The University of Manchester

LSND, MiniBooNE and Future Experiments on (Light) Sterile Neutrinos

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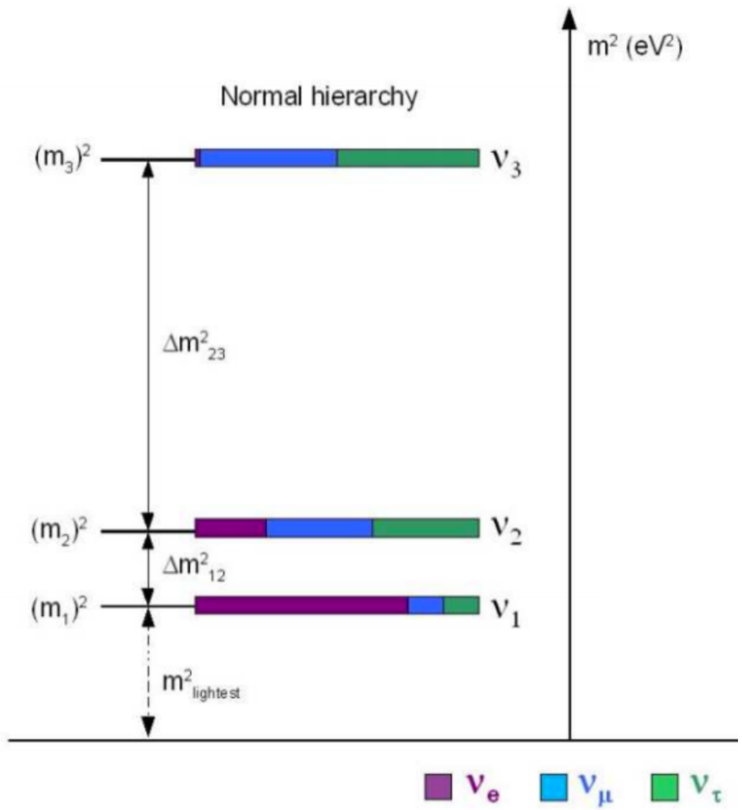
UK HEP Forum:
"Anomalies and Deviations: Looking for Clues of BSM Physics"

The Cosener's House – Nov. 5-6, 2015

All we know conclusively about light neutrinos fits in this picture…



Neutrino oscillation measurements give us
The relative sizes of the color blocks (from oscillation amplitudes, or how much neutrinos oscillate)
The m^2-spacing of the mass states (from oscillation frequencies, or how "quickly" neutrinos oscillate)

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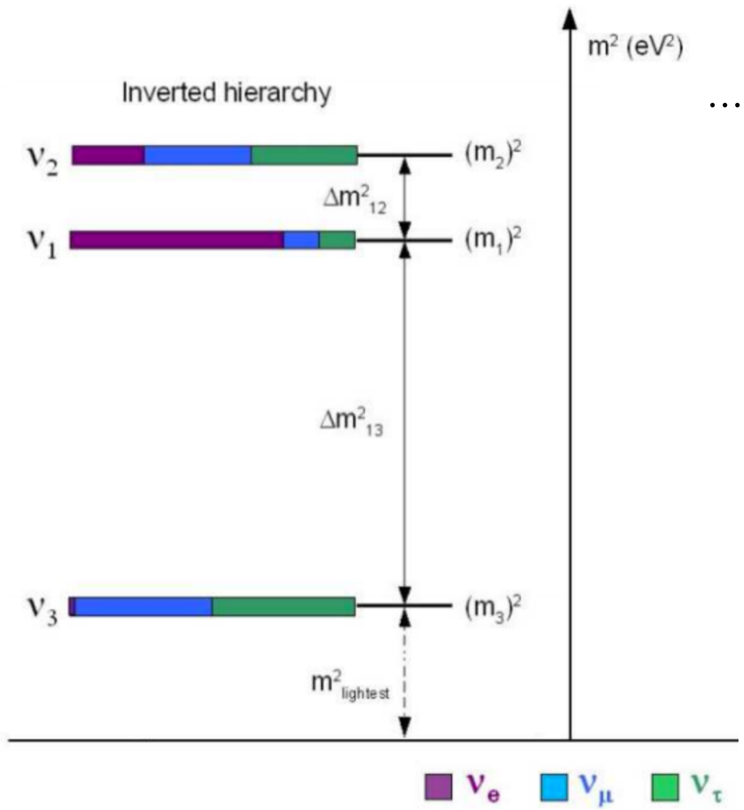

…or this picture

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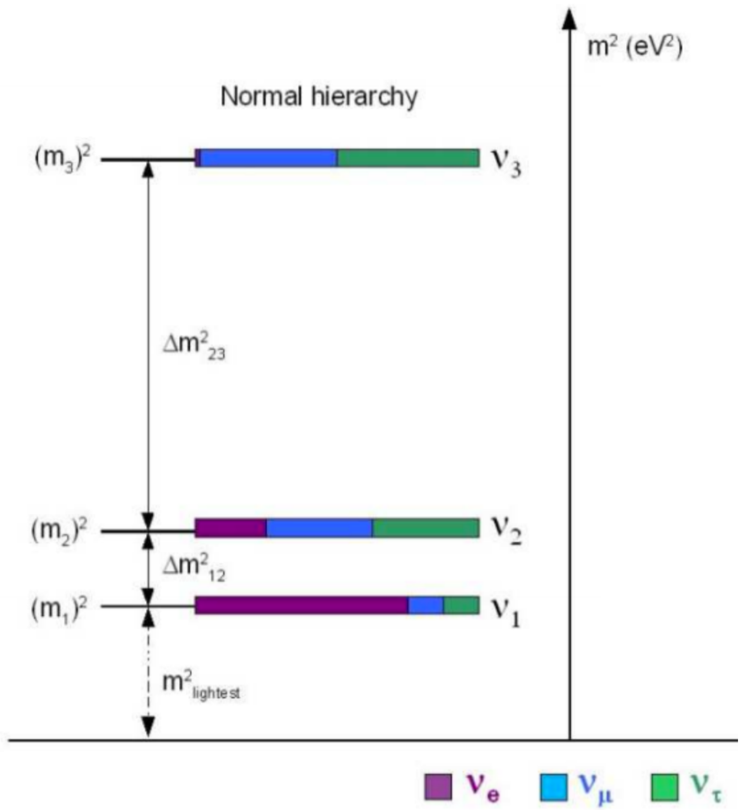


Neutrino oscillation measurements give us
The relative sizes of the color blocks (from oscillation amplitudes, or how much neutrinos oscillate)
The m^2-spacing of the mass states (from oscillation frequencies, or how "quickly" neutrinos oscillate)

Ingredients for neutrino oscillation:

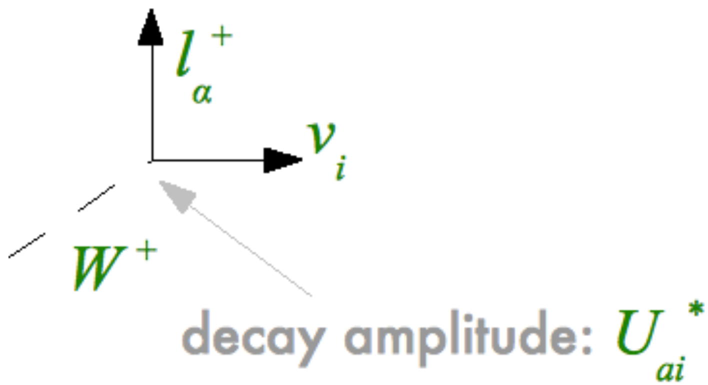
neutrinos have non-zero masses
+
(neutral) leptons mix

weak ("flavour") states

"mass" states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} e^{i\delta} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

3×3 unitary mixing matrix *U*



Neutrinos are always produced and detected as definite weak ("flavour") eigenstates,

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i} |\nu_i\rangle$$

mixing matrix element

weak ("flavour") states "mass" states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} e^{i\delta} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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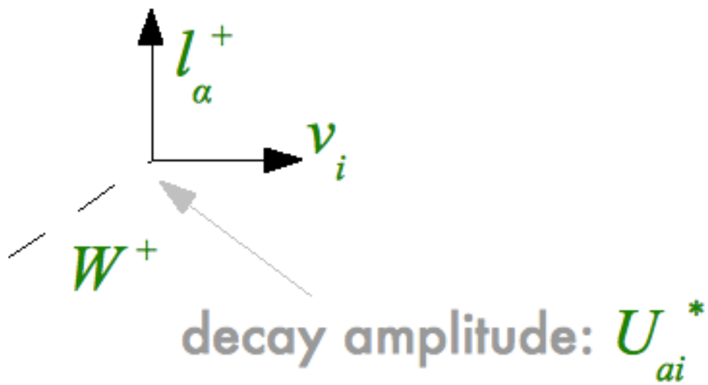

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$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i} |\nu_i\rangle$$

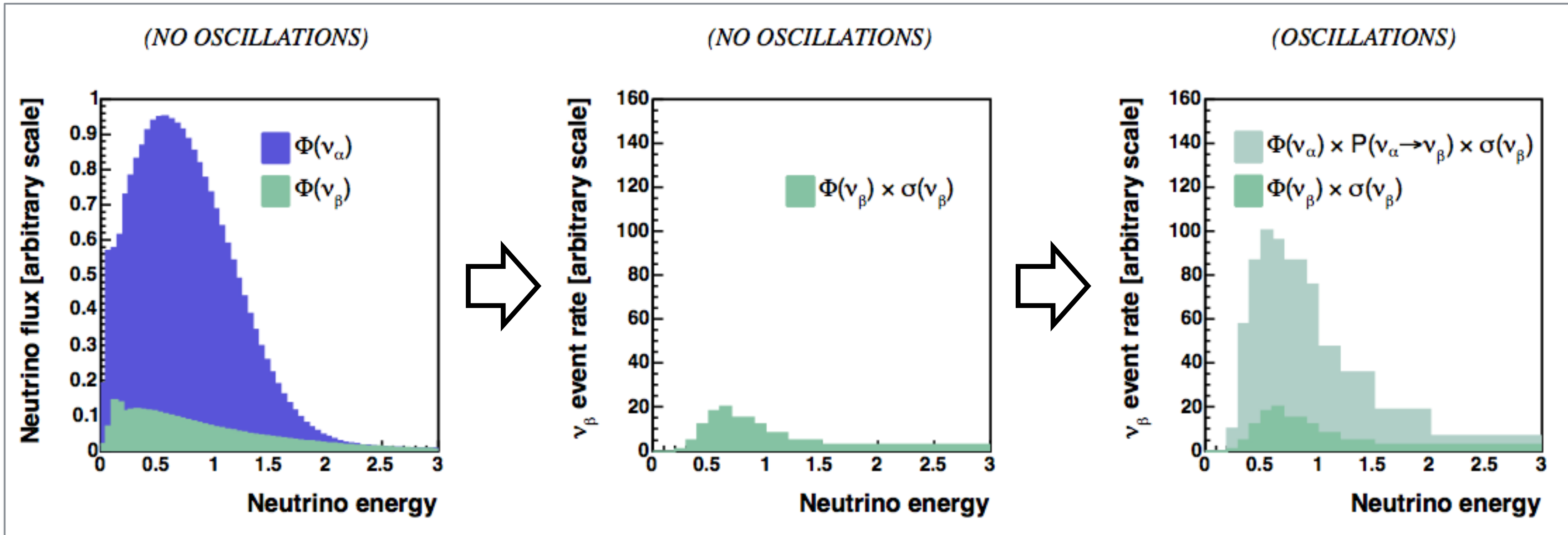
mixing matrix element

Time-evolution of flavour states manifests as oscillations:

$$P(\nu_\alpha \to \nu_\beta) = \left|\langle \nu_\beta | \nu_\alpha(t) \rangle\right|^2 = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left\{U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right\} \sin^2\left[1.27 \Delta m_{ij}^2 L/E\right]$$
$$+2\sum_{i>j} \mathrm{Im}\left\{U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right\} \sin\left[2.54 \Delta m_{ij}^2 L/E\right],$$

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

Experimental signatures of neutrino oscillations

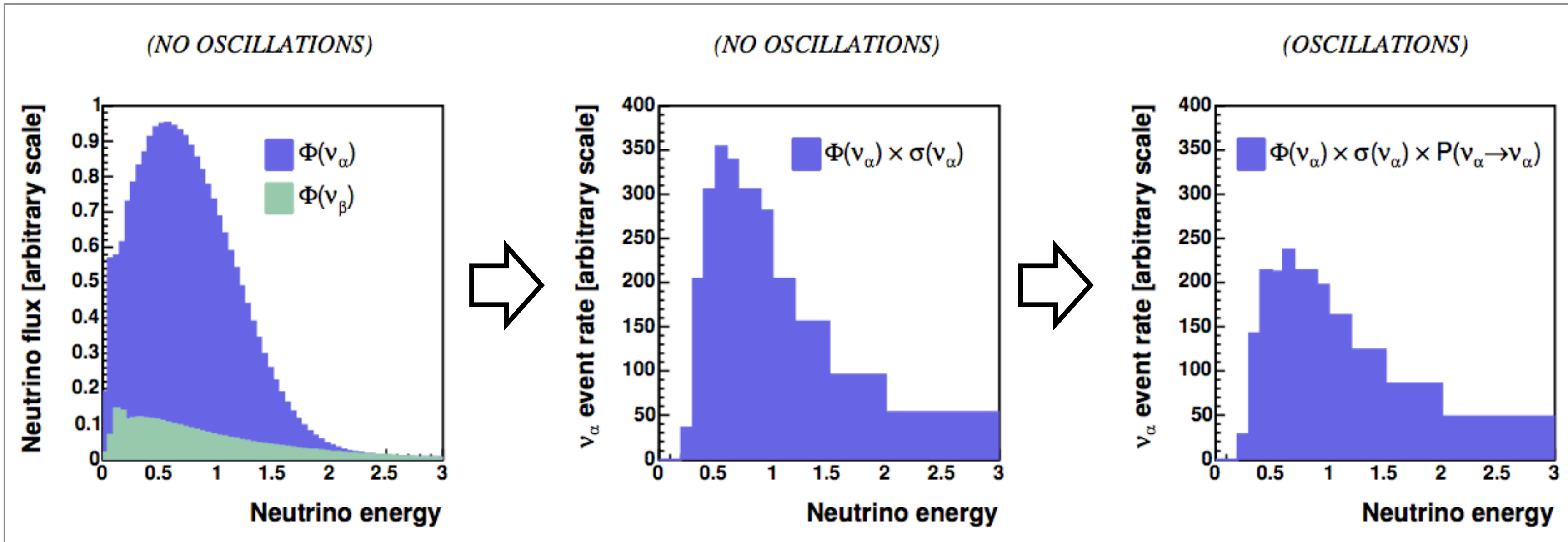


Neutrino flux is primarily ν_α, with very small ν_β contamination.
Look for excess, or **appearance**, of ν_β events with the "right" energy dependence.

Example: Two masses separated by Δm^2, and two flavour states ν_α and ν_β

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\vartheta_{\alpha\beta} \sin^2(1.27\Delta m^2 L / E)$$

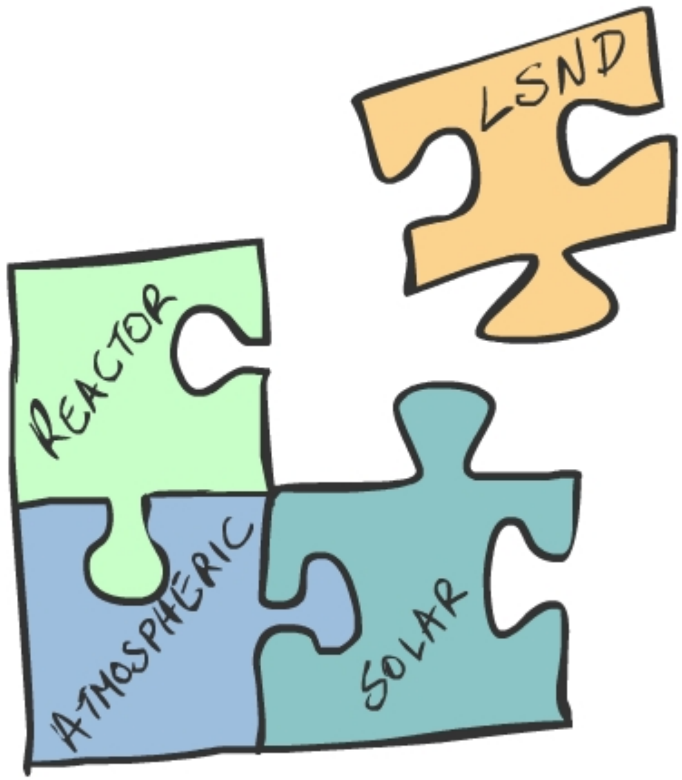
Experimental signatures of neutrino oscillations



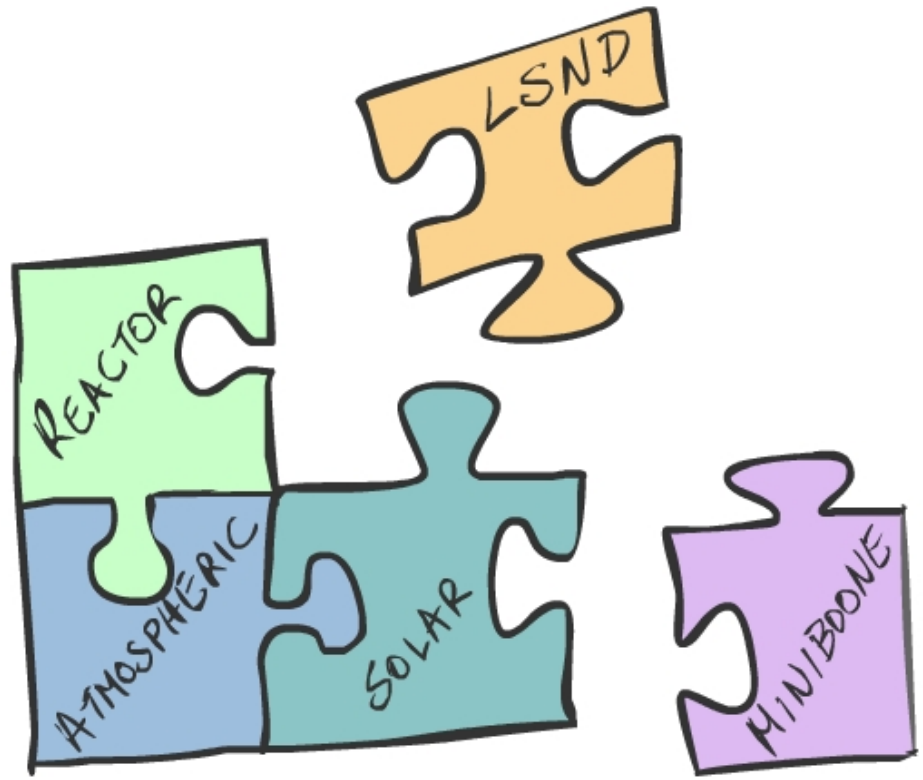
Neutrino flux is primarily ν_α, with very small ν_β contamination.
Look for deficit, or **disappearance**, of ν_α events with the "right" energy dependence.

Example: Two masses separated by Δm^2, and two flavour states ν_α and ν_β

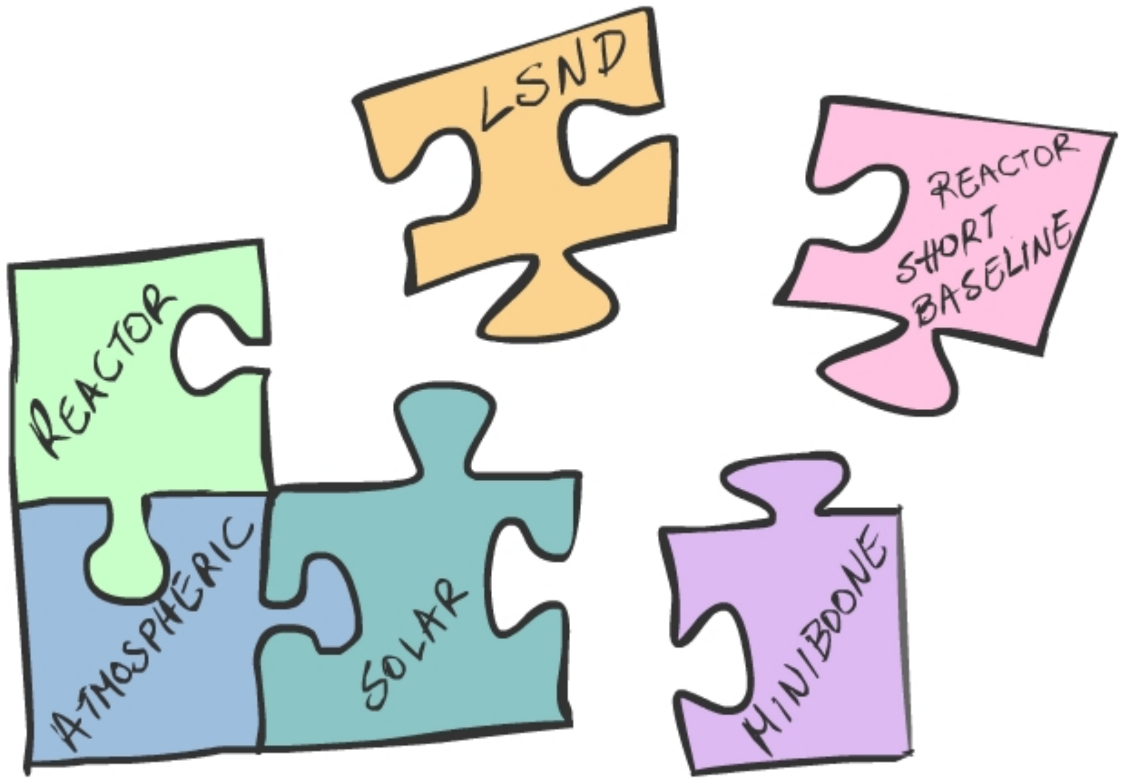
$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2(1.27 \Delta m^2 L / E)$$



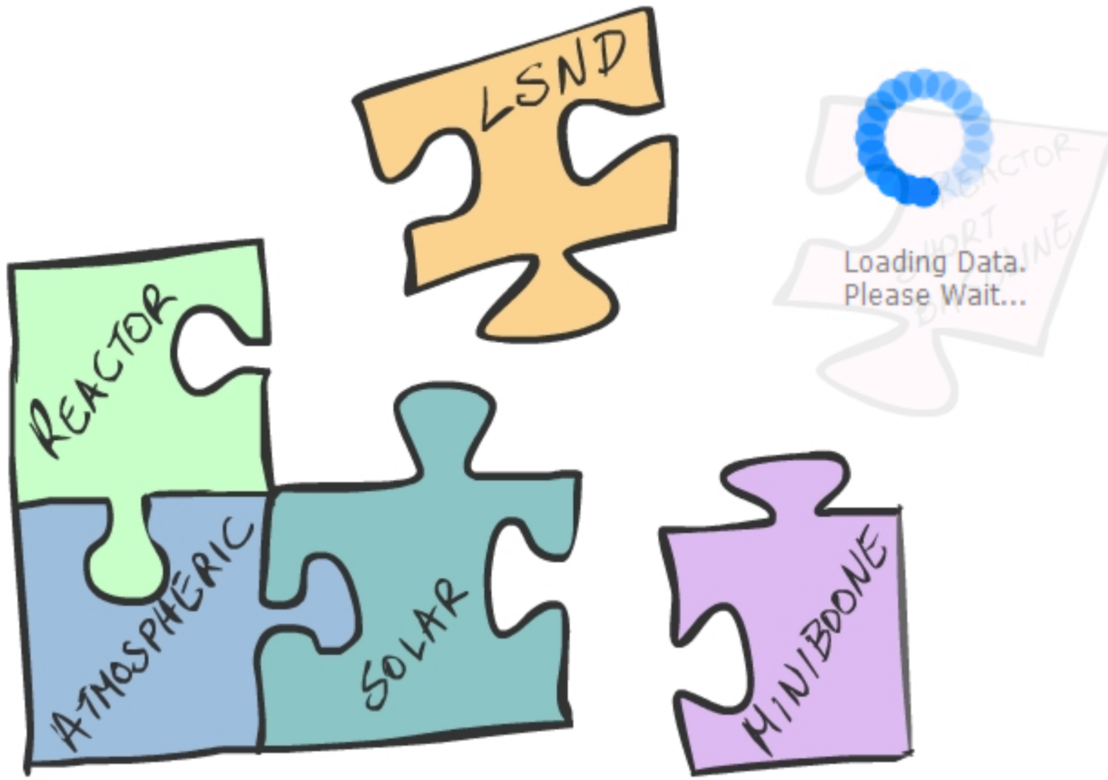
~2000



~2007


LSND
REACTOR SHORT BASELINE
REACTOR
ATMOSPHERIC
SOLAR
MINIBOONE

~2012

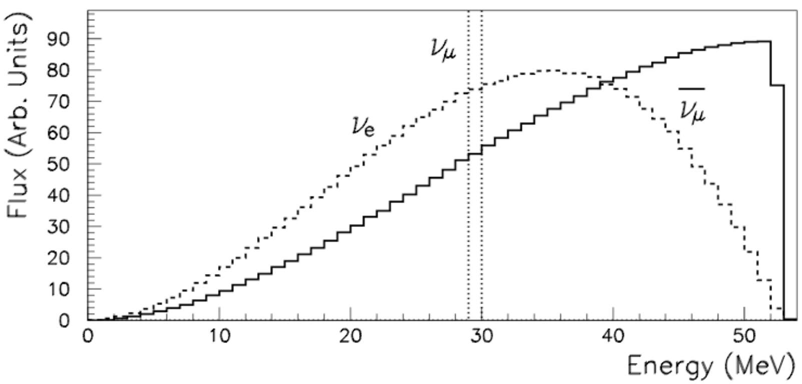

LSND
REACTOR
ATMOSPHERIC
SOLAR
MINIBOONE
Loading Data.
Please Wait...

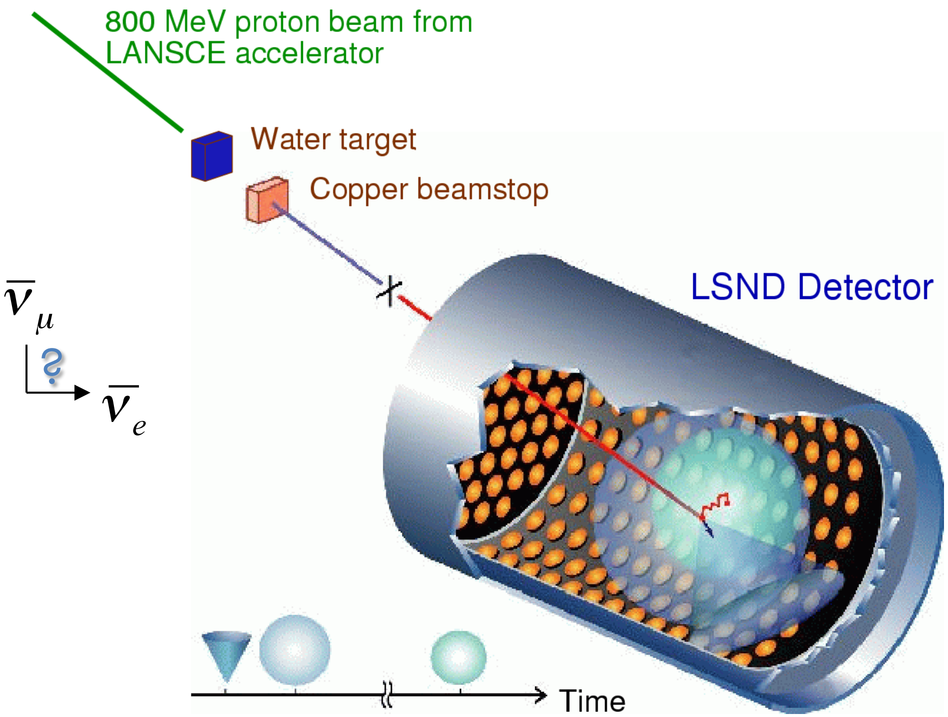
now

The LSND anomaly

μ^+ decay-at-rest experiment:

$$\pi^+ \to \mu^+ \nu_\mu$$
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\overset{?}{\hookrightarrow} \bar{\nu}_e$$





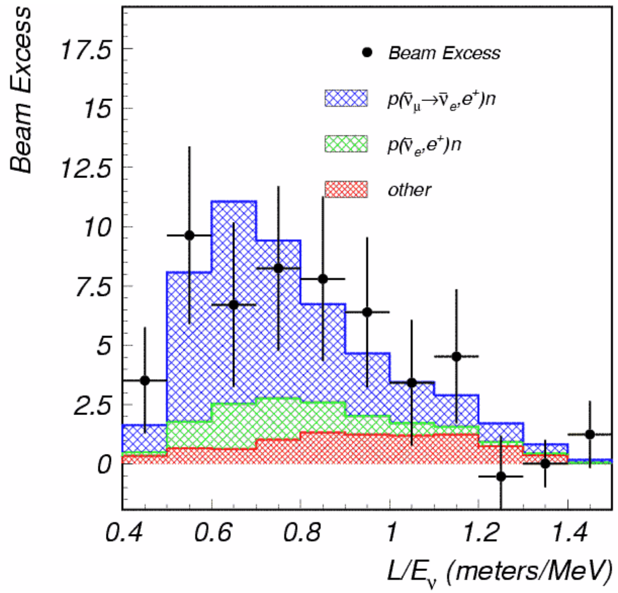
Well-predicted neutrino flux and cross-section.
Very low $\bar{\nu}_e$ backgrounds. L~30m.

$\bar{\nu}_e$ detection via inverse-beta-decay: $\bar{\nu}_e + p \to e^+ + n$
(coincidence signal)

[Phys. Rev. Lett. 75, 2650 (1995); Phys. Rev. Lett. 81,1774 (1998); Phys. Rev. D64, 112007 (2001).]

The LSND anomaly

Observed excess of $\overline{\nu}_e$ in a primarily $\overline{\nu}_\mu$ beam:



Described by "appearance" oscillation probability:

$$P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e) = \sin^2 2\vartheta_{\mu e} \sin^2(1.27\Delta m^2 L/E)$$
$$= (0.264 \pm 0.067 \pm 0.045)\ \%$$

(3.8σ significance)

[Phys. Rev. Lett. 75, 2650 (1995);
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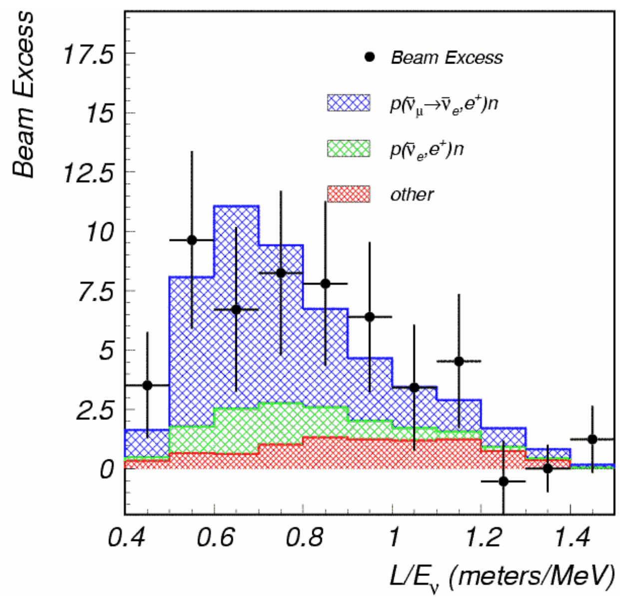
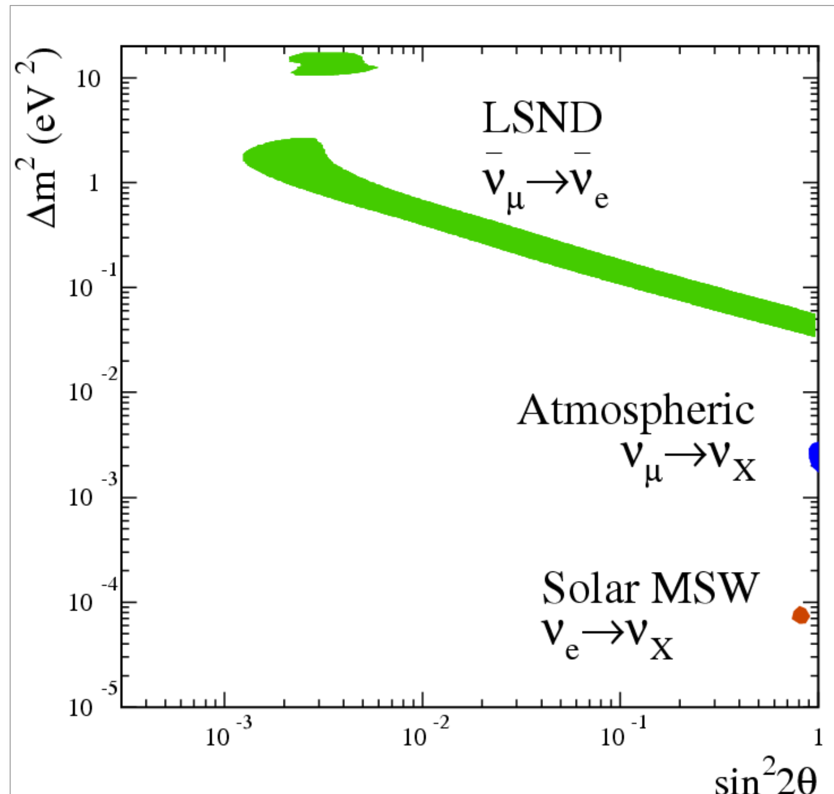


$$P(\overline{\nu}_\mu \to \overline{\nu}_e) = \sin^2 2\vartheta_{\mu e} \sin^2(1.27 \Delta m^2 L / E)$$

Points to large Δm^2
if interpreted as
two-neutrino oscillations:



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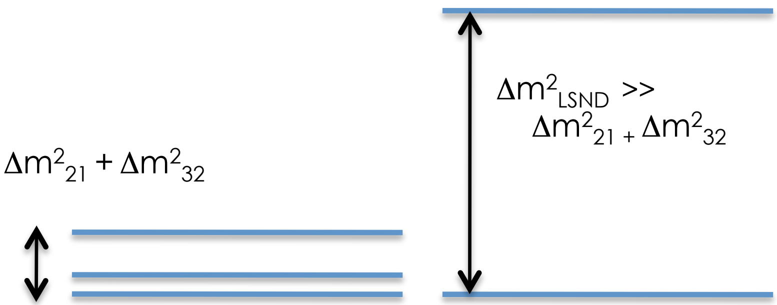
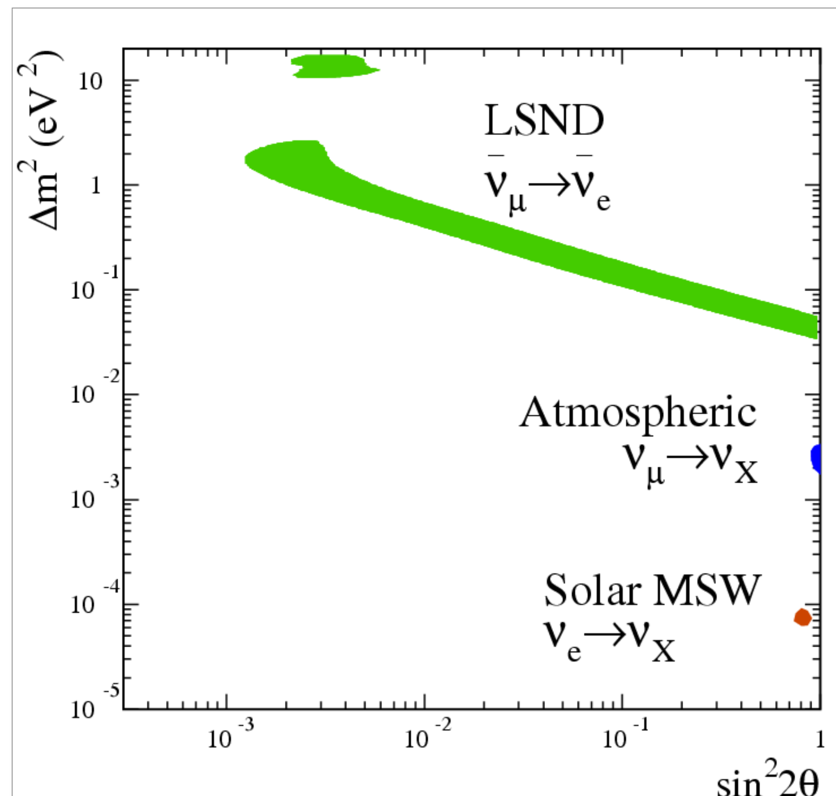
The LSND anomaly



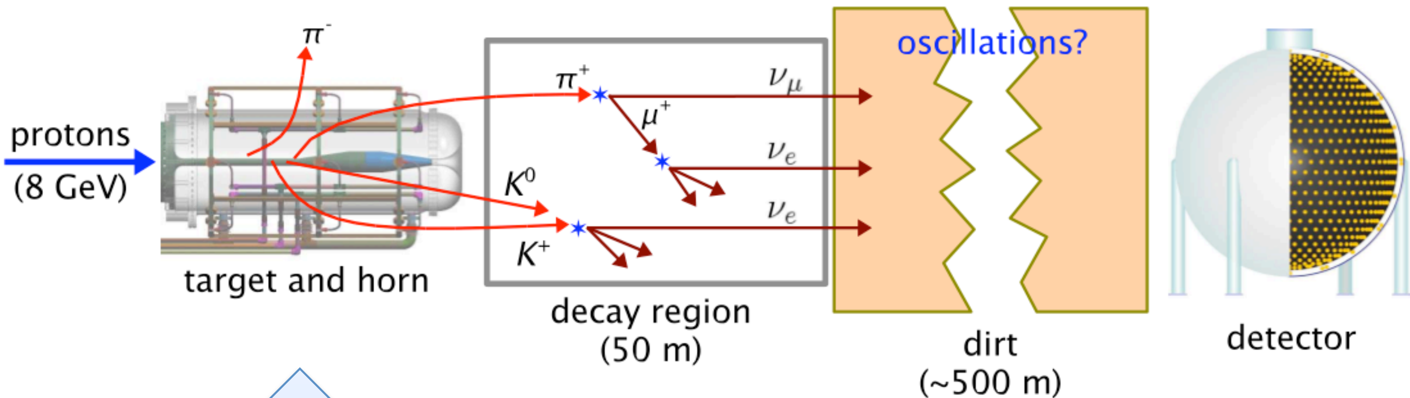
$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2 2\vartheta_{\mu e} \sin^2(1.27\Delta m^2 L/E)$$

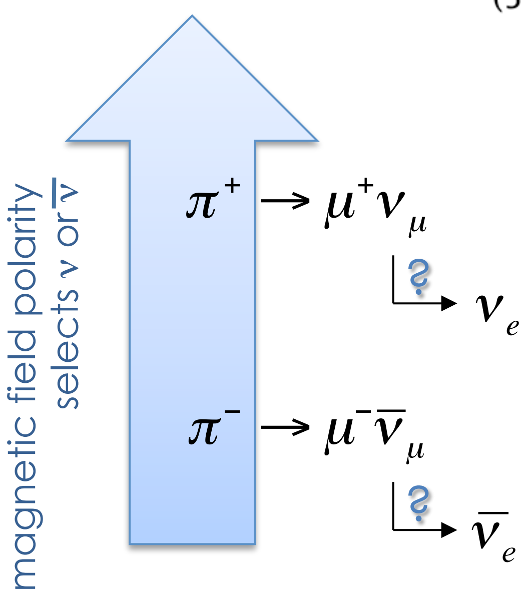


Small amplitude and extremely large oscillation frequency (Δm^2) -->
in conflict with established three-neutrino formalism!

Also, signal not seen by KARMEN experiment with same method at L ≈ 18 m.

The MiniBooNE anomaly





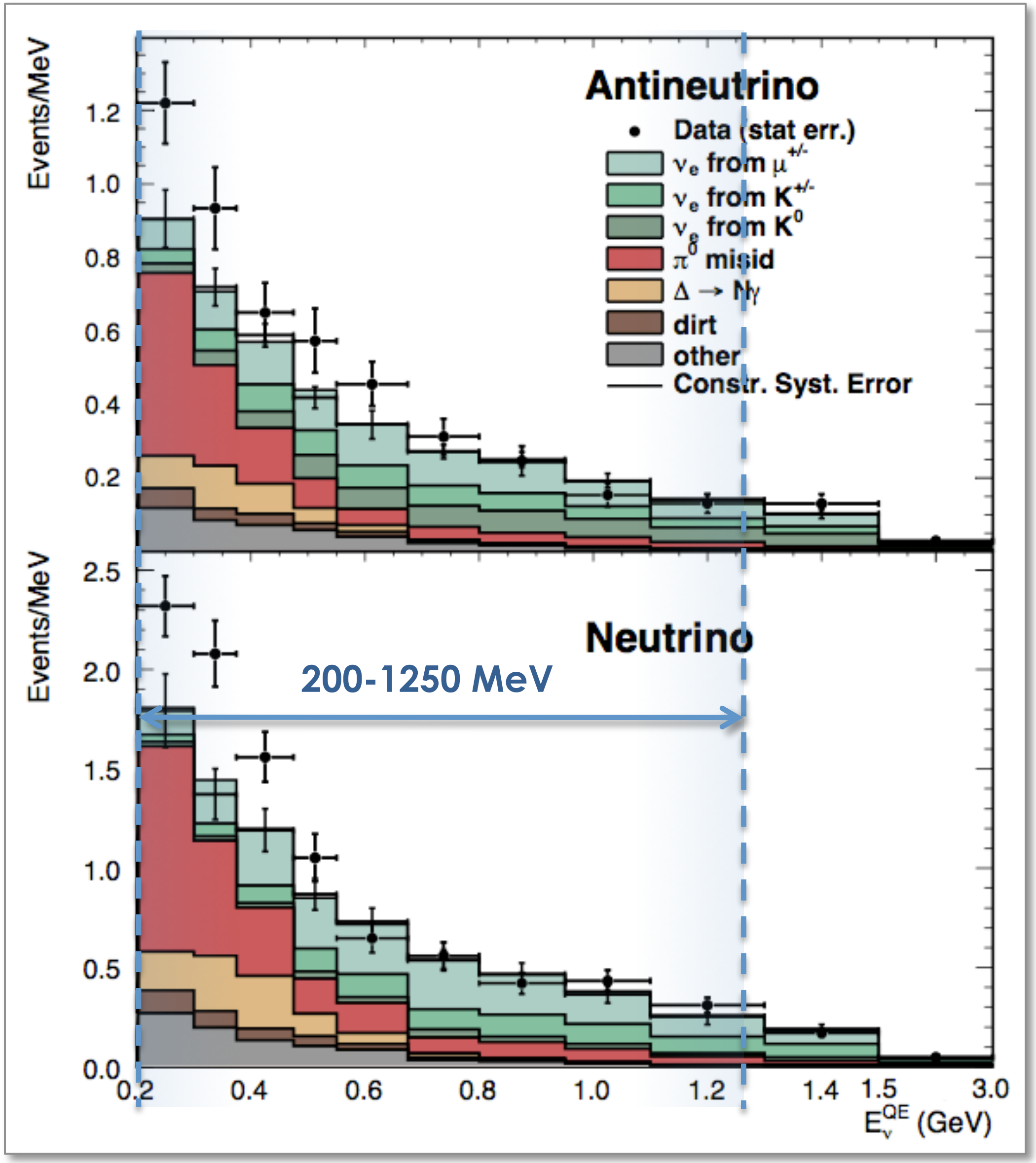
MiniBooNE measured neutrino rates at L/E ~ 1m/MeV

(similar to LSND, so sensitive to similar Δm^2)

Primarily muon neutrino beam, so looked for ν_e appearance

Both neutrino and antineutrino run.

The MiniBooNE anomaly



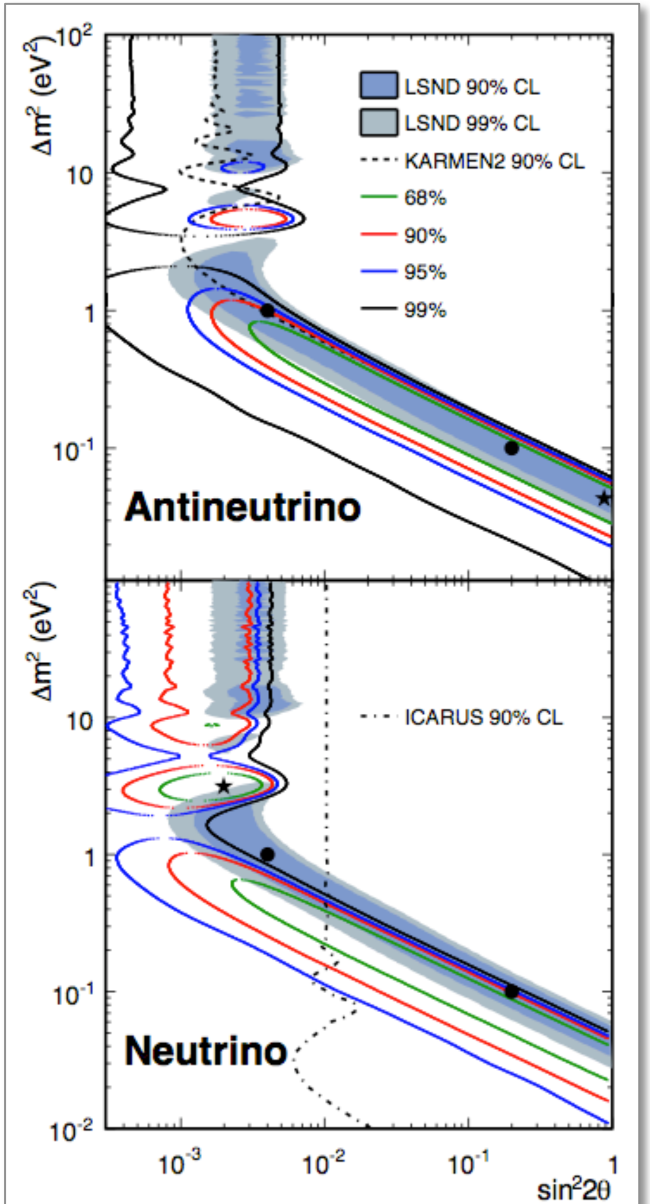
[Phys.Rev.Lett.110.161801,2013,
see also:
Phys.Rev.Lett.98.231801,2007,
Phys.Rev.Lett.102.101802,2009,
Phys.Rev.Lett.103:111801,2009,
Phys.Rev.Lett.105:181801,2010]

Oscillation signal region:
200-1250 MeV

Antineutrino search:
2.8σ excess
Excess of events is at both high and "low energy."

Neutrino search:
3.4σ excess
Excess of events is at "low energy," E < 475 MeV.

The MiniBooNE anomaly



[Phys.Rev.Lett.110.161801,2013, see also: Phys.Rev.Lett.98.231801,2007, Phys.Rev.Lett.102.101802,2009, Phys.Rev.Lett.103:111801,2009, Phys.Rev.Lett.105:181801,2010]

Antineutrino best fit:
χ^2-probability = 66%
(Δm^2, $\sin^2 2\theta$) = (0.04 eV^2, 0.88)

Background-only relative to best fit: 0.5%

Neutrino best fit:
χ^2-probability = 6.1%
(Δm^2, $\sin^2 2\theta$) = (3.14 eV^2, 0.002)

Background-only relative to best fit: 2%

Both are consistent with oscillations in general, but MiniBooNE antineutrino allowed parameters are in better agreement with LSND parameters.

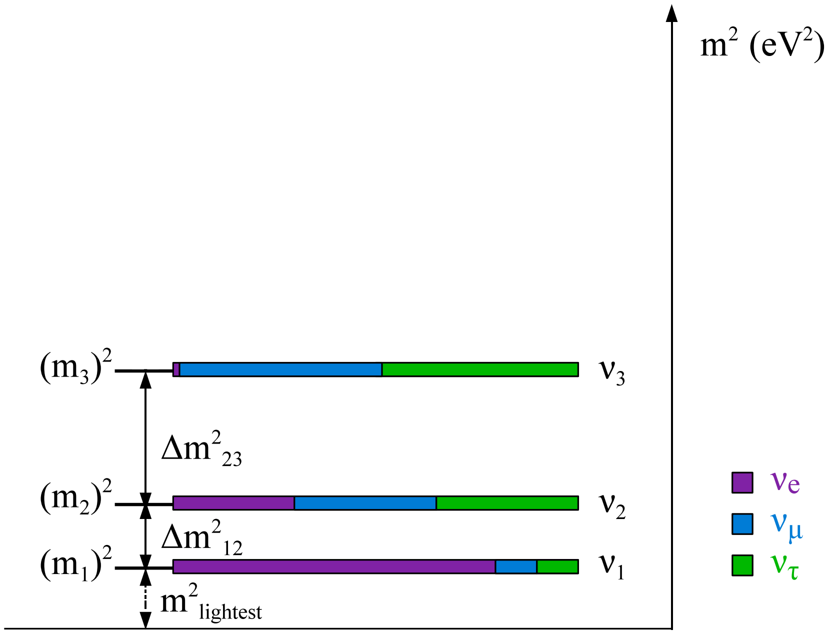
Both MiniBooNE and LSND signatures show up at similar L/E
and look like $\nu_\mu \rightarrow \nu_e$ with some probability.

Are they neutrino oscillations?

If so, Δm^2 must be large, and mixing should be small.

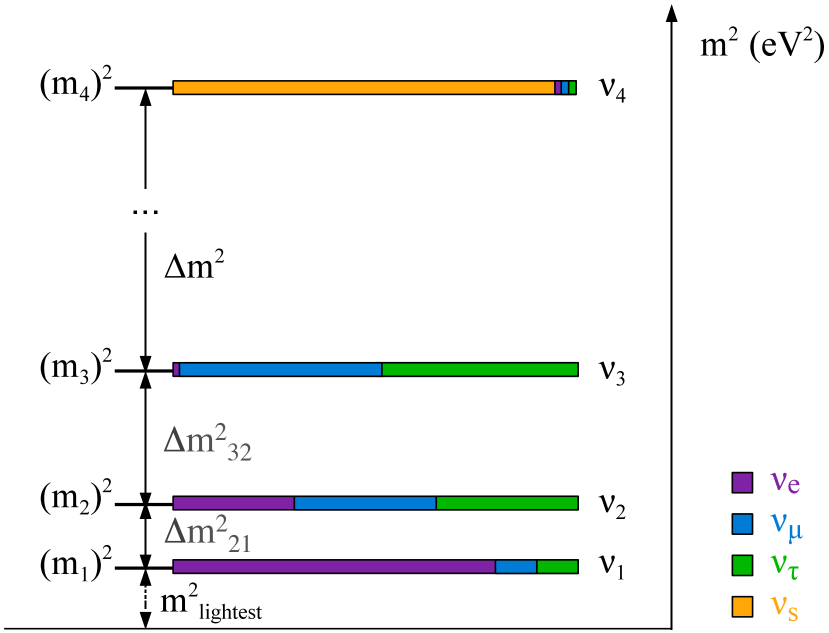
(Light) sterile neutrinos: Framework

Three neutrinos:
(e.g. NORMAL hierarchy)



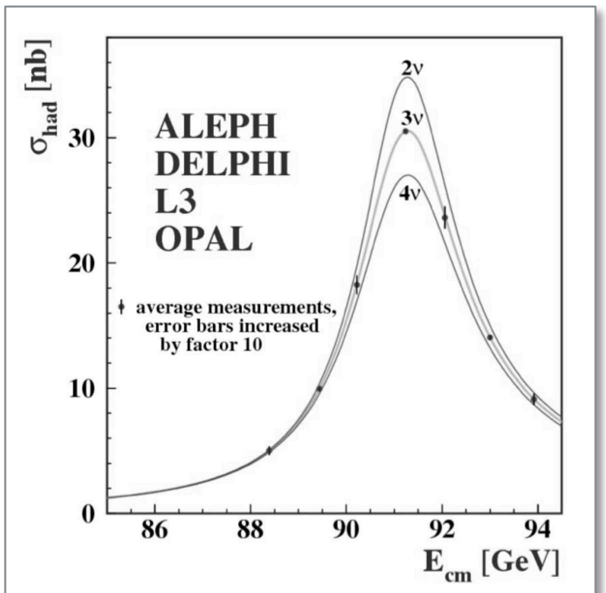
"just 3"

With a sterile neutrino:



"3+1"

ν_4 is light enough ($<m_Z/2$) to be produced in **Z decay**



$$\Gamma_{\nu\bar{\nu}} = \sum_{i,j} \Gamma[Z \to \nu_i \bar{\nu}_j]$$

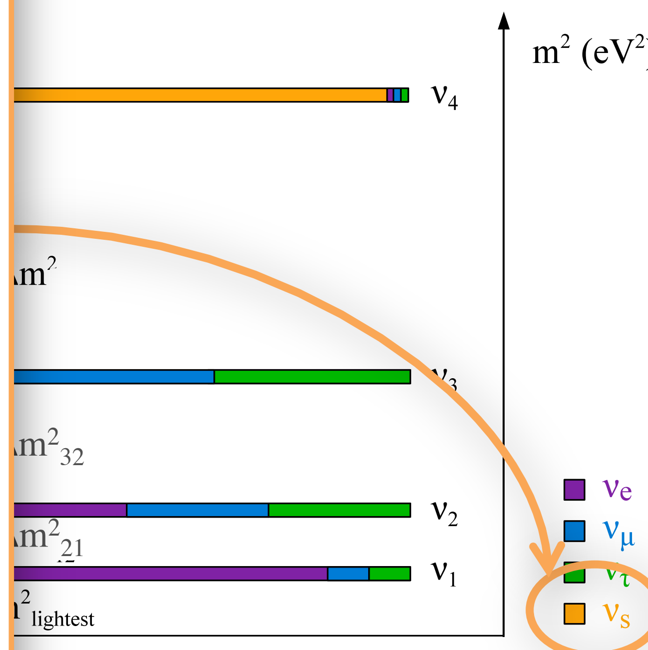
$$= \sum_{i,j} \sum_{\alpha}^{active} U^*_{\alpha i} U_{\alpha j} \sum_{\beta}^{active} U_{\beta i} U^*_{\beta j}$$

$$= \sum_{\alpha,\beta} \delta_{\alpha\beta}\delta_{\alpha\beta} = \sum_{\alpha=1}^{3} 1 = 3 \ ,$$

$$N_\nu = \frac{\Gamma_{\text{inv}}}{\Gamma_\ell} \left(\frac{\Gamma_\ell}{\Gamma_\nu} \right)_{\text{SM}}$$

[Phys. Reports 427, 257 (2006)]

→ ν_s **does not couple to the Z ("sterile")**

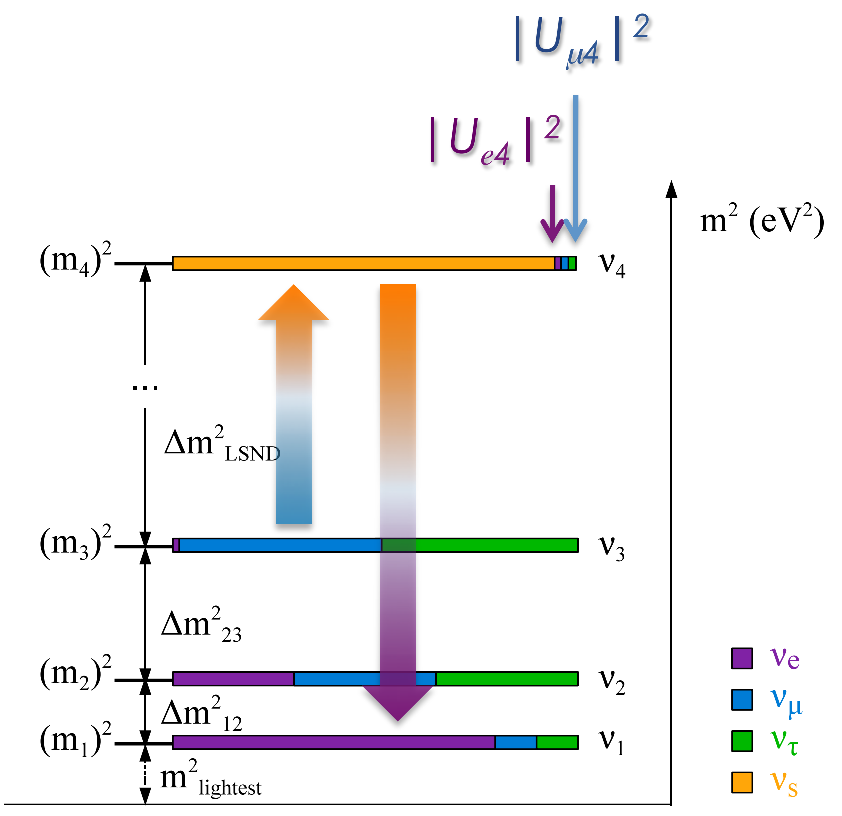


"3+1"

$\nu_\mu \rightarrow \nu_e$ appearance:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\vartheta_{\mu e} \sin^2(1.27\Delta m^2 L/E)$$

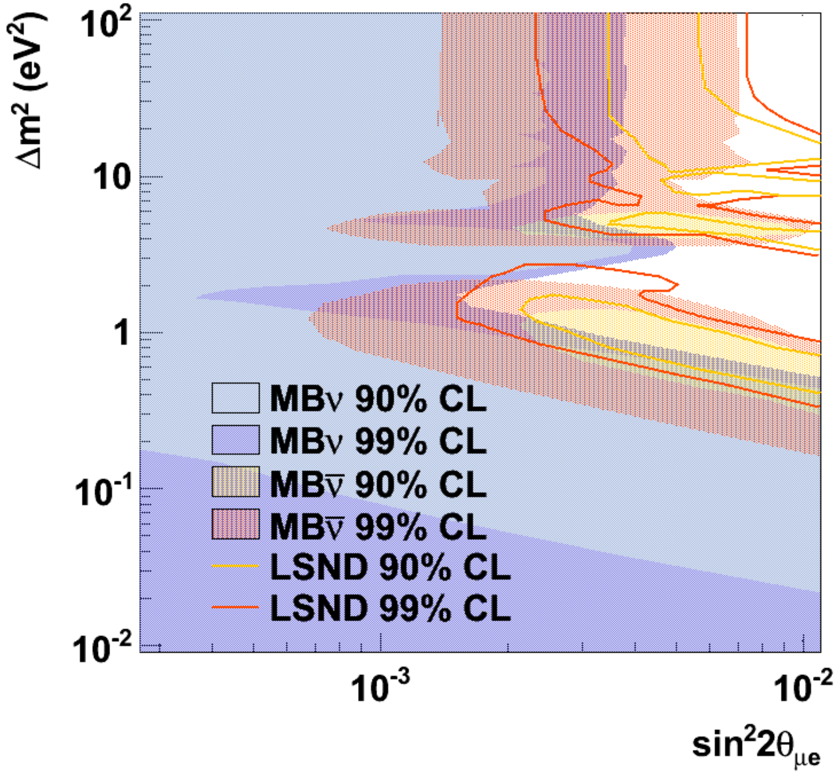
$$\rightarrow \quad 4|U_{e4}|^2|U_{\mu 4}|^2$$

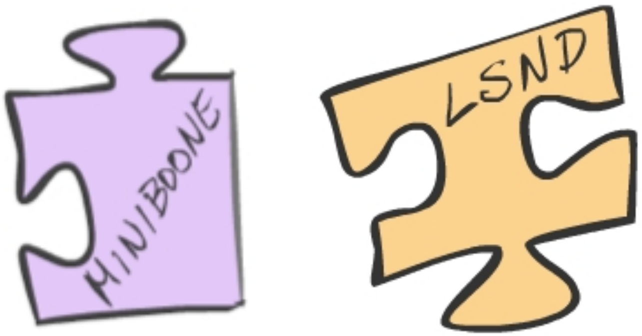


"3+1"

We approximate: m_1, m_2, $m_3 << m_4$ $\rightarrow$ m_1, m_2, $m_3 = 0$

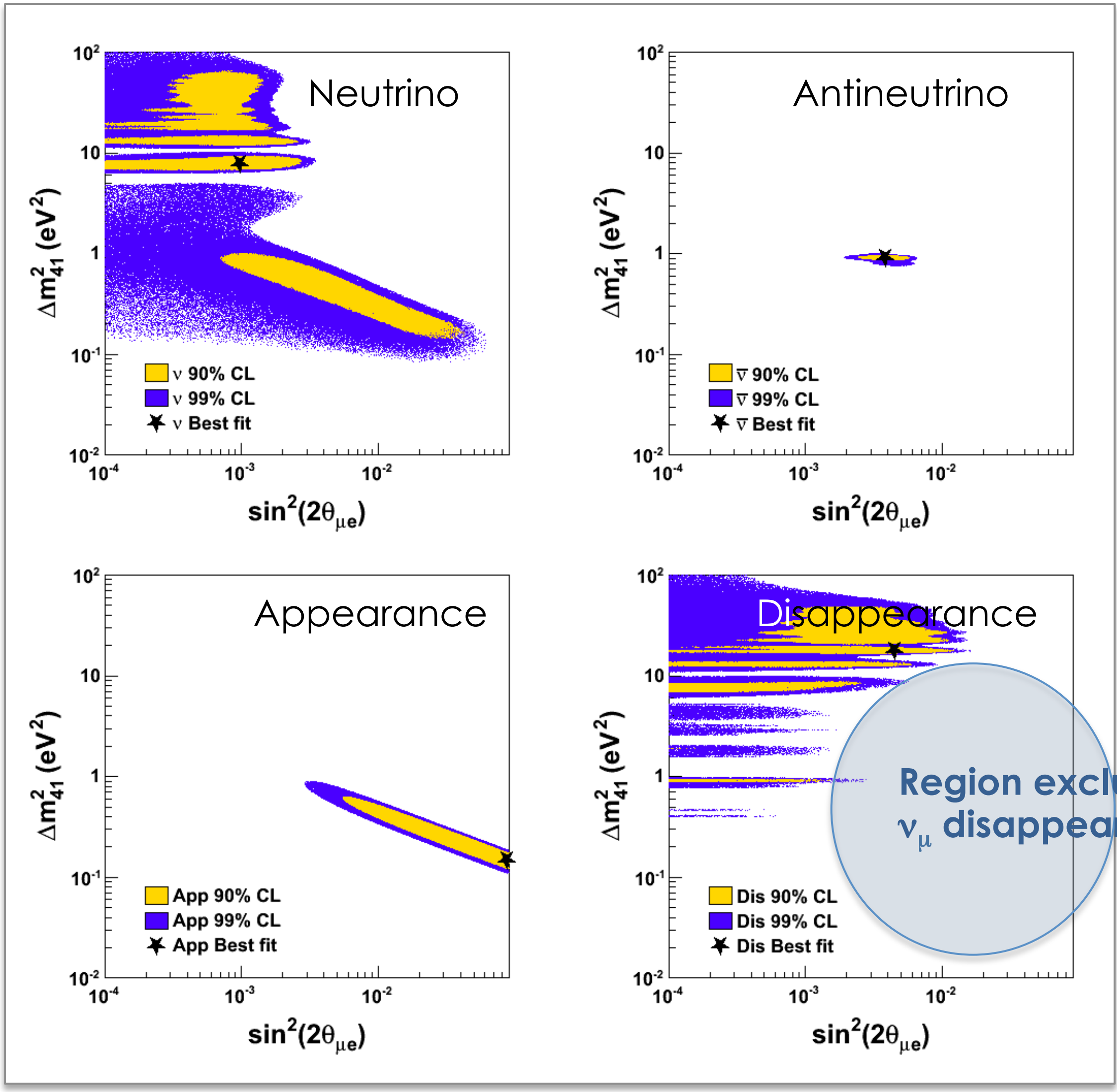
Can MiniBooNE and LSND signatures be explained
by (3+1) appearance?





A: Yes

What is the problem?



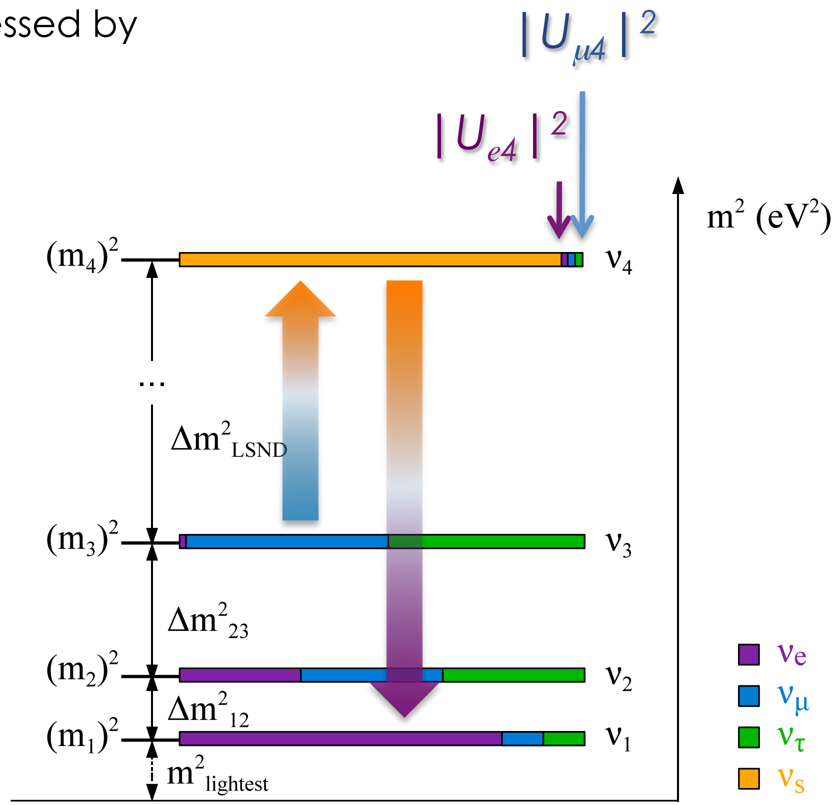
Compatibility (ν, $\bar{\nu}$) = 0.14%

Compatibility (app, dis) = 0.013%

Appearance experiments and disappearance experiments are incompatible under 3+1, due to lack of ν_μ disappearance;

appearance amplitude quadratically suppressed by disappearance amplitude:

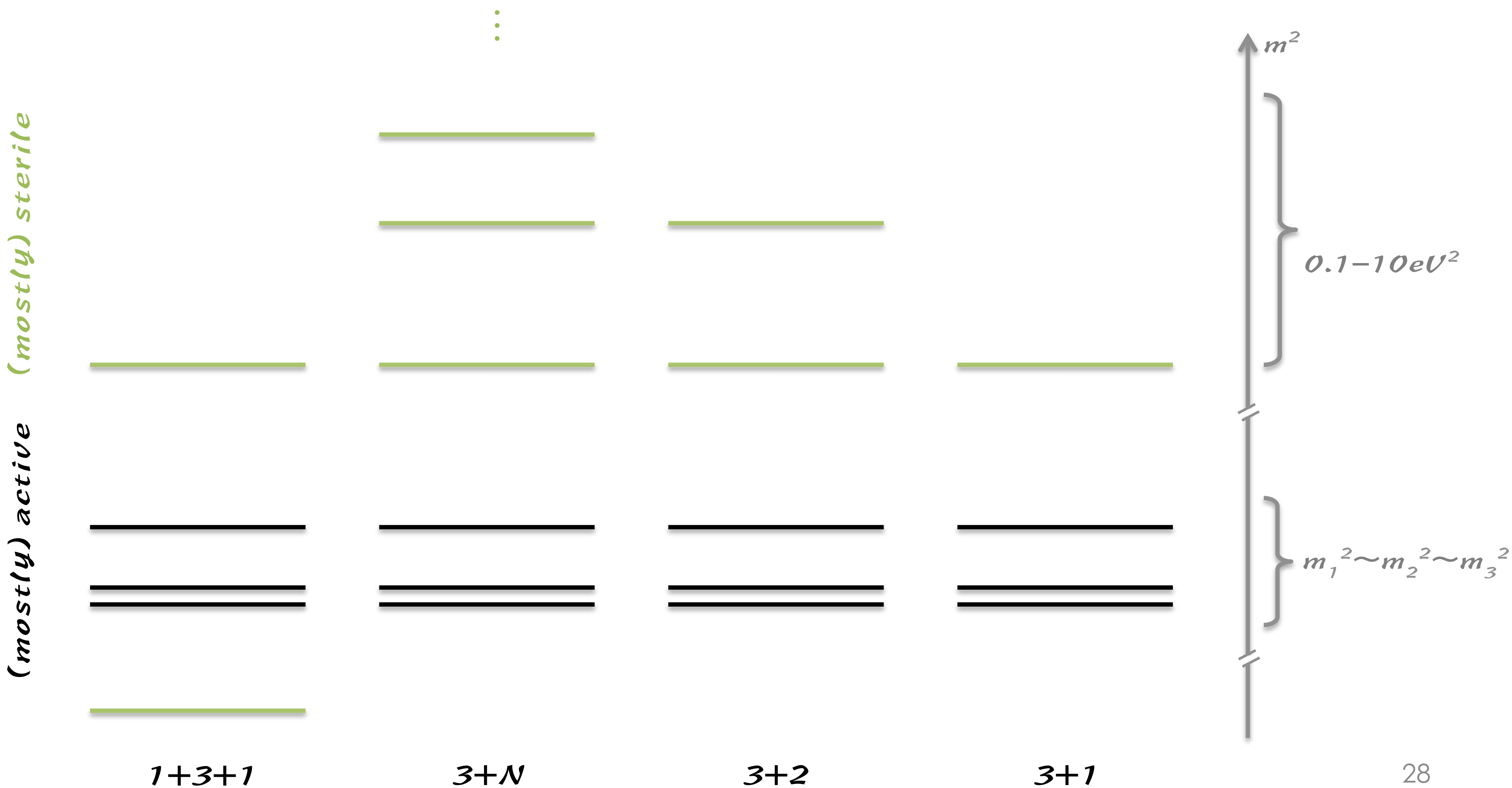
$$\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$



"3+1"

(Light) sterile neutrinos: Framework

One might try 3+1, 3+2, 3+N, 1+3+1, …



(Light) sterile neutrinos: Framework

Disappearance:

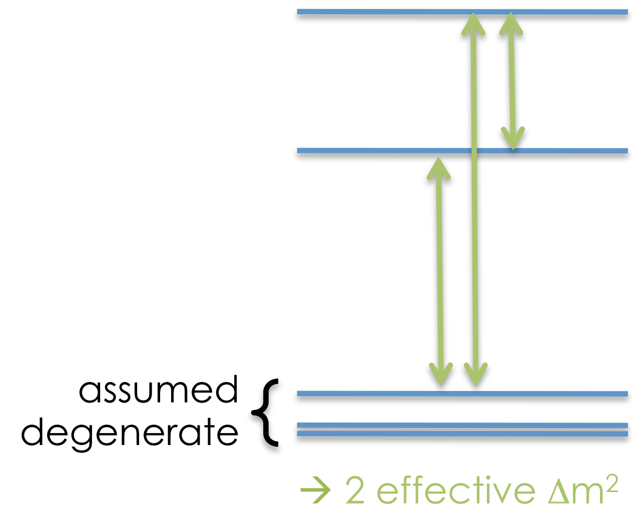
$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4[(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2) \cdot (|U_{\alpha 4}|^2 \sin^2 x_{41} + |U_{\alpha 5}|^2 \sin^2 x_{51}) + |U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2 x_{54}]$$

Appearance:

$$P(\nu_\alpha \to \nu_{\beta \neq \alpha}) = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 \sin^2 x_{41} + 4|U_{\alpha 5}|^2 |U_{\beta 5}|^2 \sin^2 x_{51} + 8|U_{\alpha 5}||U_{\beta 5}||U_{\alpha 4}||U_{\beta 4}| \sin x_{41} \sin x_{51} \cos(x_{54} - \phi_{45})$$

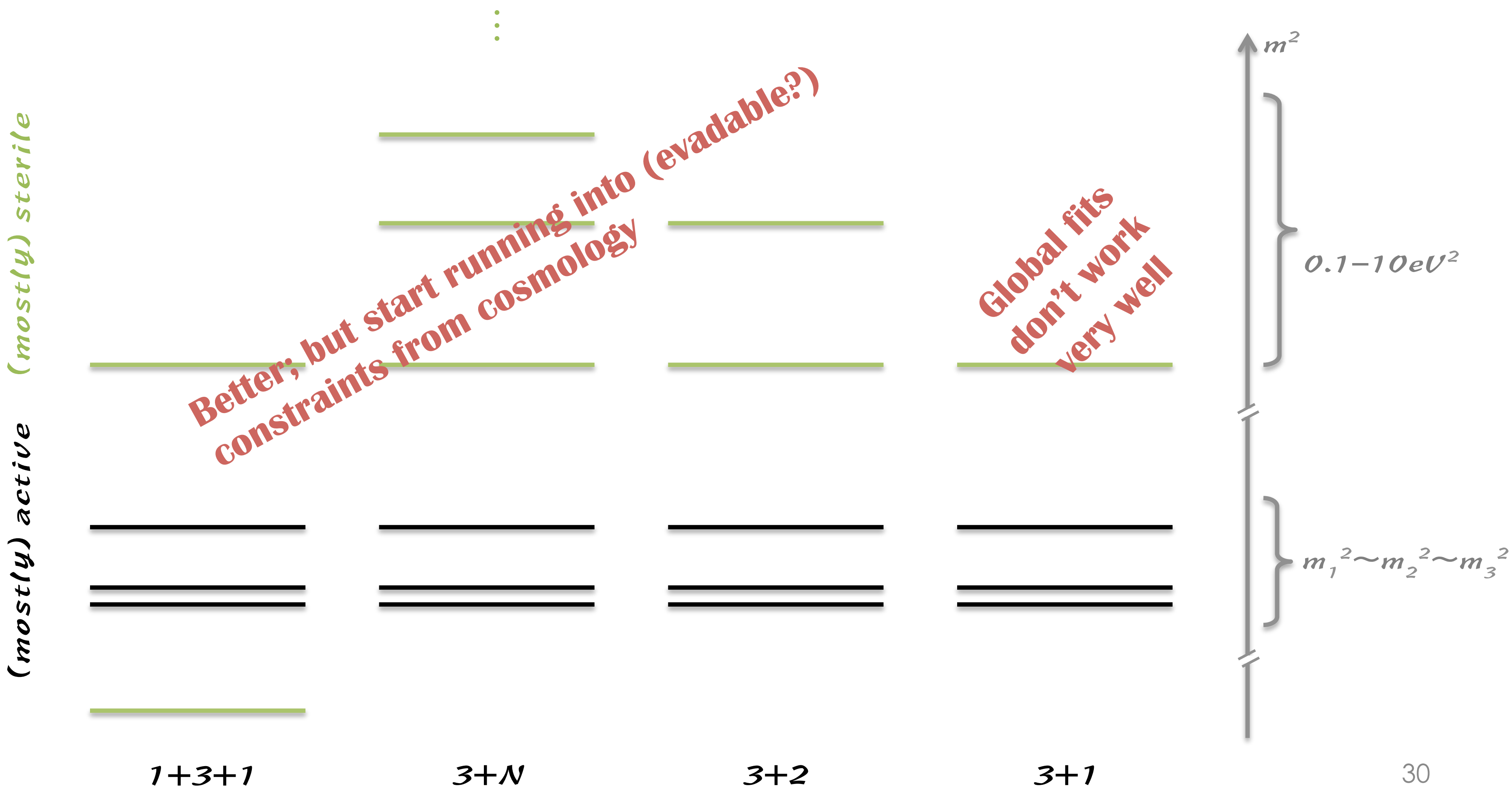
CPV phase

$$x_{ji} \equiv 1.27 \Delta m^2_{ji} L/E$$



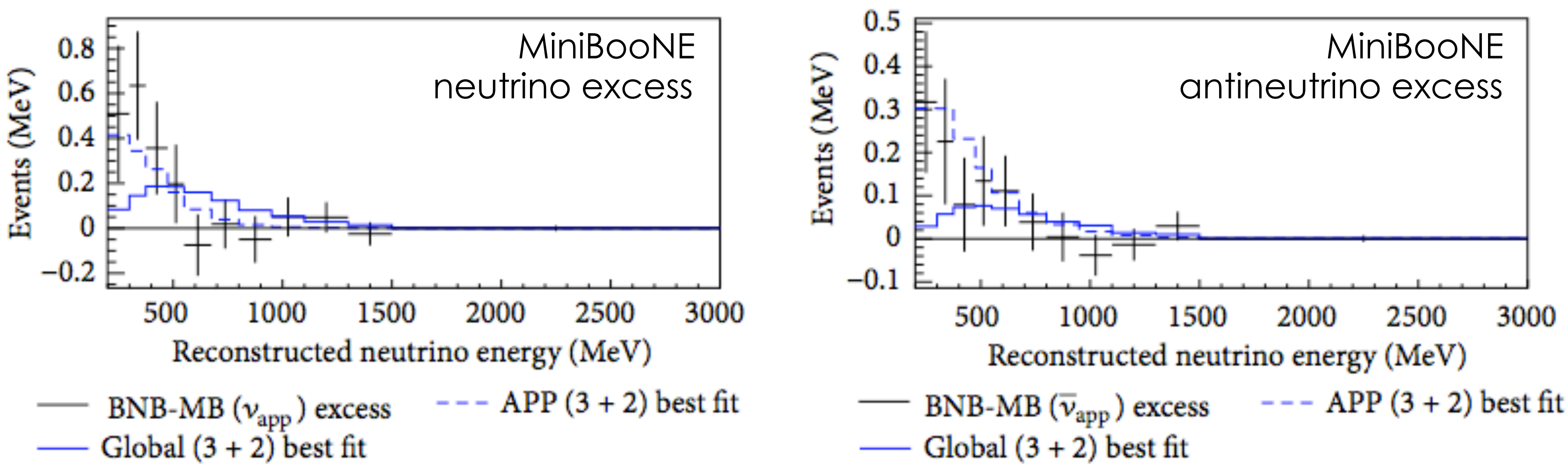
(3+2…) is attractive because of **CP violation**

(Light) sterile neutrinos: Framework



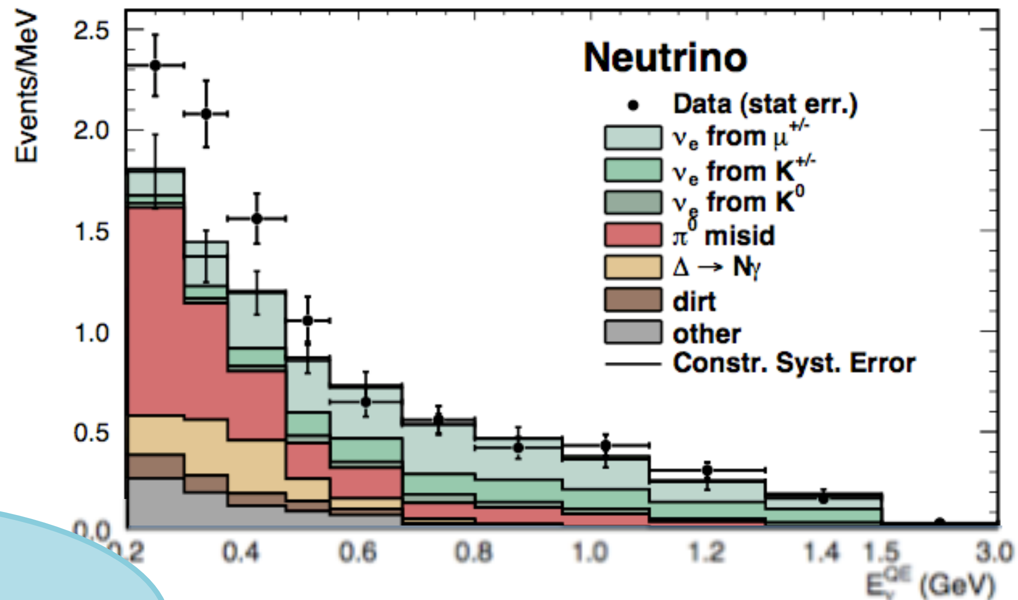
Extended models: E.g. CP violation

(3+2) global best fit



(3+2) with CP violation cannot explain
MiniBooNE low E excess, unless
we throw out disappearance
constraints!

Significant tension is contributed by
the MiniBooNE neutrino mode low energy excess

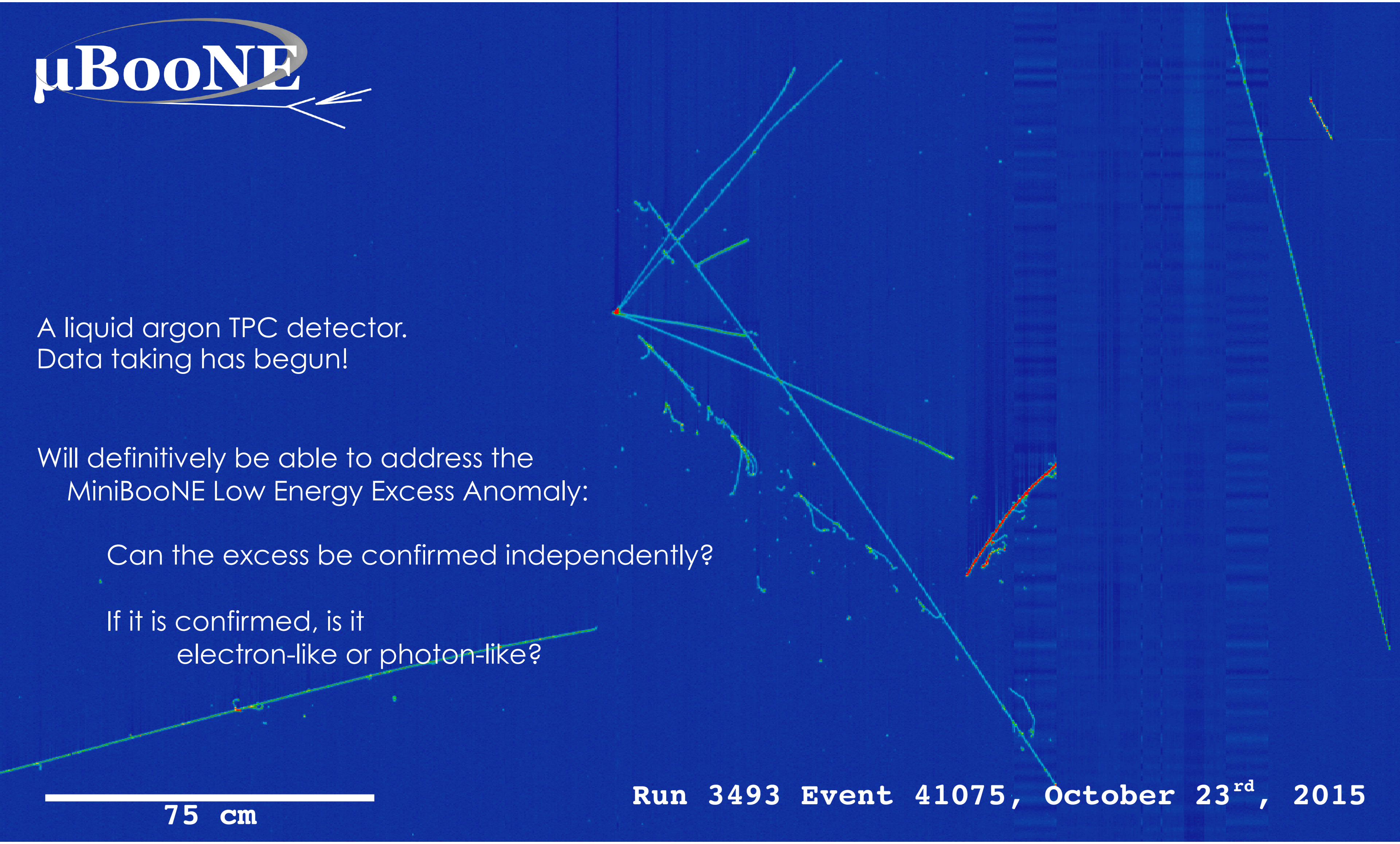


Unaccounted
ν_e / ν_μ disappearance?

Energy reconstruction?
Cross-section/nuclear
effects?

Electron-like
misestimated or new
background?

Single-photon
mis-estimated or new
background?



A liquid argon TPC detector.
Data taking has begun!

Will definitively be able to address the
MiniBooNE Low Energy Excess Anomaly:

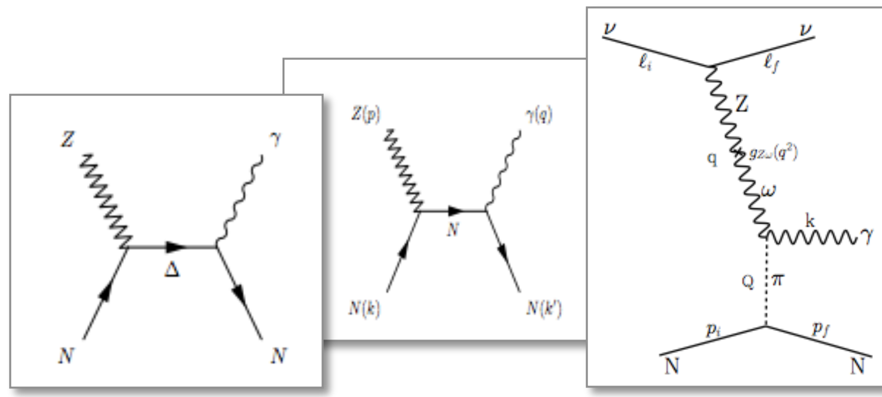
Can the excess be confirmed independently?

If it is confirmed, is it
electron-like or photon-like?

MicroBooNE

If an excess is observed and found in single **photon** events,
MicroBooNE could make the first measurement of a novel photon-production mechanism, to be included in neutrino interaction generators, as it could impact future ν_e appearance measurements

e.g.
R. Hill arXiv: 0905.0291
Jenkins et al arXiv:0906.0984
Serot et al arXiv: 1011.5913



If the excess is in single **electrons** events
MicroBooNE could be seeing ν_e appearance (sterile neutrino oscillations, NSI, extra dimensions) or be in position to measure some other new production mechanism (?)

Moving forward

- Need tests which will produce unambiguous results.

  This requires (probably multiple) definitive measurements.
  - Appearance and disappearance
  - Shape (L/E) information

- Experimental searches must carefully account for
  - Simultaneous appearance and disappearance effects
  - Neutrino energy reconstruction effects due to cross-section modeling uncertainties

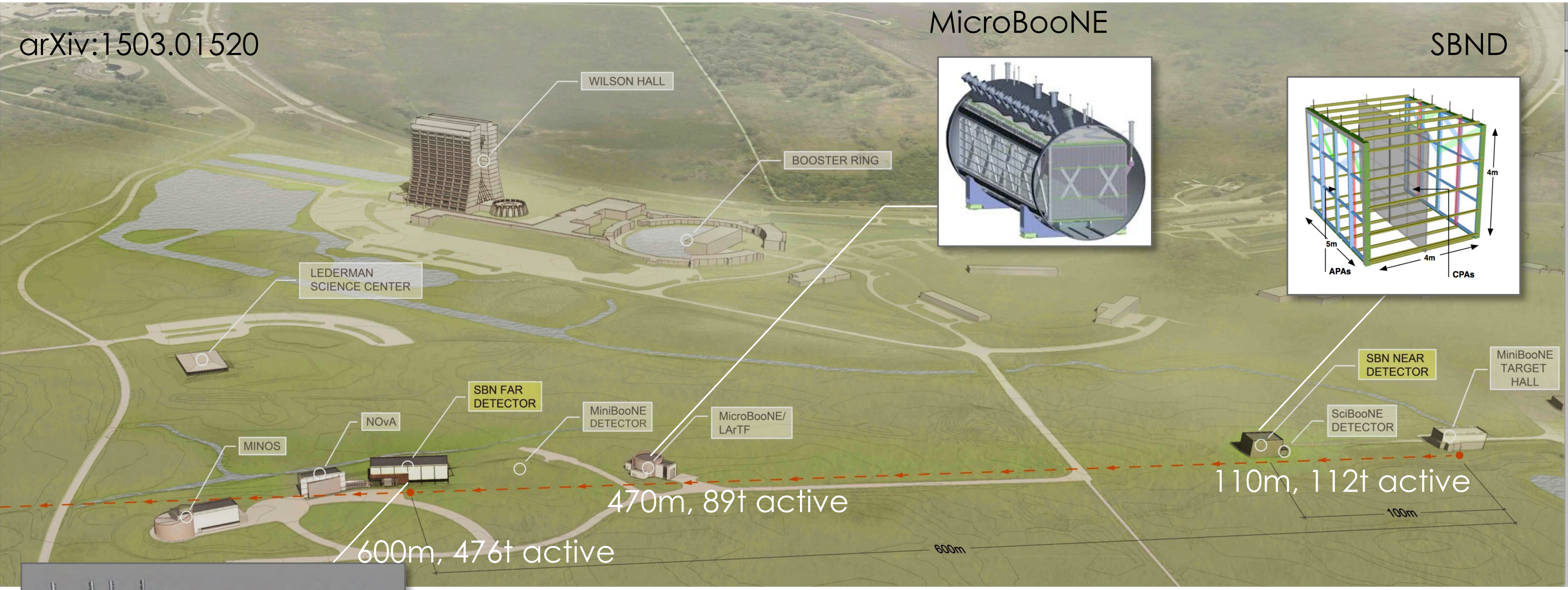
- Global fits must carefully quantify (in)compatibilities

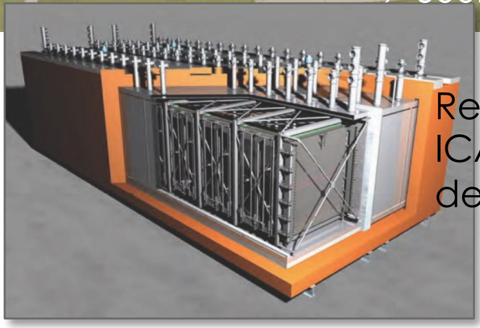
- As we advance toward precision measurements of the tree-neutrino model (e.g. at long-baselines), we must be aware of underlying assumptions.
  See, e.g., added parameter degeneracies in CPV measurements due to sterile neutrinos [Kayser; Gandhi, Masud, Prakash]

Future experiments: SBN at Fermilsb

(Beyond MicroBooNE:) Short Baseline Neutrino program at Fermilab

A **second** & **third** LArTPC placed in the BNB at Fermilab, in line with MicroBooNE





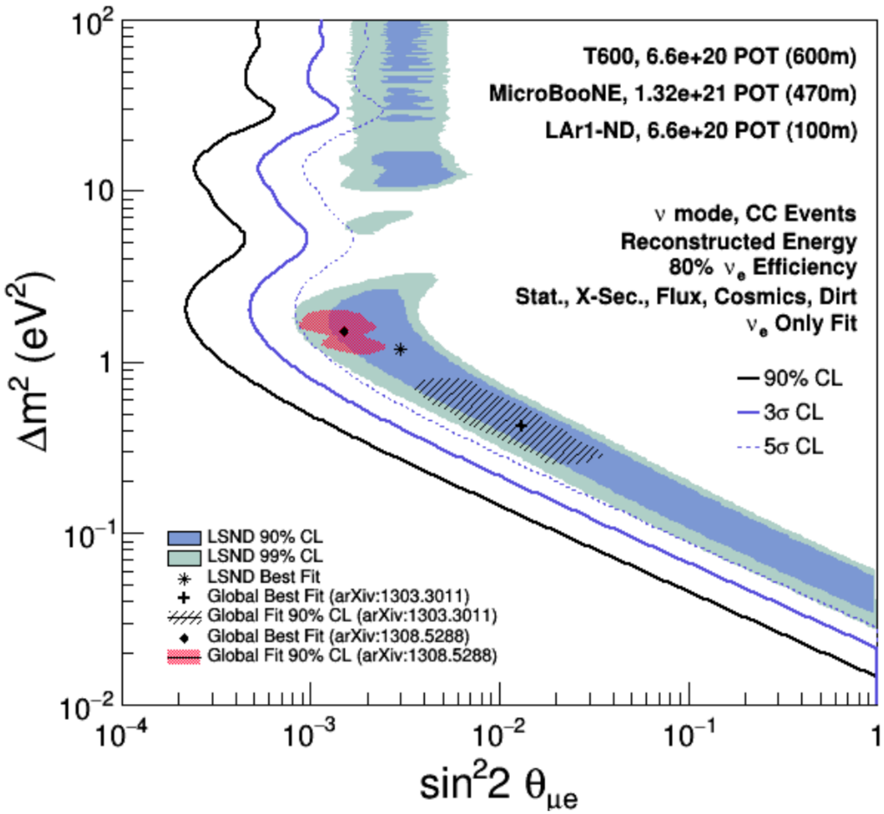
Refurbished ICARUS T600 detector

- Near/mid/far comparison for short-baseline oscillation search
- **Definitive search for sterile neutrino oscillations**

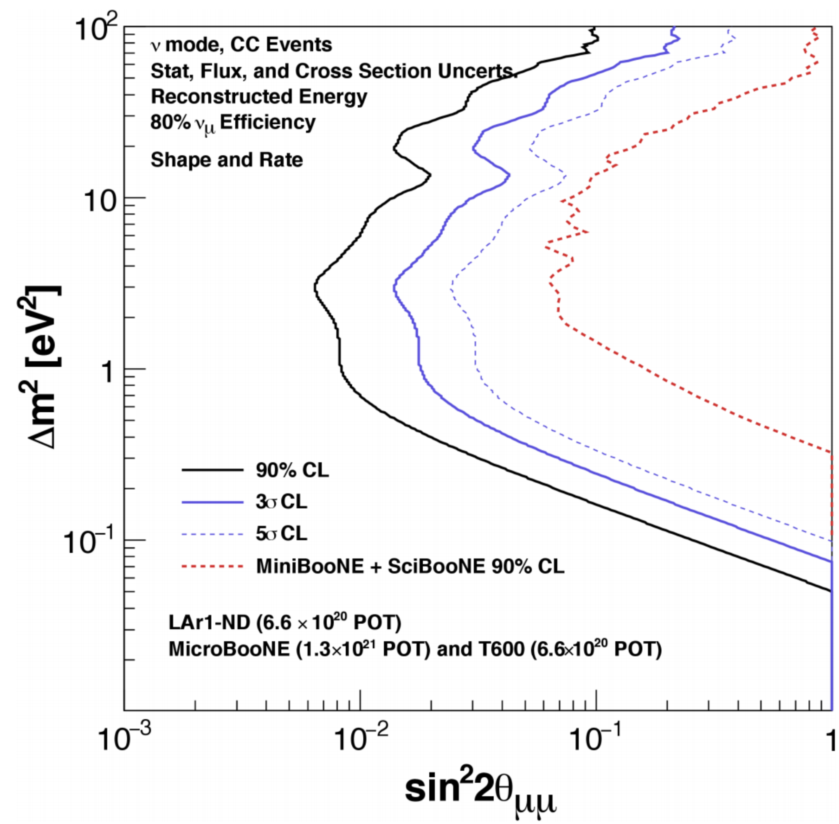
Future experiments: SBN at Fermilsb

Projected SBN Sensitivities

Appearance



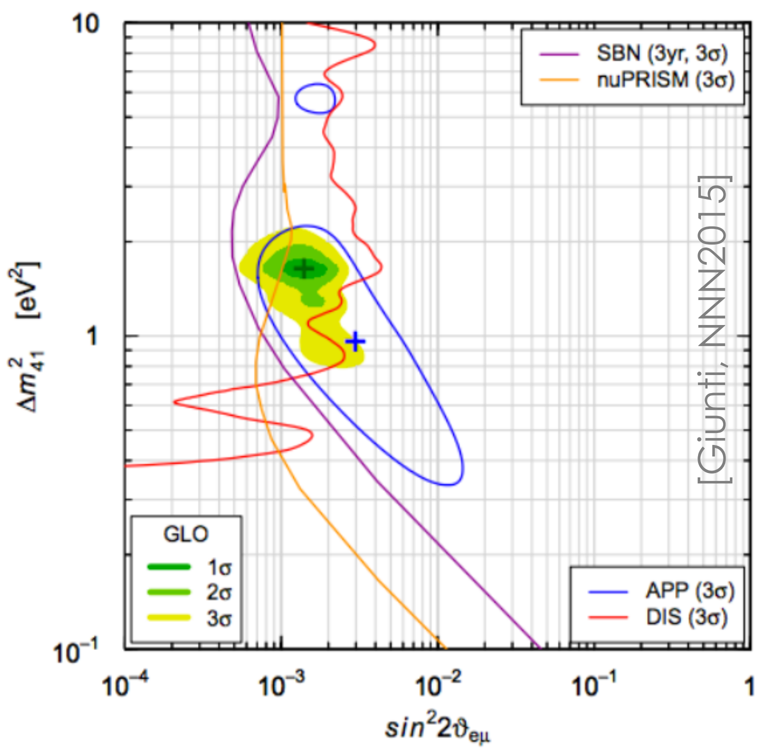
Disappearance



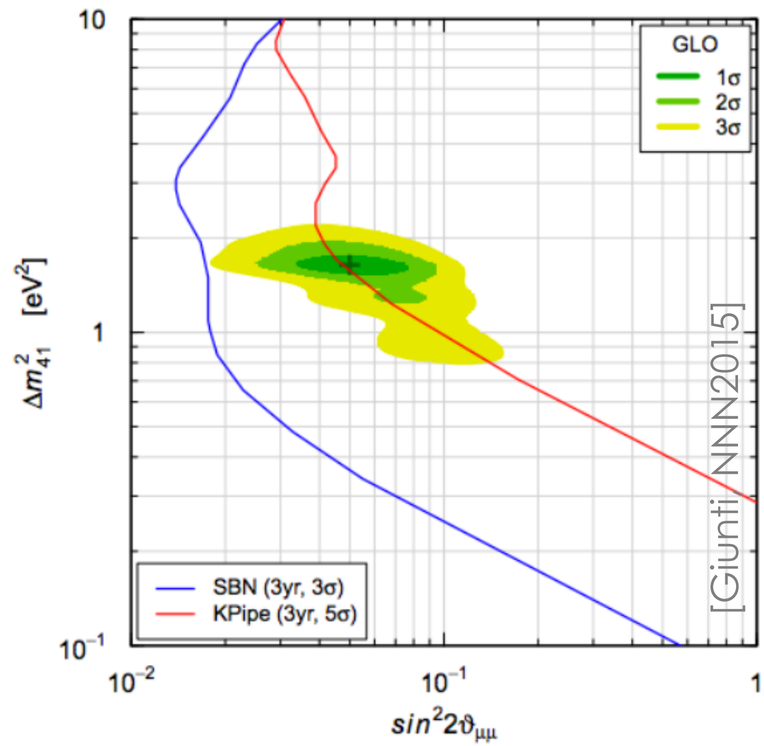
(Also sensitivity to total active→sterile disappearance)

Future experiments:

ν_e appearance



ν_μ disappearance

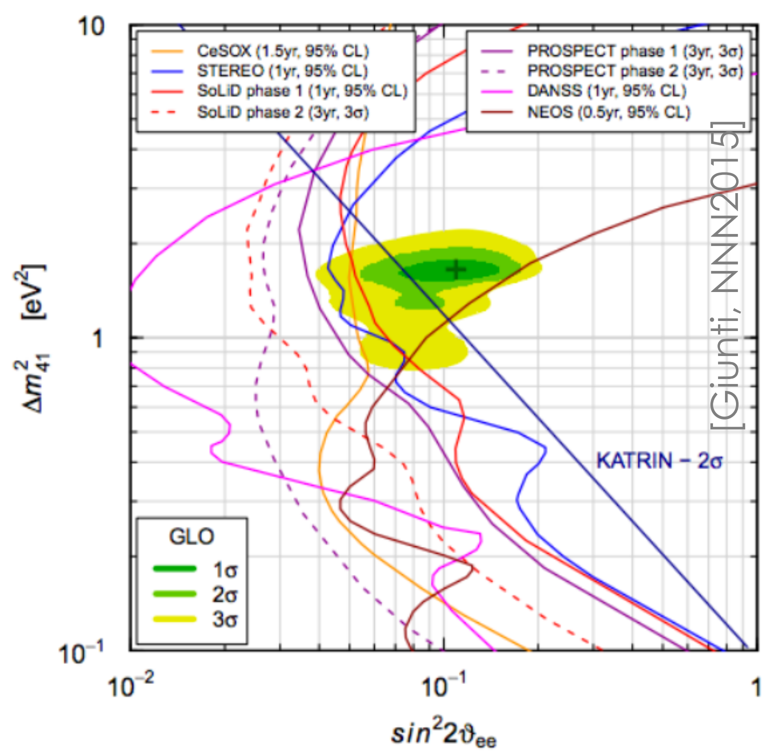


nuPRISM (J-PARC, Japan) [Wilking@NNN2015]
L ≃ 1 km
50 m tall water Cherenkov detector
$1^\circ - 4^\circ$ off-axis
can be improved with T2K ND

KPipe (Japan) [arXiv:1510.06994]
L ≃ 30-150m
120 m long detector!

Future experiments:

ν_e disappearance



CeSOX (BOREXINO, Italy)
144Ce – 100 kCi [Vivier@TAUP2015]
rate: 1% normalization uncertainty
8.5 m from detector center

KATRIN (Germany)
Tritium β decay [Mertens@TAUP2015]

STEREO (France)
L ≃ 8-12m [Sanchez@EPSHEP2015]

SoLid (Belgium)
L ≃ 5-8m [Yermia@TAUP2015]

PROSPECT (USA)
L ≃ 7-12m [Heeger@TAUP2015]

DANSS (Russia)
L ≃ 10-12m [arXiv:1412.0817]

NEOS (Korea)
L ≃ 25m [Oh@WIN2015]

The existing landscape of observed SBL signals and null signatures is difficult to interpret as (3+N) sterile neutrino oscillations.

Awaiting new, definitive experimental results which have sufficient sensitivity to address explicit models, and/or new theoretical models.

A word of caution

- How do we quantify compatibility?
- A measure of how well the parameter regions preferred by different subsets of data overlap

$$\chi^2_{PG} = \chi^2_{min,all} - \sum \chi^2_{min,i}$$

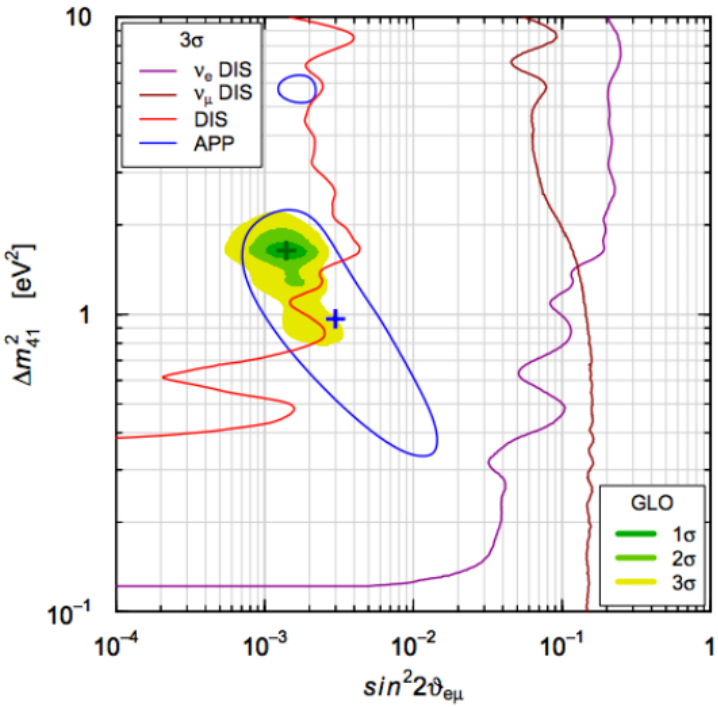
$$\textbf{compatibility, } PG = prob(\chi^2_{PG}, ndf_{PG})$$

- Unlike a χ^2 test, the PG test avoids the problem that a possible disagreement between data sets becomes diluted by data points which are insensitive to the fit

  [Maltoni & Schwetz, 2003]
- But, effect of nuisance parameters? [Collin, WIN'15]
  e.g., scaling background normalization can have an effect on ndf_{PG}

- While instructive and useful in understanding the interplay of signals and null results, the reliability of the PG test for providing meaningful quantitative statements must be carefully validated!

[PRD 88 (2013) 073008; arXiv:1507.08204]



MiniBooNE $E > 475$ MeV

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

- APP $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$: LSND ($\nu_s$), MiniBooNE (?), OPERA ($\cancel{\nu_s}$), ICARUS ($\cancel{\nu_s}$), KARMEN ($\cancel{\nu_s}$), NOMAD ($\cancel{\nu_s}$), BNL-E776 ($\cancel{\nu_s}$)
- DIS ν_e & $\bar{\nu}_e$: Reactors (ν_s), Gallium (ν_s), ν_eC ($\cancel{\nu_s}$), Solar ($\cancel{\nu_s}$)
- DIS ν_μ & $\bar{\nu}_\mu$: CDHSW ($\cancel{\nu_s}$), MINOS ($\cancel{\nu_s}$), Atmospheric ($\cancel{\nu_s}$), MiniBooNE/SciBooNE ($\cancel{\nu_s}$)

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

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

[Giunti, NNN2015]