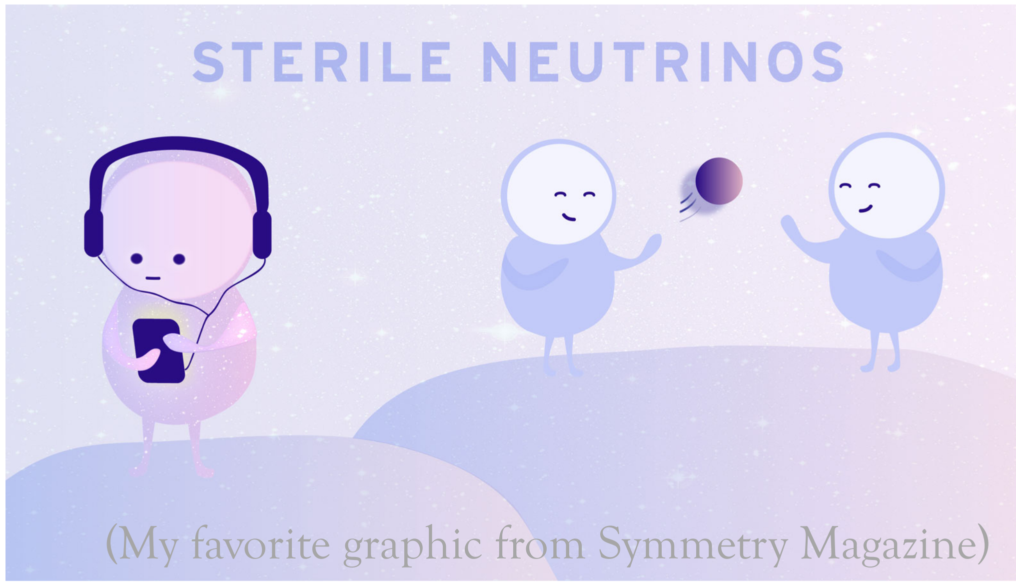
Global Fits to Models of



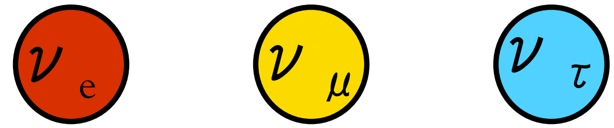
Janet Conrad,
DPF, July 30, 2019

Where Are We With Light Sterile Neutrinos?

A. Diaz[1], C.A. Argüelles[1], G.H. Collin[1], J.M. Conrad[1], M.H. Shaevitz[2]
[1] *Massachusetts Institute of Technology, Cambridge, MA 02139, USA and*
[2] *Columbia University, New York, NY 10027, USA*

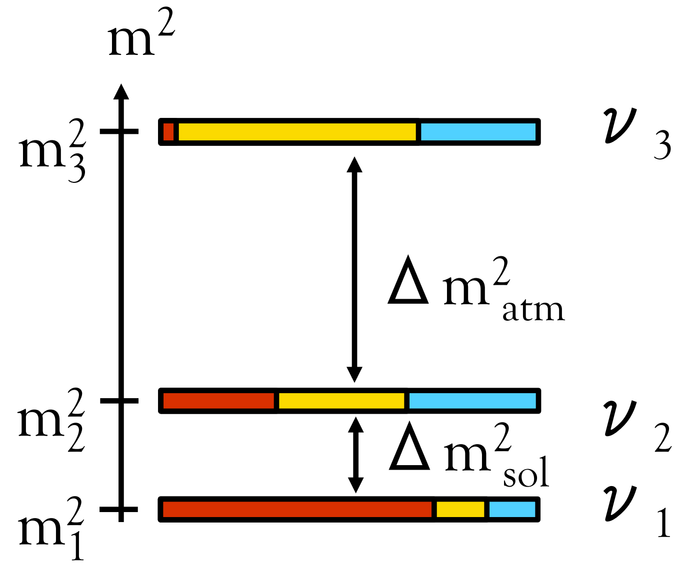
https://arxiv.org/abs/1906.00045
Submitted to Reviews of Modern Physics.

The 3 Neutrino Model:



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} & & \\ & \underset{3\times 3}{U_{\text{PMNS}}} & \\ & & \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

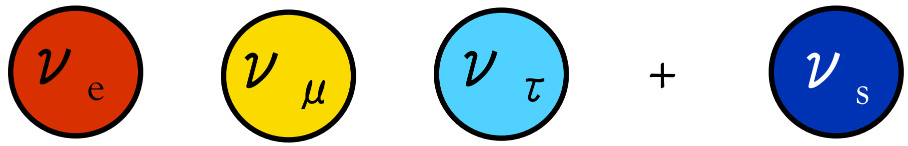
oscillations: $(\theta_{12}, \theta_{23}, \theta_{13}, \delta^{\text{CP}})$

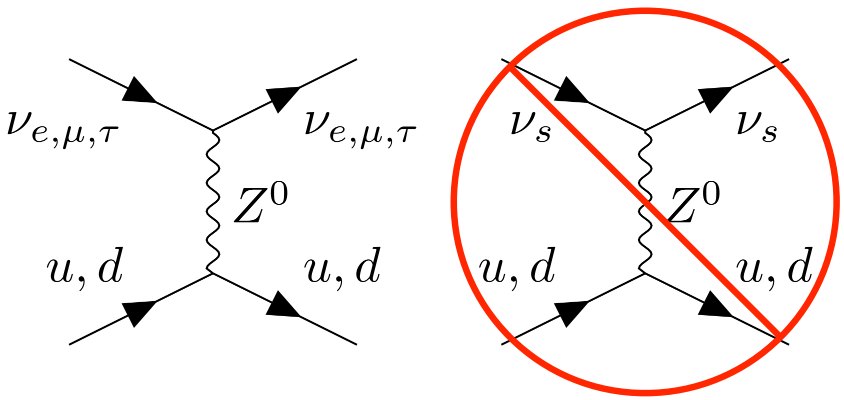


Surprisingly well constrained!
Main experimental focus now: mass hierarchy and CP violation

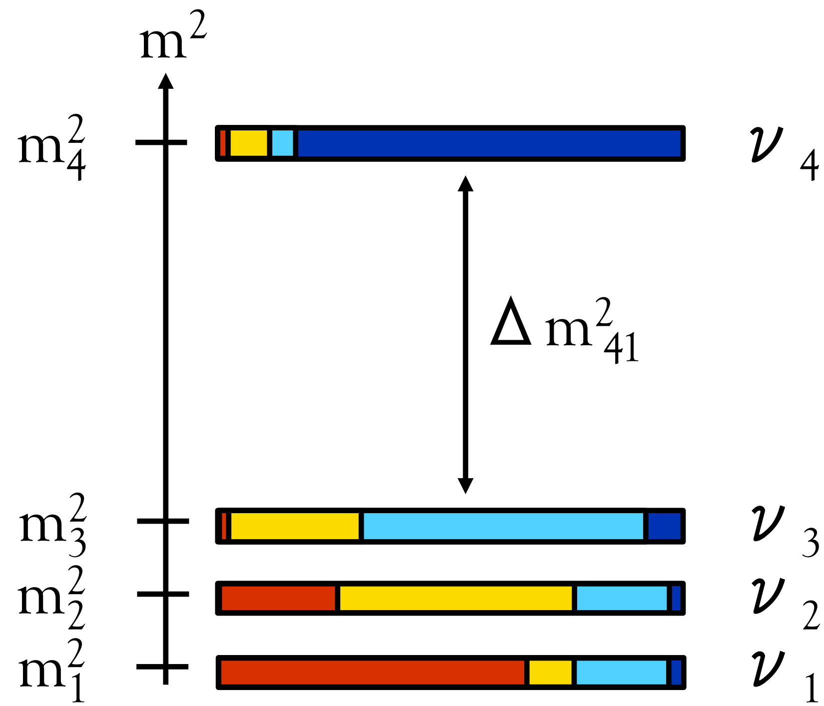
But not everything fits this picture...

Anomalies (>2σ signals) consistent w/ $\Delta m^2 \sim 1$ eV^2 oscillations → "3+1"





$$U_{3+1} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ \vdots & & \vdots & U_{\mu 4} \\ \vdots & & \vdots & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix},$$



Short-baseline
Vacuum oscillations:

$\nu_\mu \rightarrow \nu_e$

$\nu_e \rightarrow \nu_e$

$\nu_\mu \rightarrow \nu_\mu$

$U_{e4}, U_{\mu 4}, \Delta m^2$

$$
\begin{aligned}
P_{\nu_e \to \nu_e} &= 1 - 4(1 - |U_{e4}|^2)|U_{e4}|^2 \sin^2(1.27 \Delta m^2_{41} L/E) \ , \\
P_{\nu_\mu \to \nu_\mu} &= 1 - 4(1 - |U_{\mu 4}|^2)|U_{\mu 4}|^2 \sin^2(1.27 \Delta m^2_{41} L/E) \ , \\
P_{\nu_\mu \to \nu_e} &= 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2(1.27 \Delta m^2_{41} L/E).
\end{aligned}
$$

I will use
"effective mixing
angles"

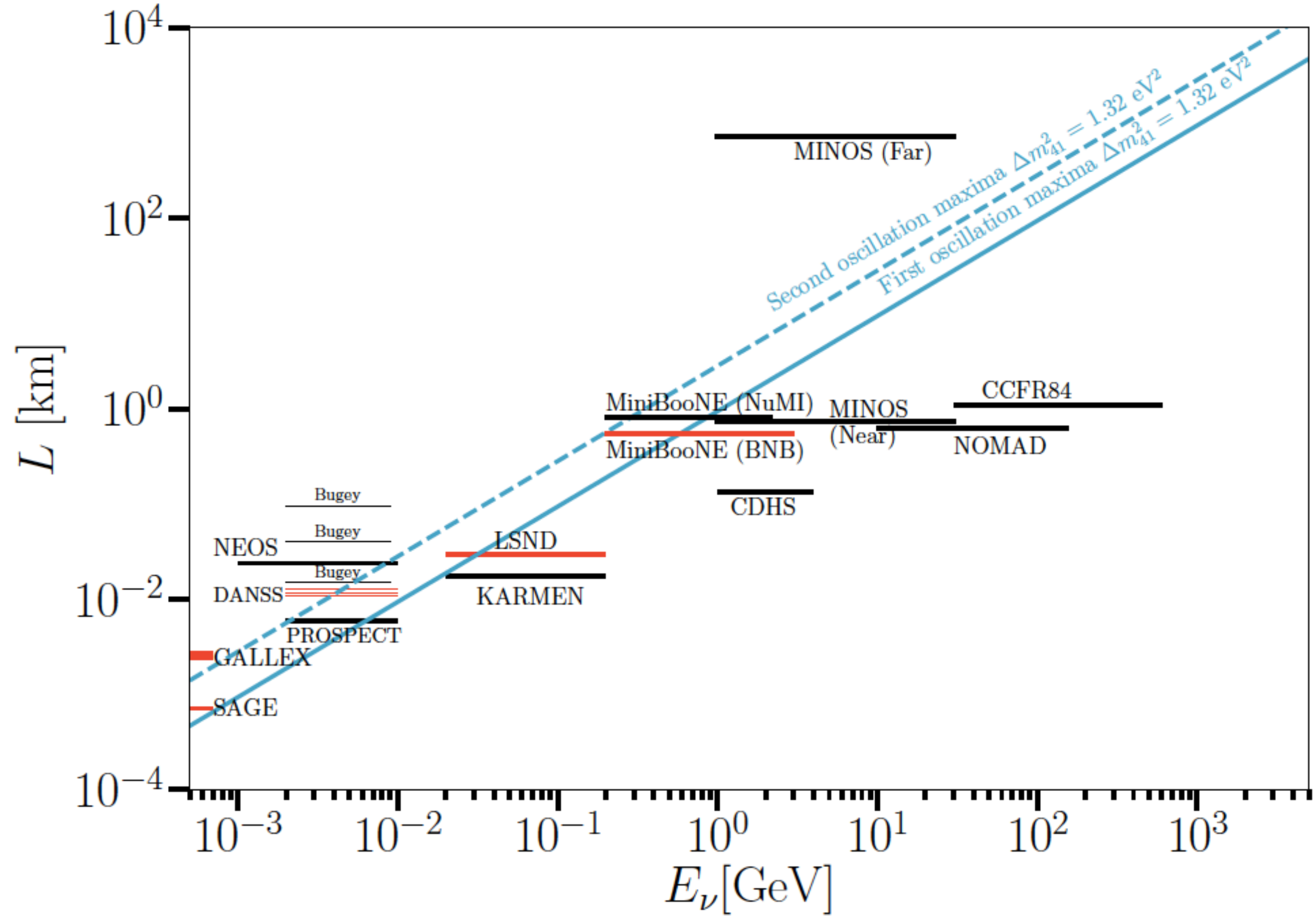
$$
\begin{aligned}
\sin^2 2\theta_{ee} &= 4(1 - |U_{e4}|^2)|U_{e4}|^2, \\
\sin^2 2\theta_{\mu\mu} &= 4(1 - |U_{\mu 4}|^2)|U_{\mu 4}|^2, \\
\sin^2 2\theta_{\mu e} &= 4|U_{\mu 4}|^2|U_{e4}|^2,
\end{aligned}
$$

Experiments we use in our fits (null and with signals)...

* have > 2σ	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$	$\nu_e \to \nu_e$
Neutrino	MiniBooNE (BNB) * MiniBooNE(NuMI) NOMAD	SciBooNE/MiniBooNE CCFR CDHS MINOS	KARMEN/LSND Cross Section Gallium *
Antineutrino	LSND * KARMEN MiniBooNE (BNB) *	SciBooNE/MiniBooNE CCFR MINOS	Bugey NEOS DANSS * PROSPECT

$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \sin^2\left(1.27\ \Delta m^2_{ij}\ (\mathrm{eV}^2)\ \frac{L(\mathrm{m})}{E(\mathrm{MeV})}\right)$$

$\Delta m^2 \sim 1\ \mathrm{eV}^2 \rightarrow$ L/E ~ 1 m/MeV or km/GeV ("Short Baseline")



$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \sin^2 \left(1.27\ \Delta m^2_{ij}\ (\mathrm{eV}^2)\ \frac{L(\mathrm{m})}{E(\mathrm{MeV})} \right)$$

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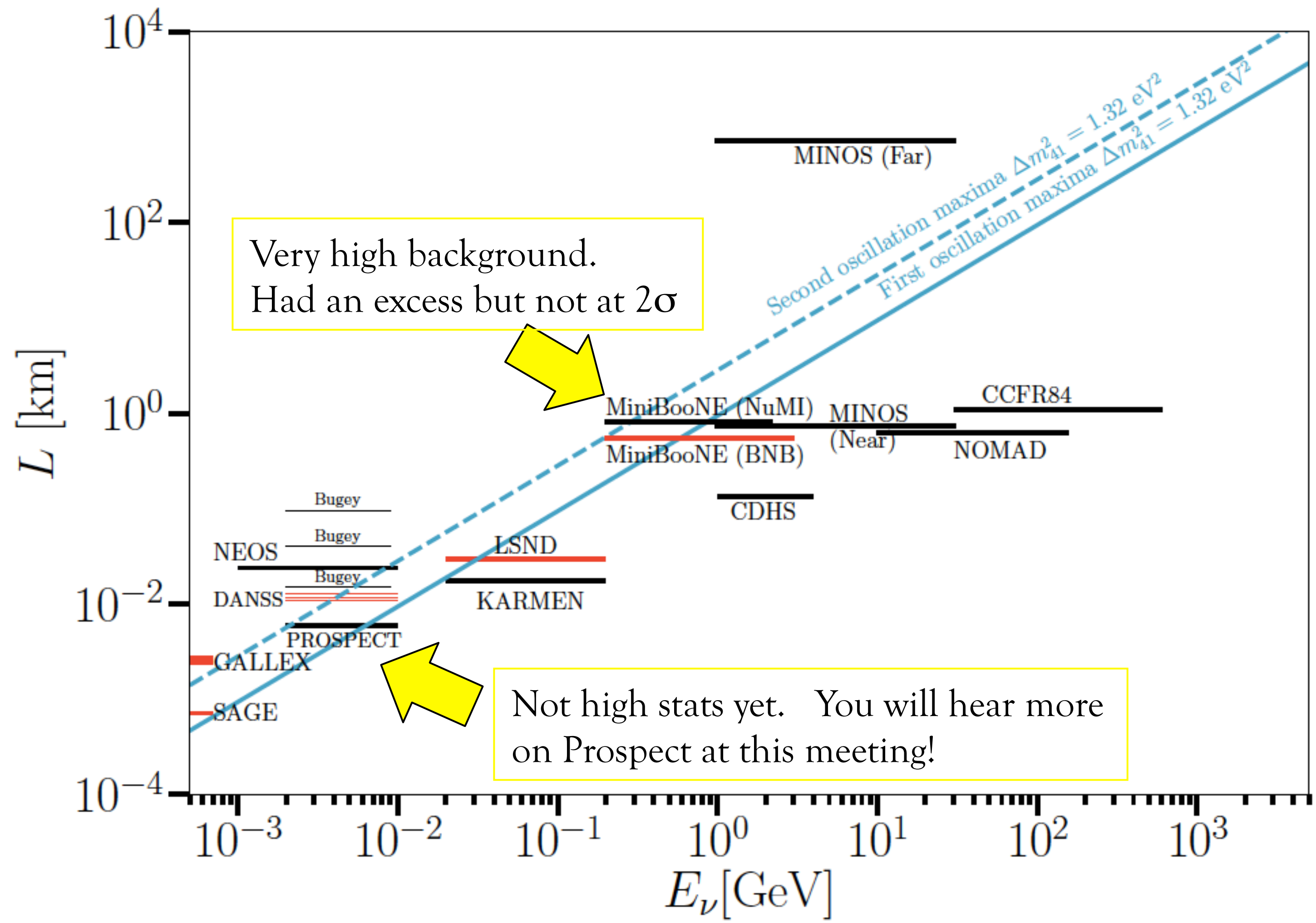
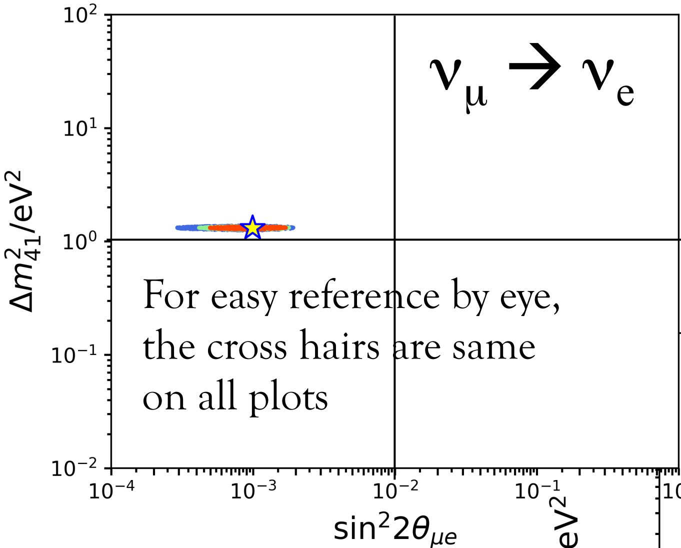
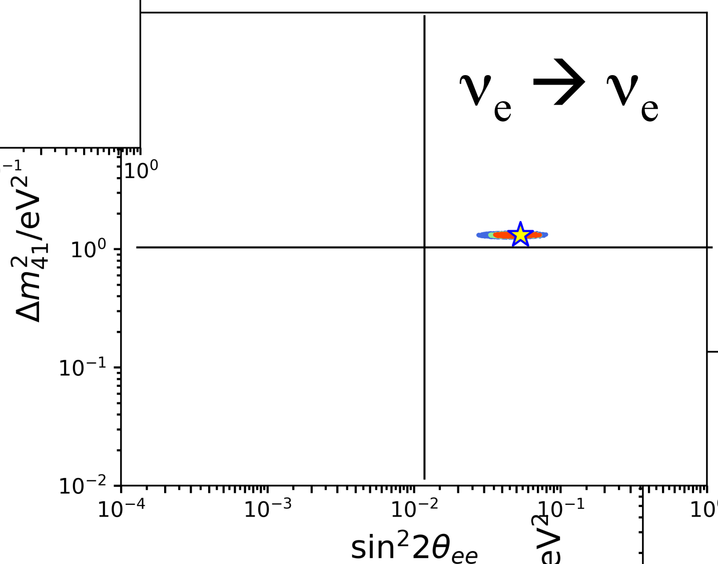
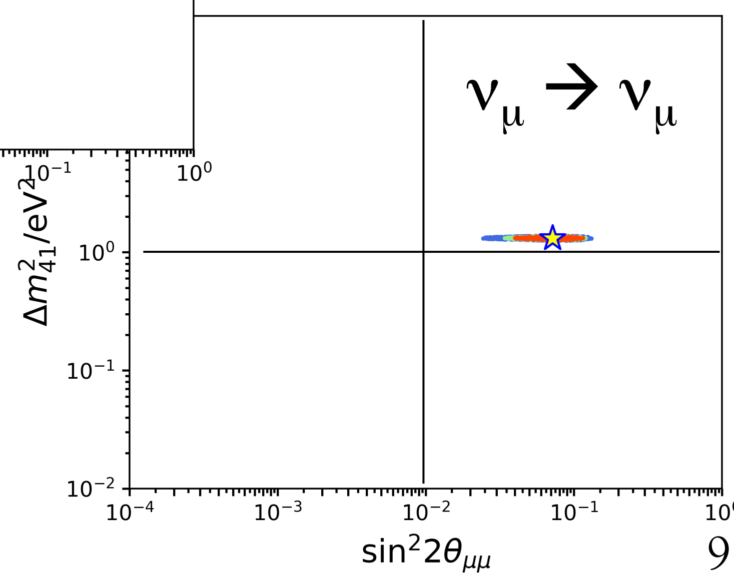


Global fit results:

Global fit	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	Δm^2_{41} $(\mathrm{eV})^2$
3 + 1	0.116	0.135	1.32







Comparing
3+1 to only-3 models:
$\Delta\chi^2$=35 for Δdof =3
→ a >5σ improvement!

Yes introducing 3+1 is a huge improvement, but there are some other important questions to ask!

I have time in this talk to explore two…

Are the data sets internally consistent?
Are there better models than 3+1?

Remember in 3+1 the parameters are:

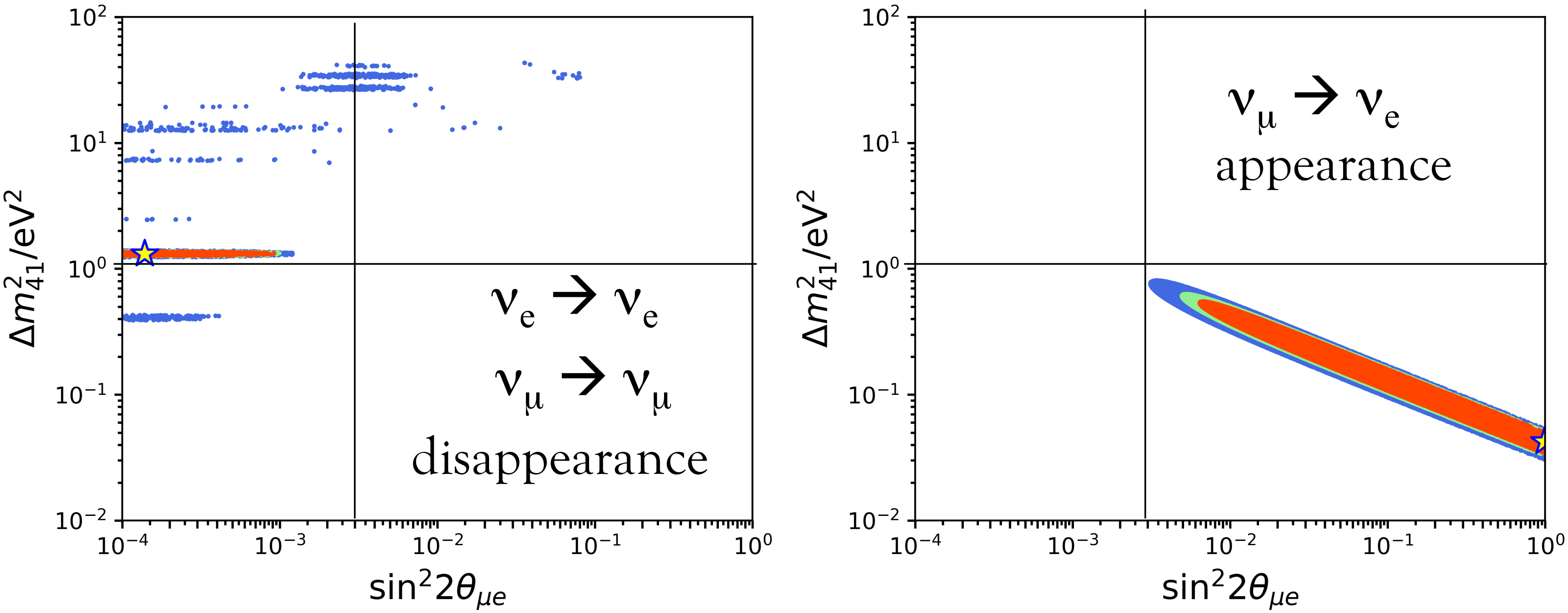
U_{e4}, $U_{\mu 4}$, Δm^2

$$\begin{aligned} P_{\nu_e \to \nu_e} &= 1 - 4(1 - |U_{e4}|^2)|U_{e4}|^2 \sin^2(1.27 \Delta m^2_{41} L/E) , \\ P_{\nu_\mu \to \nu_\mu} &= 1 - 4(1 - |U_{\mu 4}|^2)|U_{\mu 4}|^2 \sin^2(1.27 \Delta m^2_{41} L/E) , \\ P_{\nu_\mu \to \nu_e} &= 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2(1.27 \Delta m^2_{41} L/E). \end{aligned}$$

Traditionally we compare disappearance: $\nu_e \rightarrow \nu_e$ ✓

$\nu_\mu \rightarrow \nu_\mu$ ✓

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



No overlap in preferred regions!

This is the well-known "tension" within the 3+1 model

Is there a better model?

Often people look to adding additional sterile neutrinos.
3+2 adds 7 dof to the fits!
But while it helps a little with the tension, but not a lot.

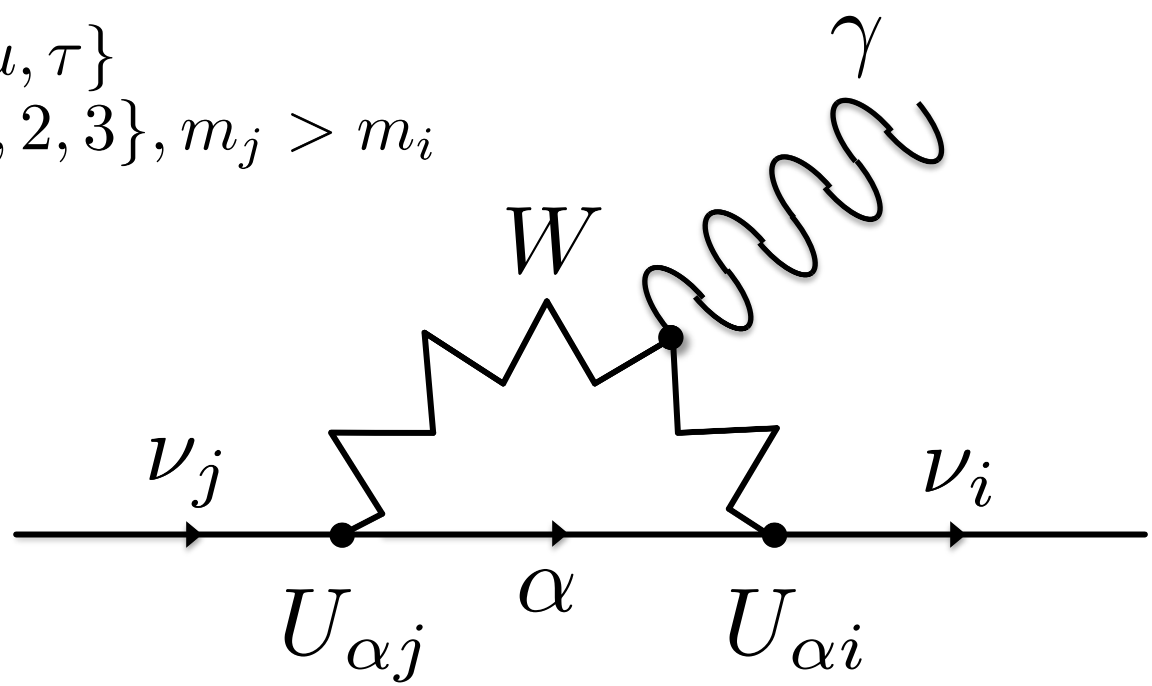
What about: 3+1+decay ?

This idea was already explored for IceCube.
https://arxiv.org/abs/1711.05921
Phys.Rev. D97 (2018) no.5, 055017

Let’s explore it for the short baseline experiments

Without a symmetry to protect it,
neutrinos mass states will decay, even in the Standard Model

$\alpha \in \{e, \mu, \tau\}$
$i, j \in \{1, 2, 3\}, m_j > m_i$

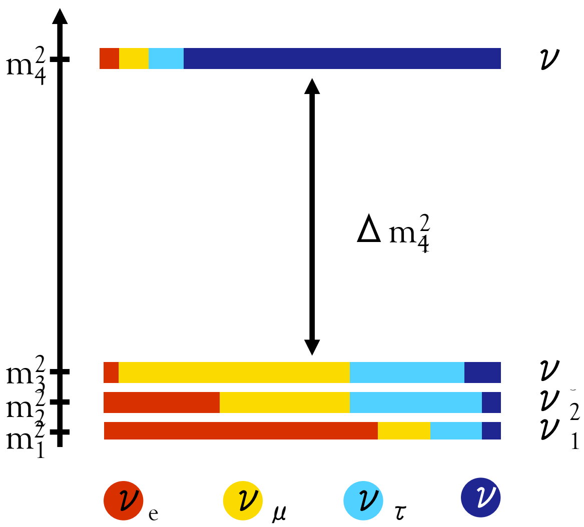


$\nu_i \rightarrow \nu_j + \gamma \;\Rightarrow$ >1E28 years!

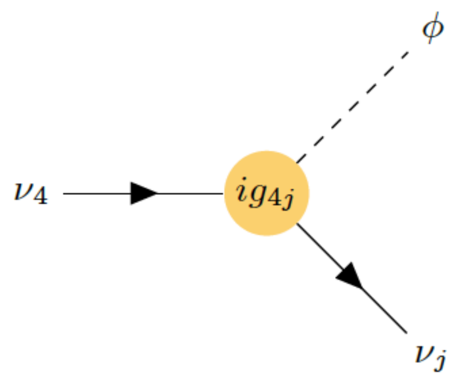
$\nu_i \rightarrow \nu_j + \gamma + \gamma \;\Rightarrow$ >1E55 years!

Decay in the case of a "sterile" flavor

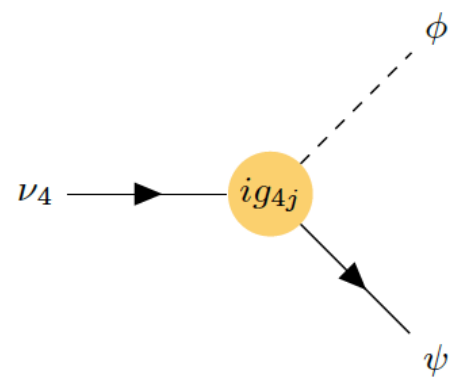
It's the mass state that decays!



We are hypothesizing a new coupling to new particle(s)



"visible"

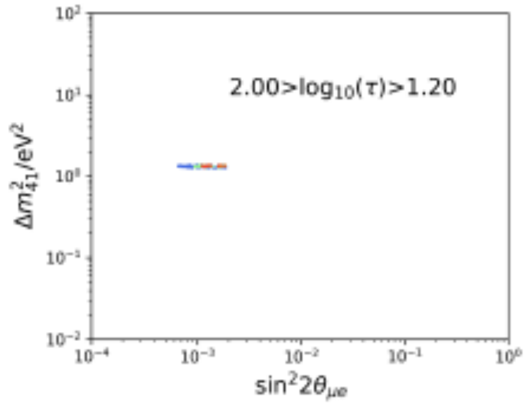


"invisible"

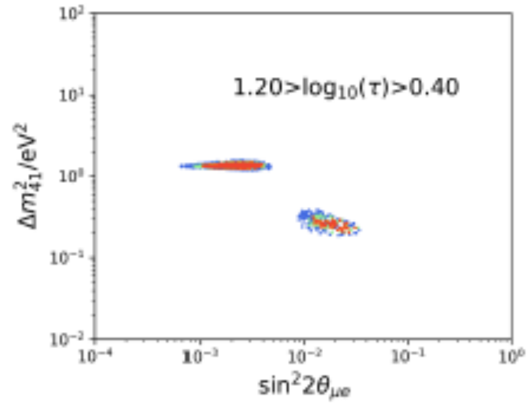
For now, this one.

It is a more economical model than 3+2 in model parameters
→ only 1 dof added

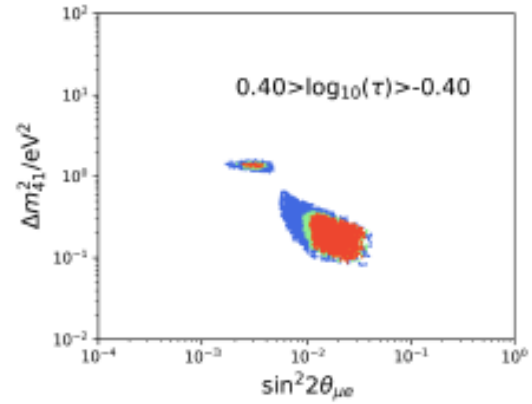
Scanning across m_4 state lifetimes…



(a) Allowed points for $1.2 < \log_{10}(\tau_4/\mathrm{eV}^{-1}) < 2.0$.



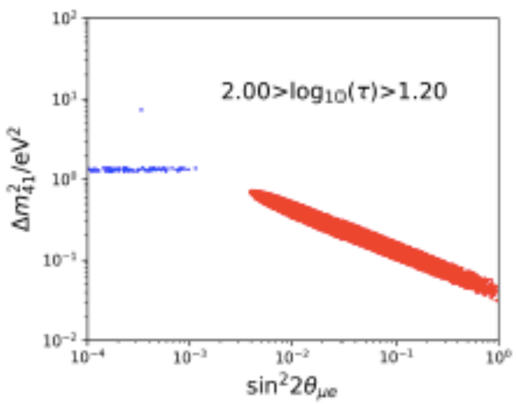
(b) Allowed points for $0.4 < \log_{10}(\tau_4/\mathrm{eV}^{-1}) < 1.2$.



(c) Allowed points for $-0.4 < \log_{10}(\tau_4/\mathrm{eV}^{-1}) < 0.4$.

The allowed regions expand!

Scanning across m_4 state lifetimes…



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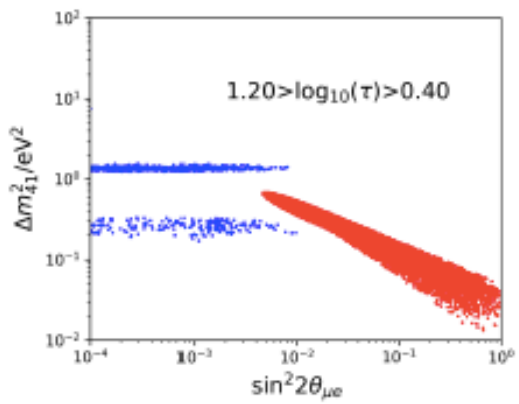

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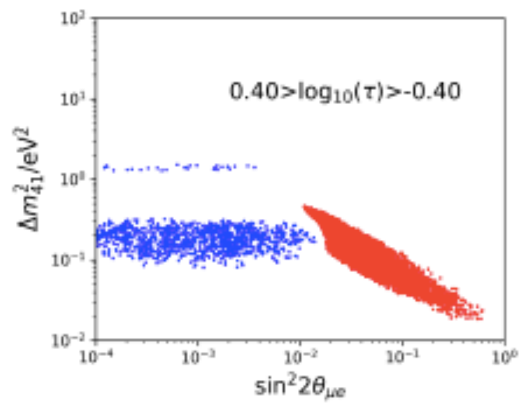


(c) Allowed points for $-0.4 < \log_{10}(\tau_4/\mathrm{eV}^{-1}) < 0.4$.

If you fit for disappearance and appearance separately, the level of agreement improves!

It still does not overlap at 2σ but it is much improved!
Fitting for the visible decay is likely to lead to agreement.

The "Parameter Goodness of Fit Test" (PG Test)

→ A comparison of the chi2 of the best fit points.
If data are drawn from the same model,
then the best fit points should agree.

$$\chi^2_{\mathrm{PG}} = \chi^2_{\mathrm{glob}} - (\chi^2_{\mathrm{app}} + \chi^2_{\mathrm{dis}}),$$

$$N_{\mathrm{PG}} = (N_{\mathrm{app}} + N_{\mathrm{dis}}) - N_{\mathrm{glob}},$$

From this you can get a p-value for agreement.
Tiny probability → unlikely that the sets agree.

M. Maltoni, T. Schwetz Phys.Rev. D68 (2003) 033020

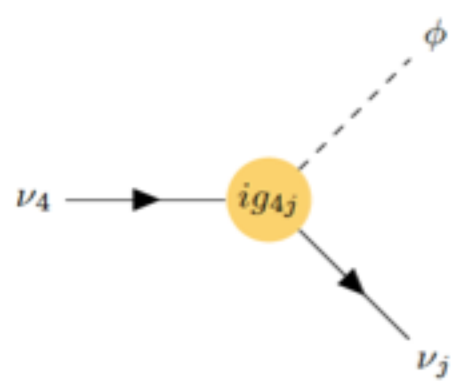
Appearance vs. Disappearance PG Test Results:

3+1 PG disagreement → 4.5σ

3+2 PG disagreement → 4.4σ

3+1+invisible decay PG disagreement → 3.2σ

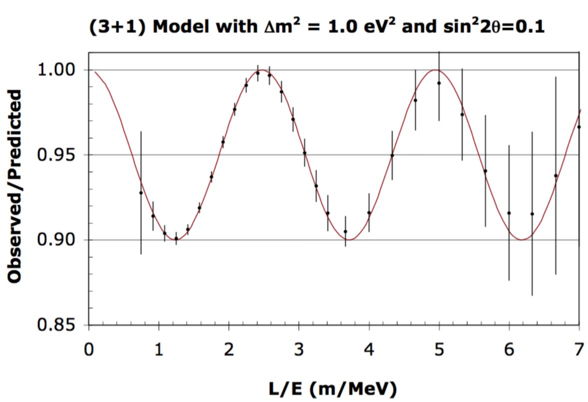
Introducing visible decay is likely to improve tension further, because visible decay "replenishes" the flux, weakening disappearance

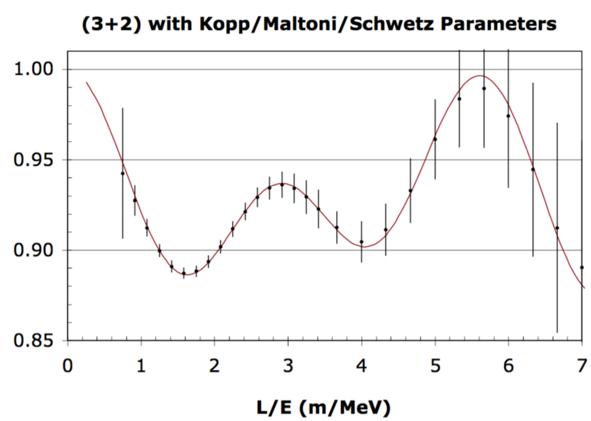


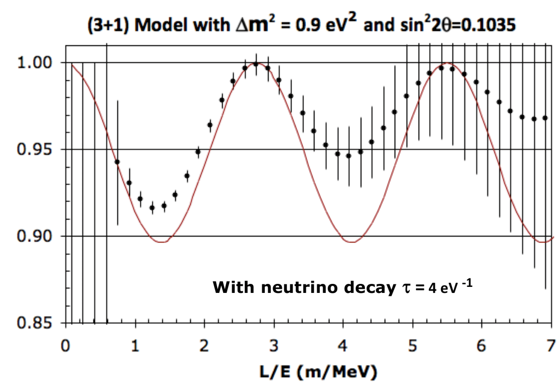
No time in this talk, but our review paper also provides…

- A text-book style introduction to oscillations and 3+1
- Bayesian fit results
- An extended discussion of the assumptions hidden in global fits.
  → They are not as exact as you might think
  (or we would like!)
- Discussion of past experiments, near future and our view of the best design for the far future (decay-at-rest based)

An example of a farther future experiment: IsoDAR







We will hear more about IsoDAR tomorrow (14:20, E. Dunton)

Conclusions:

We have published a review that provides the
latest global fits to short baseline data sets.

The overall "take-away" for 3+1 is the same as in the past…
The data strongly favor 3+1 over only-3
Yet there is tension between appearance and disappearance

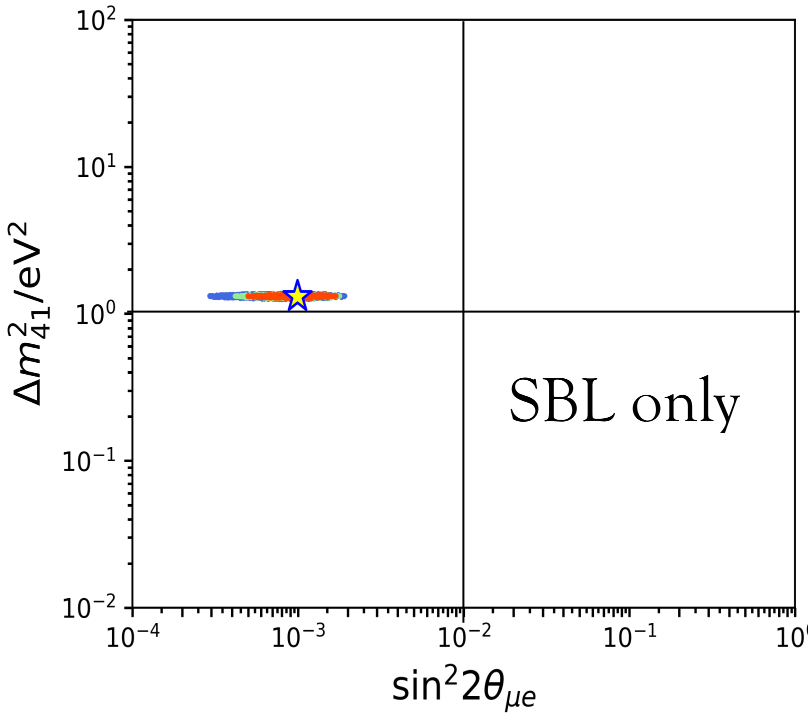
New: 3+1+decay is a significant improvement.
That model needs to be extended to "visible decay"

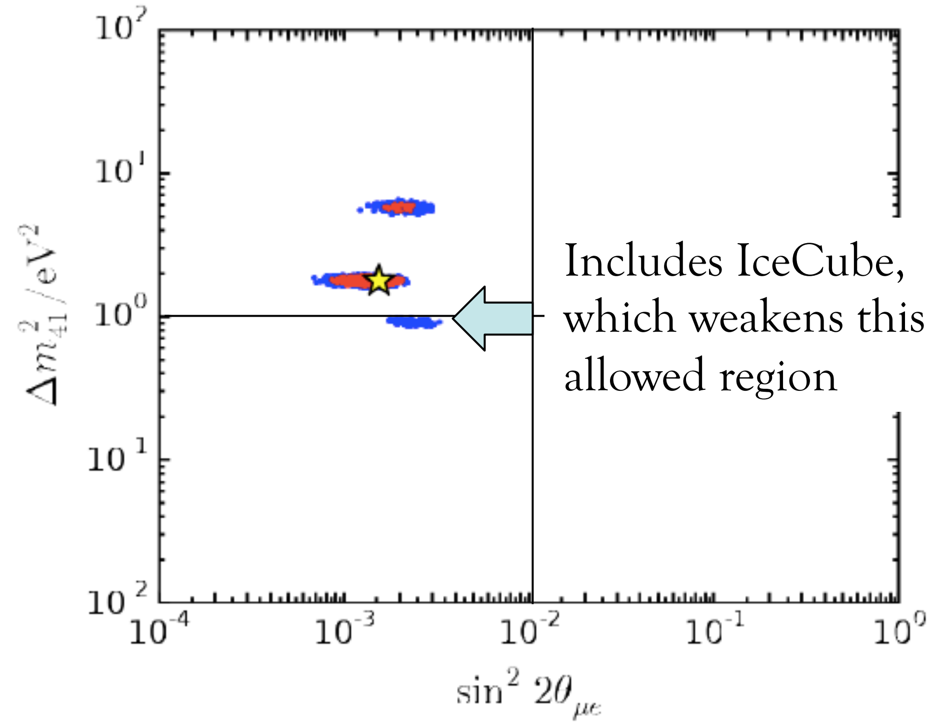
More and better data sets are needed,
the anomalies remain confusing and are not going away!
I am looking forward to the talks that follow…
Thank you!

Back Ups

$\sin^2 2\theta_{ee}$	$= \sin^2 2\theta_{14}$	$= 4(1-\|U_{e4}\|^2)\|U_{e4}\|^2$
$\sin^2 2\theta_{\mu\mu}$	$= 4\cos^2\theta_{14}\sin^2\theta_{24}(1-\cos^2\theta_{14}\sin^2\theta_{24})$	$= 4(1-\|U_{\mu 4}\|^2)\|U_{\mu 4}\|^2$
$\sin^2 2\theta_{\tau\tau}$	$= 4\cos^2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34}(1-\cos^2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34})$	$= 4(1-\|U_{\tau 4}\|^2)\|U_{\tau 4}\|^2$
$\sin^2 2\theta_{\mu e}$	$= \sin^2 2\theta_{14}\sin^2\theta_{24}$	$= 4\|U_{\mu 4}\|^2\|U_{e4}\|^2$
$\sin^2 2\theta_{e\tau}$	$= \sin^2 2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34}$	$= 4\|U_{e4}\|^2\|U_{\tau 4}\|^2$
$\sin^2 2\theta_{\mu\tau}$	$= \sin^2 2\theta_{24}\cos^4\theta_{14}\sin^2\theta_{34}$	$= 4\|U_{\mu 4}\|^2\|U_{\tau 4}\|^2$

Our latest result compared to our 2016 results…





Experiments we use in our fits … things to notice

* have $> 2\sigma$

"Unplanned"

	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$	$\nu_e \to \nu_e$
Neutrino	MiniBooNE (BNB) * MiniBooNE(NuMI) NOMAD	SciBooNE/MiniBooNE CCFR CDHS MINOS	KARMEN/LSND Cross Section Gallium *
Antineutrino	LSND * KARMEN MiniBooNE (BNB) *	SciBooNE/MiniBooNE CCFR MINOS	Bugey NEOS DANSS * PROSPECT

"Traditional" Accelerator Experiments

Reactor Experiments

The systematic uncertainties for the experiments are different.

Experiments we use in our fits … things to notice

$*$ have $> 2\sigma$

	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$	$\nu_e \to \nu_e$
Neutrino	MiniBooNE (BNB) $*$ MiniBooNE(NuMI) NOMAD	SciBooNE/MiniBooNE CCFR CDHS MINOS	KARMEN/LSND Cross Section Gallium $*$
Antineutrino	LSND $*$ KARMEN MiniBooNE (BNB) $*$	SciBooNE/MiniBooNE CCFR MINOS	Bugey NEOS DANSS $*$ PROSPECT

IceCube's 2015 result is not included in these fits. Why?

This is computing-intensive to include because it involves matter effects. Our plan is to include IceCube when they update that result in autumn.

Experiments we use in our fits … things to notice

* have > 2σ

"Unplanned"

	$\nu_\mu \rightarrow \nu_e$	$\nu_\mu \rightarrow \nu_\mu$	$\nu_e \rightarrow \nu_e$
Neutrino	MiniBooNE (BNB) * MiniBooNE(NuMI) NOMAD	SciBooNE/MiniBooNE CCFR CDHS MINOS	KARMEN/LSND Cross Section Gallium *
Antineutrino	LSND * KARMEN MiniBooNE (BNB) *	SciBooNE/MiniBooNE CCFR MINOS	Bugey NEOS DANSS * PROSPECT

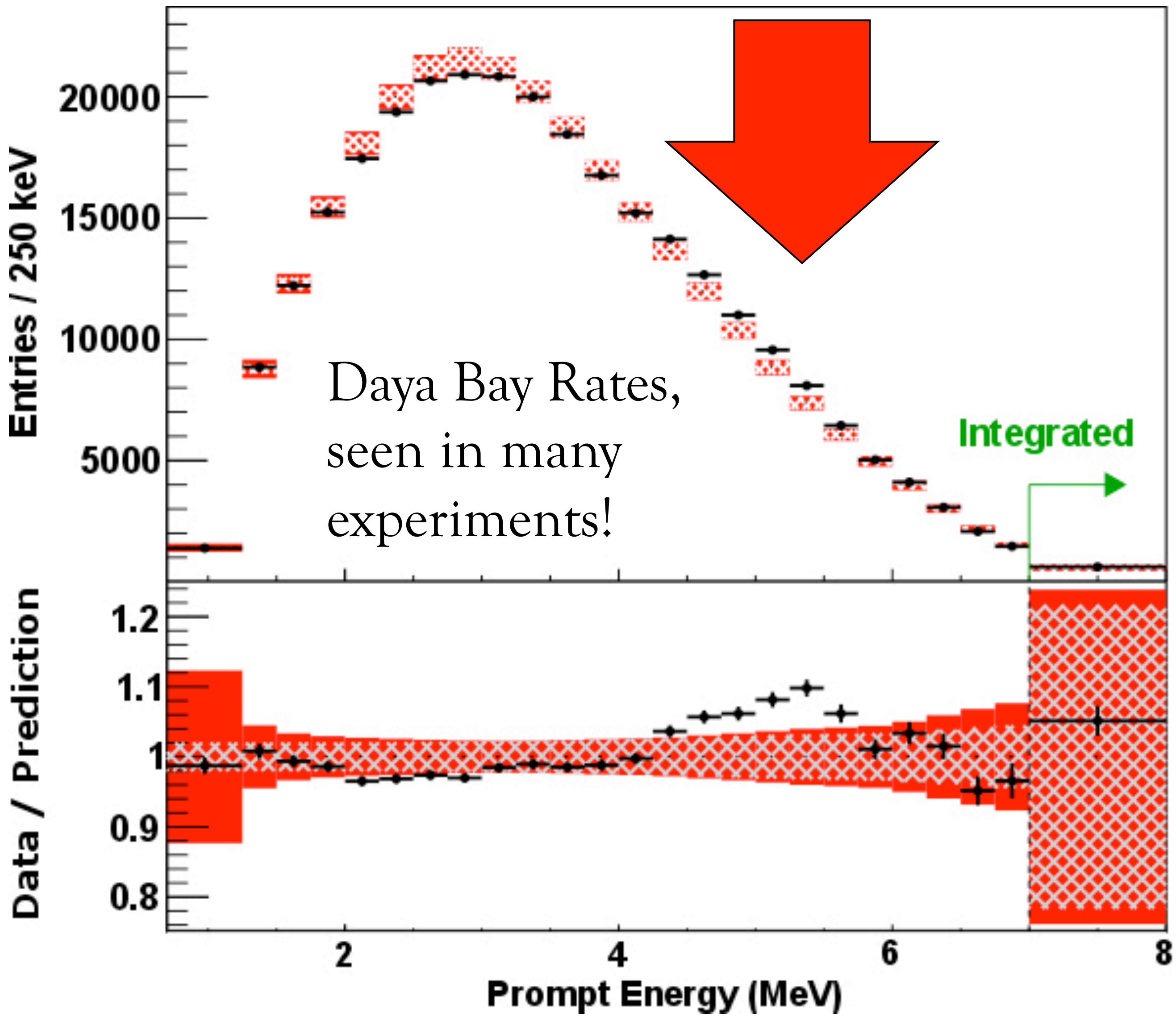
"Traditional" Accelerator Experiments

Reactor Experiments

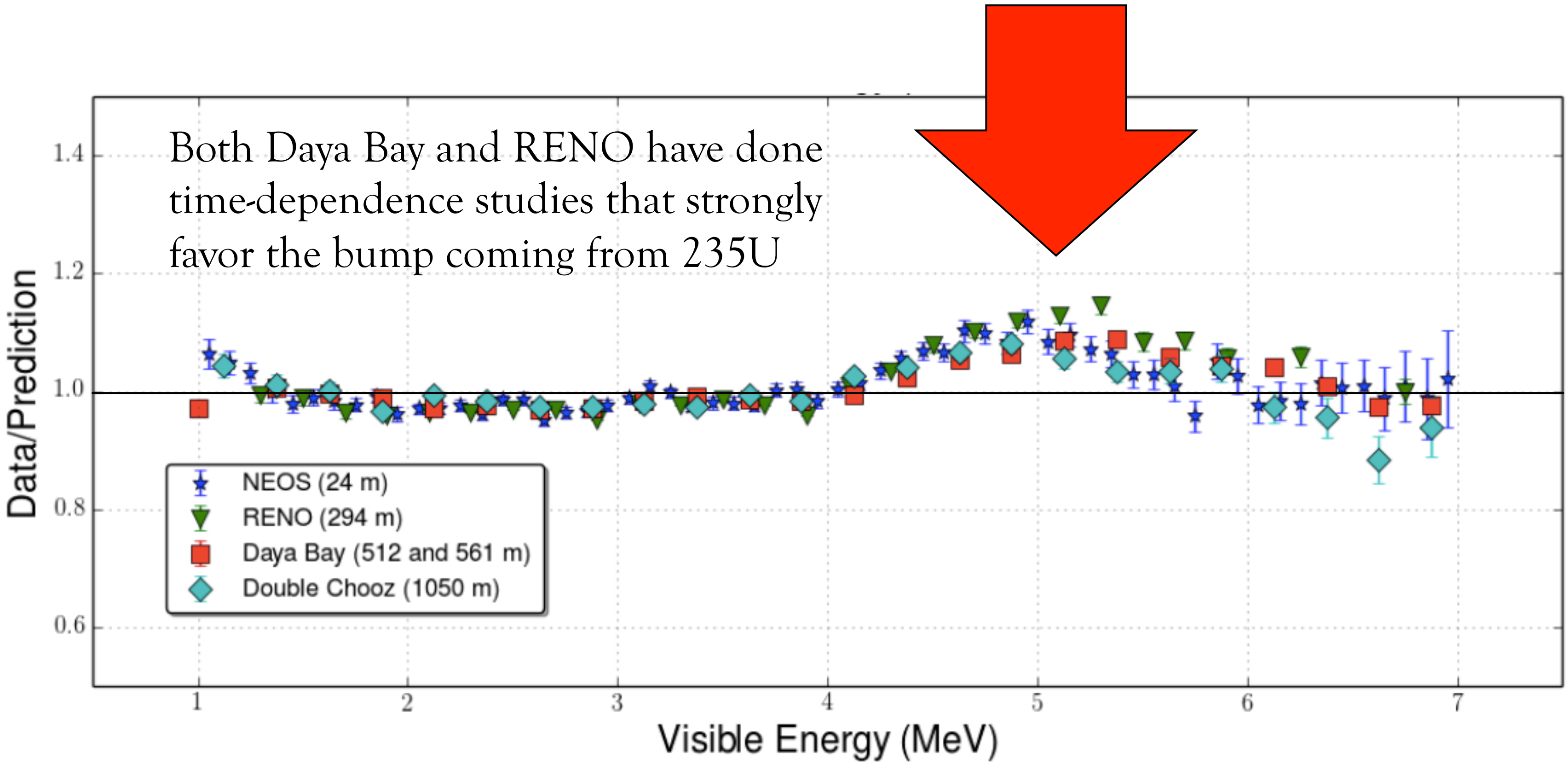
W/r/t to Reactors, we are not using…

1) Neutrino-4 results because we have outstanding questions to them
2) STEREO results because they were too recent
3) Absolute reactor rates compared to prediction (we only use ratios)

Absolute Reactor Rates: What's that bump?



Along with Daya Bay,
the 5 MeV "bump" appears in RENO, Double Chooz and NEOS!

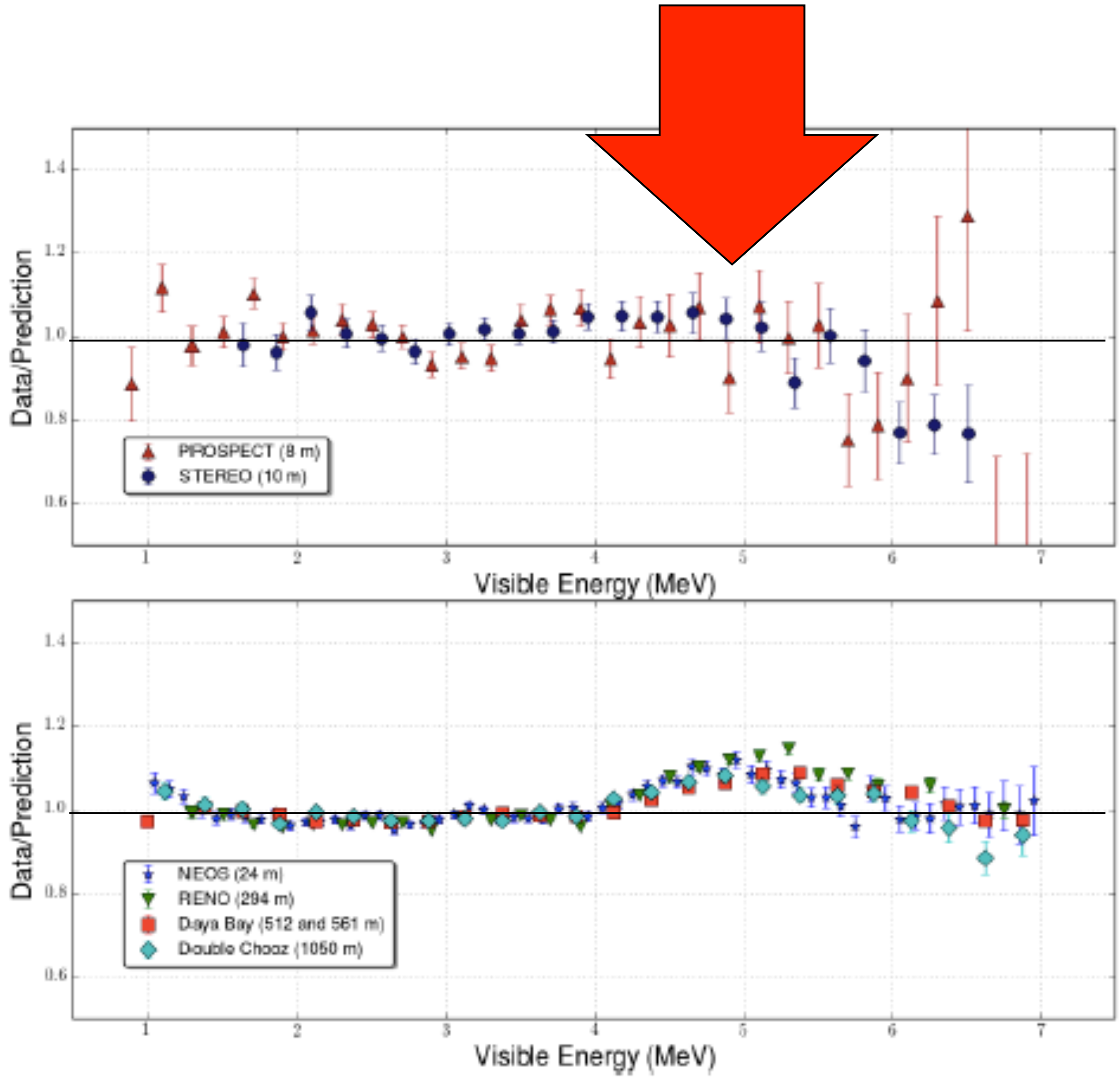


The next 4 slides examine this bump more closely

In short baseline experiments the bump seems to be suppressed? PROSPECT and STEREO are running at HFIRs (235U cores!)

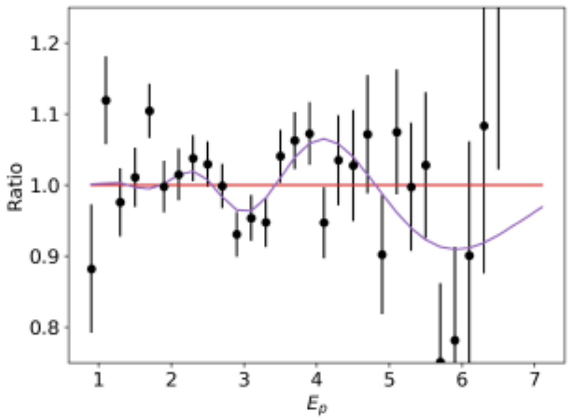
A short baseline osc. could cancel the bump.

For long baseline, the osc has averaged to ½.



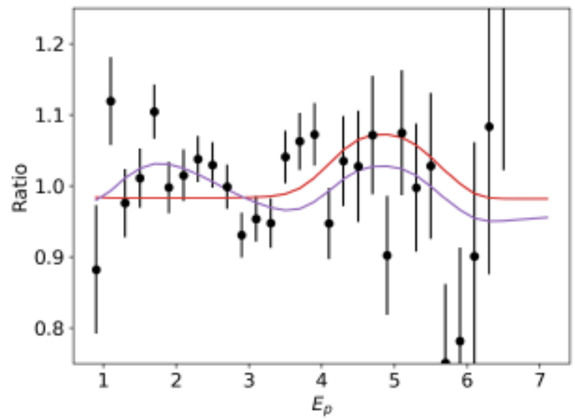
Let's look more closely…

-- no oscillation
-- best fit oscillation

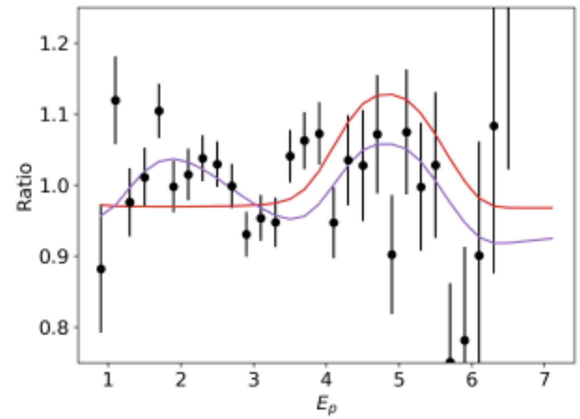


(a) No 5 MeV excess flux model.

5 MeV Excess Model is from fit to Daya Bay bump



(b) An equal 5 MeV excess for all fuel components.



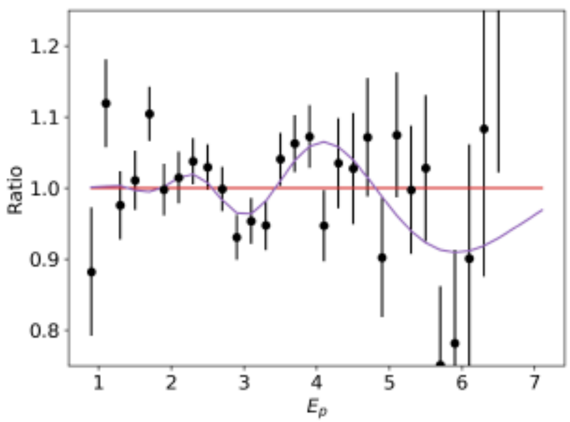
(c) A 5 MeV excess for ^{235}U only.

The no-oscillation
(Red line)
is just the Huber
flux (so flat)

Here the no oscillation adds a 5 MeV bump
represented by Huber's Gaussian fit to
the Daya Bay bump
(so the red line now has a bump)

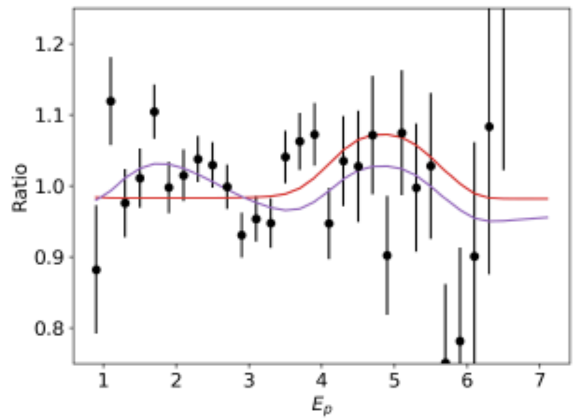
-- no oscillation

-- best fit oscillation

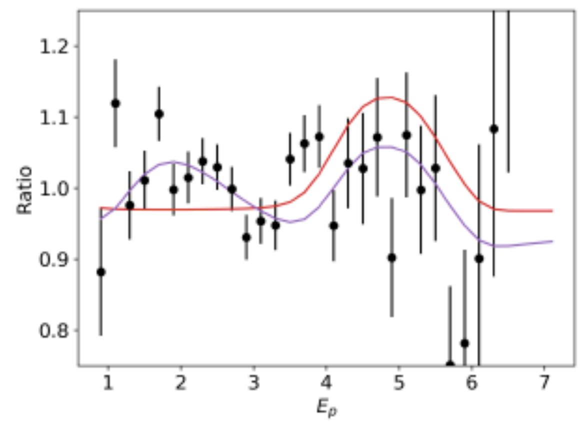


(a) No 5 MeV excess flux model.

5 MeV Excess Model is from fit to Daya Bay bump



(b) An equal 5 MeV excess for all fuel components.



(c) A 5 MeV excess for ^{235}U only.

Prospect data comes from an HFIR (so a pure U core).

Left: red bump prediction is based on assuming Daya Bay bump comes from both U and Pu

Right: Assumes Daya Bay bump is U only

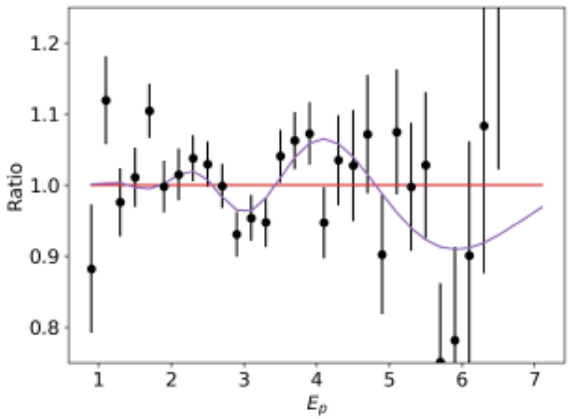
Let’s do a 3+1 fit to the Prospect data in the 3 scenarios!

See the purple lines!

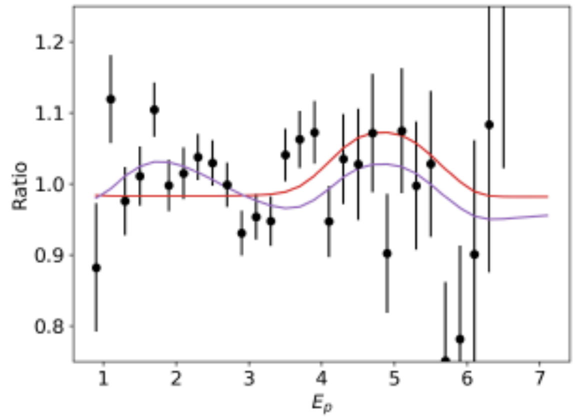
-- no oscillation

-- best fit oscillation

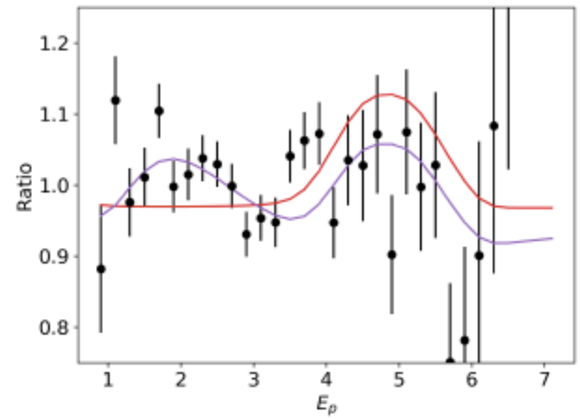
5 MeV Excess Model is from fit to Daya Bay bump



(a) No 5 MeV excess flux model.



(b) An equal 5 MeV excess for all fuel components.



(c) A 5 MeV excess for ^{235}U only.

$\Delta\chi^2/\text{dof}=12/2$

$\Delta\chi^2/\text{dof}=9/2$

$\Delta\chi^2/\text{dof}=23/2$

Oscillation model is yielding a substantial improvement!

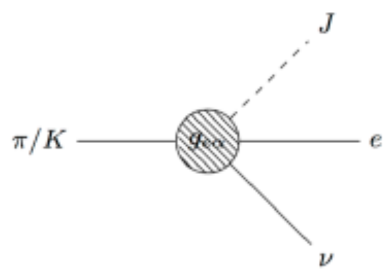
Best fit for b and c are both at about $\Delta m^2=0.95$ eV^2, $\sin^2 2\theta=0.14$

In the future we will include fits for these 3 scenarios.

Evading the flavor dependent bounds on decay (arXiv:1711.05921)

Bound from meson decays:

$$\sum_\alpha |g_{e\alpha}|^2 < 3 \times 10^{-5}$$



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

Assume only one g_{4j} is non-zero:

$$g_{\alpha\beta} = g_{4j} U_{\alpha 4} U^*_{j\beta}$$

From SBL fits:

$$U_{\alpha 4} \sim \mathcal{O}(0.1)$$

From standard measurements:

$$U_{j\beta} \sim \mathcal{O}(0.1)$$

$$\Rightarrow g_{4j} < \mathcal{O}(0.1)$$

$$\Gamma_{ij} = g_{ij}^2 m_i / 32\pi$$

$$\tau_{ij} > 10^4 / m_i$$

But if more than one g_{4j} is non-zero, cancellations may occur, decreasing the constraint on decay rate.