THE FUTURE OF NEUTRINO EXPERIMENTS

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FLORIDA STATE UNIVERSITY

DPF-PHENO 2024

Pittsburg - May 16, 2024

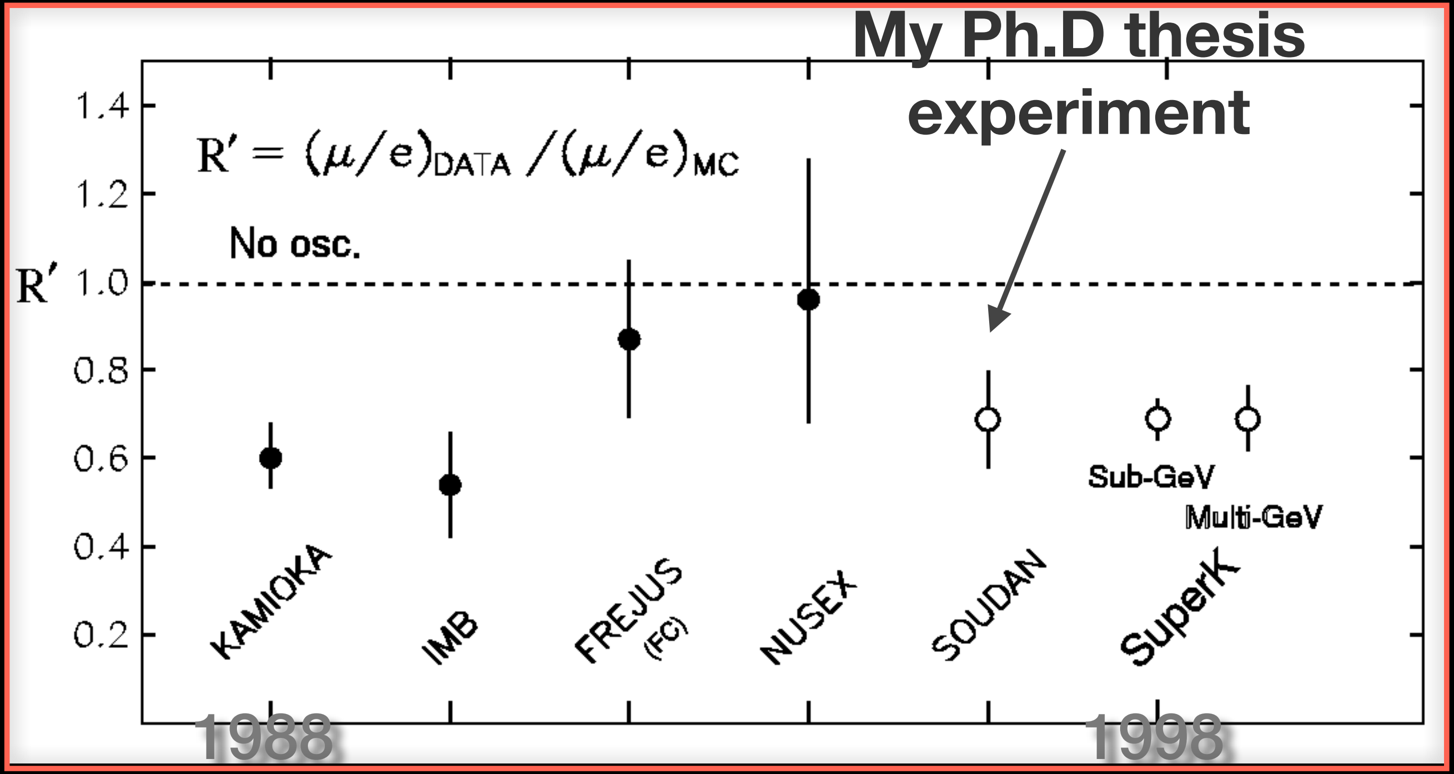
ELUCIDATING THE MYSTERIES OF NEUTRINOS

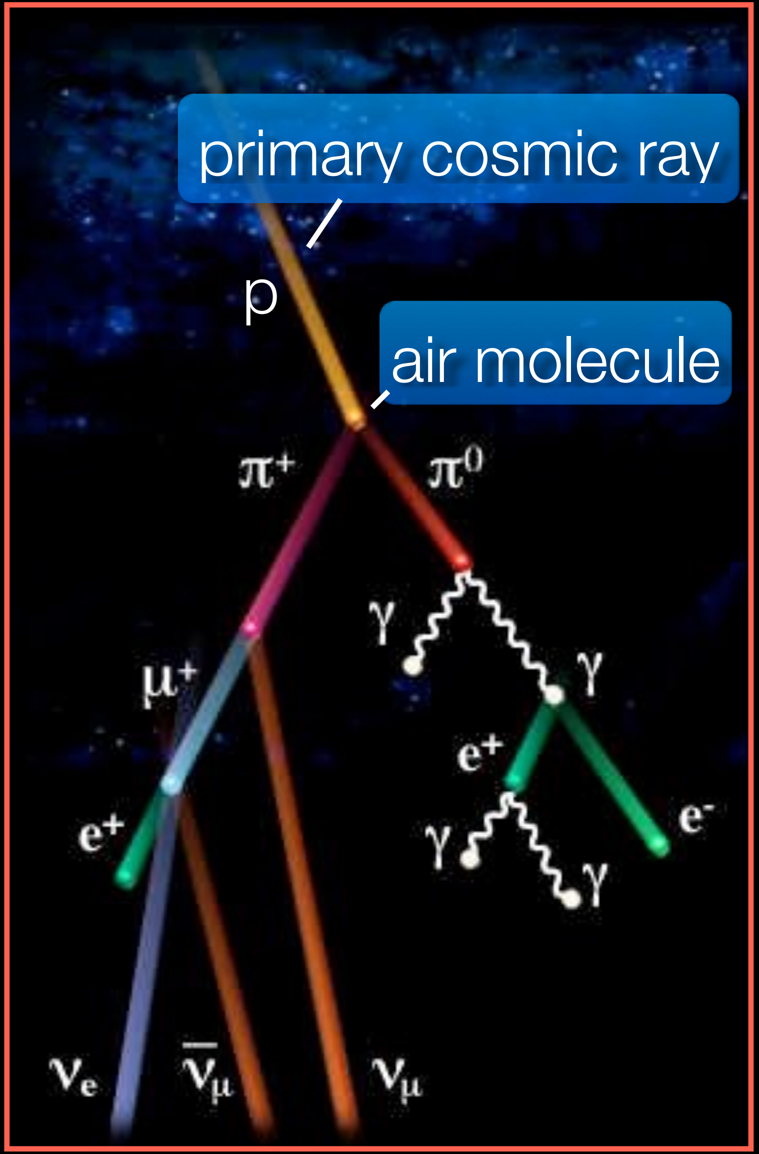
> "Neutrinos come in three types, or "flavors," which undergo quantum **oscillations**. Although the Standard Model can be augmented to accommodate neutrino mass and oscillations, we do not know in which specific way to extend the model. Moreover, different extensions make vastly different predictions about the birth of the universe. **We must further investigate the mysteries of neutrinos in order to explore the deep connections between their physics and the Standard Model."**

2023 P5 Report

THE DISCOVERY OF NEUTRINO OSCILLATIONS

- Atmospheric and solar neutrinos were where we first observed irrefutable evidence of neutrino oscillations.
- Since then we have used neutrinos from many different sources to corroborate and make precision measurements of the associated parameters.





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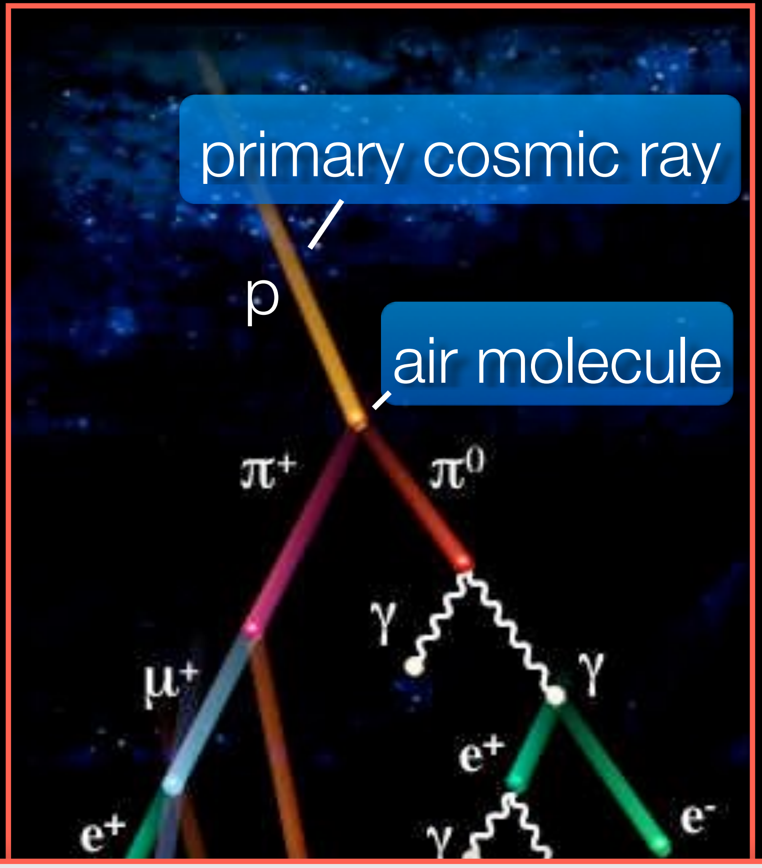
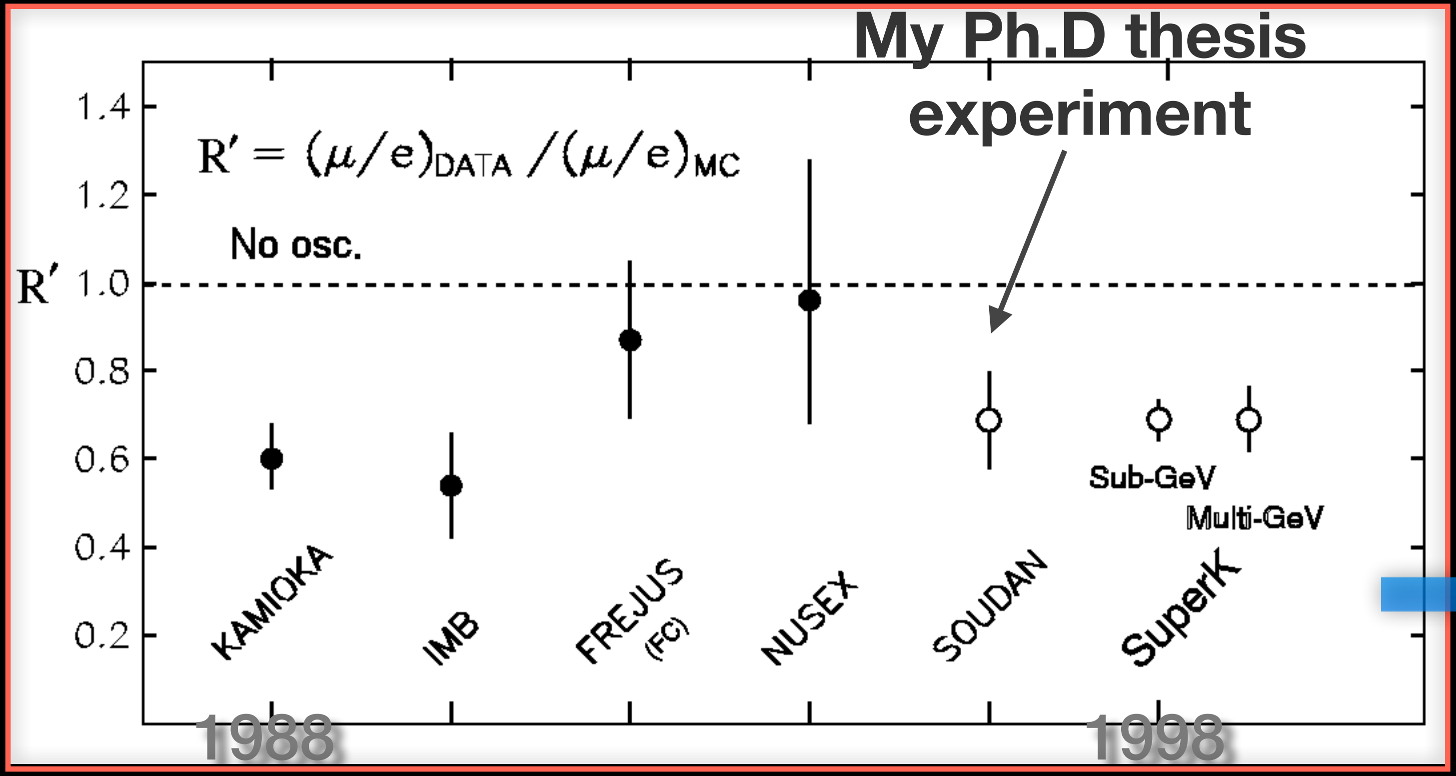
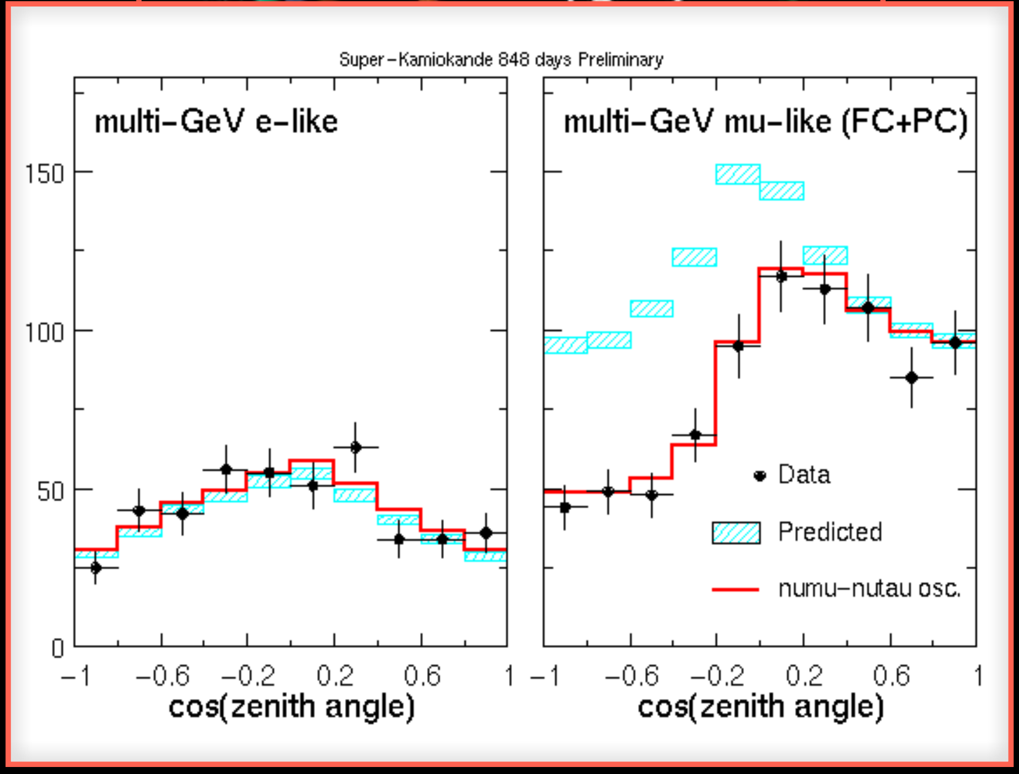



My Ph.D thesis experiment



WHAT DO WE KNOW ABOUT NEUTRINO OSCILLATIONS?

- There is a non-zero probability of detecting a different neutrino flavor than that produced at the source:

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_j U^*_{\beta j} e^{-i\frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

- Where the mixing matrix has 3 mixing angles and one phase (ignoring Majorana):

$$\mathbf{U} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric +	**Reactor** +	**Solar** +
Accelerator	**Accelerator**	**Reactor**
L/E 500 km/GeV	L/E 500 km/GeV	L/E 15,000 km/GeV

As in the quark case, the CP phase can be non-zero if all 3 angles are non-zero.

HOW WELL DO WE KNOW IT?

ATMOS LBL

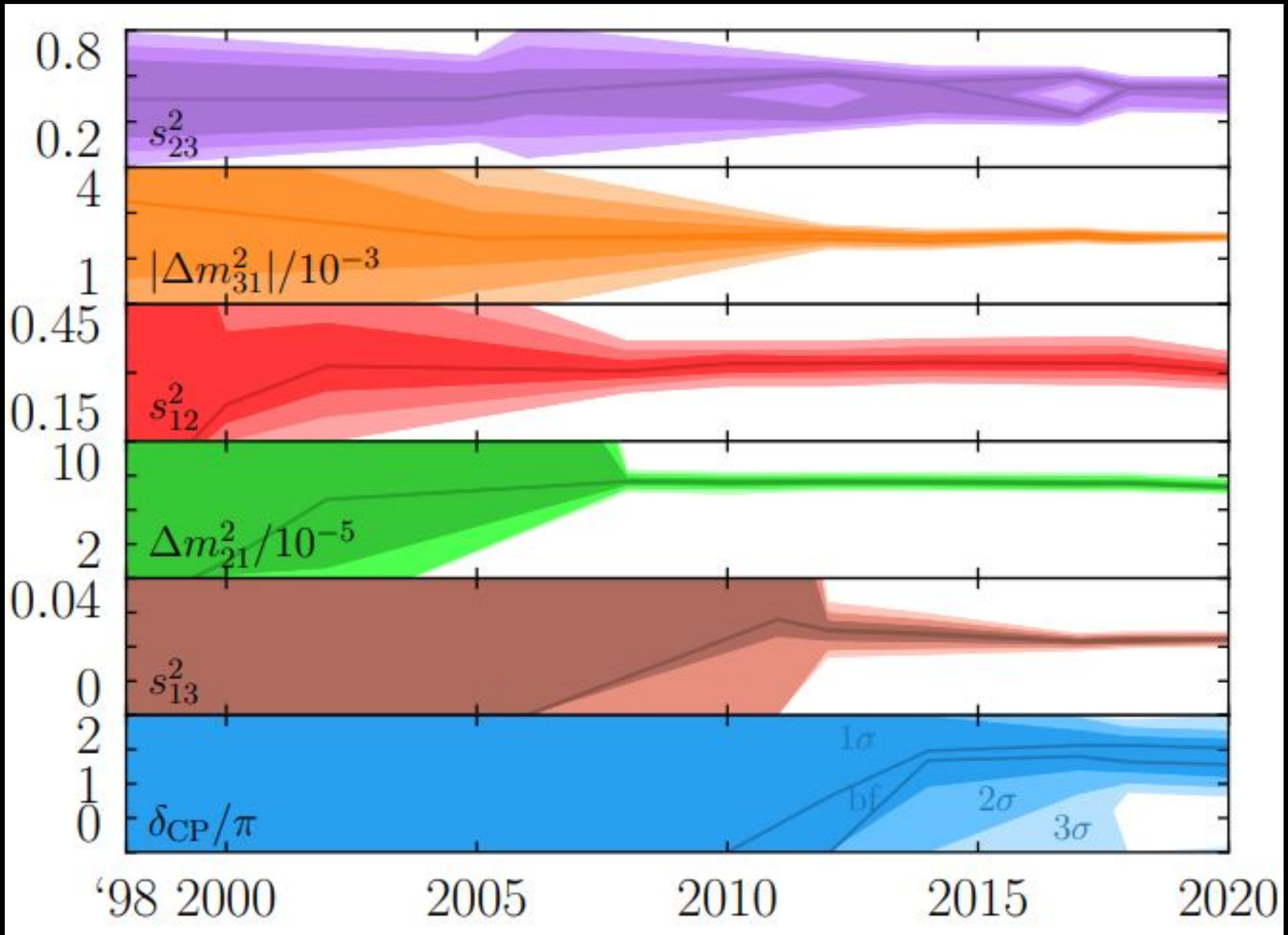
ATMOS LBL

SOLAR REACTOR

SOLAR REACTOR

REACTOR

LBL



(Snowmass: NF01 Topical Group Report)

known to

(5%)

(1.2%)

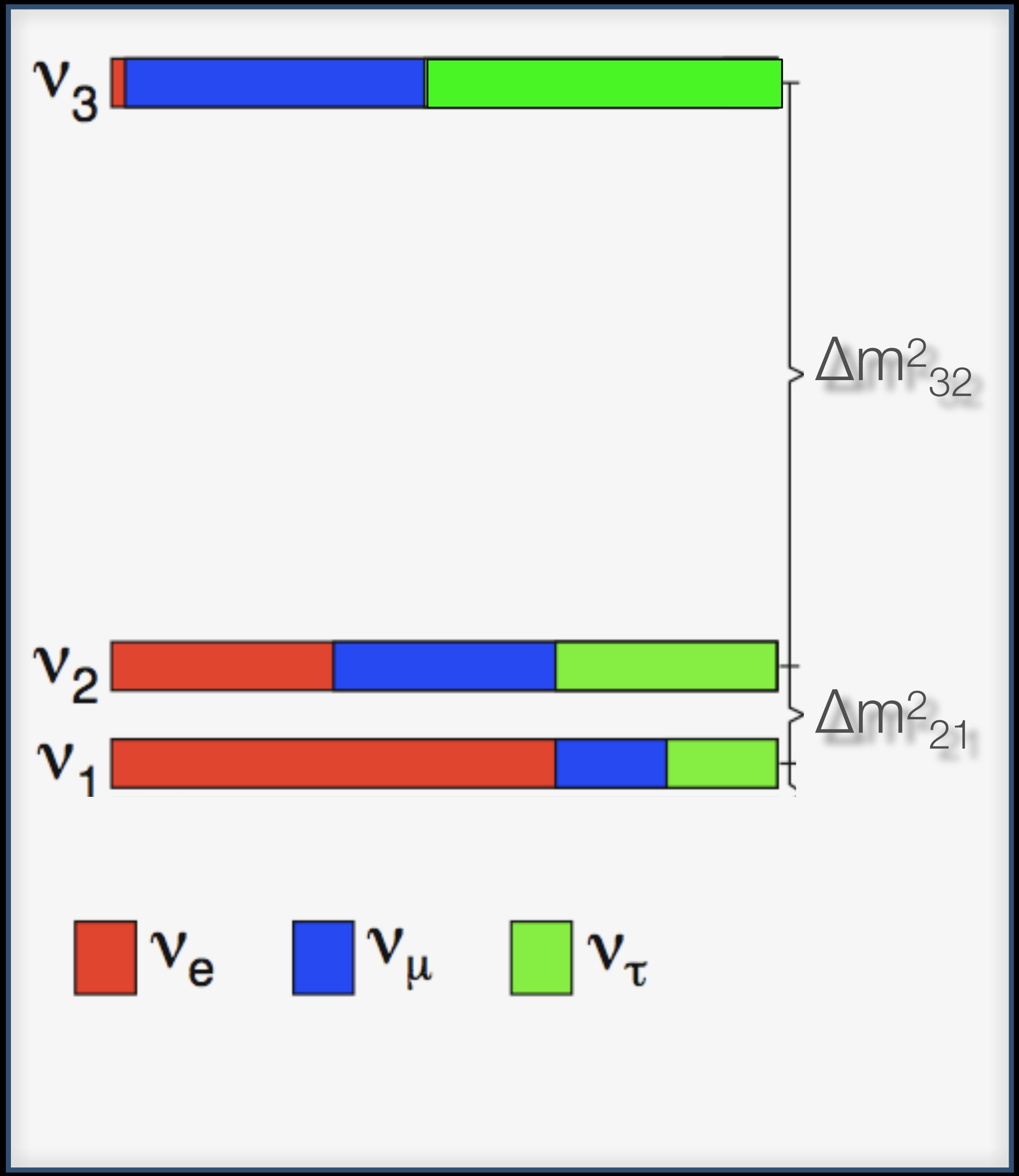
(4%)

(2.4%)

(2.7%)

- Most mixing angles and mass differences have been measured using more than one experimental technique.

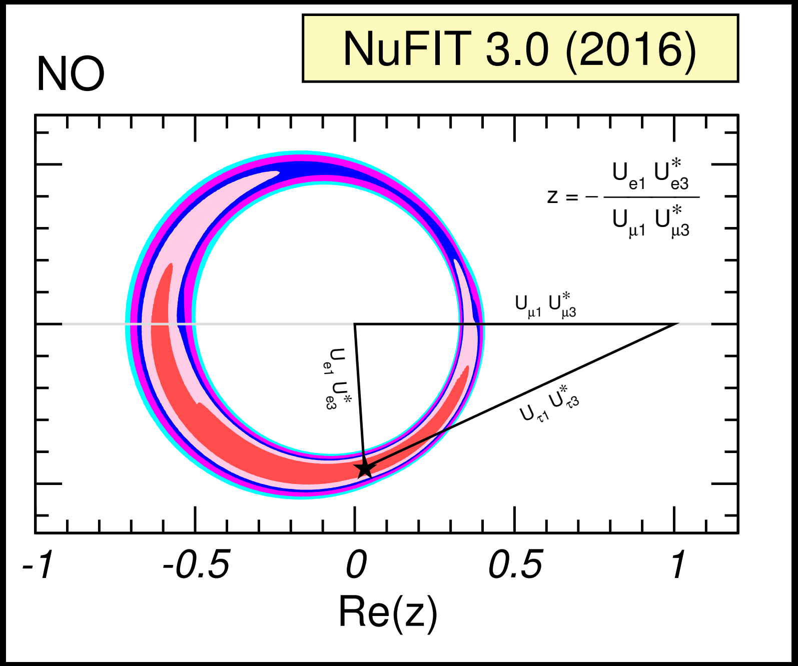
WHAT DO WE NOT KNOW?



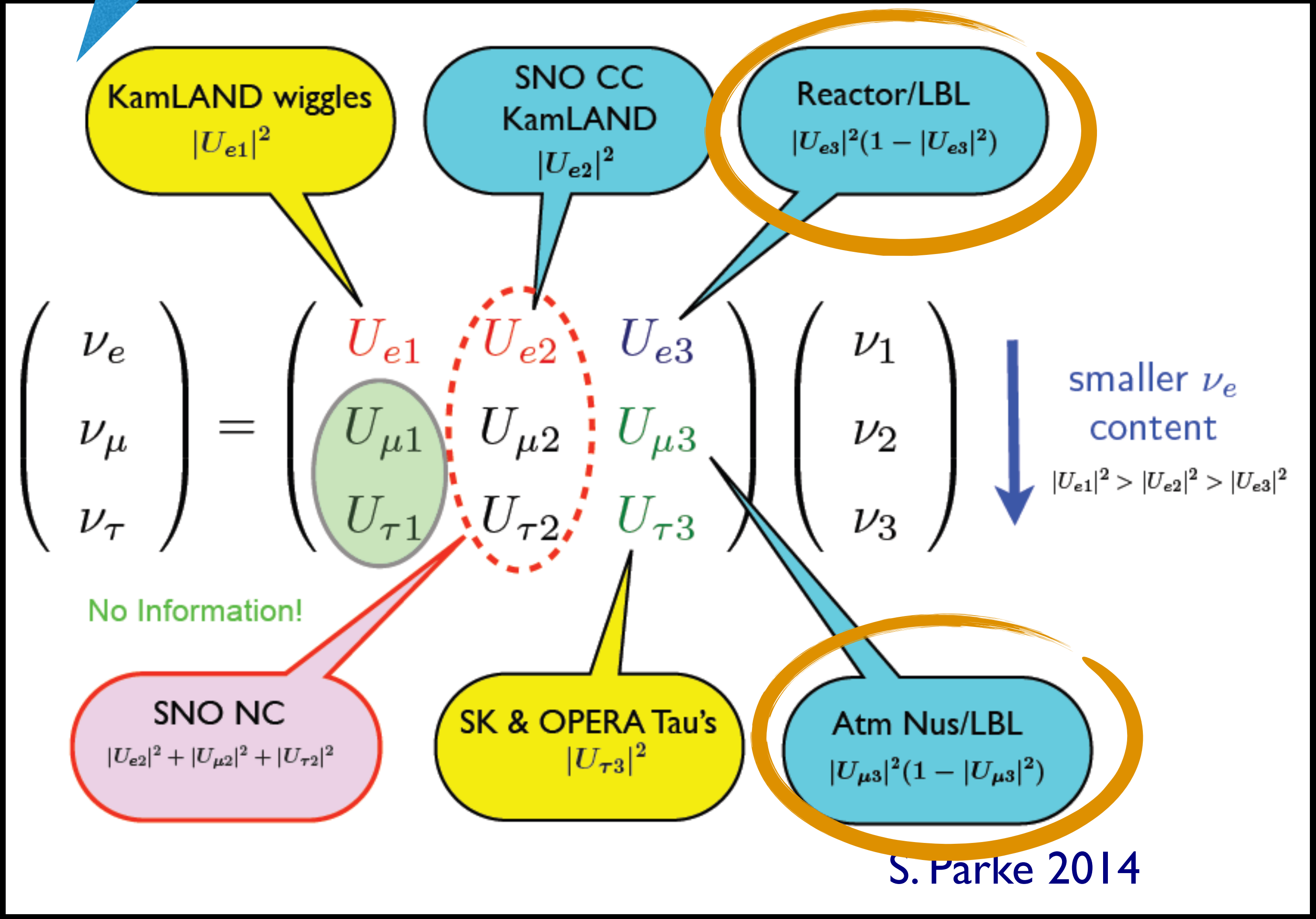
- CP violation in the lepton sector has NOT been measured.
  - May explain matter-antimatter asymmetry through leptogenesis.
- Mass ordering is NOT known for atmospheric neutrinos but known for the solar mass scale.
  - Important to be able to understand reach of experiments that study if neutrinos are Majorana or Dirac particles.
- The octant of the large mixing angle is not known!
  - In the case non-maximal mixing this uncertainty impacts our knowledge of mass hierarchy and CP violation.

REACTOR AND ACCELERATOR AS WELL AS ATMOSPHERIC NEUTRINO EXPERIMENTS SEEK TO ANSWER THESE!

HOW WELL DO WE WANT TO KNOW IT?



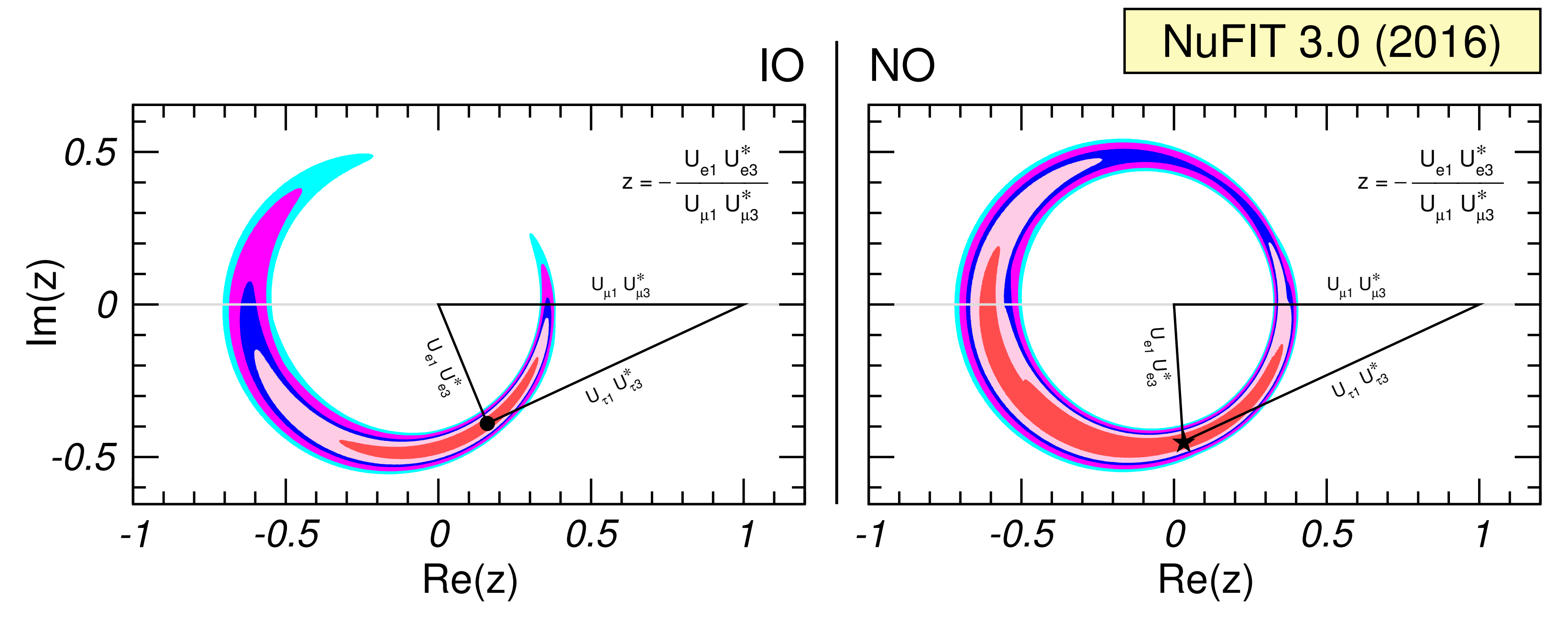
3 neutrino paradigm

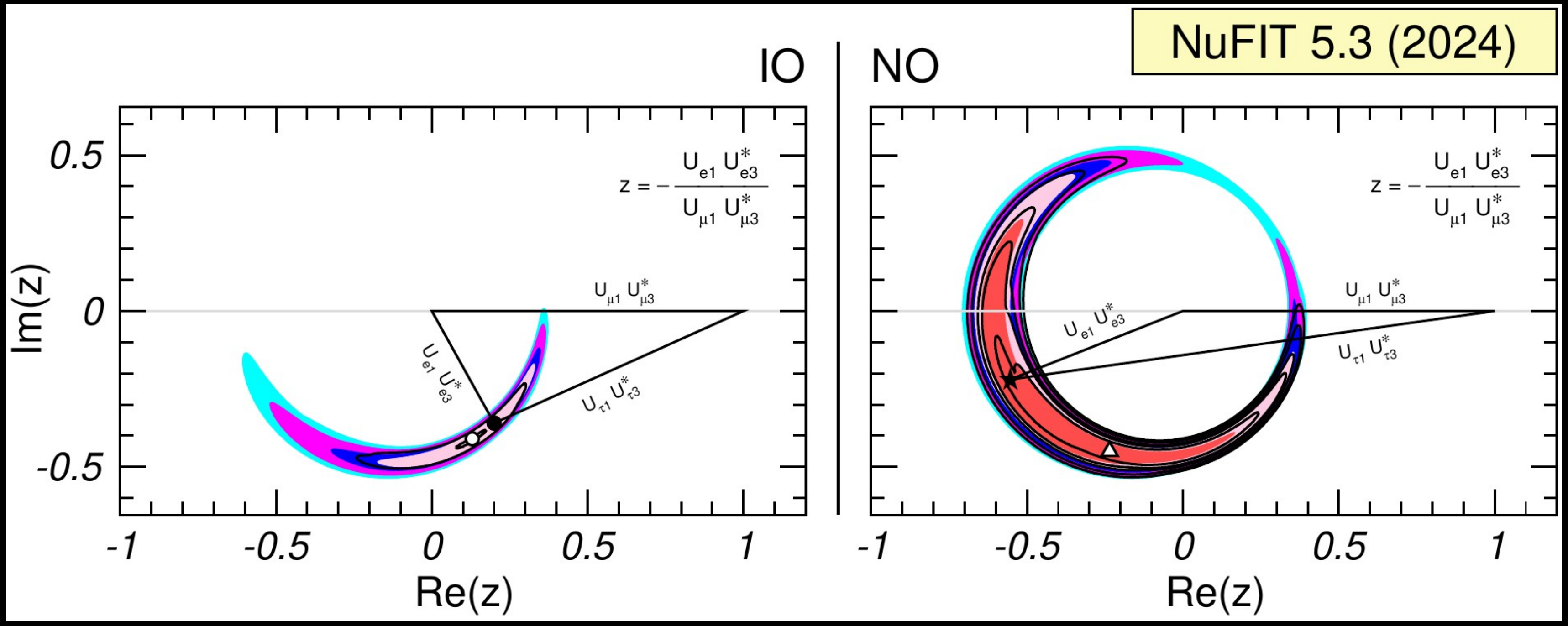


- Measuring the elements of the matrix with more than one technique is essential to paint the full picture of oscillations.

HOW WELL DO WE WANT TO KNOW IT?

8 years


NuFIT 3.0 (2016)


NuFIT 5.3 (2024)

One of the three leptonic unitarity triangle of the mixing matrix with unitarity imposed. 1σ, 90%, 2σ, 99%, 3σ CL (2 dof) allowed regions of the third vertex are drawn.

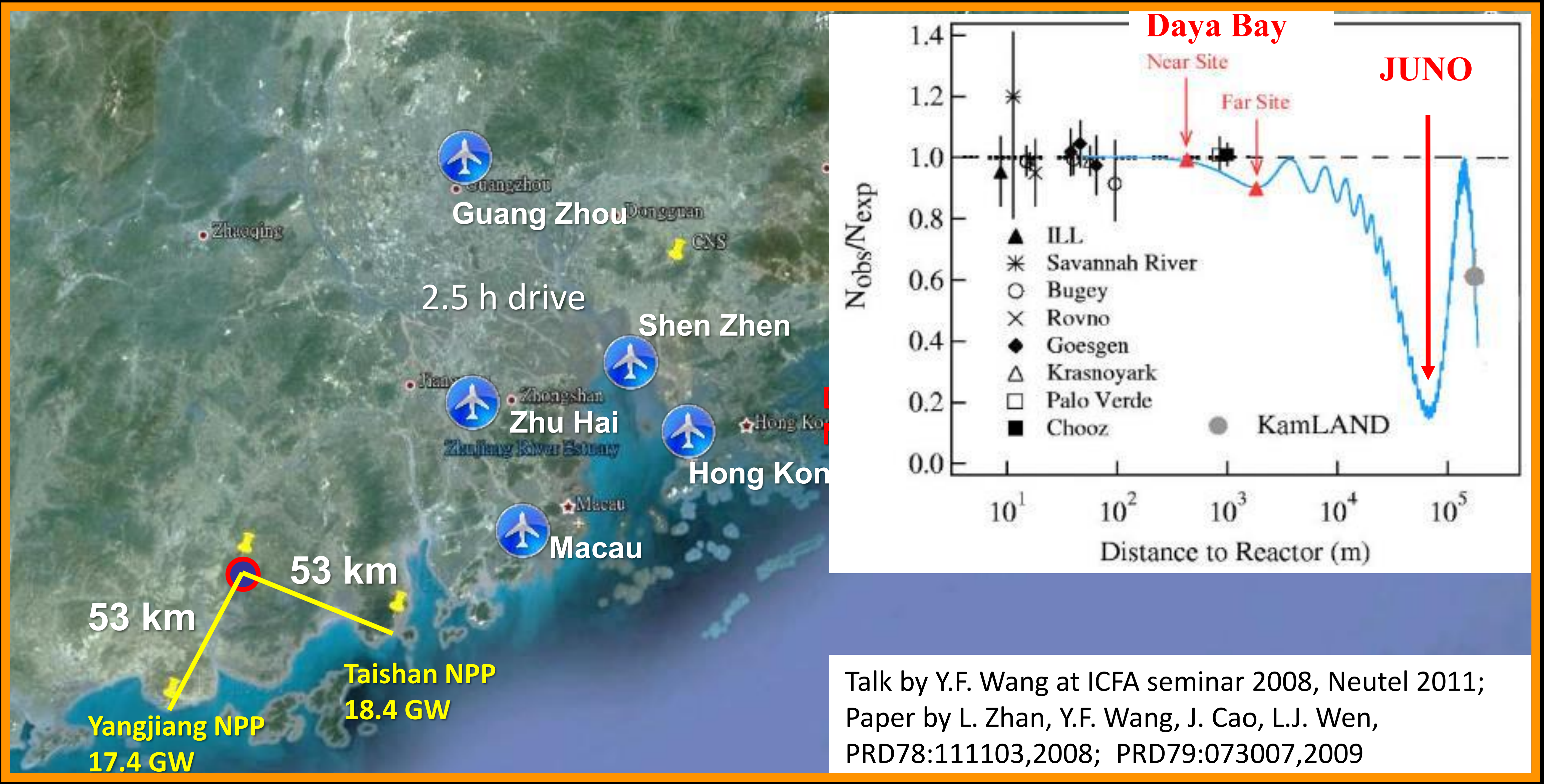
HOW DO WE MEASURE?

- We use neutrinos traveling different distances with different energy and from different sources: **reactor**, **accelerator**, atmospheric, and solar neutrinos.

- Experiments will have access to different elements of the PMNS neutrino mixing matrix.

    - These are precision tests in search of new physics!

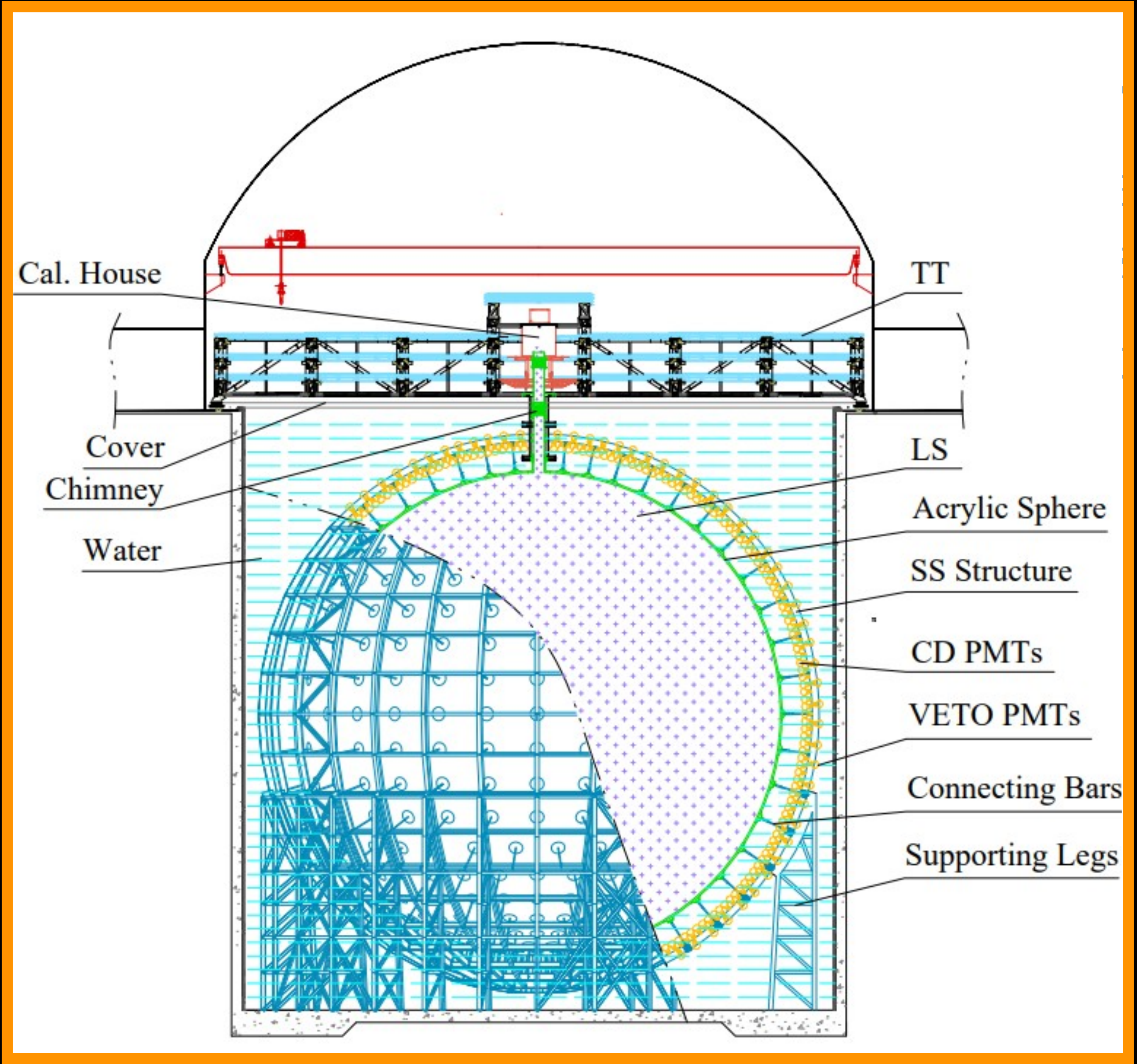
FUTURE REACTOR EXPERIMENT: JUNO



Talk by Y.F. Wang at ICFA seminar 2008, Neutel 2011; Paper by L. Zhan, Y.F. Wang, J. Cao, L.J. Wen, PRD78:111103,2008; PRD79:073007,2009

- Reactor experiments observe electron antineutrino disappearance in <1-100 km baselines. JUNO uses power plant nuclear reactors Yangjian and Taishan at 53 km in China.
- Sensitive to solar (θ_{12})and (θ_{13}) mixing angles and mass differences independent of CP violation.

FUTURE REACTOR EXPERIMENT: JUNO



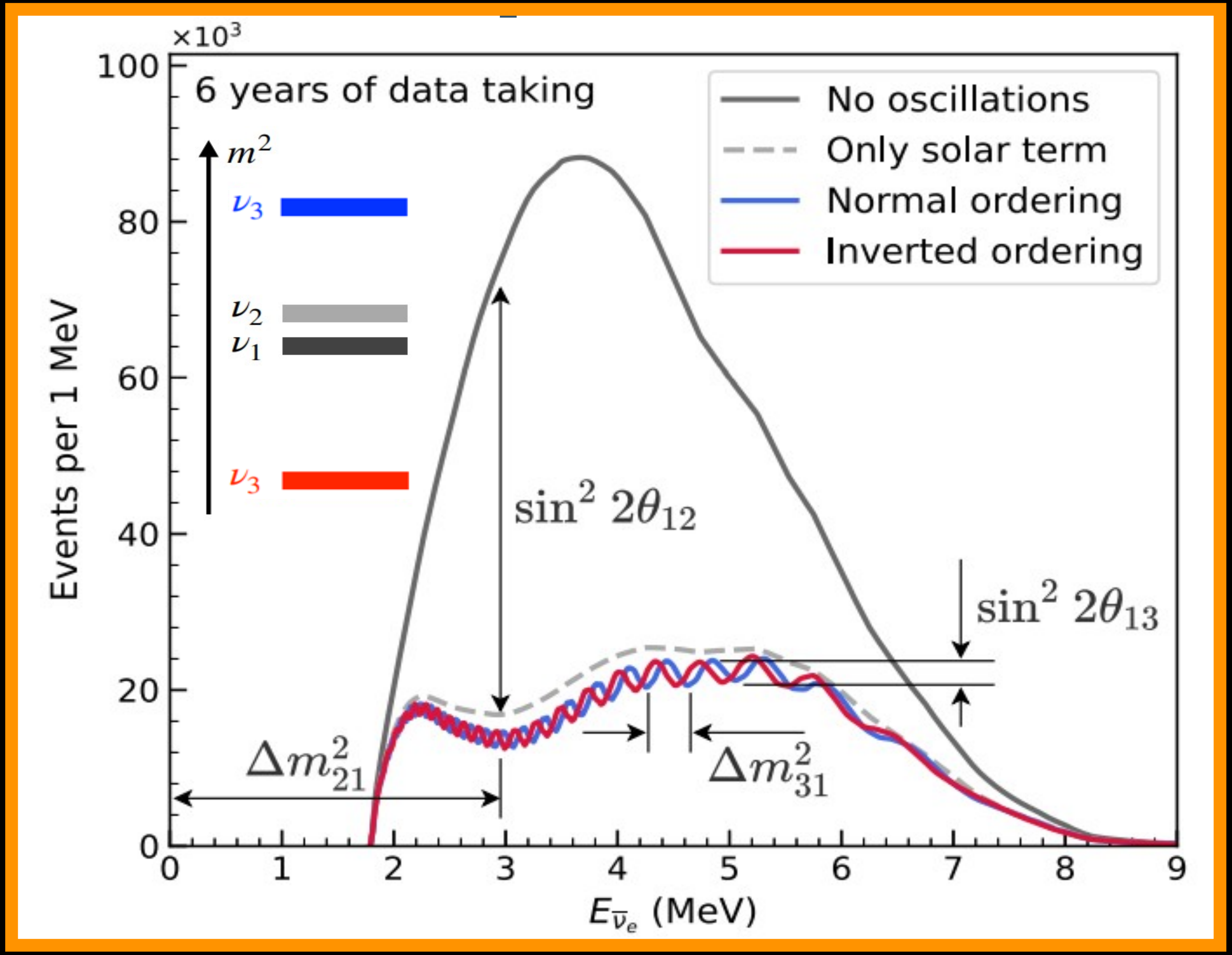
- 20kt liquid scintillator (LS) tank.
- ~20K 20" PMT and ~25K 3" PMT for 78% coverage.
- Ultra pure LS with attenuation length comparable to the tank radius.
- All low background materials.

- Civil construction completed. Expected to start data taking in 2025. Filled with water first late 2024.

FUTURE REACTOR EXPERIMENT: JUNO

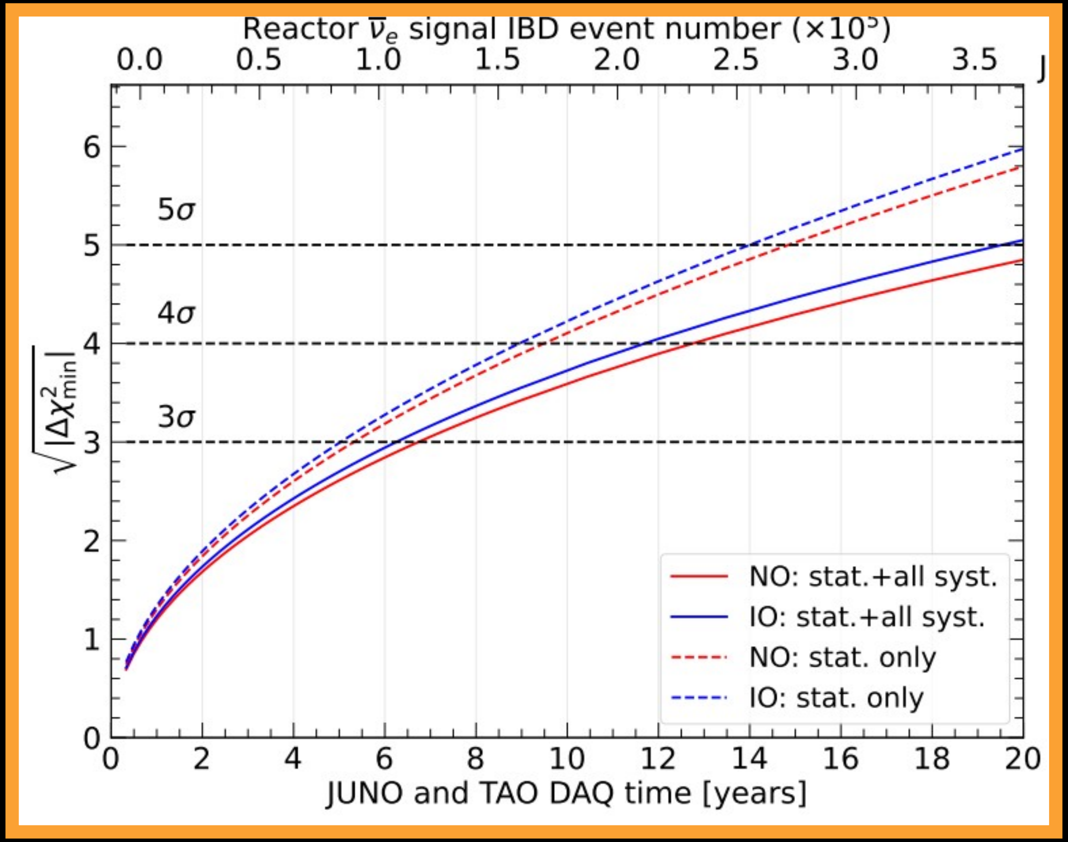
- Flux peaked at the oscillation maximum for the “solar" mixing angle θ_{12}.

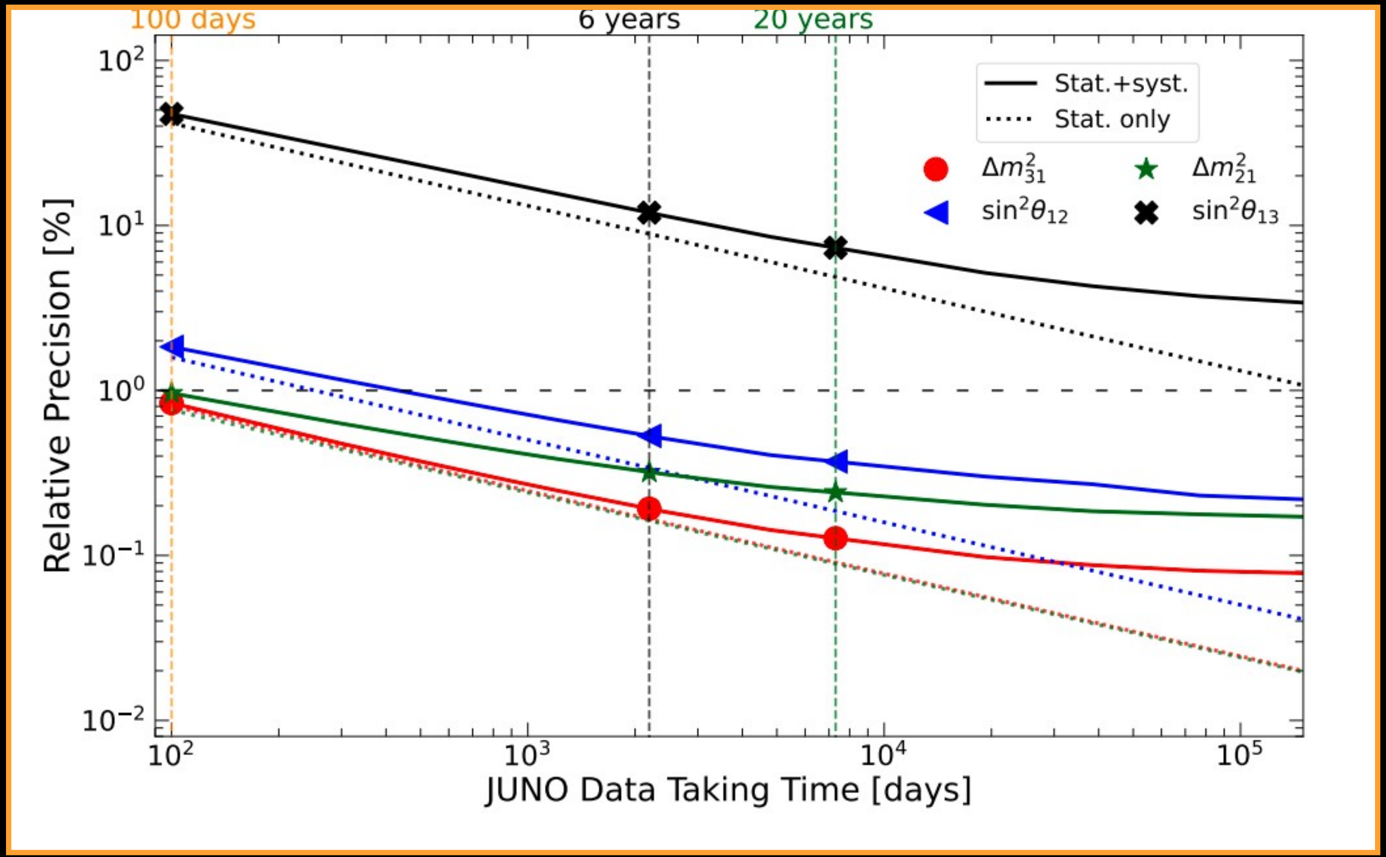
- The “atmospheric” parameters are responsible for the wiggles in the spectrum.
  - The frequency corresponds to Δm^2_{31} and the phase provides the mass ordering.



- Challenging measurement requires a 3% energy resolution at 1 MeV.

FUTURE REACTOR EXPERIMENT: JUNO

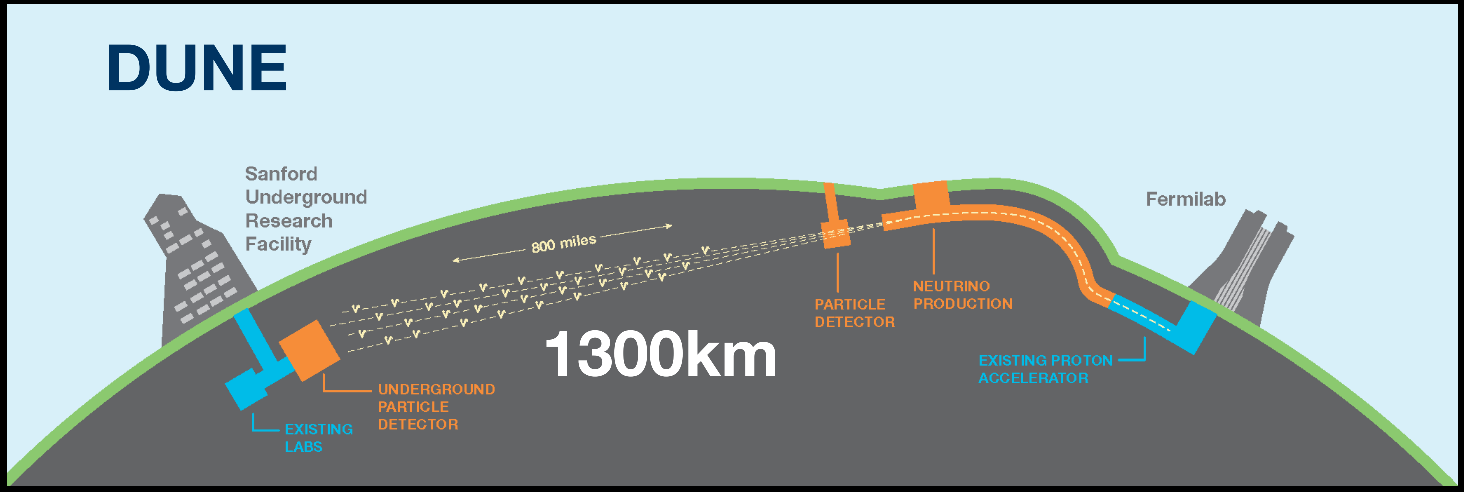


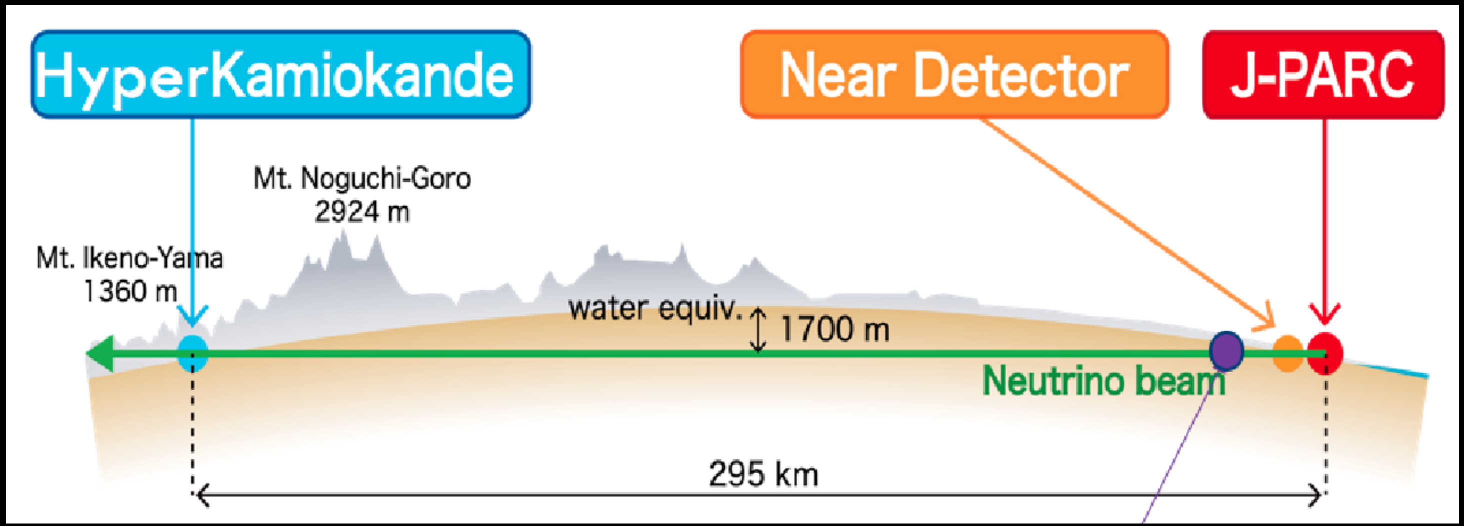


- 3 sigma mass ordering sensitivity at ~6 years of running with TAO (a reference detector).
- Expected to be better if combined with atmospheric neutrinos.
- Incredible precision (<0.5% in 6 years) for both mass differences (solar and atmospheric) and mixing angle 12.
- Far from systematic limited in the first decade.

FUTURE LONG-BASELINE EXPERIMENTS

- Higher intensity beams and larger mass to collect more neutrinos.
- High detector resolution for better background rejection.
- Highly capable near detectors to constrain systematic uncertainties from detector, flux and cross section.

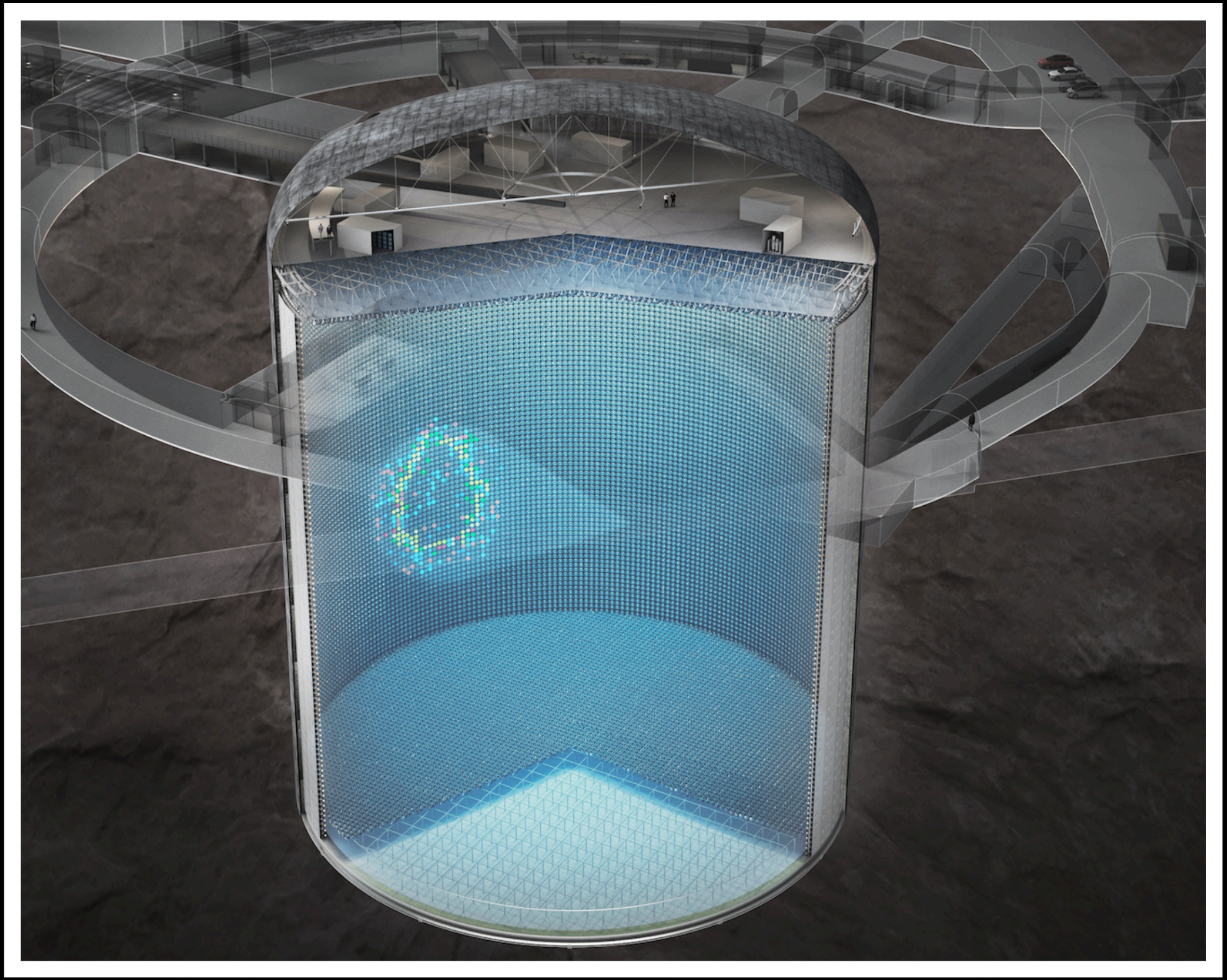




- Complementary programs in the US and Japan:
  - **very long** vs **shorter** baseline (different matter effects!)
  - **on axis** with broadband vs **off-axis** with narrow band beam

FUTURE LONG-BASELINE EXPERIMENTS: HYPER-K

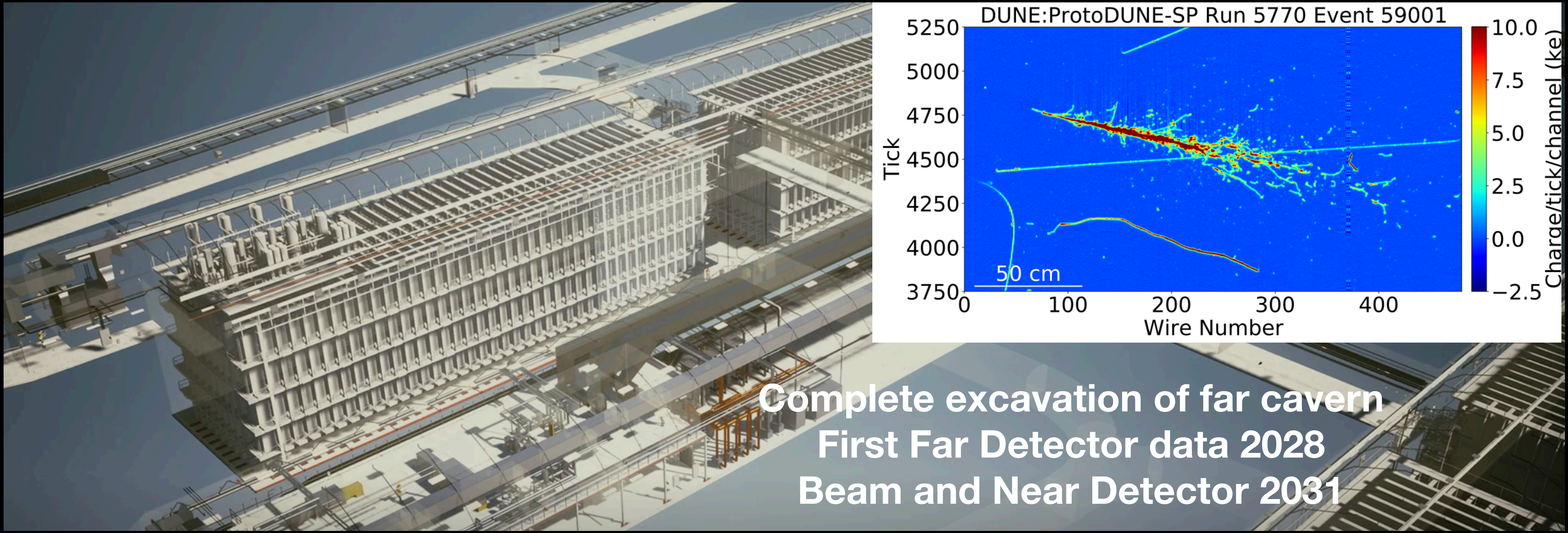
- Baseline 295 km with an off-axis beam peaked at 0.6 GeV.
  - Low beam energy, most events are quasi-elastic.
- Detector 258 kt, 8x Super-K. Very large mass for high statistics.
- Water Cherenkov detector with 20K 50cm PMTs and 1K multi-modules with 19 3” PMTs each.
  - Better coverage and calibrations than predecessor.



- Excavation of dome completed Oct 2023, barrel section is on-going. Expected to start data taking in 2027.

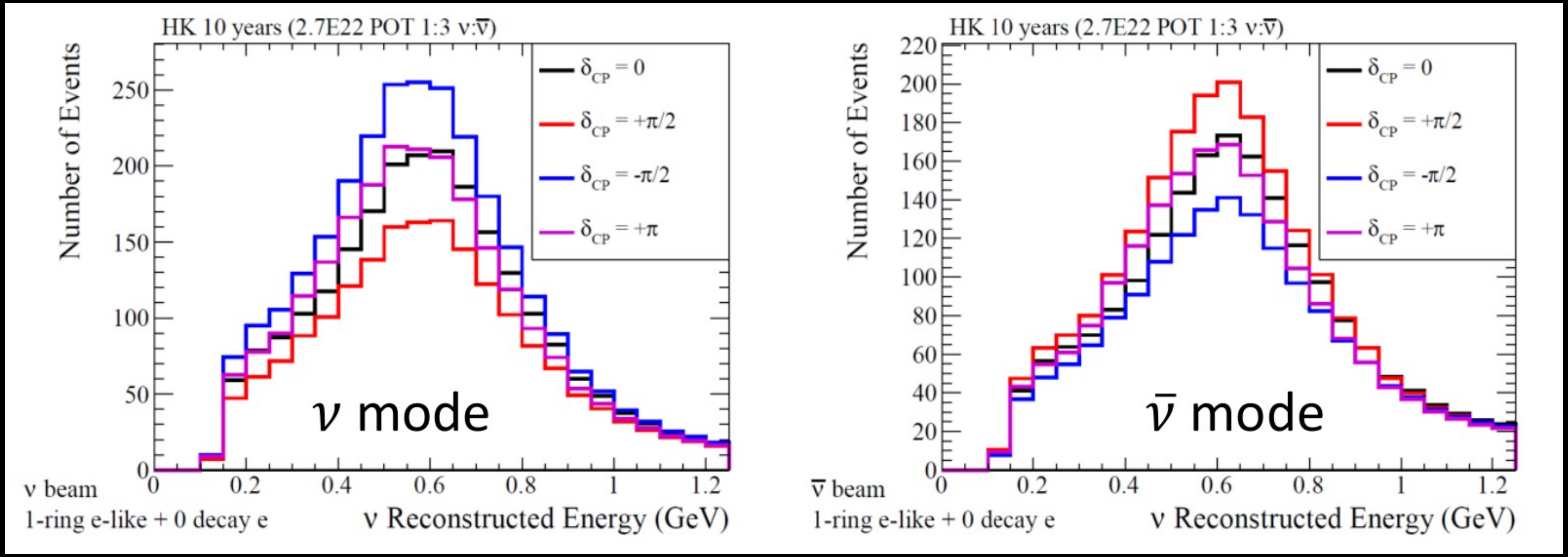
FUTURE LONG-BASELINE EXPERIMENTS: DUNE

- Baseline of 1300 km with a flux that spans the first and second oscillation maxima. Beam power > 2 MW. Planned for 40 kt in 4 modules.
- New Phase 2 plan builds 3 modules this decade with early deployment of the beam upgrades. Fourth module possible with expanded physics reach.
- Exquisite resolution liquid argon TPC detectors enable precise reconstruction over a broad range of interaction topologies from a higher energy beam.



Complete excavation of far cavern
First Far Detector data 2028
Beam and Near Detector 2031

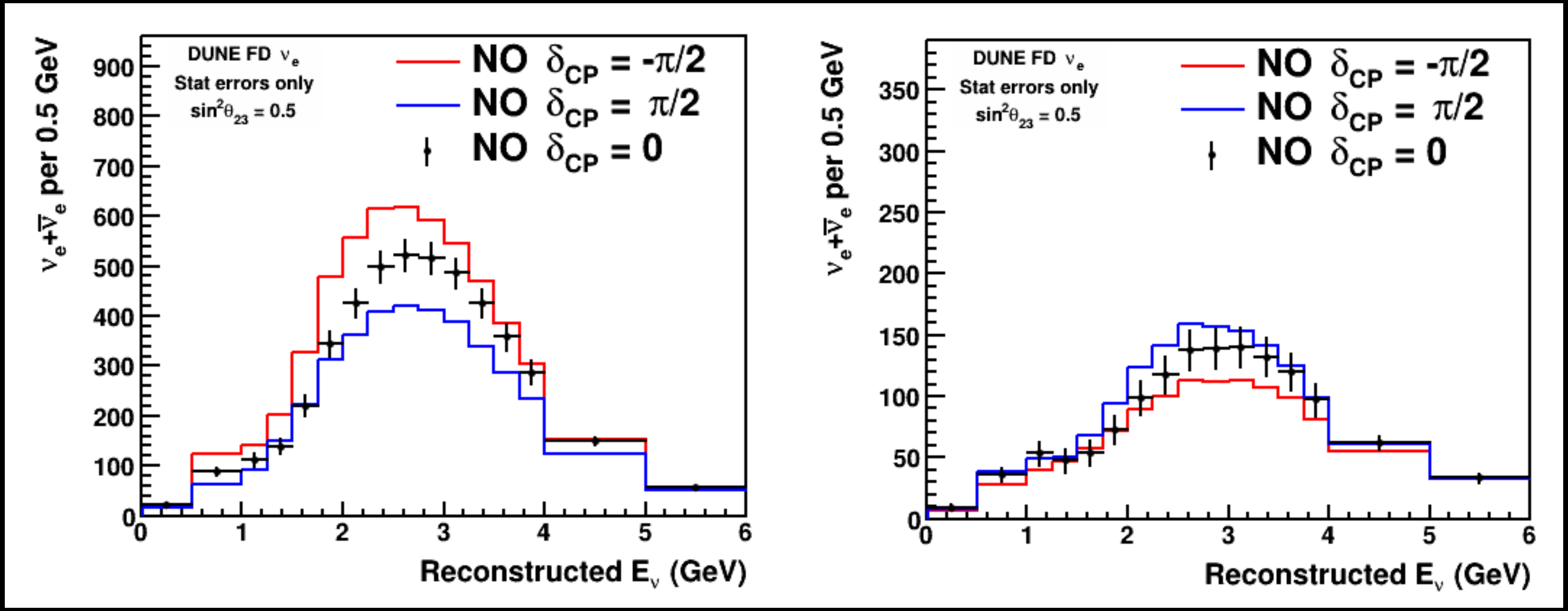
FUTURE LONG-BASELINE EXPERIMENTS: HYPER-K



C. Marshall APS 2024

- For CP violation of -π/2, Hyper-K (and DUNE) see an enhancement of ν_e appearance and a suppression of $\bar{\nu}_e$ appearance.
- Sensitive to δ_{CP}, mass ordering, θ_{23}, θ_{13} with different shapes in L/E.

FUTURE LONG-BASELINE EXPERIMENTS: DUNE



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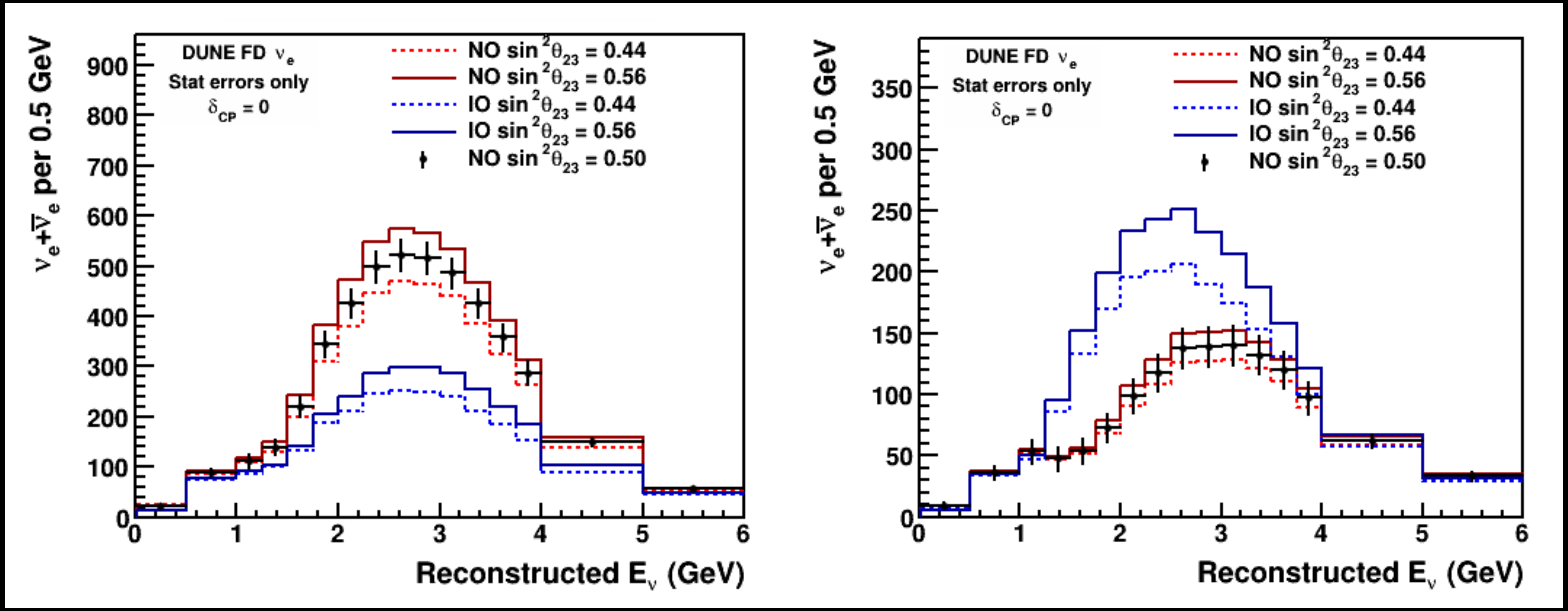

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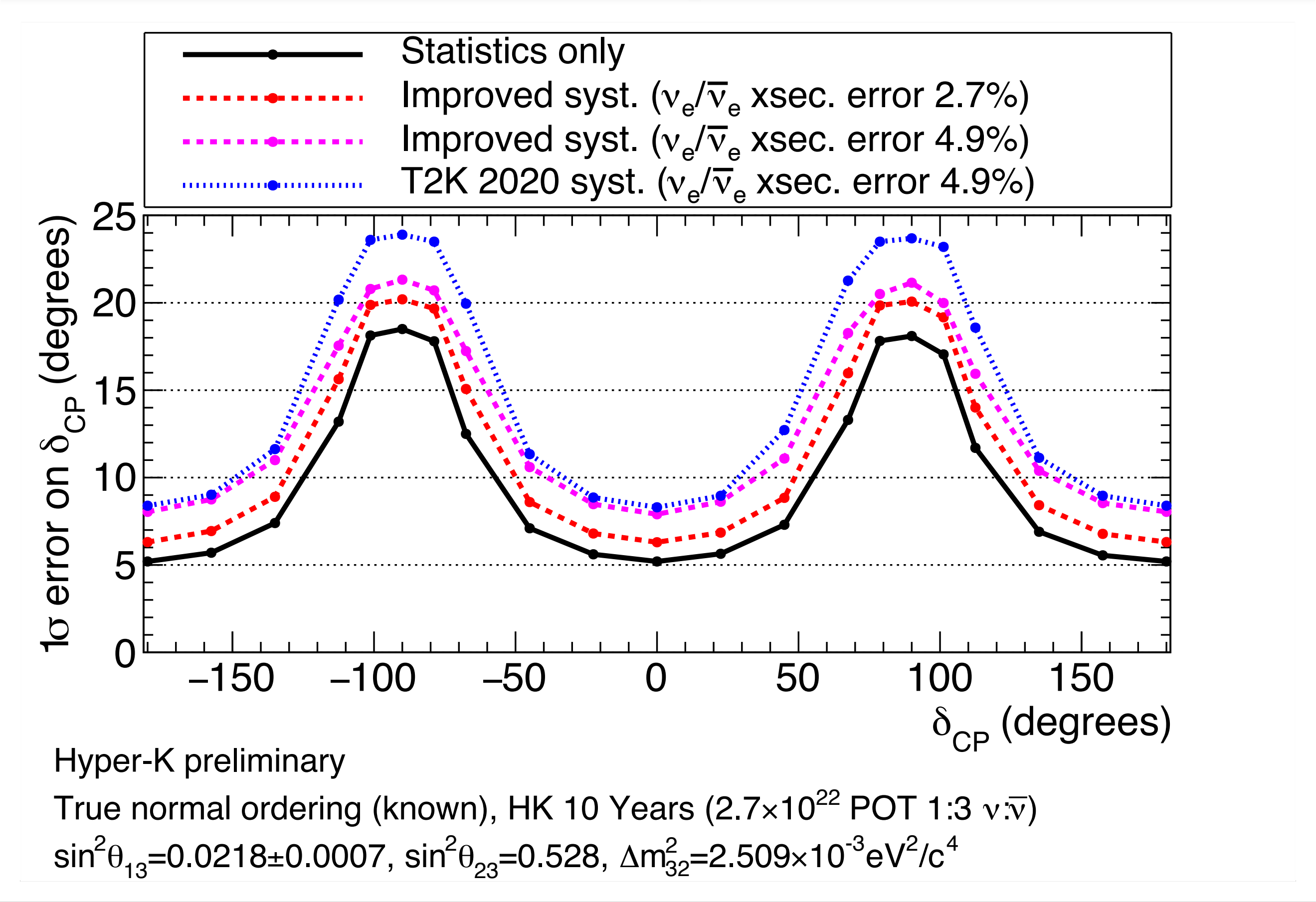
FUTURE LONG-BASELINE EXPERIMENTS: DUNE AND HYPER-K

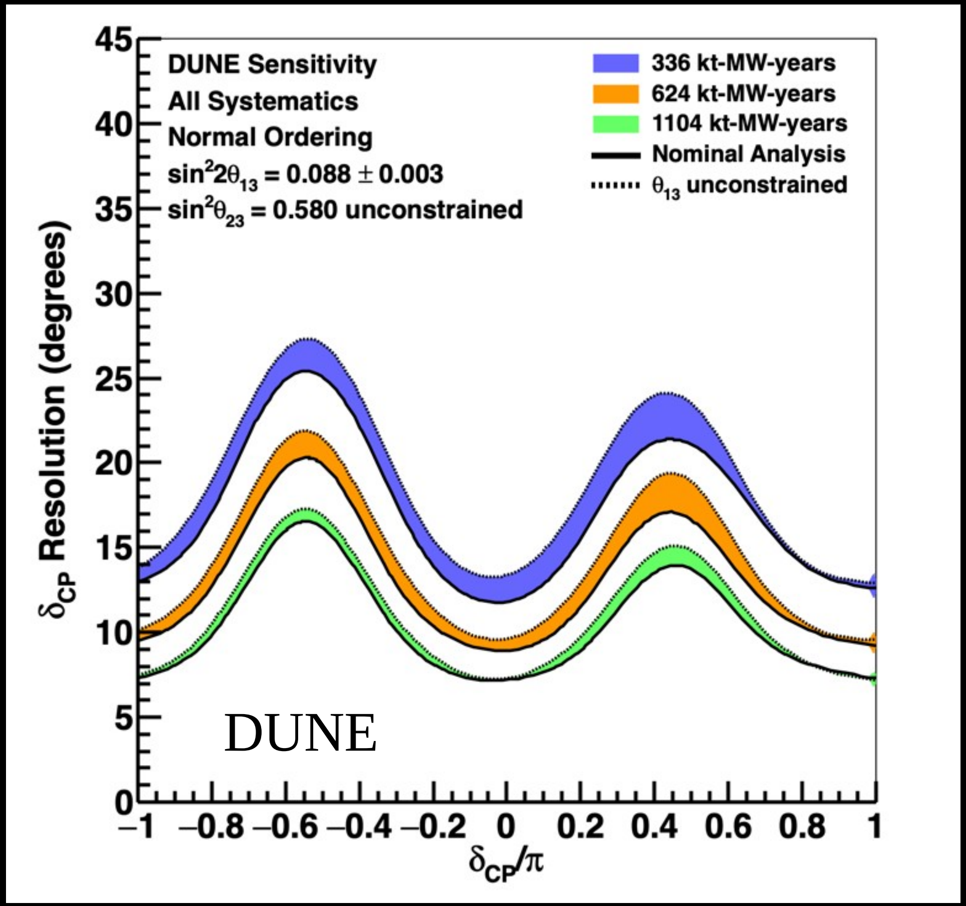
- Ultimate resolution to δ_{CP} is between 6-16°; best at 0 and π because at oscillation maximum we measure sin(δ).
- Hyper-K has better resolution at 0 due to higher peak statistics; DUNE has better resolution at ±π/2 due to broader spectrum away from oscillation maximum.



Hyper-K preliminary

True normal ordering (known), HK 10 Years (2.7×10^{22} POT 1:3 $\nu:\bar{\nu}$)

$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}\,\mathrm{eV}^2/c^4$



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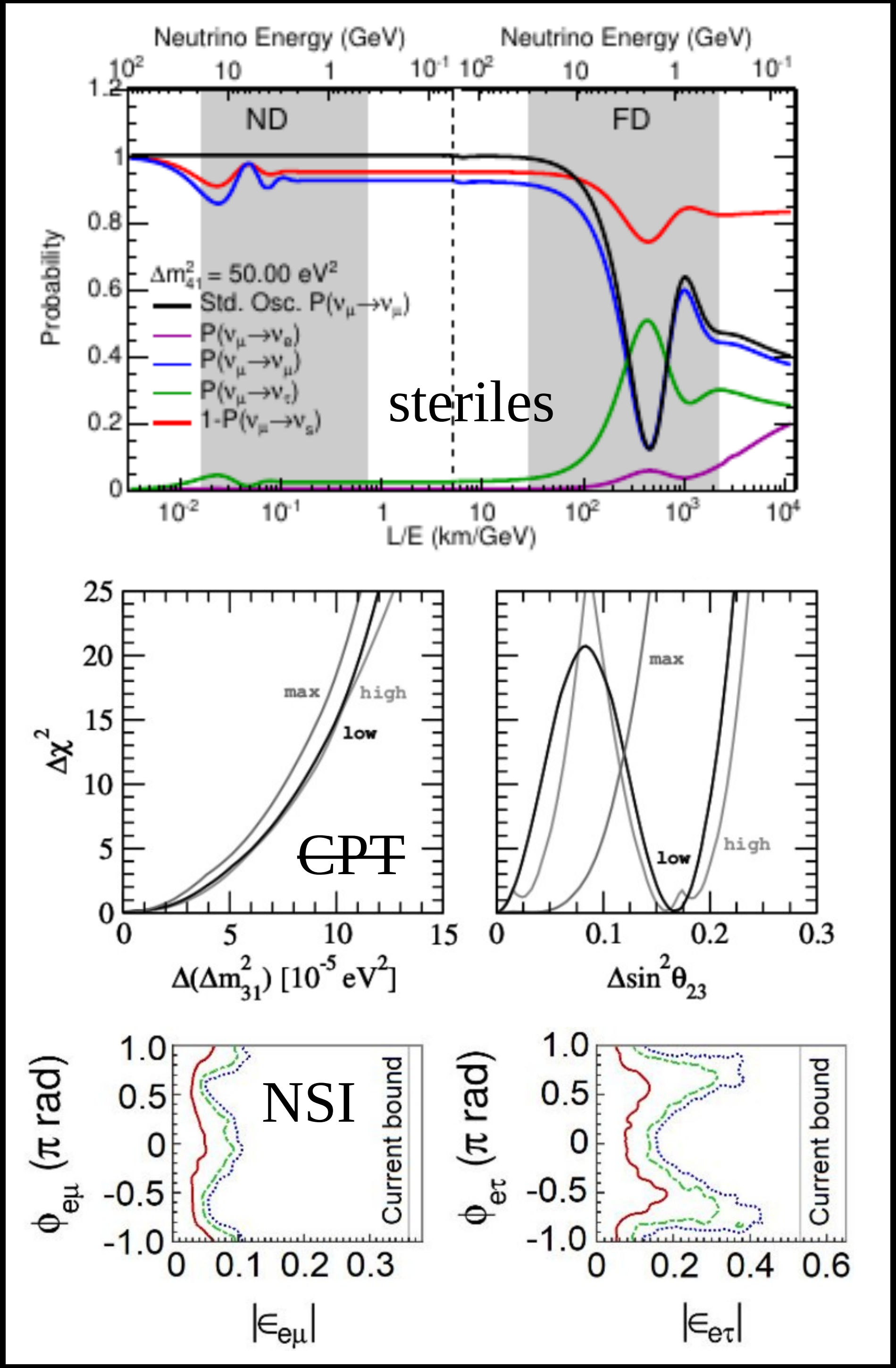
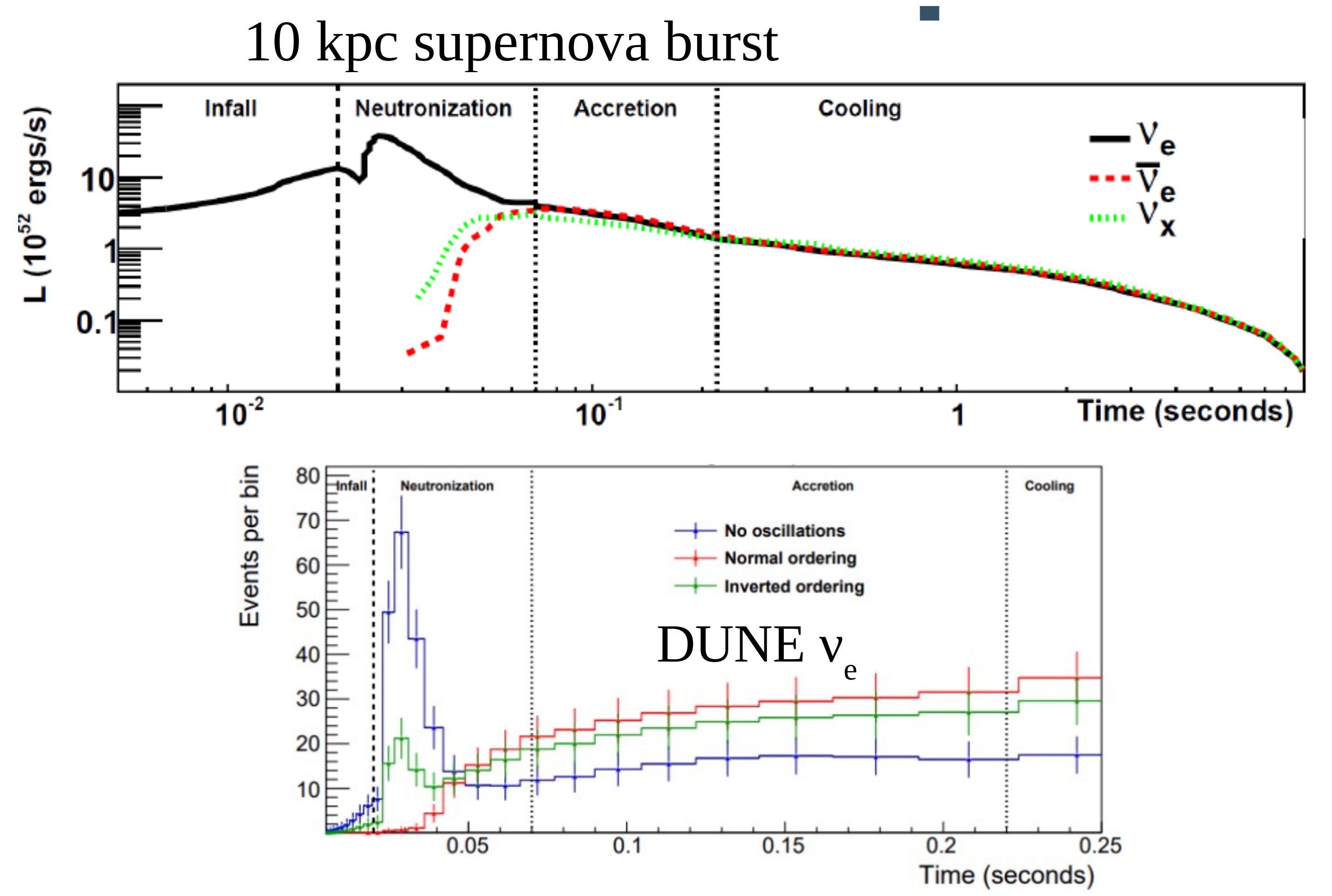
TESTING THE 3-FLAVOR OSCILLATION PARADIGM



C. Marshall APS 2024

- DUNE and Hyper-K can characterize a wide range of beyond 3-flavor oscillation effects:
    - Sterile neutrinos. For example DUNE covers a wide range of L/E at the Near and Far locations.
    - CPT violation would show as differences in the parameter for neutrinos and anti-neutrinos.
    - Non-standard interactions with matter could give rise to different effects between DUNE and Hyper-K.

SUPERNOVA NEUTRINOS



	ν_e	$\bar{\nu}_e$	ν_x
DUNE	89%	4%	7%
SK[1]	10%	87%	3%
JUNO[2]	1%	72%	27%

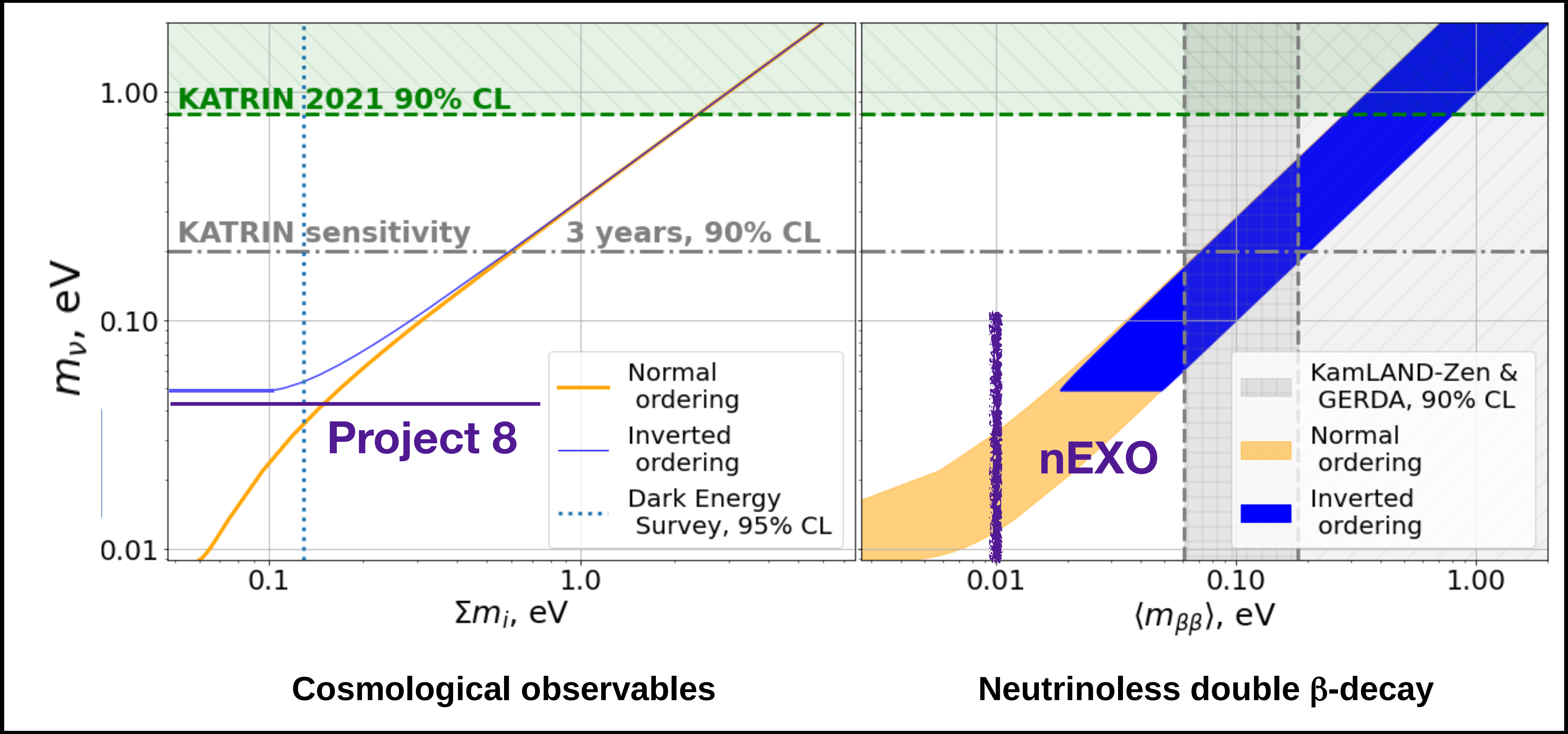
[1] Super-Kamiokande, *Astropart. Phys.* **81** 39-48 (2016)

[2] Lu, Li, and Zhou, *Phys Rev. D* **94** 023006 (2016)

- These experiments could see thousands of neutrinos from a galactic supernova burst.
- Each experiment is sensitive to a different type of neutrino enabling the study of the core collapse mechanism and the supernova evolution.

NEUTRINO MASS AND MAJORANA NEUTRINOS

- There are three ways to assess the neutrino mass scale (another thing we do not know!).
- Direct neutrino mass experiments such as Katrin measure the effective mass of electron neutrino based on kinematic parameters and energy conservation. Proposed experiment Project 8 aims to reach below the inverted ordering plateau.
- Neutrinoless double beta decay experiments seek to demonstrate neutrinos are majorana but also measure the effective majorana mass.



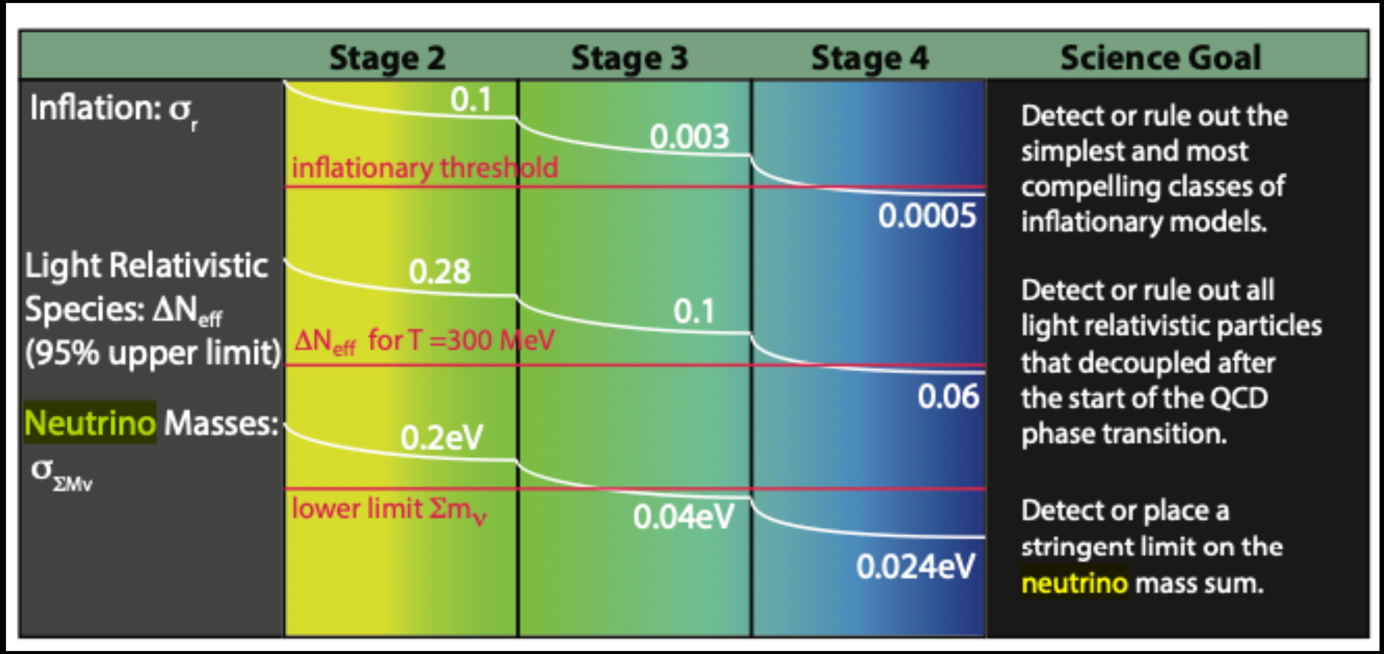
Cosmological observables **Neutrinoless double β-decay**

Alexey Lokhov Taup 2023

NEUTRINOS IN COSMOLOGY

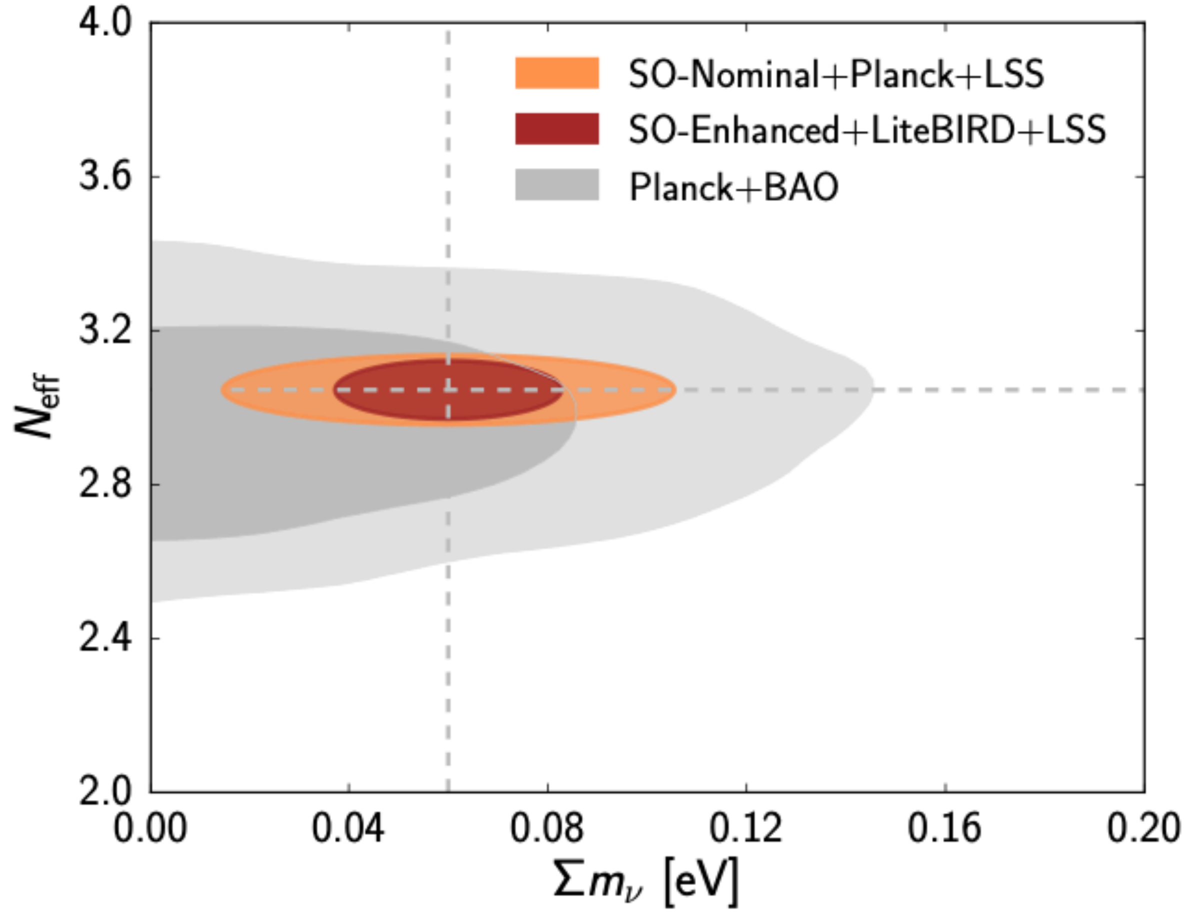
- Cosmology experiments, eg. Simon Observatory and CMB-S4, can provide measurements of **total sum of neutrino masses** and number of neutrinos and provide mass ordering preferences.

- See Z. Ahmed's talk from Wed.



	Stage 2	Stage 3	Stage 4	Science Goal
Inflation: σ_r	0.1	0.003	0.0005	Detect or rule out the simplest and most compelling classes of inflationary models.
Light Relativistic Species: ΔN_{eff} (95% upper limit)	0.28	0.1	0.06	Detect or rule out all light relativistic particles that decoupled after the start of the QCD phase transition.
Neutrino Masses: $\sigma_{\Sigma M\nu}$	0.2eV	0.04eV	0.024eV	Detect or place a stringent limit on the neutrino mass sum.

Chang et al. 2022, SNOWMASS, arXiv:2203.07638

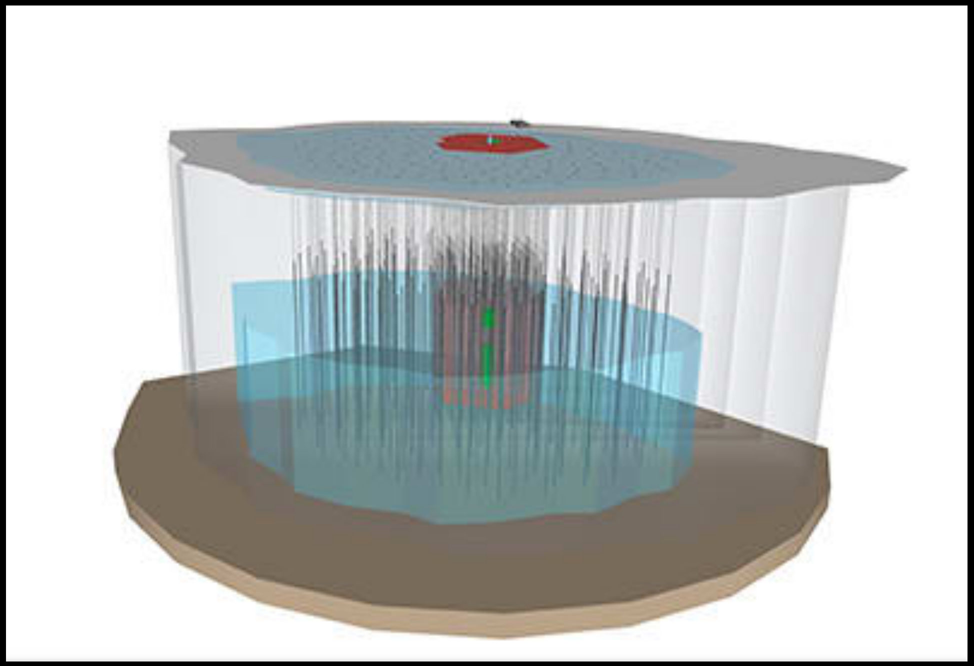


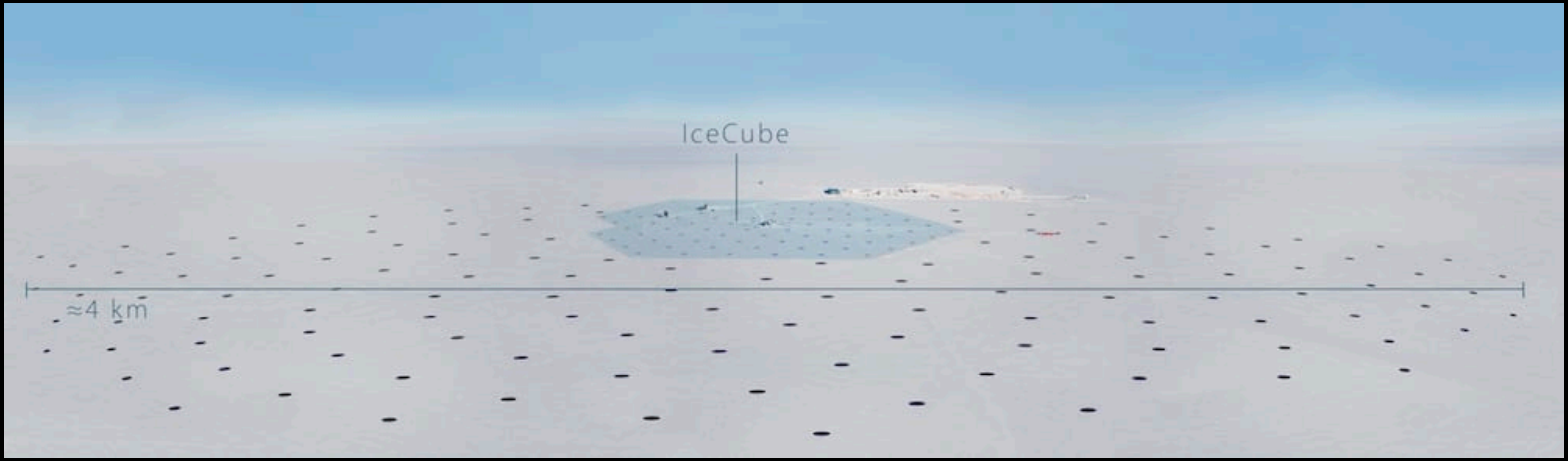
Abitbol et al. 2022, Astro2020, arXiv:1907.08284

- Measurements in all domains must be consistent or we have new physics.

NEUTRINO ASTRONOMY

- IceCube (with its current upgrade) will continue to study atmospheric neutrinos contributing to the testing of the 3-flavor oscillation paradigm.
- The next generation of IceCube (IceCube-Gen2) would double the instrumentation already deployed.
- It will uniquely provide an unprecedented view of the universe by using high-energy neutrinos above PeV.





SUMMARY

- The future of neutrino experiments is bright.
- By the start of the next decade multiple major neutrino experiments will be data-taking.
- The complementary of these experiments will allow us to stress-test the 3-flavor neutrino oscillation paradigm.
- We are entering the precision era of neutrino physics.

Backup

ELUCIDATING THE MYSTERIES OF NEUTRINOS

Index: 🟩 Operation 🟪 Construction 🟧 R&D, Research P: Primary S: Secondary

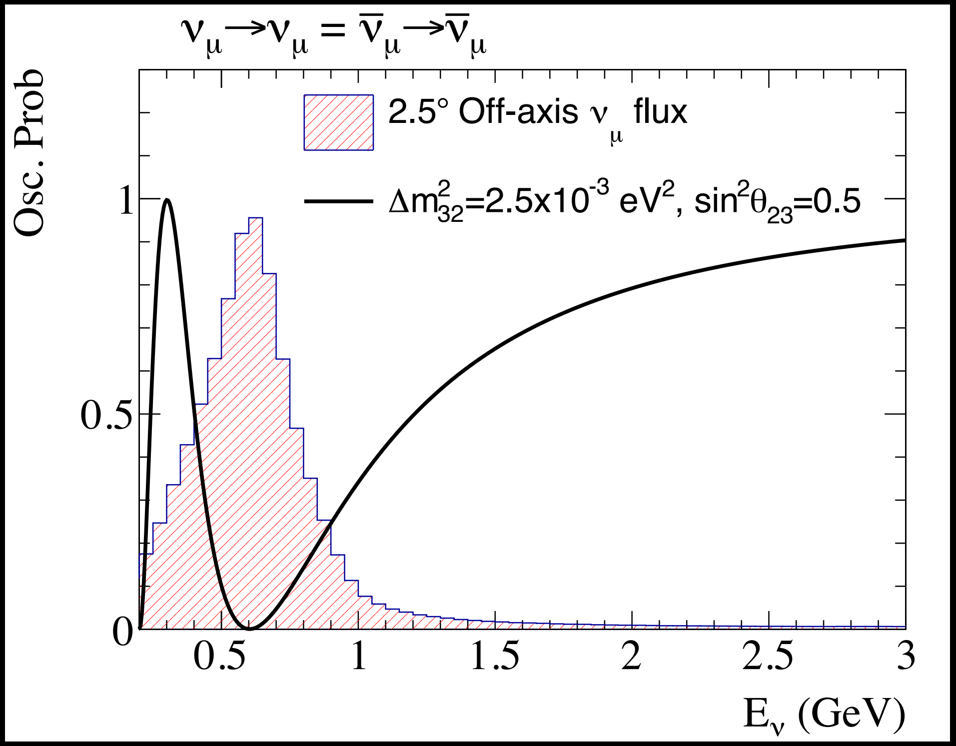
§ Possible acceleration/expansion in more favorable budget situations

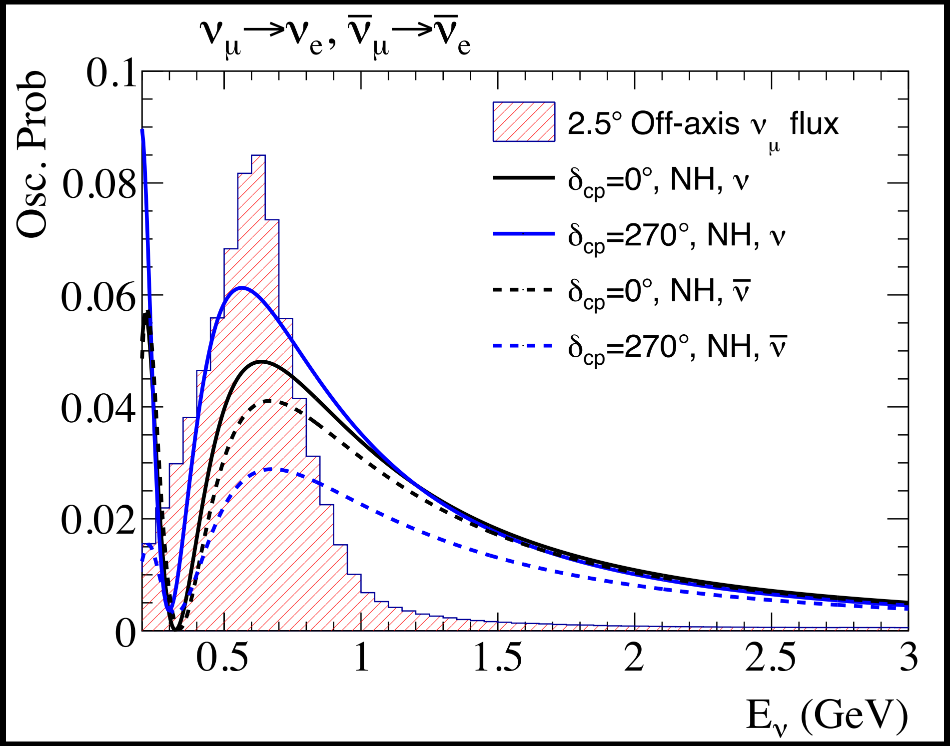
Science Experiments

Timeline	2024 – 2034	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
LHC			P	P		P	P	
LZ, XENONnT				P				
NOvA/T2K		P				S		
SBN		P				S		
DESI/DESI-II		S		S	P			P
Belle II				S		S	P	
IceCube		P		S				P
SuperCDMS				P				
Rubin/LSST & DESC		S		S	P			P
Mu2e							P	
DarkSide-20k				P				
HL-LHC			P	P		P	P	
DUNE Phase I		P				S	S	S
CMB-S4		S		S	P			P
CTA				S				P
G3 Dark Matter §		S		P				
IceCube-Gen2		P		S				P
DUNE FD3		P				S	S	S
DUNE MCND		P				S	S	
Higgs factory §			P	S		P	P	
DUNE FD4 §		P				S	S	S
Spec-S5 §		S		S	P			P
Mu2e-II							P	
Multi-TeV §	DEMONSTRATOR		P	P		P	S	
LIM		S		P	P			P

Science Drivers

MEASURING OSCILLATION PAR IN LONG BASELINE EXPERIMENTS





- Leading order dependence on **$\sin^2 2\theta_{23}$**. Little power to distinguish octant.
- Leading order dependence on **$|\Delta m^2_{32}|$**. Does not depend on mass ordering.

- Leading order dependence on $\sin^2 2\theta_{13}$ and $\sin^2\theta_{23}$. **Can separate octant.**
- Sub-leading order dependence on $\sin^2 2\theta_{13}$ and $\sin^2 2\theta_{23}$. **Can detect CP violation.**
- Sub-leading order dependence on $|\Delta m^2_{32}|$ through matter effect. **Can measure mass ordering.**

M. Wascko - Neutrino 2018

LONG-BASELINE EXPERIMENTS

- Precision is achieved by placing a detector close to the source (Near Detector) and one at or close to the oscillation maximum (Far Detector).

$$ND(\nu_\mu) = \boxed{\Phi(E_\nu) \times \sigma(E_\nu, A)} \times \epsilon_{ND}$$
$$FD(\nu_\mu) = \boxed{\Phi(E_\nu) \times \sigma(E_\nu, A)} \times \epsilon_{FD} \times P_{osc}$$

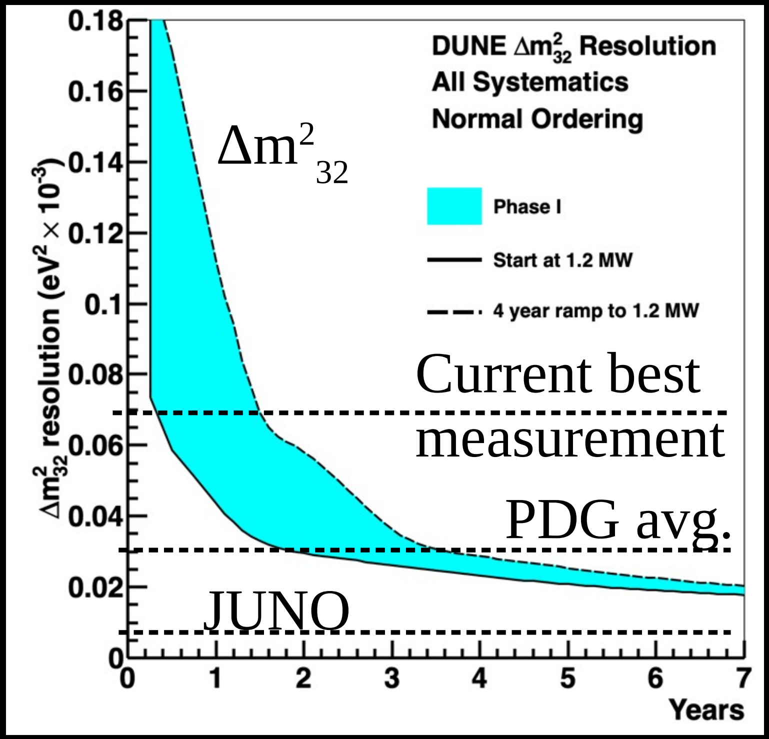
- The neutrino spectrum is measured at the ND (before oscillations), this is a combination of neutrino flux, cross section and efficiency.
- The measured spectrum is used to make a prediction of the expectation at the FD before considering oscillations.
- In the case of functionally similar detectors the flux combined with the cross sections uncertainties largely cancel.

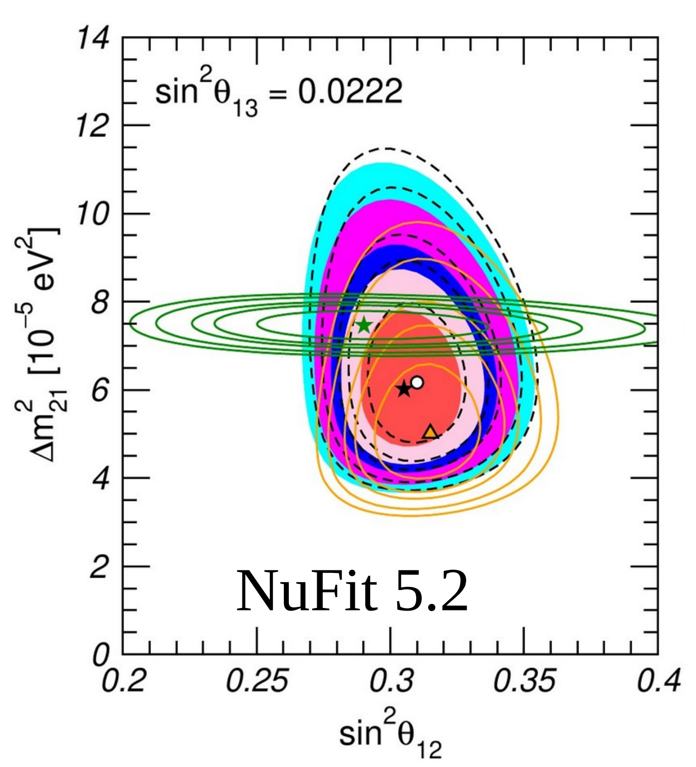
UNDERSTANDING THE FLUX, CROSS SECTIONS AND DETECTOR EFFICIENCIES IS ESSENTIAL FOR HIGH PRECISION

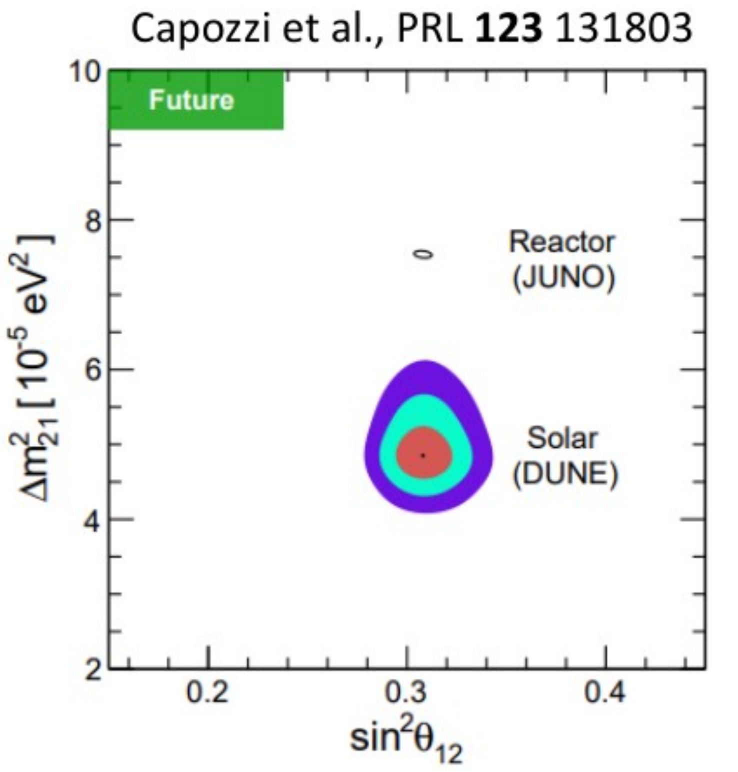
OTHER SYNERGIES

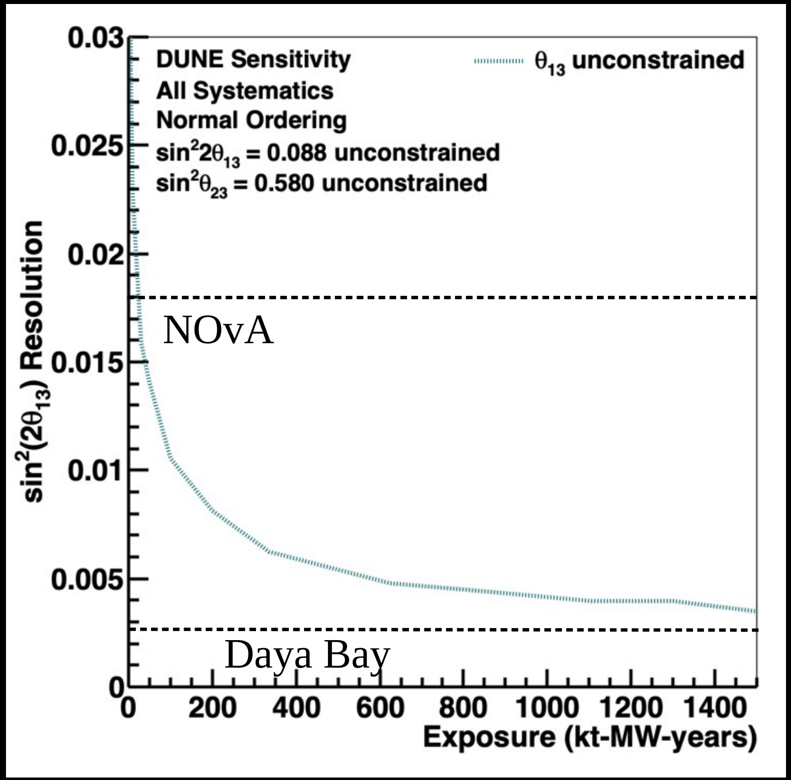
- JUNO and DUNE/Hyper-K will be measuring the atmospheric mass splitting and θ_{13} with comparable resolution from different processes which are sensitive to different matrix elements.

- JUNO and solar measurements from DUNE/Hyper-K/JUNO will also be sensitive to new physics if current tension is confirmed.



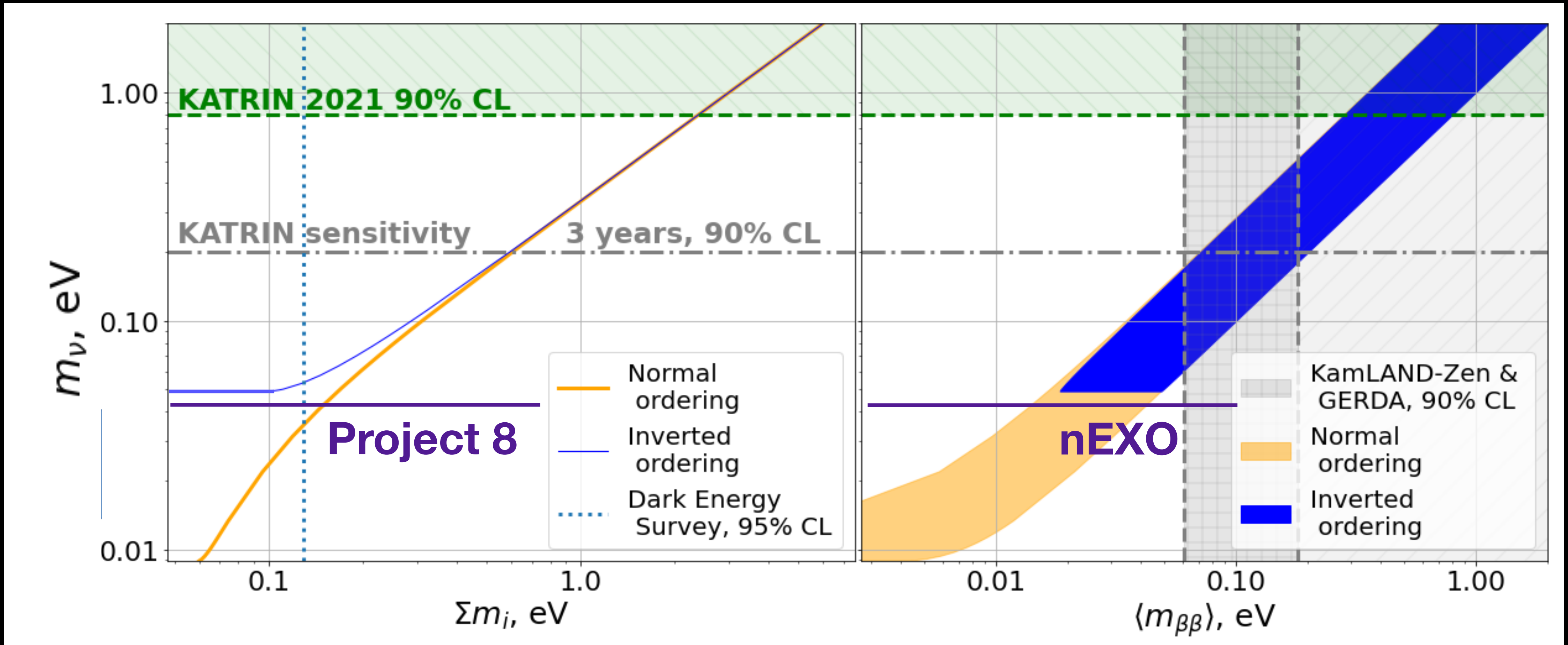



Capozzi et al., PRL **123** 131803



NEUTRINO MASS AND MAJORANA NEUTRINOS

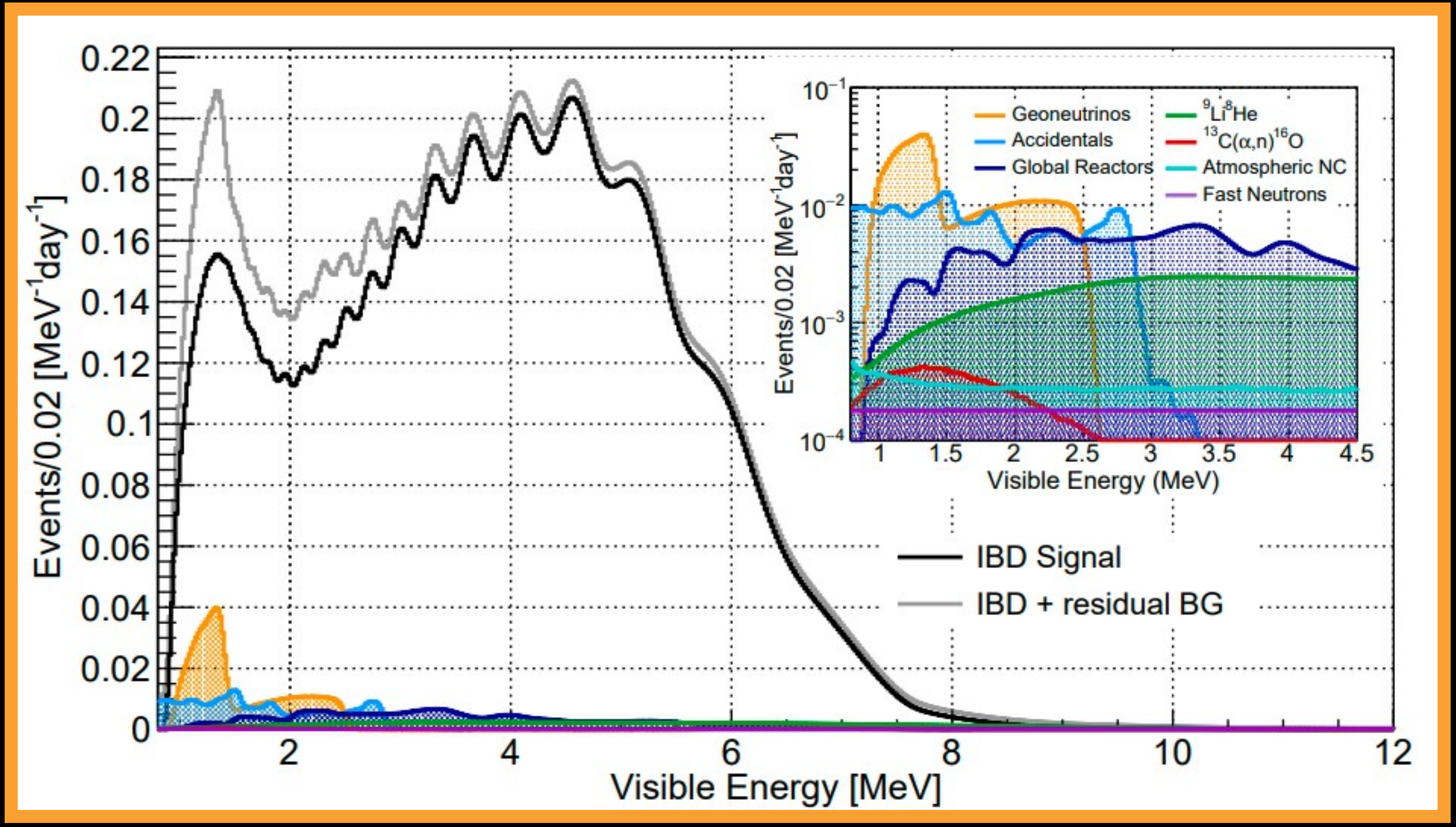
- There are three ways to assess the neutrino mass scale (another thing we do not know!).
- Direct neutrino mass experiments such as Katrin measure the effective mass of electron neutrino based on kinematics. Proposed experiment Project 8 aims to reach below the inverted ordering plateau.
- Neutrinoless double beta decay experiments seek to demonstrate neutrinos are majorana but also measure the effective majorana mass.

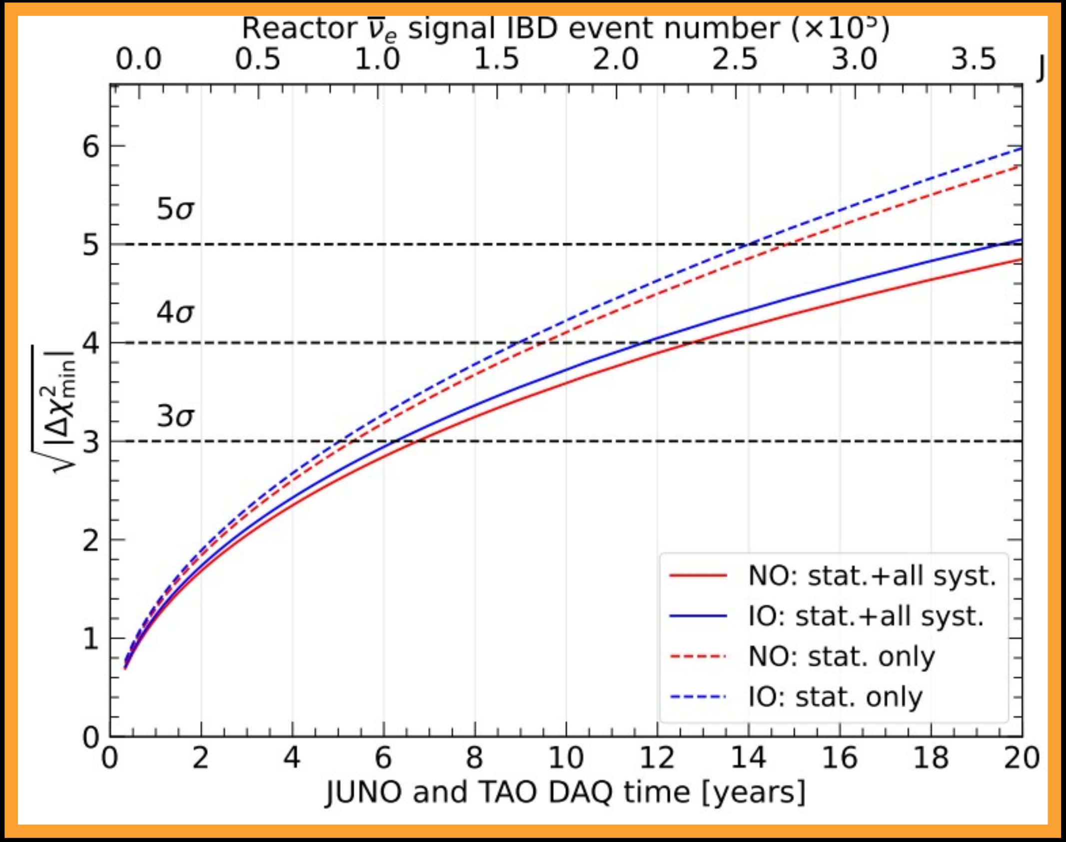


Cosmological observables **Neutrinoless double β-decay**

Alexey Lokhov Taup 2023

FUTURE REACTOR EXPERIMENT: JUNO

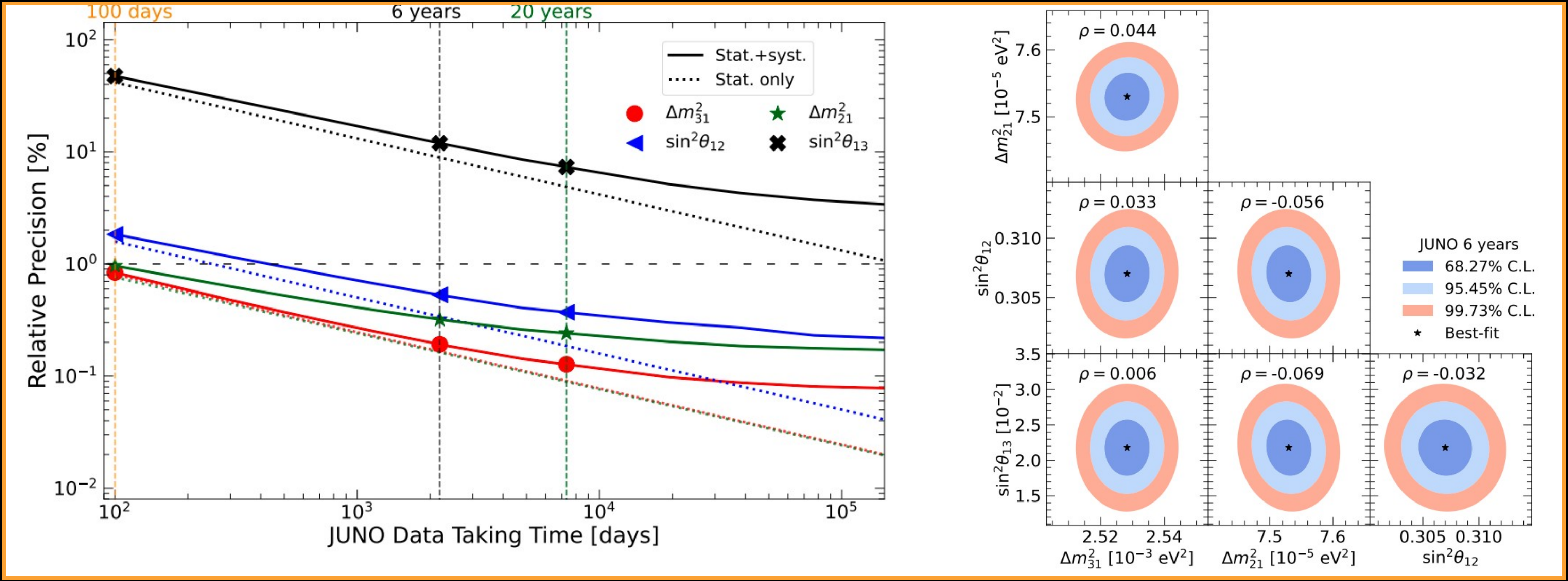




- Inverse beta decay signal ($\bar{\nu}_e + p \rightarrow e^+ + n$). Background is reduced by requiring coincidence of prompt positron and delayed neutron capture.

- 3 sigma mass ordering sensitivity at ~6 years of running with TAO (a reference detector).
- Expected to be better if combined with atmospheric neutrinos.

FUTURE REACTOR EXPERIMENT: JUNO



- Incredible precision (<0.5% in 6 years) for both mass differences (solar and atmospheric) and mixing angle 12.
- Far from systematic limited in the first decade.

NEUTRINOLESS DOUBLE BETA DECAY

- The nature of the neutrino is another aspect that is currently unknown, are neutrinos Majorana or Dirac.
- If neutrinos are Majorana, they should undergo neutrinoless double beta decay.
  - Experiments like nEXO and LEGEND are pushing for sensitivity that exceeds the half-life of 10^{28} years.
- These experiments are also measuring the effective majorana mass.