Mega-scale neutrino detectors: science and technology

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University of Manchester

INFIERI Summer School, Sao Paulo
August-September 2023

Lecture 1

- Neutrinos, their sources and detection
- Solar neutrinos
- Reactor neutrinos
- Accelerator neutrinos
- Operating long-baseline experiments

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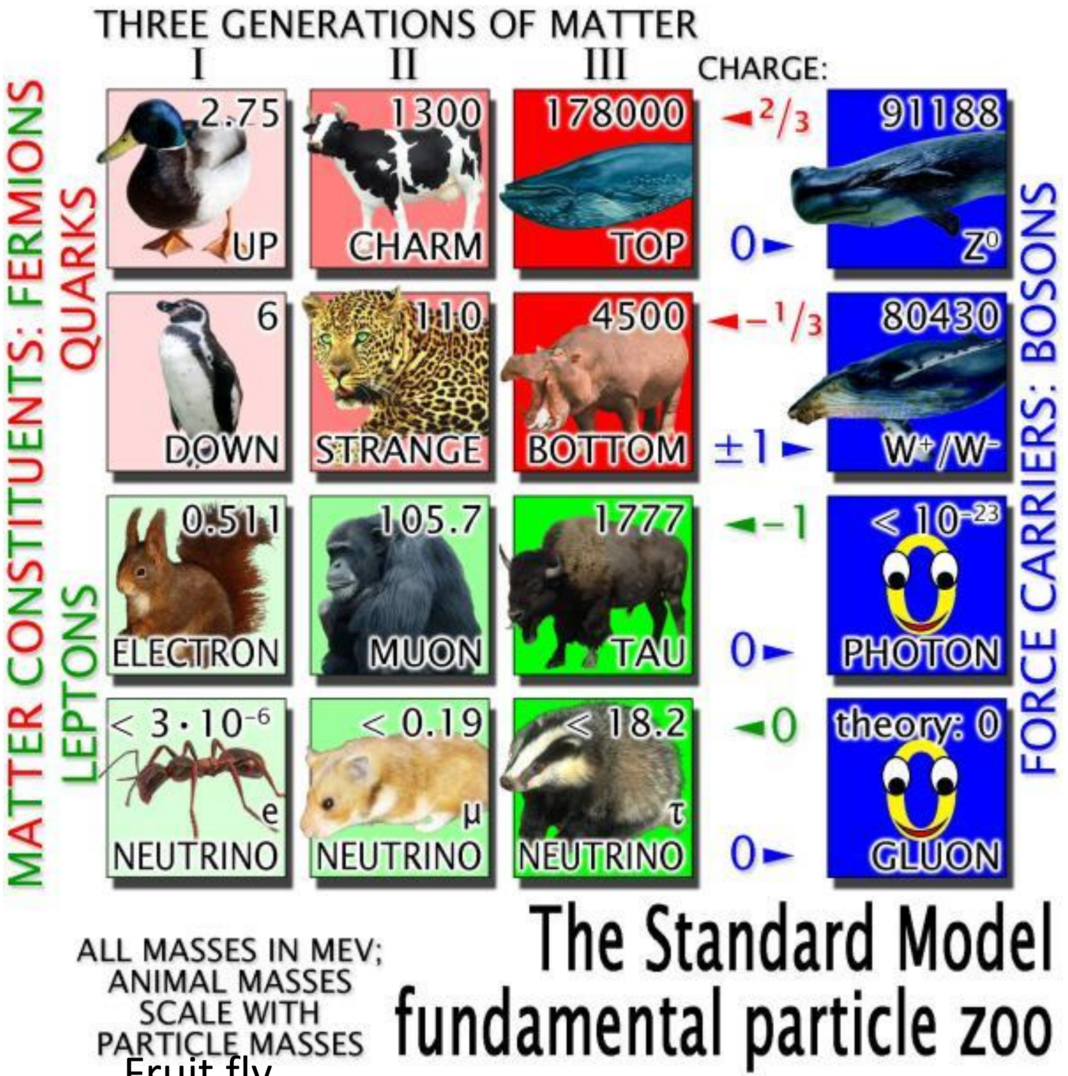
Why is this picture wrong?



Fruit fly

See talk by Marcela Carena

- Neutrinos are special:
  - their masses are much smaller than all other particle masses
  - but they are not zero (as we believed for a long time)
- Their small masses make them truly quantum mechanical objects.

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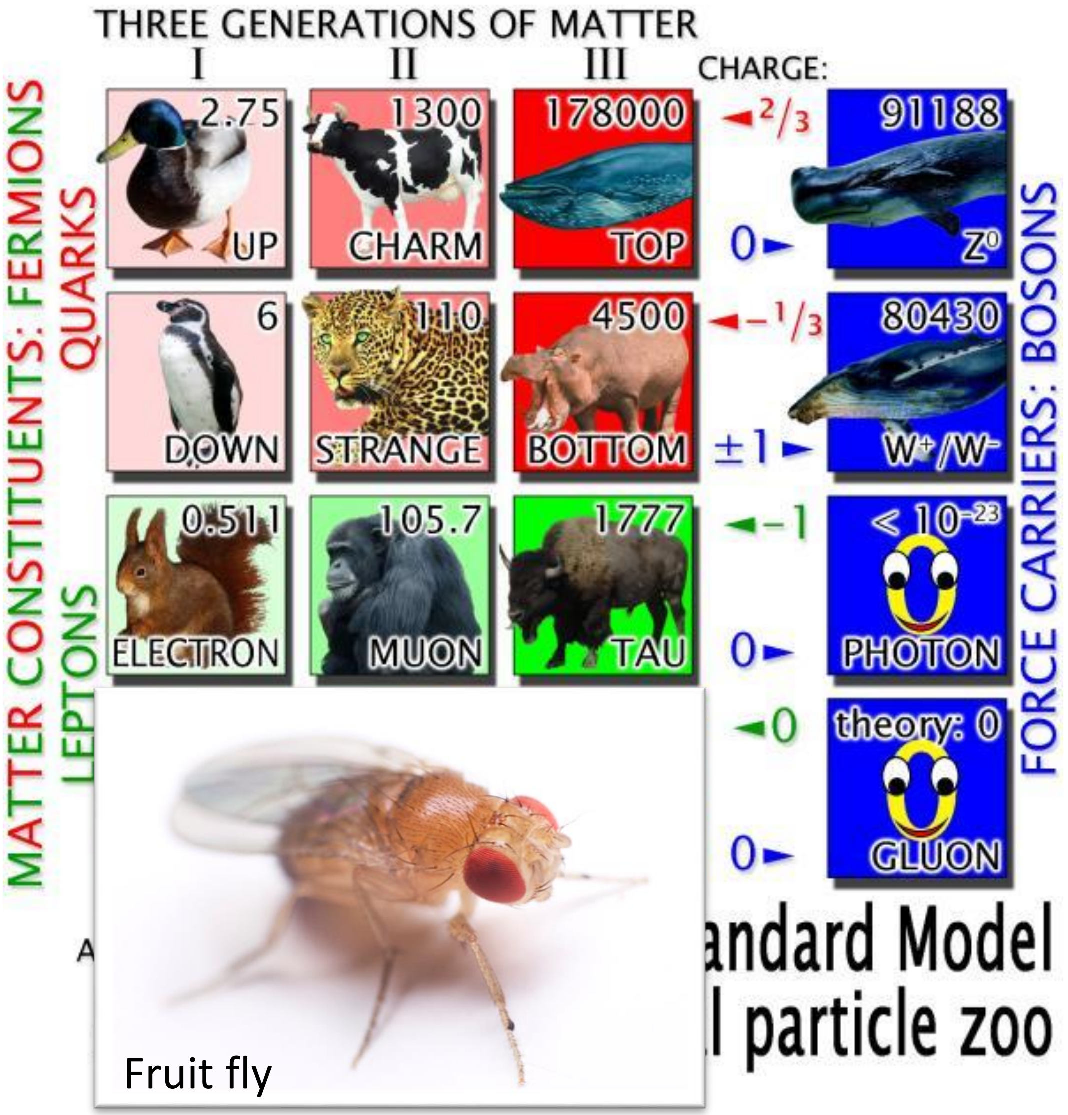
Why is this picture wrong?



- Neutrinos are special:
  - their masses are much smaller than all other particle masses
  - but they are not zero (as we believed for a long time)
- Their small masses make them truly quantum mechanical objects.
- ..and this picture confuses flavour and mass eigenstates.

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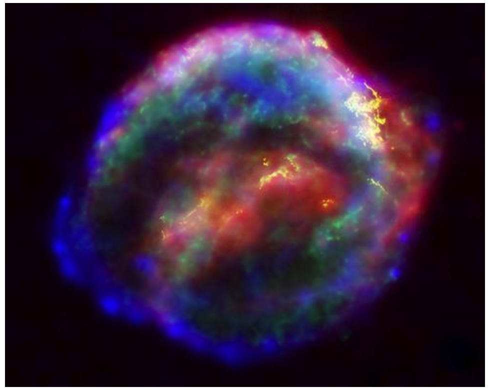
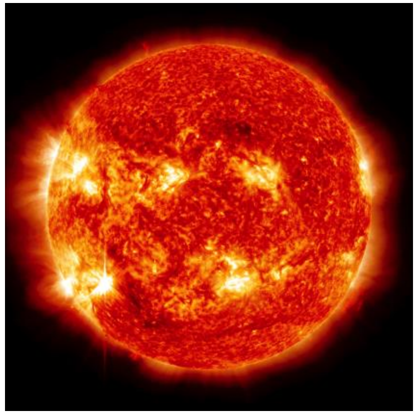
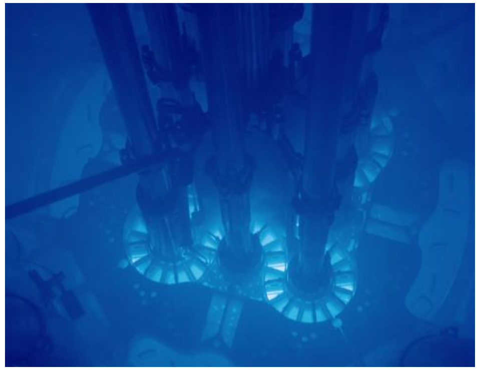
Neutrino Sources (nuclear processes)



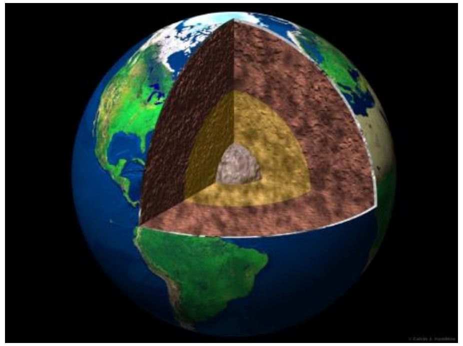
$$p + e^- \rightarrow n + \nu_e$$
$$n \rightarrow p + e^- + \bar{\nu}_e$$



$$p + p \rightarrow {}^2\mathrm{H} + \mathrm{e}^+ + \nu_\mathrm{e}$$



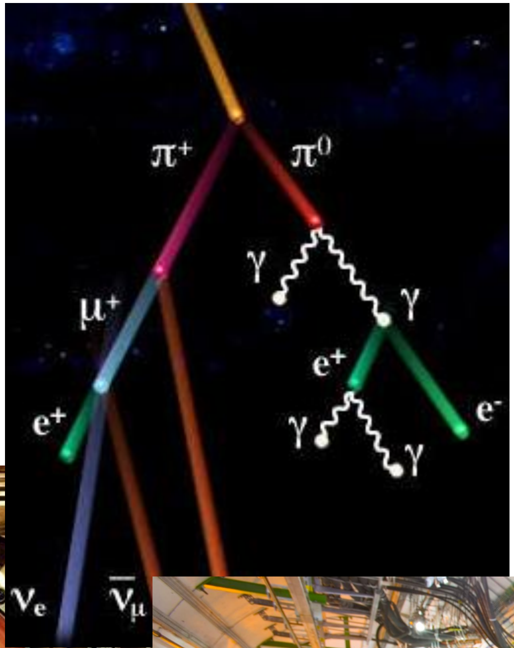
$$n \rightarrow p + e^- + \bar{\nu}_e$$

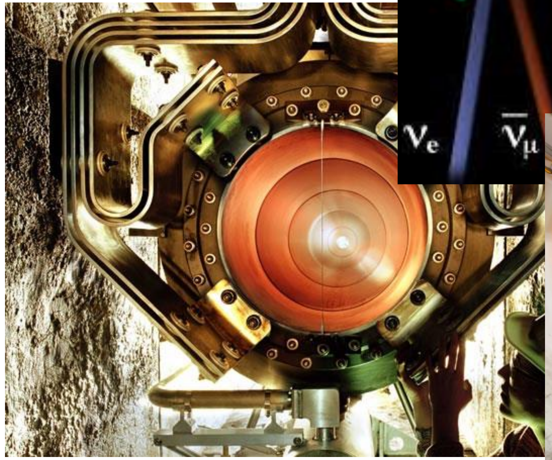


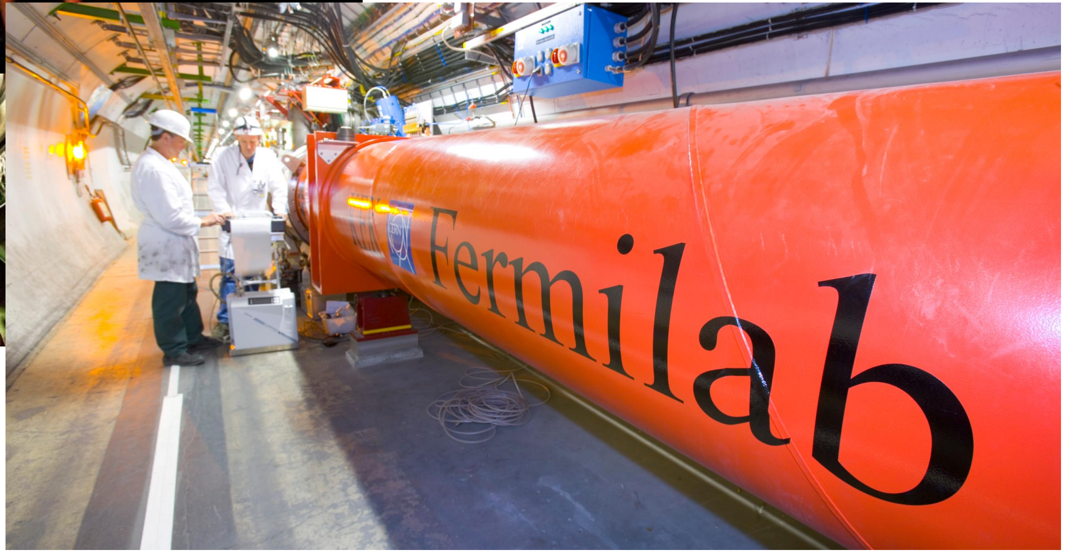
$$\begin{aligned}
{}^{238}_{92}\mathrm{U} &\longrightarrow {}^{206}_{82}\mathrm{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e \\
{}^{235}_{92}\mathrm{U} &\longrightarrow {}^{207}_{82}\mathrm{Pb} + 7\alpha + 4e^- + 4\bar{\nu}_e \\
{}^{232}_{90}\mathrm{Th} &\longrightarrow {}^{208}_{82}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e
\end{aligned}$$

- Nuclear processes are typically the source of electron-neutrinos.
- Energies ≈ 1-20 MeV
- Discovery of electron-neutrino by Cowan and Reines at the Savannah River power plant in 1956.

Neutrino Sources (charged hadron decays)







$$p + N \to \pi^{\pm} + X$$
$$\pi^{+} \to \mu^{+} + \nu_{\mu}$$
$$\mu^{+} \to e^{+} + \nu_{e} + \bar{\nu}_{\mu}$$

- Pion/kaon production and decay are main source of accelerator and atmospheric neutrinos
- Typical energies ≈ GeV, ratio of ν_{μ}:ν_{e} = 2:1.
- Discovery of muon-neutrino by Ledermann, Schwartz, Steinberger at Brookhaven in 1962.

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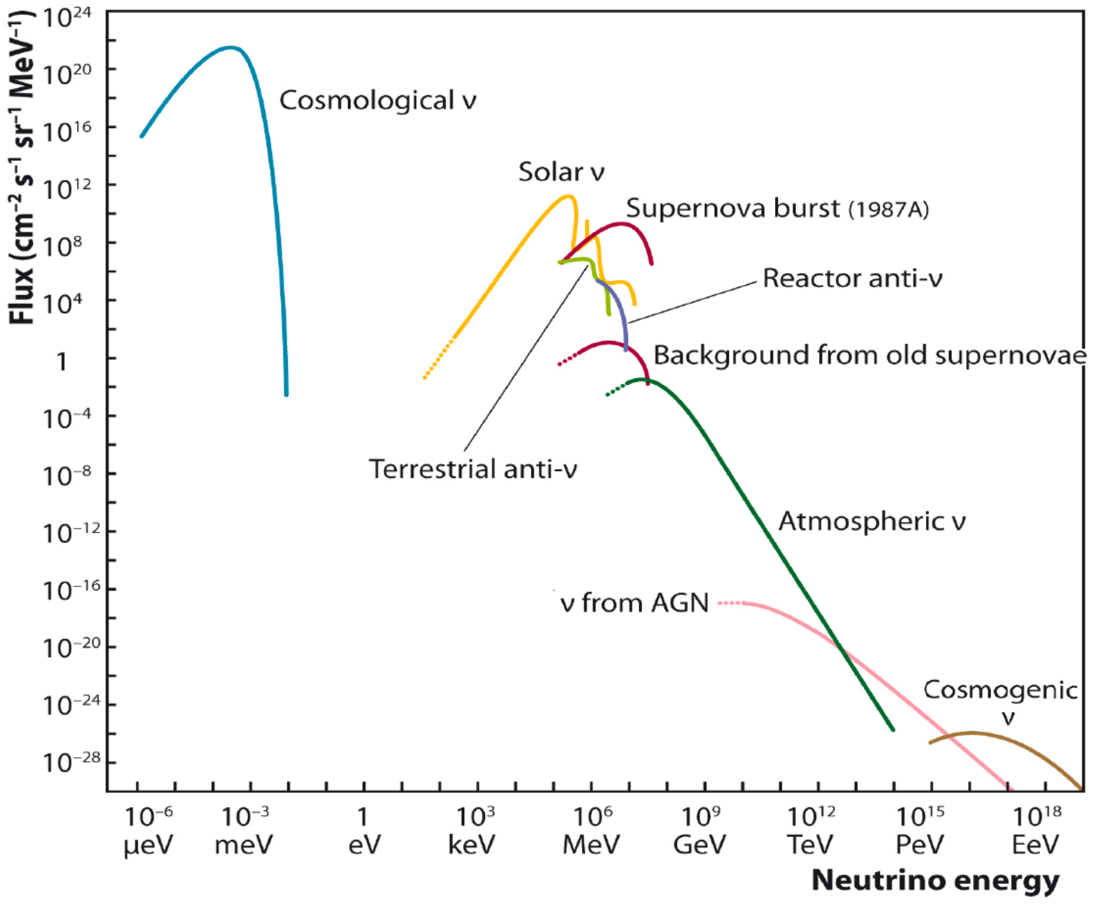
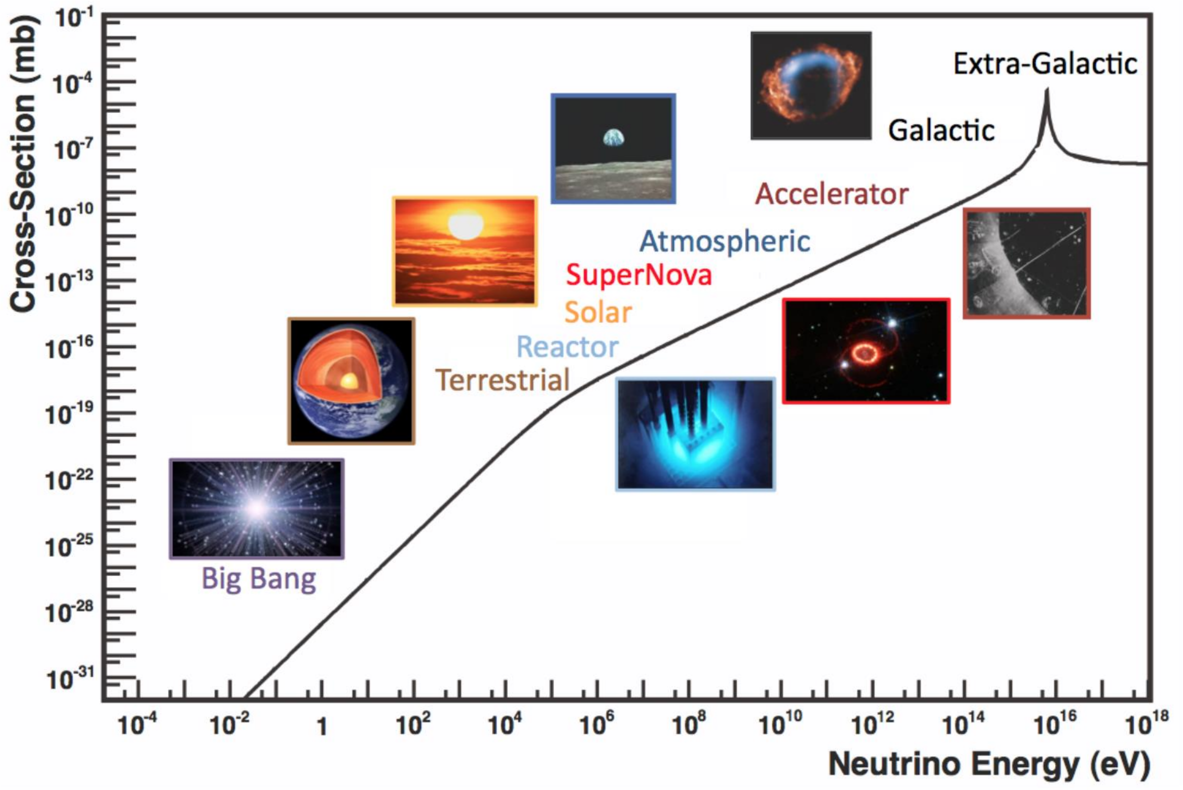
Neutrino sources, flux, and cross sections

C. Spiering, arXiv:1207.4952



J. Formaggio, G.P. Zeller, arXiv:1305.7513



C. Spiering, arXiv:1207.4952

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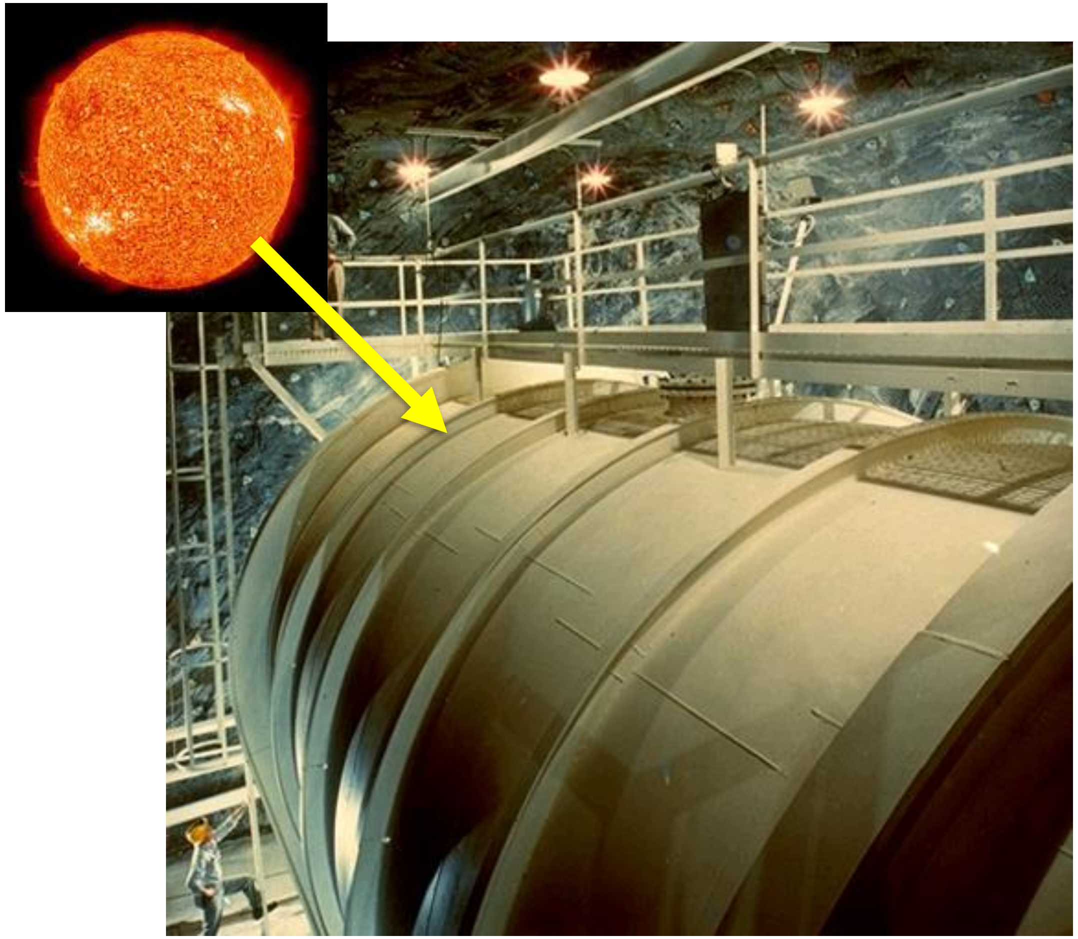
Detecting solar neutrinos

Ray Davis experiment, Homestake Mine, South Dakota

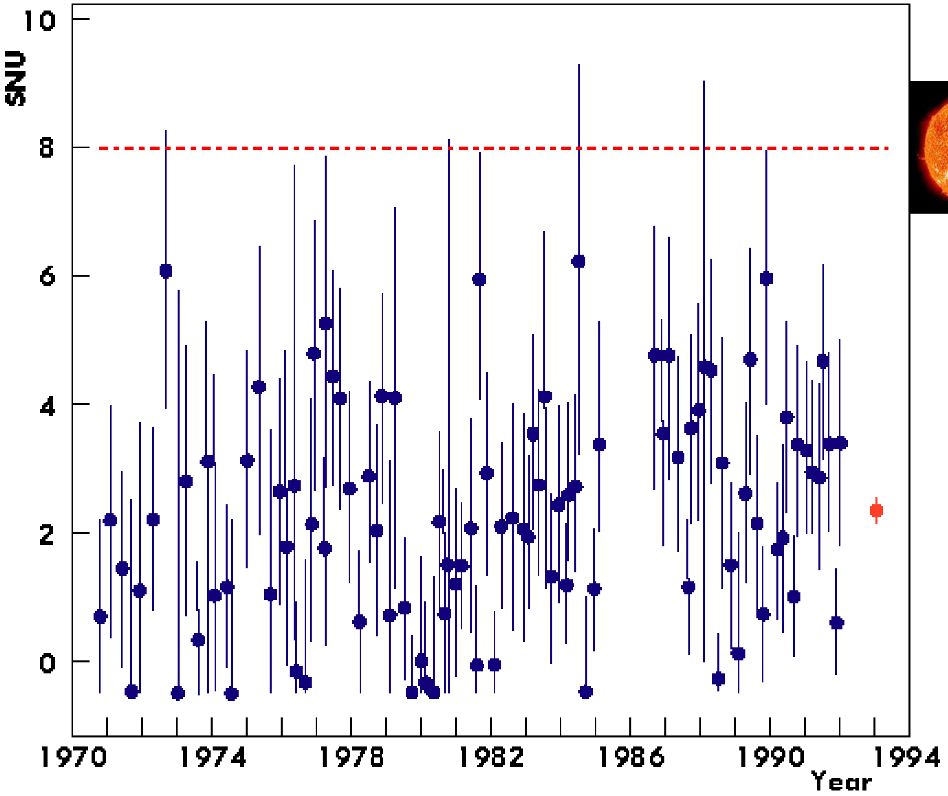


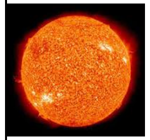
Filled with 390,000 litres of cleaning fluid (C_2Cl_4)

"Inverse β Decay"

$$\nu_e + ^{37}\mathrm{Cl} \rightarrow ^{37}\mathrm{Ar} + e^-$$

$E_\nu > 0.8$ MeV

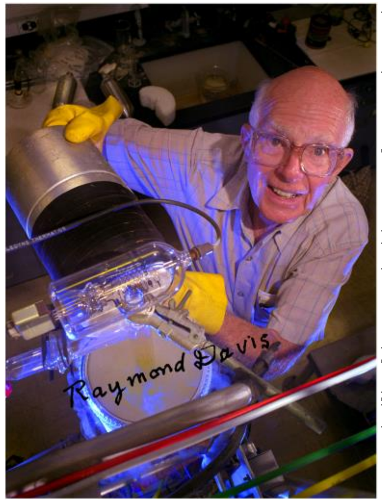




~1/3

Homestake experiment (1970-1994)

- Filter out argon and search for ^{37}Ar decay
- Detecting ~5 atoms of ^{37}Ar per day in 390,000 litres of C_2Cl_4



VOLUME 20, NUMBER 21 PHYSICAL REVIEW LETTERS 20 MAY 1968

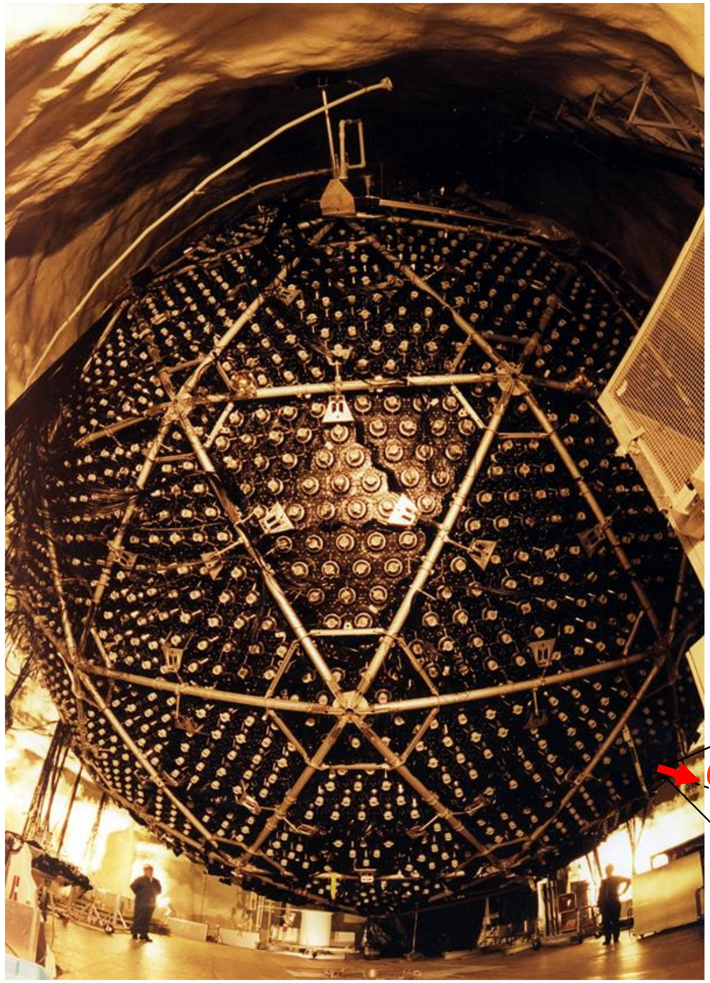
from the bottom of the tank and returned to the tank through a series of 40 eductors arranged along two horizontal header pipes inside the tank. The eductors aspirate the helium from the gas space (2000 liters) above the liquid, and mix it as small bubbles with the liquid in the tank. The pump and eductor system passes helium through the liquid at a total rate of 9000 liters per minute maintaining an effective equilibrium between the argon dissolved in the liquid and the argon in the gas phase.

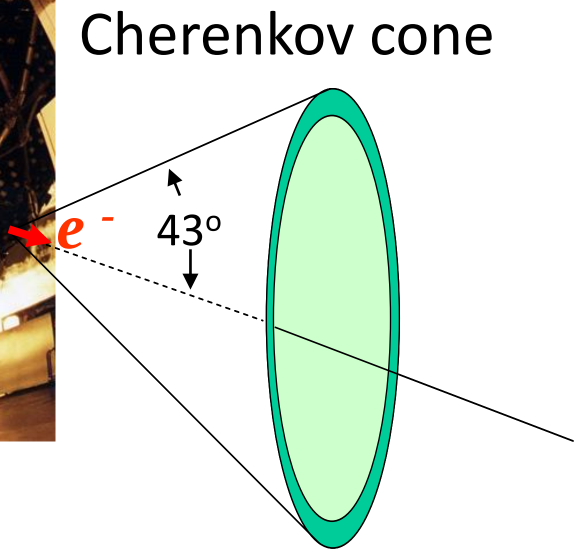
Argon is extracted by circulating the helium from the tank through an argon extraction system. Gas flow is again achieved by a pair of eductors in the tank system, and they maintain a flow rate of 310 liters per minute through the argon extraction system. The tetrachloroethylene vapor is removed by a condenser at −40°C followed by a bed of molecular sieve adsorber at room temperature. The helium then passes through a charcoal bed at 77°K to adsorb the ar-

in the mine as indicated in the diagram.

The argon sample adsorbed on the charcoal trap is removed by warming the charcoal while a current of helium is passed through it. The argon and other rare gases from the effluent gas stream are collected on a small liquid-nitrogen-cooled charcoal trap (1 cm diam by 10 cm long). Finally, the gases from this trap are desorbed and heated over titanium metal at 1000°C to remove all traces of chemically reactive gases. The resulting rare gas contains krypton and xenon in addition to argon. These higher rare gases were dissolved from the atomosphere during exposure of the liquid during the various manufacturing, storage, and transfer operations. Krypton and xenon are much more soluble in tetrachloroethylene than argon, and, therefore, they are more slowly removed from the liquid by sweeping with helium. Since the volume of krypton and xenon in an experimental run is comparable with or exceeds the volume of argon, it

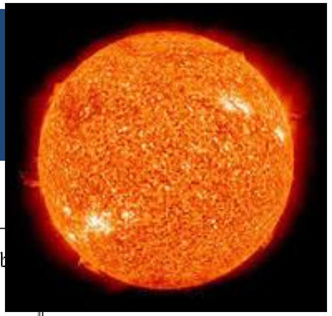
SNO Detector





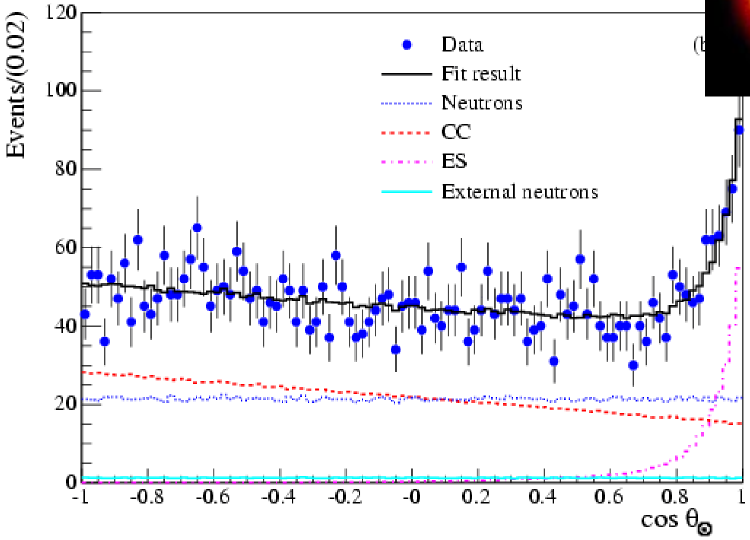
- Davis experiment only showed that some of the electron-neutrinos went missing.
- Needed a detector that can measure different neutrino flavours to confirm the 3-flavour oscillation model.
- SNO detector – filled with heavy water - is sensitive to Cherenkov light from scattered electrons and from photons produced when neutrons are captured.

Neutrino interactions in SNO

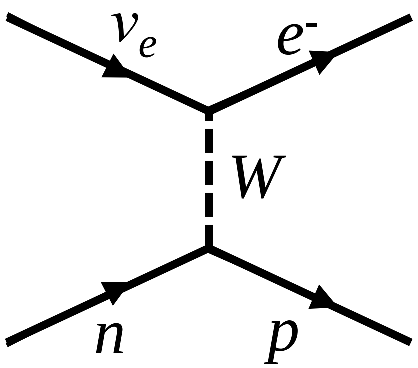


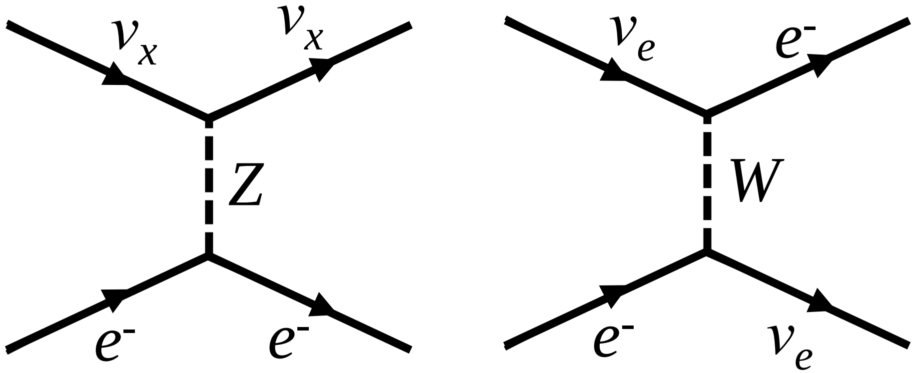
Not sensitive to neutrino direction

$$\nu_e + \text{deuteron} \rightarrow p + p + e^-$$



Sensitive to neutrino direction (we know location of the Sun)



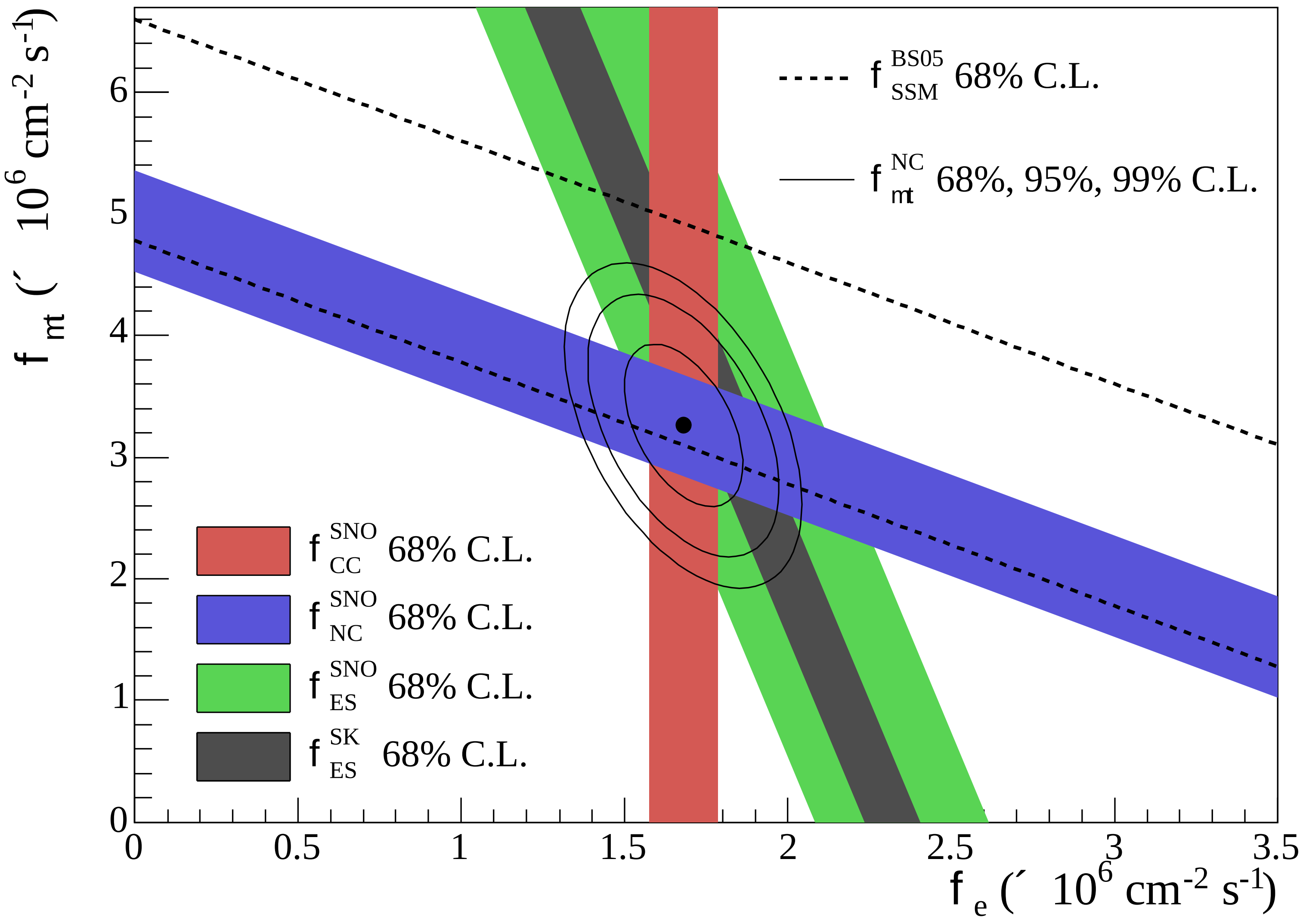


Charged Current interaction:
Sensitive only to ν_e

Elastic Scattering:
Sensitive to charged and neutral current.
ν_e dominate by a factor of 6

SNO demonstrates flavour change

muon-tau-type flux



Electron-type flux

SNO measured three different fluxes – effectively just solve a set of linear equations.

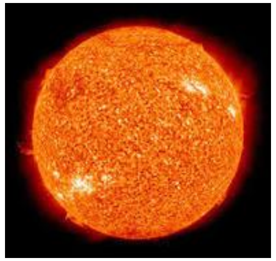
PMNS Matrix

$$\overset{\text{Flavour}}{\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}} = U_{\text{PMNS}} \overset{\text{Mass}}{\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}}$$

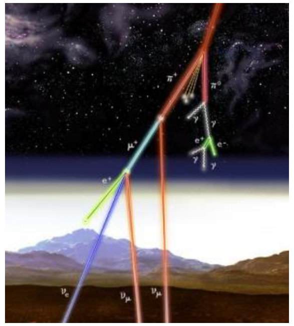
Pontecorvo–Maki–Nakagawa–Sakata

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

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



θ_{13}: mixes ν_e with ν_3
δ: complex phase



- θ_{12}: “solar mixing angle”
- mixes ν_e with ν_1 and ν_2

- θ_{23}: “atmospheric mixing angle”
- mixes ν_μ with ν_τ

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PMNS Matrix

solar | "reactor" | atmospheric

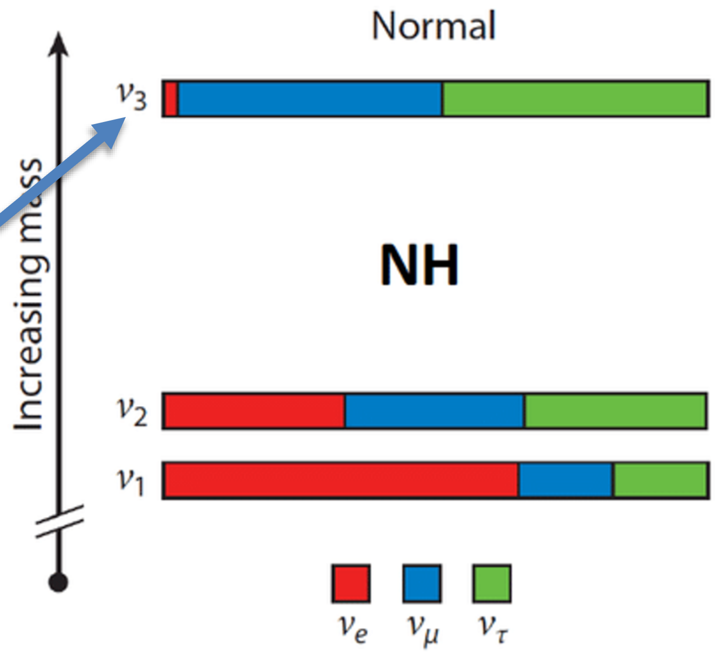
$$U_{\mathrm{PMNS}} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

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

$$\theta_{12} = 33.44^{\circ}{}^{+0.78^{\circ}}_{-0.75^{\circ}}$$

$$\theta_{23} = 49.0^{\circ}{}^{+1.1^{\circ}}_{-1.4^{\circ}}$$

- Θ_{12} and θ_{23} are large ("maximal" mixing)
- Angle θ_{13} is small and mixes ν_e with ν_3
- CPV term (δ) $\propto \theta_{13}$
- Look for ν_e mixing driven by Δm^2_{32}



$$\Delta m^2_{32} = 2.4 \times 10^{-3}\,\mathrm{eV}^2$$

$$\Delta m^2_{21} = 7.8 \times 10^{-5}\,\mathrm{eV}^2$$

The PMNS Matrix and CP violation

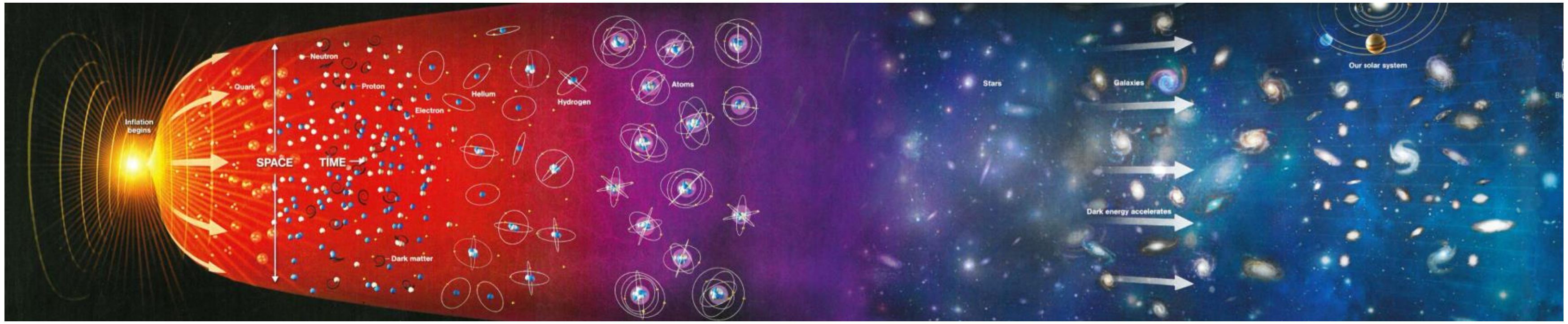
complex CP phase

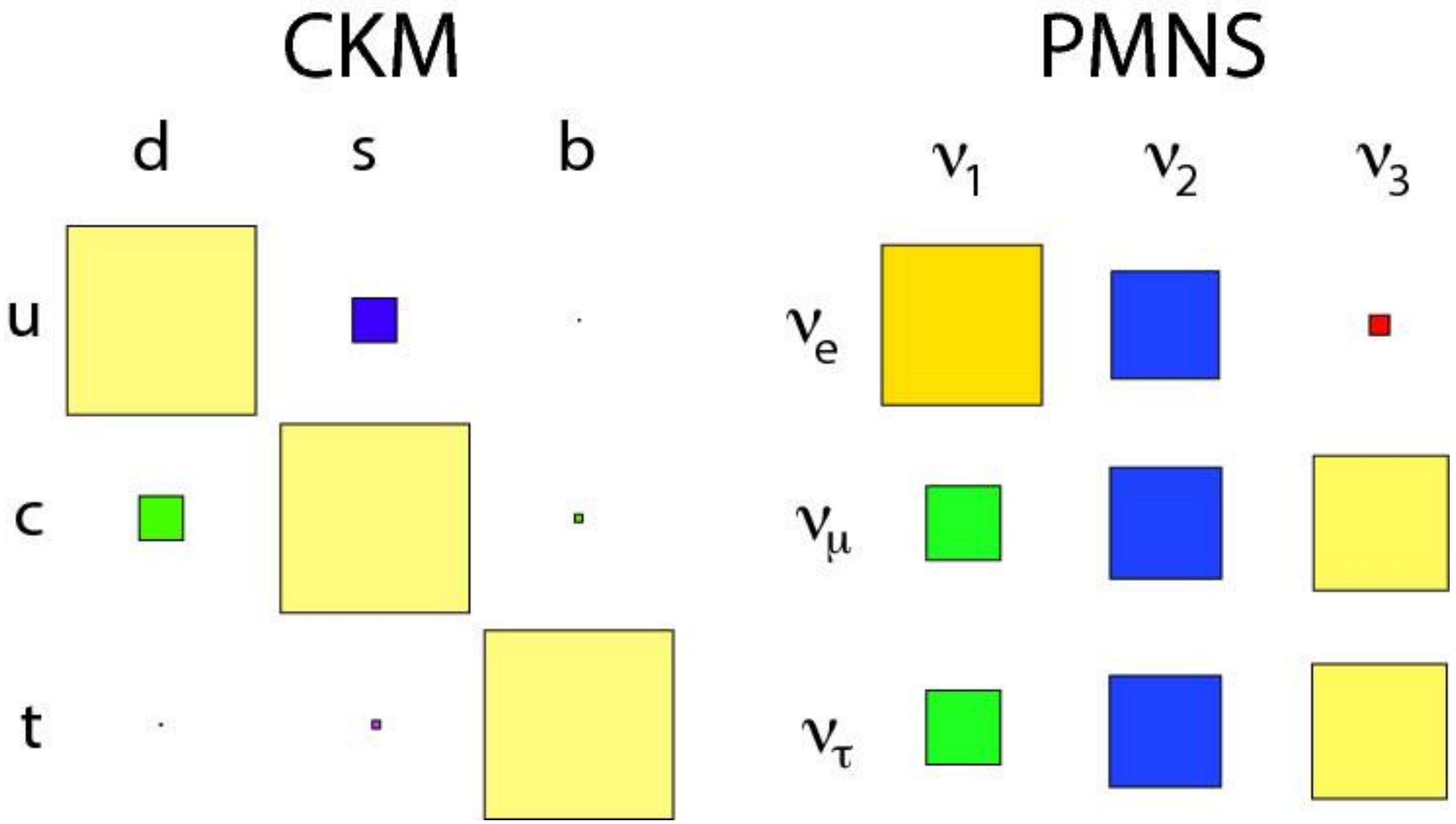
$$U_{\mathrm{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

$$\delta \neq \{0, \pi\}$$

CP Violation involving neutrinos might provide support for *Leptogenesis* as mechanism to generate the Universe's matter-antimatter asymmetry.

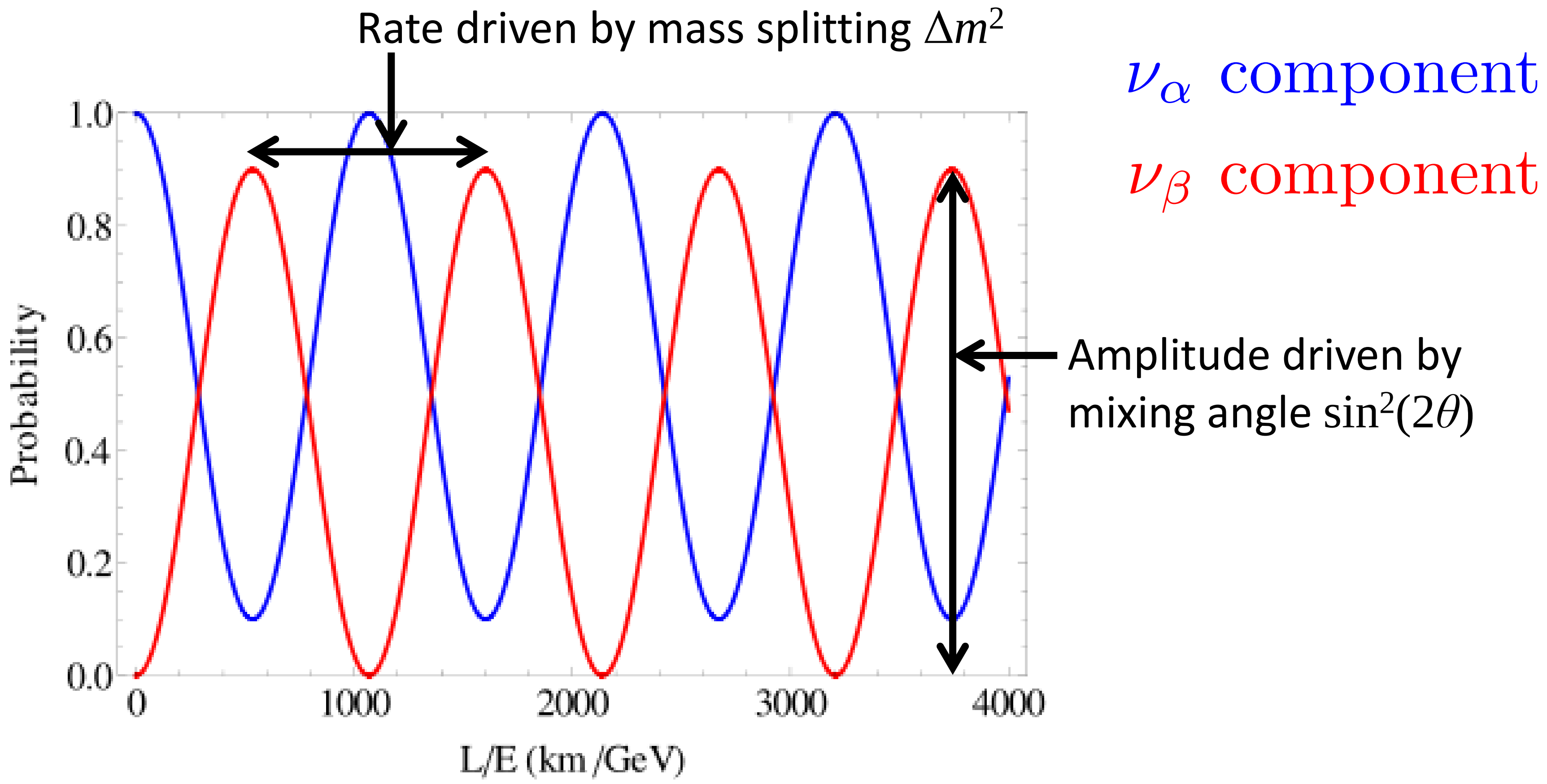




The CKM matrix is almost diagonal, while the PMNS matrix is almost uniform.

Neutrino flavour oscillations

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2_{21}[\mathrm{eV}^2]L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$



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Bruno Pontecorvo

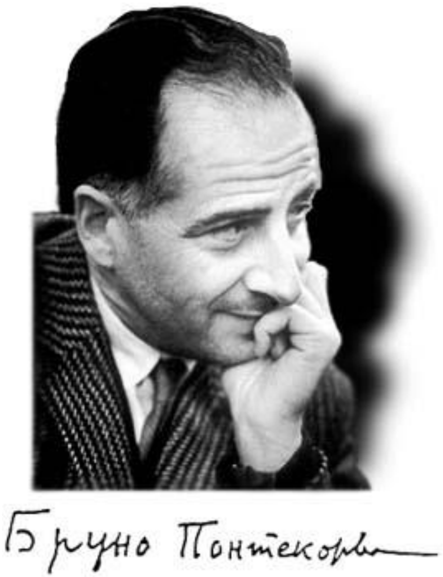
B. PONTECORVO

Joint Institute for Nuclear Research

Submitted to JETP editor October 19, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) 34, 247-249 (January, 1958)

RECENTLY the question was discussed[1] whether there exist other "mixed" neutral particles beside the K^0 mesons,[2] i.e., particles that differ from the corresponding antiparticles, with the transitions between particle and antiparticle states not being strictly forbidden. It was noted that the neutrino might be such a mixed particle, and consequently there exists the possibility of real neutrino $\rightleftarrows$ antineutrino transitions in vacuum, provided that lepton (neutrino) charge[3] is not conserved. In the present note we make a more detailed study of this possibility, in which interest has been renewed owing to recent experiments dealing with inverse beta processes.



- Concept of flavour not known at the time
- Pontecorvo hypothesized that neutrinos oscillated between particle and anti-particle states.

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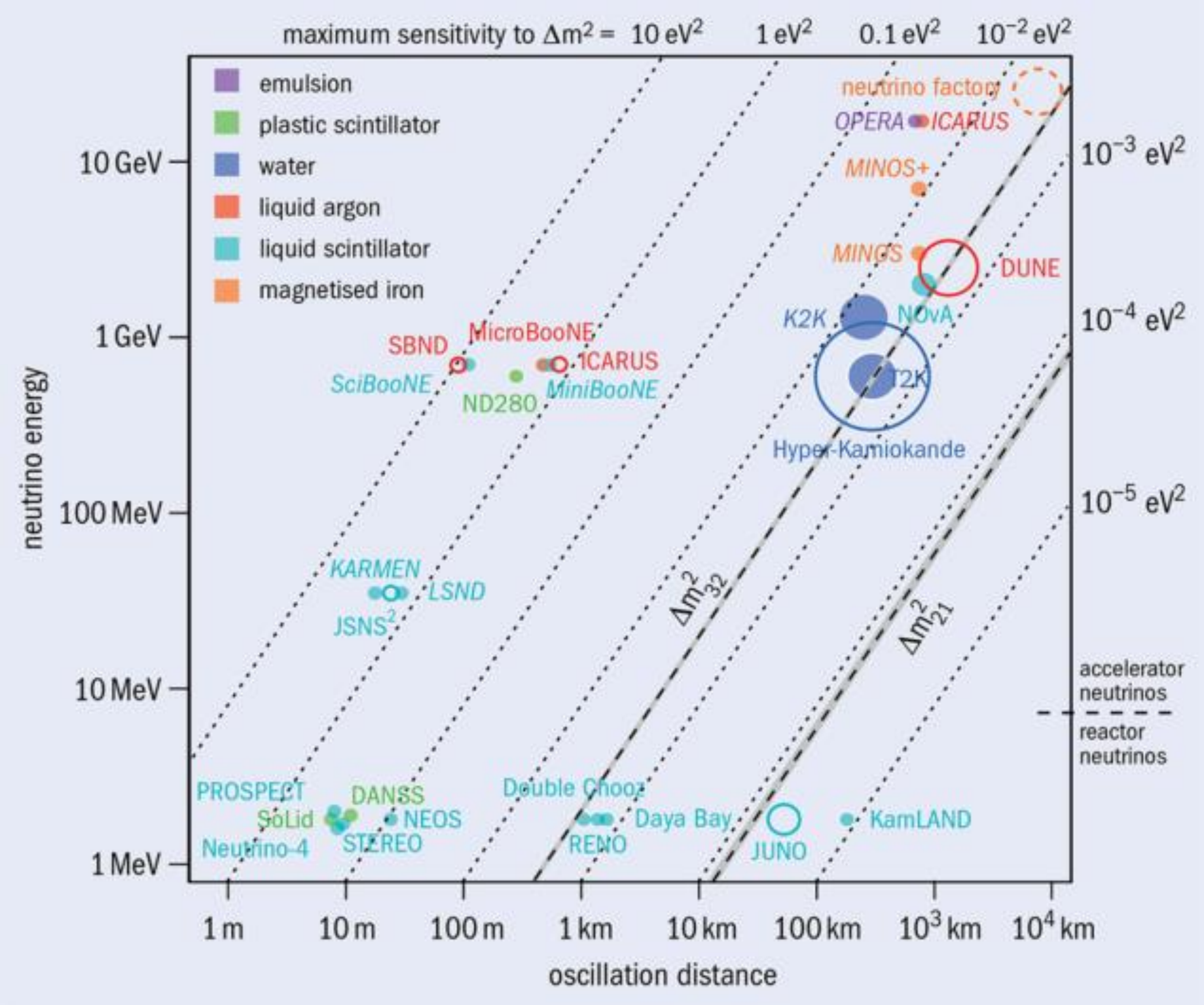
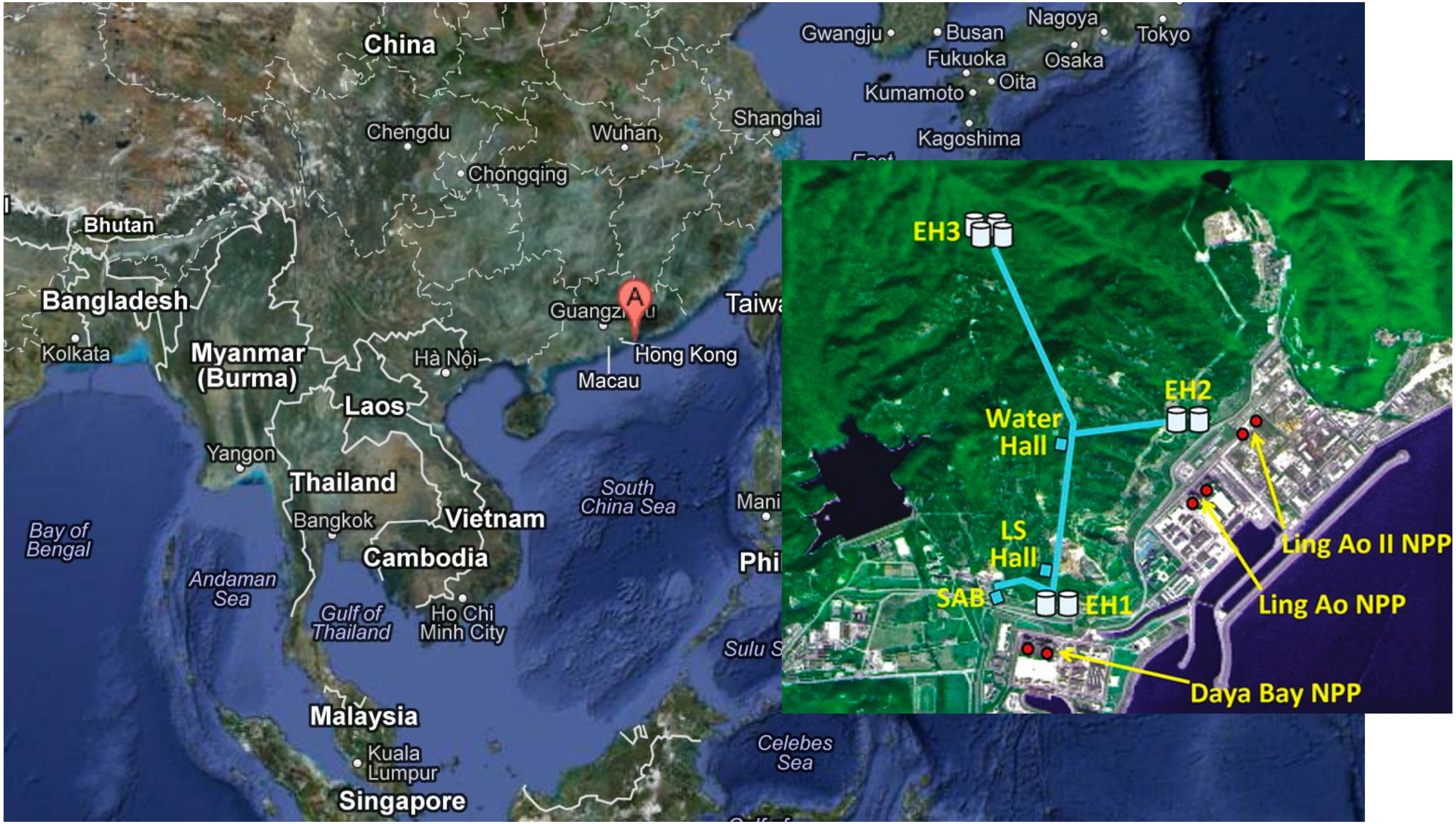
Baseline, energy, and frequency



CERN Courier, 2020

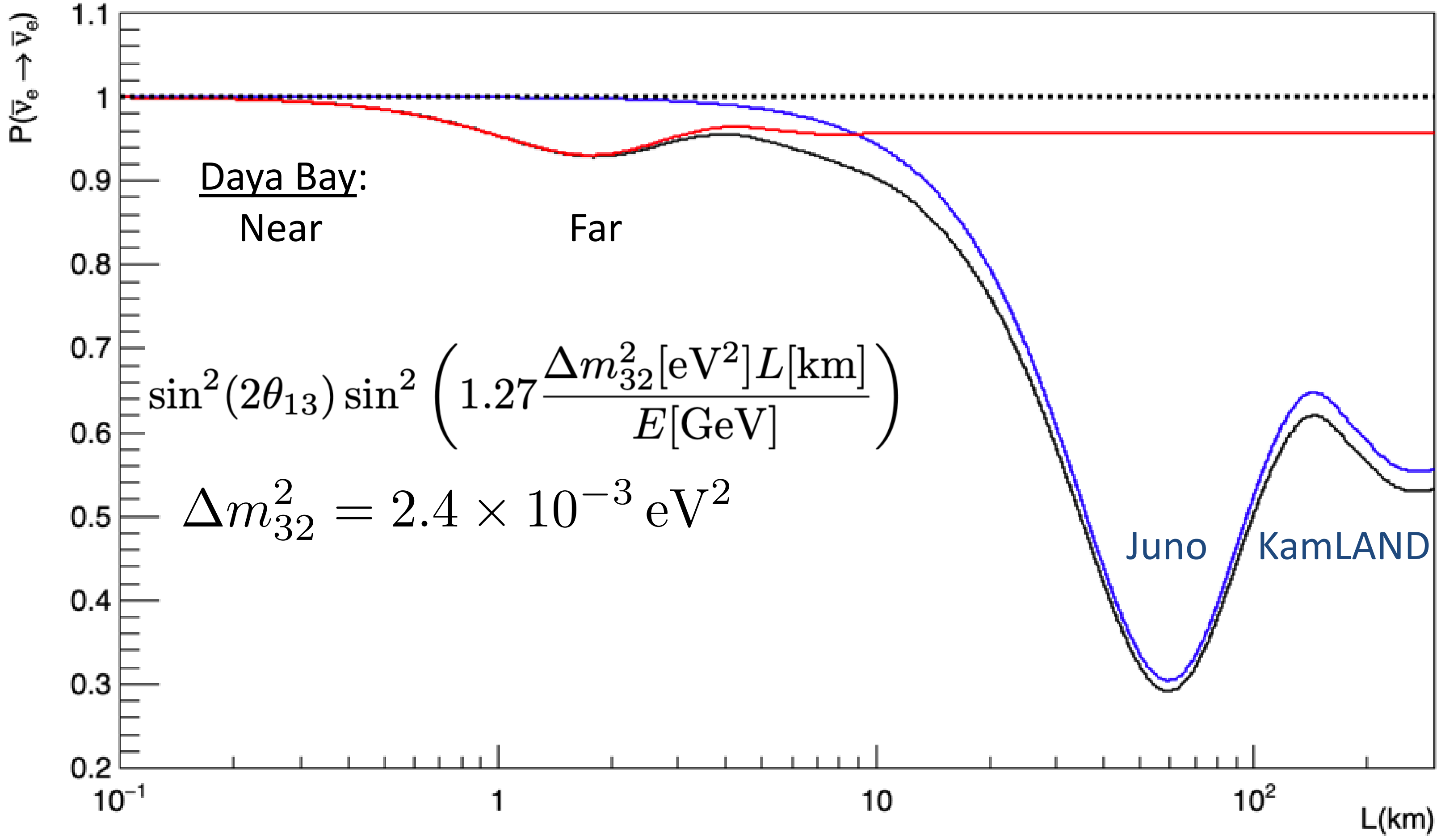
$$\frac{\Delta m^2 L}{4E}$$

Daya Bay reactor



"Reactor" Oscillations

"Survival probability" for anti-ν_e from the reactor (E ≈ 3 MeV)



- Optimize baseline
- No matter effect (short baseline)
- Need near and far detector

J. Ling, Neutrino 2020

$$\Delta m^2_{21} = 7.8 \times 10^{-5}\,\text{eV}^2$$

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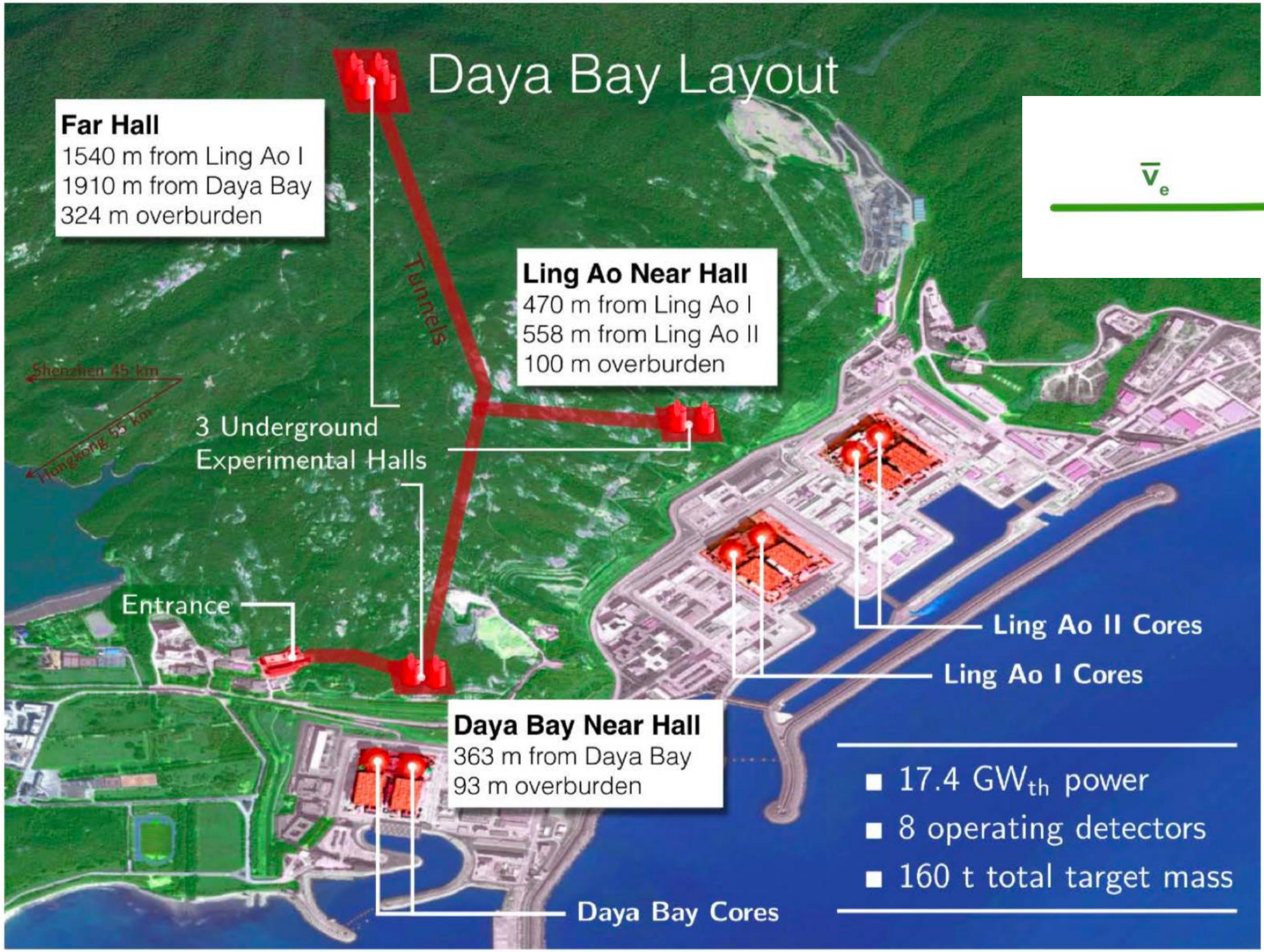
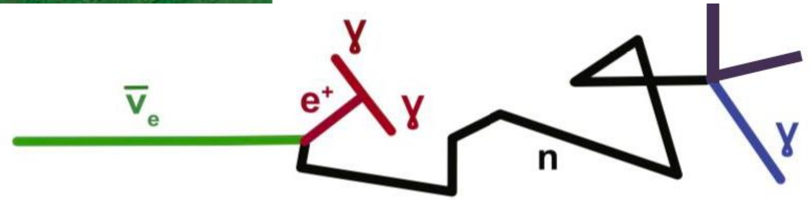
Daya Bay Layout

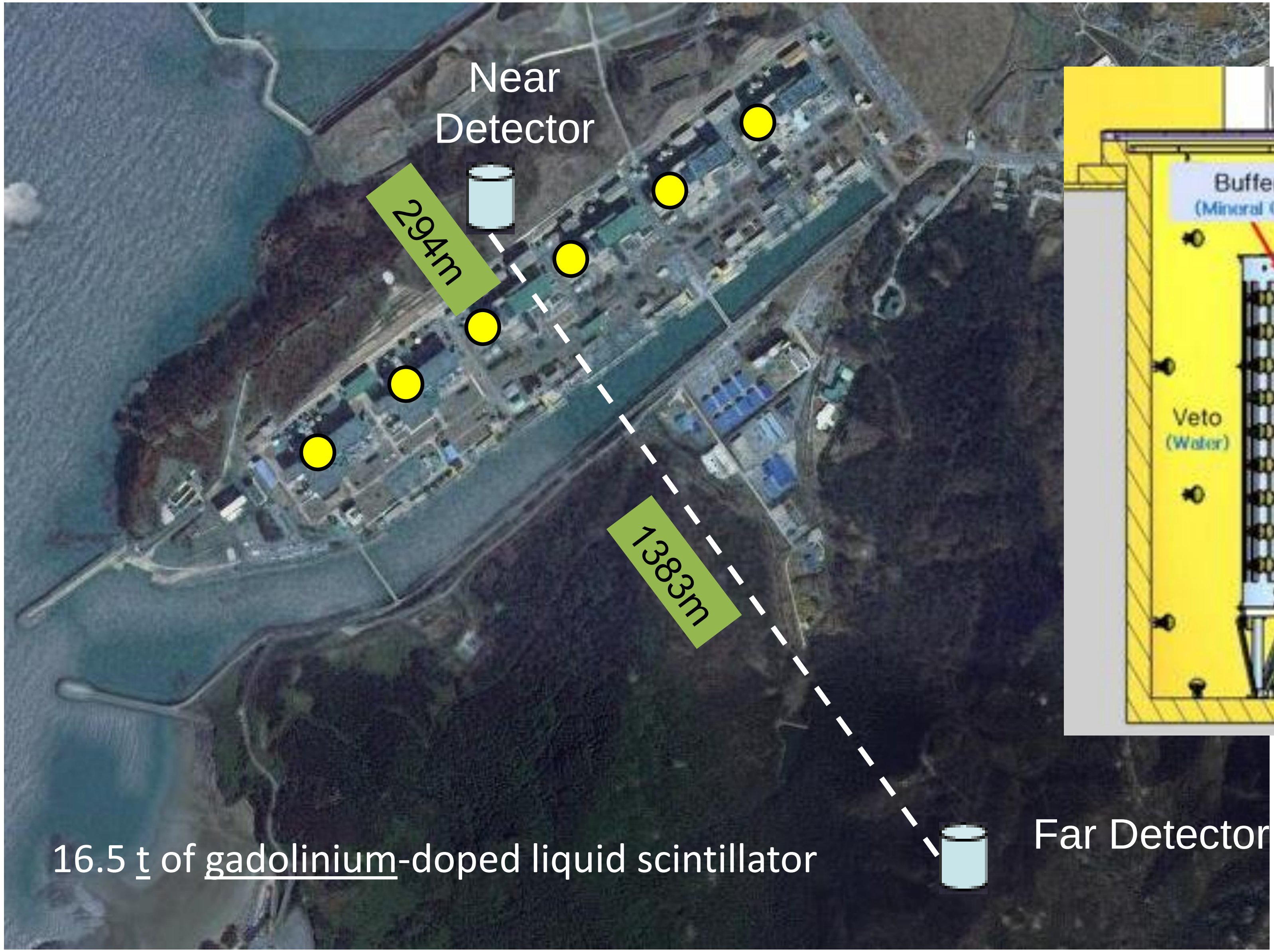


Inverse β decay (IBD)

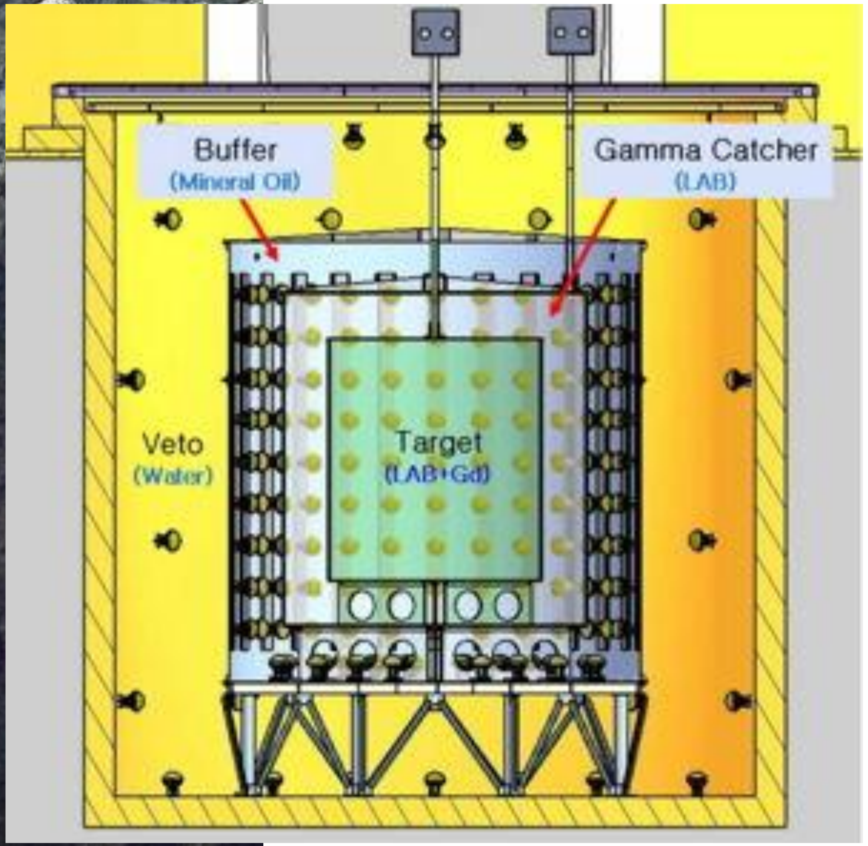


Scintillator, loaded with gadolinium (high neutron capture cross section)

RENO detector



16.5 t of gadolinium-doped liquid scintillator



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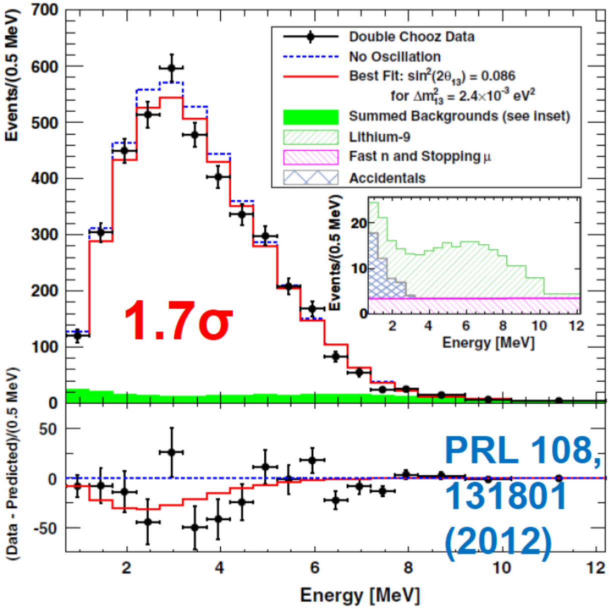
Original θ_{13} measurements (Far/Near)

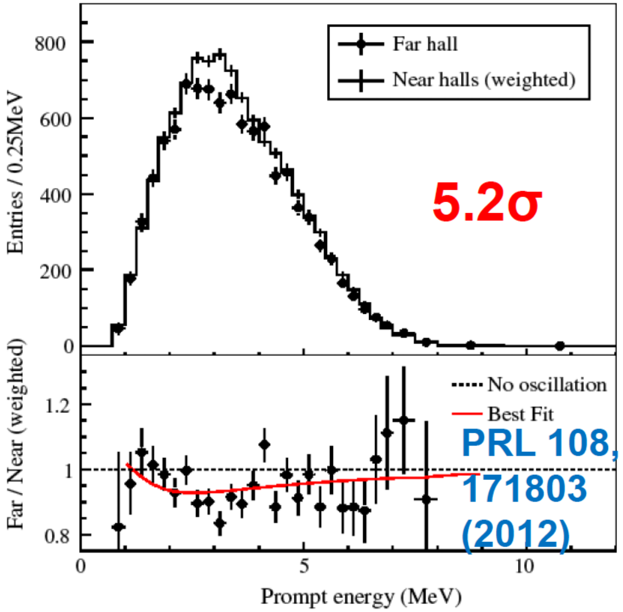
Double Chooz
with only a far detector
(Nov. 2011)



Rate+shape

$$\sin^2 2\theta_{13} = 0.086 \pm 0.041(\text{stat}) \pm 0.030(\text{syst})$$

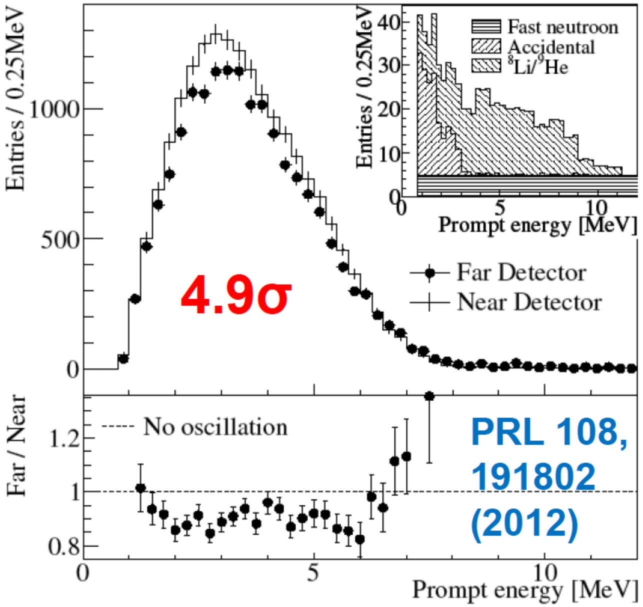
Daya Bay
(March 2012)



Rate only

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat.}) \pm 0.005(\text{syst.})$$

RENO
(April 2012)



Rate only

$$\sin^2 2\theta_{13} = 0.103 \pm 0.013(\text{stat.}) \pm 0.011(\text{syst.})$$

M.He, NNN

Jiangmen Underground Neutrino Observatory

See talk by Albert de Roeck

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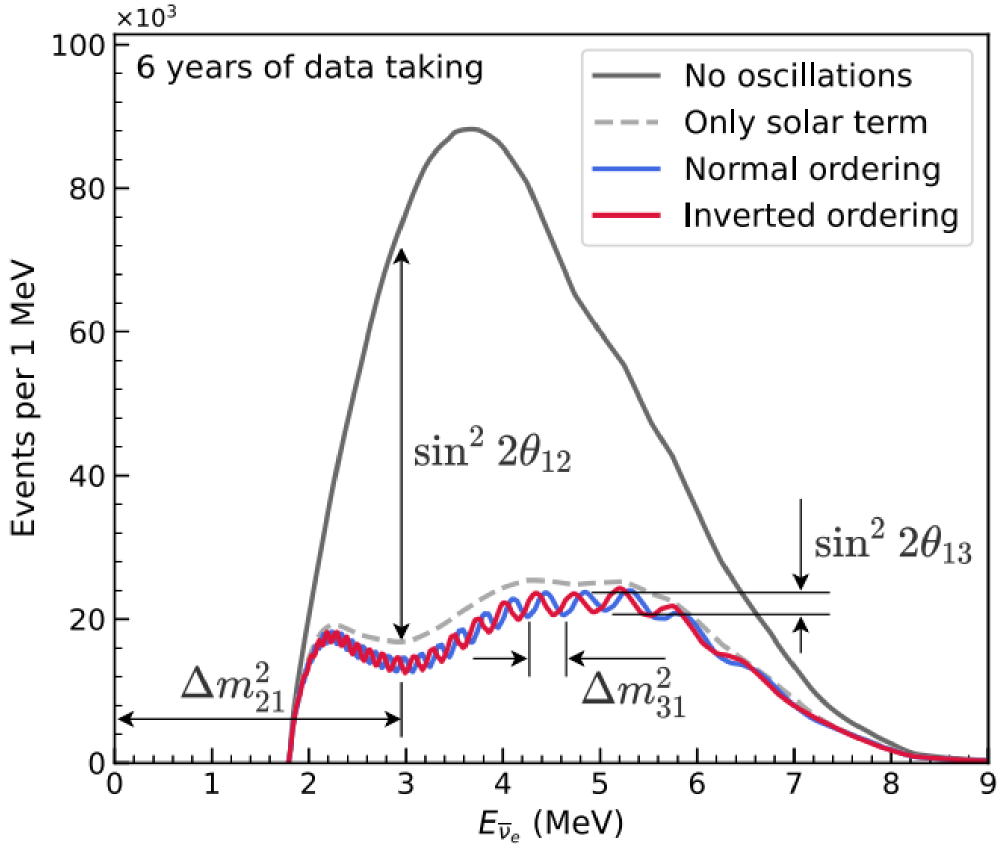
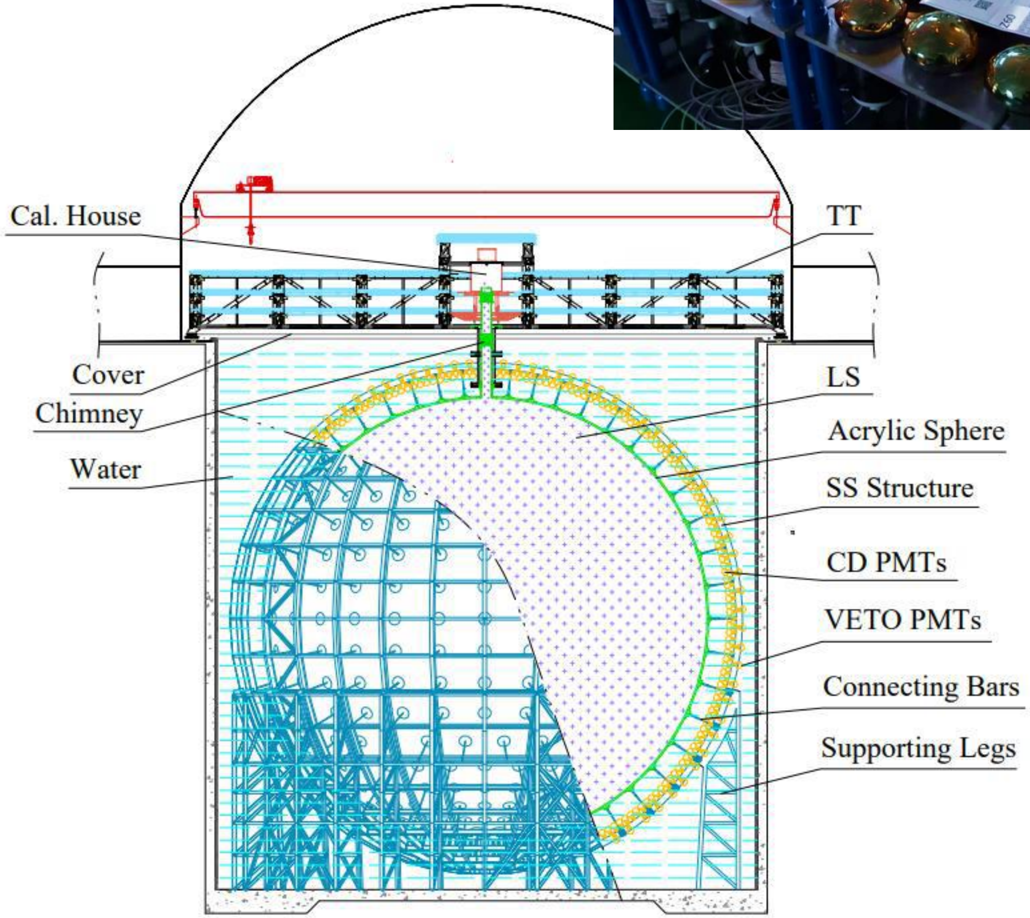
JUNO

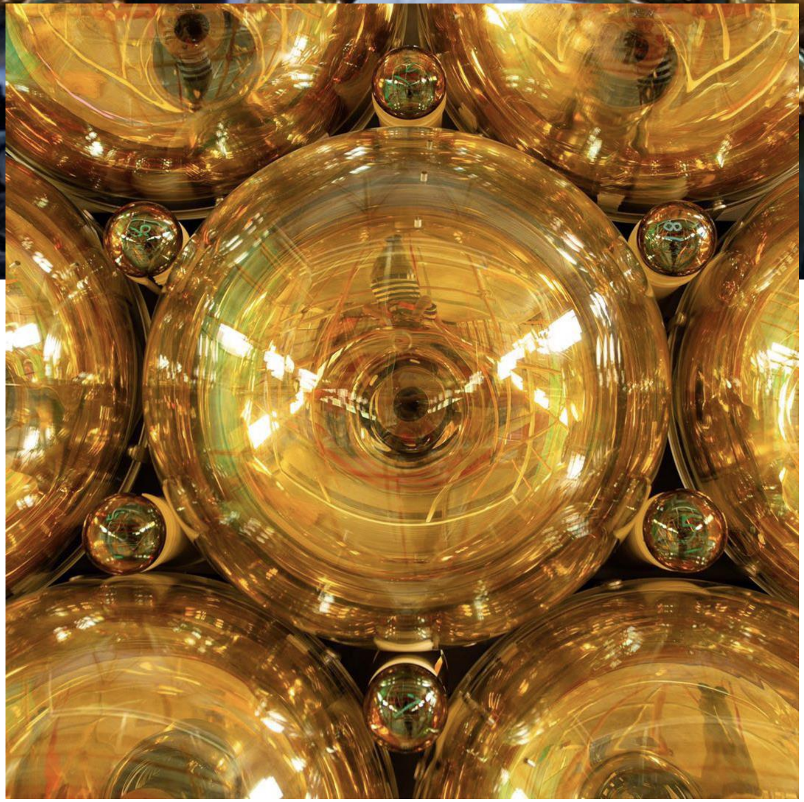


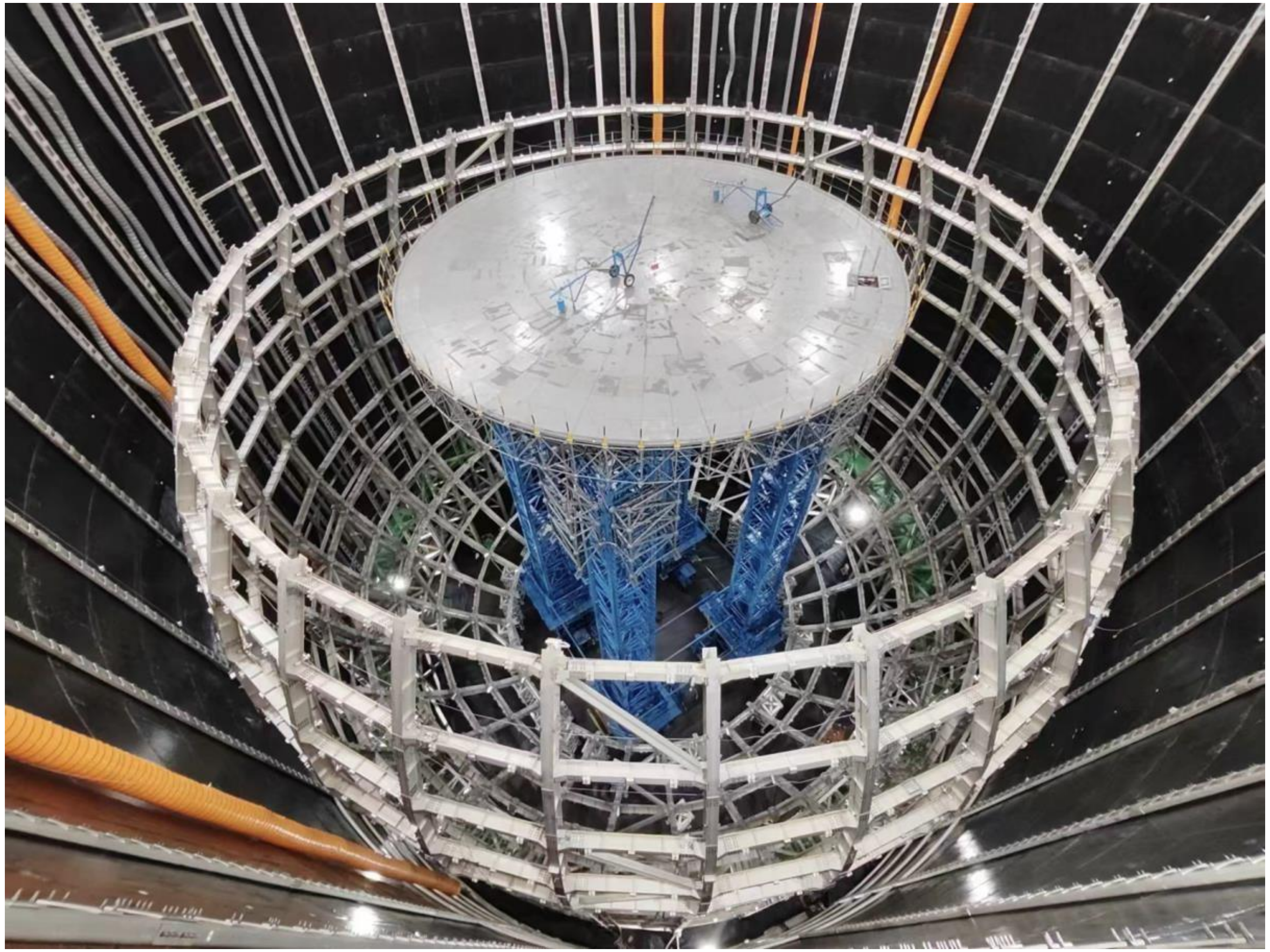
Need excellent resolution to measure mass ordering



- **Acrylic panels**
- **20012 20" PMTs + 25600 3" PMTs**
- **Liquid scintillator**

JUNO





PMNS Matrix

solar | reactor | atmospheric

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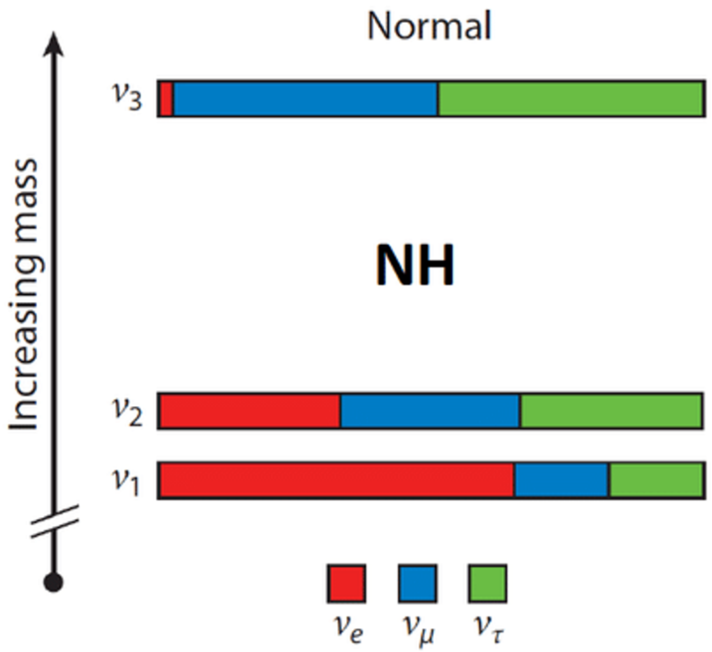
$$c_{ij} = \cos\theta_{ij};\, s_{ij} = \sin\theta_{ij}$$

$$\theta_{12} = 33.44^{\circ}{}^{+0.78^{\circ}}_{-0.75^{\circ}}$$

$$\theta_{23} = 49.0^{\circ}{}^{+1.1^{\circ}}_{-1.4^{\circ}}$$

- "Small" angle θ_{13} mixes ν_e with ν_3
- Look for ν_e mixing driven by Δm^2_{32}
- Reactor: anti-ν_e disappearance
- Accelerator: ν_e appearance in ν_μ beam

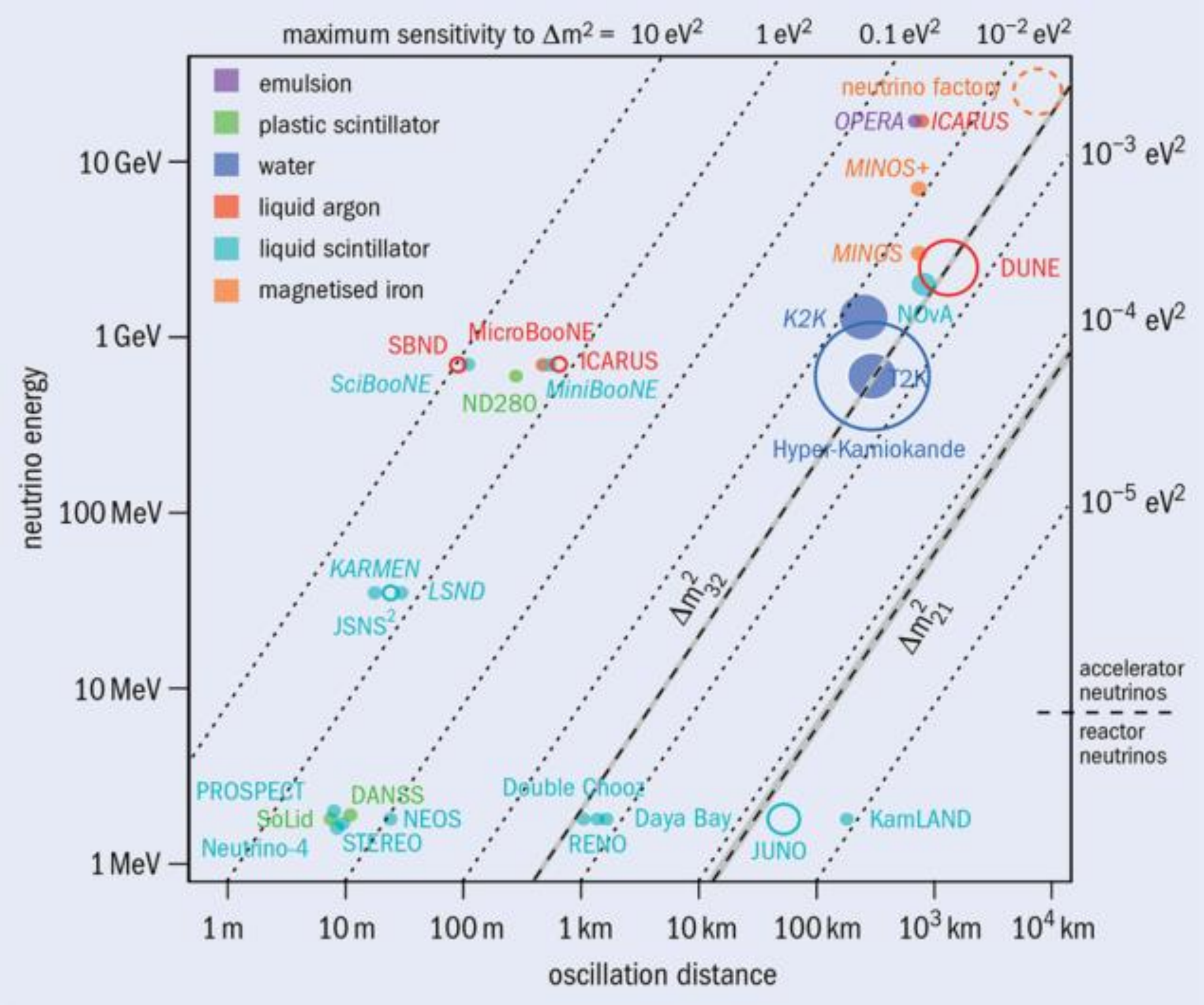
→ sensitive to θ_{13} and δ (and MO).



$$\Delta m^2_{32} = 2.4 \times 10^{-3}\,\text{eV}^2$$

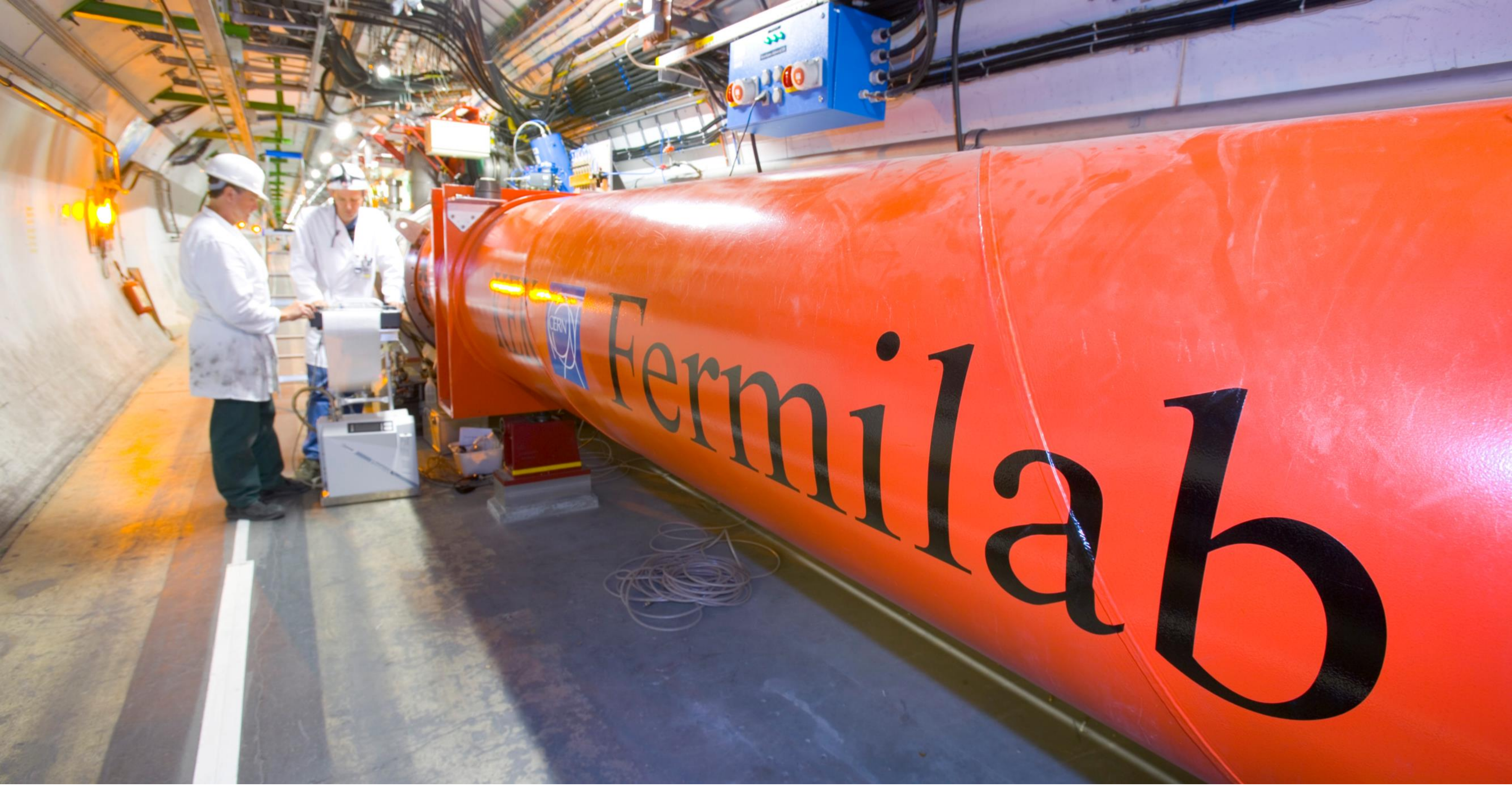
$$\Delta m^2_{21} = 7.8 \times 10^{-5}\,\text{eV}^2$$

Baseline, energy, and frequency

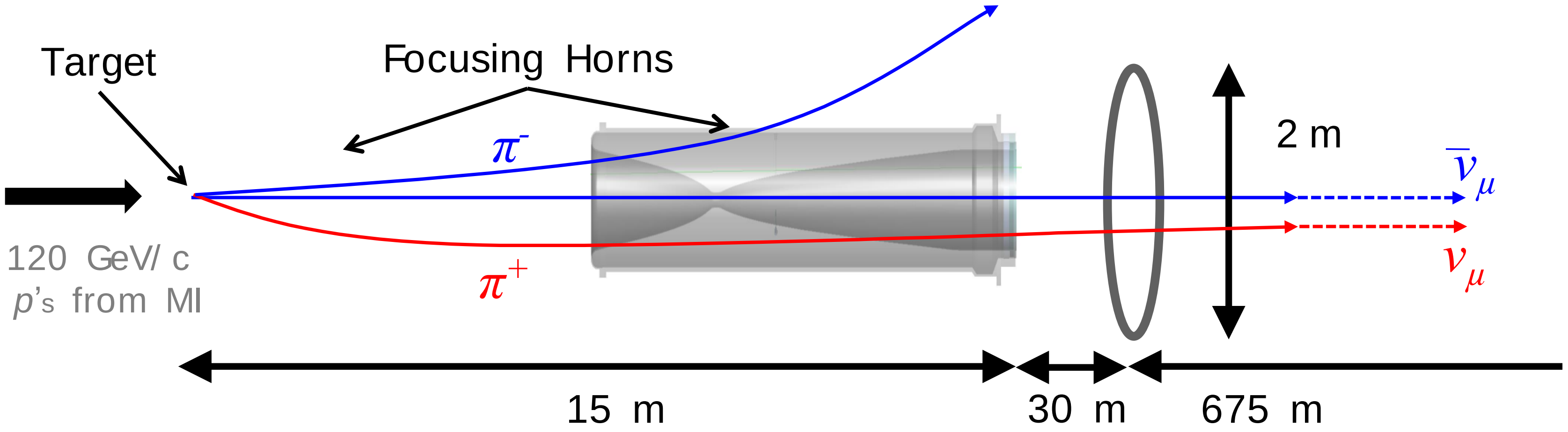


CERN Courier, 2020

$$\frac{\Delta m^2 L}{4E}$$


KEK
CERN
Fermilab

Making a neutrino beam



- As neutrinos are neutral, they cannot be focused, and a magnetic horn is thus used to focus the pions.
- Invented by Simon van der Meer at CERN.

How to make a neutrino beam

- T2K 1.3 MW prototype target production
- All graphite and titanium parts ready for final assembly and welding.
- Targets require cooling.

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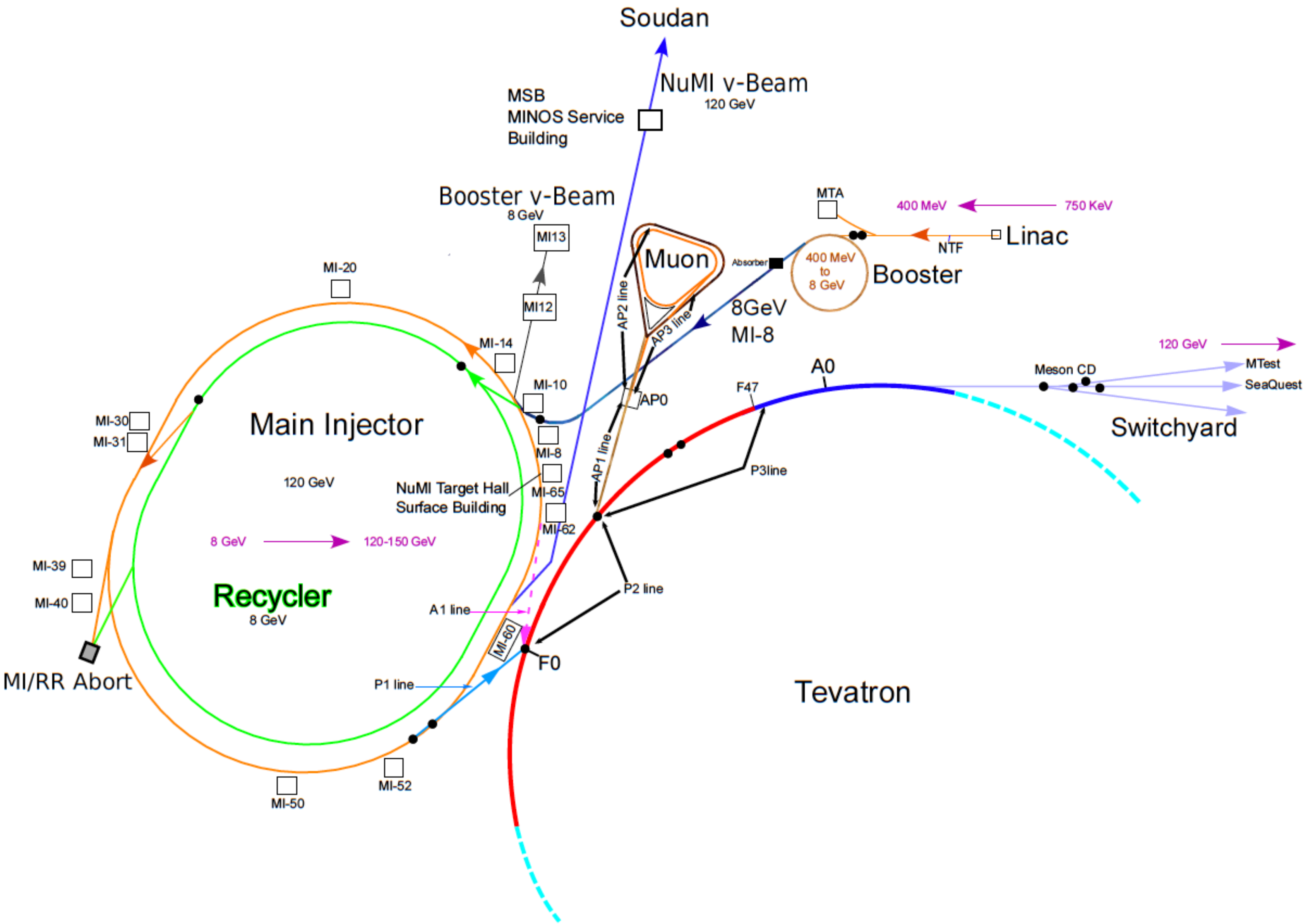
Fermilab NuMI beam



Making a neutrino beam

Pion decay at rest:

$$\overline{\nu}_l \leftarrow \pi^+ \rightarrow l^+$$

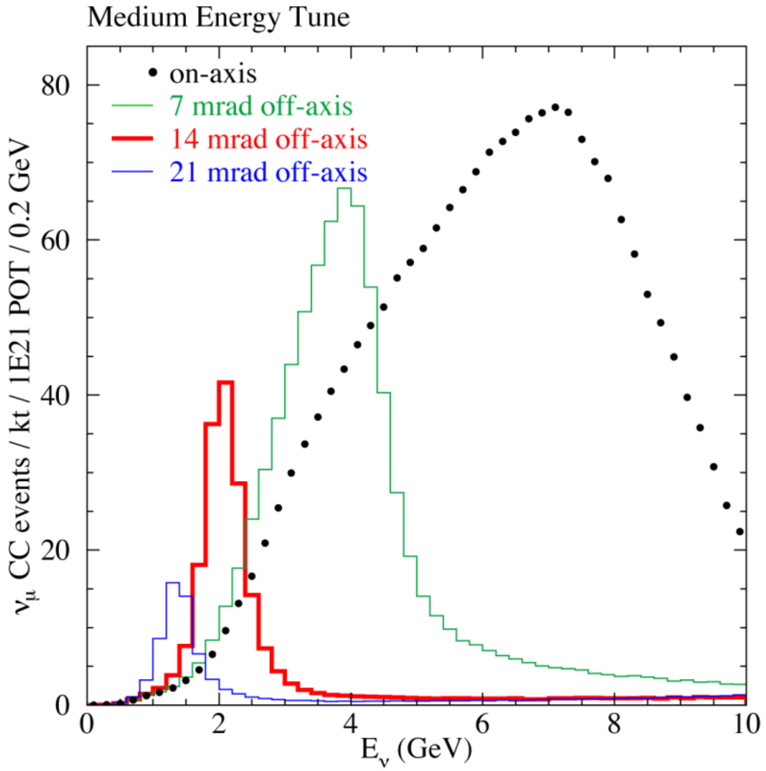
$$E_\nu^* = \frac{m_\pi^2 - m_\mu^2}{2m_\pi} = 29.8\,\mathrm{MeV}$$

Boost into lab system:

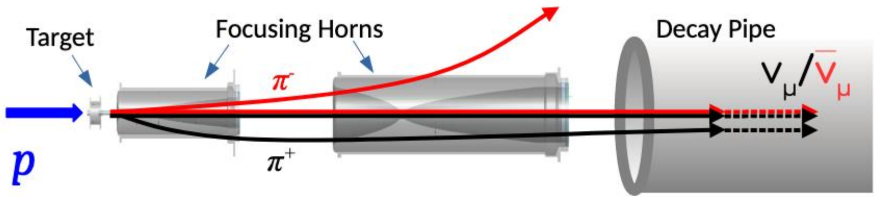
$$E_\nu = \frac{m_\pi E_\nu^*}{E_\pi - p_\pi \cos\theta} = \frac{E_\nu^*}{\gamma_\pi (1 - \beta_\pi \cos\theta)}$$

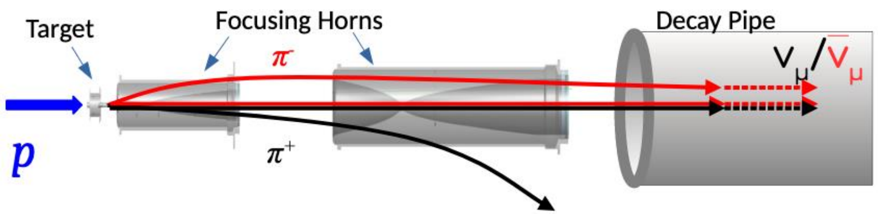
$$E_\pi = 9 \text{ GeV at } \theta = 0:$$

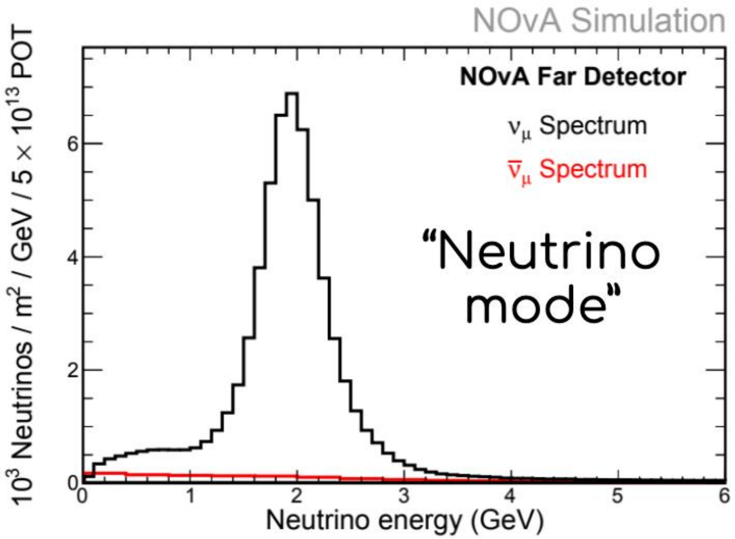
$$\gamma_\pi = 64.5 \implies E_\nu = 3.8\,\mathrm{GeV}$$



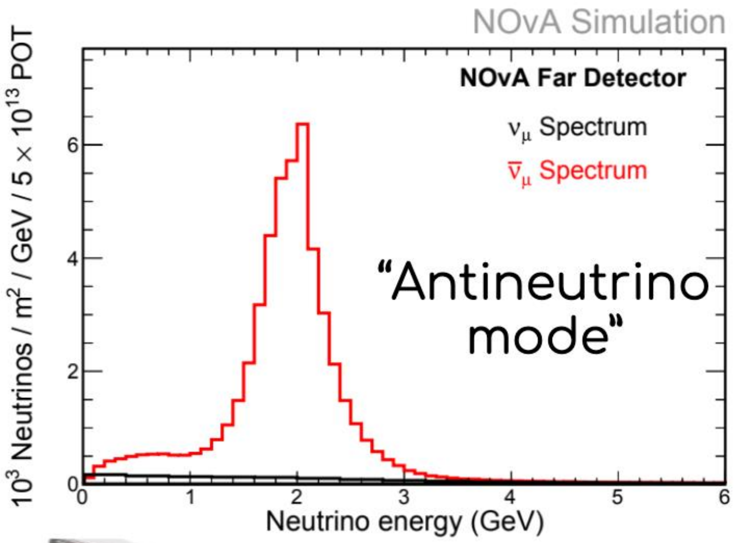
Forward/Reverse Horn Current

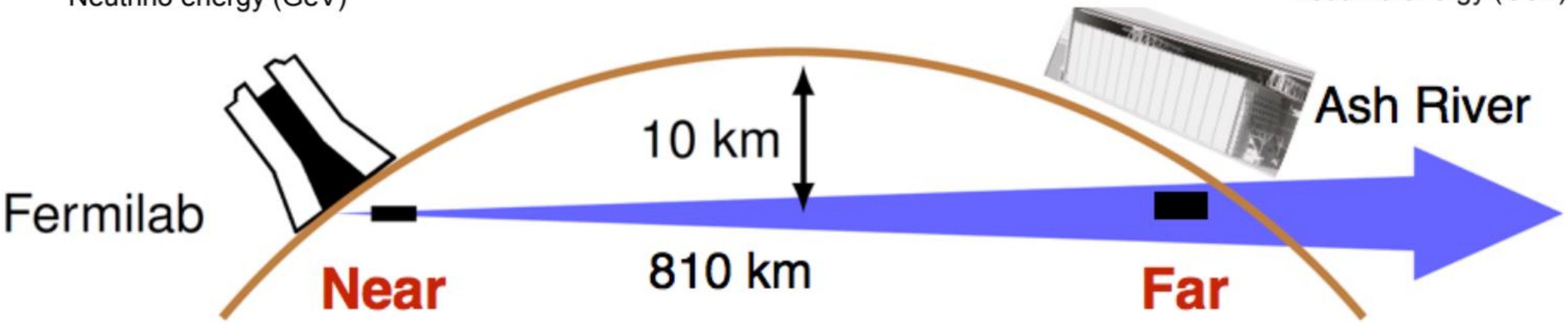




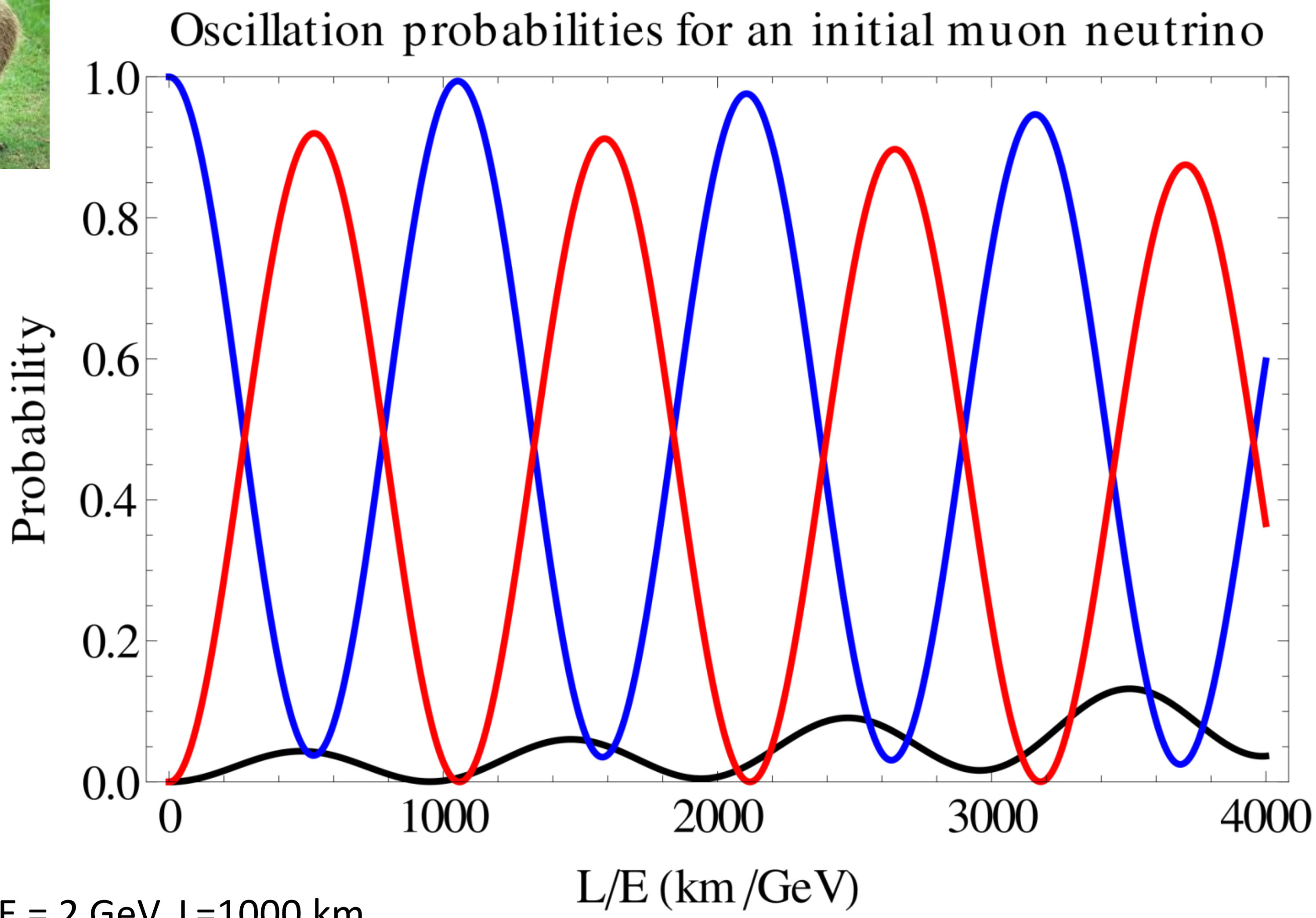


Neutrinos from NuMI beam





Interlude: where are the tau neutrinos?



Blue – muon neutrino
Red - tau neutrino
Black – electron neutrino

E = 2 GeV, L=1000 km

Baseline/Neutrino energy

CNGS ν_μ beam from CERN to Gran Sasso

Need high-energy beam to make tau-leptons!

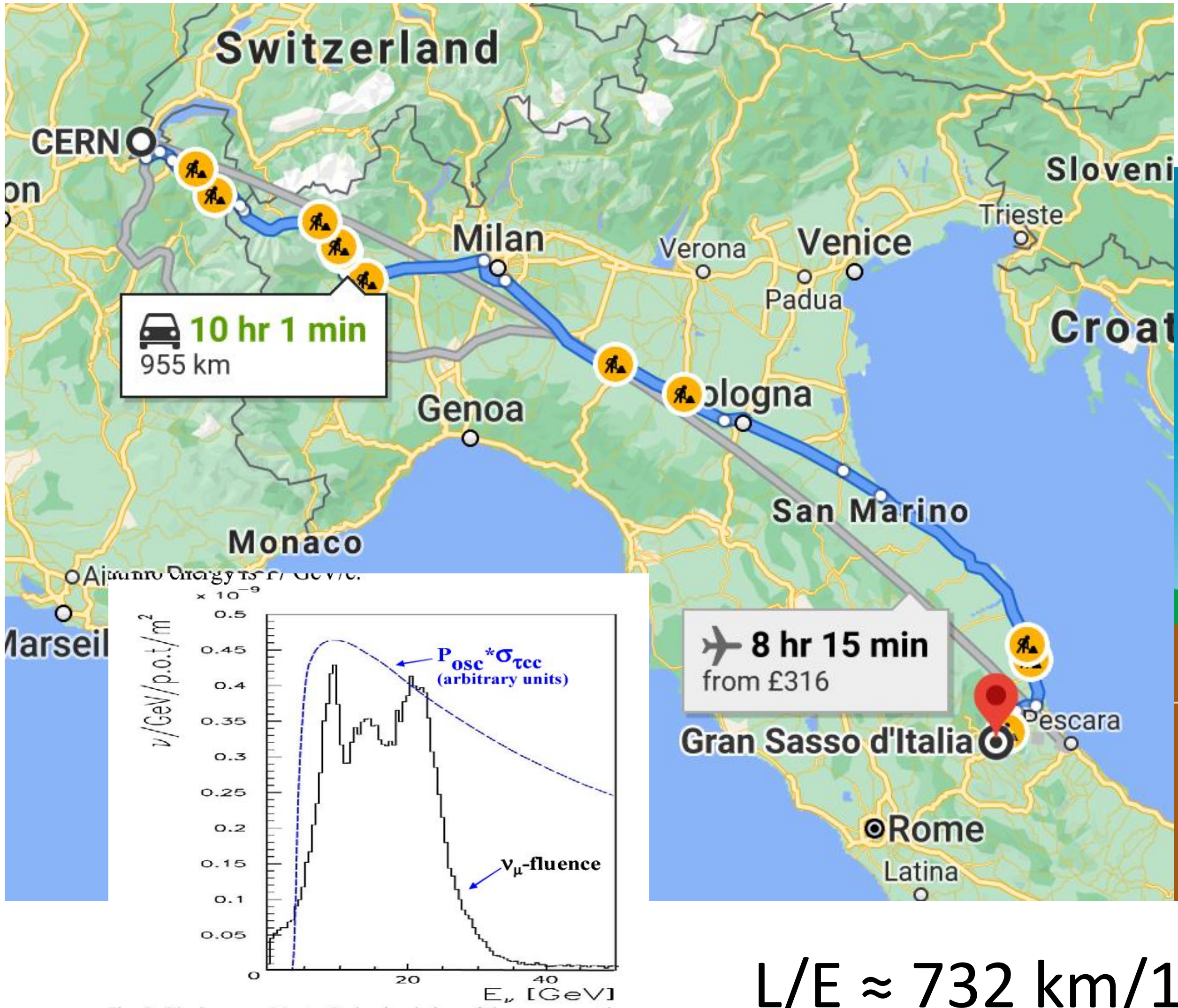
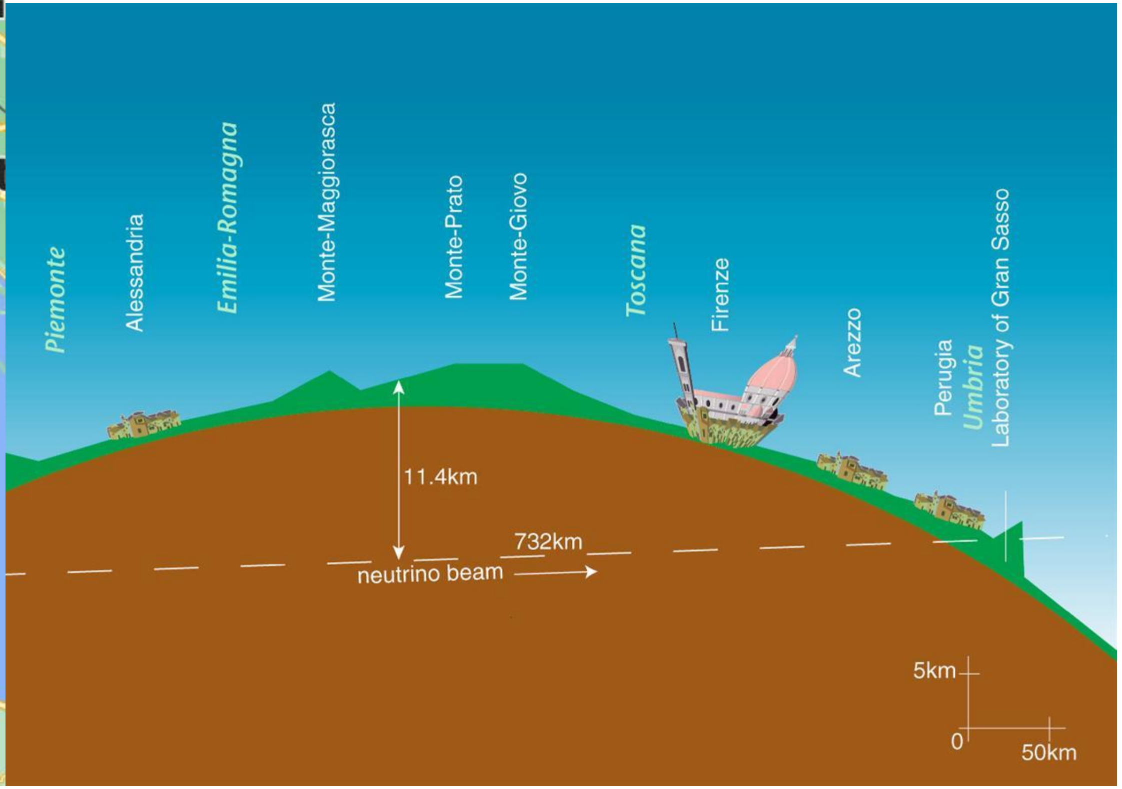


Fig. 2. Black curve: Monte-Carlo simulation of the muon-neutrino e



$$L/E \approx 732 \text{ km}/17 \text{ GeV} = 43$$

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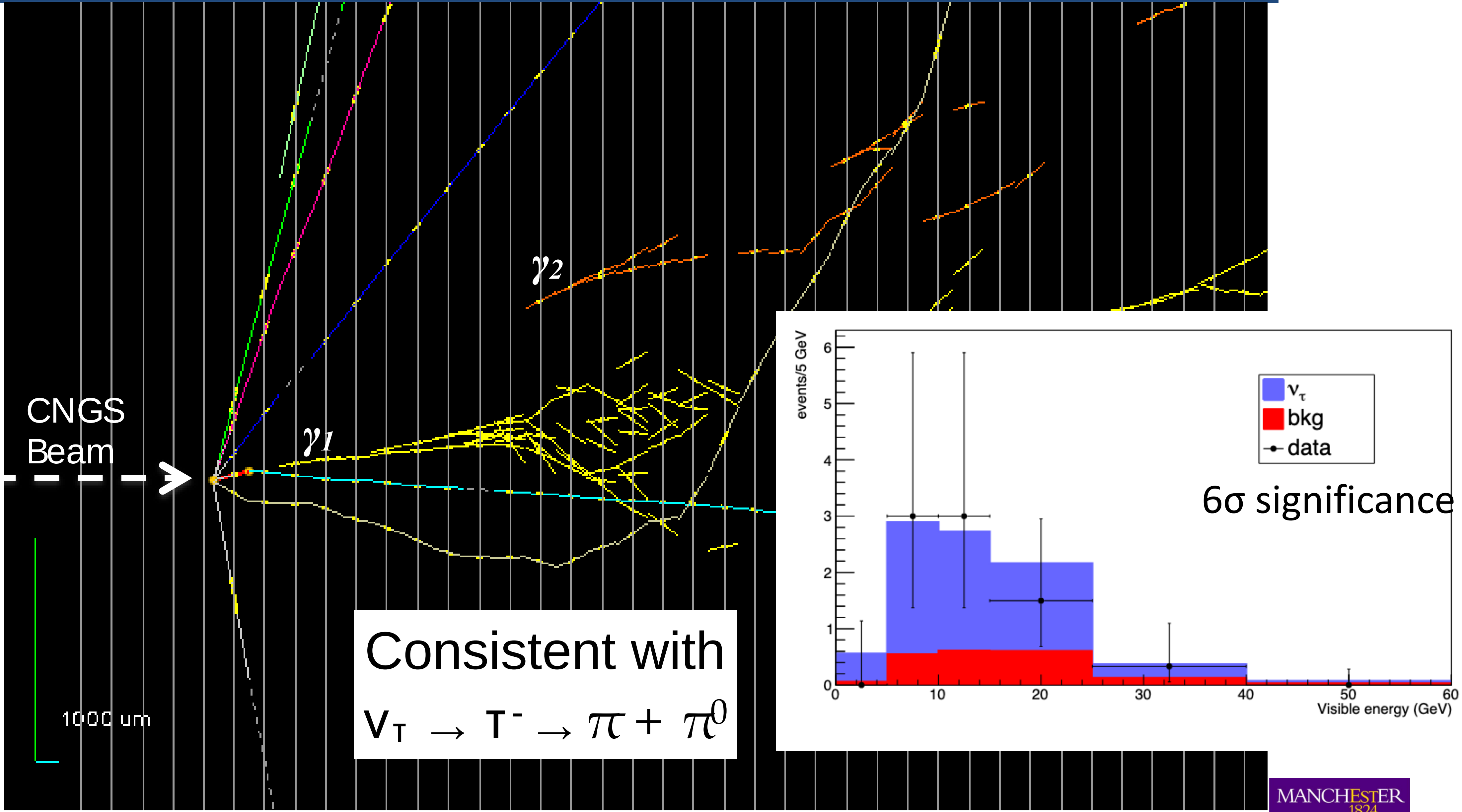
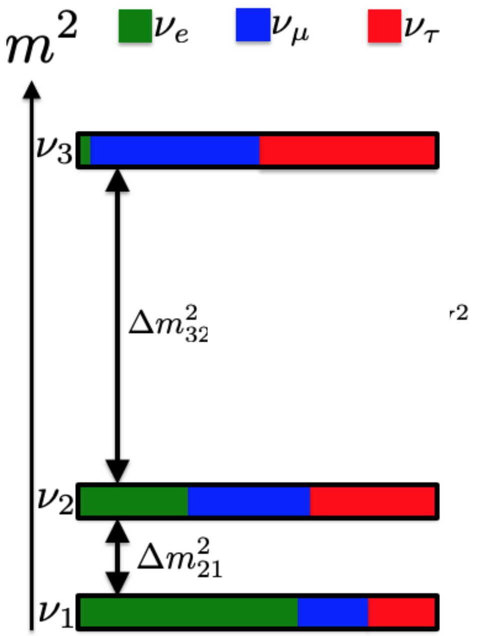
First observation of $\nu_\tau \rightarrow \nu_\tau$ appearance

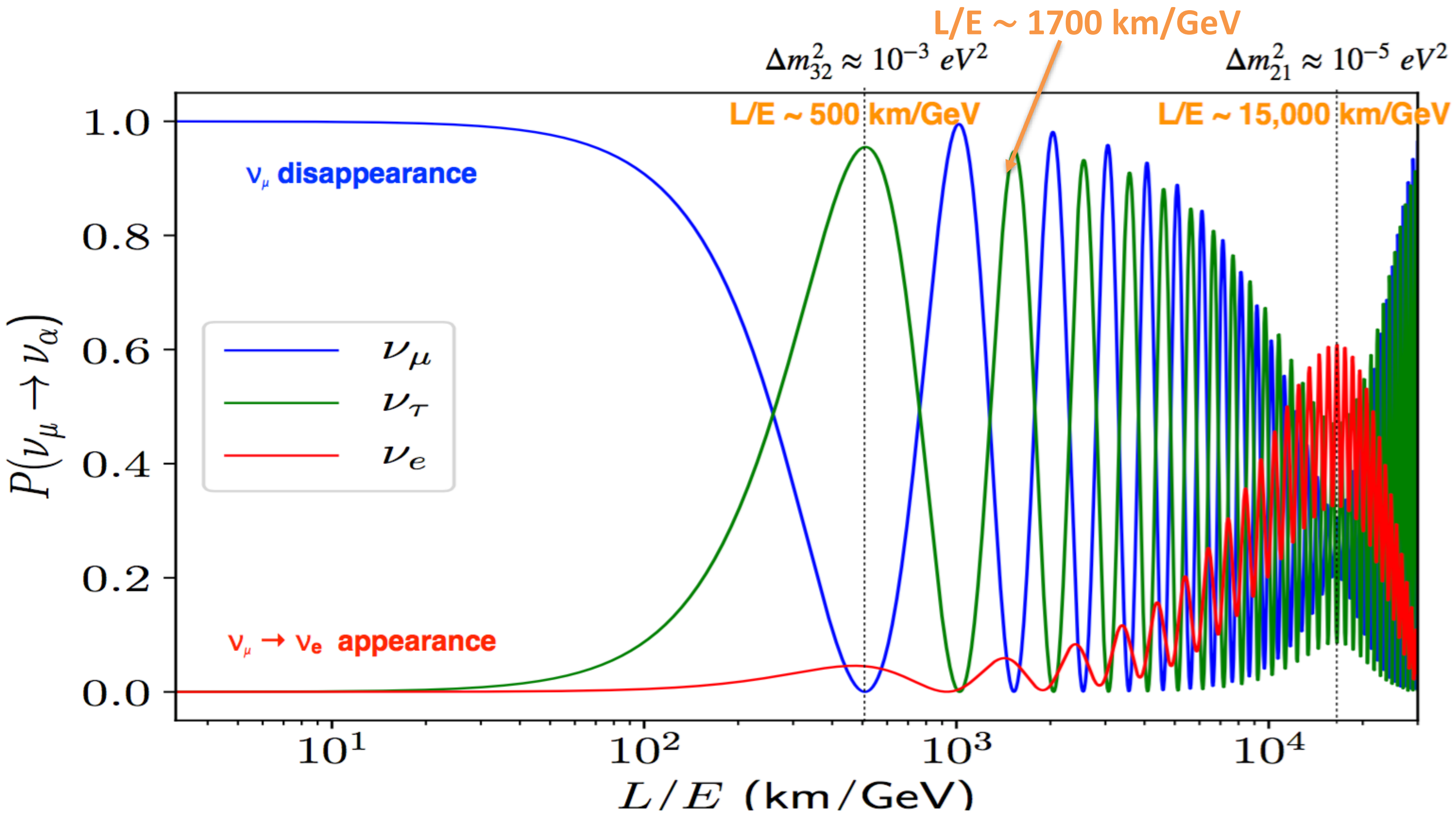


Consistent with

$\nu_\tau \rightarrow \tau^- \rightarrow \pi + \pi^0$

Long-baseline: finding the oscillation maximum





Typical neutrino beam energy is around 2.5 GeV

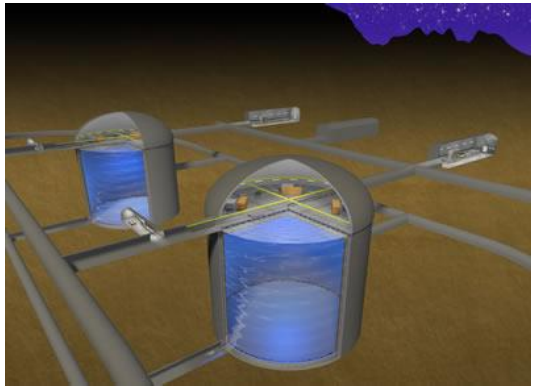
Baseline/Neutrino energy

Optimizing L/E for neutrino oscillations

$$\frac{\Delta m_{31}^2 L}{4E} \sim \frac{\pi}{2}$$

L ≈ 300 km

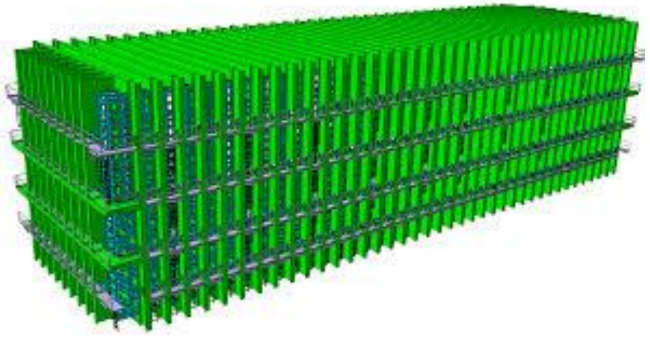
- L/E = 300 km/0.6 GeV = 500 km/GeV
- no matter effects; first oscillation maximum.
- use narrow width neutrino beam (off axis) with E < 1 GeV



e.g. Water Cherenkov (T2K,HK)

L = 1300 km

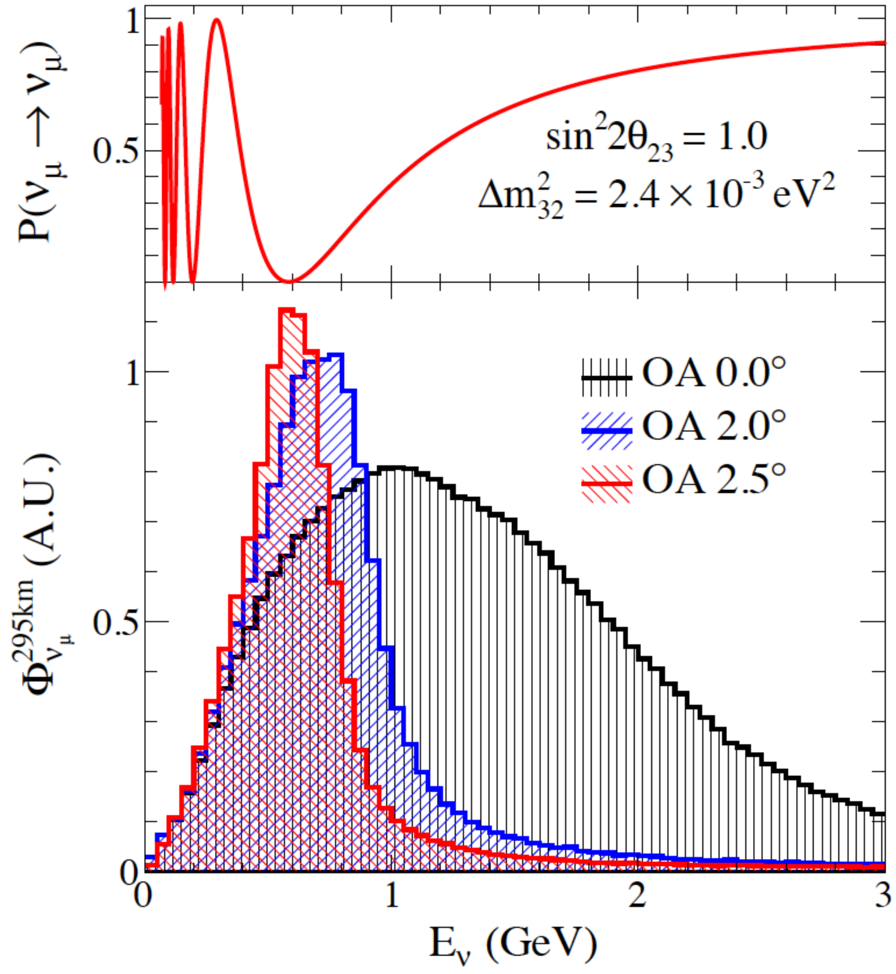
- L/E = 1300 km/2.5 GeV = 500 km/GeV (1st max),
- L/E = 1300 km/0.8 GeV = 1700 km/GeV (2nd max)
- matter effects; first and second oscillation maximum.
- use broad-band neutrino beam (on axis).



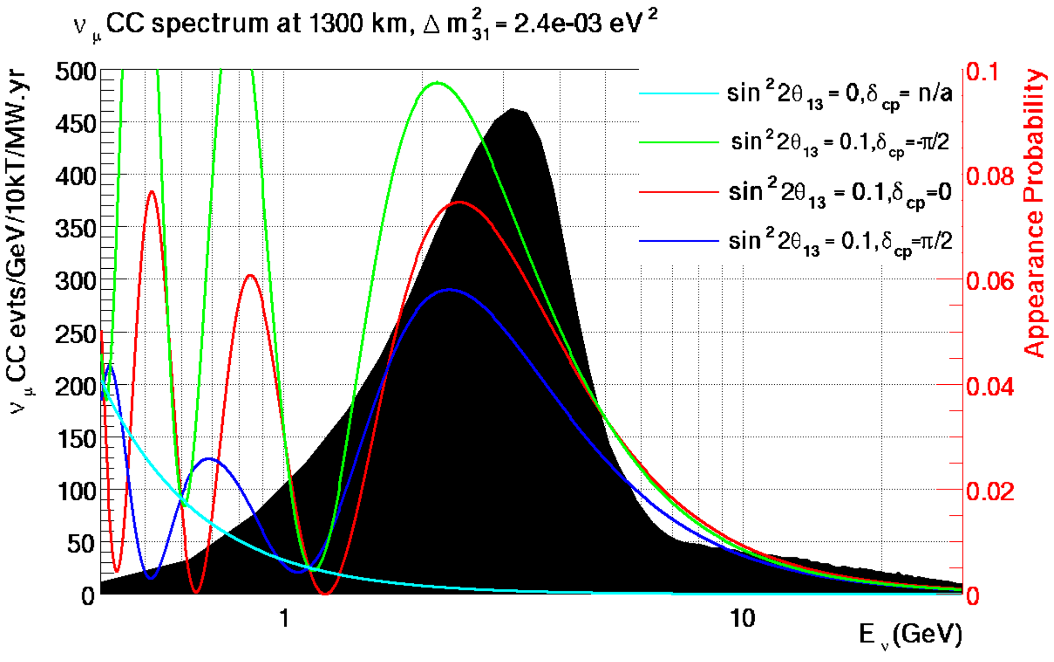
e.g. Liquid argon (DUNE)

Off-axis vs on-axis beams

T2K at 2.5 degrees



DUNE on-axis beam



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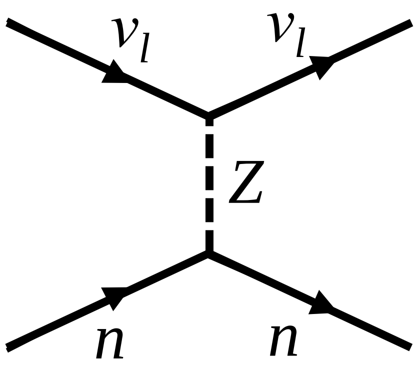
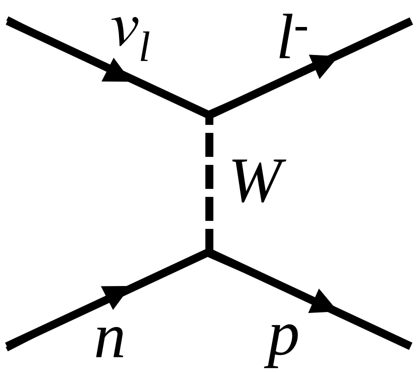
Interlude: neutrino-nucleon interaction

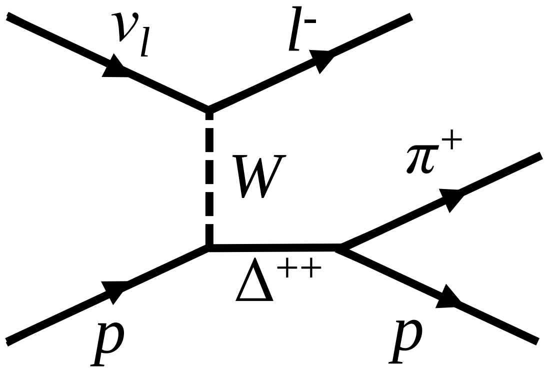


Elastic scattering

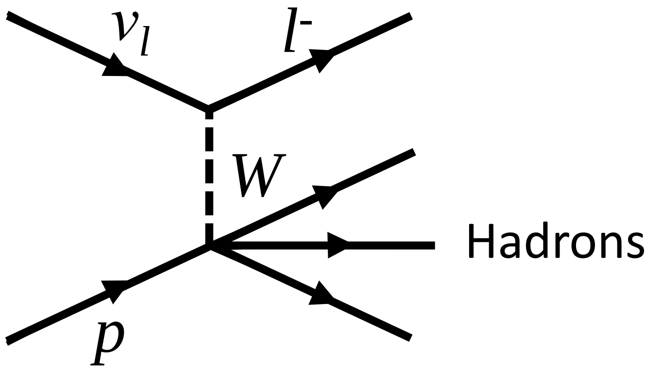


Quasi-elastic scattering
(lowest energies)

'Low-energy' neutrino beams – we need to understand the interaction of neutrinos and related nuclear effects.



Resonance
(Energies ~1 GeV)

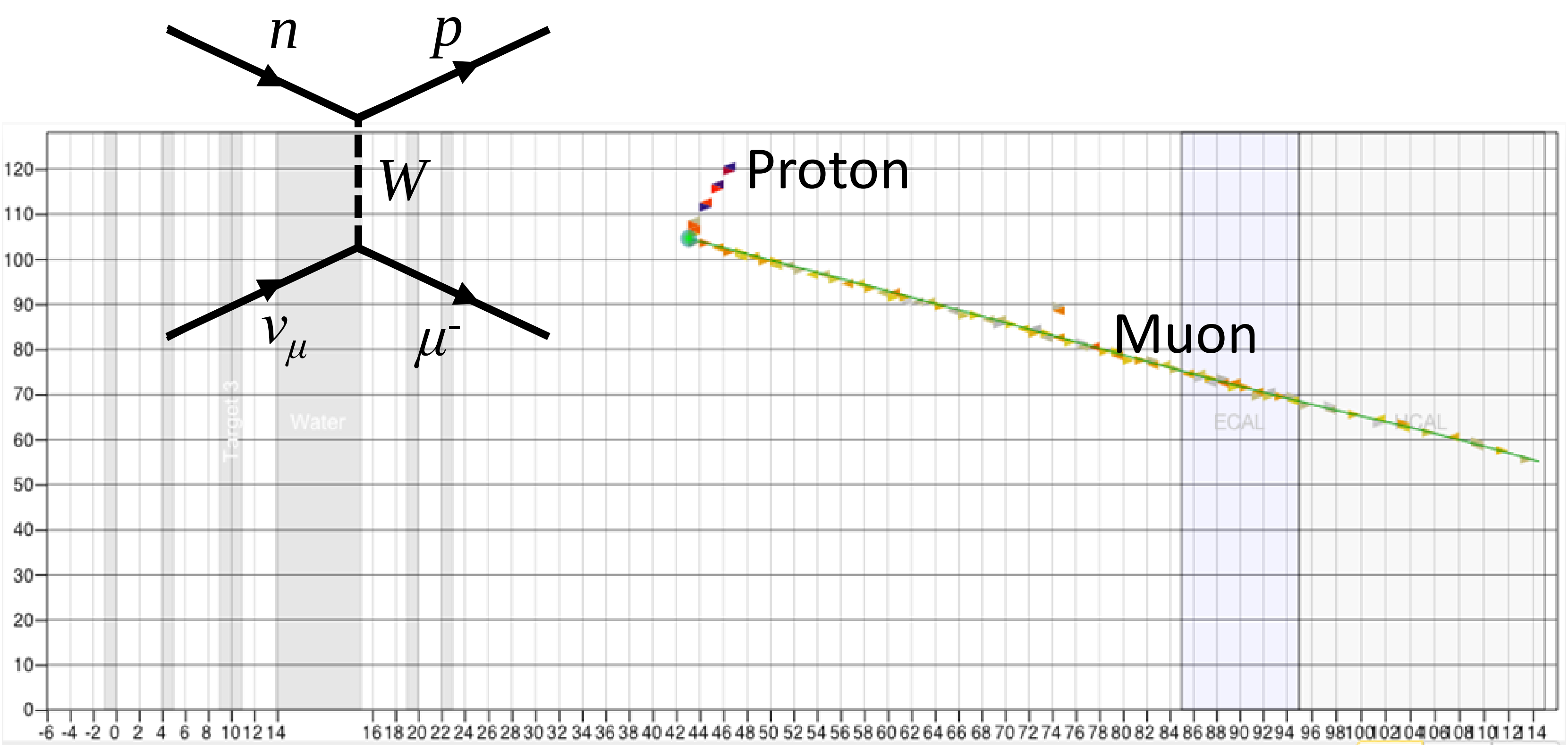


Deep inelastic scattering
Highest energies (>1 GeV)

MINERνA ν_μ quasi-elastic interaction

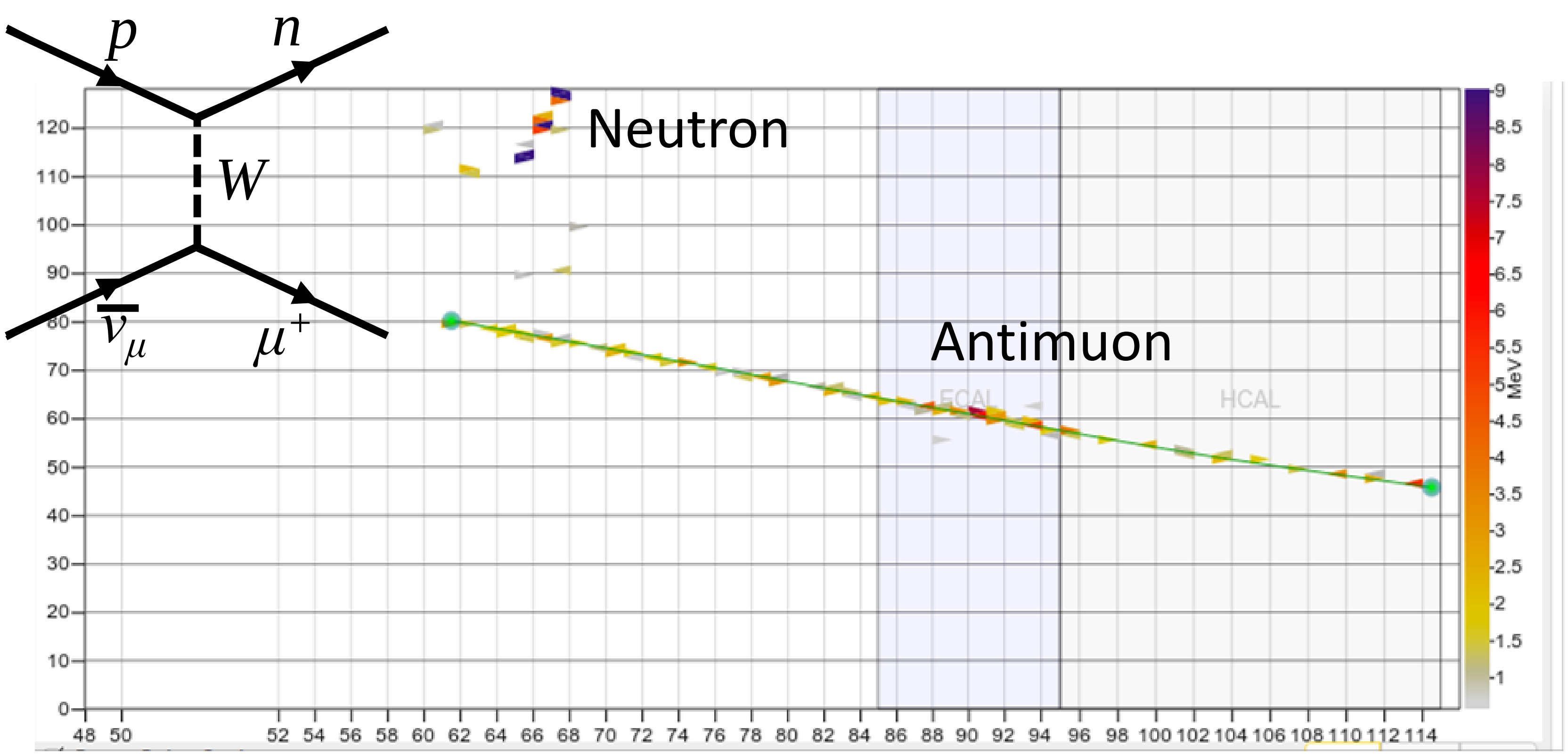
Minerva: uses active tracker

Quasielastic scattering



MINERνA ν_μ quasi-elastic interaction

Quasielastic scattering



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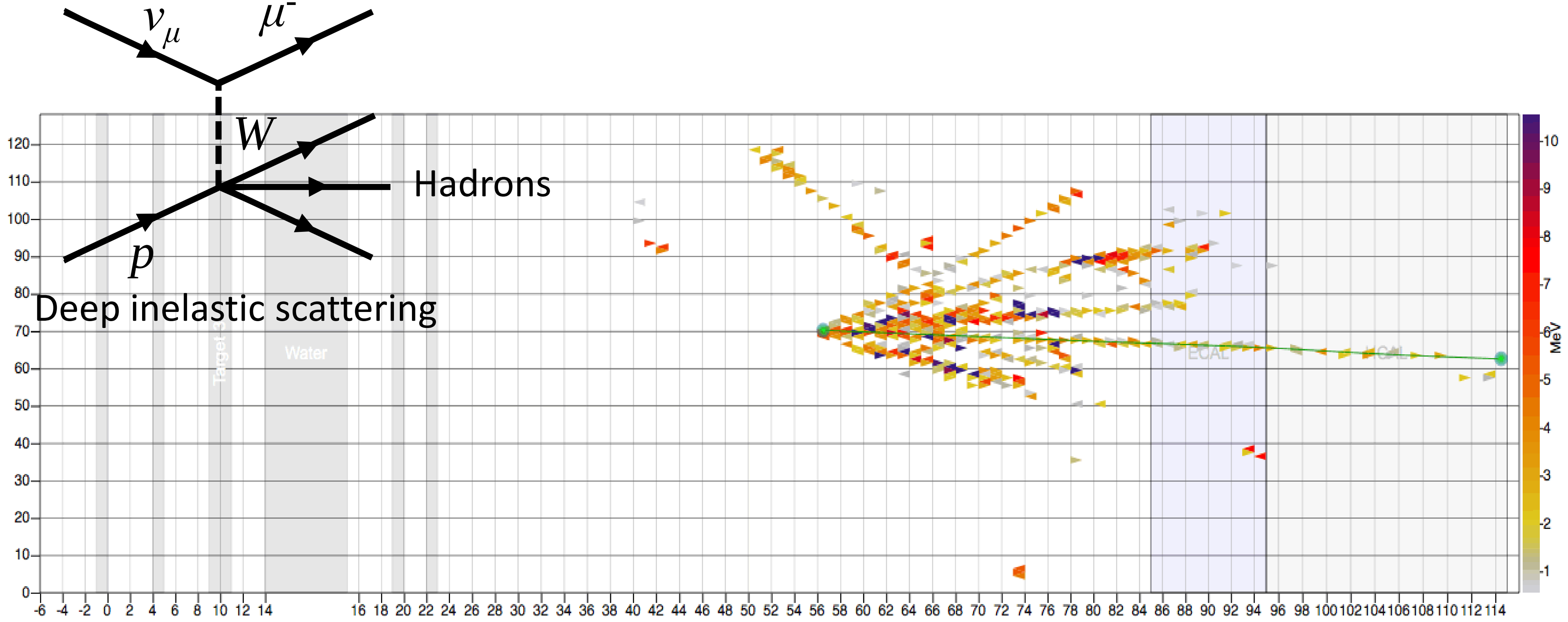
MINERνA deep inelastic scattering event



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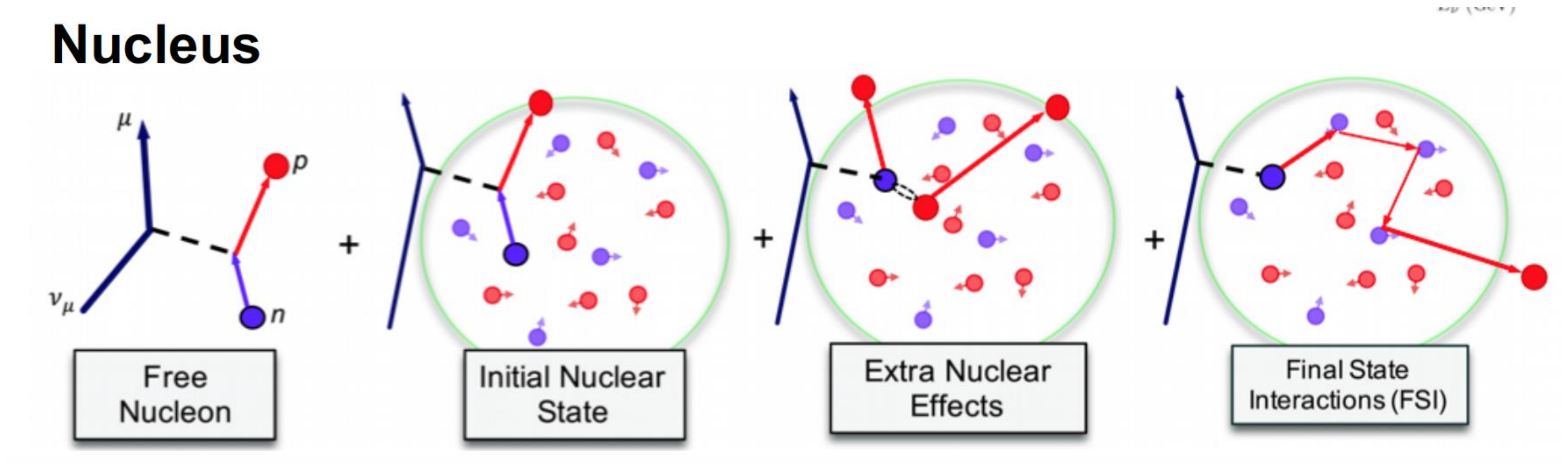
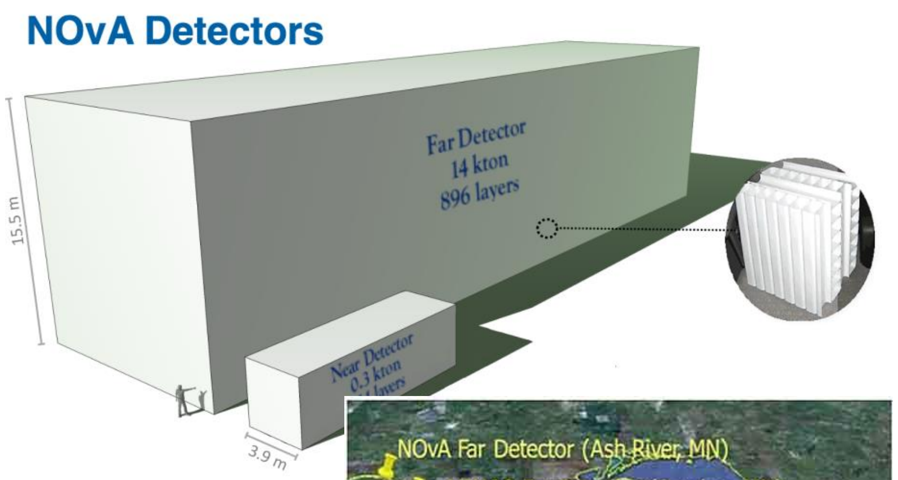
Another Complication

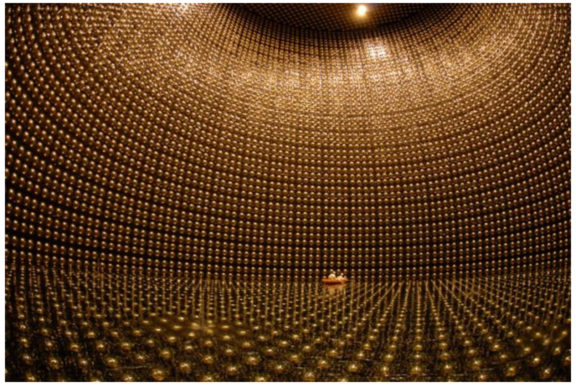
Need to understand nuclear effects – which are messy!



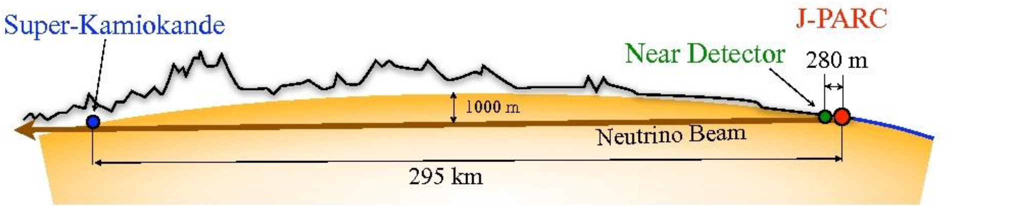
Some effects can be mitigated by use of same nuclear targets for near and far detector.

Operating Long-baseline experiments

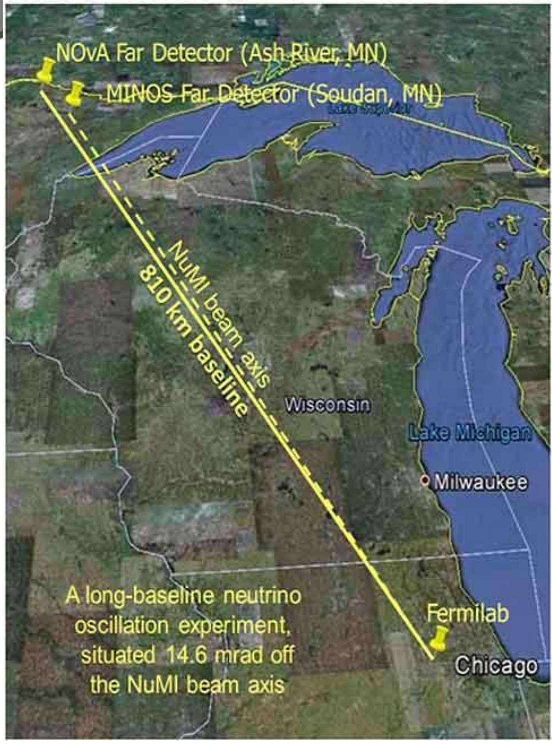


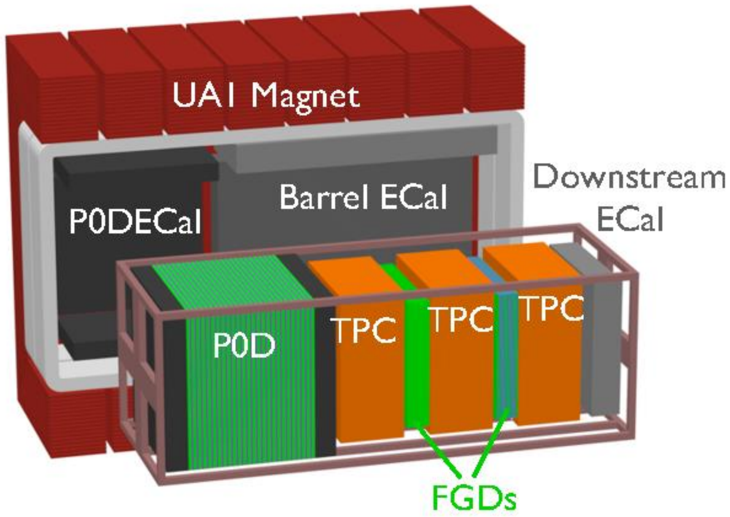


T2K baseline:
295 km



NOvA baseline:
810 km





T2K Experiment

P. Dunne,
Neutrino 2020

- Muon (anti) neutrino beam generated at J-PARC
- Beam travels 295 km to large SK far detector to be measured after oscillations
- Near detector complex, ND280 constrains beam flux and interaction cross-section before oscillation
- Important to constrain non-oscillation parts of model to avoid bias

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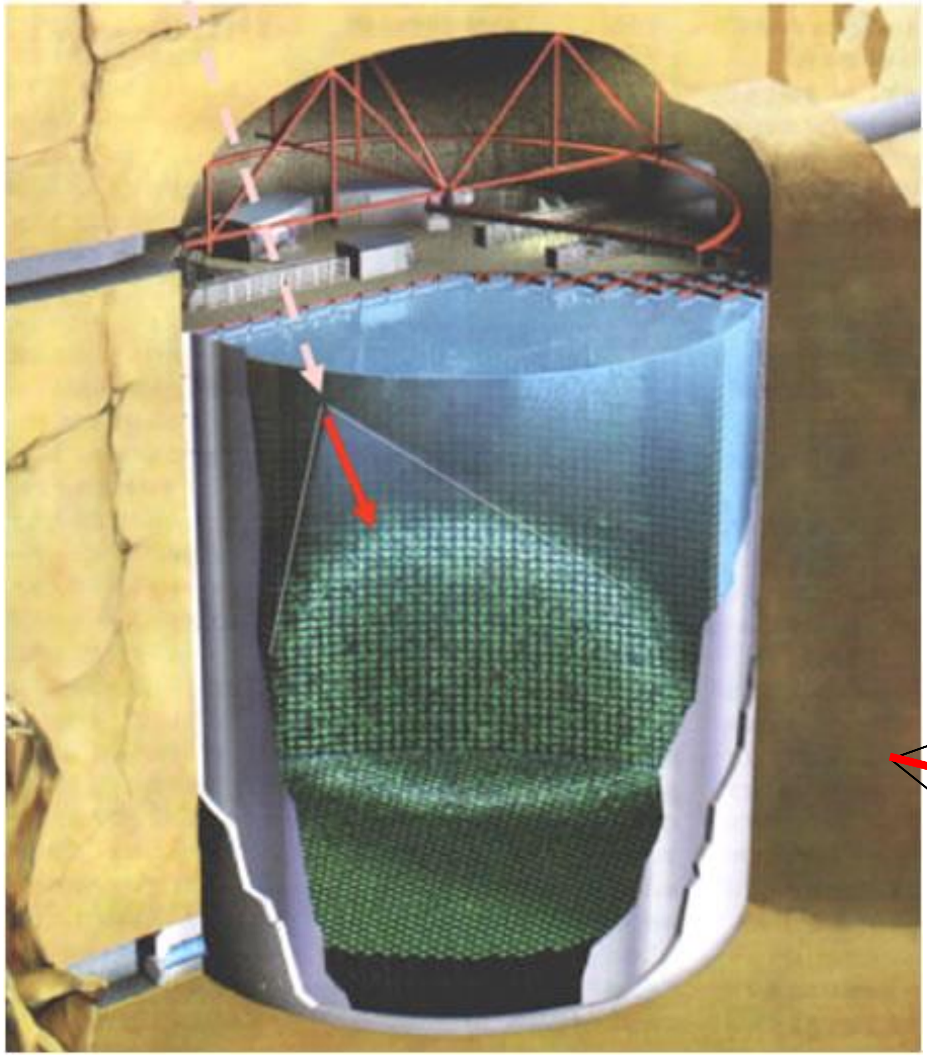
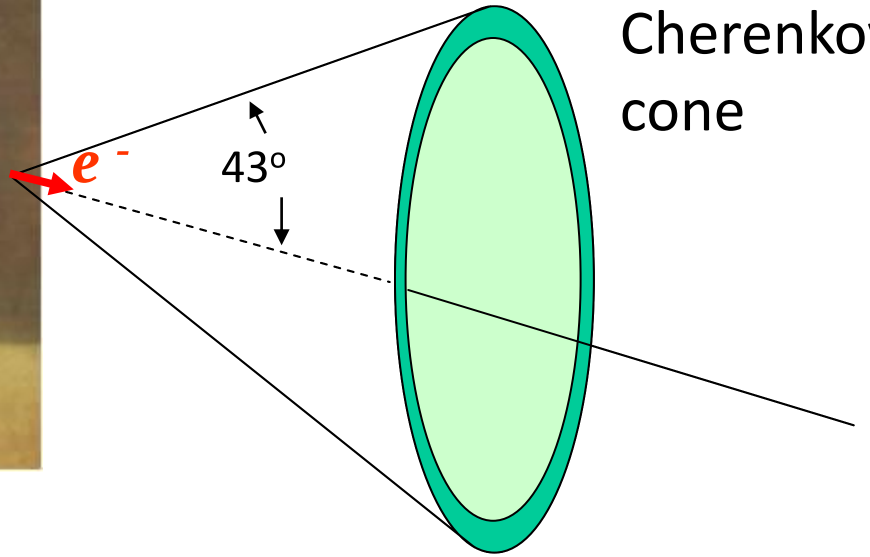
Super-Kamiokande



- 50,000 tons of water surrounded by 11,000 PMTs (20 inch).
- 1 km rock overburden
- 39.3m in diameter and 41.4m in height



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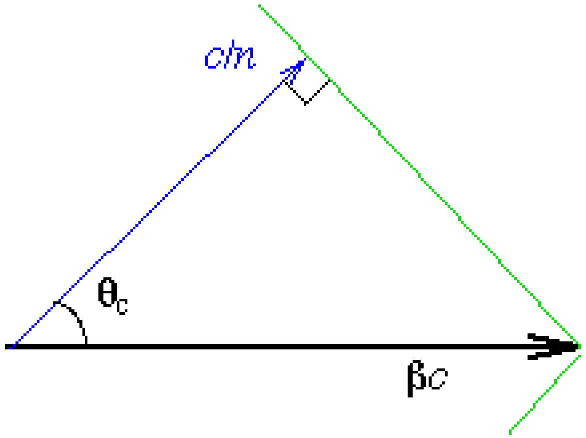
Cherenkov Radiation

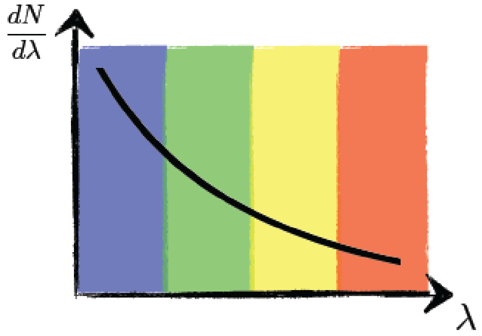


$$\cos\theta_c = \frac{ct/n}{vt} = \frac{ct/n}{\beta ct} = \frac{1}{n\beta}$$

Threshold: $\gamma > \frac{1}{\sqrt{1-n^{-2}}}$

The critical wave front is emitted at an angle
$\theta_c = \cos^{-1}(1/\beta n)$

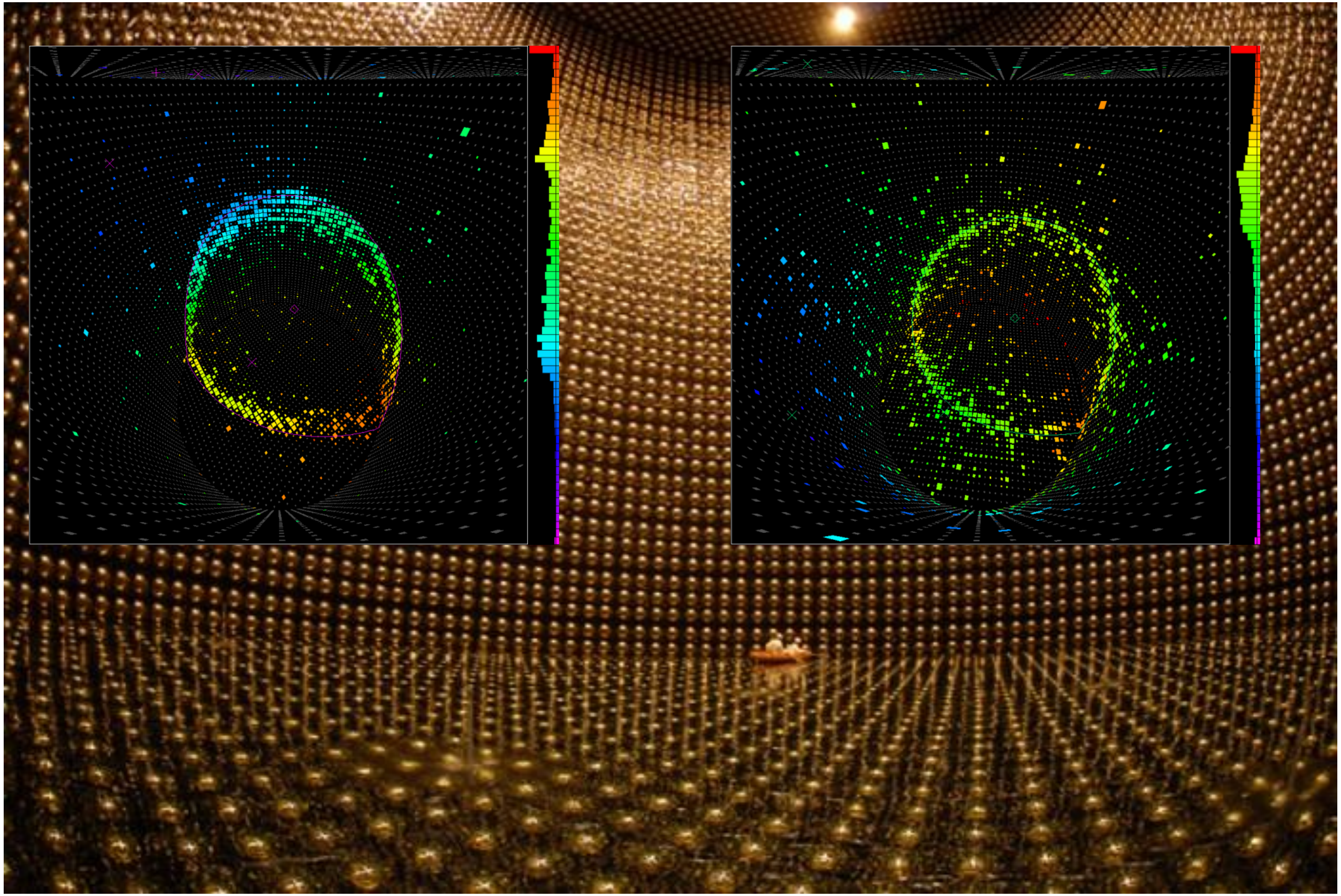
- A cone of light radiates out from each point on the particle's track.
- The Cherenkov cone angle is related to the particle’s β.



$$\frac{d^2N}{d\lambda dx} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) = \frac{2\pi\alpha z^2}{\lambda^2}\sin^2\theta_C$$

- Total number of photons N depends on θ_c and therefore on velocity β
- Measurements of θ_c and N gives β and hence, with momentum, identification

Super-Kamiokande – electron or muon ring?



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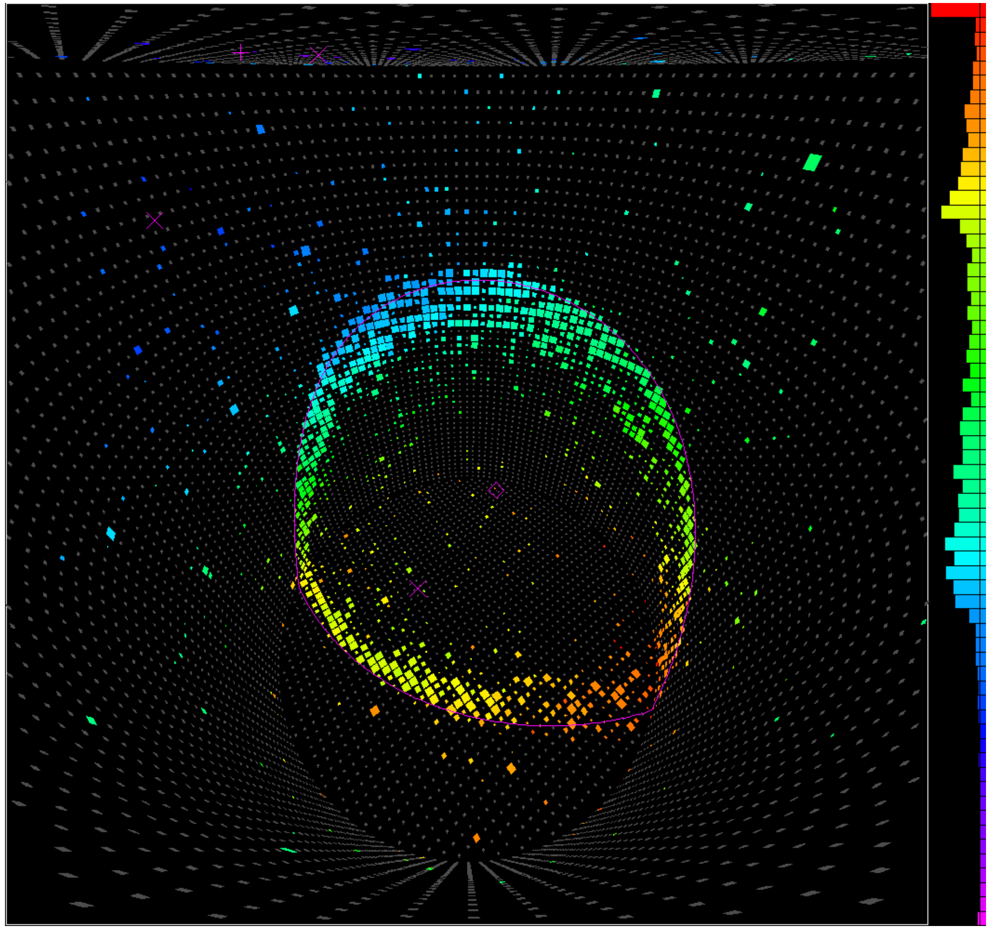

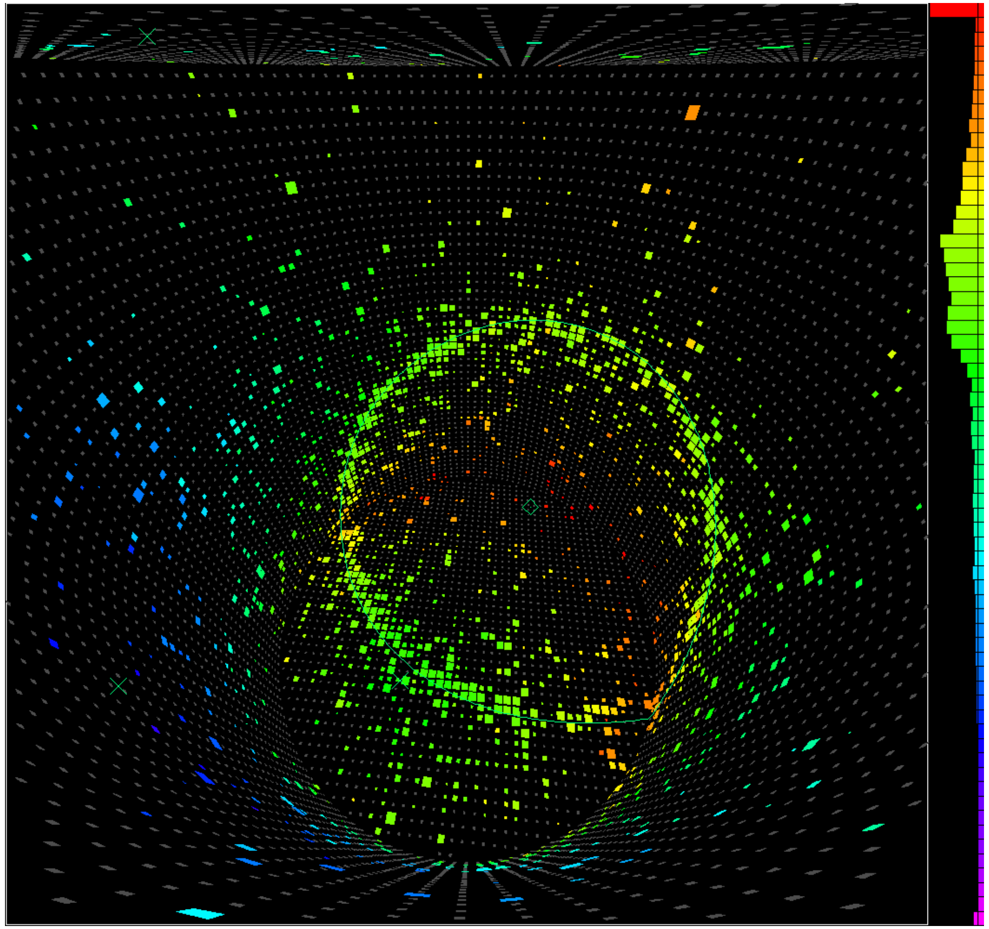

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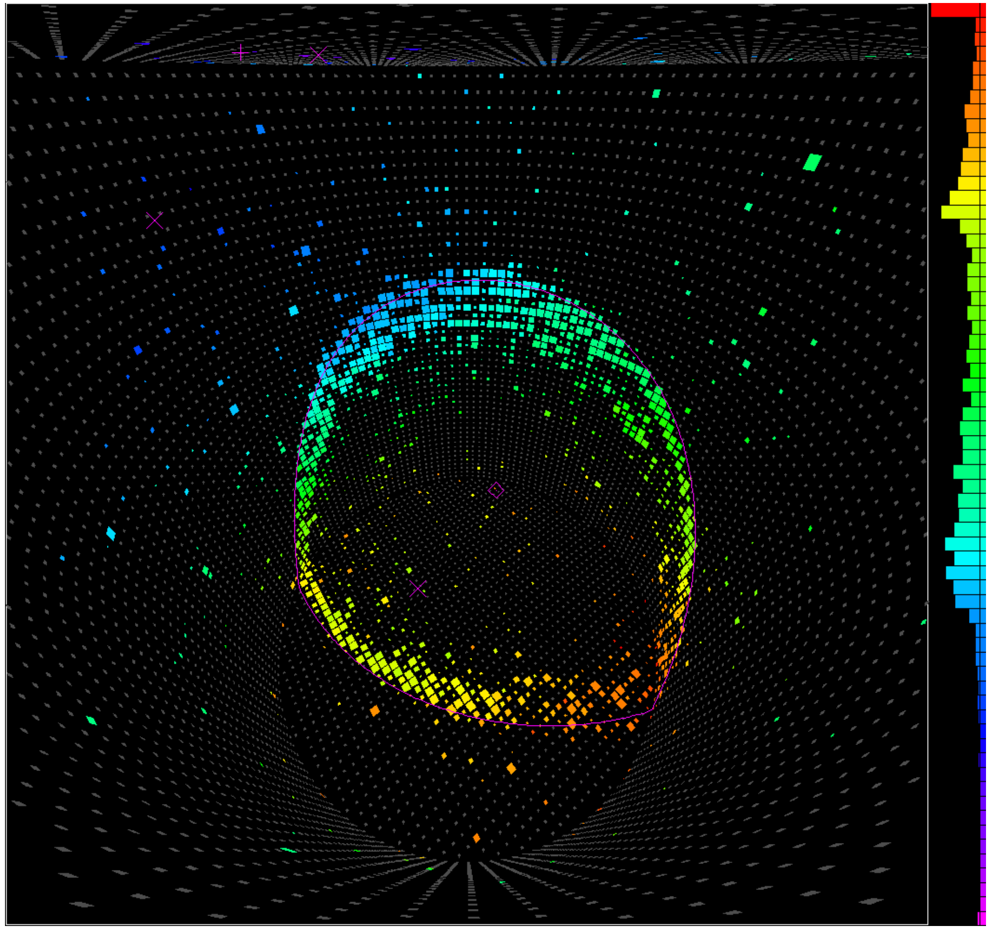
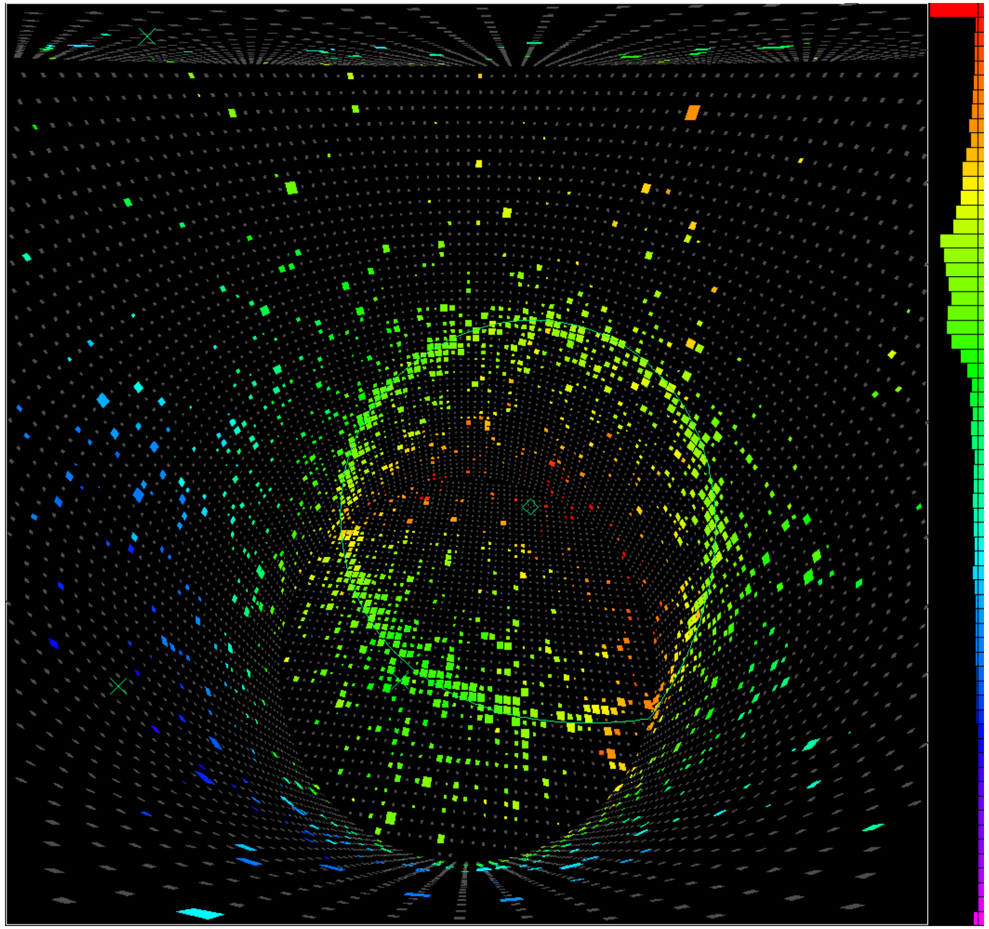


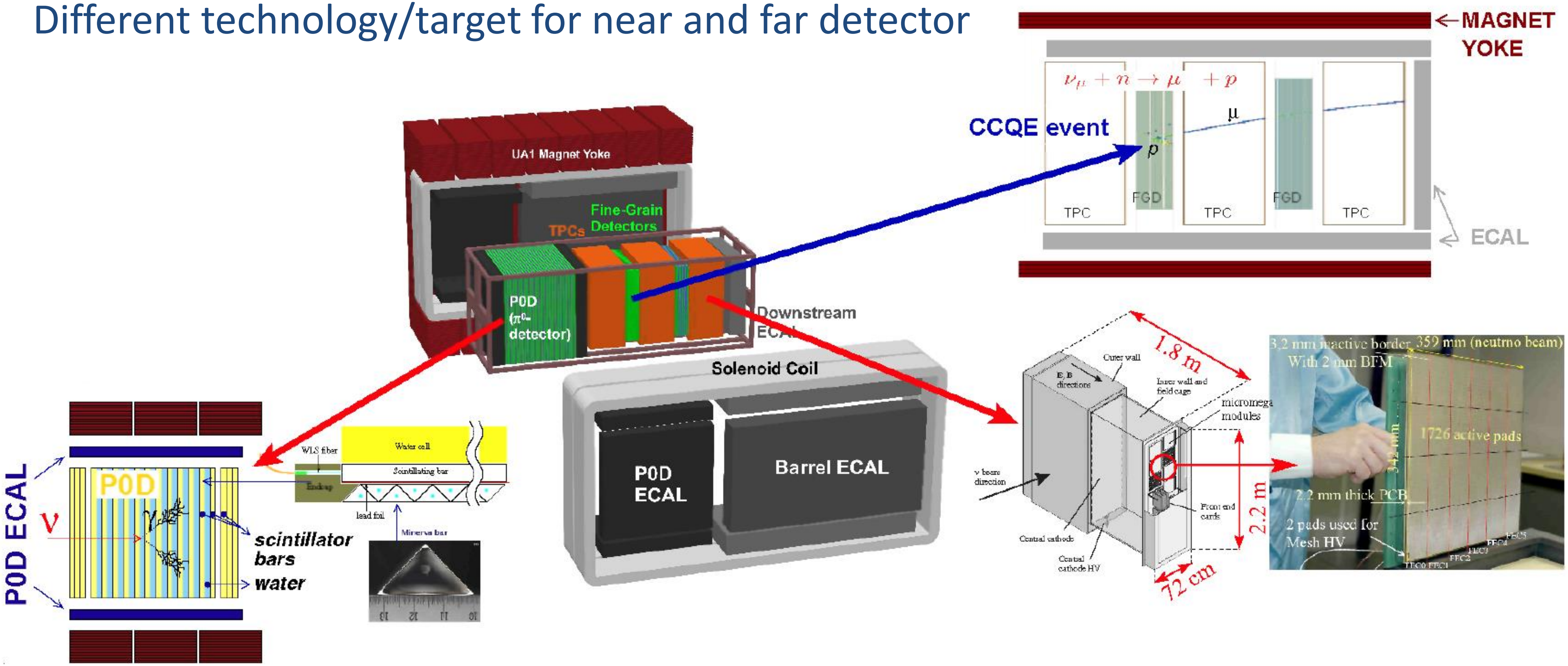
$$\nu_\mu + X \to \mu^- + X'$$



$$\nu_e + X \to e^- + X'$$

The T2K Near Detector (ND280)

Different technology/target for near and far detector



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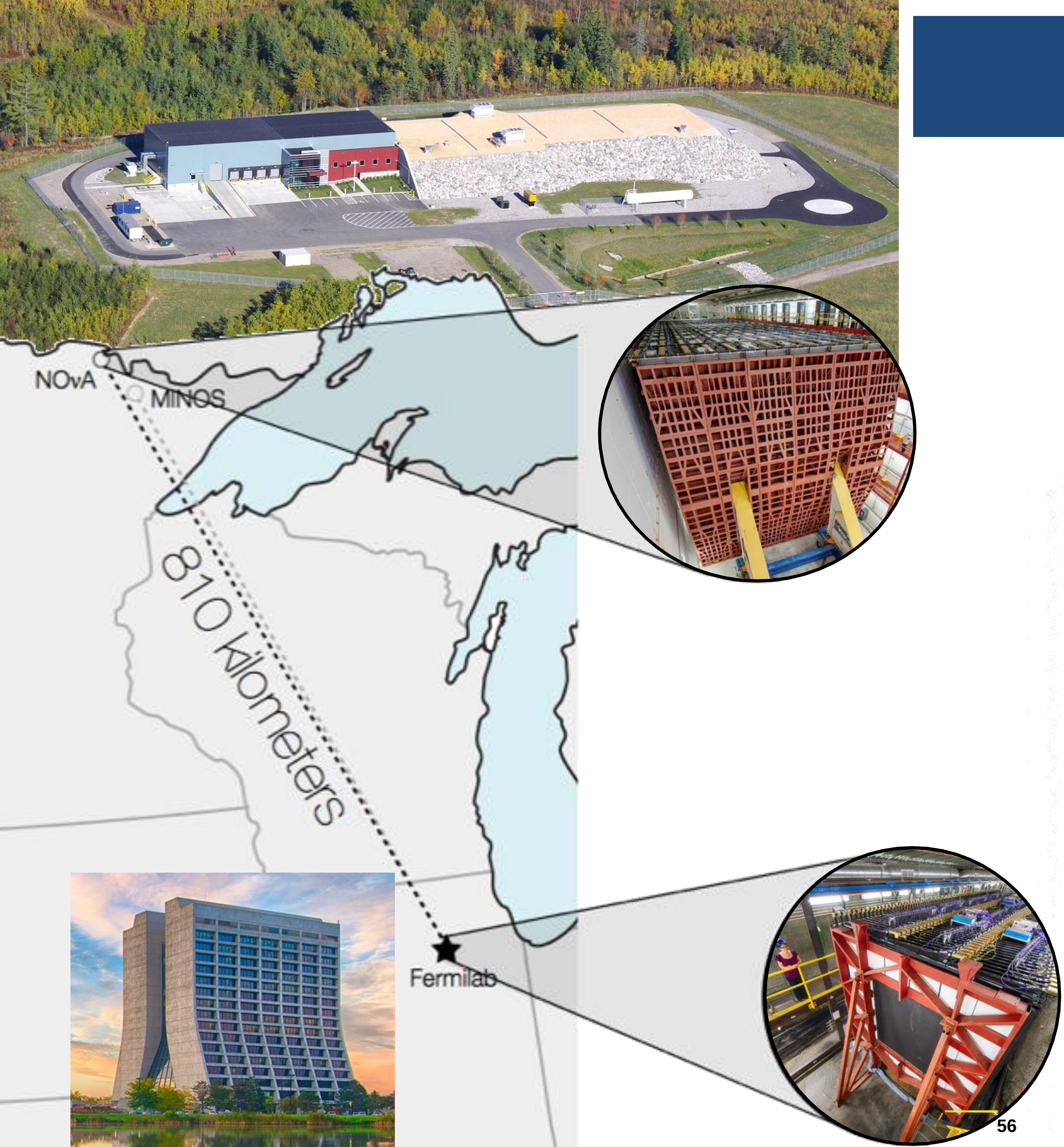
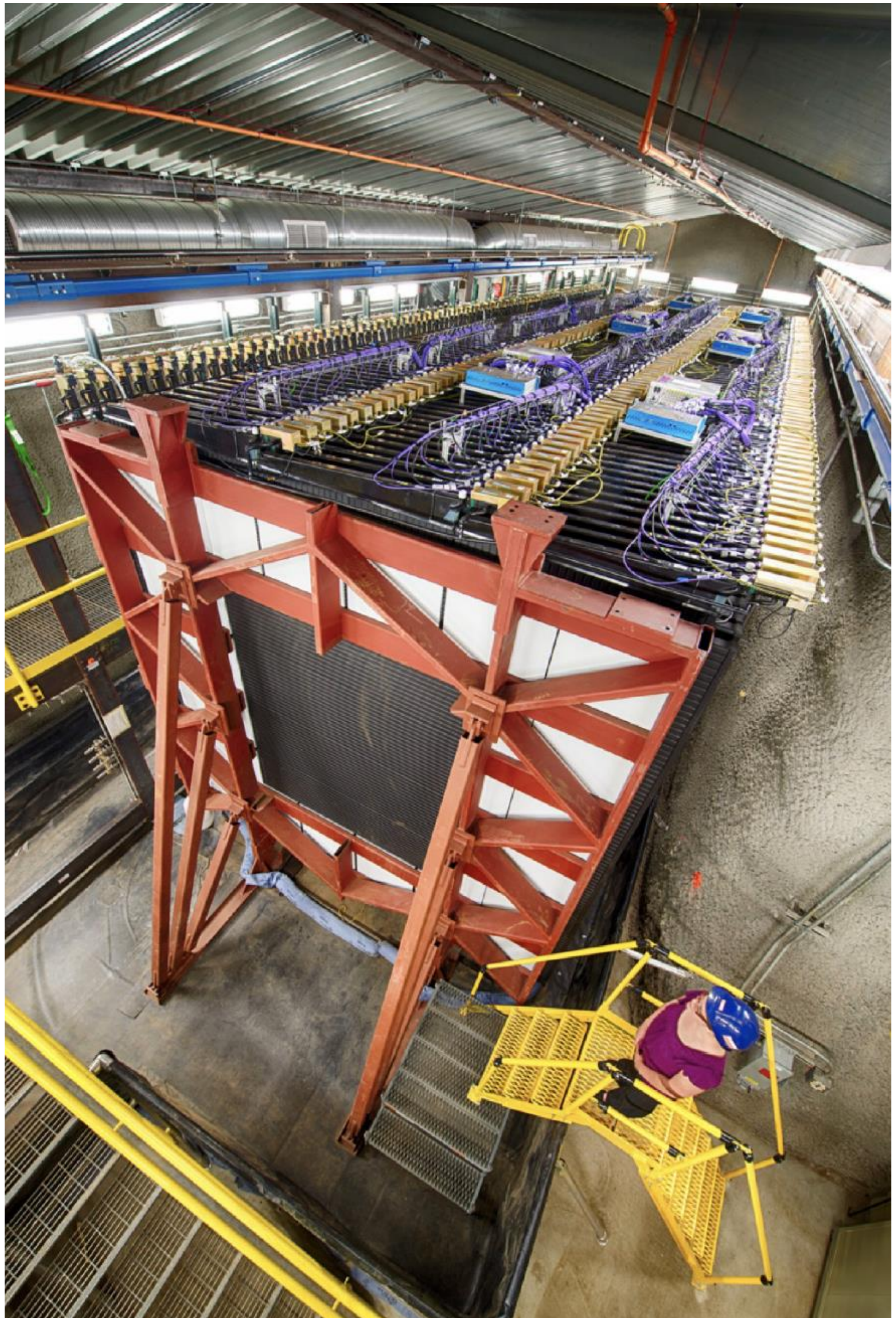


NOvA Experiment

- NuMI beam: ν_μ or $\bar{\nu}_\mu$
- 2 functionally identical, tracking calorimeter detectors
  - Near: 300 T underground
  - Far: 14 kT on the surface
  - Placed off-axis to produce a narrow-band spectrum
- 810 km baseline
  - Longest baseline of current experiments.



NOvA Experiment

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  - Near: 300 T underground
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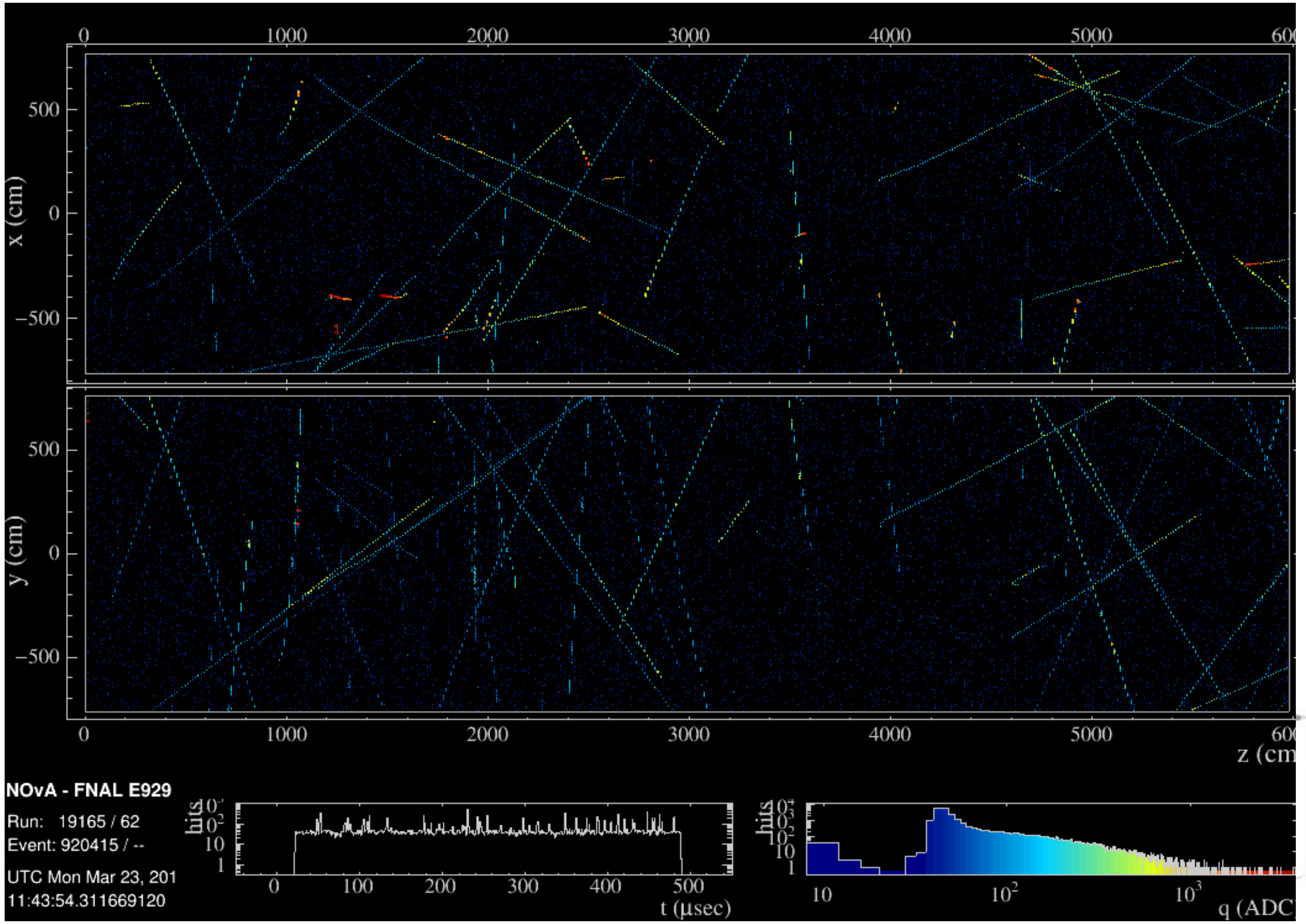
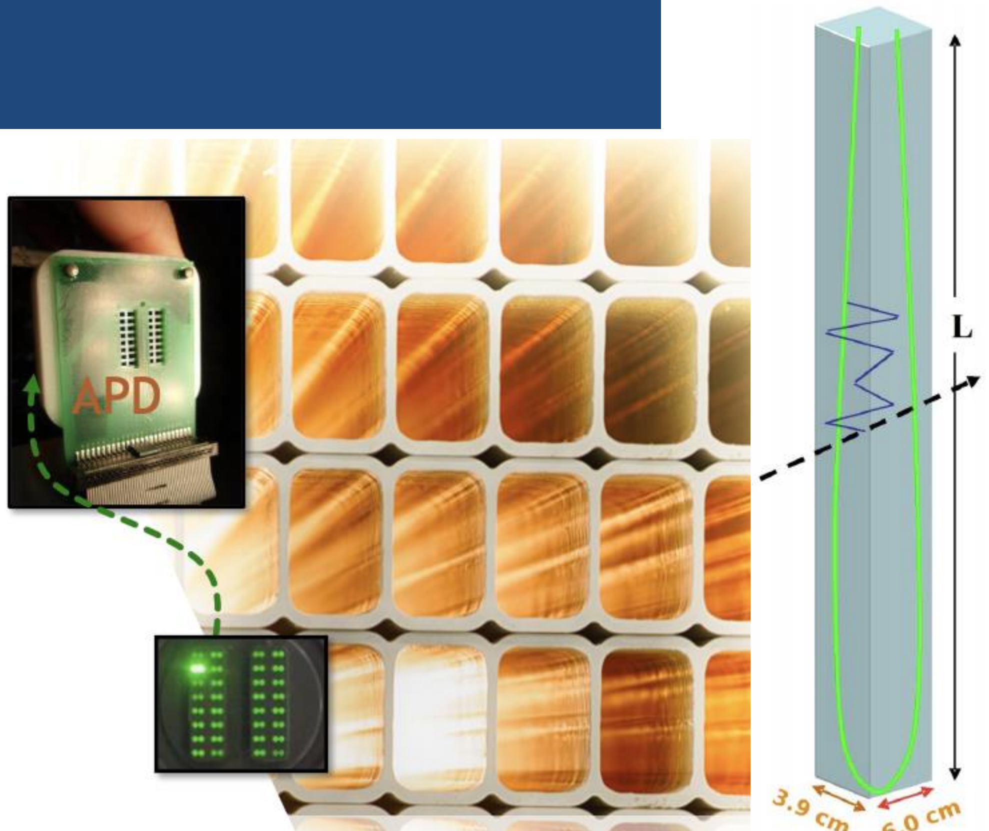
NOvA is on the surface..

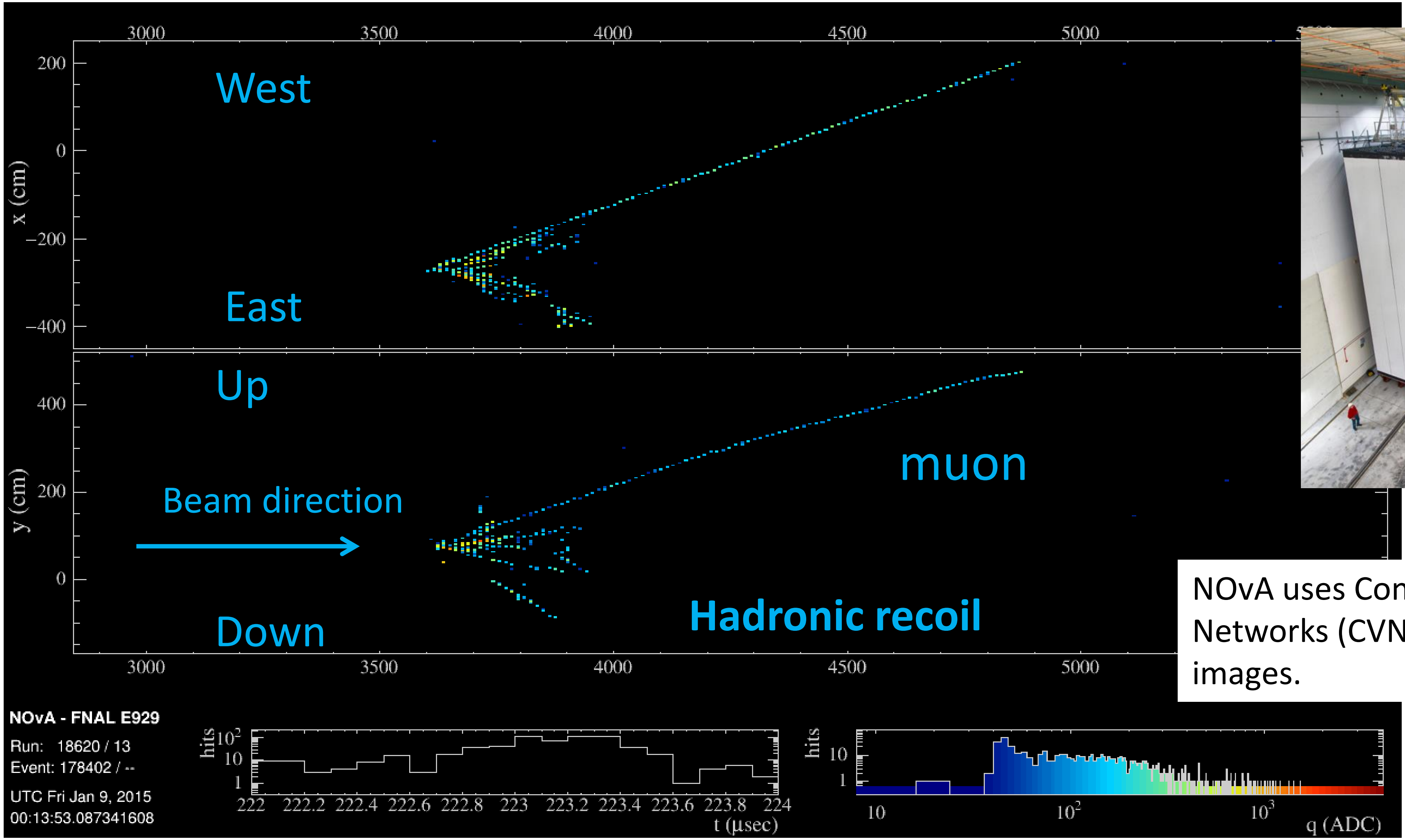




- 65% Active PVC+Liquid Scintillator
  - Mineral Oil
  - 5% pseudocumene
  - Read out via WLS fiber to APD
- Layered planes of orthogonal views
  - muon crossing far end ~40 PE
  - 0.17 X_0 per layer

- 14 kt Far Detector
- Equivalent Near Detector

NOvA Detector



NOvA uses Convolutional Neural Networks (CVNs) to reconstruct images.

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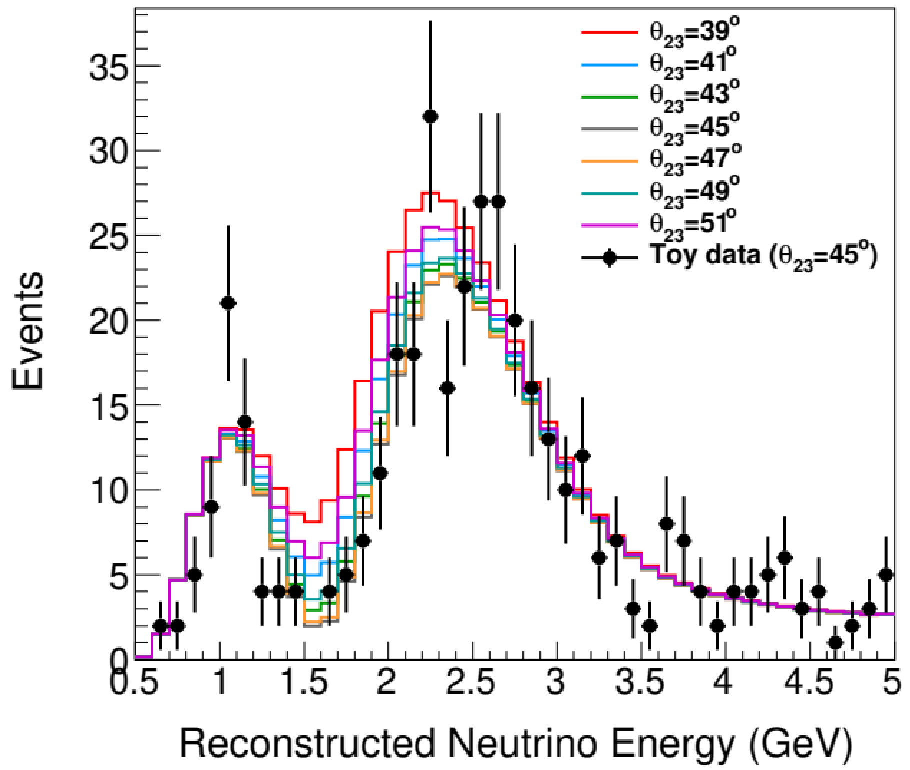
Extracting the Information

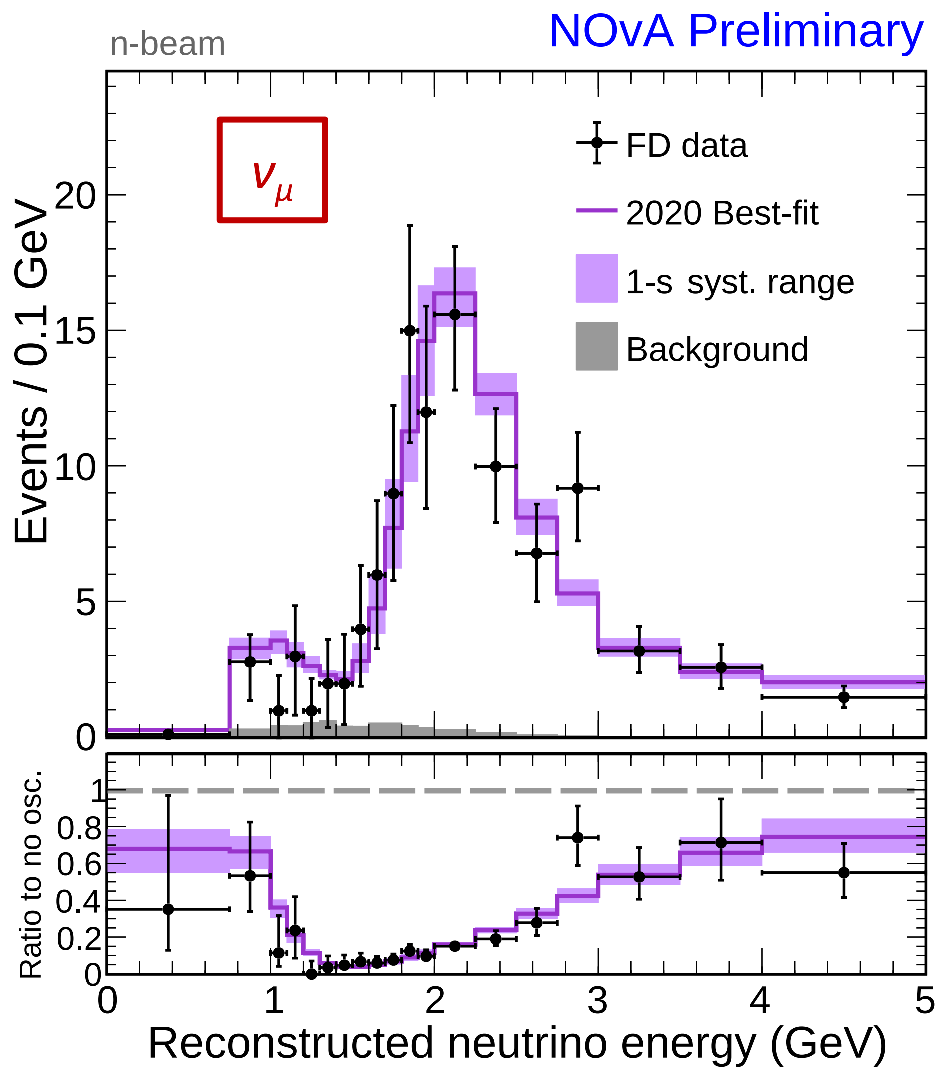


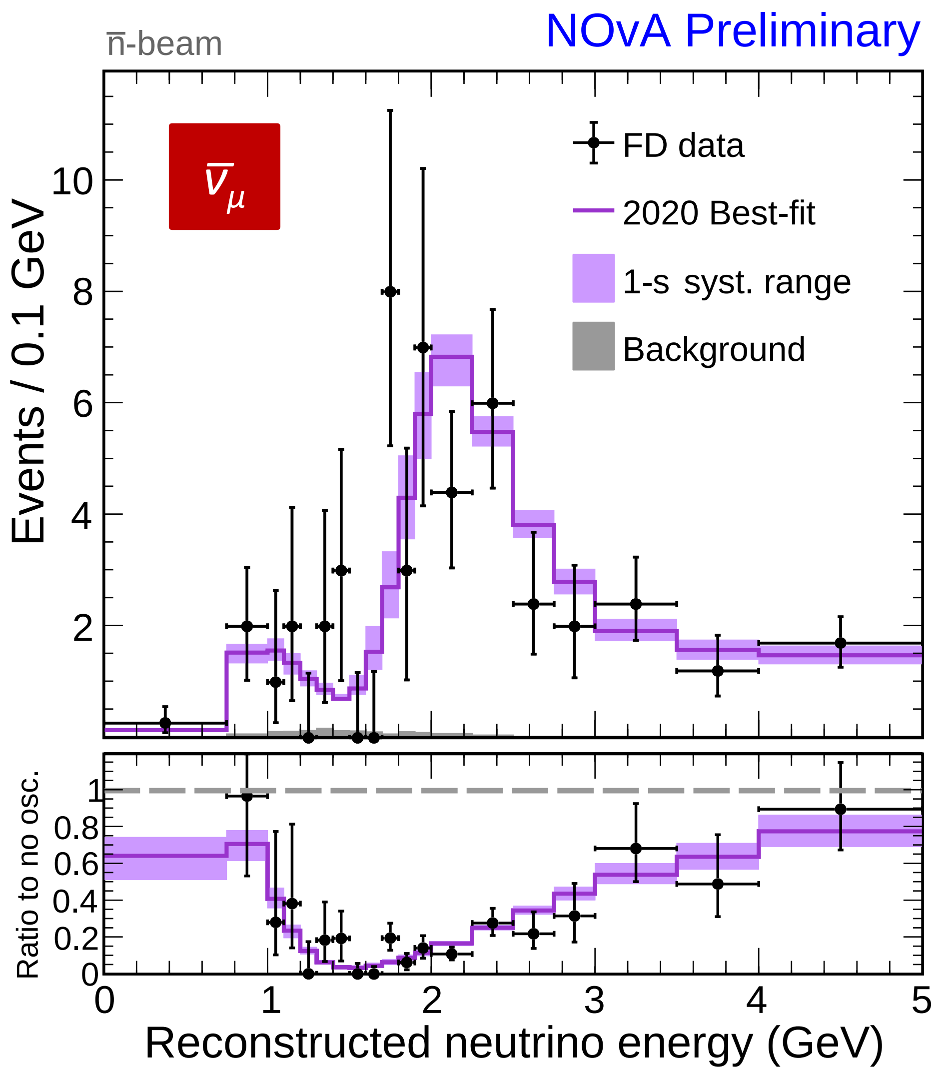
Simultaneous fits of

- Data samples in Near and Far Detector
- Electron neutrino appearance and muon neutrino disappearance
- Flux model, incl. beam monitor and hadron production (NA61-SHINE)
- Cross section models
- Detector models for Near and Far Detector
- Error correlation matrix
- Oscillations Parameters

J. Wolcott

ν_μ and $\bar{\nu}_\mu$ disappearance at the NOvA Far Detector





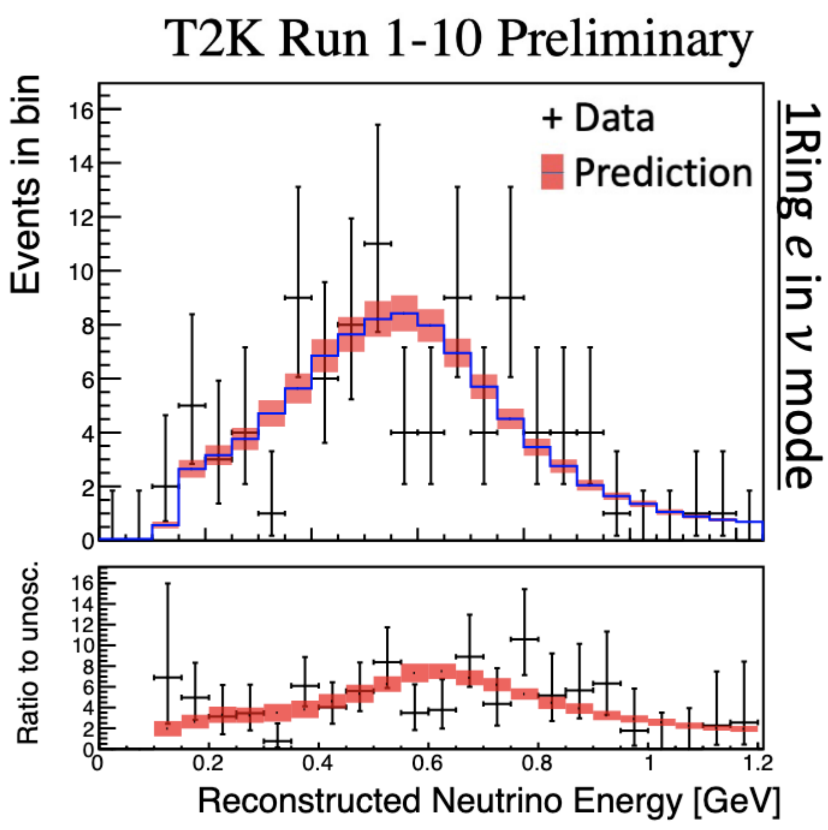
211 events, 8.2 background

105 events, 2.1 background

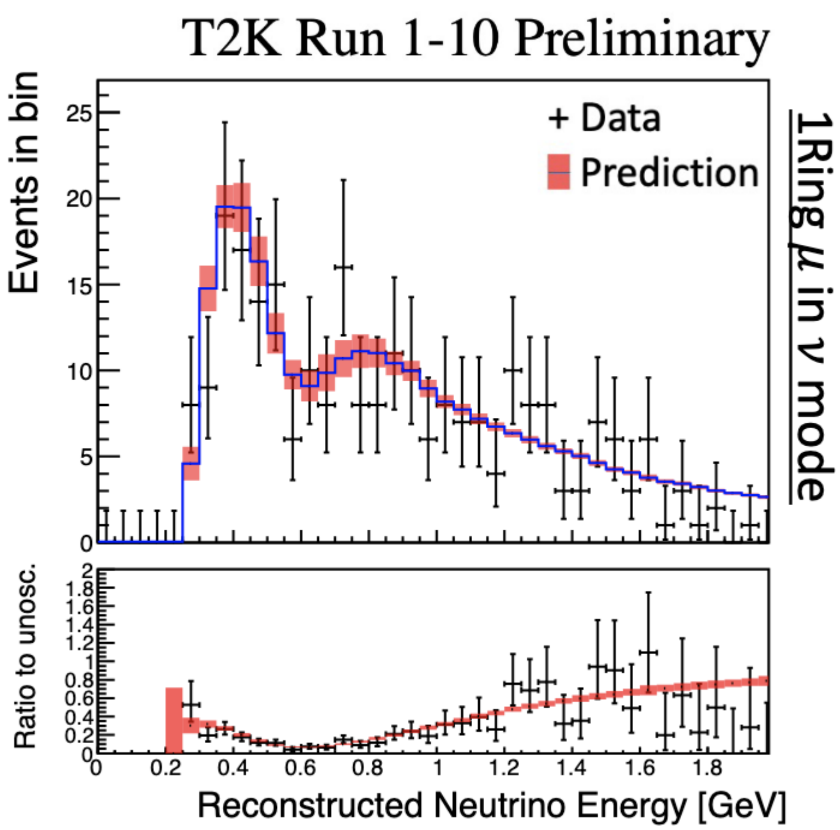
Alex Himmel, Neutrino 2020

Oscillation Samples in T2K Far Detector (SK)

Electron



Muon



<u>Five oscillation samples:</u>

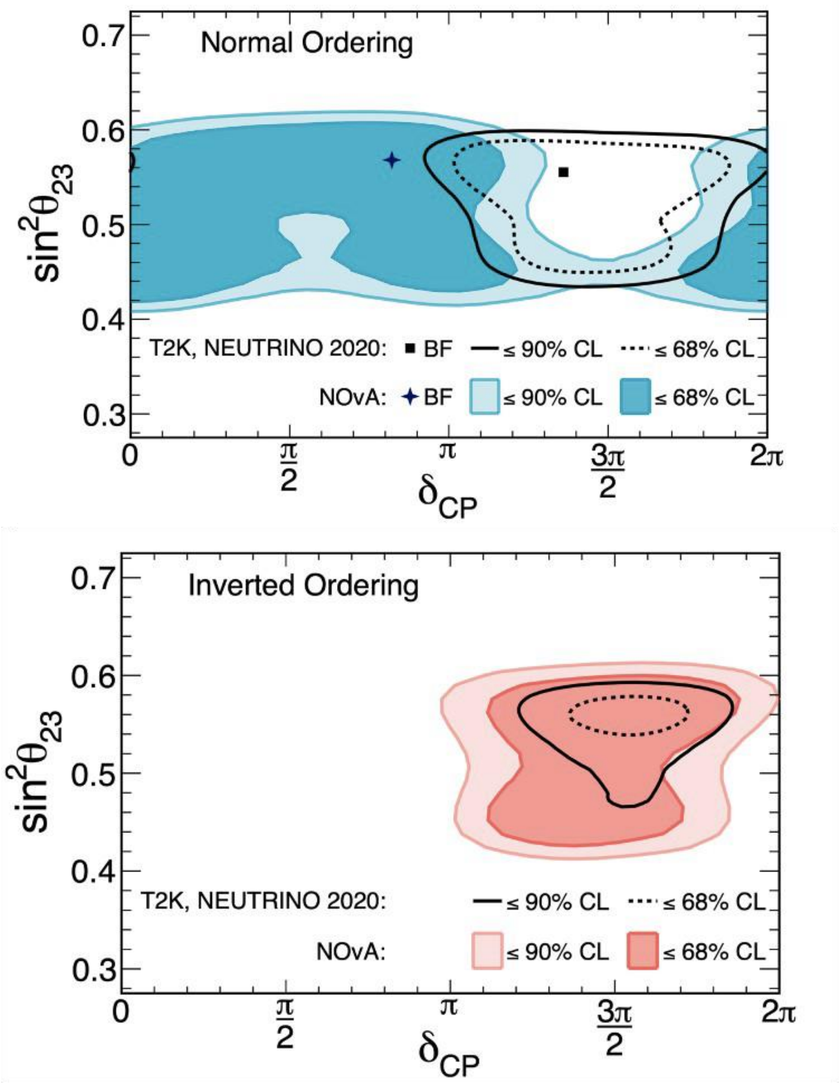
- 1 μ-like ring in ν and $\bar{\nu}$ modes
- 1 e-like ring in ν and $\bar{\nu}$ modes
- 1 e-like ring + Michel electron ring in ν mode

NOvA and T2K

- Hints for CP violation at 2-3 sigma but results results do not uniquely point towards a well-defined value

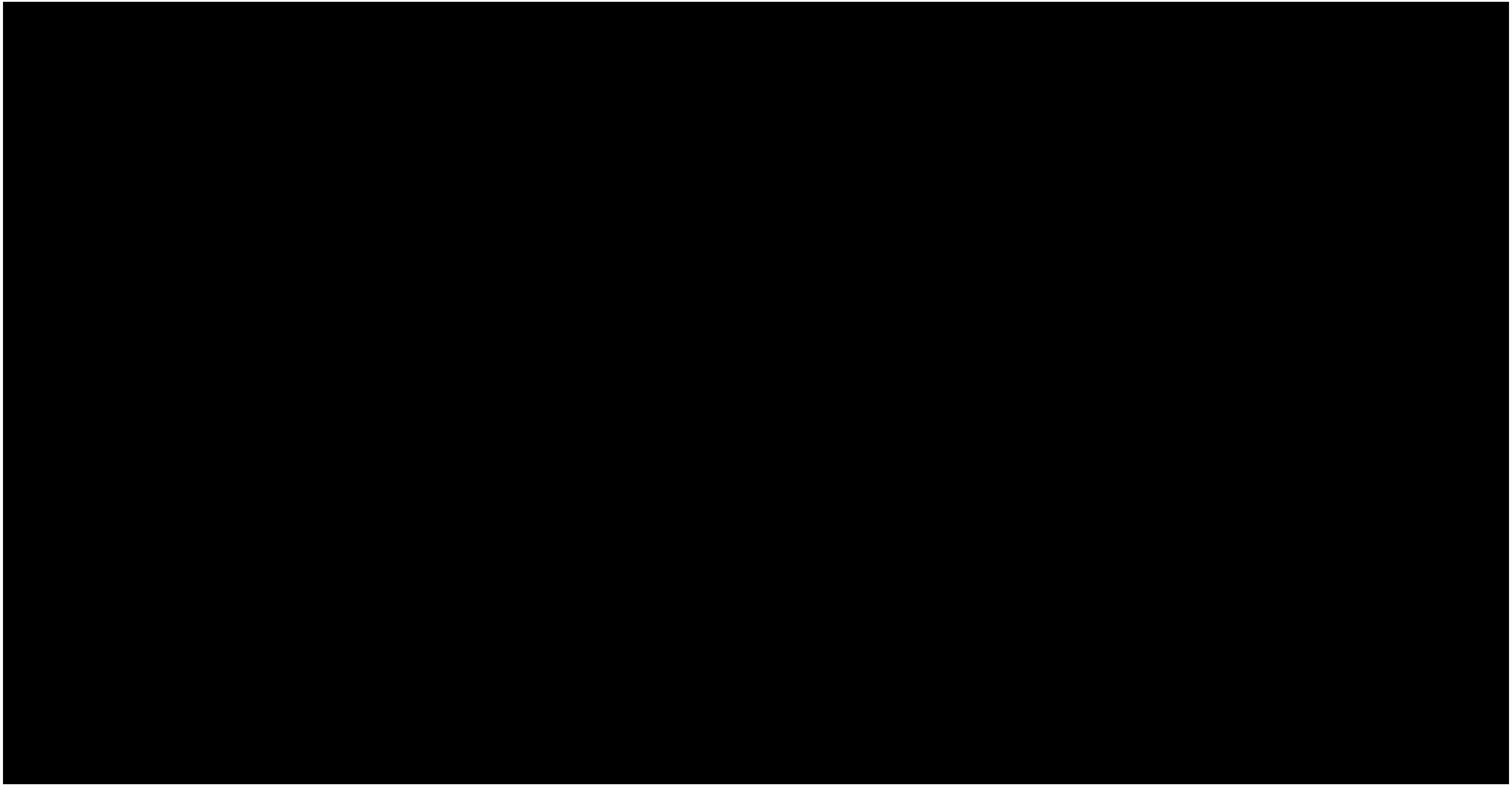
- Weak preference for Normal Ordering but current data are inconclusive.

- Need next-generation experiments to discover CPV and resolve mass ordering.



Lecture 2

- Future long-baseline experiments
- Liquid-argon detectors
- DUNE and Hyper-Kamiokande
- Sterile neutrinos at short-baselines
- Supernova neutrinos



Optimizing L/E for neutrino oscillations

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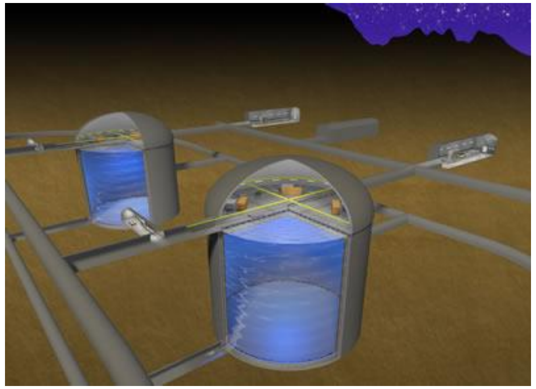
L ≈ 300 km

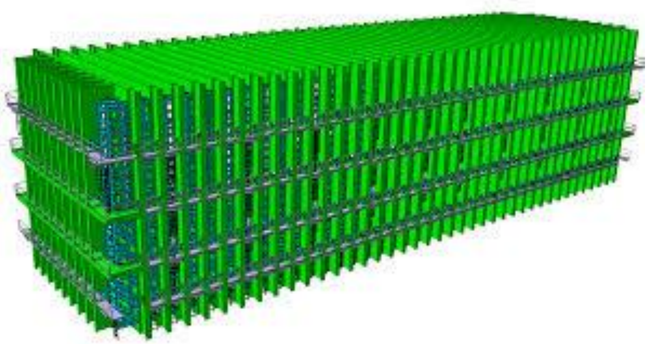
- L/E = 300 km /0.6 GeV = 500 km/GeV
- no matter effects; first oscillation maximum.
- use narrow width neutrino beam (off axis) with E < 1 GeV
- benefit from large mass



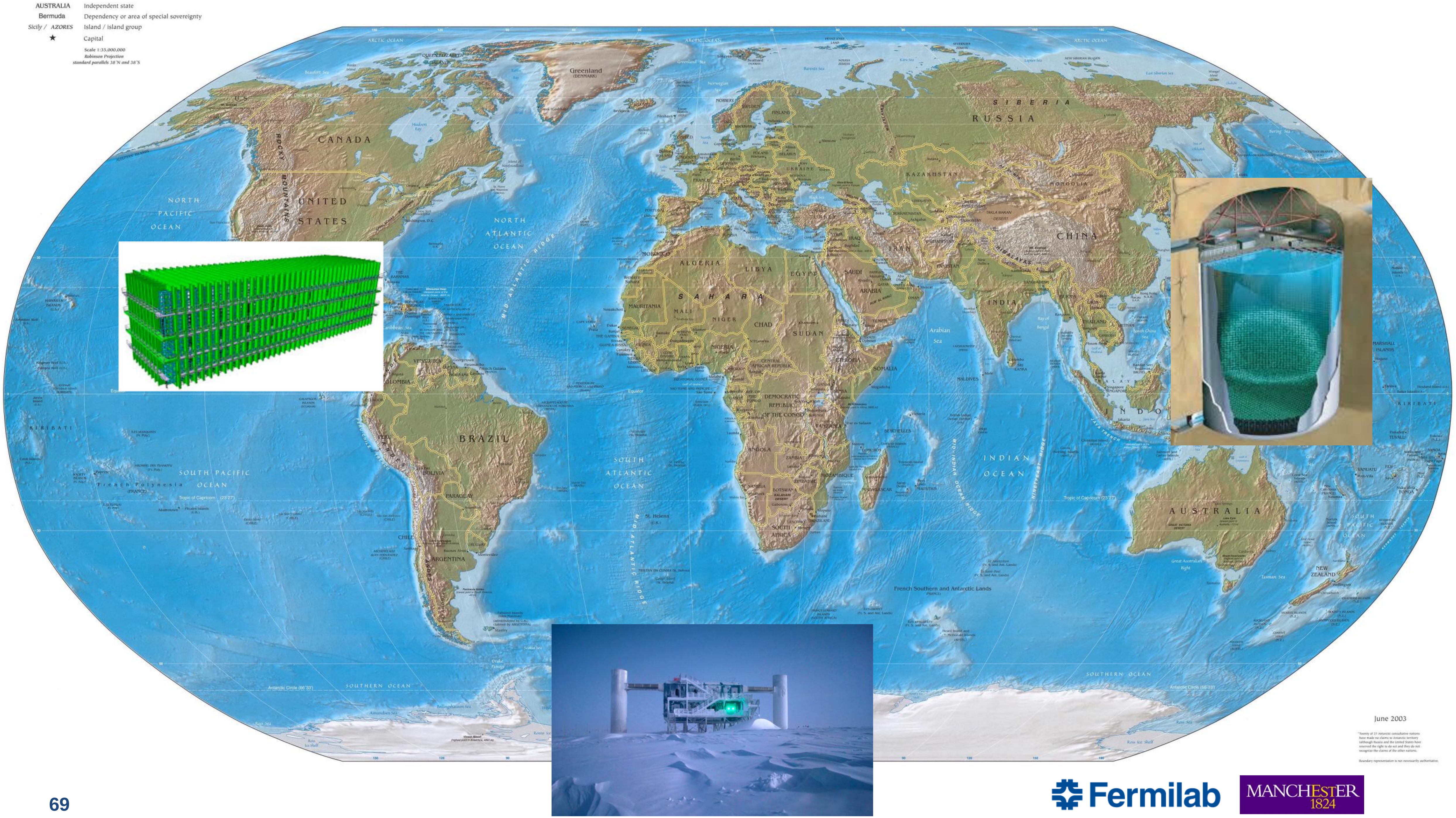
Water Cherenkov (HK)

L = 1300 km

- L/E = 1300 km/2.5 GeV = 500 km/GeV (1st max),
- L/E = 1300 km/0.8 GeV = 1700 km/GeV (2nd max)
- matter effects; first and second oscillation maximum.
- use broad-band neutrino beam (on axis).
- need good energy reconstruction



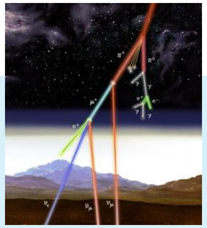
Liquid argon (DUNE)

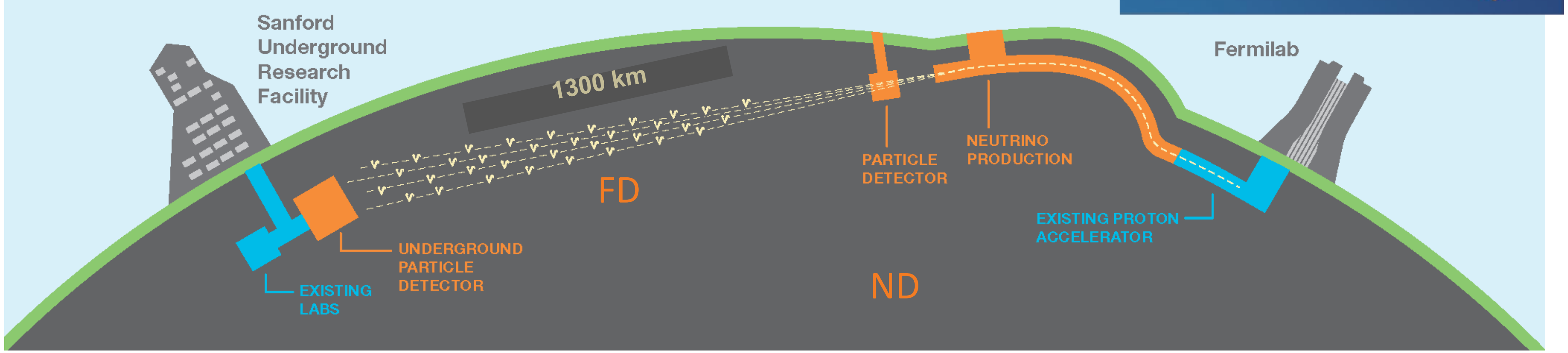


Fermilab MANCHESTER 1824

DUNE in a Nutshell



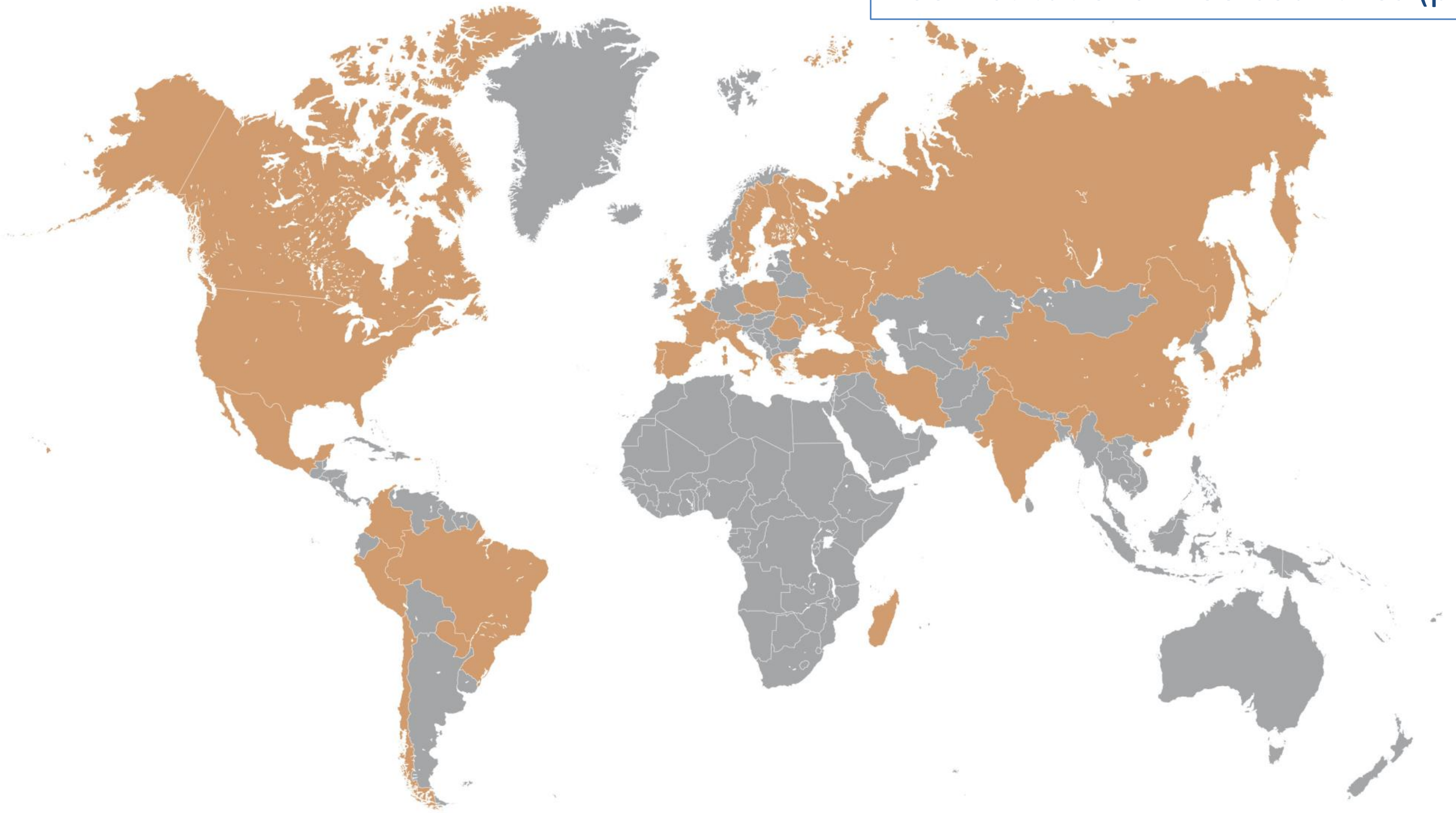




1. A high-power, wide-band **neutrino beam** (~ GeV energy range).
2. A ≈ 70 kt **liquid-argon Far Detector** in South Dakota, located 1478 m underground in a former gold mine.
3. A **Near Detector** located approximately 575 m from the neutrino source at Fermilab close to Chicago.

DUNE – a global collaboration

1317 collaborators from
208 institutions in 33 countries (plus CERN)



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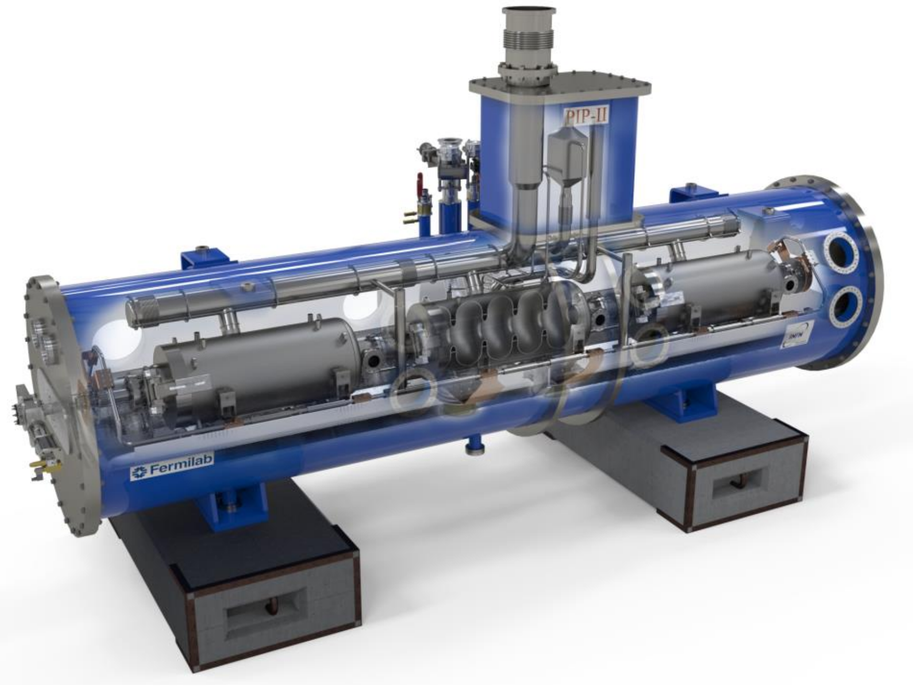
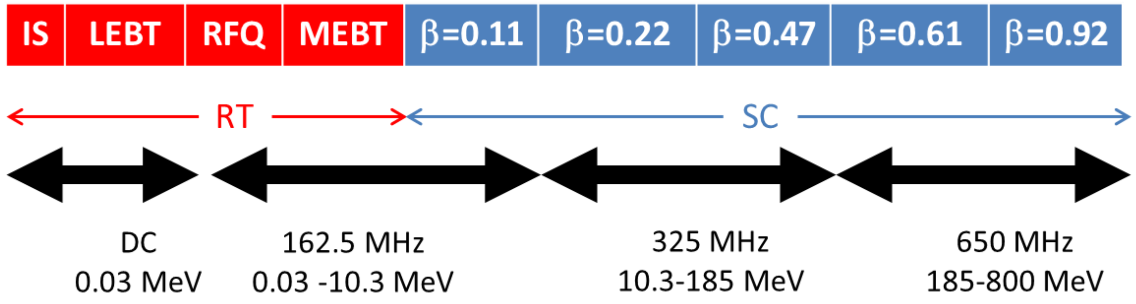
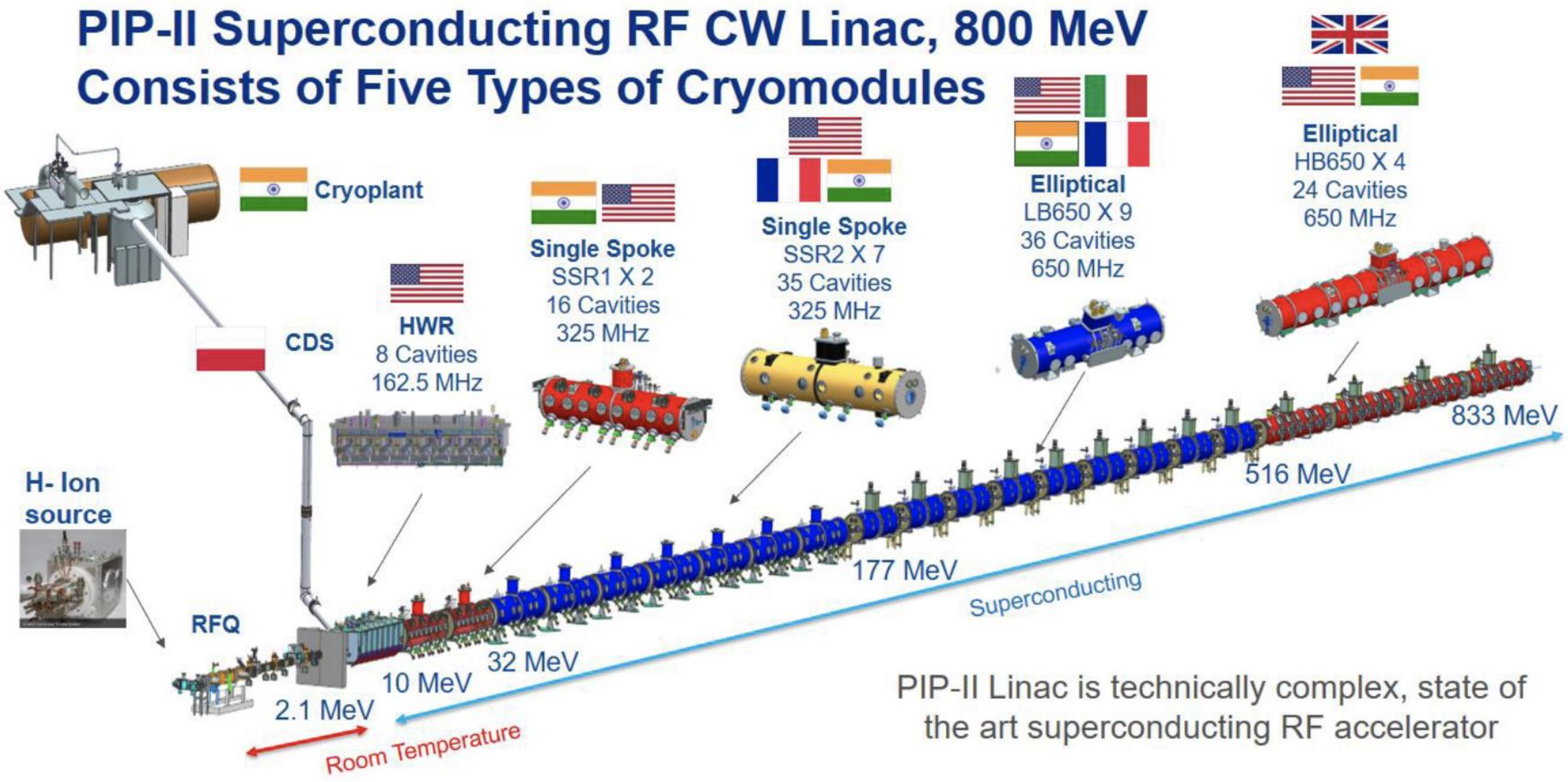
Proton Improvement Plan (PIP-II)

- Goal: Deliver world-leading beam power to the DUNE/LBNF neutrino programme while providing a flexible platform for the future
  - 1.2 MW to LBNF over 60-120 GeV;
  - upgradable to 2.4 MW
- Scope
  - 800-MeV SC Linac
  - Modifications to Booster, Recycler, Main Injector
- Broad international effort





Proton Improvement Plan (PIP-II)



Proton Improvement Plan (PIP-II)

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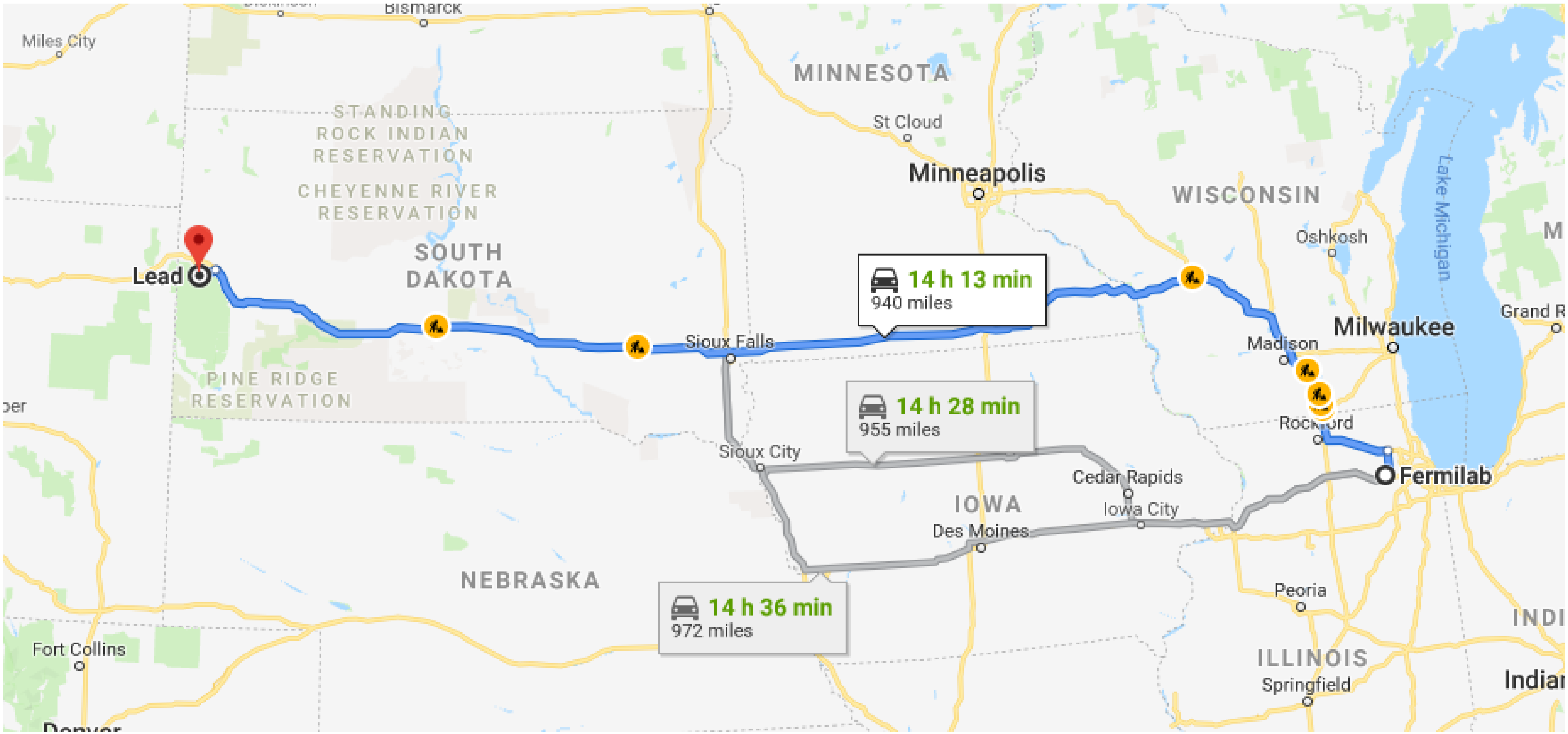
L/E = 500 km/GeV ⇒ L = 1300 km



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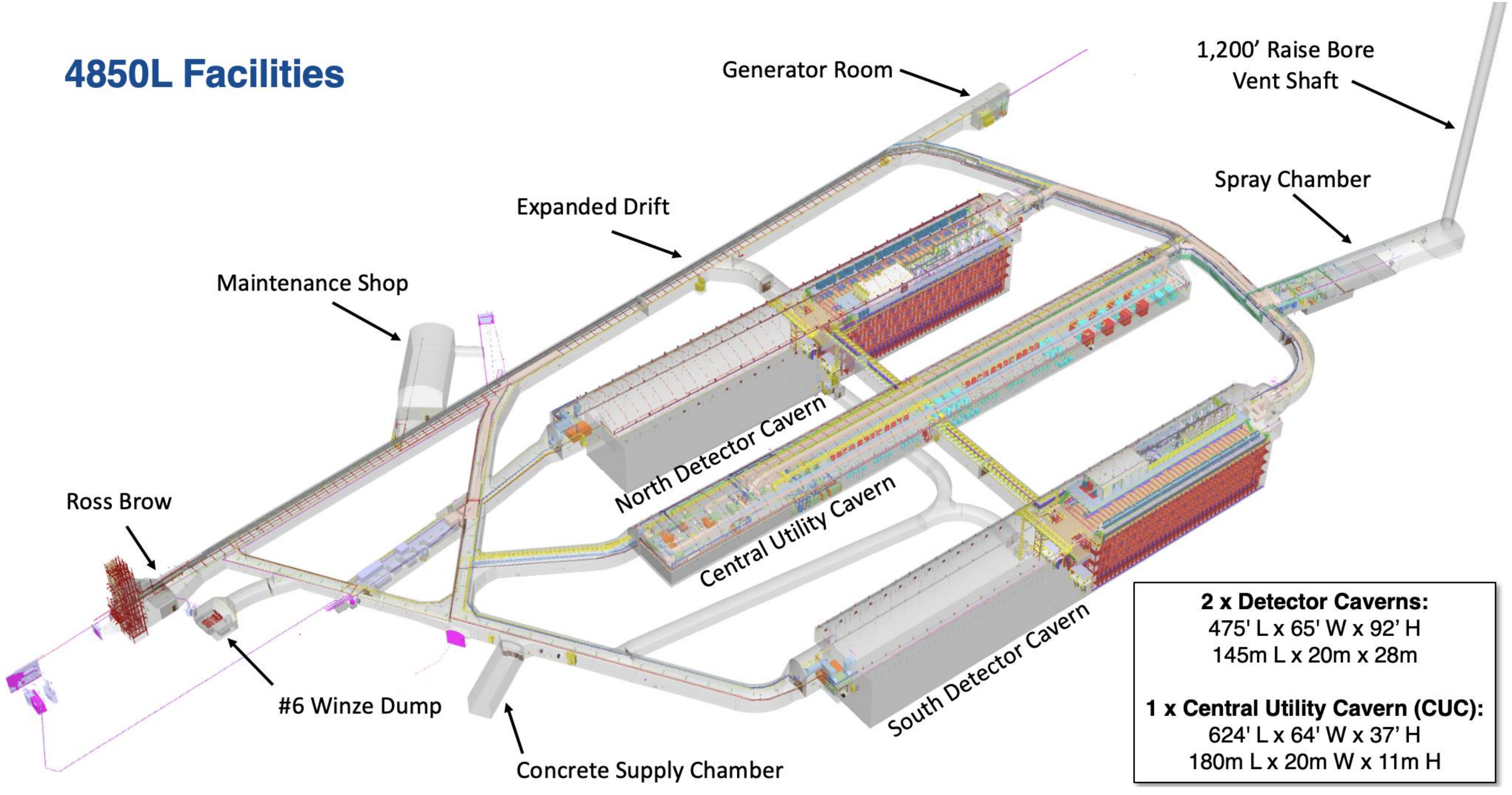
4850L Facilities



2 x Detector Caverns:
475' L x 65' W x 92' H
145m L x 20m x 28m

1 x Central Utility Cavern (CUC):
624' L x 64' W x 37' H
180m L x 20m W x 11m H

DUNE Cavern at South Dakota – 75% excavated

Sanford Underground Research Facility (SURF)

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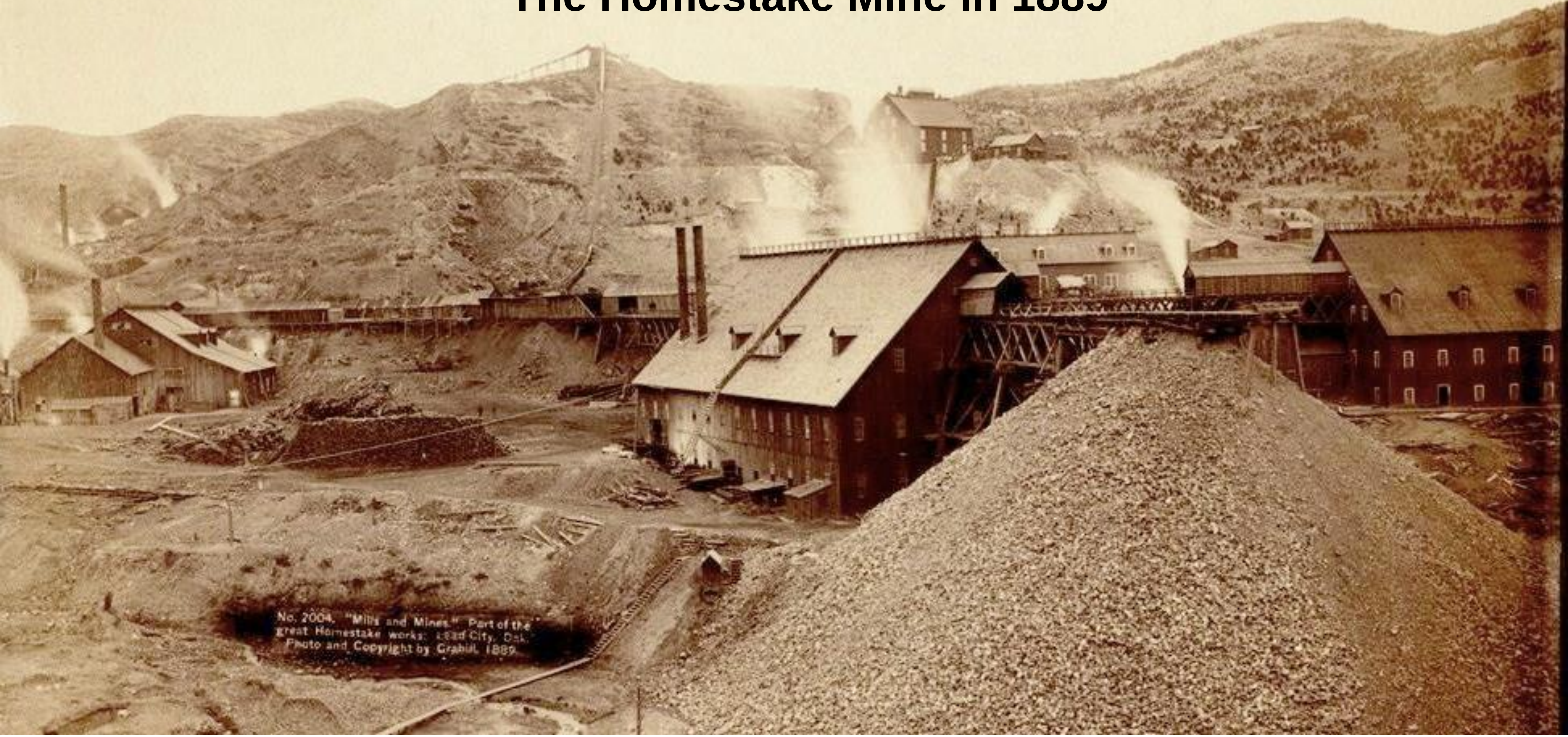
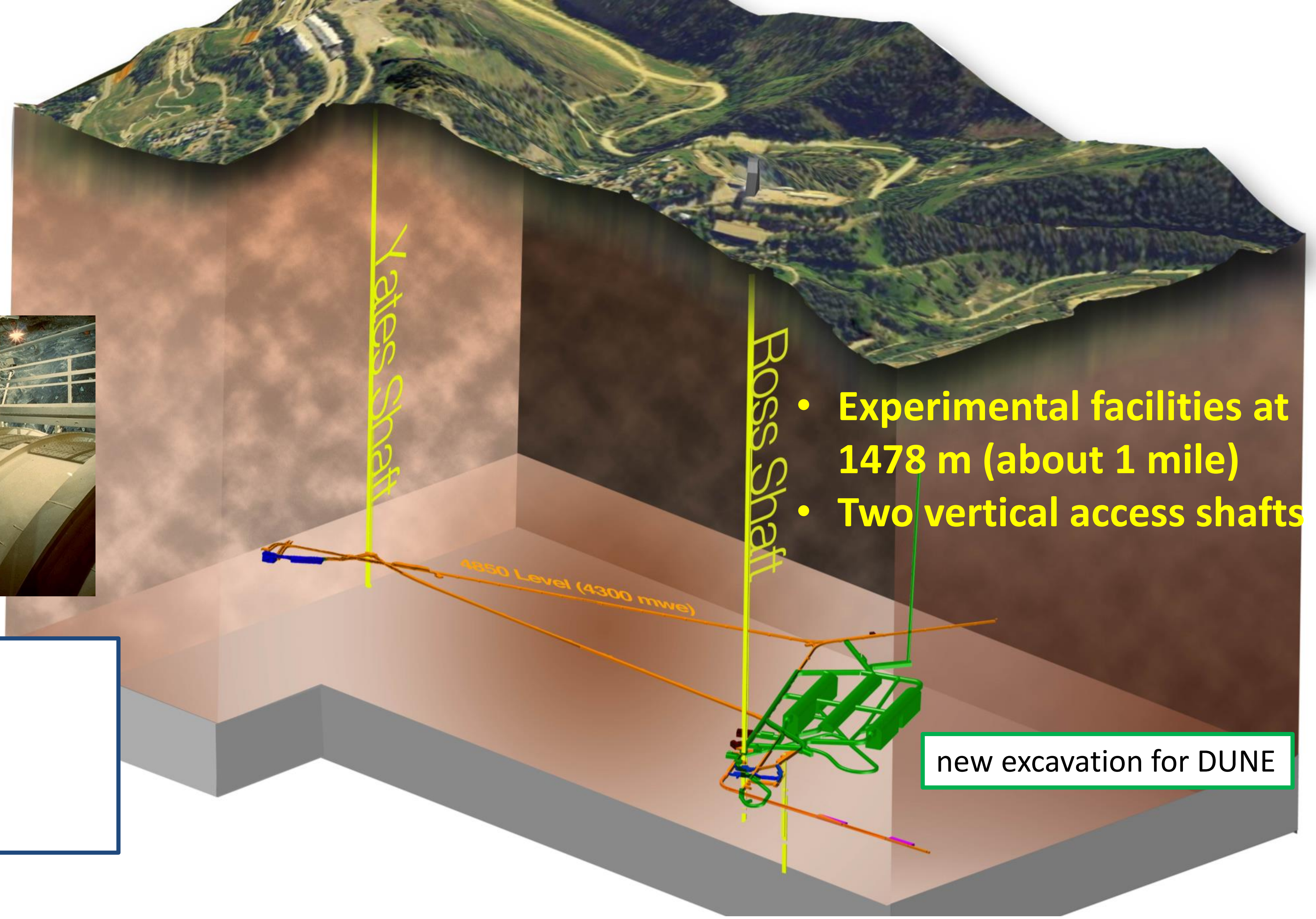
The Homestake Mine in 1889

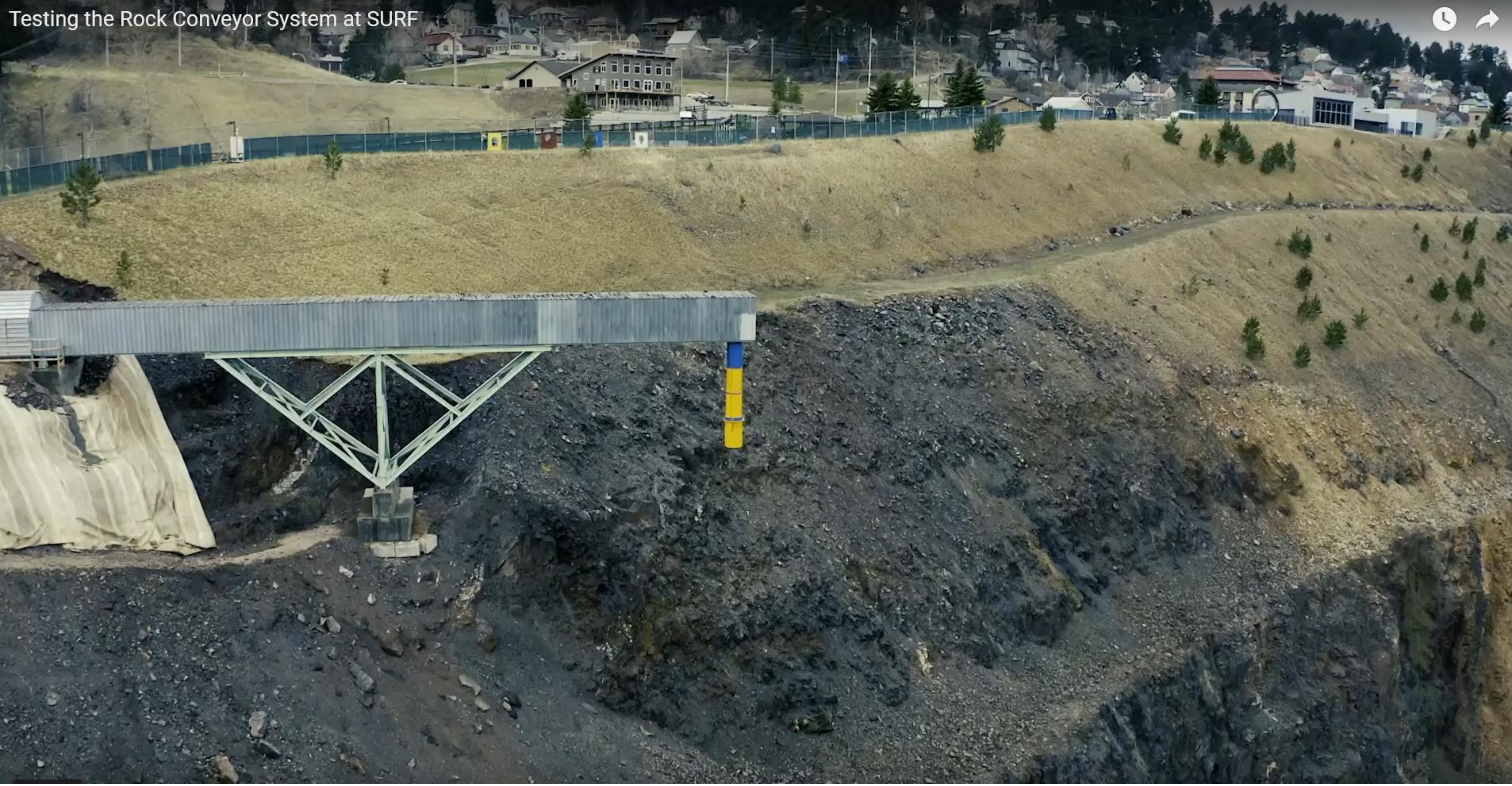




- **Experimental facilities at 1478 m (about 1 mile)**
- **Two vertical access shafts**

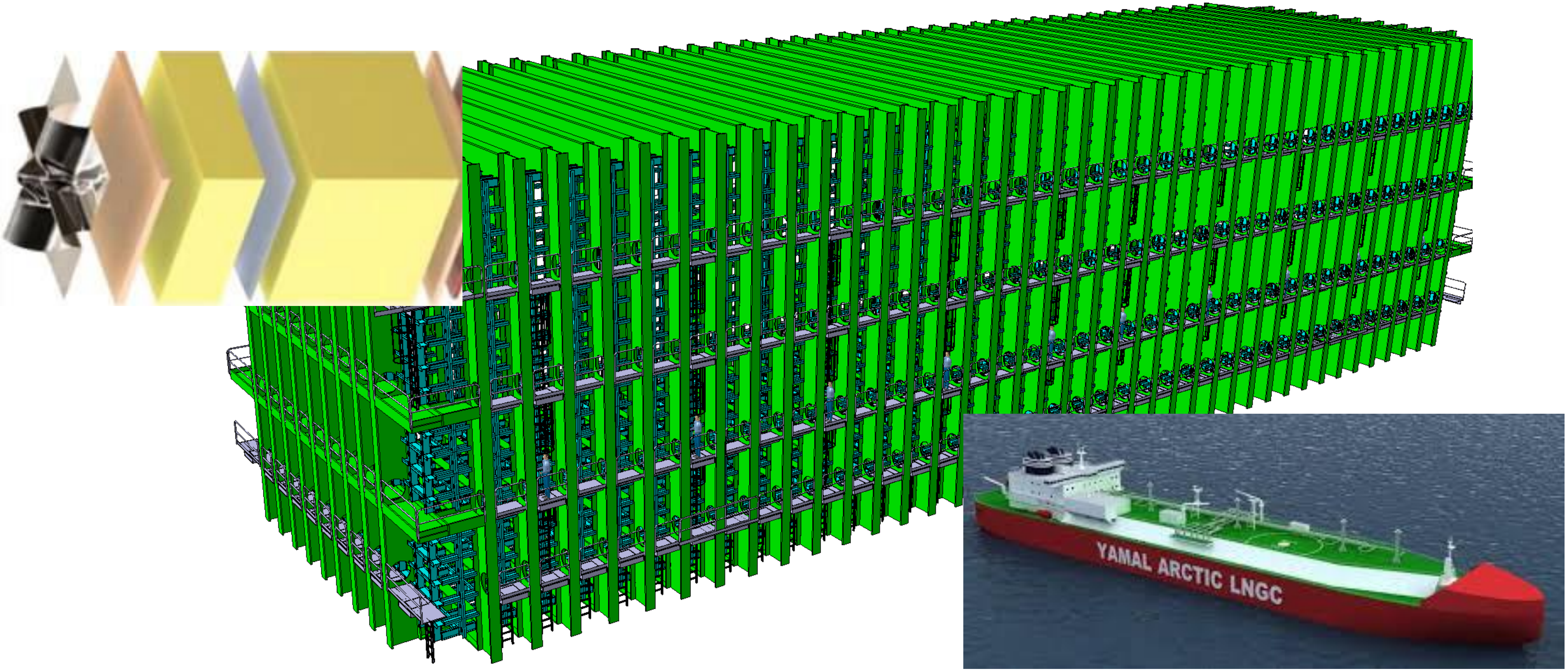
new excavation for DUNE

Davis Campus:
- LUX
- Majorana
- …
- LZ

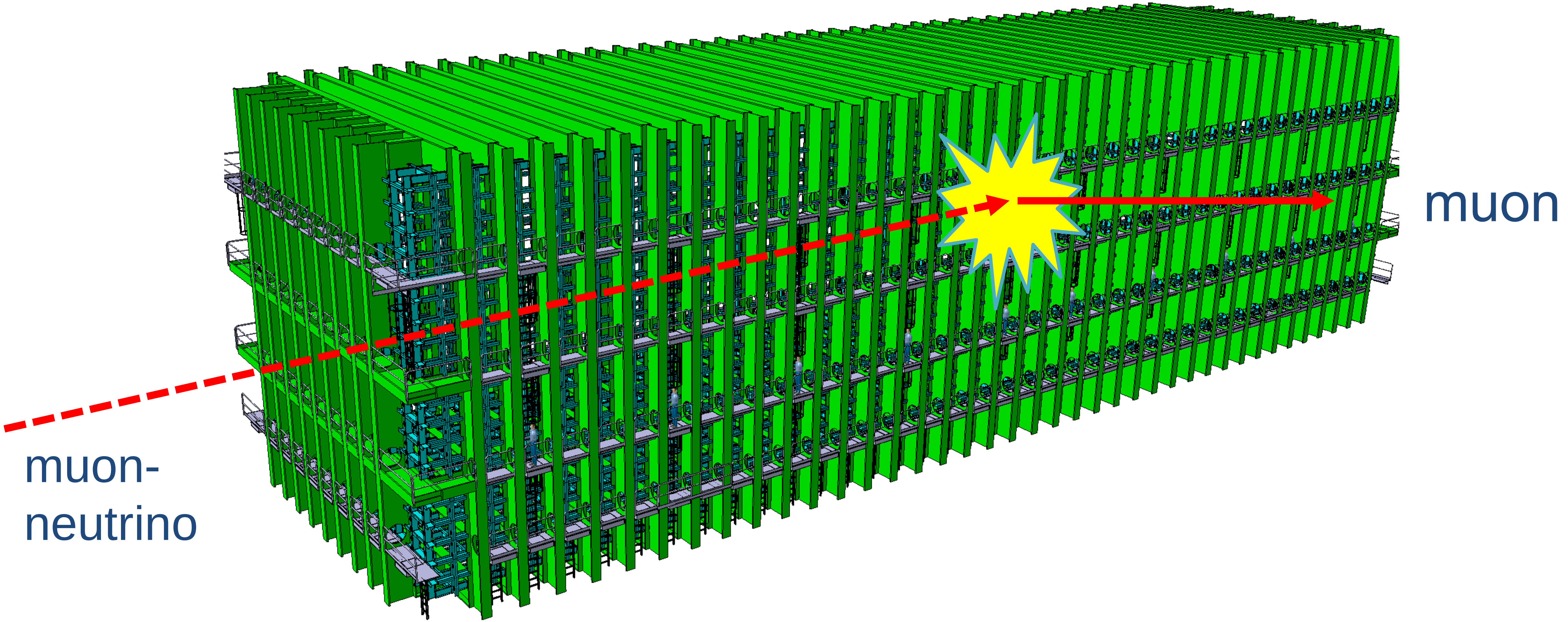

Testing the Rock Conveyor System at SURF

Four cryostats filled with liquid argon

Each of the four cryostats contains 17,000 tons of liquid argon at 89 K (-184°C or -299°F)



External Dimensions: 19 m x 18 m x 66 m



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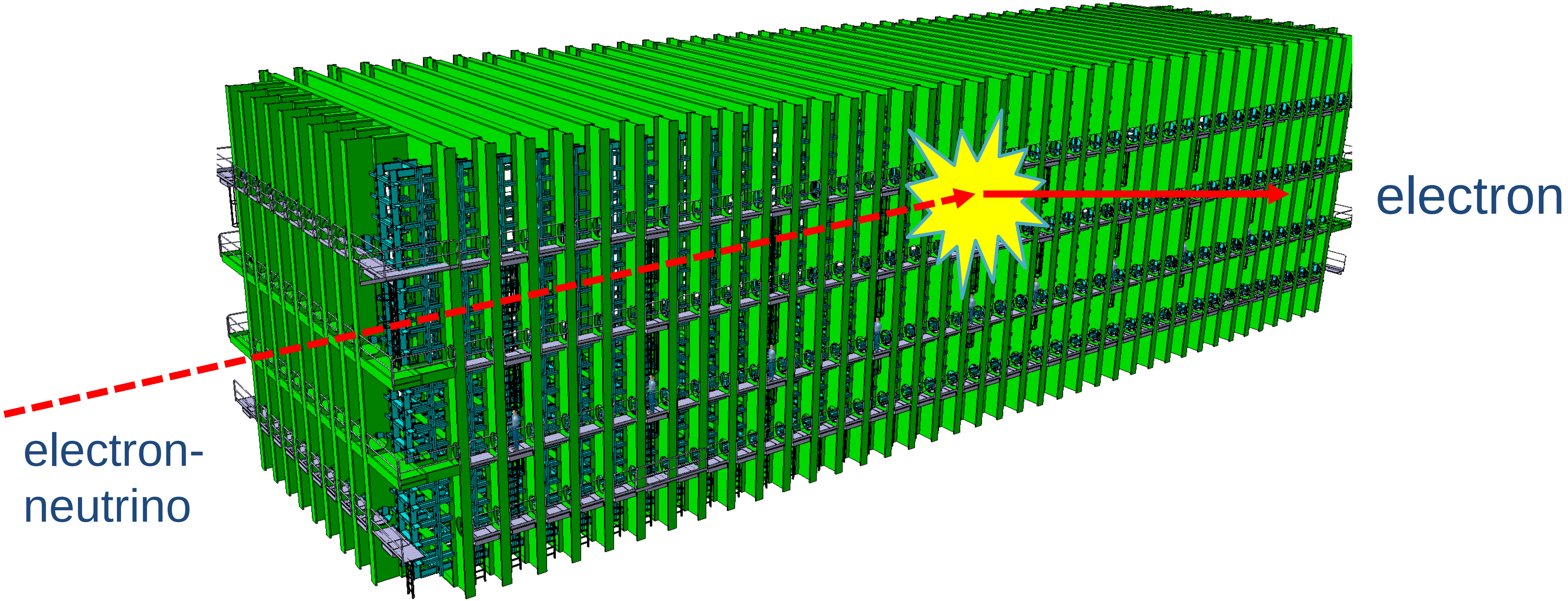

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Some history

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

EP Internal Report 77-8
16 May 1977

THE LIQUID-ARGON TIME PROJECTION CHAMBER:

A NEW CONCEPT FOR NEUTRINO DETECTORS

C. Rubbia

ABSTRACT

It appears possible to realize a Liquid-Argon Time Projection Chamber (LAPC) which gives an ultimate volume sensitivity of 1 mm^3 and a drift length as long as 30 cm. Purity of the argon is the main technological problem. Preliminary investigations seem to indicate that this would be feasible with simple techniques. In this case a multi-hundred-ton neutrino detector with good vertex detection capabilities could be realized.

G E N E V A

1977

- “Briefly, the idea consists of drifting the whole electron image of an event occurring in the noble liquid towards a collecting multi-electrode array which is capable of reconstructing the three-dimensional image (x,y,z) of the event from the (x,y) information and the drift time (t)".
- "the purity of the Argon is the main technological problem. … electron lifetimes corresponding to residual oxygen impurity content of about 4 x 10^{-2} ppm" are reachable. However, this limits "the electron mean free path to about 30 cm. Clearly, oxygen-free argon is the central problem for the LAr TPC".

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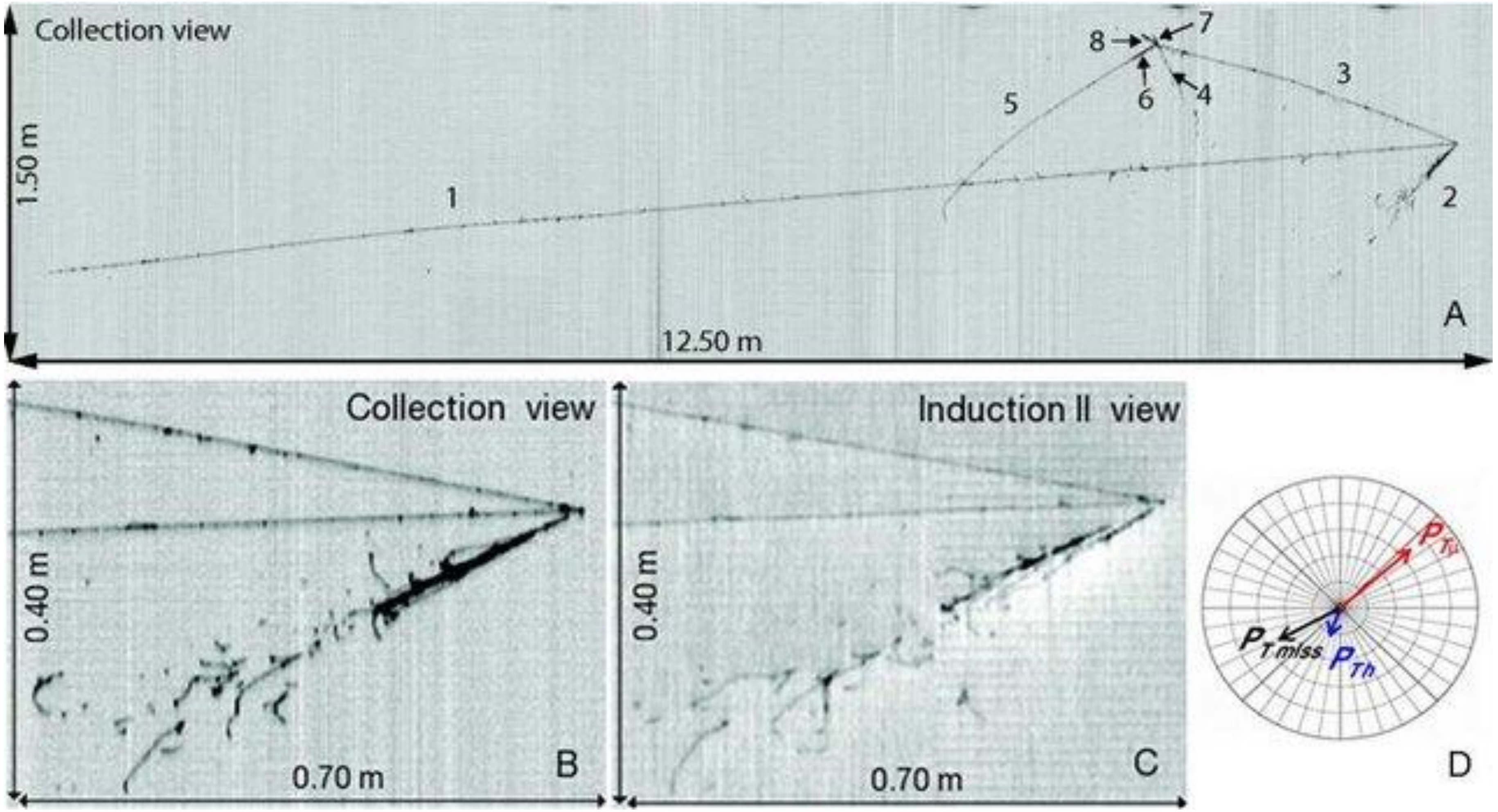
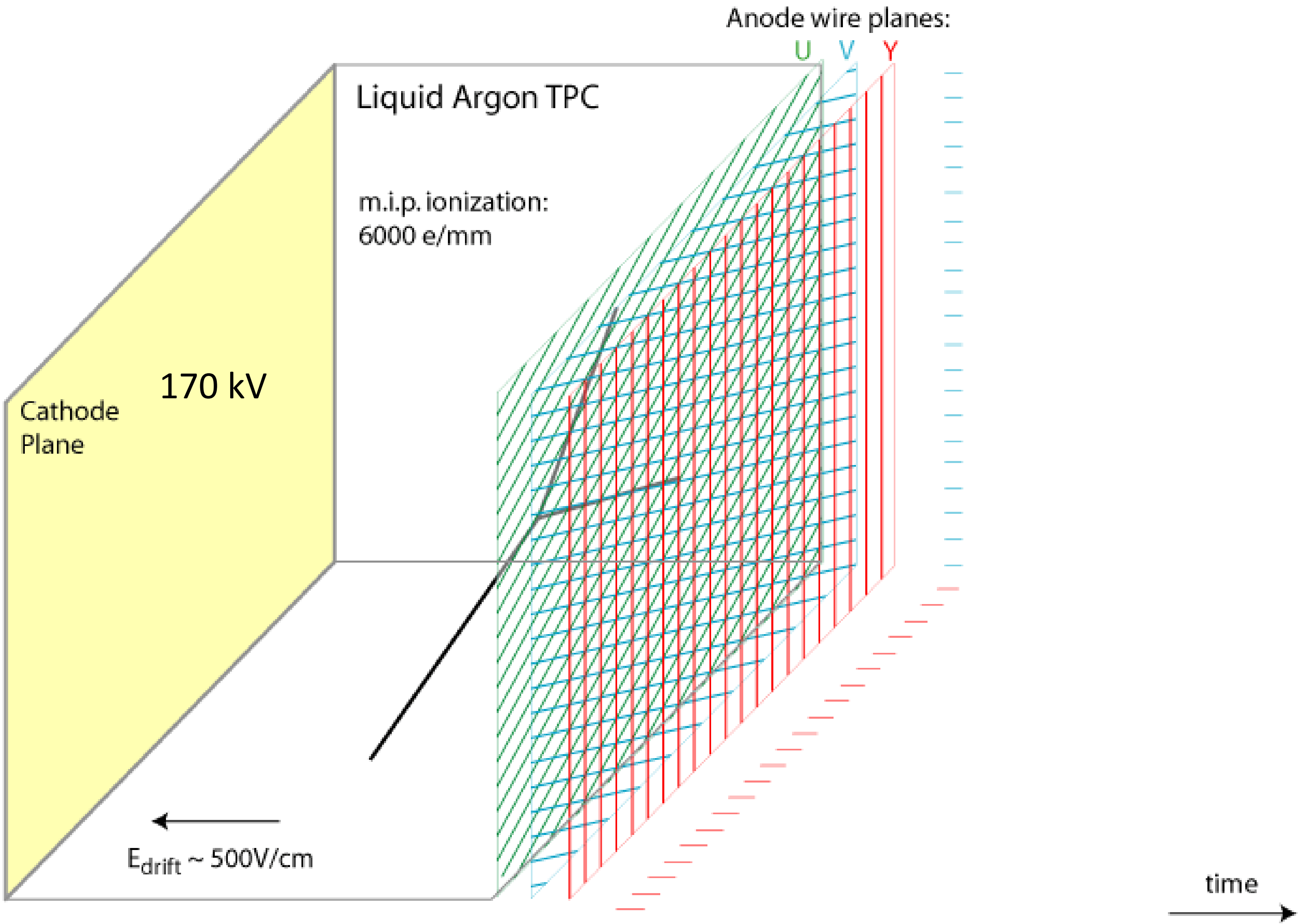
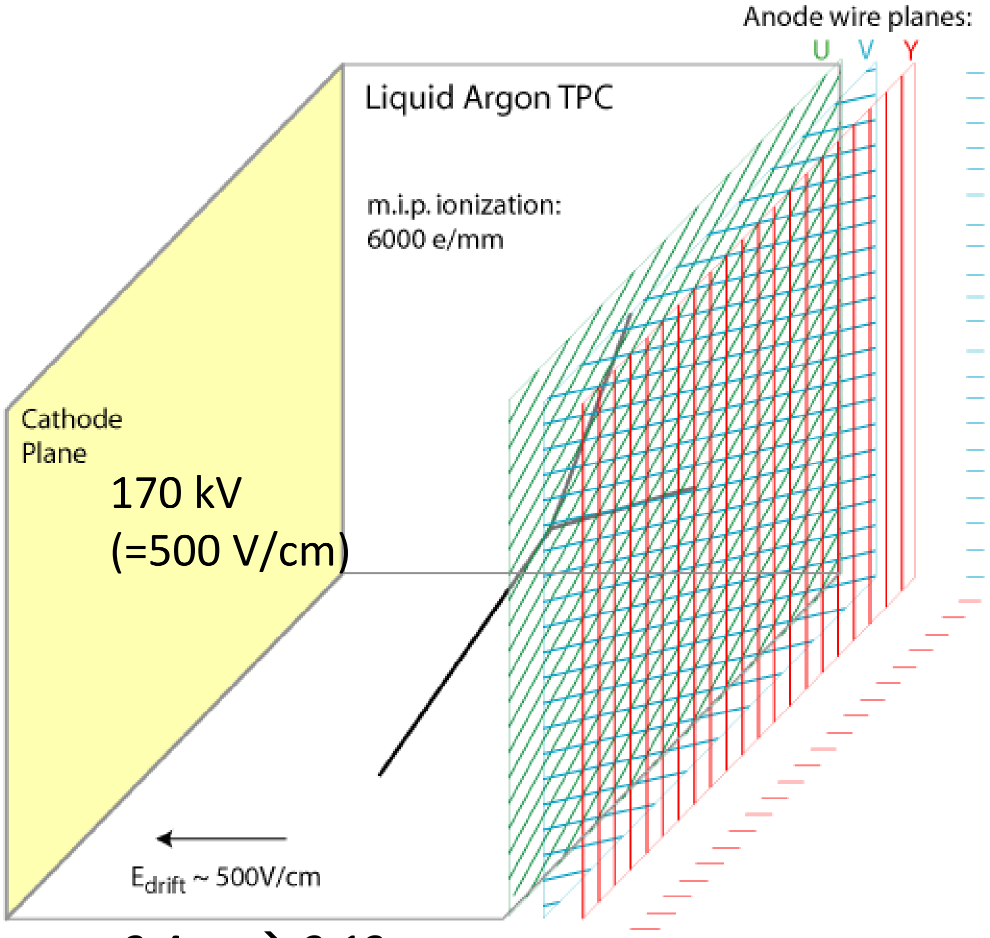
ICARUS (2010-2013)





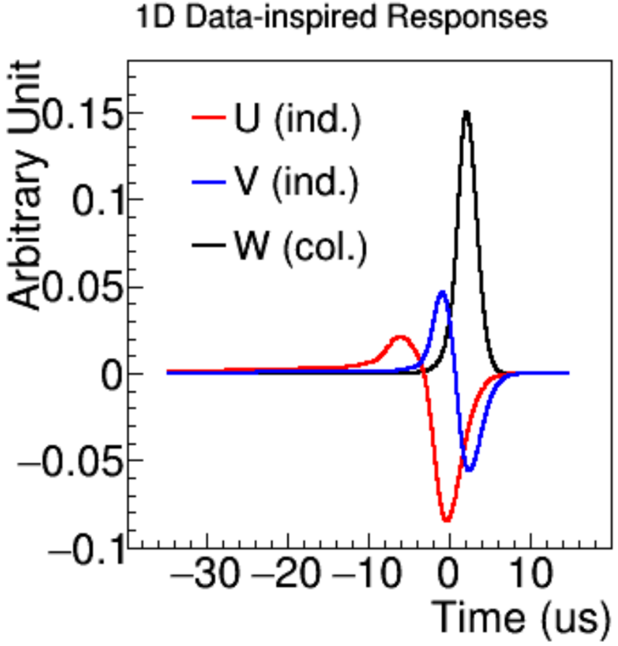
3.4 m → about 2 ms

Wire pitch ≈ 5 mm



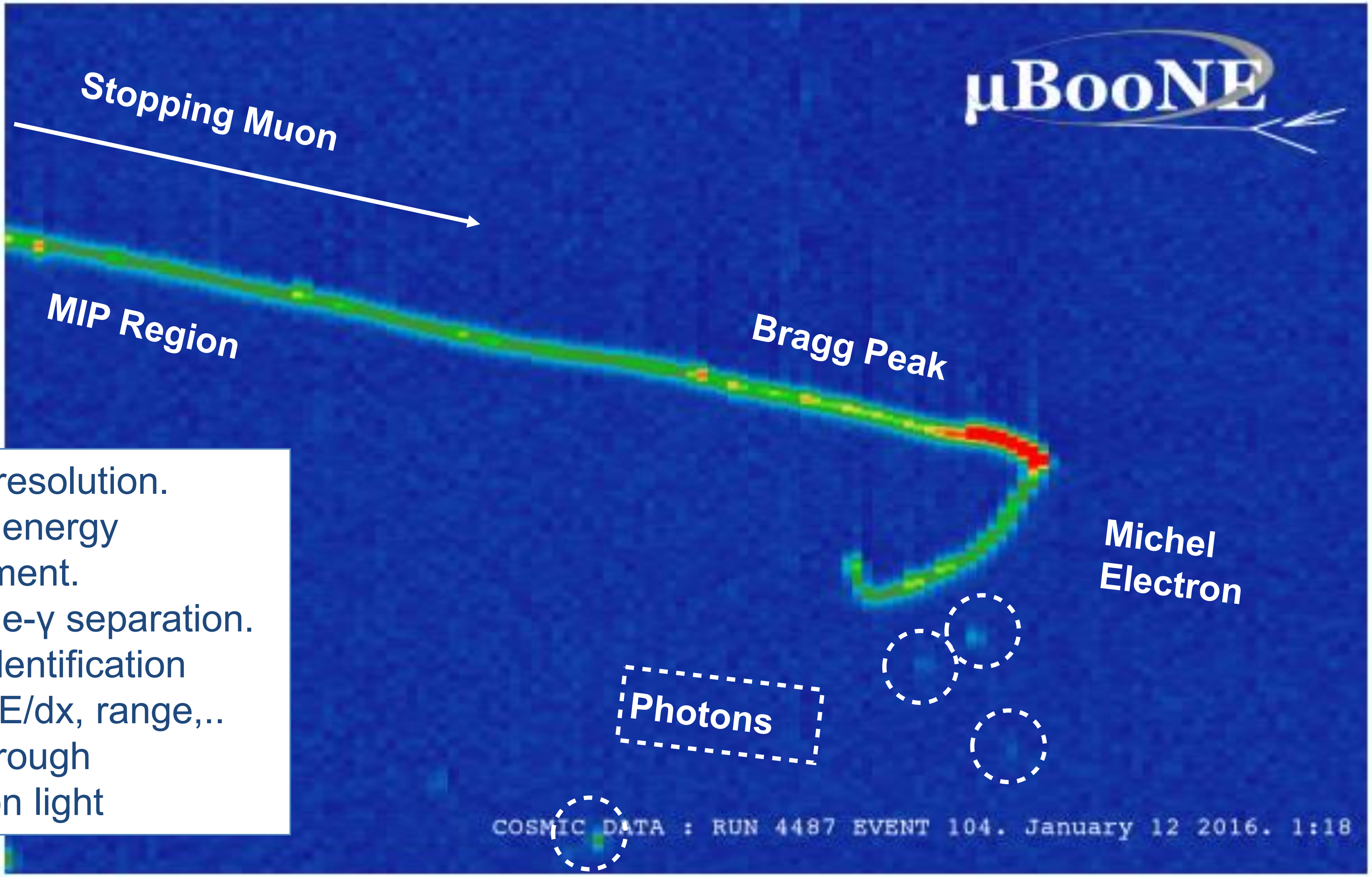
170 kV
(=500 V/cm)

3.4 m → 2.13 ms



time →

A liquid-argon "Bubble Chamber"



- Few mm resolution.
- Excellent energy measurement.
- Excellent e-γ separation.
- Particle identification through dE/dx, range,..
- Timing through scintillation light

This is an image….

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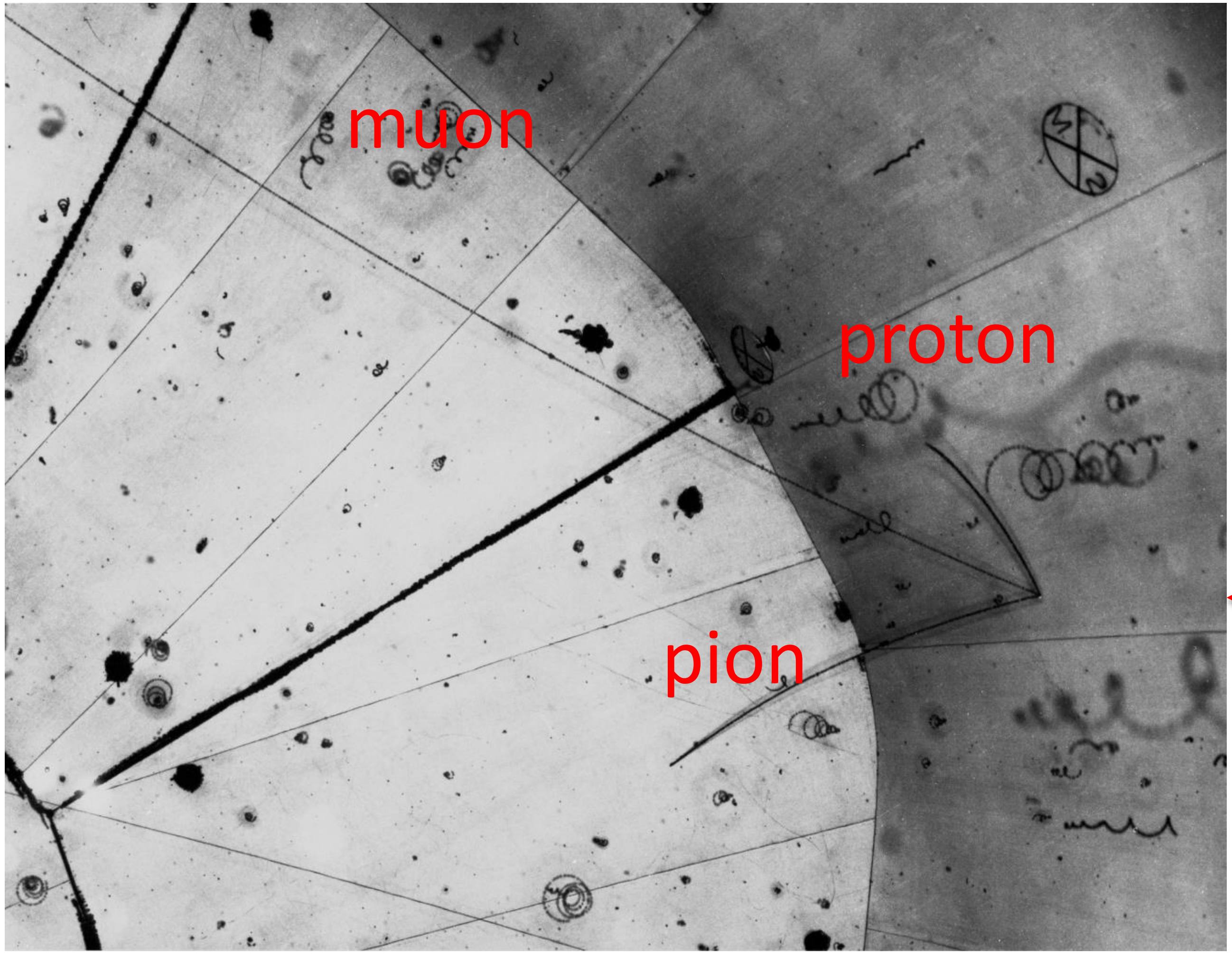
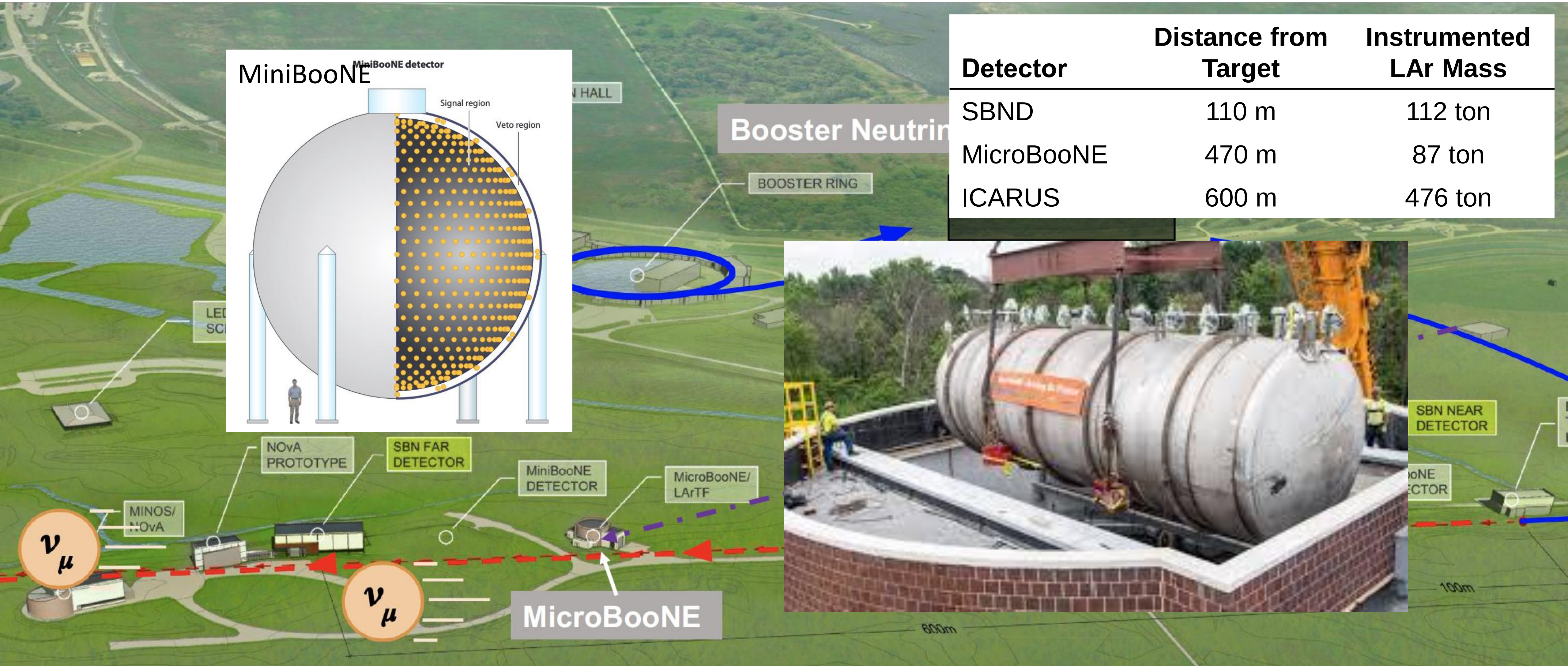
Hydrogen Bubble chamber, Argonne, 1970



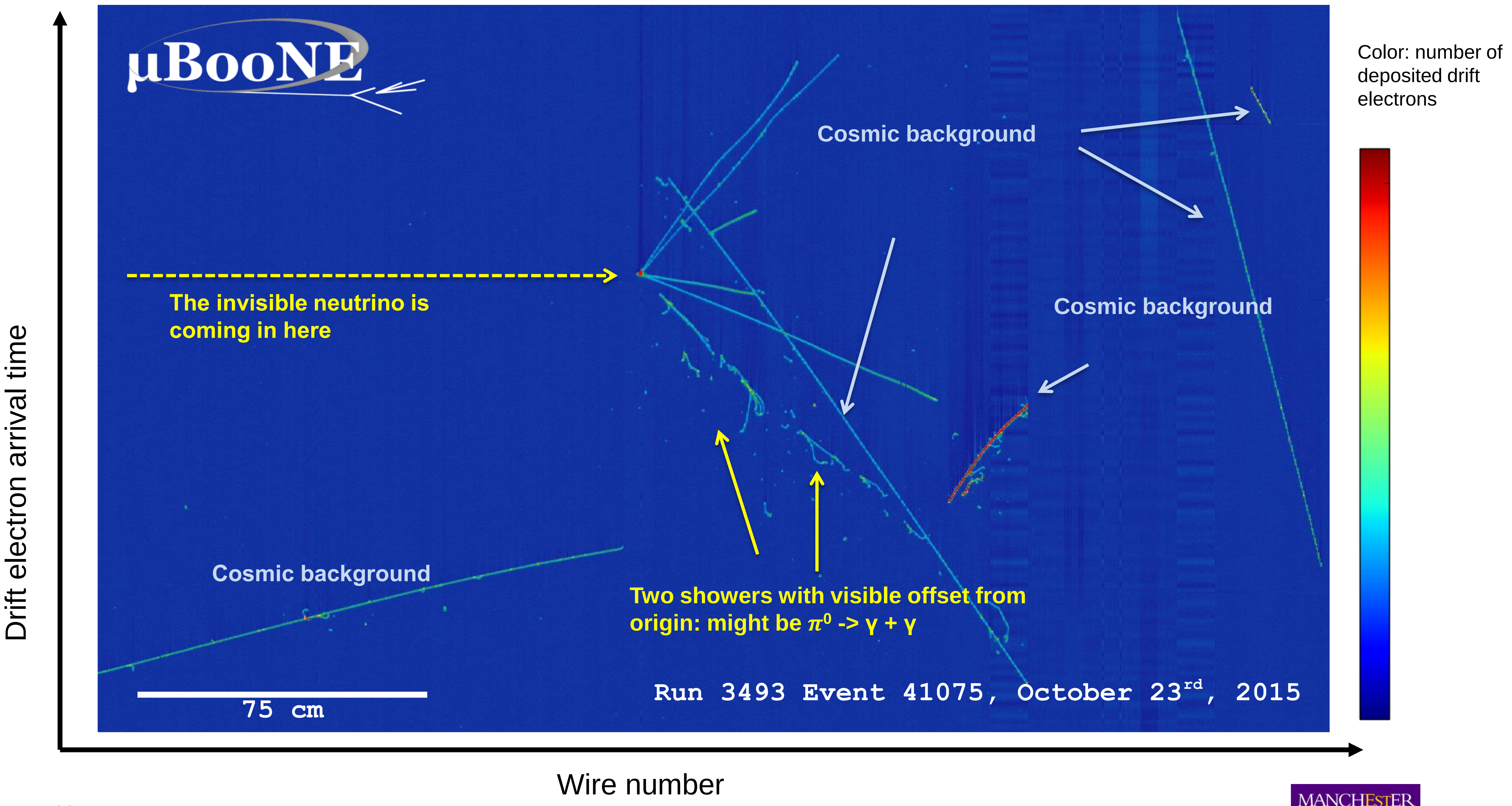
(muon)-neutrino

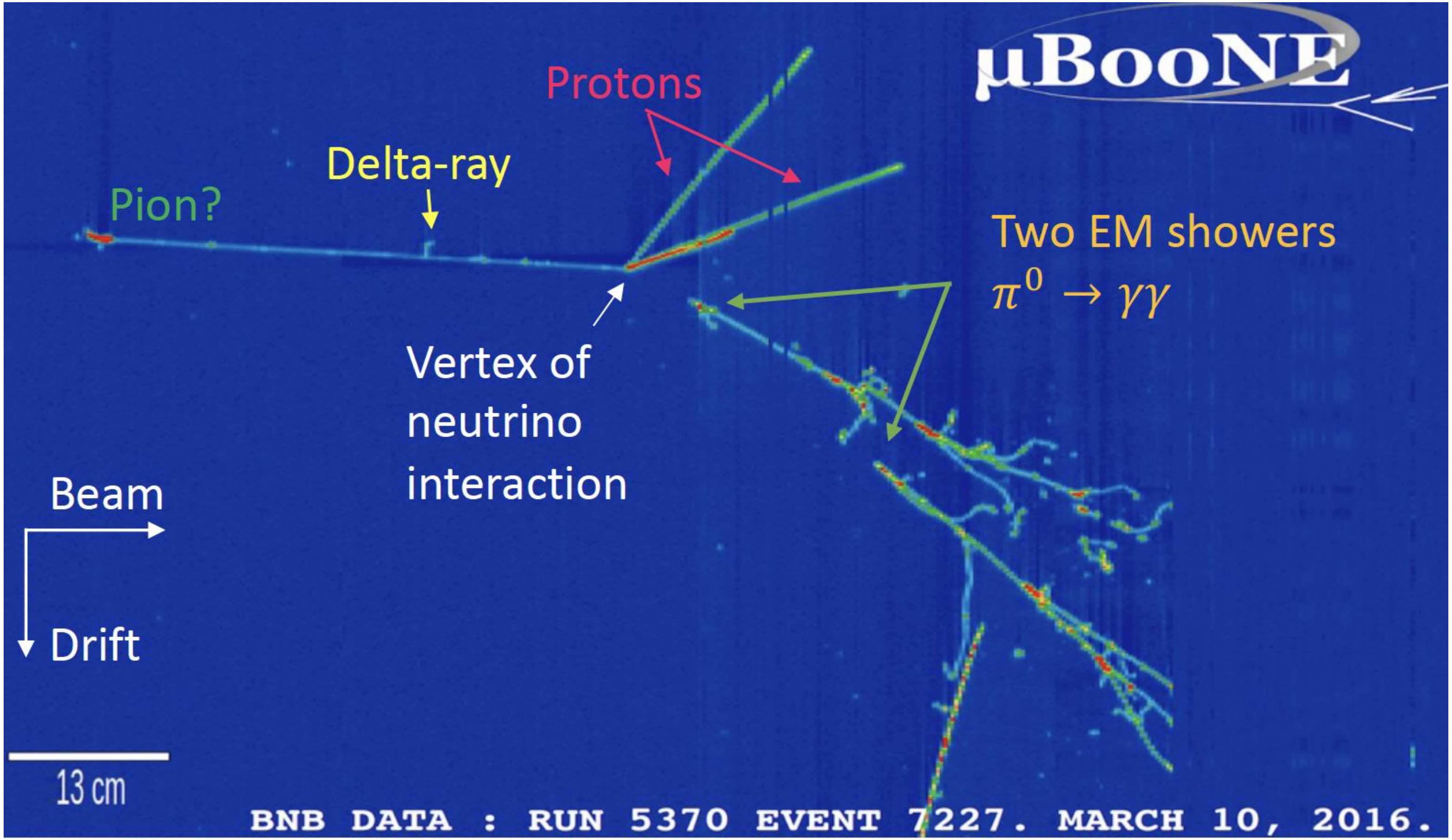
This is a photograph….

Interlude: Fermilab Short-baseline programme



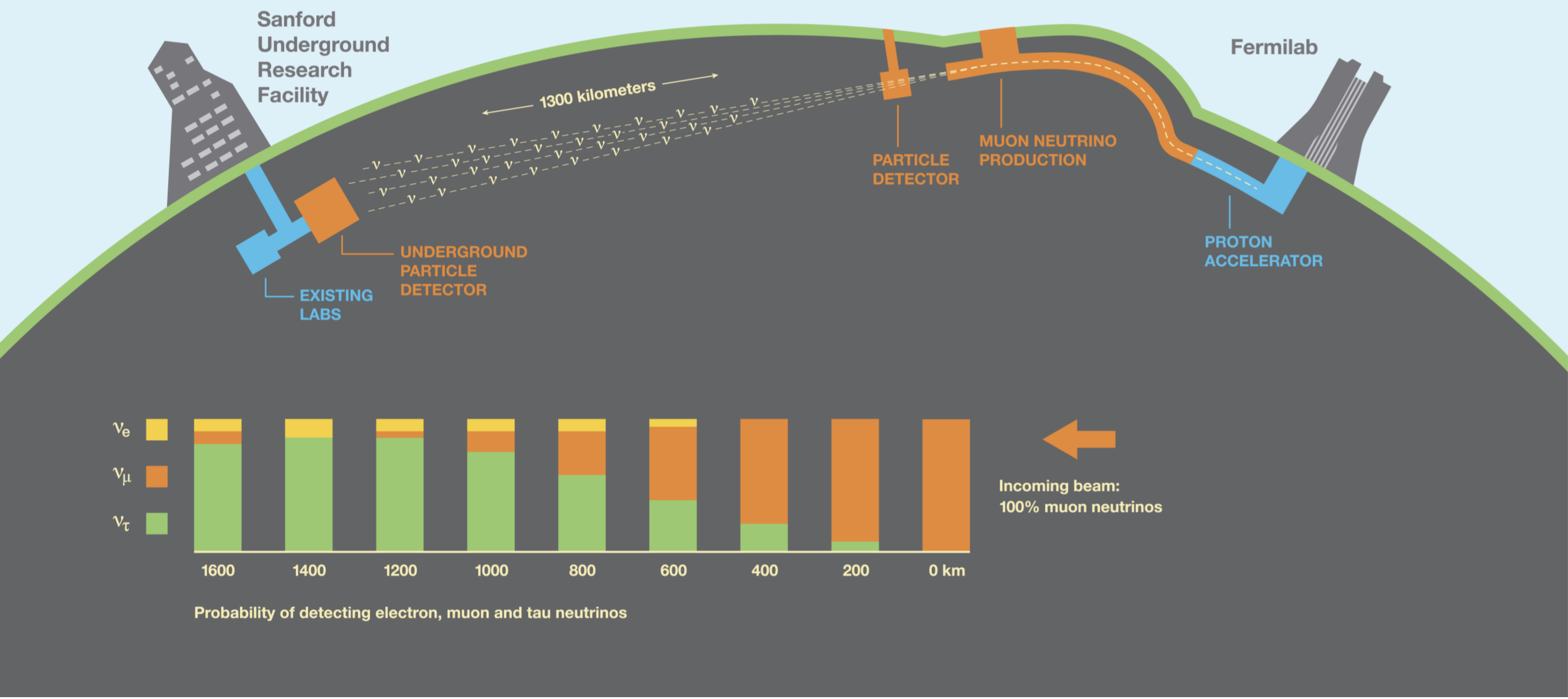
Detector	Distance from Target	Instrumented LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton


μBooNE
Color: number of deposited drift electrons
Cosmic background
The invisible neutrino is coming in here
Cosmic background
Cosmic background
Two showers with visible offset from origin: might be $\pi^0 \rightarrow \gamma + \gamma$
75 cm
Run 3493 Event 41075, October 23rd, 2015
Drift electron arrival time
Wire number

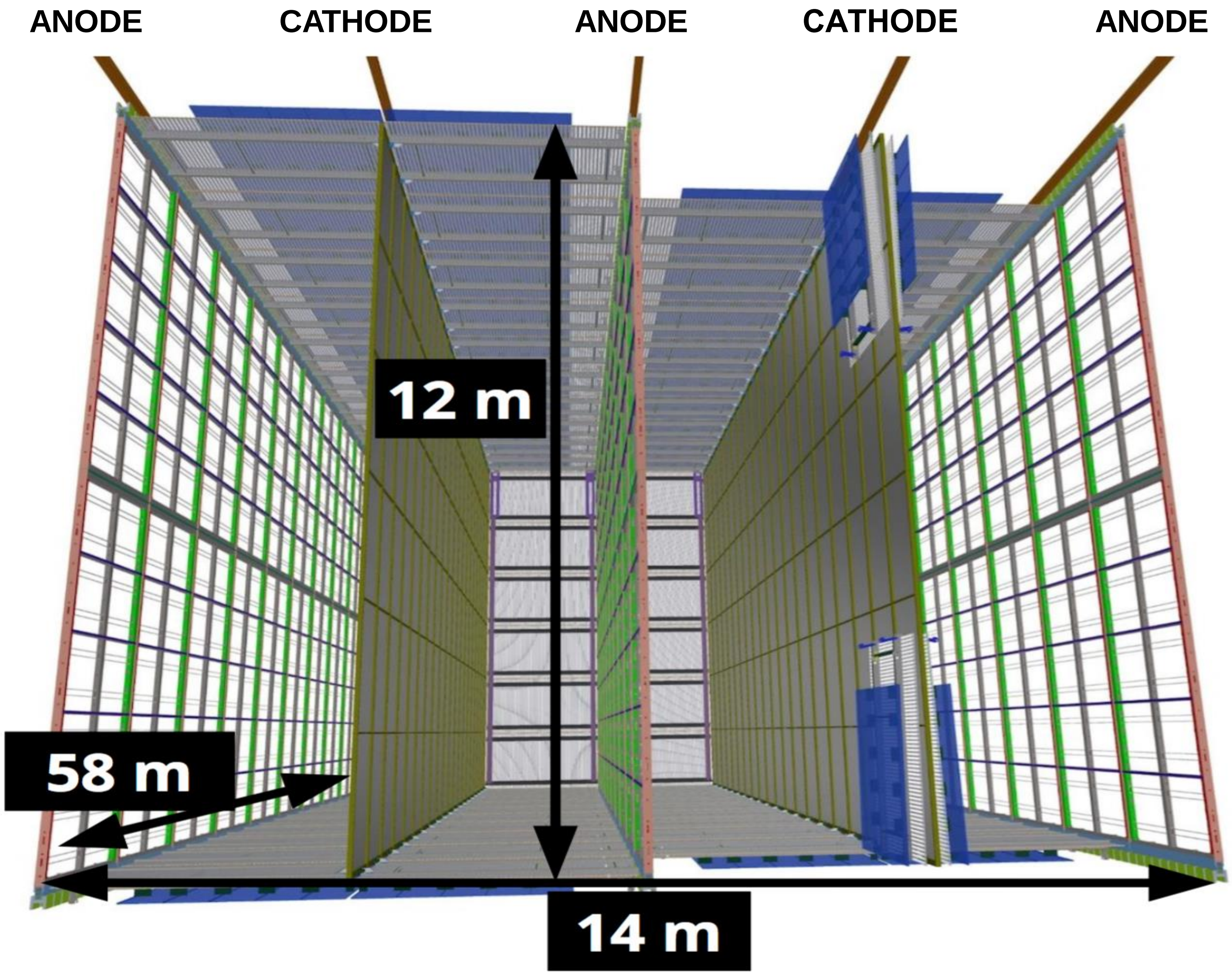


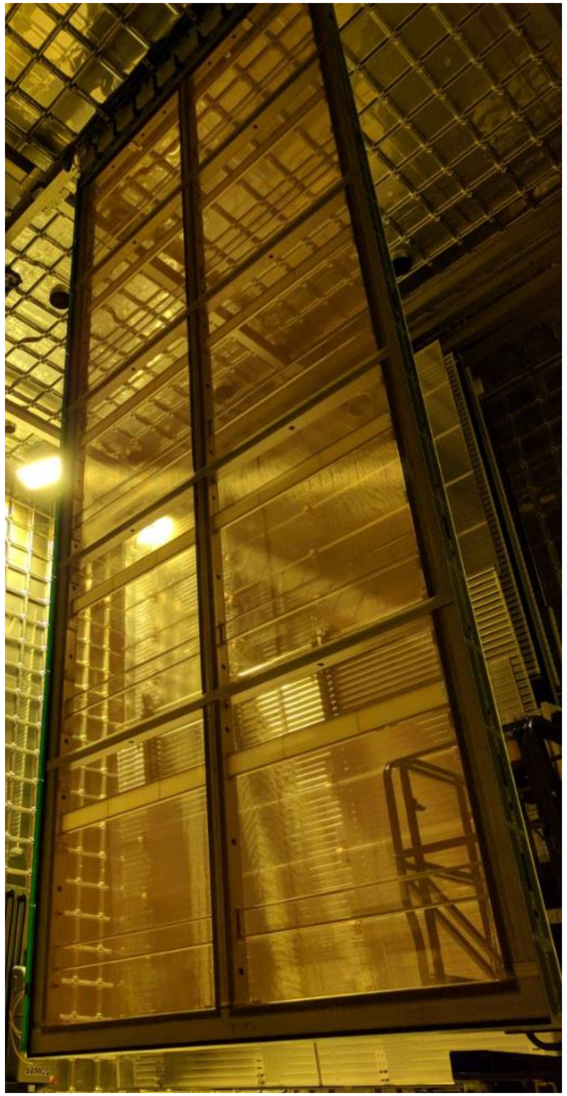
Need state-of-the-art algorithms (e.g., CVNs etc) to reconstruct these events

Deep Underground Neutrino Experiment

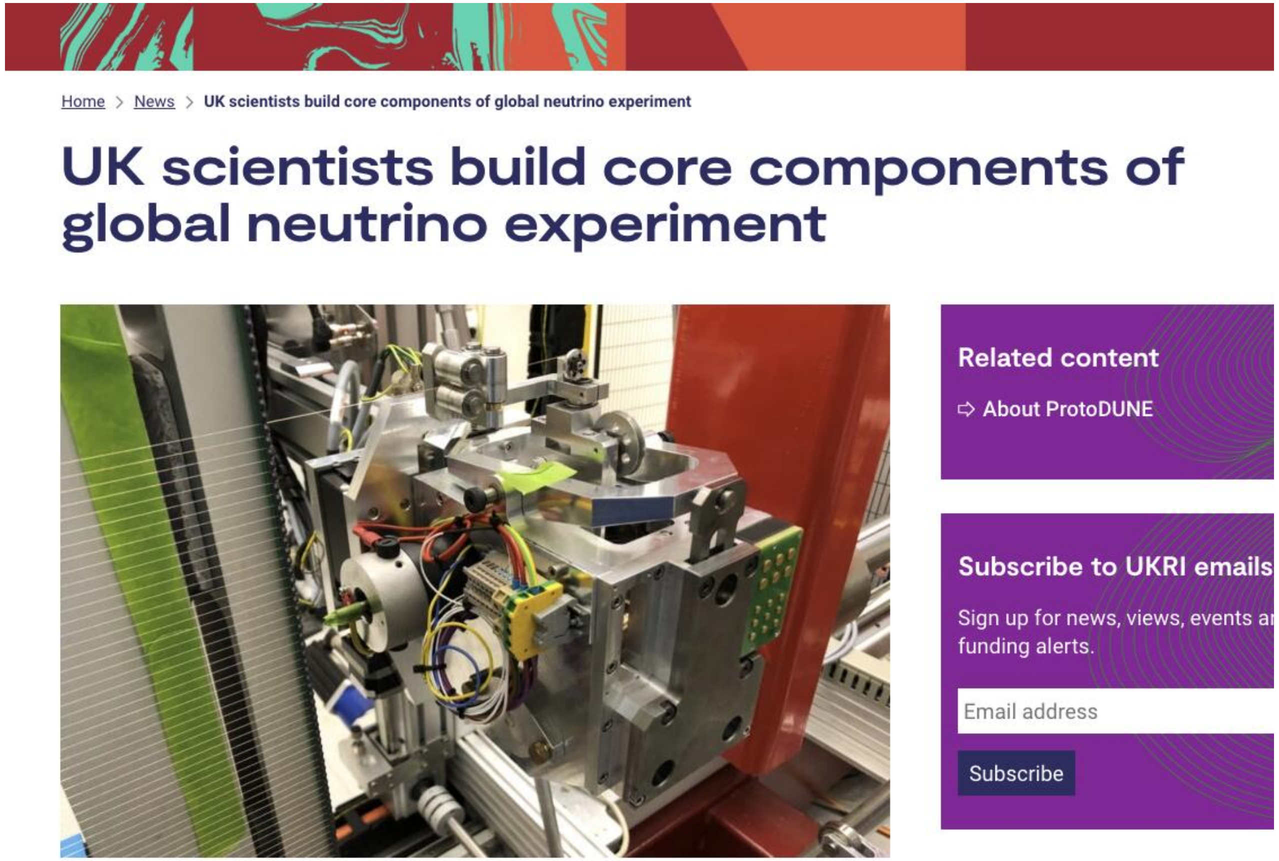


Horizontal Drift Detector (FD Module 1)





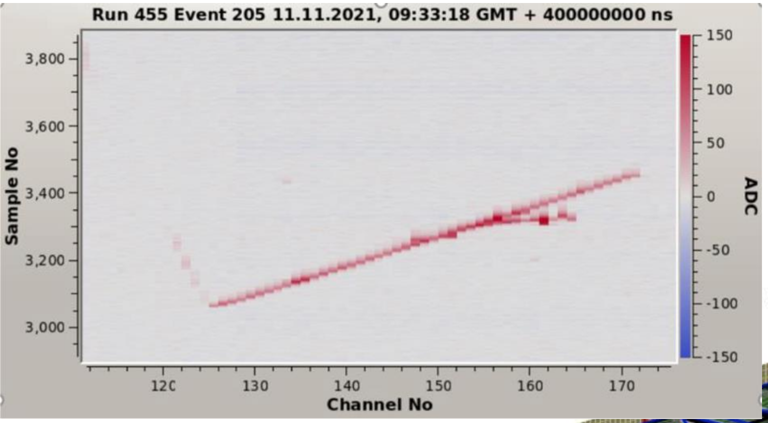
Module 1: Horizontal Drift

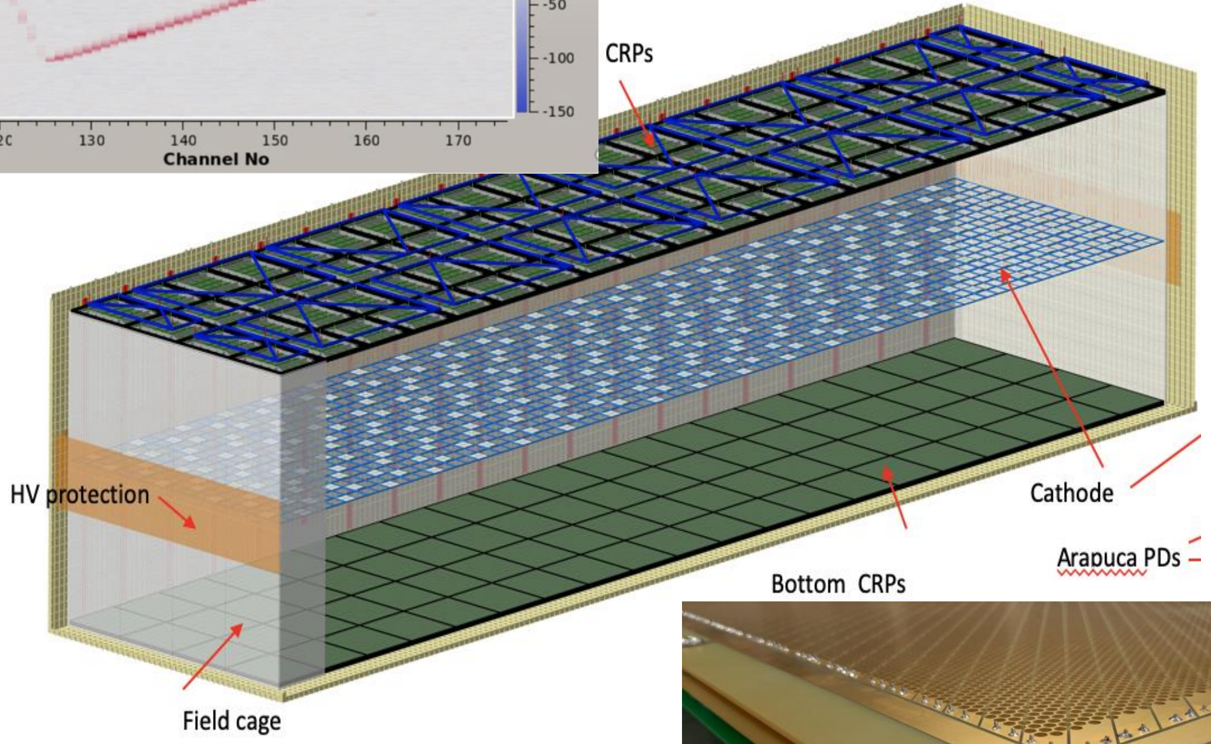


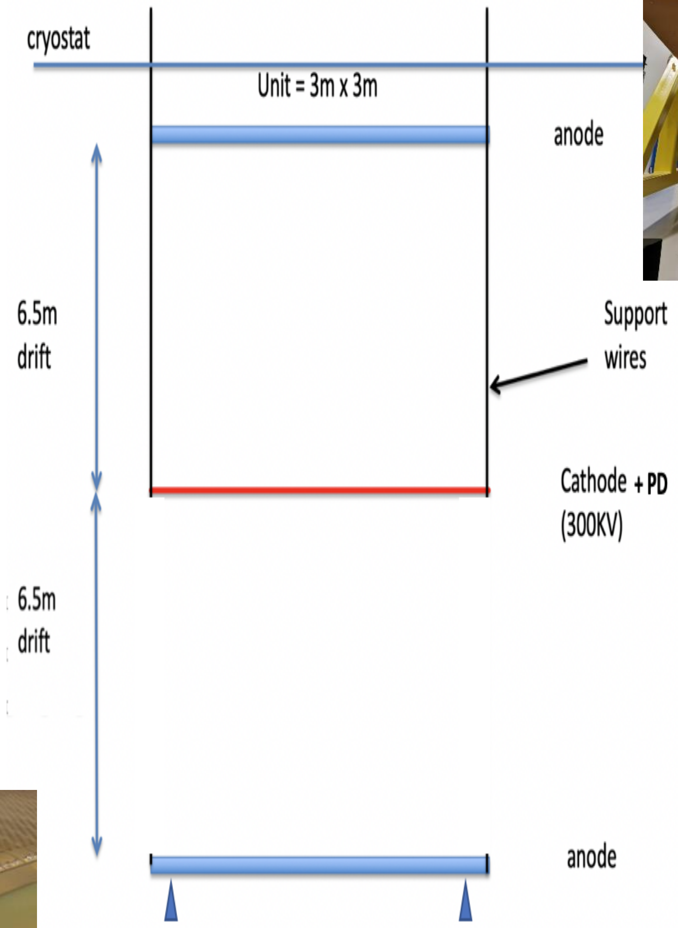
- 150 Anode Plane Assemblies (APA)
- 130 in UK and 20 in US

ProtoDUNE at CERN

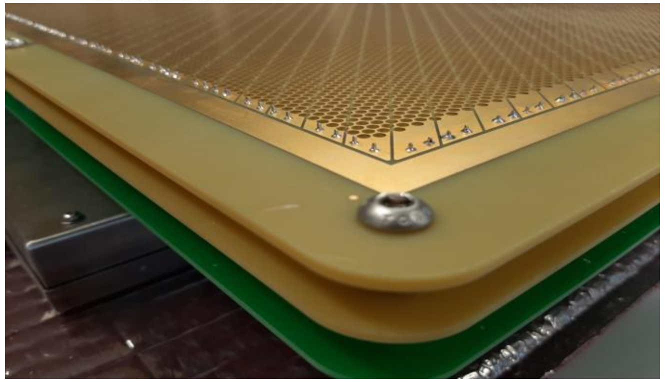
Vertical Drift Detector (FD Module 2)







Perforated Anode



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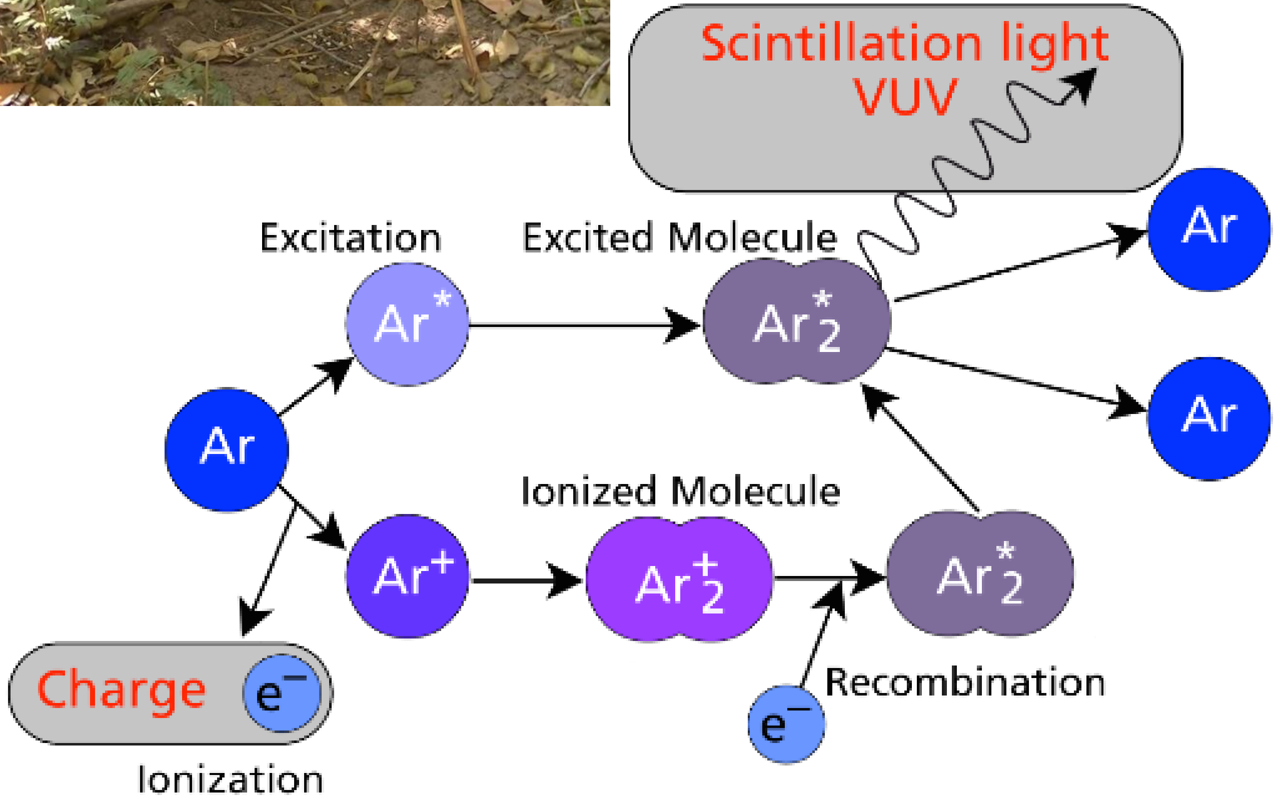
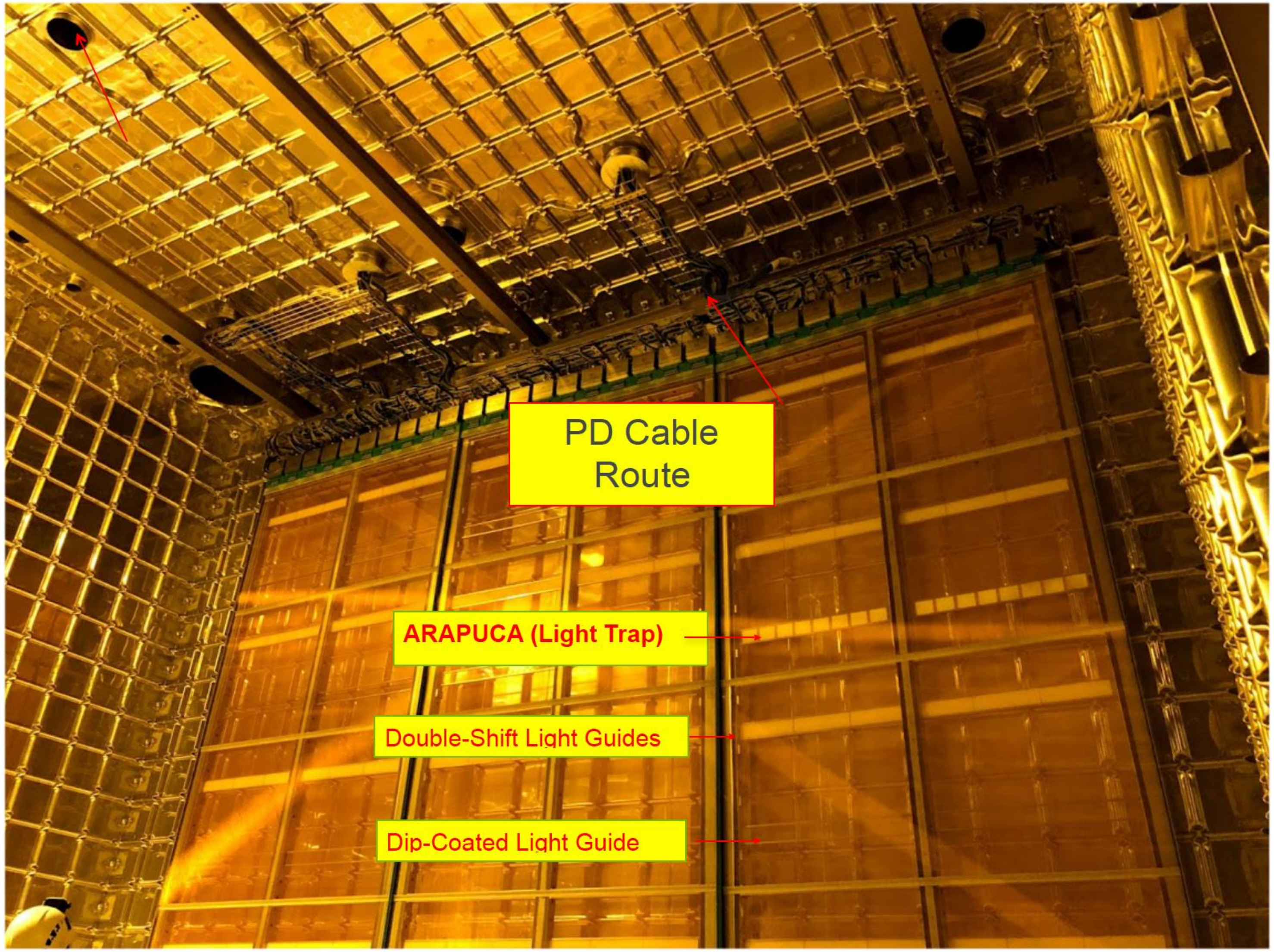
Photon Detection (Arapuca Light Trap Concept)

128 nm



- Fast (7 ns) and slower (≈1500 ns) components, corresponding to single and triplet states of excited molecule
- Argon scintillation light is very abundant (40k photons/MeV)
- Need wavelength shifter to shift VUV to visible
- Readout with PMTs, SiPMs….
- Provides timing and event reconstruction (light is fast, charge is slow!)
- Complementary to charge readout

Photon Detection

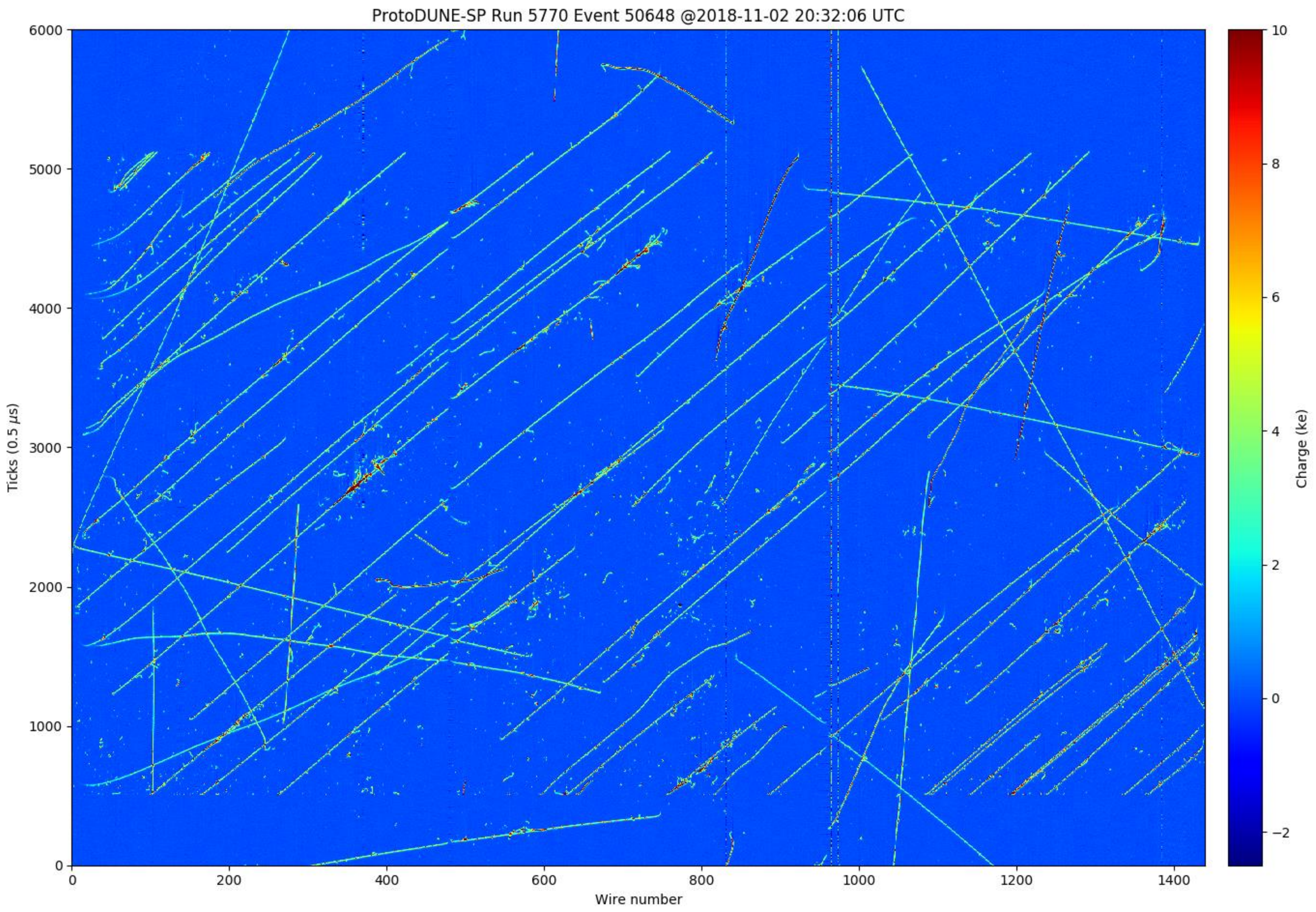


Arapuca 'traps' light with dichroic filters.

CERN Neutrino Platform


Genie
Genie
Genie AWP-20S

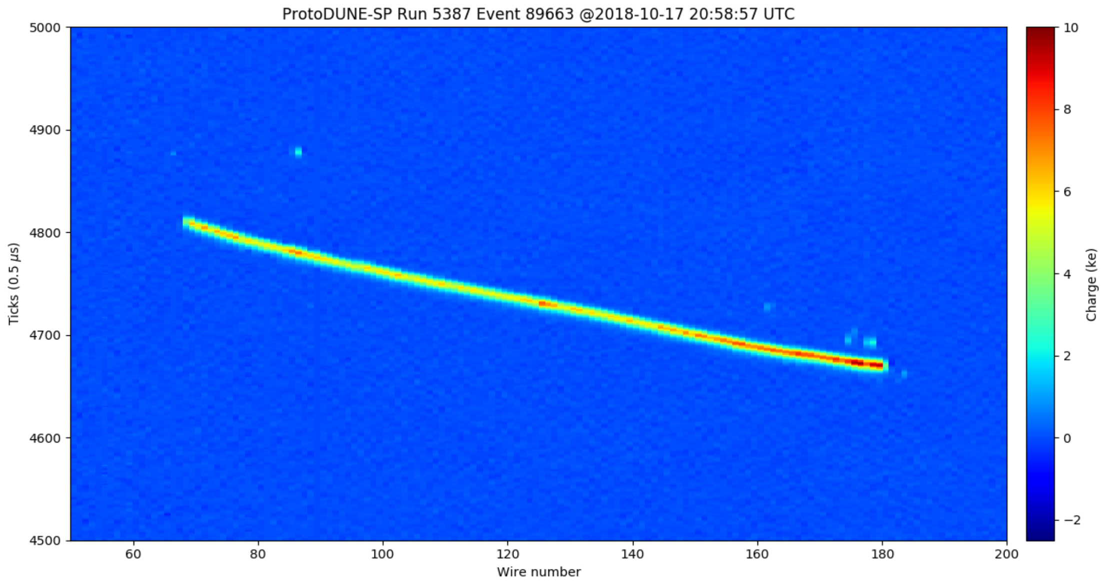
ProtoDUNE-Single Phase (HD)

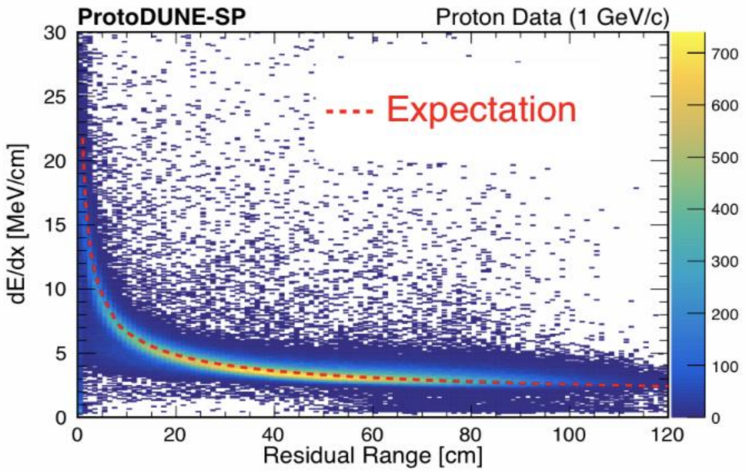


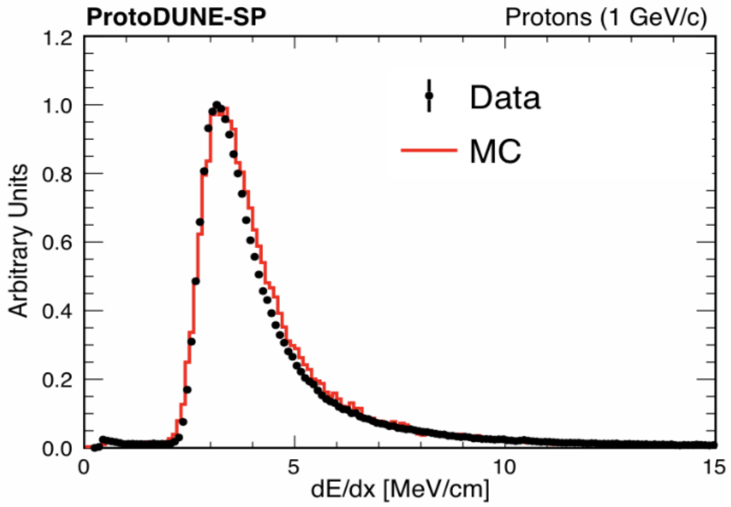
Need to correct for space charge effects!

Calorimetry with Liquid-argon

1 GeV proton







"Bethe Bloch"

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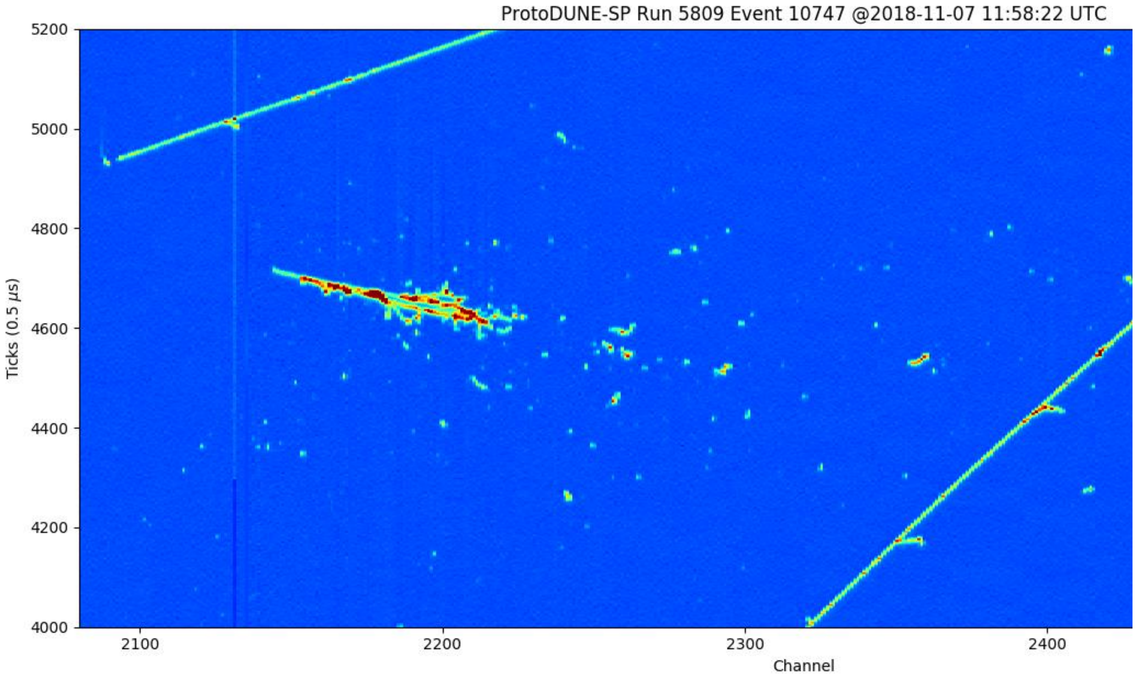
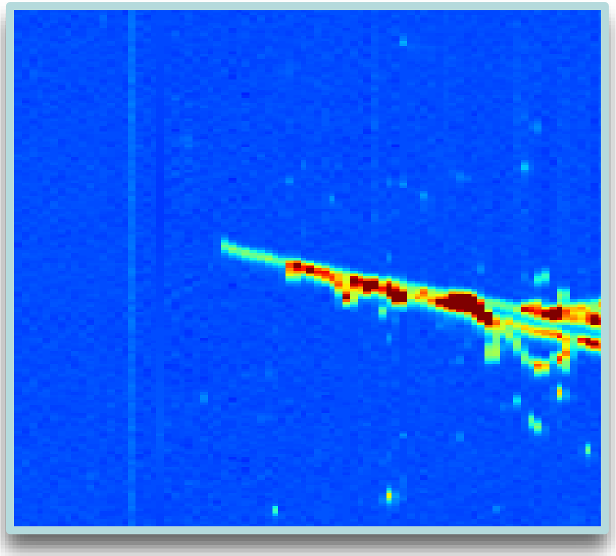
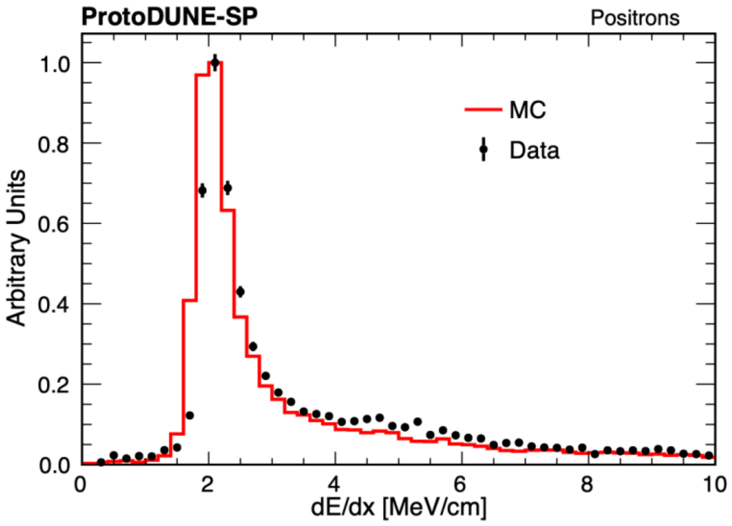
Calorimetry with Liquid-argon

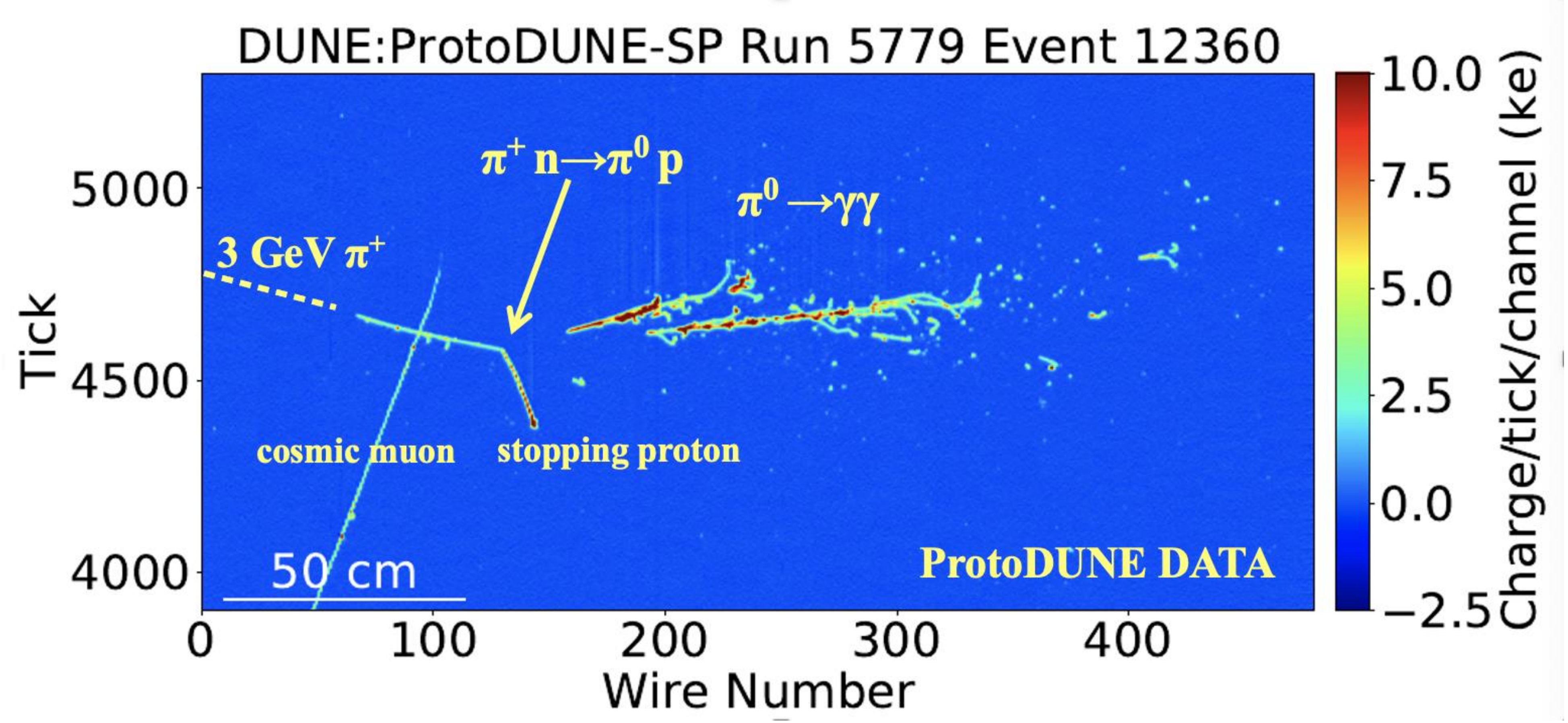
1 GeV electron





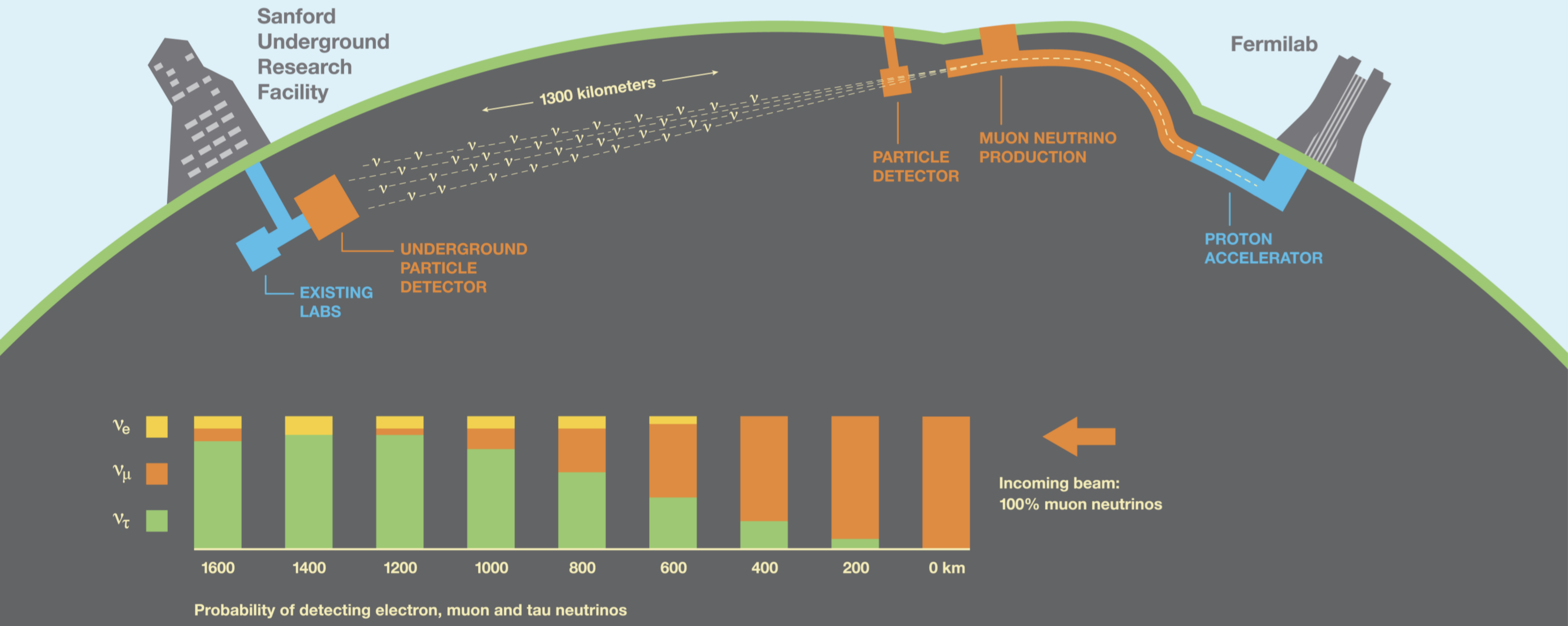


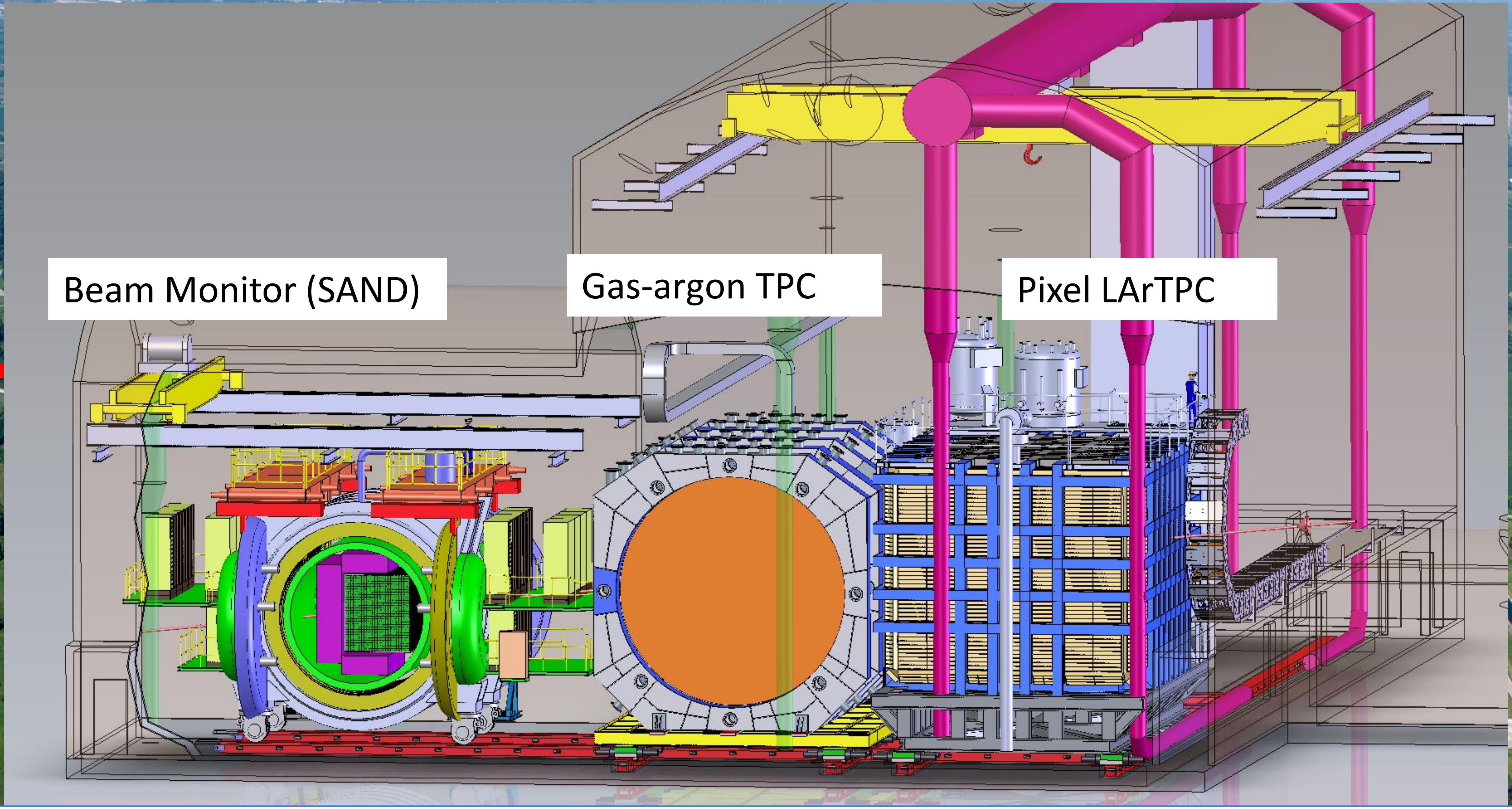
A ProtoDUNE-HD Data Event



Reconstruction of events performed by PANDORA framework with the use of Grid computing resources, both areas UK-led.

Deep Underground Neutrino Experiment

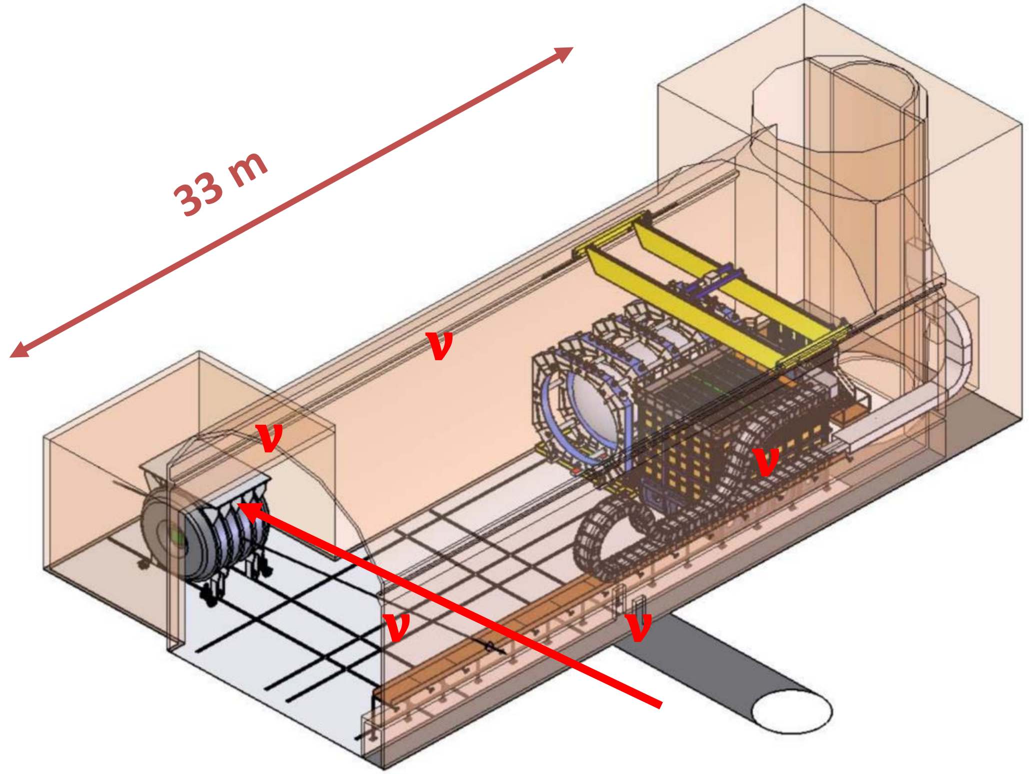


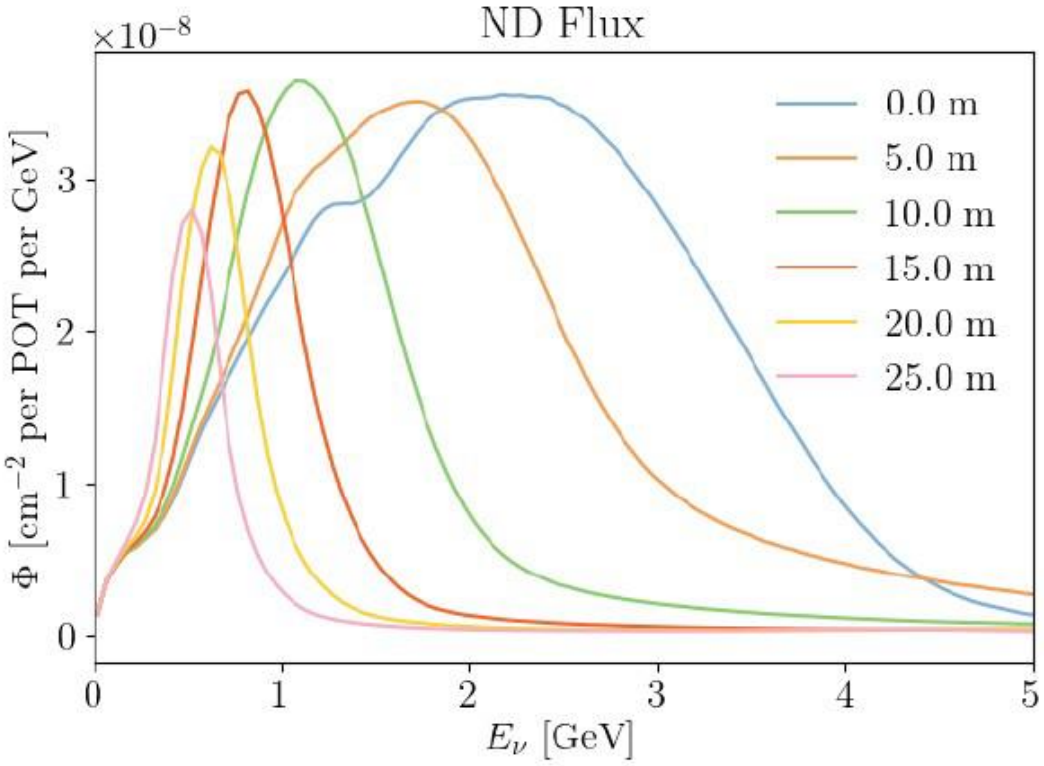


- Near Detectors constrain systematic uncertainties for long-baseline oscillation analysis
  Neutrino flux & cross-section, and detector systematics
- In addition, >100 million interactions will also enable a rich non-oscillation physics programme (e.g. BSM).

The PRISM Concept

Remember beam kinematics!



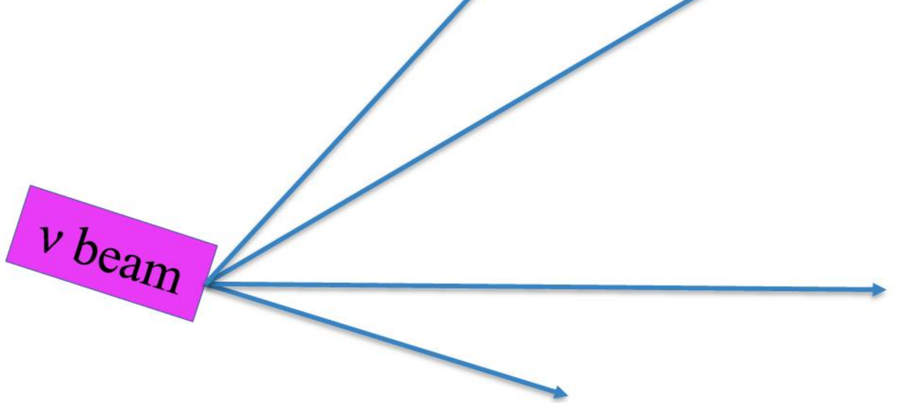


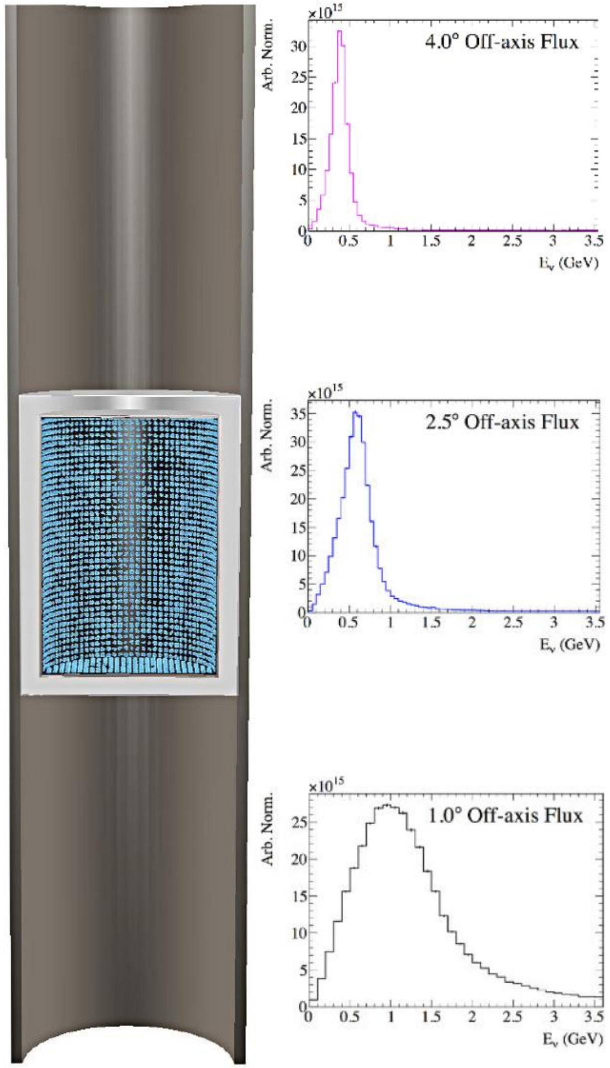
Linear superposition of spectra allows to construct oscillated flux distribution.

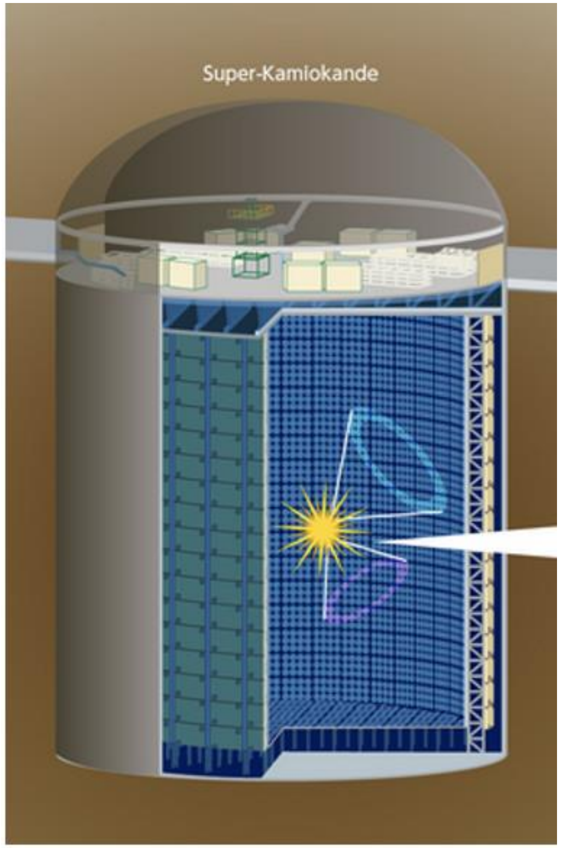
L. Pickering

PRISM concept

- Measure neutrino interactions at multiple off-axis positions
- Neutrino flux changes with position

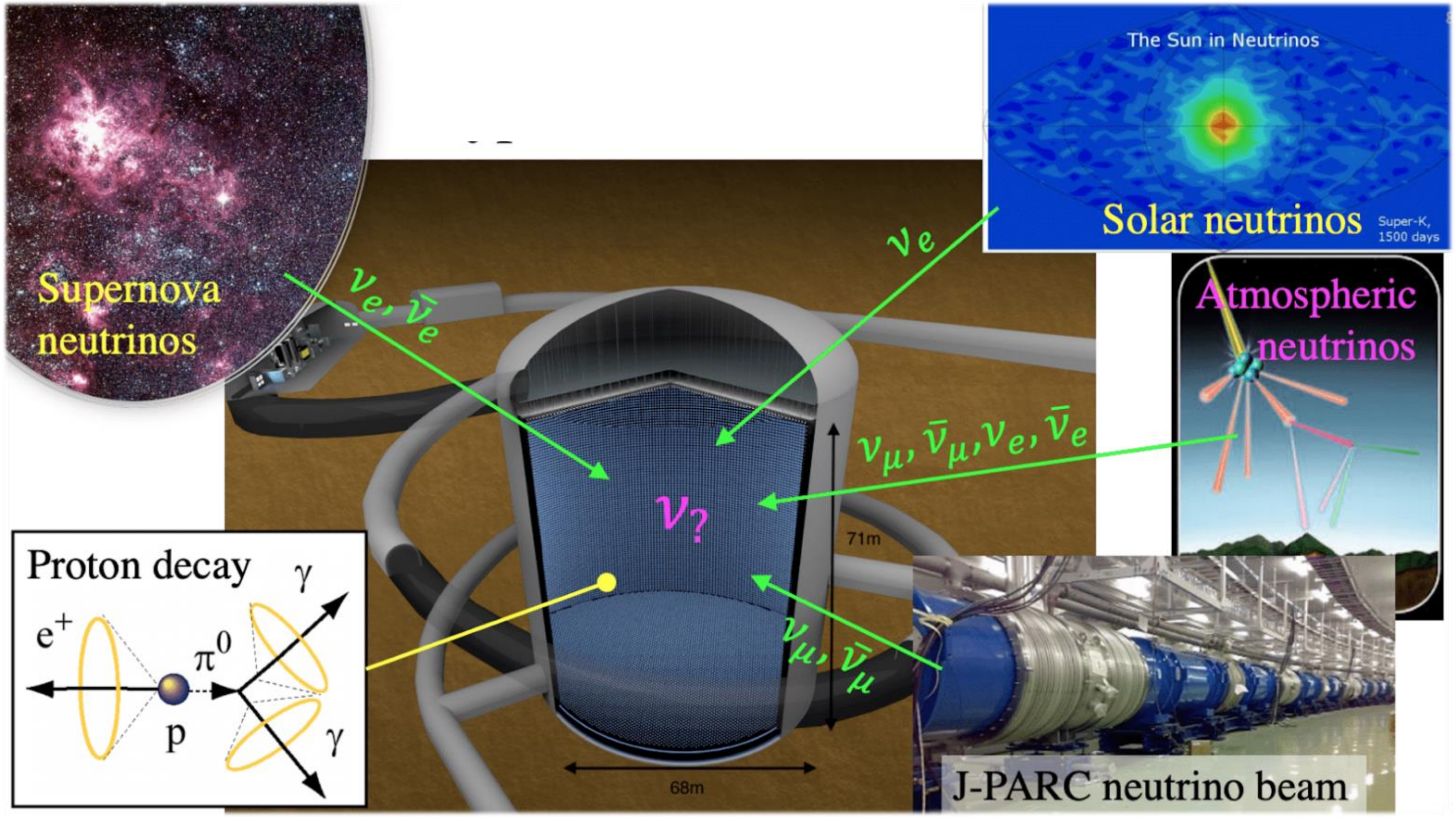






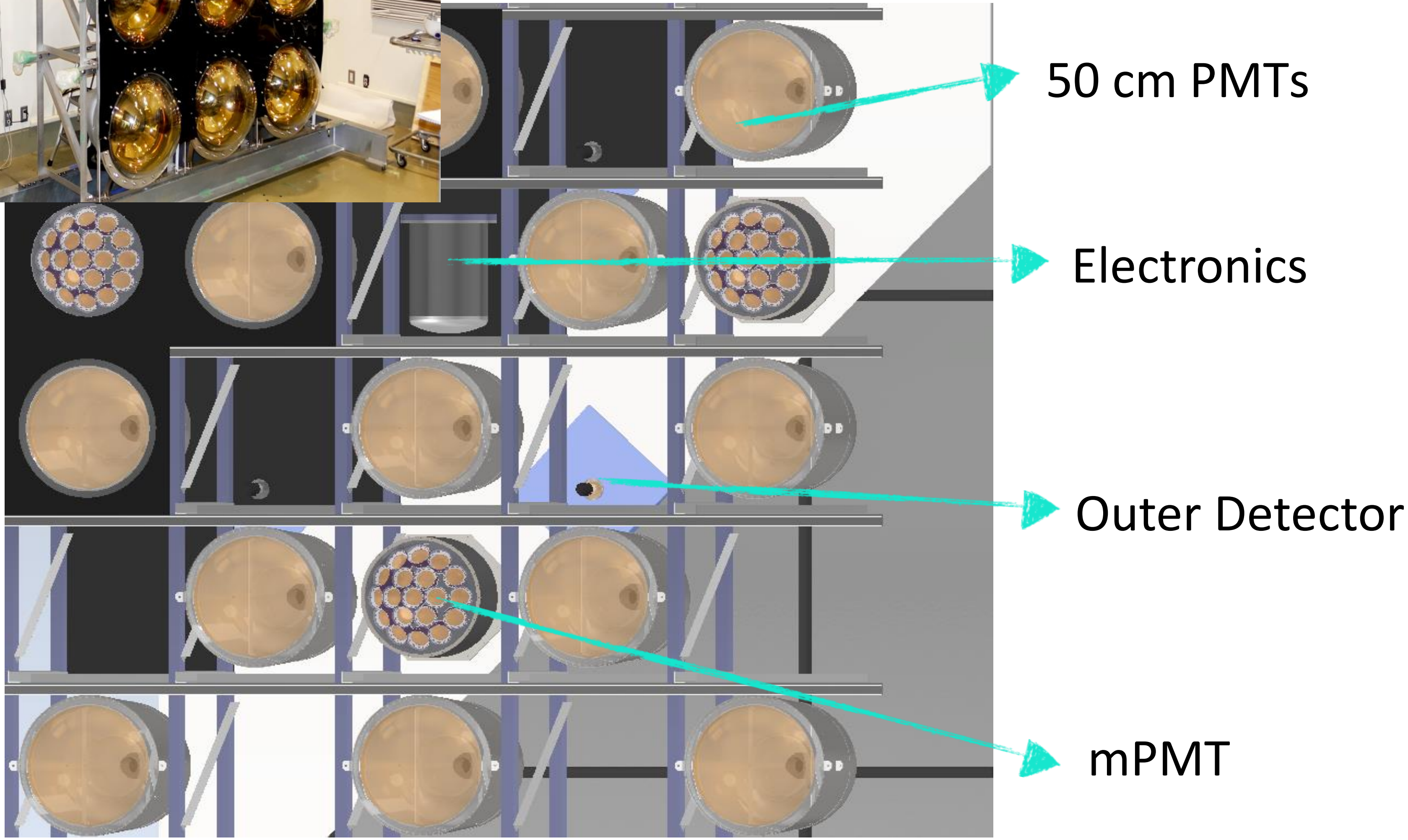
- PMT frame moving inside 10 m wide and 50 m high cylinder with water
- ICWD located at ~1-2 km, scanning the beam from 1˚ to 4˚ off-axis angle

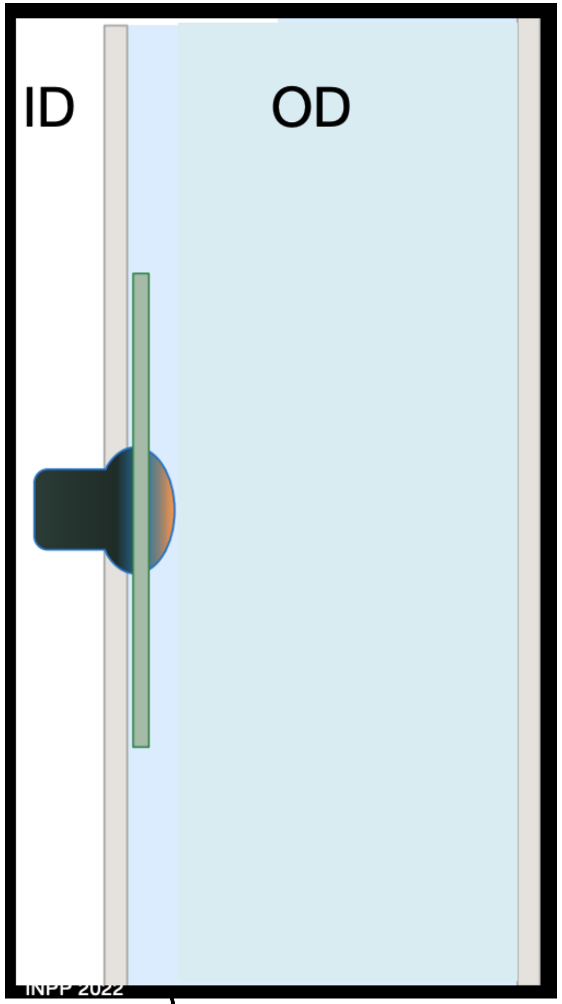
HyperKamiokande in a Nutshell



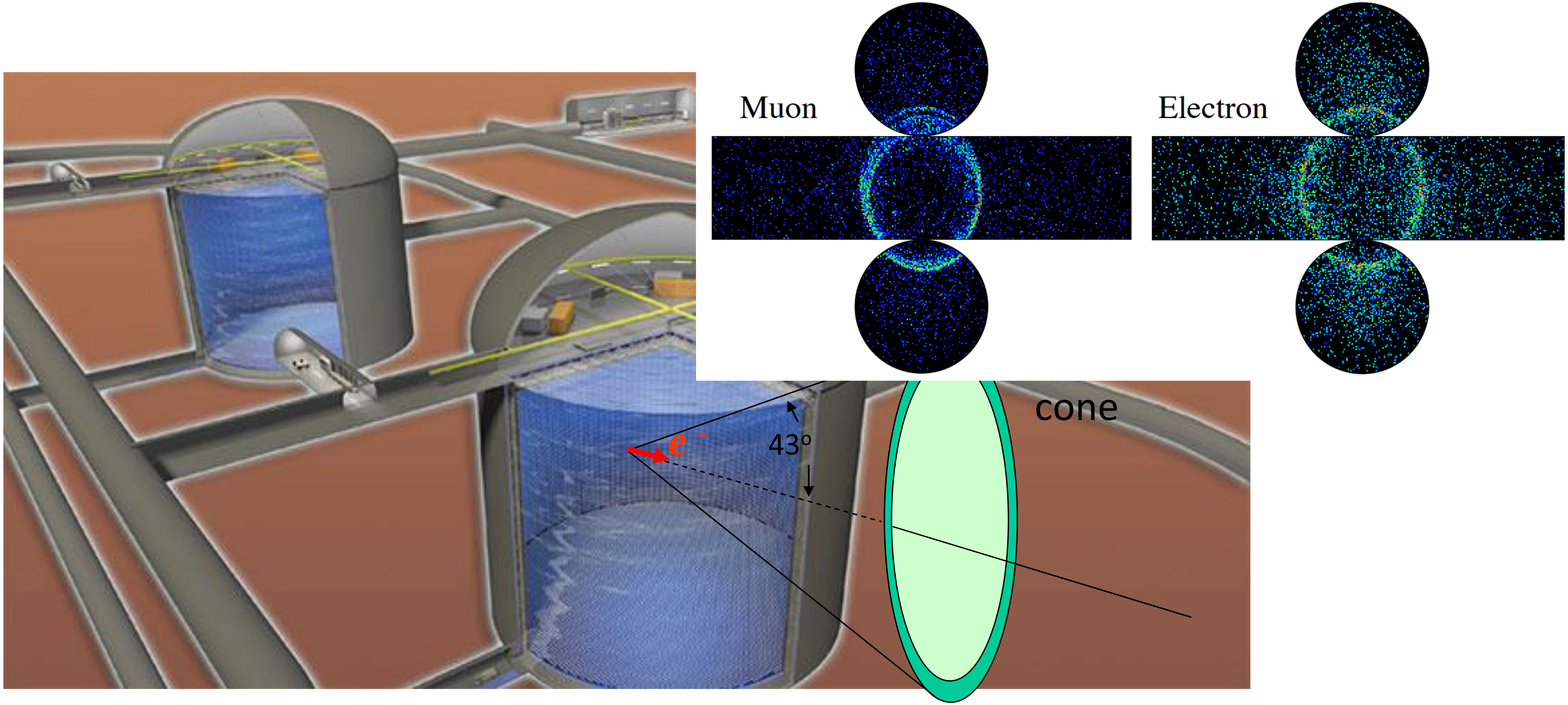
- **8.4 times larger fiducial mass** (190 kiloton) than SK with **double-sensitivity PMTs**
- New (IWCD) and upgraded (@280m) Near Detectors to control systematic uncertainties.
- J-PARC neutrino beam to be upgraded from 0.5 to 1.3 MW

HyperKamiokande



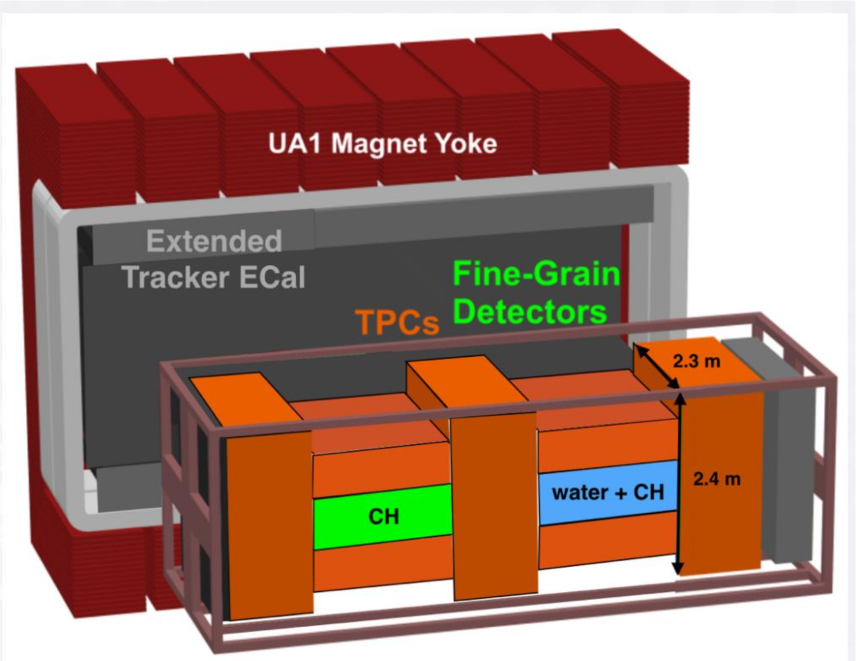


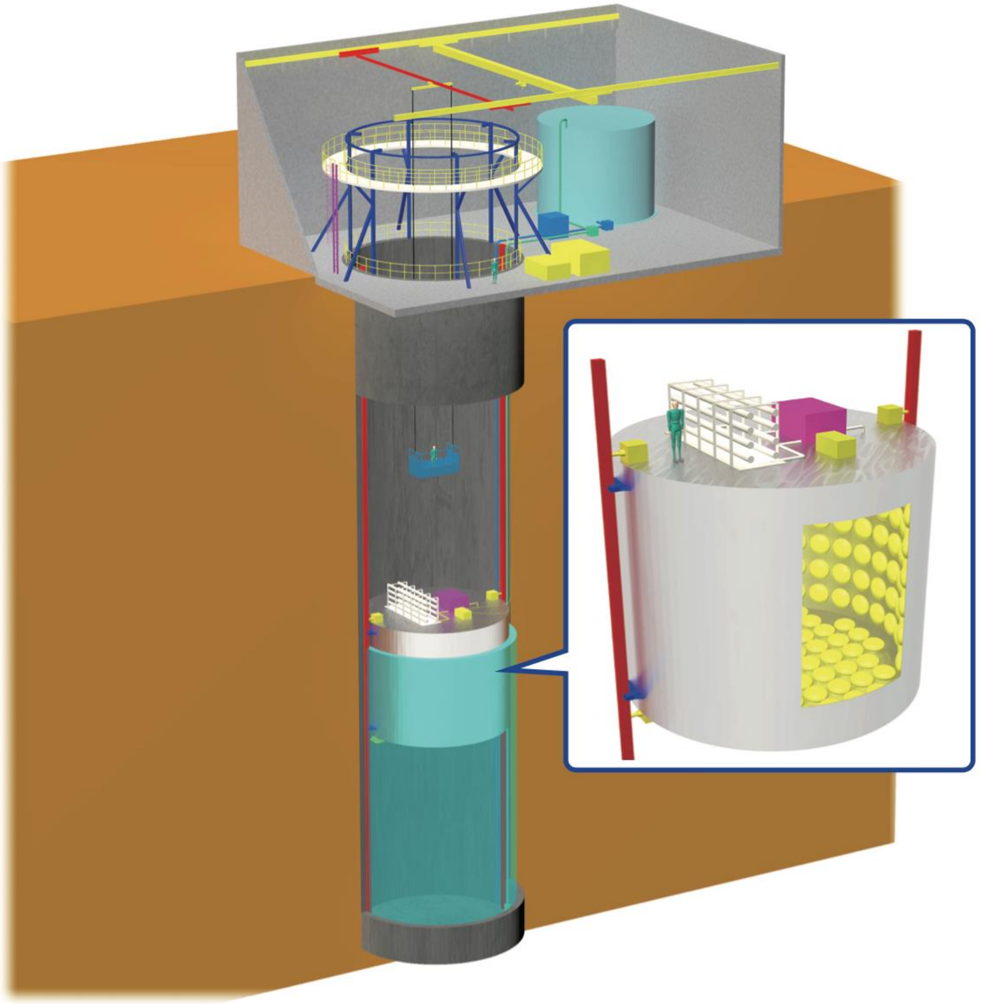
Hyper-Kamiokande



An upgraded Near Detector

- An upgraded version of the current ND280 detector.
- Addition of a 1kt Cherenkov water detector at a baseline of 1 km with vertical movement – PRISM concept

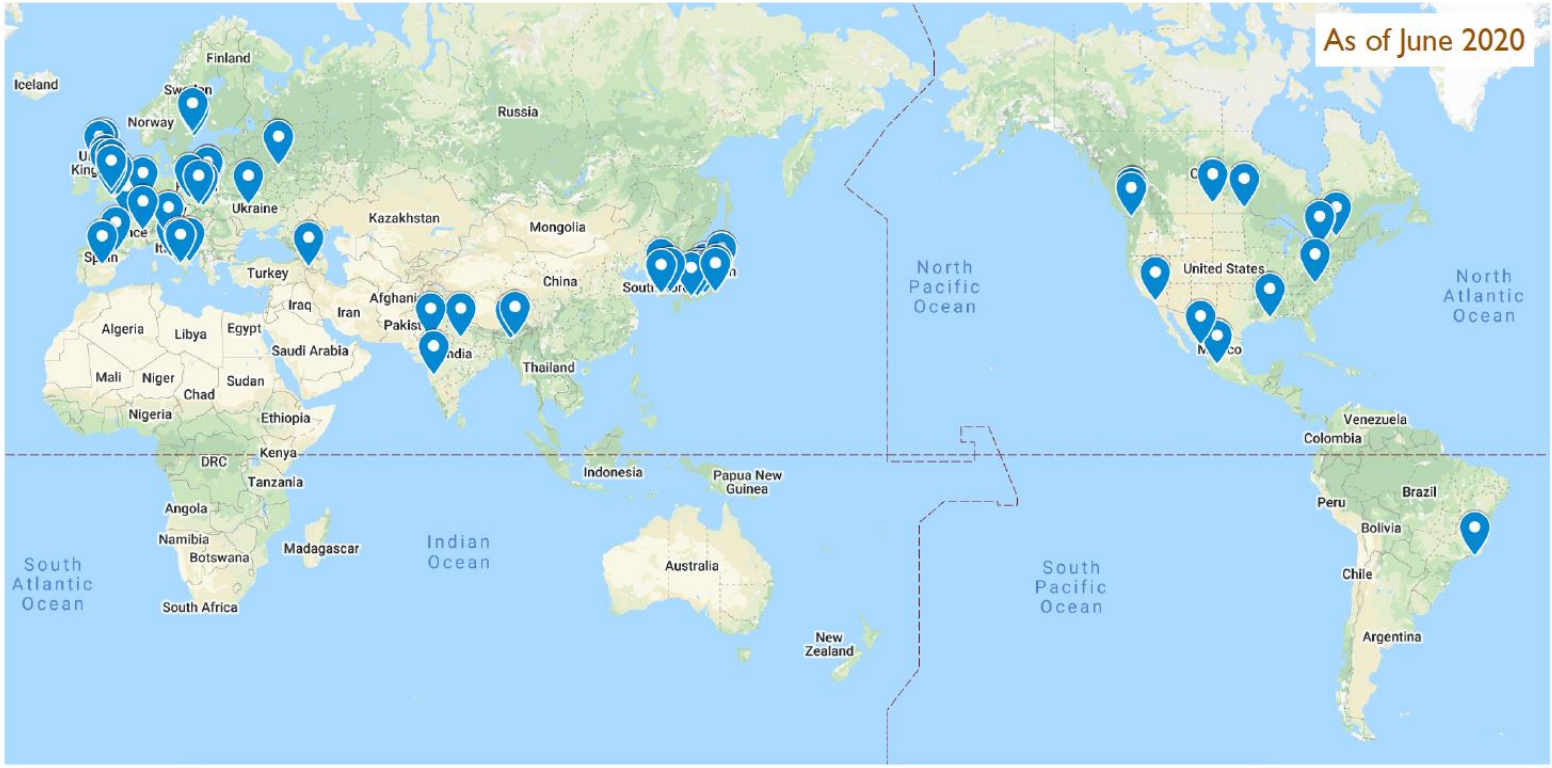




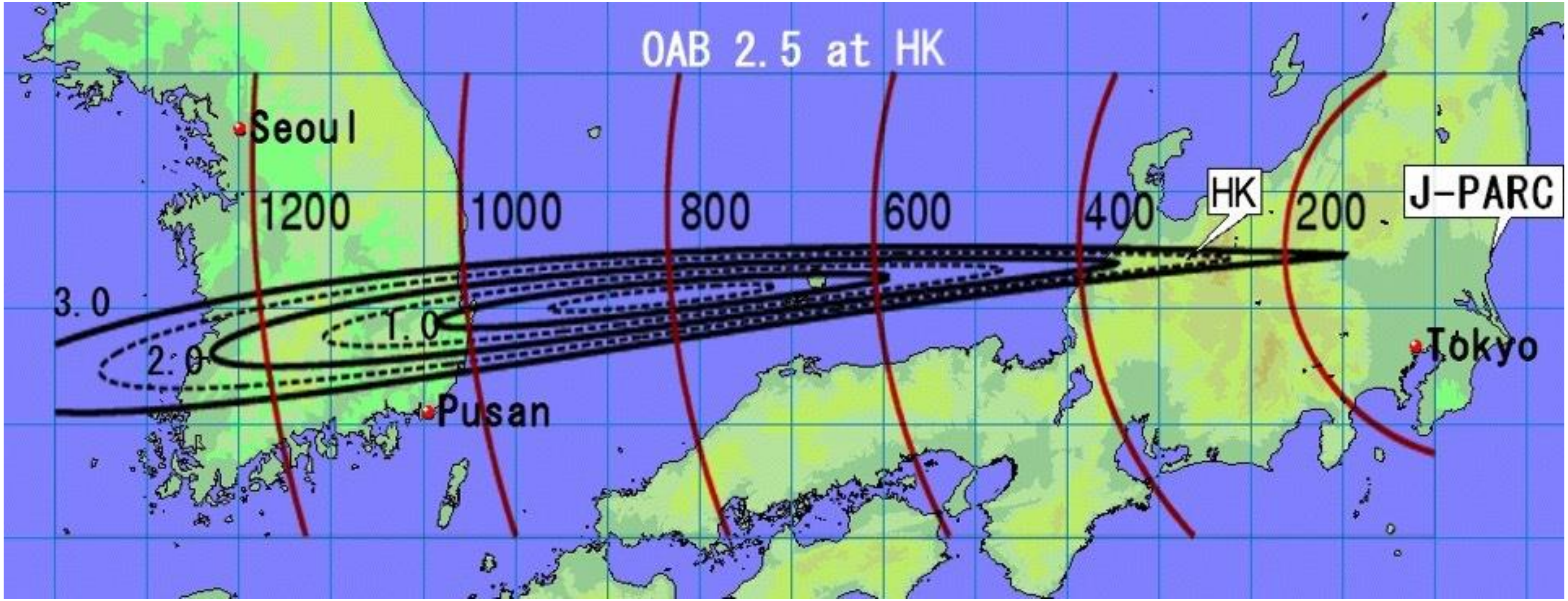
An international project

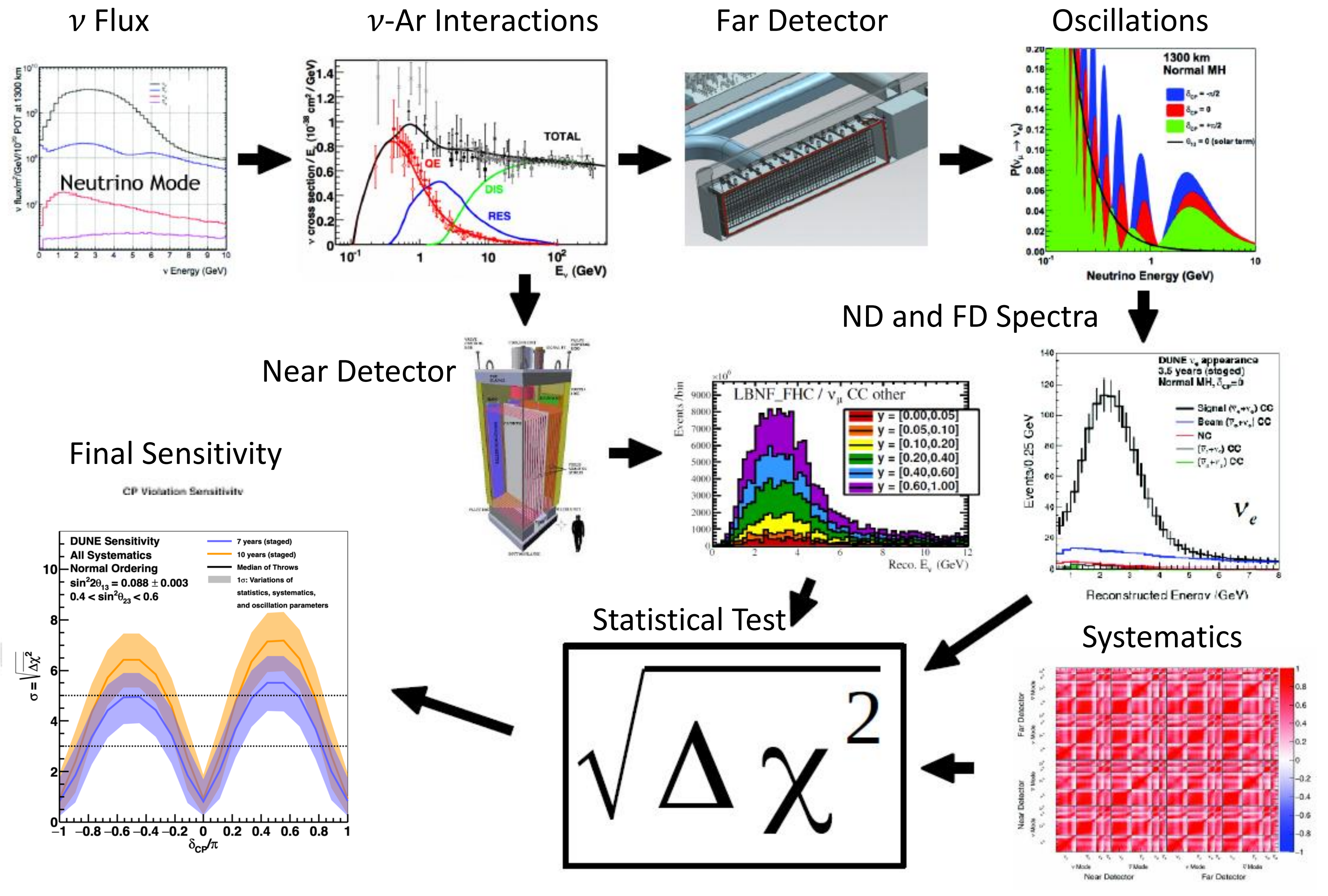
18 countries, 82 institutes, ~390 people

Hyper-Kamiokande



Hyper-Kamiokande to Korea?



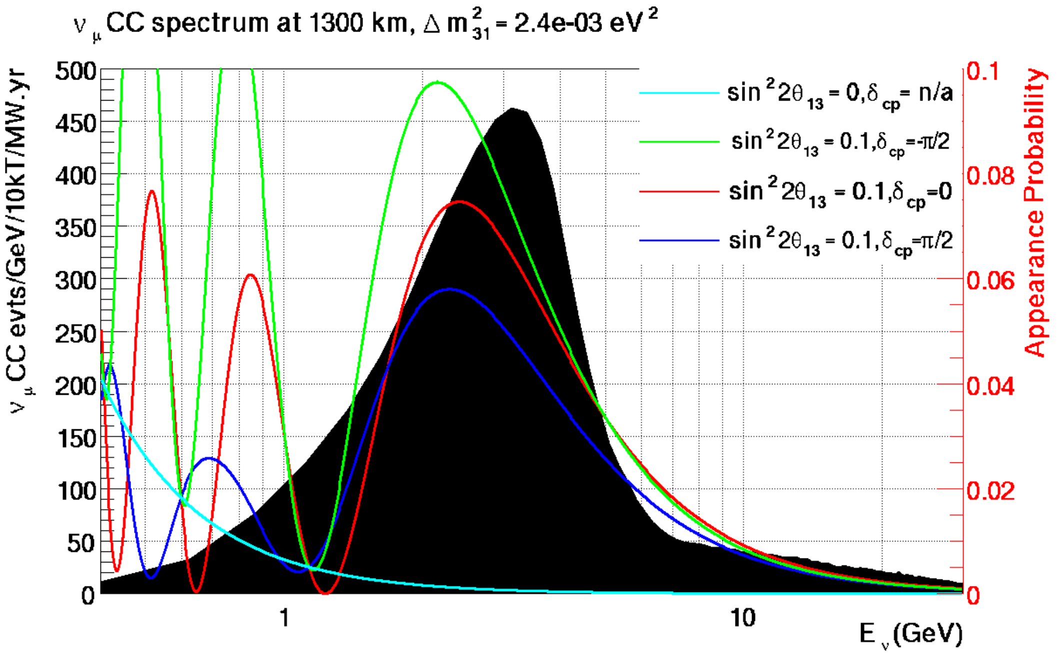

ν Flux
Neutrino Mode
ν Energy (GeV)
ν-Ar Interactions
TOTAL
QE
DIS
RES
ν cross section / E_ν (10^{-38} cm² / GeV)
E_ν (GeV)
Far Detector
Oscillations
1300 km
Normal MH
Neutrino Energy (GeV)
Near Detector
ND and FD Spectra
LBNF_FHC / ν_μ CC other
y = [0.00,0.05]
y = [0.05,0.10]
y = [0.10,0.20]
y = [0.20,0.40]
y = [0.40,0.60]
y = [0.60,1.00]
Events /bin
Reco. E_ν (GeV)
DUNE ν_e appearance
3.5 years (staged)
Normal MH, δ_{CP}=0
Events/0.25 GeV
Reconstructed Energy (GeV)
ν_e
Final Sensitivity
CP Violation Sensitivity
DUNE Sensitivity
All Systematics
Normal Ordering
$\sin^2 2\theta_{13} = 0.088 \pm 0.003$
$0.4 < \sin^2\theta_{23} < 0.6$
7 years (staged)
10 years (staged)
Median of Throws
1σ: Variations of statistics, systematics, and oscillation parameters
$\sigma = \sqrt{\Delta\chi^2}$
δ_{CP}/π
Statistical Test
$\sqrt{\Delta\chi^2}$
Systematics
Near Detector
Far Detector

ν_e appearance gives access to δ

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\,\sin^2 2\theta_{13}\,\frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2}\Delta_{31}^2$$
$$+ \sin 2\theta_{23}\,\sin 2\theta_{13}\,\sin 2\theta_{12}\,\frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)}\Delta_{31}\,\frac{\sin(aL)}{aL}\Delta_{21}\cos(\Delta_{31} - \delta)$$
$$+ \cos^2\theta_{23}\,\sin^2 2\theta_{12}\,\frac{\sin(aL)}{aL}\Delta_{21}^2$$

$$a = \frac{G_F N_e}{\sqrt{2}}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$



- ν_e appearance amplitude depends simultaneously on θ_{13}, θ_{23}, δ_{CP}, and matter effects –
- Measurements of all four possible in a single experiment.

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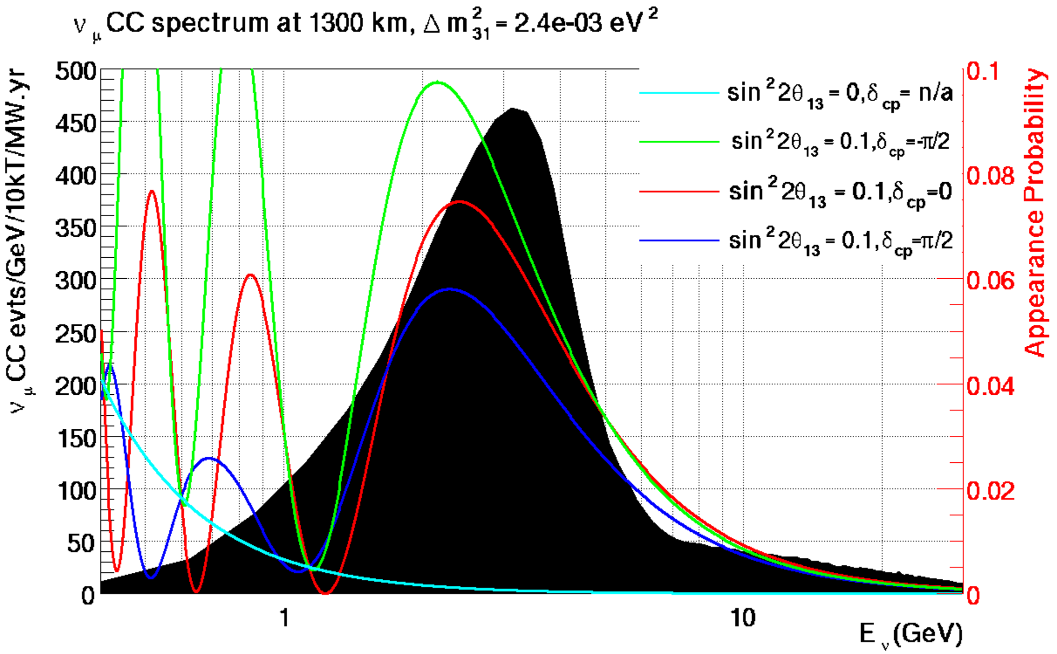
ν_e appearance gives access to δ

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2}\Delta_{31}^2$$
$$+ \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)}\Delta_{31}\frac{\sin(aL)}{aL}\Delta_{21}\cos(\Delta_{31} - \delta)$$
$$+ \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin(aL)}{aL}\Delta_{21}^2$$

$$a = \frac{G_F N_e}{\sqrt{2}}$$
$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$



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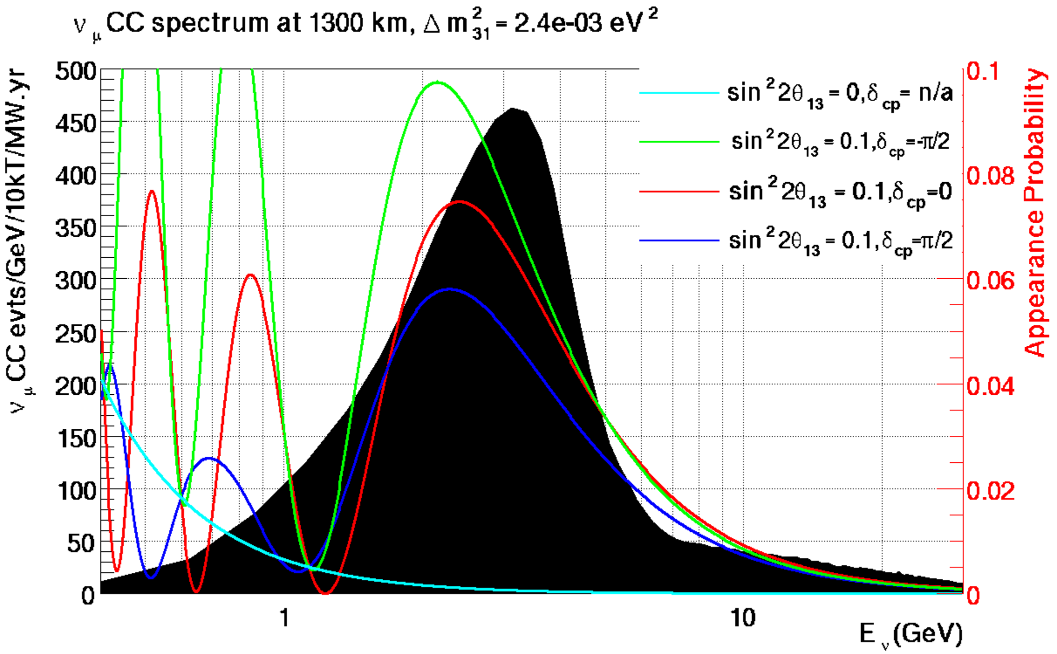
$$a = \frac{G_F N_e}{\sqrt{2}} \qquad \Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$



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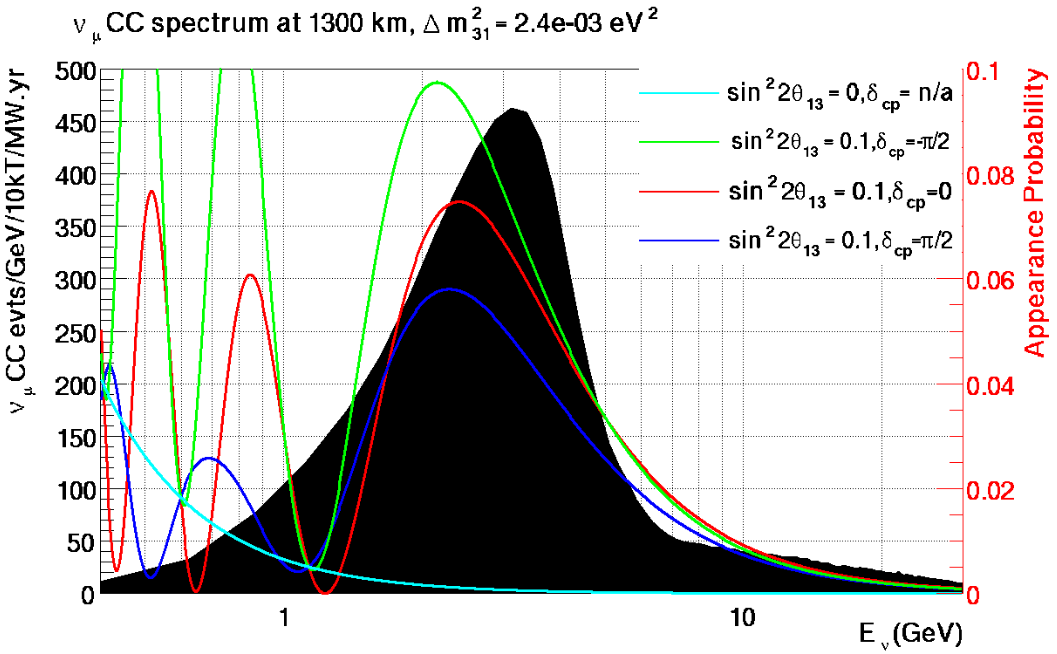
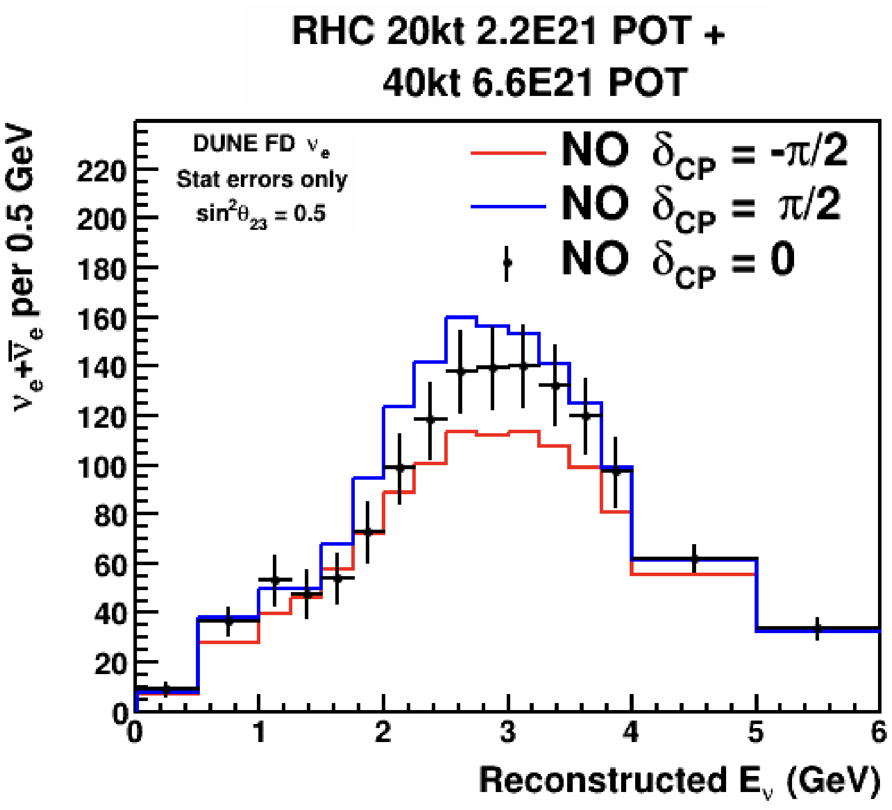
$$a = \frac{G_F N_e}{\sqrt{2}} \qquad \Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$



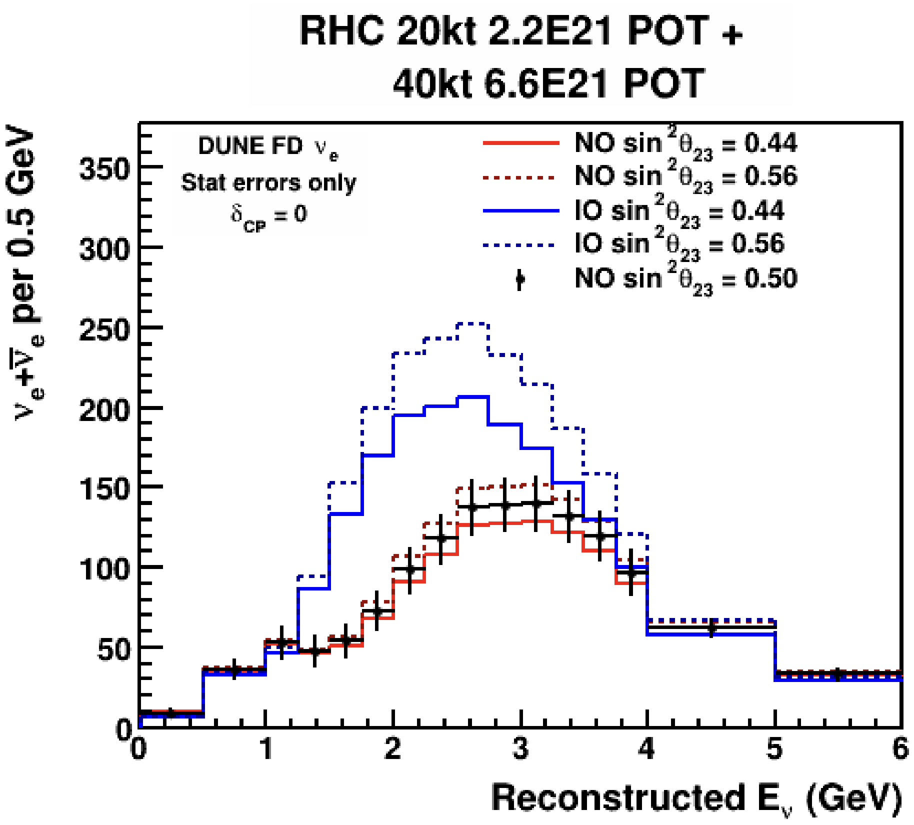
- ν_e appearance amplitude depends simultaneously on θ_{13}, θ_{23}, δ_{CP}, and matter effects –
- Measurements of all four possible in a single experiment.
- Need to resolve degeneracies (e.g., MO vs. CP).

Electron neutrino appearance

Excellent energy reconstruction needed!



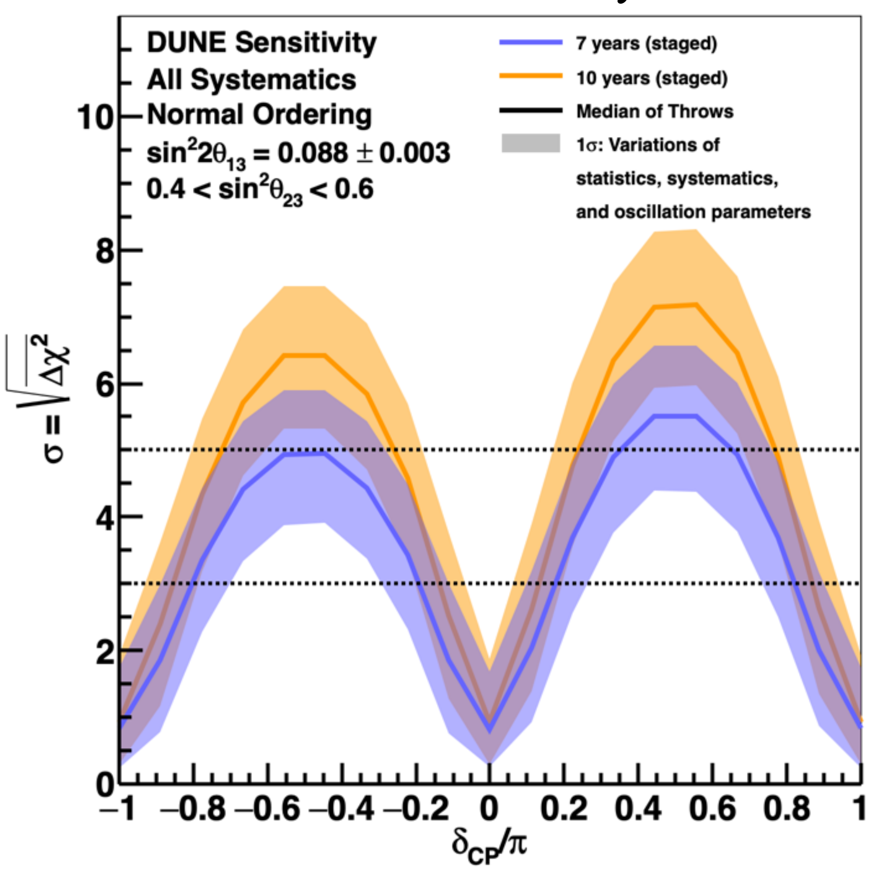
Varying δ



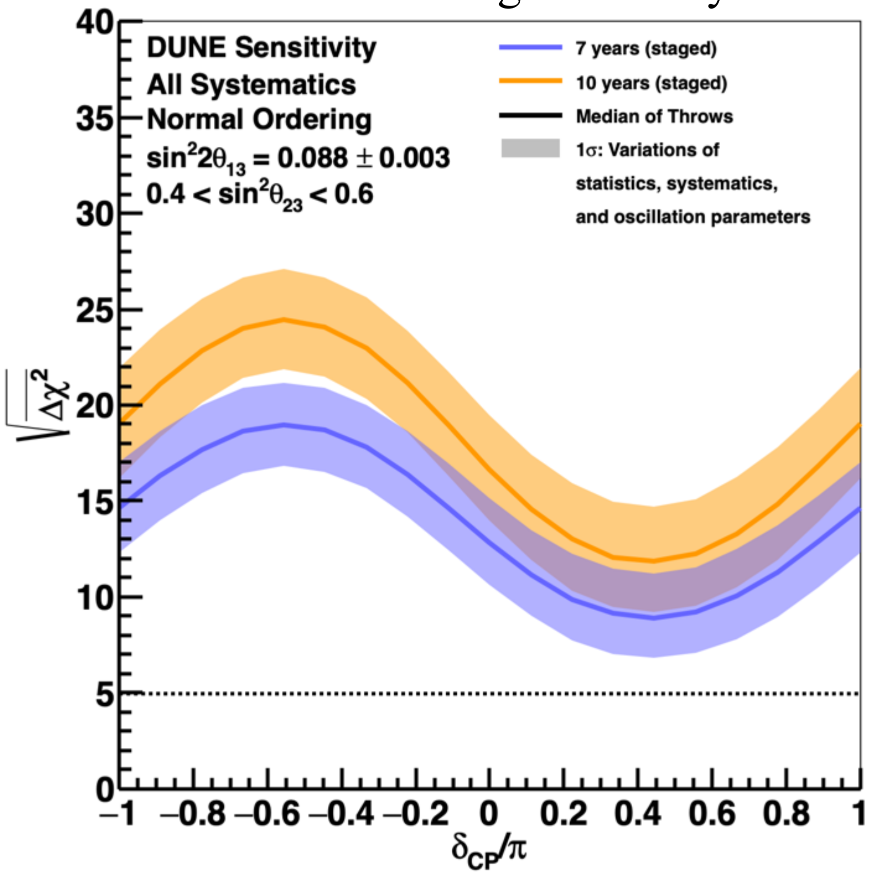
Varying mass ordering and $\sin^2\theta_{23}$

DUNE Mass ordering and CPV phase

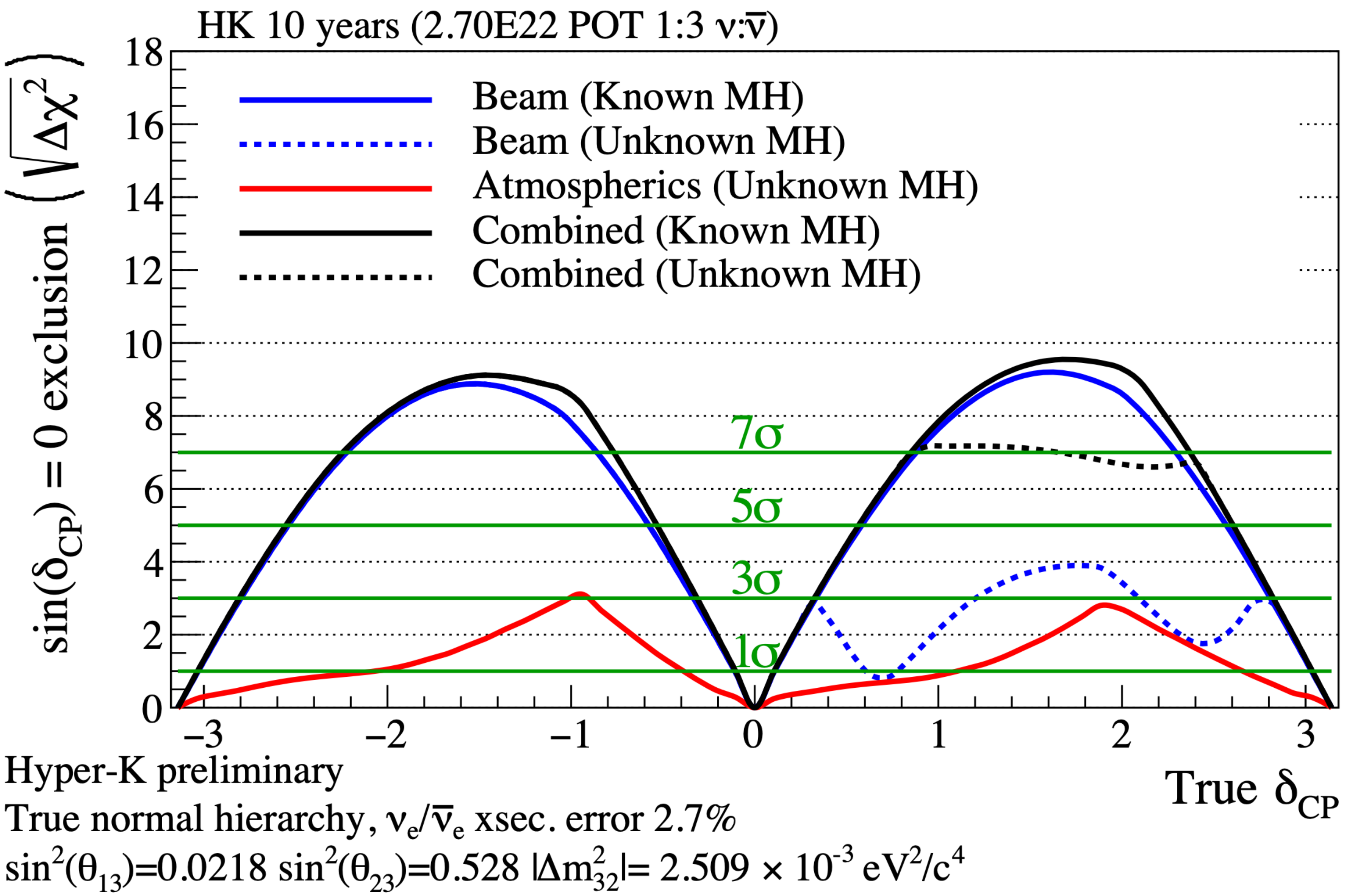
CPV sensitivity



Mass ordering sensitivity

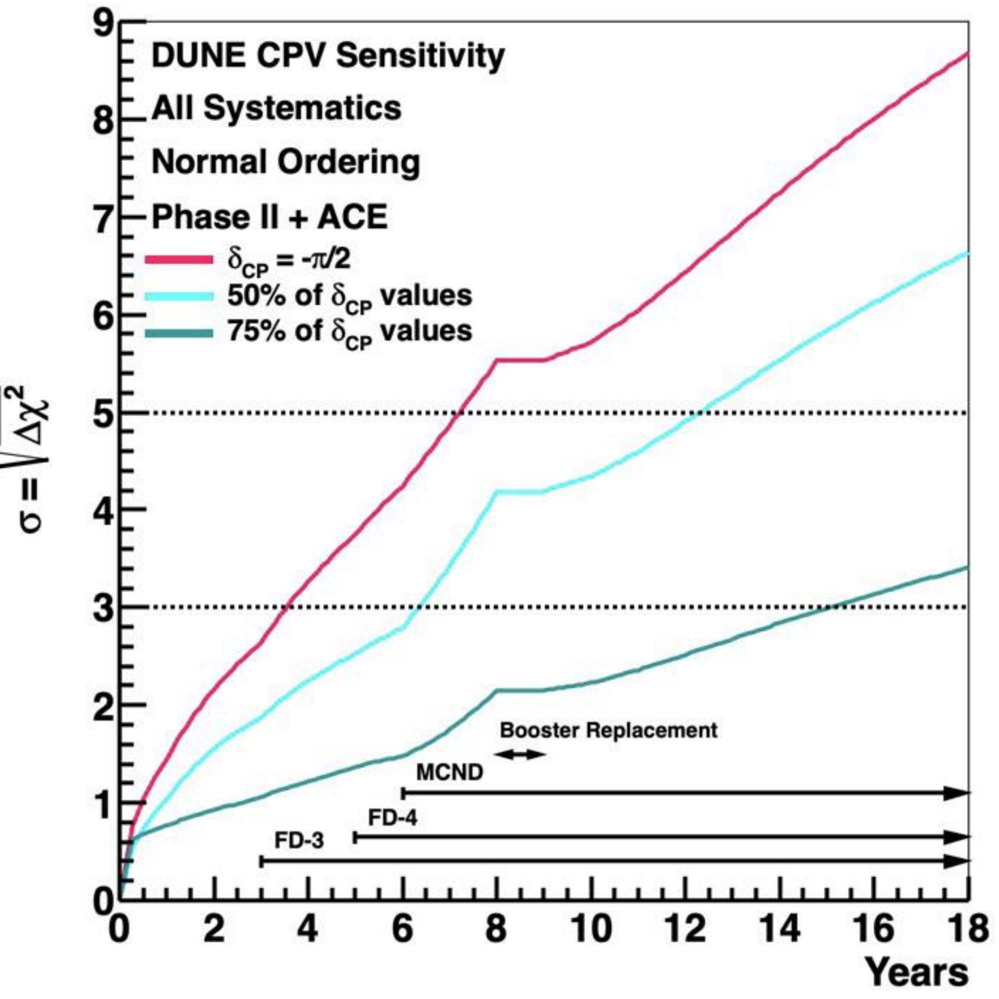


HK: Sensitivity to CP Violation



- Due to short baseline HK cannot resolve Mass Ordering/CP degeneracy.
- If Mass Ordering remains unknown, beam analysis less sensitive for some values of δ.
- Joint atmospheric and beam analysis increases sensitivity.
- If CPV maximal, HK can be fast.

DUNE: Timeline for sensitivity to CP Violation



If CP violation is maximal, we can establish it at 3 sigma in 4 years and at 5 sigma in 8 years.

Other values of the CPV phase will be more challenging – combining with Hyper-K might be beneficial.

Advantage of DUNE over Hyper-K

- broader CPV coverage
- minimal dependence on external inputs

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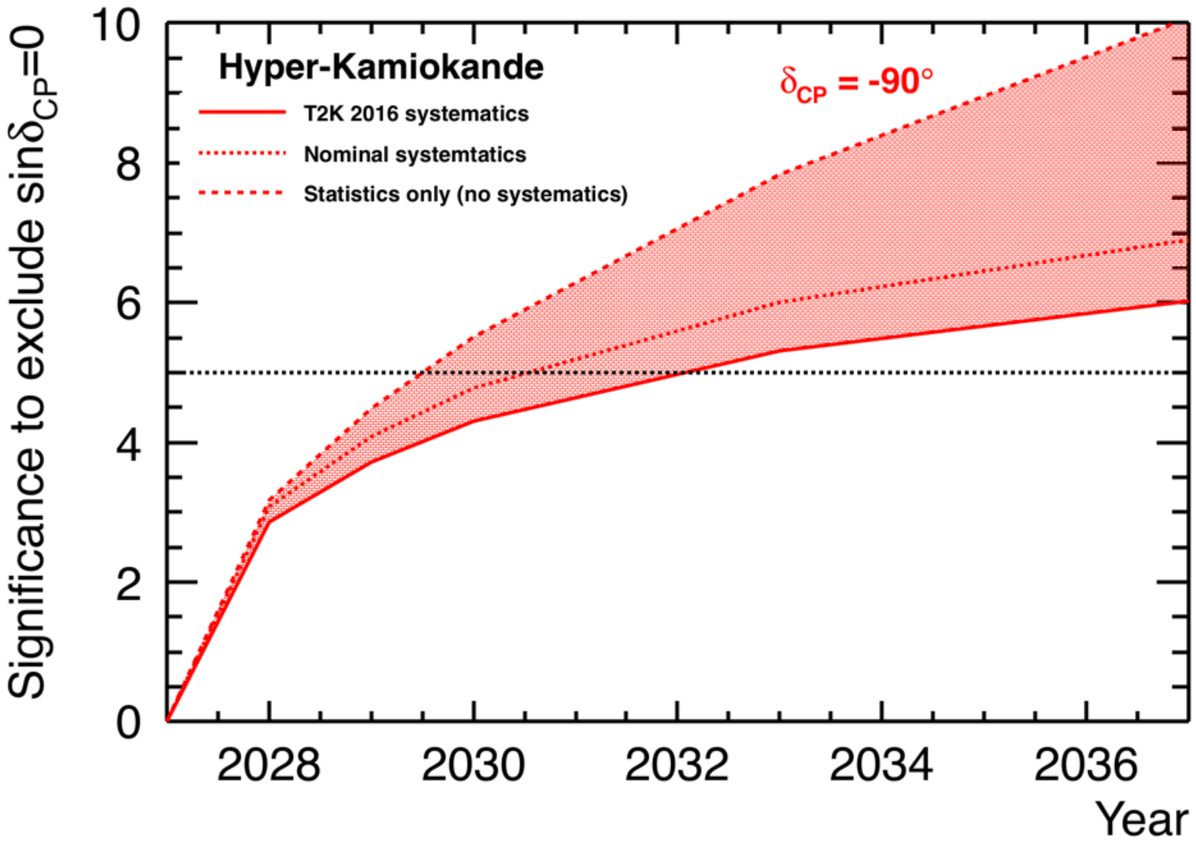
HK: Sensitivity to CP Violation



- Difficult to compare because of different assumptions about staging and startup
- Both experiments need to ramp up quickly – expected to start data taking at the end of the decade

The DUNE Science Programme

Discovery of yet unknown parameters of the lepton Yukawa sector:

- Determination of the mass ordering
- Discovery of CP violation

Observation of atmospheric, solar and SNB neutrinos:

- First observation of HEP neutrinos from the sun
- Galactic SN explosion
- Best measurement of ϑ_{12}

Measurements of PMNS parameters:

- ϑ_{23} and its octant
- Δm^2_{13}
- Precision measurement of CP phase delta

Physics beyond the standard model

- Sterile neutrinos at LBNF
- Dark matter candidates at the near detector
- Proton decay
- Boosted dark matter at far detector

Phase I: 20 kton, 1.2 MW beam

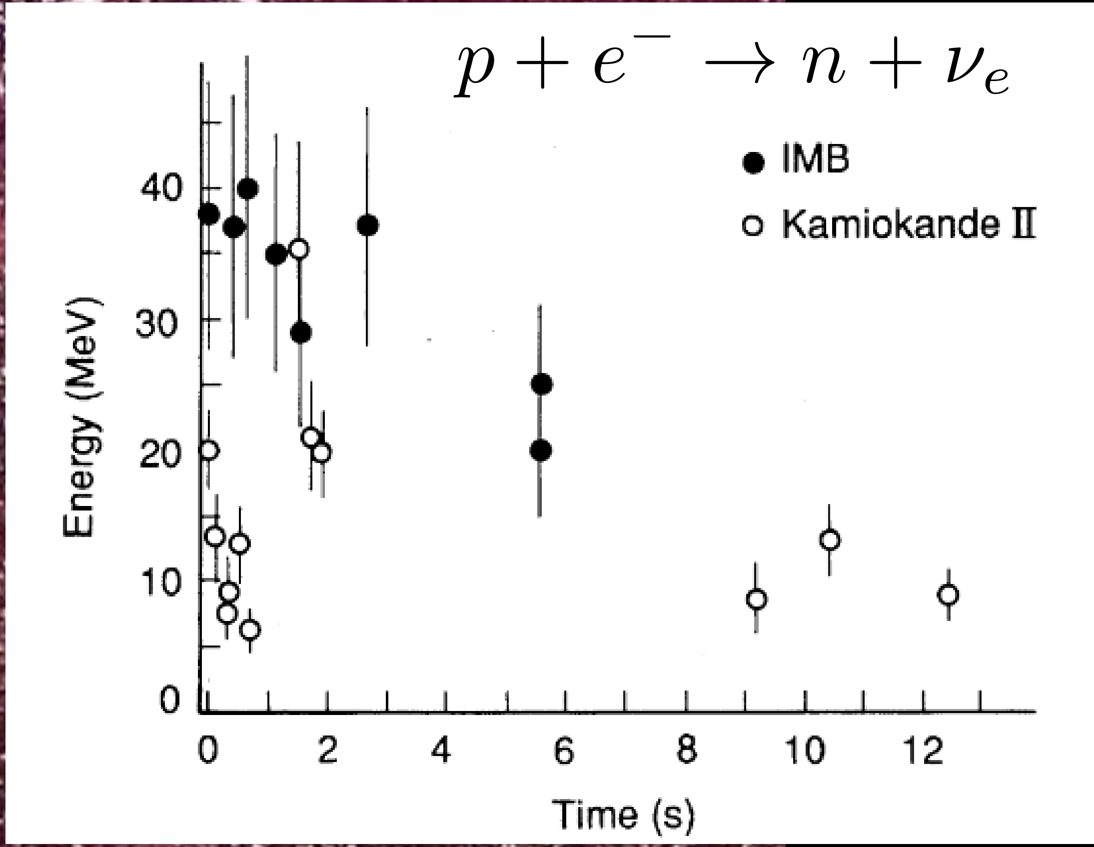
Phase II: 40 kton, 1.2 MW beam

Phase II: 40 kton, 2.4 MW beam

Supernova 1987A

in the Large Magellanic Cloud (55 kpc away)

SN1987A, about 24 neutrinos observed, 3 hours before photons.



For comparison: the Milky Way is about 34 kpc across

Fermilab
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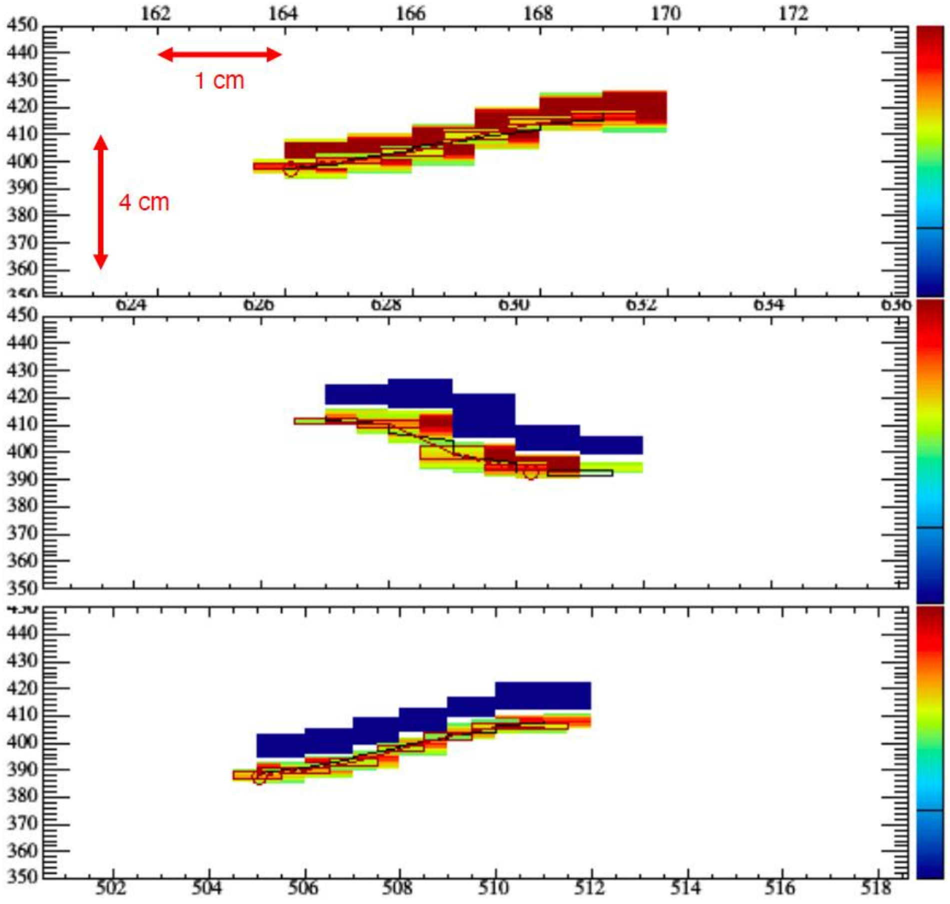
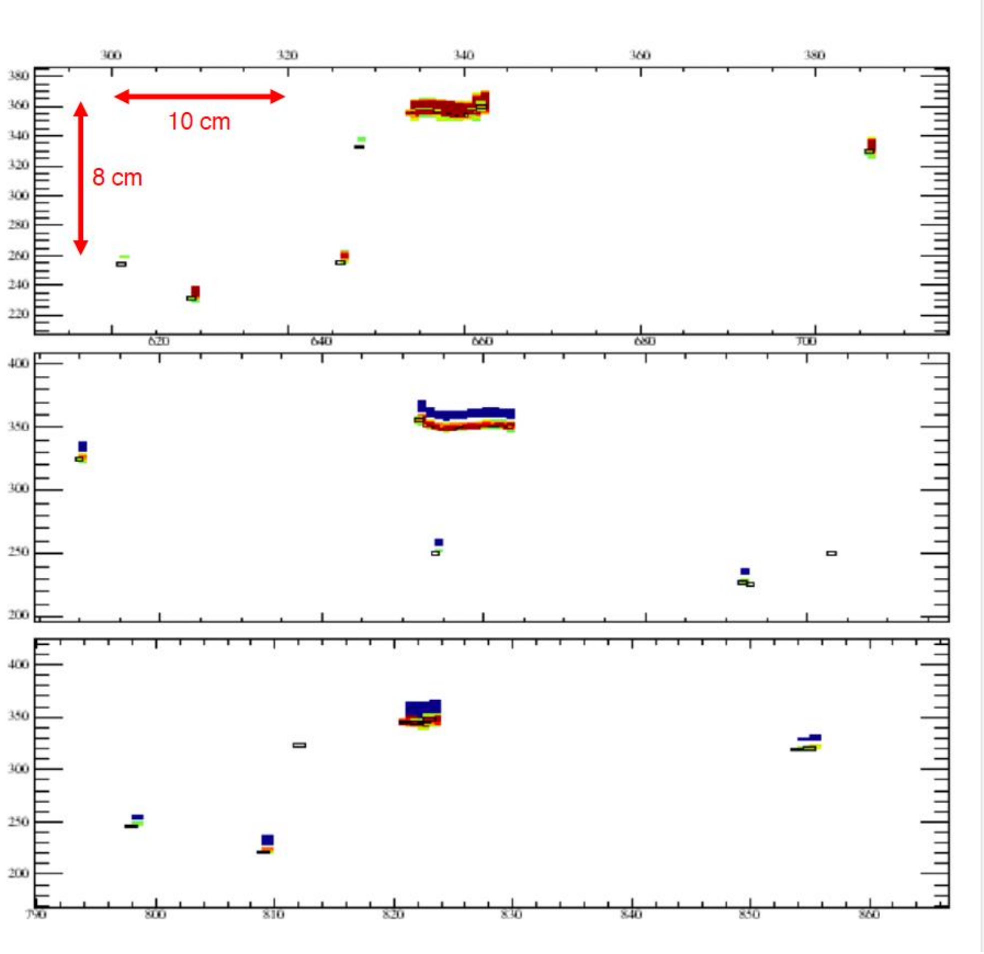
Supernova neutrinos in DUNE

$\nu_X + \mathrm{Ar} \rightarrow \nu_X + \mathrm{Ar}^*$ NC, 10 MeV

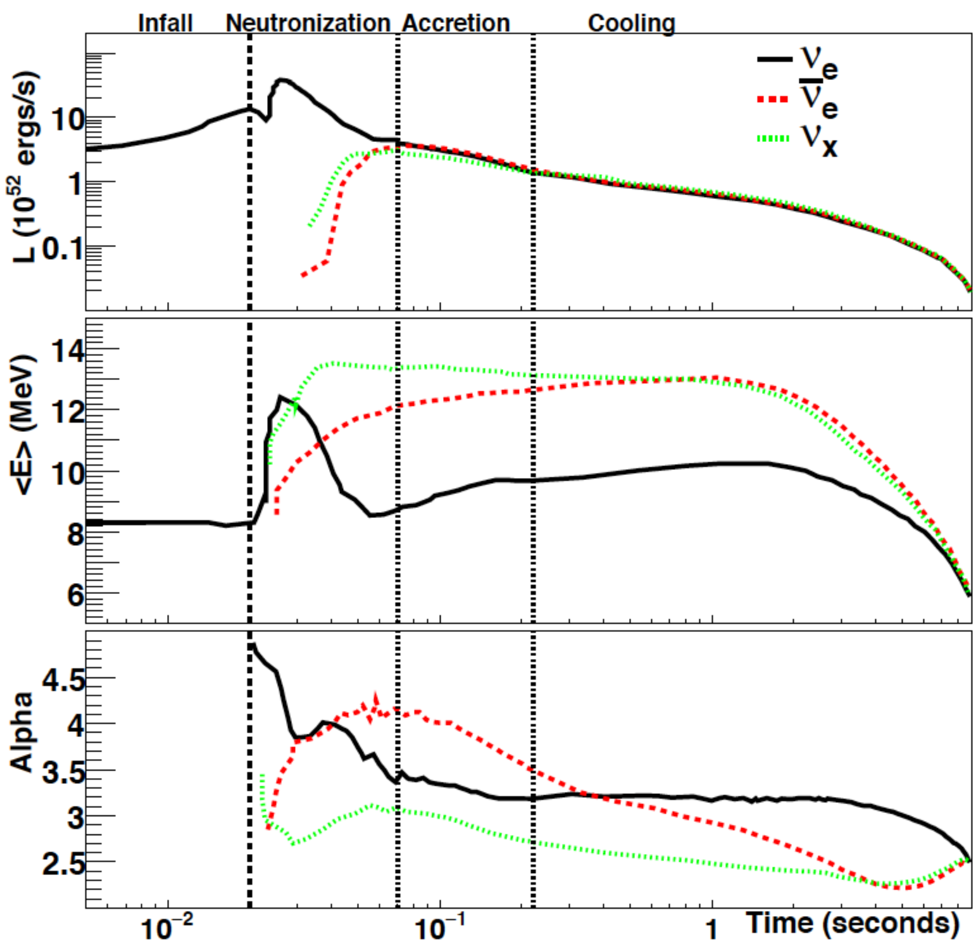


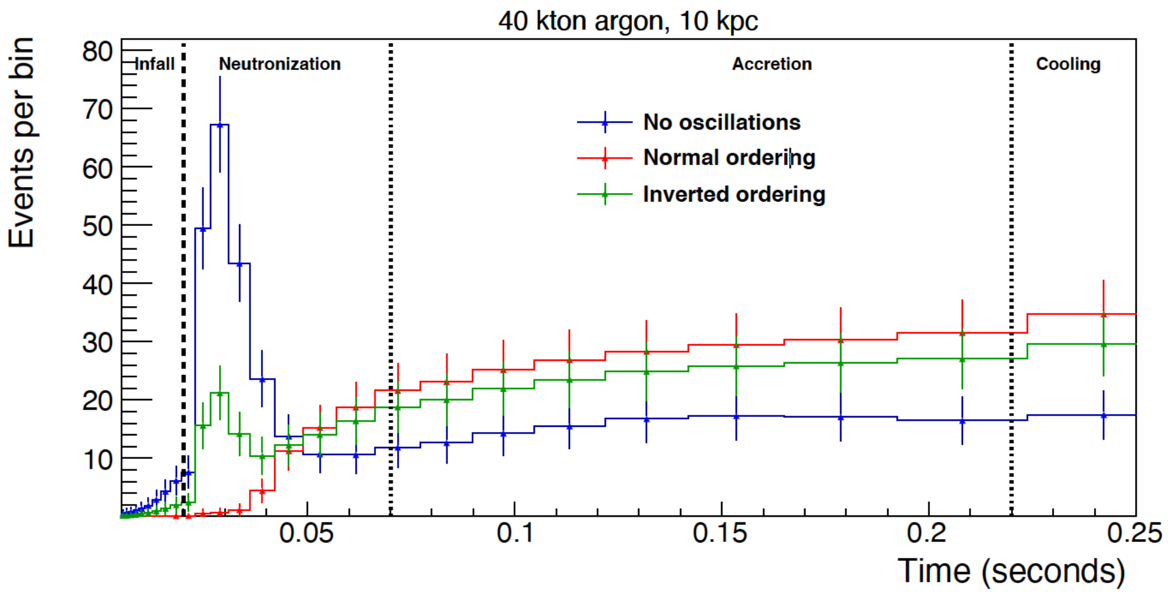
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$ CC, 20 MeV



Reconstruction through charge <u>and</u> light.

Supernova signal in DUNE



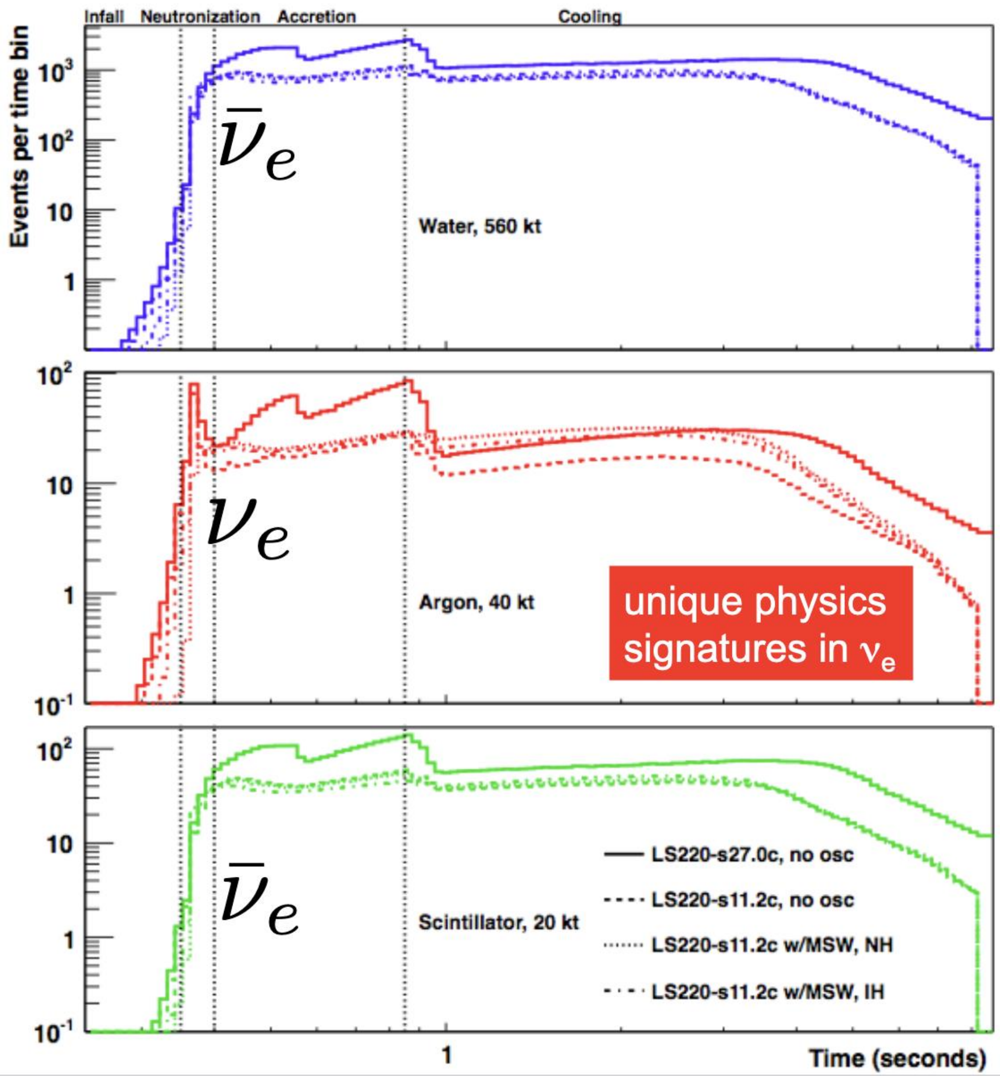


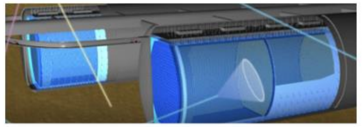
- Neutrinos arrive before the light and can trigger observation by optical telescopes.
- Potentially a signal of 1000s of neutrinos in DUNE.
- Signal will teach us both about neutrinos and about the supernova mechanism.

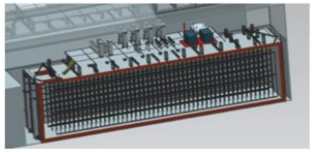
HK/DUNE Complementarity

Two models (11.2 and 27.0 solar masses, NH/IH for former)

Kate Scholberg







arXiv:1508.00785

Mega-scale neutrino detectors: science and technology

- I have only been able to cover a small amount of the rich neutrino physics programme at accelerators.
- These next-generation experiments will test the three-flavour paradigm, provide precision measurements of the neutrino sector, search for non-standard physics (sterile neutrinos, dark matter…), and much more.
- This is complemented by an exciting non-accelerator physics programme, studying solar, atmospheric, and supernova neutrinos.
- Please contact me (stefan.soldner-rembold@cern.ch) if you have any questions.