COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Overview and Status of Short Baseline Neutrino Anomalies

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Columbia University

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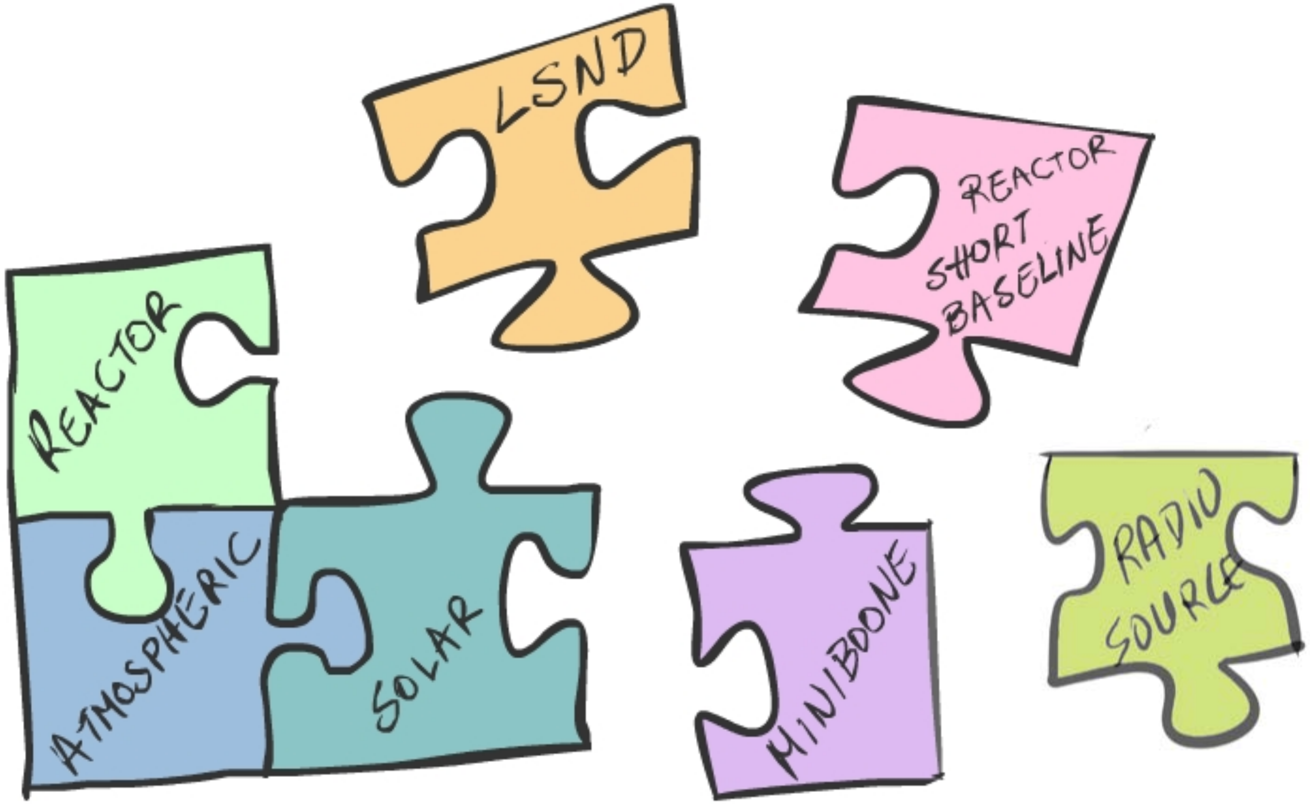
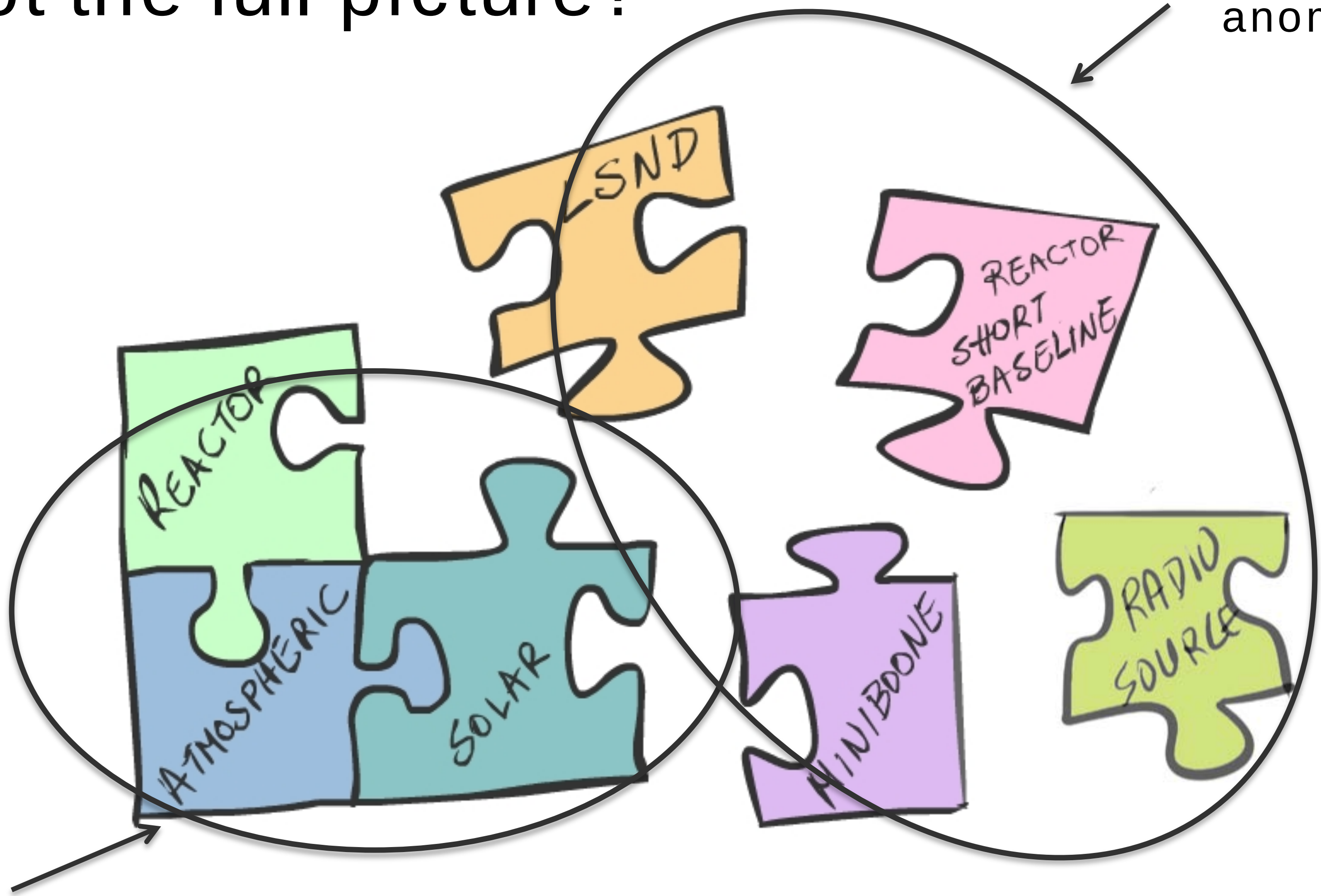
Livermore, California

Three-neutrino oscillation:
Not the full picture?



Three-neutrino oscillation: Not the full picture?

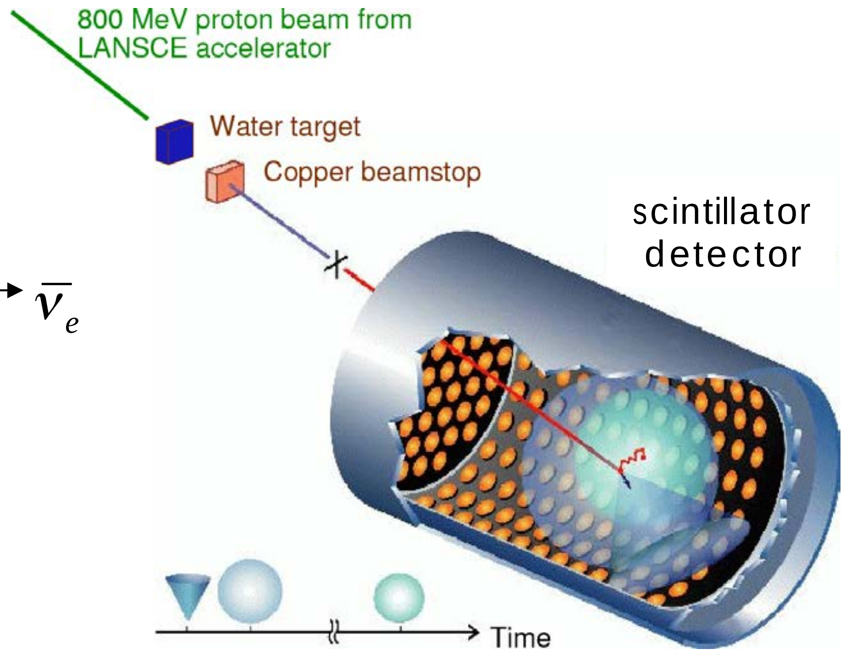
"short-baseline" anomalies

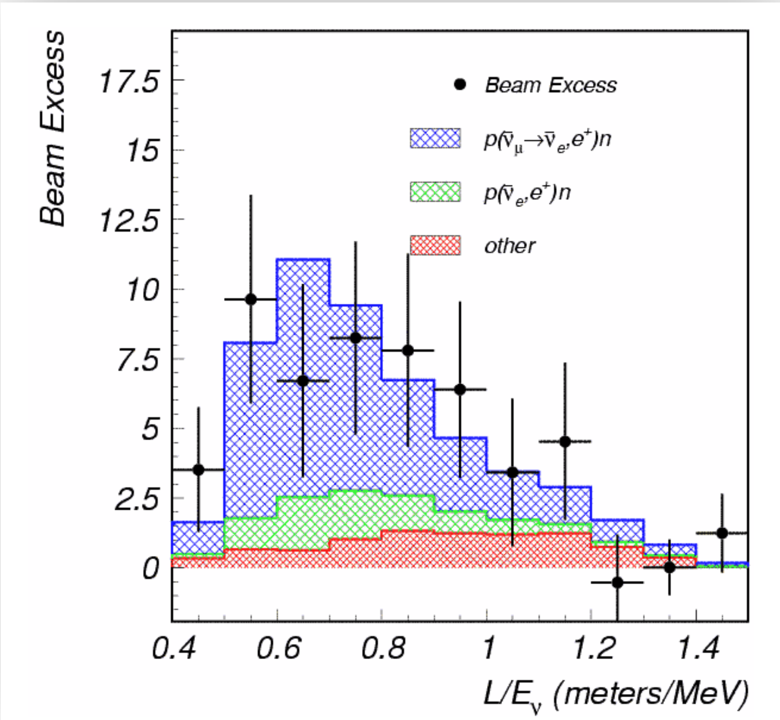


"long- and medium-baseline"

μ^+ decay-at-rest experiment:

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





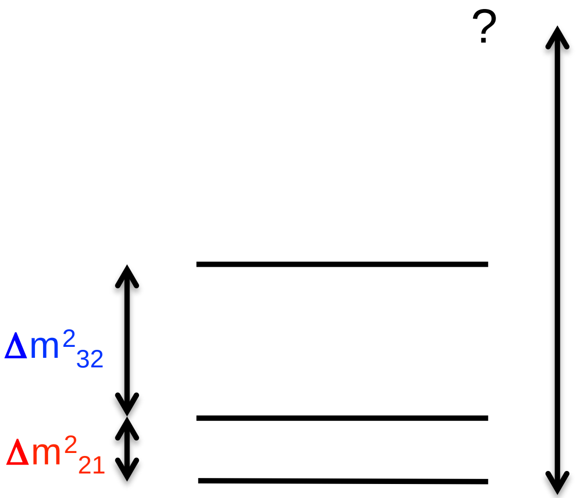
[C. Athanassopoulos et al., Phys. Rev. Lett. 75, 2650 (1995); 81,1774(1998); A.Aguilar et al., Phys. Rev. D64, 112007(2001)]

Observed excess of $\bar{\nu}_e$ described by oscillation probability:
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = (0.264 \pm 0.067 \pm 0.045)$ %

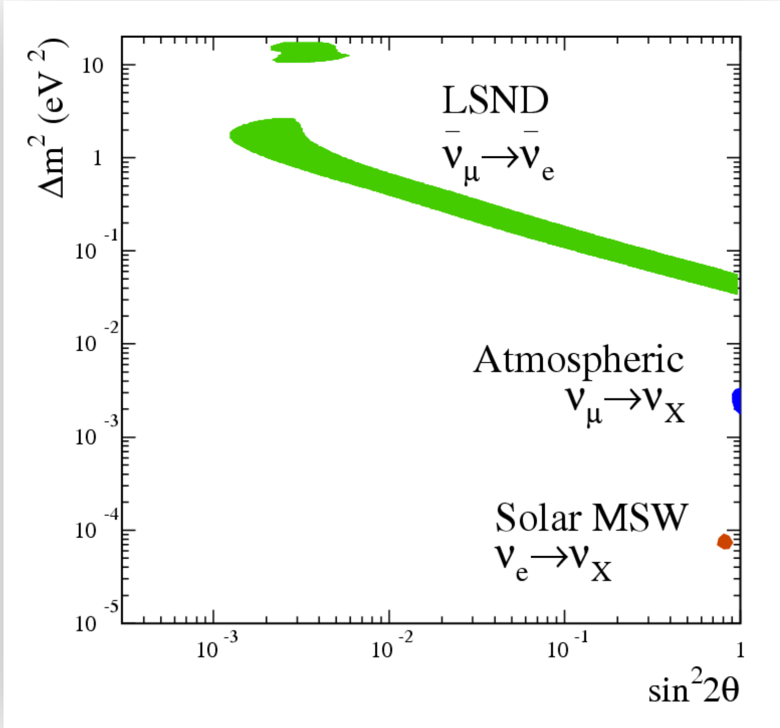
(3.8σ evidence)

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

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

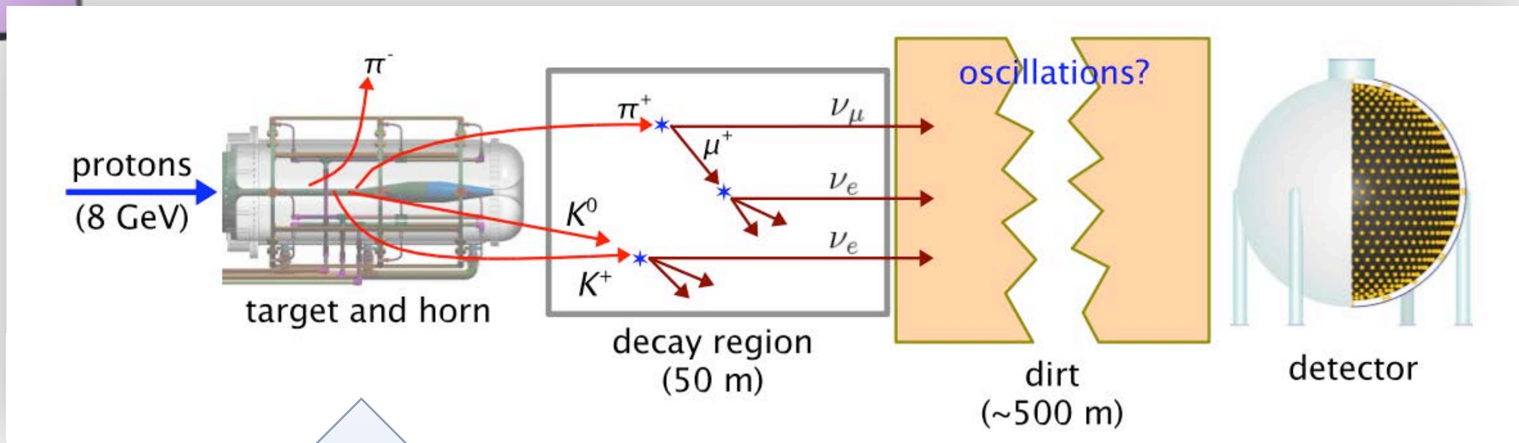


$\Delta m^2_{LSND} >> \Delta m^2_{21} + \Delta m^2_{32}$



Anomalous signature: requires at least four neutrinos to accommodate a third, independent Δm^2!

Follow-up to LSND experiment: MiniBooNE



magnetic field polarity selects ν or $\bar{\nu}$

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$\overset{?}{\rightarrow} \nu_e$

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$$

$\overset{?}{\rightarrow} \bar{\nu}_e$

Similar L/E as LSND

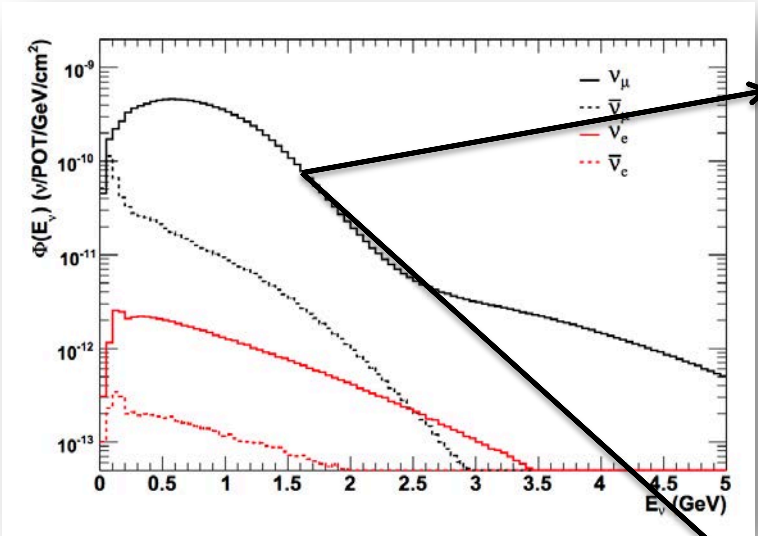
but

Different energy, beam and detector systematics

Different event signatures and backgrounds (Cherenkov detector)

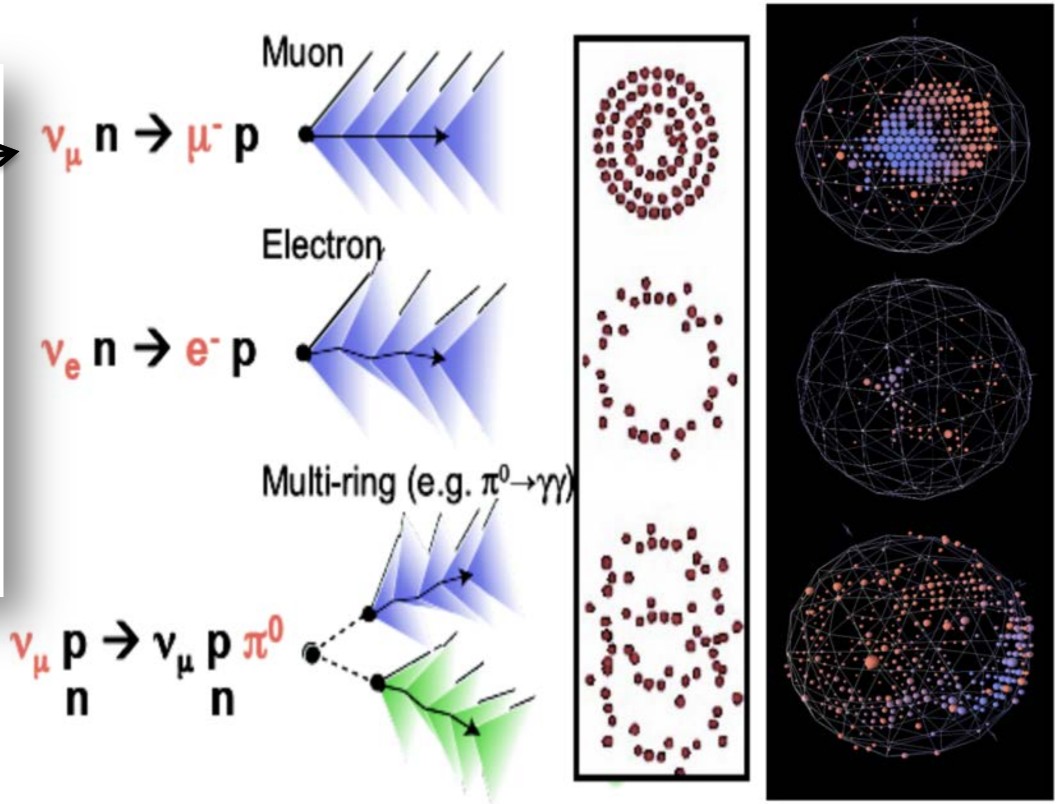
Follow-up to LSND experiment: MiniBooNE

MiniBooNE flux (neutrino mode):



[Phys. Rev. D79 (2009) 072002]

Three main event signatures:



Cherenkov ring topology provides PID

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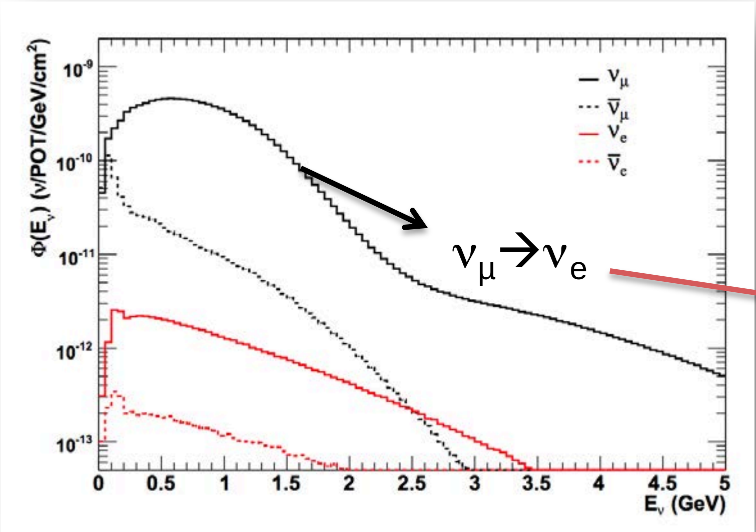
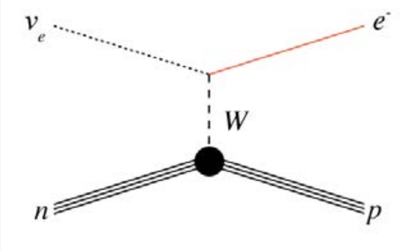


[Phys. Rev. D79 (2009) 072002]

ν_e CC QE scattering



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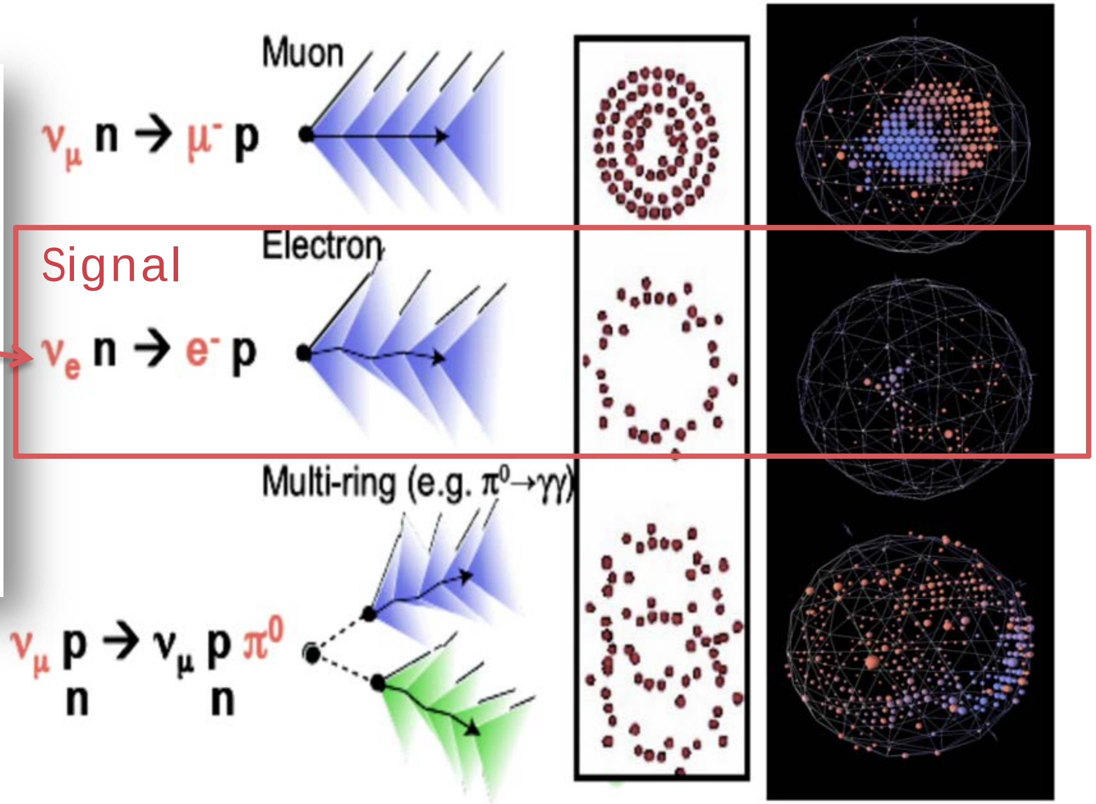

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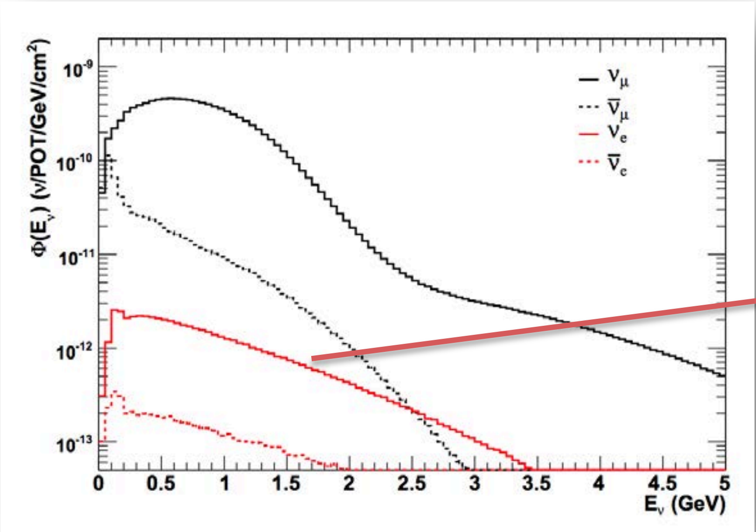

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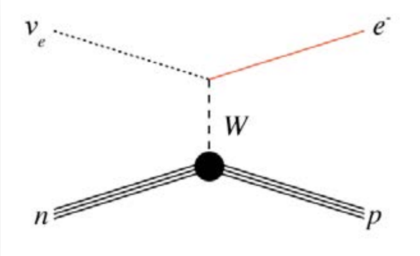

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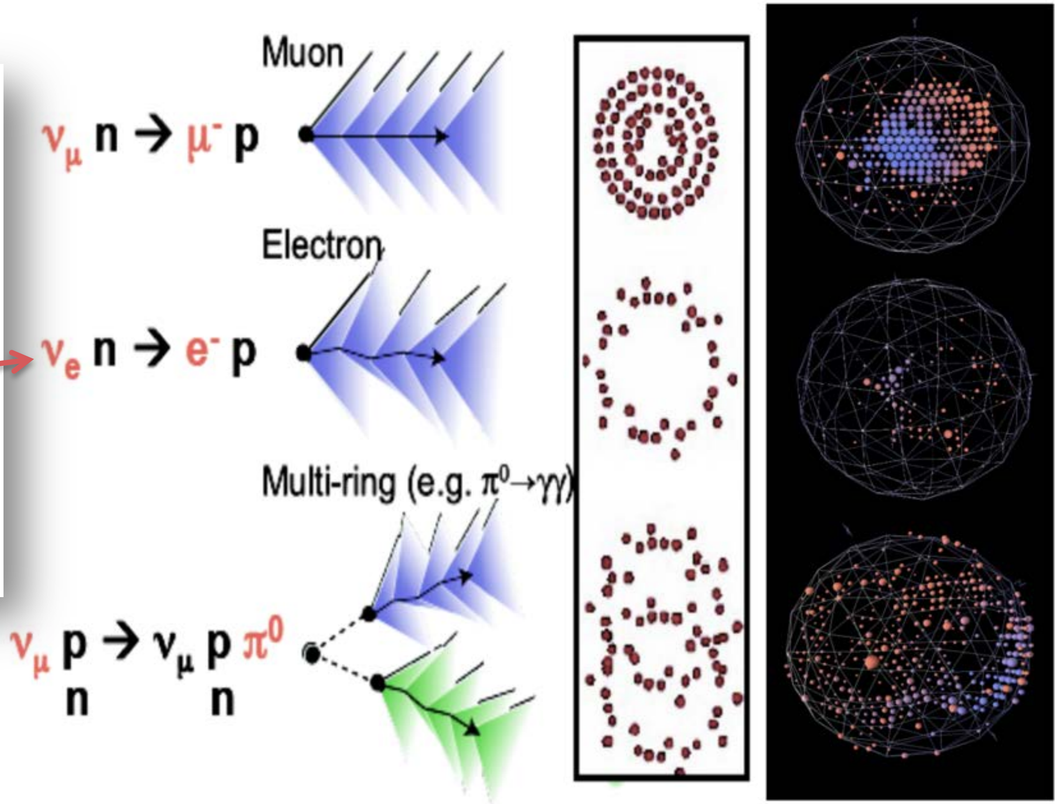
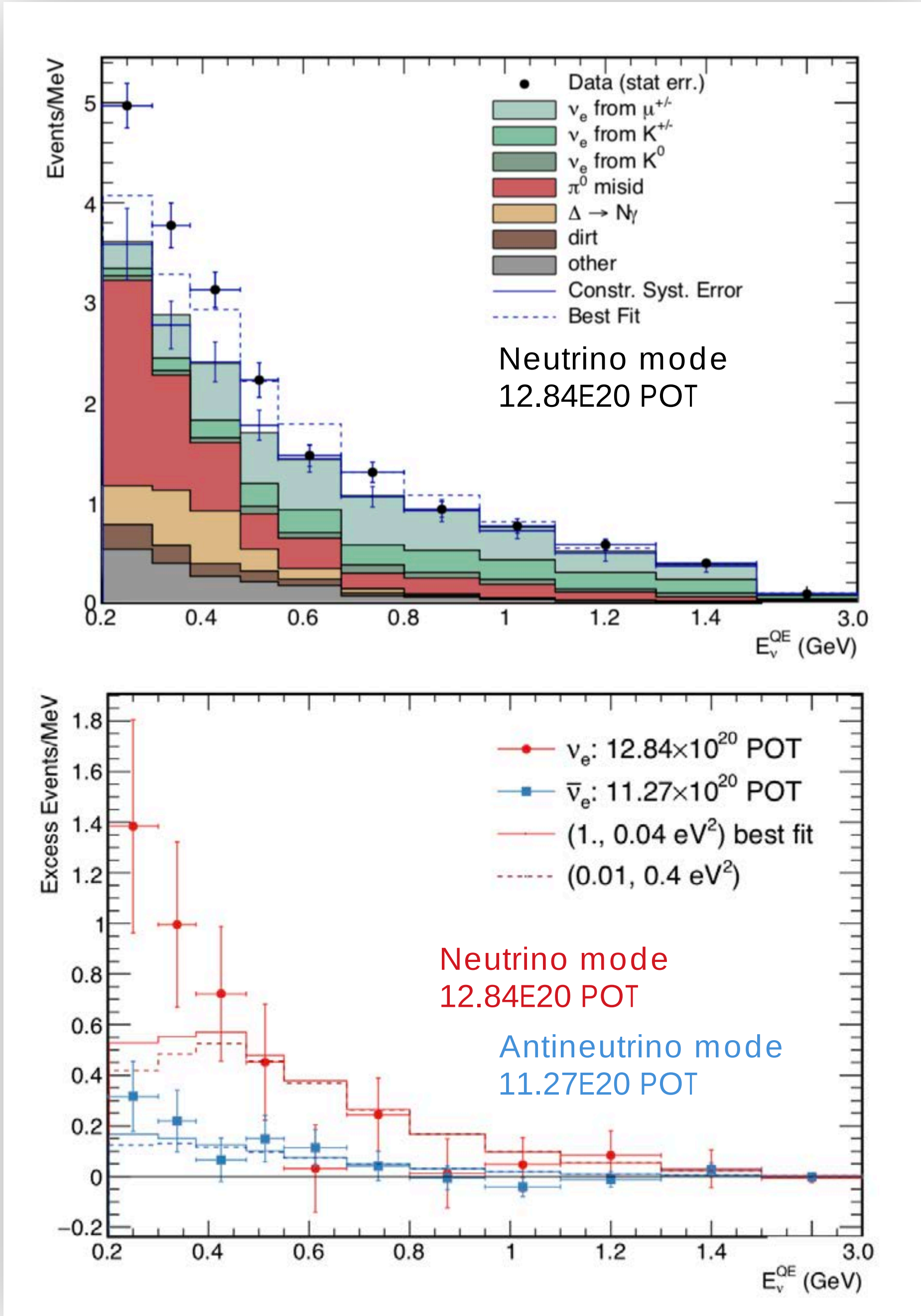


Cherenkov ring topology provides PID

MiniBooNE
2018 ν_e appearance results:

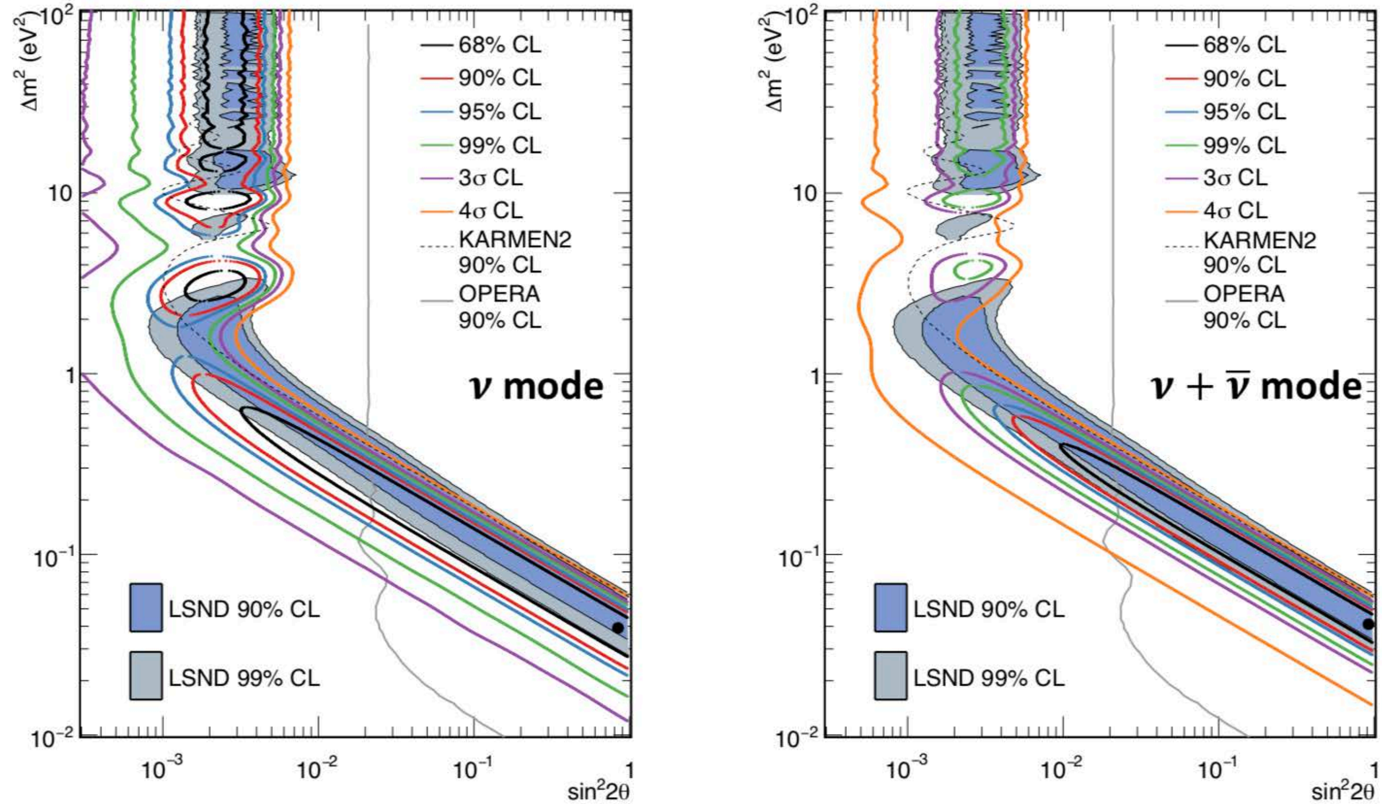


Total neutrino mode excess (12.84E20 POT):
381.2 +/- 85.2 excess events (4.5σ)
Best-fit χ^2-prob = 15%

Combined with antineutrino mode:
460.5 +/- 95.8 excess events (4.8σ)
Best-fit χ^2-prob = 20%

Neutrino mode (12.84E20 POT)

Neutrino + antineutrino combined



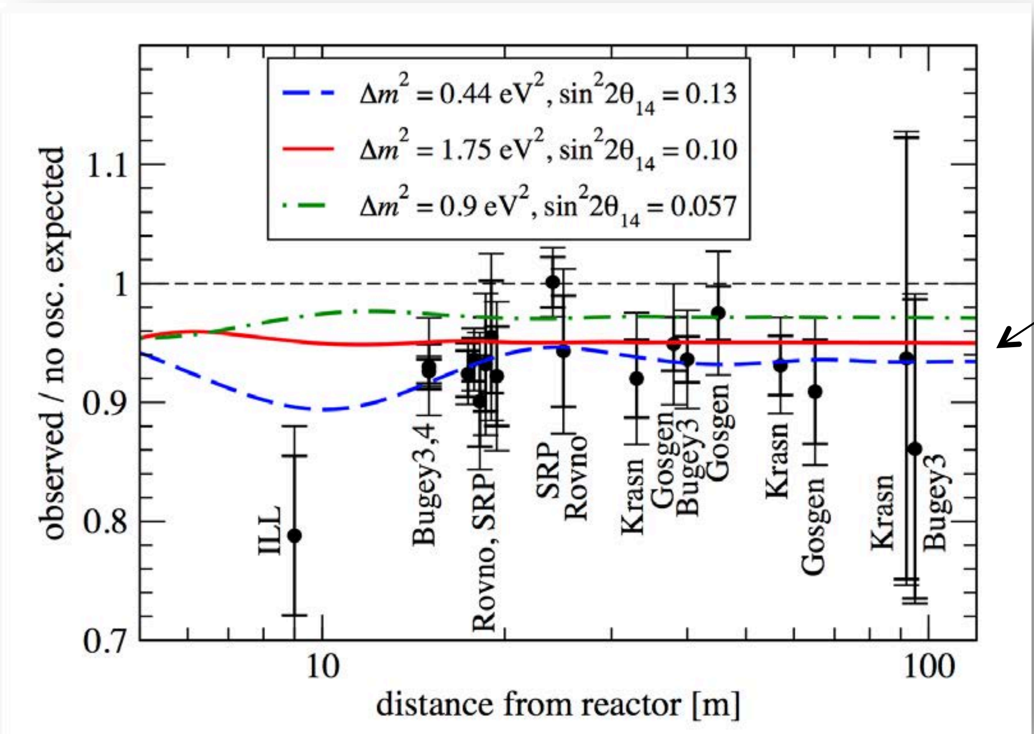
$(\Delta m^2, \sin^2 2\theta) = (0.037\ \text{eV}^2, 0.958)$
$\chi^2/ndf = 10.0/6.6$ (prob = 15.4%)

$(\Delta m^2, \sin^2 2\theta) = (0.041\ \text{eV}^2, 0.958)$
$\chi^2/ndf = 19.5/15.4$ (prob = 20.1%)

Neutrino and antineutrino fits are consistent with LSND allowed regions and high-Δm^2 oscillation interpretation

"Reactor Anomaly"

Measured $\overline{\nu}_e$ flux from reactors is 3.5% (~3σ) lower than expected from predictions
→ oscillation of $\overline{\nu}_e$ into $\overline{\nu}_s$?



[Mueller et al. 1101.2663, Huber 1106.0687]

Anomalous deficit can be interpreted as ν_e disappearance at high-Δm^2

The effect came about after re-analyses of detailed physics involved in nuclear beta-decay of fission fragments in reactors.

See talks by Anna Hayes, Alejandro Sonzogni, Anthony Onillon

"Reactor Anomaly"

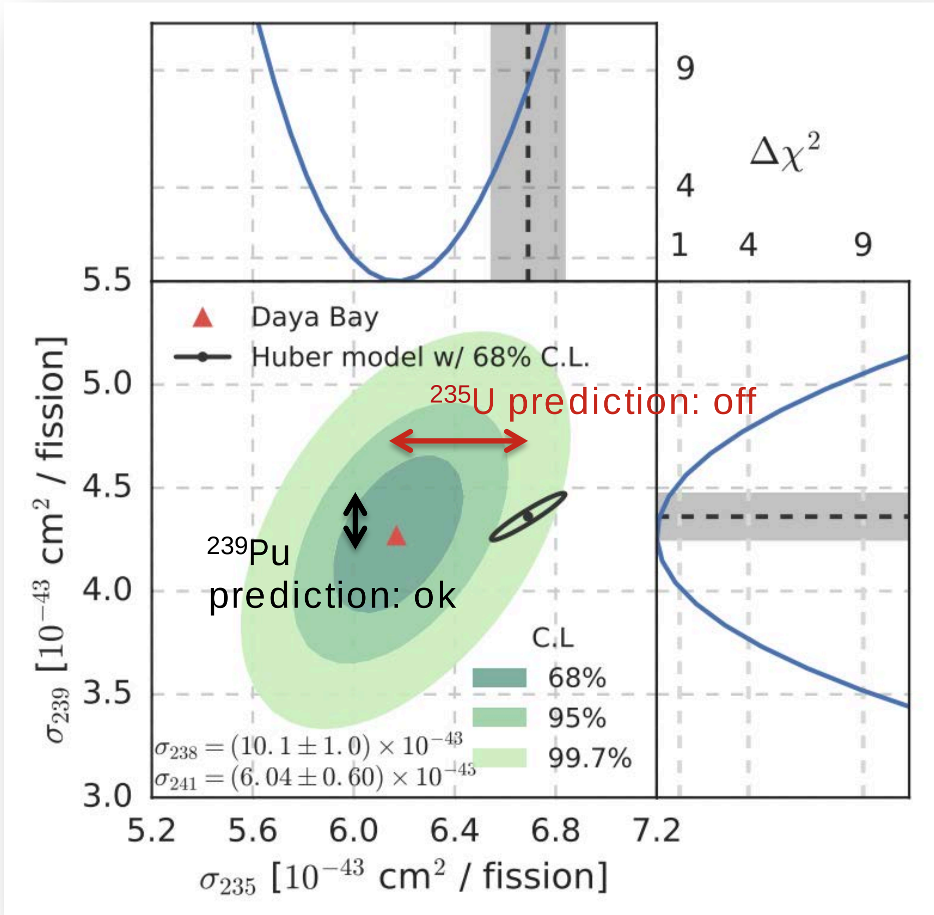
Predicting reactor $\overline{\nu}_e$ fluxes:

- Use measured β spectra from ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu fission
- Convert to $\overline{\nu}_e$ spectrum
- For single β decay, $E_\nu = Q - E_e$
- Thousands of decay branches, many not precisely known
- Use (incomplete) information from nuclear data tables…
- … complemented by a fit to effective decay branches

Anomaly has been investigated as a flux misinterpretation:
e.g. Do we see an isotope-dependent deficit? (Sterile neutrinos would lead to isotope-independent deficit.)

[e.g., Daya Bay PRL 118, 251801 (2017)]

Daya Bay
isotopic evolution
measurements:
Necessity for further flux
corrections.



But, no clear data preference
for “fit to free fluxes” over
“fixed fluxes with oscillations”

[Hernandez et al., arXiv:1709.04294]

[e.g., Daya Bay PRL 118, 251801 (2017)]

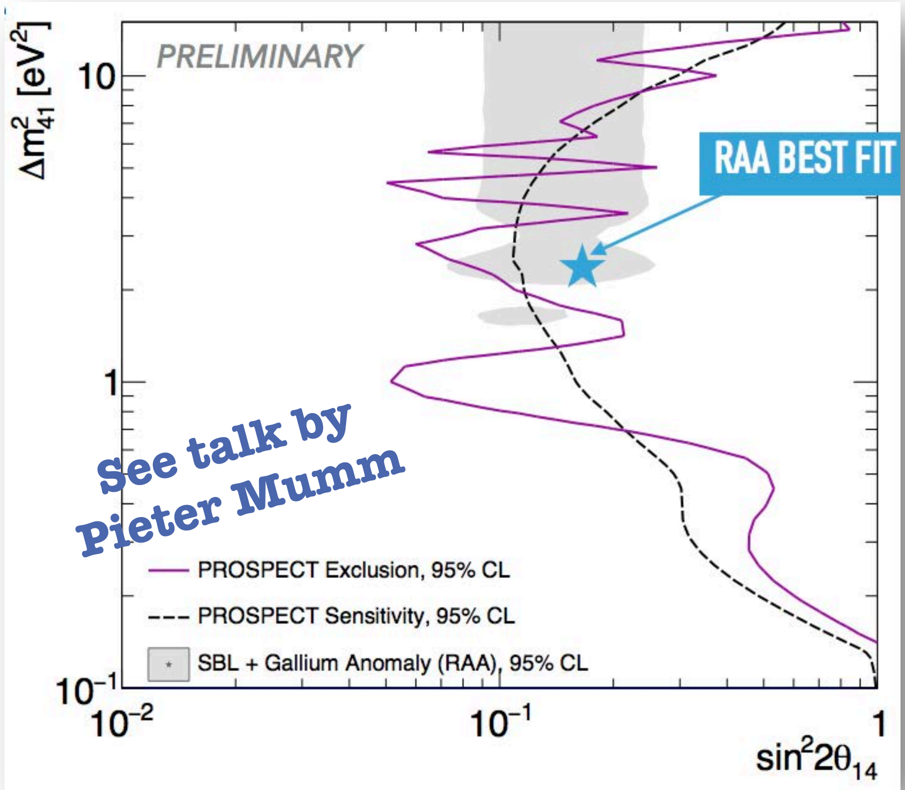
“Reactor Anomaly”

Multiple new results from SBL reactor experiments have been pouring in over the last couple of years...

but still not a clear picture of $\bar{\nu}_e$ disappearance

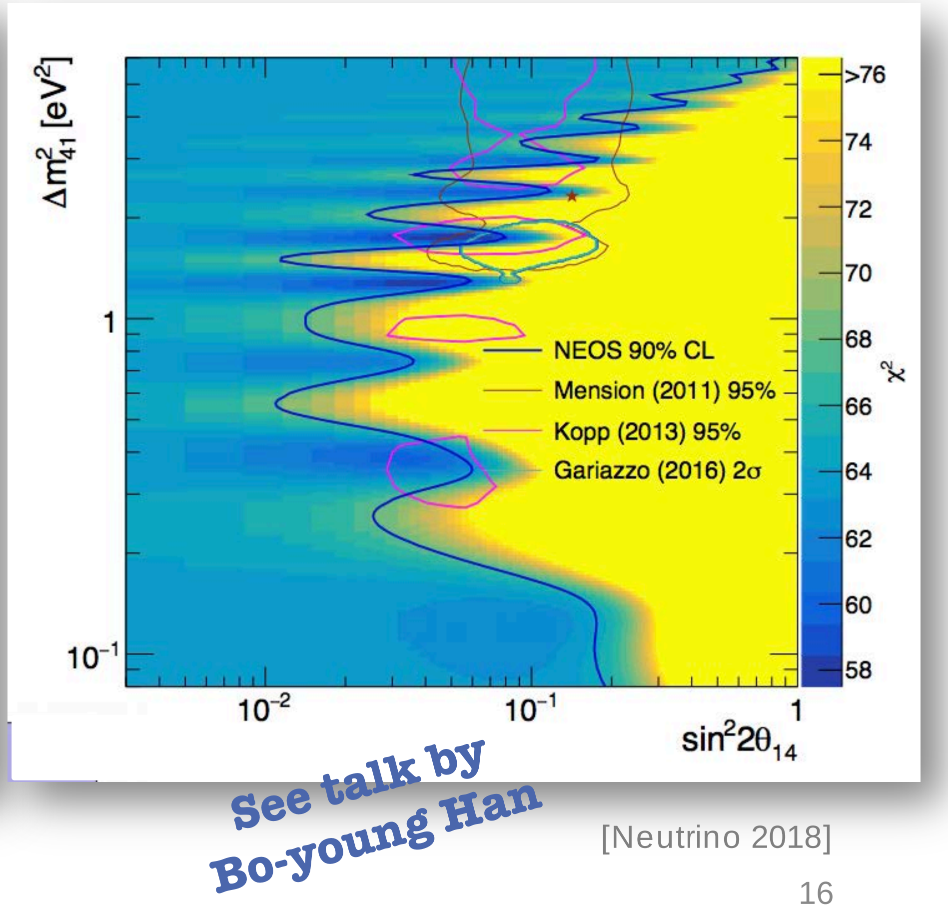
"Reactor Anomaly"

PROSPECT at High Flux Isotope Reactor:



[Neutrino 2018]

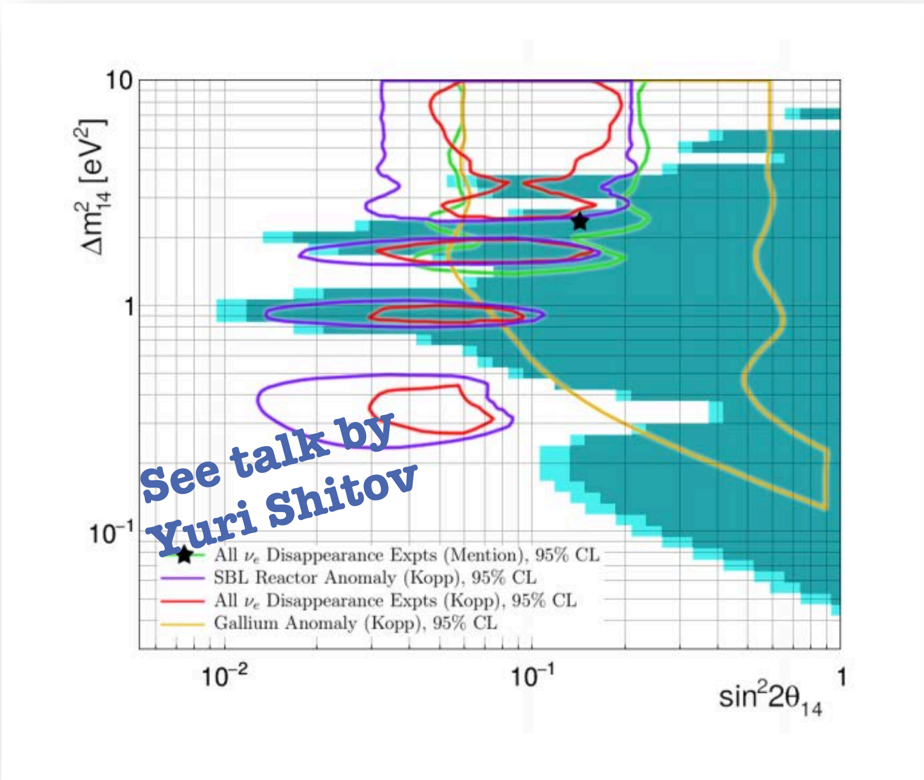
NEOS at Hanbit-5 Nuclear Reactor in Korea:



[Neutrino 2018]

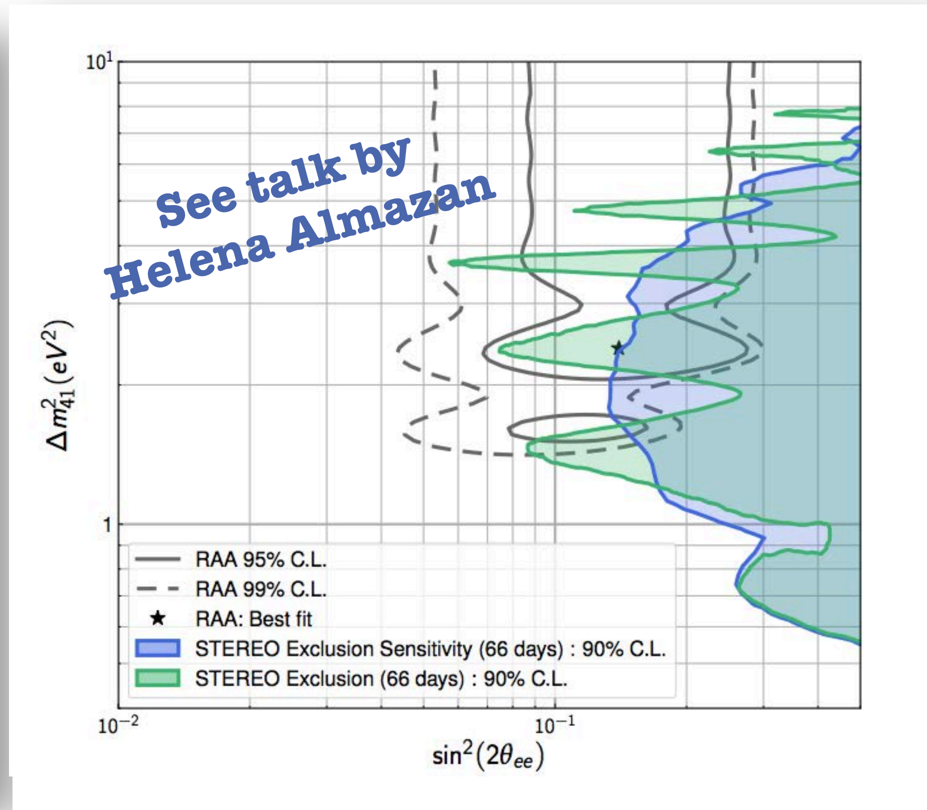
“Reactor Anomaly”

DANSS at Kalinin Nuclear Power Plant:



[https://arxiv.org/pdf/1804.04046.pdf]

STEREO at ILL:



[https://arxiv.org/pdf/1806.02096.pdf]

“Reactor Anomaly”

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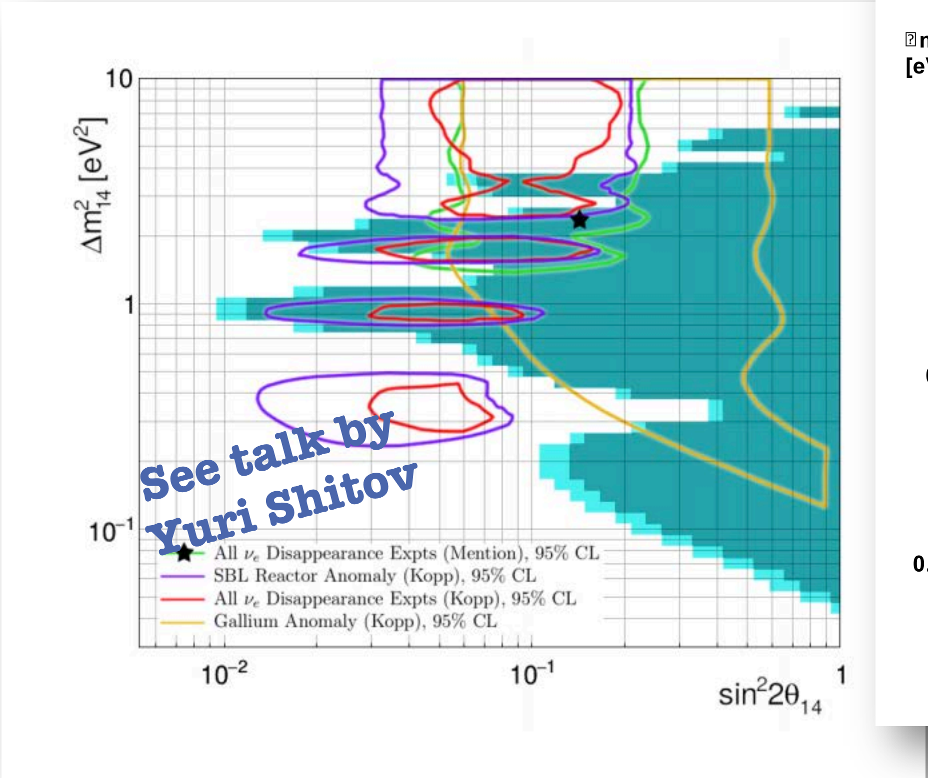
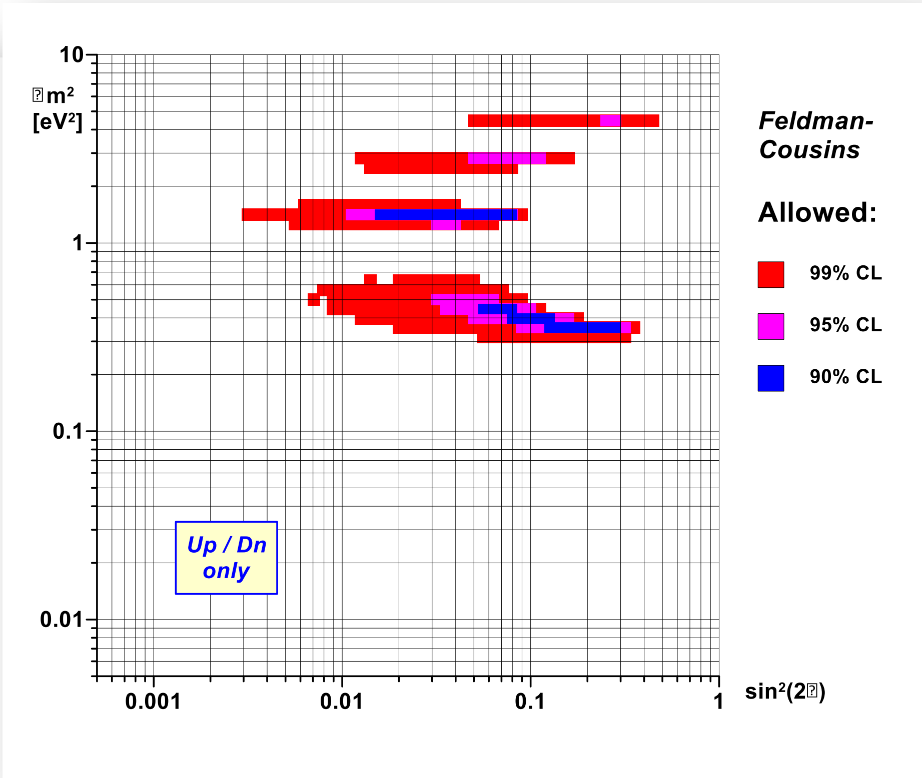


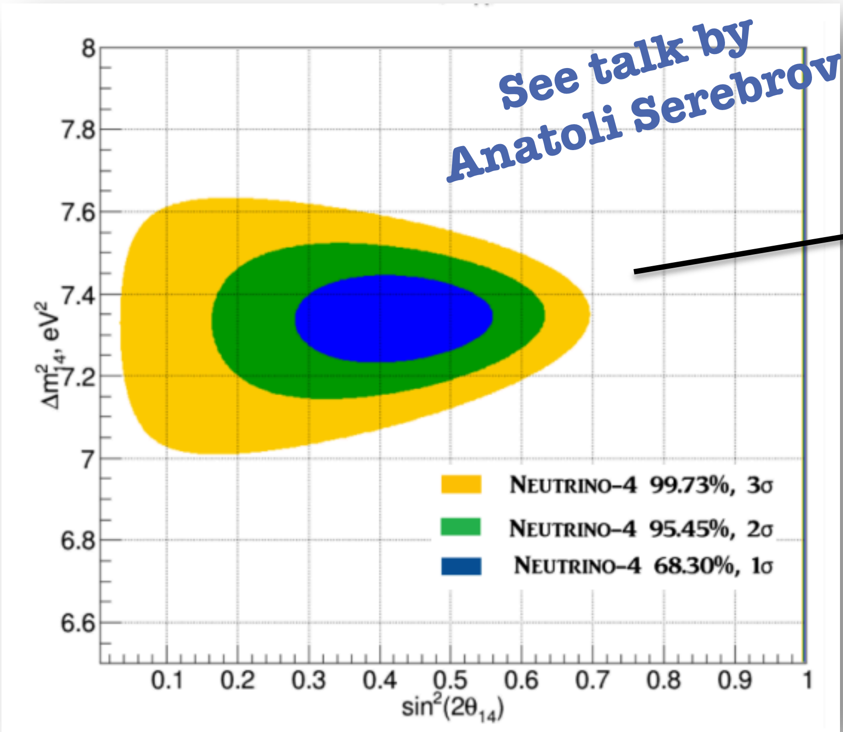
[https://arxiv.org/pdf/1804.04046.pdf]



[Neutrino 2018]

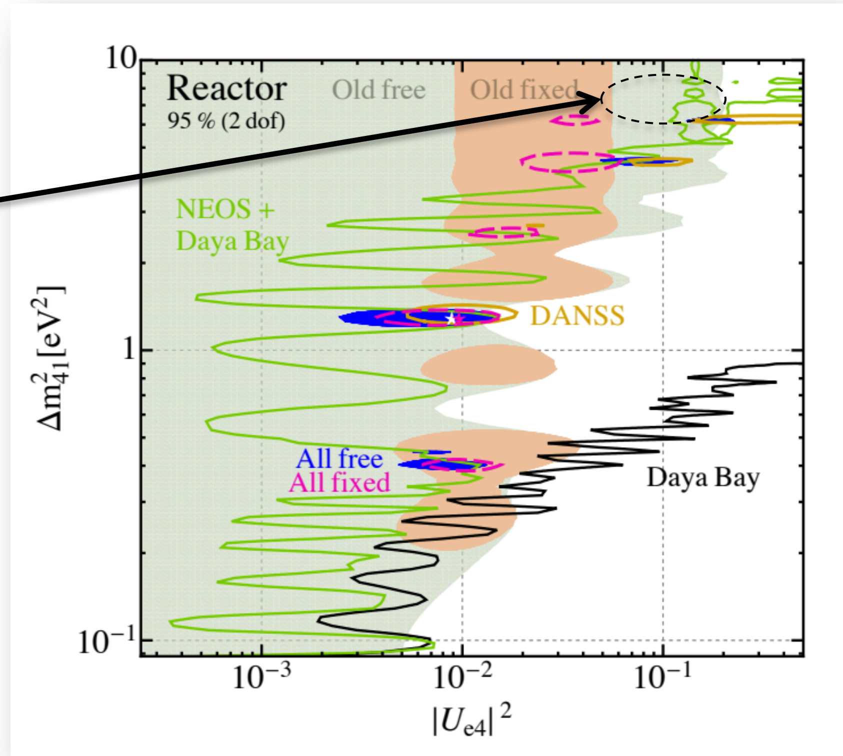
"Reactor Anomaly"

Neutrino-4 at SM-3 reactor reports a 3σ signal



[https://arxiv.org/pdf/1803.10661.pdf]

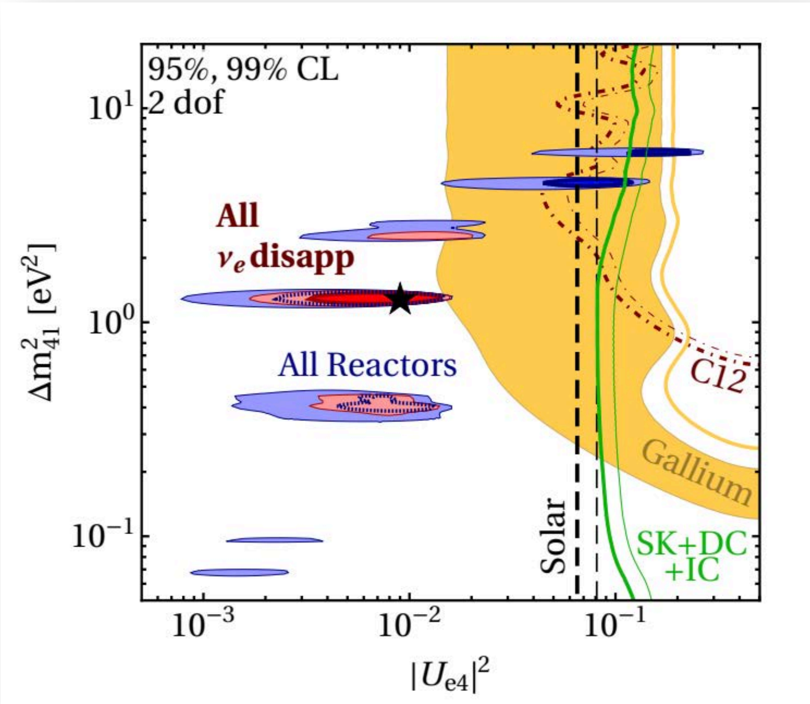
[M. Dentler, et al., JHEP 1808 (2018) 010]



Best fit excluded by PROSPECT at >95% CL [see talk by P. Mumm].

“Radioactive Source Anomalies”

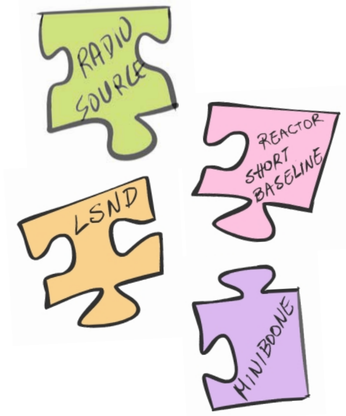
[M. Dentler, et al., JHEP 1808 (2018) 010]



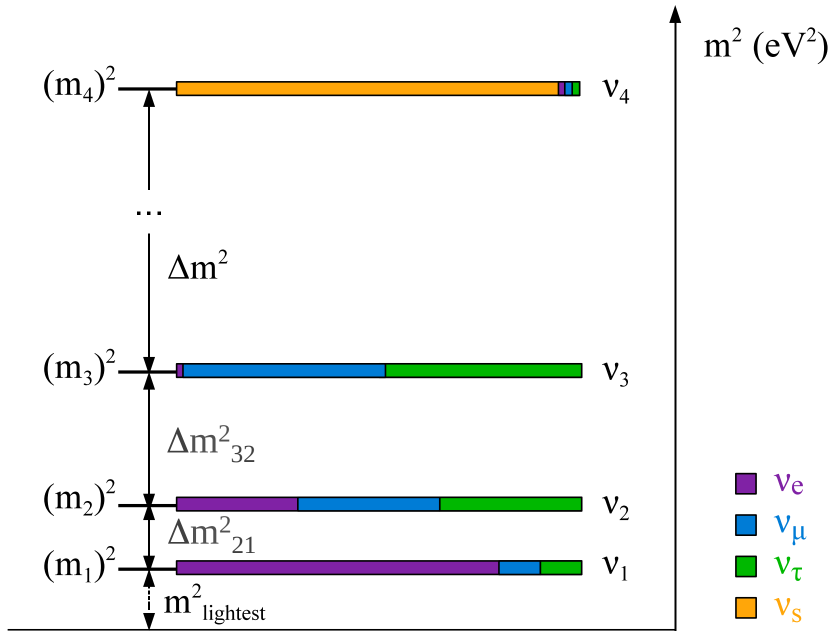
GALLEX and SAGE:
Solar neutrino experiments which used radioactive ν_e sources (Cr-51 and Ar-37) for calibration

Observed large (~20%) ν_e disappearance

How consistent are short-baseline experimental signals?



Take the simplest model: 3+1



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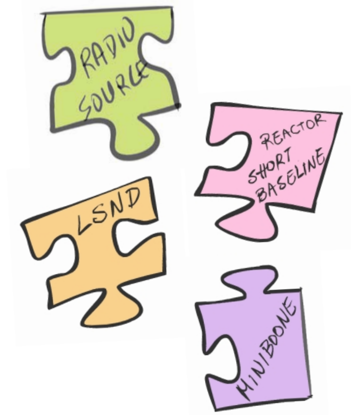
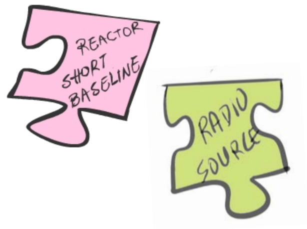
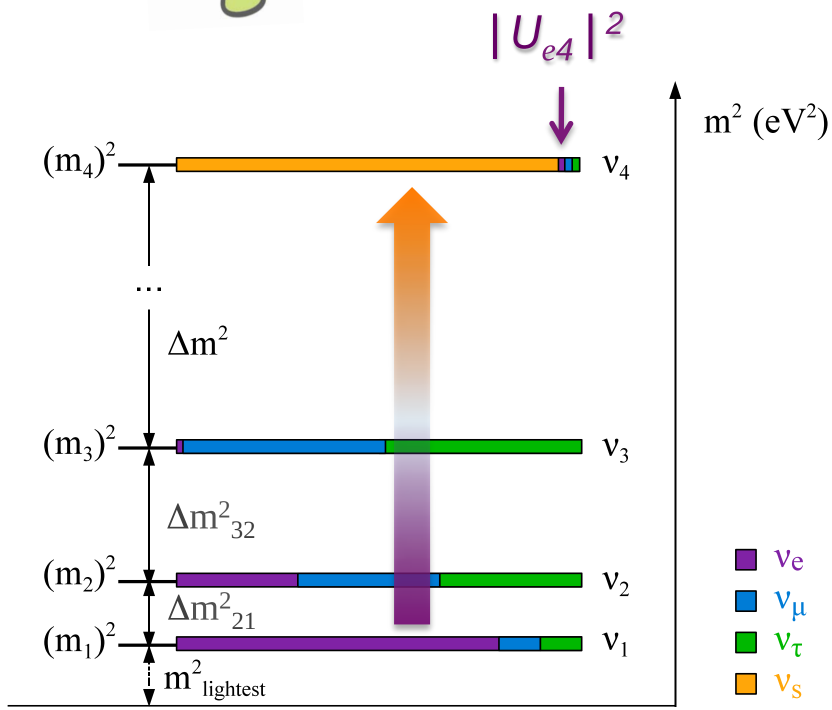


ν_e disappearance:

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\vartheta_{ee} \sin^2(1.27\Delta m^2 L/E)$$

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





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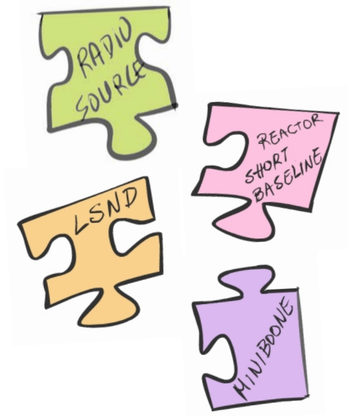


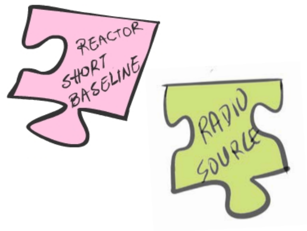
ν_e disappearance:

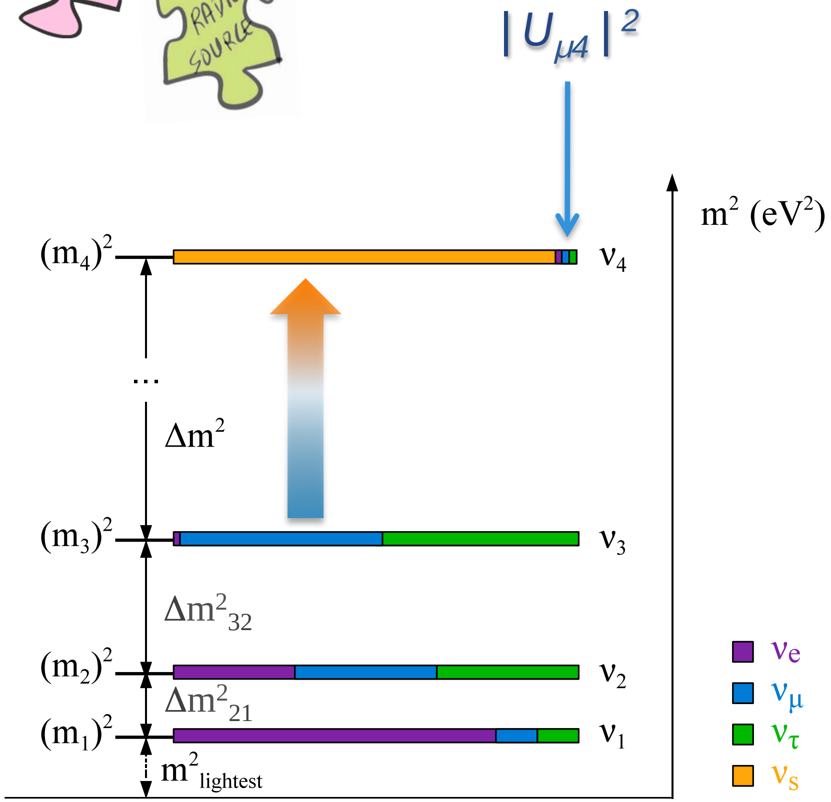
$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\vartheta_{ee} \sin^2(1.27 \Delta m^2 L / E)$$

ν_μ disappearance:

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

$$\hookrightarrow 4|U_{\mu 4}|^2 \left(1 - |U_{\mu 4}|^2\right)$$





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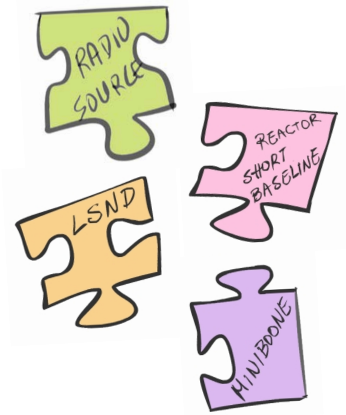

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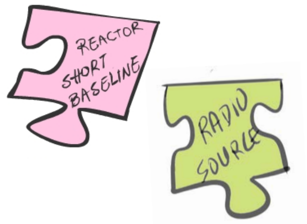
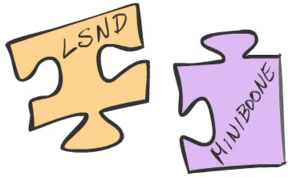


ν_μ disappearance:

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

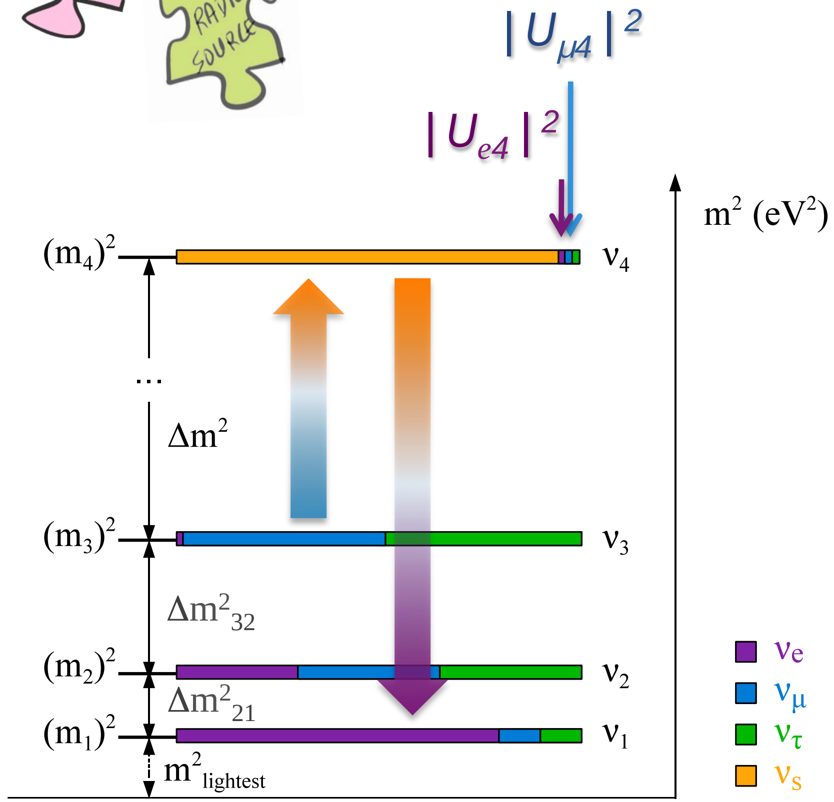


$\nu_\mu \rightarrow \nu_e$ appearance:

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

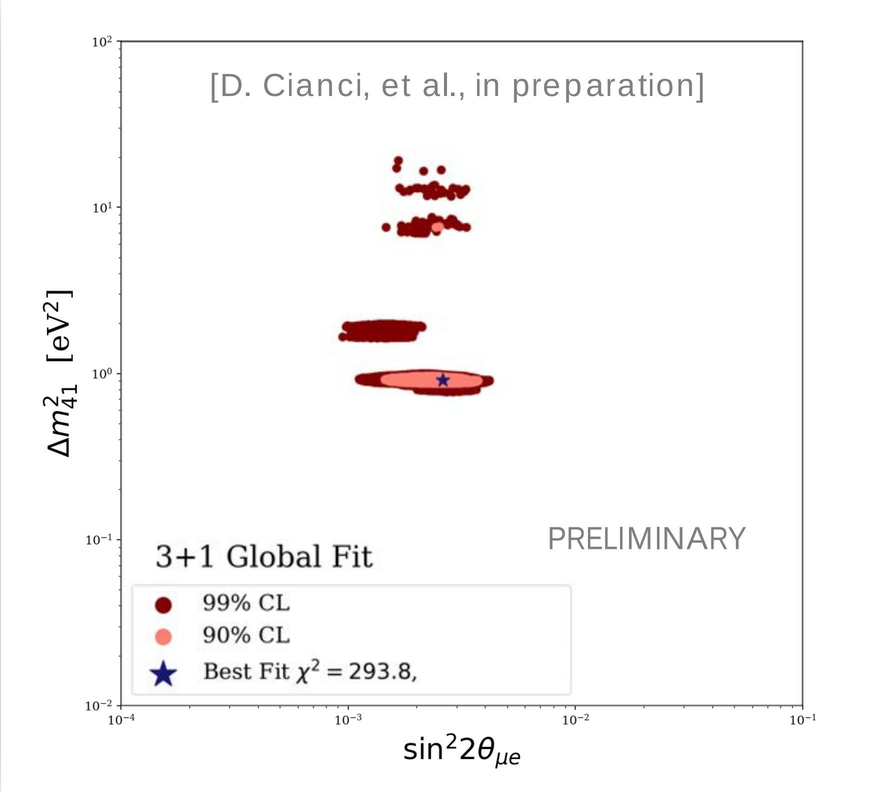
$$\hookrightarrow 4|U_{e4}|^2|U_{\mu 4}|^2$$

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



3+1 global fits

When combined with all other available experimental constraints together with MiniBooNE, LSND, Reactor SBL and radioactive source experiments, data seem to indicate a preference for a (3+1) signal



Data sets include:

- ν_e app: KARMEN, LSND, MiniBooNE (NEW ν and old $\bar{\nu}$), NOMAD, NuMI/MiniBooNE
- ν_μ dis: CCFR84, CDHS, ATM, MINOS/MINOS+ (NEW), SciBooNE/MiniBooNE
- ν_e dis: KARMEN/LSND xsec, Bugey, GALLEX/SAGE
- New reactor SBL not yet included

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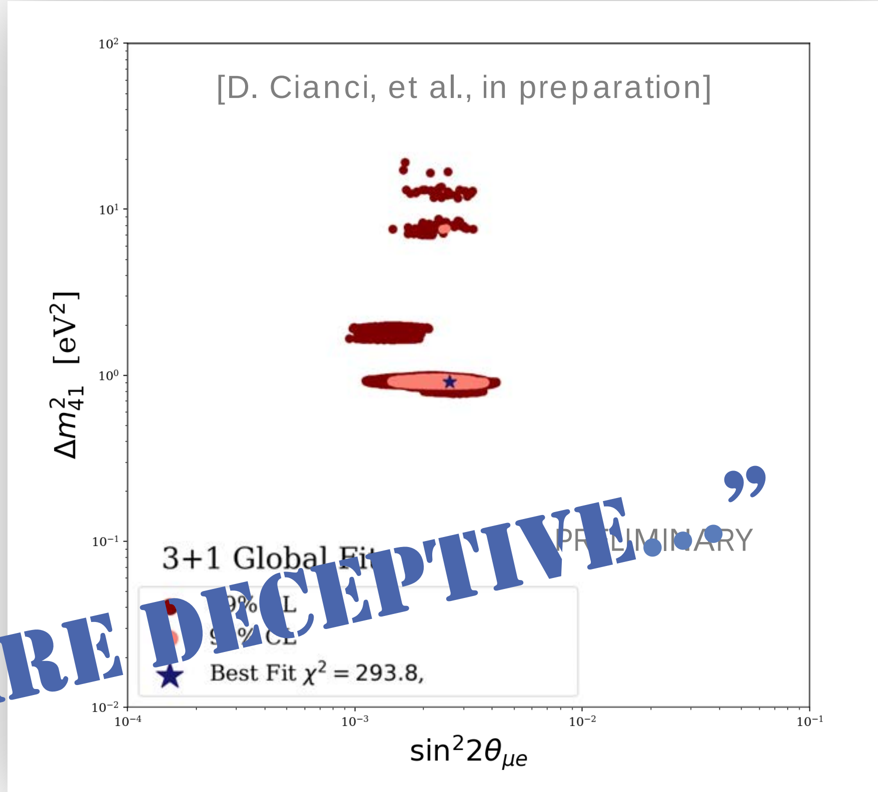


Global best fit parameters:
$\Delta m^2_{41} = 0.91 \text{ eV}^2$
$U_{e4} = 0.149$
$U_{\mu 4} = 0.171$

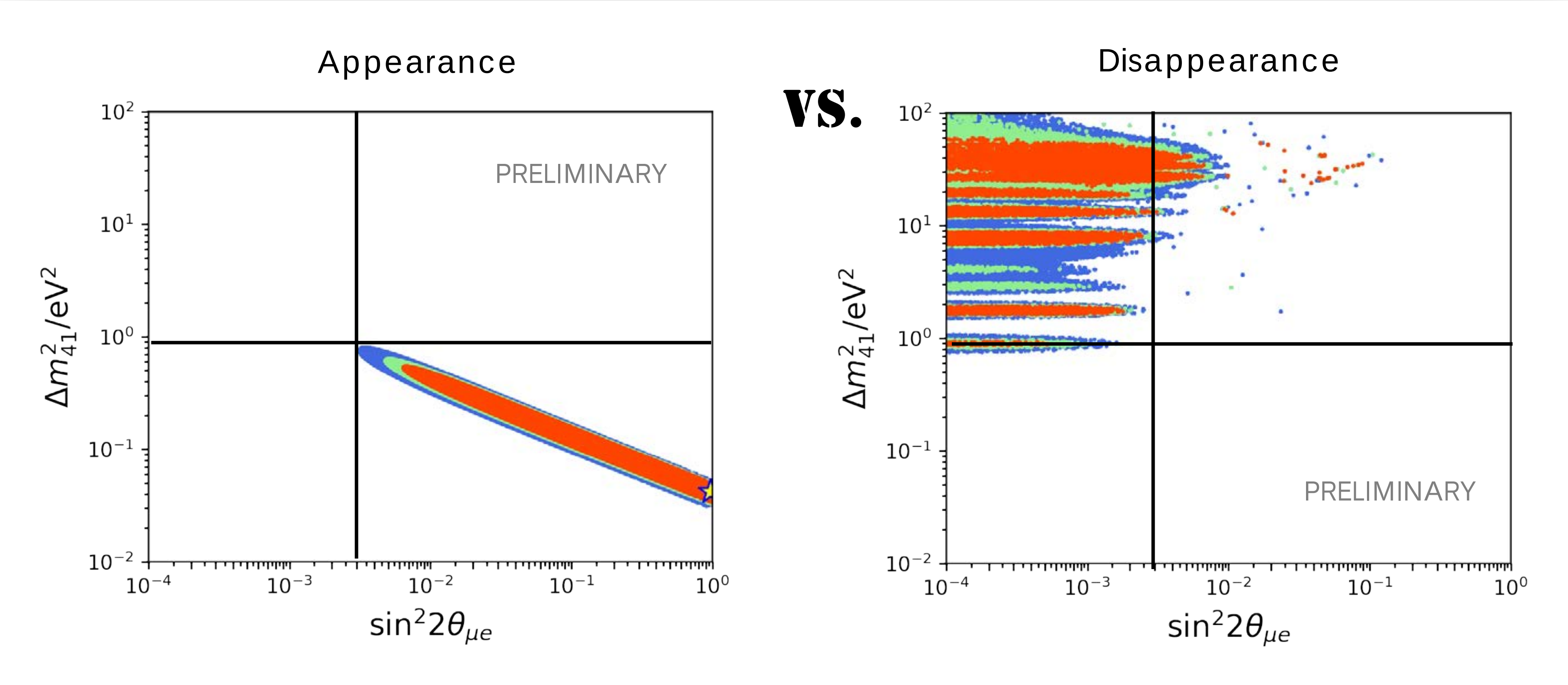
χ^2 bf = 293.8 (368 dof)
χ^2 probability = 99.8%

"APPEARANCES ARE DECEPTIVE..."

3+1 global fits

Goodness-of-fit of global (3+1) fits can be deceptive...

A closer examination reveals tension between datasets:



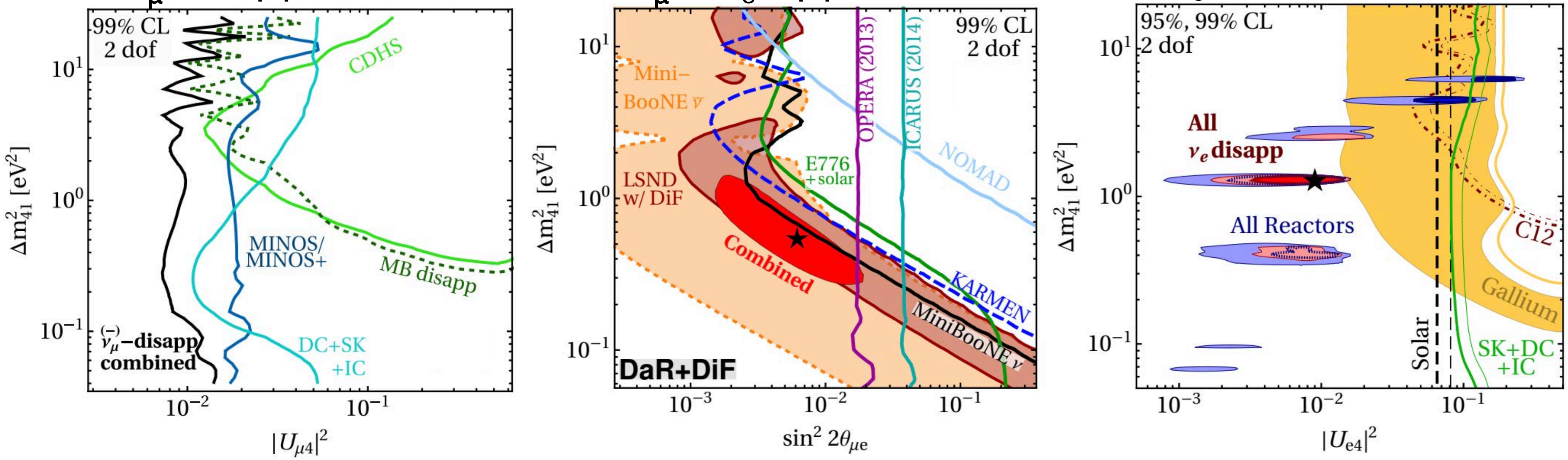
[A. Diaz, et al., ICHEP 2018]

Tension also exists among neutrino and antineutrino datasets.

3+1 global fits

[M. Dentler, et al., JHEP 1808 (2018) 010]

ν_μ disappearance | $\nu_\mu \rightarrow \nu_e$ appearance | ν_e disappearance



If one accepts (ν_e appearance and ν_e disappearance) signals as real, source of tension is ν_μ disappearance searches:

$\sin^2 2\theta_{\mu e} \sim \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$ → Implies non-zero ν_μ disappearance.

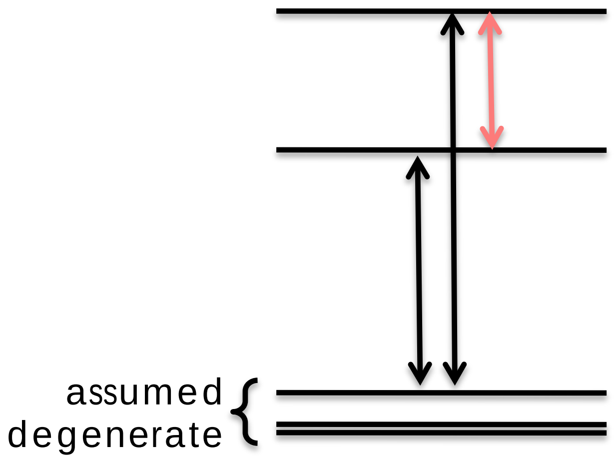
But no ν_μ disappearance has been observed!

3+2, 3+3 global fits

- Can CP violation allowed within 3+2 help?

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

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



→ two effective Δm^2

- What about more fit parameters, CP phases, in 3+3?

3+2, 3+3 global fits

With new MiniBooNE result:

[D. Cianci, et al., in preparation]

3+2

m_4	$\lvert U_{e4}\rvert$	$\lvert U_{\mu4}\rvert$	m_5	$\lvert U_{e5}\rvert$	$\lvert U_{\mu5}\rvert$	ϕ_{45}
0.68 eV	0.116	0.187	0.95 eV	0.159	0.103	5.71 rad

χ^2 bf (dof) = 244.8 (236)
χ^2 probability = 33%

(Compare, previously, χ^2 (dof) = 238.2 (236))

PRELIMINARY

3+3

m_4	$\lvert U_{e4}\rvert$	$\lvert U_{\mu4}\rvert$	m_5	$\lvert U_{e5}\rvert$	$\lvert U_{\mu5}\rvert$	m_6	$\lvert U_{e6}\rvert$	$\lvert U_{\mu6}\rvert$
0.68 eV	0.119	0.080	0.88 eV	0.139	0.086	0.97 eV	0.105	0.106

ϕ_{45}	ϕ_{46}	ϕ_{56}
5.26 rad	5.75 rad	6.03 rad

χ^2 bf (dof) = 240.5 (231)
χ^2 probability = 32%

(Compare, previously, χ^2 (dof) = 232.5 (231))

PRELIMINARY

Where do we go from here?

- Better statistical treatment of data in global fits
- Follow-up high-sensitivity, direct experimental tests (ongoing, planned and proposed sterile neutrino oscillation searches):
  - Accelerator-based: SBN, IsoDAR
  - Reactor-based: SoLiD, Neutrino-4, DANSS, NEOS, STEREO, PROSPECT, CHANDLER, …
  - Radioactive source: BEST

  See talks by Verstraeten, Park

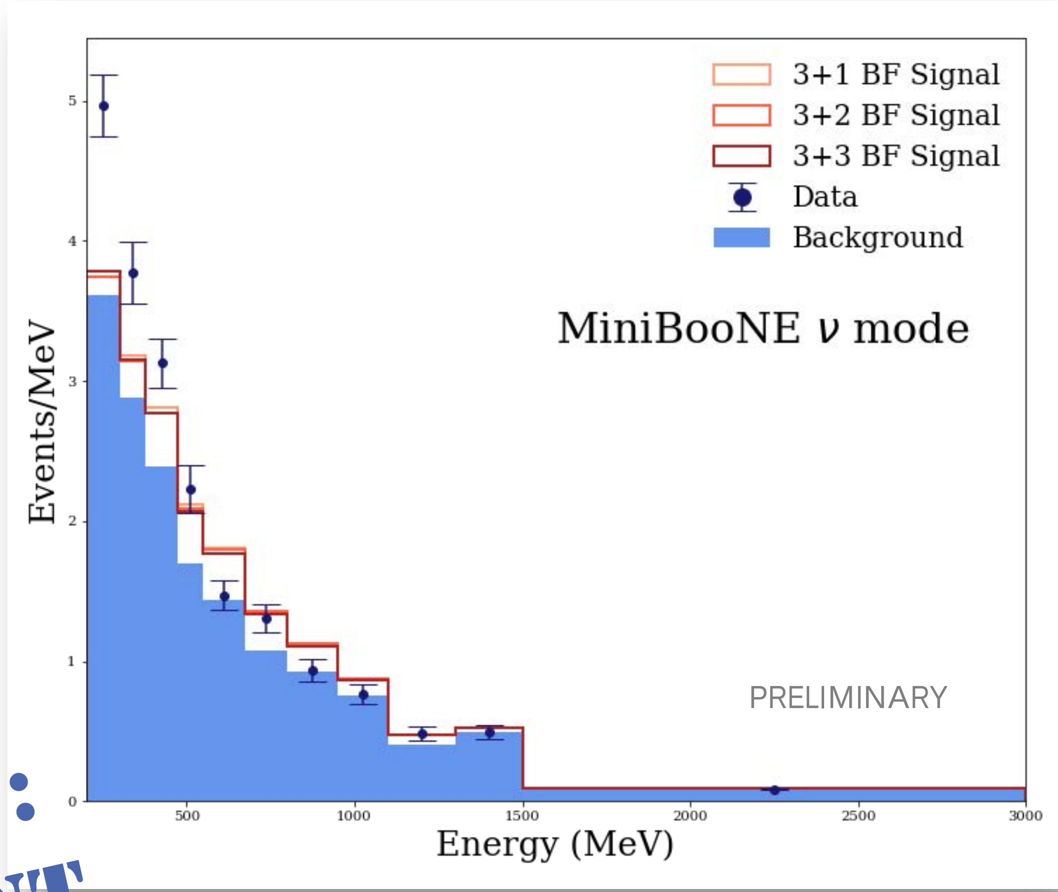
  - Also searches at long-baseline experiment near detectors and (high-energy) atmospheric neutrino experiments (MINOS/MINOS+, NOvA, T2K, IceCube/DeepCore, Super-K, …)
  - And neutral-current based searches with coherent scattering (e.g. COHERENT, CEvNS)

  See tomorrow's session on CNNS

- Alternate models: non-standard interactions, sterile neutrino decay, …

3+N global fits

Yet another shortcoming:
Failure to accommodate MiniBooNE low-energy excess



[D. Cianci, et al., in preparation]

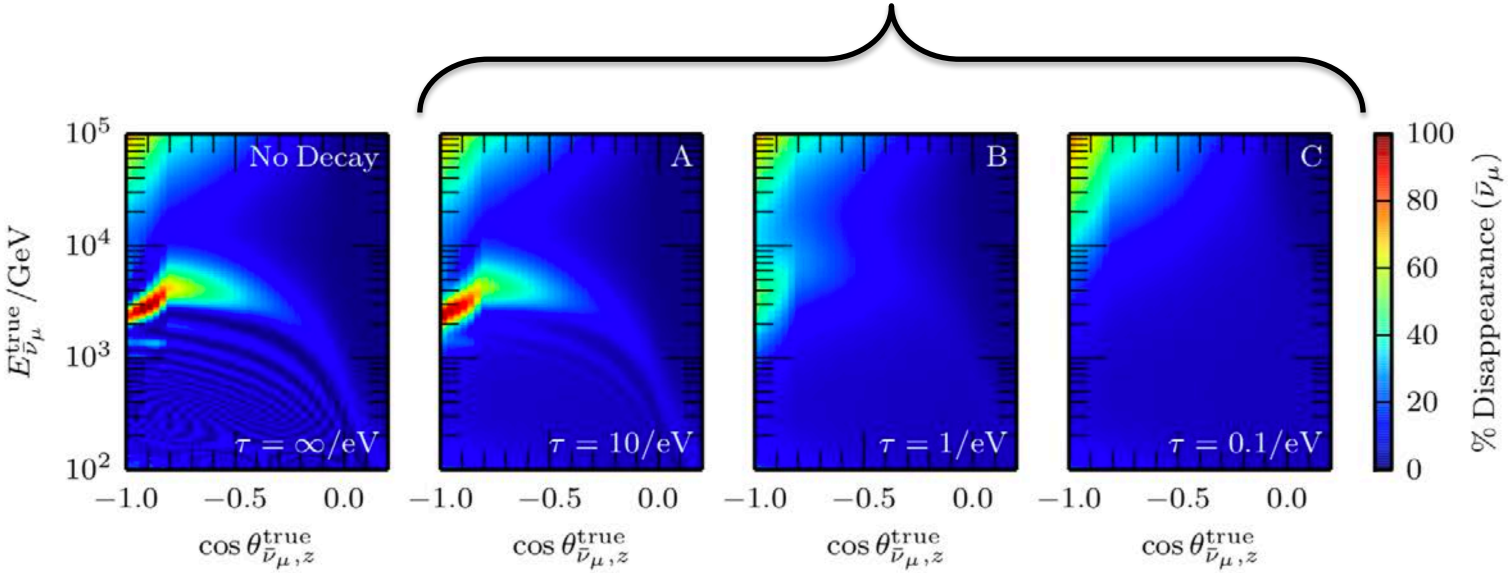
“3+N STANDARD STERILE NEUTRINOS”: INSUFFICIENT

A shift in focus?

The inability of 3+N global fits to provide a satisfactory, coherent explanation to all SBL anomalies has prompted the exploration of new (physics) ideas:

1. Sterile neutrino + decay [A. Diaz et al., ICHEP 2018]

4th (mostly sterile) neutrino mass eigenstate has finite lifetime, resulting in decoherence in neutrino propagation and no resonant matter effects
→ Evades IceCube limits from ν_μ disappearance



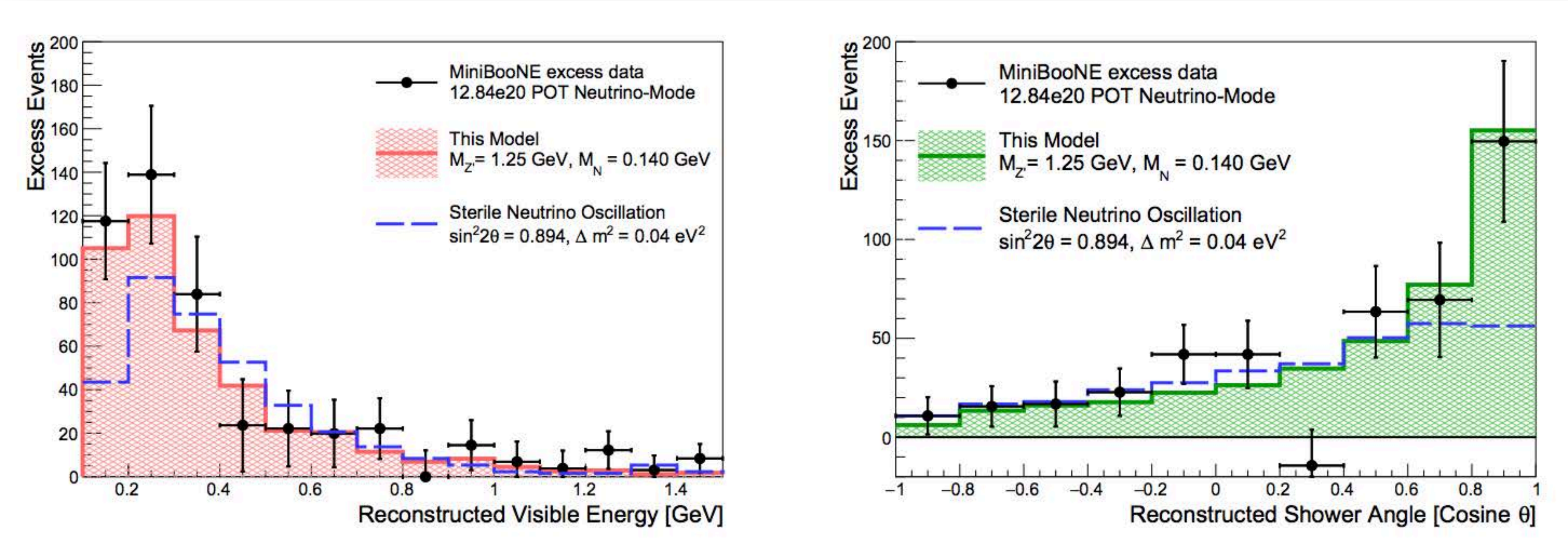
This model modestly relieves tension.

A shift in focus?

The inability of 3+N global fits to provide a satisfactory, coherent explanation to all SBL anomalies has prompted the exploration of new (physics) ideas:

2. Sterile neutrino + decay through Z' [P. Ballet, et al., arXiv:1808.02915]

$$\nu_\mu + \mathcal{N} \to \nu_4 + \mathcal{N} \qquad \nu_4 \to \nu_\alpha \, e^+ \, e^-$$



Best fit: m_4 = 0.14 GeV, $|U_{\mu 4}|$ = 1.5E-6, $m_{Z'}$ = 1.25 GeV, $|U_{\tau 4}|$ = 7.8E-4, χ^2 = 5E-6

Summary

- For the past few decades, we have been amassing anomalous excesses/ deficits of ν_e at L/E ~ 1m/MeV, from ν_μ/ν_e sources
  - LSND, MiniBooNE, reactor neutrino and radioactive source measurements at short baselines
  - Require additional, high-Δm^2 to interpret as two-neutrino oscillation → sterile neutrino(s)? In conflict with null ν_μ disappearance searches at short baselines…

- Community is resorting to: improving fits, considering alternative interpretations, and deploying new experimental tests with unprecedented sensitivity

- Need to keep an open mind:
  Solution may not be as “elegant” as one might expect!
  But it shouldn’t be out of reach!

Thank you!