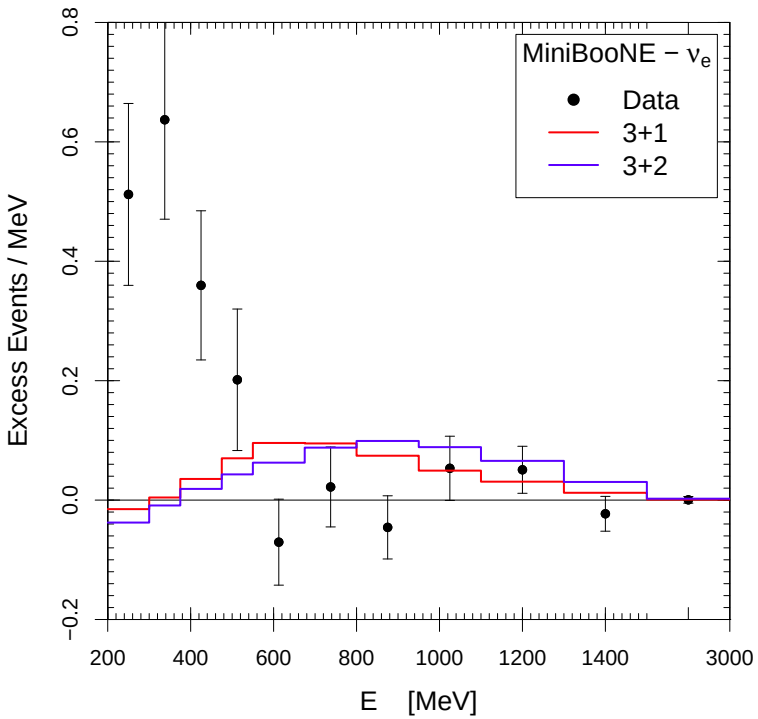
Global Fits	Our Fit		KMMS	
	3+1	3+2	3+1	3+2
GoF	5%	7%	19%	23%
PGoF	0.1%	0.04%	0.01%	0.003%

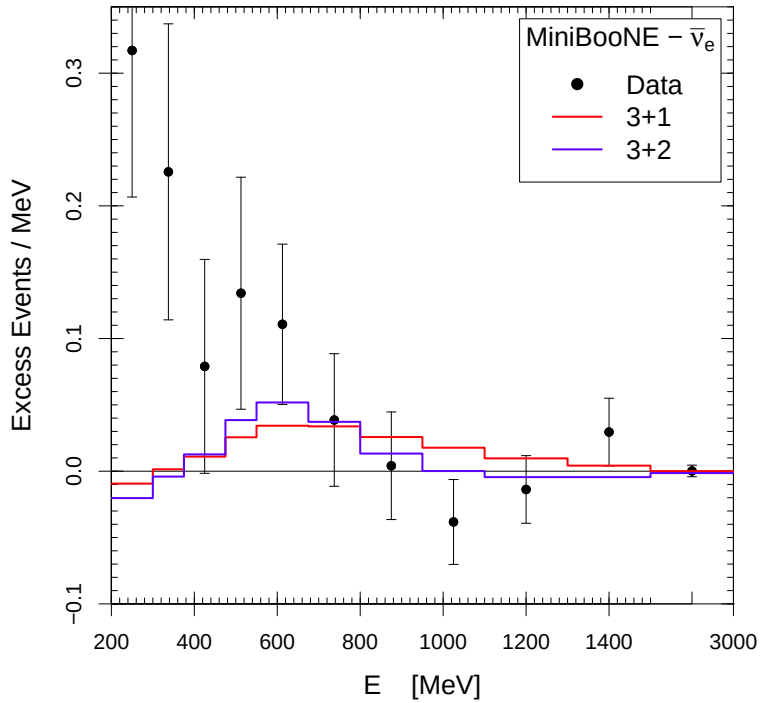
- Our Fit: 2014 update of Giunti, Laveder, Li, Long, PRD 88 (2013) 073008
- KMMS: Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050

APP-DIS 3+2 Tension:



3+2 cannot fit MiniBooNE Low-Energy Excess

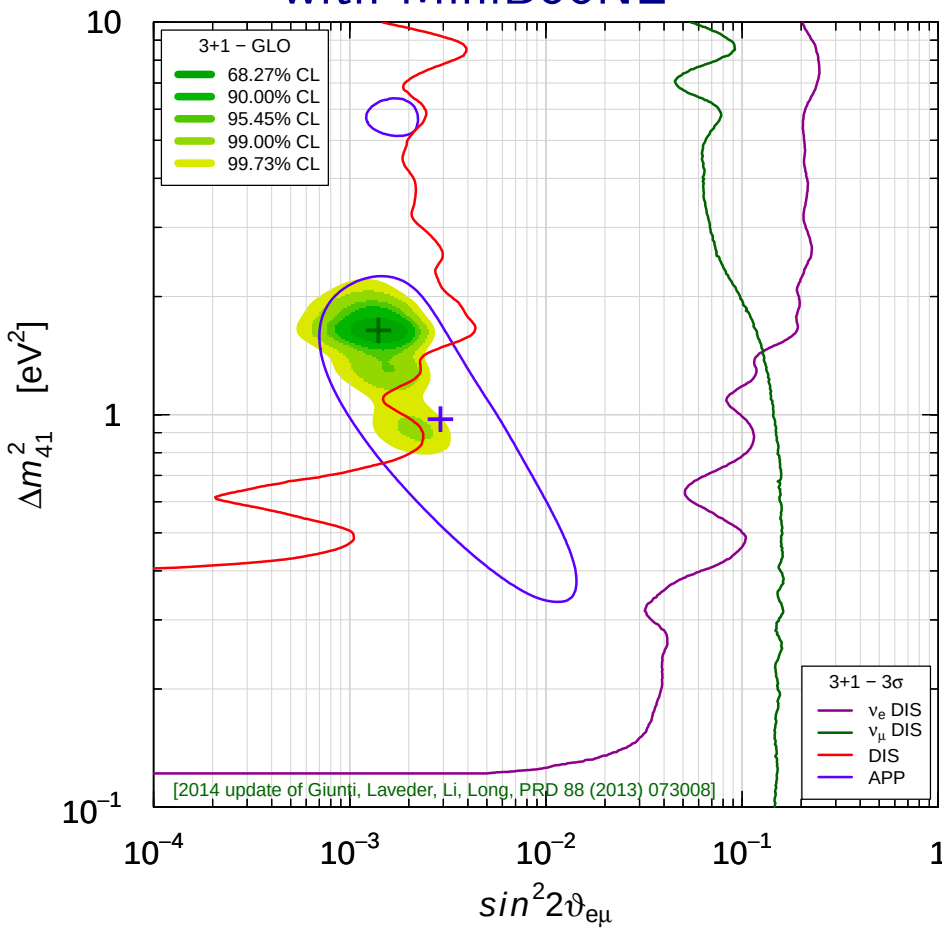




- Note difference between 3+2 ν_e and $\bar{\nu}_e$ histograms due to CP violation
- 3+2 can fit slightly better the small $\bar{\nu}_e$ excess at about 600 MeV
- 3+2 fit of low-energy excess as bad as 3+1
- Claims that 3+2 can fit low-energy excess do not take into account constraints from other data
- Conclusion: forget 3+2! (at least until new data require it)

MiniBooNE Impact in Pragmatic 3+1 Fit?

with MiniBooNE

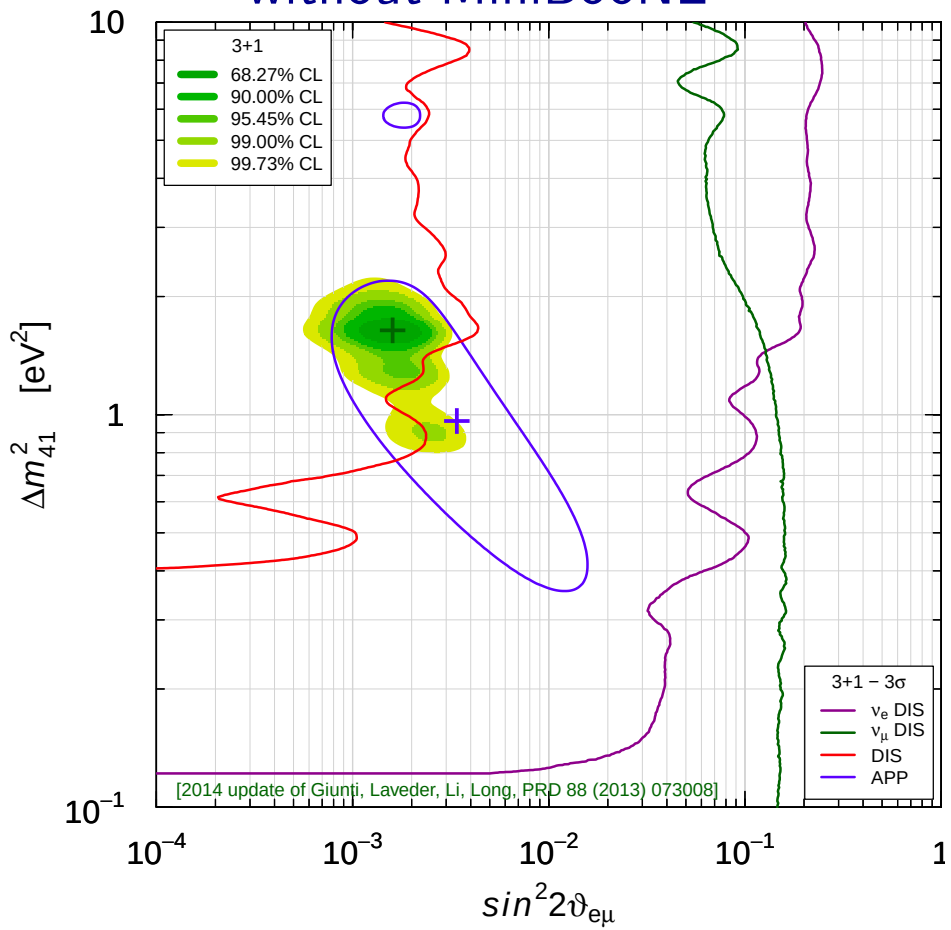


GoF = 26% PGoF = 7%

No Osc. nominally disfavored

at $\approx 6.3\sigma$ ($\Delta\chi^2/\text{NDF} = 47.7/3$)

without MiniBooNE



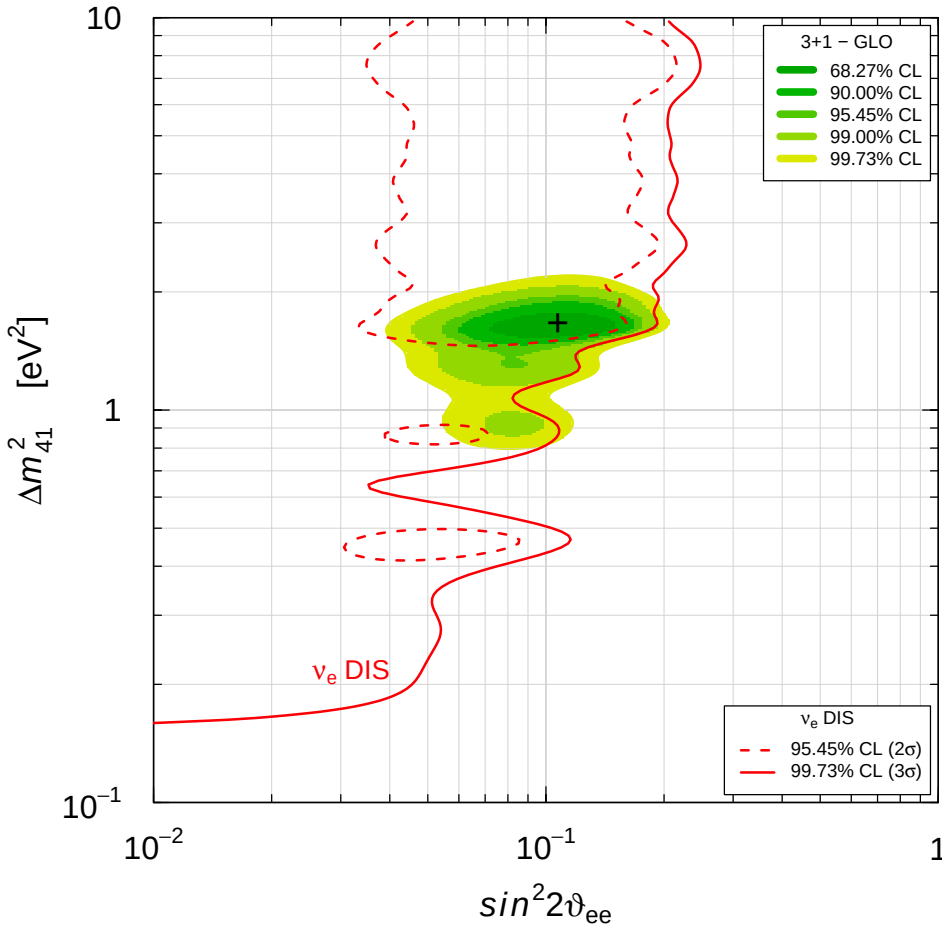
GoF = 16% PGoF = 5%

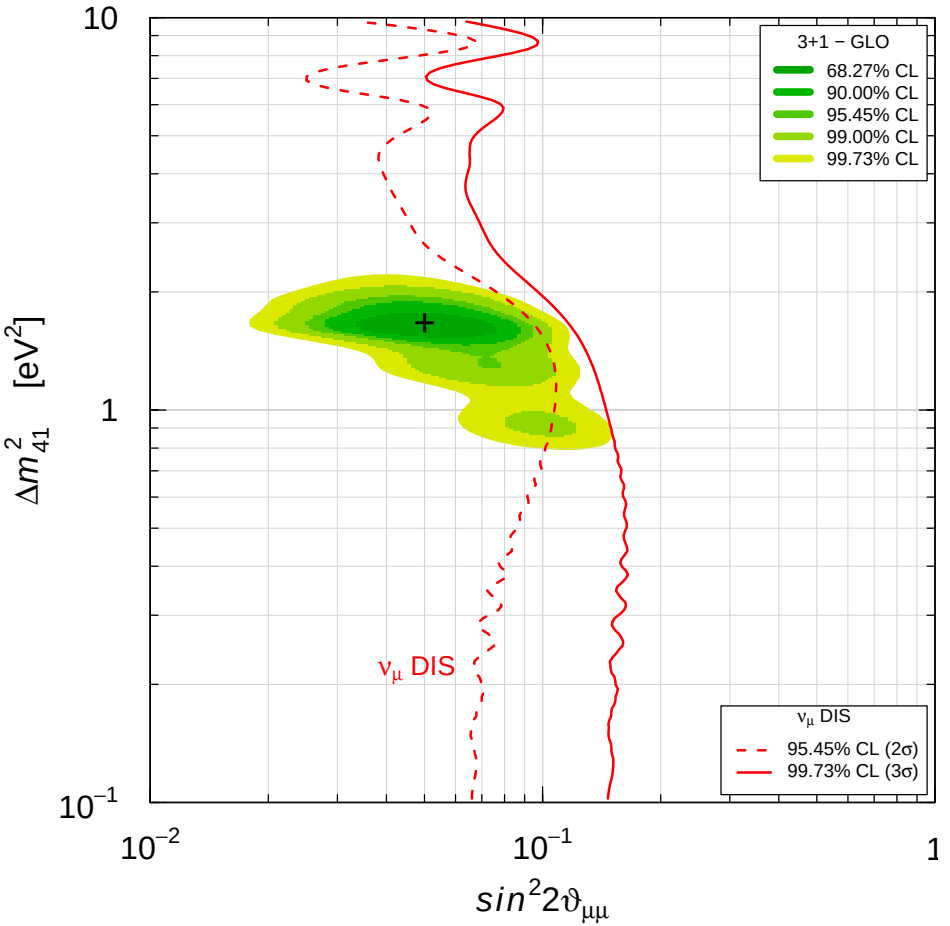
No Osc. nominally disfavored

at $\approx 6.4\sigma$ ($\Delta\chi^2/\text{NDF} = 48.1/3$)

Without LSND: No Osc. nominally disfavored at $\approx 2.6\sigma$ ($\Delta\chi^2/\text{NDF} = 11.4/3$)

ν_e and ν_μ Disappearance





Future

- Many Exciting New Experiments and Projects with Reactor $\bar{\nu}_e$, Radioactive ν_e and $\bar{\nu}_e$ Sources, Accelerator $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$
- Effects of light sterile neutrinos should also be seen in:
  - Solar neutrinos

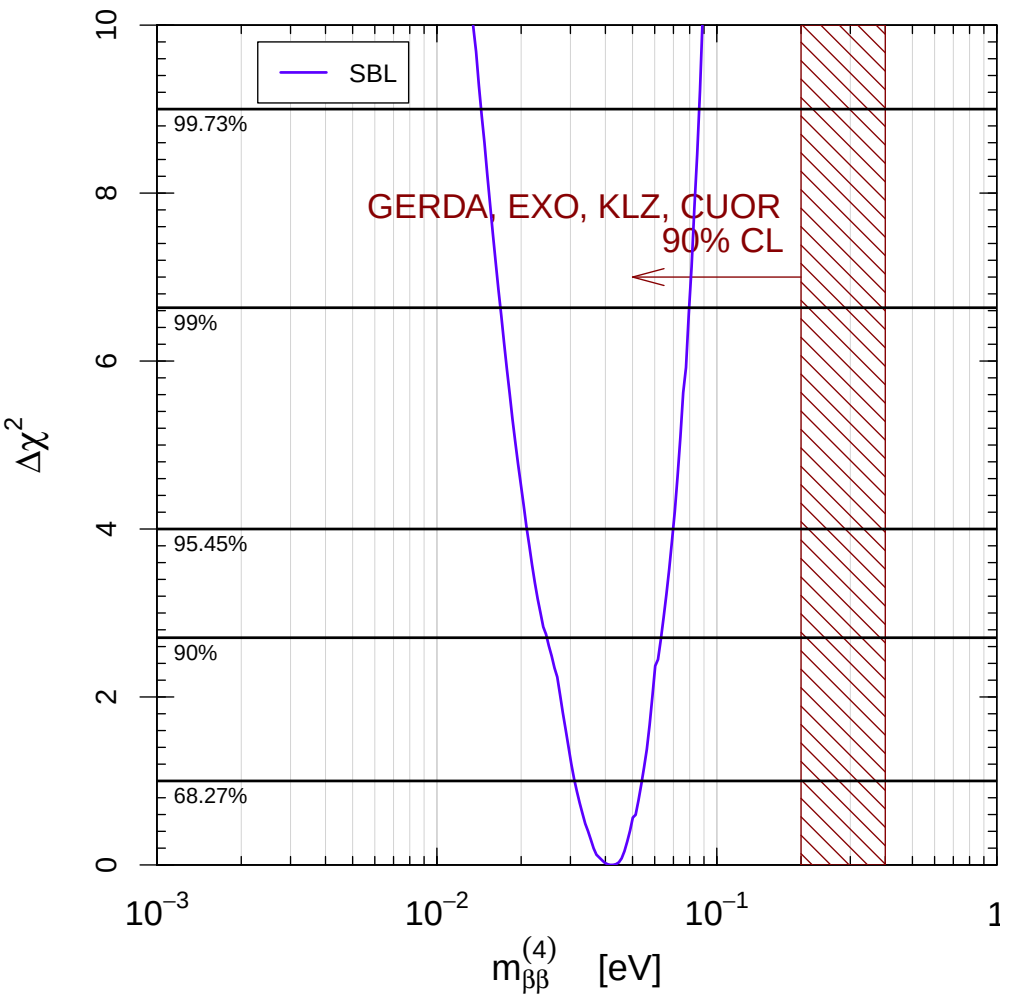
    [Dooling et al, PRD 61 (2000) 073011, Gonzalez-Garcia et al, PRD 62 (2000) 013005;
    Palazzo, PRD 83 (2011) 113013, PRD 85 (2012) 077301;
    Li et al, PRD 80 (2009) 113007, PRD 87, 113004 (2013), JHEP 1308 (2013) 056;
    Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]
  - High-energy atmospheric neutrinos (IceCube, Km3Net)

    [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, JHEP 1312 (2013) 014;
    Rajpoot, Sahu, Wang, EPJC 74 (2014) 2936]
  - 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, PRD 89 (2014) 061303;
    Esmaili, Peres, Serpico, PRD 90 (2014) 033013]

Neutrinoless Double-β Decay

$$m_{\beta\beta} = |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_{21}} m_2 + |U_{e3}|^2 e^{i\alpha_{31}} m_3 + |U_{e4}|^2 e^{i\alpha_{41}} m_4$$



Pragmatic 3+1 Fit

[Giunti, Laveder, Li, Long, 2014]

$$m^{(k)}_{\beta\beta} = |U_{ek}|^2 m_k$$

$$m_1 \ll m_4$$

$$\Downarrow$$

$$m^{(4)}_{\beta\beta} \simeq |U_{e4}|^2 \sqrt{\Delta m^2_{41}}$$

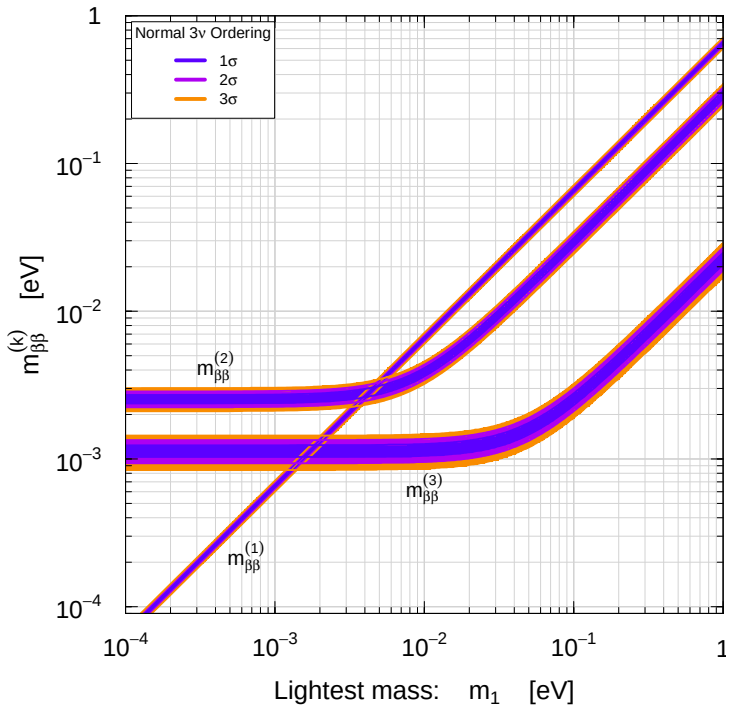
surprise:
possible cancellation
with $m^{(3\nu)}_{\beta\beta}$

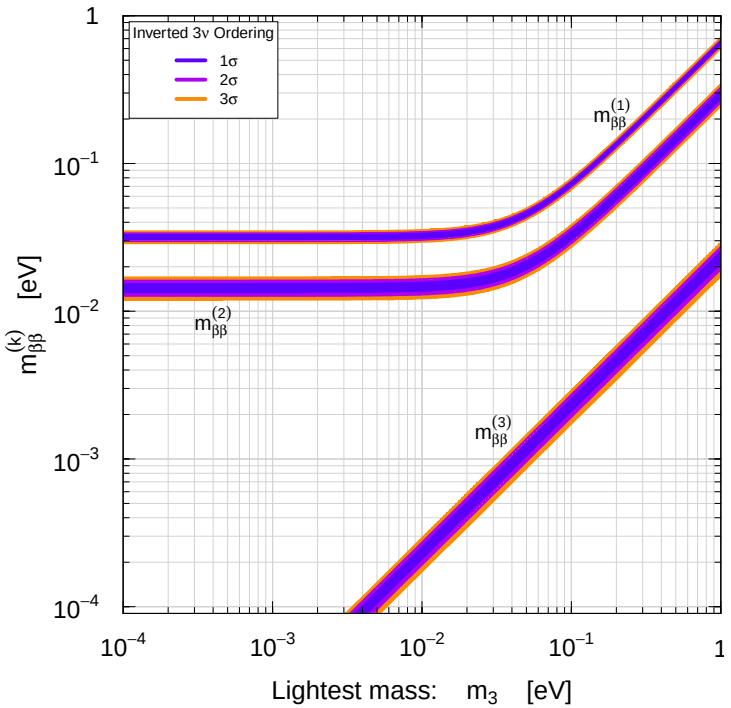
[Barry et al, JHEP 07 (2011) 091]

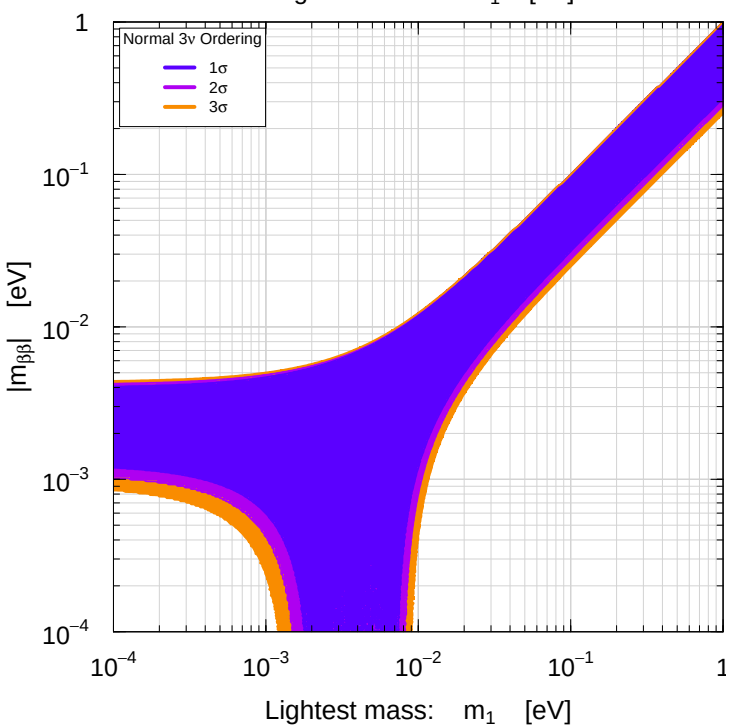
[Li, Liu, PLB 706 (2012) 406]

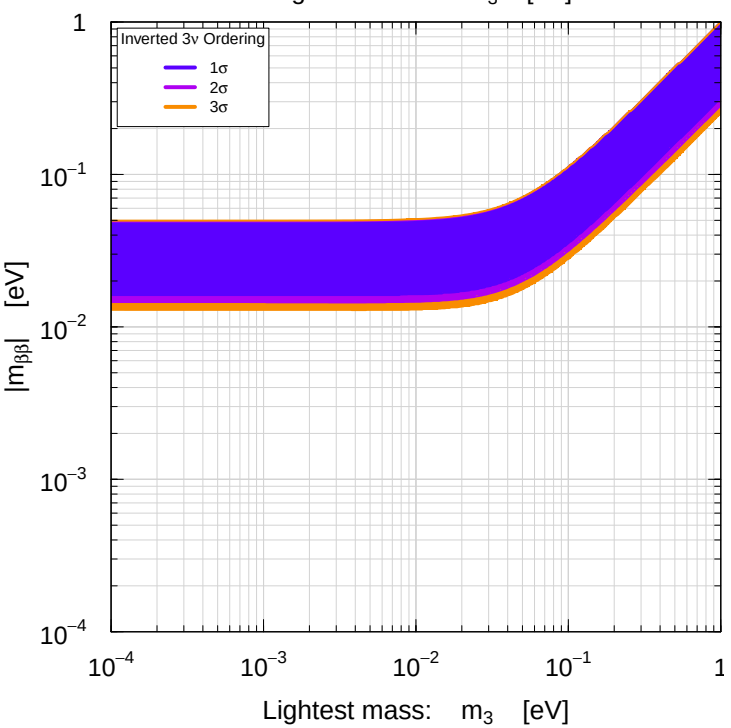
[Rodejohann, JPG 39 (2012) 124008]

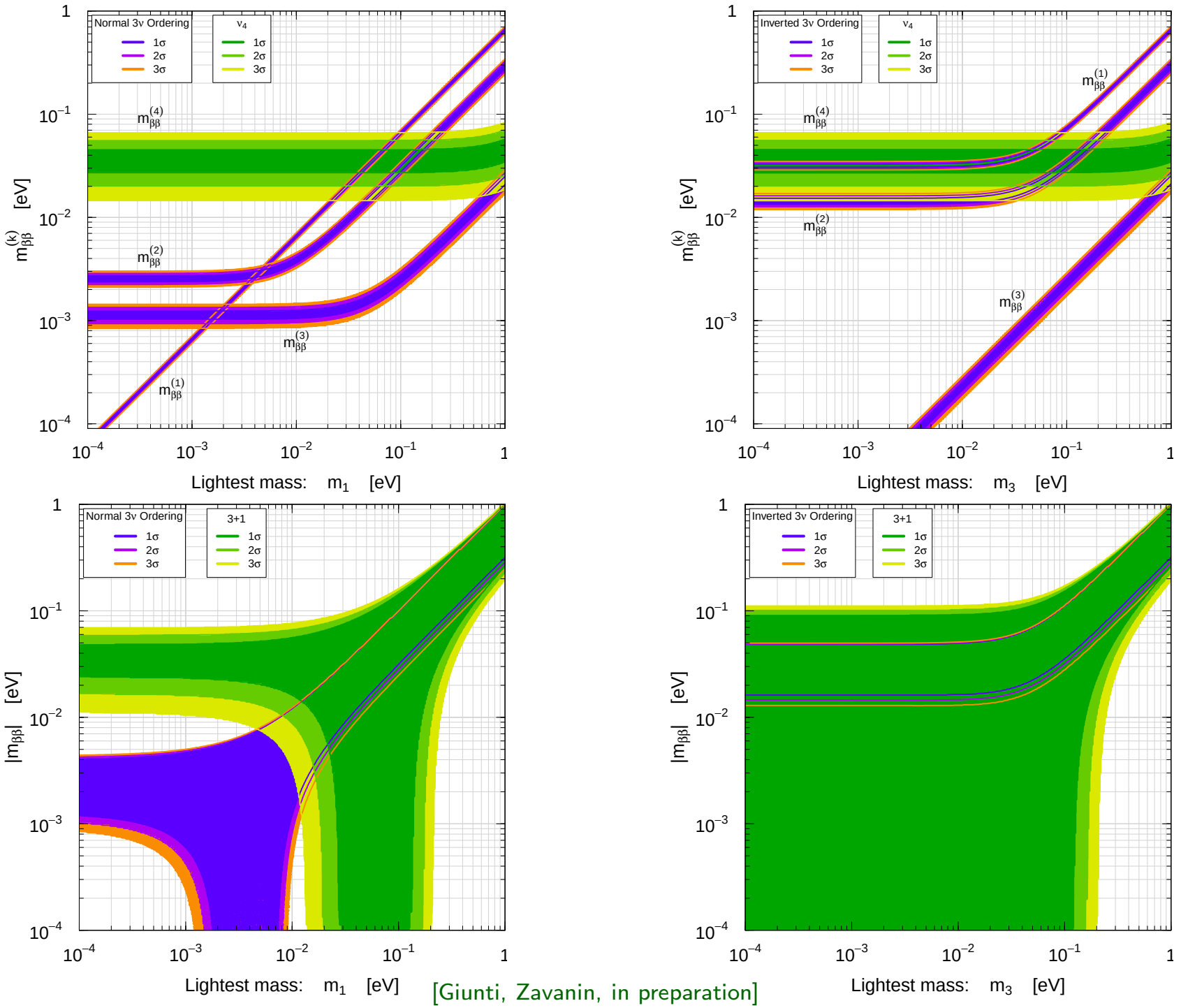
[Girardi, Meroni, Petcov, JHEP 1311 (2013) 146]


Normal 3ν Ordering
1σ
2σ
3σ
$m^{(k)}_{\beta\beta}$ [eV]
$m^{(2)}_{\beta\beta}$
$m^{(3)}_{\beta\beta}$
$m^{(1)}_{\beta\beta}$
Lightest mass: m_1 [eV]


Inverted 3ν Ordering
1σ
2σ
3σ
$m^{(k)}_{\beta\beta}$ [eV]
$m^{(1)}_{\beta\beta}$
$m^{(2)}_{\beta\beta}$
$m^{(3)}_{\beta\beta}$
Lightest mass: m_3 [eV]


Normal 3ν Ordering
1σ
2σ
3σ
$|m_{\beta\beta}|$ [eV]
Lightest mass: m_1 [eV]


Inverted 3ν Ordering
1σ
2σ
3σ
$|m_{\beta\beta}|$ [eV]
Lightest mass: m_3 [eV]



[Giunti, Zavanin, in preparation]

Cosmology

- neutrinos in equilibrium in early Universe through weak interactions:

$$\nu\bar{\nu} \leftrightarrows e^+e^- \qquad \overset{(-)}{\nu} e \leftrightarrows \overset{(-)}{\nu} e \qquad \overset{(-)}{\nu} N \leftrightarrows \overset{(-)}{\nu} N$$

$$\nu_e n \leftrightarrows p e^- \qquad \bar{\nu}_e p \leftrightarrows n e^+ \qquad n \leftrightarrows p e^- \bar{\nu}_e$$

- weak interactions freeze out $\Longrightarrow$ active $(\nu_e, \nu_\mu, \nu_\tau)$ neutrino decoupling

$$\Gamma_{\text{weak}} = N\sigma v \sim G_F^2 T^5 \sim T^2/M_P \sim \sqrt{G_N T^4} \sim \sqrt{G_N \rho} \sim H$$

$$T_{\nu\text{-dec}} \sim 1\,\text{MeV} \qquad t_{\nu\text{-dec}} \sim 1\,\text{s}$$

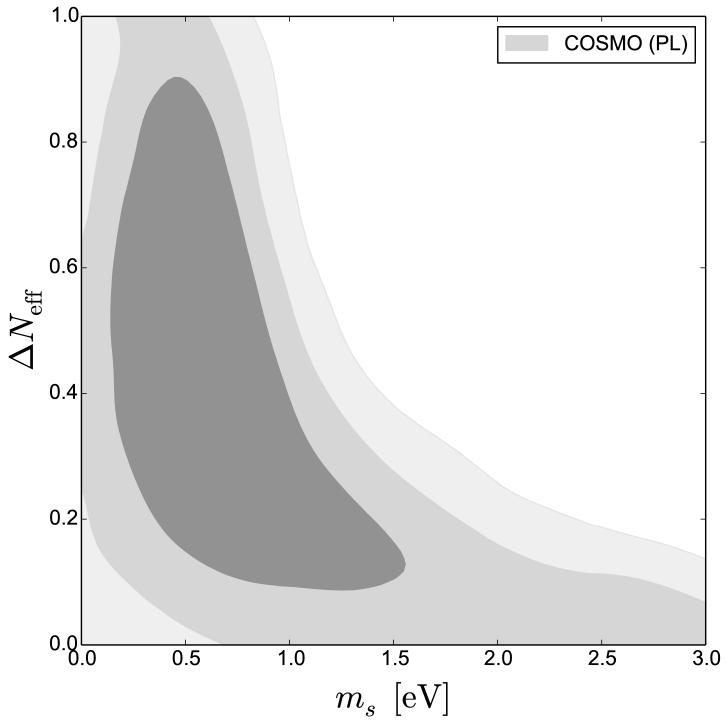
- sterile neutrinos can be produced by $\nu_{e,\mu,\tau} \to \nu_s$ oscillations before active neutrino decoupling $(t_{\nu\text{-dec}} \sim 1\,\text{s})$
- energy density of radiation before matter-radiation equality:

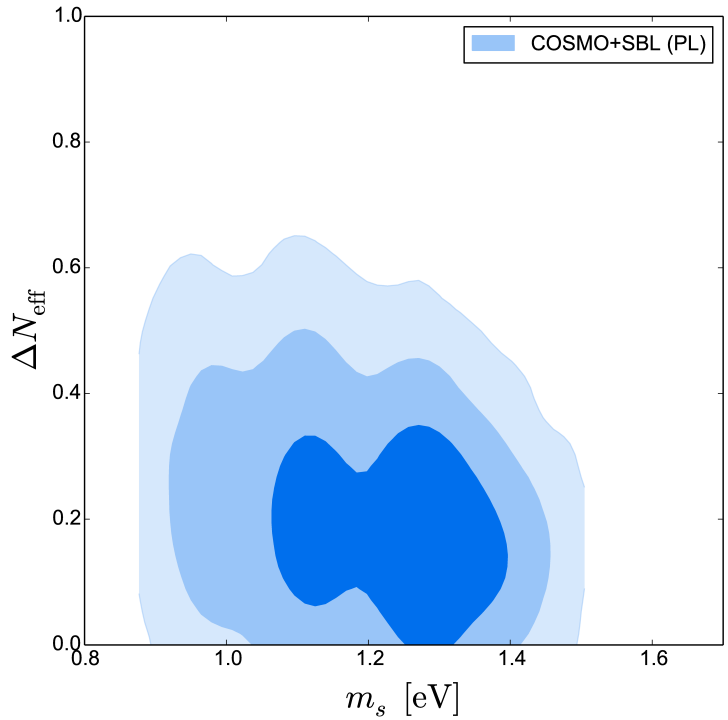
$$\rho_R = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\text{eff}}\right] \rho_\gamma \qquad (t < t_{\text{eq}} \sim 6 \times 10^4\,\text{y})$$

$$N_{\text{eff}}^{\text{SM}} = 3.046 \qquad \Delta N_{\text{eff}} = N_{\text{eff}} - N_{\text{eff}}^{\text{SM}}$$

- sterile neutrino contribution: $\rho_s = (T_s/T_\nu)^4 \rho_\nu \quad \Rightarrow \quad \Delta N_{\text{eff}} = (T_s/T_\nu)^4$

- ν_s with $m_s = \simeq \sqrt{\Delta m^2_{41}} \sim 1\,\text{eV}$ become non-relativistic at $T_\nu \sim m_s/3$ ($t_{\nu_s\text{-nr}} \sim 2.0 \times 10^5\,\text{y}$, before recombination at $t_\text{rec} \sim 3.8 \times 10^5\,\text{y}$)





[Gariazzo, Giunti, Laveder, arXiv:1412.7405]

See also:
- [Archidiacono, Fornengo, Gariazzo, Giunti, Hannestad, Laveder, JCAP 1406 (2014) 031]
- [Bergstrom, Gonzalez-Garcia, Niro, Salvado, JHEP 1410 (2014) 104]

Without oscillation data:
- [Giusarma, Di Valentino, Lattanzi, Melchiorri, Mena, PRD 90 (2014) 043507]
- [Zhang, Li, Zhang, PLB 740 (2015) 359]
- [Dvorkin, Wyman, Rudd, Hu, PRD 90 (2014) 083503]
- [Zhang, Li, Zhang, EPJC 74 (2014) 2954]

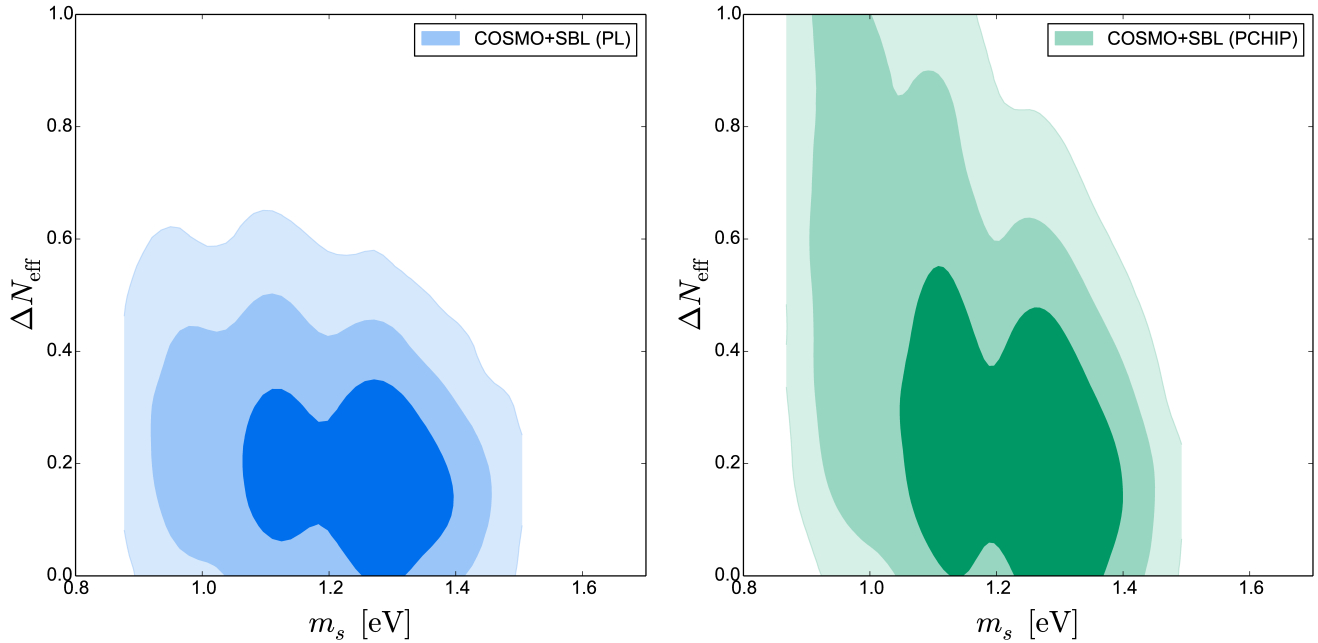
Tension between $\Delta N_{\rm eff} = 1$ and $m_s \approx 1\,{\rm eV}$

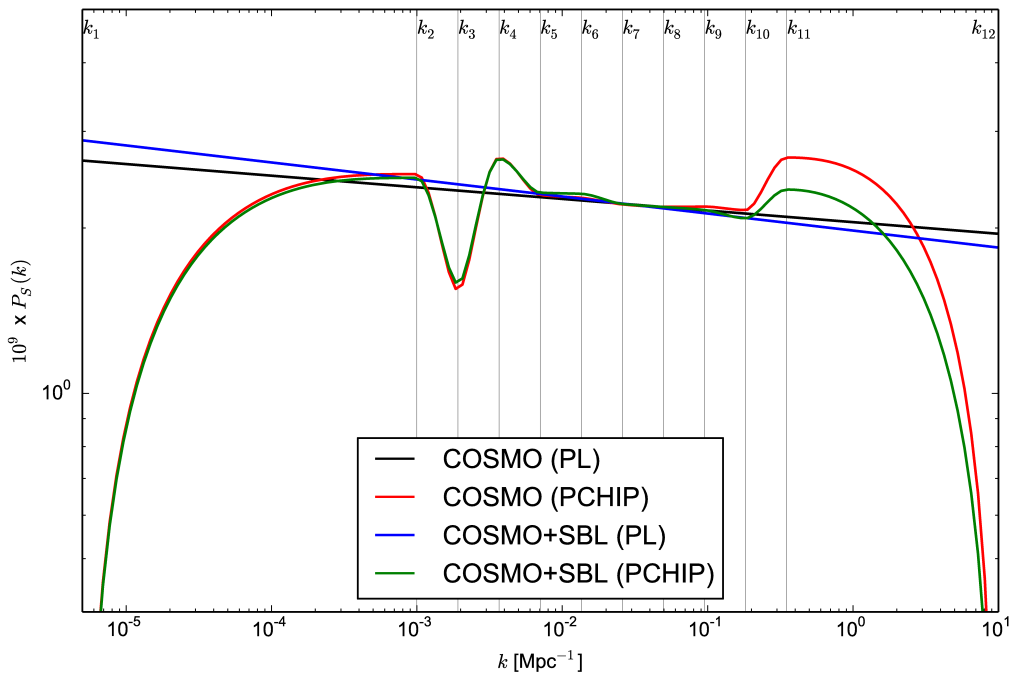
Sterile neutrinos are thermalized ($\Delta N_{\rm eff} = 1$) by active-sterile oscillations before neutrino decoupling [Dolgov, Villante, NPB 679 (2004) 261]

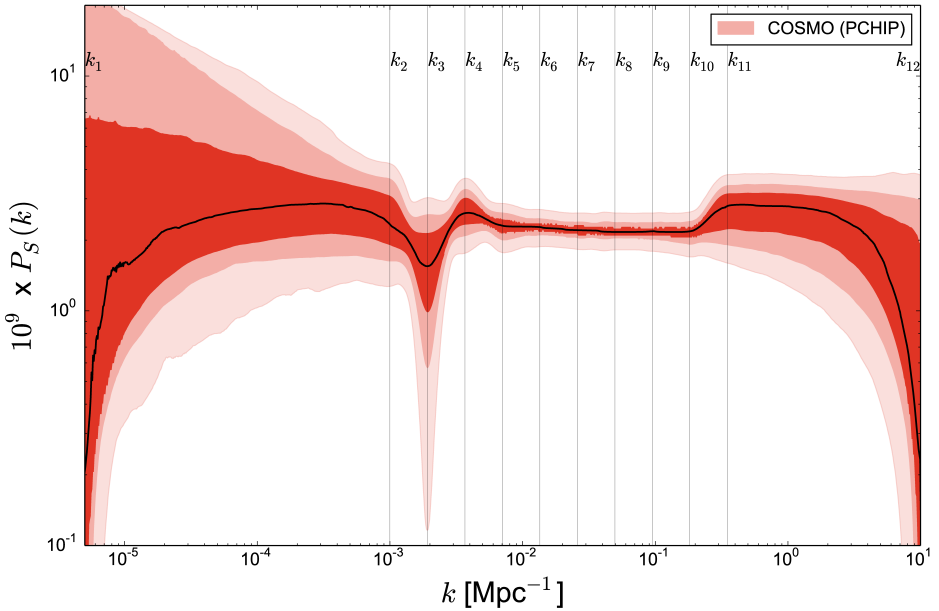
Proposed mechanisms to avoid the tension:

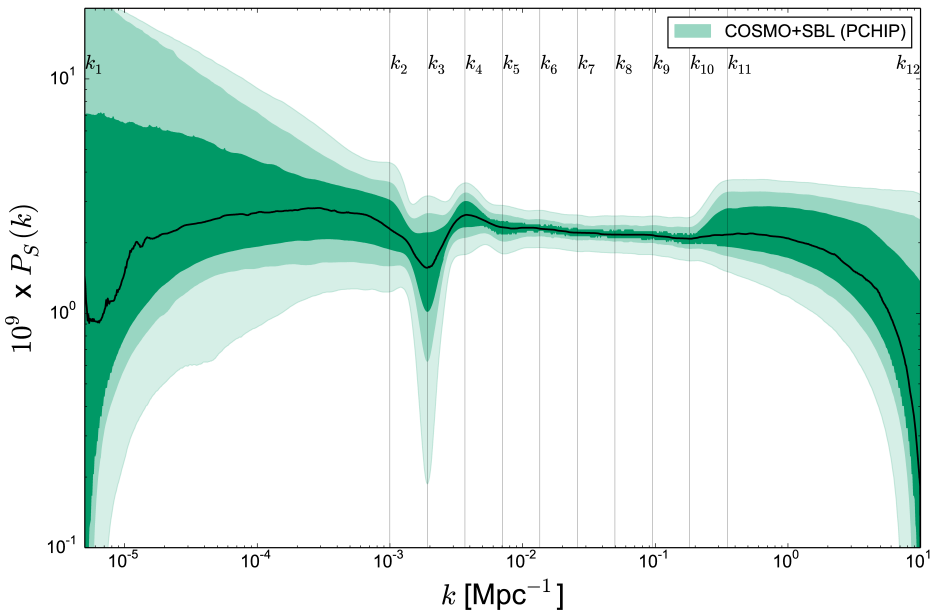
- Large lepton asymmetry [Hannestad, Tamborra, Tram, JCAP 1207 (2012) 025; Mirizzi, Saviano, Miele, Serpico, PRD 86 (2012) 053009; Saviano et al., PRD 87 (2013) 073006; Hannestad, Hansen, Tram, JCAP 1304 (2013) 032]
- Enhanced background potential due to interactions in the sterile sector [Hannestad, Hansen, Tram, PRL 112 (2014) 031802; Dasgupta, Kopp, PRL 112 (2014) 031803; Bringmann, Hasenkamp, Kersten, JCAP 1407 (2014) 042; Ko, Tang, PLB 739 (2014) 62; Archidiacono, Hannestad, Hansen,Tram, arXiv:1404.5915; Mirizzi, Mangano, Pisanti, Saviano, PRD 90 (2014) 113009, PRD 91 (2015) 025019; Tang, arXiv:1501.00059]
- A larger cosmic expansion rate at the time of sterile neutrino production [Rehagen, Gelmini JCAP 1406 (2014) 044]
- MeV dark matter annihilation [Ho, Scherrer, PRD 87 (2013) 065016]
- Invisible decay [Gariazzo, Giunti, Laveder, arXiv:1404.6160]
- Free primordial power spectrum of scalar fluctuations (Inflationary Freedom) [Gariazzo, Giunti, Laveder, arXiv:1412.7405]

Inflationary Freedom









[Gariazzo, Giunti, Laveder, arXiv:1412.7405]

Conclusions

- Short-Baseline ν_e and $\bar{\nu}_e$ Disappearance:
  - Experimental data agree on Reactor $\bar{\nu}_e$ and Gallium ν_e anomalies.
  - Problem: unknown systematic uncertainties (Reactor $\bar{\nu}_e$ flux).
  - Many promising projects to test unambiguously 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:
  - Not seen by other SBL $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ experiments.
  - MiniBooNE experiment has been inconclusive.
  - Experiments with near detector are needed to check LSND signal!
  - If $|U_{e4}| > 0$ why not $|U_{\mu 4}| > 0$? $\quad\Longrightarrow\quad \sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2 > 0$
- Pragmatic 3+1 Fit is fine: moderate APP-DIS tension.
- 3+2 is not needed: same APP-DIS tension as 3+1 and no evidence of CP violation.
- Cosmology:
  - Tension between $\Delta N_{\text{eff}} = 1$ and $m_s \approx 1\,\text{eV}$.
  - Cosmological and oscillation data may be reconciled by a non-standard cosmological mechanism.