The current experimental situation in neutrino physics

Ryan Patterson
Caltech

Aspen Center for Physics Winter Conference
"Frontiers in Particle Physics: From Dark Matter to the LHC and Beyond"

January 22, 2014

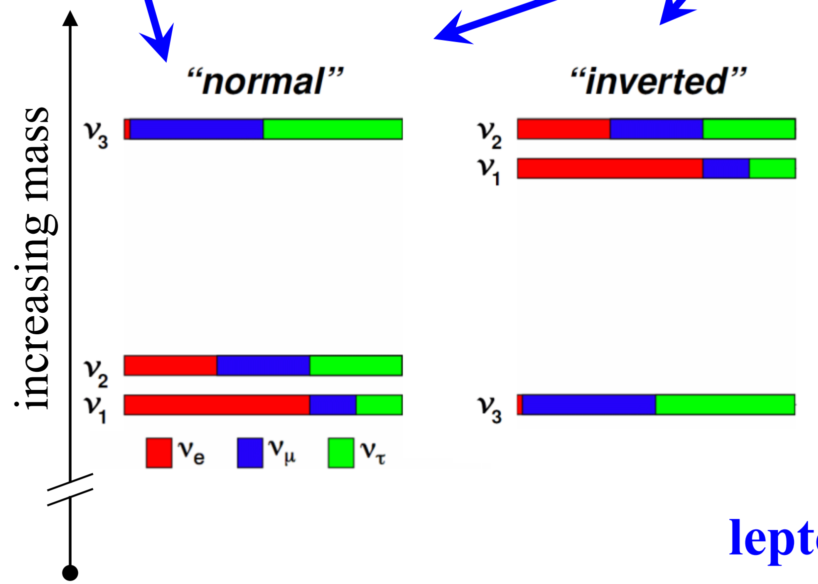
The questions

Light sterile states?
(experimental anomalies)

$|U_{\mu 3}| = |U_{\tau 3}|$?
("maximal mixing")

mass ordering?
("hierarchy")

Majorana or Dirac?



GUT-scale physics?
(see-saw connection)

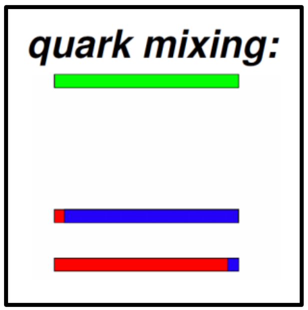
unitary?

absolute masses?

leptonic CP violation?

astrophysics/cosmology
(solar ν, supernovae, DM,
ultra-high-energy ν, CνB)

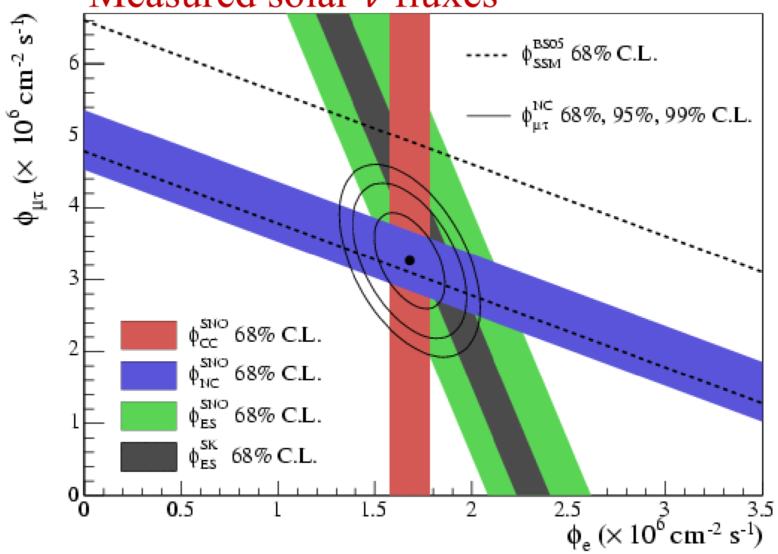
U_{PMNS} has "first-order" structure, contrast with U_{CKM}
(model building, unification,
new physics, ...)



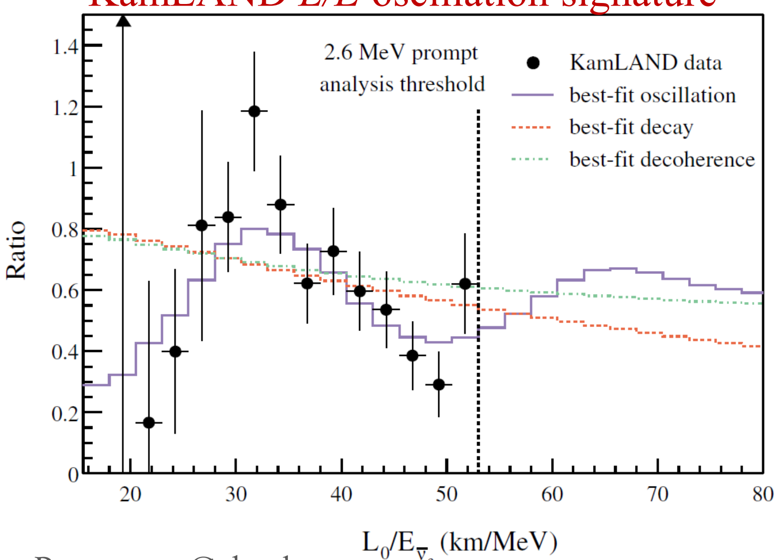
...and more *(geoneutrinos,*
nuclear processes, ν interactions)

"Solar" parameters θ_{12} and Δm^2_{21}

Measured solar ν fluxes

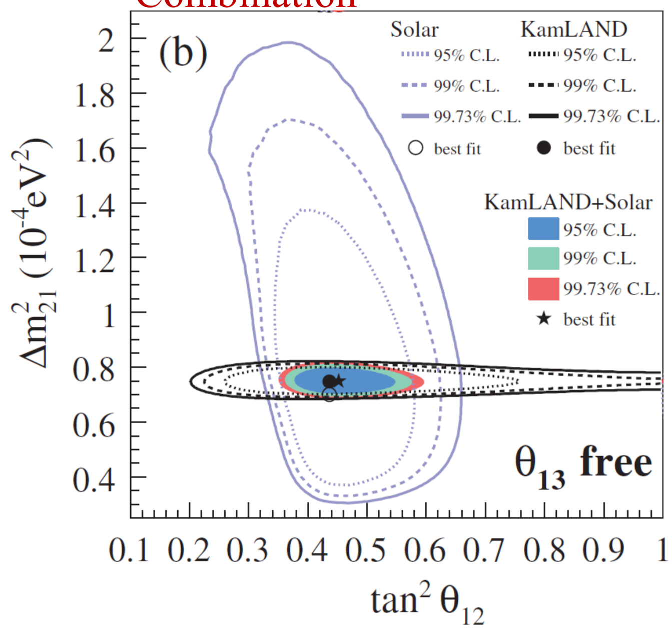


KamLAND *L/E* oscillation signature



- **SNO** *(solar)*, **Super-K** *(solar)*, **KamLAND** *(reactor)* and others
- No big change expected from current experiments
  (Future reactor expts. [e.g. JUNO] in the works)

Combination



A. Gando *et al.*, PRD **83**, 052002 (2011)

$$\Delta m^2_{21} = (7.50\,^{+0.19}_{-0.20}) \times 10^{-5}\ \text{eV}^2$$

$$\sin^2(2\theta_{12}) = 0.857\,^{+0.023}_{-0.025}$$

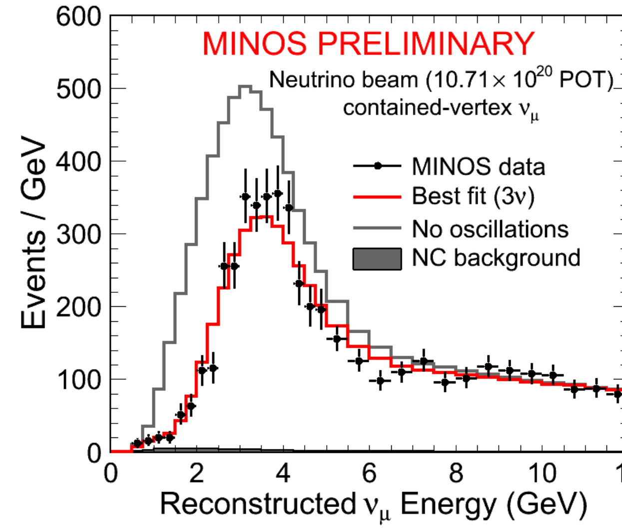
“Atmospheric” parameters θ_{23} and $|\Delta m^2_{32}|$

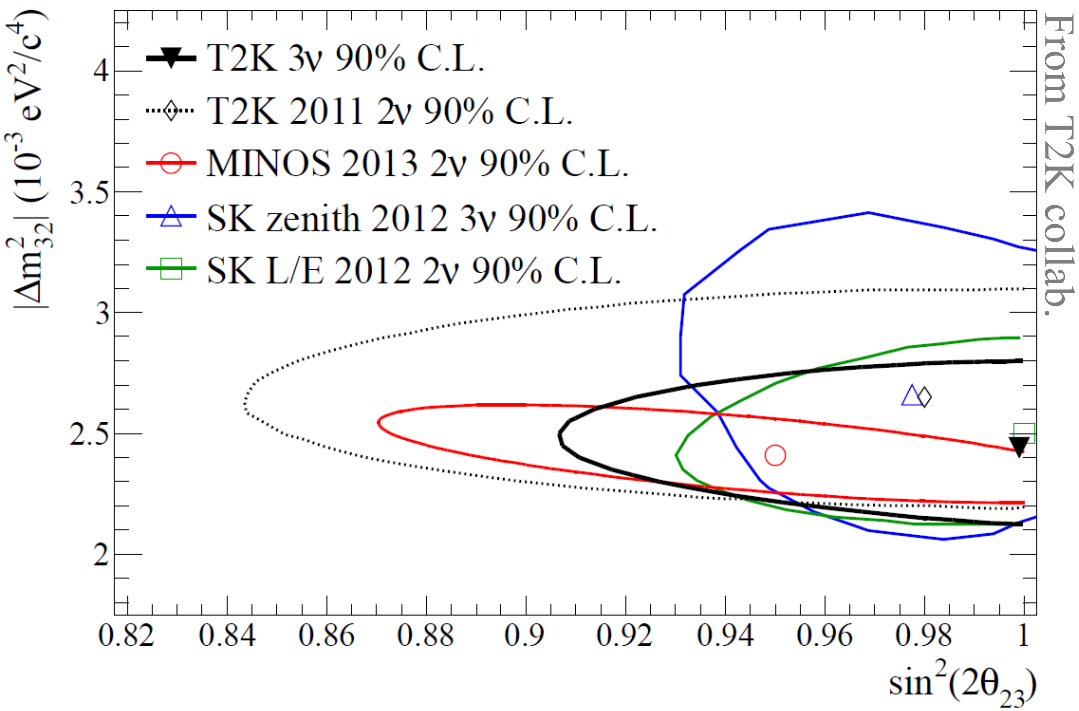
- **Super-K** *(atmospheric)*, **MINOS** *(accelerator)*, **T2K** *(accelerator) and others*
- Measurements **still rolling in** (see later).

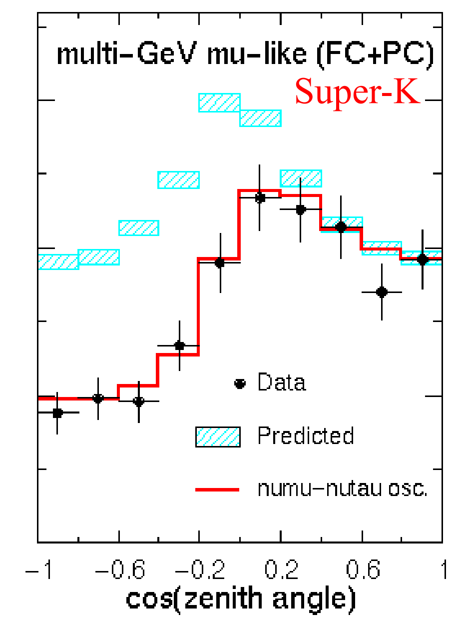
Simple but incomplete way of summarizing things (more later…)

$$|\Delta m^2_{32}| = (2.32\,^{+0.12}_{-0.08}) \times 10^{-3}\ \text{eV}^2$$

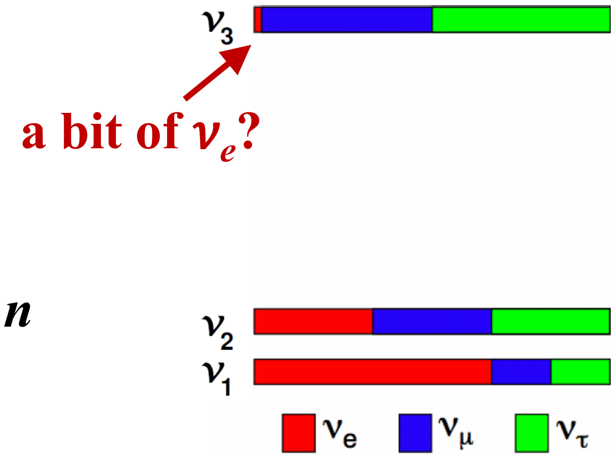
$$\sin^2(2\theta_{23}) > 0.95 \quad \text{(90\% C.L.)}$$



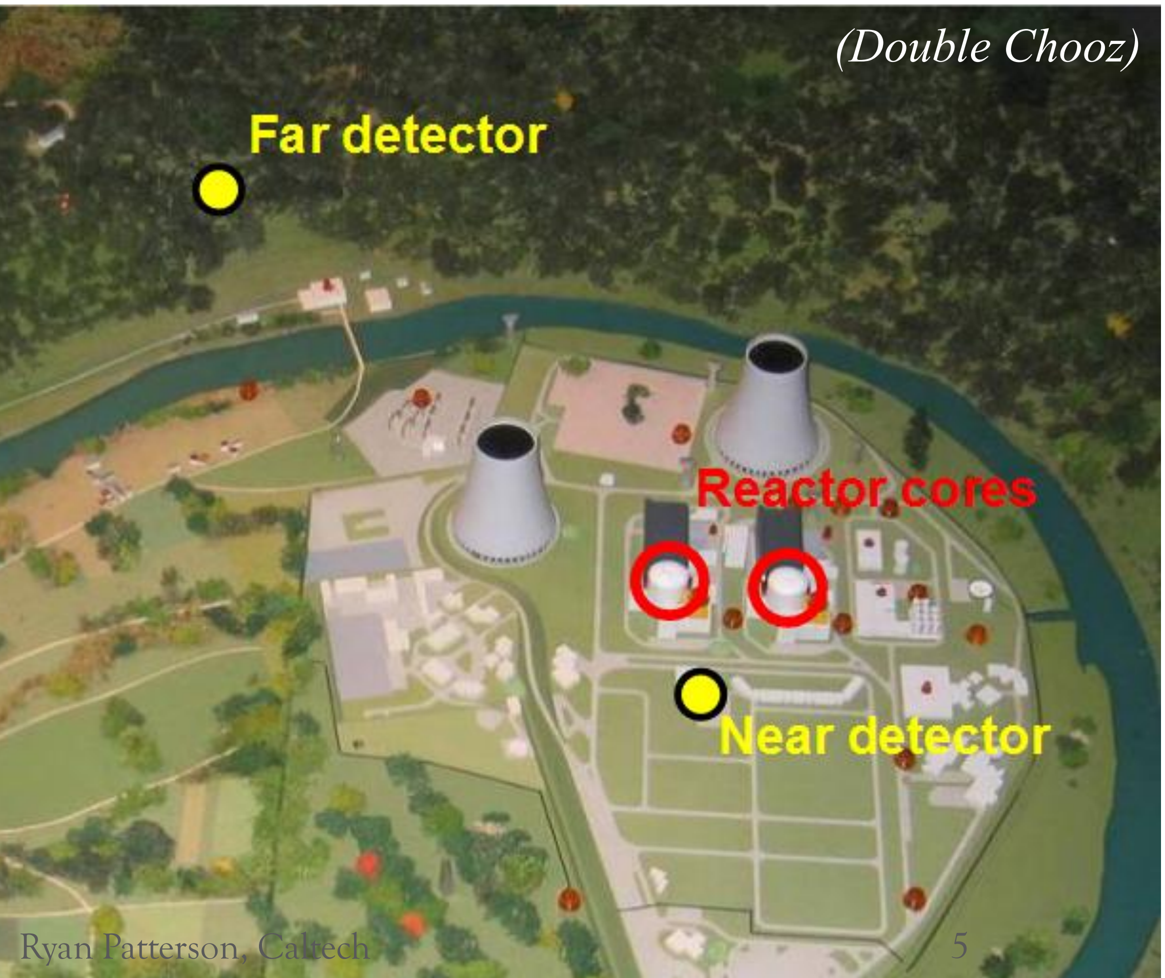


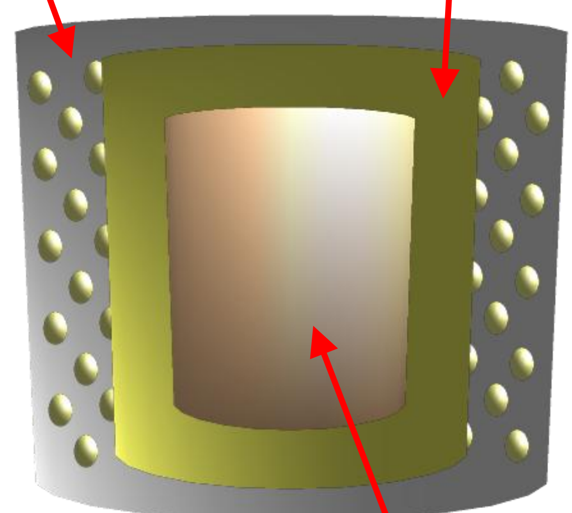


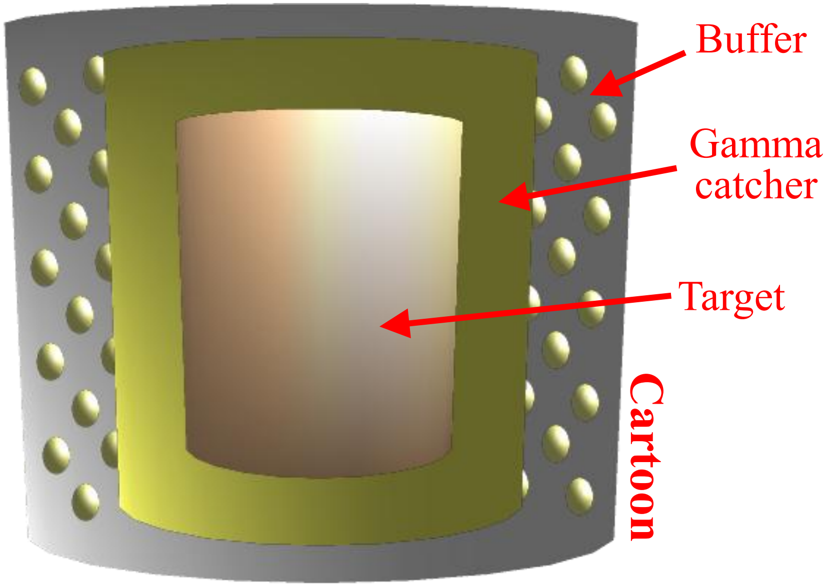
Recent prize: θ_{13}



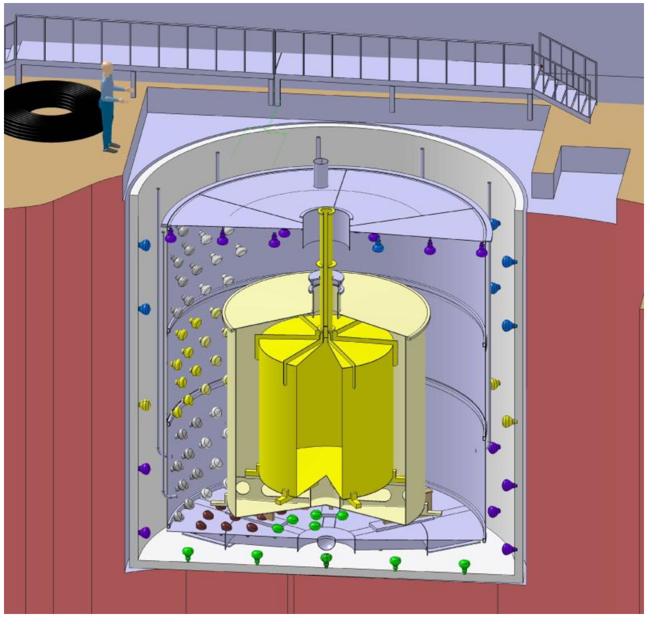
- **Last mixing angle** to be bracketed. Previously just known to be **small relative to θ_{12}, θ_{23}**
- **Reactor expts.** using inverse beta decay: $\overline{\nu}_e + p \rightarrow e^+ + n$
  prompt e^+ signal, delayed n-capture signal



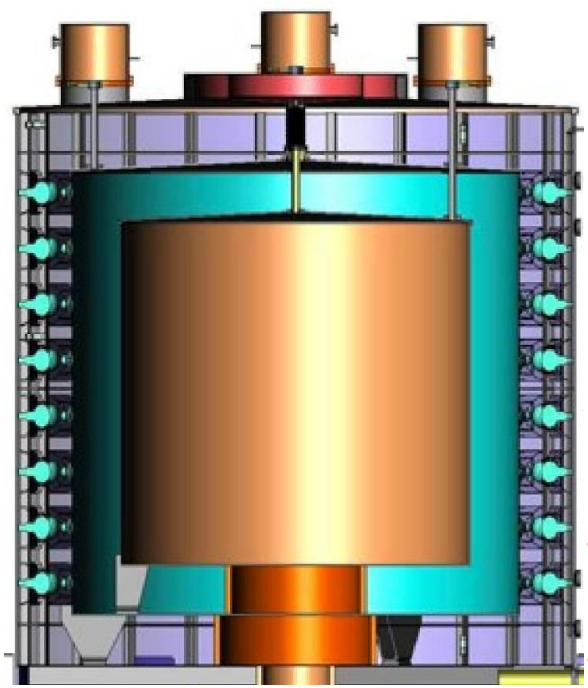




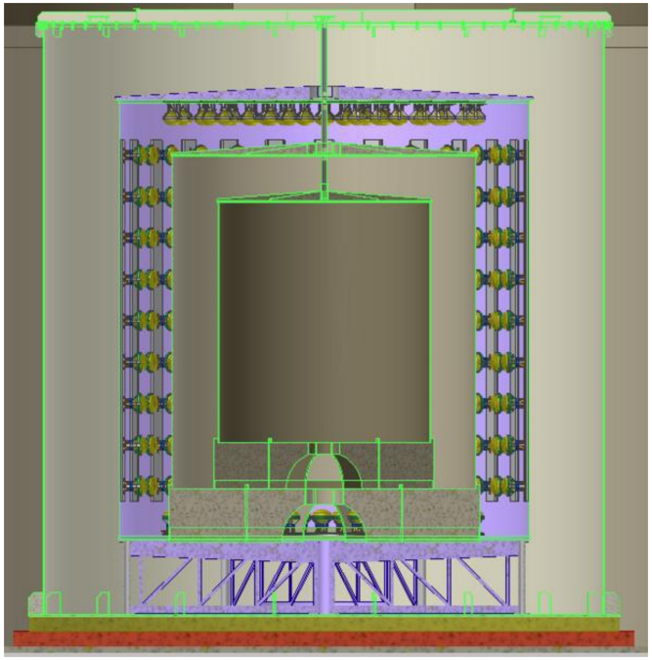
Cartoon



Double Chooz



Daya Bay



RENO

θ_{13} from reactor measurements

Daya Bay: $\sin^2(2\theta_{13}) = 0.090^{+0.008}_{-0.009}$

Multiple detector sites, 8 detectors in total, rate+shape signal extraction.
Best precision for this generation of experiments (4% by end of 2015).

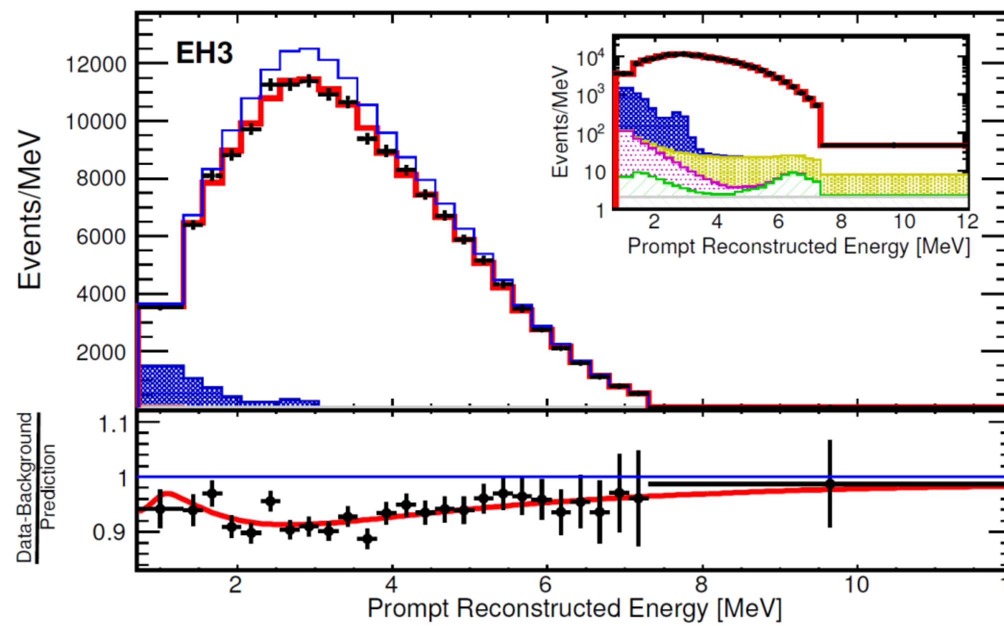
Double Chooz: $\sin^2(2\theta_{13}) = 0.097 \pm 0.035$

FD only so far, ND running to start this year.
Recent update: n-Gd, n-H captures and reactor rate modulation (bckgnd control)

RENO: $\sin^2(2\theta_{13}) = 0.100 \pm 0.018$

2 detectors, rate-only analysis so far.
7% measurement by end of 2015.

Daya Bay data as example.
Deficit consistent with oscillations.

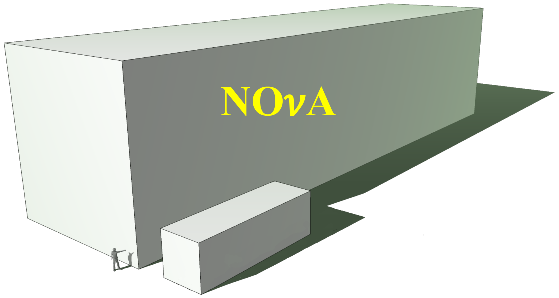


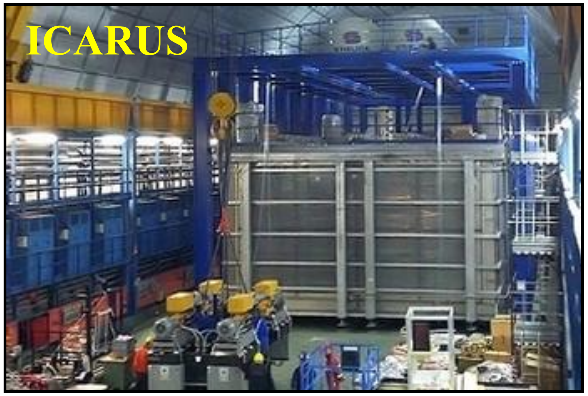
Long-baseline experiments

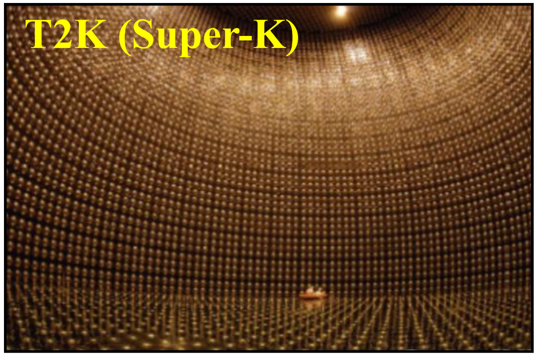
- **θ_{13}>0 ⇒ NOνA, T2K, (MINOS) can probe mass hierarchy, δ, θ_{23} octant**

  Also: **$|\Delta m^2_{32}|$, $\sin^2(2\theta_{23})$, $\nu/\bar{\nu}$ comparisons, steriles, NSI, cross sections, supernova**

- **LBL experiments with different goals:**
  OPERA (ν_τ appearance, ToF, …)
  ICARUS (LAr R&D, ν_τ appearance, steriles, …)
  Have to leave out for time…







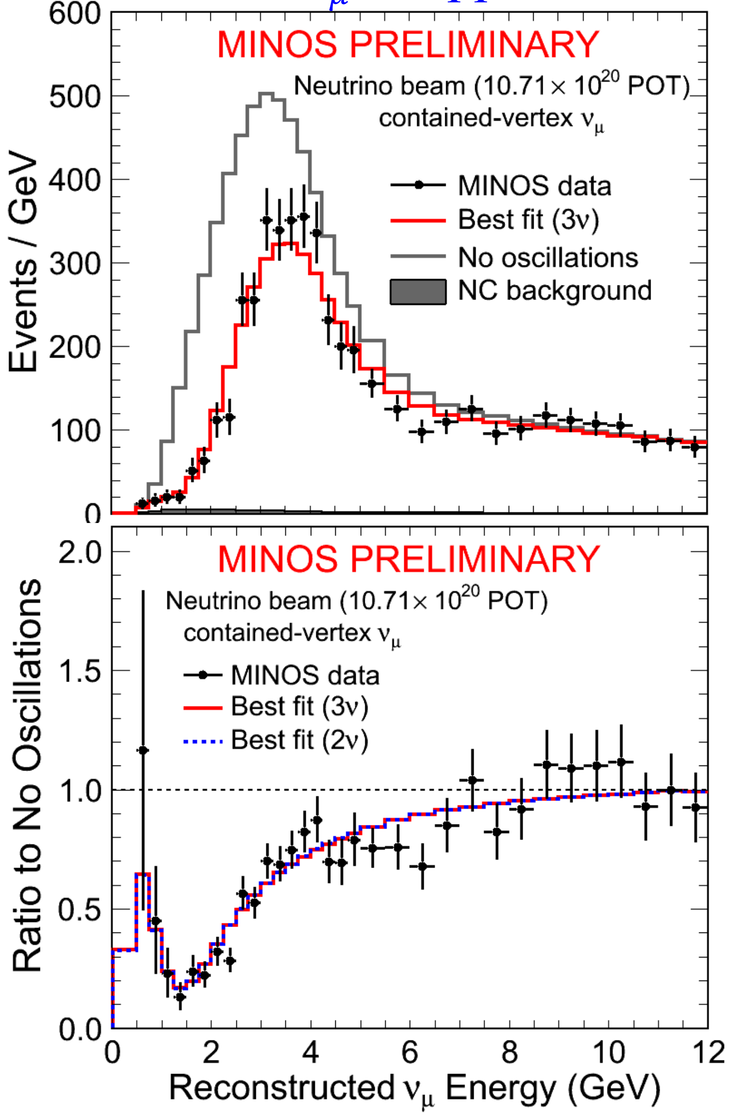
MINOS

Fermilab to Soudan, 735 km

Near and far detectors:
Steel/scintillator magnetized tracking calorimeters

New in 2013: Full MINOS data set combined in 3-flavor fit

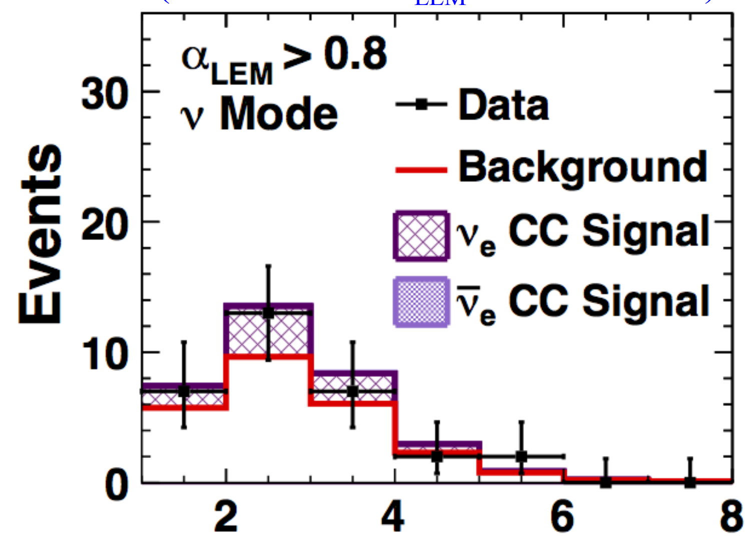
NuMI ν_μ disappearance



- **ν_μ and $\bar{\nu}_\mu$ disappearance** (NuMI beam)
- **ν_μ and $\bar{\nu}_\mu$ disappearance** (atmospheric ν)
- **ν_e and $\bar{\nu}_e$ appearance** (NuMI beam)

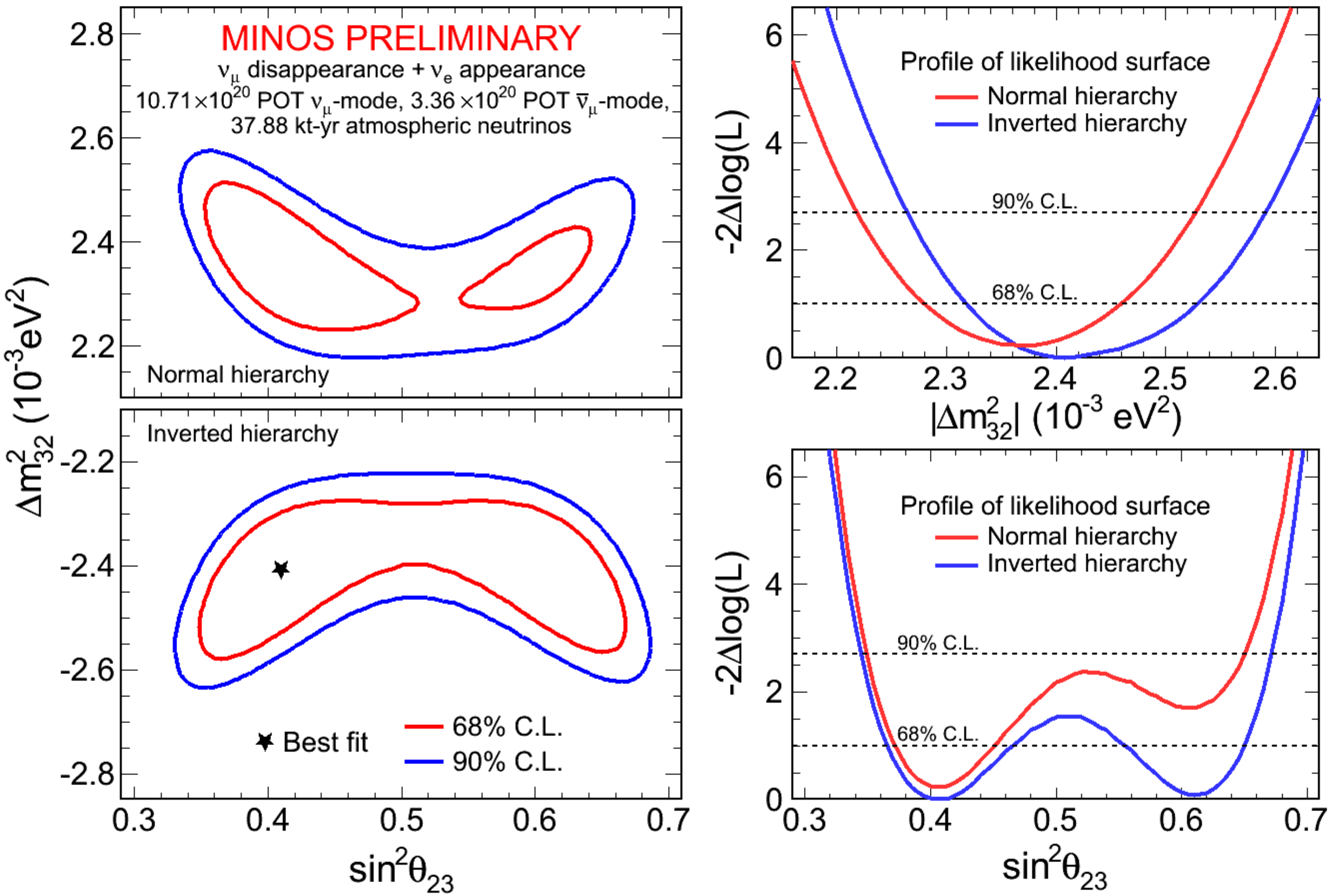
ν_e appearance

(most sensitive α_{LEM} bin shown here)



- **Confidence intervals in a portion of parameter space**
  (θ_{13} and CP phase δ marginalized out for clarity)

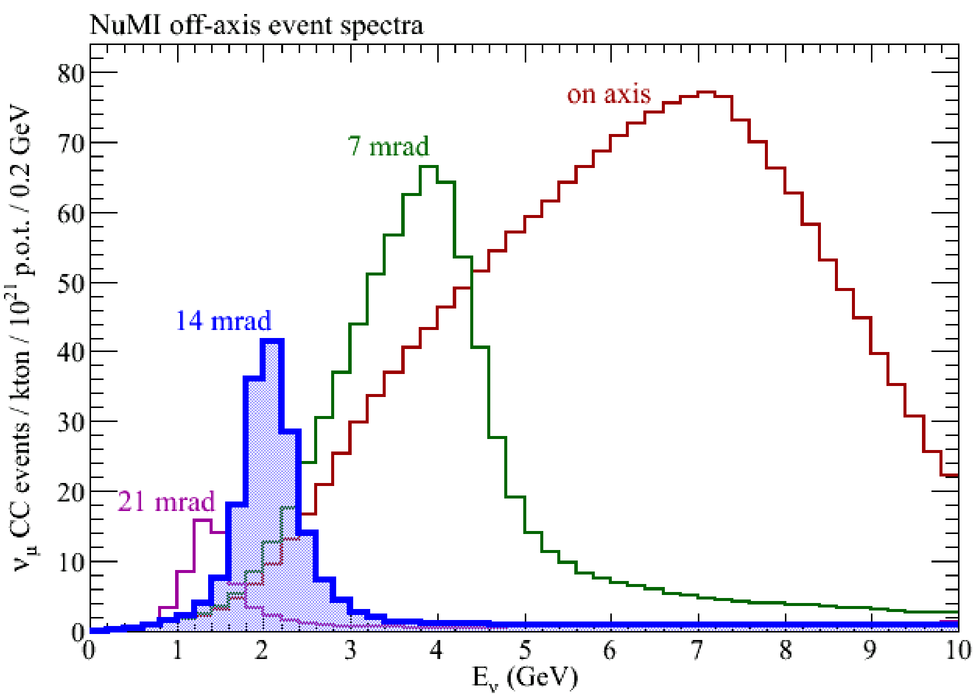
$|\Delta m^2_{32}|$ precision = 4%
Δm^2_{21} / $|\Delta m^2_{32}|$ = 3%
⇒ 2ν approximations are behind us



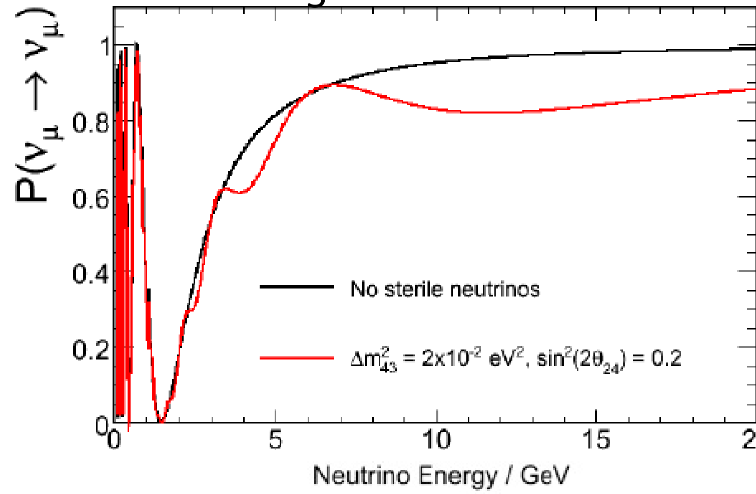
“Medium energy” NuMI

MINOS → MINOS+,
Higher neutrino energies: precisions tests and searches *(examples at right)*

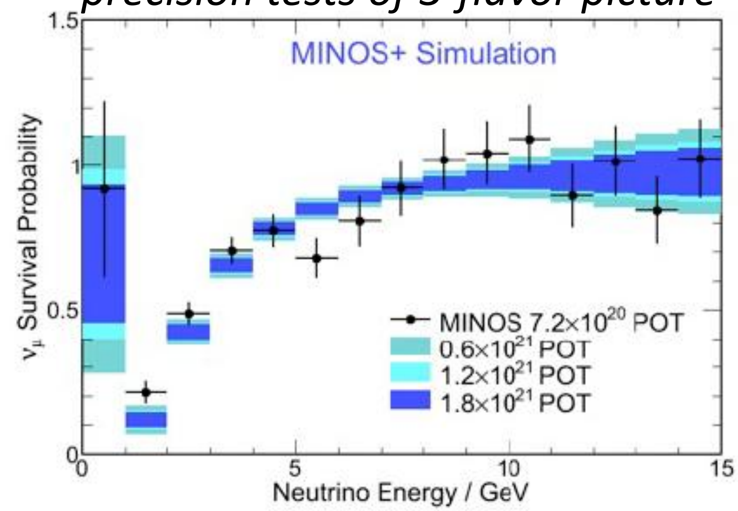
NuMI upgraded to 700 kW
(though still operating at ~400 kW pending commissioning and Booster RF upgrades)



sterile ν signature at MINOS+



precision tests of 3-flavor picture



NOνA

A broad physics scope

Using $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ …

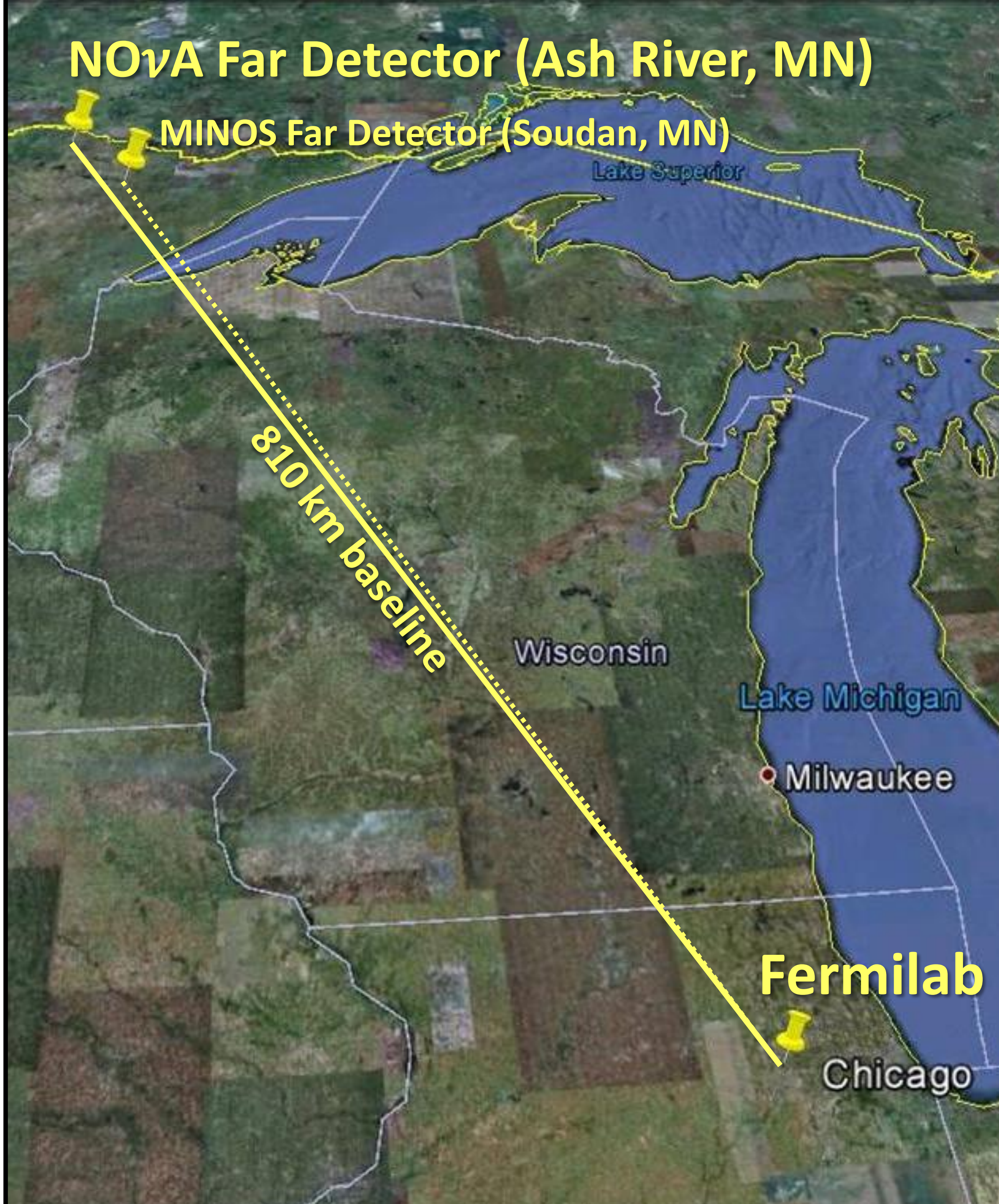
- **Measure θ_{13}** via ν_e appearance
- Determine the **ν mass hierarchy**
- Search for **ν CP violation**
- Determine the **θ_{23} octant**

Using $\nu_\mu \rightarrow \nu_\mu$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ …

- **Atmospheric parameters:** precision measurements of θ_{23} , $|\Delta m^2_{32}|$. (*Exclude* $\theta_{23}=\pi/4$?)
- **Over-constrain** the atmos. sector (*four oscillation channels*)

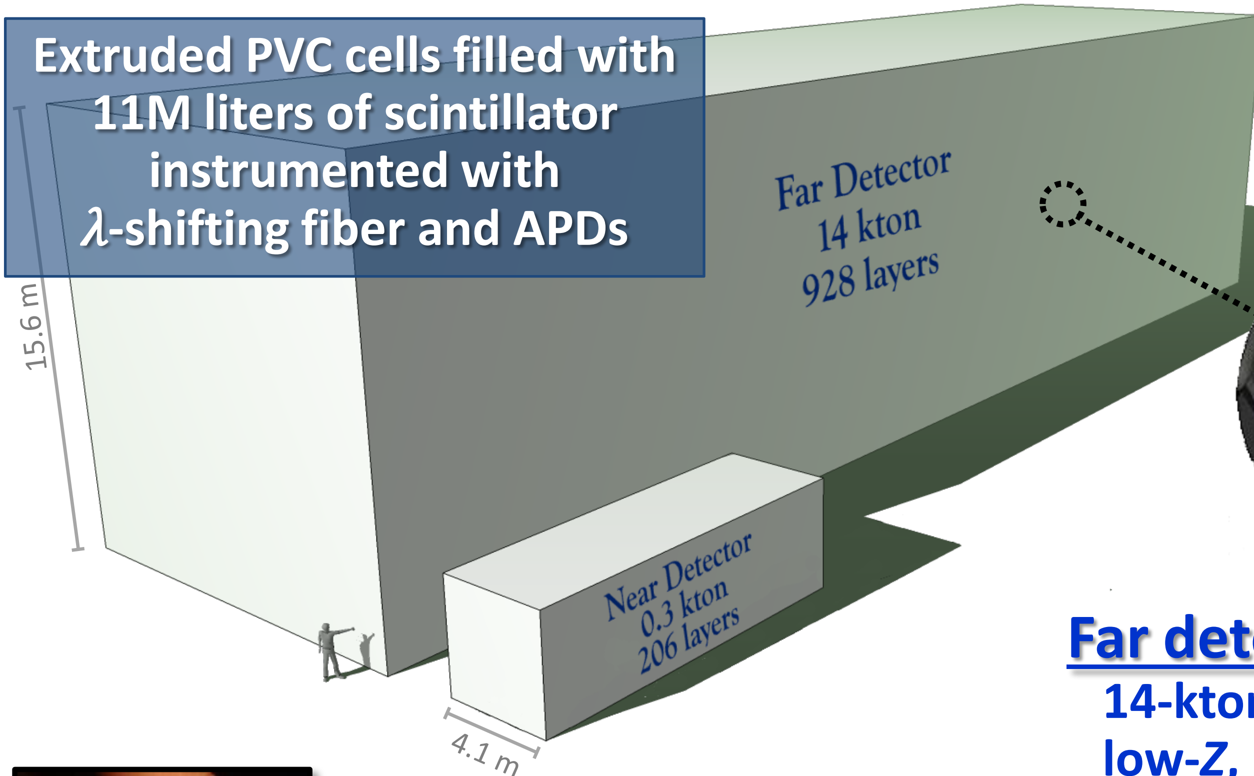
Also …

- Neutrino cross sections at the NOνA Near Detector
- Sterile neutrinos
- Supernova neutrinos
- Other exotica

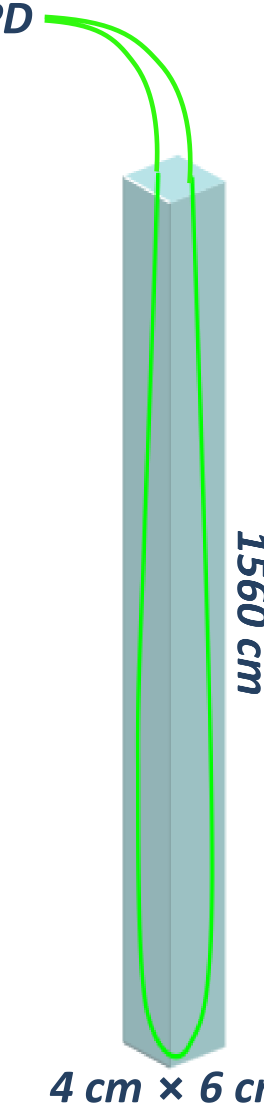


NOvA detectors

Extruded PVC cells filled with 11M liters of scintillator instrumented with λ-shifting fiber and APDs



A NOvA cell

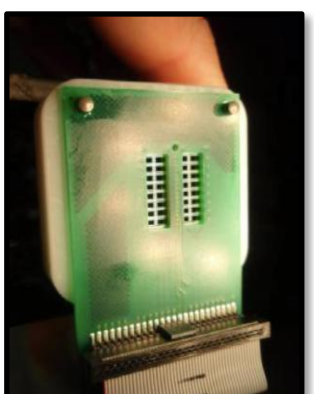


Far detector:

14-kton, fine-grained, low-*Z*, highly-active tracking calorimeter
→ *360,000 channels*

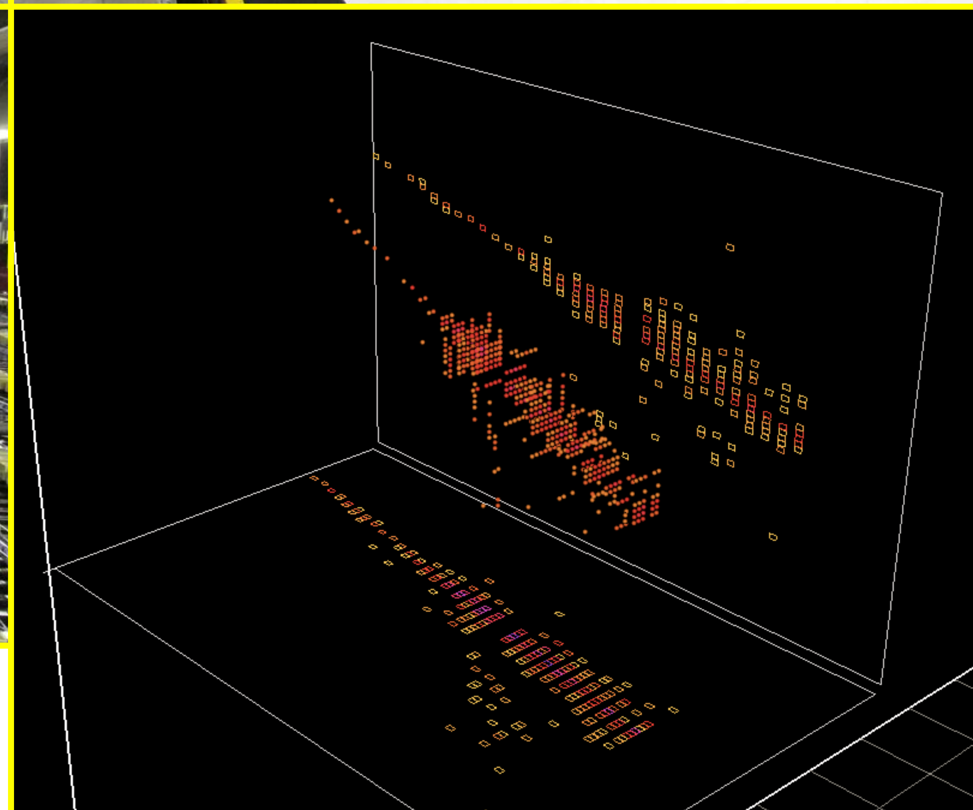
Near detector:

0.3-kton version of the same
→ *18,000 channels*



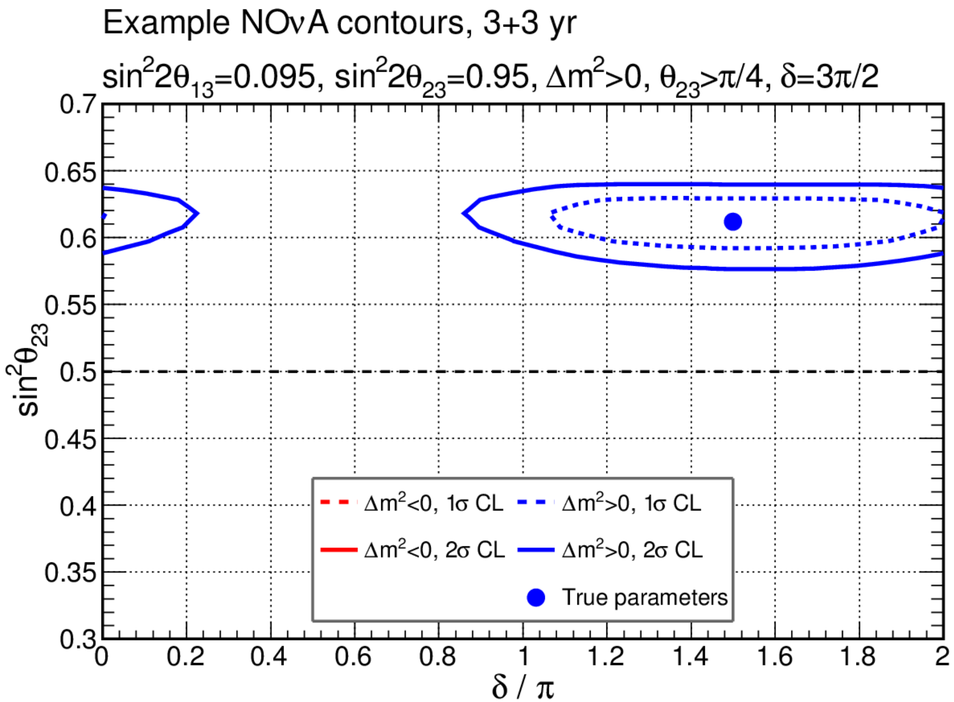
32-pixel APD ←

Fiber pairs from 32 cells →



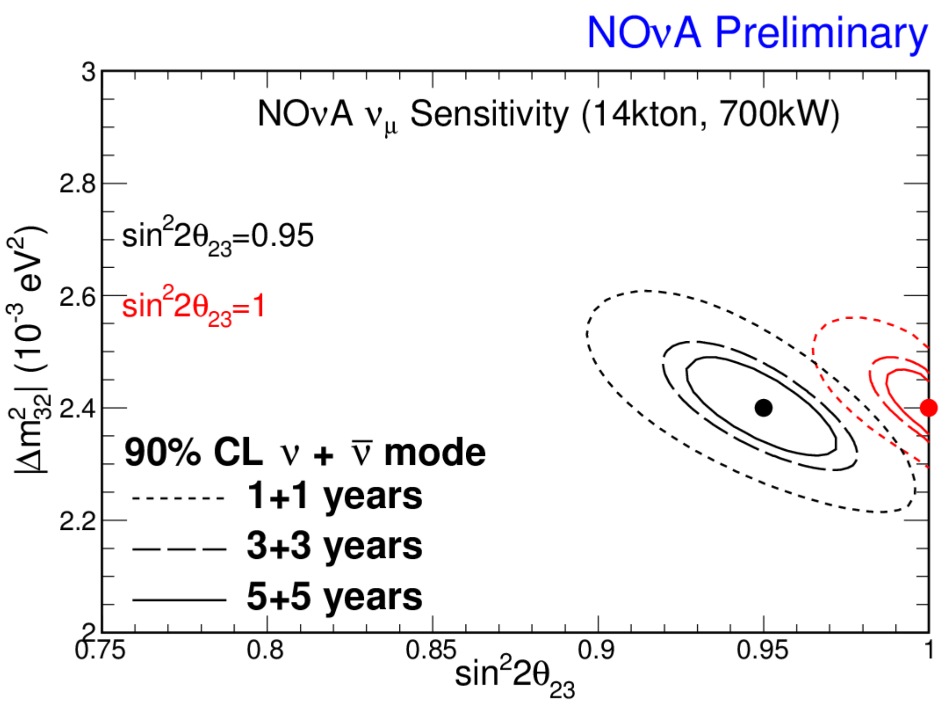
NOνA installation near completion.
At right: **cosmic event in partial FD.**

Long baseline → hierarchy sensitivity



At right: Example point in ν parameter space →

Simultaneously break ***ν_3 flavor degeneracy*** *("θ_{23} octant"), determine* ***mass hierarchy****, and constrain* ***CP phase δ****.*

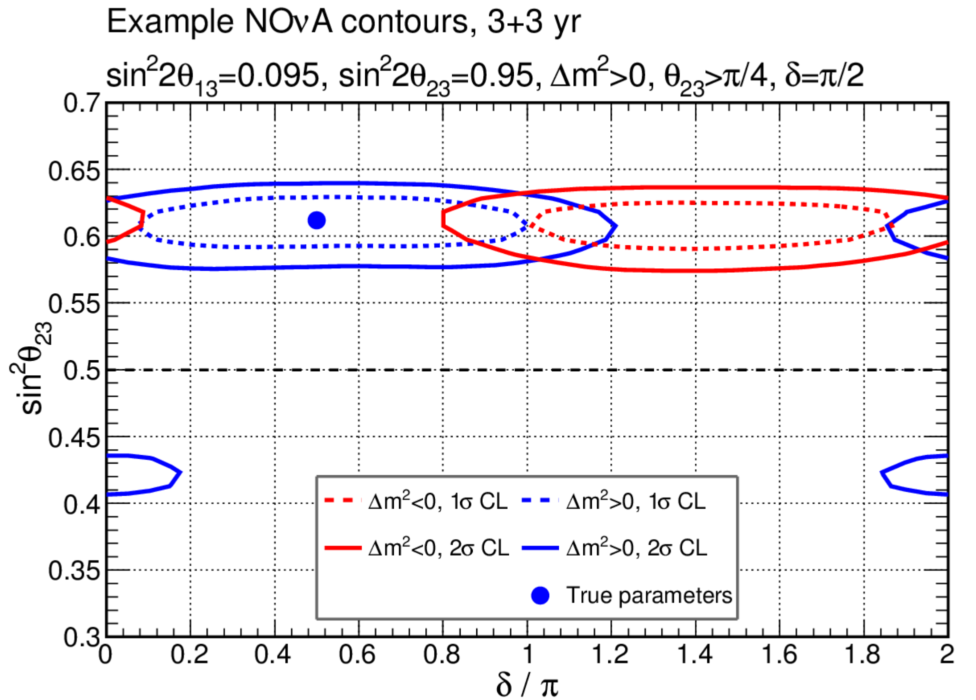


At left: ν_μ CC disappearance

(maximal and non-maximal test cases shown)

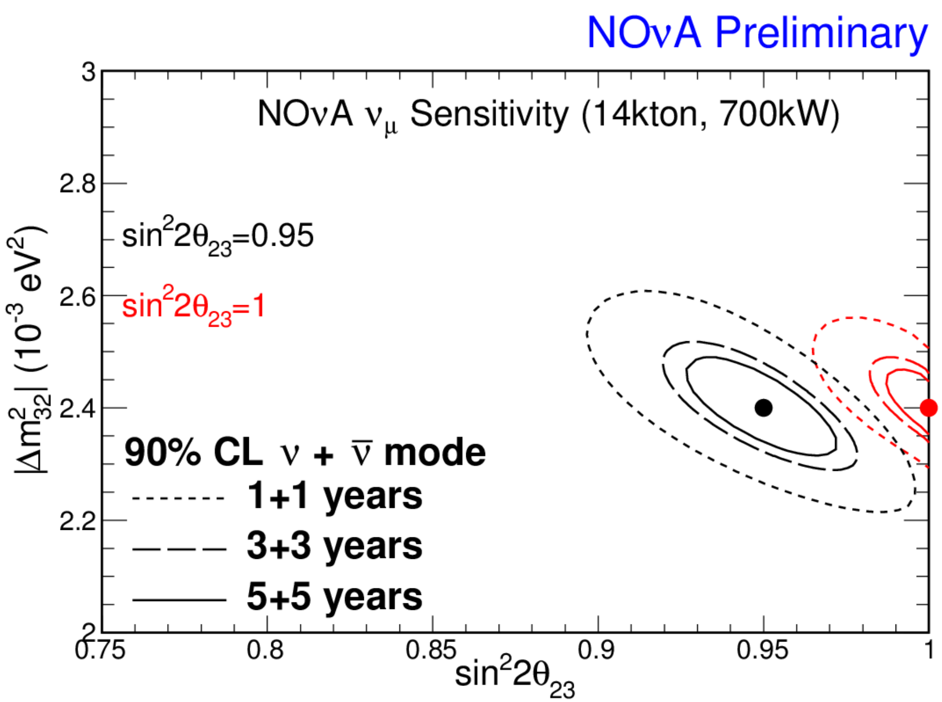
Probe down to 1% non-max. mixing

Long baseline → hierarchy sensitivity



At right: "degenerate" point ⟶

Hierarchy *and* ***δ*** *information now correlated.* ***Octant preference*** *still established.*



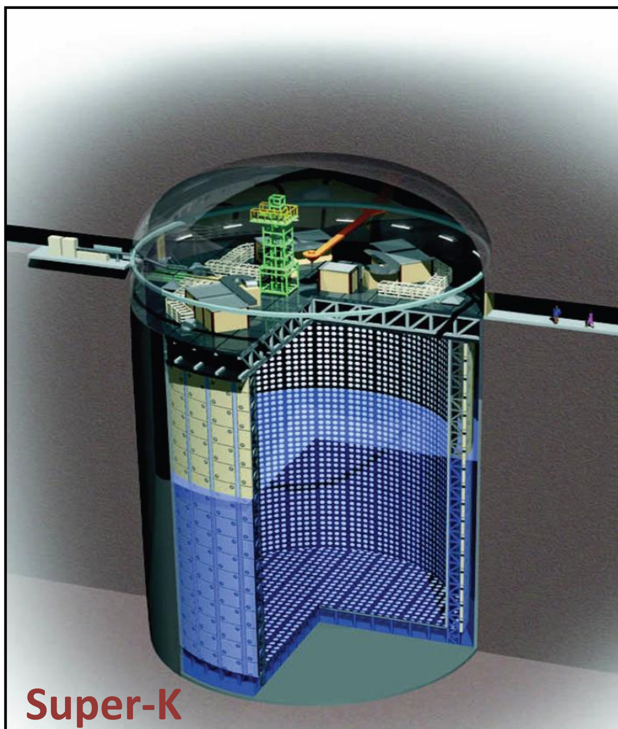
At left: ν_μ CC disappearance

(maximal and non-maximal test cases shown)

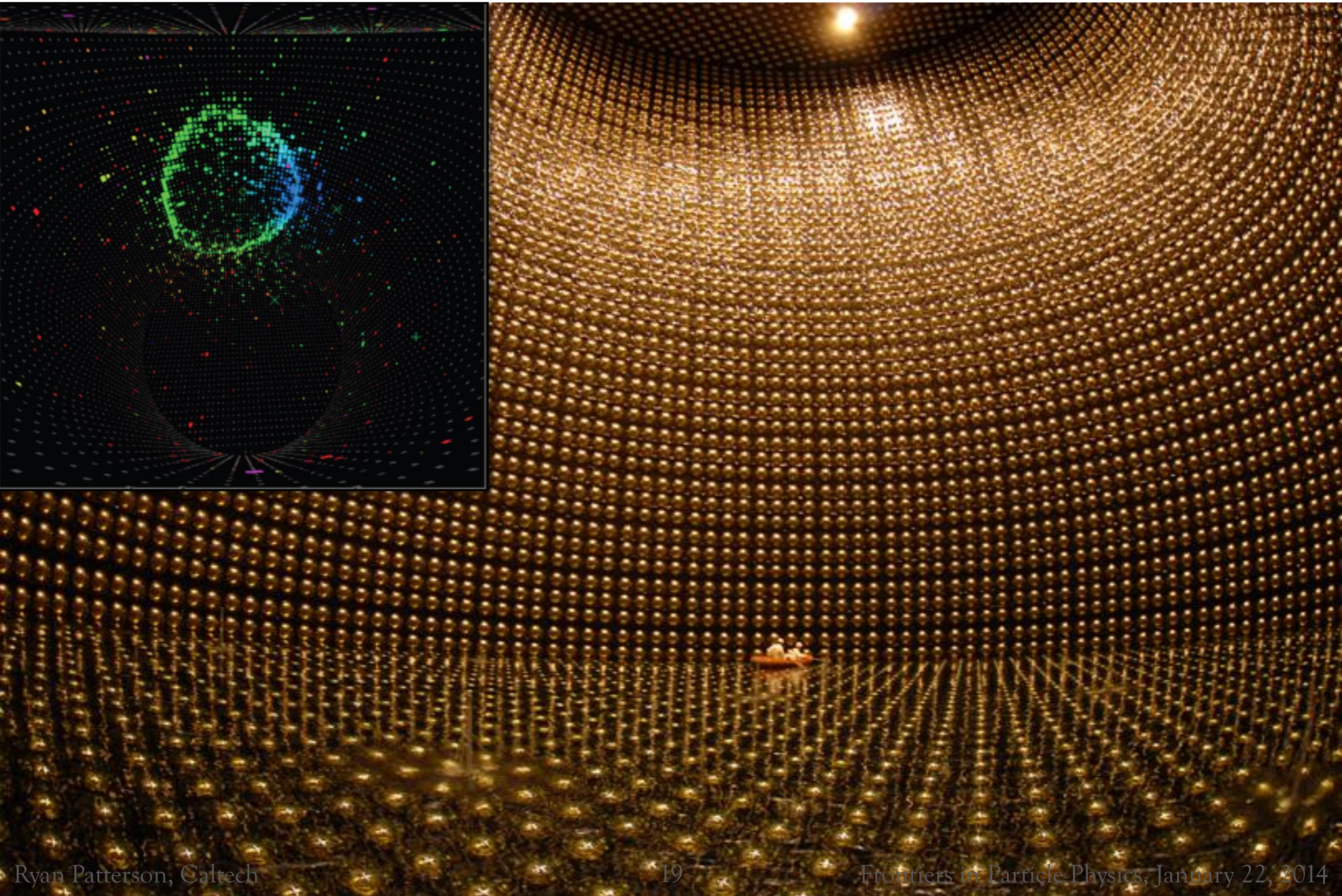
Probe down to 1% non-max. mixing

T2K

- **Tokai to Kamioka (295 km)**
- **Neutrino beam from J-PARC**
- **Existing far detector: *Super-K***
- **INGRID and ND280 near detectors**

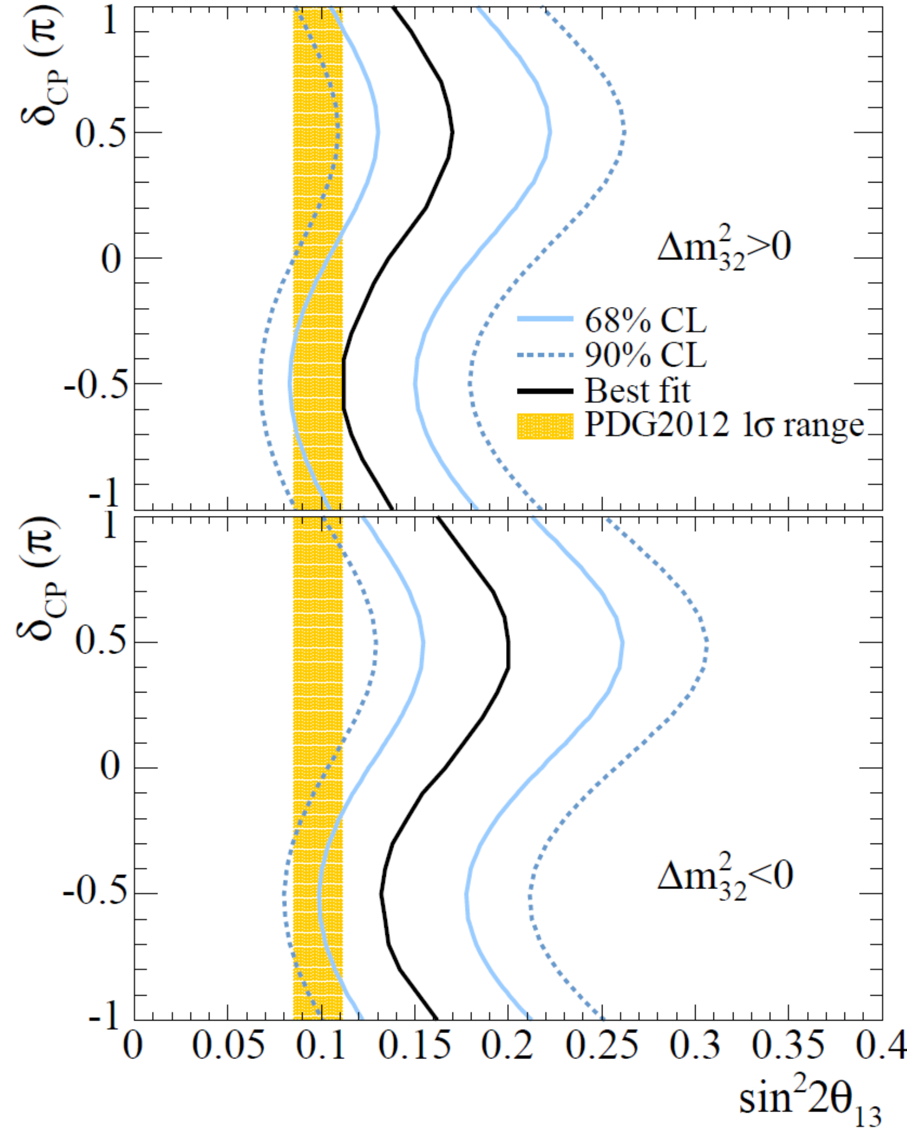


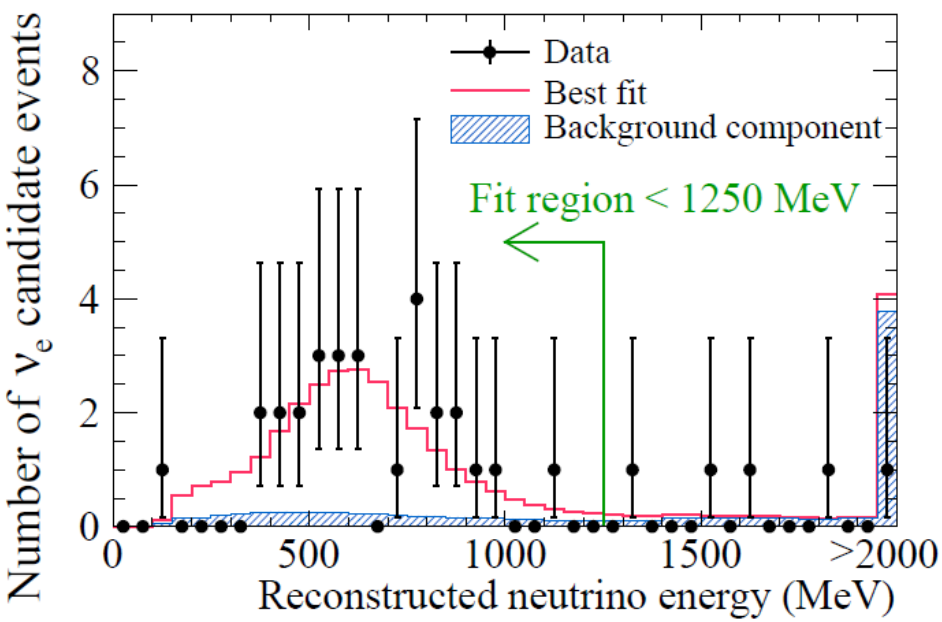
Super-K detector (far detector for T2K)



- **First conclusive observation (7.3σ) of $\nu_\mu \rightarrow \nu_e$ appearance**
  Consistent with $\overline{\nu}_e$ (reactor) disappearance results
- **Only 10% of eventual data set**
- **"Short" 295-km baseline:**
  Important role in global ν fits
  (minimal hierarchy dependence)
- **ν_μ CC channel:**
  Probe non-max. mixing to ~1%
  (First results out)

K. Abe *et al.* (T2K)
arXiv: 1311.4750





Neutrino mass

- **Cosmological observations** → sum of neutrino masses.
  Best limits so far: $\boldsymbol{\Sigma m_i}$ **< 0.2-0.6 eV**

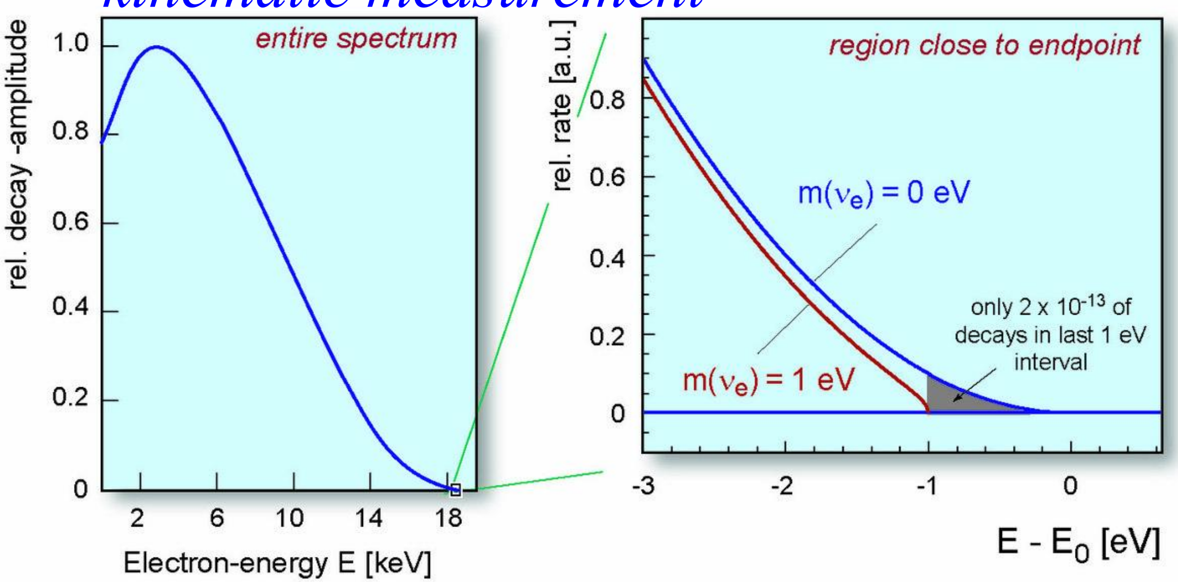
- ***β*-decay kinematic measurement** → effective electron neutrino mass, a.k.a. m_β:

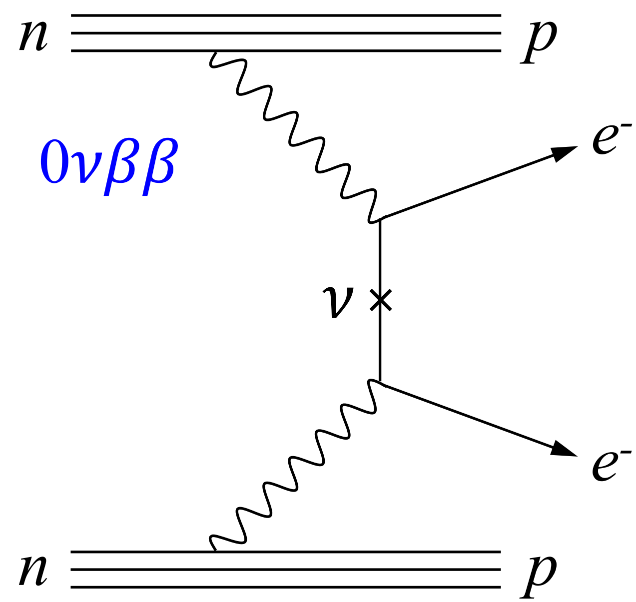
$$m_\beta^2 = \sum |U_{ei}|^2 m_i^2$$

- **0*νββ* decay process (if Majorana-*ν*-mediated)** → effective mass $m_{\beta\beta}$:

$$m_{\beta\beta}^2 = \left| \sum U_{ei}^2 m_i \right|^2$$

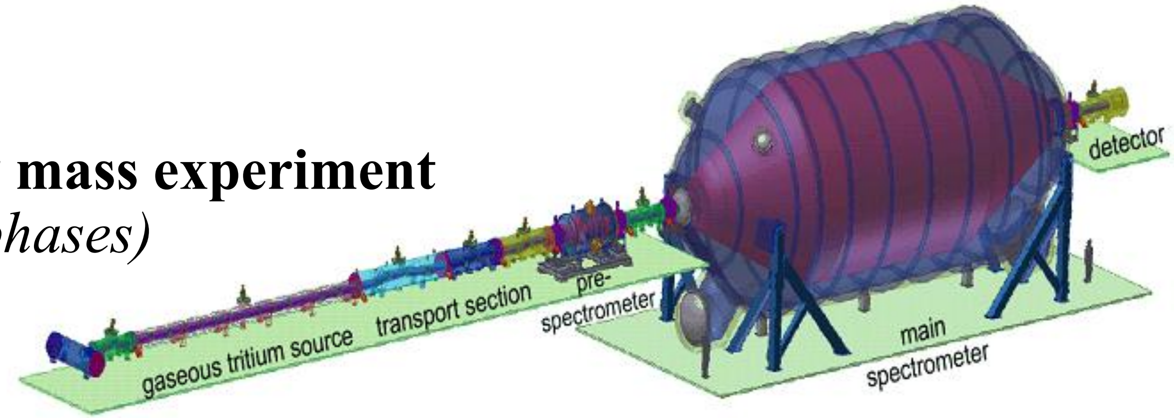
kinematic measurement



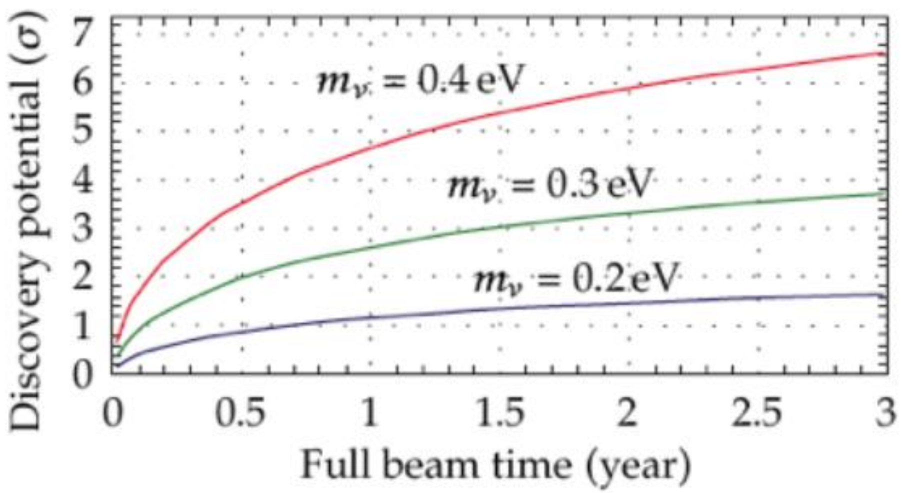


KATRIN

- **Only current kinematic ν mass experiment**
  (several others in R&D phases)
- Large **electrostatic filter** for β spectrometry
- Partial loading this year, **full tritium run in 2015**



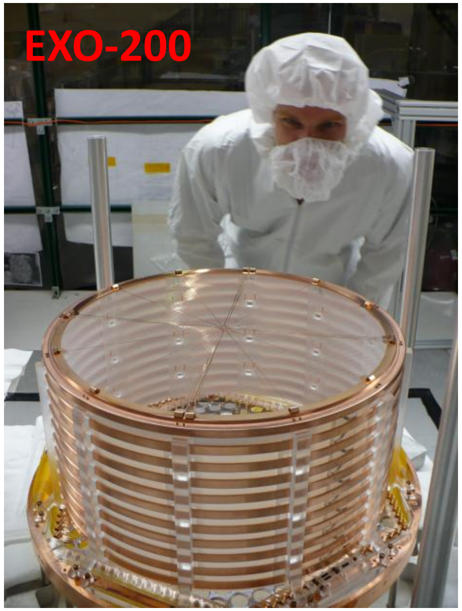
5σ reach for $m_\beta = 0.35$ eV



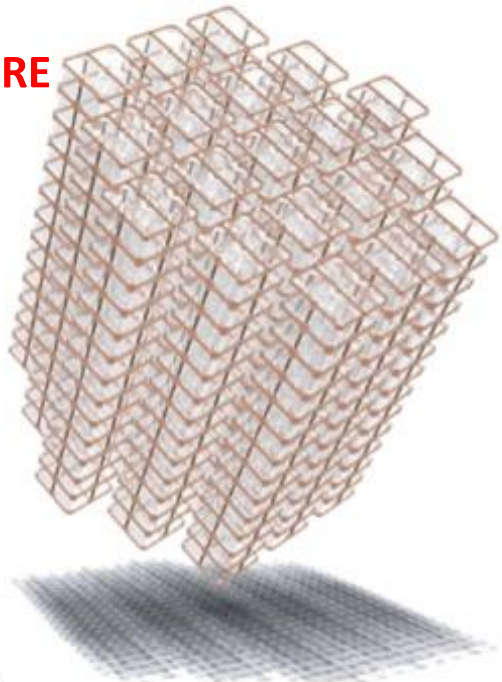
spectrometer en route to Karlsruhe

$0\nu\beta\beta$

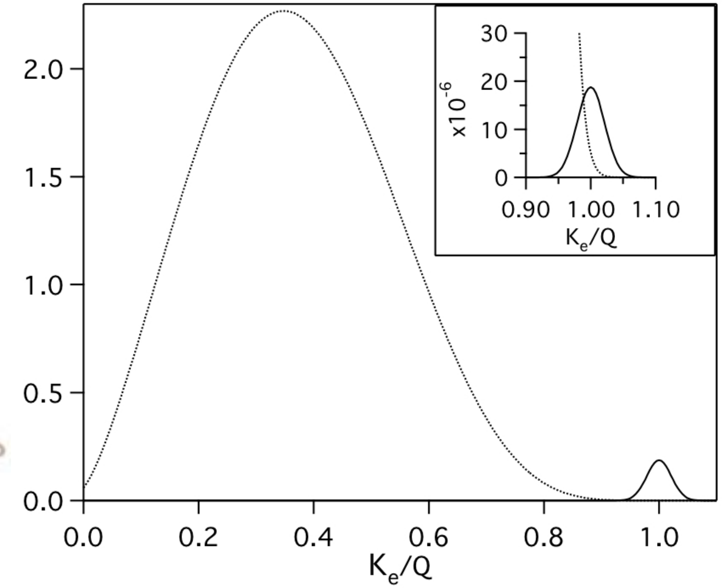
Many ...experiments
...techniques
...isotopes



CUORE

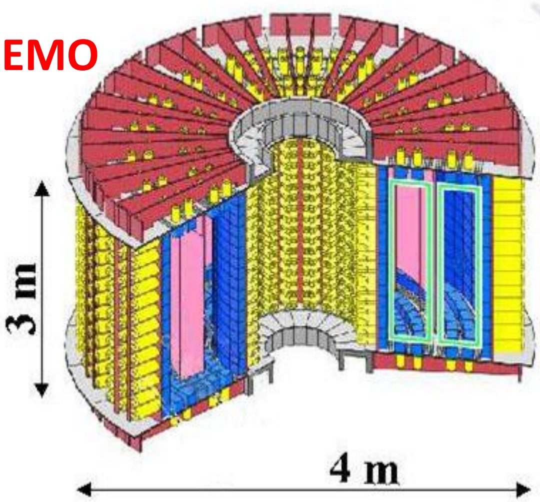


Example $0\nu\beta\beta$ signature

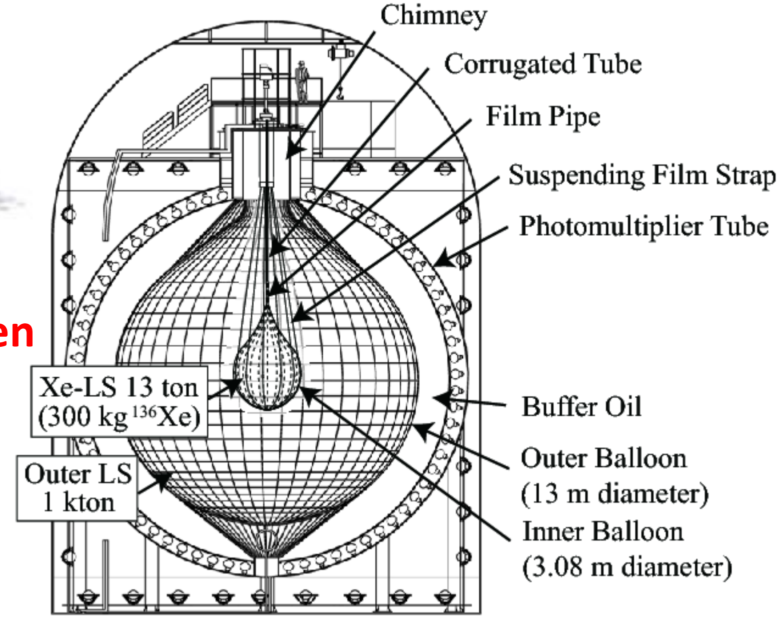


S. R. Elliott and P. Vogel, Ann. Rev. Nucl. Part. Sci. **52**, 115 (2002)

NEMO



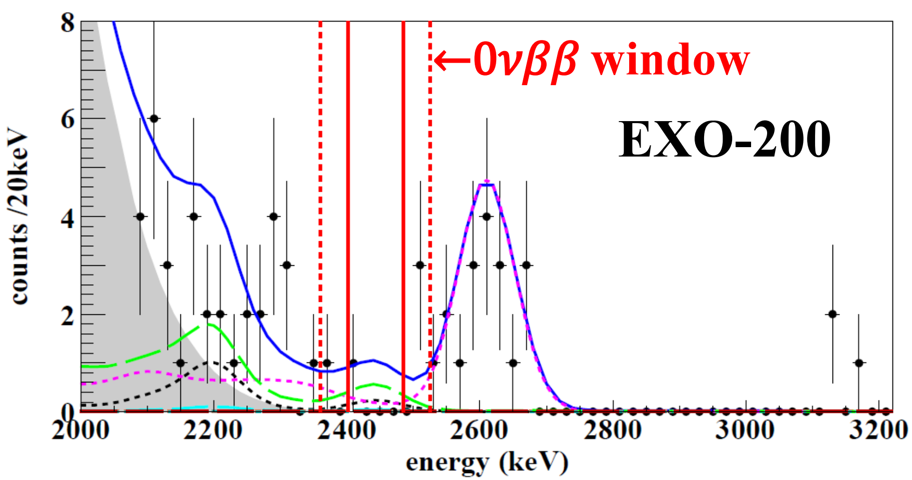
KamLAND-Zen

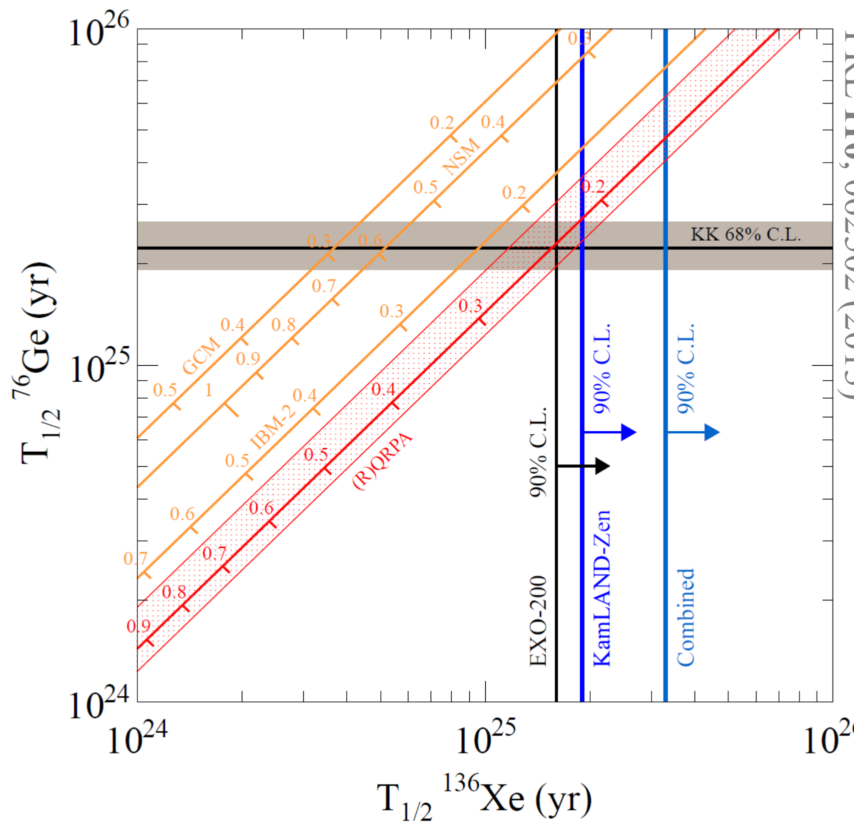


Experiments funded, under construction, or operating…

Experiment	Location	Isotope	Technique	
CUORE	LNGS	^{130}Te	bolometer	
EXO-200	WIPP	^{136}Xe	liquid TPC	← *early results below!*
GERDA	LNGS	^{76}Ge	ionization	
KamLAND-Zen	Kamioka	^{136}Xe	liquid scintillator	← *early results below!*
Majorana	SUSEL	^{76}Ge	ionization	
SNO+	Sudbury	^{150}Nd, ^{130}Te	liquid scintillator	

Controversial observation claim *(KK et al., Phys. Lett. B* ***586,*** *198 (2004))* now **refuted by EXO-200 and KamLAND-Zen results** for any available matrix element calculations





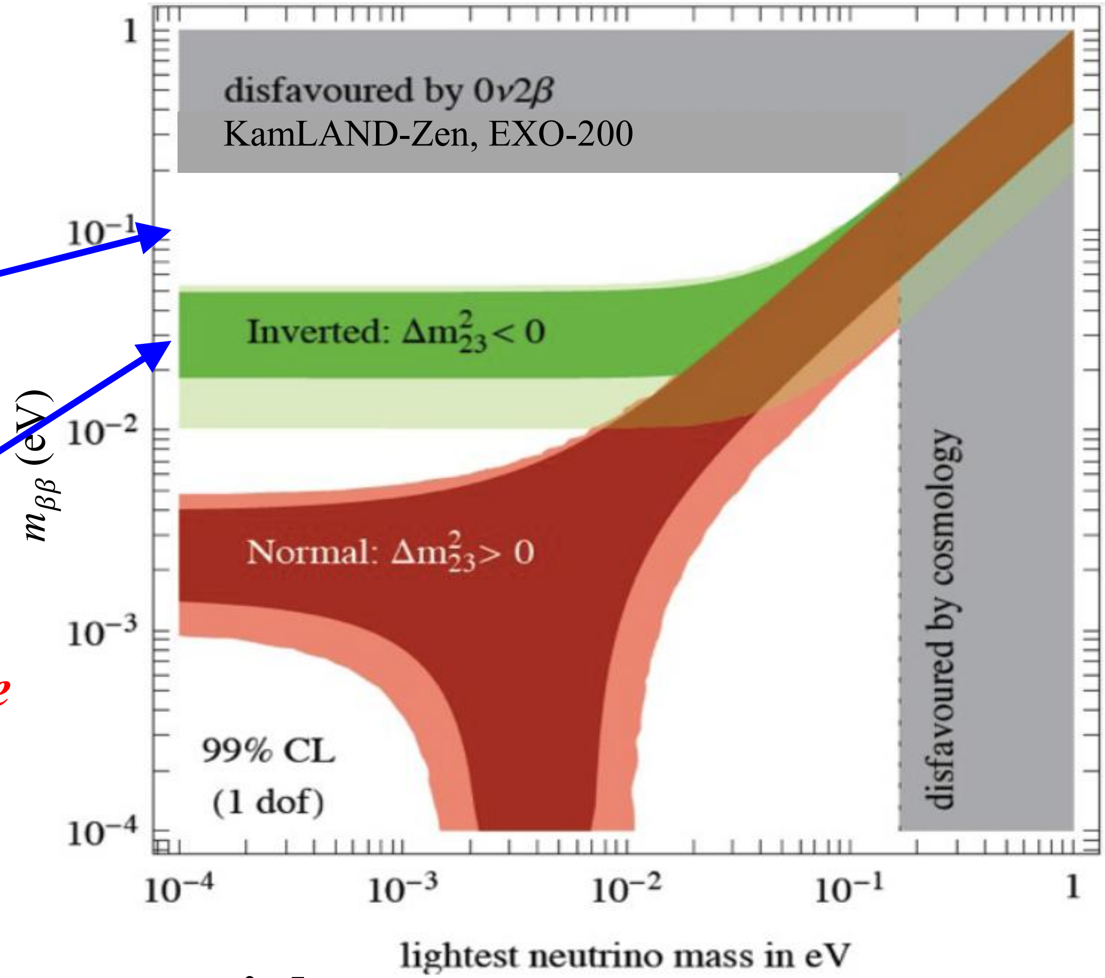
A. Gando et al. (KamLAND-Zen), PRL **110**, 062502 (2013)

Matrix element calculations lead to large uncertainties in $m_{\beta\beta}$ (factors of 2 or 3).

Approx. reach of current generation expts.

Possible SNO+ reach: novel ^{130}Te loading method
(3% loading!)

Into inverted hierarchy range

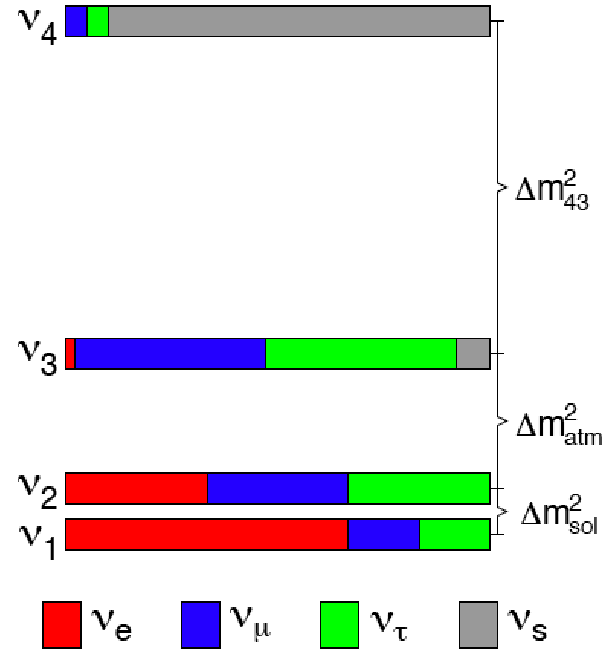


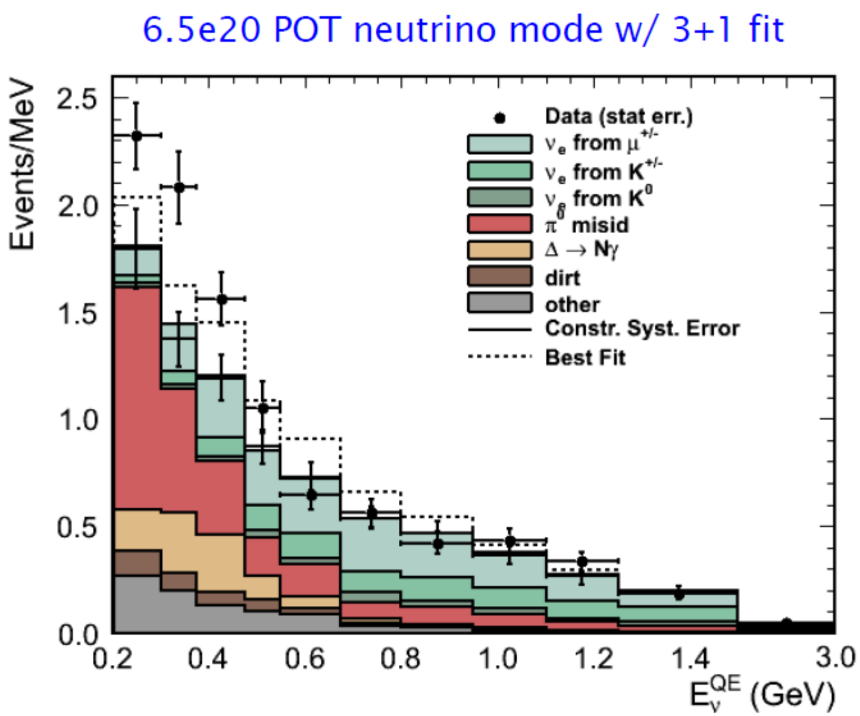
Multiple techniques, isotopes essential.

It will remain **unclear** for some time which approaches will **survive through IH and into NH territory.**

LSND, MiniBooNE, reactor, ^{71}Ga anomalies

- In mid-90s, **LSND reported $\bar{\nu}_\mu \to \bar{\nu}_e$ signal incompatible with 3-ν oscillation picture (3.8σ)**
- **Sterile neutrinos?** *(Need multiple sterile states to accommodate all of today's data.)*
- **Many null results since** *(KARMEN, Bugey, Super-K, MINOS, ICARUS)* but **none completely cover** LSND allowed region in (3+1)-ν parameter space





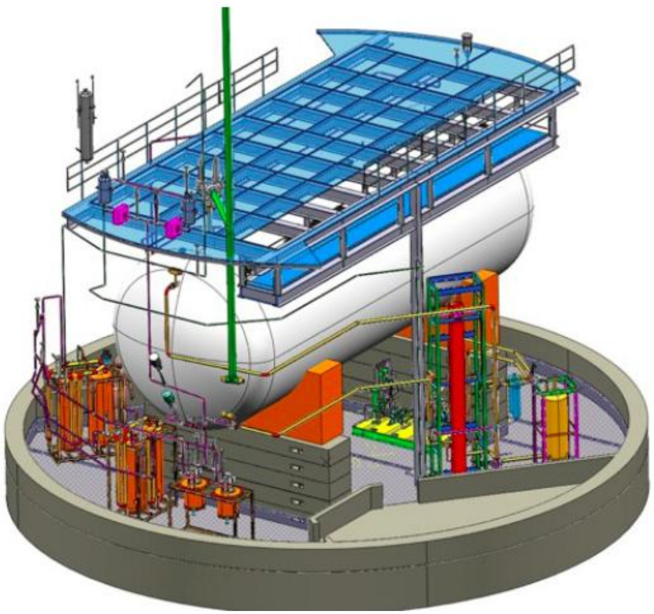
MiniBooNE:
Designed to cover LSND allowed region

First result: No evidence for oscillations
Second result: Lower energy threshold, excess seen at low energy (not a great match to osc.)
Third result (with antineutrinos): Similar excess

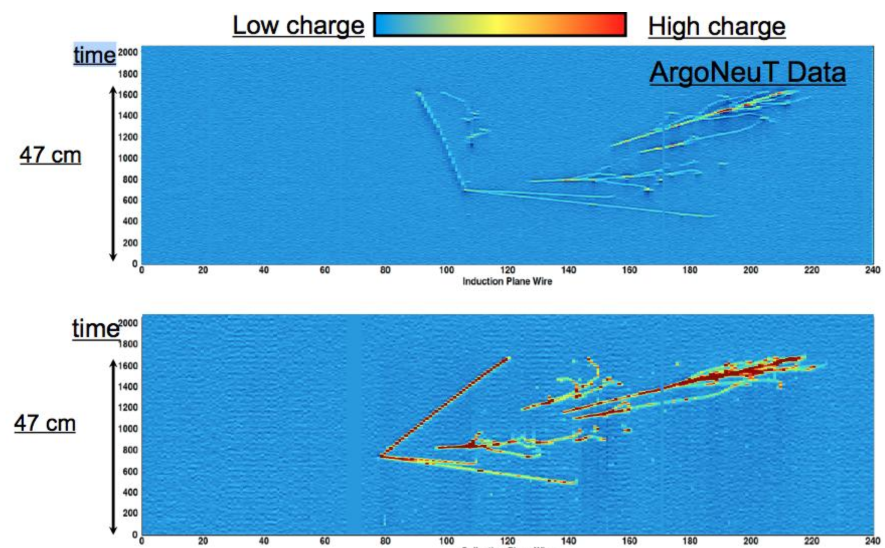
- *Also:* new reactor flux predictions suggest **unexplained deficit in past reactor data**
- *Also:* gallium solar experiments see **unexplained deficit in ν_e calibration runs**

Will need future experiments with in-detector L, E signatures to resolve all this.

- Meanwhile, for MiniBooNE low-E excess: ***Micro*BooNE**
  - → **70-ton LAr TPC:** distinguish electron or photon source of MiniBooNE excess
  - → Construction well-underway at Fermilab. **Operations this year.**



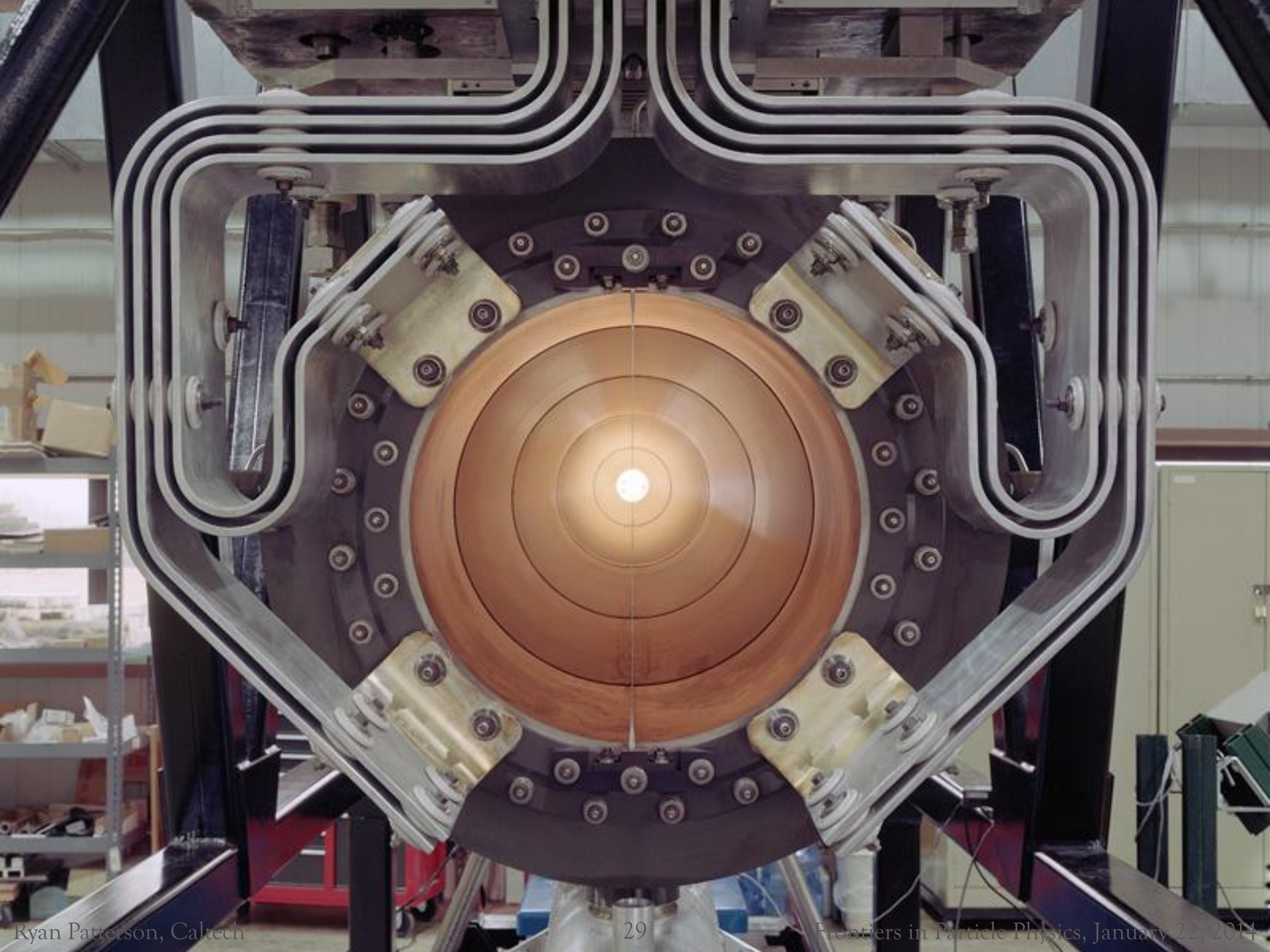
MicroBooNE



*(event display from earlier **ArgoNeuT** LAr TPC)*

Had to skip entirely…

- **ν-nucleus scattering** ***(many experiments!)***
- **Cosmological/astrophysical ν** ***(many experiments!)***
  e.g., IceCube's recent detection of 28 neutrinos above 30 TeV



Extras

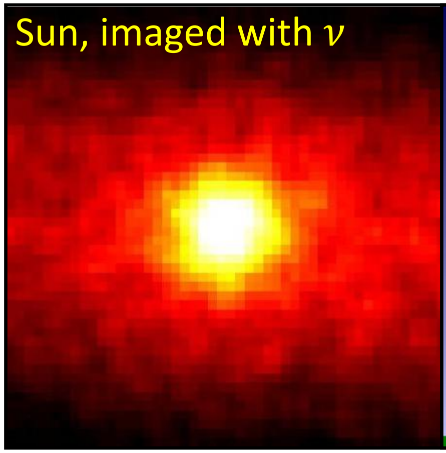
Oscillations

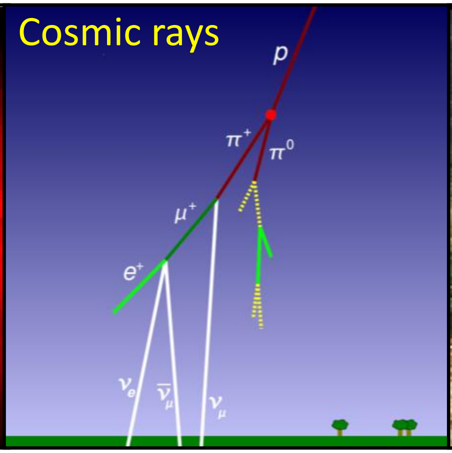
$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(L) \rangle|^2$$

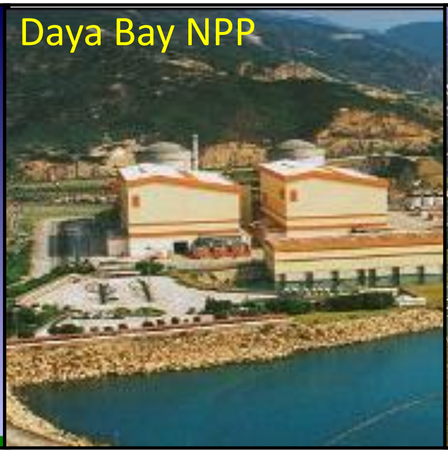
$$= \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2[1.27 \Delta m^2_{ij} L/E]$$

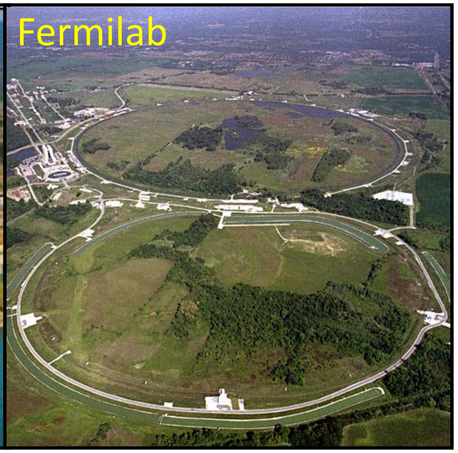
$$+2 \sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2[2.54 \Delta m^2_{ij} L/E]$$

- **Neutrino flavor oscillations** – access to ***U_{PMNS}*** and **ν mass-squared splittings**
- In past decade, **phenomenon confirmed** and the **texture of ν mixing** extracted:
  - *Experiments using **solar, atmospheric, reactor, and accelerator** ν sources*









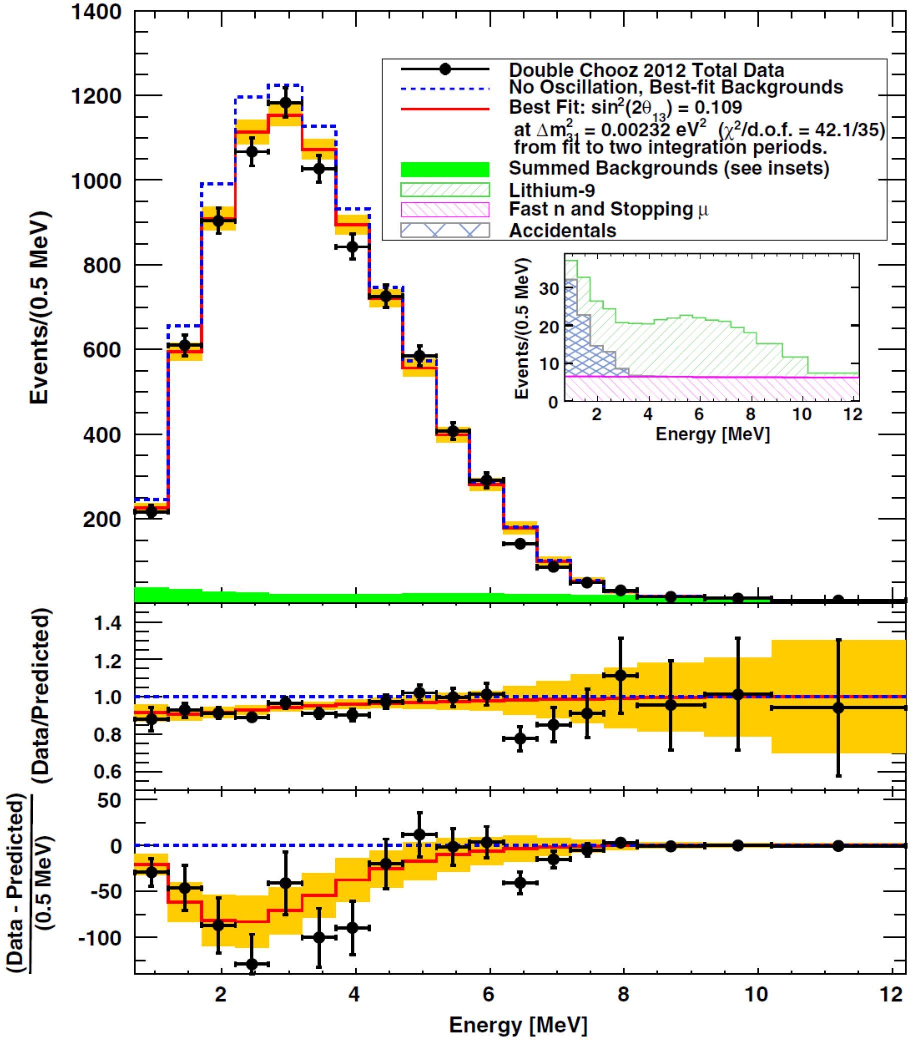
θ_{13} – the great facilitator

- **Non-zero θ_{13} definitively established; Daya Bay with most precise value:**
  $\sin^2(2\theta_{13}) = 0.090^{+0.009}_{-0.008}$
- **Makes feasible long-baseline measurements of…**
  neutrino mass hierarchy
  Potential implications in: $0\nu\beta\beta$ data and Majorana nature of ν; approach to m_β; cosmology; astrophysics; theoretical frameworks for mass generation, quark/lepton unification; Is the lightest charged lepton associated with the heaviest light neutrino?

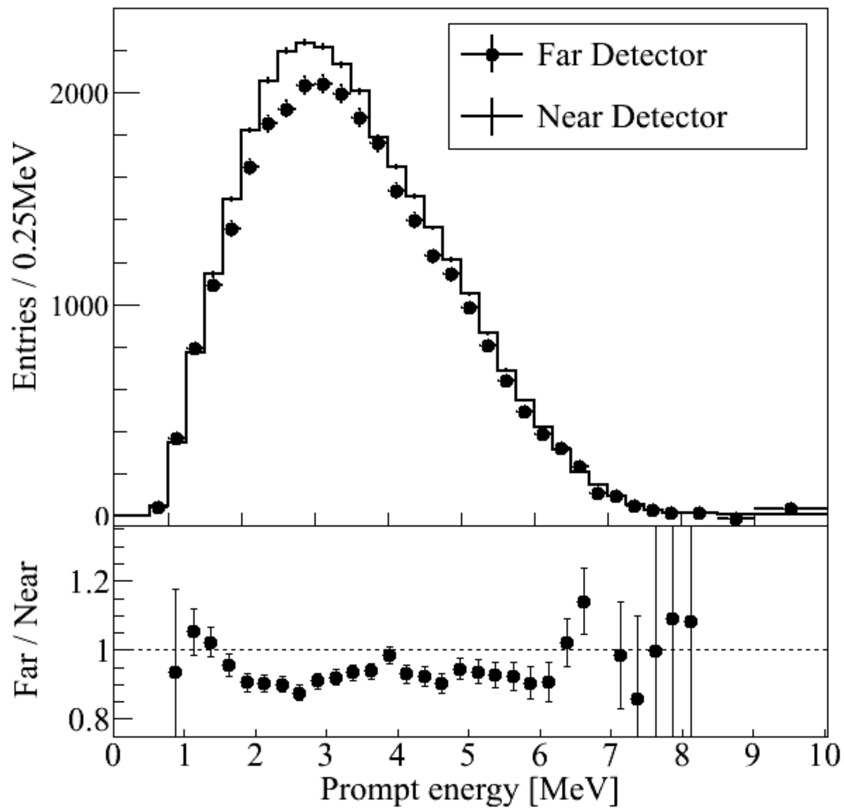
  CP phase δ
  …: cosmological baryon asymmetry through see-saw/leptogenesis; fundamental question in the Standard Model (*i.e.*, is CP respected by leptons?)

  ν^3 flavor mixing
  …: Is ν_3 more strongly coupled to μ or τ flavor?; frameworks for mass generation, quark/lepton unification

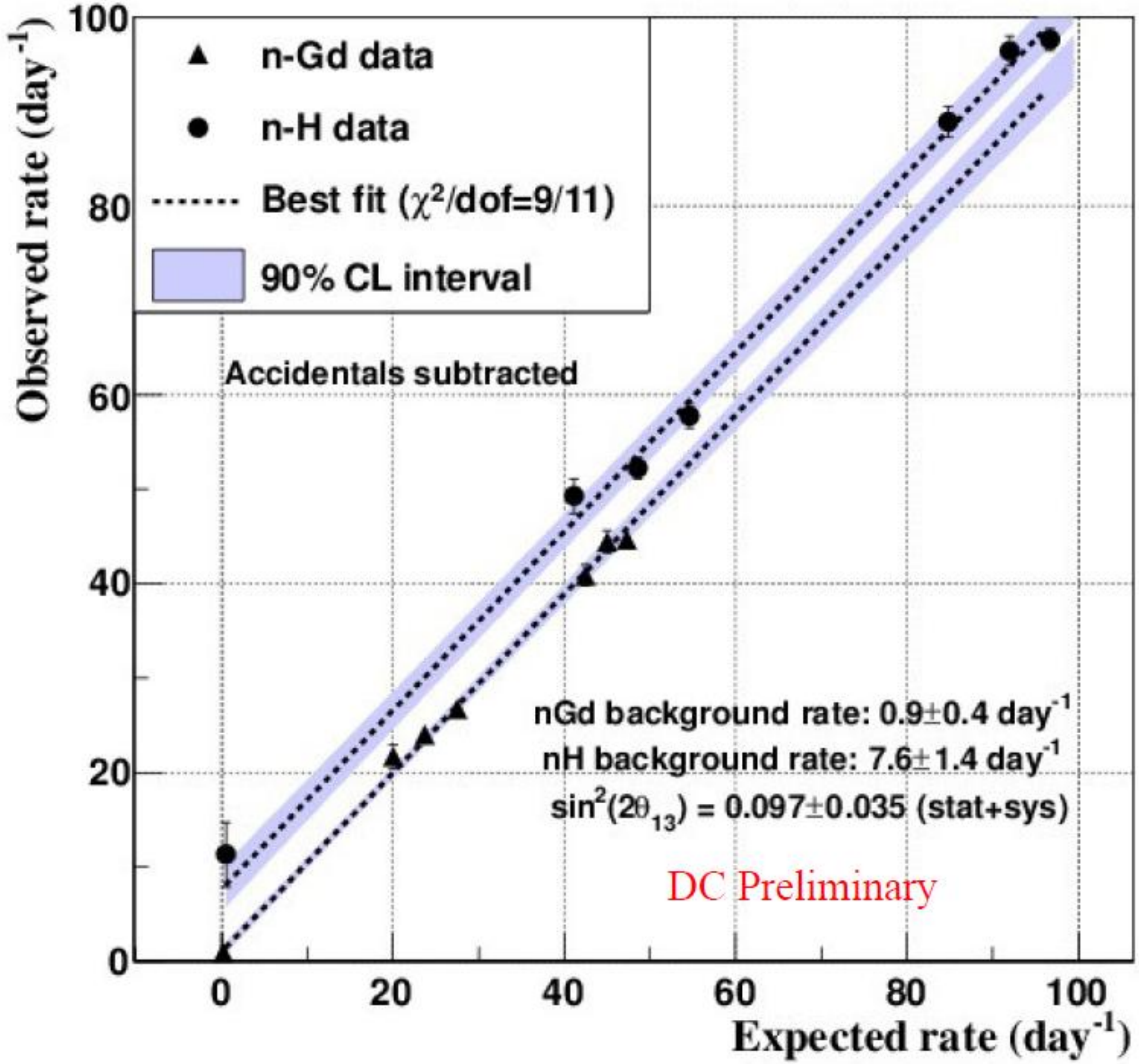
Double Chooz



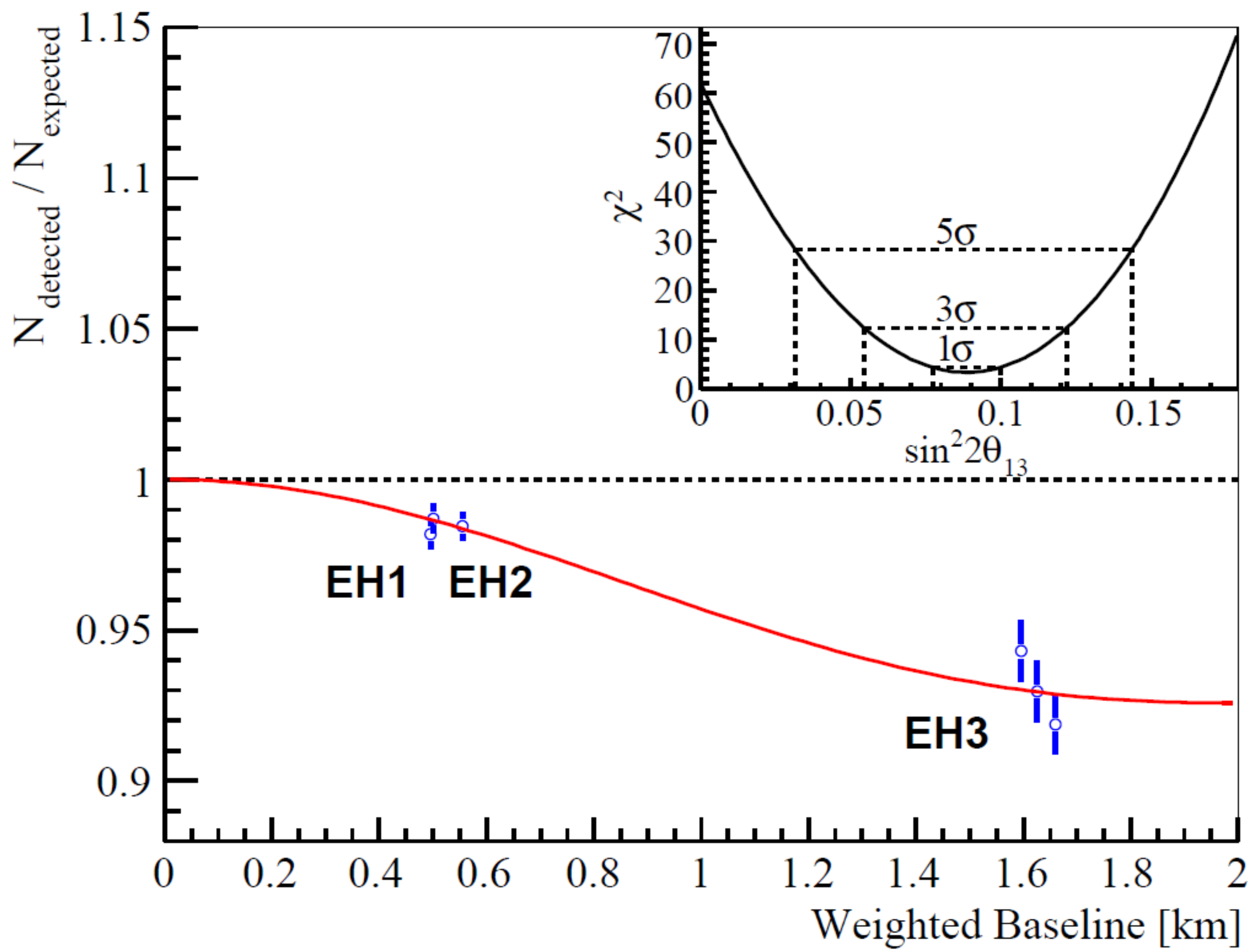
RENO



Double Chooz reactor rate modulation result



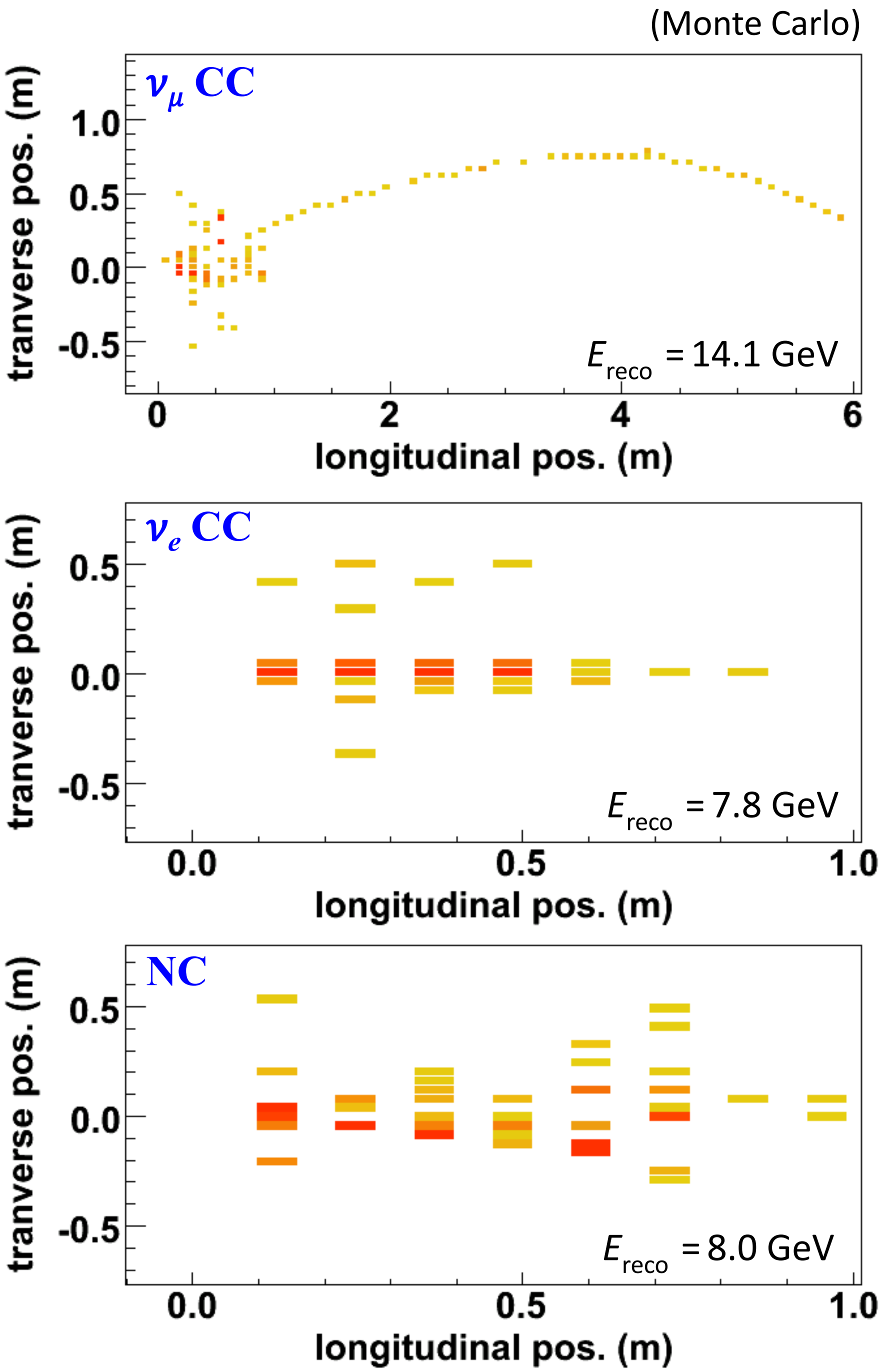
Daya Bay



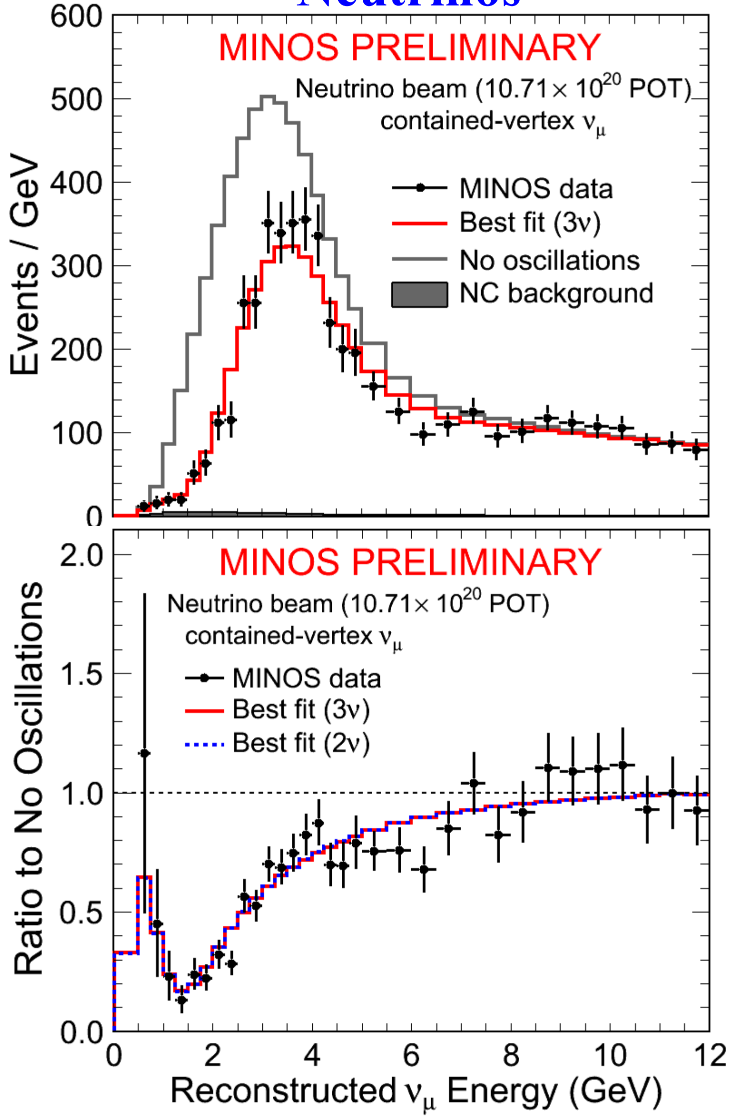
$N_{detected} / N_{expected}$
1.15
1.1
1.05
1
0.95
0.9
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Weighted Baseline [km]
EH1
EH2
EH3
χ^2
70
60
50
40
30
20
10
0
5σ
3σ
1σ
0
0.05
0.1
0.15
$\sin^2 2\theta_{13}$

MINOS

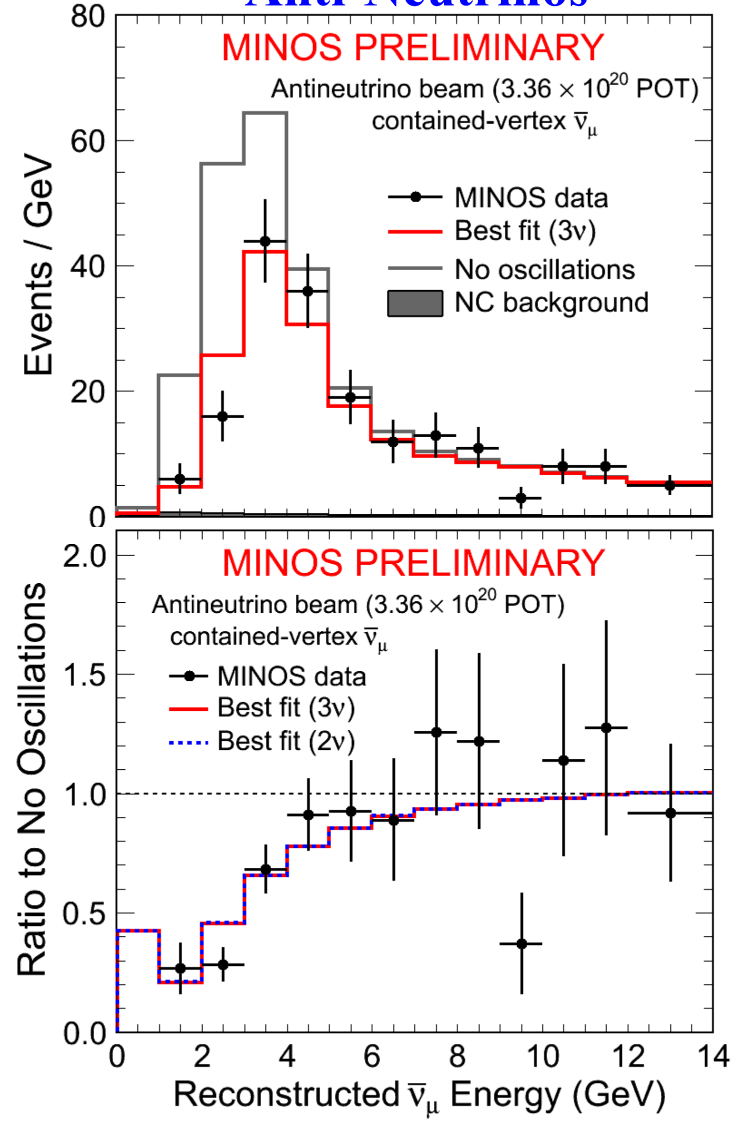
- **Magnetized steel/scintillator tracking calorimeters**
  → *"Identical" near and far detectors*
- ***Original aims:*** **accelerator-based** confirmation of "atmospheric" ν oscillation; **precision measurements** of mixing and mass splitting
- **Designed for $\nu_\mu \rightarrow \nu_\mu$ survival channel**



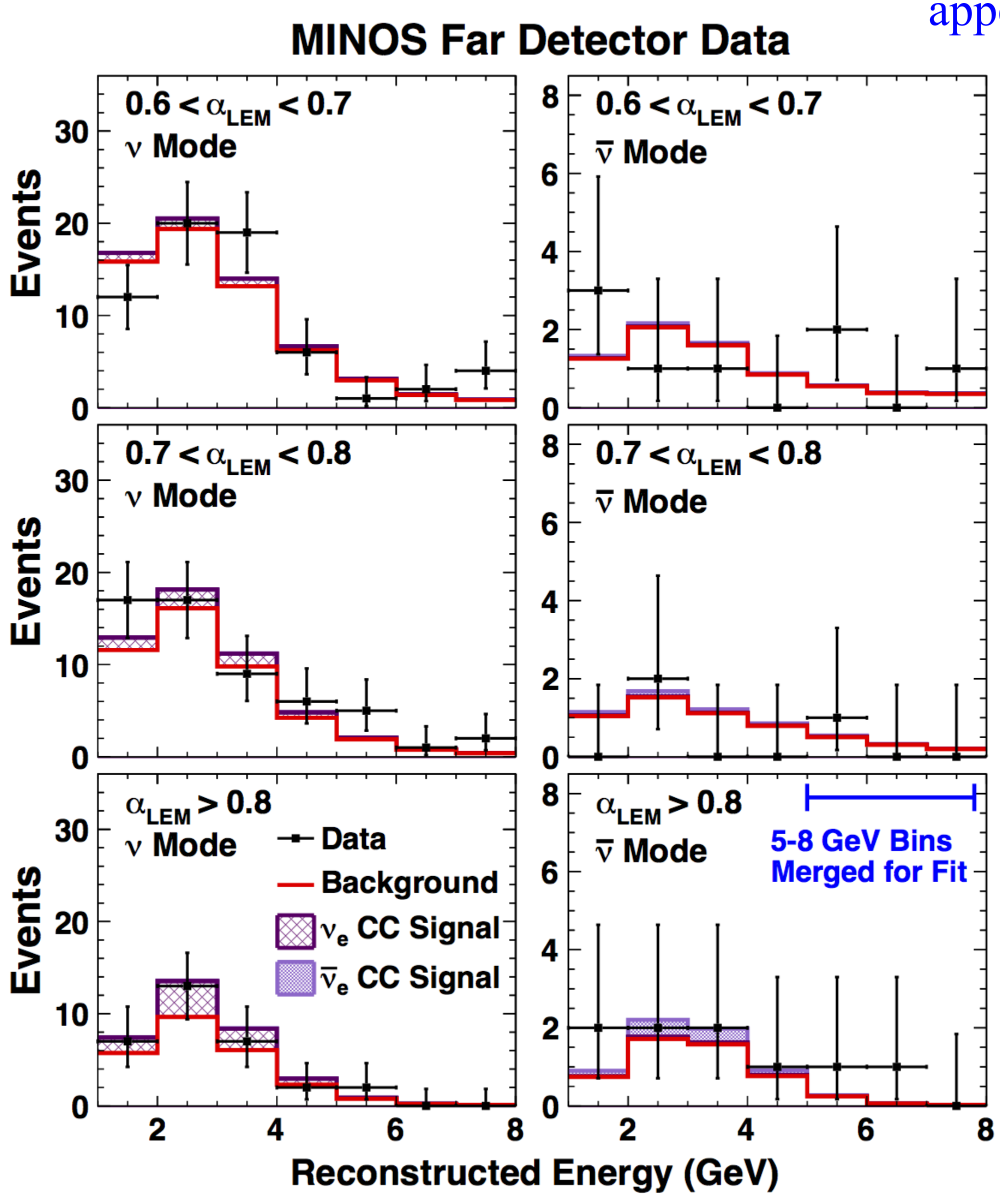
Neutrinos

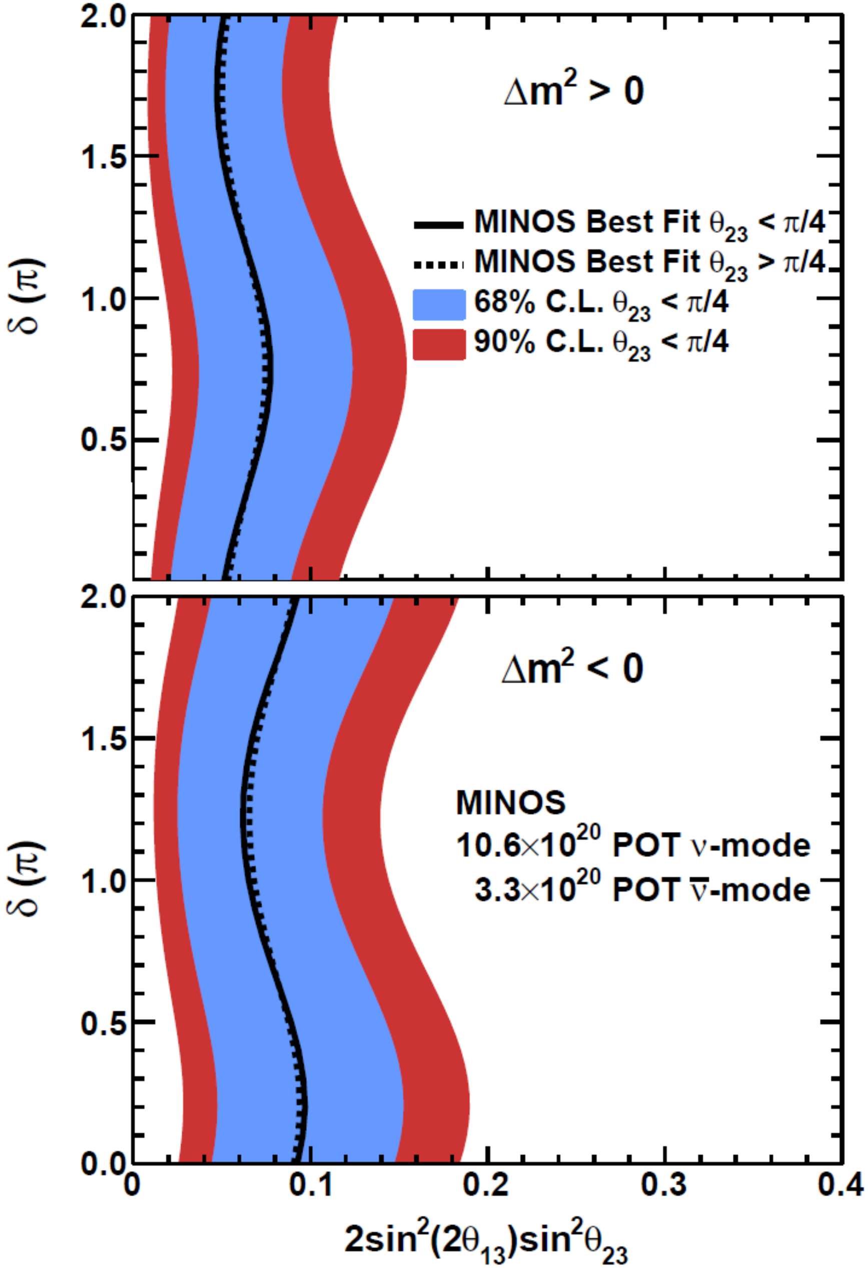


Anti-Neutrinos

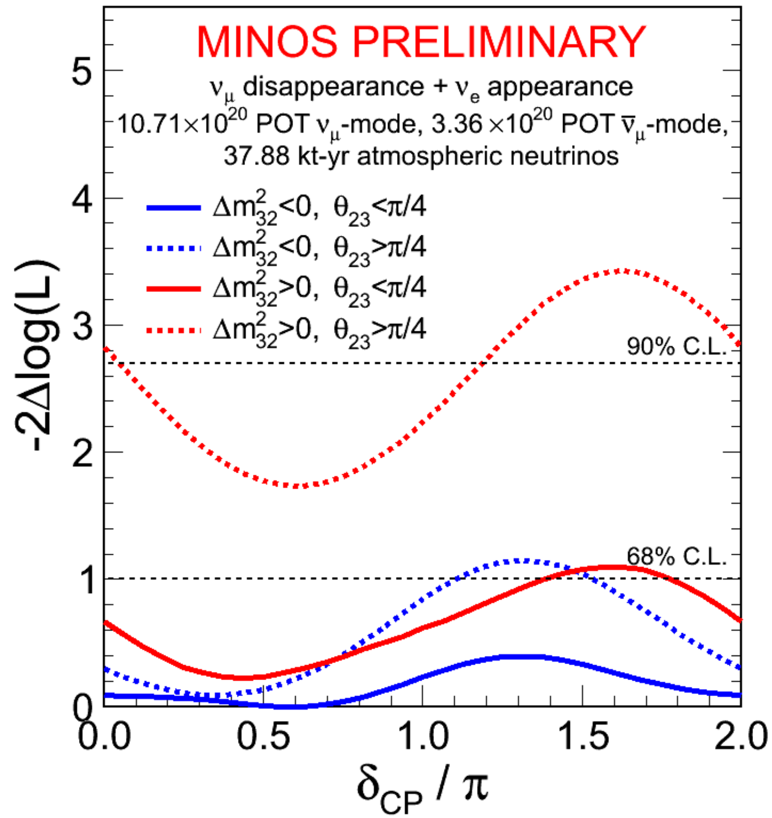


appearance channel





$\Delta m^2 > 0$
MINOS Best Fit $\theta_{23} < \pi/4$
MINOS Best Fit $\theta_{23} > \pi/4$
68% C.L. $\theta_{23} < \pi/4$
90% C.L. $\theta_{23} < \pi/4$
$\Delta m^2 < 0$
MINOS
10.6×10^{20} POT ν-mode
3.3×10^{20} POT $\bar{\nu}$-mode
$\delta\ (\pi)$
$2\sin^2(2\theta_{13})\sin^2\theta_{23}$

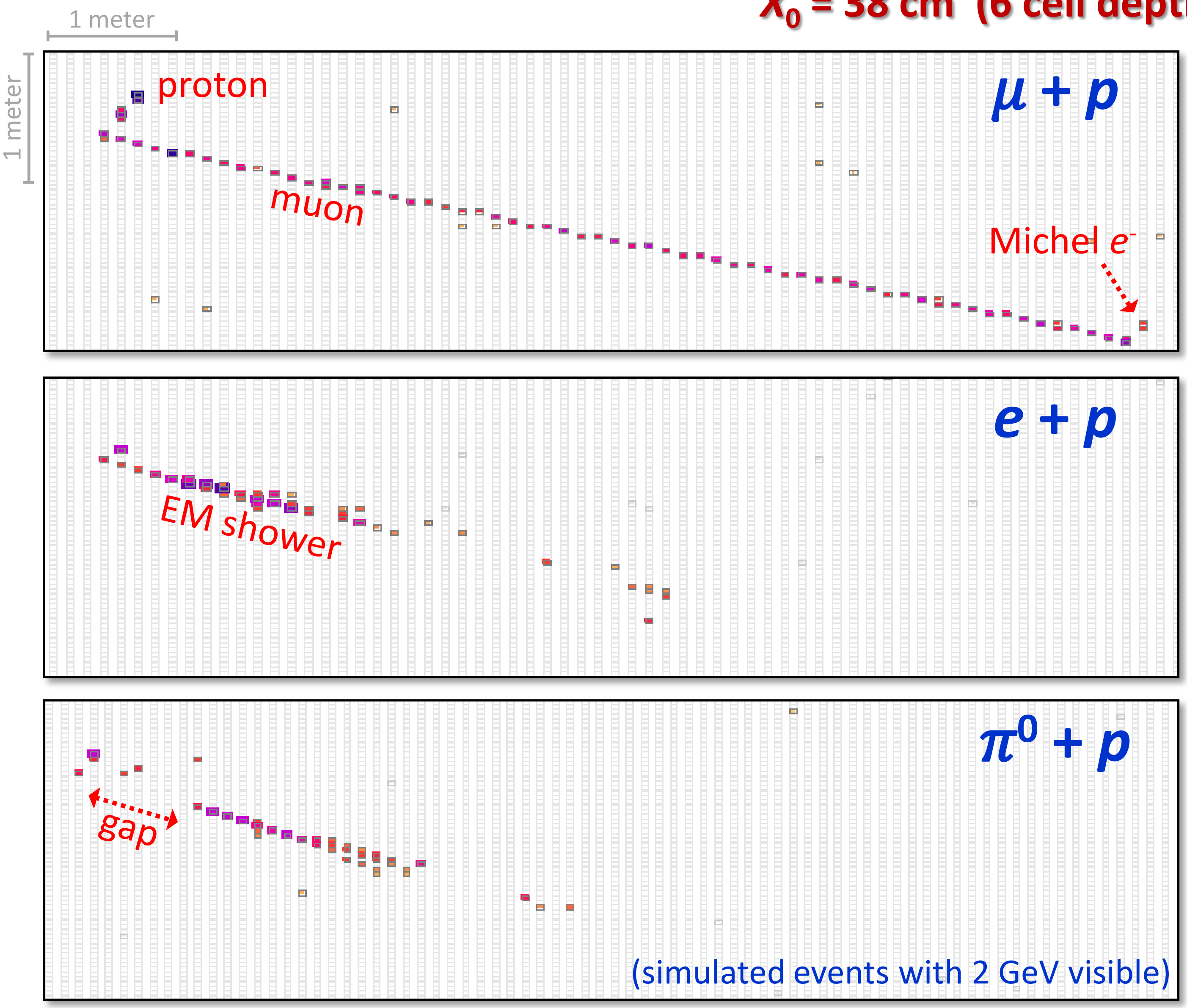


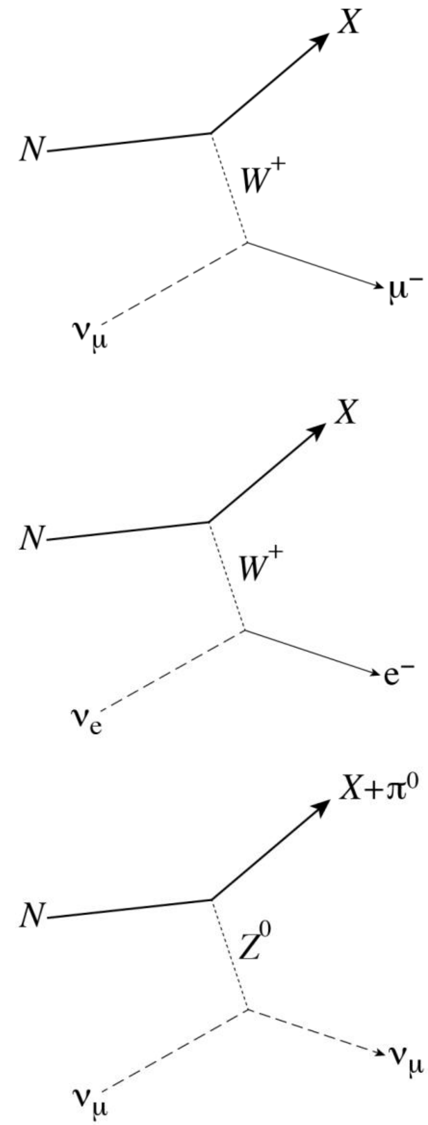
MINOS PRELIMINARY
ν_μ disappearance + ν_e appearance
10.71×10^{20} POT ν_μ-mode, 3.36×10^{20} POT $\bar{\nu}_\mu$-mode,
37.88 kt-yr atmospheric neutrinos
$\Delta m^2_{32}<0,\ \theta_{23}<\pi/4$
$\Delta m^2_{32}<0,\ \theta_{23}>\pi/4$
$\Delta m^2_{32}>0,\ \theta_{23}<\pi/4$
$\Delta m^2_{32}>0,\ \theta_{23}>\pi/4$
90% C.L.
68% C.L.
$-2\Delta\log(L)$
δ_{CP}/π

Events in NOνA

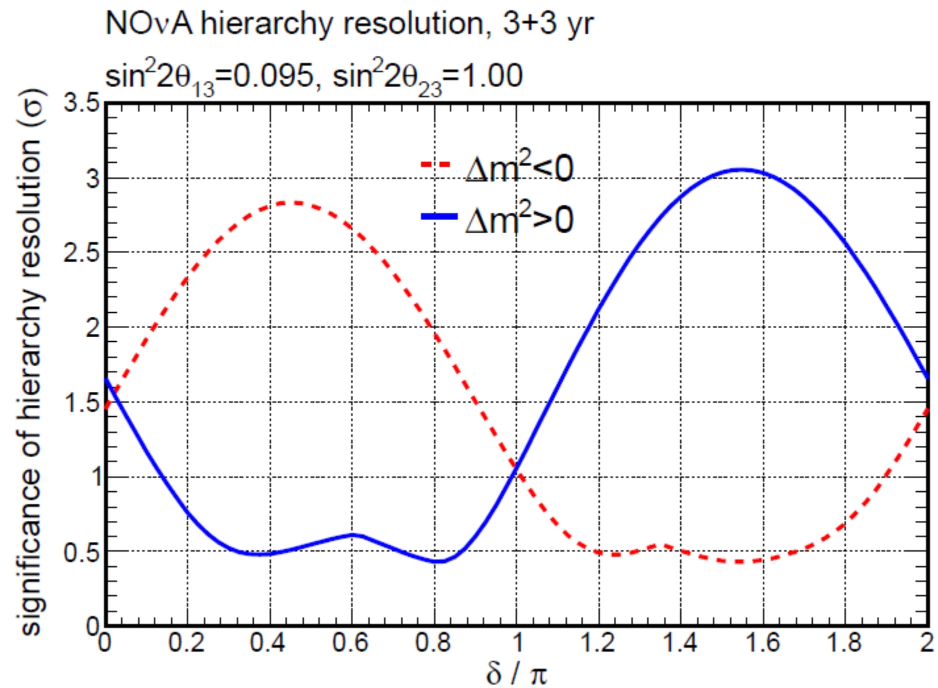
Superb spatial granularity for a detector of this scale

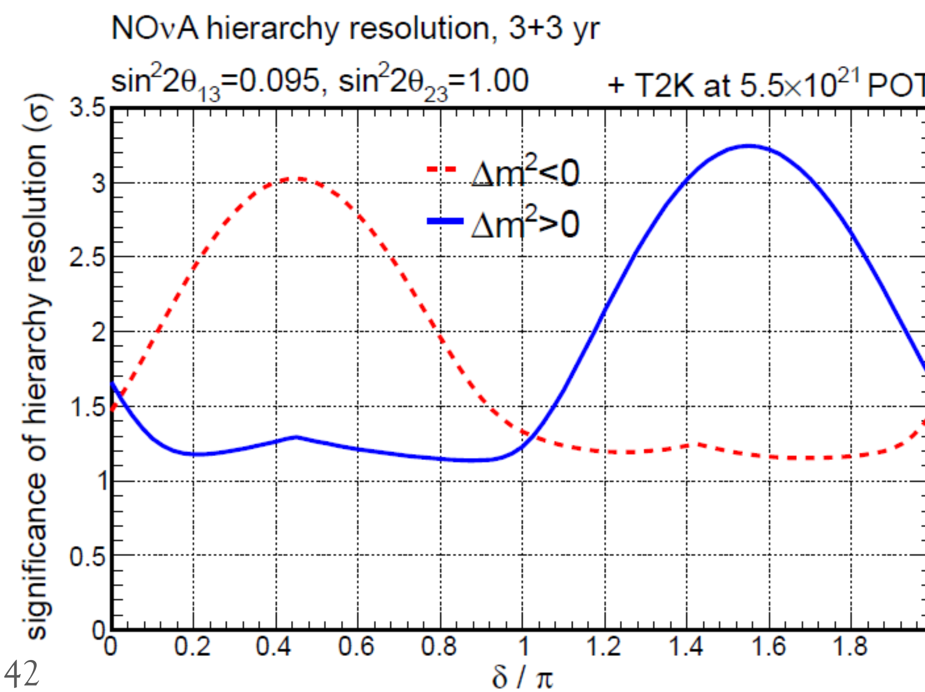
X_0 = 38 cm (6 cell depths, 10 cell widths)

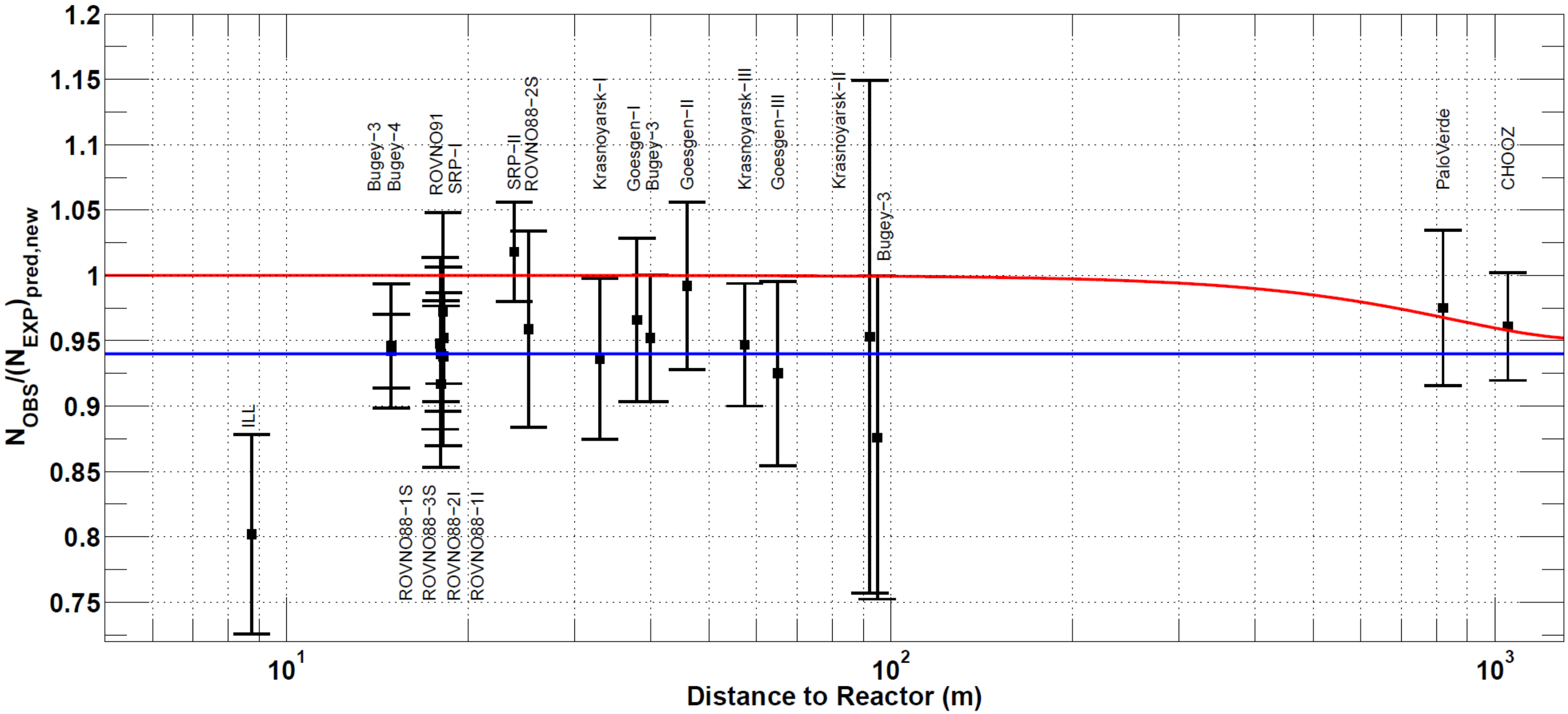




NOνA hierarchy reach vs. δ



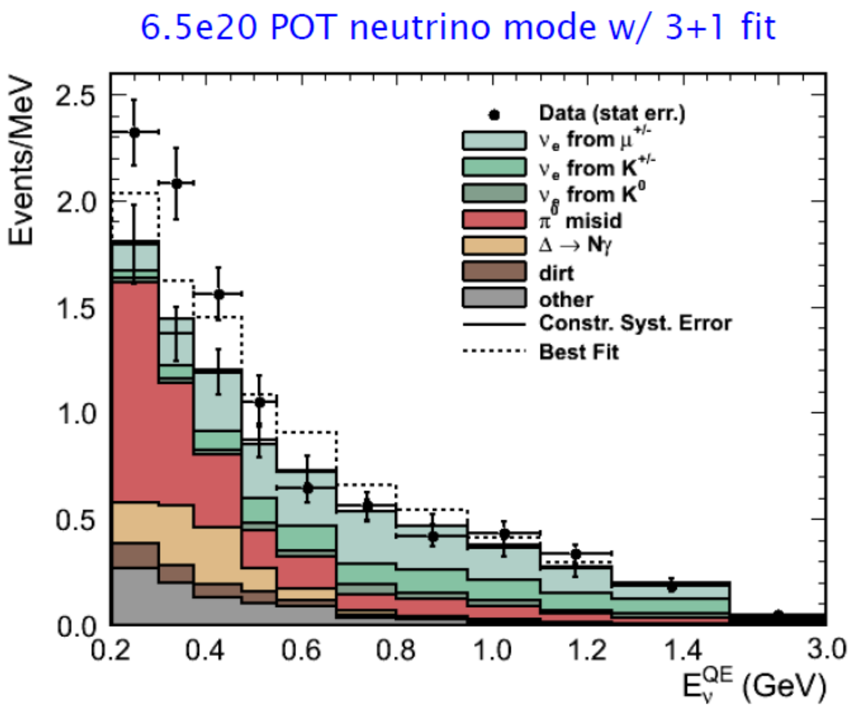


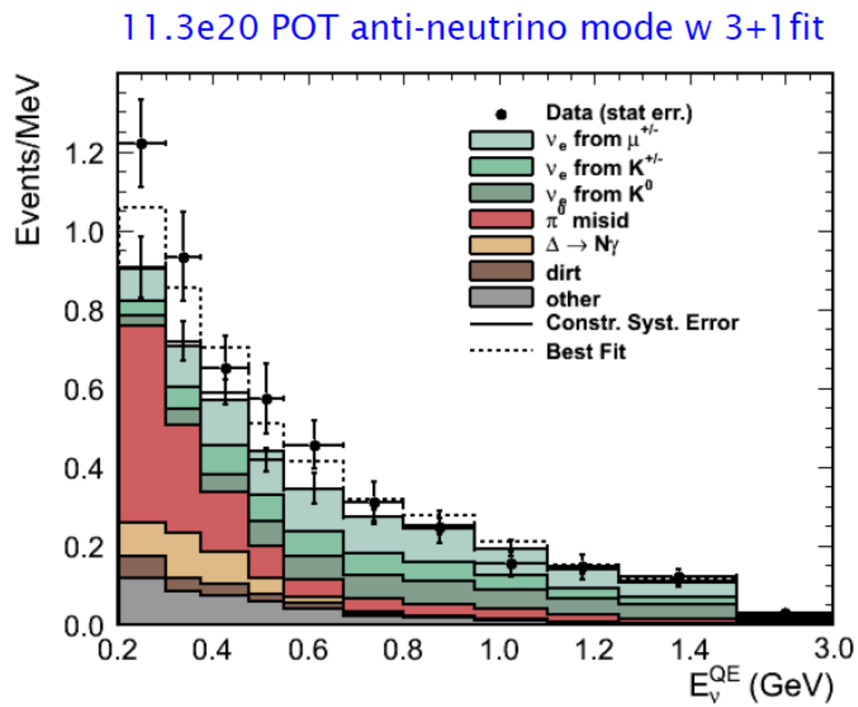


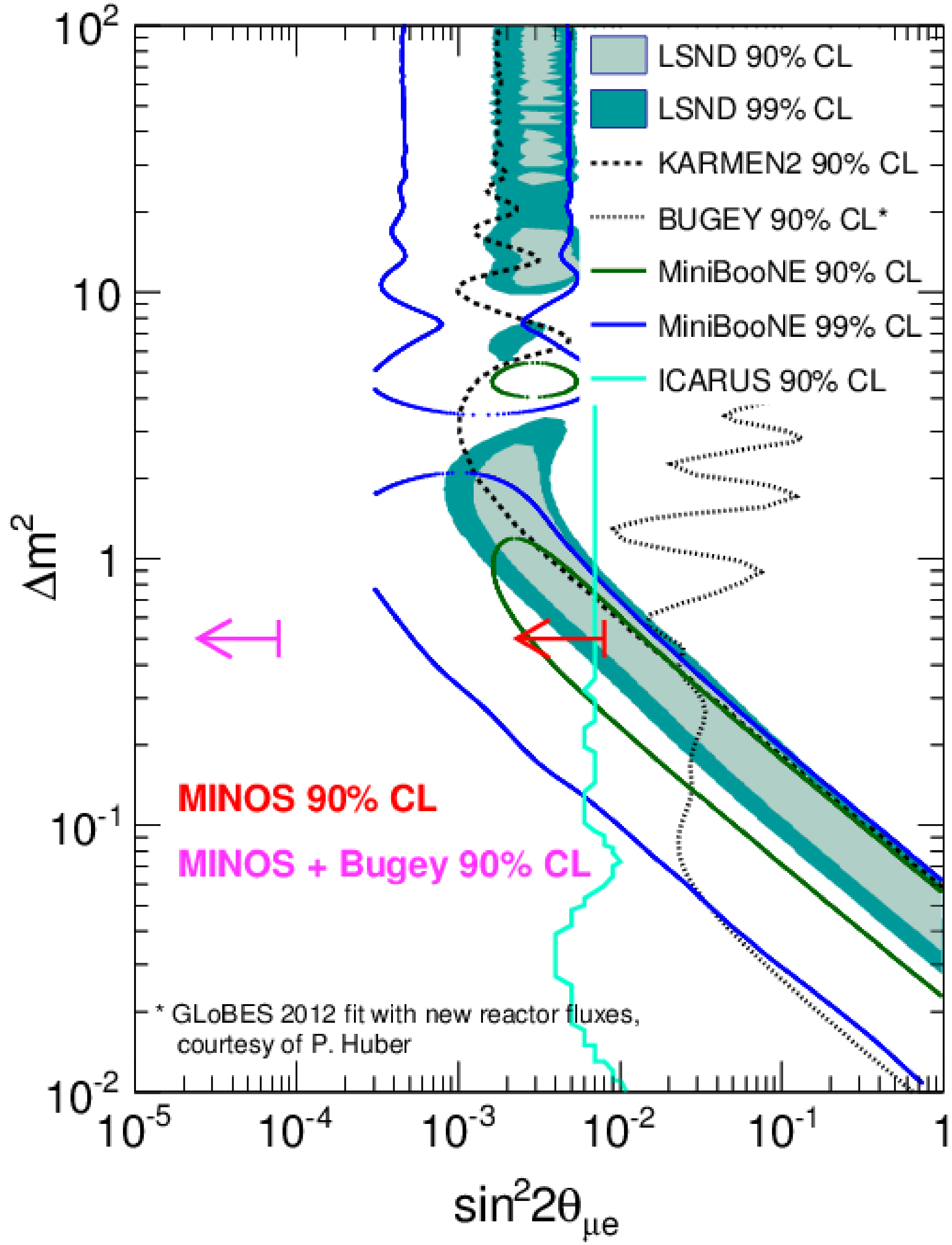
G. Mention *et al.*, Phys. Rev. D **83**, 073006 (2011)

FIG. 5. Illustration of the short baseline reactor antineutrino anomaly. The experimental results are compared to the prediction without oscillation, taking into account the new antineutrino spectra, the corrections of the neutron mean lifetime, and the off-equilibrium effects. Published experimental errors and antineutrino spectra errors are added in quadrature. The mean averaged ratio including possible correlations is 0.943 ± 0.023. The red line shows a possible 3 active neutrino mixing solution, with $\sin^2(2\theta_{13}) = 0.06$. The blue line displays a solution including a new neutrino mass state, such as $|\Delta m^2_{\rm new,R}| \gg 1$ eV^2 and $\sin^2(2\theta_{\rm new,R}) = 0.12$ (for illustration purpose only).

MiniBooNE appearance data

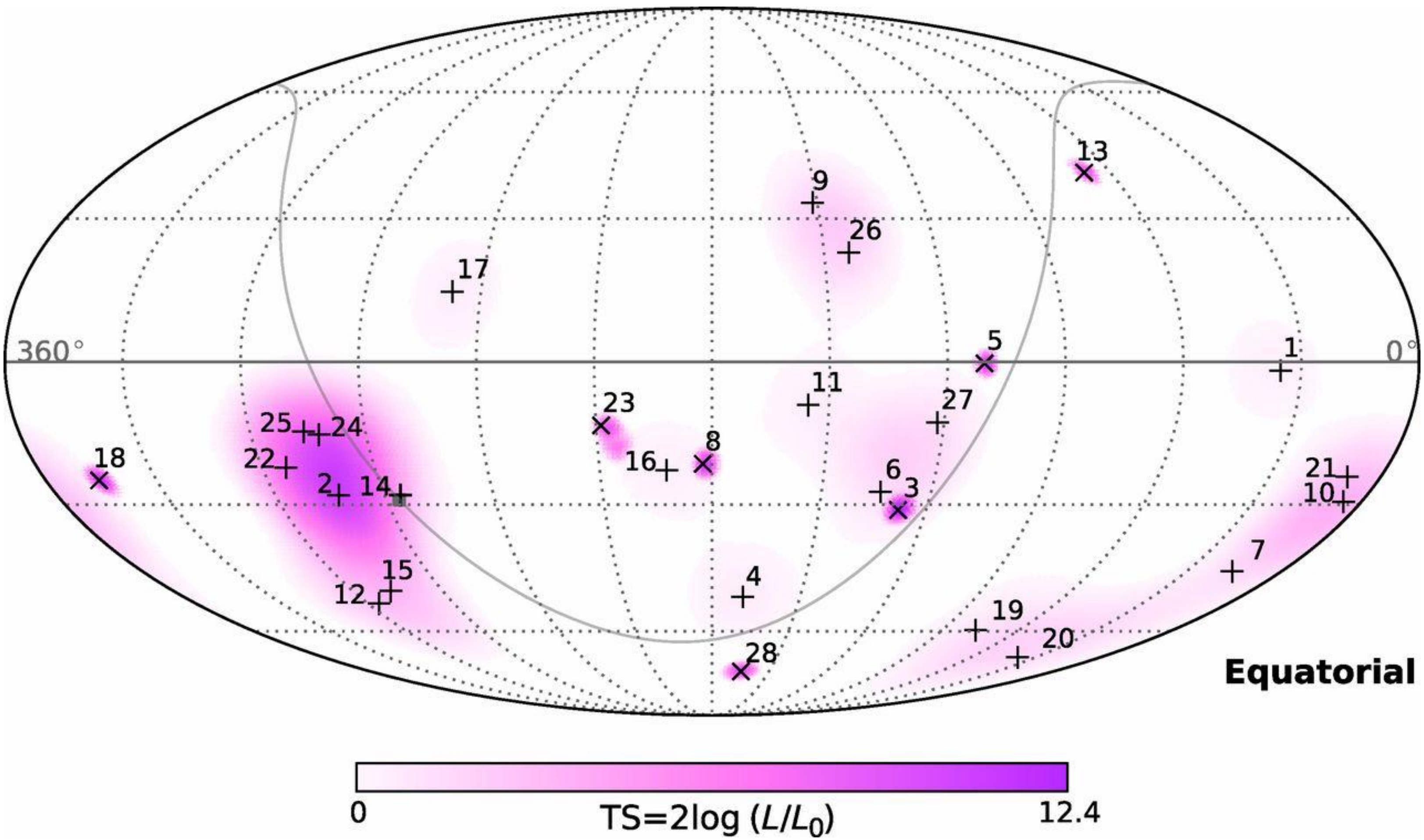




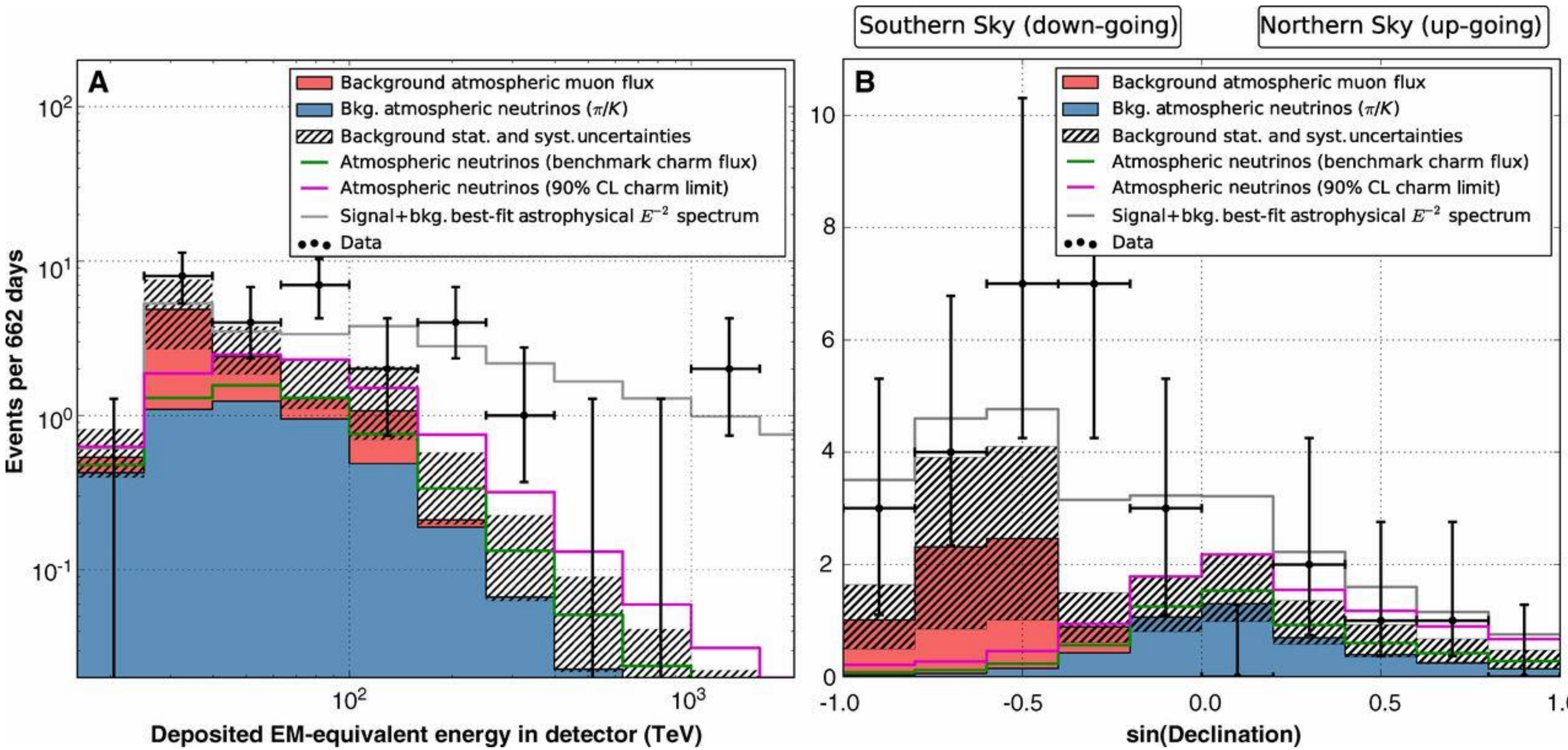


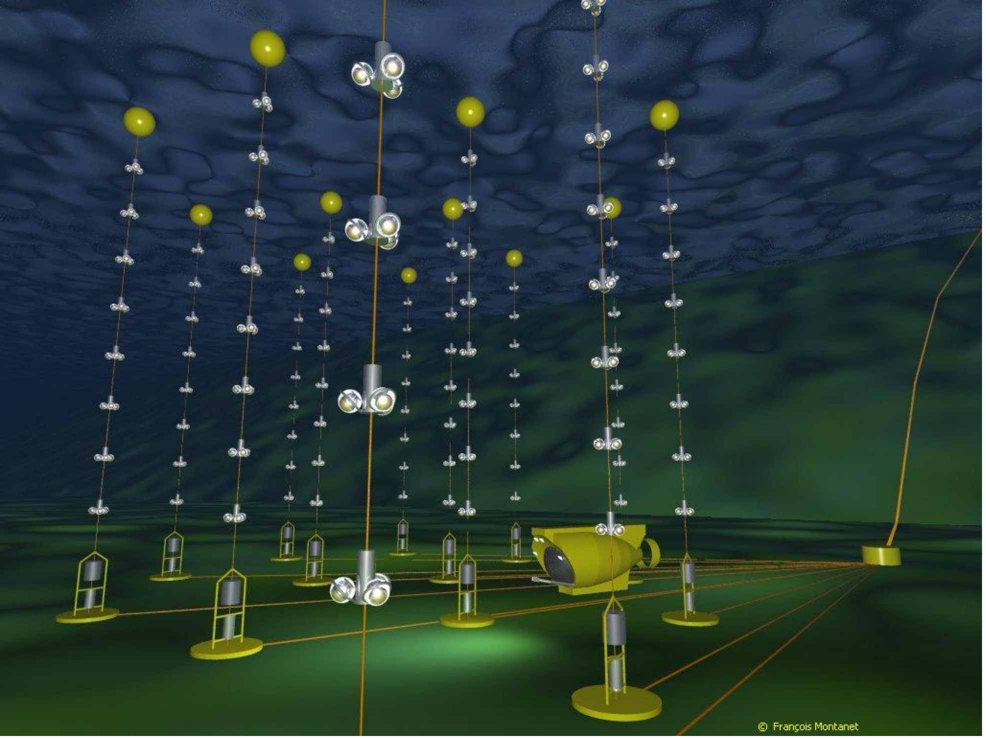
LSND 90% CL
LSND 99% CL
KARMEN2 90% CL
BUGEY 90% CL*
MiniBooNE 90% CL
MiniBooNE 99% CL
ICARUS 90% CL
MINOS 90% CL
MINOS + Bugey 90% CL
* GLoBES 2012 fit with new reactor fluxes, courtesy of P. Huber
Δm^2
$\sin^2 2\theta_{\mu e}$
10^2
10
1
10^{-1}
10^{-2}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1

M. G. Aartsen *et al.* (IceCube), Science **342**, 6161 (2013)



M. G. Aartsen *et al.* (IceCube), Science **342**, 6161 (2013)





ANTARES

IceCube