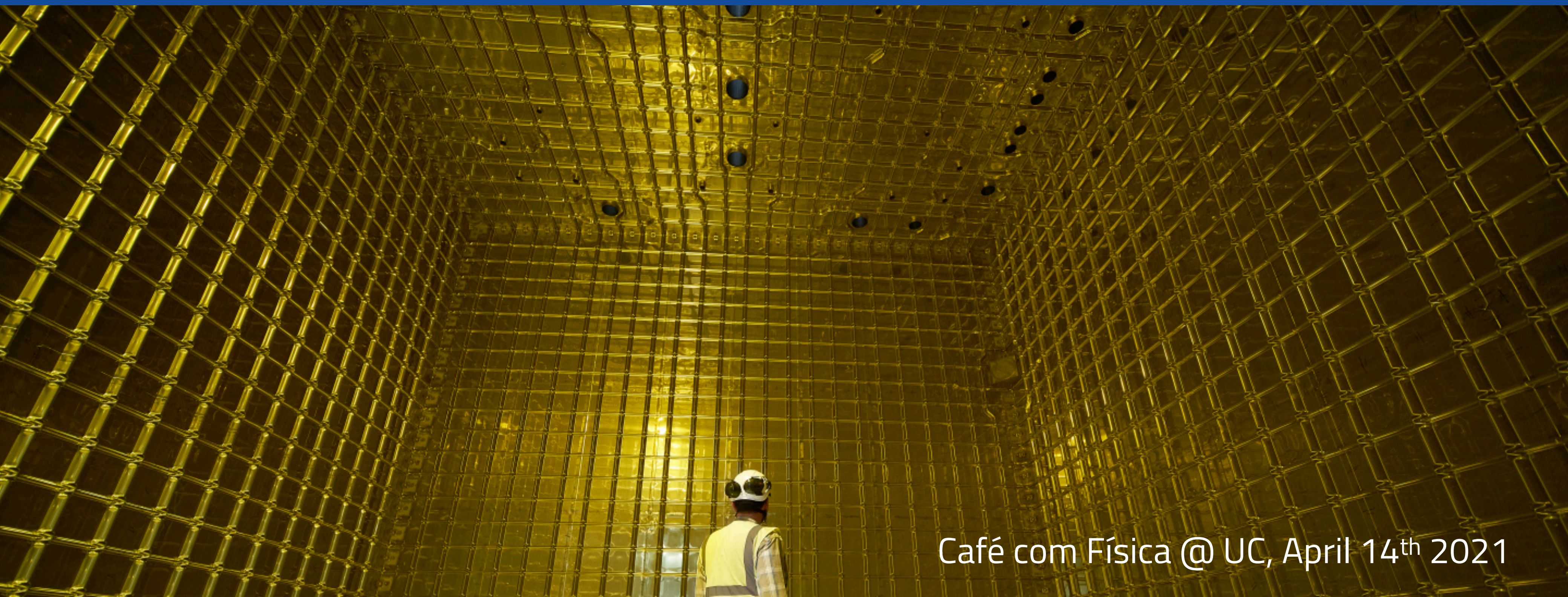
LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

DEEP UNDERGROUND
NEUTRINO EXPERIMENT

The DUNE experiment: neutrinos and the matter-antimatter asymmetry

Nuno Barros (LIP)



Café com Física @ UC, April 14th 2021

Brief history of the neutrino

Neutrinos, a desperate hypothesis to solve beta decay

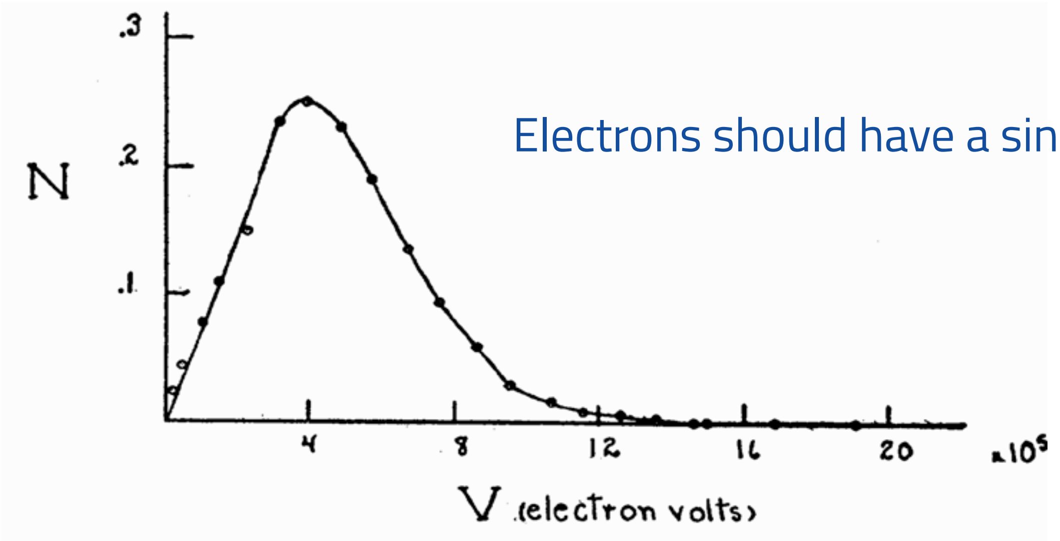
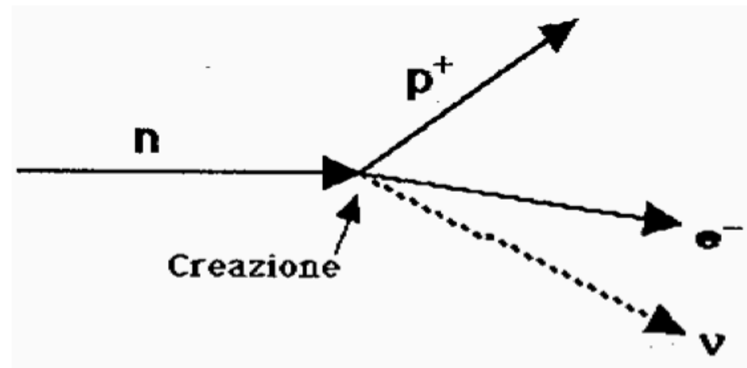


FIG. 5. Energy distribution curve of the beta-rays.

Electrons should have a single energy, not a continuous spectrum.

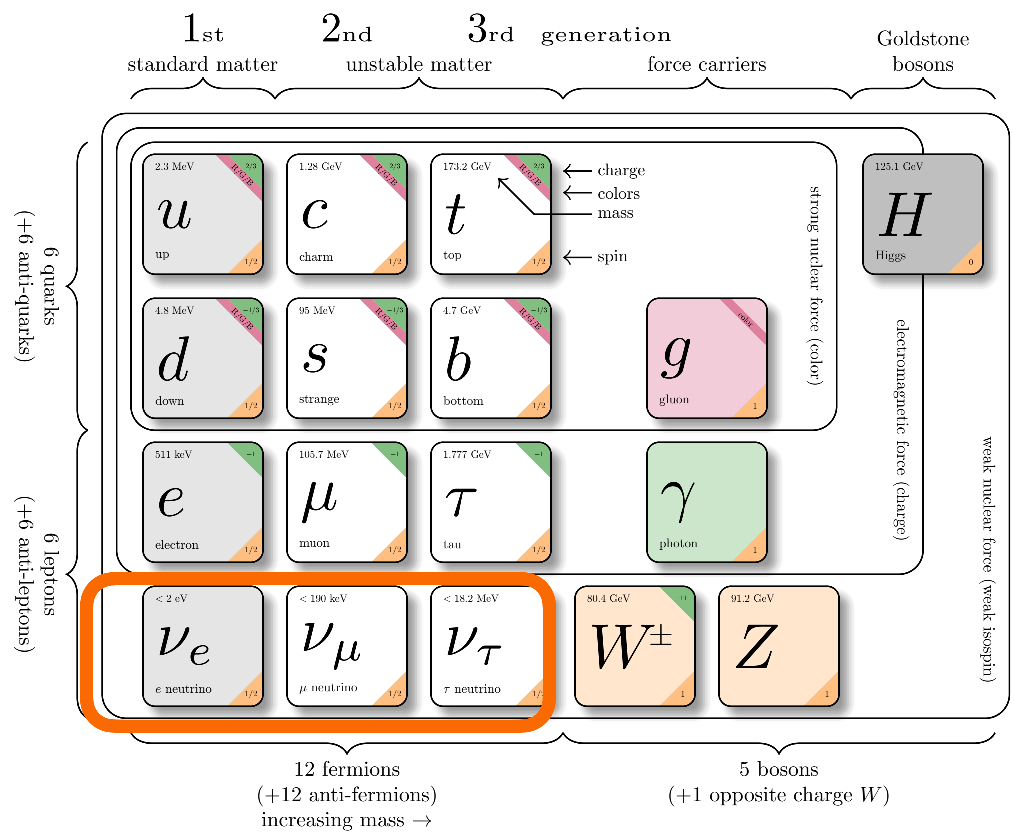


"I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do."

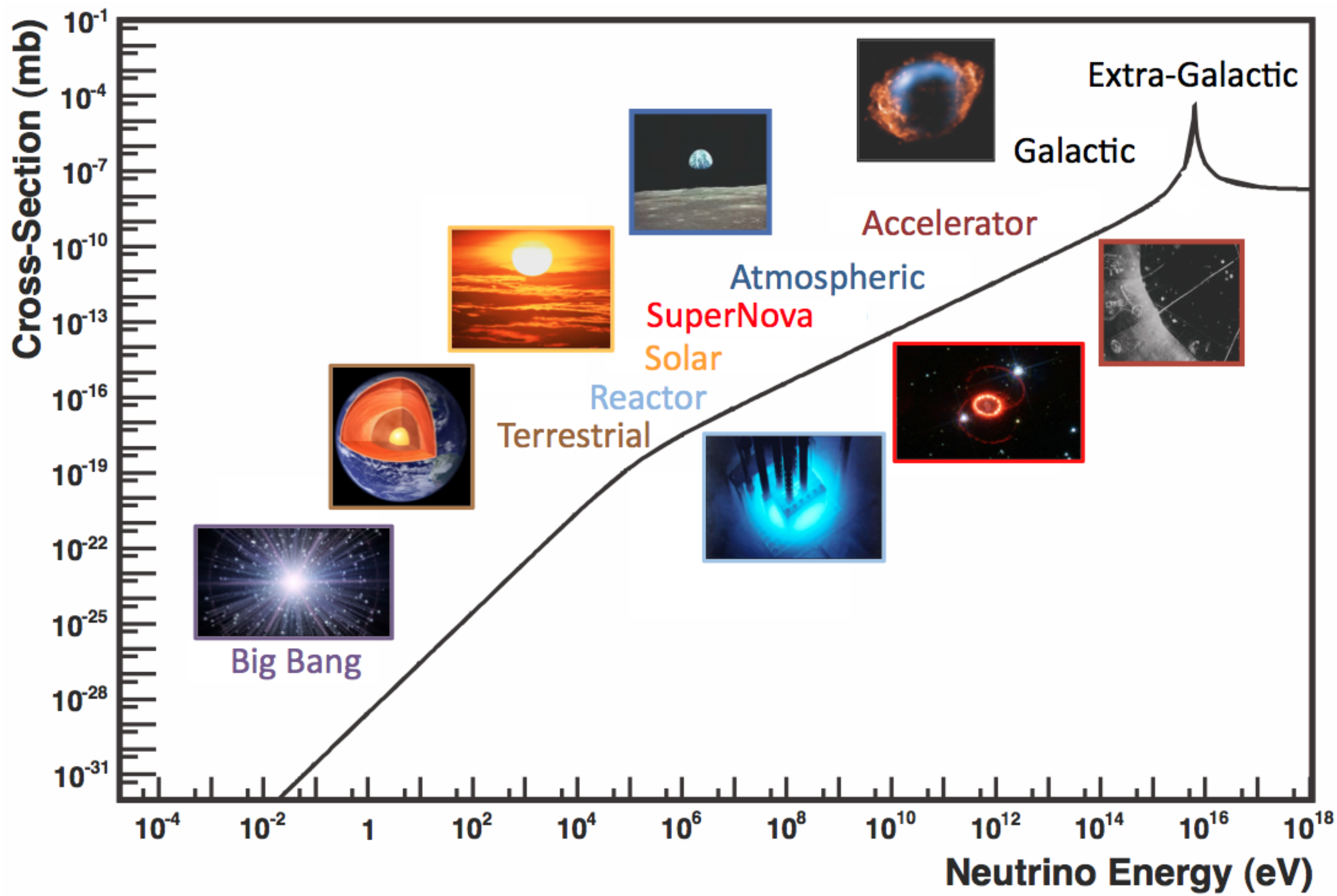
— Wolfgang Pauli (1930)

What do we know about neutrinos?

- **They are the only elementary neutral fermions**
  - Have no charge - do not participate in electromagnetism
  - Could be their own anti-particles (hold on to this thought)
- **Come in three flavours**
  - Paired to the corresponding charged leptons
- **Are very light**
  - Thought to be massless
  - Neutrino oscillations imply **massive neutrinos**
- **Interact very weakly**
  - Only subject to Weak Interaction
- **Neutrinos are always left handed**
- **Antineutrinos are always right handed**

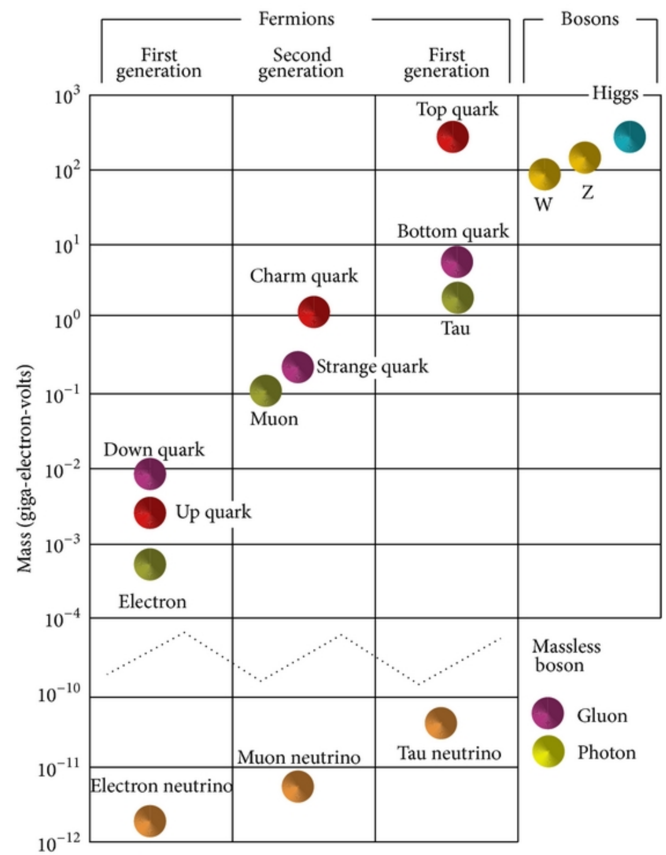


Where do neutrinos come from?



Neutrinos have mass

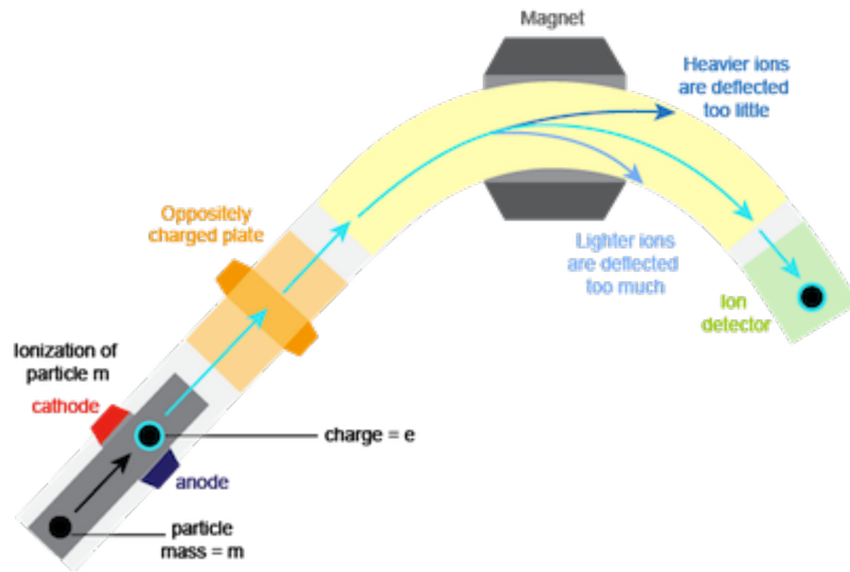
- The masses of neutrinos are much smaller than other particles
- Other particles get mass because they are "slowed down" by the Higgs field.
- Perhaps neutrinos get mass some other way?

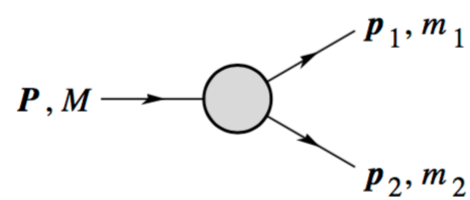


Why are neutrino masses so much smaller than all other fermions?

Measuring the Mass of Neutrinos

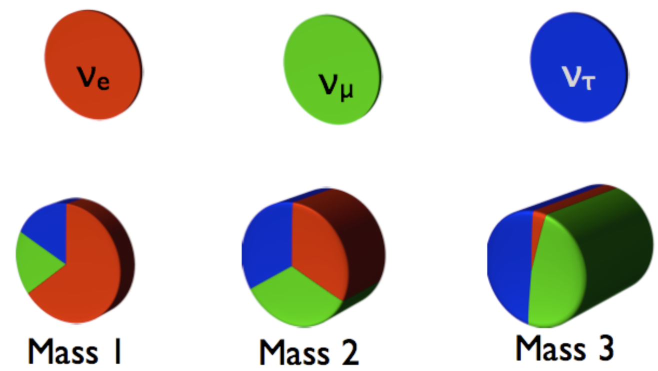
- **Neutrinos are massless in the Standard Model**
  - Searches for neutrino mass use kinematic constraints
- Measuring its mass is not an easy feat
  - Usual techniques don't work
- Measure curvature in EM field:
  - Neutrinos are neutral : no curvature in EM field
- Measure energy and momentum of daughter particles:
  - Neutrinos are the lightest particles: don't decay into other particles
- **Solution: Use quantum interference to probe the neutrino mass**





$$M^2=(E_1+E_2)^2-(\vec{p}_1+\vec{p}_2)^2$$

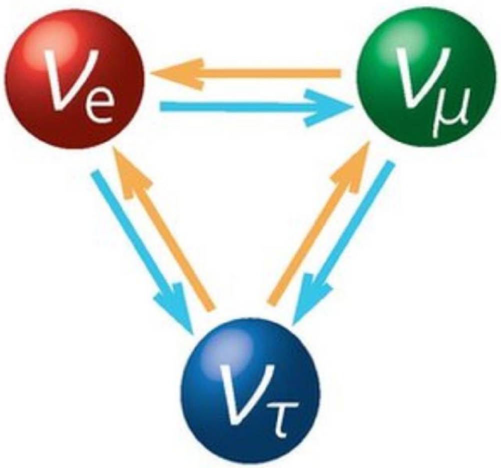
Neutrino States



- Neutrinos come in three “flavours”
  - According to the lepton they produce when they have weak CC interactions

- Neutrinos come in three masses
  - But these states are not the same!!

- **If the masses are non-zero, flavour can change when neutrinos propagate!**



Neutrino Oscillations

Short introduction with two flavours

- The weak flavour eigenstates (ν_e, ν_μ) are different from the mass eigenstates (ν_1, ν_2)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

- The weak states are mixtures of the mass states:

$$|\nu_\mu> = -sin\theta|\nu_1> + cos\theta|\nu_2>$$
$$|\nu_\mu(t)> = -sin\theta\ (|\nu_1> e^{-iE_1 t}) + cos\theta\ (|\nu_2> e^{-iE_2 t})$$

- This leads to an **oscillation probability**

$$\boxed{P_{\text{oscillation}}\left(\nu_\mu \to \nu_e\right) = \left|\left\langle \nu_e | \nu_\mu(t) \right\rangle\right|^2 = \sin^2 2\theta_{12} \sin^2\left(1.27\Delta m^2_{21}\frac{L}{E}\right)}$$

Fundamental oscillation parameters:

- θ : Magnitude of oscillation
- Δm^2 : period

Experimental parameters:

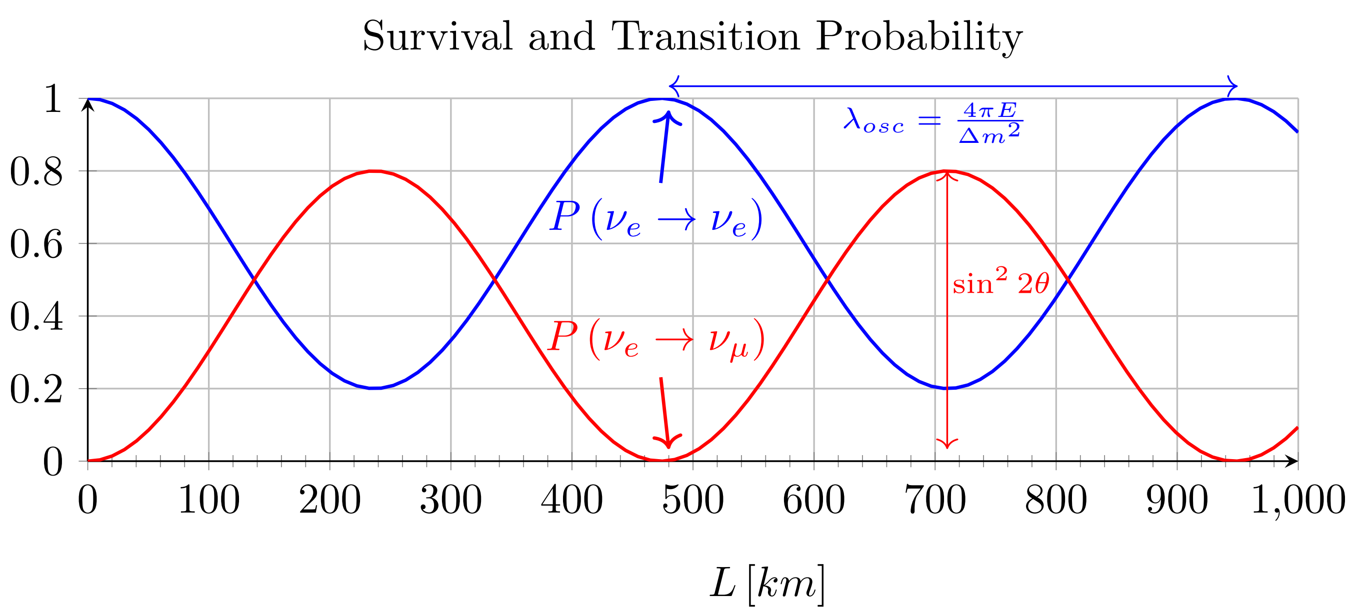
- L : Distance from source to detector
- E : Neutrino energy

Neutrino Oscillations

How to plan a neutrino oscillation experiment

$$\boxed{P_{\text{oscillation}}\left(\nu_\mu \to \nu_e\right) = \left|\left\langle \nu_e | \nu_\mu(t) \right\rangle\right|^2 = \sin^2 2\theta_{12} \sin^2\left(1.27 \Delta m^2_{21} \frac{L}{E}\right)}$$

- Choose **L** and **E** adequate to the ranges of Δm^2 of interest
- Get a suitable neutrino source (accelerator, reactor, the Sun,...)
- Collect (a lot of) data and "see" neutrinos appearing and disappearing



Neutrino Oscillations
Three flavours

- Neutrinos are parametrised by 3 masses (**m_1, m_2, m_3**), 3 angles (**θ_{12},θ_{13},θ_{23}**) and an extra complex phase **$e^{i\delta}$**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{bmatrix} 0.82 \pm 0.01 & 0.54 \pm 0.02 & 0.15 \pm 0.03 \\ 0.35 \pm 0.06 & 0.70 \pm 0.06 & 0.62 \pm 0.06 \\ 0.44 \pm 0.06 & 0.45 \pm 0.06 & 0.77 \pm 0.06 \end{bmatrix}$$

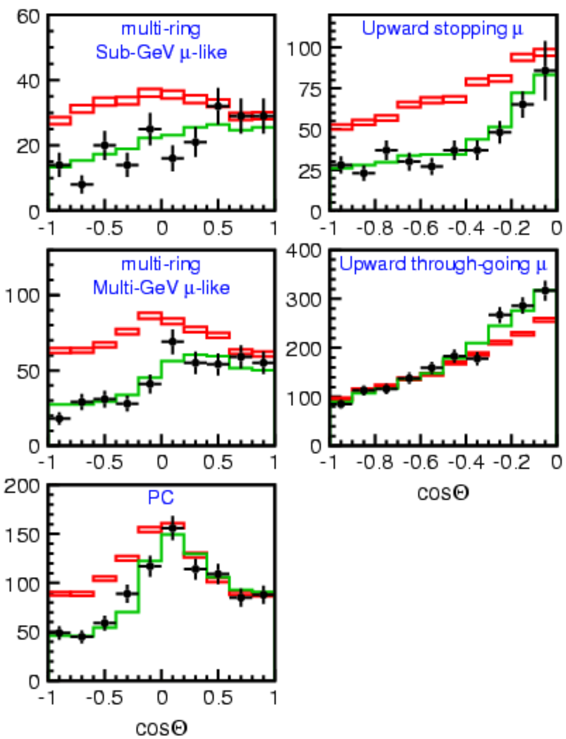
- **The phase $e^{i\delta}$ is responsible for matter/anti-matter asymmetry (CP violation)**

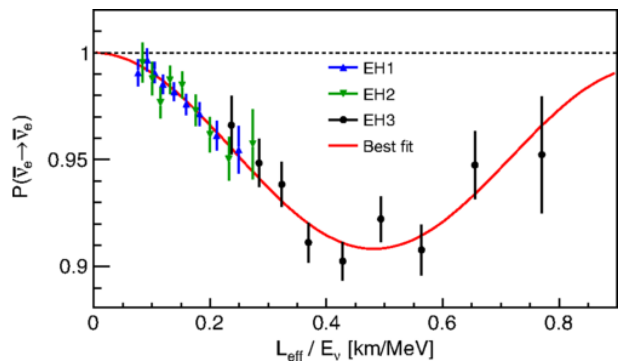
$$P\left(\nu_\mu \to \nu_e\right) \neq P\left(\bar{\nu}_\mu \to \bar{\nu}_e\right)$$

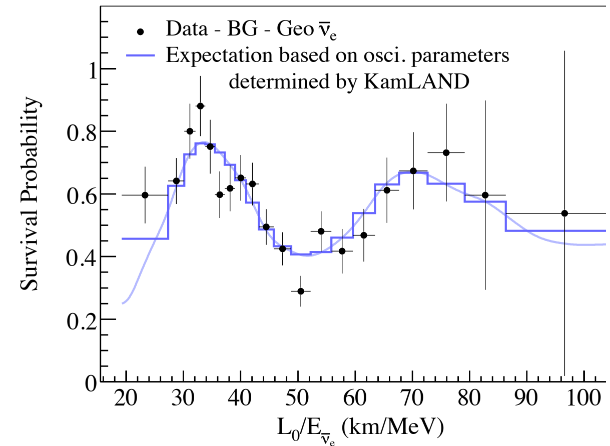
Neutrino oscillations are consistent with being mass driven

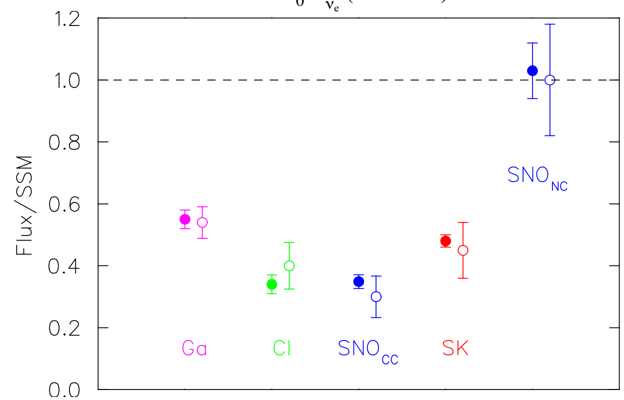
Neutrino Mass and Oscillations

What have we learned in the last ~20 years









$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Accelerator and Atmospheric

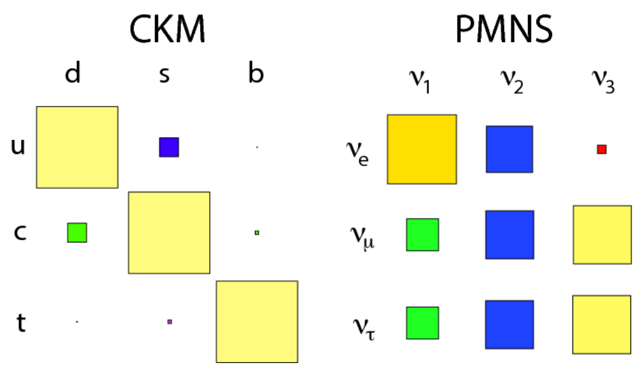
SBL reactor

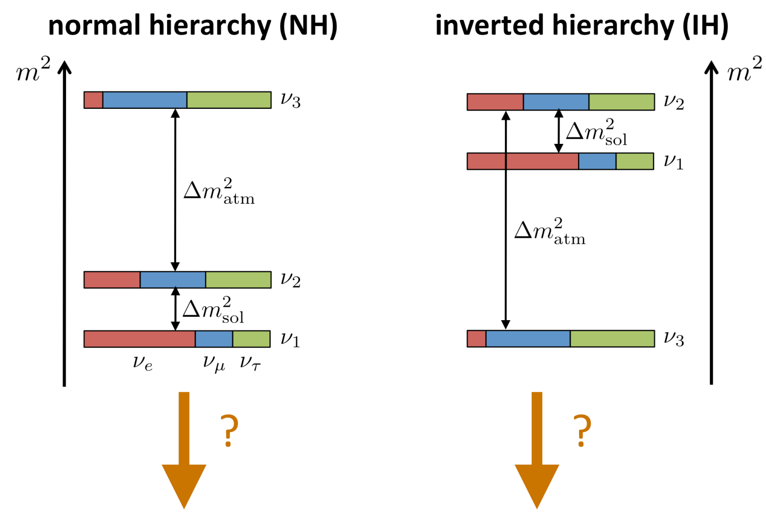
Solar + LBL reactor

Neutrinos

What haven't we learned yet ?

- **Is there CP violation in the lepton sector?**
- Which mass hierarchy is correct?
- What are the precise values of the neutrino mixing parameters?





DEEP UNDERGROUND NEUTRINO EXPERIMENT

- What is the absolute mass scale?
- **Are neutrinos Majorana or Dirac particles?**
  - A topic for another day...

SNO+

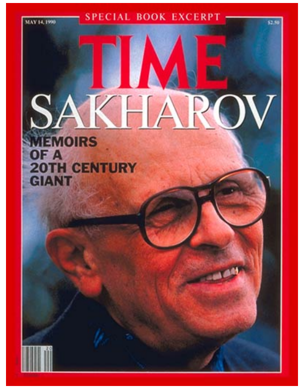
Neutrinos and matter/antimatter asymmetry

Where is all the antimatter?

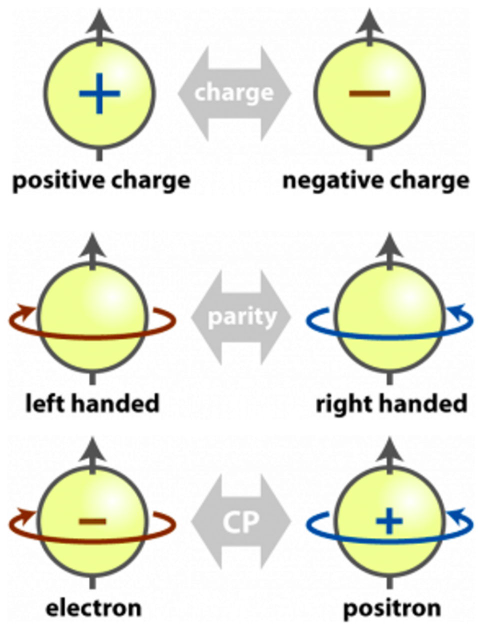
Baryon asymmetry

How do we get a matter-only Universe?

- Sakharov conditions (1967)
  - **processes that violate baryon and lepton number conservation ✓**
    - high energy "non-perturbative" effects should exist in the Standard Model
  - **departure from thermal equilibrium ✓**
    - in the extreme Big Bang conditions
  - **<u>some difference between matter and anti-matter</u>**
    - **is CP violation enough ?**



- CP violation observed in K and B mesons
  - **but it is not enough!**
- CP violation could exist in neutrinos
  - Could be enough
  - **Leptogenesis hypothesis**



Neutrinos: Dirac or Majorana?

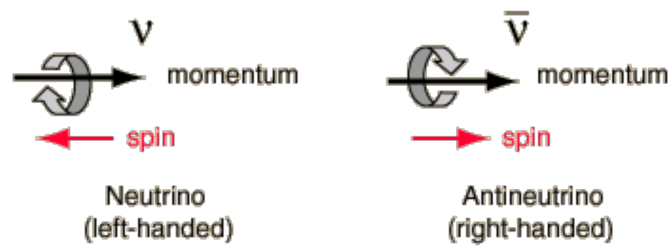
- Except for neutrinos, all fermions of the standard model are electrically charged
- Thus, **there is a distinction** between particle and antiparticle
- **For neutrinos, this is not obvious - particles could be identical to antiparticles, with only chirality/helicity distinguishing them**
  - Instead of ν_e and $\overline{\nu}_e$ we would have ν_{e_L} and ν_{e_R}
  - And the following interactions would be:
    - $\nu_{e_L} + n \rightarrow p + e^-$
    - $\nu_{e_R} + p \rightarrow n + e^+$

$e \neq e^c$

negative charge   positive charge

$\nu \neq \nu^c$????

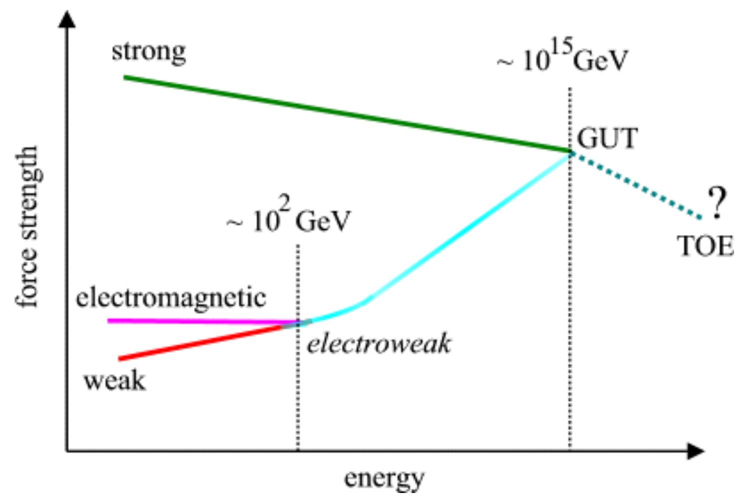
No charge to distinguish them
Are neutrinos Majorana particles?



Massive Majorada Neutrinos

- Neutrinos could their own antiparticles, with only chirality/ helicity distinguishing them
  - i.e., neutrinos could be **Majorana fermions**

- **IF** Heavy Majorana neutrinos exist, a "see-saw" mechanism can explain the smallness of masses
  - Dirac term m_D ~ 100 GeV (scale of W, Z, Higgs bosons)
  - If m_N ~10^{14} – 10^{15} GeV (GUT scale)
  - Then m_ν ~ 0.01 - 0.1 eV (expected from oscillations/limits)
    - **Interesting coincidence**



- **IF** neutrinos are Majorana fermions **AND** they violate CP they could help explain matter-antimatter asymmetry in the Universe
  - **Leptogenesis**

The DUNE Experiment

The DUNE Collaboration

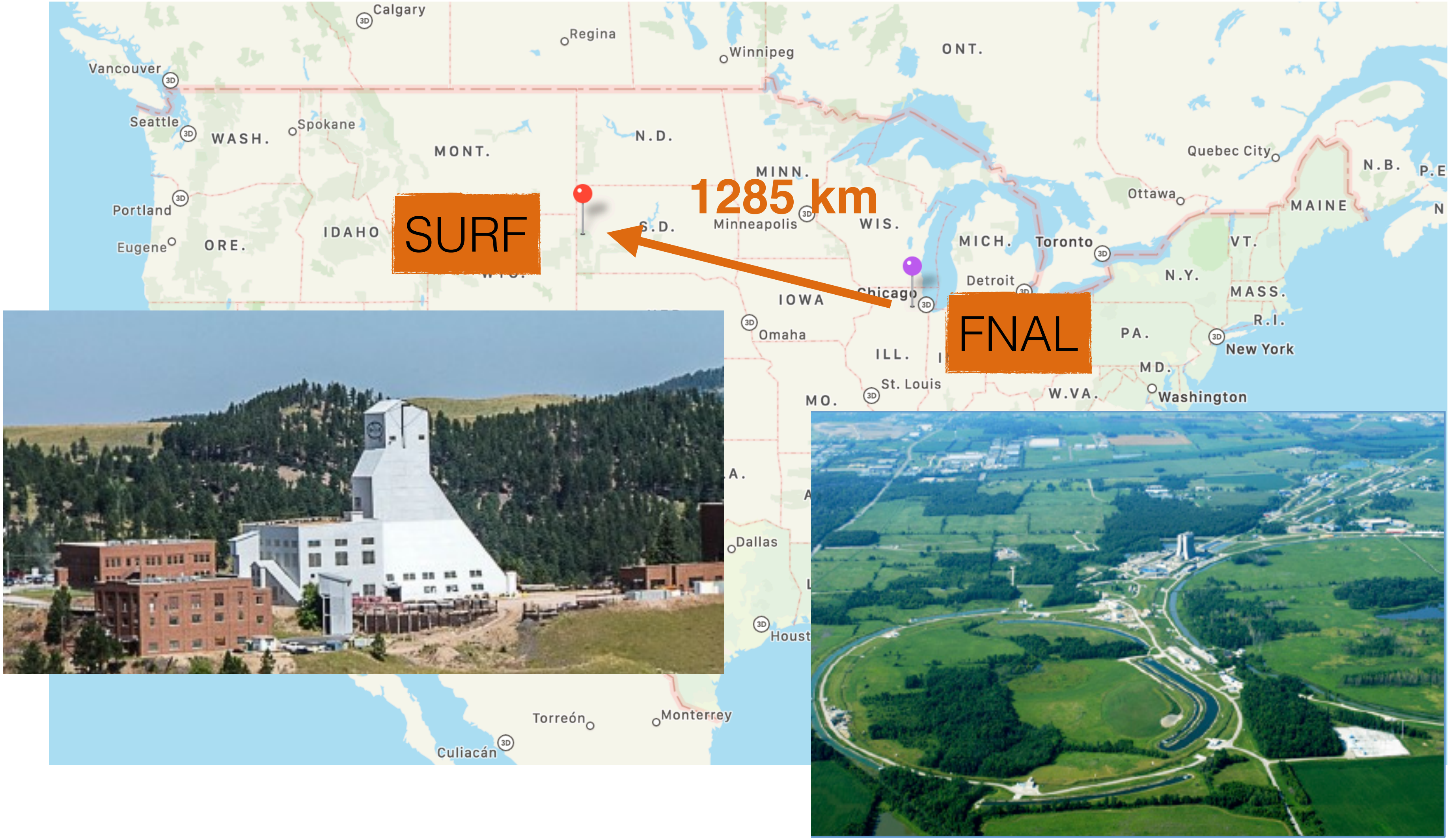
- >1000 collaborators
- >190 institutions
- 34 countries
  - plus CERN

(Lisbon and Coimbra)

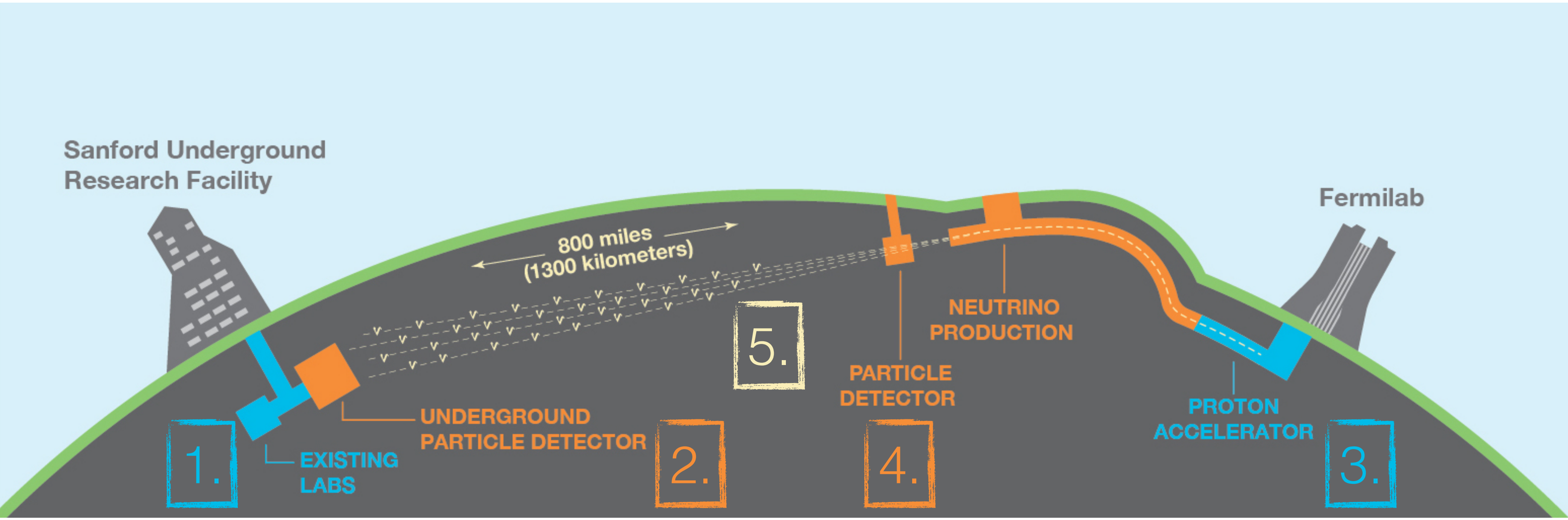
DUNE Collaboration Meeting, CERN January 2020

Continent-scale baseline

Continent-scale baseline

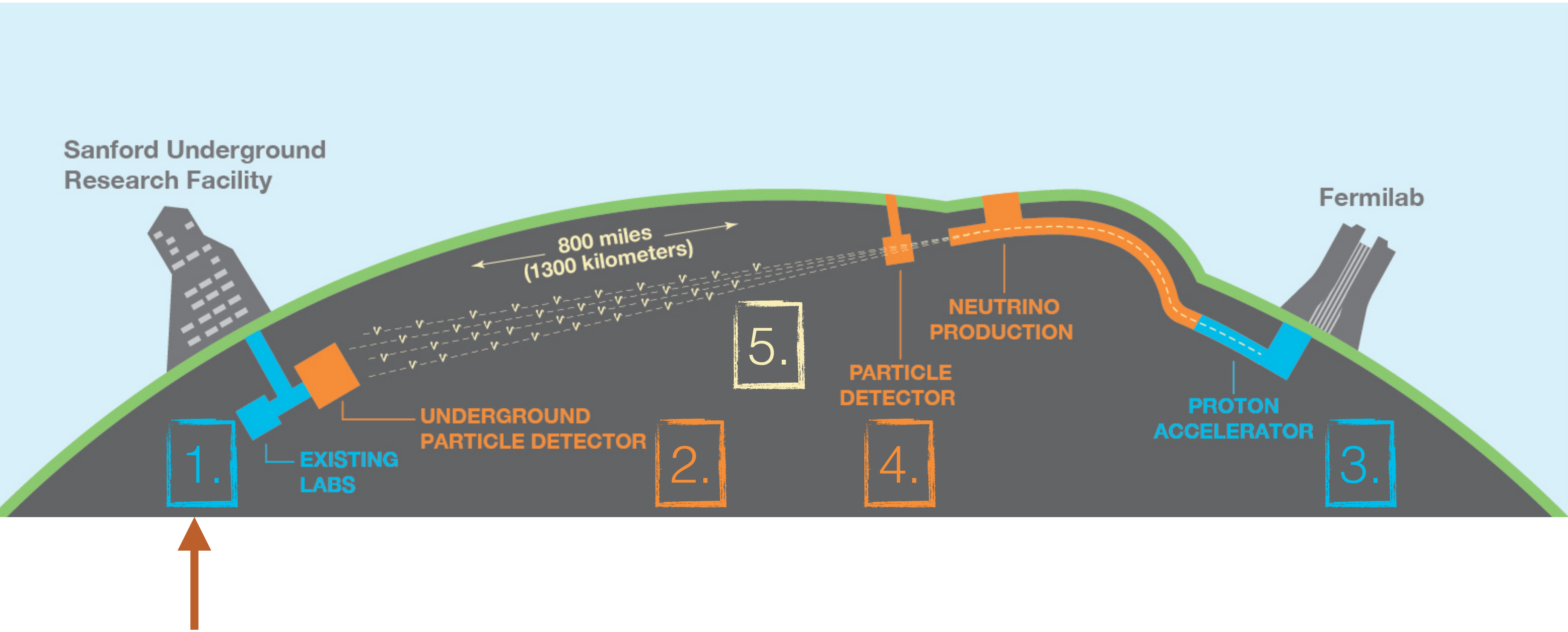


Outline of the Experiment



Outline of DUNE

Far Site



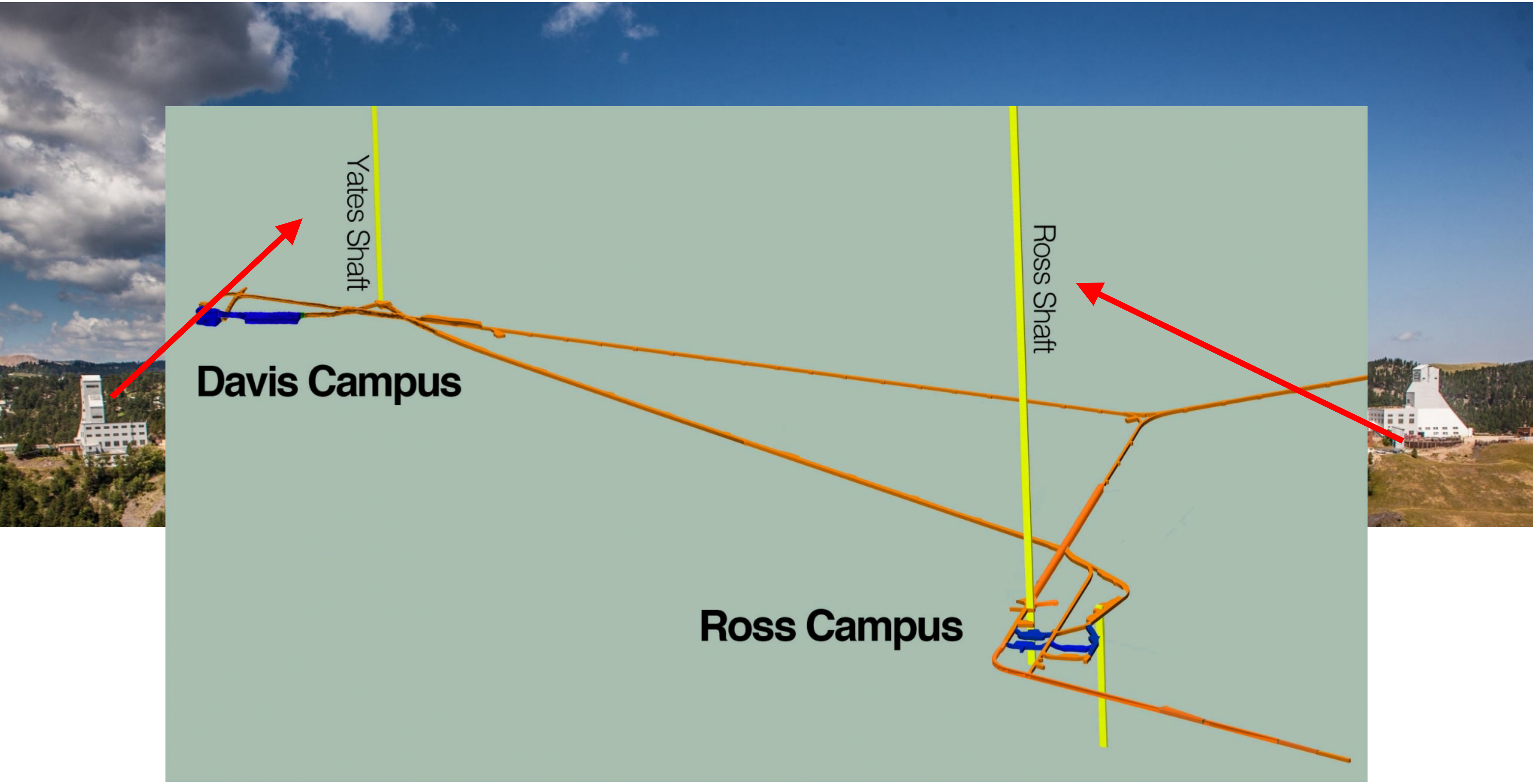
Far site

Sanford Underground Research Facility (SURF)

- Gold mine repurposed into underground laboratory
  - Deepest laboratory in the US (1.5 km underground — 4300 m.w.e.)
- Two main campuses:
  - Davis: Homestake, **LUX (LZ)**, MAJORANA
  - Ross: DUNE (possibly other ton-scale experiment in the future)

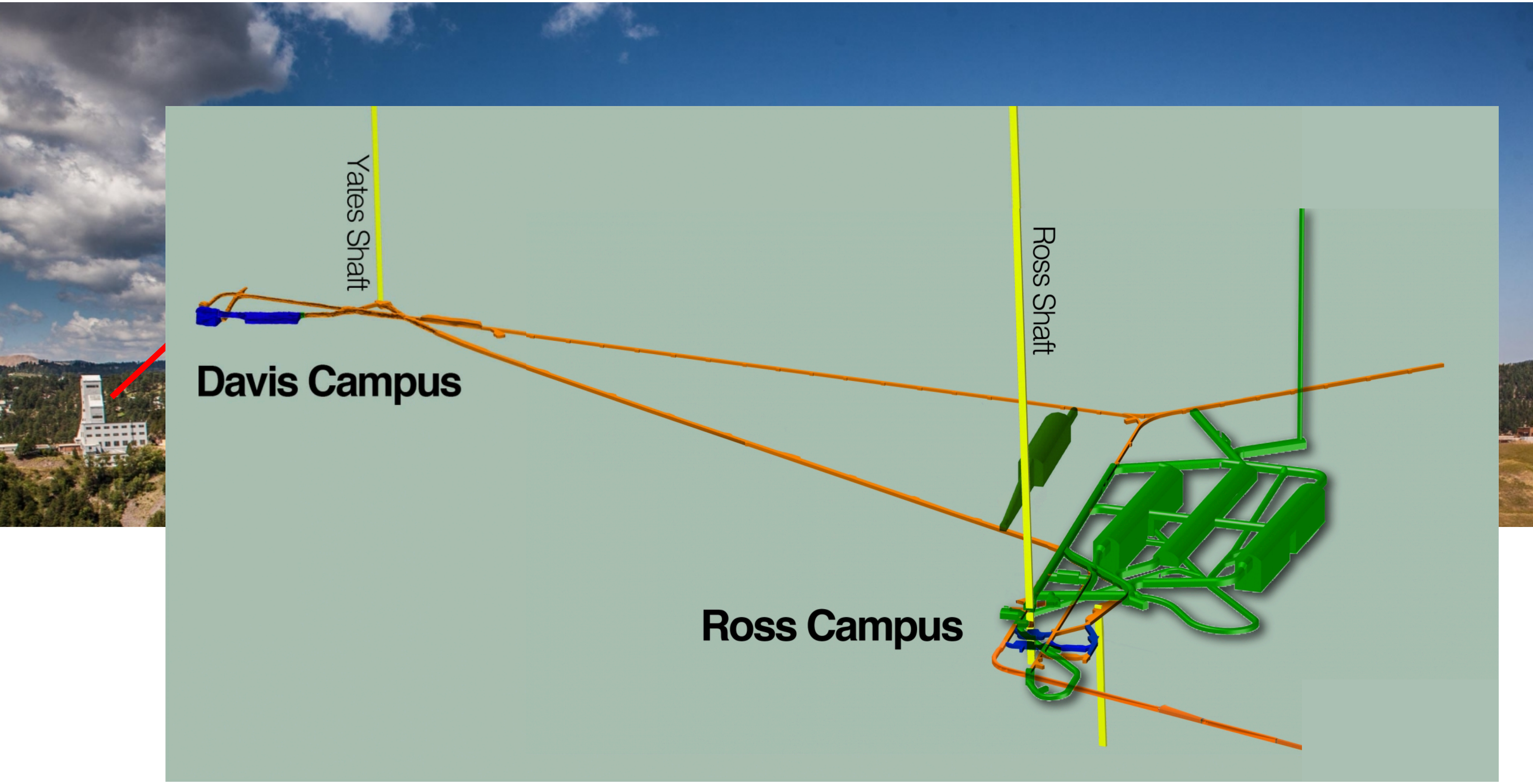
Far site

Sanford Underground Research Facility (SURF)



Far site

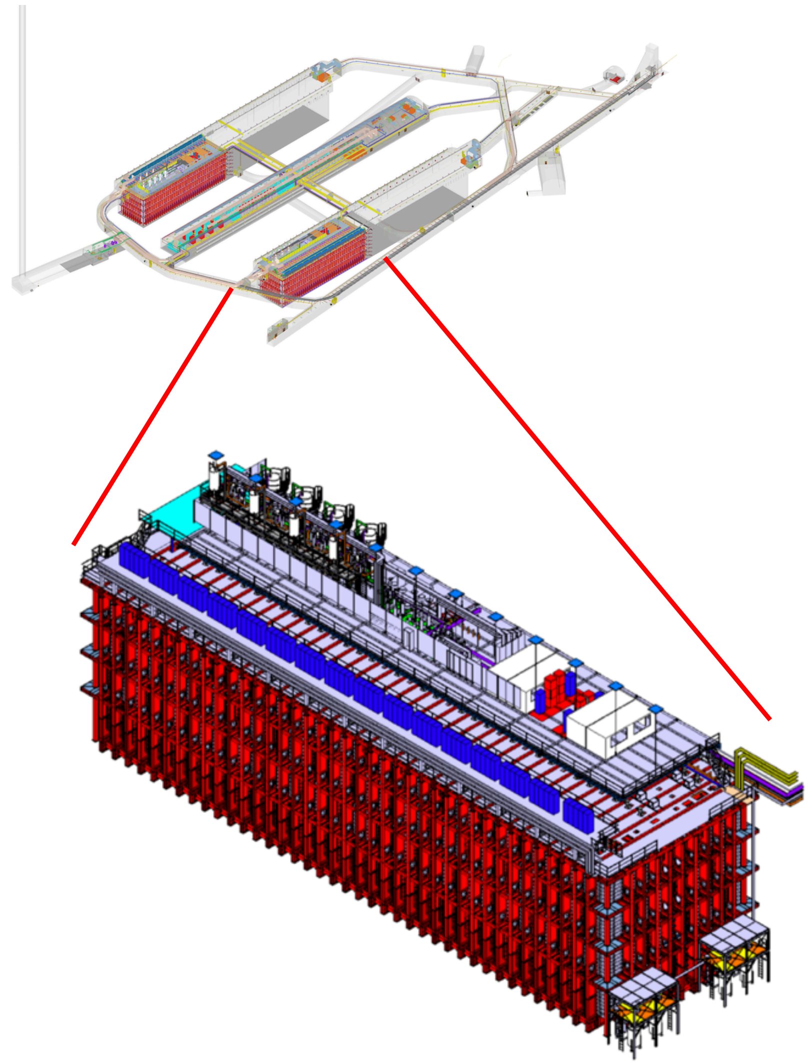
Sanford Underground Research Facility (SURF)



Far site

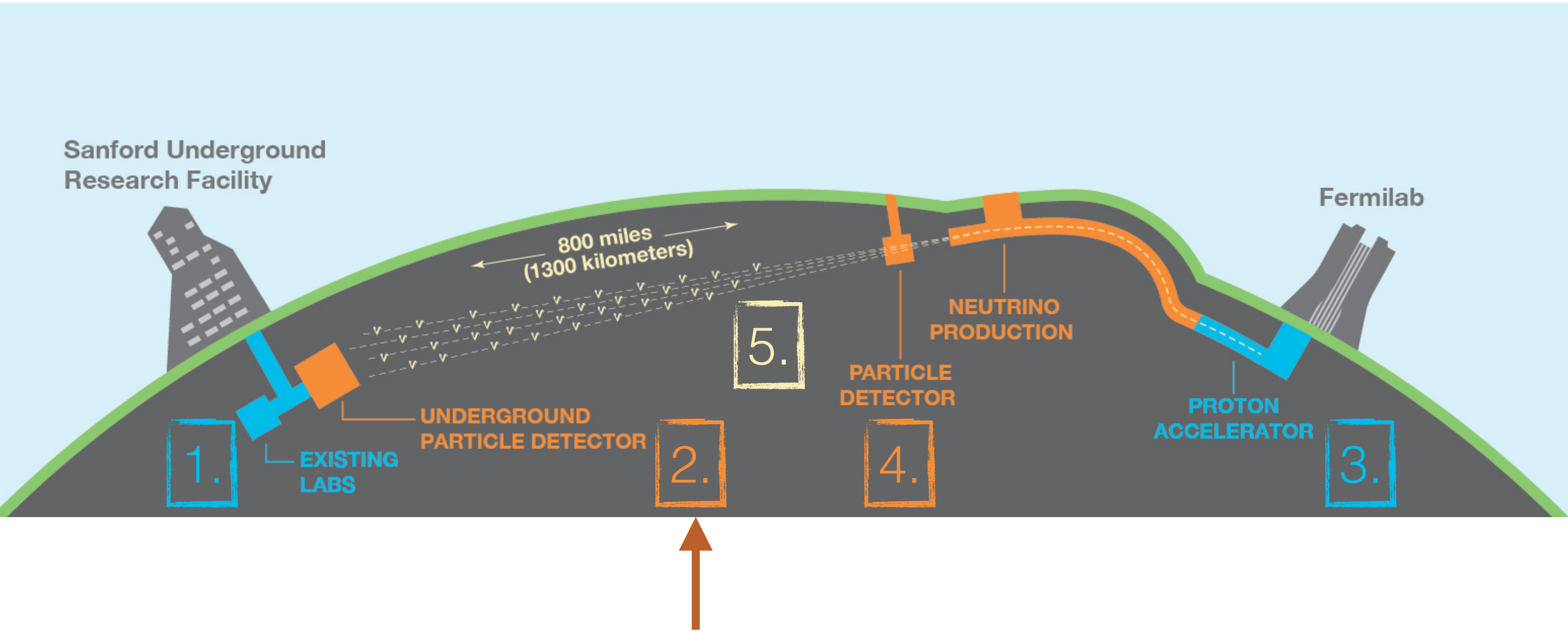
DUNE far site facility

- 5 main caverns
  - 4 detector + 1 support
    - Support : Cryogenics and DAQ
- Detectors based on LArTPC technologies
  - Same cryostat
    - 62 m x 19 m x 18 m
      - 17 kt total LAr mass (70 kt total)
      - 10 kt fiducial LAr mass (40 kt total)
- Detectors to be installed in a staged approach over several years
  - 2 detectors to be installed before beam starts (2026)



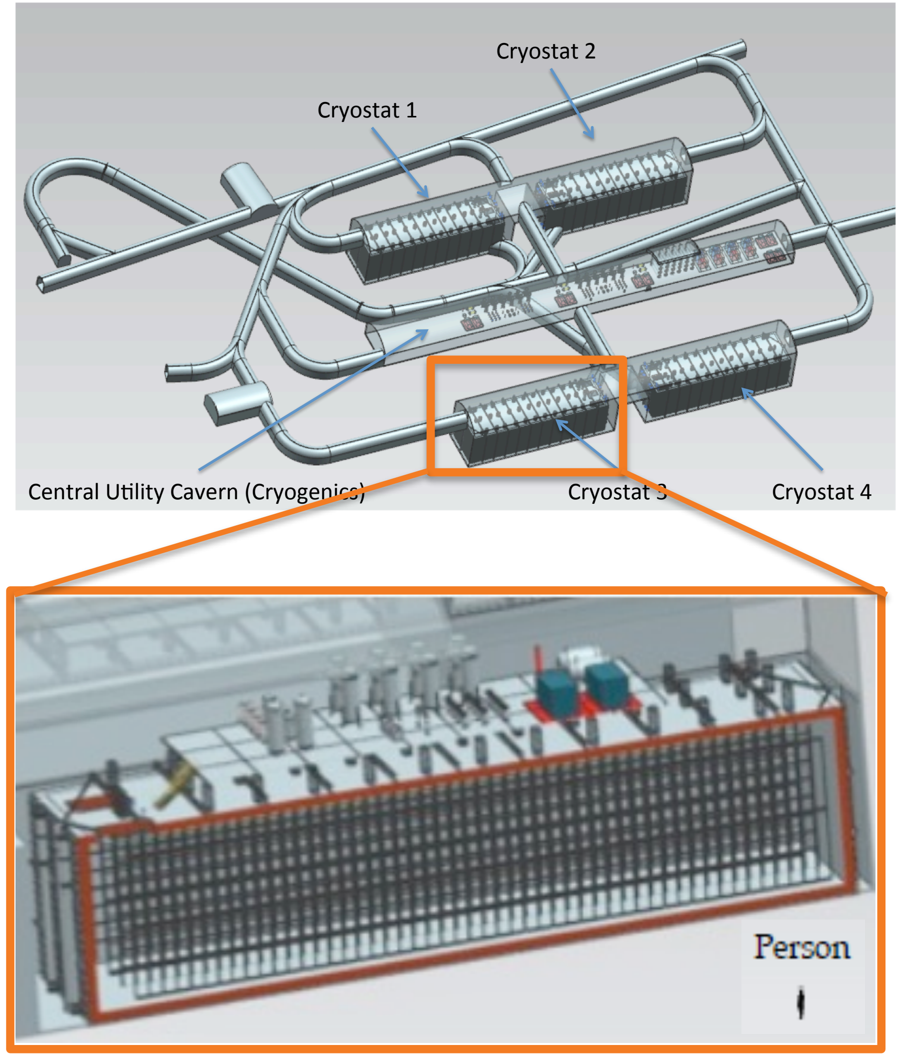
Outline of DUNE

Far detector



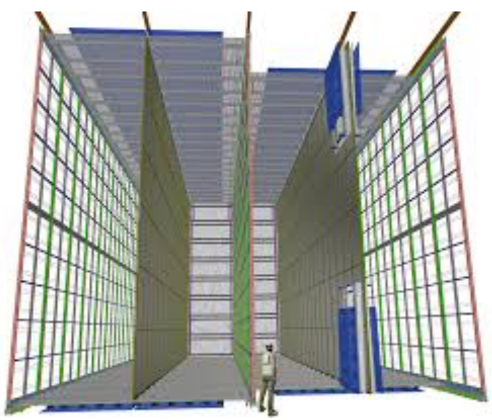
DUNE far detector

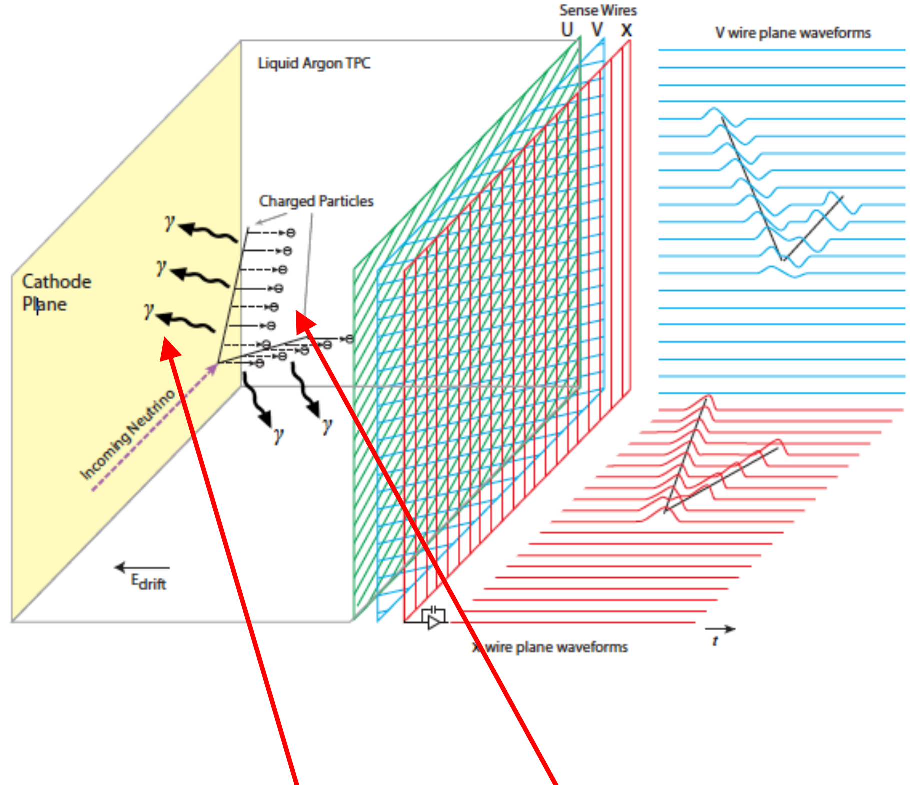
- LAr is both the target and detection medium
  - ~10 kt fiducial volume of LAr (17 kt total)
- Different LArTPC detector designs
  - Both horizontal and vertical drift designs
  - This talk will focus on horizontal drift
    - Technology confirmed for first module
- Integrated photon detection
- Modules will not be identical
  - Cryostats can accommodate different detector designs



DUNE far detector
Single-phase LArTPC

- Technology used by ICARUS, ArgoNeuT, MicroBooNE, LArIAT
- At least two modules confirmed to use this technology
  - Including first module installed
- No signal amplification
  - Requires low noise electronics

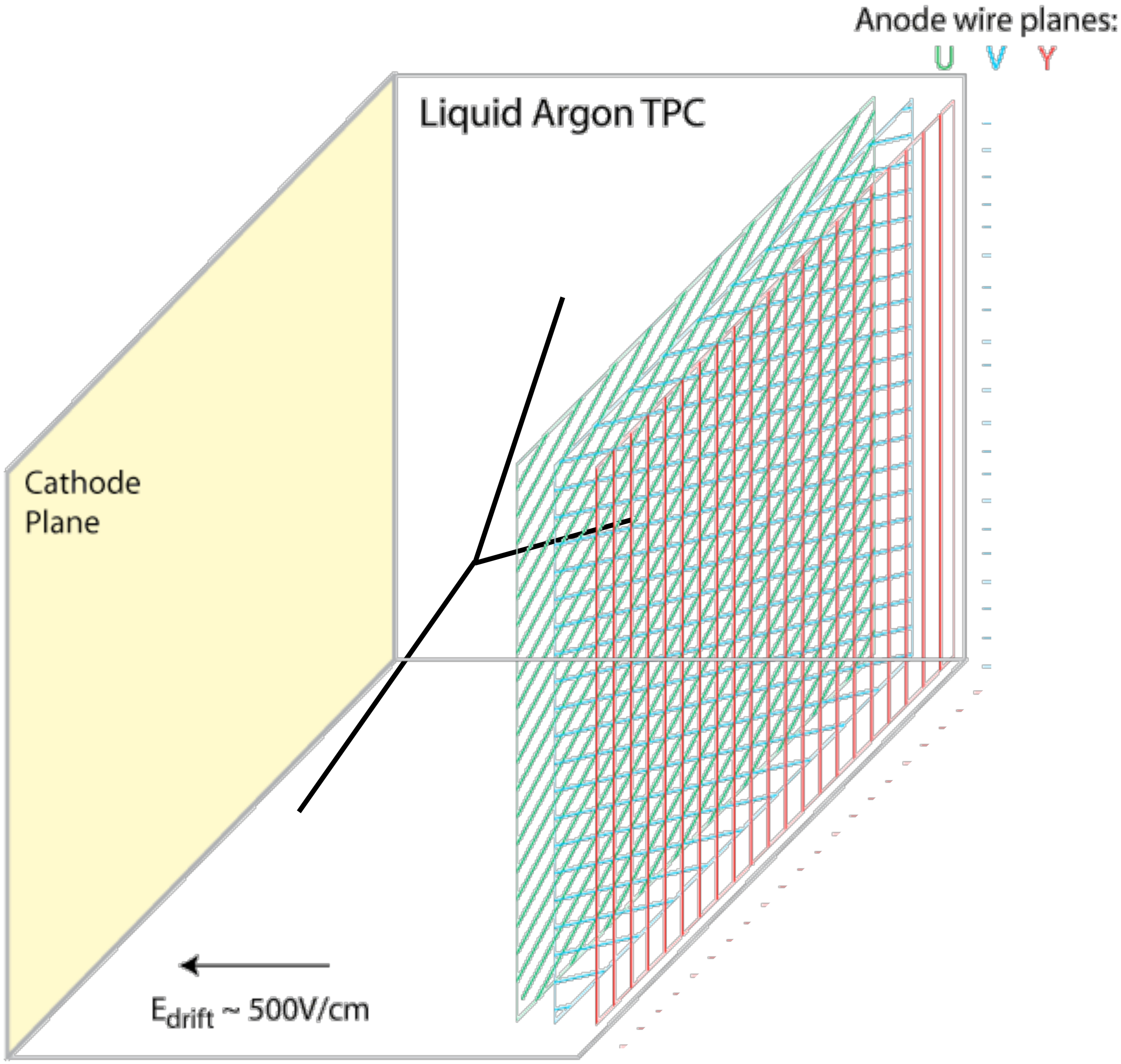




Production of both **ionisation electrons** and **scintillation photons** (trigger, t_0)

Single-phase LArTPC

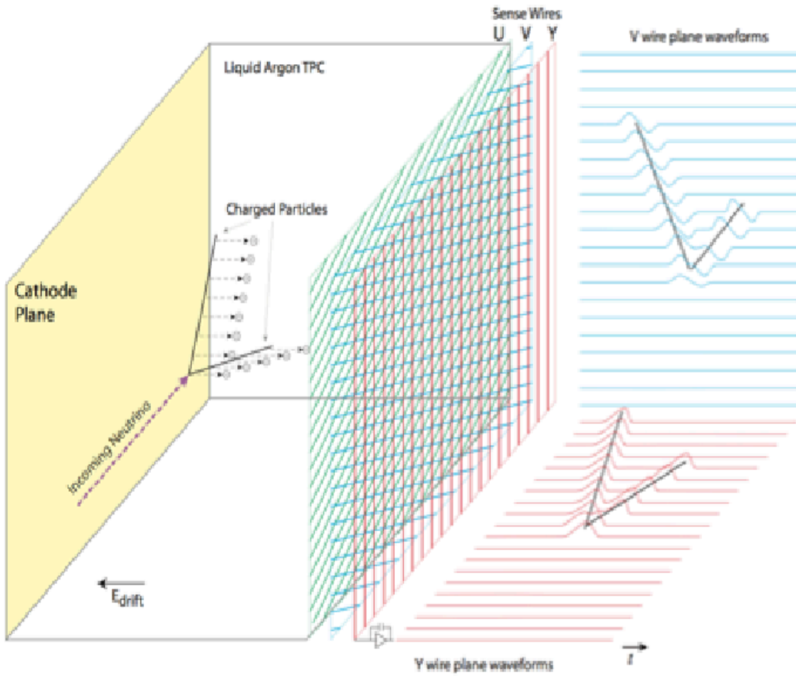
How does it work?

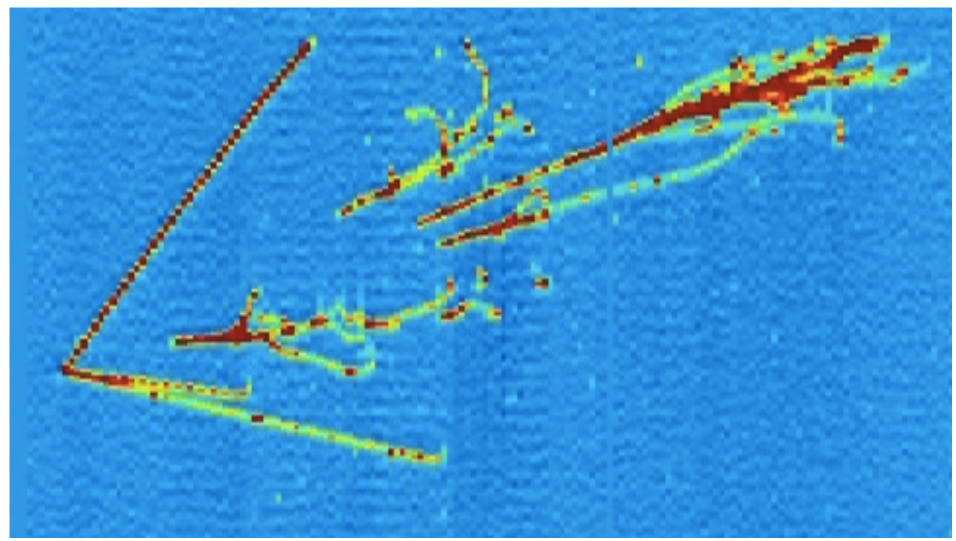


DUNE far detector
Single-phase LArTPC

- Major Challenges:
  - Event reconstruction (monolithic detector)
  - Scaling of technology

- Technology advantages:
  - Ar is cheap and readily available
  - Good dielectric, can sustain very HV
  - 3D imaging (use image processing technology for event classification)
  - Full event topology

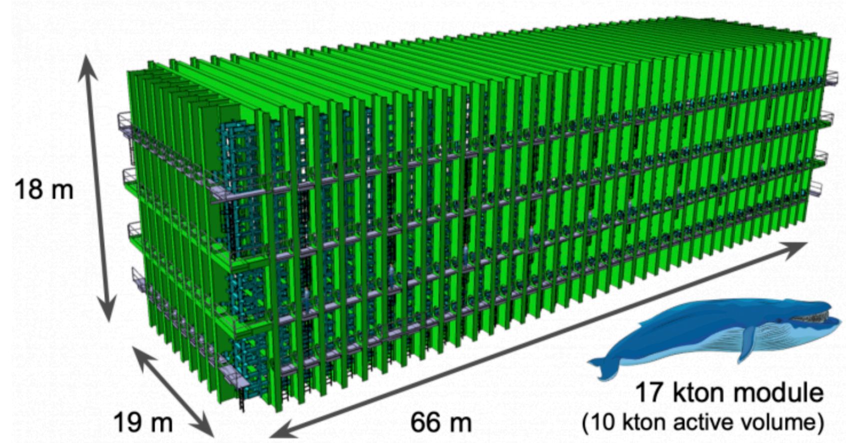


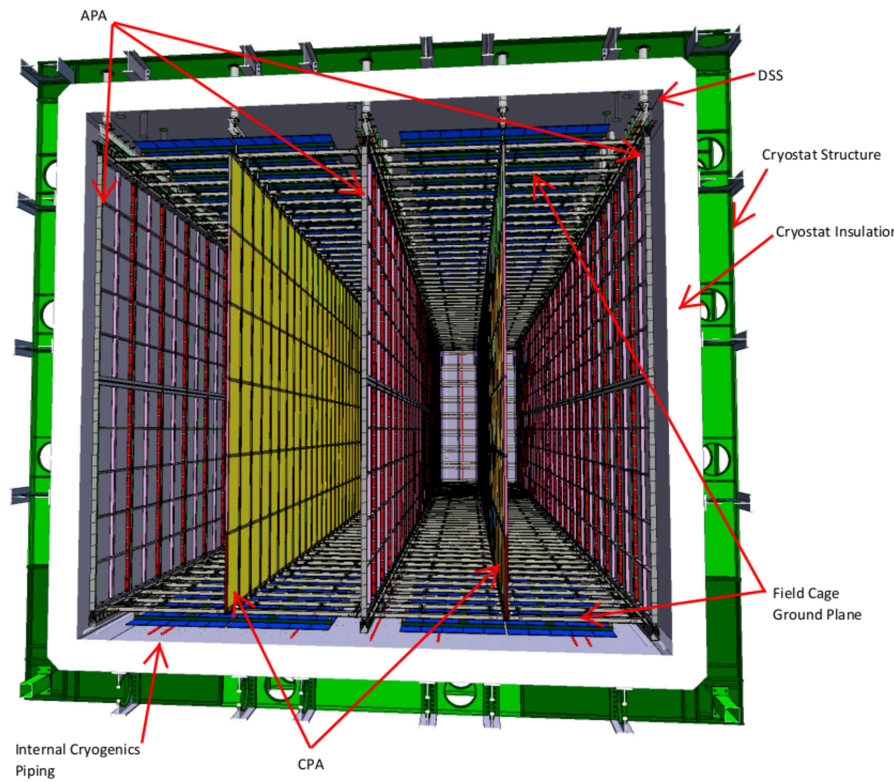


DUNE far detector

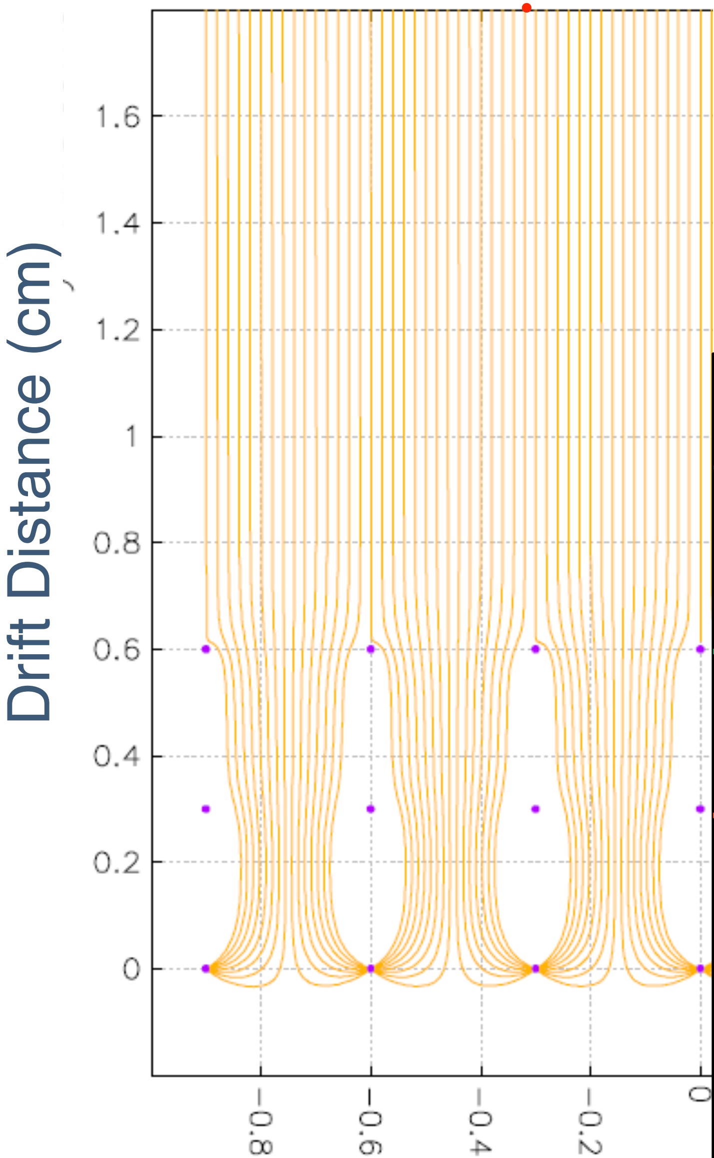
Single-phase LArTPC

- Anode wires wrap around frame to allow two drift volumes (APA)
- Drift distance: 3.5 m
- E = 500 V/cm
  - Cathode voltage : -180 kV
- 150 APAs per detector module
  - 384 000 channels
  - Continuous digitisation of ~ms waveforms

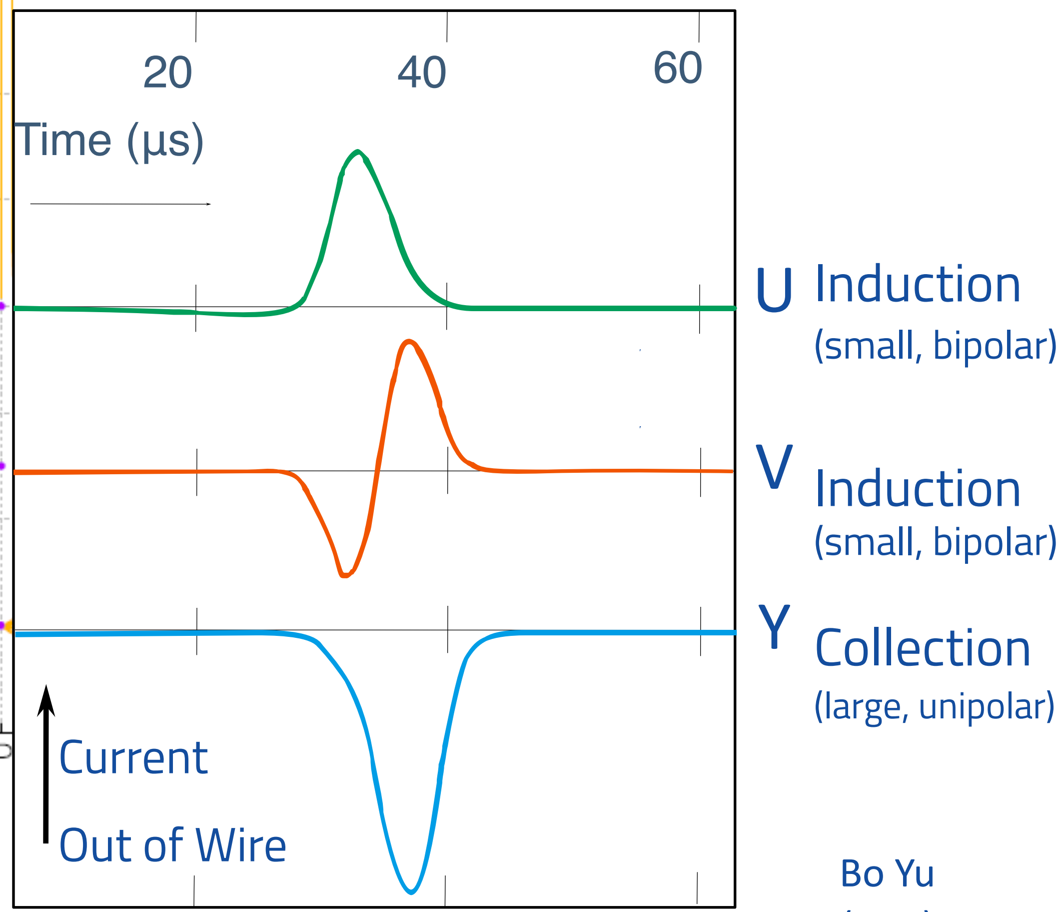




Charge Signal Formation



Induction by and **collection** of electrons on wires



Signal formation starts upon motion of the charge.

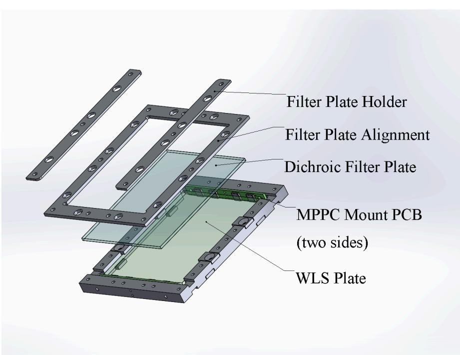
Bo Yu (BNL)

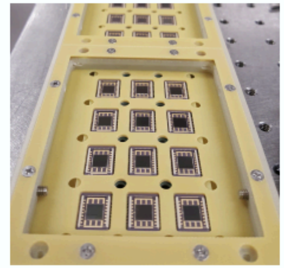
Single-phase LArTPC

Photon detection system

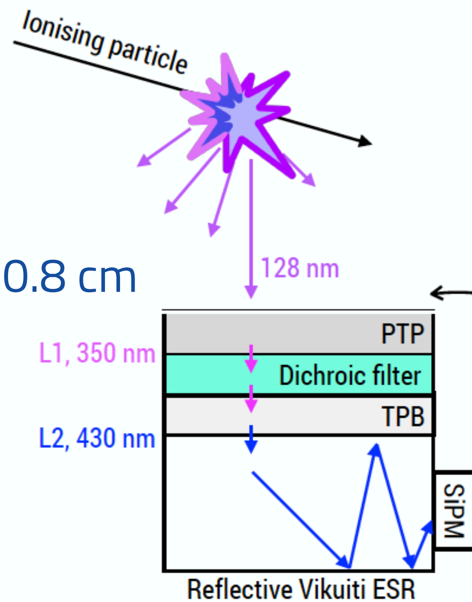
- X-ARAPUCA used as a light trap
  - WLS plate used to capture photons
    - Total internal reflection
    - Reflection from dichroic filter
  - Photons readout by SiPMs

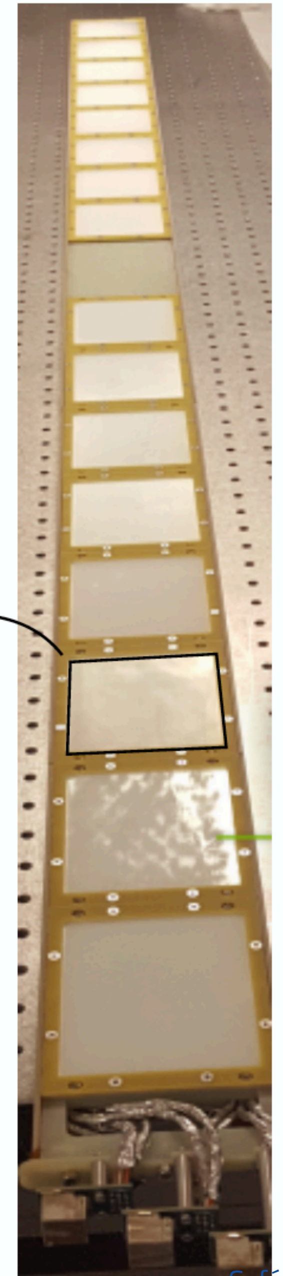
- 6000 supercells of 48.8 cm x 10 cm x 0.8 cm

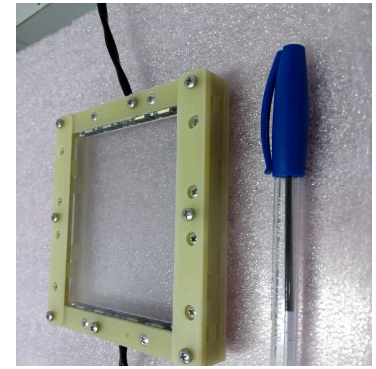


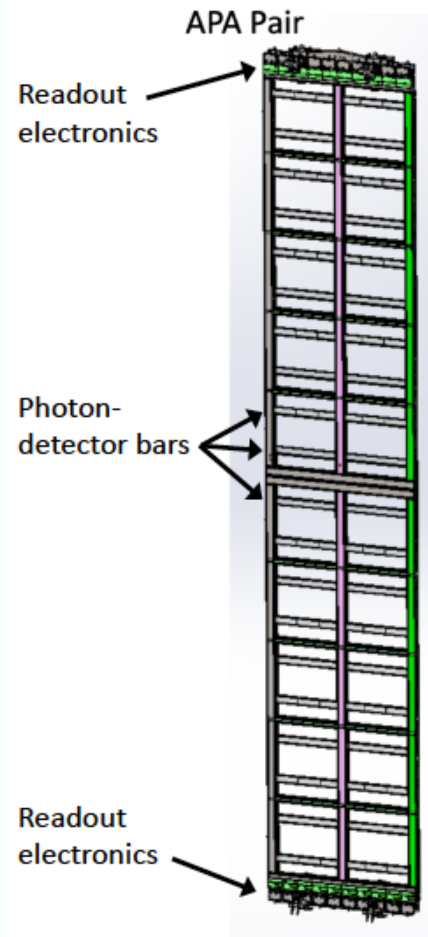


12 SiPMs in one cell



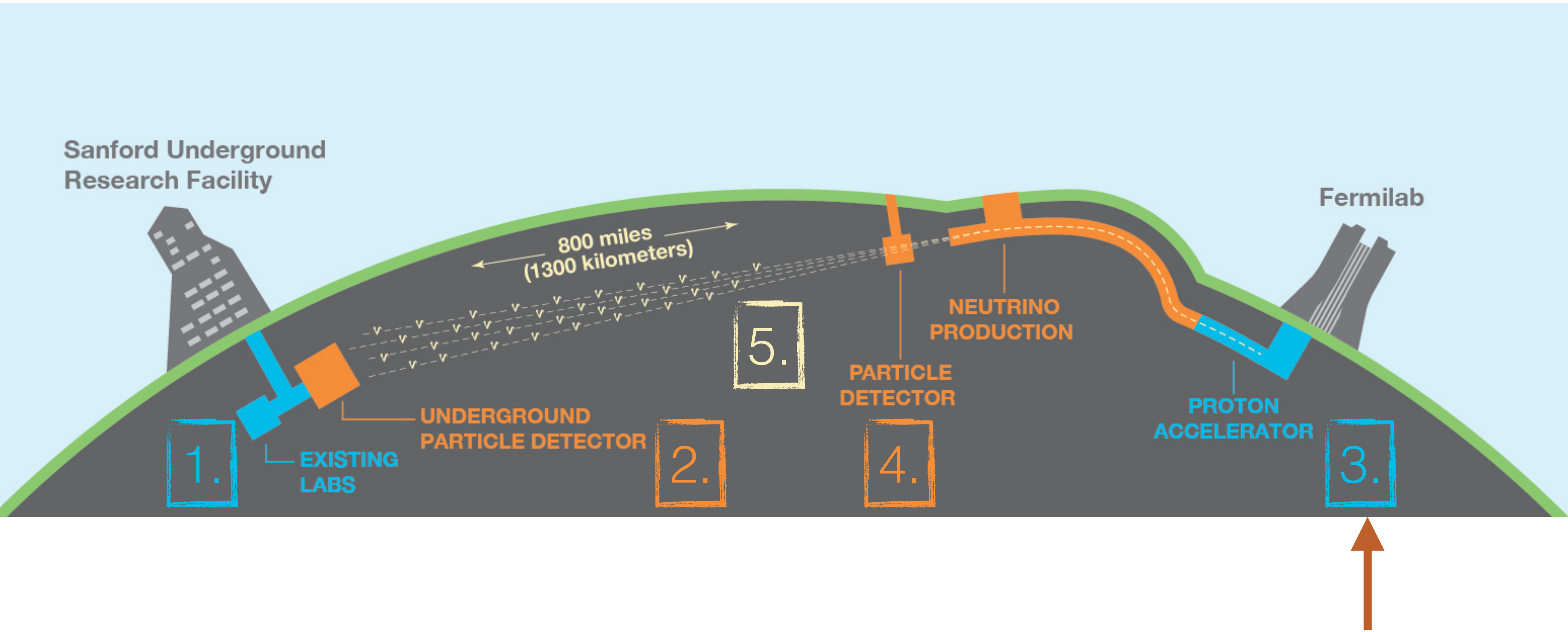






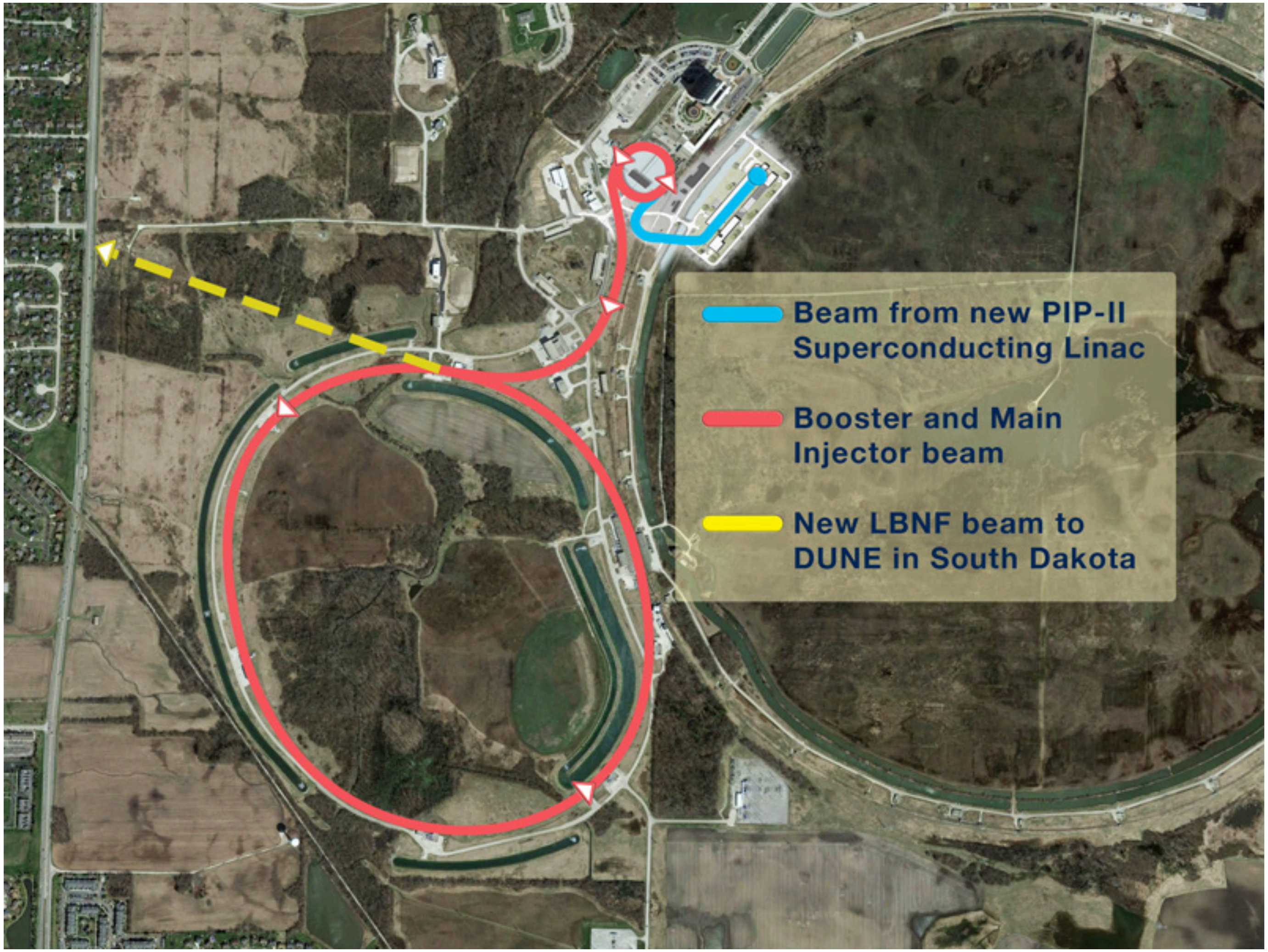
Outline of DUNE

Near Site



Near Site

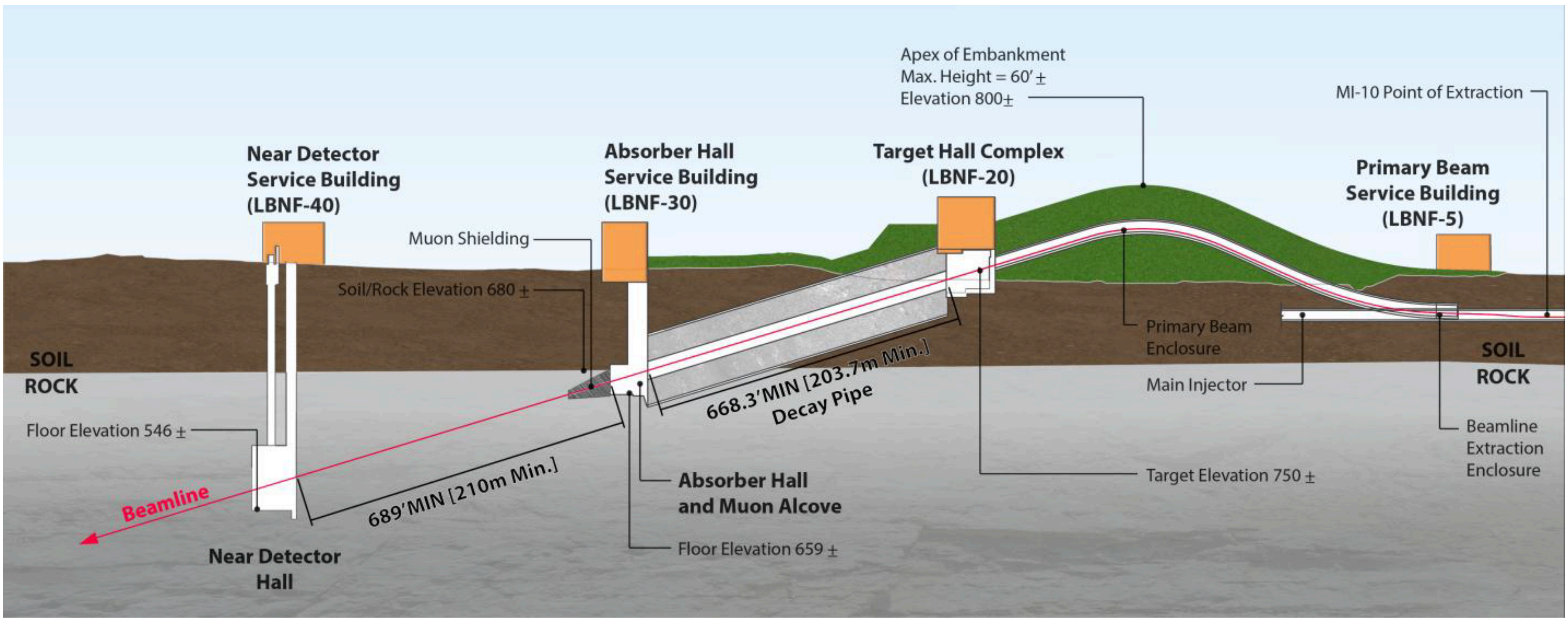
FNAL accelerator complex



Near Site
Beamline

- 1.2 MW proton beam @ 60-120 GeV (Plans exist to upgrade to 2.4 MW)
  - 10^{21} POT/year

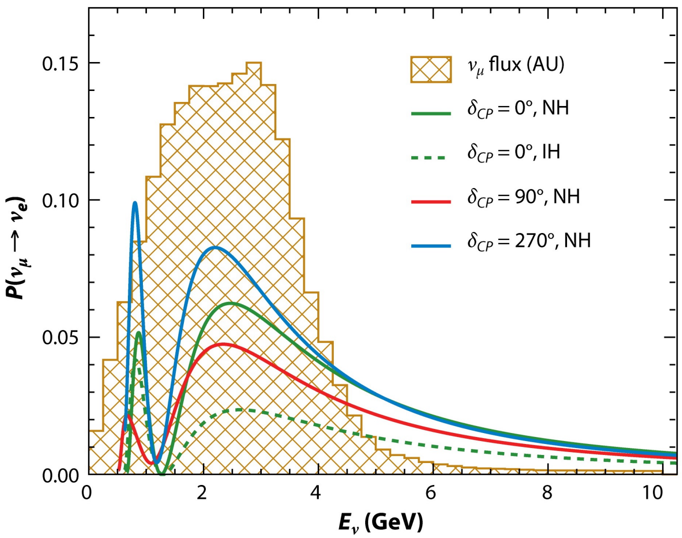
- Oriented 5.8° down
  - 18 m artificial hill created specifically for this

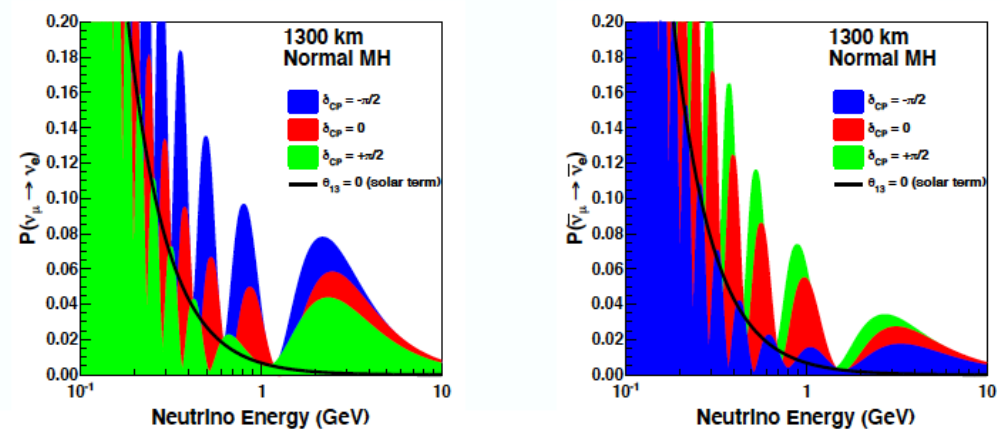


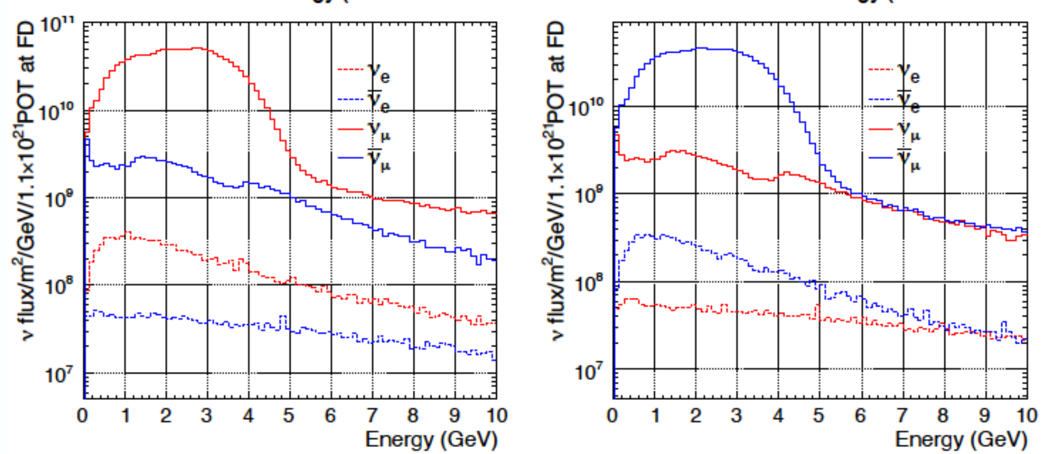
Near Site

Neutrino beam

- Horn-based on-axis wide-band neutrino beam
  - Allows sensitivity to **first and second** oscillation maxima
- Selectable polarity of horn current
  - (anti-)ν_e appearance analysis
  - (anti-)ν_μ disappearance analysis

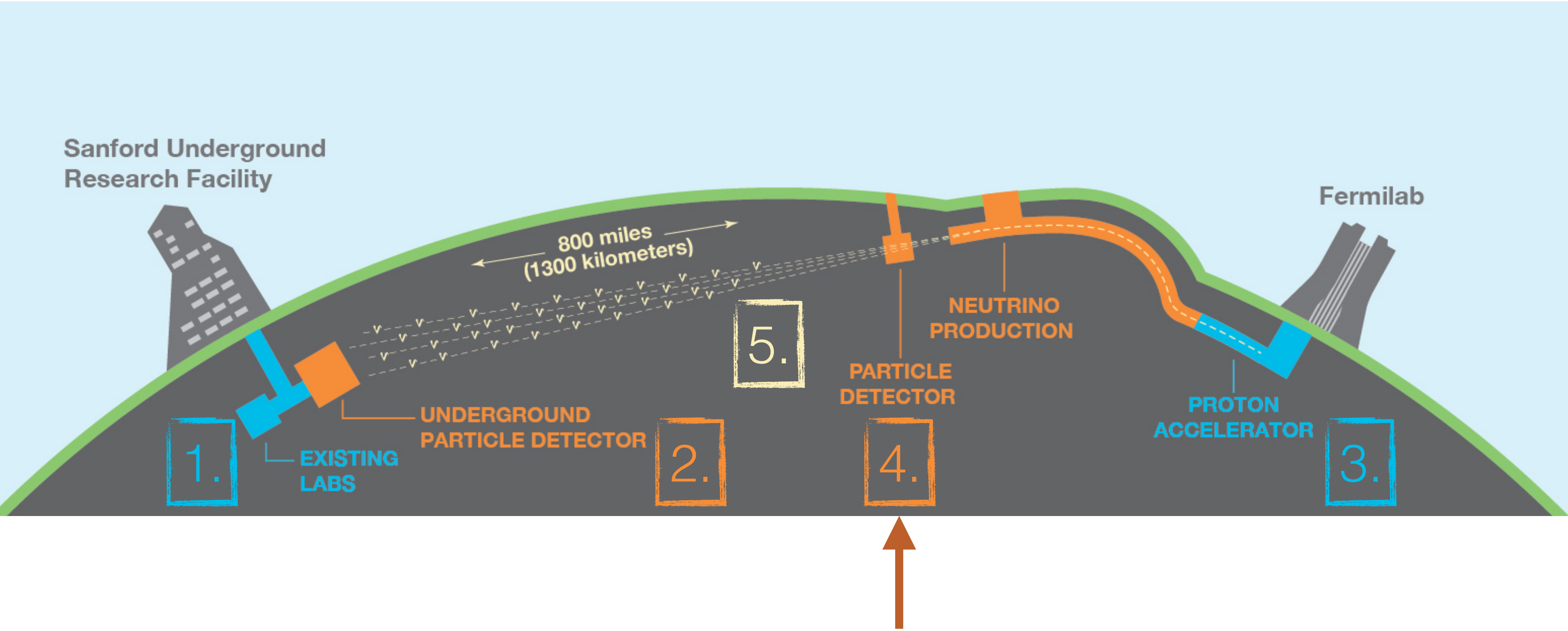






Outline of DUNE

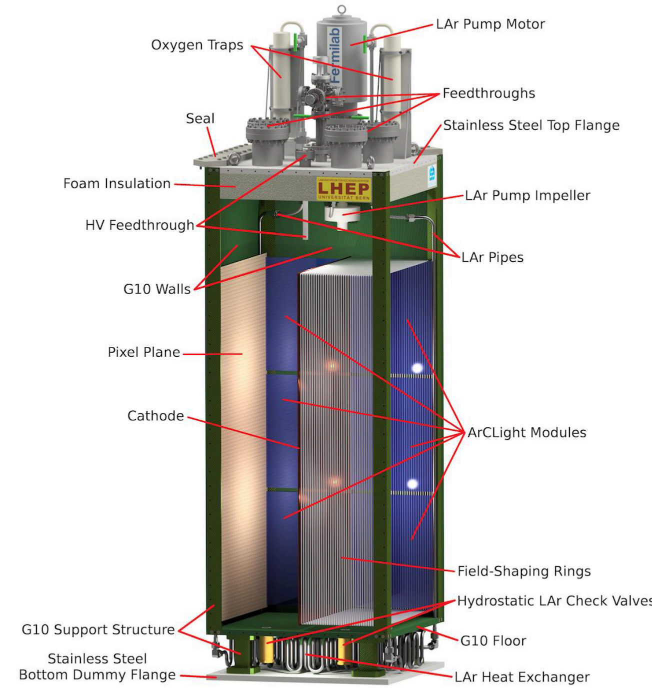
Near Detector

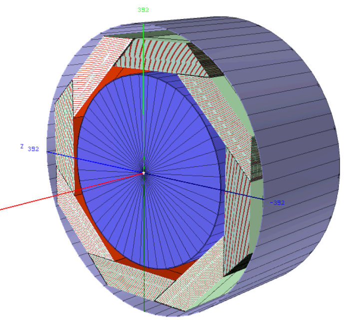


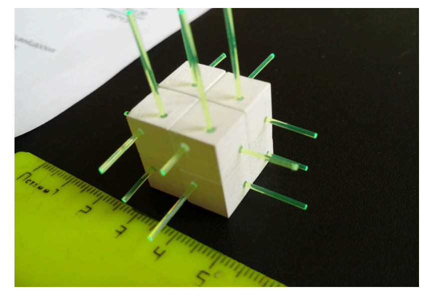
Near Detector(s)

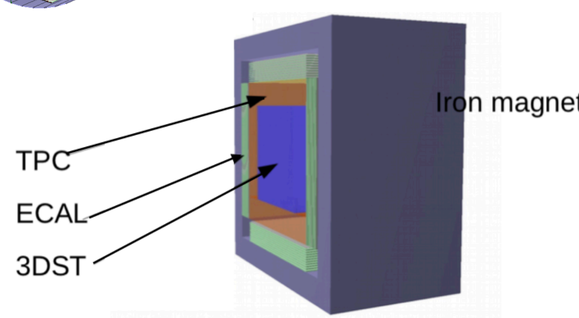
- **Objective**
  - Constrain flux and cross section systematic uncertainties
  - Can also measure 10^6 ν interactions per year

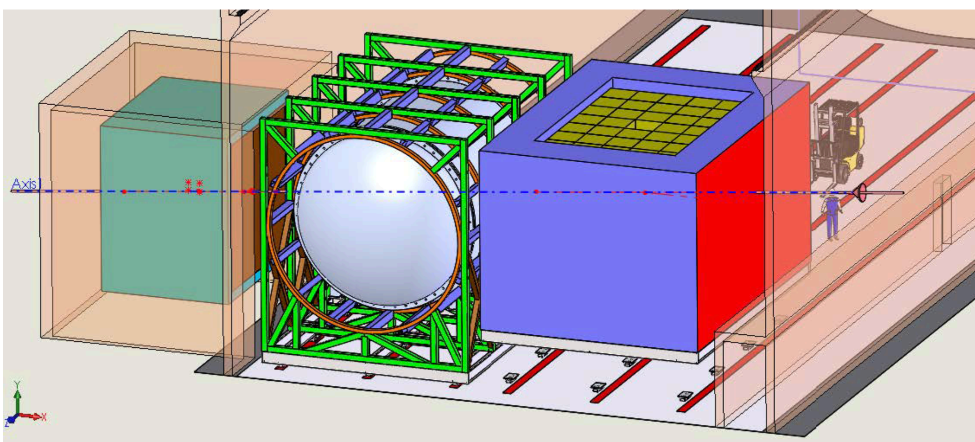
- Concept for ND:
  - **LArTPC (ArgonCube)**
  - **Multi-purpose detector (MPD)**
  - Beam monitor (3D scintillator tracker spectrometer, 3DST-S)







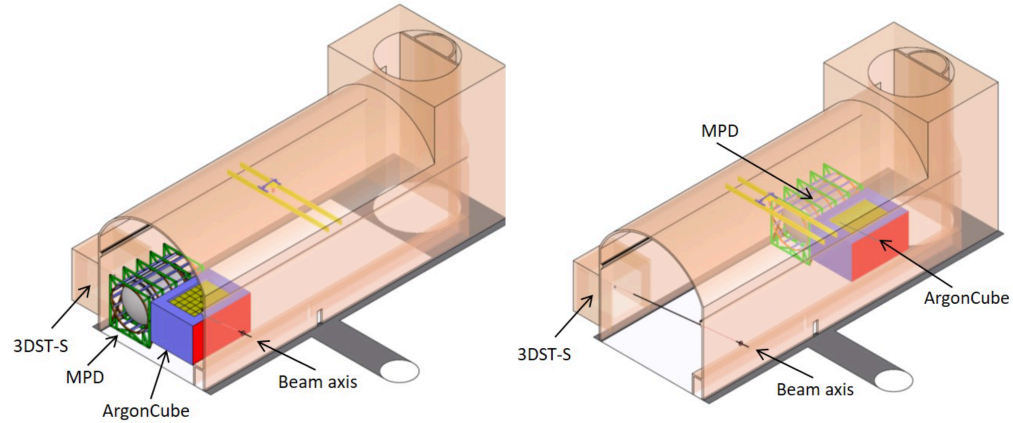


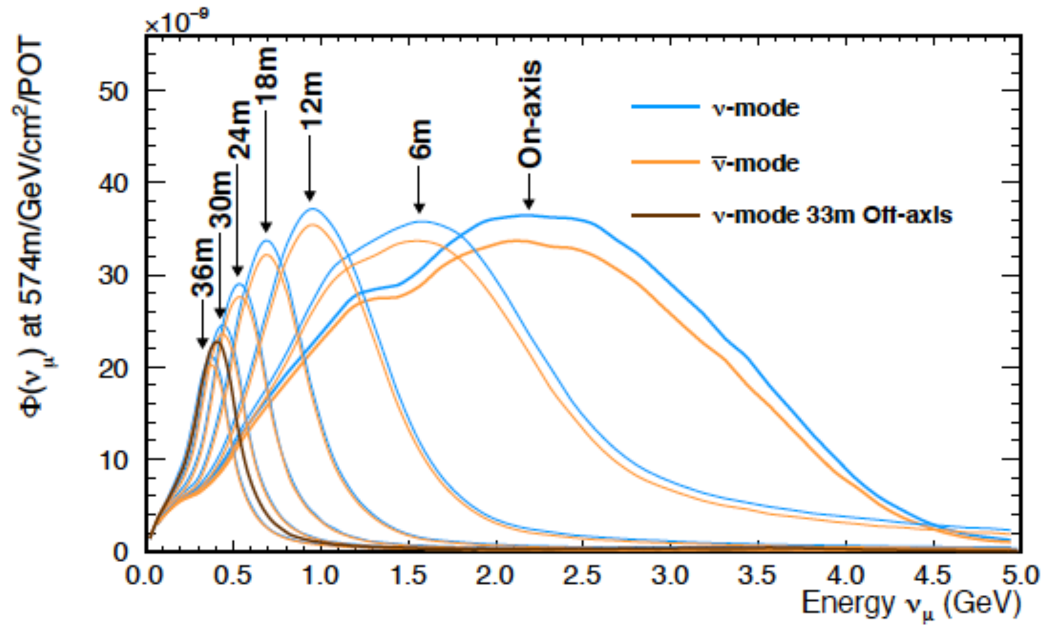


Near Detector(s)

DUNE-PRISM

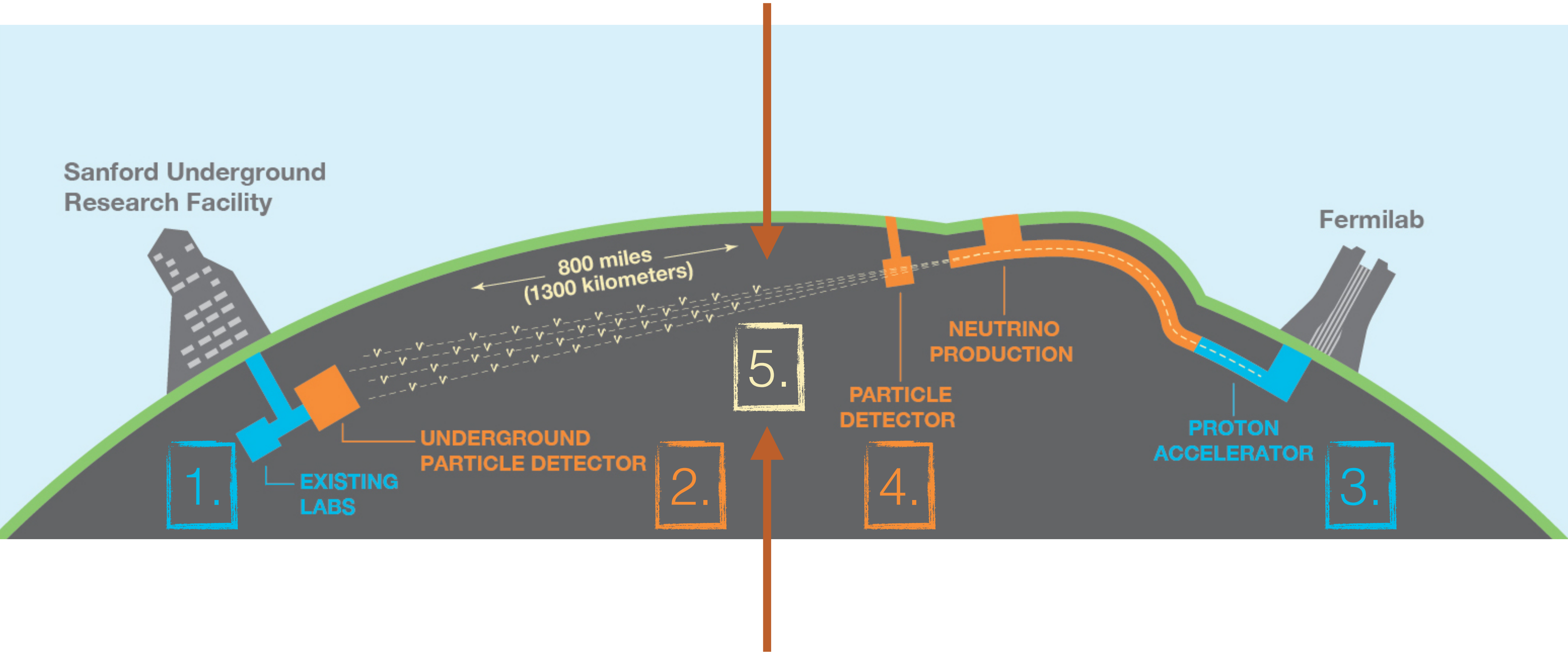
- ArgonCube and MPD are on rails
  - 3DST-S does not move to monitor beam stability
- Up to 30 m side movement
- Deconvolve flux and cross section
- Each position yields a new flux measurement





Outline of DUNE

The Physics



DUNE Physics Program

From MeV to GeV

- **Neutrino Oscillation Physics**
  - High sensitivity potential for leptonic CP violation
  - Identify the neutrino mass hierarchy
  - Precision oscillation physics and test of 3-flavor oscillations
- **Proton Decay**
  - Target SUSY-favored mode p —> K+ ν
- **SN burst physics and astrophysics**
  - Galactic core collapse supernova, unique sensitivity to νe
  - Design sensitivity to satellite galaxies
- **Atmospheric Neutrinos**
- **Neutrino Interaction Physics (Near Detector)**

E~O(few GeV)

E~O(10 MeV)

DUNE: testing the neutrino model

- **We currently have a model that has several parameters**
  - But the data that it explains is rather limited

- **What predictions from the model can we check?**
  - L/E (or just L, or just E) oscillation behaviour
  - Universality of the parameters (Δm^2, θ)
  - **CP violation if δ is non-zero**

- Neutrino oscillations give us a natural “interferometer”
  - **Anything that distinguishes flavours (or mass states) alters the pattern**

3-flavor neutrino survival probability

$$
\begin{aligned}
P\left(\nu_e \rightarrow \nu_e\right) = {} & 4 C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \Delta_{31} \\
& + 8 C_{13}^2 S_{12} S_{13} S_{23}\left(C_{12} C_{13} \cos \delta - S_{12} S_{13} S_{23}\right) \cos \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} \\
& \boxed{- 8 C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin \delta \sin \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21}} \\
& + 4 S_{12}^2 C_{13}^2\left(C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2 C_{12} C_{23} S_{12} S_{23} S_{13} \cos \delta\right) \sin^2 \Delta_{21} \\
& \boxed{- 8 C_{13}^2 S_{13}^2 S_{23}^2\left(1 - 2 S_{13}^2\right) \frac{a L}{4 E_\nu} \cos \Delta_{32} \sin \Delta_{31}}
\end{aligned}
$$

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4 E_\nu}$$

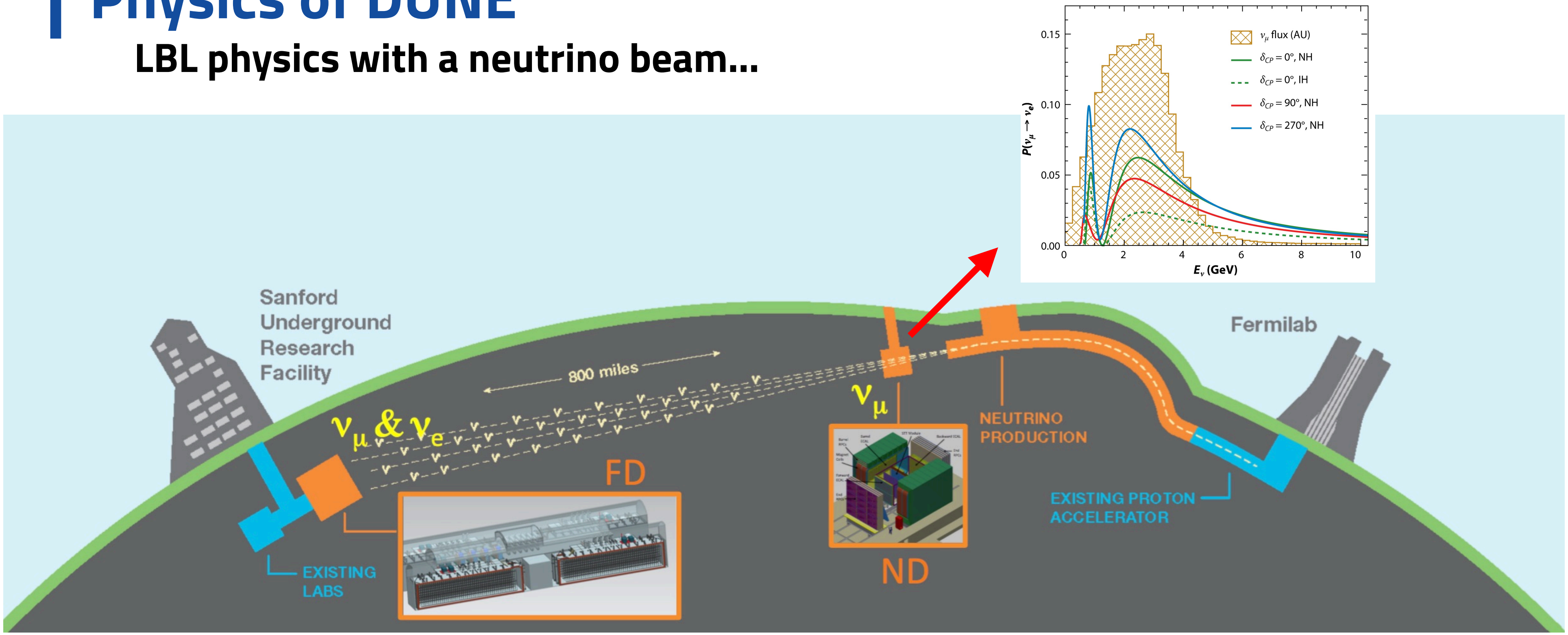
CP violating term tells us if $P\left(\nu_\mu \rightarrow \nu_e\right) \neq P\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\right)$

Matter term depends on sign of $m_3^2 - m_1^2$

DUNE is designed with both of these terms in mind

Physics of DUNE

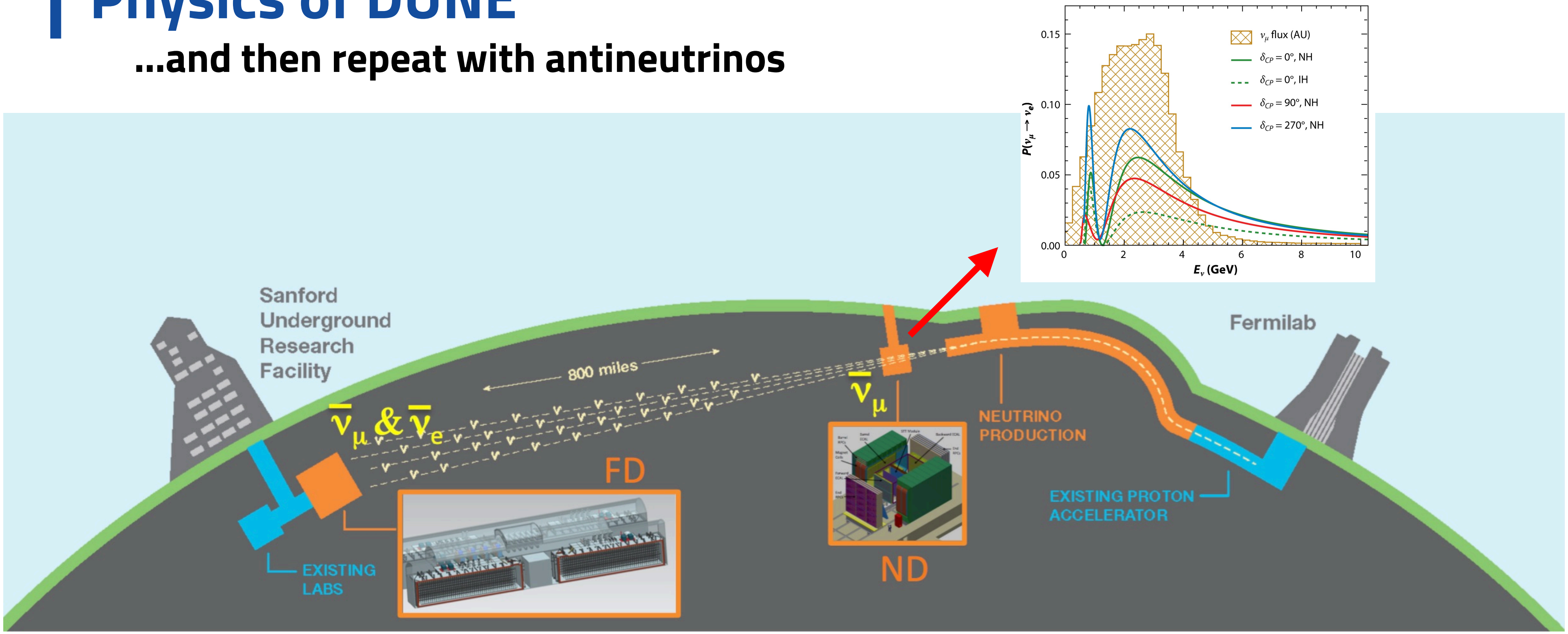
LBL physics with a neutrino beam…



- Measure **neutrino** spectra at 1300 km in a **wide band beam**
  - Near detector at FNAL : Measurement of ν_μ unoscillated beam
  - Far detector at SURF : Measure oscillated ν_μ and ν_e
  - Probe of neutrino oscillations (with matter effects) and mass hierarchy

Physics of DUNE

...and then repeat with antineutrinos



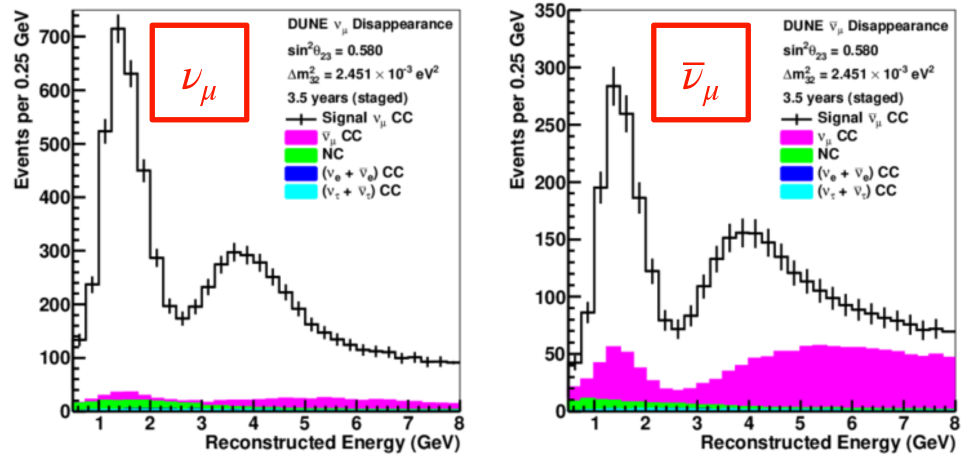
- Measure **antineutrino** spectra at 1300 km in a **wide band beam**
  - Compare oscillations of neutrinos and antineutrinos
  - **Direct probe** of CP violation in the neutrino sector

Physics of DUNE

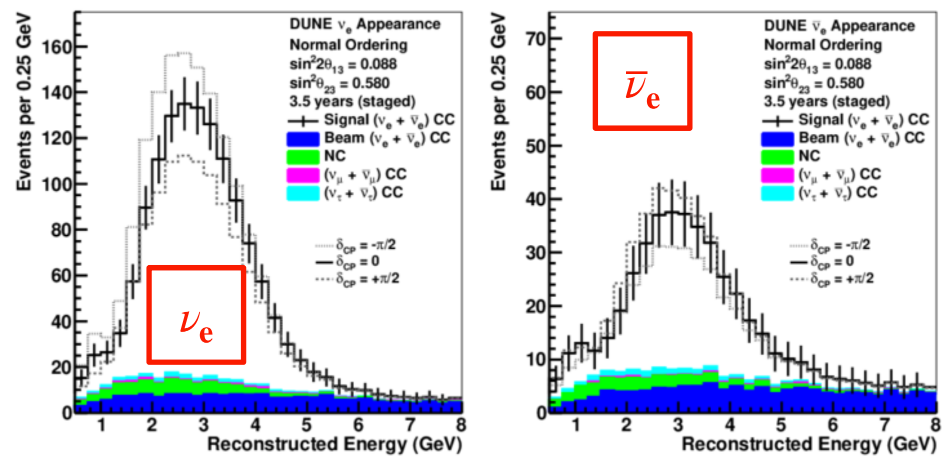
Oscillation analysis strategy

- Determine MH, δ_{CP} , θ_{23} octant, test 3-flavour paradigm and search for BSM effects (eg. NSI) **in a single experiment**
- Long baseline: matter effects are large (~40%)
- **Wide-band beam:**
  - ν_μ disappearance and ν_e appearance over range of energies
- MH and δ_{CP} effects are **separable**

(anti-)ν_μ disappearance

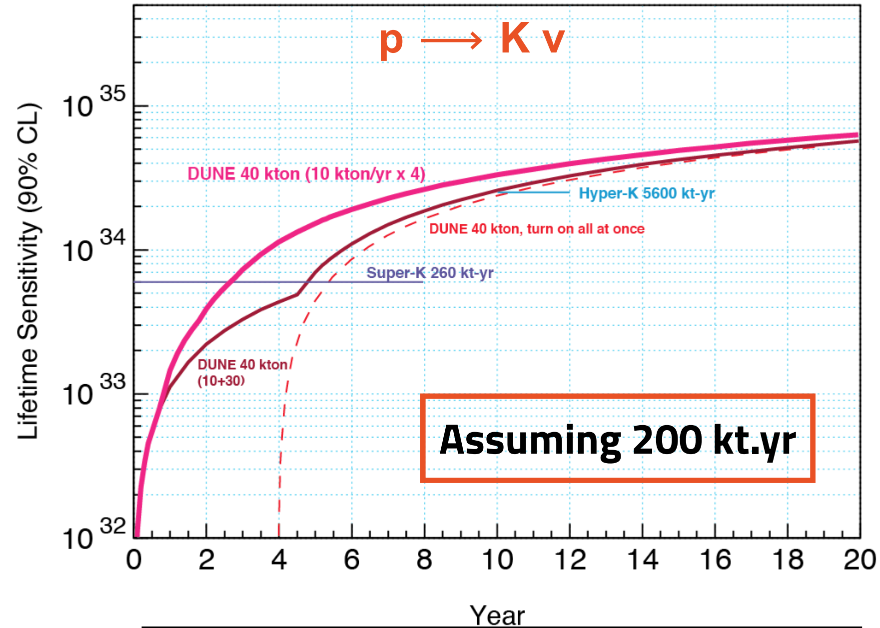


(anti-)ν_e appearance



Physics of DUNE
Nucleon Decay

- **LAr detectors are sensitive to additional decay modes**
  - proton decay modes
  - neutron decay modes
  - n-nbar oscillation modes (limited sensitivity)
- Explore tracking and calorimetry for reconstruction of final state decay products
  - low thresholds (no Cherenkov), PID
- Phenomenology is rich in the subject
  - Many modes identified (~90)
- Backgrounds estimated from atmospheric neutrino samples and using side bands
- Neutrino cross section measurements (from ND) constrain uncertainties in modes with π in the final state
- **LAr imaging and kinematics allow ~linear sensitivity improvement with exposure**

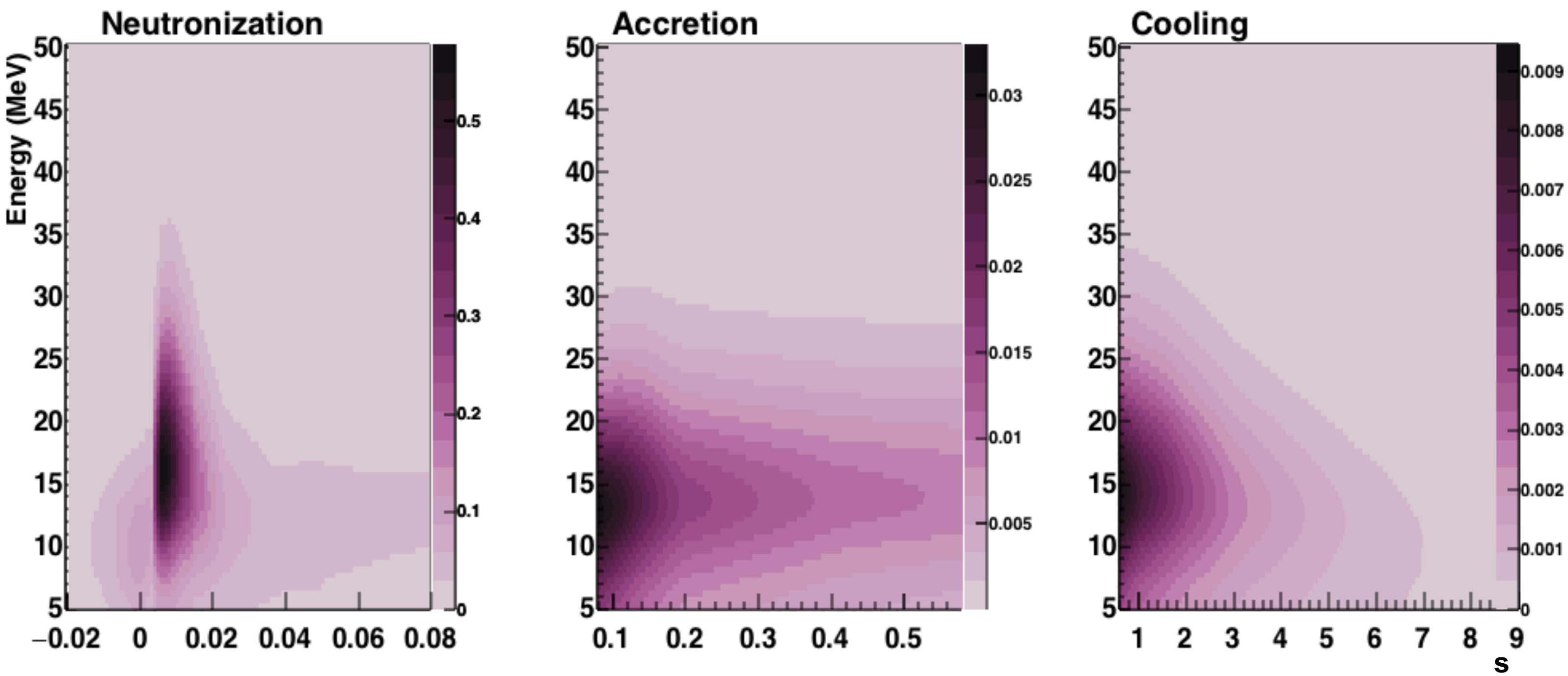


Mode	Lifetime (90%C.L.)
$p \to \nu K^+$	**>3×10^{34} yrs**
$p \to e^+\gamma$, $p \to \mu^+\gamma$	**>3×10^{34} yrs**
$p \to \mu^-\pi^+K^+$	**>3×10^{34} yrs**
$n \to e^-K^+$	**>3×10^{34} yrs**
$p \to \mu^+K^0$, $p \to e^+K^0$	>1×10^{34} yrs
$p \to e^+\pi^0$	>1×10^{34} yrs
$p \to \mu^+\pi^0$	>0.8×10^{34} yrs
$n \to e^+\pi^-$	>0.8×10^{34} yrs

Physics of DUNE

Supernova Neutrinos

- LAr detectors are mainly sensitive to νe through CC in ^{40}Ar
    - Other detectors are mostly sensitive to anti-ν_e through IBD
- Sensitivity to mass hierarchy
- **Possibility to see peak of neutronization**
    - Burst of electron neutrinos produced by core neutronization burst



Events per 0.5 MeV per ms, 40 kton @10 kpc

Physics of DUNE

Supernova Neutrinos

- LAr detectors are mainly sensitive to νe through CC in ^{40}Ar
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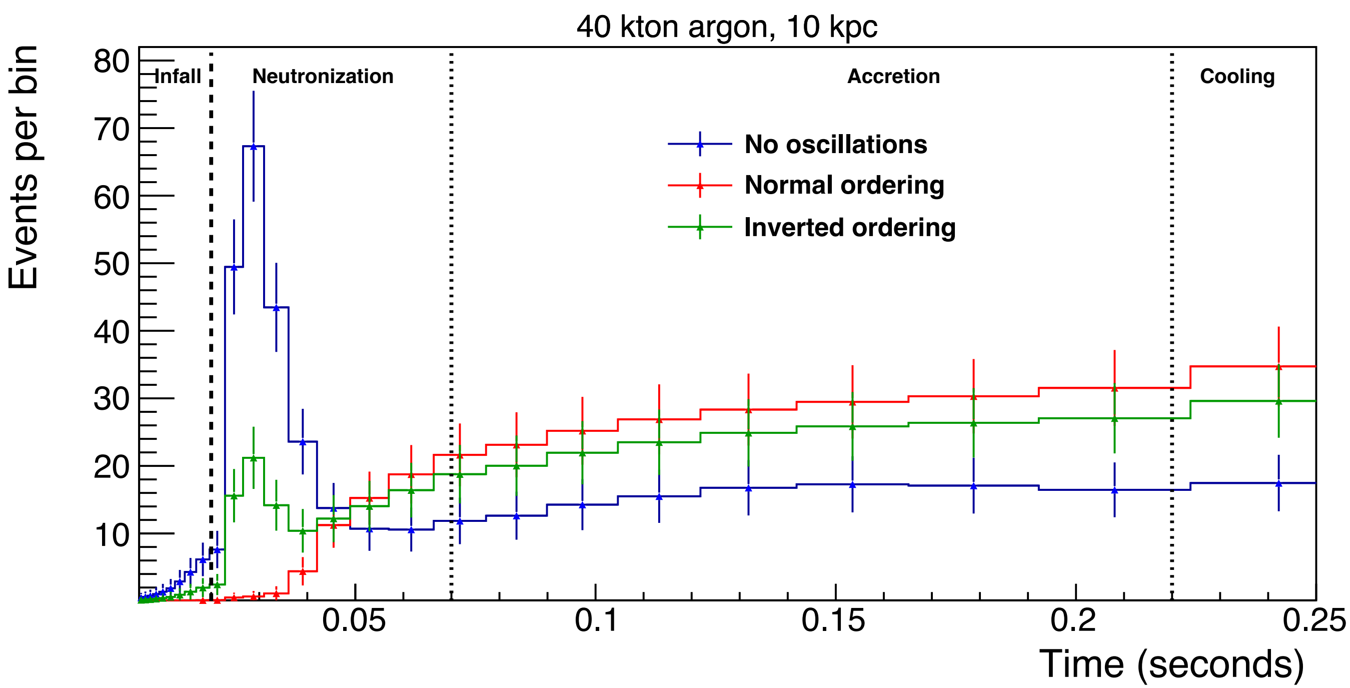


Physics of DUNE

Low Energy Neutrinos

- Elastic Scattering (ES) on electrons
  - Both neutrinos and antineutrinos

$$\boxed{\nu + e^- \rightarrow \nu + e^-}$$

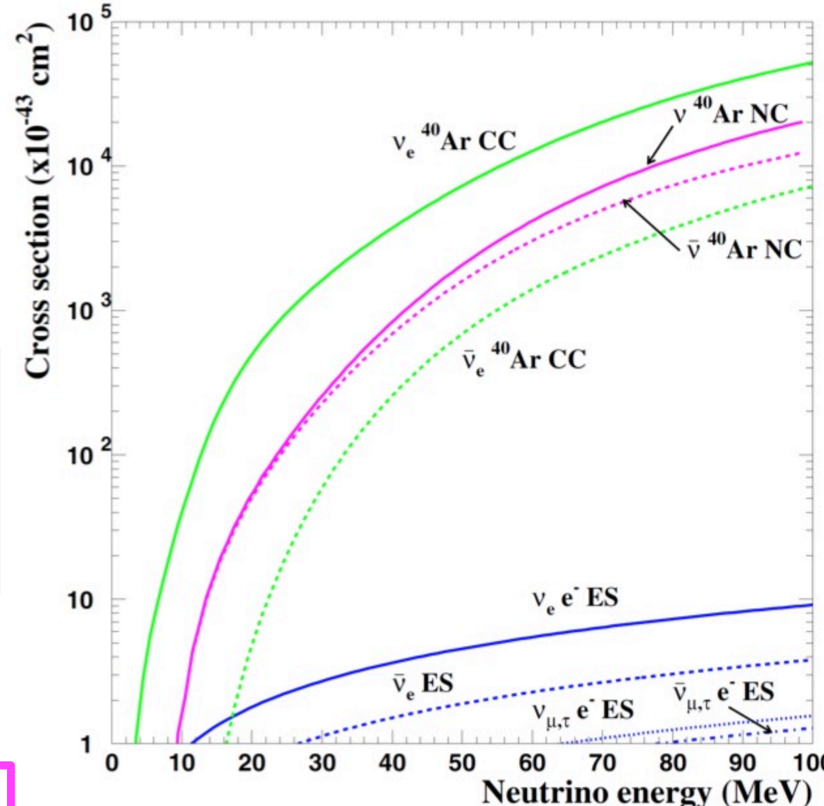
- Charged Current (CC) on Ar

$$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^- \qquad \left(E_{\nu_e} > 1.5\ MeV\right)$$

$$\bar{\nu}_e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+ \qquad \left(E_{\nu_e} > 7.48\ MeV\right)$$

- Neutral Current (NC) interactions on Ar

$$\nu + {}^{40}Ar \rightarrow {}^{40}Ar^* + \nu \qquad \left(E_{\nu} > 7.48\ MeV\right)$$

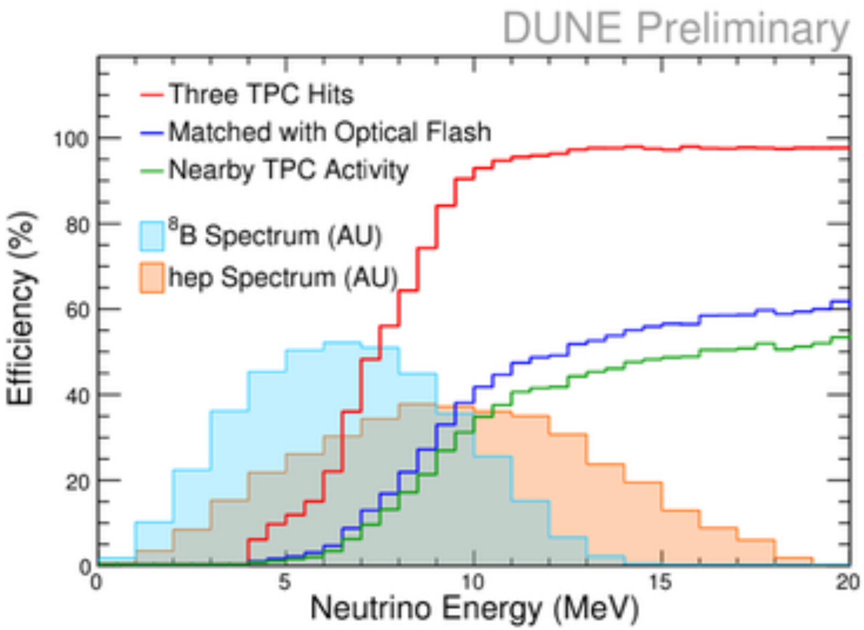


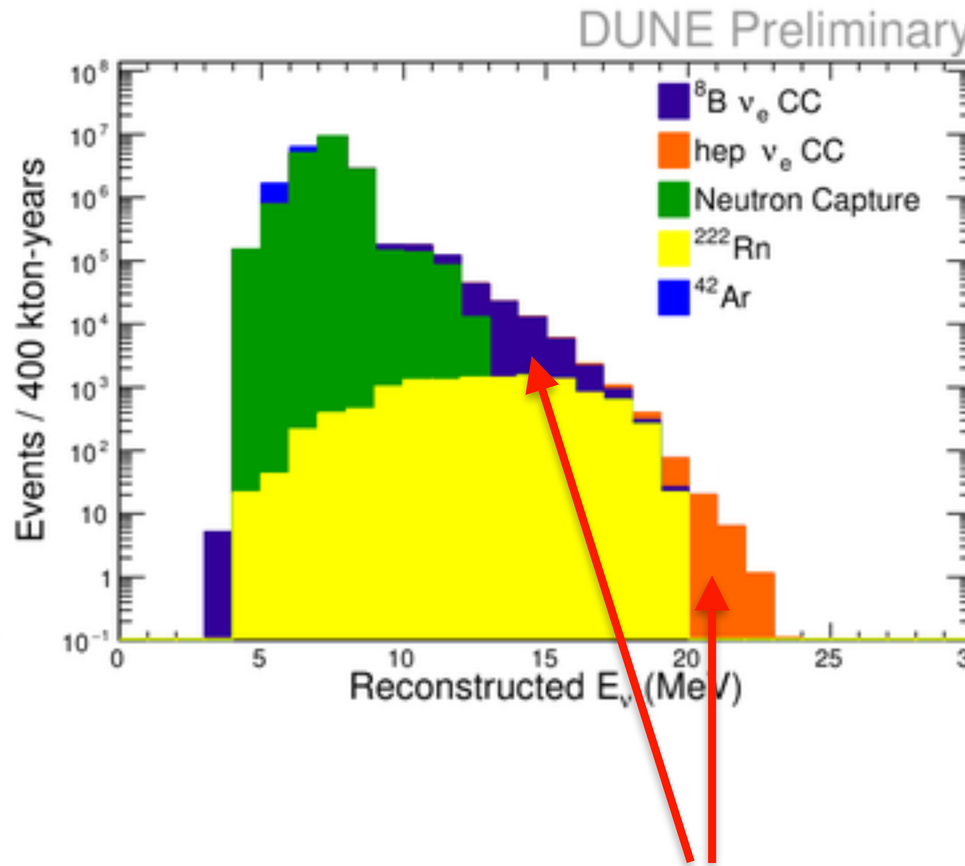
Possibility to separate the different channels by the classification of the associated photons from the K, Ar and CL de-excitation lines — specific spectral lines for CC and NC

Physics of DUNE

Solar Neutrinos: The hunt for the last flux

- Possibility to see the one missing neutrino flux (HeP solar ν)





Clear separation between ^{8}B and HeP above 19 MeV

ProtoDUNE

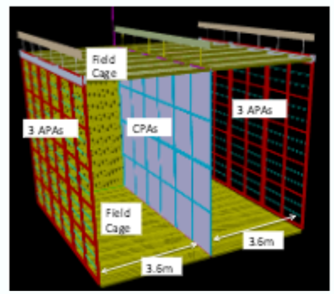
Proving and optimising the technology of DUNE

Detector development and prototyping

Why prototyping?

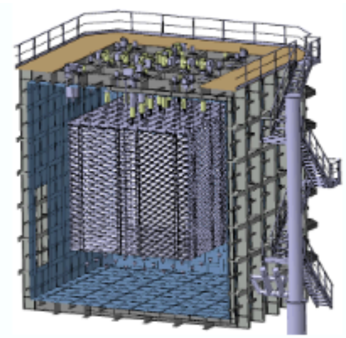
- Mitigation of risks associated with current detector designs
- Establishment of construction facilities required for full-scale production of detector components
- Early detection of potential issues with construction methods and detector performance
- **Provides required calibration of detector response to particle interactions in test beam**

35ton @ FNAL



ProtoDUNEs @ CERN

WA105 @ CERN



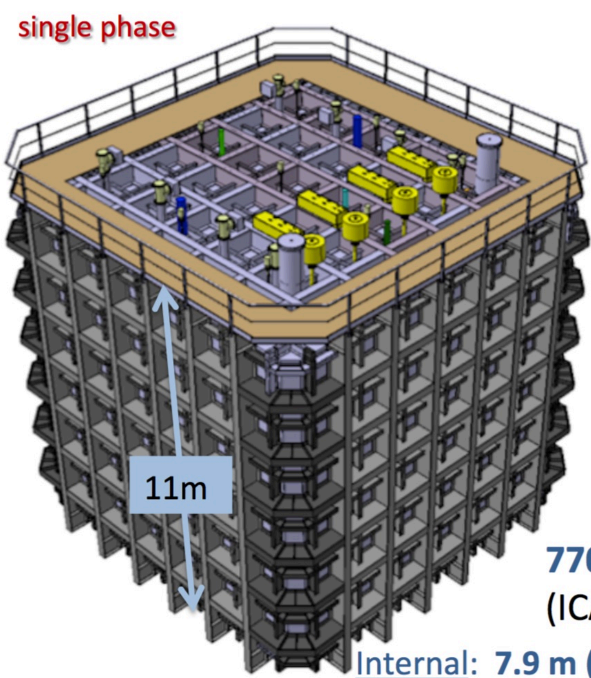
Large scale prototypes at CERN

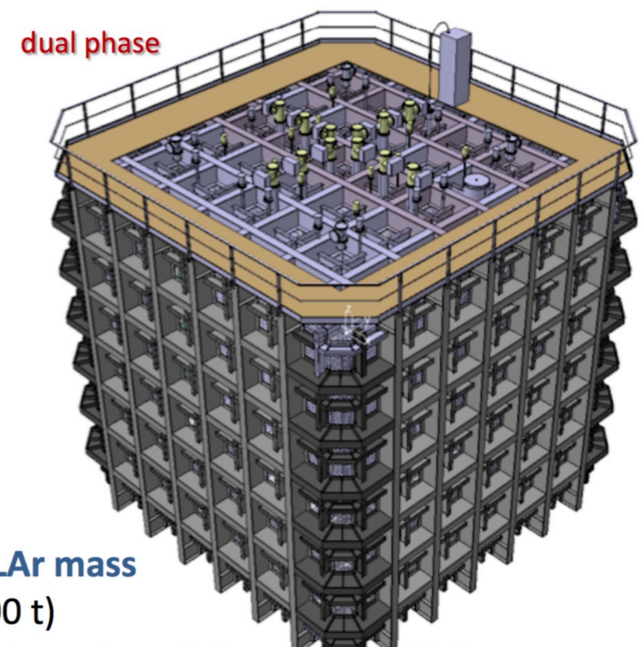
ProtoDUNE(s)

- Use nearly identical cryostats for single and dual phase protoDUNE
  - Serve as prototype for the 10 kt cryostats
  - First run completed in 2019
  - Second (last) run planned for 2022

Sandbox to test all components of the DUNE far detectors

- **Don't have a neutrino beam. Instead have a beam of particles that are the final states of neutrino interactions**





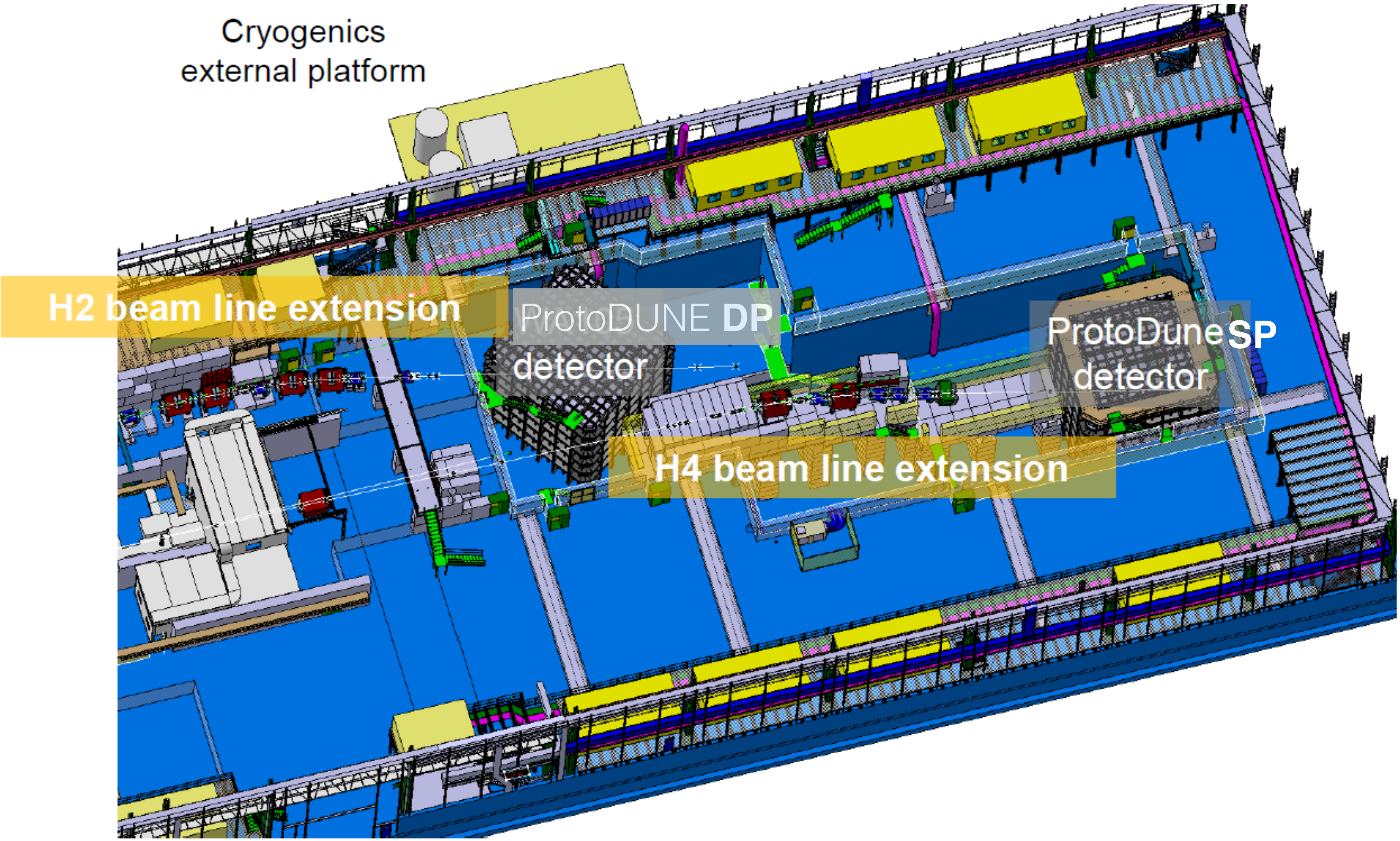
770 t total LAr mass

(ICARUS: 600 t)

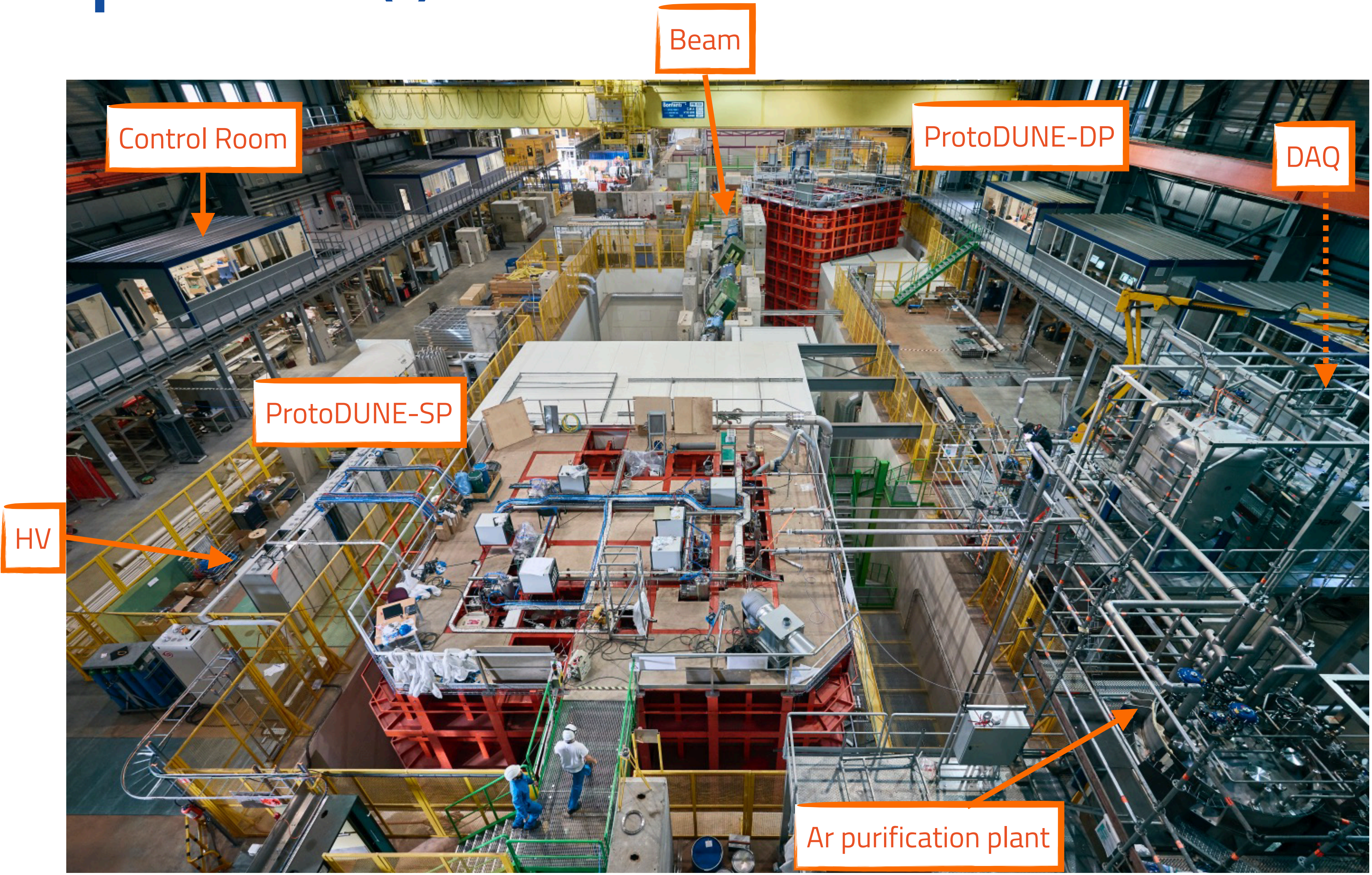
Internal: **7.9 m (Transv) x 8.5 m (Parallel) x 8.1 m (Height)**

External: **10.8m (Transv) x 11.4 m (Parallel) x 11.0 m (Height).**

ProtoDUNE(s) at CERN

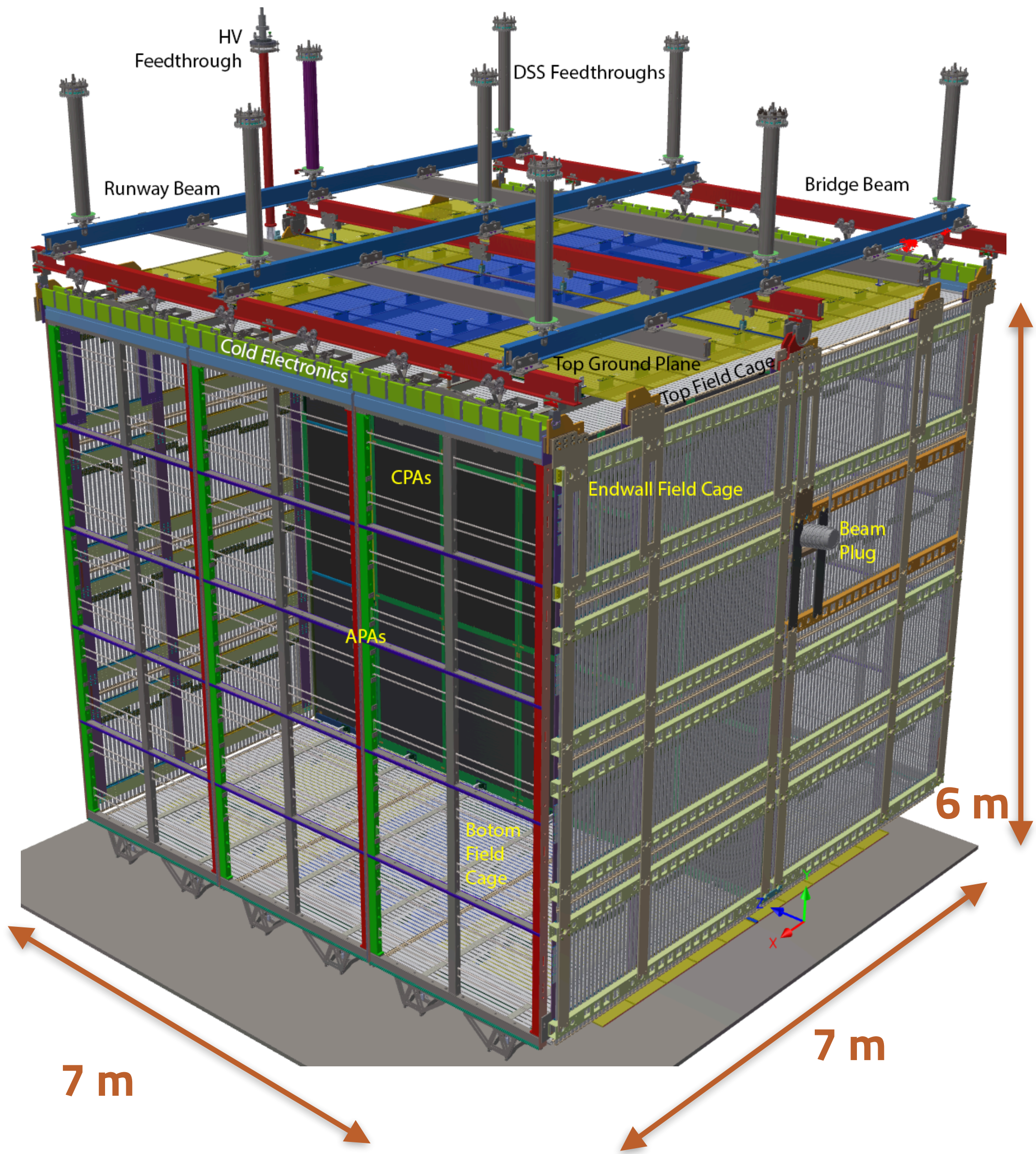


ProtoDUNE(s) at CERN



ProtoDUNE-SP (single phase)

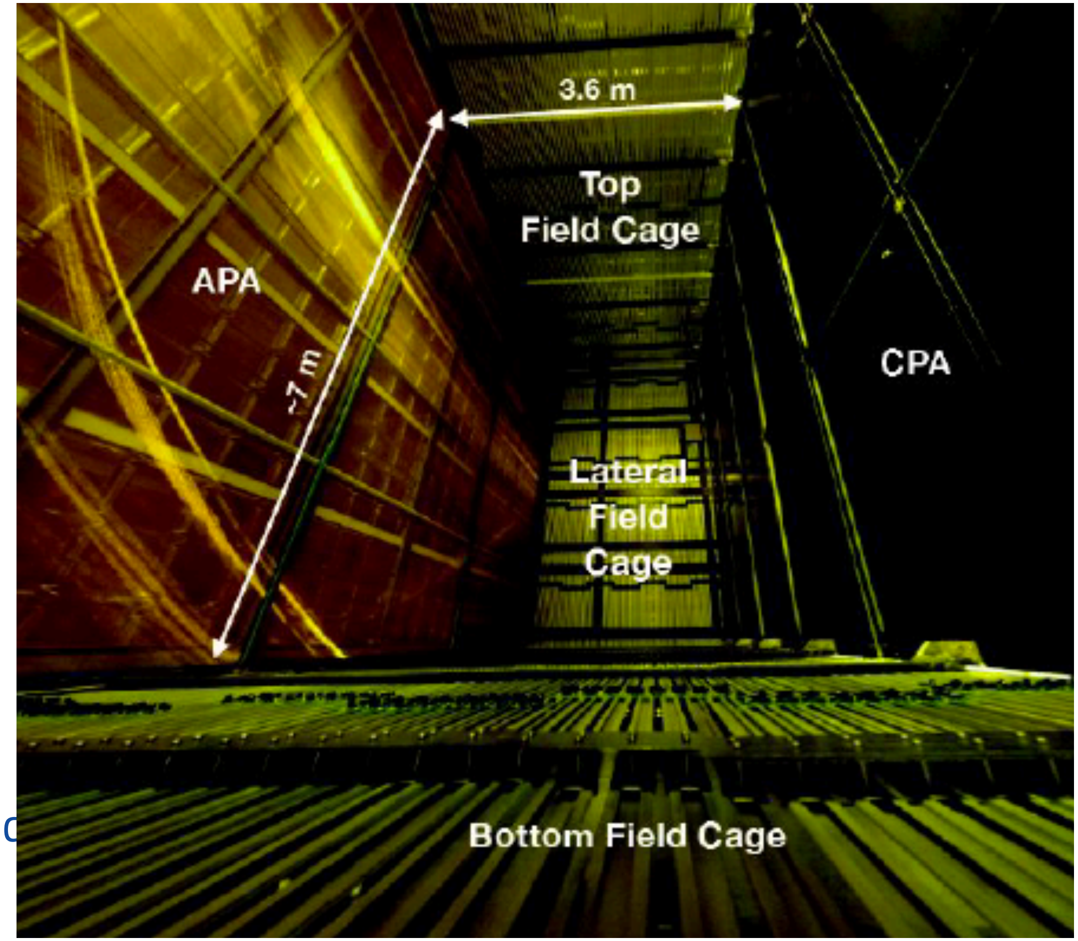
- Full scale prototype
  - Same voltage, drift distance as DUNE SP
- Both engineering and physics test
  - Test of design, installation, operation and stability
  - **Use SPS beam to generate final states of neutrino interactions**
    - **p, π, e^-, K** (for nucleon decay studies)
    - Mimic neutrino interactions in DUNE
- Measure particle response in LAr



ProtoDUNE Single Phase

Results from run I

- First beam physics run from Sep - Nov 2018
- ~4x10^6 triggers from pions, protons, kaons, electrons ranging from 0.3 - 7 GeV
- Stable running at 180 kV, ~8 ms electron lifetime, ~600 ENC
  - S/R of 38.3 before filtering
  - S/R of 40.3 after filtering
- Large sample of cosmic stopping muons used for energy calibration



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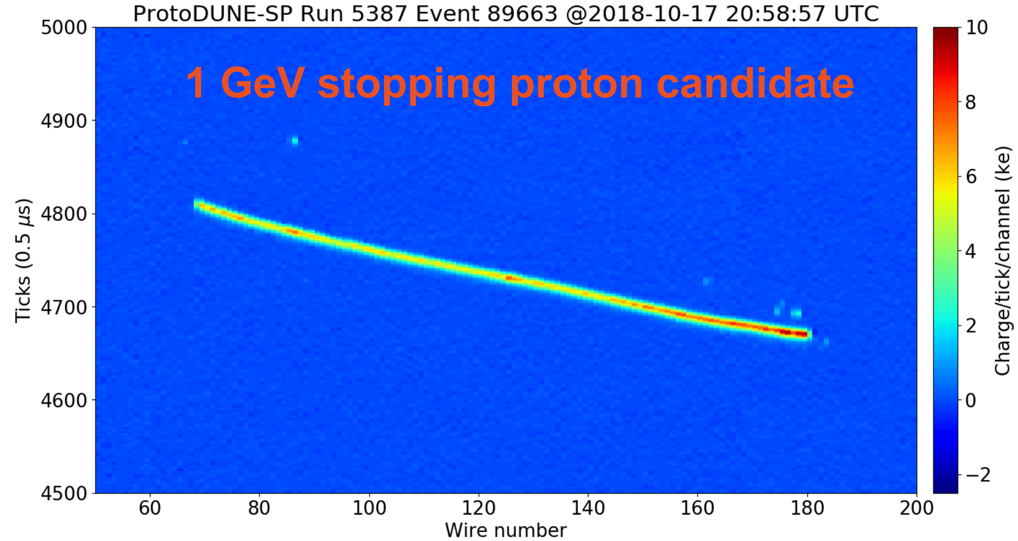
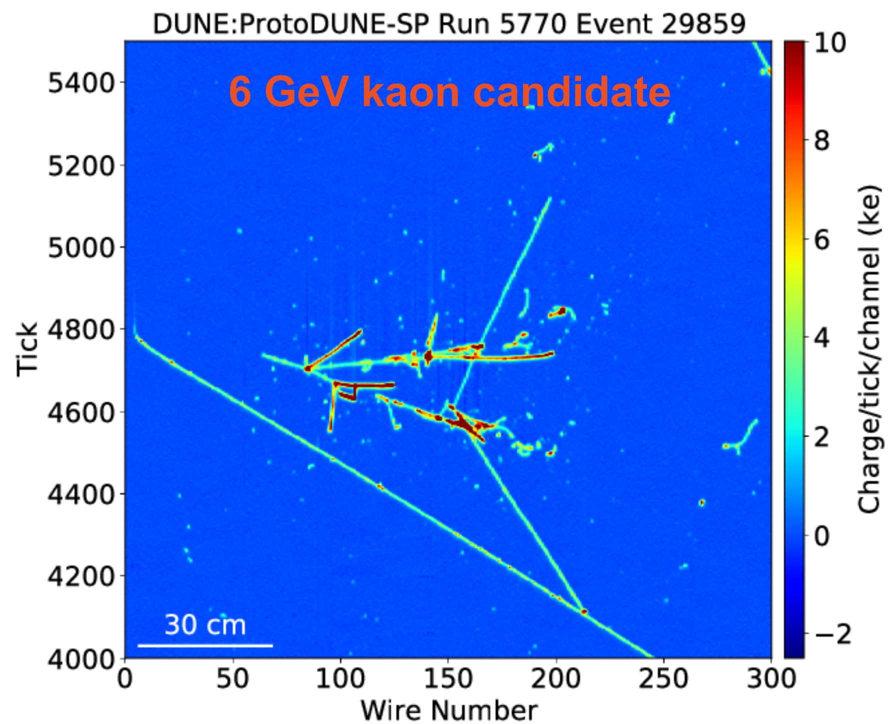




ProtoDUNE Single Phase

Summary of Run I

- 500+ days of data taking showed ProtoDUNE-SP has achieved high liquid argon purity (above 10 ms)
  - DUNE requirement: 3 ms
- Stable operation of HV system at nominal electric field (500 V/cm)
- Long term stability of the cold electronics over ~1 year period
  - S/N stable around ~40 over 1 year

- Opportunity to do extra tests for future technologies
  - Xe-Doped scintillator
  - Neutron generator for calibrations

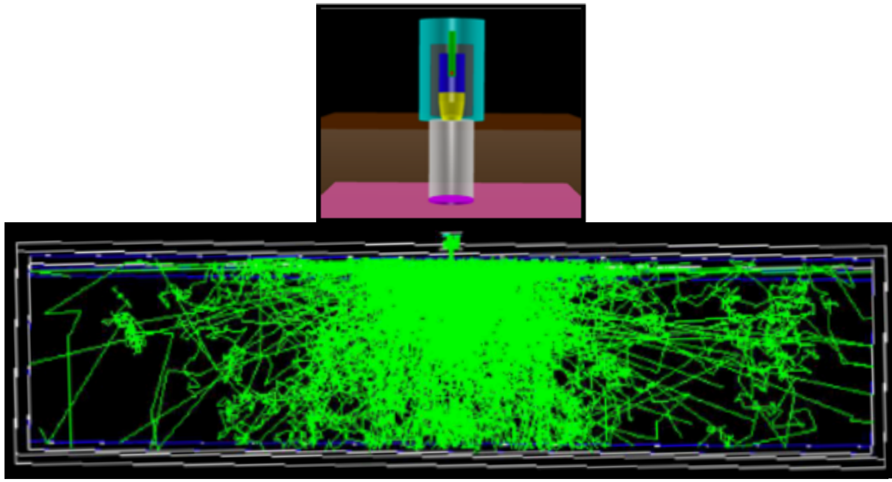
- **Currently work is being prepared for a second run in late 2021**
  - **Test of DUNE DAQ design (online software trigger)**
  - **Latest APA and photon detector (ARAPUCA) designs**
  - **Test calibration systems to be deployed in DUNE**
    - **Major LIP involvement**

LIP and DUNE

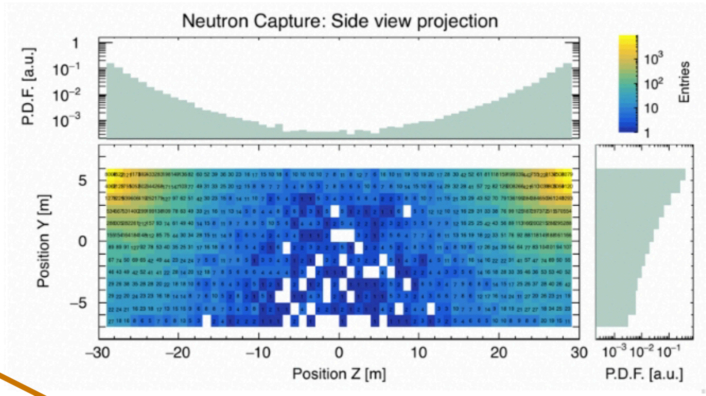
What we do

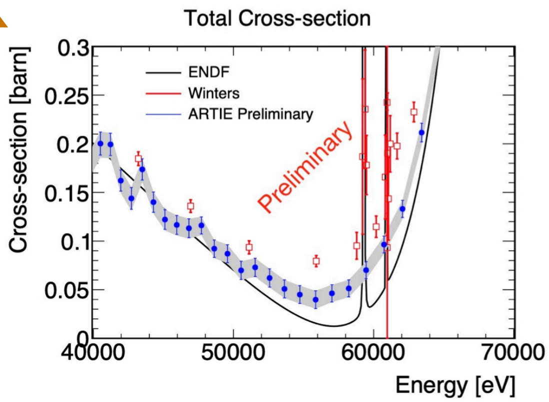
DUNE Activities at LIP

Ongoing and planned

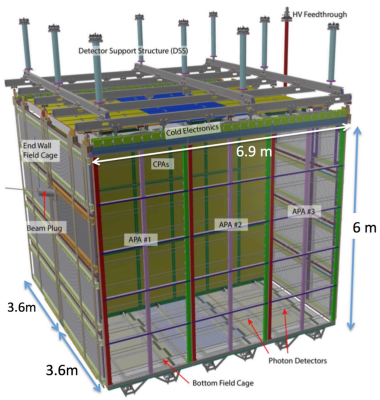


- **Detector Calibration (DUNE and ProtoDUNE)**
  - **LIP has leadership of the Calibration Consortium**
  - **Ionisation laser system**
    - Charge and optical collection calibration using a high powered laser
  - **Pulsed Neutron Source**
    - Calibration with neutron captures in Ar
  - **Search for neutron antiressonance in Argon (ARTIE)**

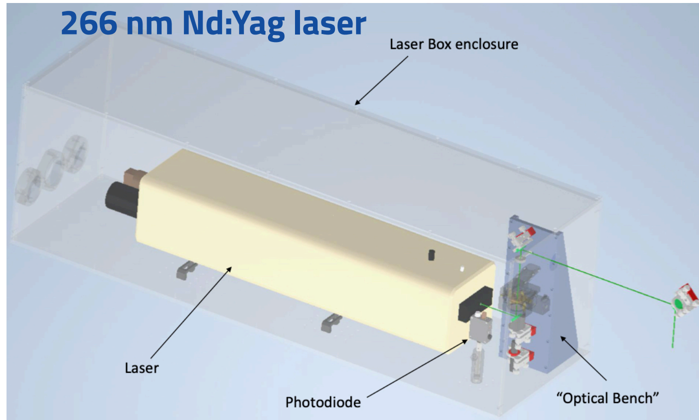


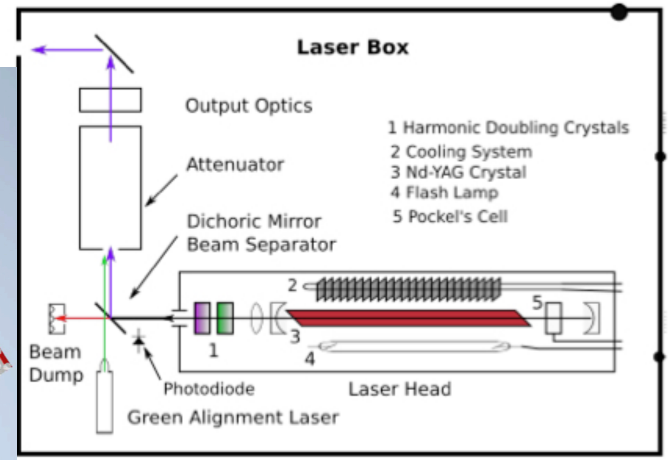


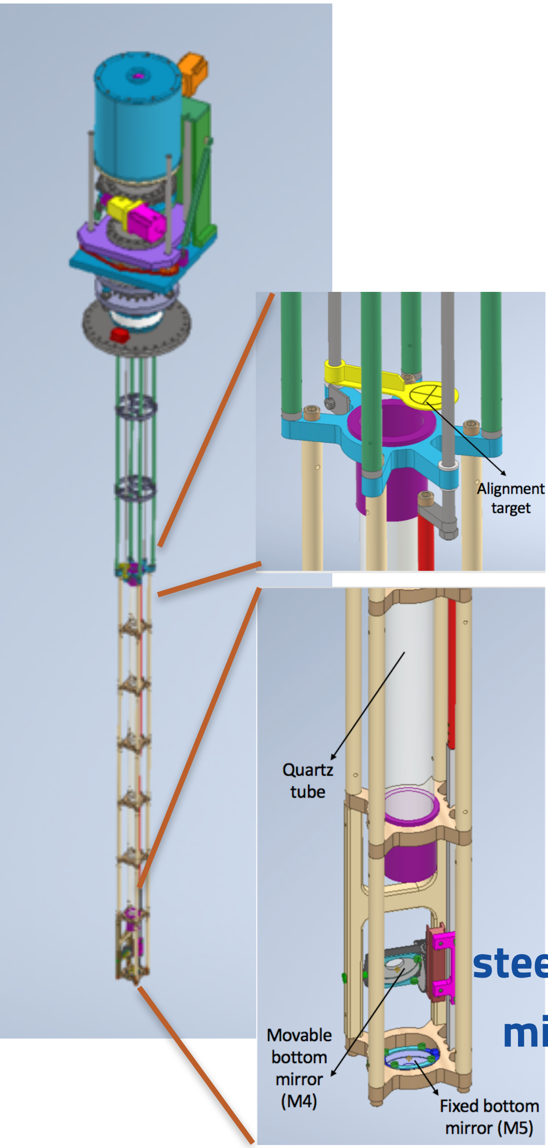
- **ProtoDUNE**
  - Trigger/DAQ
  - Electron Lifetime Measurements
  - Data analysis



Ionisation laser

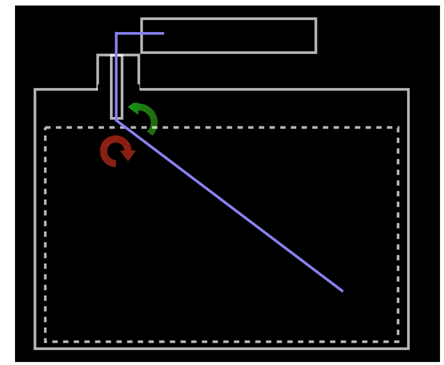






steerable mirror

- Mirror movement with 2 degrees of freedom
  - Controlled by stepper motors and encoders
  - MicroBOONE precision: 0.05 mrad. Overall 2mm@10 m
- Laser intensity controlled by attenuator



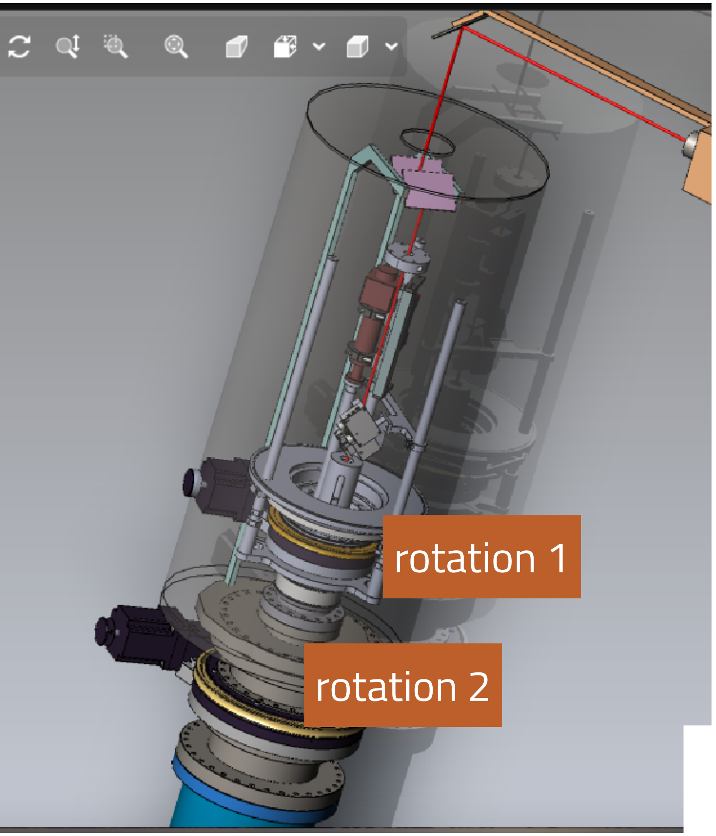
Major goals:

- Map electric field distortions in drift volume to < 1%
- Measure electron lifetime in whole drift volume

Laser Calibration

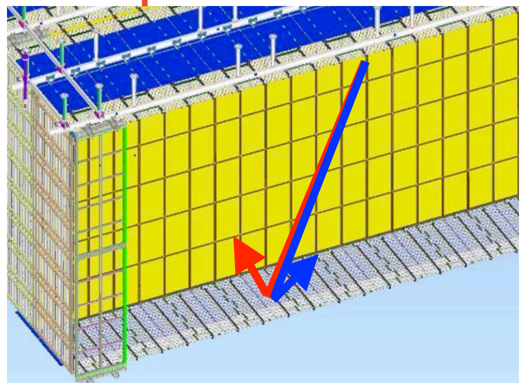
Major involvement of LIP (Lisbon, Coimbra and Mechanical Workshop)

Alternative laser periscope

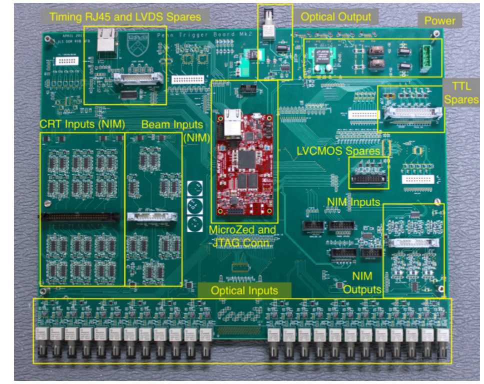


Dual rotary system adds a degree of freedom and solves low coverage due to FC shadows.

Laser position calibration



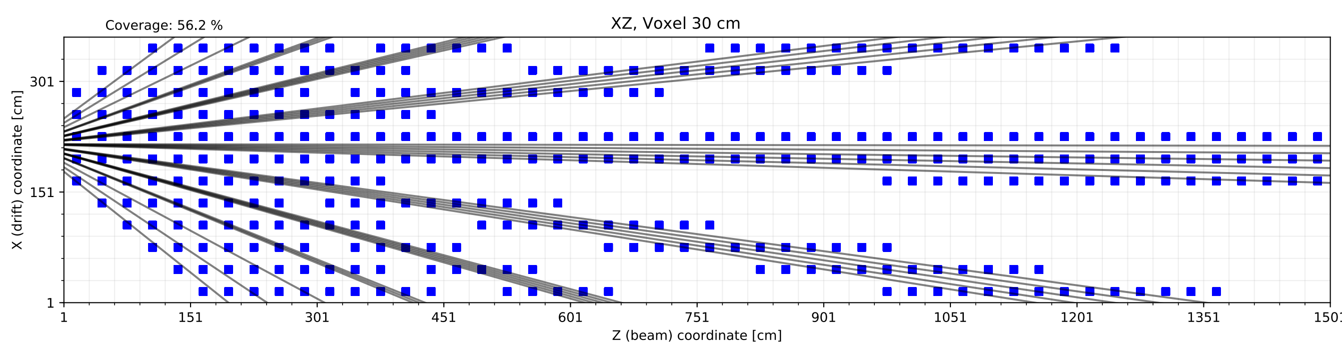
Cal/DAQ interface



Calibration/Analysis Software

- DAQ data reduction
- Run control interface
- Data Quality
- Simulation and Analysis

Collaboration with LANL for production of parts



Expected timeline for DUNE and ProtoDUNE

- ~~Late 2021~~: 2022: ProtoDUNE-SP run II
  - **Laser and neutron calibrations**, new DAQ, new instrumentation
- 2024 : Installation of first DUNE module (SP)
- 2025 : Start installing second module
  - **DUNE physics data starts with atmospheric neutrinos**
- 2026: Beam operational at 1.2 MW
  - **Start of DUNE physics data taking with beam**
  - Total fiducial mass of 20 kt
- 2027: Add third FD module
- 2029: Add fourth FD module
- 2032: Upgrade to 2.4 MW beam

Summary

- DUNE will use a broadband beam and long baseline (1300 km) to make **precise, simultaneous measurements of the mass ordering, the CP-violation phase, and the neutrino mixing angles**.

- The large mass, high granularity, and deep underground location of the DUNE far detector also provide good sensitivity to **supernova burst neutrinos and baryon non-conservation.**

- First run with prototypes completed; now preparing for **second run to happen next year**

- LIP very actively involved in detector calibrations
  - both for DUNE and ProtoDUNE
  - Coordination of Calibration Consortium

- We look forward to start operation of first far detector module in 2024, and first data with beam, near detector, and first two far detector modules in 2026!


Thank you!