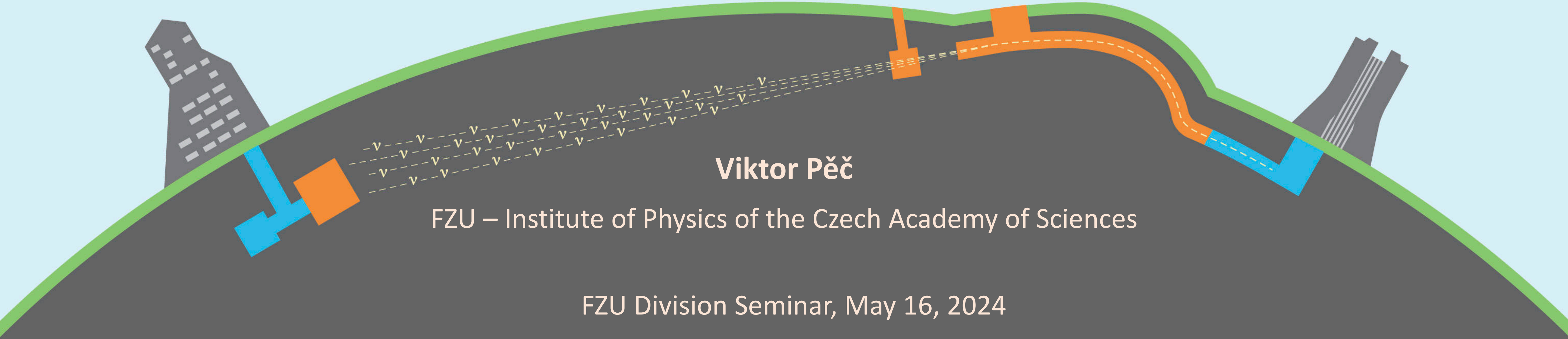
Physics at DUNE



Viktor Pěč

FZU – Institute of Physics of the Czech Academy of Sciences

FZU Division Seminar, May 16, 2024

Co-funded by the European Union

MŠMT MINISTRY OF EDUCATION, YOUTH AND SPORTS

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

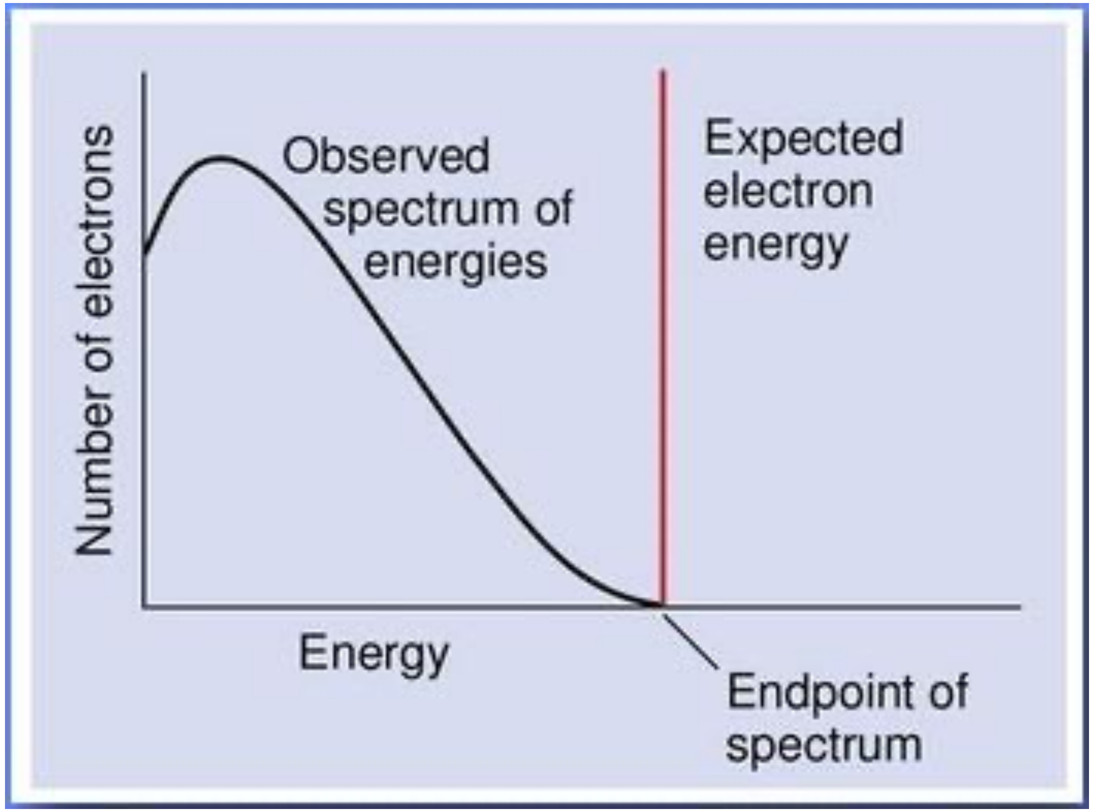
FZU Institute of Physics of the Czech Academy of Sciences

Outline

- Brief history of neutrino physics
- Neutrino oscillations
- DUNE experiment
- Supernova neutrinos
- Low E calorimetry

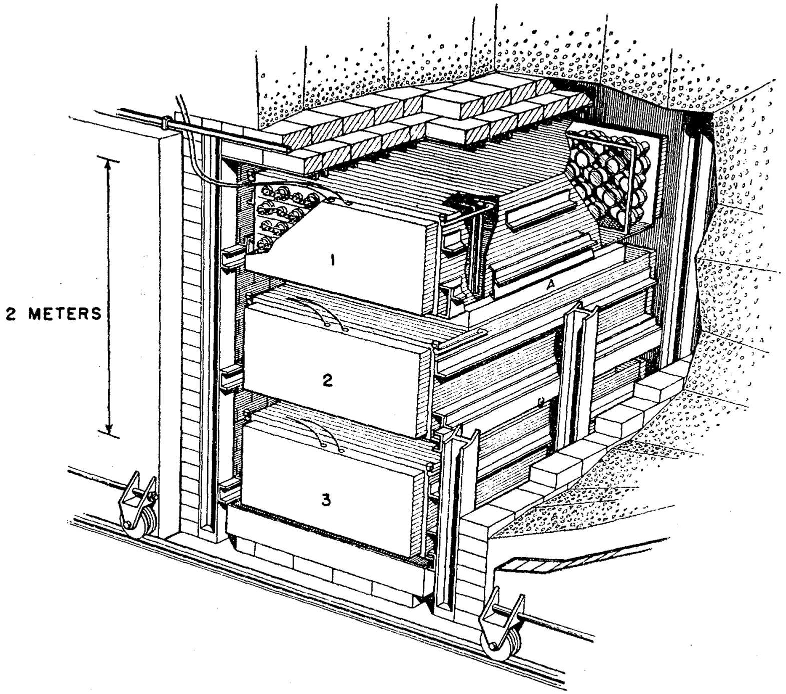
Neutrino History

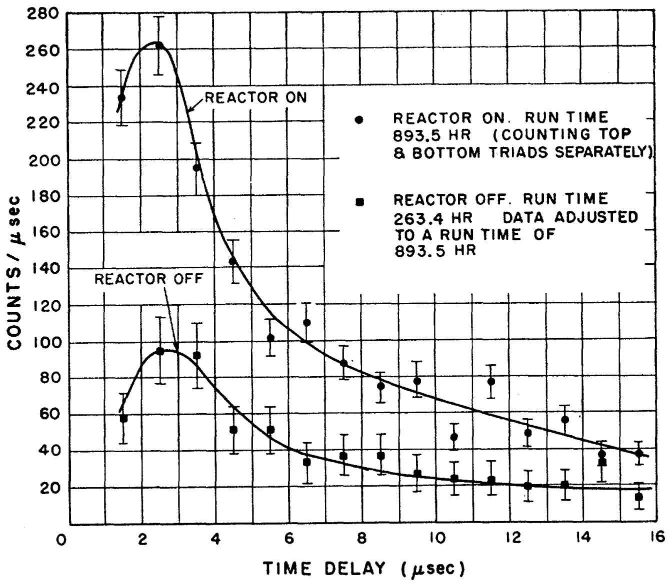
- 1930 Postulated by Pauli



Neutrino's Early History

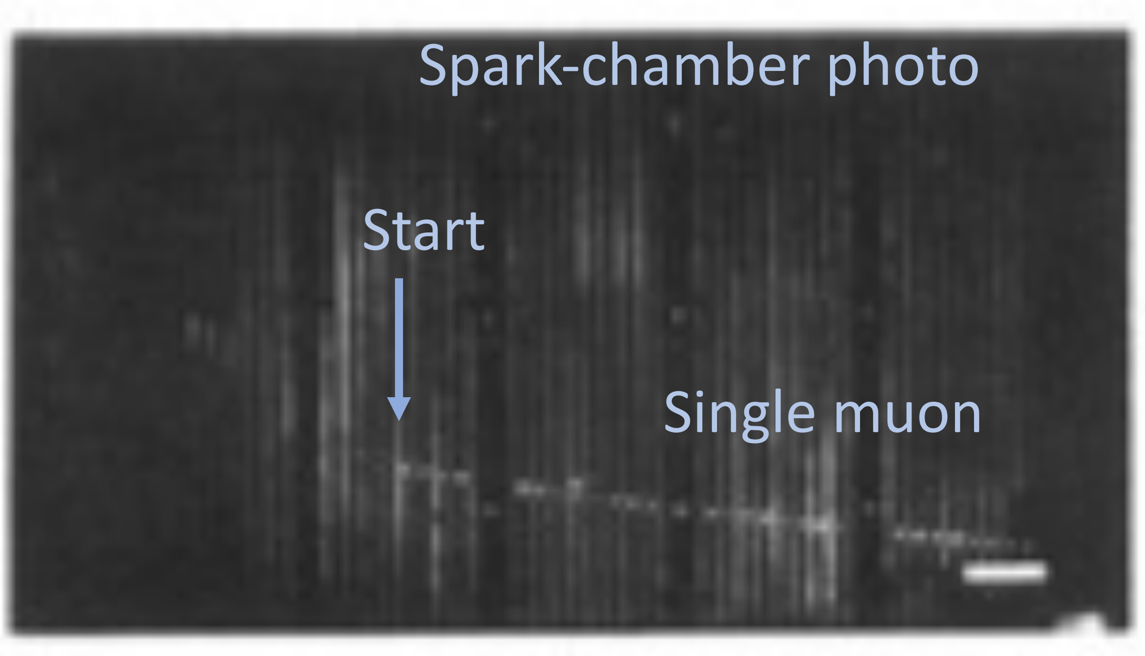
- 1930 Postulated by Pauli
- 1953-56 Detected by Cowan & Reines
  - Reactor $\overline{\nu}_e$
  - Nobel Prize 1995





Neutrino's Early History

- 1930 Postulated by Pauli
- 1953-56 Detected by Cowan & Reines
  - Reactor $\overline{\nu}_e$
  - Nobel Prize 1995
- 1962 Neutrino flavours confirmed by Lederman et al.
  - Nobel Prize 1988
  - ν_μ (ν_τ observed in 1975/2000)



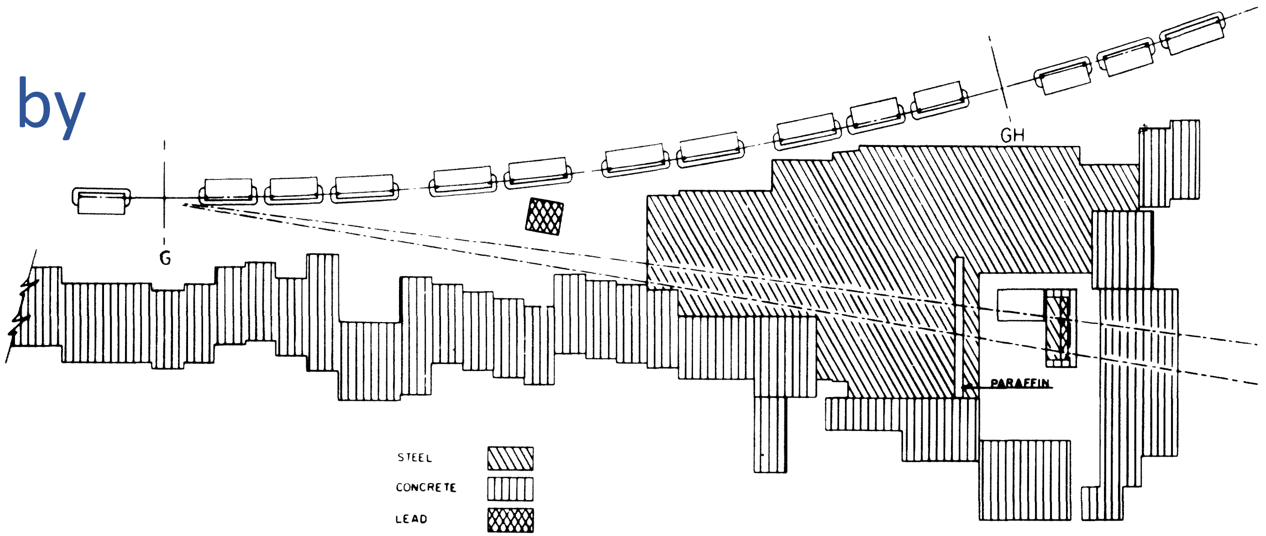
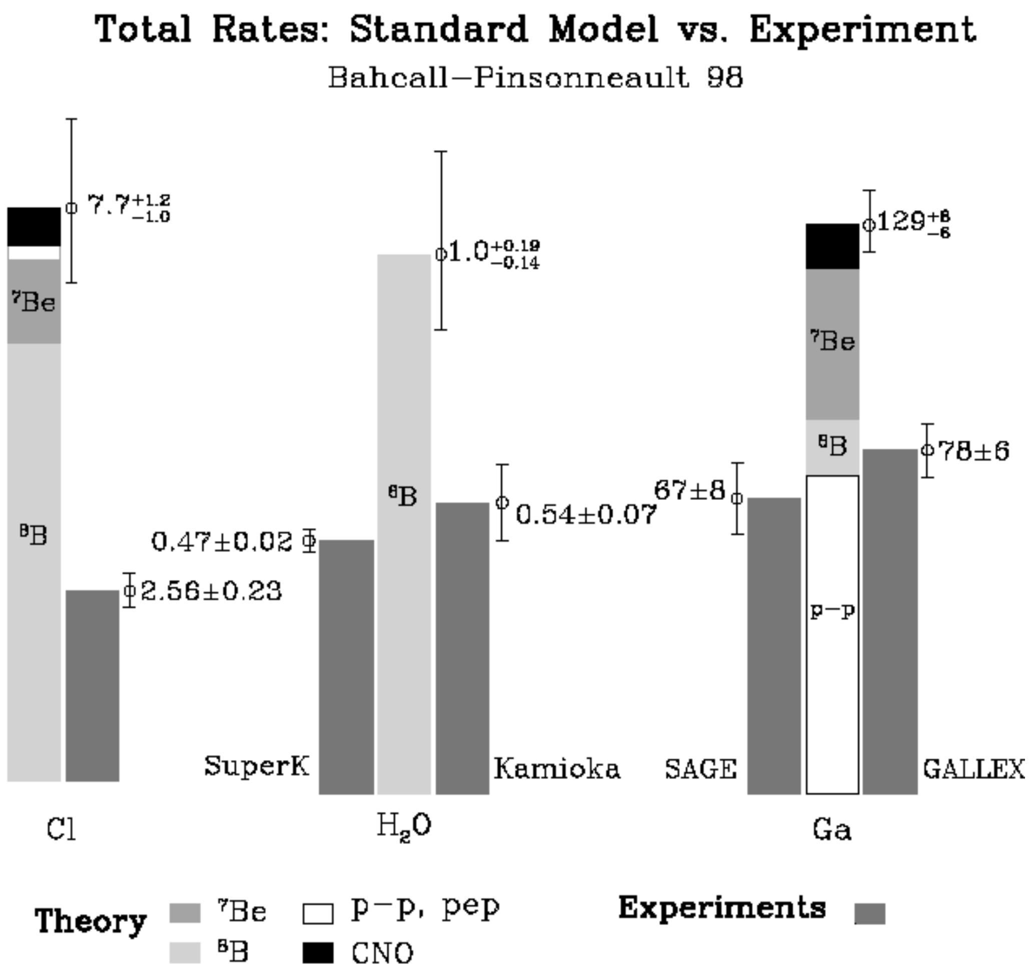


FIG. 1. Plan view of AGS neutrino experiment.

Neutrino Oscillations Era

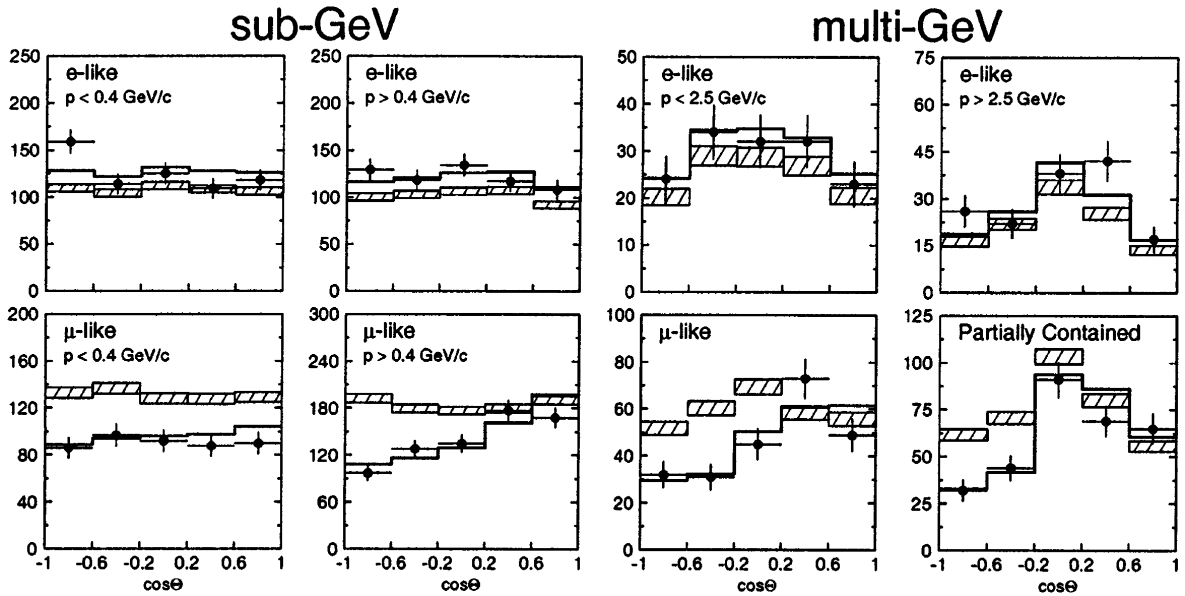
- 1960s Solar neutrino detection
  - Homestake
  - Solar neutrino problem – 1/3 ν_e observed
  - Nobel Prize in 2002 (after problem resolved)



Neutrino Oscillations Era

- Oscillations
  - 1957 proposed by Pontecorvo
  - 1978 Wolfenstein, 1985 Mikheyev-Sirmonov
    - Proposed matter effect (called MSW)
  - 1998 SuperKamiokande, 2001 SNO
    - Observed oscillation effects
    - Nobel Prize 2015

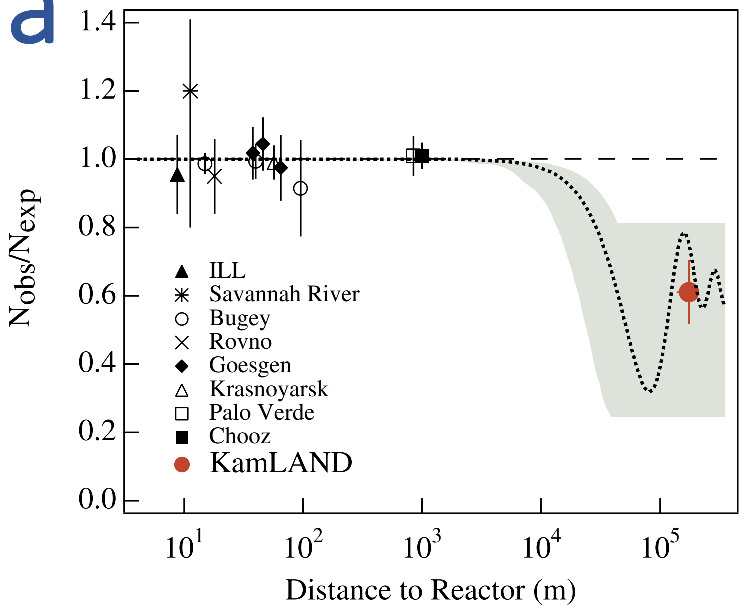
Disappearance of atmospheric ν_μ in SuperK



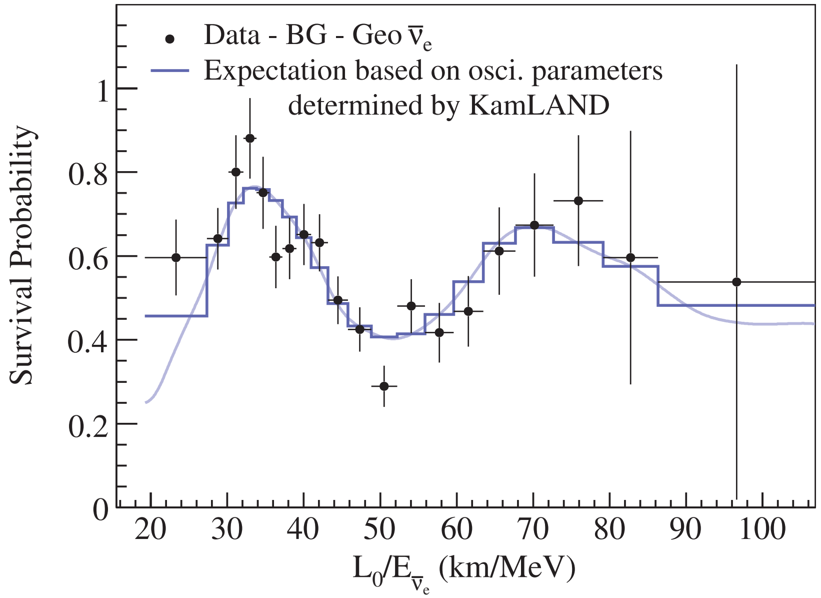
Neutrino Oscillations Era

- Oscillations
  - 1957 proposed by Pontecorvo
  - 1978 Wolfenstein, 1985 Mikheyev-Sirmonov
    - Proposed matter effect (called MSW)
  - 1998 SuperKamiokande, 2001 SNO 2001
    - Observed oscillation effects
    - Nobel Prize 2015
  - 2003/2008 KamLAND
    - Inambiguous proof of oscillations in reactor neutrinos

2003



2008



Neutrino Mixing

<Flavour| Mass> Eigenstates

$$U_{\alpha i} = \langle \nu_\alpha | \nu_i \rangle$$

Pontecorvo–Maki–Nakagawa–Sakata matrix

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & 0 & \hat{S}^*_{13} \\ 0 & 1 & 0 \\ -\hat{S}_{13} & 0 & C_{13} \end{pmatrix} \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\Phi_1} & & \\ & e^{i\Phi_2} & \\ & & 1 \end{pmatrix}$$

$$C_{jk} = \cos\theta_{jk},\ S_{jk} = \sin\theta_{jk},\ \hat{S}_{13} = e^{i\delta_{\mathrm{CP}}} \sin\theta_{13}$$

Oscillation in Vacuum

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{j>k} \mathcal{R}_e\left\{ U^*_{\alpha j}\, U_{\beta j}\, U_{\alpha k}\, U^*_{\beta k} \right\} \sin^2\left(\frac{\Delta_{jk}m^2\, L}{4E}\right)$$

$$+ 2\sum_{j>k} \mathcal{I}_m\left\{ U^*_{\alpha j}\, U_{\beta j}\, U_{\alpha k}\, U^*_{\beta k} \right\} \sin\left(\frac{\Delta_{jk}m^2\, L}{2E}\right)$$

Oscillation parameters

Parameter	Value	Precision
Δm_{21}^2	7.53×10^{-5} eV^2	2.4%
$\|\Delta m_{32}^2\| \simeq \|\Delta m_{31}^2\|$	2.45×10^{-3} eV^2	1.4%
θ_{12}	33°	4.2%
θ_{23}	47°	3.8%
θ_{13}	9°	2.8%
δ_{CP}	?	

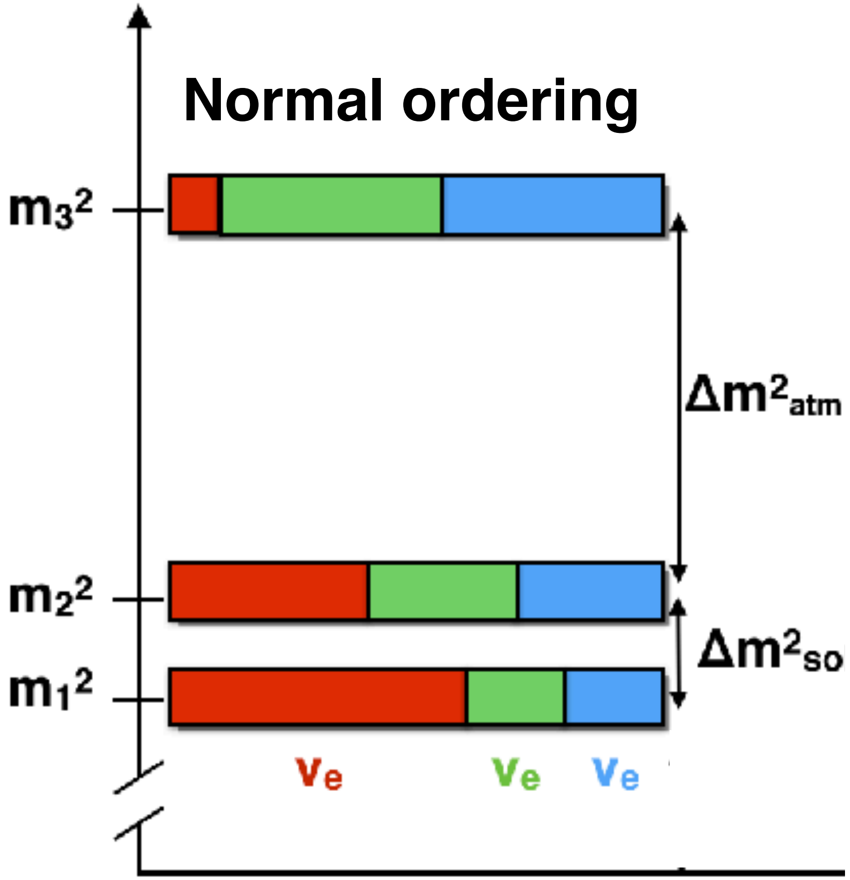
PMNS Matrix

Flavour states   Mass states

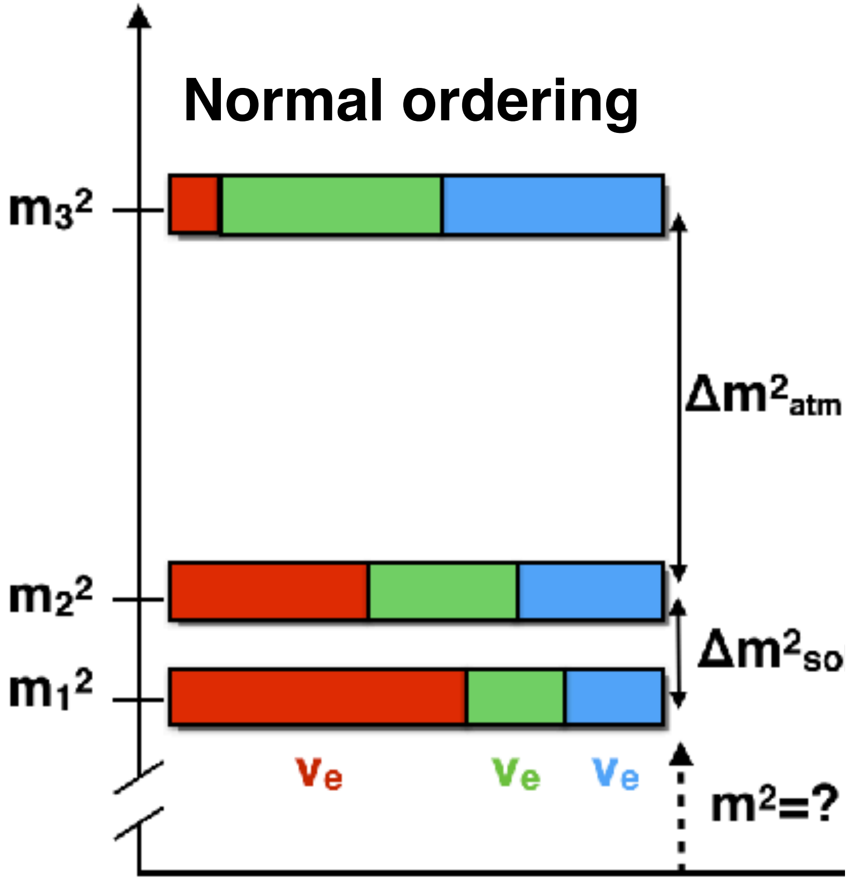
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

~ Amplitude of transition

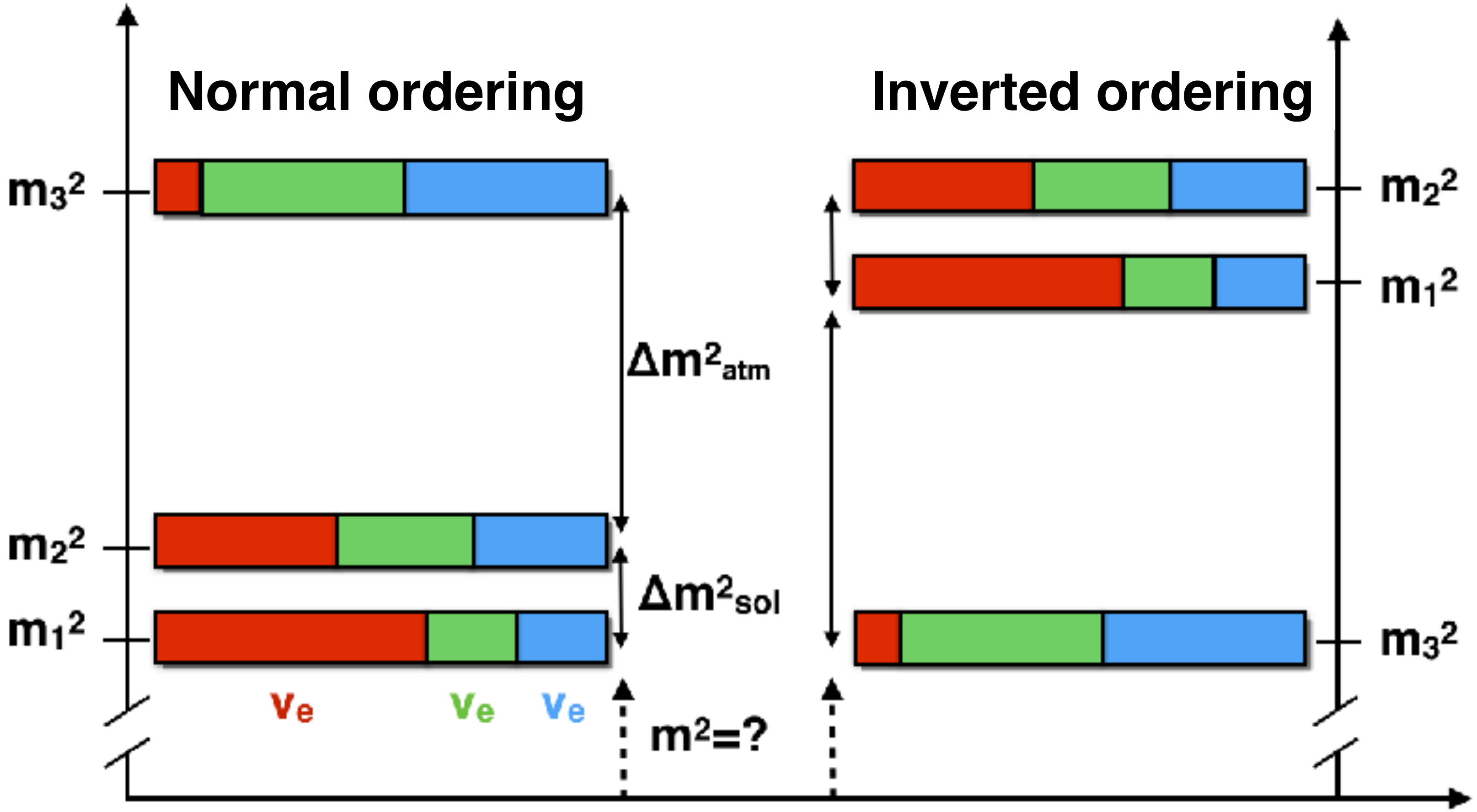
Neutrino Mass



Neutrino Mass



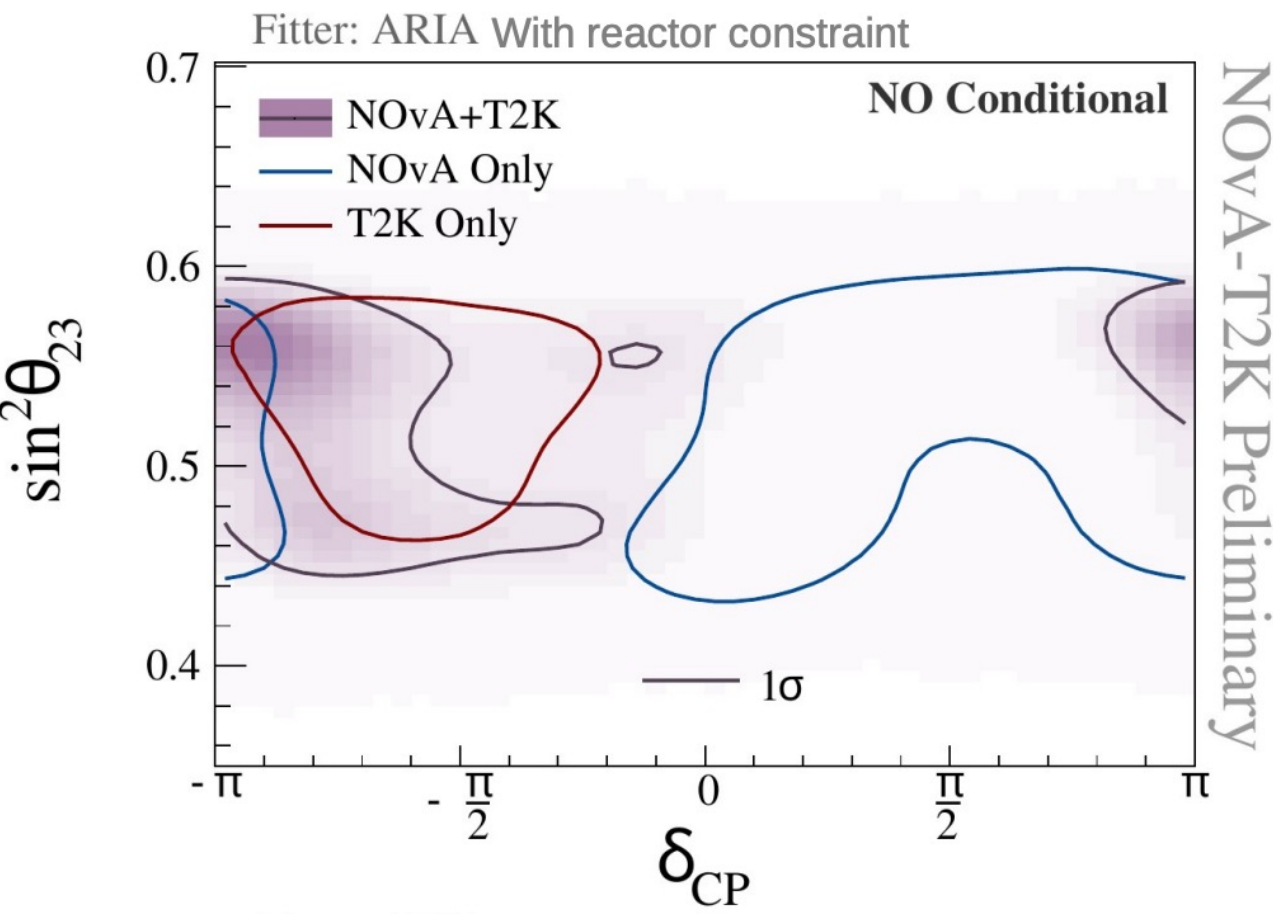
Neutrino Mass

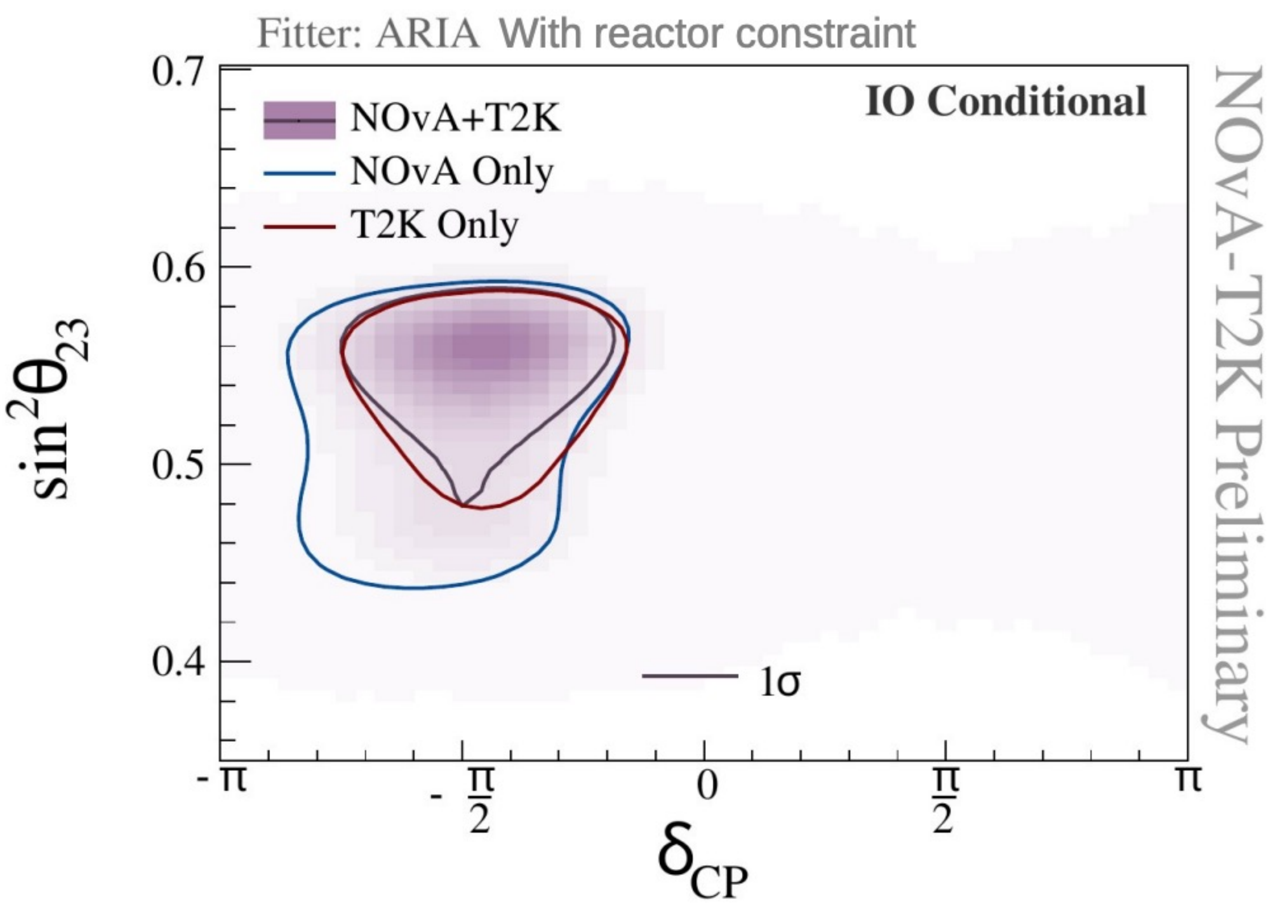


Missing – “Known Unknowns”

- $\theta_{23} \gtreqless 45°$ – **DUNE**, HyperK
- Mass ordering – JUNO, **DUNE**, HyperK
- Absolute mass – KATRIN
- Is neutrino Majorana or Dirac particle? – searches for $0\nu\beta\beta$
- CP violation and value of δ_{CP} – DUNE, HyperK

NOvA (USA) and T2K (Jpn)

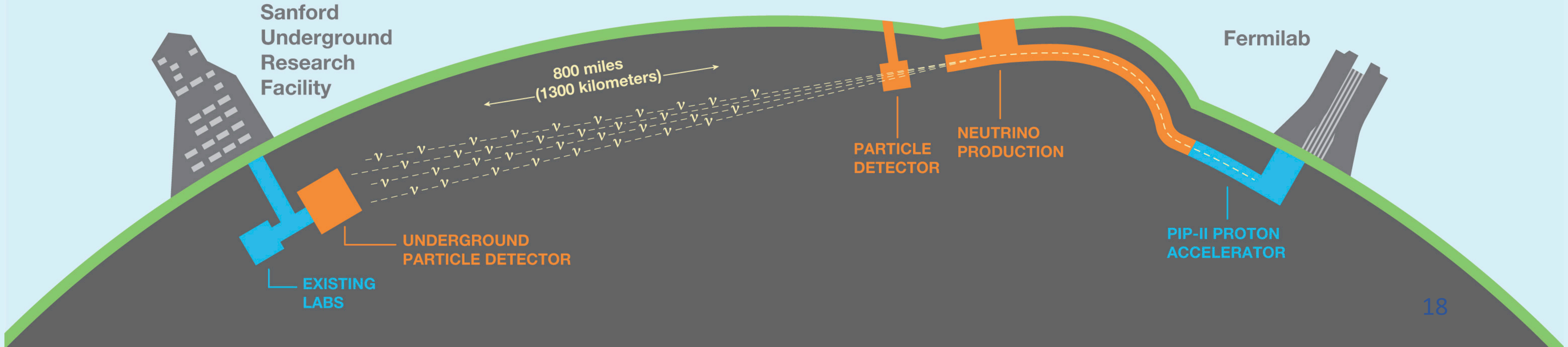




M.Sanchez, Moriond 2024

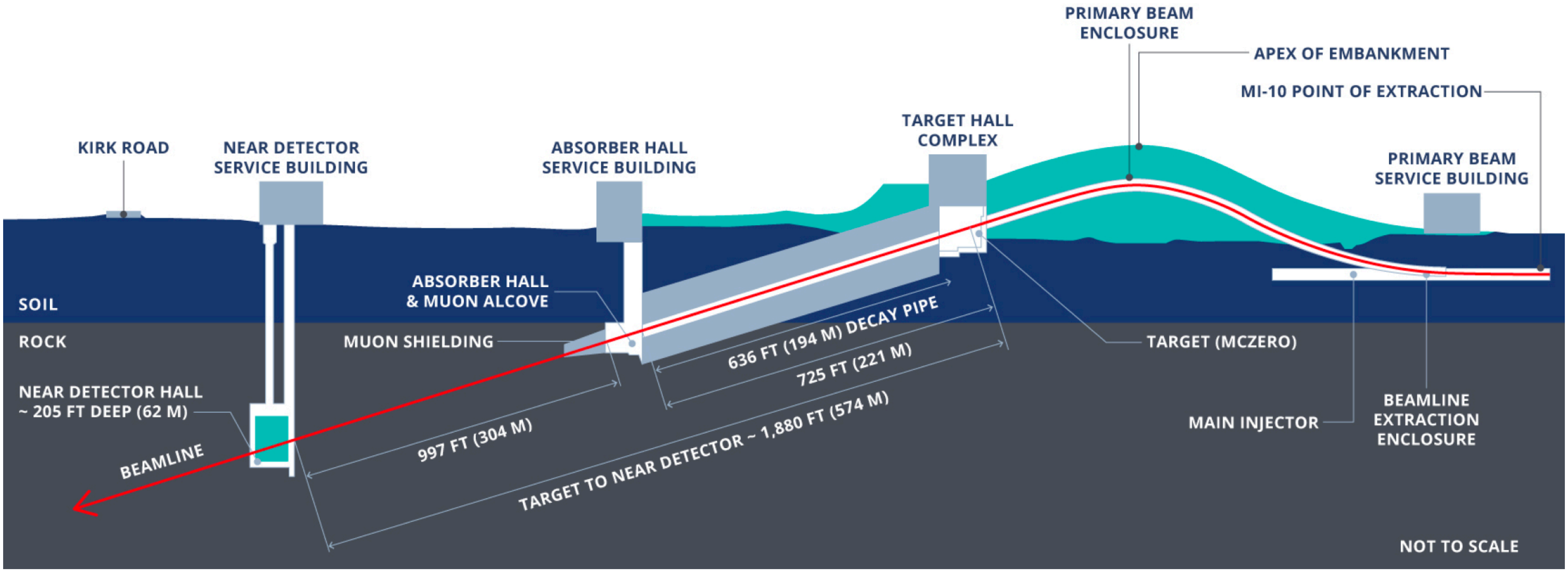
Deep Underground Neutrino Experiment

- **Goal**: precise measurement of neutrino oscillation parameters
- From oscillations of **accelerator neutrinos** over a **long baseline**



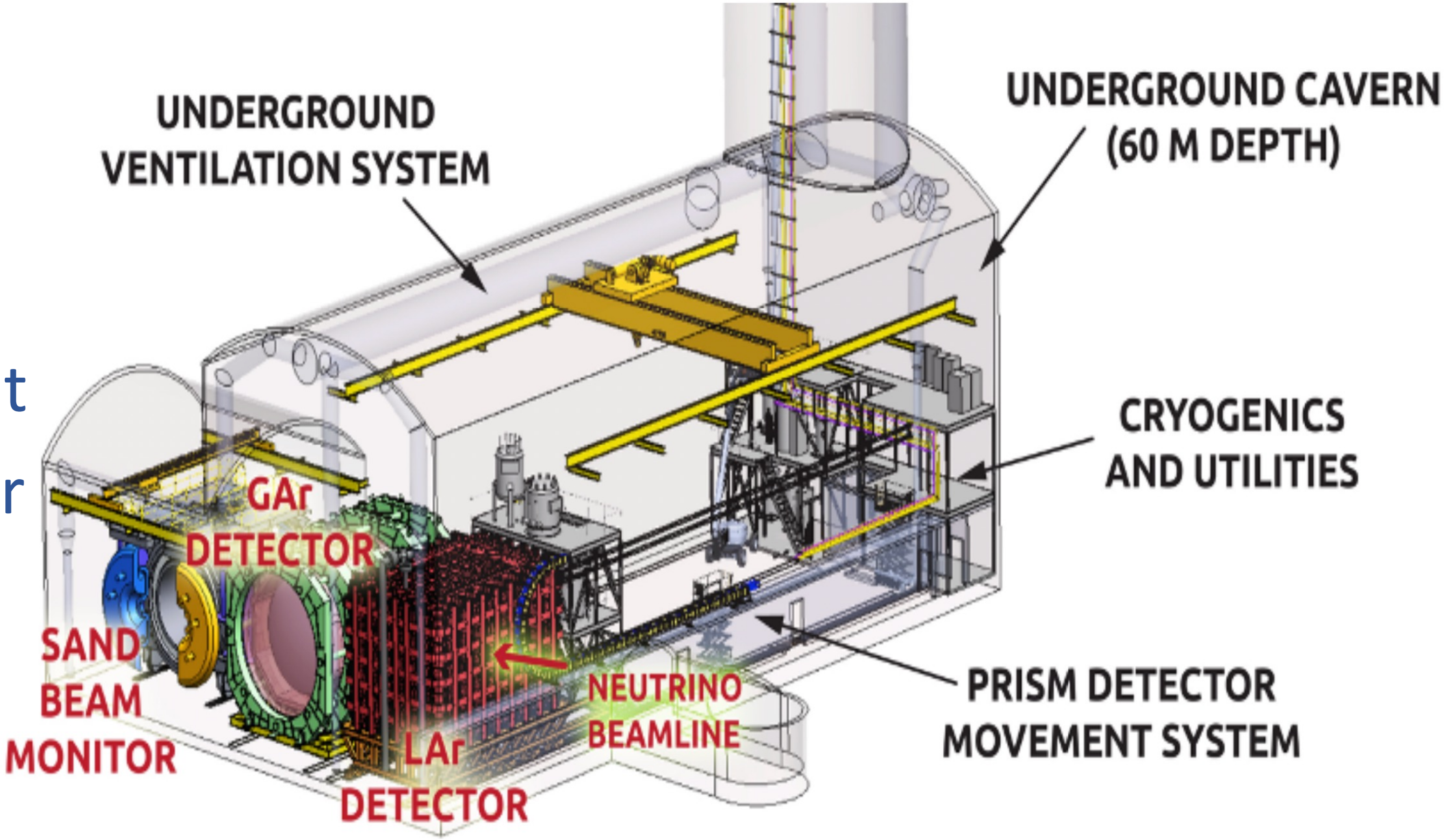

North Dakota
Minnesota
South Dakota
SURF
Wisconsin
Fermilab
Iowa
Nebraska
Illinois

Beam and Near Detector at FNAL

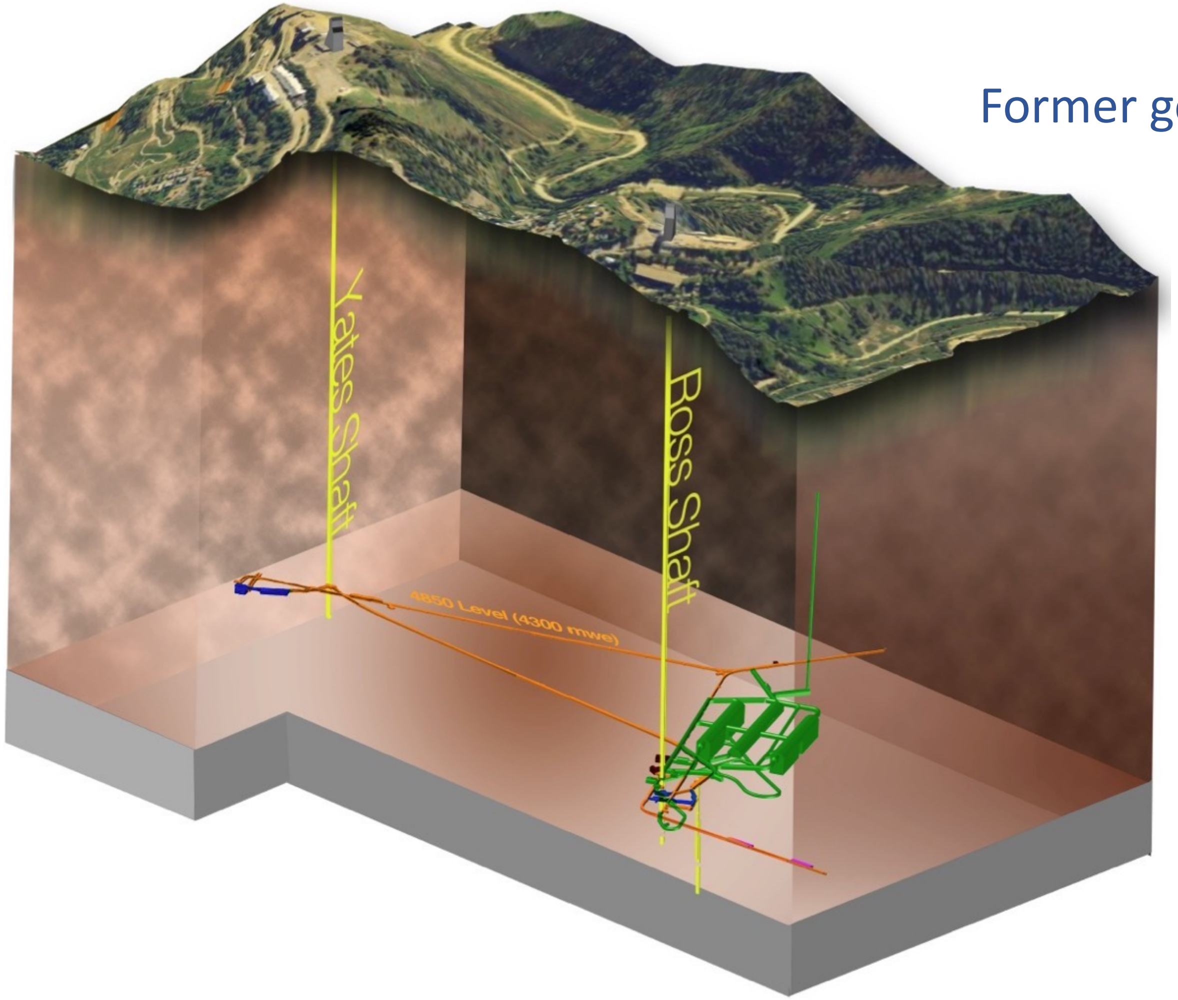


Near Detector Site

- Neutrino flux monitoring
- Cross section measurement
- Predictions for Far Detector
  - Relative measurement = constraint on systematics

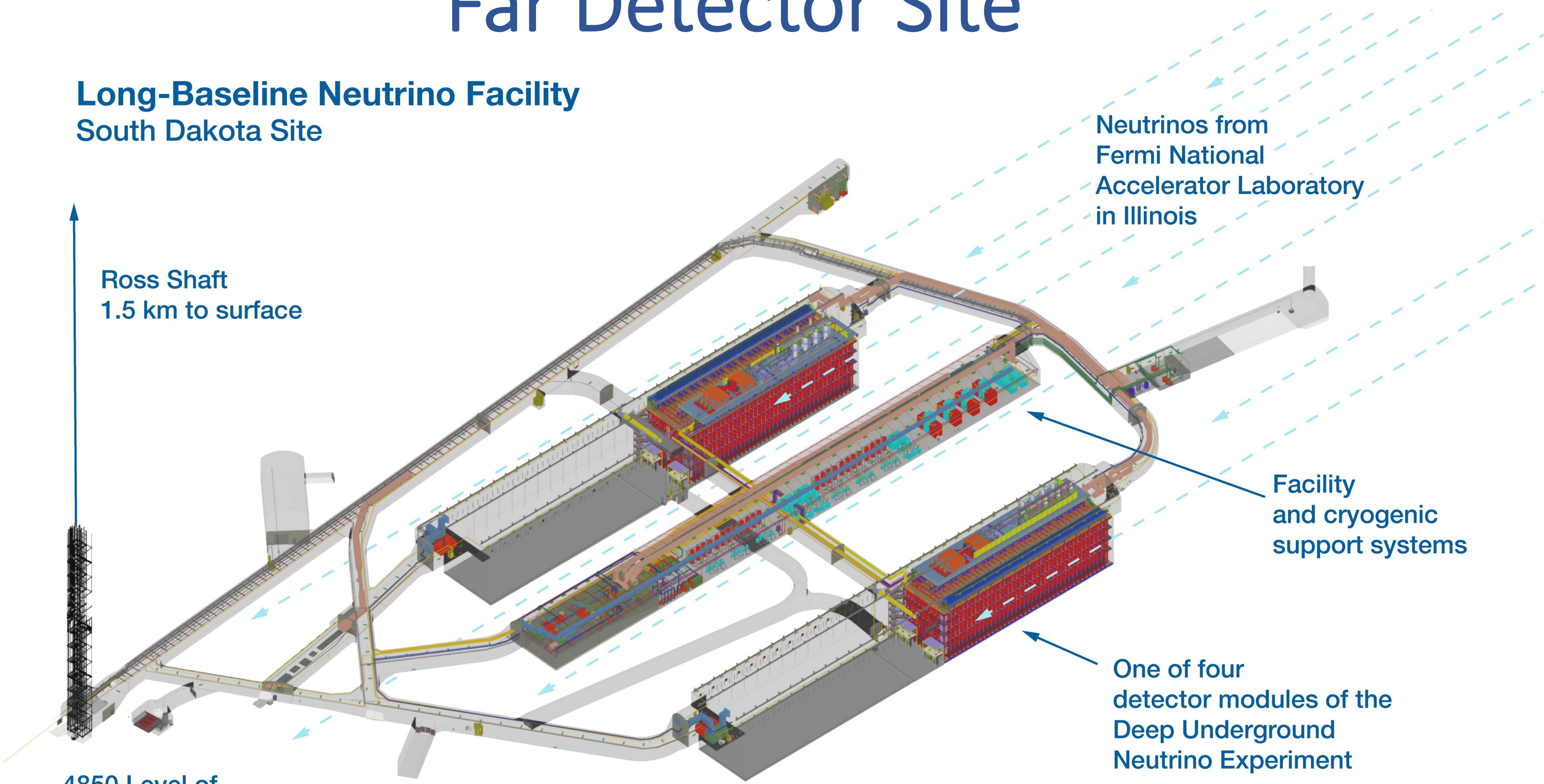


Far Detector Site

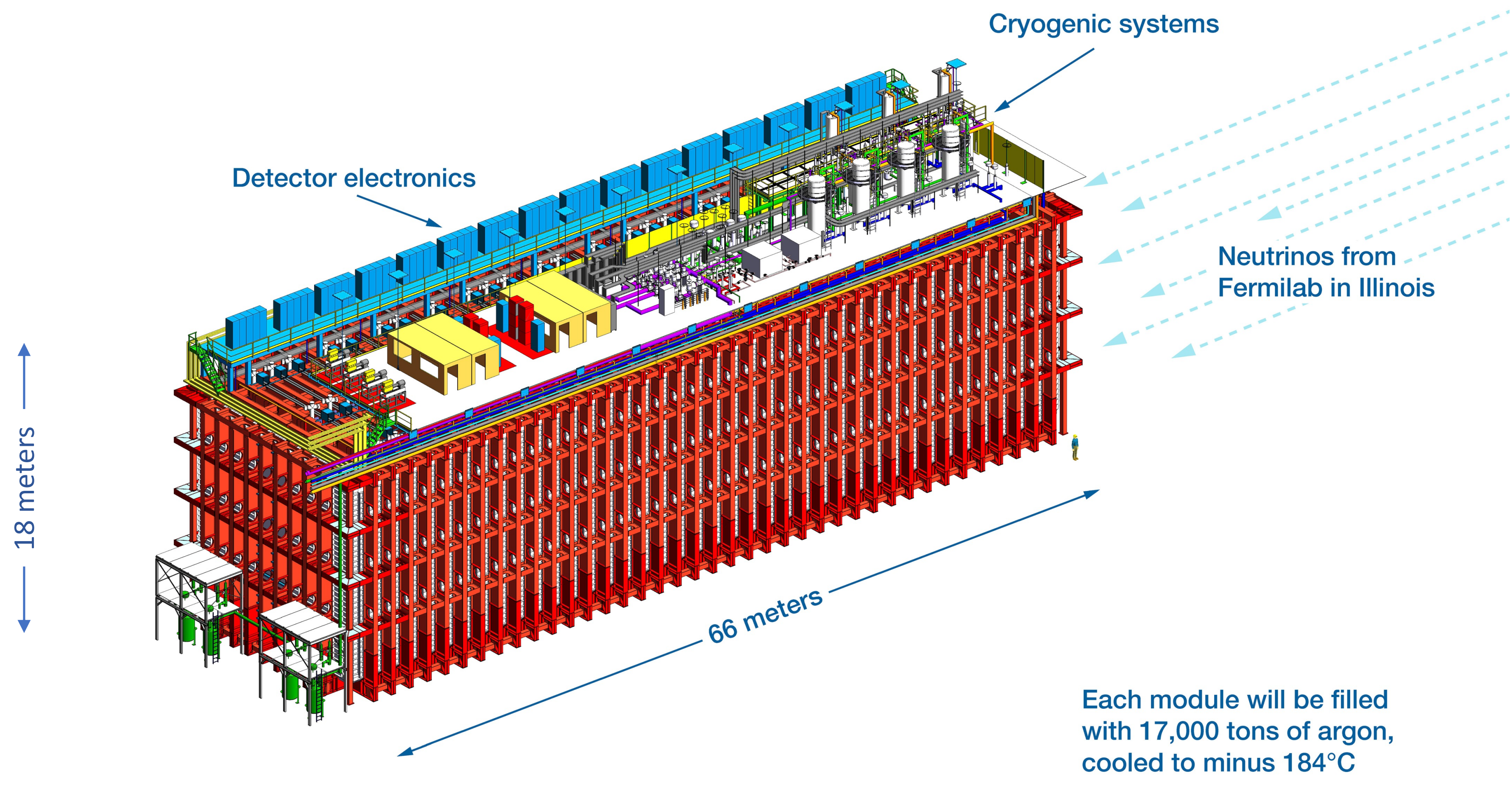


Former gold mines in South Dakota

Far Detector Site

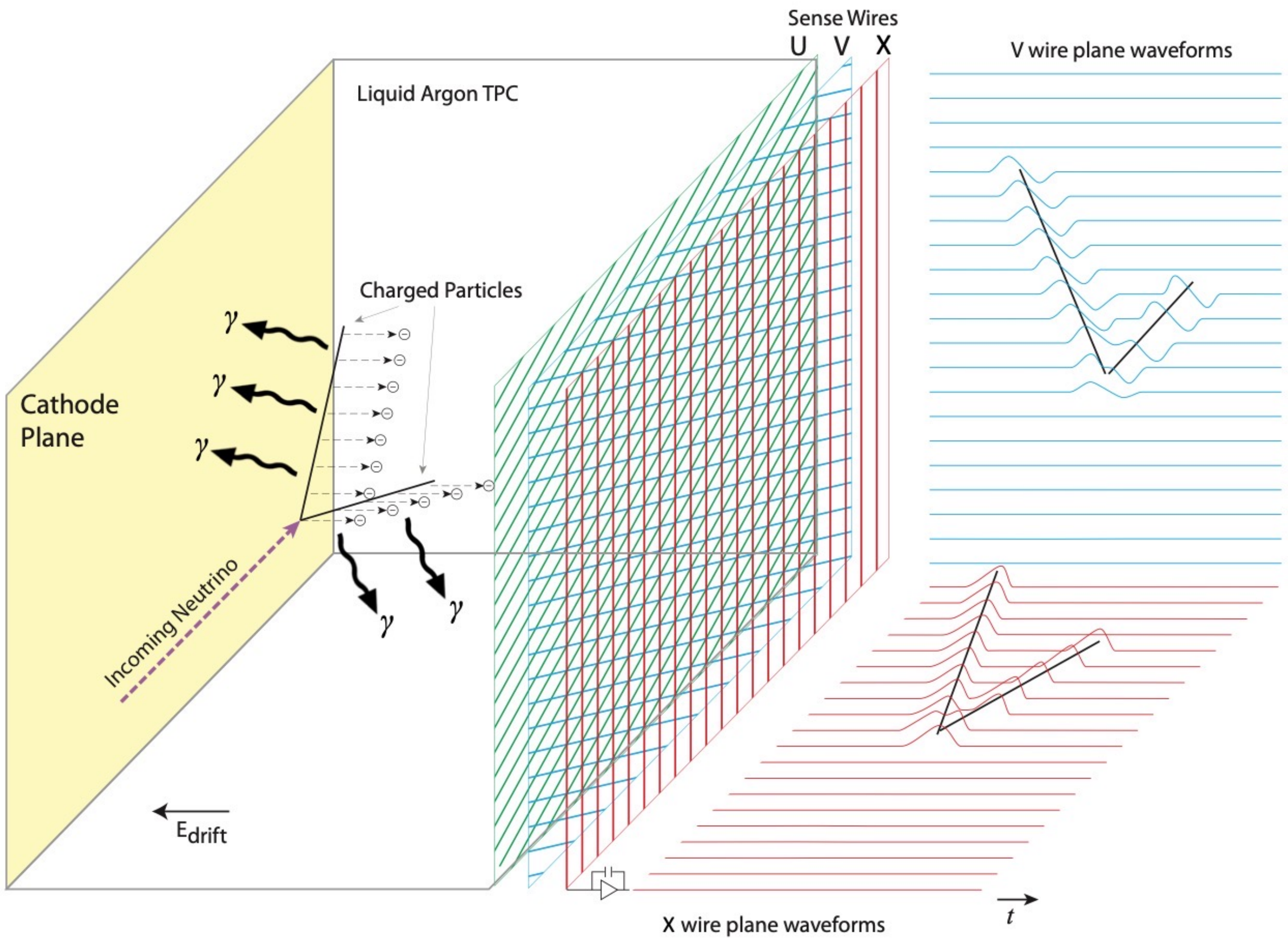


Cryostat

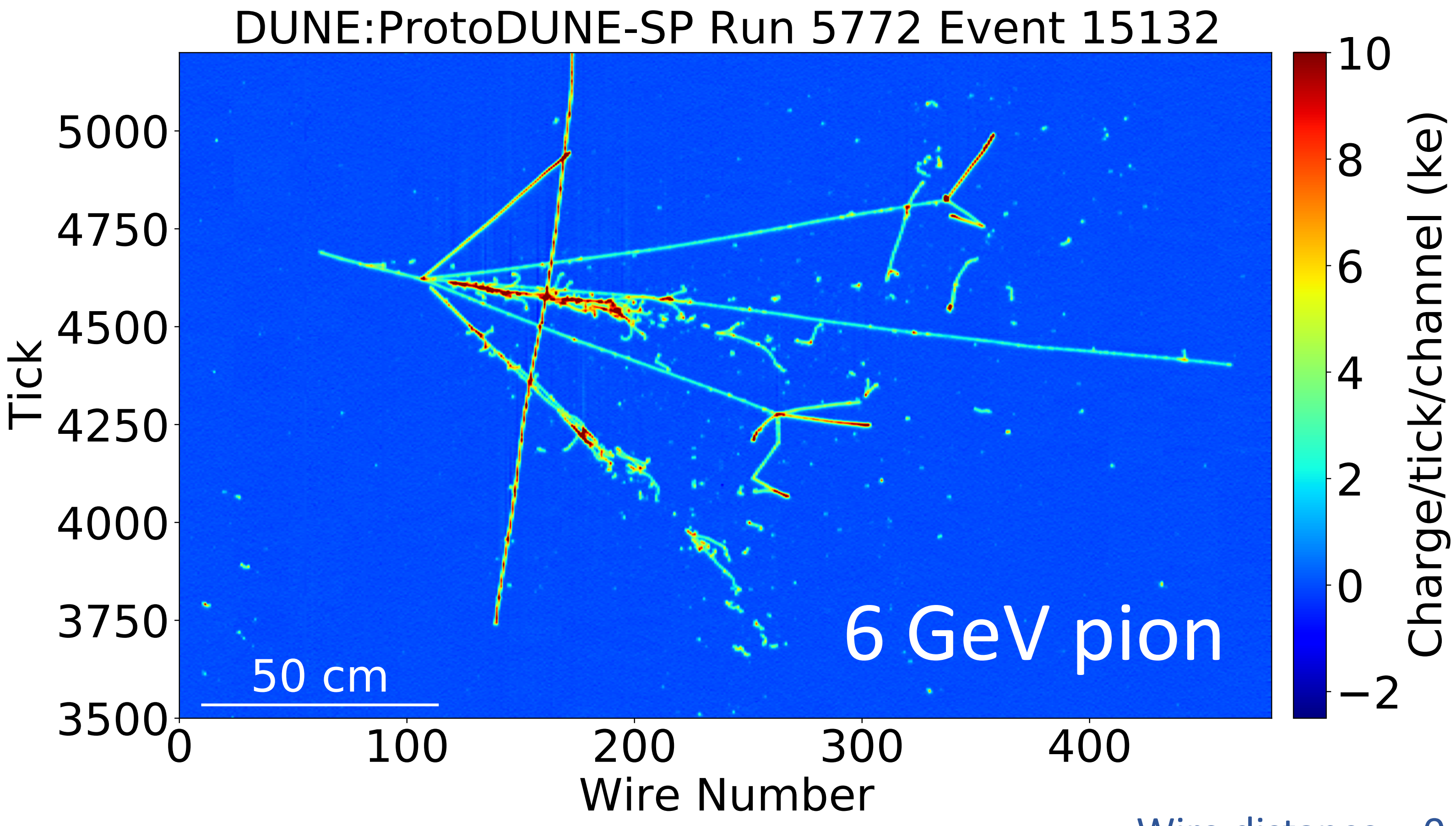

Cryogenic systems
Detector electronics
Neutrinos from
Fermilab in Illinois
18 meters
66 meters
Each module will be filled
with 17,000 tons of argon,
cooled to minus 184°C

Liquid Argon TPC – LArTPC

- 3D images from drifted charge
- Scintillation light collected by photon detection system ➔ time to anchor in drift direction



Example of ProtoDUNE Test-Beam Pion Event

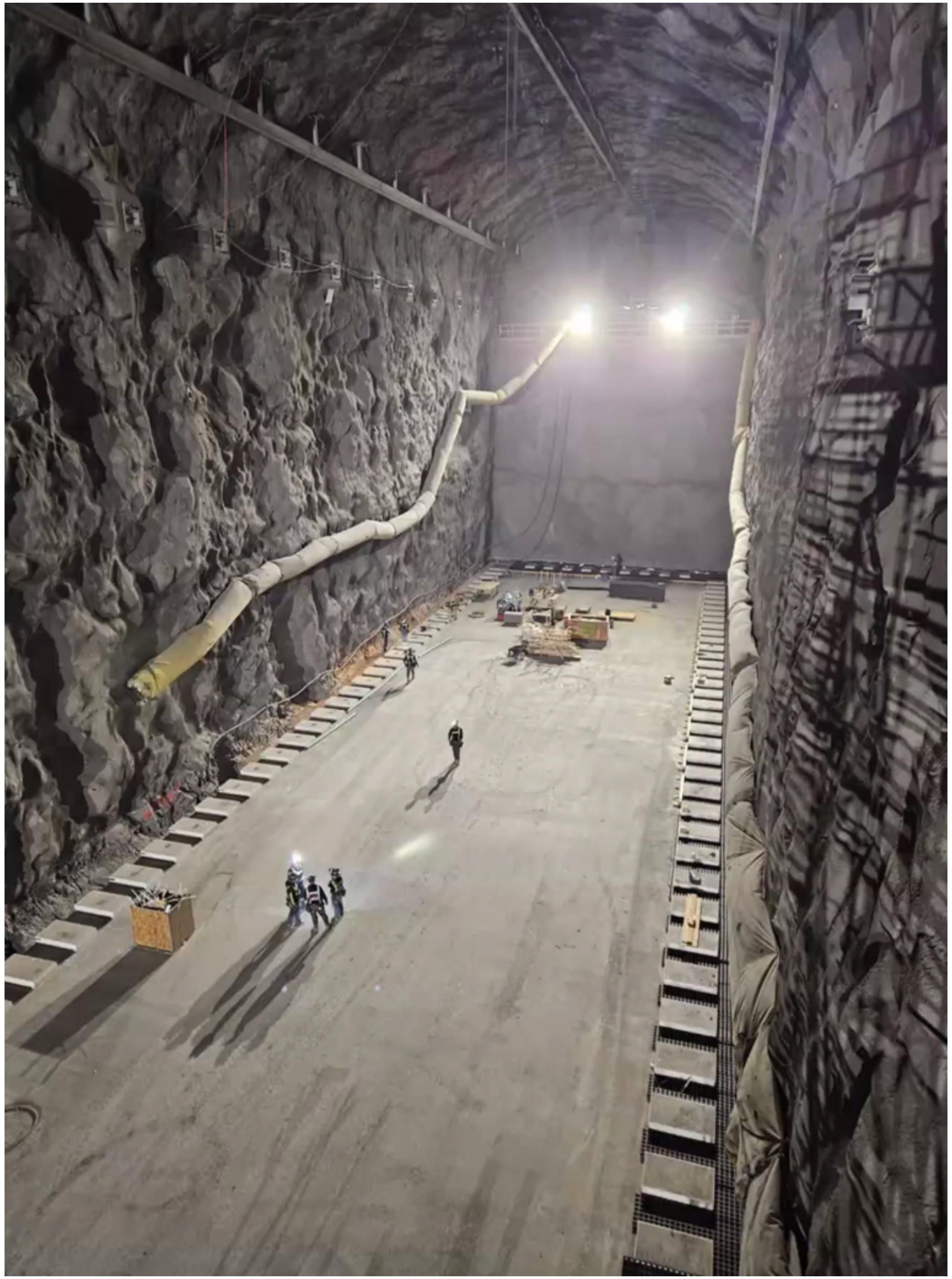


Wire distance = 0.5 cm

1 TDC = 0.5 µs

Status

- Caverns excavated!
- 1st detector expected running in about 6 years

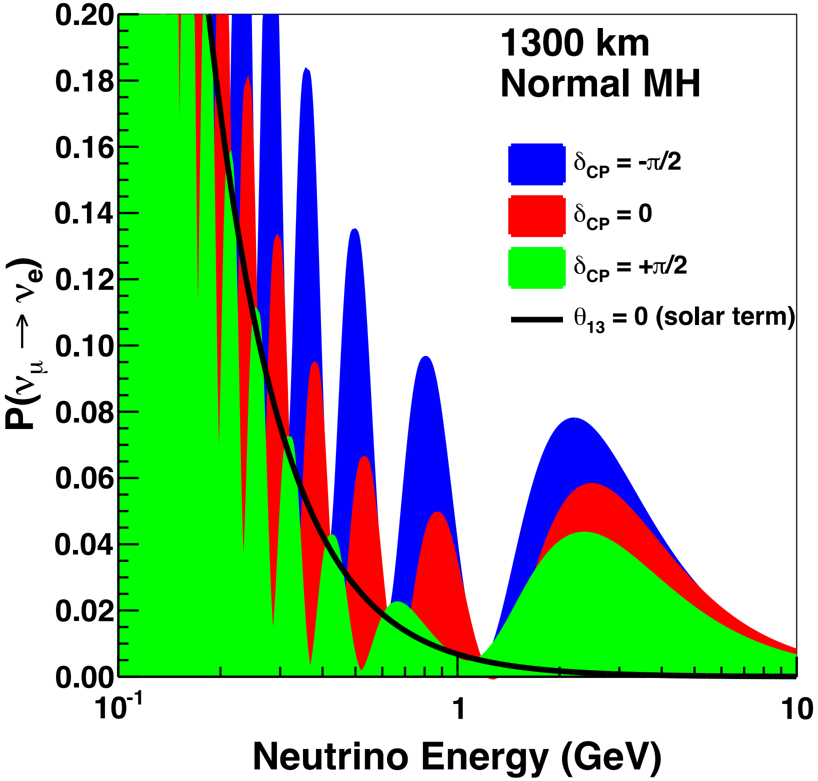


DUNE's Physics Scope

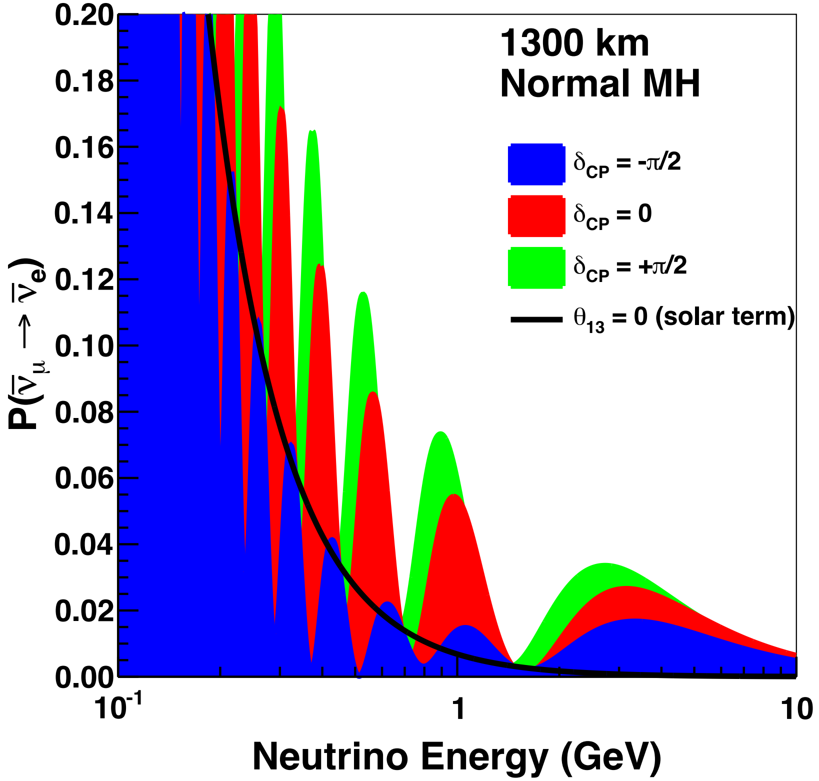
CP violation

Probability

neutrino

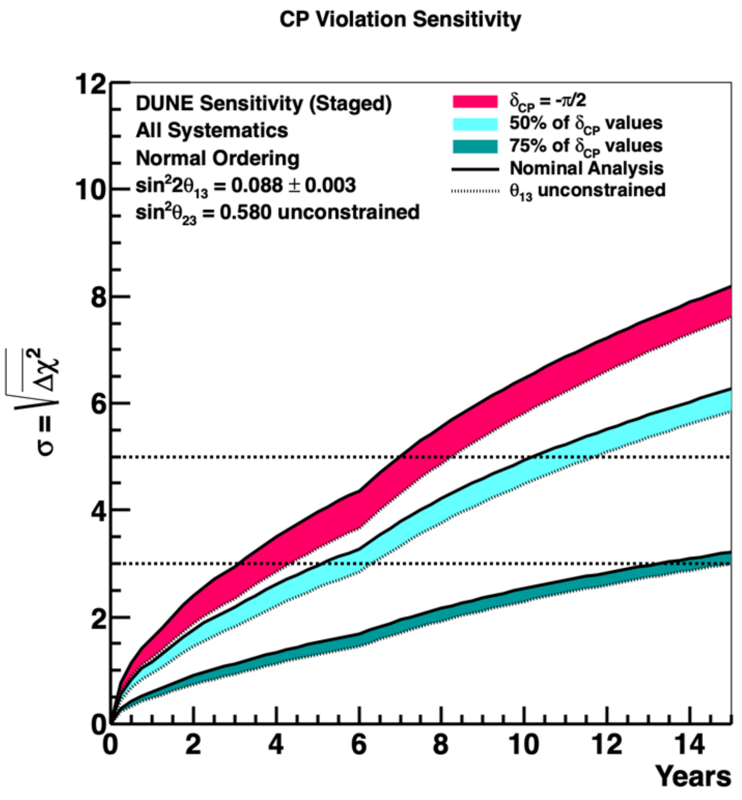


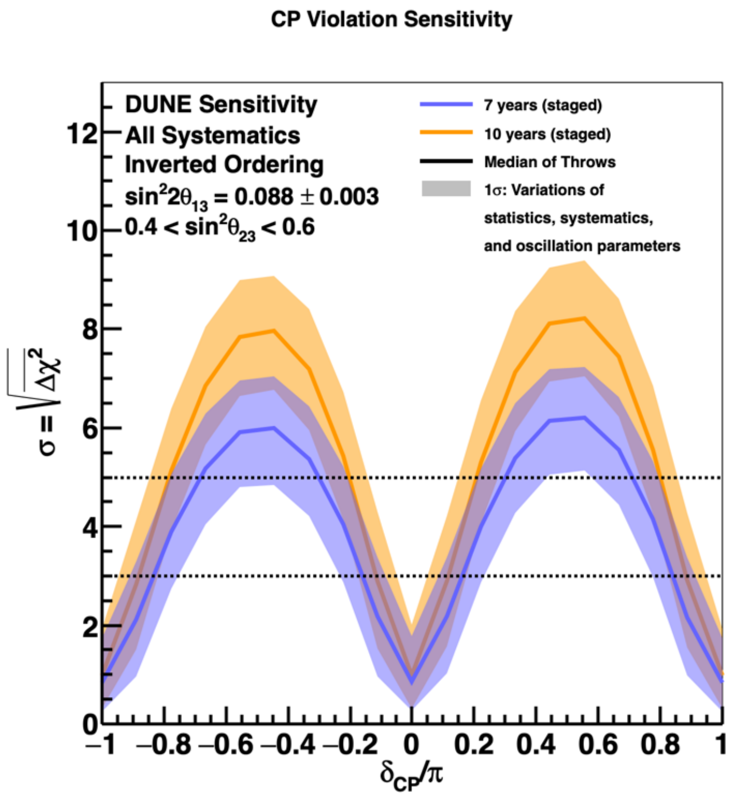
anti-neutrino



DUNE's Physics Scope

CP violation

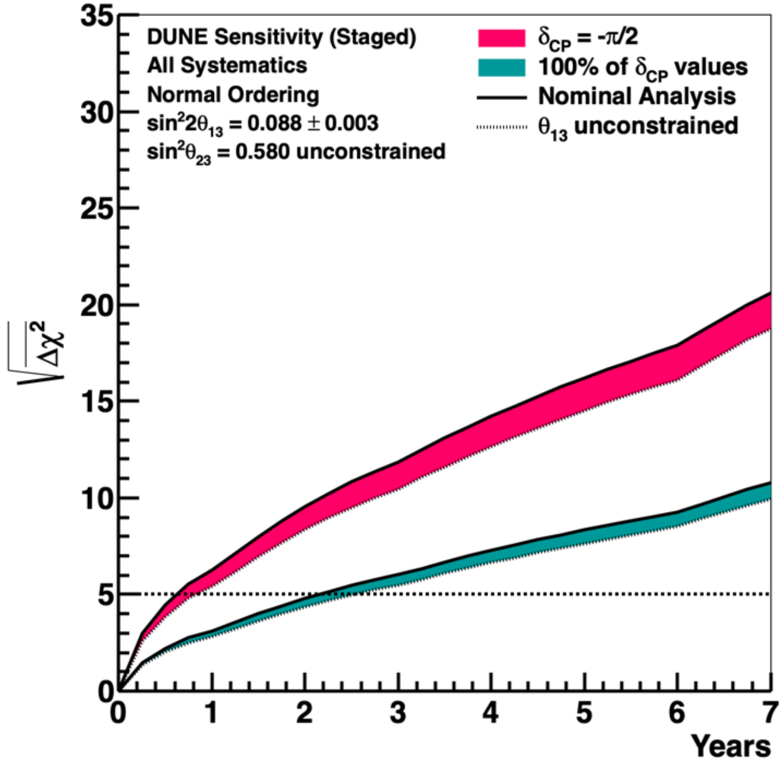


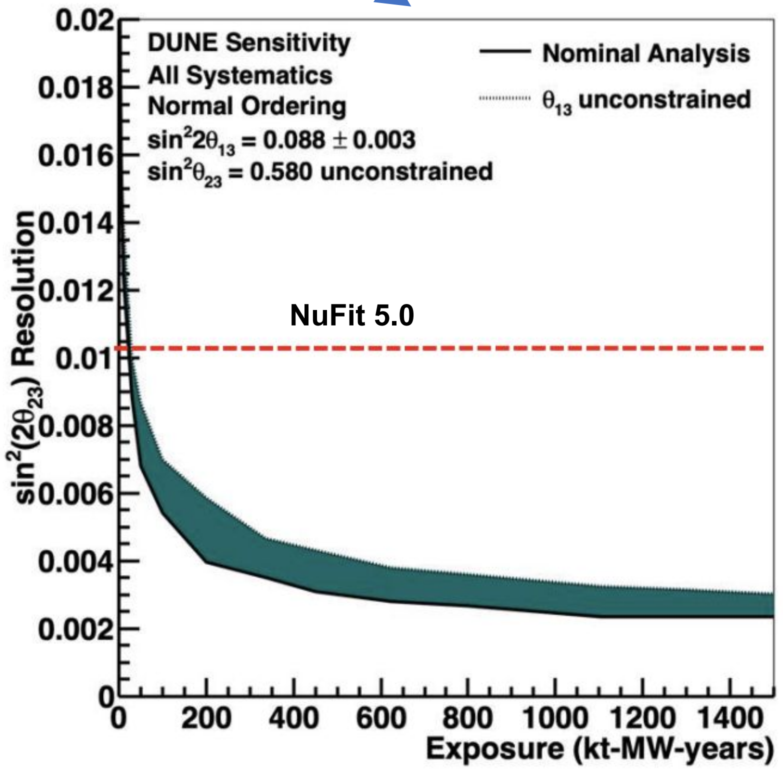


DUNE's Physics Scope

CP violation

Precision measurement: Δm_{32}^2 - mass ordering, θ_{23} - octant





DUNE's Physics Scope

CP violation

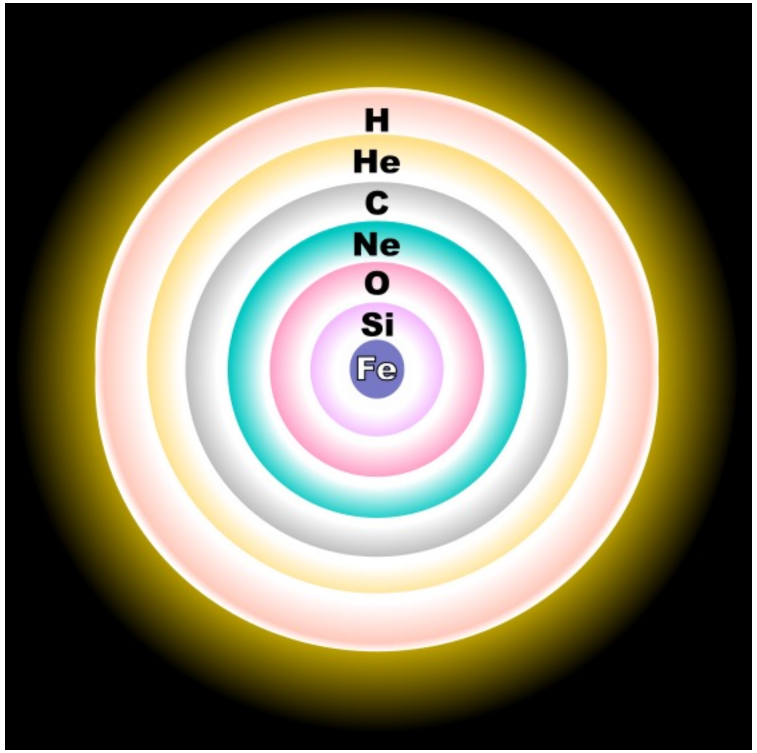
Precision measurement: $\mathbf{\Delta m_{32}^2}$ - mass ordering, $\boldsymbol{\theta_{23}}$ - octant

Non-beam physics

- BSM nucleon transitions: Proton decay, n-$\bar{n}$ transition
- Low energy neutrinos: **Supernova**, Solar

Core-collapse Supernova

- I am not an expert 😬
- One possible end of a star
- Critical mass of Fe core ~ 1.4 $M_{\odot}$
- Core collapse
- Rebound in ~10^{-2} s
- Release of energy in ν and $\bar{\nu}$
  - About 10^{53} ergs in 10^{58} neutrinos @ ~ 10 MeV
  - Small part (~1%) transformed to visible explosion

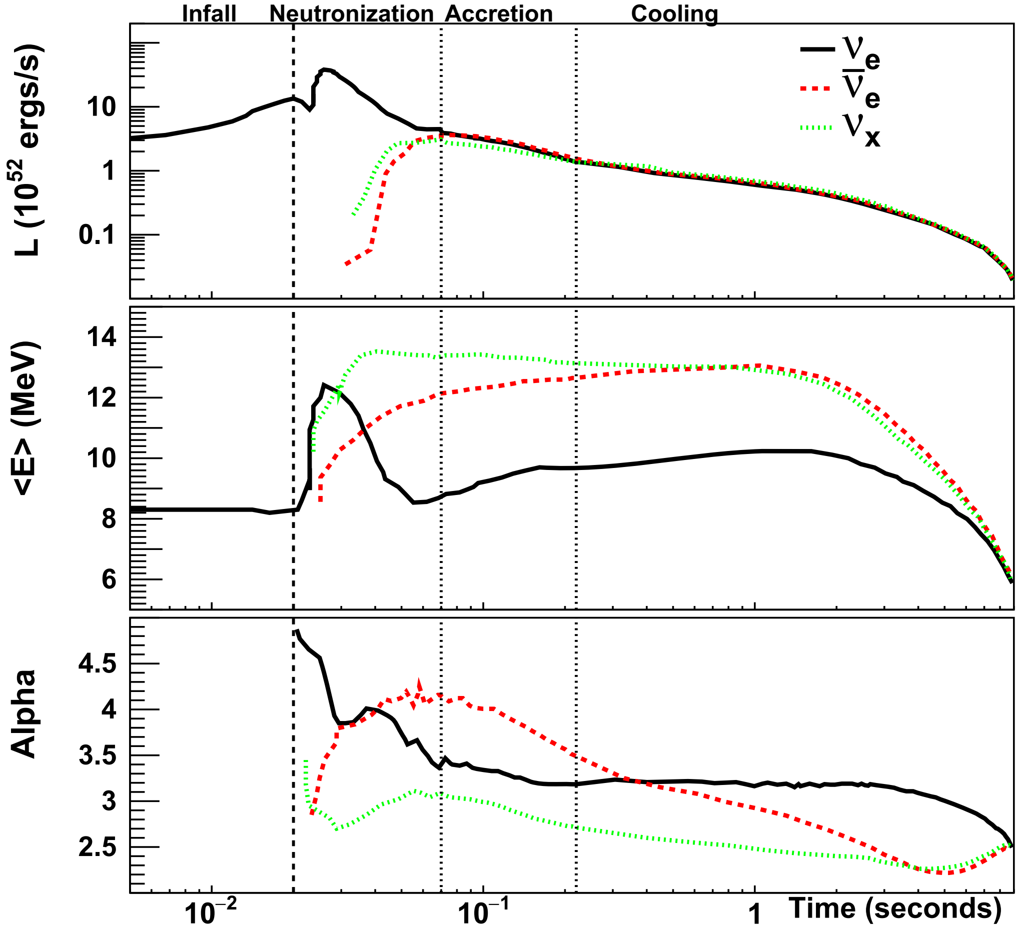


Layers not to scale, source: Wikipedia.org

Phases

- **Infall** – ν_e
- **Neutronization** – ν_e , $e^- + p \rightarrow \nu_e + n$
- **Accretion** – outer mass falls onto the core
- **Cooling** – most energy in ~10 s

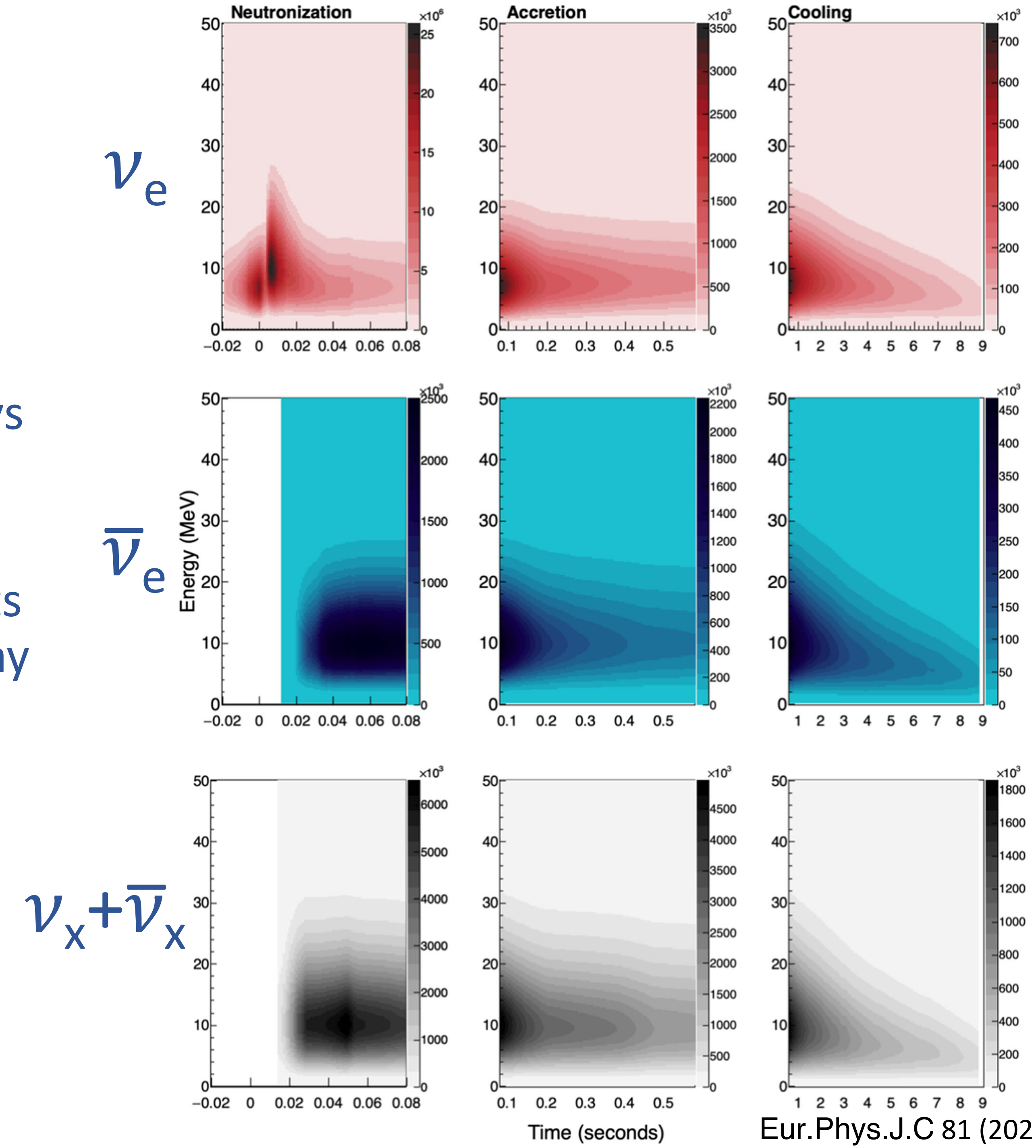
Garching model



Eur.Phys.J.C 81 (2021) 5, 423

Energy Spectrum

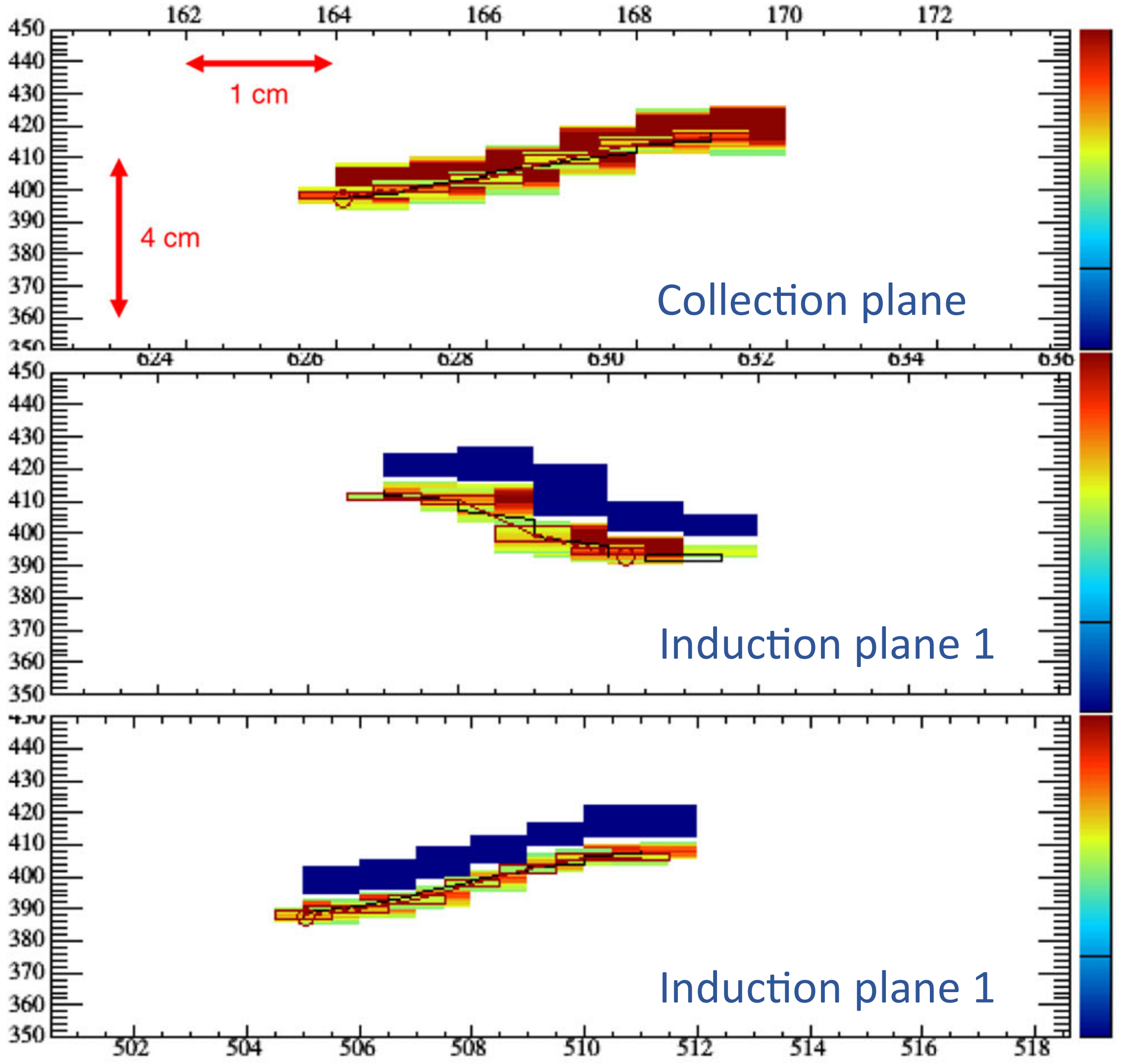
- Dependent on models
- Measuring spectrum vs time would help constraining
- Expect ~1000 ν_e events from 10 kpc (Milky Way centre)
- But very rare – once every few decades within ~20 kpc



Eur.Phys.J.C 81 (2021) 5, 423

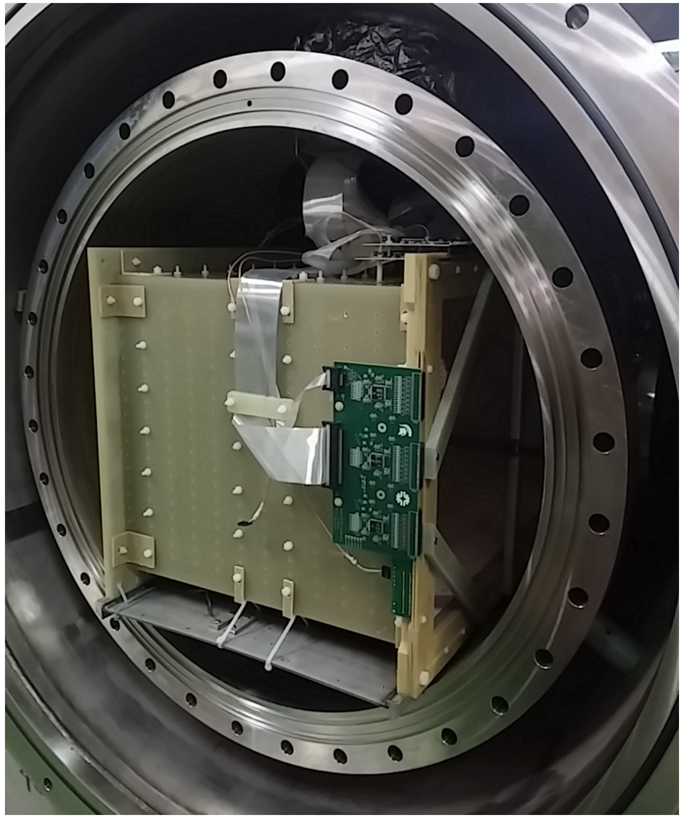
Low-E Calorimetry

Simulated elastic scattering $\nu_e + e^-$

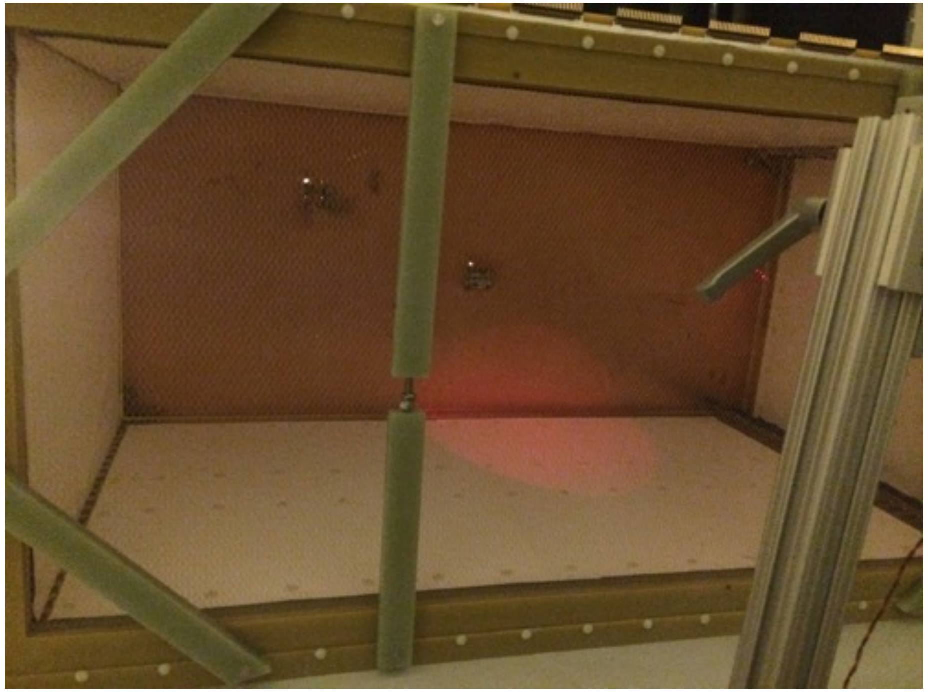


- TPC charge signal → energy
- DUNE designed for ~1 GeV
- Improvements at ~10 MeV?

LArIAT



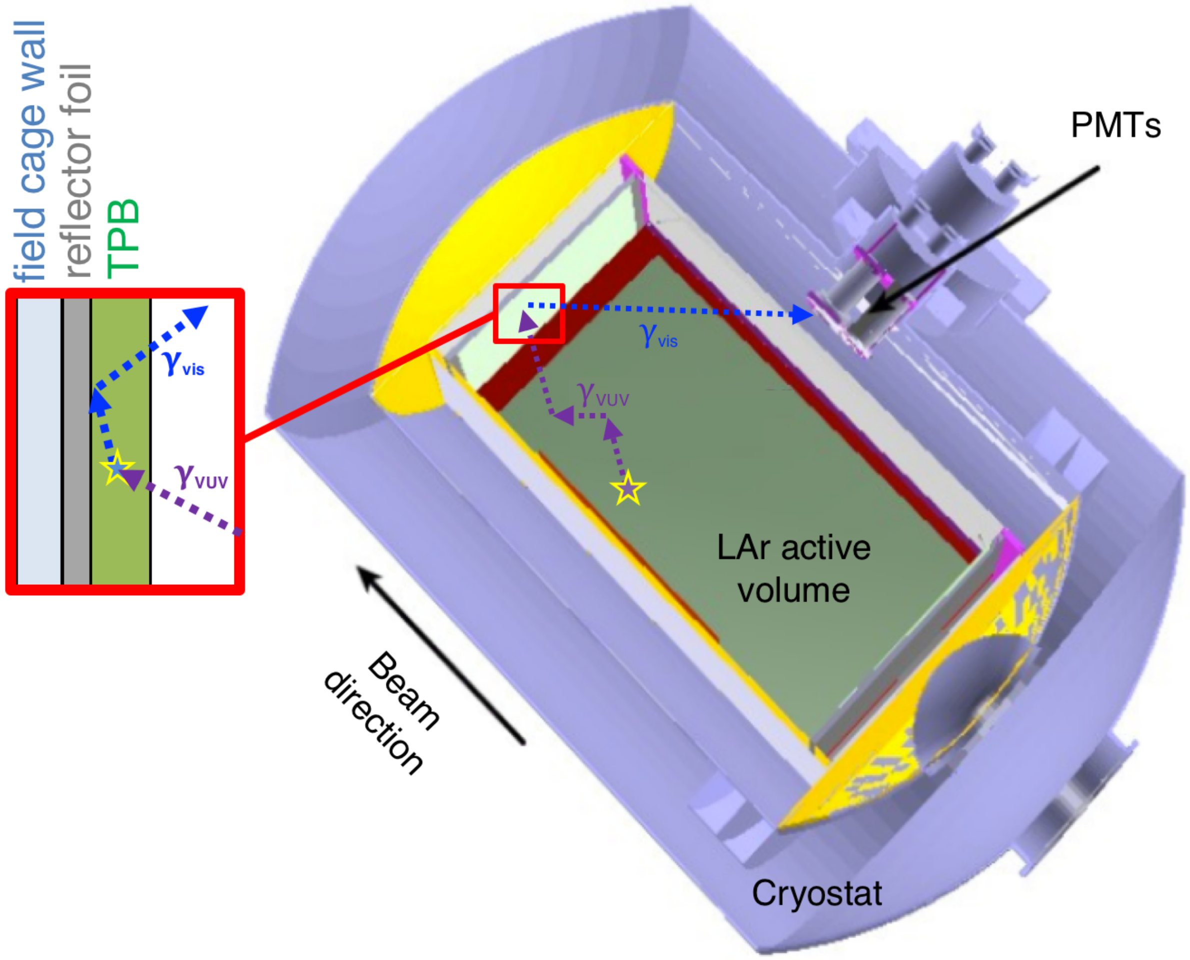
40 cm



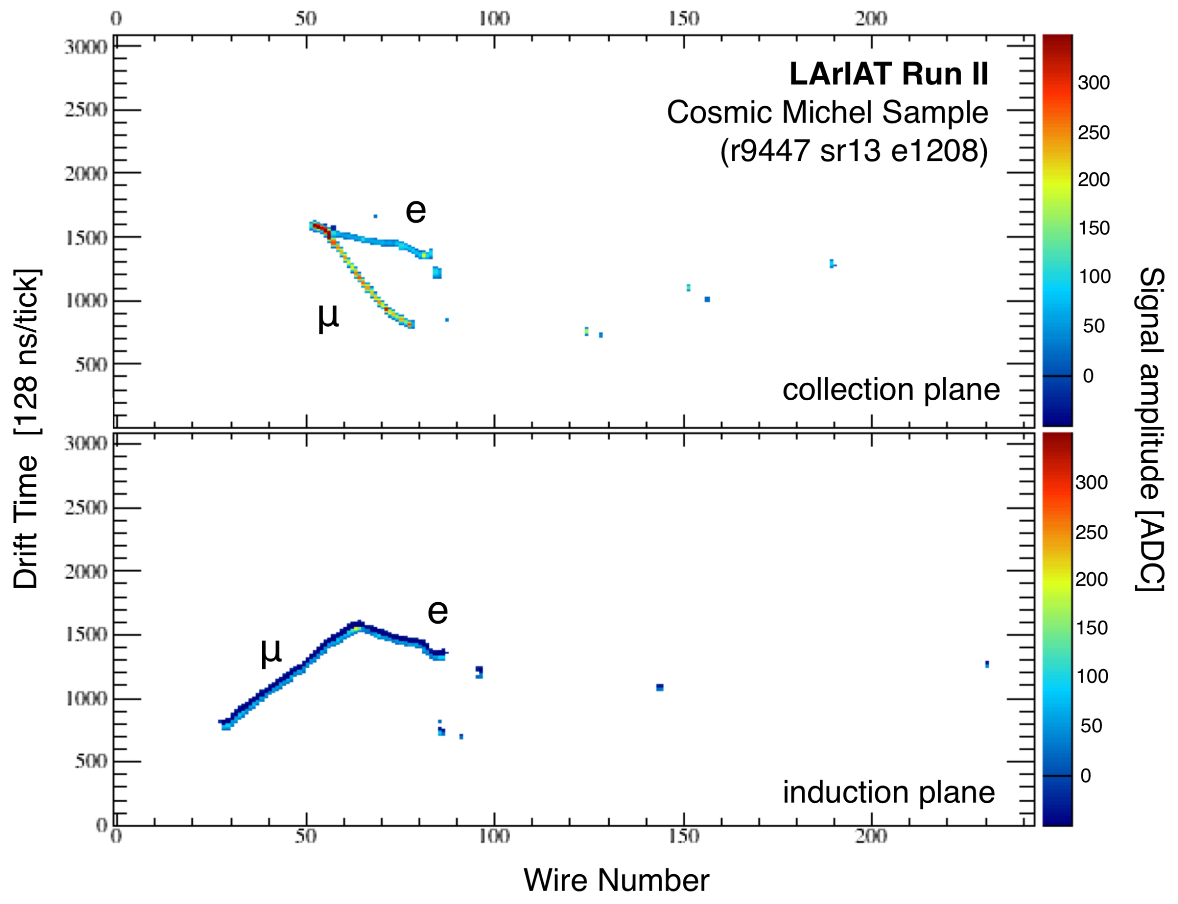
90 cm

Phys. Rev. D **101**, 012010 (2020)

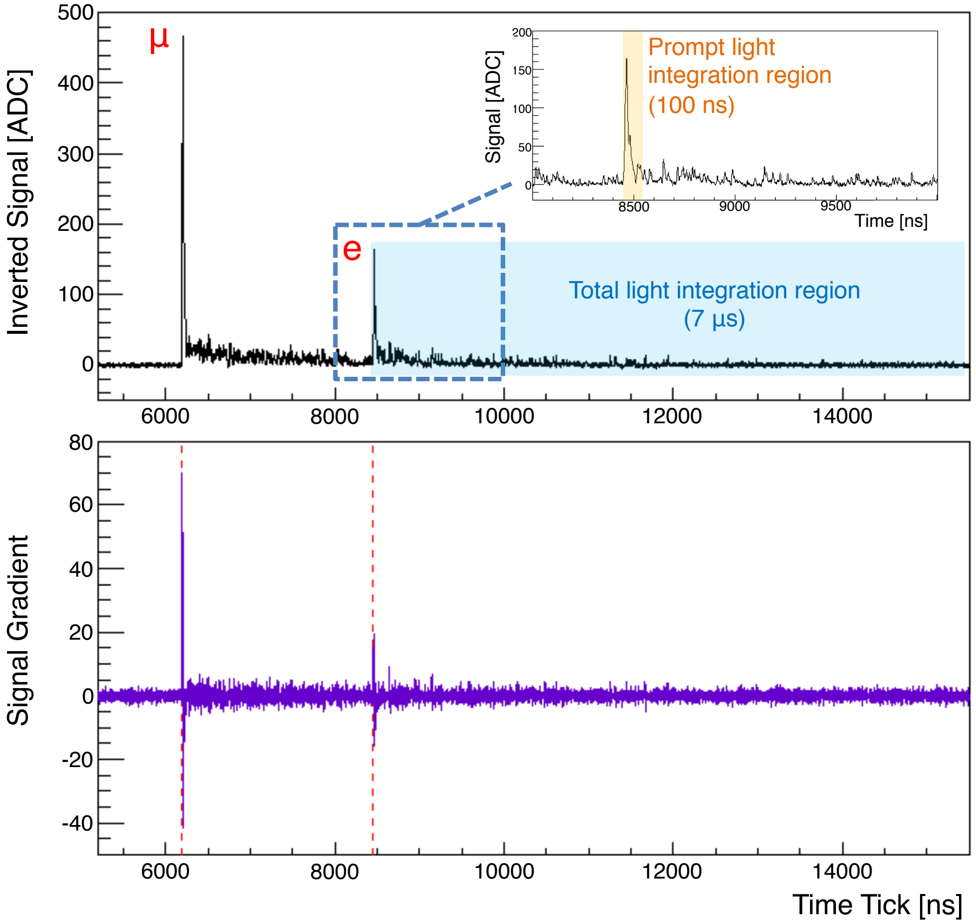
Observation of Scintillation Light



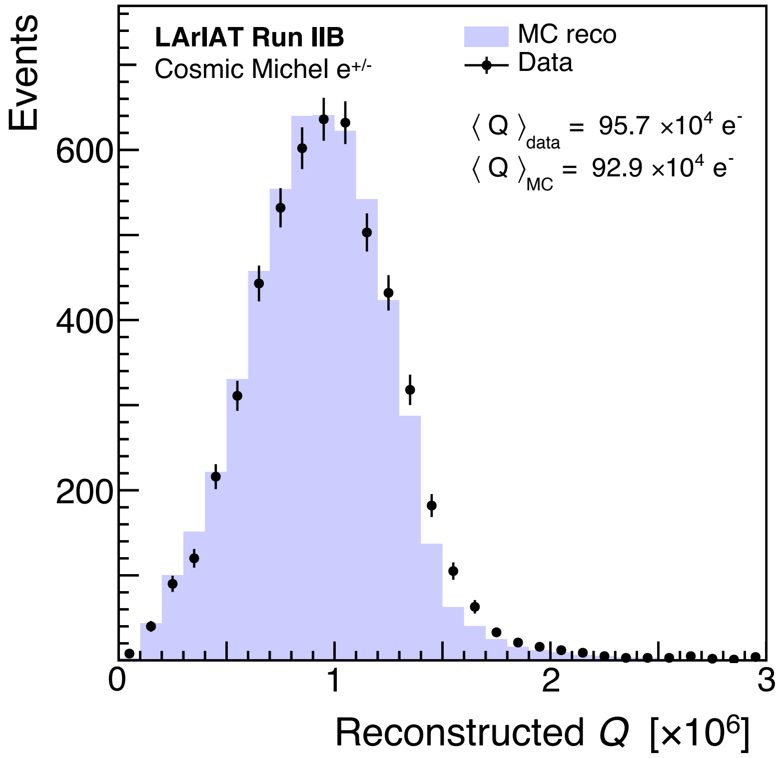
Michel Electrons from Cosmic Ray Muons

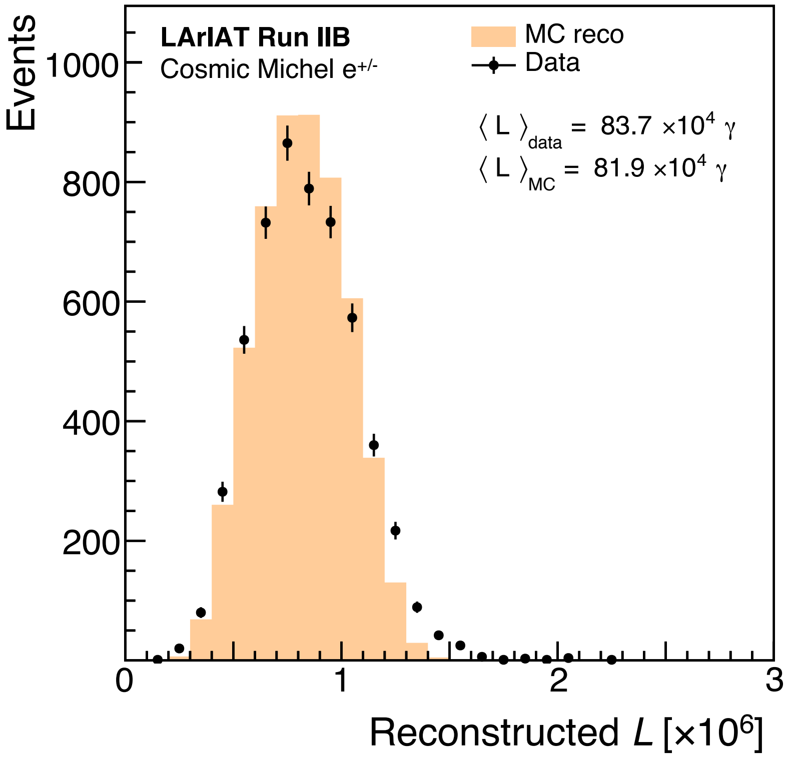


Michel Electron in PMT Signal

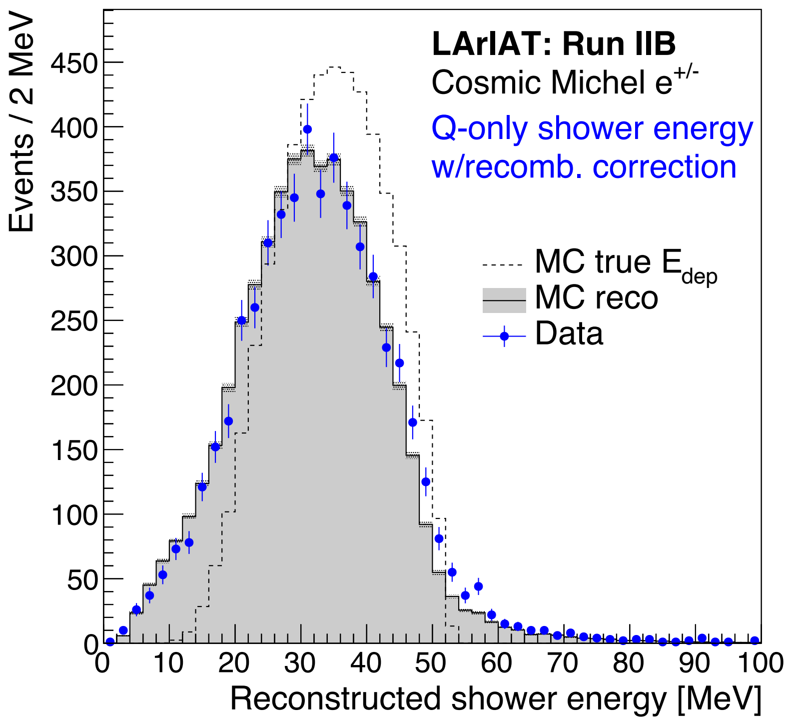


Spectrum from
Charge Light

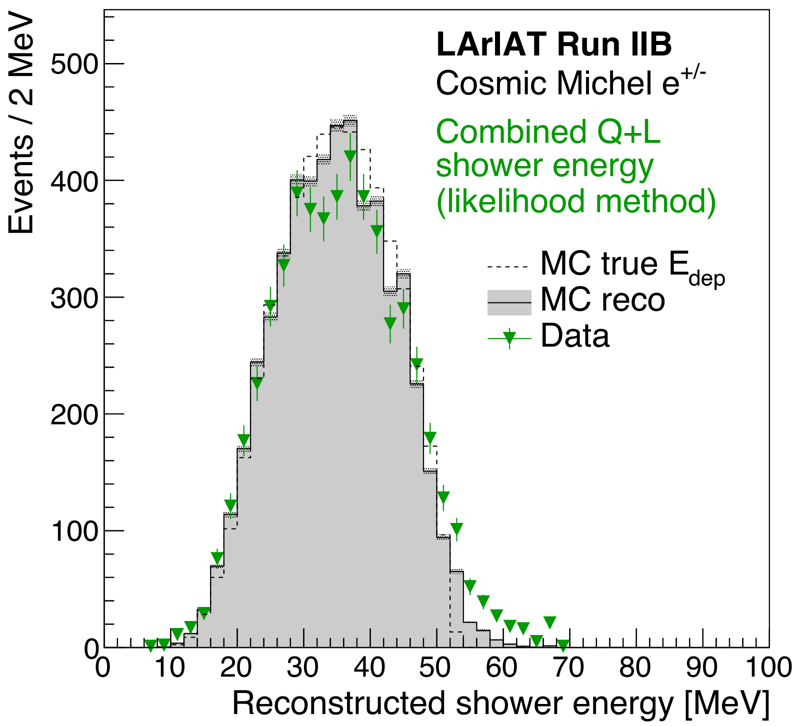




Improvements When Combined

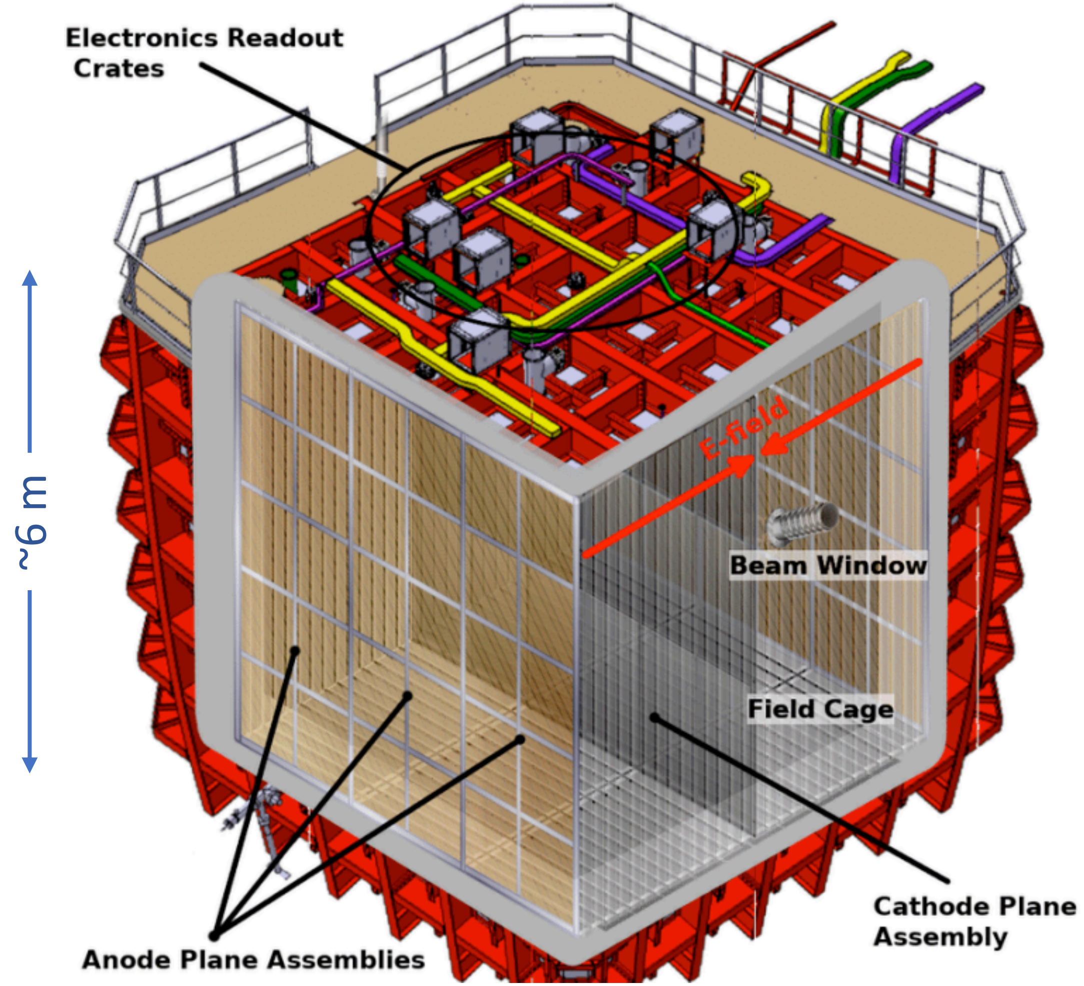


(a) ‘Q-only’ energy spectrum



(c) ‘Q+L’ maximum-likelihood energy spectrum

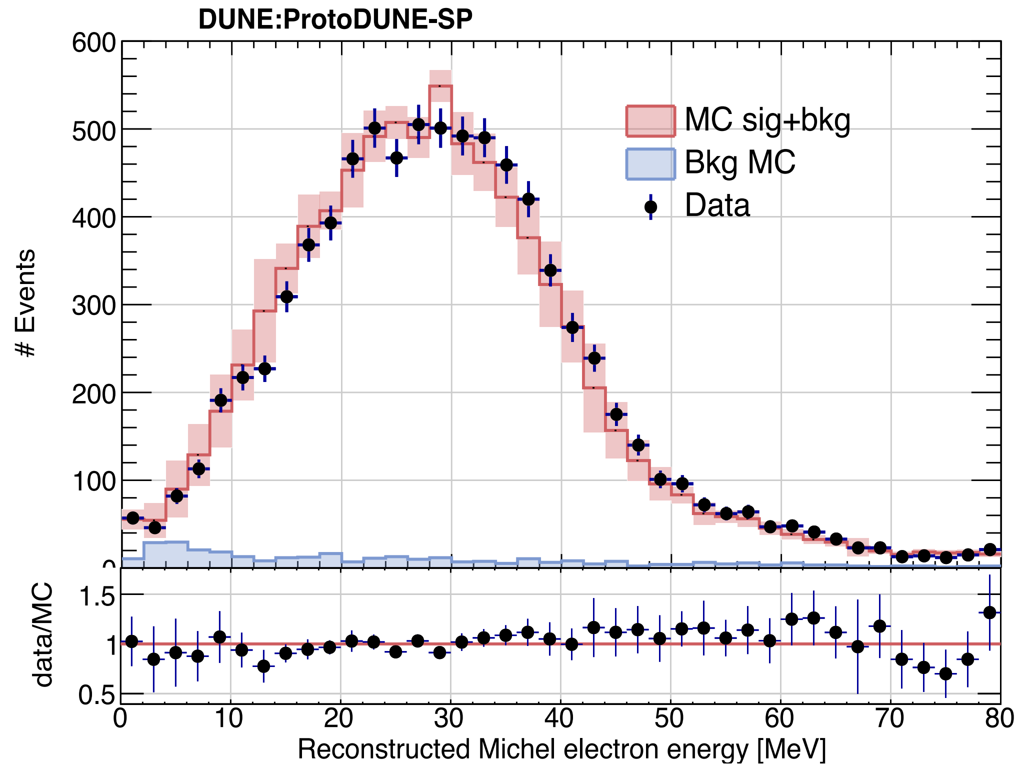
ProtoDUNE



CERN North Area

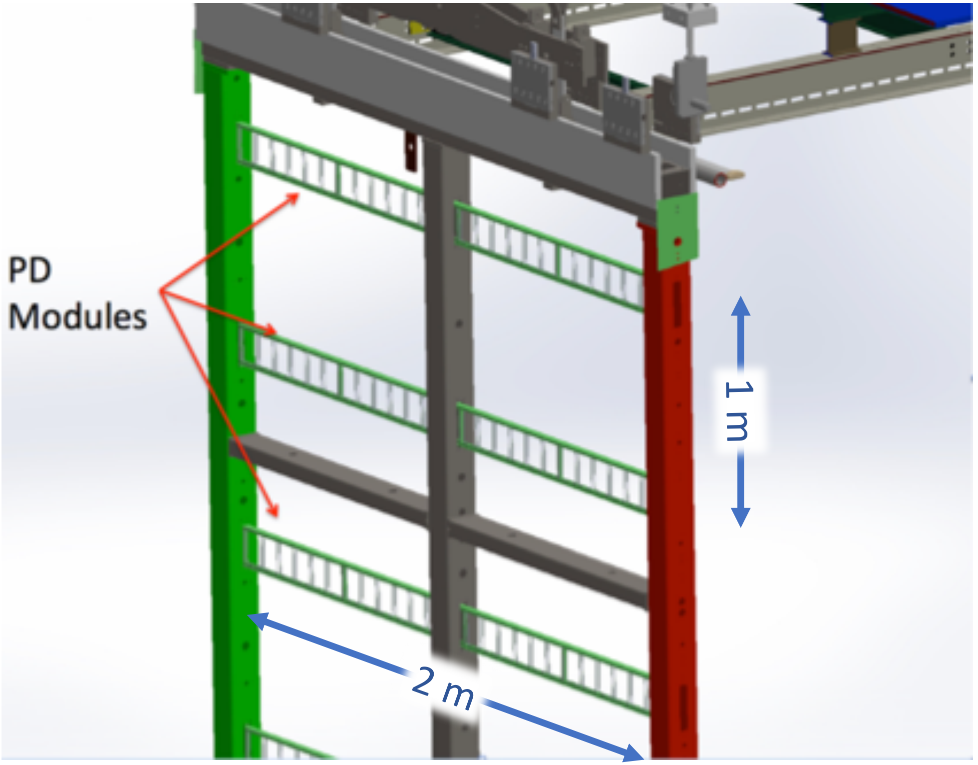
Michel electrons at ProtoDUNE

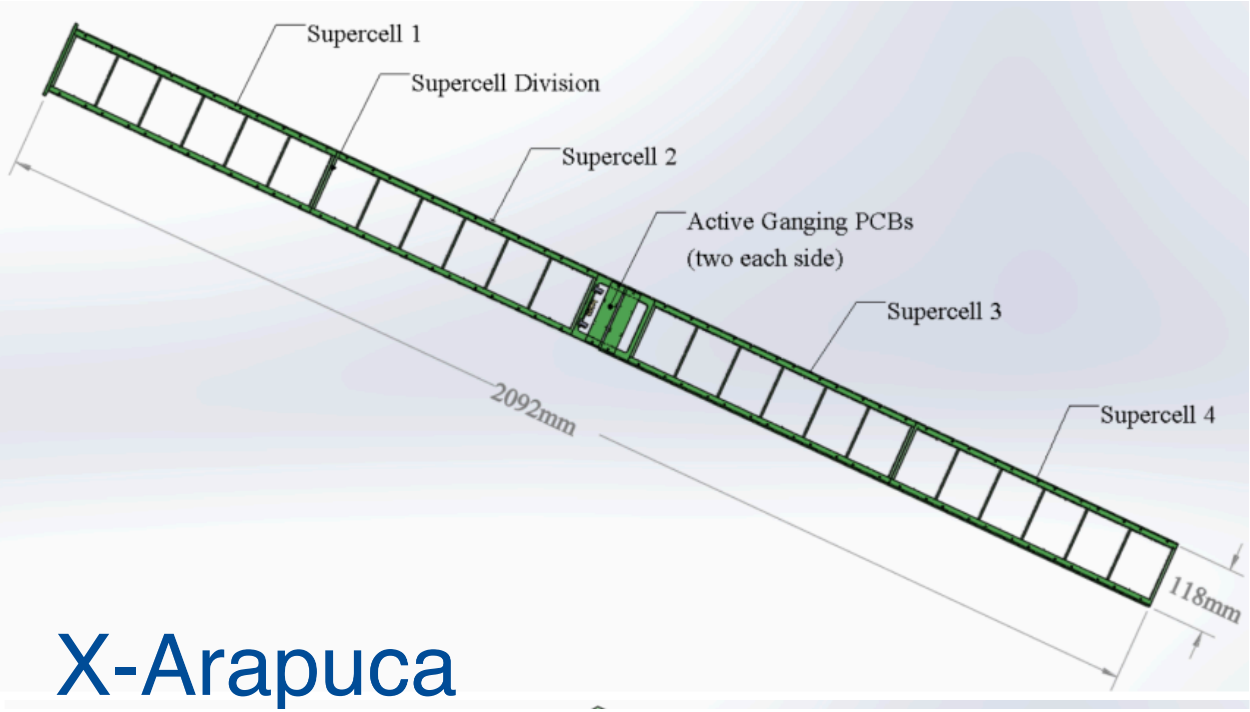
- First data from 2018/19
- Successful measurement of ME energy spectrum using just TPC charge



Light collection

- Large area light collectors



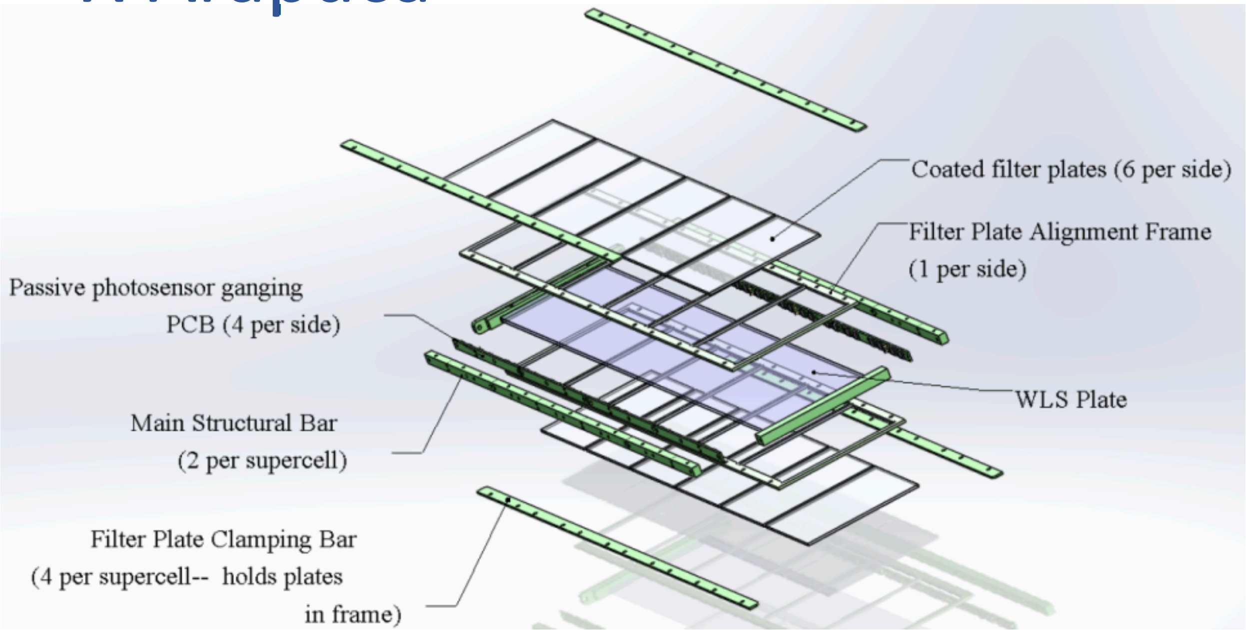


X-Arapuca

Light collection

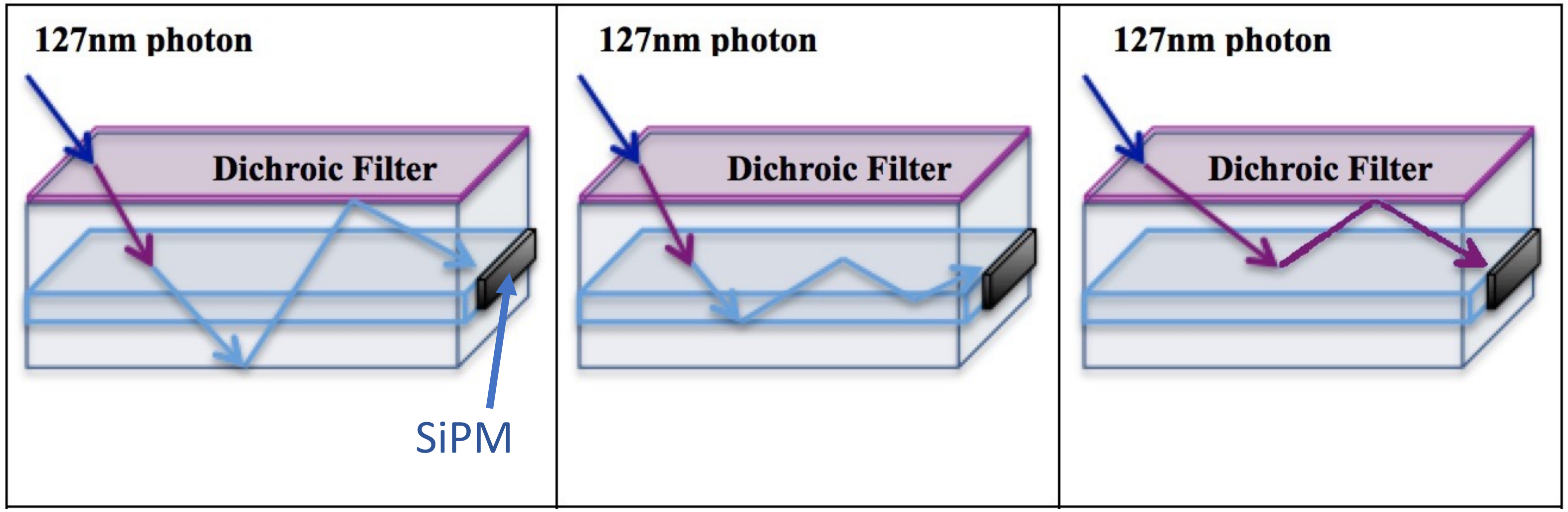
- Large area light collectors
- Multi-layered design

X-Arapuca



Light collection

- Large area light collectors
- Multi-layered design
- Photons converted to lower wavelengths and trapped!



Challenges

- Large volume = long distance for light = attenuation and scattering
- Slow component in scintillation light ~2 μs
- Electronics relaxation time ~0.5 μs

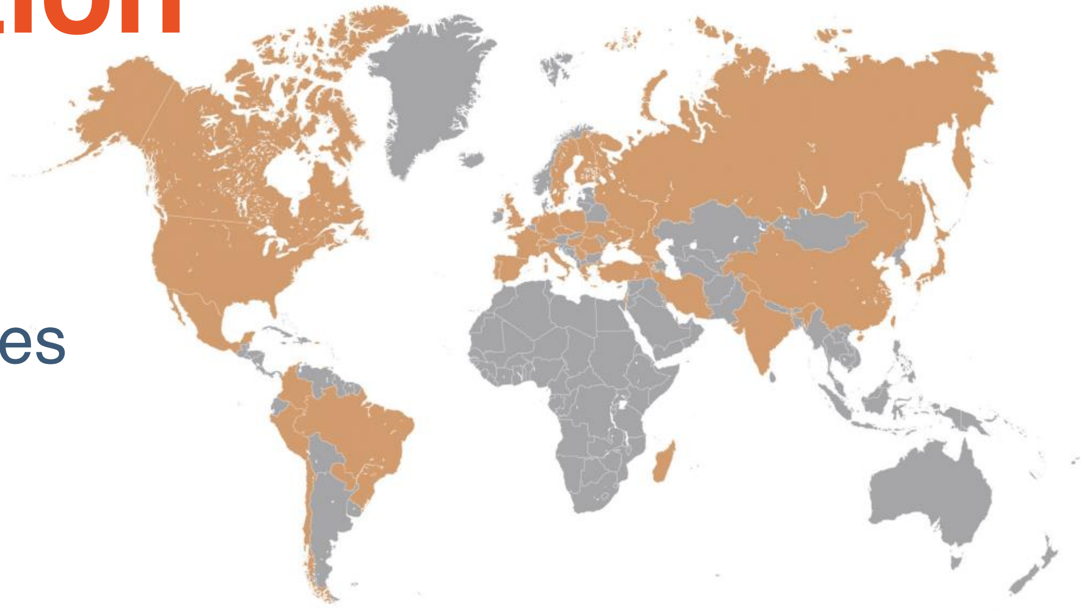
Summary

DUNE

- Will play major role in determination of CP violation in leptons
- Prepares for SN events
- Will come online around 2030
- I am working on combined calorimetry in ProtoDUNE

Backup

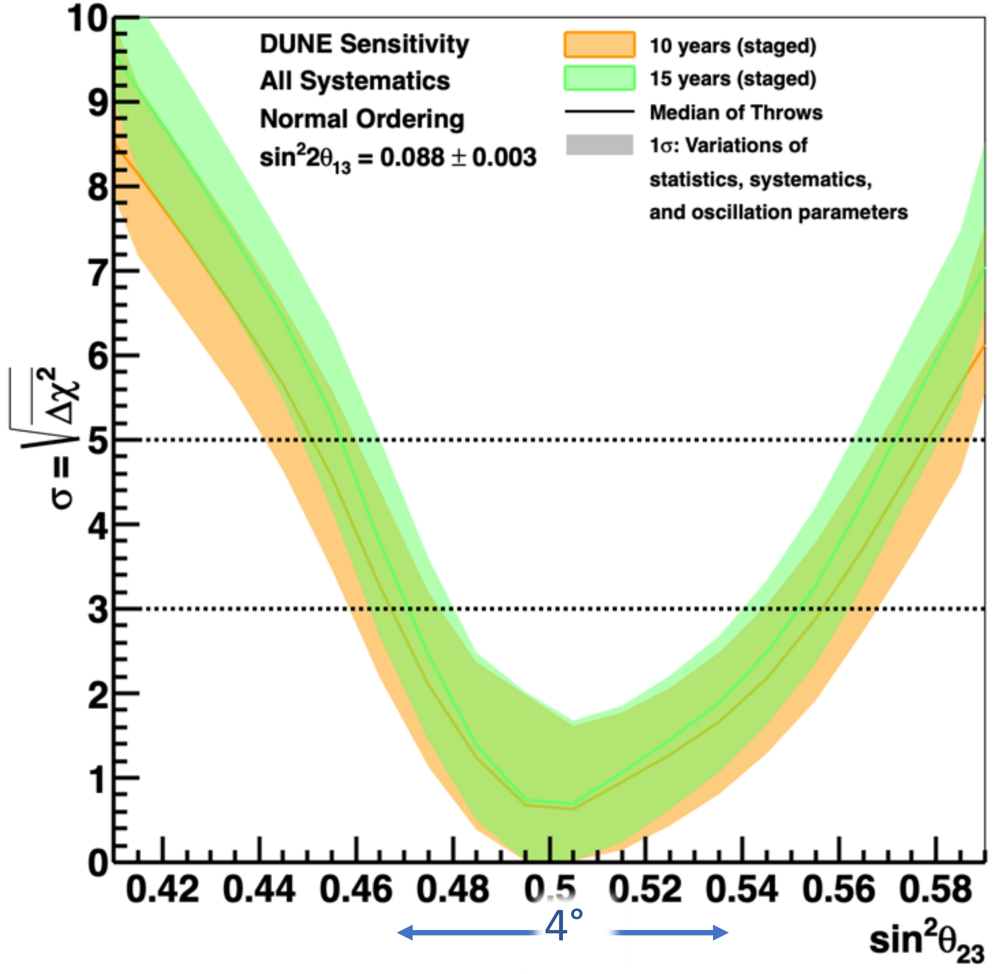
DUNE Collaboration



- 1,400+ people from
  200+ institutions in 30+ countries

DUNE Collaboration meeting at CERN, 2020

θ_{23} Octant Sensitivity



Supernova Neutrino Interaction in DUNE