Recent Results on Global Fits to Sterile Neutrino Models

Carlos Arguelles, Gabriel Collin, Janet Conrad, Alejandro Diaz, Mike Shaevitz

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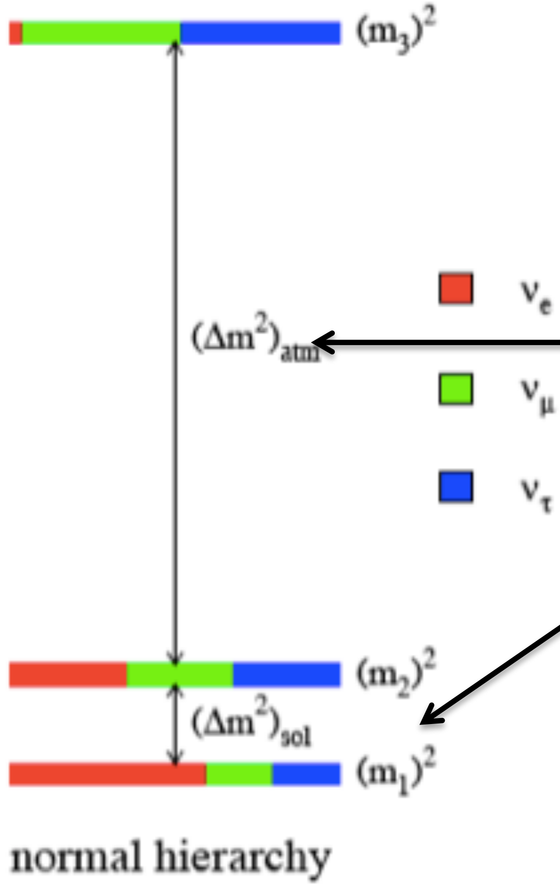
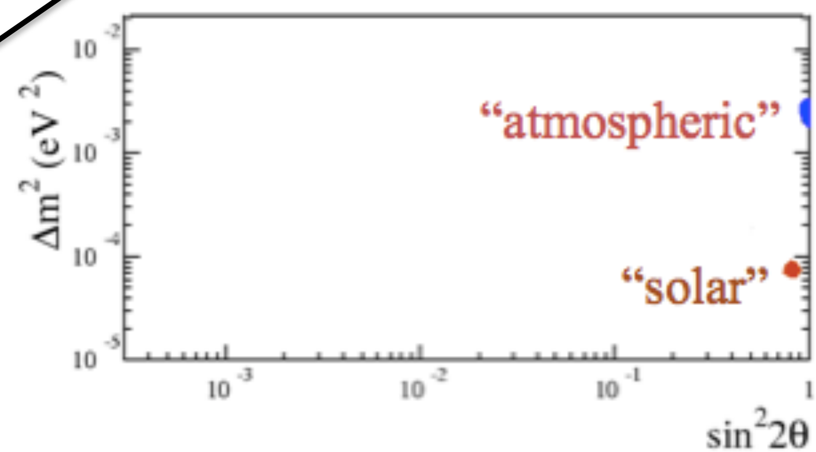
A 3ν model has been established

A 3×3 rotation matrix

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

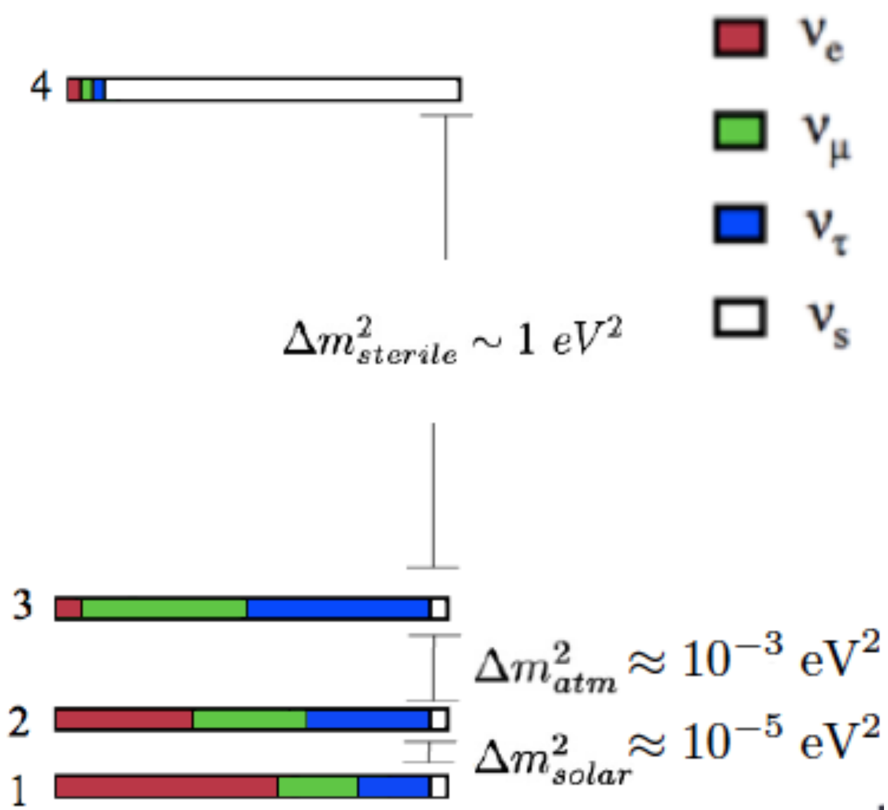


Two distinct mass splittings
"atmospheric" -- 3E-3 eV^2
"solar" -- 7E-5 eV^2



(Or potentially inverted)

But there are a set of anomalies observed! Maybe oscillations? → sterile neutrinos



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

The resulting oscillation probabilities:

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

which I can simplify further to:

$$P_{\nu_e \to \nu_e} = 1 - \sin^2 2\theta_{ee} \sin^2(1.27\Delta m_{41}^2 L/E),$$ e-flavor disappearance

$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\theta_{\mu\mu} \sin^2(1.27\Delta m_{41}^2 L/E),$$ μ-flavor disappearance

$$P_{\nu_\mu \to \nu_e} = \sin^2 2\theta_{e\mu} \sin^2(1.27\Delta m_{41}^2 L/E),$$ μ-to-e appearance

Three <u>inter-related</u> mixing angles, <u>only one</u> mass splitting.

Some accelerator/reactor expts have seen "signals" at the >2σ level, some have not.

ν_e and $\bar{\nu}_e$ appearance:

- LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  $\nu_\mu \rightarrow \nu_e$
- NuMI in MB $\nu_\mu \rightarrow \nu_e$
- NOMAD $\nu_\mu \rightarrow \nu_e$
- KARMEN $\nu_\mu \rightarrow \nu_e$

disappearance.

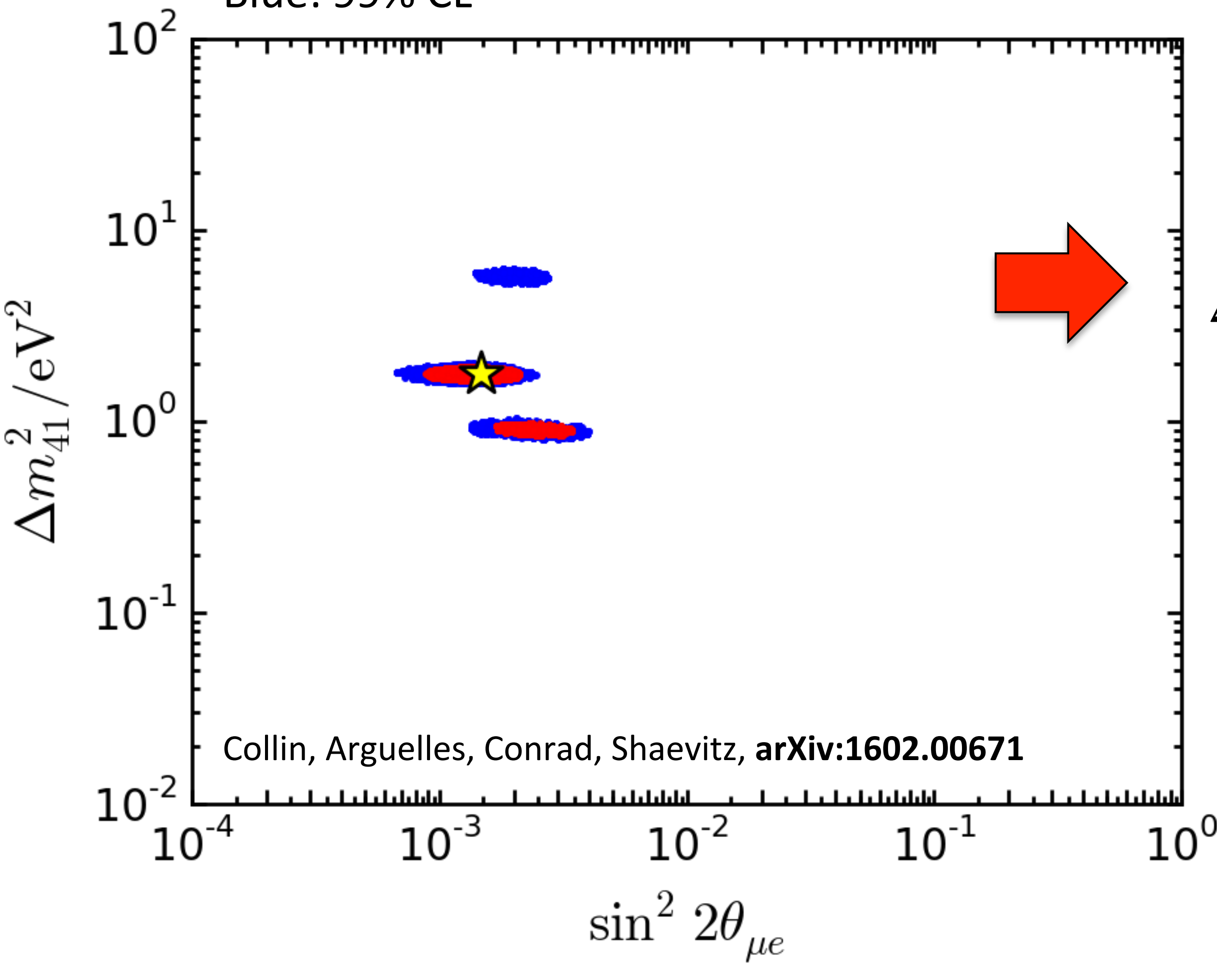
- ν_e and $\bar{\nu}_e$
  - Bugey $\bar{\nu}_e \nrightarrow \bar{\nu}_e$
  - GALLEX/SAGE
    $\nu_e \nrightarrow \nu_e$
  - KARMEN/LSND x-sec
    $\nu_e \nrightarrow \nu_e$
- ν_μ and $\bar{\nu}_\mu$
  - MINOS CC $\bar{\nu}_\mu \nrightarrow \bar{\nu}_\mu$
  - SciBooNE/MiniBooNE *
    $\bar{\nu}_\mu \nrightarrow \bar{\nu}_\mu$
    $\nu_\mu \nrightarrow \nu_\mu$
  - CCFR84 $\nu_\mu \nrightarrow \nu_\mu$
  - CDHS * $\nu_\mu \nrightarrow \nu_\mu$

No muon flavor disappearance >2σ "signals,"
but *'s indicate experiments with >90% CL "signals"

How well do these fit together?

"3 + 1 model"

Red: 90% CL
Blue: 99% CL



Best fit point:

$$\Delta m^2_{41} : 1.75\ \mathrm{eV}^2$$

$$\sin^2 2\theta_{\mu e} : 1.45 \times 10^{-3}$$

$$\chi^2 : 306.81 \quad (312\ \mathrm{dof})$$

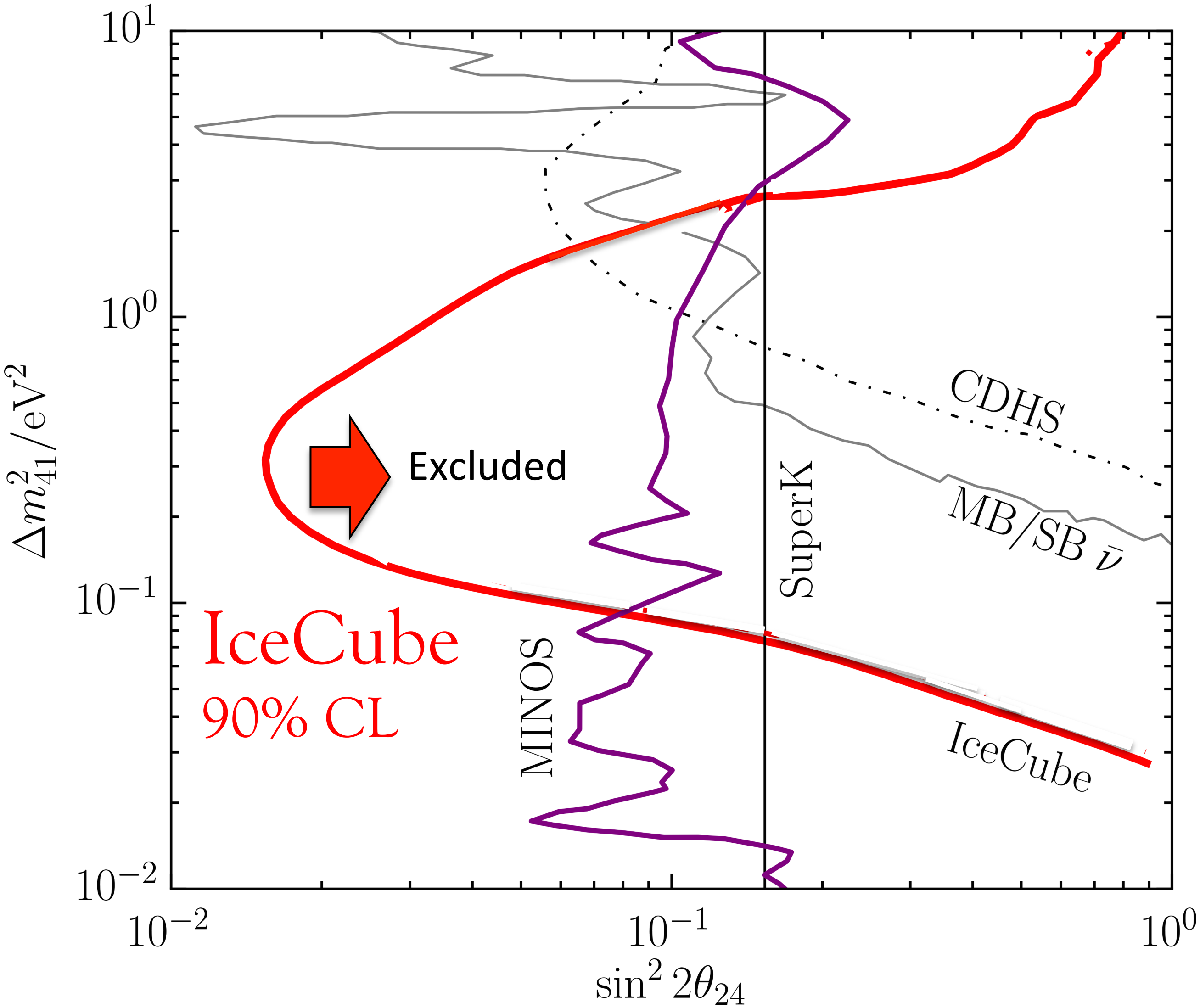
$$\chi^2_{\mathrm{null}} : 359.15 \quad (315\ \mathrm{dof})$$

$$\Delta\chi^2 : 52.34 \quad (3\ \mathrm{dof})$$

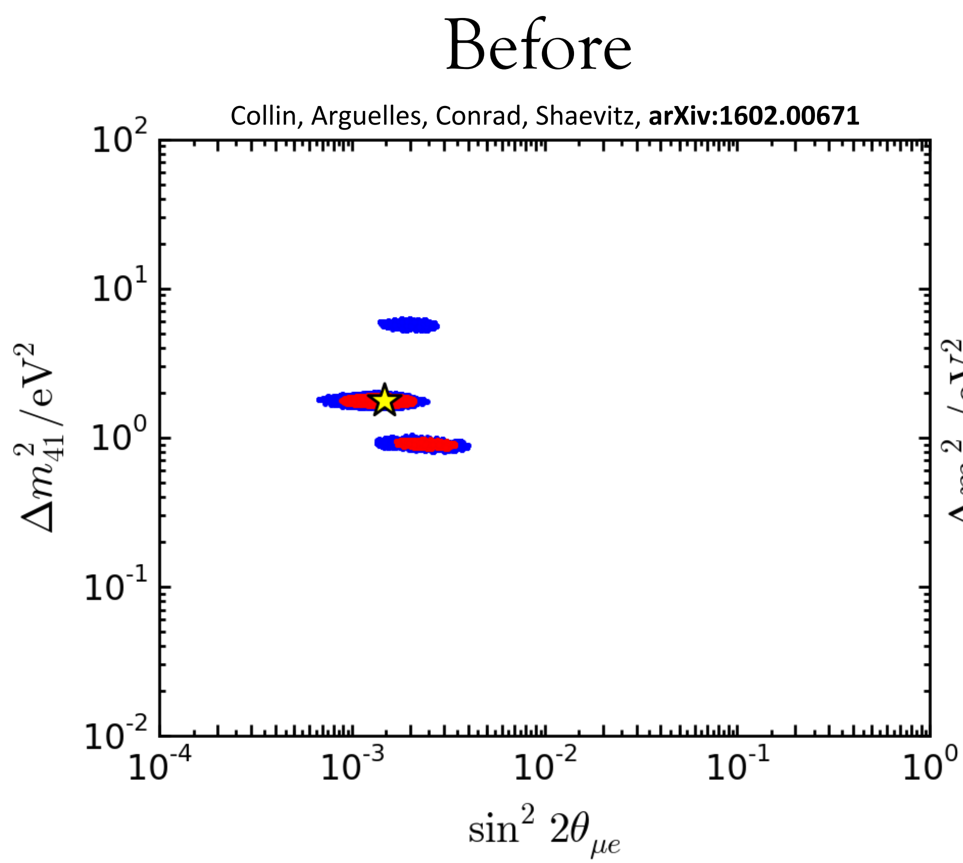
Data significantly favors a sterile model compared to an all-background model

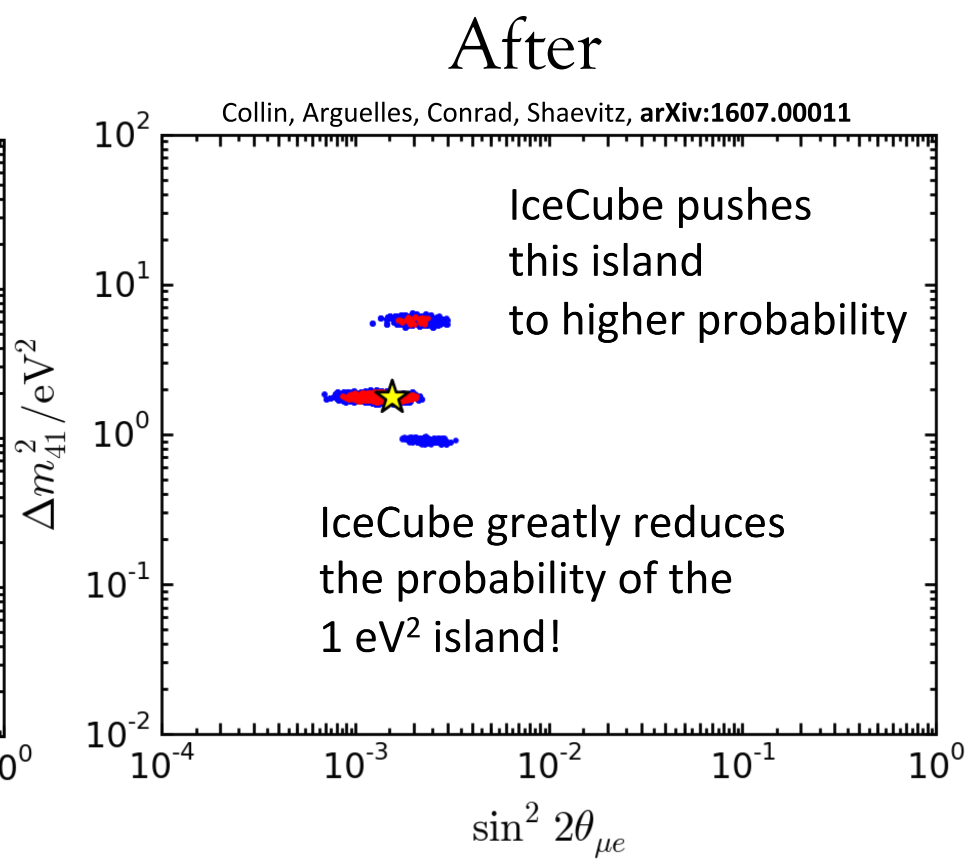
We have expanded to include the new IceCube limit

(presented by C. Arguelles, this session)



Global Fit Results





Most future experiments are optimized for 1 eV^2 and are less optimal for higher Δm^2 values…

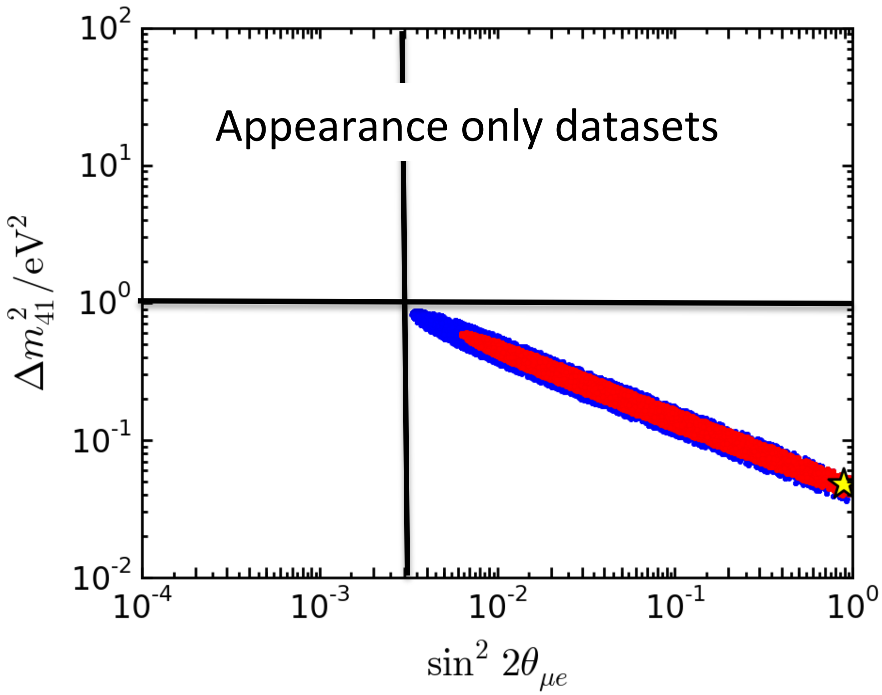
In these fits,
The sterile model is a huge improvement over the "null model"

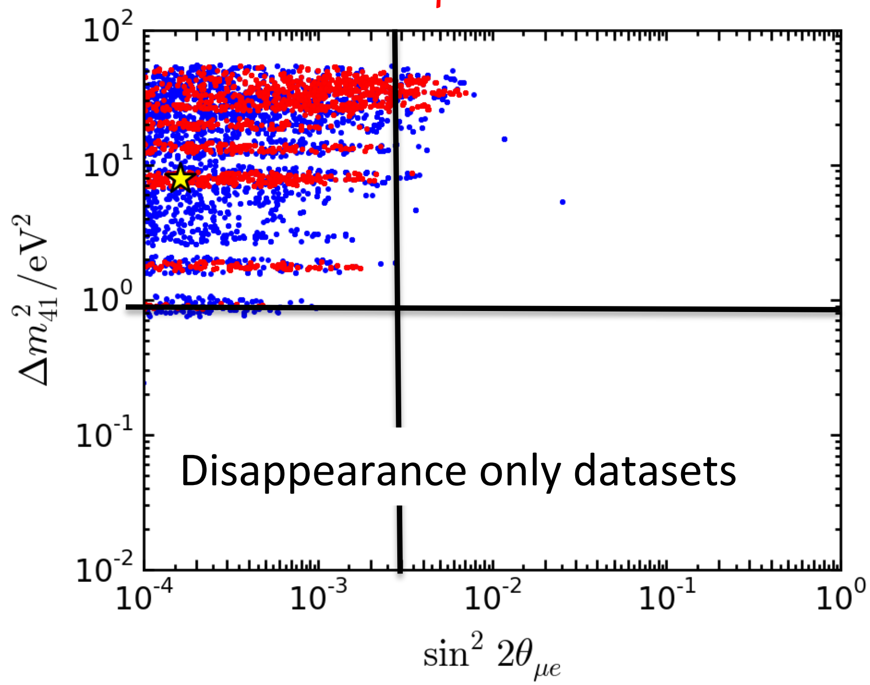
$$\Delta\chi^2/\Delta dof=52/3$$

So why isn't the matter decided???

When you divide the data set in 1/2, and fit the two halves separately, you end up with disagreeing "favored regions"
The classic example: appearance vs. disappearance...

Happens for other ways you cut the data too!





The global region is in an area of improbable overlap when two data sub-sets are fit separately

Signal is enclosed at:
Red: >90% CL
Blue: >99% CL

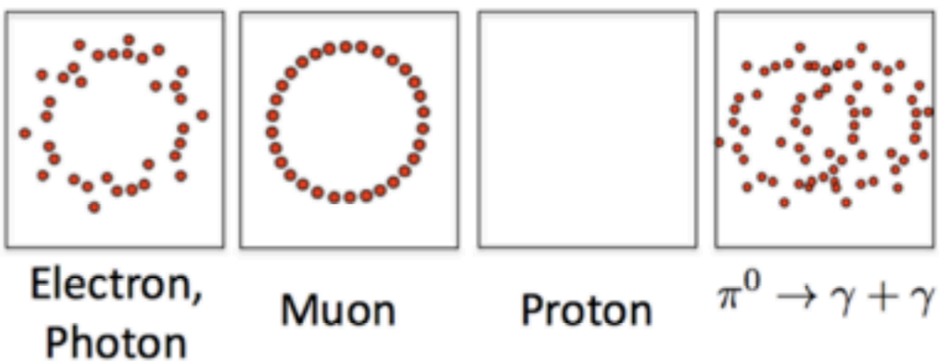
Yes, sterile fit is a big improvement, but something is odd…

"Tension" will happen if one or more data sets has a "problem" and so doesn't fit the model.

Possibility: One or more experiments suffer from
an unknown systematic effect.
→ MiniBooNE?

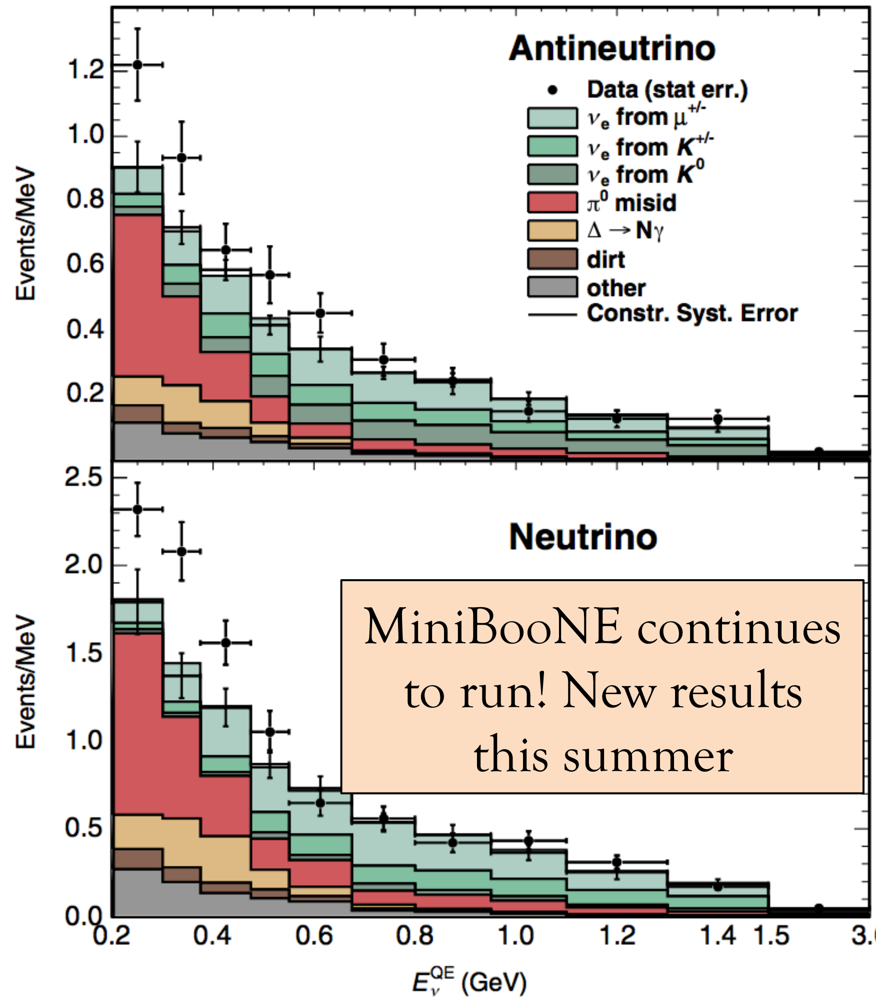
Removing MiniBooNE neutrino result (not antineutrinos) results in a big improvement in tension

- MiniBooNE could only observe Cherenkov rings.



Can we do better?

Major drive for a MicroBooNE result soon! See talk by Adrien Hourlier, Tuesday afternoon



MiniBooNE continues to run! New results this summer

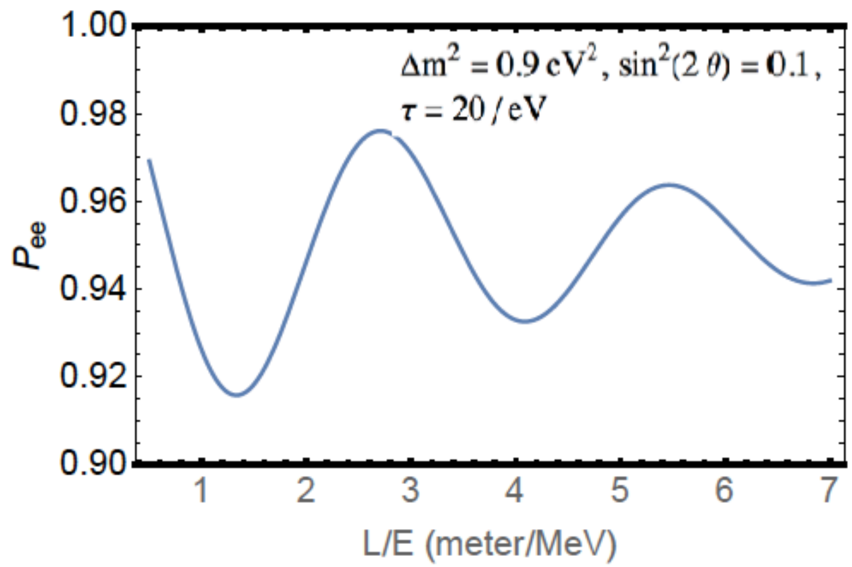
"Tension" will happen if one or more data sets has a "problem" and so doesn't fit the model.

Alternative Possibility: More complex physics.
People have explored 3+2 and 3+3 in the past.
Our fitting group is looking at 3+1+decay
(A natural extension w/ fewer additional parameters then adding extra steriles)

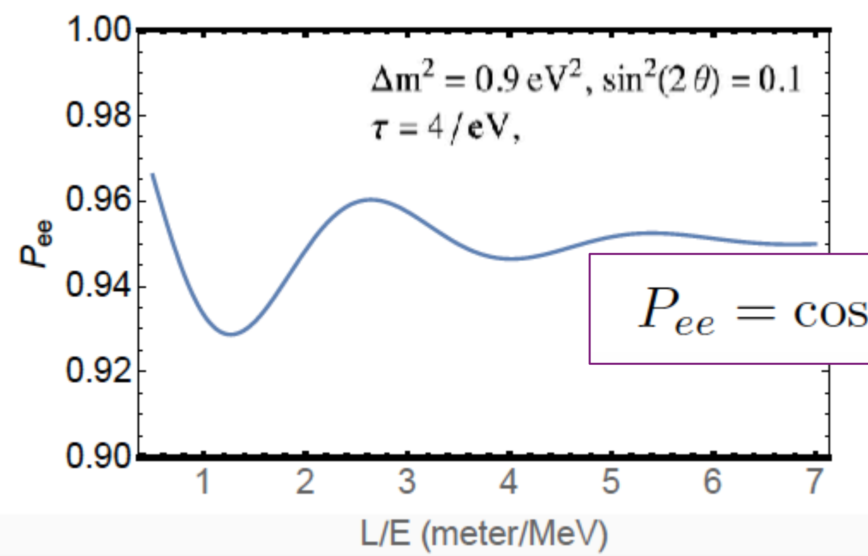
→ this idea was introduced in the talk from C. Arguelles.

$$P_{ee} = \cos^4\theta + \sin^4\theta e^{-\frac{mL}{\tau E}} + \frac{1}{2}\sin^2(2\theta)e^{-\frac{mL}{2\tau E}}\cos\left(\frac{\Delta m^2 L}{2E}\right)$$

Depending on the lifetime, **τ**, the model loses the high Δm^2 sterile signal, because the ν_4 decays away.



Can affect detectors with L/E~3 m/MeV!



$$P_{ee} = \cos^4\theta$$

What would be the consequence?

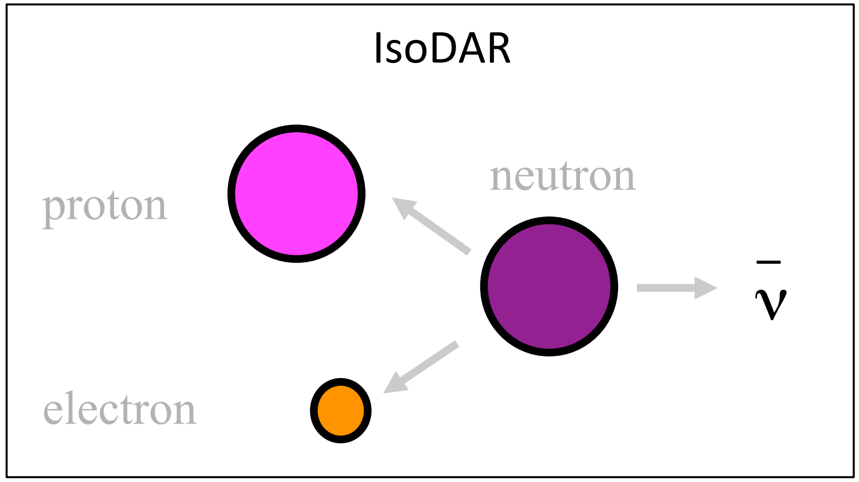
Reactor experiments may see a deficit with respect to theory
but not oscillations (since L/E~ 3 m/MeV)

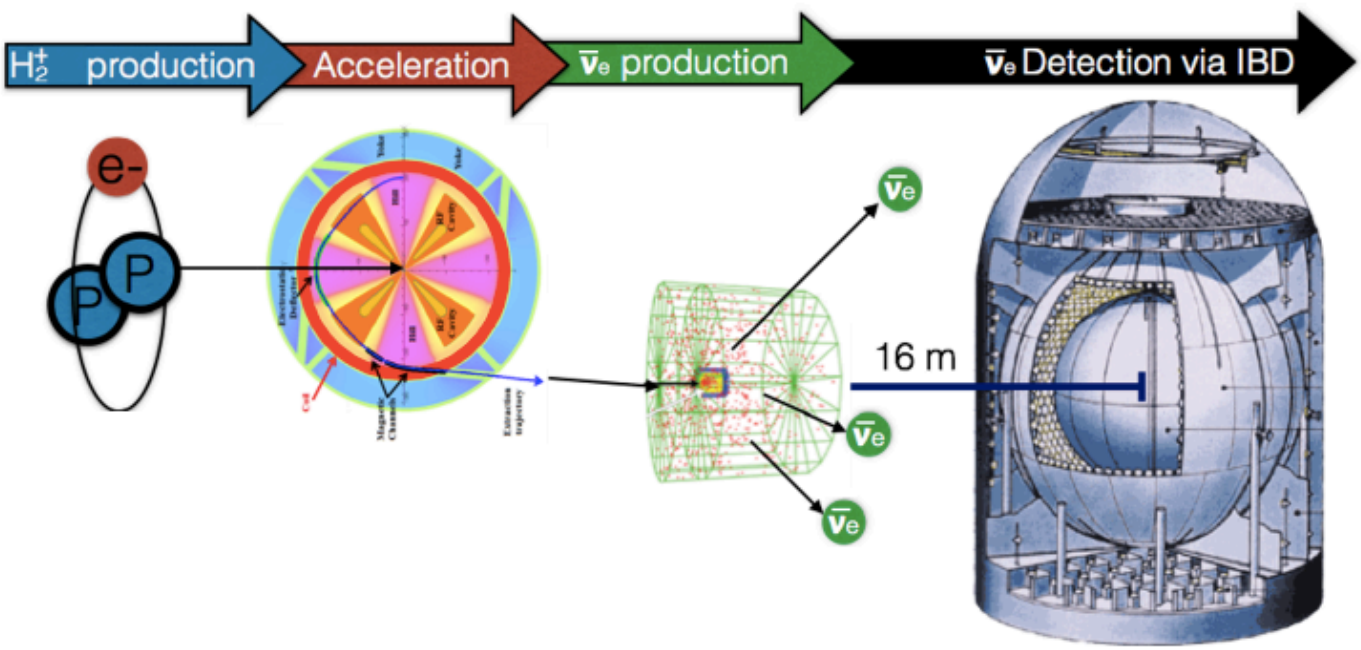
There will be a relatively small effect in LSND
and MiniBooNE, at low Δm^2

The muon-disappearance limits will be weaker
(as in the IceCube case) due to regeneration.

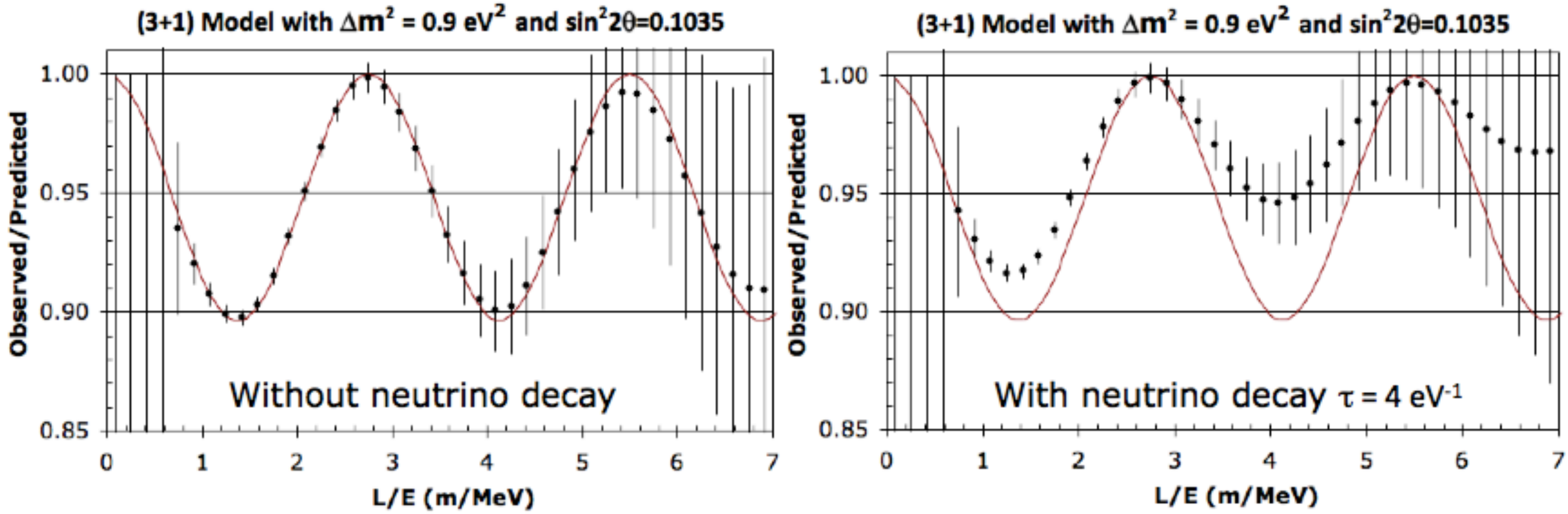
Looks interesting! Global Fits Soon!

The Smoking Gun for this Model: The signal in IsoDAR





Comparison: 3+1 without and with decay



This shows the power of experiments that can trace the oscillation wave to high precision!

Conclusion:

Even with the very powerful new IceCube null result, allowed 3+1 regions remain.

Likely more complicated physics than 3+1

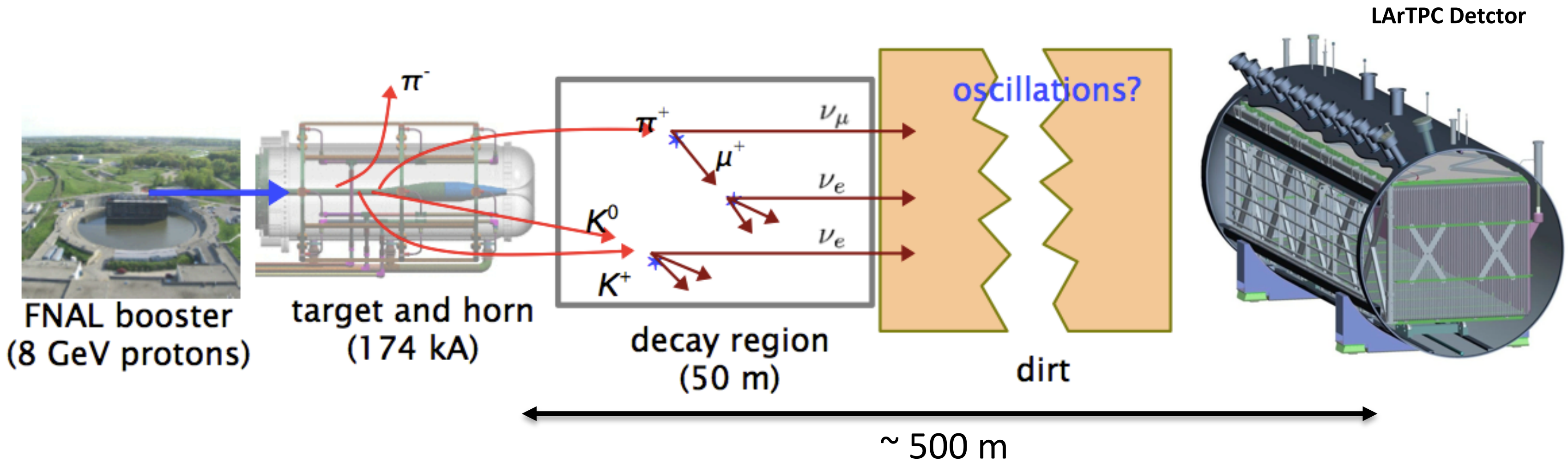
Systematic Effects? → MicroBooNE

Additional sterile neutrinos

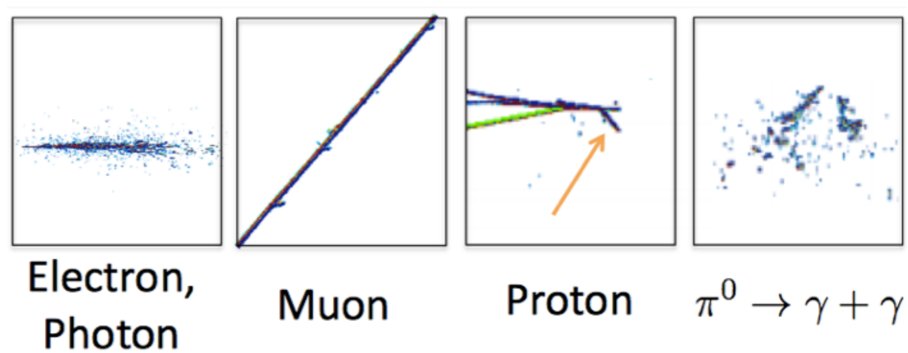
Other options, like decay.

In the end, we need experiments that trace the wave, and have low systematics.

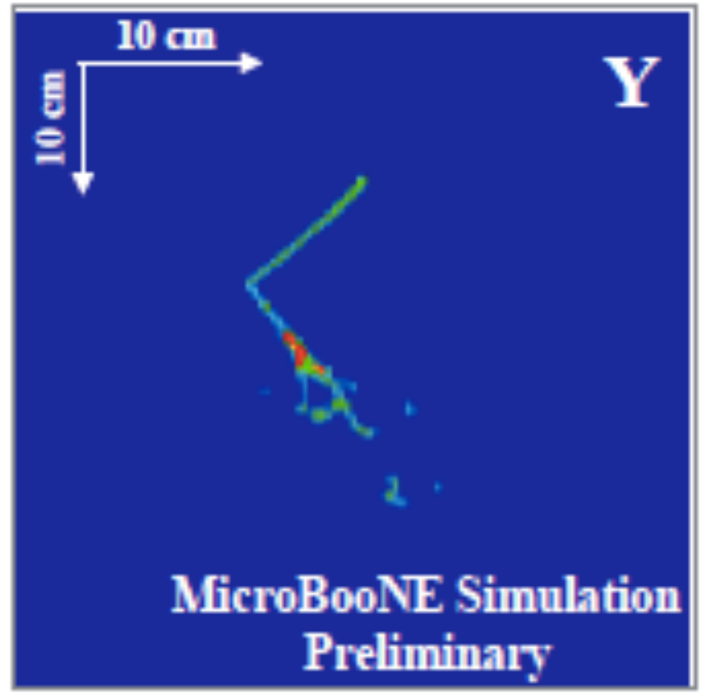
Back Up Slides



- MicroBooNE --a liquid Argon time projection chamber.
  - Much better resolution.
    - Can distinguish neutral pions from electrons well.
  - But lower statistics.



The excellent reconstruction should "kill off" the photon backgrounds, leaving only "intrinsic" ν_e background.

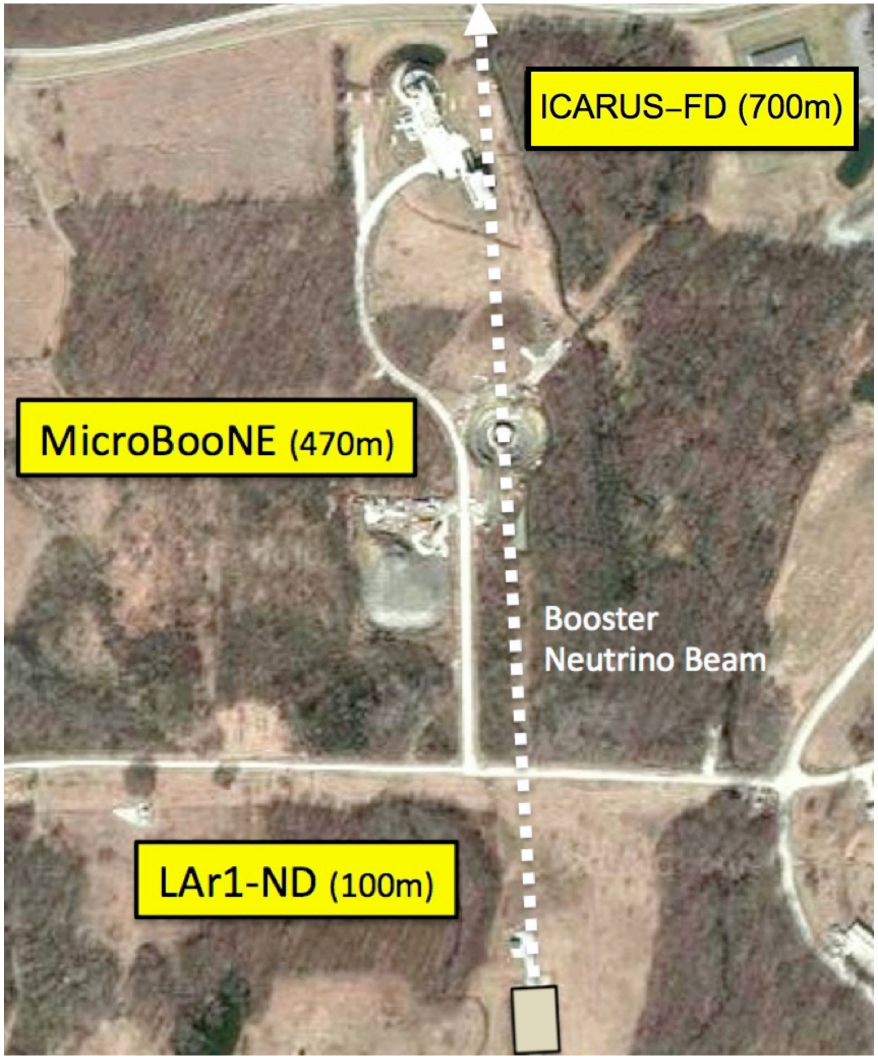


MicroBooNE will decisively show if the MiniBooNE anomaly is ν_e

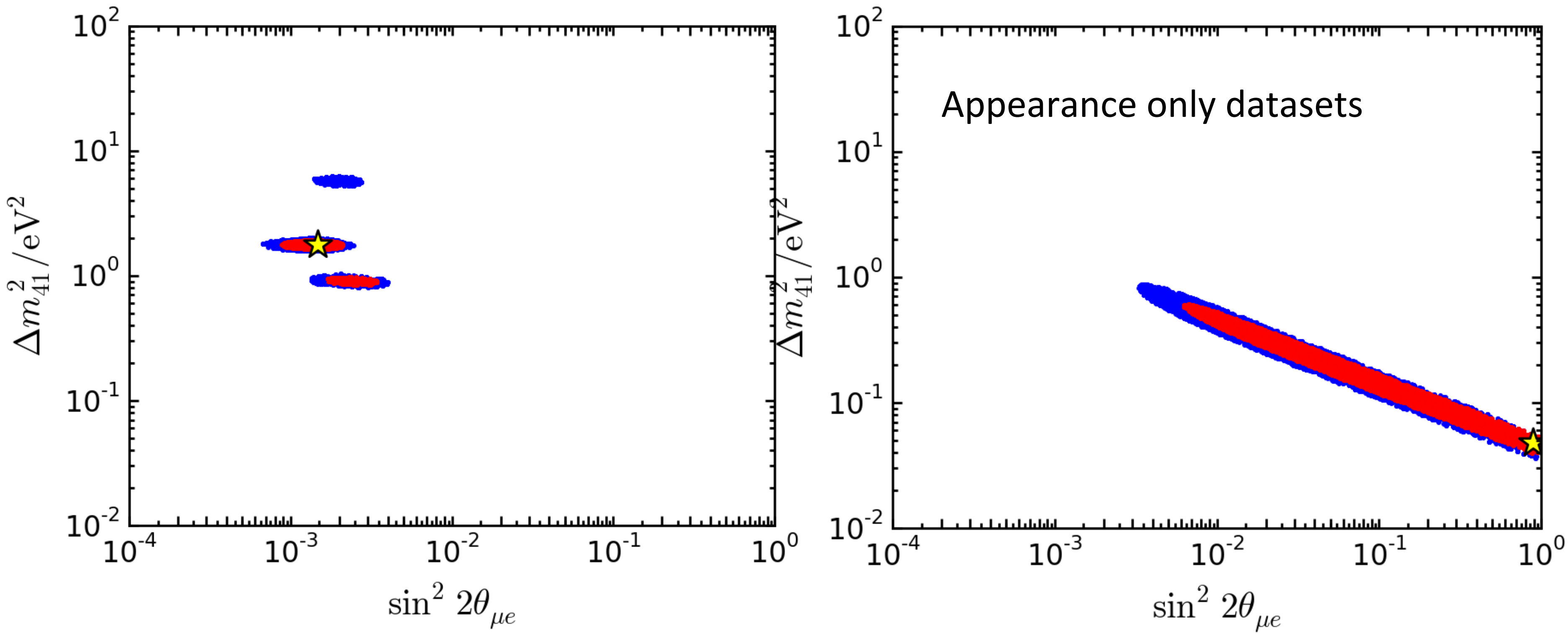
Big Implications

Either…
A signal is observed of
same size or somewhat smaller
than MiniBooNE's:
Strongly favors a 3+1 model.

Or…
Result is consistent with null:
Very hard to explain in a 3+1 model.
&
The FNAL SBN Program's
premiere physics result is ruled out!



The “three islands” are not on the Appearance-only plot. Why do they “pop out” of the global fit?



The range outside of the blue in the appearance region is still allowed, just not at >90% CL. Appearance does have an effect in the region of the islands at > 1σ

Then disappearance signals get effectively “stacked on top” in the global fit, such that these islands cross the >90% CL