Perspectives on neutrino physics

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Pittsburgh

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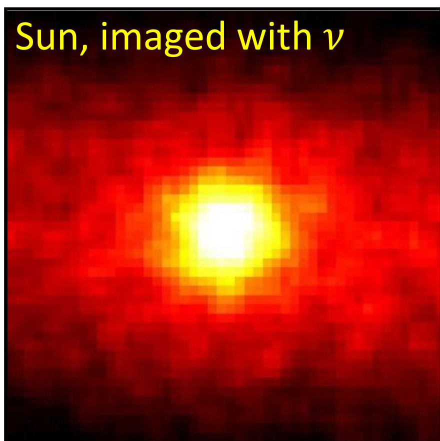
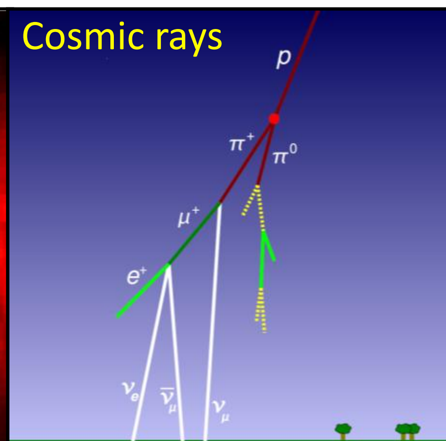
Oscillations

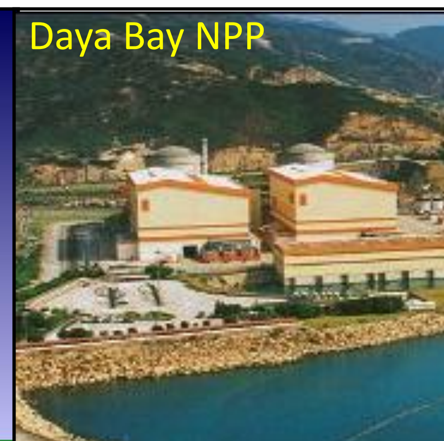
(for propagation through vacuum)

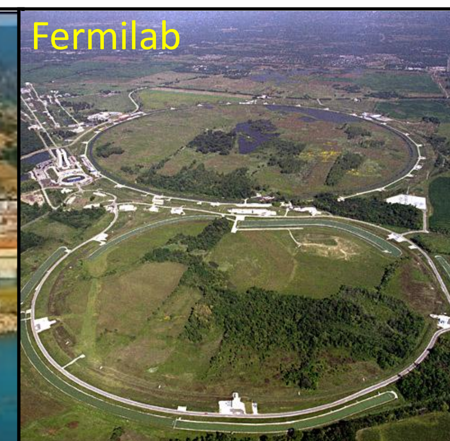
$$P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(L) \rangle|^2$$
$$= \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2[1.27 \Delta m^2_{ij} L/E]$$
$$+2 \sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin[2.54 \Delta m^2_{ij} L/E]$$

- **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*



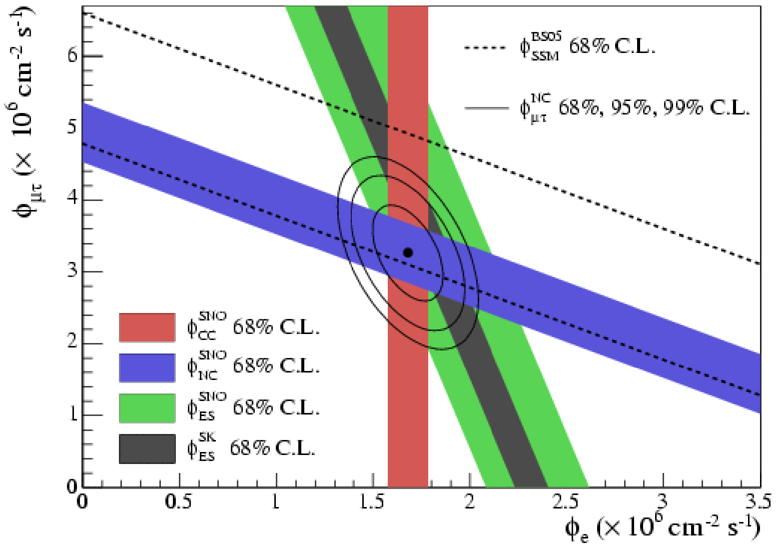




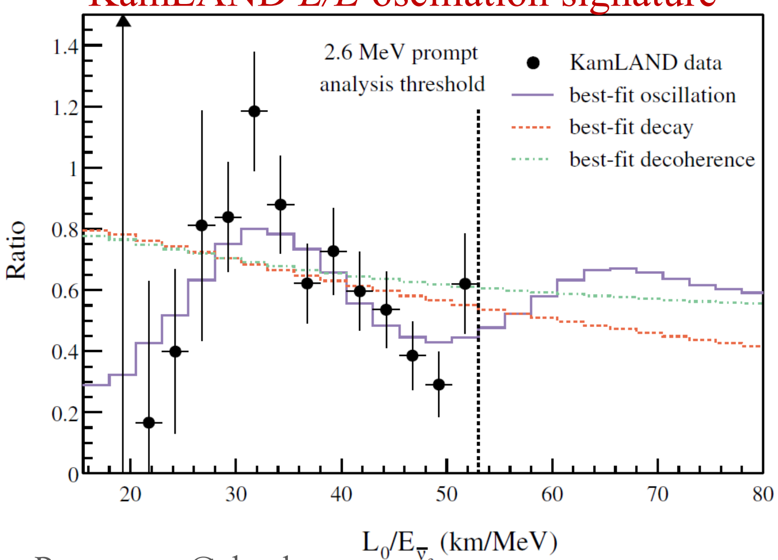


"Solar" parameters θ_{12} and Δm^2_{21}

Measured solar ν fluxes

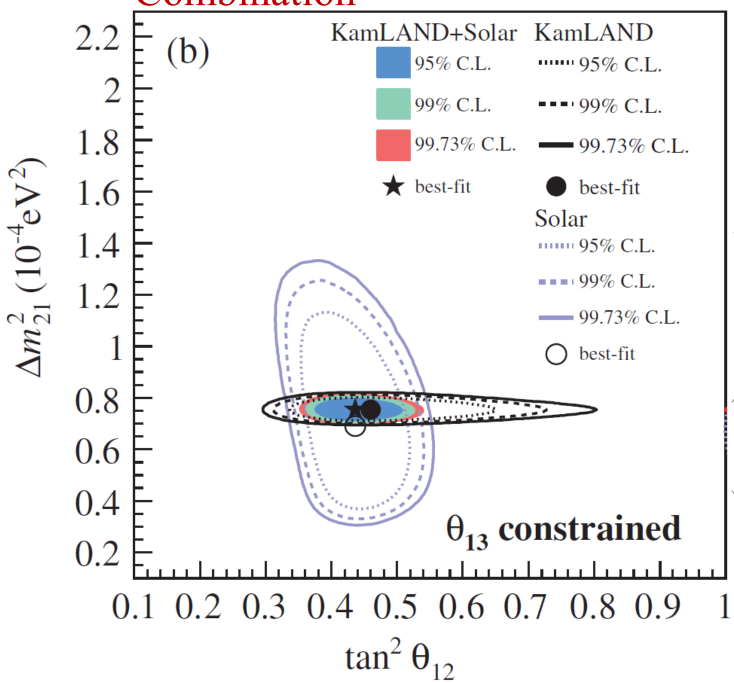


KamLAND *L/E* oscillation signature



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

Combination



A. Gando *et al.*, PRD **88**, 033001 (2013)

$$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \text{eV}^2 \quad (\ 2.4\%\ )$$

$$\sin^2\theta_{12} = 0.304^{+0.014}_{-0.013} \quad (\ 4.4\%\ )$$

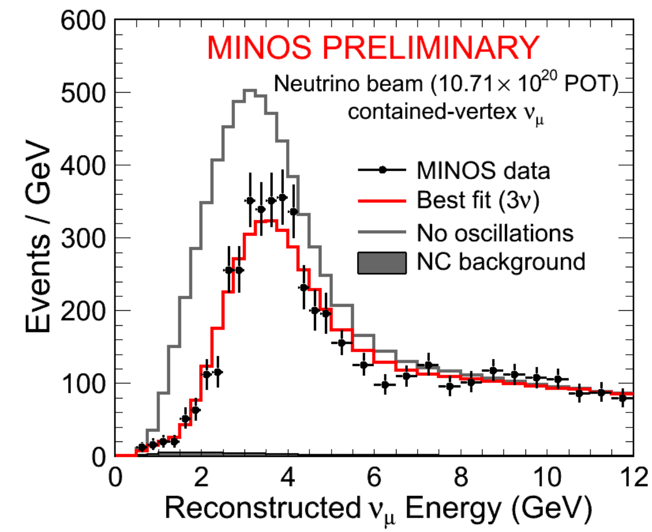
“Atmospheric” parameters θ_{23} and $|\Delta m^2_{32}|$

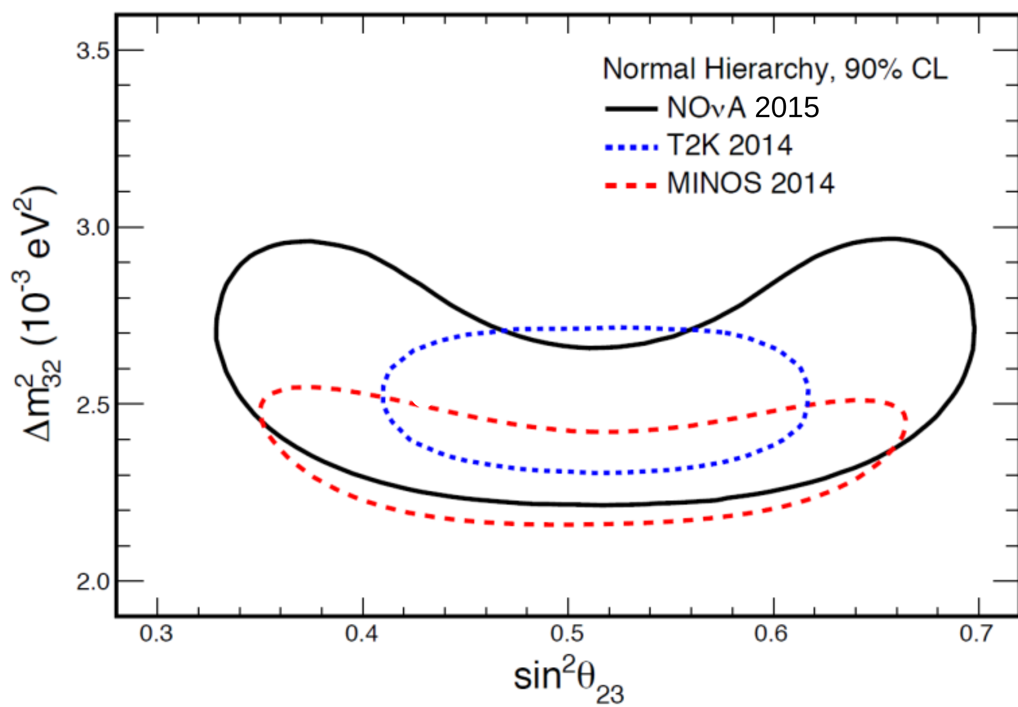
- **Super-K** *(atmos.)*, **MINOS** *(accel.)*, **T2K** *(accel.)*, **NOvA** *(accel.)*, **Daya Bay** *(reactor)*, **IceCube** *(atmos.)*, and others
- Measurements **still rolling in**…

$$\Delta m^2_{32} = (2.42 \pm 0.06) \times 10^{-3}\ \text{eV}^2 \quad (\ 3\%\ )$$

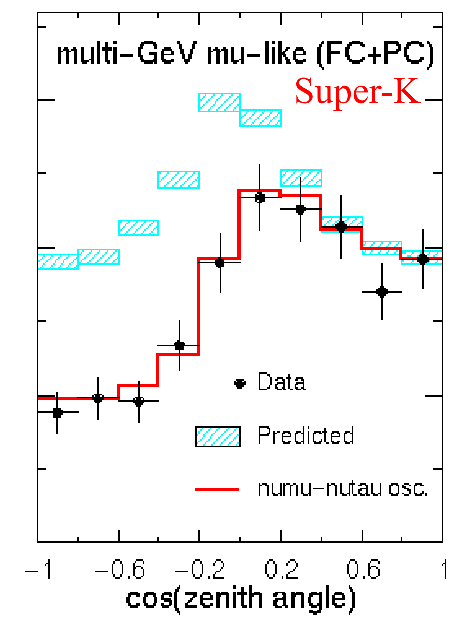
$$\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056} \quad (\ 11\%\ )$$

(for NH)





NOvA, PRD **93**, 051104(R)



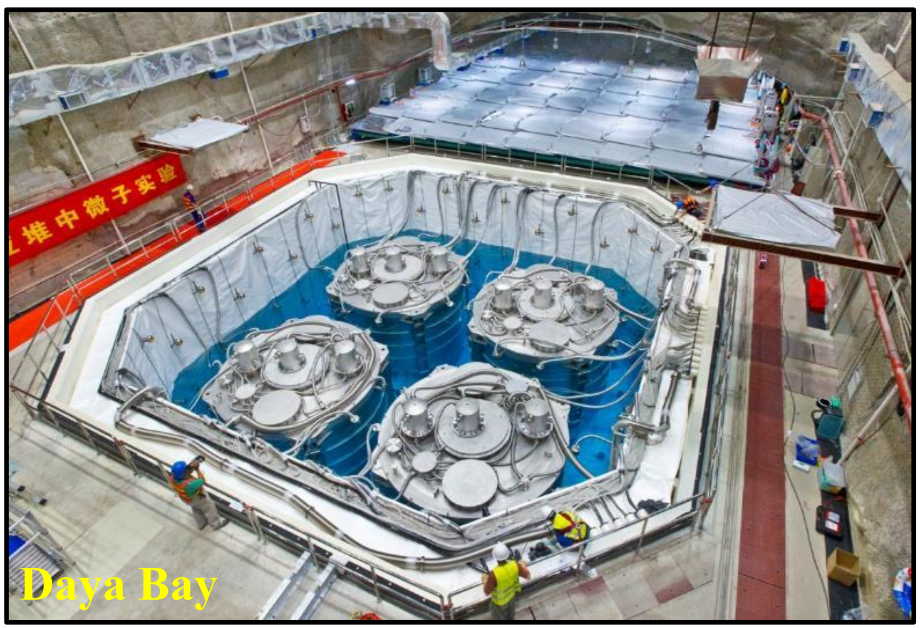
θ_{13} from reactor measurements

Daya Bay: $\sin^2\theta_{13} = 0.021 \pm 0.001$ **(5%)**

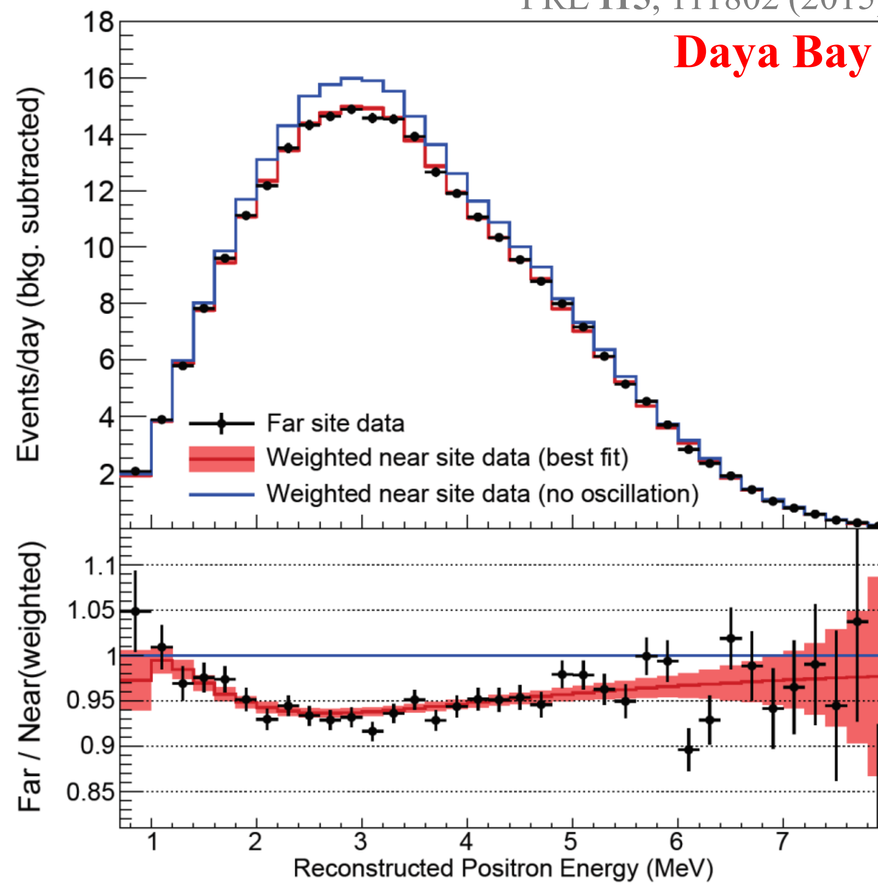
8 detectors in total, rate+shape signal extraction, combined nGd and nH results (new). Also a 4% measurement of Δm^2_{ee}. Will run until 2017.

Double Chooz, RENO are compatible

Higher central values, but errors still relatively large



PRL **115**, 111802 (2015)



Neutrinos have mass

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

FUNDAMENTAL PHYSICS **BREAKTHROUGH** PRIZE

Kam-Biu Luk and the Daya Bay Collaboration

Yifang Wang and the Daya Bay Collaboration

Koichiro Nishikawa and the K2K and T2K Collaboration

Atsuto Suzuki and the KamLAND Collaboration

Arthur B. McDonald and the SNO Collaboration

Takaaki Kajita and the Super K Collaboration

Yoichiro Suzuki and the Super K Collaboration

Questions

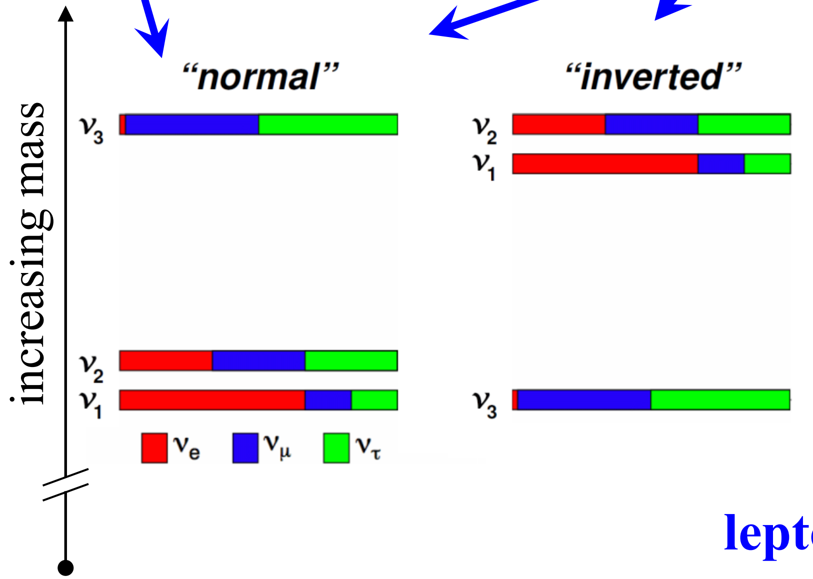
Light sterile states?
(experimental anomalies)

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

mass ordering?
("hierarchy")

Are neutrinos
Majorana or **Dirac**
fermions?

GUT-scale physics?
(see-saw connection)



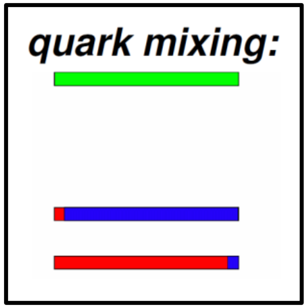
unitary?

absolute masses?

leptonic CP violation?

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

U_{PMNS} highly off-diagonal,
in contrast with U_{CKM}
(model building, unification,
new physics, ...)



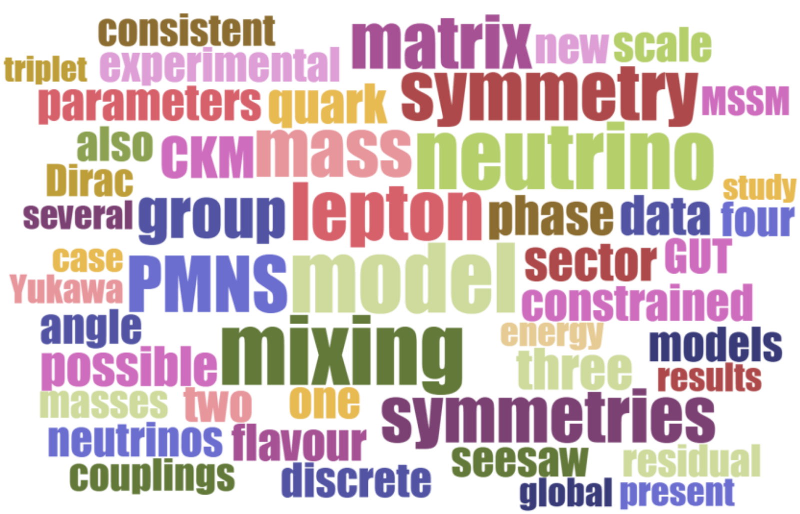
...and more *(geoneutrinos,*
nuclear processes, ν interactions)

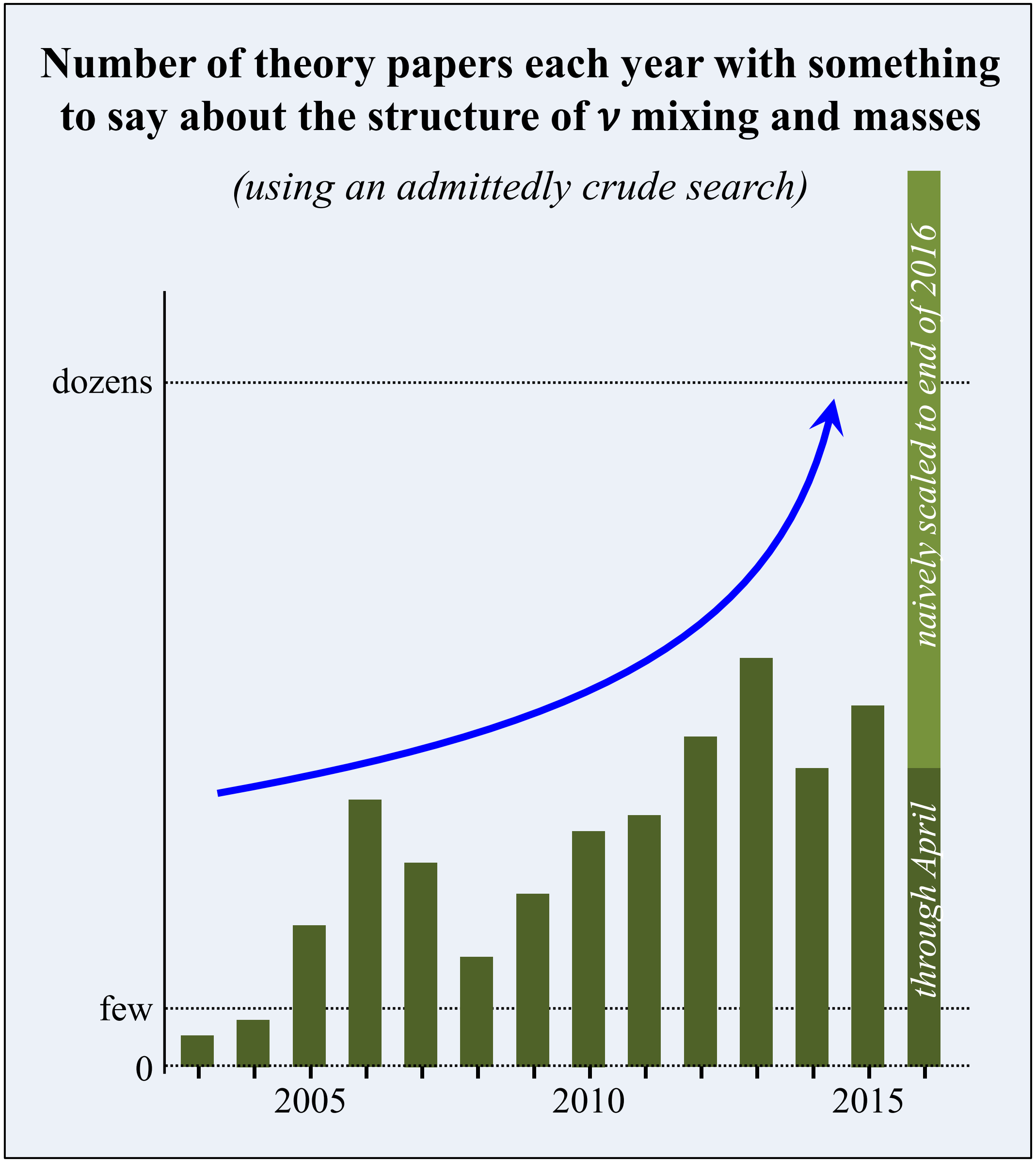
Theoretical answers?

"If you measure it,
they will come."

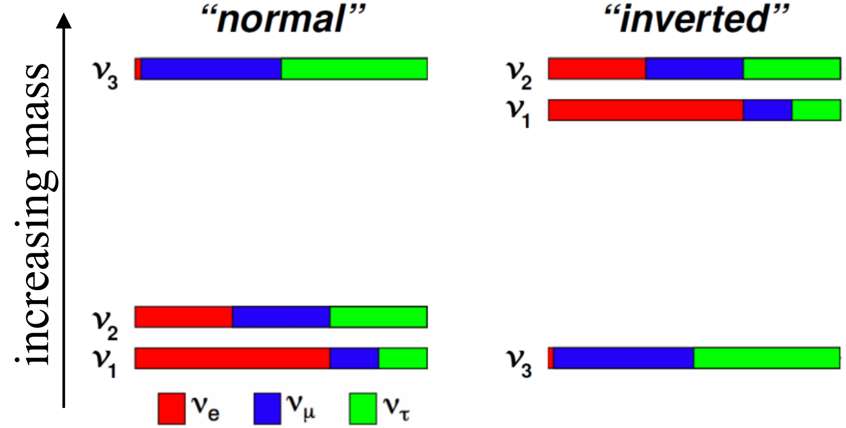
As experimental info grows, the need (and ability) to explain specific observed textures grows with it.

words in recent abstracts





$\theta_{13}>0 \;\Rightarrow\;$ LBL $\nu_\mu \rightarrow \nu_e$



Makes feasible **long-baseline measurements** of…

neutrino mass hierarchy

via matter effects that modify $P(\nu_\mu \rightarrow \nu_e)$

Implications for: $0\nu\beta\beta$ data and Majorana nature of ν; approach to m_β; astrophysics; theoretical frameworks for mass generation, quark/lepton unification; Is the lightest charged lepton associated with the heaviest light neutrino?

CP violation

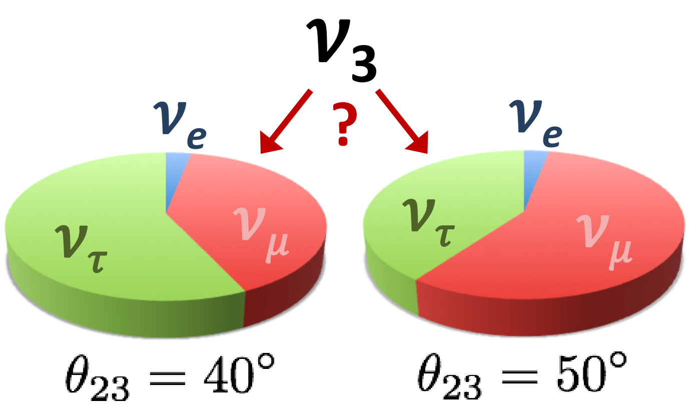
via dependence of $P(\nu_\mu \rightarrow \nu_e)$ on *CP* phase δ. Amplified by $\nu/\bar{\nu}$ comparisons.

baryon asymmetry through see-saw/leptogenesis; fundamental question in the Standard Model (is *CP* respected by leptons?)

ν_3 flavor mixing

via leading-order factor $\sin^2(\theta_{23})$

Is ν_3 more strongly coupled to μ or τ flavor?; frameworks for mass generation, unification



Long-baseline $\nu_\mu \rightarrow \nu_e$

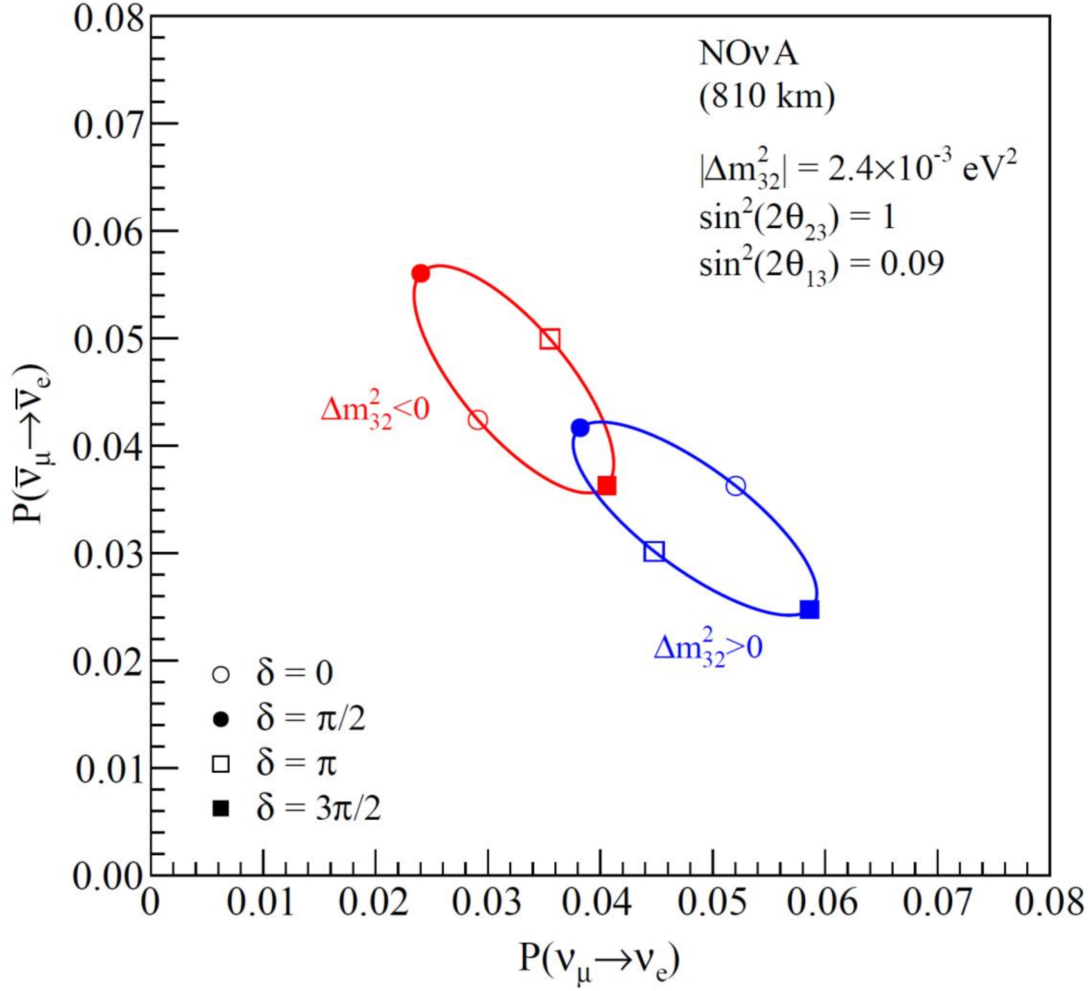
A more quantitative sketch…

At right:

$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ vs. $P(\nu_\mu \rightarrow \nu_e)$

plotted for a single neutrino energy and baseline

For fixed L/E = 0.4 km/MeV



Long-baseline $\nu_\mu \rightarrow \nu_e$

A more quantitative sketch…

At right:

$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ vs. $P(\nu_\mu \rightarrow \nu_e)$

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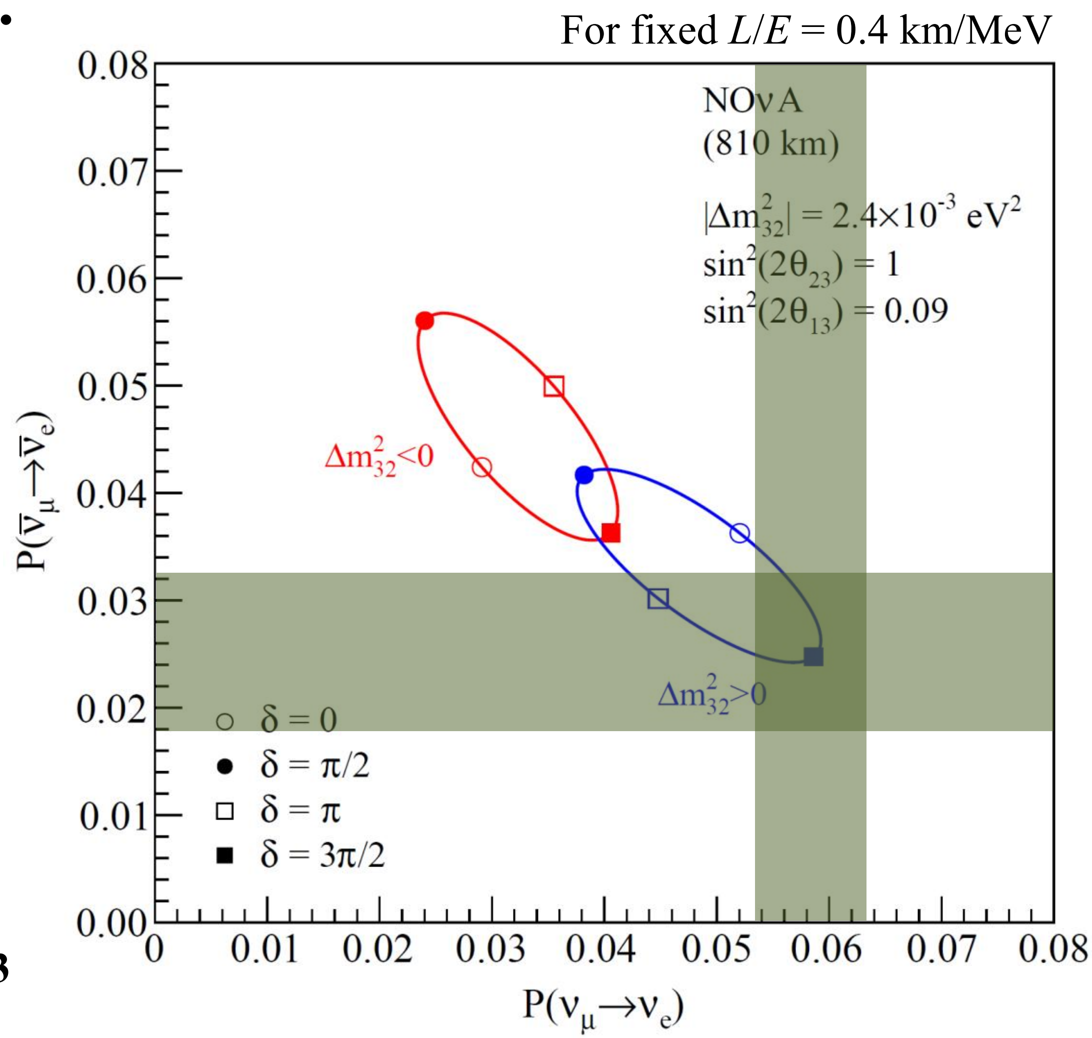
Measure these probabilities

(an example measurement of each shown)

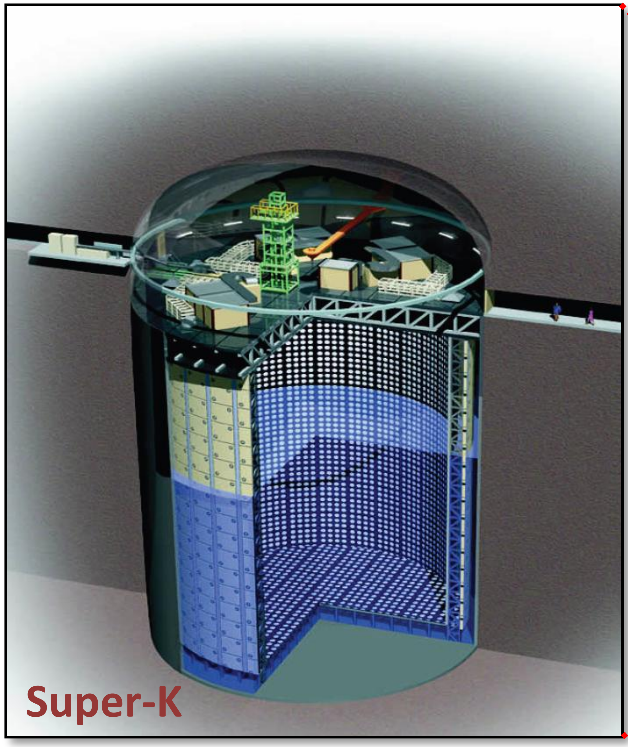
Also:

Both probabilities $\propto \sin^2\theta_{23}$



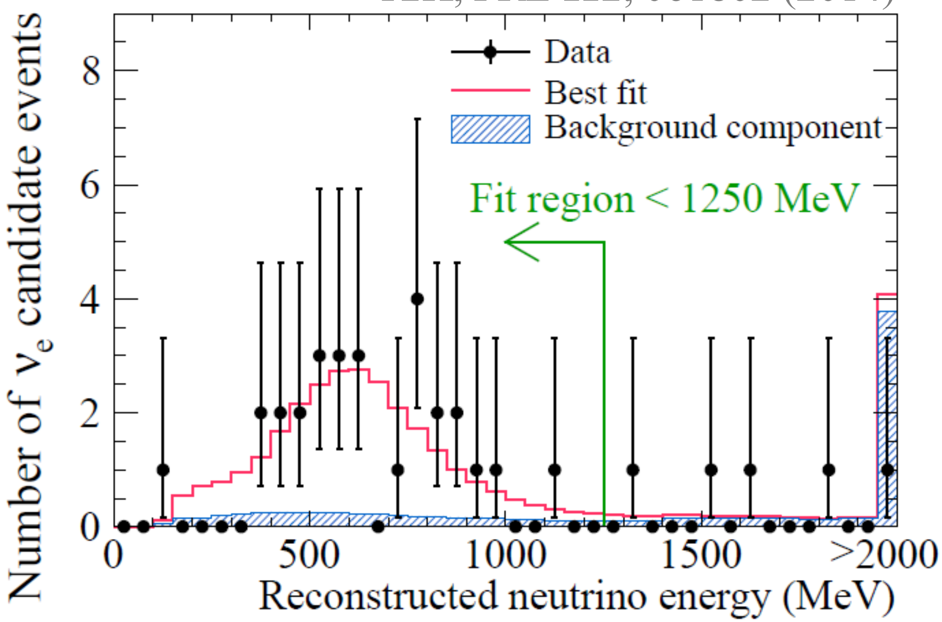
T2K

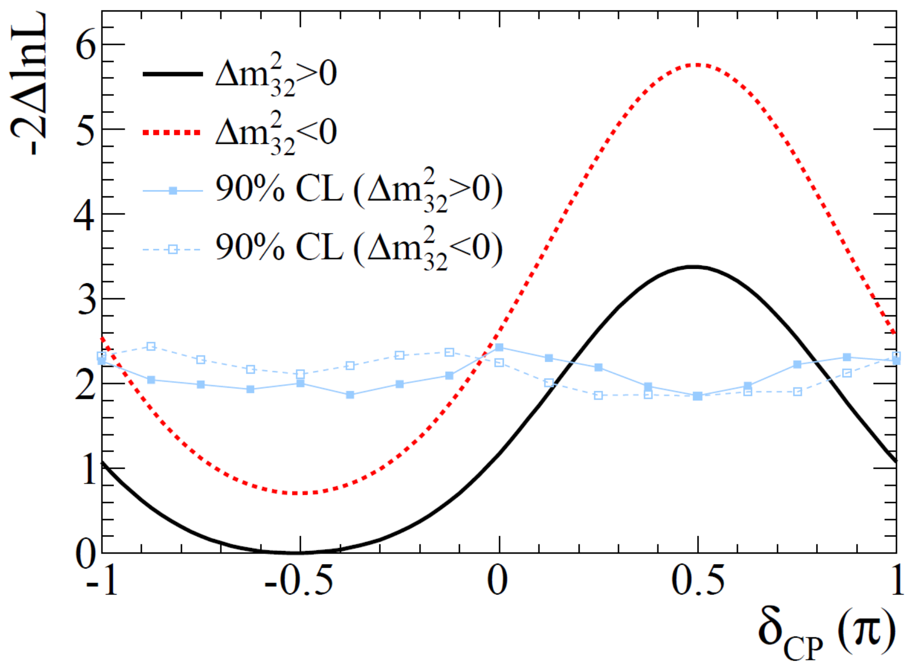
- **Tokai to Kamioka (295 km)**
- **Neutrino beam from J-PARC**
- **Storied far detector: *Super-K***
- **INGRID and ND280 near detectors**



- **2014: First definite observation (7.3σ) of $\nu_\mu \to \nu_e$ appearance**
  NH, δ=3π/2 *is best fit, but only slightly so*
- **10% of planned data set**
- **"Short" 295-km baseline:**
  Important role in global ν fits (minimal hierarchy dependence)

T2K, PRL **112**, 061802 (2014)

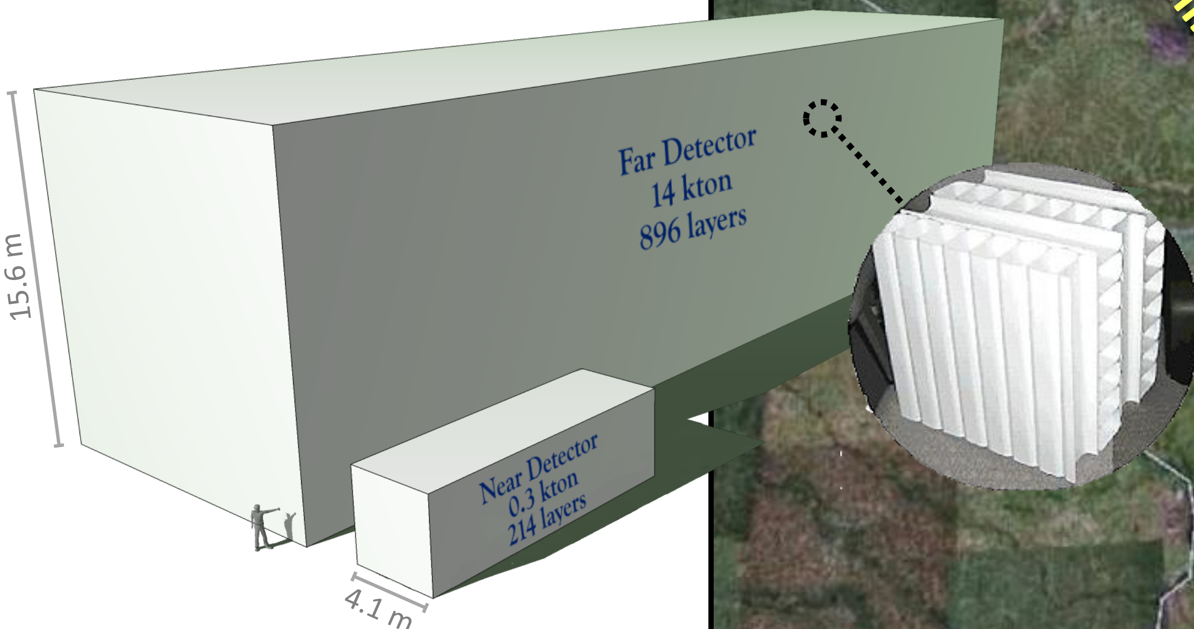


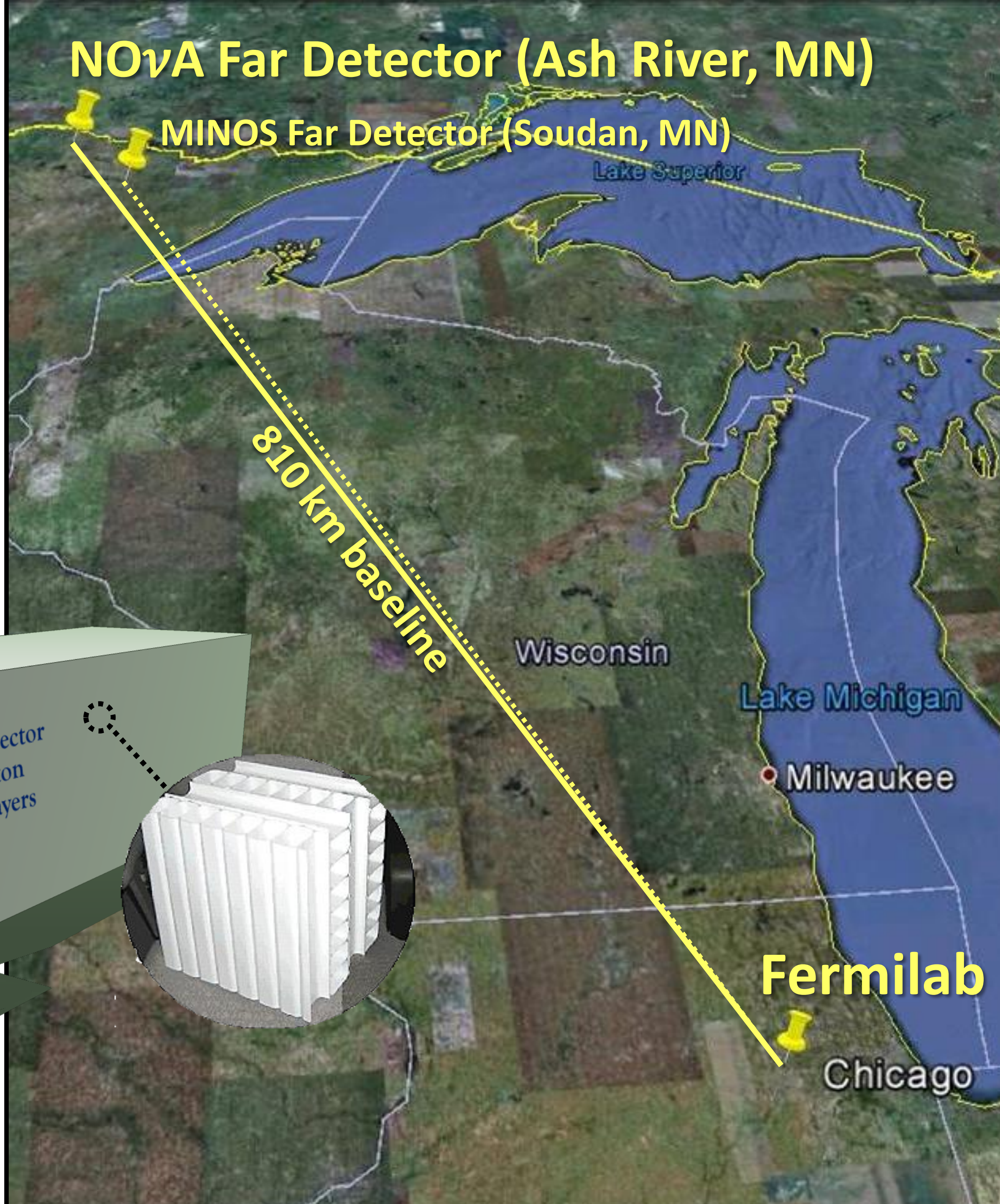


- Also, **$\bar{\nu}_\mu \to \bar{\nu}_e$ appearance** search, with 10% of planned exposure
- **3 events** observed, consistent with any oscillation parameters (or no appearance at all; bkgnd≈1.6 events)
- *Best fit is again at* **NH, δ=3π/2**, *but only (very) slightly so*

NOνA

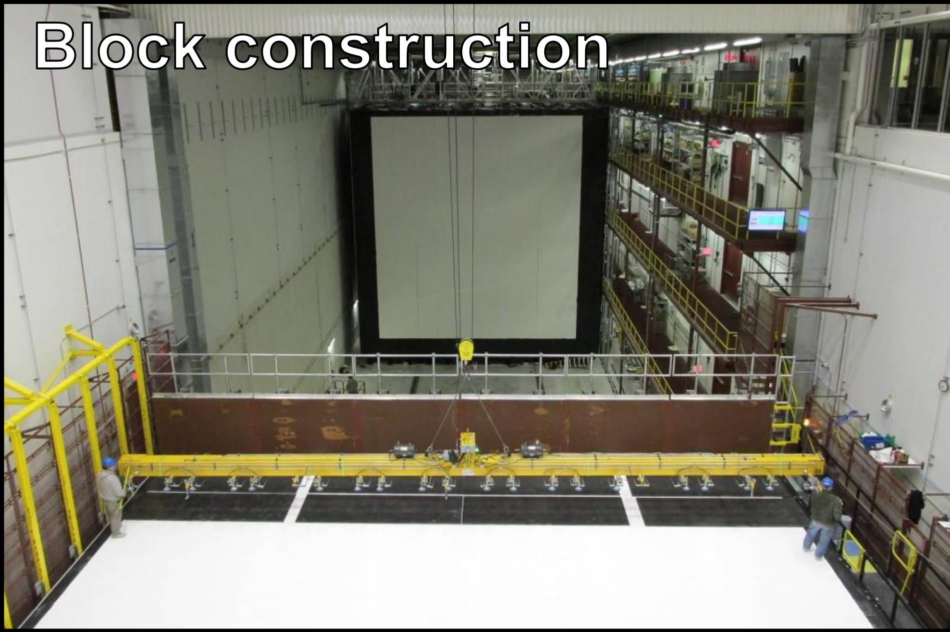
- **Fermilab to Ash River, MN**
- **Upgraded NuMI beam**
- **810 km baseline introduces significant matter effects**
  ⇒ *mass hierarchy sensitivity*
- **Functionally identical near and far detectors**
- **Full operations began 2014**





Ryan Patterson, Caltech


Far Detector site

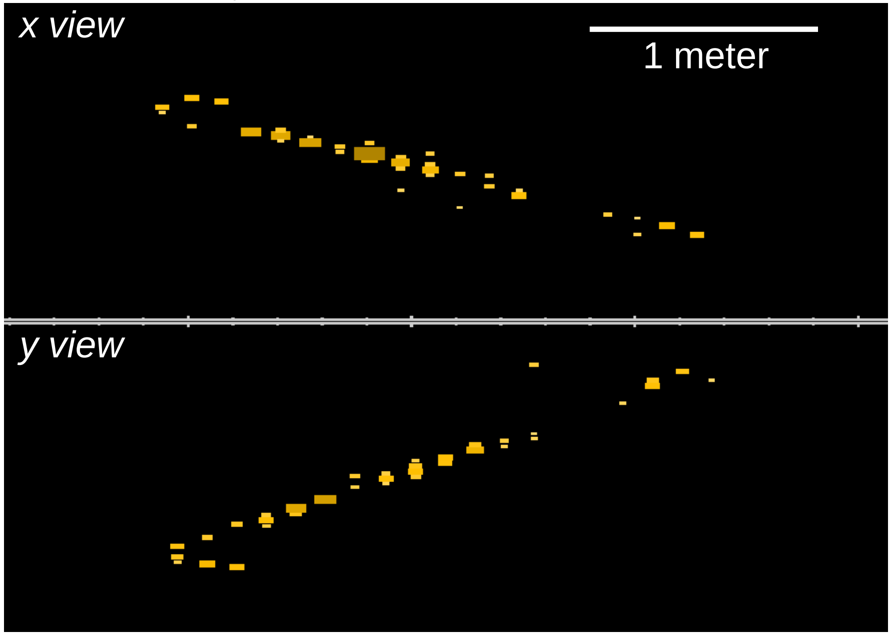

Block construction

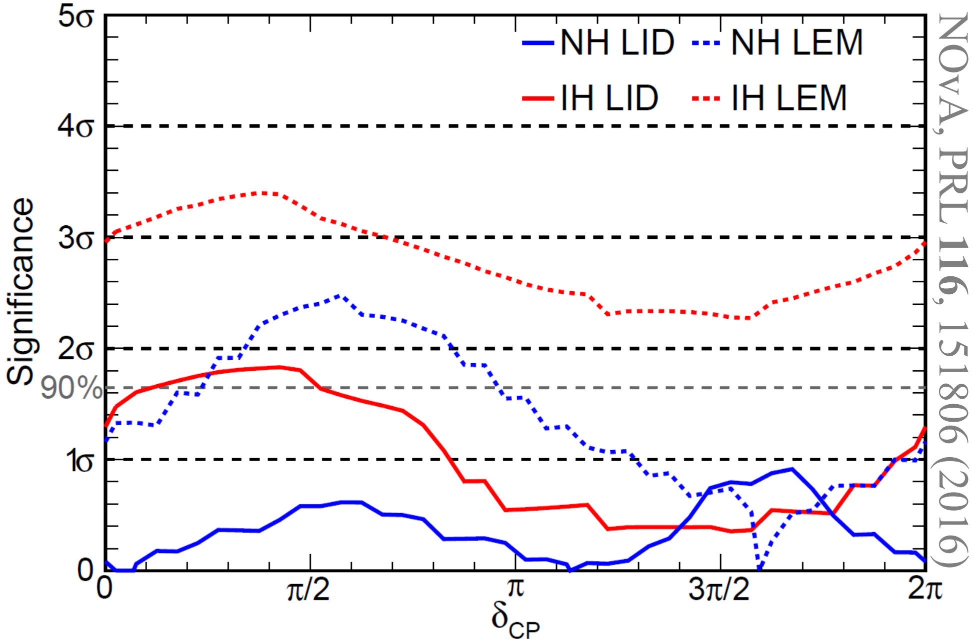

Outfitted Far Detector


Near Detector

- **2015:** **$\nu_\mu \rightarrow \nu_e$ appearance result** with small data set (7.6% of nominal exposure)
- Two complementary event selectors saw **6 and 11 events** → ***on the high end of expectations***

ν_e candidate in NOvA Far Detector

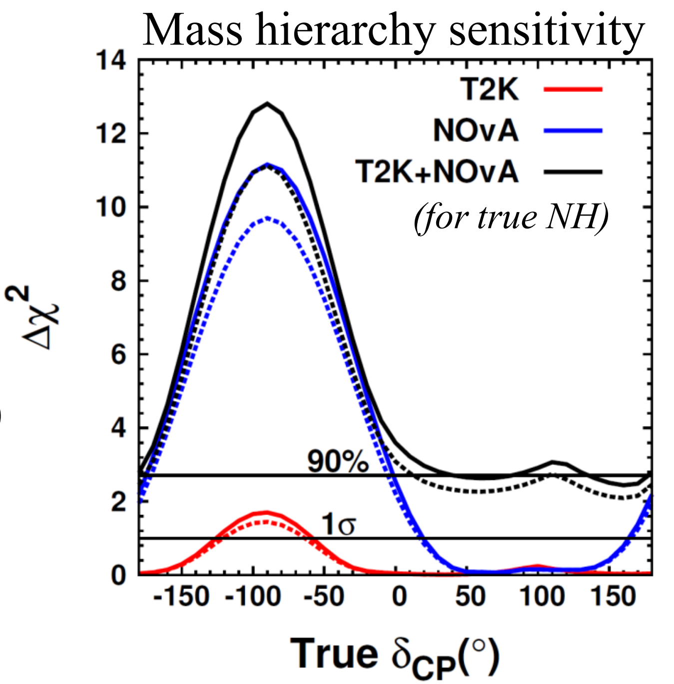




- **NH, δ near $3\pi/2$** is best fit, but only slightly so
- IH disfavored at >2.2σ for all δ by one of the selectors (*careful: look elsewhere effect*)
- New NOvA results expected this summer with twice the exposure

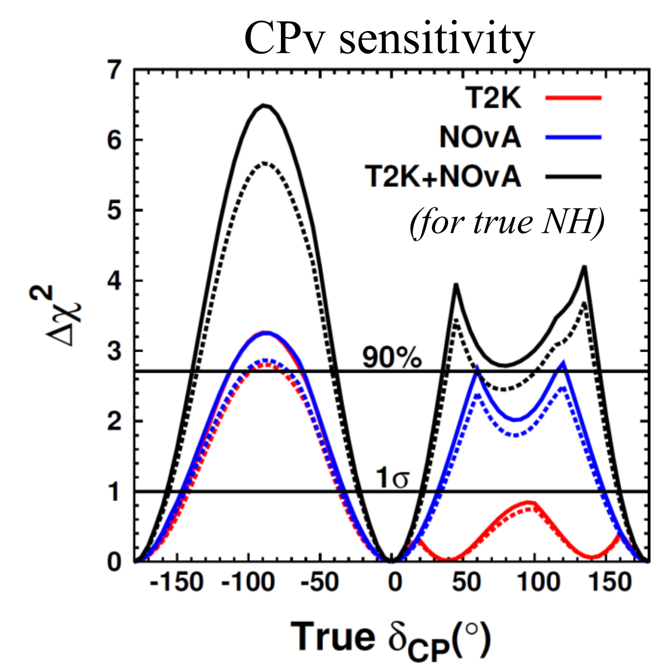
NOvA + T2K reach with planned exposures

- **Many such studies.** Shown here is:
  K. Abe *et al.* (T2K), Prog. Theor. Exp. Phys. 043C01 (2015)
- Current **best fit point** of NH, $\delta \approx 3\pi/2$ **is best case:**
  - hierarchy determination at 3.3σ (3.1σ from NOvA)
  - $\sin(\delta) \neq 0$ observation at 2.4σ
- Can still be anywhere on the map, though.



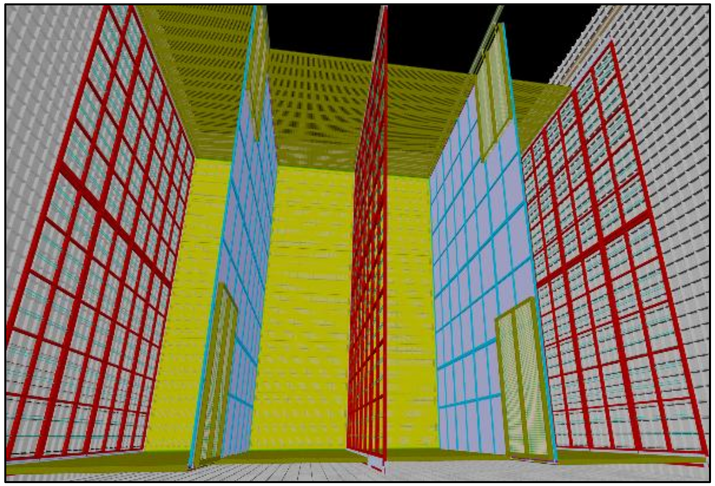
Will the planned exposures happen?

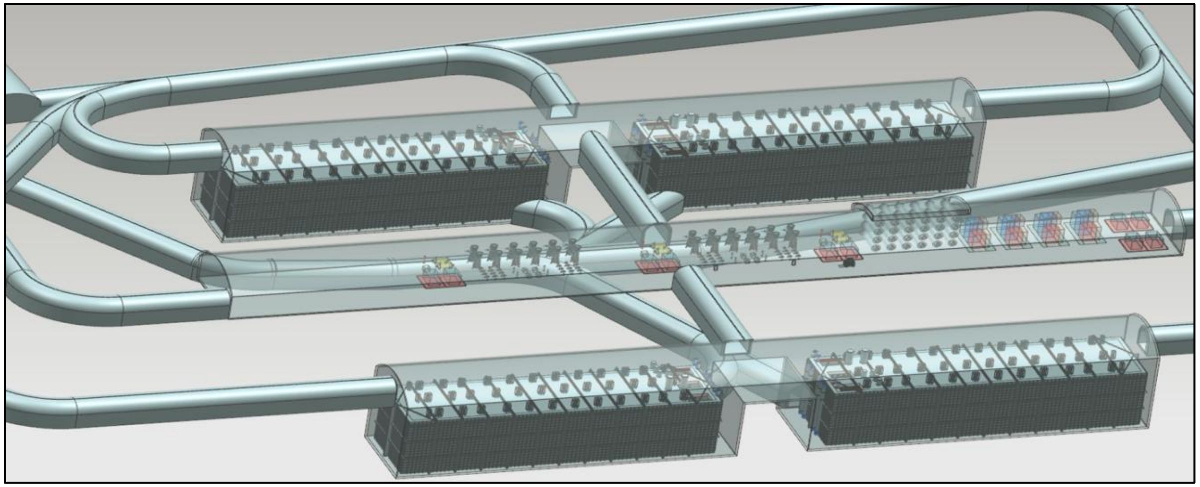
- **NOvA:** ***likely yes***
  550 kW → 700 kW possible by end of year. May involve running past 6-yr mark.
- **T2K:** ***can happen after investment***
  350 kW → 750 kW requires Main Ring upgrades (approved!) and/or increase in accelerator livetime.



DUNE

- **Next generation LBL experiment**
  Plus: supernova neutrinos, nucleon decay, atmospheric neutrinos, and near-det physics)
- **1300 km neutrino baseline**
  No parameter degeneracies can remain
- DUNE has **significant support in the agencies, laboratories, and international community.** Movement to CD-3a later this year.
- **Full-scale component prototypes** to operate at CERN over next few years. Smaller scale prototypes operating now (*e.g.*, 35-ton at FNAL)





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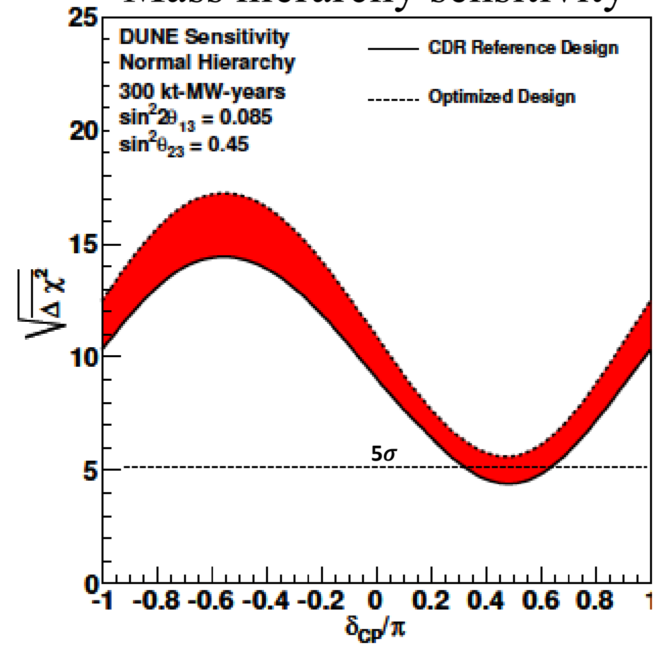
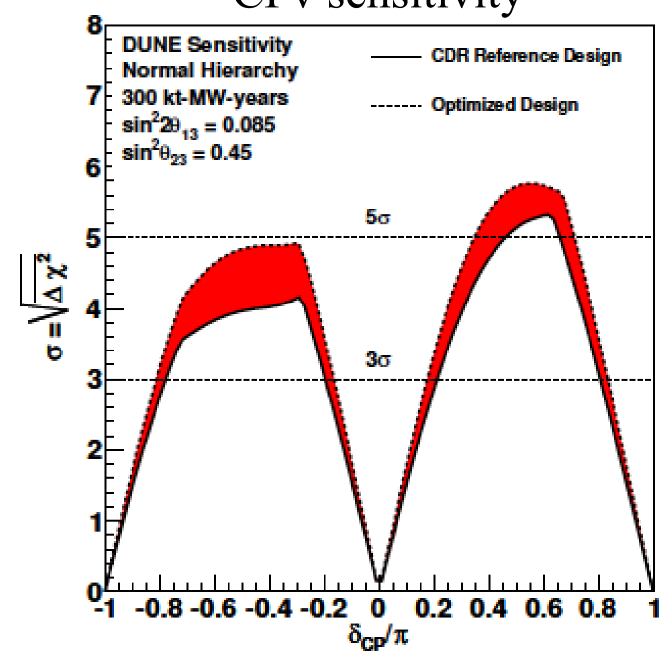
- First 20 kton + beam, ***c.* 2026**
- **CPv at 3σ for 65% of δ range; >5σ at peak**
  (beam data only)
- **Definitive** hierarchy measurement

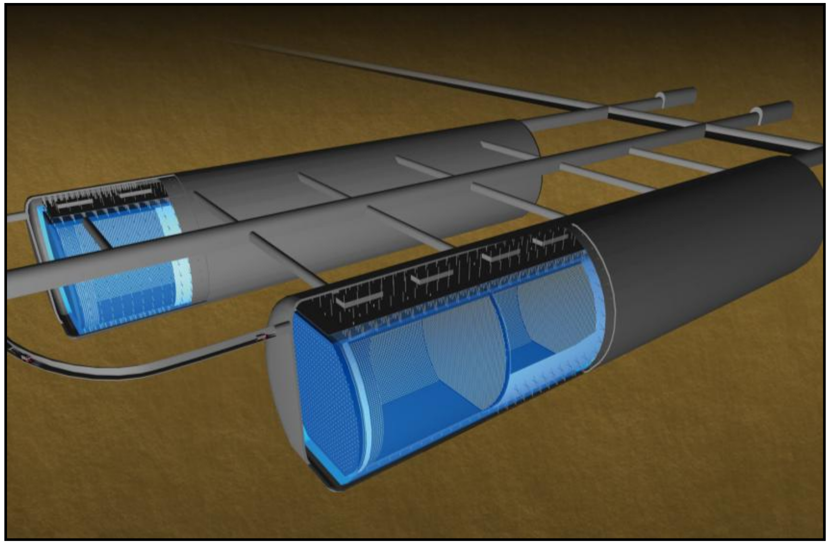
Mass hierarchy sensitivity



CPv sensitivity

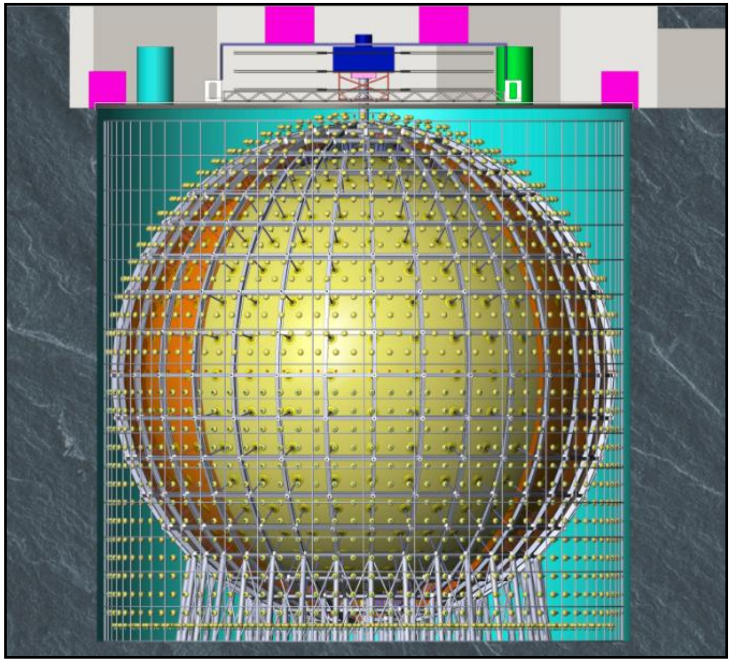


Hyper-K



- **A bigger Super-K / T2K**
  - 560 kton fiducial mass
  - Goals qualitatively similar to DUNE *(different emphasis on atmospheric and solar ν; different p-decay channels)*
  - Still gathering momentum …

JUNO



- **A bigger, better KamLAND (via Daya Bay)**
  - Precision PMNS
  - (*Possible)* 3-4σ on νMH before 2030
  - Construction has begun, concurrent with detector R&D

	KamLAND	JUNO
fiducial mass	~1 kton	20 kton
PMT coverage	~34%	~80%
energy resol'n	~6%/√E	~3%/√E
light yield	~ 250 p.e. / MeV	~ 1200 p.e. / MeV

non-trivial jump

Similarly, RENO: still gathering momentum, support

So, neutrinos have mass 

- And this mass is **rather small**
- **What are we dealing with?**
  - **Neutrinos are Majorana fermions and are pointing to new physics** *(seesaw mechanism, new states at high mass scale)*
  - **Neutrinos are just another Dirac fermion, but they couple to the Higgs very weakly?** (m_ν / $m_{\mathrm{EW}} < 10^{-12}$)
  - **Neutrinos couple to a different Higgs sector?**
  - **Other?**

- Oscillation experiments continue **looking for failures** of standard assumptions (>3 ν, non-unitary PMNS, NSI, effective CPTv)
- But to **get at neutrino mass** directly…

- **Cosmological observations** → sum of neutrino masses.

  Best limits: $\Sigma \boldsymbol{m_i}$ **< 0.23 eV** (95% C.L.) *Planck collaboration, arXiv:1502.01589*

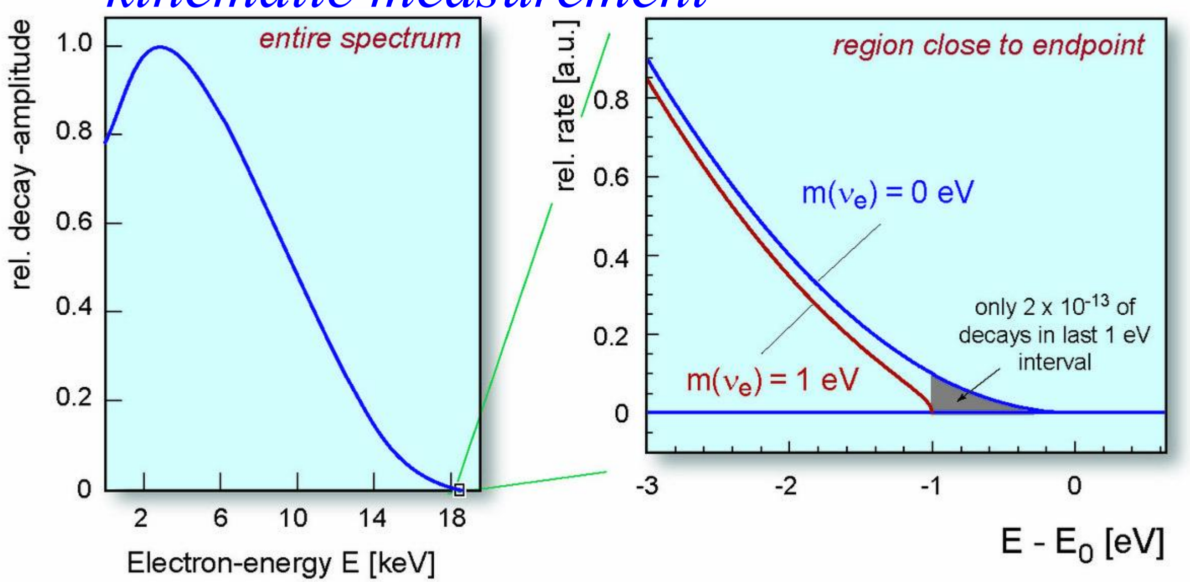
- ***β*-decay kinematic measurement** → effective ν_e mass, a.k.a. m_β:

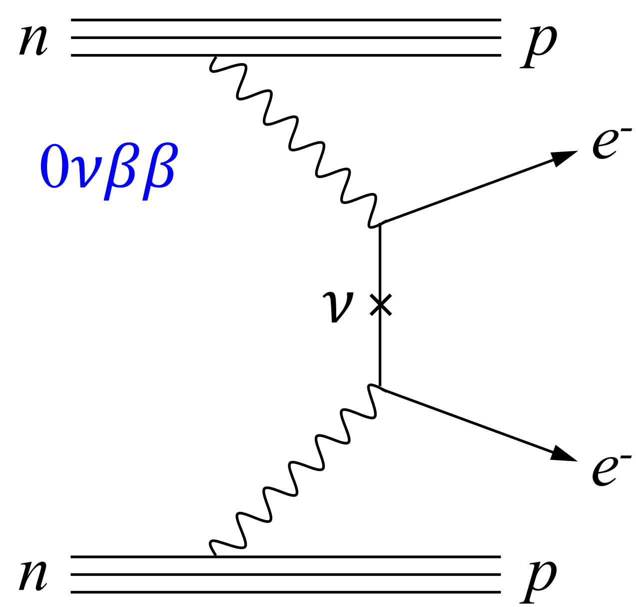
$$m_\beta^2 = \sum |U_{ei}|^2 m_i^2$$

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

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

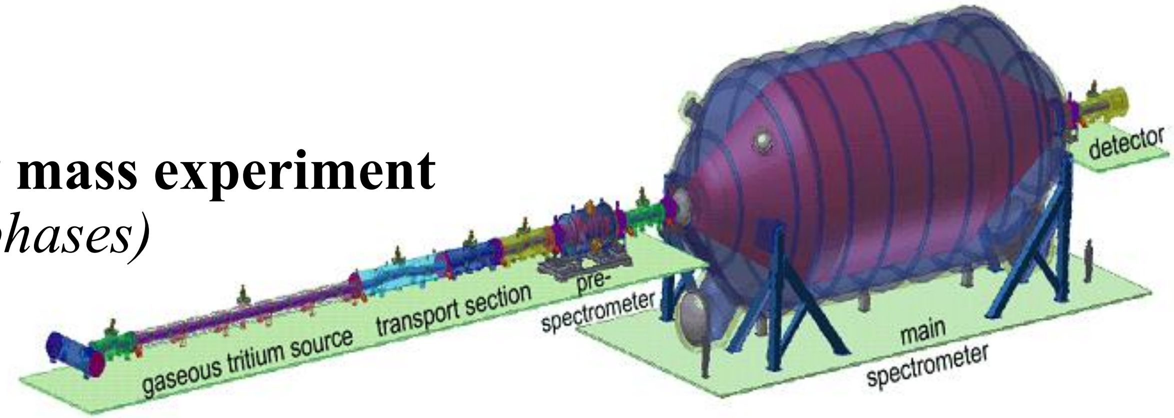
kinematic measurement



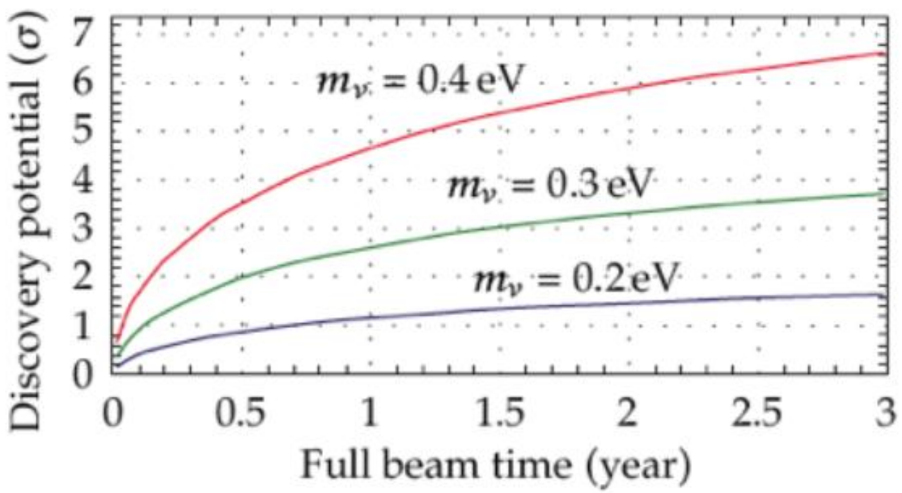


KATRIN

- **Only current kinematic ν mass experiment**
  (several others in R&D phases)
- Large **electrostatic filter** for β spectrometry
- **Tritium running expected in 2016**



5σ reach for $m_\beta = 0.35$ eV

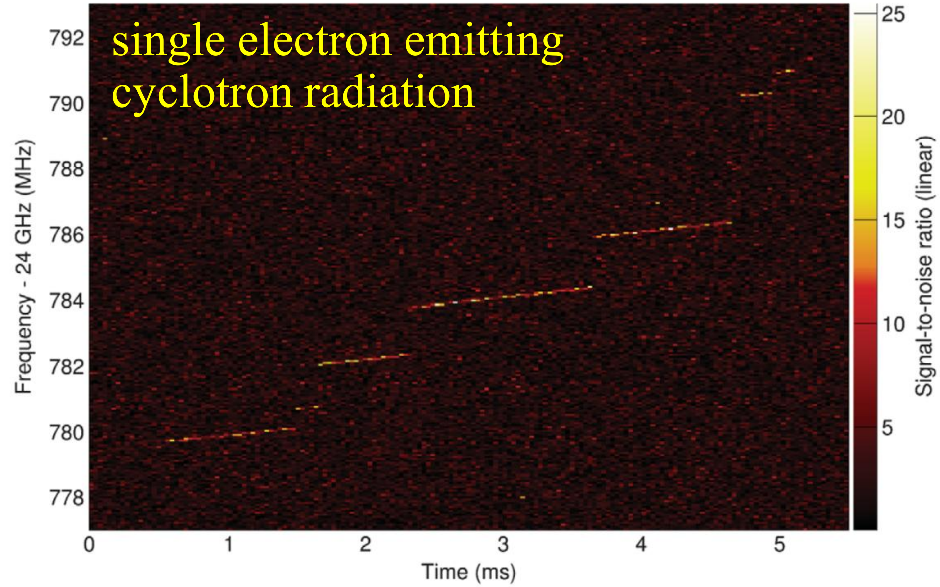


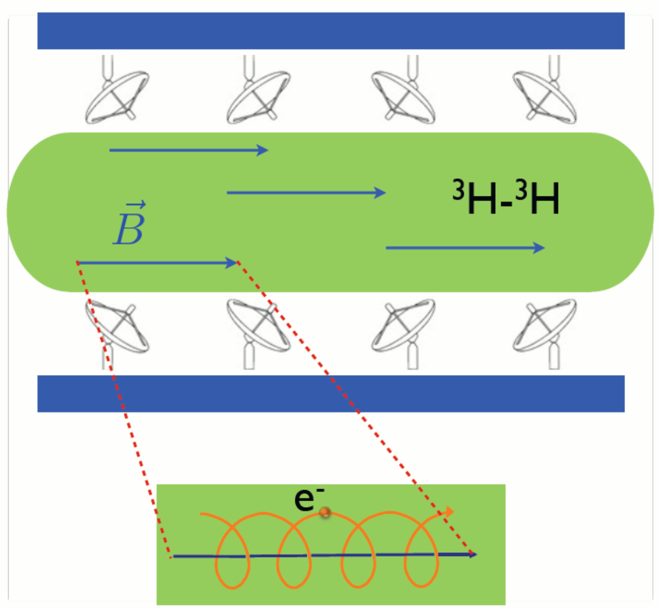
spectrometer en route to Karlsruhe

One recent R&D result of note…

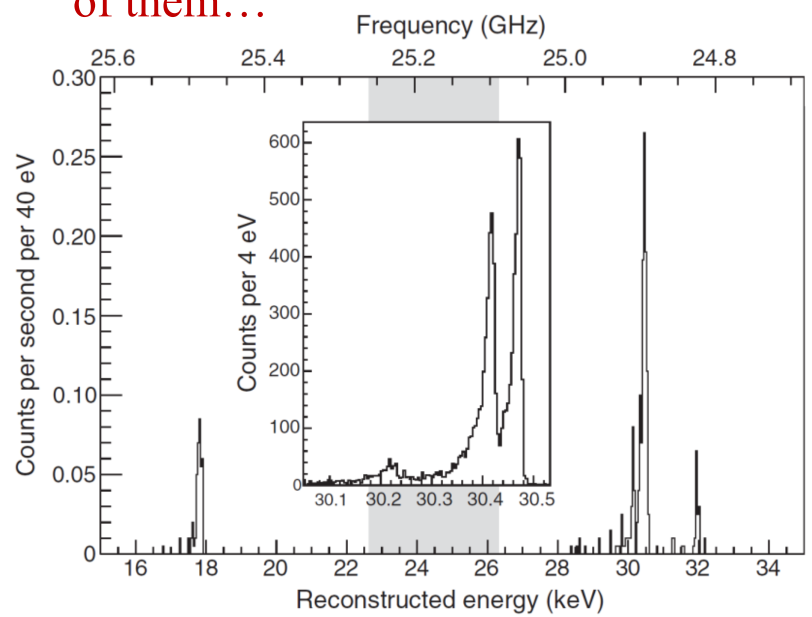
- **Project 8**: measure cyclotron frequency of single electrons
- **Entirely new spectroscopic technique**
  → *very different path to m_β*
- Compatible (in principle) with atomic tritium source
  → *pass IH mass range*

Project 8 collaboration, PRL **114**, 162501 (2015)



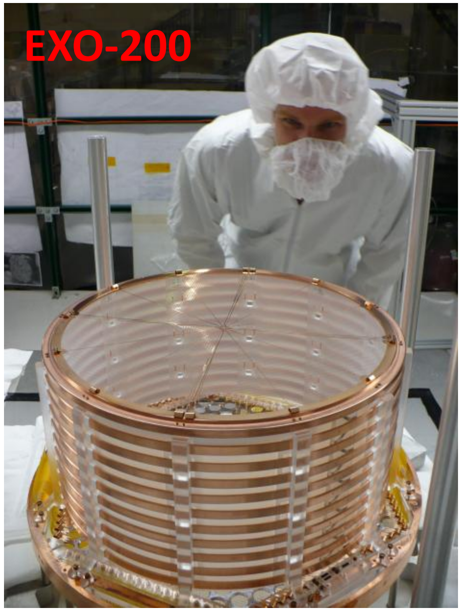


and a spectrum of them…

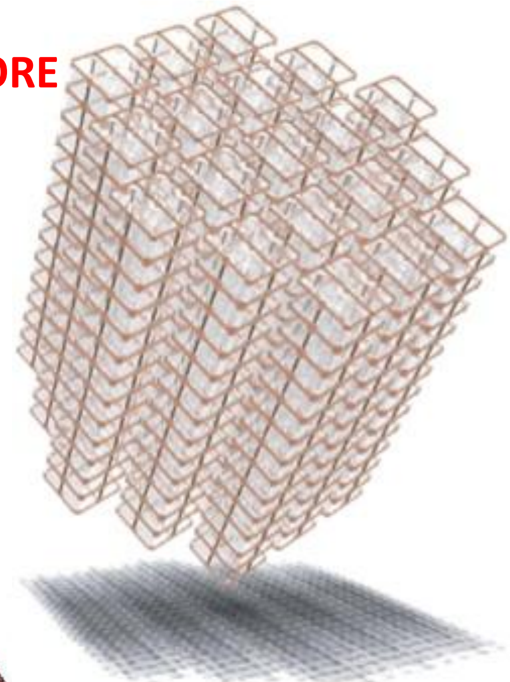


$0\nu\beta\beta$

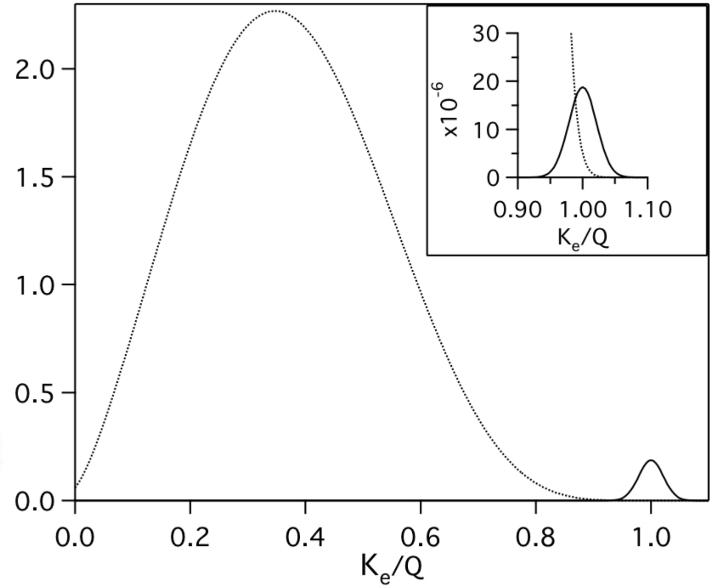
Many **...experiments (~10)**
...techniques
...isotopes



CUORE

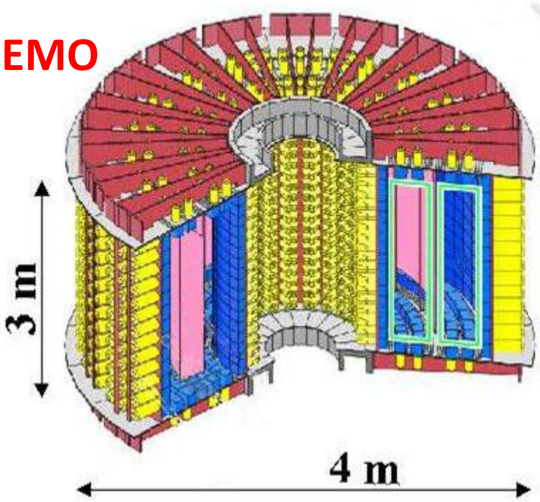


Example $0\nu\beta\beta$ signature

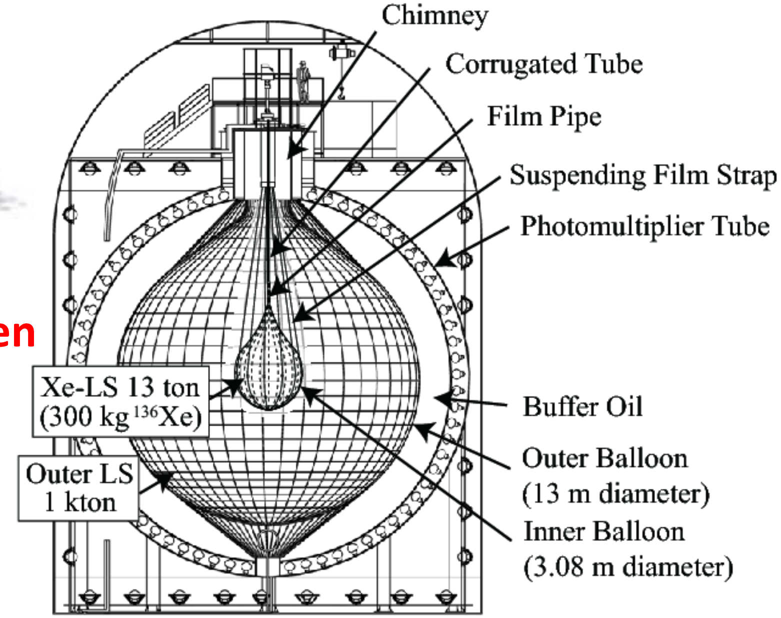


S. R. Elliott and P. Vogel, Ann. Rev. Nucl. Part. Sci. **52**, 115 (2002)

NEMO



KamLAND-Zen

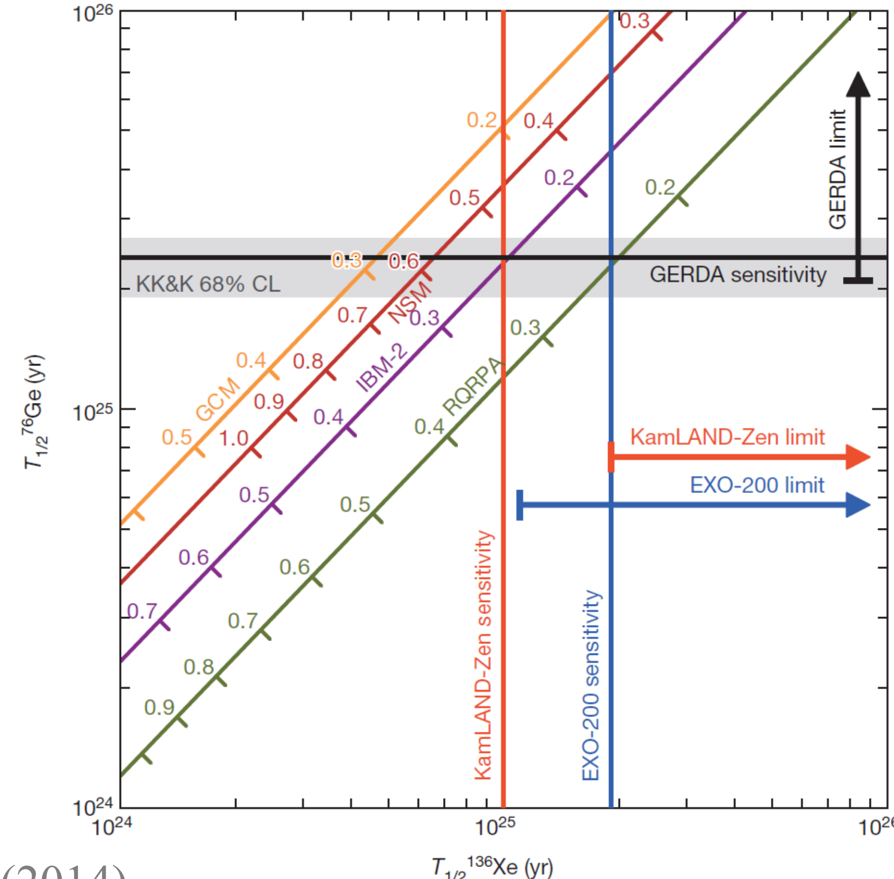


Recent results from

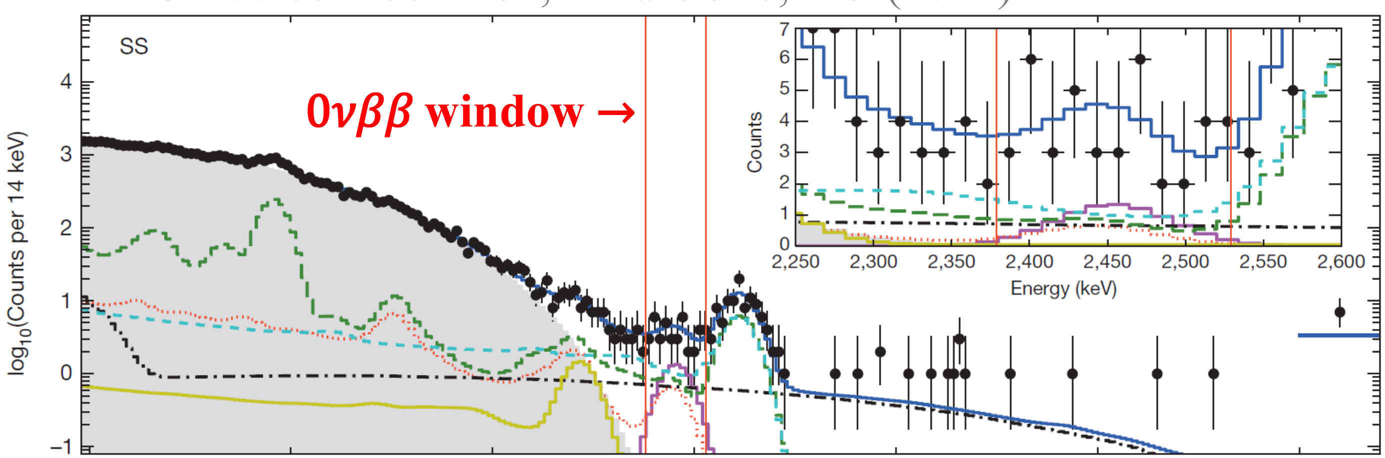
- **EXO-200** (^{136}Xe),
- **KamLAND-Zen** (^{136}Xe),
- **GERDA** (^{76}Ge)
- **CUORE** (^{130}Te)

→ *no signal so far*

Controversial 2004 claim *[KK et al., Phys. Lett. B **586**, 198 (2004)]* **still surviving,** but tension growing.



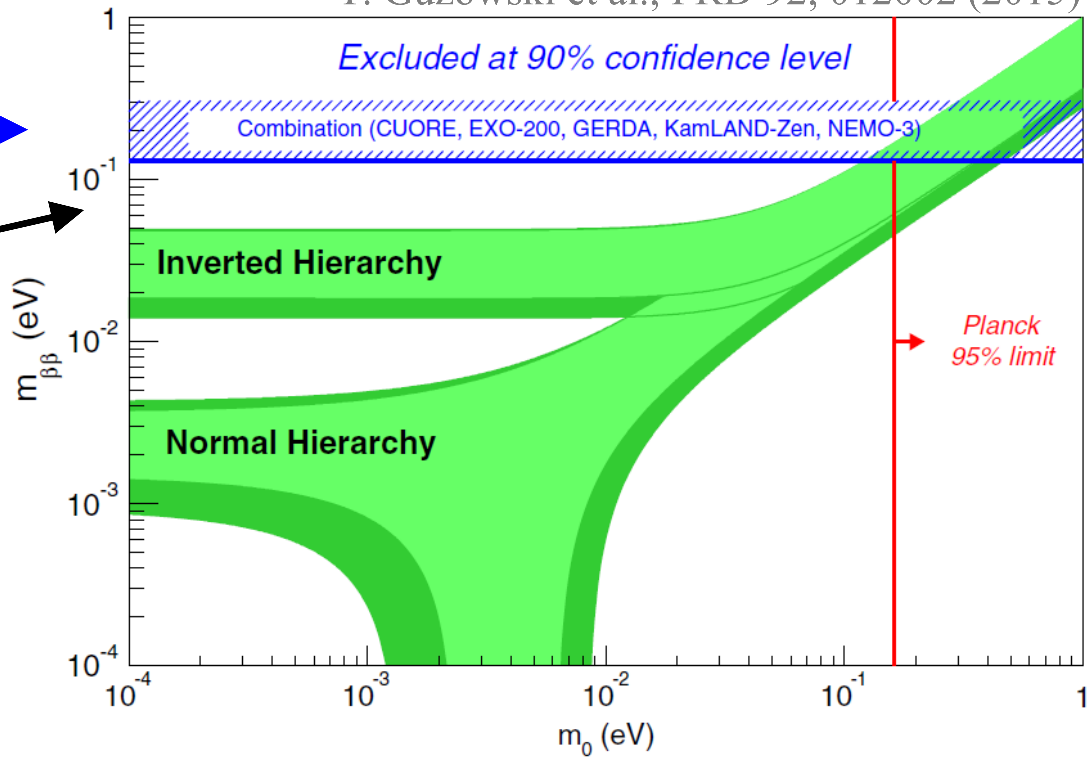
EXO-200 collaboration, Nature **510**, 229 (2014)



Nuclear matrix element calculations lead to large uncertainties in $m_{\beta\beta}$ →

Current generation of expts. →
(7 – 200 kg of ββ isotope; results through rest of decade)

P. Guzowski et al., PRD 92, 012002 (2015)



- Pushing **through IH** will require **next generation of expts,** aiming for $m_{\beta\beta}$~0.01 eV

Though, R&D leaps in current generation are still possible (e.g. enhanced ^{130}Te loading in SNO+)

Conclusion of November 2015 NSAC Report on 0$\nu\beta\beta$:

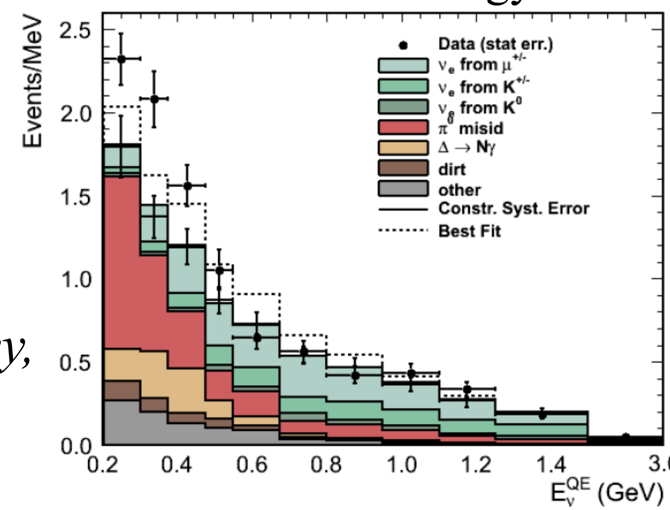
Let current activities play out for a few more years to make a better informed down-select decision for ton-scale experiments.

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

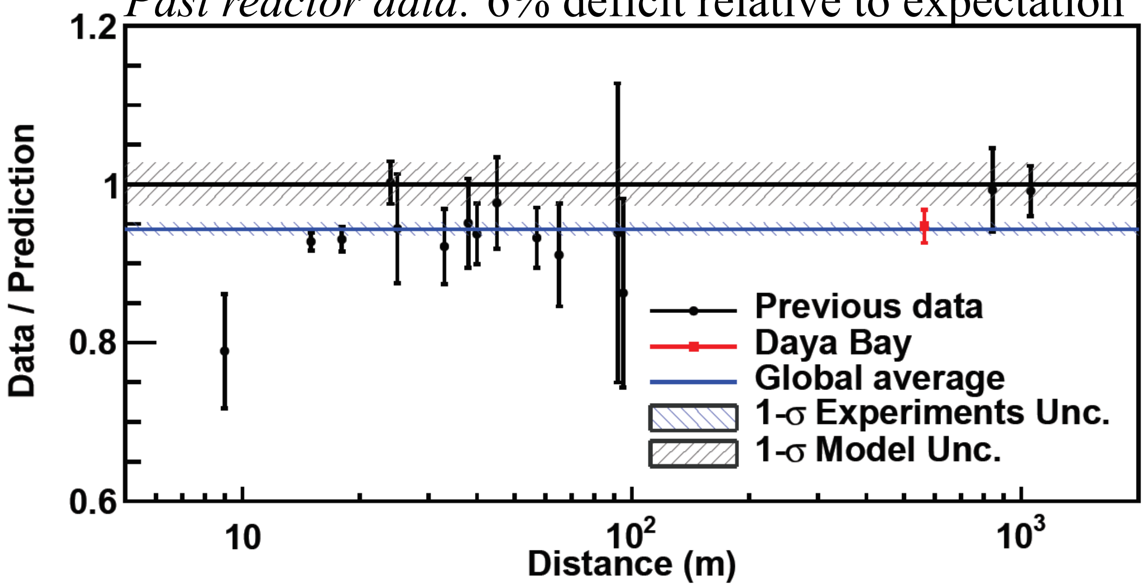
- **What's going on?**
  - **Sterile neutrinos?** *(Need multiple sterile states to accommodate all of today's data.)*
  - **Something else new?**
  - **A series of systematics issues?**

- **Many null results in past decade+** *(KARMEN, Bugey, Super-K, MINOS, ICARUS, IceCube, Planck),* **but situation lingers**

MiniBooNE low-energy excess



Past reactor data: 6% deficit relative to expectation



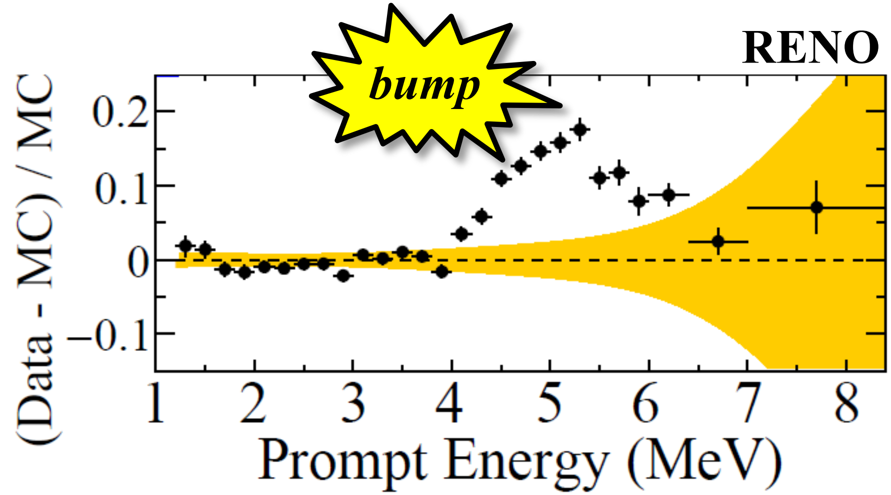
Future experiment(s) need a viable path toward…

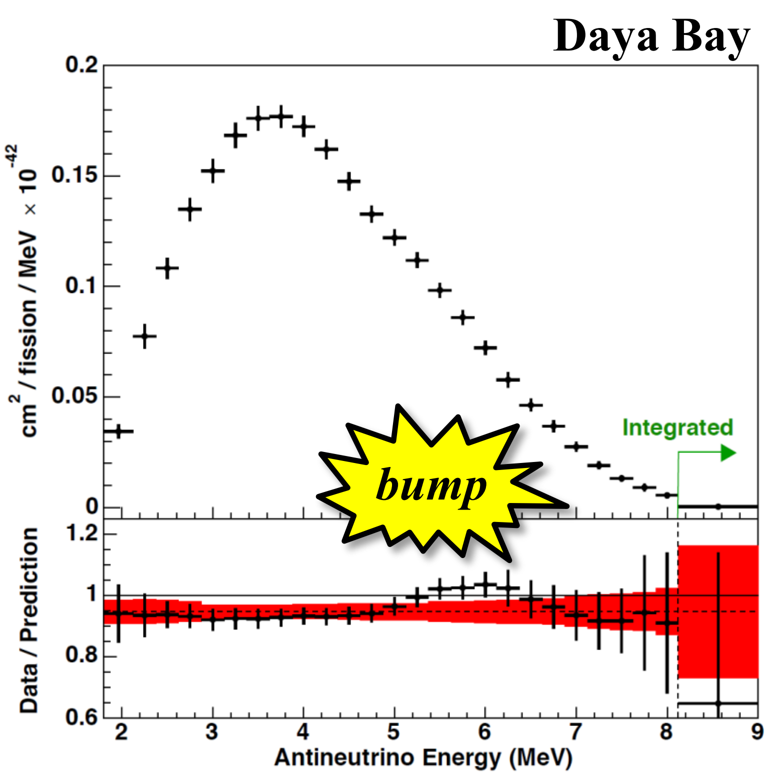
…large exposures
…minimized systematic errors
…in-detector L, E signatures
…unambiguous sensitivity

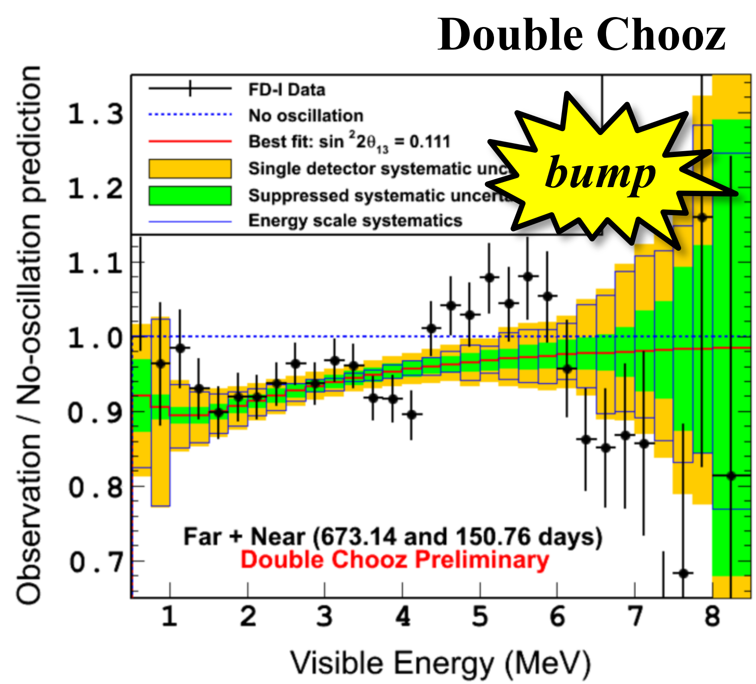
Attempts that stop short of this will only make things murkier.

Reactor flux uncertainties already known to be **underestimated**?

4 – 6 MeV excess seen in all three recent reactor flux measurements







https://indico.bnl.gov/conferenceDisplay.py?confId=918

Workshop on the Intermediate Neutrino Program (2015)

Many efforts represented, at various stages of development

$10M earmarked for a handful of these. *(Review process ~complete. Funding decisions to come soon)*

Areas most represented:

- neutrino anomalies
- detector R&D
- cross sections (incl. CEνNS)
- m_β, $m_{\beta\beta}$

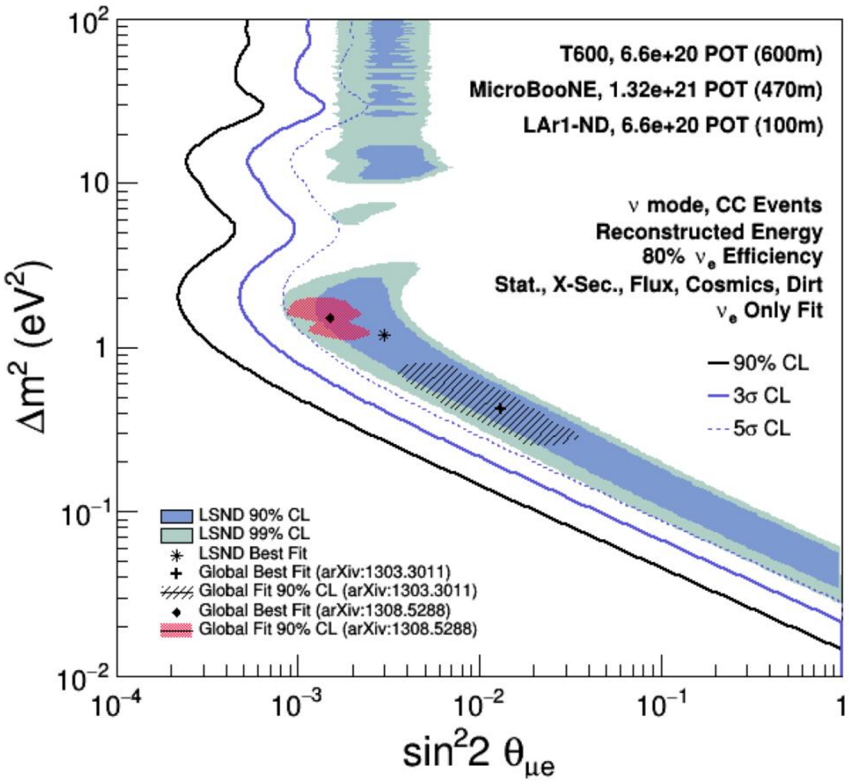
Expected Experiments at WINP

Experiment	Experiment type			Physics					Technology				
				WG#1	WG#2	WG#3	WG#4	WG#5	WG#6	WG#7	WG#8	WG#9	WG#10
	upgrade	large	self-contained	sterile	3-n mixing	interactions	properties	astro	SBN	Reactor	Source, etc	R&D	thoery
New Initiatives													
LAr1-ND			x	x		x			x			x	
ICARUS	x			x		x			x			x	
NESSiE		x		x		x			x				
Prospect			x	x						x			
NuLat			x	x						x			
JUNO		x			x					x			
PINGU	x				x			x				x	
OscSNS			x	x					x		x		
JPARC P56		x		x					x		x		
IsoDAR			x	x							x		
Coherent			x	x		x	x	x	x		x		
CENNS			x	x		x	x	x	x		x		
RICOCHET			x	x		x	x	x	x		x		
Cr-51	x			x			x			x	x		
CeSOX			x	x						x	x		
ANNIE			x			x		x	x			x	
ARA			x					x				x	
R&D and detector physics efforts towards larger experiments													
CAPTAIN	x		x			x			x			x	
ChiPS		x										x	
NuPRISM		x		y	y	x			x			x	
Watchman		x						x				x	
LArIAT			x						y			x	
LAr 35-ton		x							y			x	
7m-LAr (1-phase)		x							y			x	
WA105 (2-phase)		x							y			x	
CERN Platform		x							y			x	
NA-61		x		y	y	x			y			x	
Experiments that might propose upgrades													
Super-K	x				x			x					
T2K	x				x				x				
NOvA	x				x				x				
MINOS+	x				x				x				
MINERvA	x			y	y	x			x				
Daya Bay	x				x					x			
Double Chooz	x				x					x			
IceCUBE-2 (IceCUBE)	x				x			x					
Borexino	x				x			x					
MicroBooNE	x			x		x			x				
KamLAND	x				x		x			x		x	
SNO+	x						x	x				x	
KATRIN	x						x						
Large future initiatives that may need R&D													
ASDC		x			x		x					x	
nEXO		x					x					x	
SuperNEMO	x						x					x	
NEXT		x					x					x	
Majorana		x					x					x	
CUORE		x					x					x	
Jinping		x					x					x	
Project-8		x			x		x					x	
Daedalus		x			x			x	x		x	x	
Hyper-K		x			x			x	x			x	
ELBNF		x			x			x	x			x	

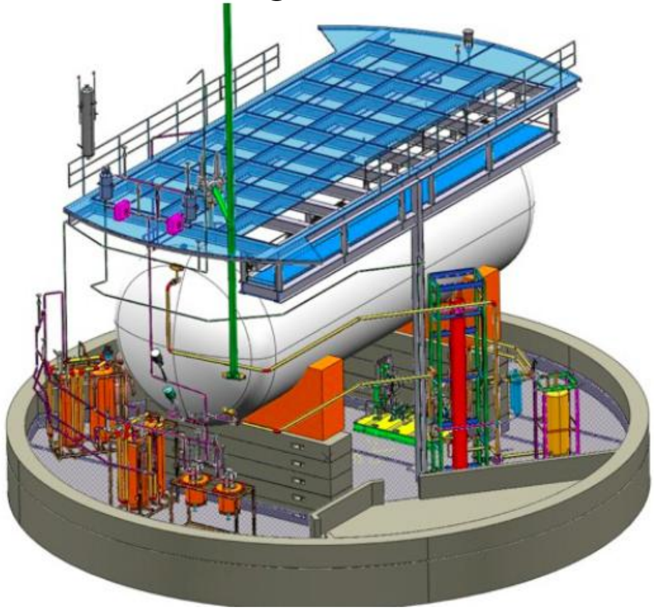
Fermilab SBN program

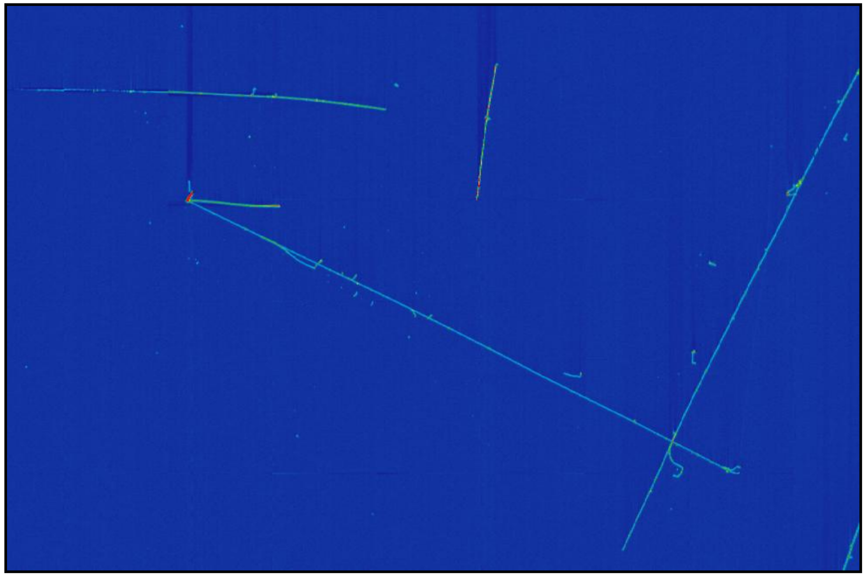
- **Funded outside** the $10M INP budget
- **MicroBooNE + ICARUS + new SBND**
- A mix of **R&D** and **physics** goals

Sensitivity shown below has caveats…



Below: MicroBooNE detector and “first light” neutrino event





Summary

- Active **experimental** and **theoretical** playing field
- **Mass hierarchy:** *Actionable info soon?*
- **Leptonic CPv:** *Primary goal of next generation LBL expts. (Hints by 2020?)*
- **Majorana vs. Dirac:** *When/if we can answer depends on the answer*
- **What's up with all the anomalies?**
- **ν scattering:** *Not discussed here; role could be large in the future; plus, new ground being broken (meson exchange currents, CEνNS)*
- **New physics lurking in neutrino sector?** *Minimal theoretical guidance; keep pushing precision and looking for chinks in the armor*