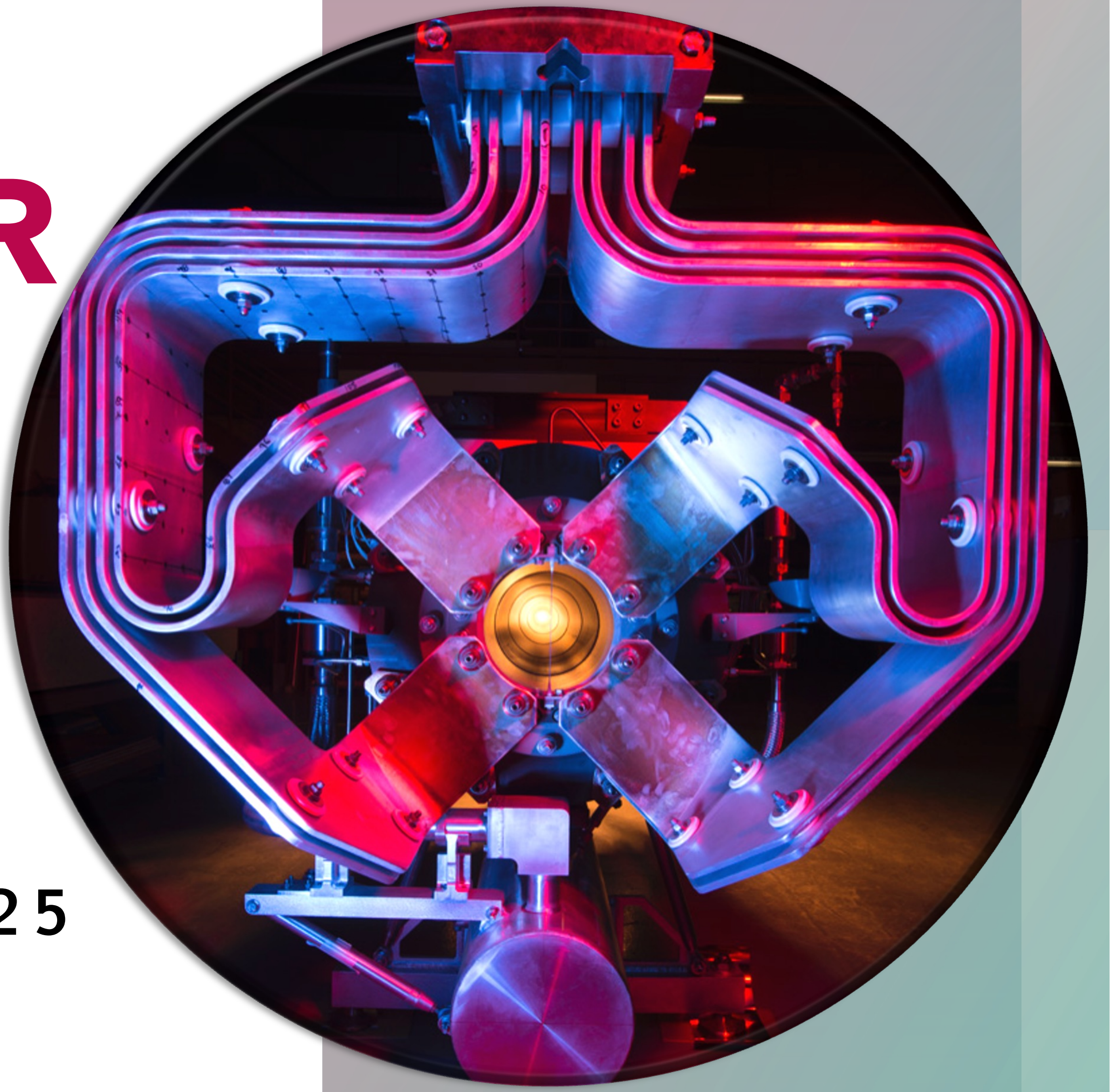
ACCELERATOR NEUTRINOS



ZOYA VALLARI

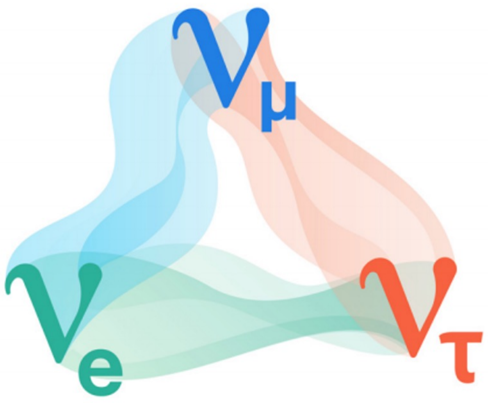
NEUTRINO UNIVERSITY 2025

JULY 9, 2025

THE OHIO STATE UNIVERSITY

NEUTRINO OSCILLATIONS THEORETICAL REVIEW

NEUTRINO OSCILLATION



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavor Eigenstates

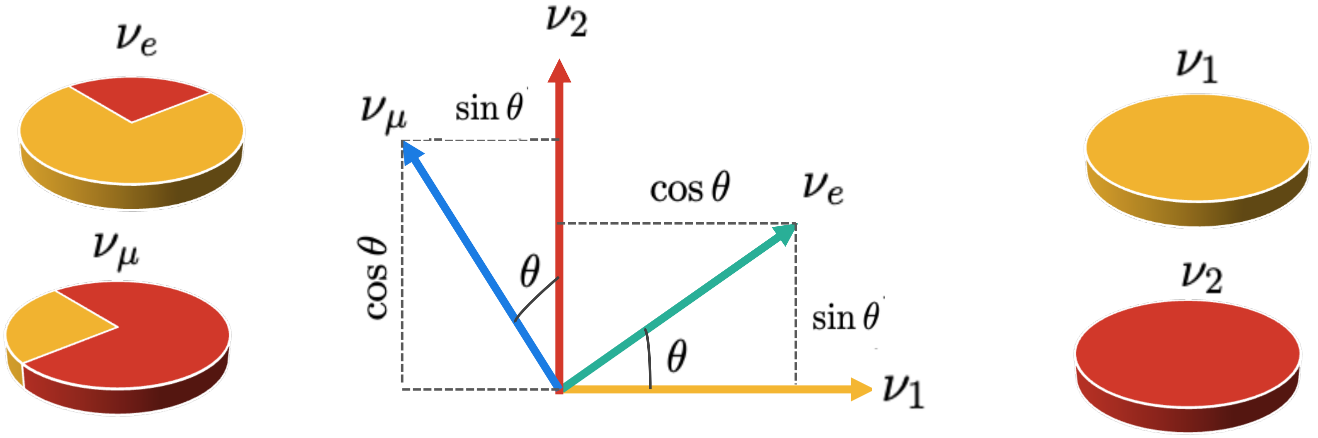
Mixing Matrix

Mass Eigenstates

TWO FLAVOR EXAMPLE

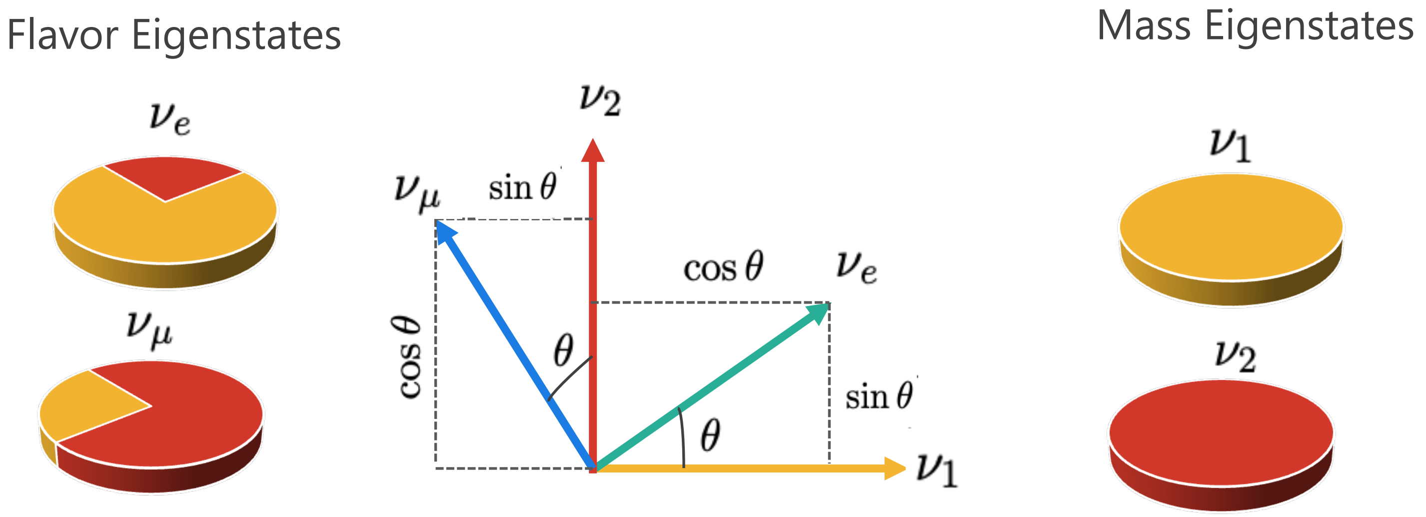
Flavor Eigenstates

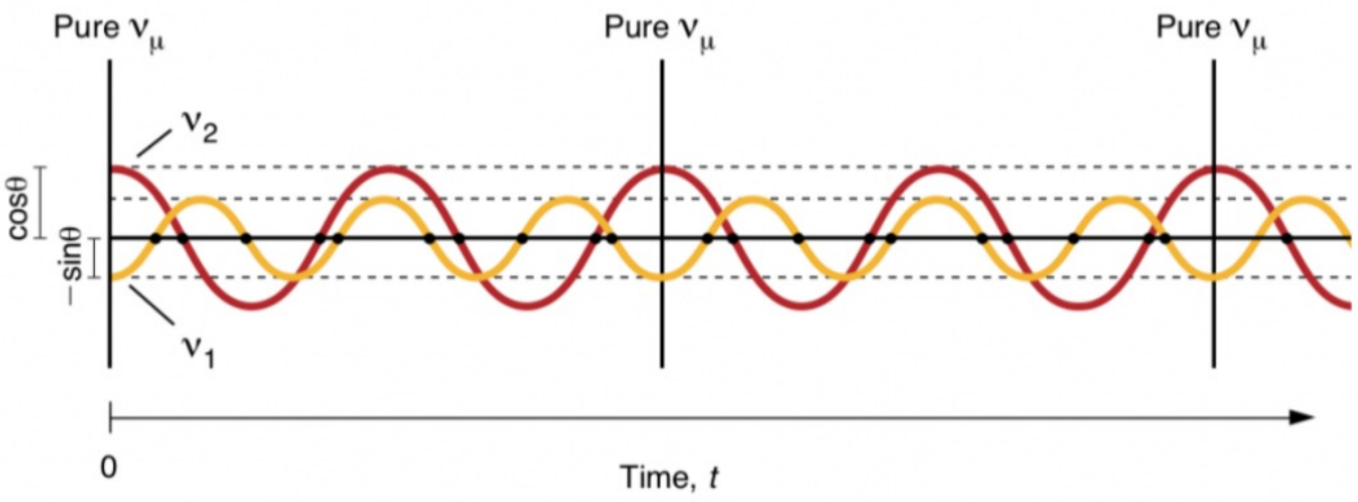
Mass Eigenstates



$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

TWO FLAVOR EXAMPLE





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

OSCILLATION: NATURE'S PARAMETERS

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

Amplitude

$$U_{\mathrm{PMNS}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$c_{ij} = \cos\theta_{ij}$$
$$s_{ij} = \sin\theta_{ij}$$

Mixing angles θ_{12} ,θ_{13} ,θ_{23} determine the magnitude of oscillation.

$$\theta_{23} \approx 45^\circ \qquad \theta_{13} \approx 8.5^\circ \qquad \theta_{12} \approx 34^\circ$$

OSCILLATION: NATURE'S PARAMETERS

$$P(\nu_\alpha \rightarrow \nu_\beta) \sim \sin^2(2\theta)\sin^2\left(\frac{\overbrace{\boxed{\Delta m_{ij}^2}}^{\text{Frequency}} L}{4E}\right)$$

Two known mass-splitting scales determine frequency of the oscillations.

ν_1 ν_2 ν_3

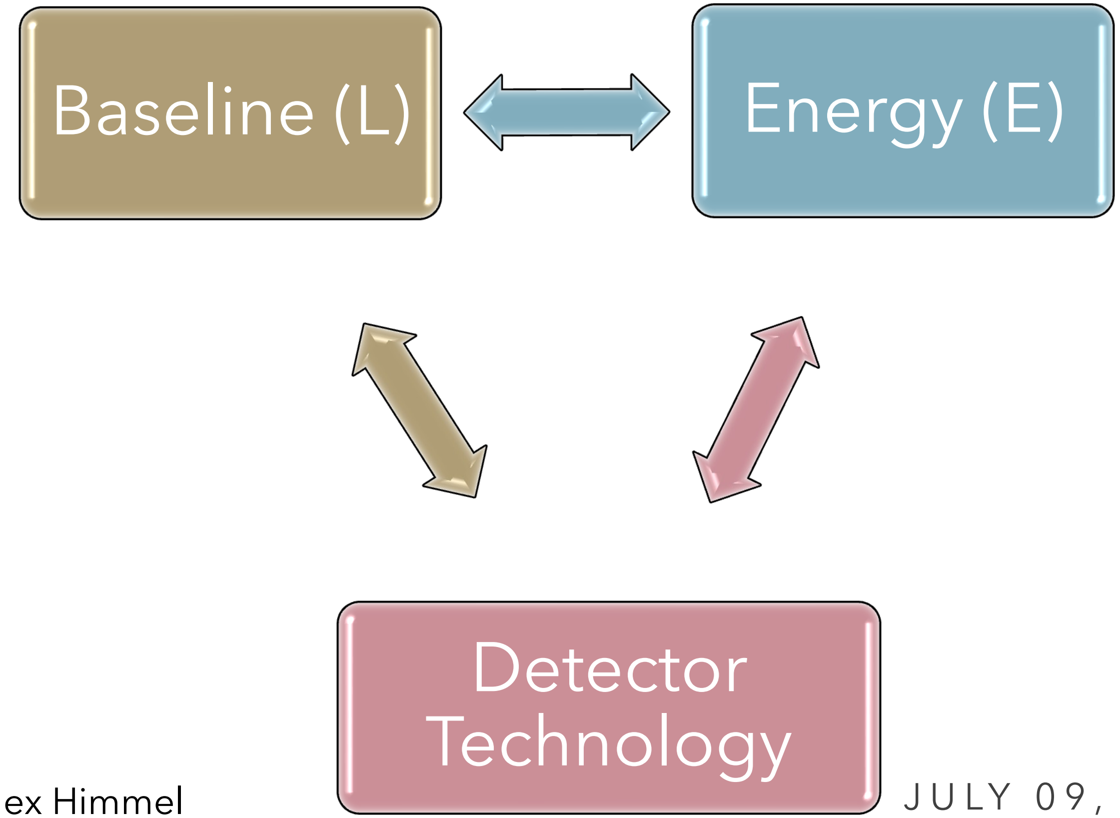
$$\underbrace{\nu_1 \quad \nu_2}_{\Delta m_{21}^2 \sim 7\times 10^{-5}\mathrm{eV}^2}$$

$$\underbrace{\quad\quad\quad \nu_3}_{|\Delta m_{31}^2| \sim 2\times 10^{-3}\mathrm{eV}^2}$$

OSCILLATION: EXPERIMENTAL PARAMETERS

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

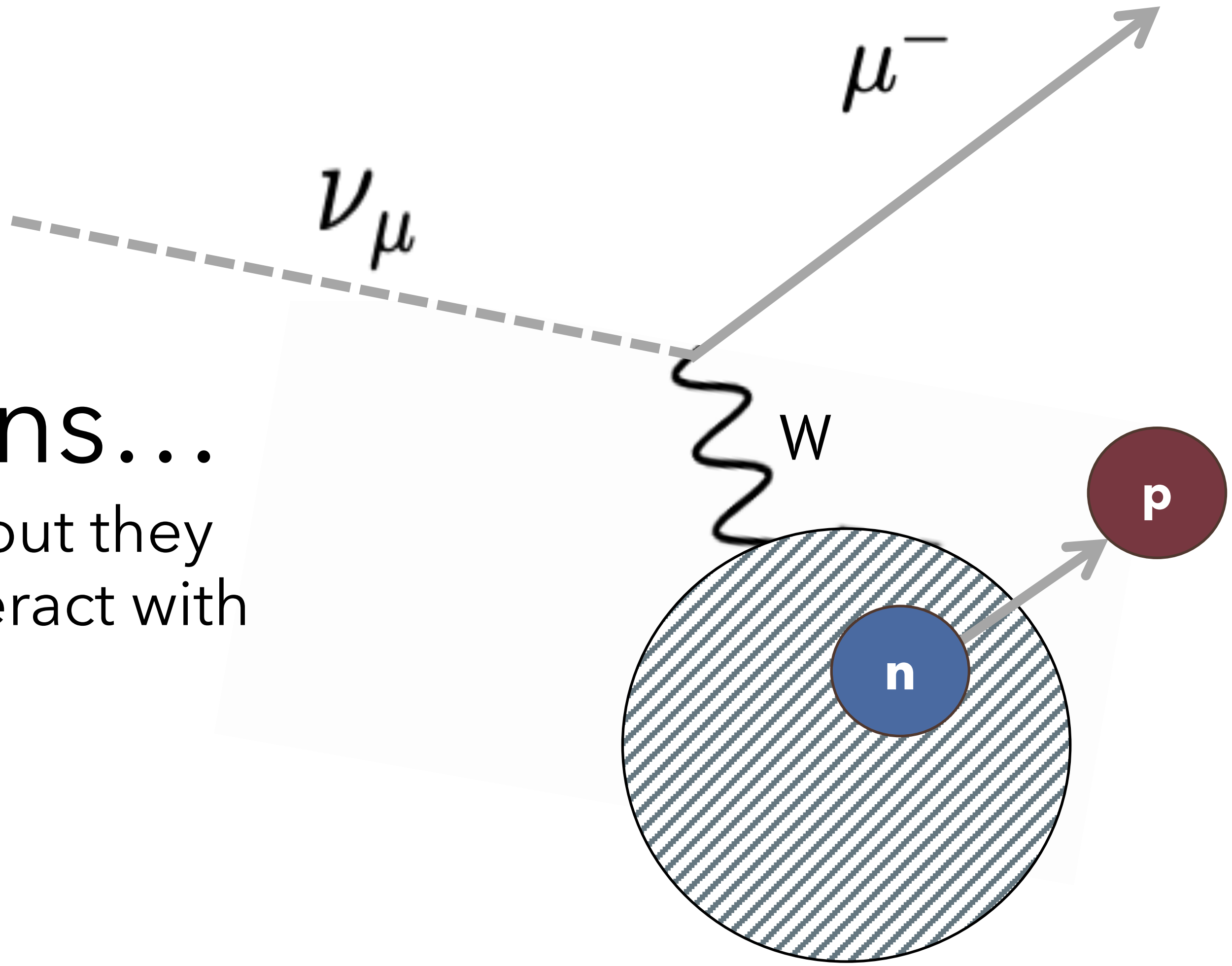
Experiments are designed with a typical L/E to optimize sensitivity to $\boldsymbol{\Delta m_{ij}^2}$ oscillation scales



Slide inspiration Alex Himmel

NEUTRINO OSCILLATIONS EXPERIMENTAL REVIEW

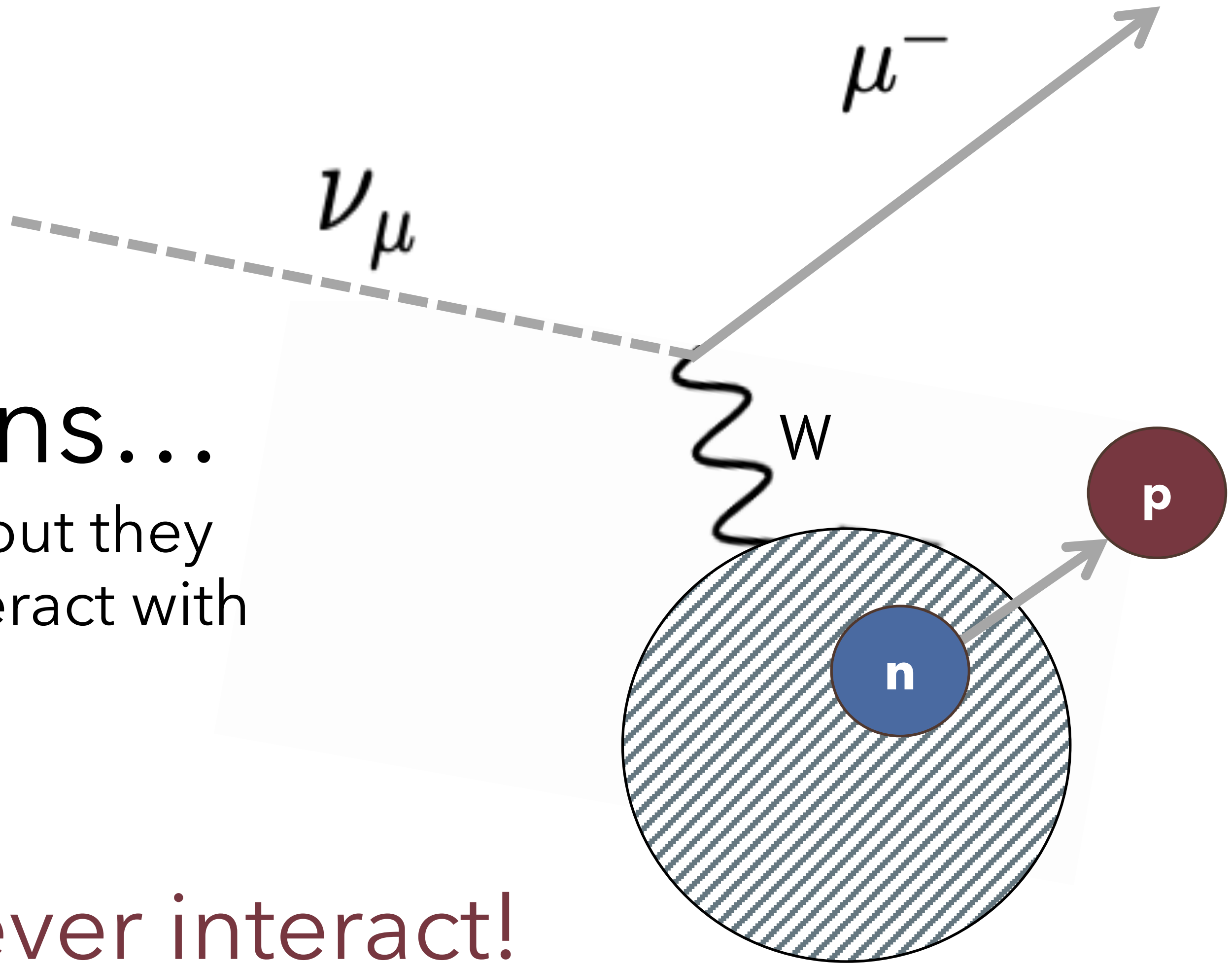
HOW TO SEE A NEUTRINO?



Through its interactions…

the neutrinos themselves are invisible, but they produce visible particles when they interact with the nucleus

HOW TO SEE A NEUTRINO?



Through its interactions…

the neutrinos themselves are invisible, but they produce visible particles when they interact with the nucleus

But they almost never interact!

NEUTRINOS ARE ELUSIVE

Neutrinos pass through anything, even the Earth – giving them the nickname: **The Ghost Particles!**

NEUTRINOS ARE ABUNDANT

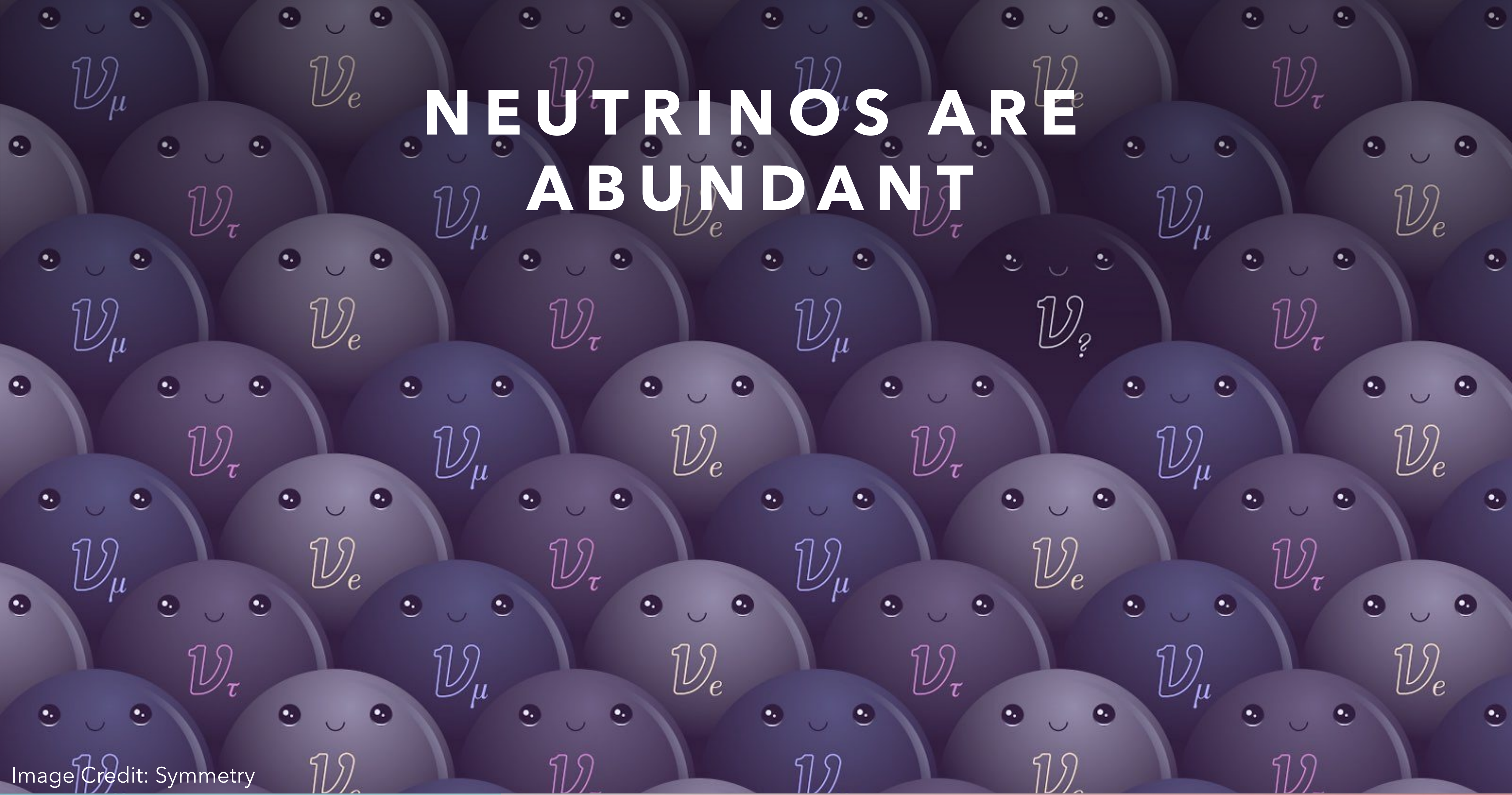
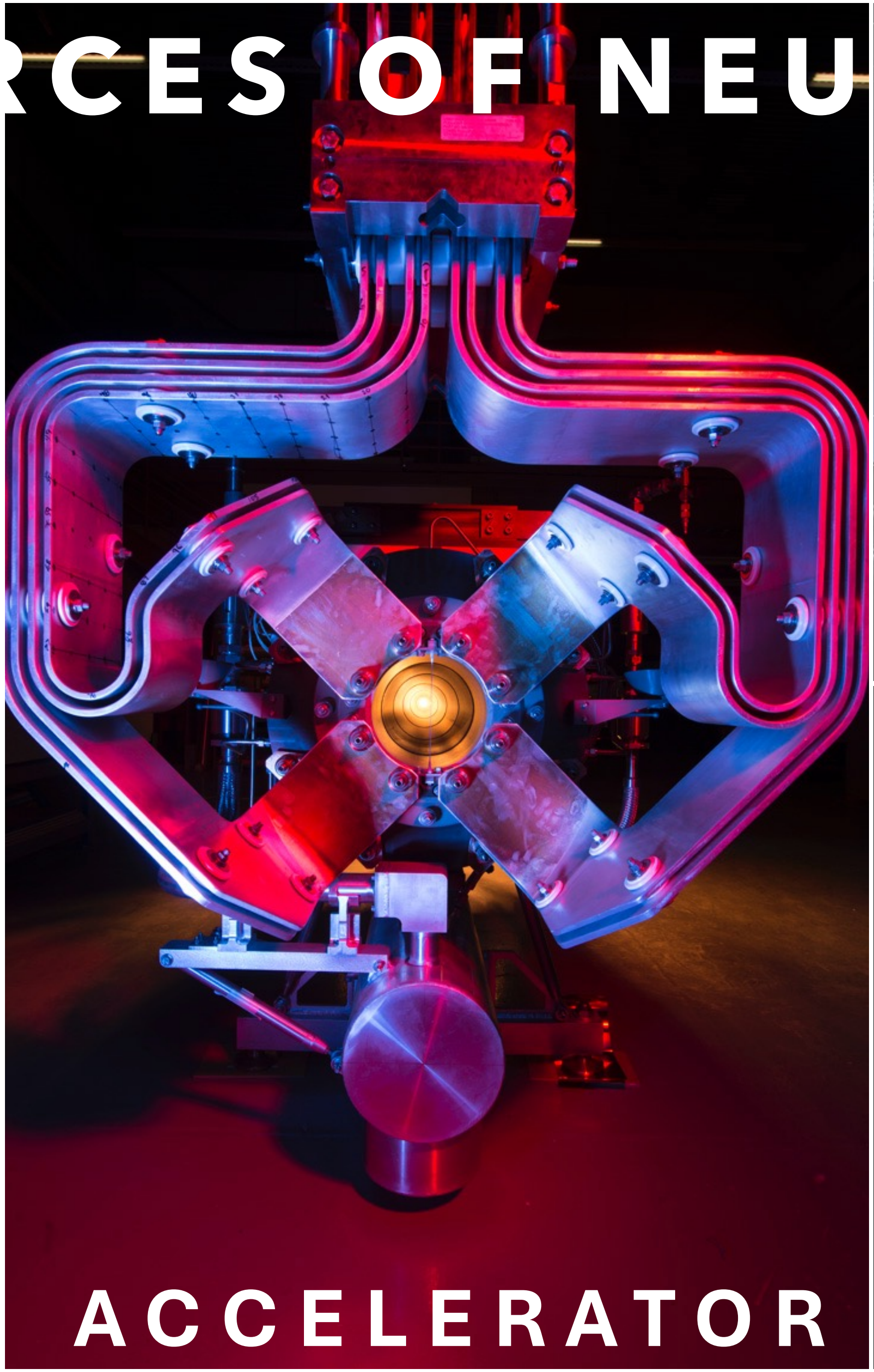
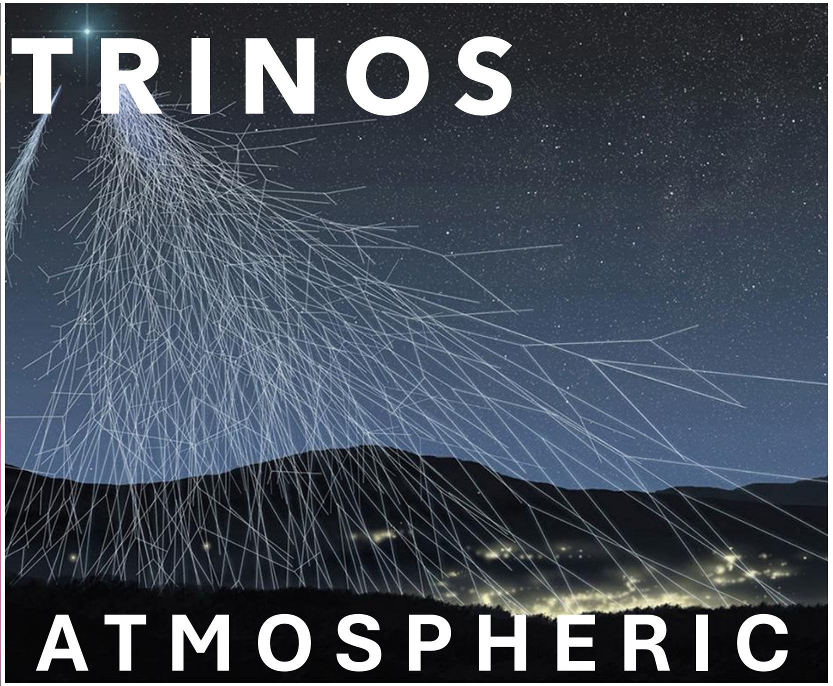
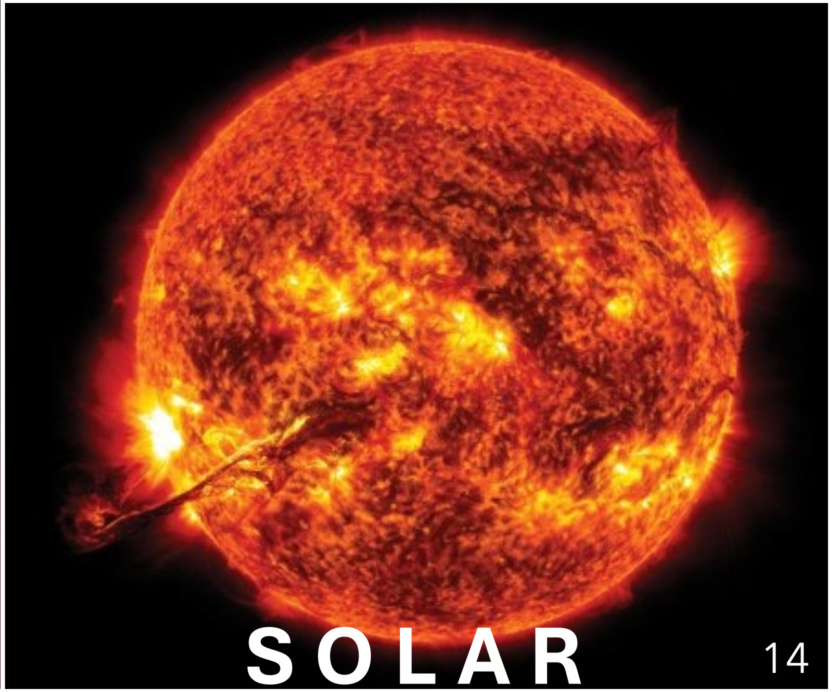


Image Credit: Symmetry

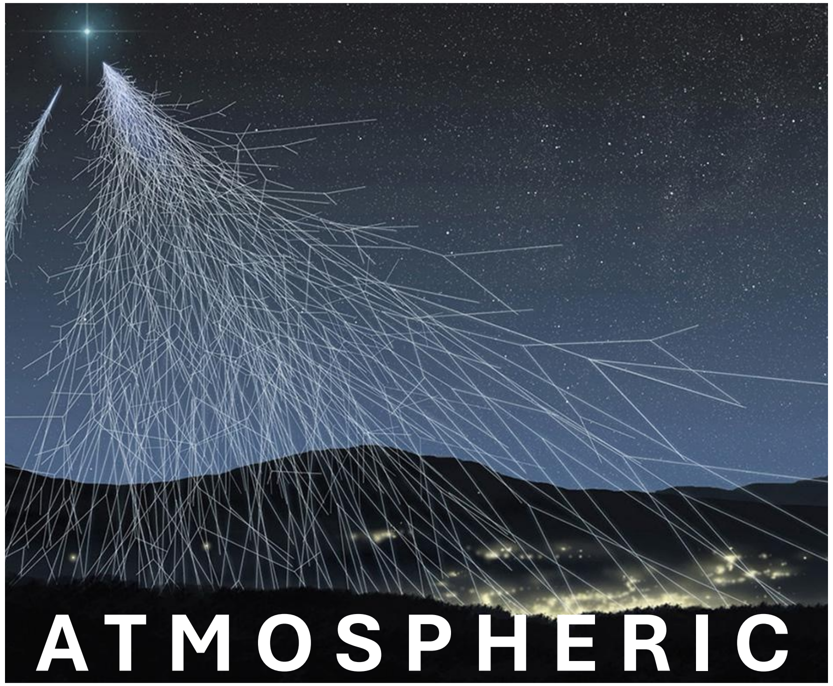
SOURCES OF NEUTRINOS

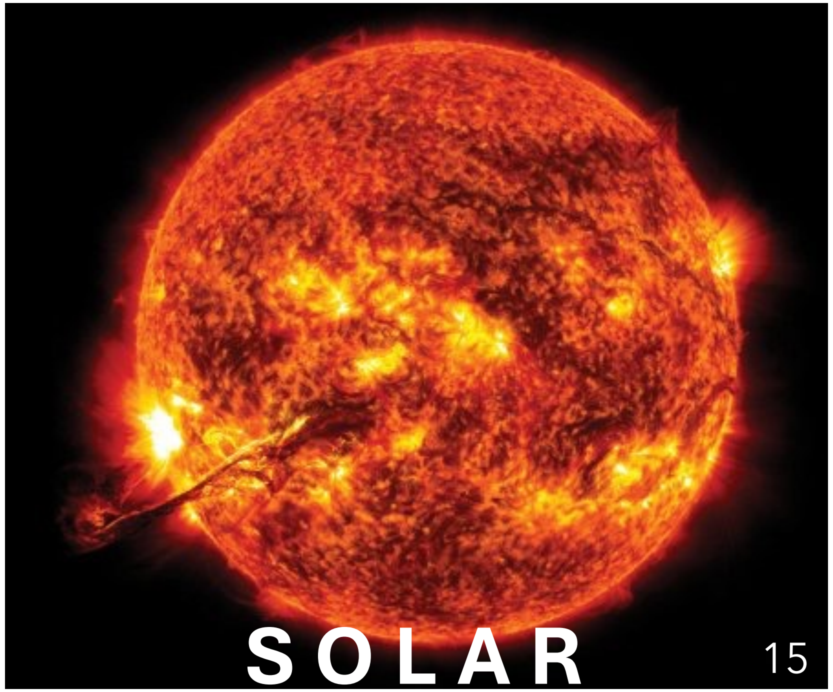




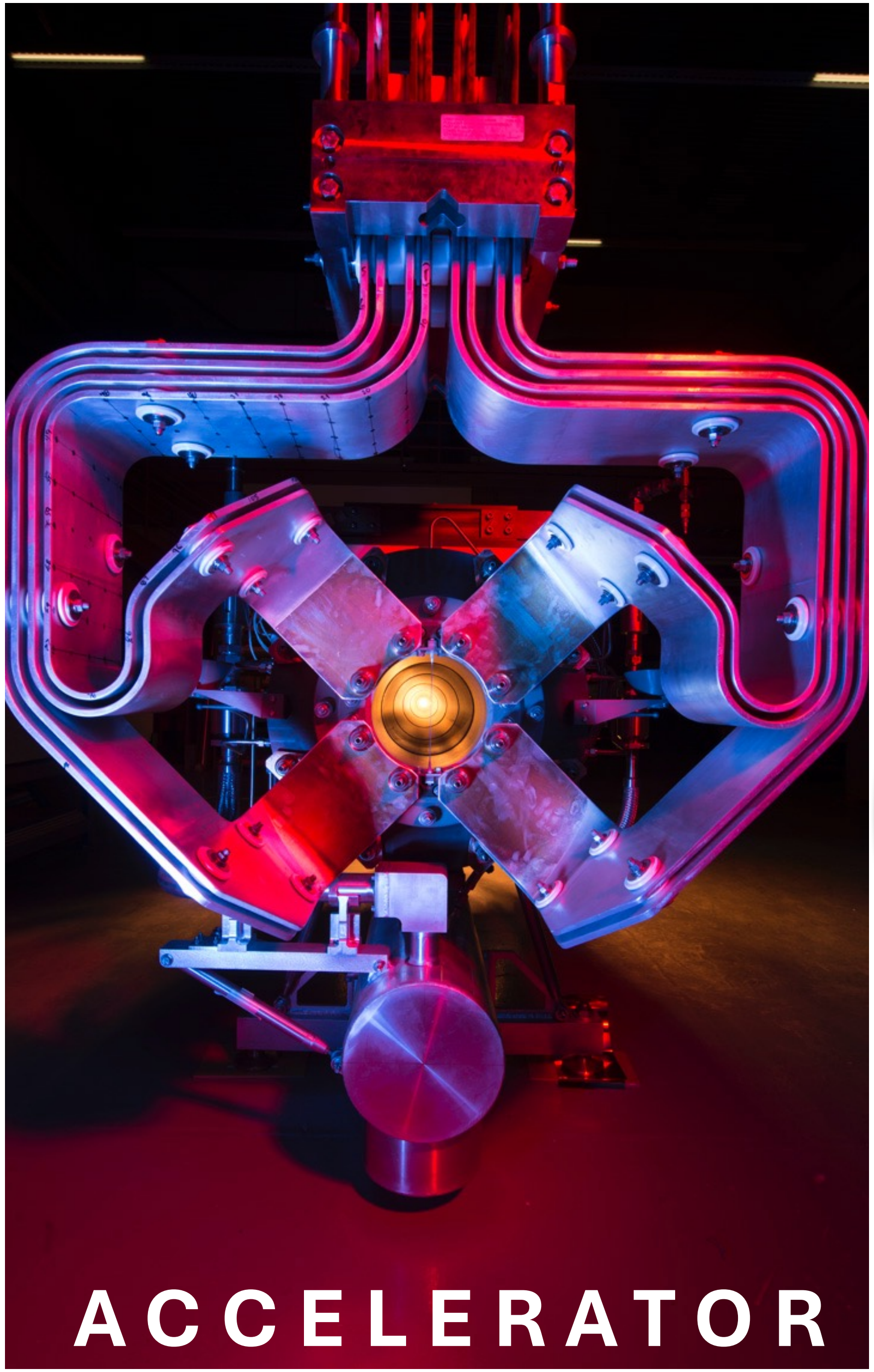


THE WILD NEUTRINOS





Slide inspiration Kate Scholberg



THE TAMED NEUTRINOS

Meet my cat : Quigley

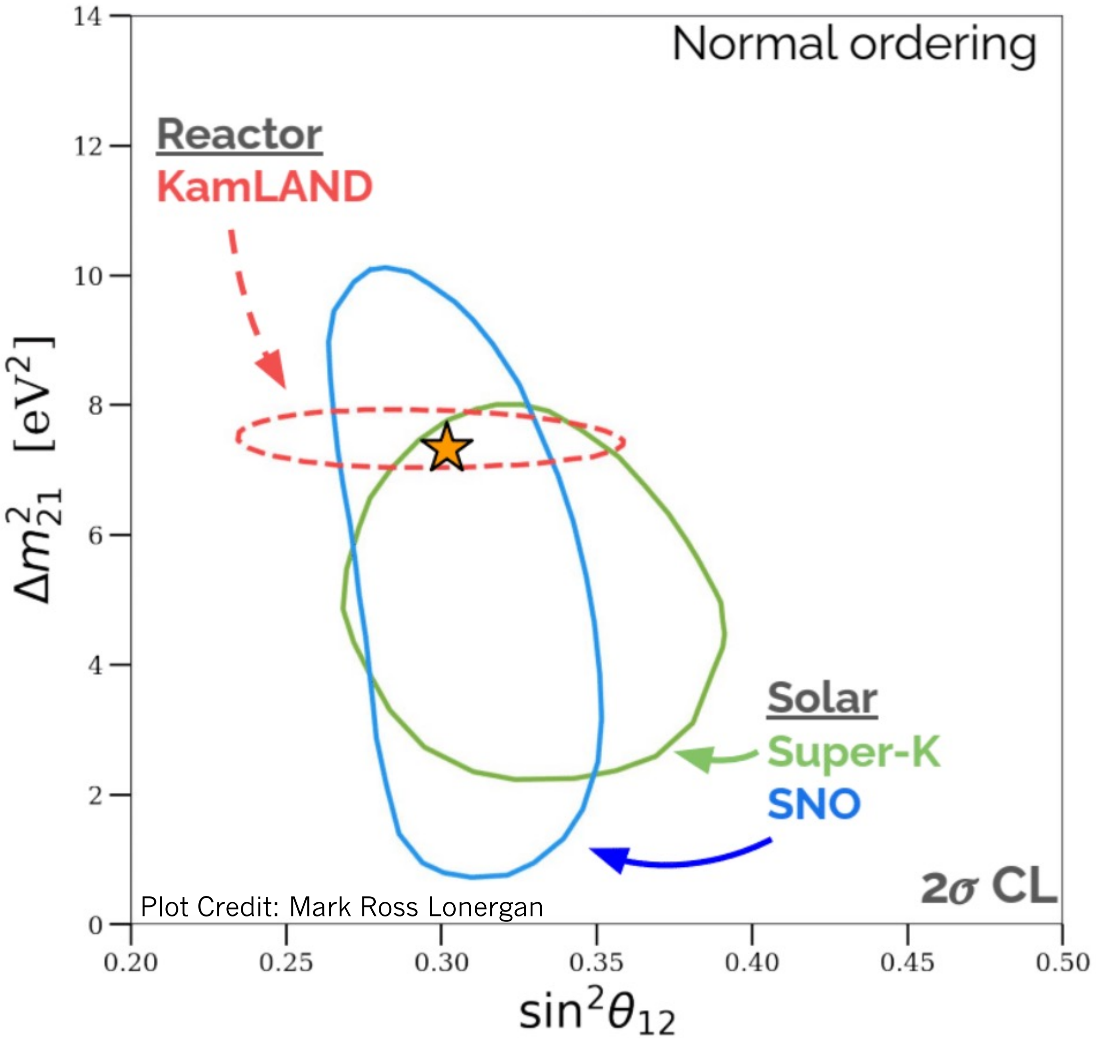
Slide inspiration Kate Scholberg

DISCOVERIES IN THE WILD… CONFIRMED WITH TAME NEUTRINOS

SOLAR

REACTOR

- Disappearance of electron neutrino from the Sun confirmed by reactor neutrino experiments!



Plot Credit: Mark Ross Lonergan

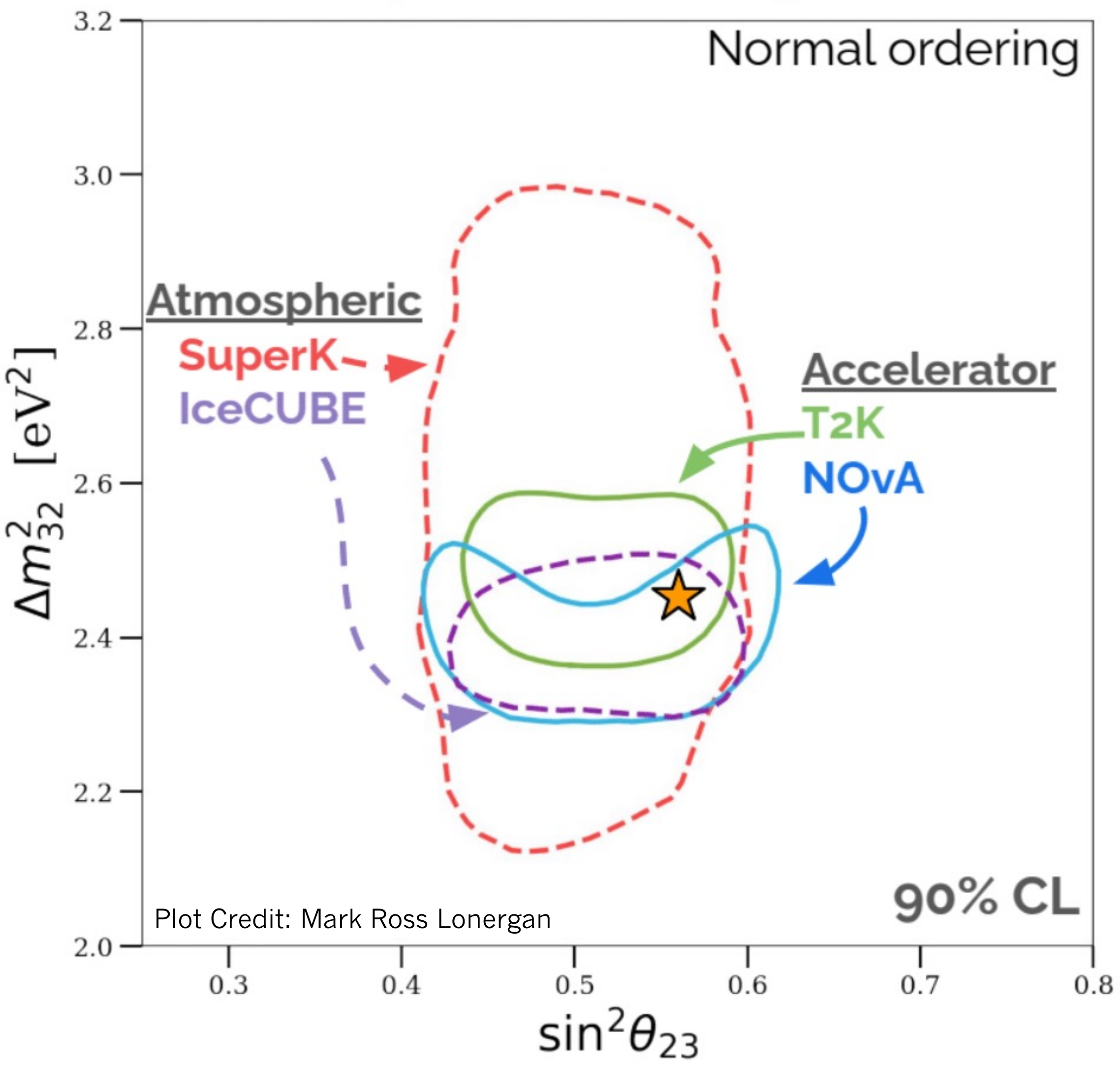
Slide inspiration Kate Scholberg

DISCOVERIES IN THE WILD… CONFIRMED WITH TAME NEUTRINOS

ATMOSPHERIC

ACCELERATOR

- Disappearance of muon neutrinos from the atmospheric experiments confirmed by accelerator neutrino experiments!



Slide inspiration Kate Scholberg

MEASURING OSCILLATIONS

$$U_{\text{PMNS}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$

Measured primarily from the following neutrino sources

Atmospheric

Accelerator

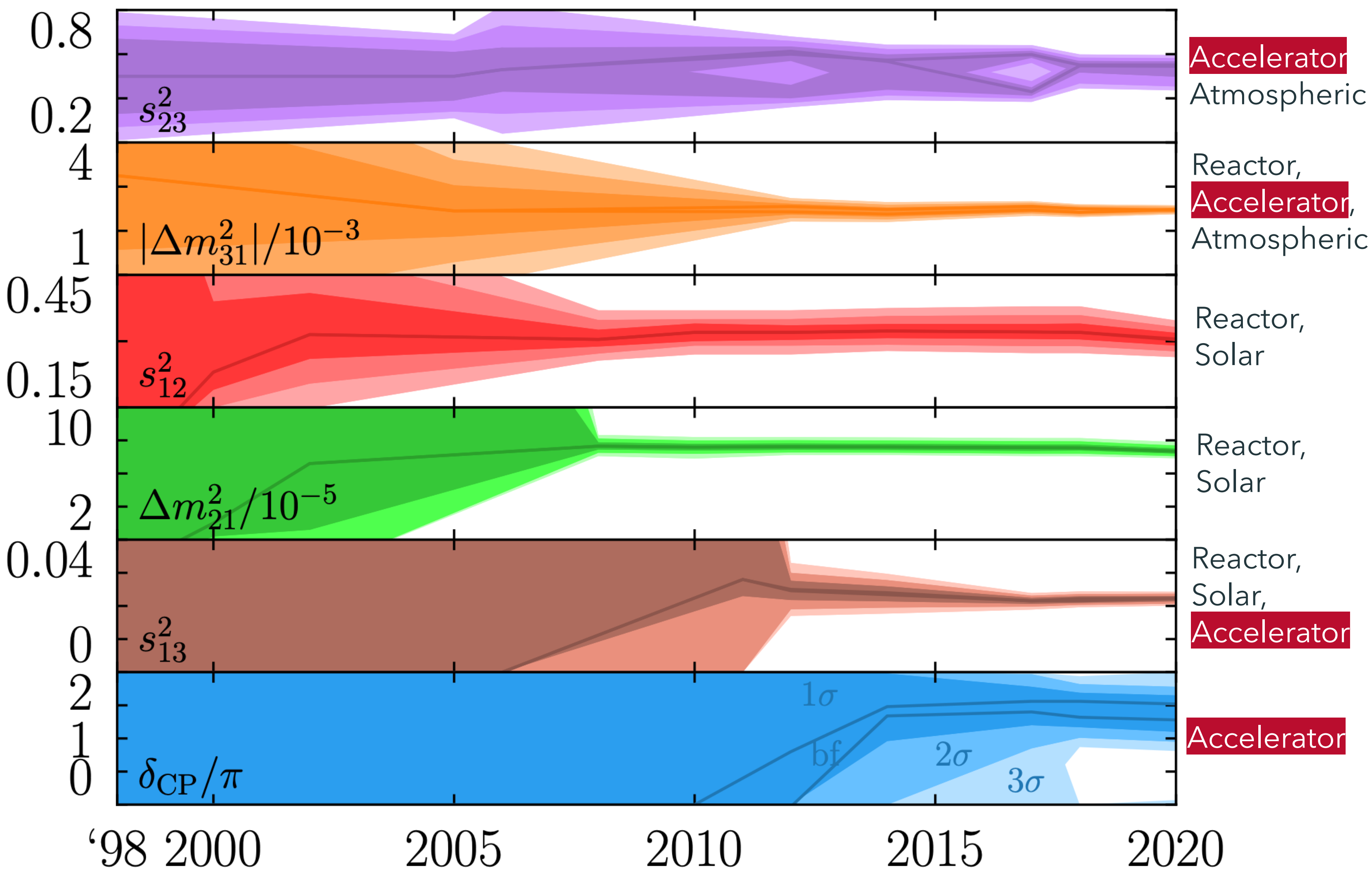

Reactor

Solar

Atmospheric/Accelerator	Accelerator/Reactor	Reactor/Solar
$\theta_{23} \sim 45^o$	$\theta_{13} \sim 8.5^o$	$\theta_{12} \sim 33^o$
$\Delta m^2_{32} \sim \pm 2.5 \times 10^{-3} eV^2$	$\delta_{CP}???$	$\Delta m^2_{12} \sim 7.5 \times 10^{-5} eV^2$

EXPERIMENTAL OVERVIEW: A 25 YEARS LONG ODYSSEY

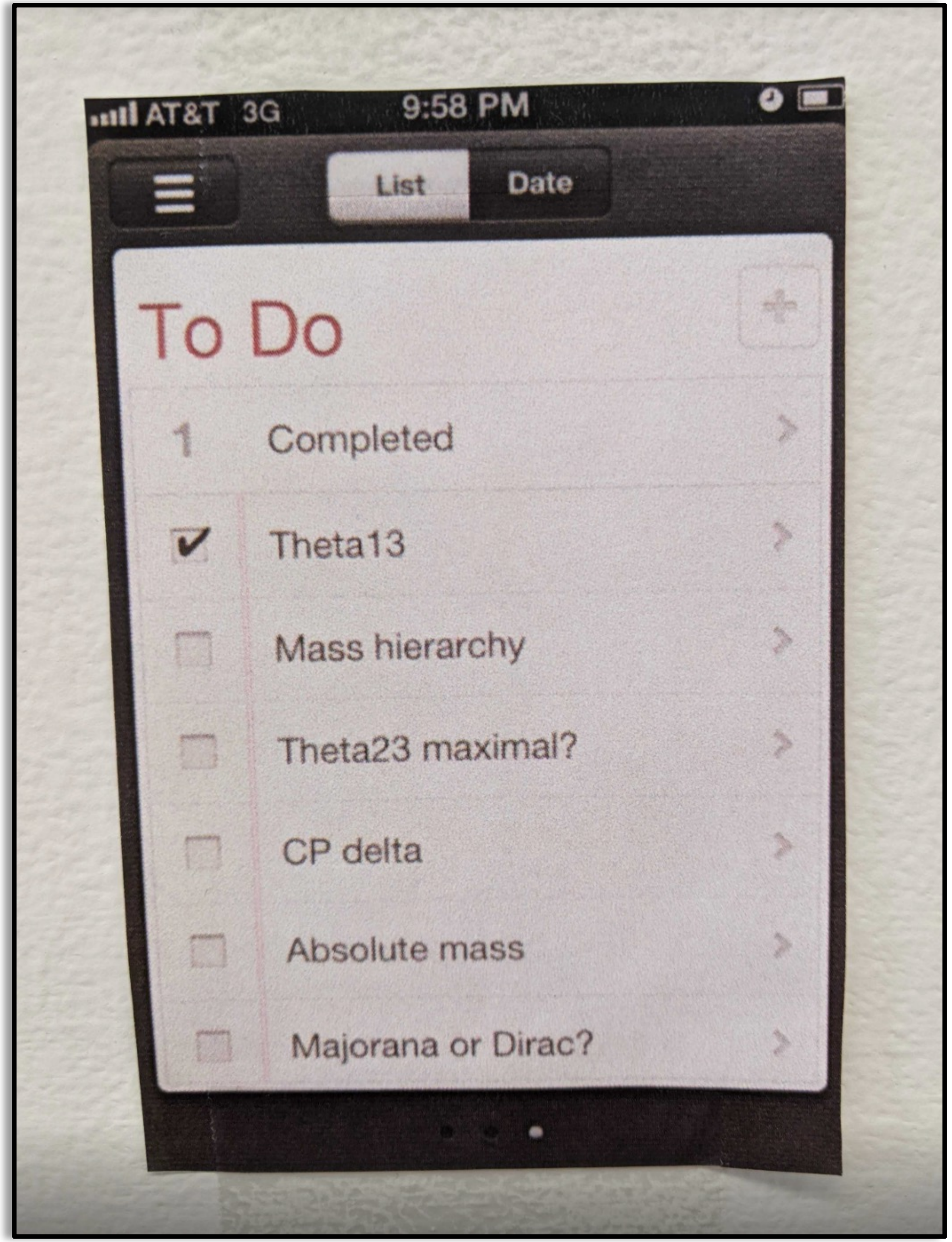
"Ultimate Goal: Not Measure Parameters but Test the Formalism": A.D. Gouvea



Snowmass NF01 report P.B. Denton et al arXiv:2212.00809

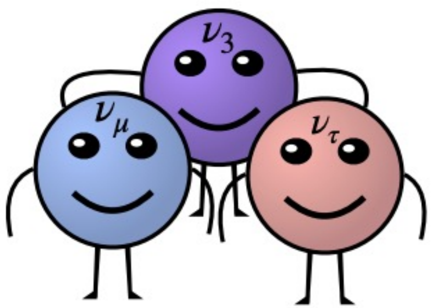
THE UNKNOWNS

As seen on WH10 floor office



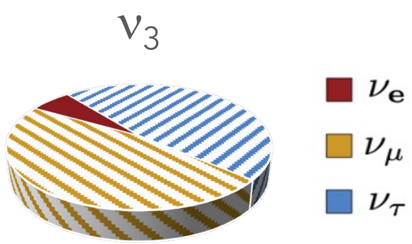
(SOME) OPEN QUESTIONS

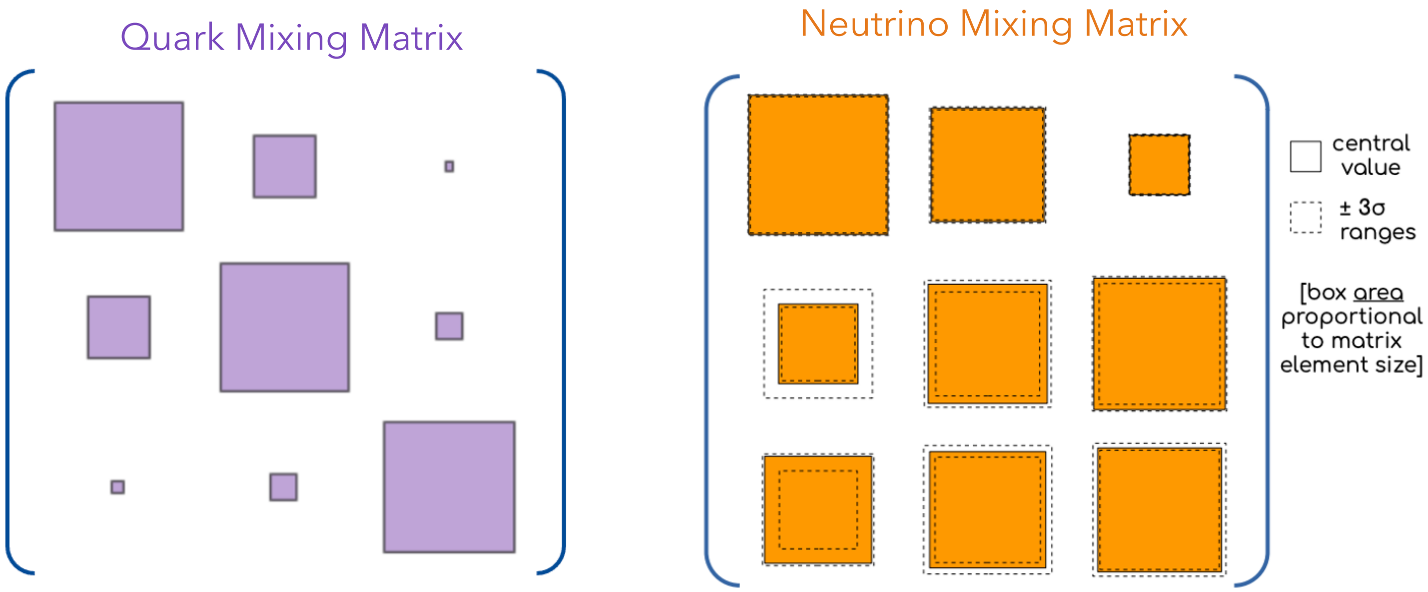
Is the θ_{23} mixing maximal?



Current Measured Value : $\theta_{23} \sim 45^\circ$

Precision : $\sin^2\theta_{23} \sim 5\%$





- Values from PDG 2020
- Values from NuFIT 5.0, arXiv:2007.14792

If θ_{23} = 45° → $|U_{\mu 3}| = |U_{\tau 3}|$

	θ_{23}	θ_{13}	θ_{12}	δ
Leptons	$\sim 45^\circ$	8.5°	34°	?
Quarks	2.4°	0.20°	13°	69°

(SOME) OPEN QUESTIONS

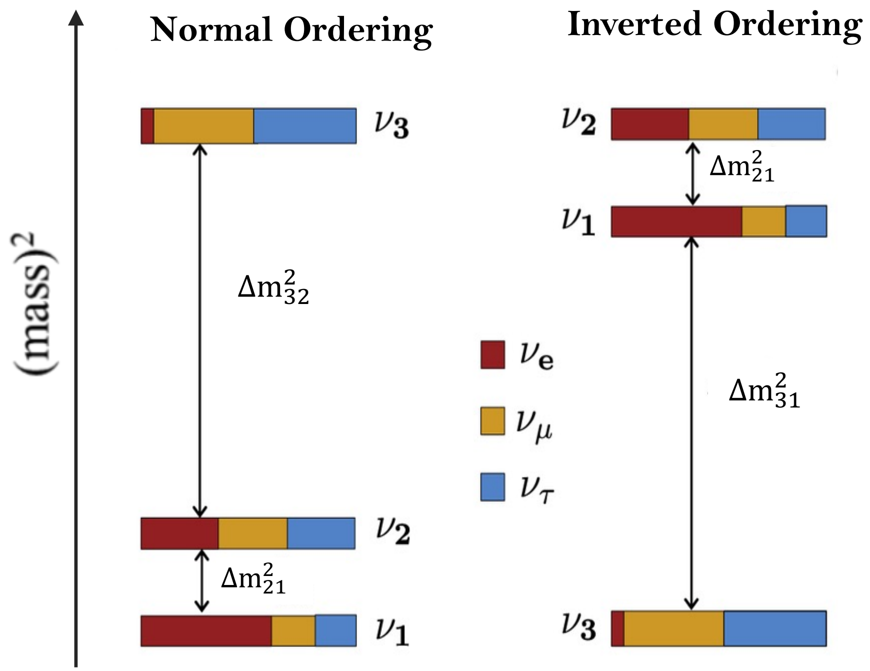
Do neutrinos violate Charge-Parity symmetry?

Do neutrinos and anti-neutrinos oscillate differently violating the CP symmetry?
Is $\sin \delta_{CP} = 0$?

Accelerator-based long-baseline oscillation experiments provide unique handle for this measurement.

(SOME) OPEN QUESTIONS

Which neutrino is the heaviest?

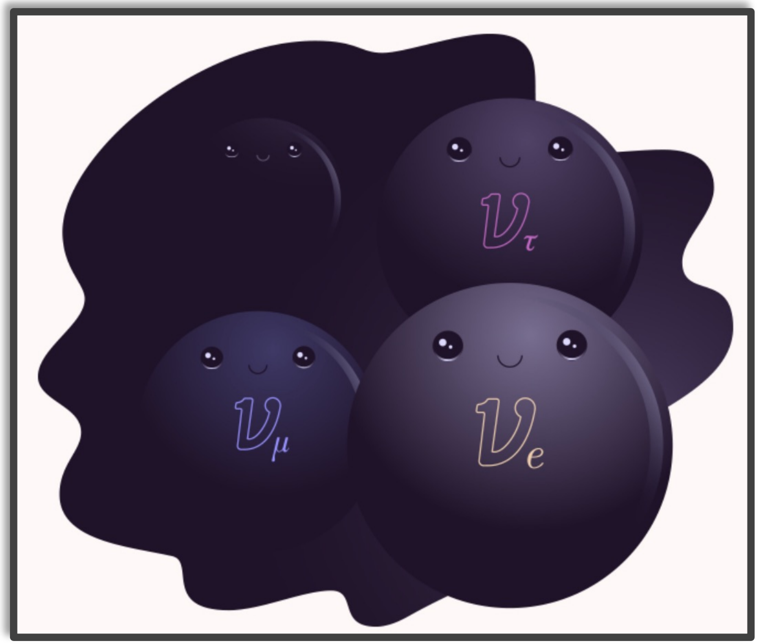


ν Mass Ordering (MO): Normal or Inverted?

Does the symmetry that determines the mass of charged leptons influences ν_1 to be the lightest neutrino or does the inverse hold?

(SOME) OPEN QUESTIONS

Is the 3-flavor paradigm of neutrino complete?



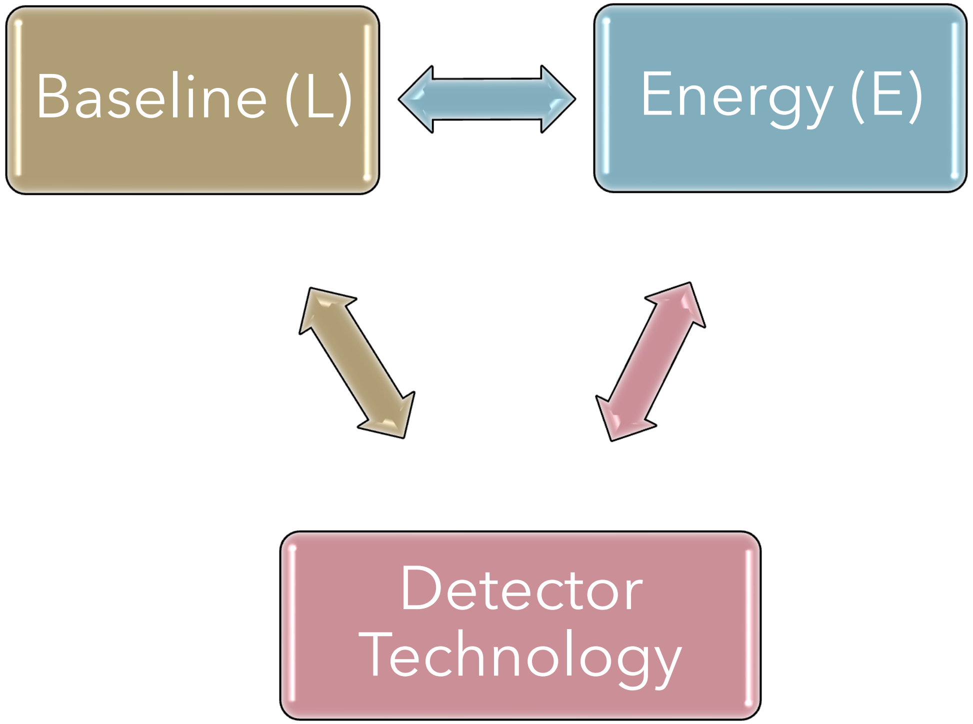
- Are there additional flavor states?
  - Heavy neutral leptons
  - Sterile neutrinos
  - Non-standard interactions
- Probing unitarity of PMNS tests robustness of 3-flavor framework!

ACCELERATOR NEUTRINOS

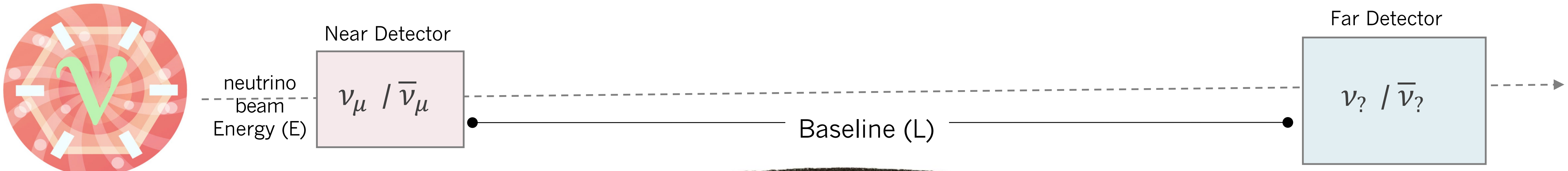
THE TAMEST OF THEM ALL…

✓ CUSTOM ✗ DEFAULT

Source	Energy	Baseline	Detector Technology
Solar	✗	✗	✓
Atmospheric	✗	✗	✓
Reactor	✗	✓	✓
Accelerator	✓	✓	✓



HOW TO BUILD AN ACCELERATOR NEUTRINO OSCILLATION EXPERIMENT?



Items Needed

- [ ] One Neutrino Beam
- [ ] Two Neutrino Detectors

HOW TO MAKE A NEUTRINO BEAM

[Symmetry Article] [YouTube how-to]

STEP 1: GRAB SOME PROTONS

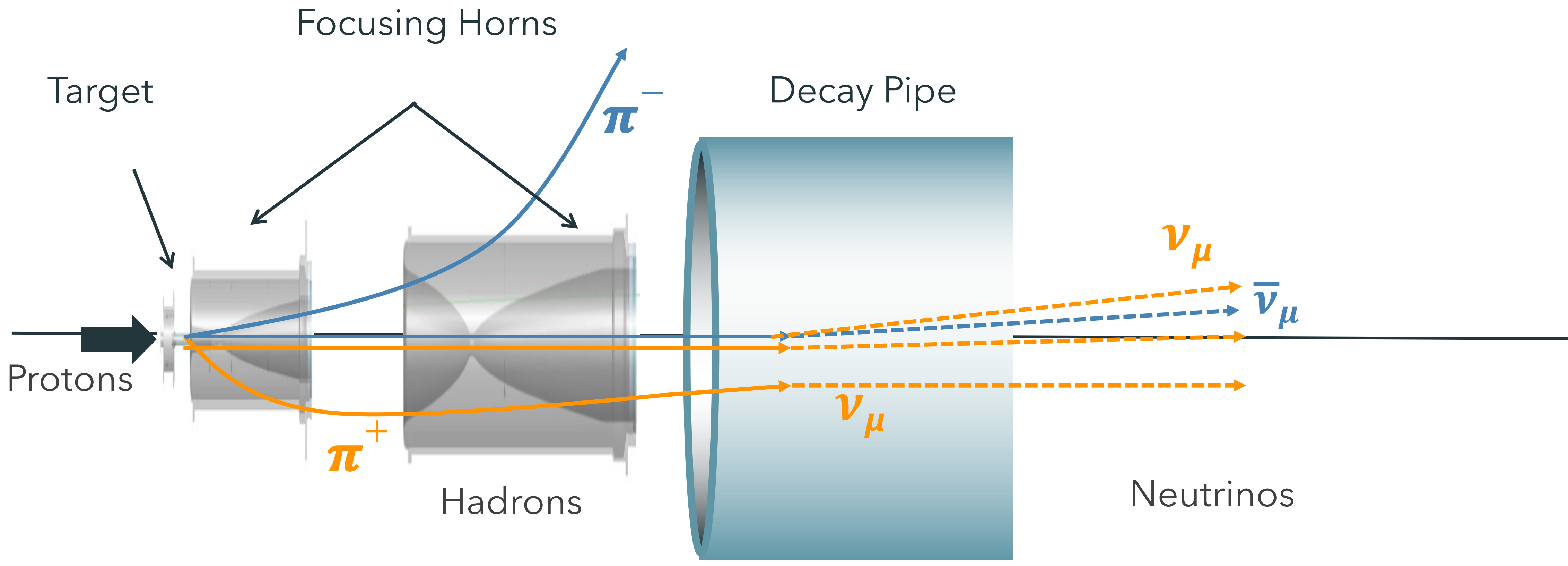
STEP 2: AIM

STEP 3: SMASH THINGS

STEP 4: FOCUS THE DEBRIS

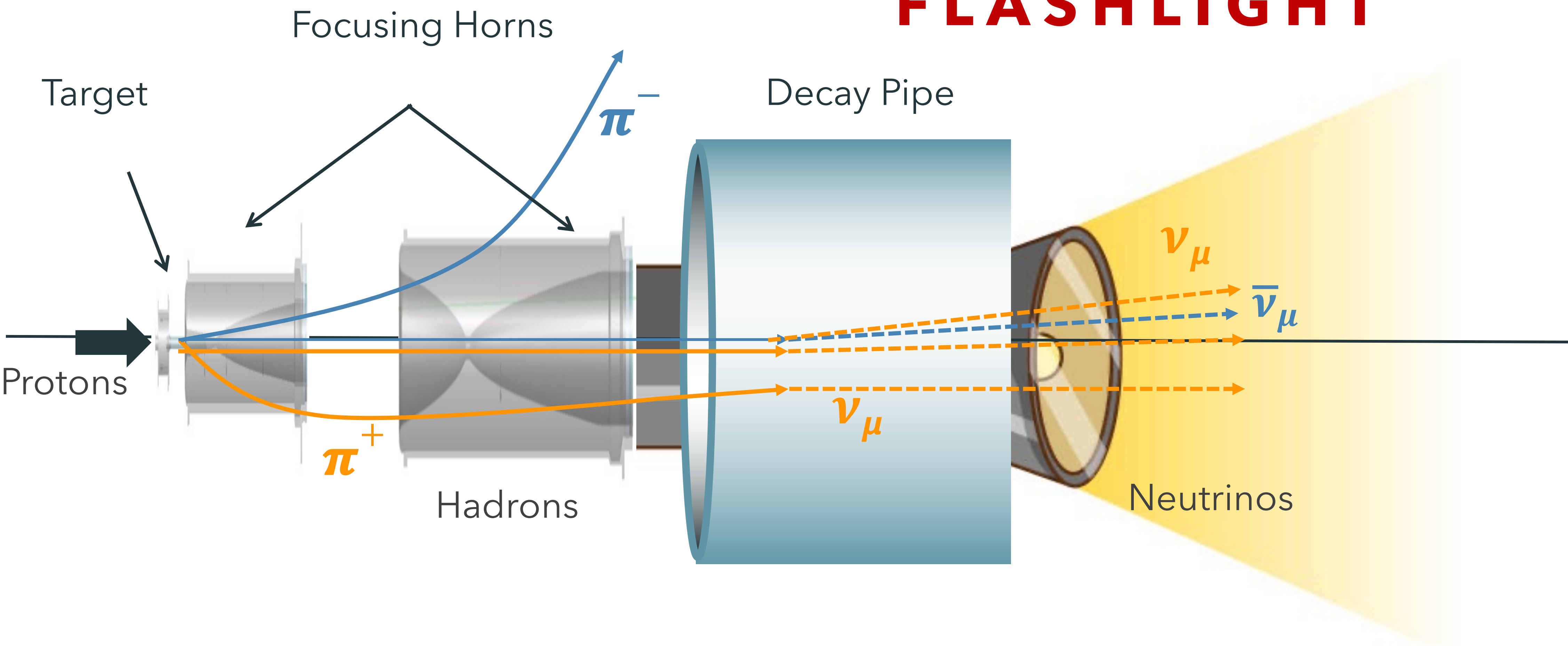
STEP 5: PHYSICS HAPPENS

HOW TO MAKE A NEUTRINO BEAM



- Reversing the polarity of the focusing horn magnets changes the sign selection of pions, resulting in a beam enhanced in antineutrinos.

HOW TO MAKE A NEUTRINO ~~BEAM~~ FLASHLIGHT



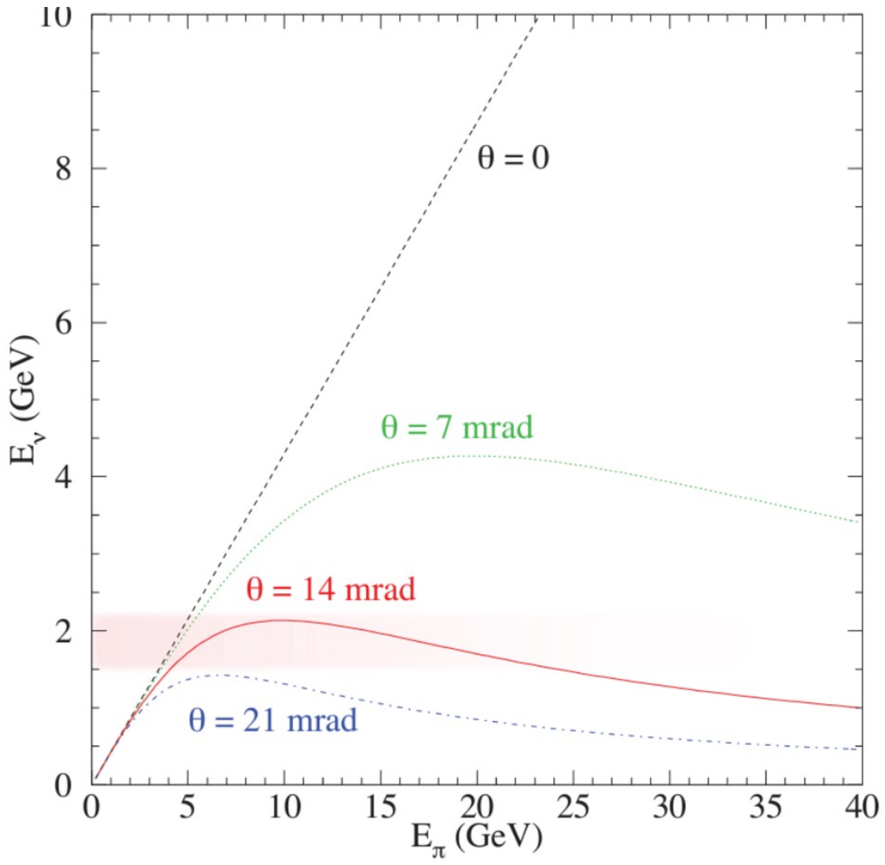
- The neutrino beam produced is analogous to a flashlight beam– spread out in space and over a range of energies, rather than being narrowly focused or monoenergetic.

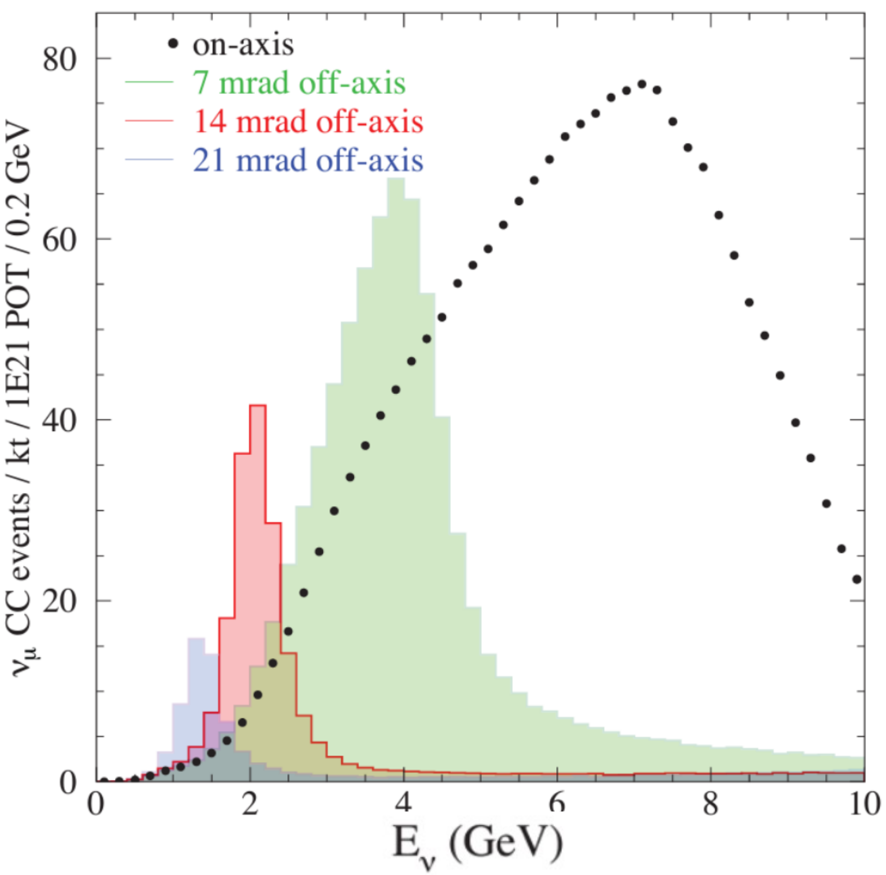
Slide inspiration Tricia Vahle

THE OFF-AXIS NEUTRINO BEAM

$$E_\nu = \frac{0.43 E_\pi}{1+\gamma^2\theta^2} \qquad \gamma = E_\pi / m_\pi$$

$\boldsymbol{\theta}$ is the angle between the pion and neutrino direction





THE OFF-AXIS NEUTRINO BEAM

$$E_\nu = \frac{0.43 E_\pi}{1 + \gamma^2 \theta^2} \qquad \gamma = E_\pi / m_\pi$$

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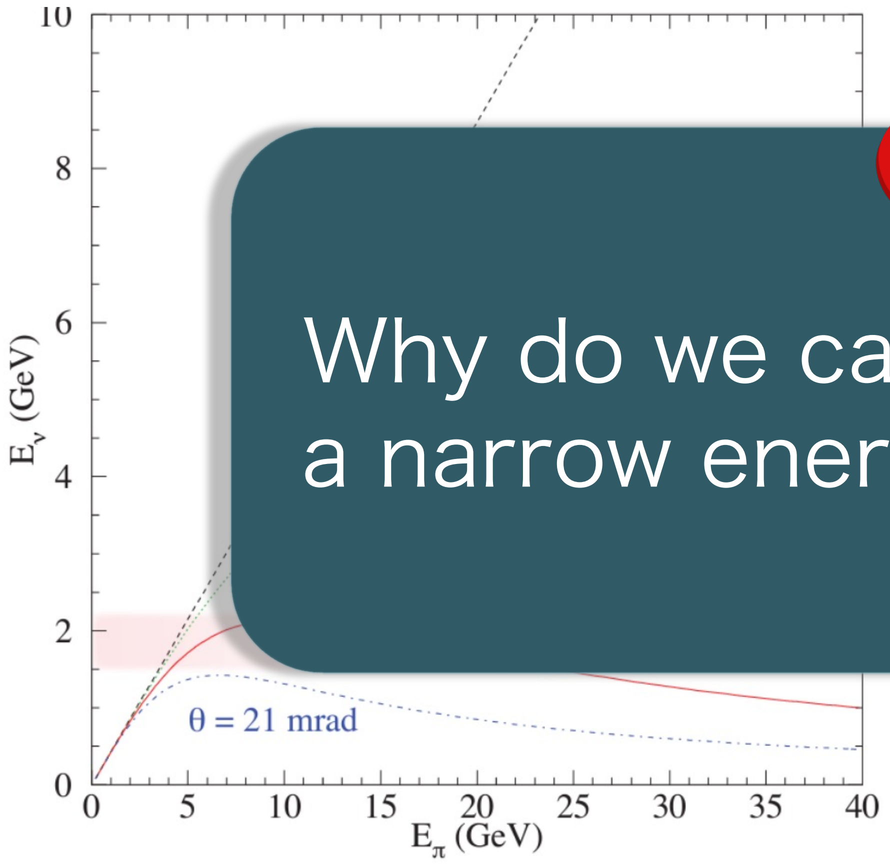
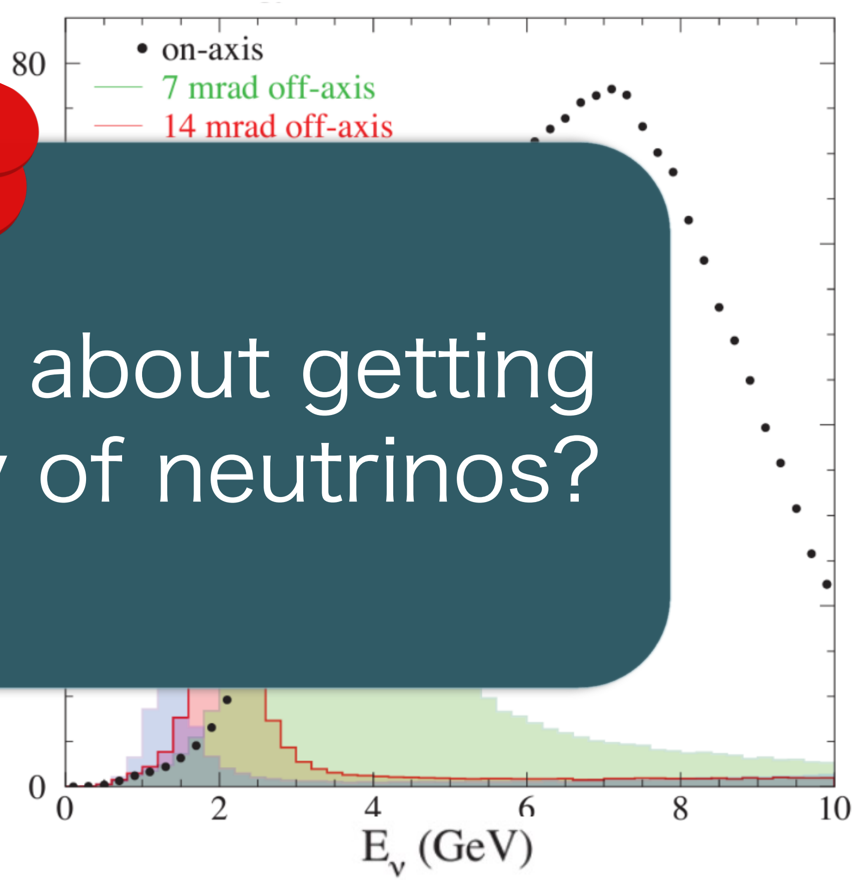
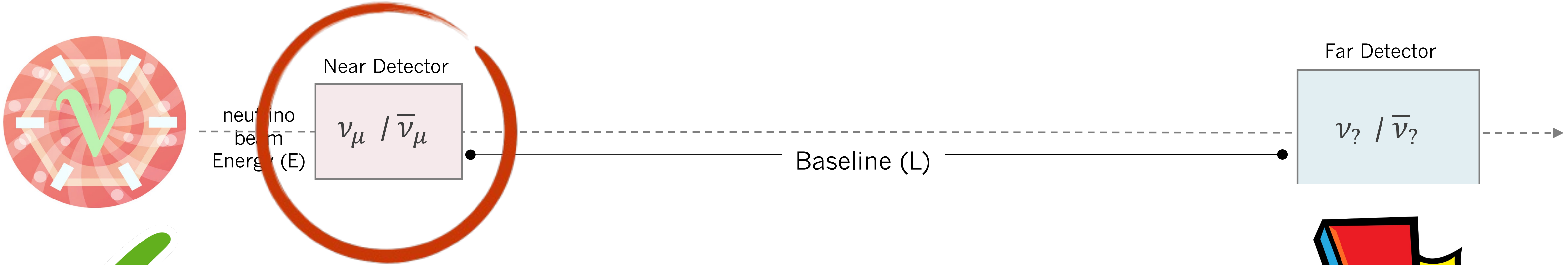




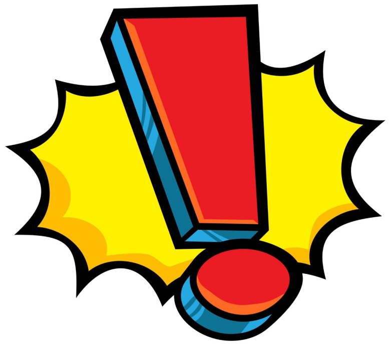
Why do we care about getting a narrow energy of neutrinos?

HOW TO BUILD AN ACCELERATOR NEUTRINO OSCILLATION EXPERIMENT?



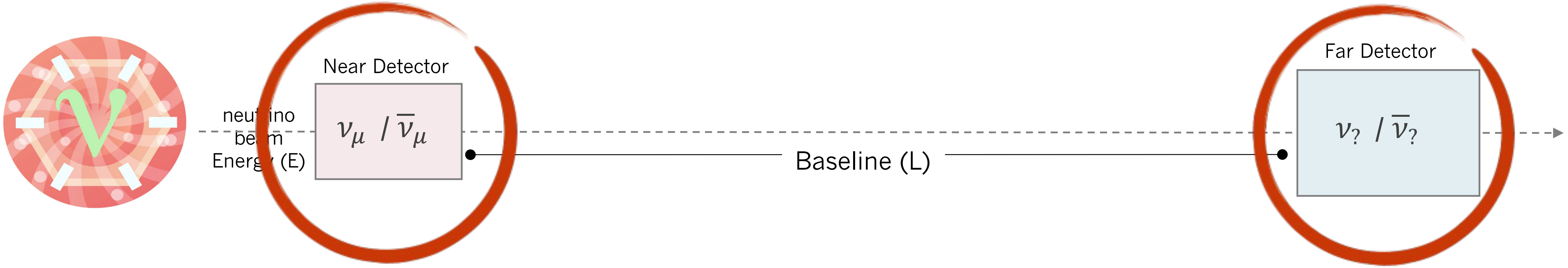
Neutrino beam of Energy E

What is this detector doing here?



Measure oscillations at the Baseline L

HOW TO BUILD AN ACCELERATOR NEUTRINO OSCILLATION EXPERIMENT?



Sample the beam
before oscillations

Measure oscillations

ROLE OF THE NEAR DETECTOR

NEAR DETECTOR

oscillation probability

cross-section

$$R(\vec{x}) = \phi(E_\nu) \times \sigma(E_\nu, \vec{x}) \times \epsilon(\vec{x}) \times P(\nu_A \to \nu_B)$$

Event rate

neutrino flux

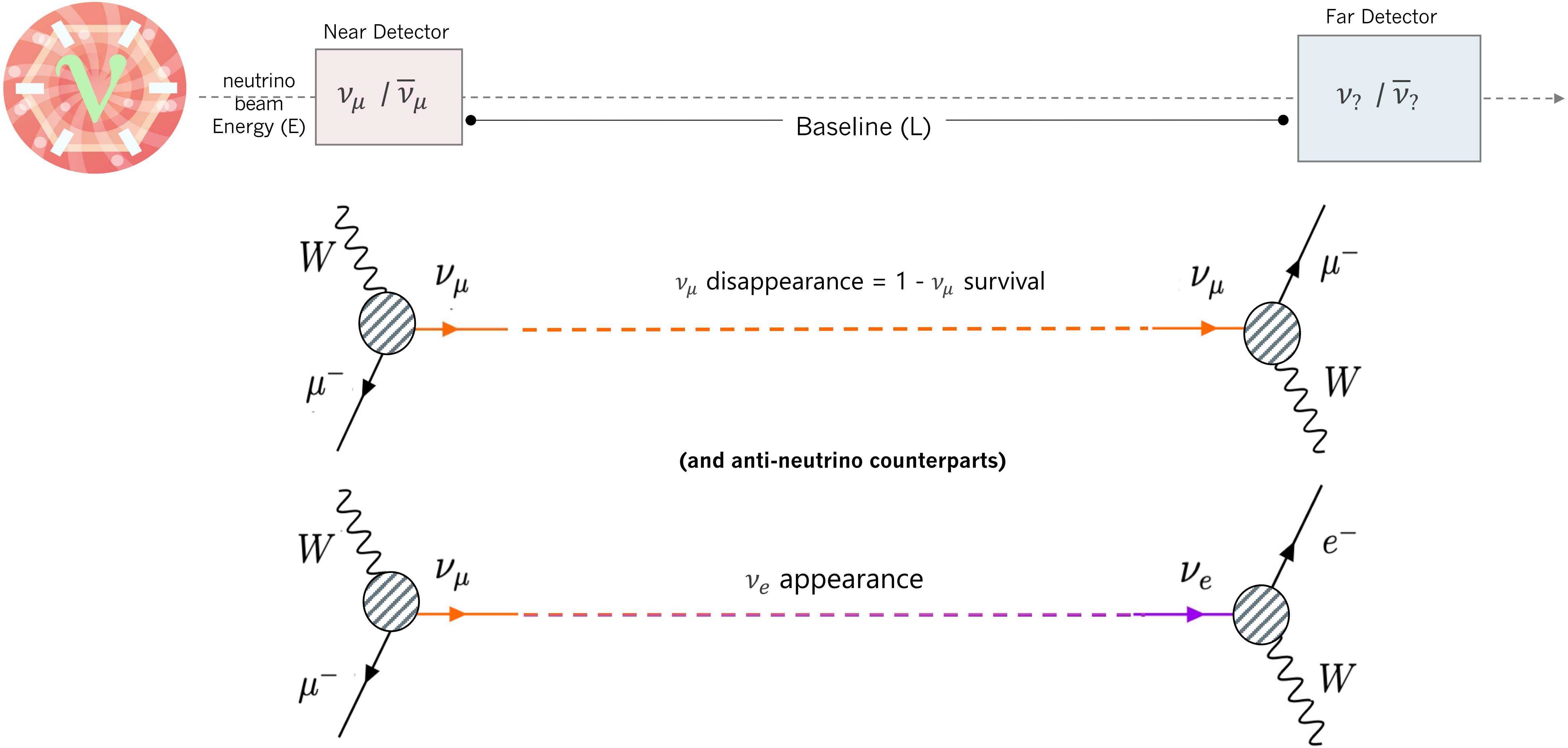
detector response

FAR DETECTOR

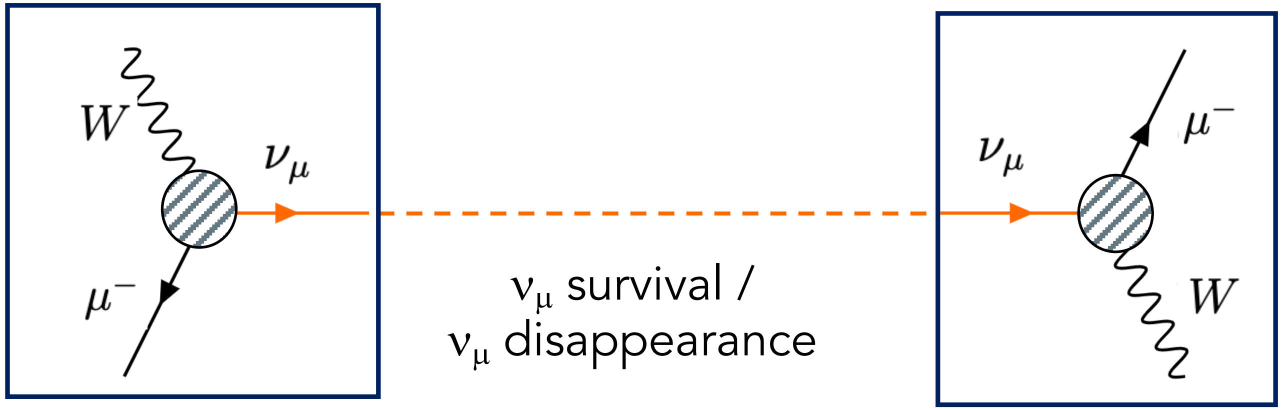
- Near Detector provides valuable data-driven cancelation and constraints on:
  - **neutrino flux**
  - **cross-section**, and
  - **detector uncertainties**

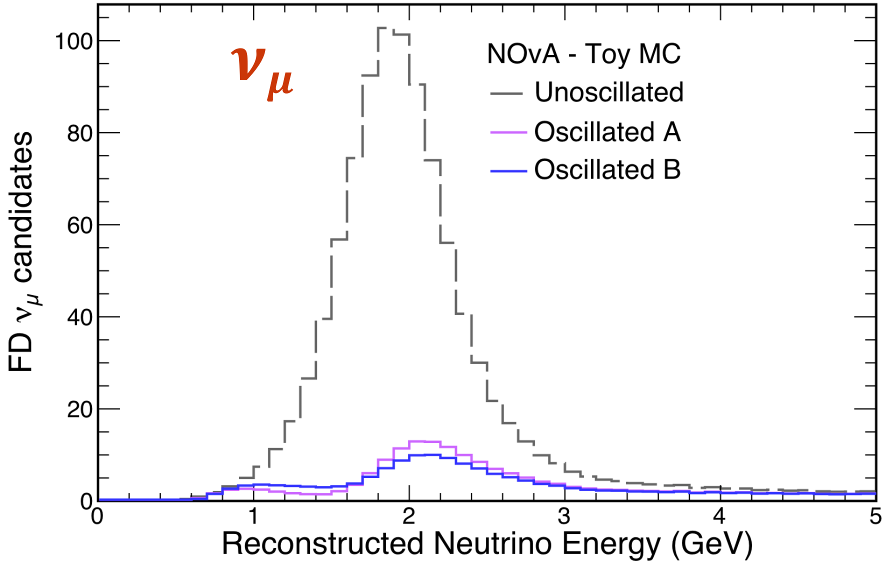
Never go on a long baseline adventure without a near detector – Anonymous.

ROLE OF THE FD

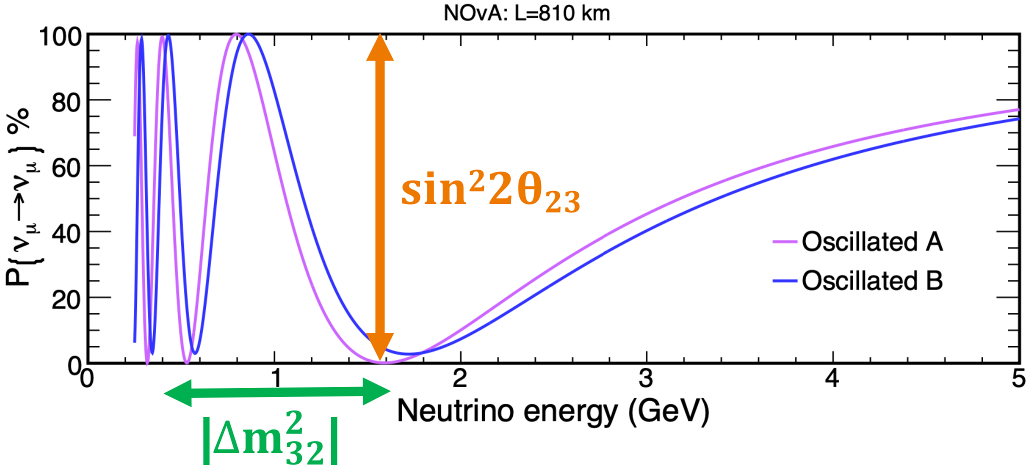


ν_μ DISAPPEARANCE AT FD



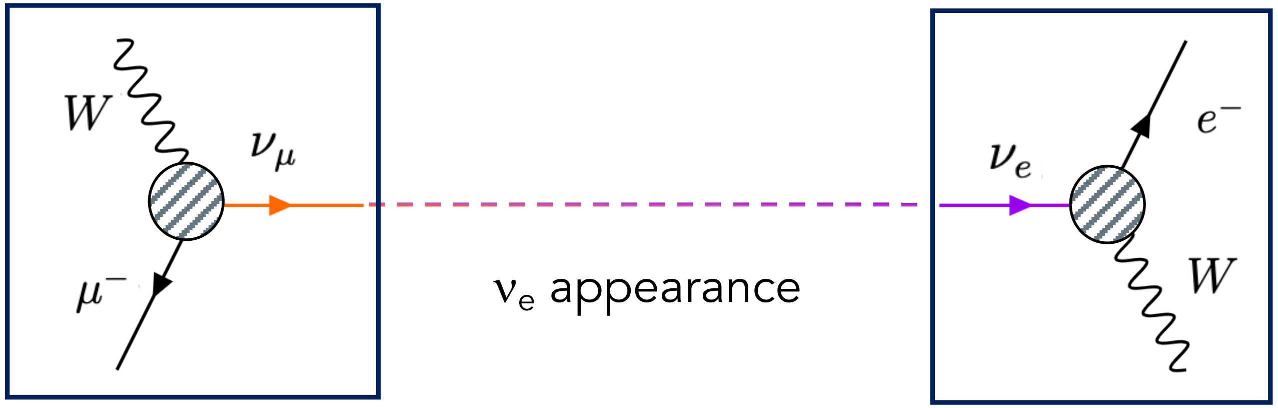


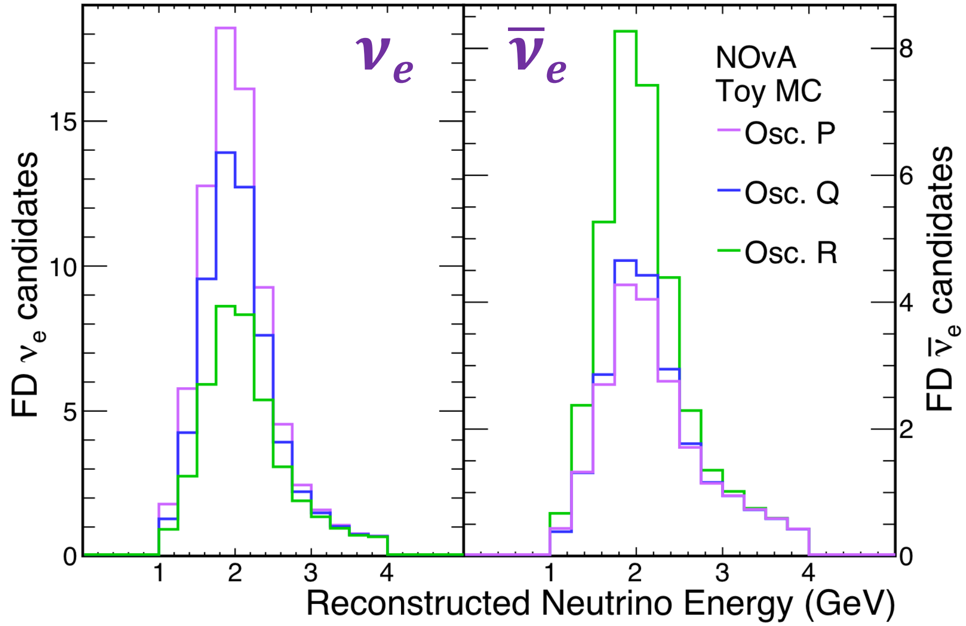
$$P\left(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu\right) \approx 1 - \boxed{\sin^2 2\theta_{23}} \sin^2\left(\boxed{\Delta m^2_{32}}\frac{L}{4E}\right)$$



- Leading order dependence on $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$
- If $\sin^2 2\theta_{23} = 1$, then maximal ν_μ disappearance.

ν_e APPEARANCE AT FD



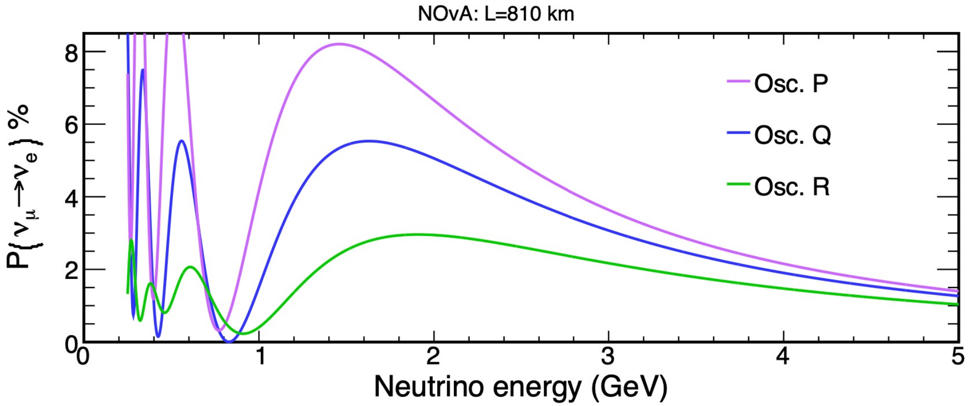


Mixing angles

Mass Ordering and $|\Delta m^2_{32}|$

CP Phase δ_{CP}

$$
\begin{aligned}
P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \simeq\ & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\
&+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31} \\
&\times\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}\pm\delta_{CP}) \\
&+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,
\end{aligned}
$$



- Opposite impact of matter effect and δ_{CP} for ν_e vs. $\bar{\nu}_e$ appearance probability.

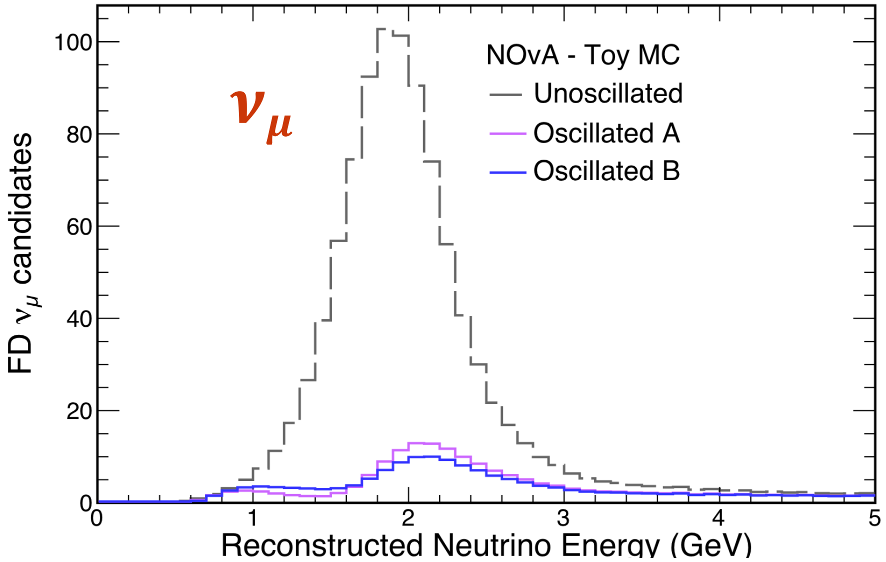
MEASURING OSCILLATIONS

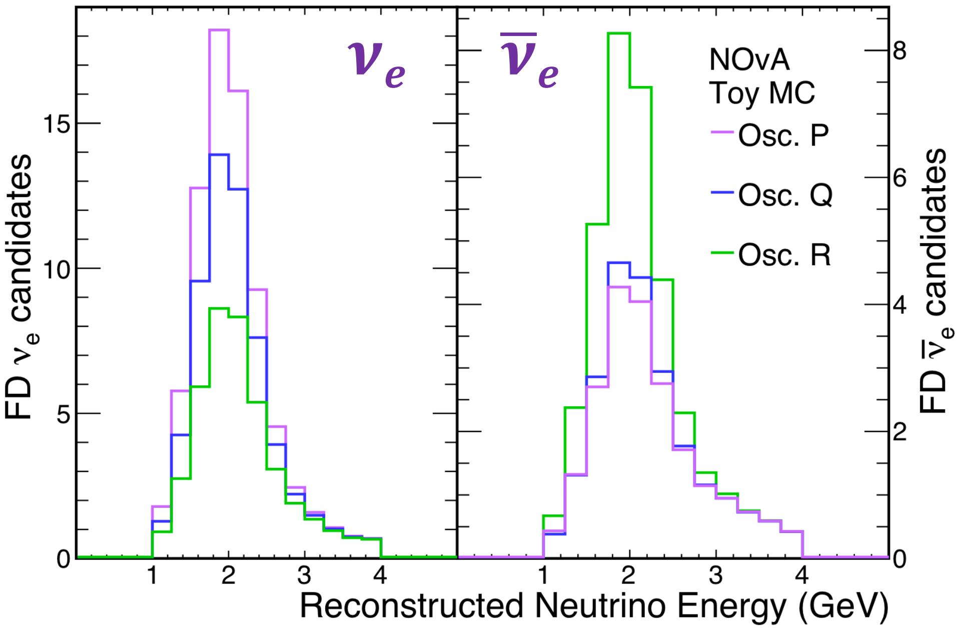
Measurement

1. **Detect** neutrino interactions.
2. **Tag** the flavor.
3. **Reconstruct** energy.

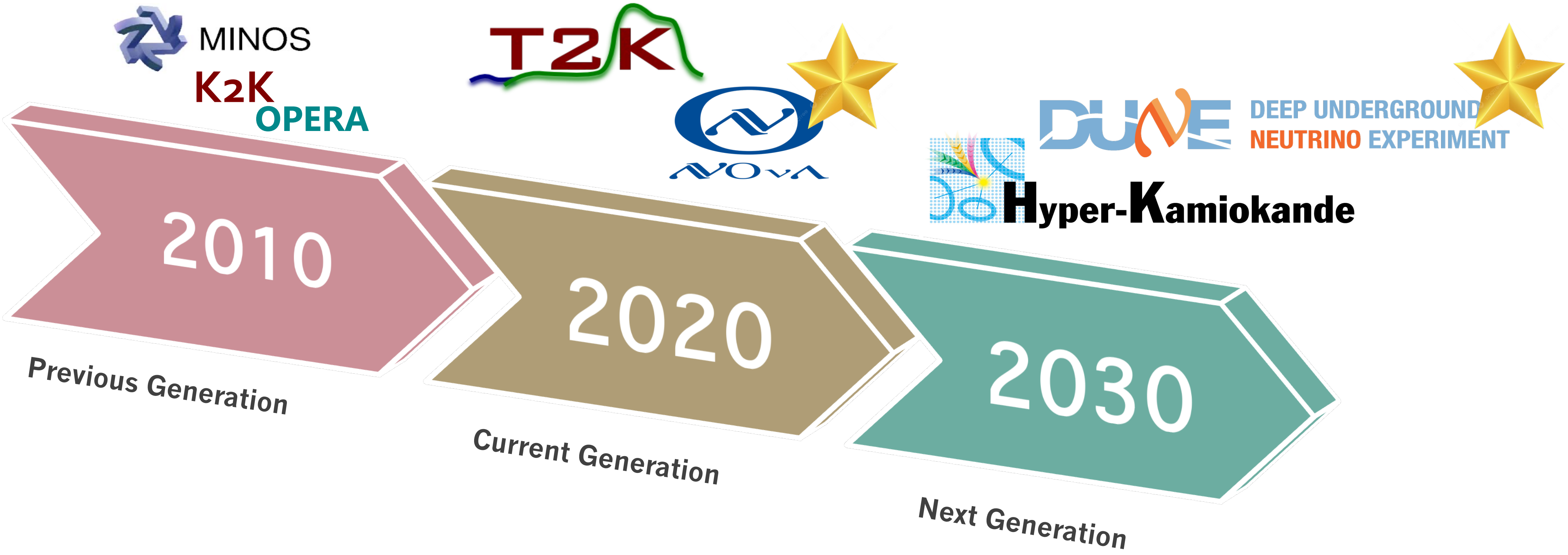
Inference

1. Compare with the no oscillation prediction.
2. Compare ν_e and $\bar{\nu}_e$ appearance rate.





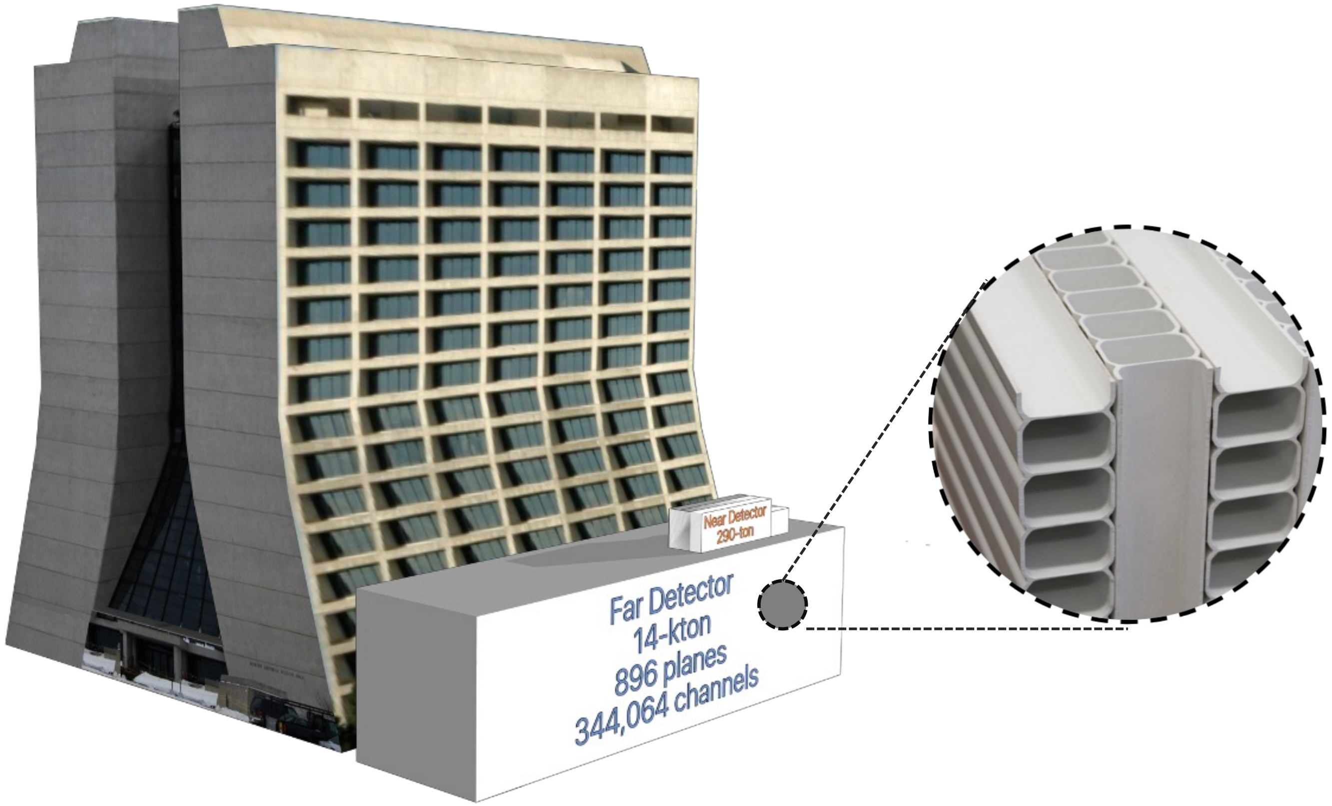
3 GENERATIONS OF LONG-BASELINE EXPERIMENTS



MEASURING OSCILLATIONS WITH NOvA

1. **Detect** neutrino interactions.
2. **Tag** the flavor.
3. **Reconstruct** energy.

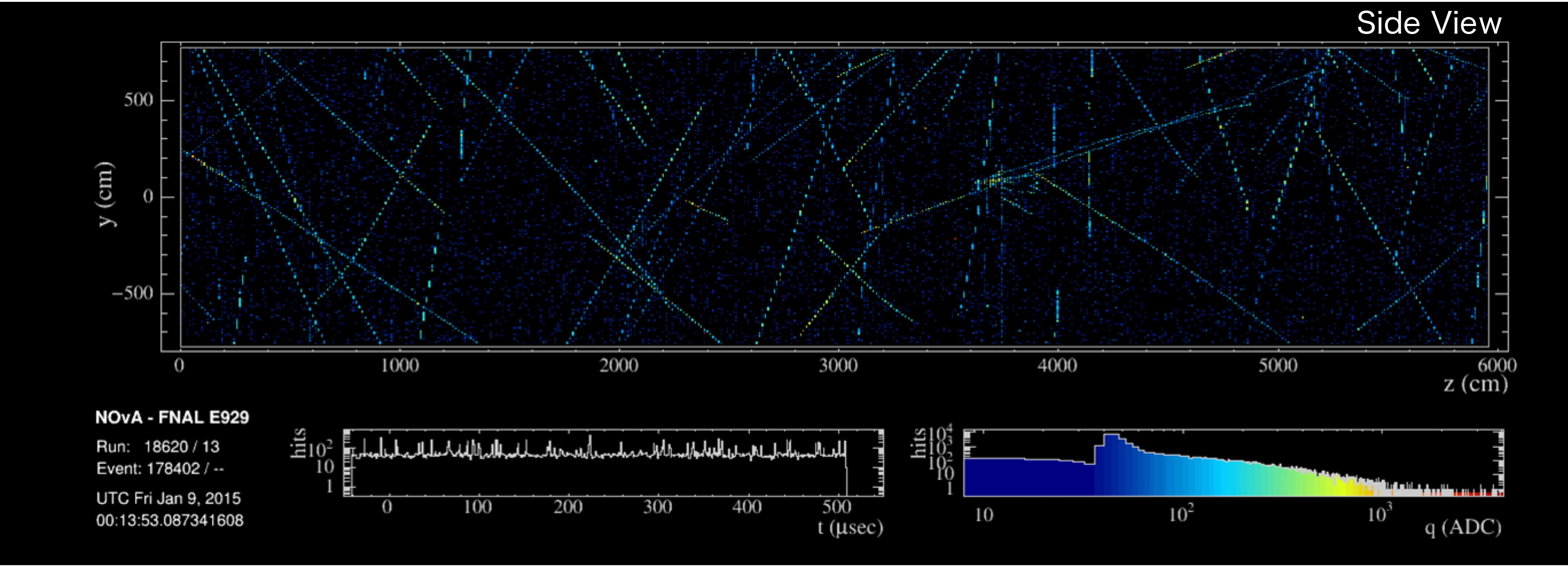
NOvA DETECTORS



NOvA FD

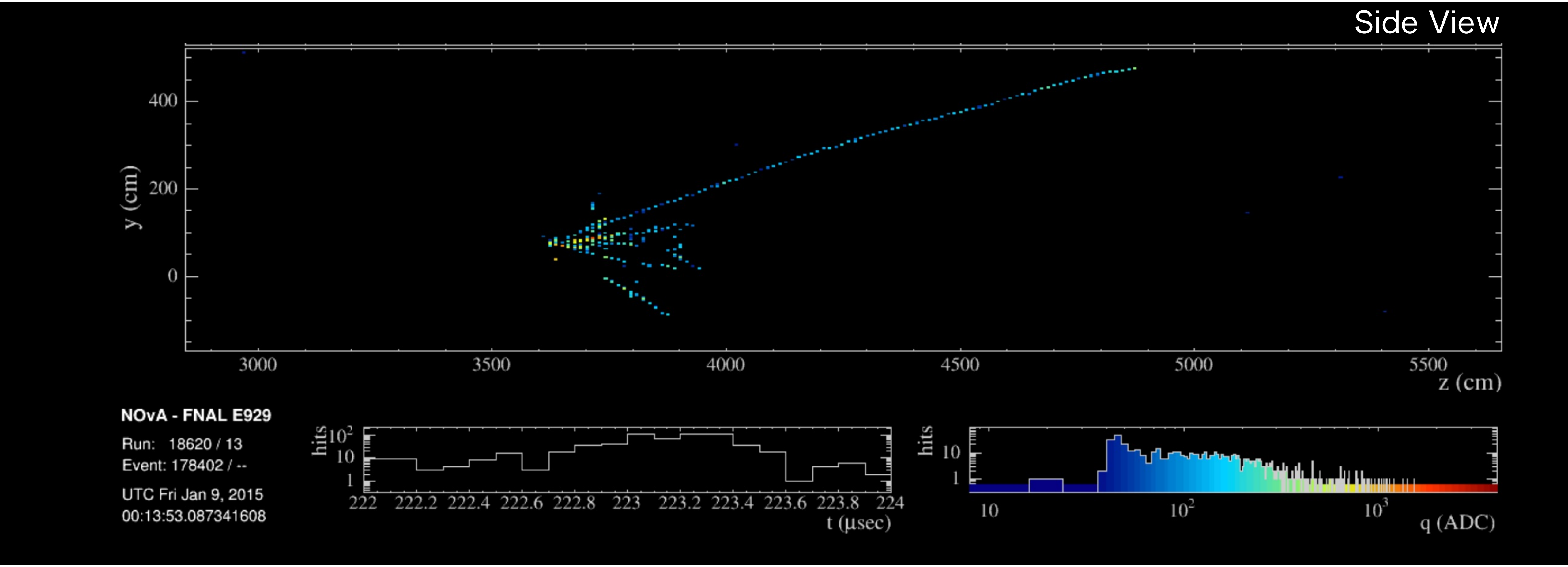
- NOvA's ND and FD are **functionally identical segmented liquid scintillator detectors.**
  - ND: ~290 t and ~100 m underground
  - FD: ~14 kt and on the surface

NOvA DETECTORS



- ~150 kHz of cosmic rays at the FD which is on the surface.

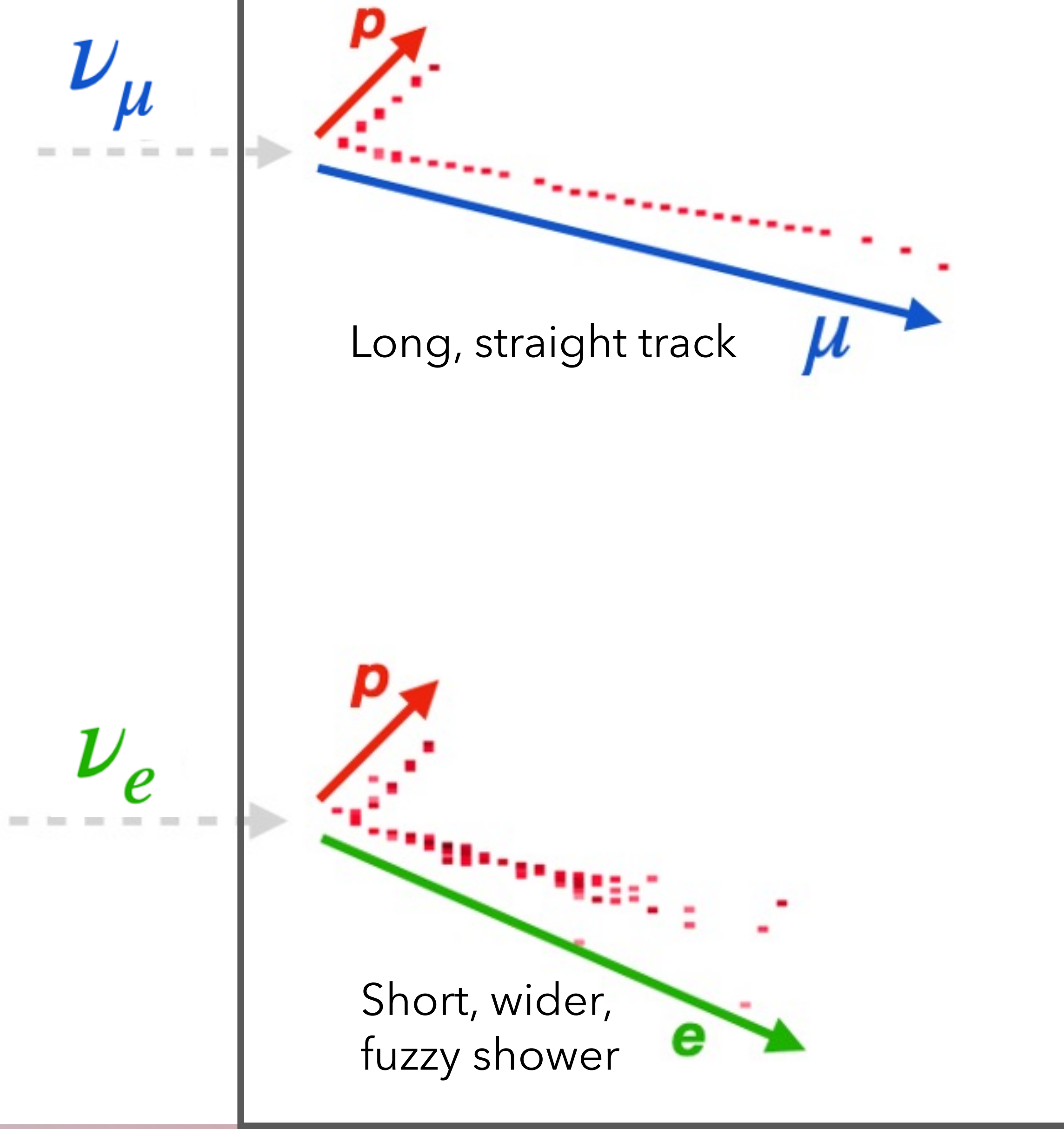
NOvA DETECTORS



- Good spatial resolution (~few cm) and timing resolution (~10ns) allows to isolate neutrino interaction from 99% of cosmic backgrounds.

TAG FLAVOR & RECONSTRUCT ENERGY

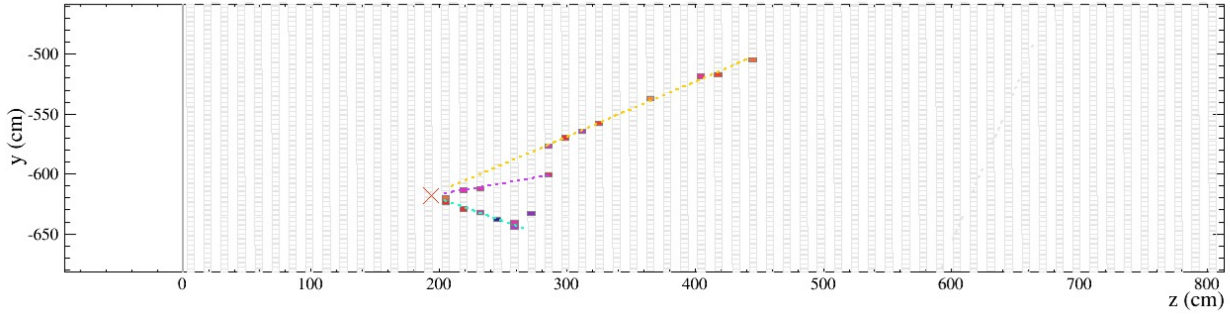
- Detectors are optimized for EM showers.
  - ~6 samples per radiation length (~40 cm) making **muon-electron** identification easy.
- Neutrino interaction candidates are identified using a **convolutional neural network (CNN)**
- Energy is reconstructed via **tracking (muon)** and **calorimetry** (**electromagnetic**, **hadronic**)



10 YEARS OF NOvA DATA

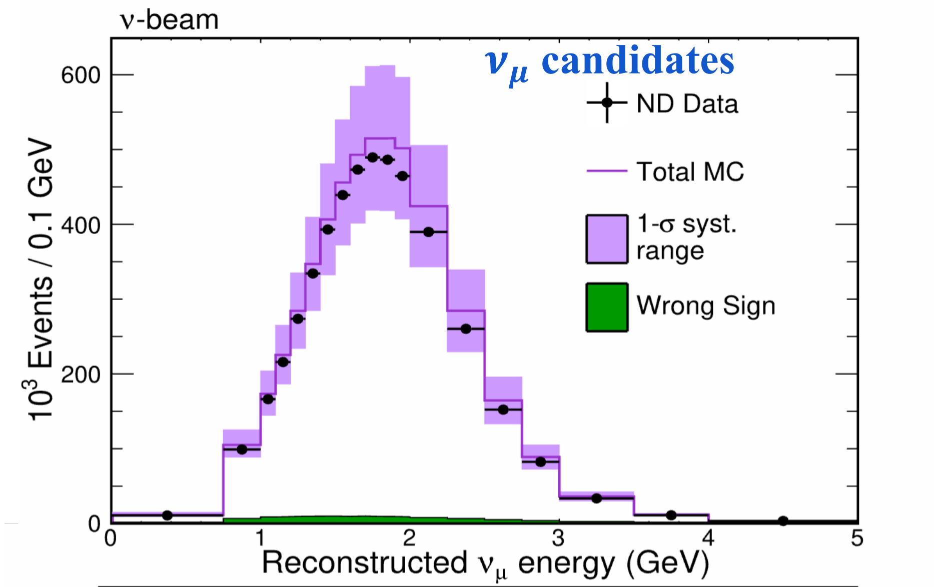
- 2024 marked 10 years of data collection!

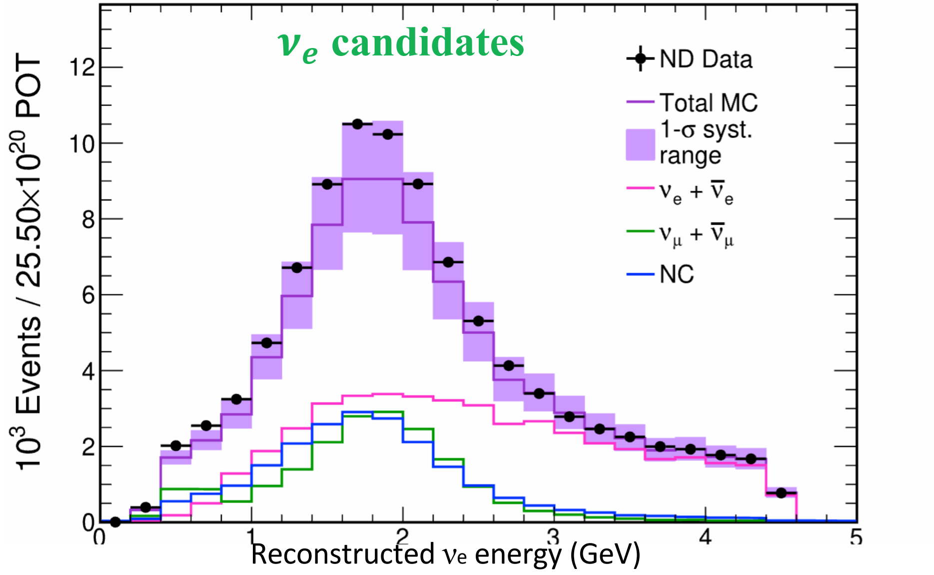
February 5th, 2014 – NOvA's Period 1 data taking began with run 12941 at 11:57 pm



February 11, 2014 - NOvA "1st Neutrino Event" Celebration in the Main Control Room

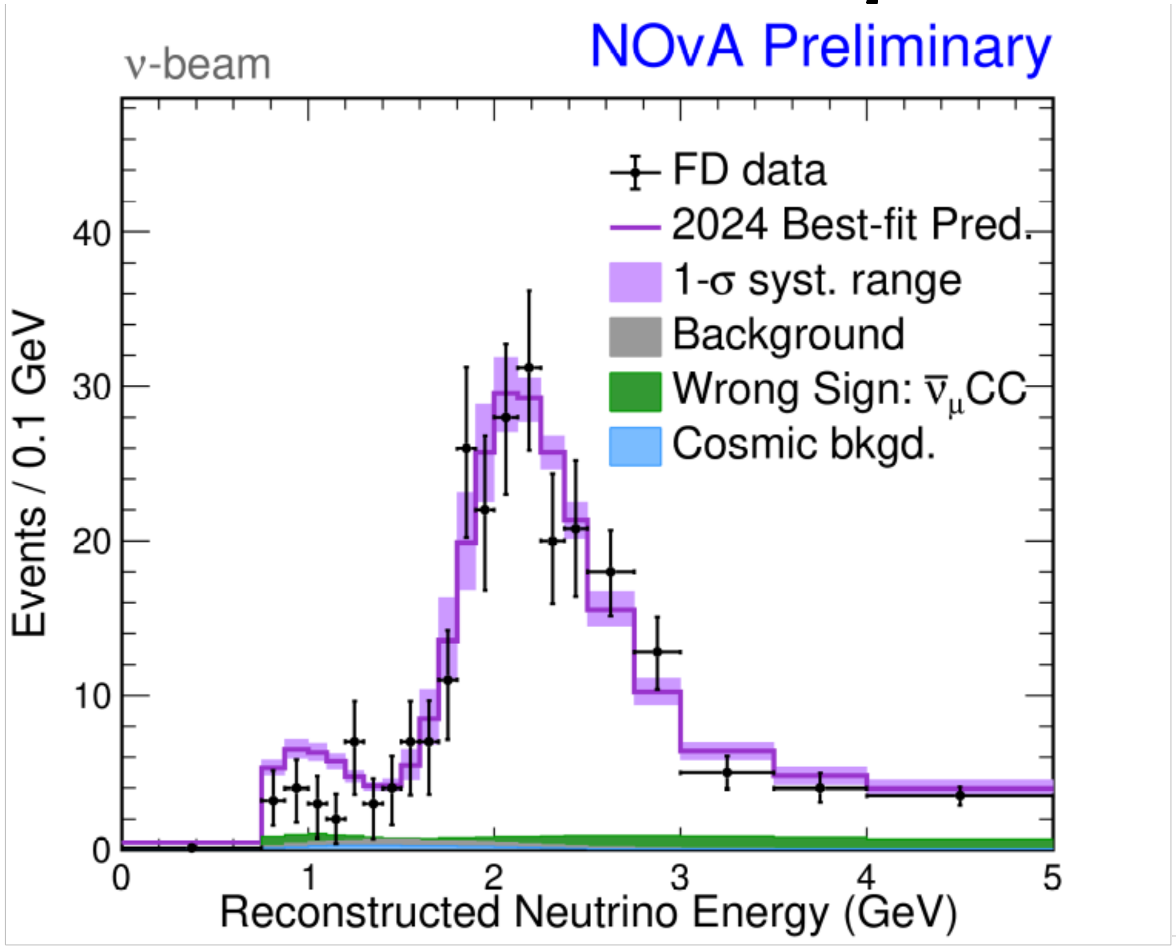
NEAR DETECTOR DATA

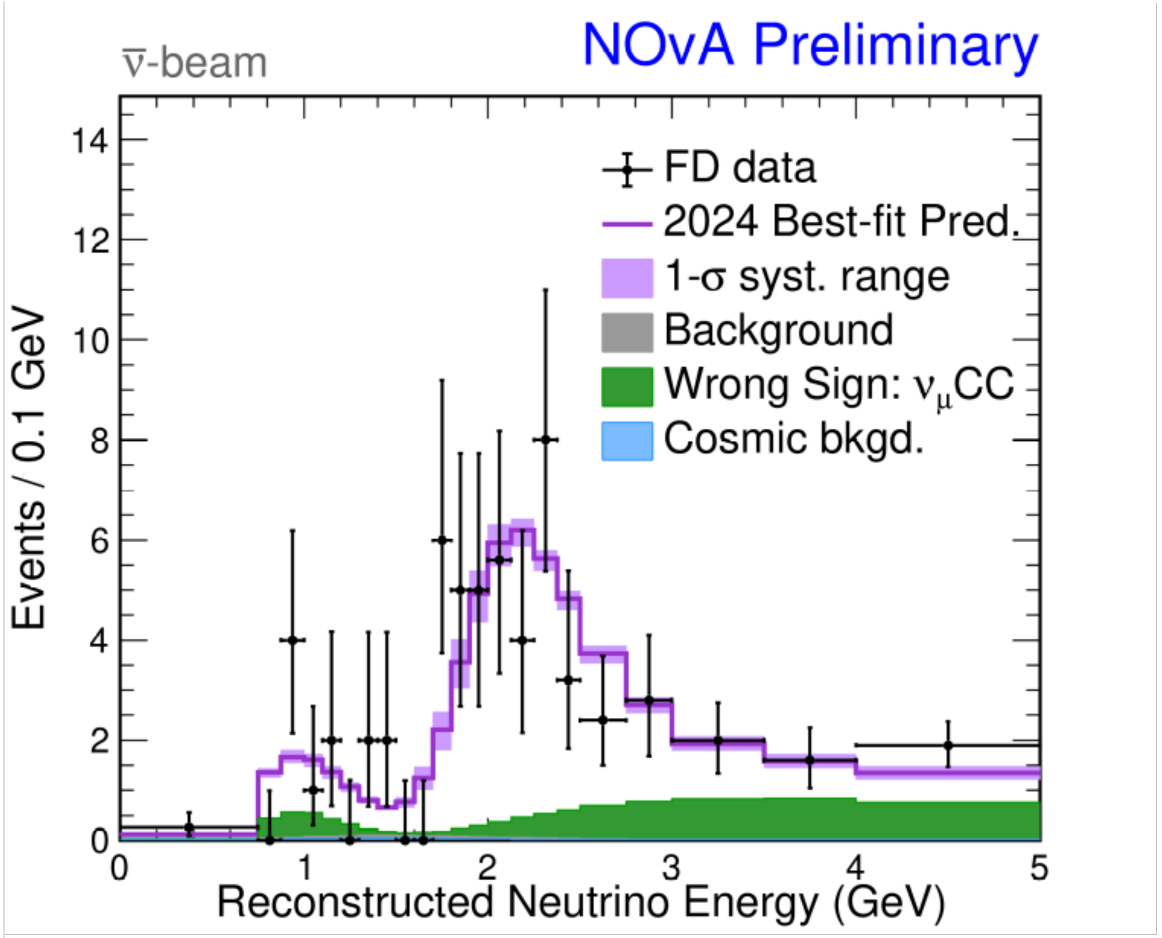




- Exceptional statistics at the ND leads to negligible statistical uncertainty.
  - **~6.5M ν_μ (~1.5M)**candidate events
    - Use this sample to predict both ν_μ and ν_e at the FD
  - **~100k ν_e** candidate events
    - Background intrinsic beam ν_e prediction at the FD.

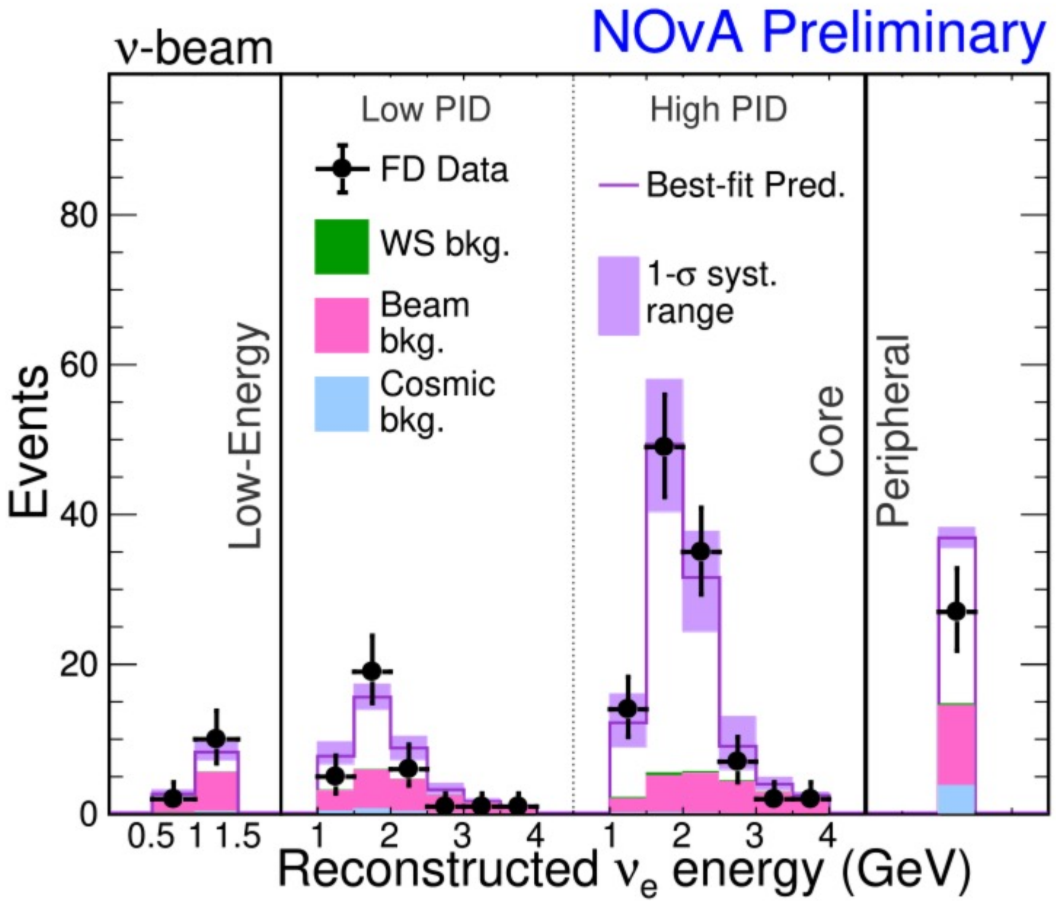
FD SAMPLES: ν_μ

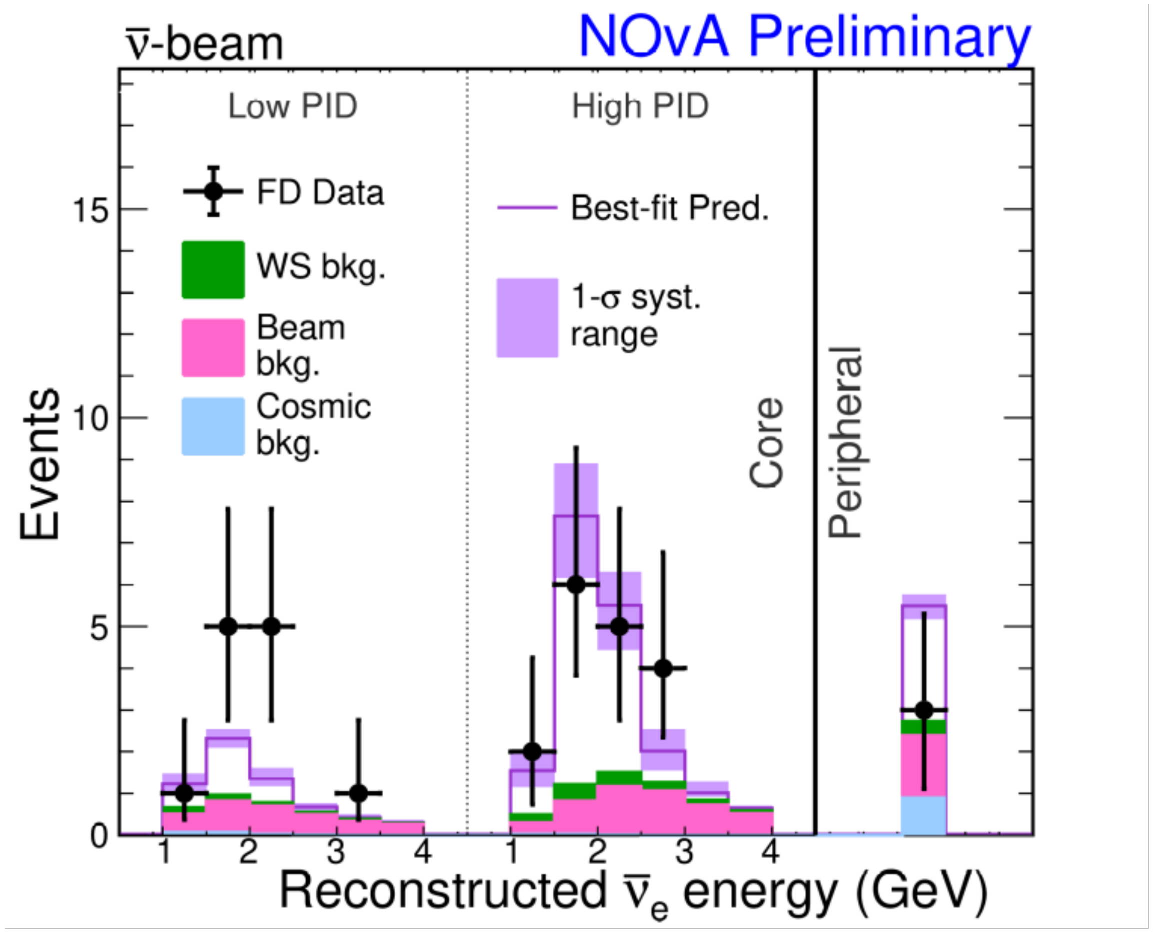




- Observed **384** $\boldsymbol{\nu_\mu}$ and **106** $\boldsymbol{\bar{\nu}_\mu}$ candidates
  - In the absence of oscillations, we'd expect ~2100 and ~500.

FD SAMPLES: ν_e

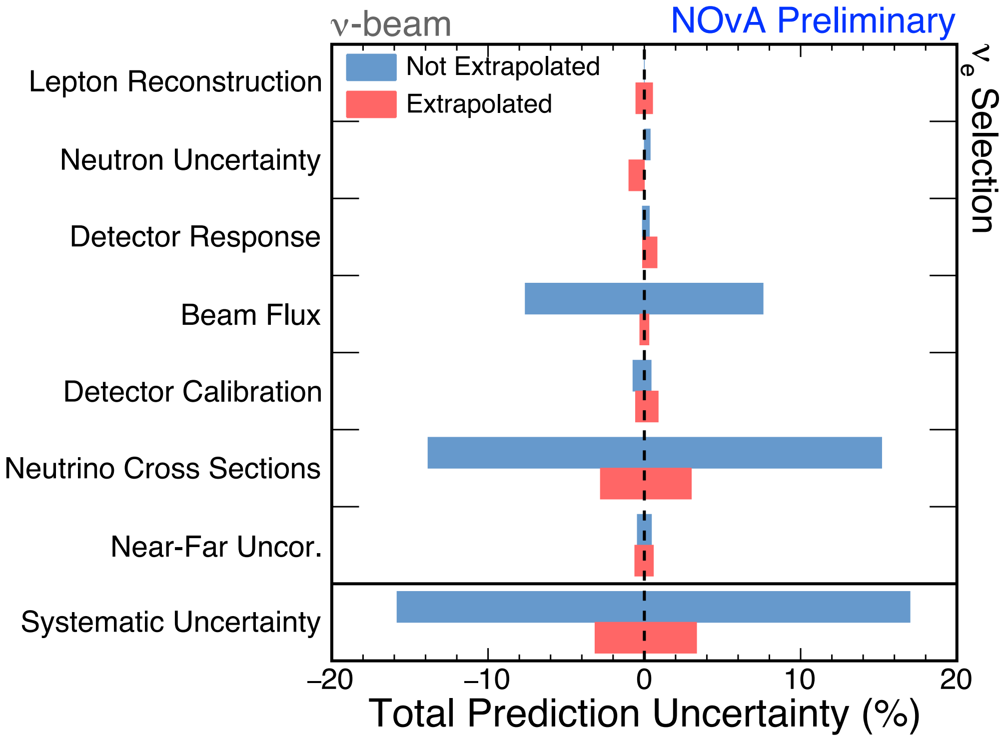




- We observe **181 ν_e** and **32 $\bar{\nu}_e$** appearance candidates.
  - The predicted backgrounds are 62 and 12 respectively.

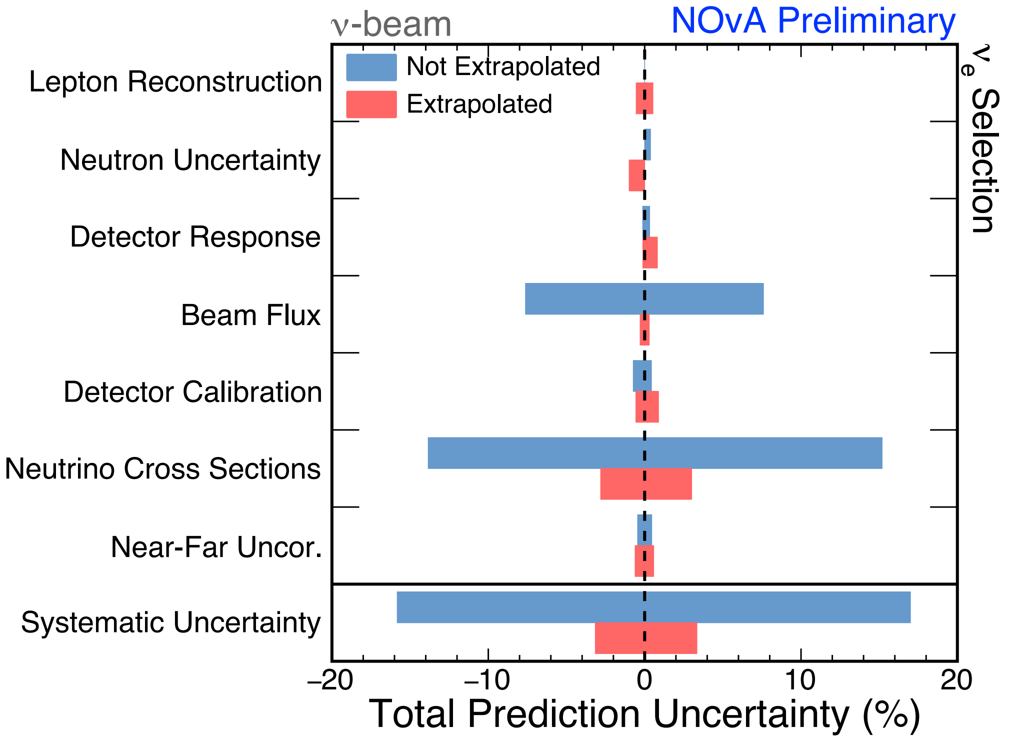
SYSTEMATICS

Example: Systematic uncertainties on the ν_e candidate count: without ND vs with ND constraints

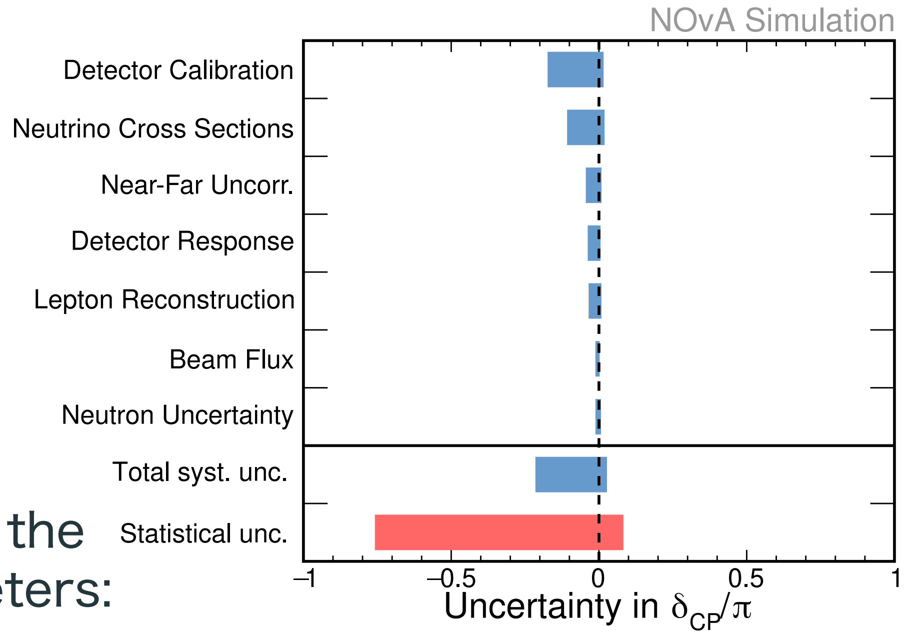


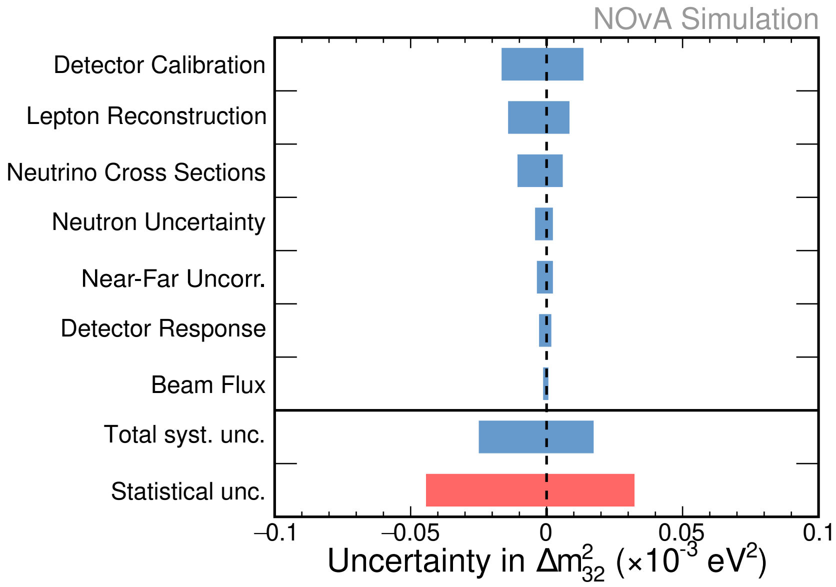
SYSTEMATICS

Example: Systematic uncertainties on the ν_e candidate count: without ND vs with ND constraints



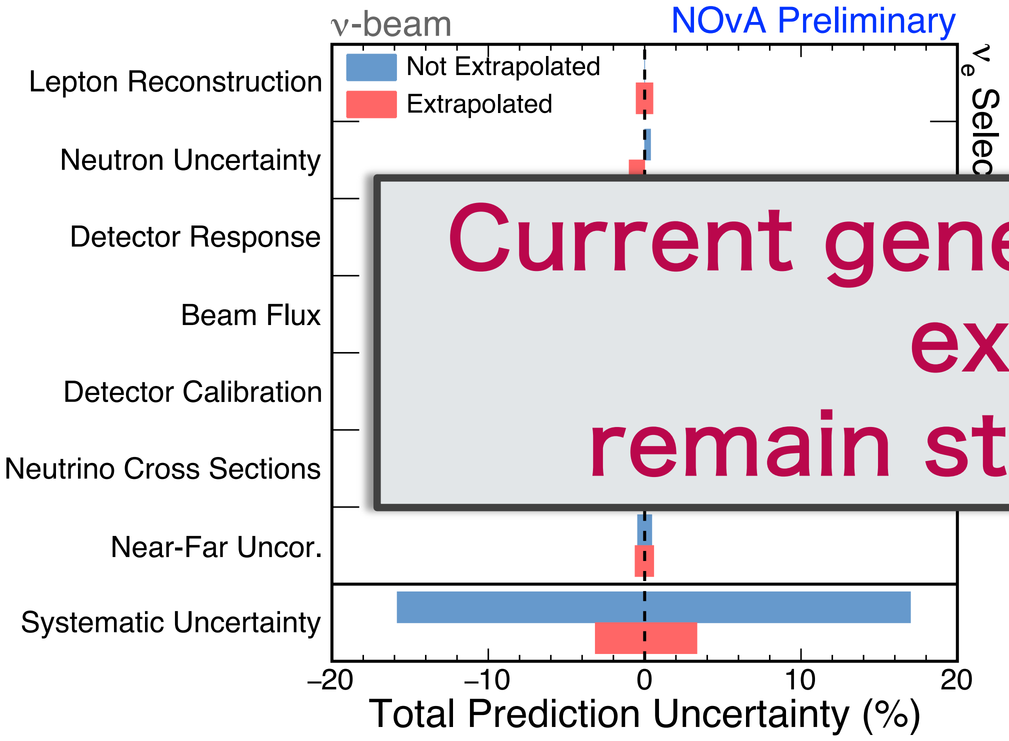
Uncertainties on the oscillation parameters: statistical vs systematic



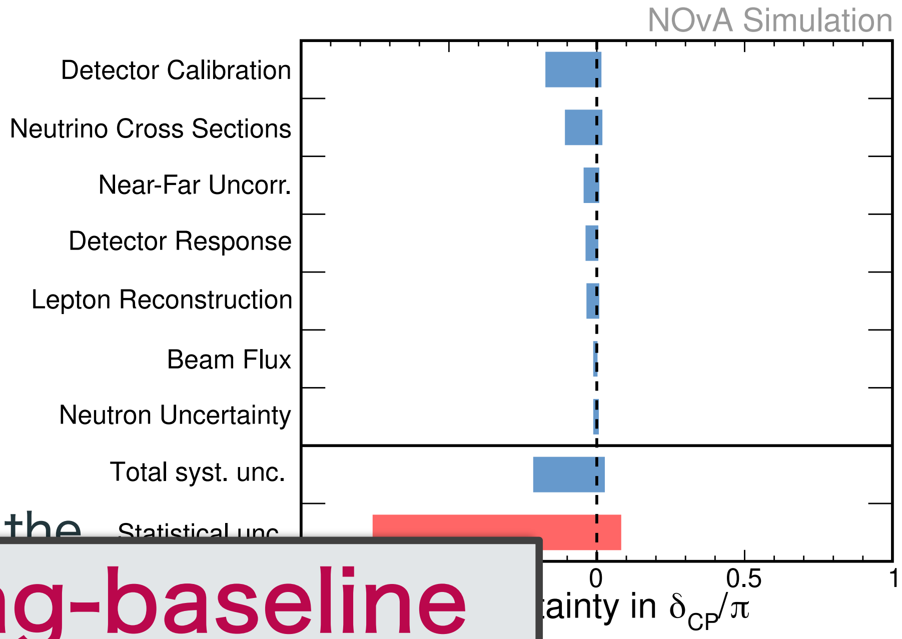


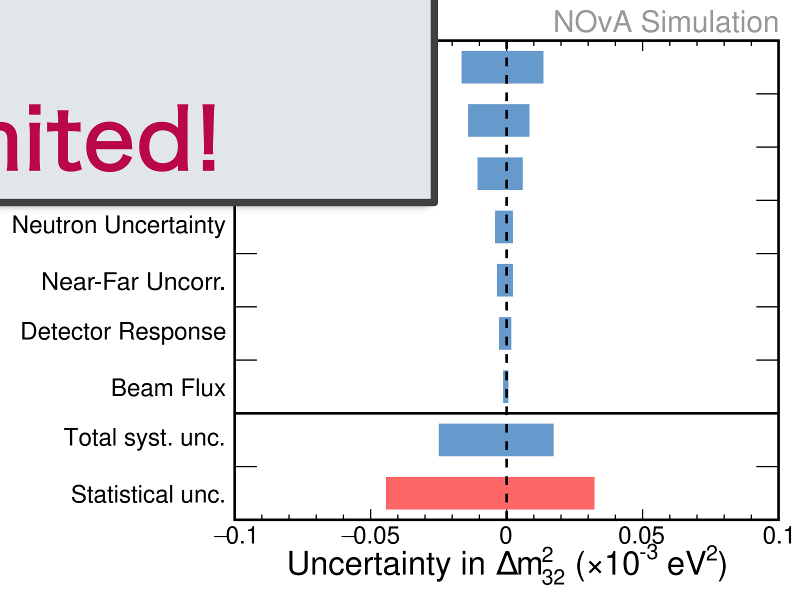
SYSTEMATICS

Example: Systematic uncertainties on the ν_e candidate count: without ND vs with ND constraints



Uncertainties on the

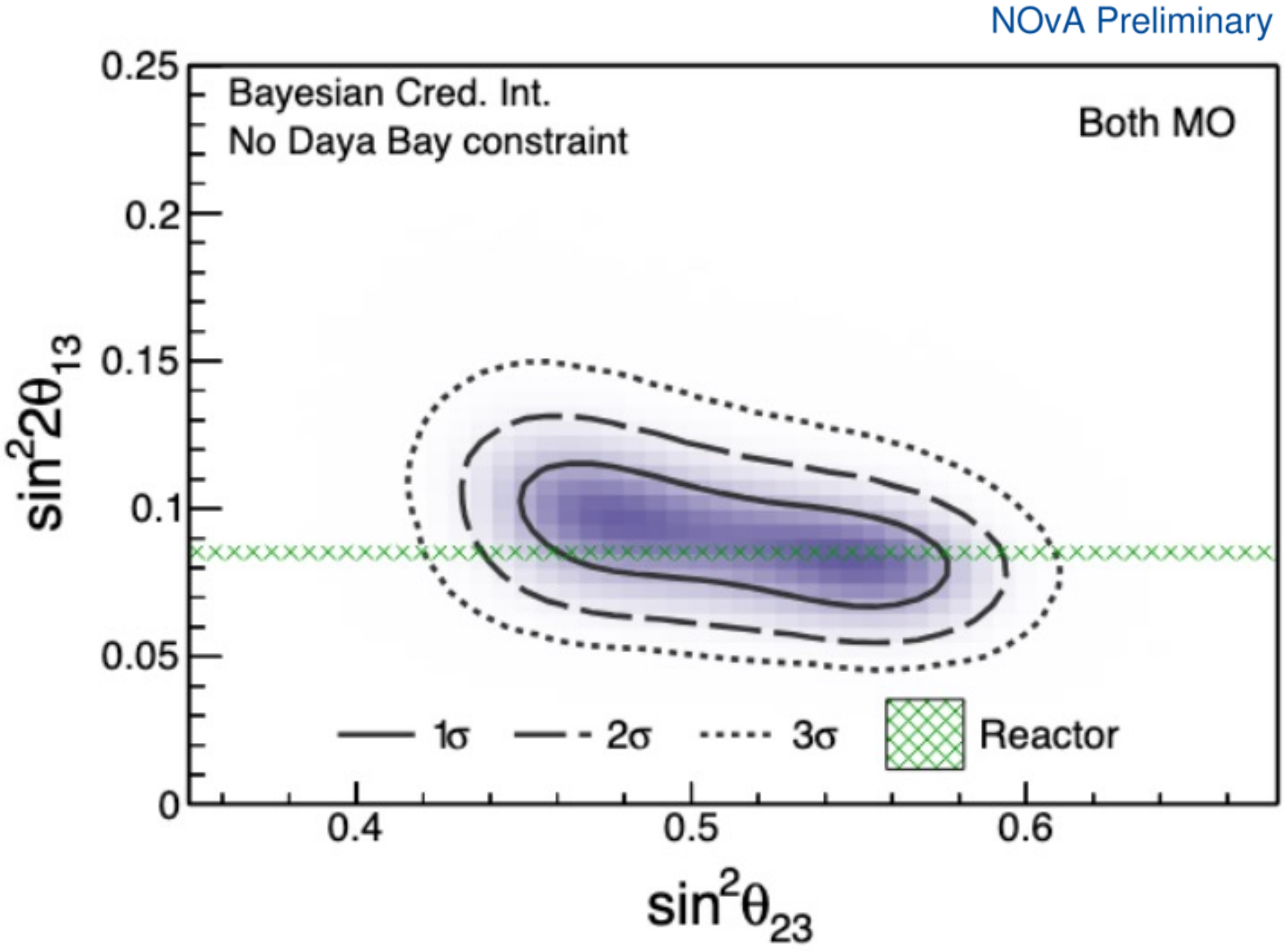




Current generation long-baseline experiments remain statistically limited!

θ_{13} vs θ_{23}

- Accelerator experiments have a degeneracy between the measurement of mixing angles θ_{13} and θ_{23}
- Reactor experiments provide a highly precise measurement of θ_{13} using distinct oscillation channels.

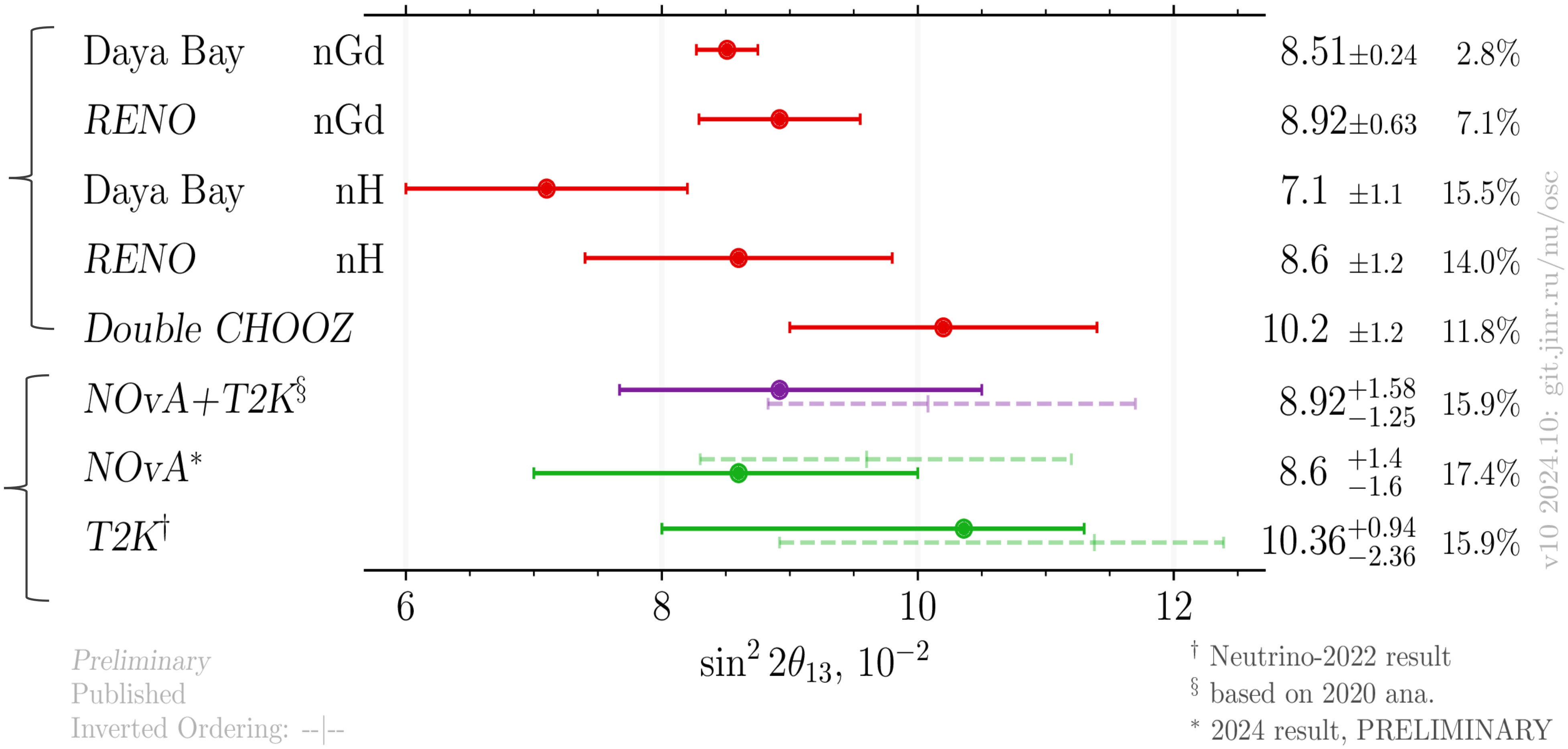


θ_{13}

Consistent measurements of θ_{13} across reactor and accelerator experiments, provides evidence of the robustness of the PMNS framework of neutrino mixing.

Reactor Experiments

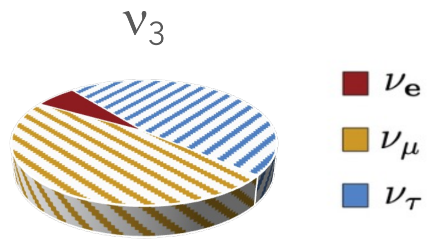
Accelerator Experiments



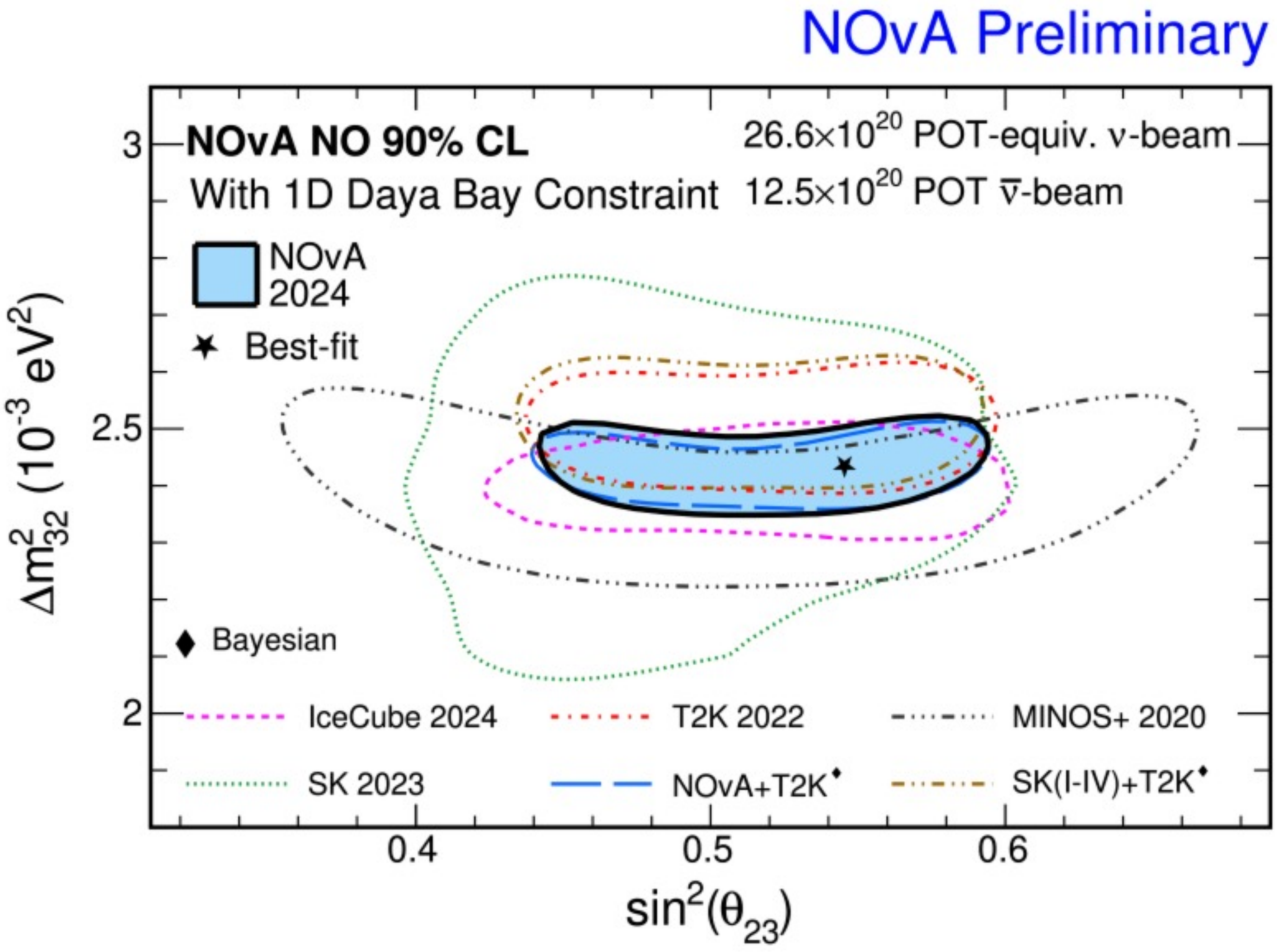
Δm^2_{32} AND θ_{23}

Note: Accelerator experiments use θ_{13} constraint from reactor experiments

- Global consistency across accelerator, atmospheric and joint-fit results.
- All data is **consistent with maximal mixing (θ_{23} = 45°)** hypothesis.

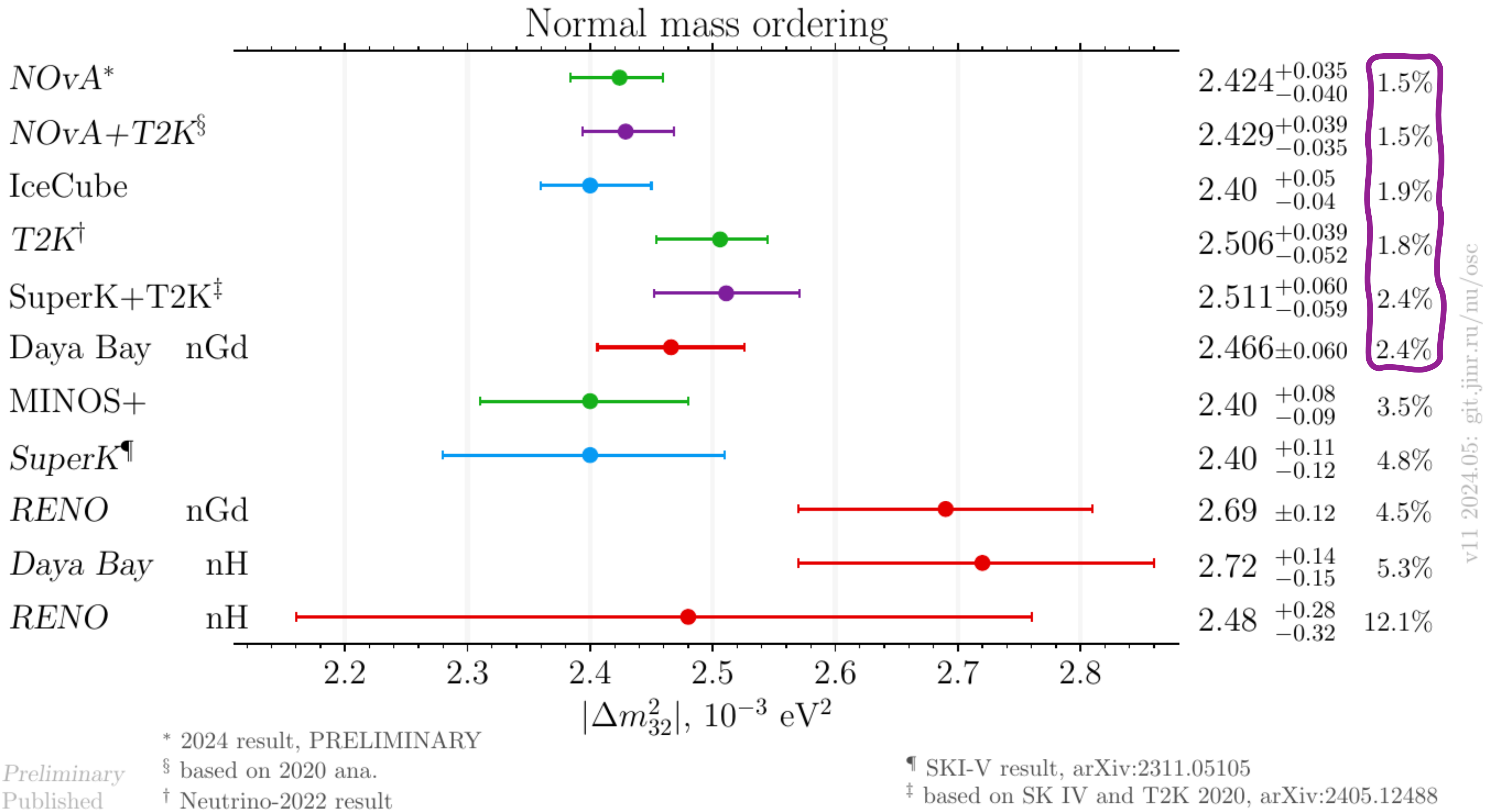


If θ_{23} = 45° → $|U_{\mu 3}| = |U_{\tau 3}|$

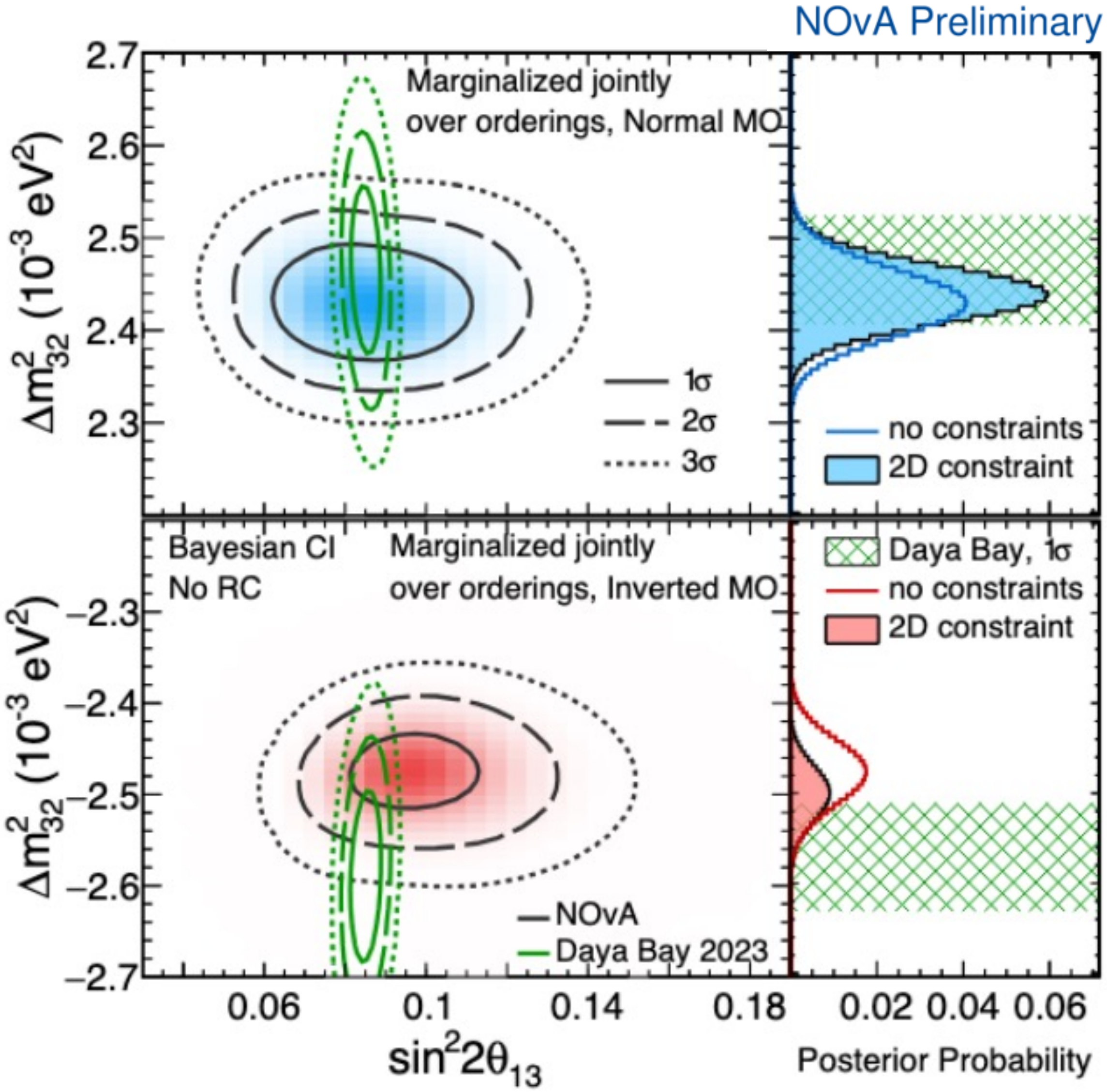


Δm^2_{32}

- Unprecedent precision on atmospheric mass-splitting in the last ~2 years.
- It is now the **most precisely measured parameter** in the framework!



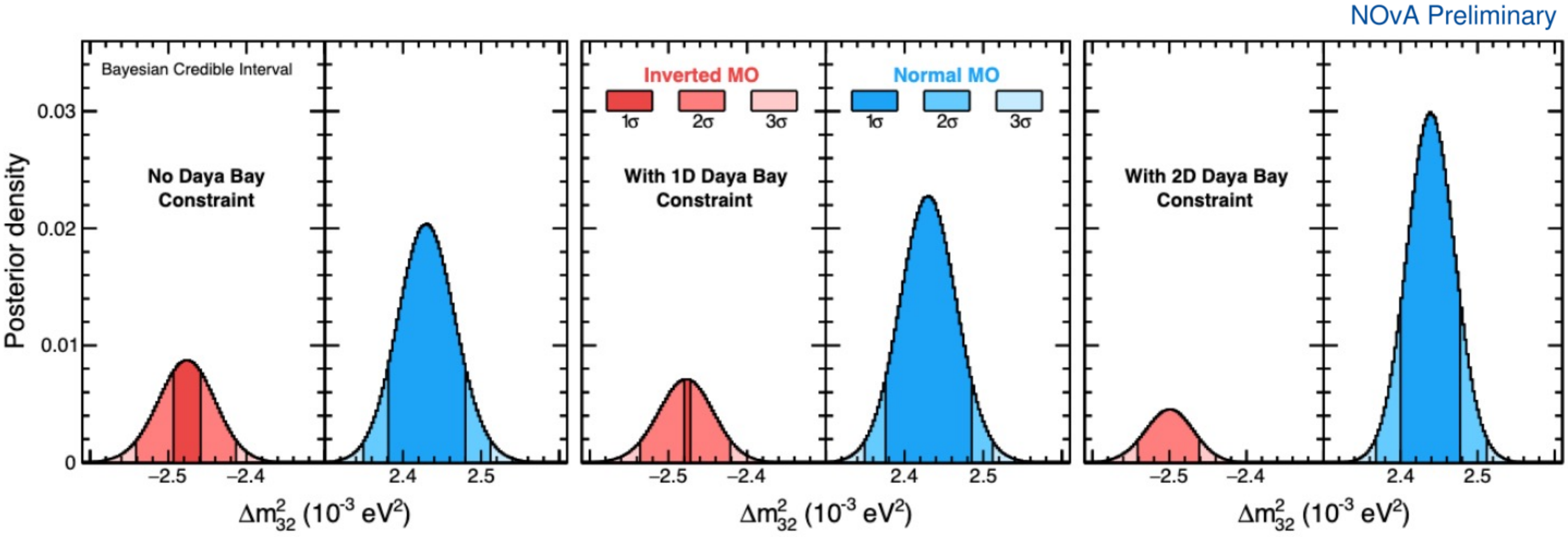
NOvA (ACCELERATOR) + DAYA BAY (REACTOR)



- Enhanced precision in Δm^2_{32} presents another* lever on measuring neutrino mass-ordering.
  - Under wrong mass ordering assumption, reactor and long-baseline measurements of Δm^2_{32} will disagree.

*Nunokawa, Parke and Funchal, PRD 72, 013009 (2005); Parke and Funchal, arXiv:2404.08733(2024)

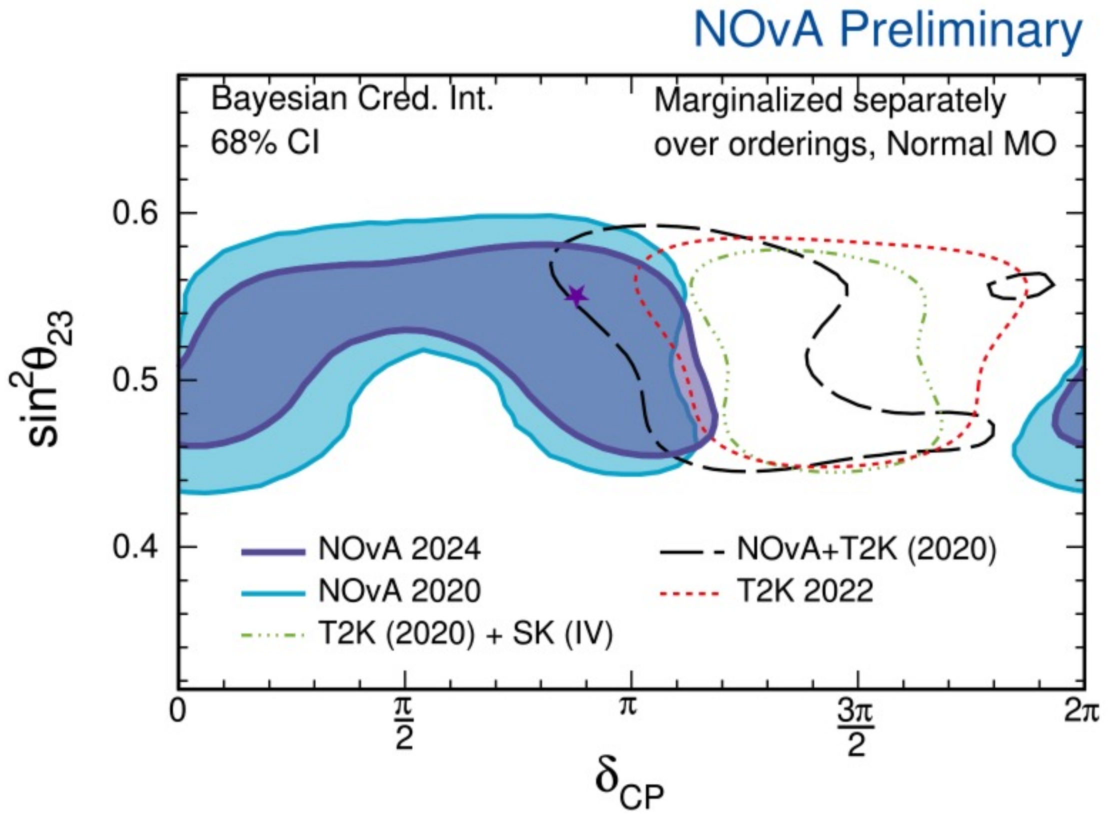
NOvA (ACCELERATOR) + DAYA BAY (REACTOR)

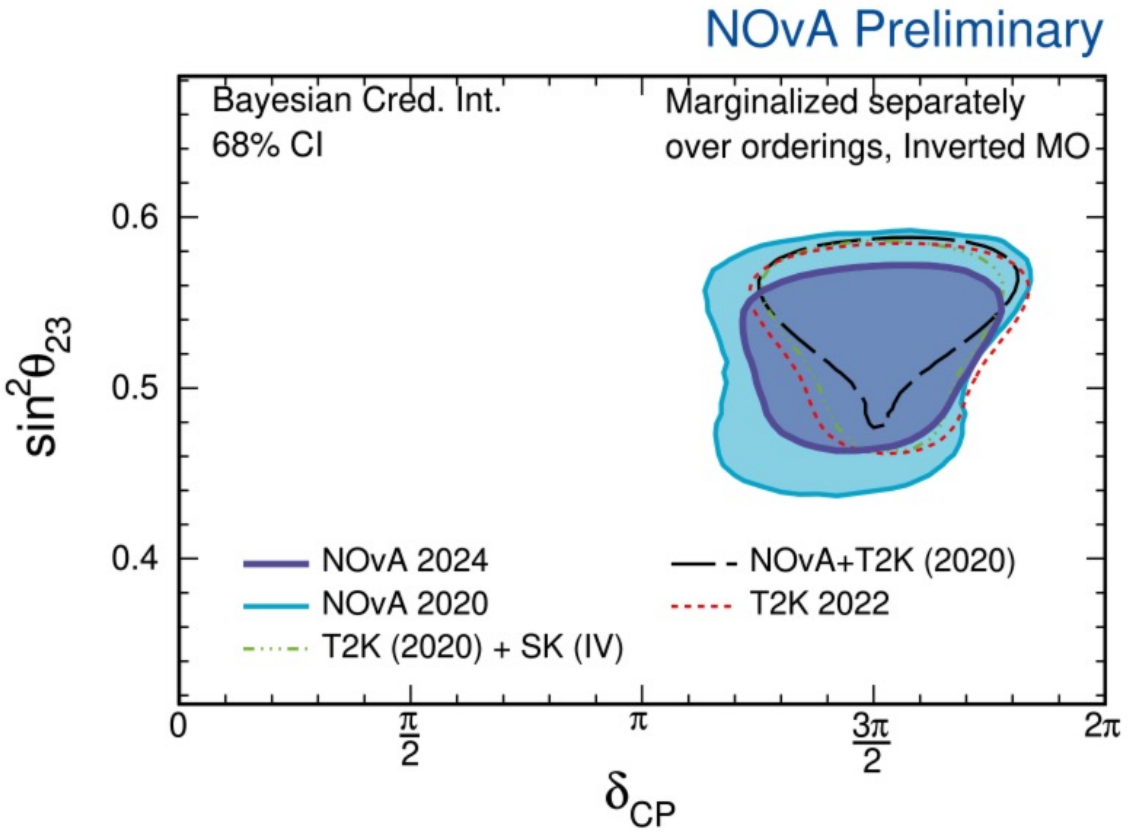


	NOvA - only w/o reactor	NOvA – only – 1D Daya Bay	NOvA - only - 2D Daya Bay
Bayes factor	**2.2** Normal/Inverted ~69% : ~31% posterior	**6.2** Normal/Inverted ~76% : ~24% posterior	**6.8** Normal/Inverted ~87% : ~13% posterior

NOvA CP PHASE : δ_{CP}

- The data disfavors large asymmetry combinations: (IO, $\delta_{CP} = \pi/2$) and (NO, $\delta_{CP} = 3\pi/2$).
- T2K, joint fits, favor different regions in Normal Ordering, same region in Inverted Ordering.

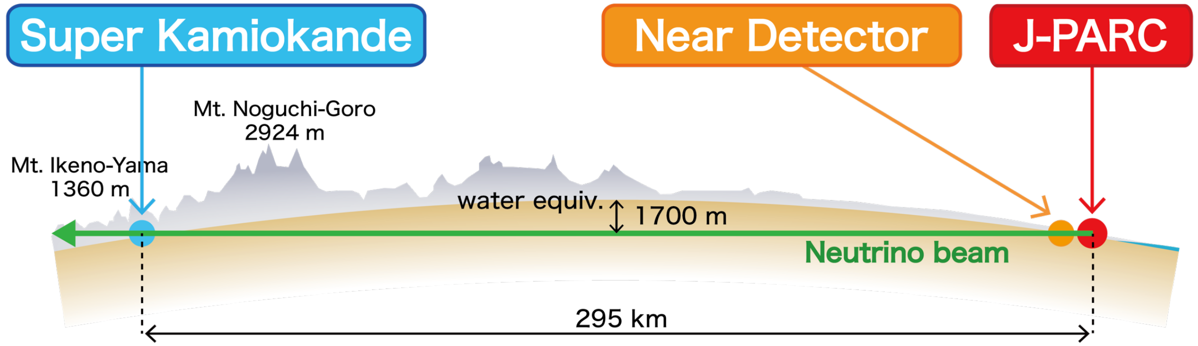




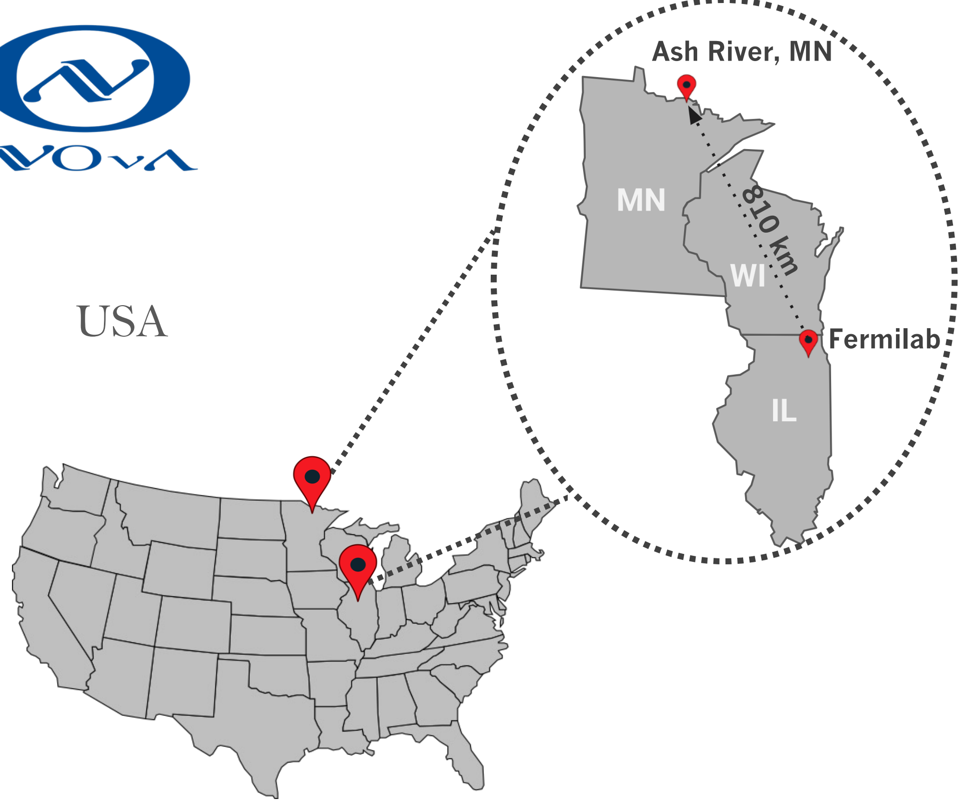
INTERLUDE: NOVA - T2K COMPLEMENTARITY

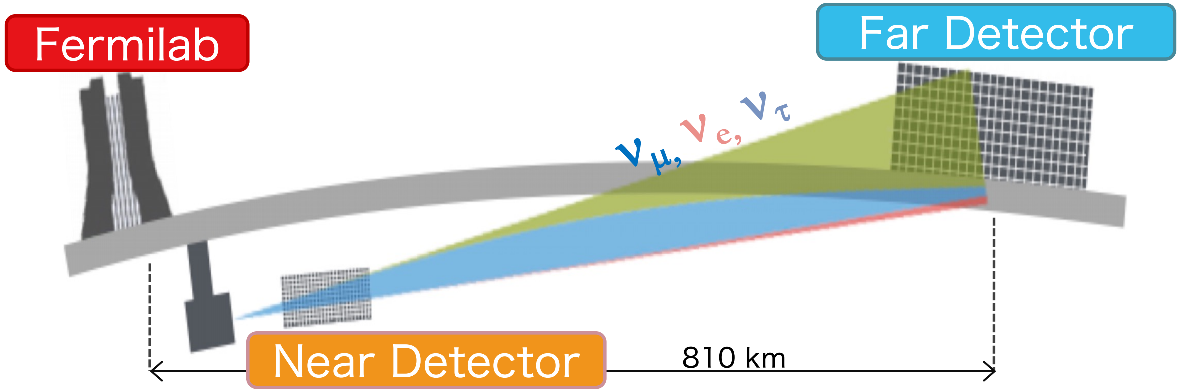
T2K


Japan
Tokai
Kamioka
295 km


Super Kamiokande
Near Detector
J-PARC
Mt. Noguchi-Goro
2924 m
Mt. Ikeno-Yama
1360 m
water equiv.
1700 m
Neutrino beam
295 km

NOvA

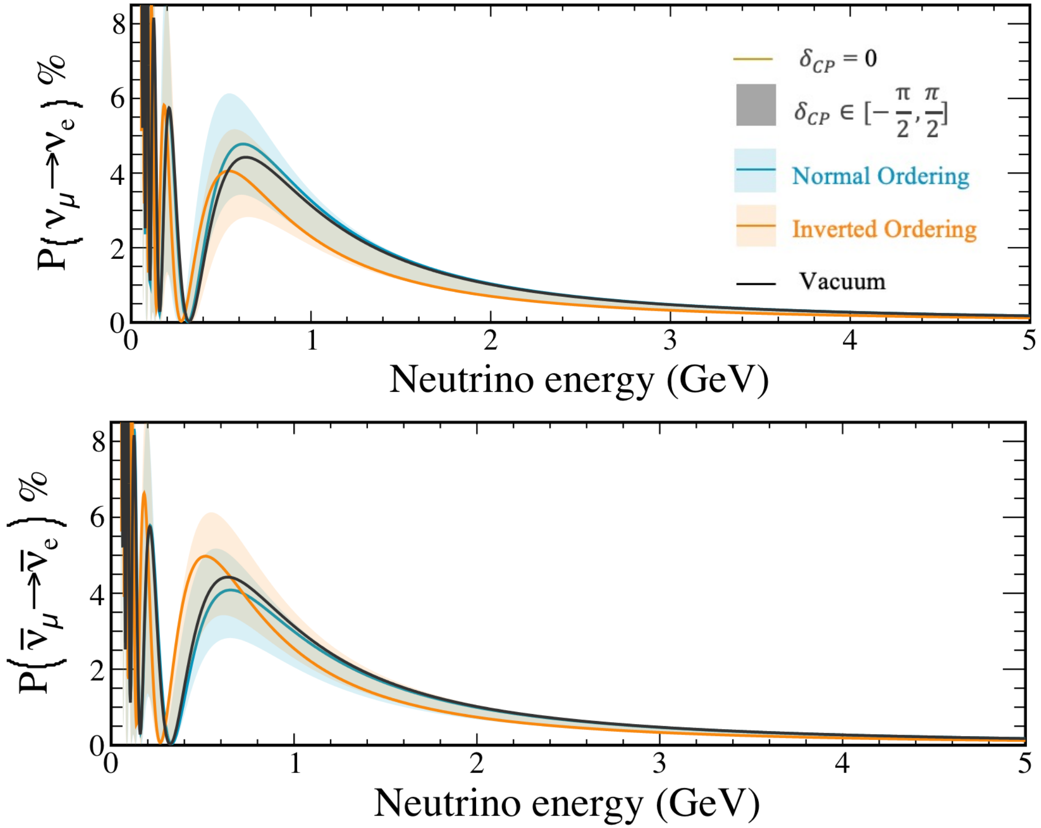

USA
Ash River, MN
MN
810 km
WI
Fermilab
IL


Fermilab
Far Detector
ν_μ, ν_e, ν_τ
Near Detector
810 km

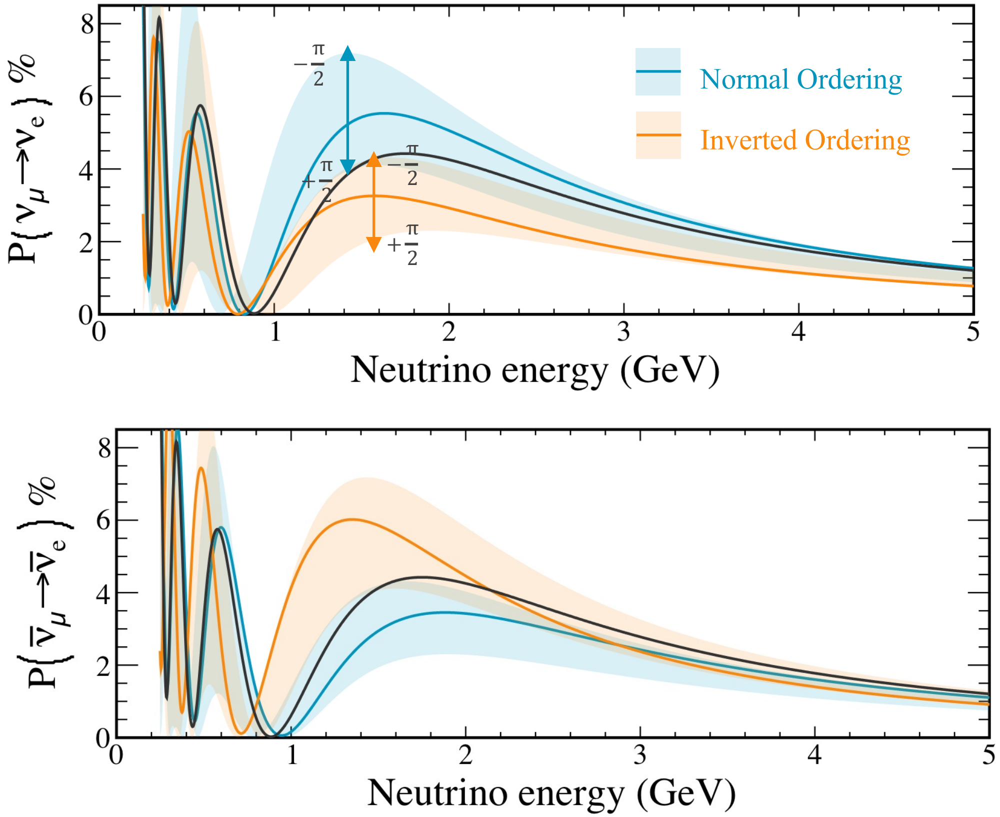
ENERGY (E) & BASELINES (L)

- Due to the different baselines and corresponding beam energies, **T2K (L: 295km, E~0.6 GeV)** measurements isolate impact of **CP violation** while **NOvA (L: 810km, E~2.0 GeV)** has significant sensitivity to **mass ordering.**

T2K: L = 295km

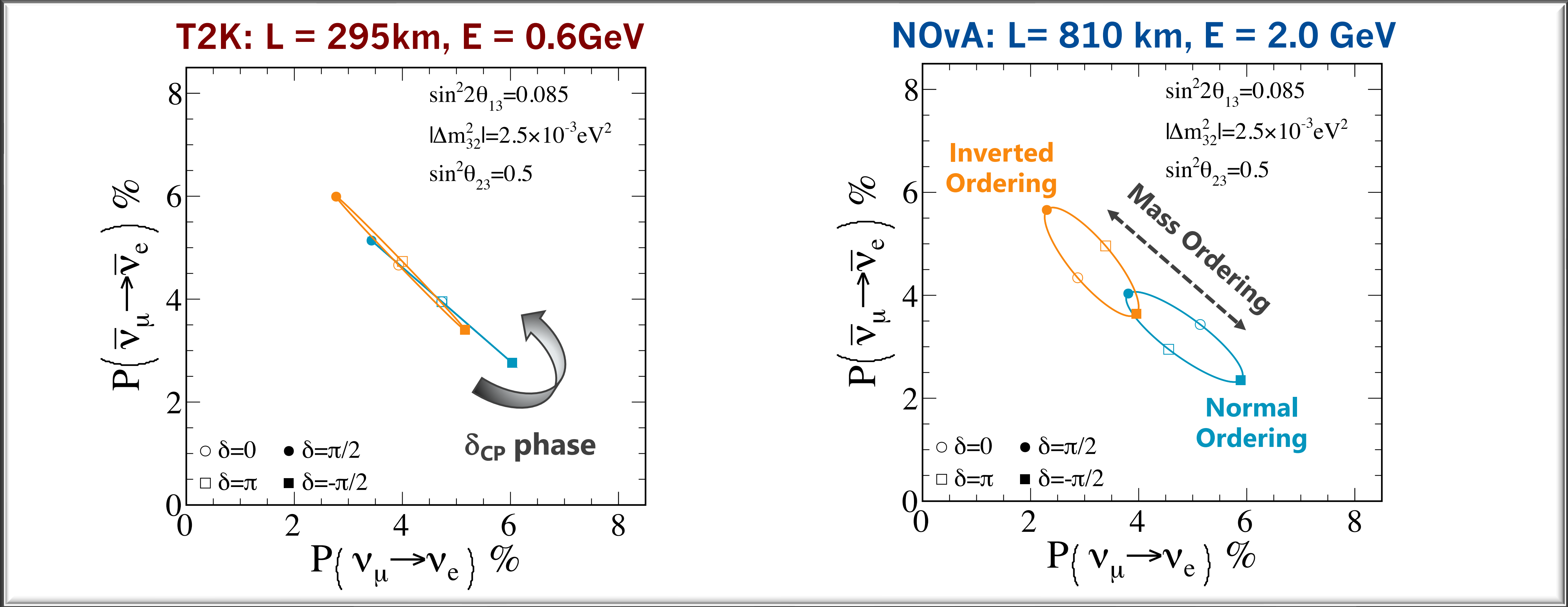


NOvA: L= 810 km



RESOLVING DEGENERACIES

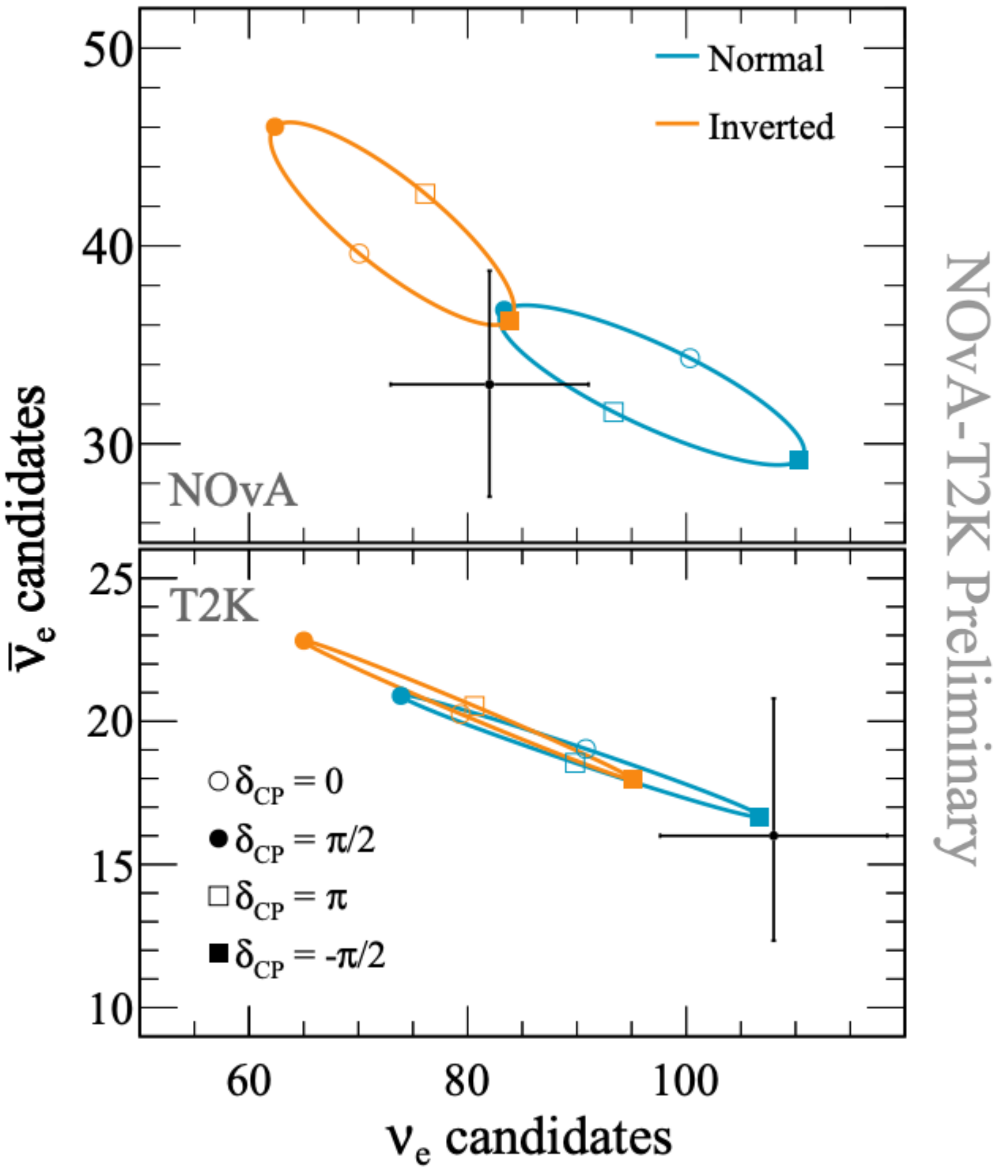
- Joint analysis probes both spaces lifting degeneracies of individual experiments.



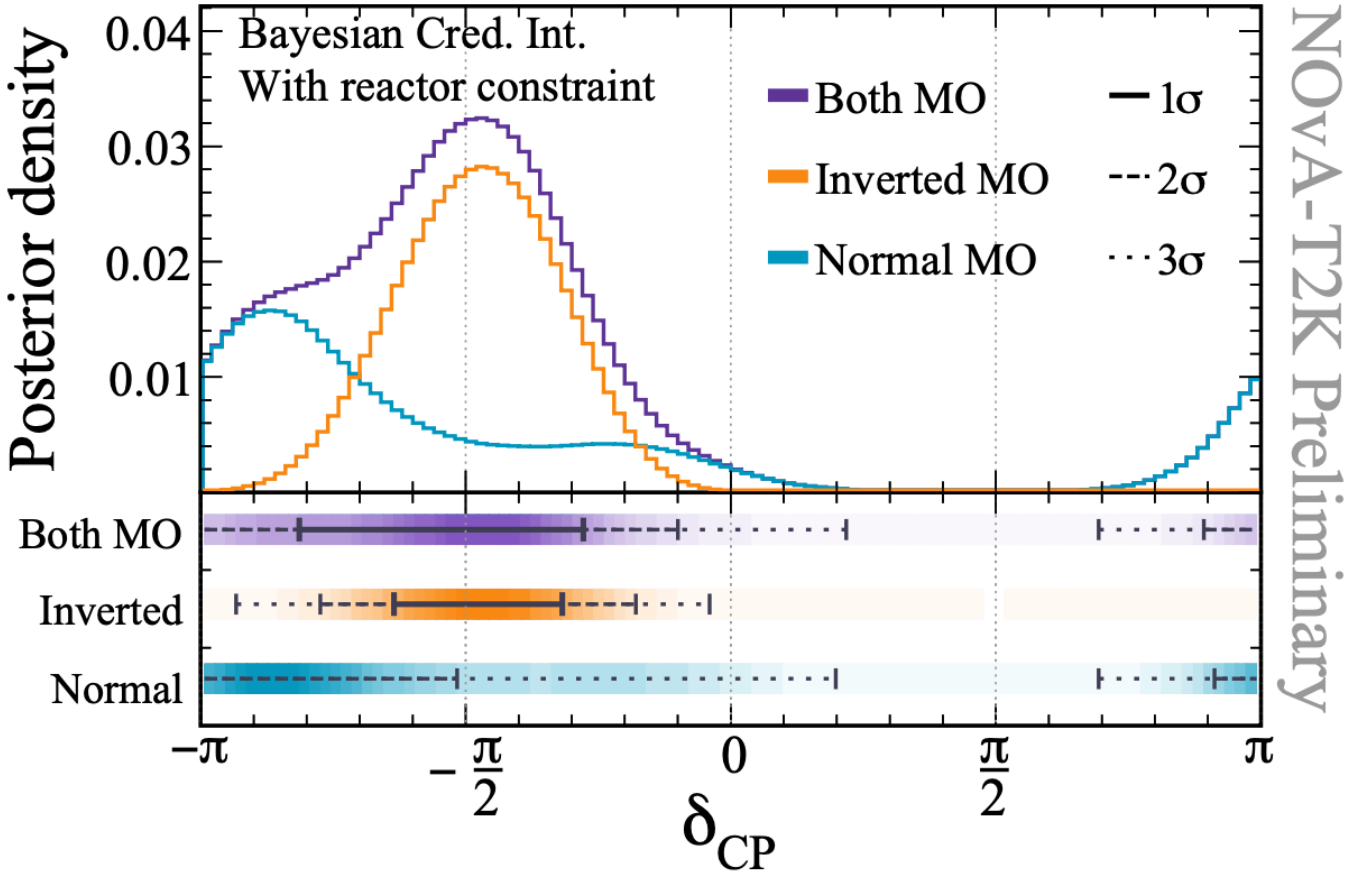
NOvA & T2K JOINT ANALYSIS DATASET

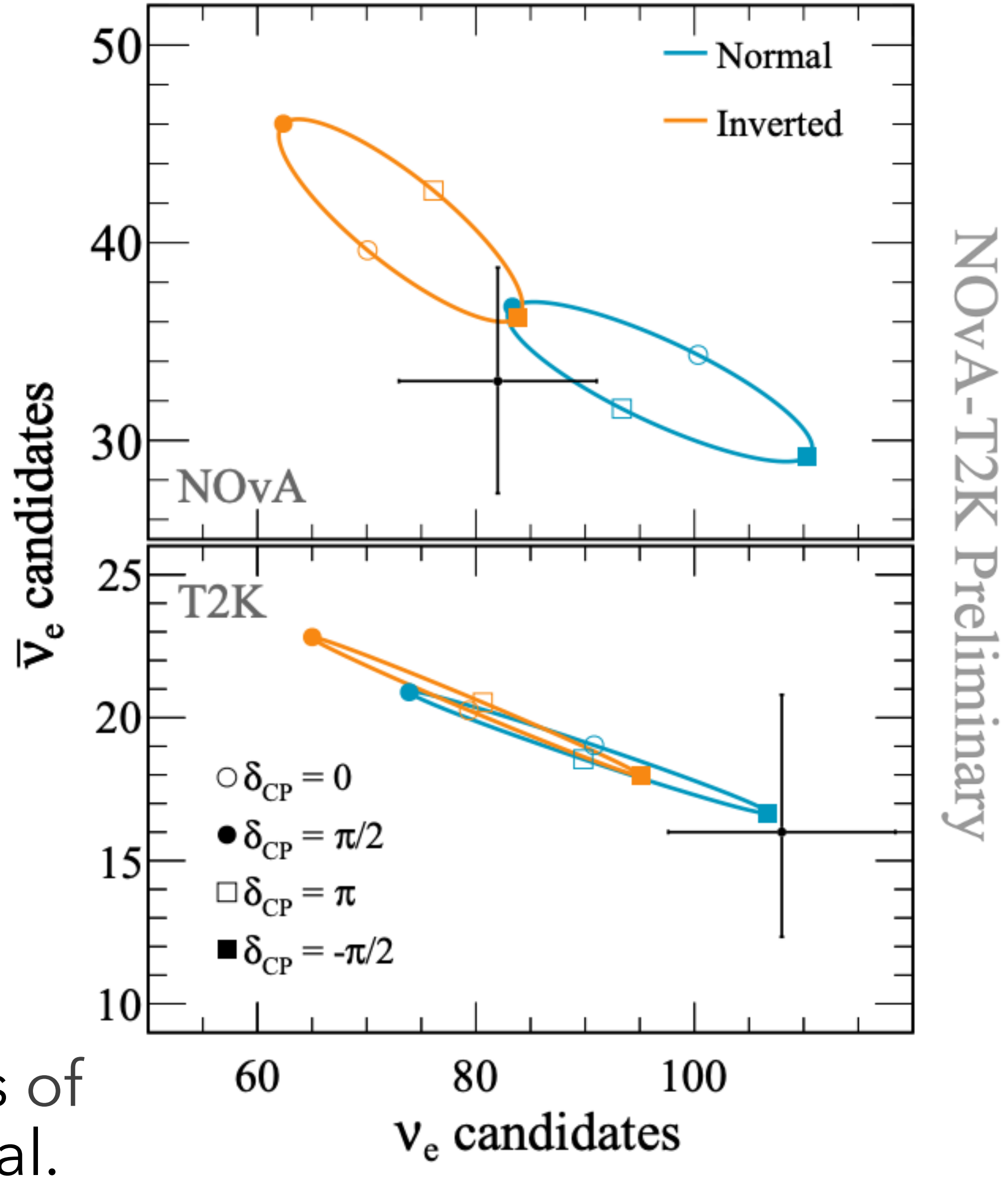
The joint-fit used **2020-era data** collected by each experiment. Using both experiments data roughly doubles the total statistics at the far detectors.

Channel	NOvA	T2K
ν_e	82	94 (ν_e) 14 ($\nu_e 1\pi$)
$\bar{\nu}_e$	33	16
ν_μ	211	318
$\bar{\nu}_\mu$	105	137



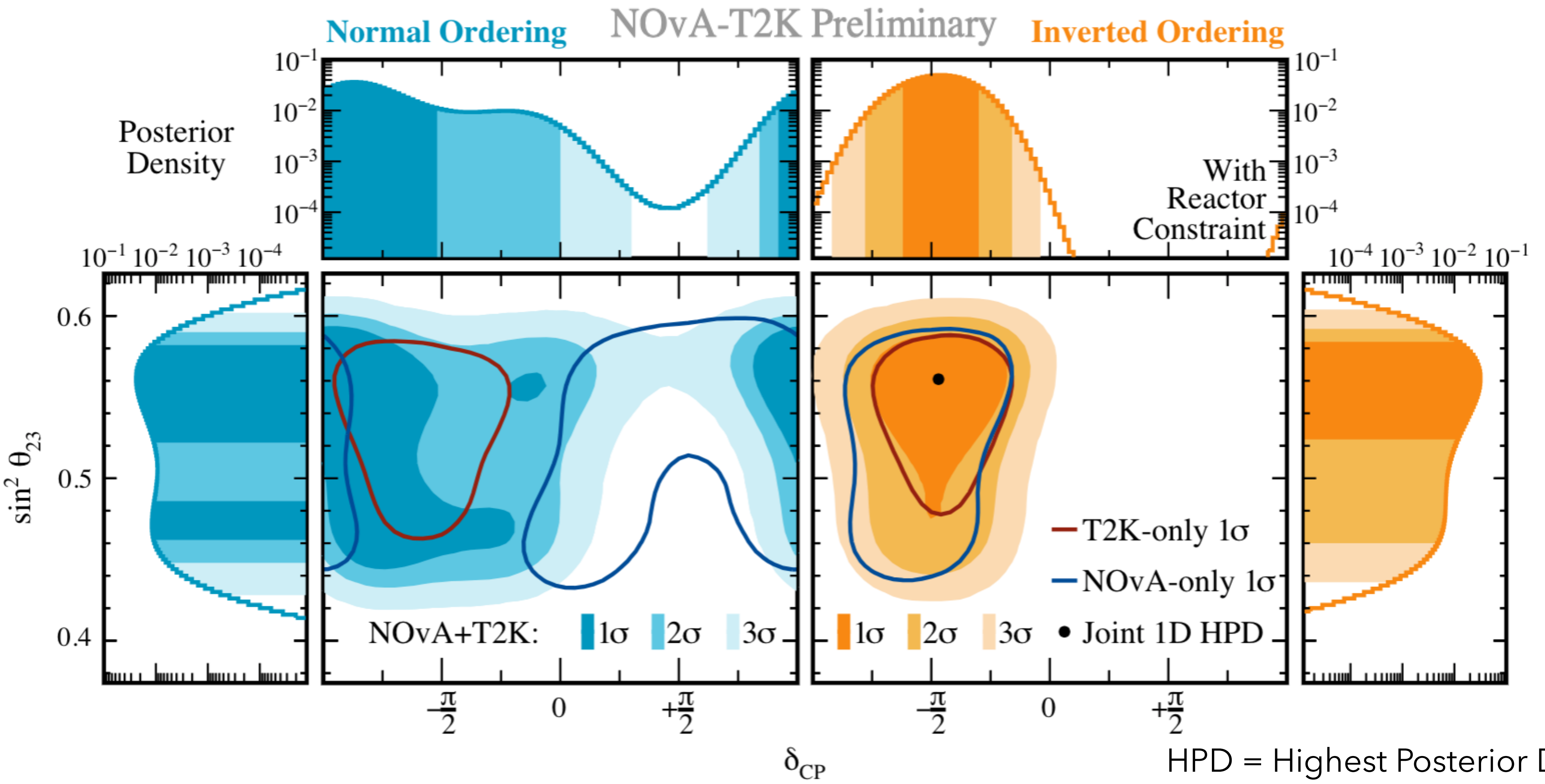
NOvA + T2K: δ_{CP}





- If the ordering is inverted, CP conserving values of δ_{CP} $(0, \boldsymbol{\pi})$ lie outside the 3-sigma credible interval.

NOvA, T2K, NOvA + T2K

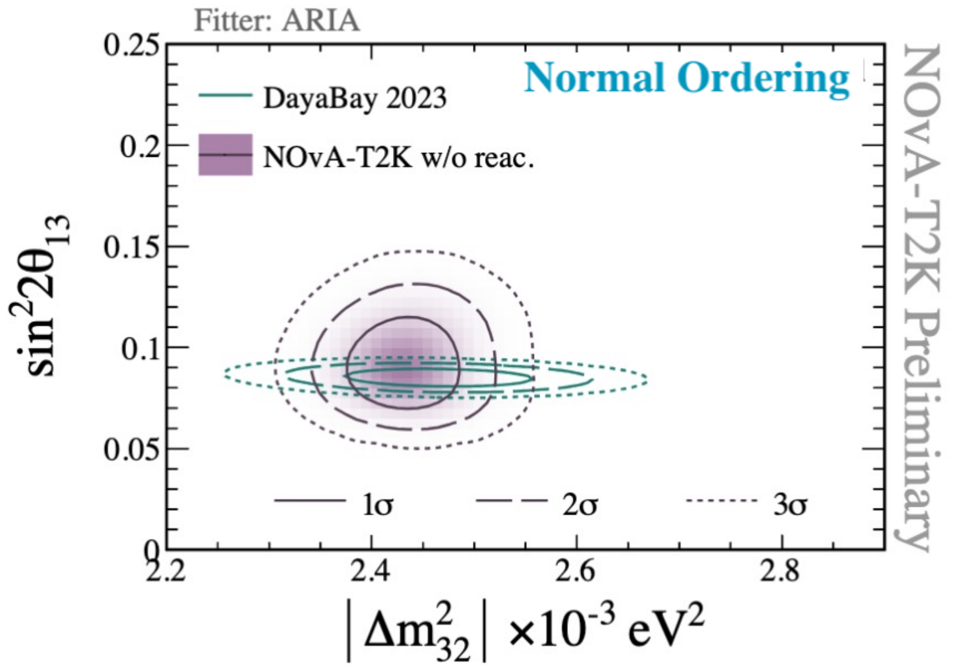


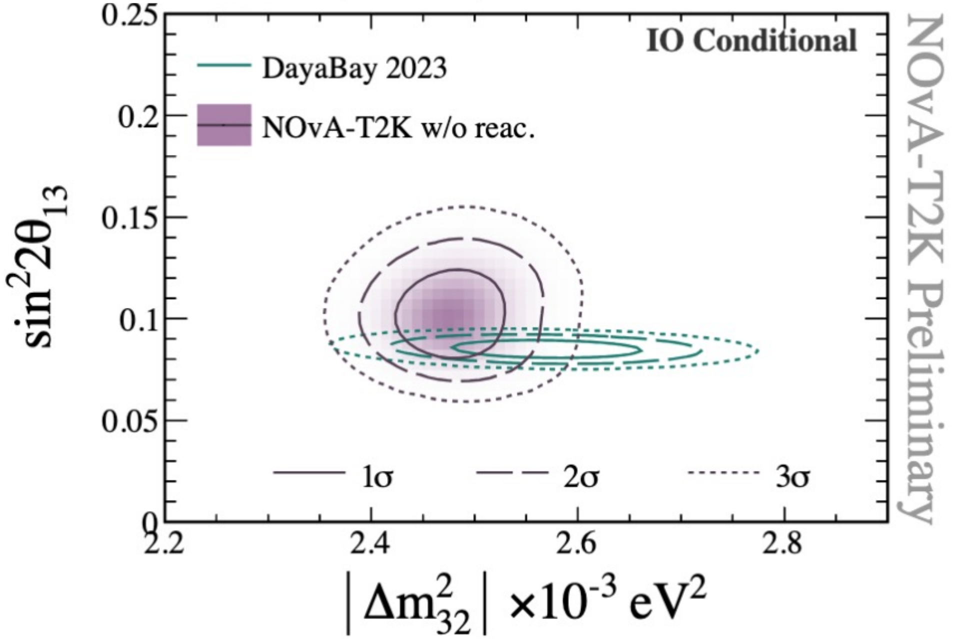
HPD = Highest Posterior Density

NOvA+T2K: MASS ORDERING

- **Small preference for the Inverted Ordering** in the joint fit whereas NOvA & T2K individually prefer Normal Ordering.
- Including the Δm^2_{32} constraint from the Daya Bay, reverse the **mass ordering preference back to the Normal Ordering**.
- **No significant preference for either mass ordering** in the joint analysis.

	NOvA - T2K w/o reactor	NOvA – T2K – 1D Daya Bay	NOvA - T2K - 2D Daya Bay
Bayes factor	**2.47** Inverted/Normal ~71% : ~29% posterior	**1.34** Inverted/Normal ~57% : ~43% posterior	**1.44** Normal/Inverted ~59% : ~41% posterior





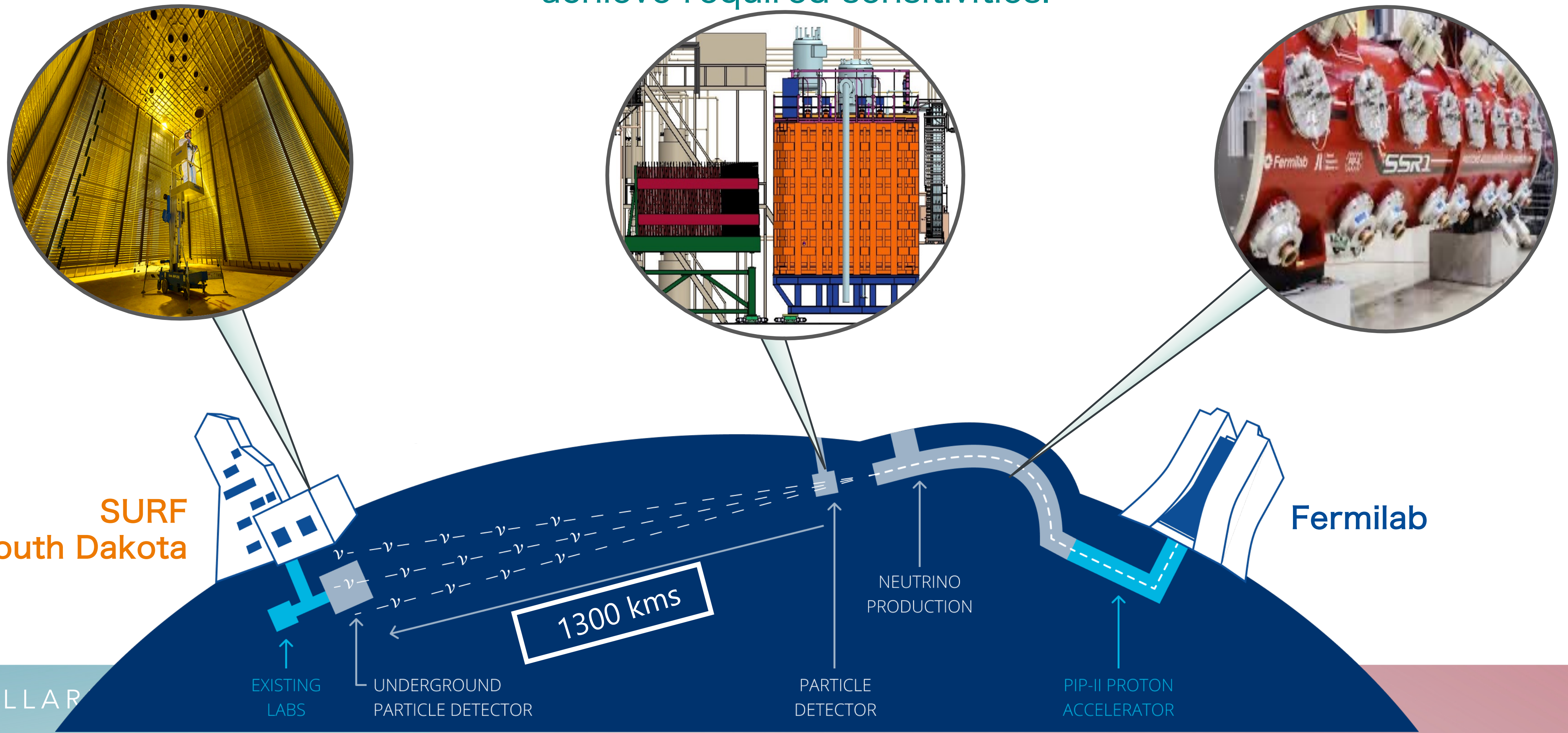
COMING UP NEXT:

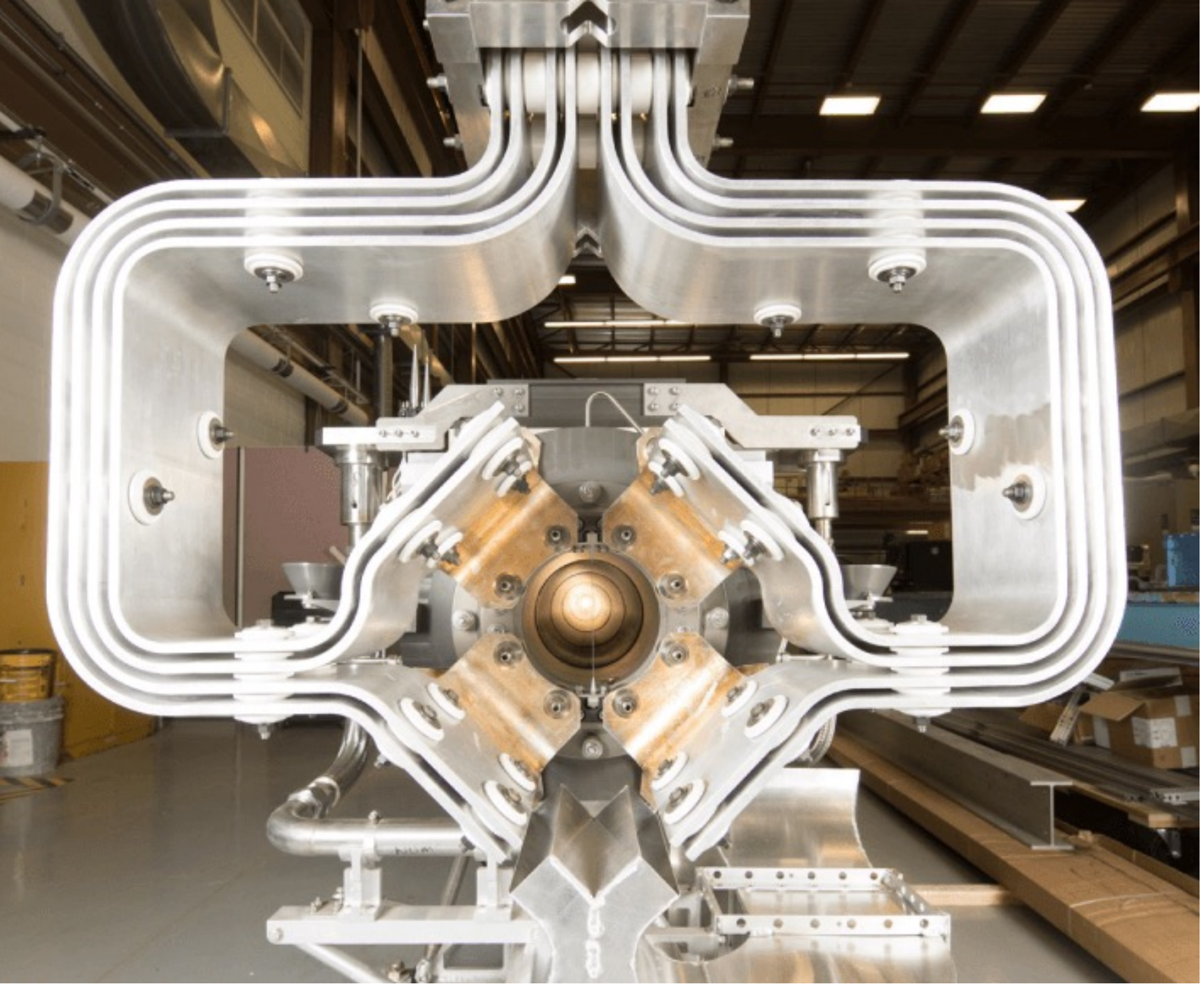
DEEP UNDERGROUND NEUTRINO EXPERIMENT (DUNE)

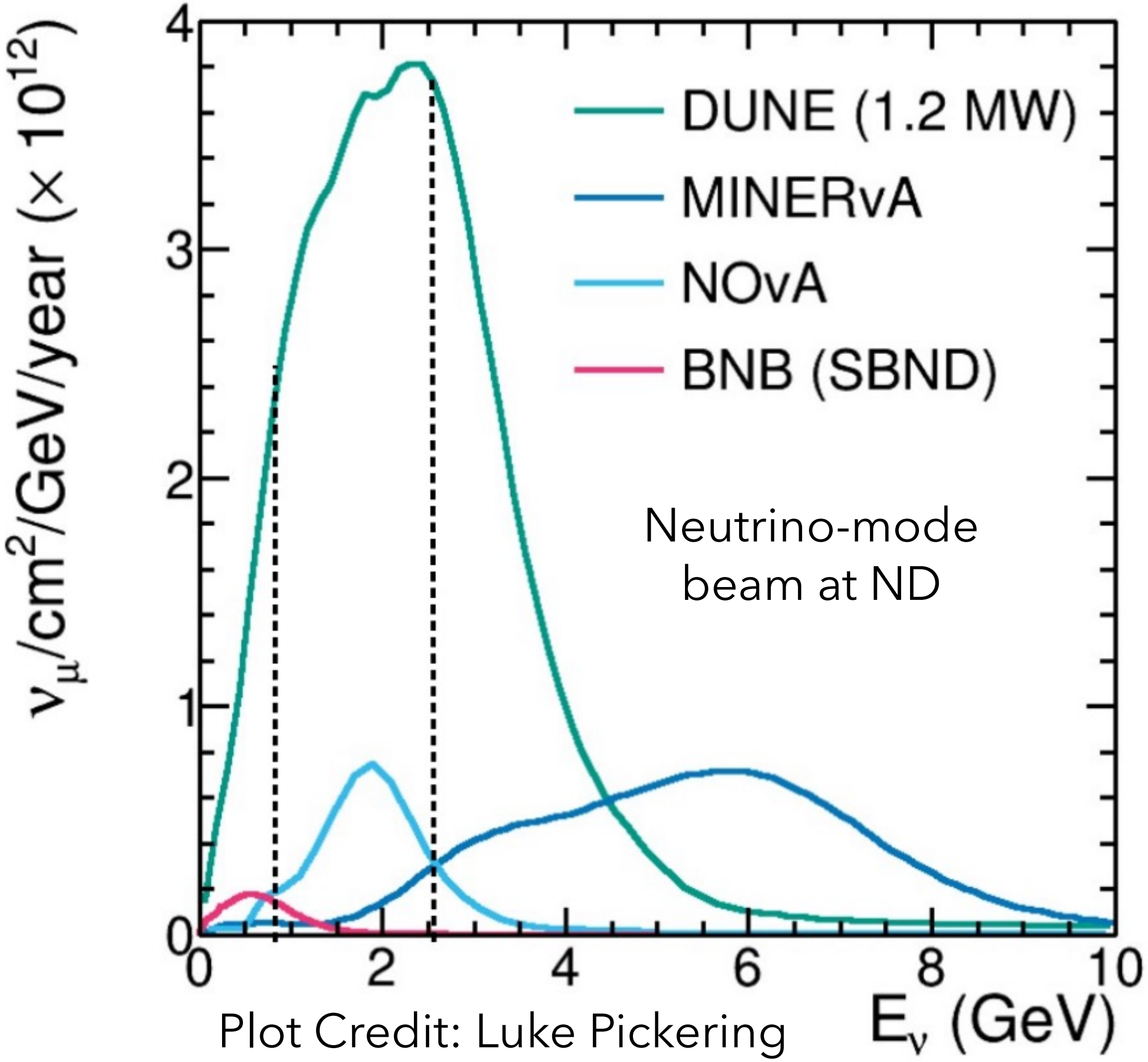
FD: 4 modules of 17 kt Liquid Argon TPC detector

ND: A suite of detectors to provide in-situ constraints and achieve required sensitivities.

LBNF Beam: Most intense accelerator neutrino beam





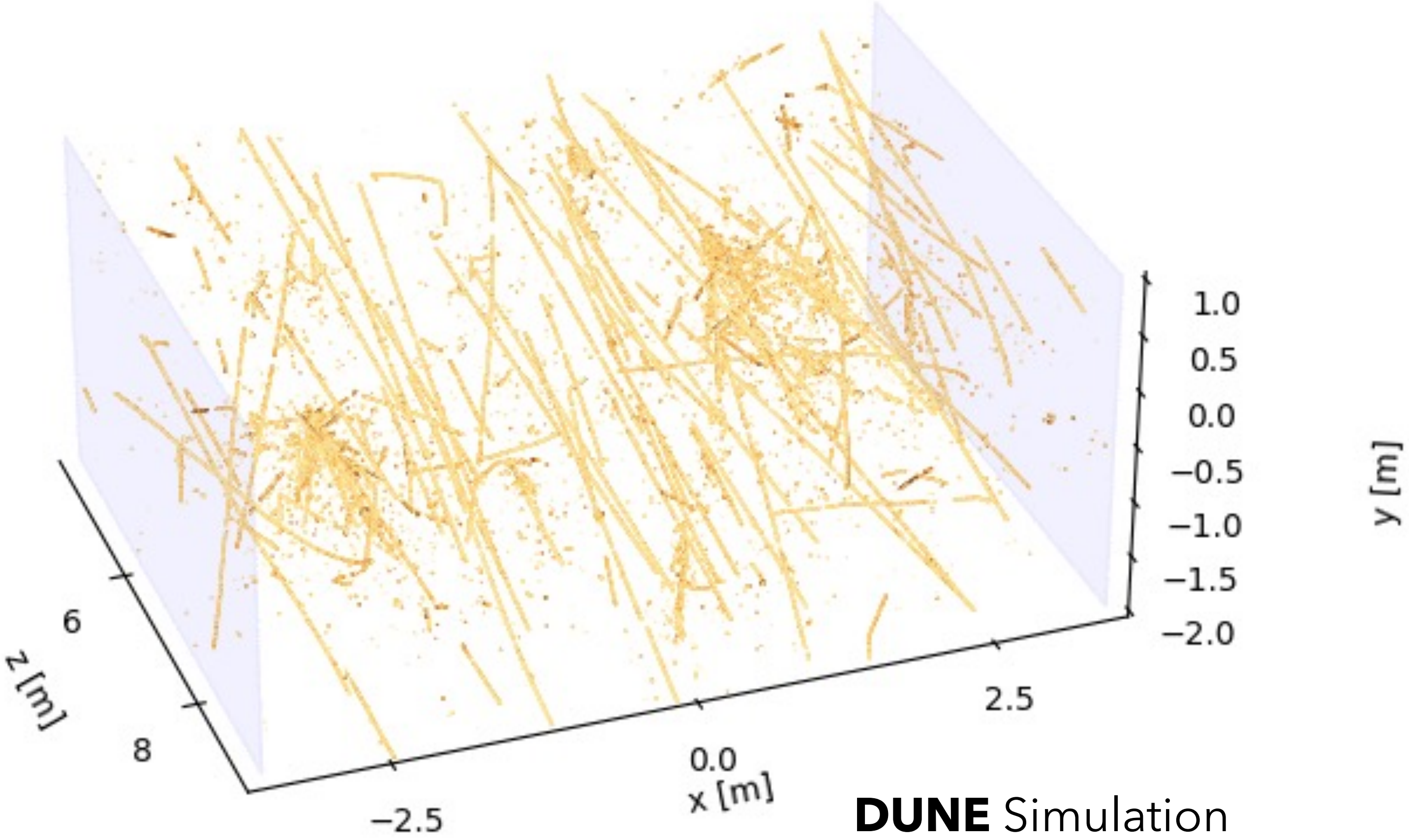


Plot Credit: Luke Pickering

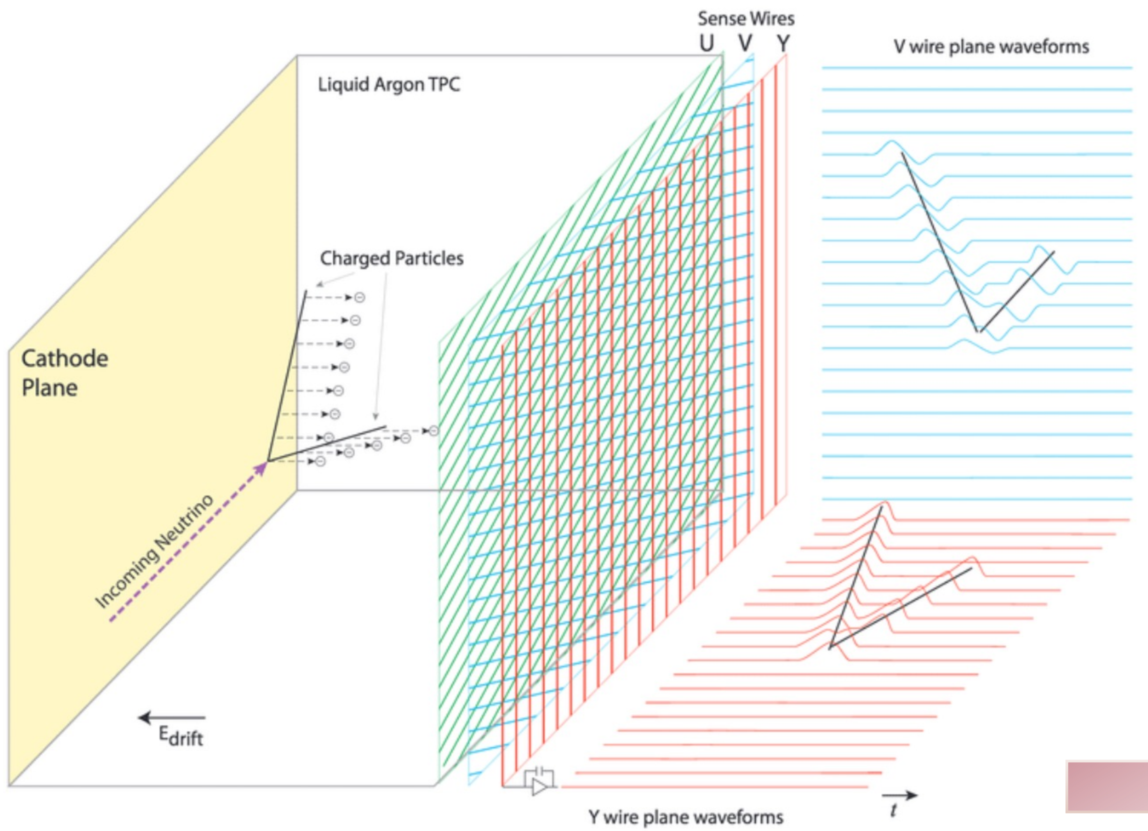
LBNF PIP-II BEAM: MOST POWERFUL ACCELERATOR NEUTRINO BEAM IN THE WORLD

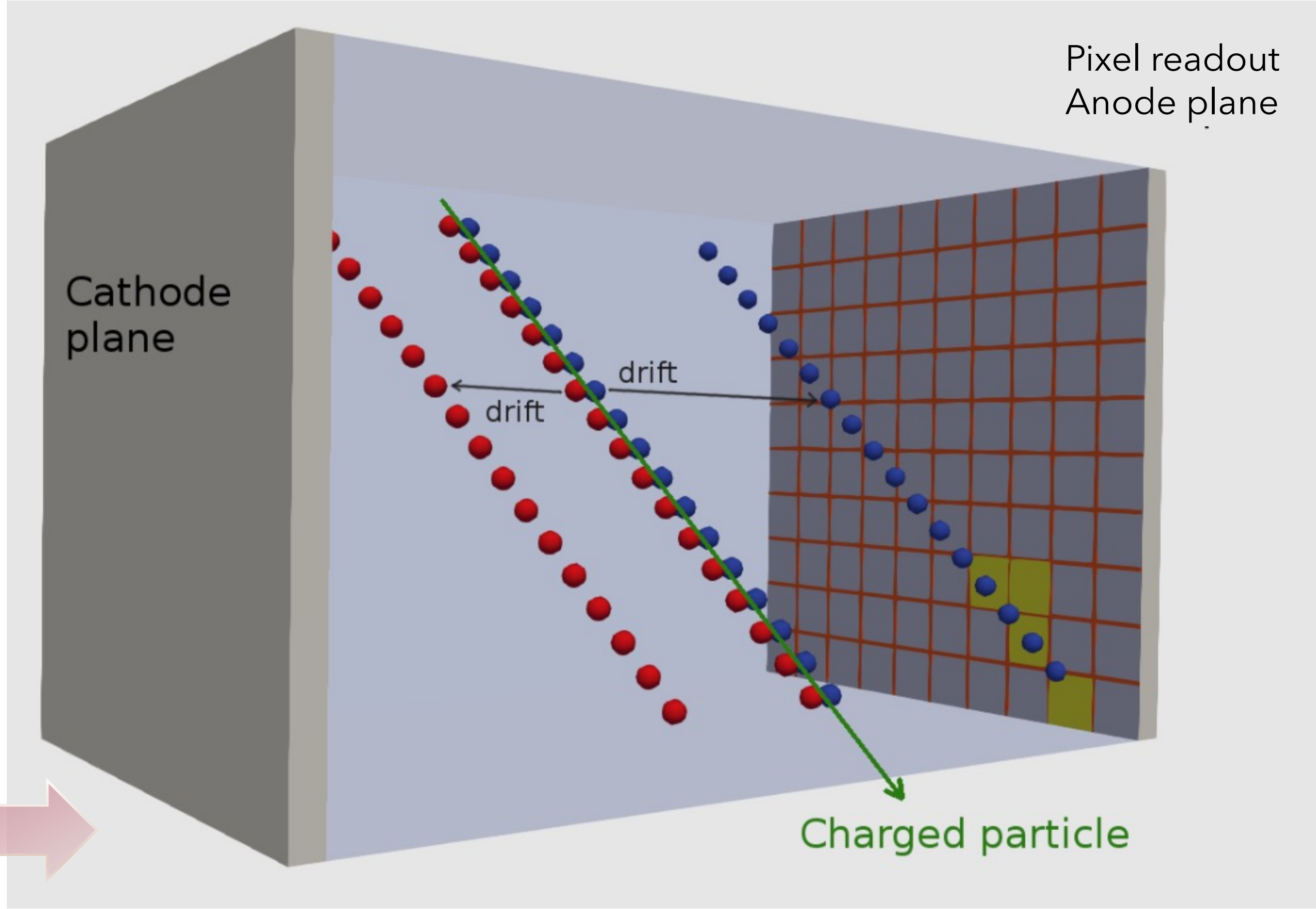
WITH GREAT POWER …

WITH GREAT POWER …
COMES GREAT PILE-UP



~100 ν interactions at DUNE ND in a single LBNF beam spill





DUNE ND-LAr: POWERED BY PIXELS

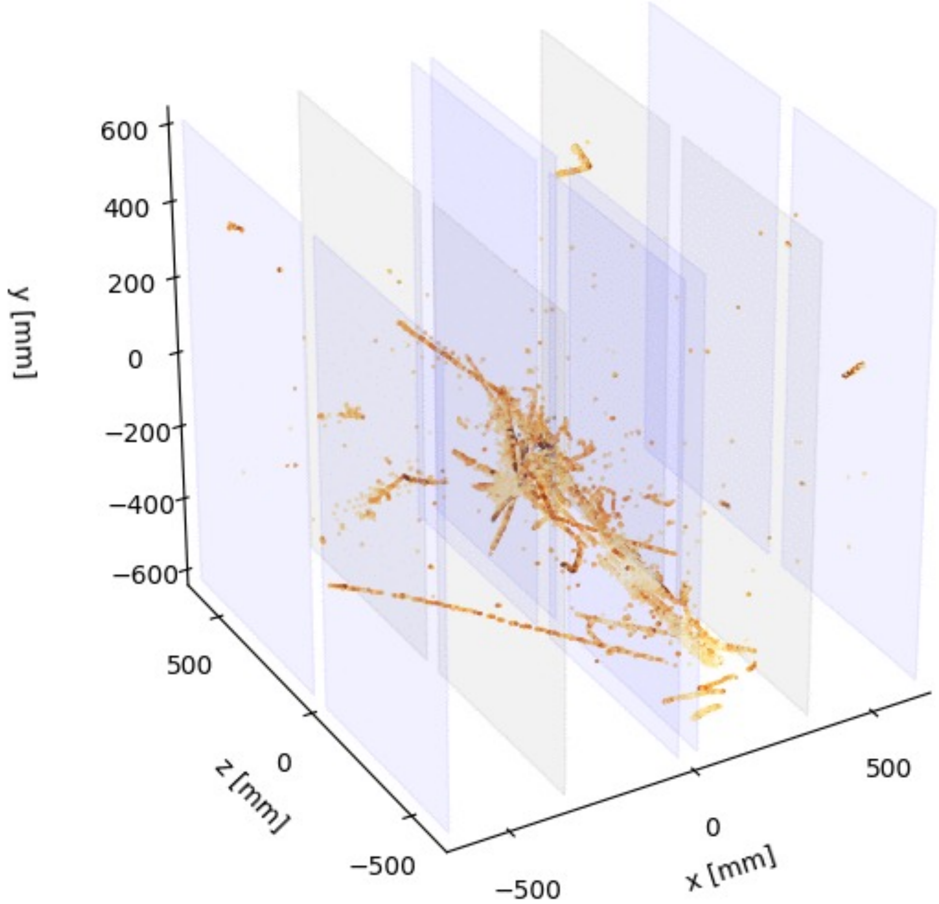
DEMONSTRATOR

DUNE ND-LAr prototype detector taking neutrino beam data!

July 2024

DUNE DATA

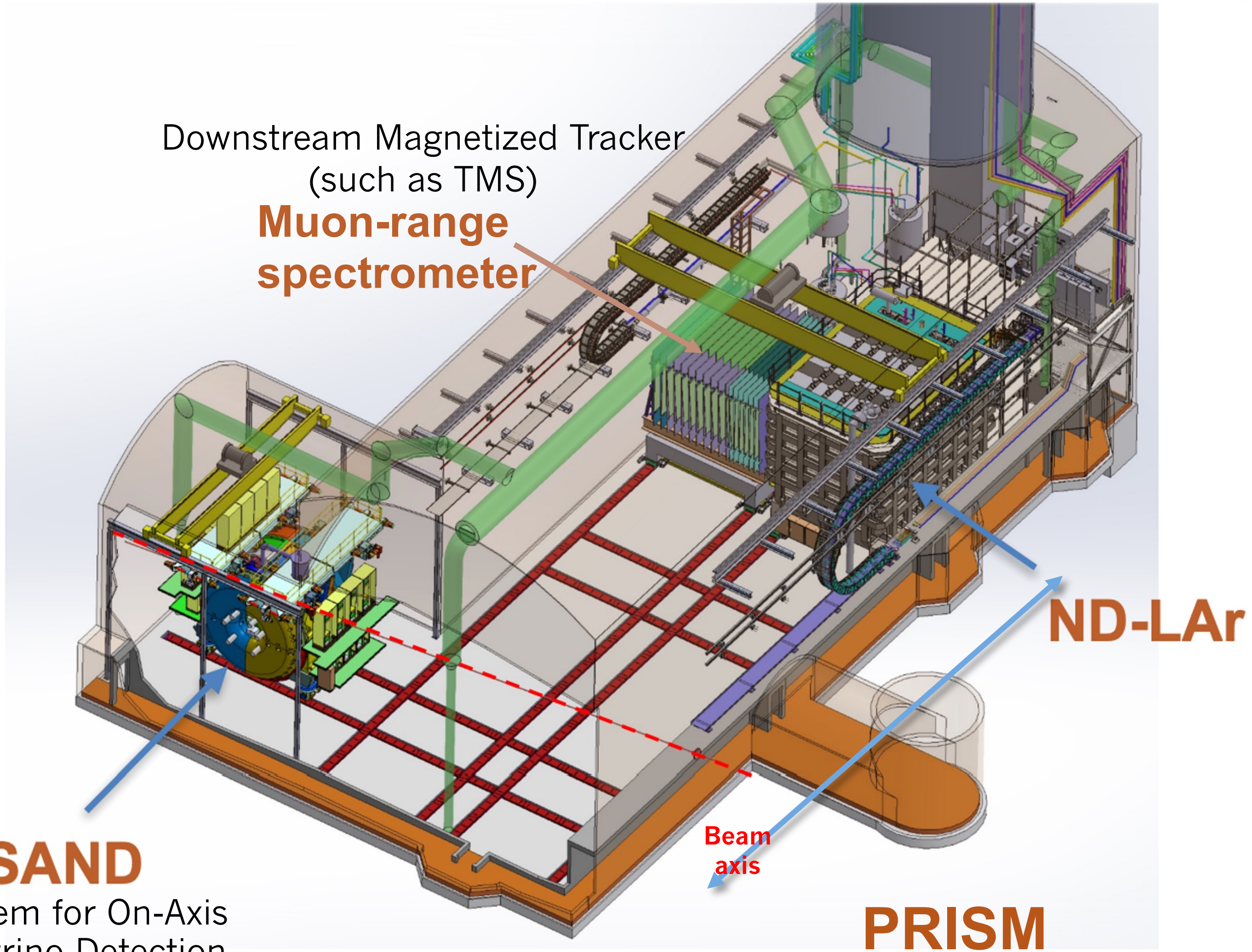
Event 20, ID 20 - 2024-07-08 00:20:14 UTC



DUNE ND COMPLEX

- ND-LAr is one of the four components of the DUNE ND complex.
- **A suite of near detectors** are designed to robustly constrain systematics and achieve required sensitivities.

Why is the DUNE ND Complex so complex?



SAND
System for On-Axis Neutrino Detection

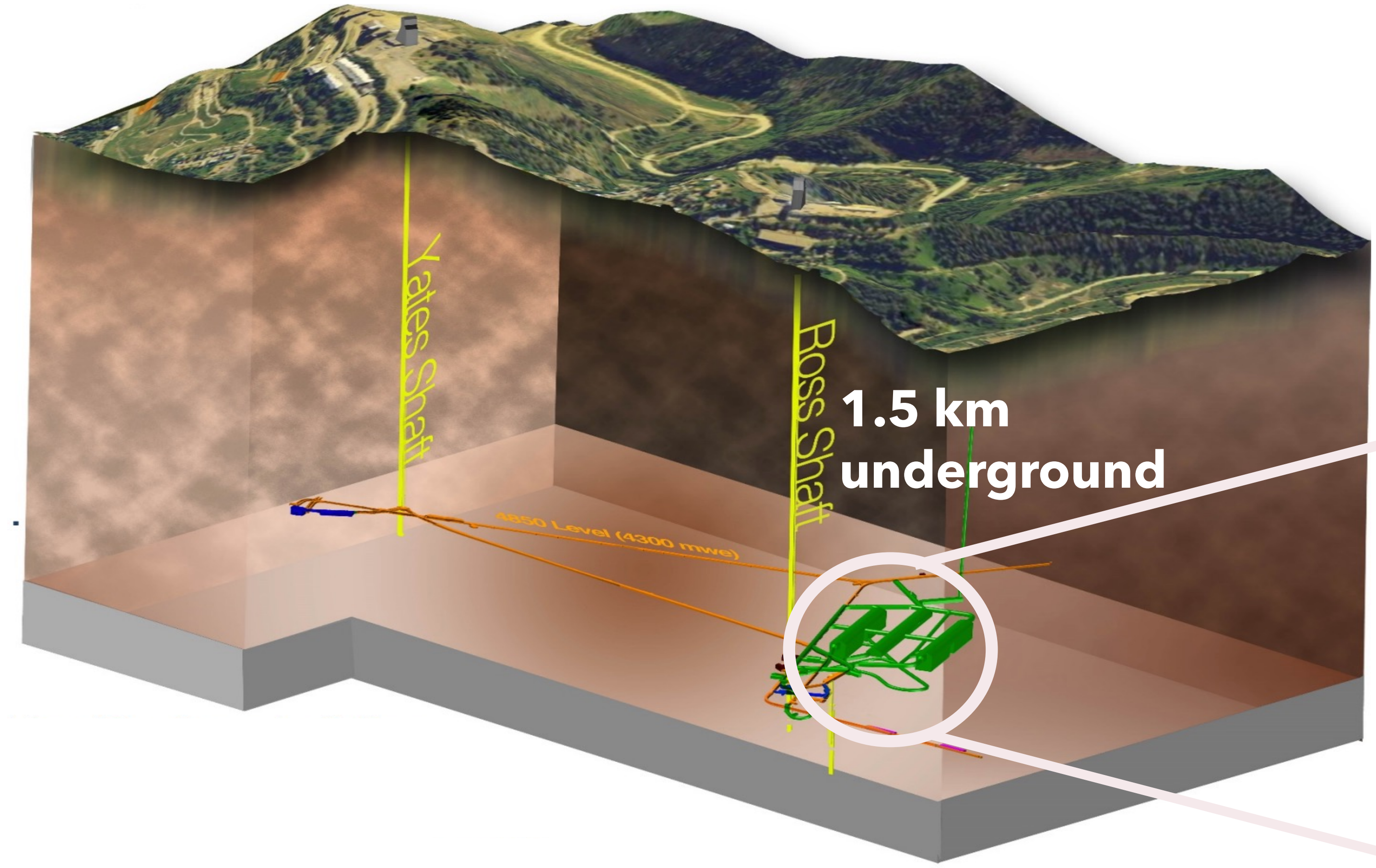
PRISM
System for moving the LArTPC and tracker up to 30m transverse to the beam

DUNE FD:

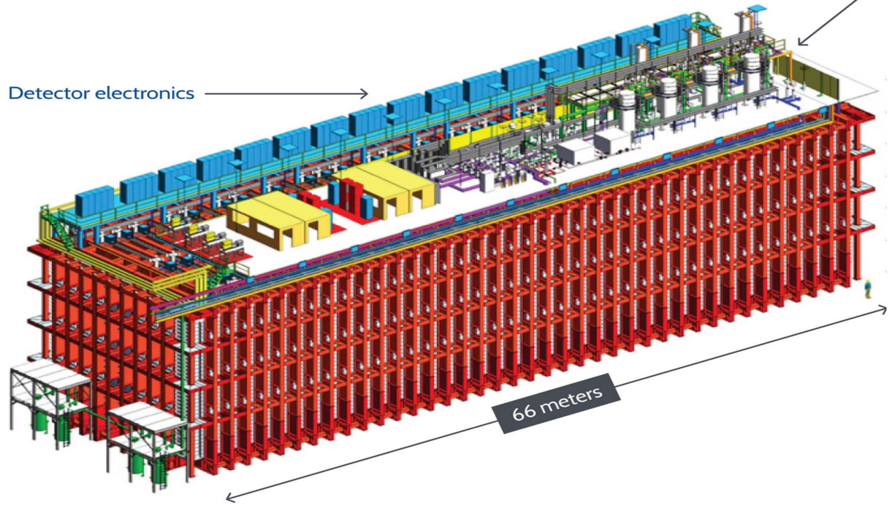
Located at a baseline of 1300 km from the beam target and 1.5 km underground

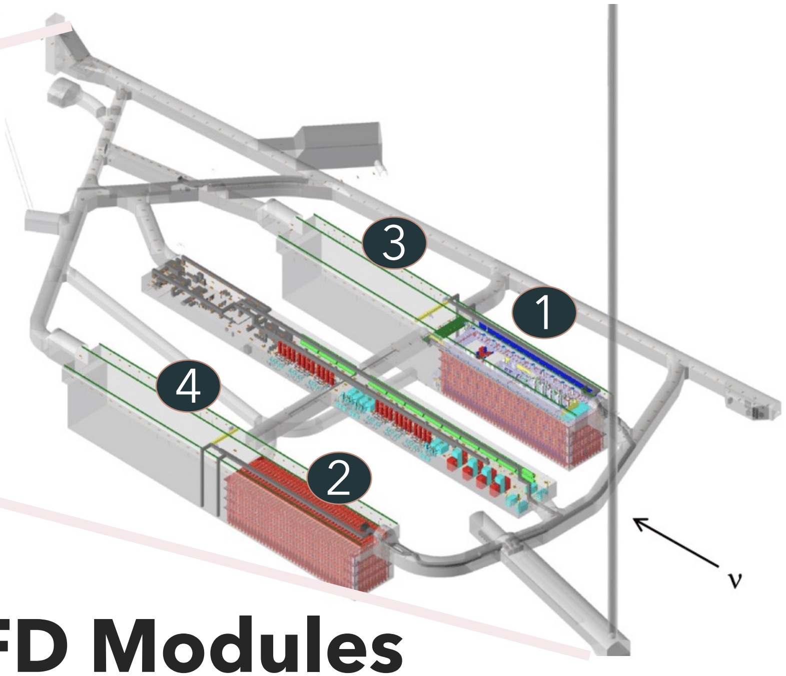
DUNE FD:

17 kt LArTPC detector



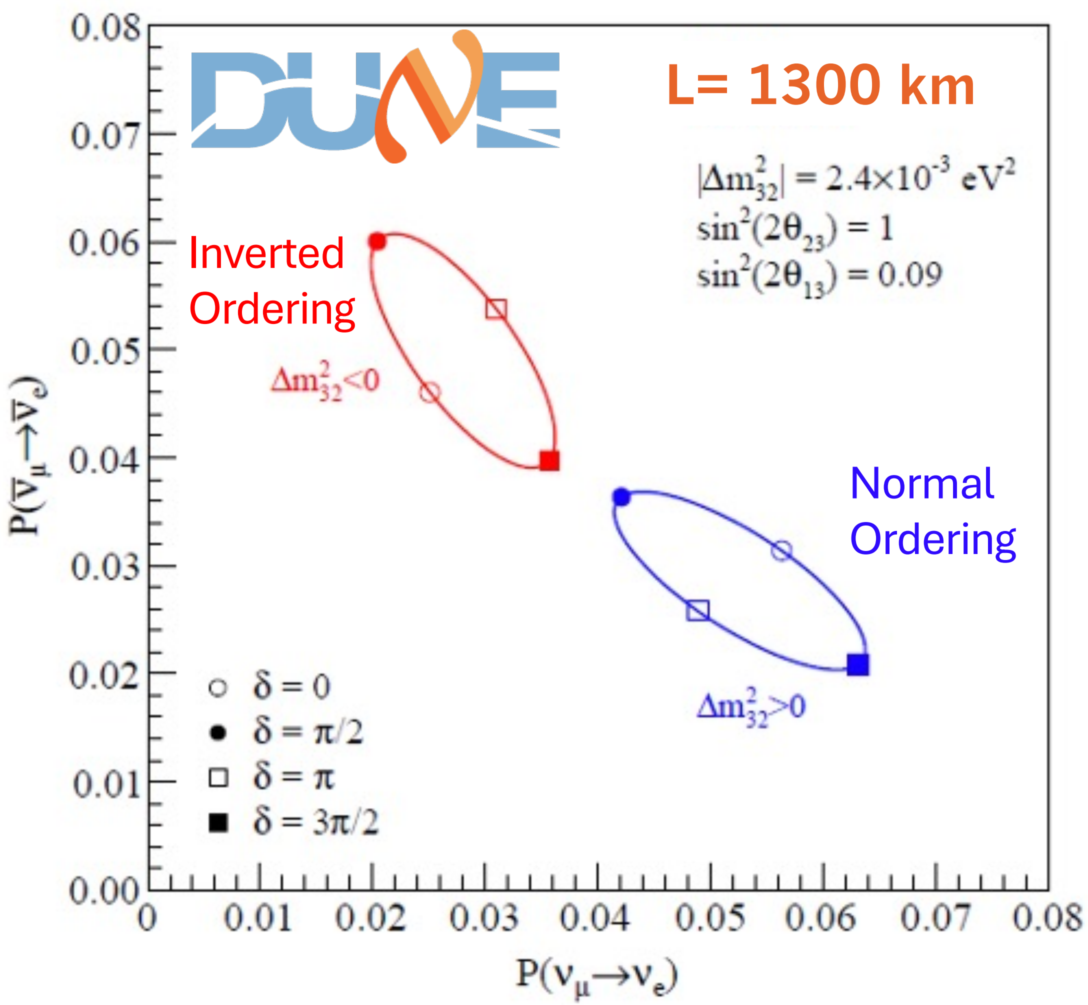
1.5 km underground

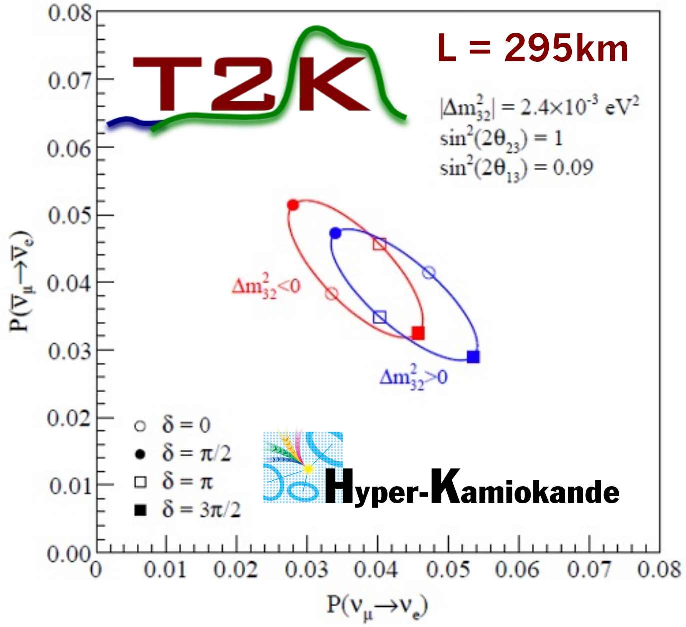


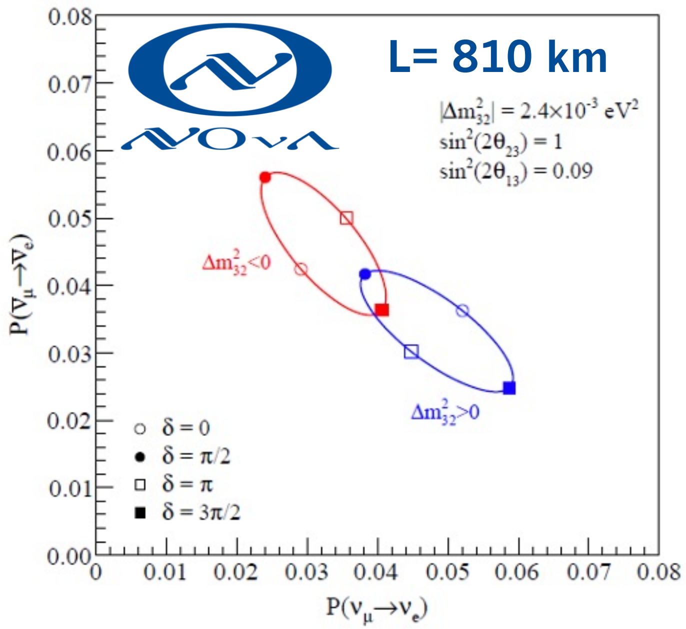


4 FD Modules

- DUNE's longer baseline and correspondingly higher neutrino energy, completely removes the degeneracy between the measurements of mass ordering and δ_{CP}

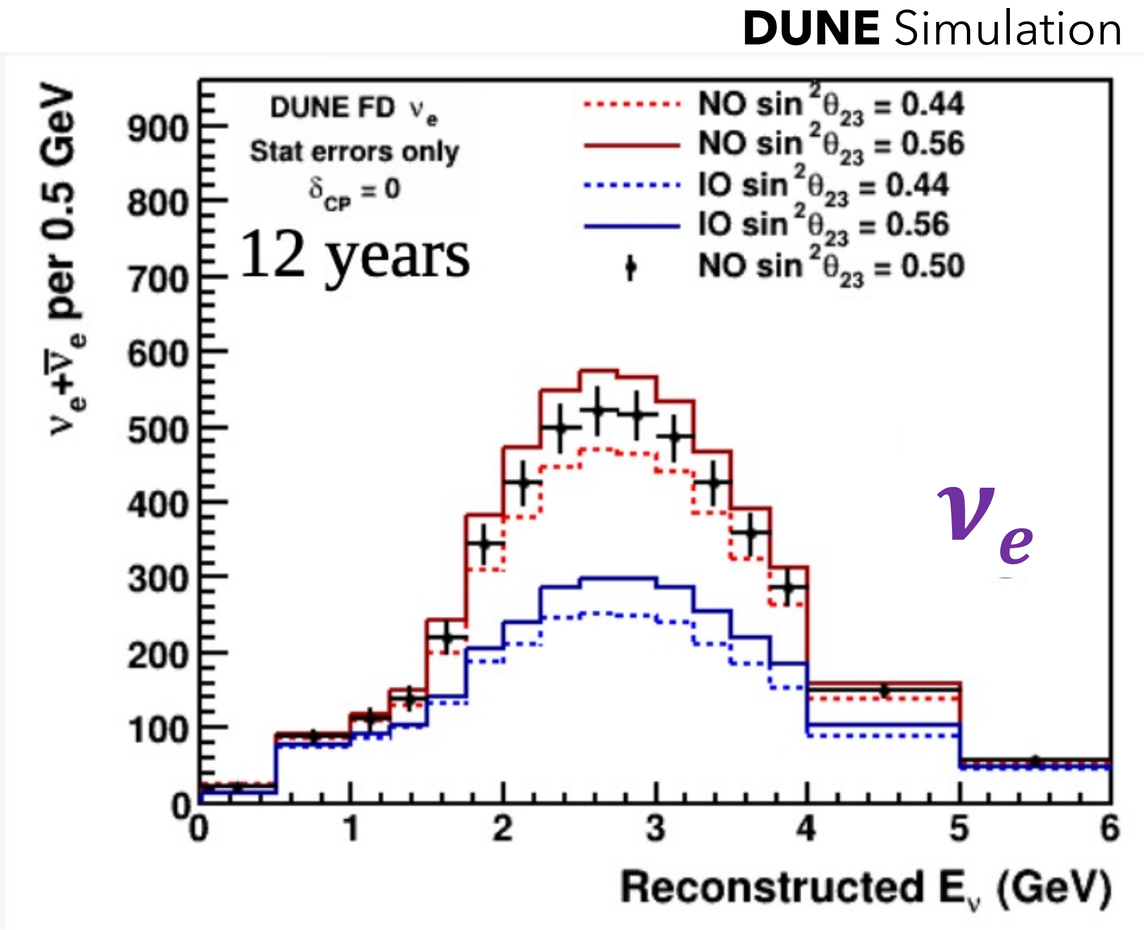


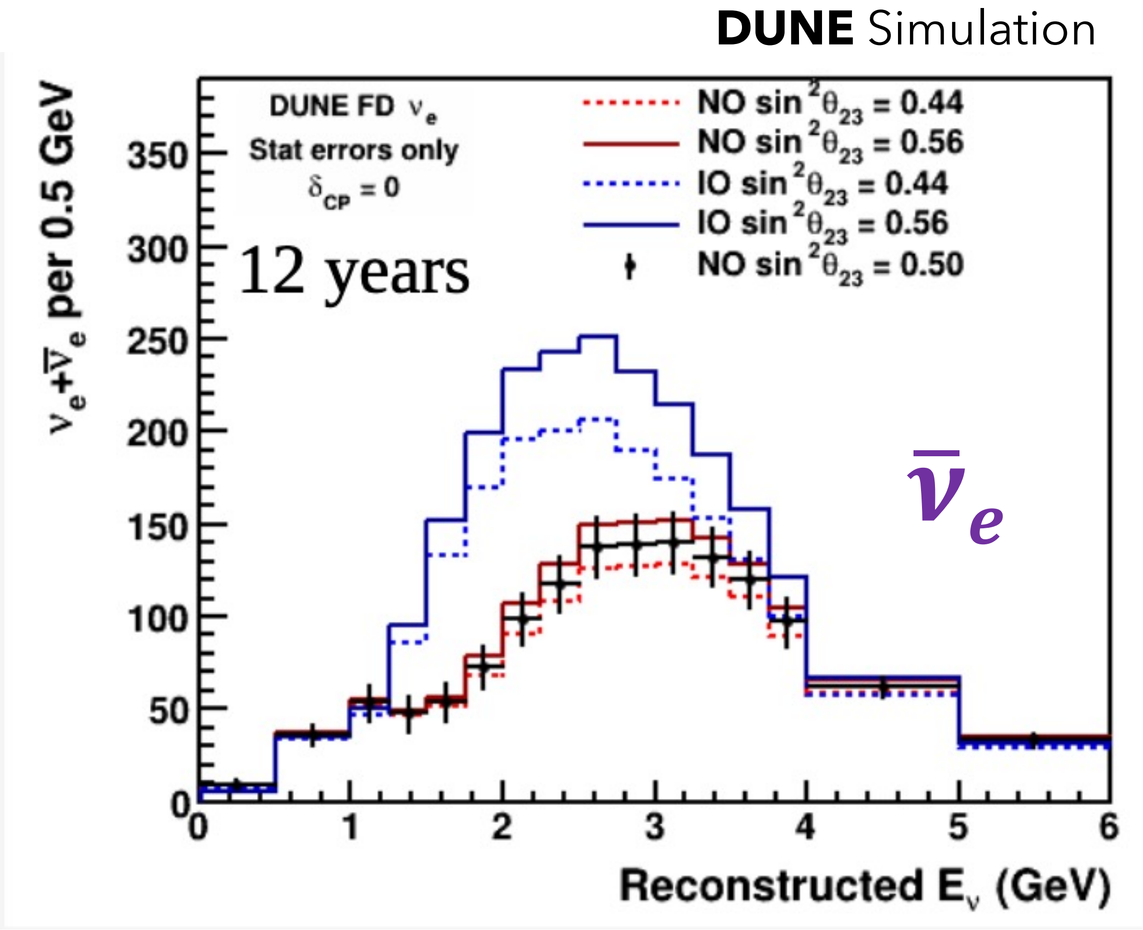




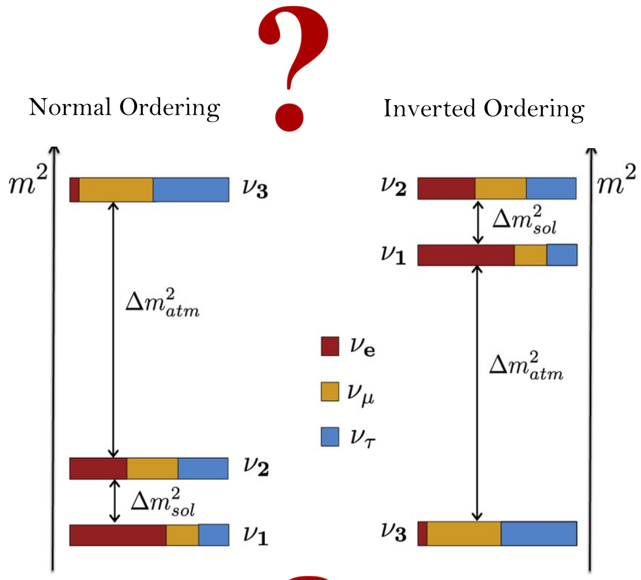
DUNE'S FUTURE DATA

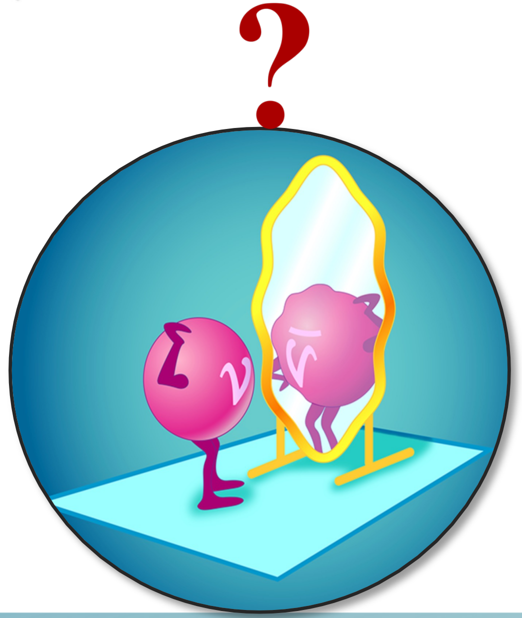
- With 10,000s of ν_μ and 1000s of ν_e collected over 10 years, DUNE will conclusively determine the mass ordering and have excellent potential to discover CP violation.





DUNE GOALS: DISCOVERY



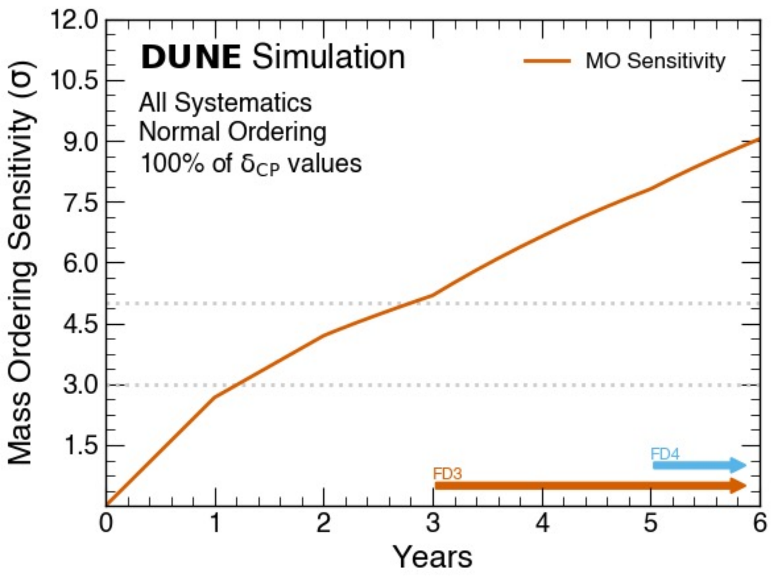


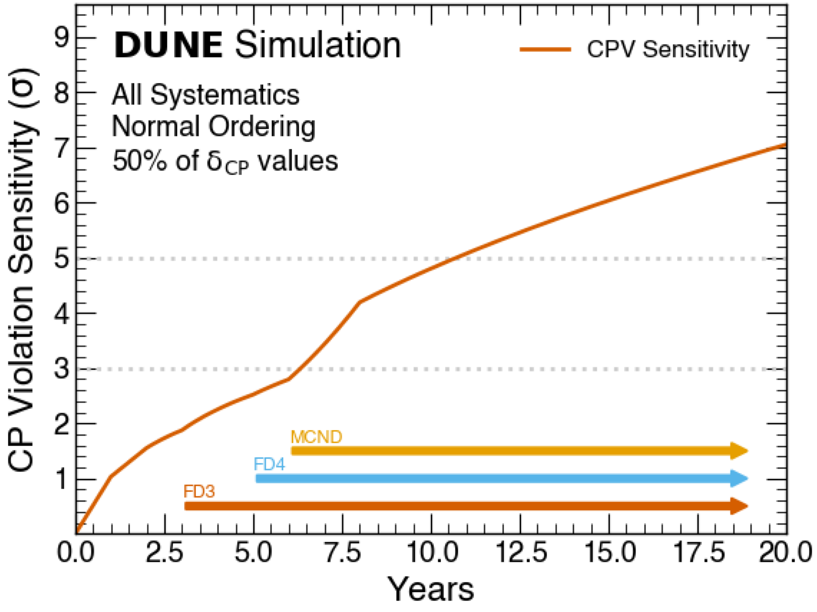
Mass Ordering(MO): Normal or Inverted?

Early milestone: DUNE will resolve MO within 1-5 years of running.

δ_{CP}: Do neutrinos violate CP?

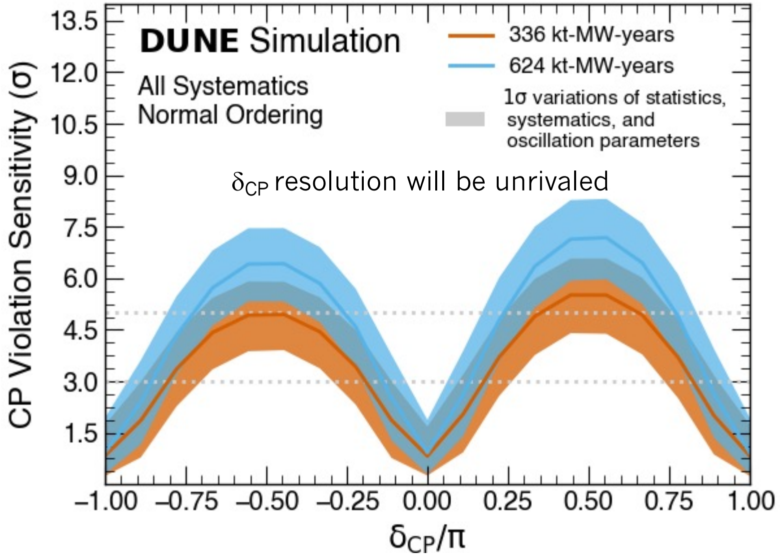
DUNE has > 5σ discovery potential for > 50% of δ_{CP} values for either MO.

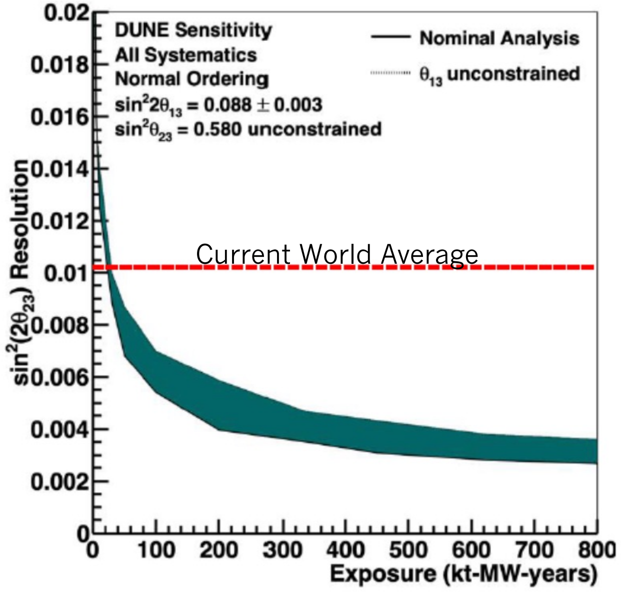




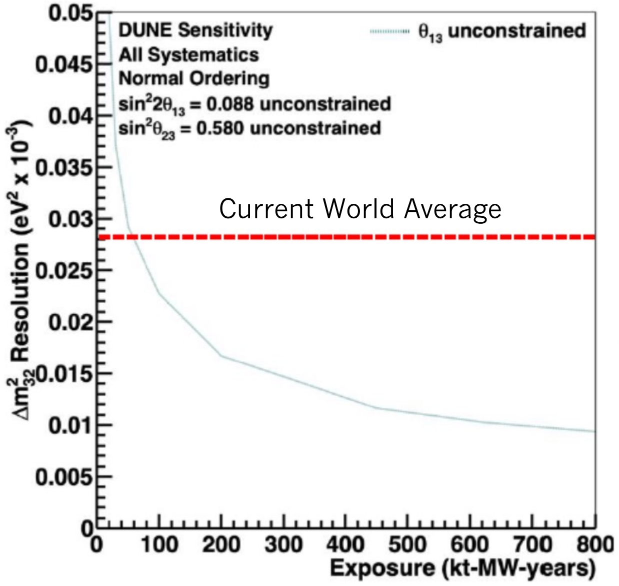
DUNE GOALS: PRECISION

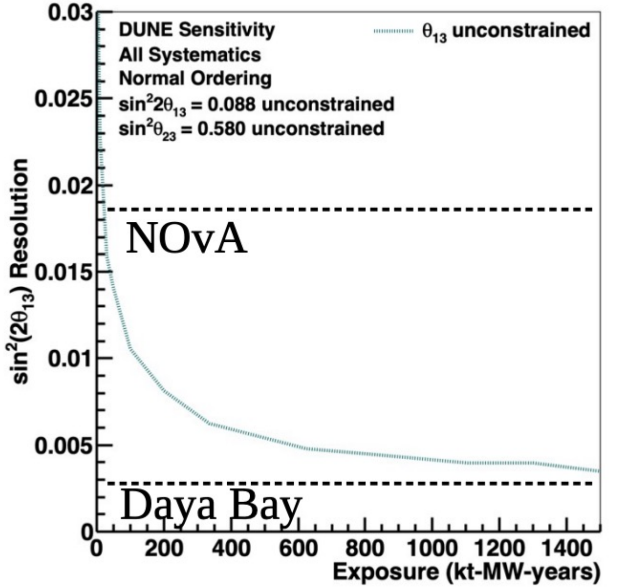
World Average from NuFit5: JHEP 09 (2020) 178





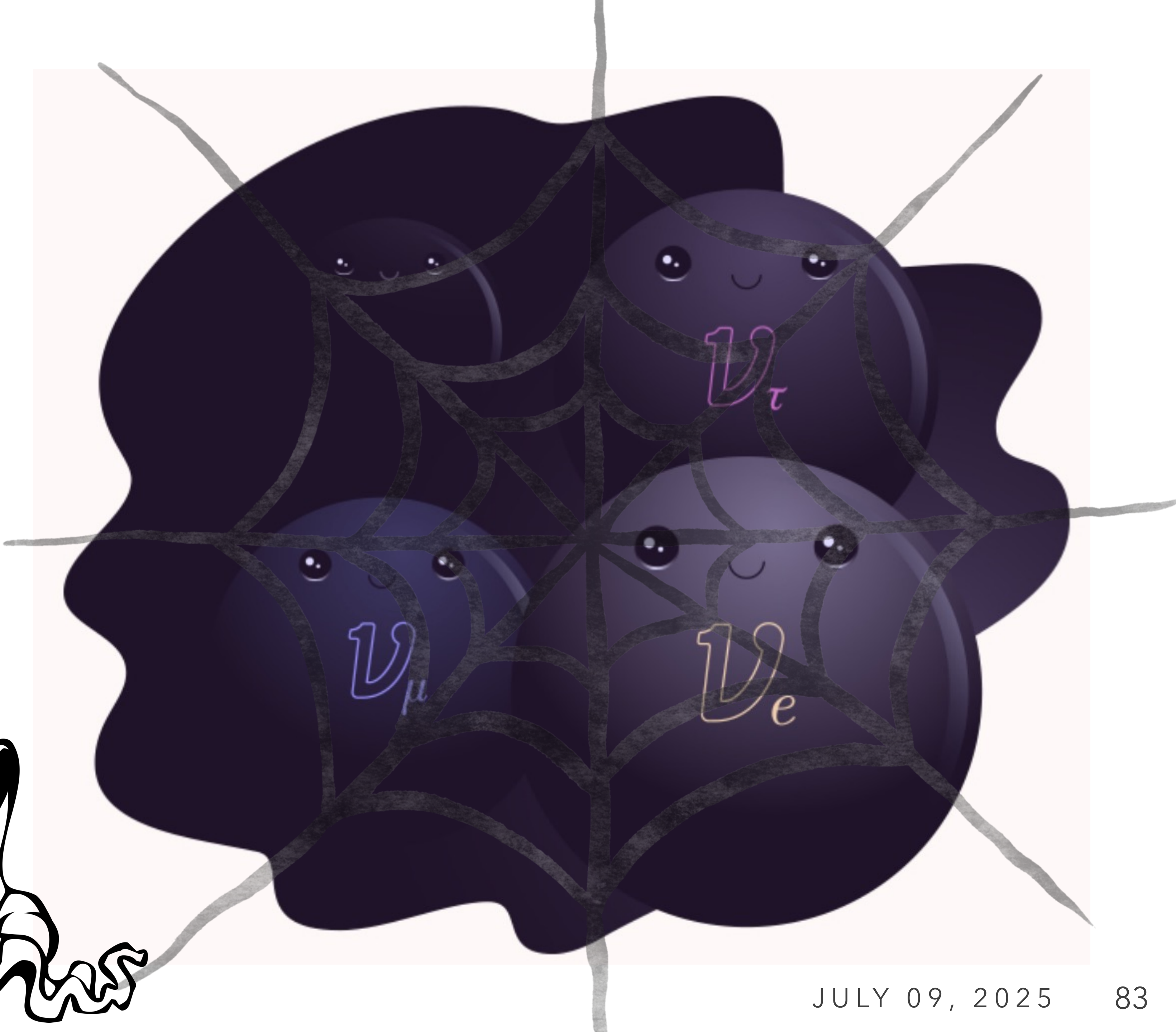
DUNE is the **best-in-class** experiment that will make unambiguous high precision measurements of Δm^2_{32}, δ_{CP}, θ_{23} and θ_{13} with a single experiment.





Enables tests of Unitarity of PMNS mixing matrix

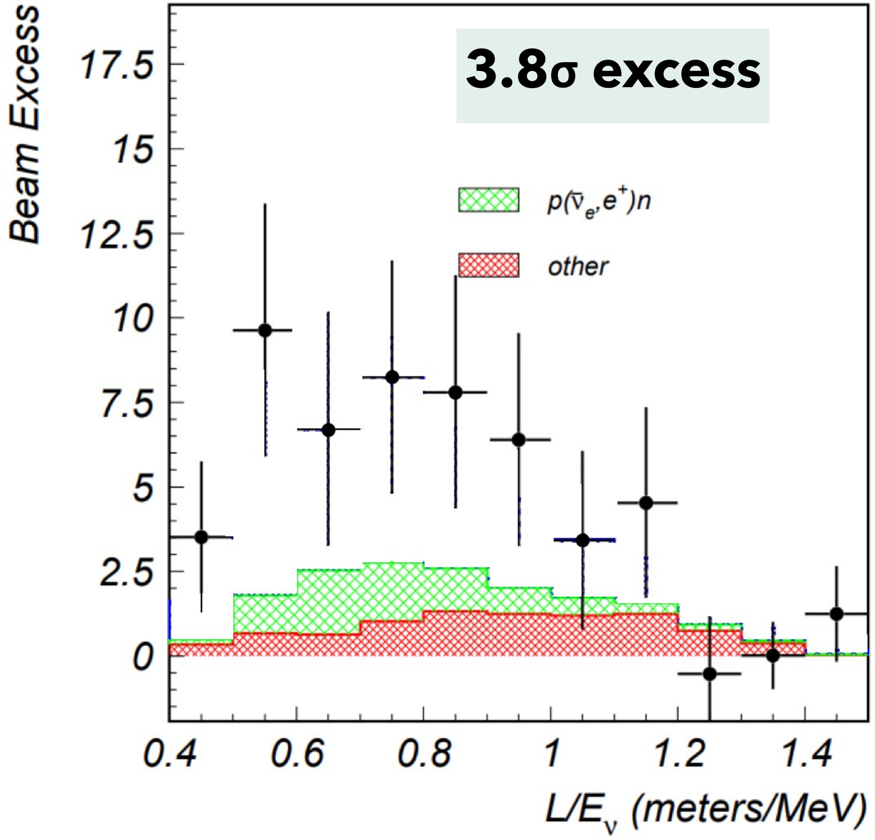
BUT, WHAT IF THE 3-NEUTRINO PICTURE IS NOT COMPLETE?



ANOMALIES, ANOMALIES

LSND

PRD 64 (2001), 112007



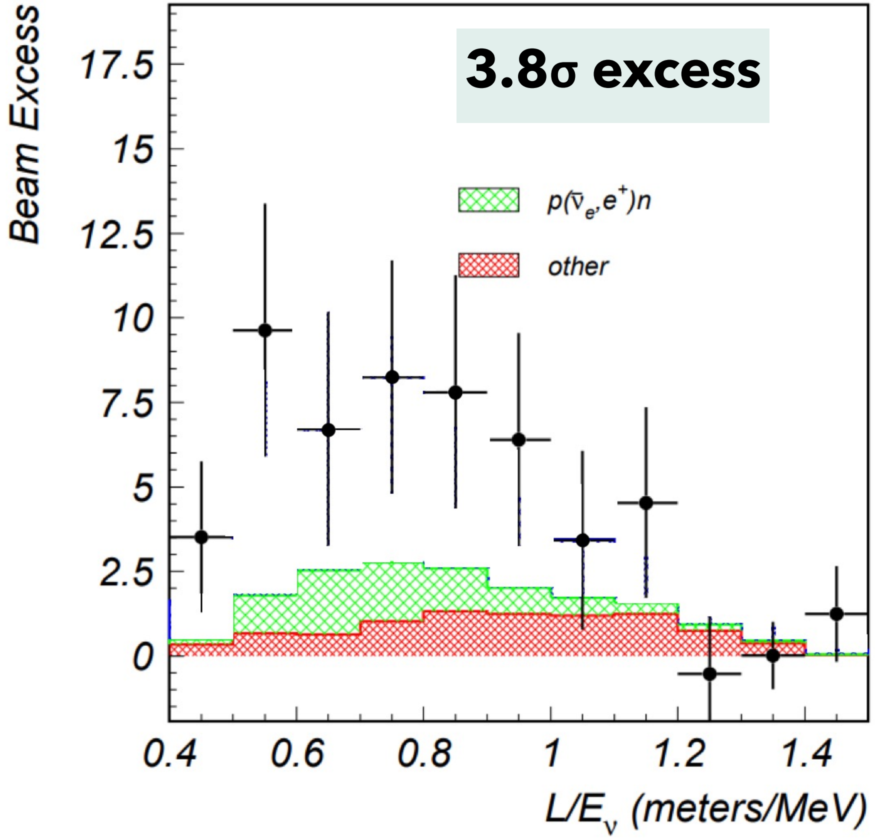
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$?

ANOMALIES, ANOMALIES

Also, Gallium Anomaly! Important to the story but not covered here ☹

LSND

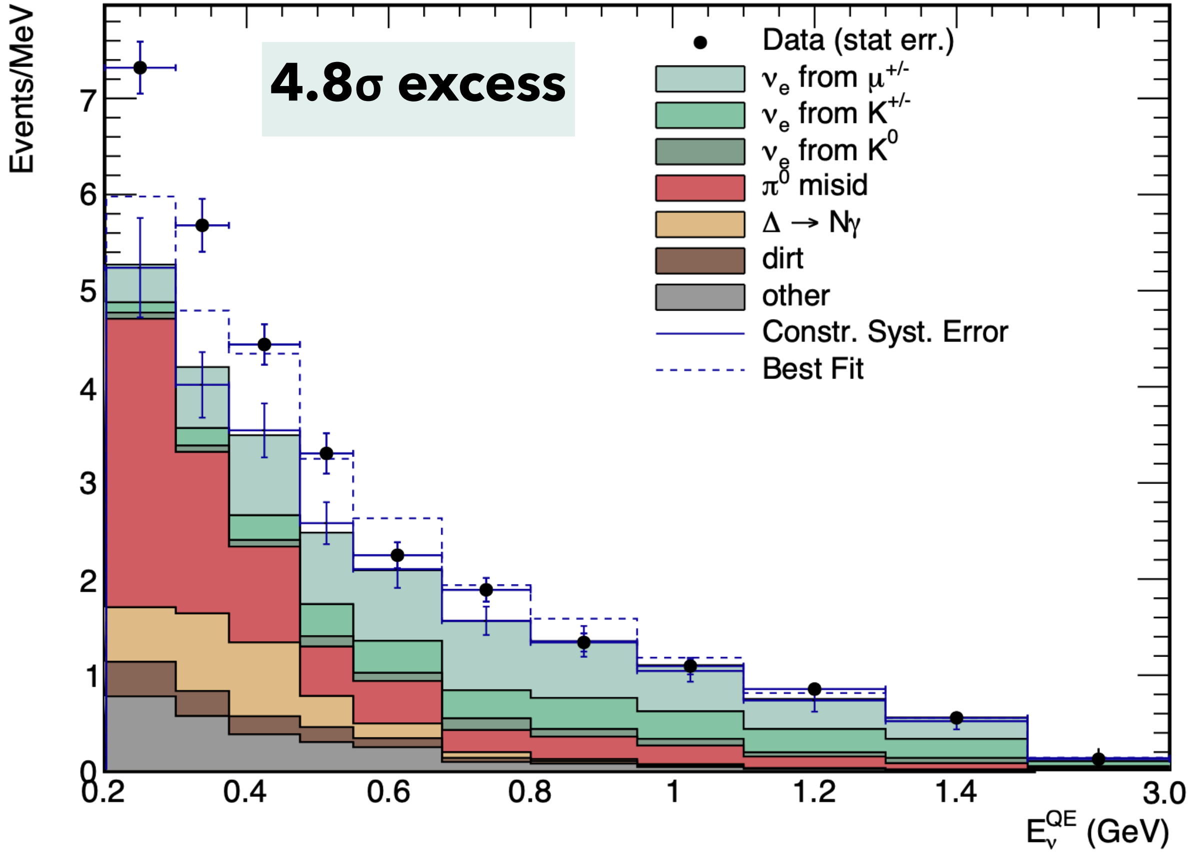
PRD 64 (2001), 112007



$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$?

MiniBOONE

PRD 103 (2021) 5, 052002



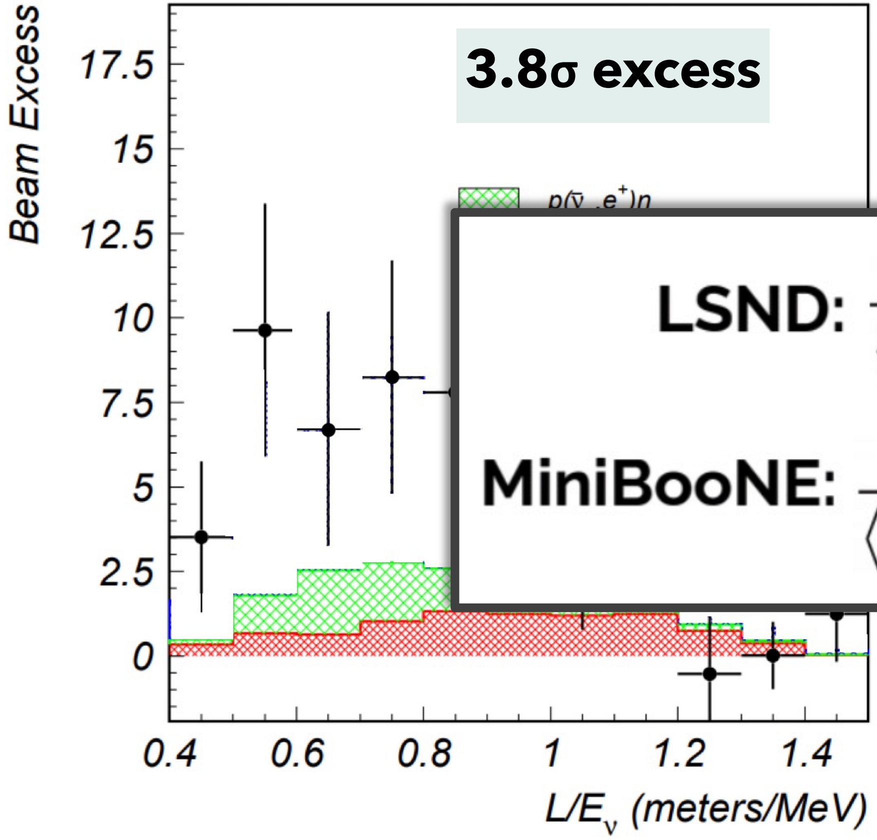
$\nu_\mu \rightarrow \nu_e$?

ANOMALIES, ANOMALIES

Also, Gallium Anomaly! Important to the story but not covered here ☹

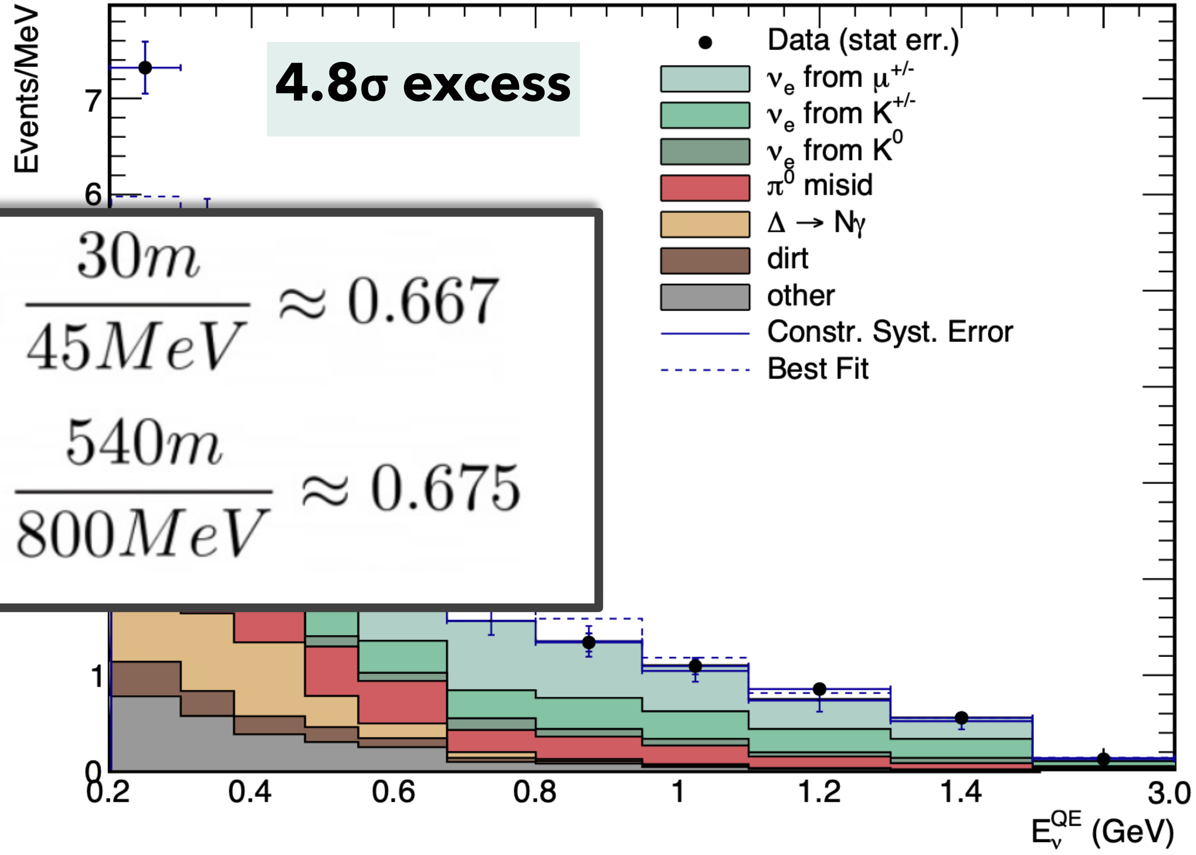
LSND

PRD 64 (2001), 112007



MiniBOONE

PRD 103 (2021) 5, 052002



LSND: $\frac{L}{\langle E_\nu \rangle} = \frac{30m}{45MeV} \approx 0.667$

MiniBooNE: $\frac{L}{\langle E_\nu \rangle} = \frac{540m}{800MeV} \approx 0.675$

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$?

$\nu_\mu \rightarrow \nu_e$?

A FOURTH NEUTRINO?

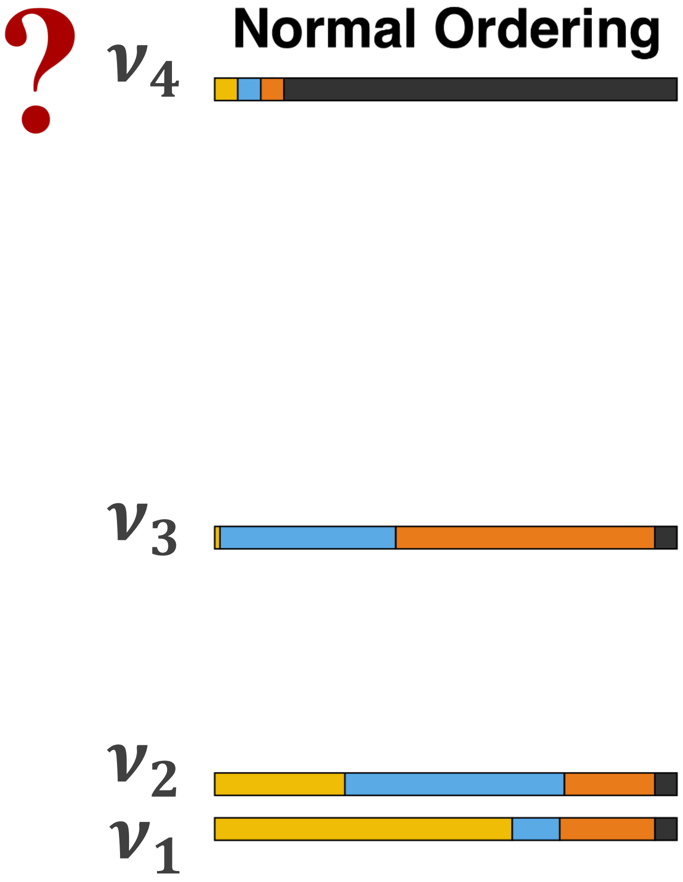


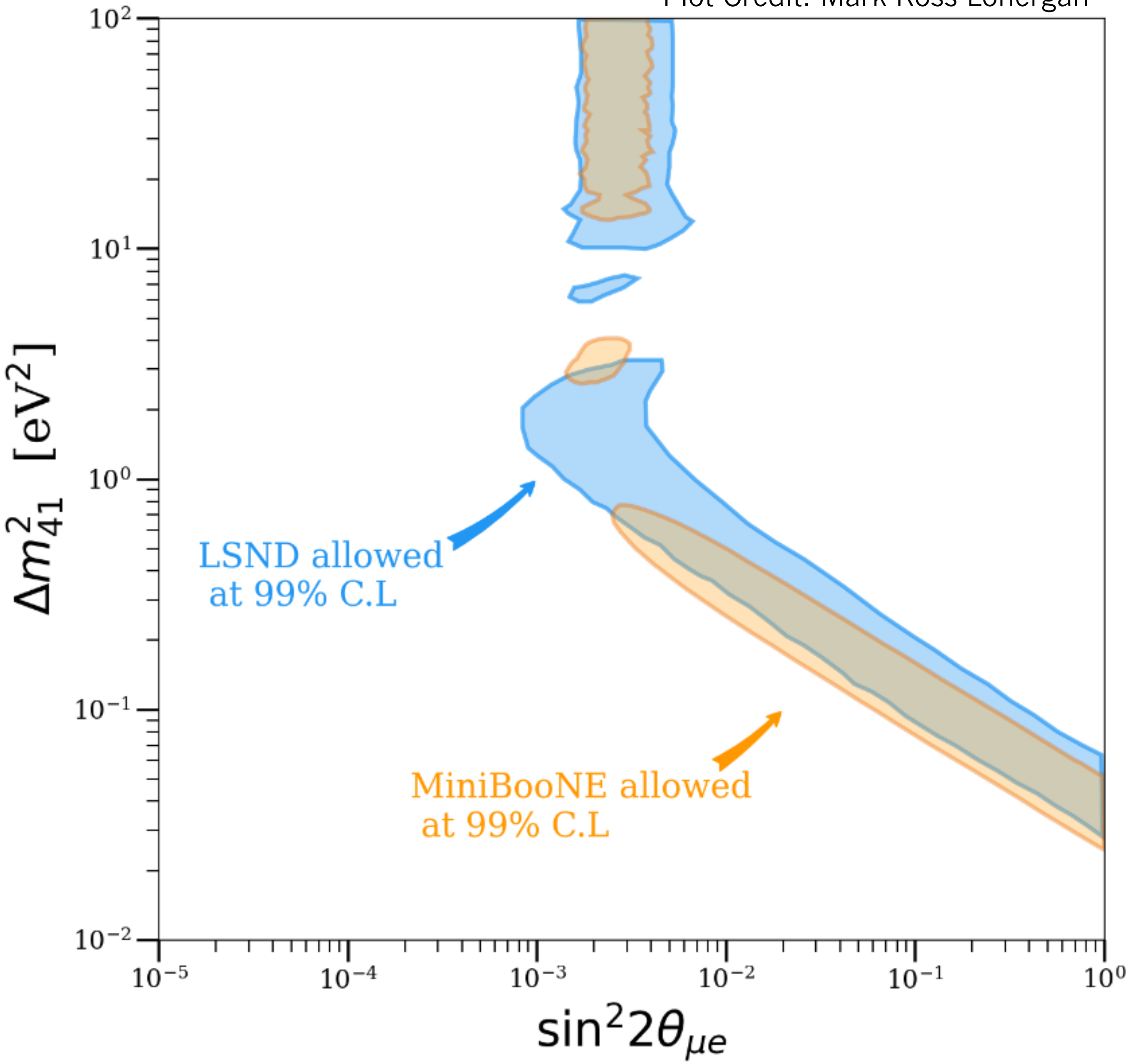
Image Credit: Adam Lister

$$\Delta m^2 \approx 1eV^2$$

$$|\Delta m^2_{31}| \sim 2 \times 10^{-3}\mathrm{eV}^2$$

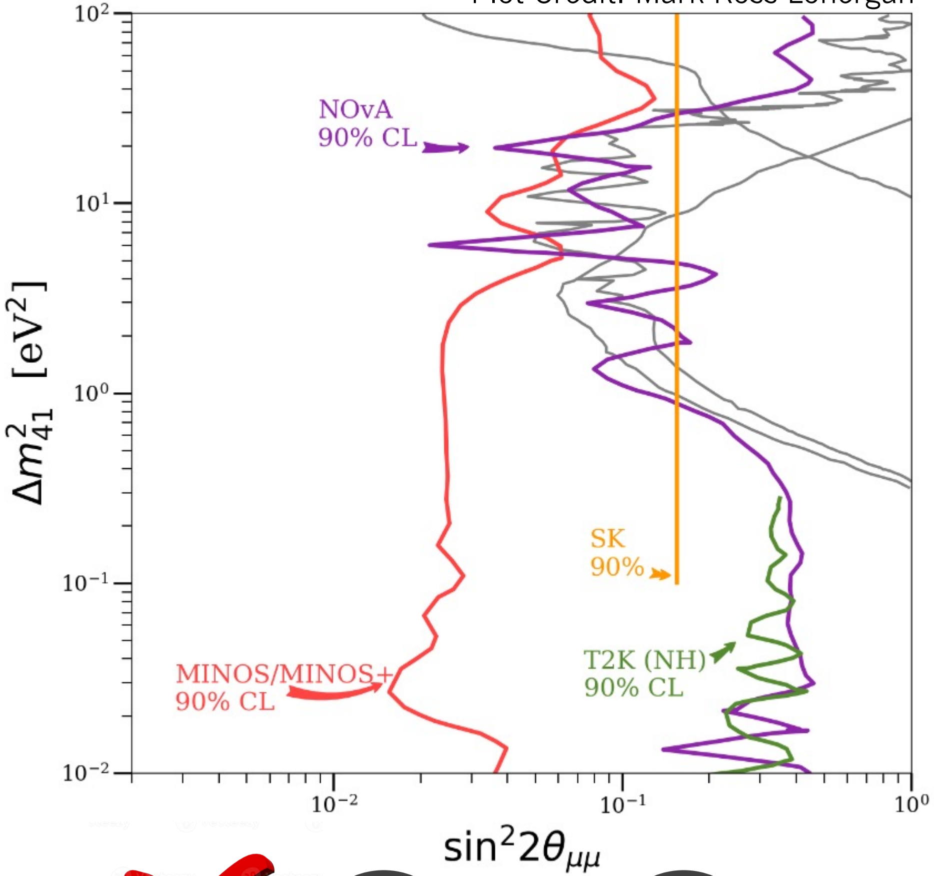
$$\Delta m^2_{21} \sim 7 \times 10^{-5}\mathrm{eV}^2$$

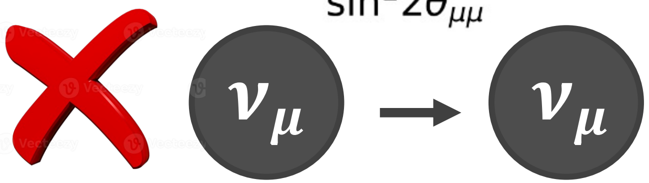
Plot Credit: Mark Ross Lonergan



HANG ON! IF THERE IS AN APPEARNACE …
HOW ABOUT THE DISAPPEARNACE

Plot Credit: Mark Ross Lonergan

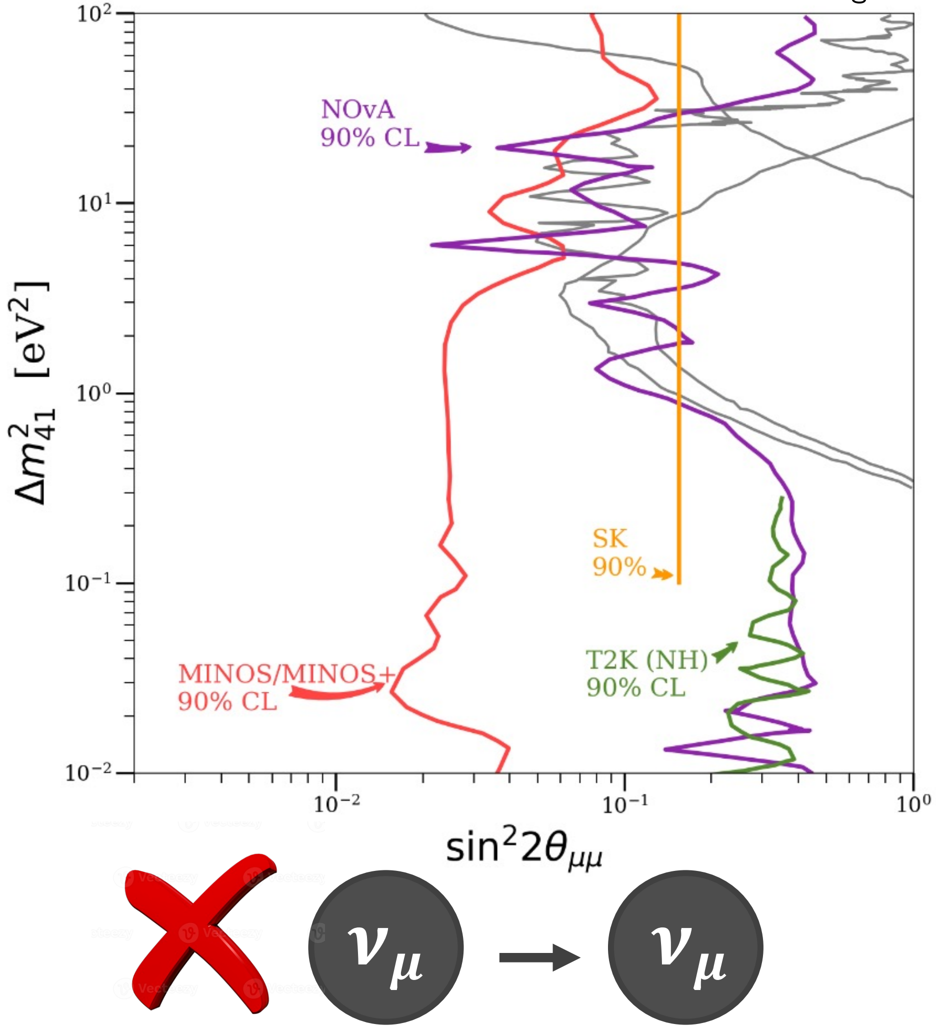




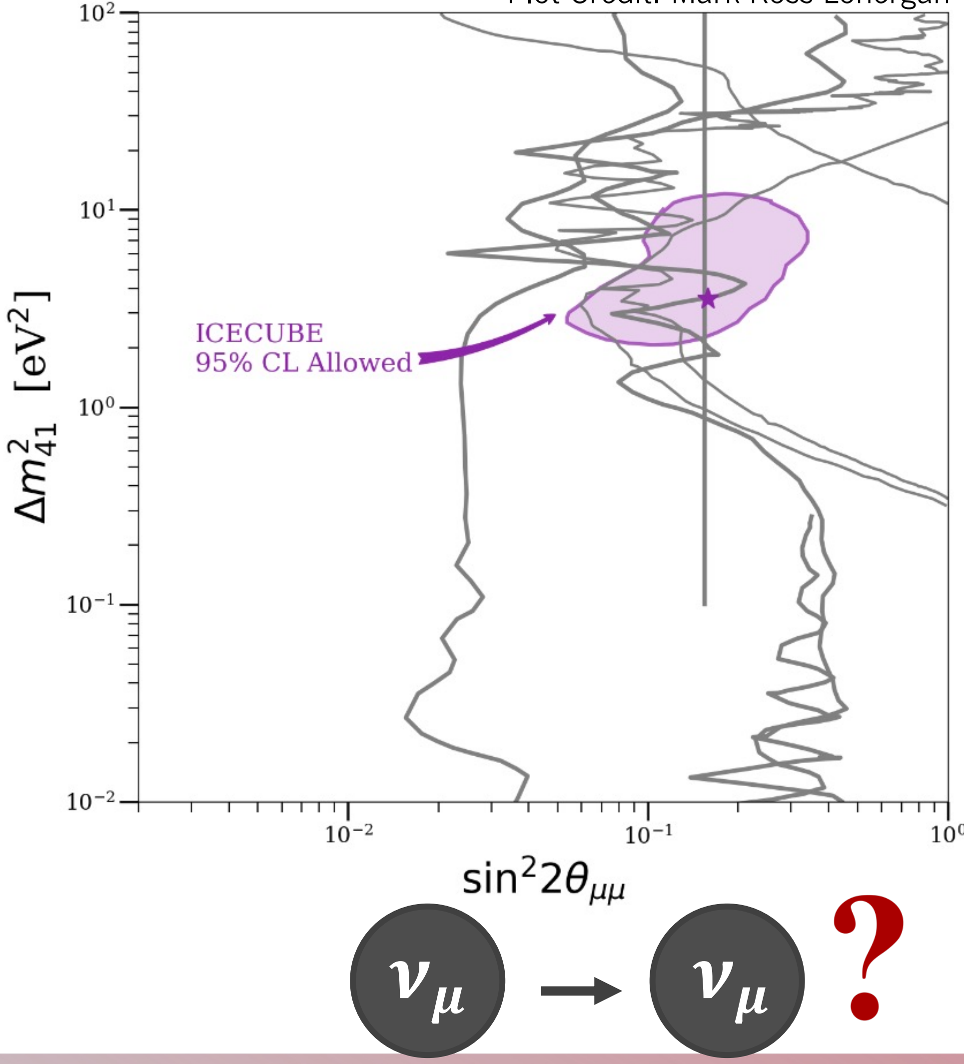
NO ANOMALIES DETECTED!

HANG ON! IF THERE IS AN APPEARNACE … HOW ABOUT THE DISAPPEARNACE

Plot Credit: Mark Ross Lonergan



Plot Credit: Mark Ross Lonergan



NEED MORE DATA TO SETTLE THIS DEBATE

Fermilab

Short-Baseline Neutrino Program

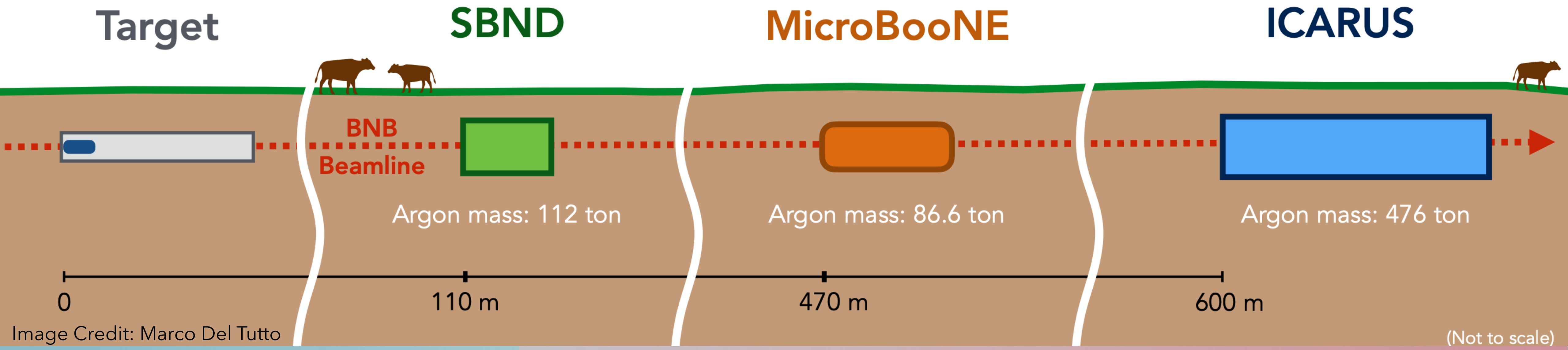
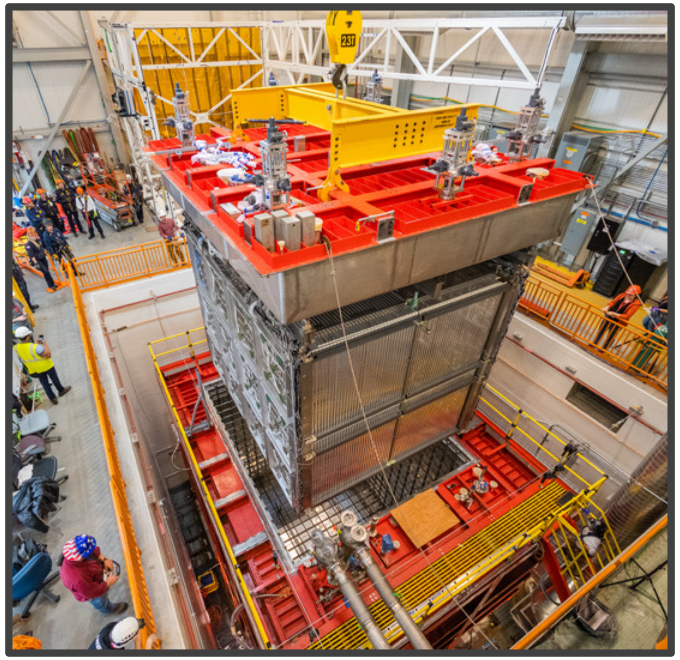


Image Credit: Marco Del Tutto



Collecting data since 2024

Ran for 5 years 2015-2020

Collecting data since 2022

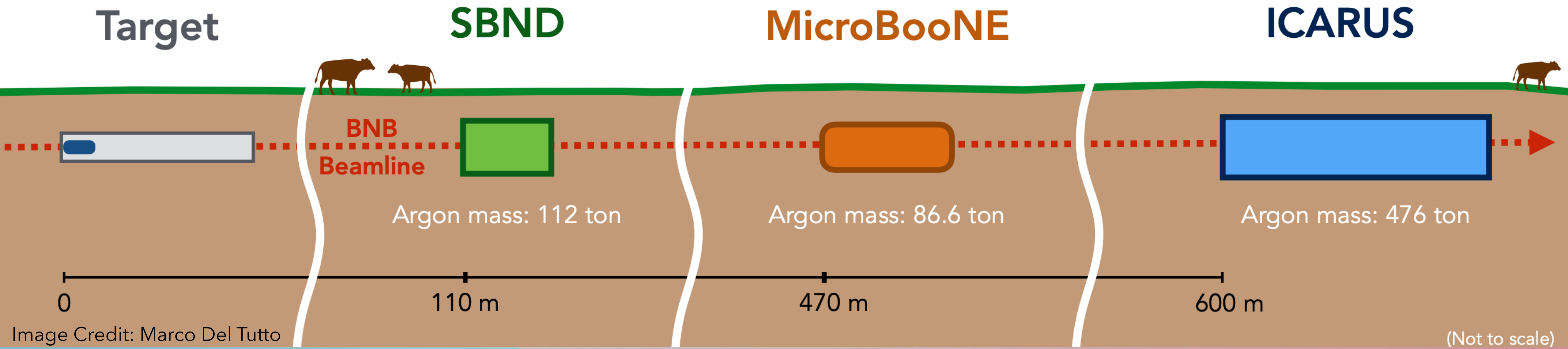
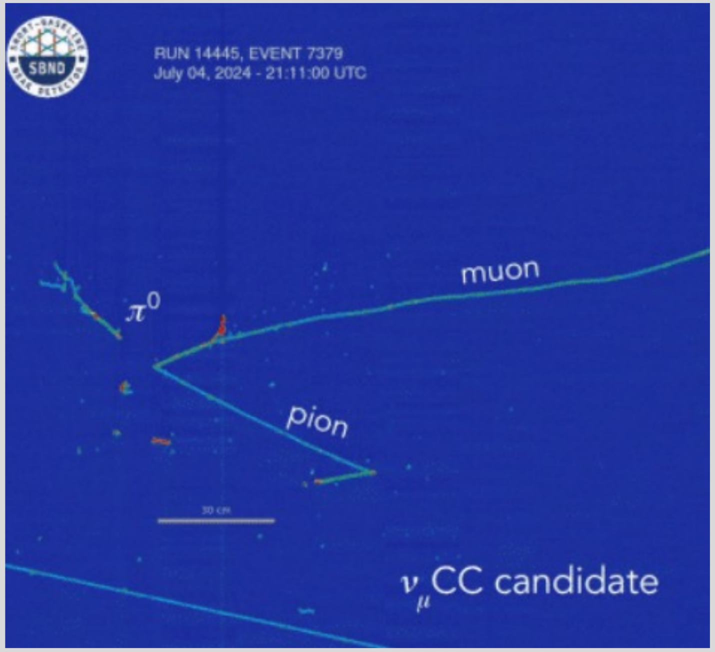
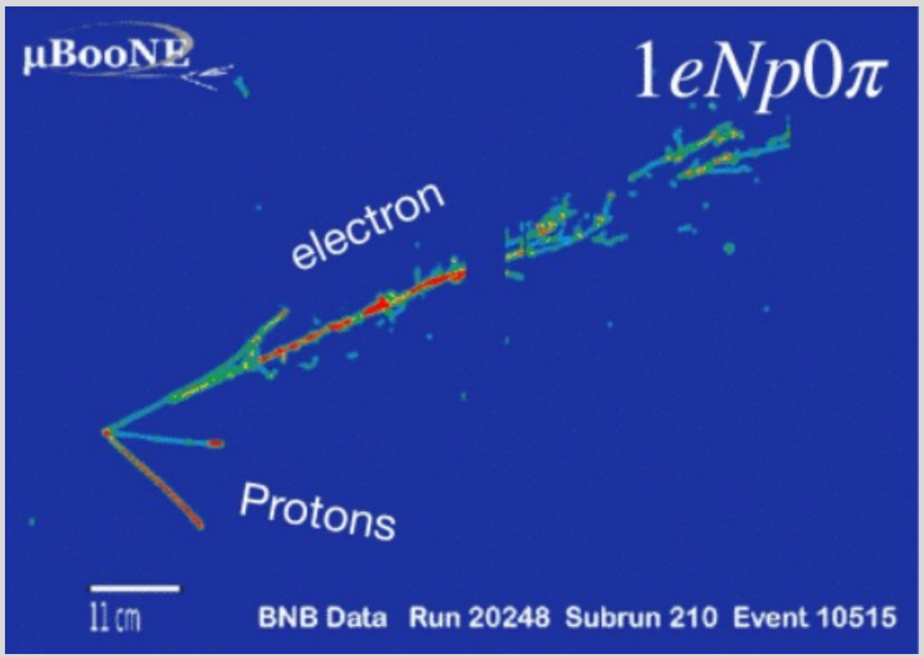


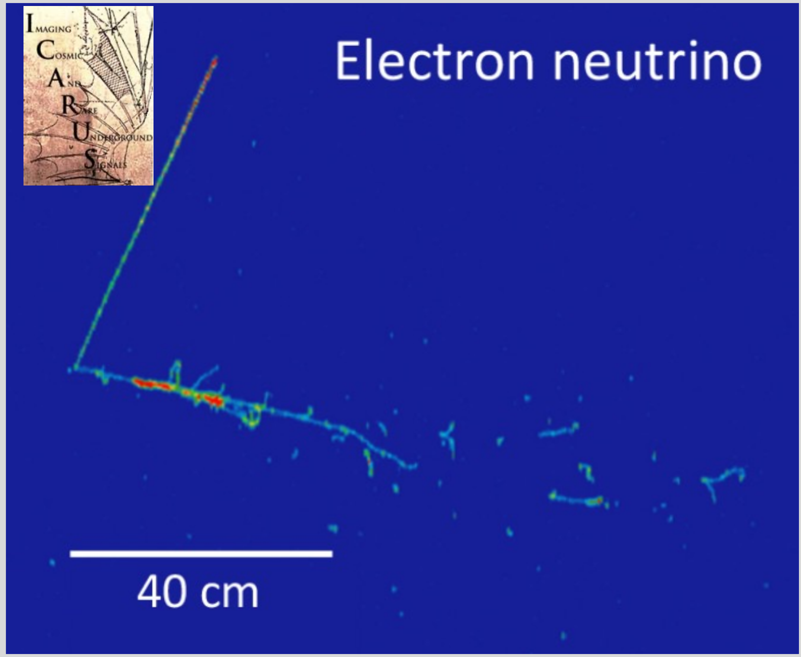
Image Credit: Marco Del Tutto



Collecting data since 2024



Ran for 5 years 2015-2020



Collecting data since 2022

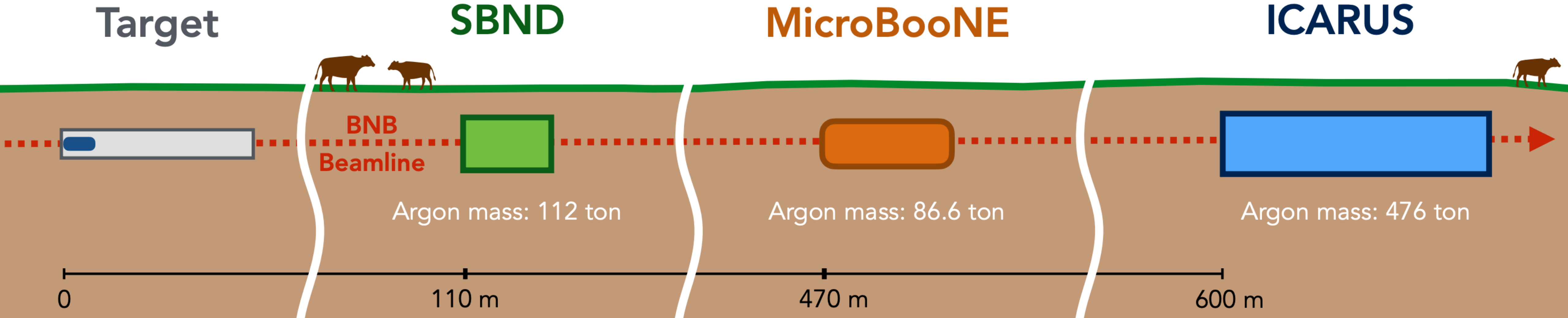
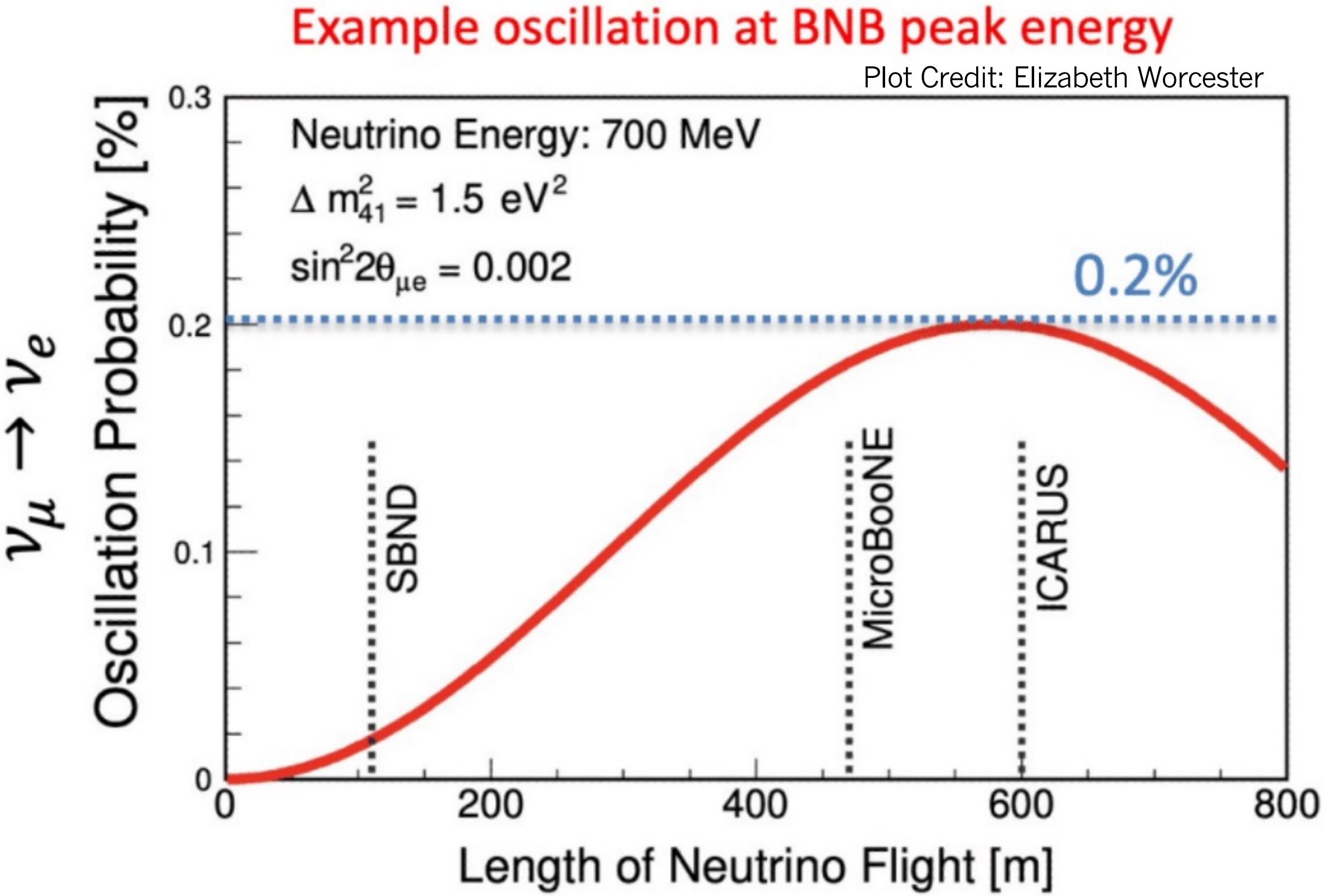
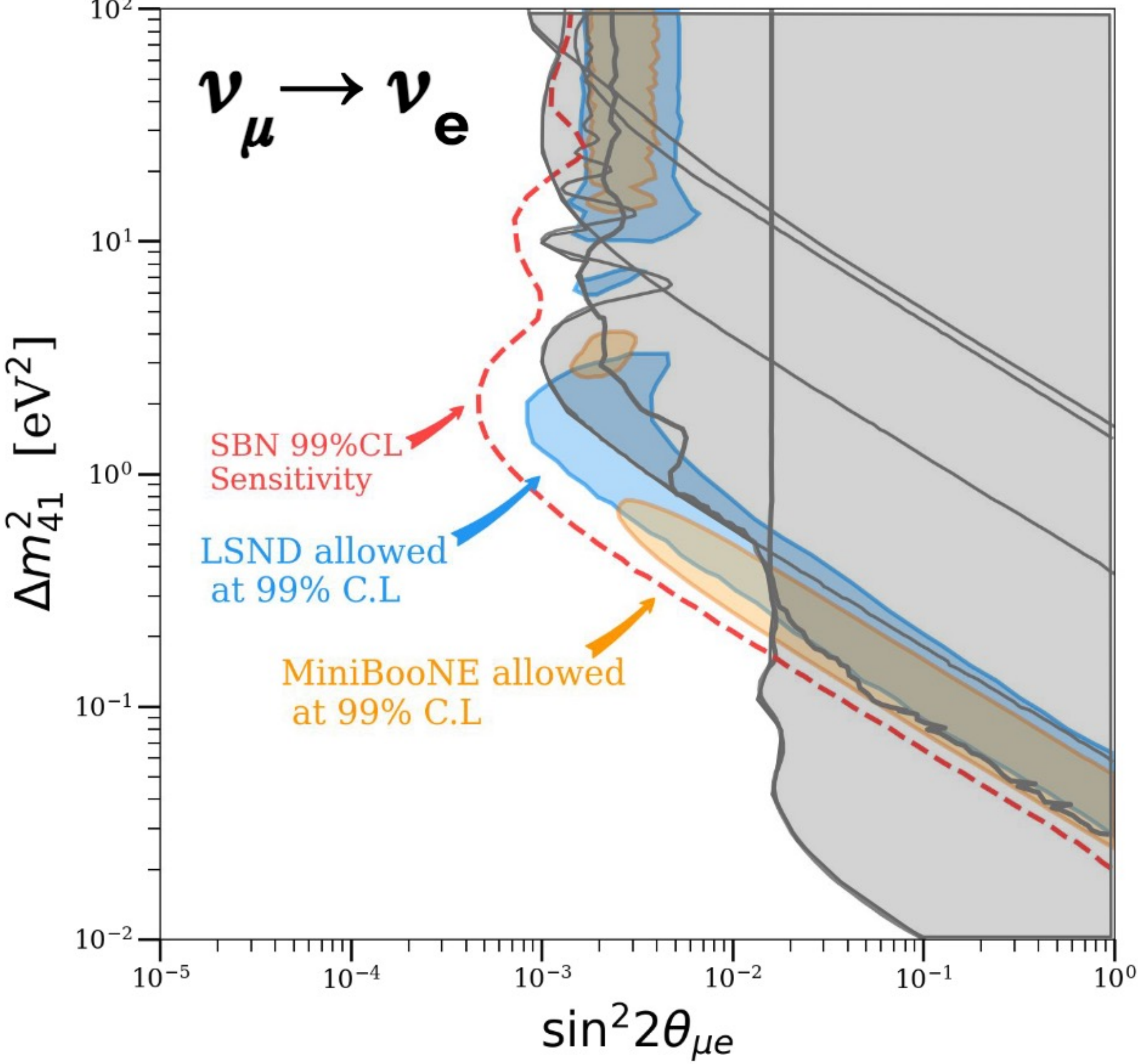


Image Credit: Marco Del Tutto

(Not to scale)

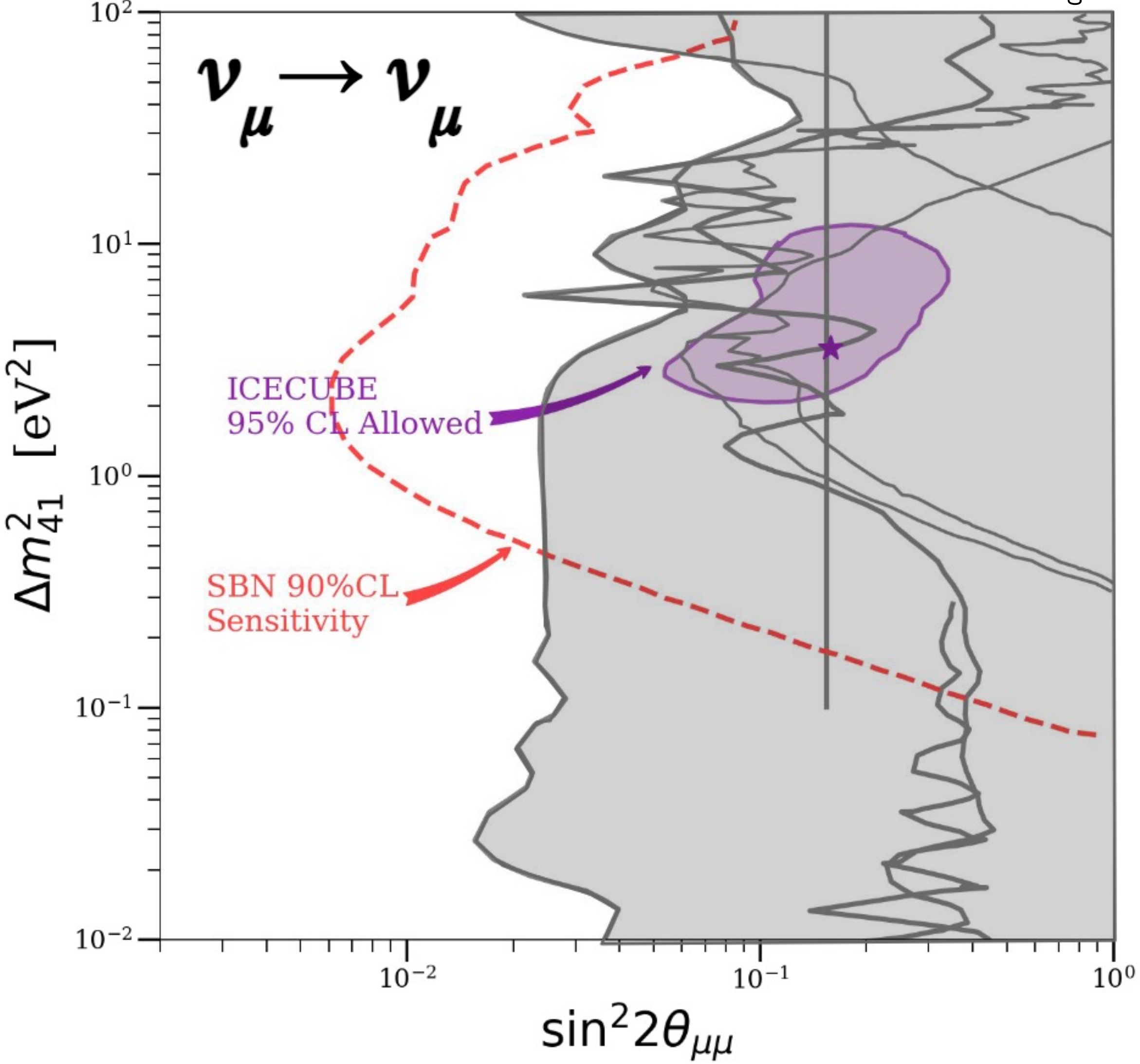
SBN SENSITIVITY



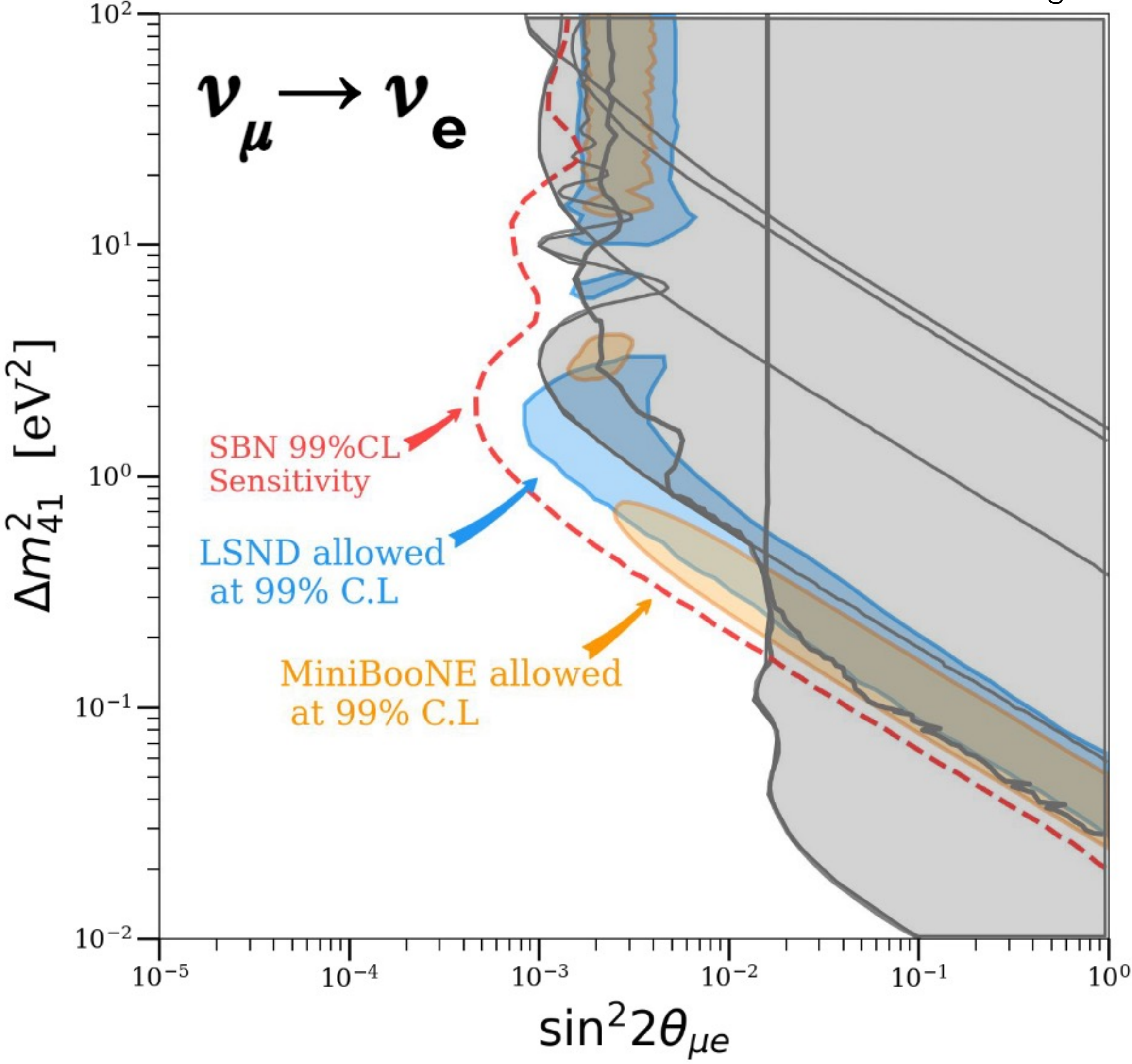


SBN SENSITIVITY

Plot Credit: Mark Ross Lonergan

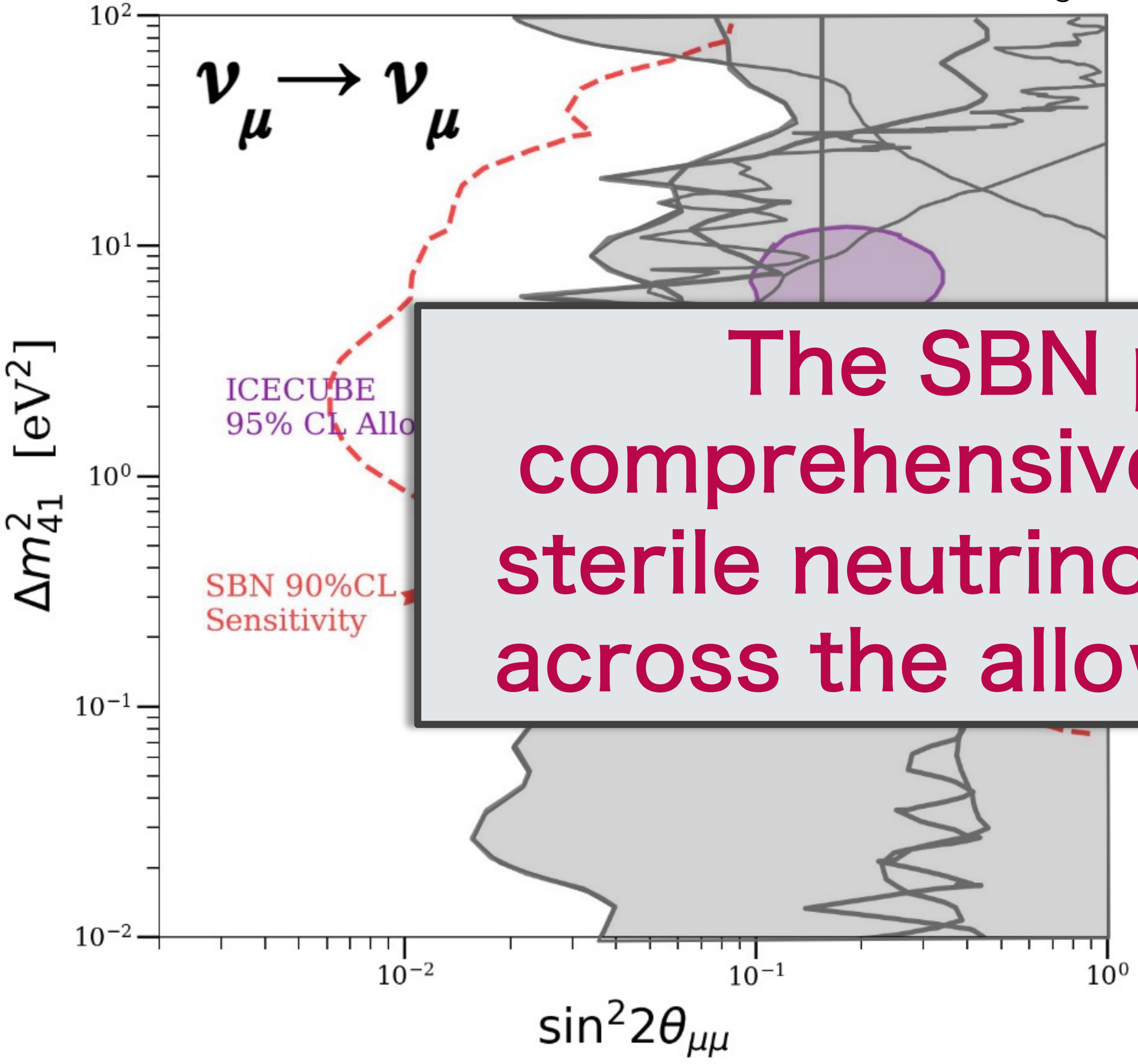


Plot Credit: Mark Ross Lonergan

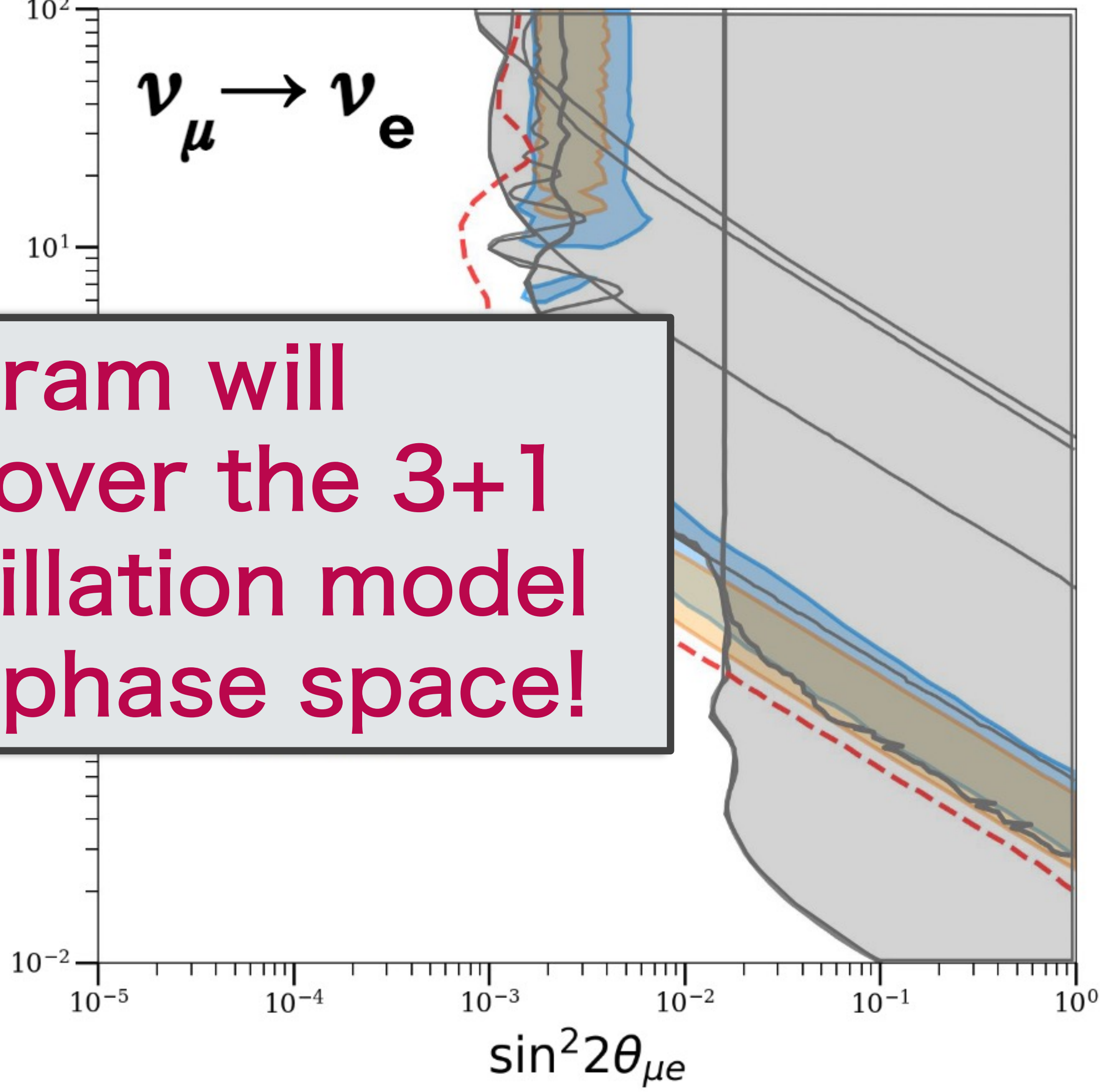


SBN SENSITIVITY

Plot Credit: Mark Ross Lonergan



Plot Credit: Mark Ross Lonergan



The SBN program will comprehensively cover the 3+1 sterile neutrino oscillation model across the allowed phase space!

BEYOND 3+1 STERILE NEUTRINO

PORTALS TO THE DARK SECTOR & OTHER NEW PHYSICS BEYOND THE STANDARD MODEL

M. HOSTERT'S TALK IN 2 WEEKS

OUTLOOK


TURN TO CLEAR VISION
QUARTERS ONLY
25¢
TO OPERATE
25¢
STEP 1
STEP 2

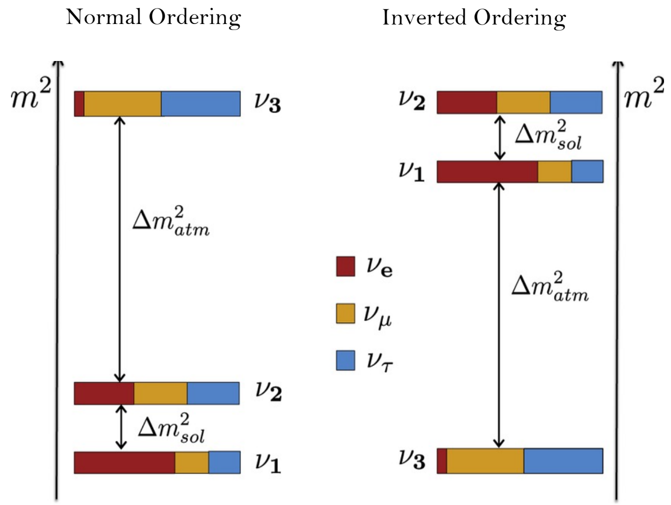
MORE NEUTRINOS ARE COMING!

NEUTRINO PHYSICS IS AT A TURNING POINT– THERE'S NEVER BEEN A BETTER TIME TO DIVE IN.

- With 25 years of experience under our belt with neutrino experiments, we better understand the 3-flavor mixing and oscillations of neutrinos!
- A new generation of experiments is underway or about to launch!

WE ARE HEADING INTO THE ERA OF PRECISION & DISCOVERY

Mass Ordering(MO): Normal or Inverted?

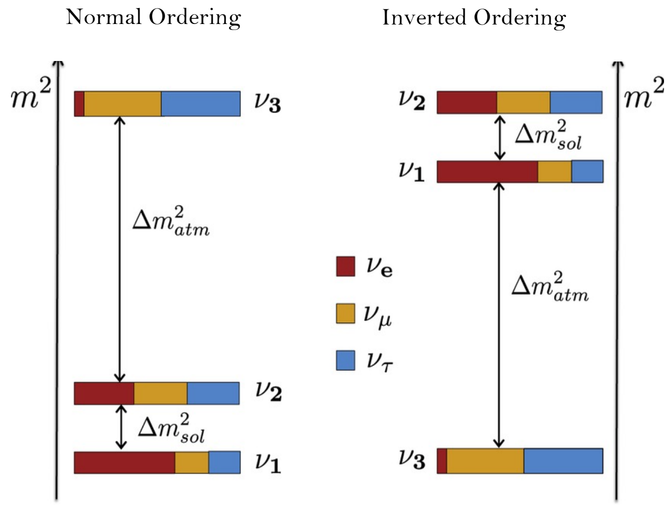


δ_{CP}: Do neutrinos violate CP?

WE ARE HEADING INTO THE ERA OF PRECISION & DISCOVERY

BUT,
keep room for surprises!

Mass Ordering(MO): Normal or Inverted?

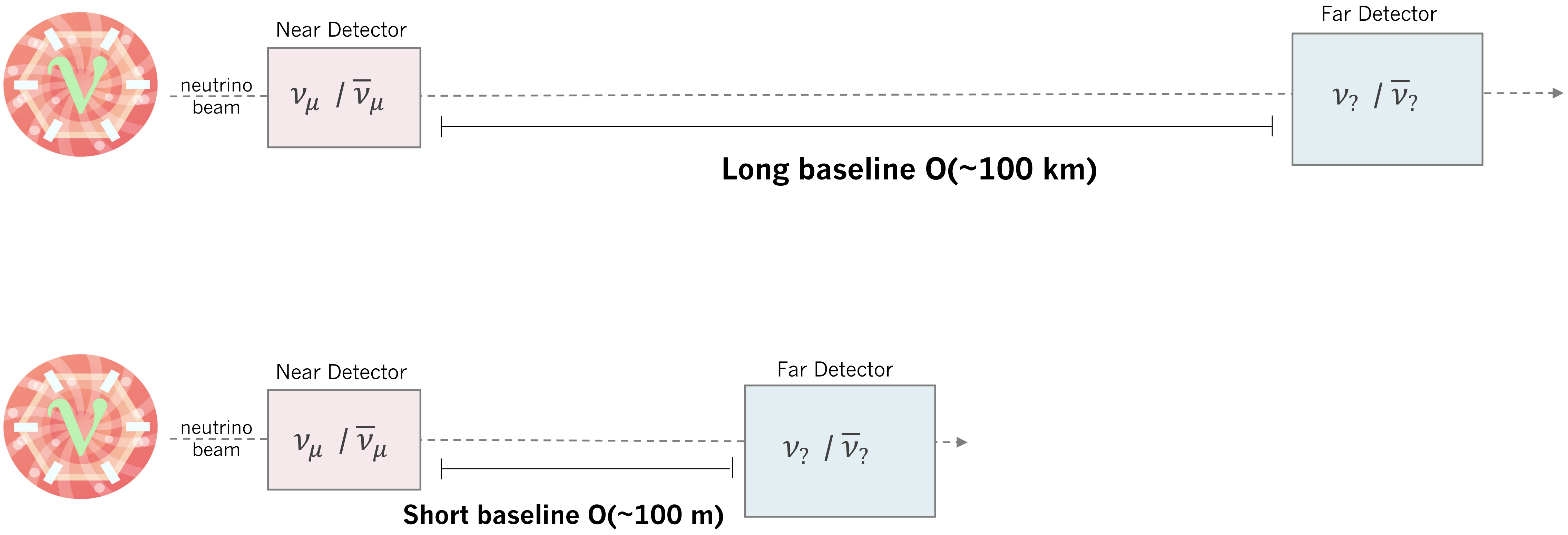


δ_{CP}: Do neutrinos violate CP?

SUPPLEMENTARY SLIDES

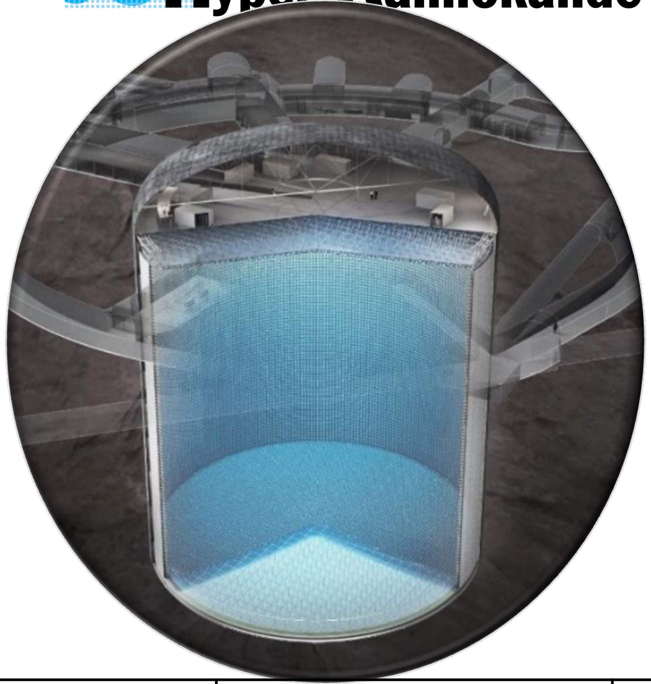
THE LONG & SHORT OF OSCILLATION MEASUREMENTS

Credit: Adam Lister & Brian Rebel

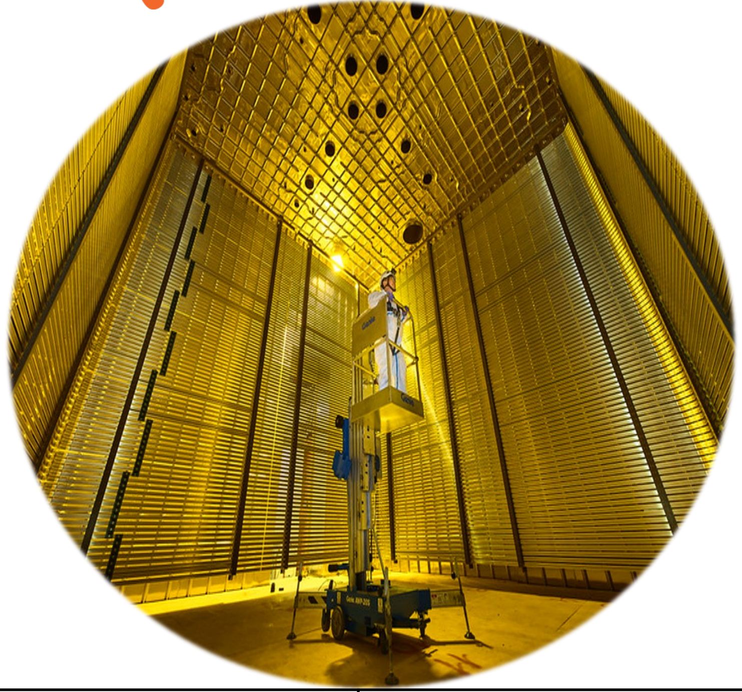


Not to scale

Hyper-Kamiokande



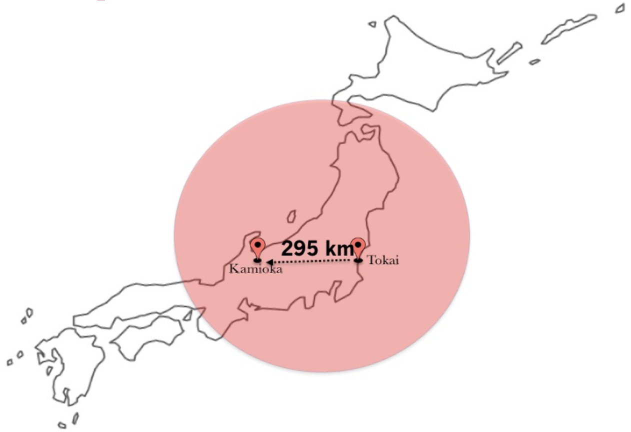
DEEP UNDERGROUND NEUTRINO EXPERIMENT

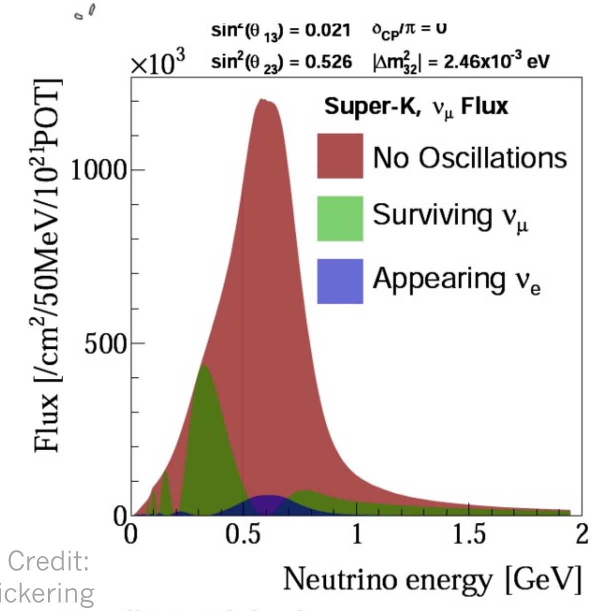


	Location	Beam	Baseline	Near Detector	Far Detector
Hyper-K	Japan (Tokai to Kamioka)	J-PARC 1.3 MW	295 km	Suite of detectors, on-and off-axis, intermediate movable Water Cherenkov detector	Water Cherenkov, 187 kt fiducial, off-axis
DUNE	United States (Fermilab to Lead, South Dakota)	LBNF 2 – 2.4 MW tunable	1285 km	Liquid argon time projection chamber + suite of detectors, on-axis, movable off-axis	Liquid argon time projection chamber, 40kt fiducial, on-axis

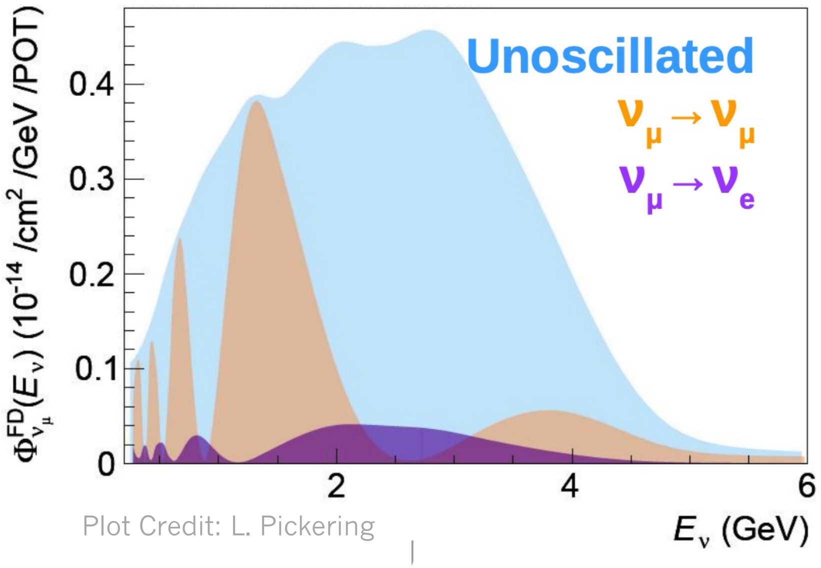
Adapted from annurev-nucl-102020-101615

These experiments are designed to study **accelerator, astrophysical, solar and atmospheric neutrinos** and **probe SM, BSM, exotic and dark matter** physics.





Plot Credit: L. Pickering



Plot Credit: L. Pickering

Hyper-Kamiokande

Hyper-K Dome: Completed

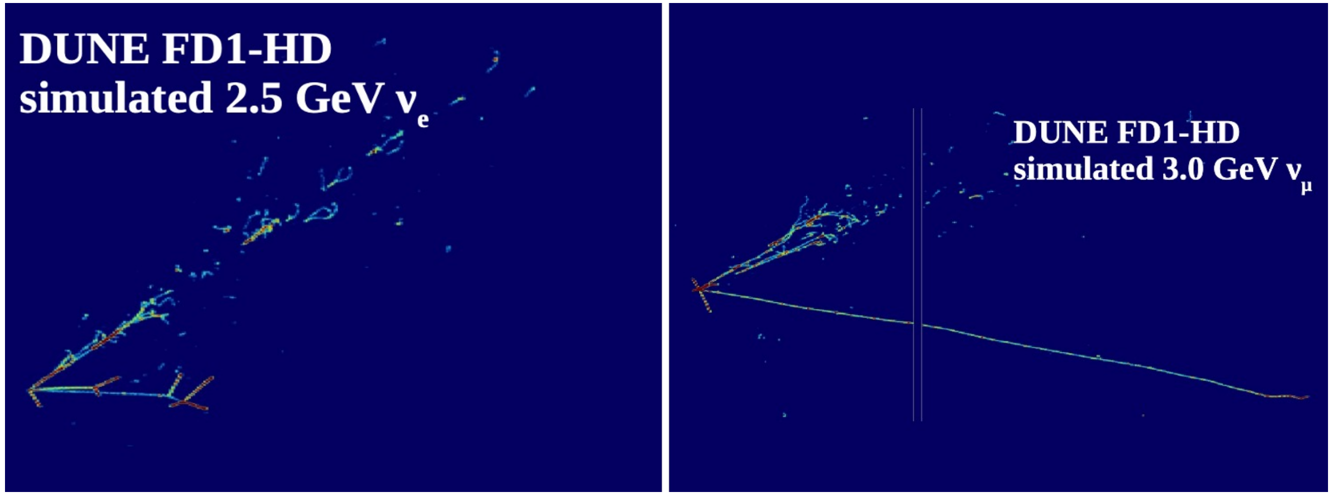
Cavern: Nearing completion?

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

DUNE FD Cavern: Completed

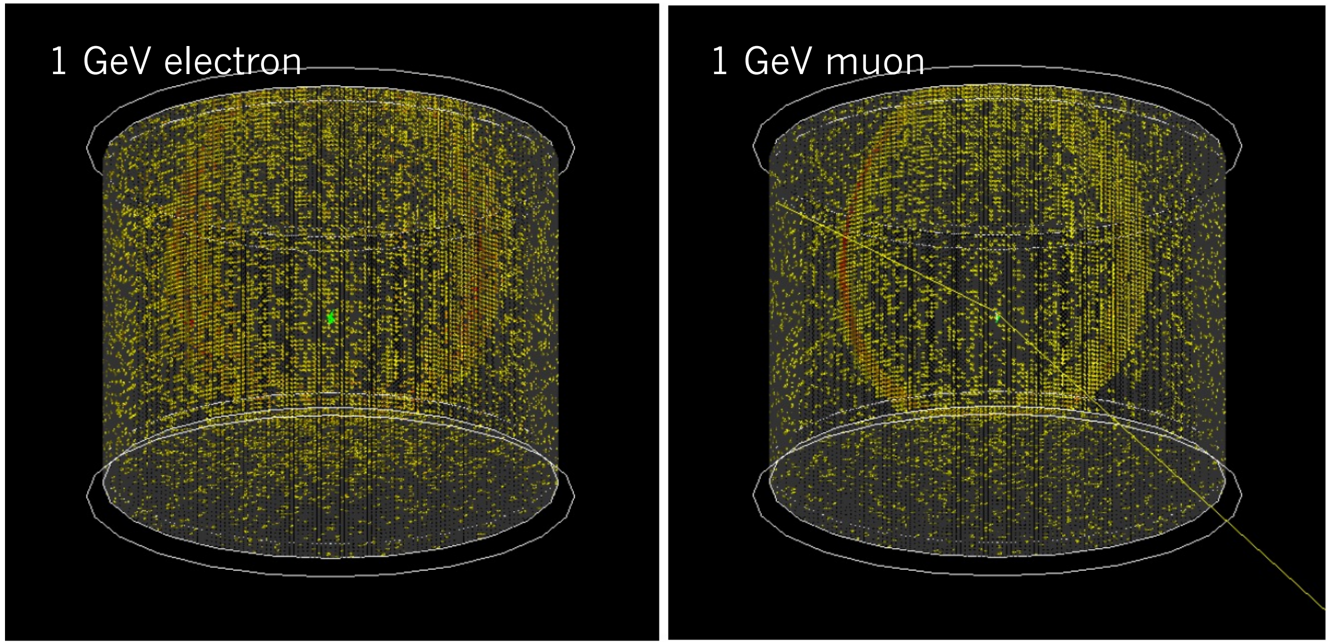
DEEP UNDERGROUND NEUTRINO EXPERIMENT

- Excellent particle identification and spatial resolution.
- Low thresholds of a few-MeV.



Hyper-Kamiokande

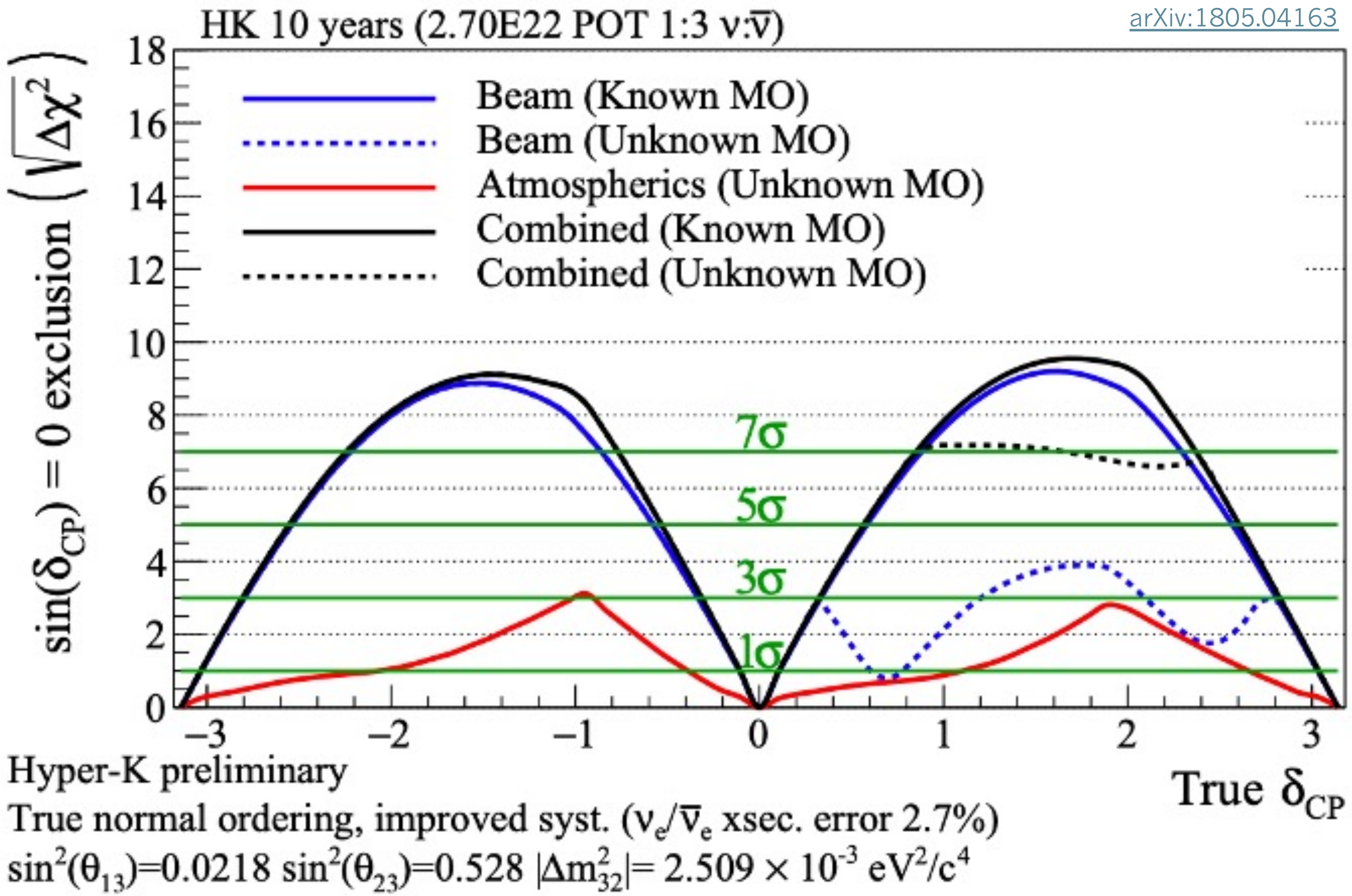
- Clean separation of muon and electron Cherenkov rings.
- Excellent timing resolution (~ns).



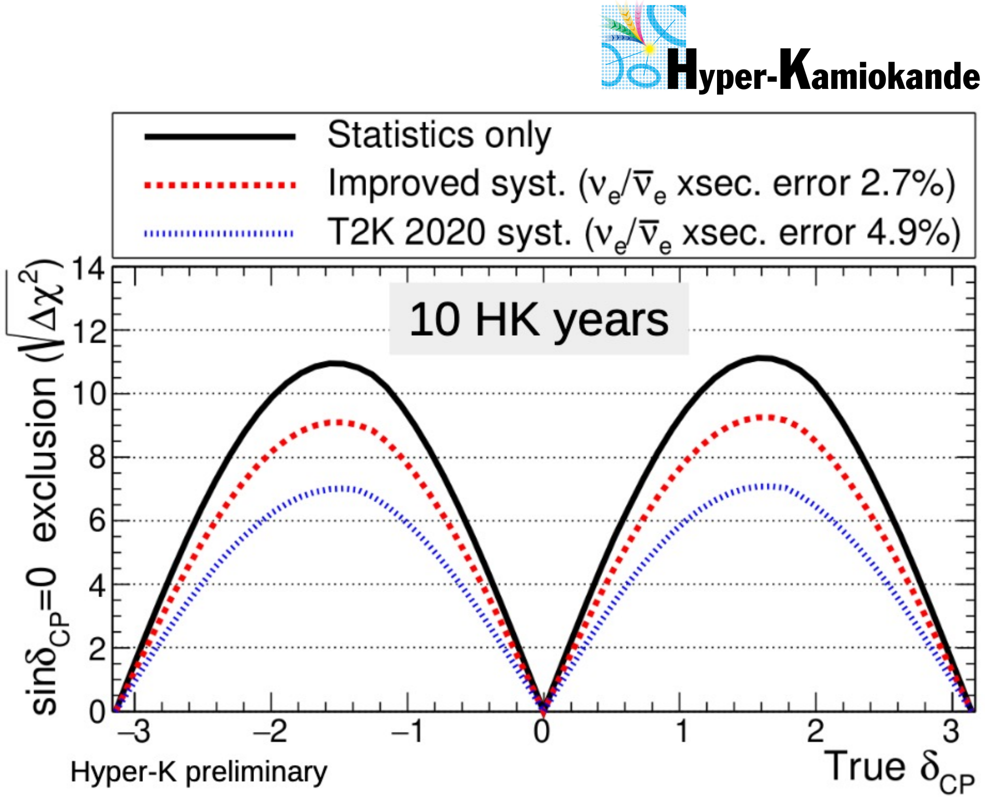
HYPER-K SENSITIVITY

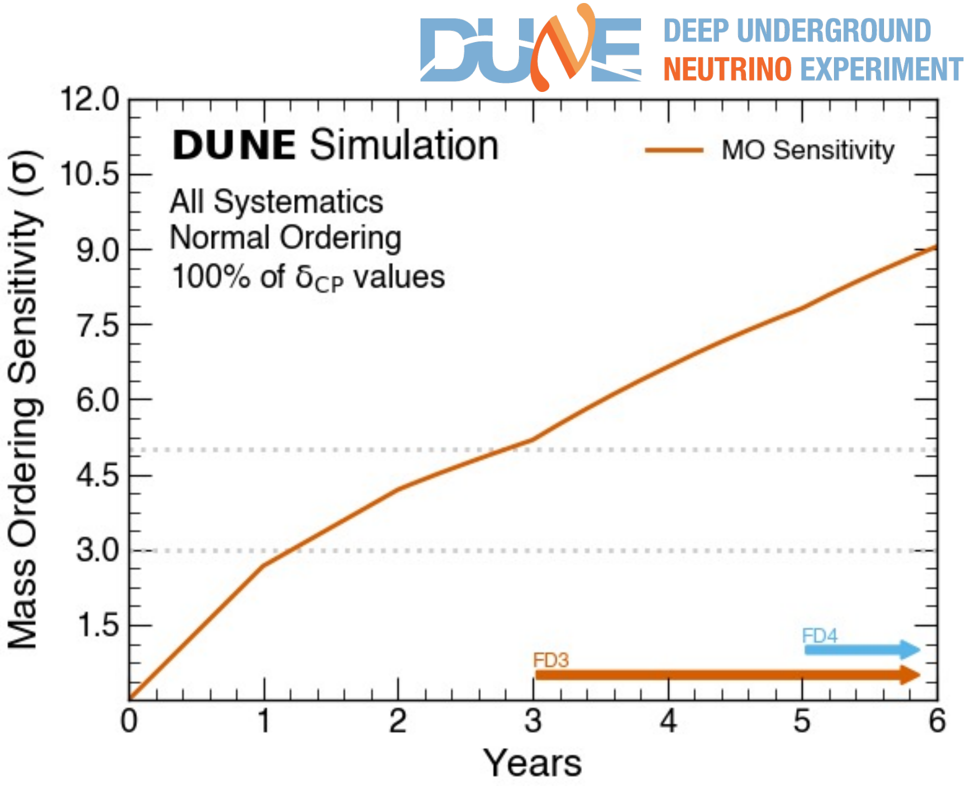
- Due to its short baseline, HK is unable to break the degeneracy between CPv and MO with only beam data.
- Atmospheric ν's partially recover CPV sensitivity, or if MO already known through DUNE/JUNO or other experimental input.

arXiv:1805.04163



DISCOVERY: MASS ORDERING & CP VIOLATION

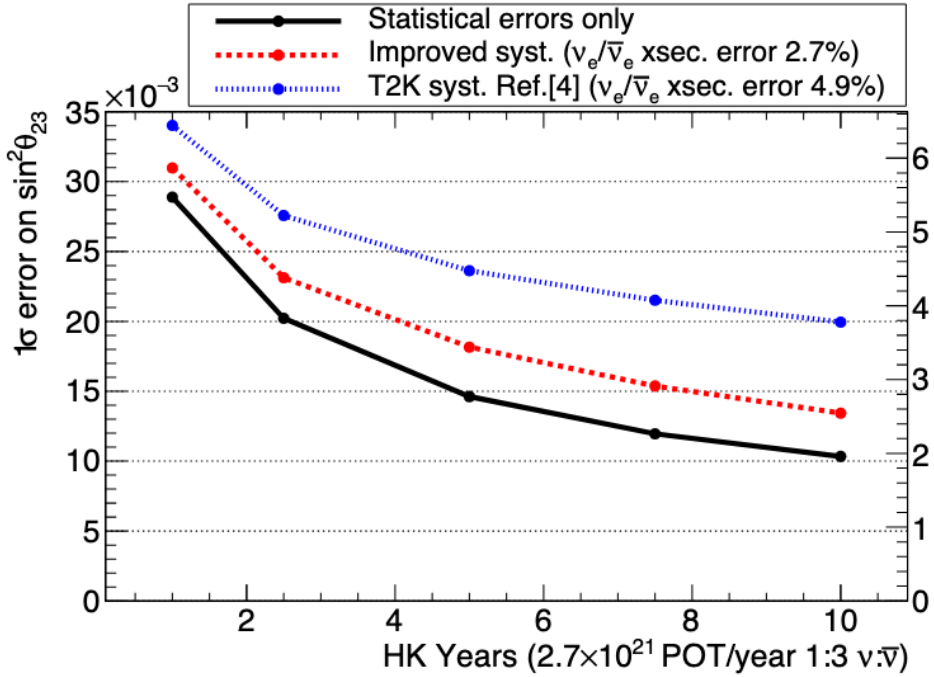


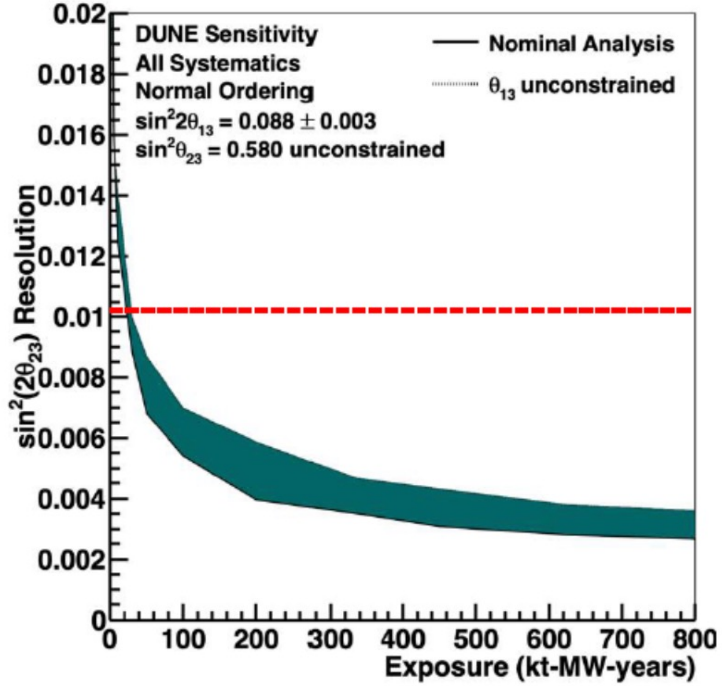


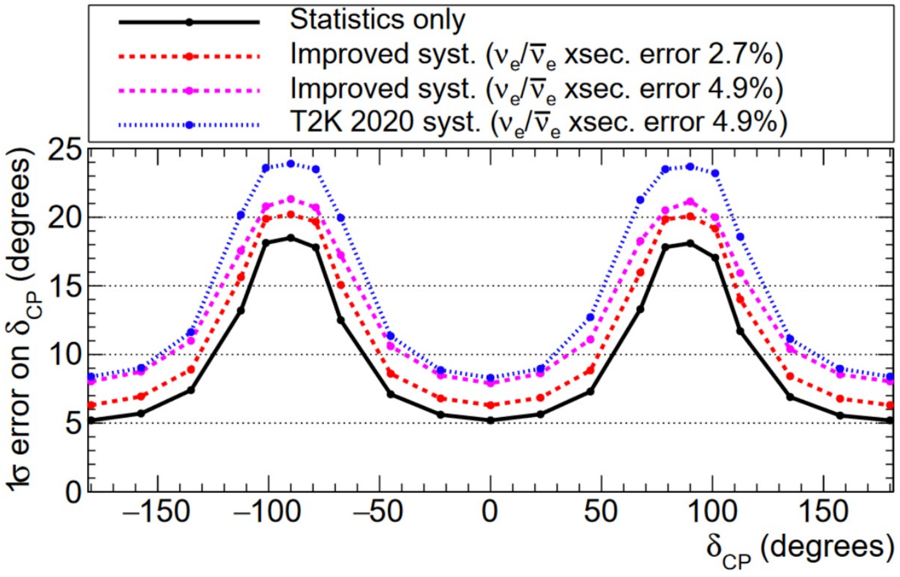
- DUNE has an unrivaled sensitivity to resolve MO for any values of other oscillation parameters.
- HK has excellent sensitivity to CP violation but has a degeneracy between CP violation and MO due to its short baseline.
  - Recover CPV sensitivity with Atmospheric ν's or if MO already known through DUNE/JUNO.

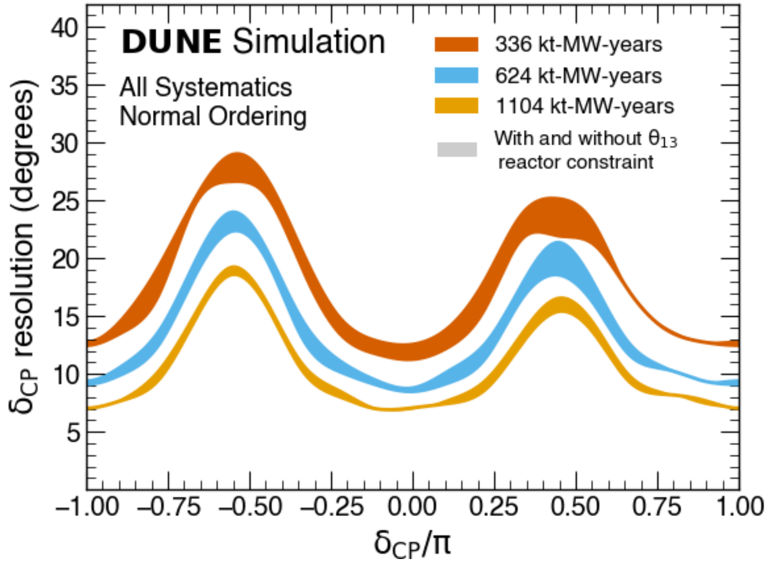
PRECISION

- Both Hyper-K and DUNE offe unprecedented precision on Δm^2_{32}, δ_{CP} , θ_{23} with multiple years of running.
- They will also probe astrophysical, **solar**, and atmospheric neutrinos, with sensitivity to the solar mixing parameters.









REQUIREMENTS OF THE NEAR DETECTOR

I. Neutrino Flux

- **Measure the flux**: not mono-energetic and not well-understood
- **Monitor beam stability**

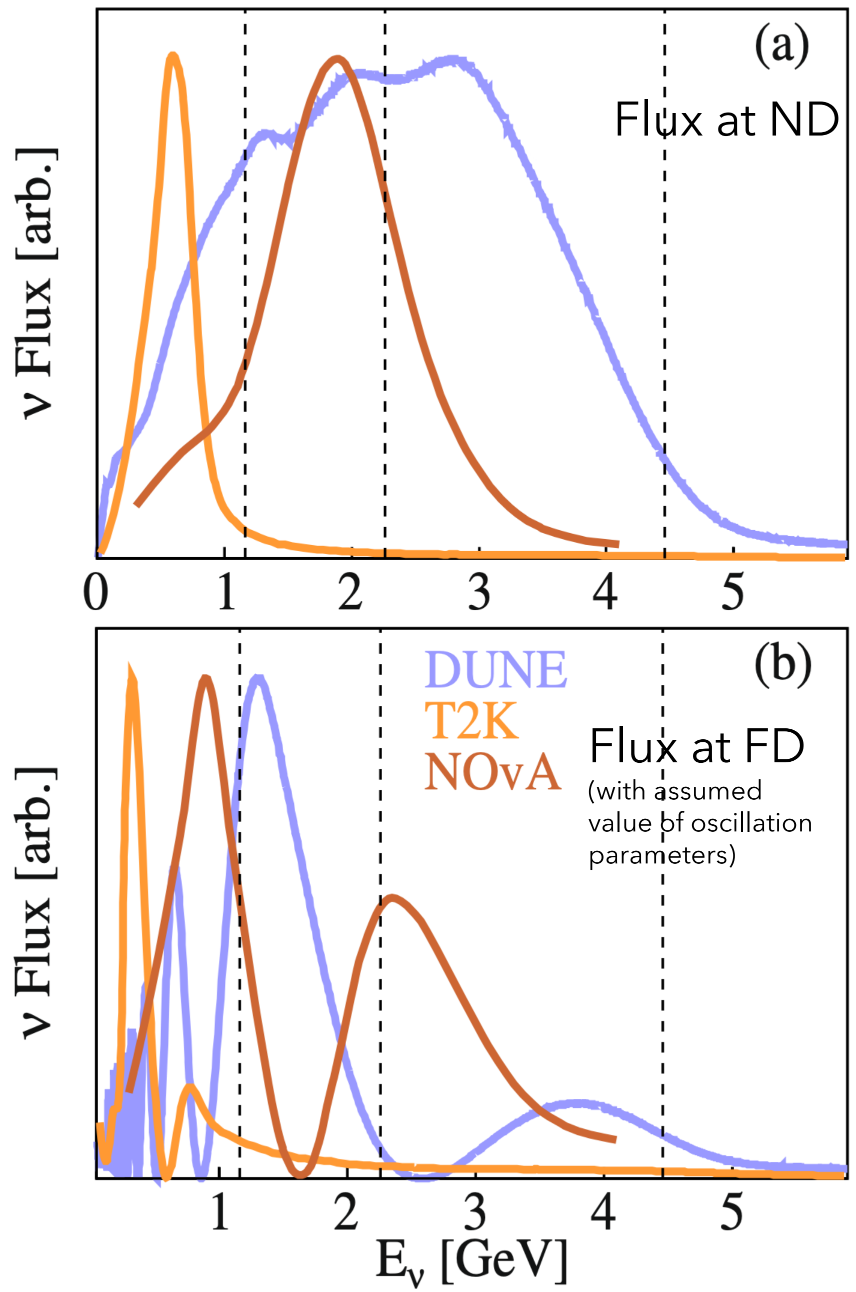
II. Neutrino Cross-Section

- Same **nuclear target** and measurements **transferable to FD**

III. Detector Uncertainties

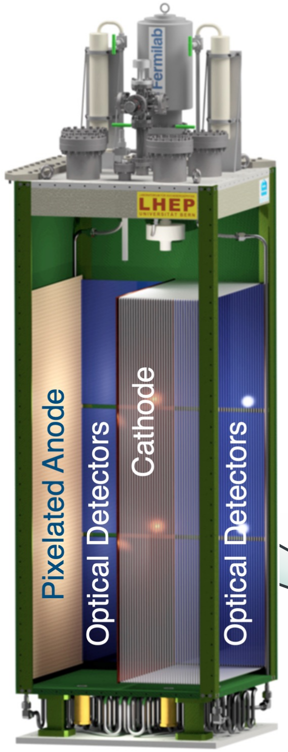
- **Similar detector technologies**

Nature **volume 599**, pages565–570 (2021)

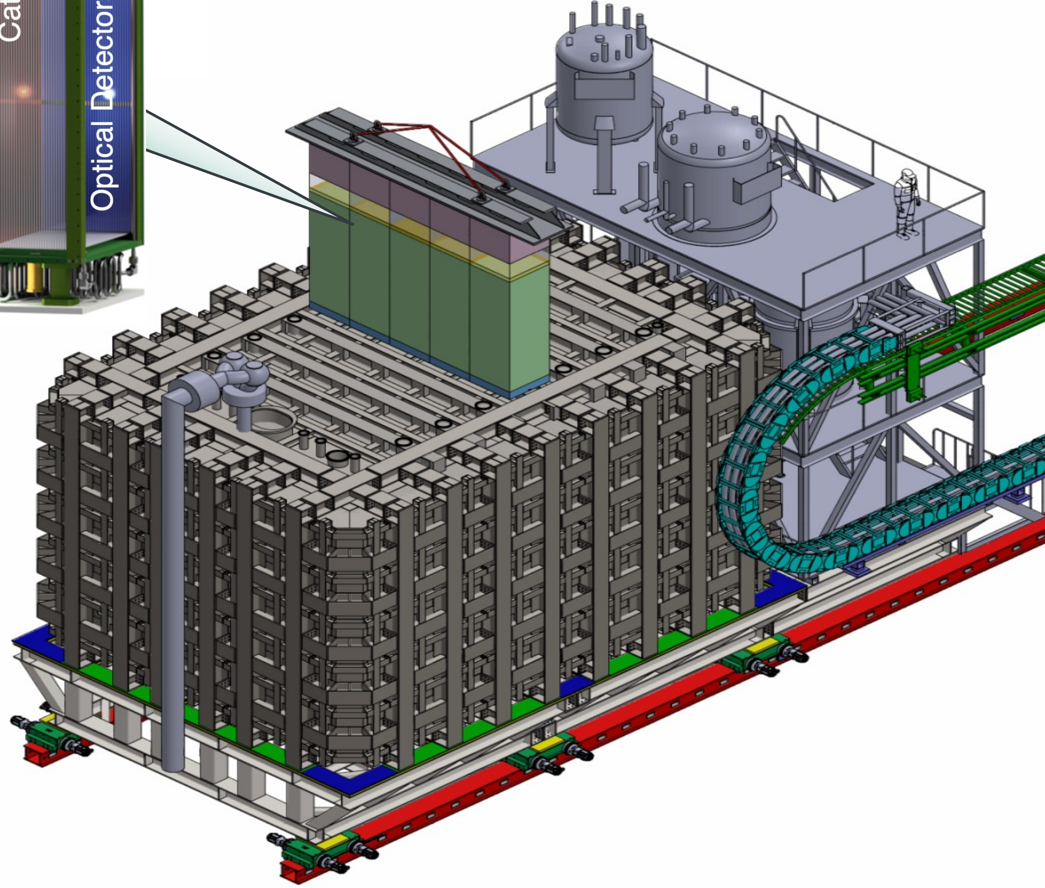


DUNE ND-LAr:
A NEXT GENERATION LArTPC

1. Modular TPC
   - ❑ short drift distances
2. Pixelated Charge readout
   - ❑ unambiguous 3D tracking
   - ❑ Always active – continuous self-triggering.
3. Optical Segmentation
   - ❑ contained scintillation light
   - ❑ high photo-coverage
4. Low-profile field cage
   - ❑ limit inactive volume

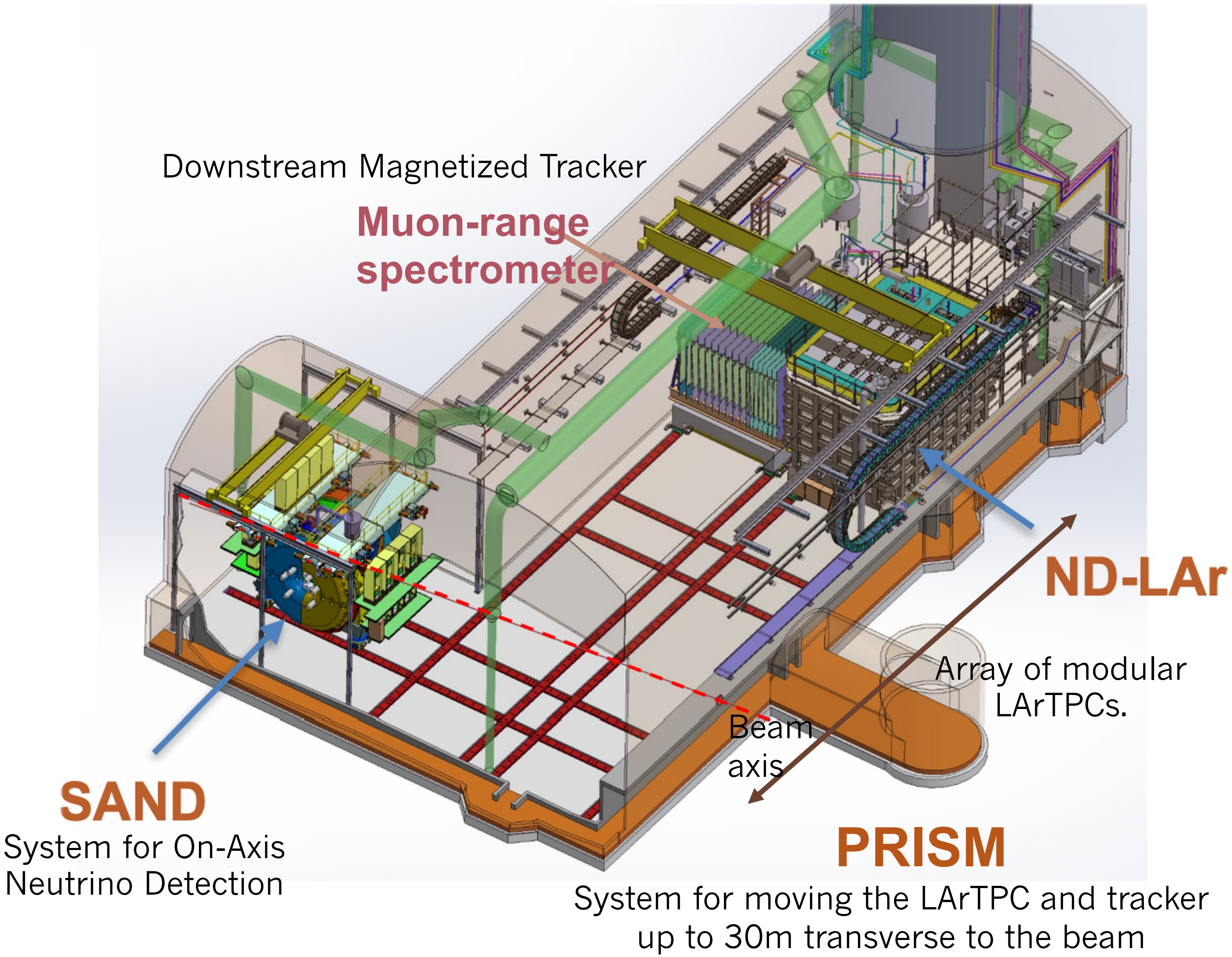


5 x 7 array of LAr TPC modules (1 m x 1m x 3m)



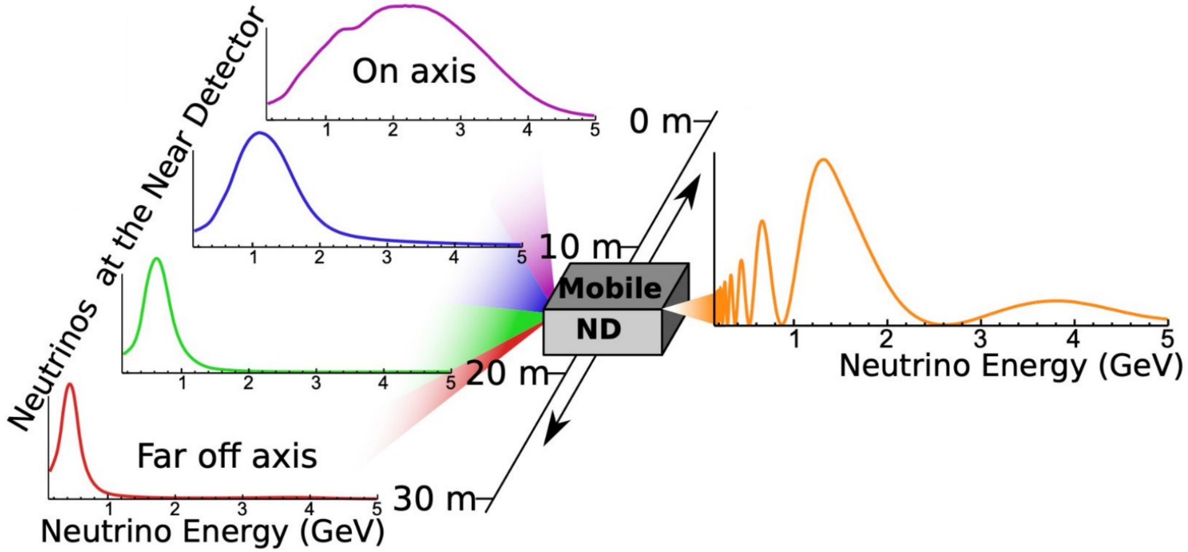
THE ND COMPLEX

- To achieve its ambitious physics goals, DUNE will need to constrain its systematics to few percent.
- **A suite of near detectors** are designed to robustly constrain systematics and achieve required sensitivities.

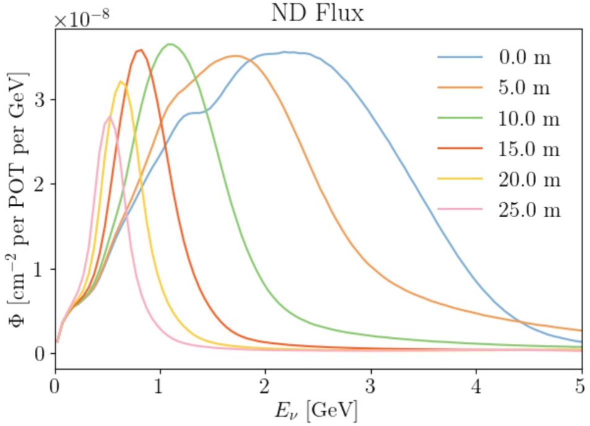


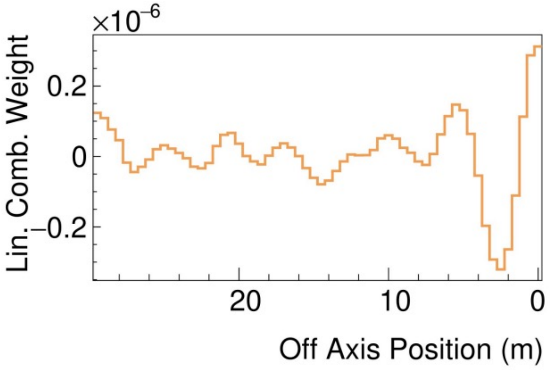
PRISM

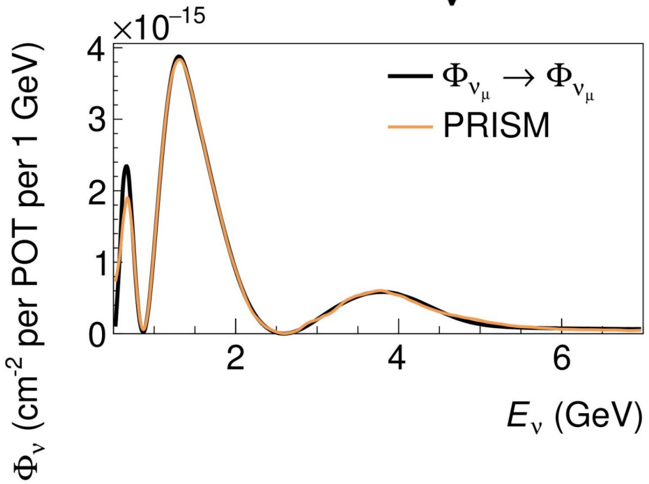
- Using a linear combination of ND flux at various off-axis position, we can construct a prediction for the oscillated FD flux.



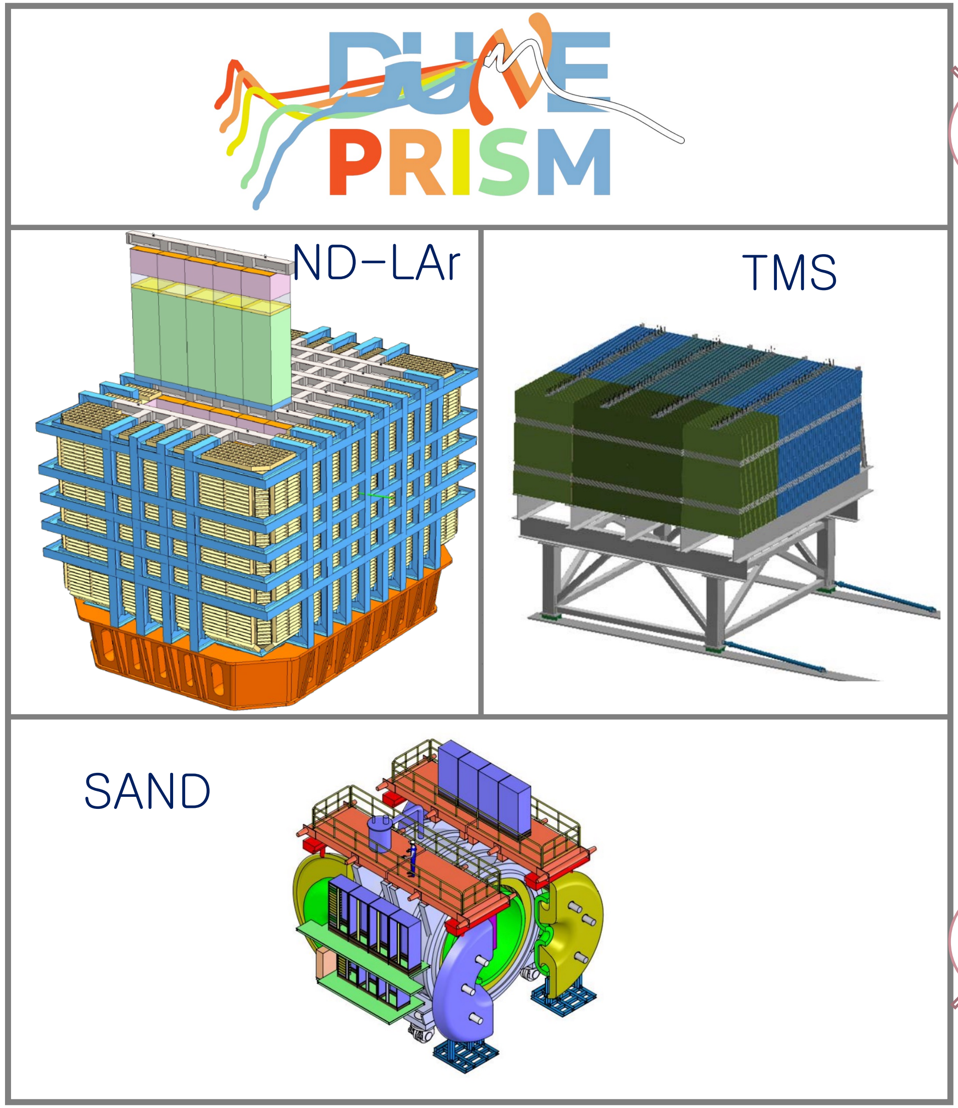
$$\Phi^{ND}(E_\nu,x) \cdot C(x) = \Phi^{FD}(E_\nu)$$







ND REQUIREMENTS



- Measurements transferable to the FD
- Constrain the cross-section model
- Measure the neutrino flux
- Obtain measurement with different fluxes
- Monitor time variations of the neutrino beam
- Operate in high-rate environment
- New exciting physics measurements to test BSM, sterile and dark-matter models.