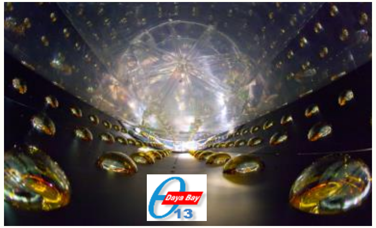
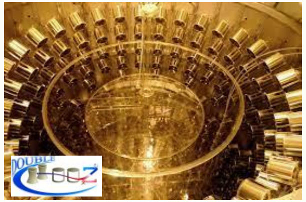
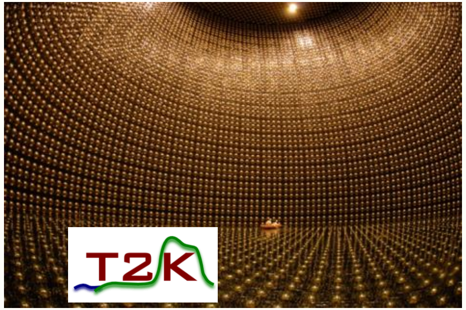


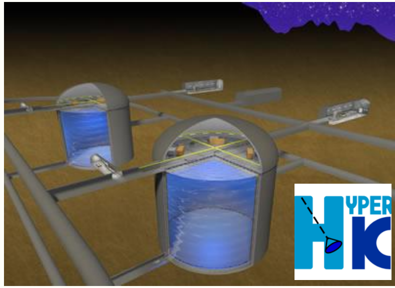


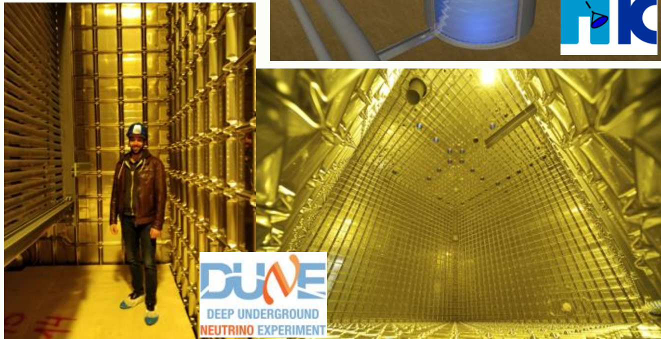


The dawn of the precision era in neutrino physics

Steven Calvez

Subatech cnrs Nantes Université

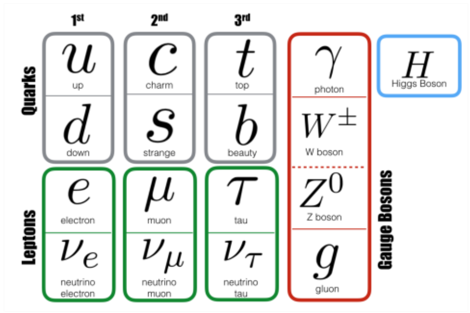




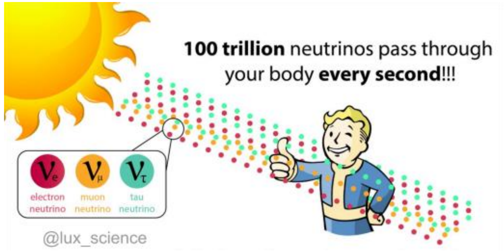
Seminar IPHC

April 10, 2024

The neutrino



- **Neutrinos** are **elementary particles** of the **Standard Model** of **Particle Physics.**



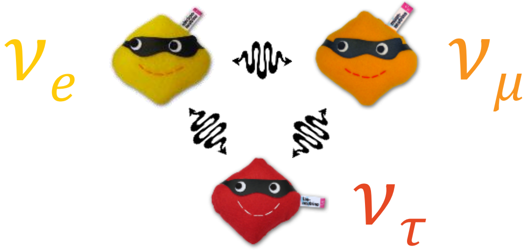
- **Neutrinos** are the **most abundant particles of matter** in the **Universe**.

- Yet, their **elusive nature** means we still know little about their **fundamental properties:**
  - **3 flavors**: electron, muon and tau neutrinos.
  - **Oscillate** from one flavor to the other…
  - …which proved neutrinos had **masses**.

1995

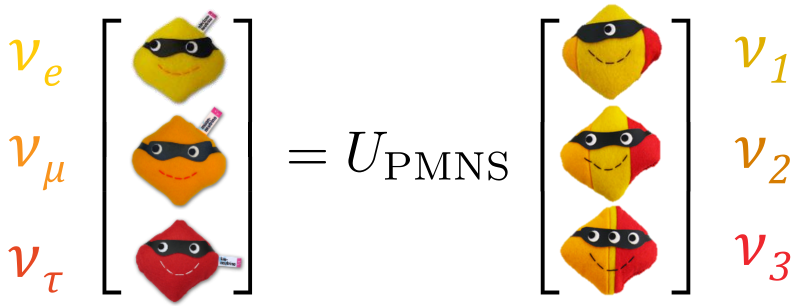
1998

2015



What do we know about neutrinos?

- **Neutrinos** are created and interact as **flavor eigenstates**, which are superposition of **mass eigenstates**.



$$c_{ij} \equiv \cos\theta_{ij} \quad s_{ij} \equiv \sin\theta_{ij}$$

$$U = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta_{\text{CP}}} \\ -s_{12}\,c_{23} - c_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\text{CP}}} & c_{12}\,c_{23} - s_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\text{CP}}} & c_{13}\,s_{23} \\ s_{12}\,s_{23} - c_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\text{CP}}} & -c_{12}\,s_{23} - s_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\text{CP}}} & c_{13}\,c_{23} \end{pmatrix}$$

Mixing angles: $\boldsymbol{\theta_{12}, \theta_{13}, \theta_{23}}$

CP-violating phase: $\boldsymbol{\delta_{CP}}$

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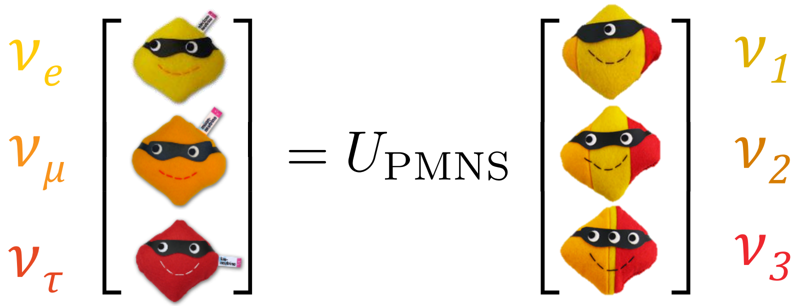

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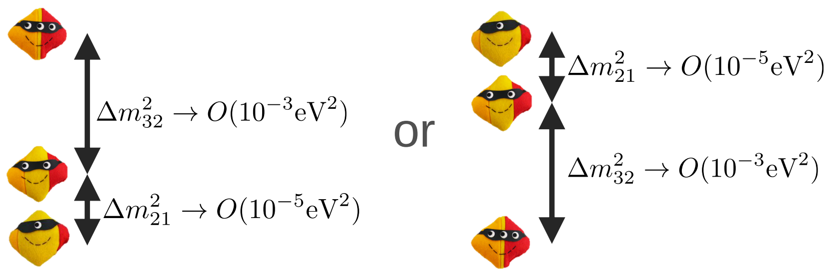
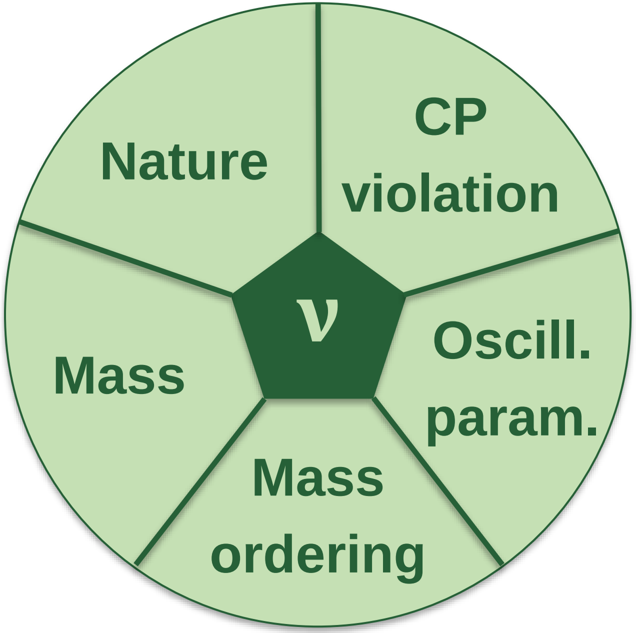
Mixing angles: $\boldsymbol{\theta_{12}, \theta_{13}, \theta_{23}}$
CP-violating phase: $\boldsymbol{\delta_{CP}}$

- Absolute **masses** and even the **neutrino mass ordering** remain unknown.

Mass squared differences:
$\boldsymbol{|\Delta m^2_{32}|, \Delta m^2_{21}}$



What are the neutrino's fundamental properties ?



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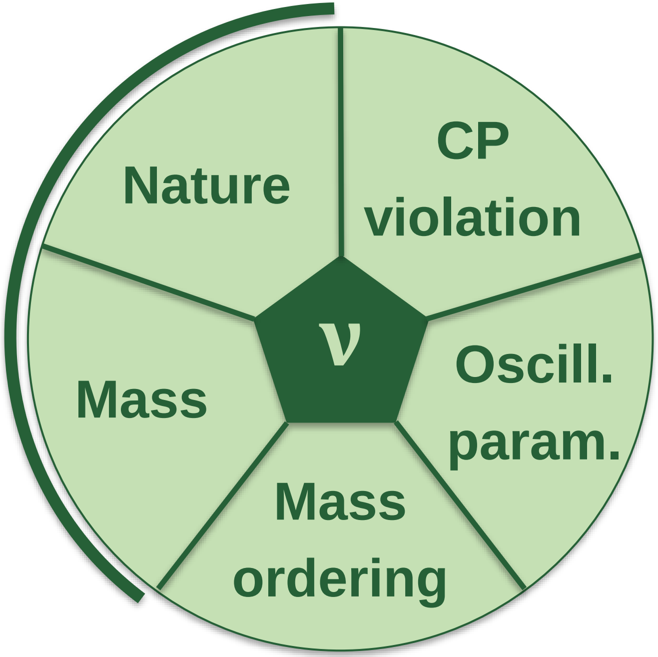
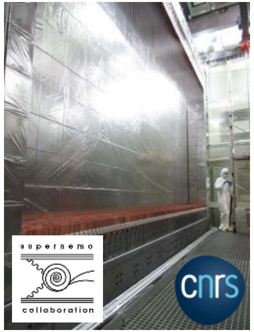
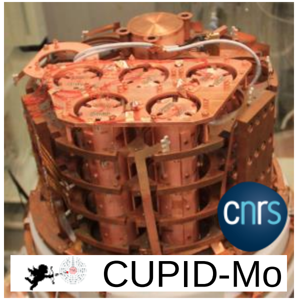
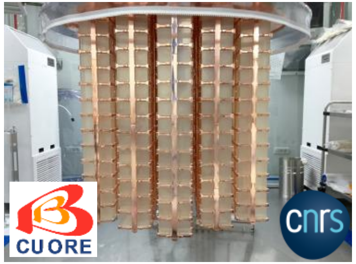


- ❑ Neutrino **nature** : Dirac or Majorana ?
  - ➢ Search for the **$0\nu\beta\beta$ decay** $\rightarrow \nu \equiv \bar{\nu}$







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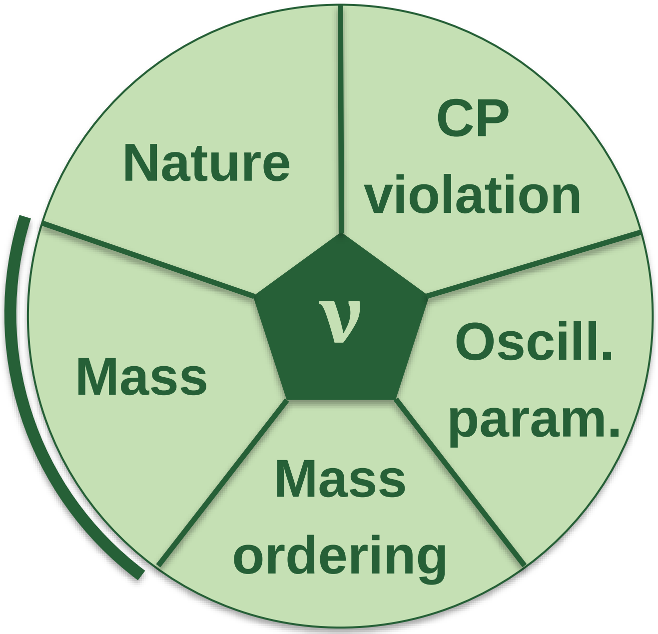
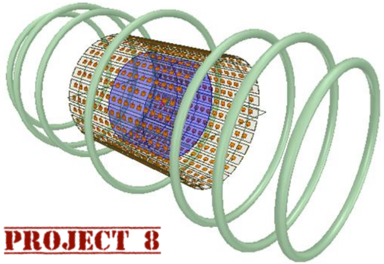
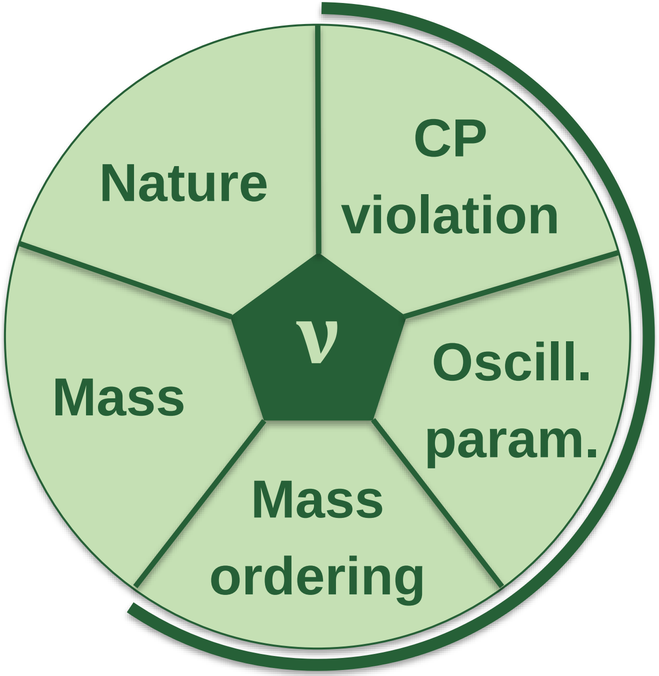


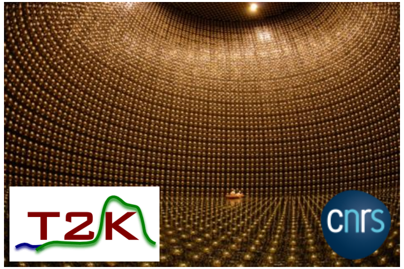
- ❑ Neutrino **masses** ?
- ➢ High precision measurement of $\boldsymbol{\beta}$**-decay** spectrum.

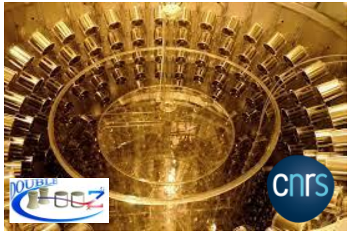


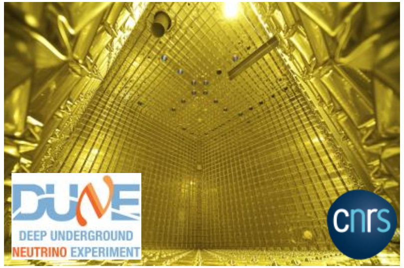
What are the neutrino’s fundamental properties ?

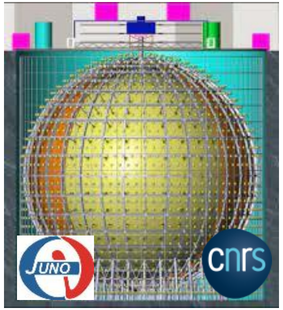


- ❑ Values of θ_{12}, θ_{23}, θ_{13}, δ_{CP} , Δm^2_{32}, and Δm^2_{21} ?
  - ➢ Study **neutrino oscillations**.

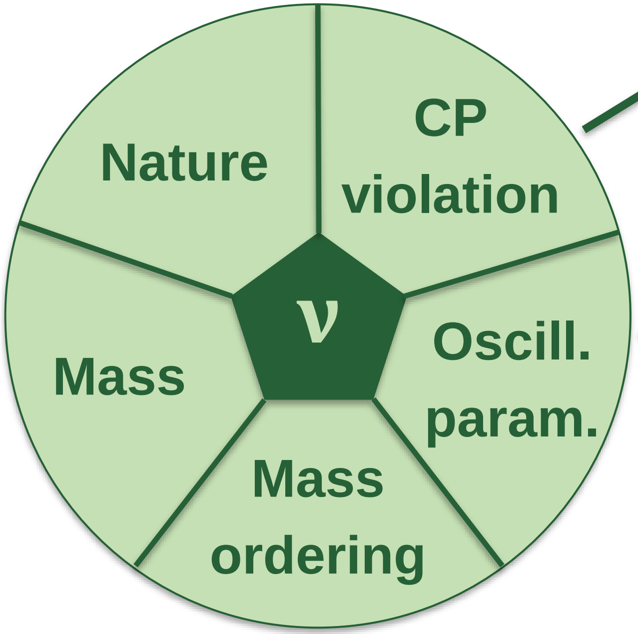








Key to a fundamental question



CP violating phase δ_{CP}

+

Precision measurement
θ_{12}, θ_{23} and θ_{13}

=

Jarlskog invariant

$$J \equiv s_{13}c_{13}^2 s_{12}c_{12}s_{23}c_{23}\sin\delta$$

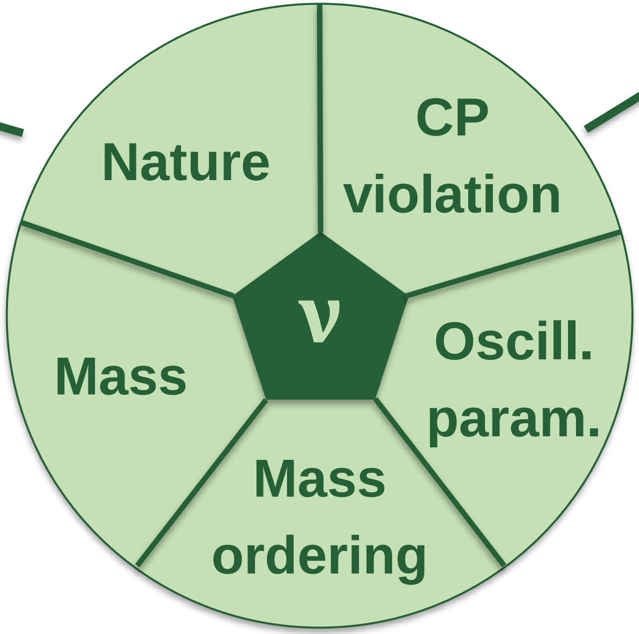
CP violation in leptonic sector

Key to a fundamental question

$0\nu\beta\beta$ decay

Lepton number violation

Leptogenesis



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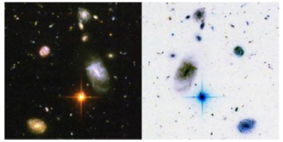


Matter-antimatter asymmetry

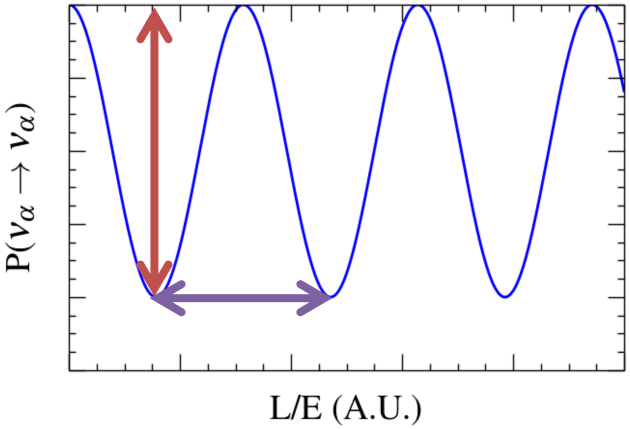
Neutrino oscillations

- **Neutrino oscillations** depend on a few parameters :
  - θ_{12}, θ_{23}, θ_{13}, δ_{CP} , Δm^2_{32}, Δm^2_{21}

- For instance, **disappearance probability** $P(\nu_\mu \to \nu_\mu)$ can be expressed as follows:

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

Amplitude **Period**



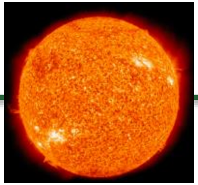
- **Experiments** study the **oscillation of neutrinos** of different **energies E** over different **baselines L**, giving them access to all the oscillation parameters.

How can we measure the neutrino oscillations parameters ?

$P(\nu_e \rightarrow \nu_e)$ ⟷ $\boldsymbol{\theta_{12}}$ Δm^2_{21}

E ~ MeV

L ~ 10^{10}m



Solar ν

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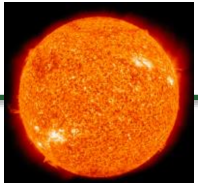


Solar ν

$P(\overline{\nu}_e \rightarrow \overline{\nu}_e)$

↗ $\boldsymbol{\theta_{13}}$ $|\Delta m^2_{32}|$

↘ $\boldsymbol{\Delta m^2_{21}}$ $\boldsymbol{\theta_{12}}$

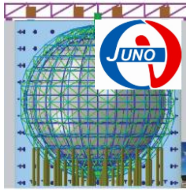
$\boldsymbol{\Delta m^2_{32}}$ θ_{13}

L ~ 10^3m

E ~ MeV

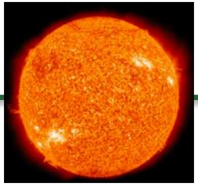
L ~ 10^4m

Reactor ν



How can we measure the neutrino oscillations parameters ?

$P(\nu_e \rightarrow \nu_e)$ ↔ $\boldsymbol{\theta_{12}}$, Δm^2_{21} — E ~ MeV, L ~ 10^{10}m

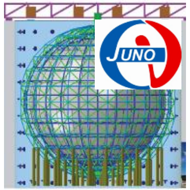


Solar ν

$P(\overline{\nu}_e \rightarrow \overline{\nu}_e)$

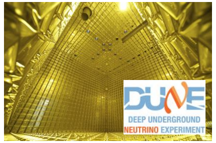
- $\boldsymbol{\theta_{13}}$ $|\Delta m^2_{32}|$ — L ~ 10^3m, E ~ MeV
- $\boldsymbol{\Delta m^2_{21}}$ $\boldsymbol{\theta_{12}}$, $\boldsymbol{\Delta m^2_{32}}$ θ_{13} — L ~ 10^4m

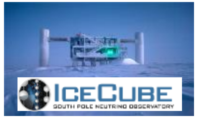
Reactor ν

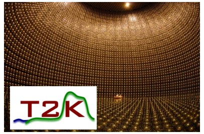


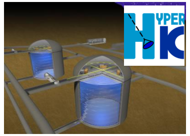
$P(\nu_\mu \rightarrow \nu_\mu)$, $P(\nu_\mu \rightarrow \nu_e)$ ↔ $\boldsymbol{\Delta m^2_{32}}$, $\boldsymbol{\delta_{CP}}$ $\boldsymbol{\theta_{23}}$, θ_{13} — E ~ GeV, L ~ 10^5-10^6m

Accelerator + Atmospheric ν





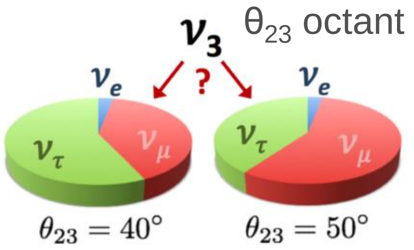


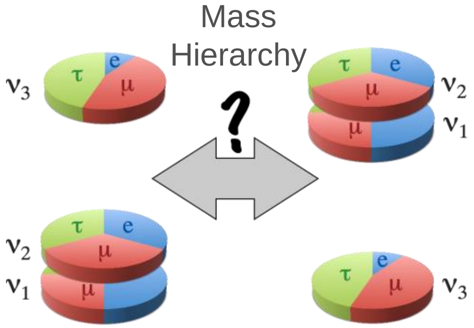


What are the main goals of Long Baseline experiments?

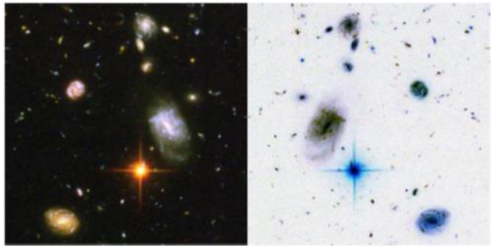
- **Long-baseline neutrino oscillation** experiments like **NOvA**, **T2K**, **DUNE** and **HyperK** study accelerator neutrino oscillations over ~100kms.

- Aim to address the following open questions:
  - What is the **value of $\boldsymbol{\theta_{23}}$** ? $\theta_{23} < 45^{o}$ or $\theta_{23} > 45^{o}$? ν_μ - ν_τ symmetry?
  - What is the **value of $\boldsymbol{\Delta m^2_{32}}$**? Normal or Inverted Hierarchy?
  - Is there **CP violation** in the lepton sector? $\delta_{CP} \neq 0$ or π ?



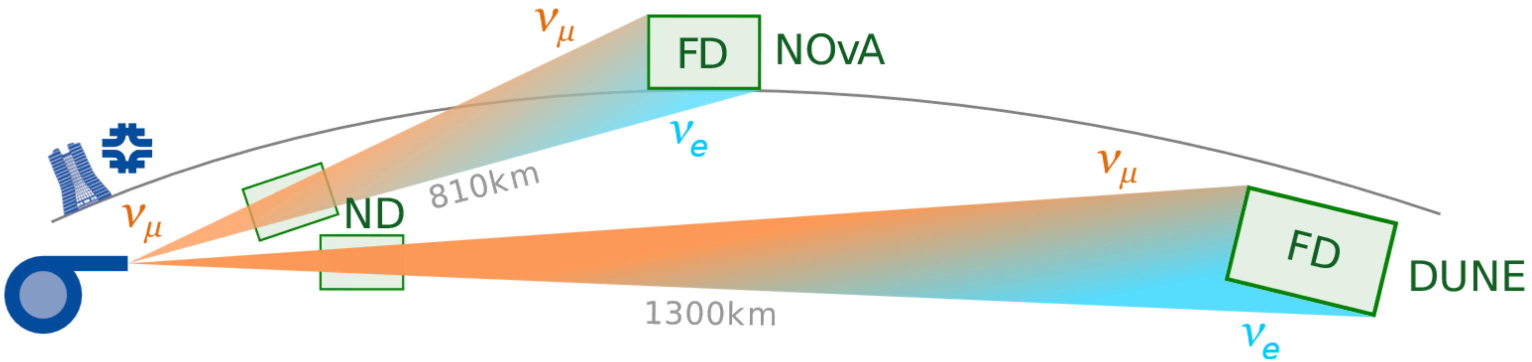


δ_{CP} ?



Principle of Long Baseline neutrino oscillation experiments

- Principle of the **NOvA** and **DUNE** experiments (similar for **T2K** and **T2HK**):
  - Produce a **beam of ν_μ** (or $\overline{\nu_\mu}$).



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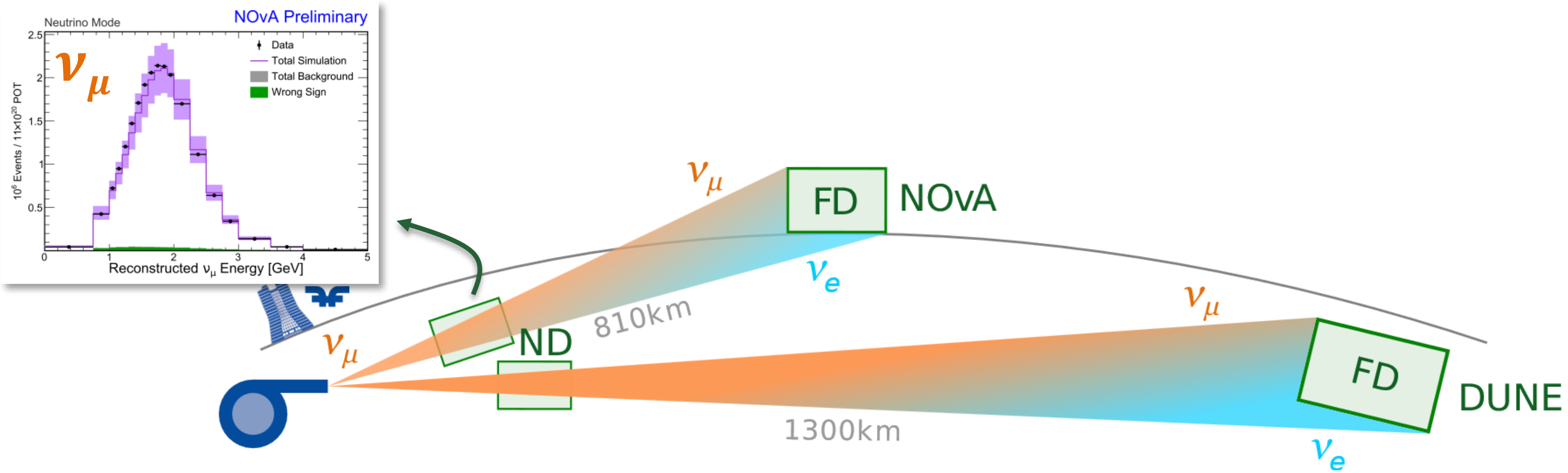

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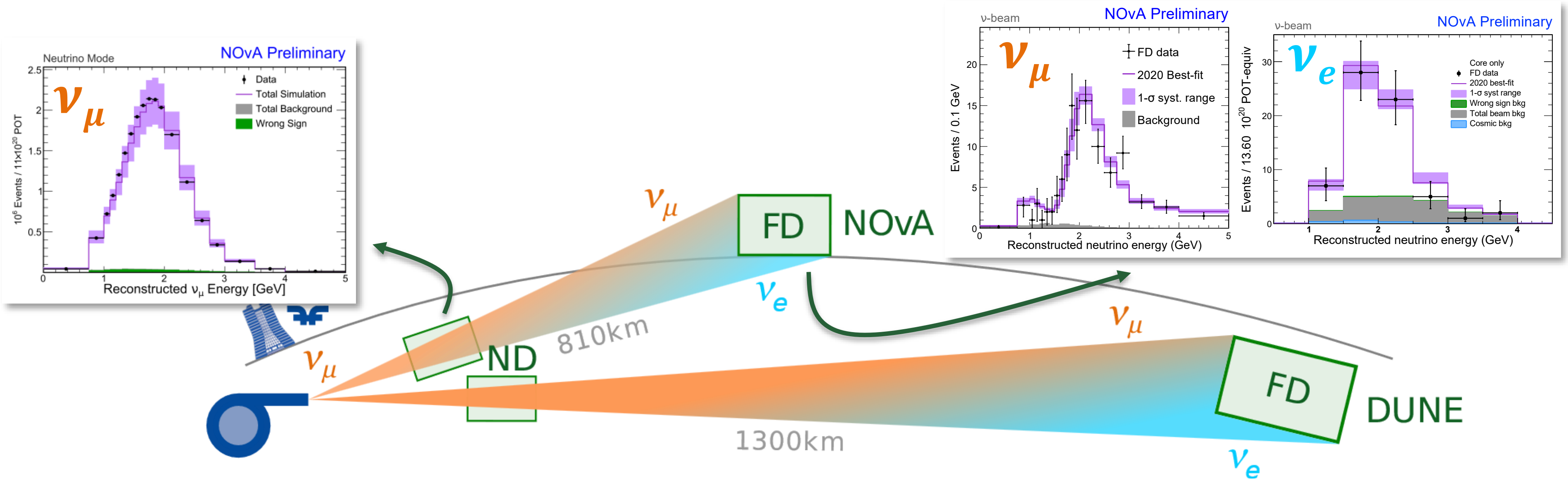
  - Measure the **ν_μ spectrum** in a **Near Detector (ND)**.
  - Measure the **disappearing ν_μ** and **appearing ν_e spectra** in a **Far Detector (FD).**



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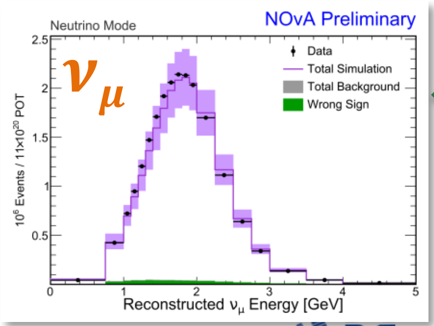
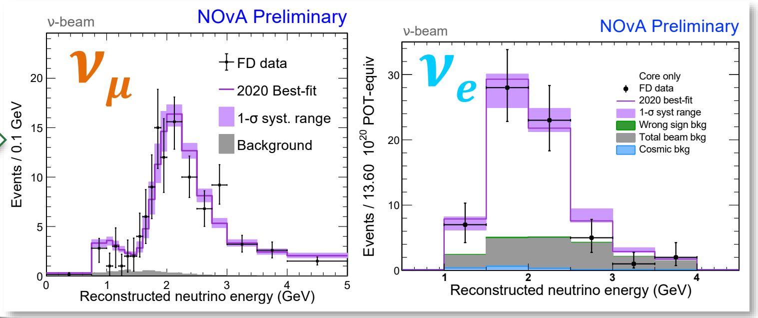
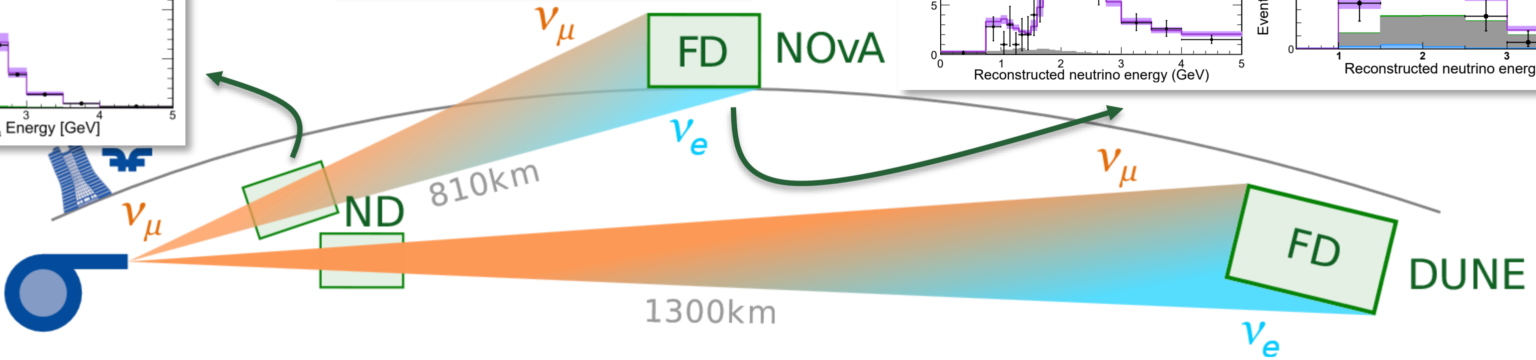
  - Measure the **disappearing ν_μ** and **appearing ν_e spectra** in a **Far Detector (FD).**
  - Extrapolate and test **oscillation parameters.**



Δm^2_{32}=2.41 × 10^{-3} eV^2
$\sin^2\theta_{23}$=0.57
δ_{CP}=0.82π



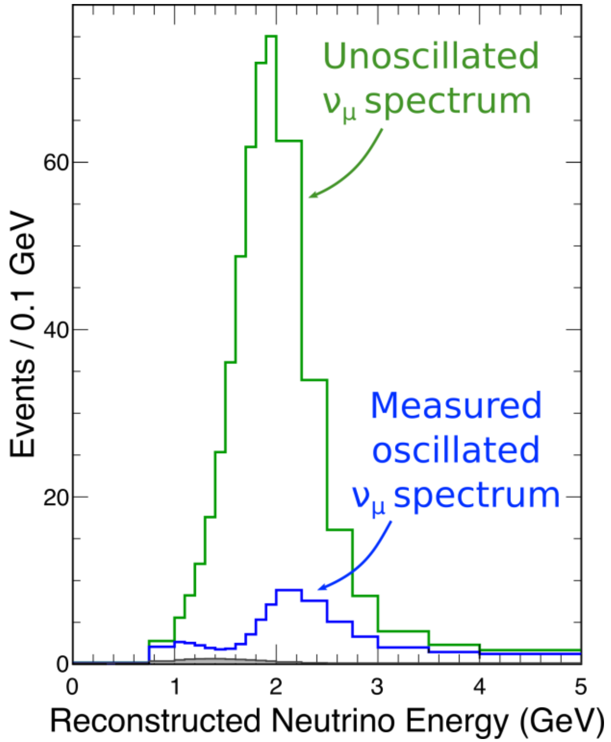


How can NOvA measure neutrino oscillation parameters?

- Measure $\boldsymbol{\nu_\mu \rightarrow \nu_\mu}$ and $\boldsymbol{\overline{\nu_\mu} \rightarrow \overline{\nu_\mu}}$ **disappearance** to constrain $\mathbf{sin^2 2\theta_{23}}$ and $|\boldsymbol{\Delta m^2{}_{32}}|$:

  - ν_μ survival probability:

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



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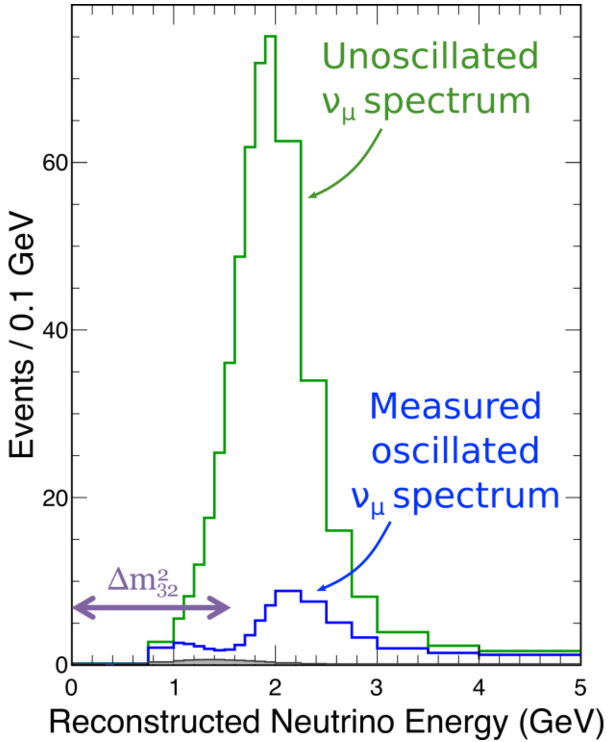
  - Location of dip → $|\boldsymbol{\Delta m^2_{32}}|$



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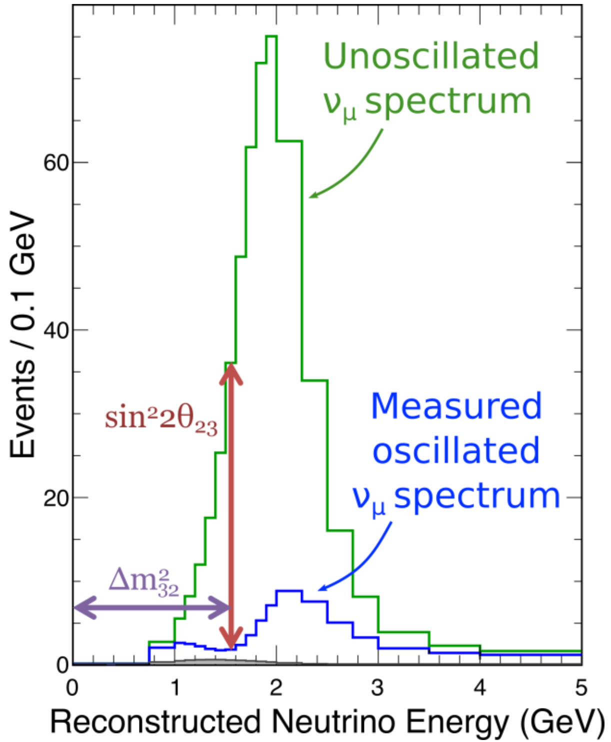
  - Location of dip → $|\Delta m^2_{32}|$

  - Amplitude of dip → $\sin^2 2\theta_{23}$



How can NOvA measure neutrino oscillation parameters?

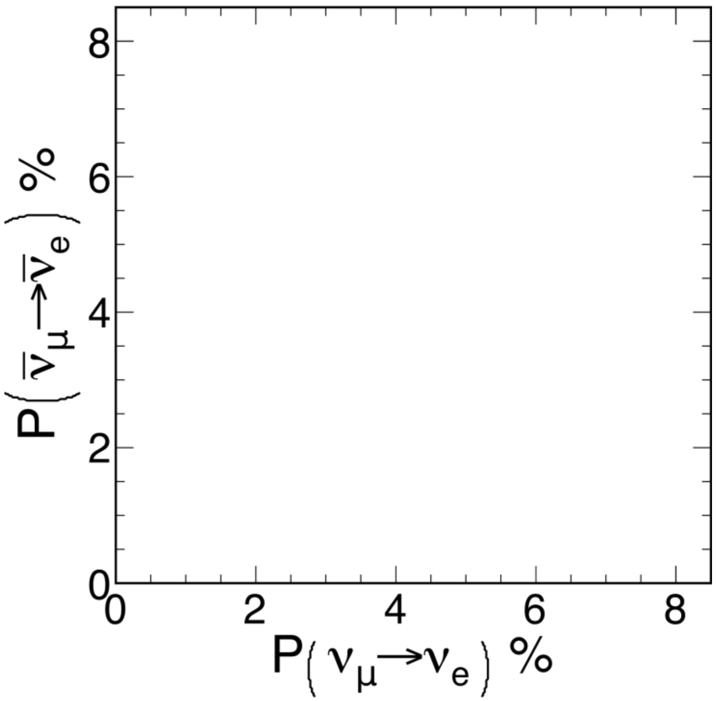
- Measure $\boldsymbol{\nu_\mu \rightarrow \nu_e}$ and $\boldsymbol{\overline{\nu_\mu} \rightarrow \bar{\nu}_e}$ **appearance** to constrain $\mathbf{sin^2\theta_{23}}$, $\boldsymbol{\Delta m^2_{32}}$ and $\boldsymbol{\delta_{CP}}$:

  - ν_e appearance probability:

$$P\left(\nu_\mu \rightarrow \nu_e\right) \approx \left|\sqrt{P_{\text{atm}}} e^{-i(\Delta_{32}+\delta_{CP})} + \sqrt{P_{\text{sol}}}\right|^2$$

$$\approx P_{\text{atm}} + P_{\text{sol}} + 2\sqrt{P_{\text{atm}} P_{\text{sol}}}\left(\cos\Delta_{32}\cos\delta_{CP} \mp \sin\Delta_{32}\sin\delta_{CP}\right)$$

$$\sqrt{P_{\text{atm}}} = \sin(\theta_{23})\sin(2\theta_{13})\frac{\sin(\Delta_{31} - aL)}{\Delta_{31} - aL}\Delta_{31}$$



How can NOvA measure neutrino oscillation parameters?

- Measure $\boldsymbol{\nu_\mu \rightarrow \nu_e}$ and $\boldsymbol{\overline{\nu_\mu} \rightarrow \bar{\nu}_e}$ **appearance** to constrain $\mathbf{sin^2\theta_{23}}$, $\boldsymbol{\Delta m^2_{32}}$ and $\boldsymbol{\delta_{CP}}$:

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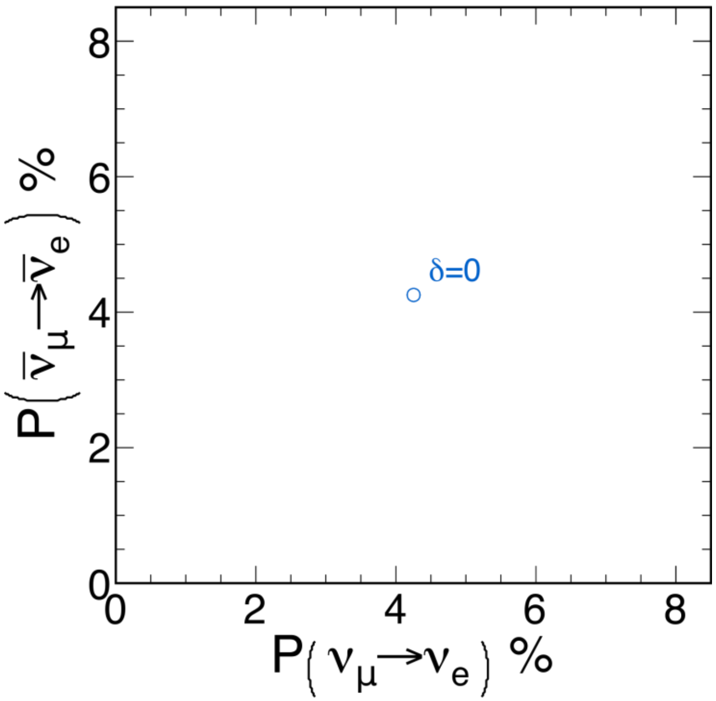

➢ In a vacuum and with no CP-violation, **ν** and **$\bar{\nu}$** oscillation probabilities are **equal**.

How can NOvA measure neutrino oscillation parameters?

- Measure $\nu_\mu \to \nu_e$ and $\overline{\nu_\mu} \to \bar{\nu}_e$ **appearance** to constrain $\sin^2\theta_{23}$, Δm^2_{32} and δ_{CP}:

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$$P(\nu_\mu \to \nu_e) \approx \left| \sqrt{P_{\text{atm}}} e^{-i(\Delta_{32}+\delta_{CP})} + \sqrt{P_{\text{sol}}} \right|^2$$

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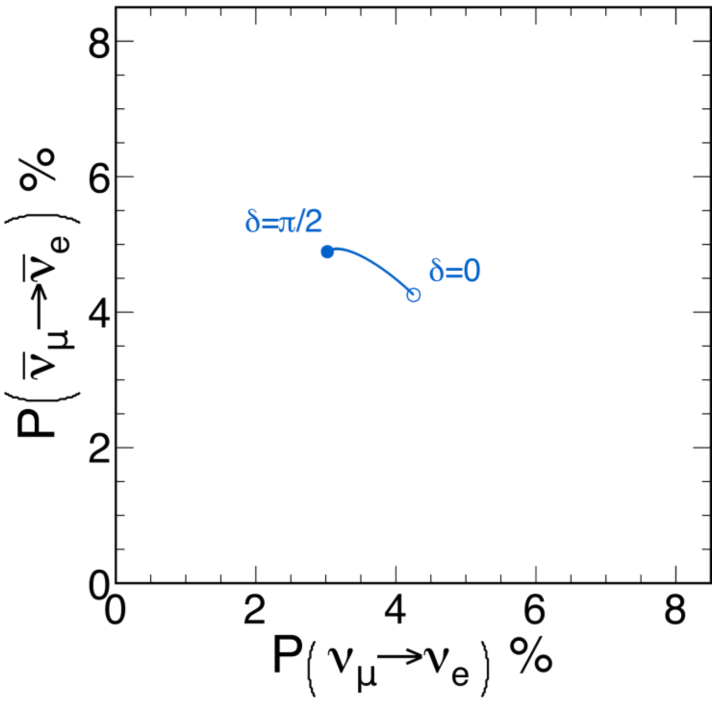
$$\sqrt{P_{\text{atm}}} = \sin(\theta_{23})\sin(2\theta_{13}) \frac{\sin(\Delta_{31} - aL)}{\Delta_{31} - aL} \Delta_{31}$$

➢ **CP-violation** generates **opposite effects** in $\boldsymbol{\nu}$ and $\boldsymbol{\bar{\nu}}$ oscillation probabilities.



How can NOvA measure neutrino oscillation parameters?

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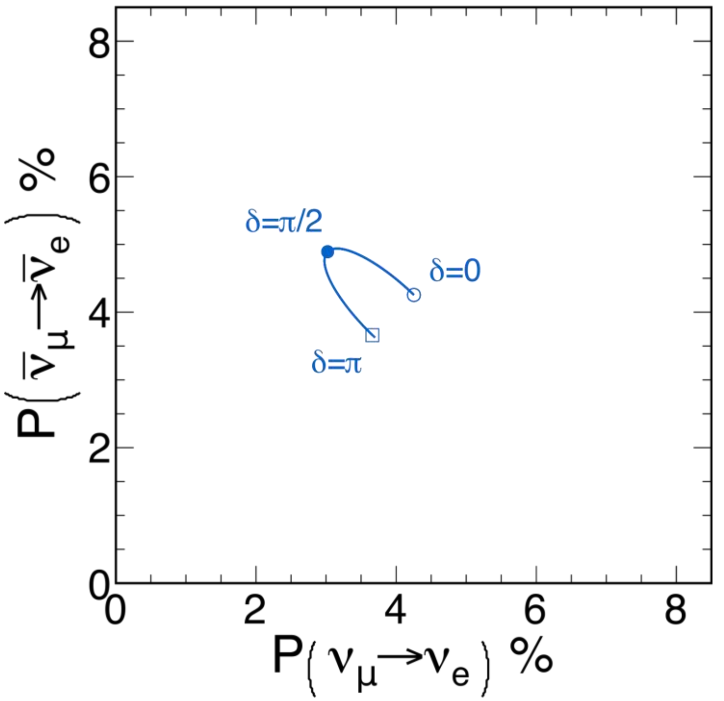
$$\sqrt{P_{\text{atm}}} = \sin(\theta_{23})\sin(2\theta_{13})\frac{\sin(\Delta_{31} - aL)}{\Delta_{31} - aL}\Delta_{31}$$

➢ Other **CP-conserving phase** yields slightly different oscillation probabilities.



How can NOvA measure neutrino oscillation parameters?

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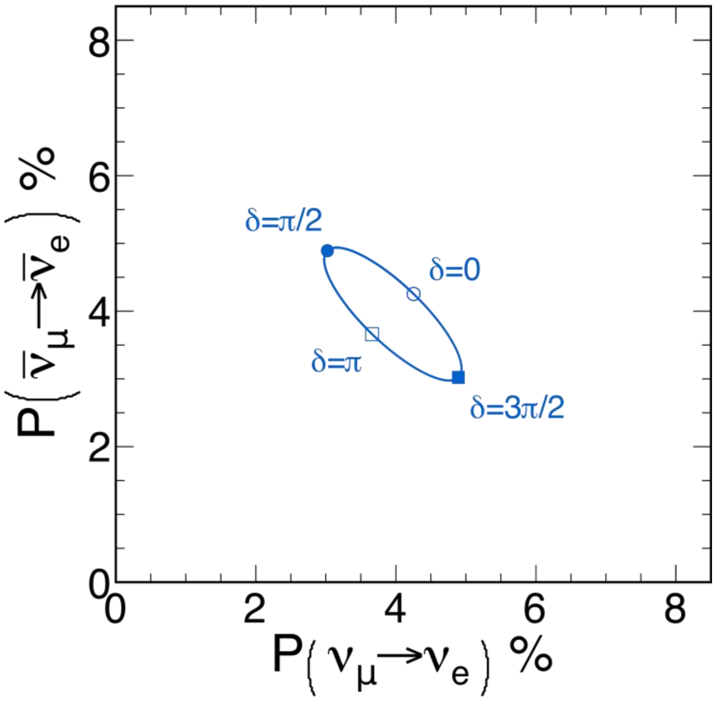
$$\approx P_{\mathrm{atm}} + P_{\mathrm{sol}} + 2\sqrt{P_{\mathrm{atm}}P_{\mathrm{sol}}}\left(\cos\Delta_{32}\cos\delta_{CP} \mp \sin\Delta_{32}\sin\delta_{CP}\right)$$

$$\sqrt{P_{\mathrm{atm}}} = \sin(\theta_{23})\sin(2\theta_{13})\frac{\sin(\Delta_{31}-aL)}{\Delta_{31}-aL}\Delta_{31}$$

➢ Other maximum violating **CP phase enhances ν_e appearance.** δ_{CP} is cyclical.



How can NOvA measure neutrino oscillation parameters?

- Measure $\boldsymbol{\nu_\mu \rightarrow \nu_e}$ and $\boldsymbol{\overline{\nu_\mu} \rightarrow \bar{\nu}_e}$ **appearance** to constrain $\mathbf{sin^2\theta_{23}}$, $\boldsymbol{\Delta m^2{}_{32}}$ and $\boldsymbol{\delta_{CP}}$:

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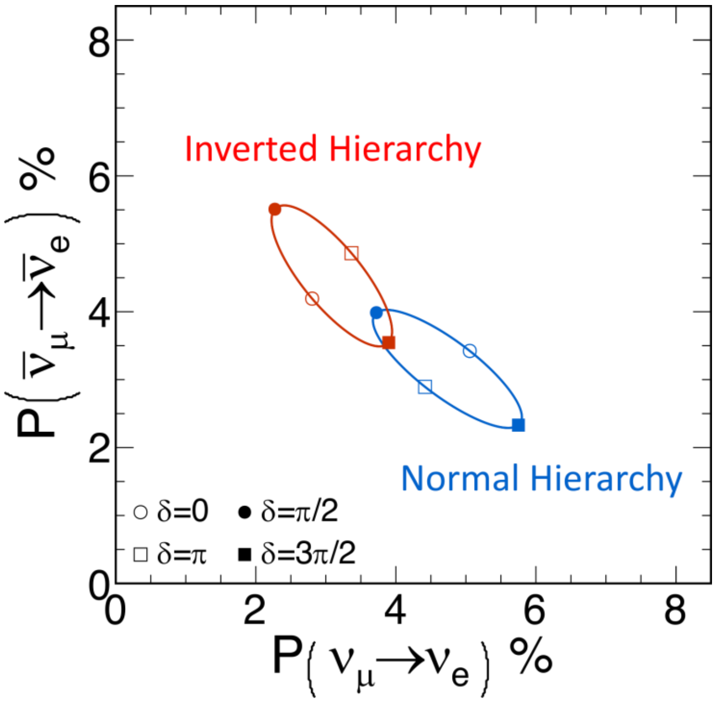
$$P(\nu_\mu \to \nu_e) \approx \left| \sqrt{P_{\rm atm}} e^{-i(\Delta_{32}+\delta_{CP})} + \sqrt{P_{\rm sol}} \right|^2$$

$$\approx P_{\rm atm} + P_{\rm sol} + 2\sqrt{P_{\rm atm}P_{\rm sol}}\,(\cos\Delta_{32}\cos\delta_{CP} \mp \sin\Delta_{32}\sin\delta_{CP})$$

$$\sqrt{P_{\rm atm}} = \sin(\theta_{23})\sin(2\theta_{13})\frac{\sin(\Delta_{31}-aL)}{\Delta_{31}-aL}\Delta_{31}$$

➢ **Matter effects** also generate opposite effects in $\boldsymbol{\nu}$-$\boldsymbol{\bar{\nu}}$ oscillations depending on the **Mass Hierarchy.**



How can NOvA measure neutrino oscillation parameters?

- Measure $\boldsymbol{\nu_\mu \rightarrow \nu_e}$ and $\boldsymbol{\overline{\nu_\mu} \rightarrow \bar{\nu}_e}$ **appearance** to constrain $\mathbf{sin^2\theta_{23}}$, $\boldsymbol{\Delta m^2_{32}}$ and $\boldsymbol{\delta_{CP}}$:

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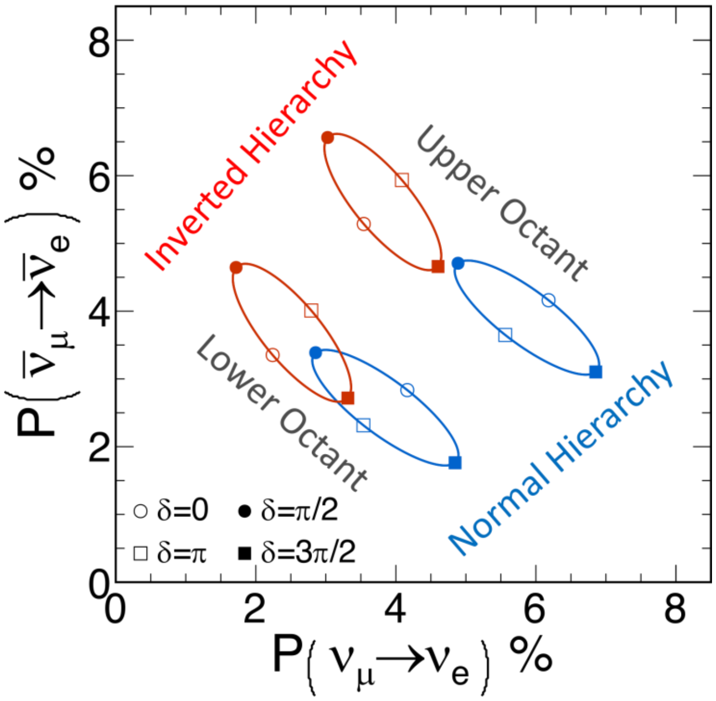
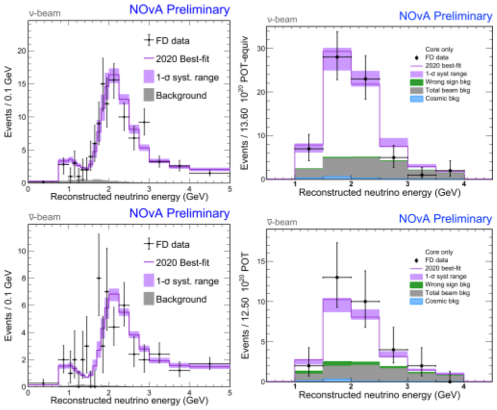
$$\approx P_{\rm atm} + P_{\rm sol} + 2\sqrt{P_{\rm atm}P_{\rm sol}}\left(\cos\Delta_{32}\cos\delta_{CP} \mp \sin\Delta_{32}\sin\delta_{CP}\right)$$

$$\sqrt{P_{\rm atm}} = \sin(\theta_{23})\sin(2\theta_{13})\frac{\sin(\Delta_{31} - aL)}{\Delta_{31} - aL}\Delta_{31}$$

➢ $\boldsymbol{\theta_{23}}$ can increase or decrease $\boldsymbol{\nu}$ and $\boldsymbol{\overline{\nu}}$ oscillations probabilities.



Constraining oscillation parameters in NOvA



- **Limited statistics** (~100s signal candidates), physical boundaries, degenerate parameter space makes reporting **statistically accurate measurements** challenging.

- Frequentist approach in NOvA: generate and fit **millions of pseudoexperiments** (*arXiv:2207.14353*) on **supercomputers** (*CHEP2018*).

- **Normal Ordering** favored at **1.0σ** level.

- Exclusion of :
  - **δ_{CP} = 3π/2 NH** at >**2σ**
  - **δ_{CP} = π/2 IH** at >**3σ**

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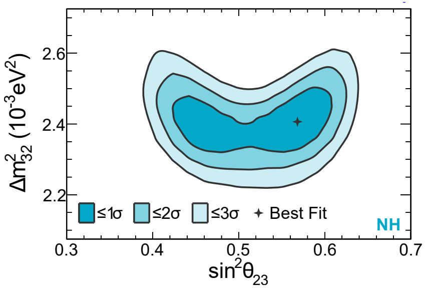
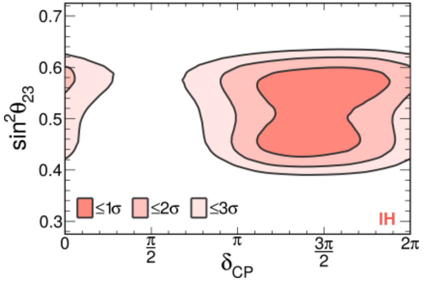
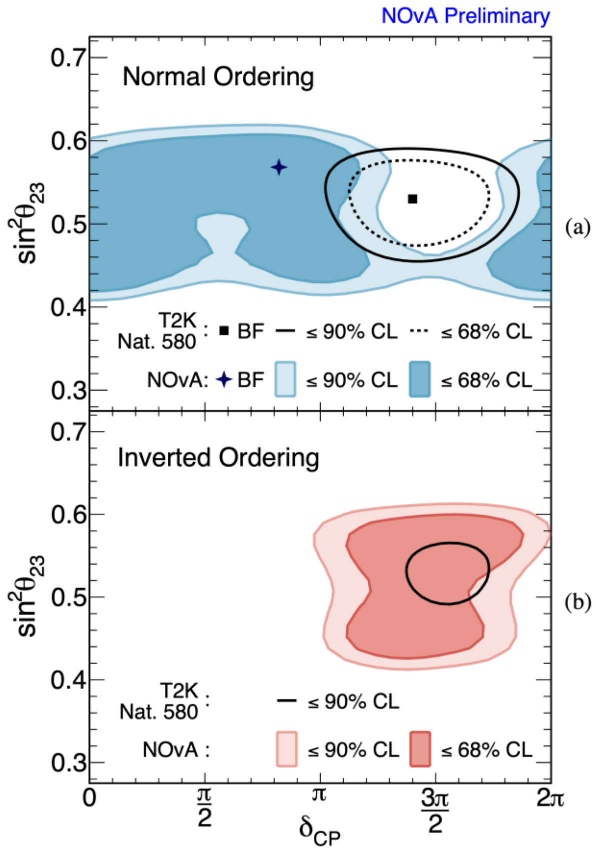




Latest NOvA-T2K results

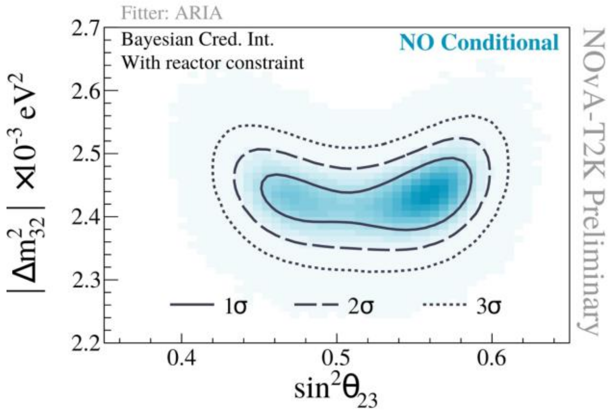
- **First joint NOvA-T2K** oscillation analysis results recently released . Next few figures from :
  - Fermilab seminar
  - KEK seminar.

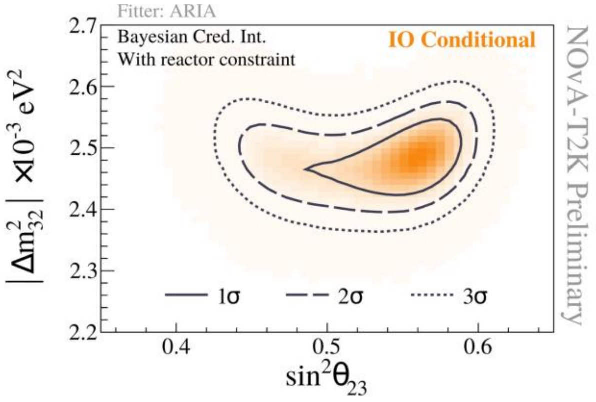
- Particularly **interesting** given **slight tension** in preferred regions of the parameter space.

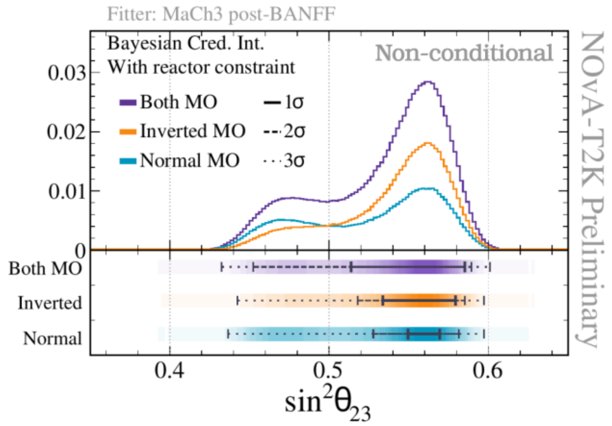


Latest NOvA-T2K results: $\sin^2\theta_{23}$

- Slight preference for the **θ_{23} upper octant**.
- **Maximum mixing** still compatible with measurements.

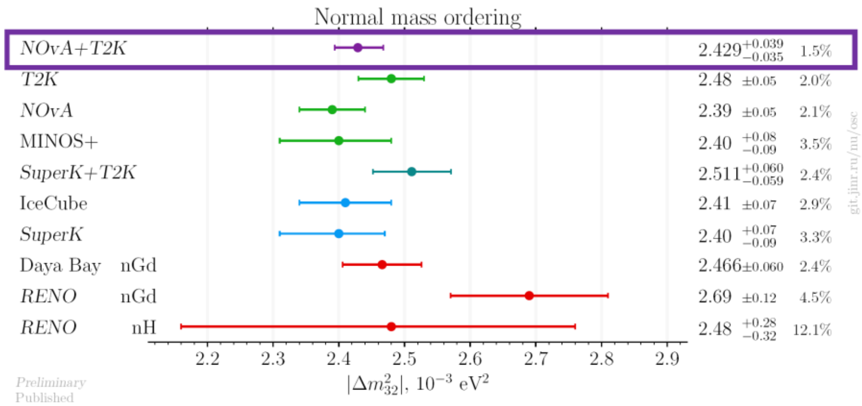


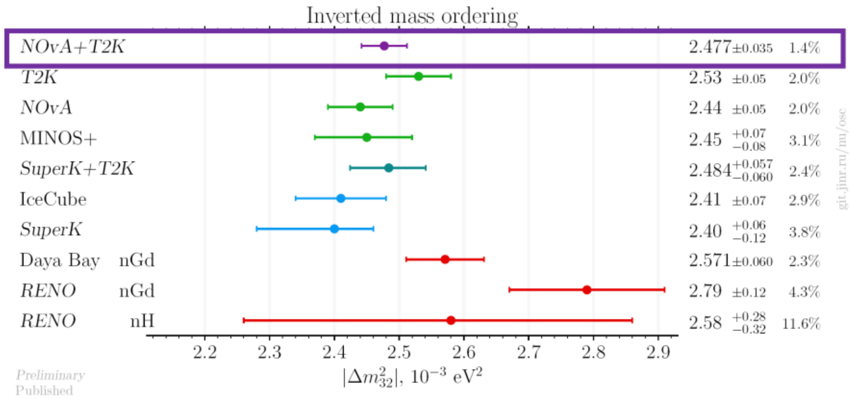




Latest NOvA-T2K results: Δm^2_{32}

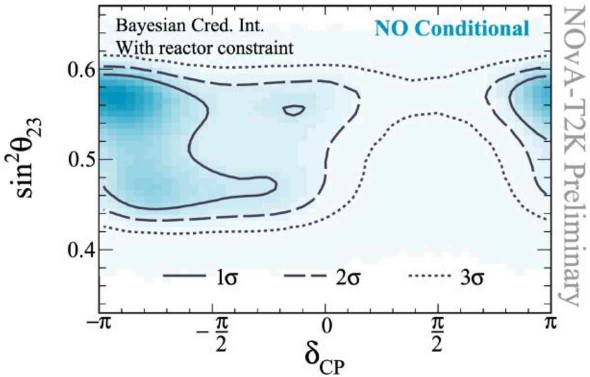
- **Joint NOvA-T2K analysis** provides the **most accurate** measurement of Δm^2_{32}.
- Δm^2_{32} is the most precisely known parameter, yet we still don't know **its sign**.

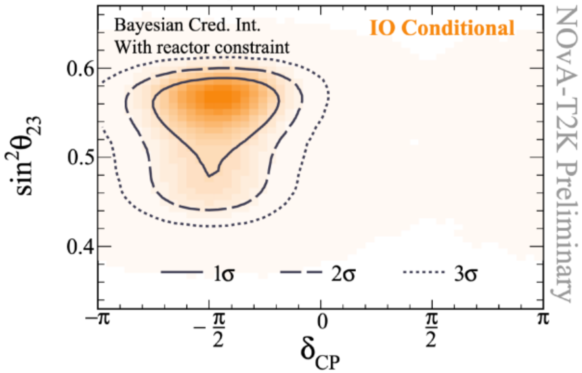


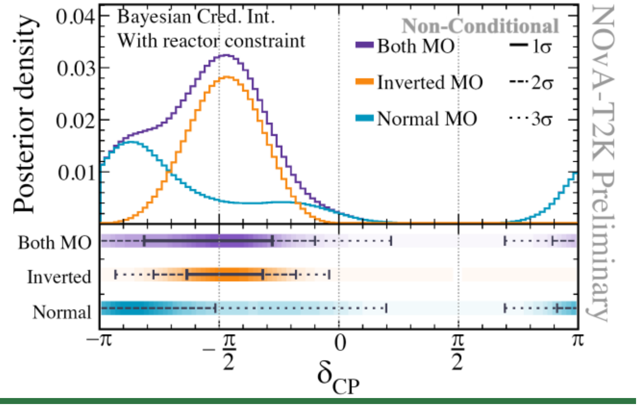


Latest NOvA-T2K results: δ_{CP}

- Combination in Normal Ordering:
  - Less stringent constraint on parameter space allowing wider range of values.
  - **CP conservation** slightly preferred.
- Combination in Inverted Ordering:
  - Enhanced preference for **maximum CP violation.**
  - **CP conservation** (0, π) **disfavored** (outside 3σ credible interval).
- **$\delta_{CP}=\pi/2$** outside 3σ interval in both orderings.



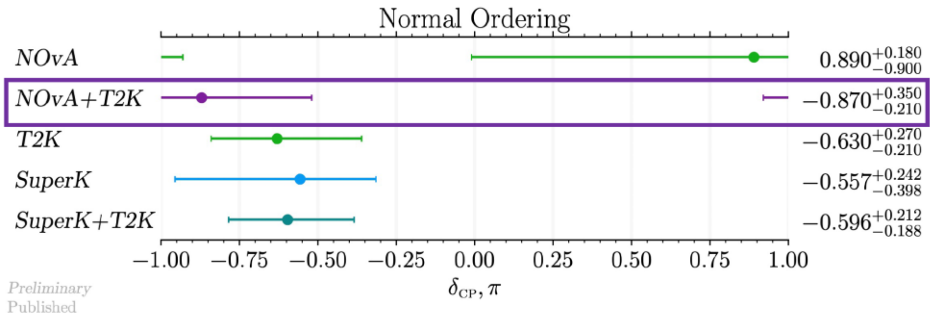


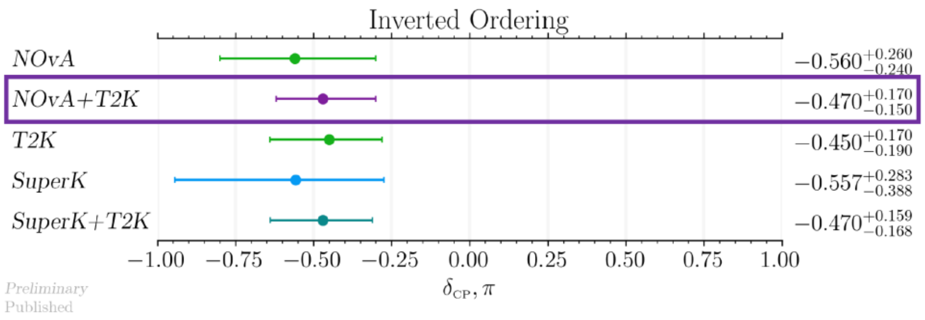


Latest NOvA-T2K results: δ_{CP}

- **Precision** on $\boldsymbol{\delta_{CP}}$ **improved** in **Inverted Ordering.**

- But **uncertainties** on $\boldsymbol{\delta_{CP}}$ remain **large** (~30%), especially in Normal Ordering.





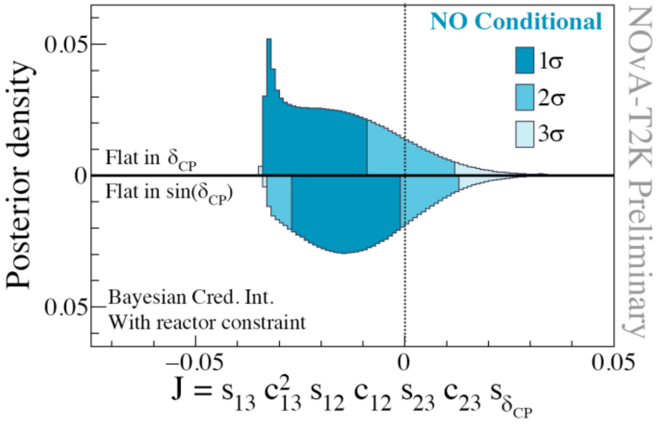
Latest NOvA-T2K results: δ_{CP}

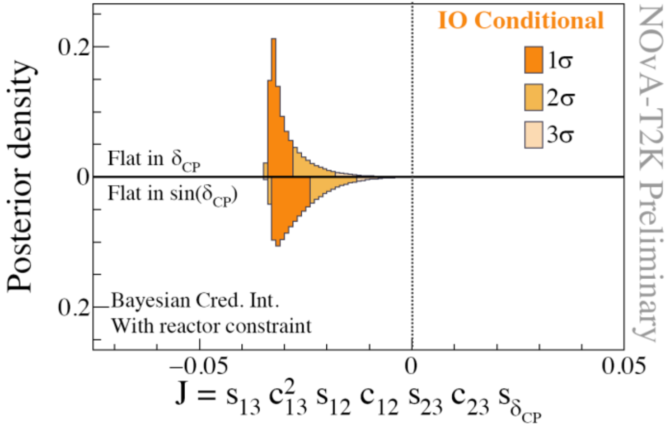
- **Jarlskog invariant** quantifies **CP-violation** in lepton and quark sectors.

$$J \equiv s_{13}c_{13}^2 s_{12}c_{12}s_{23}c_{23}\sin\delta$$

- **Broad range** of values allowed in **Normal Ordering**.

- **CP conservation**, i.e. J=0, **outside 3σ interval** in **Inverted Ordering**.

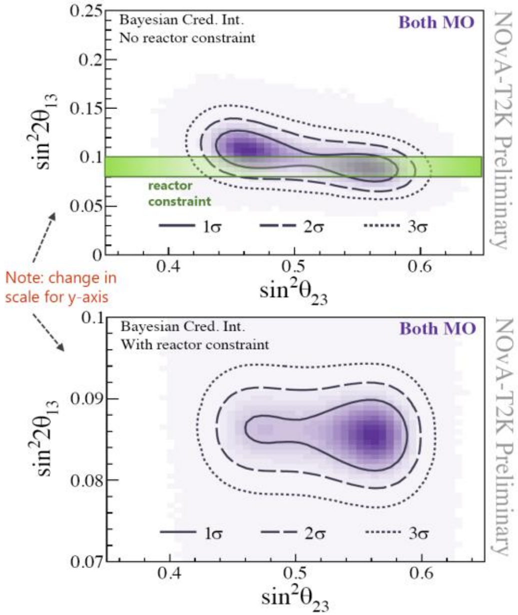


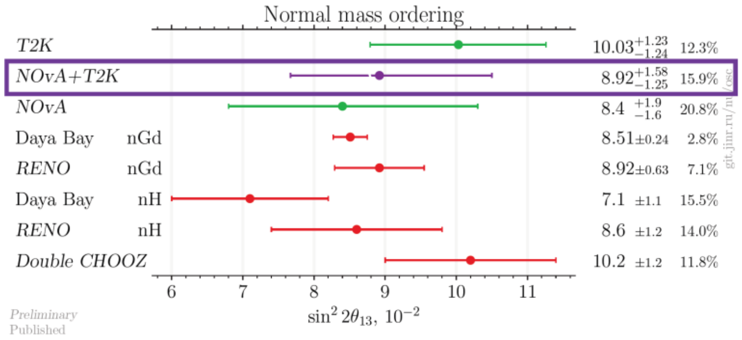


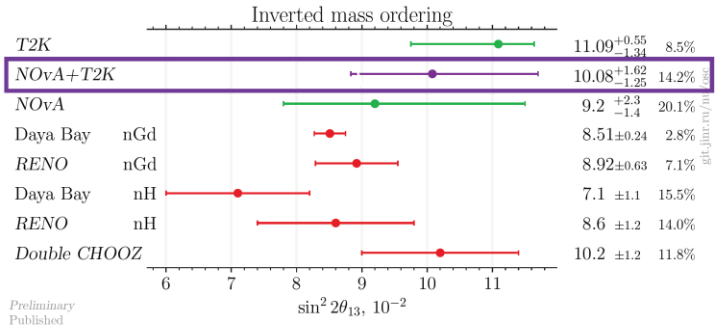
Latest NOvA-T2K results: $\sin^2\theta_{13}$

- **$\sin^2\theta_{13}$** is a subdominant degenerate term in LBL oscillations.

- Measurements compatible with **reactor experiments** but not competitive.

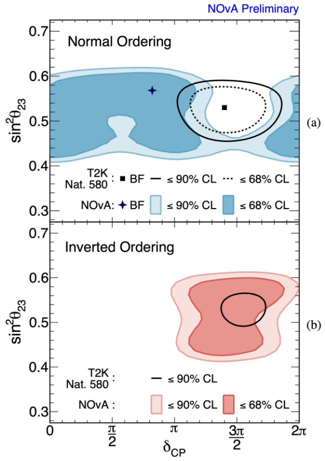




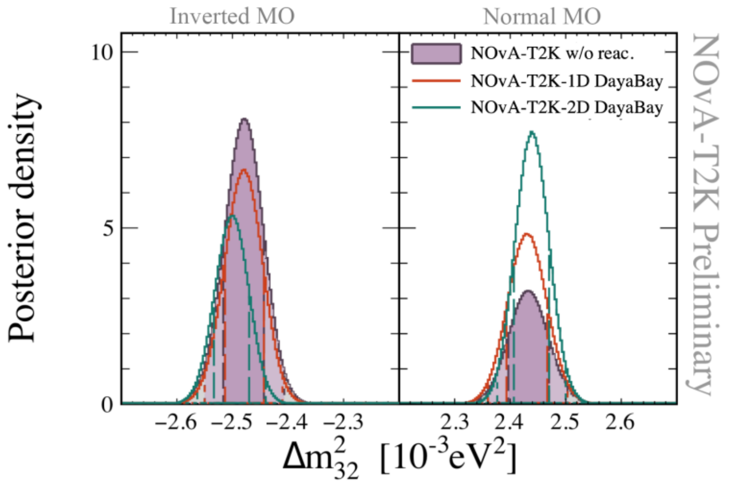


Latest NOvA-T2K results: neutrino mass ordering

- Still no strong preference for the **neutrino mass ordering** :
  - Each experiment individually **favors Normal Ordering**.
  - Joint fit flips the **preference for Inverted Ordering** (IO 58%, NO 42%).
  - Including an external constraint on Δm^2_{32} (and θ_{13}) brings back the slight **preference for Normal Ordering** (IO 59%, NO 41%).

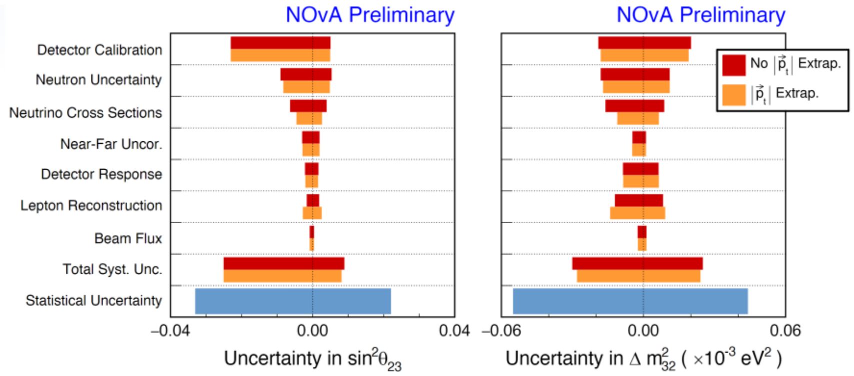


- **JUNO** will provide a **very precise measurement of Δm^2_{32}** which will help **LBL experiments** resolve the **neutrino mass ordering**.



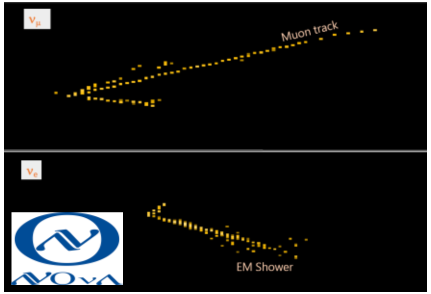
Current limitations of LBL experiments

- **NOvA** and **T2K** measurements are still **statistically limited**.
- Expected to **double their datasets** over next **few years**.



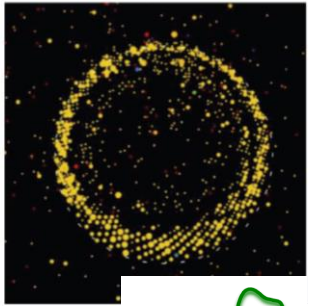
- **Neutrino cross-sections** would become the **dominating uncertainty** in next-generation experiments within a few months if they are not better understood today:
  - Study **neutrino-nucleus interactions** in **Near Detectors** and compare/feed **models**.
  - Contributed to the **measurement** of **neutrino cross-sections** of some of the main **interaction channels** with **NOvA ND**:
    - $\bar{\nu}_e$ + N $\rightarrow e^+$ + X : world first double-differential measurement.
    - ν_μ + N $\rightarrow \mu^-$ + $\pi^\pm$ + X : first double-differential measurement in NOvA.

Next generation of LBL experiments in numbers



- ❑ **14kt** segmented liquid scintillator
- ❑ **700 kW** neutrino beam
- ❑ **810 km** baseline

- ❑ **55kt** water Cherenkov
- ❑ **500 kW**
- ❑ **295 km**



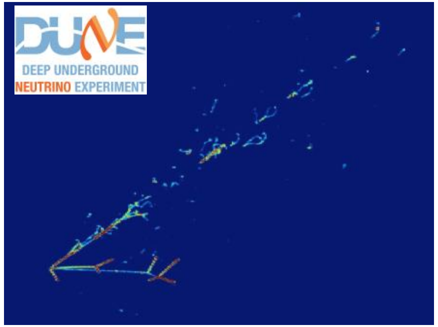
T2K

➢ Longer baseline → More matter effects → **NMO**

➢ Improved technologies
➢ Larger detectors
➢ Higher beam power

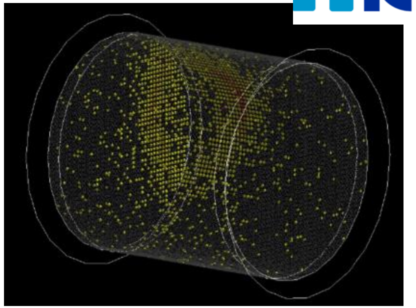
➢ Same baseline → More statistics → $\boldsymbol{\delta_{CP}}$

HYPER K



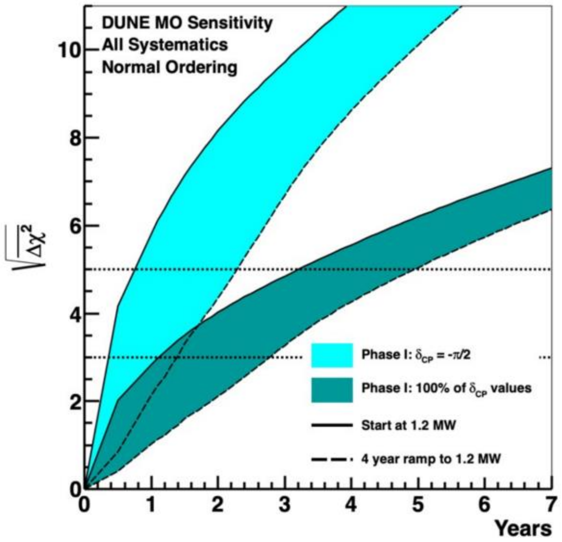
- ❑ **40kt** Liquid Argon TPC
- ❑ **1.2-2.4** MW
- ❑ **1300 km**

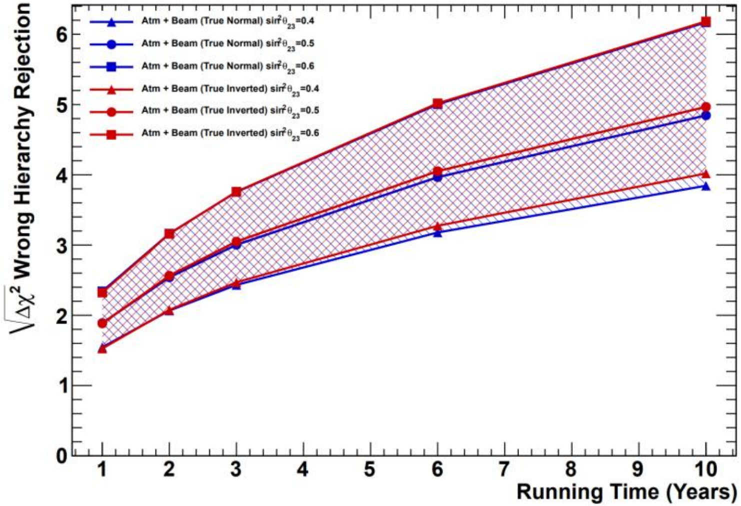
- ❑ **187kt** water Cherenkov
- ❑ **1.3 MW**
- ❑ **295 km**



DUNE and HyperK sensitivity to Neutrino Mass Ordering

- **NMO determination** at **5σ** guaranteed with **DUNE** in Phase I.
  - In **1 year** in most favorable case.
  - After **4 years** regardless of θ_{23} and δ_{CP} values.
- **HyperK** has more **modest sensitivity** to **NMO** because of **shorter baseline**:
  - **5σ after 6 years** in most favorable case.

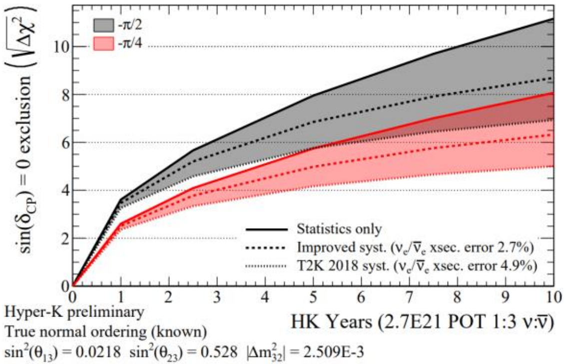


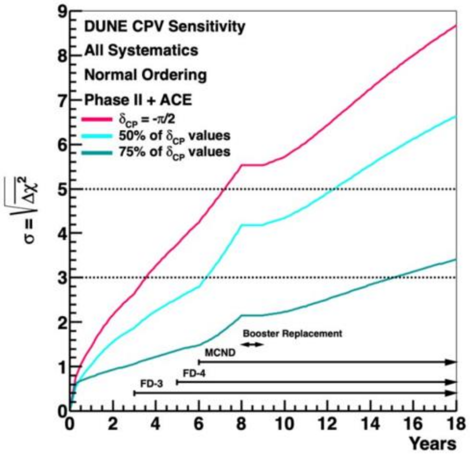


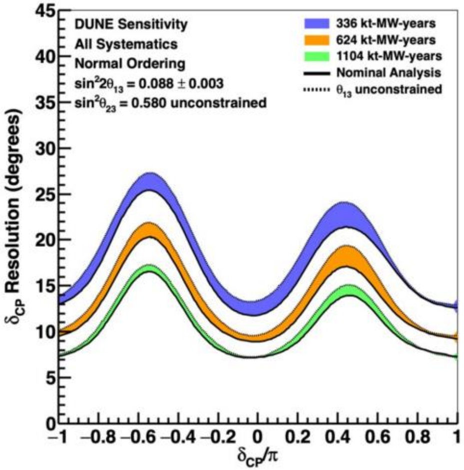
DUNE and HyperK sensitivity to δ_{CP}

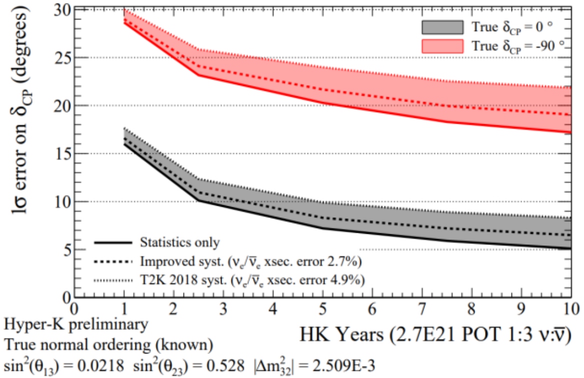
- **HyperK** has **better sensitivity** to $\boldsymbol{\delta_{CP}}$ than **DUNE:**
  - **HyperK** can **exclude CP conservation (>3σ)** in just **1 year** in the most favorable case.
  - **DUNE** needs favorable $\boldsymbol{\delta_{CP}}$ to reach same **3σ sensitivity.**

- They will ultimately reach **7º- 20º precision** on $\boldsymbol{\delta_{CP}}$.









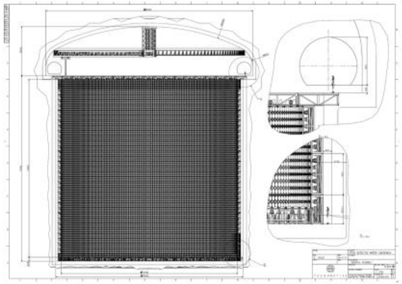
ESSnuSB+

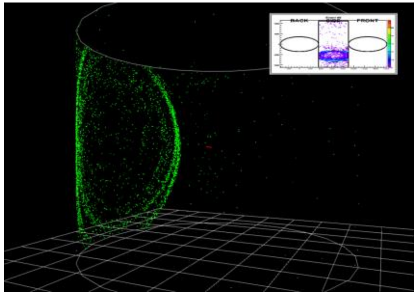
- **ESSnuSB+** is a future **next-generation LBL experiment**.

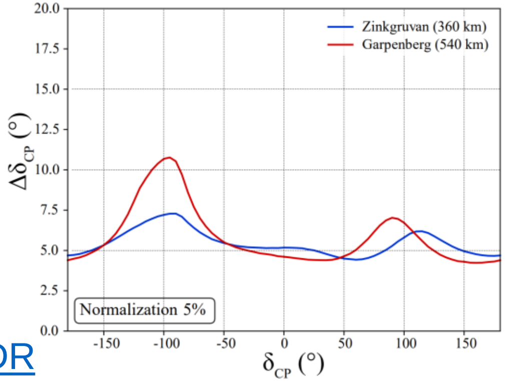
- **ESSnuSB+** plans to measure $\boldsymbol{\nu_e}$ **appearance** at second probability maximum:
  - 5-10 MW neutrino beam
  - 540 kton water Cherenkov far detector
  - 360-540 km baseline

➢ **5º- 7º precision** on $\boldsymbol{\delta_{CP}}$ after **10 years**.

➢ **5σ discovery** of **CP violation** for **71% of $\boldsymbol{\delta_{CP}}$ values**.



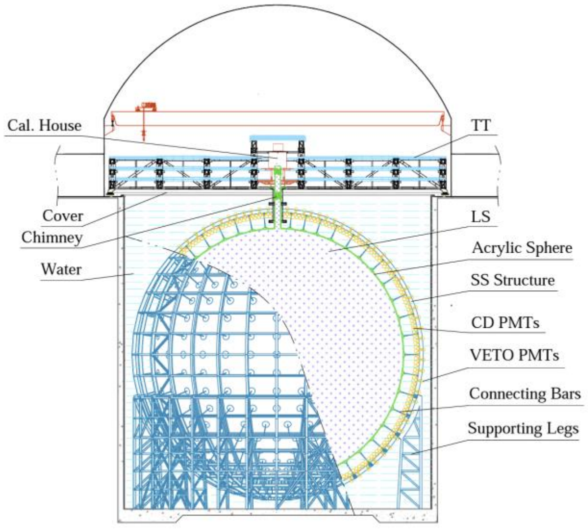


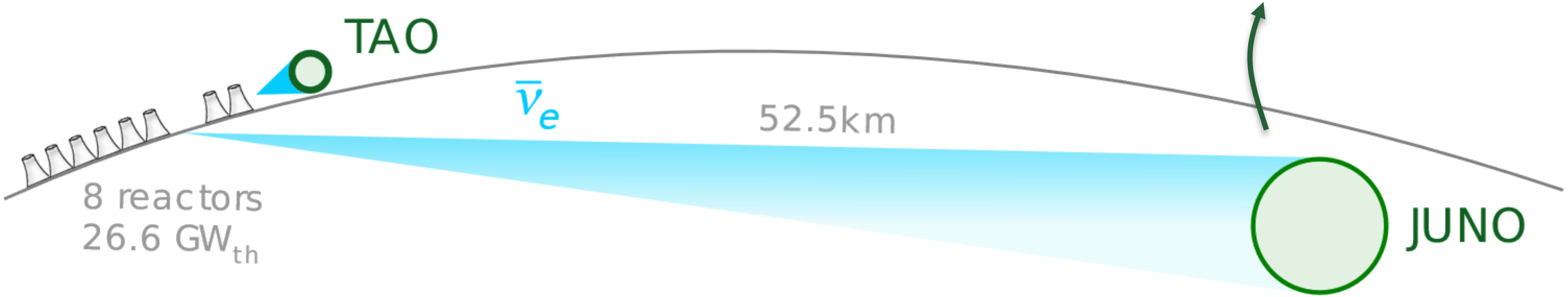


CDR

Jiangmen Underground Neutrino Observatory

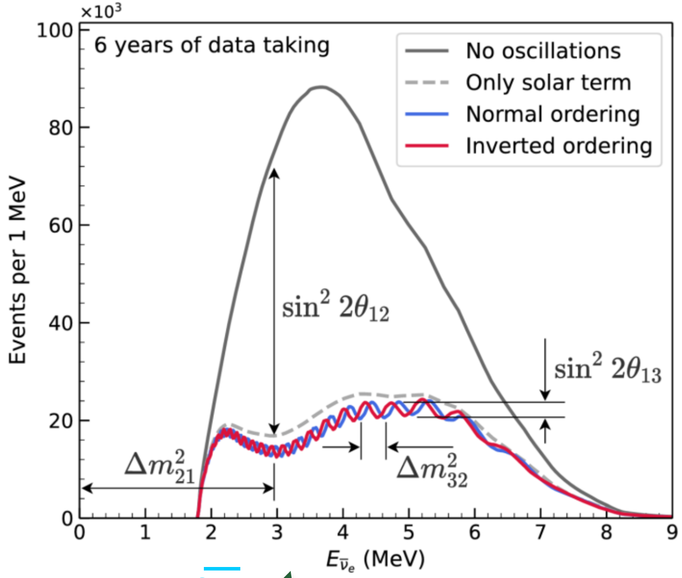
- **JUNO** is a **20-kton Liquid Scintillator** neutrino observatory located in Southern China.

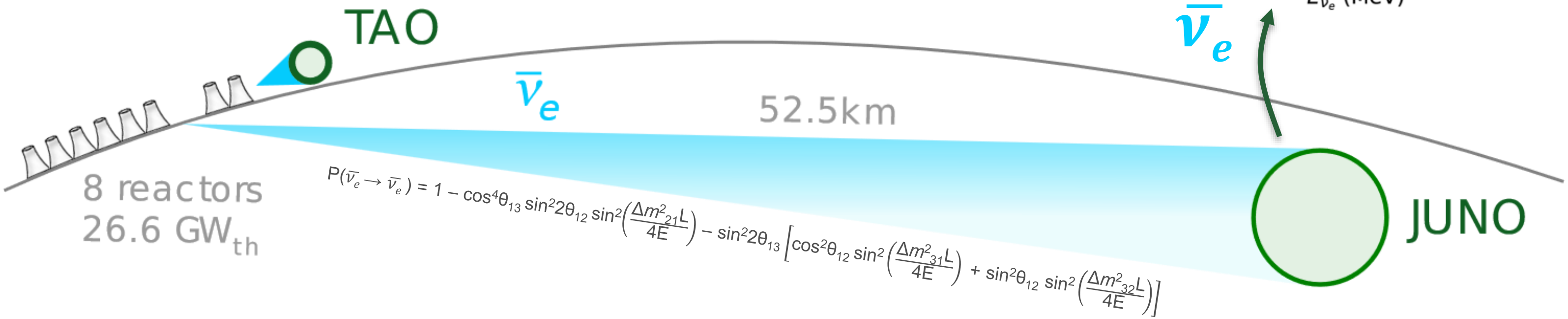




Jiangmen Underground Neutrino Observatory

- **JUNO** is a **20-kton Liquid Scintillator** neutrino observatory located in Southern China.
- JUNO studies **reactor electron antineutrino disappearance** over a medium baseline to:
  - Determine the **neutrino mass ordering.**
  - Measure $\boldsymbol{\Delta m^2_{31}}$, $\boldsymbol{\Delta m^2_{21}}$, and $\boldsymbol{\sin^2 2\theta_{12}}$.





JUNO key experimental features

- **Large statistics**
  - 20-kton Liquid Scintillator (LS)
  - Powerful nuclear reactors (26.6 GW_{th})
- **Energy resolution: 3% @ 1MeV**
  - High photon yield, highly transparent LS
  - Very high PMTs coverage (78 %)
  - High PMT efficiency (30%)
- **Low background**
  - 650m or 1800 m.w.e overburden
  - Efficient veto system (>99.5%)
  - Material screening, clean environment
- **Precise knowledge of reactor spectra**
  - Satellite detector TAO

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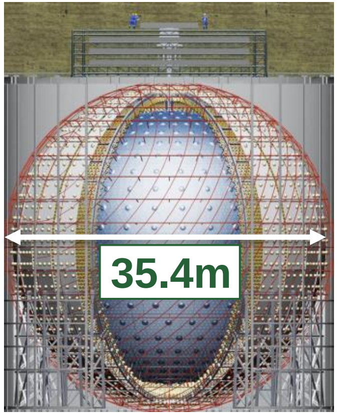

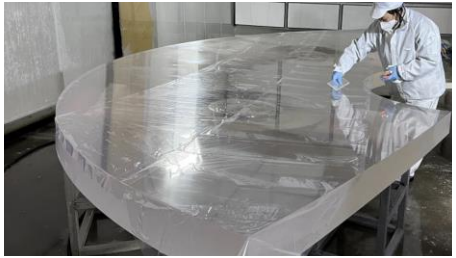

- **20kton LS**: LAB + 2.5g/L PPO + 3 mg/L bis-MSB
- **Osiris**: measures radiopurity of LS.

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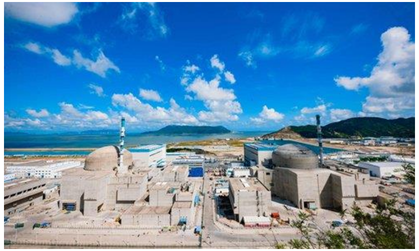
Taishan



Yangjiang

- Two nuclear power plants
- 8 reactor cores
- **26.6 GW_{th}**

Reactor	Power (GW_{th})	Baseline (km)	IBD Rate (day^{-1})	Relative Flux (%)
Taishan	9.2	52.71	15.1	32.1
Core 1	4.6	52.77	7.5	16.0
Core 2	4.6	52.64	7.6	16.1
Yangjiang	17.4	52.46	29.0	61.5
Core 1	2.9	52.74	4.8	10.1
Core 2	2.9	52.82	4.7	10.1
Core 3	2.9	52.41	4.8	10.3
Core 4	2.9	52.49	4.8	10.2
Core 5	2.9	52.11	4.9	10.4
Core 6	2.9	52.19	4.9	10.4
Daya Bay	17.4	215	3.0	6.4

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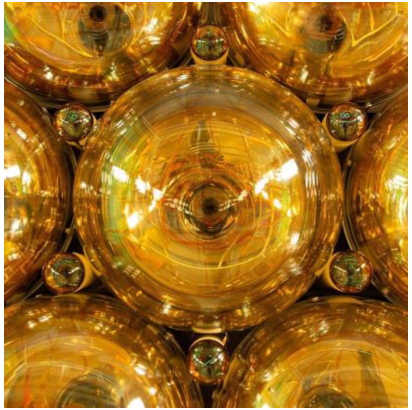

- 17,512 **20" PMTs** + 25,600 **3" PMTs**

		LPMT (20-inch)		SPMT (3-inch)
		Hamamatsu	NNVT	HZC
Quantity		5000	15012	25600
Charge Collection		Dynode	MCP	Dynode
Photon Detection Efficiency		**28.5%**	**30.1%**	25%
Mean Dark Count Rate [kHz]	Bare	15.3	49.3	0.5
	Potted	**17.0**	**31.2**	
Transit Time Spread (σ) [ns]		1.3	7.0	1.6
Dynamic range for [0-10] MeV		[0, 100] PEs		[0, 2] PEs
Coverage		75%		3%
Reference		arXiv: 2205.08629		NIM.A 1005 (2021) 165347

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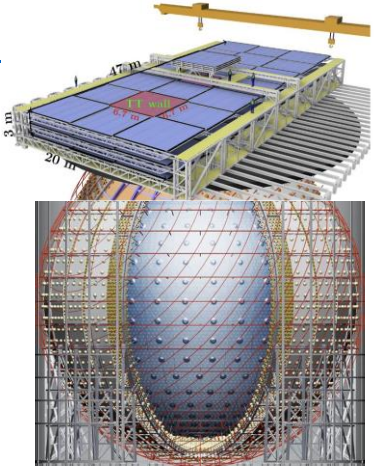
- **650m overburden**: 4Hz of cosmic muons in LS
- **Top Tracker**: arXiv:2303.05172
  - ○ Opera plastic scintillator
- **Outer Cherenkov Detector**:
  - ○ 35 kton ultrapure water
  - ○ 2400 20” PMTs



- **Veto strategy** :

57 reactor $\bar{\nu}_e$ + 127 ^{9}Li + 40 ^{8}He events/day

⬇

47 reactor $\bar{\nu}_e$ + 0.8 ^{9}Li/^{8}He events/day

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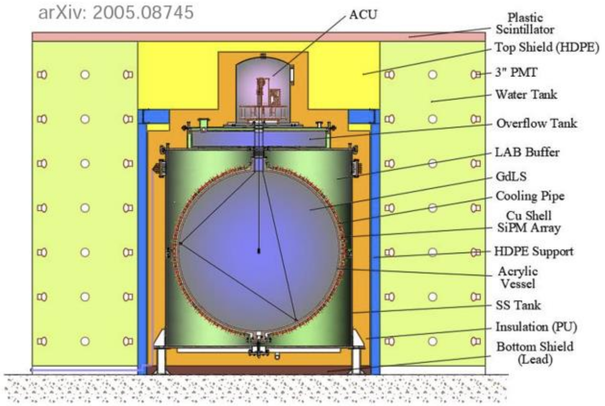
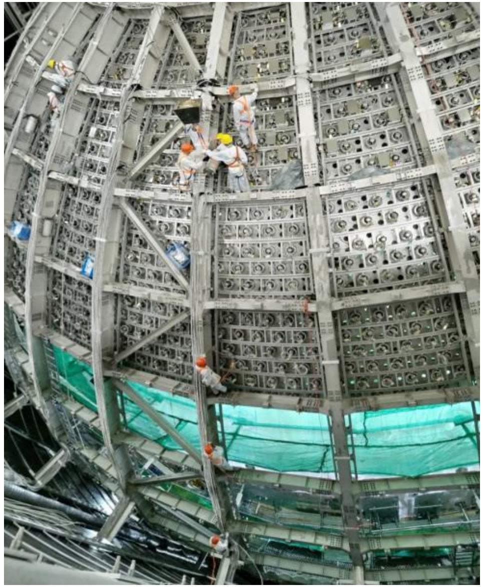


- **TAO** can perform a precise measurement of **reactor $\bar{\nu}_e$ spectrum**:
  - 44m from reactor → 20 times JUNO event rate
  - 2.8 ton Gd-LS, 1 ton fiducial volume
  - 4500 PEs/MeV
  - SiPM: 94% coverage with 50% PDE
  - ➢ Energy resolution <2% @ 1 MeV
  - ➢ Sub-percent shape uncertainty

Updates on JUNO construction

- **Support Structure** completed.
- 50% of **Acrylic Vessel** installed.
- Top hemisphere **fully instrumented**.
- **Detector completion** and **first data** expected by **mid-2025**.



June 2023

Double calorimetry strategy

- Unprecedented **energy resolution** of **3% @ 1 MeV** :

$$\frac{\sigma_{E_{\mathrm{vis}}}}{E_{\mathrm{vis}}} = \sqrt{\left(\frac{a}{\sqrt{E_{\mathrm{vis}}}}\right)^2 + b^2 + \left(\frac{c}{E_{\mathrm{vis}}}\right)^2}$$

Stochastic term
✓ High N_{PE}

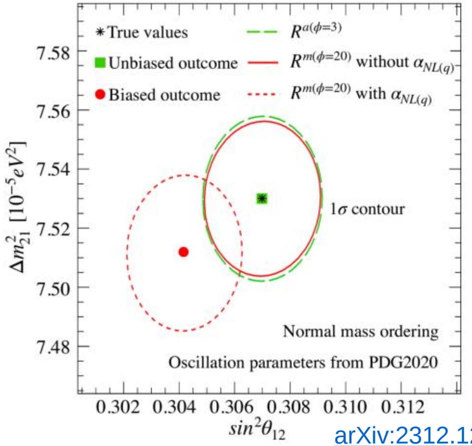
Non-stochastic term (stability, uniformity, linearity…)

- Critical for the determination of the **neutrino mass ordering**.

- **Large photomultipliers** could exhibit **non-linear behavior** (high energy events, edge of detector, etc.).

➢ Use **small photomultipliers** to detect and control **non-linearity effects** (e.g arXiv:2312.12991).

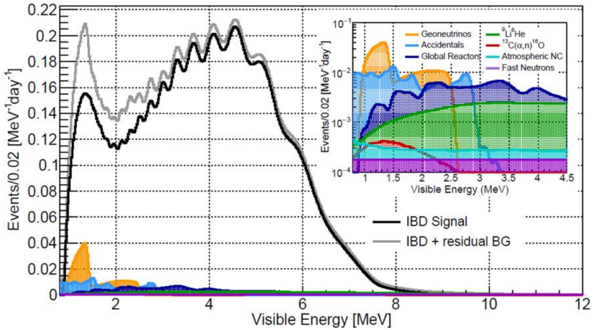
Illustration of impact of LPMTs non-linearity



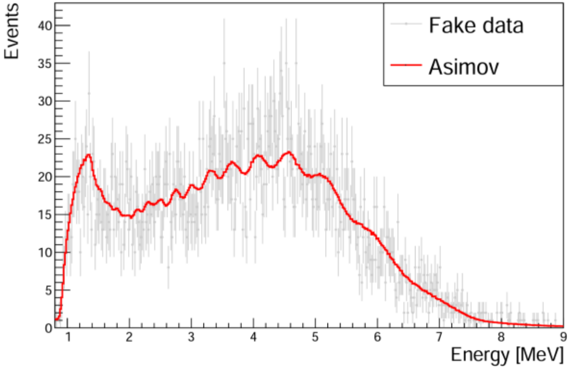
arXiv:2312.12991

JUNO oscillation analysis

- **First data mid-2025**.
- Development of **analysis framework ongoing**.
- Development of **oscillation analysis** and **realistic sensitivity studies**.
- Updated **Neutrino Mass Ordering sensitivity** coming soon!
- Preparing the **statistical framework** for measurements at low exposure, e.g. **first 100 days**.

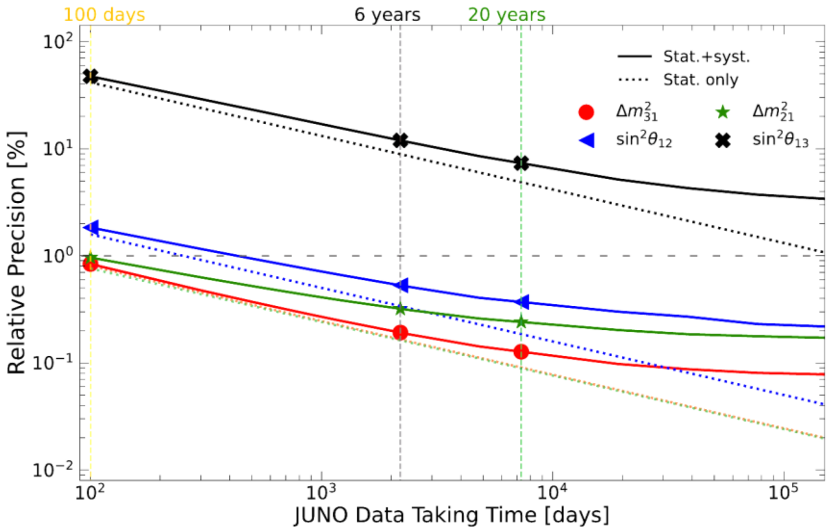


Example spectrum at 100 days



Precision measurement of neutrino oscillations parameters

- **JUNO** will provide an **order of magnitude improvement** over current knowledge of **Δm^2_{31}, Δm^2_{21},** and **$\sin^2\theta_{12}$.**

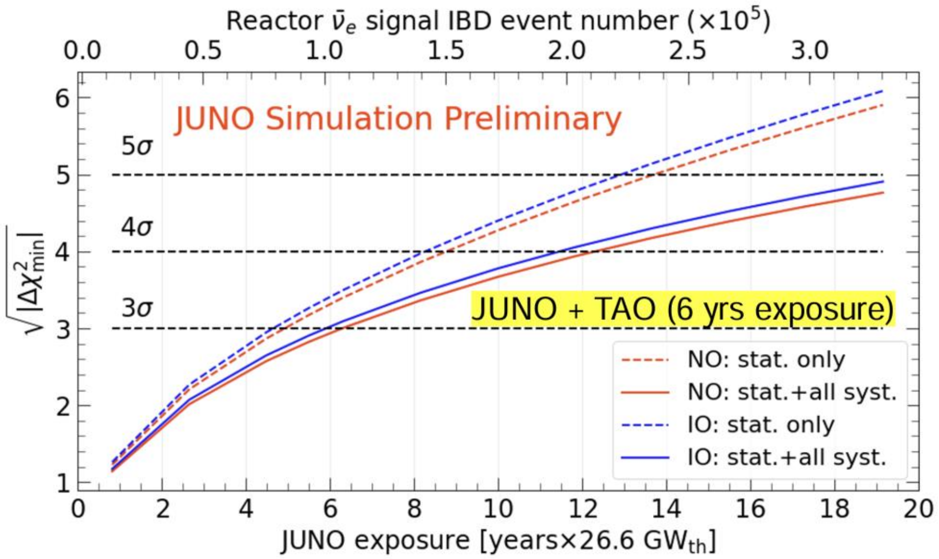


arXiv:2204.13249v1

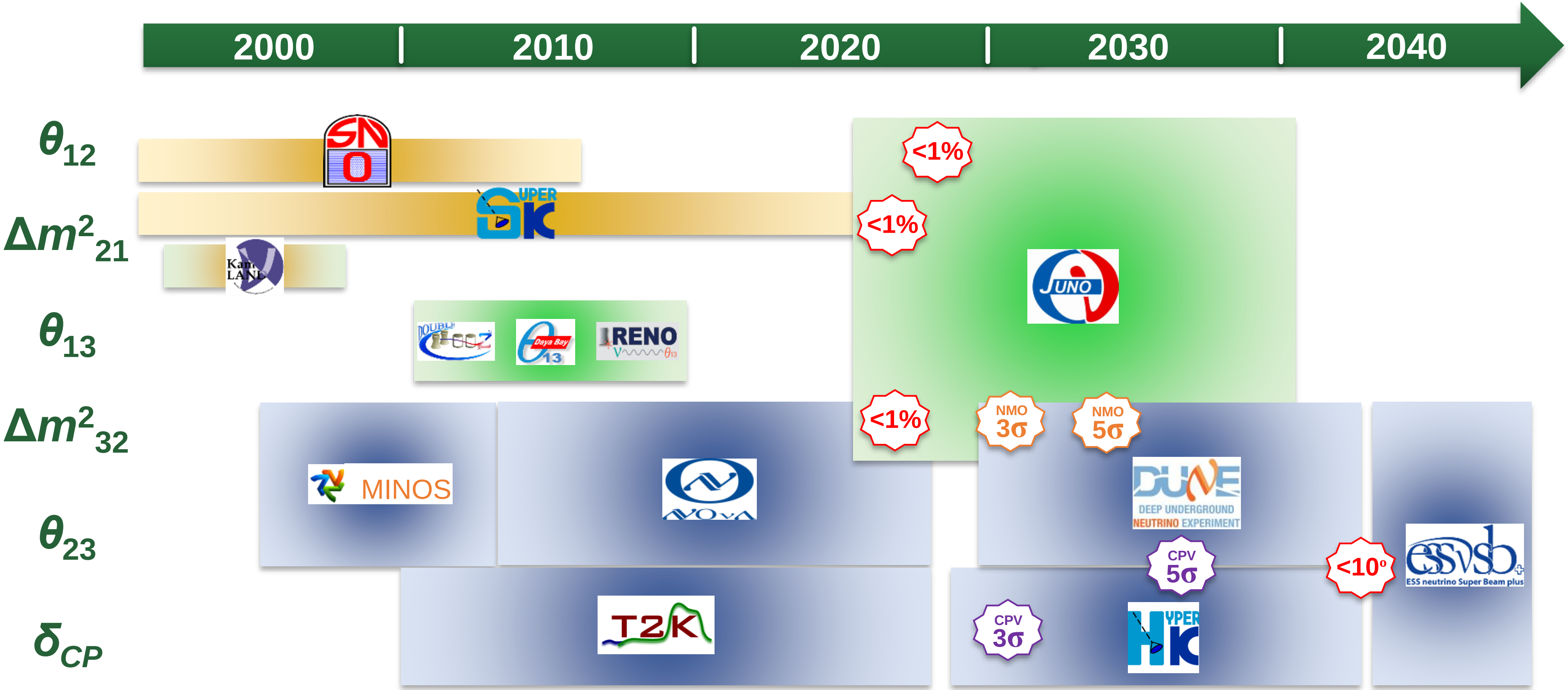
	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (0.5%)	±0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	±0.0007 (3.2%)	±0.010 (47.9%)	±0.0026 (12.1%)	±0.0016 (7.3%)

JUNO sensitivity to neutrino mass ordering

- **JUNO** will independently determine the **neutrino mass ordering** with a **3σ sensitivity** in **6 years.**
- Updated **sensitivity** coming soon.



Dawn of the precision era in neutrino oscillation physics



Conclusions

- **Very exciting time** for **neutrino physics** !

- **JUNO** will be the **first experiment** to perform **sub-percent precision measurements** of the **neutrino parameters**.

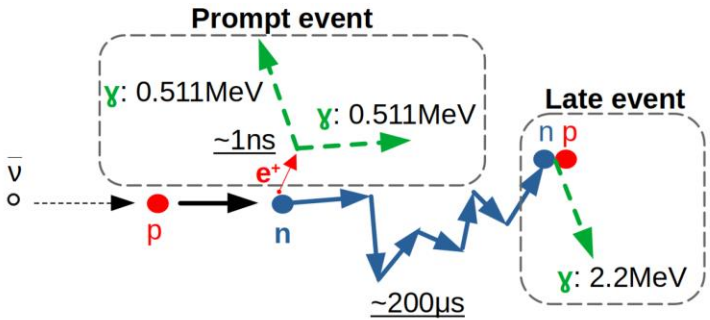
- **DUNE** and **HyperK** will further complete the **neutrino picture**.

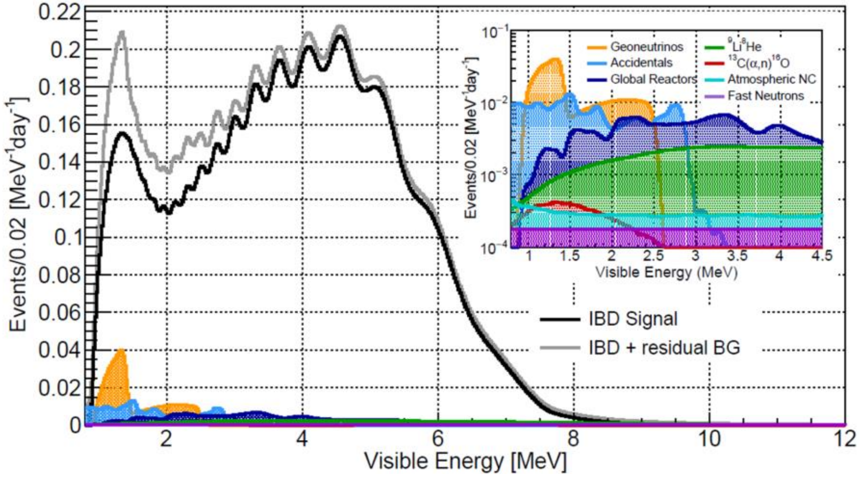
- With **precision measurements** over the next **10-20 years**, it will be possible to:
  - Precisely **quantify CP-violation** (Jarlskog invariant): answer to **baryon asymmetry** ?
  - Test **unitarity** of **PMNS matrix**: window for **physics beyond the Standard Model**.
  - Better understand **origin of mass and flavor**.

Backup

Signal in JUNO

- **47 IBD per day** expected:
  - Prompt + delayed signals to strongly suppress backgrounds.
  - 7% backgrounds, mostly below 3MeV.
  - ~10^5 IBD candidates in 6 years.





JUNO uncertainties

- **Statistical** and **systematic uncertainties** for **6 years**.

6 years	$\Delta\chi^2_{min}$ (stat. + 1 syst.)
Statistics	11.3
Stat.+Flux error	-0.6
Stat.+Backgrounds	-1.4
Stat.+Nonlinearity	-0.4
Stat.+Others	< -0.05
Total	9.0

JUNO Simulation Preliminary

Δm^2_{31}	1σ (%)
Statistics	0.17
Reactor:	
- Uncorrelated	< 0.01
- Correlated	0.01
- Reference spectrum	0.05
- Spent Nuclear Fuel	< 0.01
- Non-equilibrium	< 0.01
Detection:	
- Efficiency	0.01
- Energy resolution	< 0.01
- Nonlinearity	0.04
- Backgrounds	0.04
Matter density	0.01
All systematics	0.08
Total	0.19

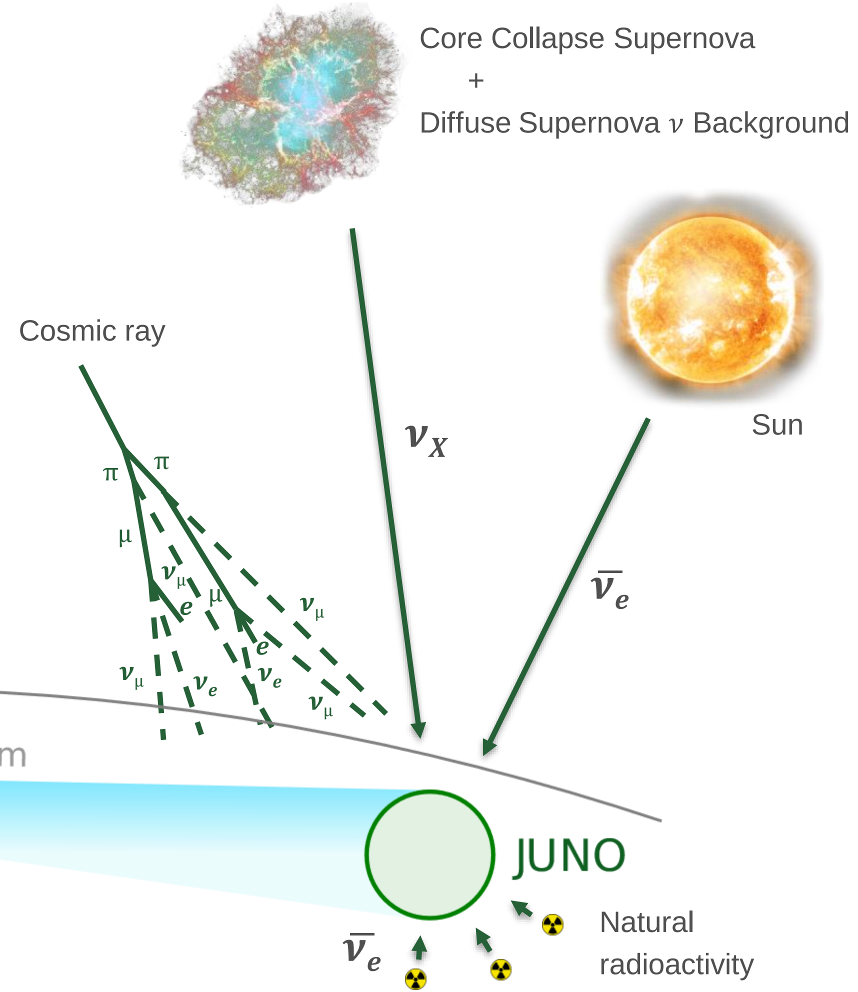
Δm^2_{21}	1σ (%)
Statistics	0.16
Reactor:	
- Uncorrelated	0.01
- Correlated	0.03
- Reference spectrum	0.07
- Spent Nuclear Fuel	0.07
- Non-equilibrium	0.14
Detection:	
- Efficiency	0.02
- Energy resolution	0.01
- Nonlinearity	0.05
- Backgrounds	0.18
Matter density	0.01
All systematics	0.27
Total	0.32

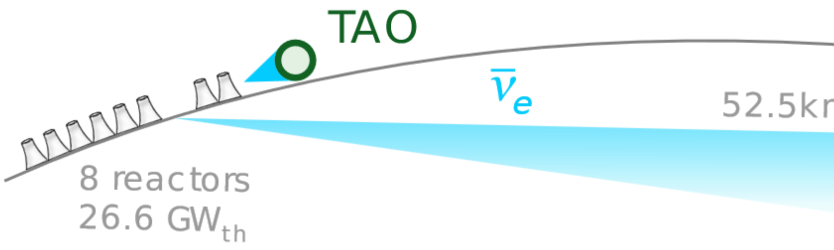
$\sin^2\theta_{12}$	1σ (%)
Statistics	0.34
Reactor:	
- Uncorrelated	0.10
- Correlated	0.27
- Reference spectrum	0.09
- Spent Nuclear Fuel	0.05
- Non-equilibrium	0.10
Detection:	
- Efficiency	0.23
- Energy resolution	0.01
- Nonlinearity	0.09
- Backgrounds	0.20
Matter density	0.07
All systematics	0.40
Total	0.52

$\sin^2\theta_{13}$	1σ (%)
Statistics	8.94
Reactor:	
- Uncorrelated	2.53
- Correlated	6.83
- Reference spectrum	3.48
- Spent Nuclear Fuel	1.55
- Non-equilibrium	2.65
Detection:	
- Efficiency	5.81
- Energy resolution	0.39
- Nonlinearity	2.09
- Backgrounds	4.89
Matter density	0.98
All systematics	8.16
Total	12.11

Neutrino landscape in JUNO

Neutrinos	Energy range	Rate in JUNO
Atmospheric	0.1 – 100 GeV	100s / year
Solar	0 – 16 MeV	100s / year ^{8}B
Supernova burst	0 – 100 MeV	7500 at 10 kpc
DSNB	0 – 100 MeV	2-4 / $\bar{\nu}_e$ year
Geoneutrinos	0 – 3 MeV	400 / year





Solar neutrinos

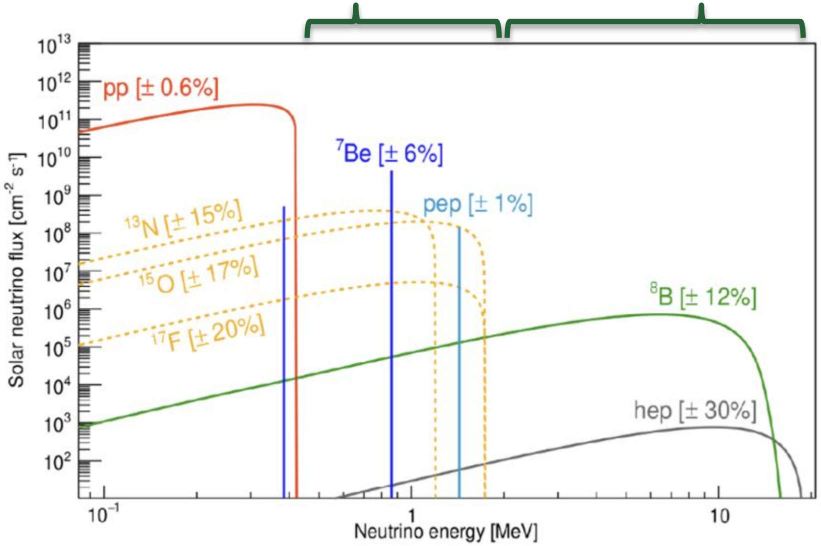
- **JUNO** sensitive to both **high** and **intermediate energy** solar neutrinos.

JUNO sensitivity to ^{7}Be, *pep*, and CNO solar neutrinos

arXiv:2303.03910

Model Independent Approach of the JUNO ^{8}B Solar Neutrino Program

arXiv:2210.08437

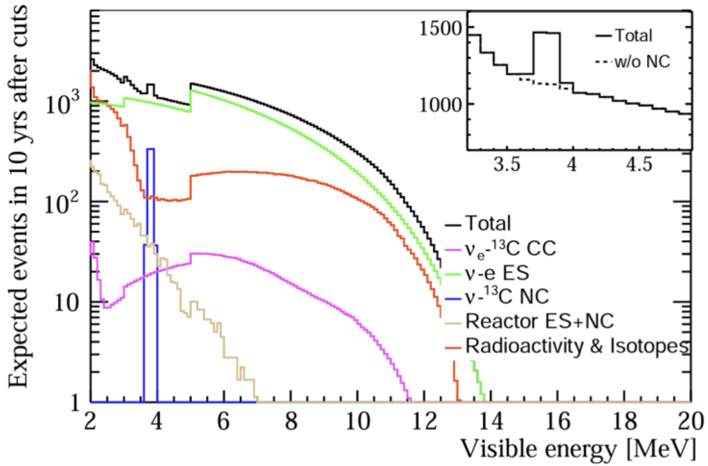


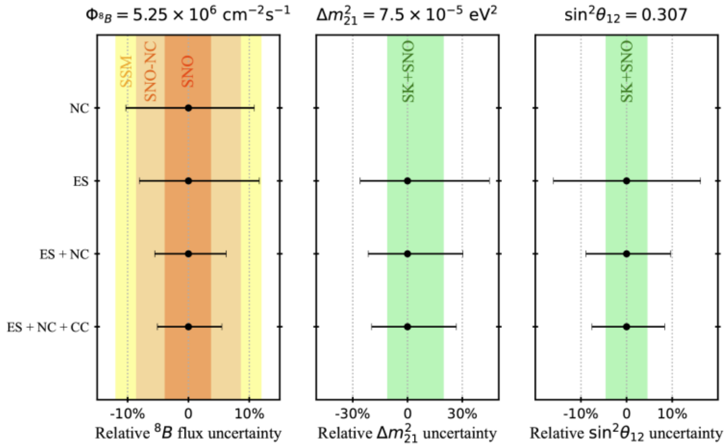
arXiv:2210.08437

High energy solar neutrinos

- Model independent detection of **^{8}B neutrinos** via three interaction channels **CC, NC** and **ES**:
  - 5% uncertainty on **^{8}B neutrino flux**
  - 20% uncertainty on **Δm^2_{21}**
  - 8% uncertainty on **$\sin^2\theta_{12}$**

	Channels	Threshold [MeV]	Signal	Event numbers [200 kt×yrs]	Event numbers after cuts
CC	$\nu_e + {}^{13}\mathrm{C} \rightarrow e^- + {}^{13}\mathrm{N}\,(\frac{1}{2}^-;\mathrm{gnd})$	2.2 MeV	$e^- + {}^{13}$N decay	3929	647
NC	$\nu_x + {}^{13}\mathrm{C} \rightarrow \nu_x + {}^{13}\mathrm{C}\,(\frac{3}{2}^-;3.685\,\mathrm{MeV})$	3.685 MeV	γ	3032	738
ES	$\nu_x + e \rightarrow \nu_x + e$	0	e^-	3.0×10^5	6.0×10^4

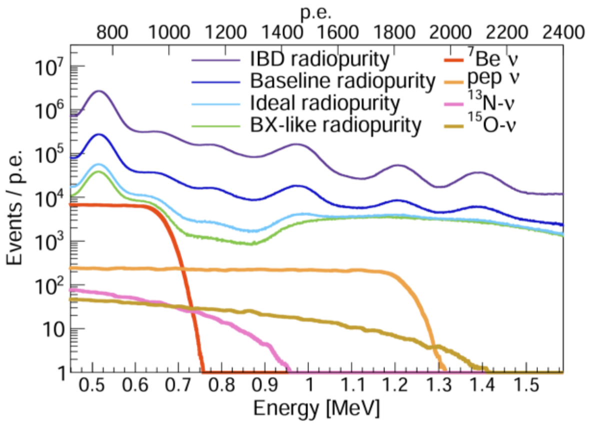




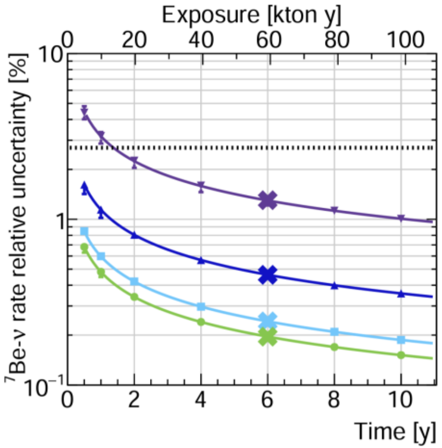
arXiv:2303.03910

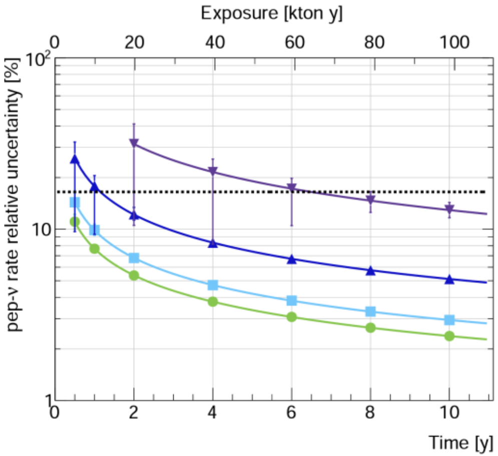
Intermediate energy solar neutrinos

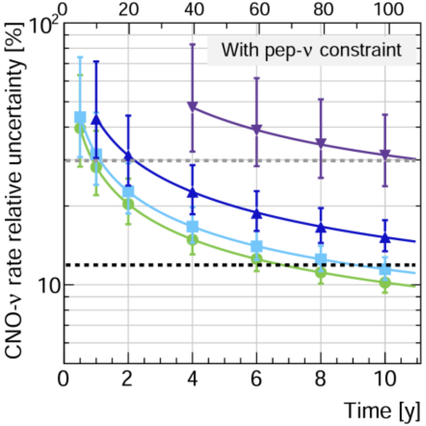
- Possible thanks to **radiopurity** efforts.
- **World leading constraints** after a few years.
- Day/Night asymmetry sensitivity <1%.



Radiopurity scenario: BX-like Ideal Baseline IBD

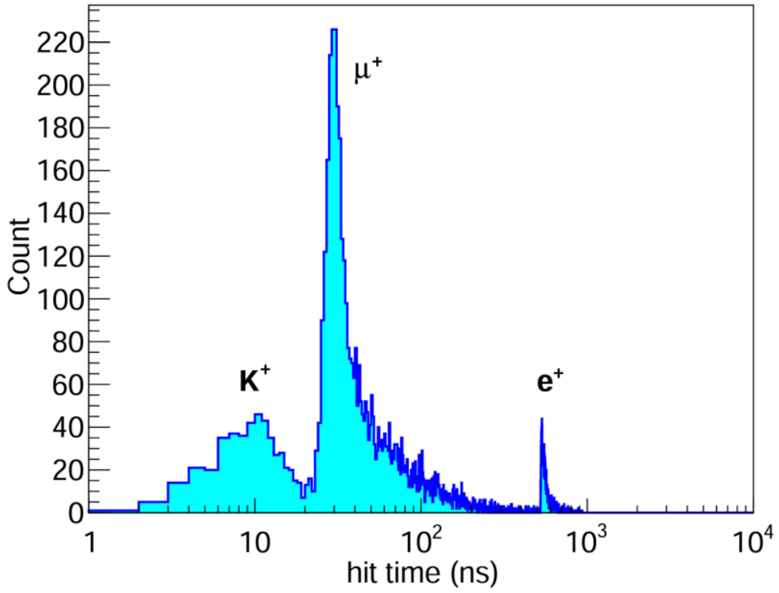






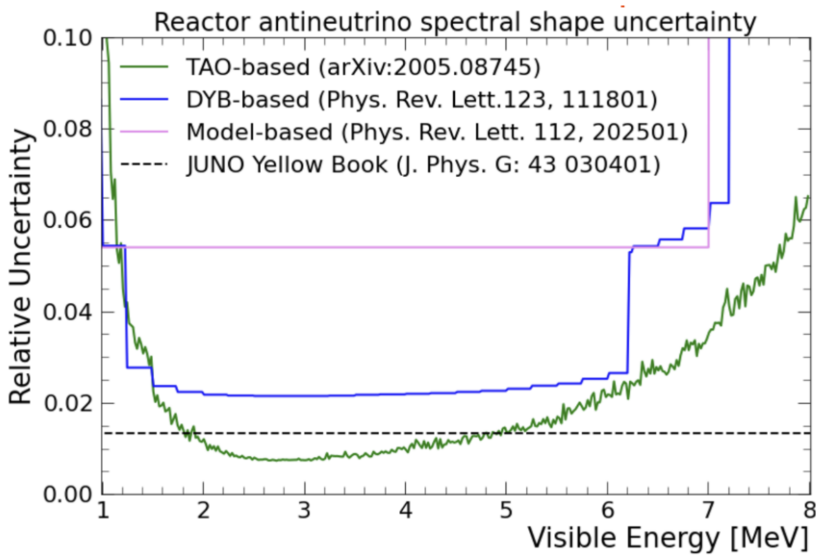
Proton decay

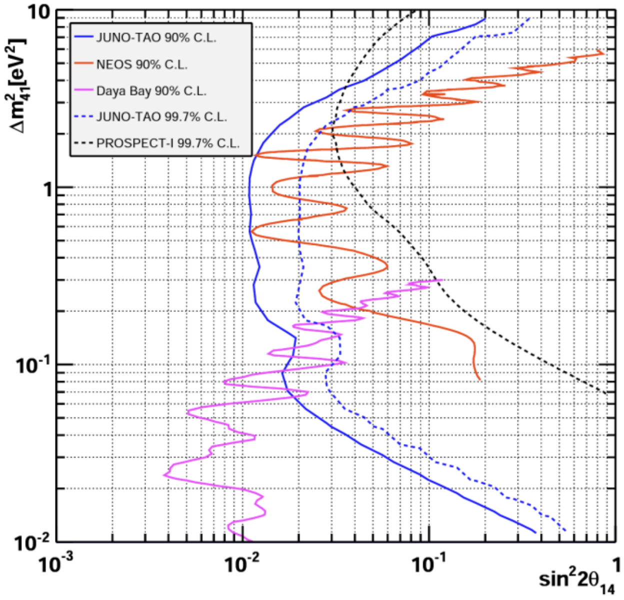
- **$p \rightarrow \bar{\nu}\ K^{+}$** : three-fold coincidence to detect proton decay with high efficiency (36.9%).
- Good energy resolution helps reduce the backgrounds: less than 0.2 events after 10 years.
- Competitive limit on **proton lifetime** of **9.6×10^{33} years** for 200 kton-year exposure.
- More details in [arXiv:2212.08502](https://arxiv.org/abs/2212.08502) .



TAO

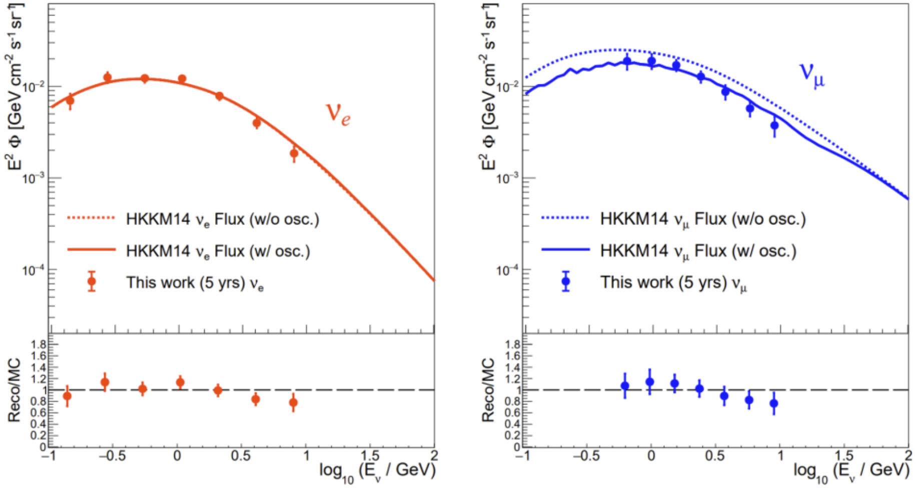
- **Sub-percent precision** on reactor neutrino **spectrum shape**.
- **TAO** can search for **sterile neutrinos**.





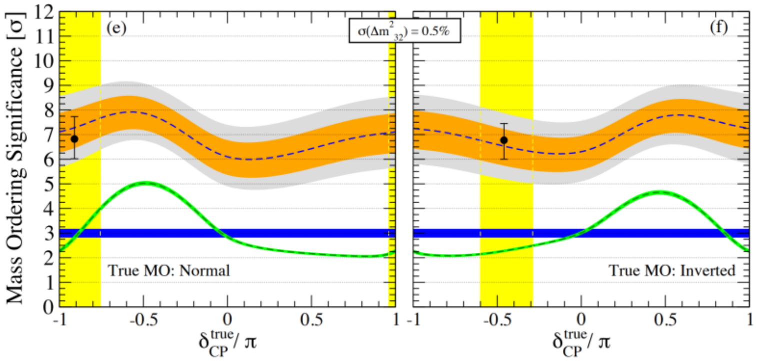
Atmospheric neutrinos

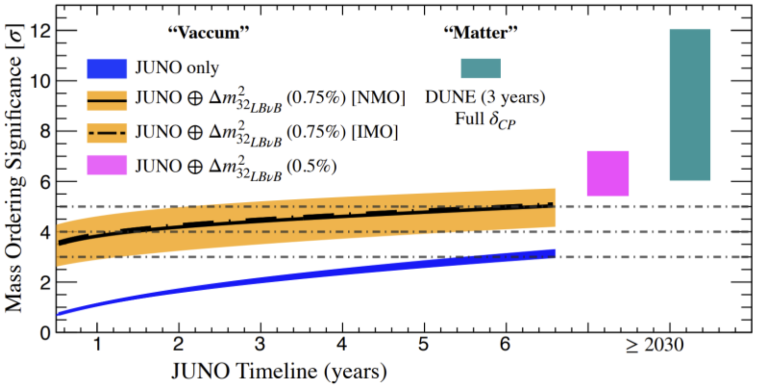
- Detect and discriminate **ν_e and ν_μ CC interactions** through **event time profile**.
- Sensitivity to **NMO** through **matter effects**: **0.7-1.4σ** in 6 years.
- Can be combined with **reactor NMO analysis**.

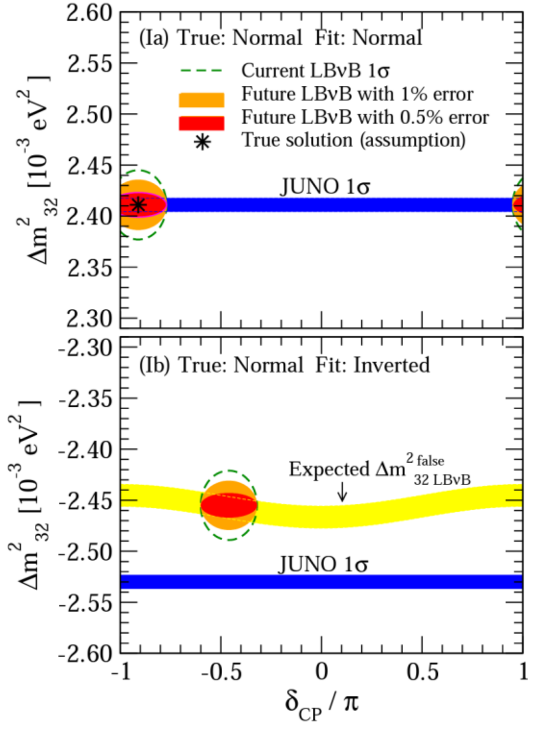


JUNO + LBL combination

- Better rejection of the wrong hypothesis via combination: [arXiv:2008.11280](https://arxiv.org/abs/2008.11280)

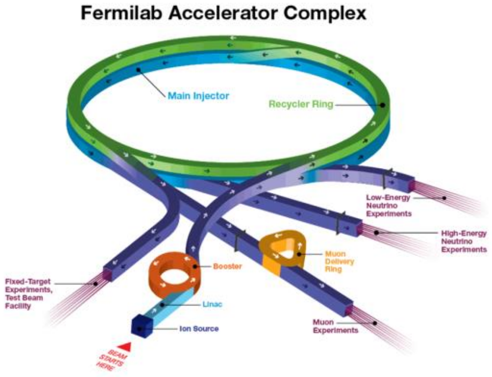


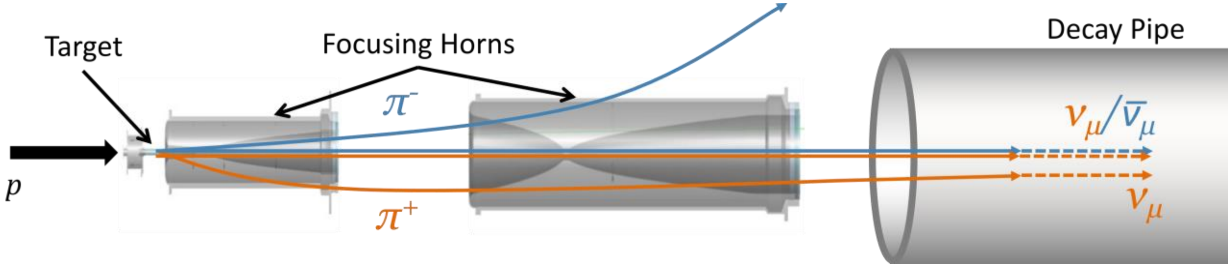




How are neutrinos produced?

- **Protons** are **accelerated** and smashed into a **target**. **Focusing magnets** allow us to select the charge of the short-lived daughter particles which produce mostly **neutrinos** or **antineutrinos** as they **decay**.

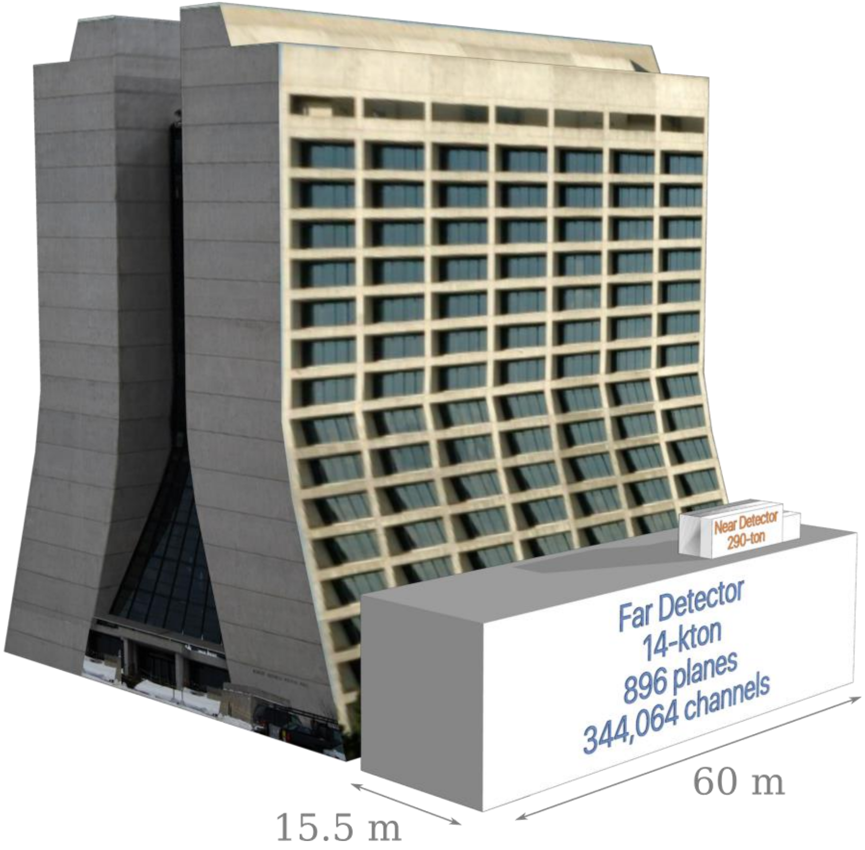





MW-capable target


MW-capable horn

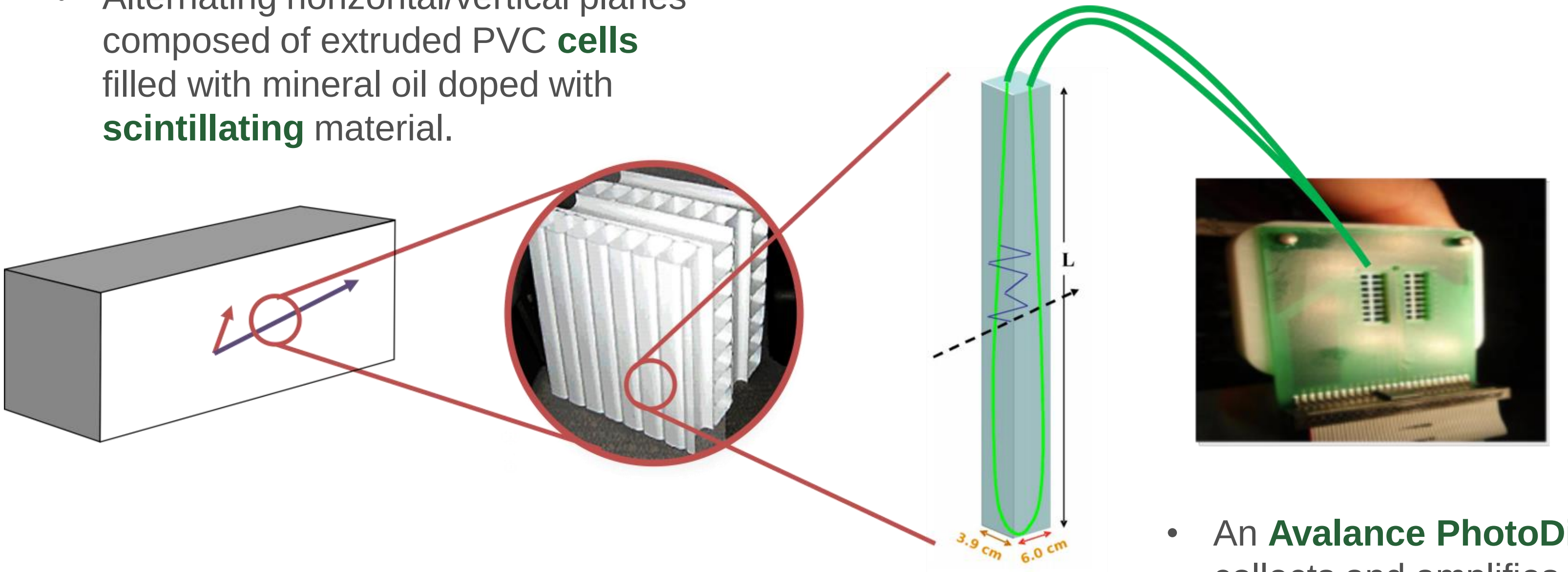
How are neutrinos detected?



- The NOvA **Near Detector** and **Far Detector** are both **segmented liquid scintillator** detectors providing **3D tracking** and **calorimetry**.
- **Near Detector**:
  - 290 tons.
  - 350 ft underground at Fermilab.
- **Far Detector**:
  - 14 ktons.
  - 810km away on the surface in Minnesota.

How are neutrinos detected?

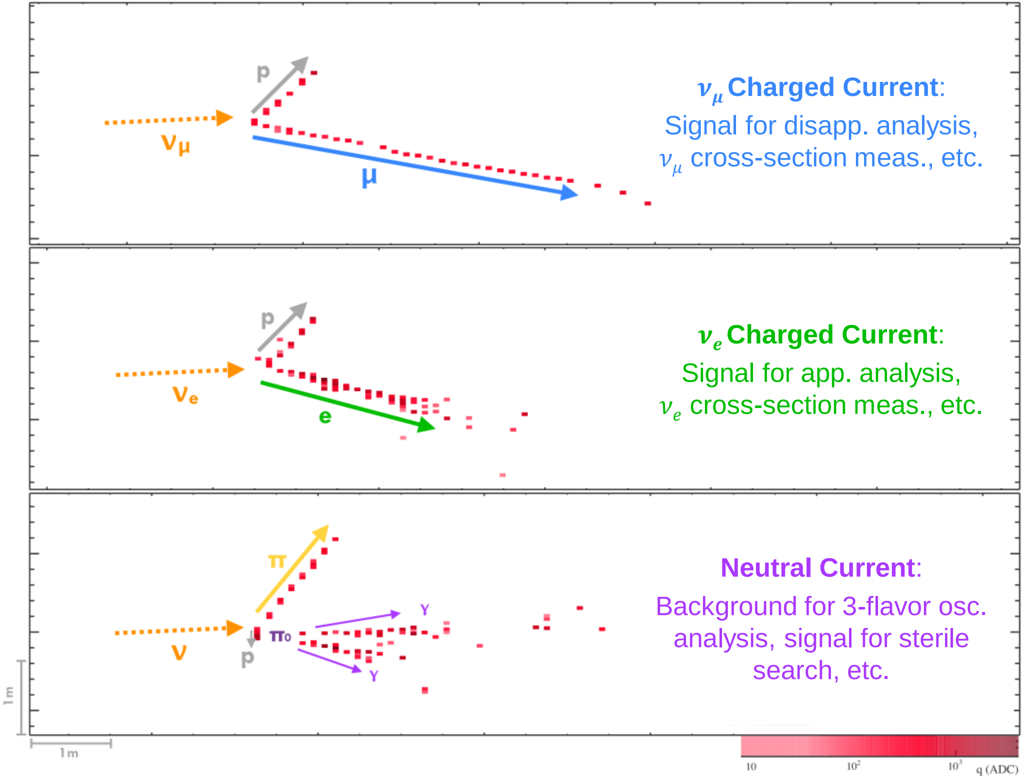
- Alternating horizontal/vertical planes composed of extruded PVC **cells** filled with mineral oil doped with **scintillating** material.



- **Charged particles** ionize the medium and produce **scintillation light**. The light is picked up by **wavelength shifting fibers**.
- An **Avalance PhotoDiode** collects and amplifies the **light signal**.

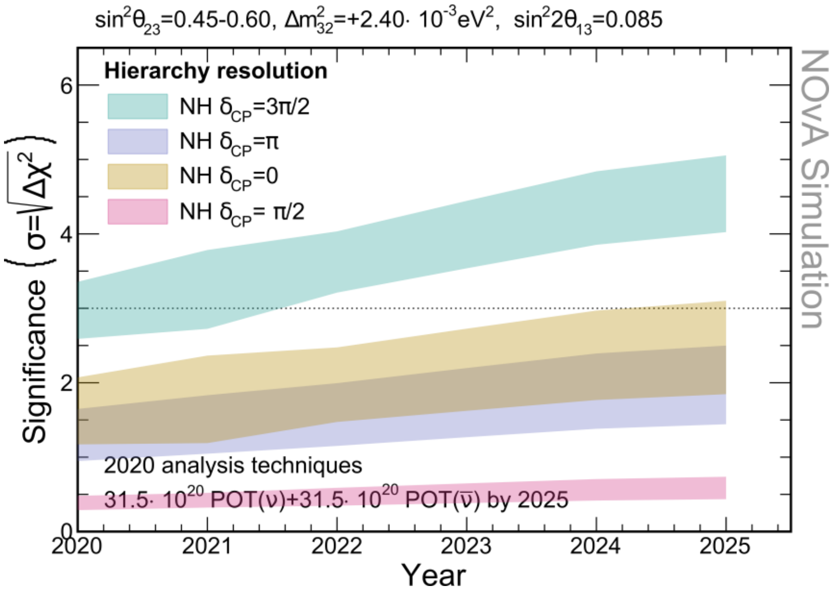
What do neutrino events look like in NOvA?

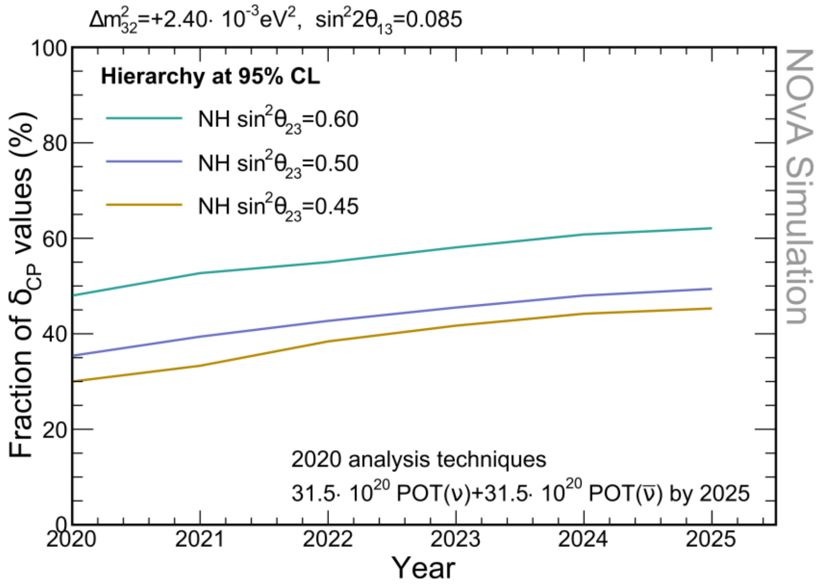
- Use **Machine Learning** techniques to **select** and **identify** neutrino interactions.



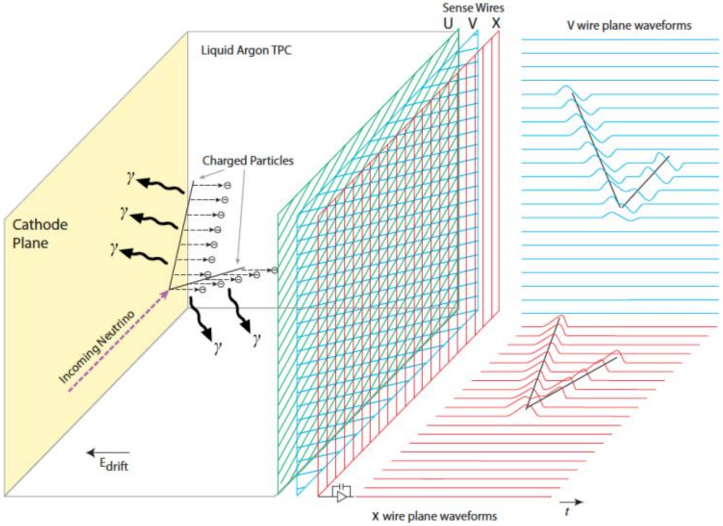
What is NOvA's future sensitivity?

- Run until **2026**, accumulating more than **3×10^{21} POT** in both $\boldsymbol{\nu}$ and $\boldsymbol{\bar{\nu}}$ modes.
- Could reach **5σ sensitivity** to **Mass Hierarchy** for most favorable parameters.
- Probe the majority of $\boldsymbol{\delta_{CP}}$ **values** at **2σ-level**.

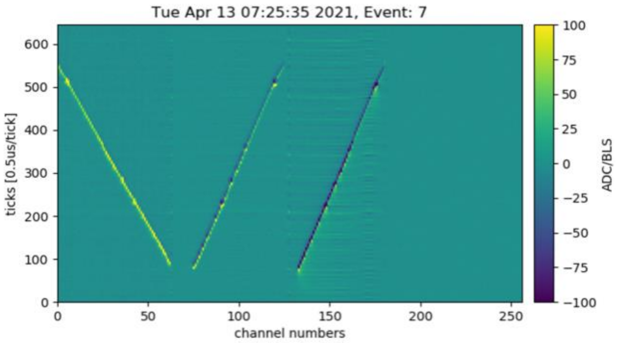




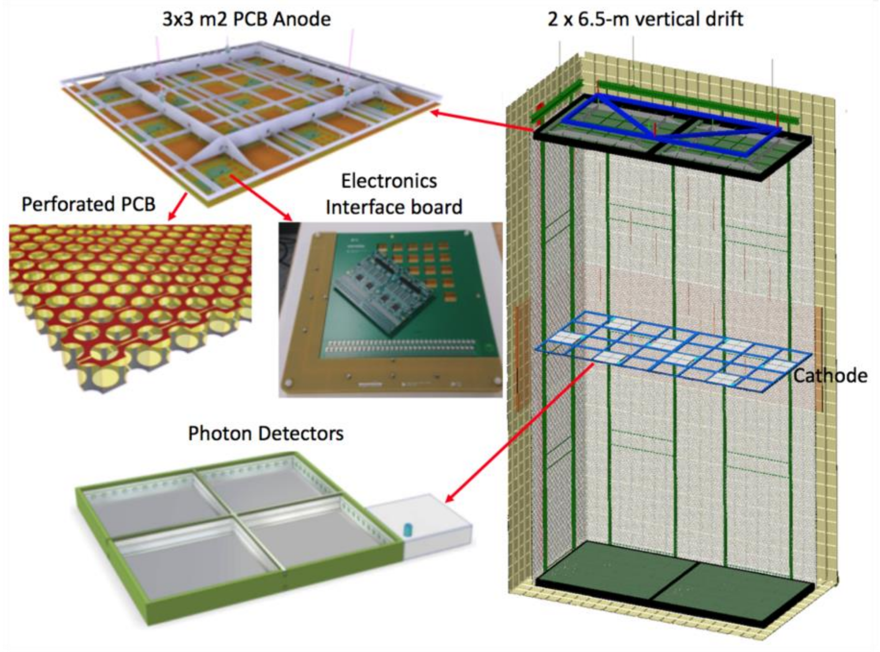
DUNE LArTPC



Sense Wires
U V X
V wire plane waveforms
Liquid Argon TPC
Charged Particles
Cathode Plane
Incoming Neutrino
E_{drift}
X wire plane waveforms
t



Tue Apr 13 07:25:35 2021, Event: 7
ticks [0.5us/tick]
channel numbers
ADC/BLS



3x3 m2 PCB Anode
2 x 6.5-m vertical drift
Perforated PCB
Electronics Interface board
Cathode
Photon Detectors

Asymétrie matière-antimatière

- Explication par baryogénèse sous Conditions de Sakharov :
  1) Violation du nombre baryonique.
  2) Violation de Charge et de Charge-Parité.
  3) Interactions hors-équilibre.

- Neutrino de Majorana (L-violation) et sphalérons (B+L-violation) satisfont 1).

- Observation de violation de CP satisferait 2).

- Désintégration de neutrino lourds satisfait 3).