CAPTAIN – Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrino

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University of Hawaii at Manoa
(on behalf of the CAPTAIN collaboration)

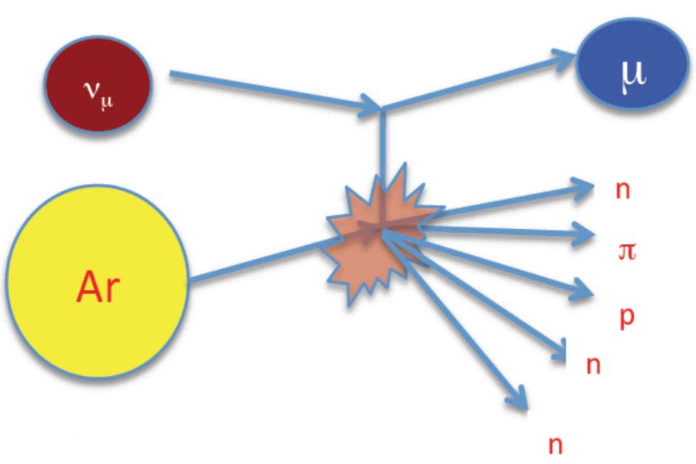
INFO 15, Santa Fe, July 13~17th, 2015

Physics Motivations

- The CAPTAIN program is designed to make measurements of scientific importance to long-baseline neutrino physics and physics topics that will be explored by large underground detectors (DUNE).
- There is only limited data available in neutrino energy range relevant for the long-baseline neutrino experiment.
- Cross-section for interaction of neutrinos at low energy (15 MeV) are poorly known which is an important part for DUNE physics program (SN ν detection).
- There is no neutron-argon measurements that is important for event reconstruction in neutrino-argon interactions and understanding of the neutron related background.
- CAPTAIN will directly address these topics that are either significant requirements or can navigate the DUNE experiment design.

Neutron Measurements Plan

- Neutron runs at Los Alamos Neutron Science Center (LANSCE).
  - Impact both medium and low energy neutrino runs.
  - Detection and identification of de-excitation events decide whether or not SN NC interactions are detectable.
  - Counting and evaluating neutron energy in LArTPC.
  - Final state topology, multiplicity, and identity of the visible particles produced along with neutron kinematic properties.
  - Spallation products (bkg to SN and maybe ν_e appearance).



Medium Energy Neutrino Measurements Plan

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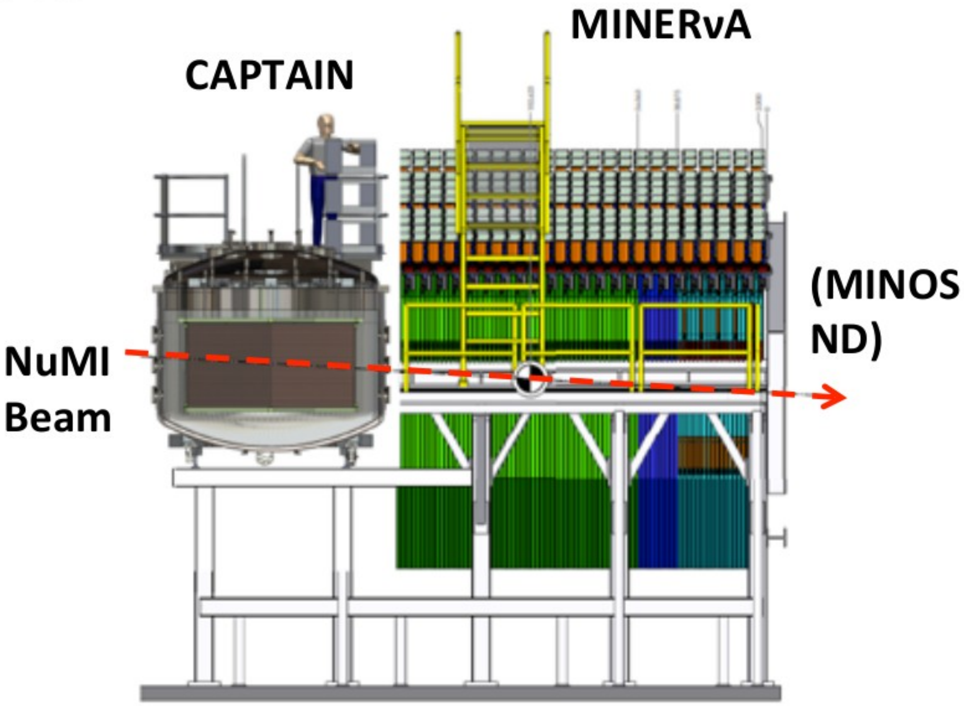
- Medium energy neutrino runs at NuMI beamline (on-axis).
  - Neutrino energy 1~10 GeV complementary to MicroBooNE experiment (0.5~2 GeV).
  - Full CC cross-section is needed for oscillation analysis. The long-baseline experiment simply will not work without it.
  - Detailed studies of CC and NC inclusive and exclusive channels in the important and poorly understood neutrino energy range where baryon resonances dominate.
  - Evaluation of energy reconstruction technique developed from neutron studies.
  - A proposal recently submitted to the Fermilab PAC. Will form a joint collaboration with members from both the CAPTAIN and MINERvA.



Low Energy Neutrino Measurements Plan

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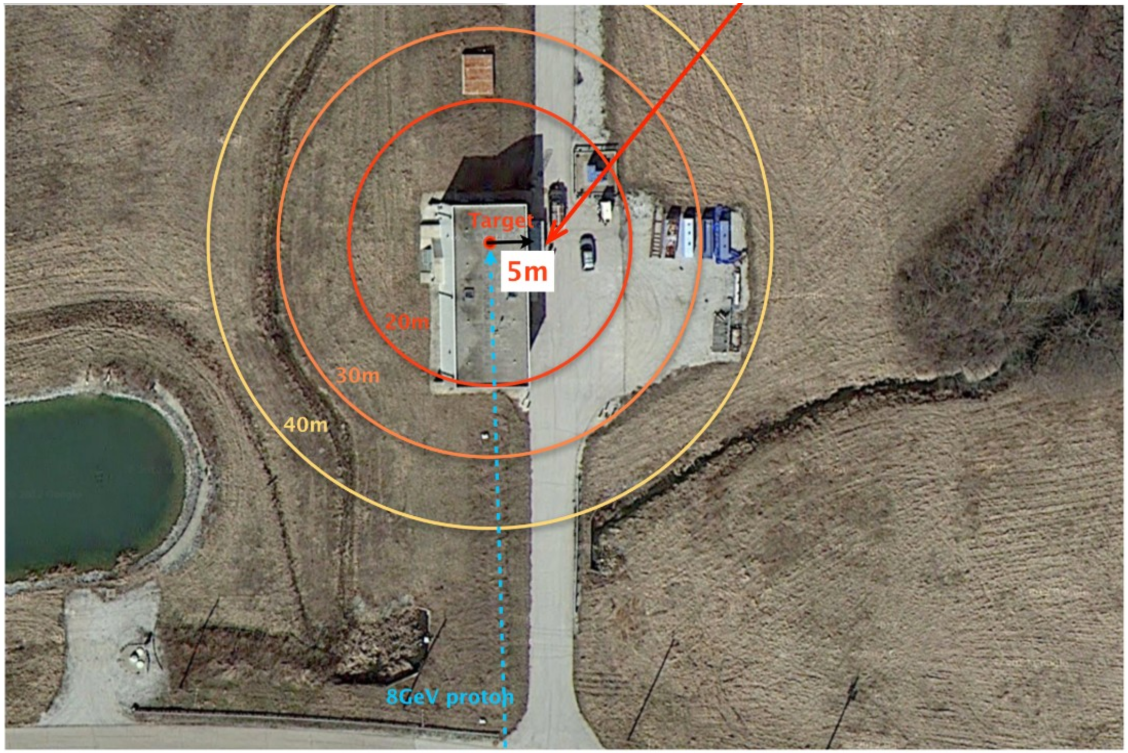
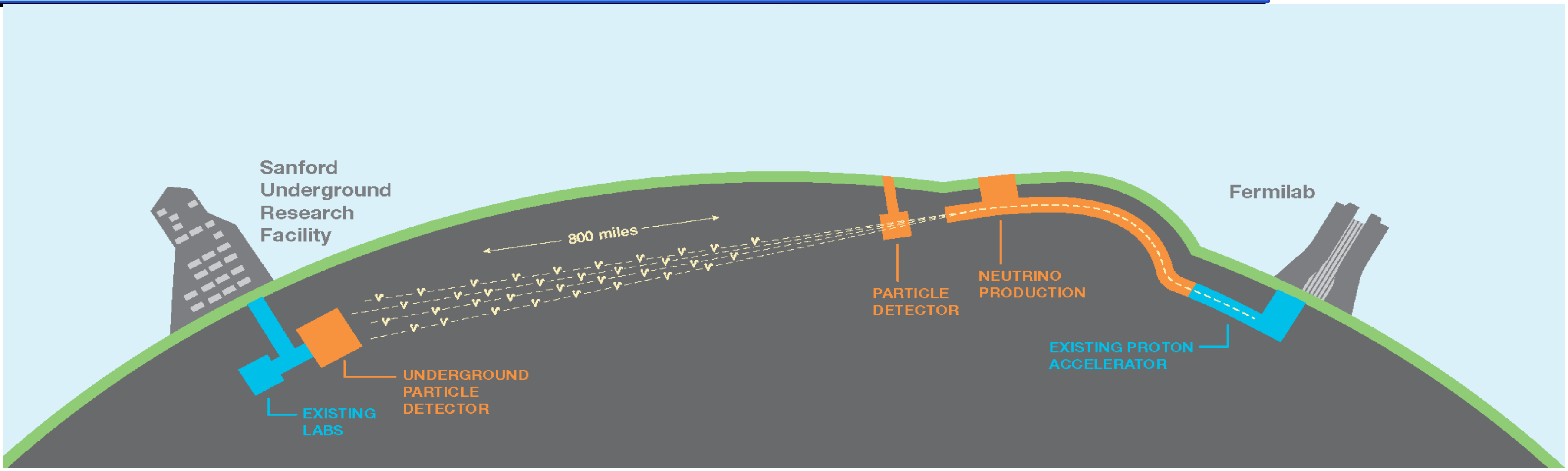
- Low energy neutrino runs at BNB
  - Low energy neutrino of O(10) MeV
  - First low-energy neutrino measurements in LArTPC.
  - Critical for SN ν detection.
  - Measure the neutrino-argon cross-section to 10%
  - Affect the specification of photon detector and DAQ systems for DUNE.



DUNE Experiment



- CP (Charge Parity) violation in neutrino sector.
- Mass hierarchy.
- Precision measurements of neutrino oscillation parameters.
- Proton decay.
- Supernovae Neutrinos.

- World's most intense beam at Fermilab
- Detector position: Sanford Underground Research Facility in Lead, SD
- Detector baseline: 1300 km
- Detector size: 40 kt
- Underground depth: 4850 feet
- Detector technology: Liquid Argon Time Projection Chamber (LArTPC)

Discovery potential relies on detailed understanding of neutrino-argon interactions.

Supernova Explosion

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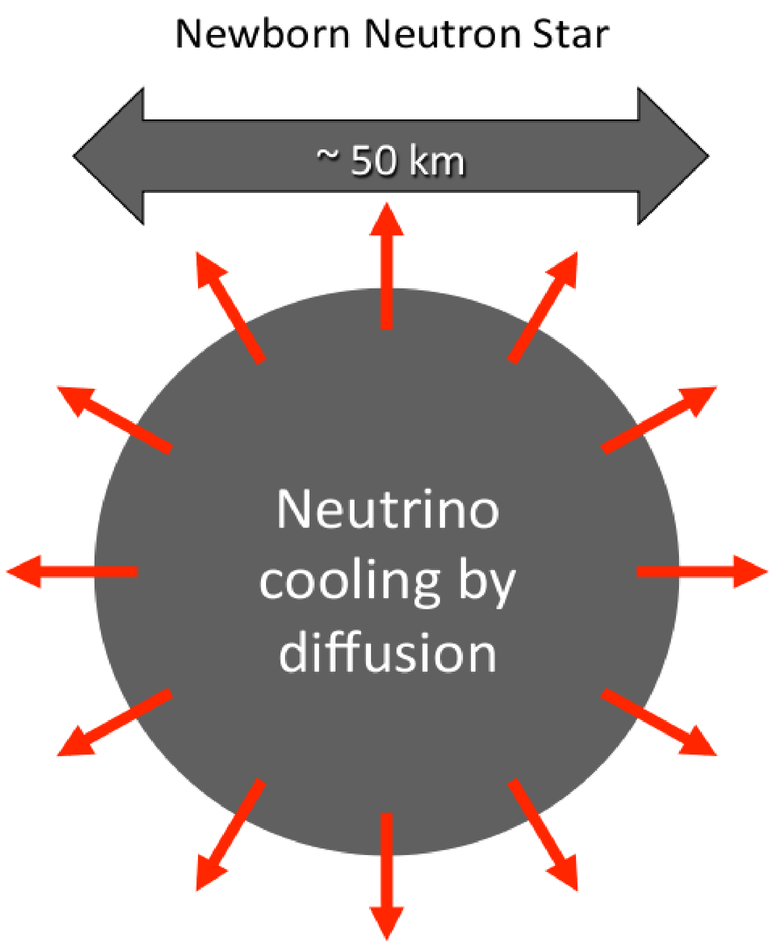

Gravitational binding energy

$E_b \approx 3 \times 10^{53}$ erg $\approx$ 17% $M_{SUN} c^2$

This shows up as:

99% Neutrinos

1% Kinetic energy of explosion (1% of this into cosmic rays)

0.01% Photons, outshine host galaxy

Neutrino luminosity:

$L_\nu \approx 3 \times 10^{53}$ erg / 3 sec

$\approx 3 \times 10^{19} L_{SUN}$

While it lasts, outshines the entire visible universe

Large Underground Detectors for SN Neutrinos

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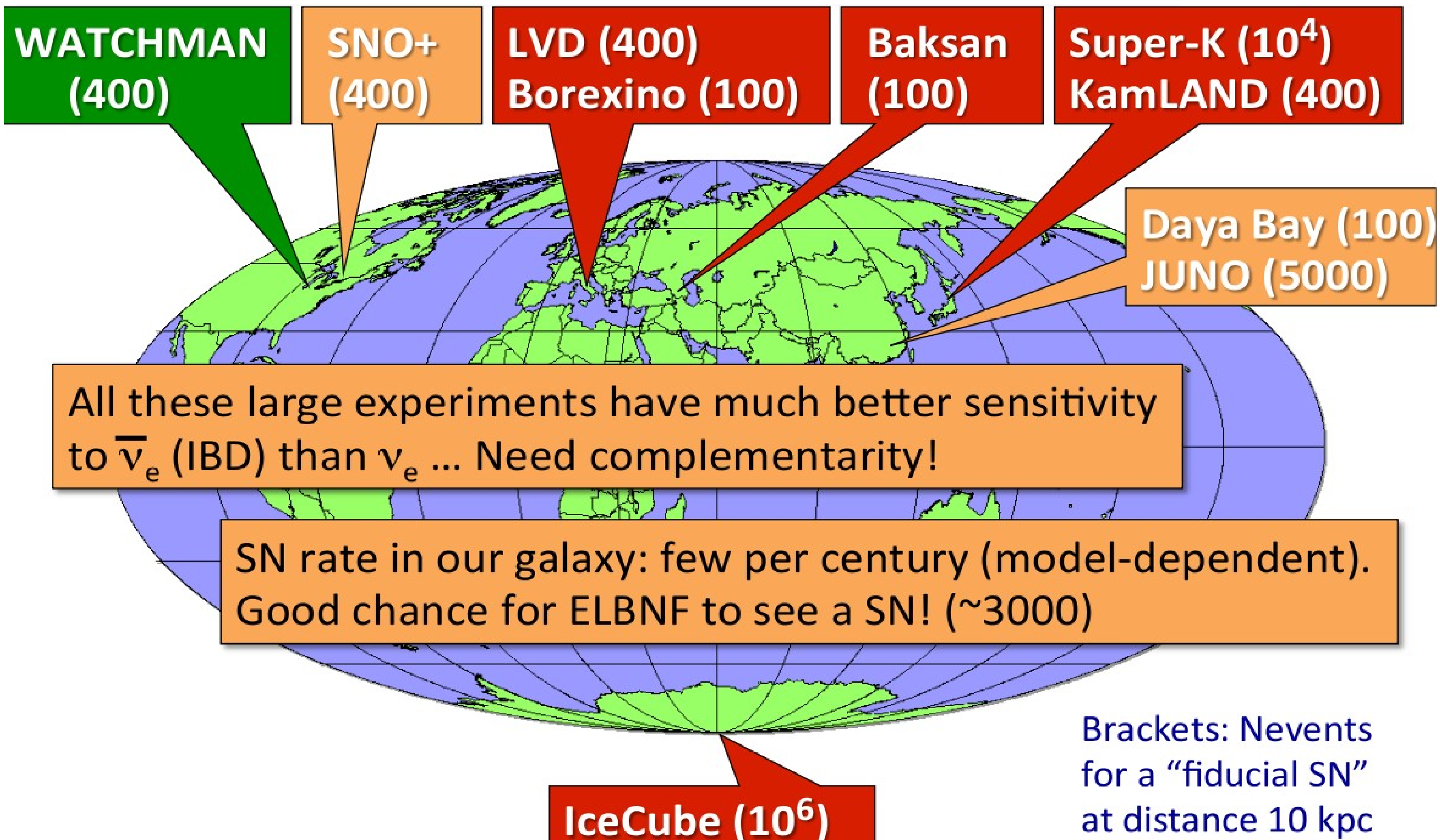


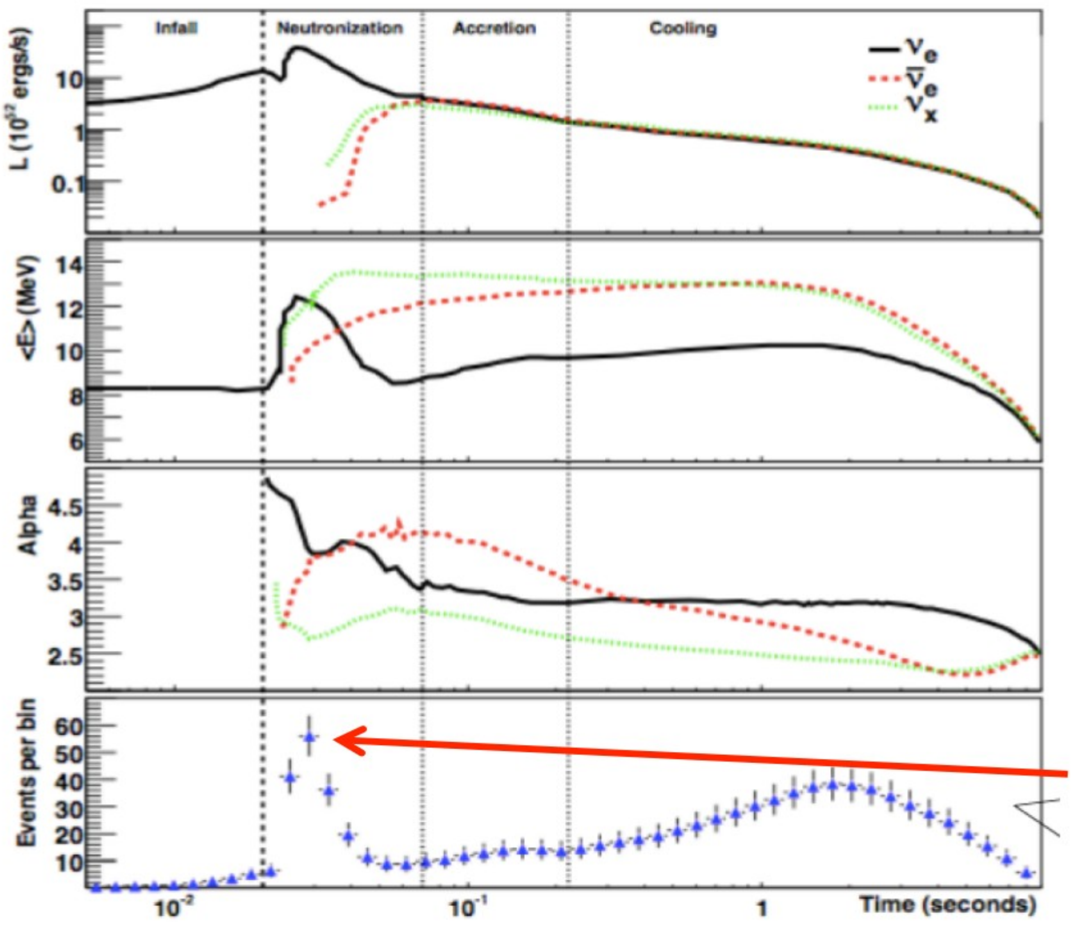
All these large experiments have much better sensitivity to $\overline{\nu}_e$ (IBD) than ν_e … Need complementarity!

SN rate in our galaxy: few per century (model-dependent). Good chance for ELBNF to see a SN! (~3000)

Brackets: Nevents for a "fiducial SN" at distance 10 kpc

Detection of the SN Neutronization Burst

$p + e^- \rightarrow n + \nu_e$



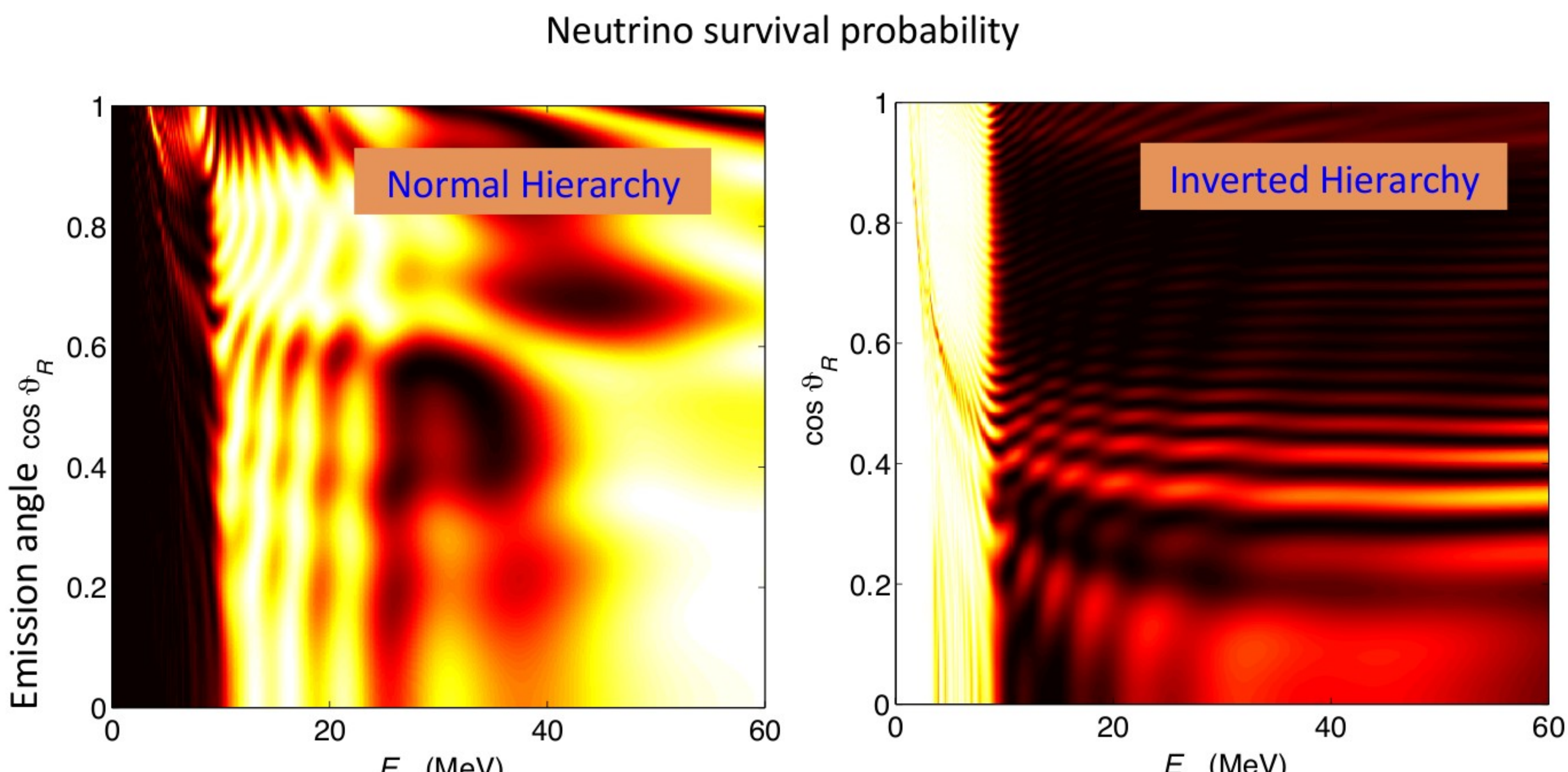
Burst is only 20 ms long and is essentially all ν_e

Mean energy of events is low, 10–12 MeV

IMB/Kamiokande detected higher energy cooling neutrinos, not neutrinos from the neutronization process

Potential for ν_e detection in liquid argon by ELBNF

Neutrino Survival Probability



E<10 MeV, oscillate to other species
E>10 MeV, preserve flavor

E<10 MeV, preserve flavor
E>10 MeV, oscillate to other species

H. Duan, G. M. Fuller, and Y. Qian, Ann. Rev. Nucl. Part. Sci. 60 (2010) 569
arXiv:1001.2799 hep-ph

SN Event Rates at 10 kpc

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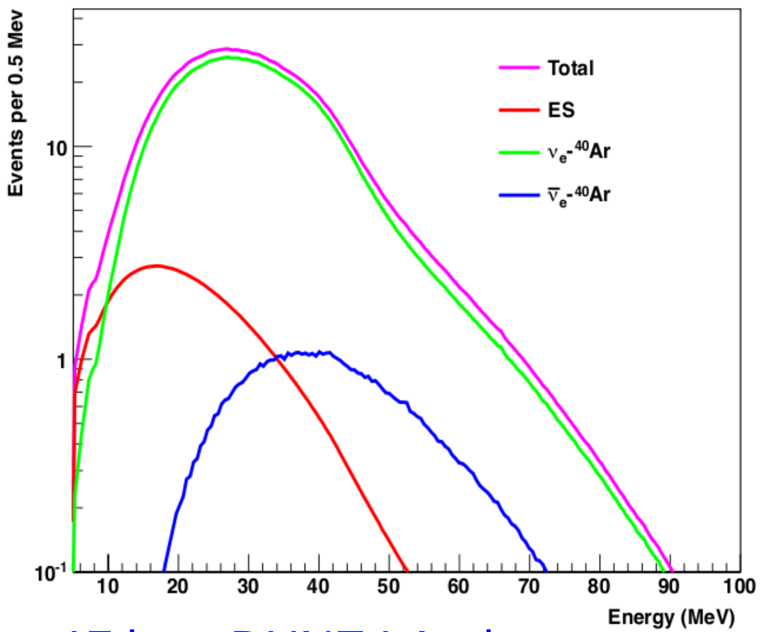

17 kton DUNE LAr detector

K. Scholberg: arXiv 1205.6003 astro-ph
GKVM model: arXiv 0902.0317 hep-ph
(Gava, Kneller, Volpe, McLaughlin)

Rates in nominal 34 kton ELBNF detector:

$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$ (CC) 2848

$\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$ (CC) 134

$\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$ (NC) 200 (A. Hayes)

Allow calibration of total released energy in neutrinos

$\nu_x + e^- \rightarrow \nu_x + e^-$ (ES) 178

ES cross-section has been measured. Perserve neutrino direction

Keys to success:

- Accurate measurements of the CC and NC cross-sections
- Ability to clearly tag $^{40}K^*$ and $^{40}Ar^*$ using de-excitation γs
- Ability to reject neutron spallation backgrounds
- Energy resolution and event timing

CAPTAIN

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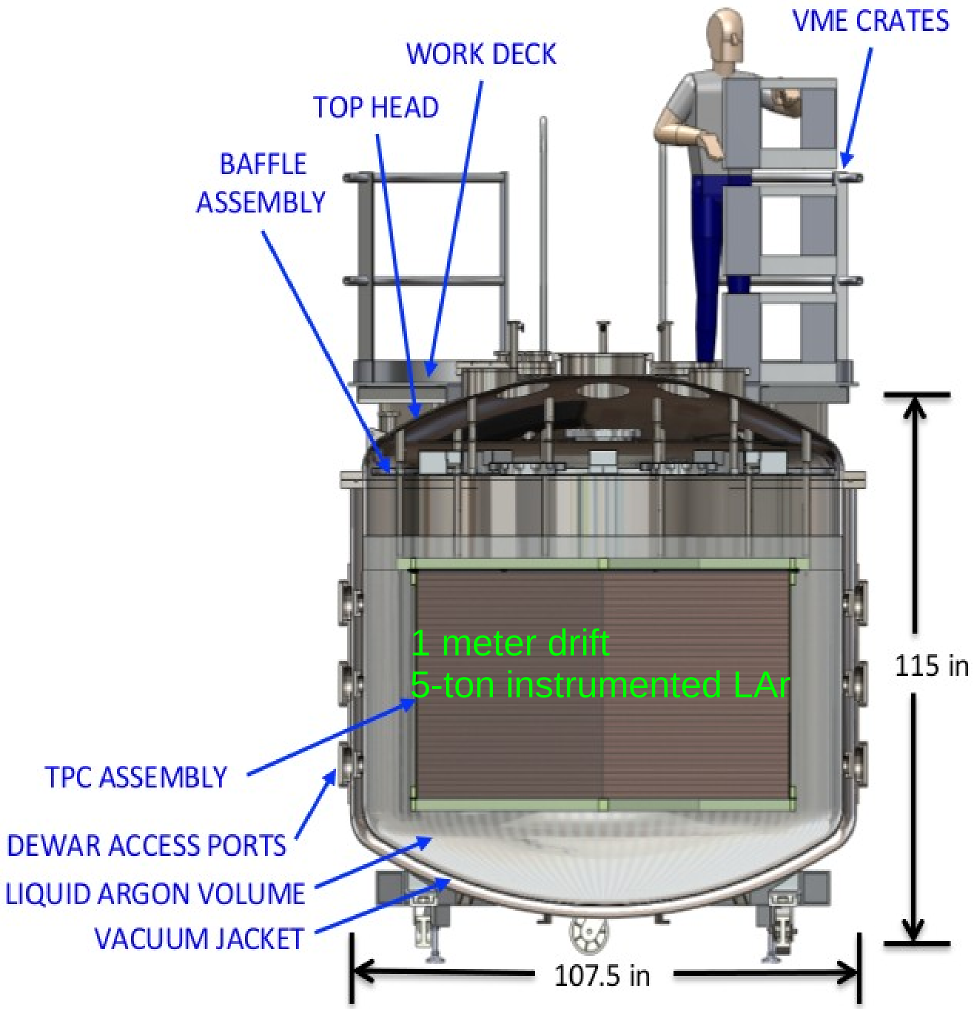
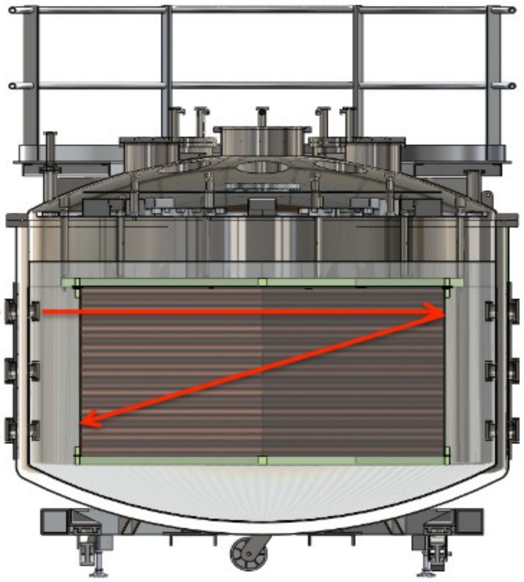
- Funded by LANL Laboratory Directed Research and Development (LDRD), now a multi-institutional collaboration (list in last page)
- Full-scale TPC and a prototype
- 7700 L cryostat (**Portable and evacuable**)
- 500 V/cm drift field and 1.6 mm/μs drift velocity
- 2001 channels (667/plane), 3 mm pitch and wire spacing
- Laser calibration system
- Photon detection system (Hamamatsu R8520-500 PMTs)
- MicroBooNE cold electronics
- Purification system design based on MicroBooNE and LAPD



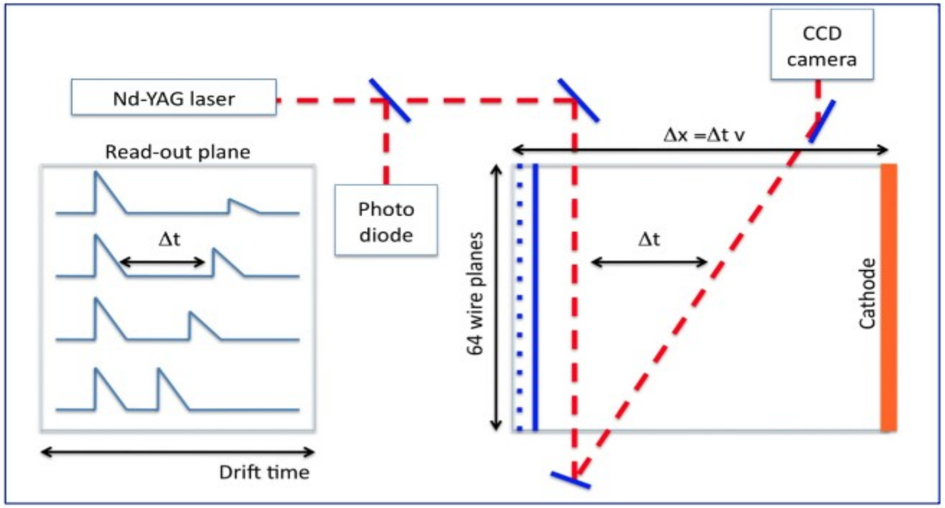
Laser Calibration System

Laser Calibration System

266 nm, 90 mJ, 3 ns pulse



Nd-YAG frequency quadrupled Quantel Brilliant-b laser: 4.66 eV
LAr ionization potential: 13.78 eV (3 photons)



4 optical ports:
- 2 @ 15cm from anode
- 2 @ 15 cm from cathode

Recombination in LAr: only a fraction of the ionization charge survives after t_{drift}:

$$Q_{meas} = Q_{dep}\, R e^{-t_{drift}/\tau}$$

measure the electron lifetime in-situ

Test bed for DUNE laser calibration system

Photon Detection System

- Simulations show a few PE/MeV for MIP in TPC would improve projected energy resolution by 10~20%.
- Anti-correlation between scintillation photons and ionization electrons observed in liquid Xenon.
- Need to be tested in LAr.
- Can be used for neutron energy determination by measuring TOF.
- 128 nm scintillation light shifted to 420 by TPB.
- Will test a variety of techniques for DUNE photon detection system.
  - Wavelength shifters
  - Light guides or doped panels
  - SiPMs, larger cryogenic PMTs or avalanche photodiode arrays
  - Calibration system for PD system
    - Laser
    - UV or blue LEDs

CAPTAIN Status

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- Cryostat, electronics, field cage in hand
- Purification system at vendor (expect delivery ~Fall 2015)
- Planned TPC wiring at UC Irvine during summer 2015
- Expected commissioning: FY16
- Neutron data at WNR neutron beam after commissioning
- Ready to be deployed at FNAL: end of FY16 (NuMI and BNB)

Arrived at LANL (08/2014)

CAPTAIN Purification System Status

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a view of heat shields

Filter skid frame assembly
with pump mounted

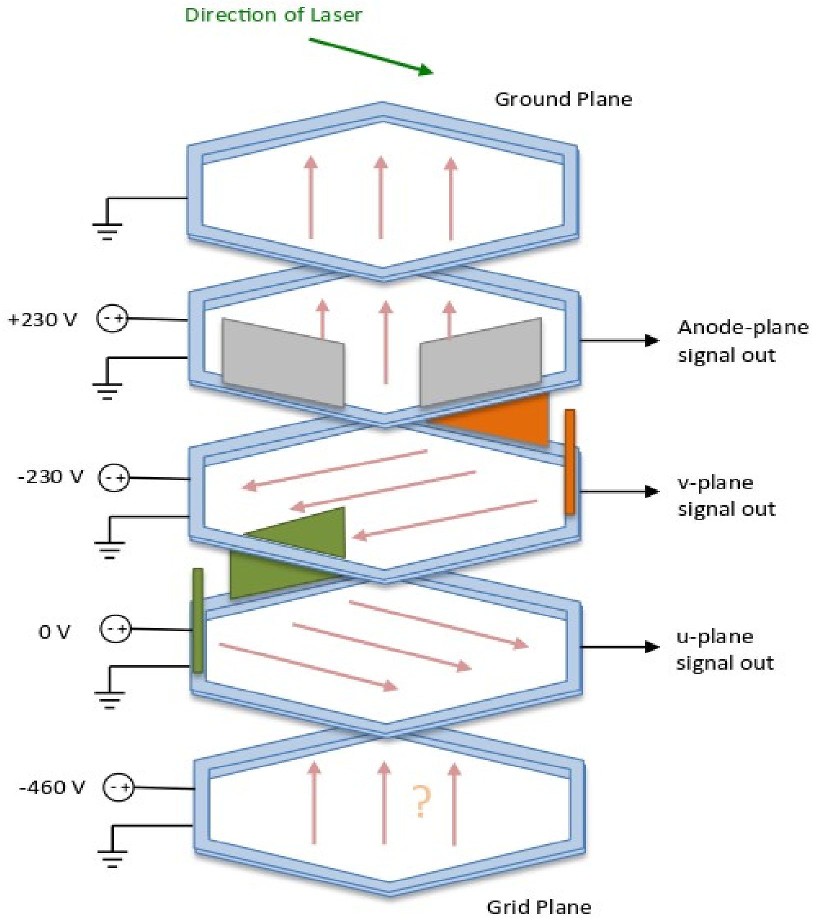
Thermocouples
mounted to inner vessel

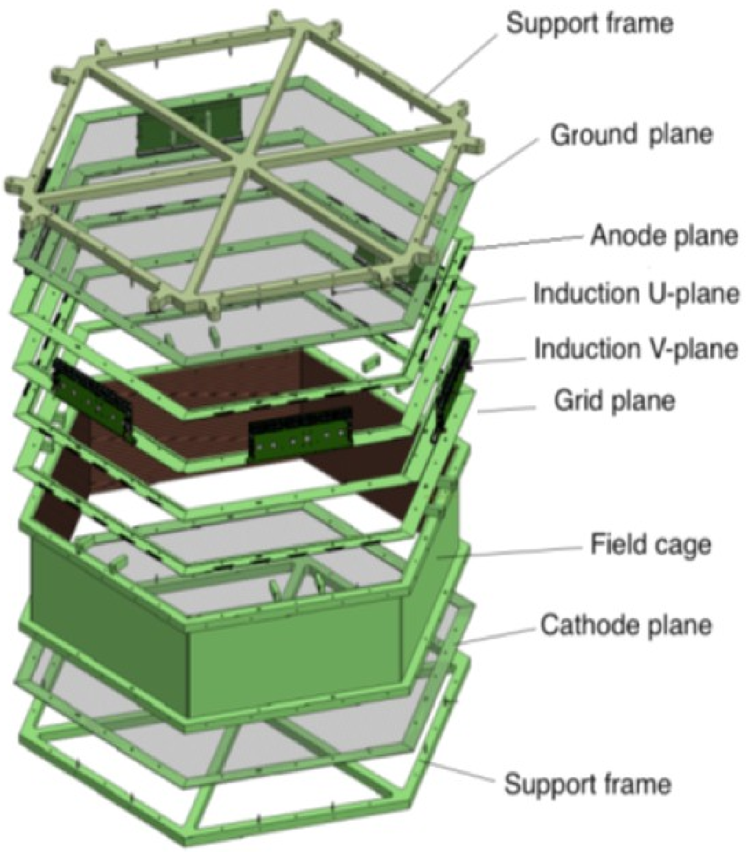
At Eden Cryogenics

Mini-CAPTAIN

- UCLA Cryostat, 1700 L of liquid argon, a smaller version of CAPTAIN.
- Vacuum jacket 60.25” in diameter, 64.4” in height.
- 948 active channels (316/plane), 3 mm pitch and wire spacing.
- Drift distance 32 cm, apothem 0.5 m.
- Testing of laser calibration system and improvement.
- Will allow for development of DAQ software and provide much needed operational experience for CAPTAIN.

Mini-CAPTAIN Wire Plane & Structure

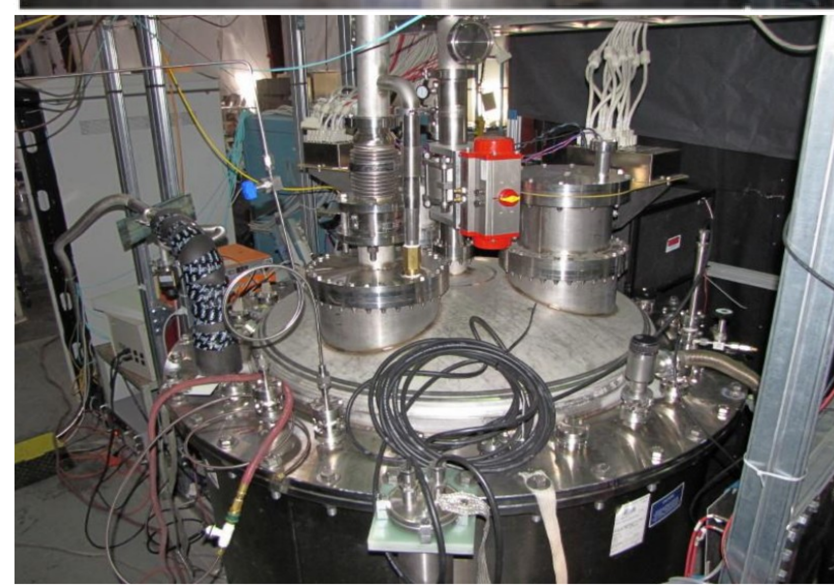




U and V wires are oriented ± 60 degrees to anode wires

Mini-CAPTAIN Status

- Liquid nitrogen fill in Summer 2014: test electronics and TPC, test heat load.
- 1st LAr engineering run in Fall 2014: development of filling procedure, test cryogenic and purification system, DAQ development, laser system testing.
- 2nd LAr engineering run in March 2015: further development of above items plus installation of recirculation system, integration with muon system.
- 3rd LAr engineering run began June 2015: more development of electronics and recirculation system.
- Will be taken to WNR to take neutron data 10/15.



Mini-CAPTAIN Purity

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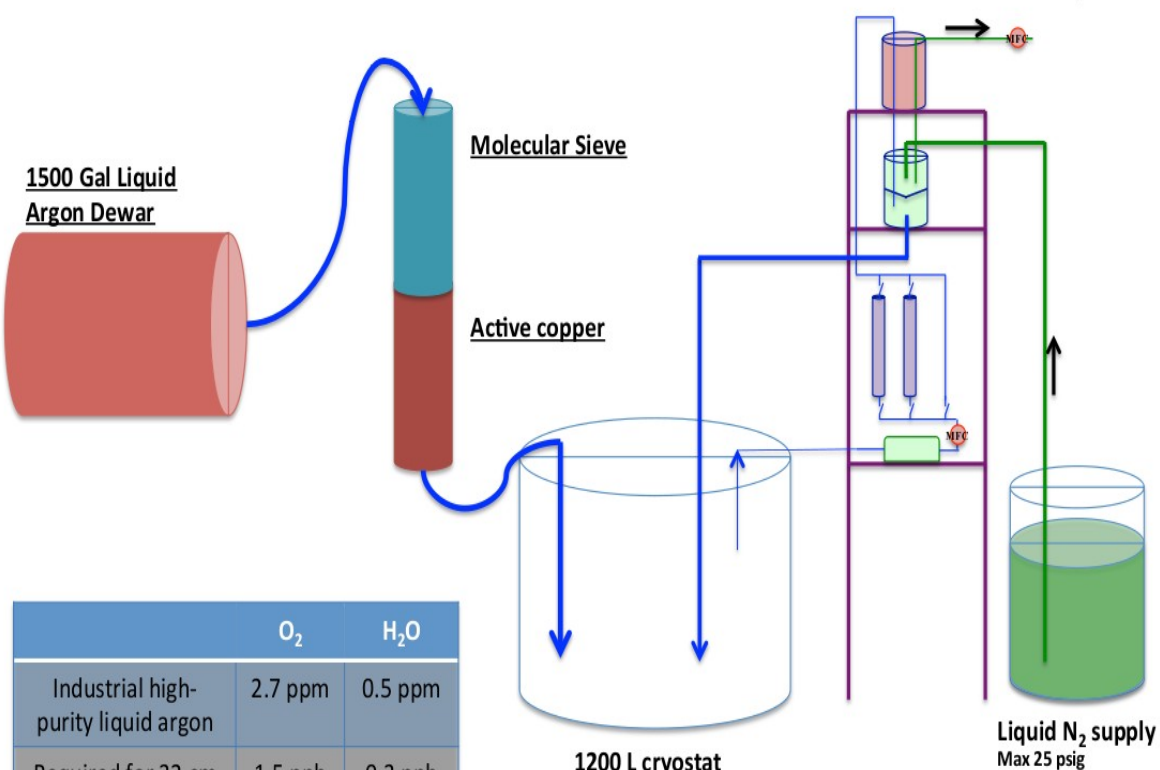
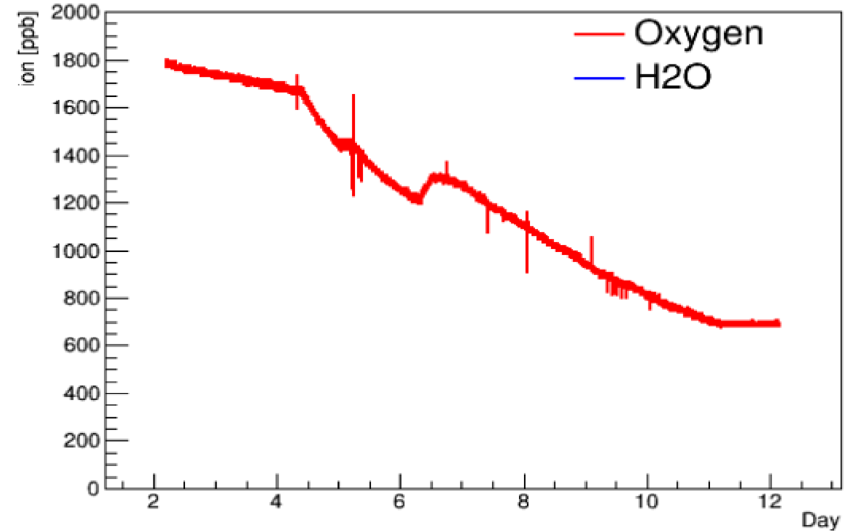
MiniCAPTAIN Cryogenics and Purification system consists of:

1) An inline **liquid argon filter**
2) A **gas recirculation system** including a condenser and filters

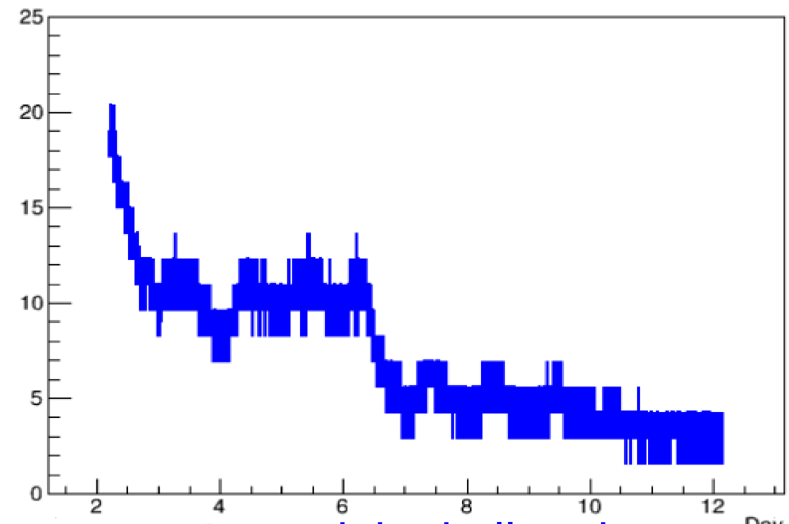


	O_2	H_2O
Industrial high-purity liquid argon	2.7 ppm	0.5 ppm
Required for 32 cm drift distance	1.5 ppb	0.3 ppb

Courtesy of Q. Liu



Need additional month to reach 1 ppb



Around the ball park

Univ. Of Hawaii Contributions

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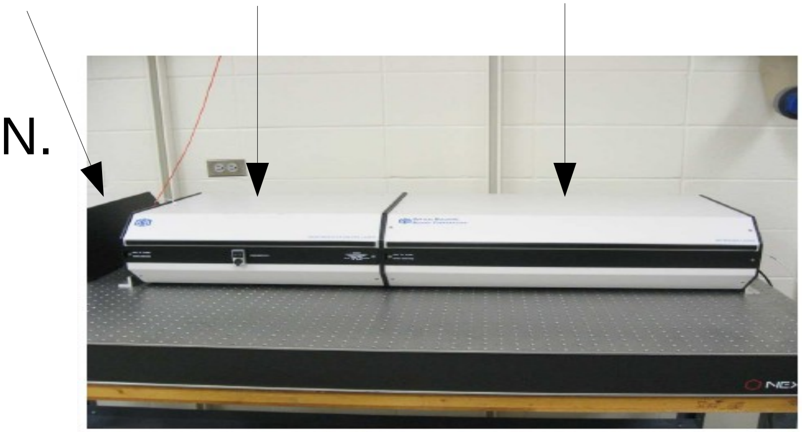
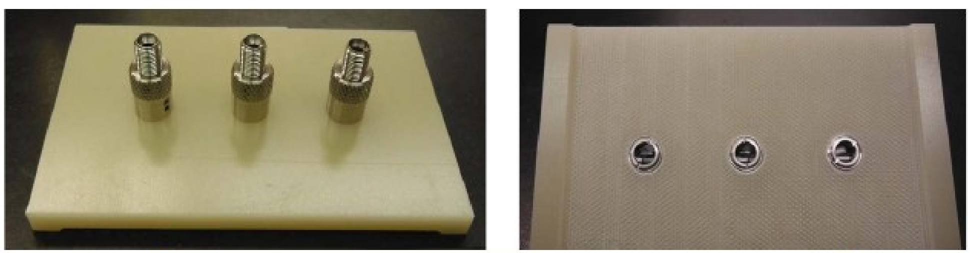


- Our group
  - Fiber Alignment Arrays (FAA) for Mini-CAPTAIN.
  - Laser Position Sensors (LPS) for CAPTAIN.
- Myself
  - Leading effort in offline data analysis and simulation.
  - SiPMs (DUNE PD sensor selections and characterizations; potential candidate in LPS and replacement of UV PMTs in CAPTAIN PDS).

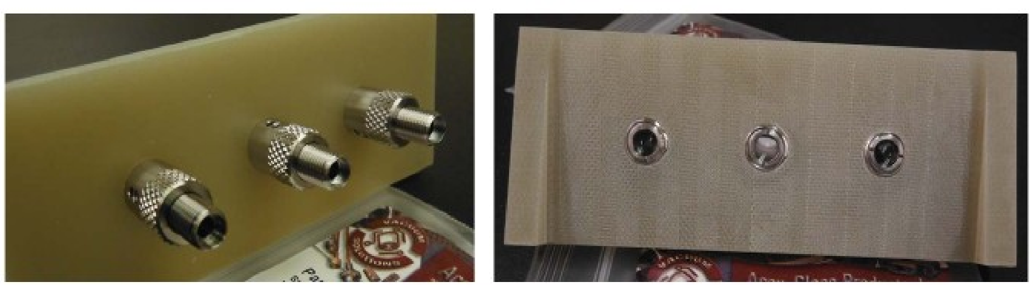
FAA & LPS

The FAA is glued on the outside of FR4 and observe the signal with Hamamatsu 6780-04 PMTs.

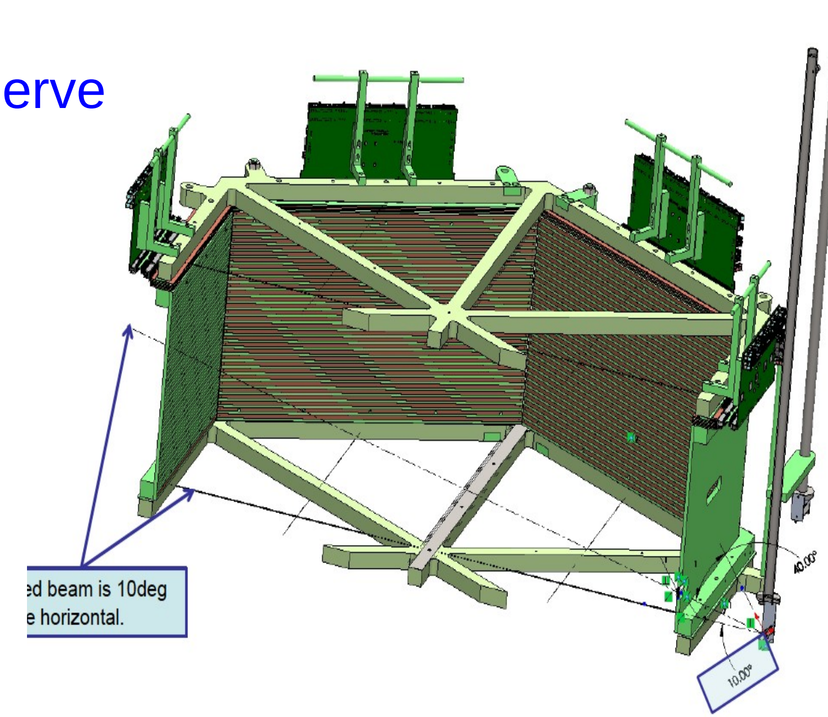
Fiber Alignment Arrays (FAA) for mini-CAPTAIN:
m-C will use fiber-optics and PMTs for laser alignment.



Normal incidence FAA panel with Accuglass coupling lenses.



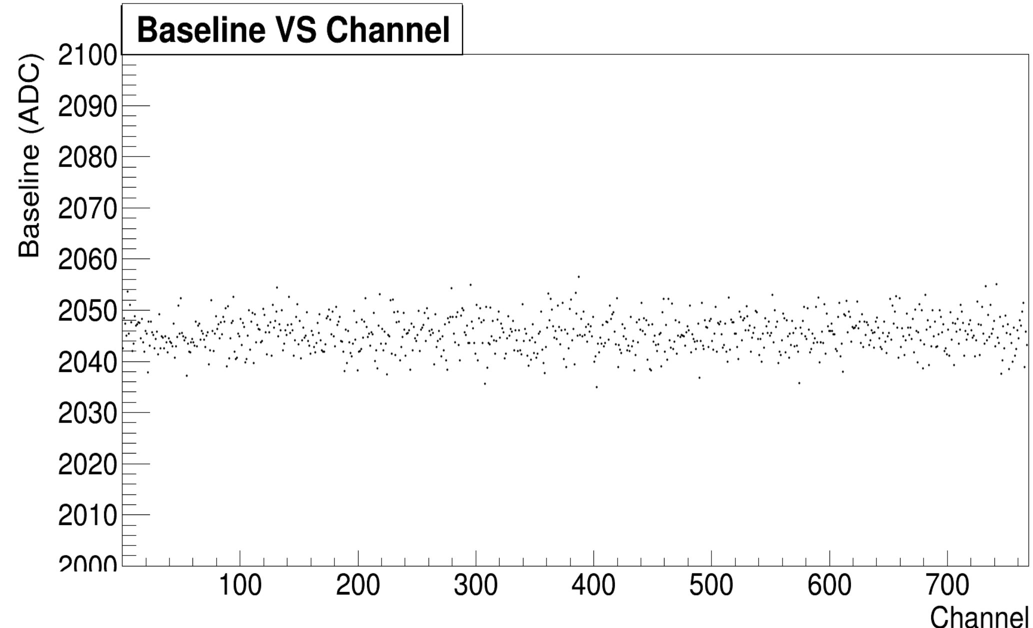
10deg incidence FAA panel with Accuglass coupling lenses.

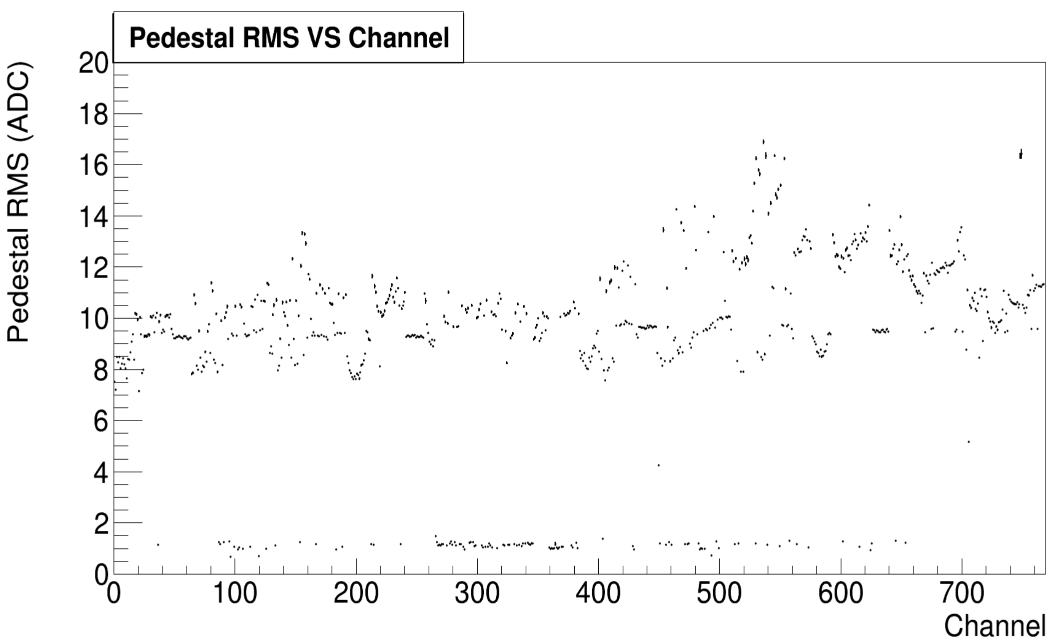


LPS R&D is underway. Currently GaP photodiode (Marc Rosen's idea) is being tested since it does not need bias voltage support which do not require additional feed-through in CAPTAIN.

MiniCAPTAIN Offline Data Analysis

- Algorithm development for cosmic μ induced pulse searching
- TPC wire calibration using injected pulser





- TPC data quality check (newly developed package in CAPTAIN software):
  - Baseline
  - Pedestal RMS
  - “Shut off” effect
  - Pulse search (7σ)
  - Event timing
  - FFT
  - Pulser signal calibration graphs

SiPM Characterizations

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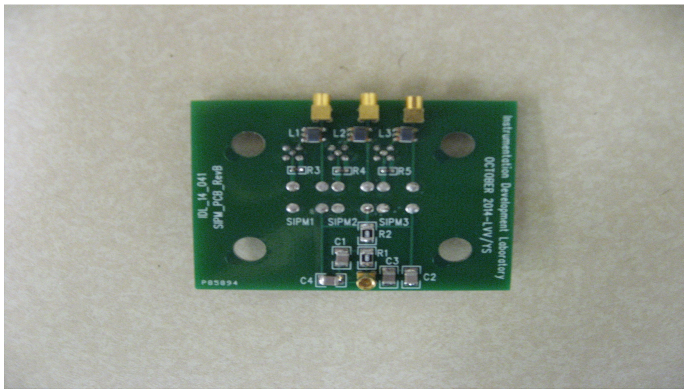
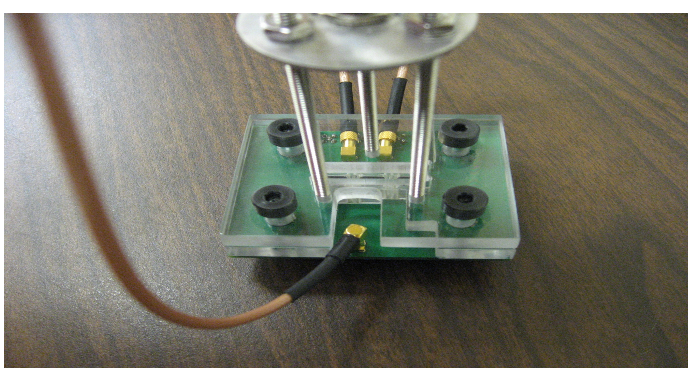
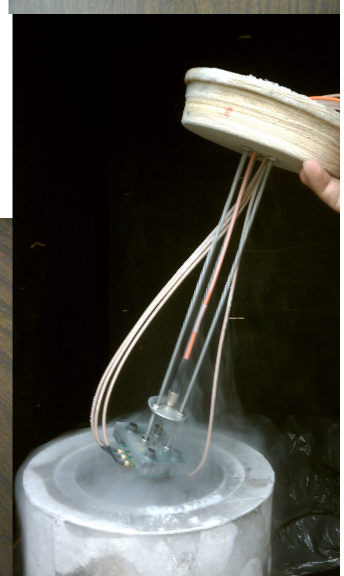
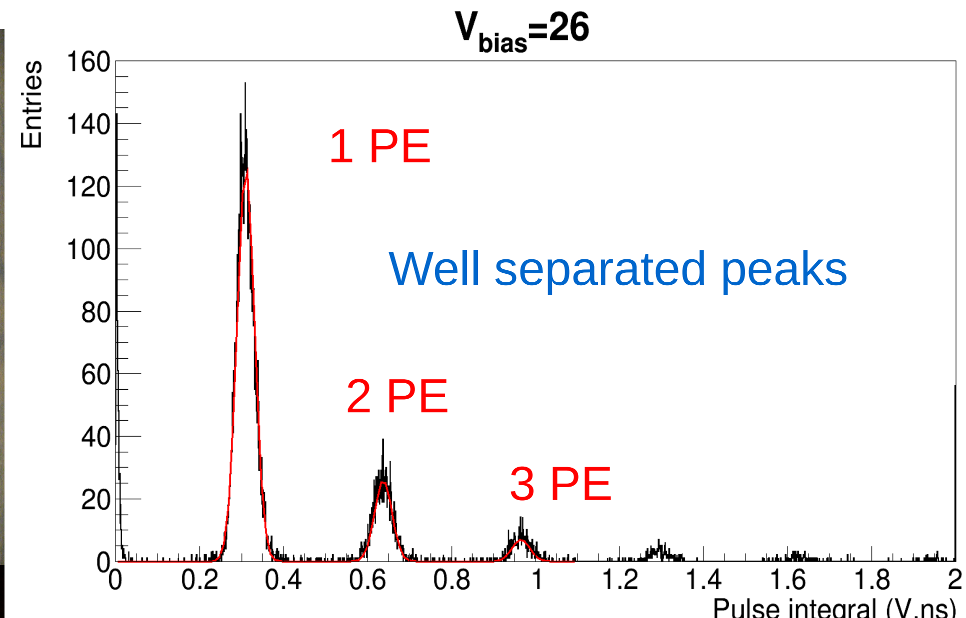
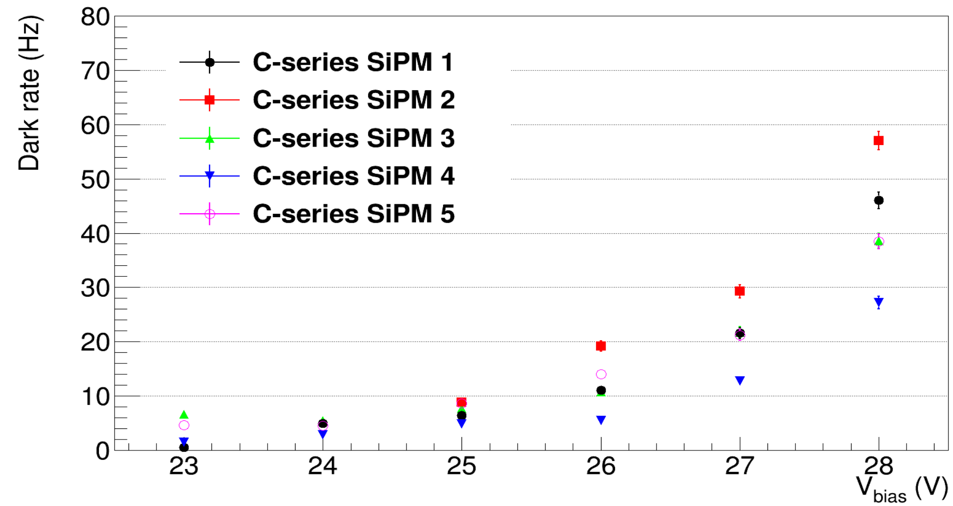


- My own PCB design
- Pogo pin connections
- LN_2 test









~5 Hz in cryostat (2.5V over-voltage)

Neutron Studies at the Weapons Neutron Research (WNR) Facility

Neutron Studies at the Weapons Neutron Research (WNR) Facility

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- Such measurements have not been performed before. (unique)
- Will impact both medium and low energy neutrino detections.
- Planed on 2016 Fall.
  - High Intensity neutron runs
  - Low Intensity neutron runs

High Intensity Neutron Runs

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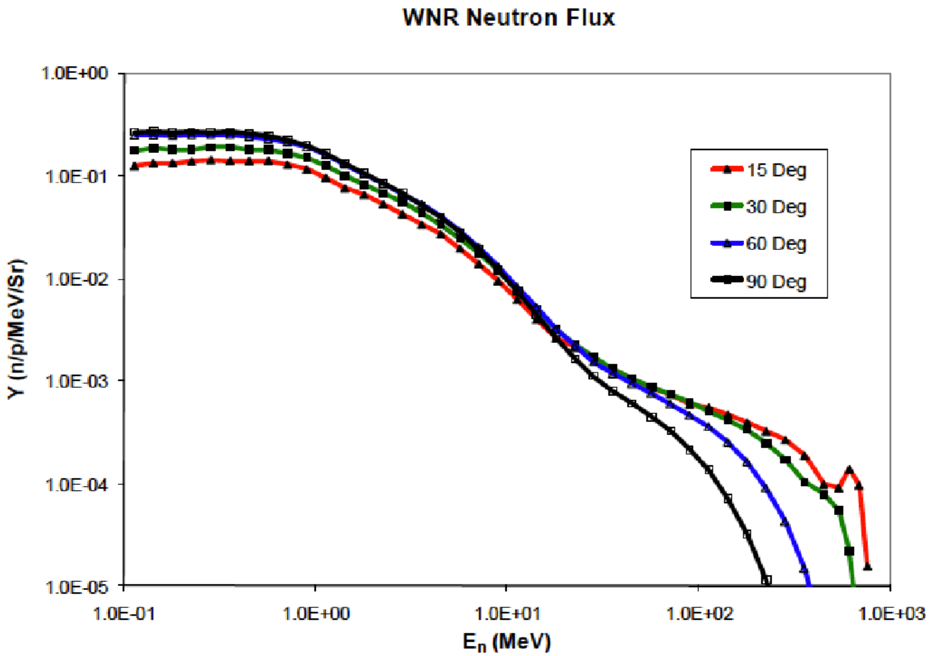
- A day of running produce years worth of neutron spallation events.
- Study background for surface detector.
  - Neutron production of isotope ^{40}Cl constitutes an important background to SN neutrino detection.



Similar to cosmic ray spectrum, but much more intense

Low Intensity Neutron Runs

- Low intensity runs allow to correlate specific topologies with E_n via TOF.
  - Low energy:
    - Study reconstruction capabilities of $^{40}Ar^*$ de-excitation in LarTPC.
    - Investigate n-induced and ν-induced interaction on argon.

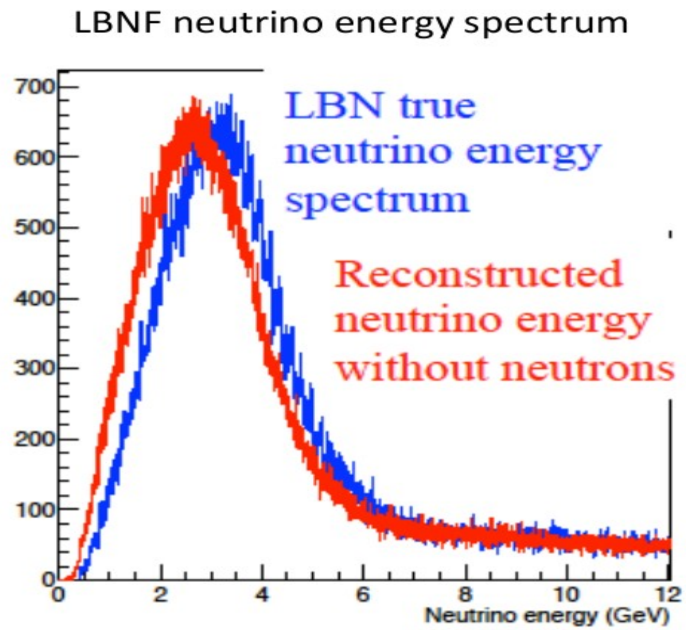
$$\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^* \text{ (NC)}$$

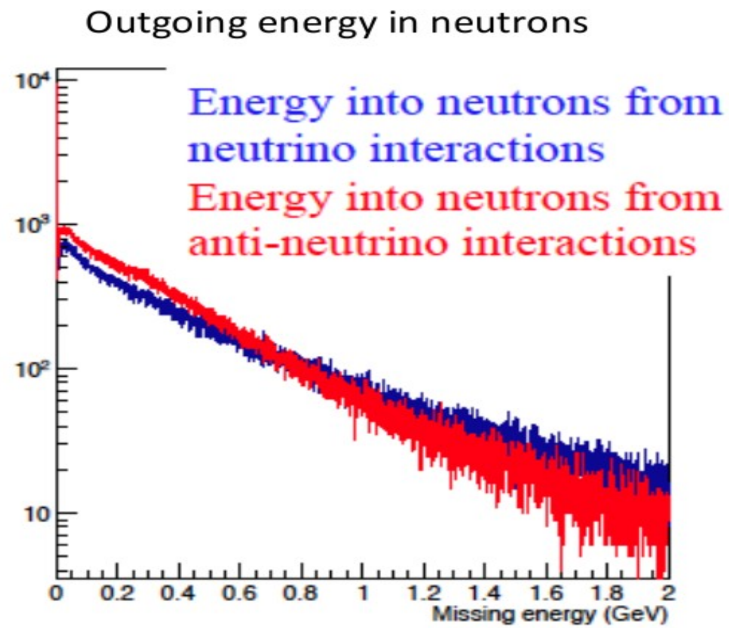
$$n + {}^{40}Ar \rightarrow n + {}^{40}Ar^*$$

  - High energy (above 400 MeV):
    - Final state topology, multiplicity and identity studies. Compare with existing models, improve them and use them in DUNE simulation.
    - High energy cosmogenic neutron can produce π^0 that can mimic ν_e appearance.

Event Reconstruction with Neutron

- Neutron will travel some distance from the vertex which complicates the reconstruction.
- Characterize neutron interactions to understand energy carried by neutrons in neutrino interactions with argon.
- Characterize reconstruction efficiency of such events.



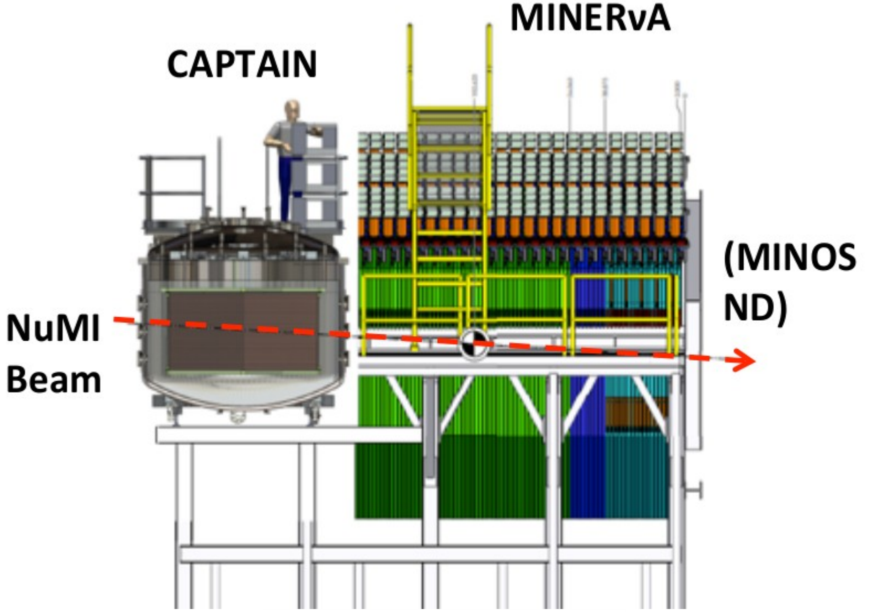


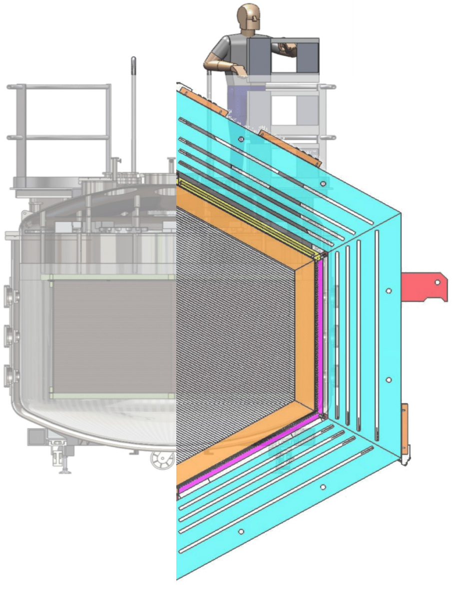
Neutrons can carry away significant amounts of energy from the vertex of the interaction and the energy carried away is different between neutrinos and anti-neutrinos

CAPTAIN-MINERvA in the NuMI Beam

CAPTAIN-MINERvA in the NuMI Beam

- Medium-energy (1.5~5 GeV, 1st oscillation maximum for DUNE at a baseline of 1300 km) neutrino interactions are poorly understood on any nucleus.
  - Data available from a very small Argoneut detector (low statistics)
  - CAPTAIN 20X fiducial mass than Argoneut.
  - Containment: all but lepton and neutrons.
- Ideal test-bed for DUNE reconstruction.
- Only high-statistics measurements of neutrino-argon in this energy range before DUNE.





CAPTAIN-MINERvA Deployment

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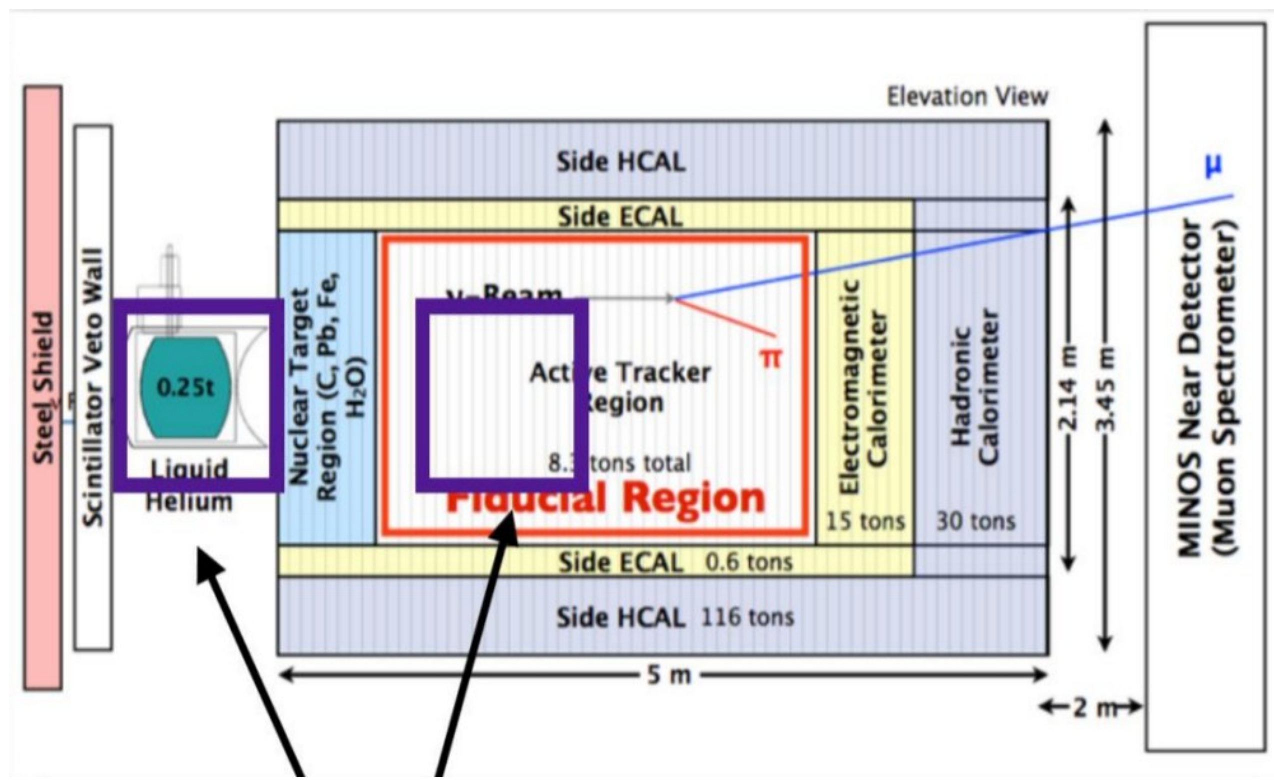
- CAPTAIN → vertex detector.
- MINERvA → track detector of outgoing particles.
- Can be used in measuring the cross-section ratio of LAr to other nuclei.
- MINOS ND → downstream μ spectrometer (μ charge and momentum).
- Study cross-section, particle ID and event reconstruction important for DUNE.

Two possible locations:

1) Replace the He target with CAPTAIN (Default)

2) Remove the nuclear targets and part of the tracker (this would only be considered after MINERvA has accumulated 12e20 POT in antineutrino mode, earliest 2018)



Cross-Section

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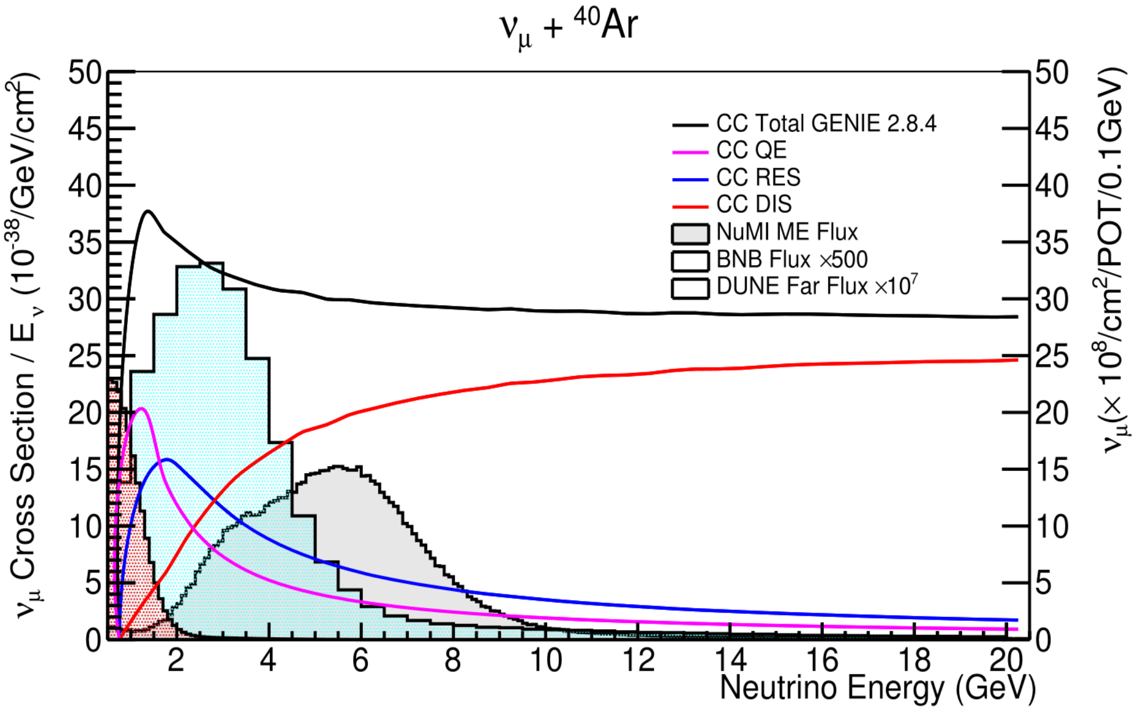
- A large sample of neutrino-argon data to tune the model. (not rely on extrapolations, and also can test extrapolations mostly based on other nuclear targets)



CAPTAIN-MINERvA could serve as a model for DUNE near detector system. The direct ratio measurements of neutrino-argon to neutrino-(C, Fe, Pb, LHe, water) has minimum systematic uncertainties especially on ν flux.

Simulation Study

University of Hawaiʻi Mānoa

$(6\text{x}10^{20}$ POT)	CC events with muon reconstructed (MINOS or MINERvA) Events w/ reco μ	CC events with muon reconstructed by MINOS Events w/ reco μ and charge
CCQE-like	916k	784k
$CC1\pi^{\pm}$	1953k	966k
$CC1\pi^{0}$	1553k	597k

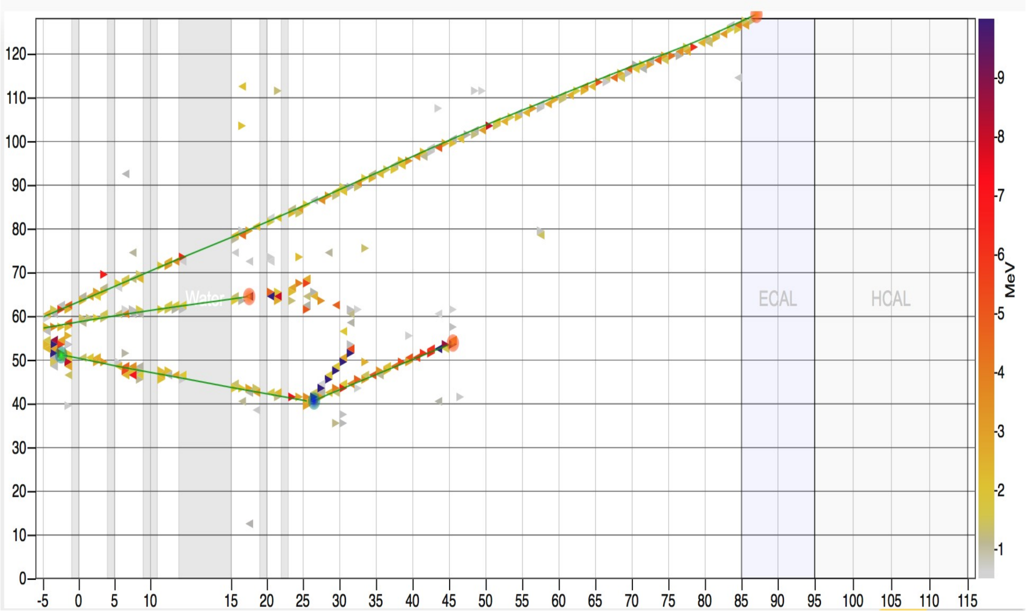
These statistics are adequate for the physics goals; the downstream position would yield higher statistics.

- 12.5M CC interactions within the TPC for an exposure of $6\text{x}10^{20}$ POT
- 64% of CC events will have muon reconstructed by MINOS or MINERvA
- For remaining CC interactions, CAPTAIN will have some ability to reconstruct muons that miss MINERvA or MINOS by looking for MIP-like tracks

Energy Reconstruction

- Depends on containment of hadronic energy and reconstruction of the outgoing μ.
- For CC interactions, ~20% will have the hadronic energy contained.
- This means 10-15% (64%x20%) of CC interactions will have all the hadronic energy contained and have a μ reconstructed by MINOS or MINERvA (64%).
- This subset of events will have the best reconstructed energy resolution that is important for the cross section measurements and can be used to test the reconstruction methodologies developed using neutron measurements.

A neutrino interaction on LAr upstream of the MINERvA detector; the hadronic system is fully contained within MINERvA.



MINERvA can be used as a hadronic calorimeter for events where final state particles exit CAPTAIN.

CAPTAIN in the Booster Neutrino Beam (BNB)

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CAPTAIN in the Booster Neutrino Beam (BNB)

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MĀNOA

BNB @ FNAL

Cross-Section & Reconstruction

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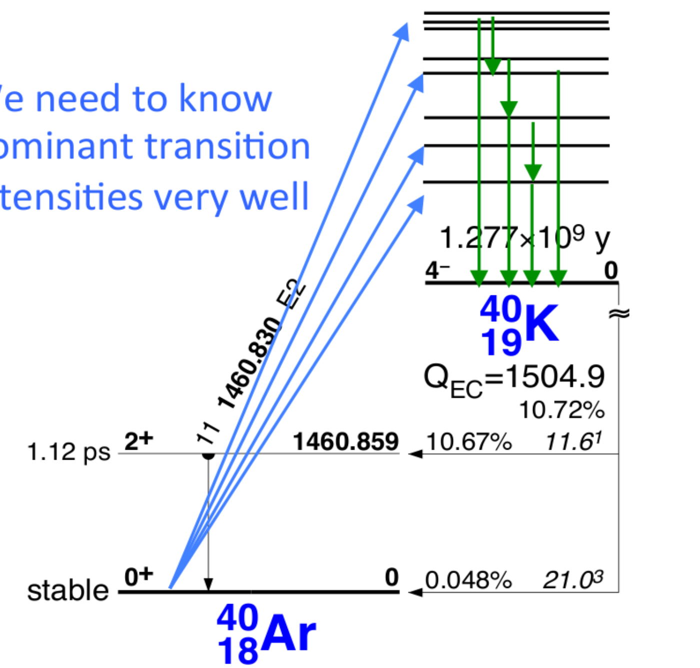
P5 recommendation:
"The (ELBNF) experiment should have the demonstrated capability to search for SN bursts..."

- The cross-section has never been measured and has theoretical uncertainties of 10~15%.
- Goal: Measure the neutrino-argon cross-section to 10%.
  - 4e+20 standard configuration
  - 2e+20 beam off-target configuration
- To reconstruct neutrino energy, one has to know the energy of outgoing e^- and the $^{40}K^*$ de-excitation γ. This means we need to know the levels and branching fraction of the γs.
- Test the ability of detecting SN ν with LAr detectors (triggering and timing). Potentially influence the DUNE PD design.

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

We need to know dominant transition intensities very well



(3rd forbidden) transition to ground state of potassium

Deployment Options

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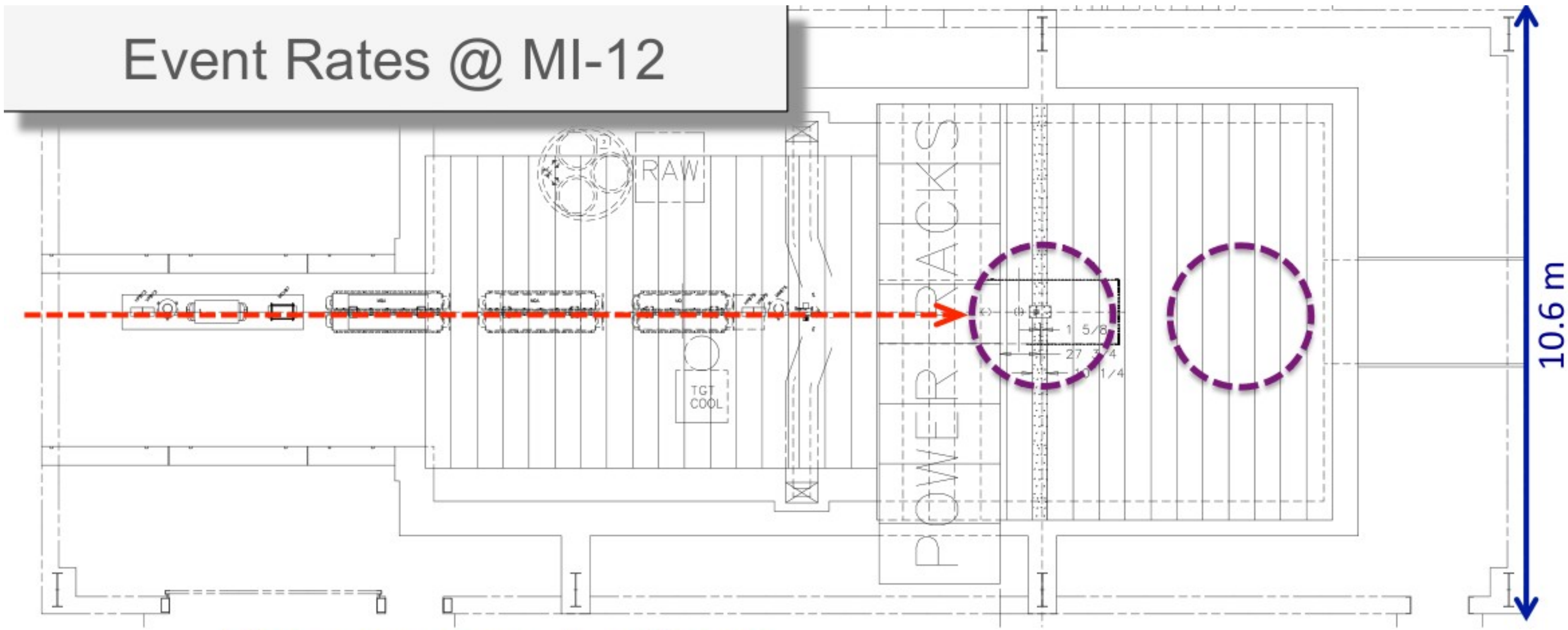
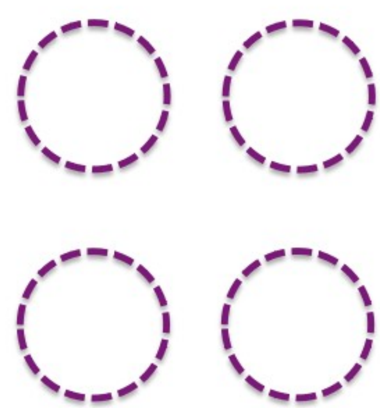
Event Rates @ MI-12



Alignment w. target & collimator

x (m)	d (m)	Nevt (CC)	Nevt (CC)
0	8.4	354	375
7.3	11.1	217	229
11.3	14.1	145	152



Rates: 2e20 POT (1 yr) & 100% efficiency

Neutron Background Shielding

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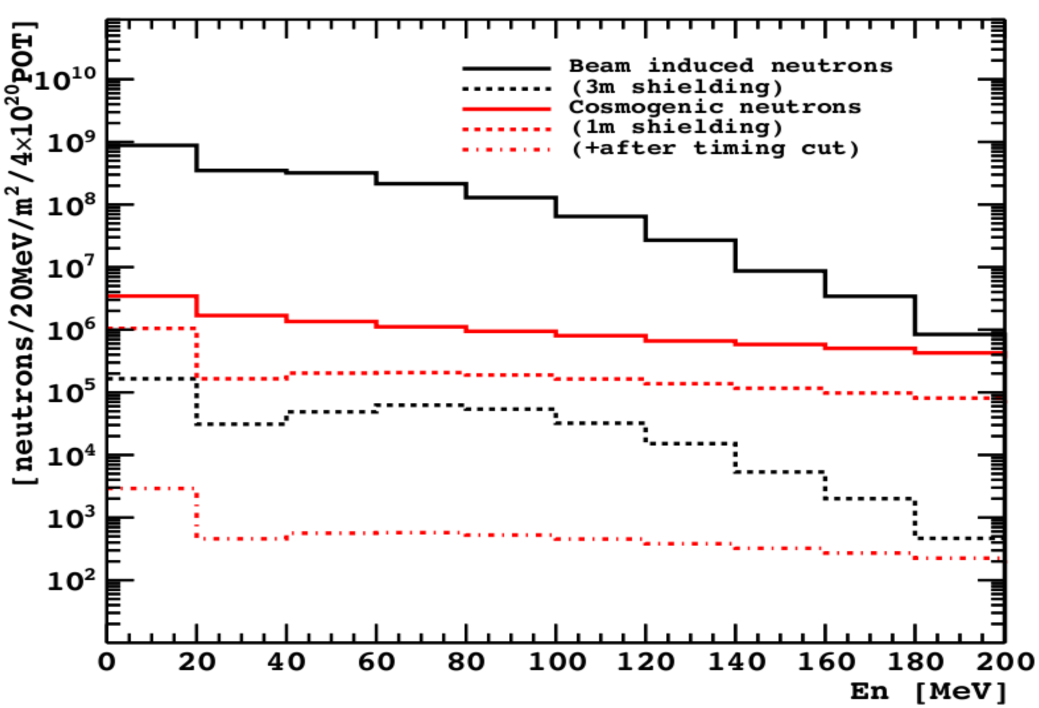
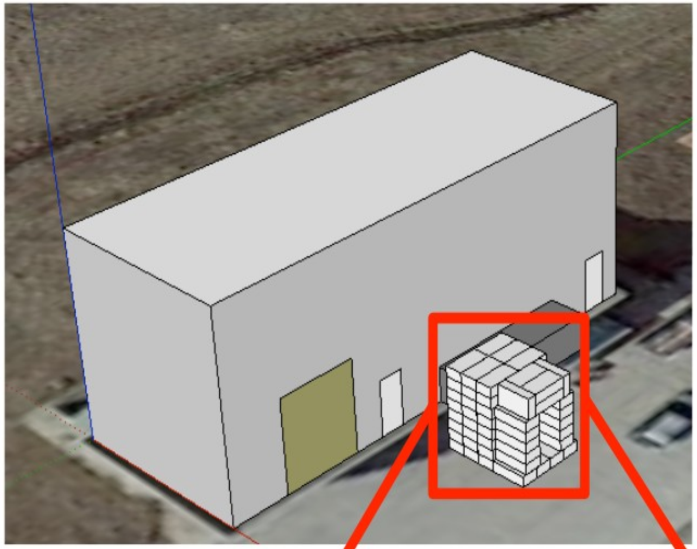
Need neutron background measurement from SciBath ~April 2015.

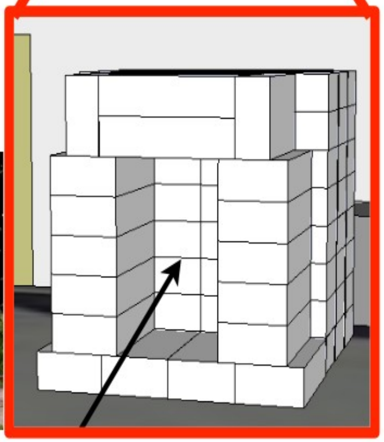
Concrete Shielding:

- 3m on side (3~4 order of magnitude reduction)
- 1m on top

Distance = 10 m from target







Neutrino Flux around MI-12

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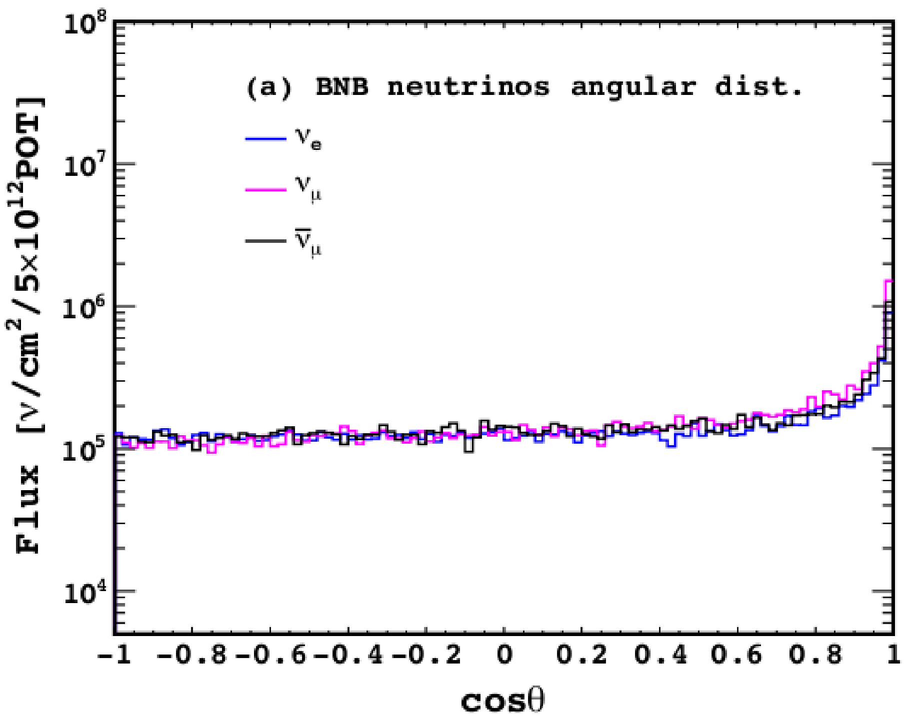
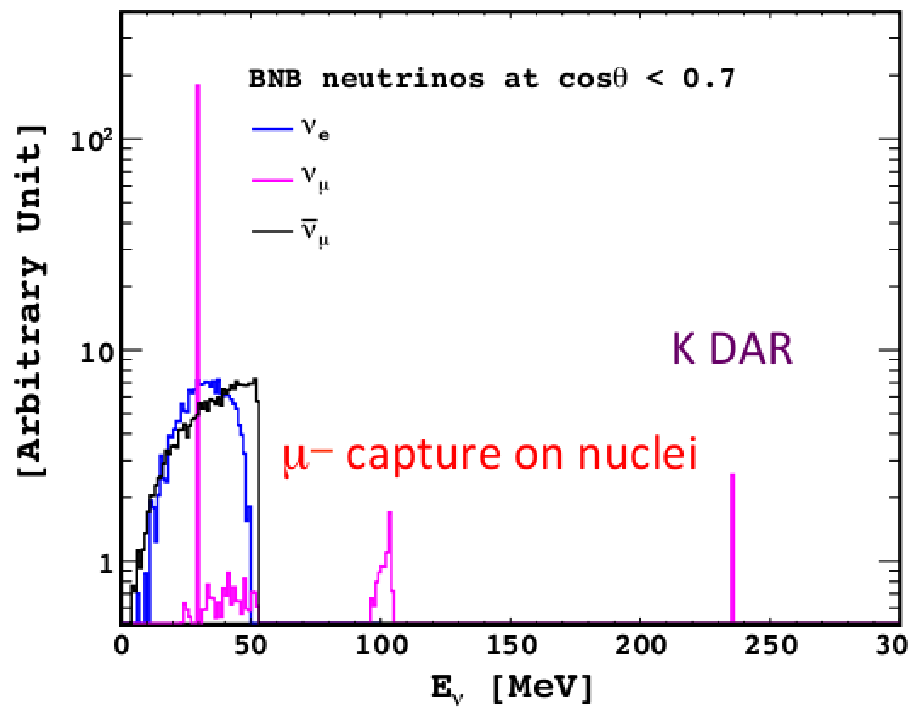
S. Brice calculation for CENNS 20 m from MB target using modified MB G4 code

Phys. Rev. D89 (2014) 072004 (arXiv 1311.5958 physics.ins-det)





For 5e+12 ppp at 5 Hz: neutrino flux is $\Phi = 5 \times 10^5\ \nu/cm^2/s$/flavour

Conclusions

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- CAPTAIN will make significant contributions to the development of DUNE.
- CAPTAIN will make unique measurements of neutron-argon and neutrino-argon interactions relevant to long baseline neutrino experiment.
- CAPTAIN will measure DAR ν XS on LAr at BNB direct relevance to DUNE SN detection.
- The detector will serve as a test bed for various calibration and detection strategy schemes, especially regarding laser calibration and photon detection.

Collaboration

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