FUTURE NEUTRINO EXPERIMENTS

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FUTURE NEUTRINO EXPERIMENTS

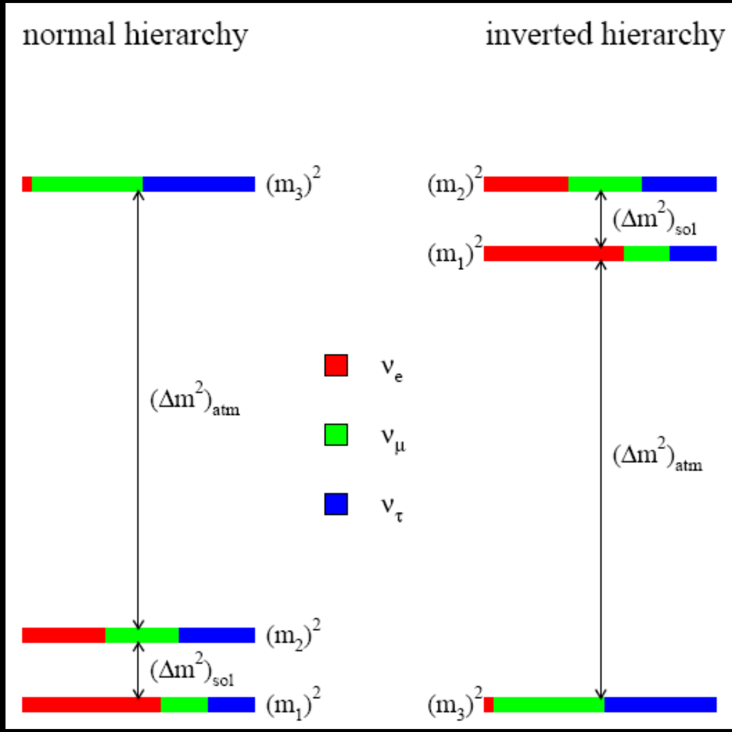
- Neutrino physics has a number of unanswered questions.
  - Oscillation Physics
  - Mass
  - Dirac / Majorana
  - Astophysics

- I will focus on the future experiments for neutrino oscillations in this presentation
  - Three very large experiments are under construction and are due to start taking data “soon”
  - The age of precision neutrino measurements is about to commence

OPEN QUESTIONS IN NEUTRINO OSCILLATION PHYSICS

Neutrino mixing is characterised by the PMNS matrix.

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



Open questions

- Mass Ordering
- CP Violating Phase δ
- Octant of θ_{23}, is it maximal?
- Is U_{PMNS} unitary

HOW CAN WE ADDRESS THESE QUESTIONS?

- Three general methods are available

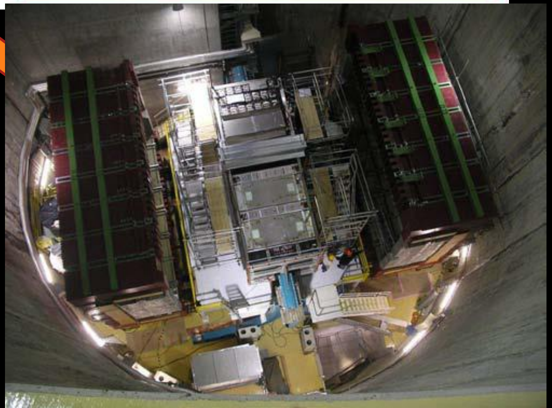
- Long baseline neutrino beams
- Atmospheric neutrinos
- Reactor neutrinos

WHERE ARE WE NOW?

- Long baseline experiments T2K & Noνa
  - Hints of CP violation and mass ordering
- Atmospheric neutrinos SK & Icecube
  - Contribute to mass ordering constraint
- Reactor neutrinos Daya Bay & Kamland (+ solar)
  - Pure θ_{13} measurement and $\Delta m^2_{12}, \theta_{12}$

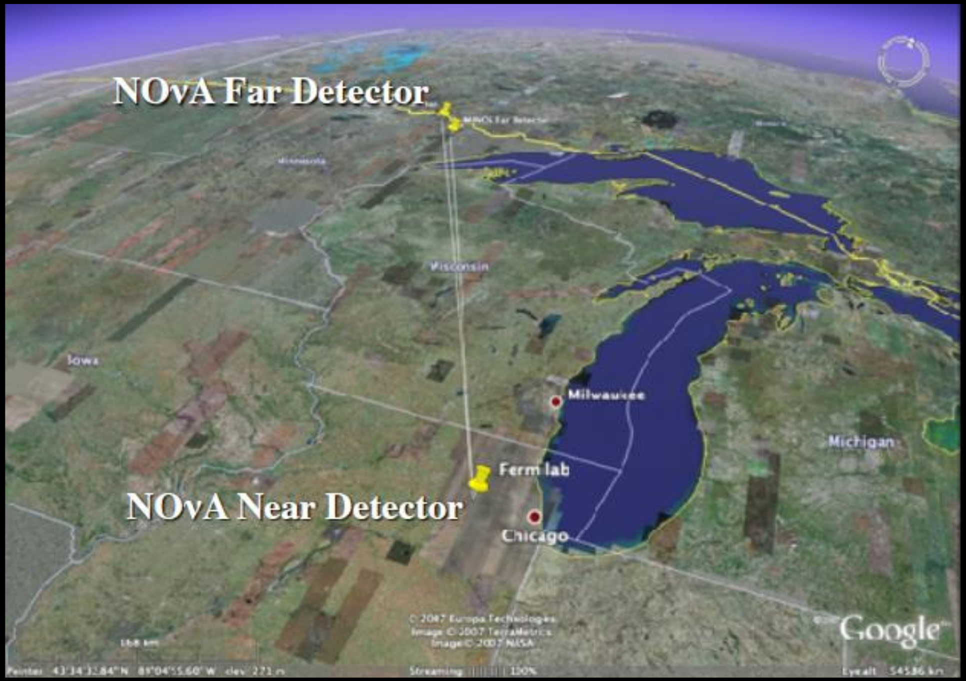
T2K EXPERIMENT

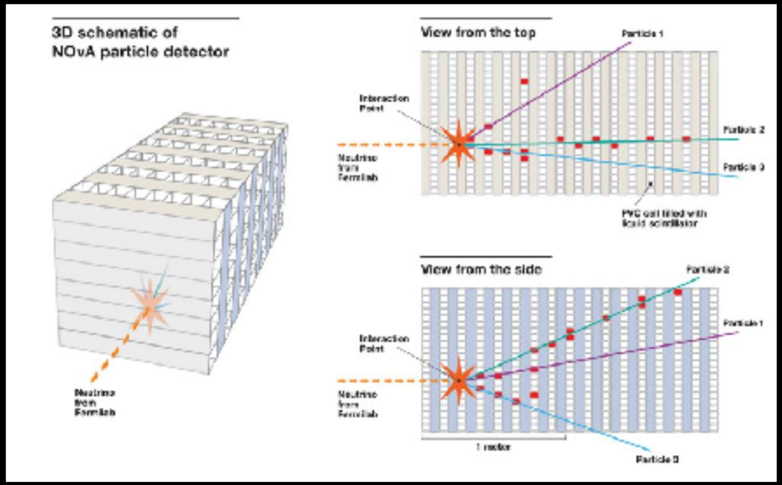
- 295km baseline – matter effect small
- Narrow band neutrino beam Epeak ~600 MeV
- First measurements using off-axis beam technique



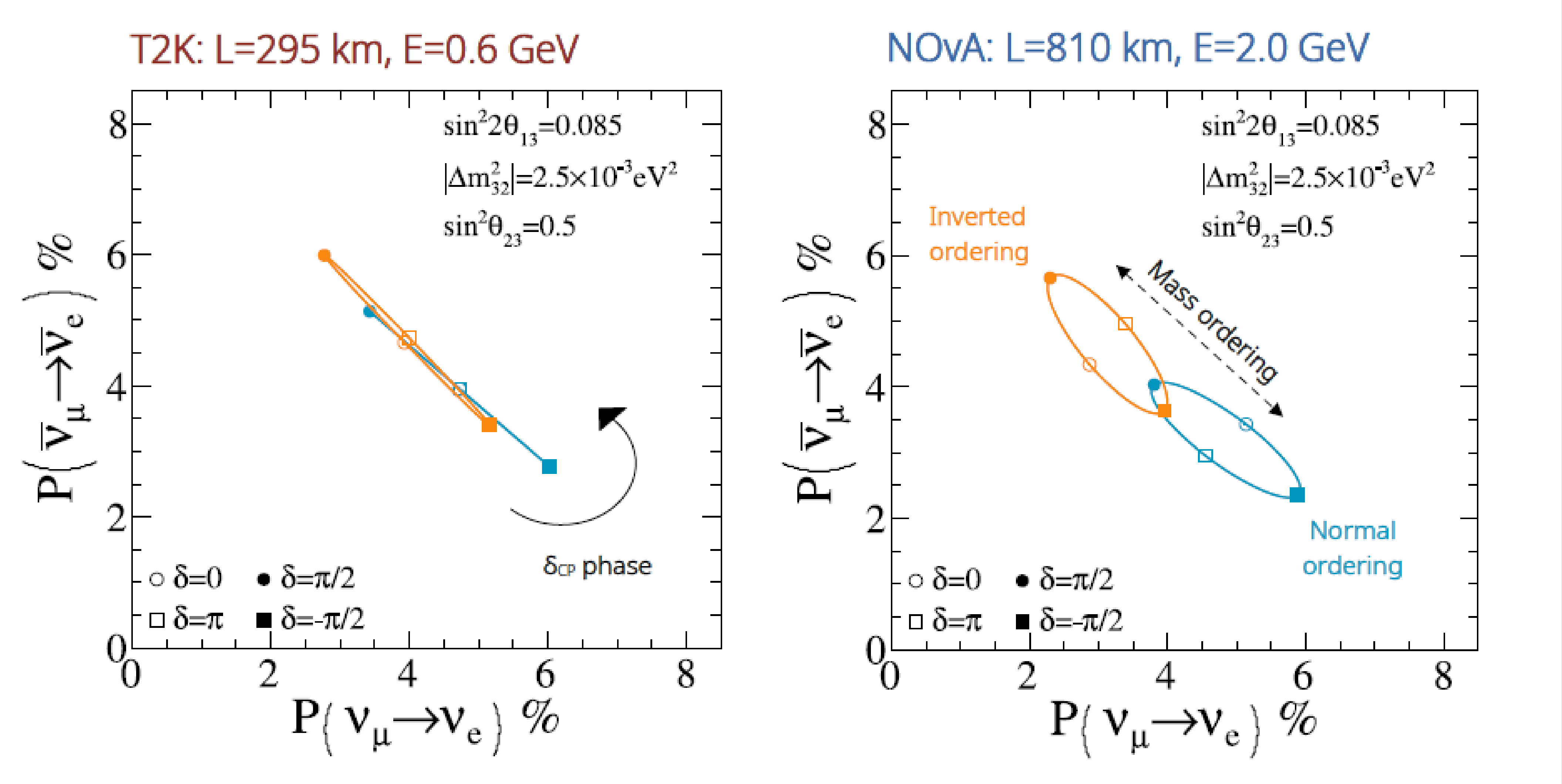
NOνA

- 810 km baseline
- E_{peak} ~ 2 GeV
- 14 kton high granularity liquid scintillator detector
  - Near detector is the same technology

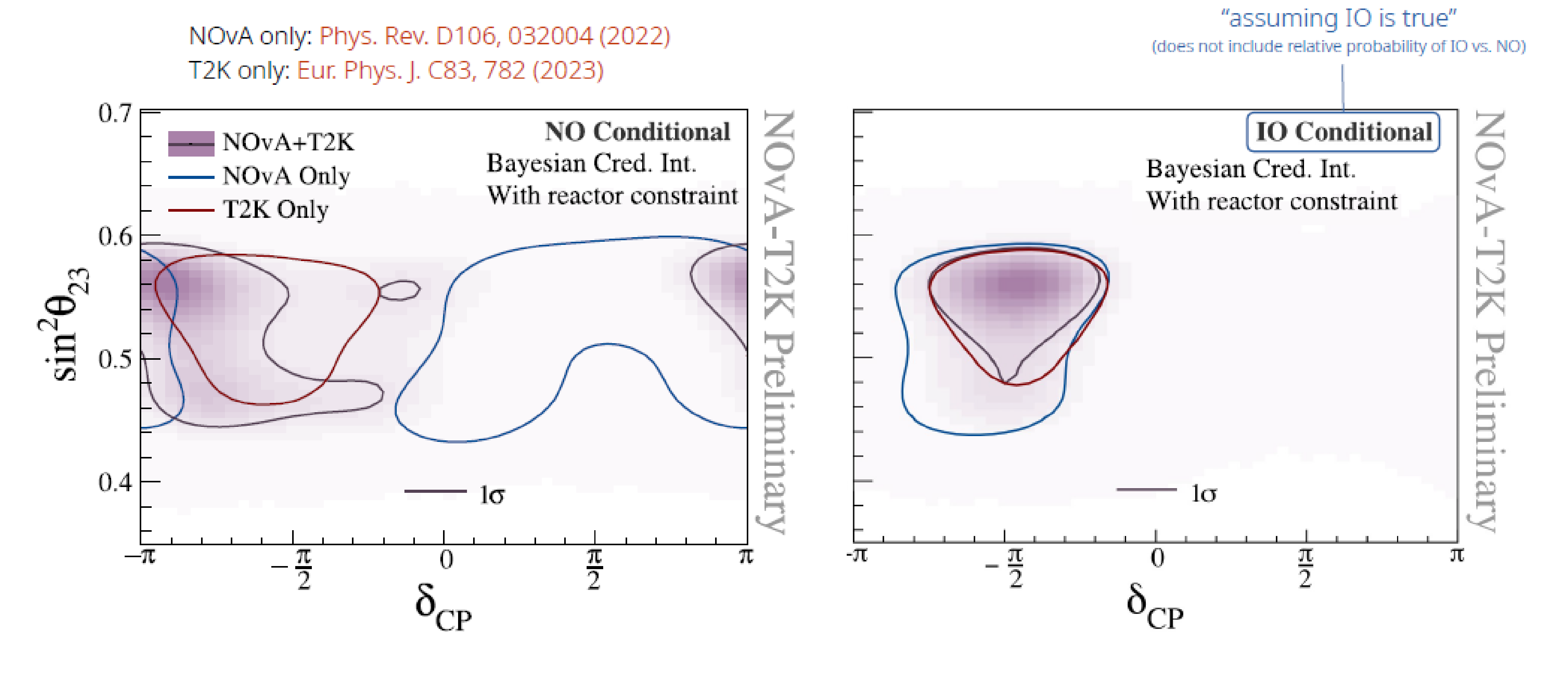




T2K & NOνA


T2K: L=295 km, E=0.6 GeV
NOvA: L=810 km, E=2.0 GeV
sin²2θ13=0.085
|Δm²32|=2.5×10⁻³eV²
sin²θ23=0.5
Inverted ordering
Mass ordering
Normal ordering
δCP phase
δ=0
δ=π/2
δ=π
δ=-π/2
P(ν̄μ→ν̄e) %
P(νμ→νe) %

JOINT FIT

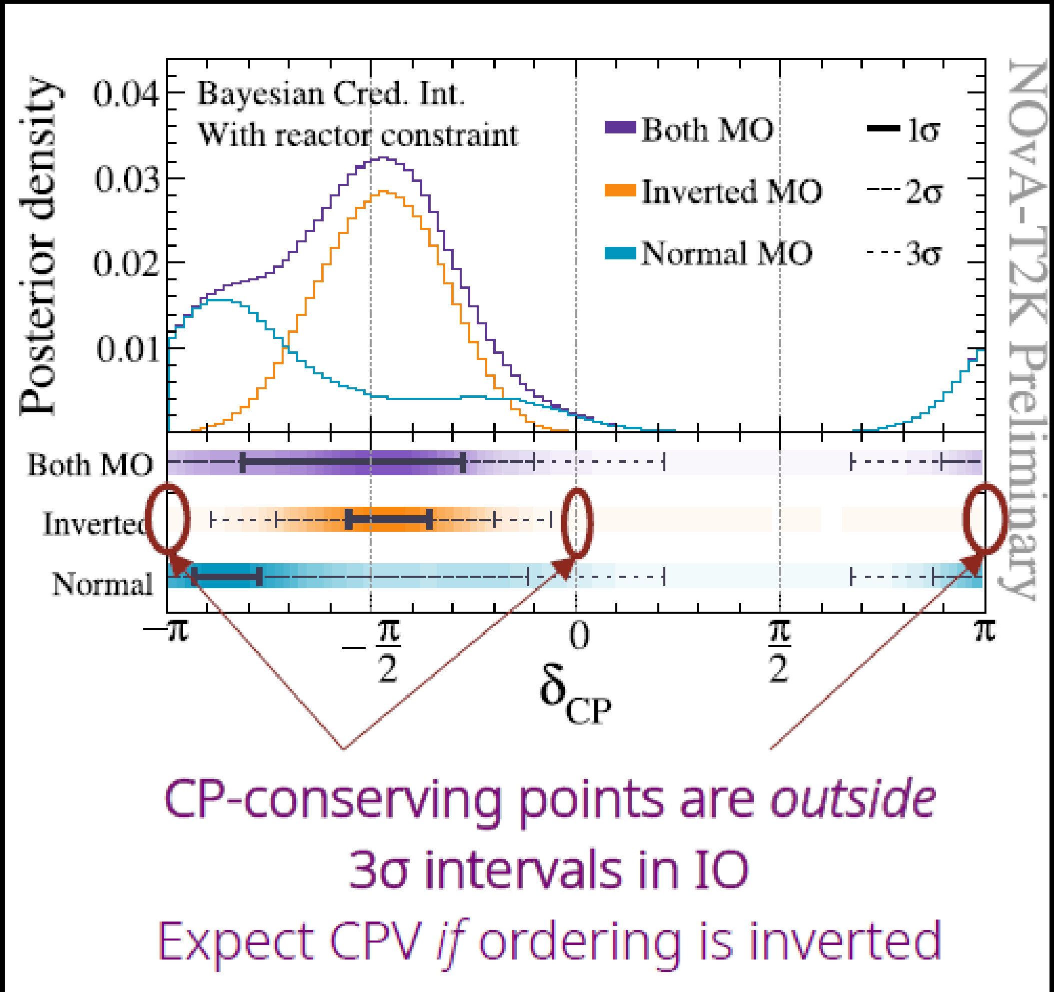


Splits the difference in NO

Improves the constrain in IO

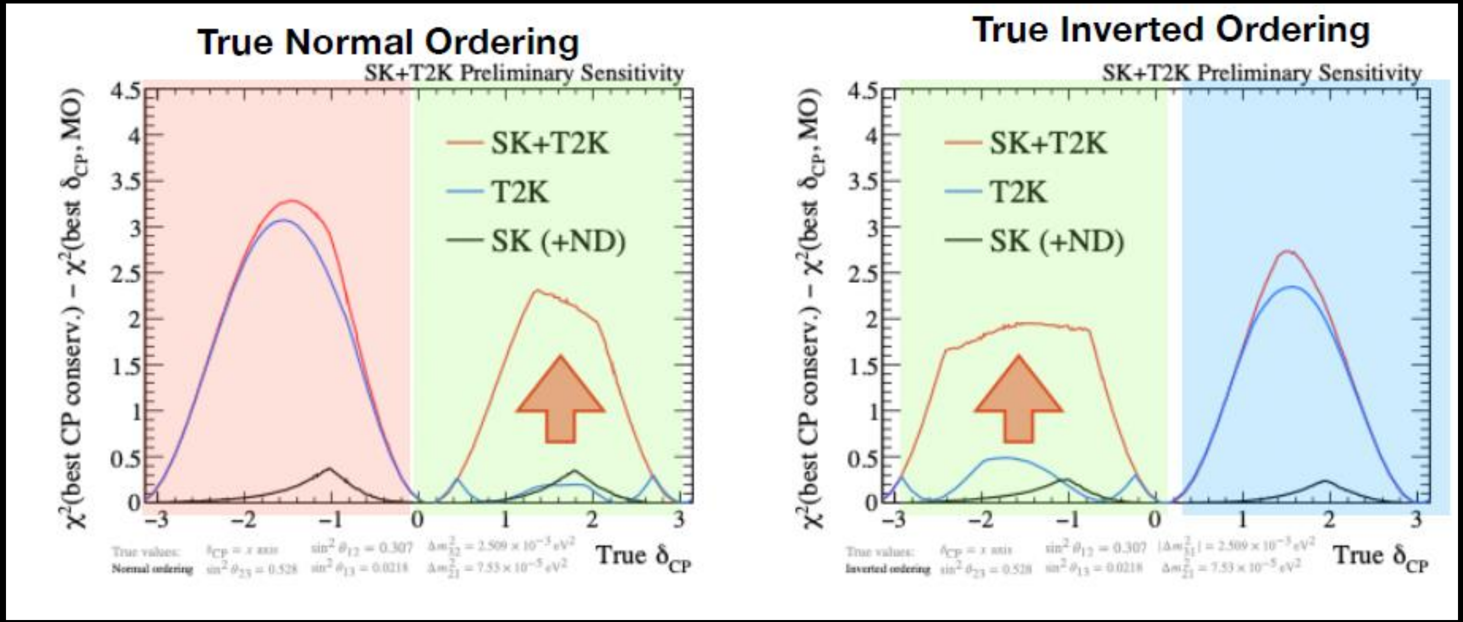
JOINT FIT

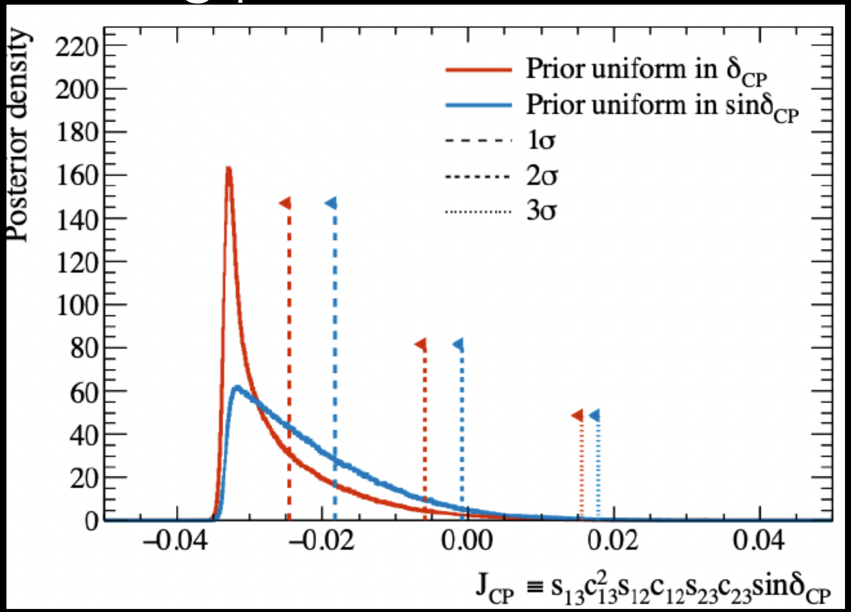
- Precision measurement of Δm^2_{23}
  - $(2.477 \pm 0.035) \times 10^{-3} eV^2$
- Mild preference for IO but it depends on how the θ_{13} constraint is implemented.
- In IO CP conservation is excluded at 3σ



T2K SK JOINT FIT

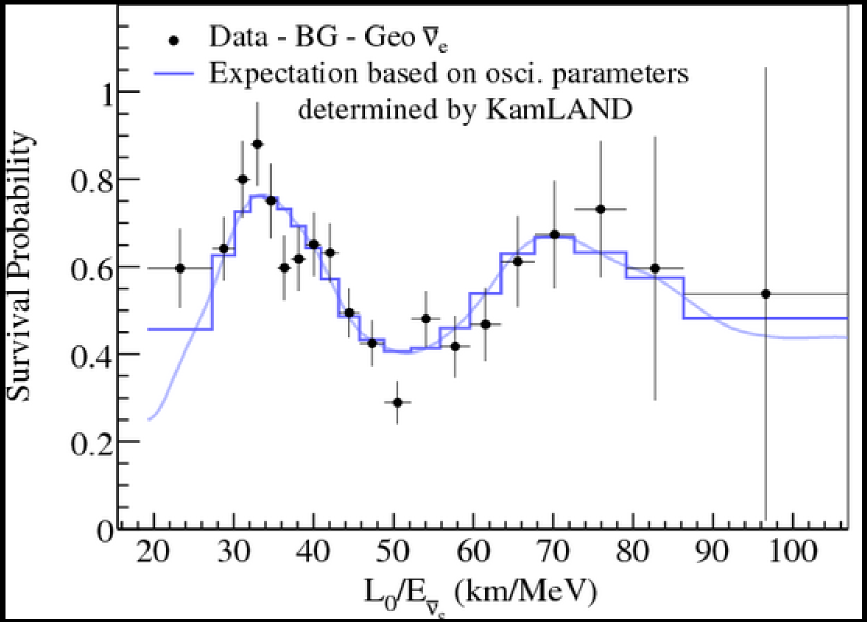
- We can also do joint fits between beam and atmospheric data
  - Beam – strong CP sensitivity
  - Atmospheric – strong mass ordering sensitivity
- Unify models
  - Neutrino interactions
  - Detector Systematics
- CP conserving value of Jarlskog invariant excluded at 1.9-2σ
- Normal ordering preferred



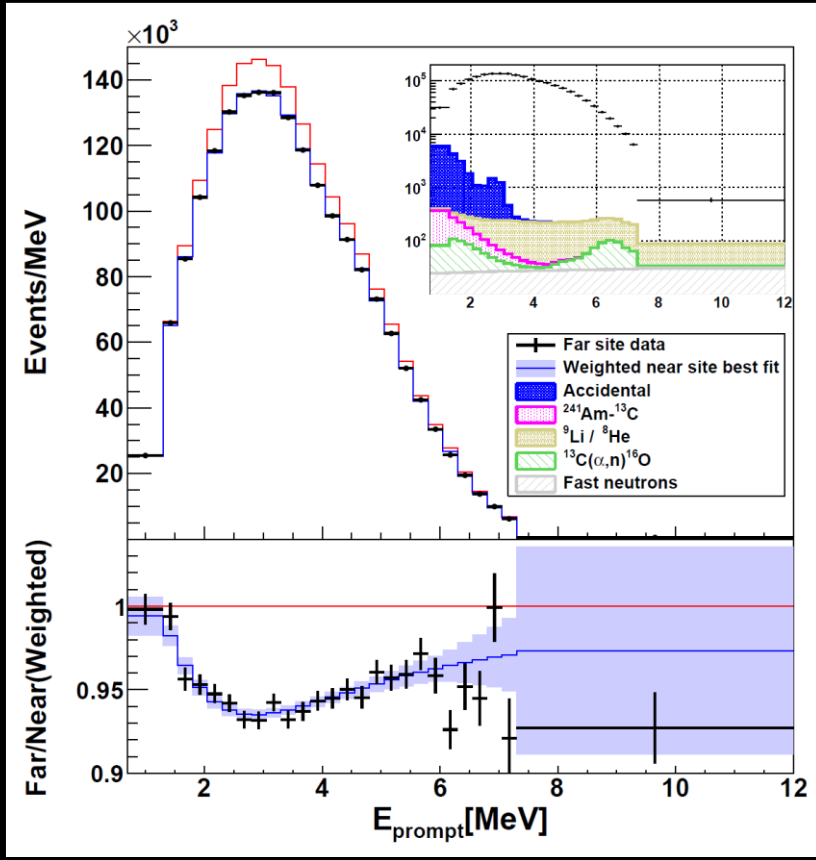


REACTOR NEUTRINOS

- Different effects at different baselines
- Short baseline – θ_{13}, Δm^2_{31}
- Longer baseline θ_{12}, Δm^2_{12}



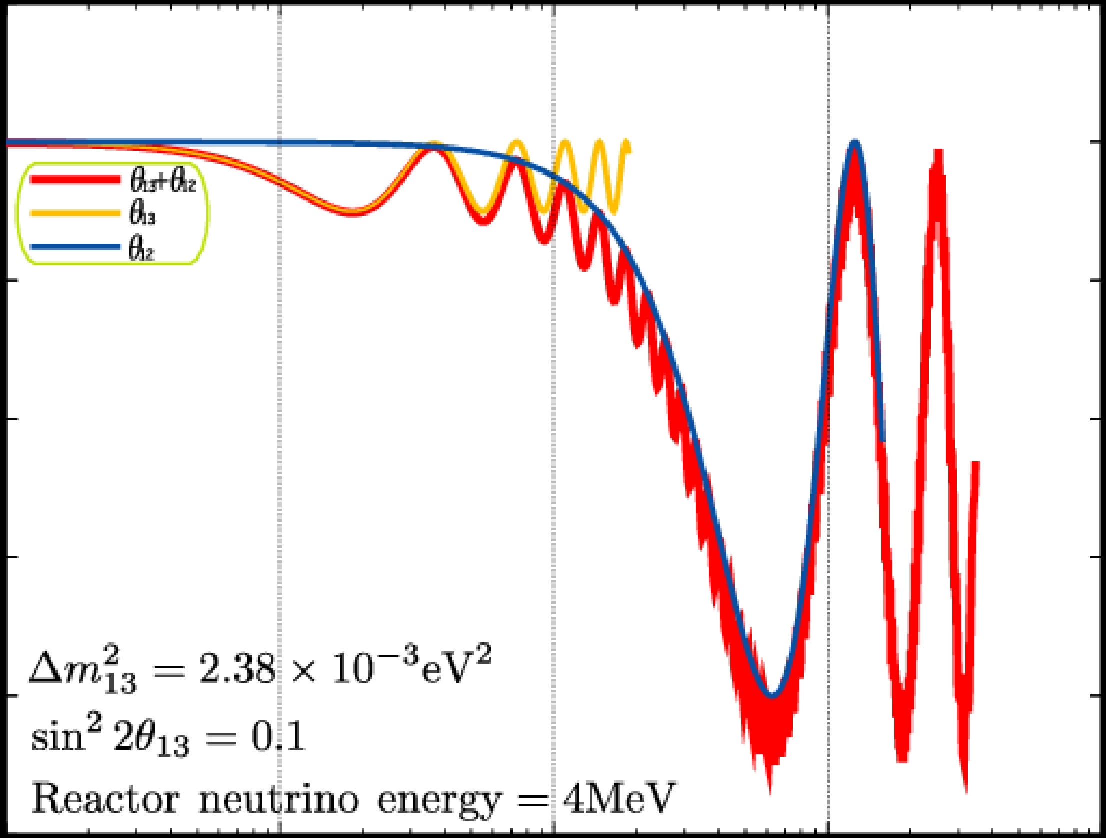
KamLAND effective L/E



Daya Bay θ_{13}

DIFFERENT BASELINES

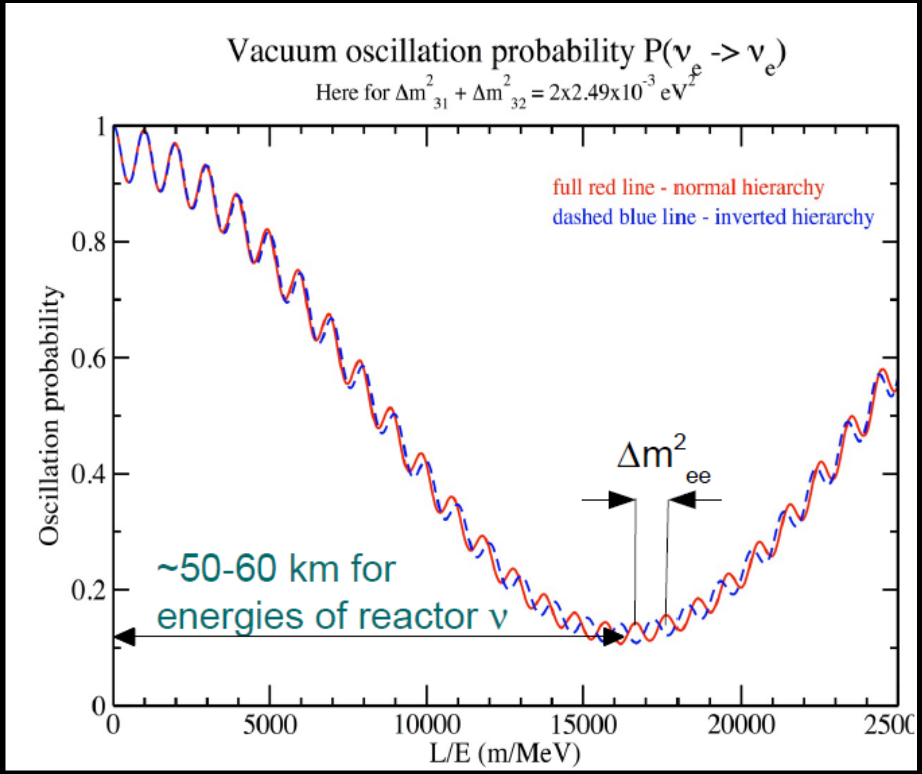
- For reactor neutrinos the two Δm^2 values interfere in the survival probability
- We can tune our baseline to select the oscillations we want to measure
- Note the extra wiggle on top of the oscillation at longer baseline



THE WIGGLE

$$p(\bar{\nu_e} \to \bar{\nu_e}) \approx 1 - cos^4\theta_{13} sin^2 2\theta_{12} sin^2\left(\Delta m^2_{21}\, {L}/{4E}\right) - sin^2 2\theta_{13}\, sin^2(\Delta m^2_{ee}\, {L}/{4E})$$

- For the full oscillation calculation Δm^2_{31} and Δm^2_{32}terms beat against each other.
- Different results for each mass ordering
- Can be measured at the right baseline with enough statistics and energy resolution



DETECTING REACTOR NEUTRINOS

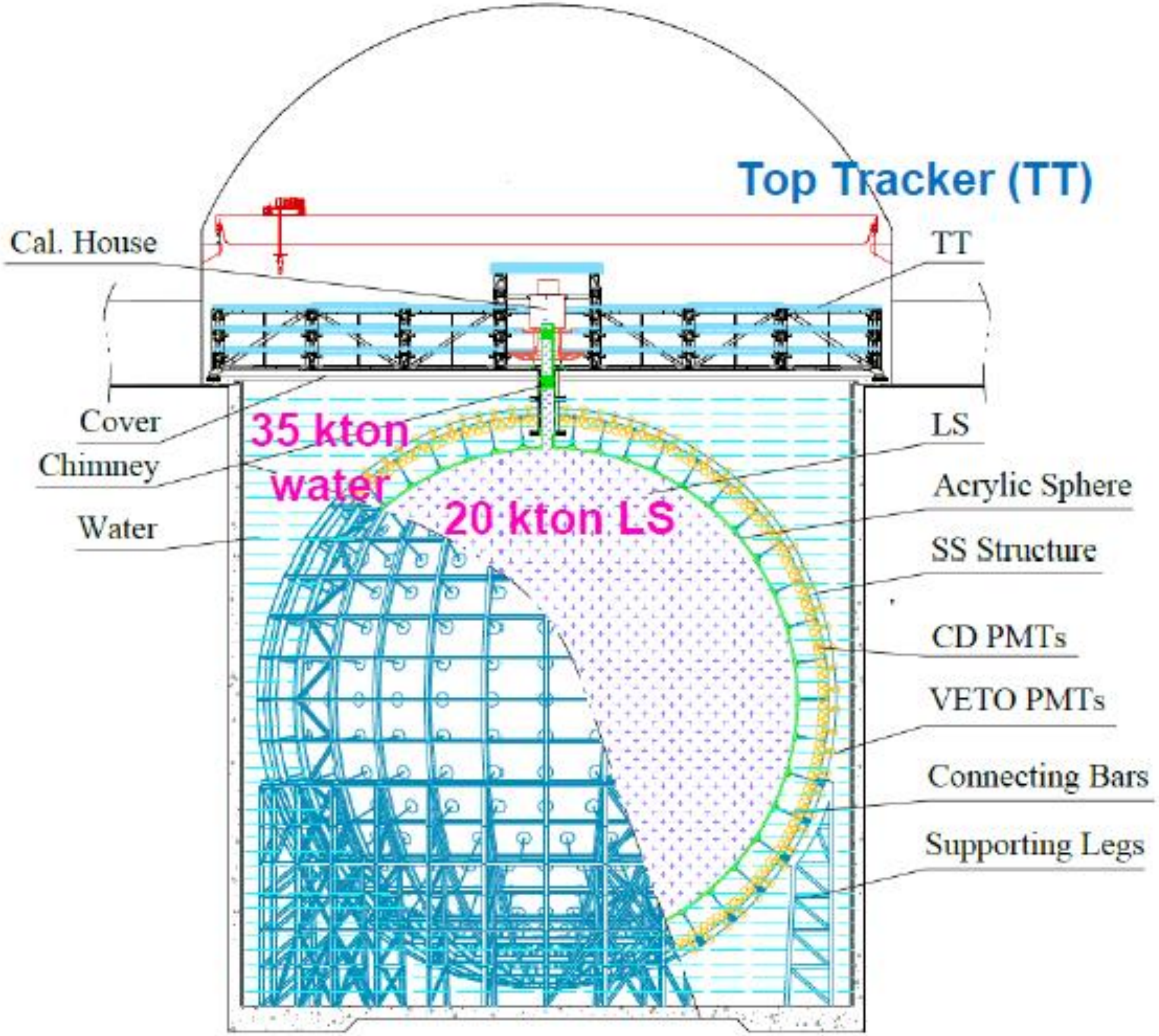
- Classical reaction: inverse proton decay
  - $\bar{\nu_e} + p \rightarrow e^+ + n$
- Double signal : positron and delayed 2.2 MeV gamma from neutron capture
  - Strongly suppress backgrounds
- Determine neutrino energy from positron energy
- Everything we need for this measurement. Large liquid scintillator detector will work.

JUNO

JUNO

- JUNO is a 20 kton liquid scintillator detector located 53 km from two nuclear power plants
- Its located 700 m underground and aims for a 3% energy resolution
- JUNO-TAO is a near detector to provide precision measurement of the reactor flux

JUNO Detector



Acrylic Sphere:

Inner Diameter (ID): 35.4 m

Thickness:12 cm

Stainless Steel (SS) Structure:

ID: 40.1 m, Outer Diameter (OD): 41.1 m

17612 20-inch PMTs, 25600 3-inch PMTs

Water pool:

ID: 43.5 m, Height: 44 m, Depth: 43.5 m

2400 20-inch PMTs

PMT SYSTEMS

- Dual calorimetry system
- 20012 20 inch PMTs
- 25600 3.1 inch PMTs
- Maximise photocoverage
  - Essential to achieve energy resolution
- Cross calibrate each system
  - Reduce detector systematics

JUNO Site

Surface buildings / campus

- **Office / Dorm**
- Surface Assembly Building
- LAB storage (5 kton)
- Water purification / Nitrogen
- Computing
- Power station
- Cable train

~200 people working onsite now

Inside the detector

Liquid Scintillator

ID#235, LS Purification | ID# 238, Optical charactr
ID#472, OSIRIS | ID#618, OSIRIS hardware

- **LAB + 2.5 g/L PPO + 3 mg/L bis-MSB**
  - ⇨ Attenuation length: LAB > 24m, LS > 20 m
  - ⇨ Minimum U/Th requirement (for NMO) < 1e-15 g/g, aiming at 1e-17 g/g for solar and future 0νββ

- **All 60 ton PPO delivered, U/Th < 0.1 ppt**
- **Bis-MSB complete production soon (< 5 ppt)**
- **Plants commissioned individually and jointly**
- **20 kton LAB to be delivered, U/Th ~ 1 ppq**

5000 m³ LAB storage tank

1) Al_2O_3 for optical transparency

2) Distillation for radiopurity

2.4%

Mixing LAB with PPO and bis-MSB

97.6%

Mixing

1800 m SS pipes to underground

3) Water extraction to remove radioactive impurities

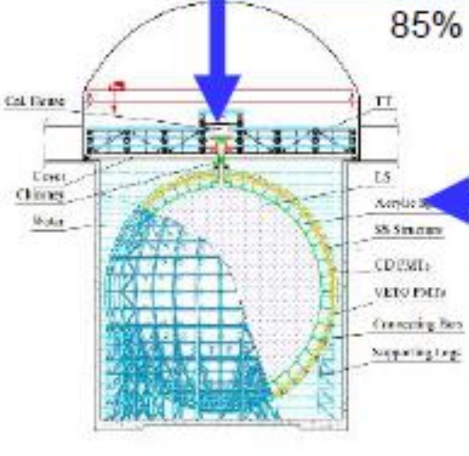
4) Gas stripping to remove Rn and O_2

15%

Commissioning

Monitoring pre-detector (OSIRIS)

85%



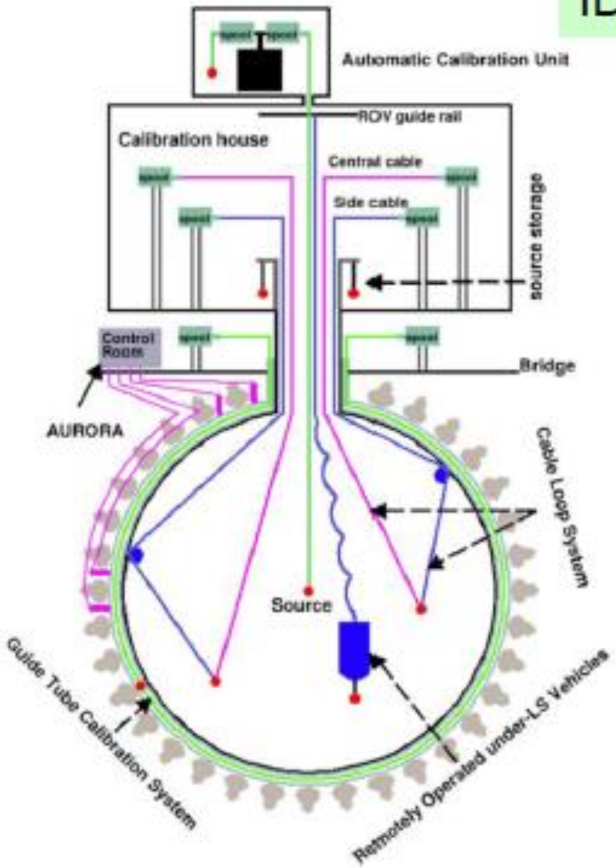
Calibration and Expected Energy Resolution

- **Four systems** for 1D, 2D, 3D scan with multiple sources
- **Energy scale** and **non-linearity** will be calibrated to **<1%** using γ peaks and cosmogenic ^{12}B beta spectrum

JHEP 03 (2021) 004

ID#320, Calibration strategy

ID#283, Natural radioactivity



Calibration house

All systems ready for installation

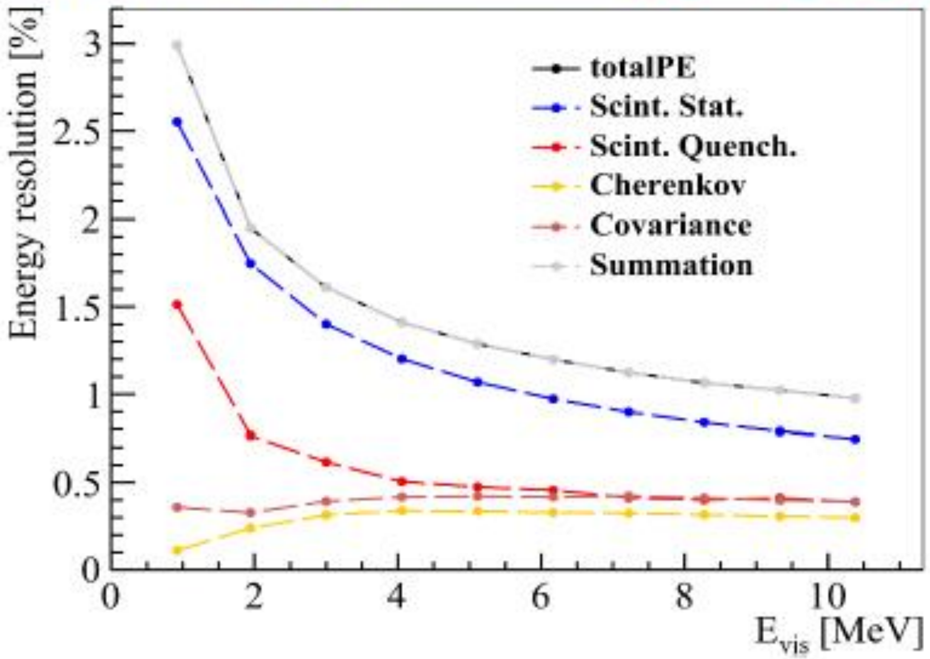
arXiv:2405.17860 (2024)

For positron

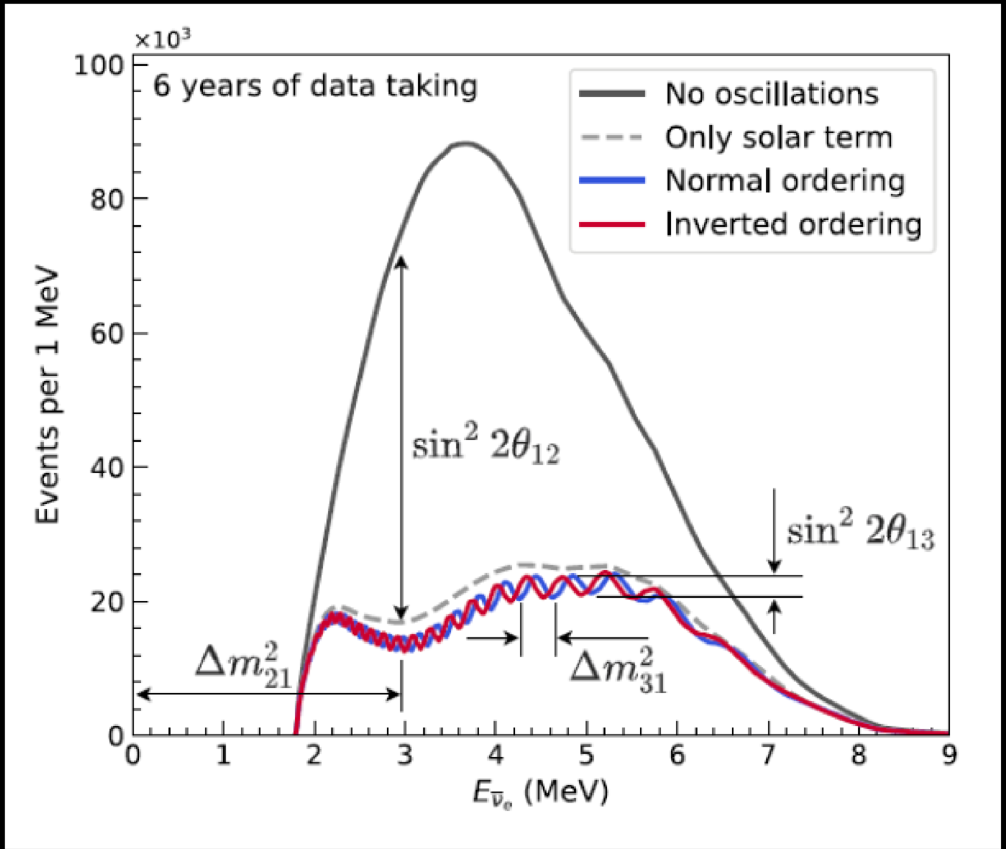
$$\frac{\sigma}{E_{vis}} = \sqrt{\left(\frac{2.61\%}{\sqrt{E_{vis}}}\right)^2 + (0.64\%)^2 + \left(\frac{1.20\%}{E_{vis}}\right)^2}$$

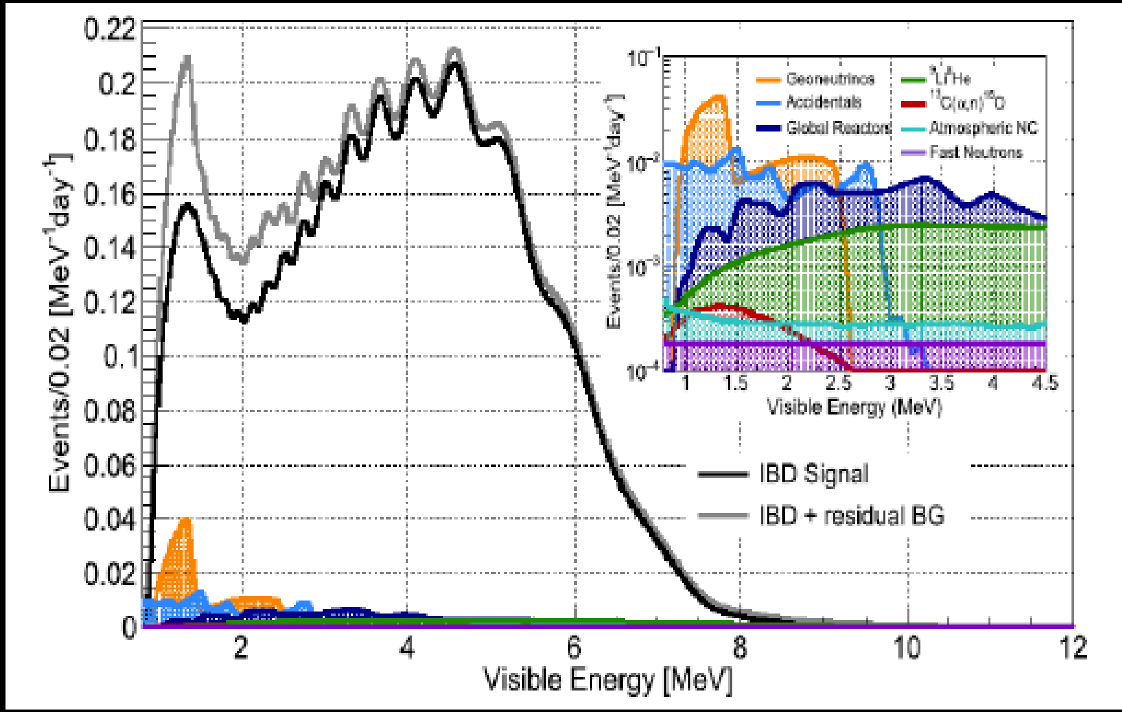
Photon statistics | Constant term | Dark noise, Annihilation -induced γs

Expected energy resolution: **2.95% @1MeV**



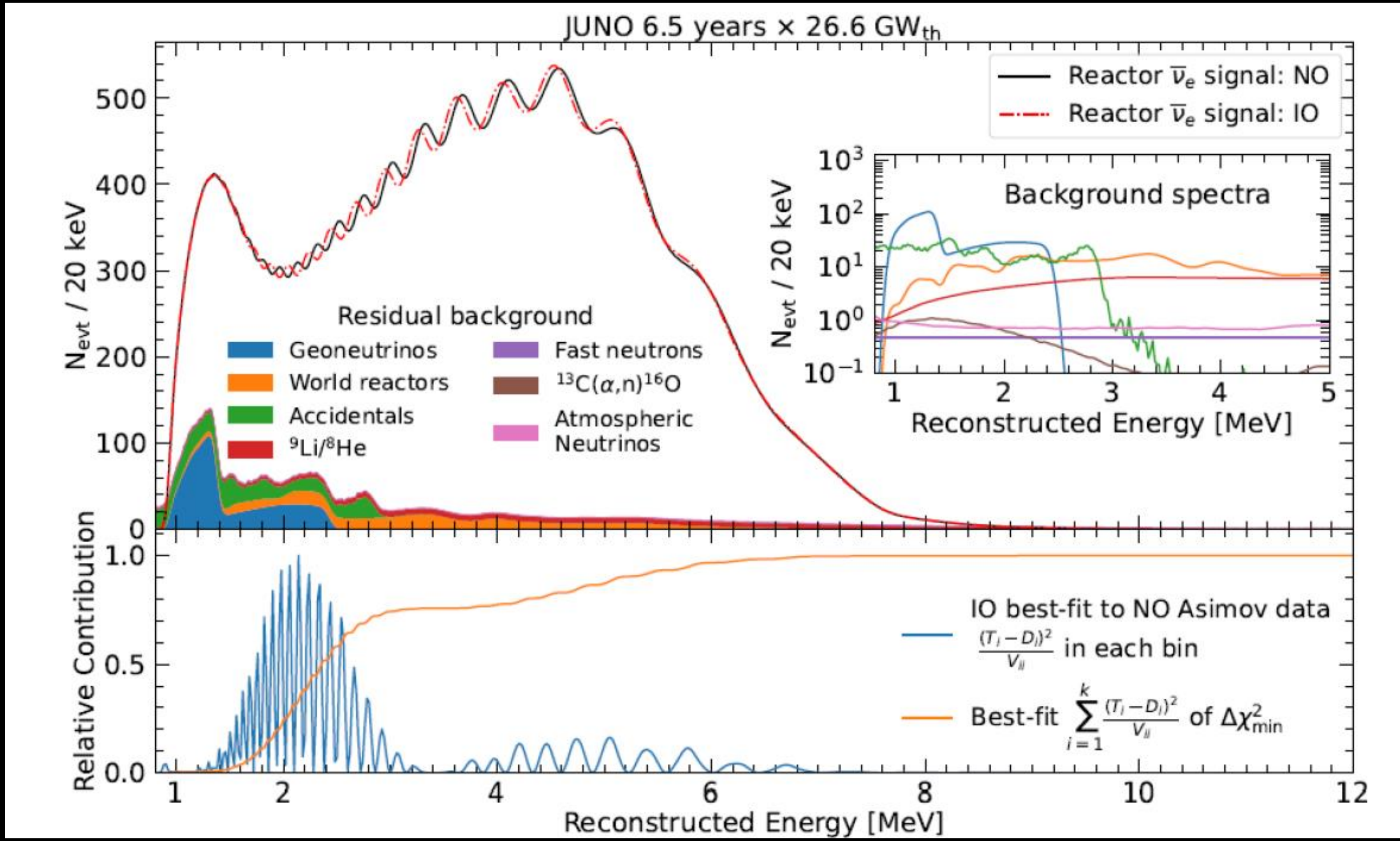
OSCILLATION PARAMETERS

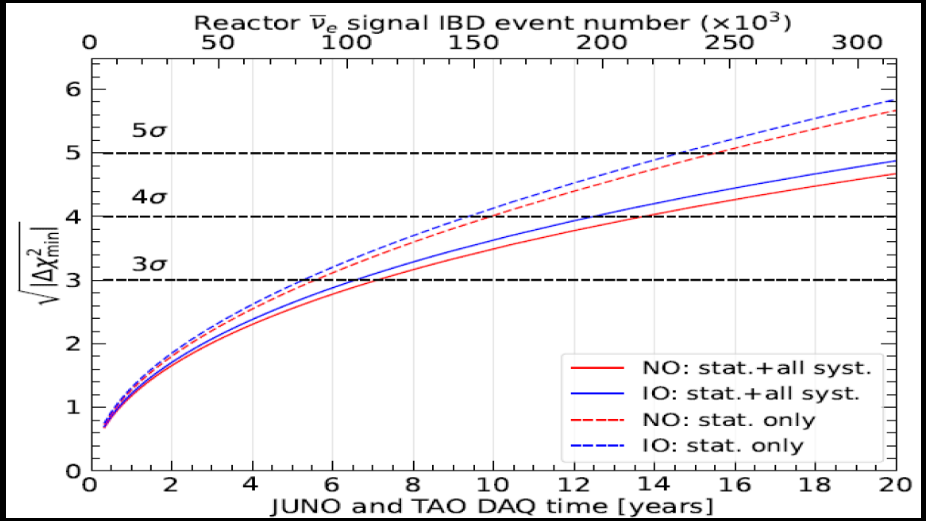




World leading measurement in 100 days
$(\theta_{12}, \Delta m^2_{21}, |\Delta m^2_{32}|)$
<0.5% precision in 6 years

MASS ORDERING



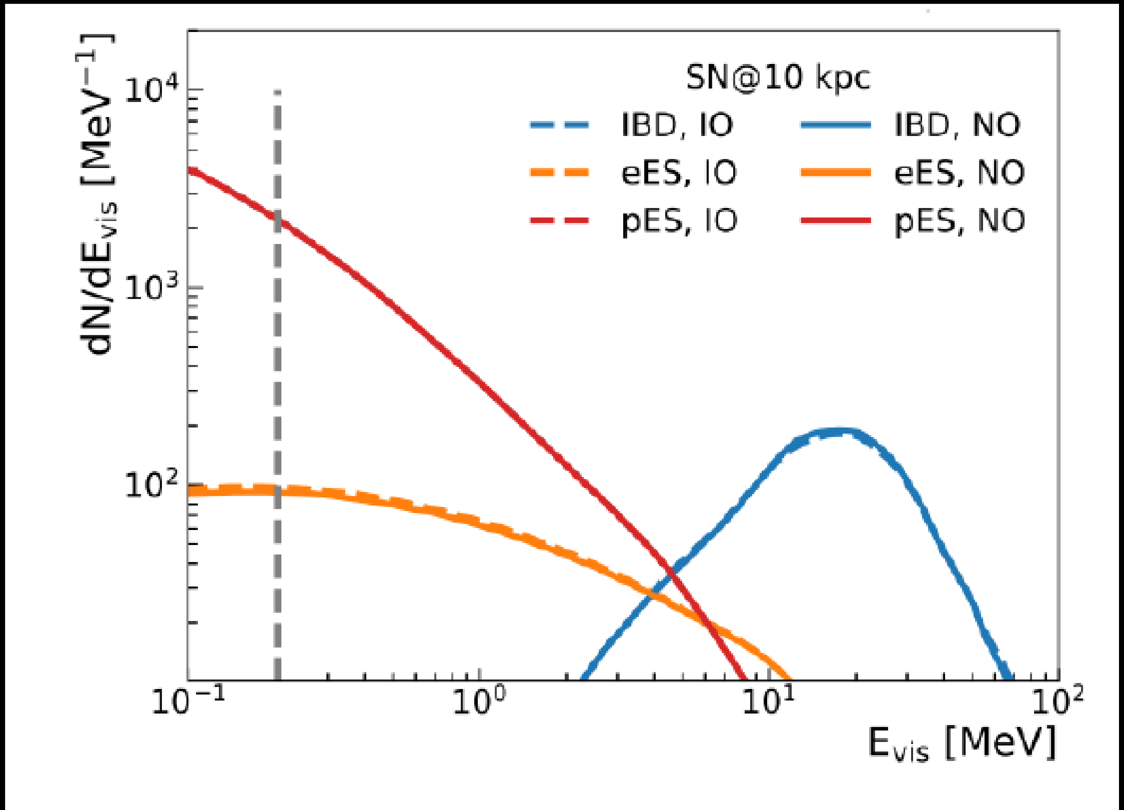


Obtain 3σ sensitivity in 6-8 years

Expect further improvements in sensitivity with joint analysis with JUNO and global atmospheric neutrinos

OTHER PHYSICS AT JUNO

- Supernova Neutrinos
  - Burst
    - Three detection channels
    - Multiflavour sensitivity
  - Diffuse SN neutrino background
    - 5σ in 10 years
- Solar neutrinos
  - Improve Borexino for ^{7}Be, pep, CNO
- Atmospheric neutrinos
- Nucleon Decay



SN Signal at JUNO

JUNO STATUS

- JUNO construction is nearing completion
  - Aim to finish construction this year
  - Finish filling in 2025
- JUNO-TAO will be installed at the Taishan plant in 2024
- Expect data taking from the end of next year and first results in 2026 & 27

LONG BASELINE EXPERIMENTS

- While JUNO uses reactor neutrinos, we also create neutrino beams directly
- We can exploit the rich physics of $\nu_\mu \rightarrow \nu_e$
- We already discussed the latest from T2K and Noνa doing this

LONG BASELINE EXPERIMENTS

$$p(\nu_\mu \to \nu_e) = sin^2 2\theta_{13} sin^2\theta_{23} sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

$$+\,8c^2_{13}s_{12}s_{13}s_{23}(c_{12}c_{13}cos\delta - s_{12}s_{23}s_{13})cos\Phi_{32}sin\Phi_{31}sin\Phi_{12}$$

$$-8c^2_{13}c_{12}c_{23}s_{12}s_{13}s_{23}sin\delta\ sin\Phi_{32}sin\Phi_{31}sin\Phi_{12}$$

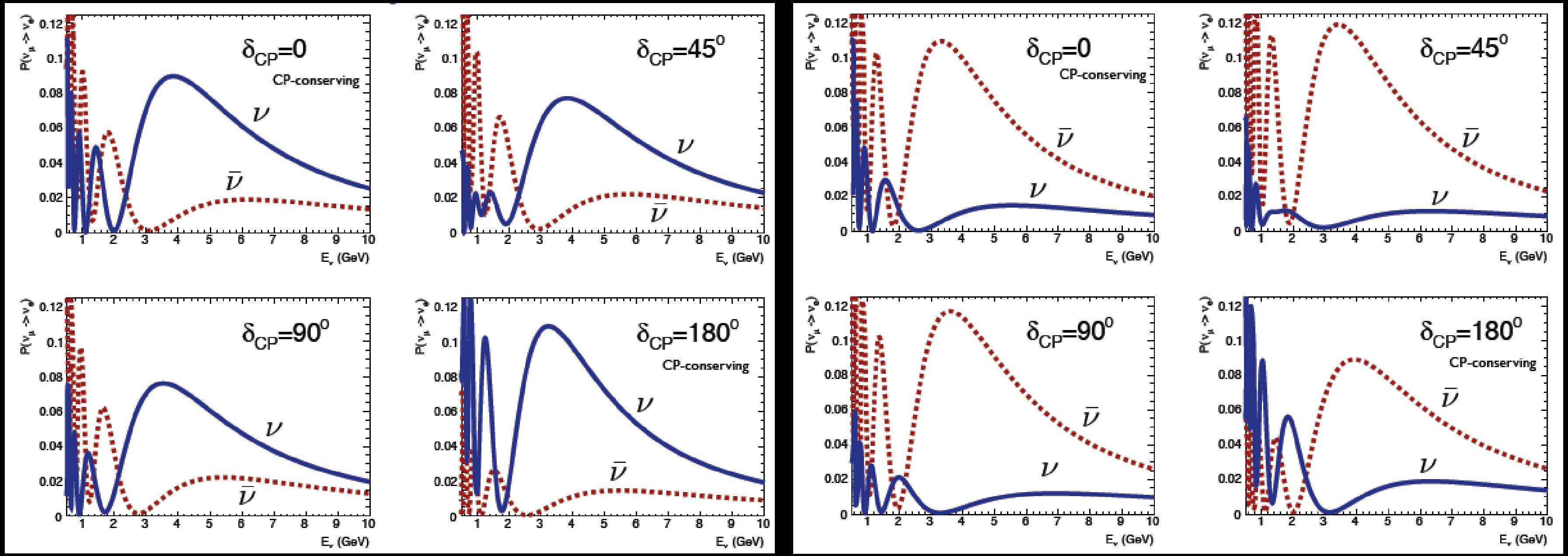
$$+4s^2_{12}c^2_{13}(c^2_{12}c^2_{23} + s^2_{12}s^2_{23}s^2_{13} - 2c_{12}c_{23}s_{12}s_{13}s_{23}cos\delta)sin^2\Phi_{12}$$

$$-8c^2_{13}s^2_{13}s^2_{23}(1 - 2s^2_{13})\frac{aL}{4E}cos\Phi_{32}sin\Phi_{31}$$

- Leading order term
  - Drives appearance
- CP Even term
  - Impact on spectrum
- CP odd term
  - Changes sign for antineutrinos
- Solar term
  - Little impact in LBL
- Matter term
  - Grows with L and E
  - Mass Ordering
  - Changes sign for antineutrinos

IMPACT ON SPECTRUM

NH IH



More relative neutrino appearance – NH, CP = $-\pi/_2$
More relative antineutrino appearance – IH, CP = $+\pi/_2$

LAGUNA LBNO Spectra – shows indicative results

Note the impact on the second oscillation maximum

LONG BASELINE EXPERIMENTS

- Flux ~ $1/L^2$
- Matter Effect ~ E , L at fixed L/E

- Shorter baseline
  - More statistics
  - Reduced matter effect
  - Sensitivity to δ_{CP}
- Longer baseline
  - Lower statistics
  - Enhanced matter effect
  - Sensitivity to mass ordering and δ_{CP}

- Strong complementarity between experiments at different baselines

- Current generation
  - T2K
    - Shorter baseline
    - Narrow beam
  - Noνa Longer baseline
    - Longer baseline
    - Narrow beam

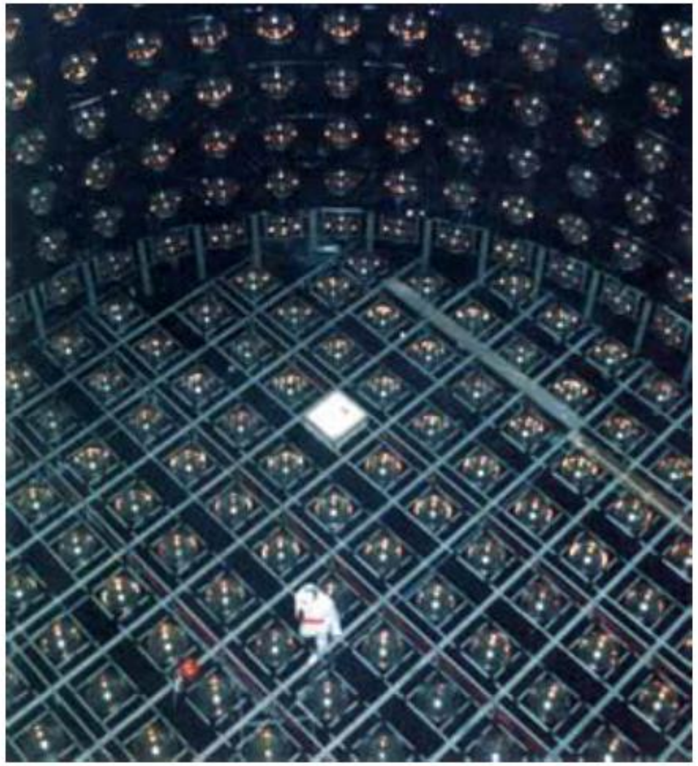
- Future
  - Hyper-Kamiokande
    - Shorter baseline
    - Narrow beam
  - DUNE
    - Longer baseline
    - Wideband beam

DESIGN YOUR OWN LBL EXPERIMENT

- Choose baseline
  - Fixes E to tune to oscillation maximum
  - Shorter baseline → Lower Energy
- How do you reconstruct your neutrino energy?
  - This depends on the dominant interaction
- Shorter baseline (E < ~1 GeV)
  - Dominated by CCQE
  - Need to reconstruct lepton momentum & direction
- Longer baseline (E > ~ 1 GeV)
  - Multi particle final states
  - Calorimetric reconstruction
- Design detector with one or other in mind
  - Must also have excellent electron/muon separation
- Design your near detector
  - Constrain your flux and cross sections
  - Match nuclear targets
  - Constrain the systematic on neutrino energy reconstruction
    - Non CCQE events (e.g. 2p2h)
    - Neutral particle production
- Select your beam type
  - Narrow (via off axis technique)
  - Wide band

HYPER KAMIOKANDE

3rd generation underground water Cherenkov detector in Kamioka

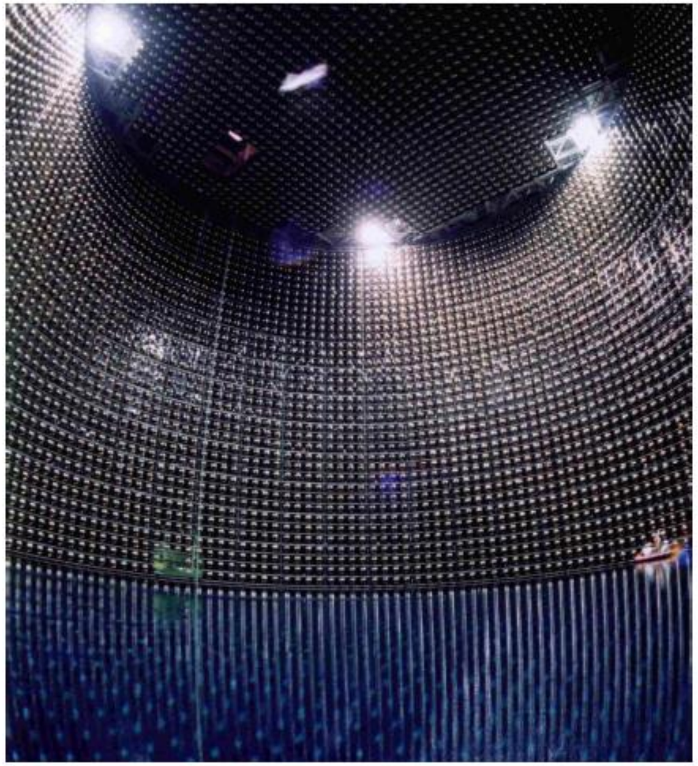


Kamiokande

(1983-1996)

- Atmospheric and solar neutrino “anomaly”
- Supernova 1987A

Birth of neutrino astrophysics

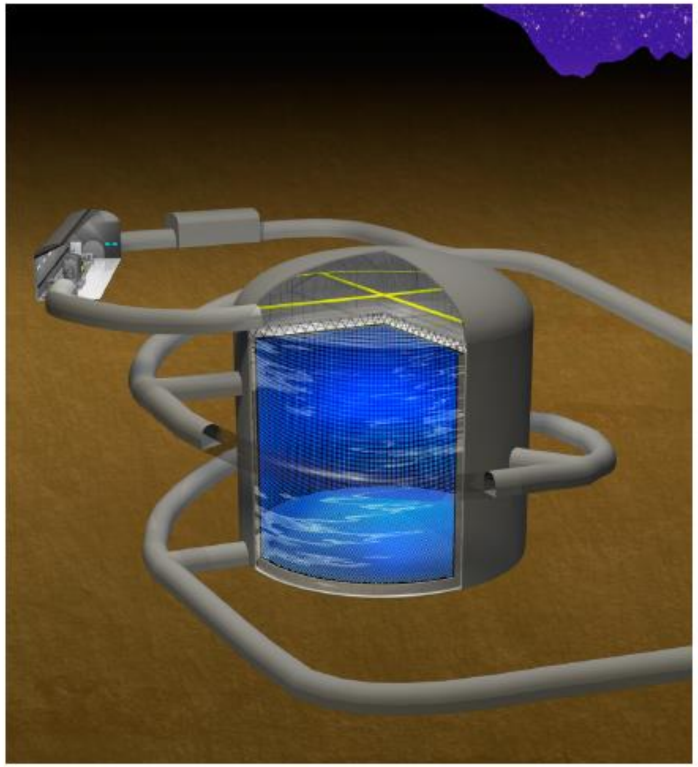


Super-Kamiokande

(1996 - ongoing)

- Proton decay: world best-limit
- Neutrino oscillation (atm/solar/LBL)
  - All mixing angles and $\Delta m^2 s$

Discovery of neutrino oscillations



Hyper-Kamiokande

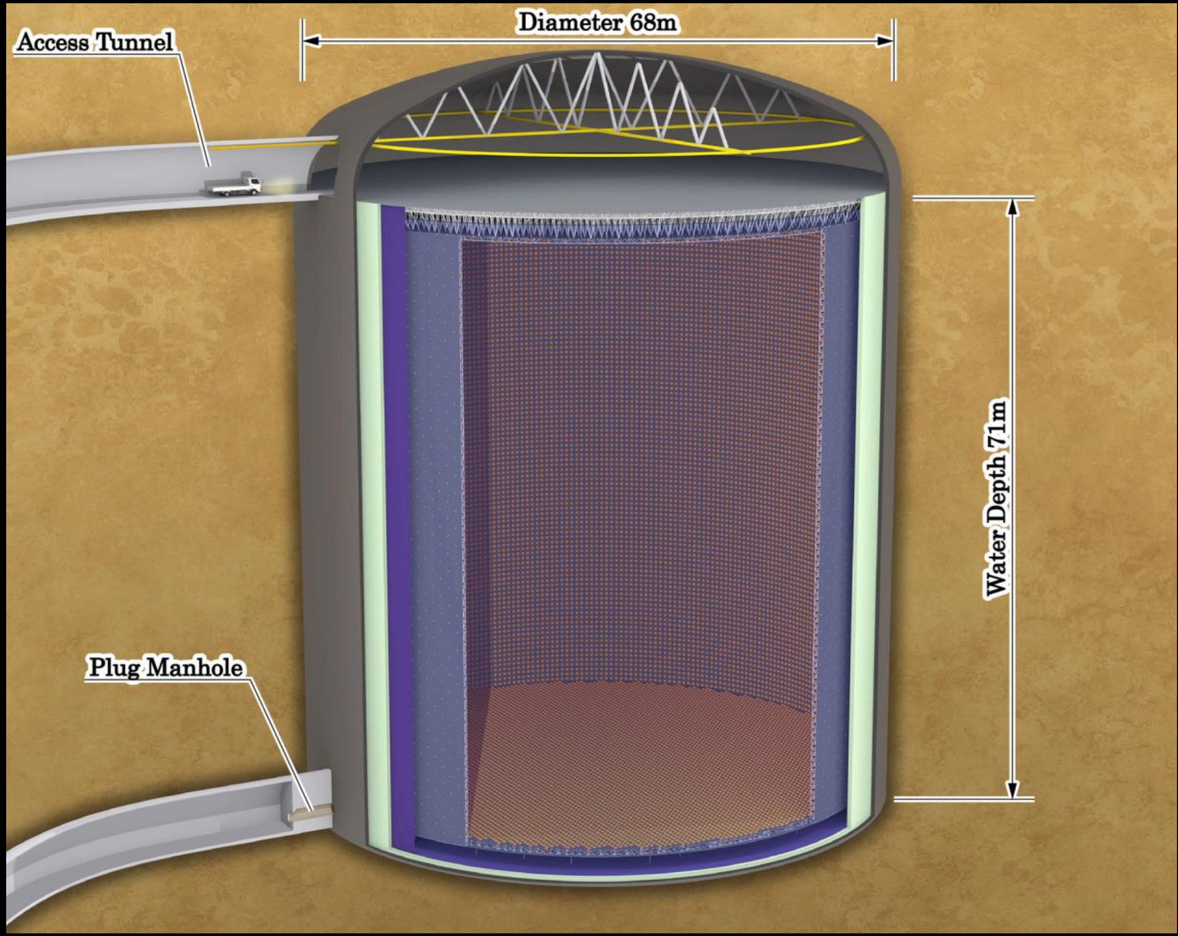
(start operation in 2027)

- Extended search for proton decay
- Precision measurement of neutrino oscillation including CPV and MO
- Neutrino astrophysics

Explore new physics

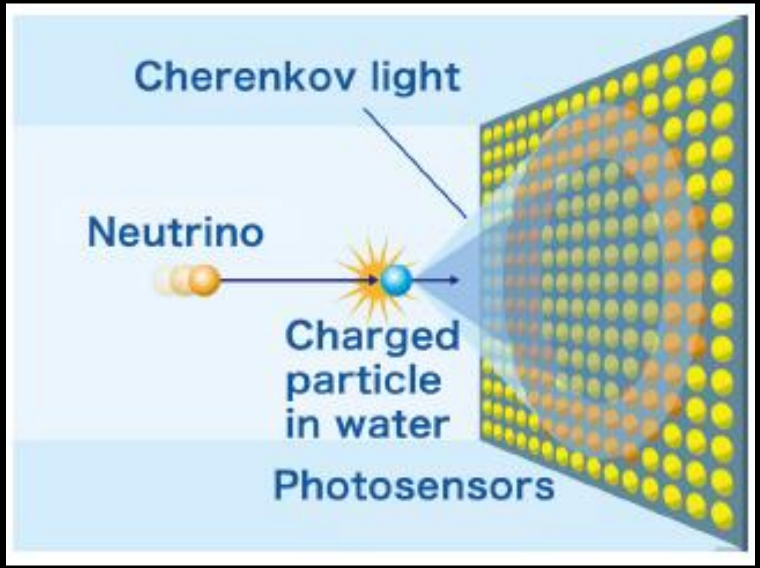
THE HYPER-KAMIOKANDE DETECTOR

- 258 kton Water Cherenkov detector
  - ~ 8 times larger than Super-Kamiokande
- 20000 50 cm PMTs
- 800 mPMTs
- 3600 OD units
  - 8 cm PMT
  - Wavelength shifting plate

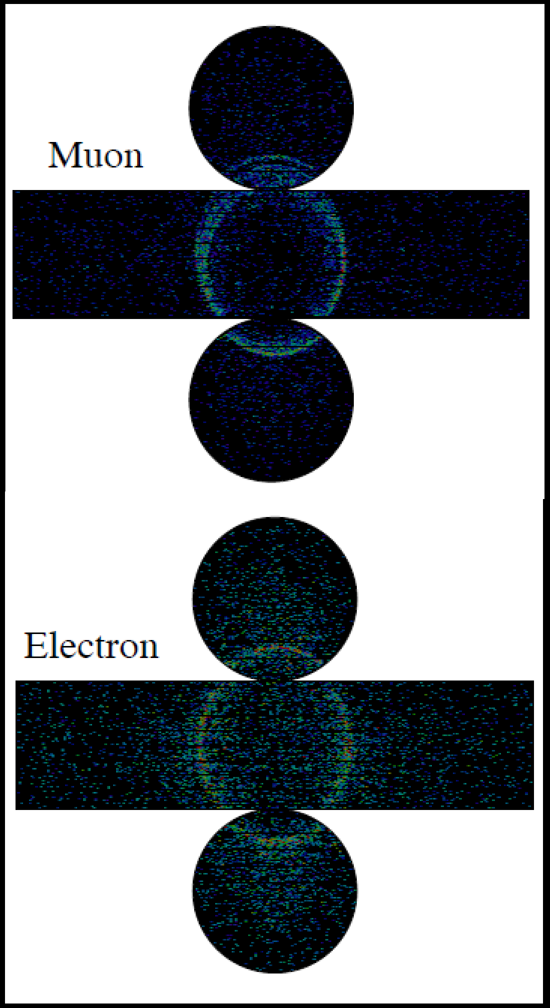


WATER CHERENKOV TECHNIQUE

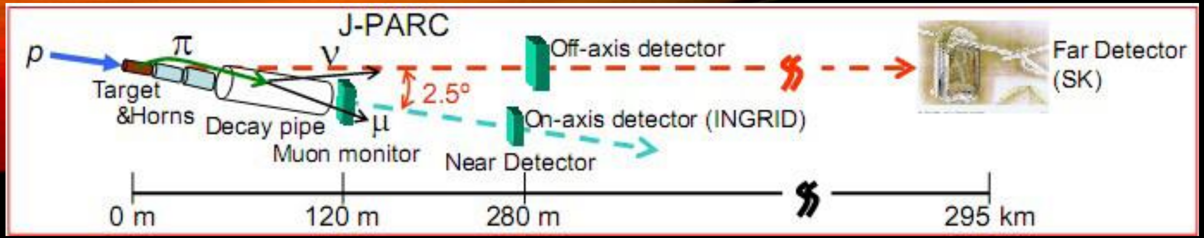
- Observe the Cherenkov Ring from charged particles
  - Optical "Sonic Boom" from faster than light (in water) particles
- >99% μ/e separation
- Momentum Reconstruction from charge collection



Sharp Ring

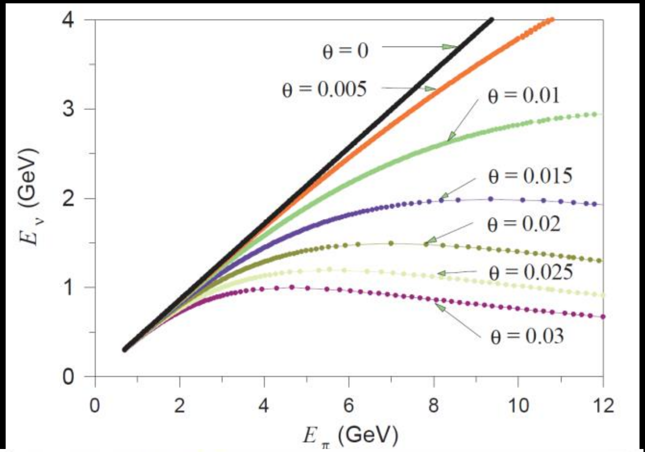


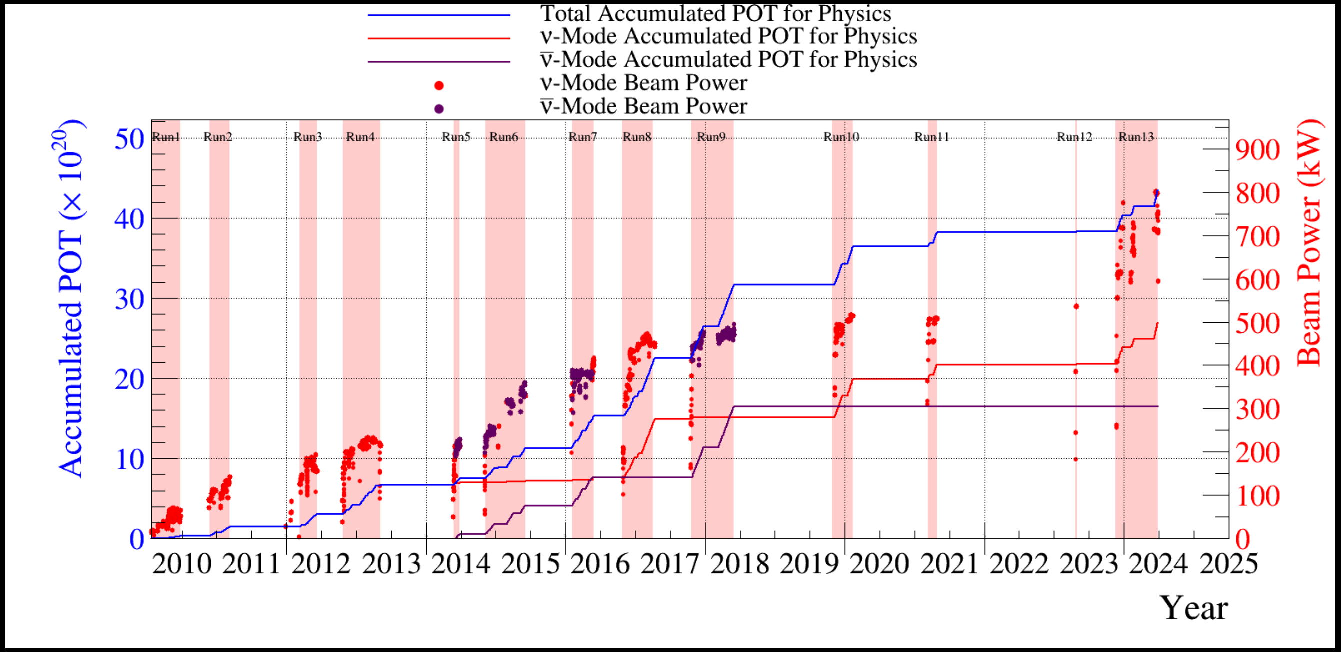
Fuzzy Ring

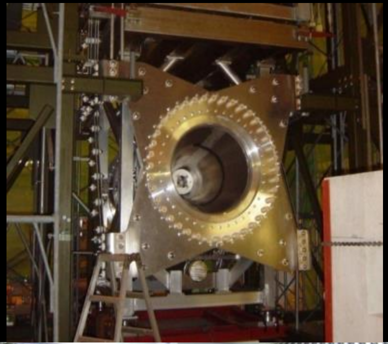


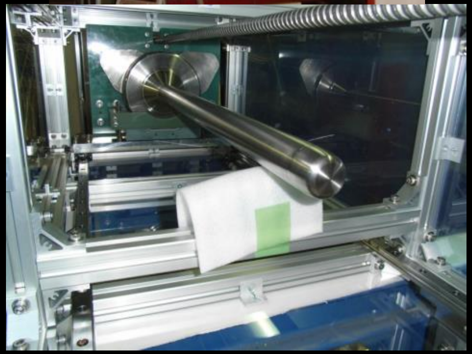
NEUTRINO BEAM

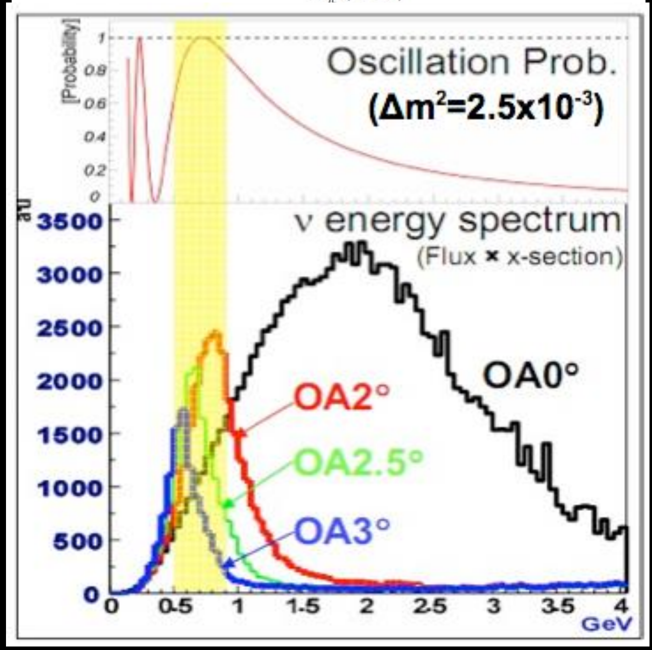
- Upgrade JPARC beamline
  - Towards 1.3 MW
  - 800 kW operation achieved in June
  - Further improvements by speeding up cycle from 1.36 → 1.16 s
- Uses off-axis technique to achieve narrow band beam

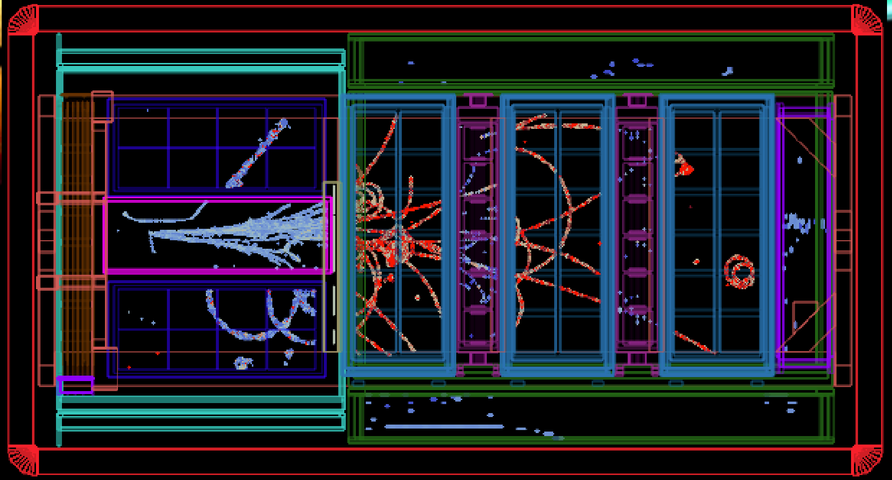




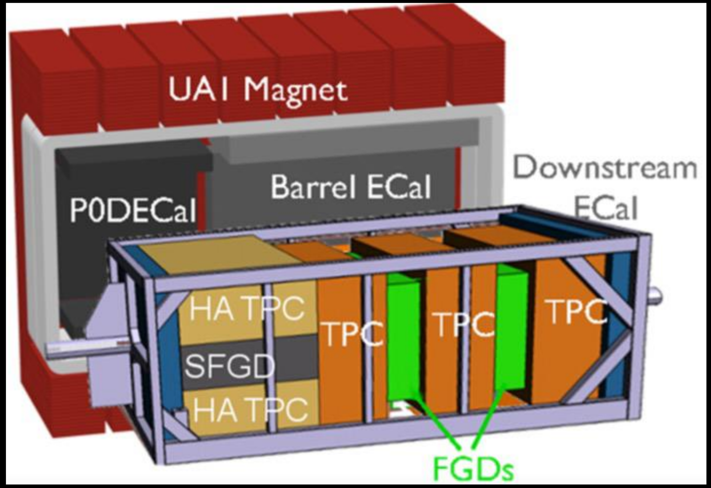




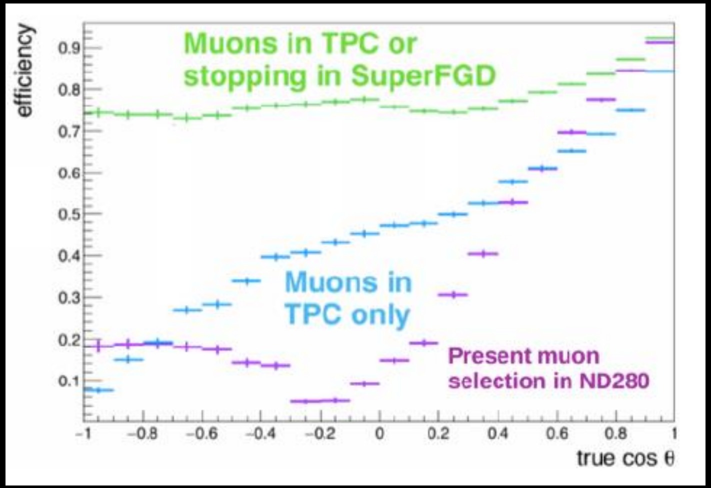




ND280

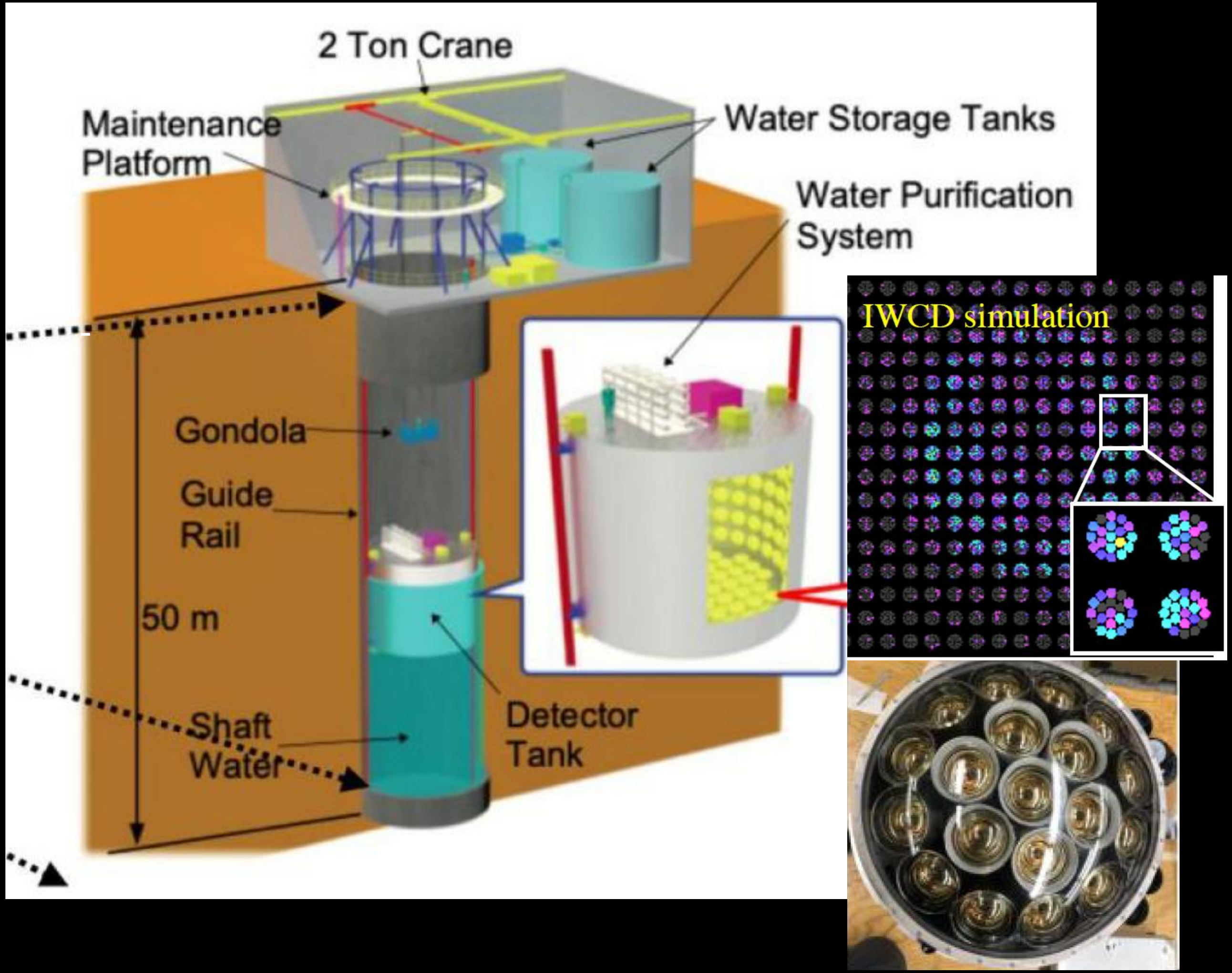


- ND280 upgrade is part of the T2K experiment and will still be online at start of Hyper-K
  - Now operational
- New Detectors
  - sFGD
  - hTPCs
  - Time of flight
- Constrain predictions for far detector
  - Measure flux X cross section
- Magnetised so can measure wrong sign backgrounds
- Detailed kinematic measurements to constrain and develop cross section models

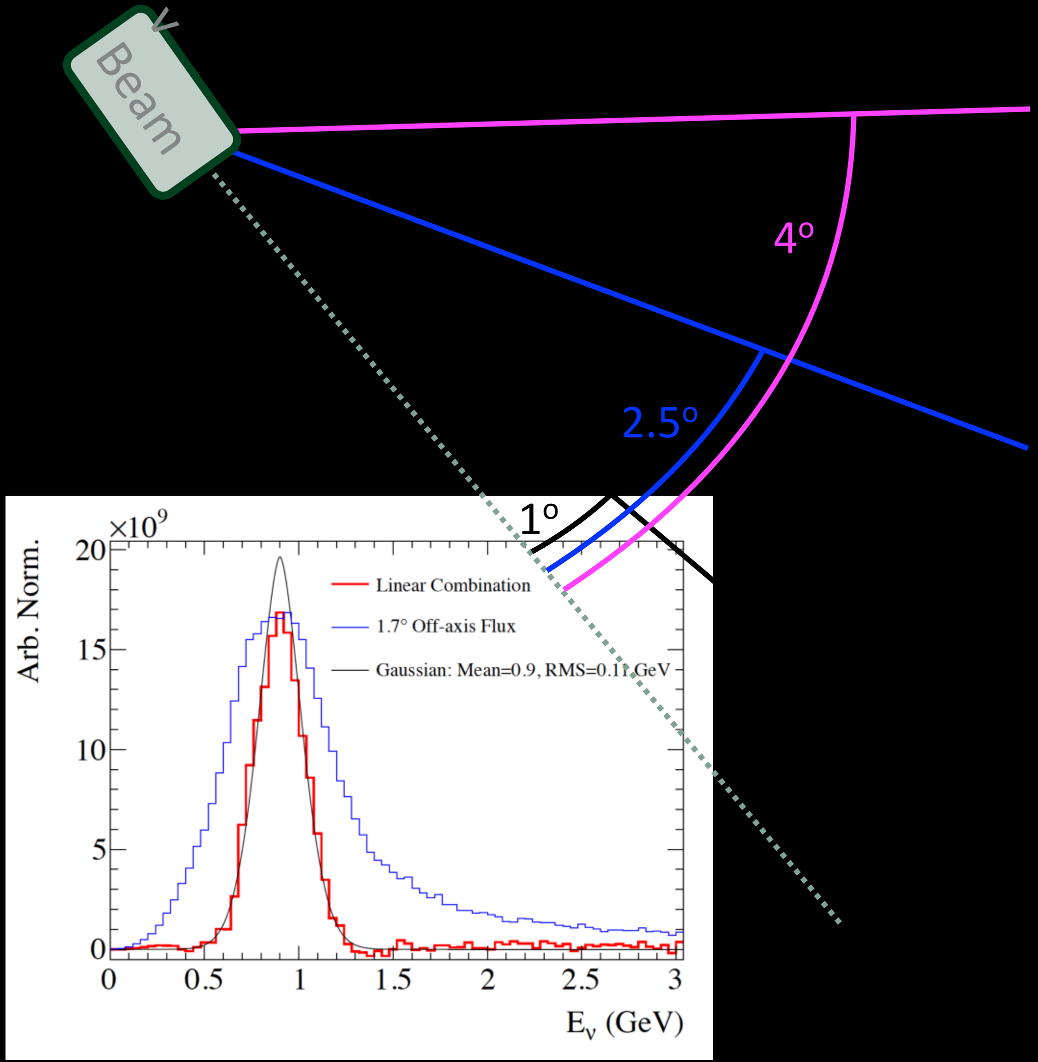


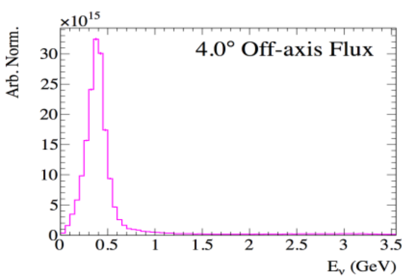
IWCD

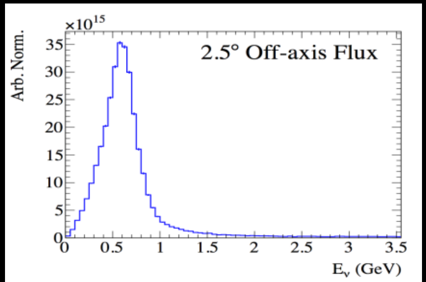
- Approx 1 km from neutrino target
- 1 kton scale water Cherenkov
  - Use mPMTs for readout
  - Move detector up and down shaft to sample different off- axis angles
- Constrain neutrino energy mis-reconstruction
- Measure electron neutrino cross sections

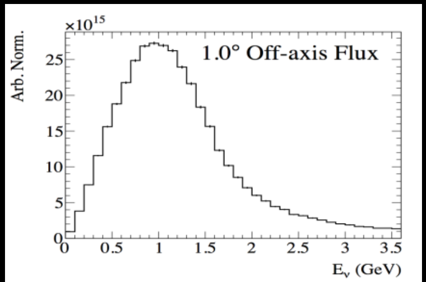


A MOVEABLE DETECTOR





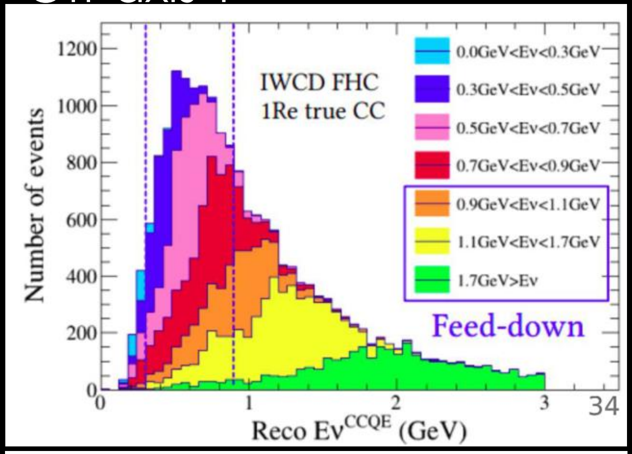


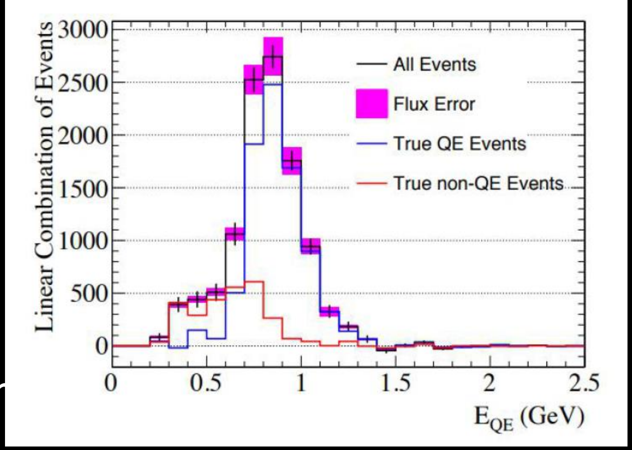


WHAT CAN WE DO WITH IWCD?

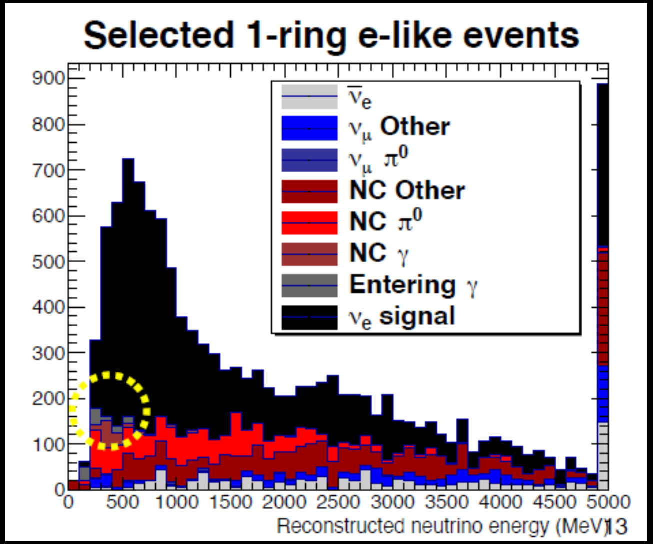
- Non quasi elastic events can reconstruct to lower neutrino energy if interpreted as CCQE
- This feed down affects neutrino energy reconstruction
- By moving the detector through the beam we sample different neutrino spectra
  - The feed down can be understood
- Can construct linear combinations of samples to measure feed down
- Self-shielding detector, significantly lower backgrounds for ν_e measurement

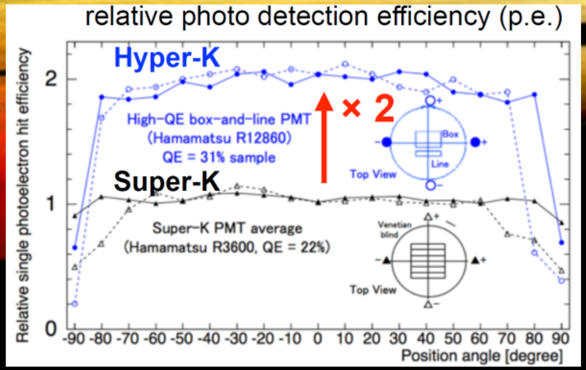
Off-axis 1°





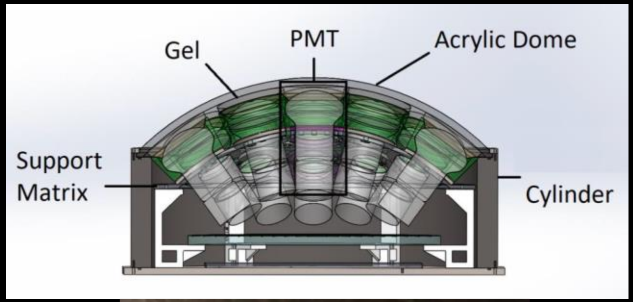
A quasi-monochromatic beam of 900 MeV





PHOTOMULTIPLIER TUBES

- 20 000 Hamamatsu 50 cm box-and-line PMTs
  - Production, delivery and QA ongoing
  - ~X2 efficiency of SK PMTs
- ~800 multi PMT modules
  - 19 3 inch PMTs
  - Improved detector calibrations
- ~3600 8 cm OD PMTs with wavelength shifting plate



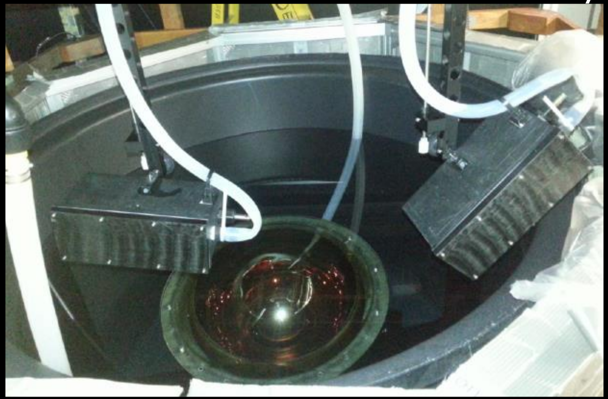
Ni/Cf

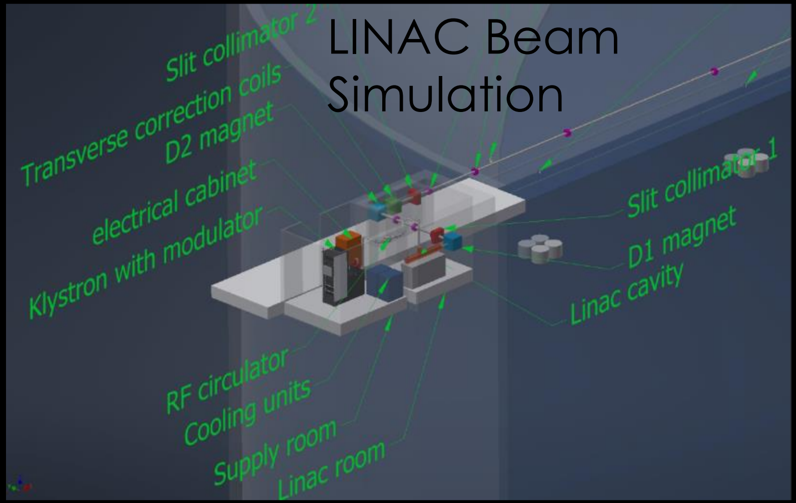
Photogrammetry Testing

CALIBRATION

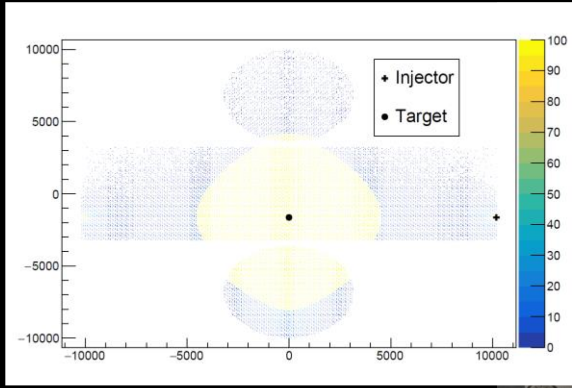
- Optical Sources, radioactive sources and control samples
- Determine detector parameters and measure systematics
- Precalibration Programme & Photogrammetry
- Light Injection
  - Diffusers and collimators
  - mPMT system
  - OD injectors
- Electron Linac
  - 3-24 MeV electrons
- Radioactive Sources
  - DT Source - ^{16}N
  - AmBe + BGO – tagged neutrons
  - Ni/Cf - 9 MeV γ cascade
- Aim to suppress detector error < 1%

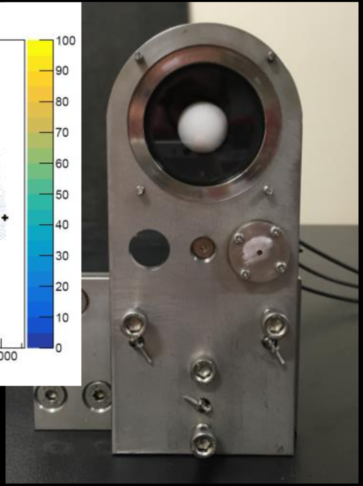
PhotoSensor Test Facility



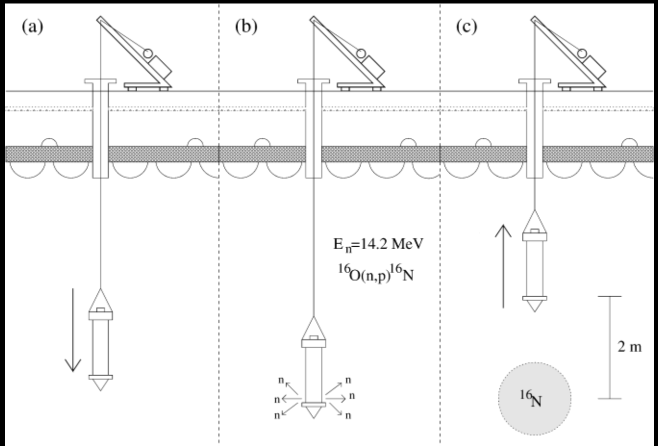


LINAC Beam Simulation



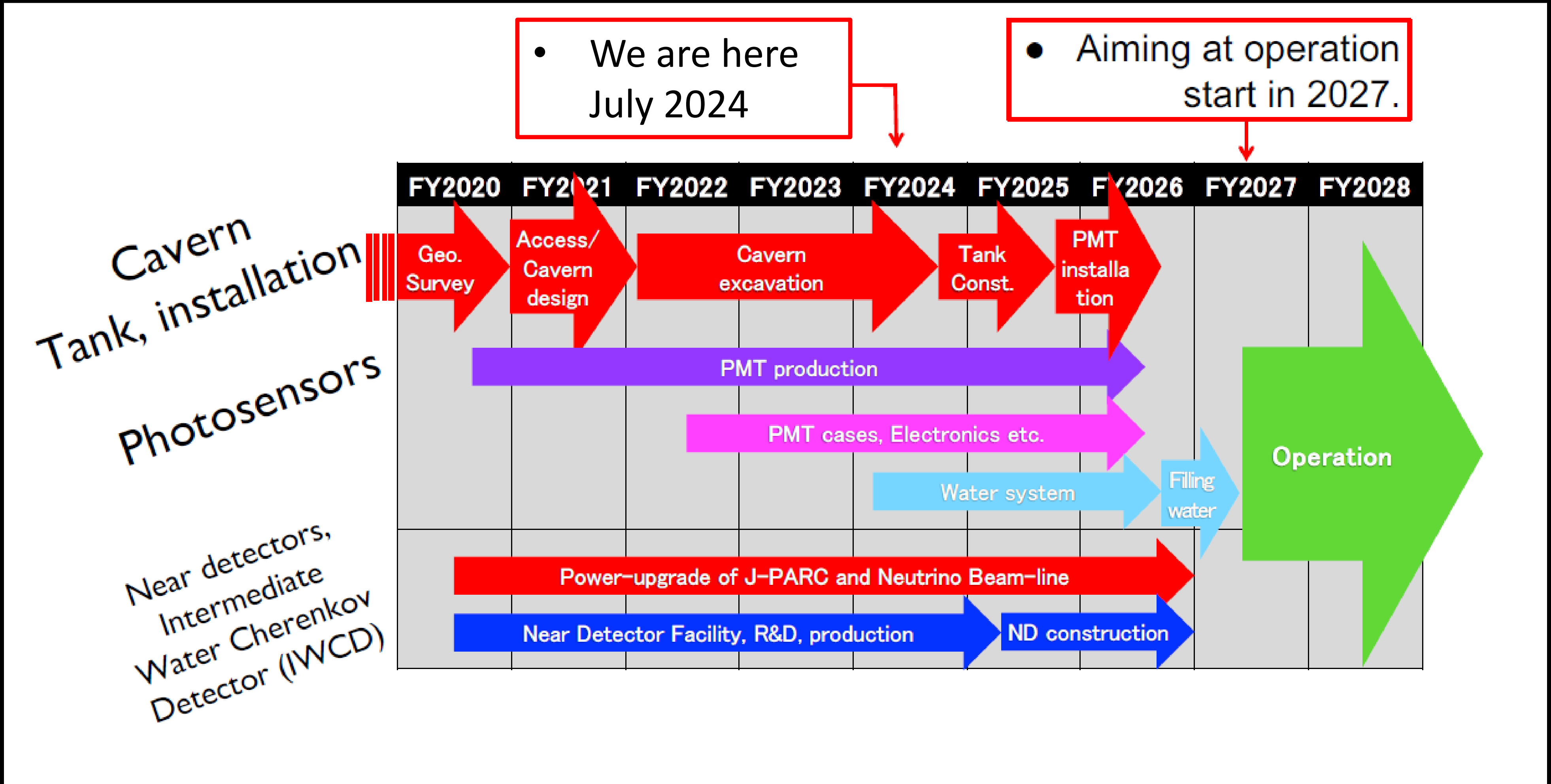


Light Injectors

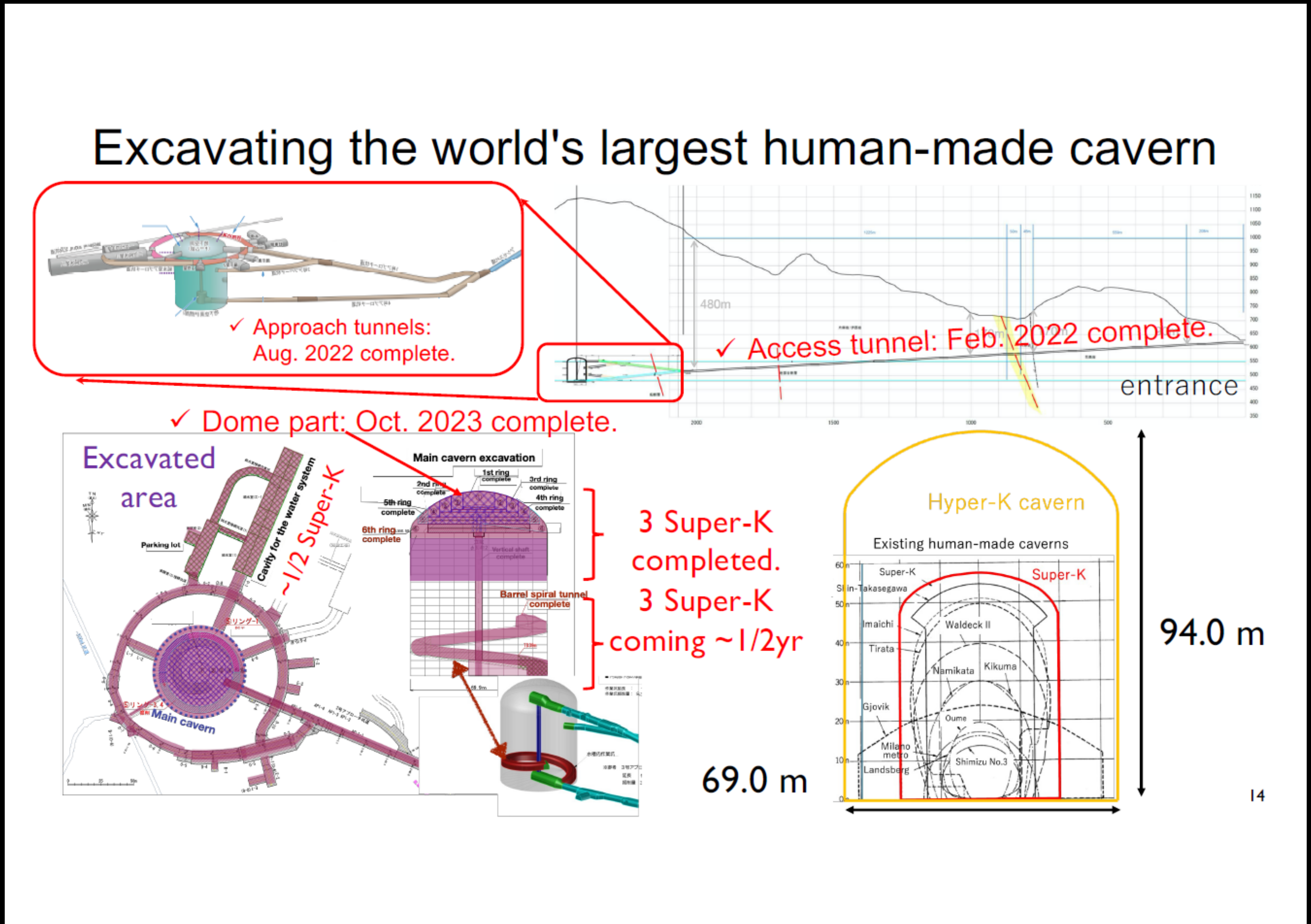


DT Operation

CONSTRUCTION SCHEDULE



CAVERN CONSTRUCTION

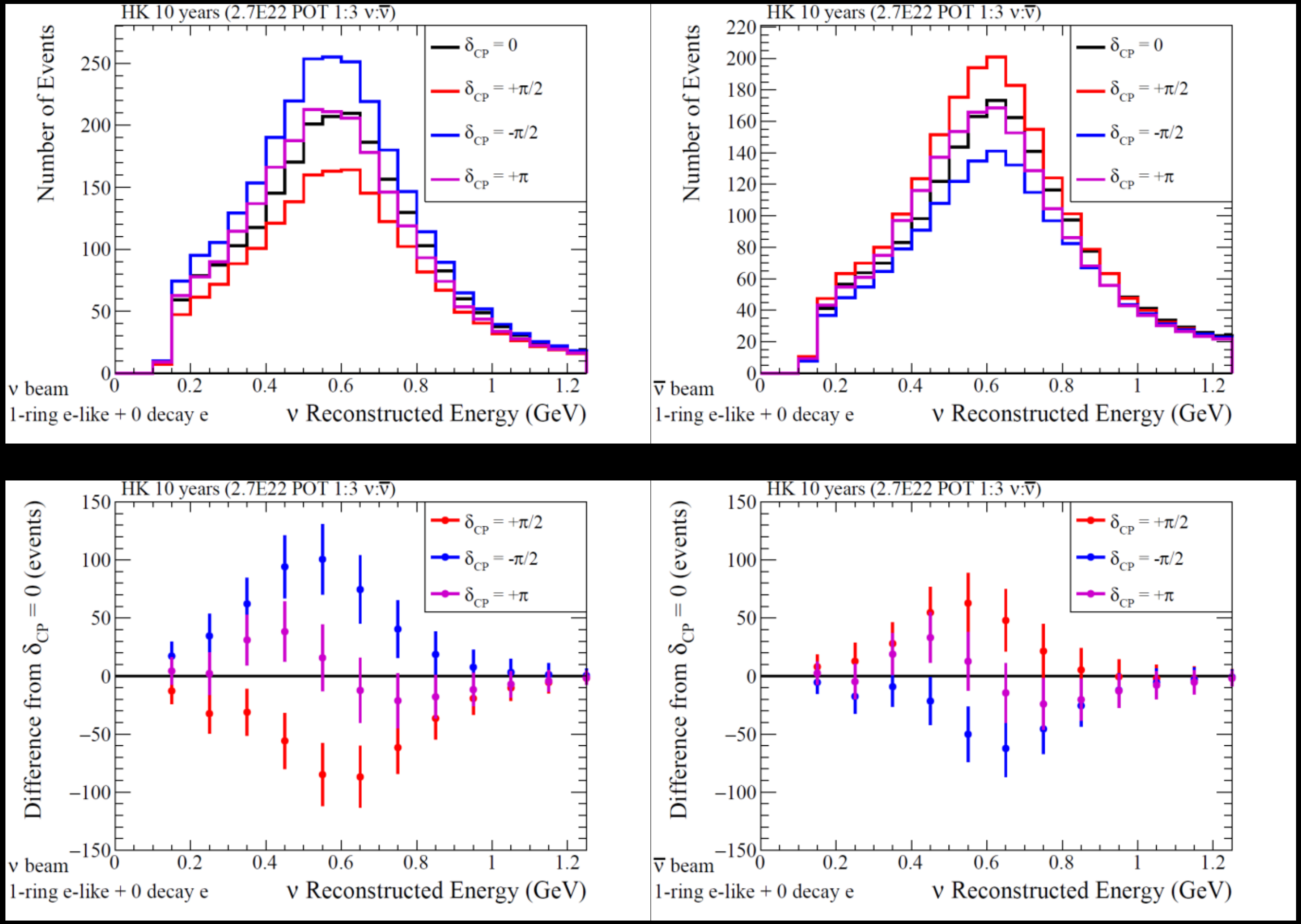


Oct. 3, 2023 Completion of the dome (dia. 69 m, height 21 m, ~1 Super-K)

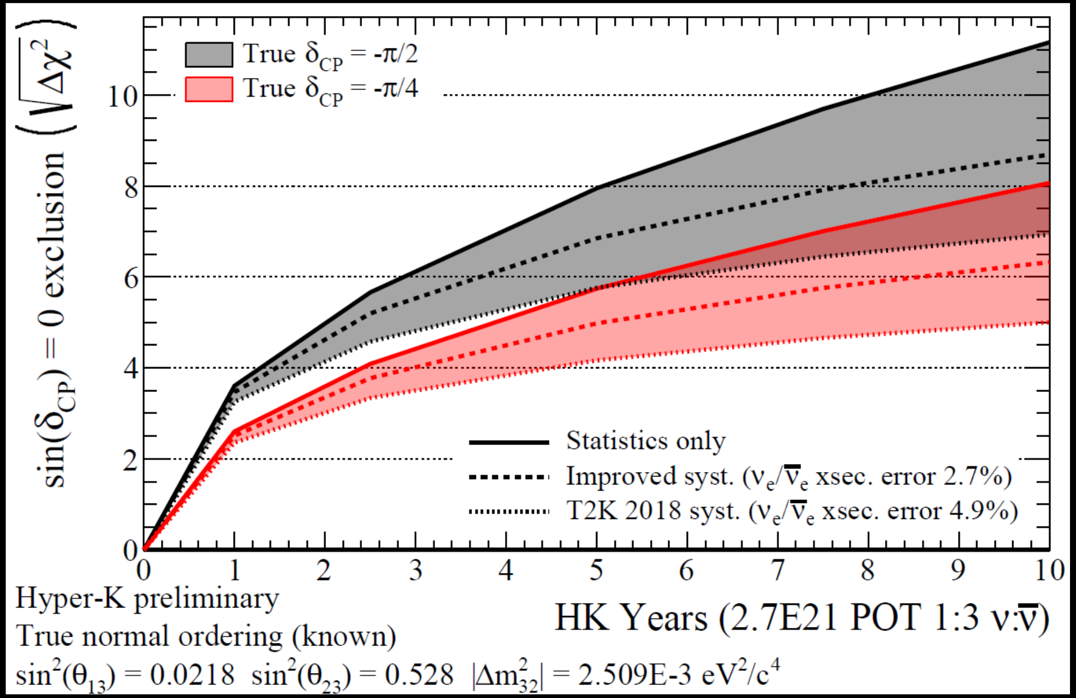
Excavation of the HK cavern will be completed by the end of this year!

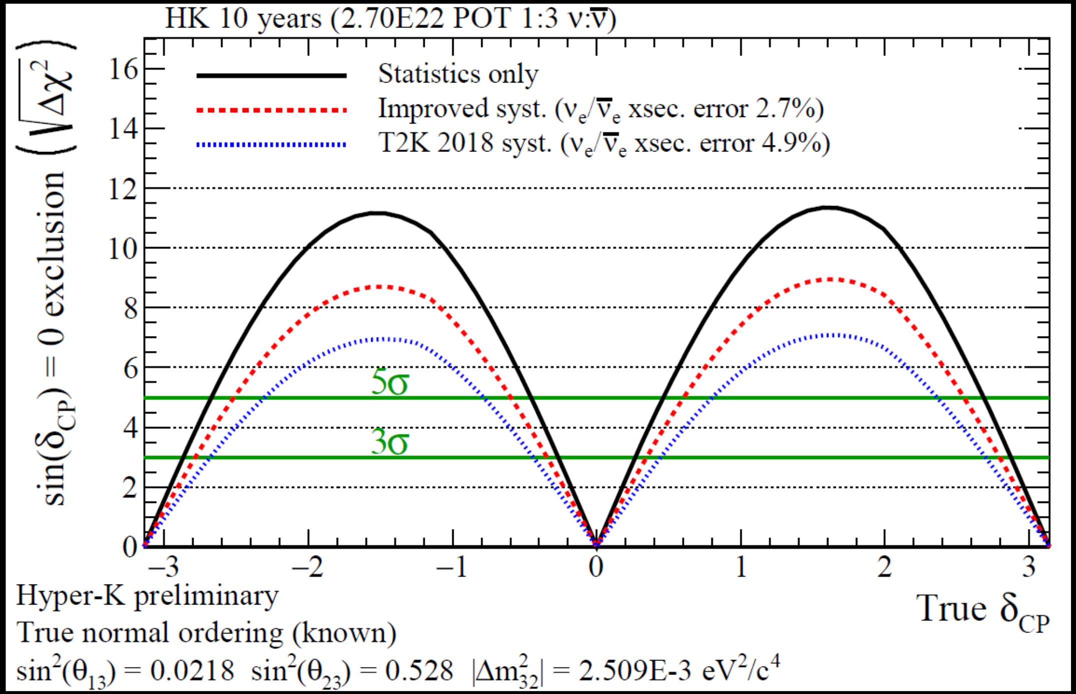
WHAT DO WE SEE IN HK?

- Electron and muon like rings
  - Spectrum and rate
  - Neutrino and antineutrino running
- Rate and spectrum depend on δ_{CP}
- Systematics
  - Flux
  - Cross Sections
  - Cross section effects on neutrino energy reconstruction
  - Energy Scale/Resolution
  - Particle Identification
  - Reconstruction



CP MEASUREMENT PROSPECTS

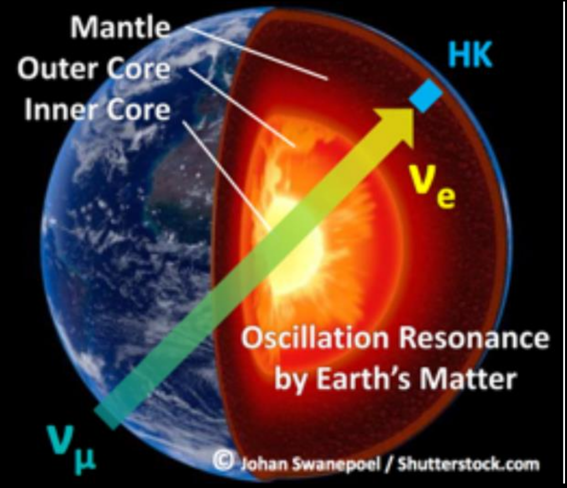


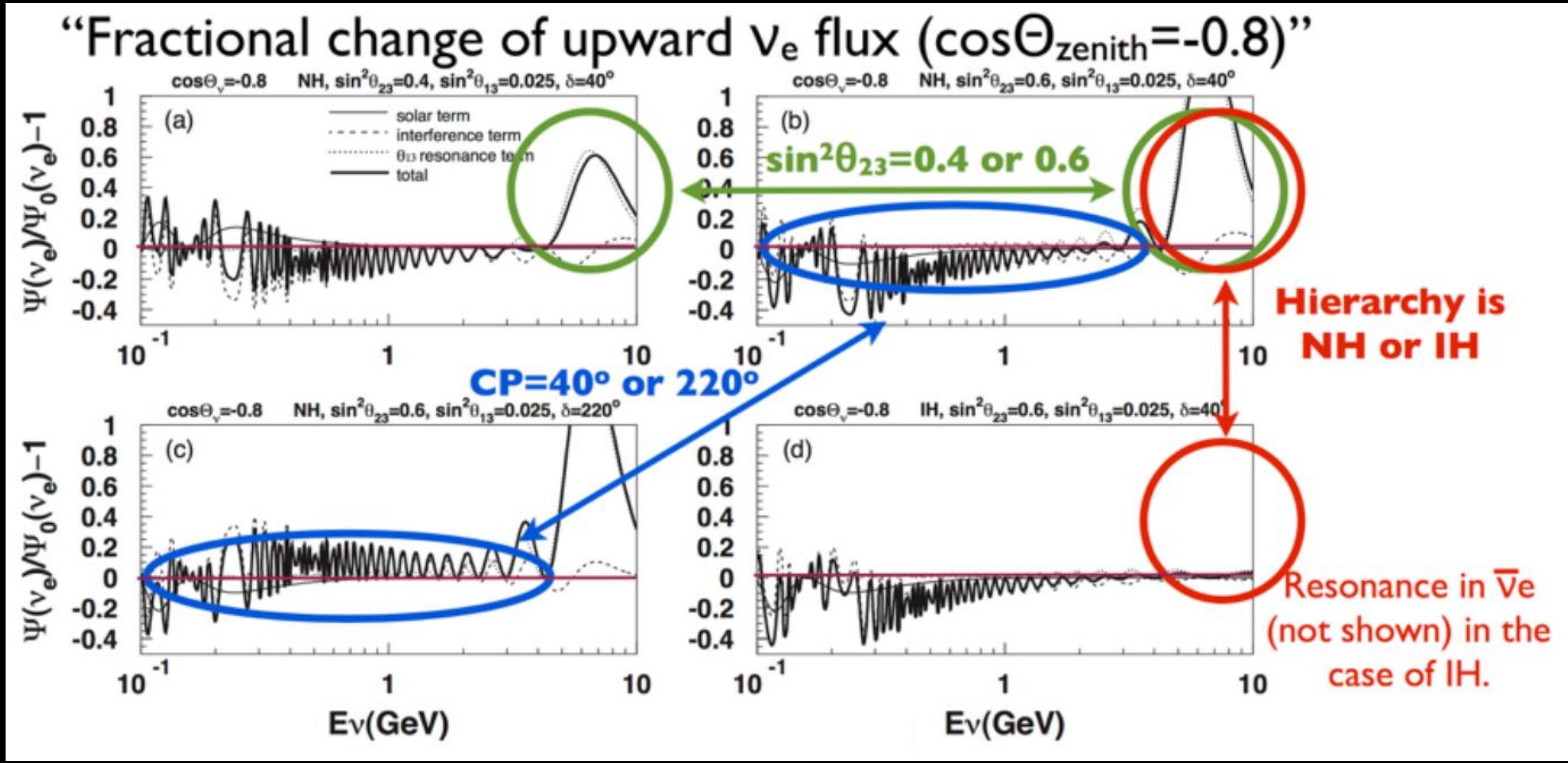


- With known mass ordering can achieve 5σ CP conservation exclusion for true δ_{CP}=-π/2 in 2-3 years
- After 10 years 60% of parameter space excluded at >5σ

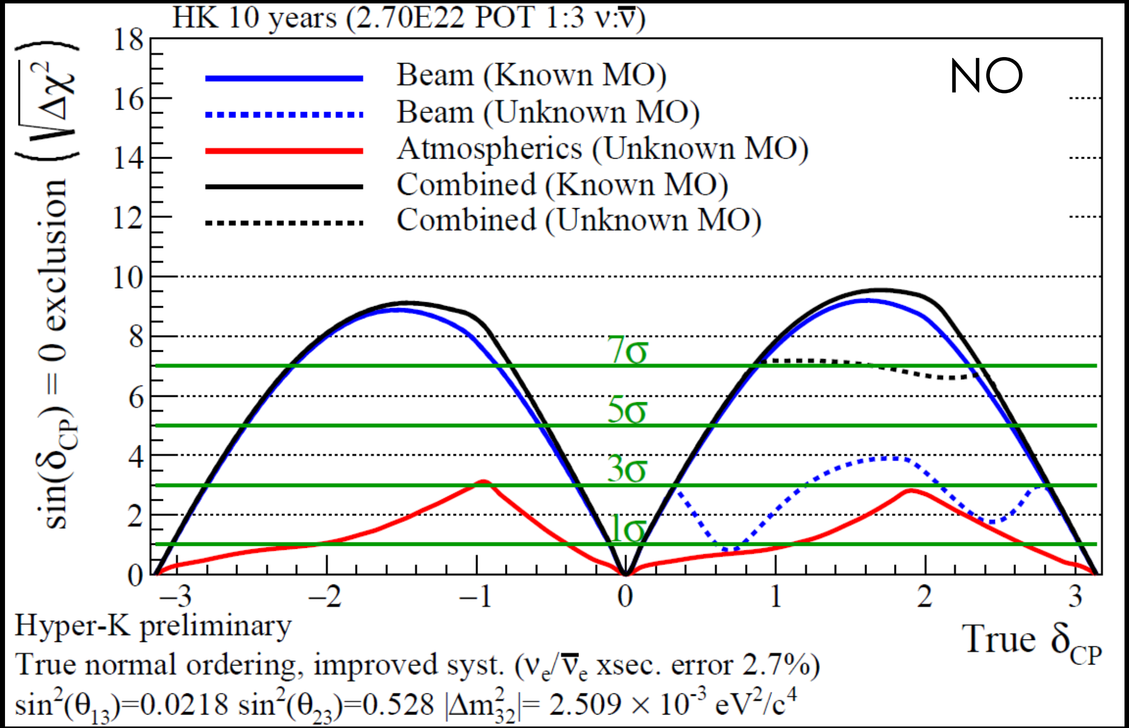
ATMOSPHERIC NEUTRINOS

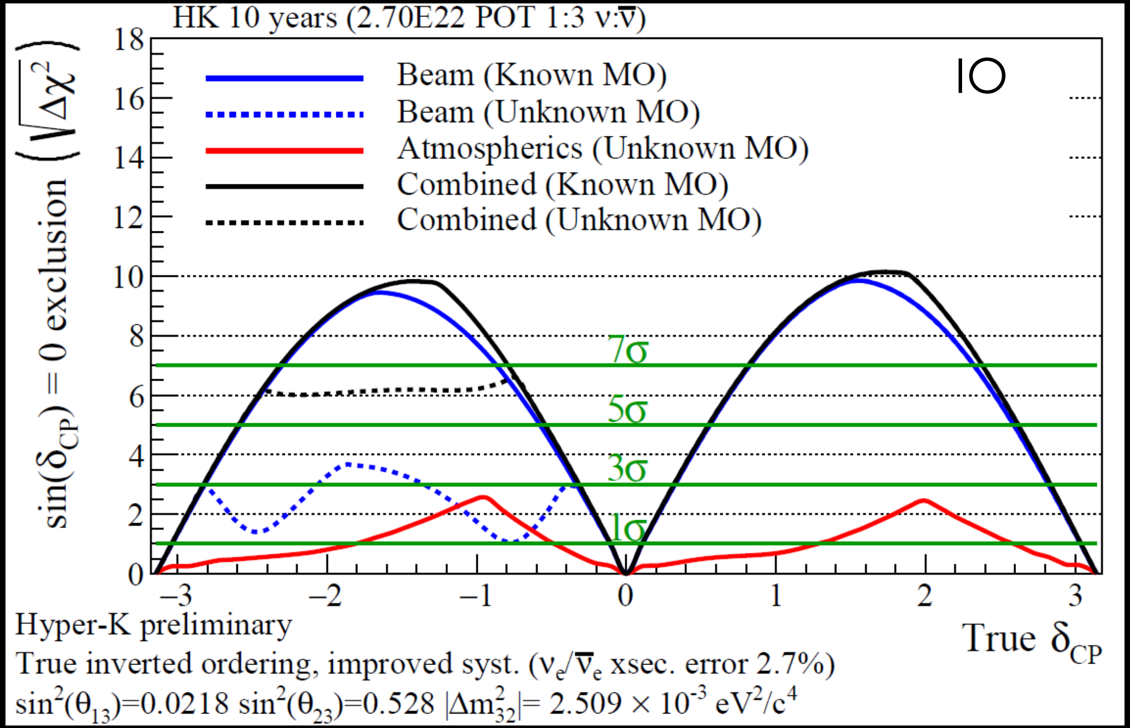
- Exploit the matter effect for atmospheric neutrinos as they pass thought the mantle and core
- Sensitivity to mass hierarchy, δ_{CP} and octant
- ~80 events/day in HK





COMBINE BEAM AND ATMOSPHERICS

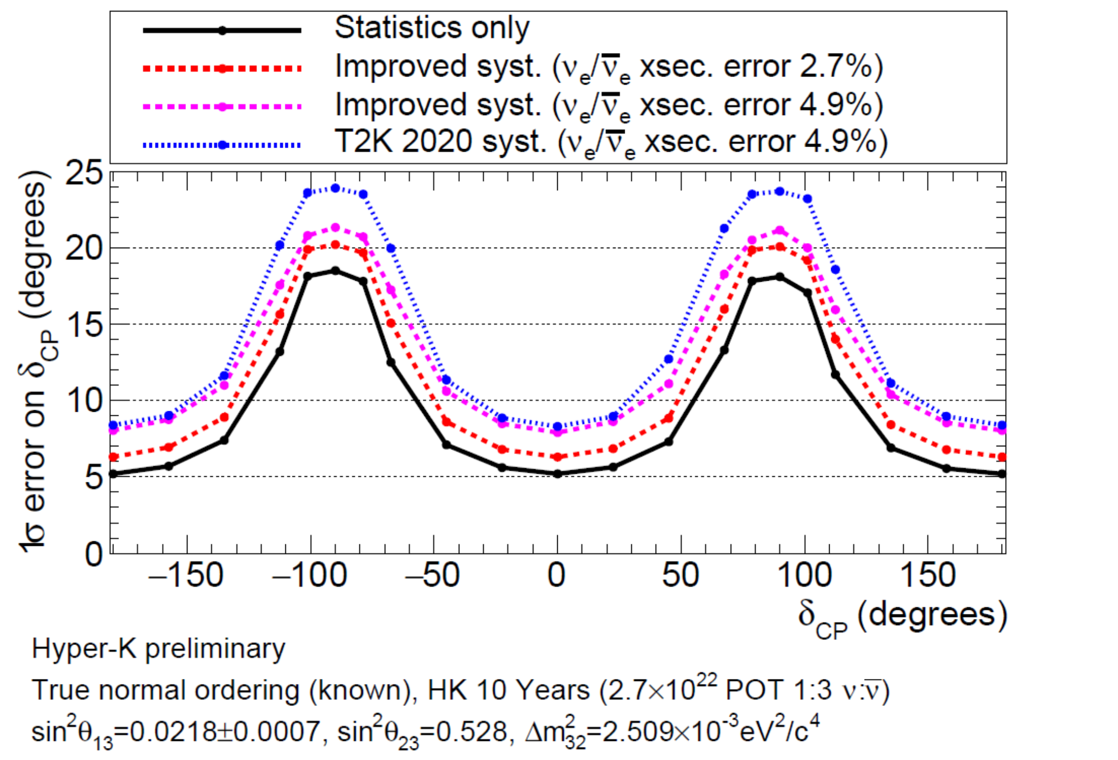




Break degeneracy between mass ordering and δ_{CP} and recover coverage

PRECISION MEASUREMENT OF δ_{CP}

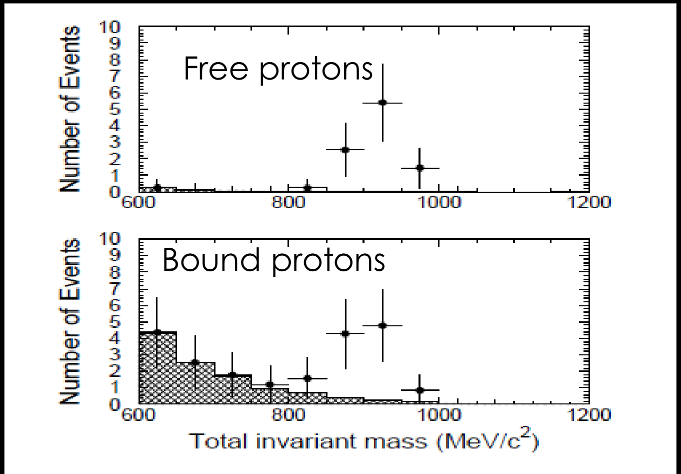
- As well as discovering CP violation aim to measure δ_{CP} precisely.
- Depends on value of δ_{CP}
    - Near CP conserving values ~6°
    - Close to $\pm\pi/2$ ~20°
- Strongly depends on achieving best possible systematics
    - Flux
    - Cross section
    - Detector



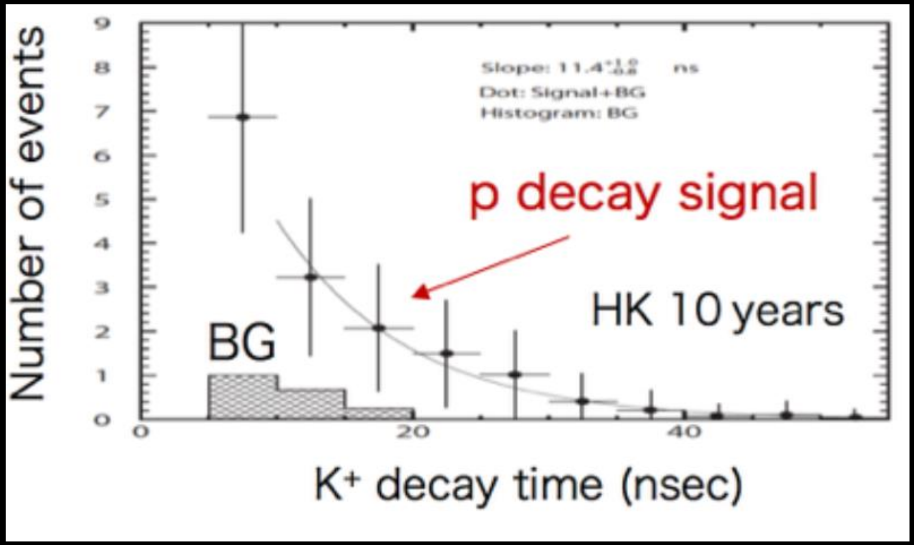
PROTON DECAY

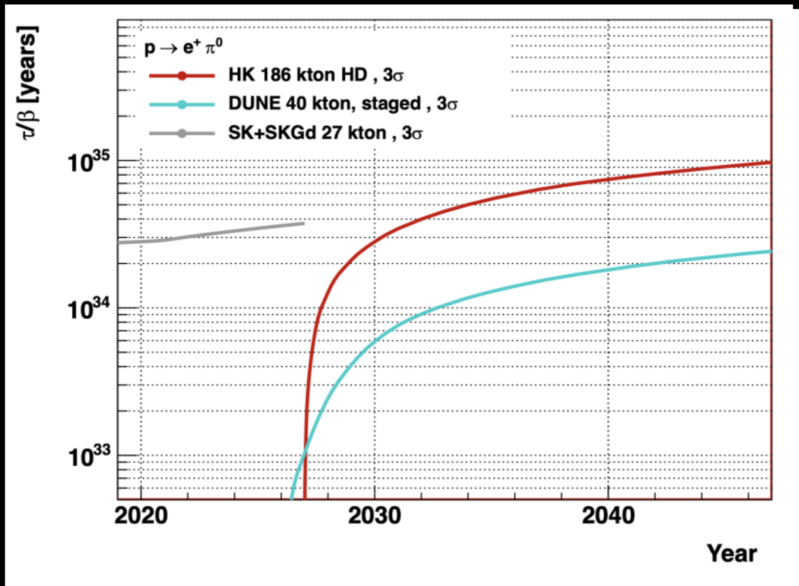
- Proton decay is predicted by grand unified theories
- Suppression by $^1/_{M_X^4}$ very long lifetimes
- HK is only realistic option to probe 10^{35} years

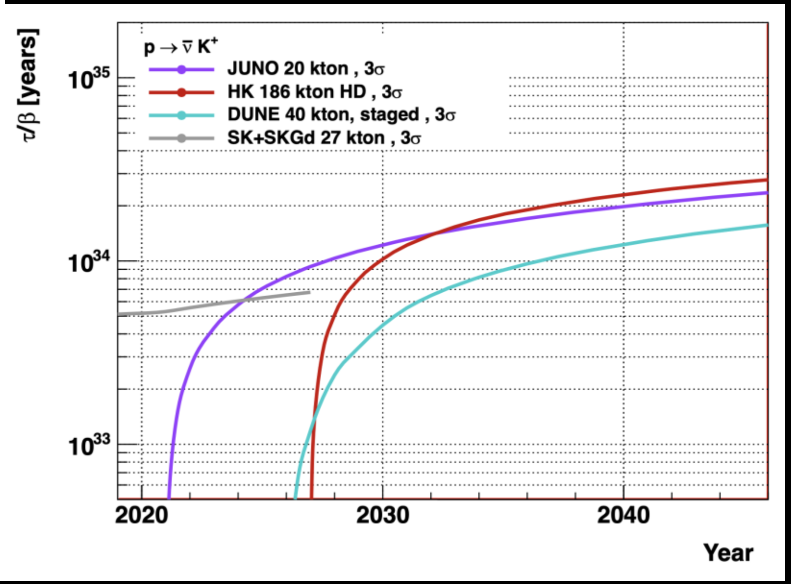
$p \to e^+\pi^0$



$p \to K^+\nu$

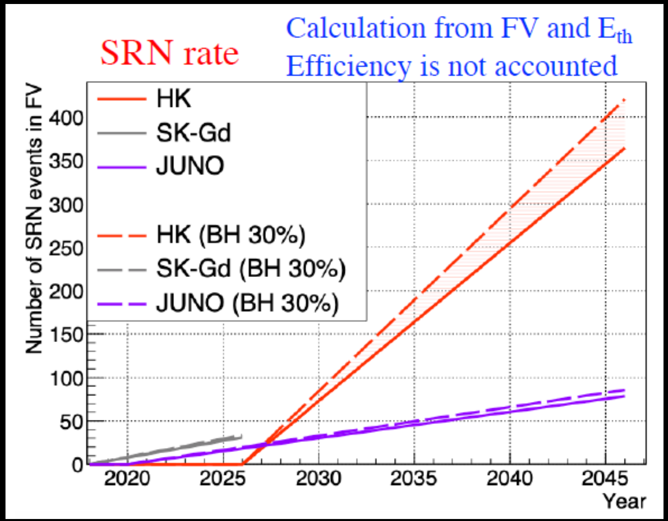


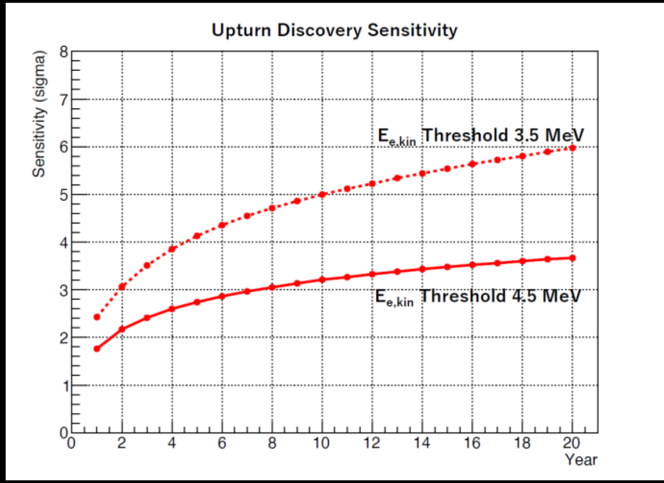


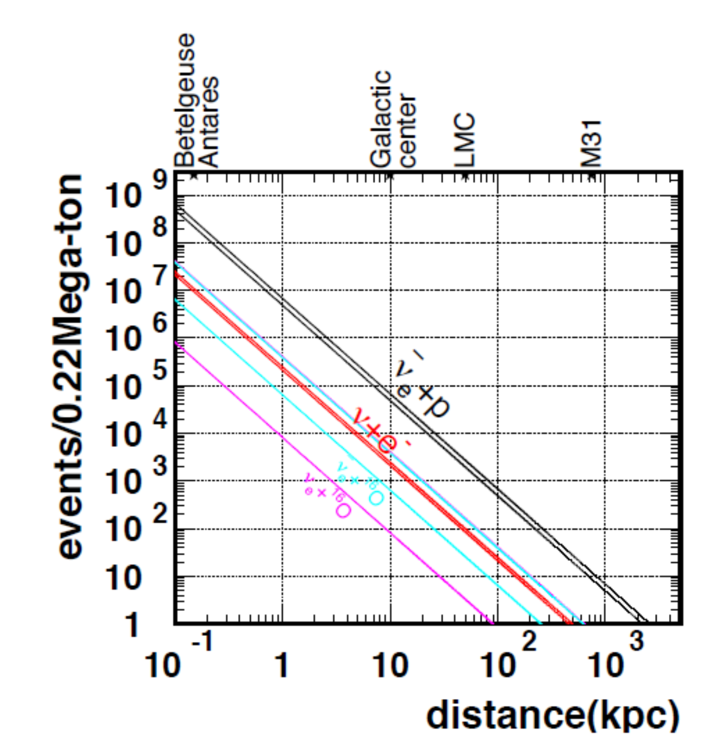


OTHER HK PHYSICS

- Supernova neutrinos
  - Burst
    - 70k events for SN at 10 kpc
    - Alert with 1° pointing
  - Diffuse SN background
    - 4 events/ yr with neutron tag
- Solar neutrinos
  - Upturn search
  - Day night asymmetry measurement
    - Check compatibility of solar and reactor parameters





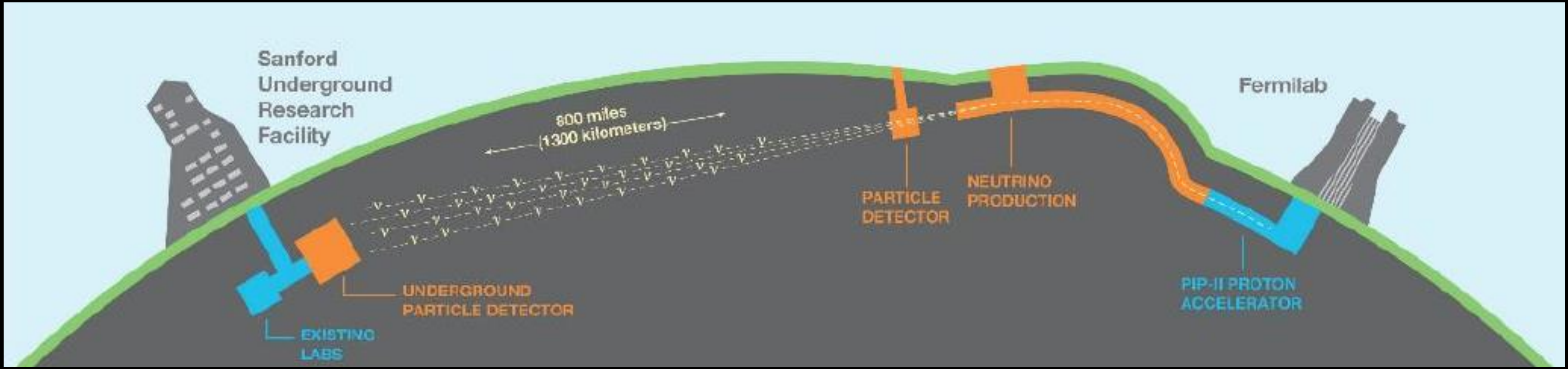


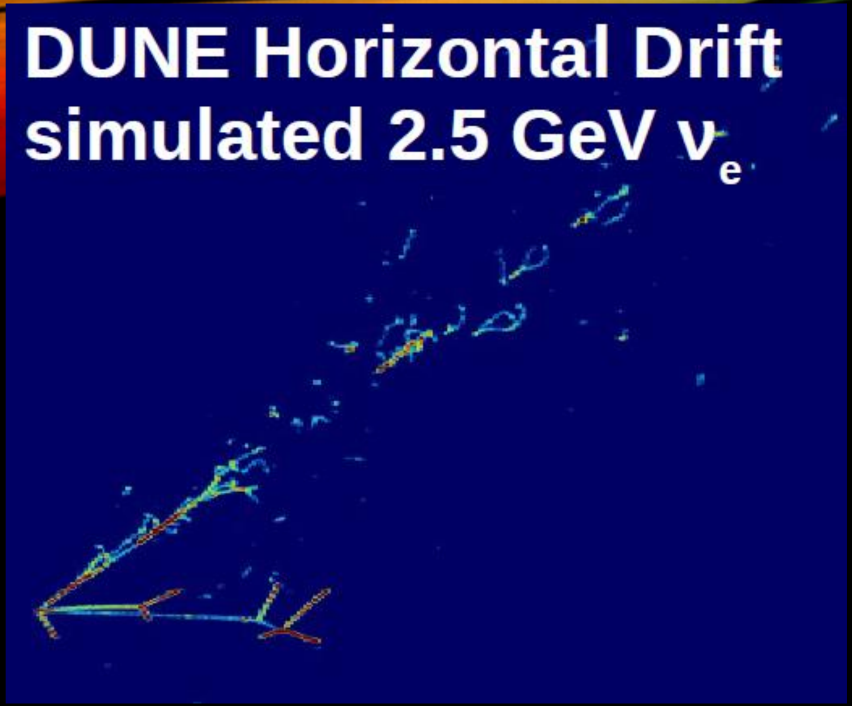
DUNE

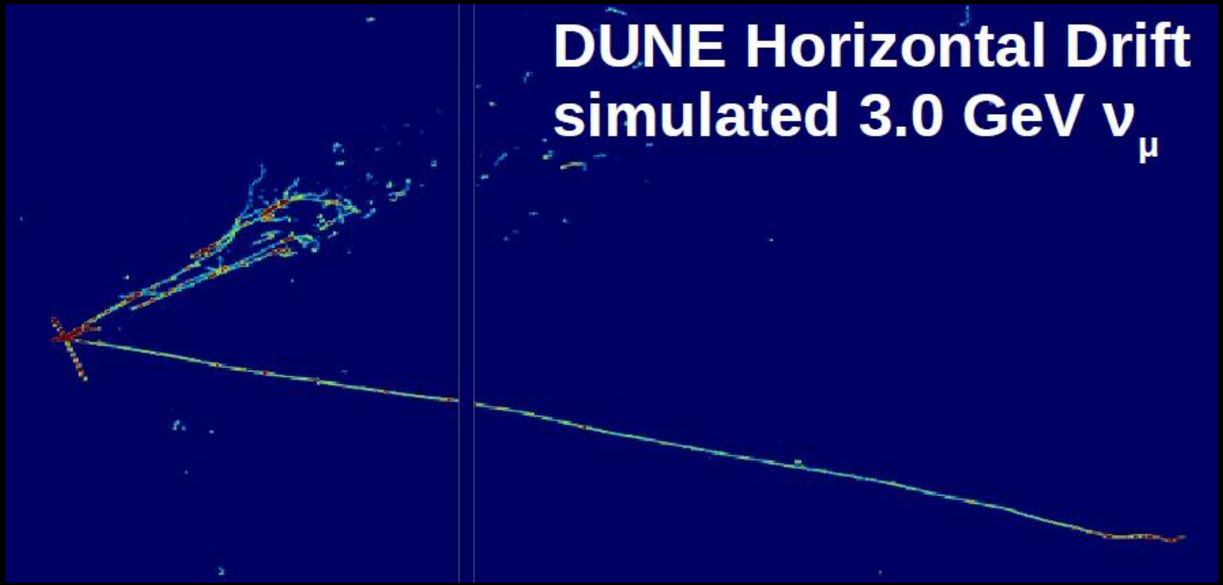
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

THE DUNE EXPERIMENT

- Wideband neutrino beam >2 MW
- Modular 40 kt fiducial mass liquid argon TPC
- 1300 km baseline FNAL →Sandford
- Near detector complex including a movable detector







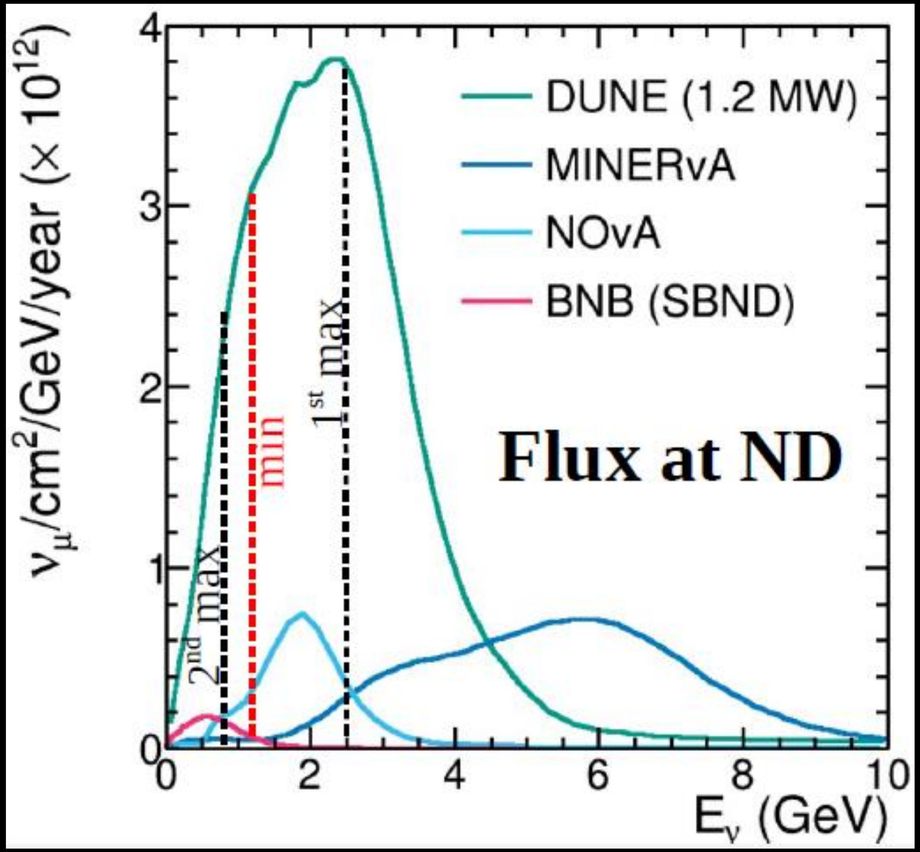
LIQUID ARGON TPC

- 60% of interactions at DUNE energies have final state pions
- LAr TPC allow precise reconstruction of final state
- Excellent separation of e/μ and e/γ
- Aim for 4 detectors 17 kt each
  - 12 x 12 x 60 m

LBNF BEAMLINE

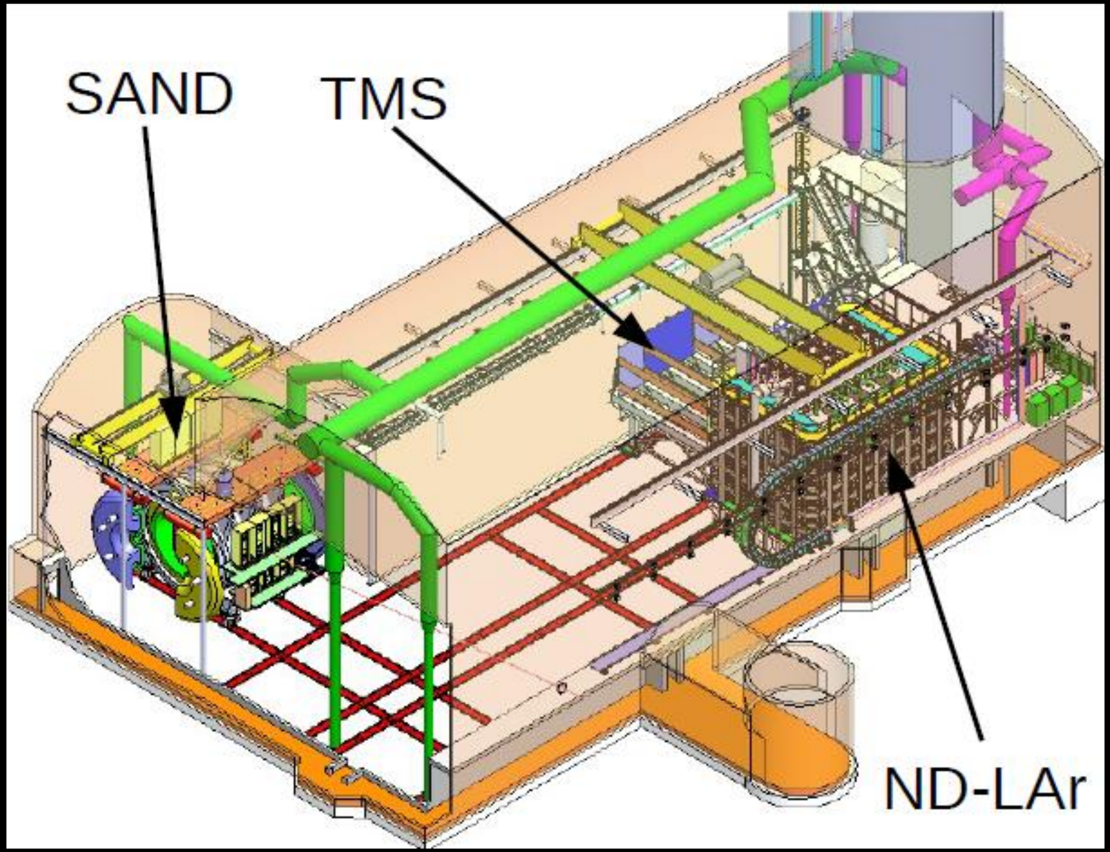
- Wideband beam
  - On axis
  - High flux between first and second oscillation maximum

- Working towards 2 MW beam
  - Aim to double frequency of spills from MI



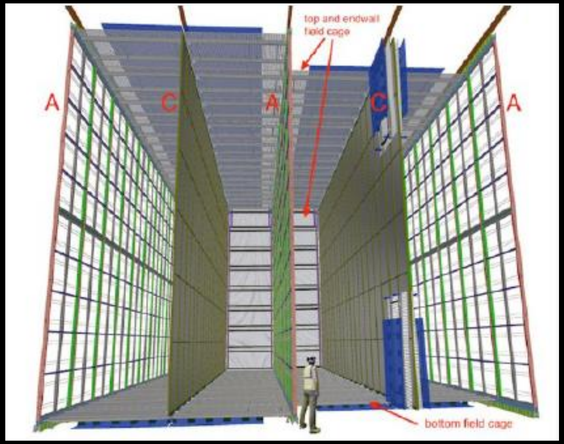
NEAR DETECTORS

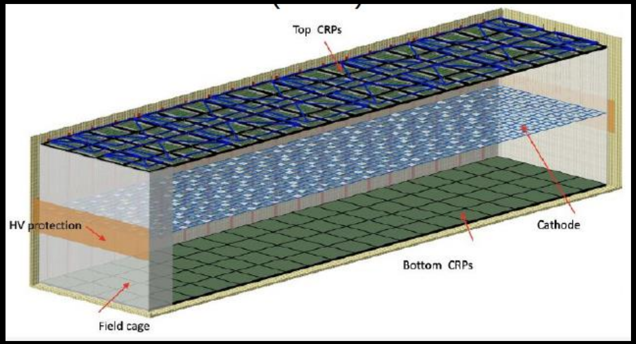
- Movable LAr TPC with muon spectrometer
  - Use off axis effect to measure different spectra
  - Constrain cross sections and neutrino energy reconstruction as a function of neutrino energy
- SAND detector
  - On axis
  - Beam monitor
  - Repurpose solenoid magnet and ECAL from KLOE
  - Add a low-density tracker



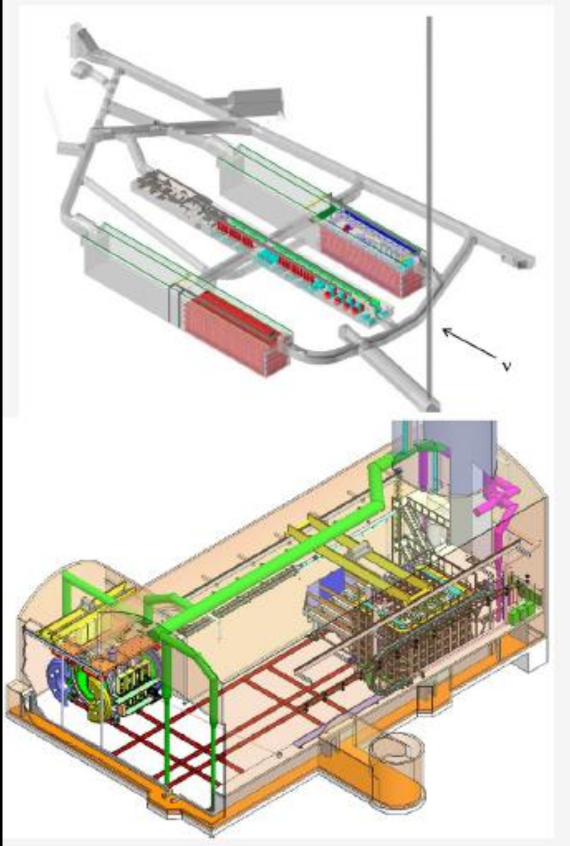
DUNE PHASE I

Horizonal Drift



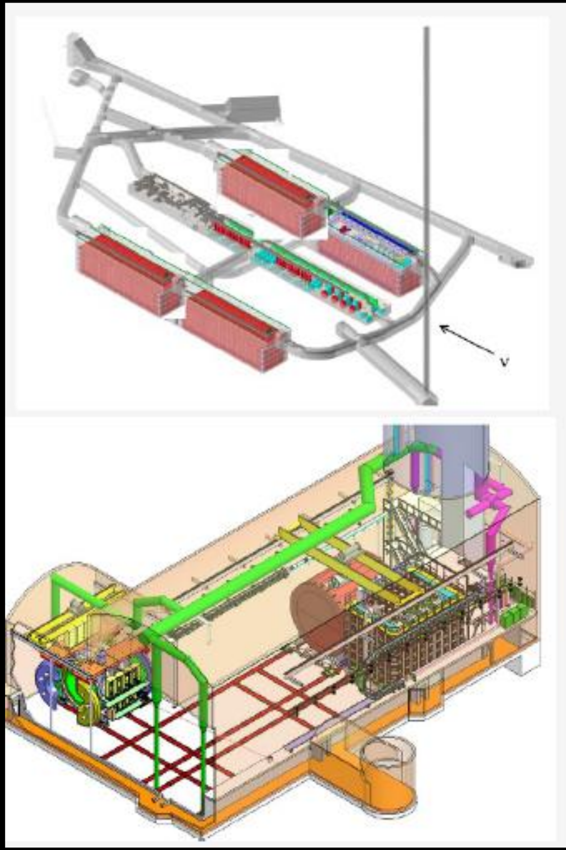


Vertical Drift



- Full near and far site facility
- Two 17 kt Lar TPCs
  - Horizontal Drift module
  - Vertical Drift module
- 1.2 MW neutrino beamline
- Near detectors
  - Moveable LAr TPC + muon catcher
  - SAND

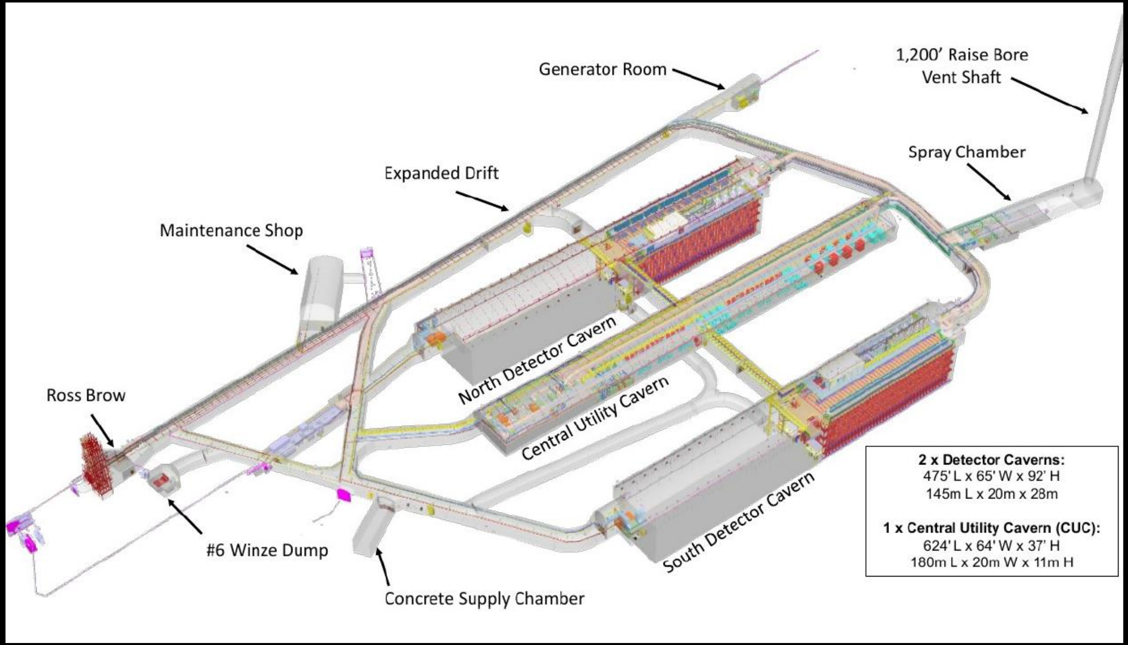
DUNE PHASE II



- Two additional FD modules
  - 3 LAr TPC
  - 4 Module of opertunity

- Upgrade beamline to >2 MW

- More capable near detector
  - High pressure gas Ar TPC

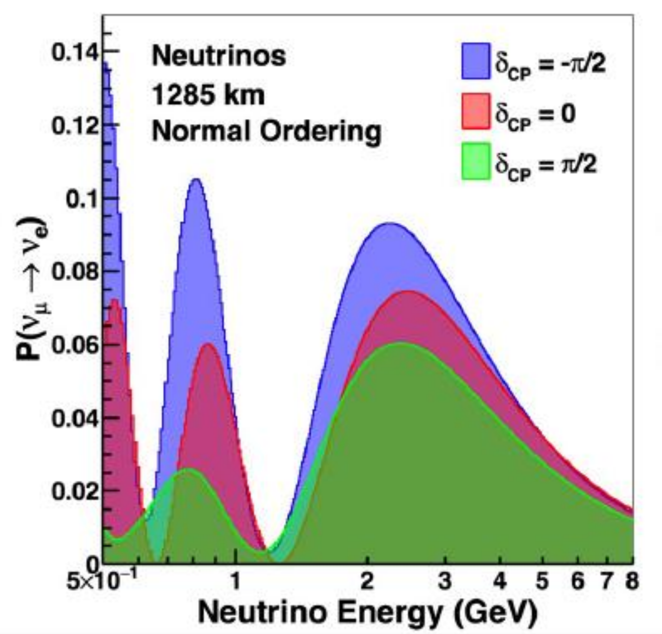


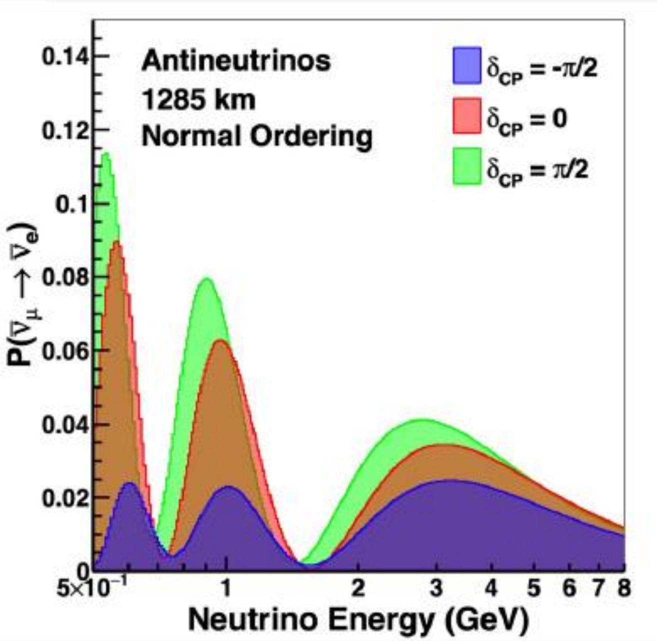
DUNE CONSTRUCTION

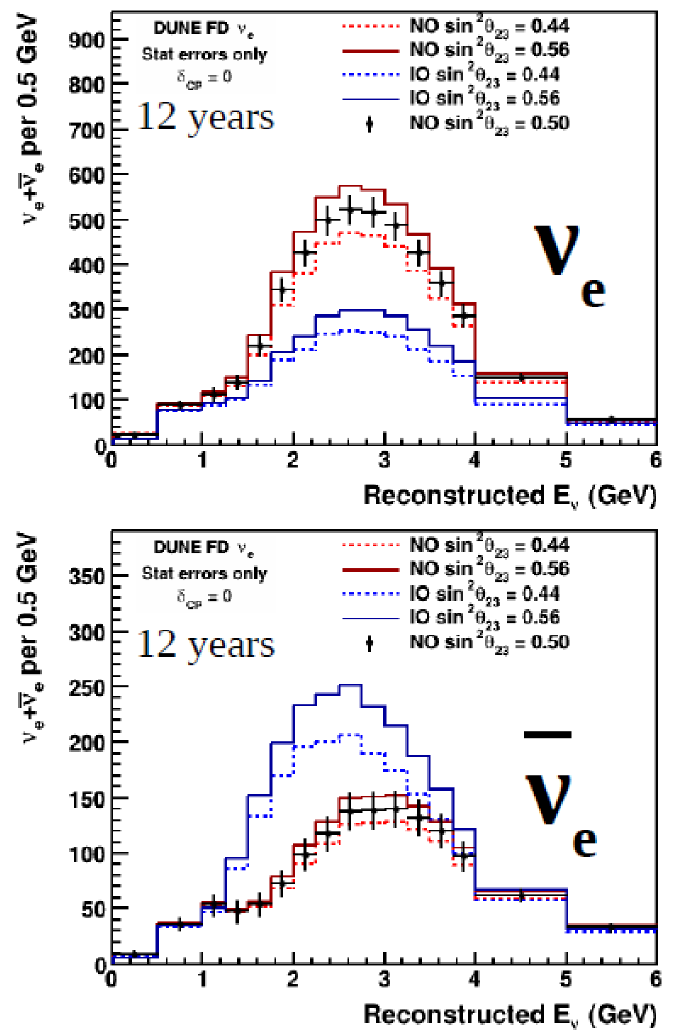
- Far site excavation has been completed
- Building and site infrastructure until mid 2025
- Far detector installation in 2026&27

- Purge and fill with Argon 2028
- First physics by early 2029
- Beam and near detectors from 2031

WHAT DOES DUNE MEASURE?



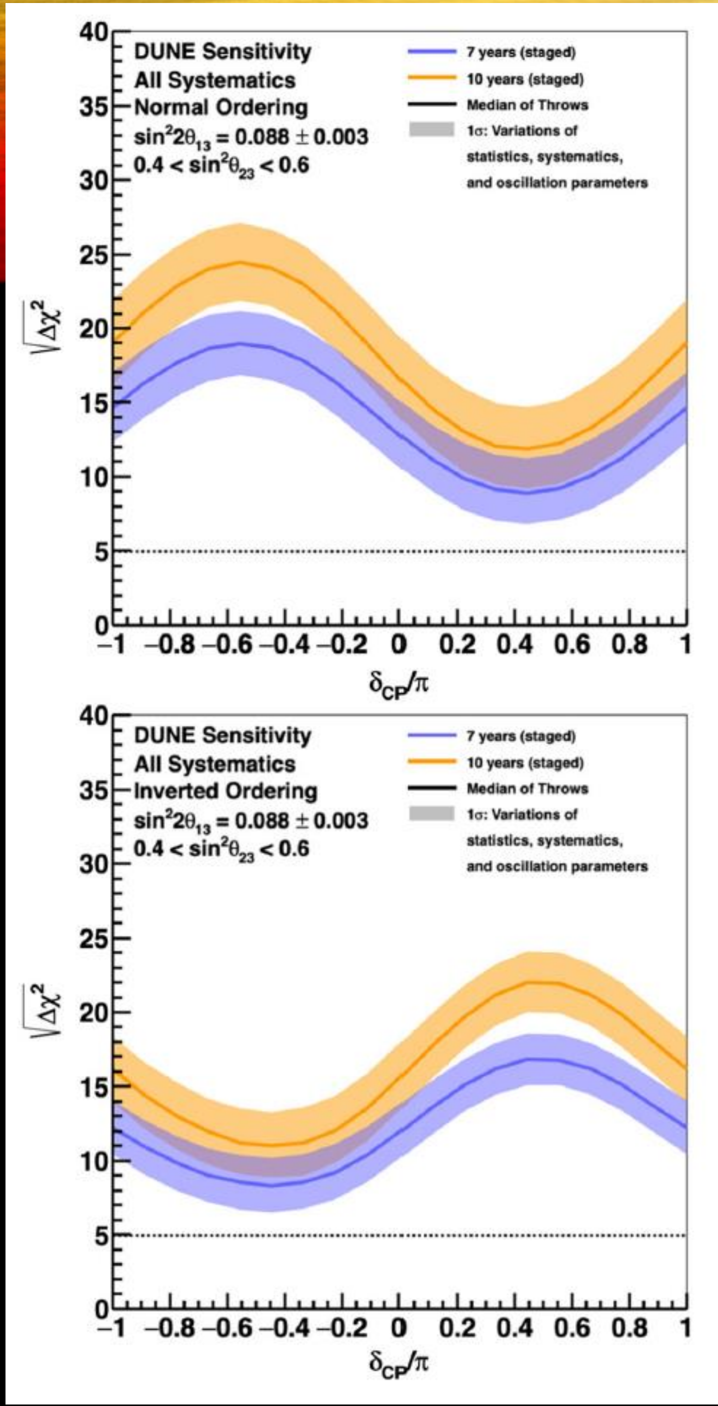




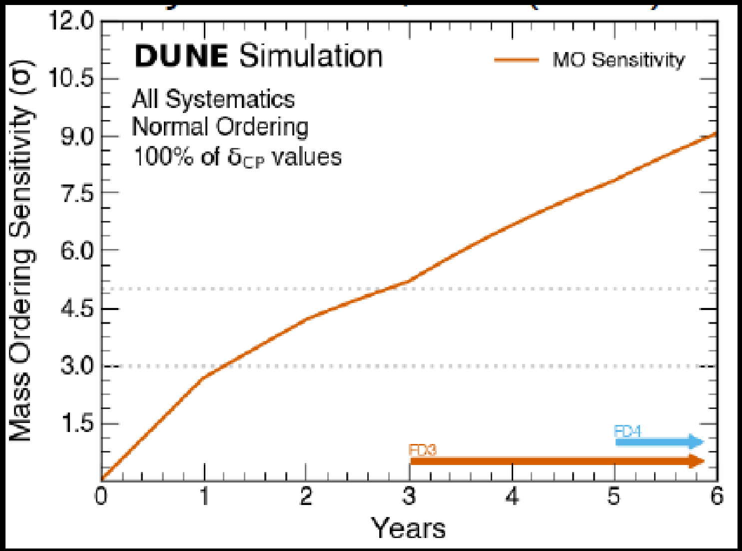
- DUNE aim to measure neutrino and antineutrino oscillations as a function of L/E

- Test the three-flavour model
- Measure oscillation parameters

- Full 5σ sensitivity to MO for all PMNS parameters



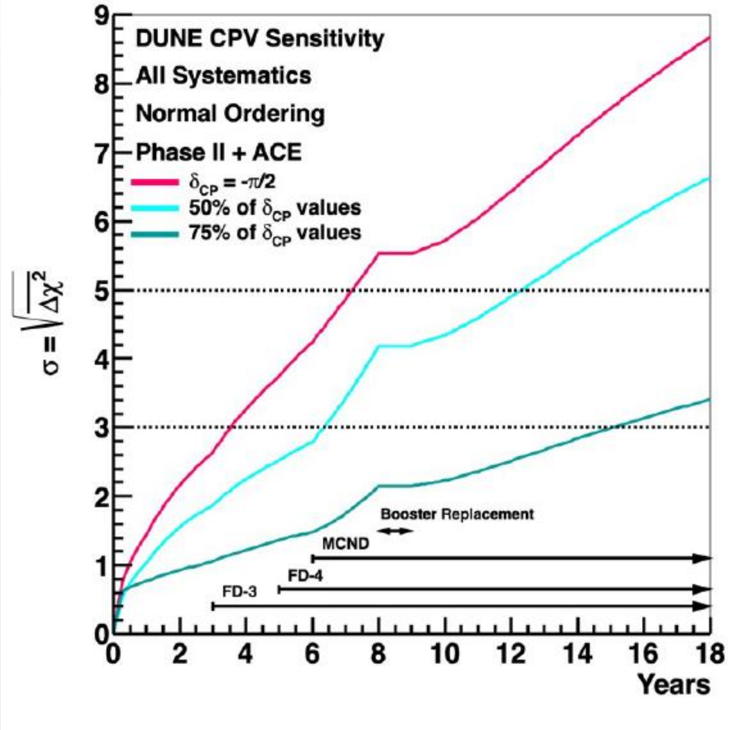
SENSITIVITY TO MASS ORDERING

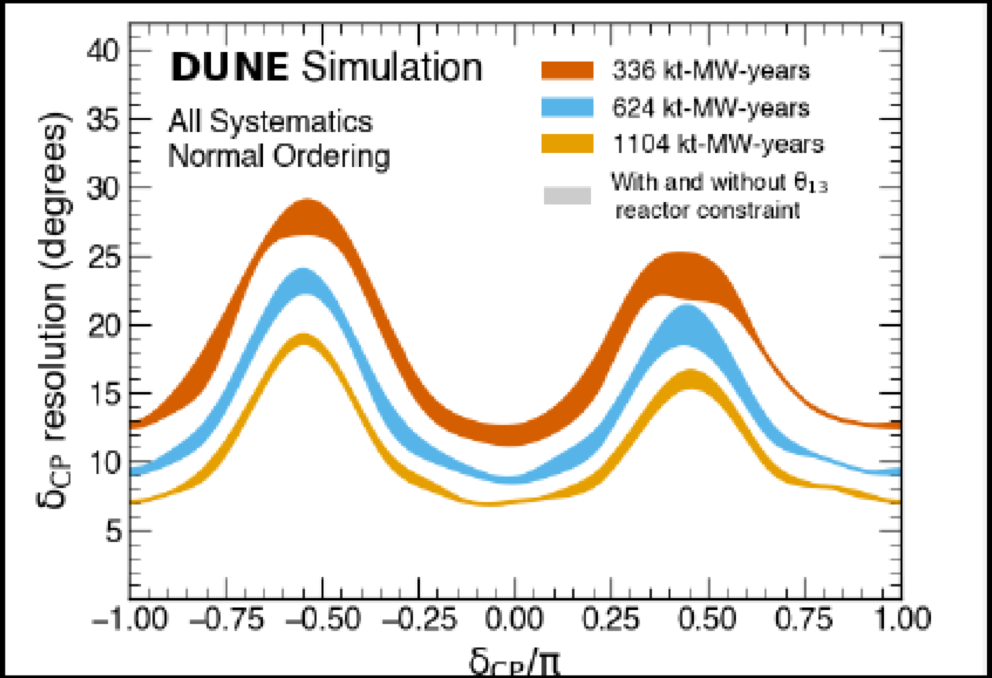


Worst case scenario physics parameters

- DUNE is very sensitive to the mass ordering
  - Longer baseline
  - More matter effect
  - More mass ordering sensitivity
- 5σ exclusion of wrong ordering in 1 – 3 years.

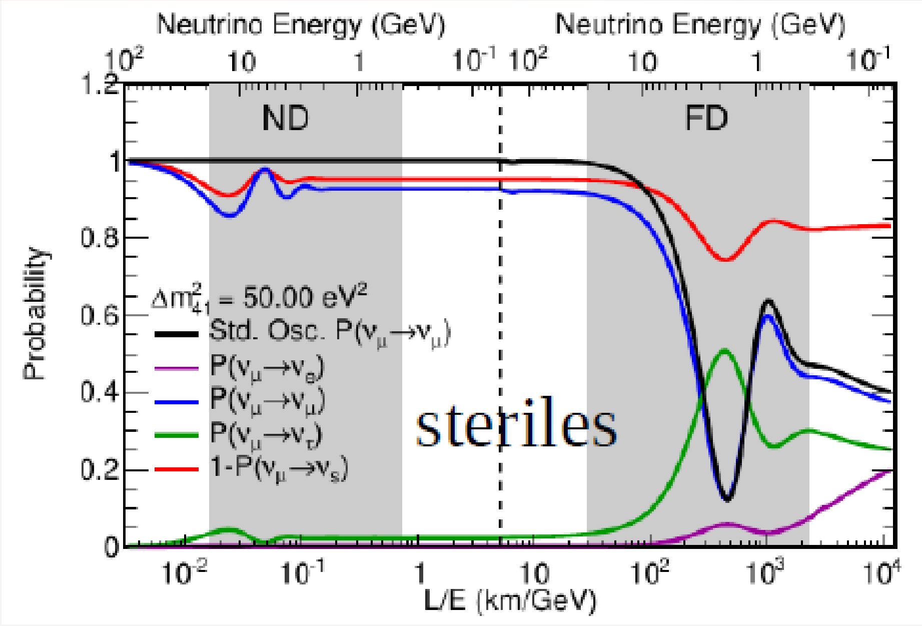
CP SENSITIVITY

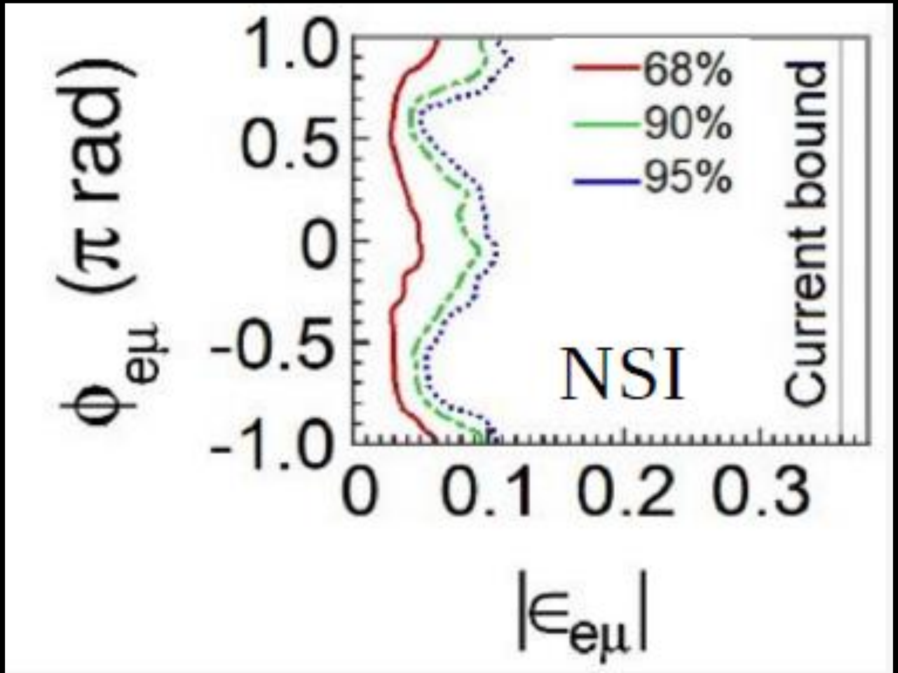




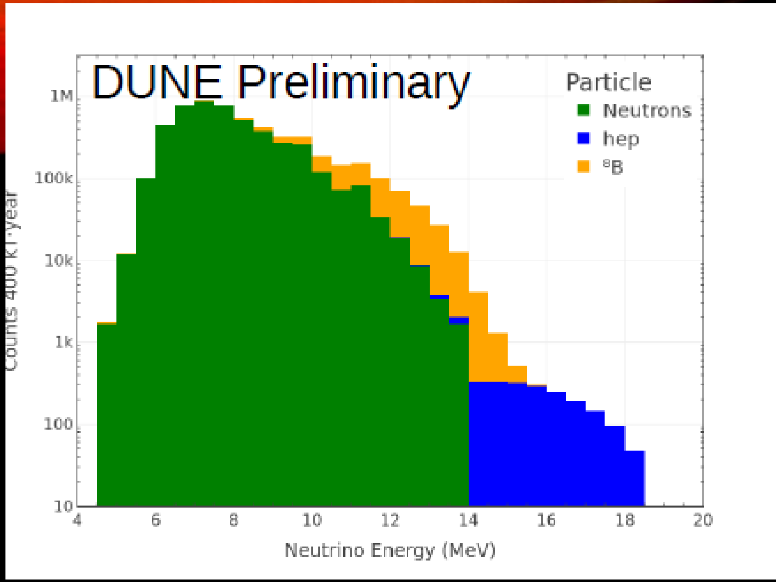
- CP sensitivity in DUNE is through full spectral fit
  - Help to decouple from mass ordering
  - Good to start testing PMNS model
- 5σ coverage of 50% of δ_{CP} values in 12 years
- Smallest final error on δ_{CP} around CP conserving values

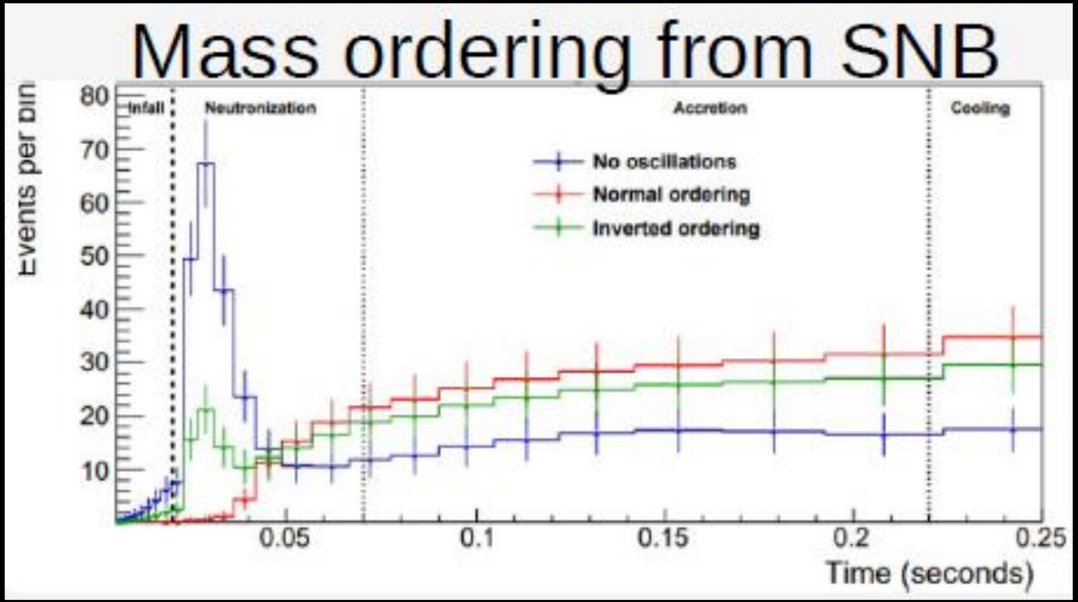
BEYOND THREE FLAVOUR OSCILLATIONS





- Broad range of L/E at ND and FD
  - Search for non-SM oscillations
- High statistics in neutrino and anti-neutrino mode
- Very large matter effect
  - Unique sensitivity to some NSI models



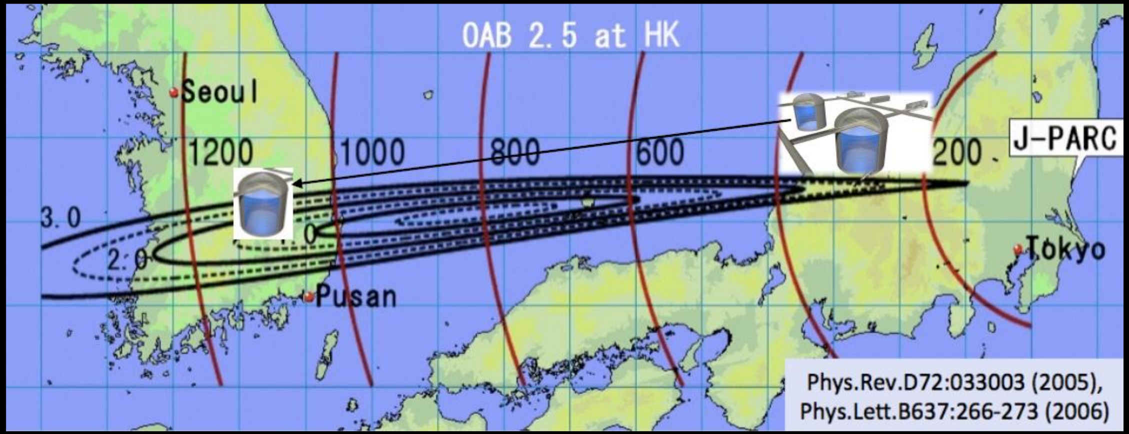


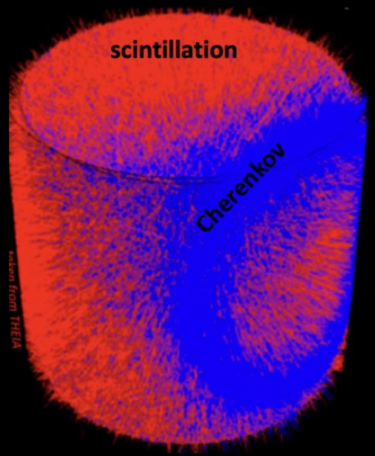
OTHER DUNE PHYSICS

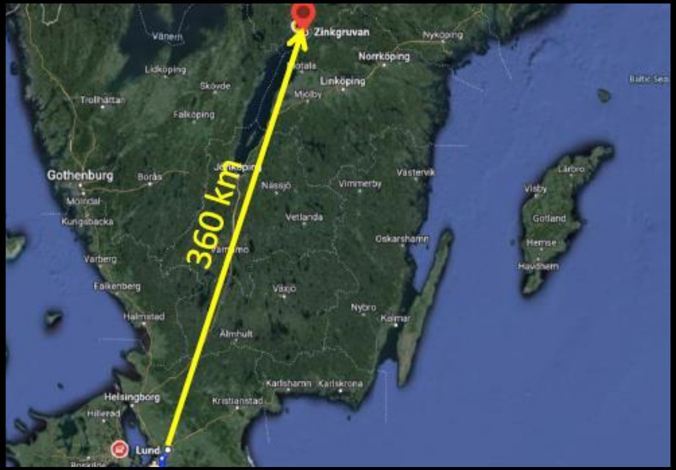
- Solar neutrinos
  - Interaction of ν_e with Ar gives improved spectral sensitivity
  - Can make first measurement of hep neutrinos
- Atmospheric neutrinos
  - DUNEs first high energy neutrino measurements
  - Hadron reconstruction improves angular resolution
- Supernova neutrinos
  - Primary sensitivity to ν_e
  - Access to neutronization peak

LONG BASELINE FURTHER DOWN THE ROAD

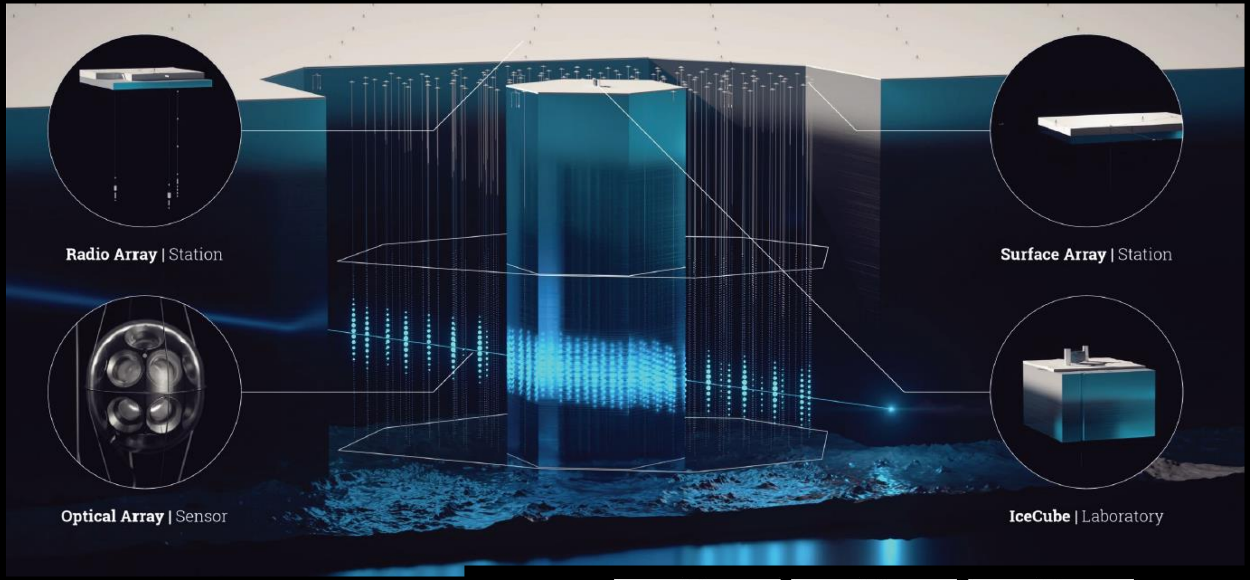
- The impact of oscillations at the second maximum is enhanced.
- Experiments may want to follow this up
  - KNO
  - ESSνSB
- DUNE module of opportunity
  - Could be a different technology
  - THEIA
    - WBLS detector
    - Scintillation and Cherenkov
    - Opens up new possibilities





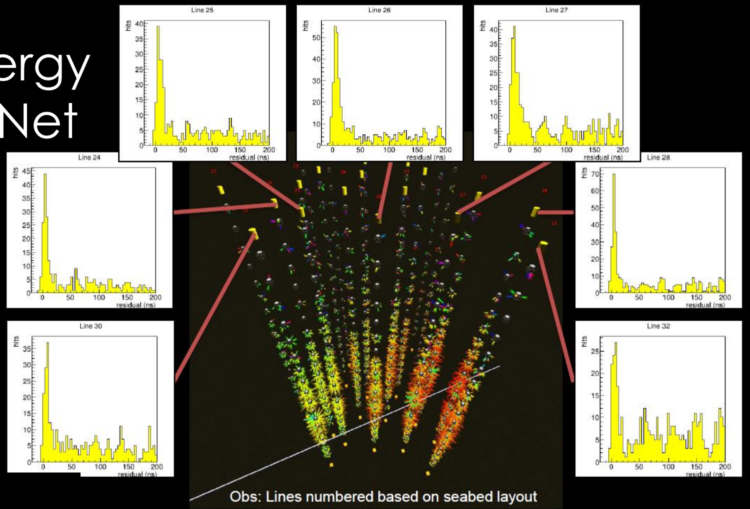


BEYOND OSCILLATIONS



- Neutrino Telescopes
  - Very successful first 10 years of IceCube
  - ICECube – Gen 2
    - 5X effective area
    - 2x angular resolution
    - Includes Radio array
  - Northern Hemisphere Telescopes
    - KM3Net
      - Now under construction
      - First data with first strings already taken
    - P1
      - In the Pacific off Victoria
    - BAIKAL-LVD
- Neutrino mass experiments
  - Katrin++
  - Project 8
  - ECHo and Holmes
- And more…….

Ultra high energy event in KM3Net



SUMMARY

- We are approaching the precision measurement phase for neutrino oscillations
  - Excellent prospects to discover CP violation, mass ordering and octant in the next 10 years
  - Should think ahead: how do we verify the PMNS model
- Three very large experiments to start in this period
  - JUNO
  - Hyper-Kamiokande
  - DUNE
- It's a broad field there are many other smaller experiments as well and I didn't even mention the neutrino factory…..

THANK YOU FOR LISTENING