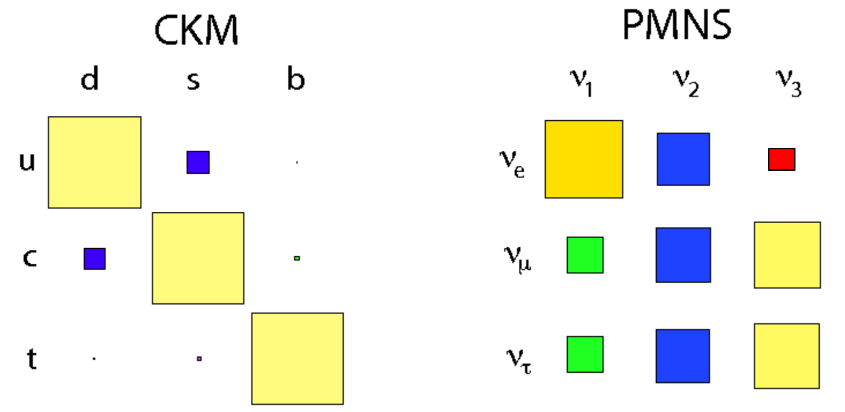
LONG-BASELINE NEUTRINOS OVERVIEW AND OUTLOOK

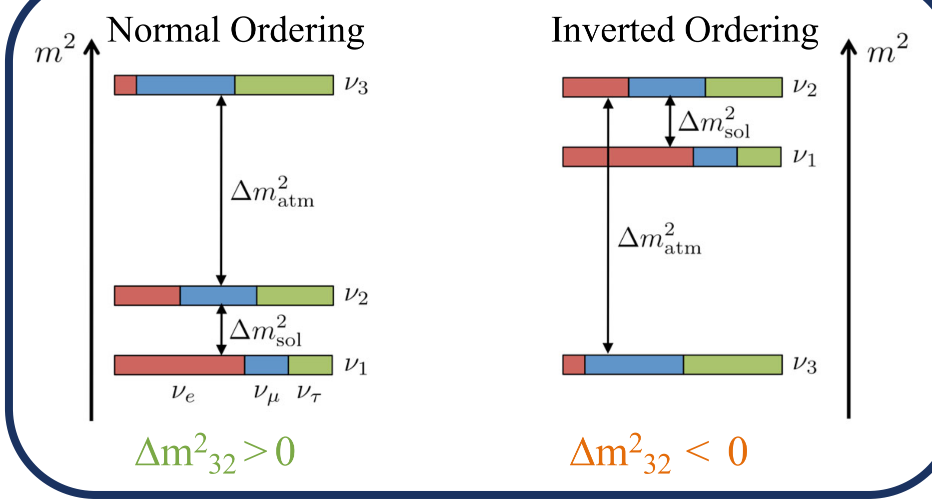
JENNIFER RAAF, FERMILAB

ASPEN WINTER CONFERENCE 2019

NEUTRINOS: BIG PICTURE VIEW



Credit: S.F. King, J. Phys. Conf. Ser. 631 (2015) 012005



Are the CKM and PMNS matrices related? Why do they look so different? Are their structures connected to the masses? What is the absolute mass scale? Are neutrinos Dirac or Majorana particles?

Are there more than 3 light neutrinos?

Is there leptonic CP violation?

May help to explain our matter-dominated universe

Is the atmospheric mixing angle maximal?

If so, new symmetry? If not, which octant is it in?

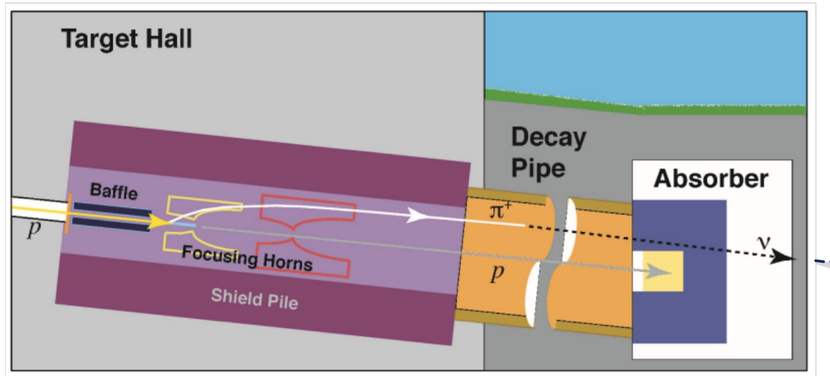
What is the neutrino mass ordering?

Not knowing confuses the CP violation picture

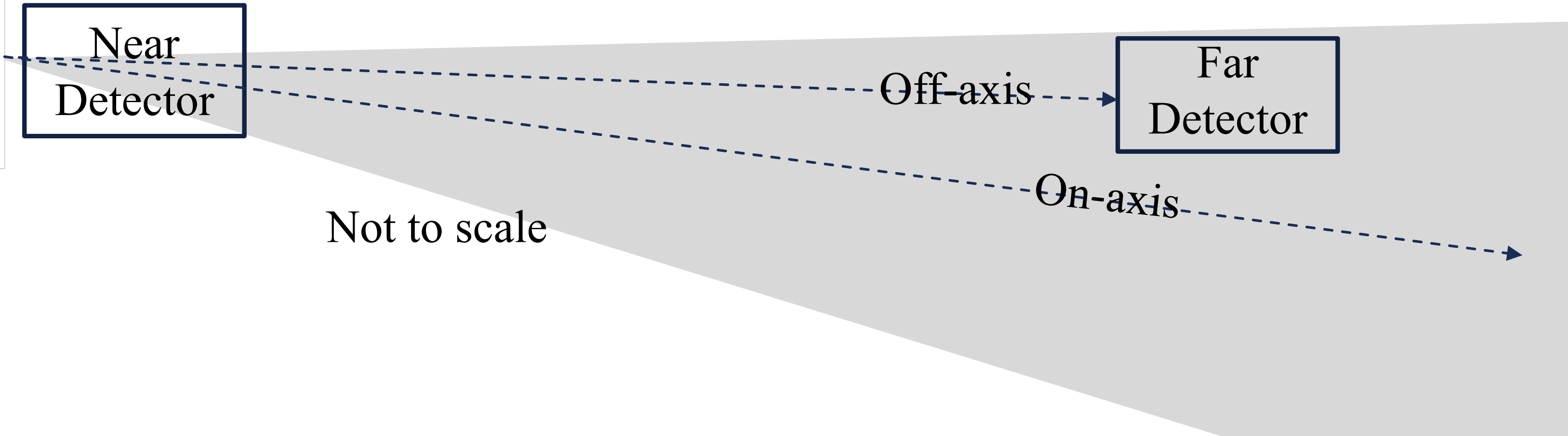
Answer has a big impact on $0\nu\beta\beta$

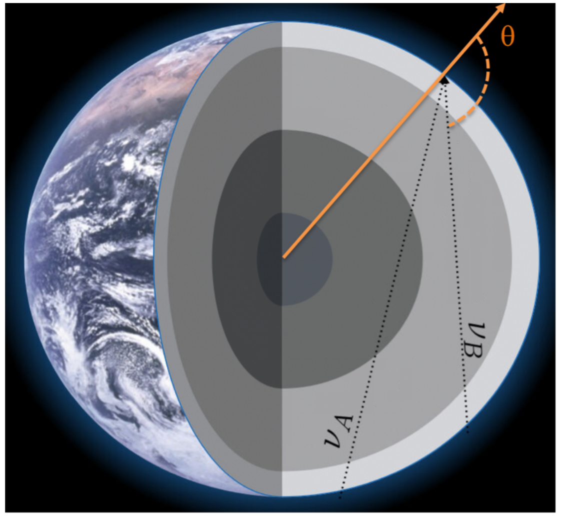
Study these questions with long-baseline neutrinos

WHAT DO WE MEAN BY LONG BASELINE?



- Accelerator neutrinos (fixed target experiments)
  - Baseline at fixed distance from neutrino source (~100's km)
  - On-axis (broad energy spectrum) vs. off-axis (narrow spectrum)



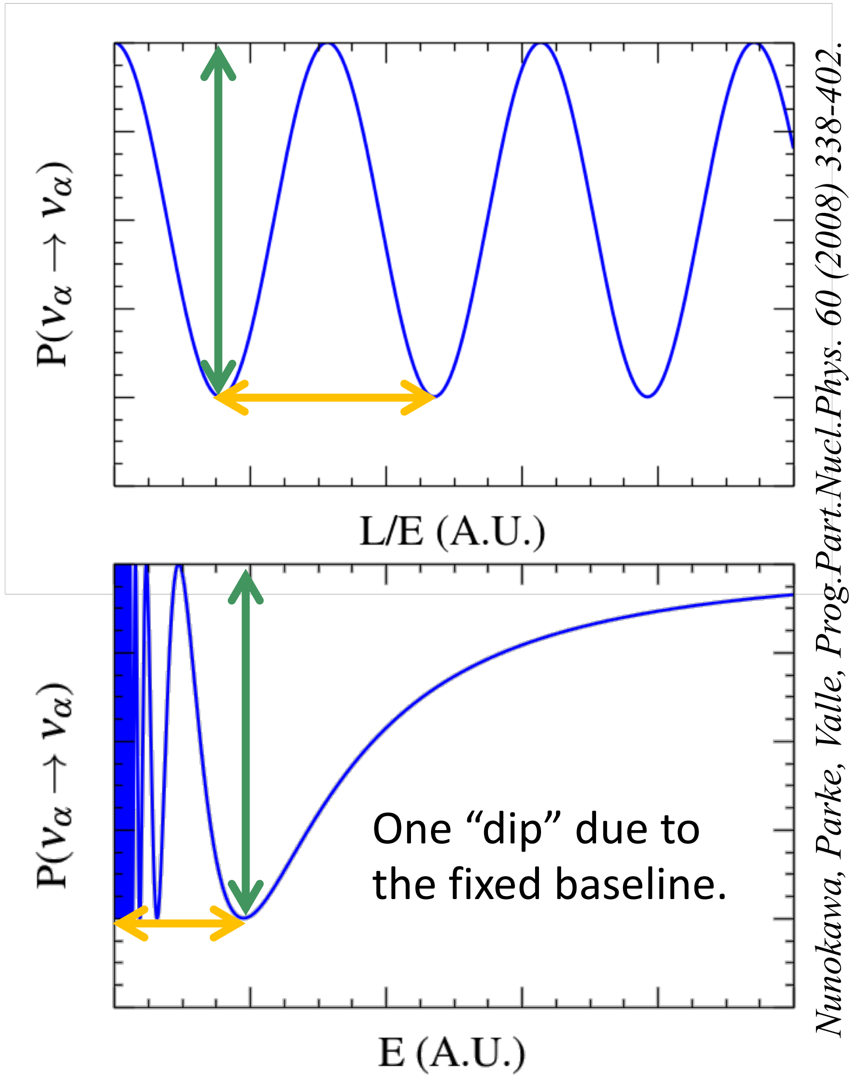


- Atmospheric neutrinos
  - Much longer range of baselines (~10-10,000 km)
  - Wide range of energies (~100 MeV- many TeV)
  - Possibility to study many aspects of oscillation, but at the price of not knowing the baseline of each event very well → some effects are smeared

WHY LONG BASELINE?

- Study oscillation effects by comparing the neutrino beam near the production target (before they have oscillated) with neutrino beam at some distance
  - Disappearance is dominant effect
  - Can also study subdominant appearance of other neutrino flavors

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \left(\sin^2(2\theta_{13}) \sin^2(\theta_{23}) + \cos^4(\theta_{13}) \sin^2(2\theta_{23}) \right) \sin^2\left(\frac{\Delta m^2 L}{4E} \right)$$



COMPETING EFFECTS IN OSCILLATION PROBABILITY

Matter Effect: $a = G_F N_e \sqrt{2}$

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$

$$P(\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - (+)aL)}{(\Delta_{31} - (+)aL)^2} \Delta_{31}^2$$

Leading term

$$+ \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \cos\theta_{13} \frac{\sin(\Delta_{31} - (+)aL)}{(\Delta_{31} - (+)aL)} \Delta_{31} \frac{\sin(aL)}{aL} \Delta_{21} \cos(\Delta_{32}) \cos\delta$$

CP-conserving term

$$- (+) \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \cos\theta_{13} \frac{\sin(\Delta_{31} - (+)aL)}{(\Delta_{31} - (+)aL)} \Delta_{31} \frac{\sin(aL)}{aL} \Delta_{21} \sin(\Delta_{32}) \sin\delta$$

CP-violating term

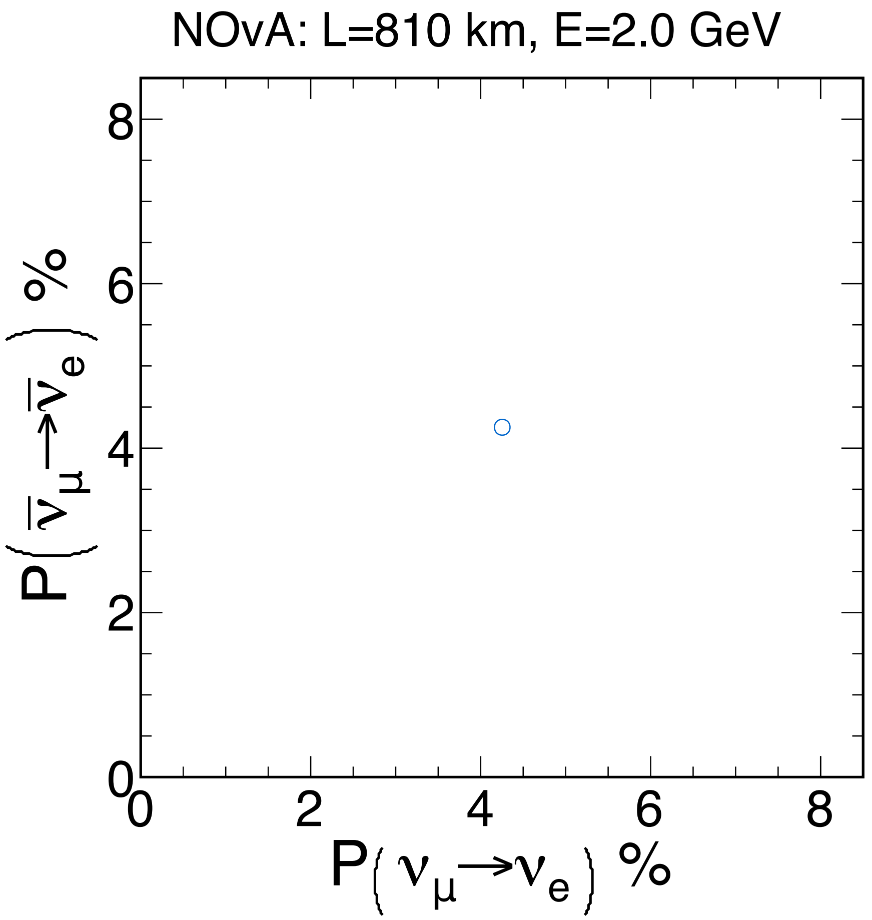
$$+ \cos^2\theta_{13} \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(aL)}{(aL)^2} \Delta_{21}^2.$$

"solar" term

- The "appearance" channel contains all of oscillation parameters, but the measurement is complicated by competing effects
  - Different sets of parameter values can give the same oscillation probability (degeneracies make it difficult to determine the true parameter values)

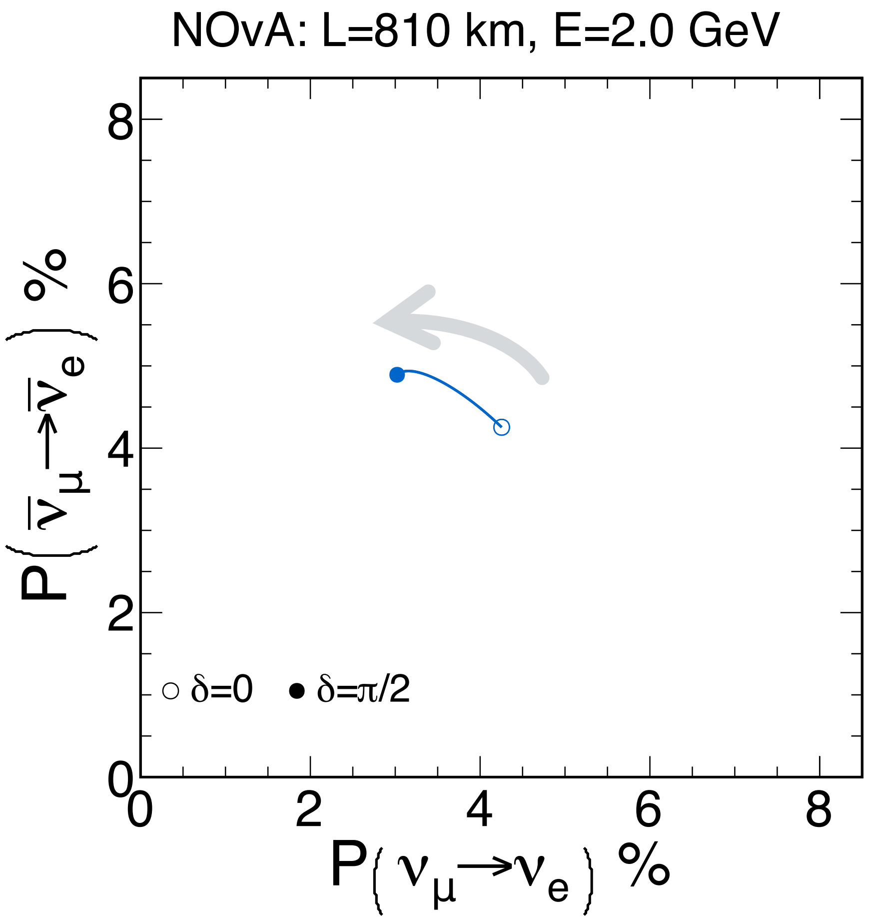
DEGENERACIES MUDDY THE WATERS

- Probability of anti-ν_e appearance vs. ν_e appearance for a single neutrino energy and baseline
- In vacuum, and if no CP violation, equal probabilities



DEGENERACIES MUDDY THE WATERS

- Probability of anti-ν_e appearance vs. ν_e appearance for a single neutrino energy and baseline
- In vacuum, and if no CP violation, equal probabilities
  - CP violation through δ_{CP} enhances anti-ν_e appearance and suppresses ν_e appearance



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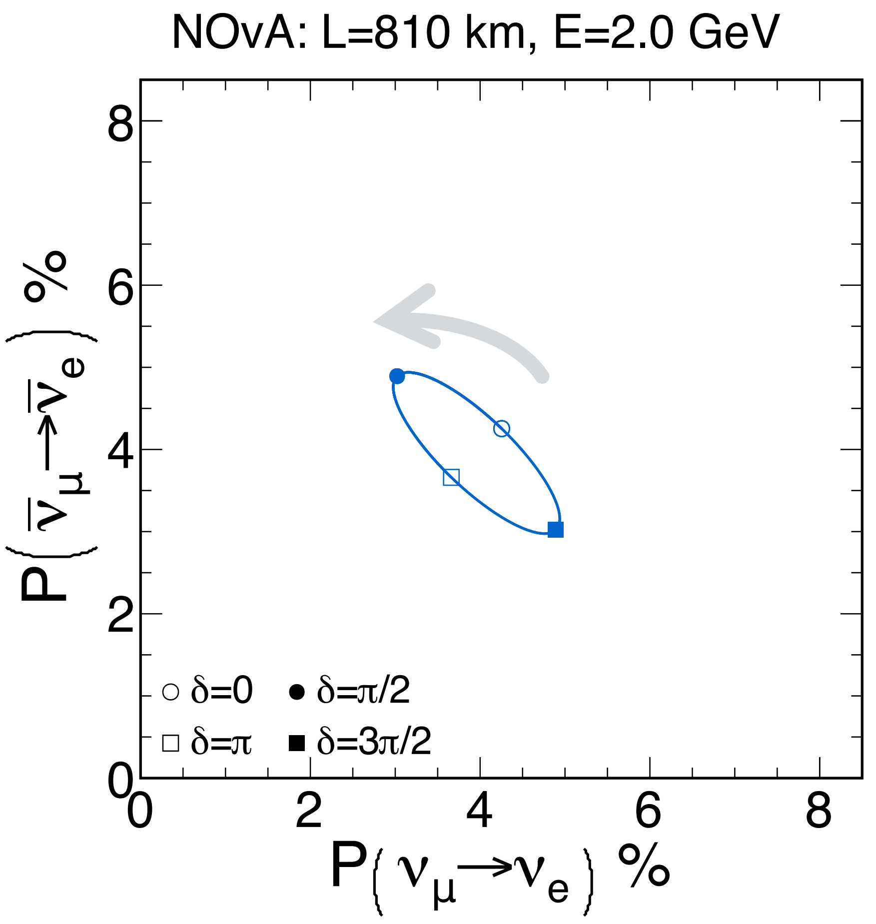
  - Moving through the full range of possible δ_{CP} values traces out an ellipse



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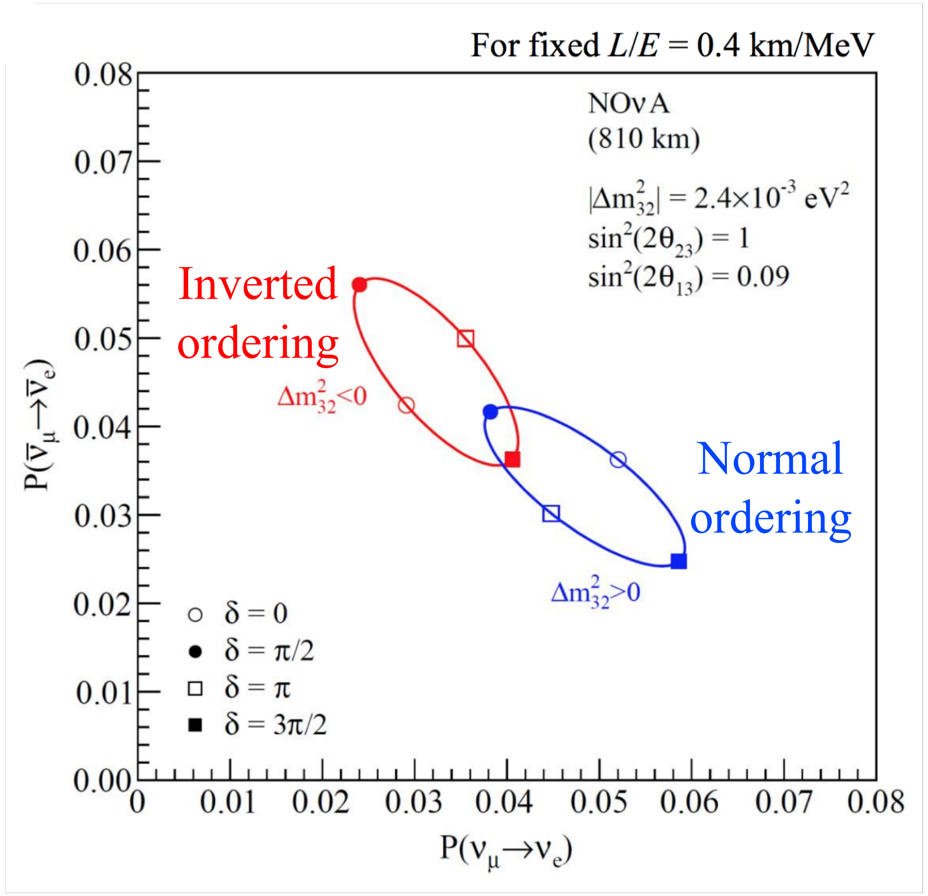
- Propagation through matter and mass ordering also have opposite effects on neutrinos and antineutrinos



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  - Moving through the full range of possible δ_{CP} values traces out an ellipse
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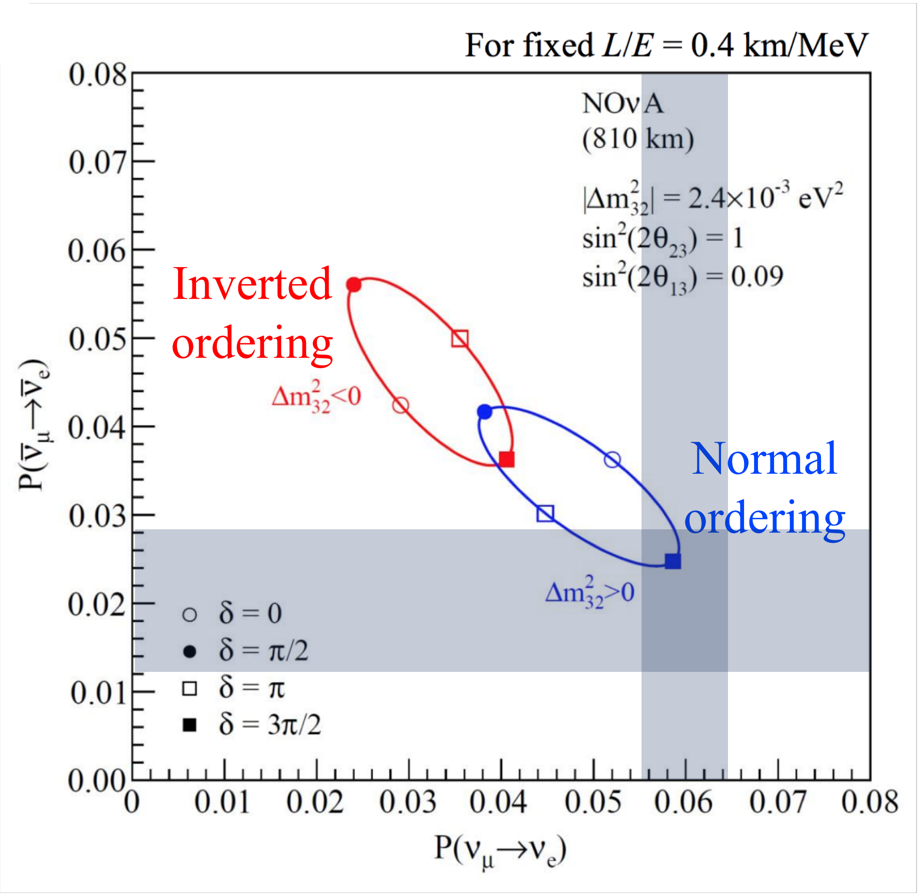
- Maybe you get lucky and measure something in an unambiguous region…



DEGENERACIES MUDDY THE WATERS

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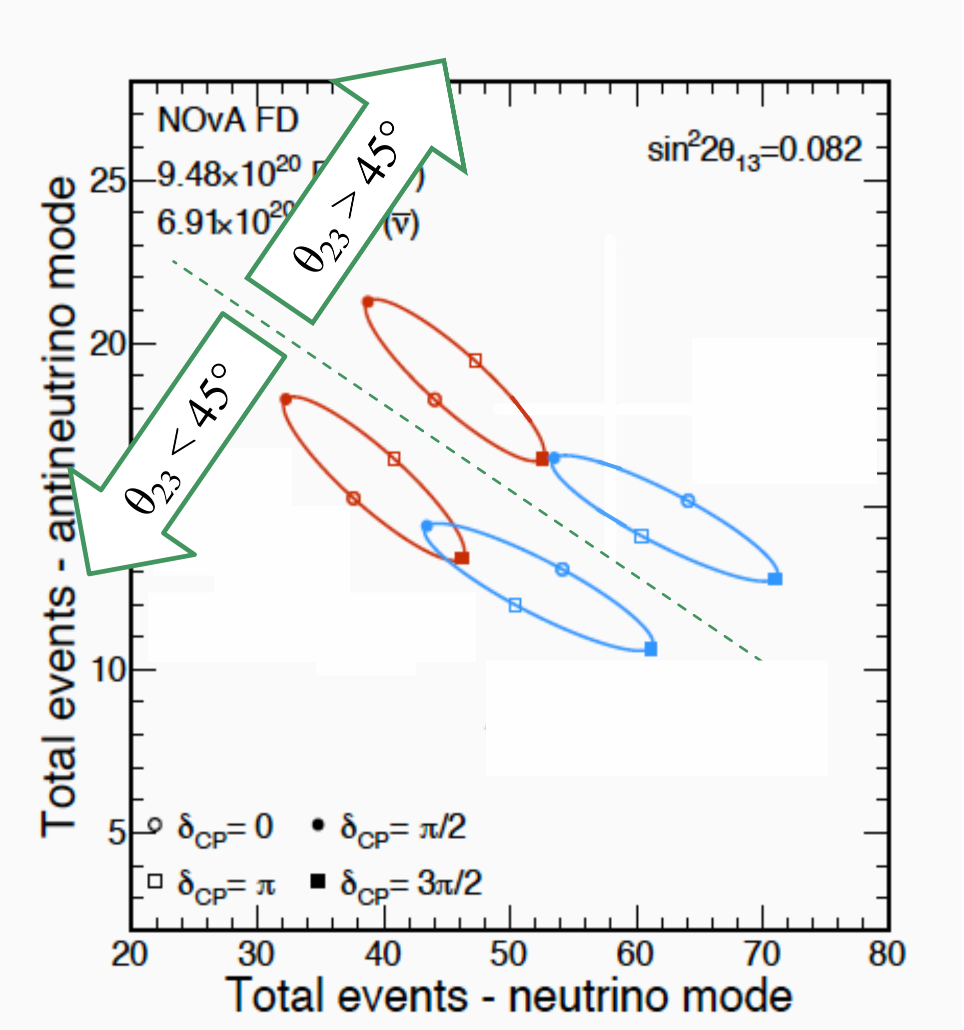
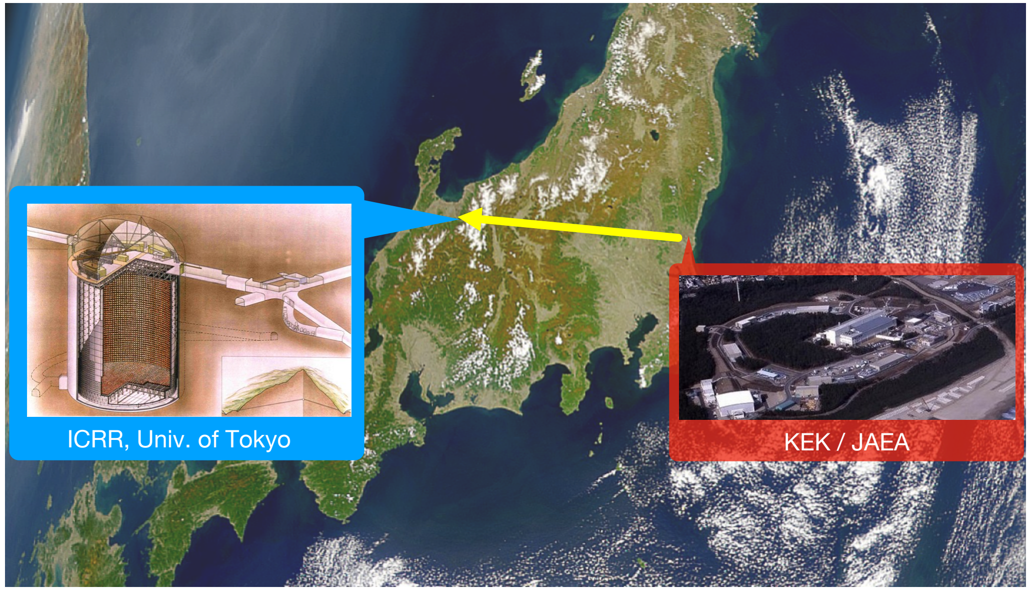
  - CP violation through δ_{CP} enhances anti-ν_e appearance and suppresses ν_e appearance
  - Moving through the full range of possible δ_{CP} values traces out an ellipse
- Propagation through matter and mass ordering also have opposite effects on neutrinos and antineutrinos
- Probabilities are also proportional to $\sin^2\theta_{23}$, so non-maximal θ_{23} has a big effect



Everything affects everything else.

OSCILLATIONS IN LONG-BASELINE EXPERIMENTS: T2K, NOVA, OPERA



Tokai to Kamioka (**T2K**): 295 km

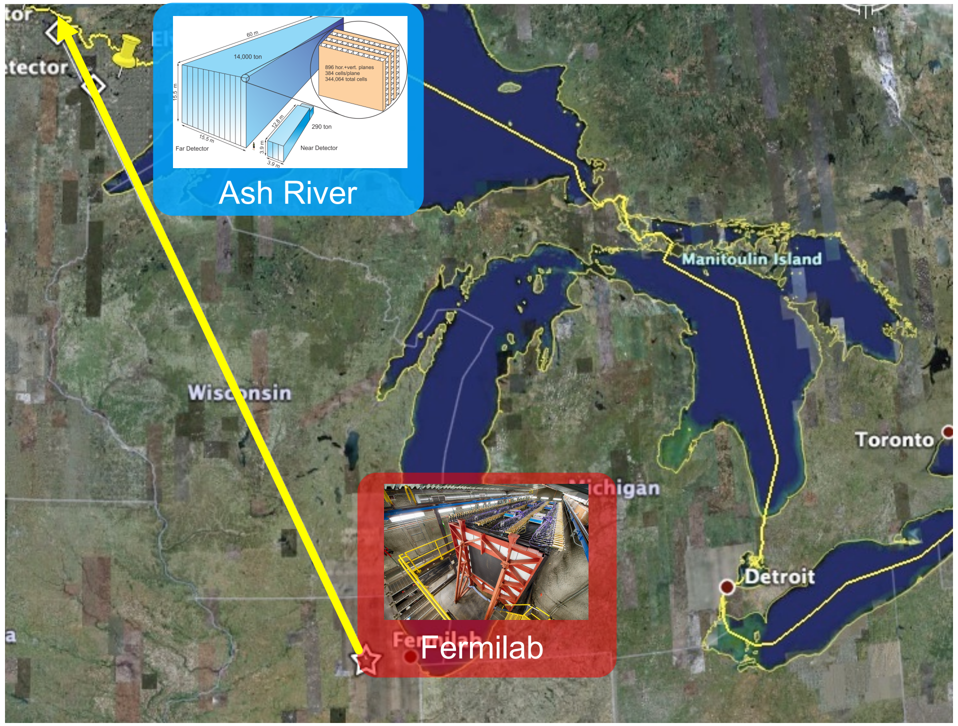
ν_μ disappearance

ν_e appearance

Fermilab to Ash River (**NOvA**): 810 km

ν_μ disappearance

ν_e appearance

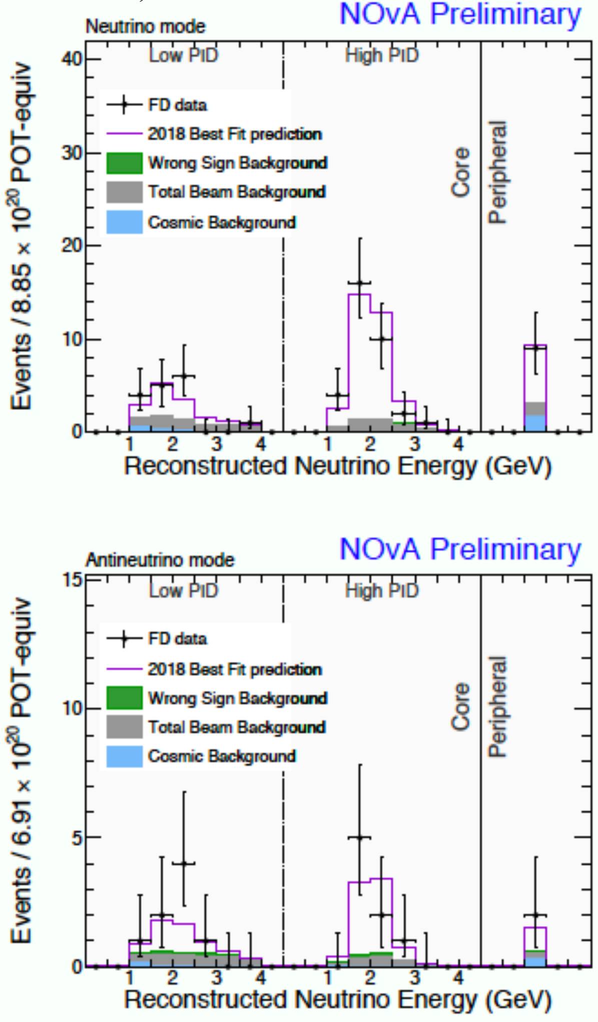


CERN to Gran Sasso (**OPERA**): 730 km

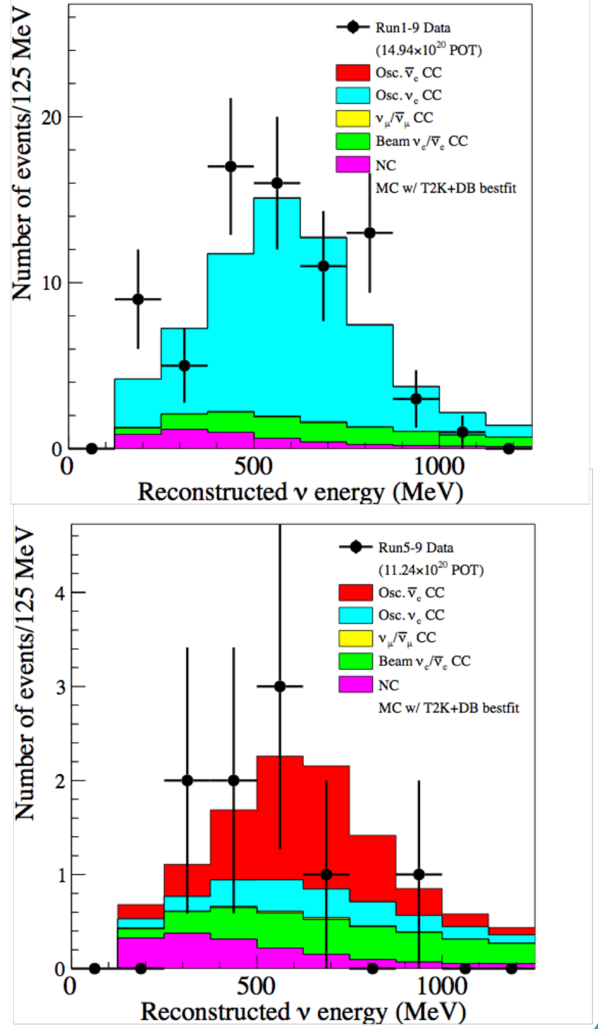
ν_τ appearance

FIRST MEASUREMENTS OF APPEARANCE

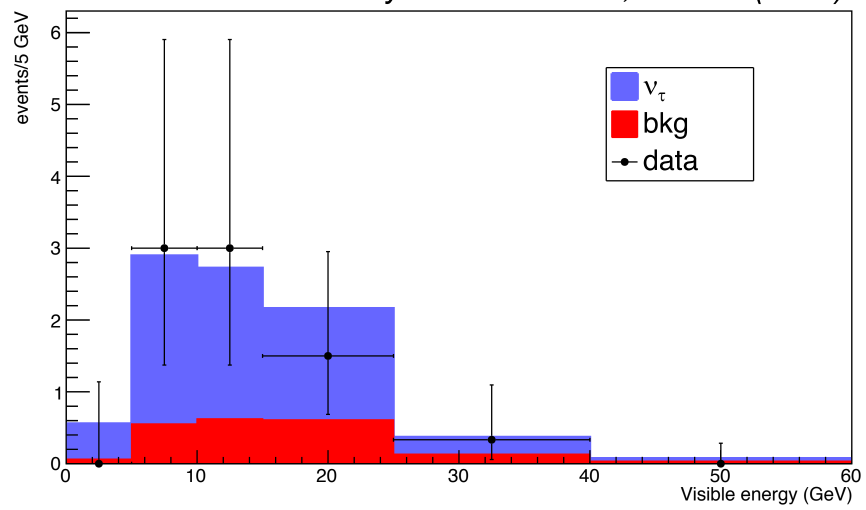
M. Sanchez, Neutrino 2018



M. Wascko, Neutrino 2018 T2K Preliminary



OPERA *Phys. Rev. Lett* ***120****, 211801 (2018)*



- NOvA and T2K changed the landscape by observing appearance for the first time
  - T2K first observed in ν_e
  - NOvA first observed in anti-ν_e
- OPERA sees ν_τ appearance!

T2K & NOVA MEASUREMENT STRATEGIES

	T2K	NOvA
Off-axis angle	44 mrad (2.5°)	14.6 mrad (0.8°)
Mean neutrino energy	0.6 GeV	2 GeV
Baseline	295 km	810 km
L/E	**0.49 km/MeV**	**0.41 km/MeV**
Detector type	Near: Multipurpose tracker Far: Water Cherenkov	Near & Far: segmented liquid scintillator

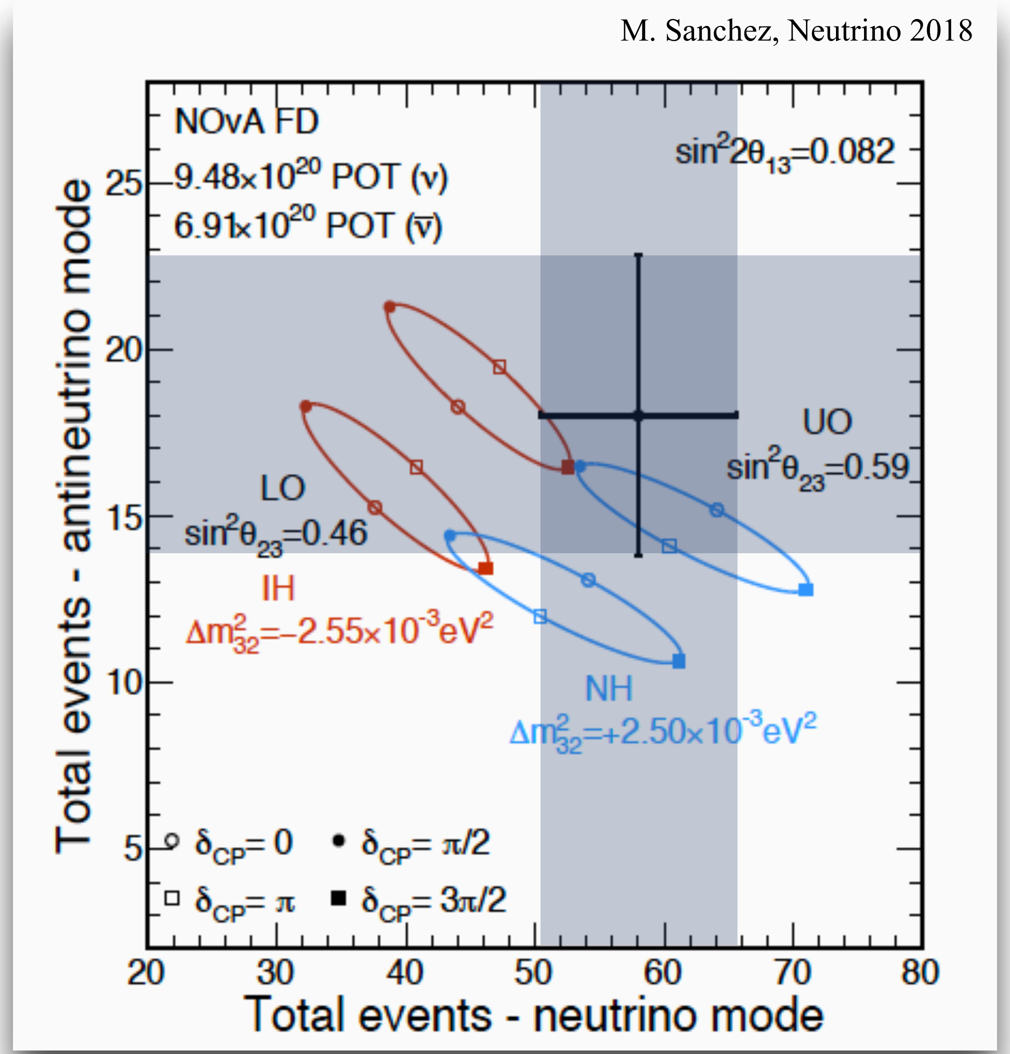
- Perform simultaneous fit for:
  - ν_μ disappearance
  - anti-ν_μ disappearance
  - ν_e appearance
  - anti-ν_e appearance

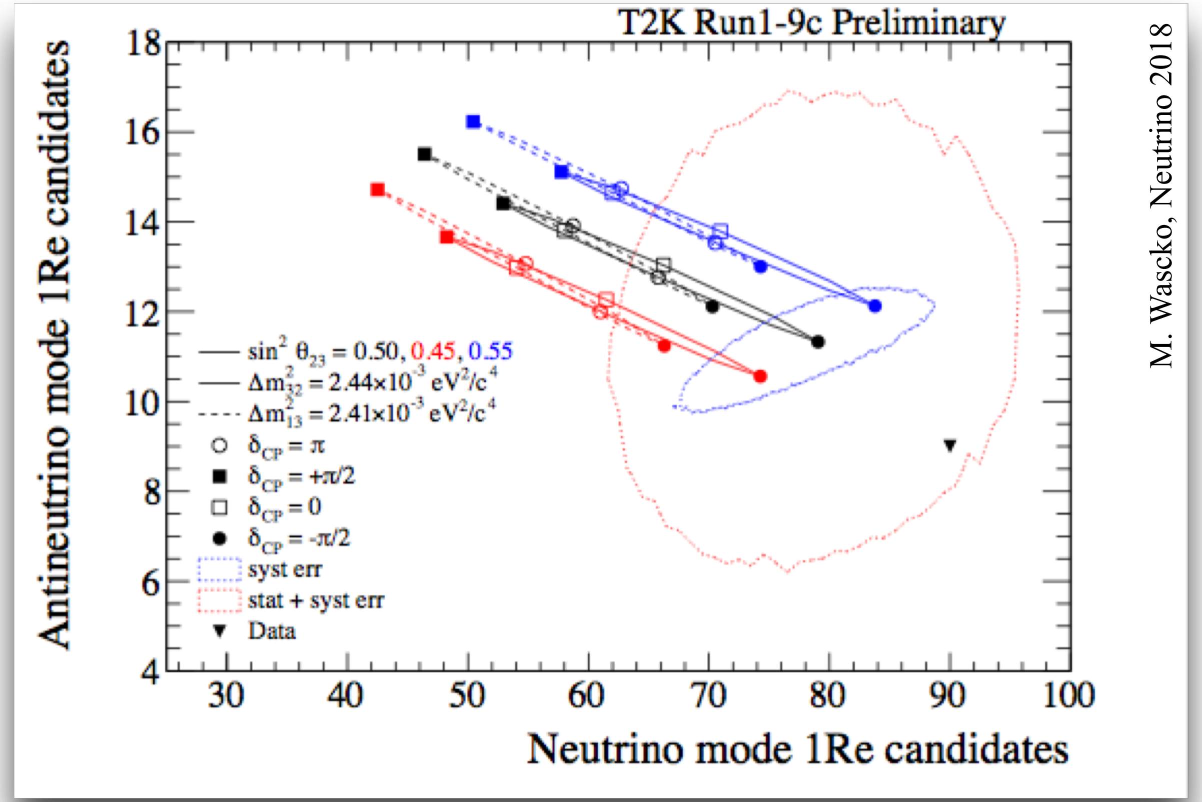
Constrain reactor & solar oscillation parameters to best fit values from solar and reactor experiments.

Outputs of fit: Is CP violated? What is the preferred mass ordering? Is the atmospheric mixing maximal?

… but there is still some ambiguity due to degeneracies

NOVA & T2K



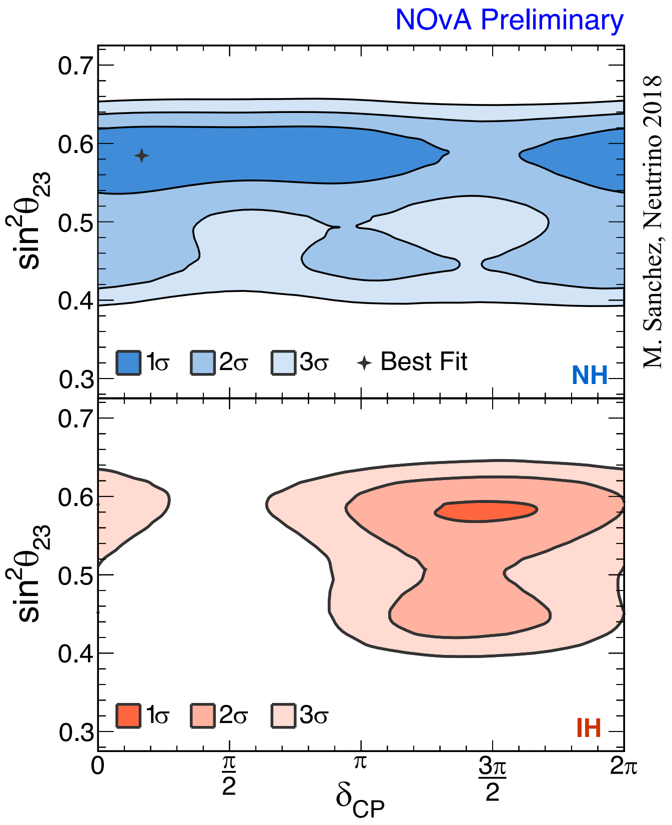


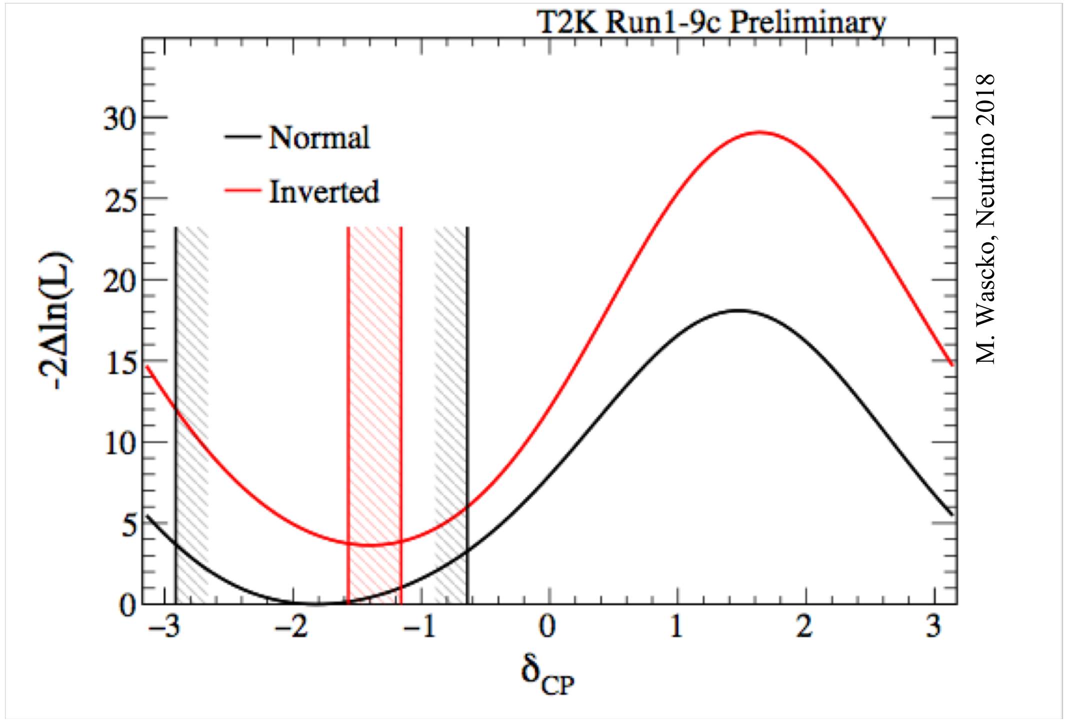
- N.B.: Plots assume a single energy when drawing curves

NOVA & T2K ALLOWED REGIONS

Normal ordering

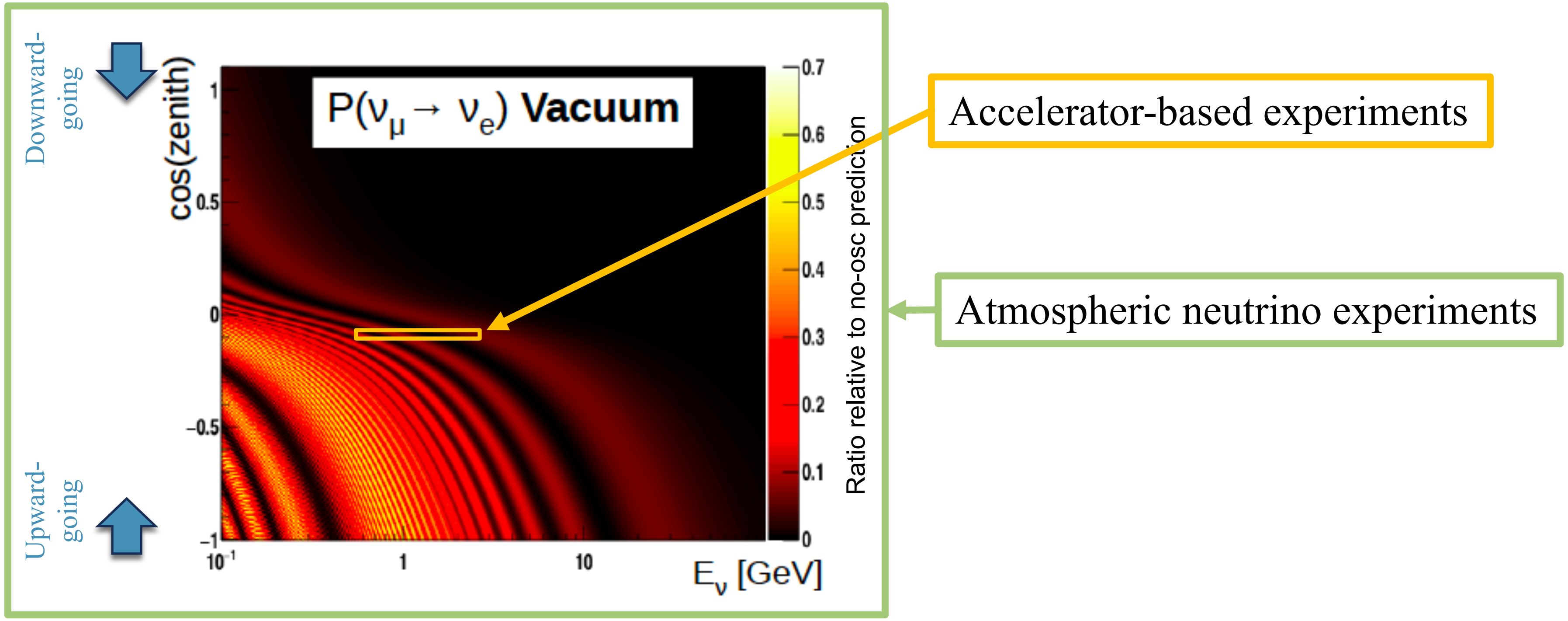
Inverted ordering

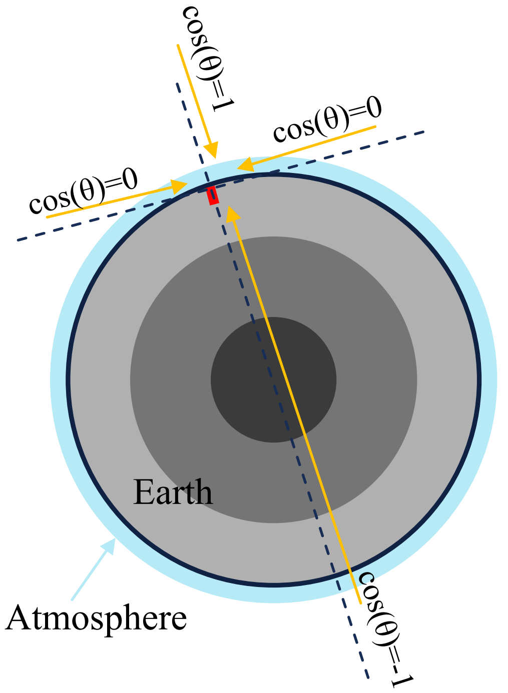




- NOvA can determine the mass ordering if Nature is nice enough to put δ_{CP} and θ_{23} in favorable ranges. Inverted mass ordering at $\delta_{CP} = \pi/2$ is disfavored at >3σ.
- T2K is not really sensitive to mass ordering, but has a weak preference for normal ordering, and disfavors CP-conserving points (at 2σ level) regardless of mass ordering assumption

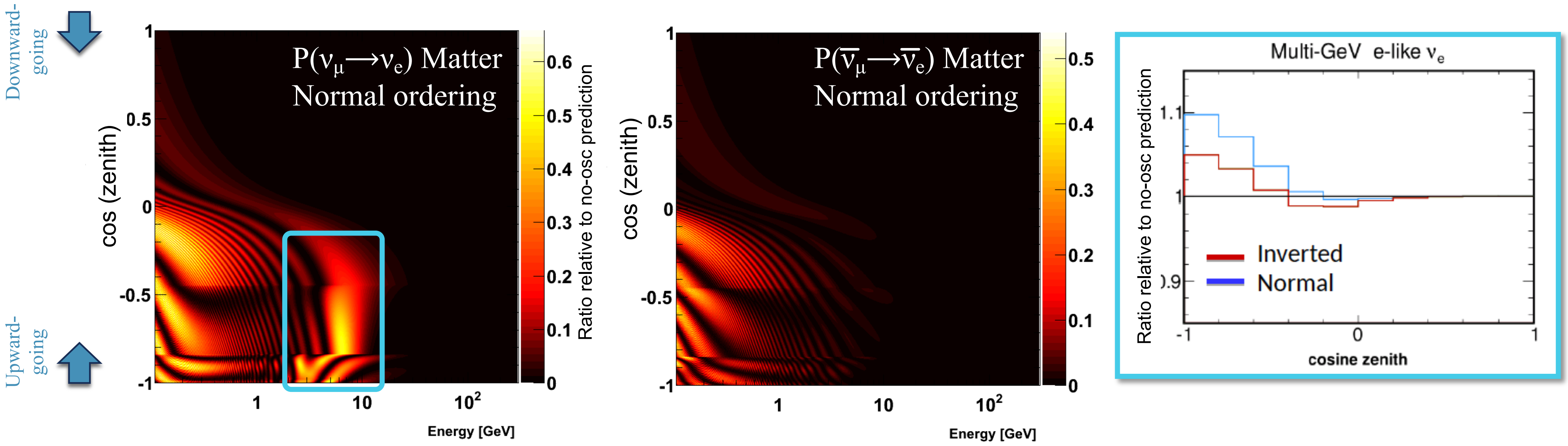
LONGER BASELINES: ATMOSPHERIC NEUTRINOS





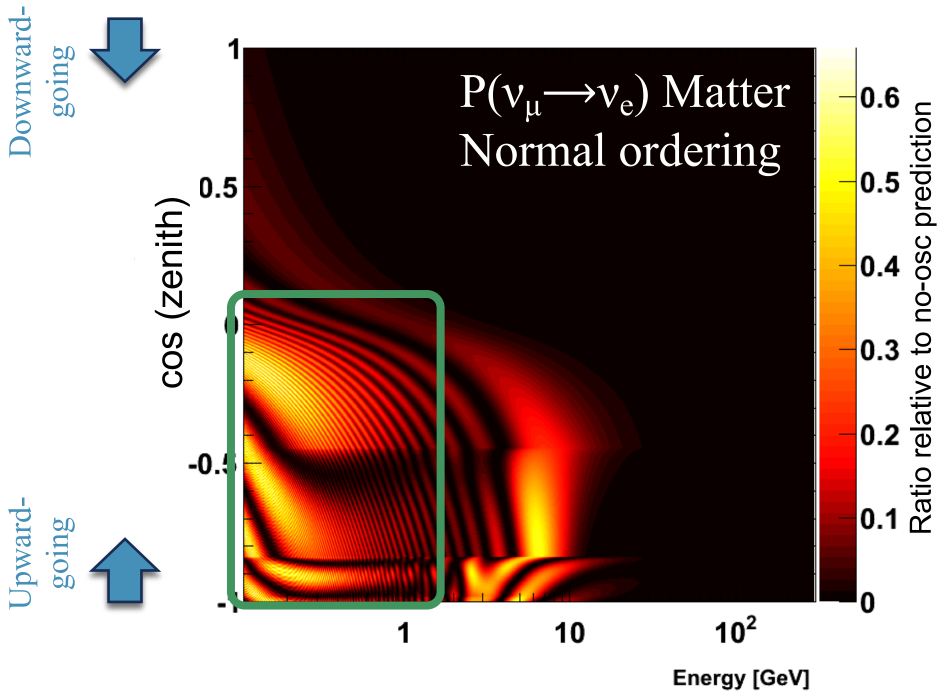
- Oscillogram: map appearance probability in baseline vs. energy
- Separate events into bins of energy and zenith (pathlength), separate electron-like from muon-like events
- Some ability to do statistical separation of neutrinos/anti-neutrinos

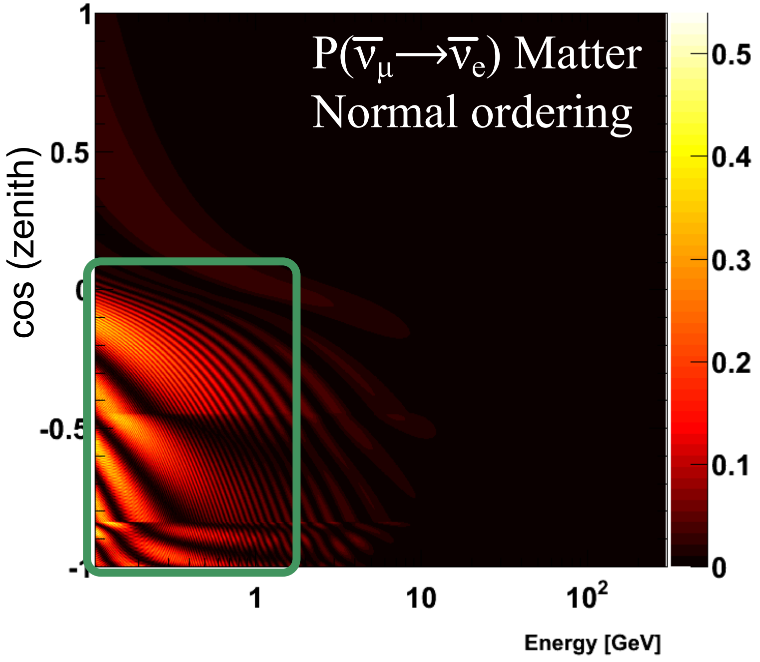
MASS ORDERING WITH ATMOSPHERIC NEUTRINOS

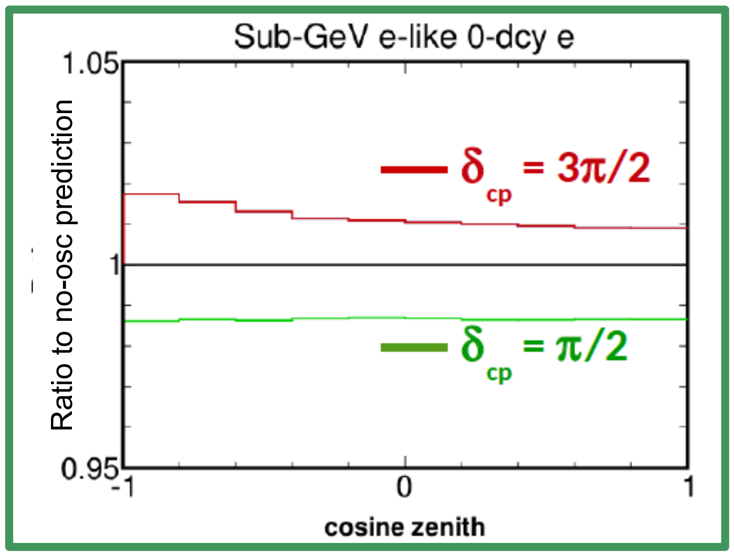


- Matter effects create resonant oscillations between 2~10 GeV
  - If true mass ordering is normal: resonance only in ν
  - If true mass ordering is inverted: resonance only in anti-ν

CP VIOLATION WITH ATMOSPHERIC NEUTRINOS

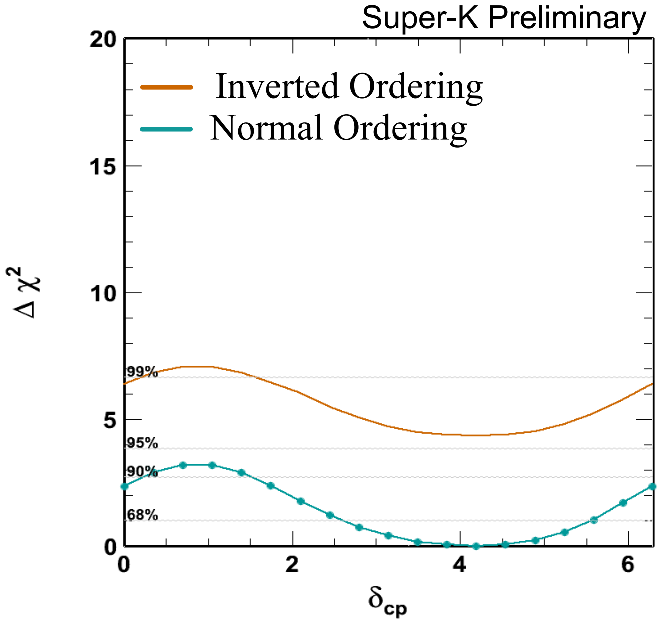


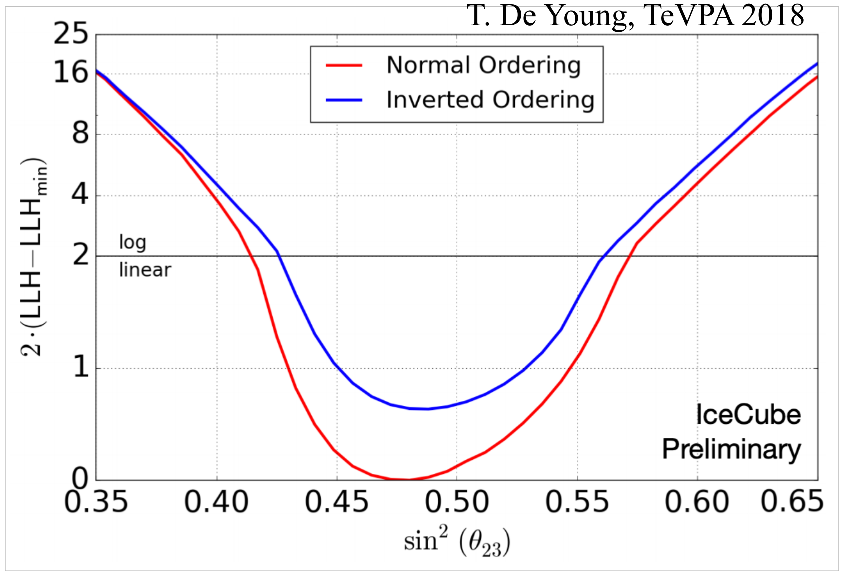


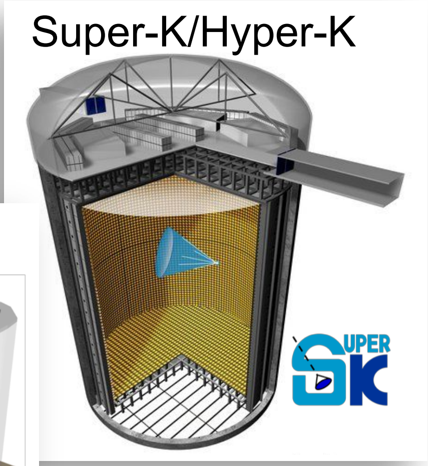


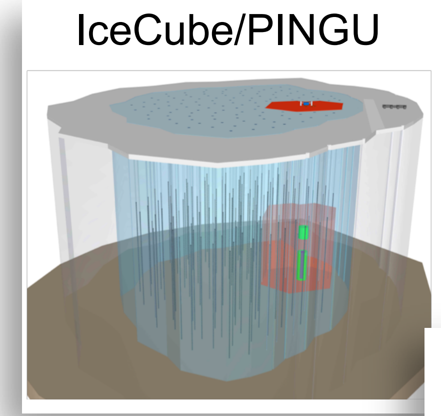
- CP violation shows up at low energies

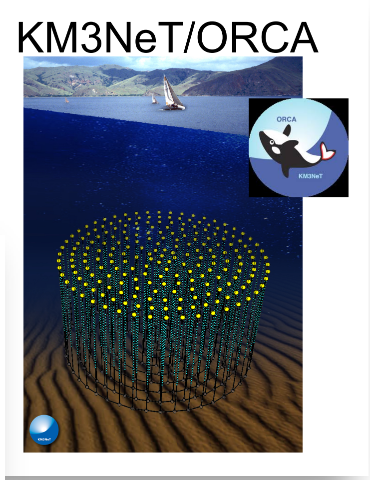
ATMOSPHERIC NEUTRINO EXPERIMENT RESULTS

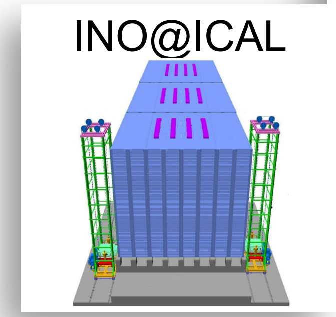












- Sensitivity in atmospheric ν's experiments is currently weak
  - Super-K weakly favors normal ordering and $\delta_{CP} \sim 1.33\pi$
  - IceCube <1σ preference for normal ordering & non-maximal atmospheric mixing
- Operating and soon-to-be operating atmospheric ν experiments may be able to determine mass ordering before the next generation of long-baseline experiments

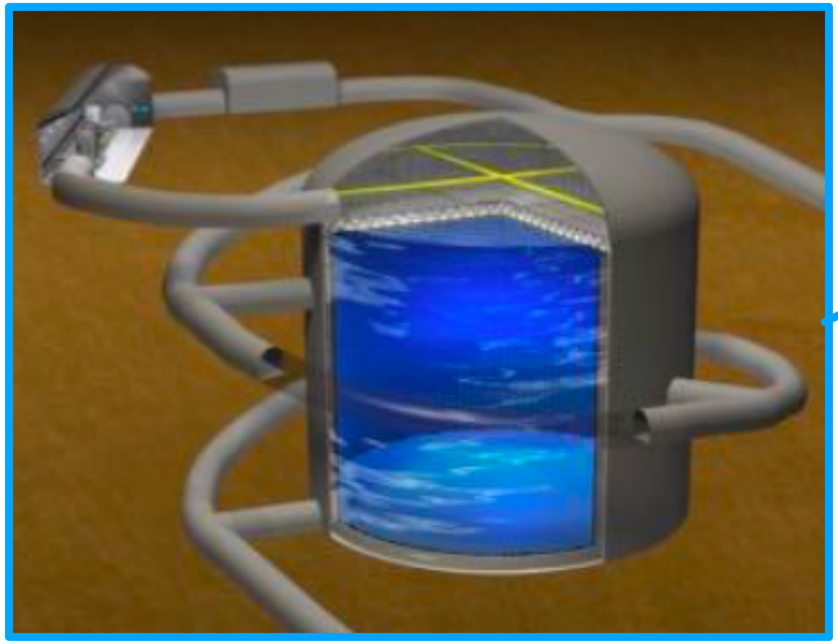
WHAT WE KNOW AND WHAT'S NEXT

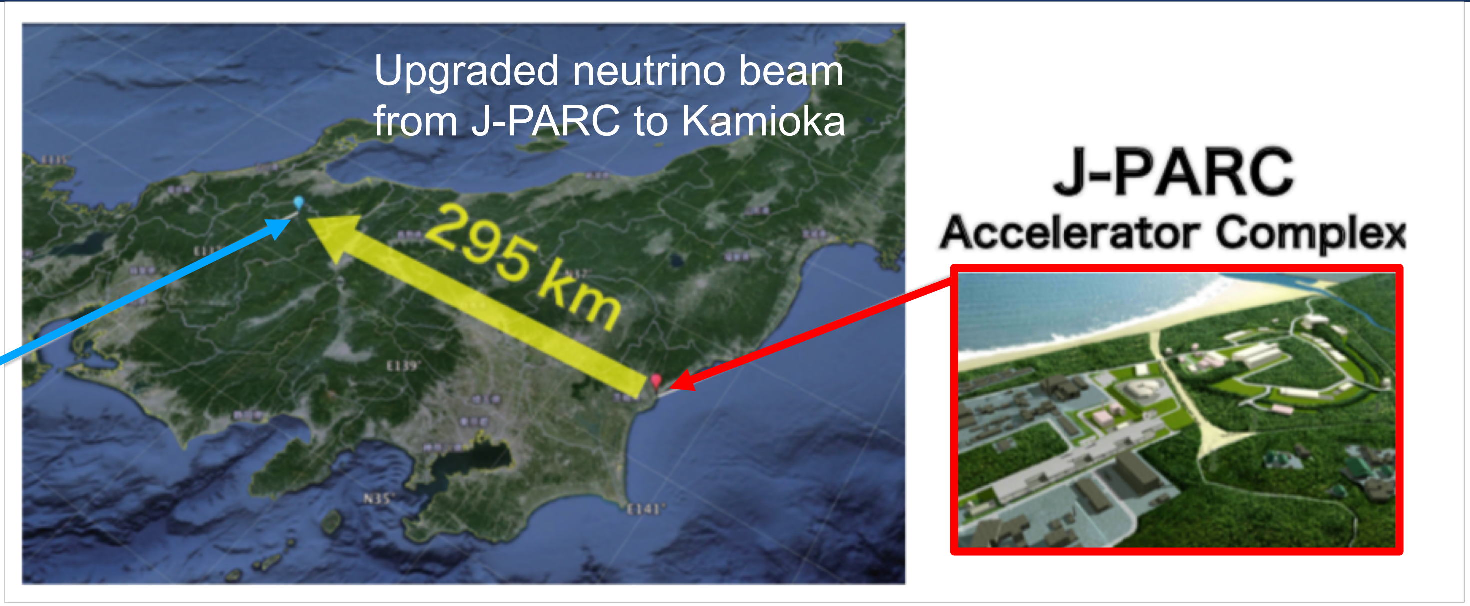
- If Nature is kind, mass ordering may be determined by NOvA and/or atmospheric experiments
- T2K + NOvA, with more data, may give us a hint that CP is violated (3σ at best)
- In order to precisely measure CP violation (at $>5\sigma$), we need the next generation of experiments: Hyper-K and DUNE

PRESENT & FUTURE

	T2K/Hyper-K	NOvA	DUNE
Off-axis angle	44 mrad (2.5°)	14.6 mrad (0.8°)	0° (on axis)
Mean neutrino energy	0.6 GeV	2 GeV	3 GeV
Baseline	295 km	810 km	1300 km
L/E	**0.49 km/MeV**	**0.41 km/MeV**	**0.43 km/MeV**
Detector type	Near: Multipurpose tracker Far: Water Cherenkov	Near & Far: segmented liquid scintillator	Near: LArTPC + magnetized multipurpose tracker Far: LArTPC

HYPER-KAMIOKANDE

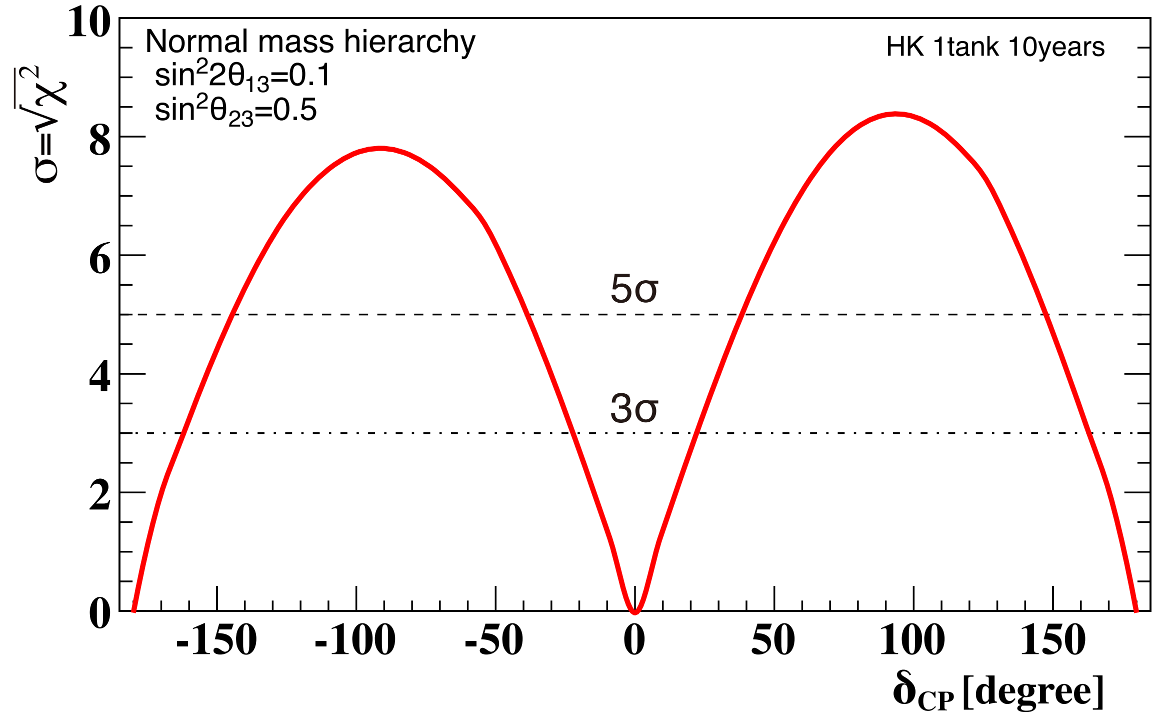


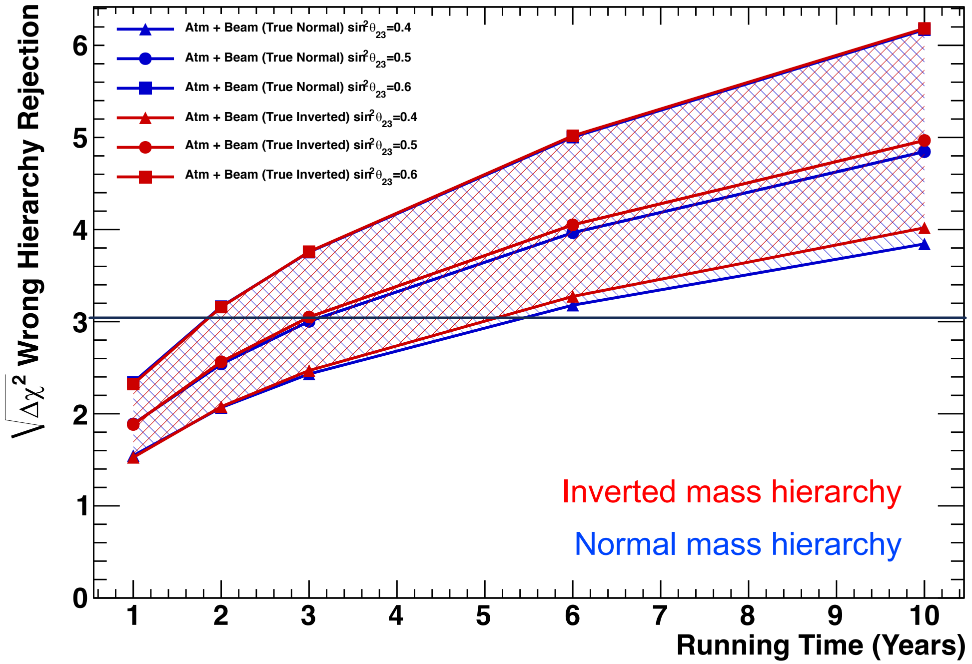


Design report released in May, arXiv:1805.04163

- Gigantic neutrino and nucleon decay Water Cherenkov detector— (186 kton FV, 10x Super-K)
- MW beam from upgraded J-PARC complex, narrow-band beam (2.5° off-axis)
- Aiming for construction start 2020

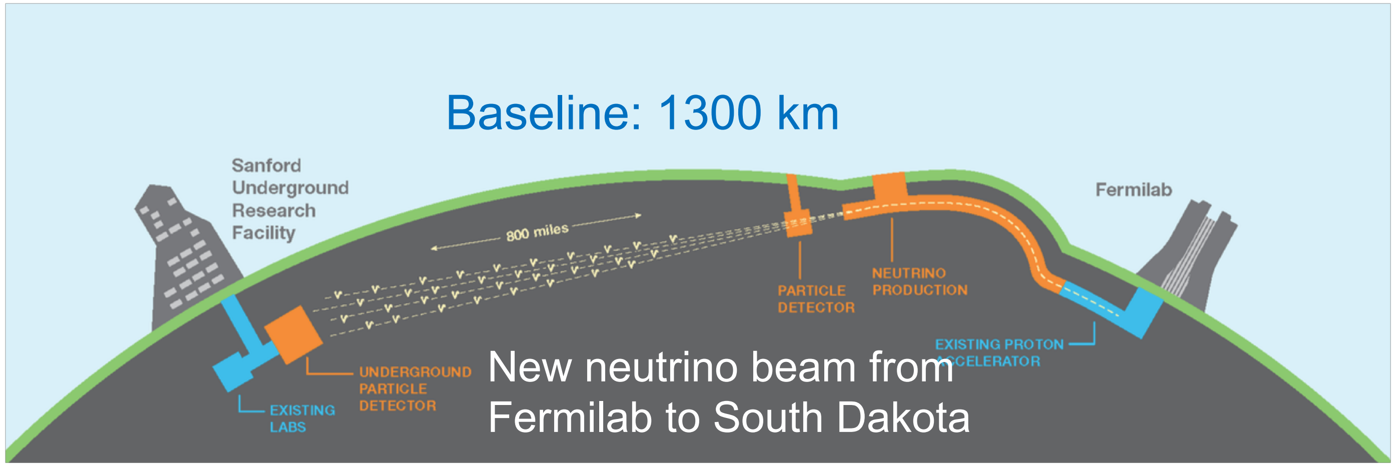
HYPER-K SENSITIVITIES





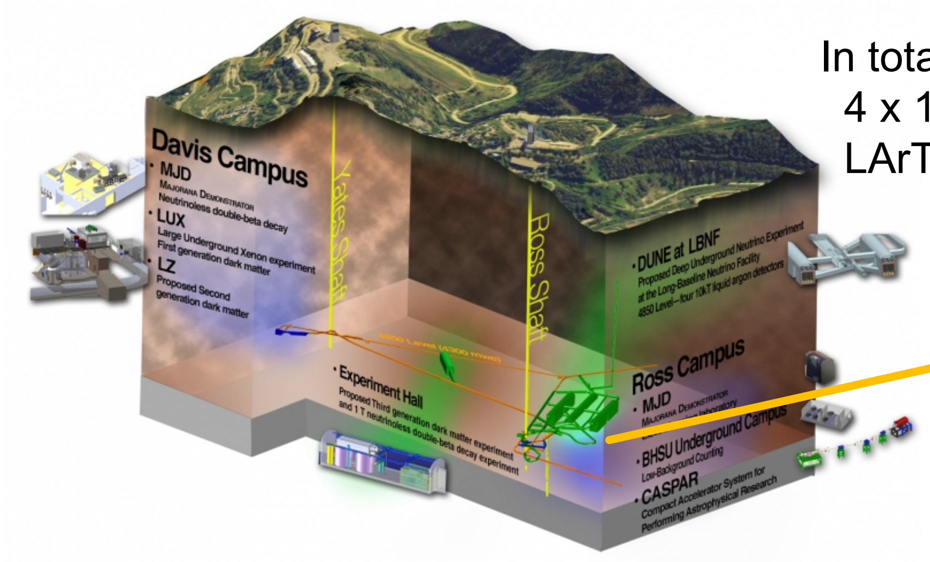
- If mass ordering is known, HK can exclude CP conservation for most of the δ_{CP} space
- Not sensitive to mass ordering with beam neutrinos alone, but will collect a huge sample of atmospheric neutrinos as well
  - Fitting atmospheric + beam neutrinos together improves sensitivity to reject wrong mass ordering

DEEP UNDERGROUND NEUTRINO EXPERIMENT (DUNE)

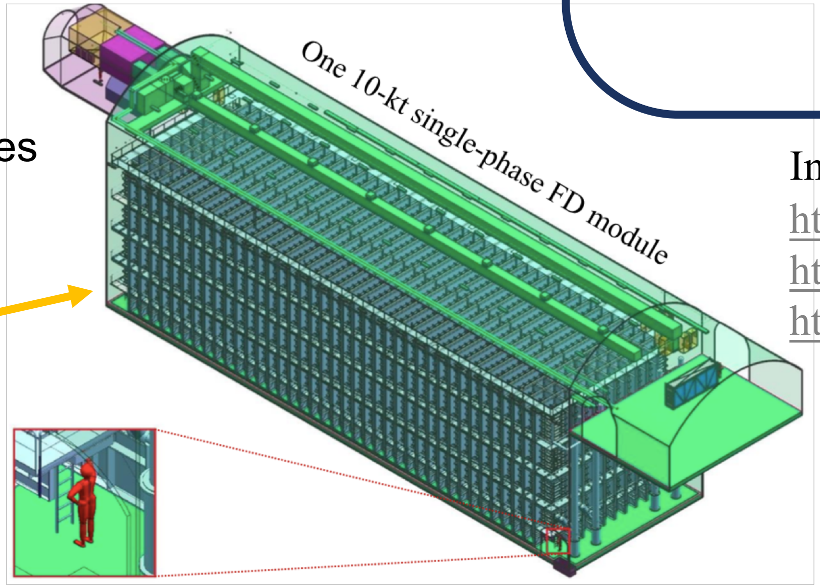


Timeline (construction start in 2020's):

Year 0:	20-kt FD with 1.07 MW (80-GeV) beam and initial ND constraints
Year 1:	30-kt FD
Year 3:	40-kt FD and improved ND constraints
Year 6:	upgrade to 2.14 MW (80-GeV) beam (technically limited schedule)

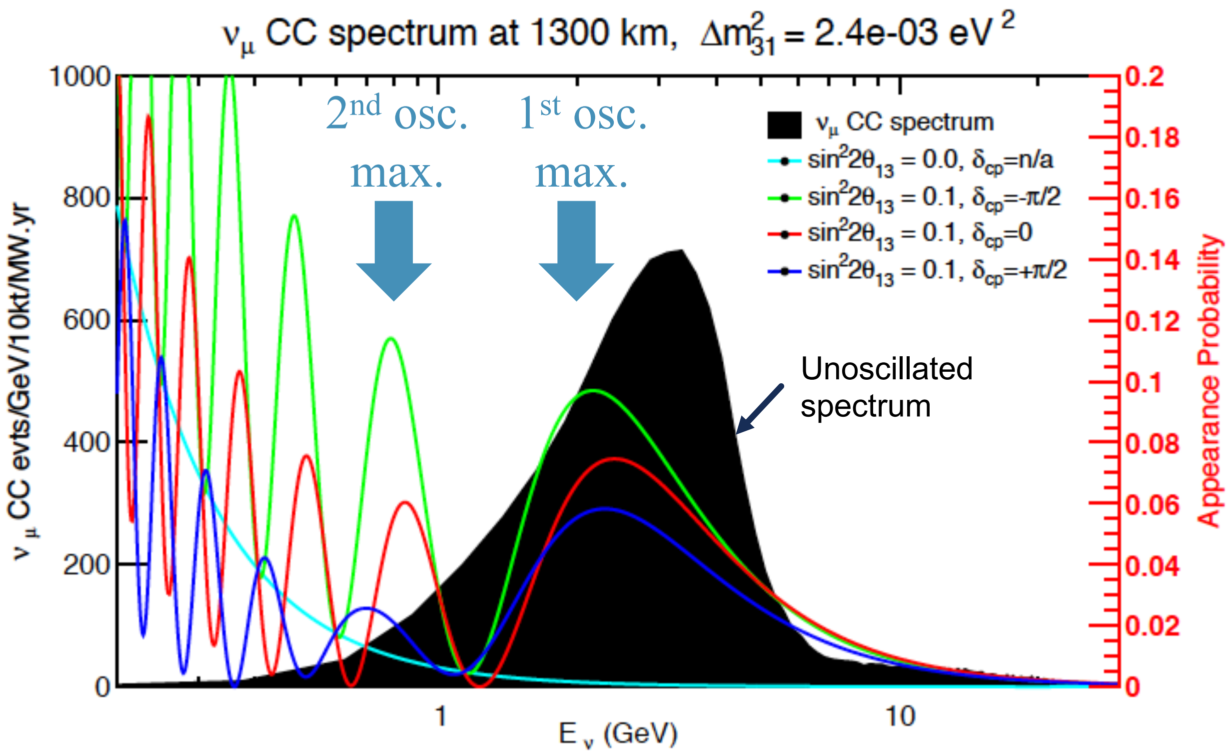


In total:
4 x 10kton FV LArTPC modules



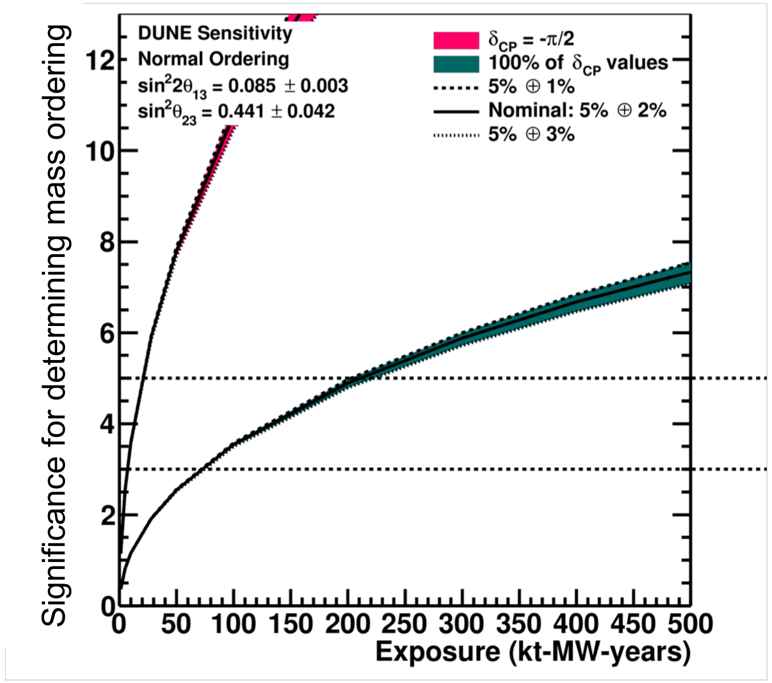
Interim Design Report (3 volumes)
https://arxiv.org/abs/1807.10334
https://arxiv.org/abs/1807.10327
https://arxiv.org/abs/1807.10340

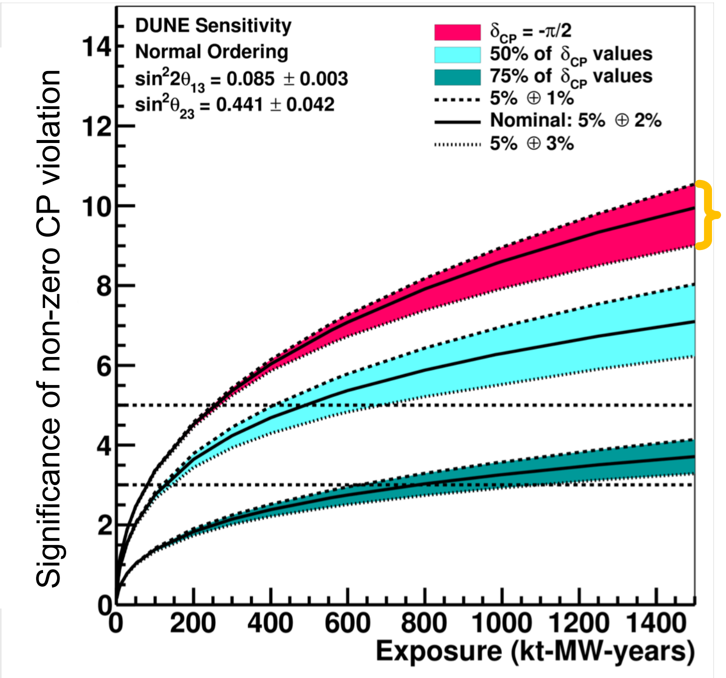
DUNE'S WIDEBAND NEUTRINO BEAM



- The DUNE Far Detector site will be on-axis of the neutrino beam
  - Broad energy spectrum
  - Measure CP violation by 2 methods
    - Neutrinos vs. anti-neutrinos
    - Relative heights of first and second oscillation maxima give another handle
- Long baseline (1300 km) means more matter effect
  - Helps to separate effects in appearance probability
- Also possible to search for ν_τ appearance at higher energies
  - First time to directly observe all three species in one experiment

DUNE CP VIOLATION AND MASS ORDERING SENSITIVITY





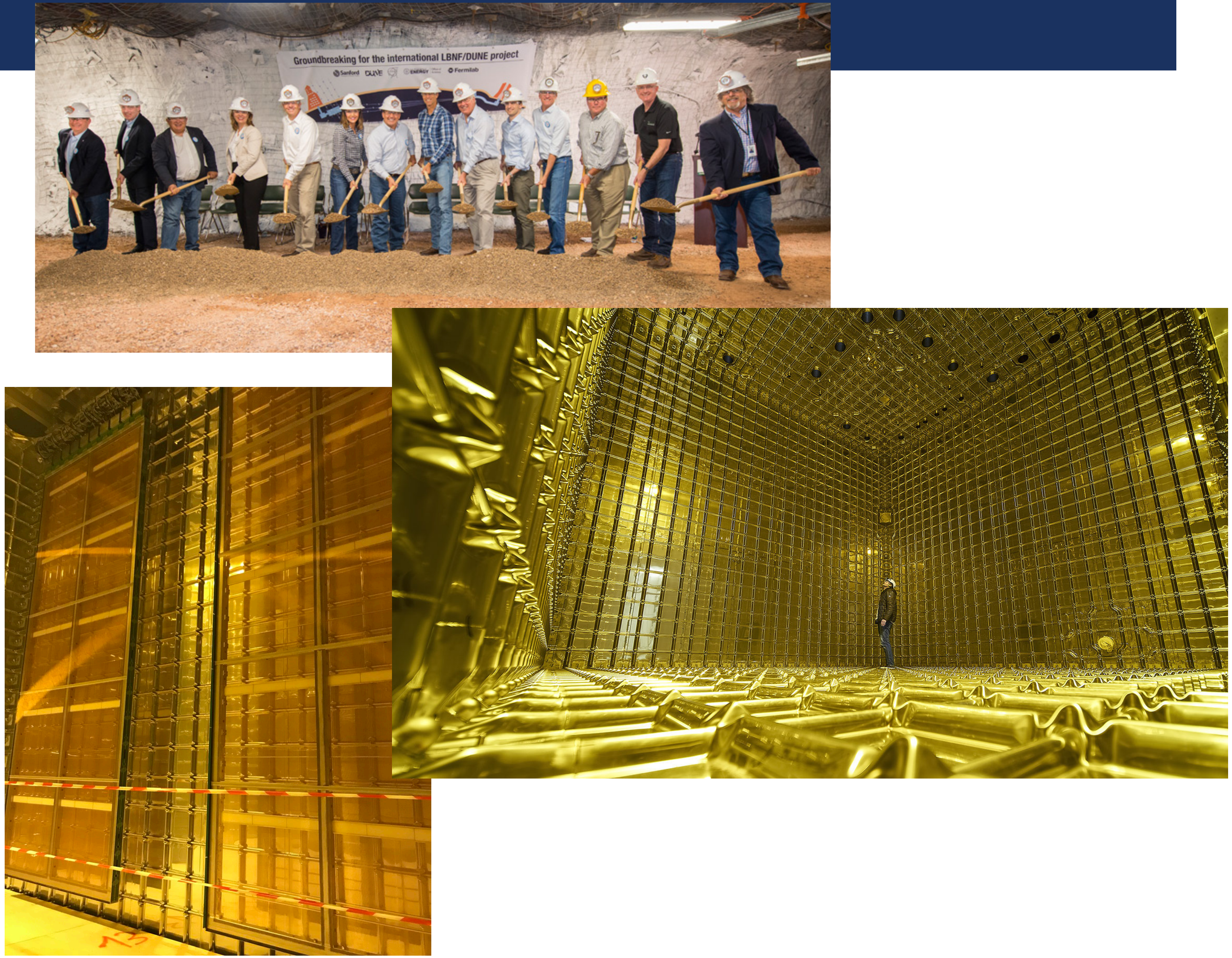
1-3% ν_e normalization uncertainty

Note: sensitivities depend strongly on the true values in Nature.

- Earth matter effects cause a large asymmetry (40% w/o CP violation) in ν and anti-ν oscillation probabilities
  - Larger than the maximum possible asymmetry from δ_{CP}
  - DUNE will be able to resolve mass ordering for all values of δ_{CP} and θ_{23}
- If $\delta_{CP} = -\pi/2$, DUNE will have a 5σ discovery of mass ordering after ~20 kton-MW-years
- After ~700 kt-MW-years, DUNE will be able to make a 5σ measurement for 50% of the possible δ_{CP} values (or sooner, if $\delta_{CP} = -\pi/2$)

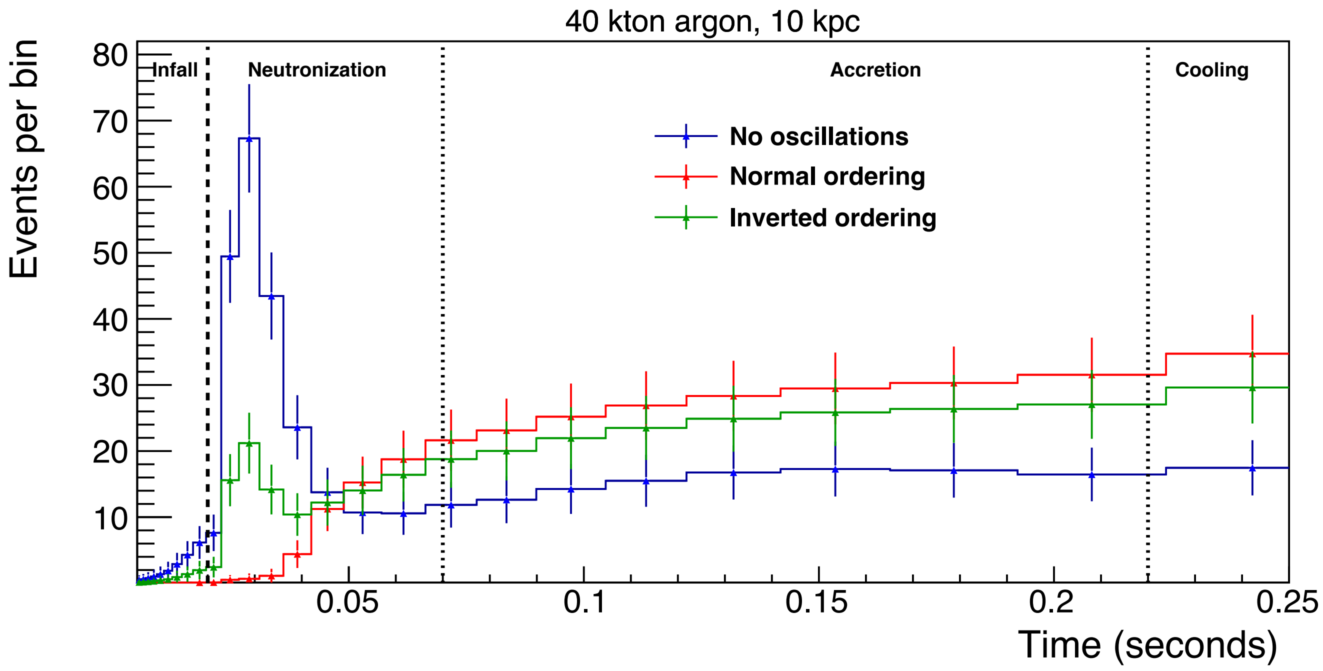
DUNE IS UNDERWAY!

- Groundbreaking was in 2017
- Pre-excavation construction work is ongoing in South Dakota
- The first large prototype detector (ProtoDUNE-SP) is operational and taking data at CERN
- The second prototype detector (ProtoDUNE-DP) is currently being assembled
- R&D is taking place around the globe



BROAD PHYSICS PROGRAMME

- **Supernova neutrinos**
  Very rich in supernova and particle physics
  DUNE & Hyper-K are complementary
  (DUNE sensitive to ν_e, HK sensitive to anti-ν_e)



- **Diffuse supernova neutrino background**
  Never observed!

- **Atmospheric neutrinos & proton decay**
  Large exposures, low background environments

- **Non-standard neutrino interactions**

- **Light sterile neutrinos**

- **Dark Matter**

- **As well as much more… and new ideas are welcome!**

SUMMARY

- The collection of neutrino experiments are making steady progress in testing the paradigm of three-flavor neutrino mixing and working to answer the remaining questions
- In the short term, if Nature has chosen favorable values, NOvA, T2K, and atmospheric neutrino experiments may determine the mass ordering and see hints of CP violation
- But the next generation of experiments is needed to complete the picture:
  - Mass ordering will be determined (no matter what are the true the values of δ_{CP} and θ_{23})
  - Measurement of CP-violating phase, δ_{CP}
  - Also hosting a rich experimental programme of non-oscillation physics

Thank you!