DUNE and ProtoDUNE

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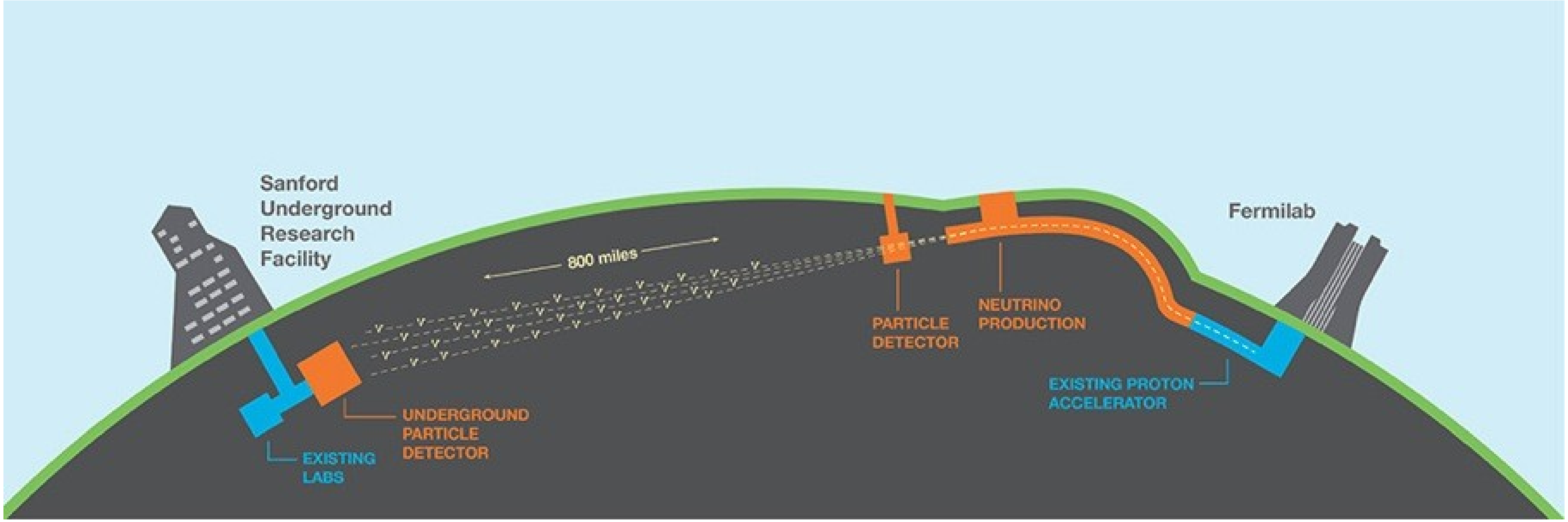
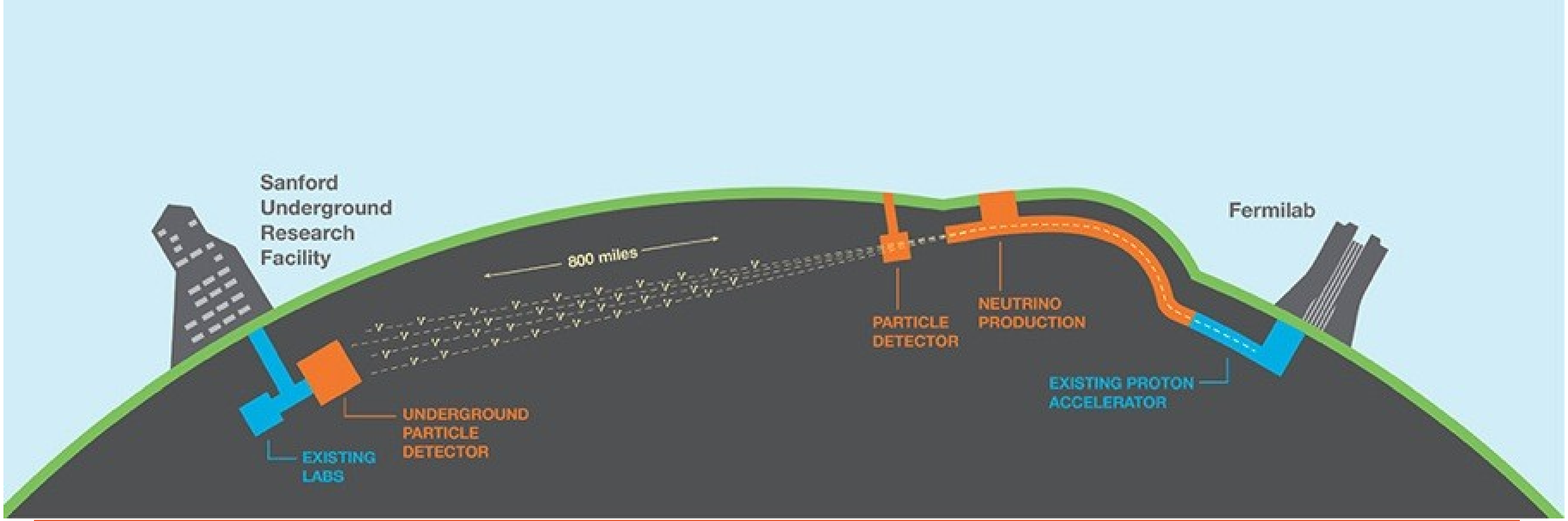
10th Terascale Detector Workshop 2017, Hamburg

13/04/2017



Outline

- The physics of DUNE
- Detecting neutrinos with LArTPCs
- Building large scale LArTPCs – protoDUNE at CERN.

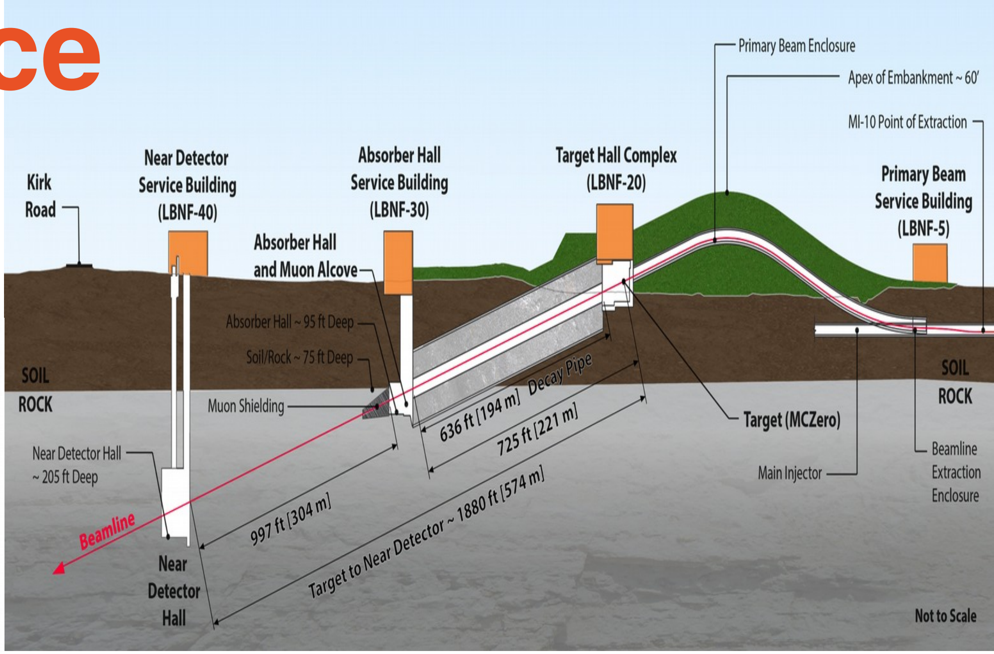


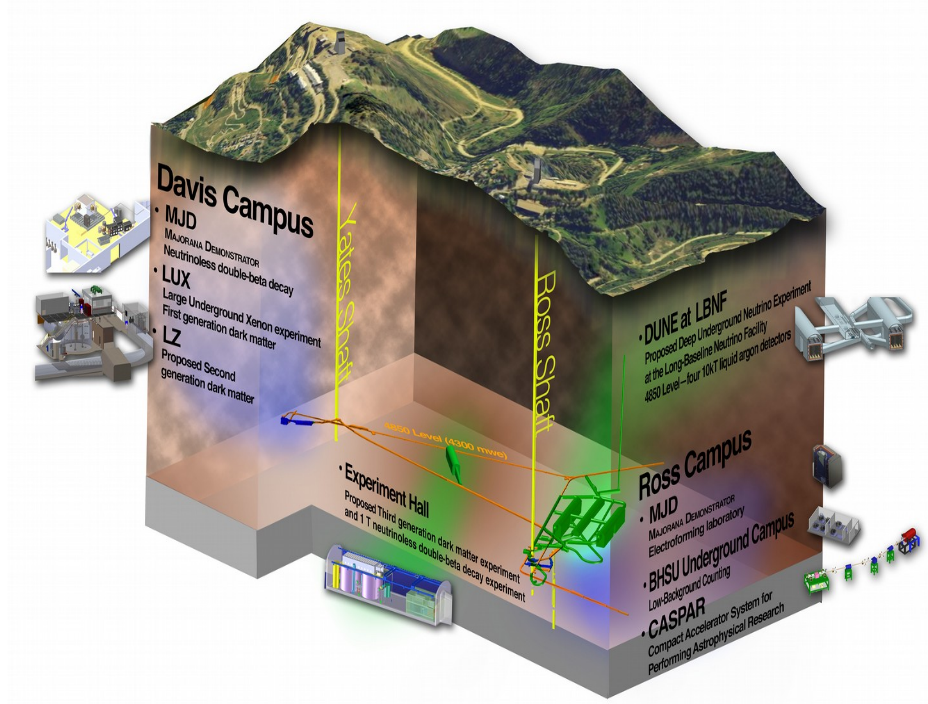
DUNE collaboration

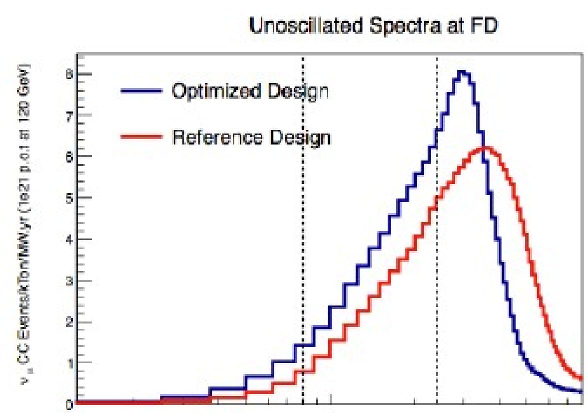
>900 collaborators from 30 countries

CERN Collaboration Meeting, January 2017

DUNE at a glance







Neutrino energy (GeV)

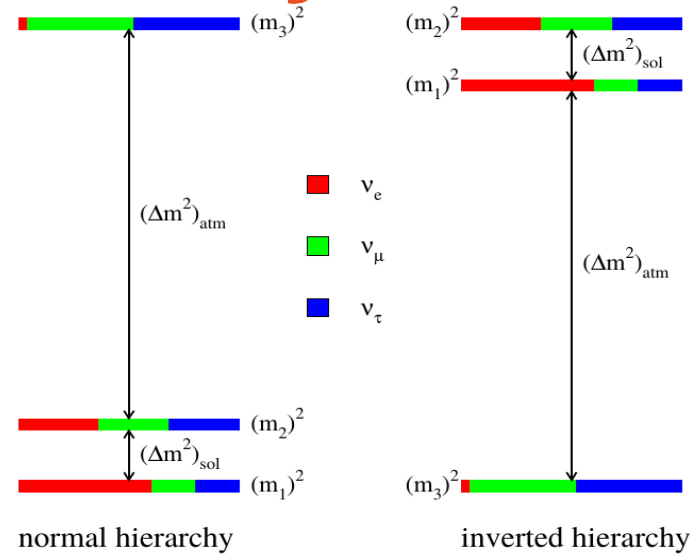
Neutrino beam with power up to 2 MW from Fermilab to SURF, Lead in South Dakota.

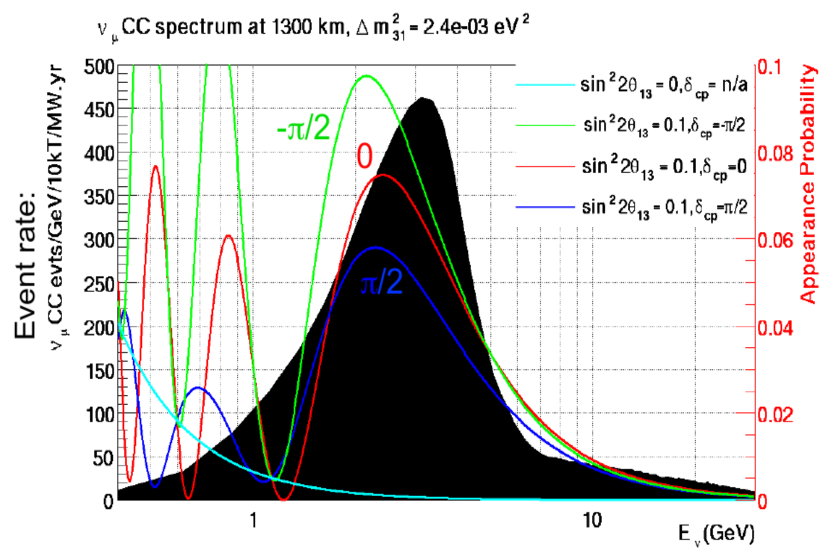
DUNE physics programme: Big Questions in Neutrino Physics

- Oscillation Physics:
  - Mass Hierarchy
  - CP Violation in the lepton sector
  - Precise tests of the 3 neutrino paradigm
- Nucleon Decay
  - New detector technology offers sensitivity to less explored decay channels
- SuperNova burst neutrinos & Astrophysics
  - Sensitivity to neutrinos offers complementarity with other detector technologies
- Precision neutrino interaction physics (Near Detector)

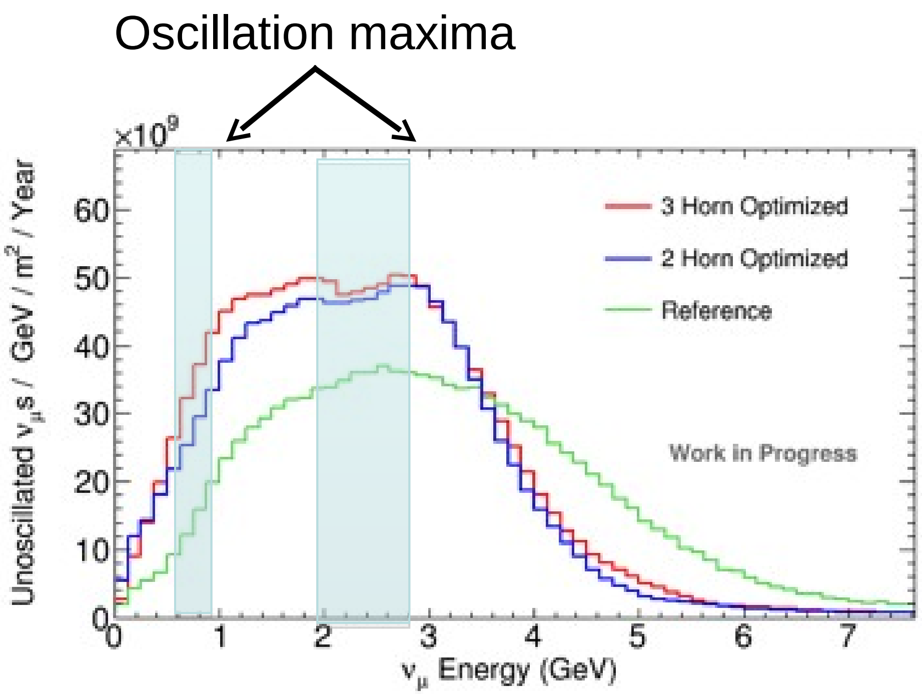
Neutrino Oscillation Physics

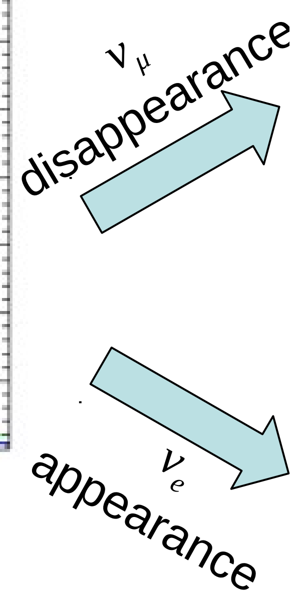
- Measure Neutrino Spectra at 1300 km with a wide-band beam
- DUNE will be able to determine MH and θ_{23} octant, probe CPV, test 3-flavor paradigm.
- Looking for $\nu_e(\bar{\nu}_e)$ appearance in a ν_μ $(\bar{\nu}_\mu)$beam
- Rates affected by δ_{CP} and mass hierarchy

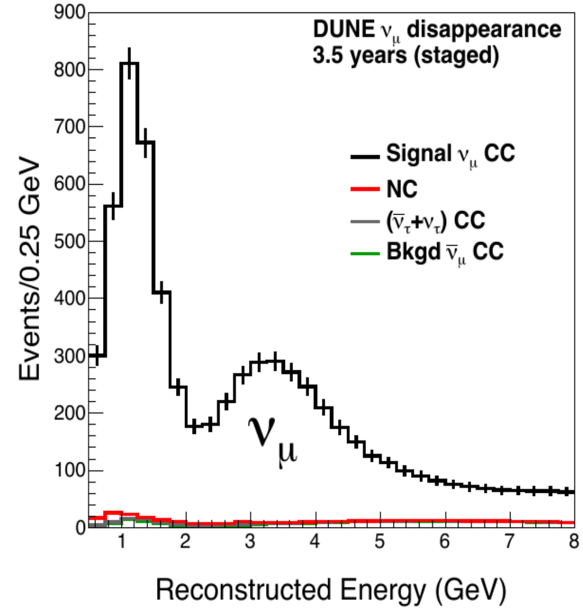


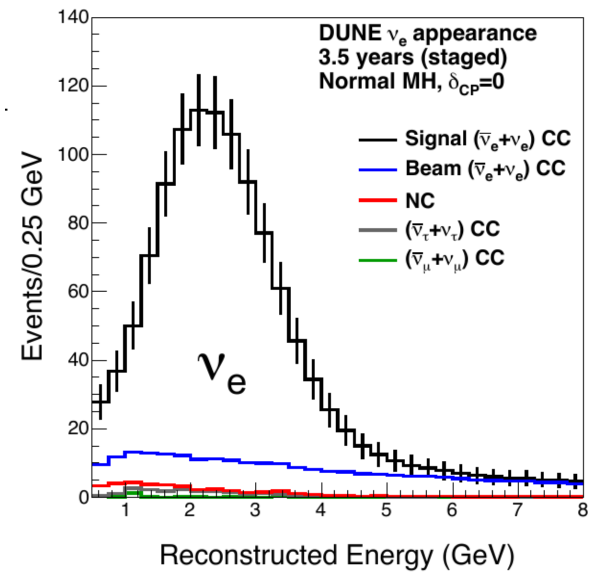


ν_μ beam



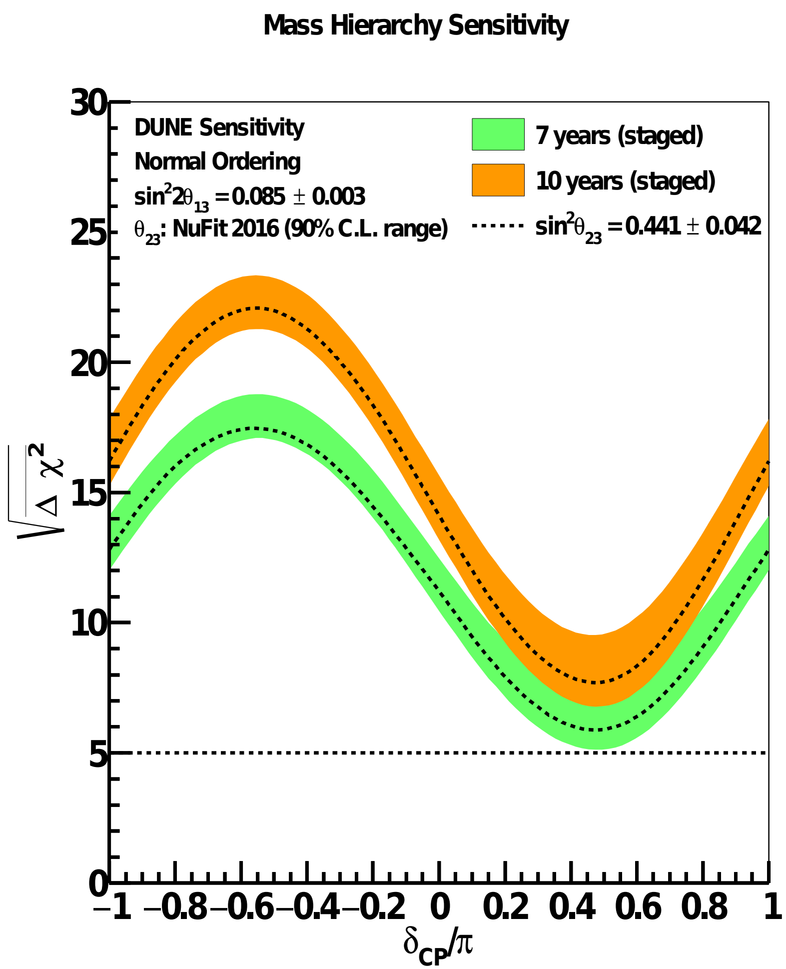


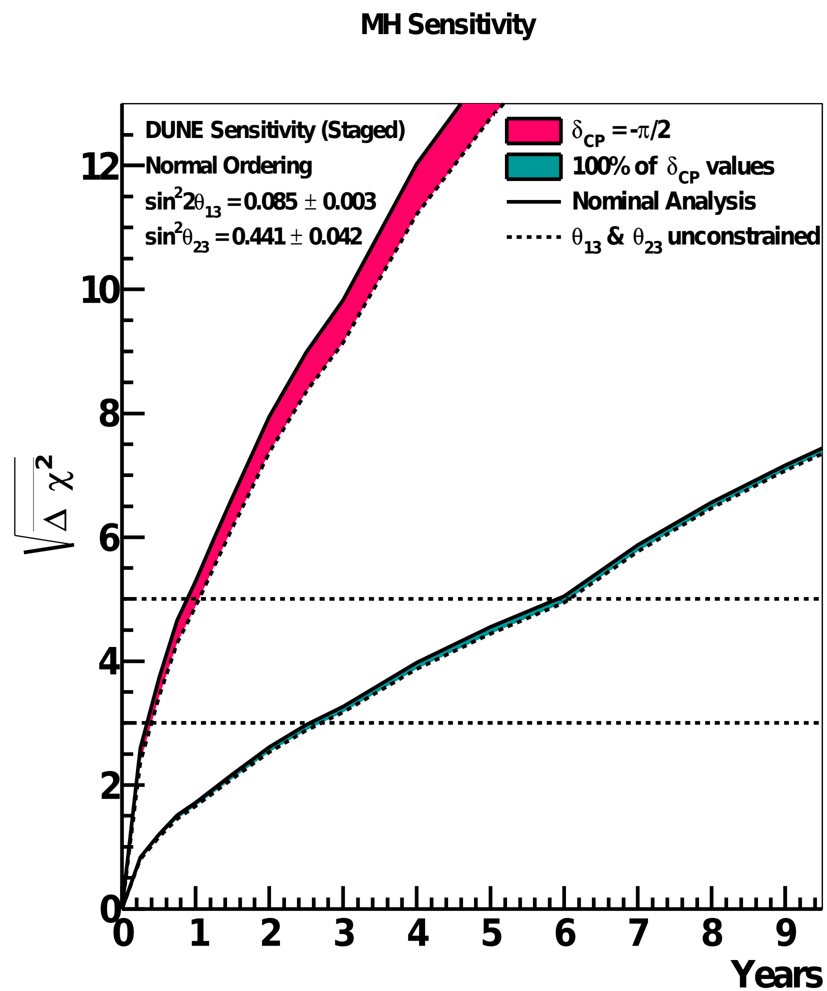




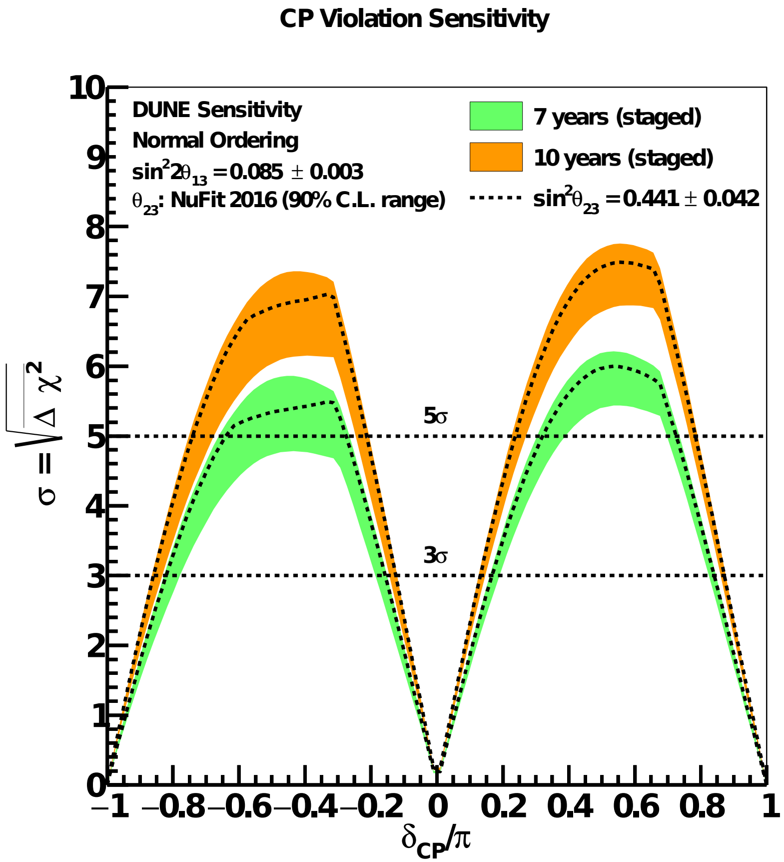
- **wide band beam:**
  - Measure ν_e appearance and ν_μ disappearance over range of energies
  - MH & CPV effects are separable

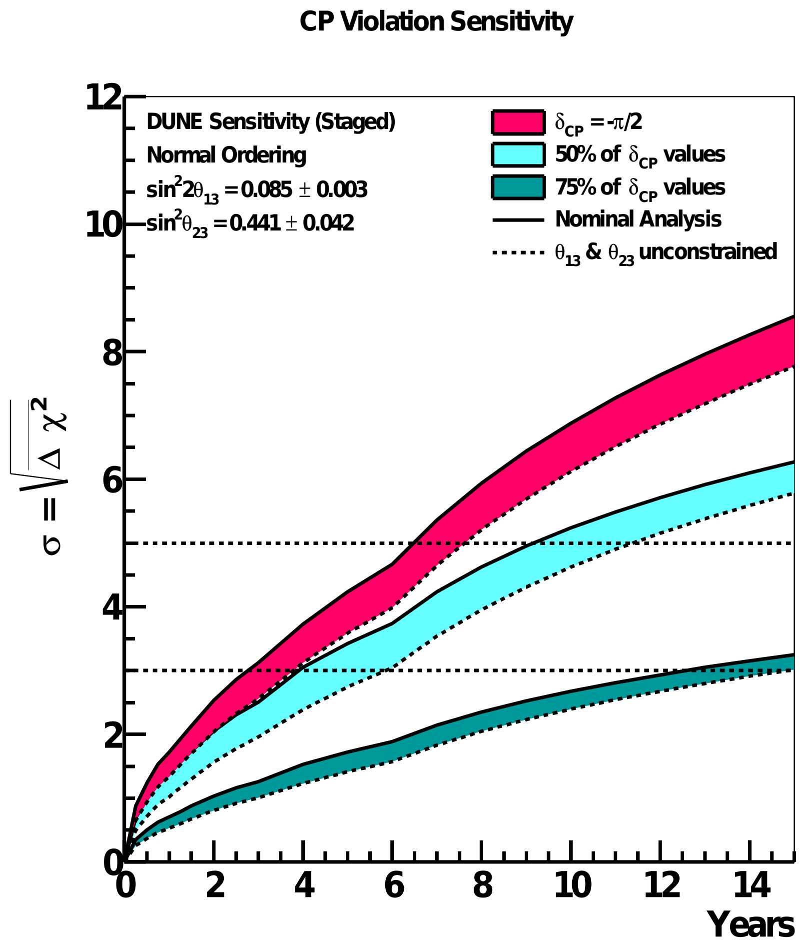
Physics Performance vs Exposure: MH





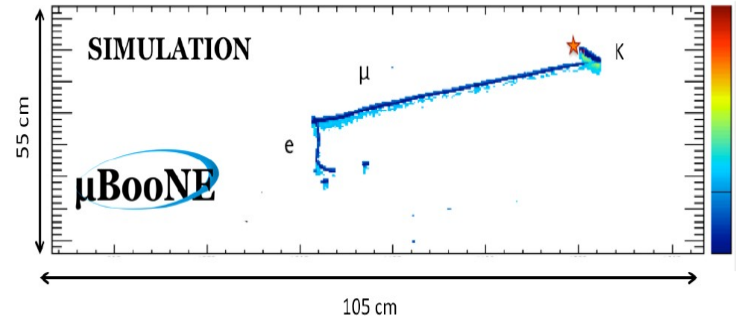
Physics Performance vs Exposure: CPV

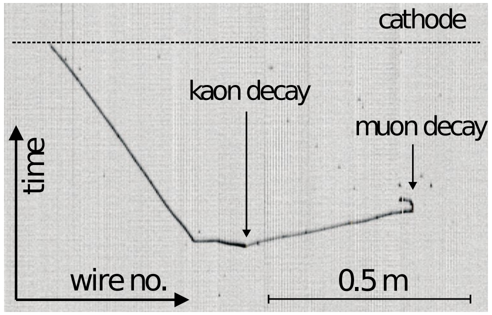




Proton decay

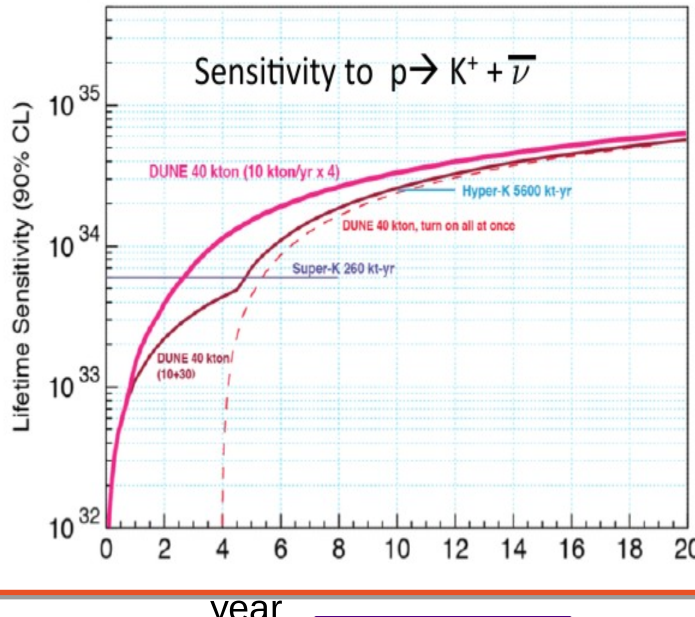
- GUT models predict proton decays
- LAr detectors are much more sensitive to several nucleon decay modes (especially with kaons)
- Low thresholds + good event reconstruction and PID





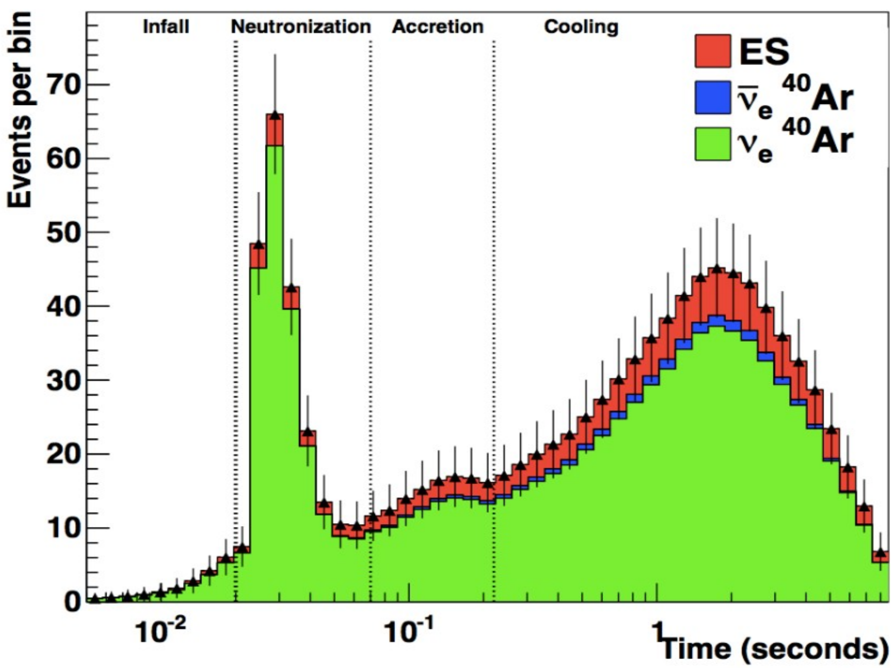
$K \rightarrow \mu\nu_\mu \;\; \mu \rightarrow e\nu_e\nu_\mu$

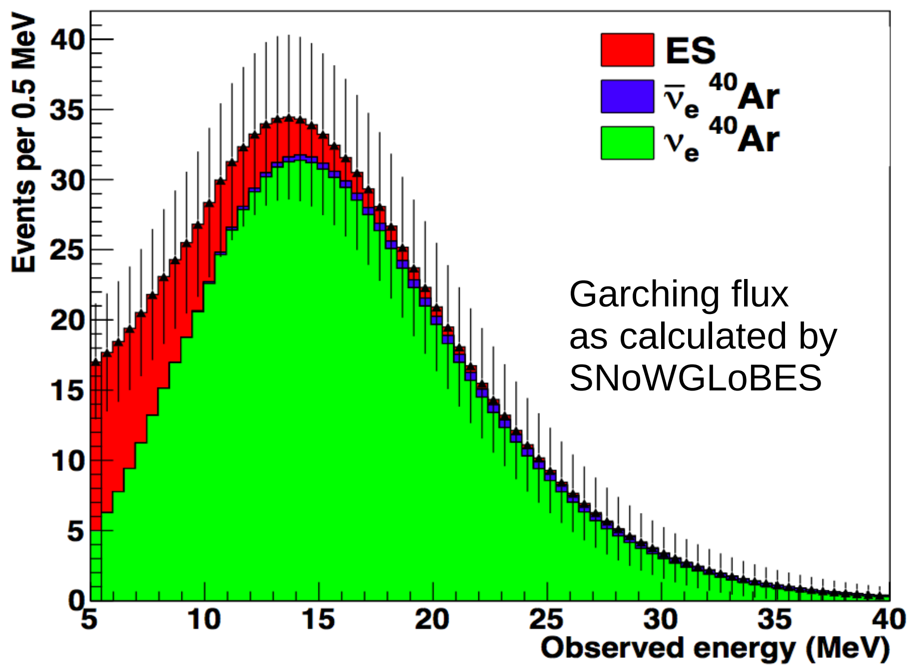
Decay Mode	Water Cherenkov		Liquid Argon TPC	
	Efficiency	Background	Efficiency	Background
$p \rightarrow K^+\overline{\nu}$	19%	4	97%	1
$p \rightarrow K^0\mu^+$	10%	8	47%	< 2
$p \rightarrow K^+\mu^-\pi^+$			97%	1
$n \rightarrow K^+e^-$	10%	3	96%	< 2
$n \rightarrow e^+\pi^-$	19%	2	44%	0.8



Supernova Neutrinos

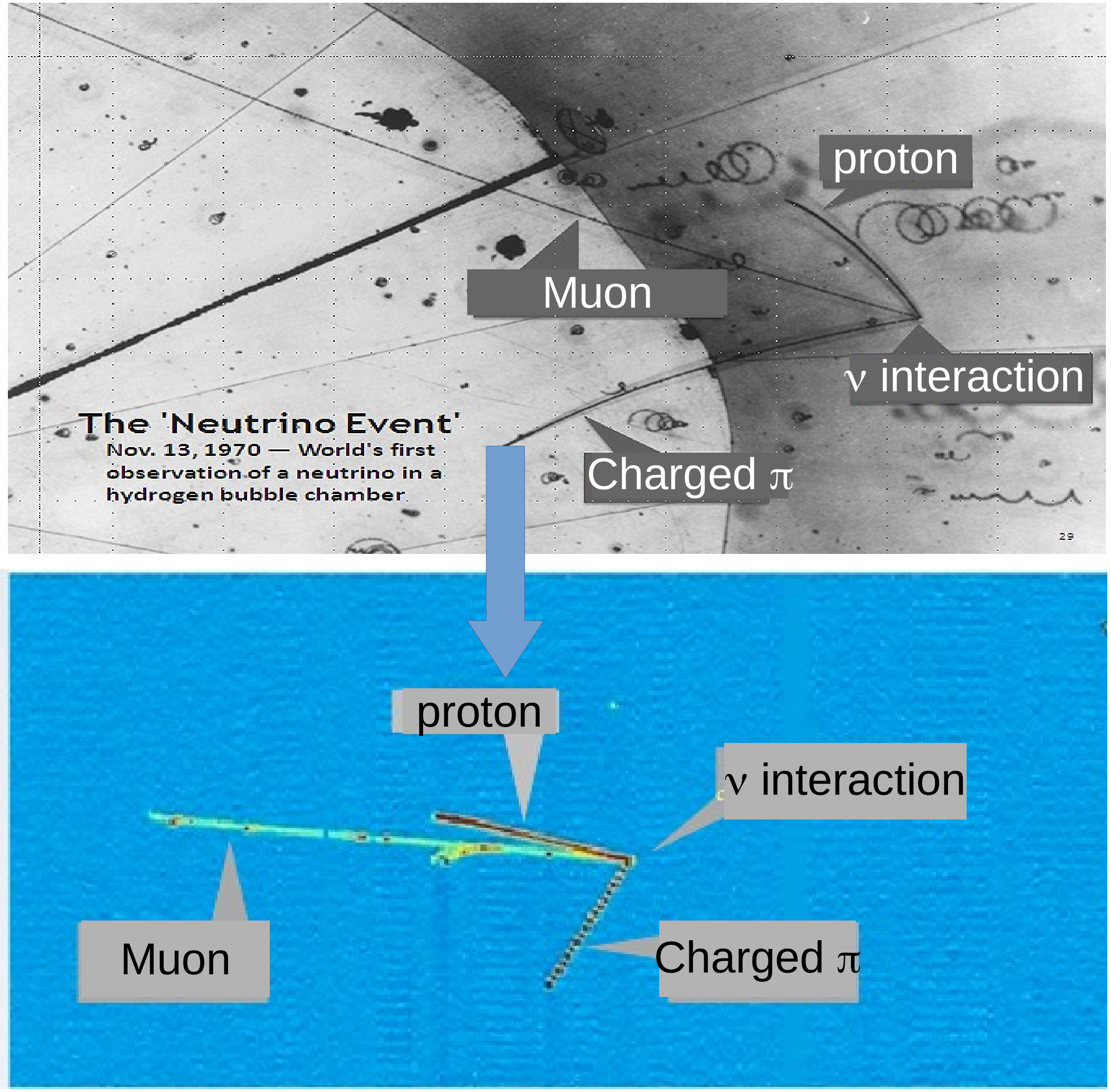
- LAr detectors are mainly sensitive to ν_e via: $\boldsymbol{\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*}$
- Sensitivity to neutronization burst
- Sensitivity to mass hierarchy



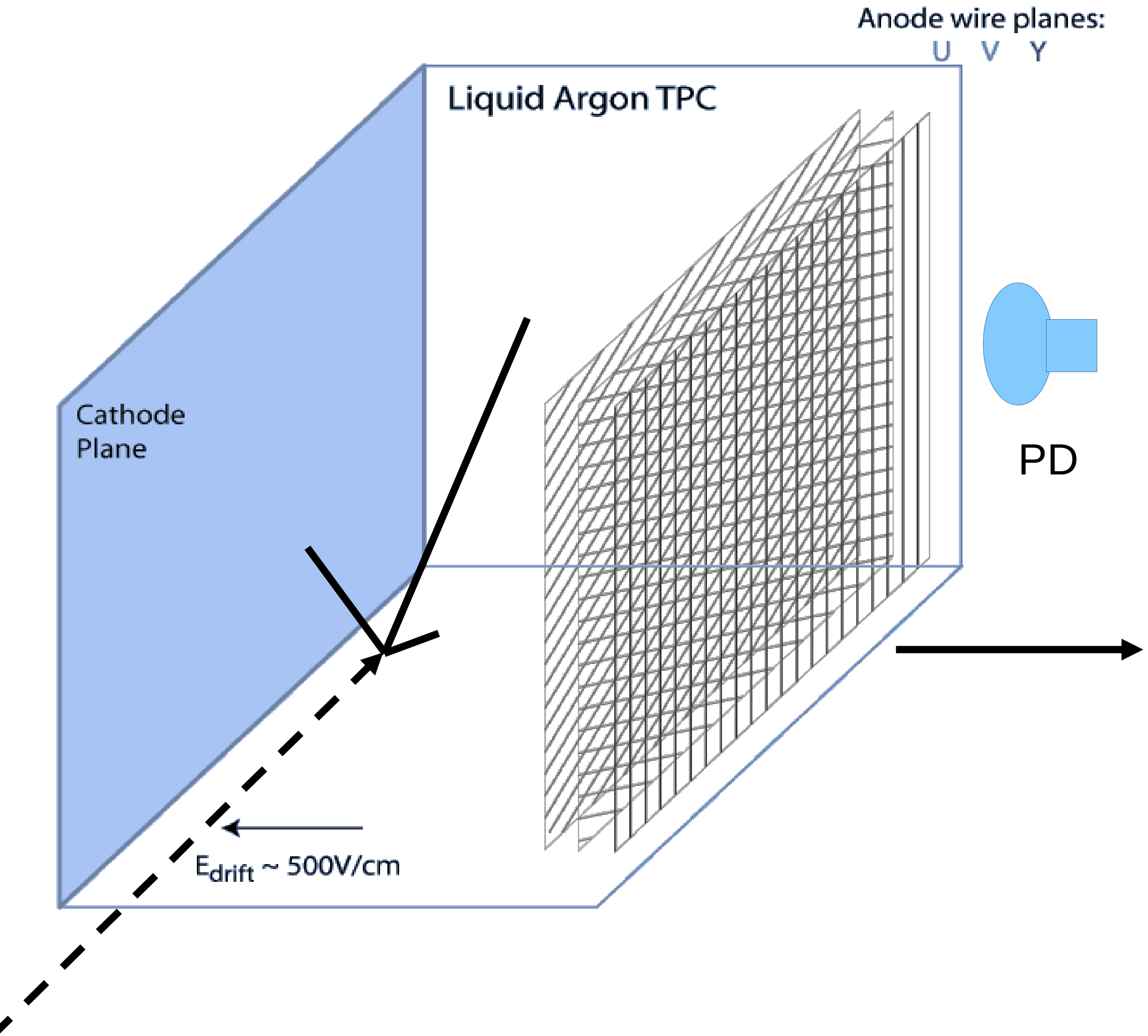


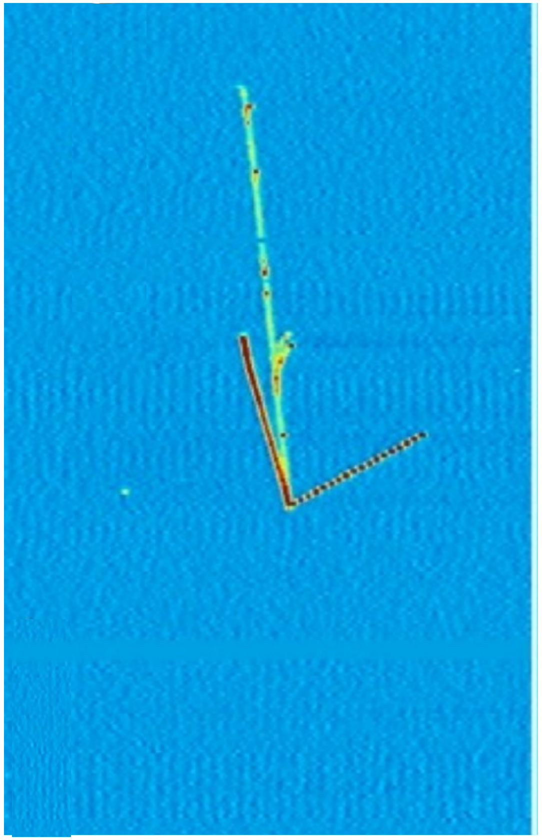
Why Liquid Argon?

Bubble chamber quality of data with added full calorimetry.



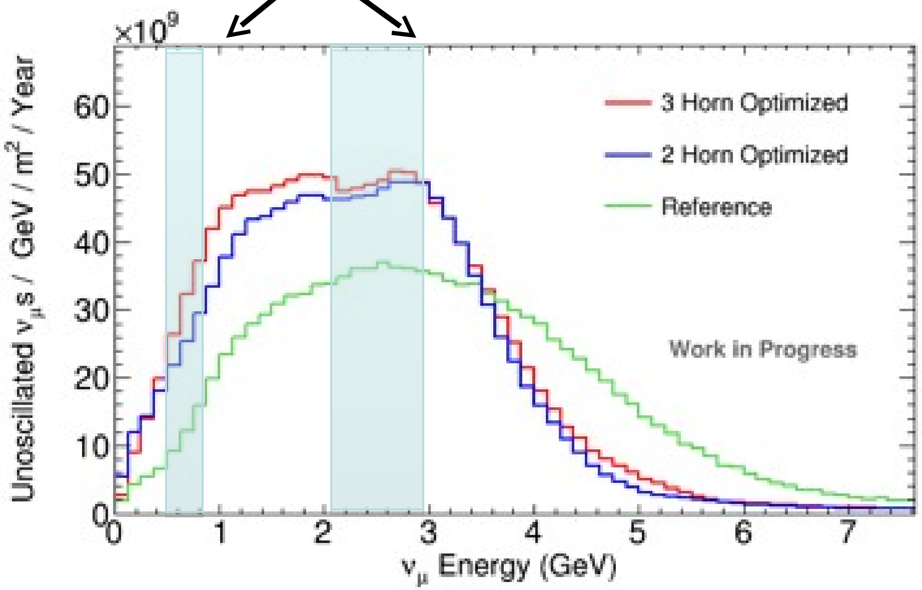
LArTPCs


Anode wire planes:
U V Y
Liquid Argon TPC
Cathode
Plane
PD
E_drift ~ 500V/cm

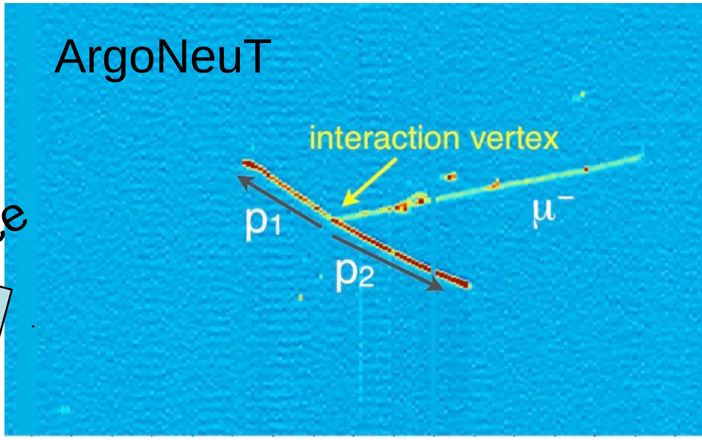


ν_μ beam

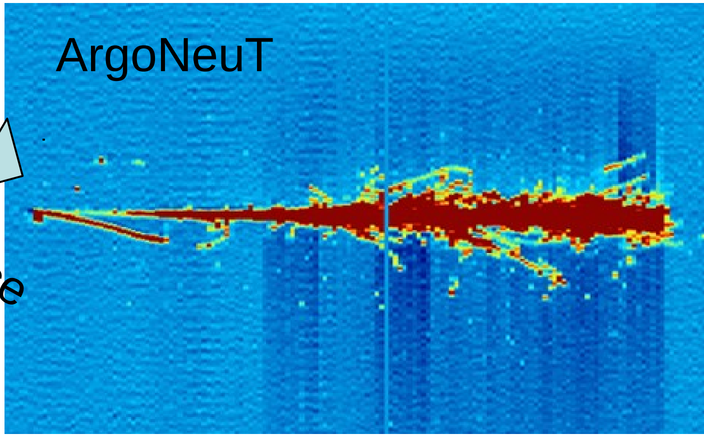
Oscillation maxima



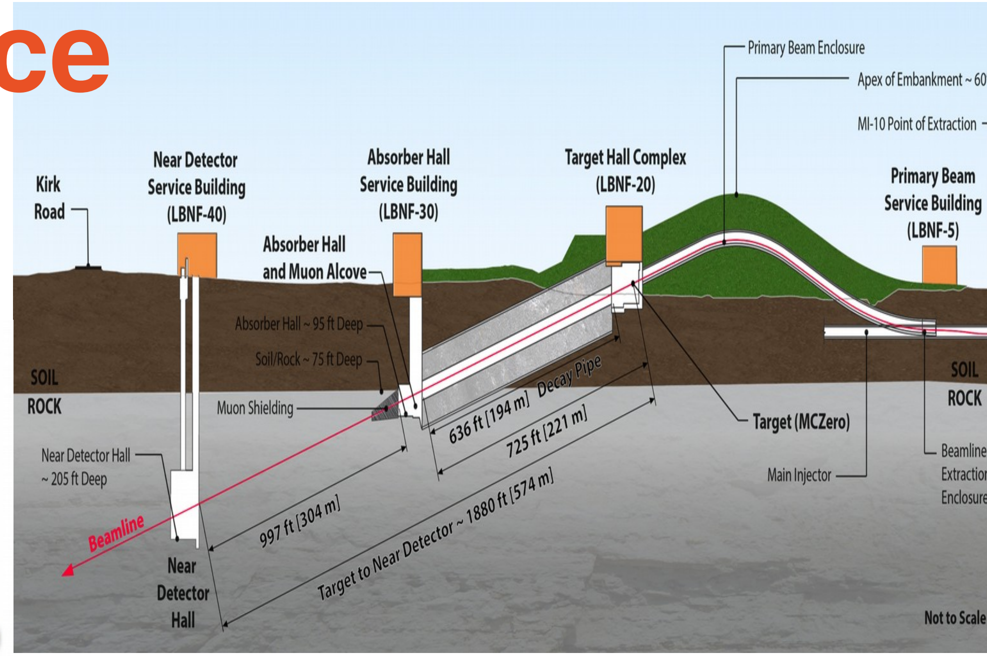
ν_μ disappearance

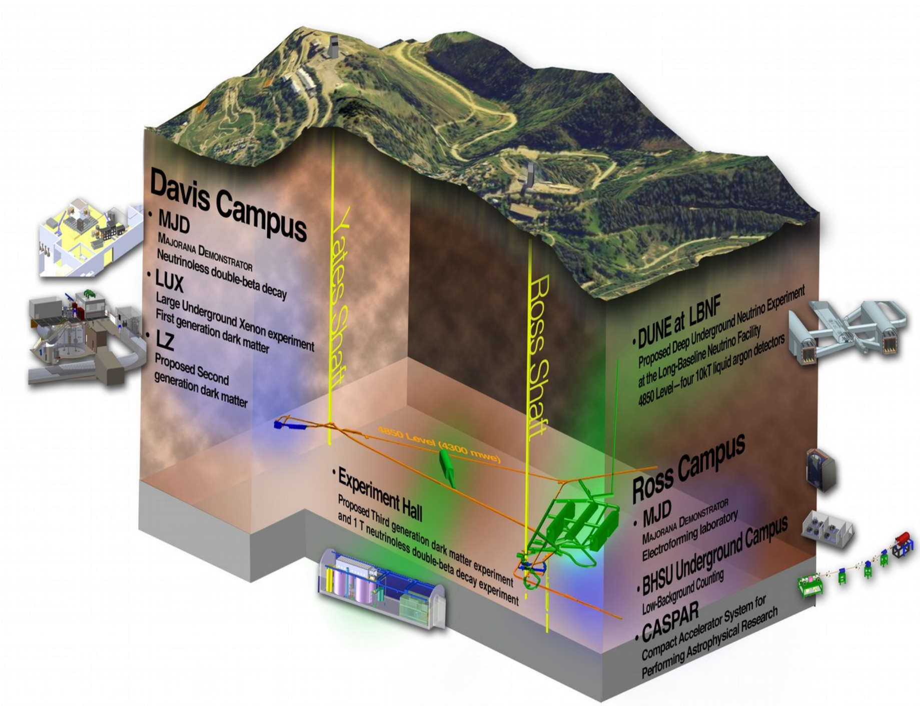


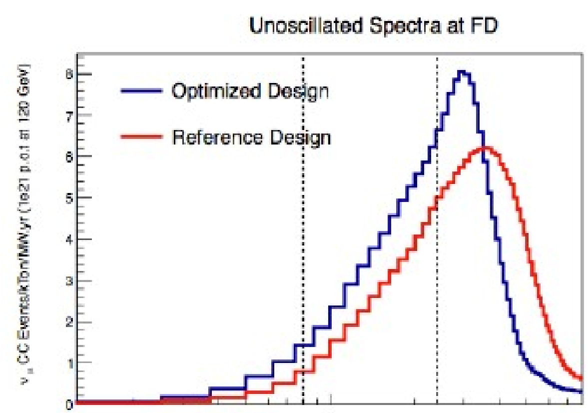
ν_e appearance



DUNE at a glance





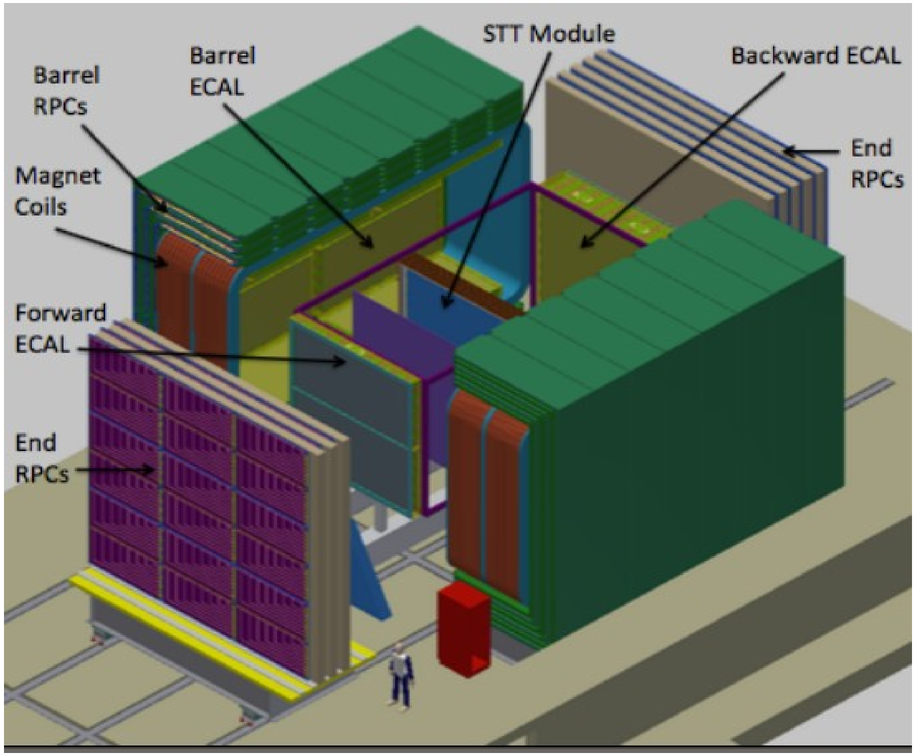


Neutrino energy (GeV)

Neutrino beam with power up to 1.2 MW from Fermilab to SURF, Lead in South Dakota.

DUNE Near Detector

- Fine Grained straw-tube tracker inside of 0.4 T magnetic field surrounded by lead-scintillator ECal and RPC muon tracker
- Other designs under consideration:
  - LAr TPC
  - High Pressure GAr TPC
  - Hybrid
- Still open question. Plan to establish soon: many opportunities to contribute.

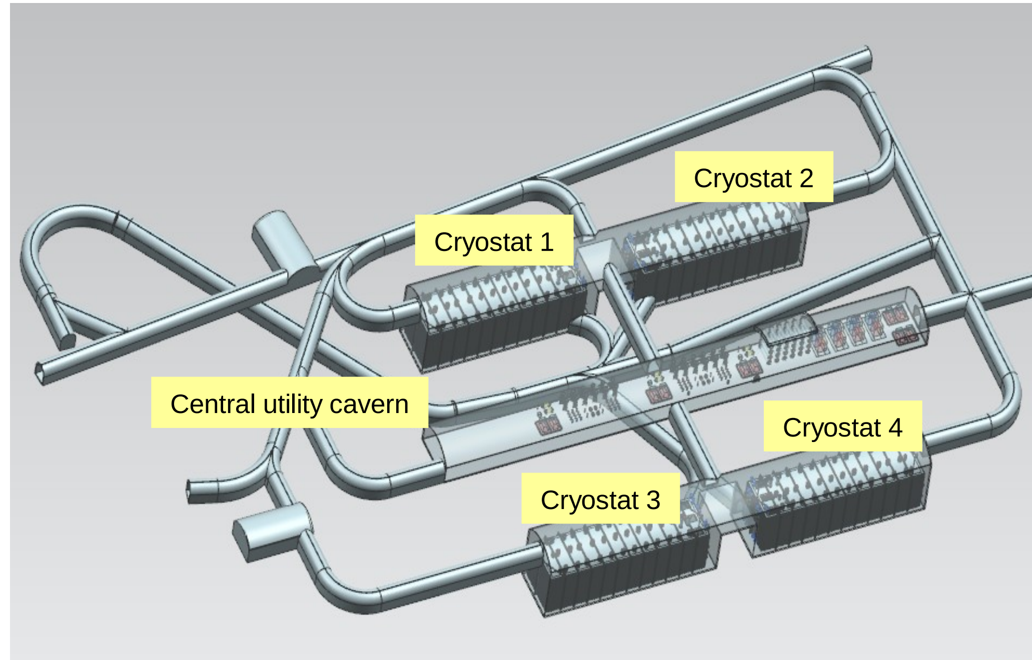


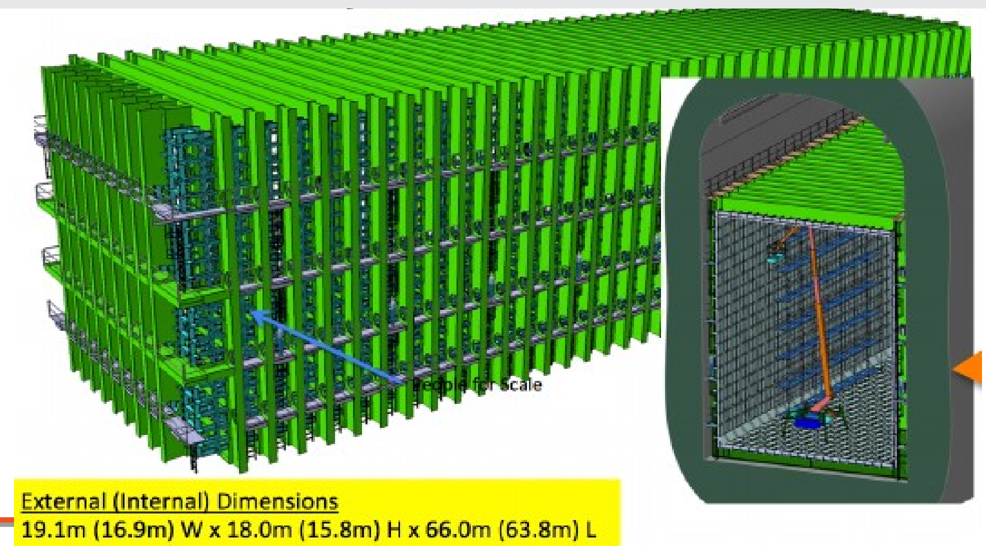
See recent ND workshop at Fermilab:

https://indico.fnal.gov/conferenceOtherViews.py?view=standard&confId=13620

Far Detector

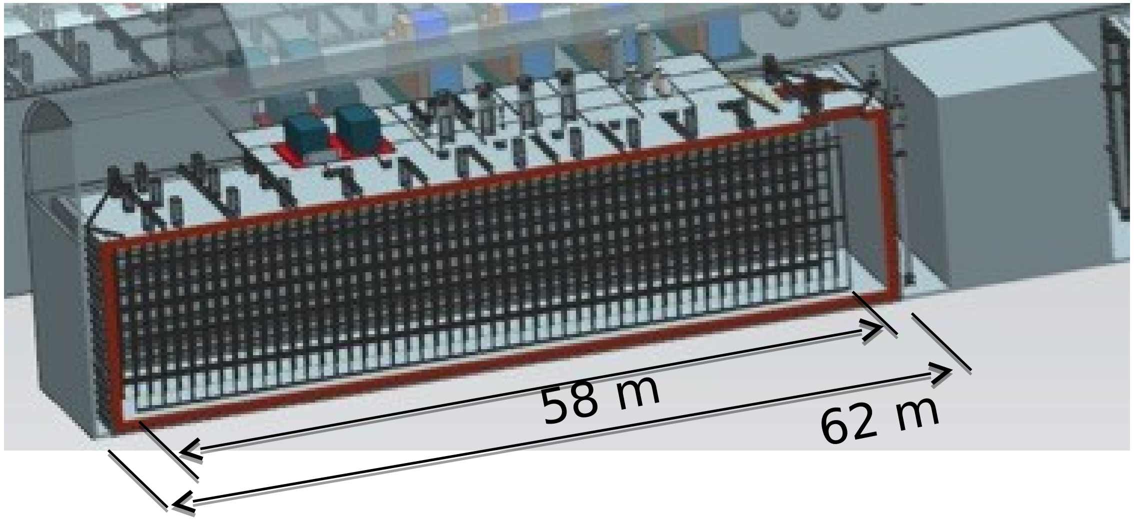
- Four ~10 ktonne liquid argon modules
- Full detector built in stages
- ~40 ktonne total fiducial volume
- Steel-supported membrane cryostat technology
- Three caverns: two to support the modules and a central utility space

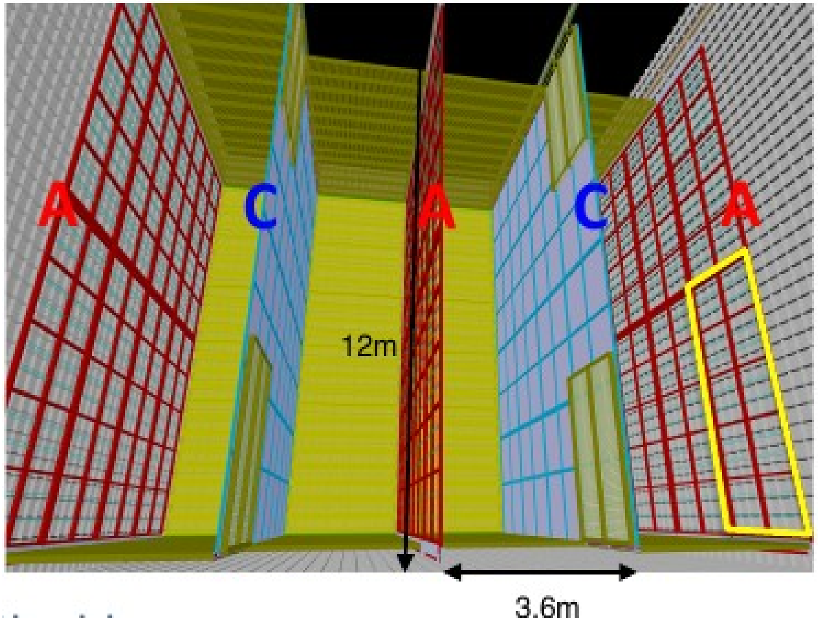




Single Phase LAr Detector
(reference design)

- First 10 kt detector will be single phase.
- Active volume:
  12m x 14m x 58 m
- 17.1/13.8/11.6 kton Total/Active/Fiducial mass
- 150 Anode Plane Assemblies (APA)
- 200 Cathode Plane Assemblies
- A:C:A:C:A arrangement
- Cathode planes (CPA) at -180kV: 3.6 m drift length

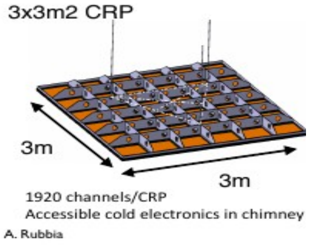




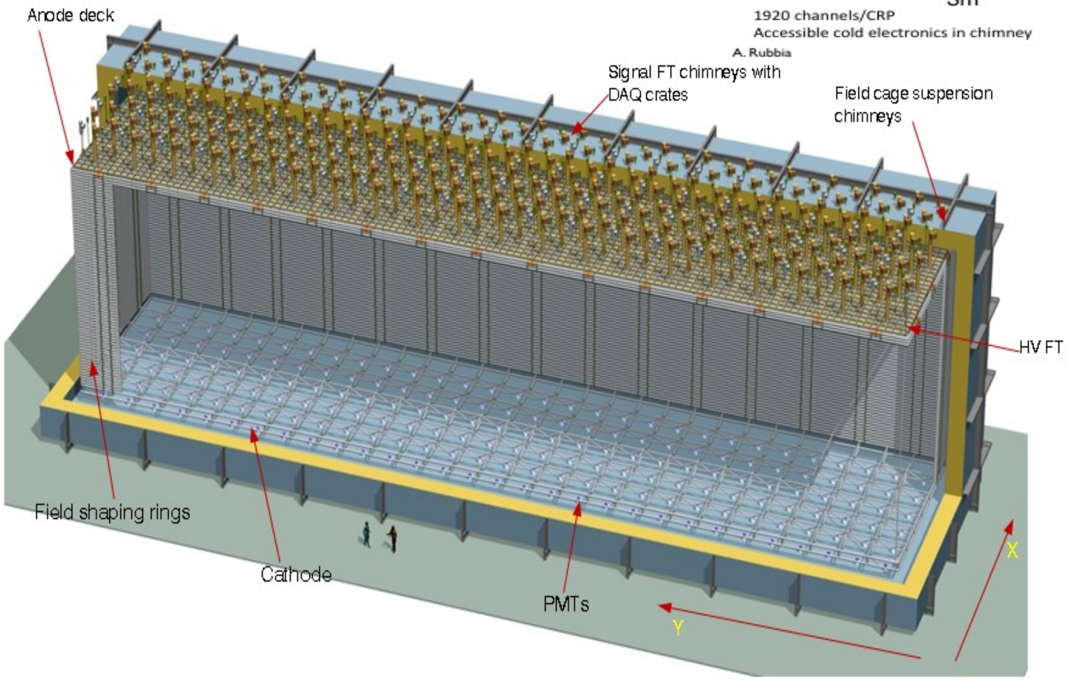
Dual Phase Lar Detector
(alternative design)

Modularity allows using different detector designs

- A dual-phase implementation of a DUNE FD module is the **alternative design** in the CDR



- $3x3m^2$ CRP modules at the gas-liquid interface.
- Hanging field cage and cathode @600kV (12 m drift)
- Decoupled PD system (720 8" PMT)
- 12.1/10.64 kton Active/Fiducial mass

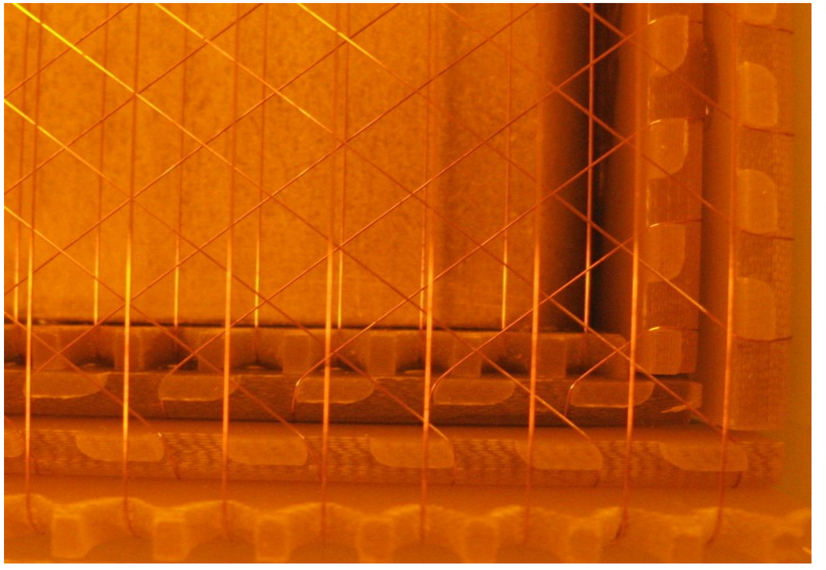


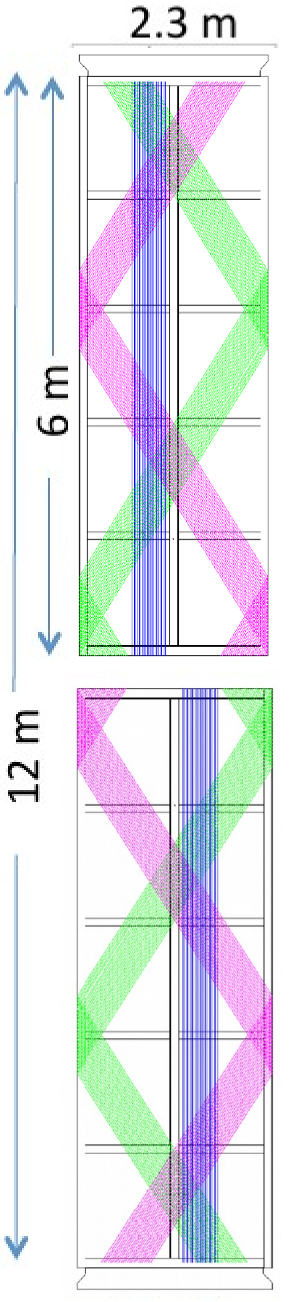
APA design

Wrapped Anode Plane Assemblies (APA).

Construction sites being set up in Europe and USA.

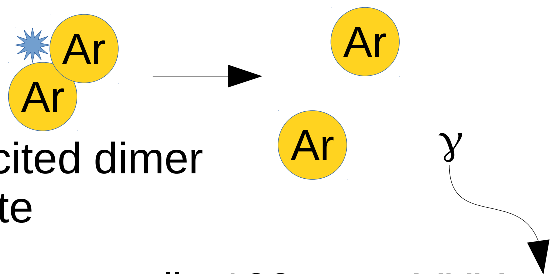
First produced APAs will be installed in protoDUNE





Scintillation light in argon

Emission:



Excited dimer state

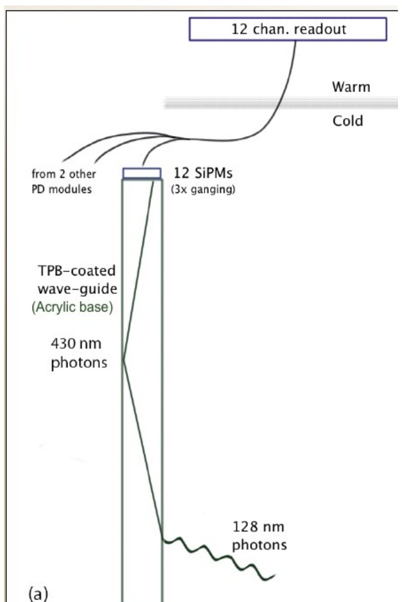
Photons are all ~128 nm – VUV

Detection:

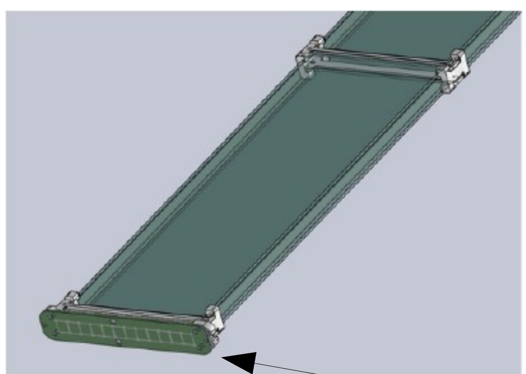
Need to use Wavelength shifting compounds, like TPB.

Evaporate on PMTs

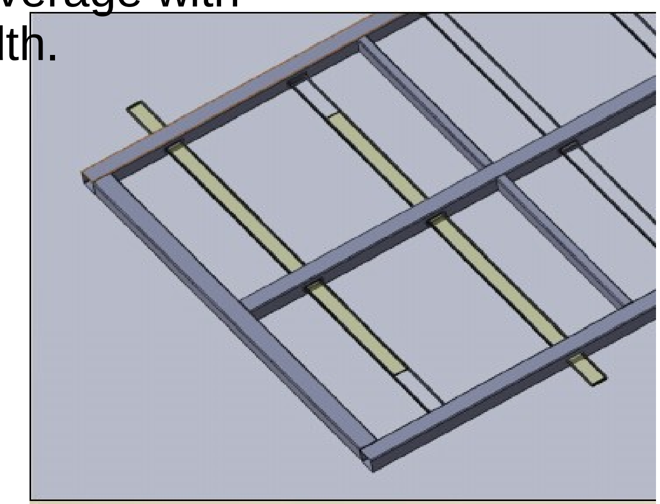
Double phase design



WLS coated wave-guides



Single Phase Design, Large coverage with small width.

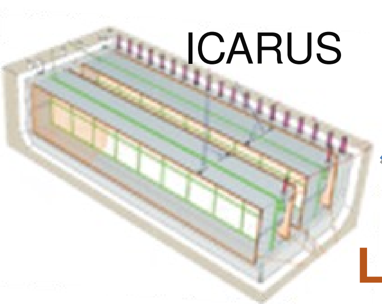


Readout by 12 SiPM.

Far Detector development Path

Development and prototyping through the Fermilab SBN and CERN neutrino platform programmes

Single-Phase



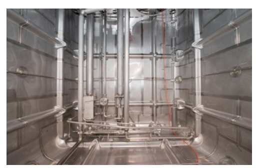
ICARUS

SBL

LBL

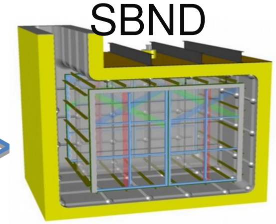
MicroBooNE

2015

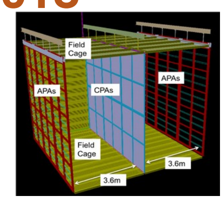


35-t prototype

SBND

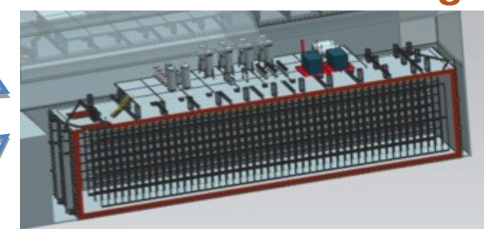


2018



protoDUNE

DUNE Reference Design

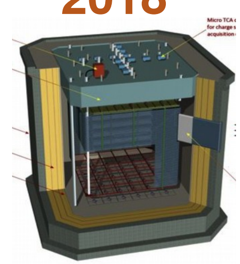


Dual-Phase

2016

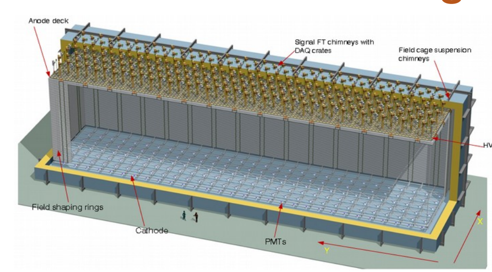
WA105: 1x1x3 m³

2018

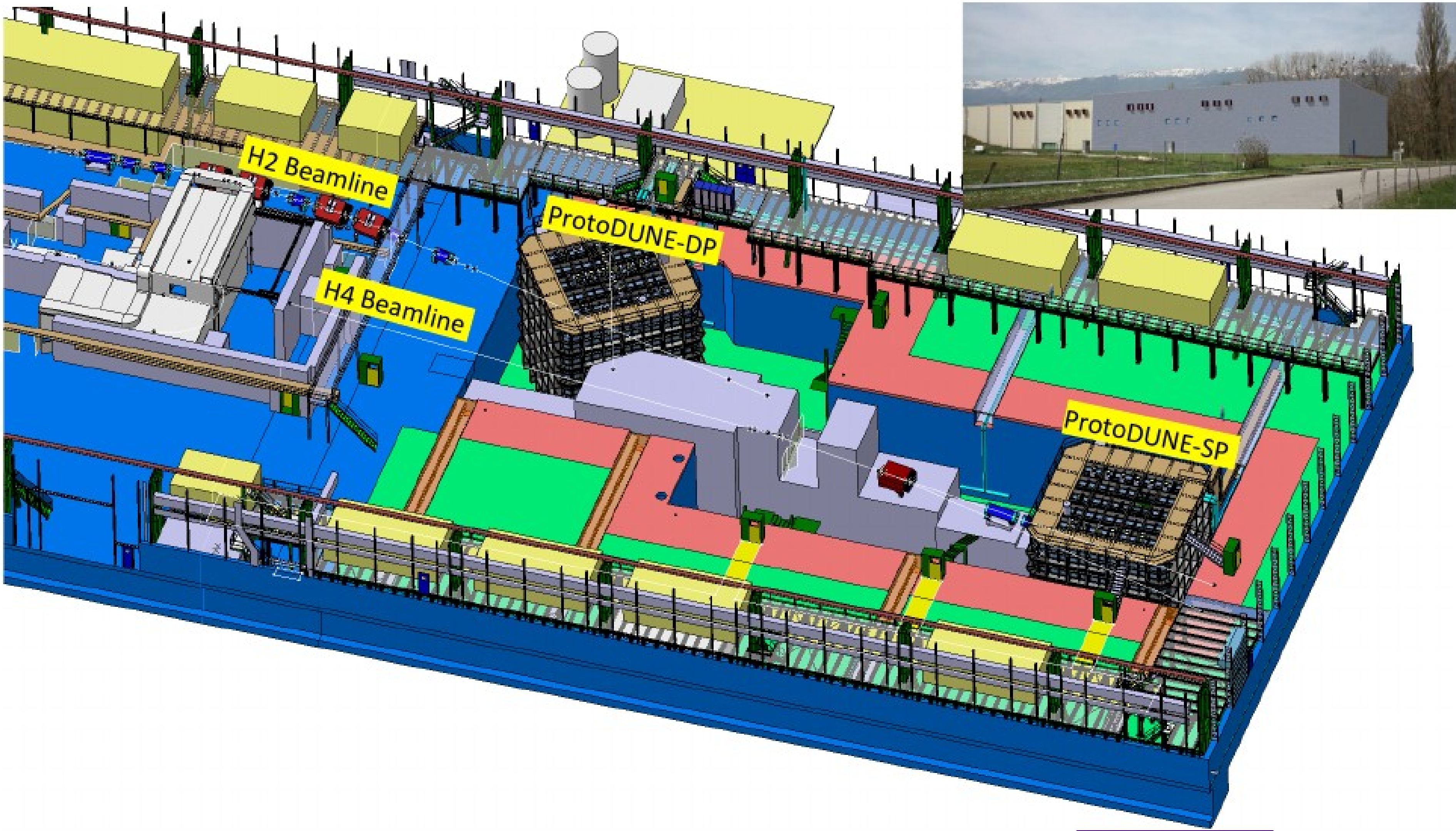


WA105

DUNE Alternative Design

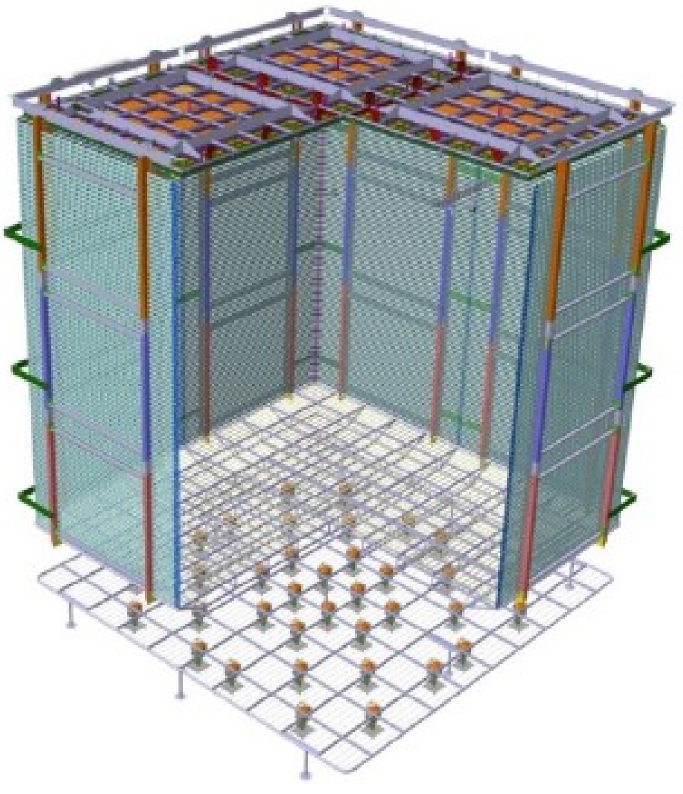


ProtoDUNE's in the CERN north area

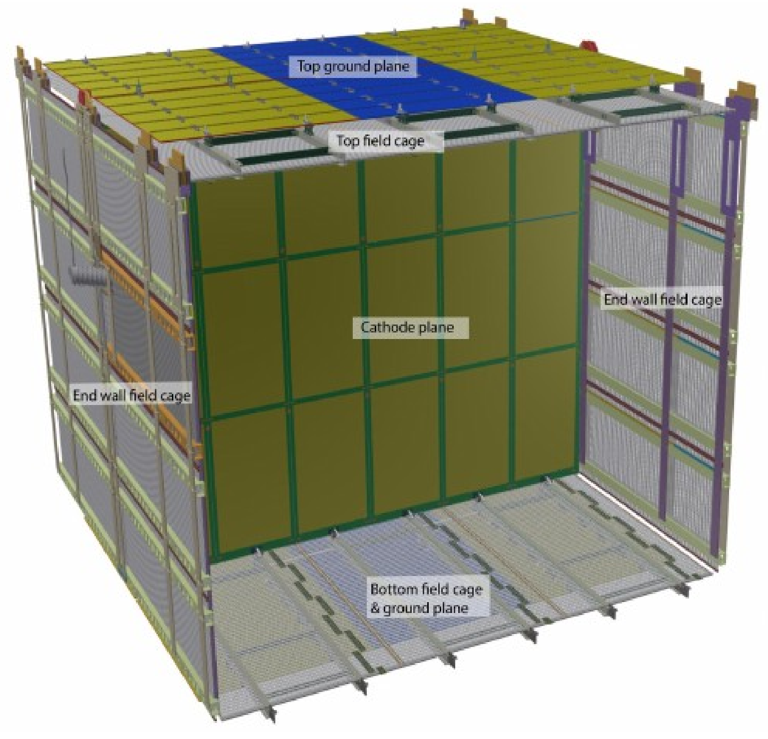


ProtoDUNE's at CERN

- Two large scale prototypes on CERN beamline.

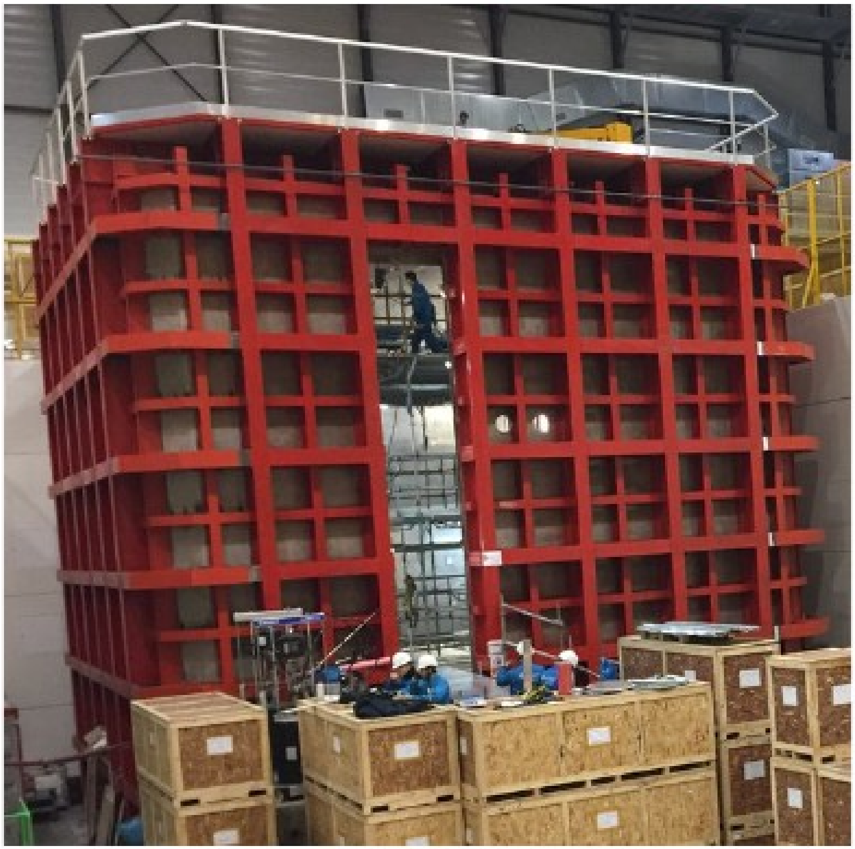


Double Phase

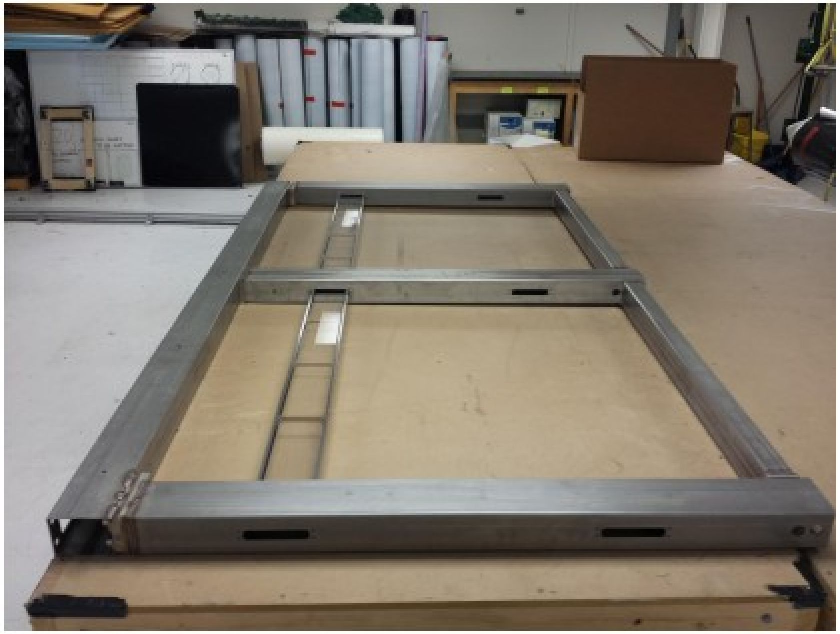


Single Phase

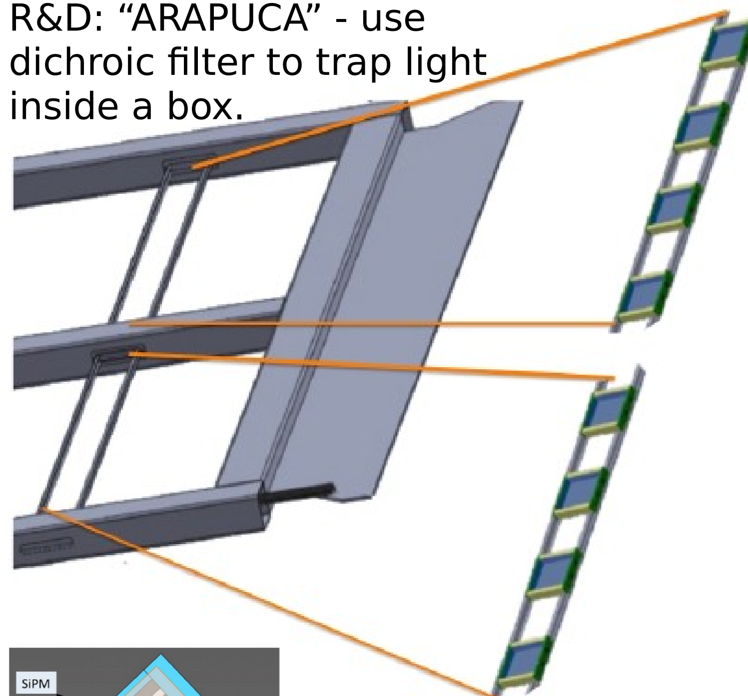
Cryostats being built

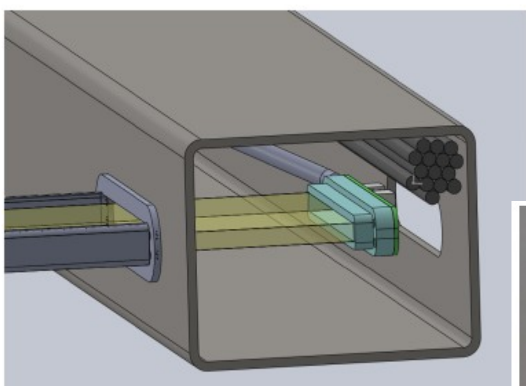


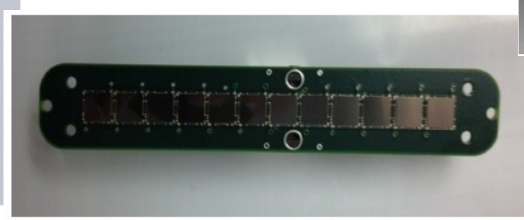
Light detection in protoDUNE-SP

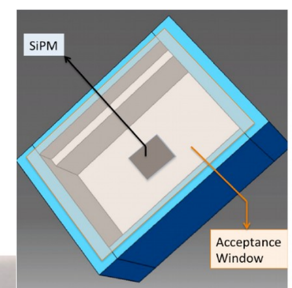


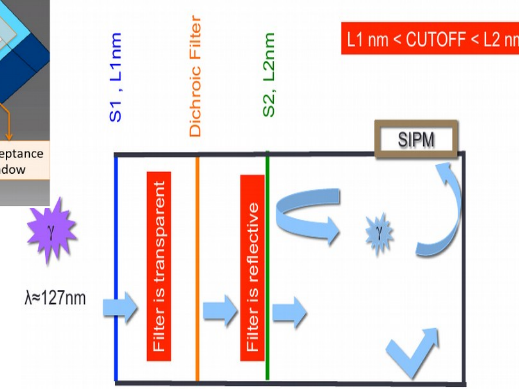
R&D: “ARAPUCA” - use dichroic filter to trap light inside a box.



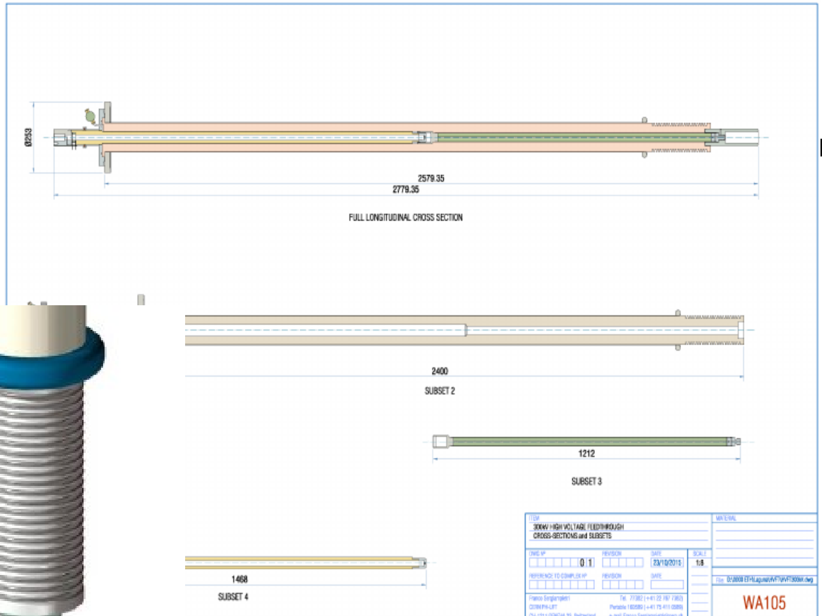


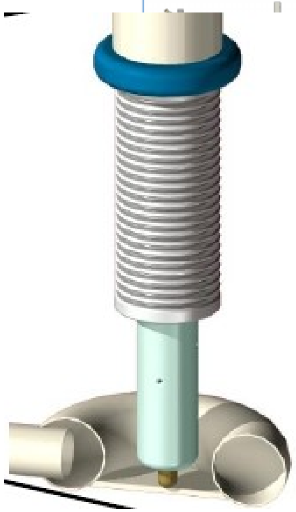




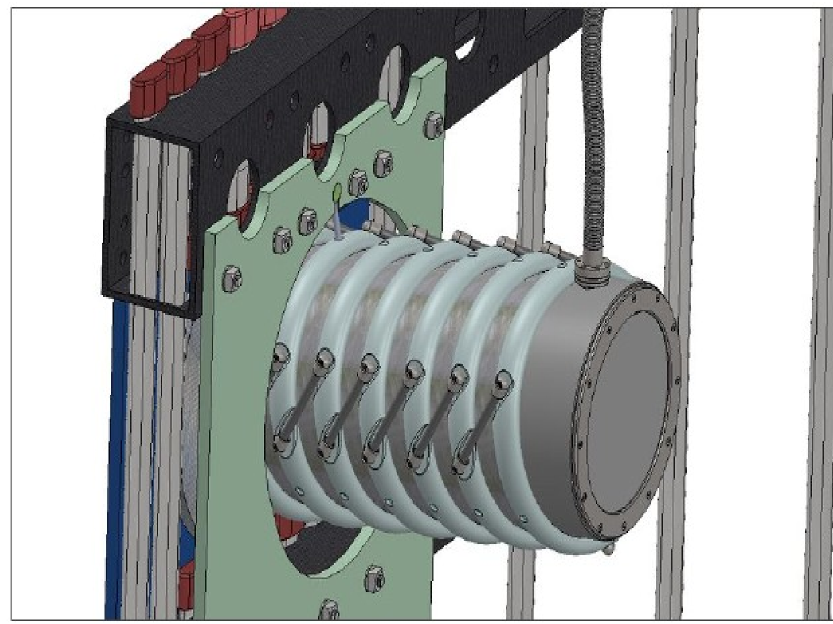


Getting HV and beam into the detector



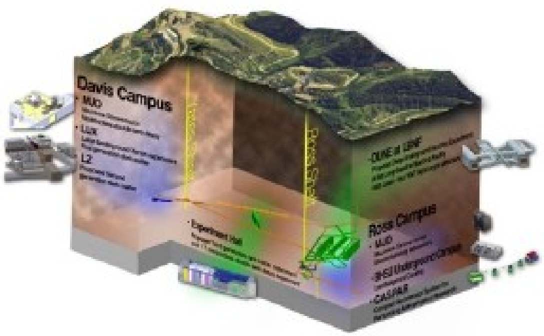


- HV Feedthrough needs to hold -180kV in LAr



- Beam plug filled with gas nitrogen – minimizes amount of material beam needs to traverse before field cage.

DUNE and ProtoDUNE timelines



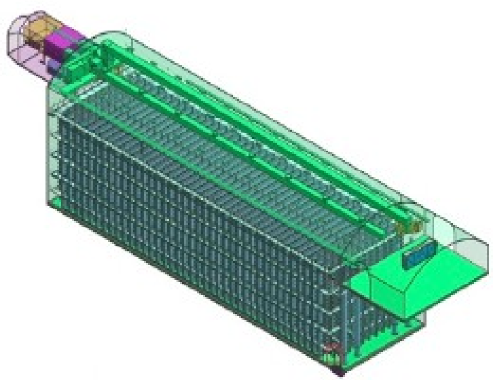
2017: Far Site Construction Begins

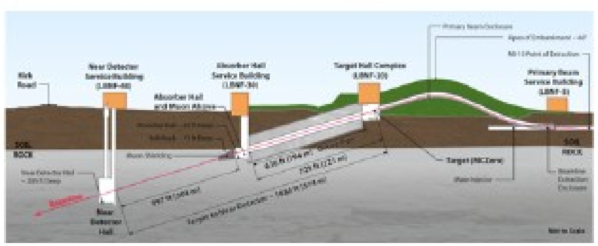
2018: protoDUNEs at CERN

2021: Far Detector Installation Begins

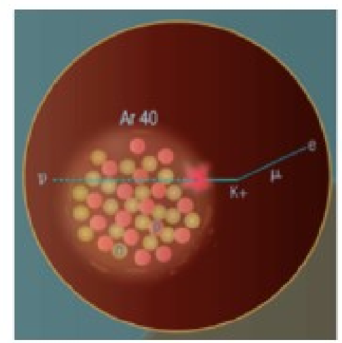
2024: Physics Data Begins (20 kt)

2026: Neutrino Beam Available





The CERN Neutrino Platform



Beam power: 1.07 MW at 80 GeV
Planned upgrade to > 2 MW

Summary

- DUNE will use a beam of neutrinos from Fermilab to SURF, to address fundamental questions in neutrino physics:
  - Is there CP violation in the neutrino sector?
  - What is the mass ordering?
- Broad physics programme including nucleon decay and supernova neutrinos (underground location).
- The first detector is scheduled to start construction in 2021.
- Intensive effort to build large scale prototypes (protoDUNEs) on charged particle beam at CERN ongoing!
- First protoDUNE data in 2018!

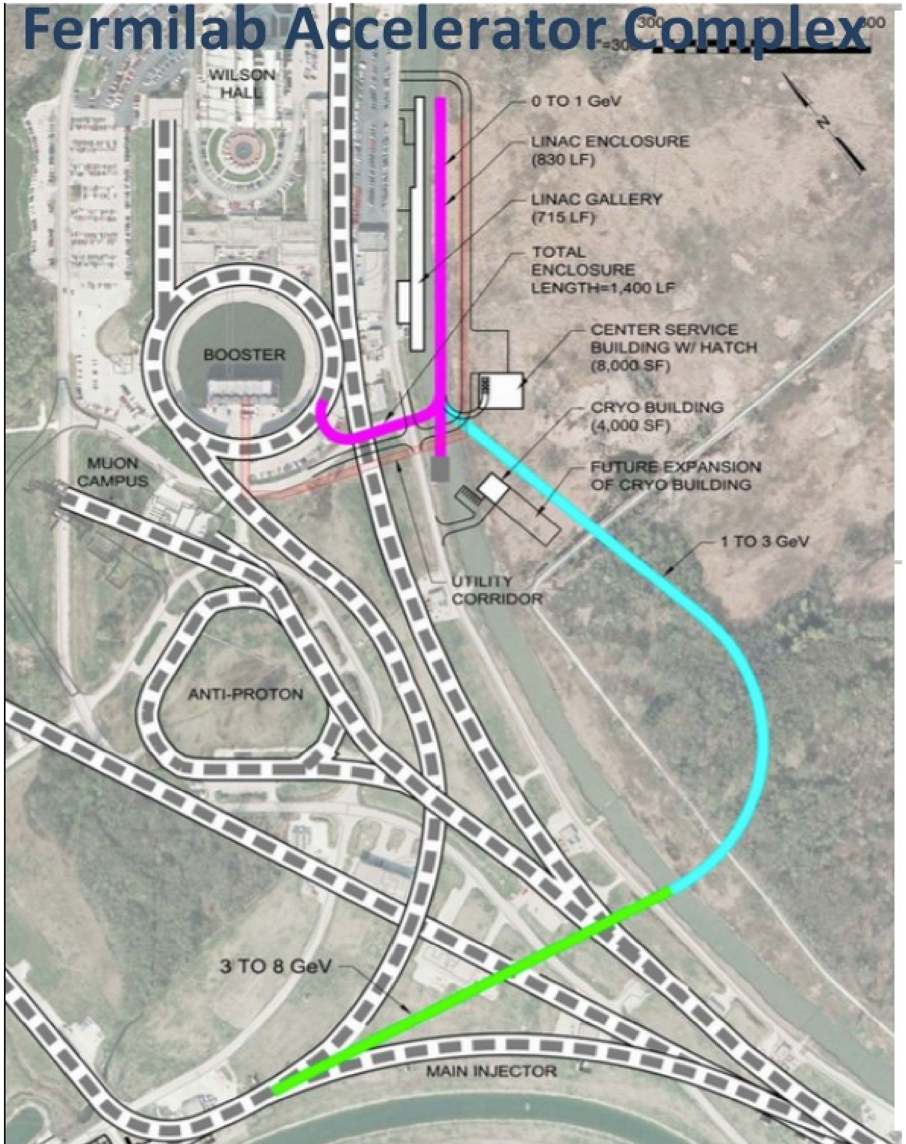
Thank You!

Backup

Fermilab Accelerator Complex

Main Injector Design Intensity: 700 kW (expected by 2/2016)

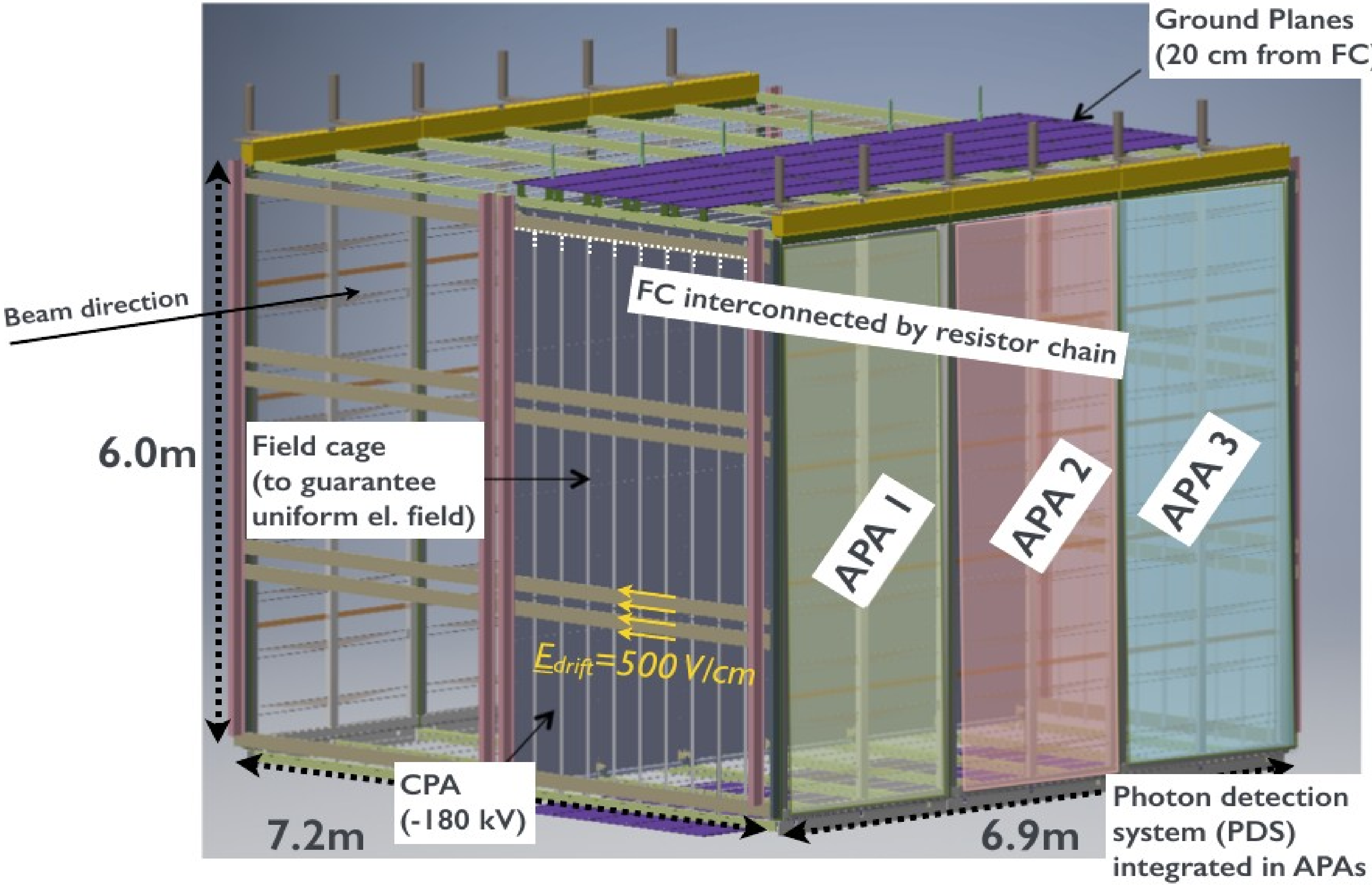
Proton Improvement Plan II and III



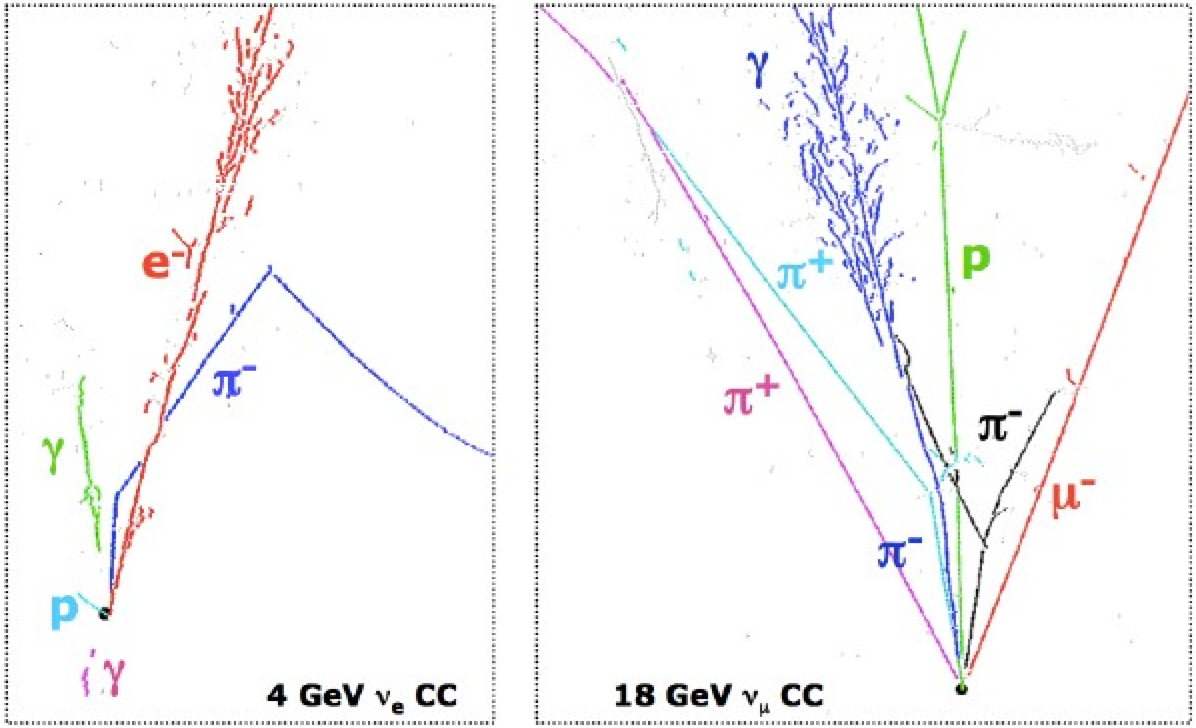
Upgrades to increase proton yield

- PIP II: (Ready by ~2025)
  MI beam power → 1.2 MW
  - Upgrade to 800 MeV linac
  - Booster and MI rep. rates increased.
- PIP III: (> 2025)
  MI beam power → 2.3 MW
  - Upgrade to 8GeV linac
    OR
  - Upgrade to 2GeV linac and
  - Replace booster with rapid cycling synchrotron (RCS)

protoDUNE-SP



Other challenges: event reconstruction



- Need to reconstruct tracks and showers, measure their energy and perform particle identification.
- Complex event topologies require sophisticated algorithms
- Automatisation a major challenge, multivariate techniques.

Oscillation Physics Milestones

- Best case scenario:
  - reach **3σ** CPV sensitivity with ~70 kt MW year
  - reach **5σ** MH sensitivity with ~20 kt MW year

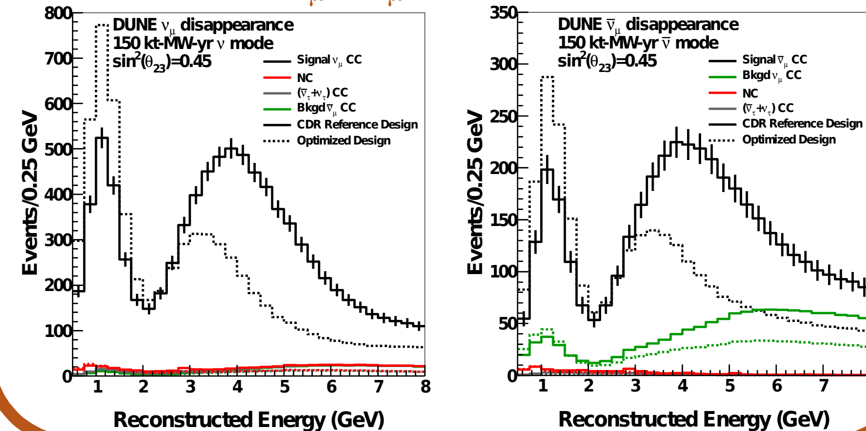
Physics milestone	Exposure $\text{kt} \cdot \text{MW} \cdot \text{year}$ (reference beam)	Exposure $\text{kt} \cdot \text{MW} \cdot \text{year}$ (optimized beam)
1° θ_{23} resolution ($\theta_{23} = 42^\circ$)	70	45
CPV at 3σ ($\delta_{\rm CP} = +\pi/2$)	70	60
CPV at 3σ ($\delta_{\rm CP} = -\pi/2$)	160	100
CPV at 5σ ($\delta_{\rm CP} = +\pi/2$)	280	210
MH at 5σ (worst point)	400	230
10° resolution ($\delta_{\rm CP} = 0$)	450	290
CPV at 5σ ($\delta_{\rm CP} = -\pi/2$)	525	320
CPV at 5σ 50% of $\delta_{\rm CP}$	810	550
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	1200	850
CPV at 3σ 75% of $\delta_{\rm CP}$	1320	850

Looking for the Signal

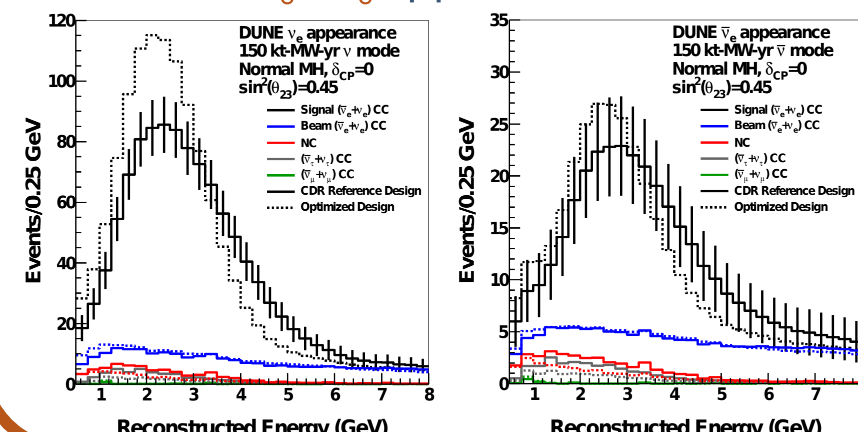
- Wide-band beam:
  - Measure ν_e appearance and ν_μ disappearance over range of energies
  - MH & CPV effects are separable

Assumes: $\sin^2 2\theta_{13}=0.084$, $\sin^2 2\theta_{23}=0.45$, $\Delta m^2_{31}=2.47 \times 10^{-3}$

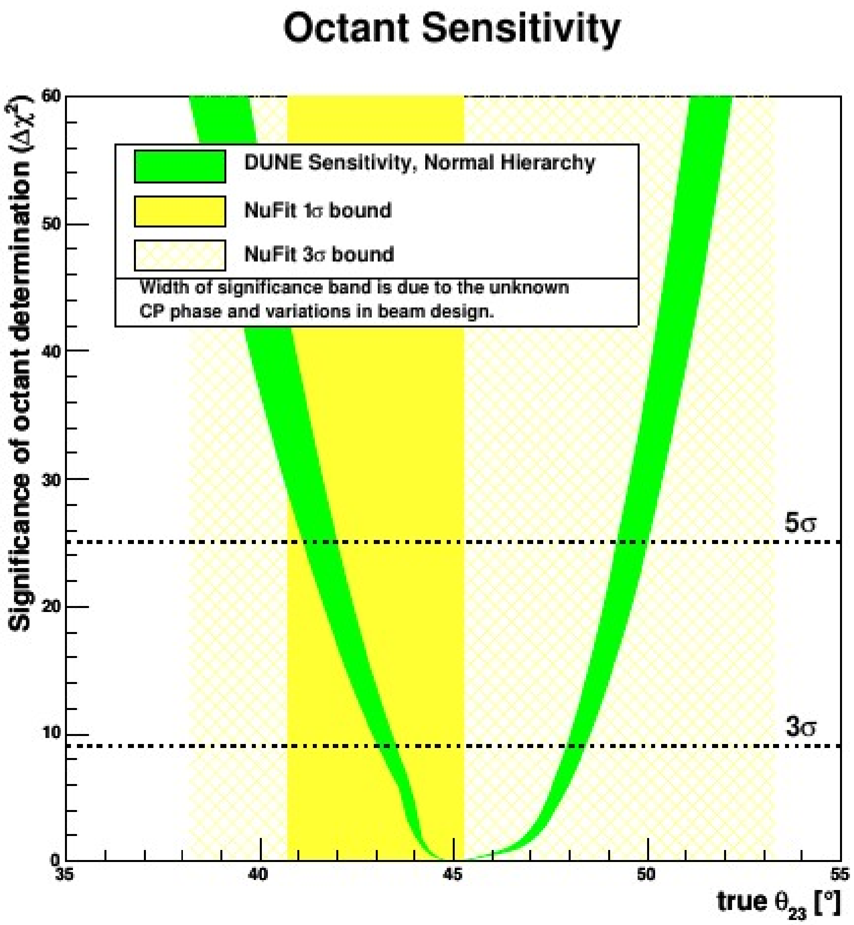
ν_μ / $\bar{\nu}_\mu$ disappearance

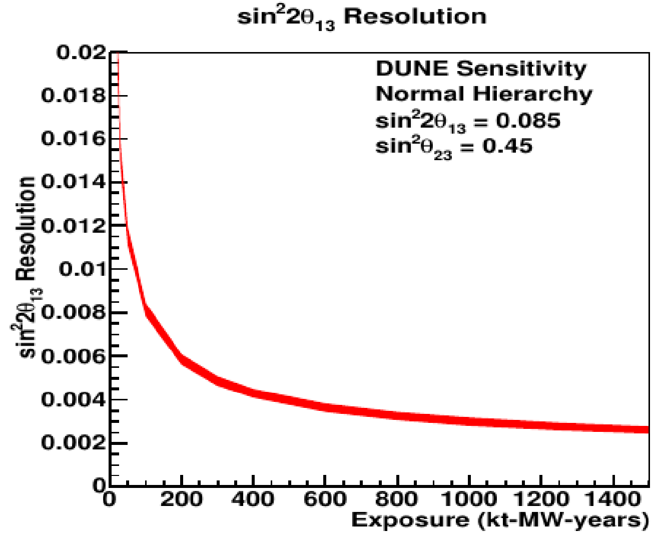


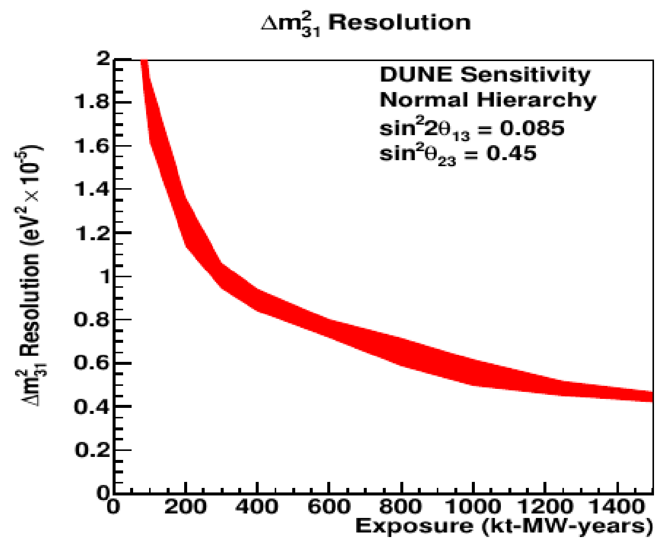
ν_e / $\bar{\nu}_e$ appearance



θ_{23} and Octant Sensitivity





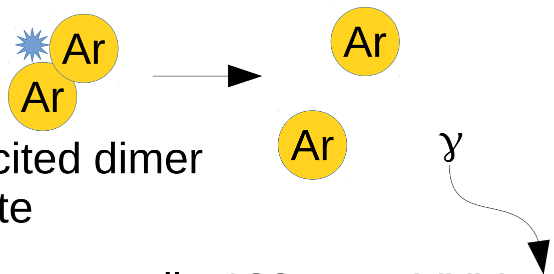


Timeline

- July 2015 "CD-1 Refresh" review. Conceptual design review. - **Completed!**
- Oct 2015: protoDUNE **approved** at CERN
- Dec 2015 CD-3a CF Far Site. Needed to authorize far site conventional facilities work including underground excavation and outfitting. - **Completed!**
- 2017 Ongoing shaft renovation at SURF complete
- 2017 Start of far site conventional facilities.
- 2018 Testing of "full-scale" far detector elements at CERN
- 2019 Technical Design review
- 2021 Ready for start of installation of the first far detector module
- 2024 start of physics with one detector module
  - Additional far detector modules every ~2 years.
- 2026 Beam available
- 2026 Near detector available
- 2028 DUNE construction finished

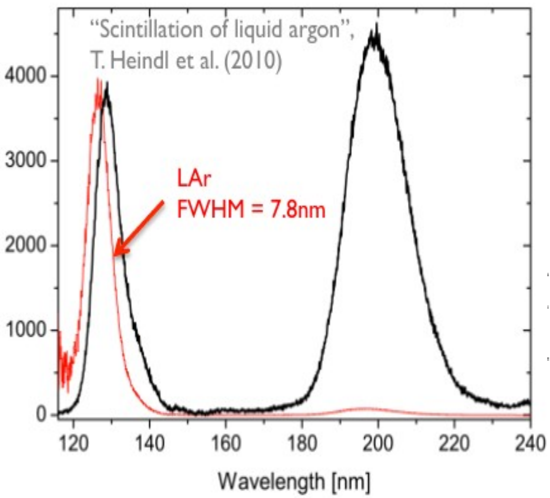
Scintillation light in argon

Emission:



Excited dimer state

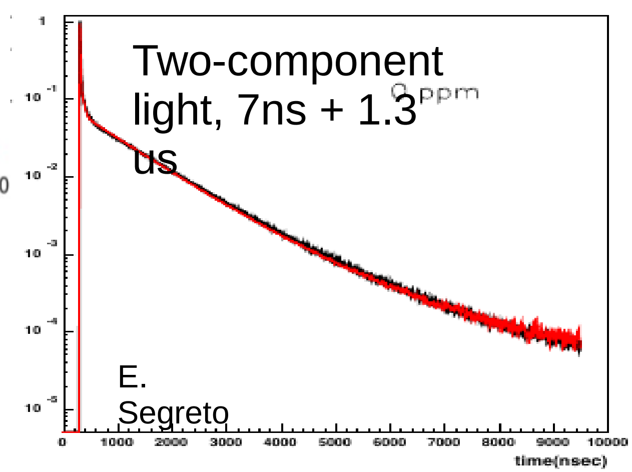
Photons are all ~128 nm – VUV



Transport:

Liquid argon is mostly transparent to its scintillation.

At longer distances Rayleigh scattering ~55m f(λ) and absorption, e.g. on nitrogen ~30 m @2ppm N2 begin play a role. Note high refractive index ~1.5 for VUV.



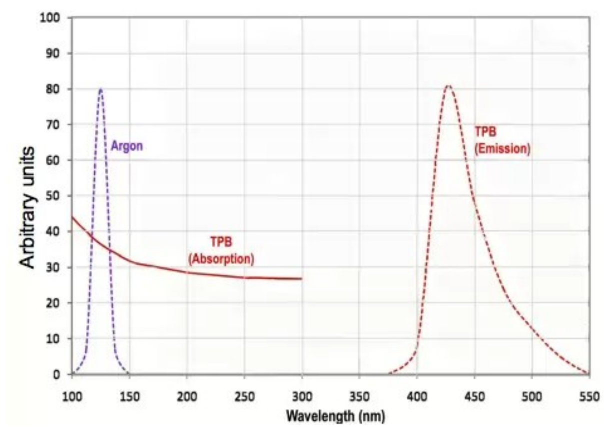
Two-component light, 7ns + 1.3 us

E. Segreto

Detection:

Liquid argon is almost the only thing transparent to its scintillation.

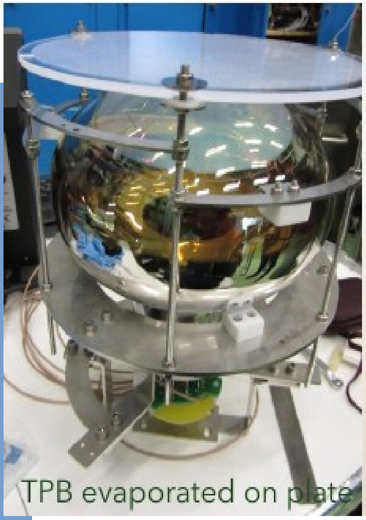
Detection is challenging – most often need to use Wavelength shifting compounds, like TPB.

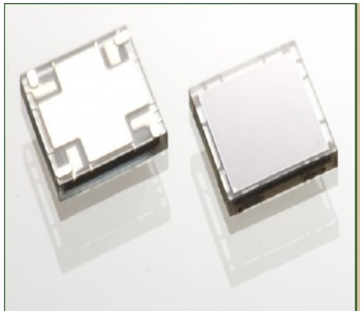


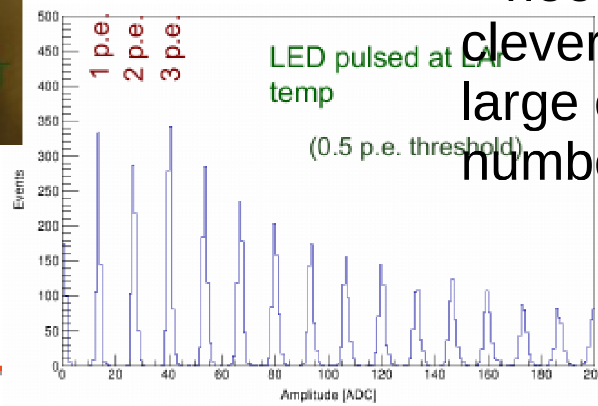
PMTs vs SiPMs

PMTs

- Proven detector technology in liquid argon.
- Excellent timing resolution ~ ns.
- e.g. Hamamatsu R5912 8” PMTs
- Small channel/active area ratio.
- Non-negligible size, relatively high voltage.





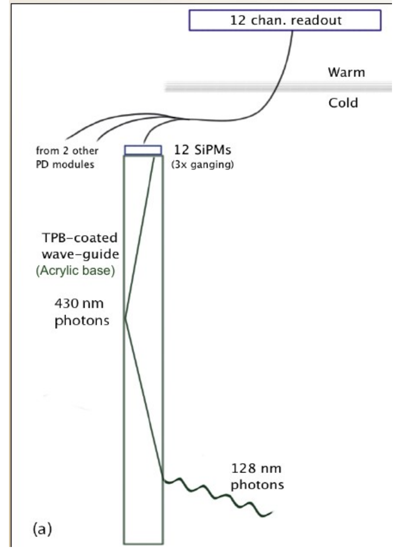


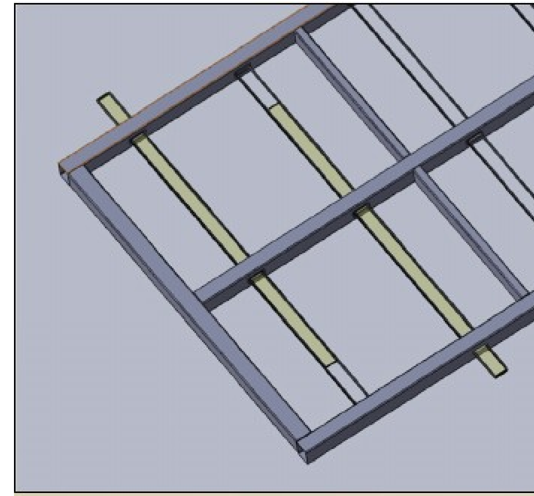
SiPMs

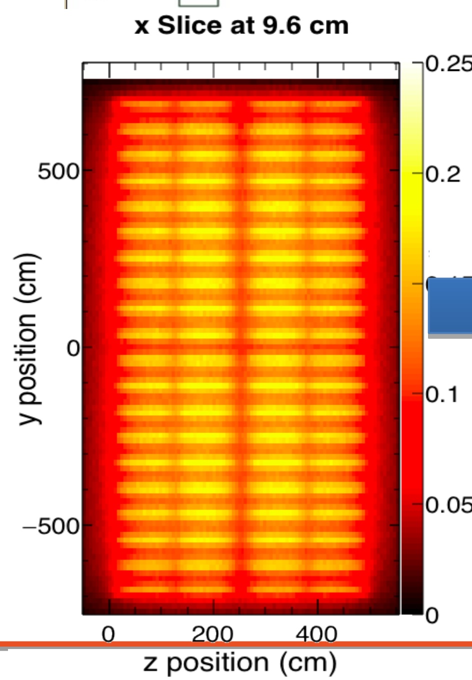
- SiPMs: Relatively new on the block.
- Excellent performance in liquid argon. Small voltage needed to operate.
- Small active size – need to be clever to avoid large channel number.

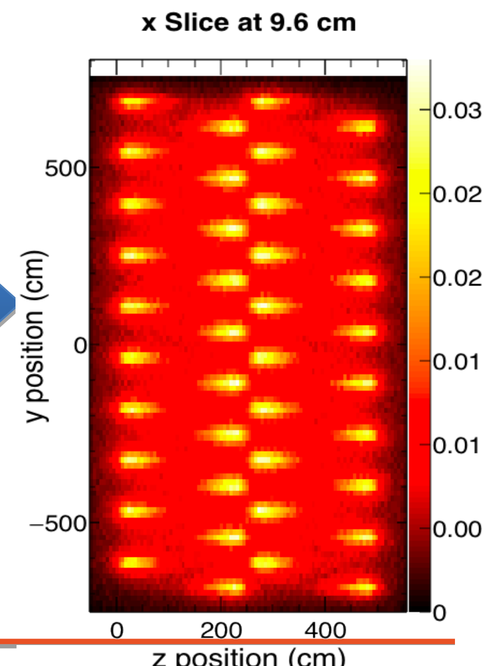
SiPMs and coated bars

- WLS coated bars coupled to SiPMs (current DUNE baseline design).
- SiPM timing not as good as PMTs (Industry is working on this).
- Photon travel time in bar adds to this.
- Work ongoing to minimize attenuation in bars.
- Will be tested in 35ton – prototype soon.

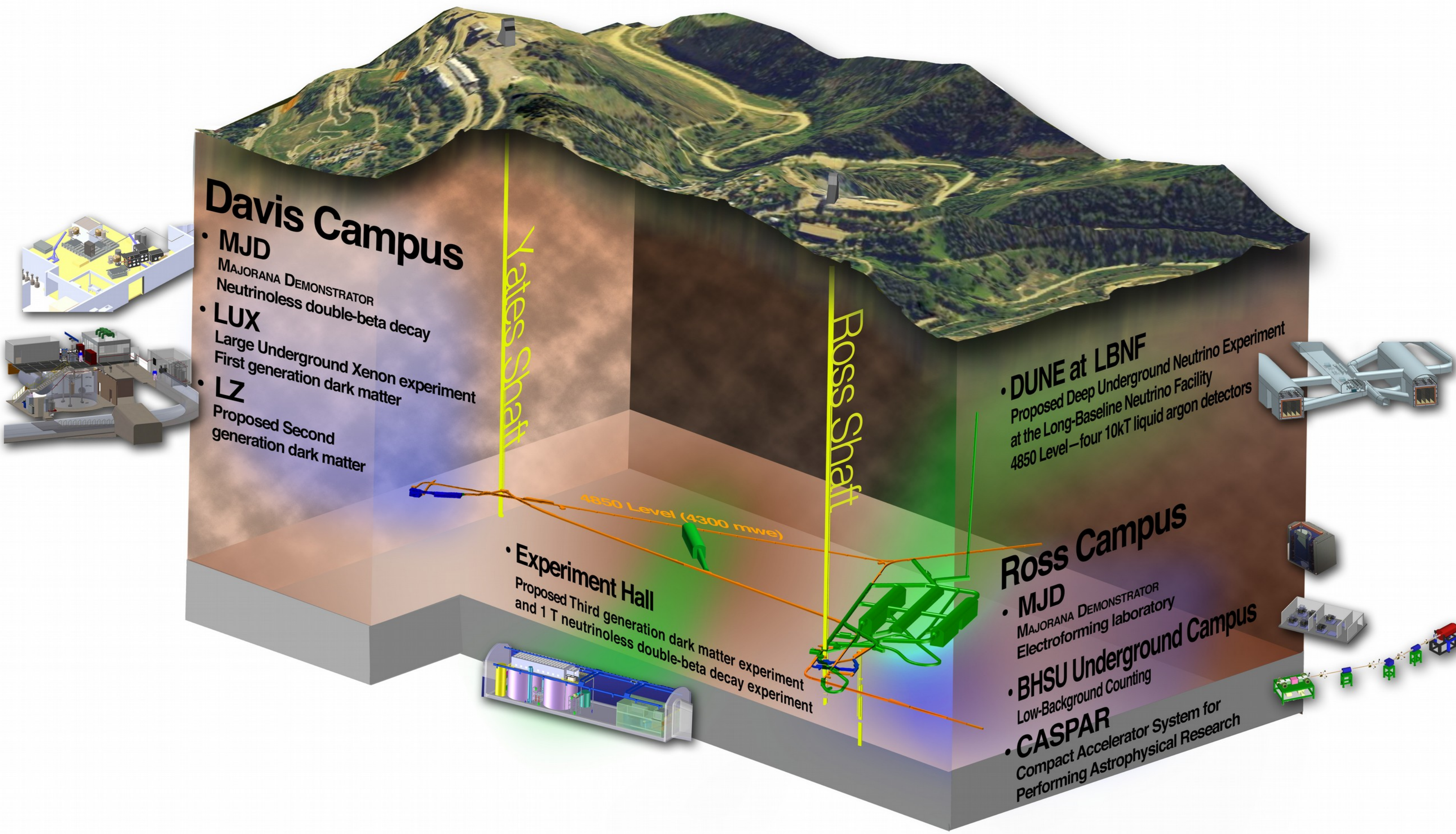








DUNE @ SURF


Davis Campus
• MJD
Majorana Demonstrator
Neutrinoless double-beta decay
• LUX
Large Underground Xenon experiment
First generation dark matter
• LZ
Proposed Second generation dark matter
Yates Shaft
Ross Shaft
4850 Level (4300 mwe)
• Experiment Hall
Proposed Third generation dark matter experiment and 1 T neutrinoless double-beta decay experiment
• DUNE at LBNF
Proposed Deep Underground Neutrino Experiment at the Long-Baseline Neutrino Facility
4850 Level—four 10kT liquid argon detectors
Ross Campus
• MJD
Majorana Demonstrator
Electroforming laboratory
• BHSU Underground Campus
Low-Background Counting
• CASPAR
Compact Accelerator System for Performing Astrophysical Research

SURF: South Dakota Underground Research Facility

- Experimental Facilities at 4850 ft level
- Facility donated to the State of South Dakota for science in perpetuity
- Two vertical access shafts for safety
- Ross shaft refurbishment in progress and is ~55% complete
- Working two 12 hour shifts/day in order to be done by 2017
- Will allow large excavations at SURF in 2017!

LBNF/ DUNE Schedule Summary Overview