Neutrino oscillation experiments: Present and future

Ryan Patterson
Caltech

Conference on Flavor Physics and CP Violation
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Neutrino oscillations

$$P(\nu_\alpha \to \nu_\beta) \sim \sin^2\left(\Delta m^2_{ij} \frac{L}{4E}\right)$$

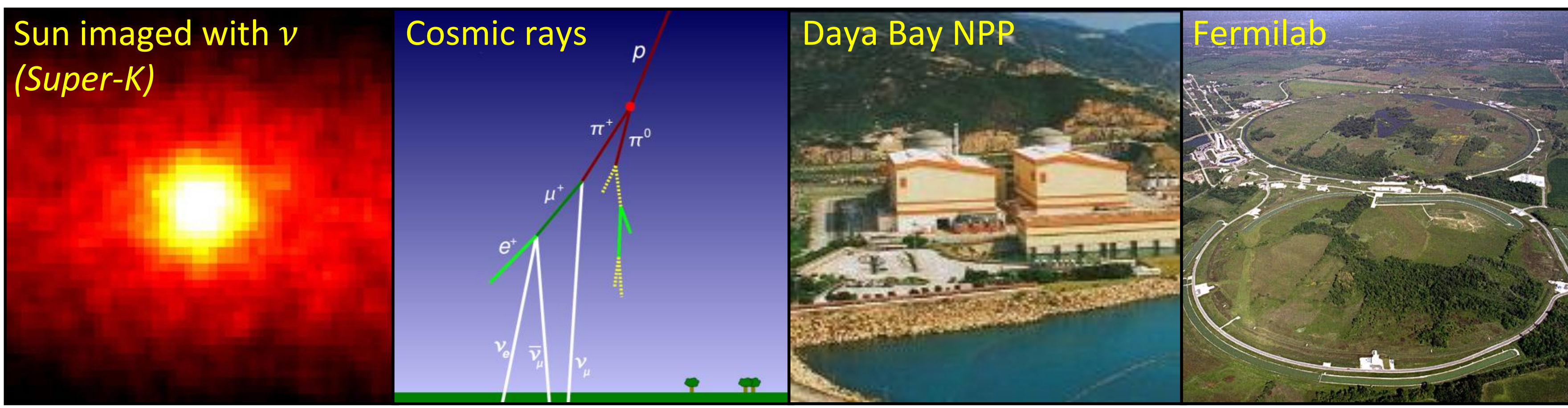
L: travel distance ("baseline")

E: neutrino energy

A **given source** has characteristic ***E*** (and $\boldsymbol{\nu_\alpha}$).
Suggests optimal ***L*** for **maximizing oscillations.**

(simplified picture ⇒ exceptions)

solar, atmospheric, reactor, and accelerator *ν* sources



Experimental overview

3-flavor oscillations

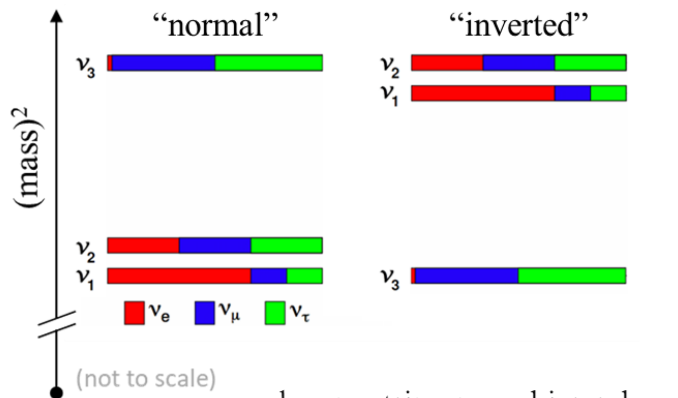
Parameters best constrained by various sources

Solar (MSW), Reactor (~60 km)	}	Δm^2_{21}	θ_{12}			
Reactor (~2 km)	→	$\|\Delta m^2_{32}\|$	θ_{13}			
Atmospheric	→	$\|\Delta m^2_{32}\|$	θ_{23}	[νMO]		
Accelerator (LBL)	→	$\|\Delta m^2_{32}\|$	θ_{23}	νMO	δ_{CP}	[θ_{13}]

→ $\sin^2\theta_{ij}$ and $|\Delta m^2_{ij}|$ all measured to ~few percent

Next "structural" questions

Neutrino mass ordering (νMO)?



a.k.a. neutrino mass hierarchy

Leptonic *CP* violation?

$\sin\delta_{CP} \neq 0$

Maximal mixing?

$\theta_{23} = 45°$

$(|U_{\mu 3}| = |U_{\tau 3}|)$

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Accelerator (LBL) → $|\Delta m^2_{32}|$ θ_{23} νMO δ_{CP} [θ_{13}]

→ **$\sin^2\theta_{ij}$** and **$|\Delta m^2_{ij}|$** all measured to ~few percent

Needs:

- Address structural unknowns (*e.g.*, at right)
- Testing mass/flavor models ↔ improved precision
- Direct unitarity tests (currently rather poor)

(And outside the scope of oscillation experiments: m_ν? **Majorana or Dirac**?)

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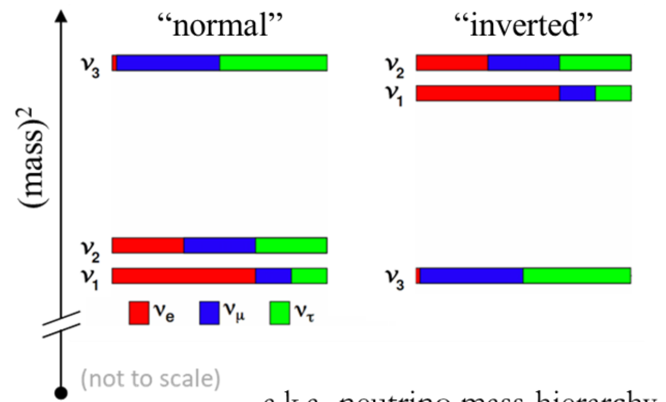

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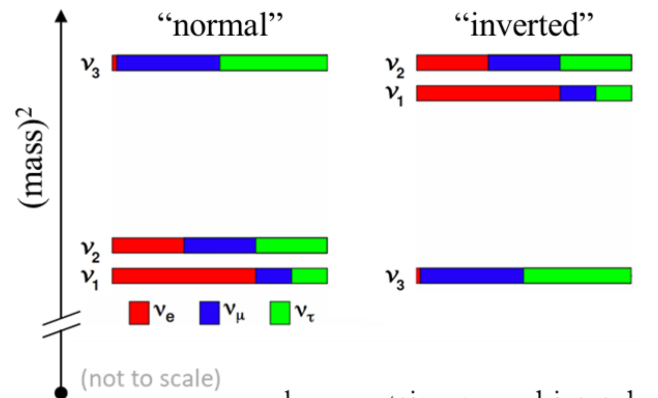

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These classes of experiment expected to have significant new oscillation results in the near term

Will spend some time here before looking to the future…

Leptonic *CP* violation?

$\sin\delta_{CP} \neq 0$

Maximal mixing?

$\theta_{23} = 45°$

$(\lvert U_{\mu 3}\rvert = \lvert U_{\tau 3}\rvert)$

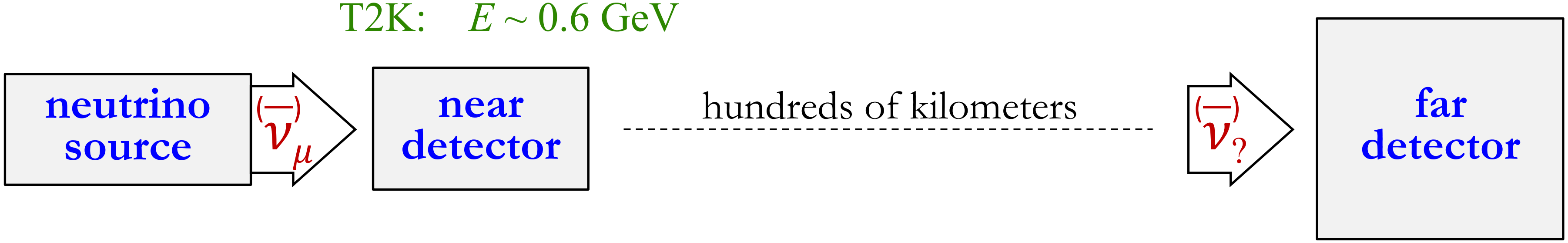
Accelerator-based long-baseline experiments

NOvA, T2K $\rightarrow$ DUNE, T2HK/Hyper-K

(current) (next-gen)

Sketch

★ NOvA: $E \sim 2$ GeV
T2K: $E \sim 0.6$ GeV

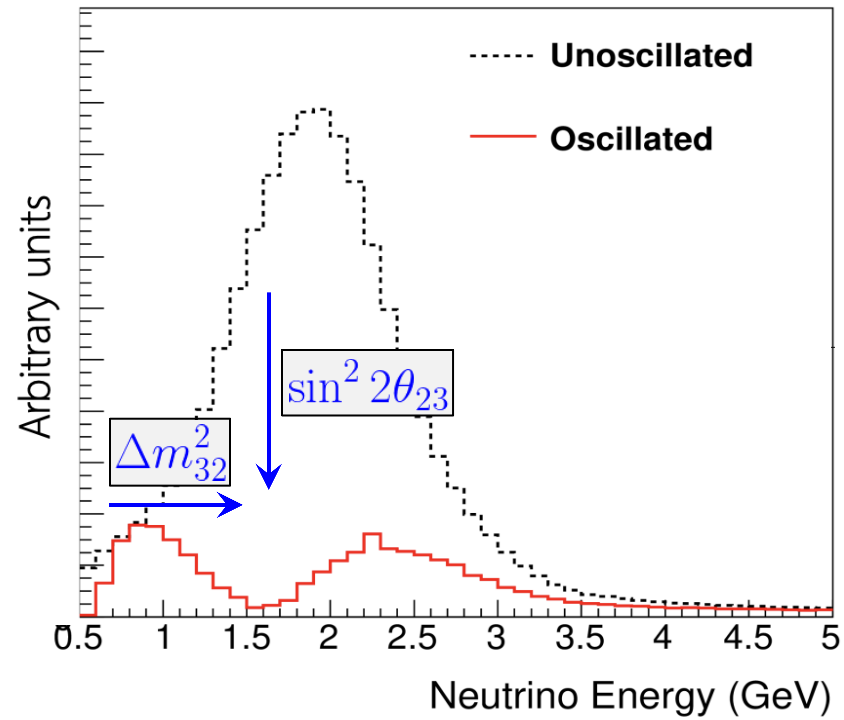


ν_μ disappearance

$$P(\nu_\mu \to \nu_{e,\tau}) \approx \sin^2 2\theta_{23} \sin^2\left(\Delta m^2_{32} \frac{L}{4E}\right)$$

experimental data are **consistent with unity**
(*i.e.*, maximal mixing)

ν_μ events in Far Detector
(NOvA-like example)



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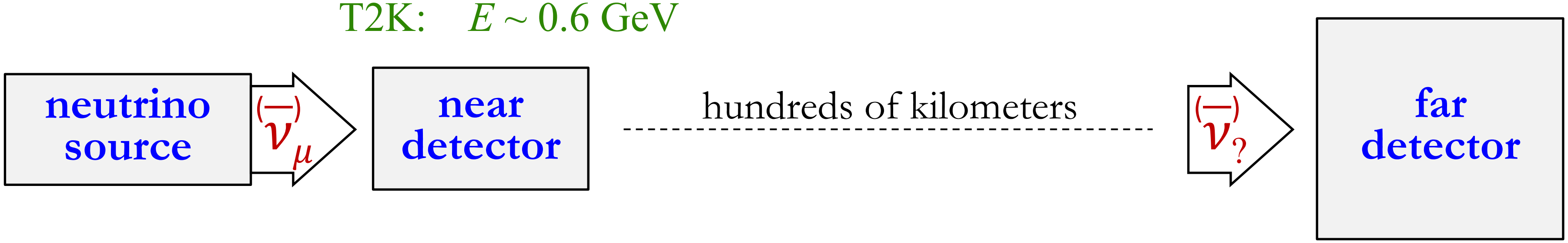

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experimental data are **consistent with unity** (*i.e.*, maximal mixing)

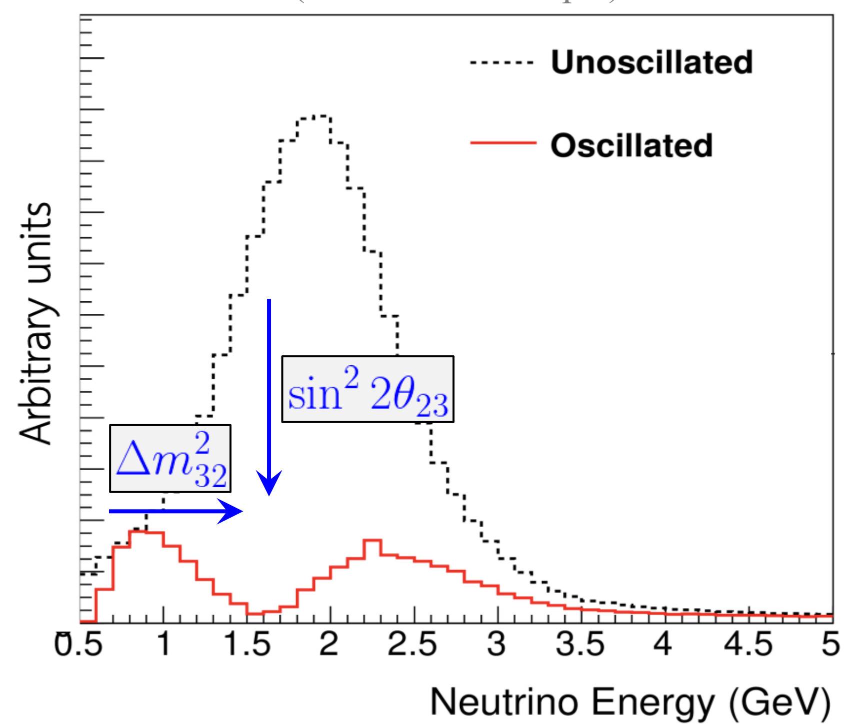
ν_e appearance

$$P(\nu_\mu \to \nu_e) = \ldots$$

…a much more involved function of the parameters of interest.

Significant connections to $\boldsymbol{\theta_{13}}$, $\boldsymbol{\theta_{23}}$, $\boldsymbol{\delta_{CP}}$, and the **neutrino mass ordering***

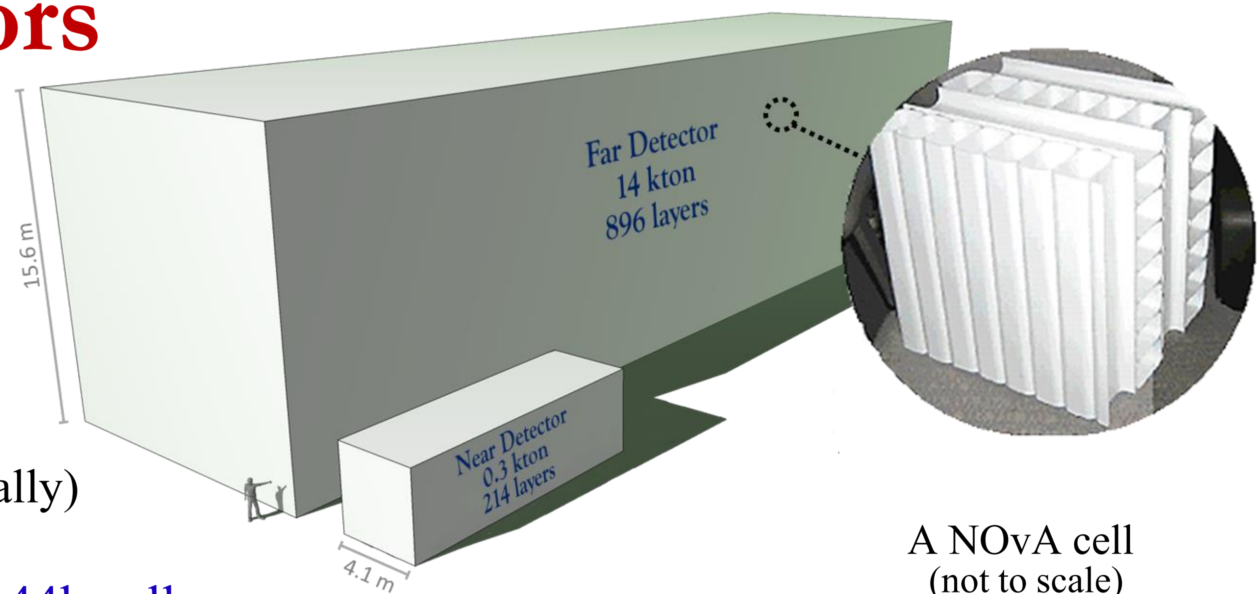
ν_μ events in Far Detector
(NOvA-like example)



*due to the neutrinos passing through matter

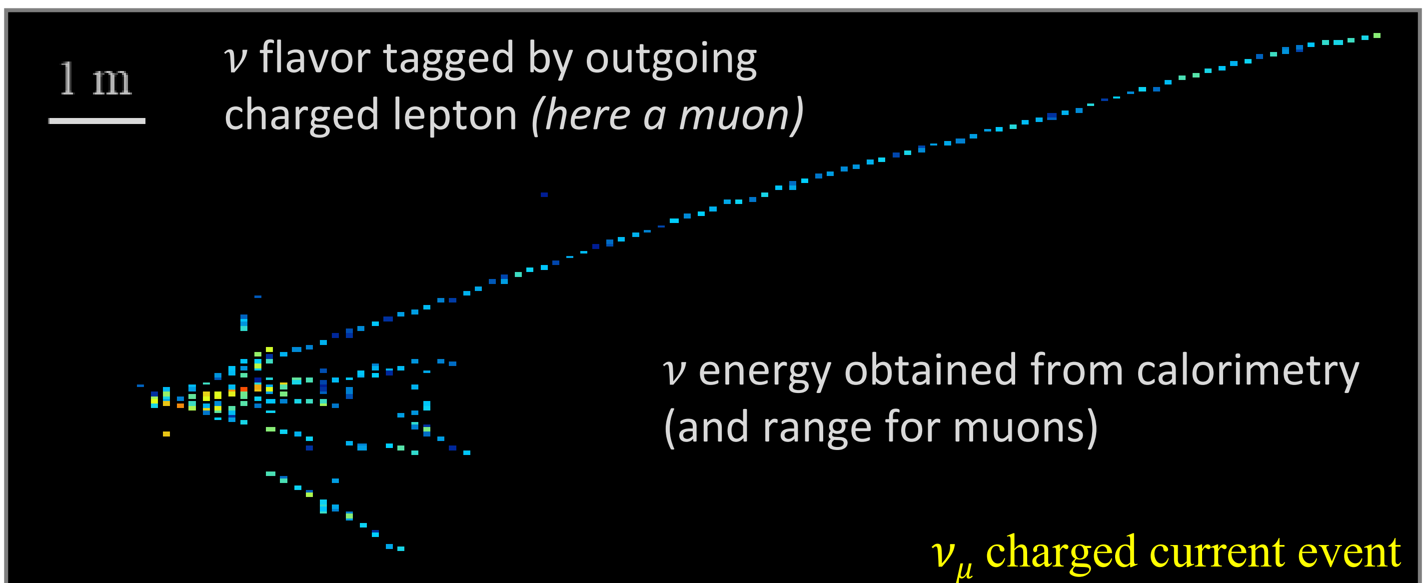
NOvA detectors

- Liquid scintillator cells
- Fiber-to-APD readout
- **FD and ND functionally identical by design**
  → Differ only in size (essentially)

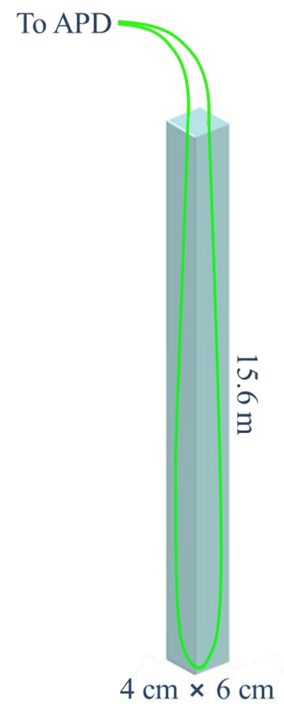


Far detector: 14 kton, 344k cells

Near detector: 0.3 kton, 20k cells



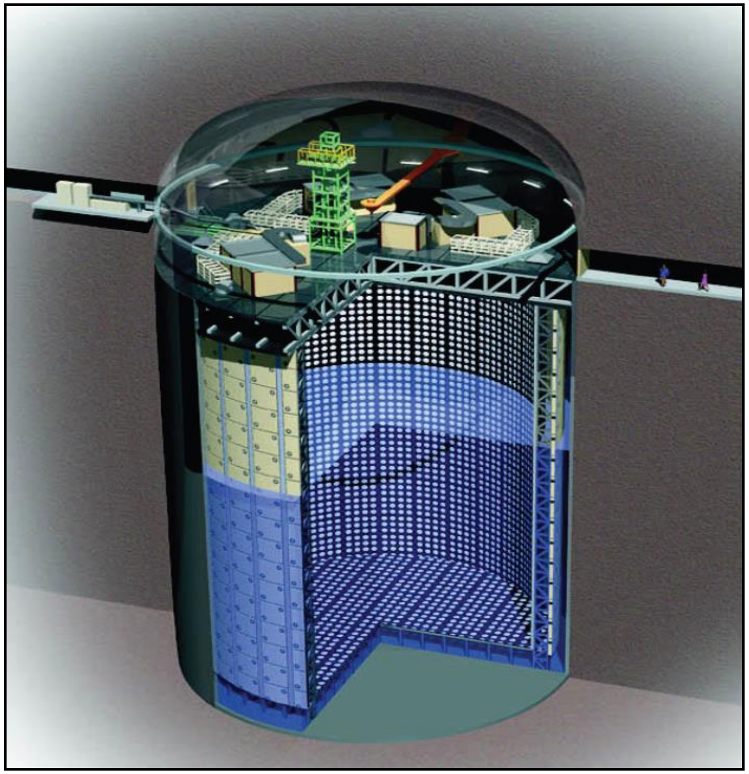
A NOvA cell
(not to scale)



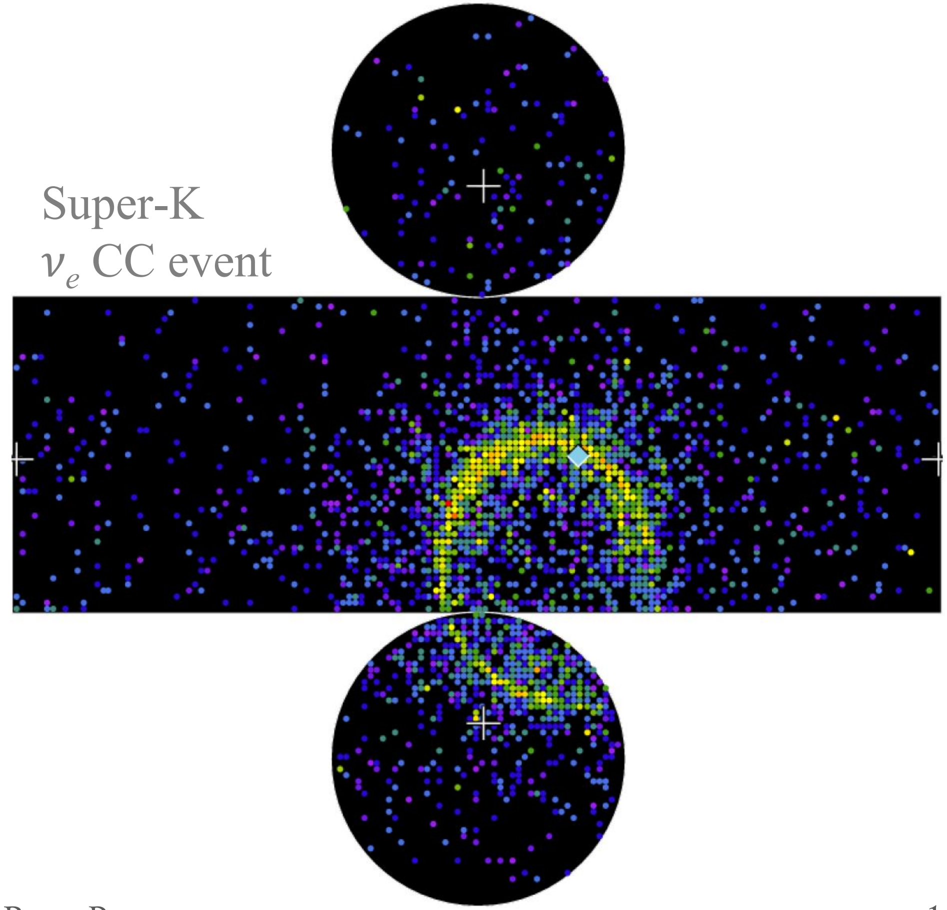
T2K (far) detector

- The long-running **Super-Kamiokande** detector
- 50-kton water Cherenkov detector
- 11,000 20” PMTs on inner surface (40% coverage)

Super-Kamiokande



Super-K ν_e CC event

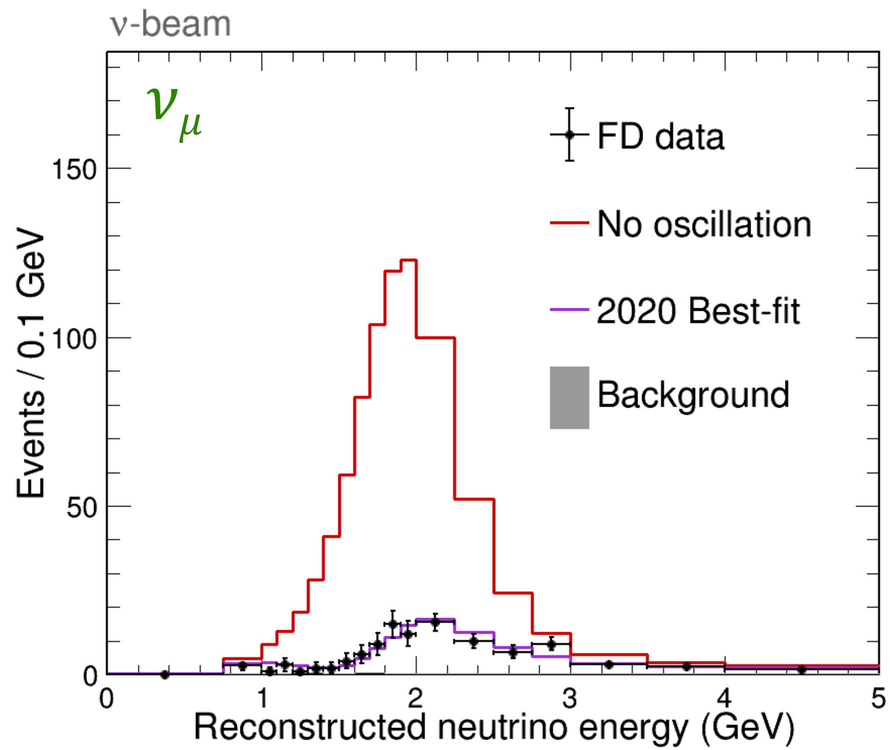


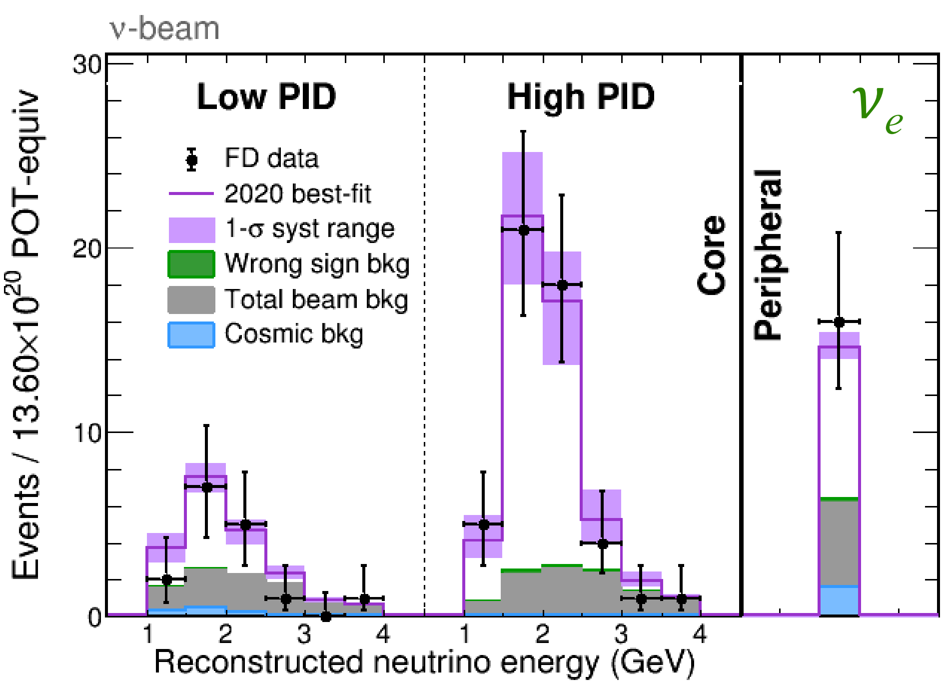
- ***e/μ* discrimination** from ring characteristics
- E_ν **~ 0.6 GeV**
  ⇒ relatively simple final states
  ($e.g.$, $\mu + p$ or $\mu + p + \pi$)
  ⇒ protons below Cherenkov threshold
- E_ν from **reconstructed lepton momentum** (and kinematics)

NOvA FD data

At right: ν_μ CC candidate events ("disappearance")

Below: ν_e CC candidate events ("appearance")





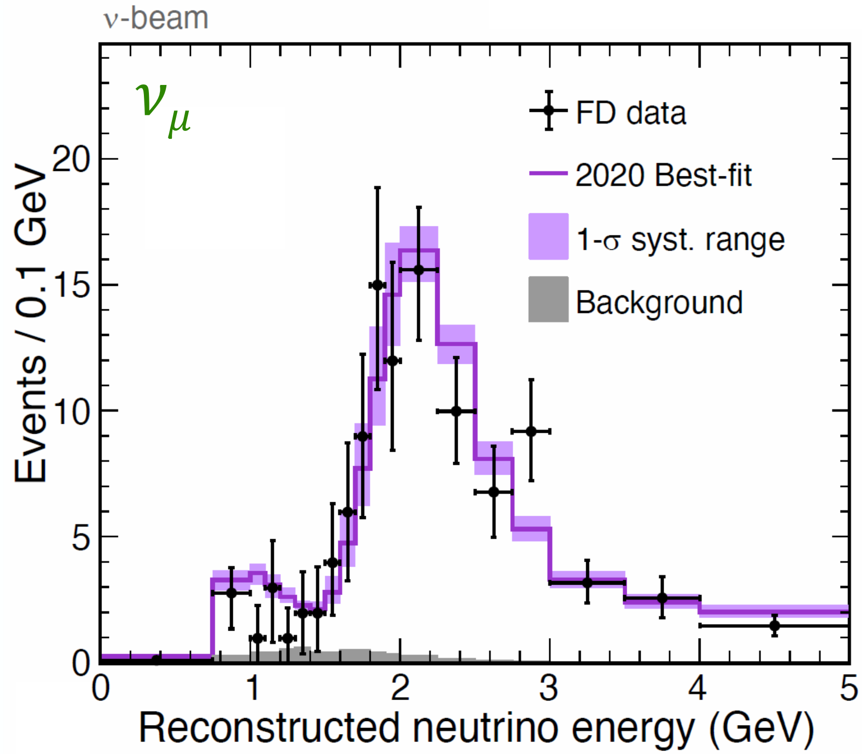
Not shown, but important pieces of oscillation fit:

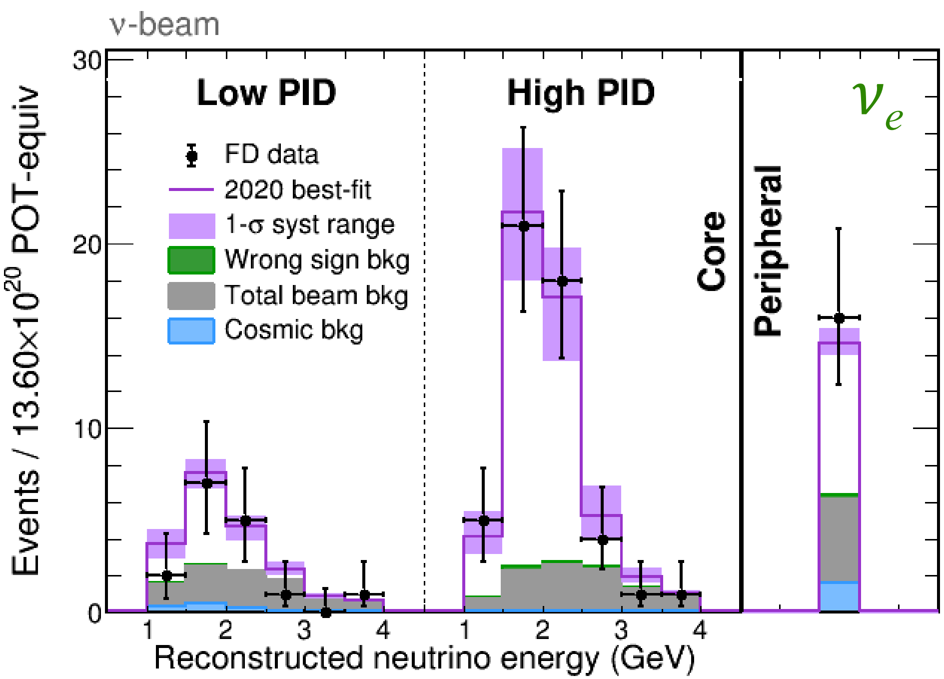
- $\overline{\nu}_\mu$ and $\overline{\nu}_e$ samples!
- Breakdown of $\nu_\mu/\overline{\nu}_\mu$ samples by hadronic energy fraction

NOvA FD data

At right: ν_μ CC candidate events ("disappearance")

Below: ν_e CC candidate events ("appearance")





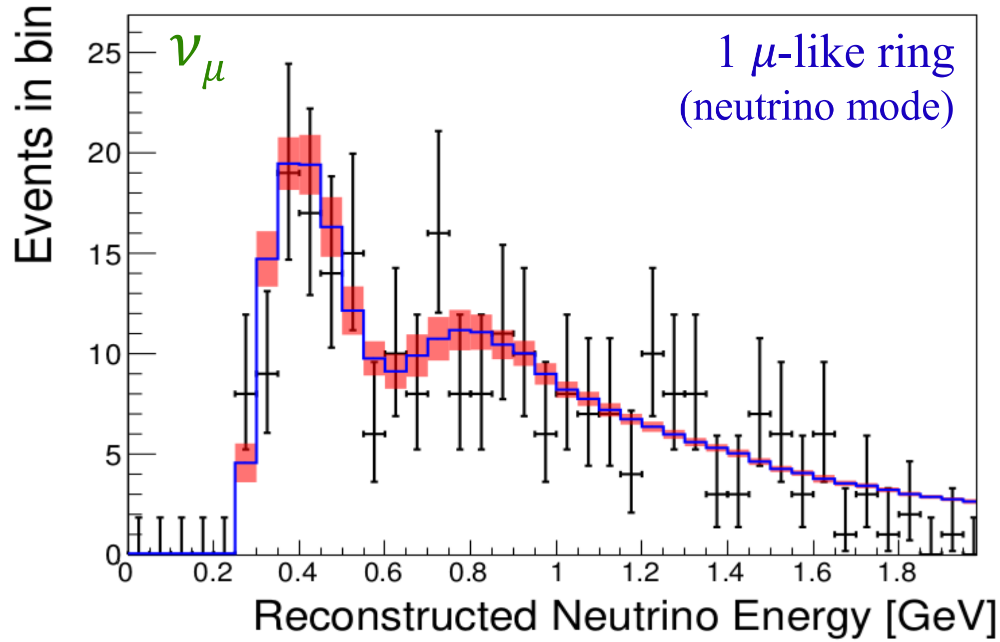
Not shown, but important pieces of oscillation fit:

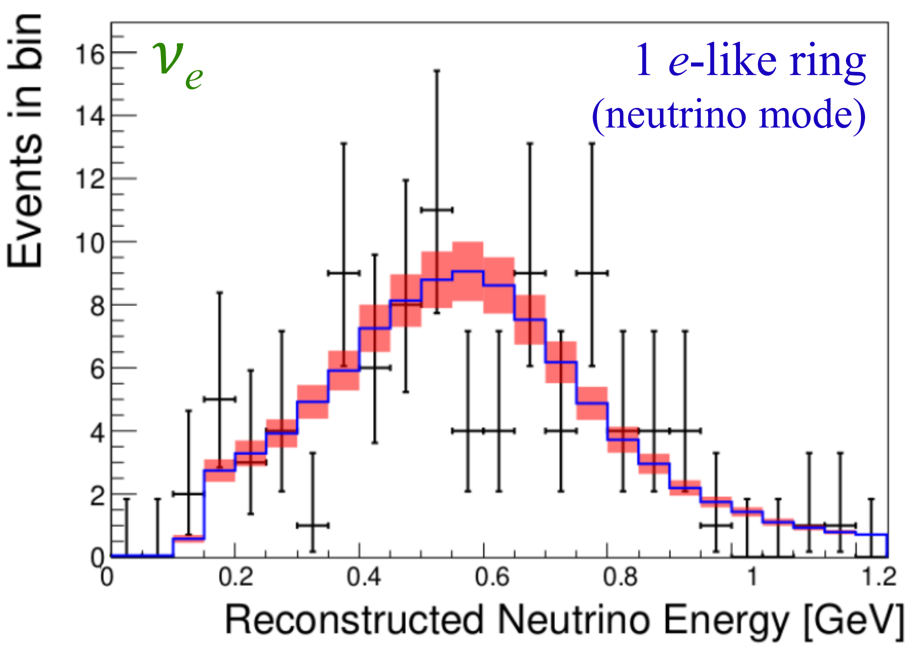
- $\bar{\nu}_\mu$ and $\bar{\nu}_e$ samples!
- Breakdown of $\nu_\mu/\bar{\nu}_\mu$ samples by hadronic energy fraction

T2K FD data

At right: ν_μ CC quasi-elastic candidate events

Below: ν_e CC quasi-elastic candidate events

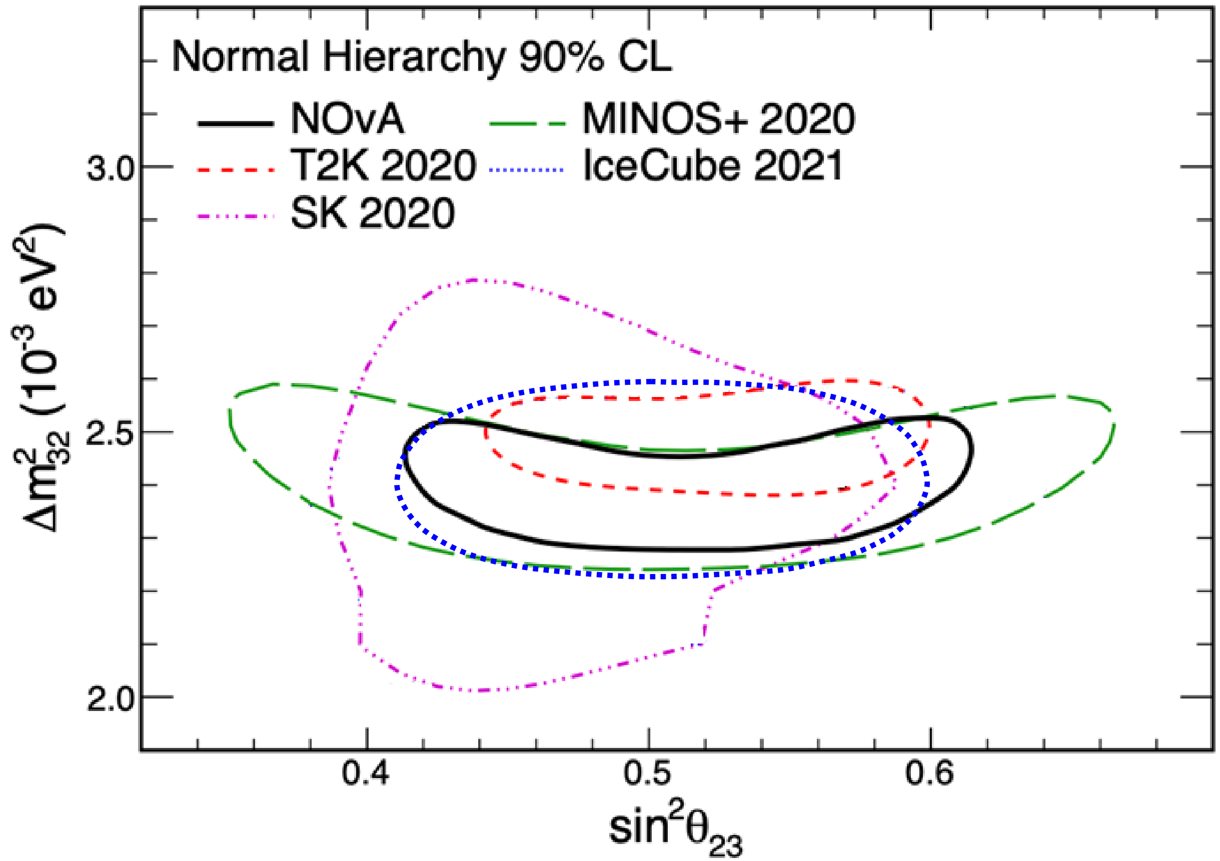




Not shown, but important pieces of oscillation fit:

- $\overline{\nu}_\mu$ and $\overline{\nu}_e$ samples!
- Additional "1e with Michel" sample ($e^- + \pi^+$ final state)

Δm^2_{32} and θ_{23}



Will come back to the atmospheric ν experiments.

Daya Bay reactor experiment also impactful in $|\Delta m^2_{32}|$.

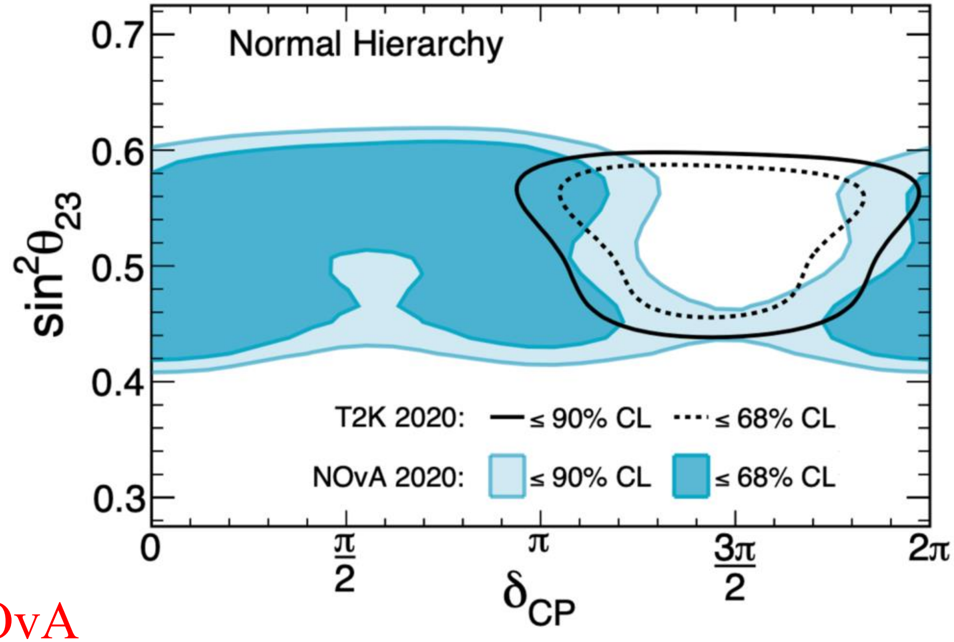
- $|\Delta m^2_{32}|$ **precision:** 1.1% on global average given a mass ordering
- Still no evidence of deviation from **maximal mixing** ($\sin^2\theta_{23} = 0.5$)

LBL ν_e appearance

$P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ depend on:

$|\Delta m^2_{32}|$ θ_{13} — constrained separately

θ_{23} νMO δ_{CP} — determined primarily here



Measurement ambiguities possible

Complementarity between T2K and NOvA

***T2K*: minimal νMO sensitivity**

***NOνA*: good νMO sensitivity**

Current best fits land in the **normal ordering**, but only at **polar opposite δ_{CP} values**

In slightly less favored inverted ordering, **good agreement in δ_{CP}**

Inter-collaboration joint fits underway:

NOvA + T2K and also **T2K + SuperK***

Results expected later this year

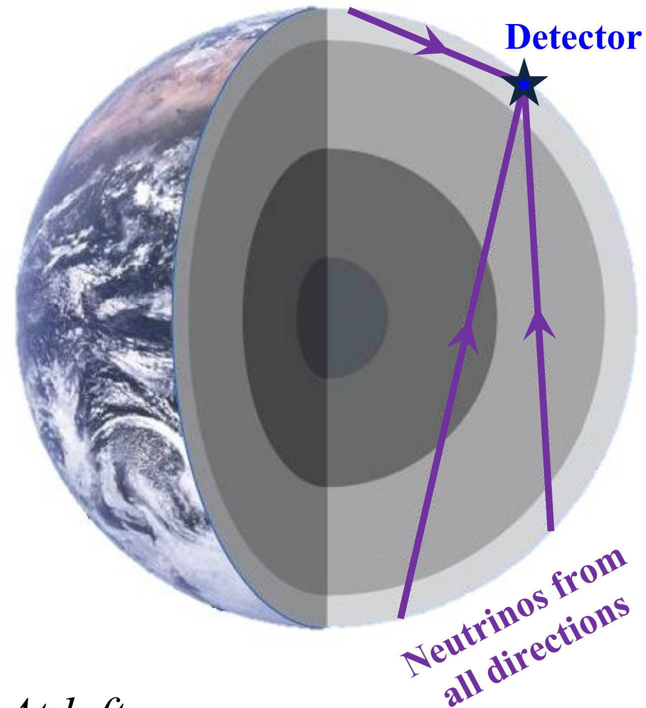
>2.5× increase in LBL exposures anticipated (vs. currently analyzed) through *c.* 2027

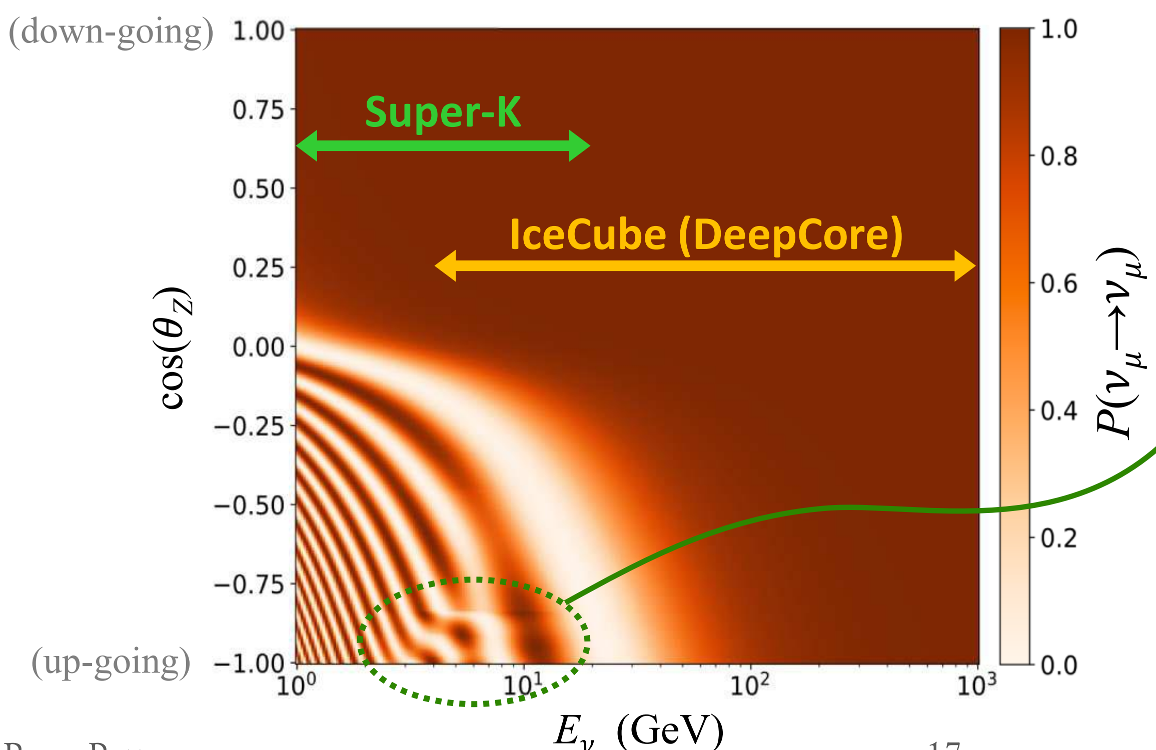
* SuperK atmospheric ν data: 1.3σ preference for normal ordering

Oscillations with atmospheric neutrinos

Atmospheric ν oscillations

- **ν from cosmic ray interactions in atmosphere**
  Relevant energies: ~1 – 1000 GeV
- **Broad spectrum**, mixture of initial flavors
- Baseline varies with ν incident angle
  $L \sim 10^1$ to 10^4 km
- $\nu_\mu \to \nu_\mu$ and $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\tau$ (above τ prod. threshold)





At left:

Regular oscillation pattern

plus

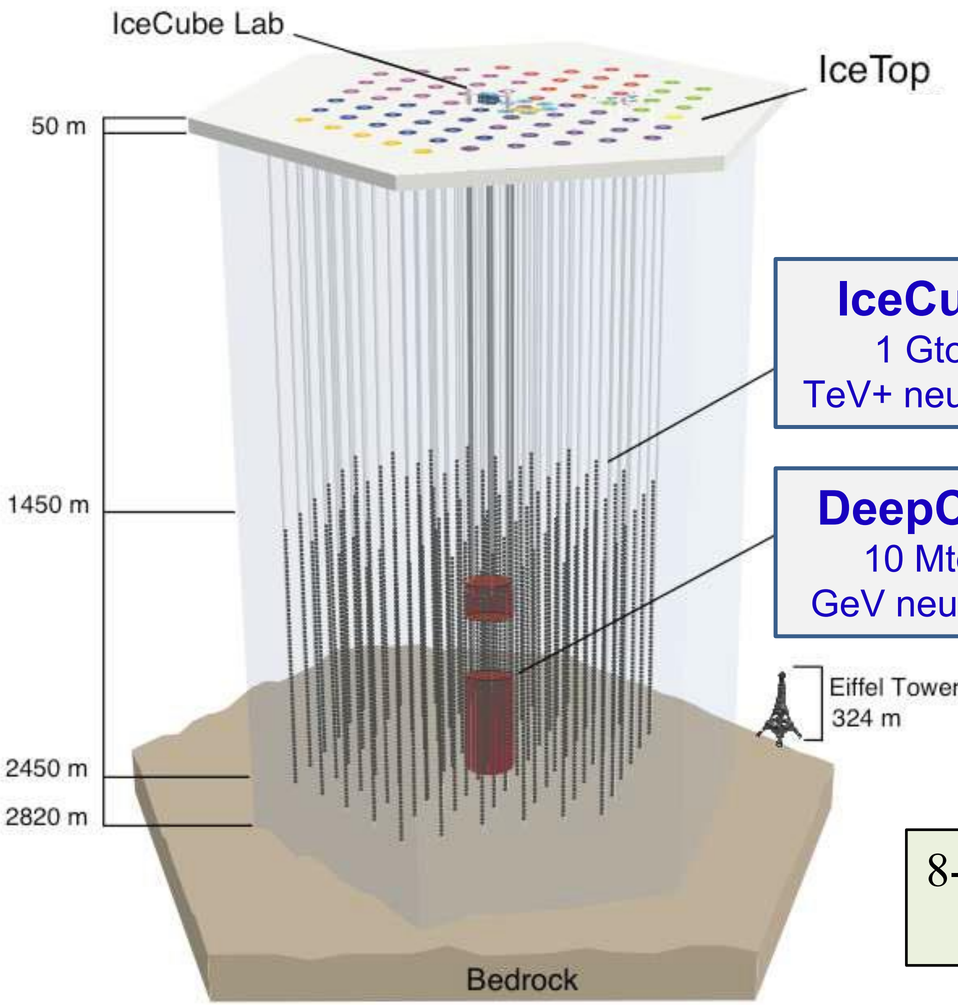
Localized distortion due to resonant matter effects
⇒ *ν mass ordering*

E_ν , θ_Z smearing is significant
(not shown in this cartoon!)

Super-K detector described already

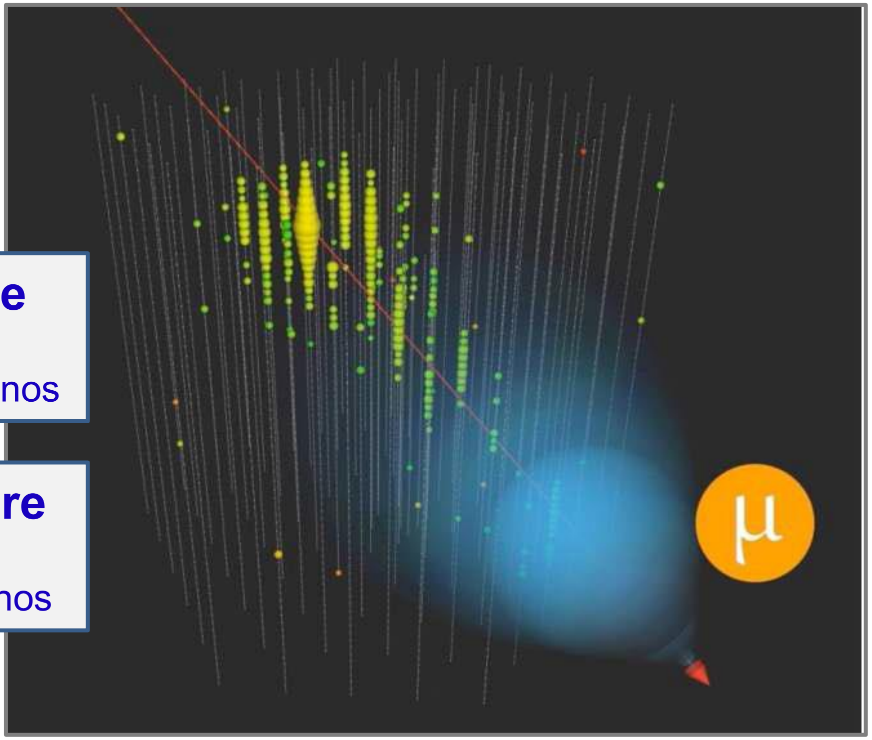
- *Underway:* **Gd doping** → improved neutron tagging ($\nu/\bar{\nu}$ separation)

IceCube / DeepCore



IceCube
1 Gton
TeV+ neutrinos

DeepCore
10 Mton
GeV neutrinos



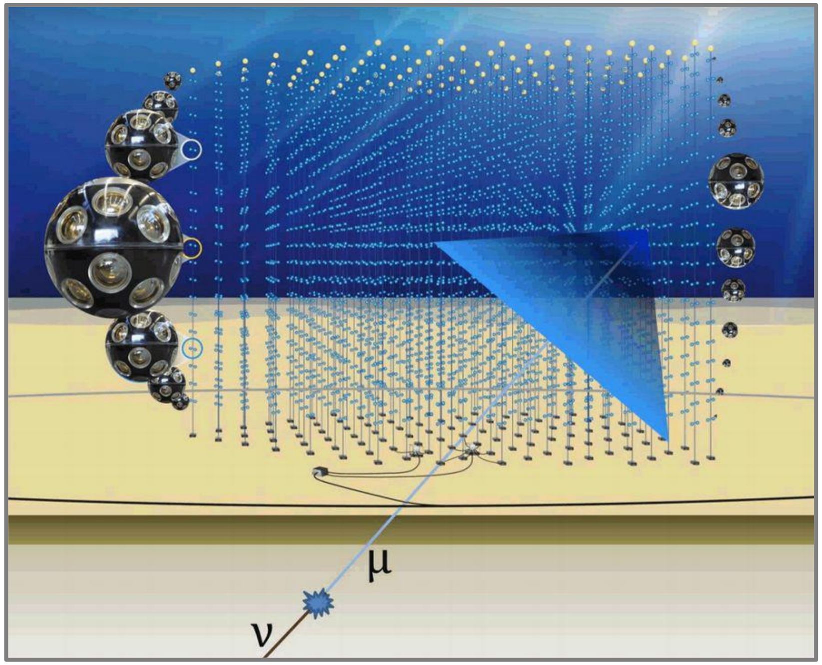
8-yr oscillation data set (*results shown earlier*)
→ **23,000 selected events!**

DeepCore analysis improvements (*c.* 2022)

→ **>200k neutrinos**, all flavors. Competitive oscillation sensitivity w/ LBL expts.
→ **ν_τ appearance:** 10k events, expecting 11% precision on normalization (PMNS unitarity)

A bit later on the timeline…

ORCA/KM3NeT



IceCube Upgrade

→ **2 Mton sub-array** in 10 Mton DeepCore (and other improvements)
→ **Drop threshold** to 1 GeV

ORCA/KM3NeT

→ **7 Mton PMT array** in Mediterranean
→ Optimized for ~1 – 100 GeV
→ *Currently:* Preliminary operations with 5% deployment

Competitive **ν mass ordering** reach ultimately (few to several σ)

Synthesizing ~5 yr projections (so, *c*. 2027)

Precision on θ_{12}, θ_{13}, Δm^2_{21}

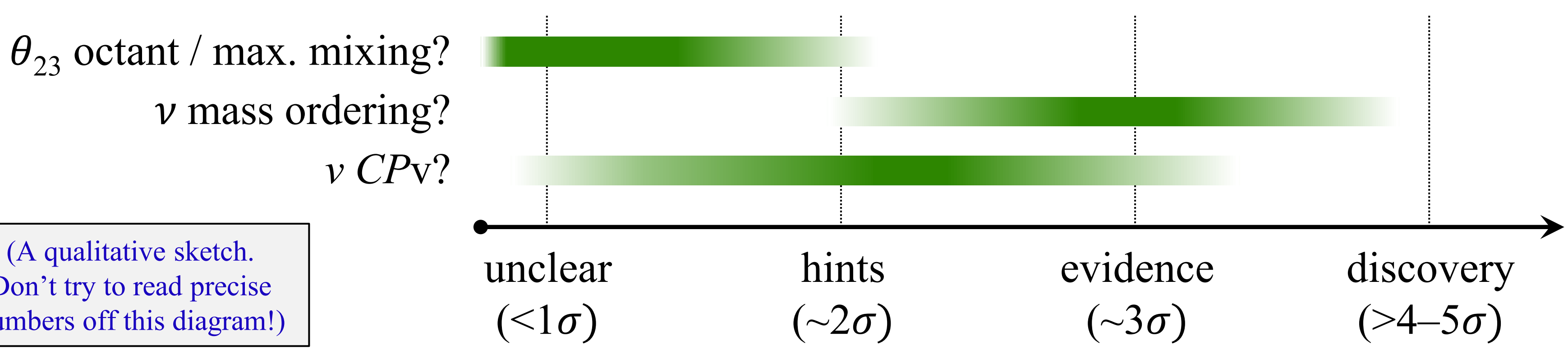
→ Minimal changes until next-gen experiments *(e.g., JUNO)*

Precision on θ_{23}, $|\Delta m^2_{32}|$

→ Some gains to come in current generation. Large gains in next-gen.

★ **3-flavor "structural" questions**

→ Reach heavily depends on (*still unknown!*) actual answers



(A qualitative sketch. Don't try to read precise numbers off this diagram!)

Synthesizing ~5 yr projections (so, *c.* 2027)

Precision on θ_{12}, θ_{13}, Δm^2_{21}

All possible outcomes have natural next steps

if ambiguities	→	**aim for clarity**
if evidence	→	**aim for discovery**
if discovery	→	**aim for characterization**

…and ultimately toward the precision era in leptonic flavor

θ_{23} octant

ν mass ordering?

ν *CP*v?

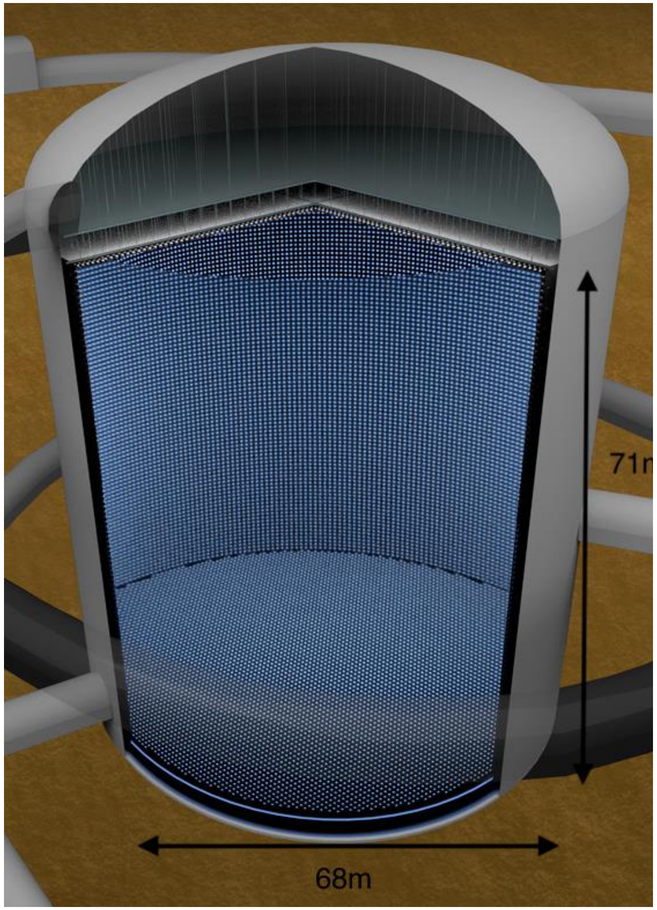
unclear ($<1\sigma$) — hints ($\sim 2\sigma$) — evidence ($\sim 3\sigma$) — discovery (>4–5σ)

(A qualitative sketch. Don't try to read precise numbers off this diagram!)

The next steps…

Next-generation LBL experiments

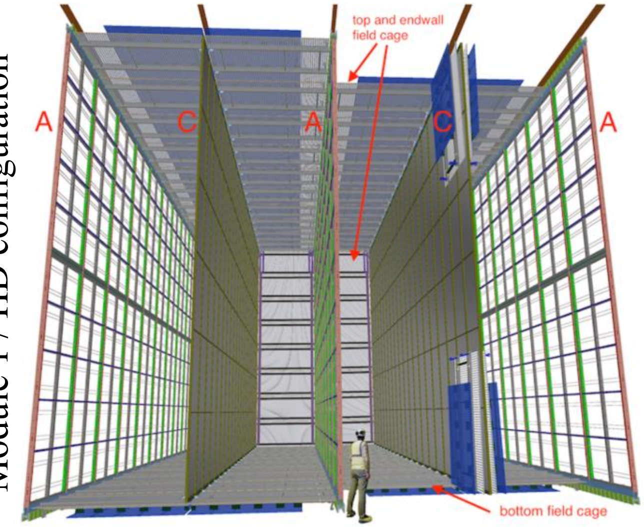
Hyper-K / T2HK

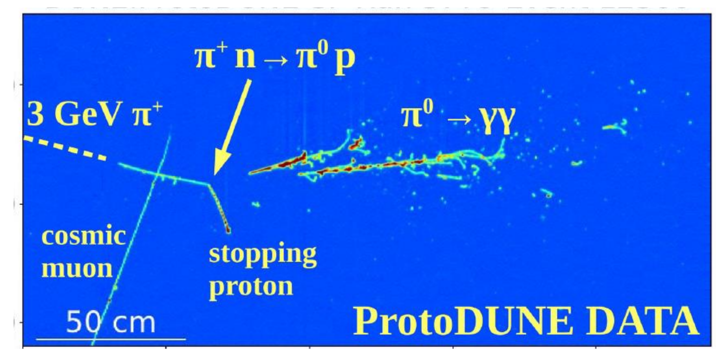


- 187-kt fid. volume water Cherenkov detector
- 1.3 MW off-axis beam from J-PARC
- 295 km oscillation baseline

DUNE

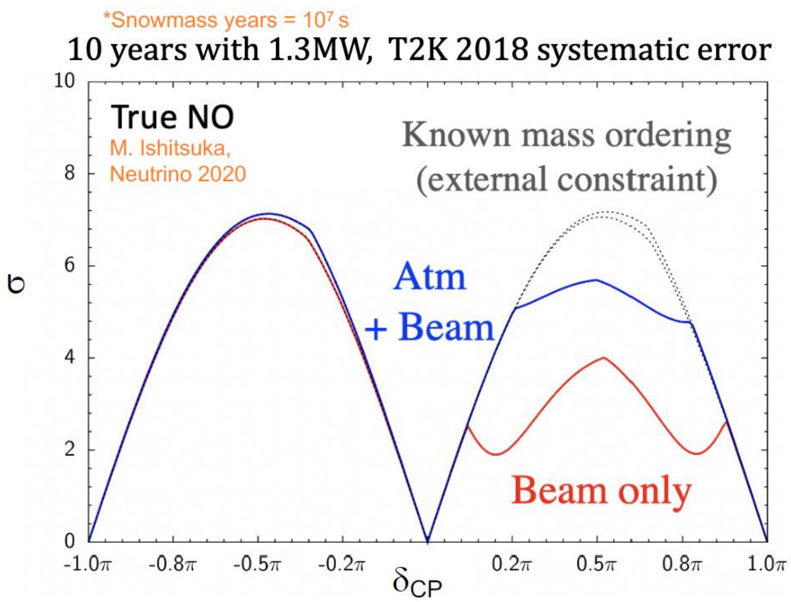
Module 1 / HD configuration



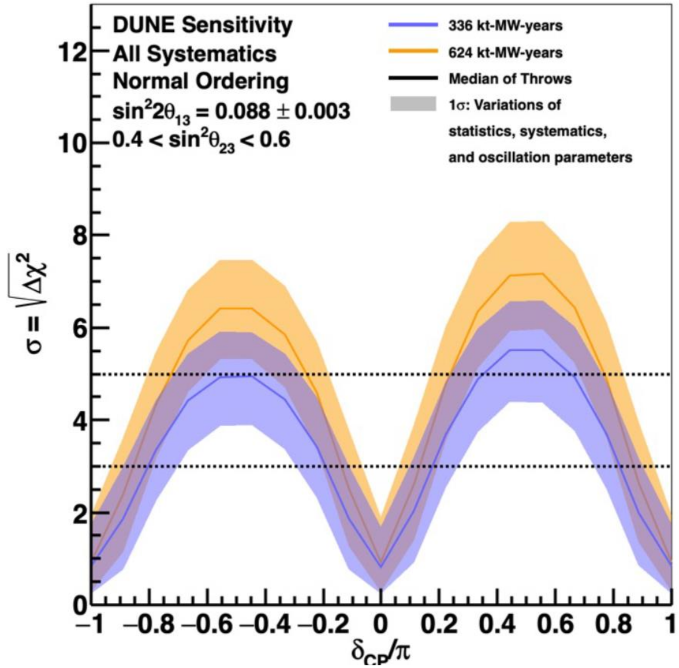


- >40-kt fiducial volume liquid argon TPC
- 1.2 – 2.4 MW broad-band beam from FNAL
- 1300 km oscillation baseline

Hyper-K / T2HK



DUNE



*CP*v reach

- Same baseline as T2K. Can use atmospheric data to help with mass ordering.

- Long baseline → **Definitive (>5σ) mass ordering determination quickly** for all parameter space

looking at both…

5σ *CP*v reach for >50% of parameter space. Precision PMNS measurements.

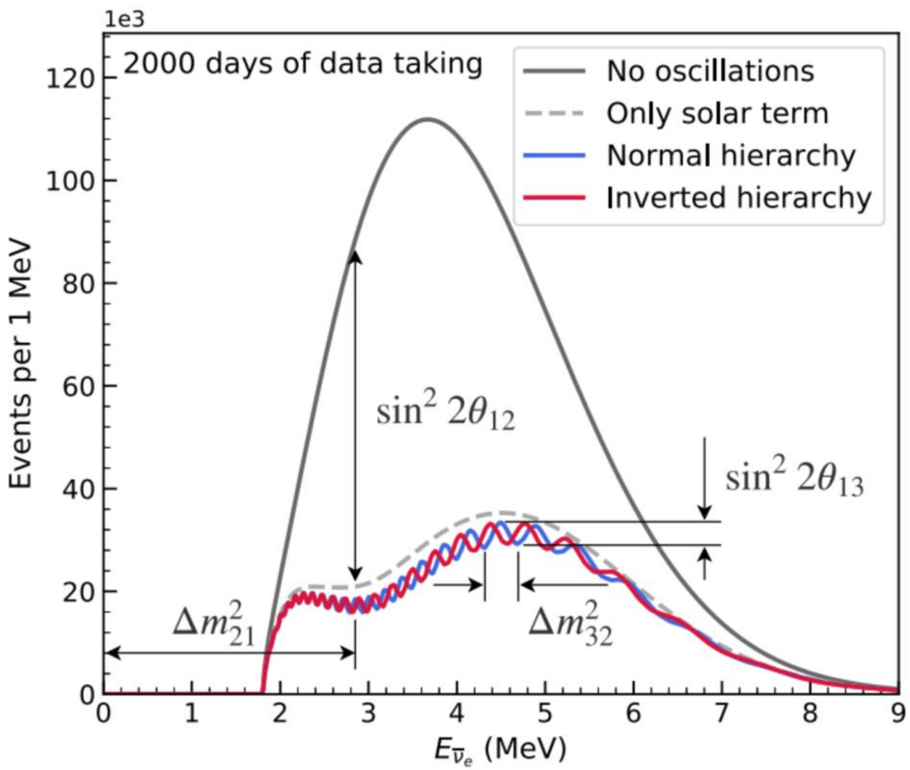
Civil construction underway. **First physics data toward end of this decade.**

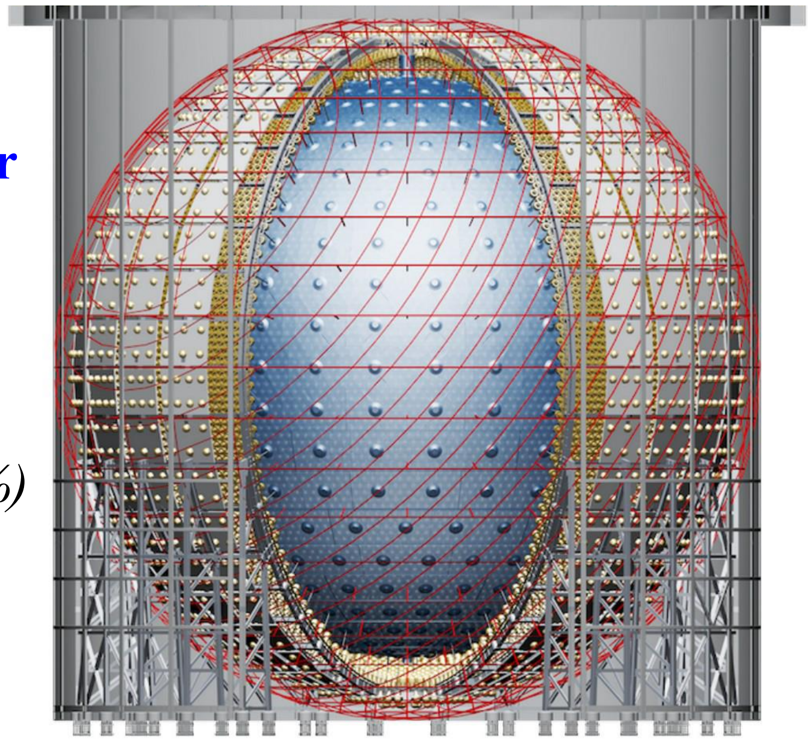
Highly complementary in detector design, systematics mitigation, and broader science program

JUNO

- 20 kton open-volume **liquid scintillator detector**
- **Oscillations at $L \approx 50$ km with reactor $\bar{\nu}_e$**
  (Plus atmospheric, solar, geo, supernova ν)

- Designed for **highly efficient light collection**
  strong requirements on energy resolution (3%) and linearity/scale uncertainties (<1%)





- **Sub-percent measurements of θ_{12}, $|\Delta m^2_{ij}|$**
- Novel approach to **mass ordering**:
  → Direct spectral measurement of all Δm^2_{ij}-driven oscillation contributions
- **Construction well underway.** Start of operations planned for 2023
  → *3σ νMO by end of decade*

Closing

- Several experiments with a range of time scales are poised to provide **the next answers in the neutrino sector.**
- In this short talk, I have **only scratched the surface** of the broad programs of the experiments discussed here.

  (*e.g.*, measurements related to astrophysics, baryon number violation, sterile neutrinos, dark matter, and other BSM physics)