CAPTAIN Program

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Motivation

- CAPTAIN is 7-ton LAr TPC to study interaction of Ar with neutrons and low energy neutrinos.

- Why?

- In the light of the DUNE (Deep Underground Neutrino Experiment) future 40 kton LAr TPC, it is essential to measure interaction cross-sections for interaction of neutrons and neutrinos with Ar that are currently unknown

- DUNE goals – use neutrino oscillations to:
  - Determine the neutrino mass ordering
  - Measure lepton CP-violation phase
  - Execute underground physics program: detection of galactic-core supernovae neutrinos, search for nucleon decay

DUNE and LBNF

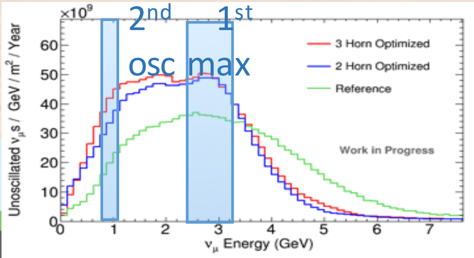
DUNE consists of:

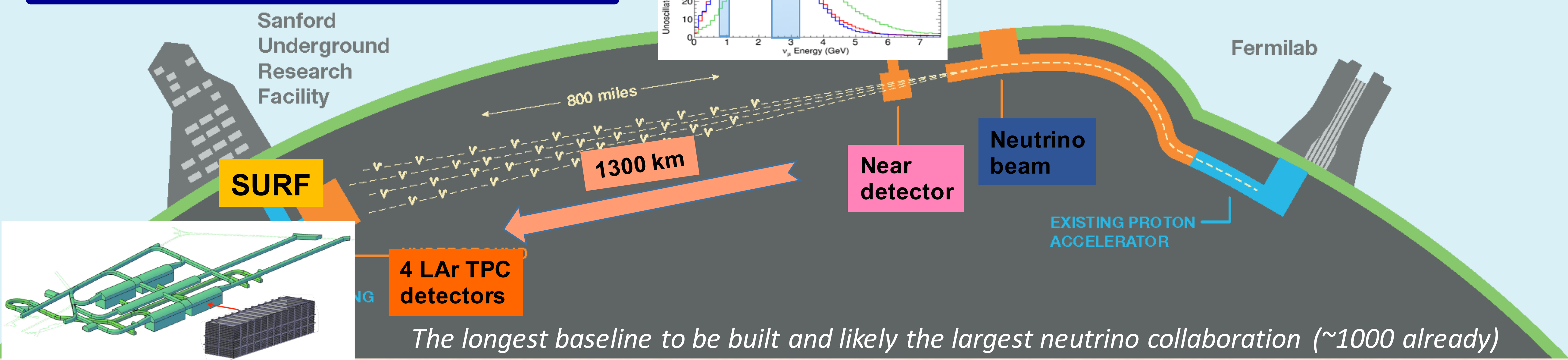
- Far Detector (FD): 4 LAr TPC at SURF
- 40 kton (fiducial) at 1.5 km depth (4300 mwe)
- Near Detector (ND)
- International science collaboration

LBNF (LBN Facility) - **wide-band, on-axis neutrino beam** for DUNE. Unprecedented beam power:

1.2 MW → 2.4 MW
(2026) (II phase)

$\bar{\nu}_\mu/\nu_\mu$ beam: FNAL → FD
1300 km Long Baseline





The longest baseline to be built and likely the largest neutrino collaboration (~1000 already)

DUNE Physics Program Core

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{\tilde{B}_\mp}\right)^2 \sin^2\left(\frac{\tilde{B}_\mp L}{2}\right) + c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{A L}{2}\right) + \tilde{J}\,\frac{\Delta_{12}}{A}\,\frac{\Delta_{13}}{\tilde{B}_\mp} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\tilde{B}_\mp L}{2}\right) \cos\left(\pm\delta - \frac{\Delta_{13} L}{2}\right)$$

Change of sign for antineutrinos

A. Cervera et al., Nucl. Phys. B 579 (2000)

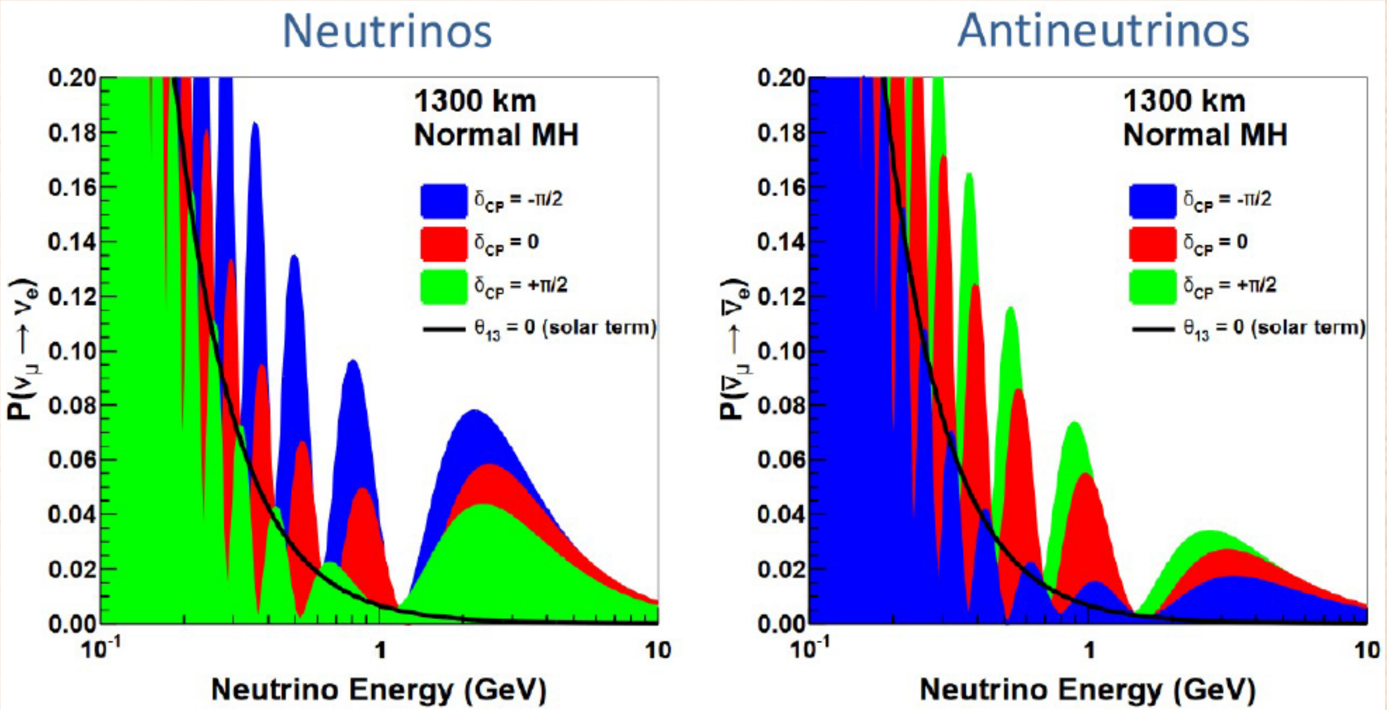
$$\tilde{J} \equiv c_{13}\ \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}$$

$\theta_{13}, \Delta_{12} L, \Delta_{12}/\Delta_{13}$ are small

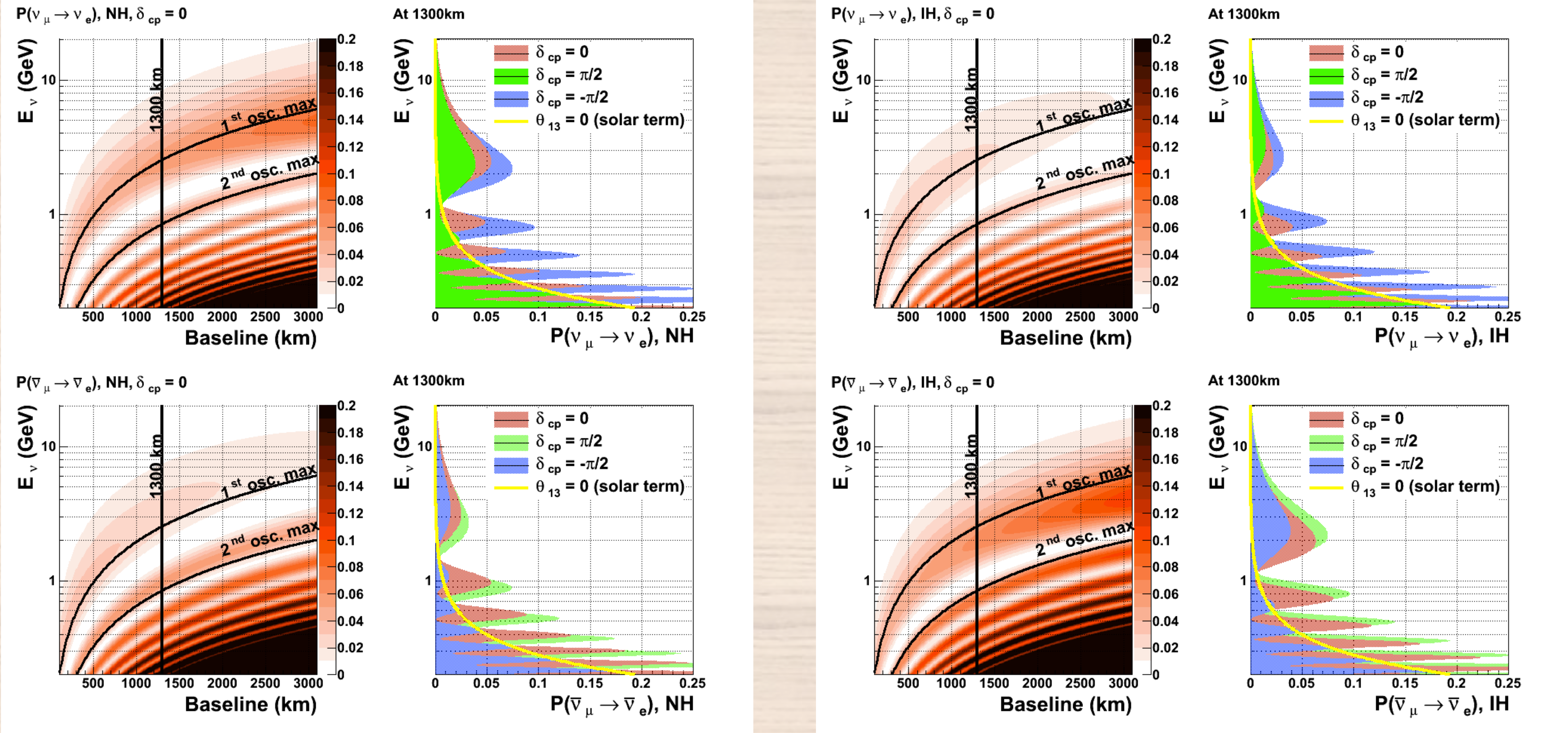
Matter density

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu},\ \ \tilde{B}_\mp \equiv |A \mp \Delta_{13}|,\ \ A = \sqrt{2} G_F N_e$$

- Measure transition probabilities for muon neutrinos and antineutrinos through matter!
- Prob. depends on L&E and nu flavor.
- Oscillations in wide band beam effective for simultaneous measurement of MO, δ_{CP} and ν mixing angles.



Expectations in Case of NMO and IMO



Expected event rates for measurements: δ_{CP}, MO and Oscillations

- Measurements (δ_{CP}, MO, θ_{23}, θ_{13}) rely on analysis of 4 combined samples (optimized beam, 56% LBNF uptime, $\delta = 0$, $\theta_{23} = 45°$, NuFIT parameters, fast MC det. response):

ν mode / 150 kt-MW-yr	νe appearance	νμ disappearance
Signal events (NH / IH)	**945 (521)**	**7929**
Wrong-sign signal (NH /IH)	13 (26)	511
Beam νe background	204	–
NC background	17	76
Other background	22	29

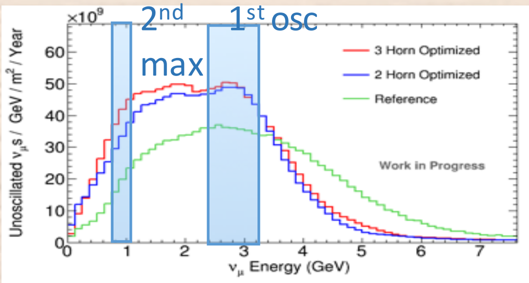
Anti-ν mode / 150 kt-MW-yr	νe appearance	νμ disappearance
Signal events (NH / IH)	**168 (438)**	**2639**
Wrong-sign signal (NH /IH)	47 (28)	1525
Beam νe background	105	–
NC background	9	41
Other background	13	18

40 kt · 1.1 MW · 3.5 yr = 150 kt-MW-yr

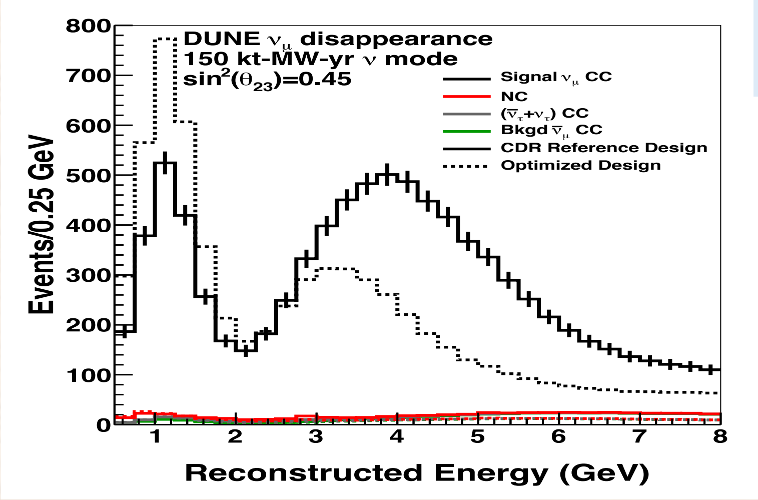
Neutrino spectra in DUNE

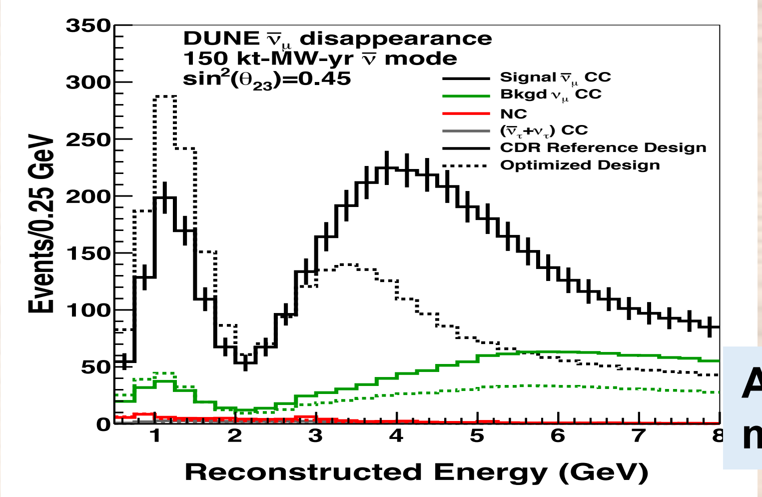
Long baseline: Matter effects are large ~ 40%

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

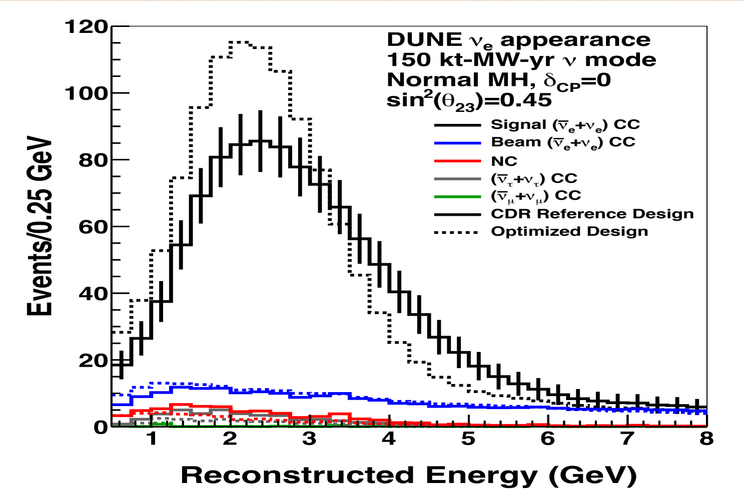


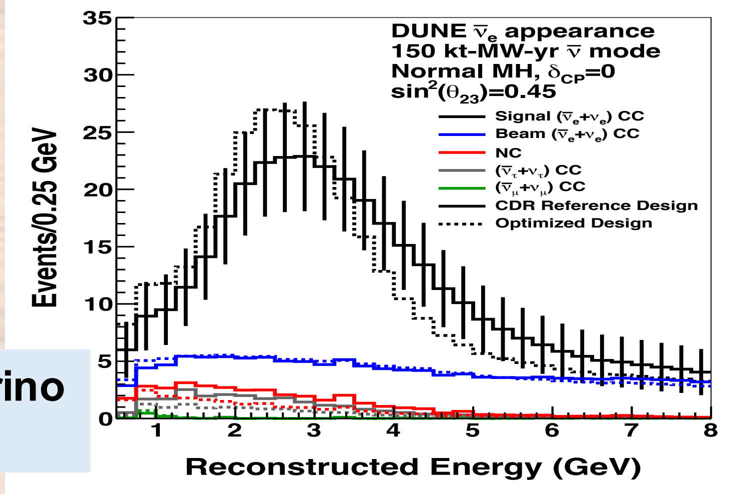
Neutrino mode





ν_μ / $\bar{\nu}_\mu$ disappearance





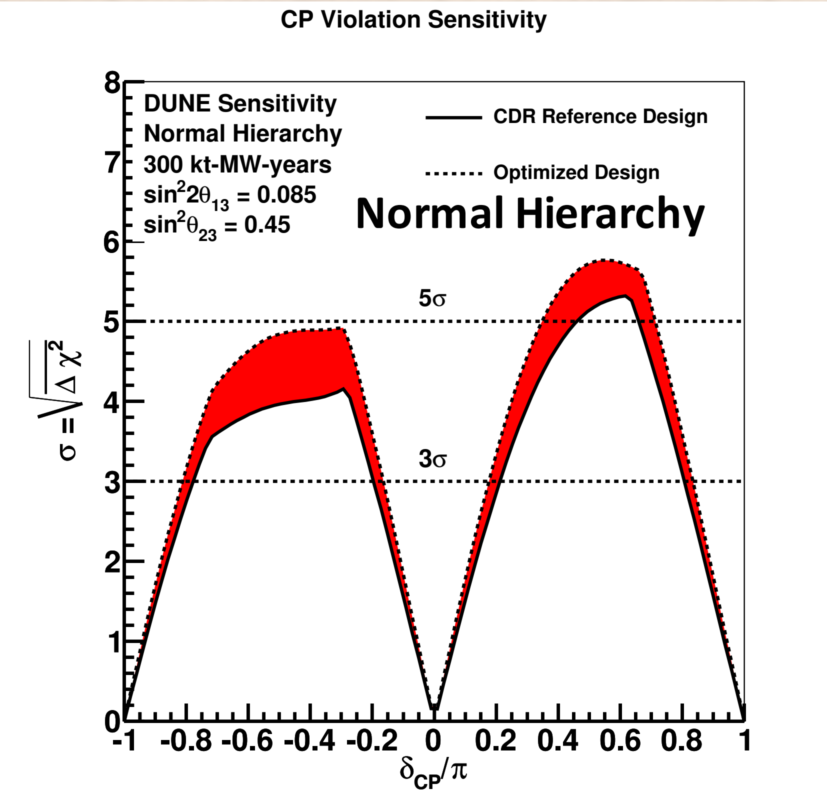
Anti-Neutrino mode

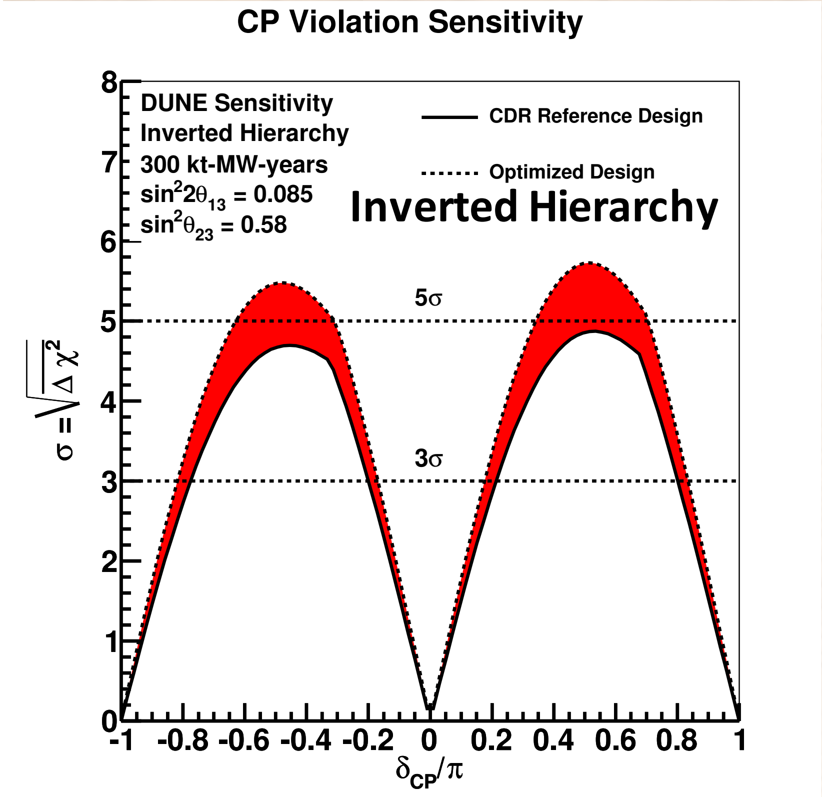
ν_e / $\bar{\nu}_e$ appearance

Dependence of CP Violation on MO

- Sensitivity to CPV after 300 kt-MW-yrs
- Software configuration available on arXiV: 1606.09550

- Bands represent range of beam configurations

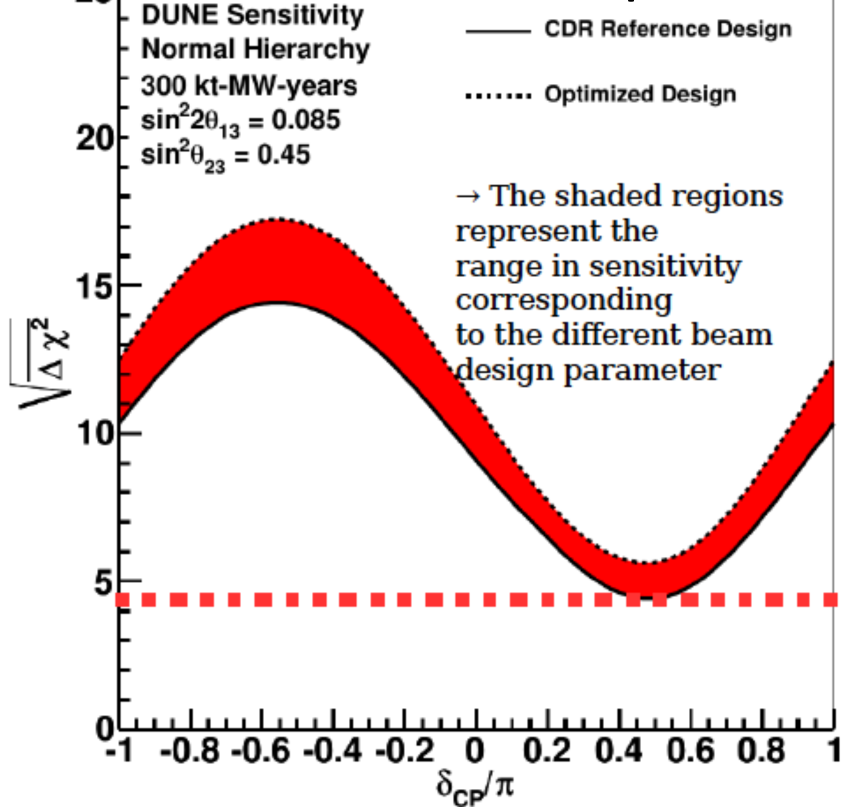


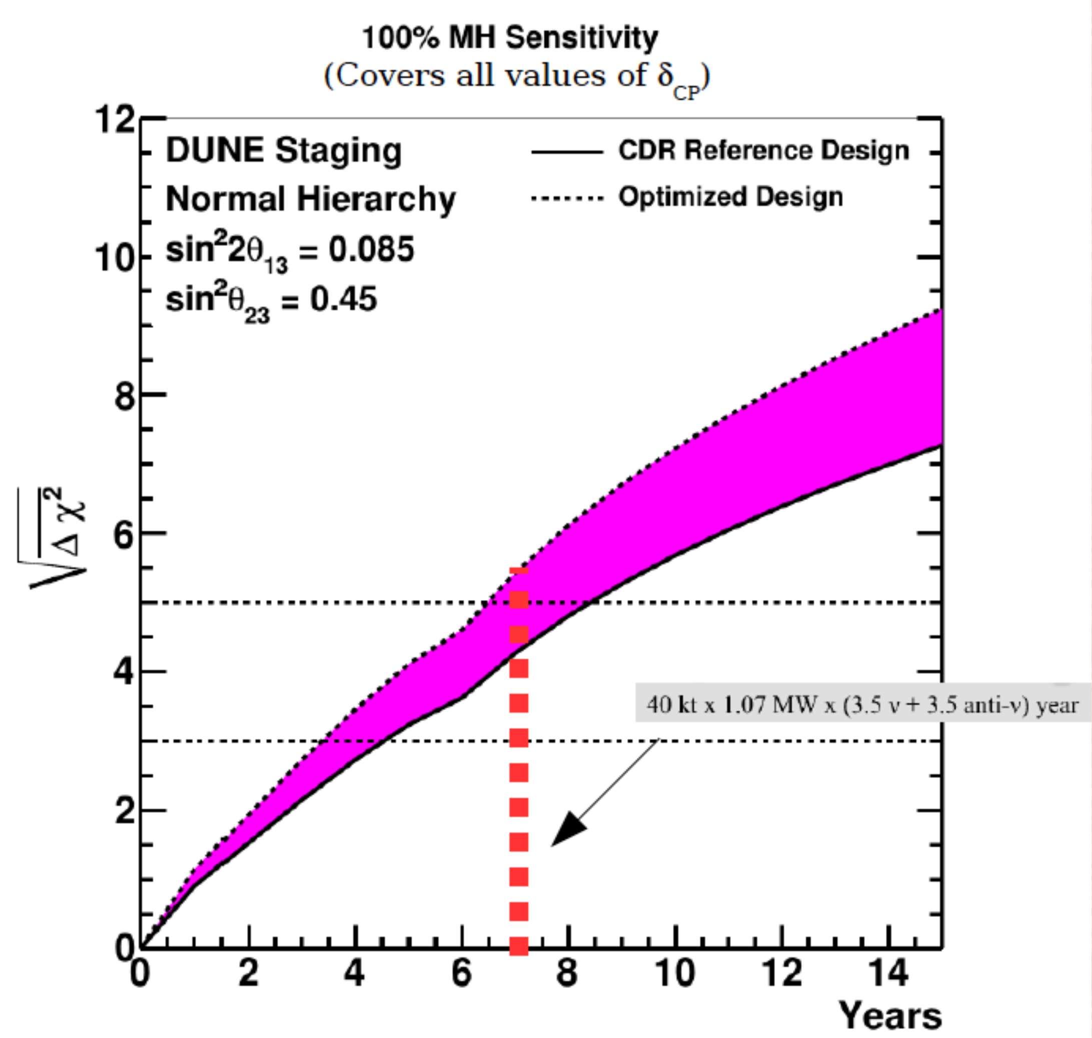


DUNE: CPV and MO sensitivity

- Sensitivity to MO as:
  - function of exposure in kton-MW-yrs and
  - Fraction of δ_{CP} values with given sensitivity or greater.

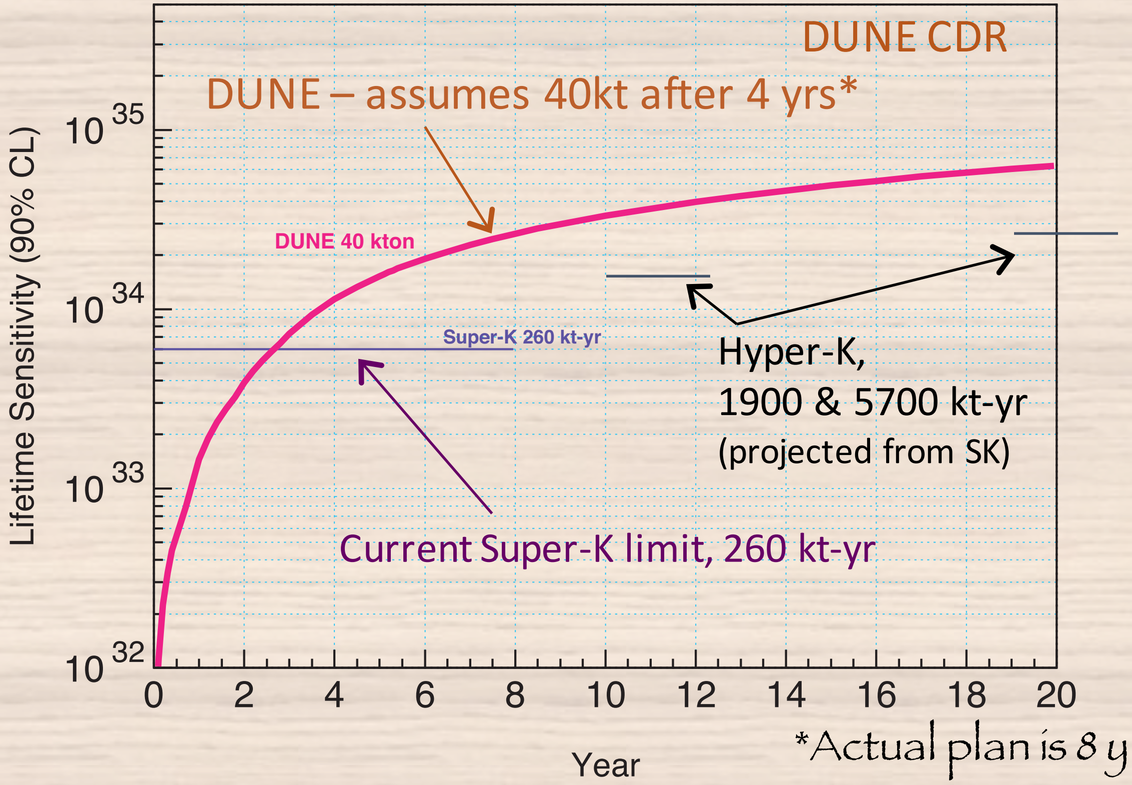
MO for all values of CPV phase

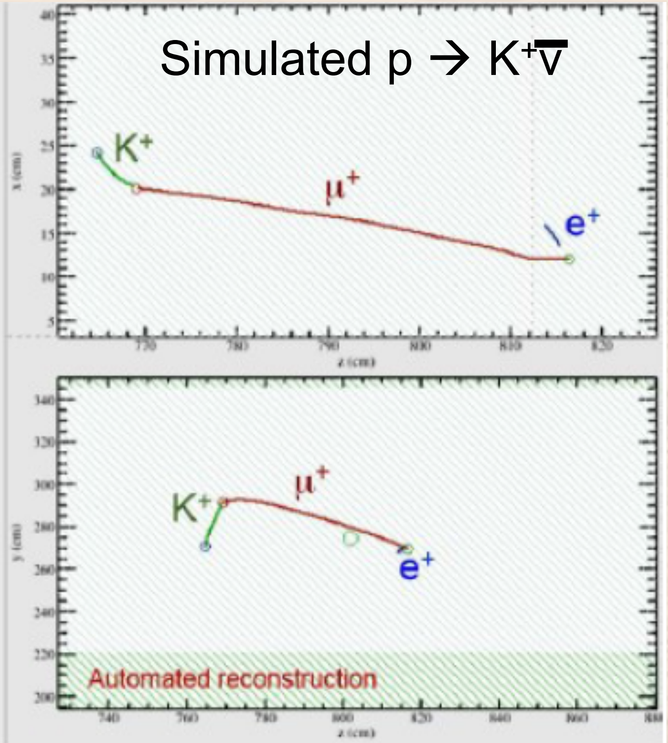




Nucleon Decay Sensitivity

- ✓ Proton decay – test of baryon number conservation.
- ✓ May explain matter-antimatter asymmetry.
- ✓ Many accessible modes, including SUSY favored: $p \rightarrow K^+ \bar{\nu}$
- ✓ Sensitive, bkg. free searches thanks to imaging, dE/dx and calorimetry in LAr TPC.





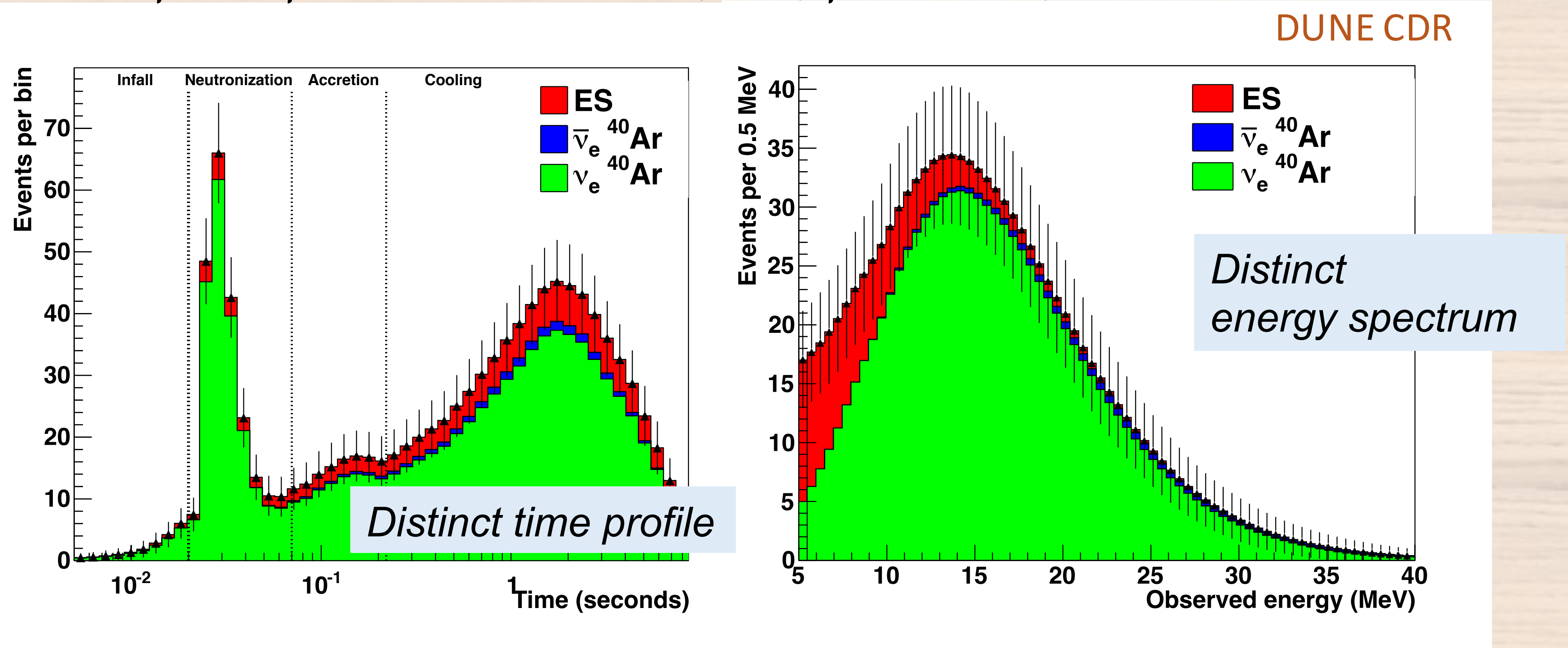
*Actual plan is 8 yrs to reach 40kt;

Supernovae Neutrino Burst Detection

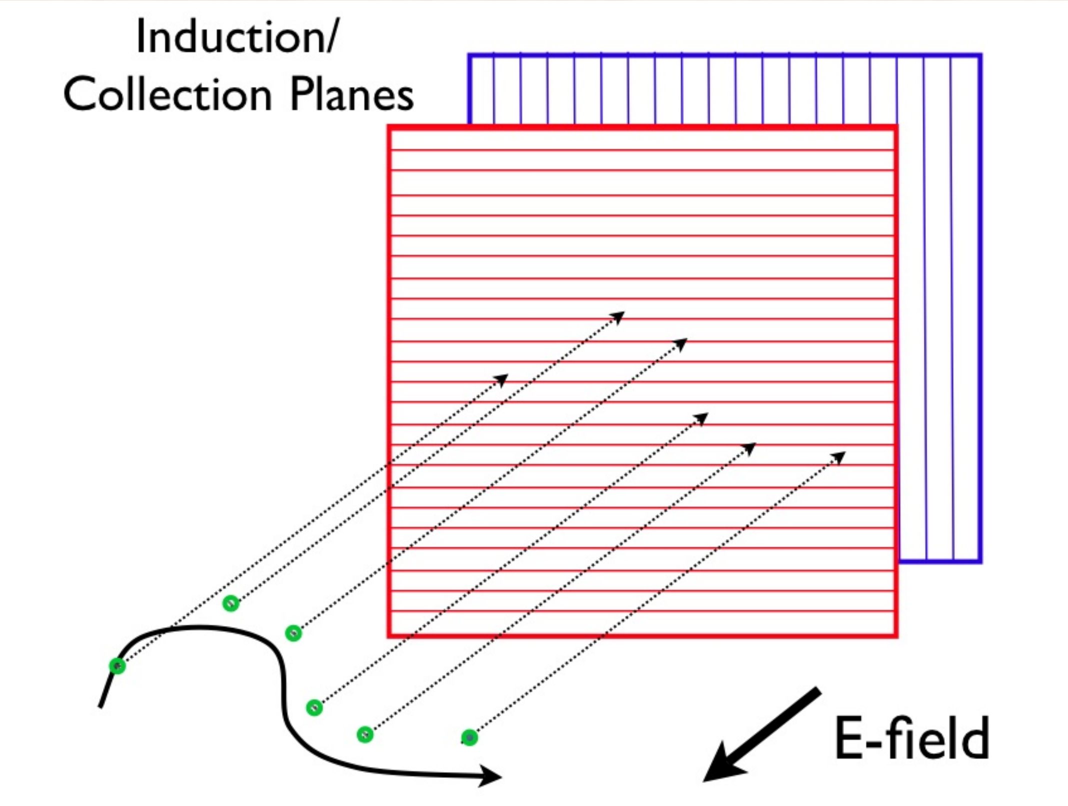
- About 99% of the gravitational binding energy of the proto-neutron star goes into neutrinos → few thousand events expected for galactic SN
- Dominant process: $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$

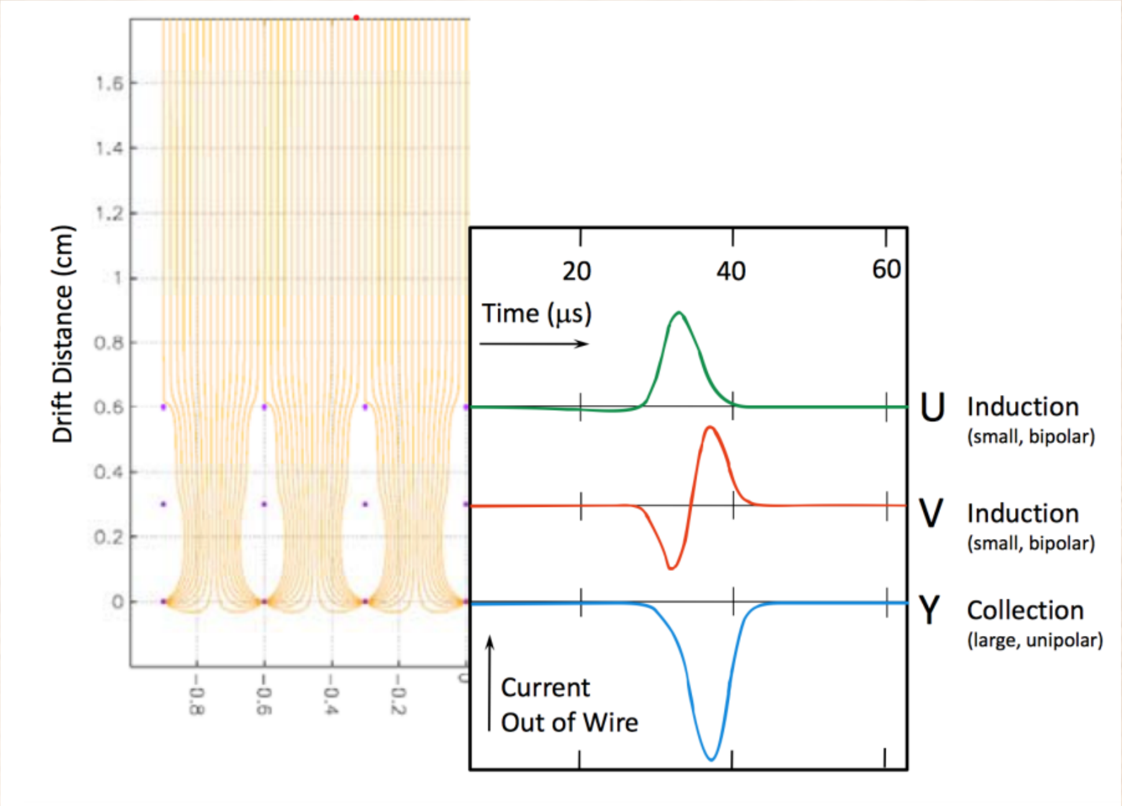
**Contrary to water/LS Detectors – antinu dominate*

- LAr uniquely sensitive to CC current electron neutrino interactions and neutronization process at ~30ms.
- Elastic event – may give directionality.
- Expect 2-3 core-collapse supernovae in the Milky Way per century ≈ 3500 neutrinos in DUNE for SN@



FD technology – Liquid Argon Time Projection Chamber

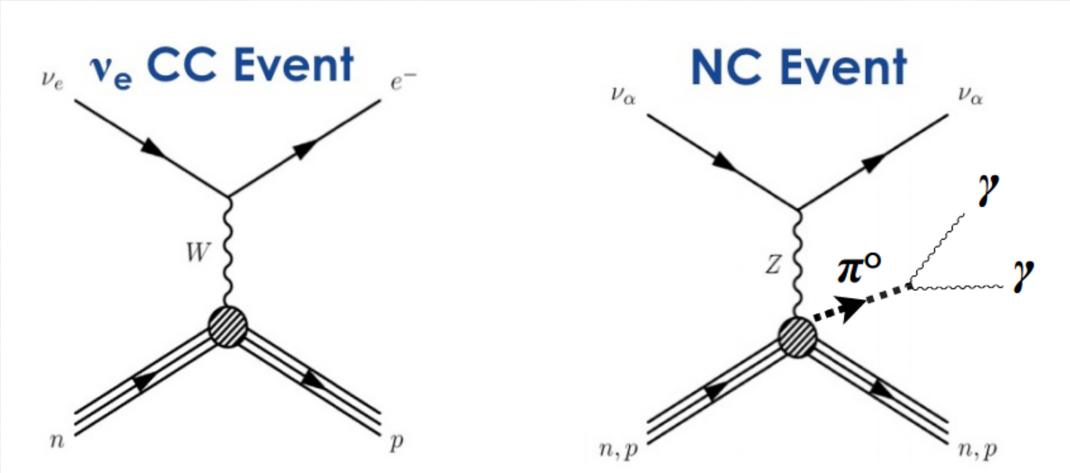


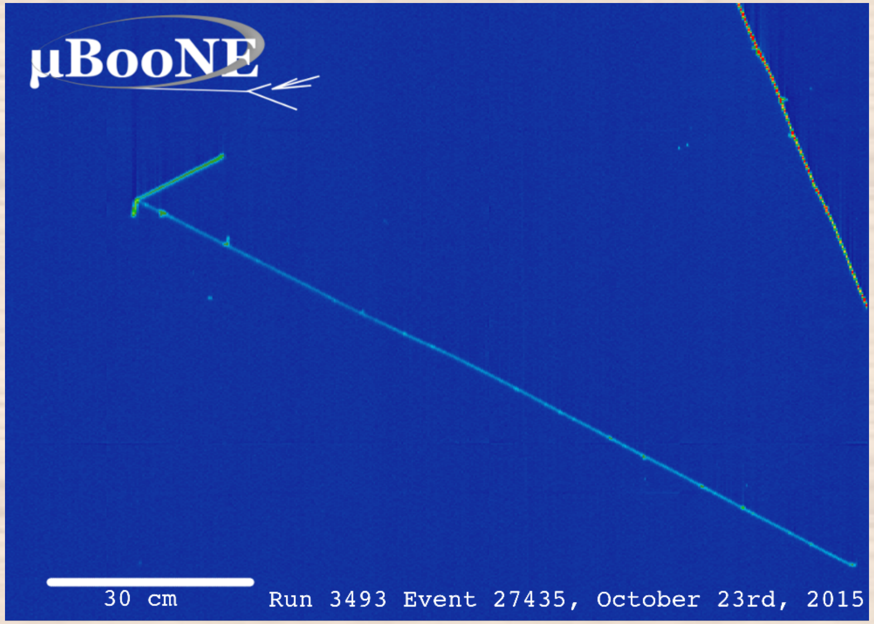


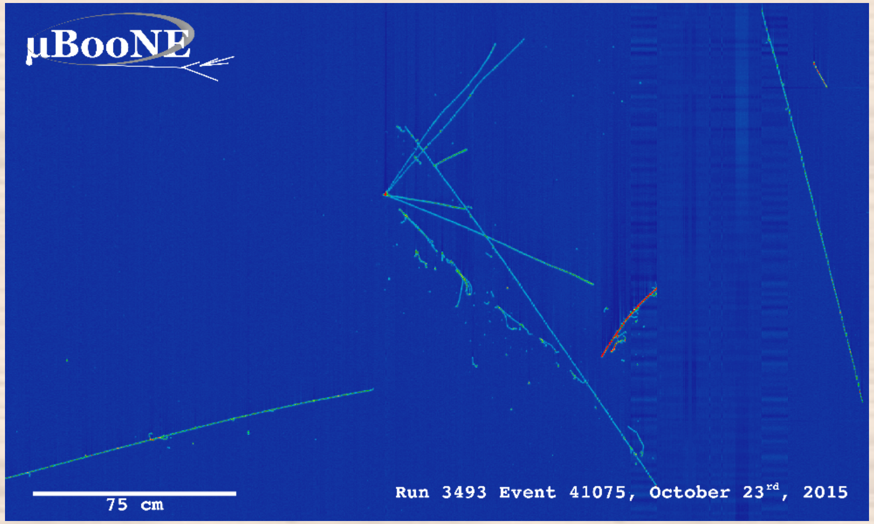
- LAr TPC: excellent tracking and calorimetry
- High resolution, 3D reconstruction – charged particles ionize Ar; electrons drift to anode wires (~ms) for xy coordinate; drift time – z coordinate
- Ar scintillation light (~ns) detected by photon detectors – provides t_0

Why use LArTPCs for neutrino physics?

- Dense target for neutrino interactions
- Ample ionization/scintillation for detection
- Good efficiency and background rejection
  - Good e/gamma separation – important for electron neutrino appearance searches

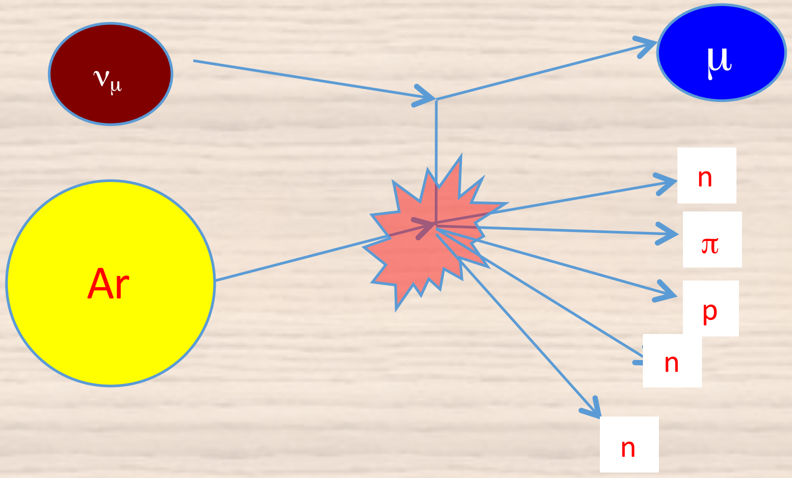




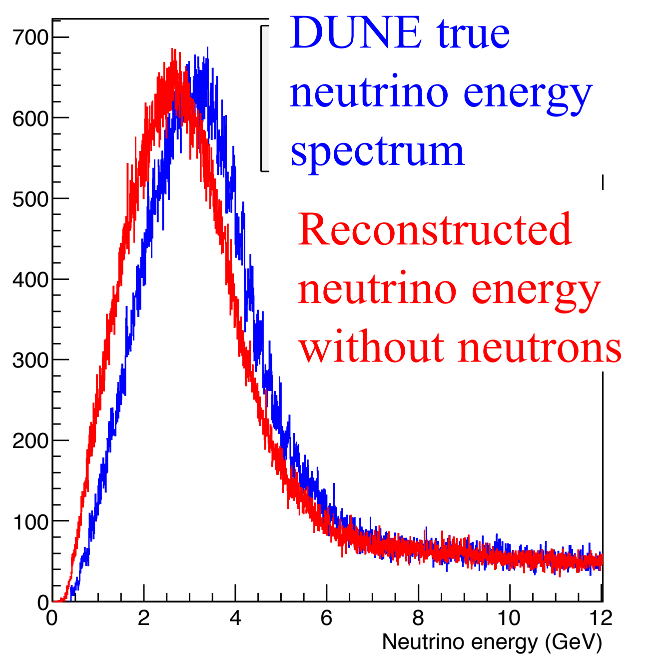


DUNE Physics Requirements

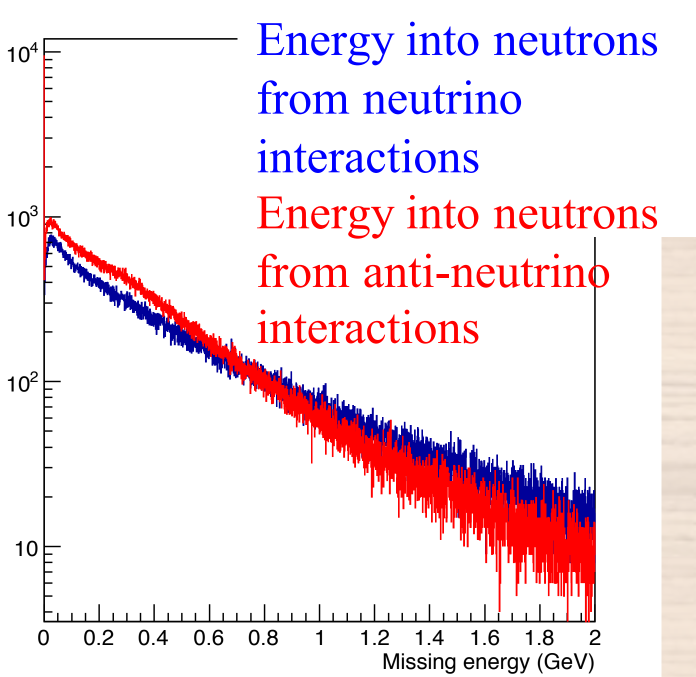
- DUNE utilizes a broad-band neutrino beam – must reconstruct the true neutrino energy based on visible particles to succeed;
- Oscillations depend on true neutrino energy!
- Critical to understand the correlation between true and reconstructed neutrino energy – especially any differences between neutrinos and anti-neutrinos



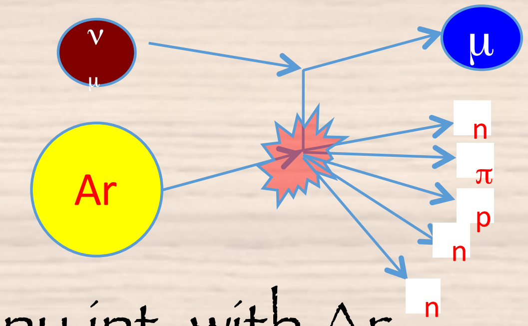
DUNE Neutrino Energy Spectrum



Outgoing energy in neutrons



DUNE Physics Challenges



- Challenges:
  - Neutron event signatures in Ar; # and E of emitted neutrons in nu int. with Ar unknown
  - Higher-energy neutron-induced processes that could be backgrounds to e nu appearance, e.g. $^{40}\mathrm{Ar}(n,\pi^0)^{40}\mathrm{Ar}^{(*)}$ not measured
  - Neutron production of spallation products on Ar unknown
  - CC and NC cross sections in the neutrino energy range relevant for supernova neutrino detection not measured (only theoretical predictions available)
  - Correlation between true neutrino energy and visible energy for events in the neutrino energy range relevant for supernova neutrino detection unknown

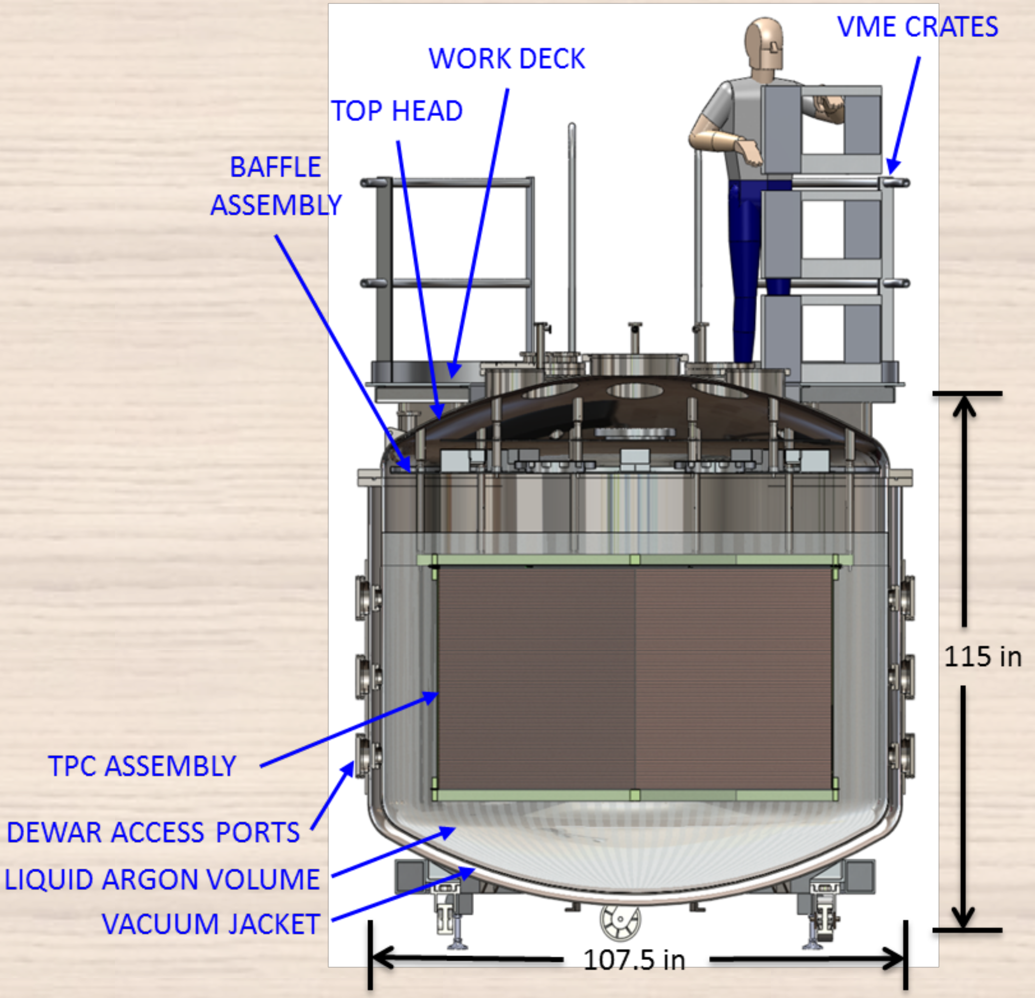
- *How can CAPTAIN, and its prototype mini-CAPTAIN detector, help?*

→ deployment of LAr TPCs in a wide energy neutron beam at LANL and subsequent deployment in the stopped pion source for low energy neutrino run

CAPTAIN - and MiniCAPTAIN

CAPTAIN - Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos

- Liquid argon TPC detector:
  - Portable and evacuable cryostat
  - 5 tons of instrumented liquid argon
- TPC:
  - Hexagonal prism, 1 m vertical upward drift
    ($E \approx 500$ V/cm, $v_d \approx 1.6$ mm/μs)
  - 2001 channels (667/plane), 3 mm pitch and wire spacing
- Laser calibration system
- Photon detection system



- **Mini-CAPTAIN (mC)**: a smaller prototype detector, yet large enough to make interesting physics measurements:
  - 0.4 tons of instrumented LAr & 30 cm of vertical upward drift

CAPTAIN Hardware Status

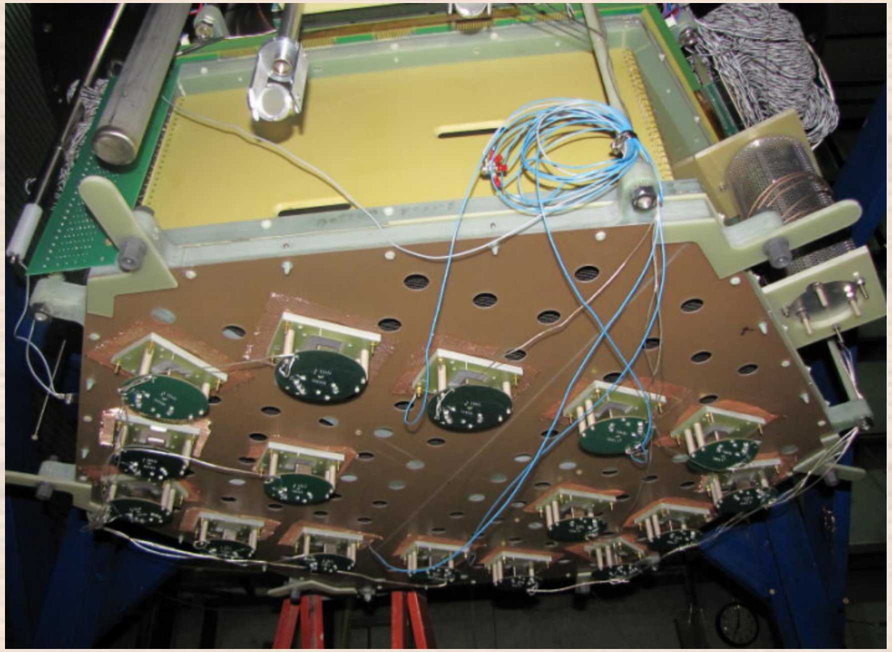
- Many components used in Mini-CAPTAIN will be utilized for CAPTAIN, but some are still missing:
  - All electronics has been tested as part of Mini-CAPTAIN's commissioning
  - Recirculation system for liquid argon purification is in hand and installed on Mini-CAPTAIN (switch from gas to liquid recirculation)
  - Some wire plane and field cage components are in hand; wire planes and full TPC have not been assembled
  - Cryostat has been built and pressure tested
  - Motorized optical feedthrough for the laser system (computer-controlled laser alignment) fabricated

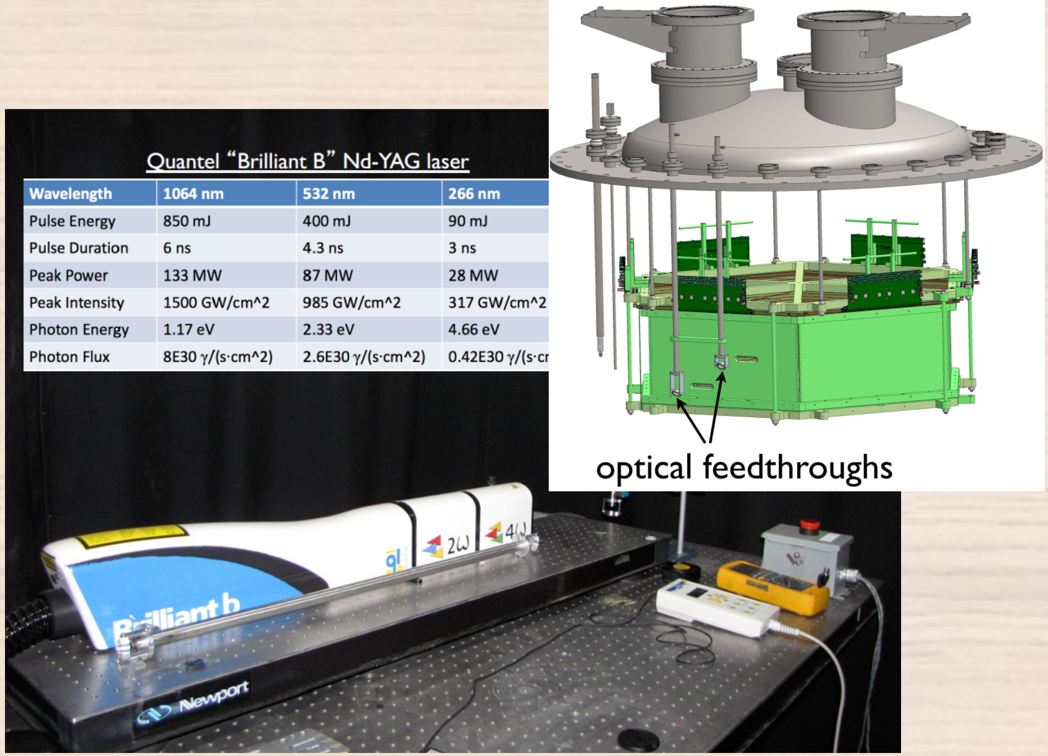
Mini-CAPTAIN Status

- Built as a prototype for CAPTAIN, but due to its large size → excellent opportunity for physics running
- A couple of engineering and one physics runs in the past two years:
  - liquid nitrogen fill to test electronics and TPC
  - test cryogenic and purification system, DAQ development, laser system testing
  - installation of gas (now changed to liquid) recirculation system, integration with muon system
  - more development of electronics and recirculation system

Mini-CAPTAIN Detector

- 400-kg instrumented mass of liquid argon – 2-tons of total liquid argon
- Hexagonal TPC, 3-mm wire pitch, 1000-channels, 0.5-meter apothem, 32-cm height
- Field cage generates 500-V/cm electric field – electrons drift upward
- Photomultiplier Tube-based photon detection system (PDS) for time-of-flight
- 266 nm NdYag laser system and laser positioning system for accurate laser beam positioning



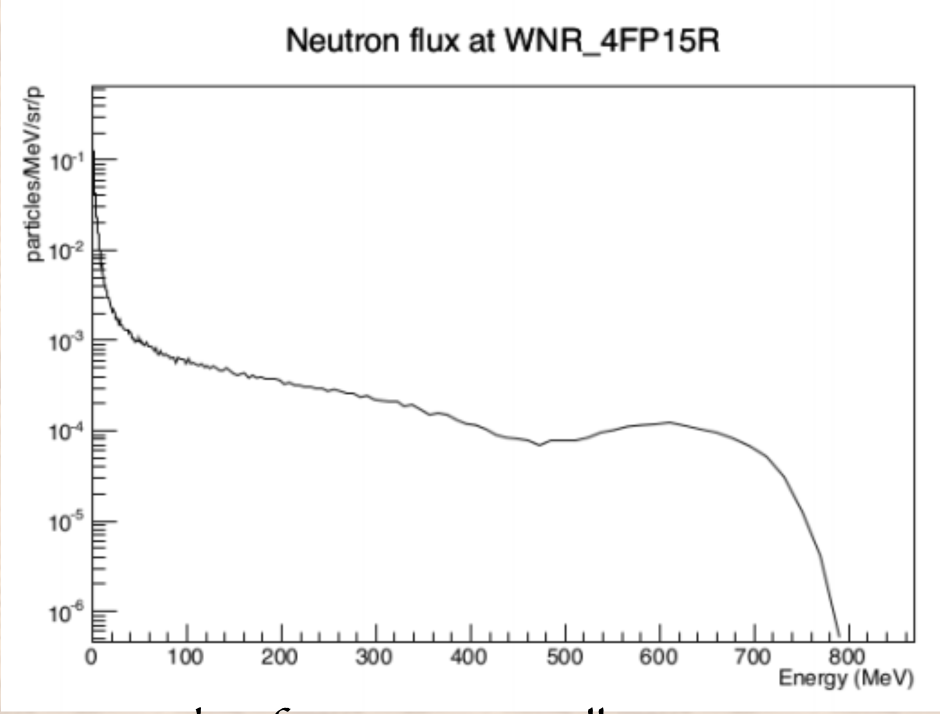


Quantel "Brilliant B" Nd-YAG laser

Wavelength	1064 nm	532 nm	266 nm
Pulse Energy	850 mJ	400 mJ	90 mJ
Pulse Duration	6 ns	4.3 ns	3 ns
Peak Power	133 MW	87 MW	28 MW
Peak Intensity	1500 GW/cm^2	985 GW/cm^2	317 GW/cm^2
Photon Energy	1.17 eV	2.33 eV	4.66 eV
Photon Flux	8E30 γ/(s·cm^2)	2.6E30 γ/(s·cm^2)	0.42E30 γ/(s·cr

Mini-CAPTAIN in neutron beam

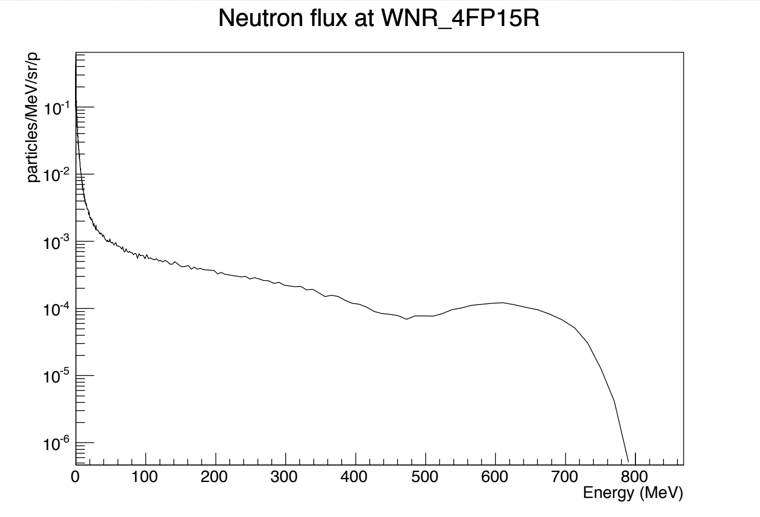
- Mini-CAPTAIN utilizes neutron beam at Los Alamos Neutron Science Center (LANSCE) at LANL
- Initial run – one week in February 2016
  - Data had limited quality (good photon detection, BUT short tracks)
  - Next run – two weeks in July 2017
  - Will utilize laser calibration to cross-check purity via laser induced tracks across the detector

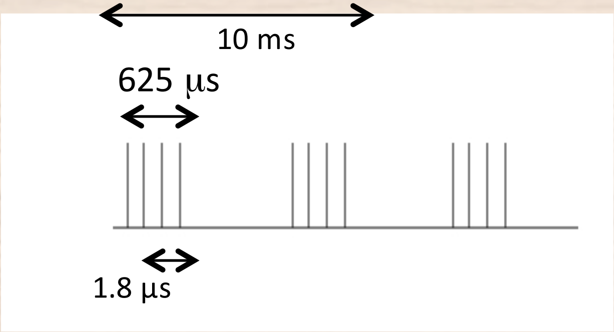


Planned measurements:

- High intensity neutrons: a single day of running will produce years worth of neutron spallation events
- Low-intensity high-energy neutrons: address neutron energy reconstruction for DUNE by studying the signature of neutrons of known kinetic energy (by time-of-flight) : the multiplicity and identity of the visible particles in the final state and their kinematic properties.
- Low-intensity low-energy neutrons: Identifying de-excitation events in LAr, i.e. study $n^{40}Ar \rightarrow n^{40}Ar^{(*)}$ to gain insight into identifying NC interactions of supernova neutrinos $n^{40}Ar \rightarrow n^{40}Ar^{(*)}$

Neutron Flux at mini-CAPTAIN

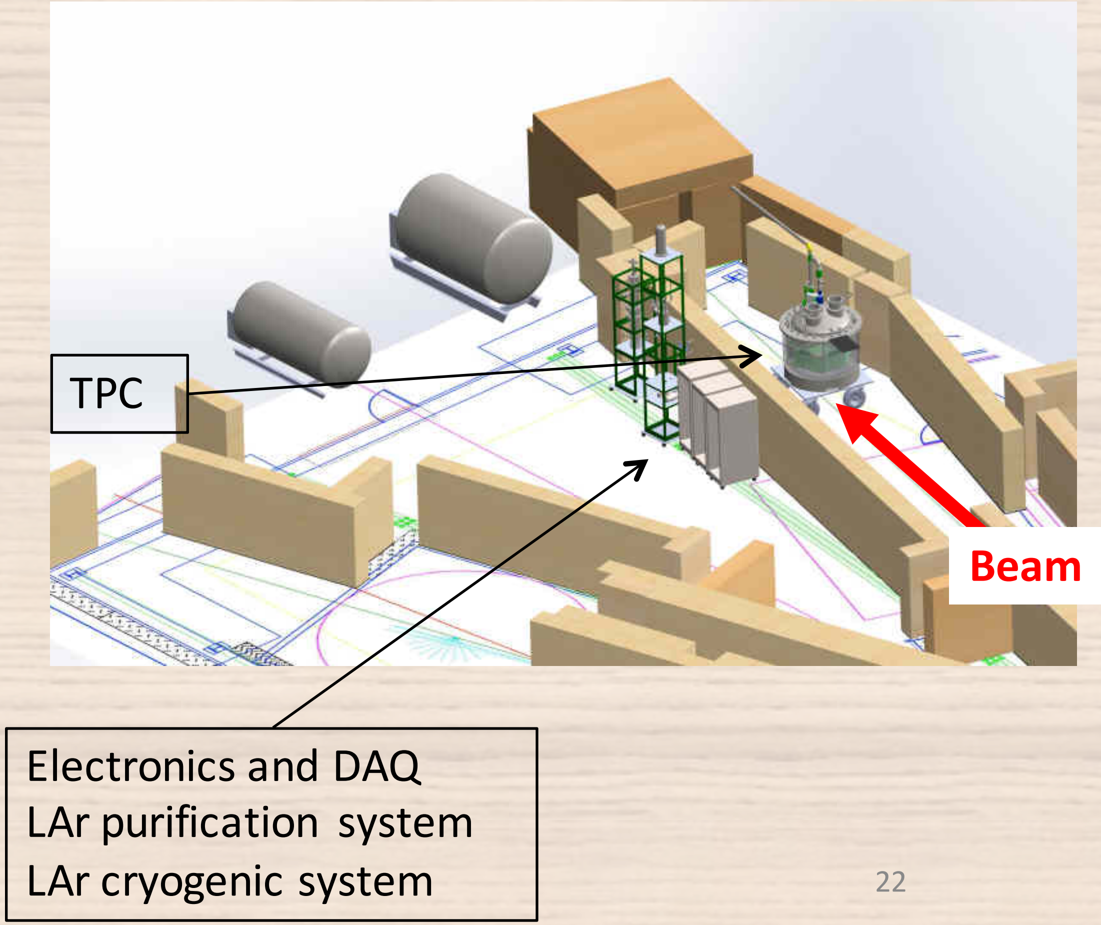




- 20 MeV neutron mean free path in LAr ~ 25 cm -> almost all neutrons will interact
- No more than few neutrons/drift time (200 μs for Mini-CAPTAIN)
- Achieved by narrowing the shutter jaws thanks to their wedge-like shape along the beam direction
- The incoming flux will be measured using a ~1cm thick scintillator + PMT
  - Thin enough to intercept ~ 1 neutron in 100
  - Thick enough to obtain an overall 5% statistical accuracy in 1 minute at 3 n/macropulse

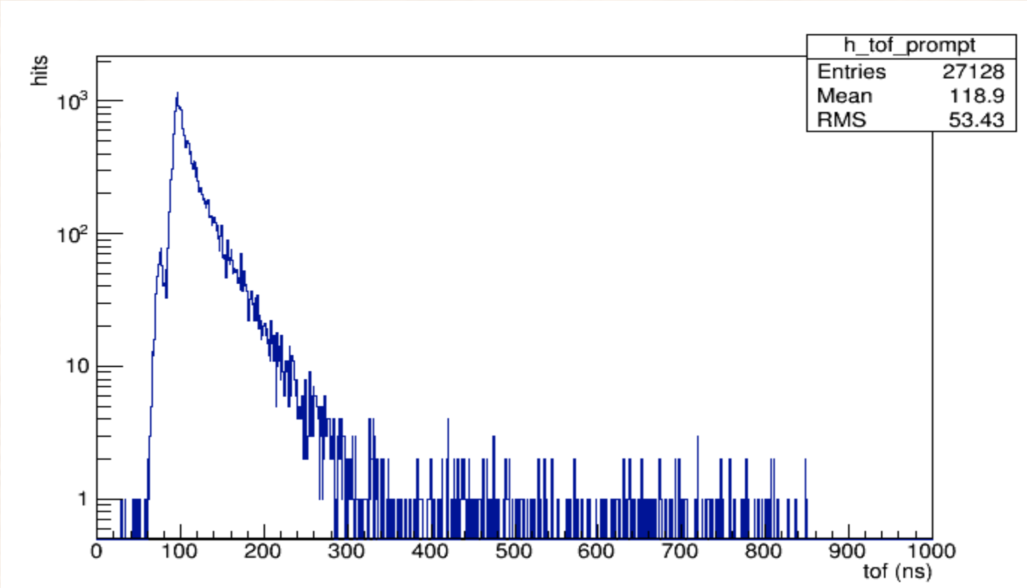
Mini-CAPTAIN Neutron Run Setup

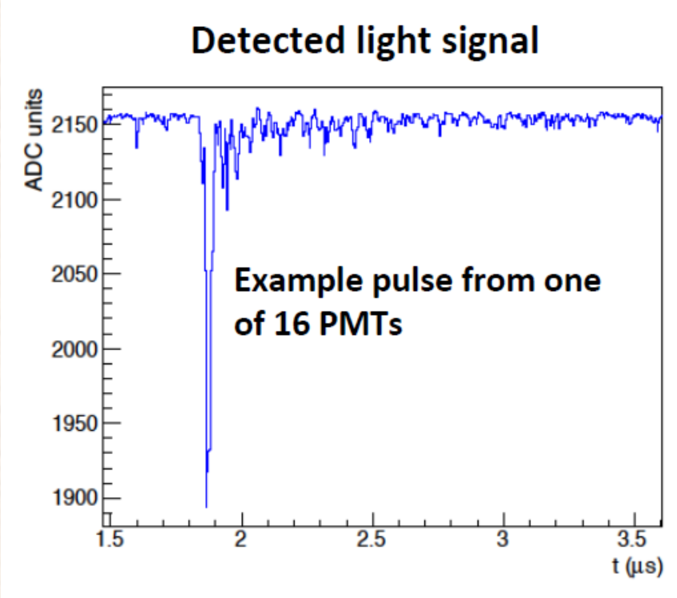
- Using time-of-flight techniques, correlate a visible interaction in mC with a neutron of a specific kinetic energy.
- Photon detection system and scint. counter used for TOF.



Outcomes of the February 2016 neutron run - PDS

- 16 1-inch PMTs immersed in LAr, facing the TPC up to observe scintillation in LAr.
- Excellent performance of 15 out of 16 PMTs in the PDS – good enough for t_0.
- Adequate time resolution to observe gamma peak in TOF spectrum.





Outcomes of the February 2016 neutron run - TPC

- TPC electronics and field cage stable during the run.
- Oxygen and water < 1 ppb required, but oxygen sensor stopped working before the run above 1 ppb. Initially, Ar fill at 1 ppm.
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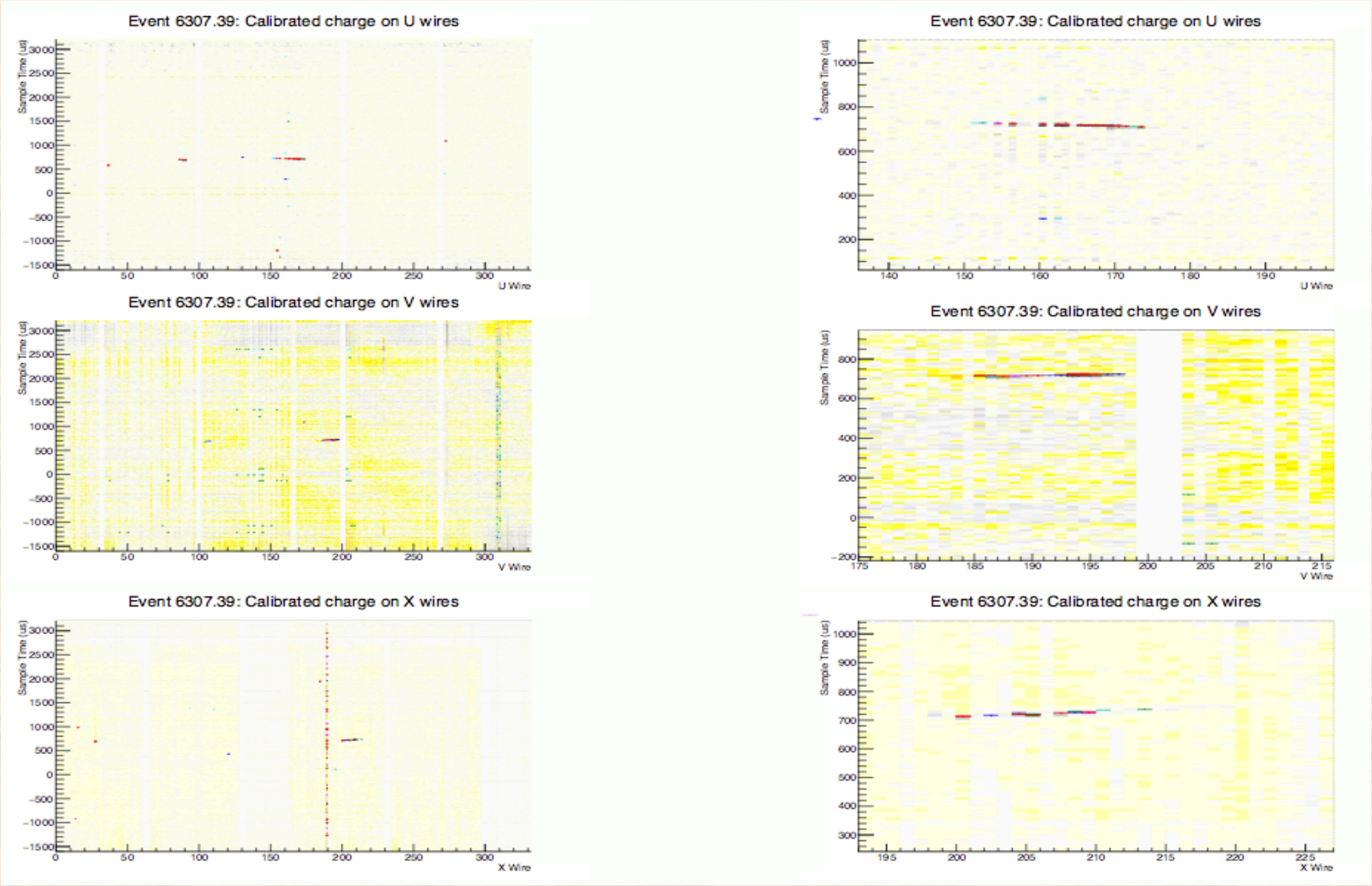
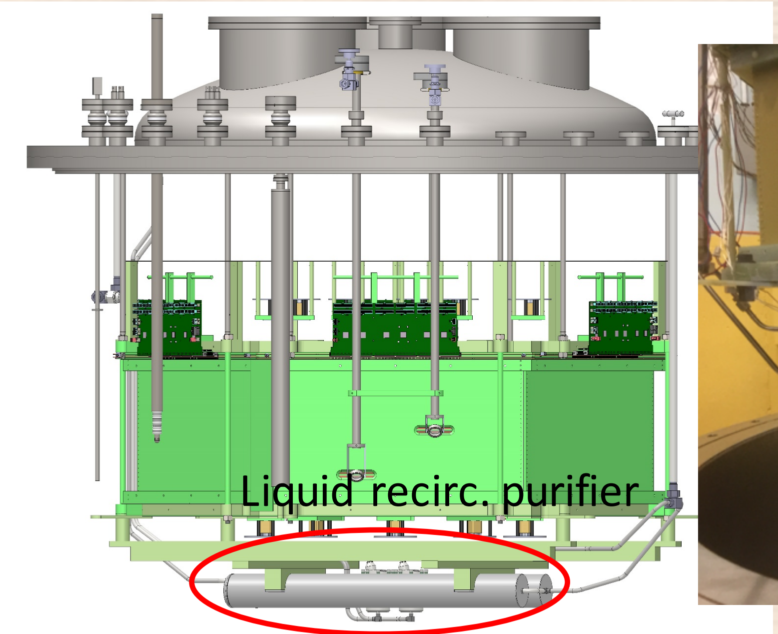
- LAr purity not adequate to see tracks across the whole drift distance
- Electrons lifetime measured from data ~ 20 ms
- Need ~200 ms lifetime to see ionization produced near the cathode plane – 1 ppb of oxygen and water



Improvements toward July 2017 neutron run with mC

- New in-liquid purification system installed in April 2017 – a similar system was used to achieve 5m drift in a different detector.
- Added 16 more PMTs to the top of the TPC to light collection efficiency for low energy n-Ar int-s.
- Added laser calibration system for in-situ calibration of the tracks (laser calibration performed 2 years ago during commissioning, but not in the beam run).
- Added laser positioning system to mC field cage on the outside.



CAPTAIN Future

- CAPTAIN was scheduled to run at Fermilab in their medium and low energy neutrino beams – but the program was terminated in late Spring 2016.
- As an alternative, we have been investigating opportunities to run at the Spallation Neutron Source (SNS) at Oakridge national lab.
- Provides intense neutrino beam from stopped pion source in the energy range of interest for supernovae neutrino detection.

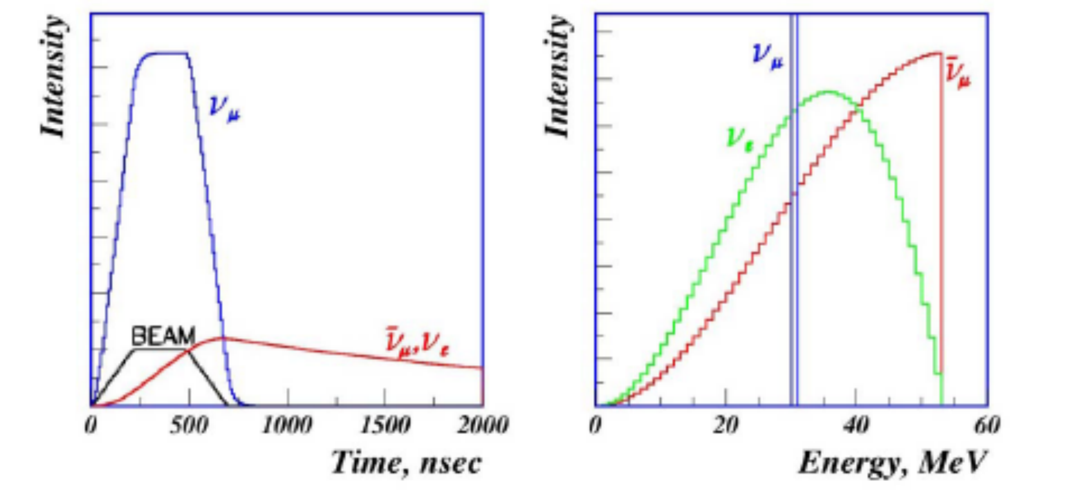


Figure 1. Time and energy distributions for different neutrino flavors produced at the SNS.

arxiv.org/pdf/0807.2801

Goal: Study neutrino-argon interactions in the energy range relevant for supernova detection

Cross sections have never been measured in this energy range and have large theoretical uncertainties.

Measure the neutrino-argon xsec to about 10% for neutrino energies of O(10) MeV.
Test the ability of detecting SNe with LAr detectors (triggering, timing).

Summary and Outlook

- DUNE will provide the most comprehensive measurement of CP-violation angle and mass ordering, and will have unique detection abilities for supernovae neutrinos and nucleon decay.
- If not determined before, DUNE will measure MO with 5σ C.L. by 2032.
- However, crucial to this program is:
  - accurate reconstruction of true neutrino energy based on visible particles including neutrons.
  - Measurement of neutrino-Ar interaction c-s in the low energy range, known only theoretically at this point, and important for supernovae neutrino measurement.
- Mini-CAPTAIN is in unique position to characterize neutron interactions in Ar with July 2017 run.
- CAPTAIN will measure neutrino-Ar xsec at 10% and validate ability of Ar TPC to detect neutrinos in the supernovae neutrino energy range.

Thank you!

- *CAPTAIN Collaboration:*
  - Scientists from: Alabama, ANL, LBL, BNL, UC Davis, UC Irvine, UCLA, UPenn, FNAL, Hawaii, Houston, Indiana, LANL, LSU, New Mexico, South Dakota, South Dakota State, Stony Brook
  - Spokesperson: Christopher Mauger (Upenn)
  - Deputy Spokesperson: Clark McGrew (Stony Brook)