Status and Prospects of Short Baseline Neutrino Experiments

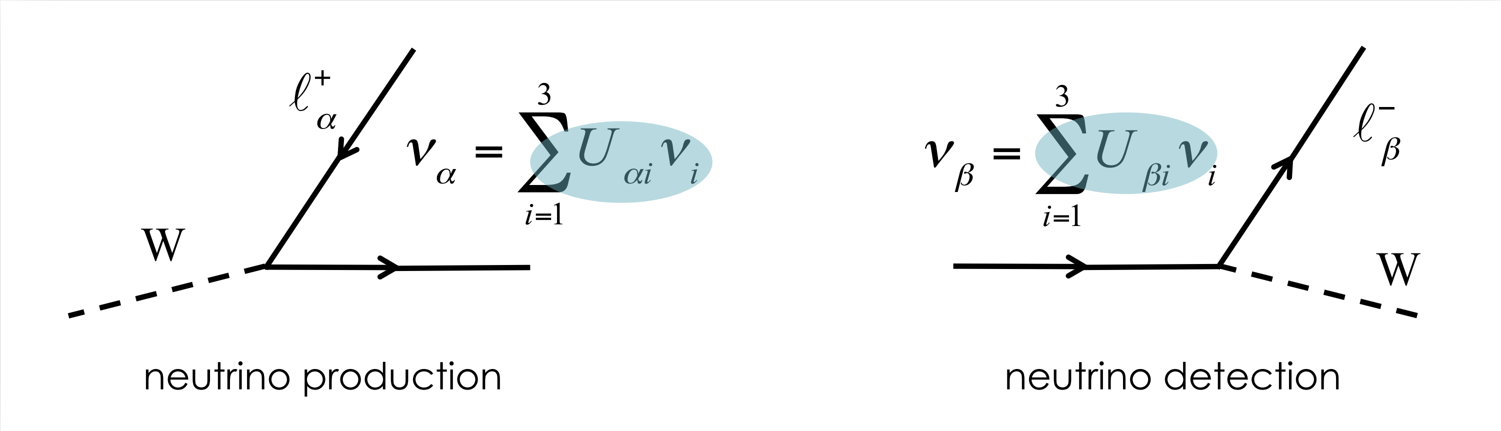
Georgia Karagiorgi
Columbia University

25th Anniversary of Rencontres du Vietnam on "Windows of the Universe"

ICISE, Quy Nhon, Vietnam

Neutrino oscillations *in a nutshell*

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



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

$$+2\sum_{i>j} \mathrm{Im}\left\{U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right\}\sin\left[2.54\Delta m^2_{ij}L/E\right],$$

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

Neutrino oscillations *in a nutshell*

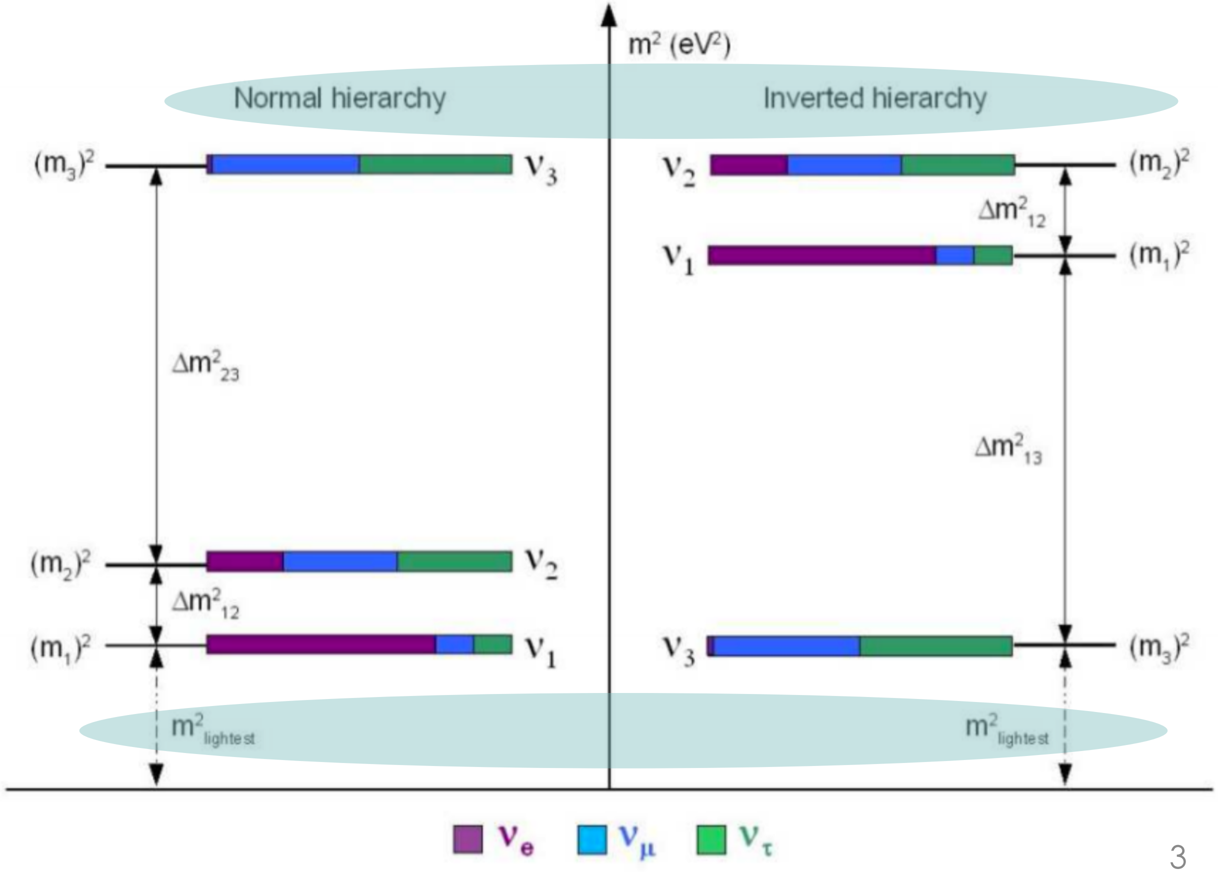
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3}e^{i\delta} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Parameters which are yet to be determined.

CP violation phase

If non-zero, could provide clues about matter-antimatter asymmetry in our universe.

Accessible through accelerator-neutrino oscillation measurements at long baselines.



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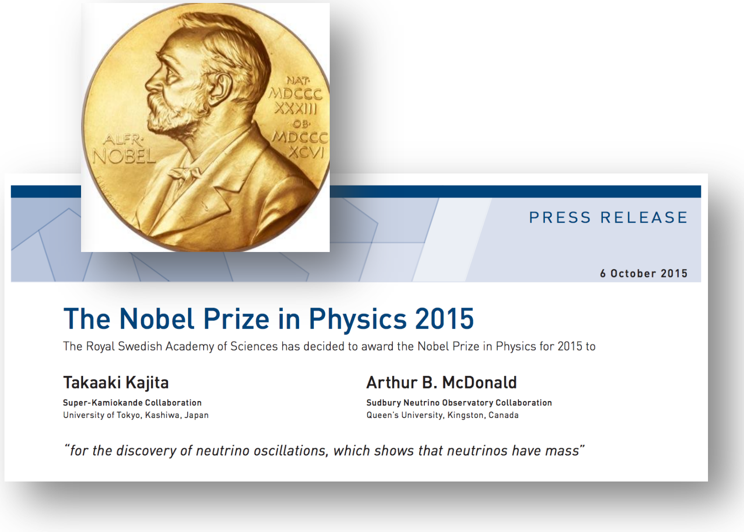

PRESS RELEASE

6 October 2015

The Nobel Prize in Physics 2015

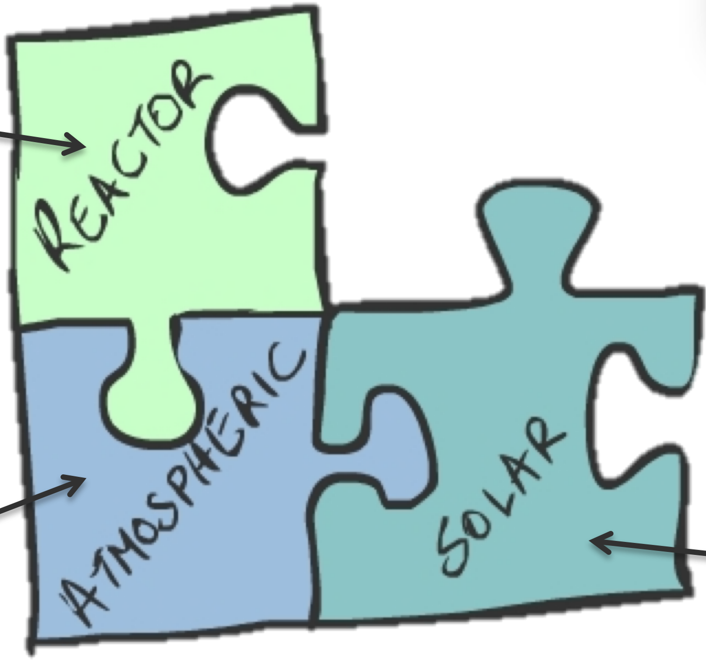
The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2015 to

Takaaki Kajita
Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

Arthur B. McDonald
Sudbury Neutrino Observatory Collaboration
Queen's University, Kingston, Canada

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

also accelerator
long-baseline



also accelerator
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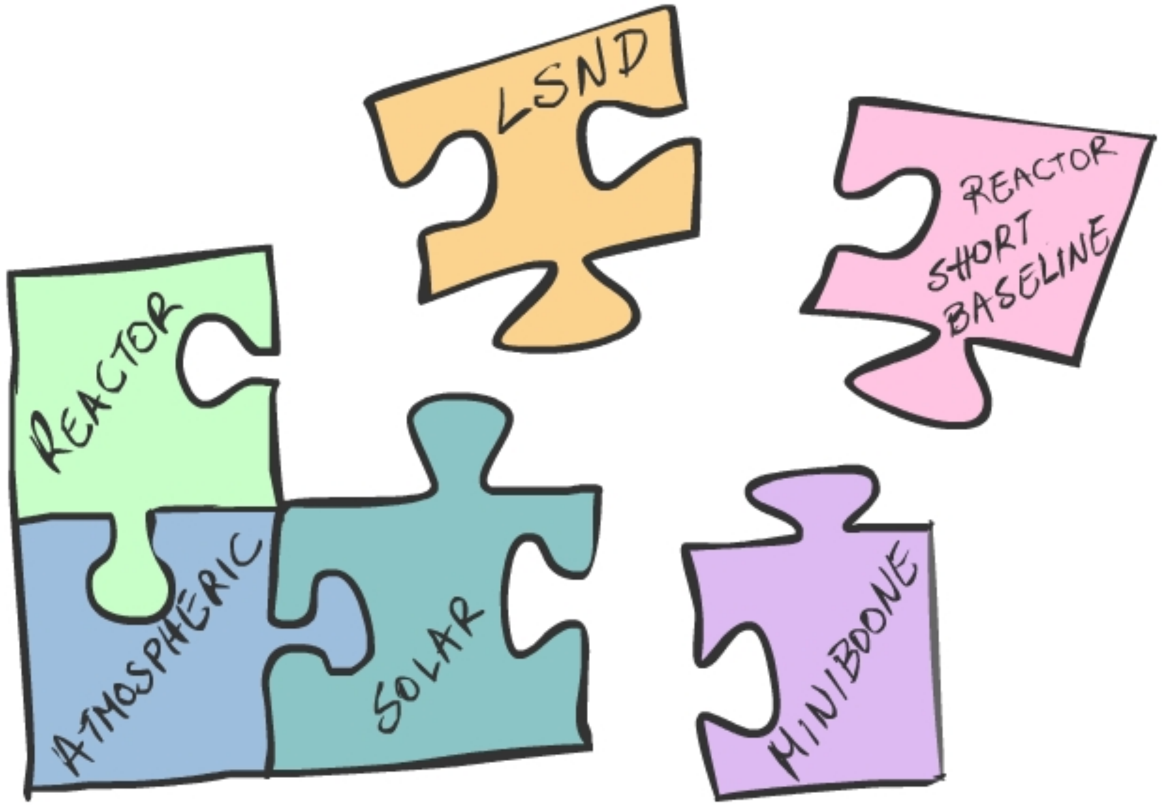
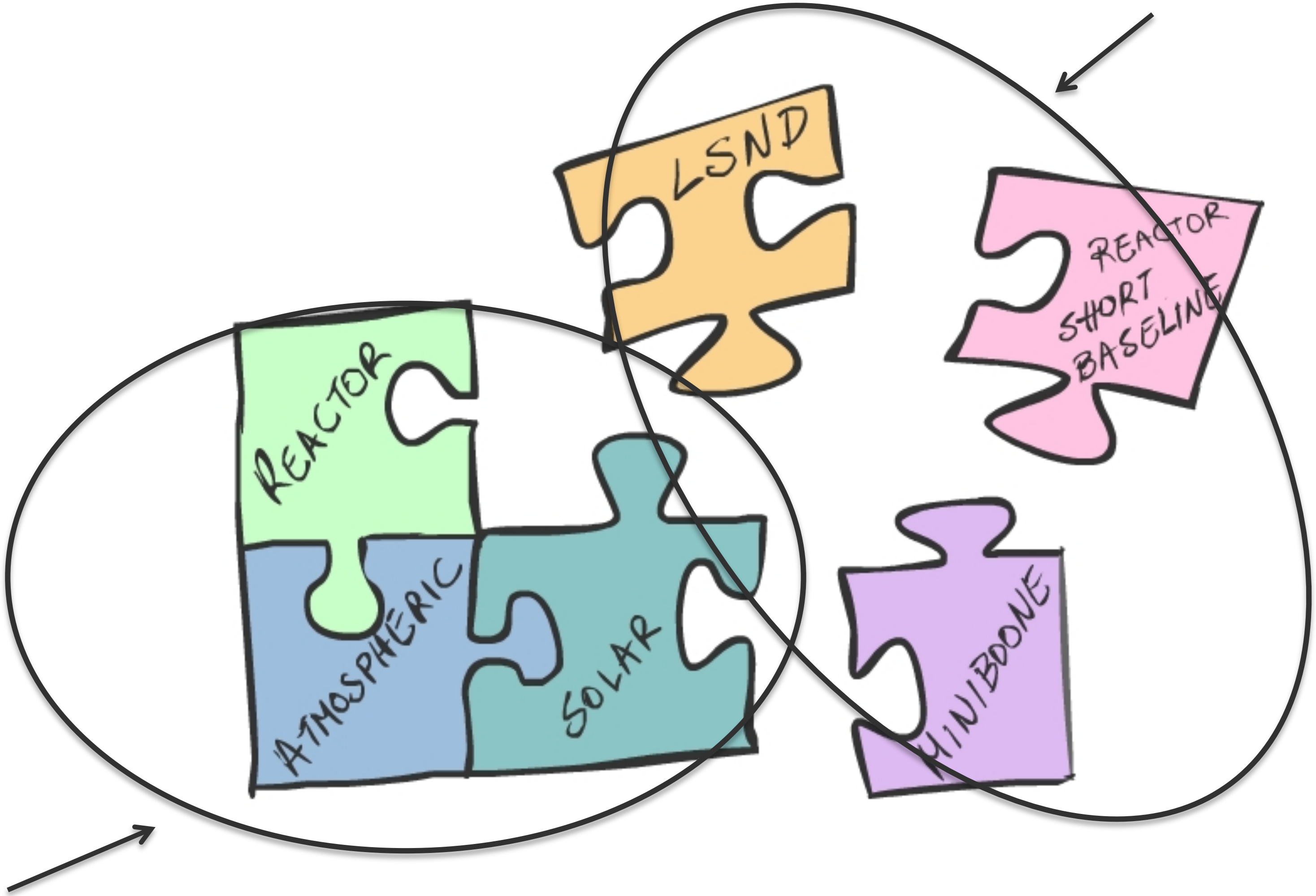
also reactor
long-baseline

Not the full picture?



Not the full picture?

"short-baseline"



"long- and medium-baseline"

Neutrino oscillations *at "short baselines"*

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

$$+2\sum_{i>j} \mathrm{Im}\left\{U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right\} \sin\left[2.54 \Delta m_{ij}^2 L/E\right],$$

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

P is maximal when (1.27 Δm^2_{ij} L/E) ~ $\pi/2$

- For Δm^2_{21} = 7.37E-5 eV^2,
  L ~ 10-200 km for typical energies E ~ 1 MeV – 10 MeV

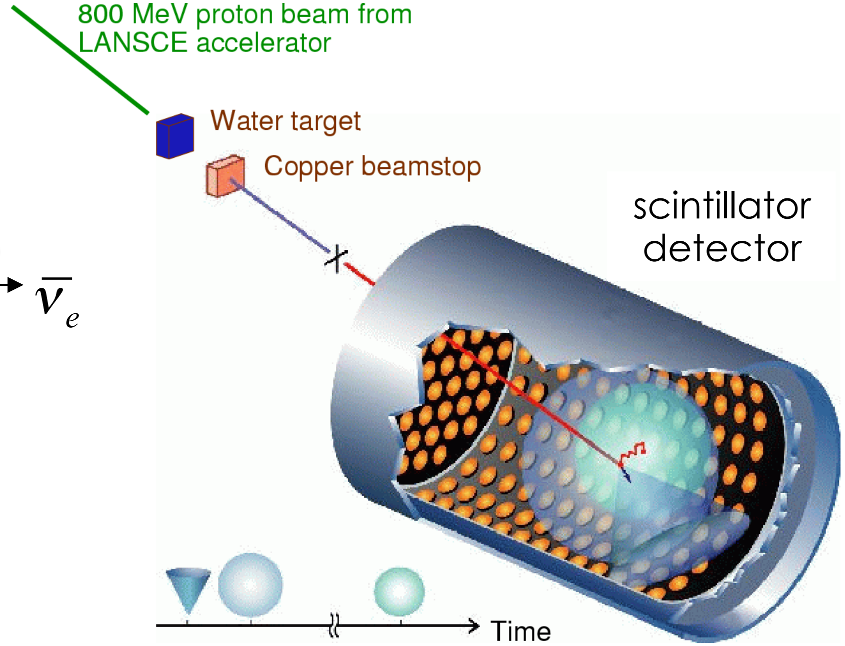
- For Δm^2_{31} = 2.55E-3 eV^2,
  L ~ 1 km - 5,000km for E ~ 1 MeV – 10 GeV

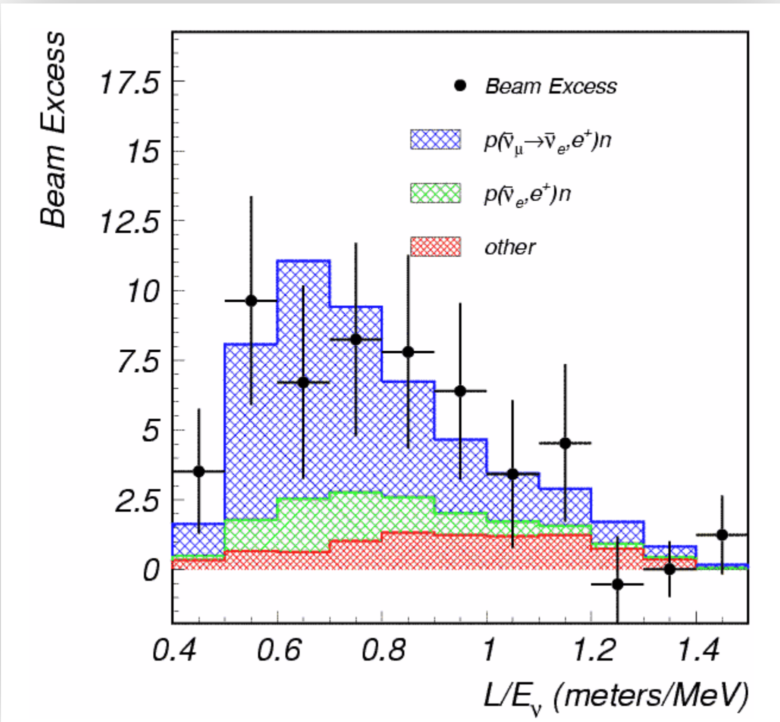
- At **short-baselines**:
  L ~ 1 m – 1 km for E ~ 1 MeV – 10 GeV

  → sensitive to much **higher Δm^2_{ij}** !

μ^+ decay-at-rest experiment:

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





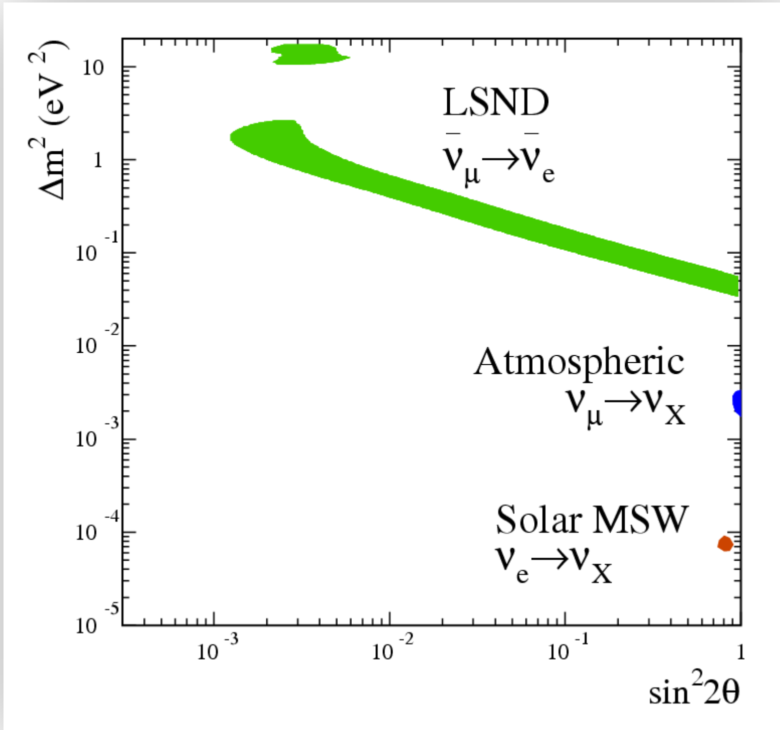
[C. Athanassopoulos et al., Phys. Rev. Lett. 75, 2650 (1995); 81,1774(1998); A.Aguilar et al., Phys. Rev. D64, 112007(2001)]

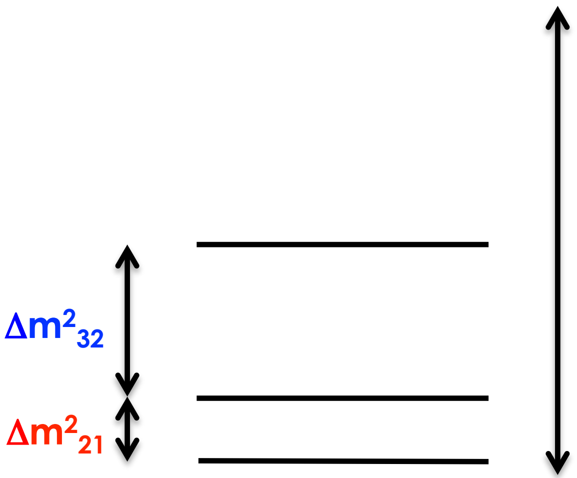
Observed excess of $\bar{\nu}_e$
described by oscillation probability:
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = (0.264 \pm 0.067 \pm 0.045)\ \%$

(3.8σ evidence)

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

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

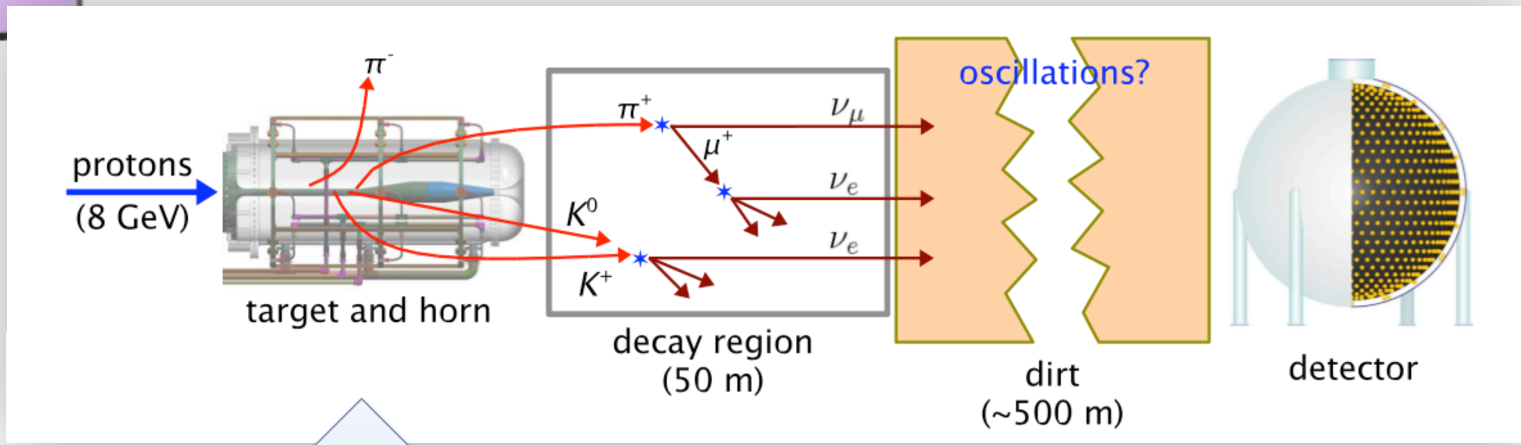




$\Delta m^2_{LSND} >> \Delta m^2_{21} + \Delta m^2_{32}$

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 $\bar{\nu}$

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

? $\rightarrow \nu_e$

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

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

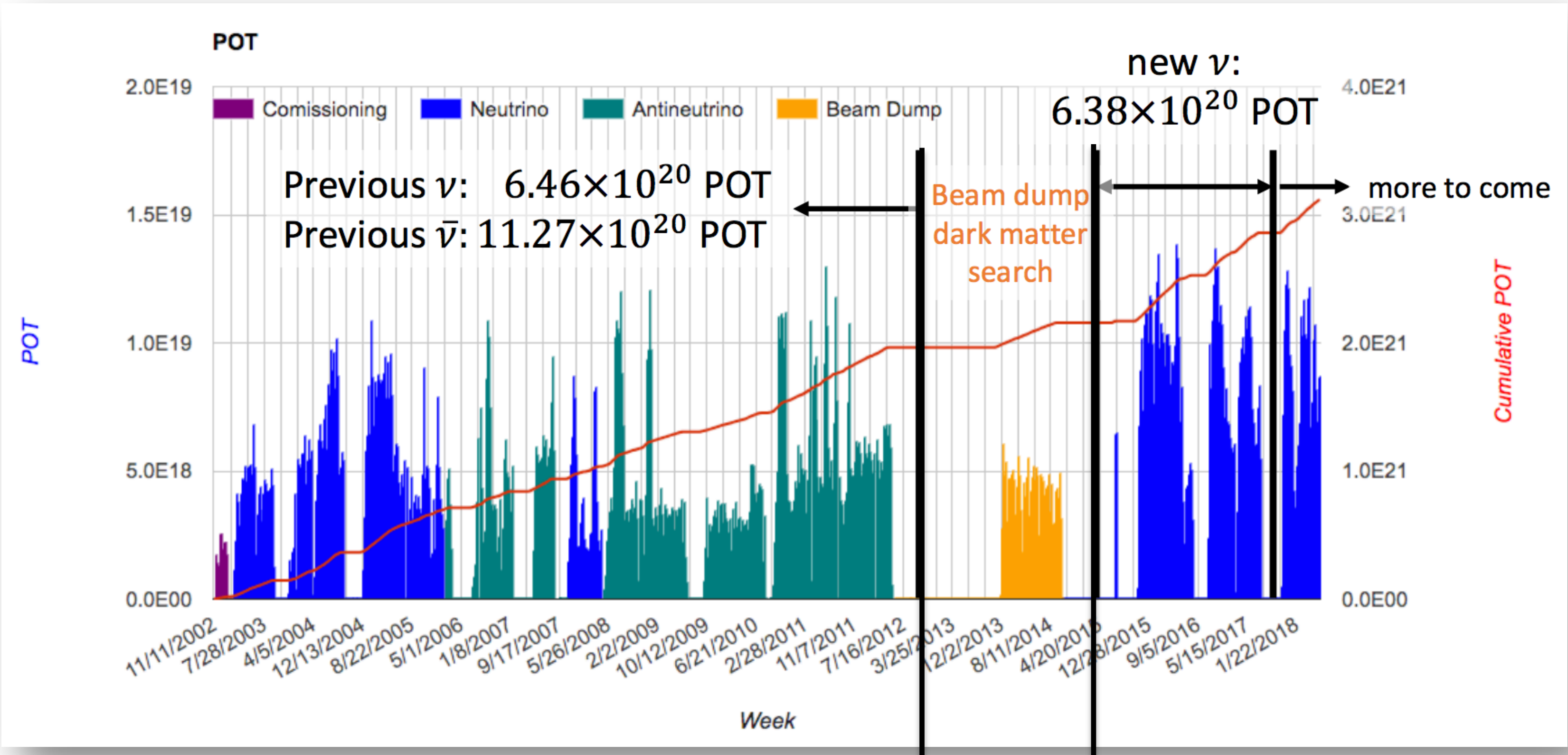
Similar L/E as LSND

but

Different energy, beam and detector systematics

Different event signatures and backgrounds (Cherenkov detector)

MiniBooNE beam run periods and ν_e appearance results:



"Old results": ν and $\bar{\nu}$ data

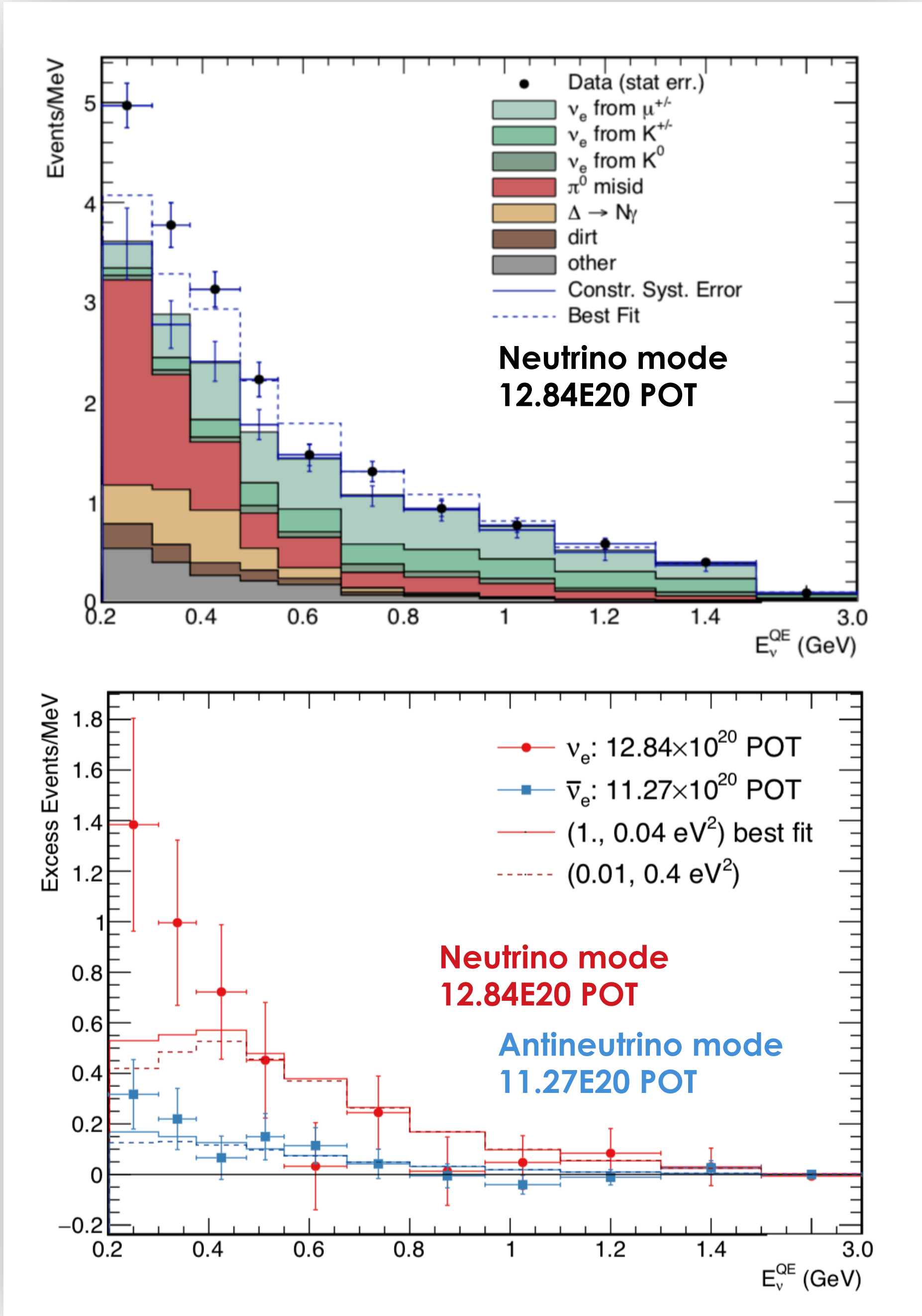
"New results": ν data

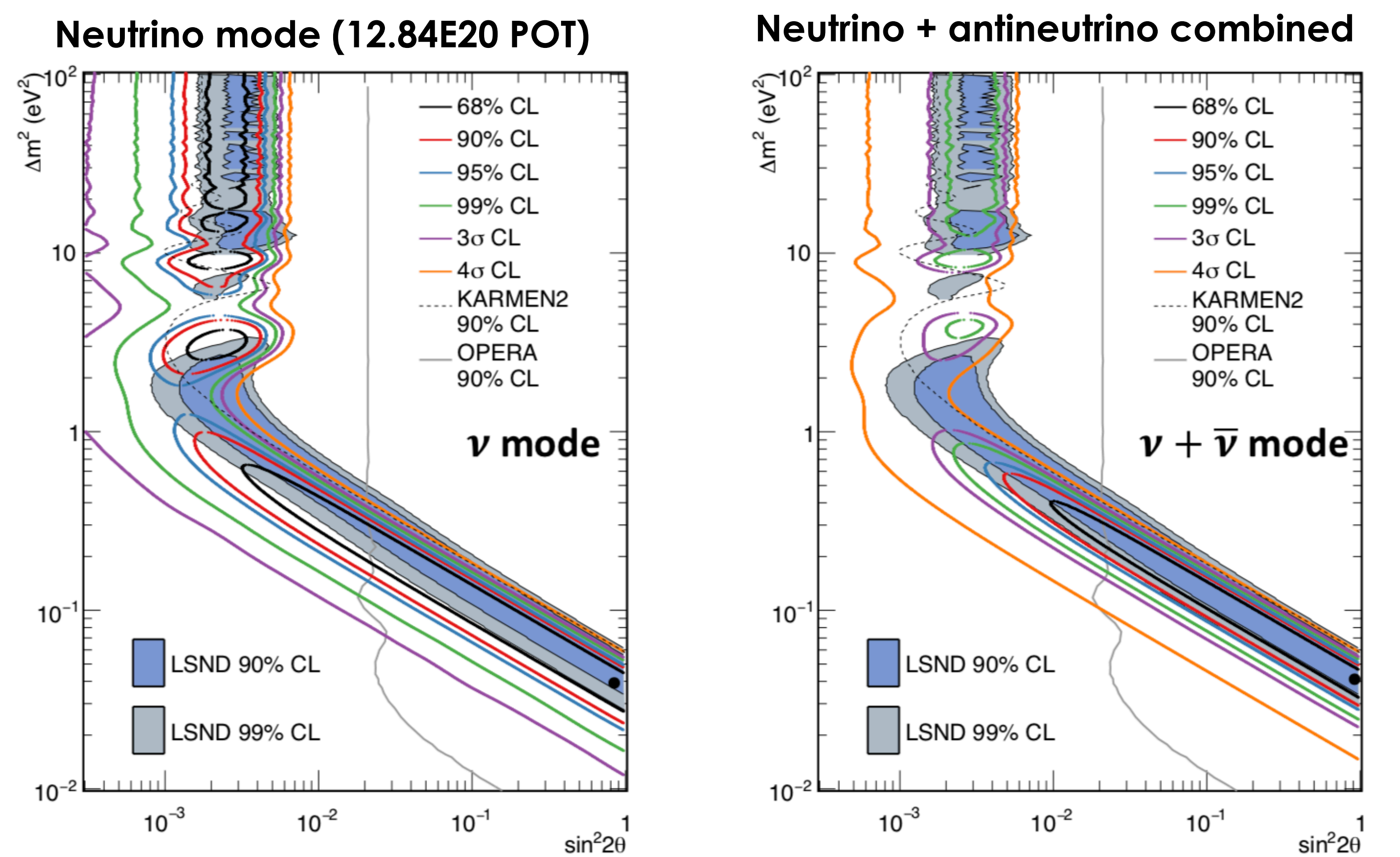
[Latest MiniBooNE ν_e appearance results: arXiv:1805.12028]

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

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

Observed excesses in neutrino and antineutrino mode have become more consistent relative to past results.





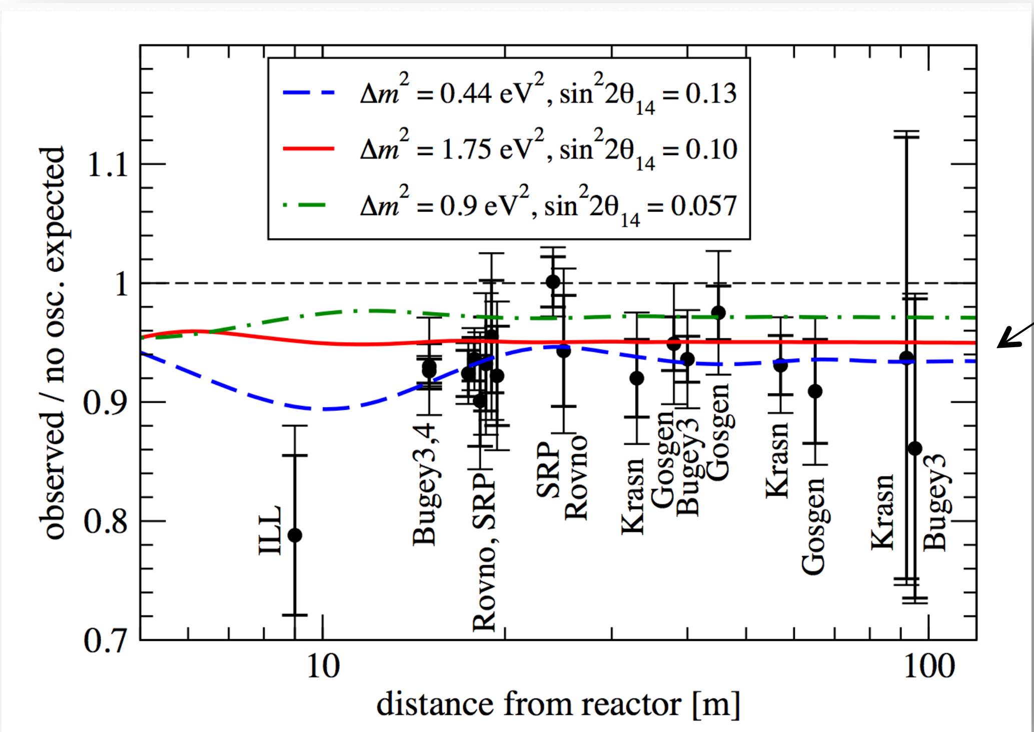
$(\Delta m^2, \sin^2 2\theta) = (0.037\ \mathrm{eV}^2, 0.958)$
$\chi^2/ndf = 10.0/6.6$ (prob = 15.4%)

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

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

"Reactor Anomaly"

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



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.

[Mueller et al. 1101.2663, Huber 1106.0687]

"Reactor Anomaly"

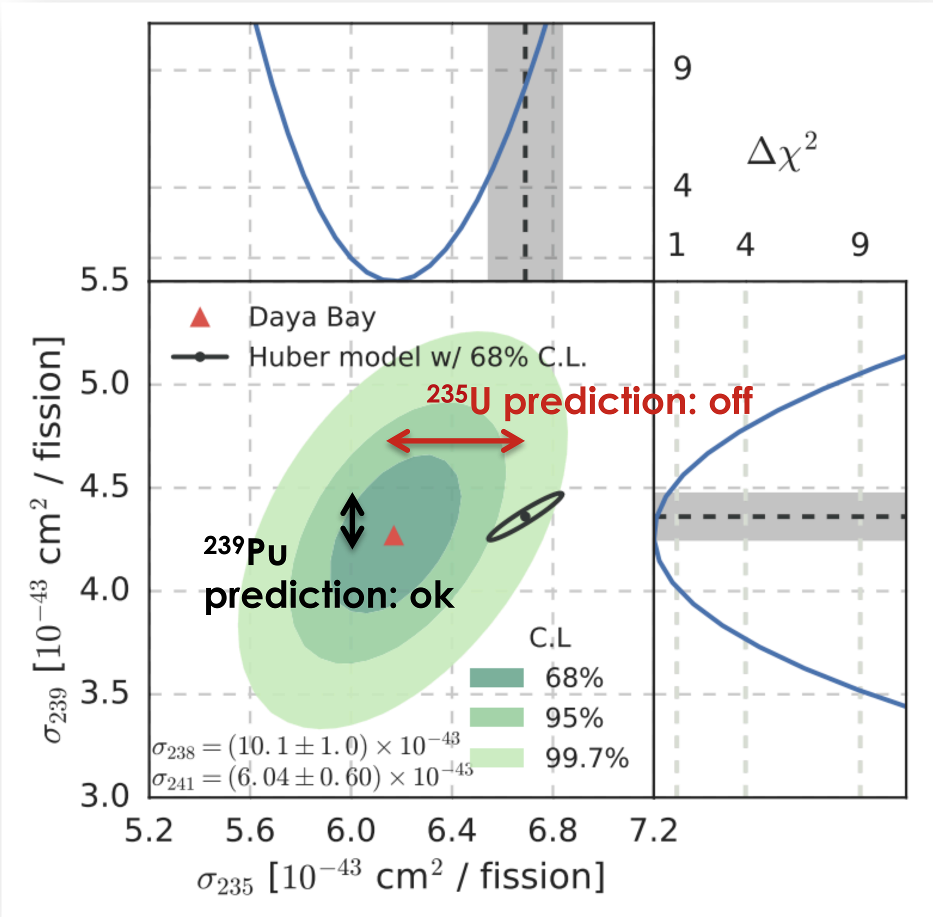
Predicting reactor $\bar{\nu}_e$ fluxes:

- Use measured β spectra from ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu fission
- Convert to $\bar{\nu}_e$ 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]

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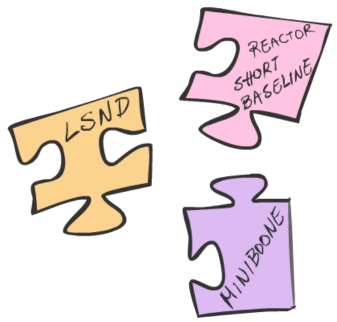
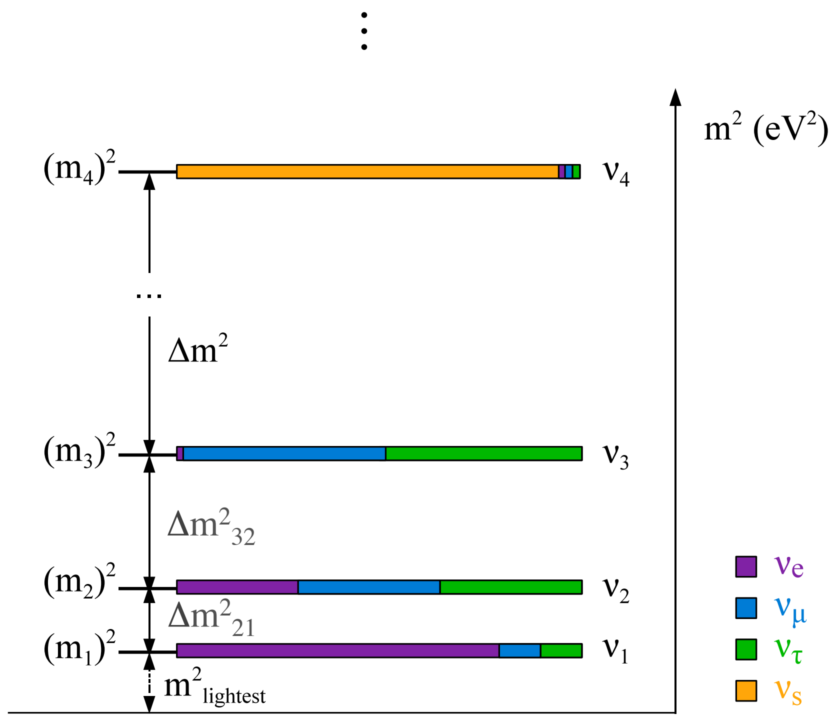
How consistent are short-baseline experimental signals?



Additional neutrino mass states?

→ 3 active + *N sterile neutrinos*



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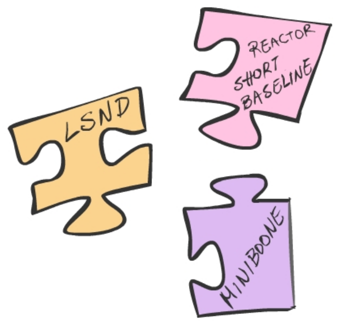
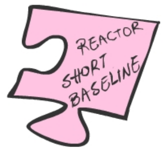
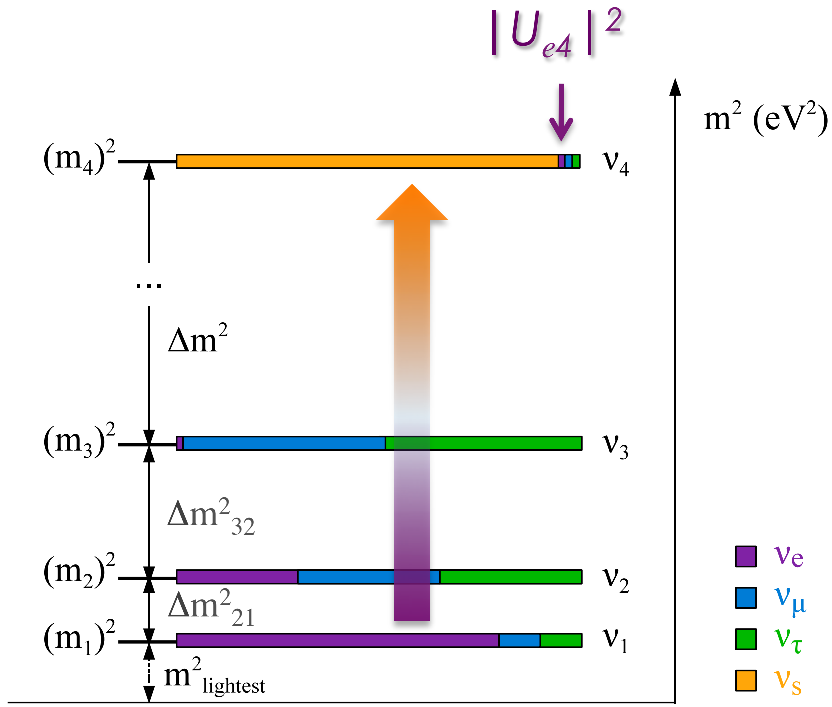


ν_e disappearance:

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

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





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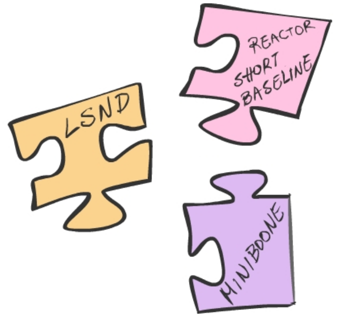

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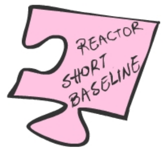
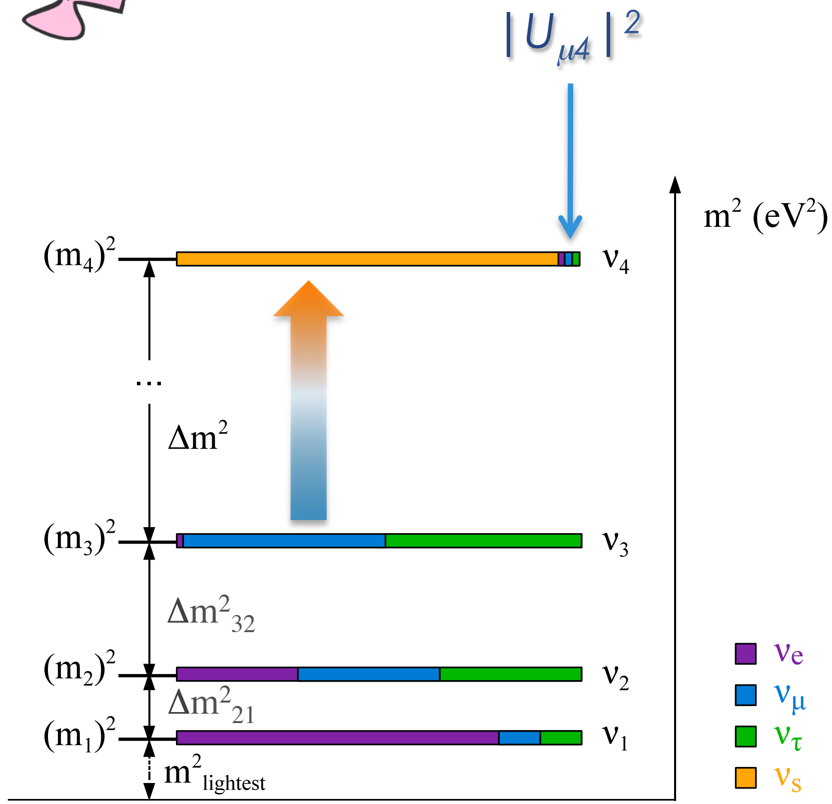


ν_μ disappearance:

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

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



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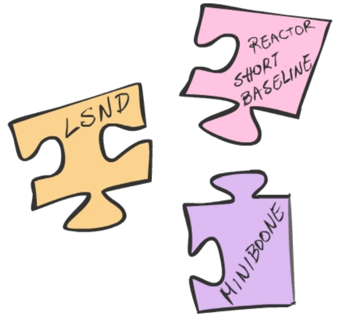

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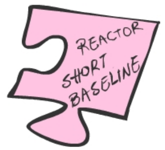

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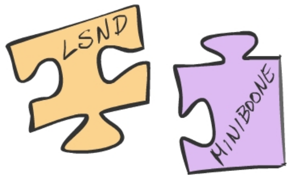
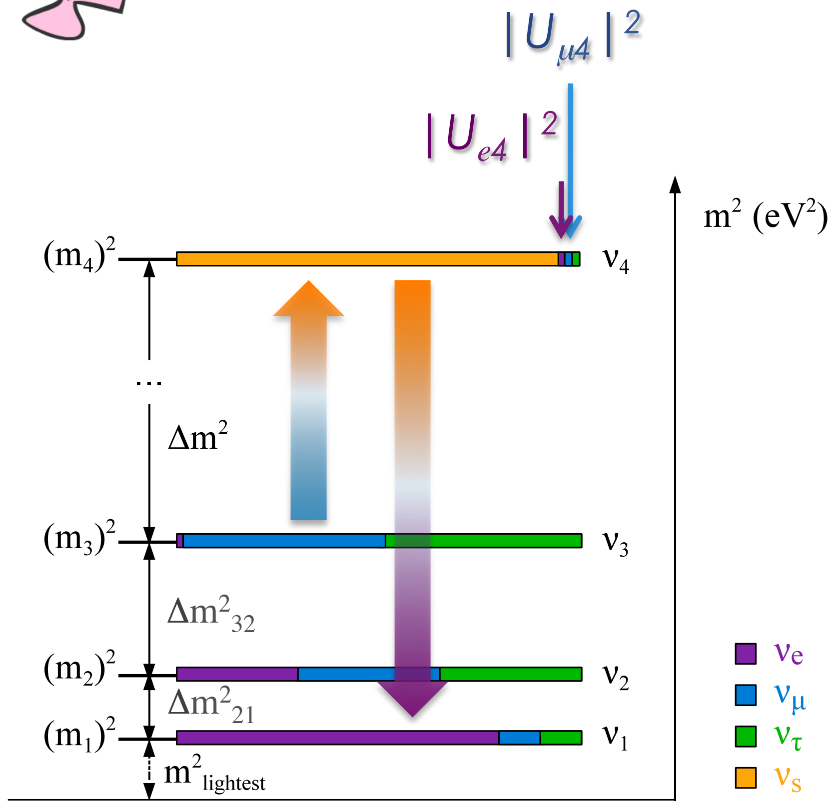


$\nu_\mu \rightarrow \nu_e$ appearance:

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

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

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

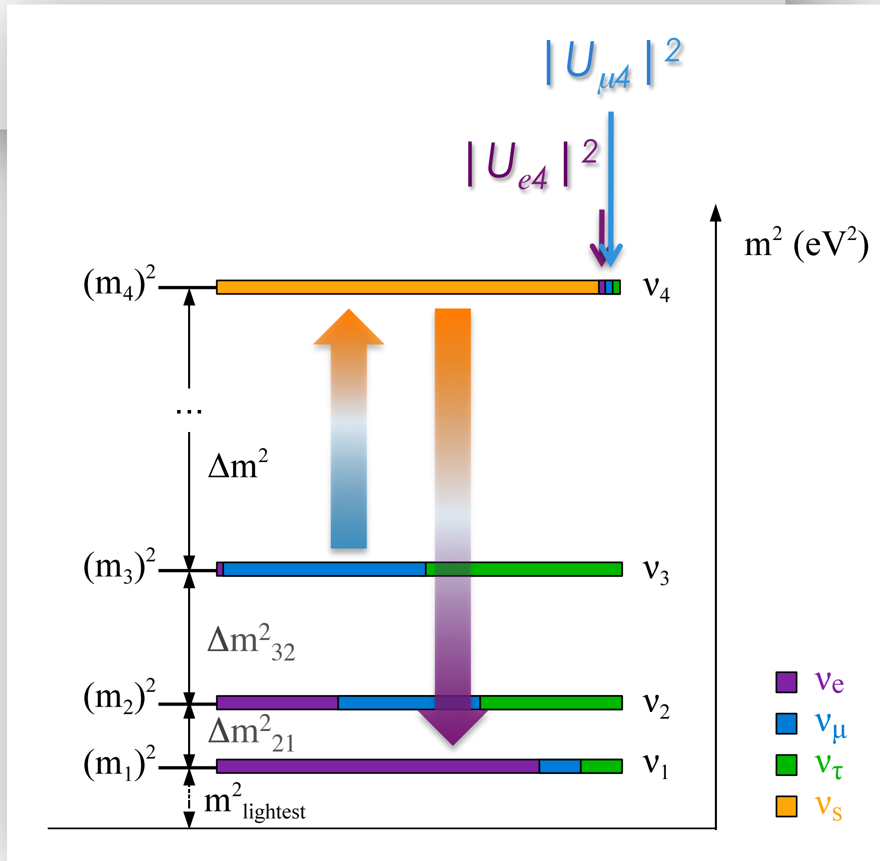


Global fits

$\overset{(-)}{\nu}_\mu$ disappearance	$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ appearance	$\overset{(-)}{\nu}_e$ disappearance
CDHS	MiniBooNE ν	Bugey, Chooz
CCFR84	MiniBooNE $\bar{\nu}$	KARMEN/LSND (xsec)
SuperK/K2K (atm)	LSND	Gallium
MiniBooNE (dis)	KARMEN	
MINOS-CC	NOMAD	
MINOS-NC	NuMI-MB	

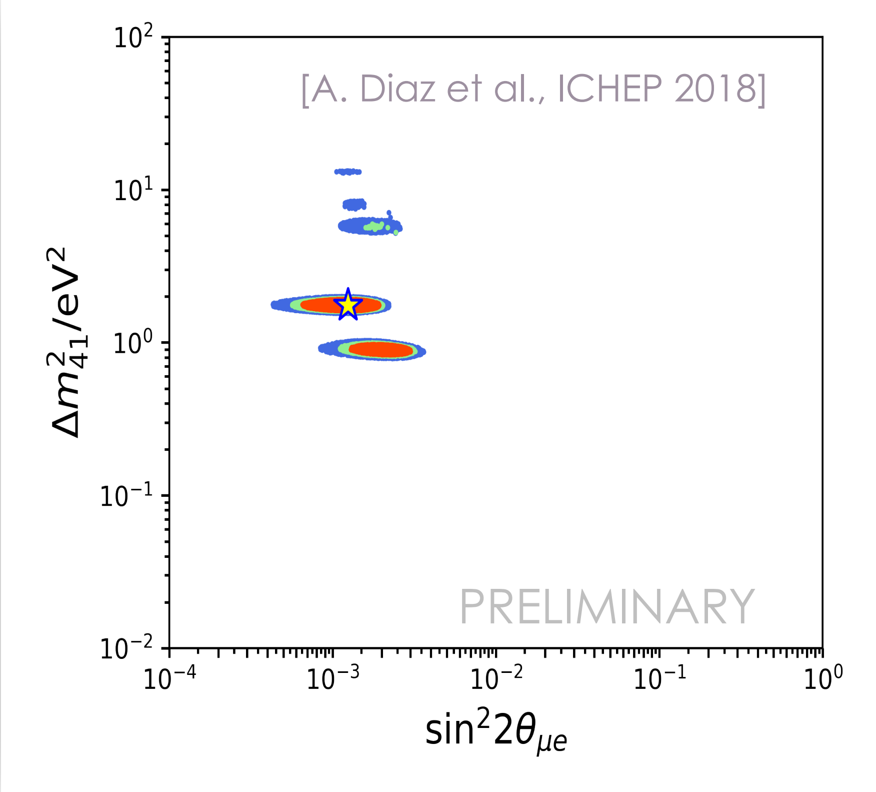
[See A. Diaz et al, ICHEP 2018;
Conrad et al, Adv.High Energy Phys. 2013 (2013) 163897;
GK et al, Phys.Rev. D80 (2009) 073001;
similar analyses by Maltonii, Schwetz, Kopp and others as well]

Also, recently:
IceCube, OPERA, and other MINOS+ analyses
[See, e.g. G. Collin et al., PRL 117, 221801 (2016)]



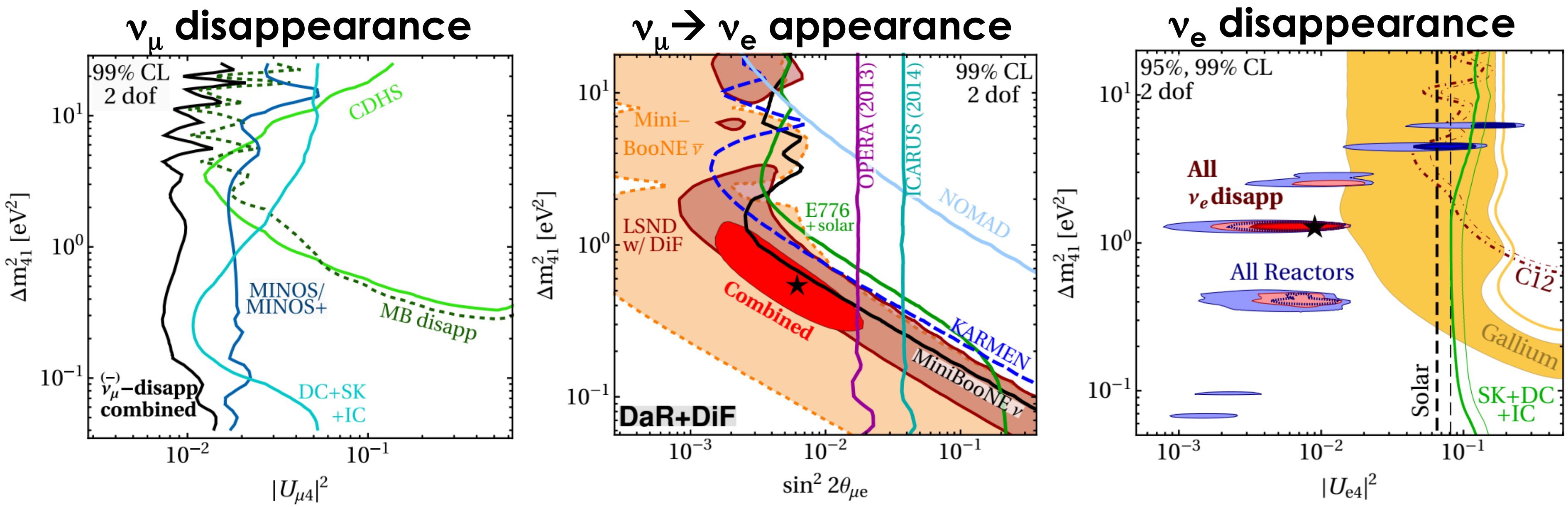
Global fits

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



BUT, results are still inconclusive, due to **tension with ν_μ disappearance searches** at short baselines ($\sin^2 2\theta_{\mu e} \sim \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$ implies non-zero ν_μ disappearance, but none has been seen!)

Global fits



[M. Maltoni, Neutrino 2018]

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What's next?

- Better statistical treatment of data in global fits

- Alternate models: 3+2, 3+3, non-standard interactions, heavy sterile neutrino decay, ...

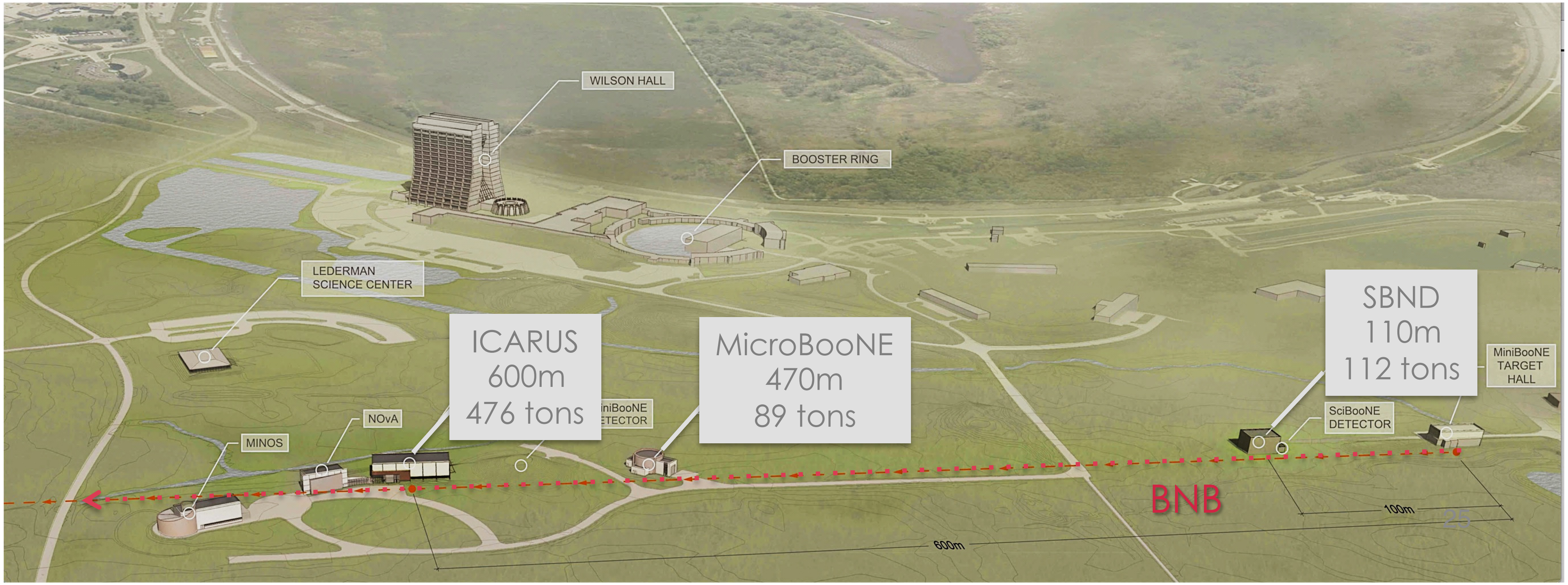
- More sensitive experimental tests
  - Reactor-based: **SoLiD, DANSS, NEOS, STEREO, PROSPECT**
  - Accelerator-based: **SBN**
  - Also searches at long-baseline experiment near detectors and (high-energy) atmospheric neutrino experiments

SBN @ Fermilab

A trio of liquid argon time projection chamber (LArTPC) detectors

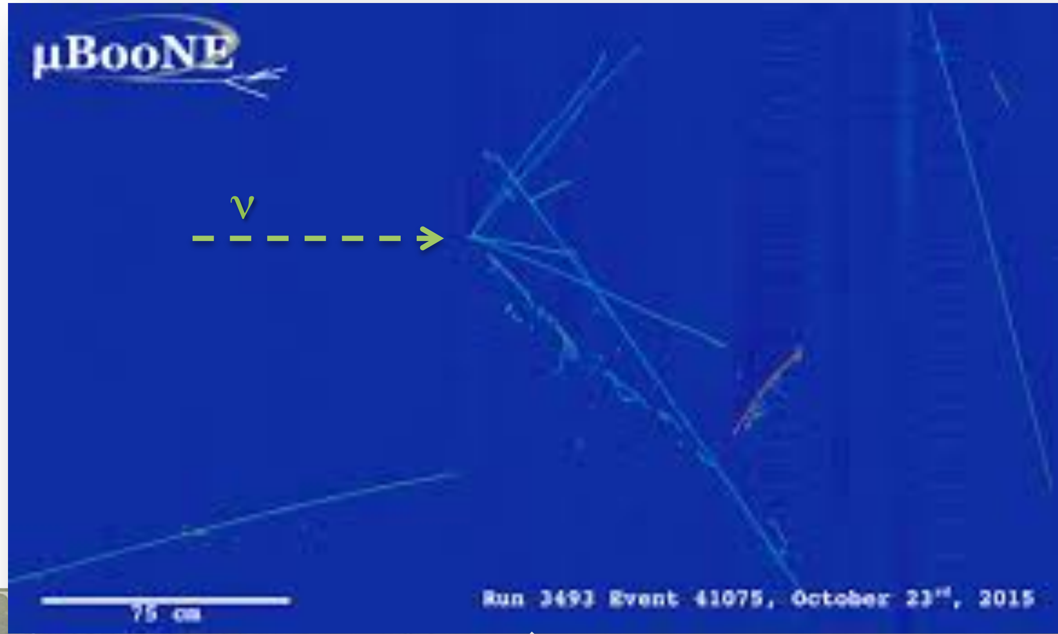
Aim: A definitive test of MiniBooNE/LSND sterile neutrino oscillation interpretation.

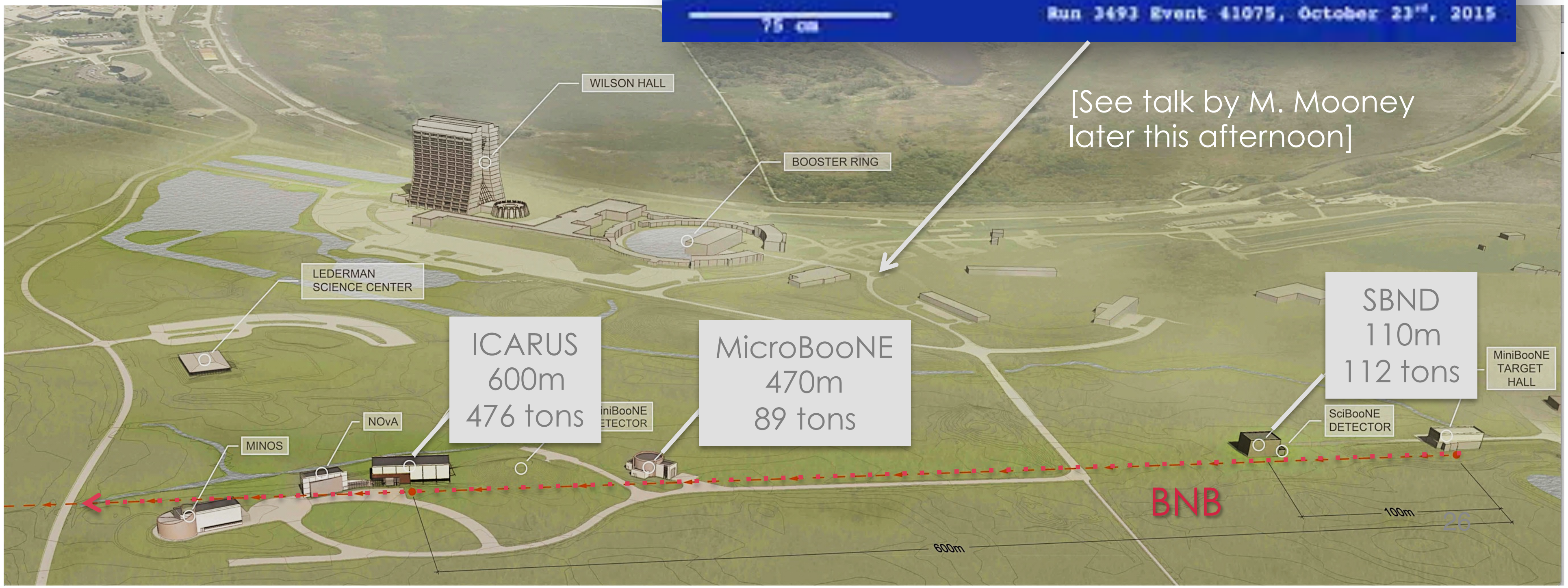
SBND: Under construction; expected to begin operations in early 2020
MicroBooNE: Operating detector, taking data since Oct. 2015!
ICARUS: Under installation; expected to begin operations in 2019



SBN @ Fermilab

LArTPC's: provide high-resolution 2D→3D imaging of charged particles produced in neutrino interactions in liquid argon.

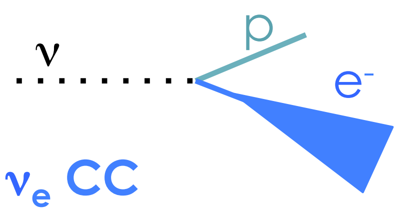


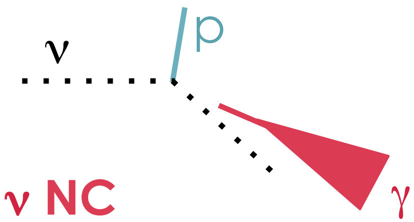


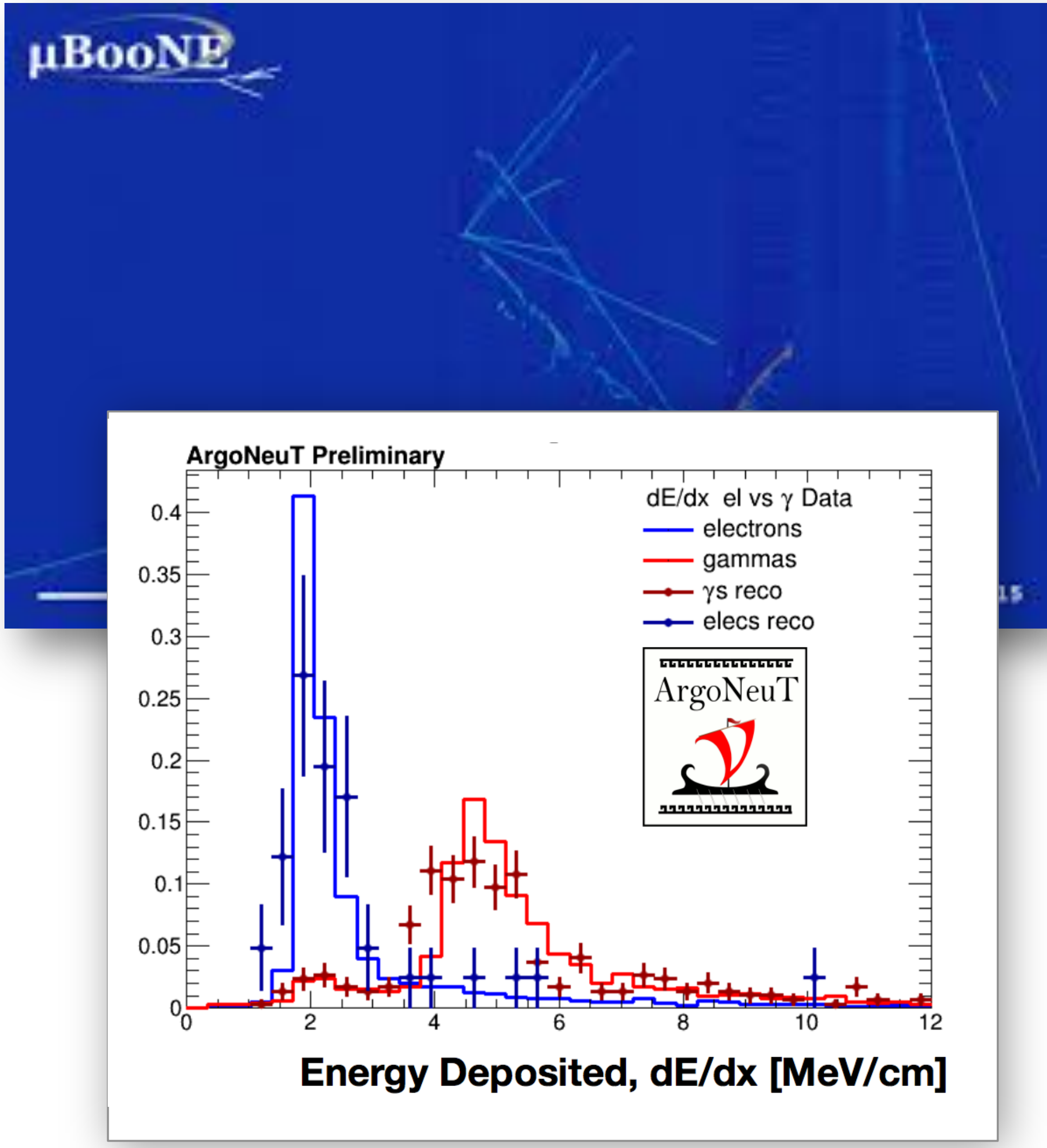
SBN @ Fermilab

Neutrino events with γ are differentiated on the basis of:

1. Detached shower vertex from neutrino interaction vertex
2. Larger dE/dx deposited at the beginning of the shower (2 MIP vs 1 MIP)



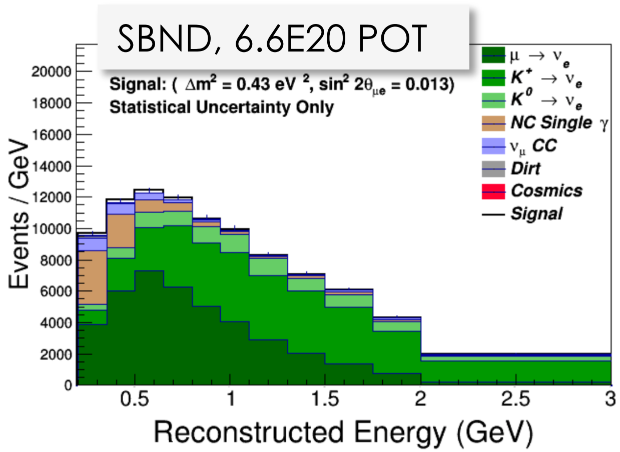


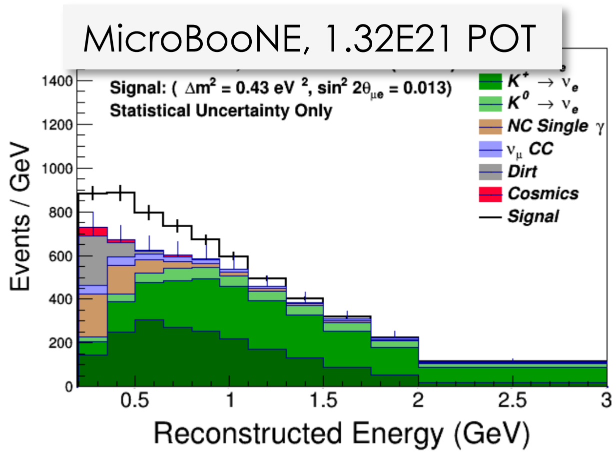


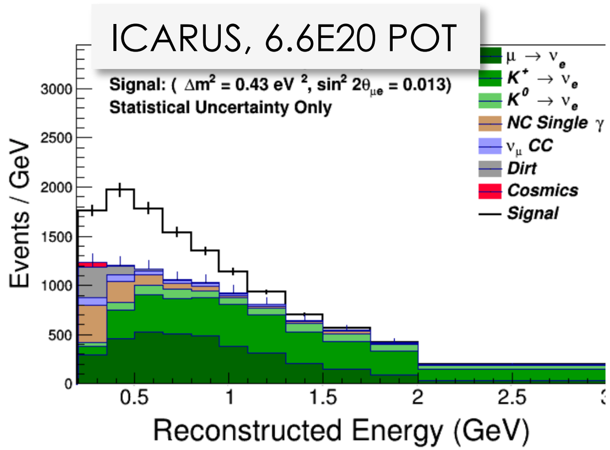
Typical e/γ separation: ~90% → Ideal technology for ν_e measurements

SBN @ Fermilab

SBN ν_e appearance channel search: (3+1)







[SBN Proposal 2015]

SBN @ Fermilab

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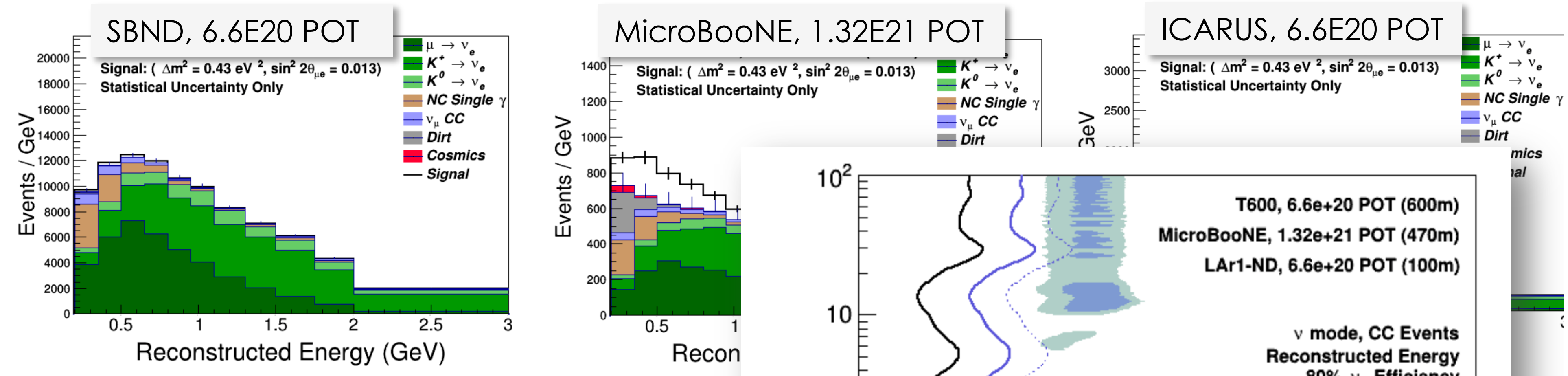
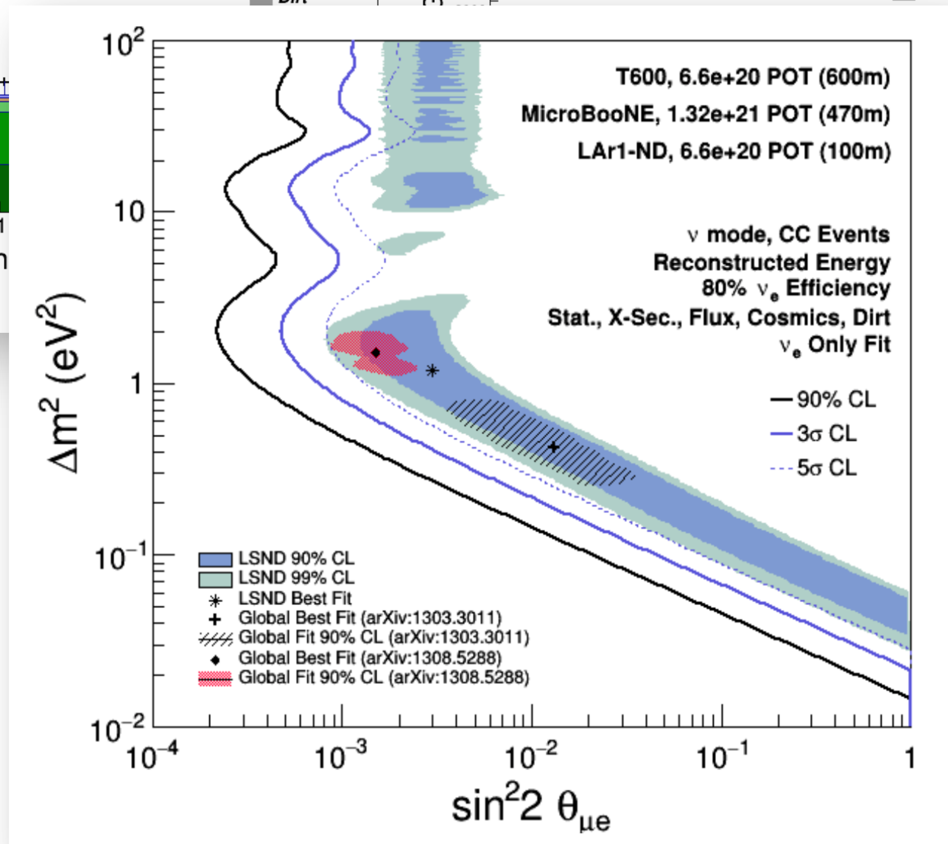


[SBN Proposal 2015]

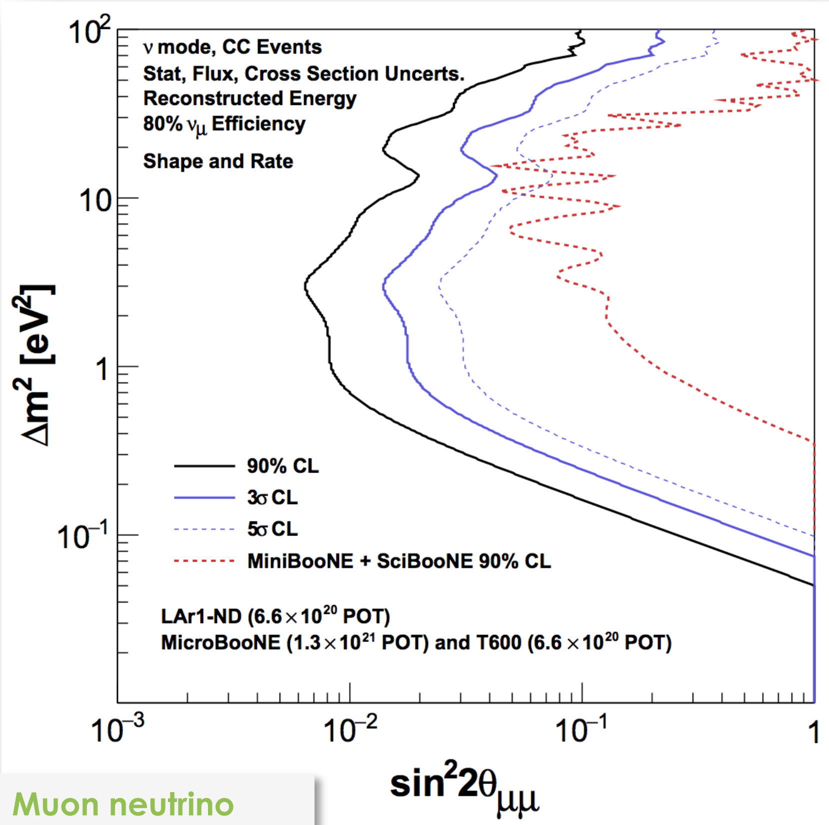


SBN will be able to test existing indications for ν_e appearance at 5σ level!

SBN @ Fermilab

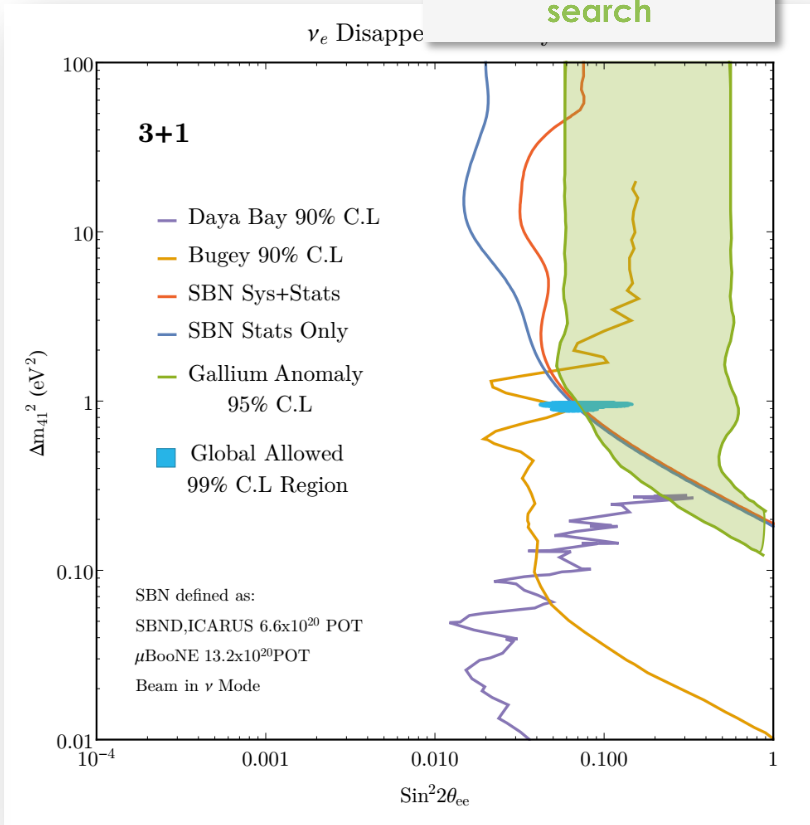
In addition to ν_e appearance…

Electron neutrino disappearance search



[SBN Proposal 2015]

Muon neutrino disappearance search

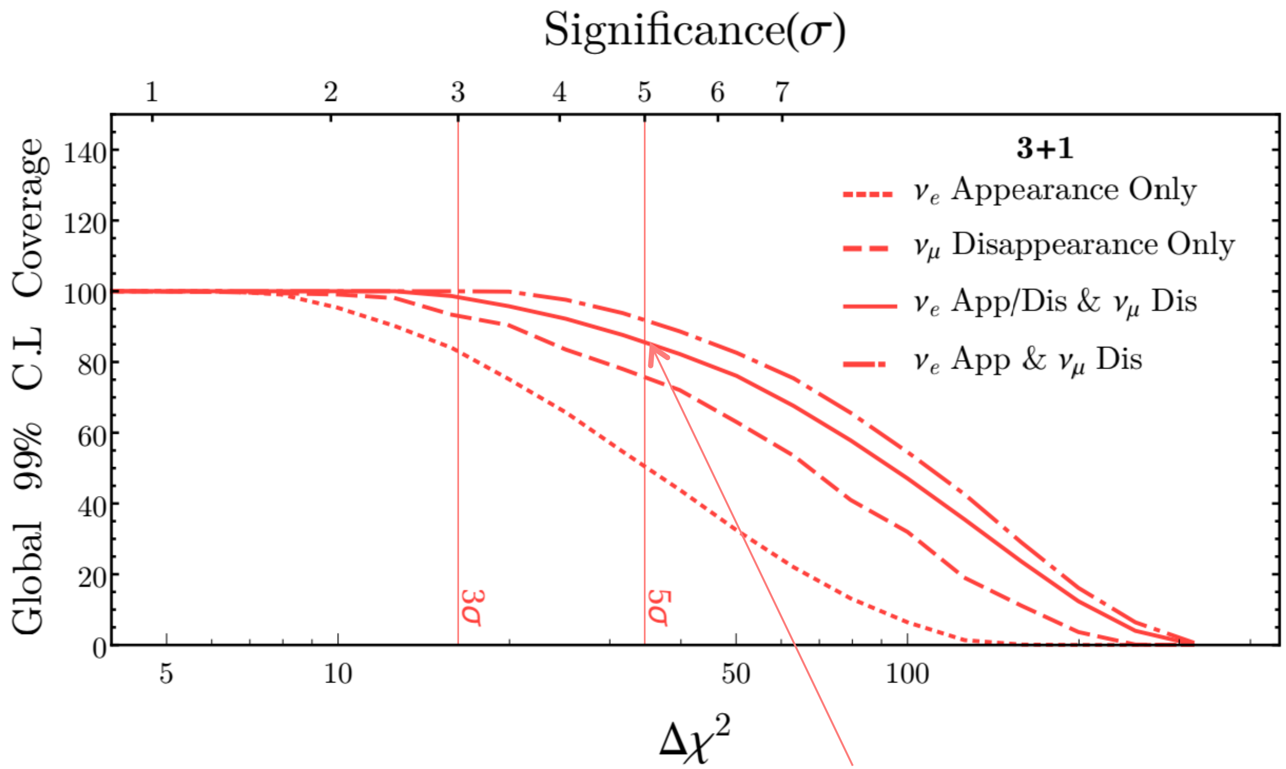


[Cianci, et al, arXiv:1702.01758]

SBN can probe multiple oscillation channels! (Shown here independently)

SBN @ Fermilab

[D. Cianci et al., Phys. Rev. D 96, 055001 (2017)]

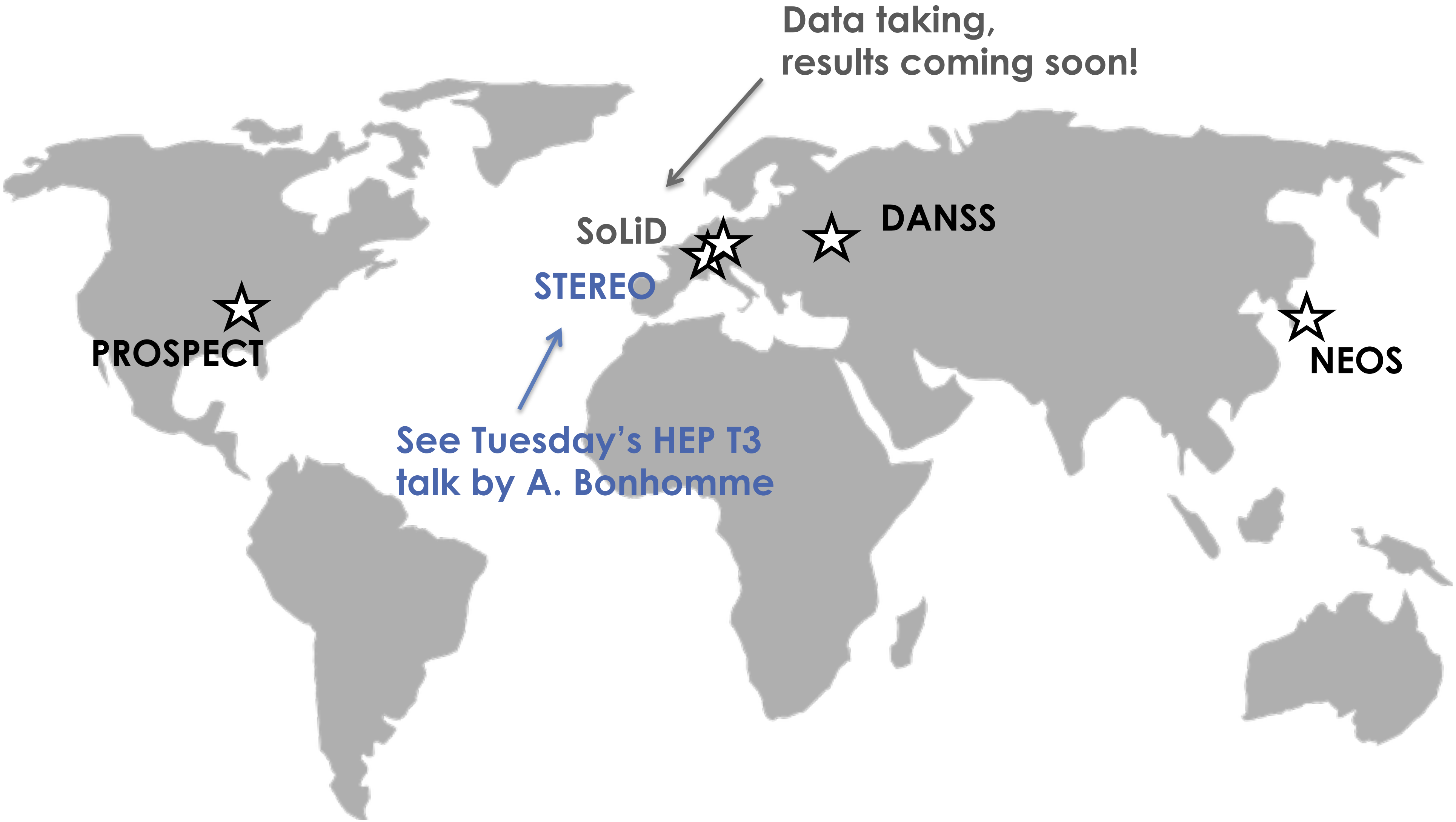


- ν_e app/dis and ν_μ disap search: 85% coverage of 99%CL allowed phase-space at 5σ

- Overall sensitivity to 3+1 greatly enhanced when combining multiple oscillation channels in the fit!
- Simultaneous search for ν_e and ν_μ disappearance without consideration of ν_e disappearance overestimates sensitivity.

Reactor SBL searches

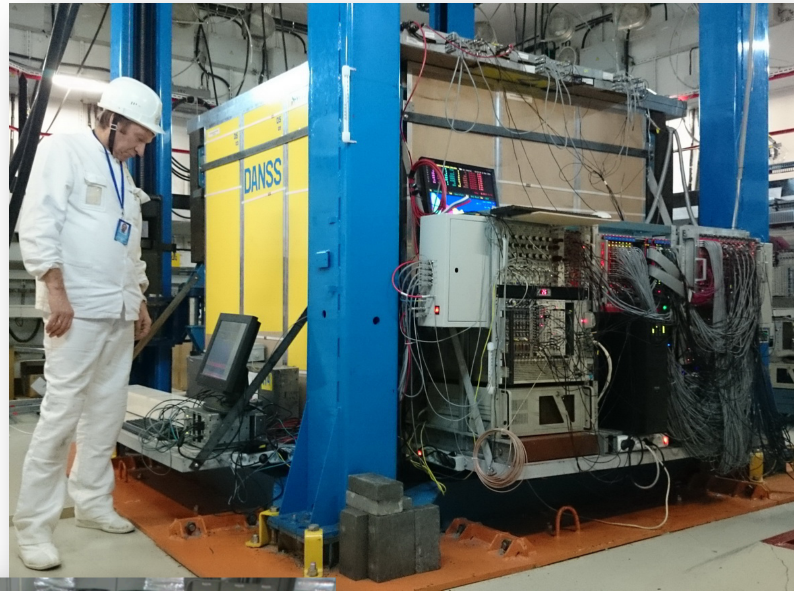
Reactor SBL searches



Reactor SBL searches

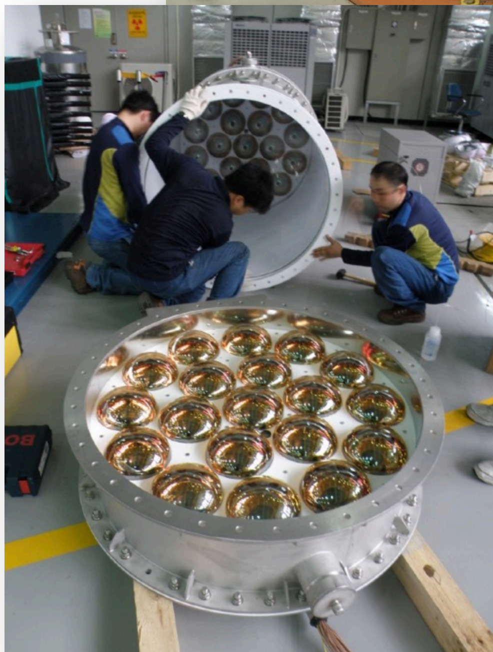
DANSS at Kalinin Nuclear Power Plant:

- Solid-state scintillator detector
- Compact, segmented, movable (10.7-12.7 m) detector
- Data taking since April 2016; analysis data in Oct. 26
- Preliminary results at Neutrino 2018



NEOS at Hanbit-5 Nuclear Reactor in Korea:

- Liquid scintillator detector
- Compact, homogeneous, 24m from reactor core
- Data taking during Aug. 2015-May 2016
- First results at Neutrino 2018



Reactor SBL searches

DANSS at Kalinin Nuclear Power Plant:

- Solid-state scintillator detector
- Compact, segmented, movable (10.7-12.7 m) detector
- Data taking since April 2016; analysis data in Oct. 26
- Preliminary results at Neutrino 2018

NEOS at Hanbit-5 Nuclear Reactor in Korea:

- Liquid scintillator detector
- Co
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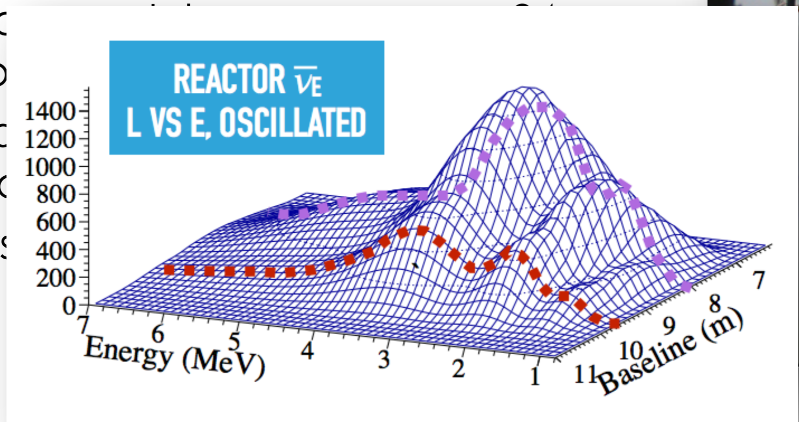
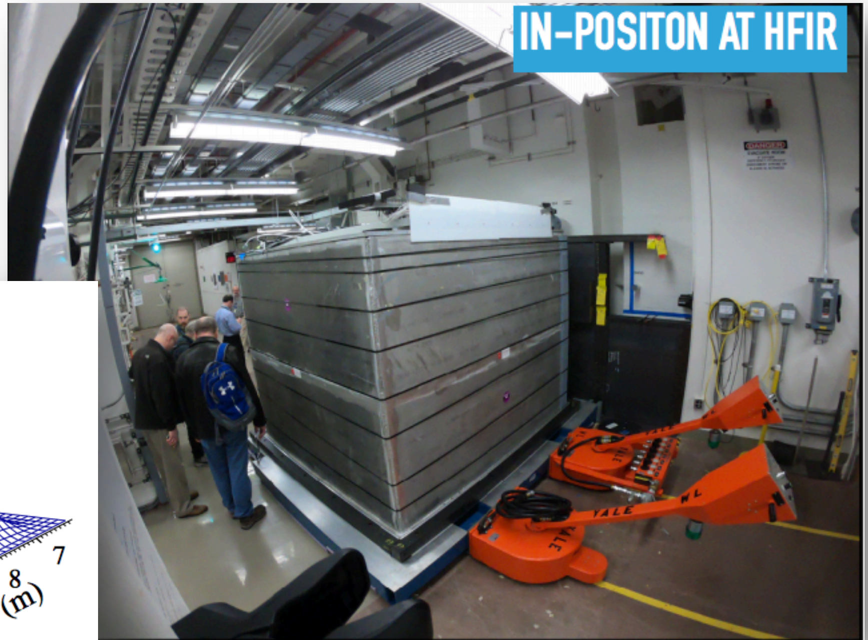
- Do
  Mo
- Firs



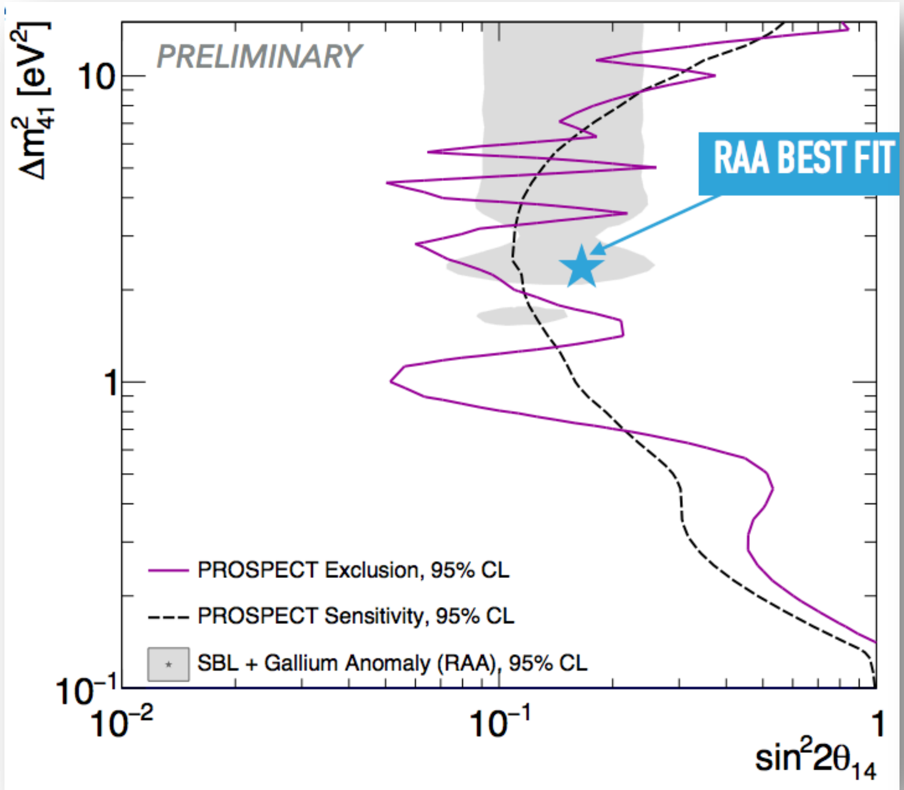
PROSPECT at High Flux Isotope Reactor in US

- 6Li-loaded liquid scintillator
- Compact, segmented, movable (7-9 m) detector
- Data taking since March 2018
- First results in June 2018 [arXiv: 1806.02784]

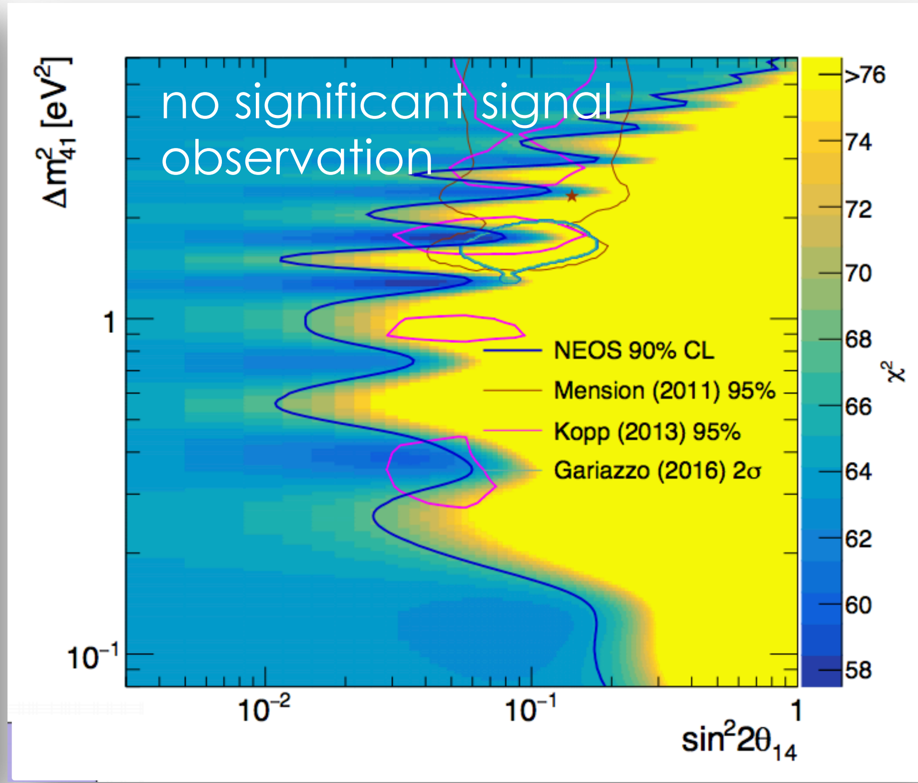


Reactor SBL searches

PROSPECT at High Flux Isotope Reactor:



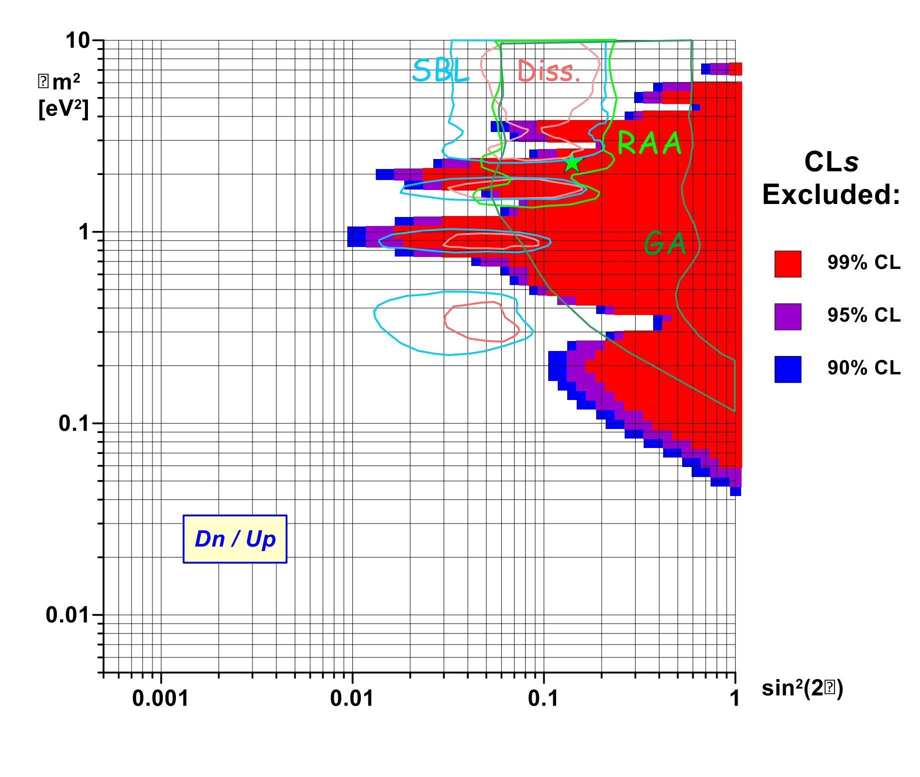
NEOS at Hanbit-5 Nuclear Reactor in Korea:

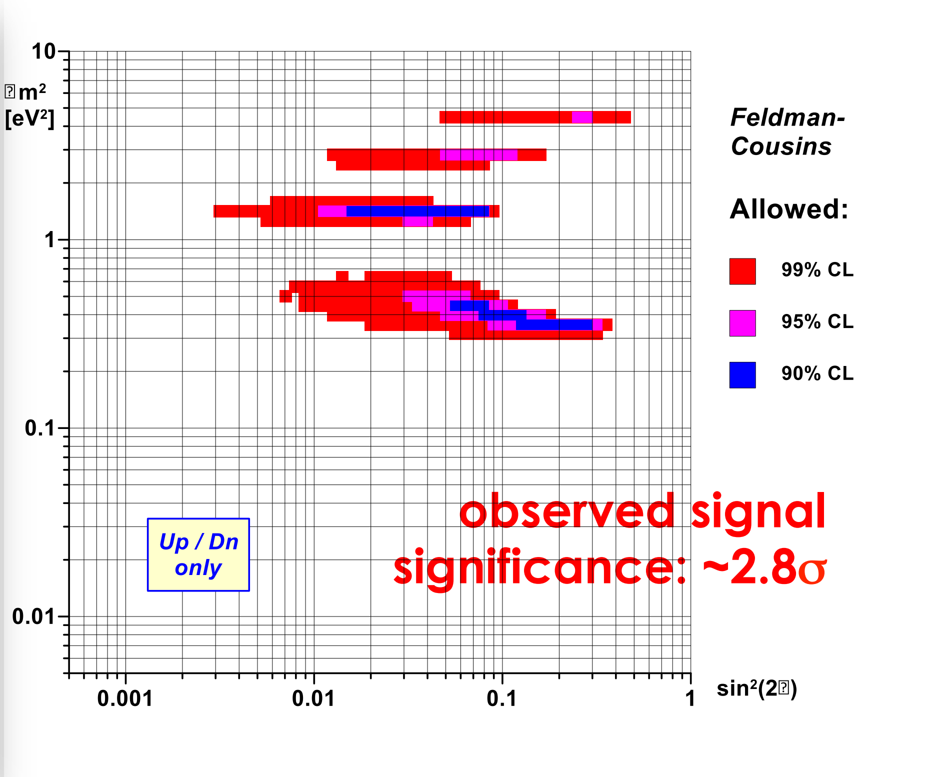


No significant signals observed by PROSPECT or NEOS...

Reactor SBL searches

DANSS at Kalinin Nuclear Power Plant:





Multiple phenomenology groups are in the process of including new reactor short-baseline results into global fits to sterile neutrino oscillations. (Maltoni & Schwetz, Conrad & Shaevitz, GK and others).

Summary

- Since the mid nineties (and earlier, with calibration source measurements for radiochemical experiments), we have been amassing anomalous excess/deficits of ν_e at L/E ~ 1m/MeV, from ν_μ and ν_e sources
  - LSND, MiniBooNE, reactor neutrino measurements at short baselines
  - Require additional, high-Δm^2 to interpret as two-neutrino oscillation → sterile neutrino(s)?
  - But 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:
  - SBN accelerator-based program at Fermilab coming online by 2020
  - Several experiments at very short baselines near reactors, with new results this summer from DANSS, STEREO, PROSPECT, and NEOS, and highly anticipated results coming soon from SoLiD.

- Stay tuned!

Thank you!