Future Neutrino Facilities (from a flavor perspective)

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Flavor Physics and CP Violation

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Outline

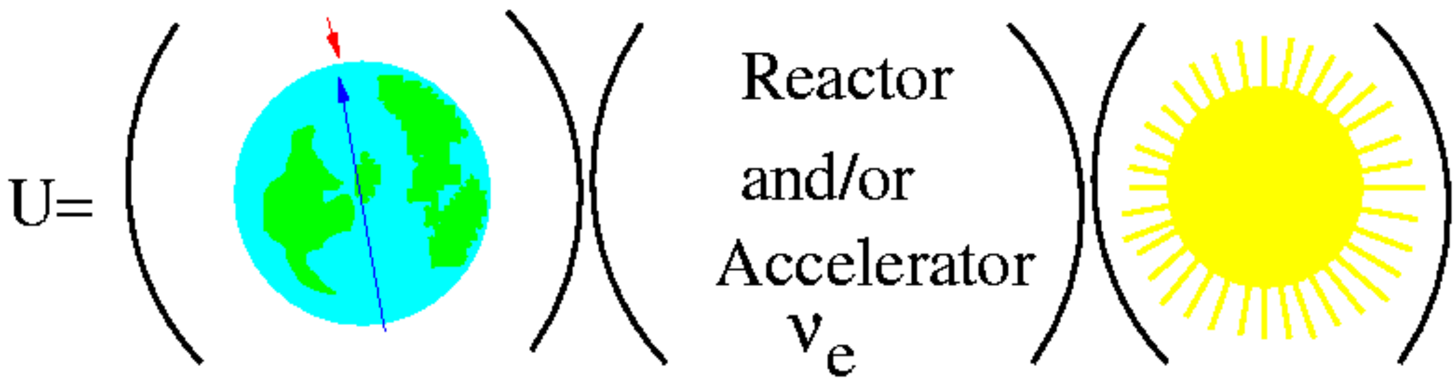
- Flavor Physics in the Lepton Sector and what we can learn
  - The pattern of neutrino masses
  - Whether they violate CP conservation
  - Something even more unexpected
- Flavor Measurements at new facilities
  - ICECUBE → PINGU
  - Hyper-K
  - DUNE
- Big goals mean big challenges
  - Learning to build bigger better detectors
  - Learning to make more precise predictions for Far Detectors
  - Learning about the nucleus (see K. McFarland's talk)

Flavor Physics with Neutrinos

When the weak and mass eigenstates are not the same:
3x3 Unitary matrix, defined by 3 mixing angles and one phase

Call them $\theta_{12}, \theta_{23}, \theta_{13}, \delta$ if $s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$, then

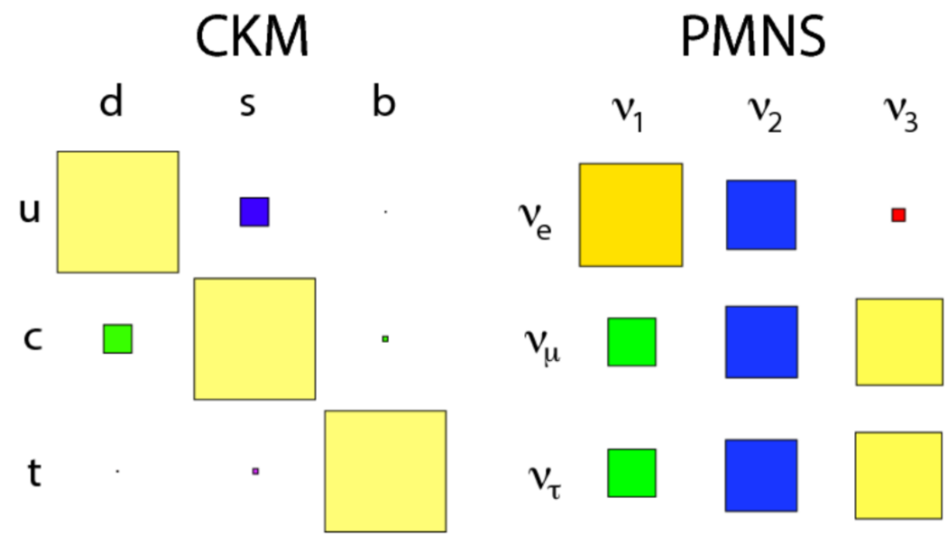
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



- A lot more complicated than 2ν's: $P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)$

Why look for CP violation with leptons?

- Same reason you have looked for it in quark sector: why is there no antimatter today?
- Maybe neutrinos oscillate differently from anti-neutrinos!

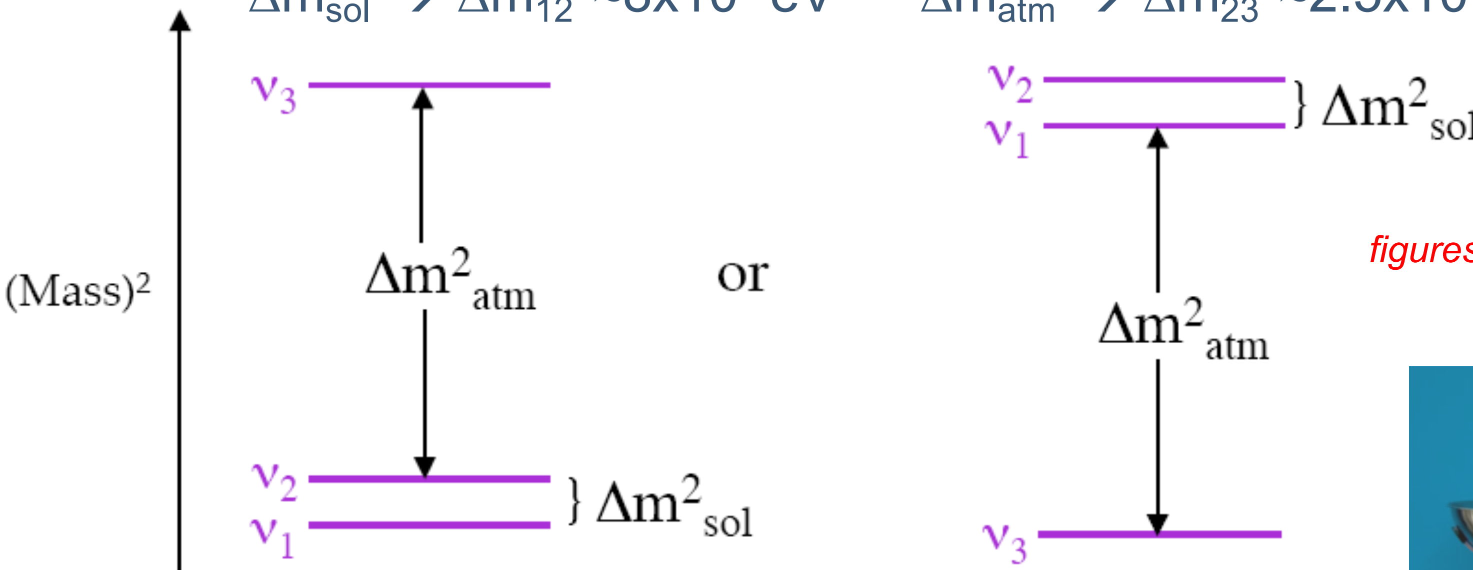


https://arxiv.org/abs/1212.6374

What else do we want to know?

- Do neutrino mass states have the same mass structure as the charged fermions?

$\Delta m_{sol}^2 \rightarrow \Delta m_{12}^2 \approx 8 \times 10^{-5} eV^2$ $\Delta m_{atm}^2 \rightarrow \Delta m_{23}^2 \approx 2.5 \times 10^{-3} eV^2$

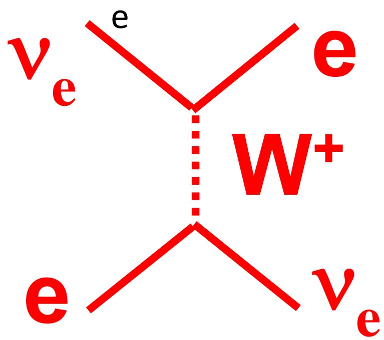


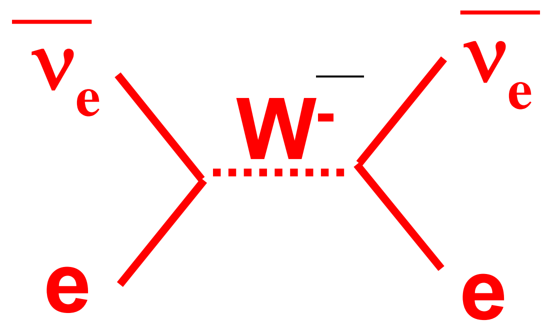
figures courtesy B. Kayser

- By sending neutrinos through the earth, you can become sensitive to this difference because the earth is full of electrons

Measuring Mass Ordering

- Electrons in the earth act on ν_e and $\bar{\nu}_e$'s differently from eachother, and from ν_μ or ν_τ





Wolfenstein, PRD (1978)

- For 2 generations… $P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)$

$$x = \frac{2\sqrt{2} G_F n_e E_\upsilon}{\Delta m^2}$$

$n =$ e⁻ density

$$\sin^2 2\Theta_M = \frac{\sin^2 2\Theta}{\sin^2 2\Theta + (\pm x - \cos 2\Theta)^2}$$

$$L_M = L \times \sqrt{\sin^2 2\Theta + (\pm x - \cos 2\Theta)^2}$$

Bad news: this complicates search for CP violation,

Good news: it means you can measure the mass ordering

3-generation $\nu_\mu \rightarrow \nu_e$ Probabilities

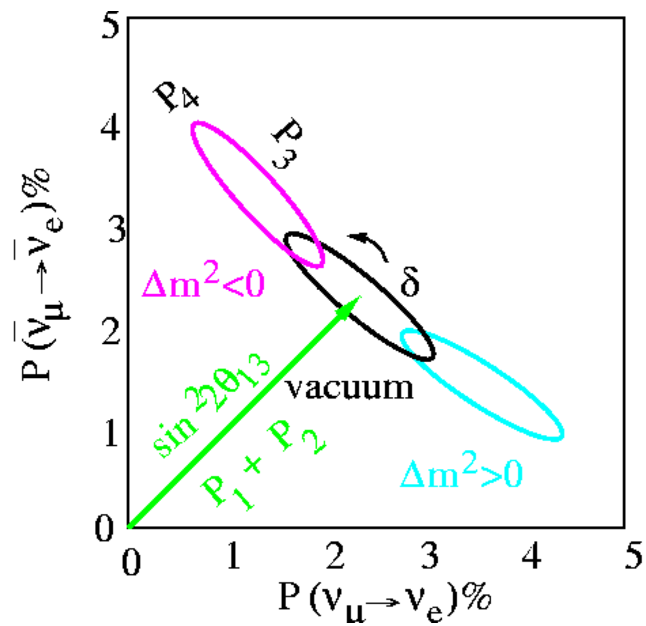
- $P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$

$$P_1 = \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\frac{B_\pm L}{2}$$

$$P_2 = \cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\frac{AL}{2}$$

$$P_3 = J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$$P_4 = \mp J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

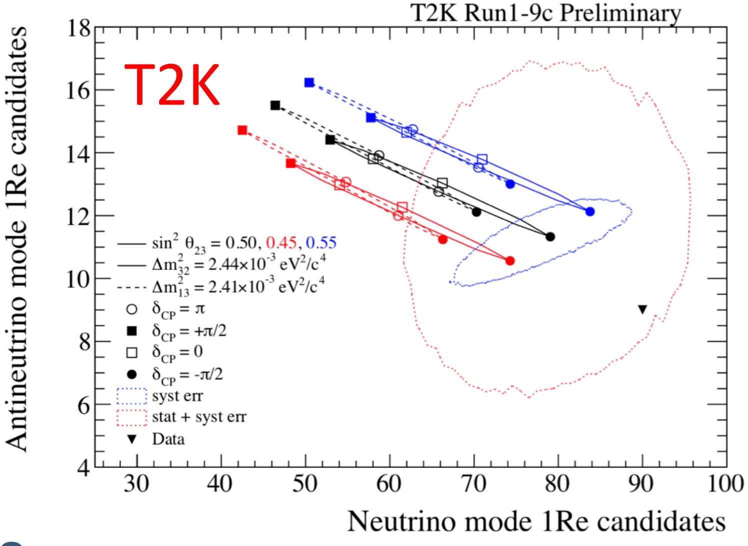


Minakata & Nunokawa JHEP 2001

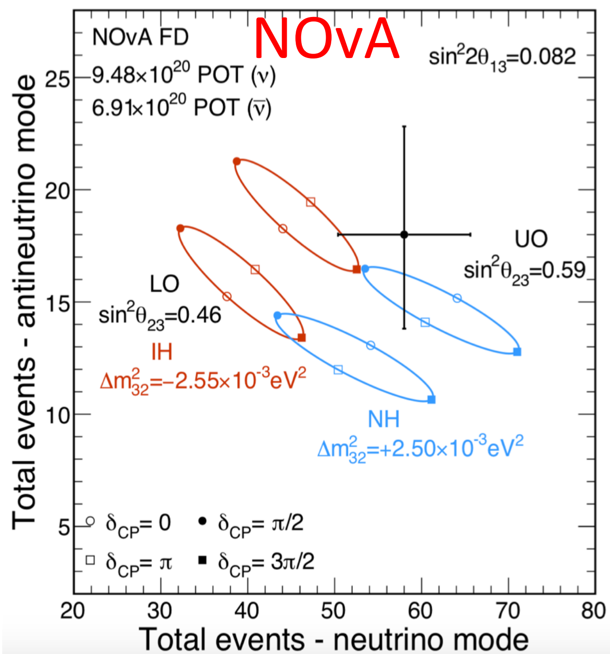
- Much more complicated than 2-generation mixing
- Interference between atmospheric and solar terms is where CP violation arises
- Size of that interference is function of all angles, including θ_{13}
- Measurement at one L and E is not enough!

Why make new facilities?

- Today's accelerator ν experiments cover narrow energy bands, statistics come slowly…
- What to see precision across broad energy range
  - Need intense beam & huge detectors
  - Need to distinguish neutrino flavor
  - Need to understand much better how neutrinos leave energy in a detector!
- Three strategies:
  - All Mass ordering, no ~~CP~~: PINGU
  - All ~~CP~~, almost no mass ordering: Hyper-K
  - Sensitivity to both: DUNE



M. Wascko, ν2018

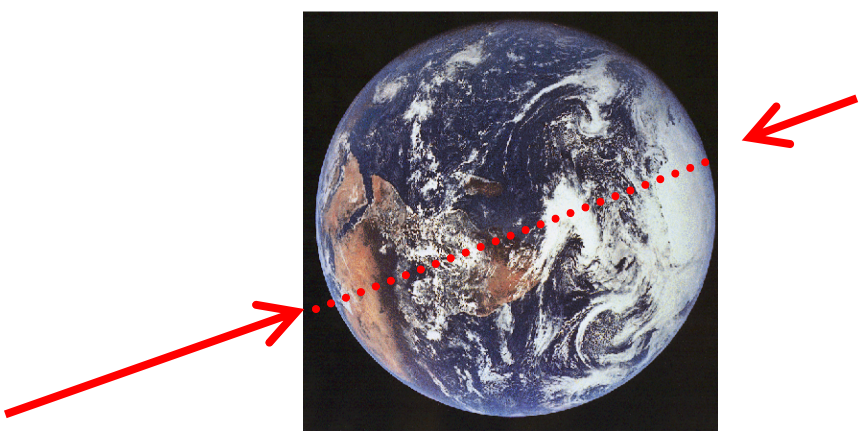


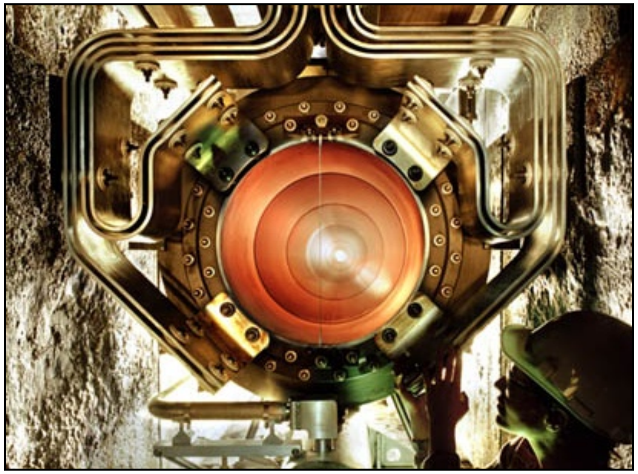
M. Sanchez, ν2018

Neutrino Sources

- Atmosphere
  - Protons hit upper atmosphere
  - Pions and Kaons are produced and decay
  - Flavor Ratio: 2 ν_μ per ν_e
  - ν/anti-ν ratio: depends on the neutrino energy

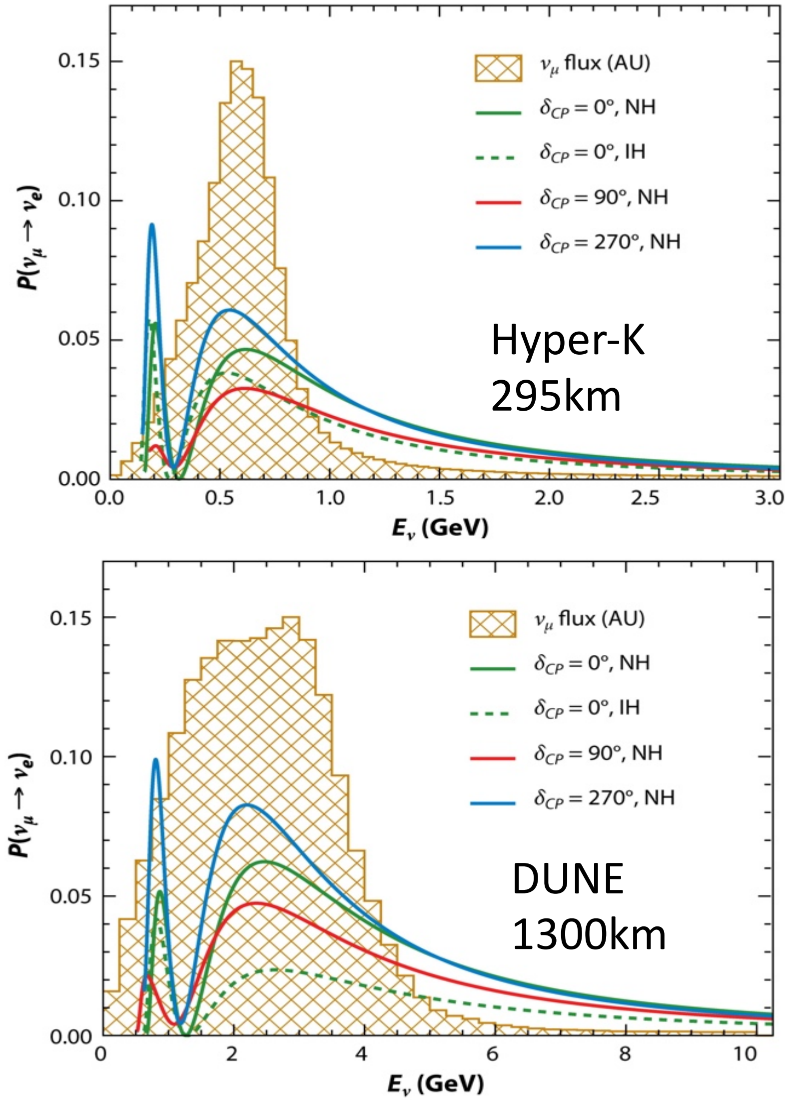
- Accelerator Beams
  - Protons hit a C or Be target
  - Pions and Kaons produced and are focused then decay
  - Flavor Ratio: ~100 ν_μ per ν_e
  - ν/anti-ν ratio: depends on focusing, but ~95% pure at peak





Flavor Physics in DUNE and Hyper-K

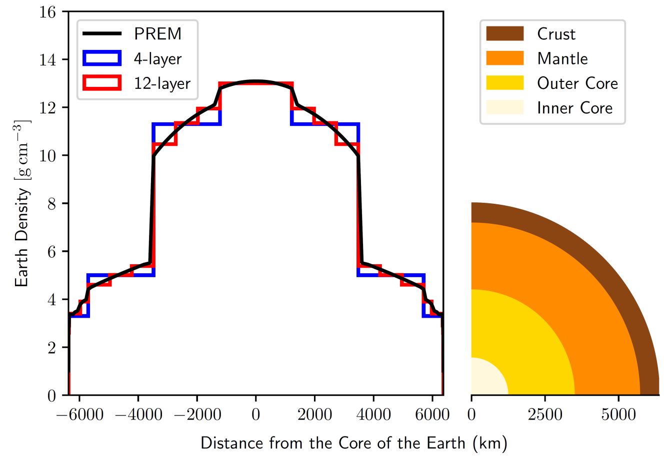
- Neutrino Spectra cover between 1 and 2 oscillation maxima, Normal and Inverted Hierarchy shown here for no CP violation
- 2 different approaches:
  - Narrow band to focus events and sensitivity on oscillation maximum
  - Broad band to map out oscillation shape over wide range
  - Hyper-K uses upgraded T2K beamline in J-PARC
  - DUNE uses new beamline at Fermilab



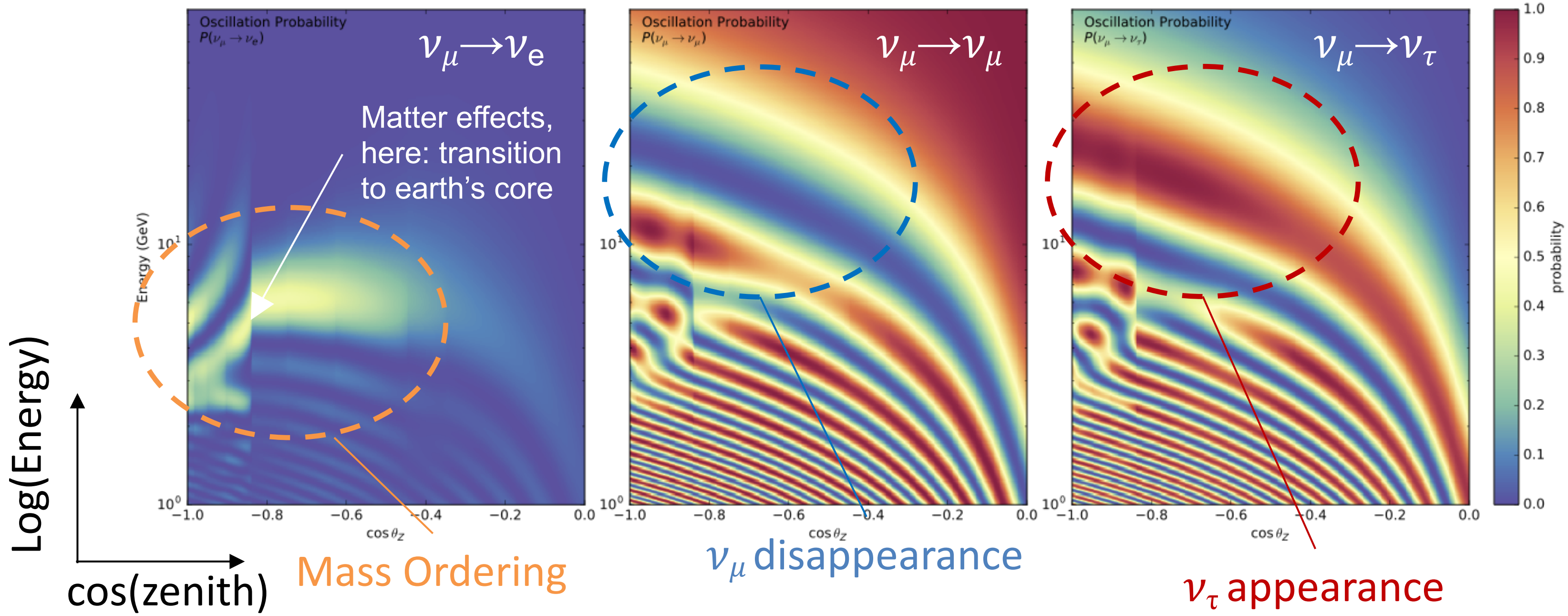
Diwan MV, et al. 2016.
Annu. Rev. Nucl. Part. Sci. 66:47–71

Flavor Physics in PINGU

- By separating out muon neutrinos by energy and zenith angle, try to distinguish between normal and inverted mass ordering

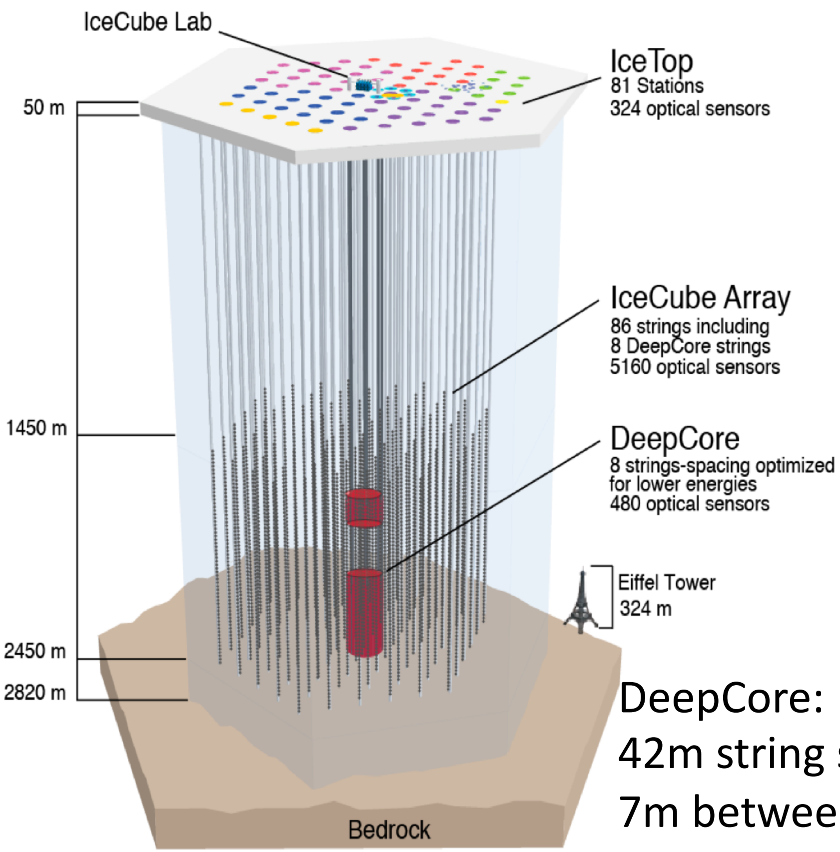


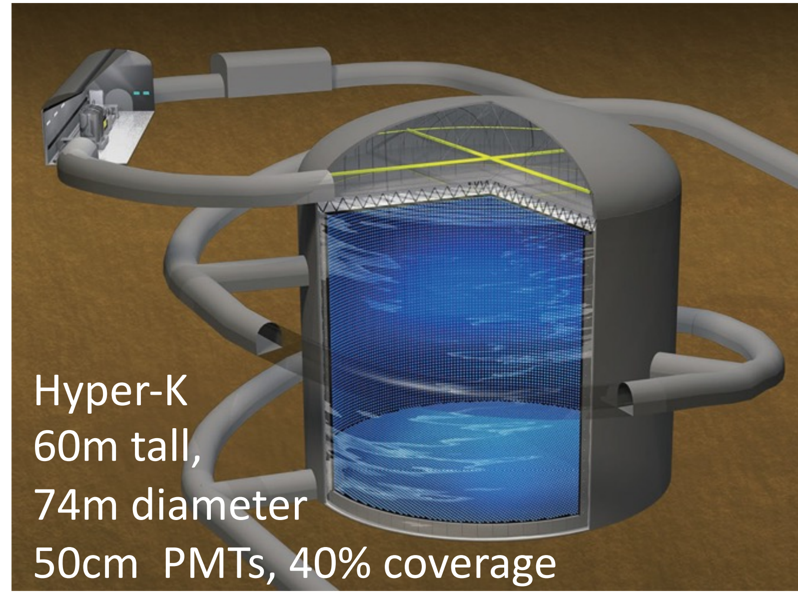
hep-ex 1902.07771

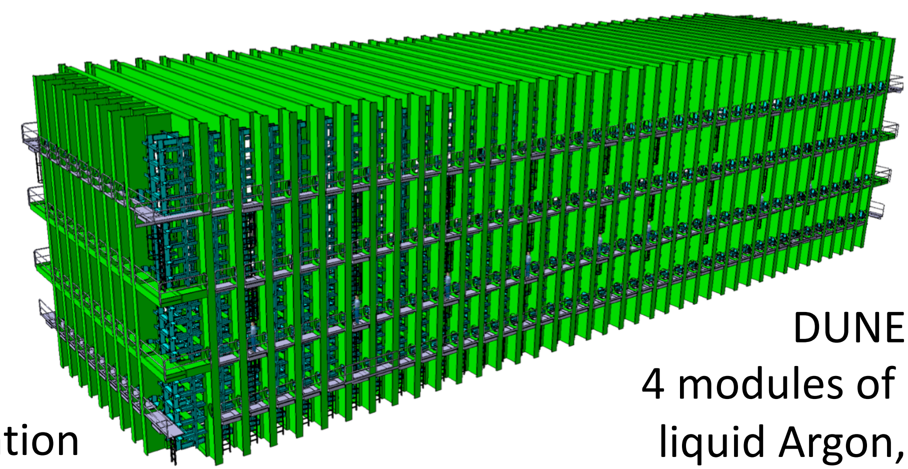


Neutrino Detectors

- ICECUBE, Hyper-Kamiokande, DUNE: 3 very different detectors, different sizes, different granularity



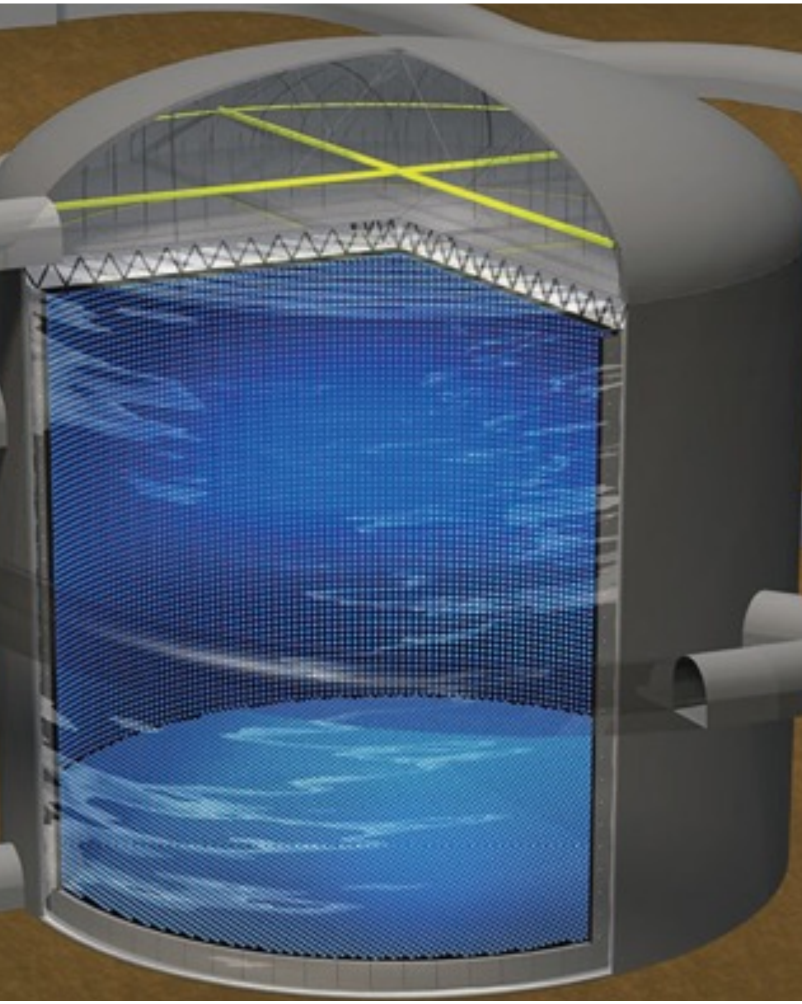




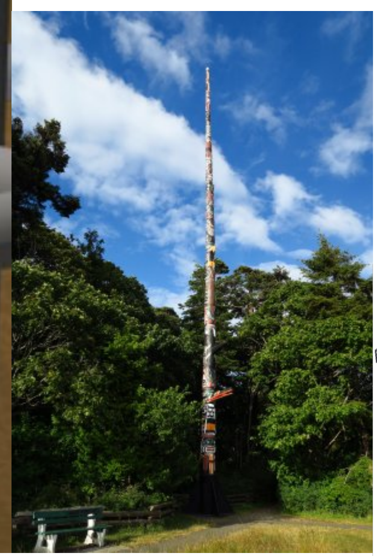
DeepCore:
42m string separation
7m between each PMT
PINGU: 2.4 and 7m PMT separation

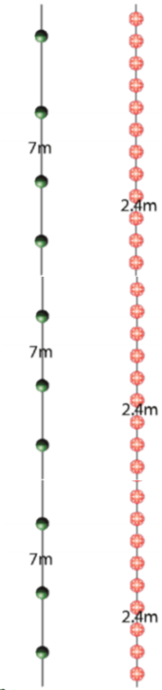
DUNE
4 modules of
liquid Argon,
Active: 60m x 12m x 14m
Wire pitch ~4.7mm.

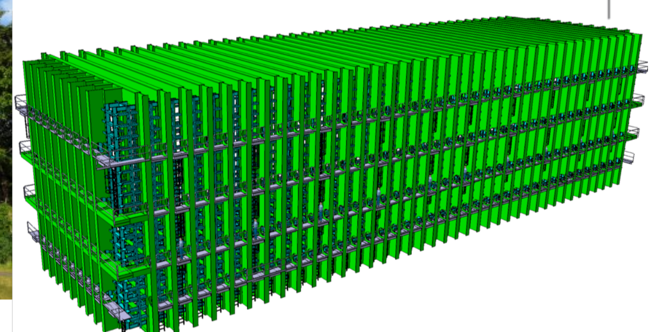
What can you do in 40m?



- I got to see the world’s largest free-standing totem pole in Beacon Hill Park yesterday: 40m tall

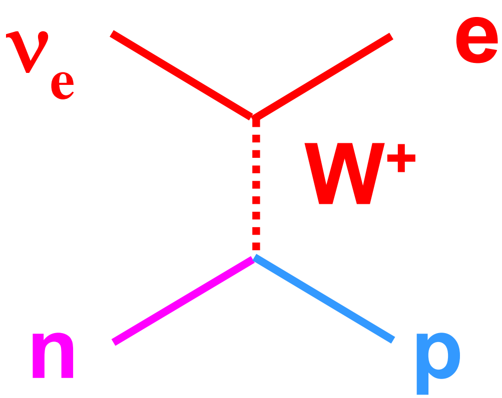




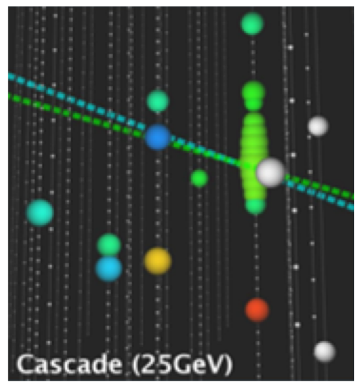


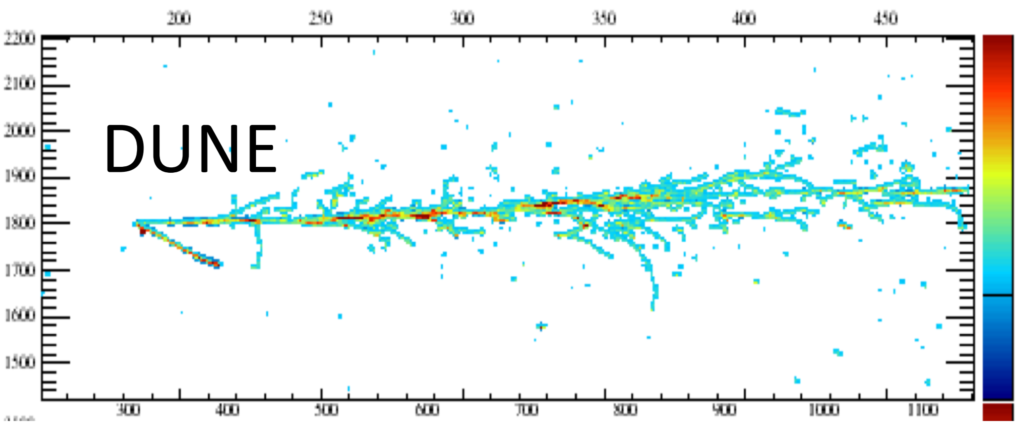
Neutrino Interactions

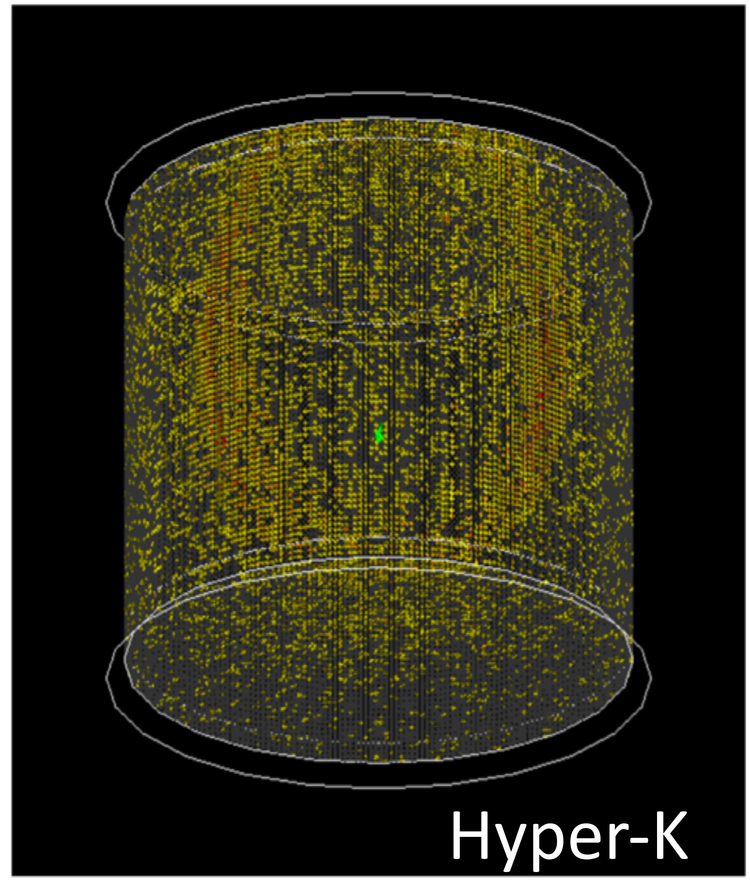
- ν_e charged current interactions, 3 very different ways



Deep Core



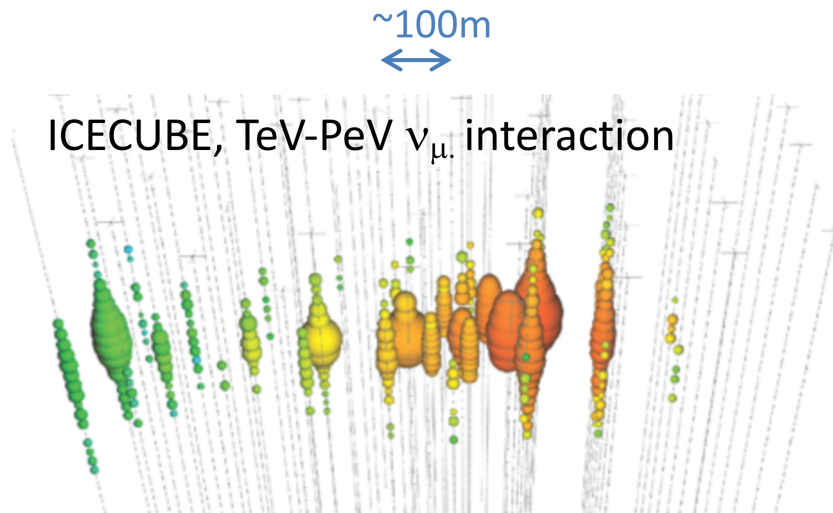


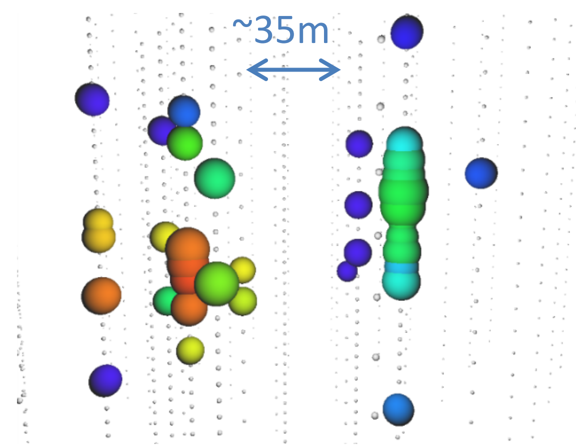


But beware: neutrinos can interact in a lot more complicated ways than this…

Neutrino Detection: Cerenkov

- ICECUBE and Hyper-K
  - Use Cerenkov radiation in water or ice to see secondary charged particles produced by neutrinos interacting on nuclei
  - ICECUBE sees high energy showers and muons that extend past those showers





Deep Core GeV ν interaction

Neutrino Detection: Cerenkov

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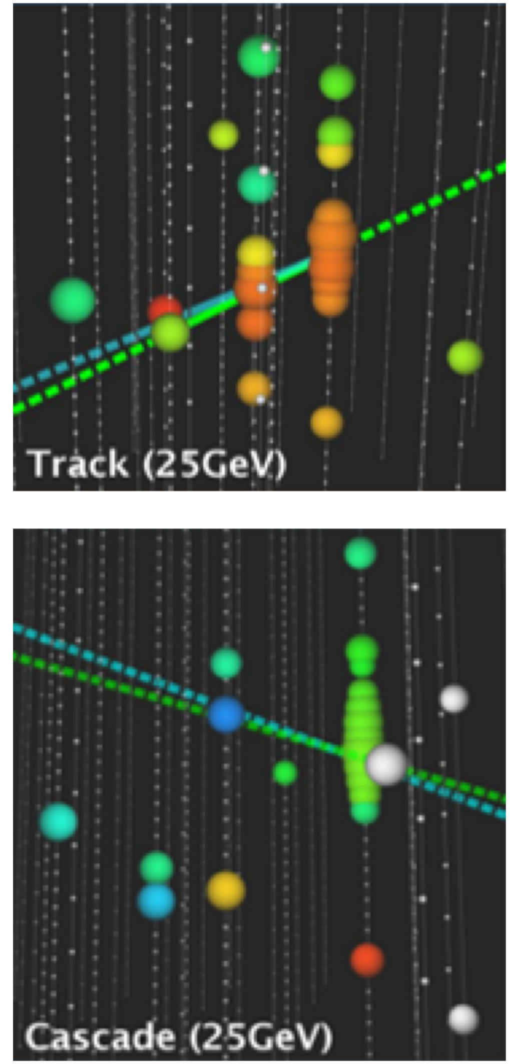
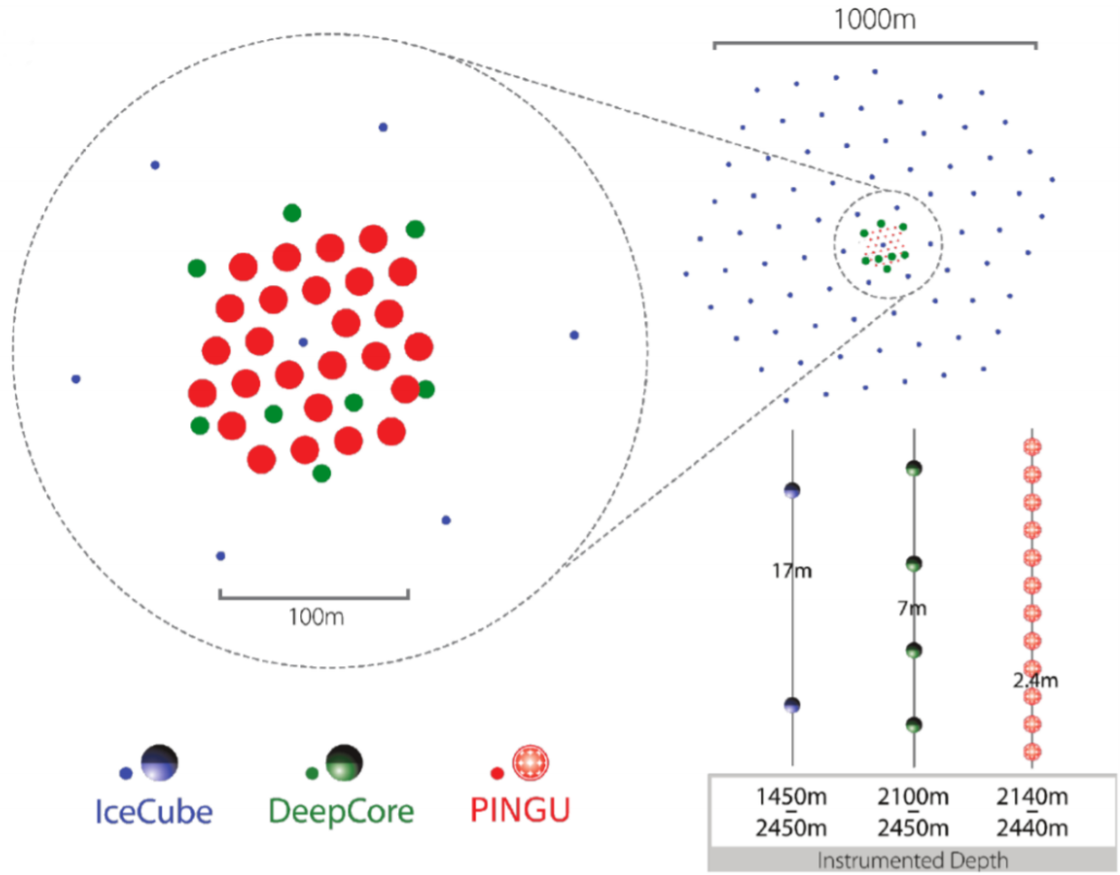


Deep Core Event displays courtesy Philipp Eller

From ICECUBE to PINGU

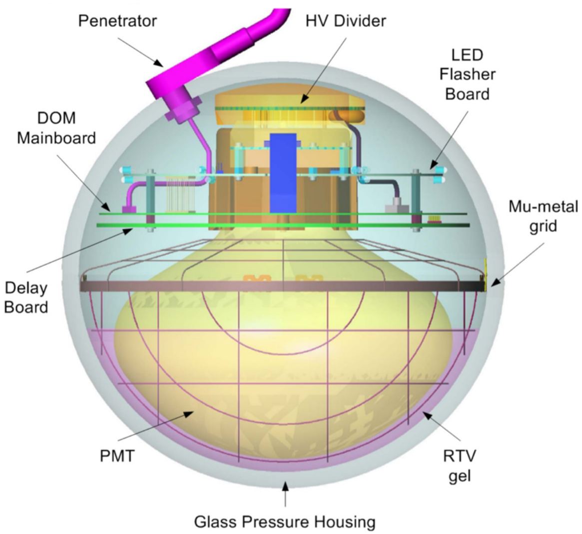
- PINGU
  - 7 for phase I, but then…
  - 26 strings, 100 optical modules each
  - Different optical modules
  - New Calibration system



Graphics courtesy P. Eller

PINGU Preparations

- Focus on Optical performance and string separation
- New Calibration strategies: add new strings but with more calibration devices on board (LED's to get better inner-PMT spacing



Current Design

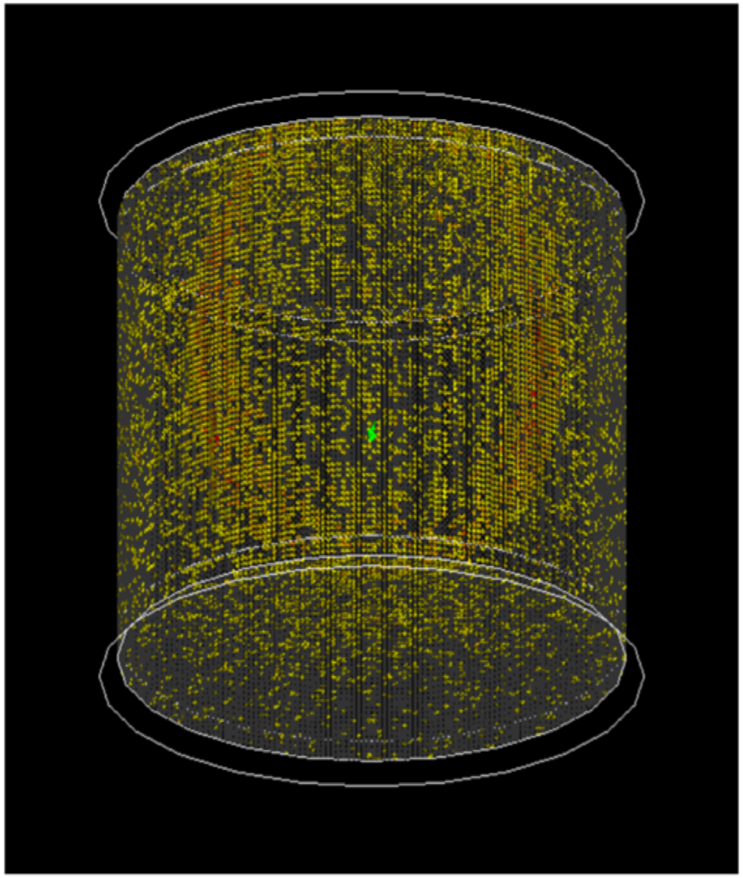
EGG-2 Design

New Multi-PMT Design

Neutrino Detection: Cerenkov

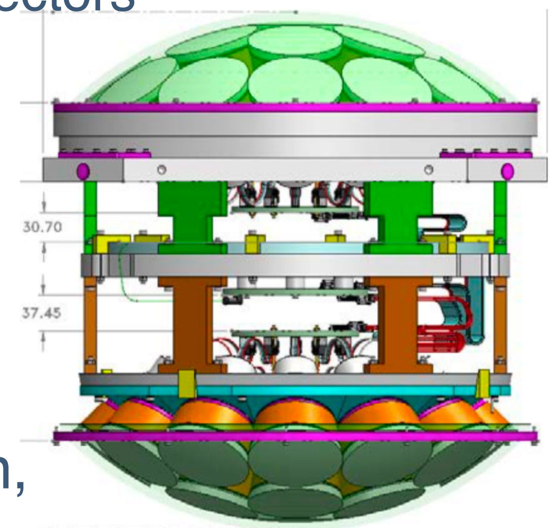
- ICECUBE and Hyper-K
  - Use Cerenkov radiation in water or ice to see secondary charged particles produced by neutrinos interacting on nuclei
  - Hyper-K running at energies where you see final lepton and maybe evidence of a pion through $\pi \to \mu \to e$ decay chain

Hyper-K 700MeV $\nu_{e.}$ interaction



Hyper-K Preparations

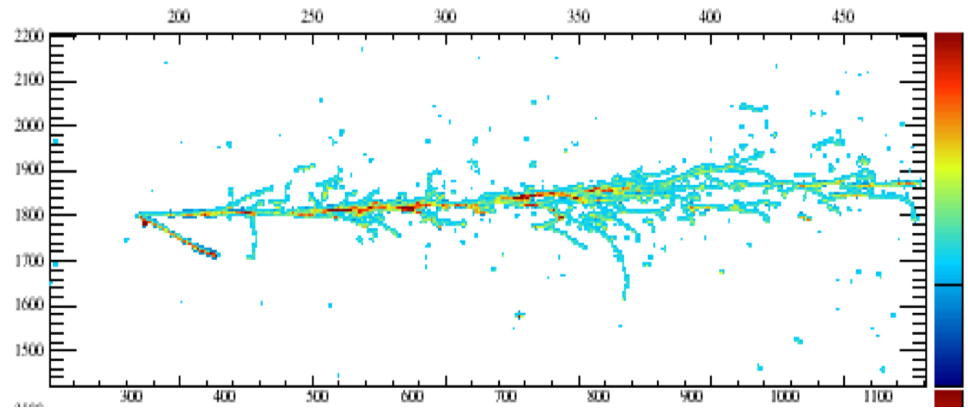
- Improvements in Optics:
  - Multi-PMT investigations for Near and Far Detectors
  - make sure phototubes can survive an an implosion in the tank
  - Higher efficiency photocathodes
  - Improve electronics readout to take high rate from supernovae



- Aside….Gd doping: better neutron detection, better sensitivity to reactor antineutrinos
  - Super-K was emptied in 2018, leaks repaired, filled with pure water
  - Preparing Super-K detector for addition of Gd
  - Ultimately if this went into Hyper-K the low energy physics reach would be enormous (solar and reactor neutrinos)

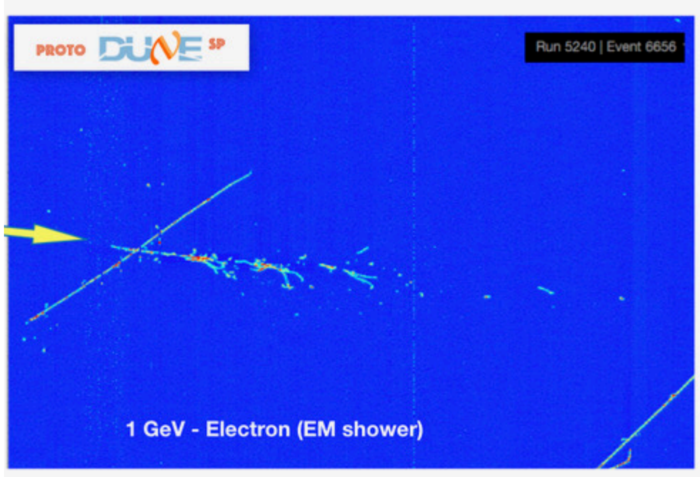
Neutrino Detection: TPC

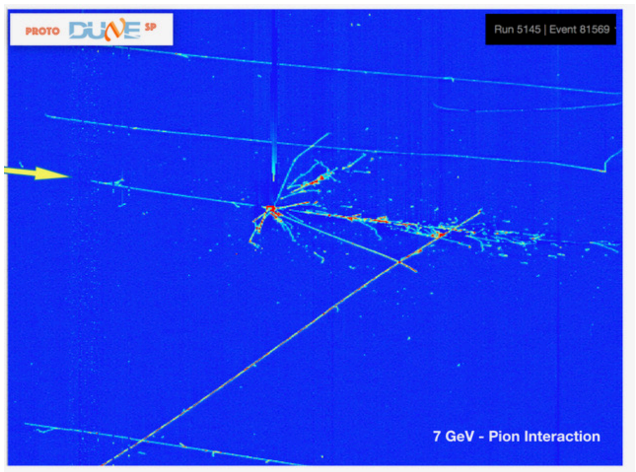
- Electronic bubble chamber that lets you see most final state particles (except neutrons)
- Liquid Argon gives you ionization electrons (slow) and scintillation light (fast)



Simulated ν_e+Ar to e+p+X event

Electron and pion test beam events in ProtoDUNE at CERN





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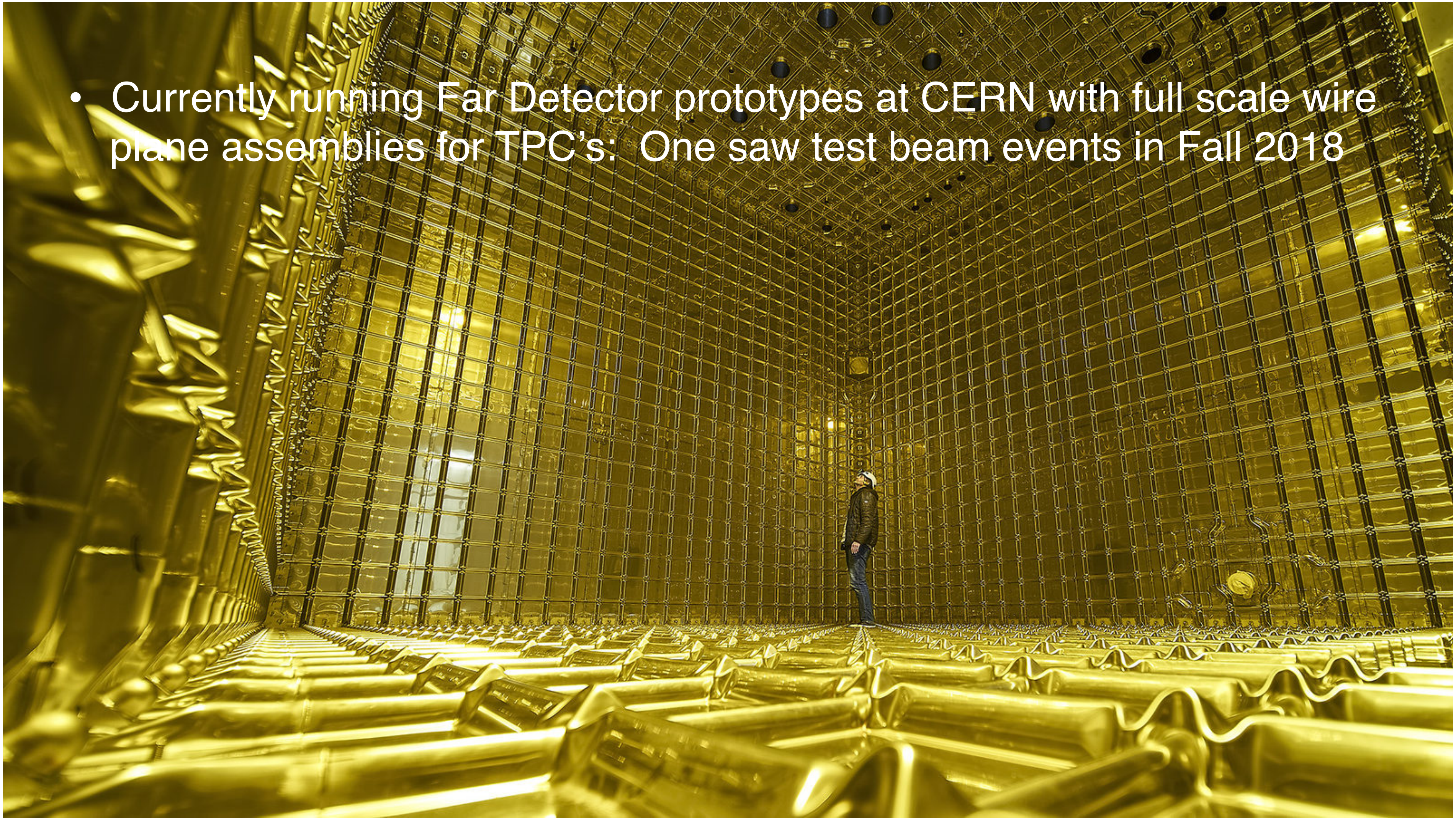
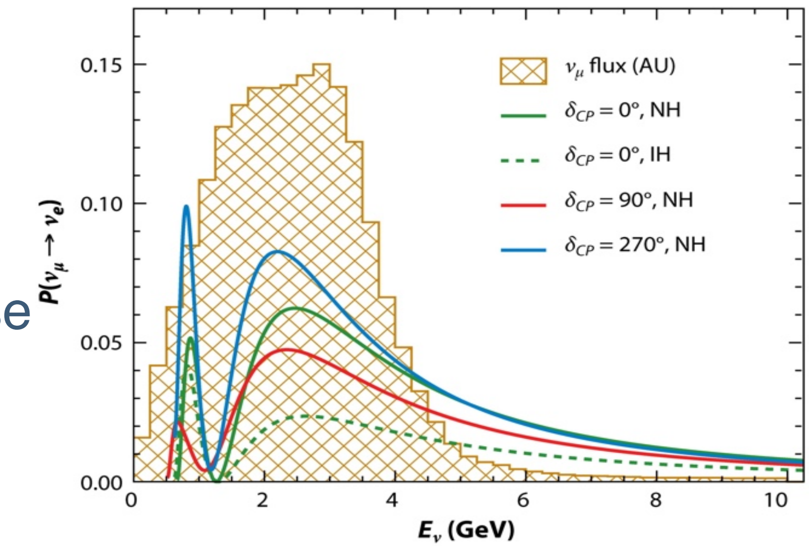
DUNE Preparations

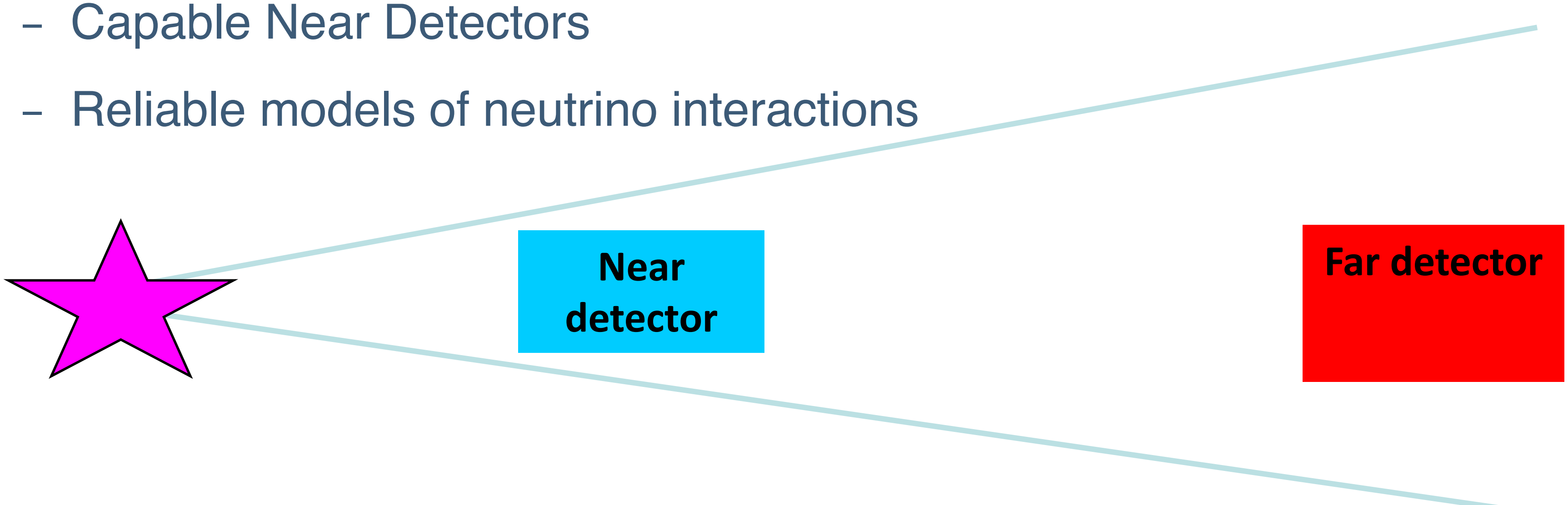
- Currently running Far Detector prototypes at CERN with full scale wire plane assemblies for TPC's: One saw test beam events in Fall 2018



The role of Near Detectors

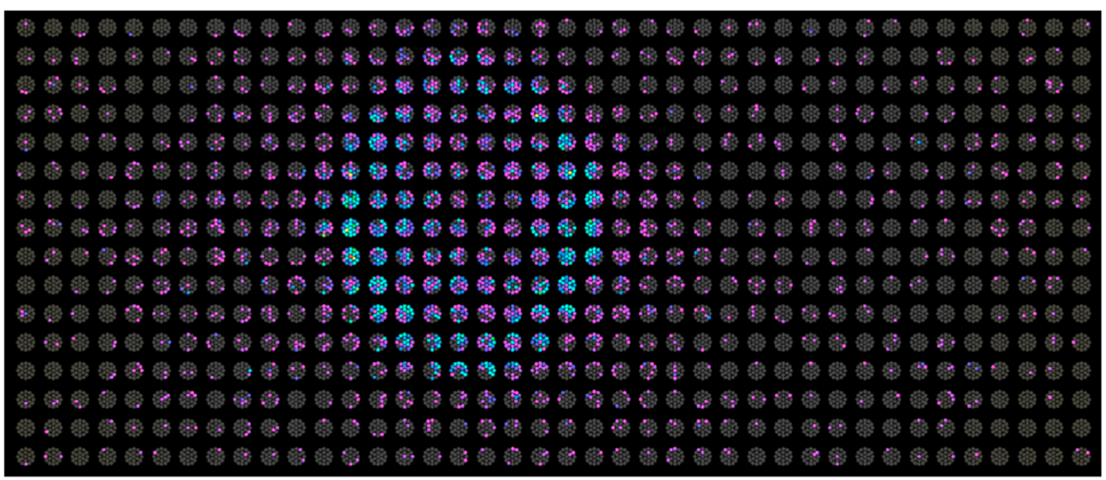
- Rates at far detector depend on many things:
  - flux, cross section, detector response
- Need several handles to get the best predictions
  - Capable Near Detectors
  - Reliable models of neutrino interactions

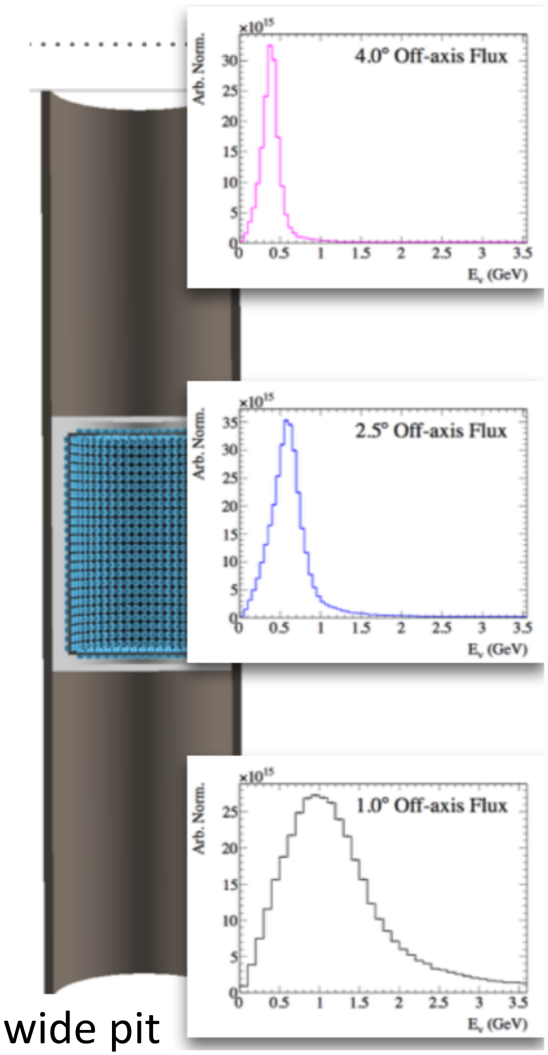




Near Detector for Hyper-Kamiokande

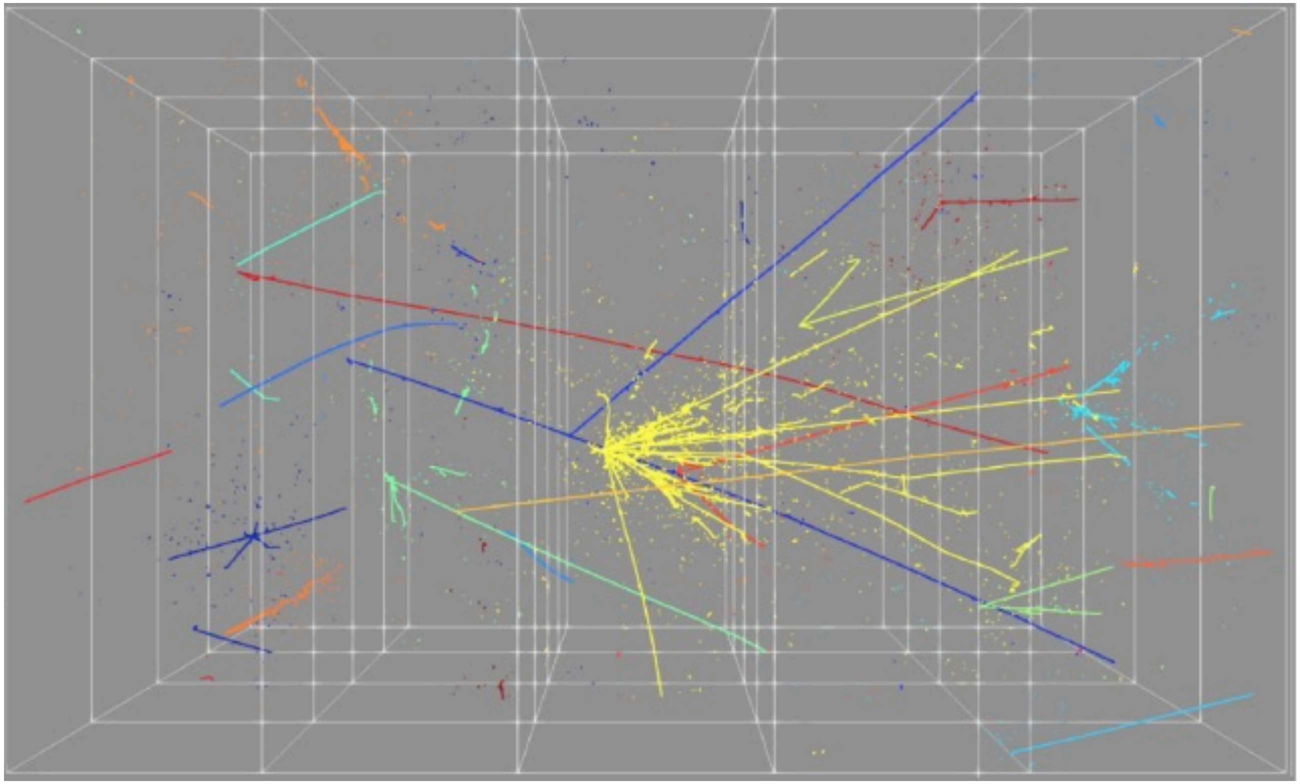
- T2K near detector complex still there!
- NuPRISM: keep water Cerenkov technology, but look at event spectra at different angles
- Decouple flux and interaction uncertainties by adding known change to flux
- Challenge: how do you make sure the detector acceptance differences can be predicted?





10m wide pit

Near Detector for DUNE

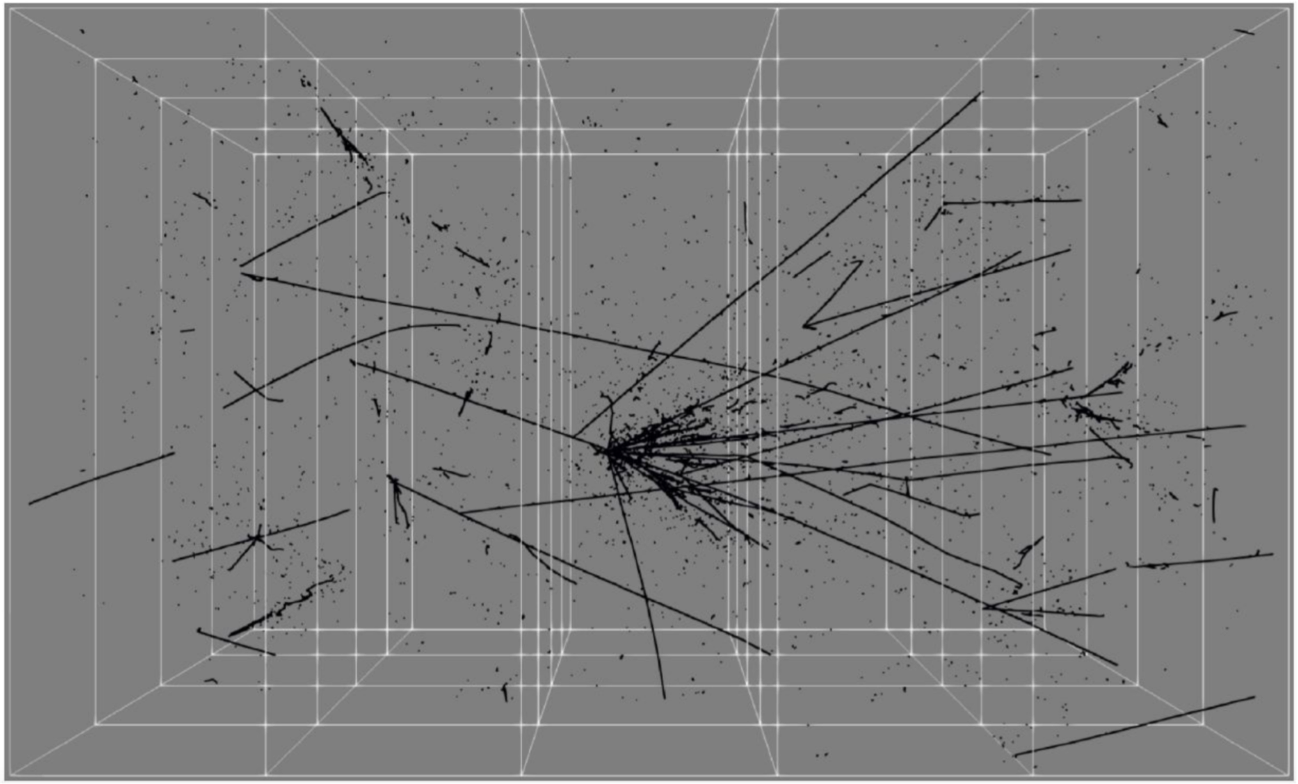


Challenge for TPC with wire plane readout: For a $4x3x5m^3$ of LAr at ~1km: each color is different ν, 37M Charged Current ν_μ interactions/year

(80 GeV p, $1.5x10^{21}$ POT)

- Beam is so intense in near detector hall, need design change
- Challenge: still need to measure how well the far detector design can identify interactions!
- Solution: Modular design, pixels instead of wires to read out signals

Near Detector for DUNE



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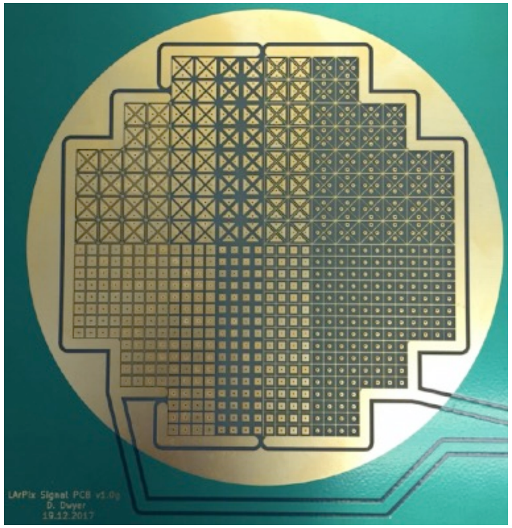
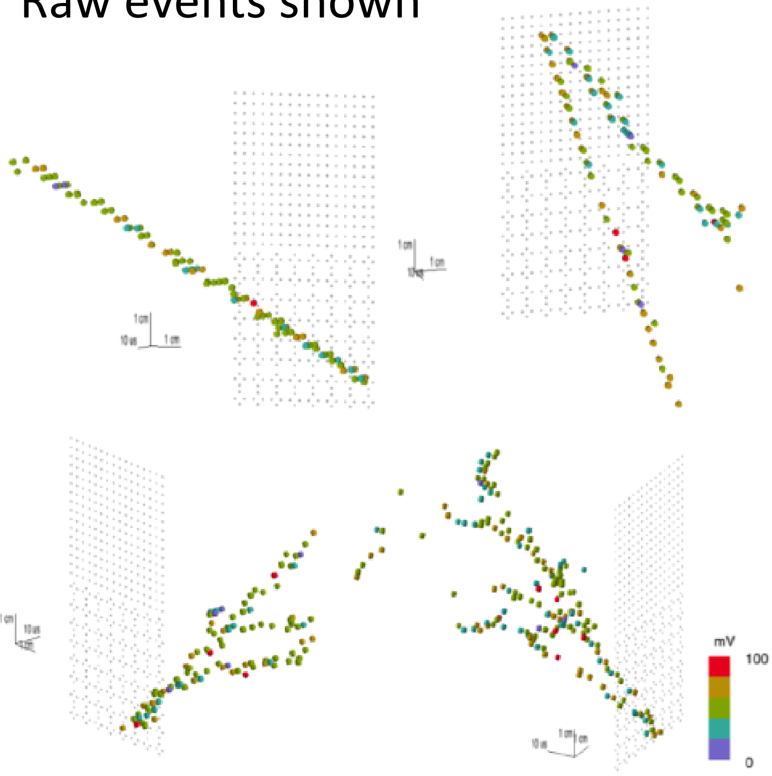
From wires to pixels in a TPC

- Pileup is reduced if you are reading out much less Argon per channel
- Challenge: exponential growth of number of readout channels
- Need low power on each readout channel to not boil the argon!



Cosmic ray interactions in test system using pixels across a 4.8x9.6cm^2 area, 60cm drift
Raw events shown

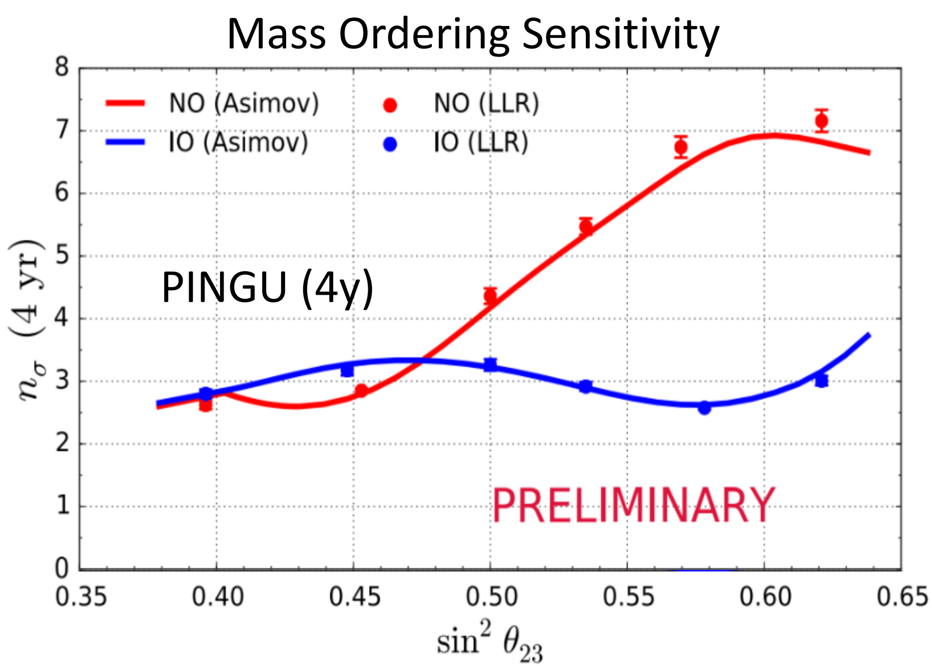


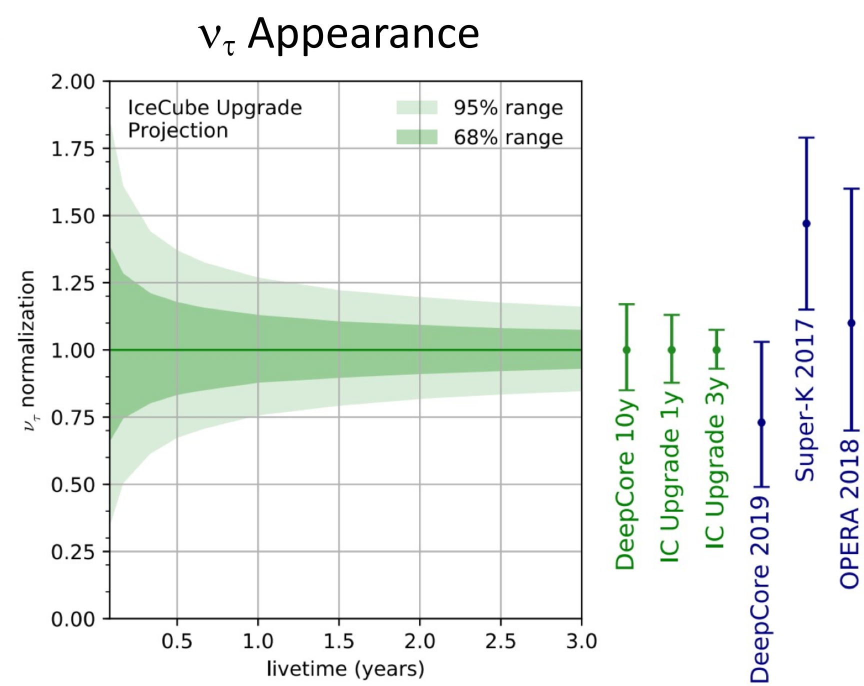
D. Dwyer et al, JINST 13 (2018) no.10, P10007

Near term: Testing soon in current 6GeV ν beam!

PINGU Physics Reach

- PINGU is 26 strings, 7m and 2.4m separation
- Small mixing enhances matter effects, can exclude wrong mass ordering

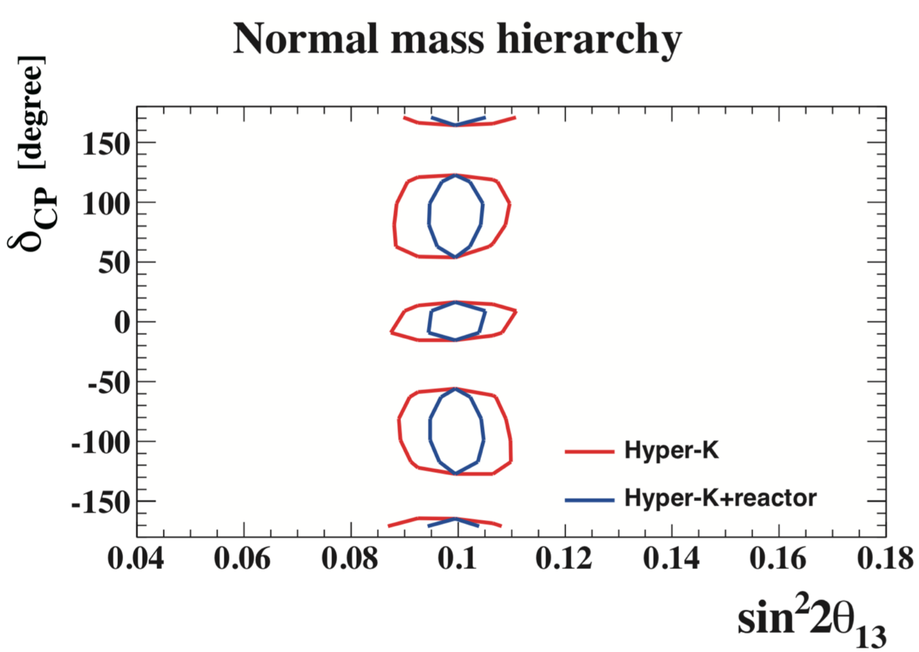


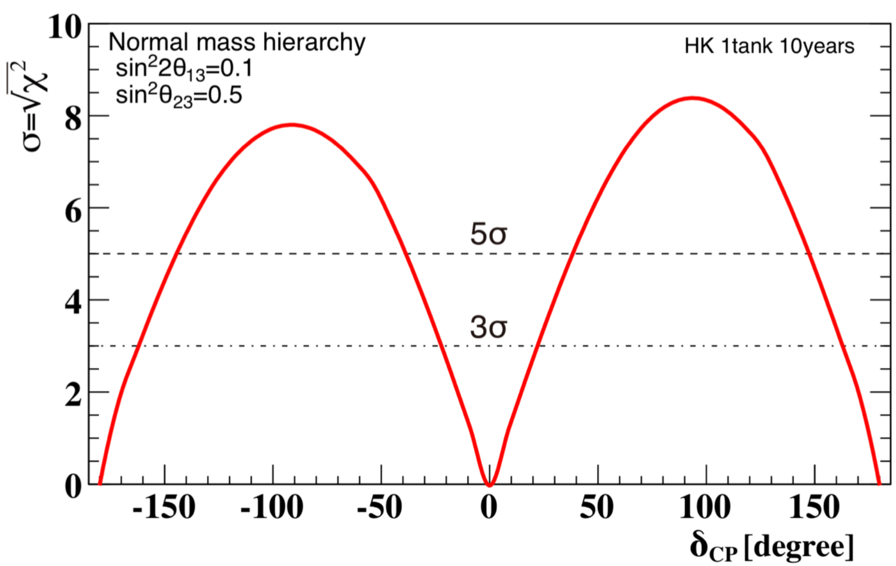


https://arxiv.org/abs/1401.2046

Hyper-Kamiokande Physics Reach

- Sensitivity shown assumes mass ordering is known, sensitivity is comparable for either mass ordering



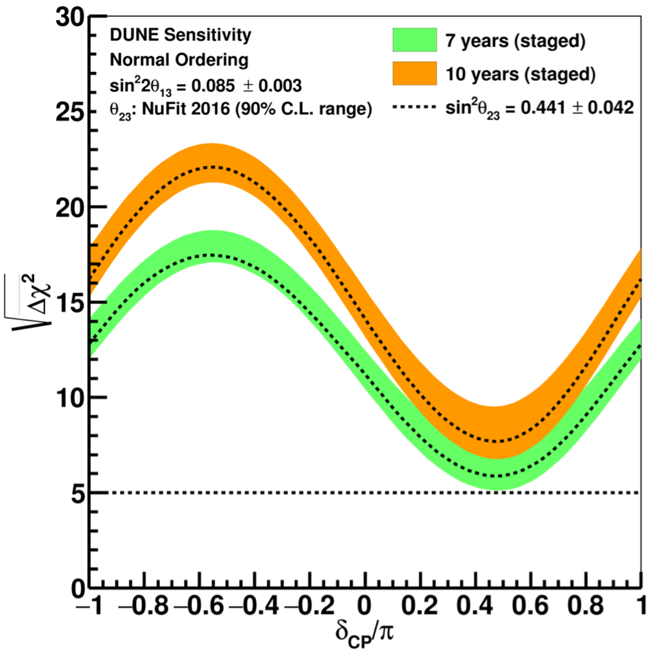


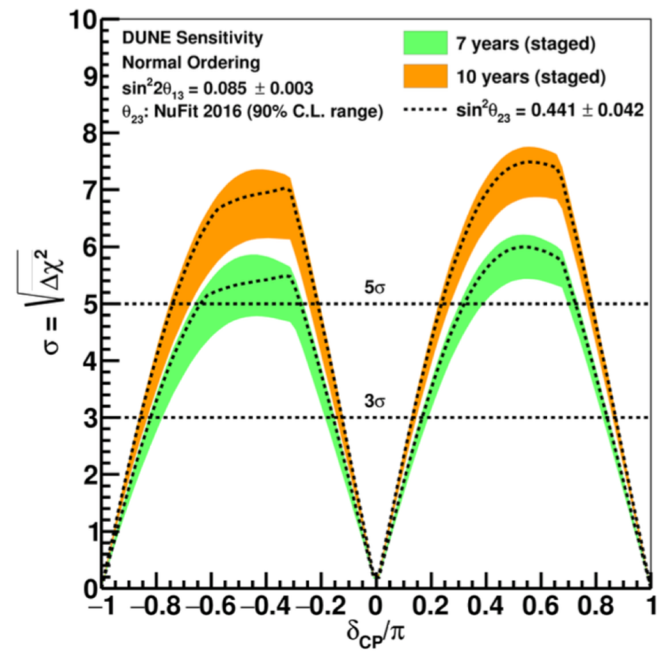
arXiv:1805.04163, Hyper-K Design Report

DUNE Physics Reach

- Mass Ordering: should get to see this in first few years
- CP Violation: definitive test over 50% of parameter space!
- Able to test the framework with broad energy range
- Sensitive to supernovae burst, expect 1000's of events

Mass hierarchy



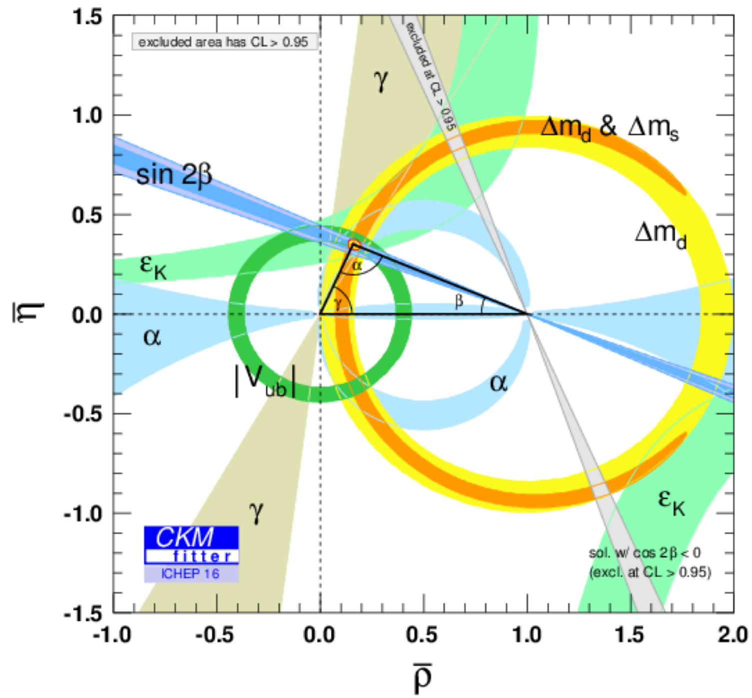


CP VIOLATION

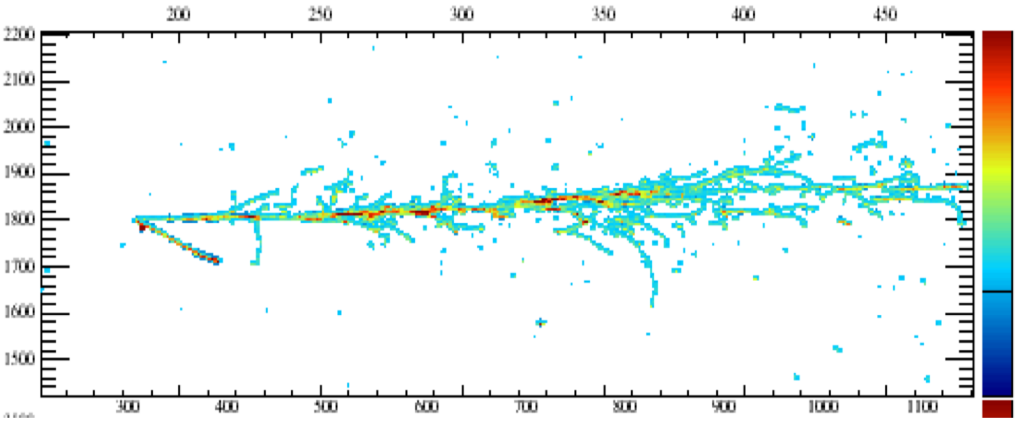
arXiv:1807.10334, DUNE Interim Design Report

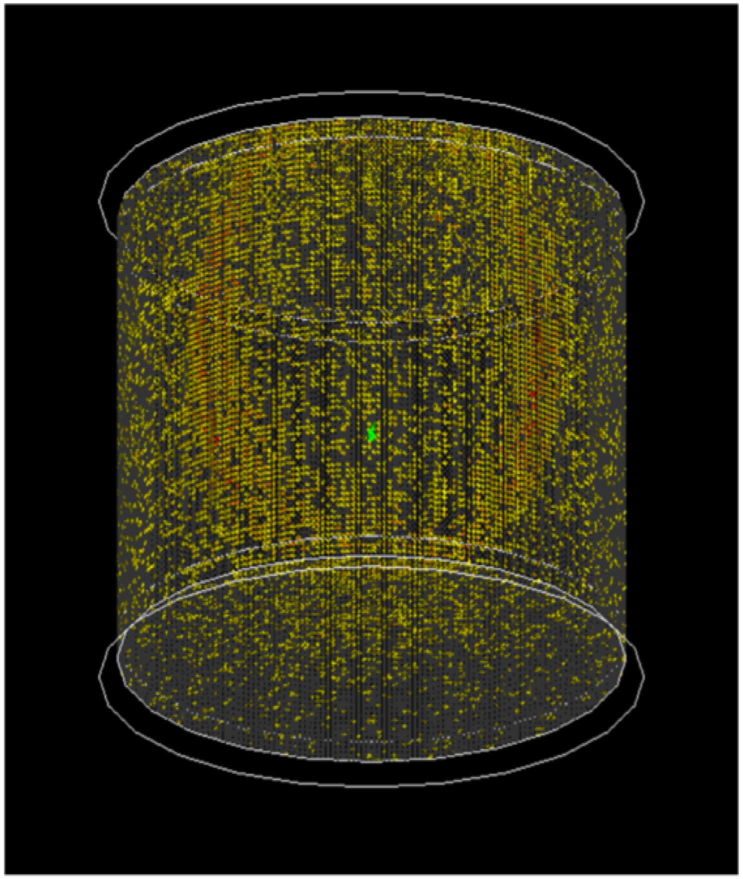
Conclusions

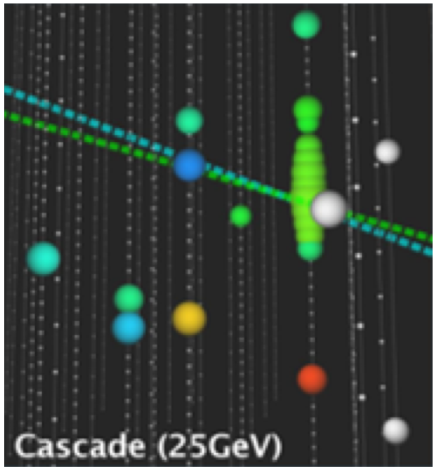
- Several new facilities on the horizon for ν Flavor Physics, mid-2020's start dates for all
- Very different detectors and beams provide most complete picture: equivalent unitarity triangle
  - PINGU –Mass Ordering
  - Hyper-K –CP Violation at 0.6GeV
  - DUNE—CP Violation and Mass Ordering over broad energies



- We have our work cut out for us:
  - New exciting ideas for Near Detectors to make sure we can meet the high statistics at the far detector with precise predictions







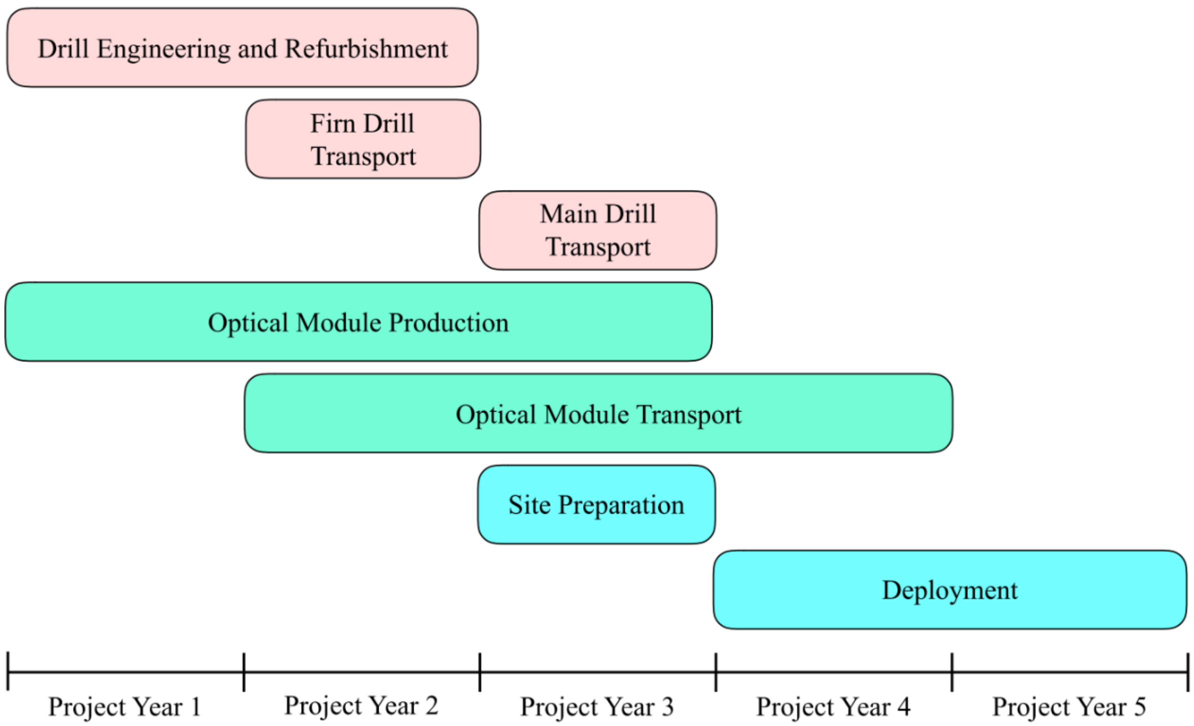
Thank you!
Merci!

Thanks to Phillip Eller and Masashi Yokoyama for information and graphics

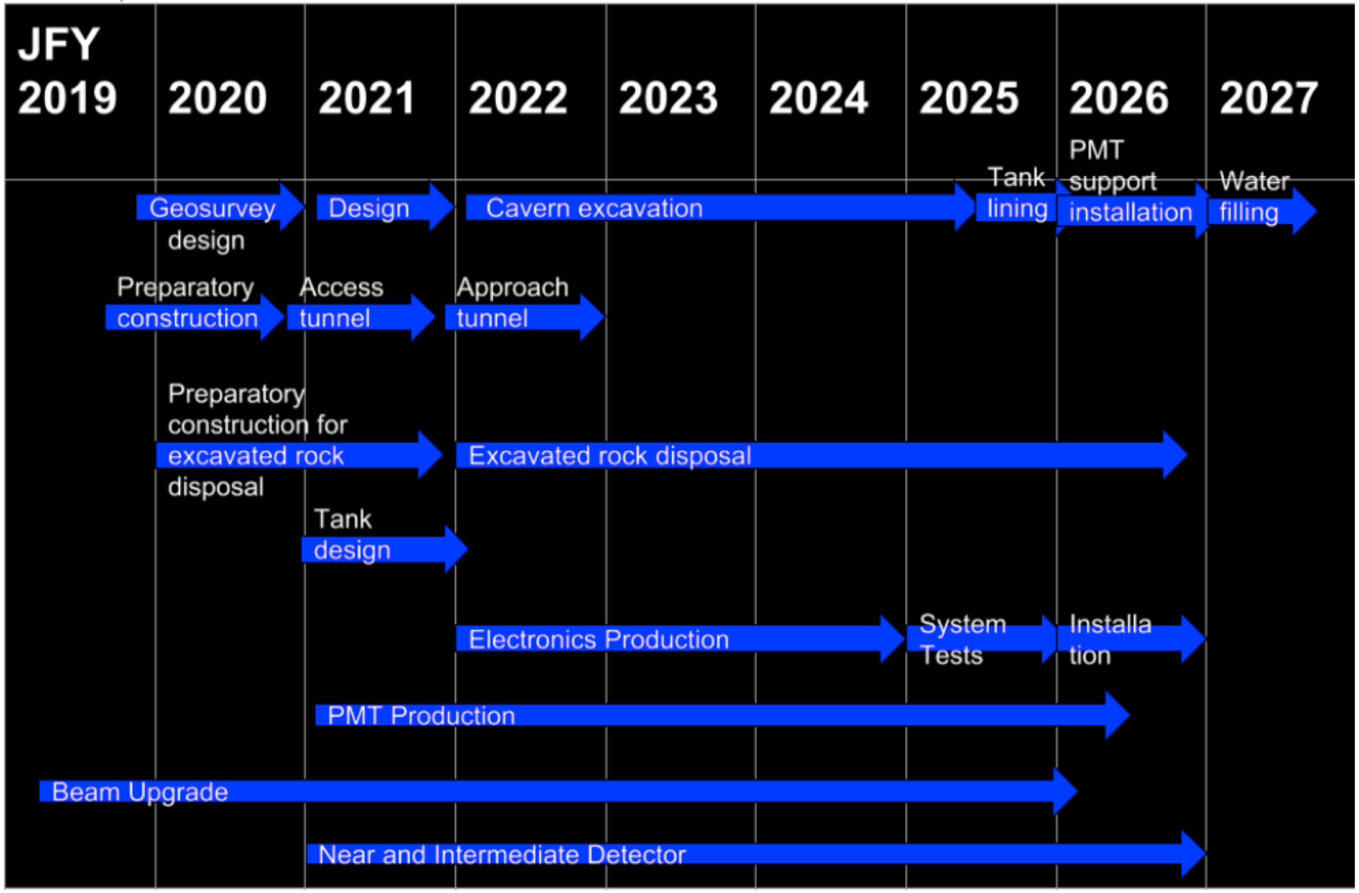
Backup Slides

ICECUBE TIMELINE

- 7-string upgrade approved by National Science Foundation, deployment planned for 2022/23
- Rough timeline (here for "full" PINGU = even more strings)



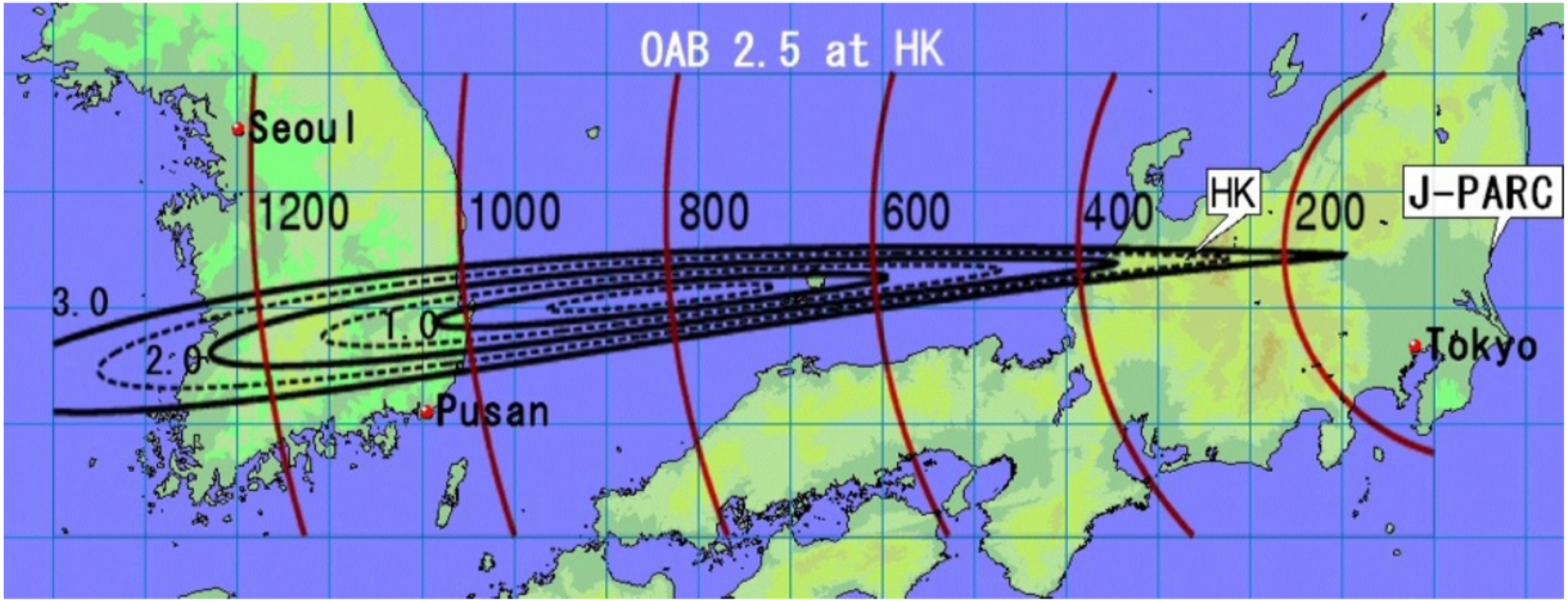
Hyper-K Construction Timeline



- 2018: Japanese seed funding, U. Tokyo commits to 2020 start
- 2019: start of funding applications in participating countries

Hyper-K in Korea?

- Considering putting second detector at 1100km, which puts the first maximum at 2GeV, 2^{nd} Maximum at 750MeV



DUNE Timeline

2018: protoDUNEs at CERN

↓

2019: Technical Design Report

↓

2019: Far Site Primary Excavation Begins

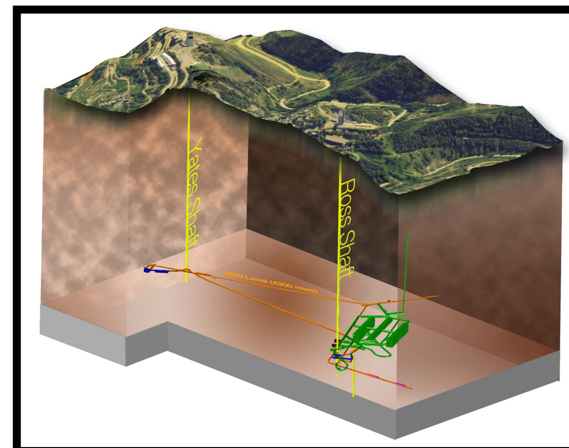
↓

2022: First Module Installation Begins

↓

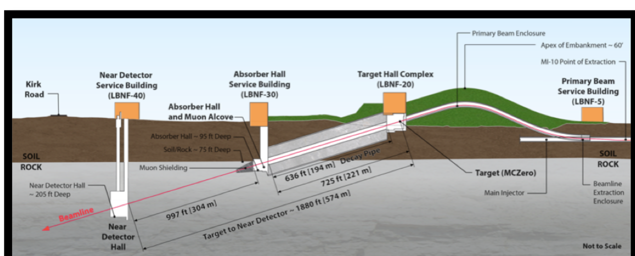
2026: Neutrino Beam Available

DUNE Far Detector Interim Design Report (2018)
arXiv:



Physics data as soon as 1st module complete

- Atmospheric νs
- SNB and solar νs
- Baryon number violation
- Detector calibration

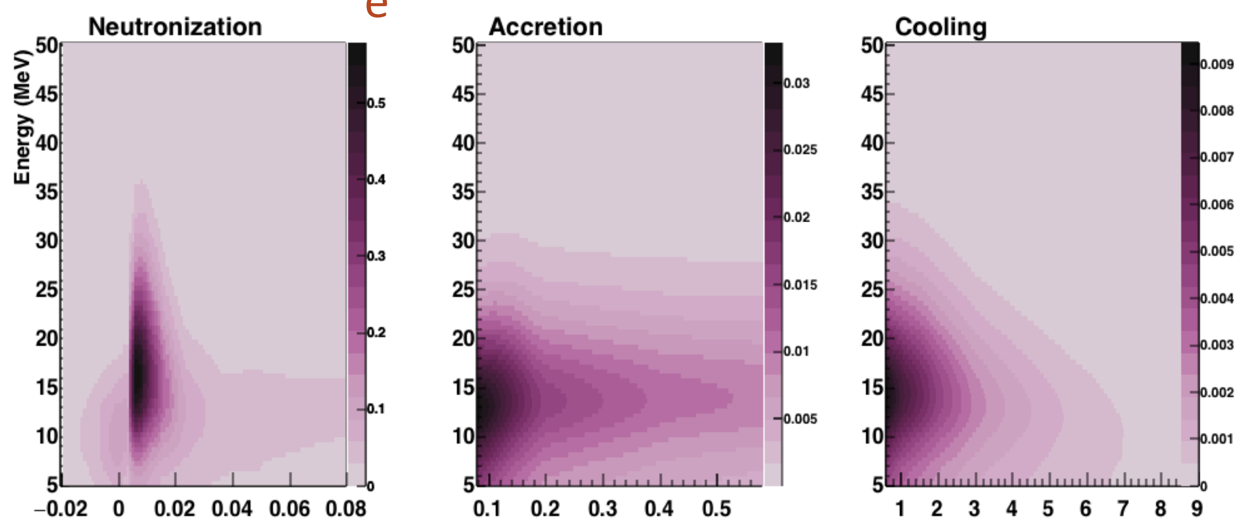


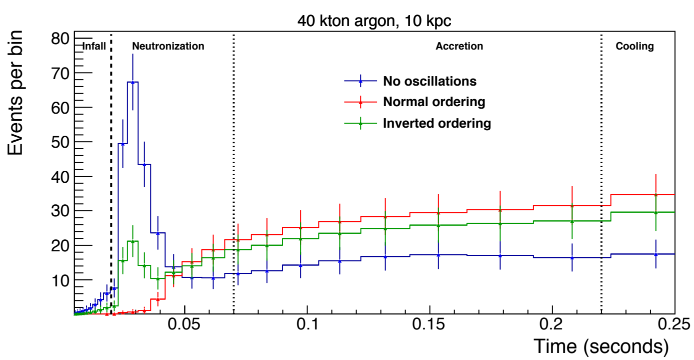
E. Worcester, ν2018

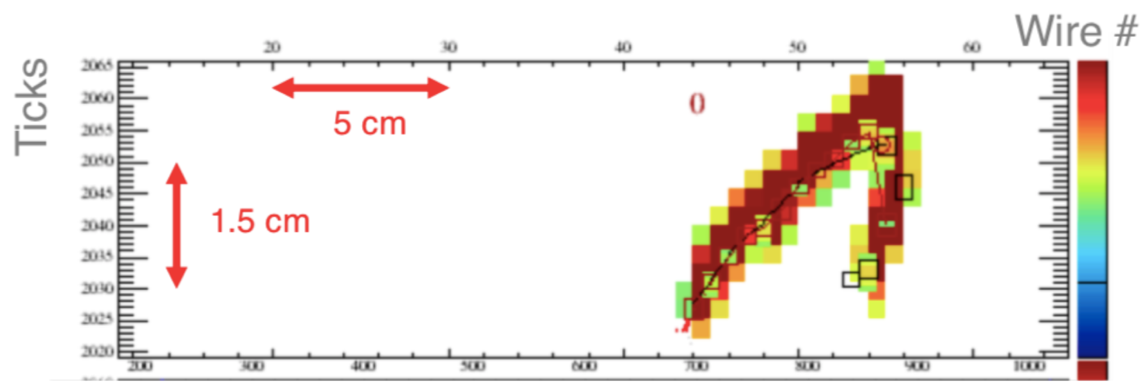
DUNE and Supernova Burst

- In DUNE, the signal dominated by electron neutrinos:
- Events per 0.5 MeV per ms, 40 kton @10 kpc

$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$



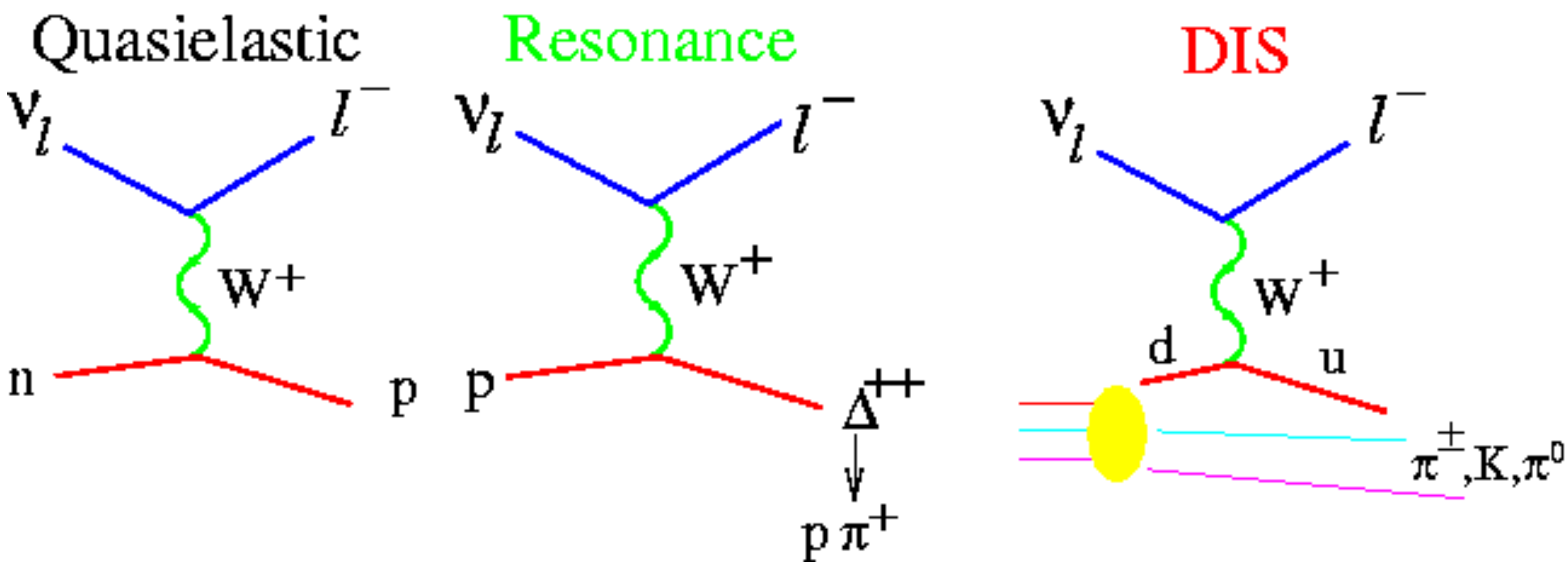




DUNE Simulation 30 MeV ν

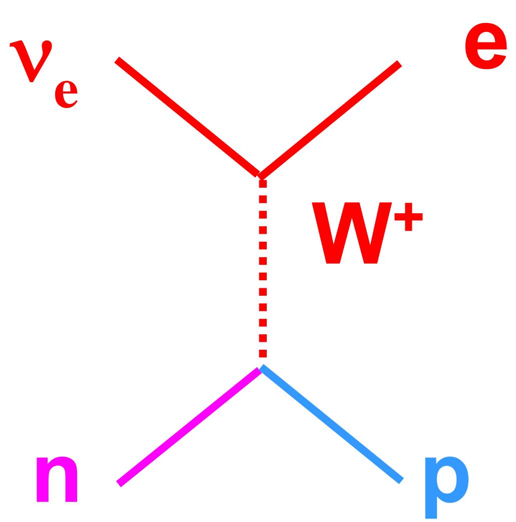
Neutrino Interactions at a few GeV

- Optics analogy: the wavelength of your probe determines what you can see
- High energy neutrinos can transfer more momentum, which means they can see smaller structure (quarks)



Measuring Neutrino Energy

- Should be easy, right?
  - Assume neutron at rest
  - IF you know initial direction of neutrino…
  - Final direction and energy of electron should suffice to get to the neutrino energy



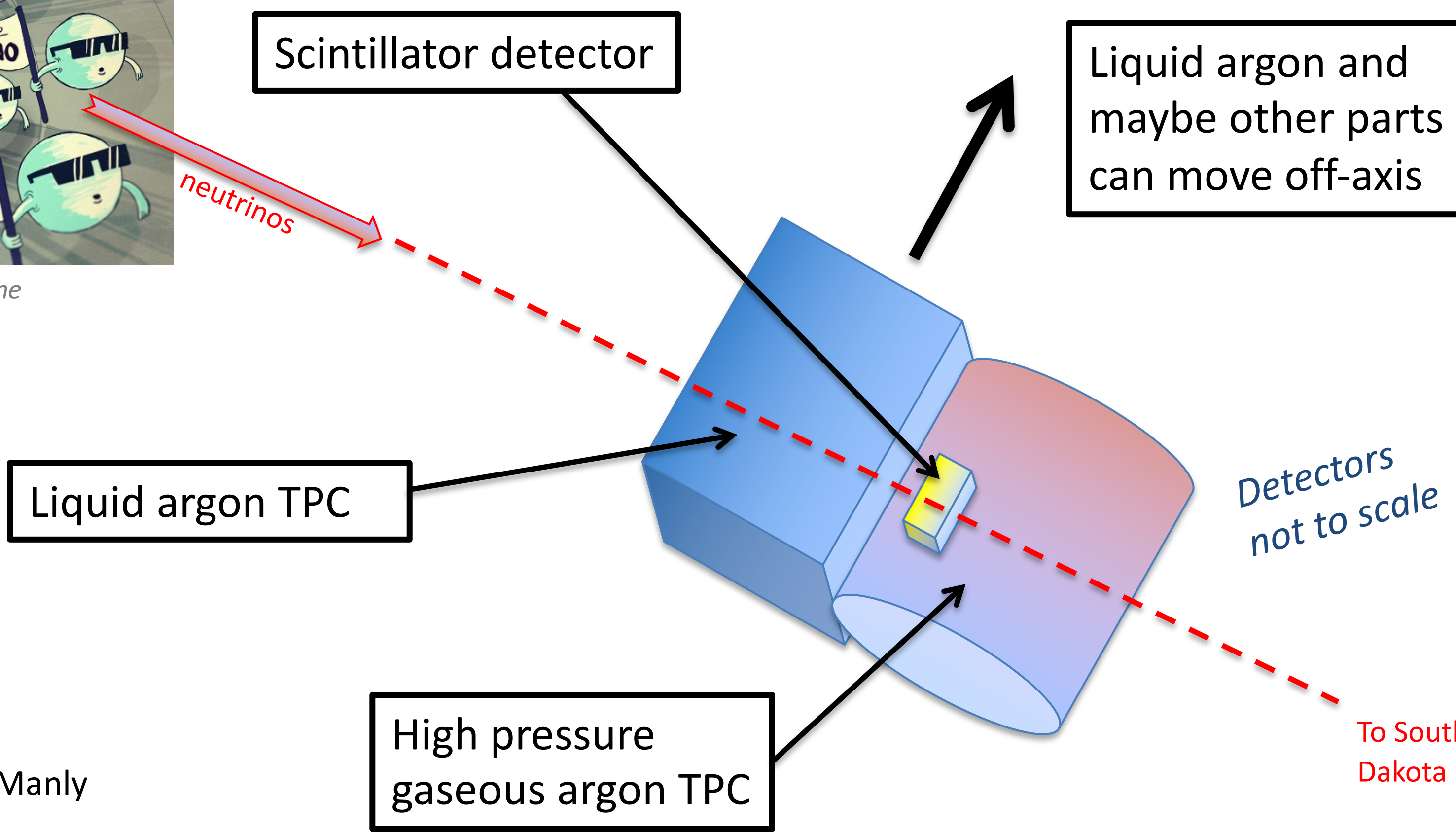
$$E_\nu^{QE} = \frac{2\left(M_n - E_B\right)E_\mu - \left[\left(M_n - E_B\right)^2 + m_\mu^2 - M_p^2\right]}{2\left[\left(M_n - E_B\right) - E_\mu + \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu\right]}$$

$E_\mu = T_\mu + m_\mu$	Muon Energy
M_n, M_p, m_μ	Neutron, Proton, Muon Mass
E_B	Binding Energy (~30 MeV)
θ_μ	Muon Angle w.r.t. Neutrino Direction

Components of DUNE's Near Detector

- Several different detector technologies to play different roles
- Similar design concept as T2K's near detector suite

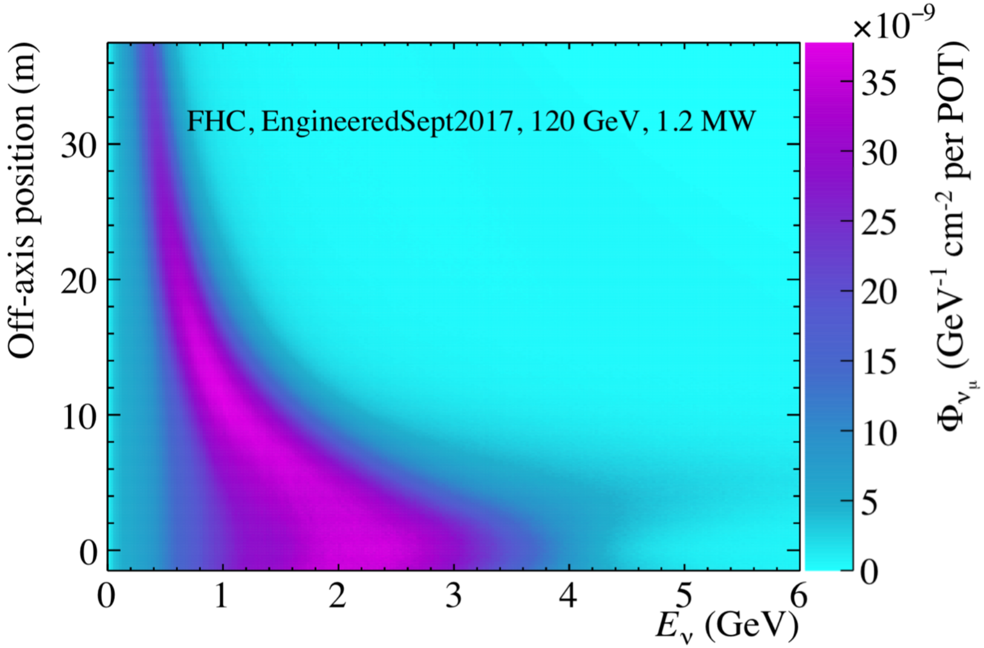
Fig. from Symmetry Magazine

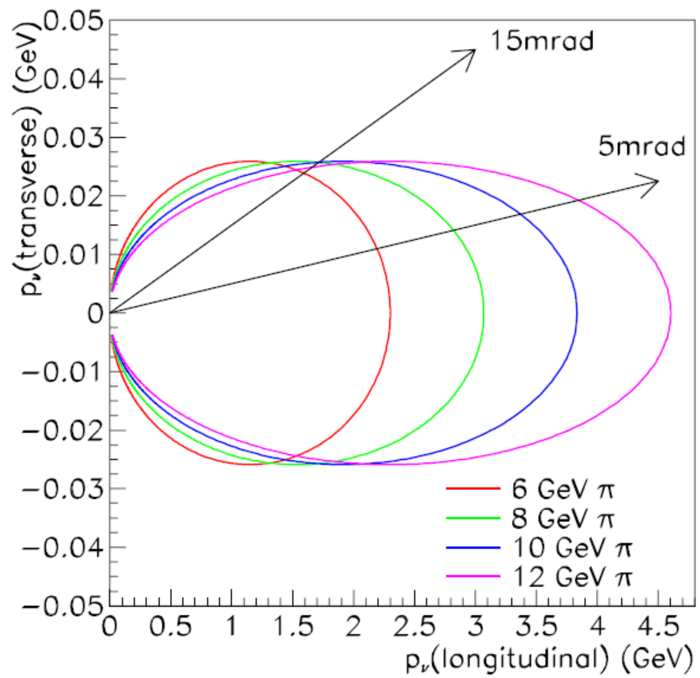


Graphics courtesy S. Manly

Near detector on and off axis

- Neutrinos mostly made from 2-body decays: specific relationship between neutrino energy and pion energy and decay angle





- Test model of neutrino energy showing up in detector by having same detector in many off axis angles