Neutrino Oscillations

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University of Manchester

Academic Training Lecture Programme
May 2021

MANCHESTER 1824

Lecture 3

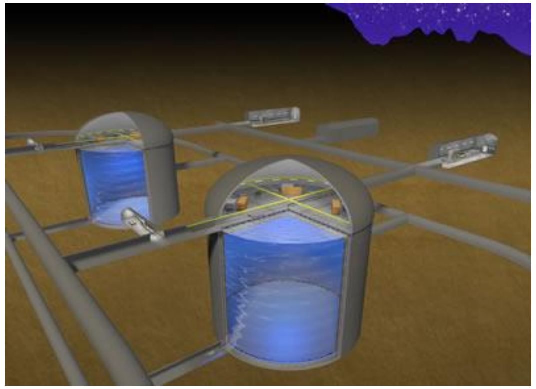
Future long-baseline experiments

Optimizing L/E for neutrino oscillations

$$\boxed{\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2}}$$

L ≈ 300 km

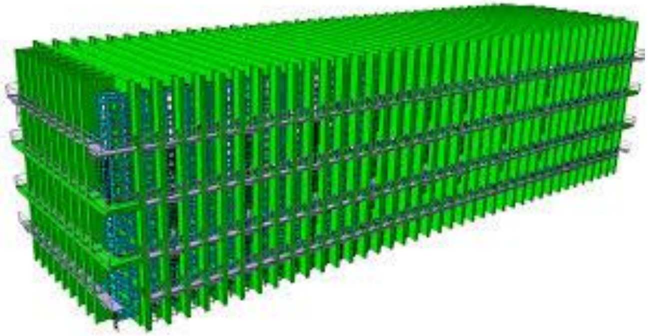
- L/E = 300 km /0.6 GeV = 500 km/GeV
- no matter effects; first oscillation maximum.
- use narrow width neutrino beam (off axis) with E < 1 GeV
- benefit from large mass



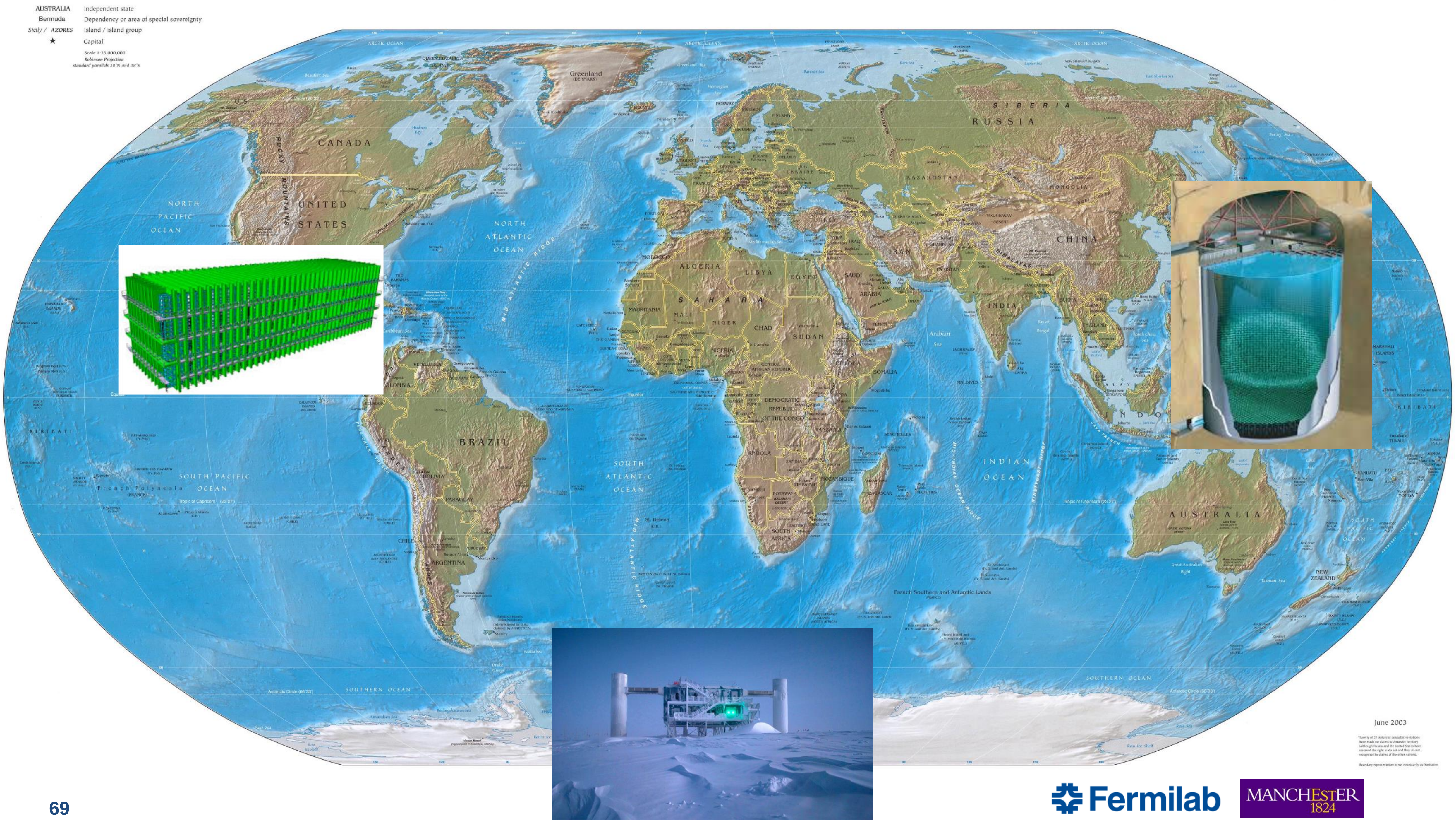
Water Cherenkov (T2K,HK)

L = 1300 km

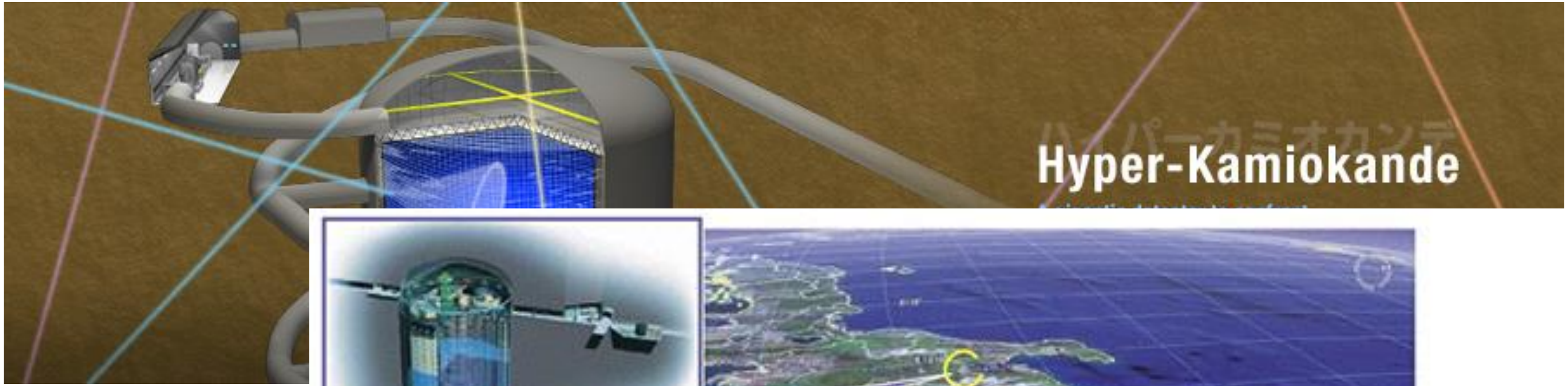
- L/E = 1300 km/2.5 GeV = 500 km/GeV (1^{st} max),
- L/E = 1300 km/0.8 GeV = 1700 km/GeV (2^{nd} max)
- matter effects; first <u>and</u> second oscillation maximum.
- use broad-band neutrino beam (on axis).
- need good energy reconstruction



Liquid argon (DUNE)

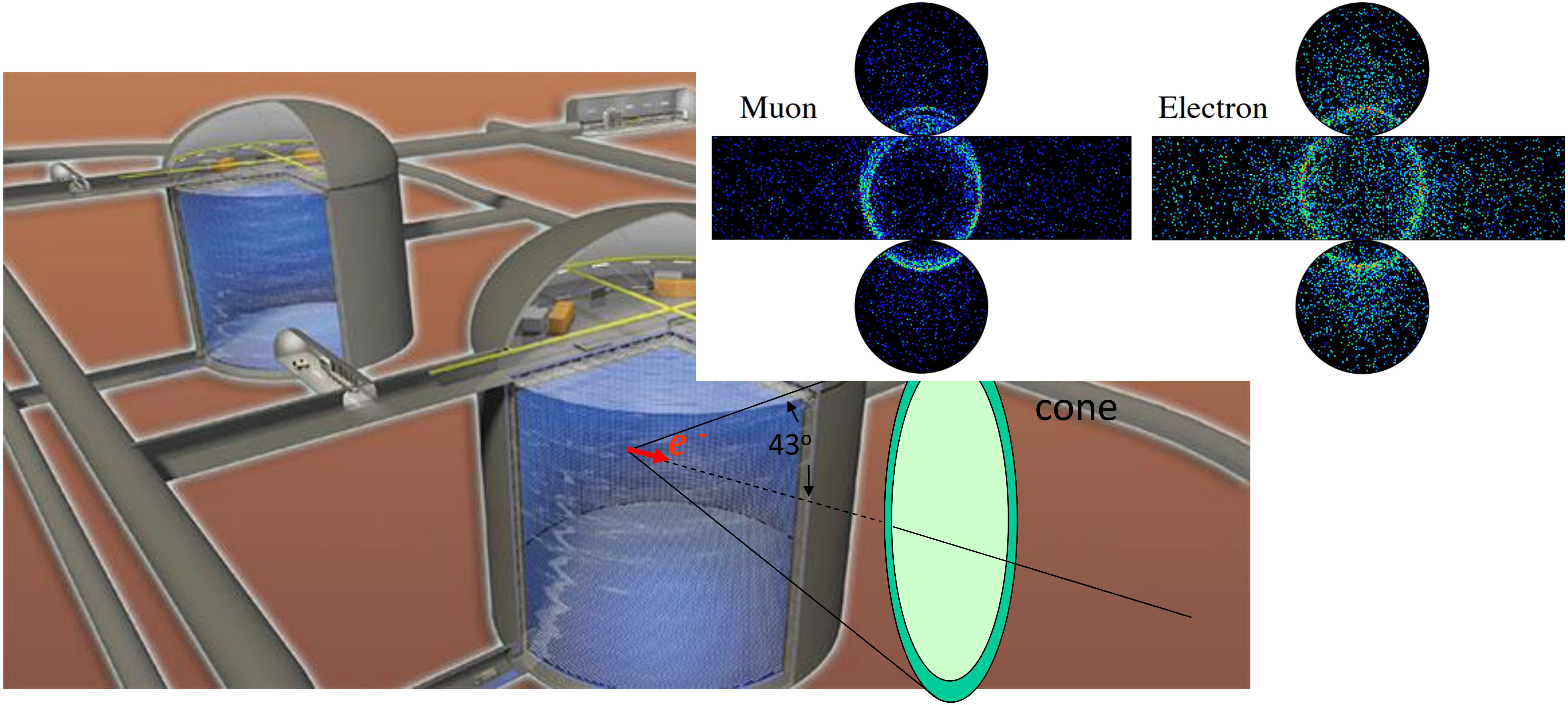

AUSTRALIA Independent state
Bermuda Dependency or area of special sovereignty
Sicily / AZORES Island / island group
Capital
Scale 1:35,000,000
Robinson Projection
standard parallels 38°N and 38°S
ARCTIC OCEAN
Greenland (DENMARK)
CANADA
UNITED STATES
NORTH PACIFIC OCEAN
NORTH ATLANTIC OCEAN
RUSSIA
SIBERIA
KAZAKHSTAN
MONGOLIA
CHINA
INDIA
ALGERIA
LIBYA
EGYPT
SAHARA
MALI
NIGER
CHAD
SUDAN
NIGERIA
ETHIOPIA
SOMALIA
DEMOCRATIC REPUBLIC OF THE CONGO
TANZANIA
ANGOLA
ZAMBIA
MOZAMBIQUE
BOTSWANA
SOUTH AFRICA
MADAGASCAR
BRAZIL
BOLIVIA
PARAGUAY
CHILE
ARGENTINA
SOUTH PACIFIC OCEAN
SOUTH ATLANTIC OCEAN
INDIAN OCEAN
AUSTRALIA
NEW ZEALAND
SOUTHERN OCEAN
French Southern and Antarctic Lands
KIRIBATI
June 2003

Hyper-Kamiokande



	Super-K	Hyper-K
Overburden	1000 m	650 m
Number of ID PMT	11,000	40,000
Photo-coverage	40%	40% (×2 sensitivity)
Total/Fiducial vol.	50 / 22.5 kton	260 / 188 kton

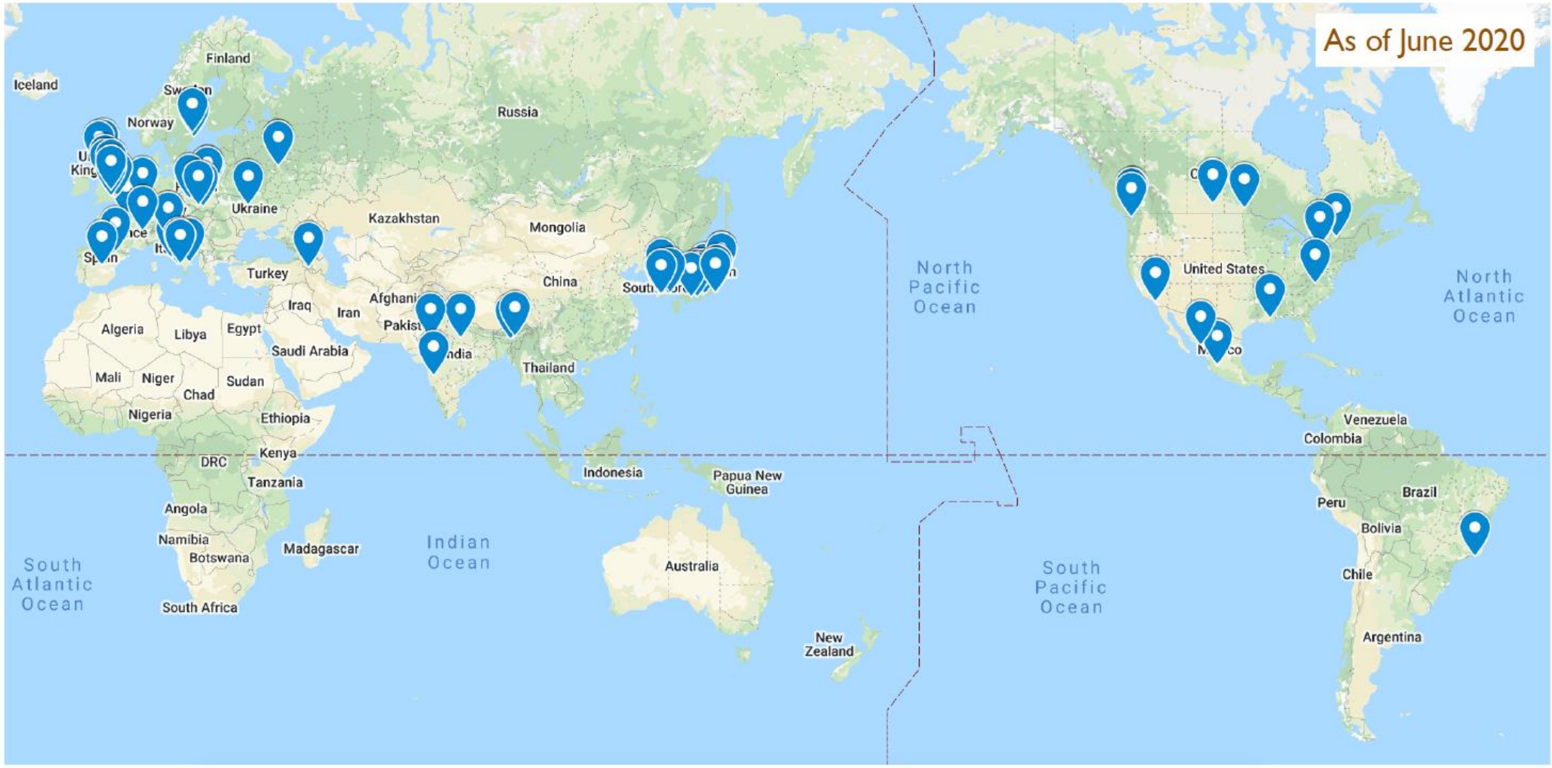
Hyper-Kamiokande



An international project

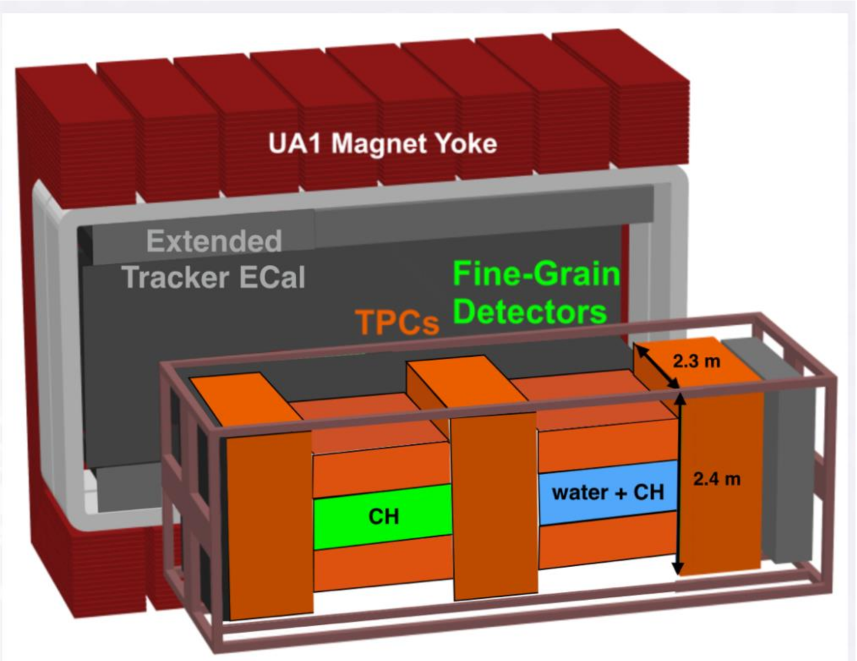
18 countries, 82 institutes, ~390 people

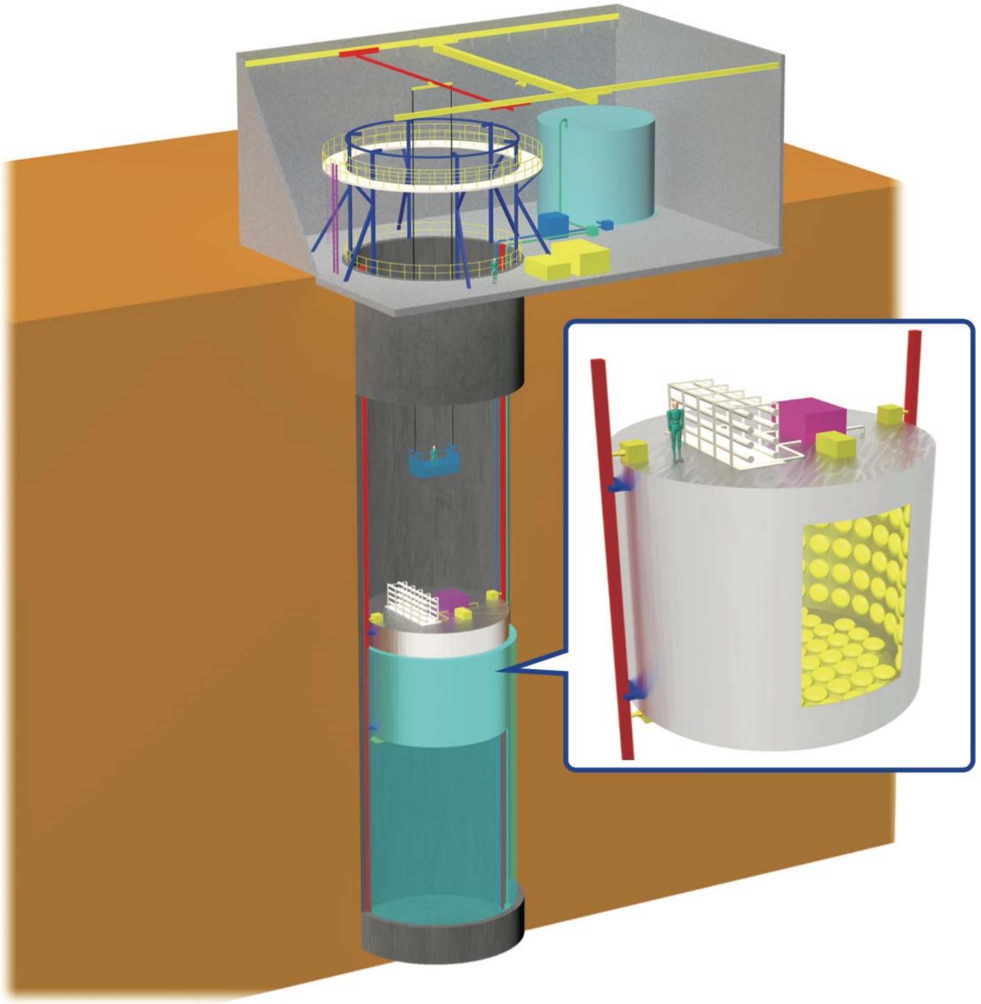
Hyper-Kamiokande



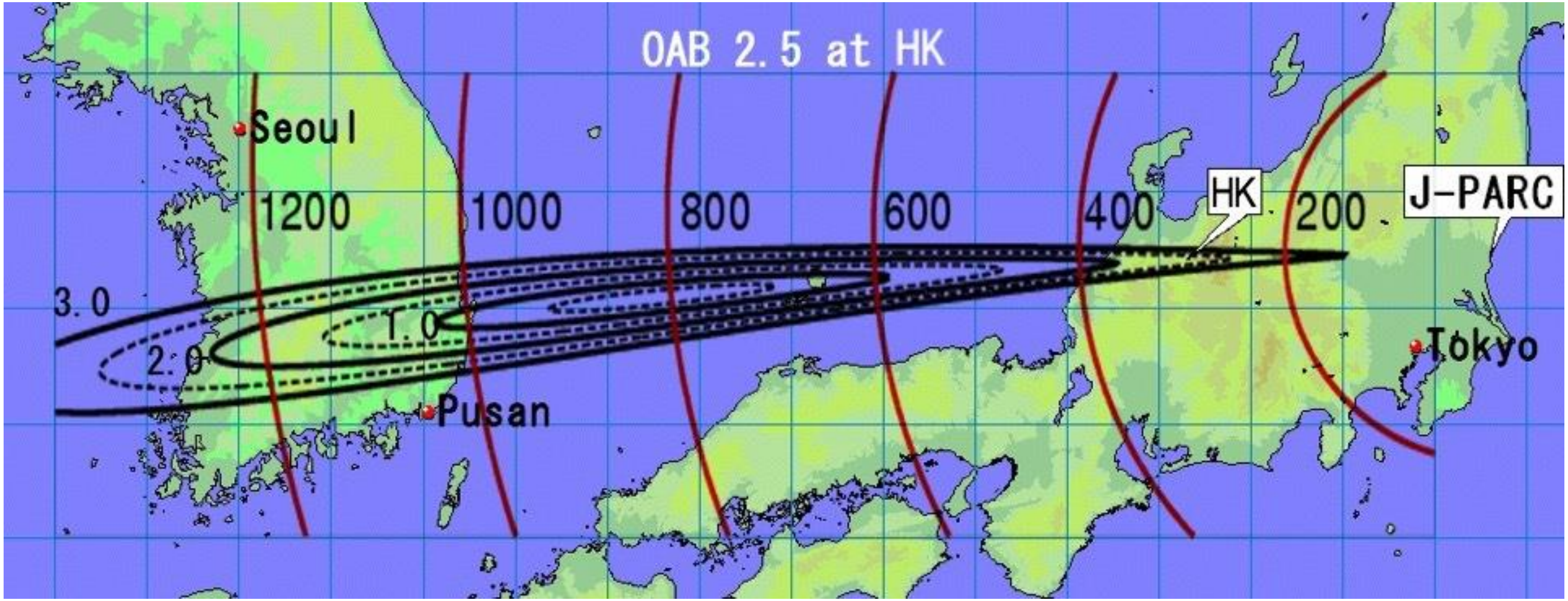
An upgraded Near Detector

- 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

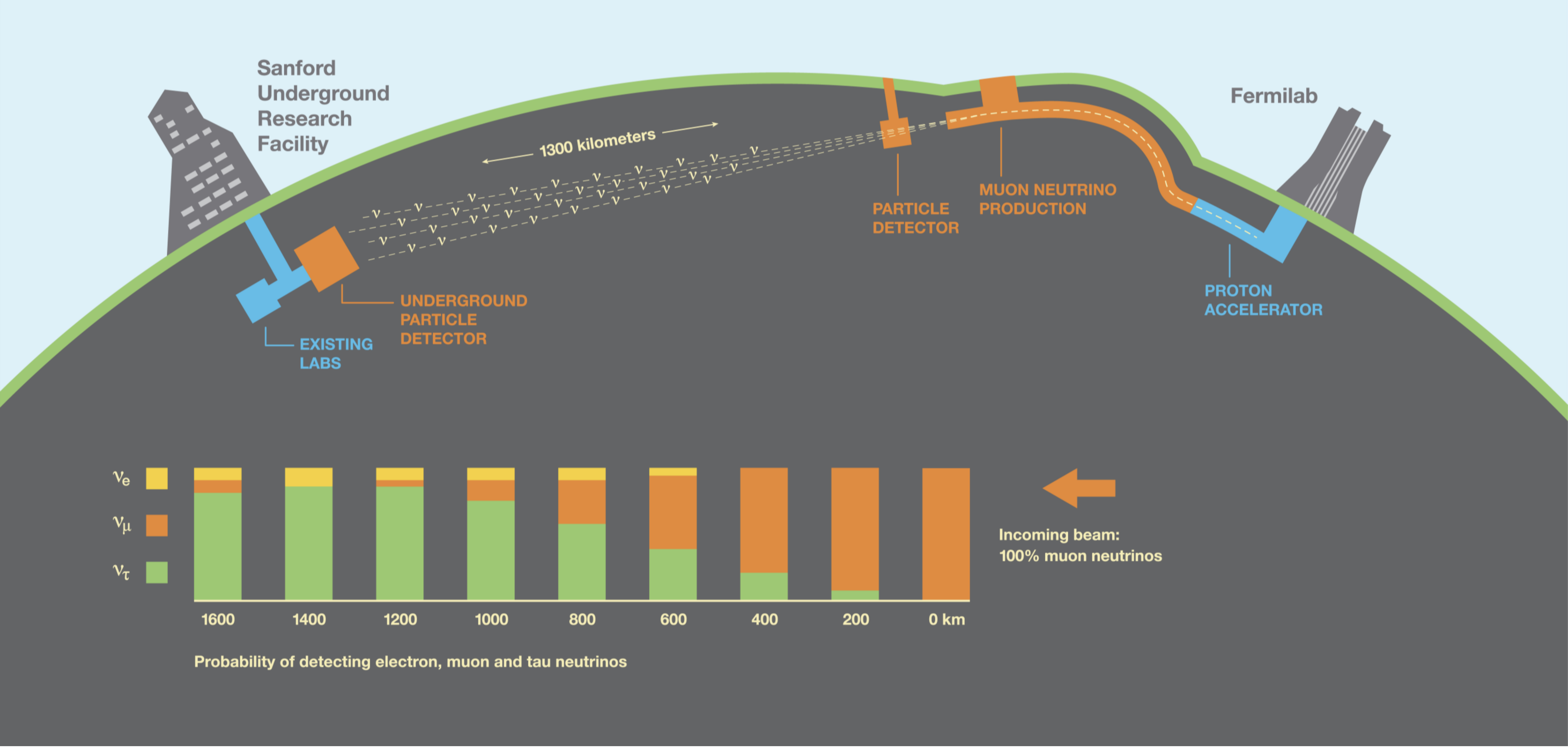




Hyper-Kamiokande to Korea?



Deep Underground Neutrino Experiment



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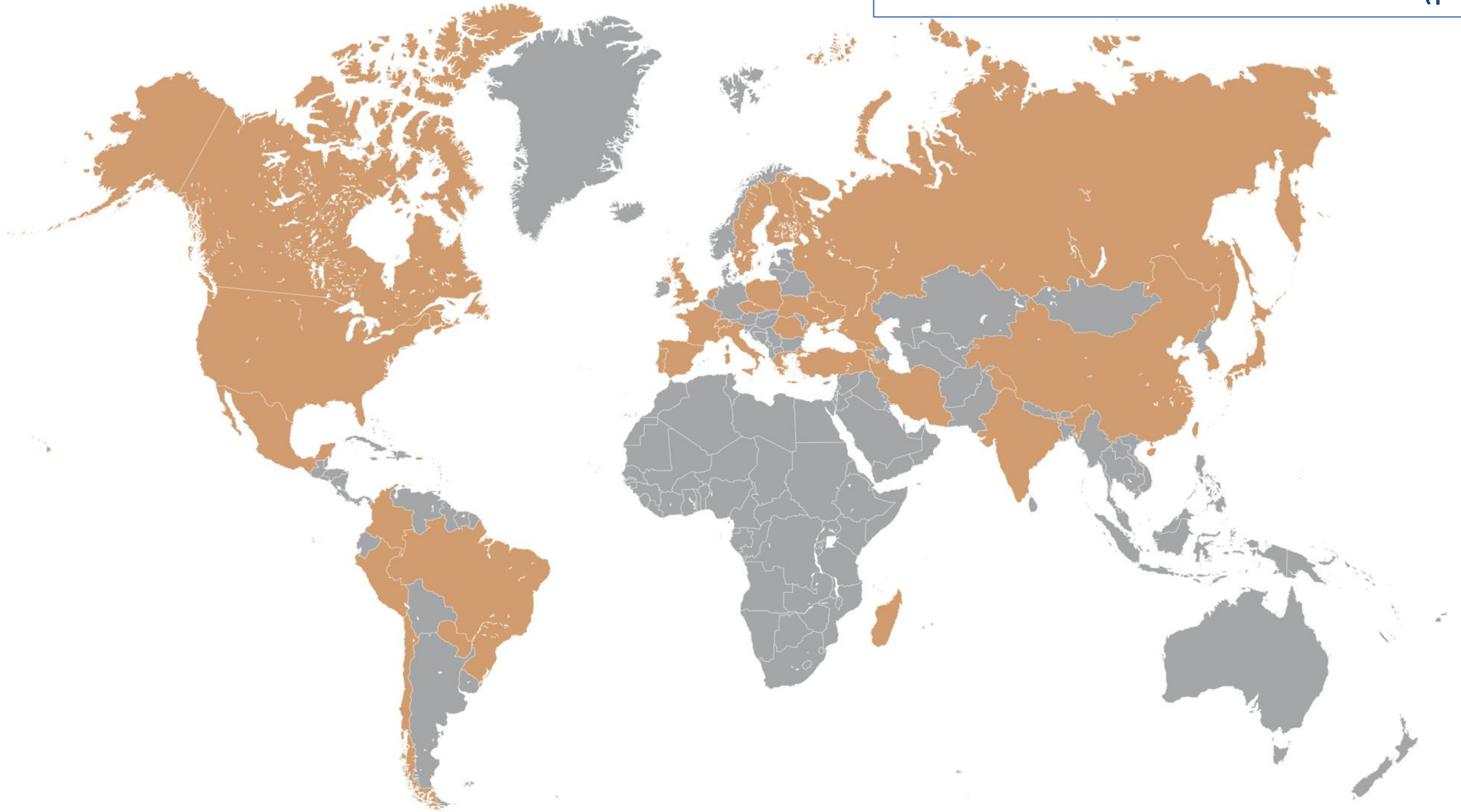
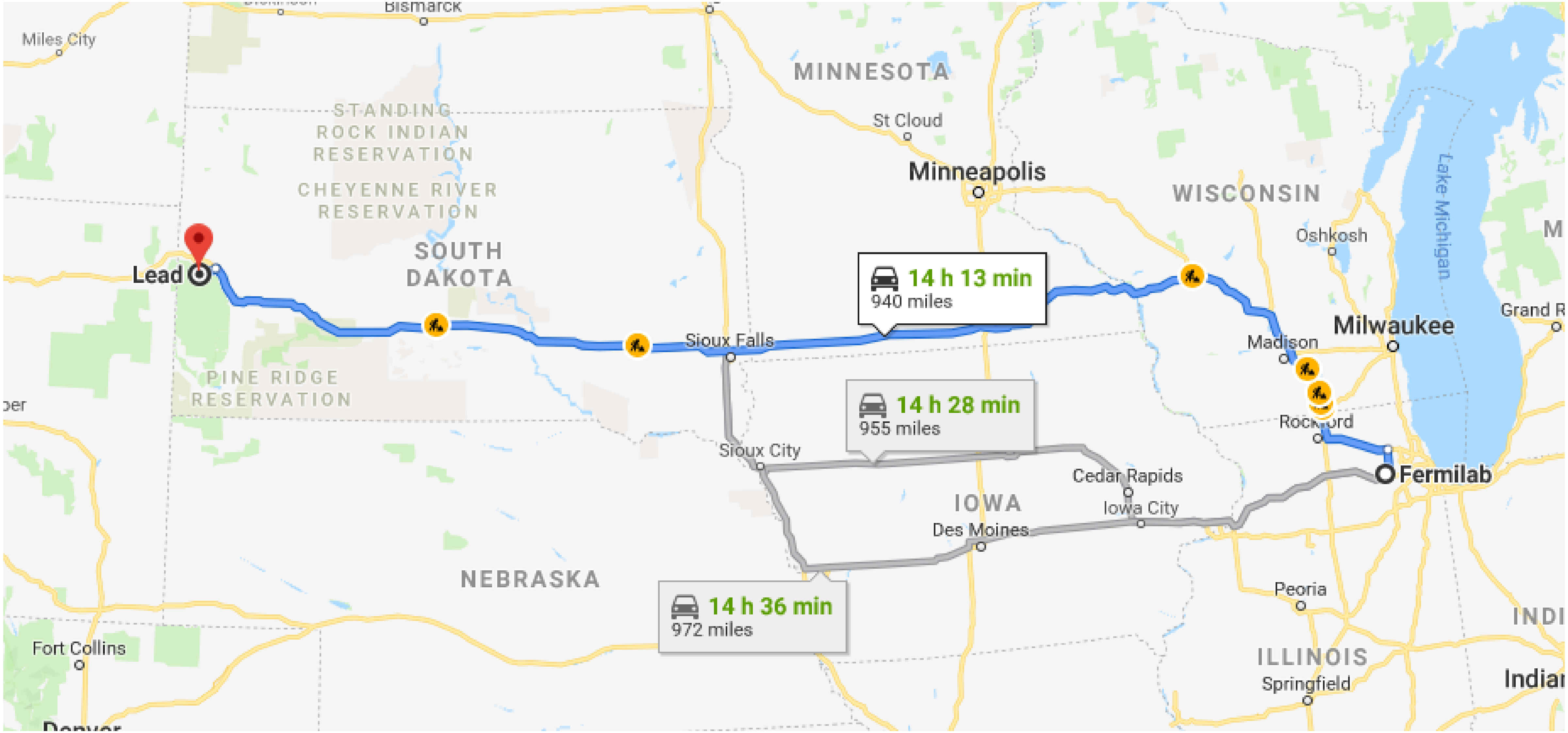
April 2015

DUNE – a global collaboration

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



L/E = 500 km/GeV ⇒ L = 1300 km



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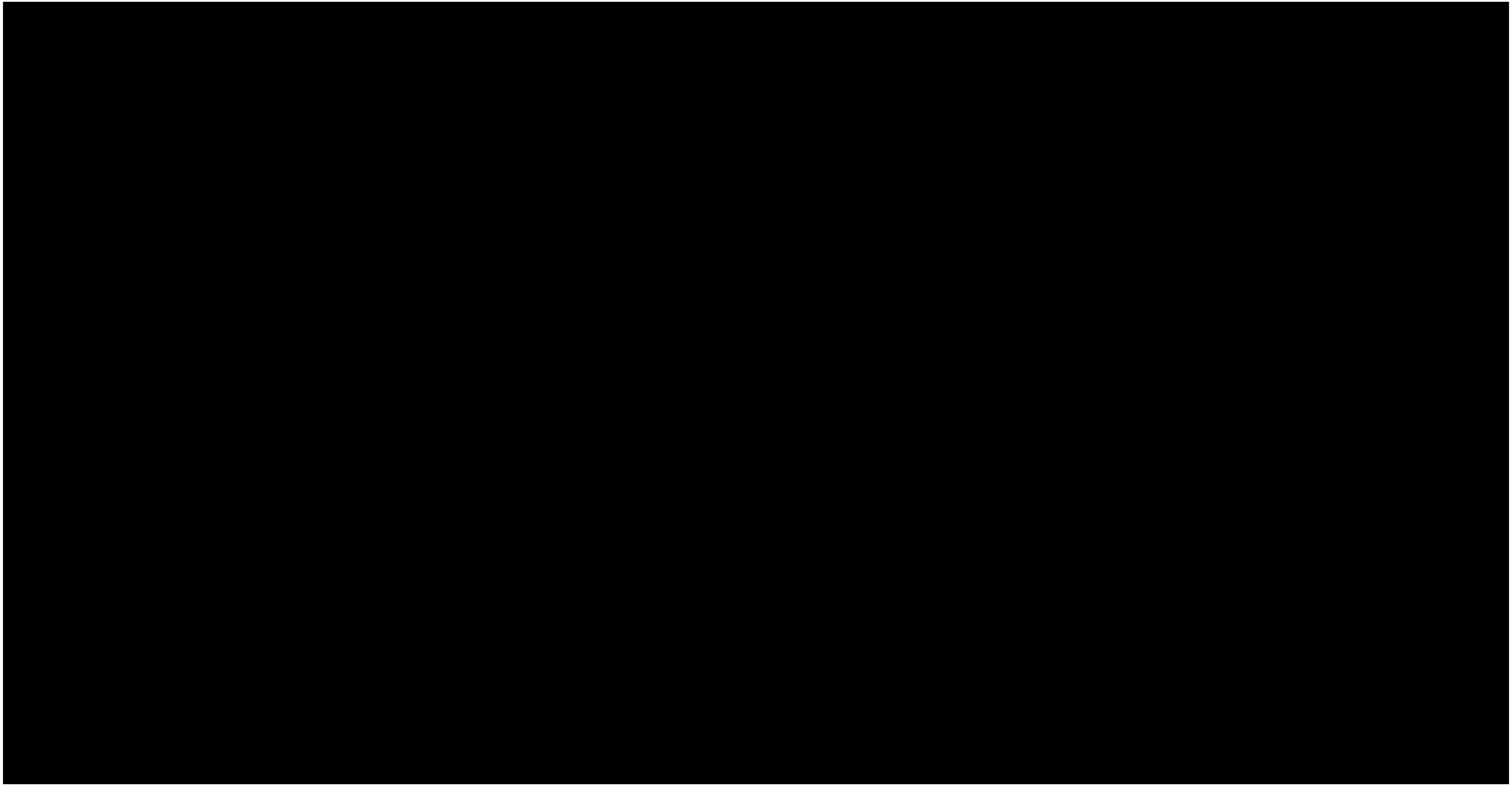
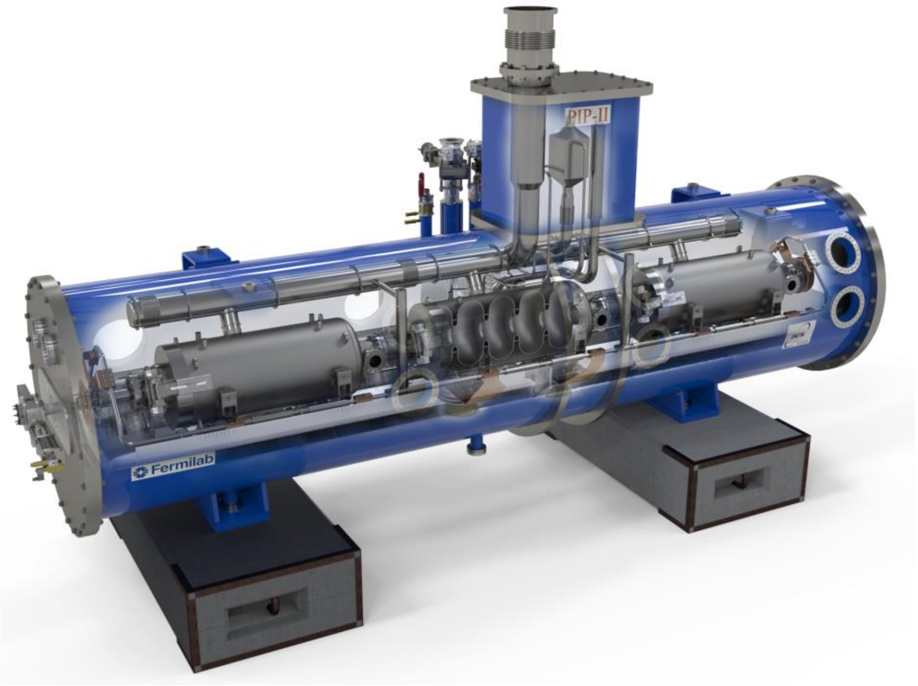
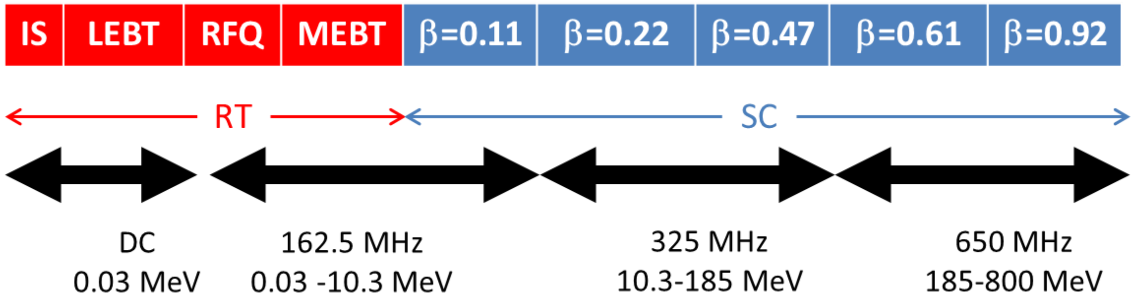


Proton Improvement Plan (PIP-II)

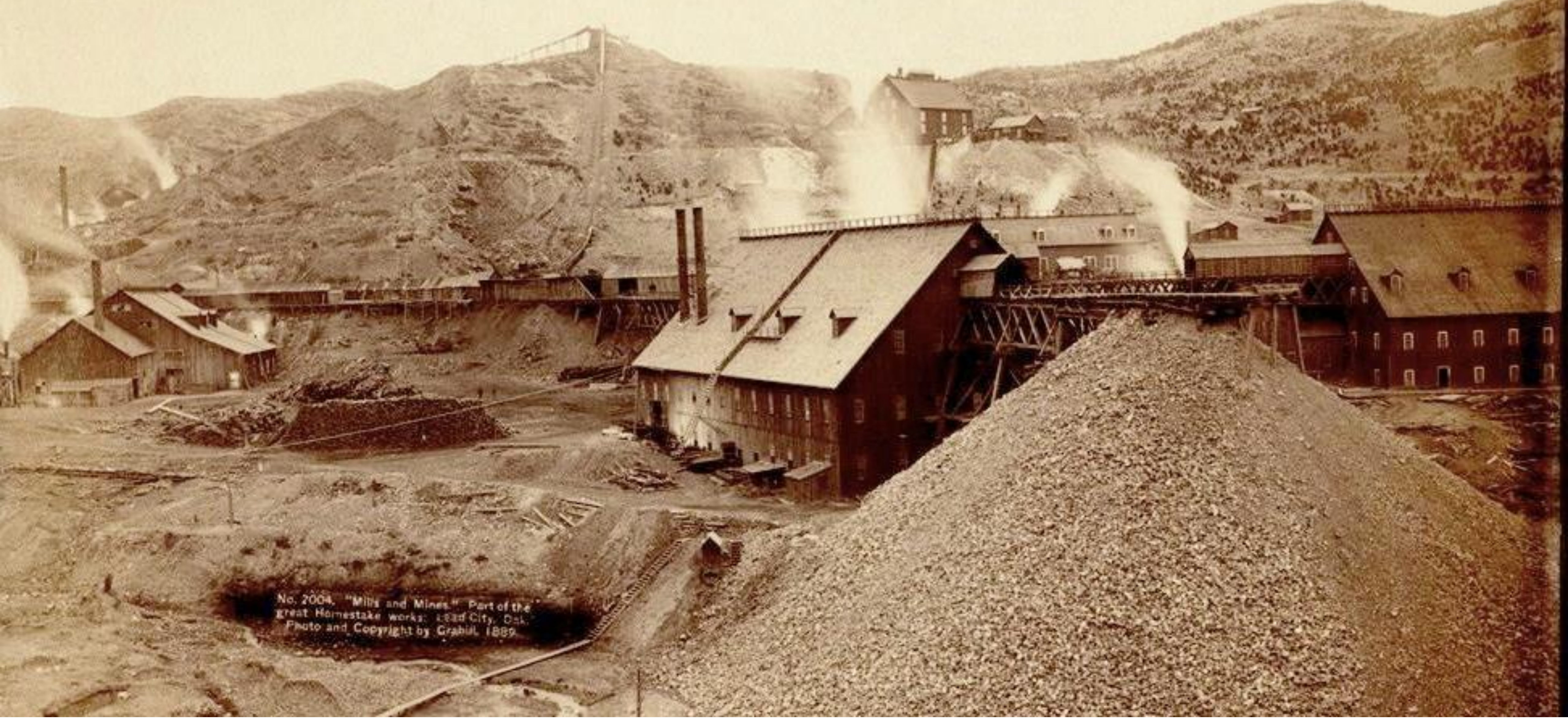
- Goal: Deliver world-leading beam power to the DUNE/LBNF neutrino programme while providing a flexible platform for the future
  - 1.2 MW to LBNF over 60-120 GeV;
  - upgradable to 2.4 MW
- Scope
  - 800-MeV SC Linac
  - Modifications to Booster, Recycler, Main Injector
- Broad international effort



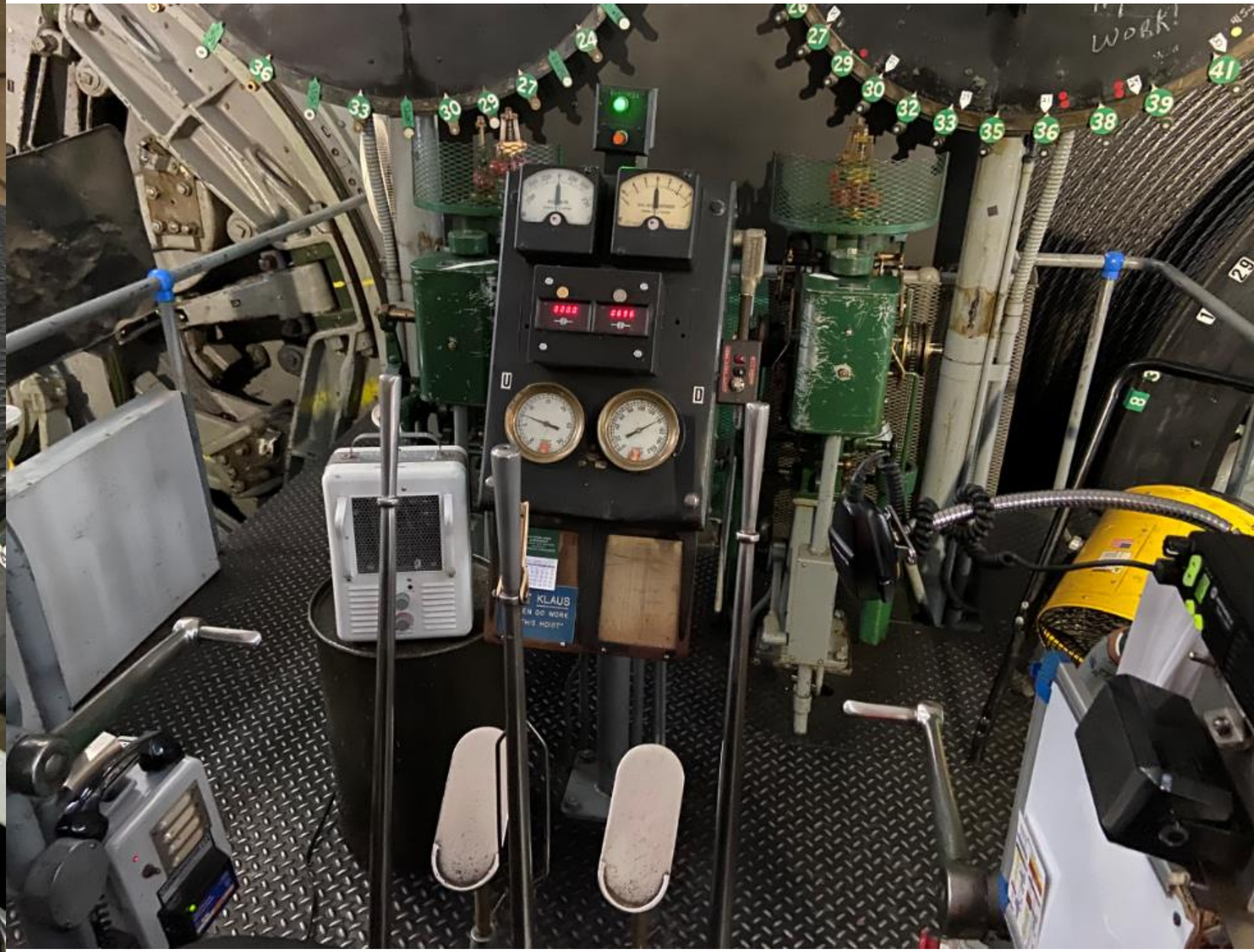


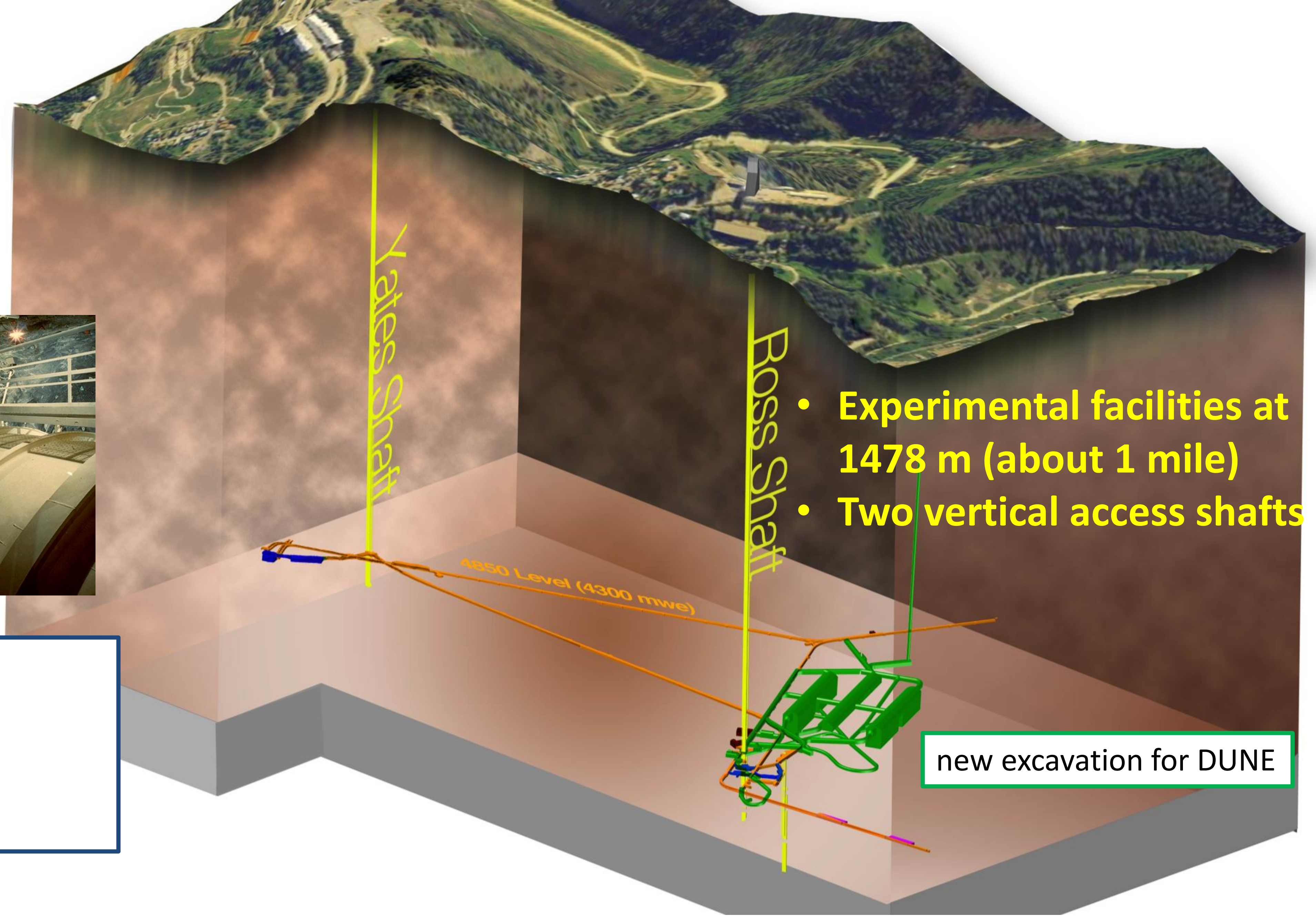
Sanford Underground Research Facility (SURF)

The Homestake Mine in 1889



Hoist technology upgrade (Tardis?)





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

Davis Campus:
- LUX
- Majorana
- …
- LZ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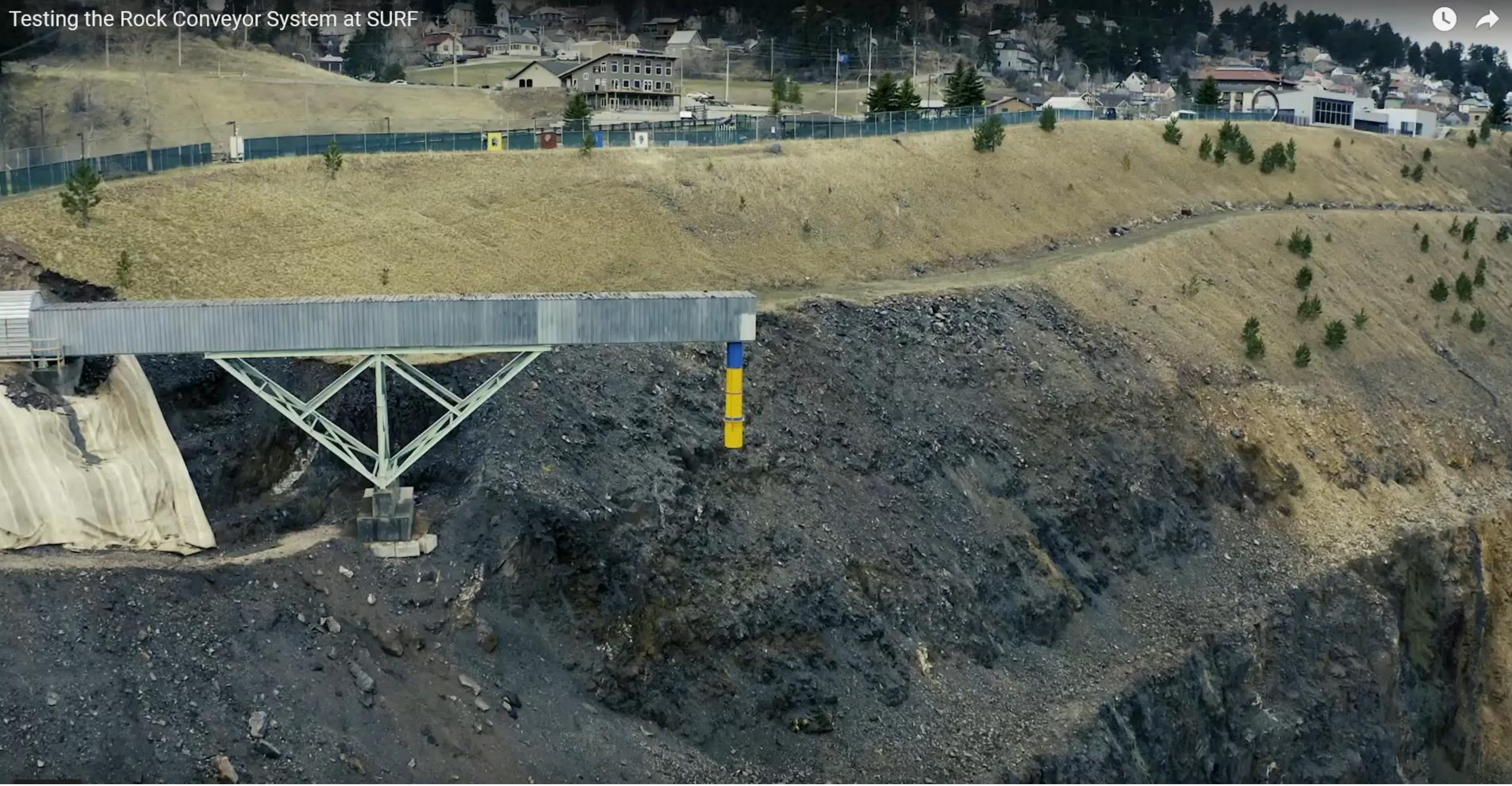
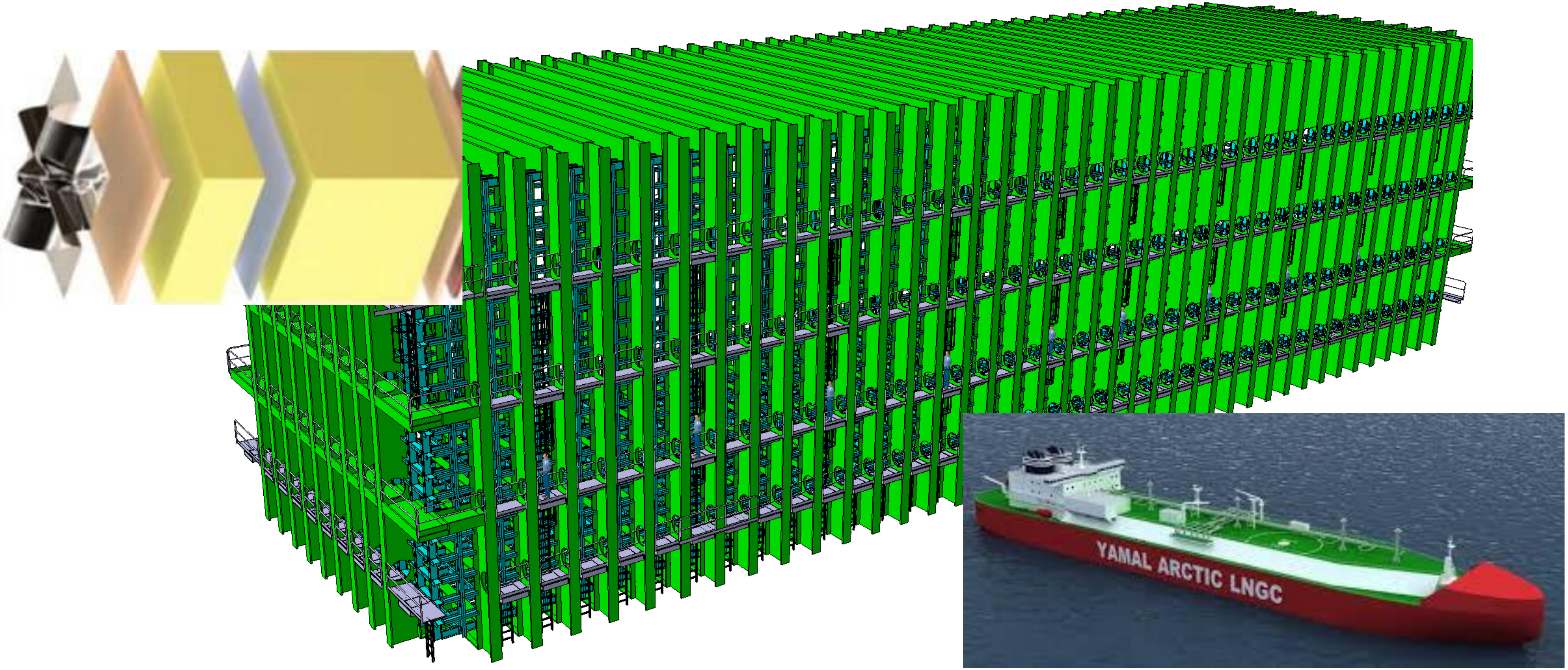

Testing the Rock Conveyor System at SURF

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)



<u>External Dimensions: </u>19 m x 18 m x 66 m

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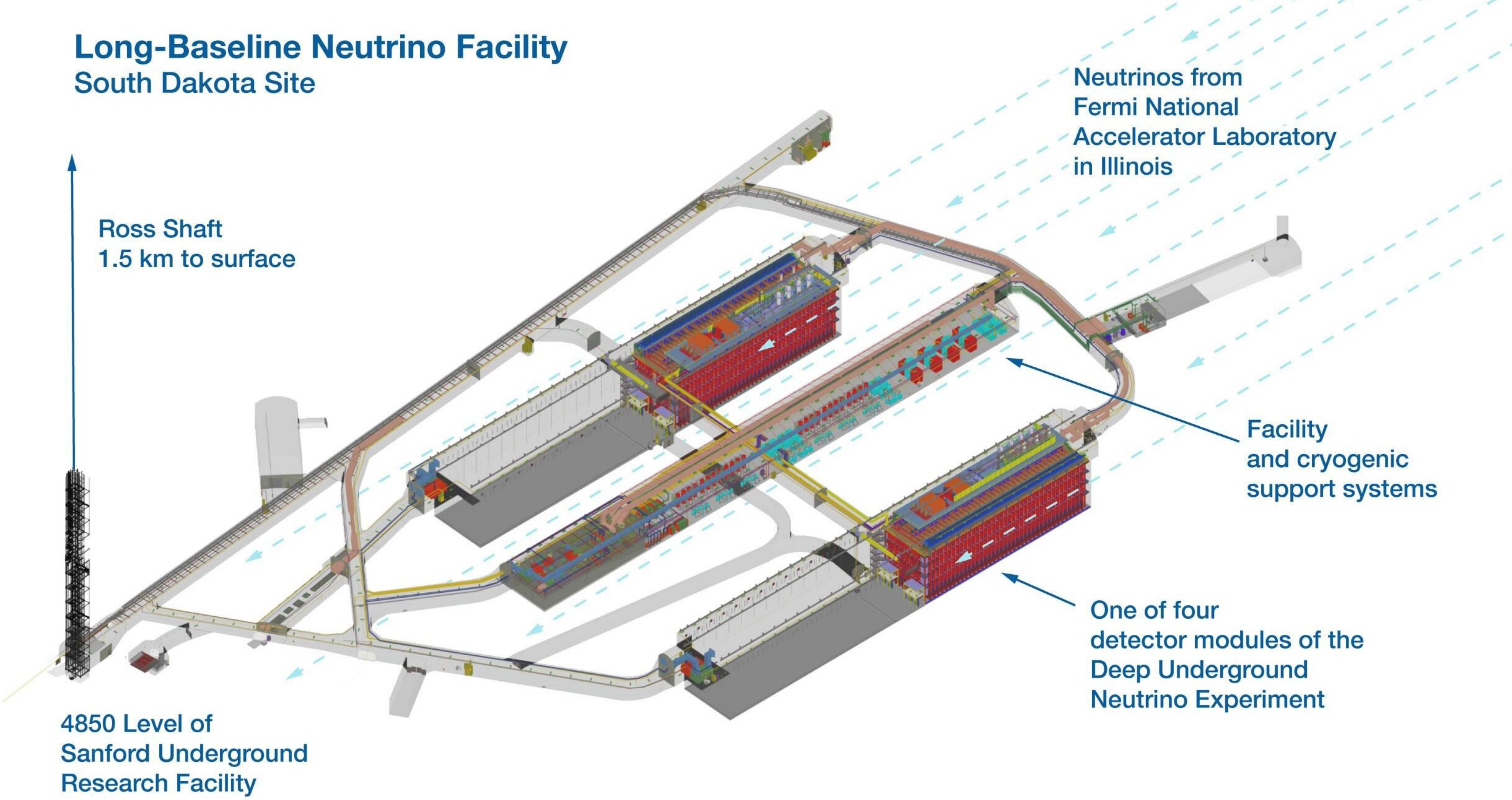
Long-Baseline Neutrino Facility
South Dakota Site



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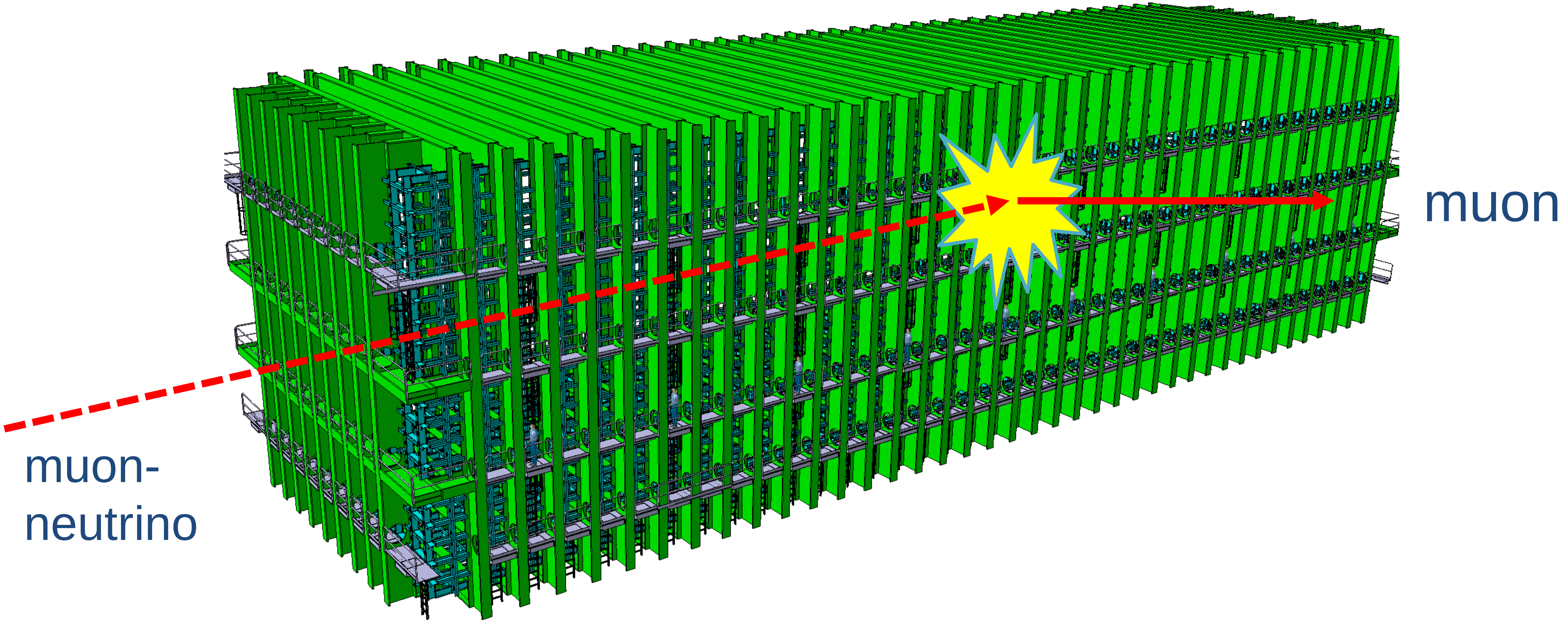
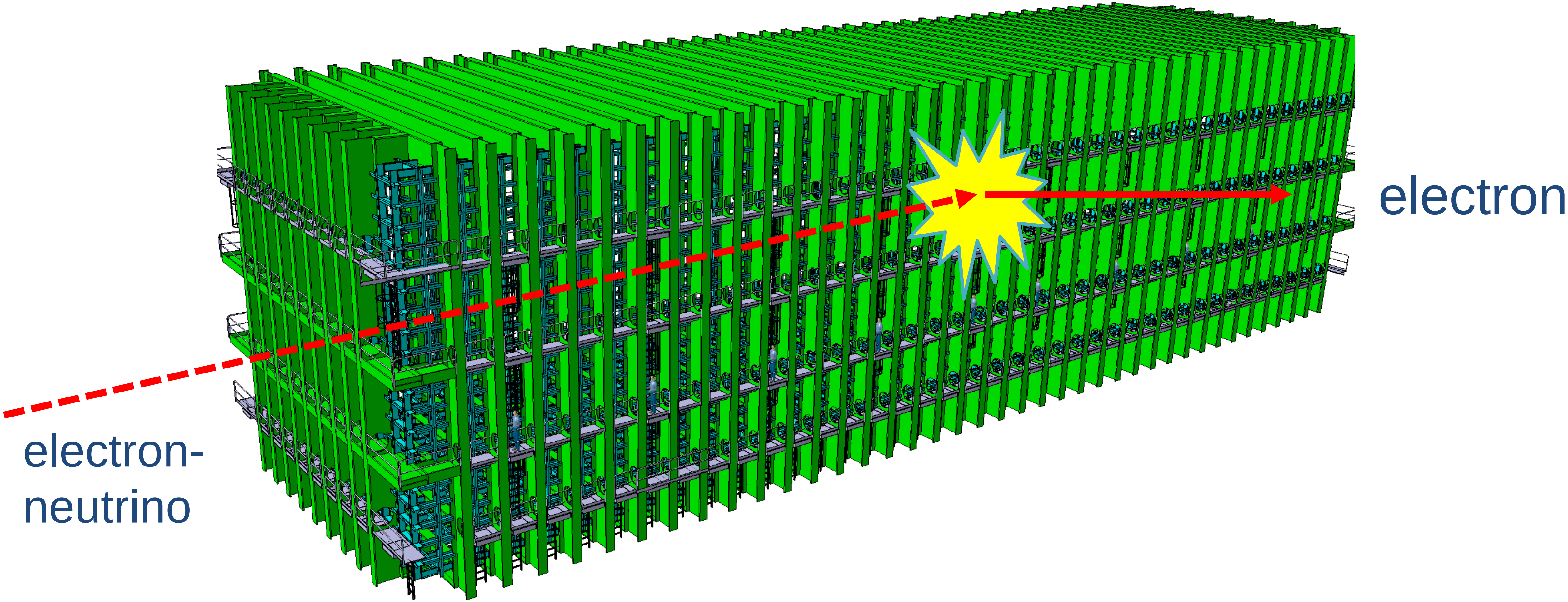
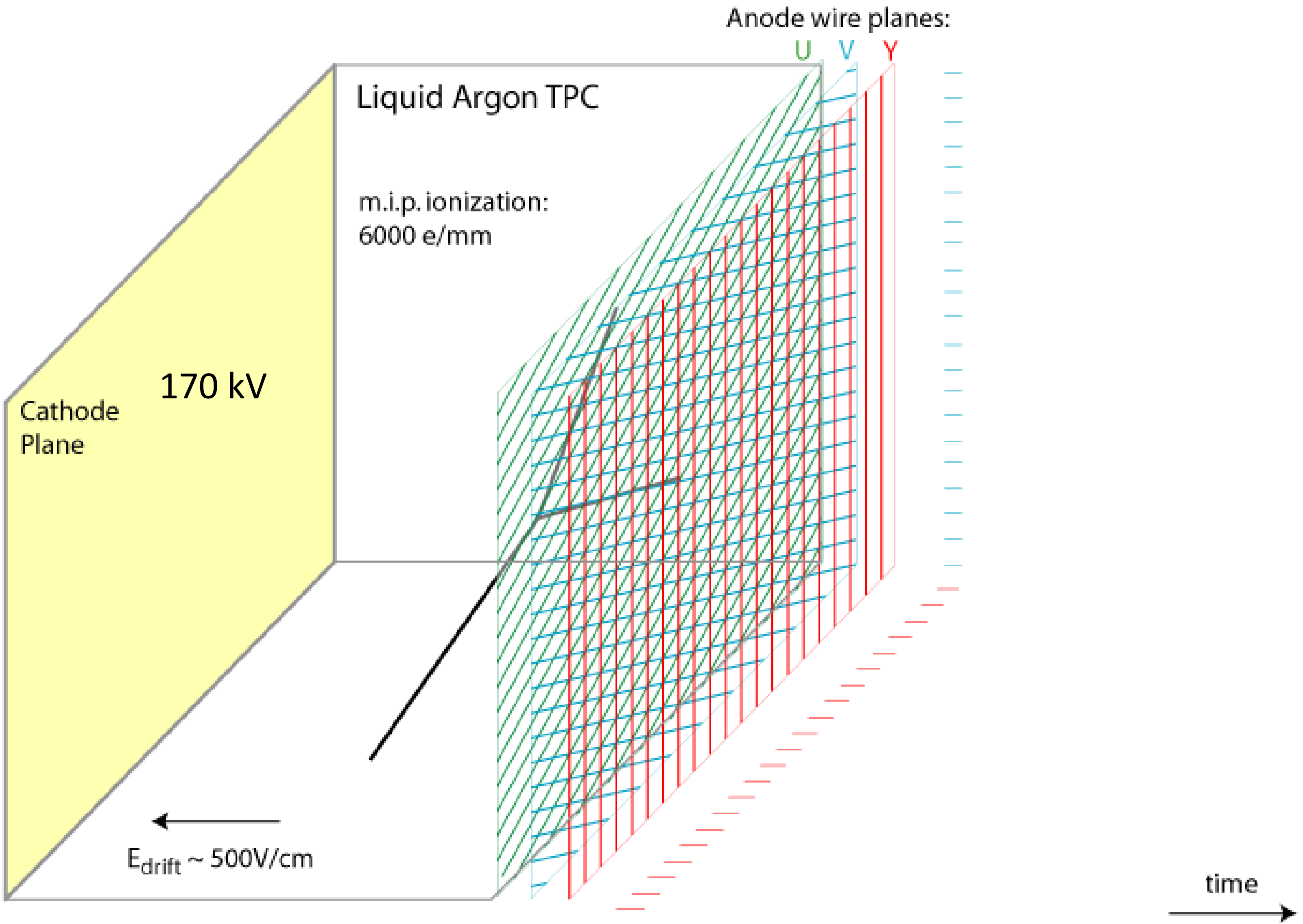
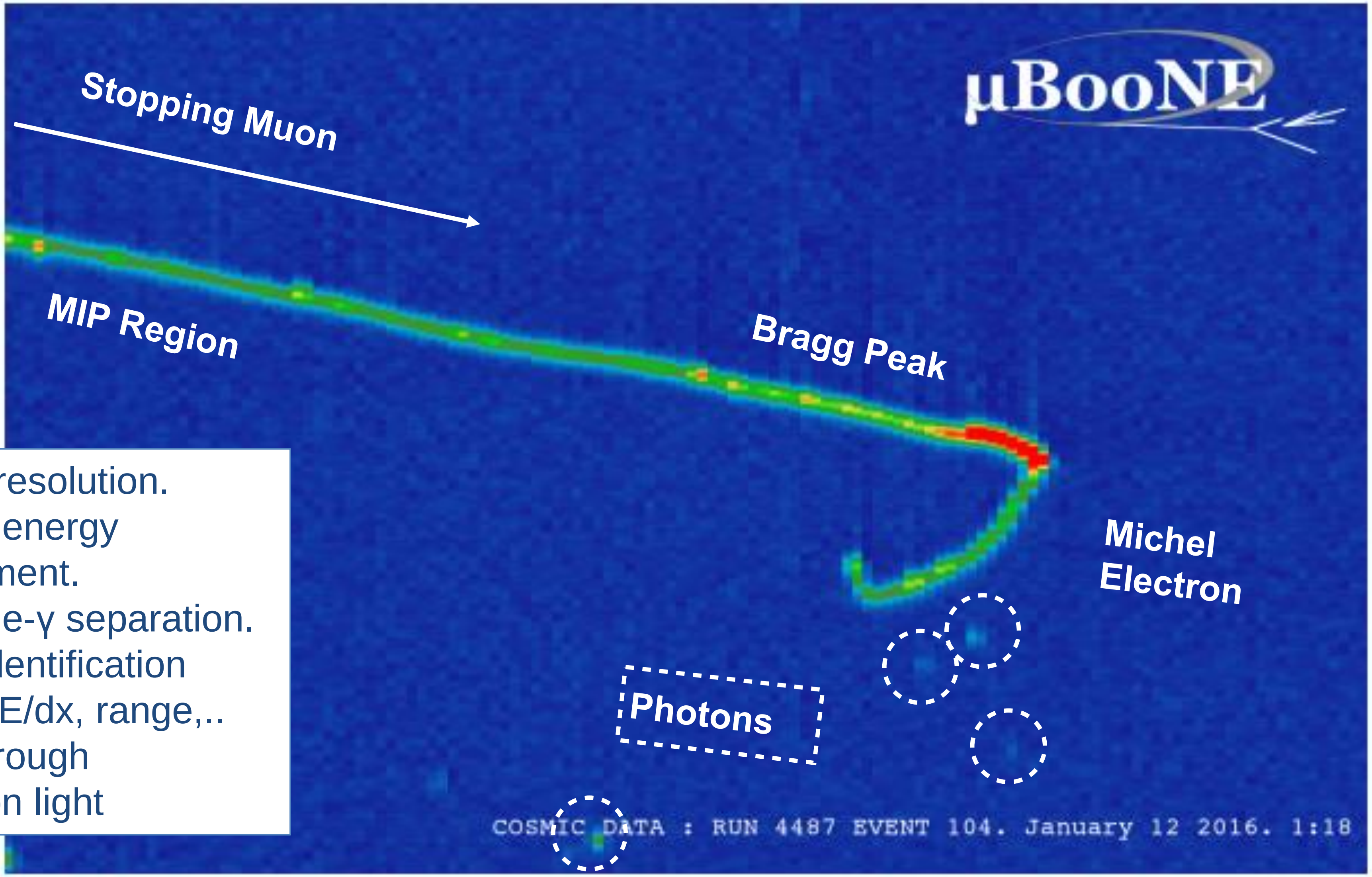

muon
muon-
neutrino


electron
electron-
neutrino

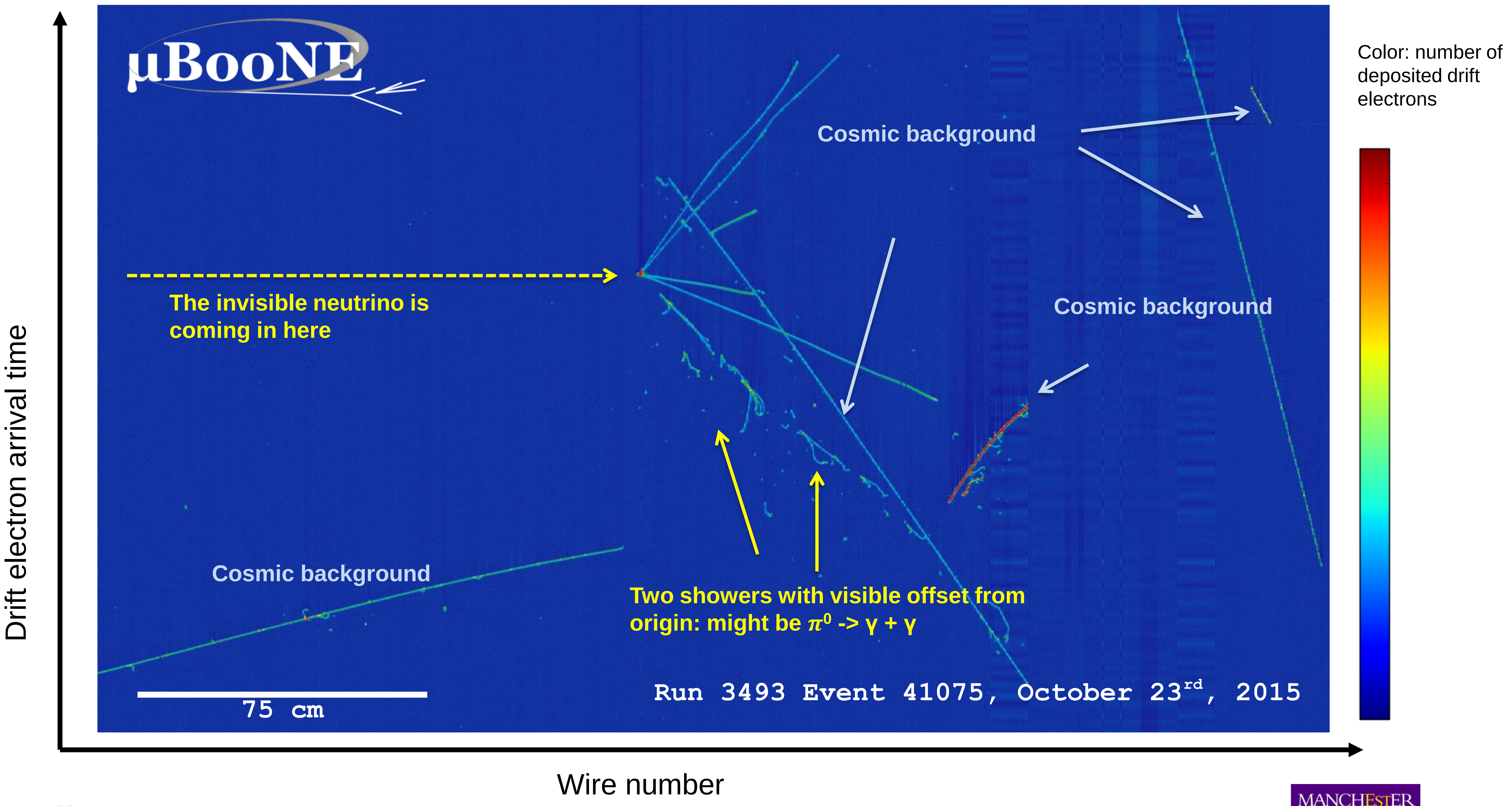


3.4 m → about 2 ms

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



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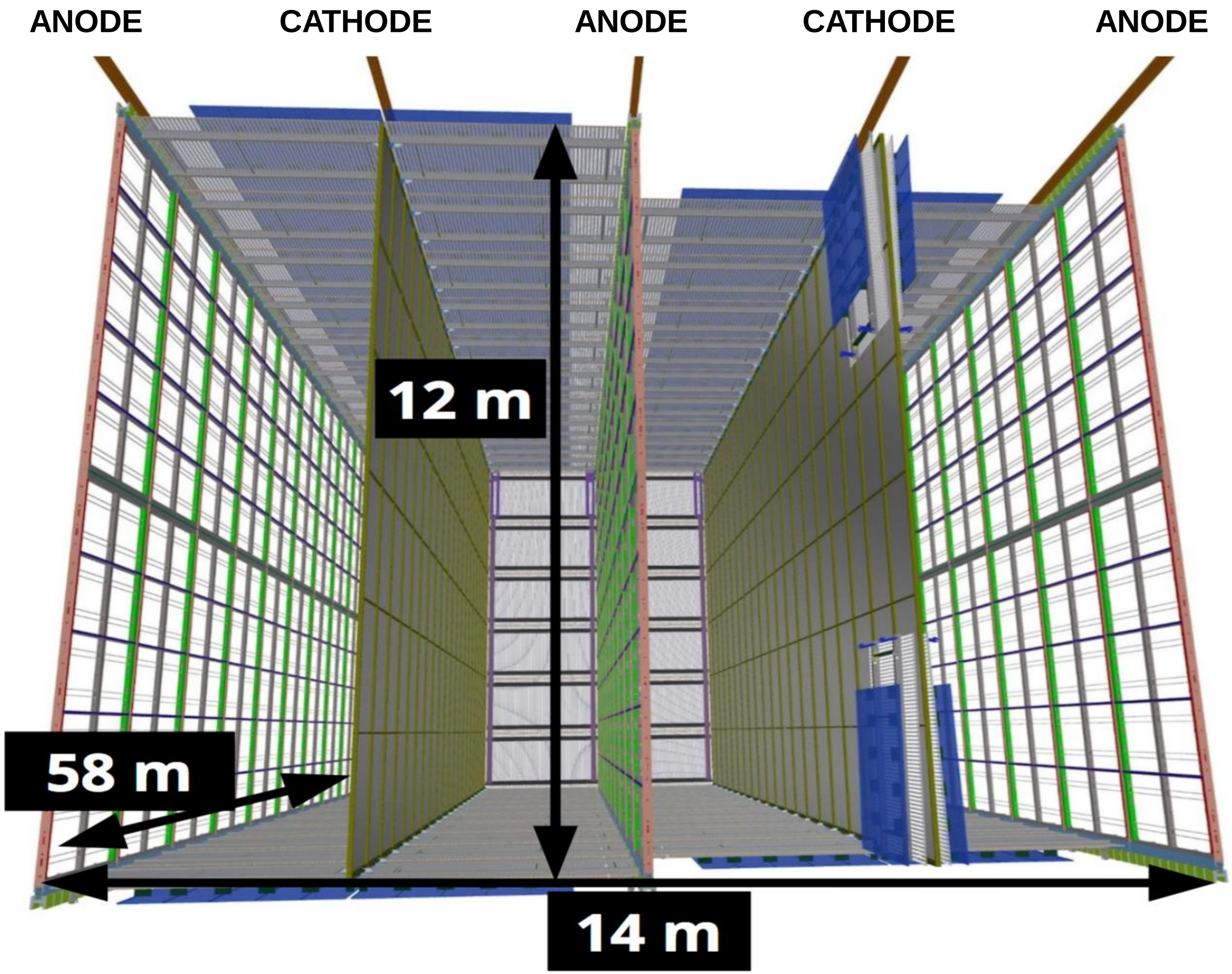
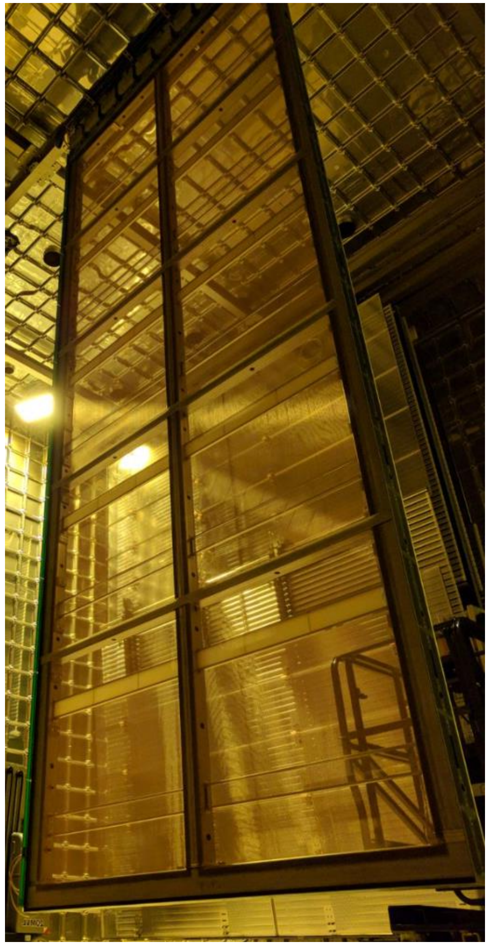
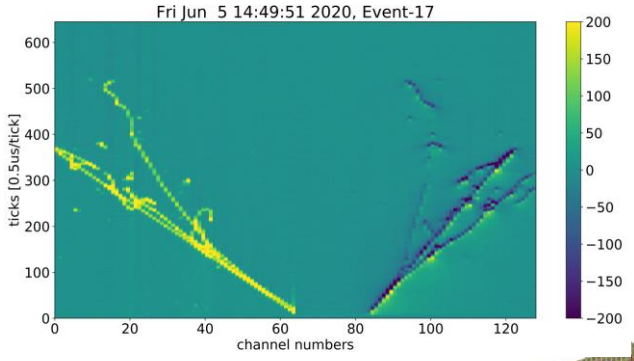
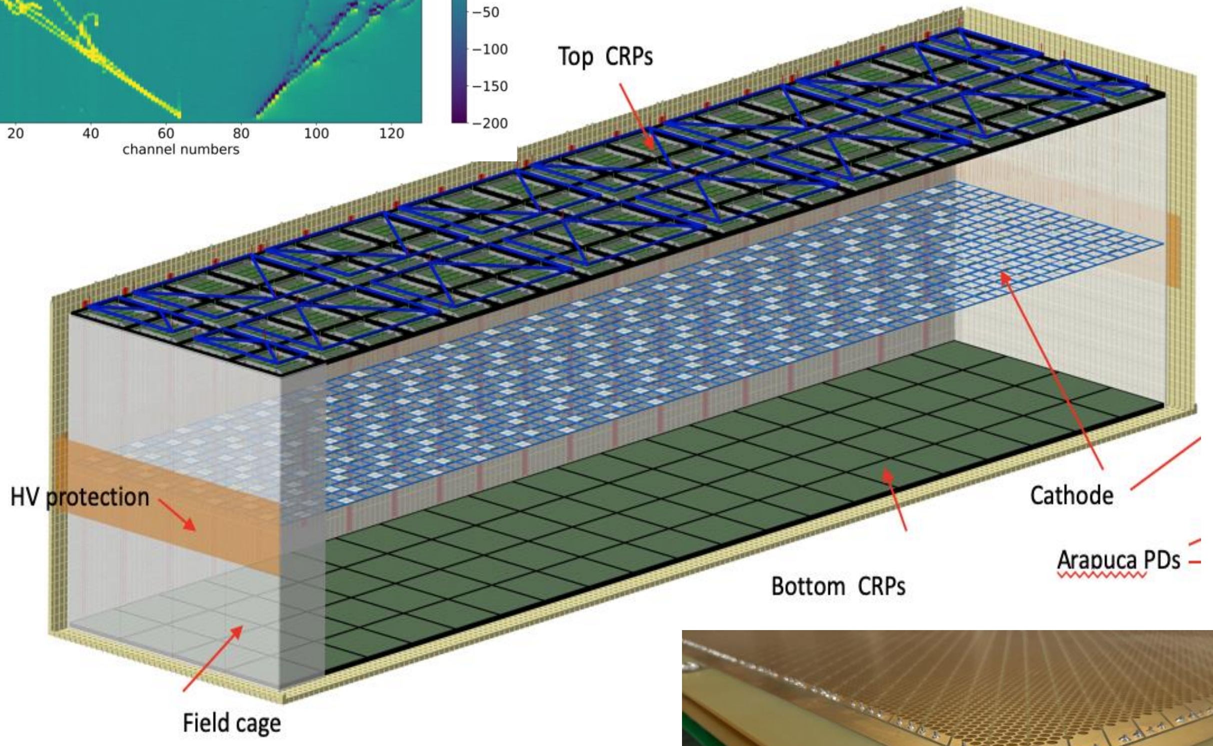
Horizontal Drift Detector (Module 1)

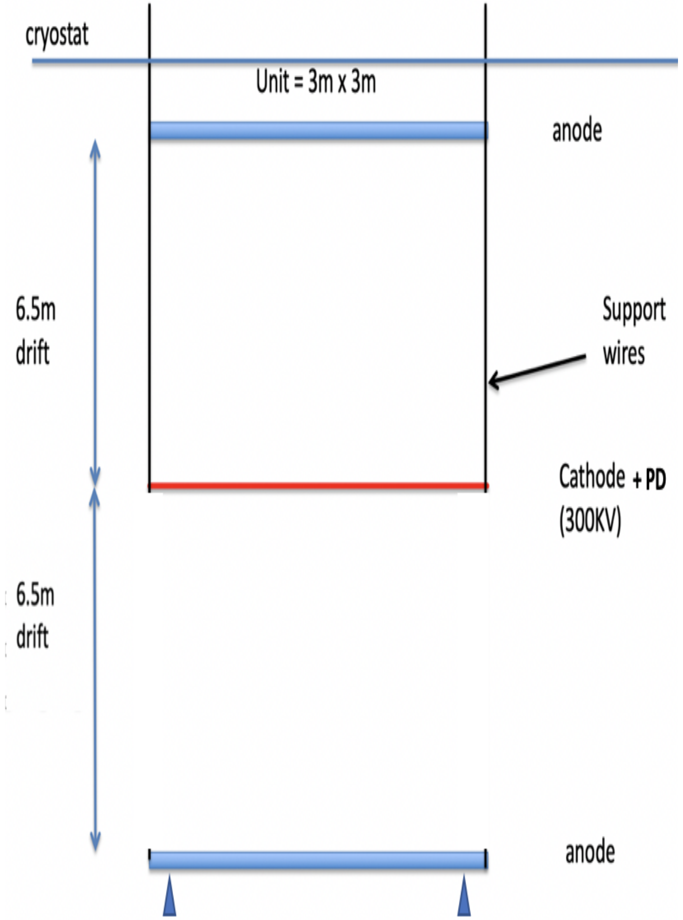




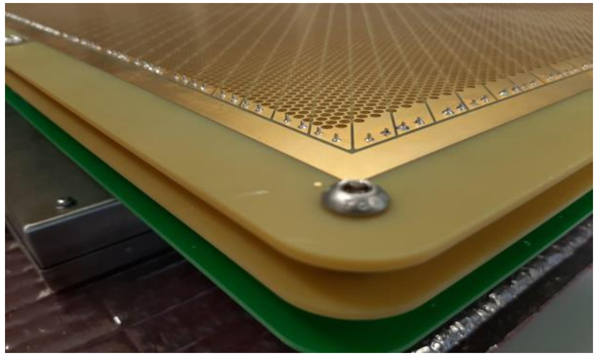
Vertical Drift Detector (Module 2)







Perforated Anode



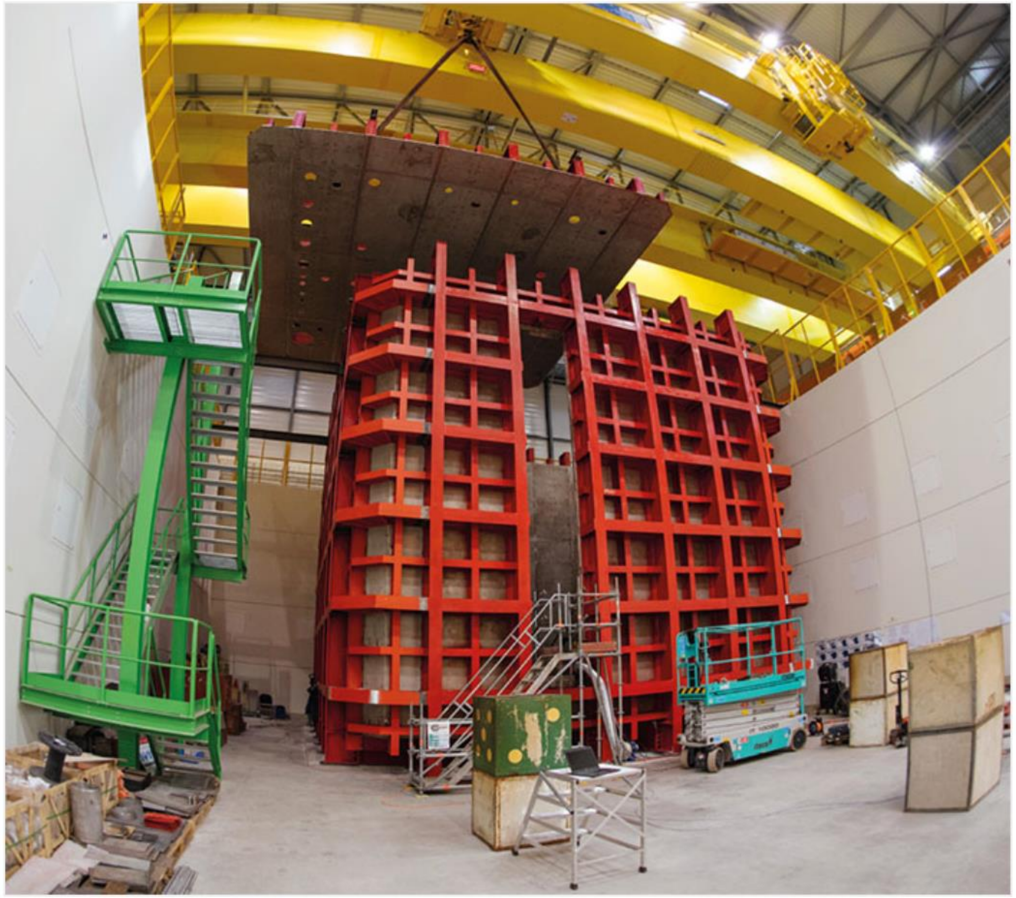
CERNCOURIER | International high-energy physics CERN IOP

FEATURE

ProtoDUNE revealed

15 February 2017

CERN makes rapid progress toward prototype DUNE detectors.

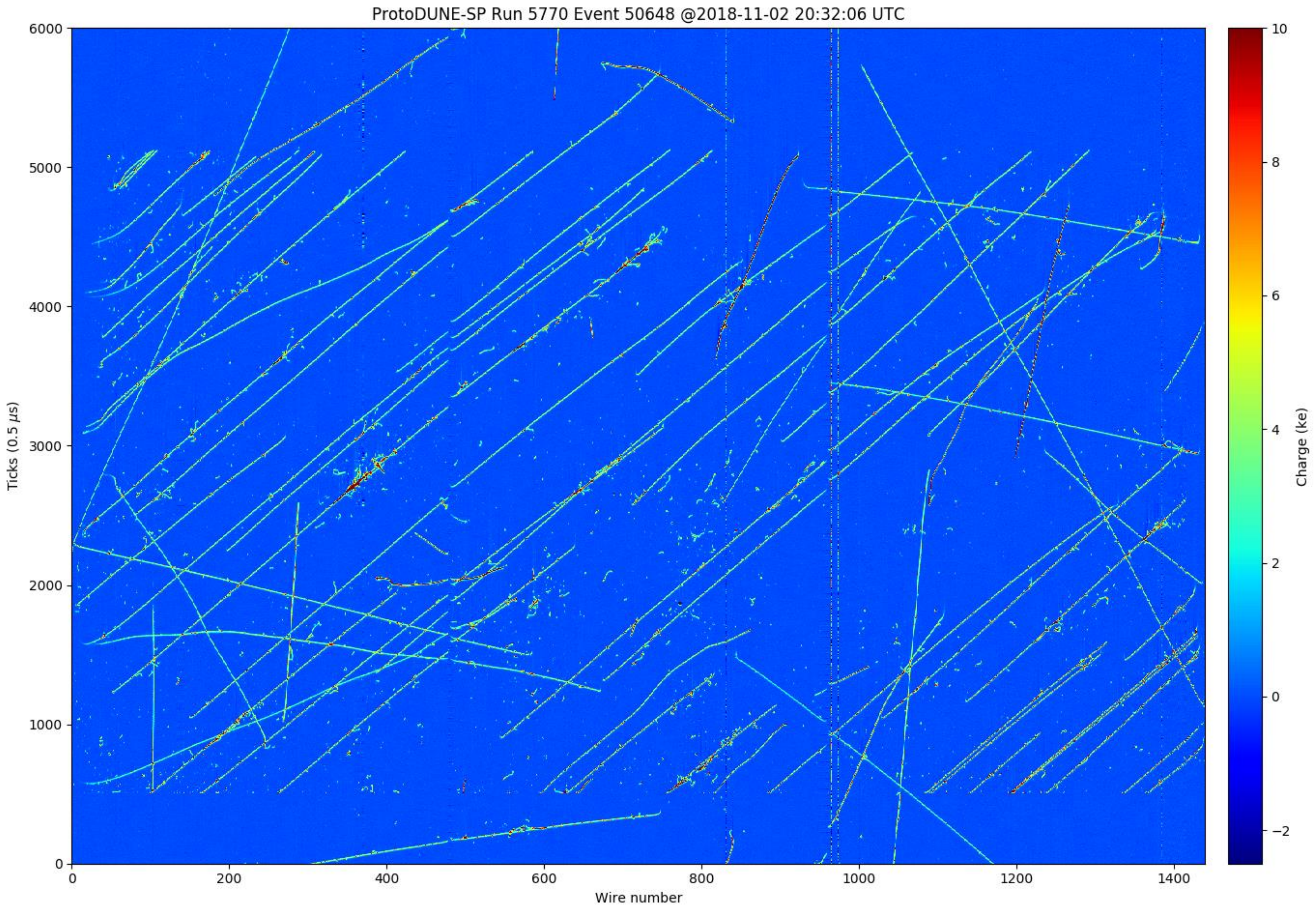


Outer vessel

CERN Neutrino Platform


Genie
Genie
Genie AWP-20S

ProtoDUNE-Single Phase (HD)



Need to correct for space charge effects!

ProtoDUNE-Single Phase (HD)

Journal of Instrumentation

OPEN ACCESS

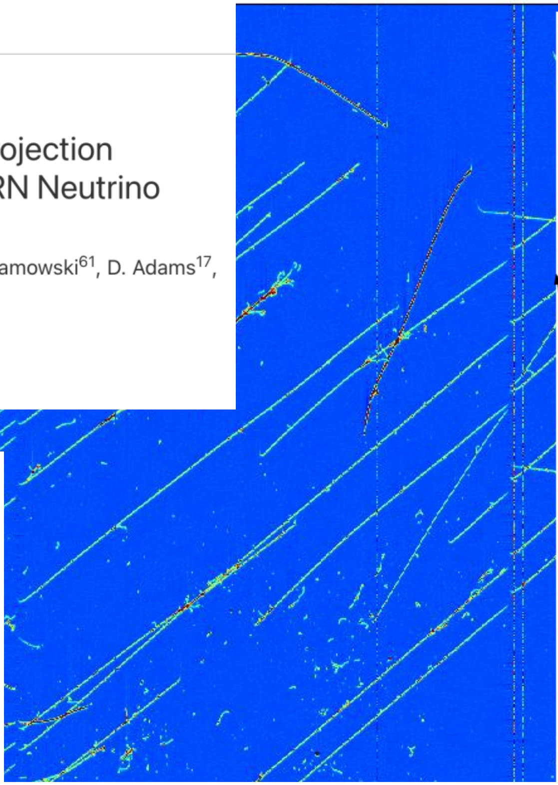
First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform

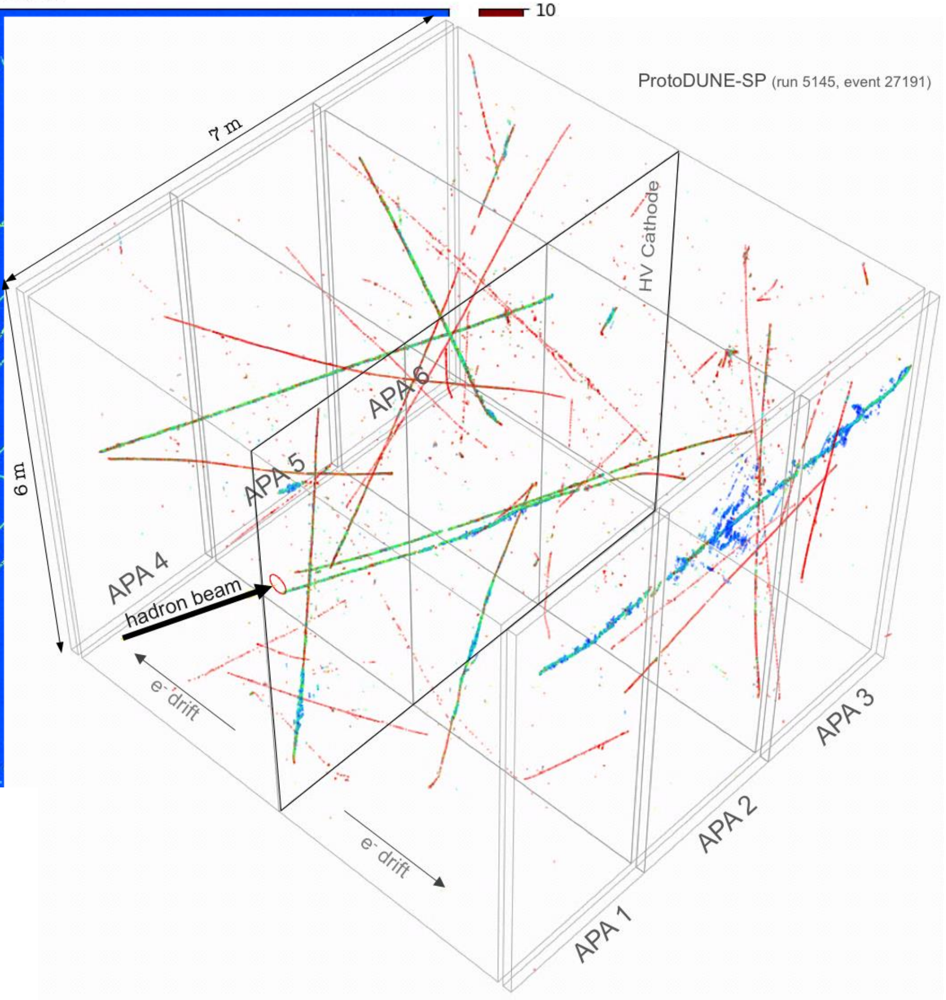
B. Abi[142], A. Abed Abud[21,118], R. Acciarri[61], M.A. Acero[8], G. Adamov[65], M. Adamowski[61], D. Adams[17], P. Adrien[21], M. Adinolfi[16], Z. Ahmad[182] + Show full author list

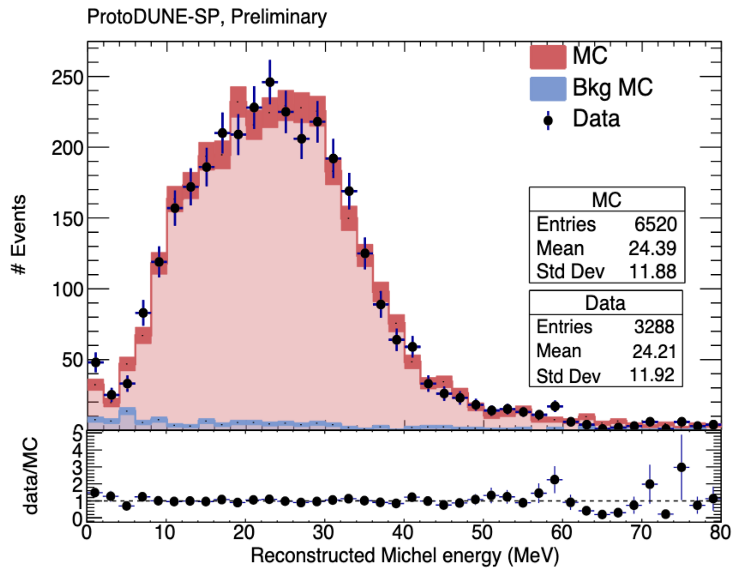
Published 3 December 2020 • © 2020 CERN

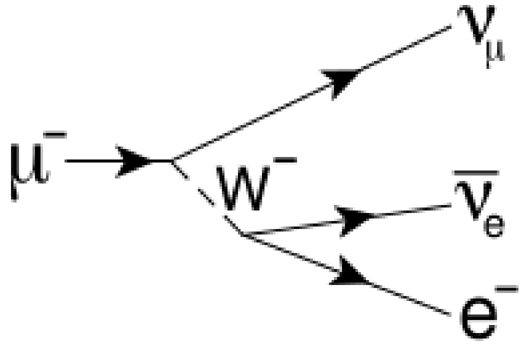
Journal of Instrumentation, Volume 15, December 2020

Citation B. Abi *et al* 2020 *JINST* 15 P12004

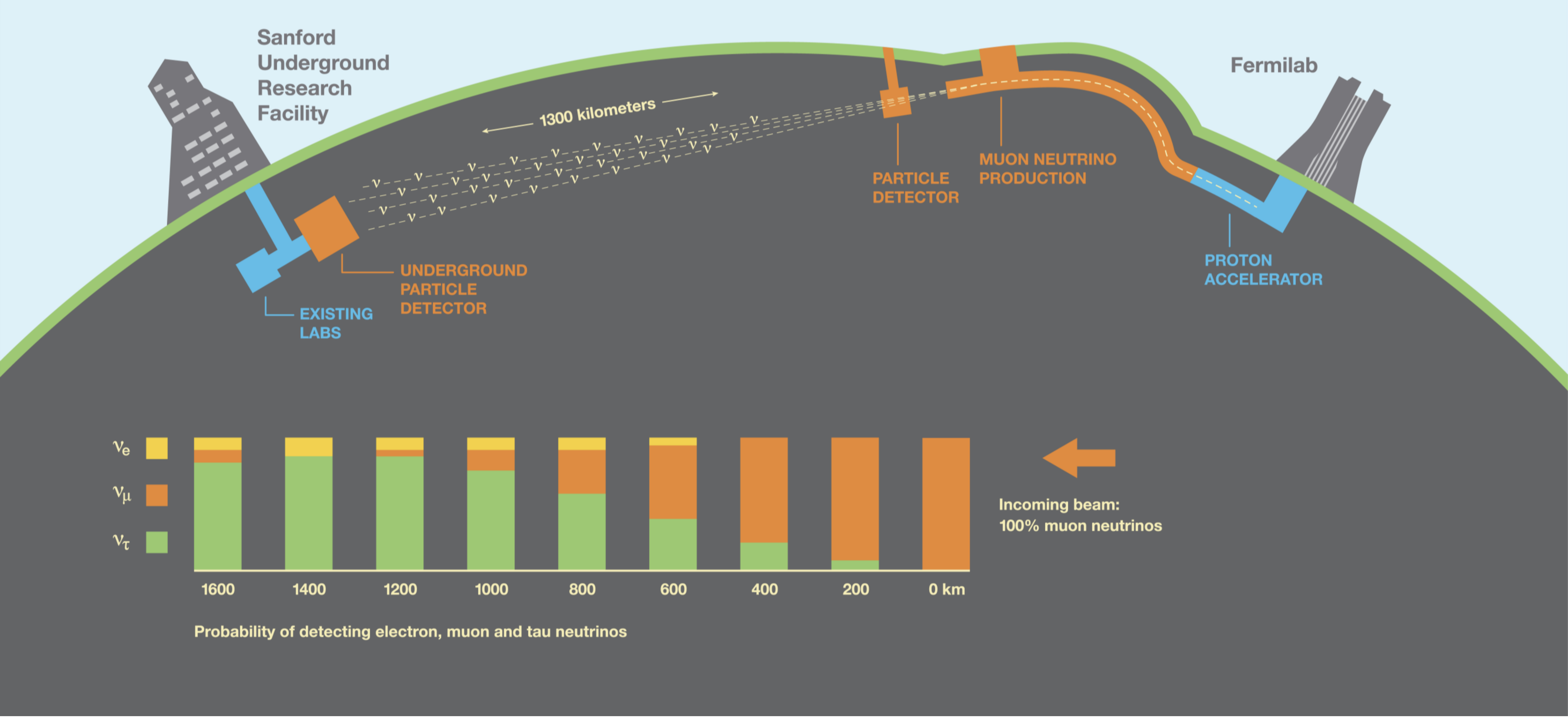


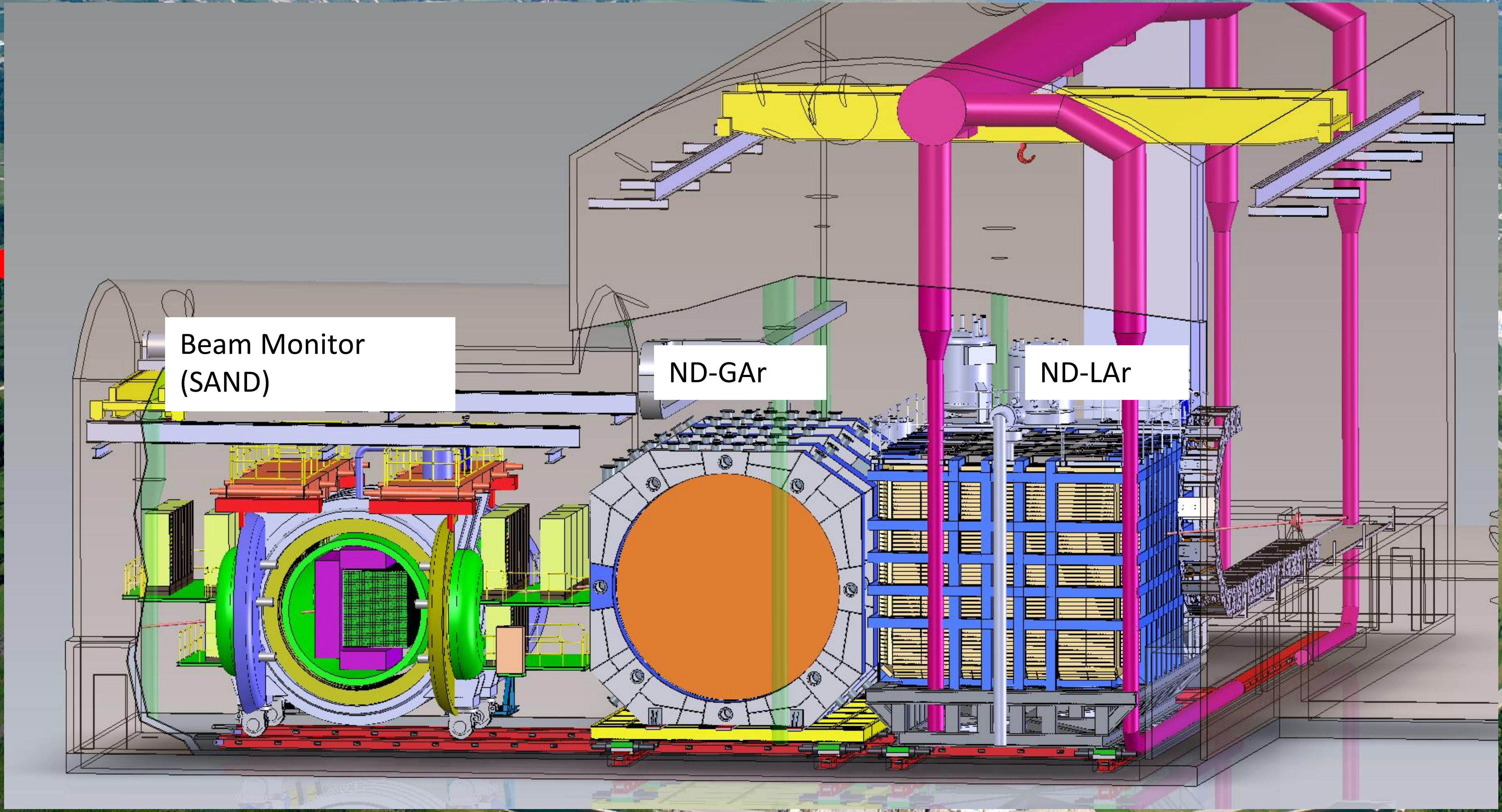




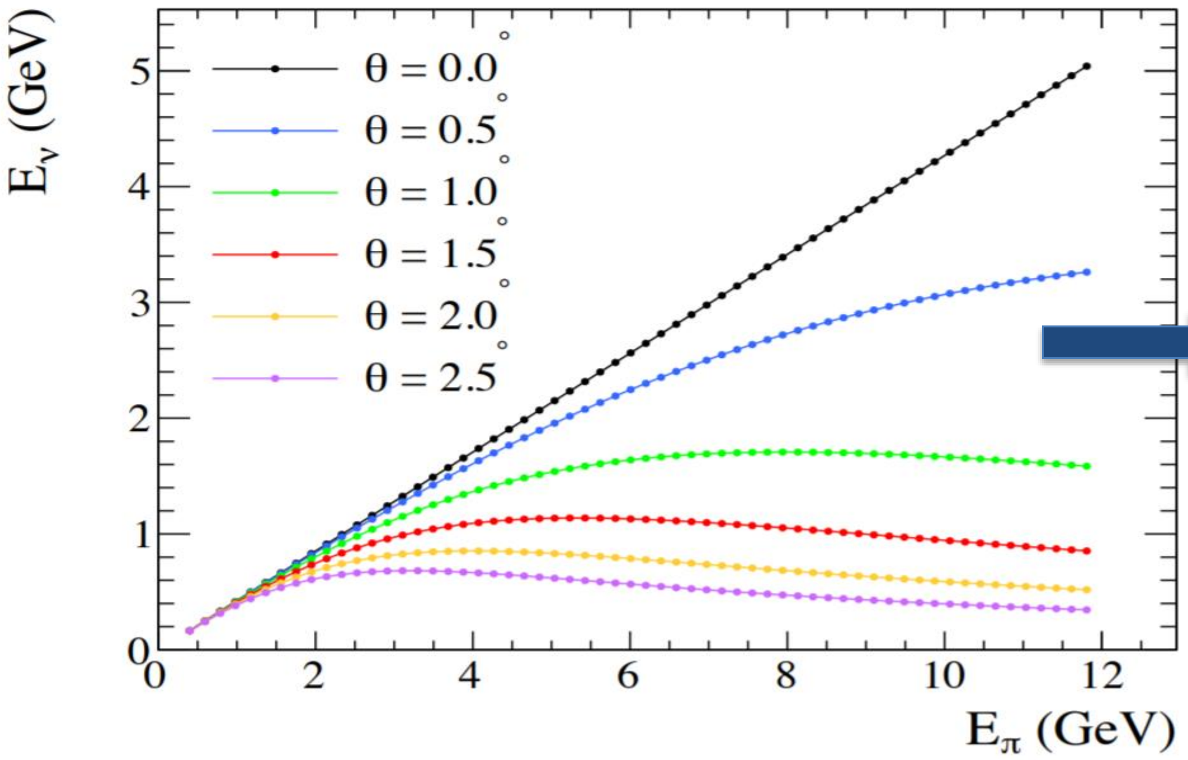


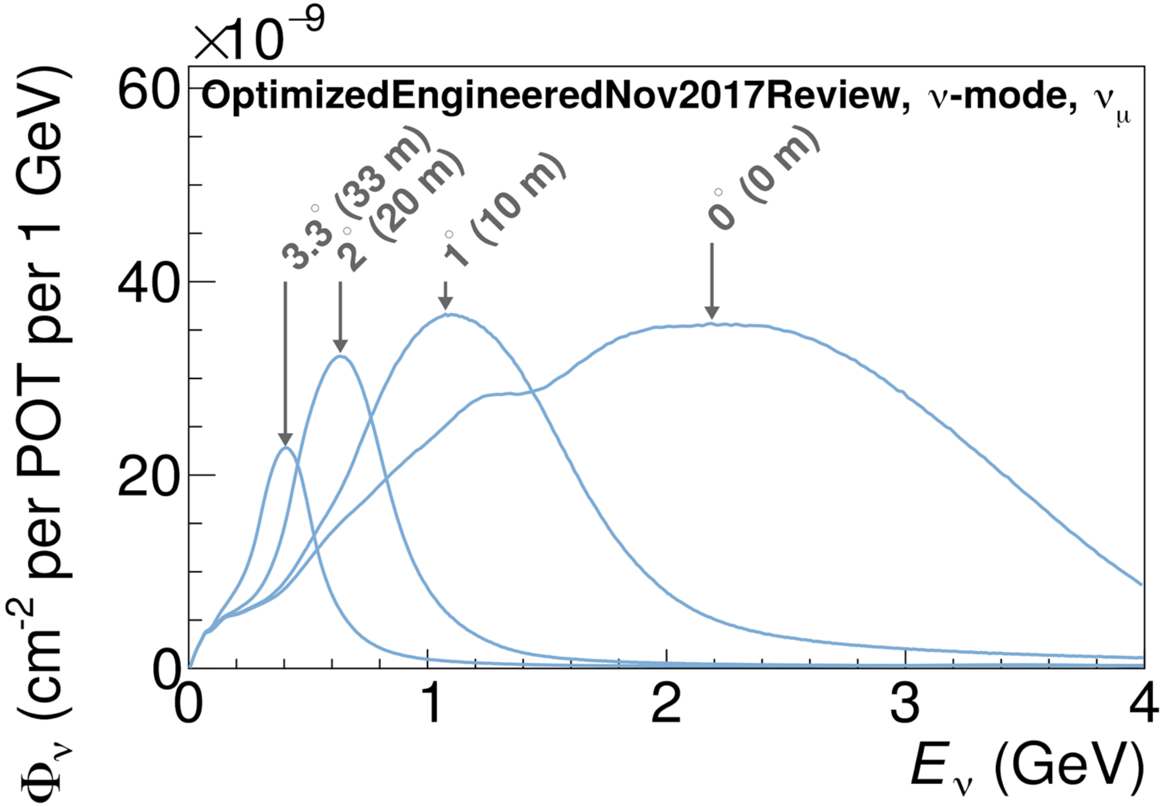
Deep Underground Neutrino Experiment




Beam Monitor
(SAND)
ND-GAr
ND-LAr

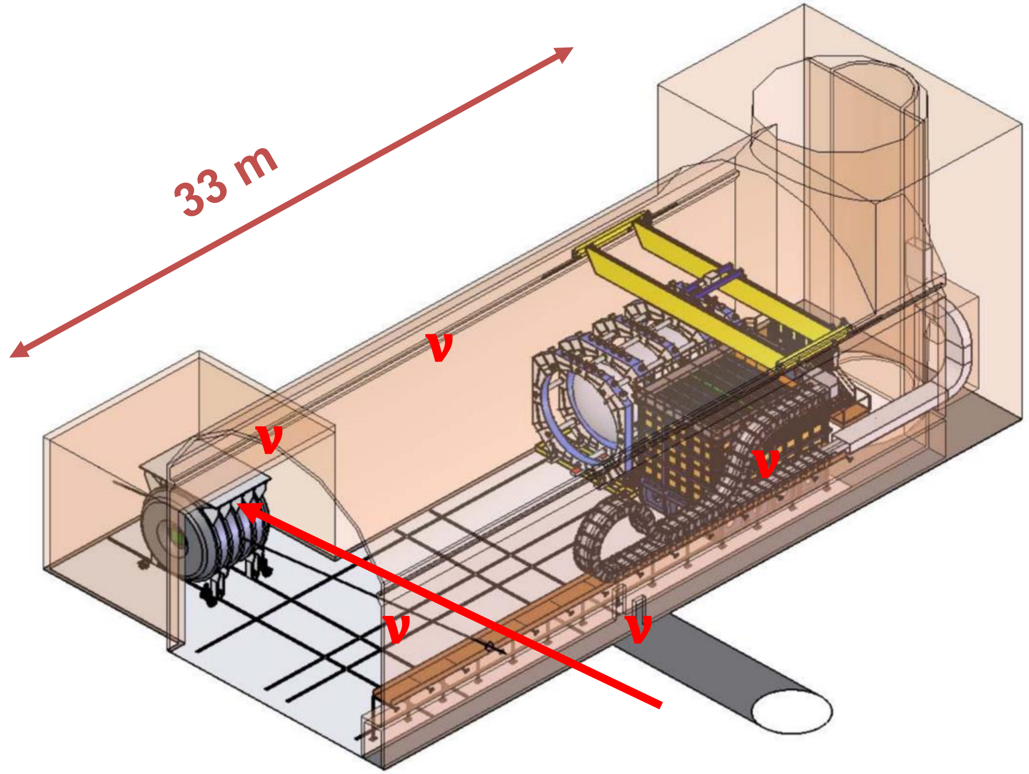
The PRISM Concept

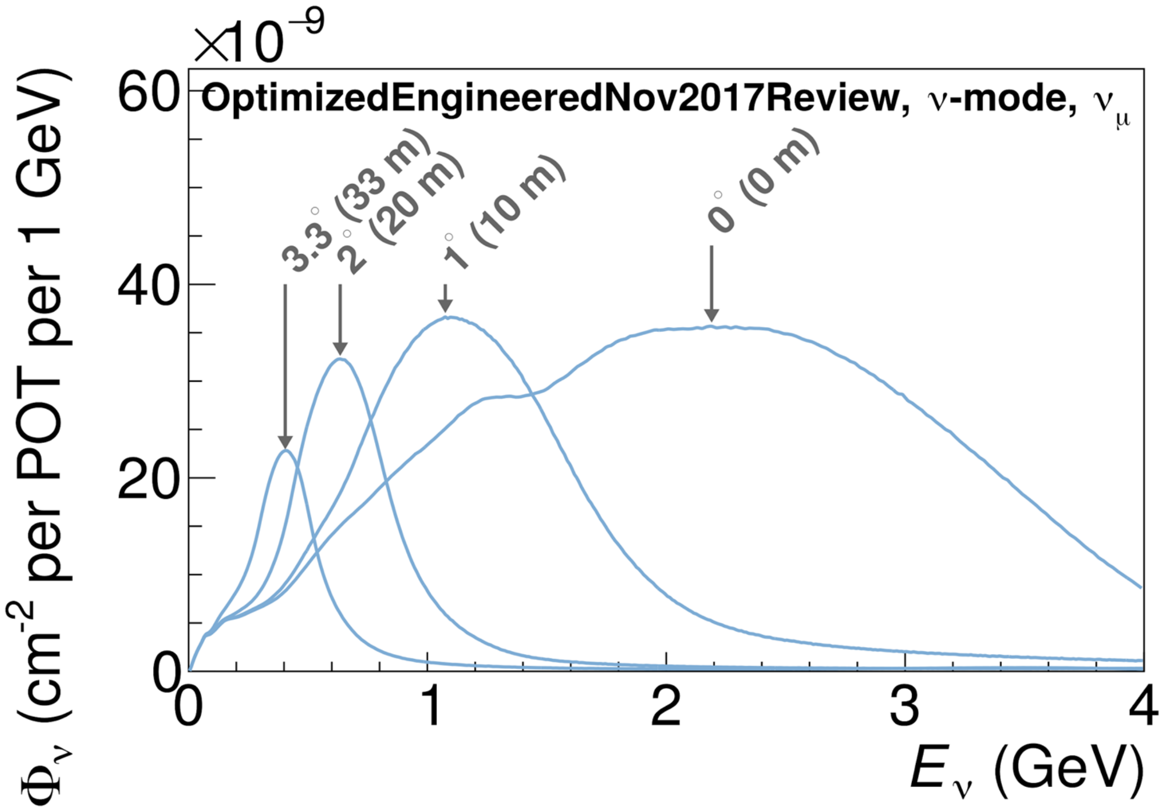




K. Duffy, L. Pickering

The PRISM Concept



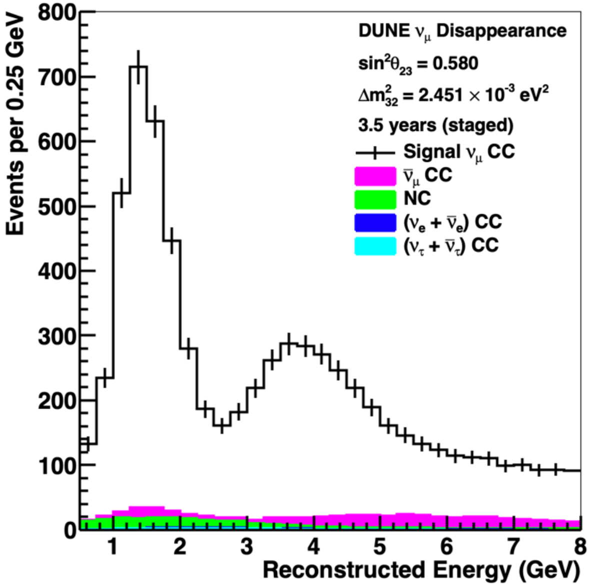


L. Pickering

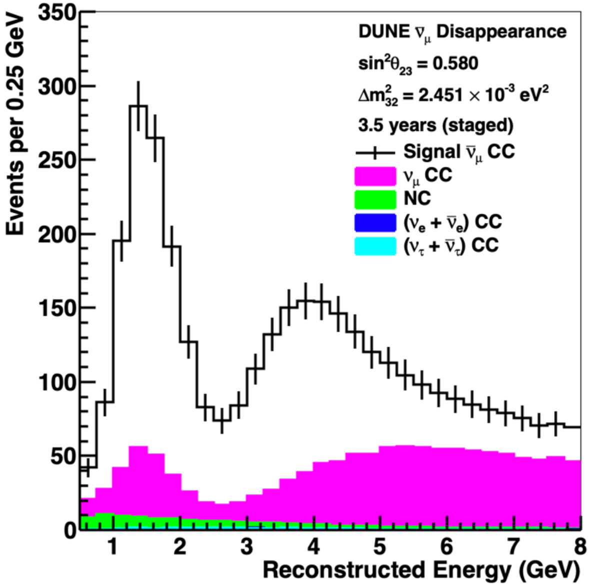
Linear superposition of spectra allows to construct oscillated flux distribution.

DUNE ν_μ disappearance

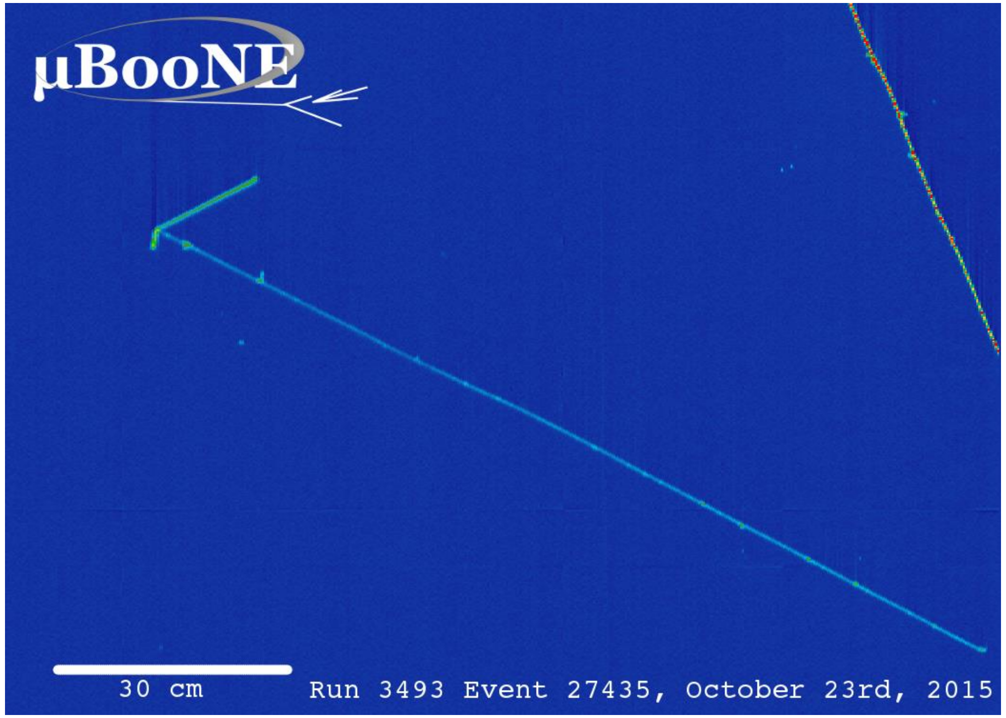
- Rates for running for 7 years with both neutrinos and anti-neutrinos
- Excellent energy reconstruction crucial for broad band beam



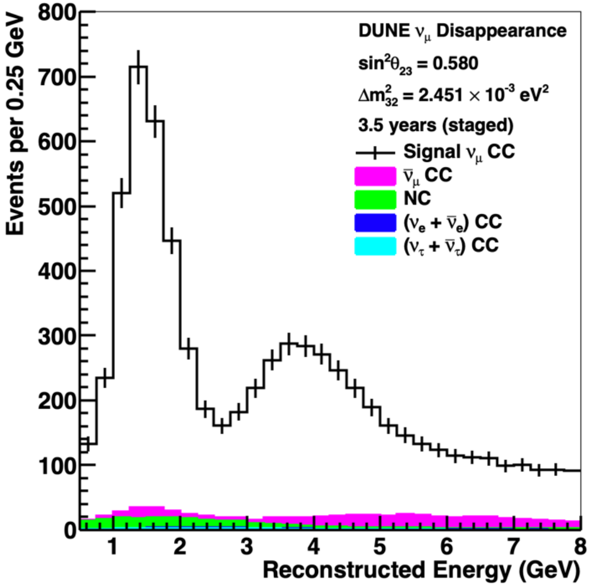
ν_μ



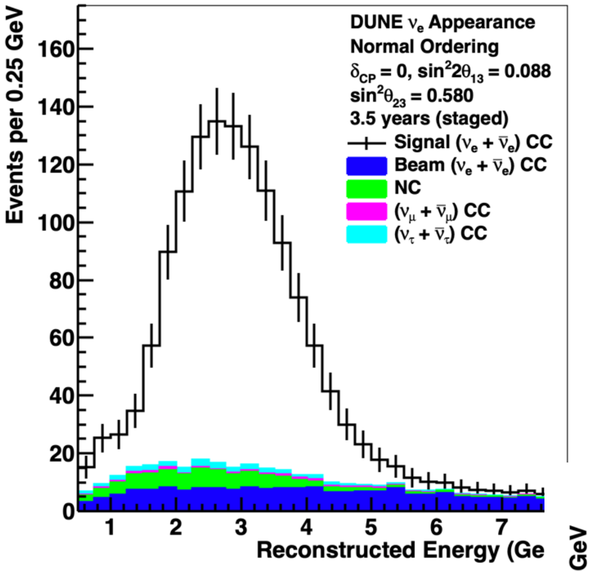
anti-ν_μ



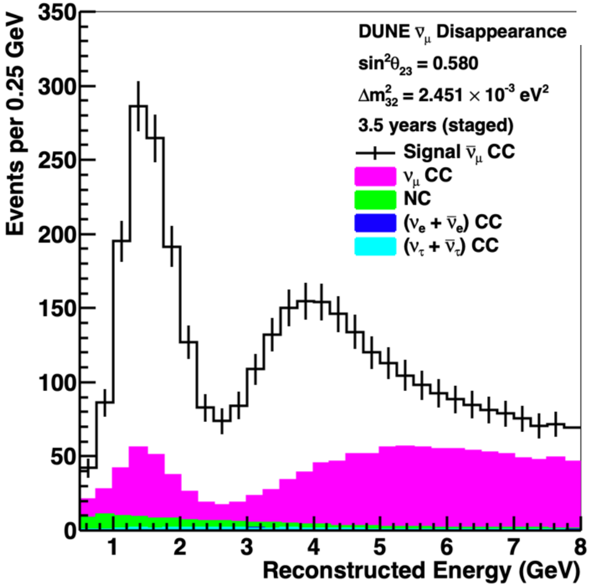
DUNE ν_μ disappearance/ ν_e appearance



ν_μ

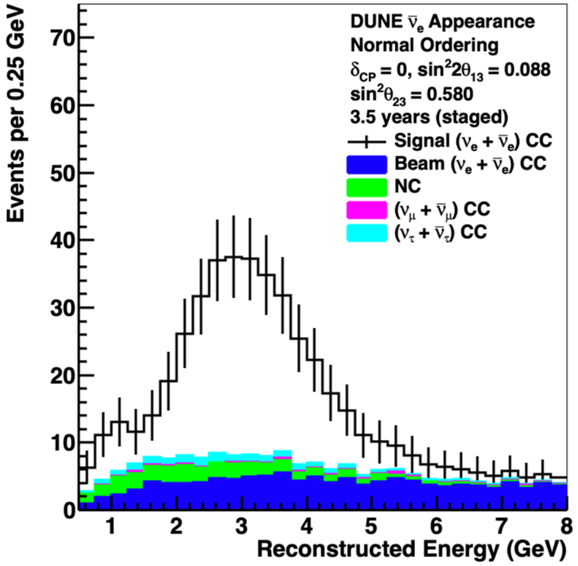


ν_e



anti-ν_μ

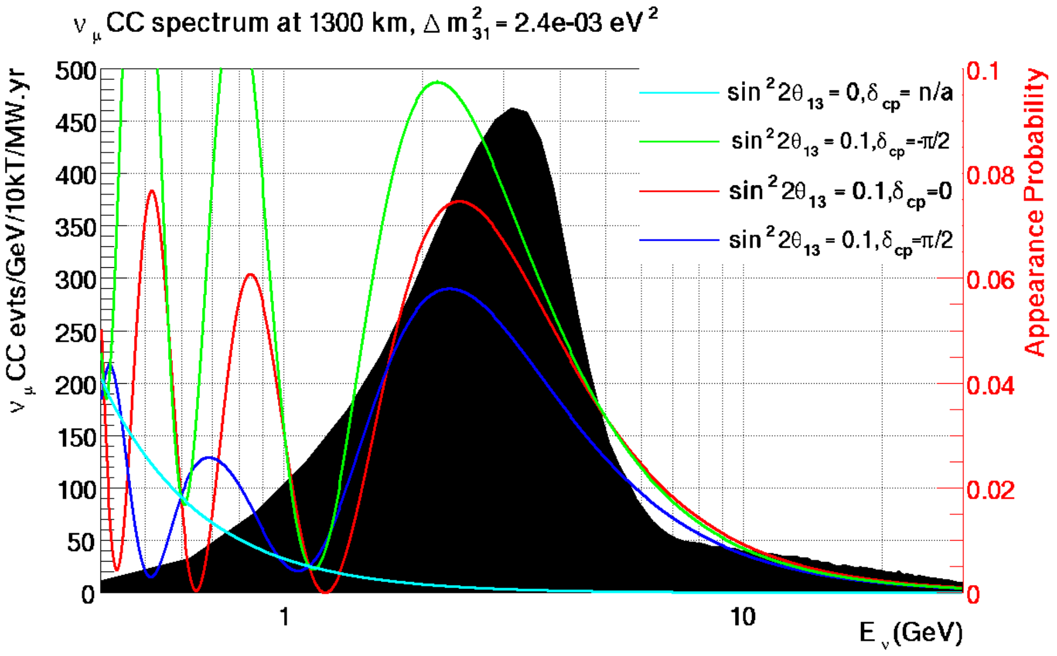
anti-ν_e



ν_e appearance gives access to δ

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

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



- 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

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$$+ \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)}\Delta_{31}\frac{\sin(aL)}{aL}\Delta_{21}\cos(\Delta_{31} - \delta)$$
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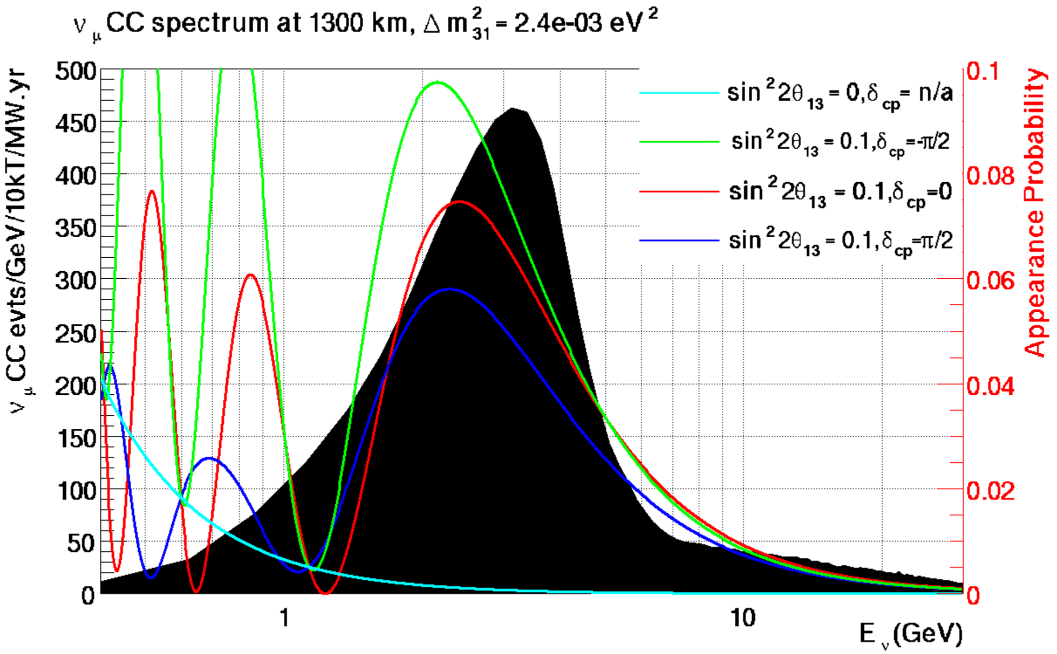

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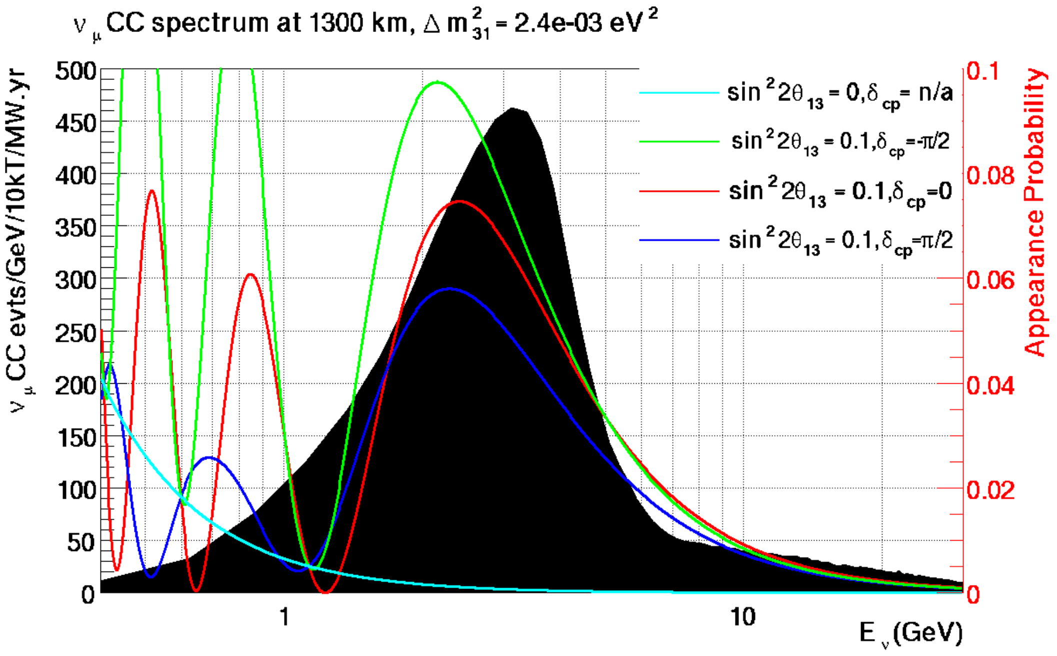
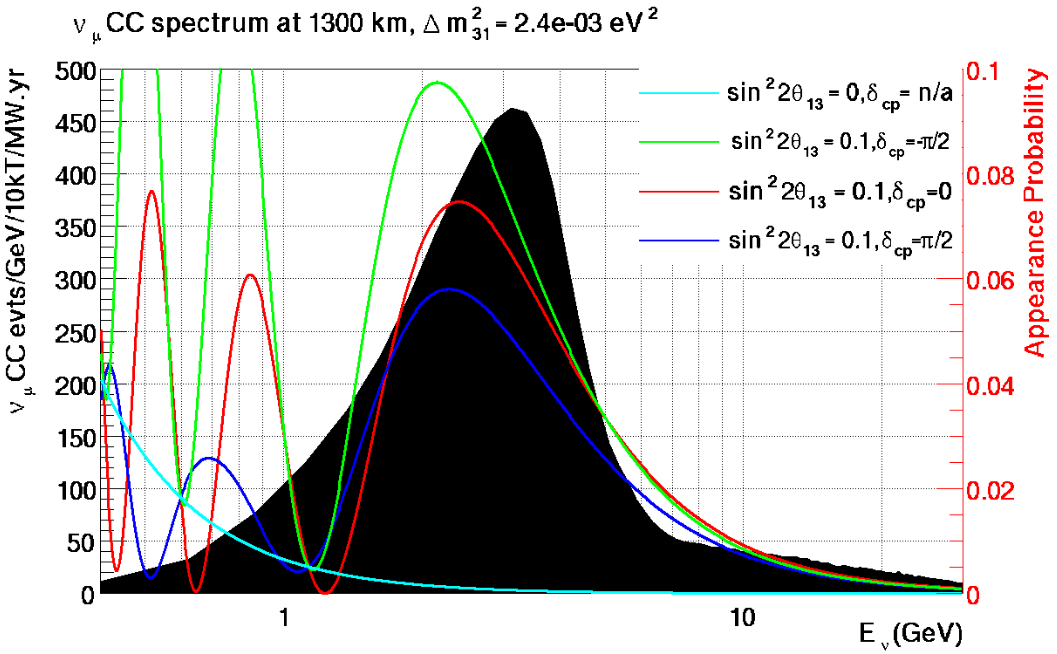


- ν_e appearance amplitude depends simultaneously on θ_{13}, θ_{23}, δ_{CP}, and matter effects –
- Measurements of all four possible in a single experiment.

ν_e appearance gives access to δ

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

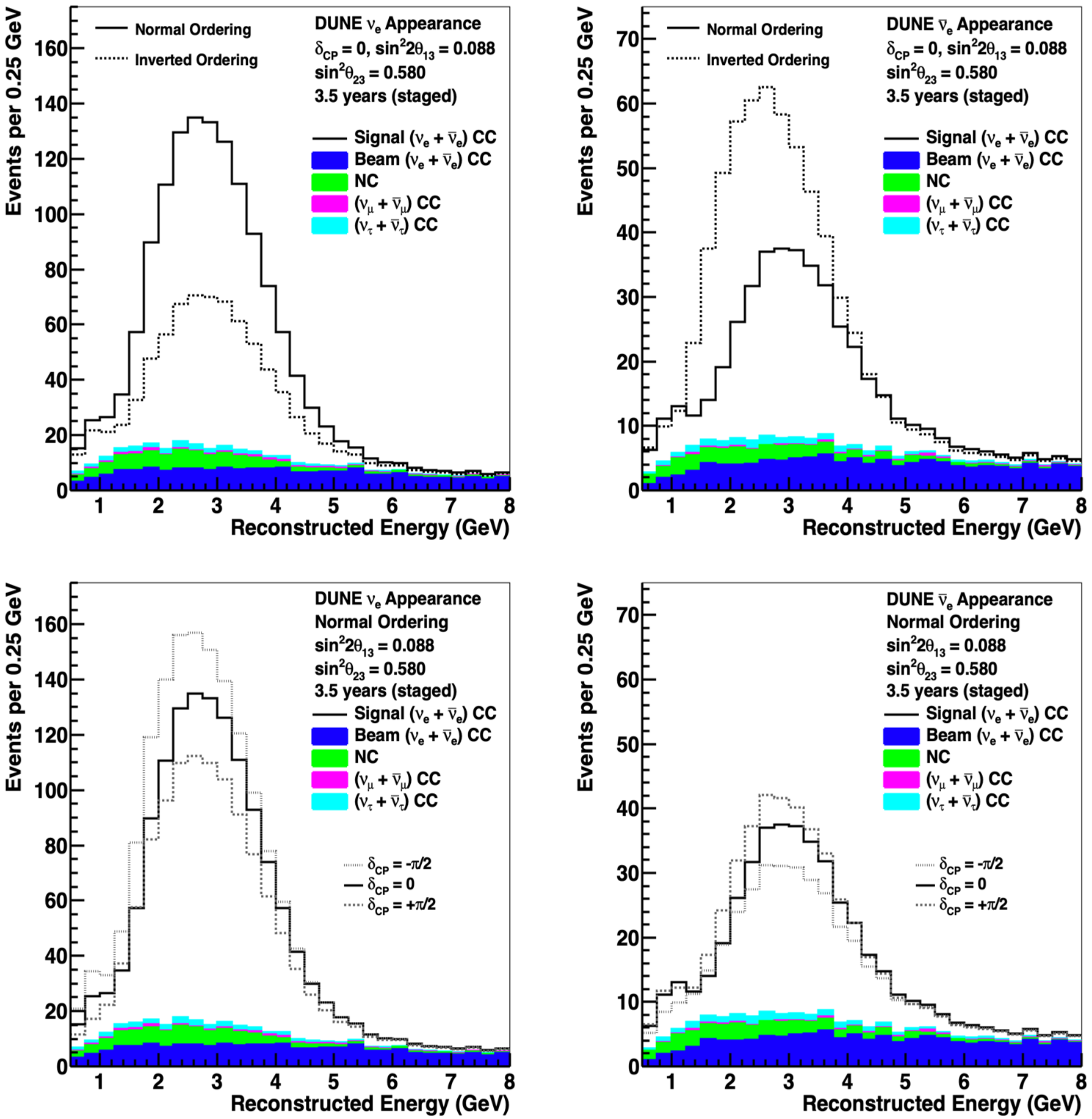
$$a = \frac{G_F N_e}{\sqrt{2}}$$
$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$



- 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.
- Need to resolve degeneracies (e.g., MO vs. CP).

MANCHESTER 1824

ν_e appearance (MO/CP phase)

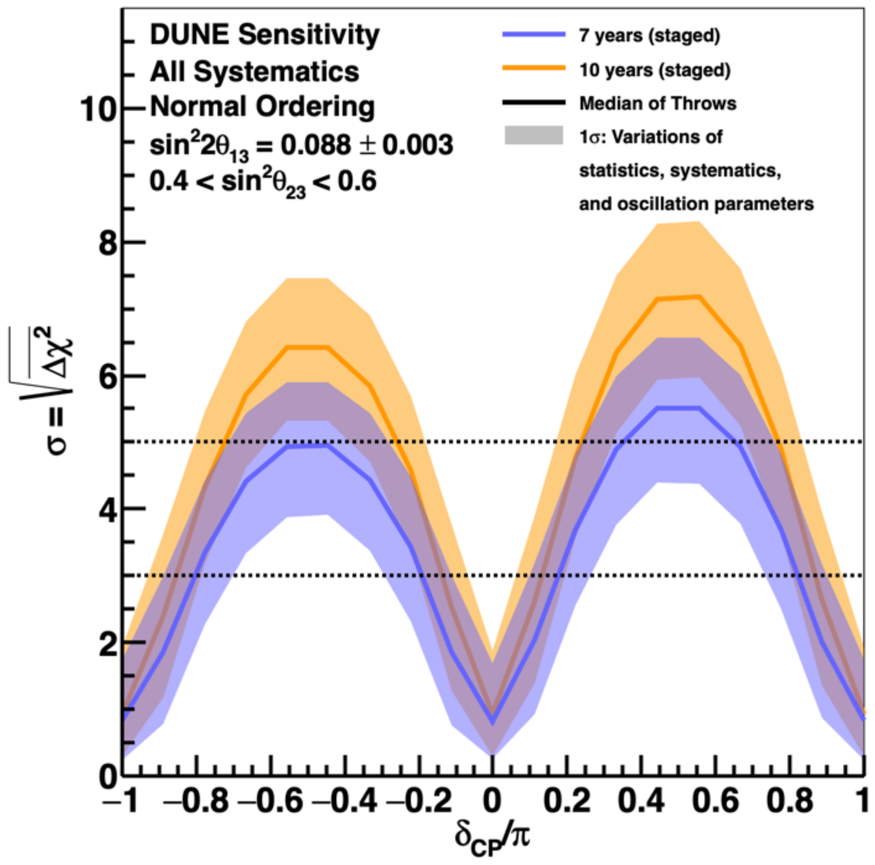


variation with mass ordering

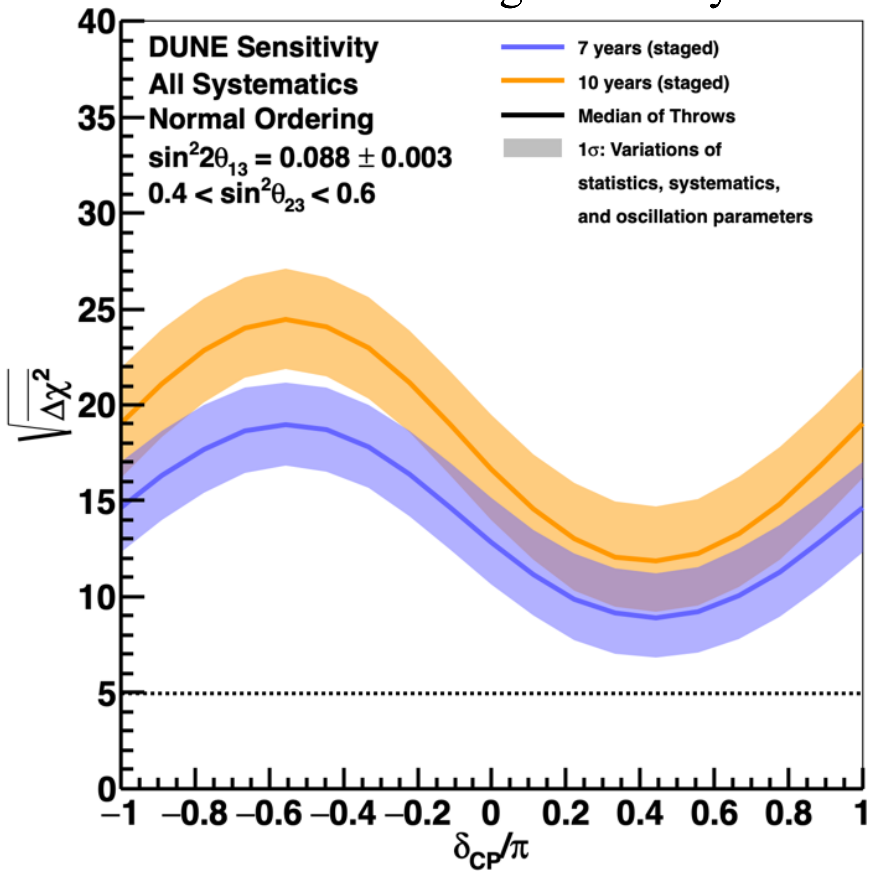
variation with δ_{CP}

DUNE Mass ordering and CPV

CPV sensitivity

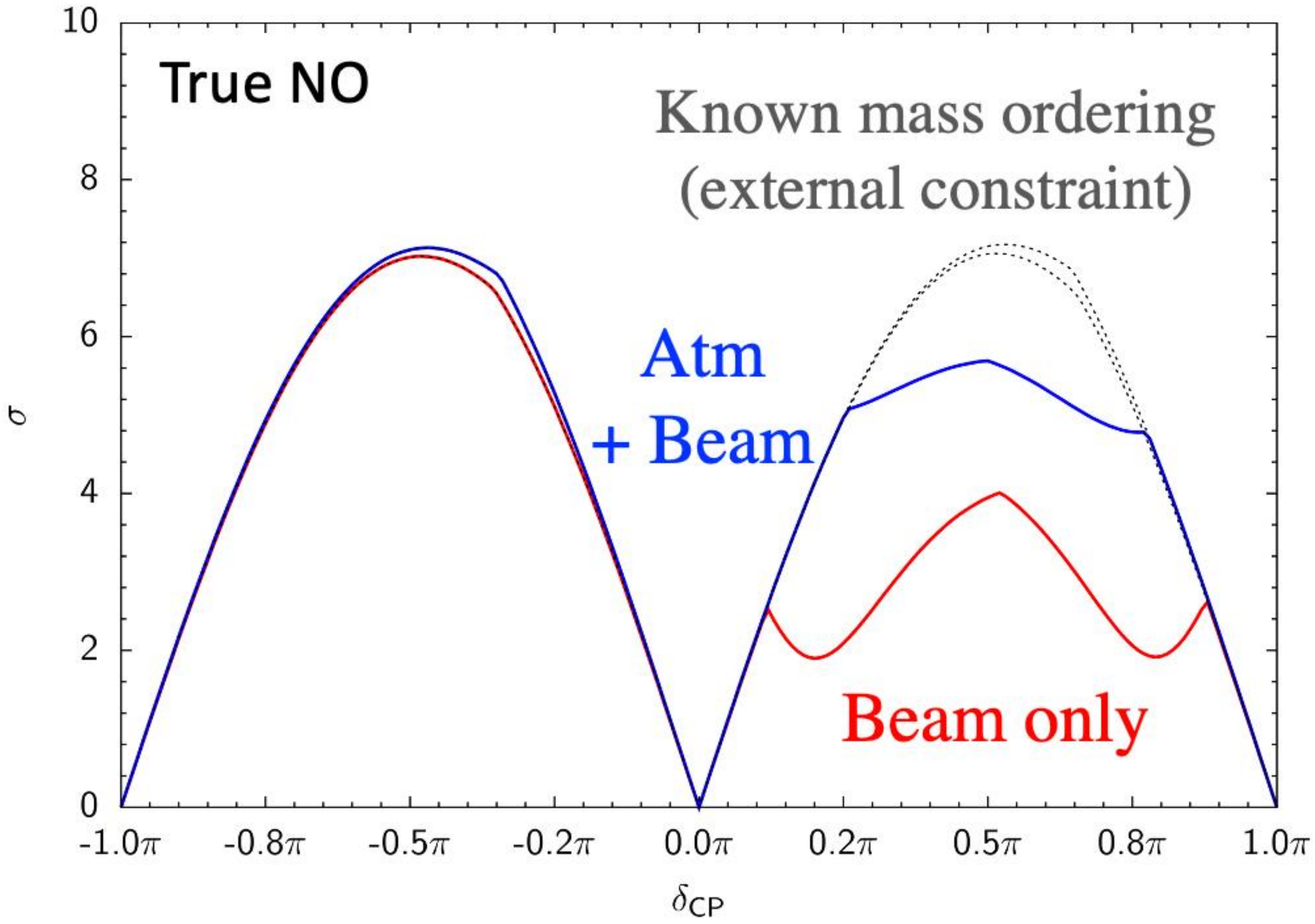


Mass ordering sensitivity



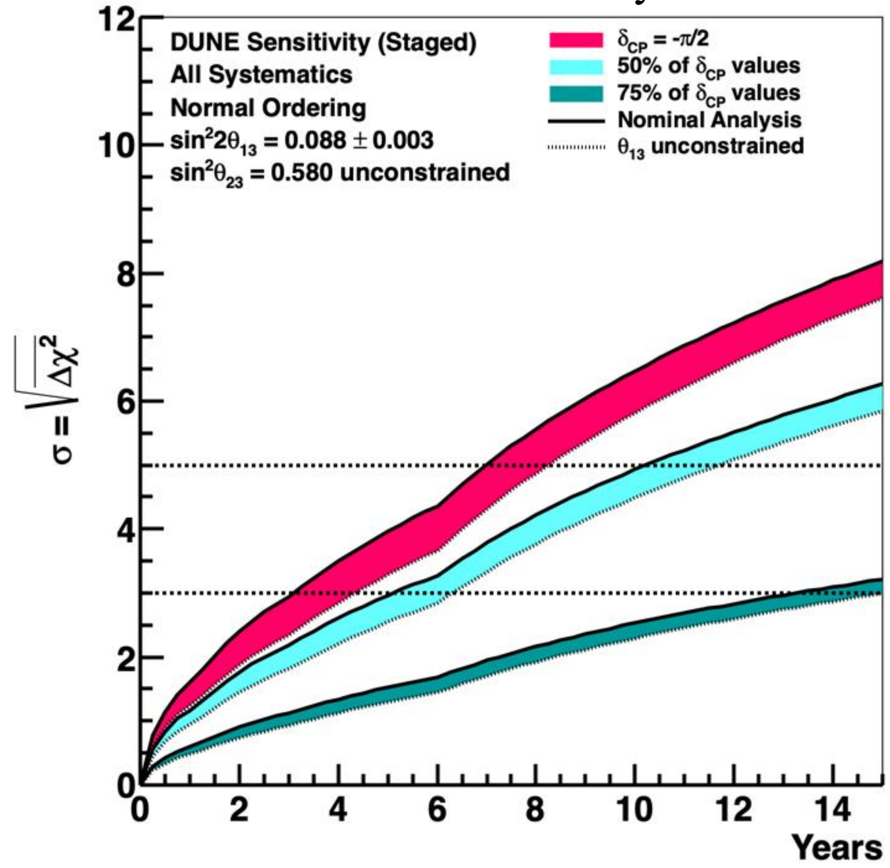
Hyper-Kamiokande CPV only

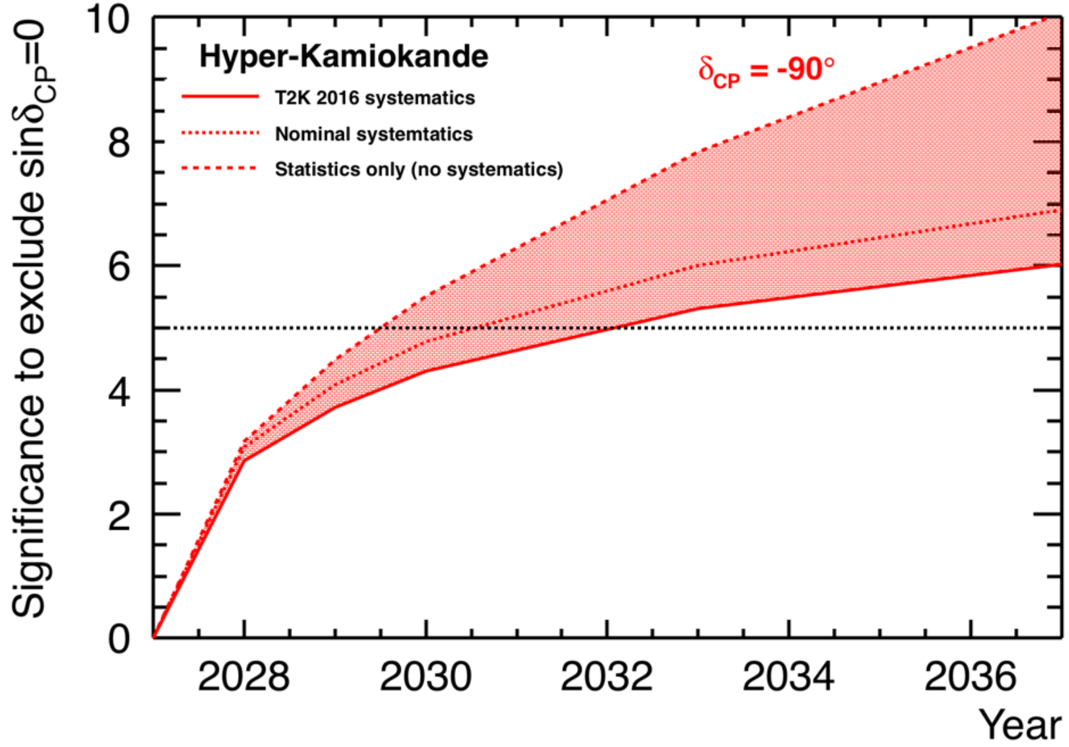
Mass ordering either constrained by external measurement or by atmospheric neutrinos



Sensitivity versus time

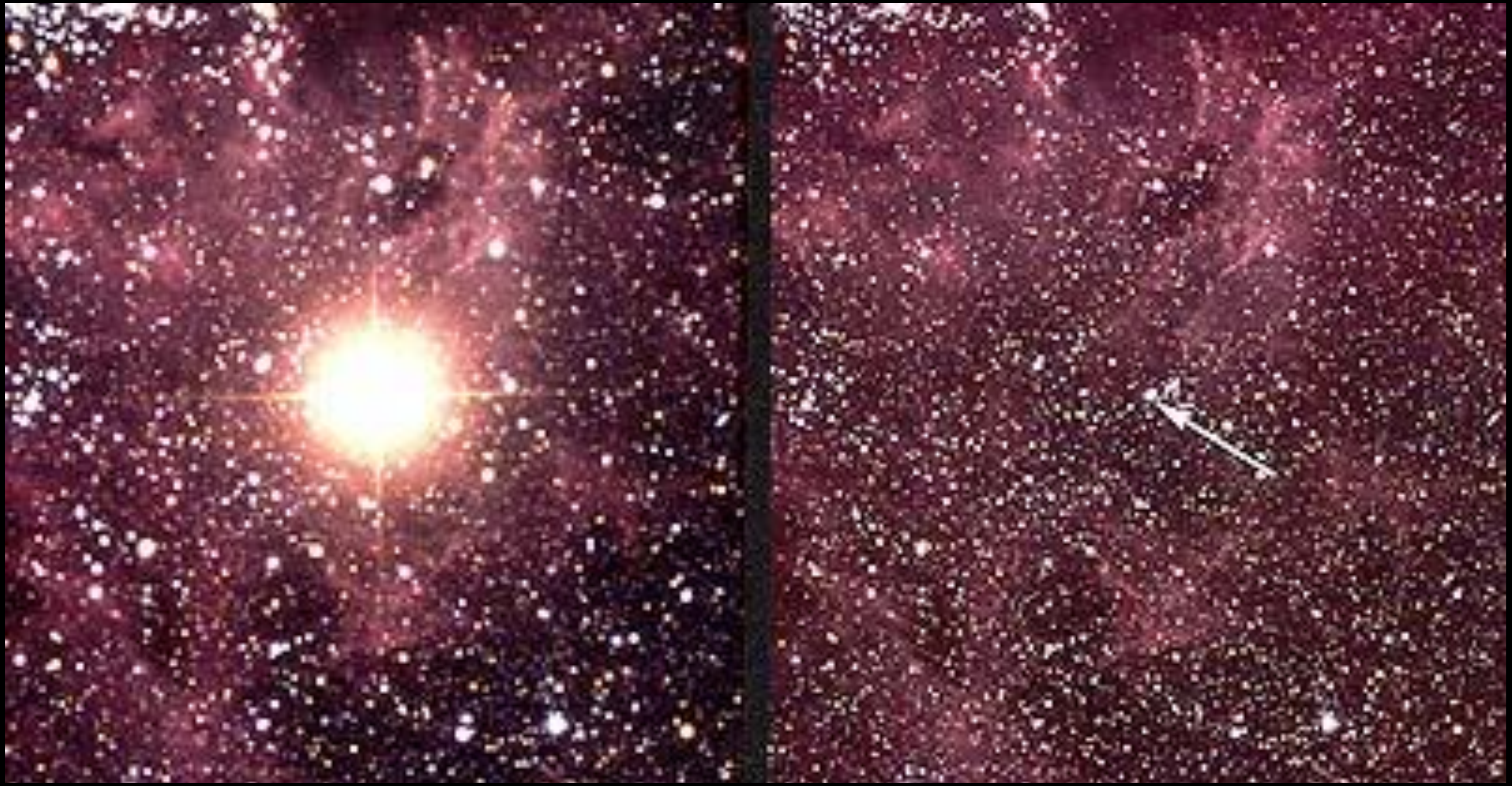
*CP*v sensitivity





- 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

Supernova 1987A
in the Large Magellanic Cloud (55 kpc away)

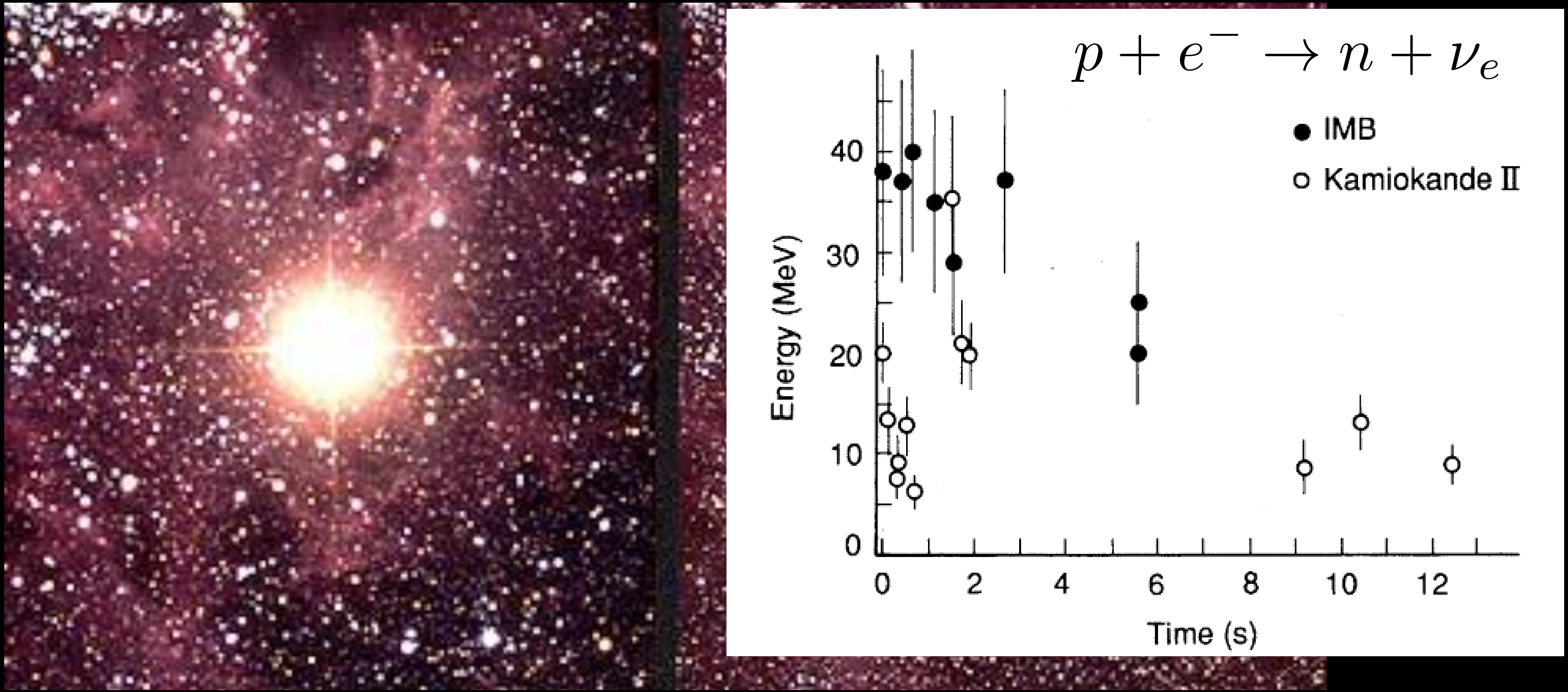


For comparison: the Milky Way is about 34 kpc across

Supernova 1987A

in the Large Magellanic Cloud (55 kpc away)

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

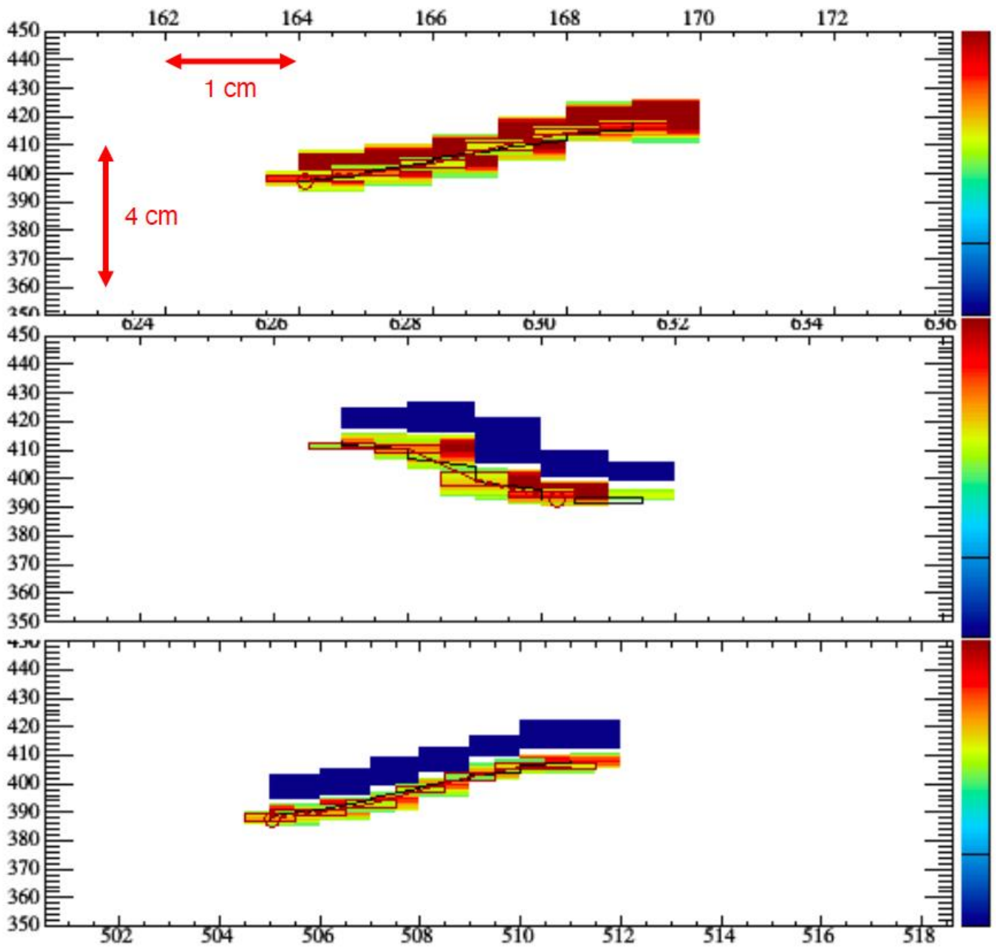


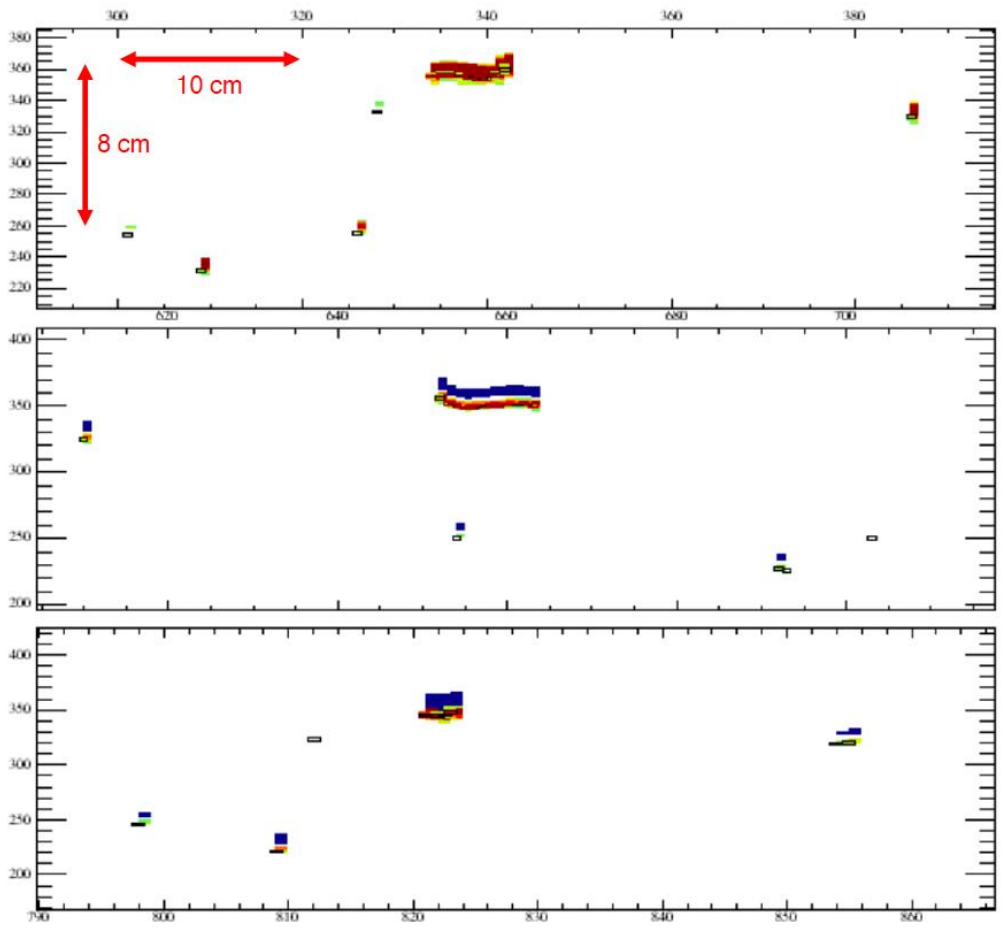
For comparison: the Milky Way is about 34 kpc across

Supernova neutrinos in DUNE

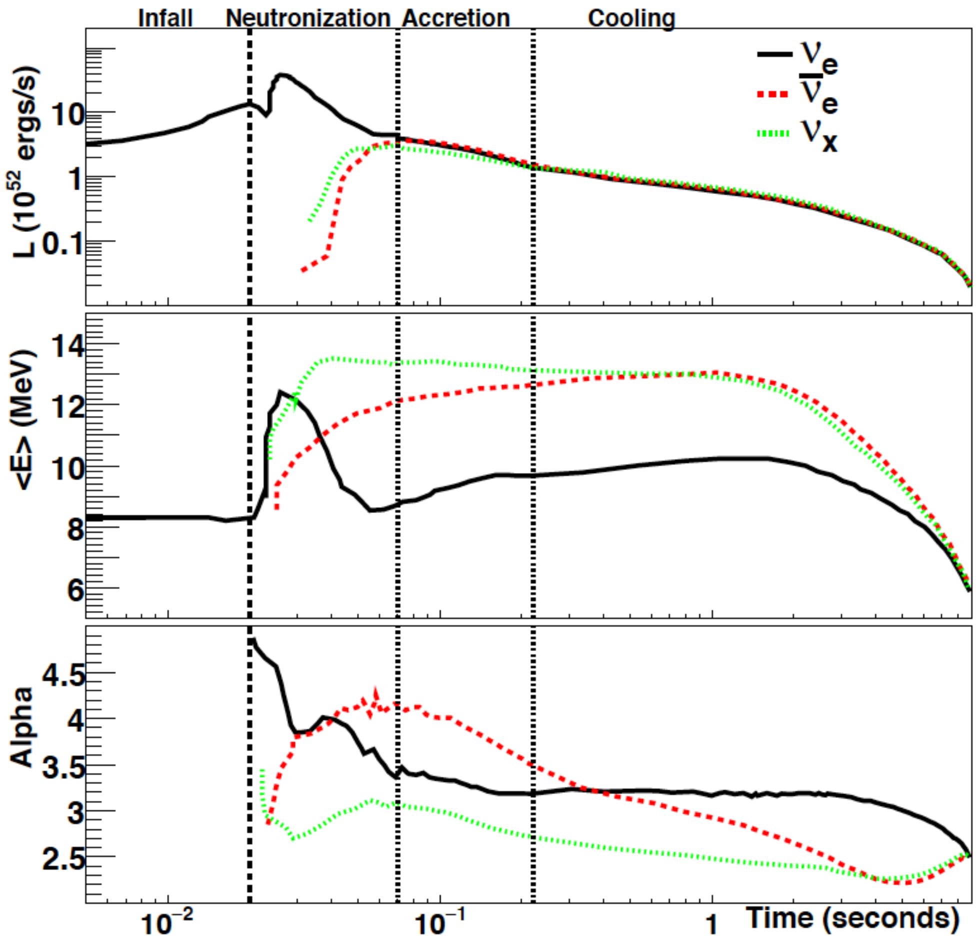
$\nu_X + \mathrm{Ar} \rightarrow \nu_X + \mathrm{Ar}^*$ NC, 10 MeV

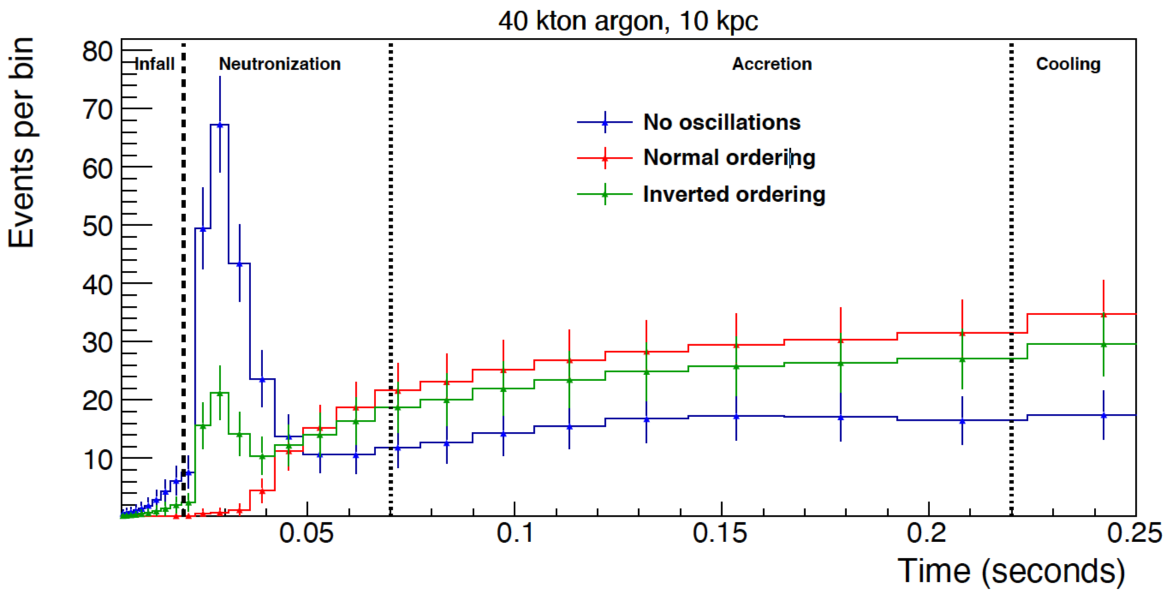
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$ CC, 20 MeV





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.

Neutrino physics at accelerators

- 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.