The Liquid-argon Neutrino Programme

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University of Manchester
PPAP Meeting, Birmingham
13 September 2019

*non-argon programme (NOvA)
covered by Dave Wark

CP Violation and the PMNS Matrix

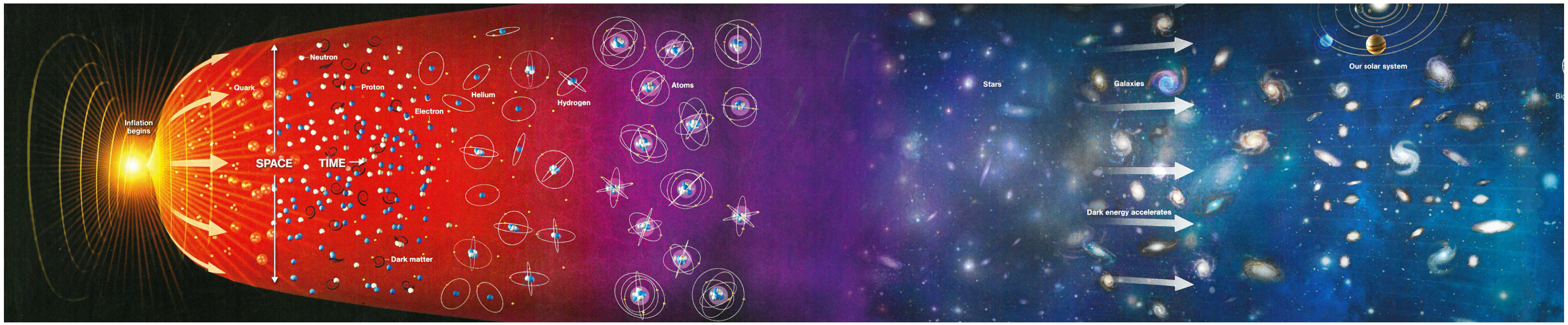
complex CP phase

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

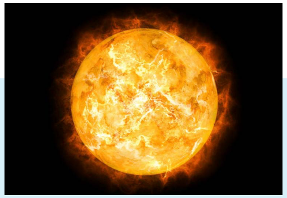
$$U_{\mathrm{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 &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

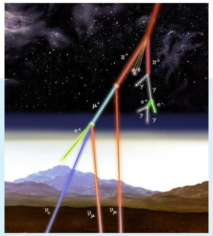
$$s_{ij} = \sin\theta_{ij}\ ;\ c_{ij} = \cos\theta_{ij}$$

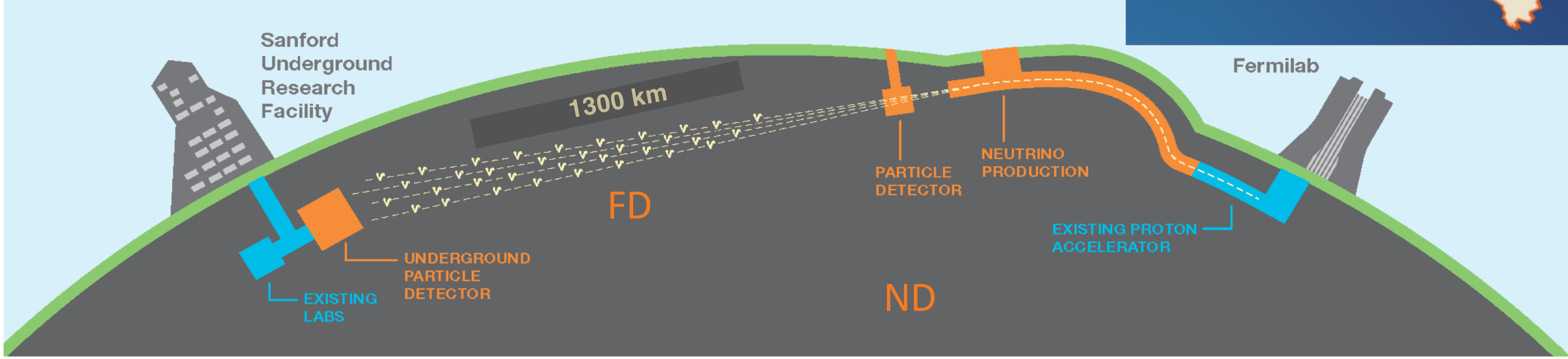
CP Violation in the lepton sector might provide support for *Leptogenesis* as mechanism to generate the Universe's matter-antimatter asymmetry.

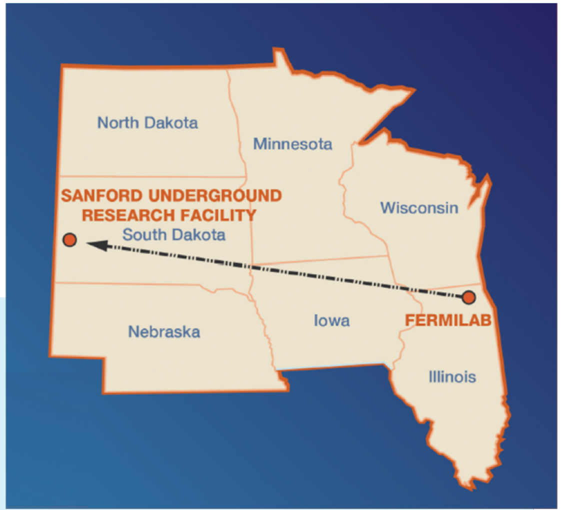


DUNE in a Nutshell









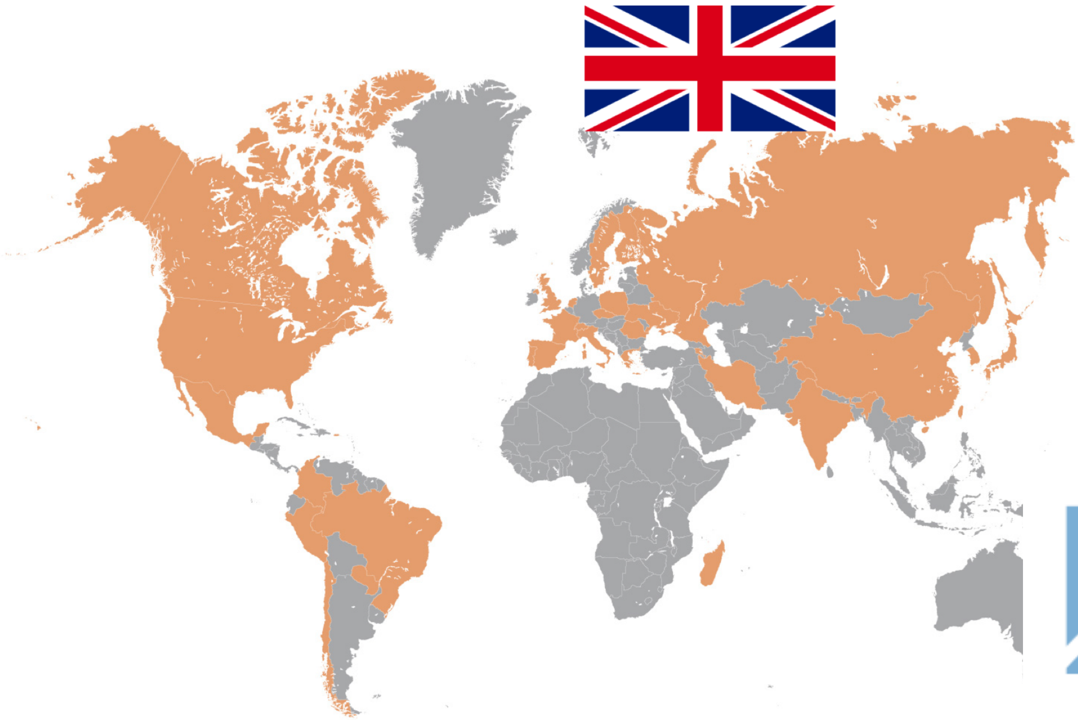
1. A high-power, wide-band neutrino beam (~ GeV energy range).
2. A ≈ 40 kt liquid-argon Far Detector in South Dakota, located 1478 m underground in a former gold mine.
3. A Near Detector located approximately 575 m from the neutrino source at Fermilab close to Chicago.

First DUNE Meeting - 2015

Prioritization by P5 panel in US and European Strategy Update in 2013 crucial for DUNE formation.

DUNE – a global collaboration

1106 collaborators from 182 institutions in 31 countries



UK is a major collaborator on DUNE

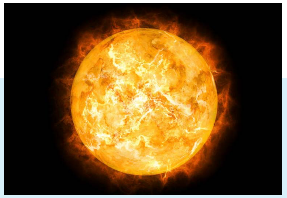
DEEP UNDERGROUND NEUTRINO EXPERIMENT

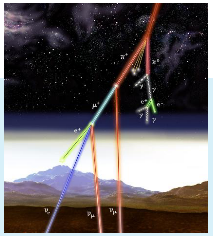
DUNE - UK

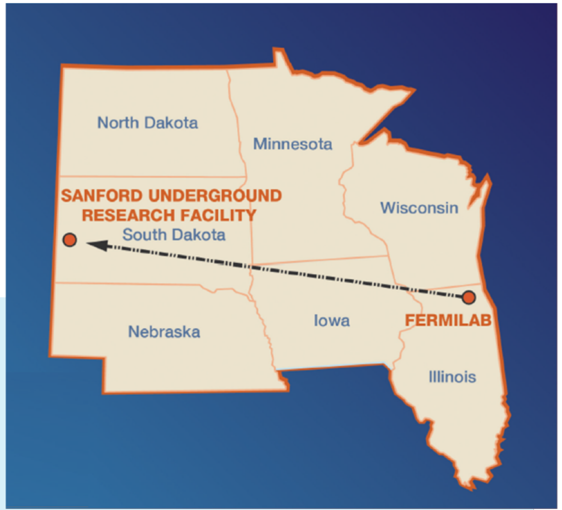
DUNE-UK

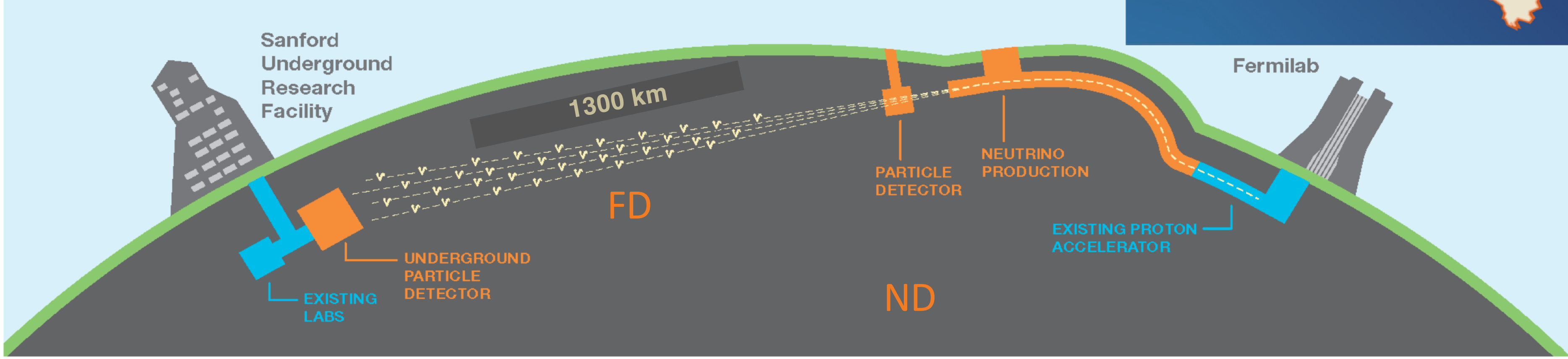
J. Bracinik, F. Gonnella, E. Goudzovski, S. Hillier, N. Lurkin, A. Sergi, R. Staley, A. Watson, (**University of Birmingham**); M. Adinolfi, P. Baesso, J. Brooke, D. Cussans, D. Newbold, S. Paramesvaran, K. Petridis, J. Rademacker, (**University of Bristol**); J. Marshall, L. Escudero, M. Thomson (**University of Cambridge**); P.E.L. Clarke, F. Muheim, M. Needham (**University of Edinburgh**); K. Long, J. Pasternak, J. Pozimski (**Imperial College**); S. Pascoli (**IPPP, Durham**); A. Blake, D. Brailsford, G. Chapman, J. Nowak, J. Statter (**Lancaster University**); C. Andreopoulos, G. Christodoulou, S. Dennis, T. Jones, K. Mavrokoridis, K. Hennessy, D. Payne, M. Roda, P. Sutcliffe, C. Touramanis (**University of Liverpool**); A. Bitadze, J. Freestone, A. Furmanski, J. Evans, D. Garcia Gamez, P. Guzowski, J. Pater, M. Perry, S. Söldner-Rembold, A. Szelc (**University of Manchester**); B. Abi, F. Azfar, G. Barr, M. Bass, R. Guenette, J. Martin-Albo, A. Weber (**University of Oxford**); A. Grant, A. Muir, S. Smith (**STFC Daresbury Laboratory**); A. Kaboth, R. Preece, W. Qian, A. Weber (**STFC Rutherford-Appleton Laboratory**); C. Booth, V. Kudryavtsev, N. McConkey, T. Gamble, M. Malek, C. Pidcott, M. Robinson, N. Spooner, M. Wright (**University of Sheffield**); M. Baird, J. Davies, L. Falk, W. Griffith, J. Hartnell, S. Peeters, B. Zamorano (**University of Sussex**); M. Cascella, C. Ghag, A. Holin, L. Manenti, R. Nichol, D. Waters (**University College London**); G. Barker, S. Boyd, M. Haigh, N. Grant, Y. Ramachers (**University of Warwick**).

DUNE in a Nutshell









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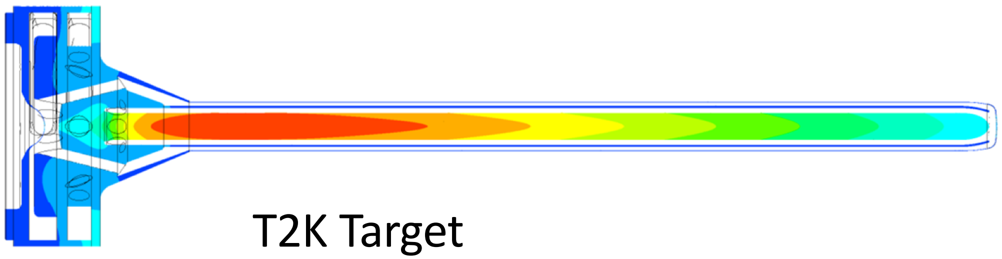
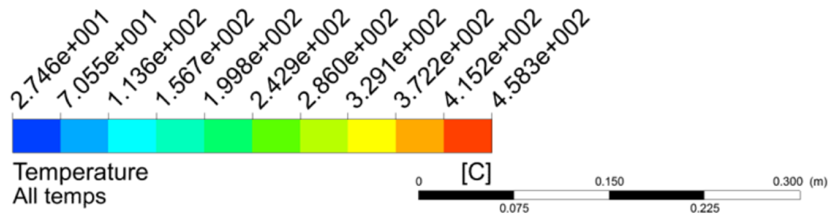
Target work at RAL

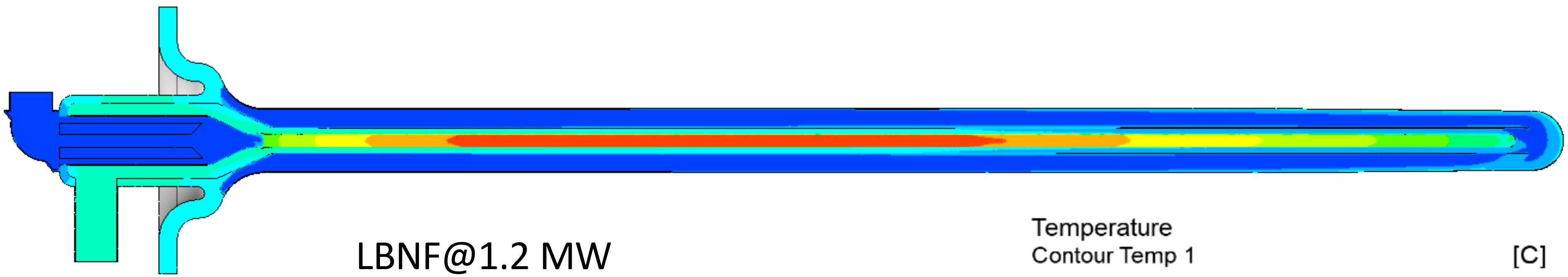
Chris Densham



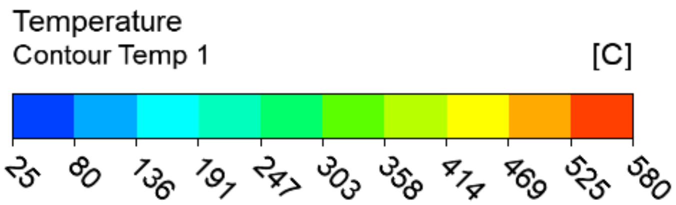
T2K Target



current experience up to 500 kW

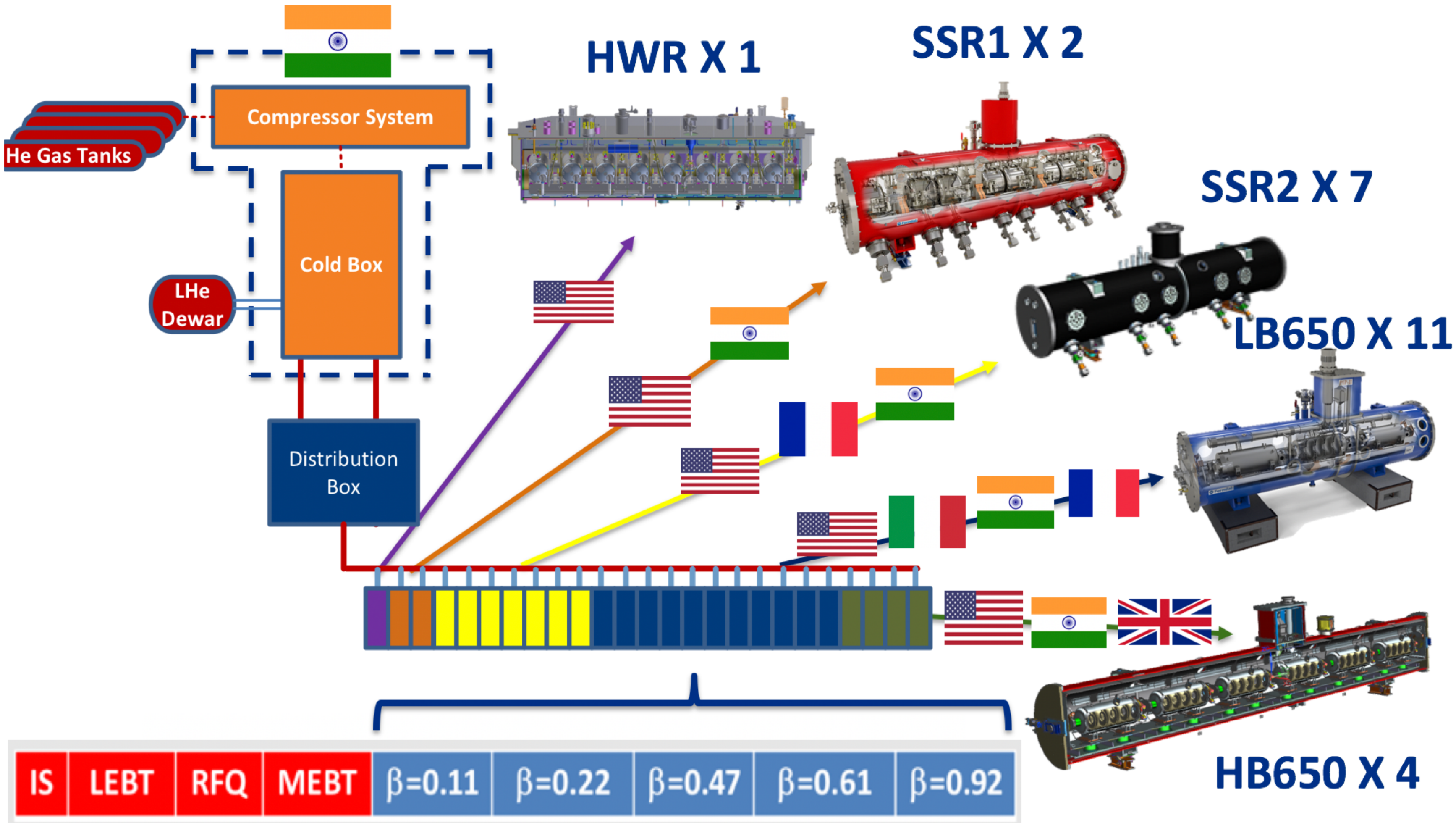


LBNF@1.2 MW

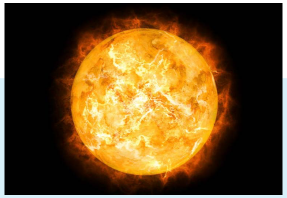


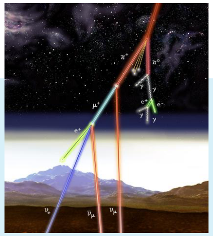
PIP-II: International Project

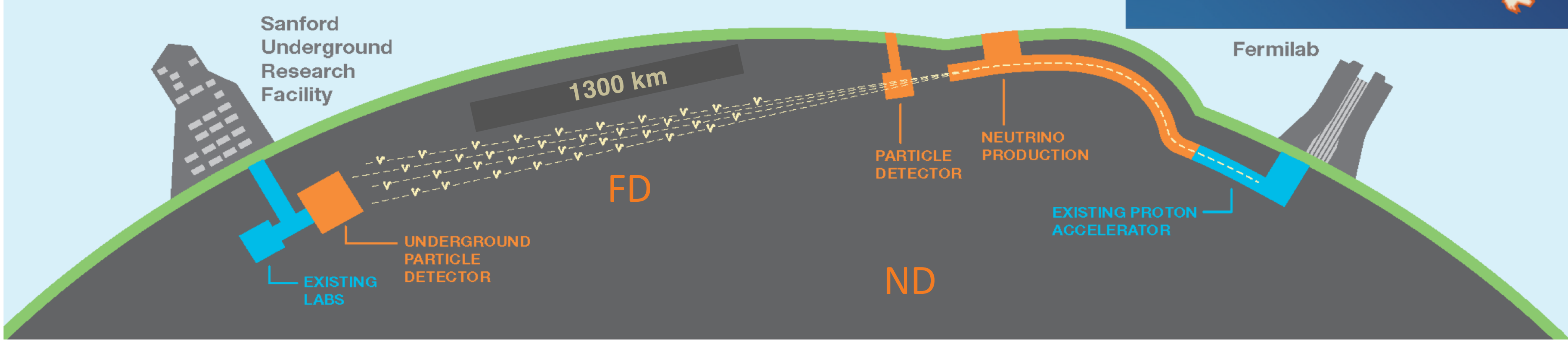
up to 2.4MW of beam power by 2030.

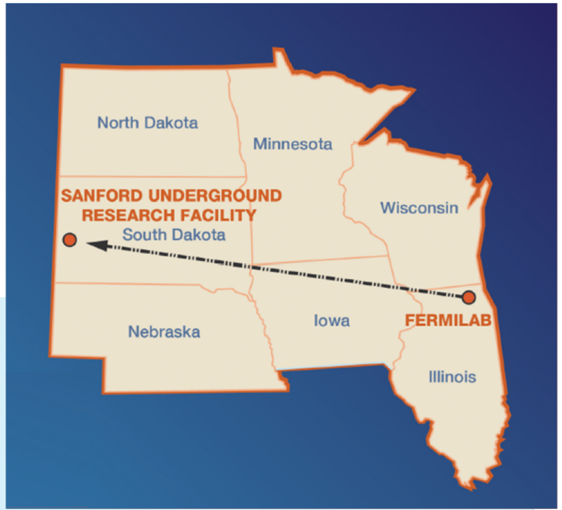


DUNE in a Nutshell









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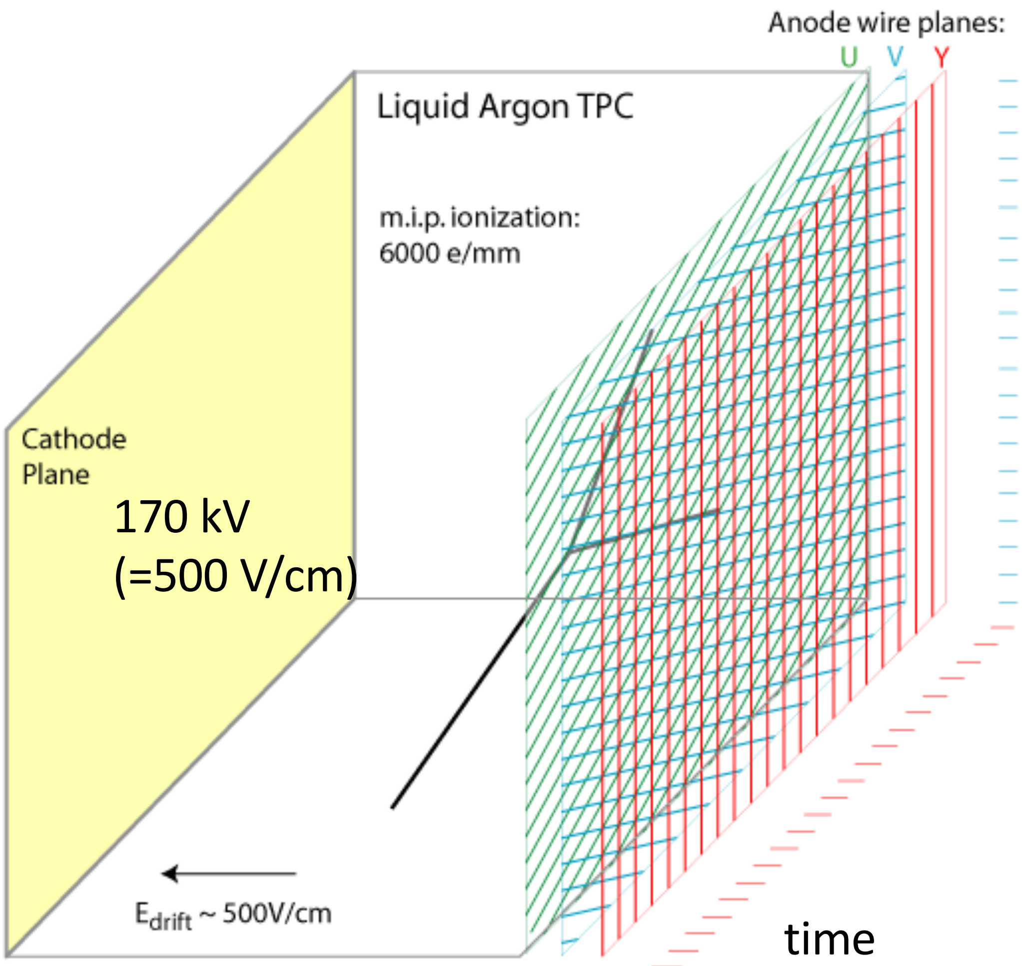
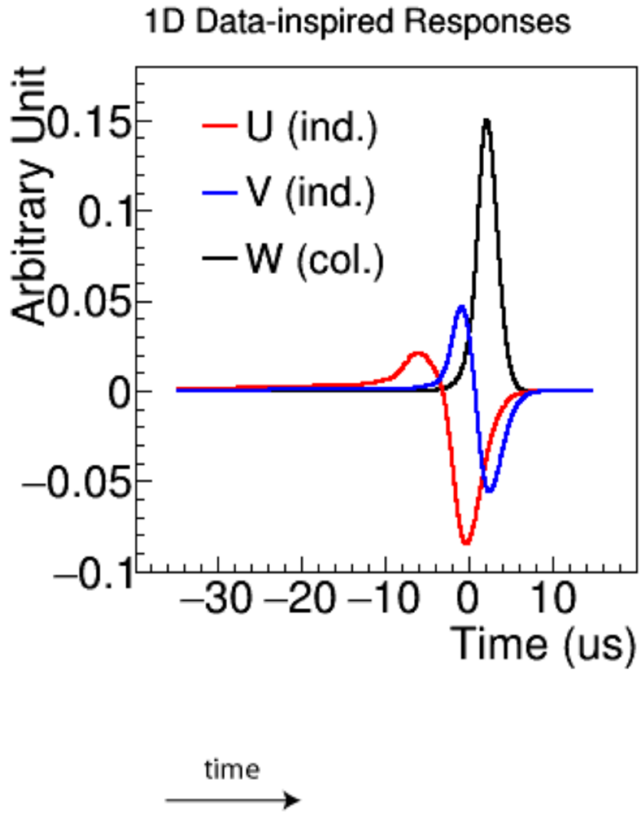
Time Projection Chamber (Single Phase)

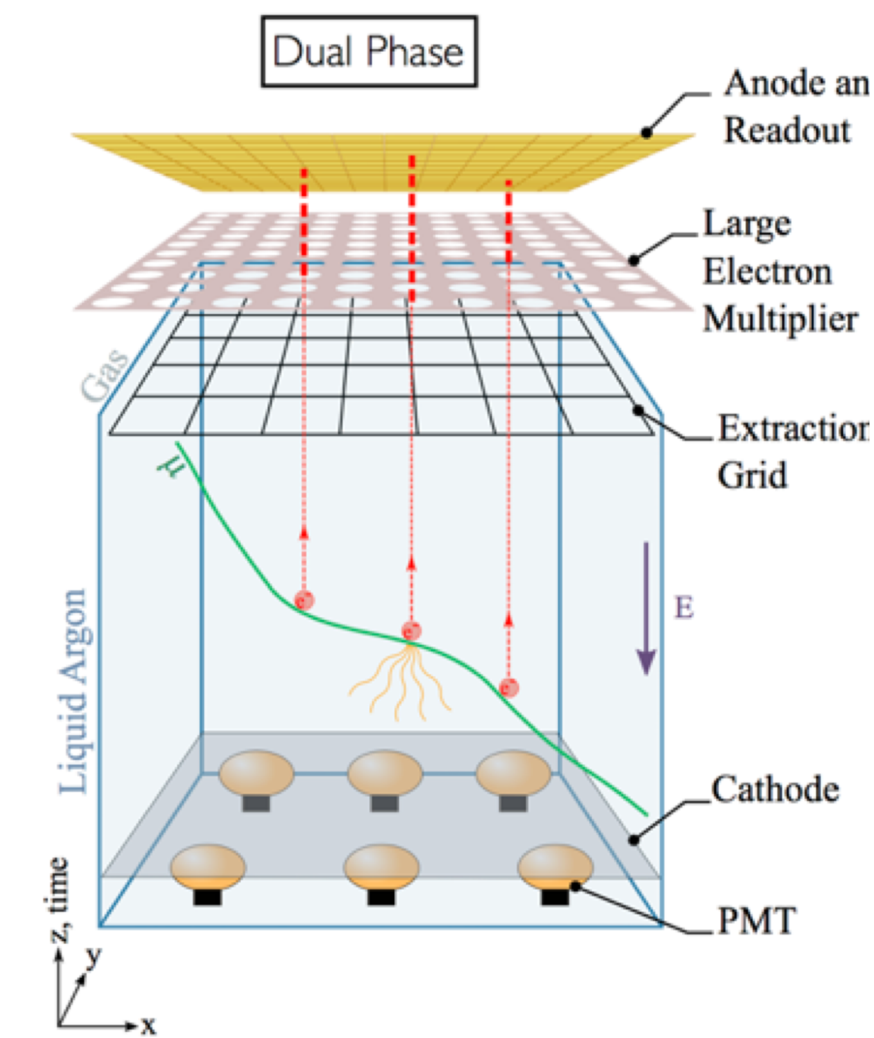
Wire pitch ≈ 5 mm



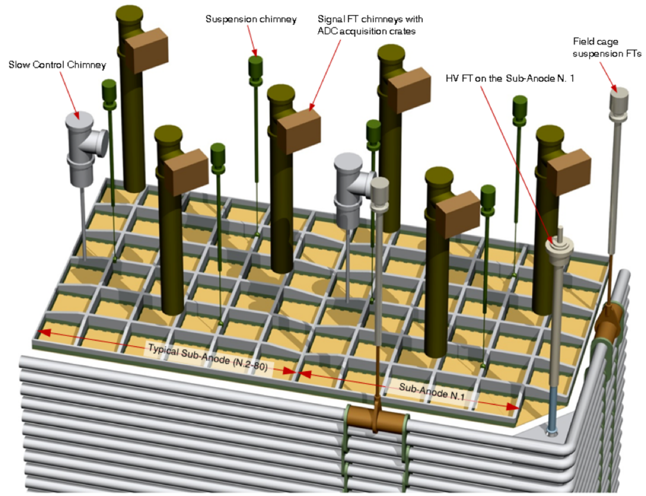
3.4 m → 2.13 ms



Time Projection Chamber (Dual Phase)



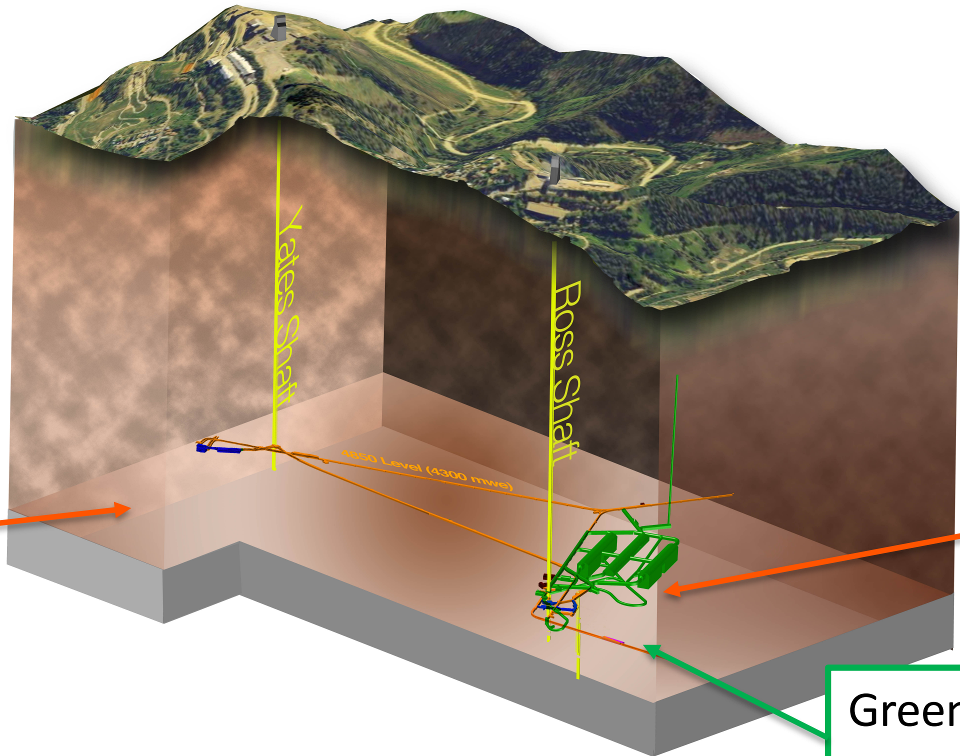
- Larger drift distance (12 m)– higher fields (600 kV)
- Potentially better signal to noise
- Readout/HV access through chimneys



Underground Laboratory SURF

DUNE Far Detector site

- Sanford Underground Research Facility (SURF), South Dakota
- Four caverns on 4850 level (~ 1 mile underground)

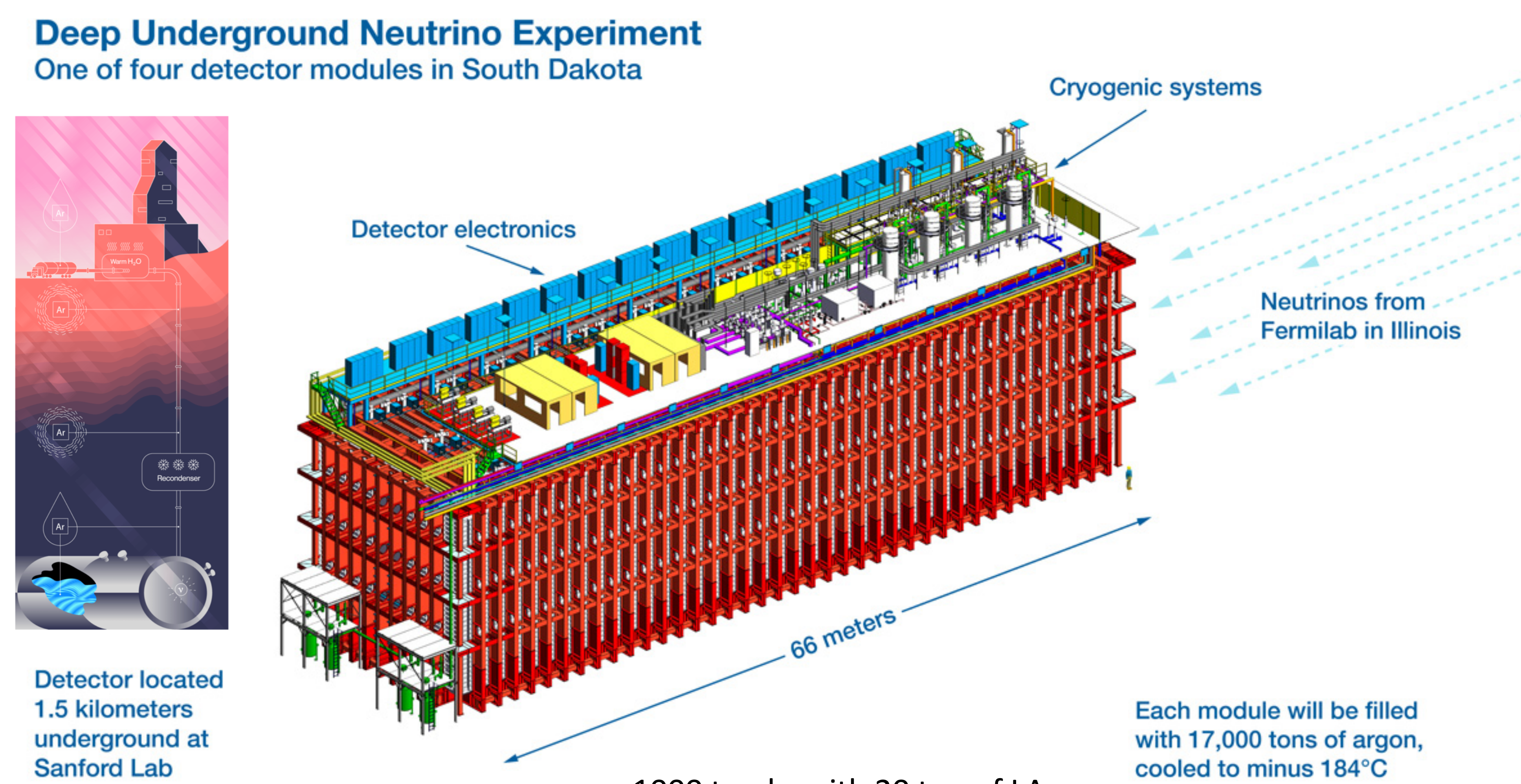


Davis Campus:
- LUX
- Majorana
- …
- **LZ**

Ross Campus:
- CASPAR
- …
- **DUNE**

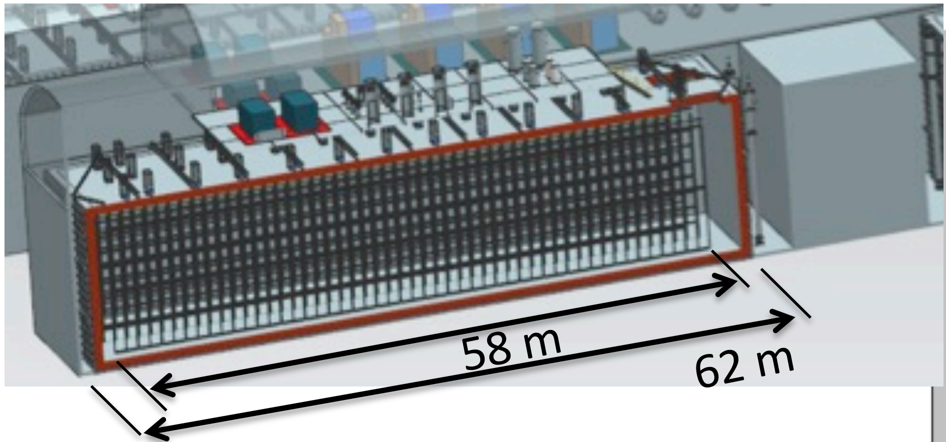
Green = new excavation commenced in 2017

Free-standing steel cryostat

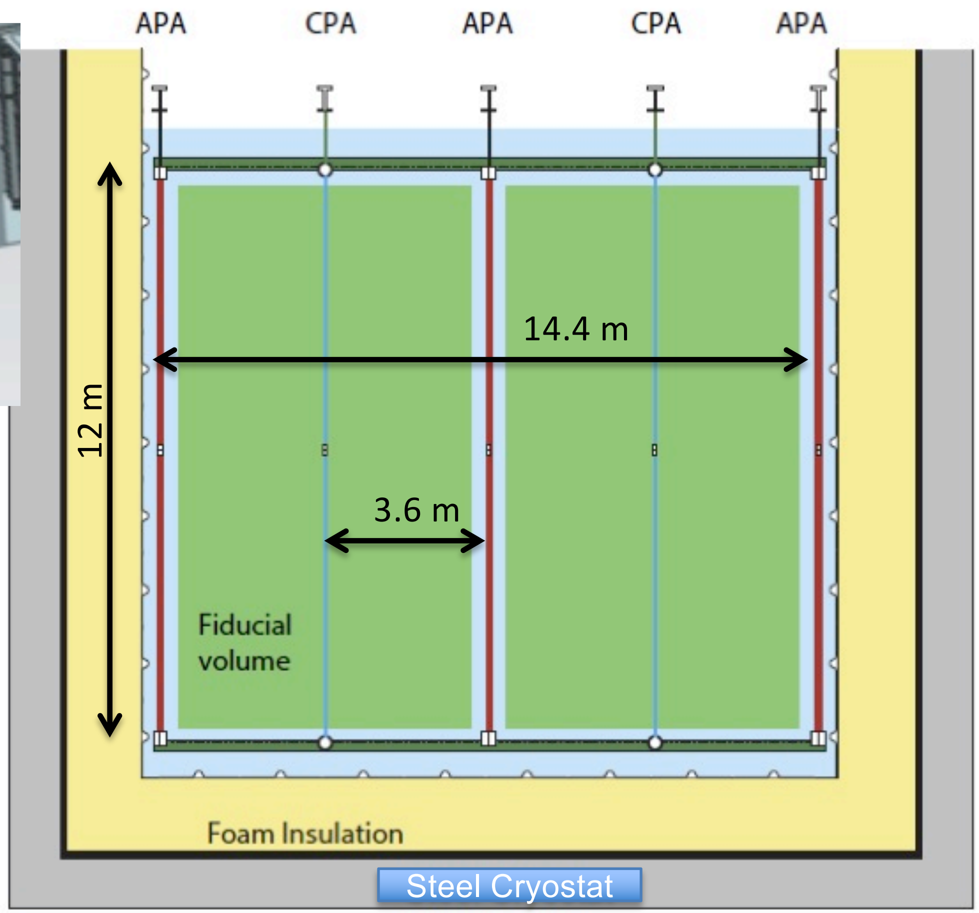


1000 trucks with 20 ton of LAr

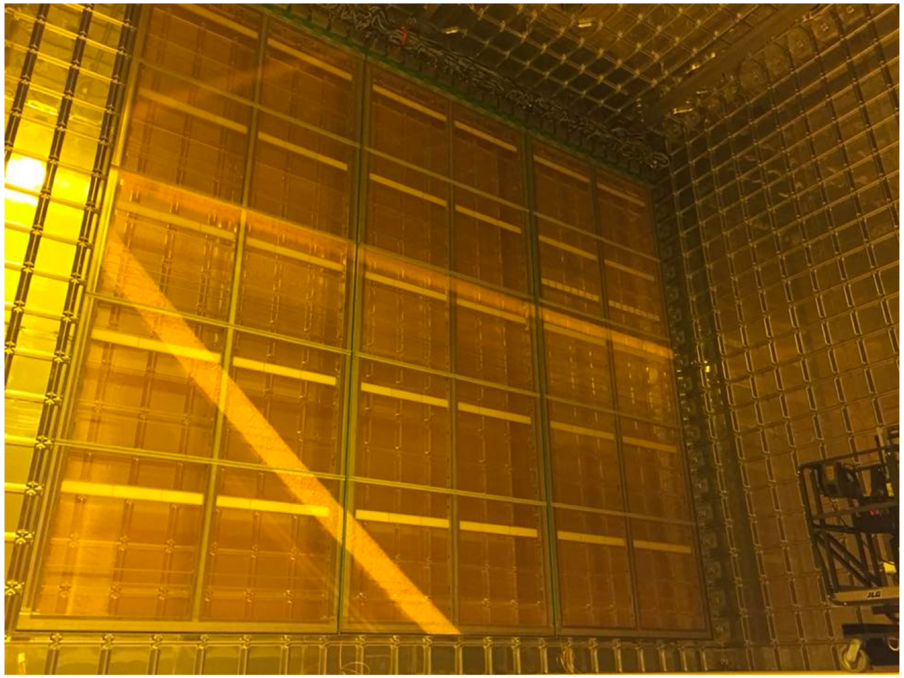
Two single-phase detectors



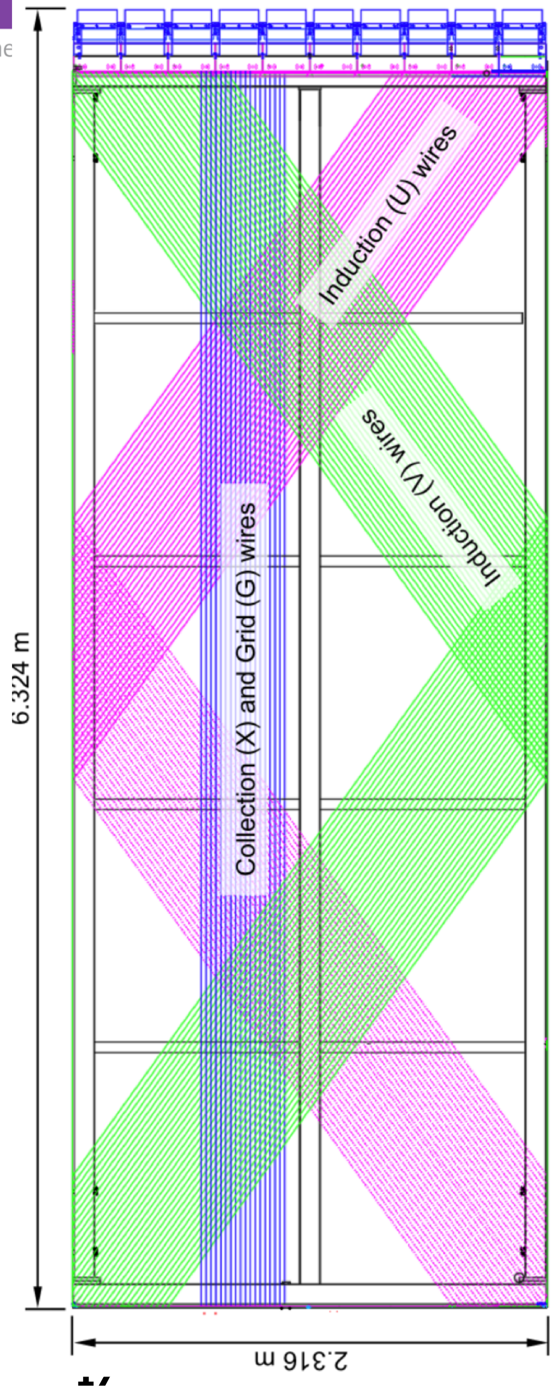
- 150 Anode Plane Assemblies (APA) per detector
  - Cold electronics 384,000 channels
- Cathode planes (CPA) at 180 kV
  - 3.6 m max drift length



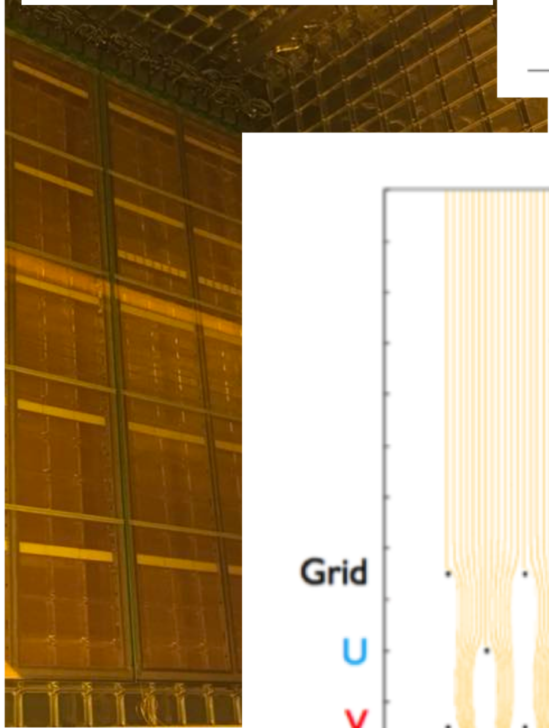
Anode Plane Assemblies



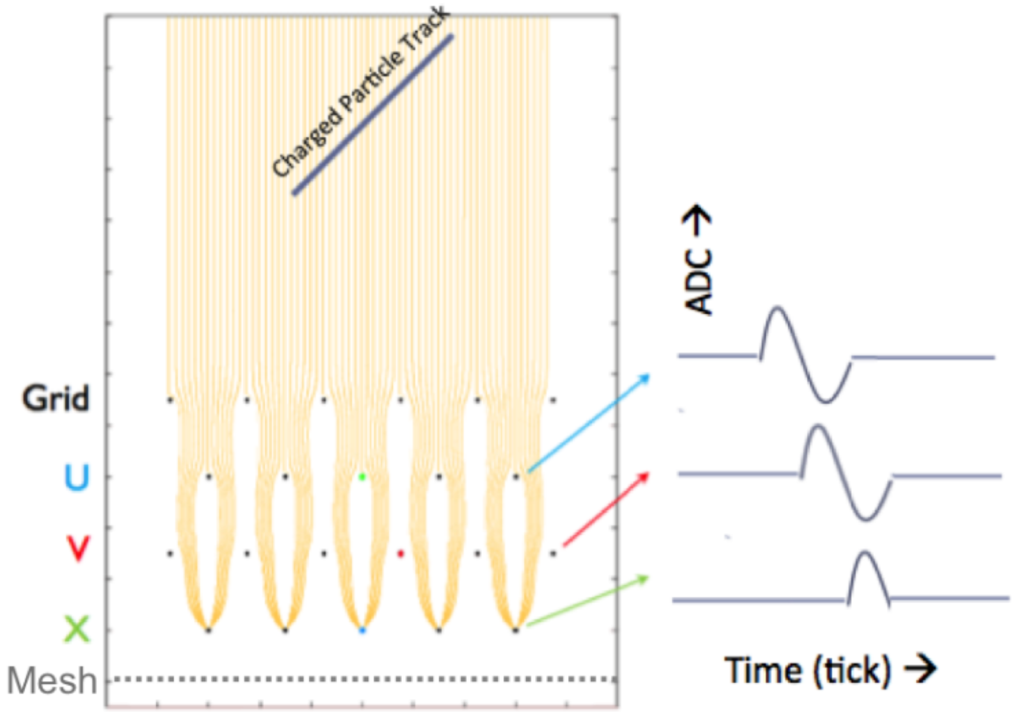
- Four wire planes
  - x, u, v, g
- 6 x 2.3 m
- 5.5k wires on each APA
- 35.7^{o} winding angle on u and v layers
- ~5 mm wire pitch



Read out at the top

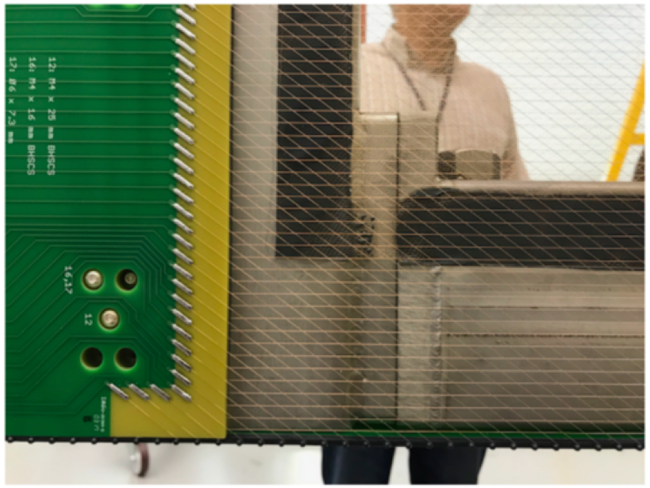


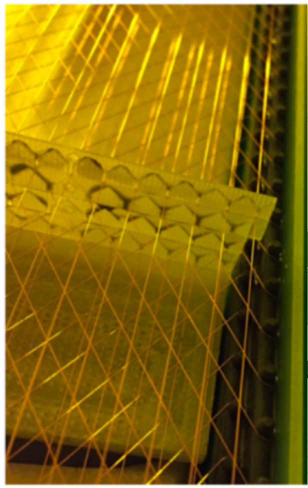
Anode Plane	Bias Voltage
G - Grid	−665 V
U - Induction	−370 V
V - Induction	0 V
X - Collection	820 V
Grounding Mesh	0 V

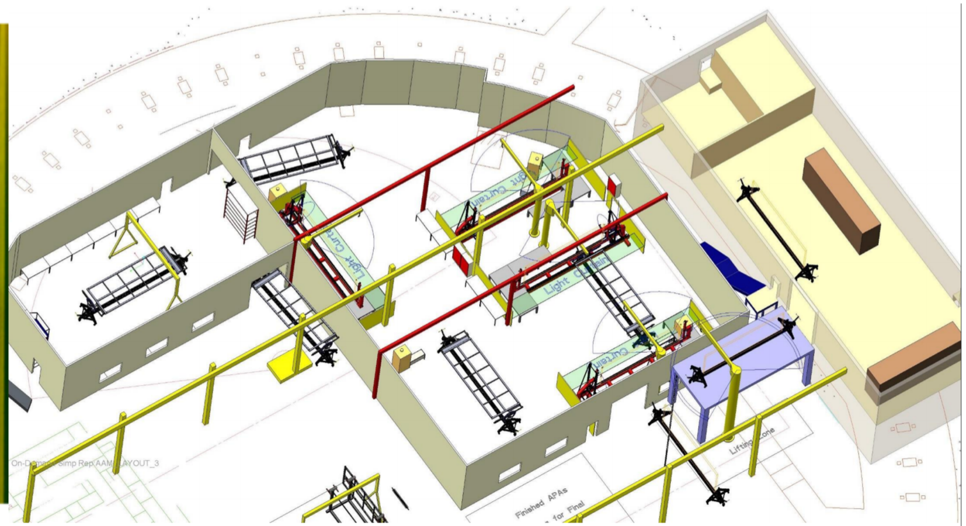


MANCHESTER
1824
The University of Manchester

Production factory at the Daresbury Laboratory





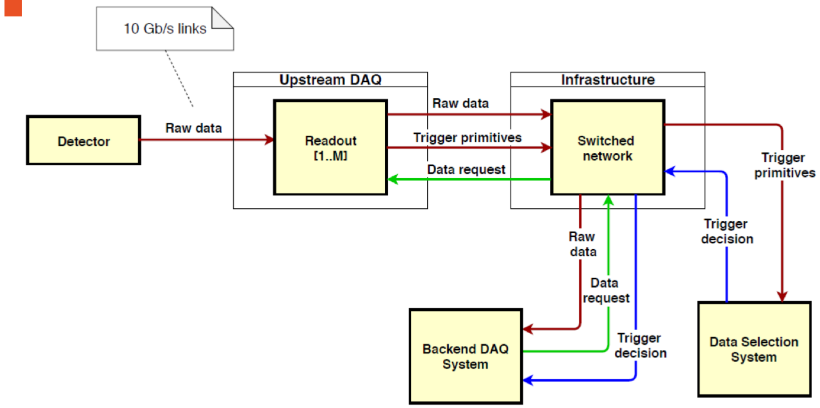


Data Acquisition

Each module (150 APAs x 2560 wires x 2 MHz x 12 bit) produces

1 TB/s

of continuous data.



DAQ Overview

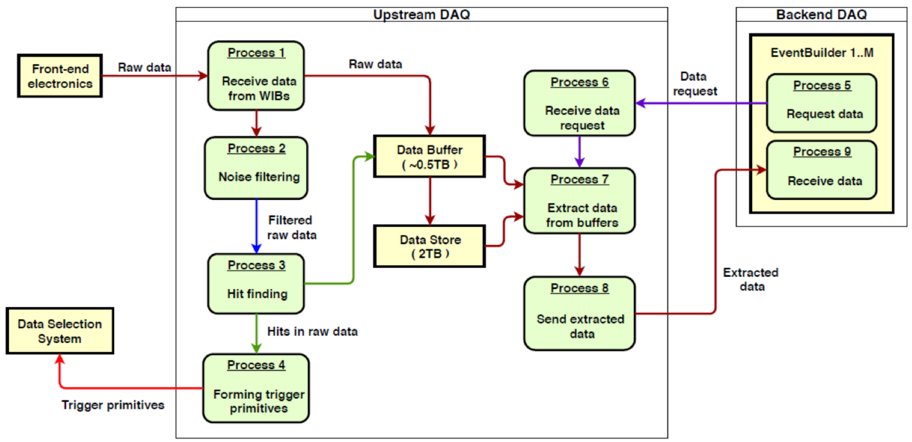
Key requirements for the trigger and data storage:

- >99% efficiency for particles depositing > 100 MeV
- >95% efficiency for a galactic supernova burst

Tasks for the up-stream DAQ:

- Noise filtering
- Hit finding to provide information for trigger
- Buffer data for trigger
  - 10 s to wait for possible supernova trigger
  - 30 s to store supernova trigger to allow readout

Store less than 30 PB/year



Upstream DAQ Overview

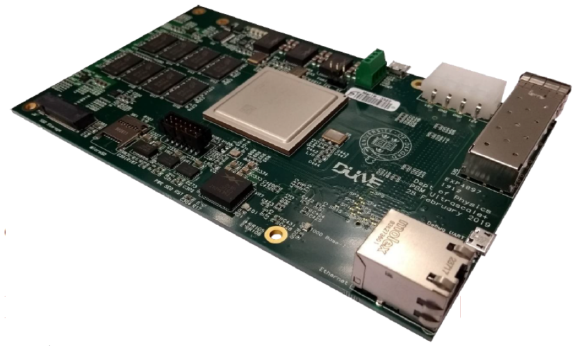
Data Acquisition and Triggering

Status:

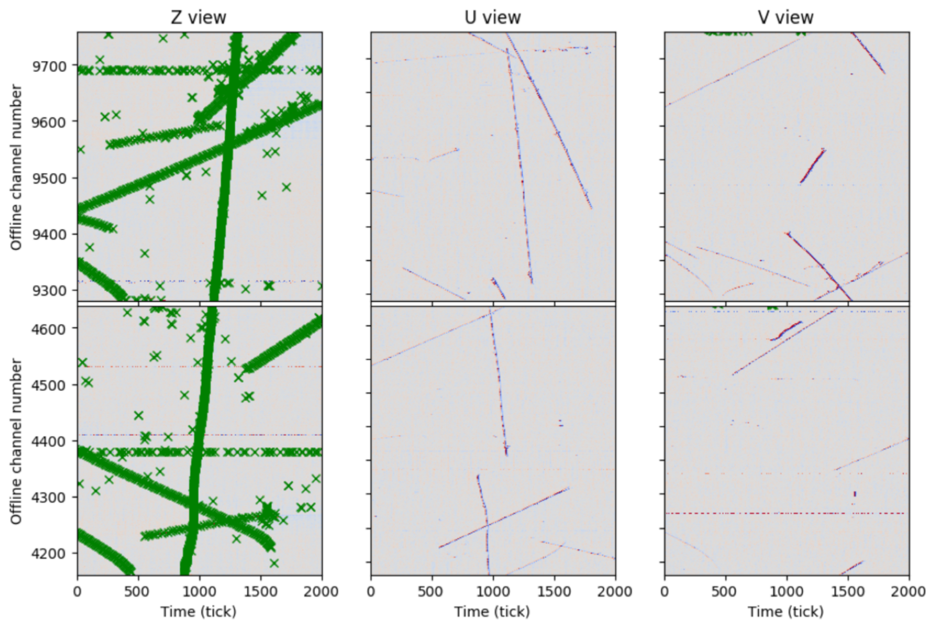
- First prototype of Processing and Buffering Module produced by Oxford: complex, dense multilayer board with high-speed lines (May 2019)
- Self-triggering has been successfully used in ProtoDUNE to test hit finding and trigger algorithms in software

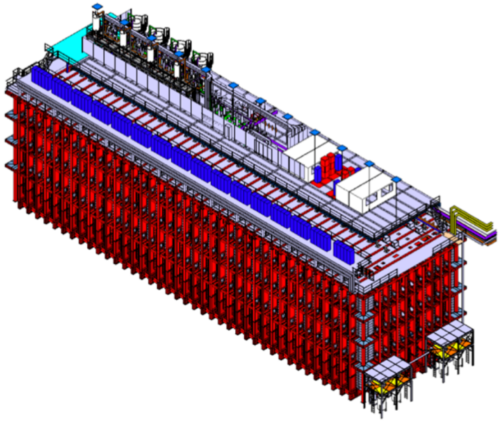
Future:

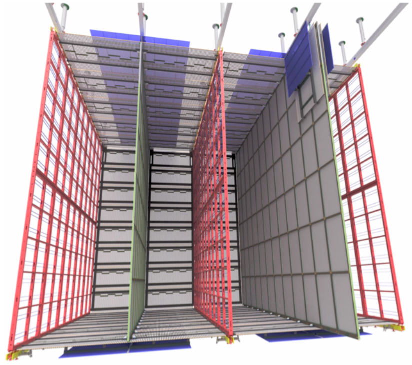
- Implement firmware onto FELIX and test hit finding with trigger
- Integrate PBM (buffering) with FELIX to create DUNE specific FELIX board
- ProtoDUNE-II (March 2021) to test full prototype readout

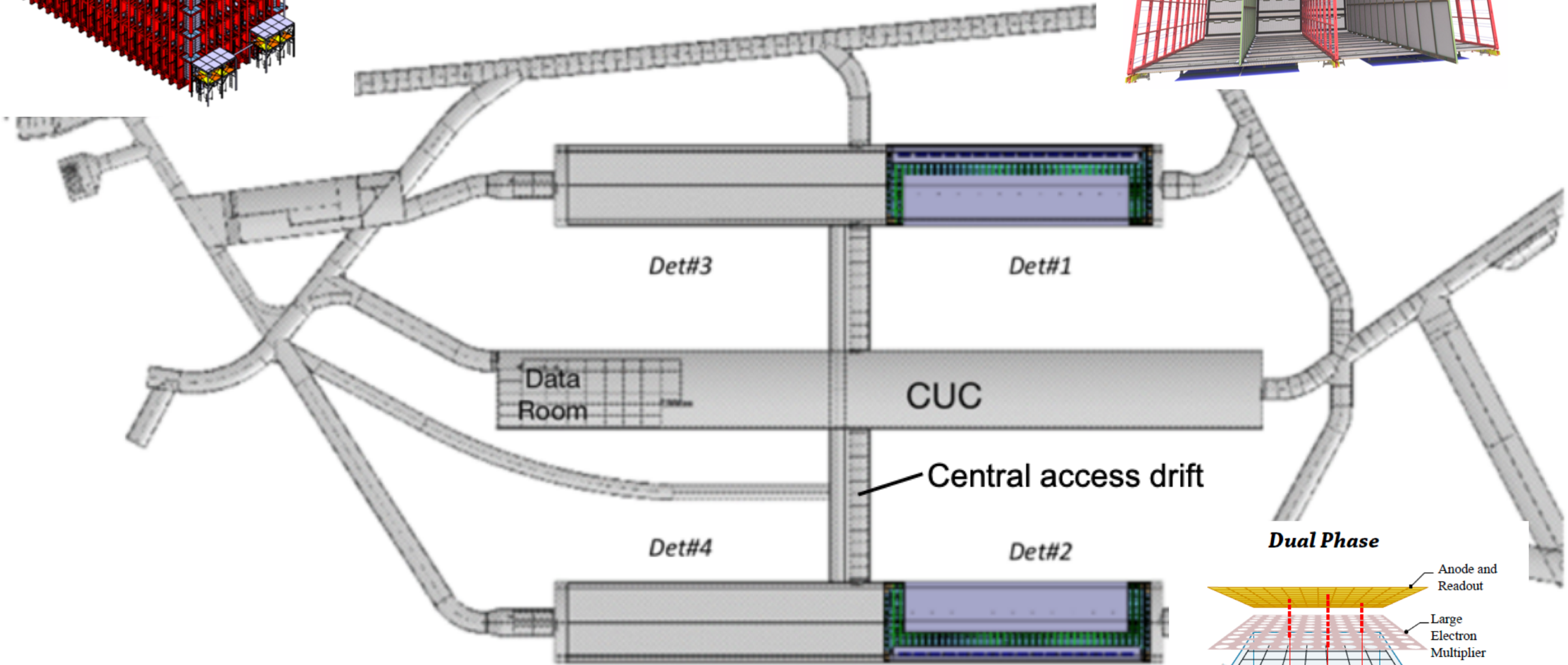


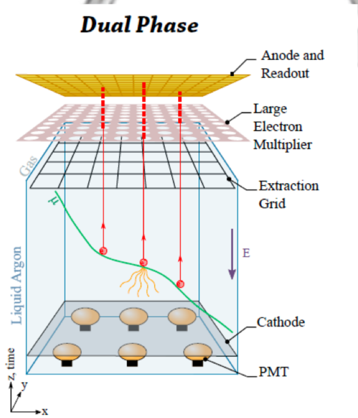
Hits from self-trigger algorithm (collection wires only)





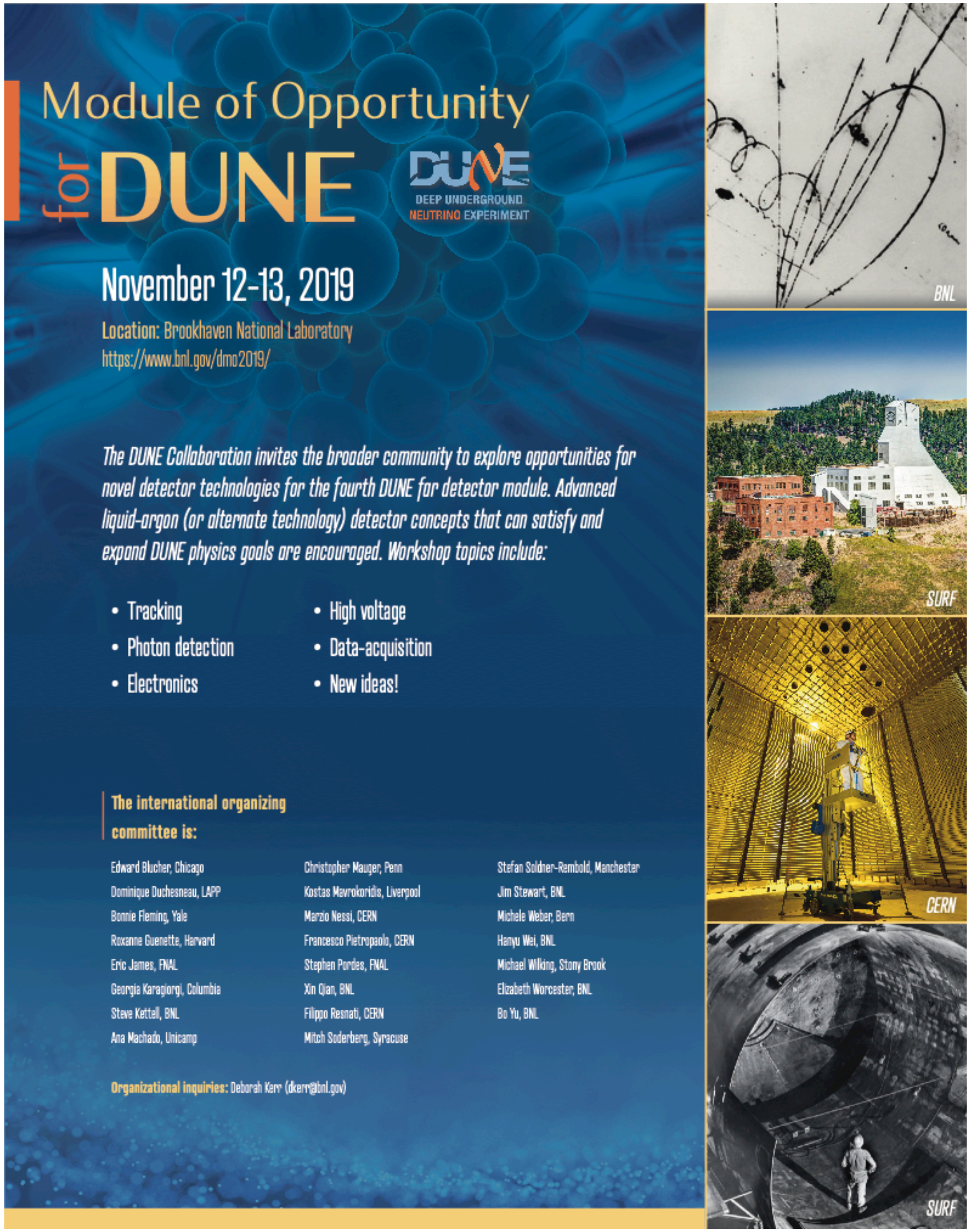






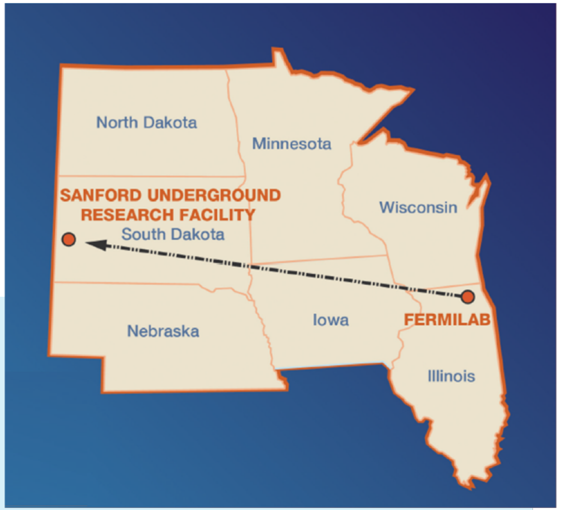
<u>2+1+1 Model:</u>

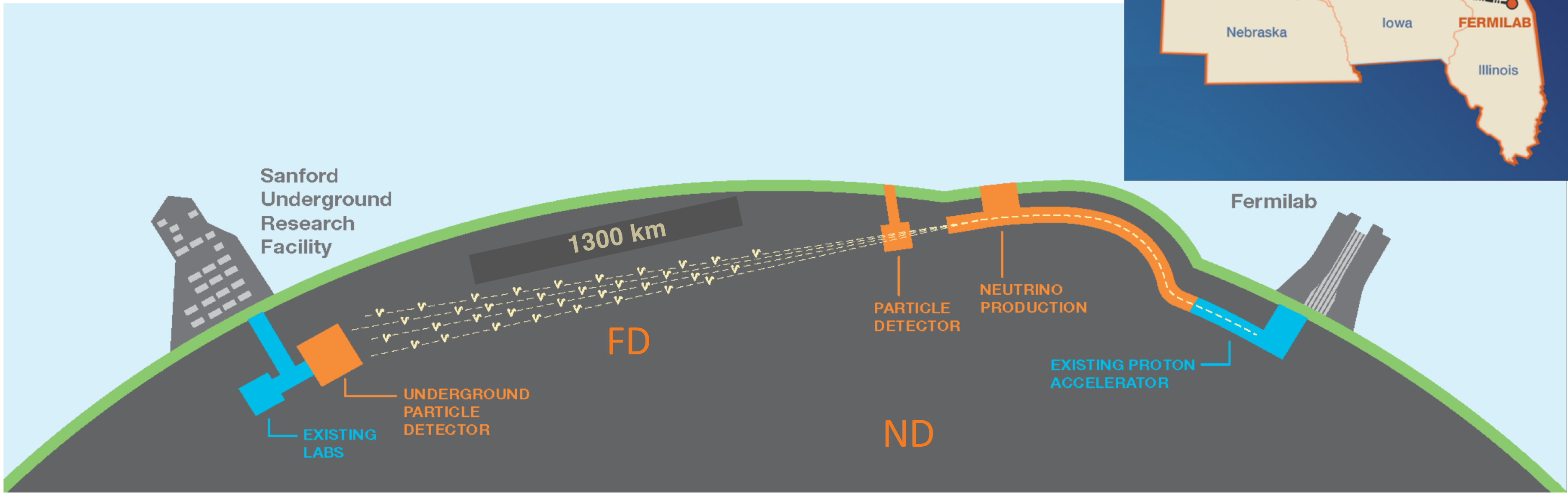
Sequencing (SP-SP-DP vs SP-DP-SP) will depend
On ProtoDUNE results and resources



Module of Opportunity
for DUNE
DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT
November 12-13, 2019
Location: Brookhaven National Laboratory
https://www.bnl.gov/dmo2019/
The DUNE Collaboration invites the broader community to explore opportunities for novel detector technologies for the fourth DUNE far detector module. Advanced liquid-argon (or alternate technology) detector concepts that can satisfy and expand DUNE physics goals are encouraged. Workshop topics include:
• Tracking
• Photon detection
• Electronics
• High voltage
• Data-acquisition
• New ideas!
The international organizing committee is:
Edward Blucher, Chicago
Dominique Duchesneau, LAPP
Bonnie Fleming, Yale
Roxanne Guenette, Harvard
Eric James, FNAL
Georgia Karagiorgi, Columbia
Steve Kettell, BNL
Ana Machado, Unicamp
Christopher Mauger, Penn
Kostas Mavrokoridis, Liverpool
Marzio Nessi, CERN
Francesco Pietropaolo, CERN
Stephen Pordes, FNAL
Xin Qian, BNL
Filippo Resnati, CERN
Mitch Soderberg, Syracuse
Stefan Soldner-Rembold, Manchester
Jim Stewart, BNL
Michele Weber, Bern
Hanyu Wei, BNL
Michael Wilking, Stony Brook
Elizabeth Worcester, BNL
Bo Yu, BNL
Organizational inquiries: Deborah Kerr (dkerr@bnl.gov)
BNL
SURF
CERN
SURF

DUNE in a Nutshell





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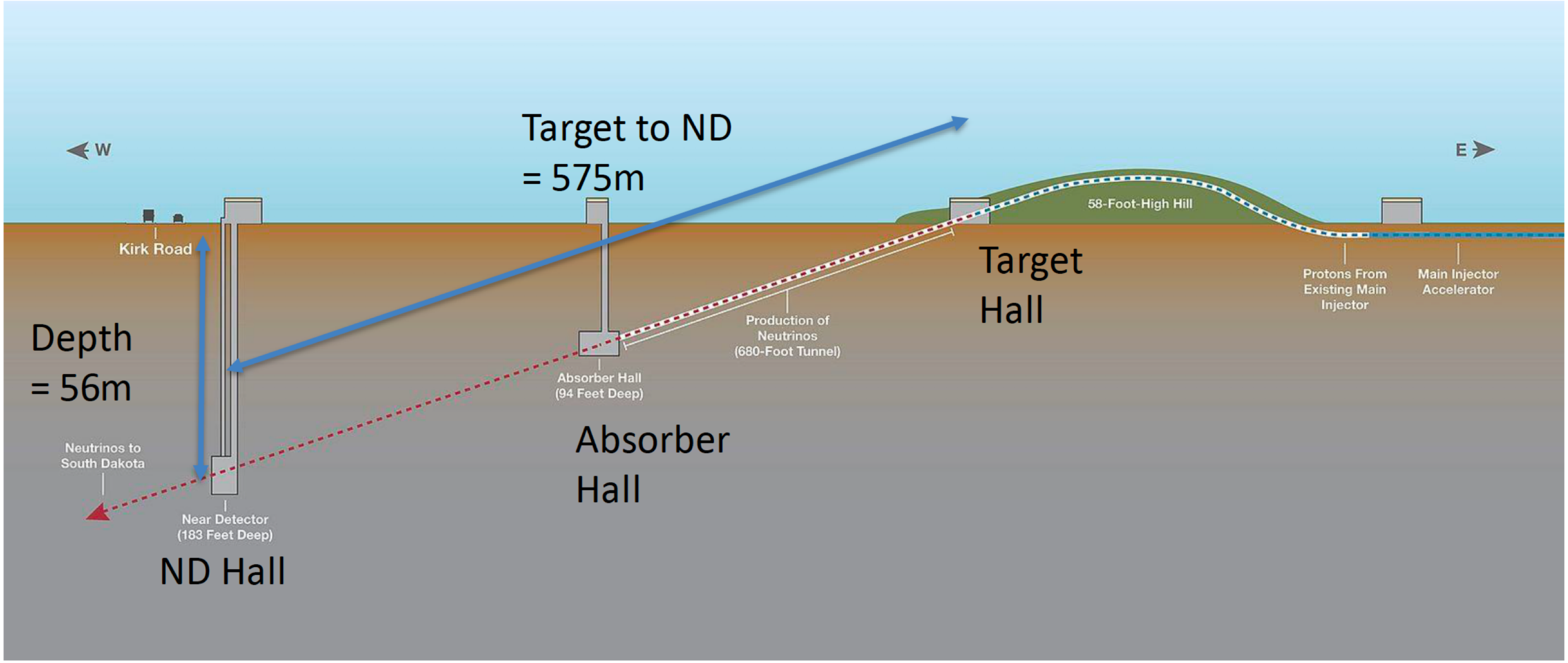
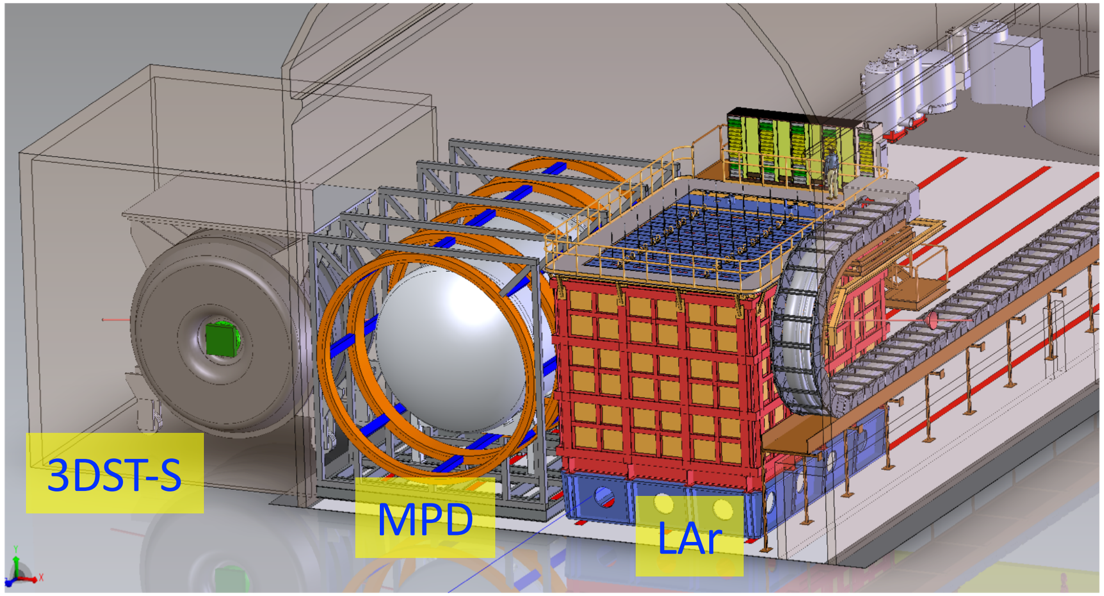
Near Detector Complex



- 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

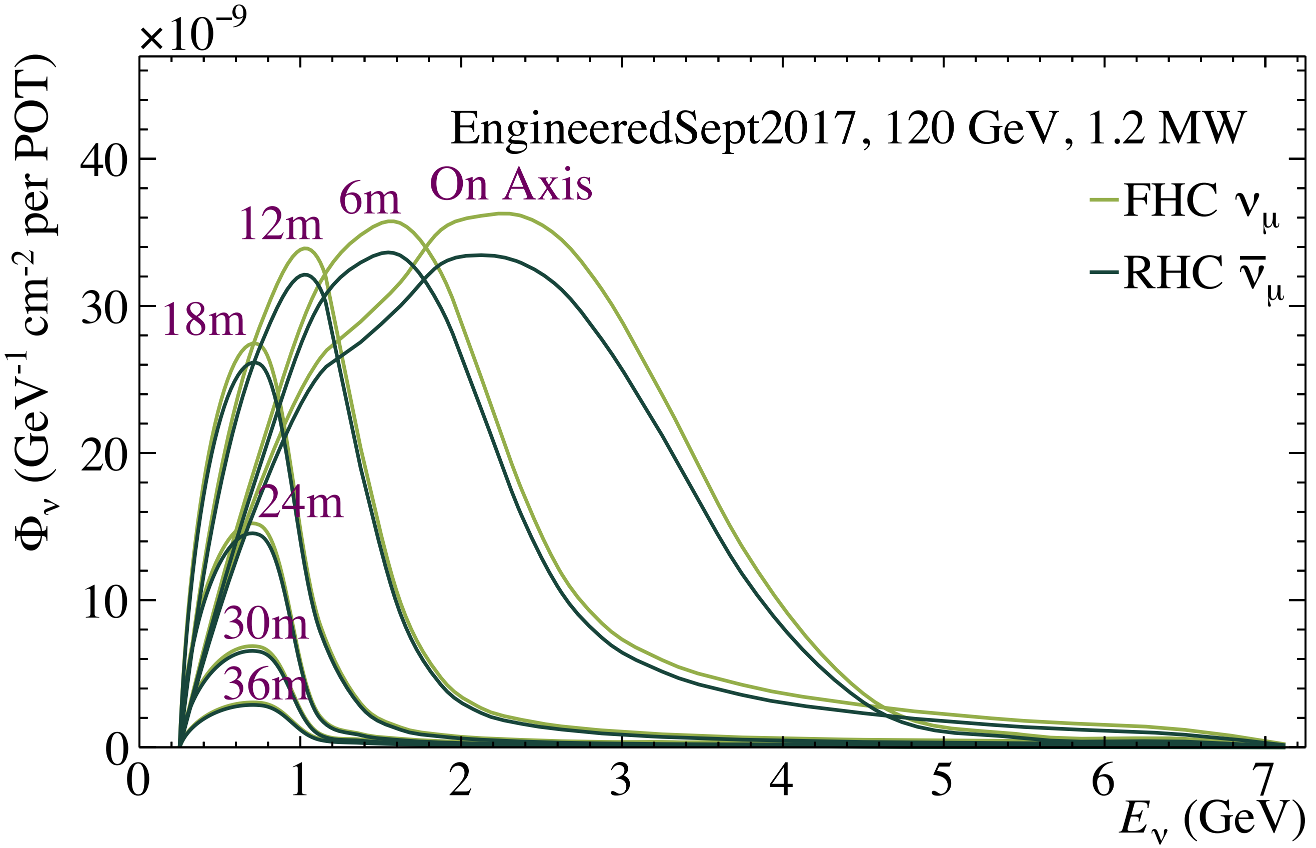
Near Detector Reference Design



- Highly segmented liquid-argon TPC (ArgonCube)
- Magnetized High Pressure Gas Argon TPC (MPD)
- Electromagnetic calorimeter/Muon Chambers
- Superconducting magnet
- On-axis beam spectrometer (KLOE magnet+3DST-S)

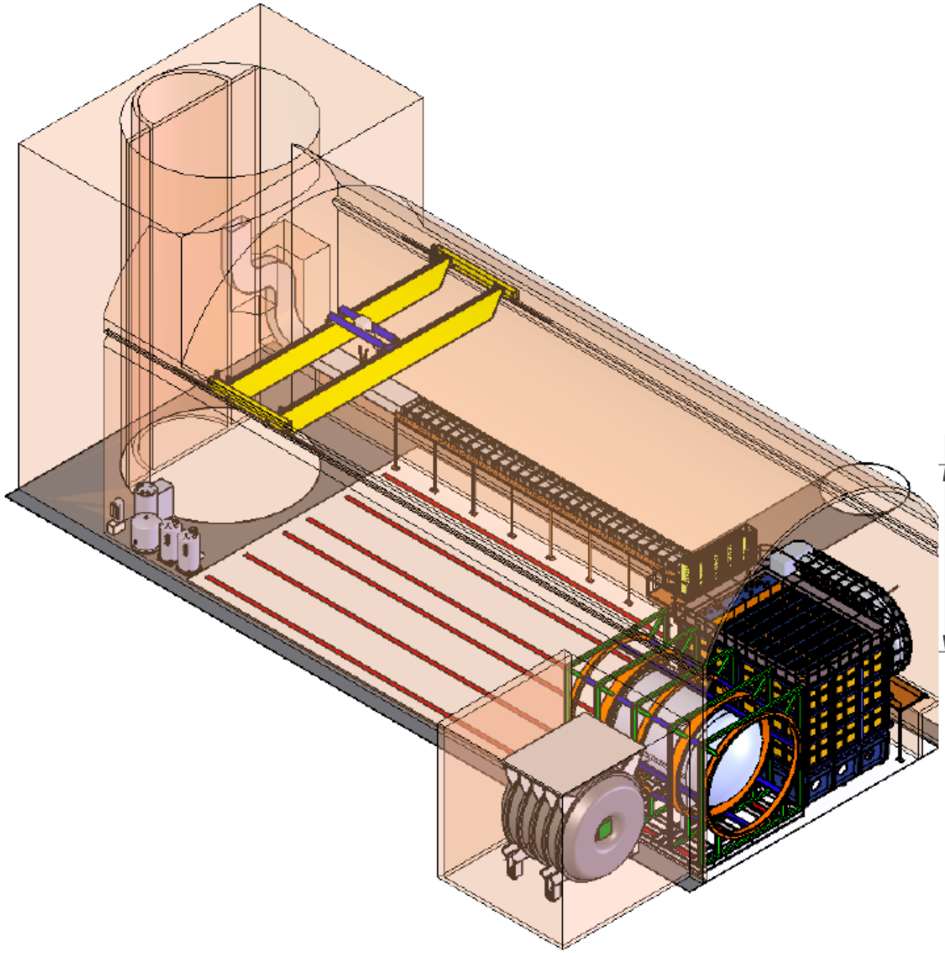
The DUNE Near Detector

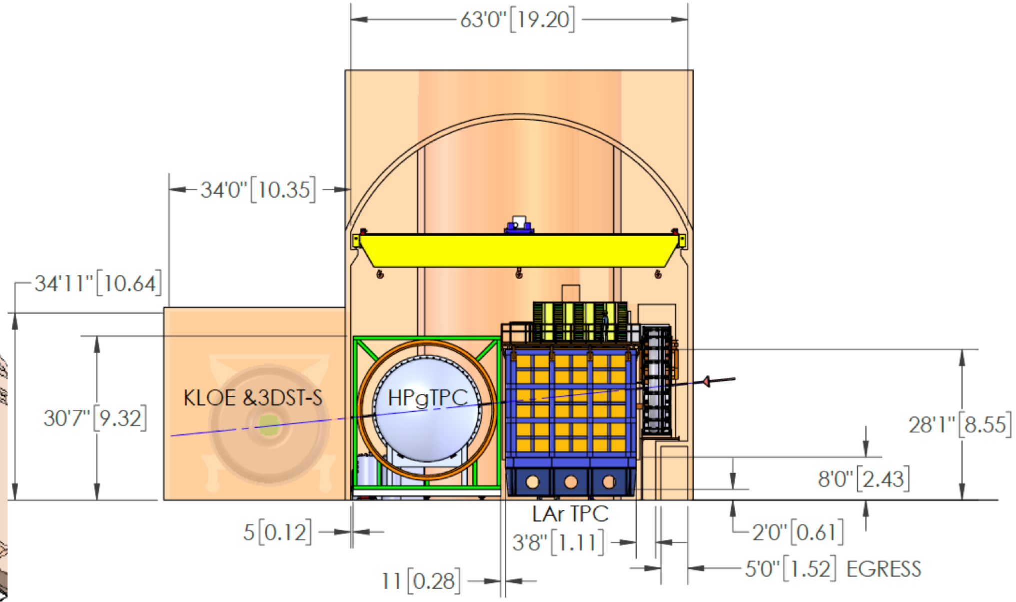
Capability to move ND for off-axis measurements (DUNE-Prism)



Gives us the ability to change neutrino energy in a controlled way

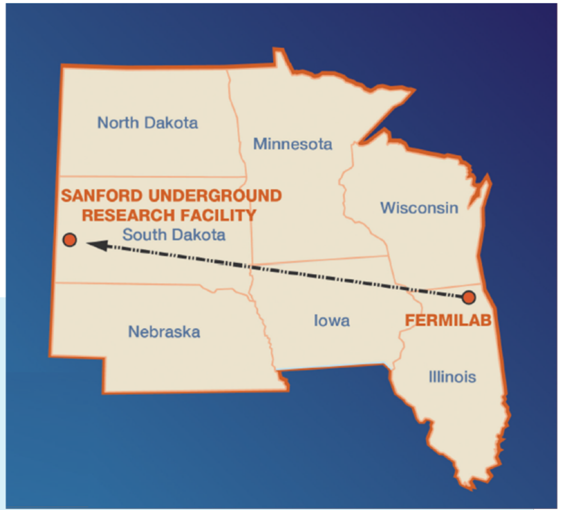
The DUNE Near Detector

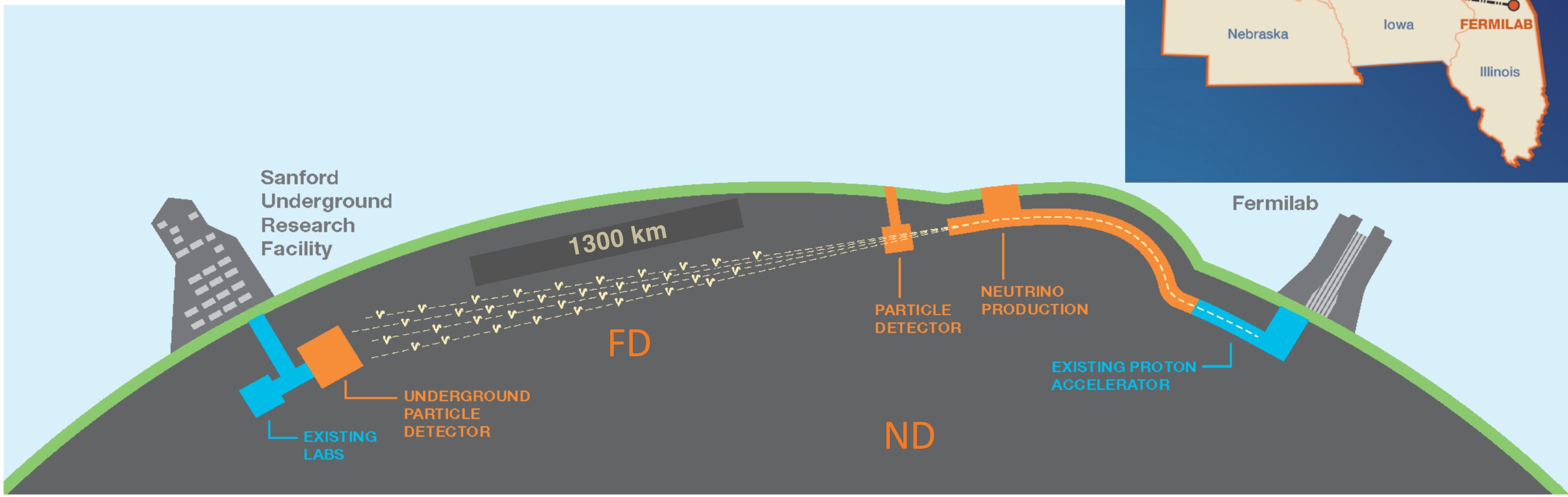




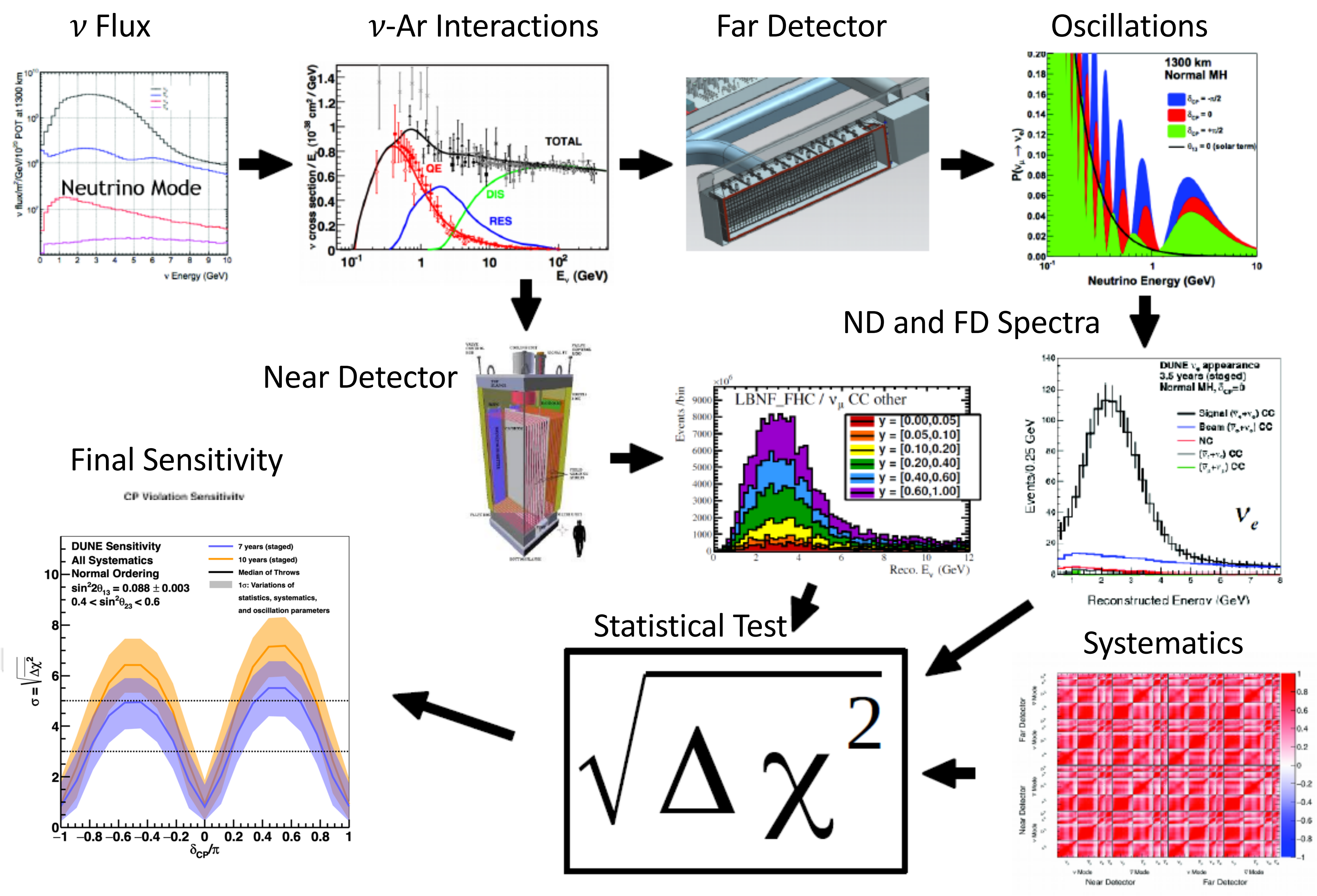

DUNE Near Detector Workshop
21 - 23 October • DESY
https://indico.fnal.gov/event/21340/
You are invited to attend this open workshop
to learn about opportunities and potential
for international participation!
Physics opportunities • High pressure gas TPC • Detector magnets • Calorimetry
DESY
Fermilab
DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

DUNE in a Nutshell





1. A high-power, wide-band neutrino beam (~ GeV energy range).
2. A ≈ 40 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.


ν Flux
Neutrino Mode
ν-Ar Interactions
TOTAL
QE
DIS
RES
Far Detector
Oscillations
1300 km
Normal MH
Neutrino Energy (GeV)
ND and FD Spectra
Near Detector
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]
Reco. E_ν (GeV)
Reconstructed Energy (GeV)
Final Sensitivity
CP Violation Sensitivity
DUNE Sensitivity
All Systematics
Normal Ordering
7 years (staged)
10 years (staged)
Median of Throws
1σ: Variations of statistics, systematics, and oscillation parameters
Statistical Test
$\sqrt{\Delta\chi^2}$
Systematics
Near Detector
Far Detector

DUNE Technical Design Report

Detailed documentation of all **scientific**, **technical**, and **managerial** aspects of DUNE

~2000 pages over five volumes

Deep Underground Neutrino Experiment (DUNE)

Technical Design Report

Volume I:

Introduction to DUNE

132 collaborators from 16 institutions in UK

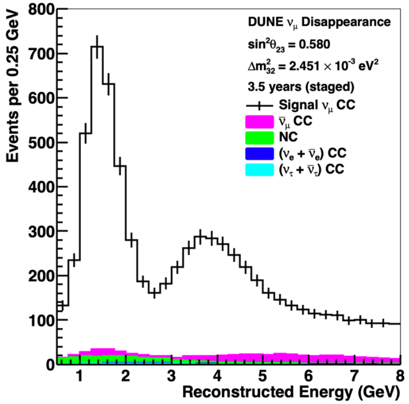
*

A major milestone for the collaboration

DUNE (Dis-)appearance Signals

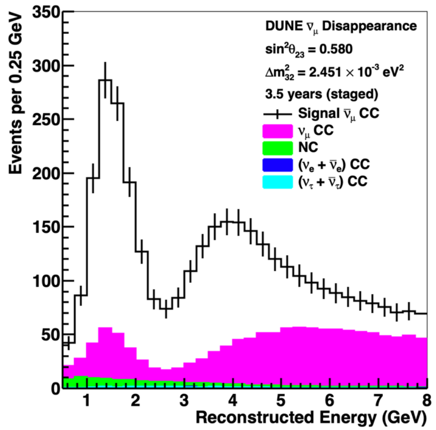
Run for 7 years with both neutrinos and anti-neutrinos

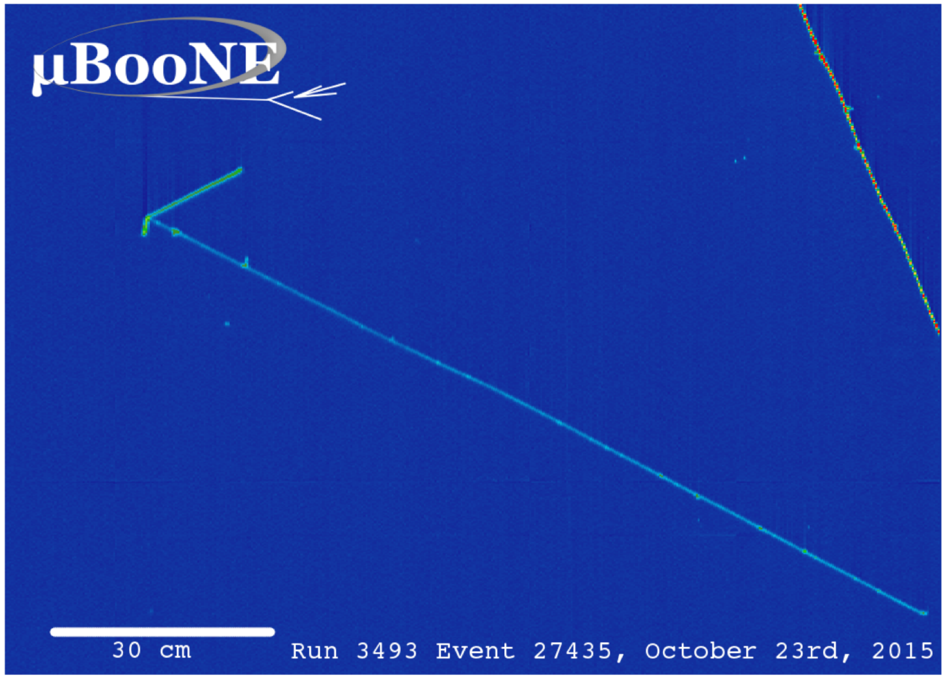
muon-neutrino disappearance



ν_μ

anti-ν_μ



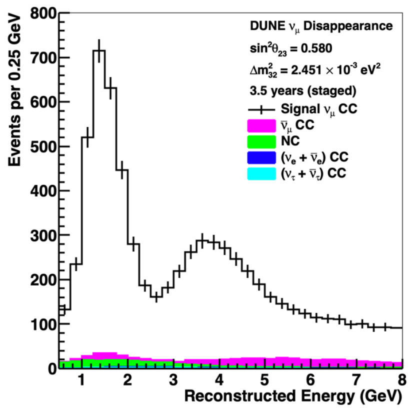


DUNE (Dis-)appearance Signals

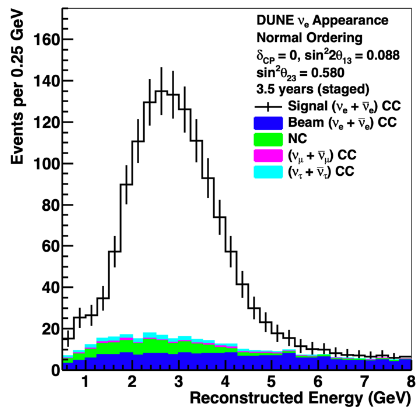
Run for 7 years with both neutrinos and anti-neutrinos

muon-neutrino disappearance

electron-neutrino appearance



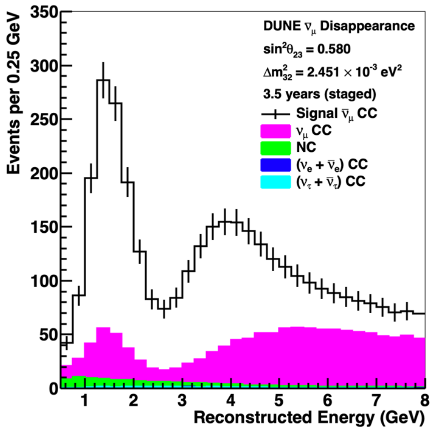
ν_μ



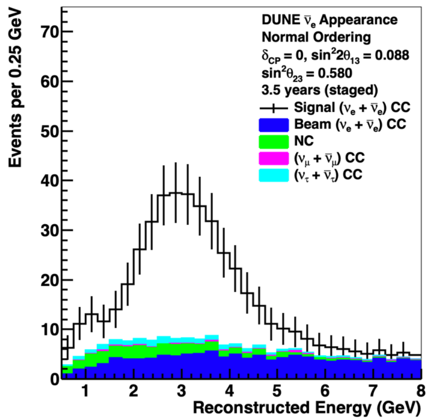
ν_e

[7 years of data]

anti-ν_μ

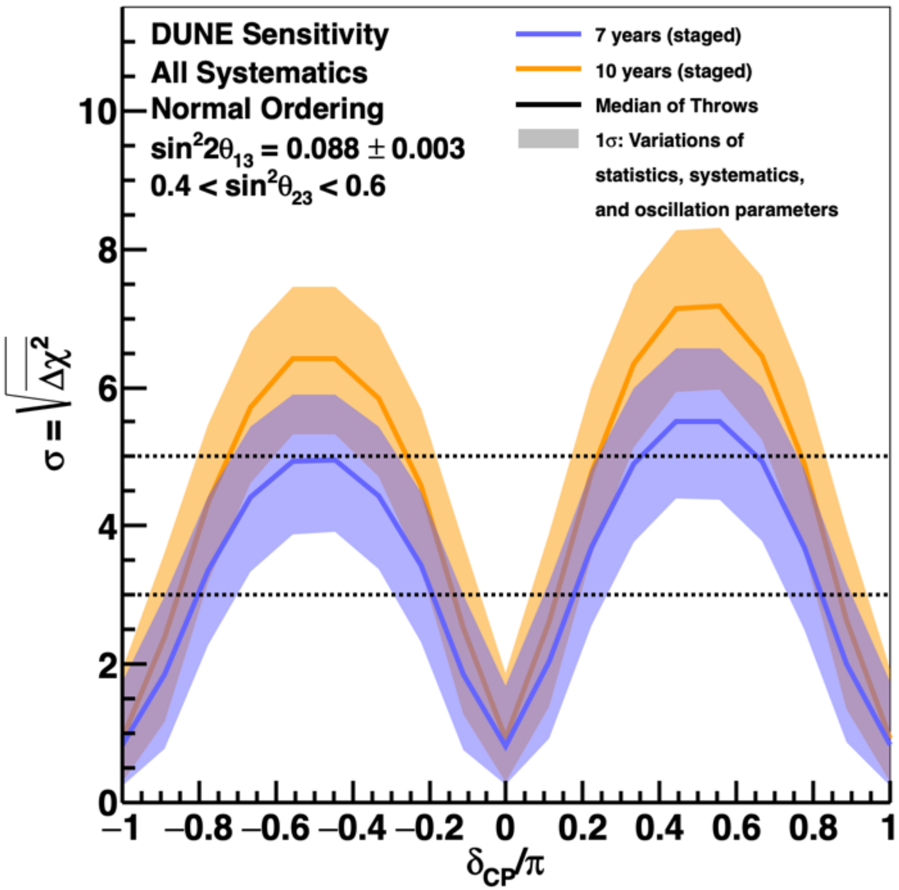


anti-ν_e

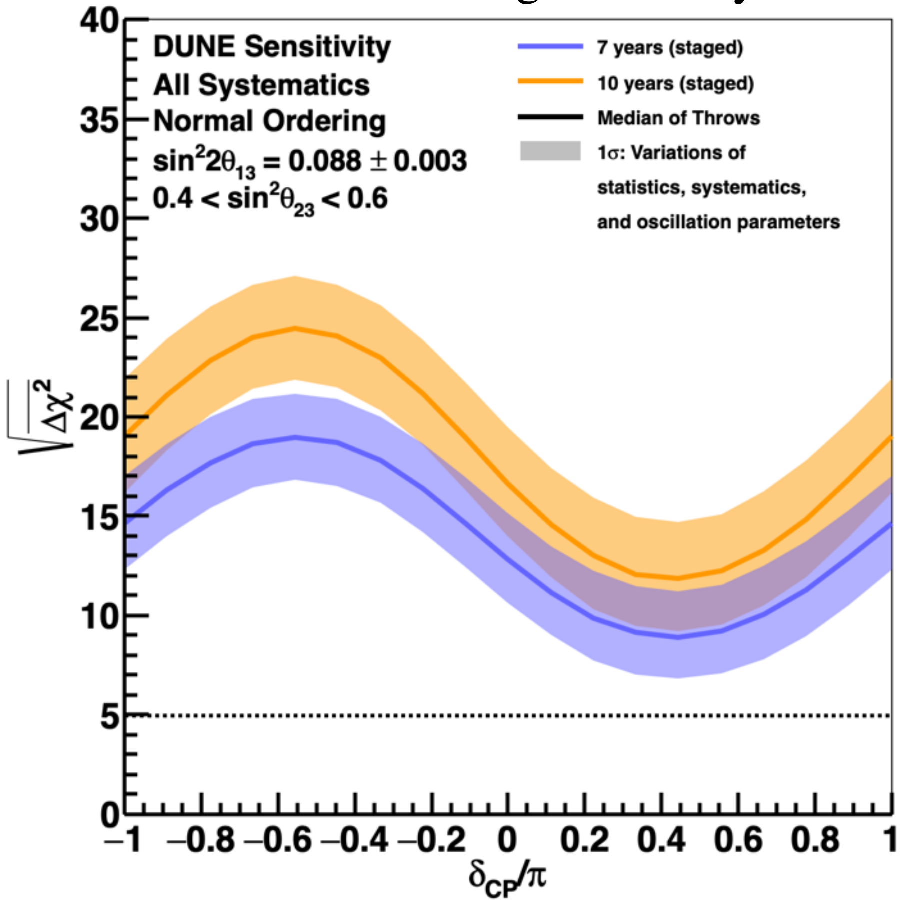


Mass ordering and CPV

*CP*v sensitivity



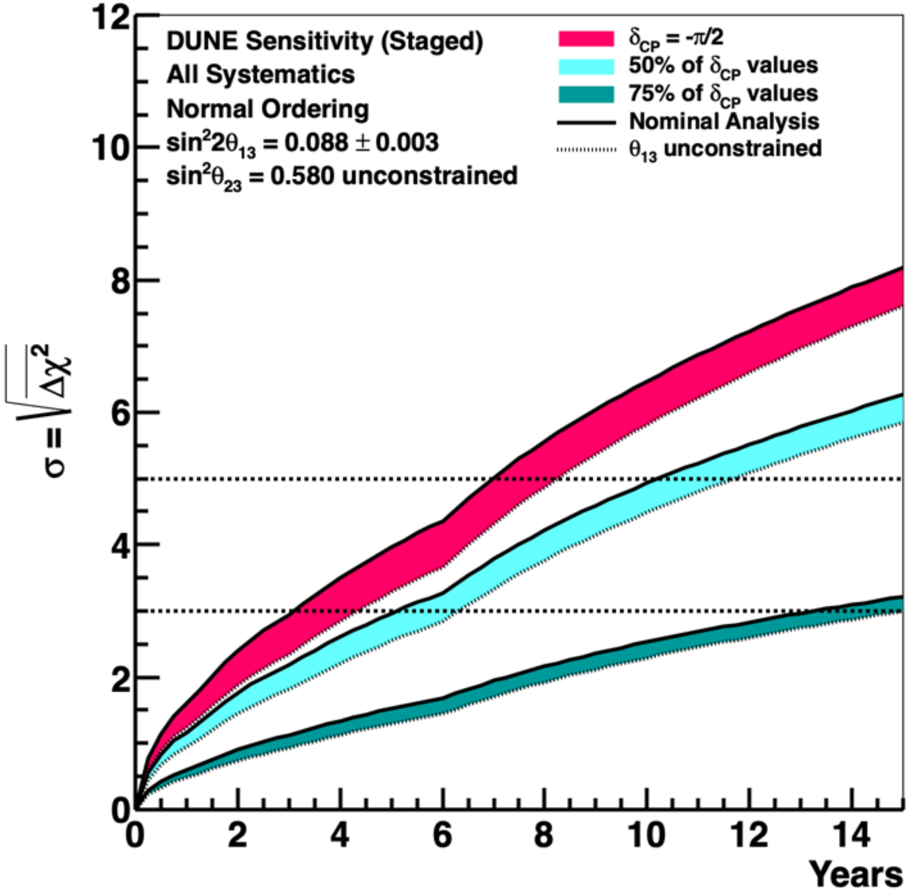
Mass ordering sensitivity



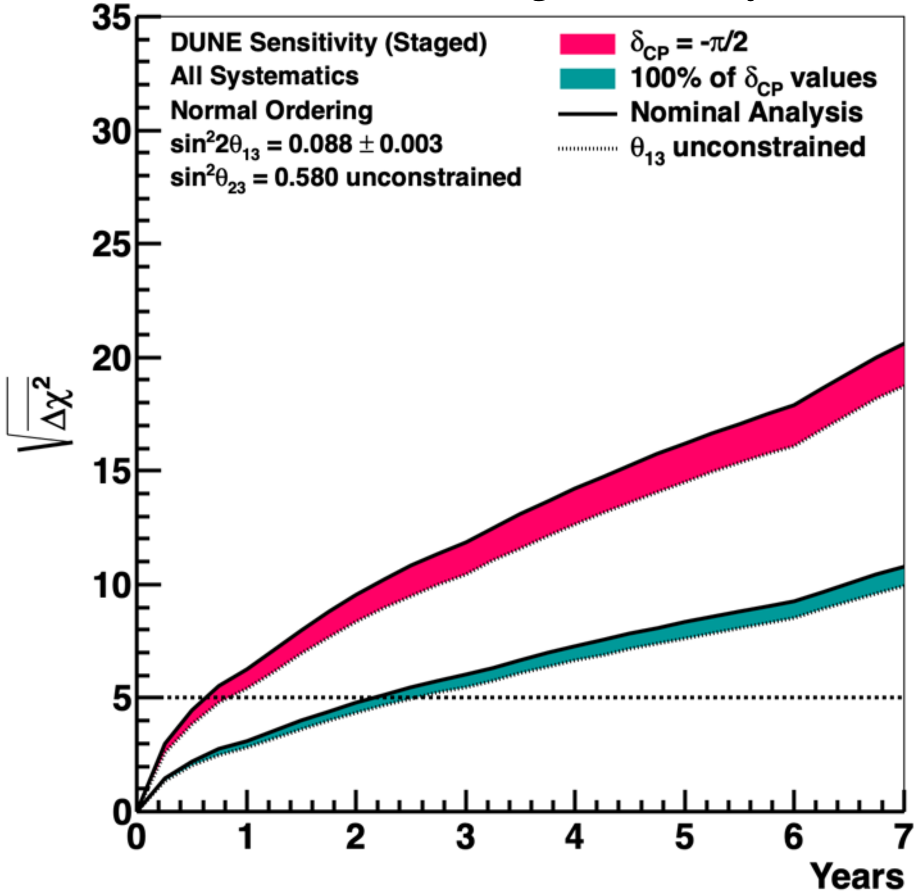
Moving quickly towards CPV discovery!

Sensitivity versus time

*CP*v sensitivity

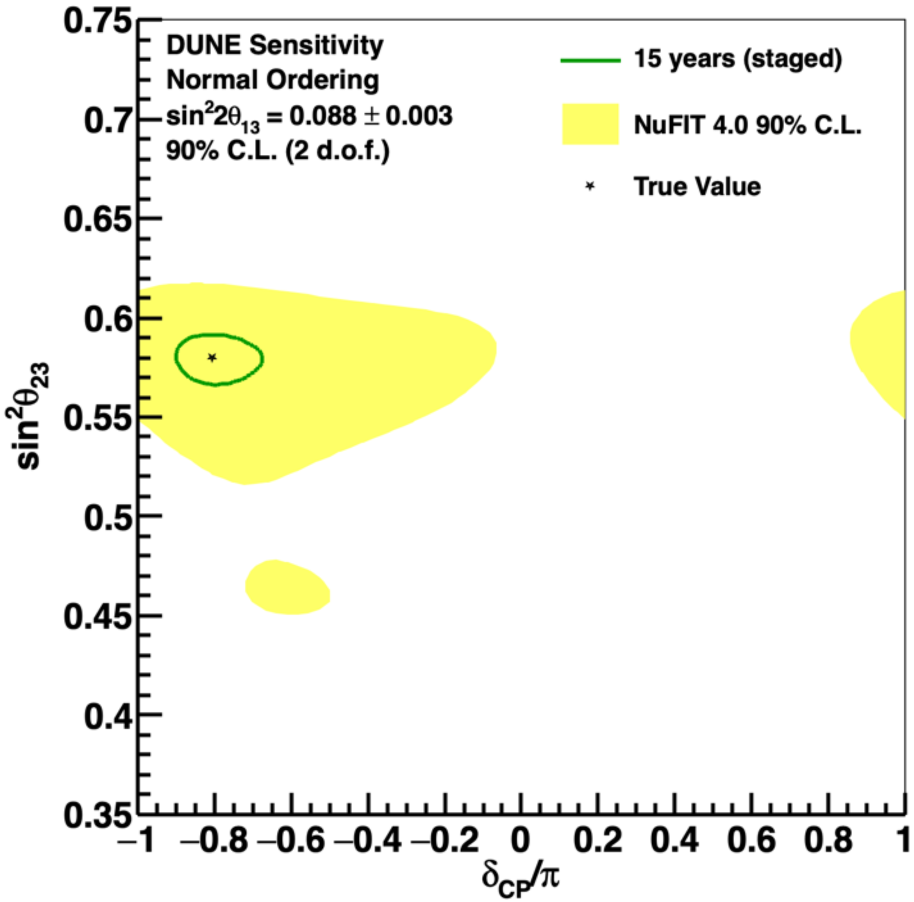


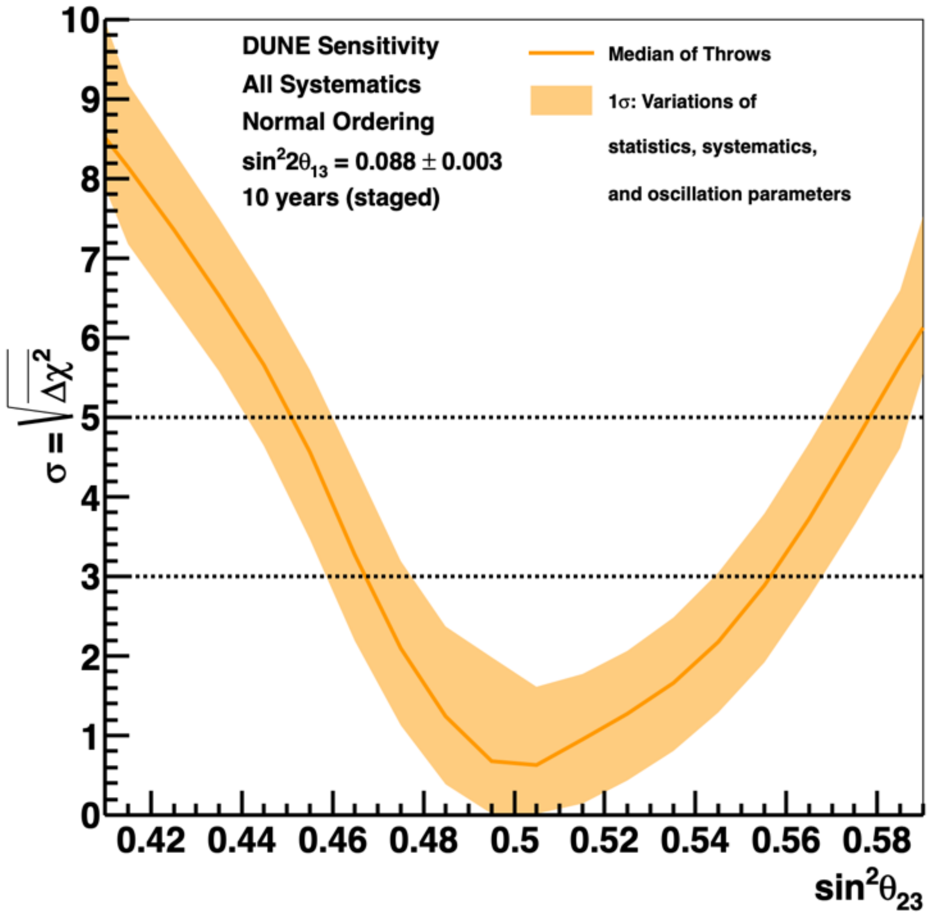
Mass ordering sensitivity



Staged approach: interesting measurements will be made throughout the DUNE physics programme!

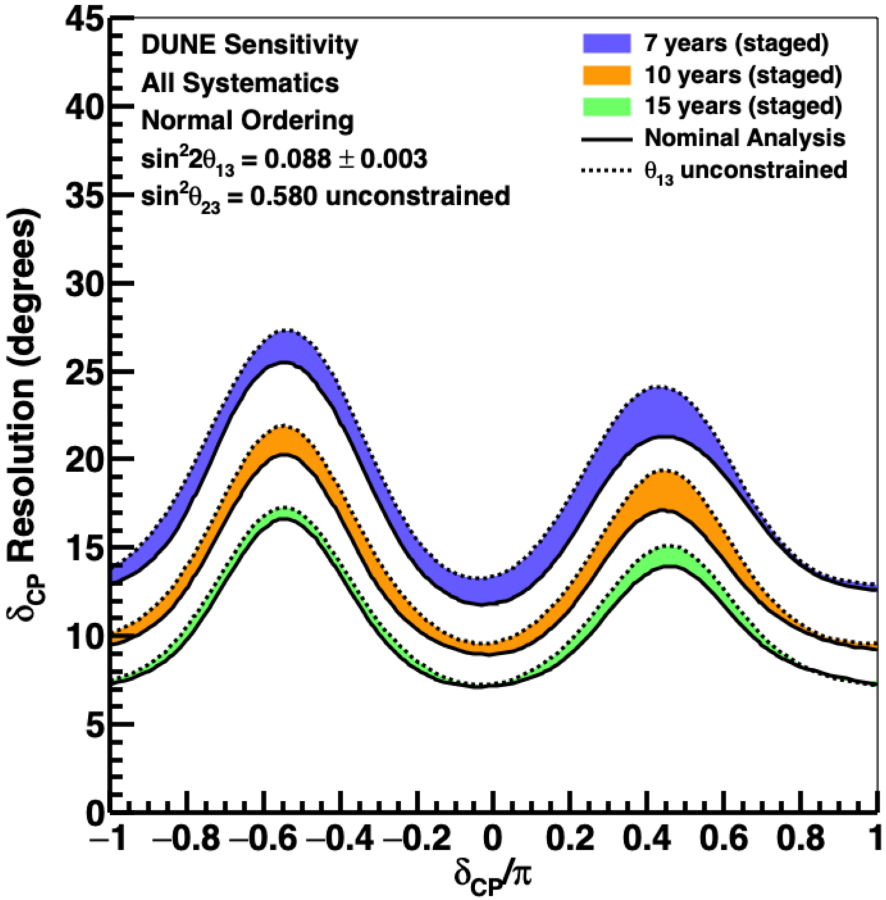
Beyond discovery: precision measurements

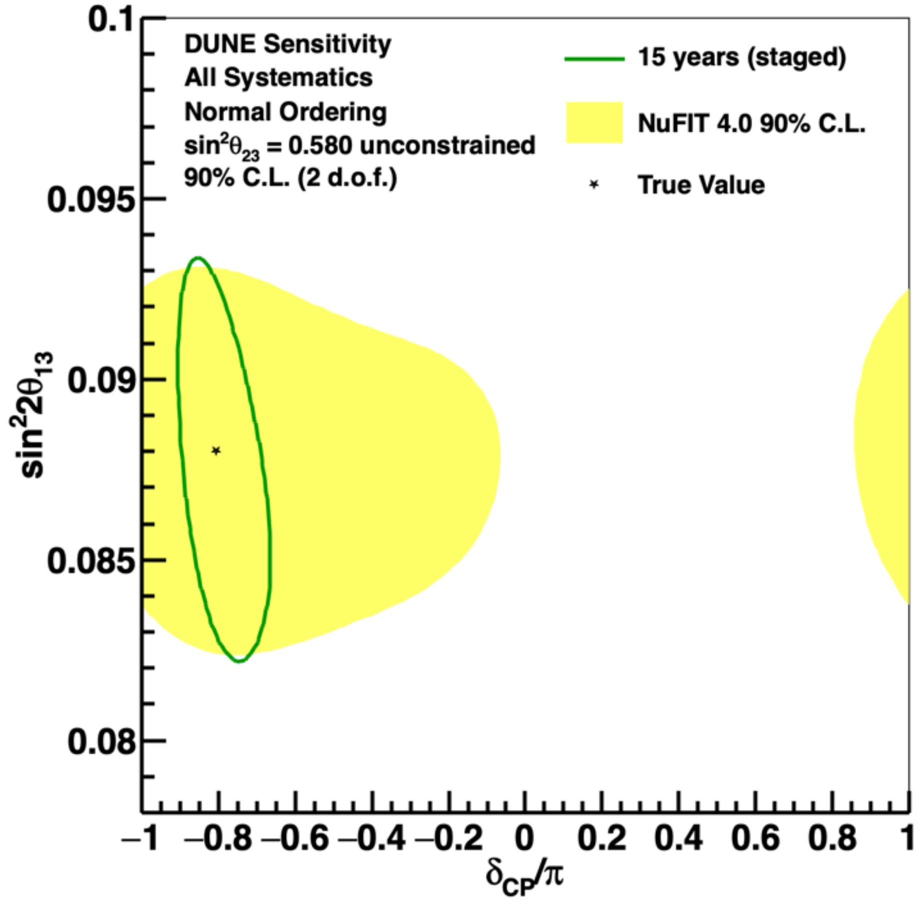




Significance depends on true value of θ_{23}

Beyond discovery: precision measurements





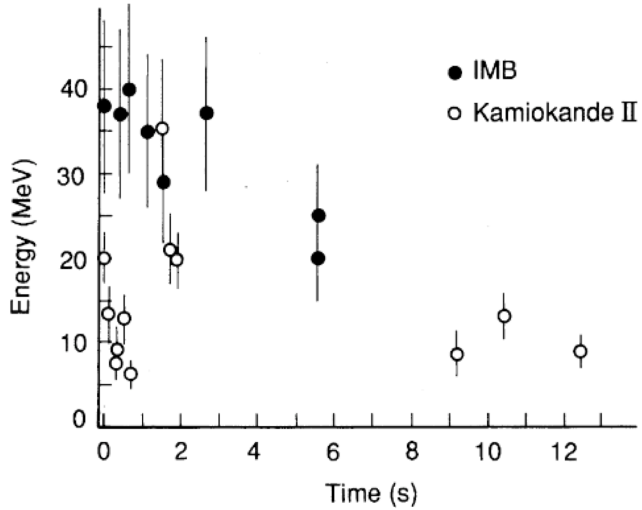
Comparable precision to quark sector in a single experiment

Ultimate precision on θ_{13} comparable with reactor experiments

Supernova Neutrinos

Astrophysical neutrinos, e.g. from a galactic supernova, probe physics at astrophysical scales:

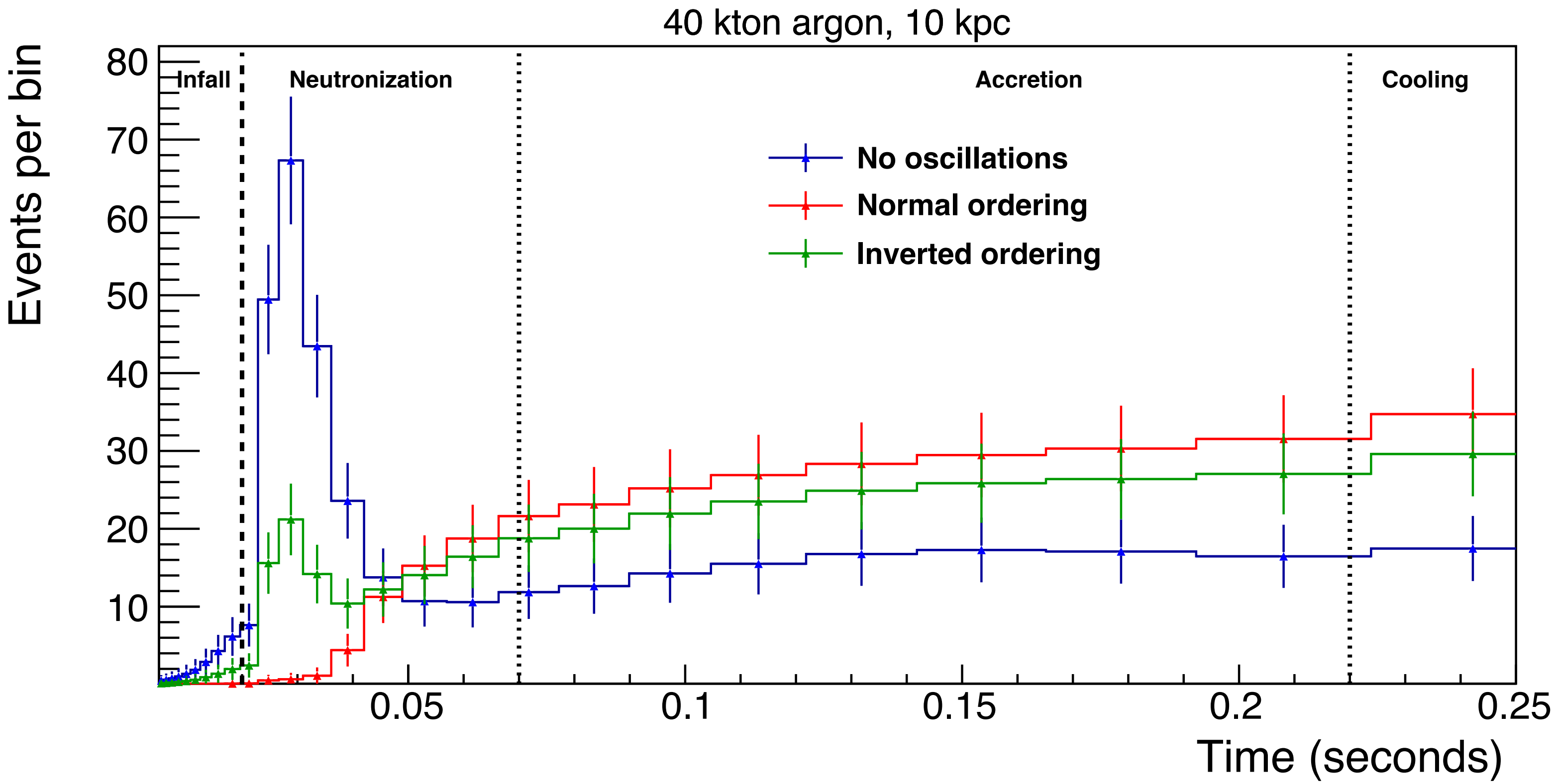
- 99% of the binding energy of a core-collapse supernova emitted through neutrinos (0.01% as light).
- Probes both supernova properties and neutrino physics.



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

Supernova Neutrinos

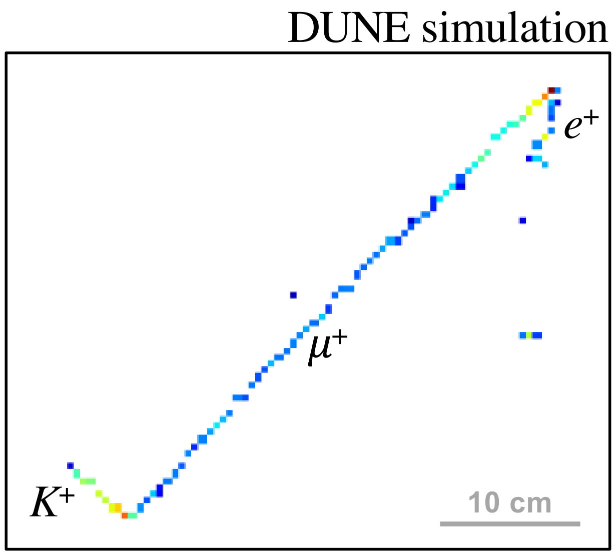
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

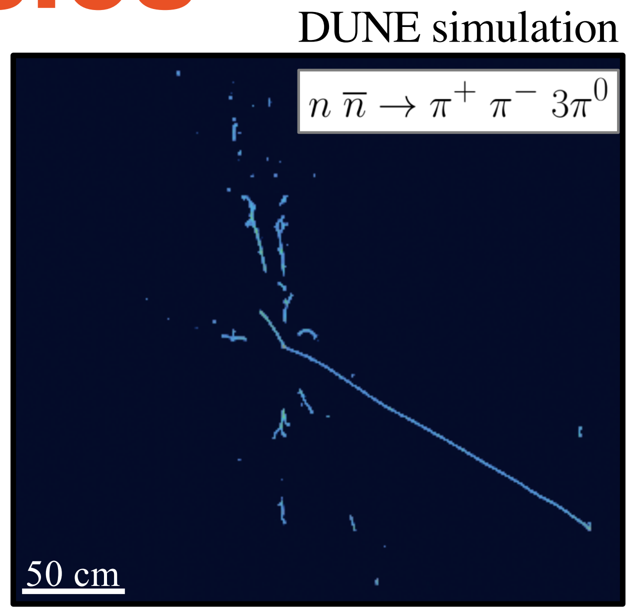


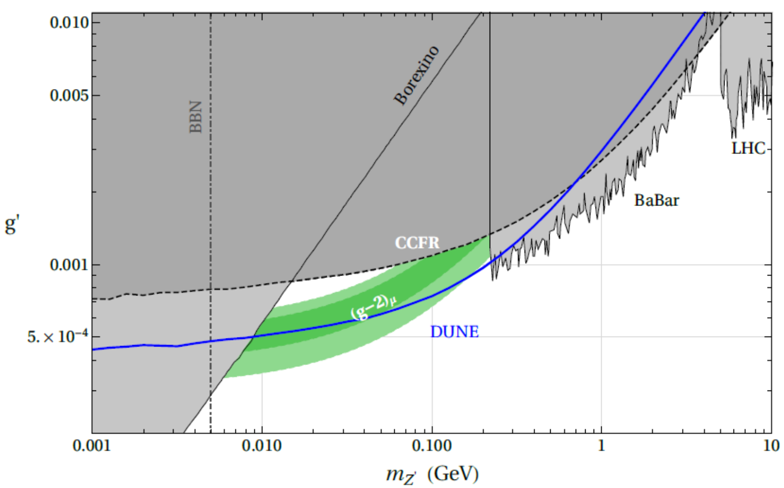
About 3000 events would be expected in a 40 kt fiducial mass liquid argon detector for a supernova at a distance of 10 kpc.

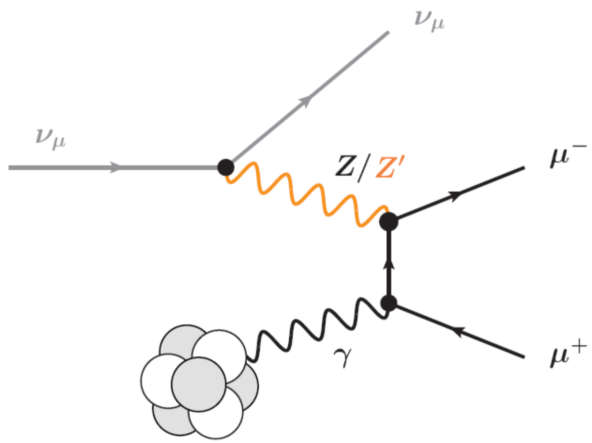
Measurement at early times tests mass ordering and SNB model

..lots of other physics

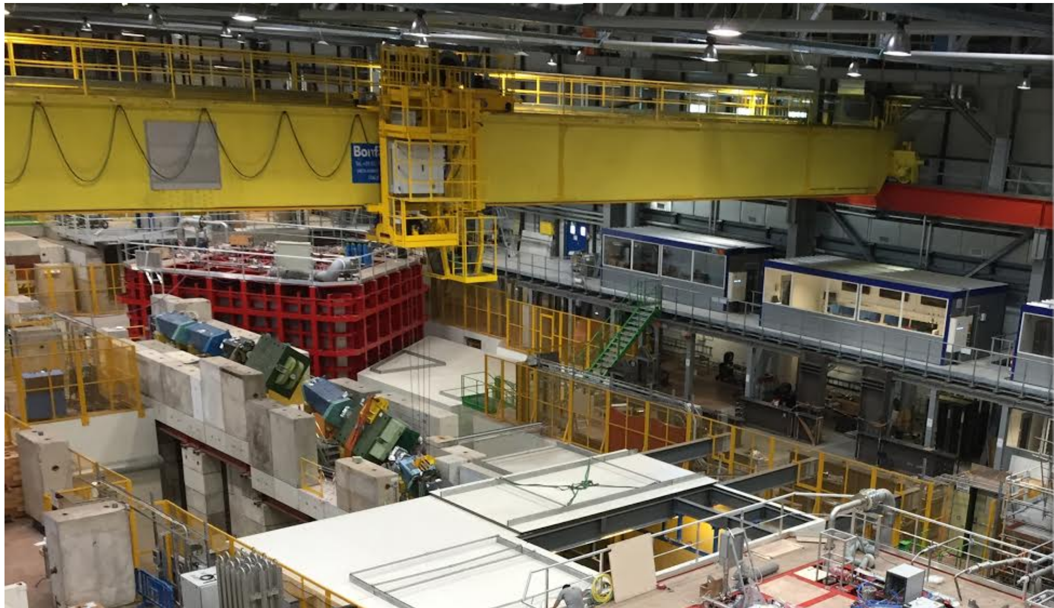








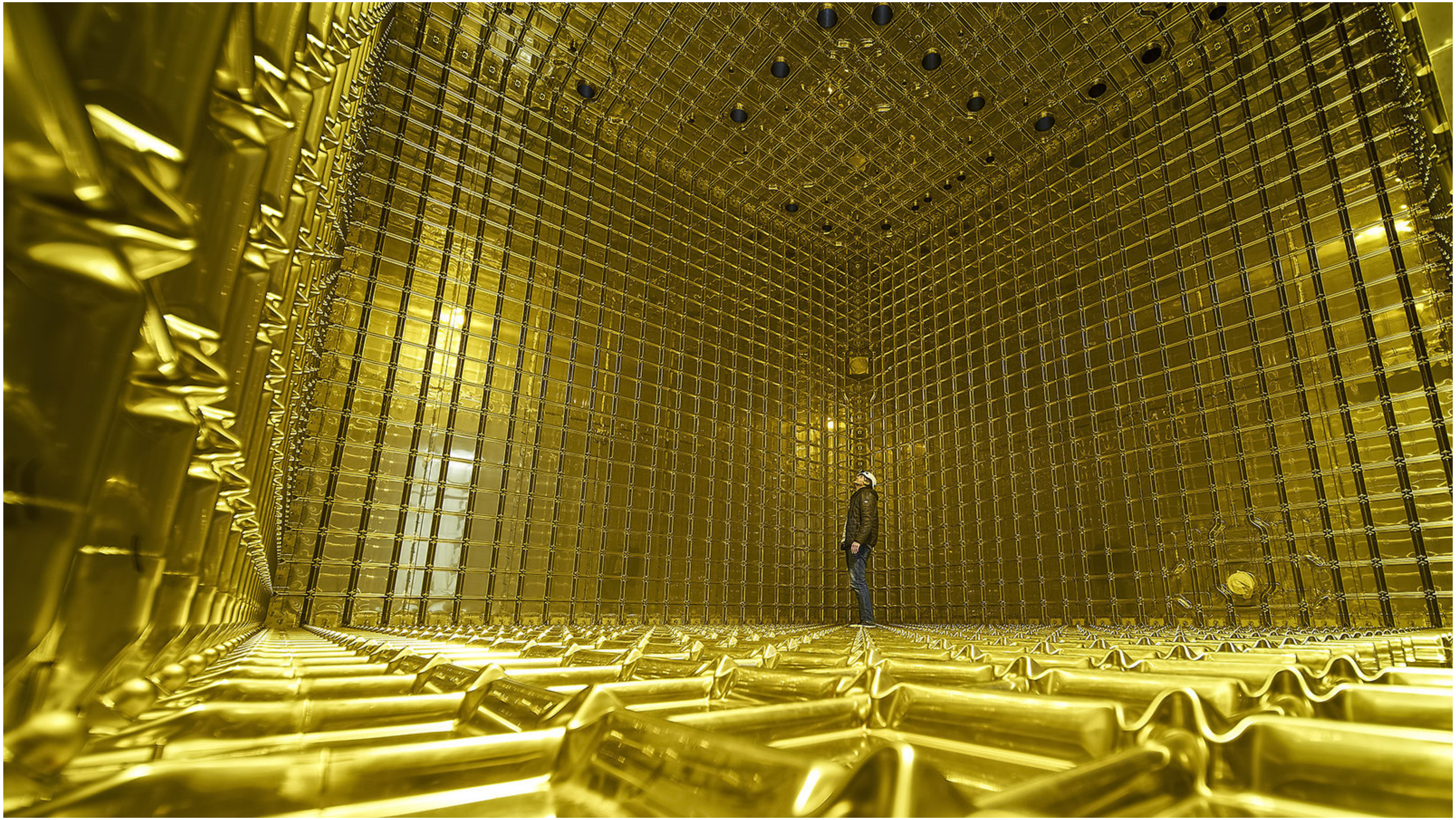
ProtoDUNEs



Dec 2015

Goals of ProtoDUNE:

- Demonstrate and validate technology choices
- Calibrate using charged particle beams
- Physics programme: dark matter, cross-sections on argon

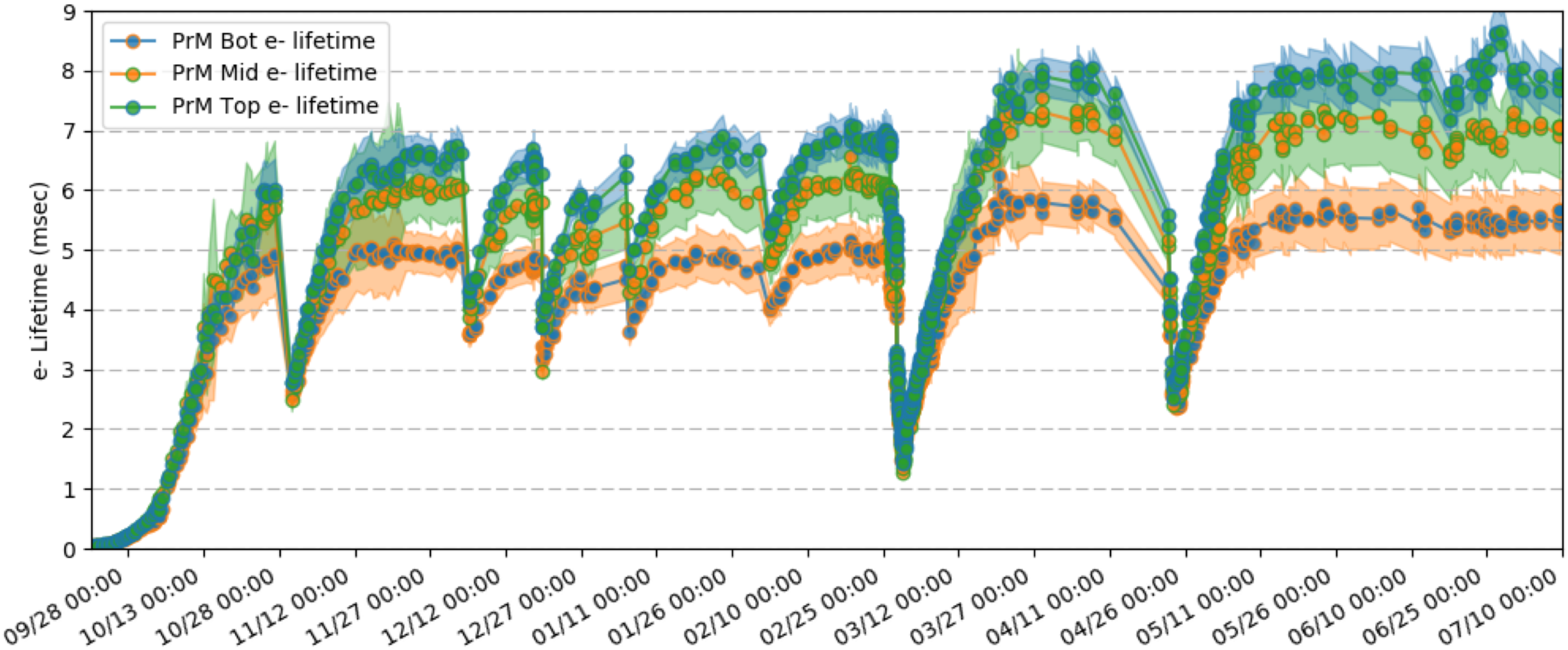


ProtoDUNE

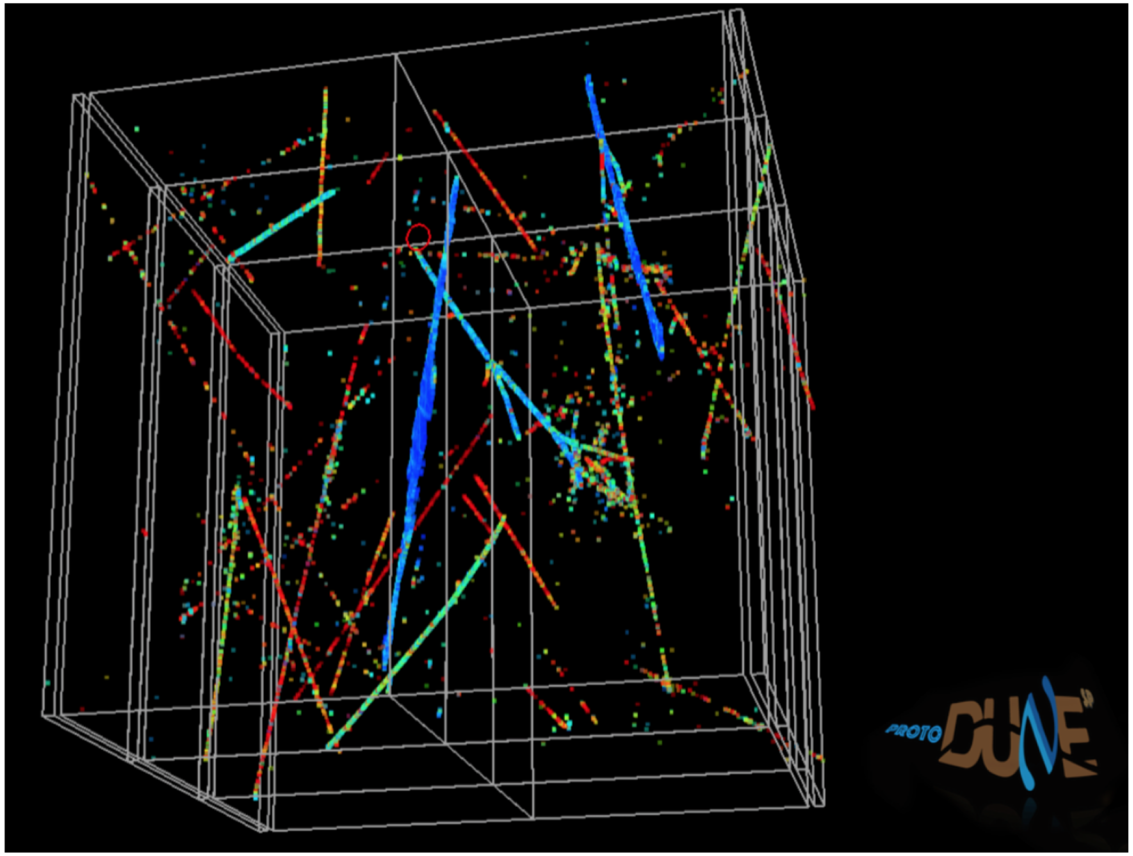
Single-Phase

Dual-Phase

Argon purity/electron lifetime

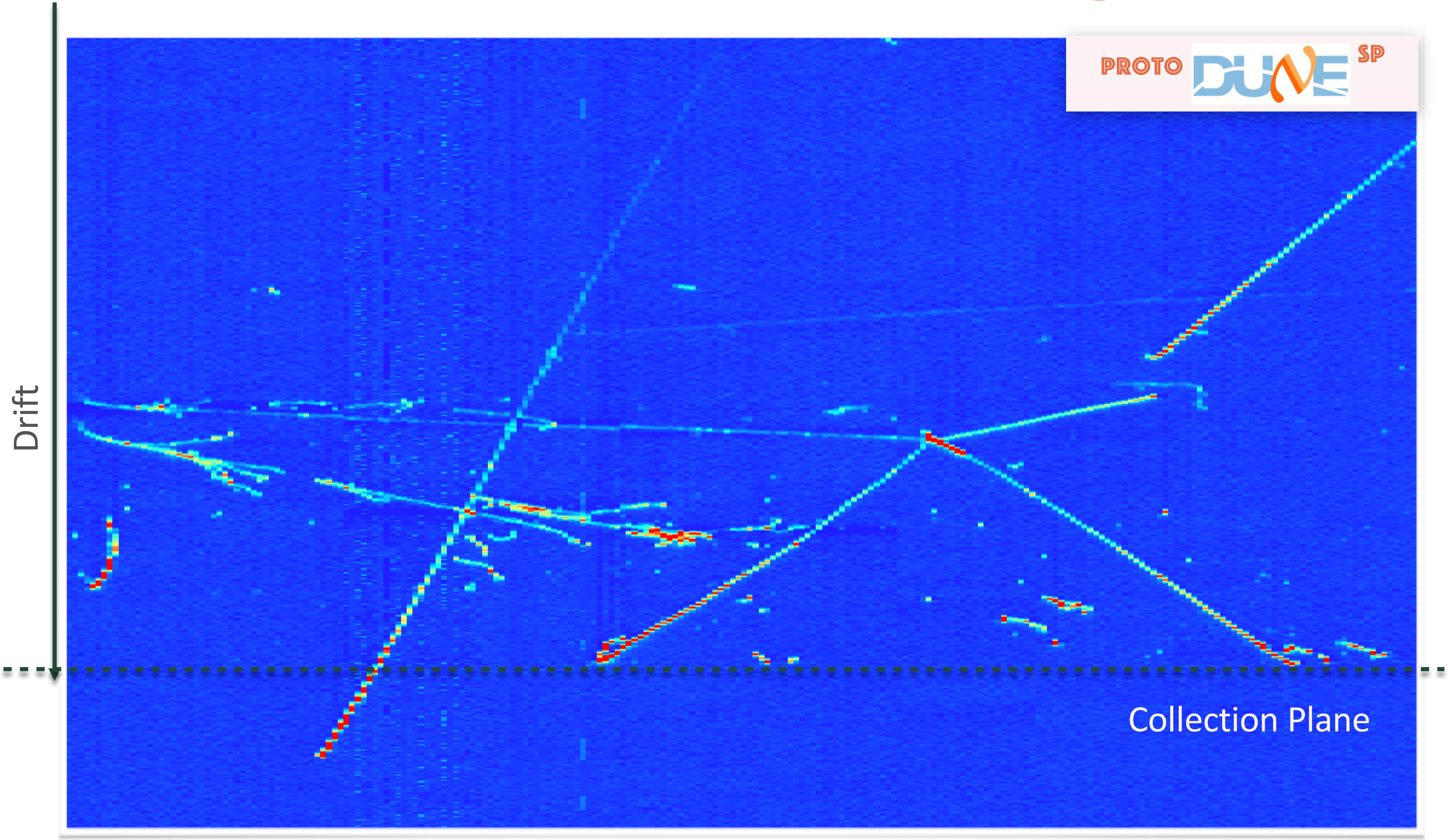


Purities of 6 ms (in electron lifetime) correspond to about 10 m drift



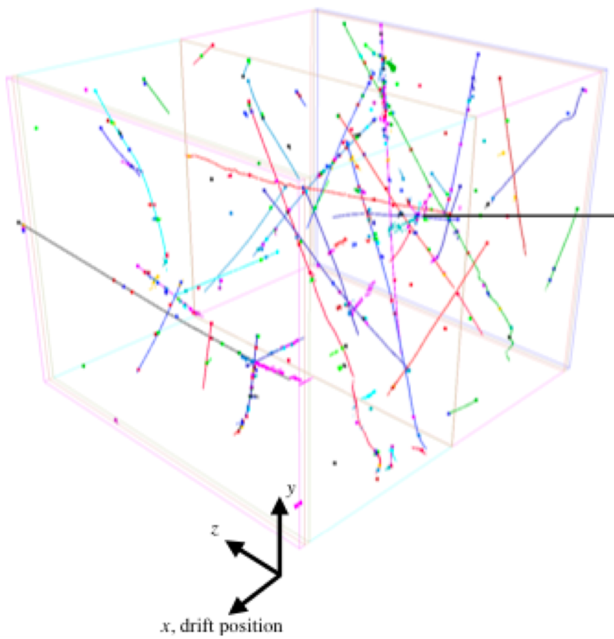
- Space charge effects caused by cosmic rays (on surface).
- They distort the drifting electric field, which affects both the reconstruction.
- Shift of about 30 cm in the reconstructed z position at detector front.
- The effects are being measured and calibrated.

Pion Interaction (4 prongs)

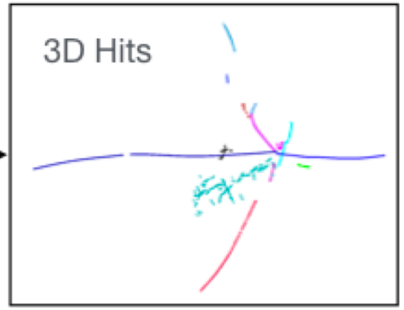


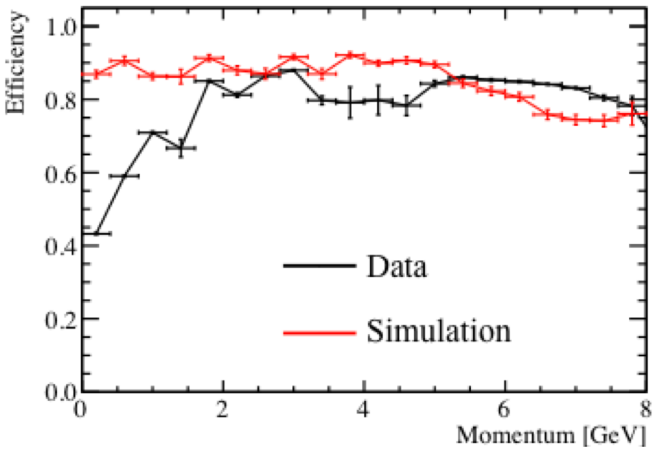
Pandora Reconstruction

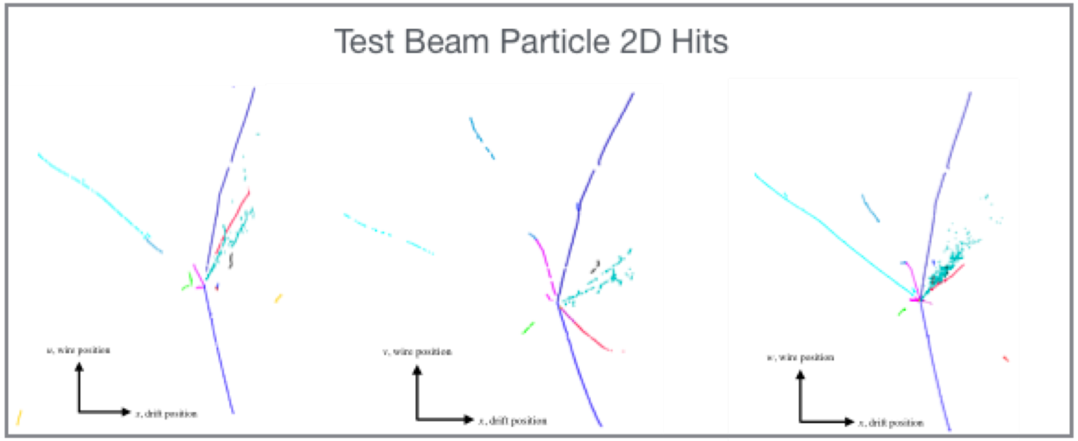
- The Pandora reconstruction is working well on data.
- The reconstruction efficiency for test beam particles are broadly comparable in data and simulation.
- Further work is ongoing to resolve the discrepancies.



Reconstructed Test Beam Particle







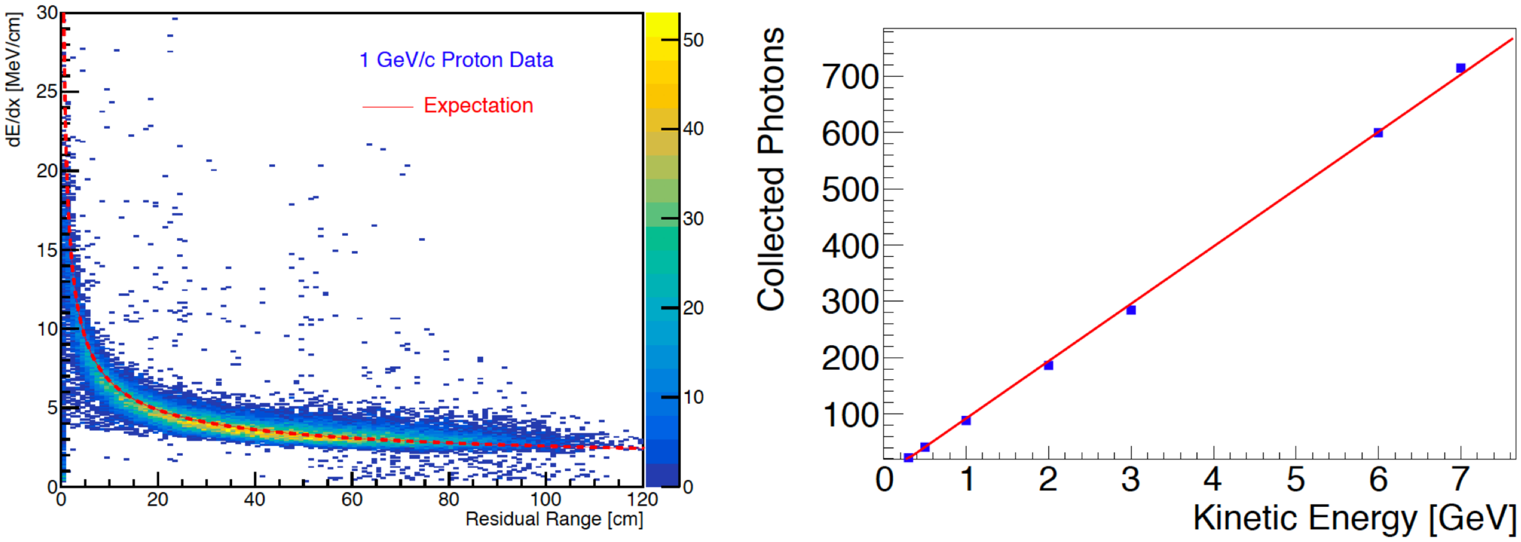


Figure 1.11: Calibrated dE/dx versus residual range measured by TPC for 1 GeV/c stopping protons (left) and response of ARAPUCA photon-detector module in APA3 as a function of incident electron kinetic energy (right).

- Beam and cosmic ray data – stable operation at design voltage
- Excellent S/N, lifetime, light yield and linearity
- Good agreement between measured specific energy loss (dE/dx) and expectations from simulations.
- Excellent photon-detector response (see talk by Ettore Segreto)

DUNE Timeline

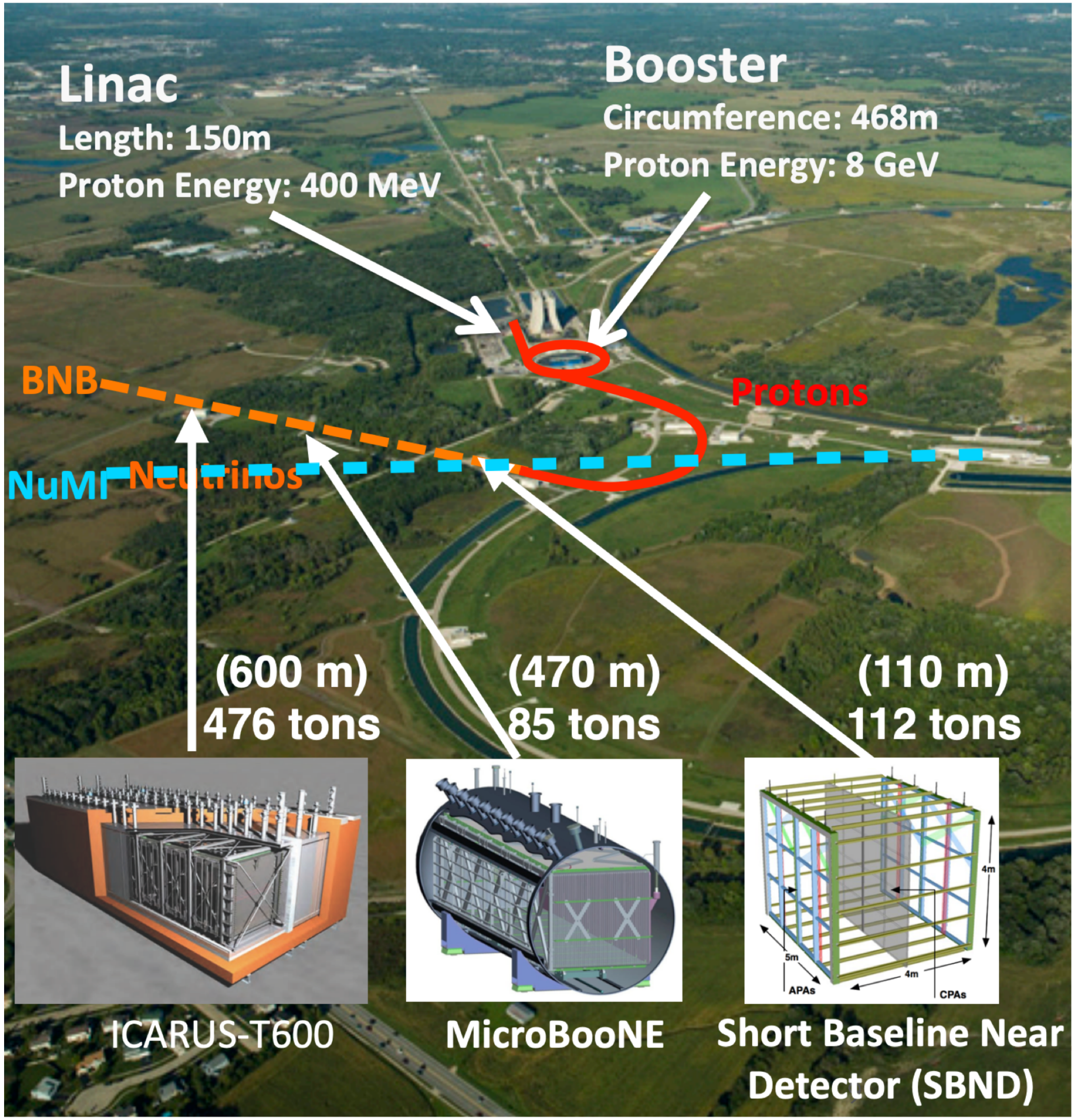
- Technical Design Report finalized this year – important milestone.
- ProtoDUNE-1 SP continues to take data; ProtoDUNE-2 DP is seeing first tracks.
- ProtoDUNE-2 phase using final detector designs planned for 2021/22.
- Preparation of the DUNE far site (excavation, infrastructure) is a complex project which requires detailed project planning.
- US project approval (CD2/CD3) for LBNF/DUNE-US expected for 2020 with subsequent start of excavation work. The US project baselining will define final schedule.
- The current DUNE milestones are:

  Start of Detector 1 Installation: August 2024

  Start of Detector 2 Installation: August 2025

- Physics data as soon as first module is complete – start of an exciting long-term physics programme.

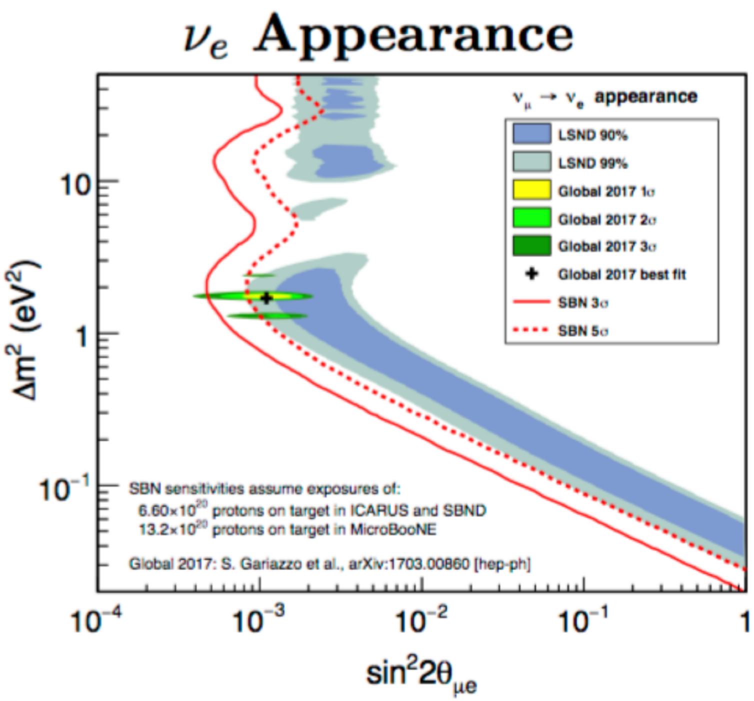
Fermilab SBN programme



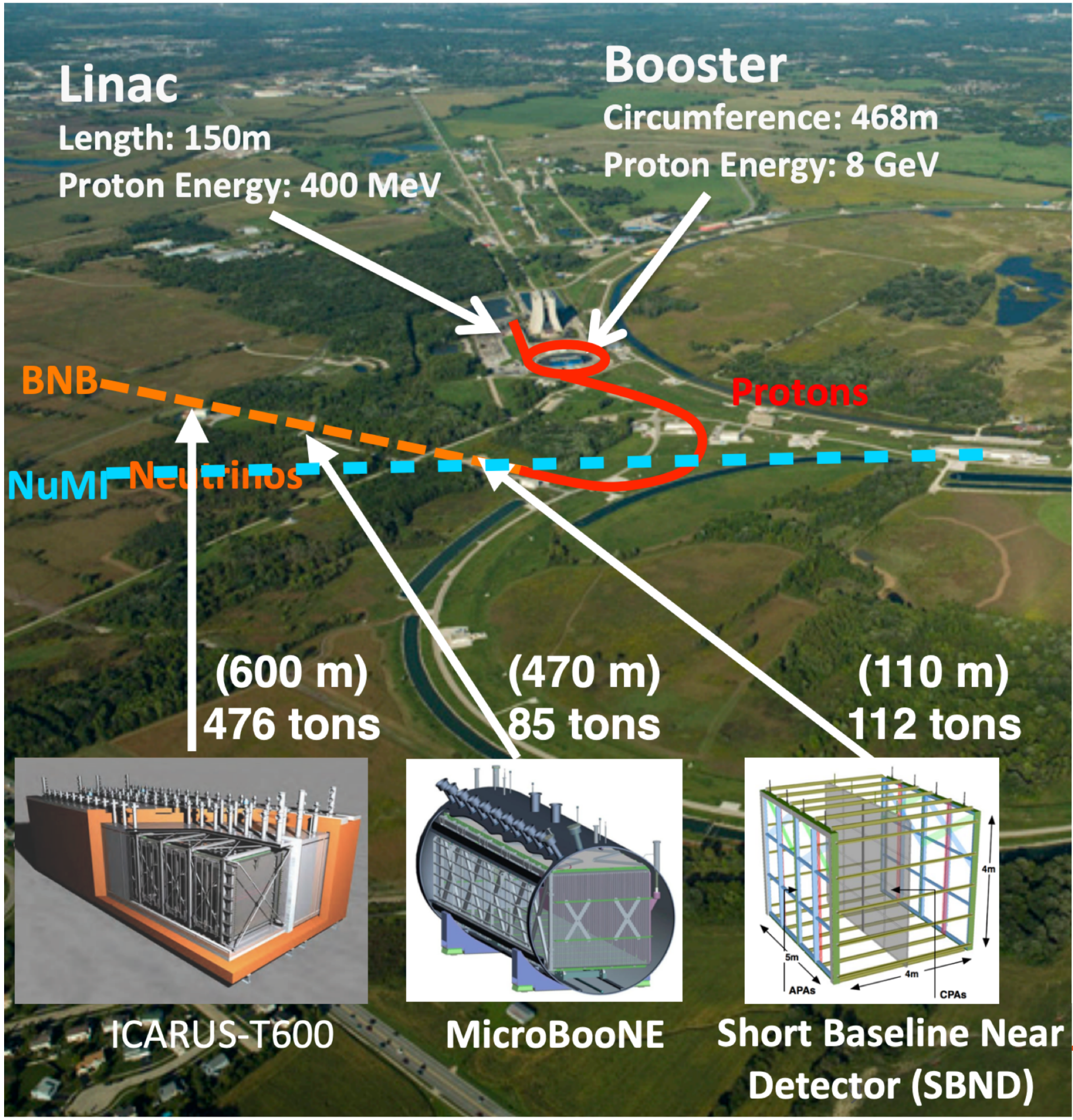
A three-baseline LAr project

- SBND, MicroBooNE, ICARUS-T600

Covers the entire LSND region at 5σ



Fermilab SBN programme



- A three-baseline LAr project
  - SBND, MicroBooNE, ICARUS-T600
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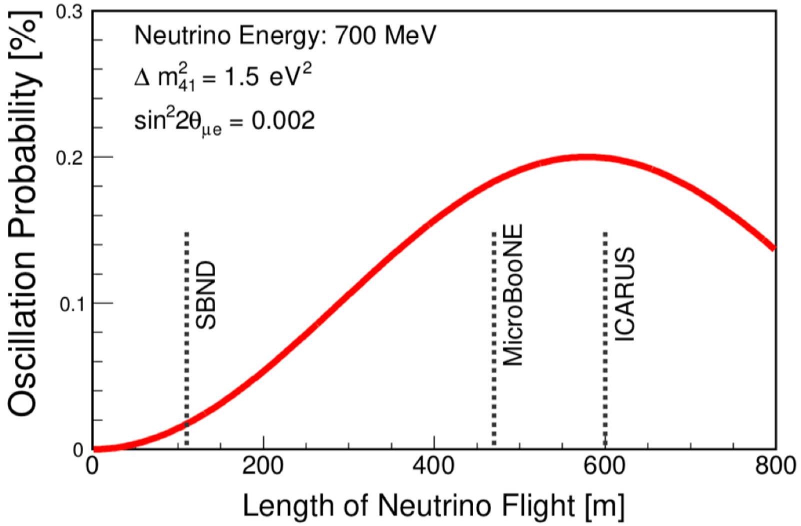


MicroBooNE

•Current UK collaboration on MicroBooNE:

➢ 5 institutions

➢ 24 collaborators (8 academics, 4 postdocs, 12 PhD students).

➢ 6 PhD theses completed so far.

University of Oxford

The University of Warwick

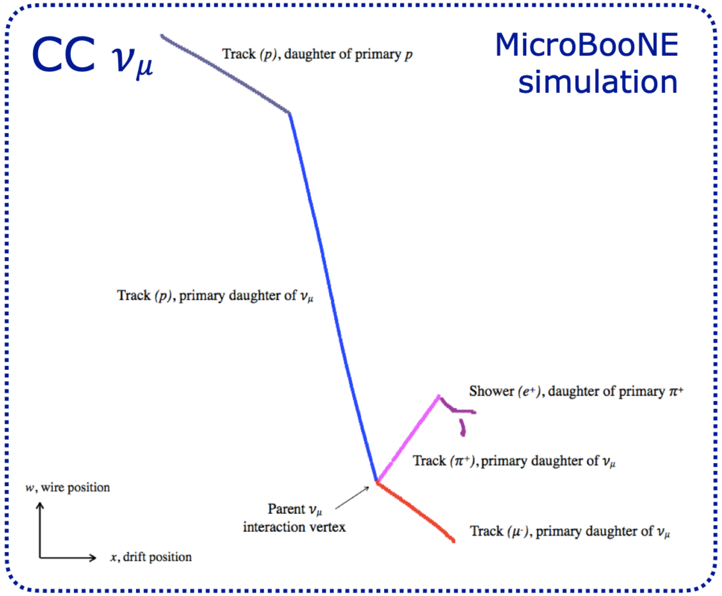
Lancaster University

University of Cambridge

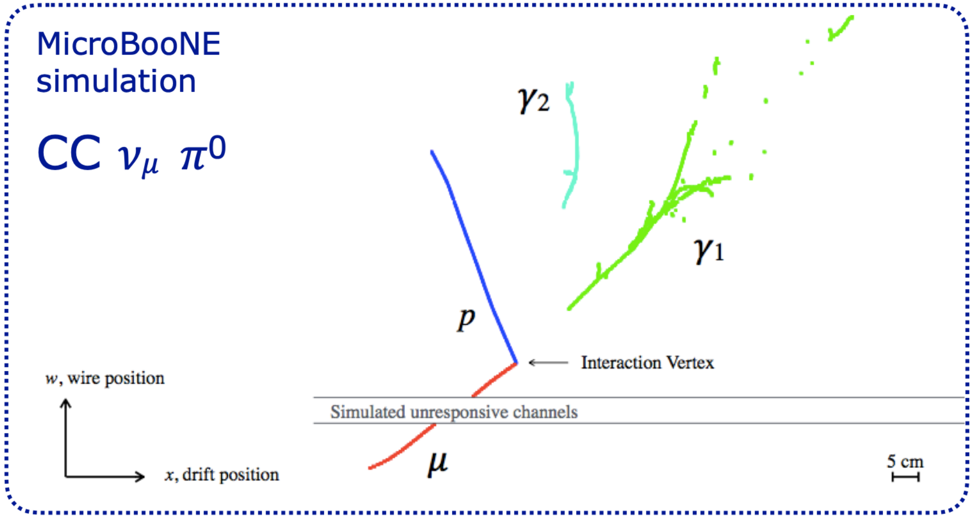
Manchester 1824 The University of Manchester

Pandora Pattern Recognition

- Pandora is a well-established toolkit for pattern recognition in fine-grain detectors.
  - ➢ Implements a highly modular approach, using many focused algorithms to incrementally reconstruct each event.
  - ➢ Embedded in LAr neutrino programme.

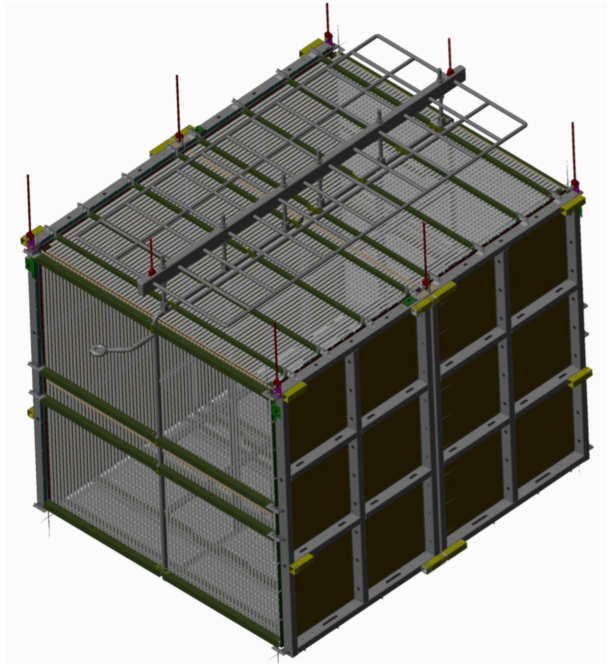


- Pandora reconstruction for LAr-TPC detectors has been pioneered on MicroBooNE, and forms the basis of all published physics results so far:
  - ➢ CC inclusive cross-section: arXiv:1905.09694 (2019) (accepted by PRL)
  - ➢ CC π^0 cross-section: PRD 99, 091102(R) (2019)
  - ➢ Final-state multiplicities: EPJC 79, p248 (2019)



EPJC 78, p82 (2018)

Short-Baseline Near Detector



Lancaster University

MANCHESTER 1824
The University of Manchester

UNIVERSITY OF LIVERPOOL

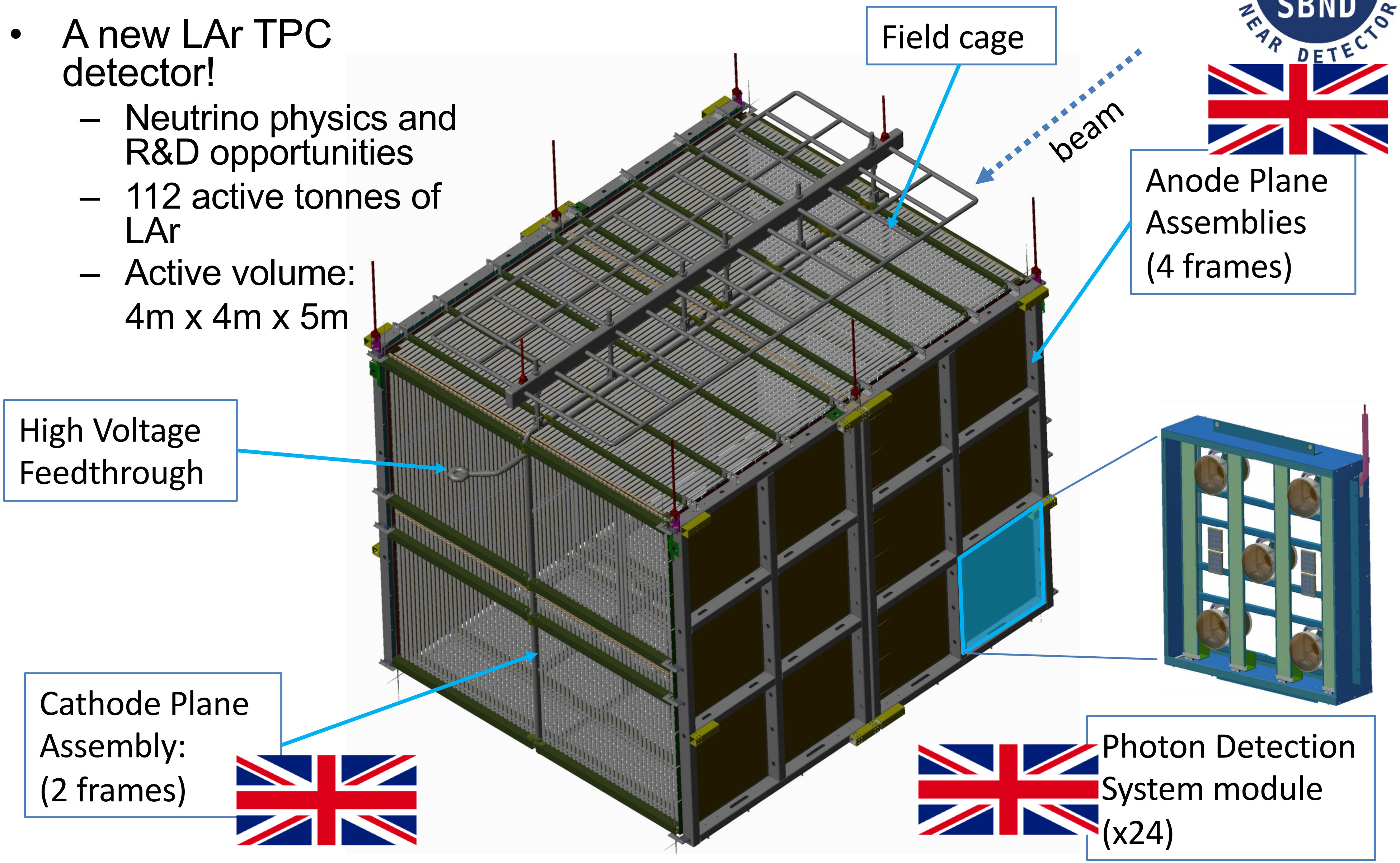
The University Of Sheffield.

US
UNIVERSITY OF SUSSEX

UCL

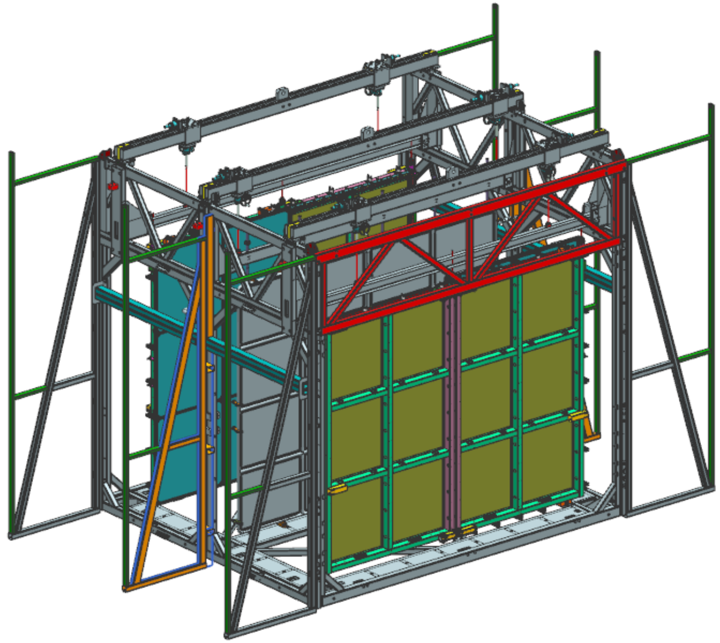
The Short-Baseline Near Detector

- A new LAr TPC detector!
  - Neutrino physics and R&D opportunities
  - 112 active tonnes of LAr
  - Active volume: 4m x 4m x 5m



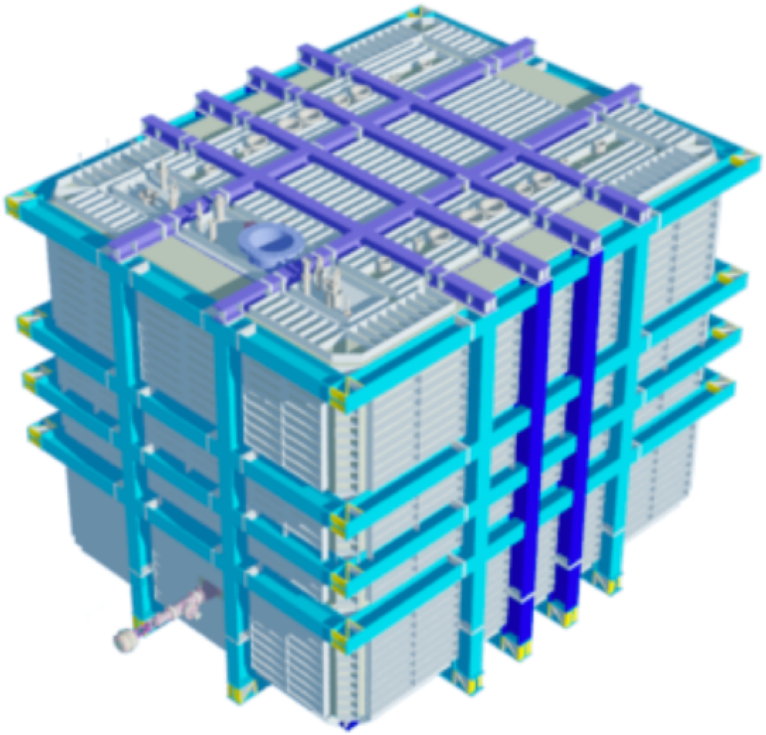
Current Status

- Work ongoing in 3 locations:
  - TPC assembly, DAQ and cold electronics testing at DAB
  - Cryogenics installation at SBN-ND
  - Cryostat pre-fabrication at CERN
- Major TPC components and DAQ hardware all at Fermilab
- First Cold Electronics at Fermilab and tested
- TPC alignment and transportation frame is under construction



Membrane Cryostat

- Currently under construction at CERN
- 3rd generation prototype for DUNE
- Shipment and assembly at FNAL SBN-ND in fall 2019



Thanks to everyone who provided material for this talk

Summary

- UK is leading international collaborator on the liquid-argon neutrino programme (DUNE, MicroBooNE, SBND).
- European Strategy has been crucial for the successful formation of DUNE as a global collaboration.
- UK on DUNE focuses on APA construction, DAQ, data reconstruction.
- UK also makes important contributions to LBNF/PIP-II.
- ProtoDUNE-I has been a major success, ProtoDUNE-II planned for 2021/22.
- Future opportunities: Near Detector (e.g gas TPC), fourth module (pixel readout)..
- Rich detector R&D and physics programme for the coming decade(s).