Stony Brook University

26th International Workshop on Weak Interactions and Neutrinos (2017)

CAPTAIN: Current Neutron and Future Stopped Pion Measurements

Clark McGrew
Stony Brook Univ.
for the
CAPTAIN
Collaboration

(C)ryogenic (A)pparatus for (P)recision (T)ests of (A)rgon (I)nteractions with (N)eutrinos†

†or (N)eutrons

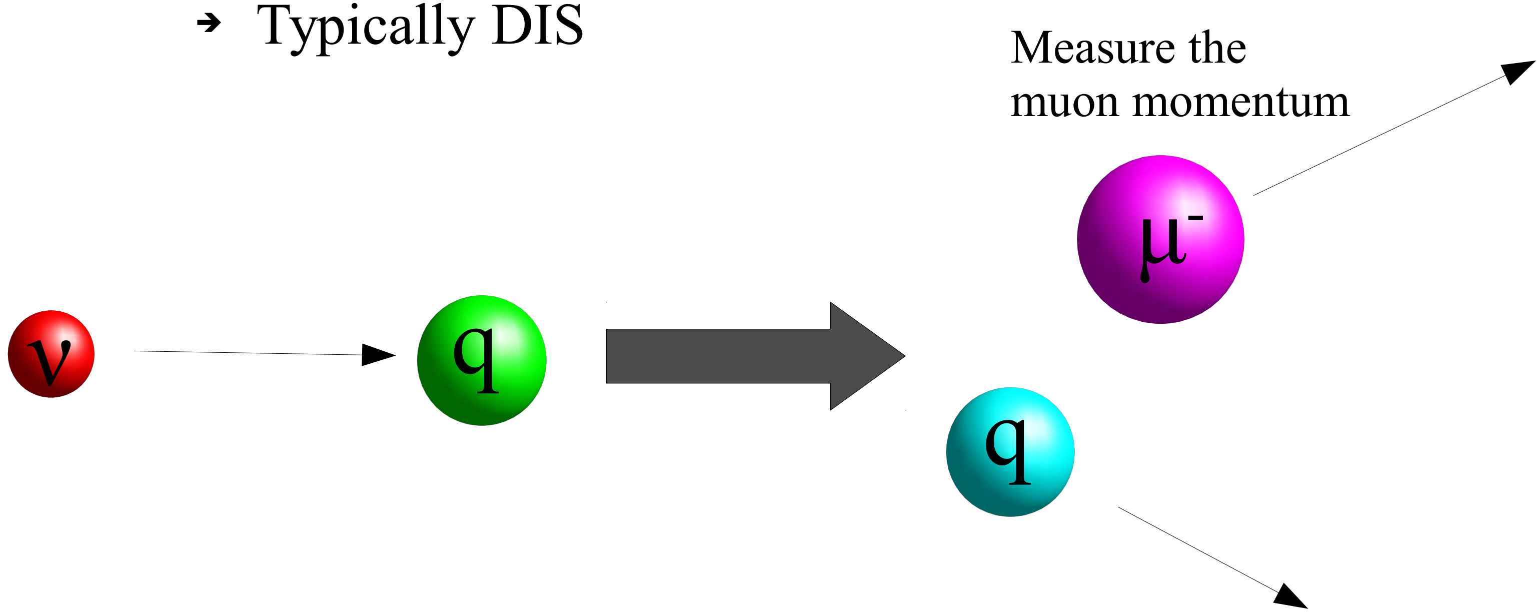
CAPTAIN Physics Program

Neutron Beam
Low-Energy Neutrino Beam

- Low-energy neutrino physics related
  - Measure neutron production of spallation products
  - Benchmark simulations of spallation production
  - Measure the neutrino CC and NC cross-sections on argon in the same energy regime as supernova neutrinos
  - Measure the correlation between true neutrino energy and visible energy for events of supernova-neutrino energies
- Medium-energy neutrino physics related
  - Measure neutron interactions and event signatures (e.g. pion production) to improve understanding of neutrino interactions emitting neutrons.
  - Measure higher-energy neutron-induced processes that could be backgrounds to ν_e appearance e.g. $^{40}Ar(n,\pi^0)^{40}Ar^{(*)}$

DUNE Neutrino Energy Reconstruction (E_ν >2.5 GeV)

- The DUNE inclusive cross section measurement can calculate the neutrino energy as the total energy visible in the detector.
  - Typically DIS



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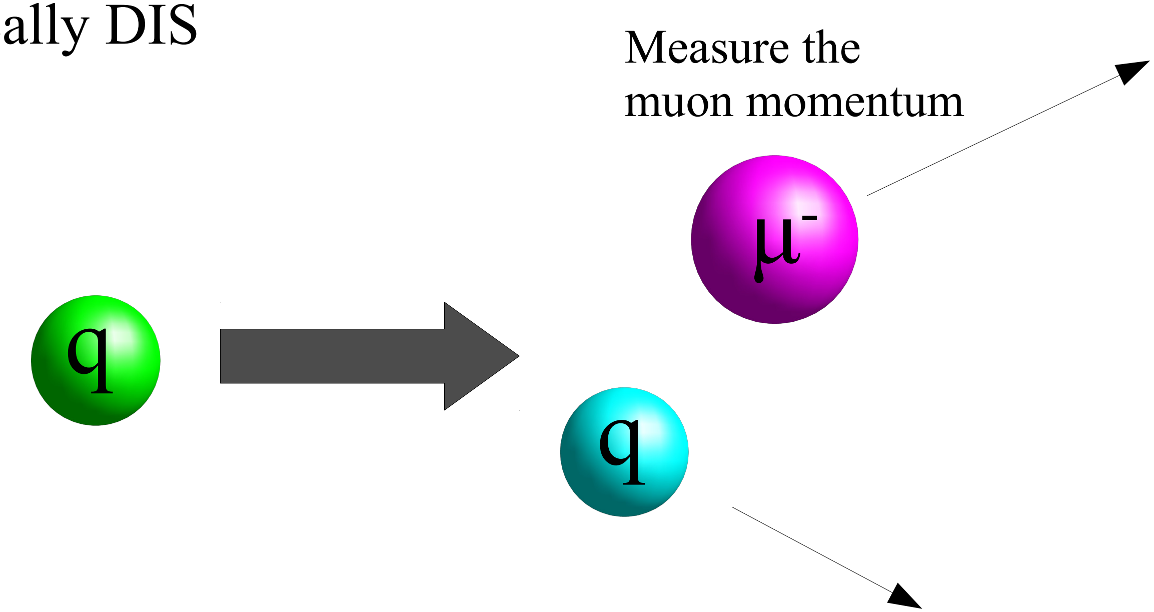

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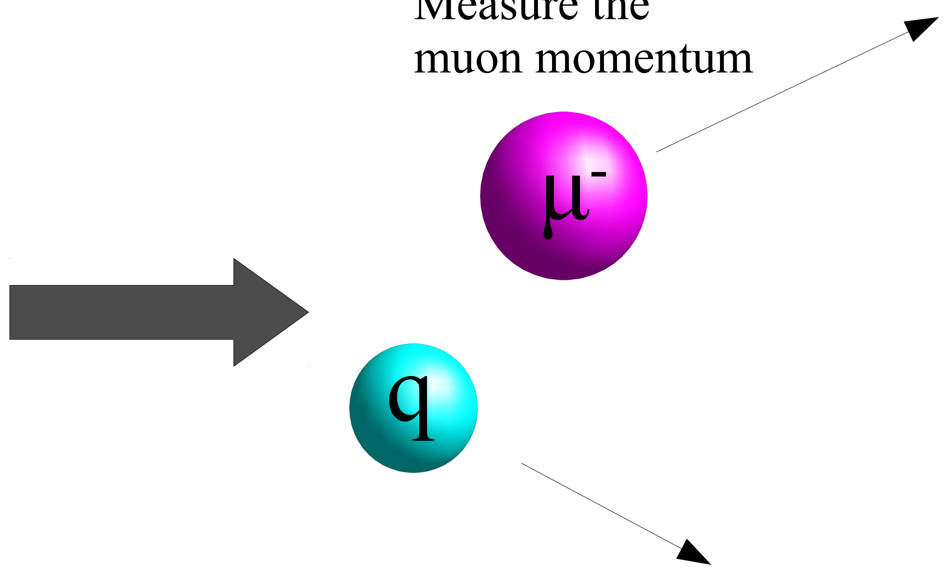
Measure the muon momentum



Assume quark is at rest

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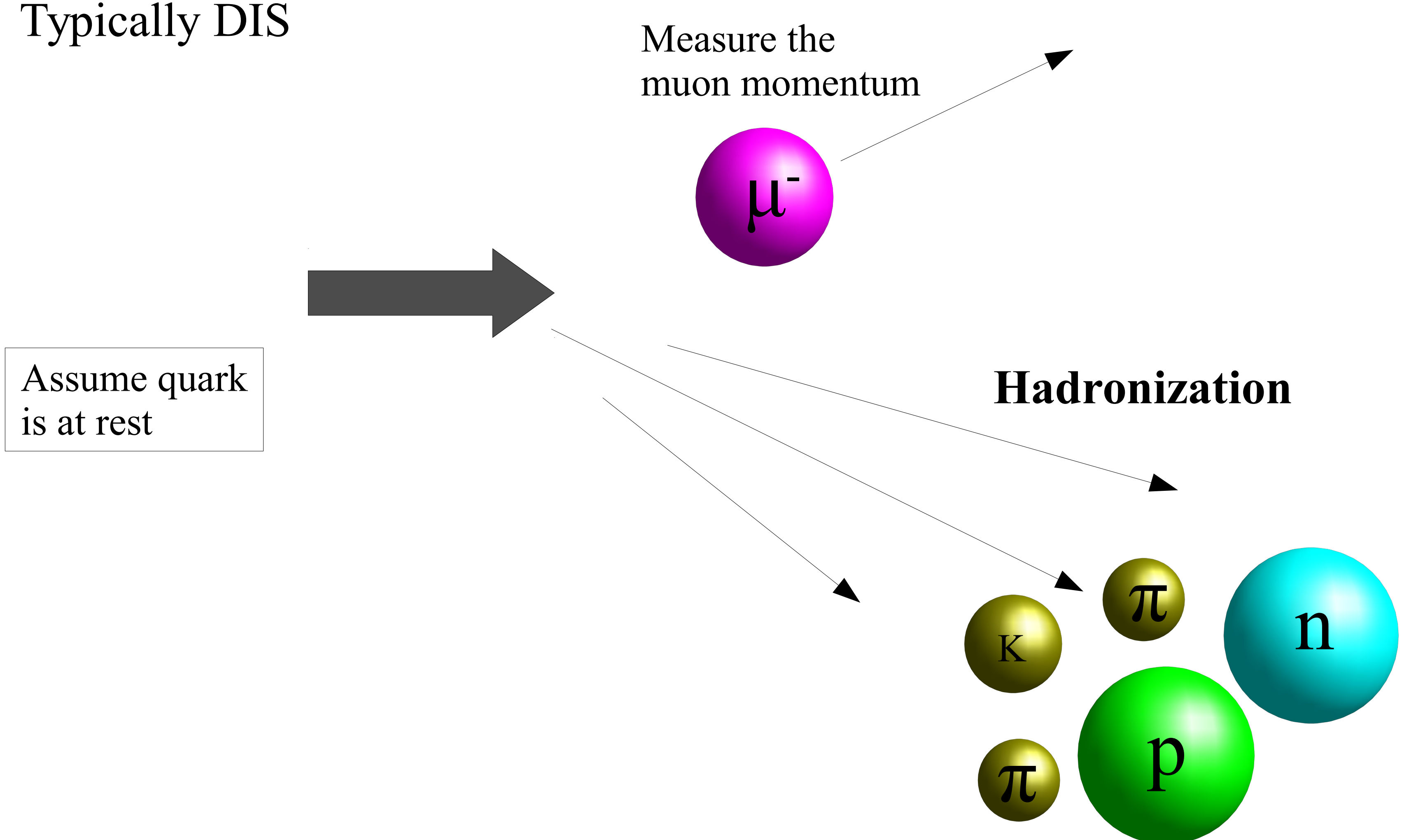

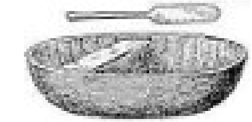

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Reconstruct neutrino energy with what is left

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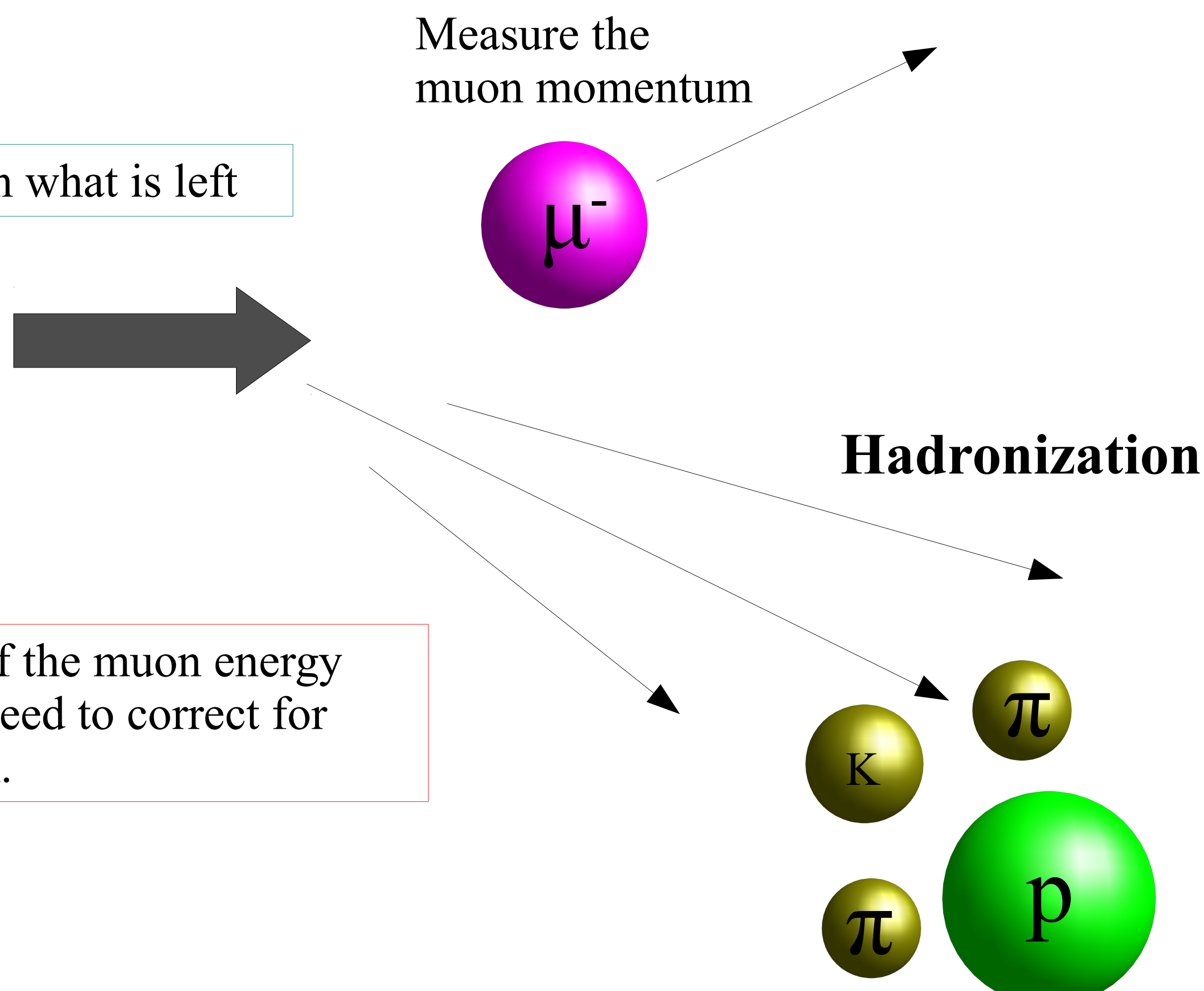

Neutrino energy is the sum of the muon energy and hadron energy, but you need to correct for energy that escapes detection.

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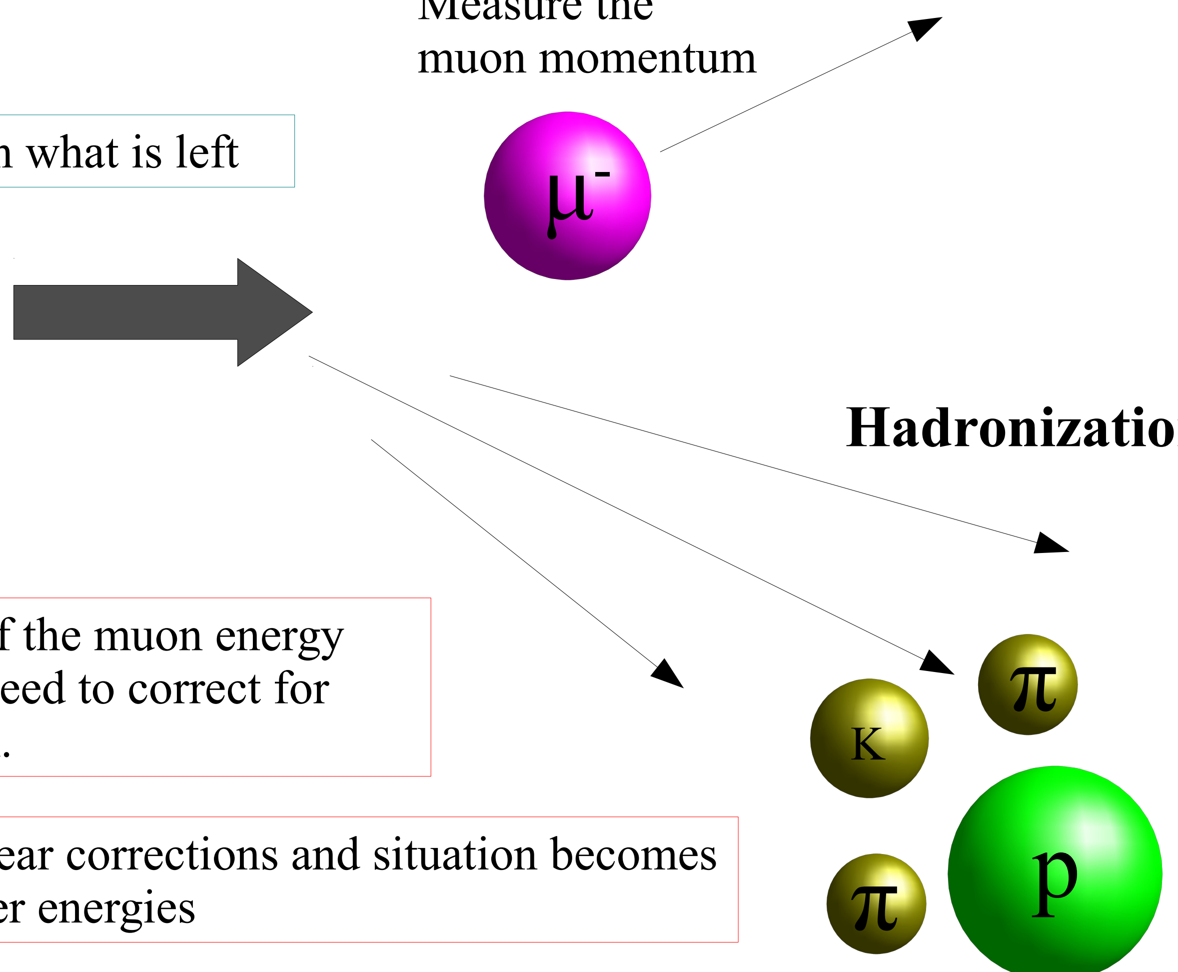


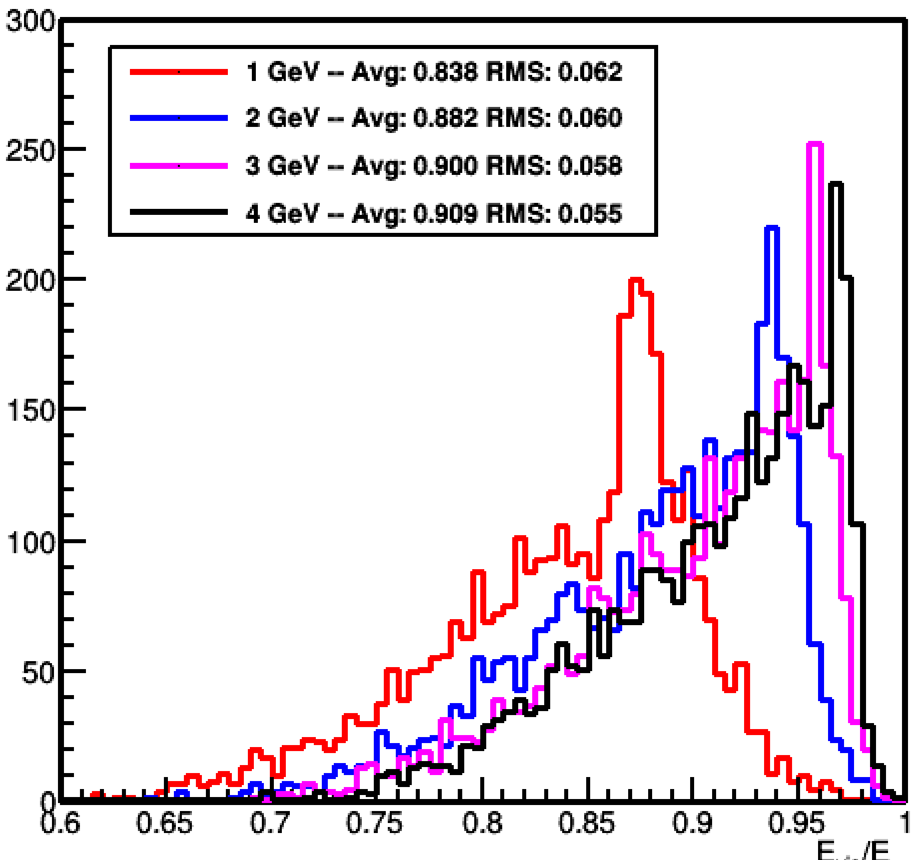
Neutrino energy is the sum of the muon energy and hadron energy, but you need to correct for energy that escapes detection.

Still doesn’t address nuclear corrections and situation becomes more complicated at lower energies

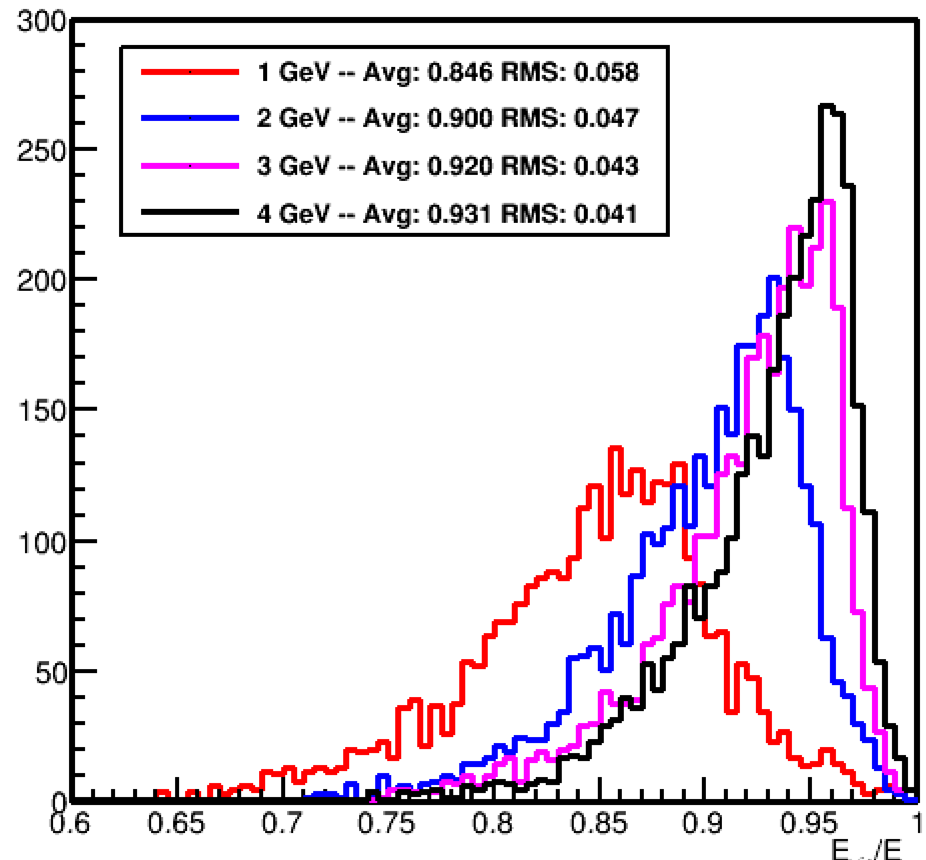
Fraction of E_ν Creating Ionization in Argon

- The ratio of visible energy to neutrino energy is different for neutrinos and anti-neutrinos
  - Intrinsic CP violation term in the energy scale in addition to effects of oscillation

Muon Neutrino

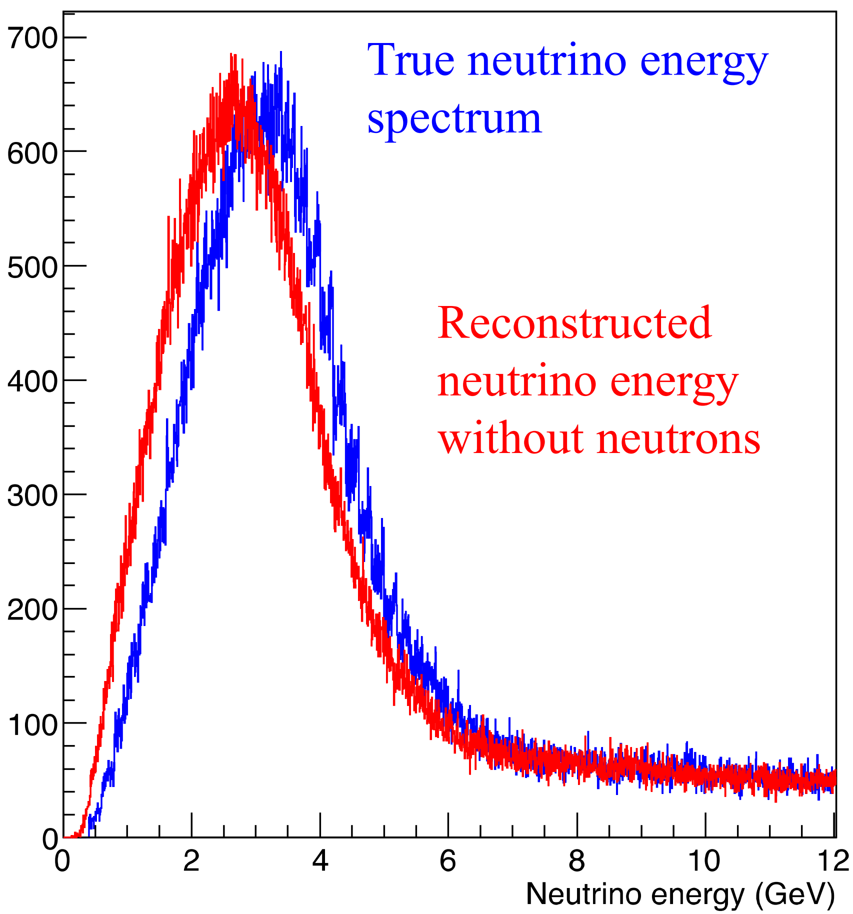


Muon Anti-neutrino

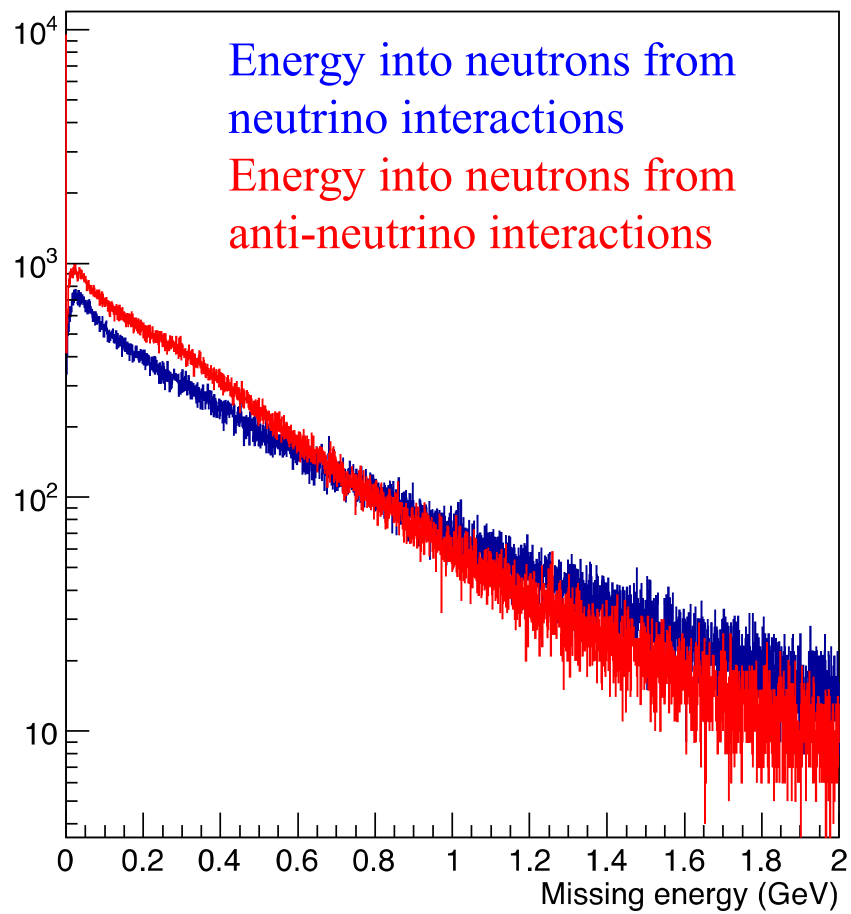


Reconstructed E_ν without Neutrons

LBNF Neutrino Energy Spectrum



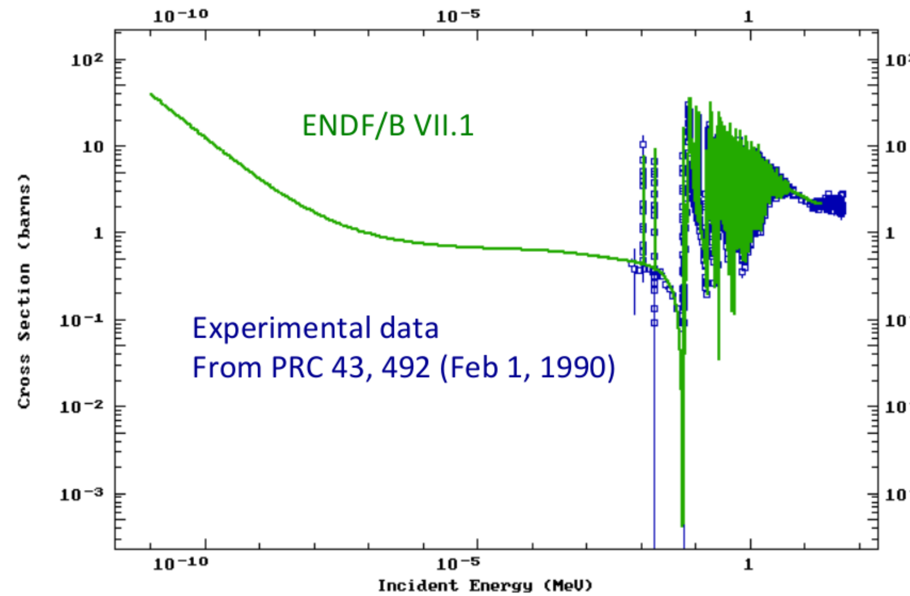
Outgoing energy in neutrons

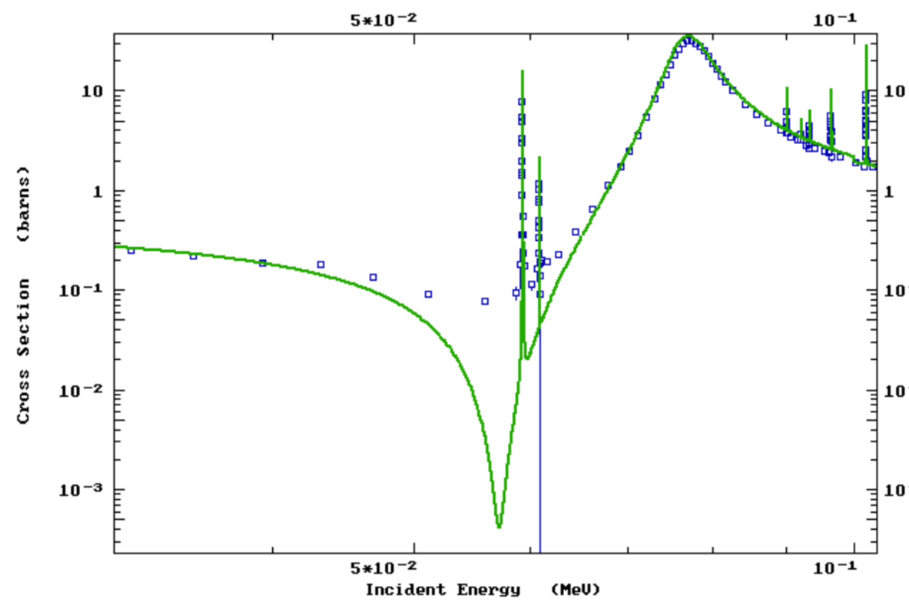


Elena Guardincerri

Neutrons in Argon

- Cross-section data only published to 50 MeV (kinetic)
- There is a predicted negative resonance makes argon transparent at 55 keV
    - Neutron above the resonance should survive 100's μs
    - Significant discrepancy between data and ENDF





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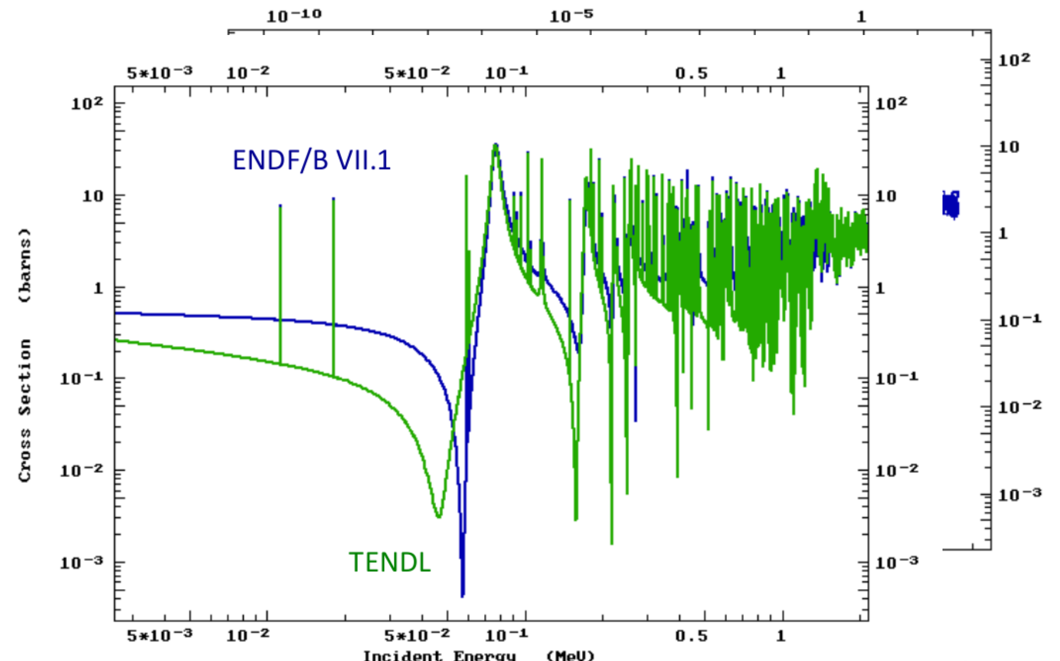

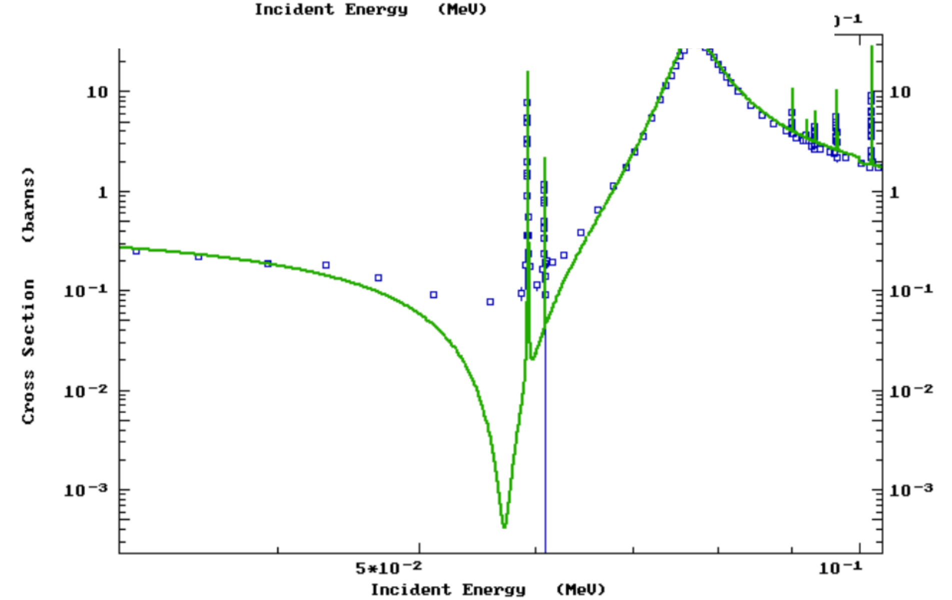

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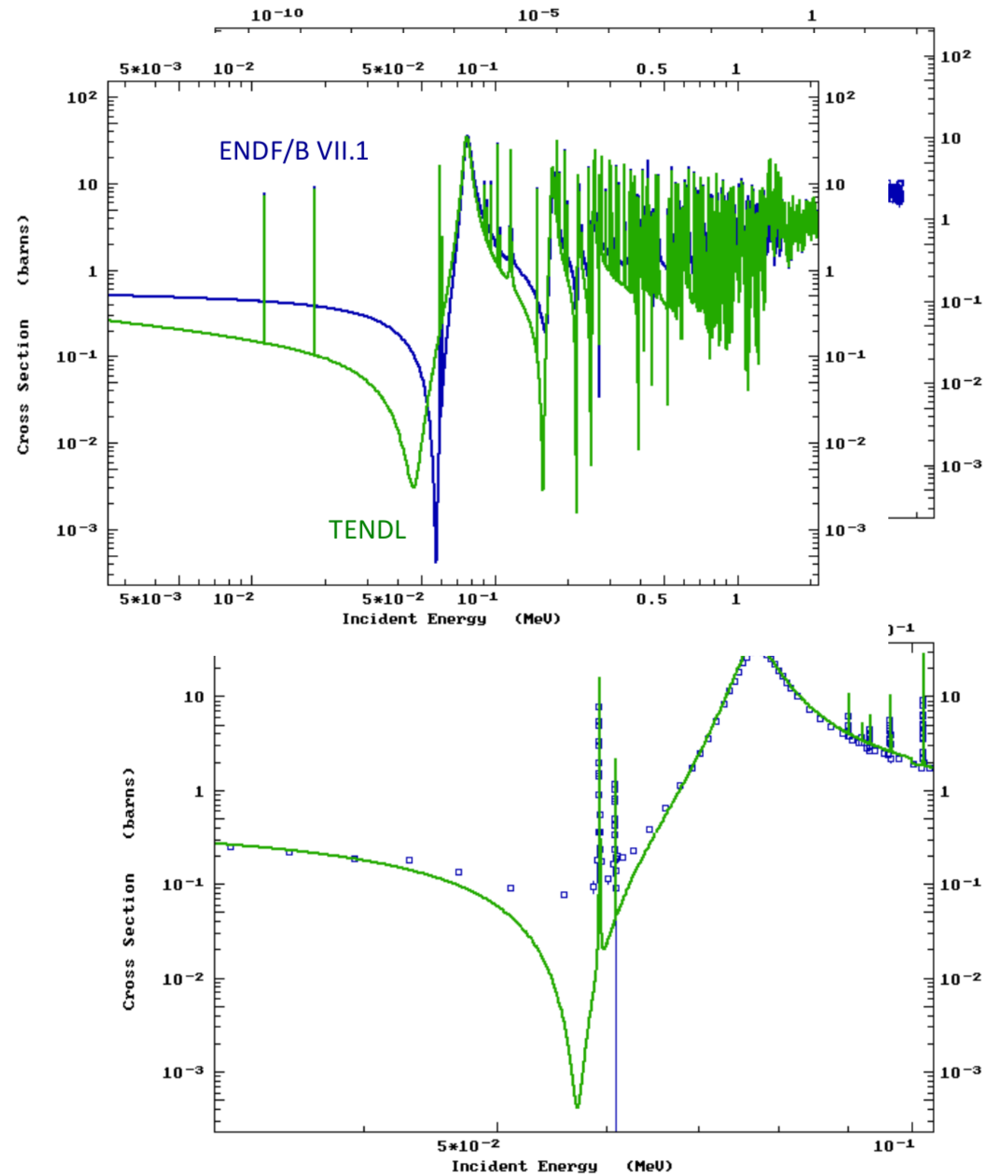
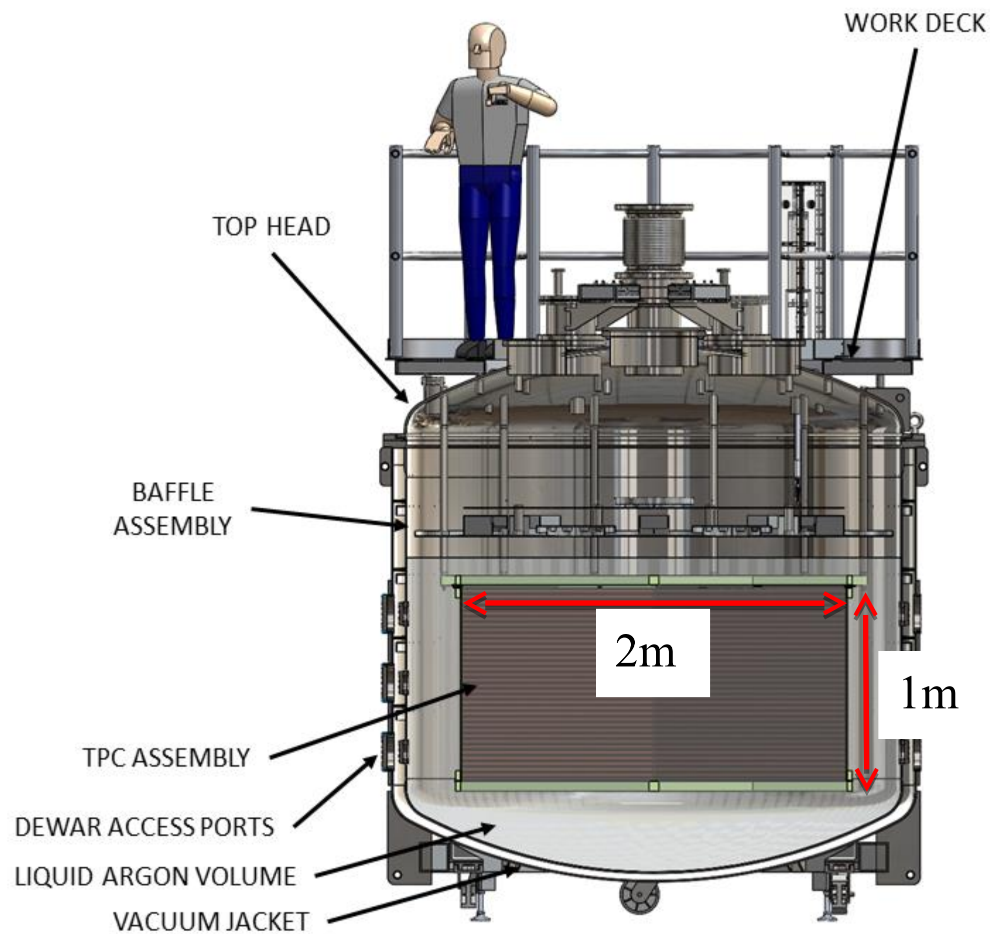
- Measure the cross-section with mini-CAPTAIN
  - Up to 800 MeV
  - We will look for presence neutron capture signature



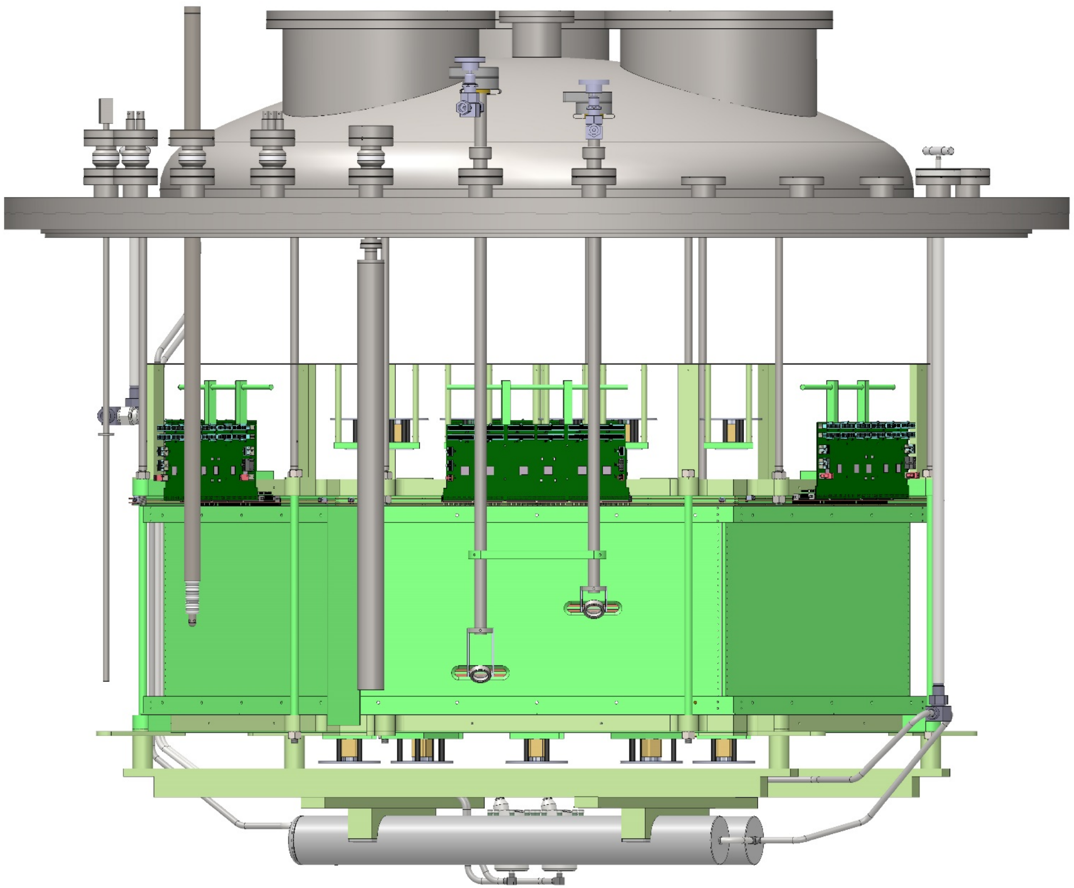
The CAPTAIN Detectors

- CAPTAIN
  - hexagonal TPC with 1m vertical drift, 1m apothem, ~1800 channels, 3mm pitch, 5 instrumented tons
    - Disambiguate most hits in 3D
  - Cryostat with indium seal
    - Can be opened and closed
  - Photon detection system
  - Laser calibration system
  - Moving toward commissioning in '18
- miniCAPTAIN
  - Hexagonal TPC with 32 cm drift, 50cm apothem, ~600 channels, 3 mm wire pitch, 400 kg instrumented
  - Cryostat on loan from UCLA
    - Indium seal for access
  - 24 PMT light detection system
- Both use same same cold electronics and electronics chain as MicroBooNE
  - front end same as DUNE



CAPTAIN Cryostat Delivered to LANL in 2014

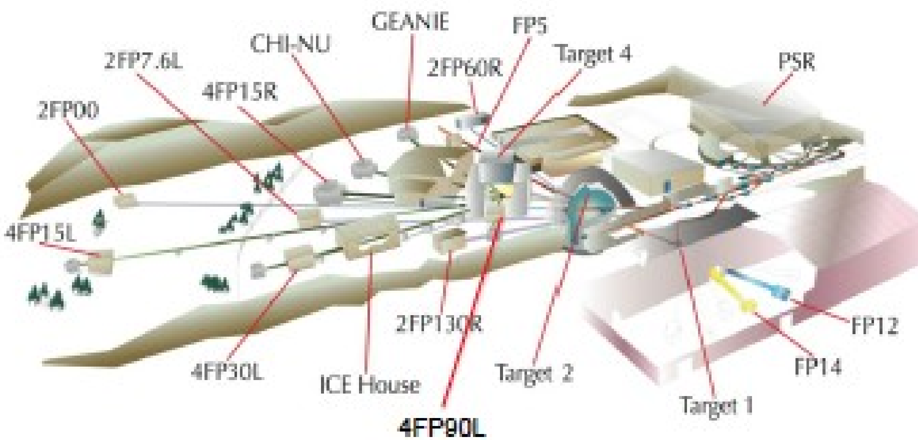
The miniCAPTAIN Detector



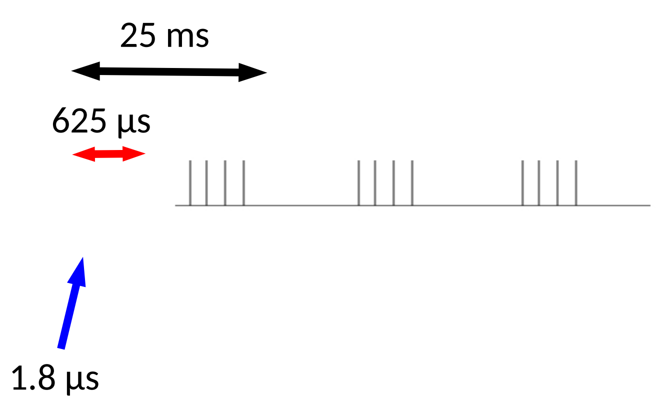
- Hexagonal (50 cm apothem or "1m diameter") with 32 cm drift
  - 500 V/cm drift
- 3 wire planes with 3mm pitch (332 wires per plane)
- 24 PMT photon detection system (above and below drift region)
- Laser calibration system

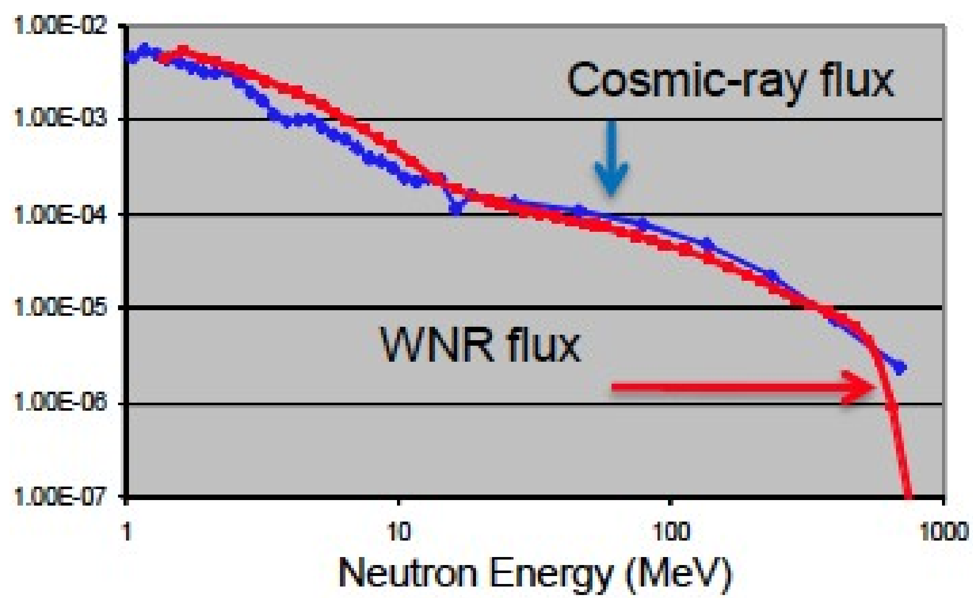
Neutron Beam at LANL

- Los Alamos Neutron Science Center WNR facility provides a high flux neutron beam with a broad energy spectrum similar to the cosmic-ray spectrum at high altitude



- Time structure of the beam
  - sub-nanosecond micro pulses 1.8 μs apart within a 625 μs long macro pulse
  - Repetition rate: up to 40 Hz

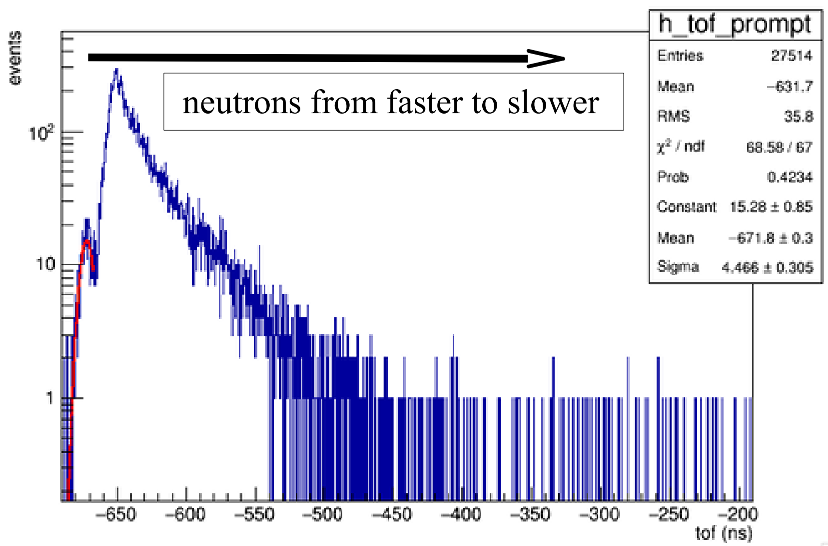




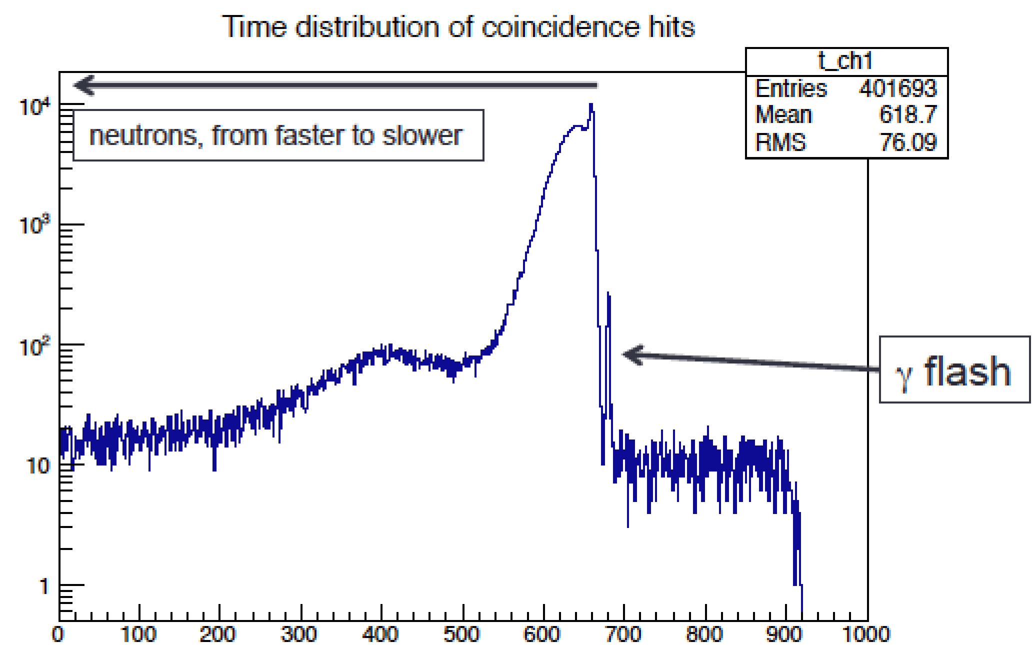
Neutron Time Of Flight

Time of flight measured in the LANSCE WNR neutron beam

- Extremely low beam power
    - 1 micropulse per macropulse is filled with protons



Neutron t.o.f. measured by Argon scintillation in miniCAPTAIN using the photon detection system.

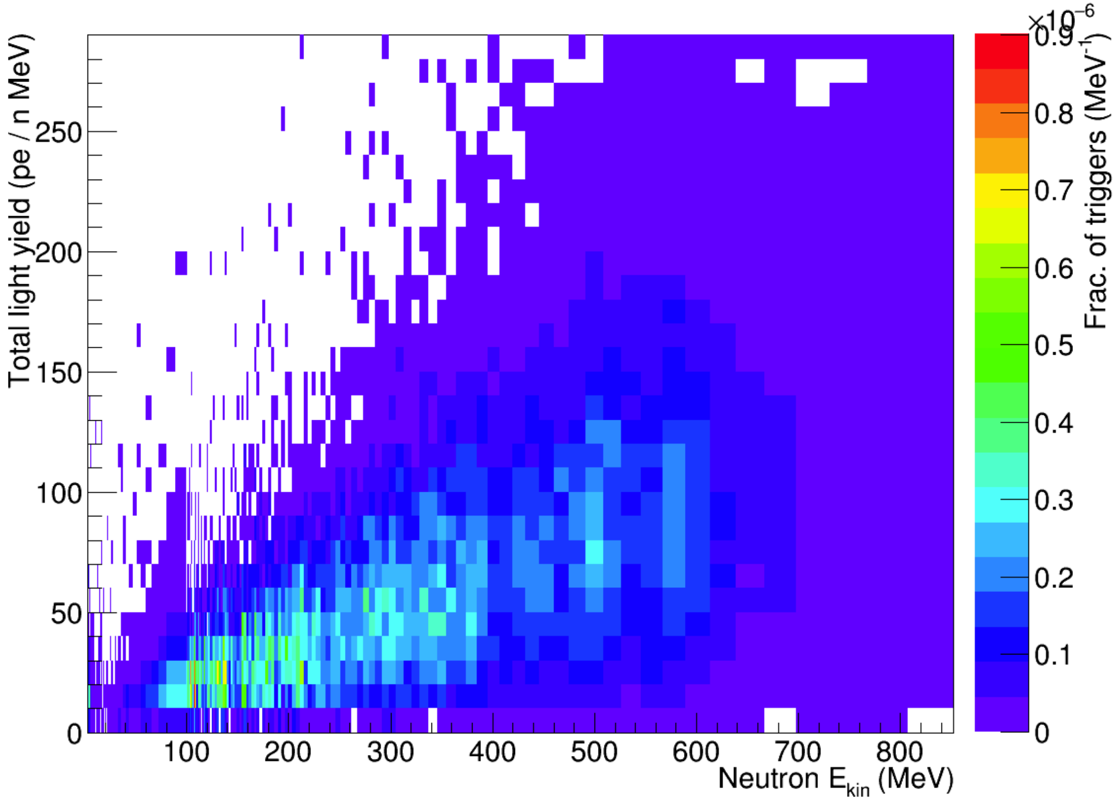


Neutron t.o.f. measured using plastic scintillator (to normalize flux). Efficiency vs energy calibrated vs a well known fission detector

Neutron Kinetic Energy Spectrum

on Argon

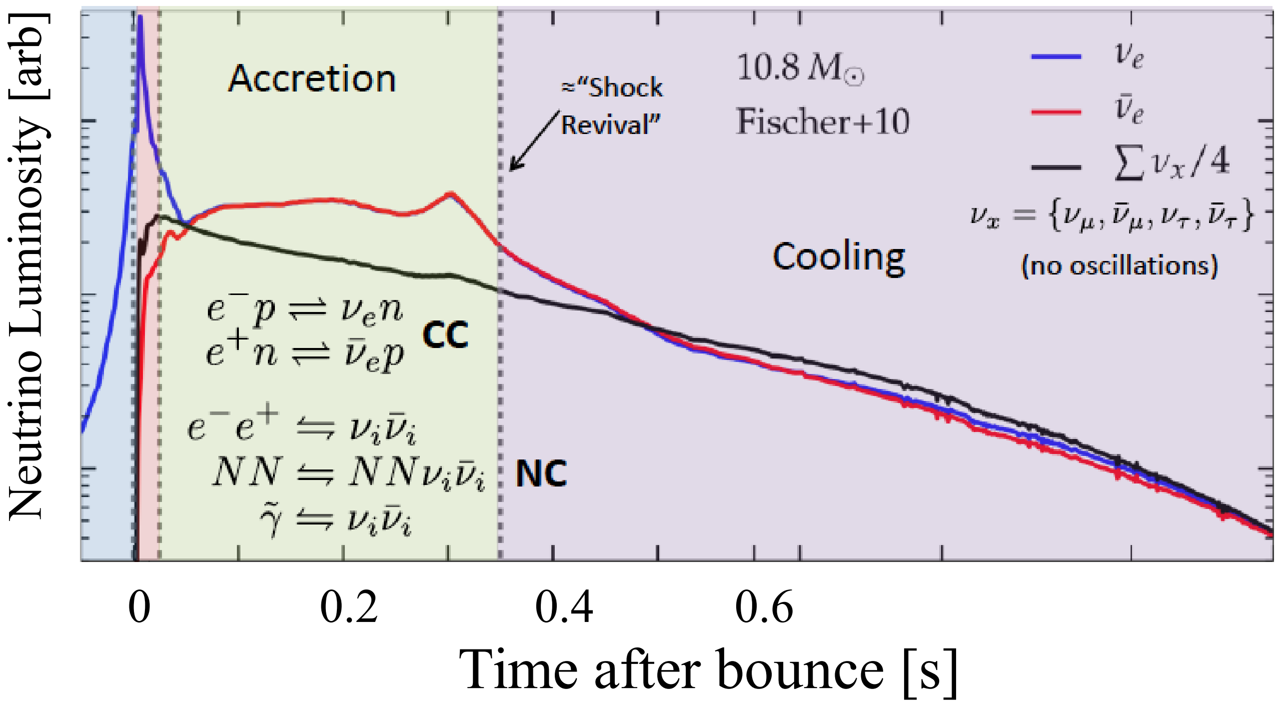
- Photon detection system data from engineering run analyzed
- Neutron energy is determined event by event using the time of flight for events in Argon
    - Not efficiency corrected
    - Not flux normalized
    - Interaction length is shorter than TPC

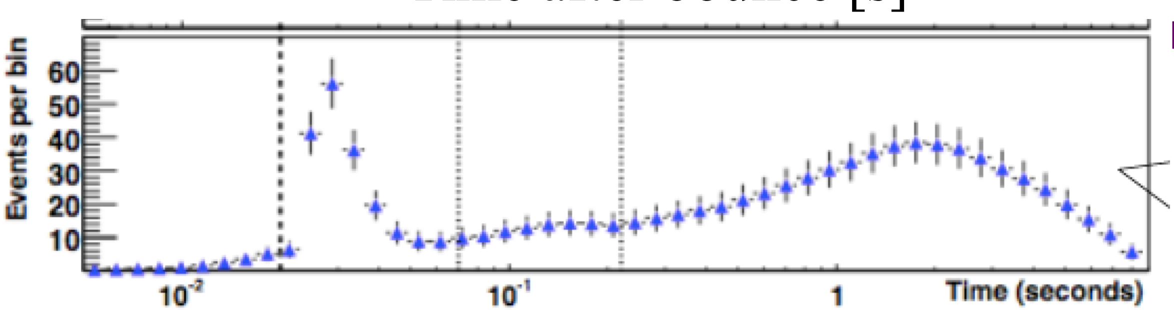


- Full TPC & PDS will be used at WNR this year
    - Currently being filled in beam-line

- 2017 Physics run goals
    - Cross-sections
        - Differential partial cross-section on Ar.
            - e.g. π^o, p, $\pi^{\pm}$ production
    - Library of event signatures
        - Light yeld vs energy
        - Ionization vs energy
        - Ionization vs light yeild

Neutronization only visible in ν_e





Events in 34 kton LAr at 10 kpc (Asimov expectation)

- Burst is only 20 ms long and is essentially all ν_e
- Mean energy of events is 10-12 MeV
- IMB/Kamiokande detected higher energy cooling neutrinos
  - Not neutrinos from neutronization
- DUNE has potential for ν_e detection

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

P5 recommendation:

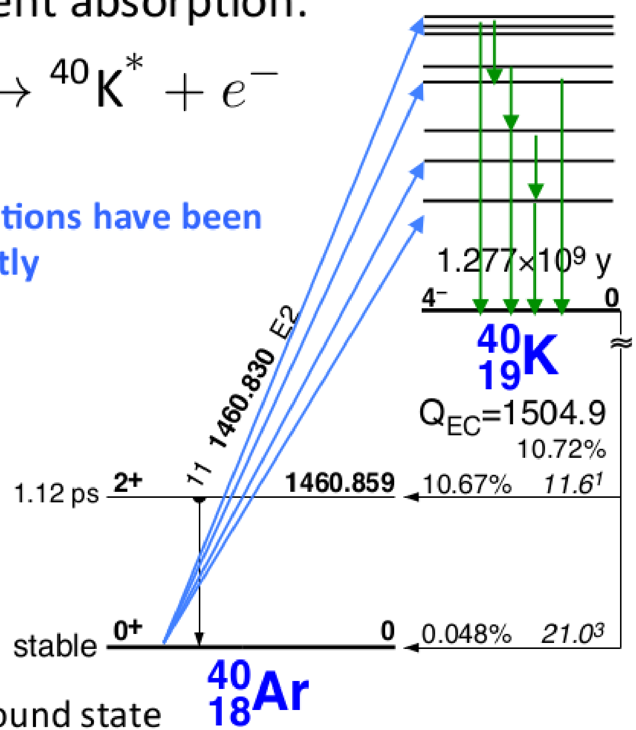
"The (ELBNF) experiment should have the demonstrated capability to search for SN bursts..."

Supernova neutrinos in DUNE

Charged-current absorption:

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

At least 25 transitions have been observed indirectly



(ground state to ground state is 3rd forbidden transition)

Transition levels are determined by observing de-excitations (γ's and nucleons)

Reconstructing true neutrino energy:

Q is determined from de-excitation gammas and nucleons

Outgoing e⁻ Energy | Energy donated to transition | Nuclear Recoil Energy (negligible)

$$E_\nu = E_e + Q + K_{\text{recoil}}$$

Total cross-section:

We have limited knowledge the transition intensities

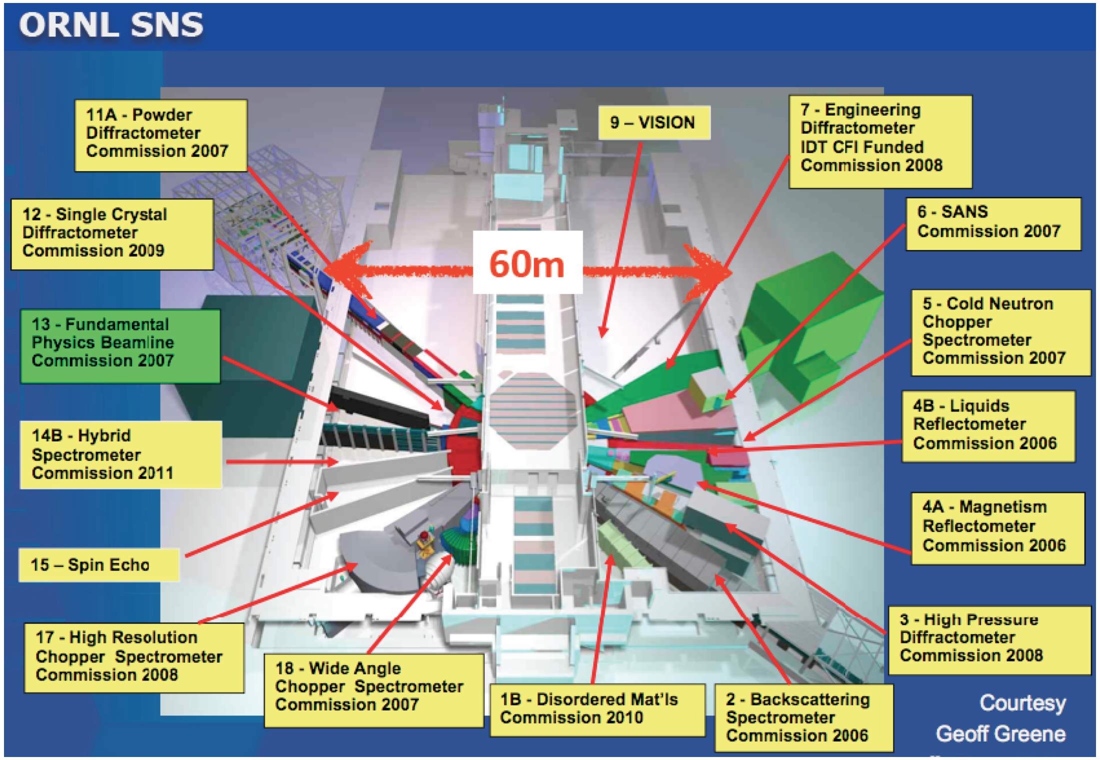
$$\sigma(E_\nu) = \frac{G_F^2 \cos^2(\theta_{ud})}{\pi \hbar^4 c^3} \sum_i p_i W_i F(Z, W_i)[B_i(GT) + B_i(F)]$$

9

Chris Grant (BU) at recent CAPTAIN meeting

SNS as a D.A.R. ν Source

- Possible measurement at SNS
  - 1 GeV beam at 1 MW
- Physics Questions
  - Total neutrino cross section below 50 MeV
  - Electron differential cross section [$dE_e/d(DAR)$]
- Detector development questions:
  - Rate consistency with cross-section
  - Light yield
  - Neutrino/background discrimination
  - Triggering for a large detector

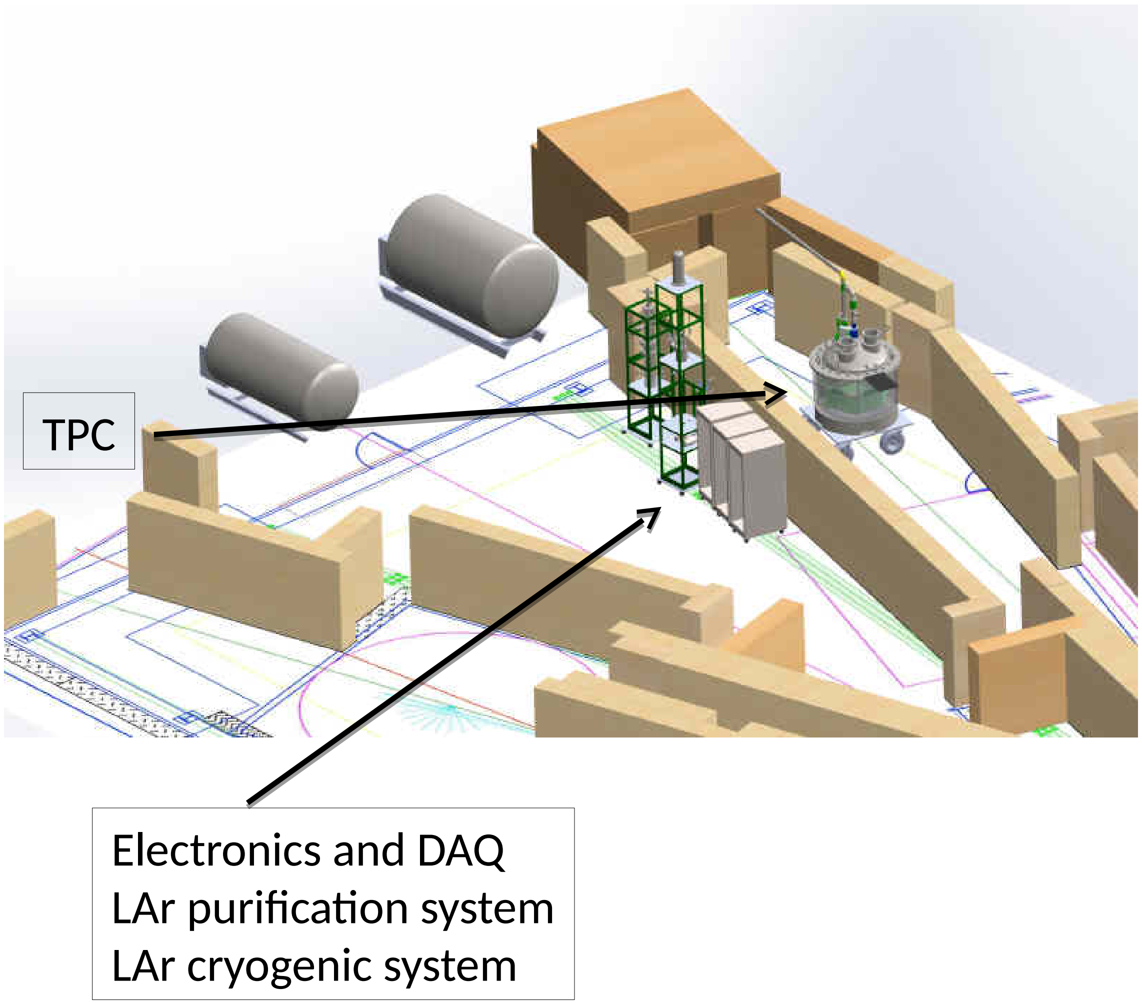


Final Thoughts

- CAPTAIN provides an ideal set of instruments to make crucial supporting measurements for DUNE physics program.
  - All of the questions are driven by a need to understand neutrino-nucleus (Ar) interactions.
    - Even the neutron-argon measurements
- A large LAr detector will provide critical measurements if we can observe a SN
  - But we need to understand the neutrino cross section below 50 MeV to design the detector (DUNE), and understand any signal if we see it.
- The current CAPTAIN run plan includes several measurements
  - Neutrons on argon
    - Data at WNR starting on July 11
  - Low energy neutrino cross sections
    - Measured at a stopped pion neutrino source
- There are opportunities with CAPTAIN for new collaborators
  - Data almost here for neutron running
  - Important low energy ν+Ar data in the future

Backup Slides

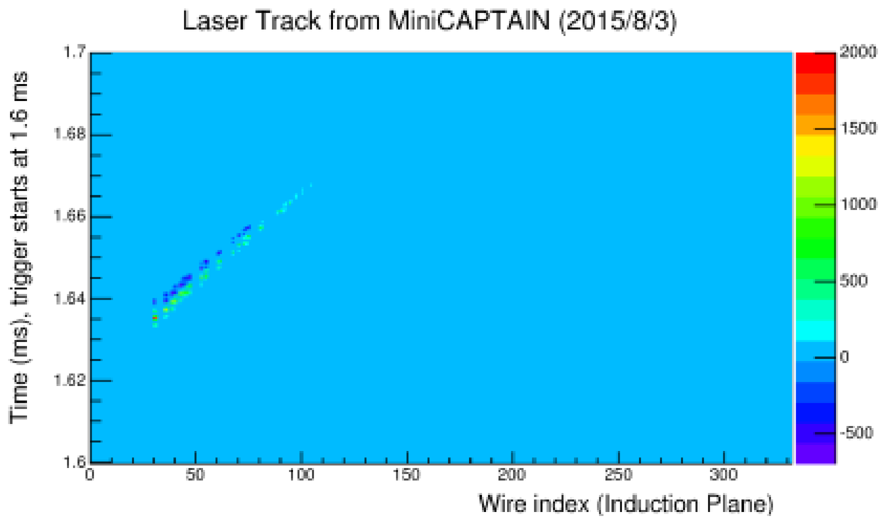
mini-CAPTAIN Operation

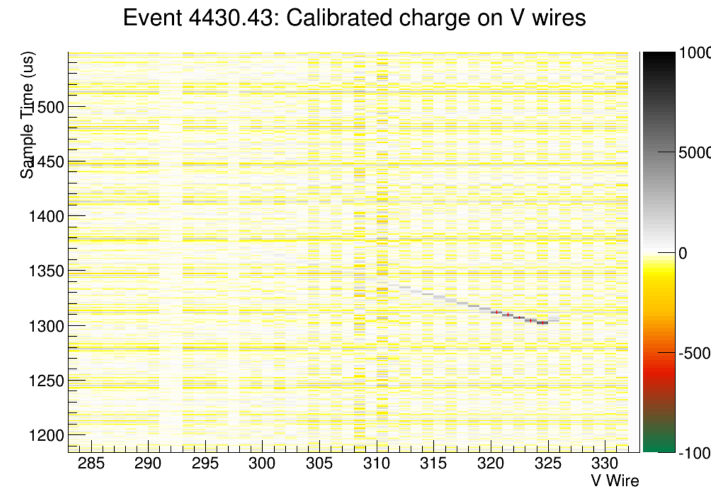


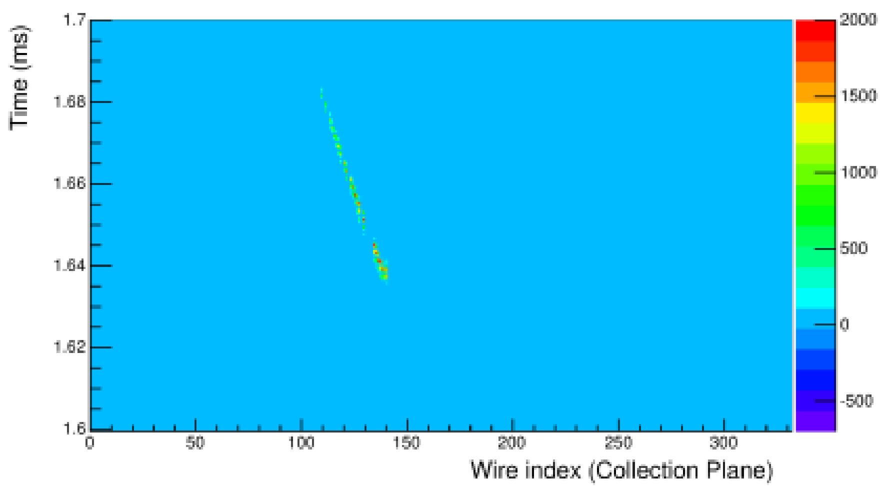
mini-CAPTAIN installed in the WNR 15R beam line

Assembled at LANL with cosmic ray commissioning during Summer 2015
WNR @ LANSCE engineering run during January 2016
WNR @ LANSCE physics run from 11-28, July 2017

First signals in miniCAPTAIN

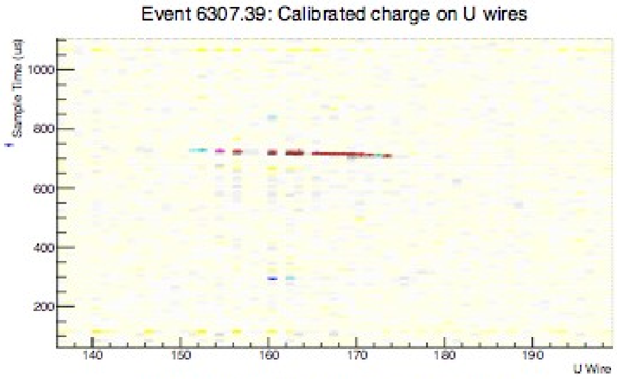


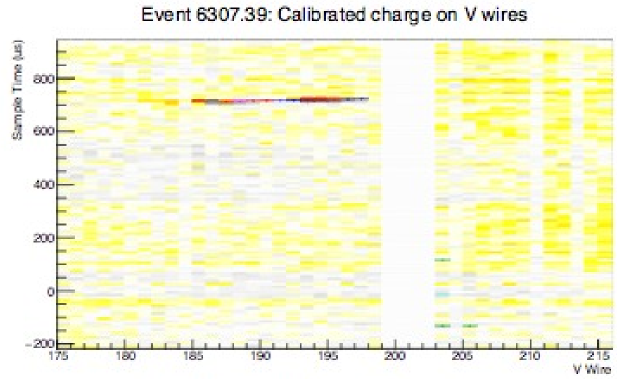


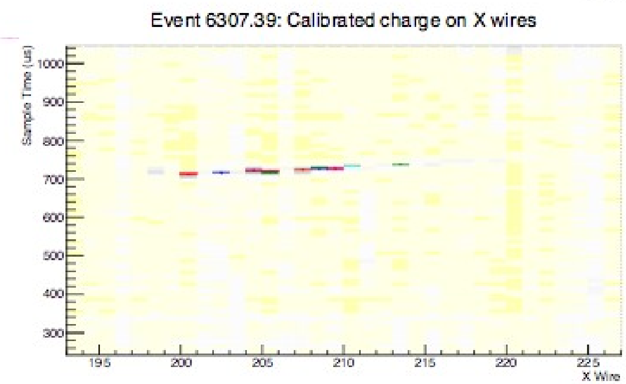


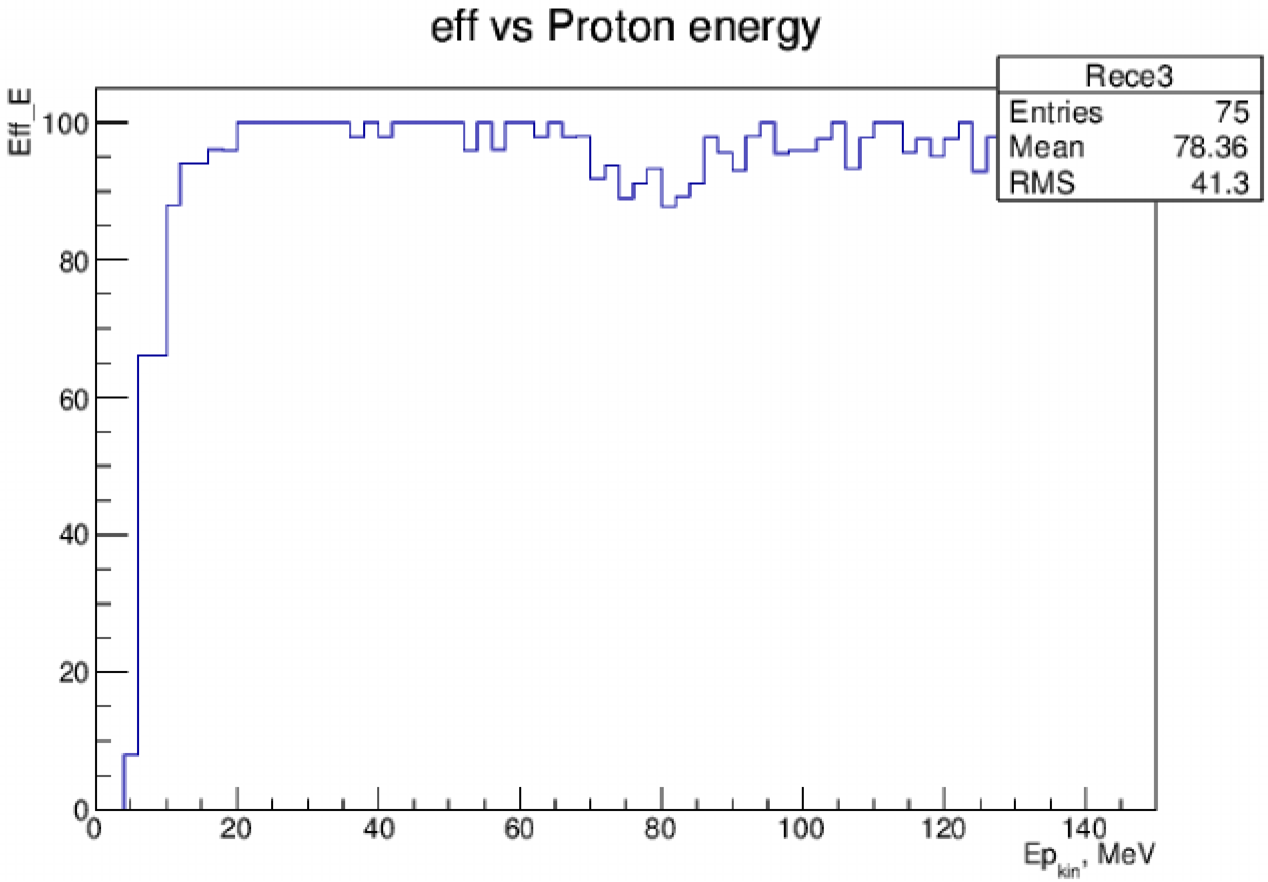
- First drift signals collected during summer 2015 commissioning
  - Electron lifetime was ~20μs w/o indium seal to ease access to TPC (will add for physics run)

mini-CAPTAIN Events (From the Engineering Run)

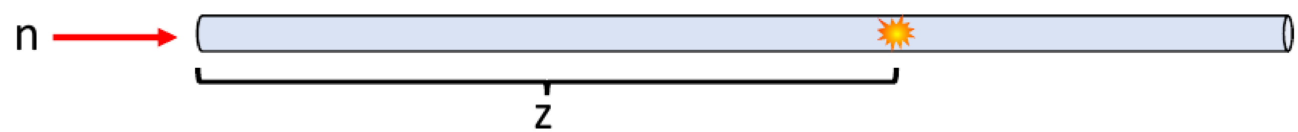


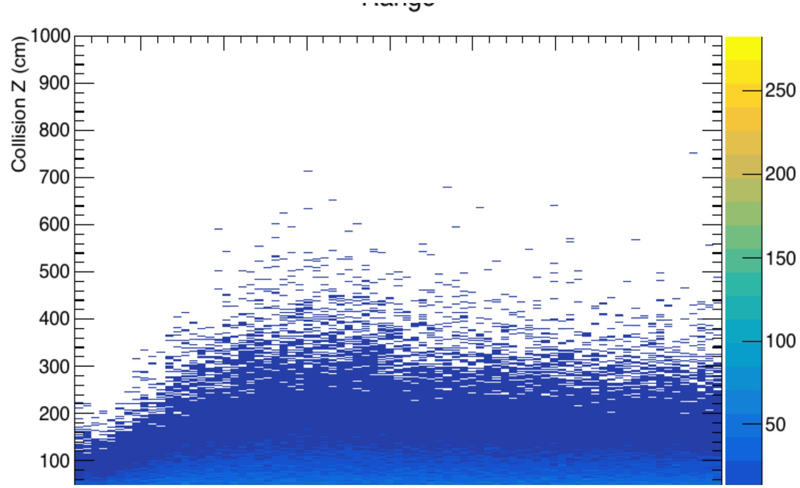






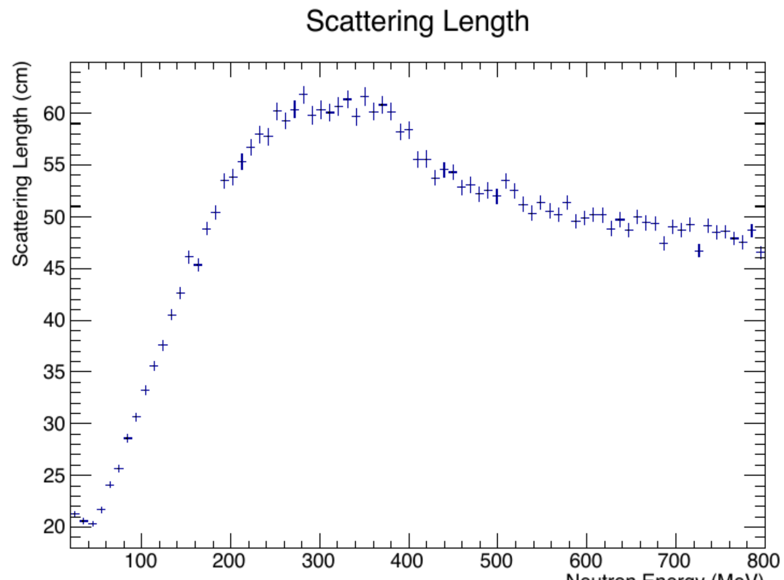
Neutron Cross Section Measurement

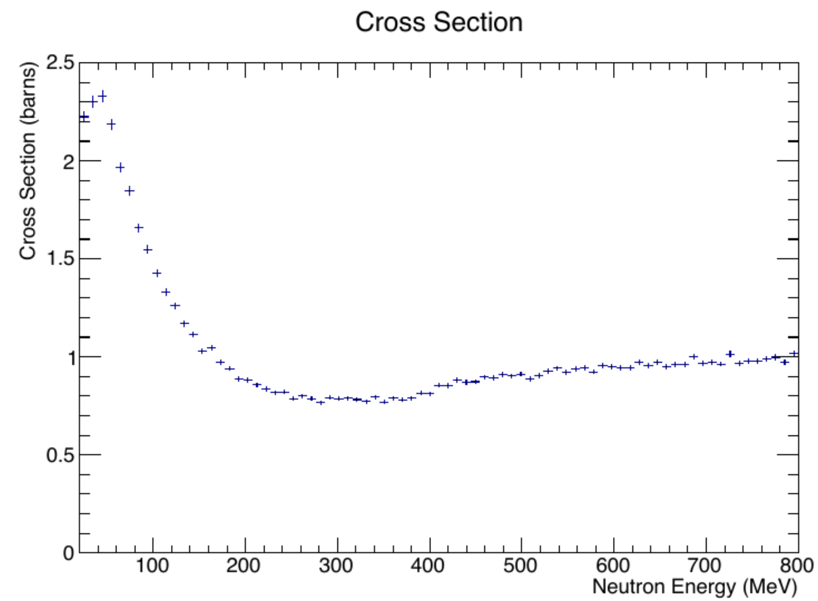




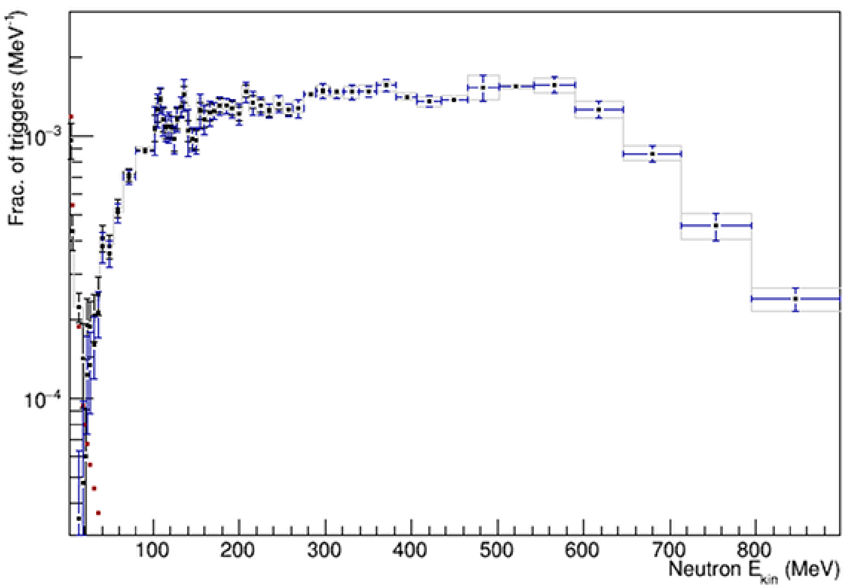
The total cross section is measured by determining the extinction rate for a particular event topology

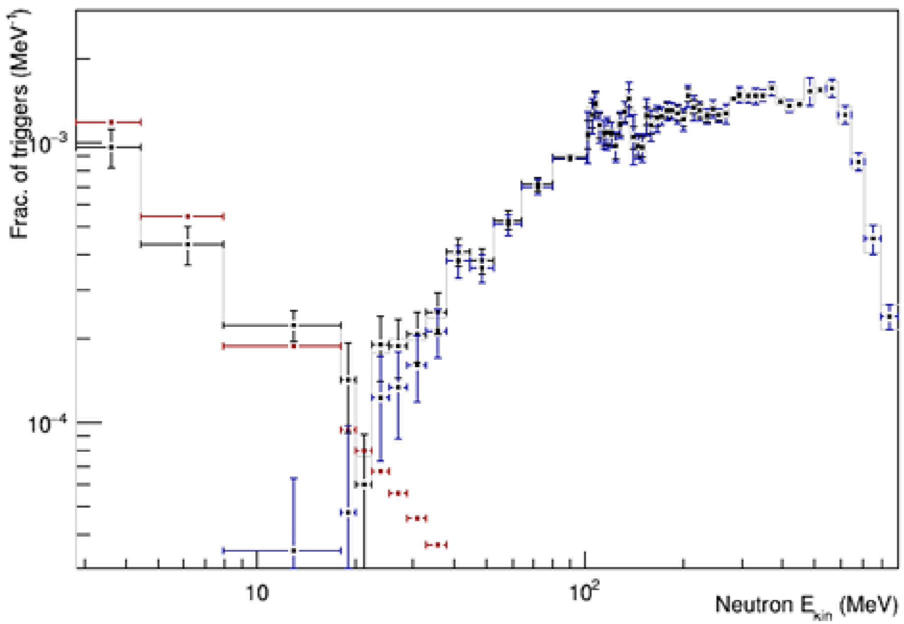
We will use n + Ar → p + X (not seen)





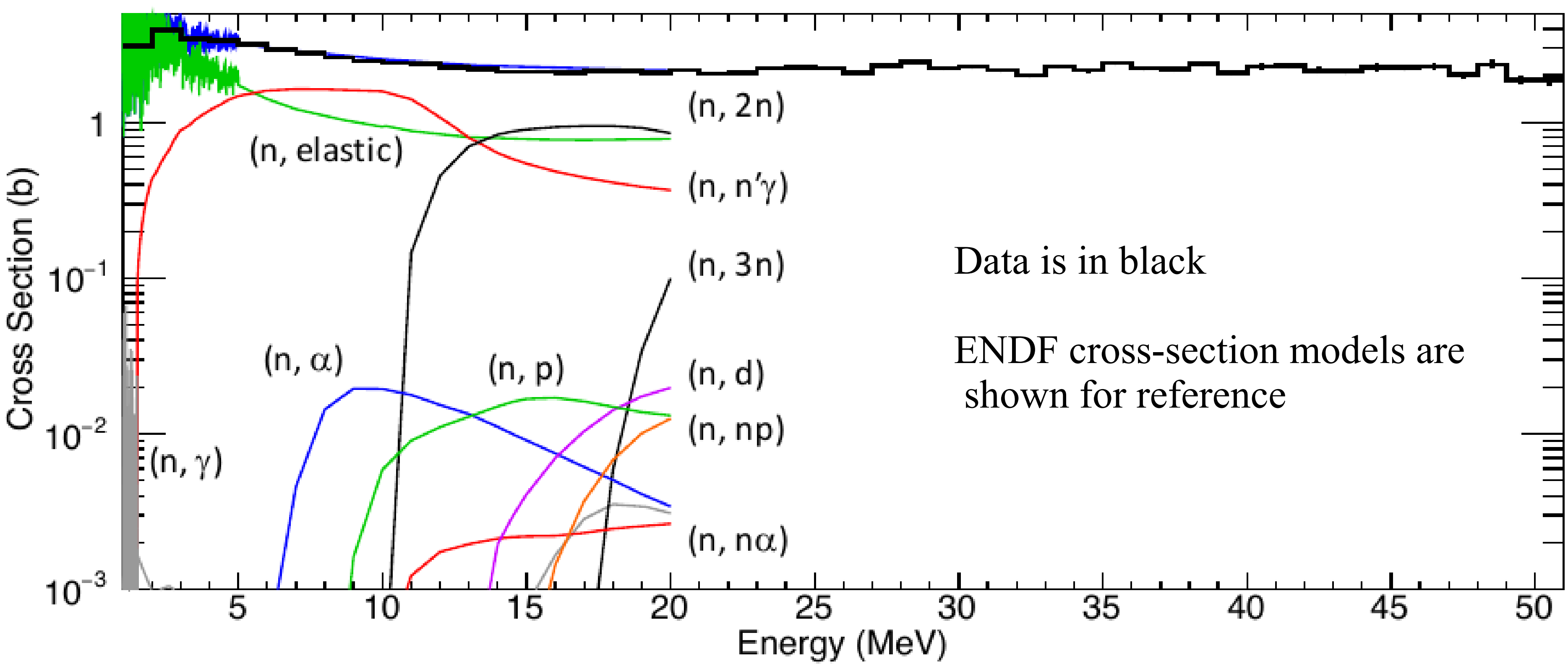
Neutron Kinetic Energy Spectrum





Neutron Cross-Sections on Argon

R.R. Winters et al., Phys Rev C 43, 492 (1991) – nndc.bnl.gov

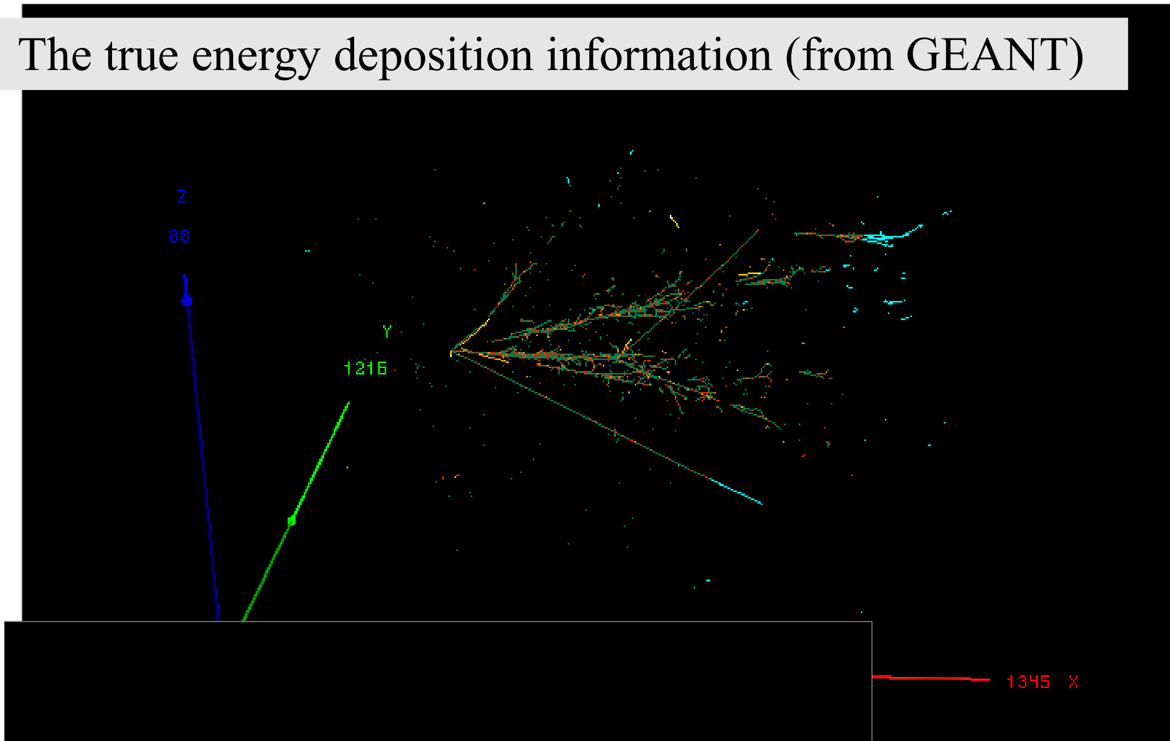


Data is in black

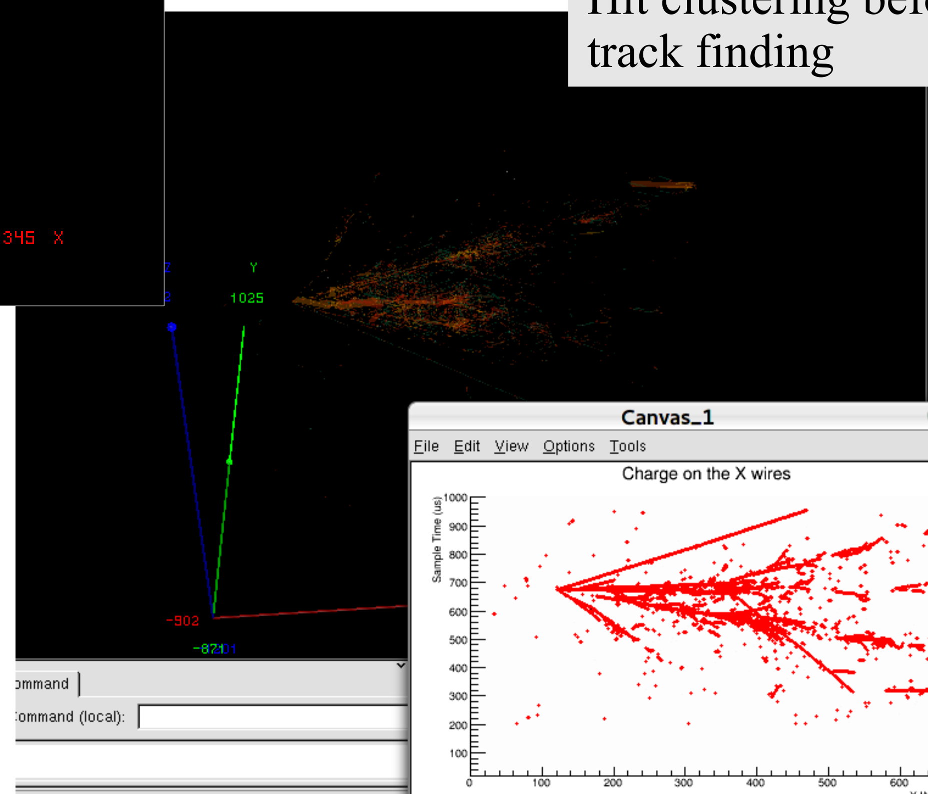
ENDF cross-section models are shown for reference

Reconstructing CAPTAIN Events

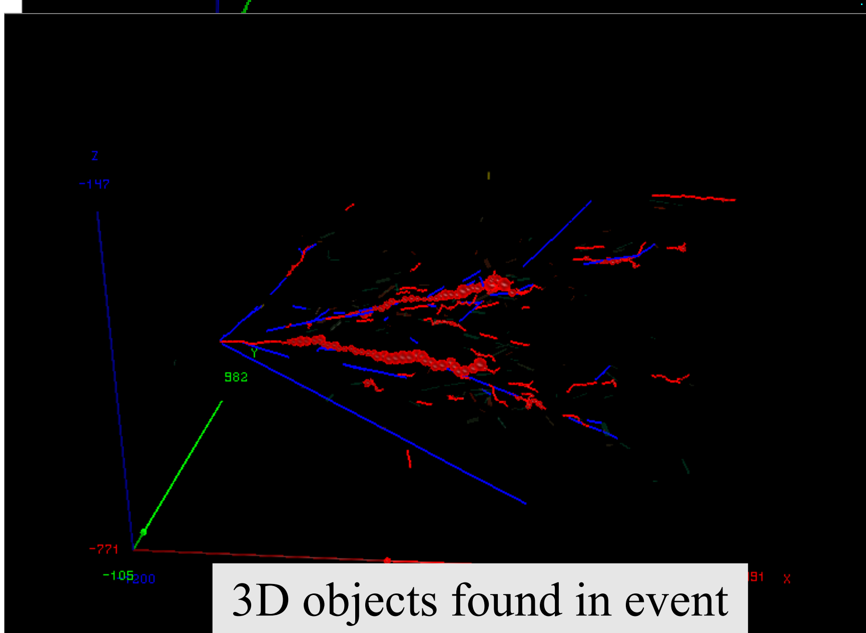
12 GeV muon neutrino producing:
- 4.0 GeV π^+
- 2.2 GeV neutron
- 2.2 GeV photon
- 2.0 GeV π^o
- 1.7 GeV muon
- 390 MeV π^+
- 312 MeV π^{-}



The true energy deposition information (from GEANT)

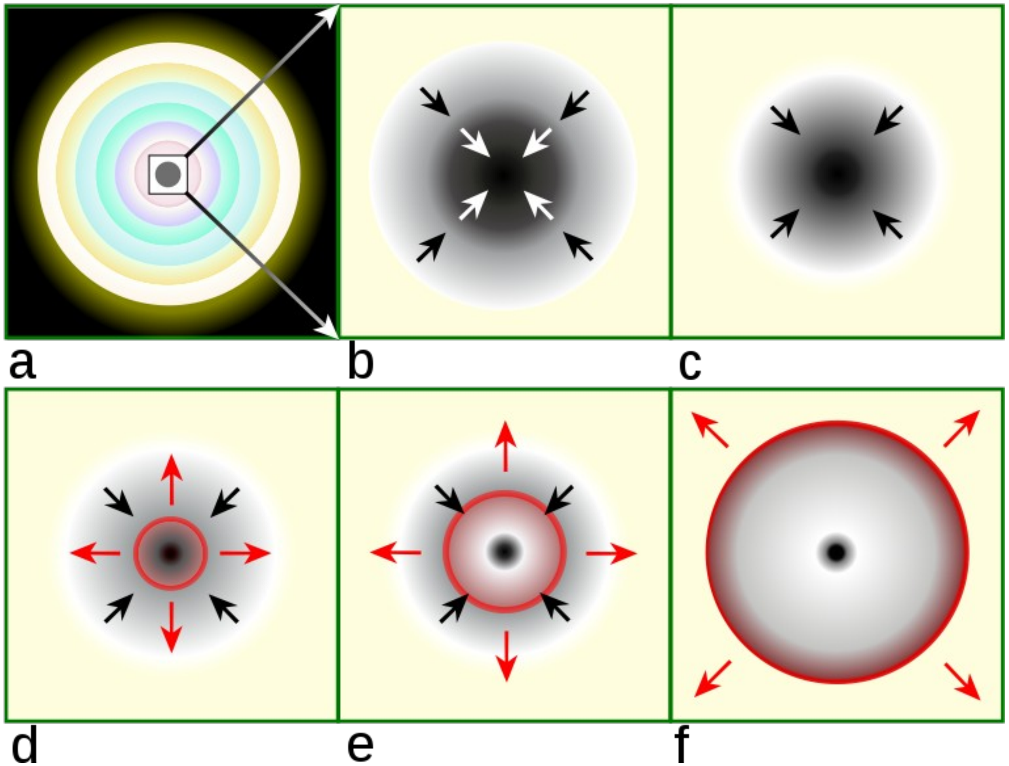


Hit clustering before track finding



3D objects found in event

Supernova Neutrinos



"Core collapse scenario" by Illustration by R.J. Hall. Redrawn in Inkscape by Magasjukur2 - File:Core collapse scenario.png. Licensed under CC BY-SA 3.0 via Wikimedia Commons - http://commons.wikimedia.org/wiki/

- Supernova bursts in our galaxy are a fantastic source of neutrinos
- Proto-neutron star deep in the core
- Infalling matter bounces – creates shock
- Shock stalls – reheated by neutrino interactions
- Significant fluxes in < 10 seconds
- Argon uniquely sensitive to CC electron neutrino interactions – complementary to water Cherenkov detectors sensitive to CC electron anti-neutrino interactions

- ν + Ar cross-sections have never been measured
  - Absolute cross-sections uncertain
  - Visible energy vs. neutrino energy
- We want to measure CC electron neutrino interactions at supernova energies
  - Test ability to detect SNe with LAr
    - Triggering, timing, reconstruction

from C. Mauger

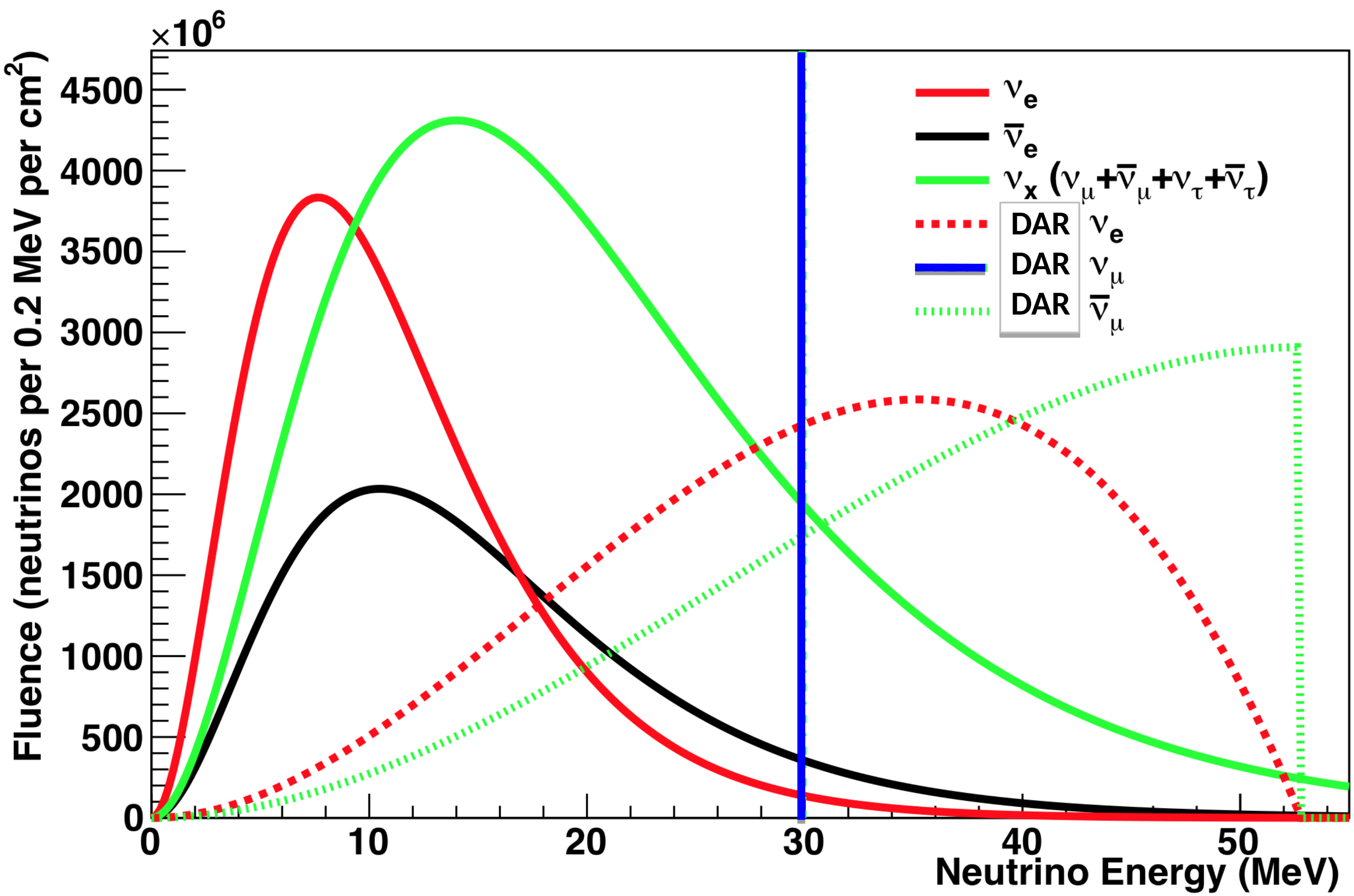
P5 recommendation:

"The (ELBNF) experiment should have the <u>demonstrated</u> capability to search for SN bursts…"

O(10 MeV) Neutrino Source: Stopped Pion Facilities

DAR flux: very well understood (analytic):

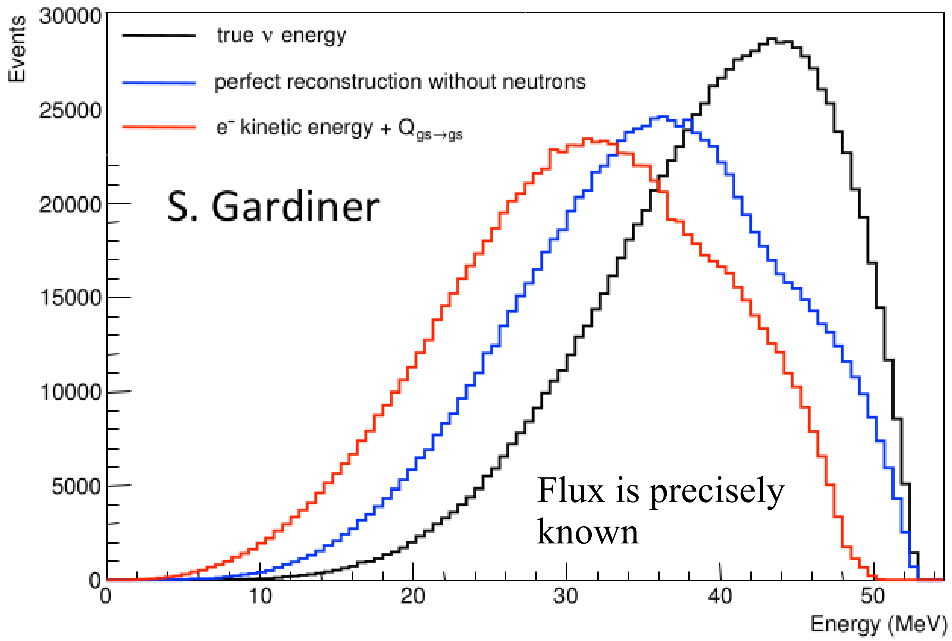
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\downarrow$$
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$



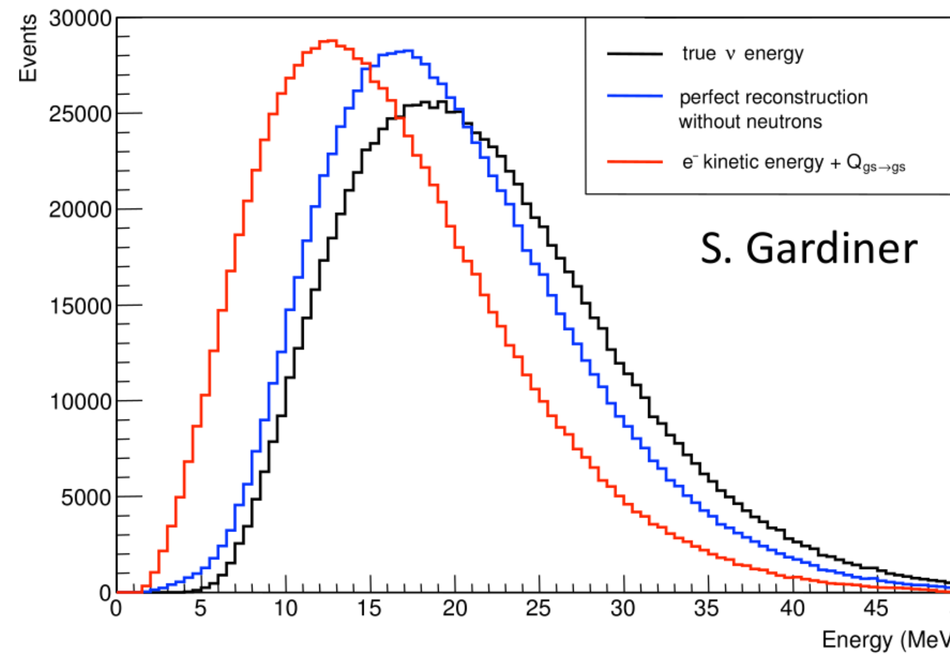
Stony Brook University

What (might be) measured in LAr

Muon decay-at-rest ν_e spectrum



Supernova cooling spectrum (T = 3.5 MeV)



- Where does the energy go?
  - $^{40}K^*$ deexcitation (predicted)
    - 58% photons
    - 36% single n + photons
    - 4% single proton + photons
    - 1% everything else

What (might be) measured in LAr

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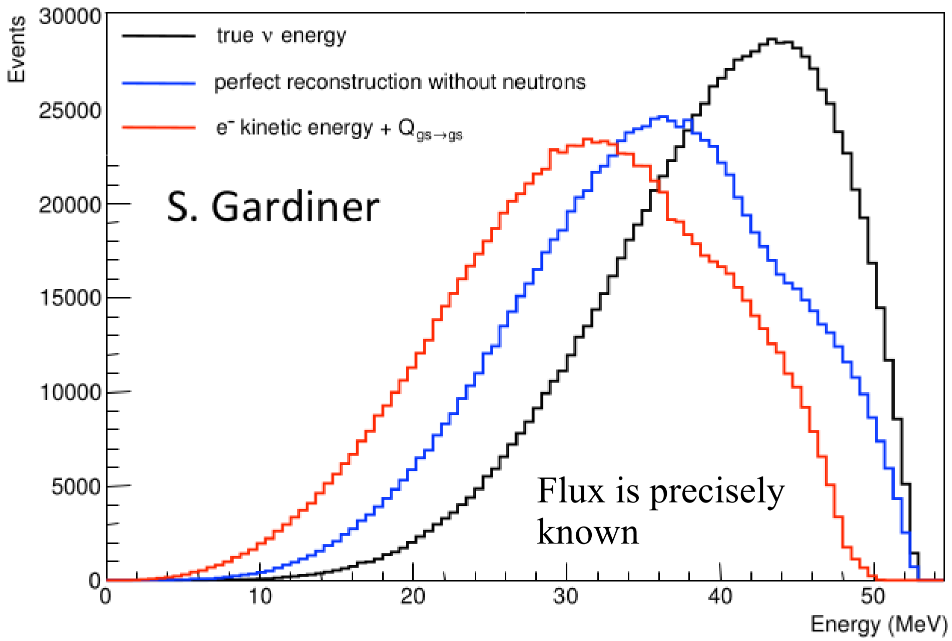

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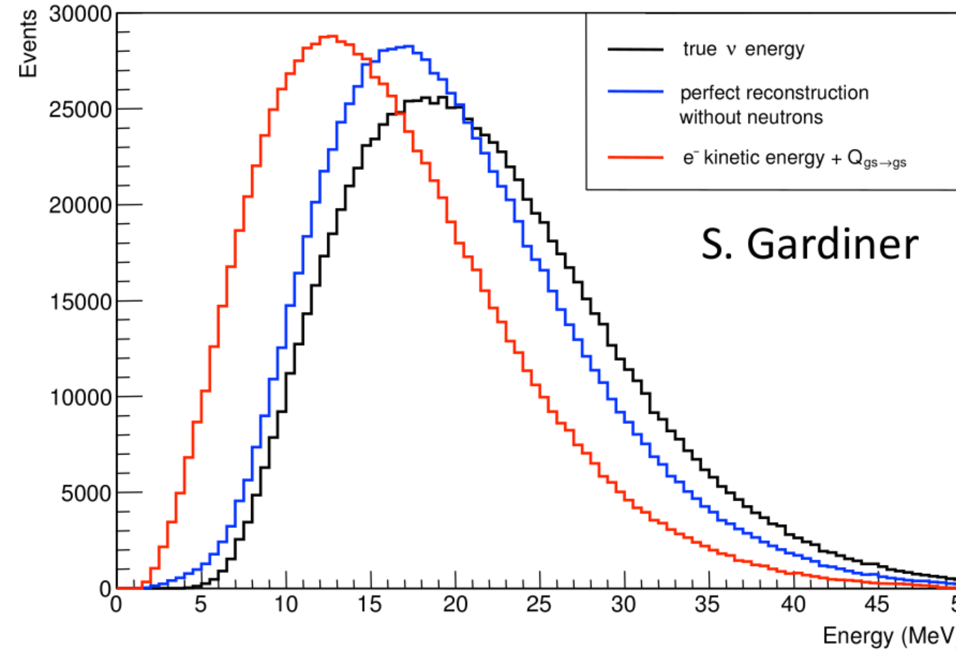

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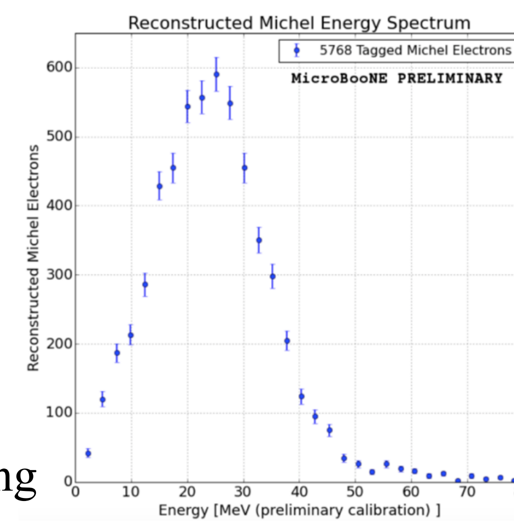
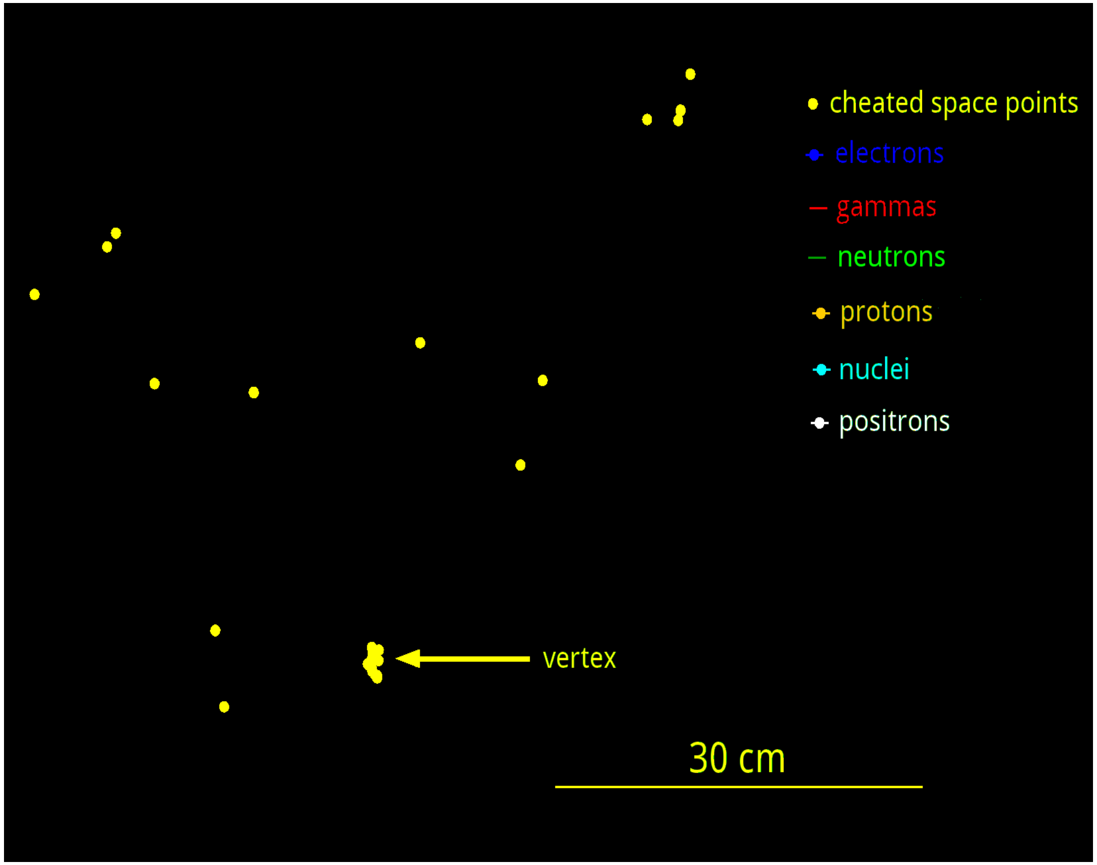


Electron energy also challenging

“Typical” SN ν_e interaction in LAr

- Neutrino interaction predicted by MARLEY
- Detector simulation vs LArSoft
  - Hit reconstruction via “cheated analysis”
- Typical event radius will be several 10’s of cm
  - Determined by argon radiation length
- Neutrons not visible in this plot
  - GEANT4 says event radius is meters



Steven Gardiner (UCD)

DUNE Physics Challenges

- Observation of Supernova Neutrinos
  - In SN1987a we saw several hands full of events in about 4 kton of world-wide target
  - Next SN?
    - 10's of kton of $\bar{\nu}_e$ target world wide (e.g. Water, Oil)
    - LAr will see ν_e
- Search for Proton Decay
  - LAr is largely background free for several modes favored by supersymmetric models (e.g. $p \rightarrow K^+\nu$)
- Long Baseline Neutrino Oscillation Physics
  - Determination of mass hierarchy
  - Maximum θ_{23}?
    - See recent tension between NOvA and T2K
  - Observation/Measurement of CP violation in neutrino oscillations
    - Maximal CP Violation? (see hints from DayaBay/NOvA/T2K)