Stony Brook University

Neutrinos in Nuclear Physics

CAPTAIN: Low energy neutrino cross sections on argon

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

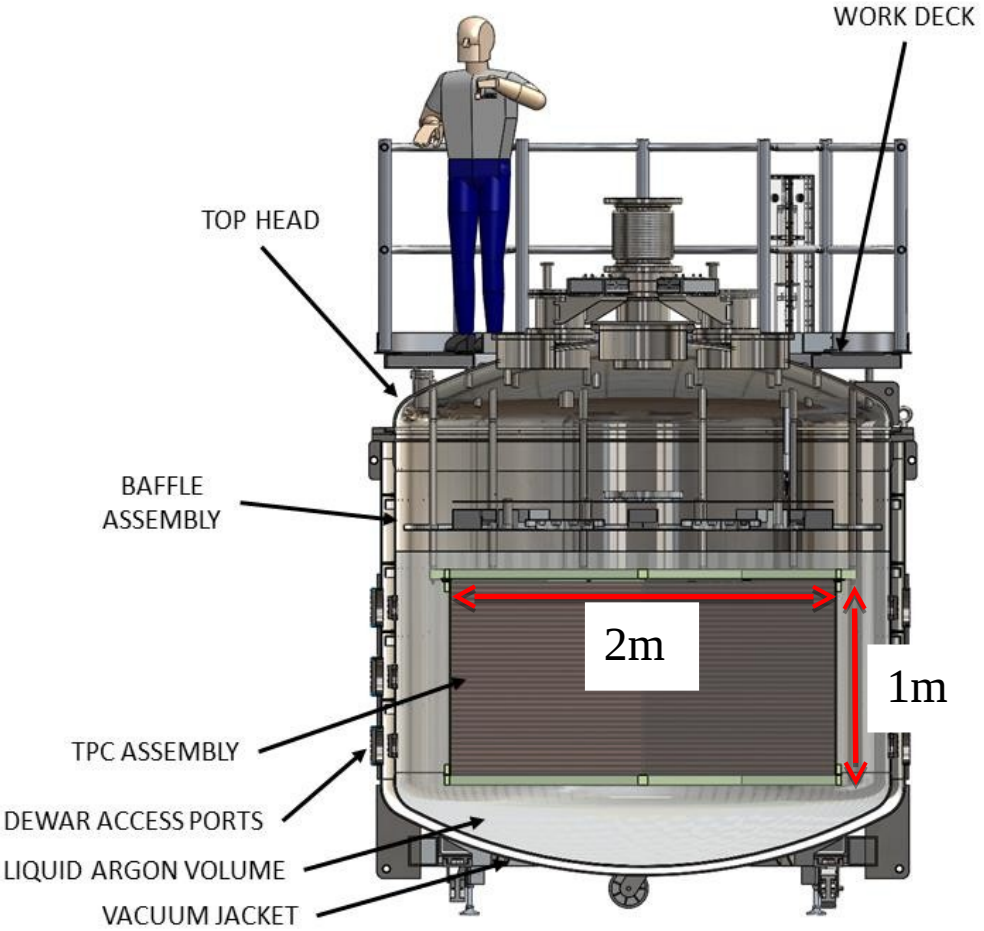
CAPTAIN Physics Program

Neutron Beam
Low-Energy Neutrino Beam
Medium-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 allow us to constrain number and energy of emitted neutrons in neutrino interactions
  - Measure higher-energy neutron-induced processes that could be backgrounds to ν_e appearance e.g. $^{40}Ar(n,\pi^0)^{40}Ar^{(*)}$
  - Measure inclusive and exclusive channels neutrino CC and NC cross-sections/event rates in a neutrino beam of appropriate energy
  - Test methodologies of total neutrino energy reconstruction with neutron reconstruction

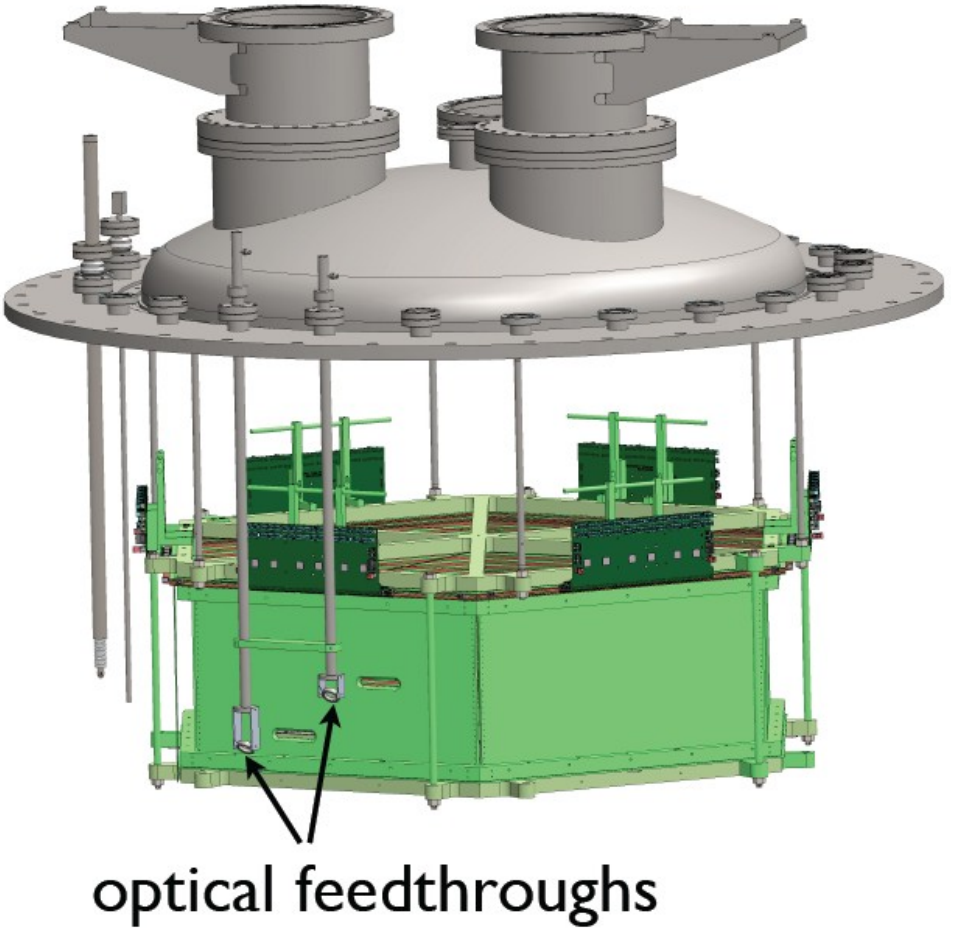
The CAPTAIN Detectors

- 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 '17 /'18
- miniCAPTAIN
  - Hexagonal TPC with 30 cm drift, 50cm apothem, 600 channels, 3mm pitch, 400 instrumented kg
  - Cryostat on loan from UCLA
    - Indium seal for access
  - 16 PMT light detection system
- Both use same same cold electronics and electronics chain as MicroBooNE
  - front end same as DUNE



CAPTIAN Cryostat Delivered to LANL in 2014

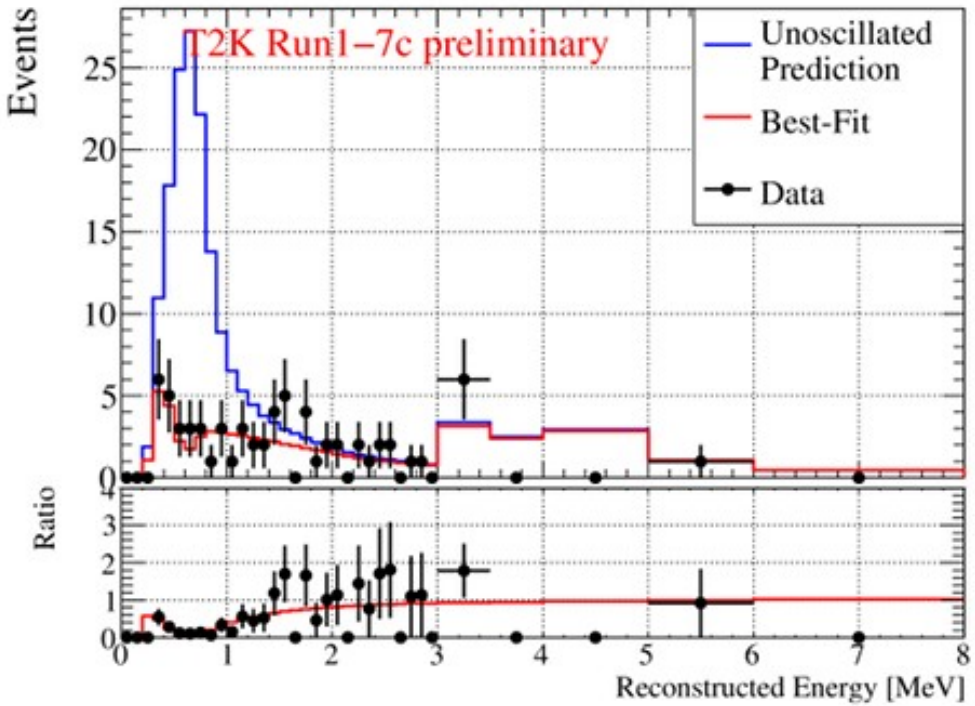
The miniCAPTAIN Detector



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

E_ν Reconstruction: An Inverse Process

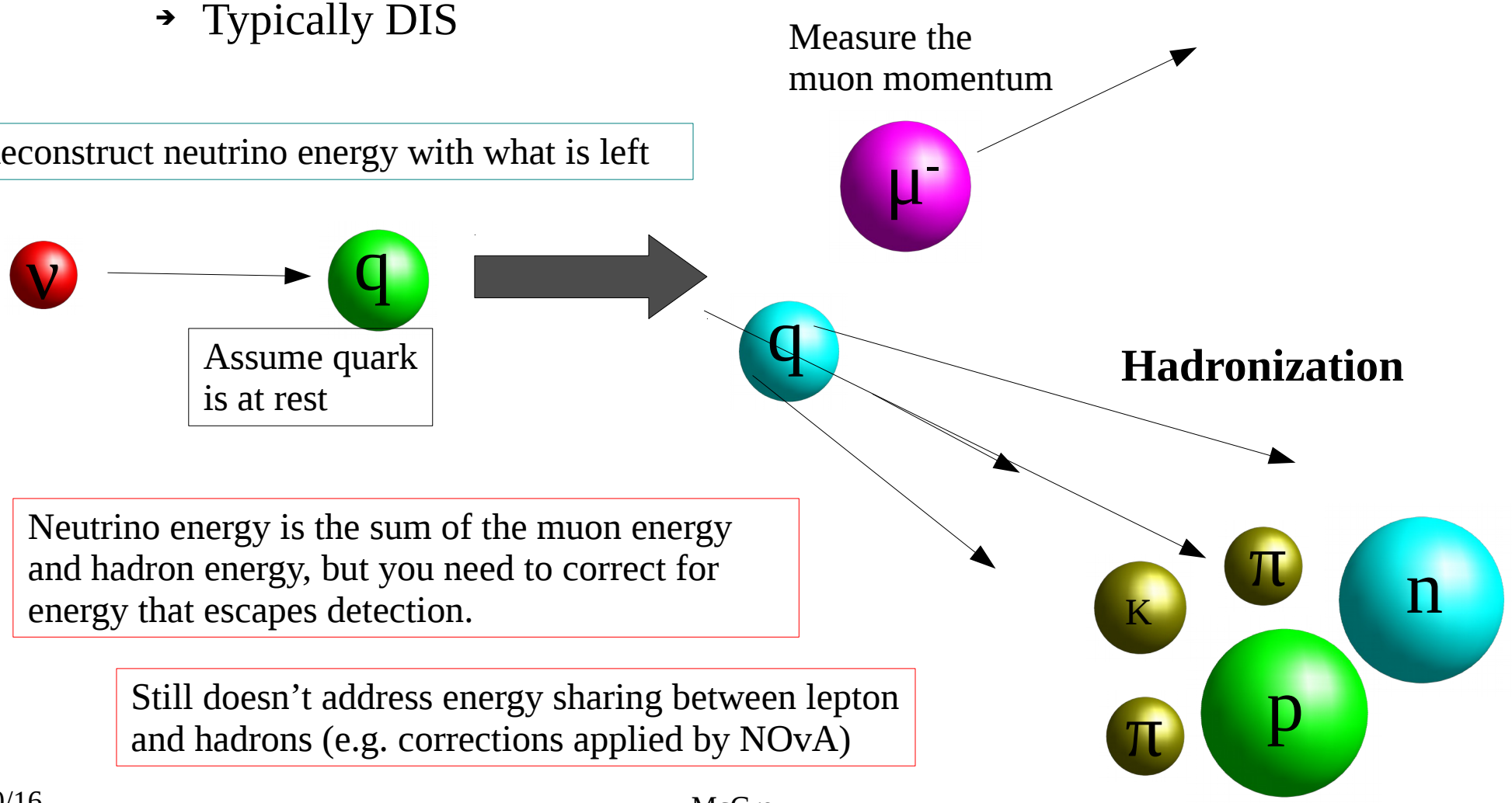
- For oscillation physics, measure flux at two distances.
  - Measure a distribution of neutrino interactions
  - Find the flux by unfolding the efficiency and cross section
- The efficiency needs to be constrained by calibration
- The cross section is constrained by measurement, but depends on model
  - The produced final states provoke different detector responses so the differential cross sections are needed for energy reconstruction.
- However, in an oscillation experiment
  - The near detector flux used to measure the cross section is very different from the far detector flux.
  - Cross section modifications that introduce asymmetries in the energy reconstruction can hide in the near detector data



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

Reconstruct neutrino energy with what is left



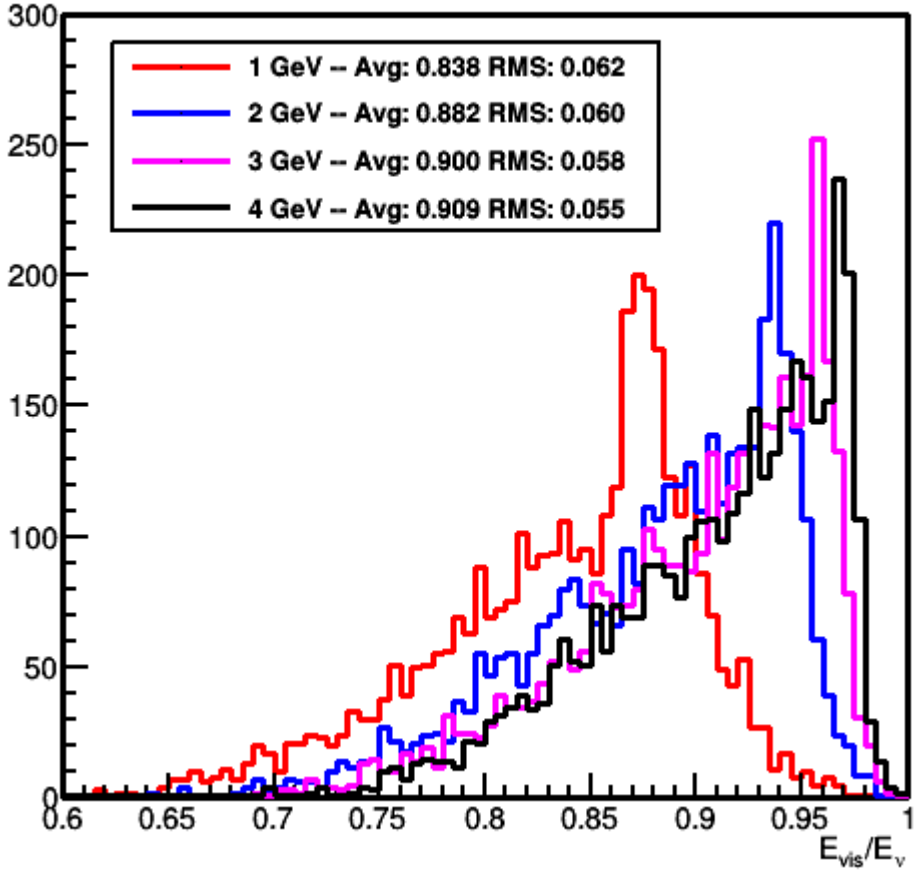
Neutrino energy is the sum of the muon energy and hadron energy, but you need to correct for energy that escapes detection.

Still doesn't address energy sharing between lepton and hadrons (e.g. corrections applied by NOvA)

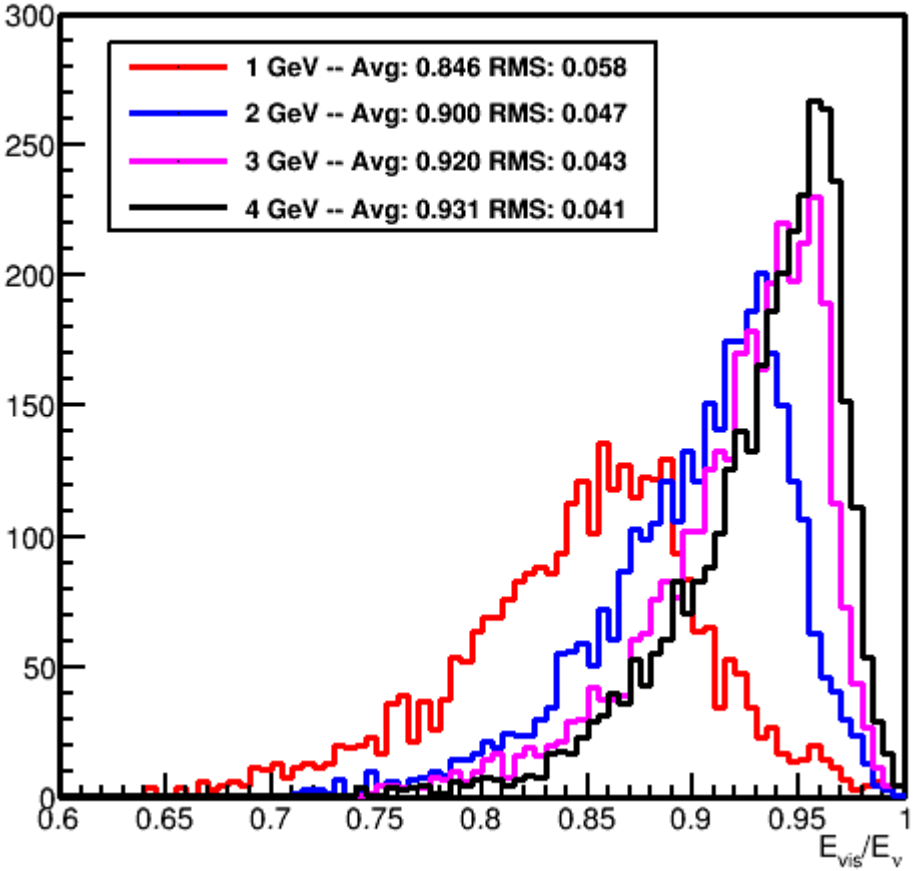
Fraction of E_ν that is Visible

- The ratio of visible energy to neutrino energy is different for neutrinos and anti-neutrinos
  - Intrinsic CP violation term underneath the oscillation CP signal

Muon Neutrino

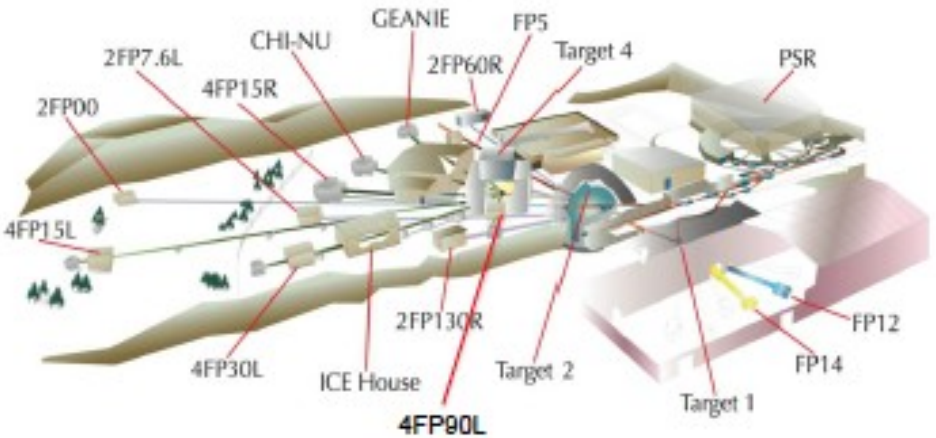


Muon Anti-neutrino

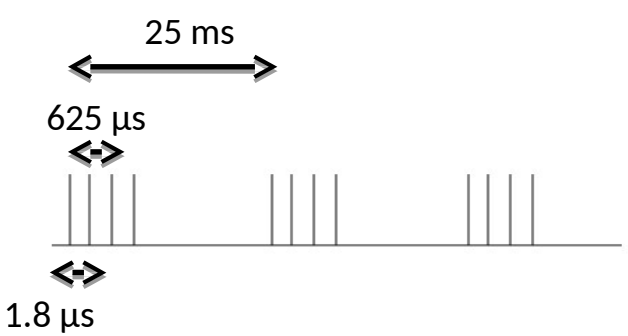


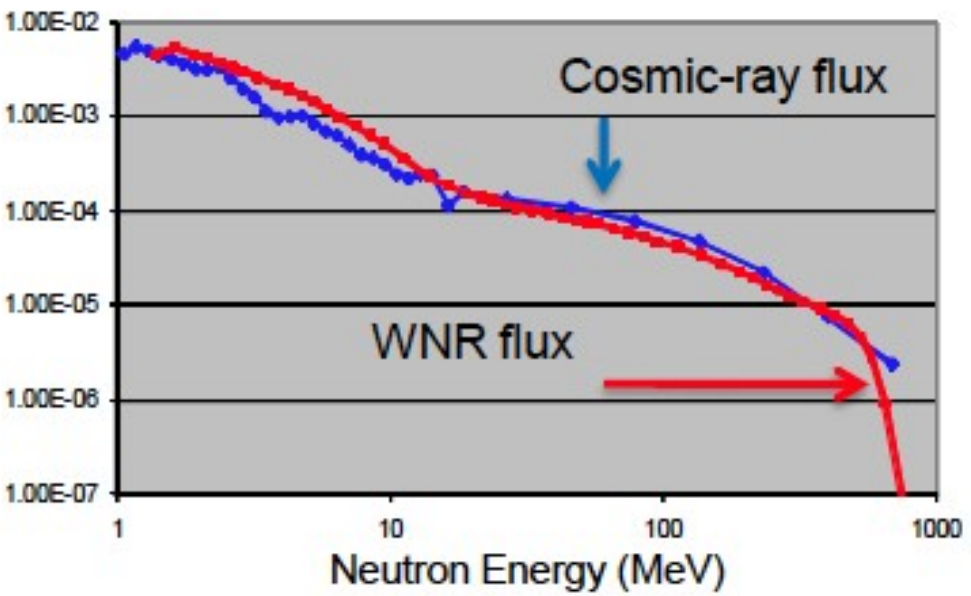
Neutron Beam at LANL

- 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 microseconds apart within a 625 μs long macro pulse
  - Repetition rate: 40 Hz

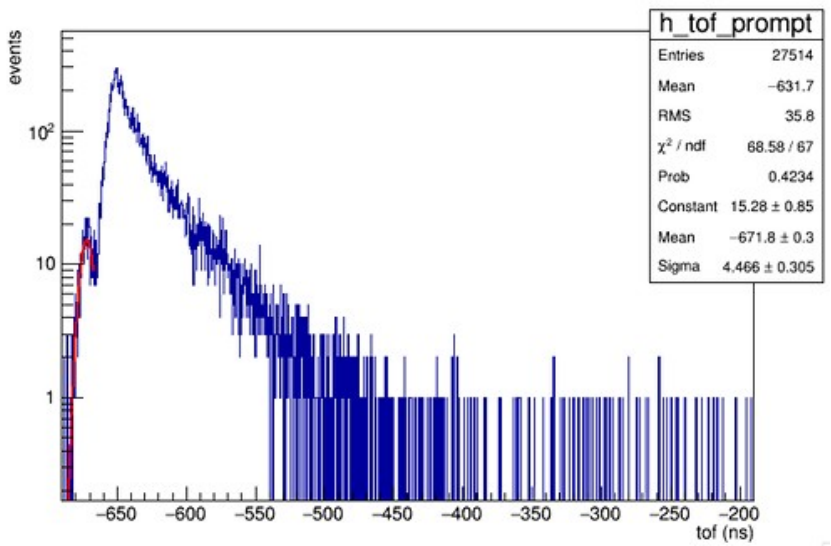




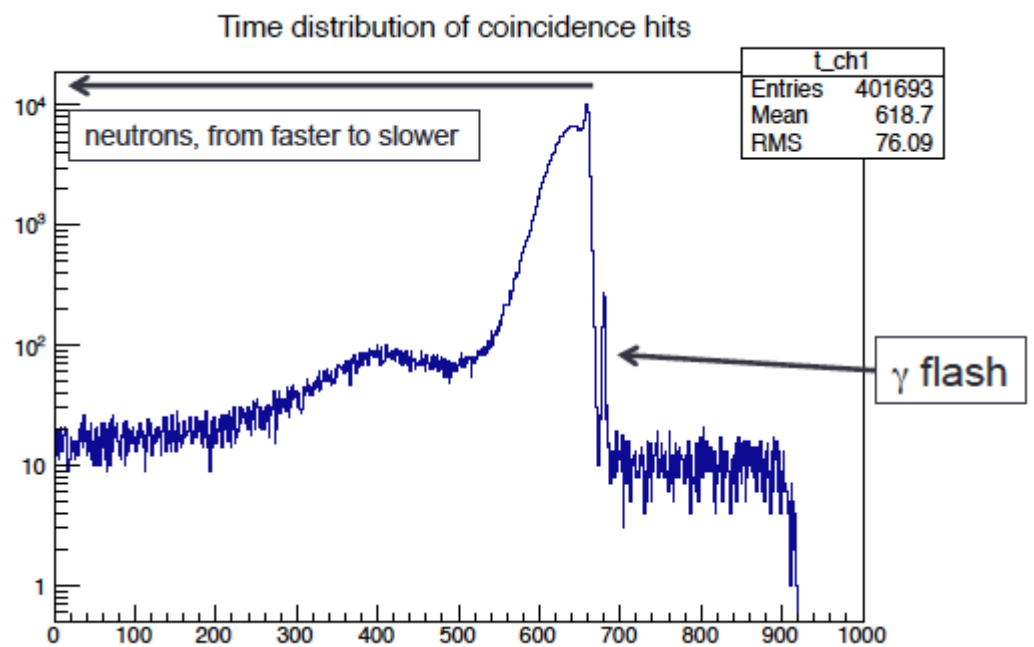
Neutron Time Of Flight

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.

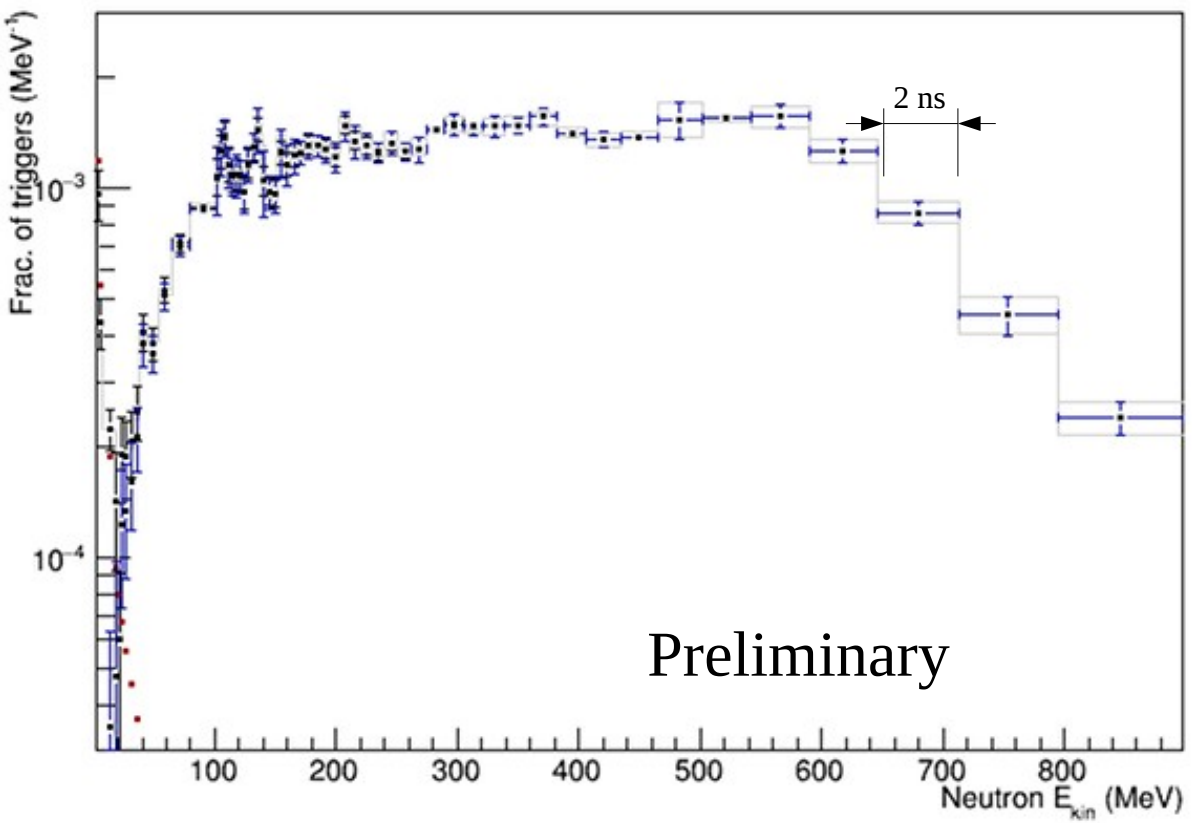


Neutron t.o.f. measured using plastic scintillator (to normalize flux). Efficiency vs energy calibrated vs a well known fission detector

Neutron Kinetic Energy Spectrum

on Argon

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

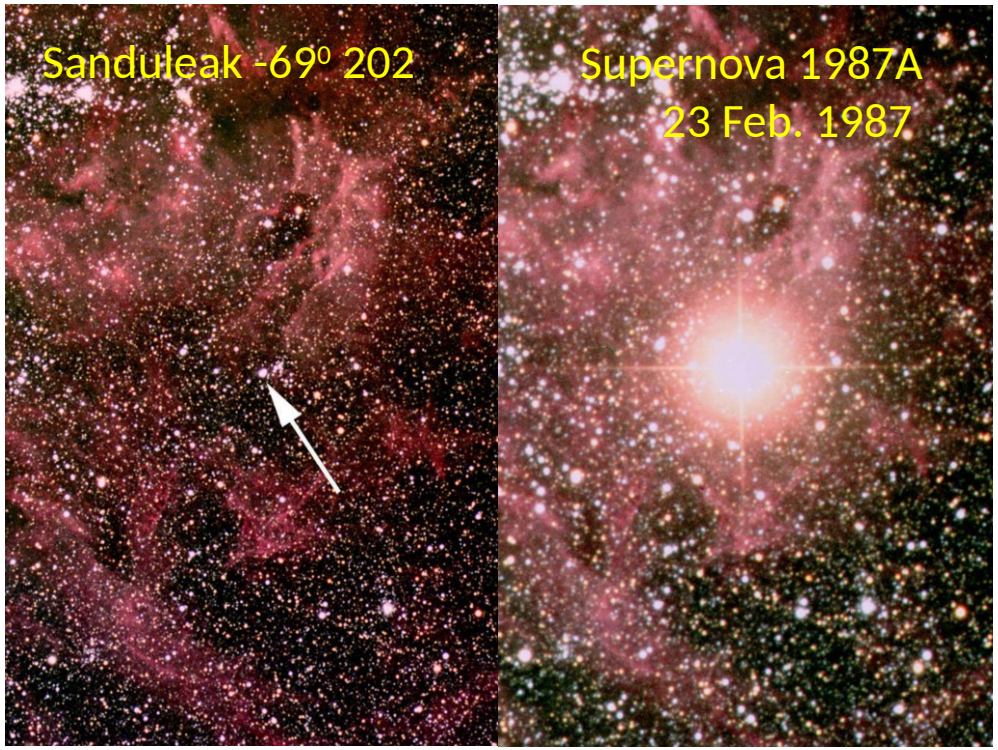


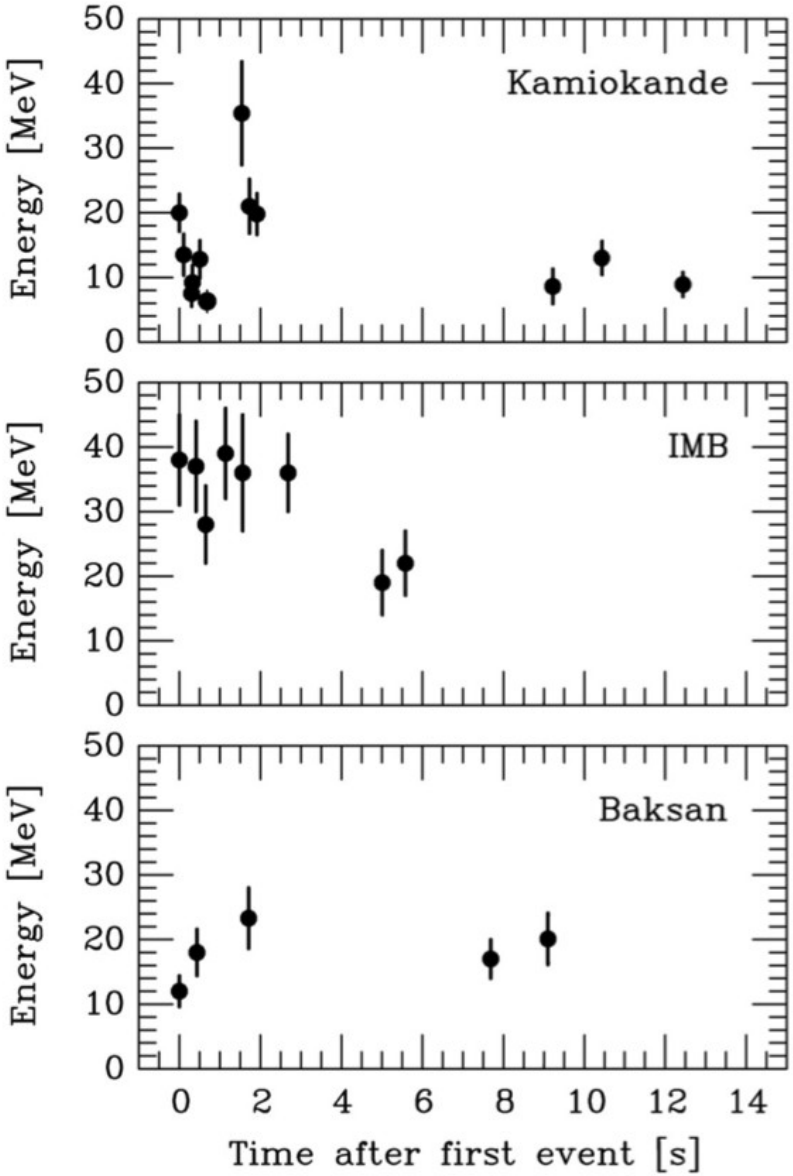
- Full TPC & PDS will be collected at WNR in June/July 2017
  - Already see strong signal in n+Ar → X+p
- Physics run goals
  - Cross-sections
    - Differential partial cross-section on Ar.
      - e.g. π^o, p, $\pi^{\pm}$ production
  - Library of event signatures
    - Light yeld vs energy
    - Ionization vs energy
    - Ionization vs light yeild

Physics from the 1987A Supernova (LMC; 51 kpc)

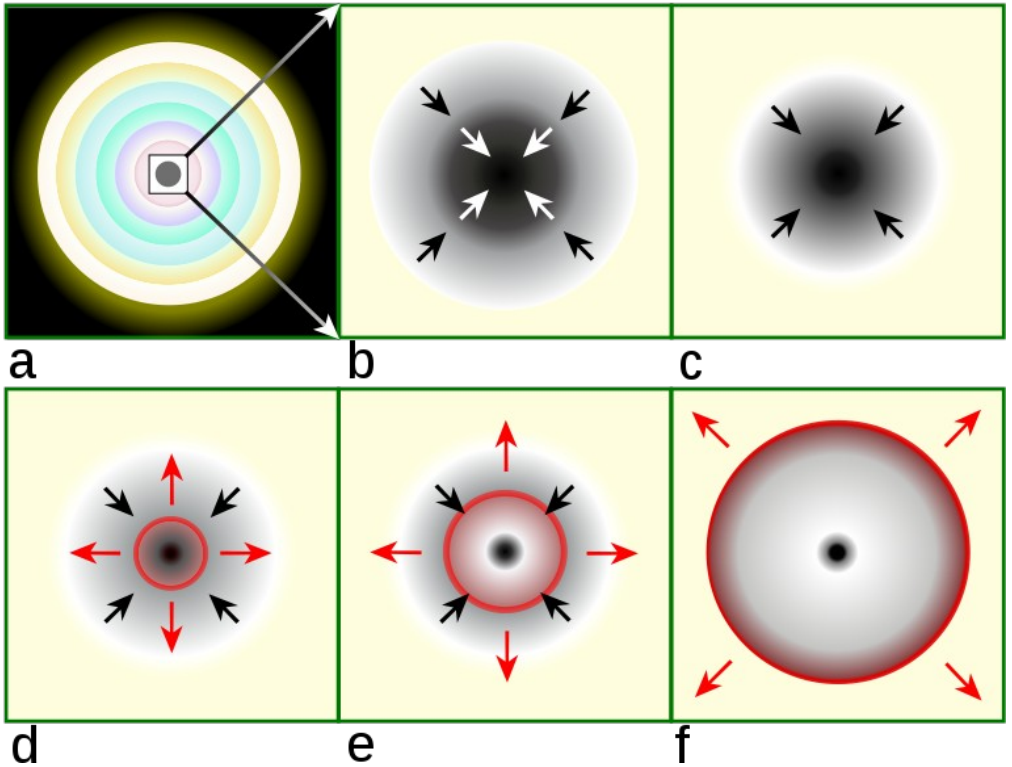
SN-1987A: average of **1 citation every 10 days for last 26 years** – only 20 (26) events total!

- Most precise straightforward test of weak equivalence
- Direct neutrino TOF with 10^5 LY baseline
- Limits on neutrino decay over 10^5 years





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 demonstrated capability to search for SN bursts…"

Large Underground Detectors for SN Neutrinos

WATCHMAN (400)

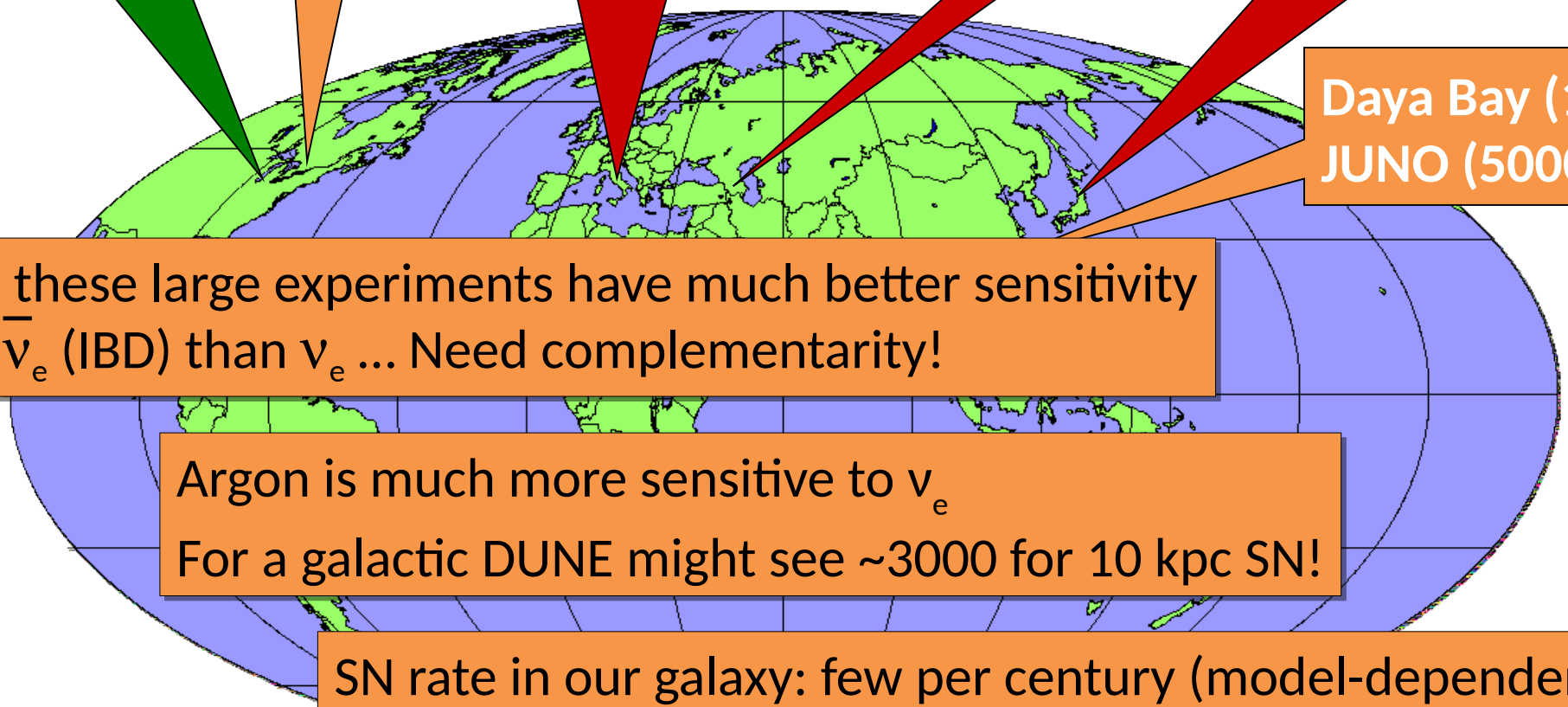
SNO+ (400)

LVD (400)
Borexino (100)

Baksan (100)

Super-K (10^4)
KamLAND (400)

Daya Bay (100)
JUNO (5000)



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

Argon is much more sensitive to ν_e

For a galactic DUNE might see ~3000 for 10 kpc SN!

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

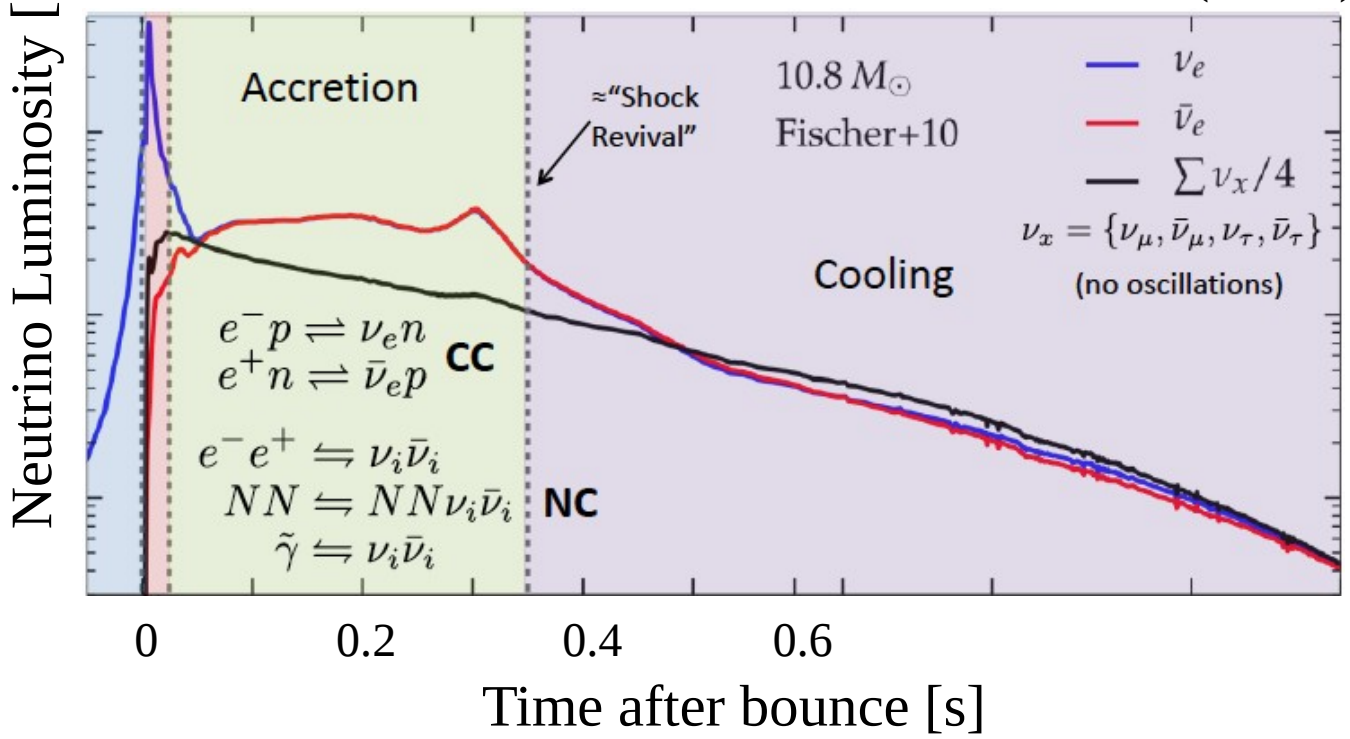
IceCube (10^6)

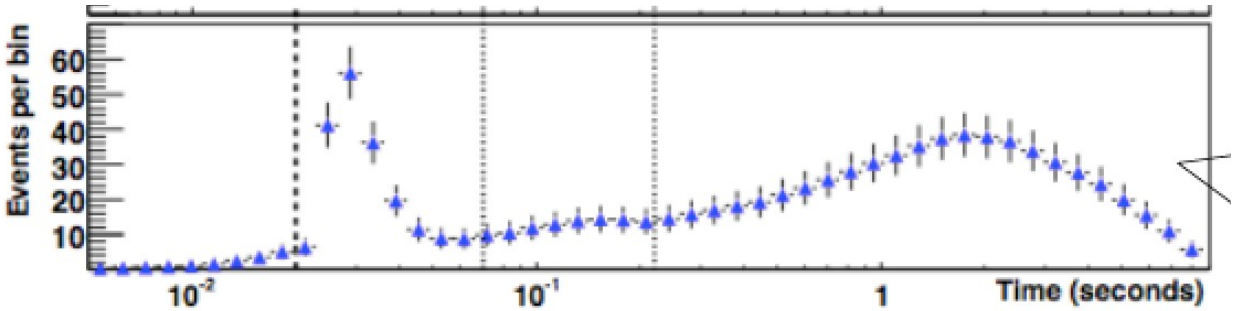
Brackets: Nevents
for a "fiducial SN"
at distance 10 kpc

Neutronization only visible in ν_e

(better in LAr than H_2O)

B. Messer (ORNL)





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 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

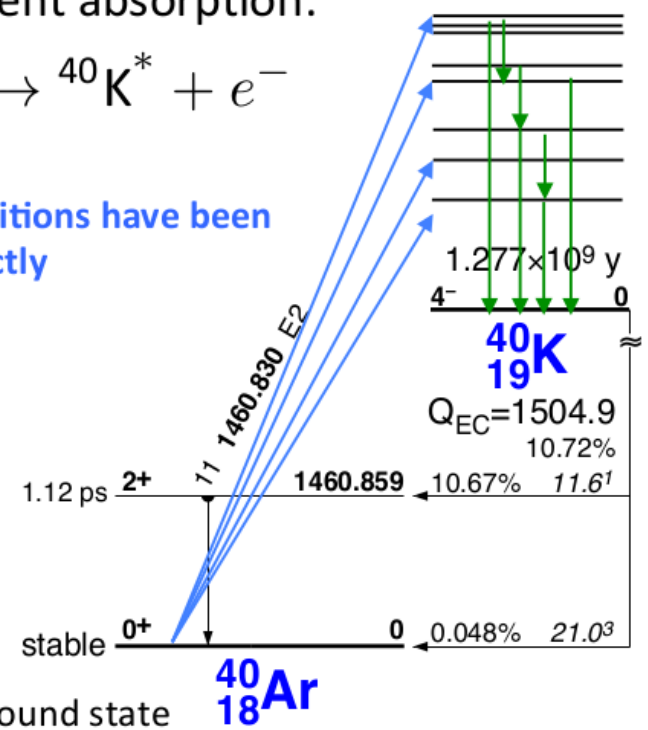
K. Scholberg: arXiv 1205.6003 astro-ph
GKVM model: arXiv 0902.0317 hep-ph
(Gava, Kneller, Volpe, McLaughlin)

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)

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

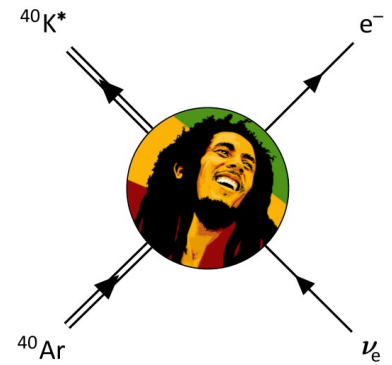
We have limited knowledge the transition intensities

Total cross-section:

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

Chris Grant (BU) at recent CAPTAIN meeting

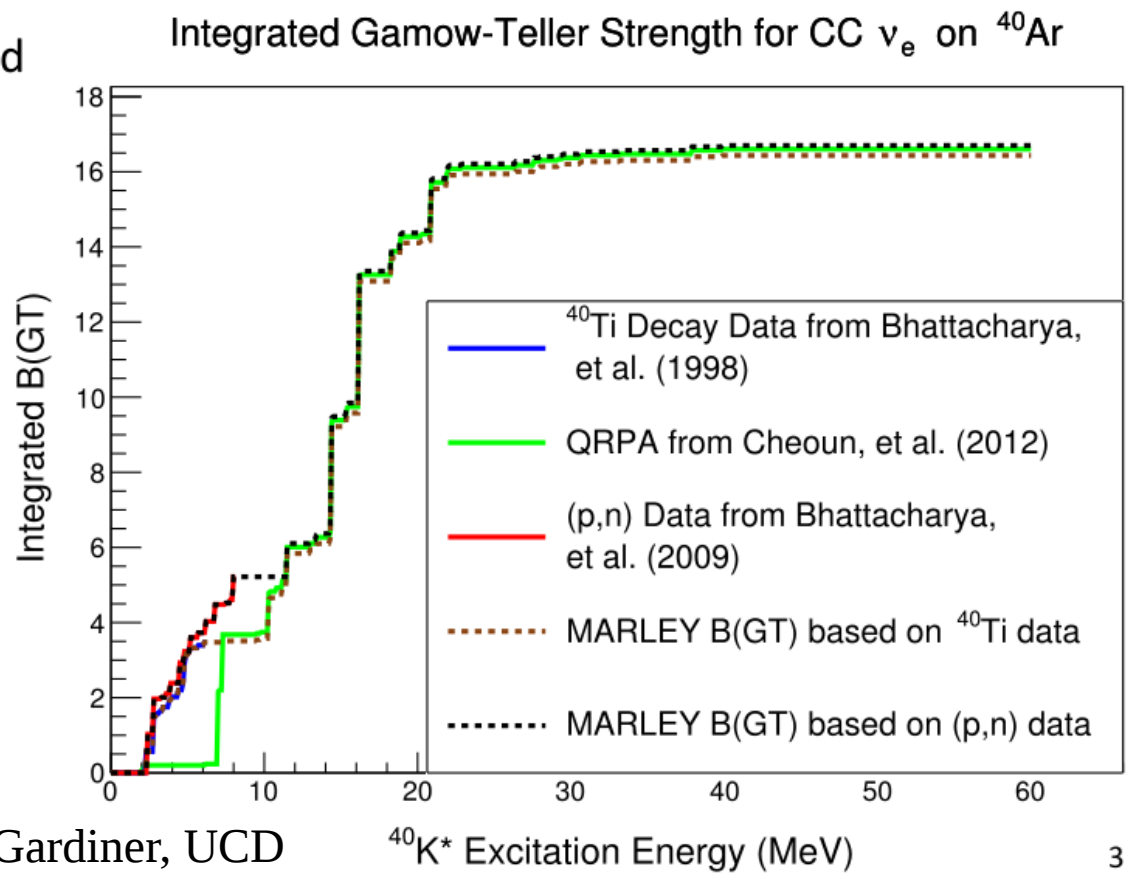
MARLEY $^{40}Ar(\nu_e, e^-)^{40}K^*$ cross section mode



- Under the allowed approximation, the differential cross section to a particular nuclear level is given by

$$\frac{d\sigma}{d\Omega} = \frac{G_F{}^2 \left|V_{ud}\right|^2}{4\pi^2} \left|\mathbf{p}_e\right| E_e\, F(Z_f, E_e) \times \left[(1+\beta_e \cos\theta_e)B(F) + \left(\frac{3-\beta_e\cos\theta_e}{3}\right) B(GT)\right]$$

- MARLEY uses tabulated B(F) and B(GT) values to compute cross sections
- The NUCLEARREACTION class samples two-two scattering final states using this cross section
  1. $^{40}K^*$ excited level
  2. e^- energy
  3. e^- direction
- De-excitation of the final nucleus is simulated next



S. Gardiner, UCD

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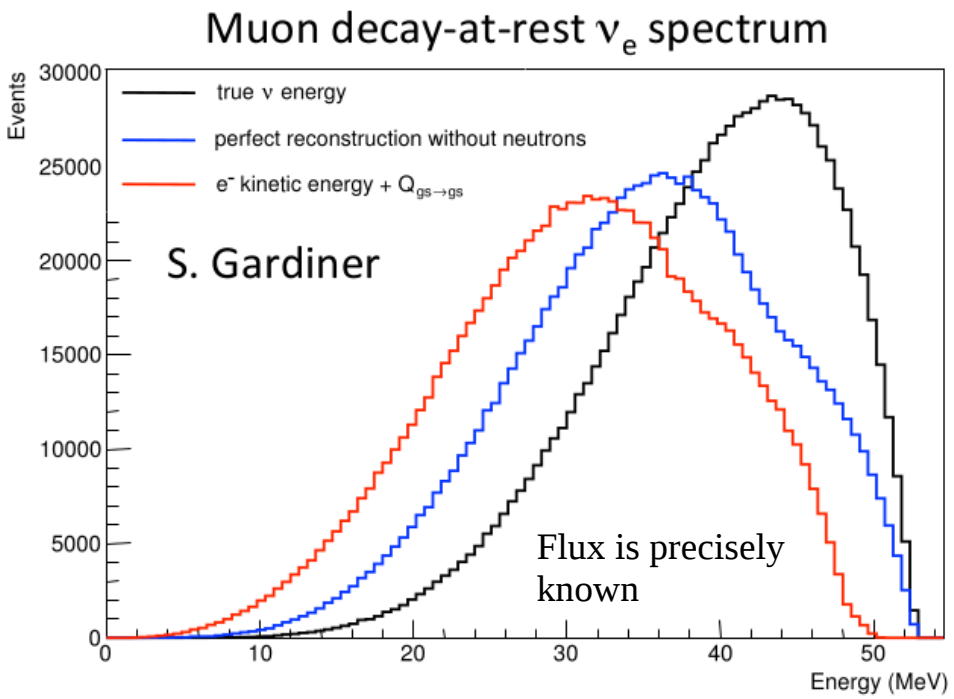
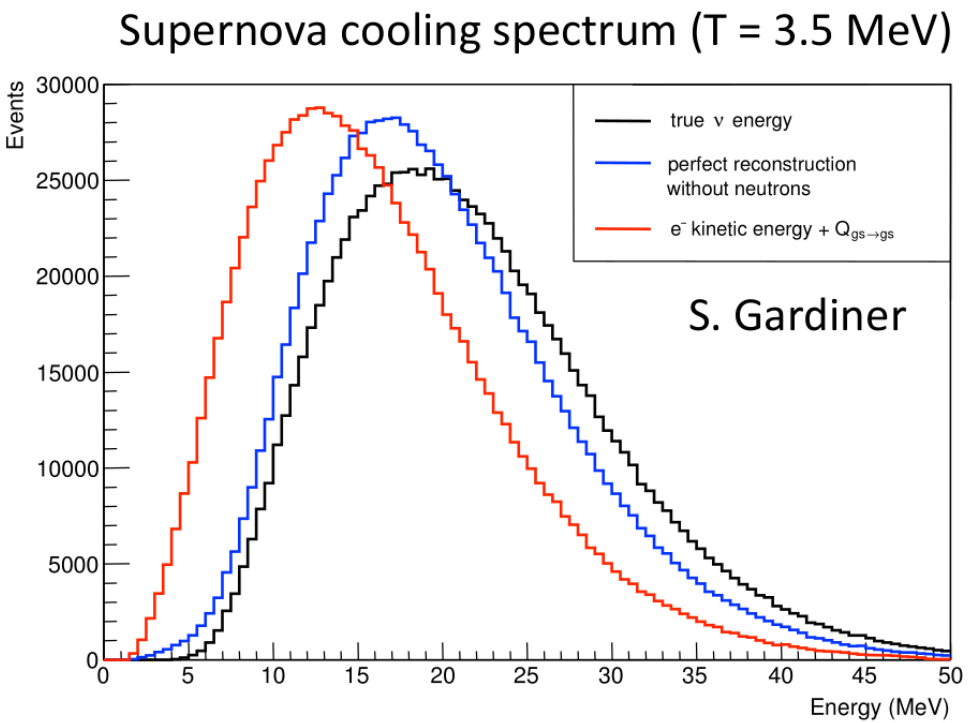
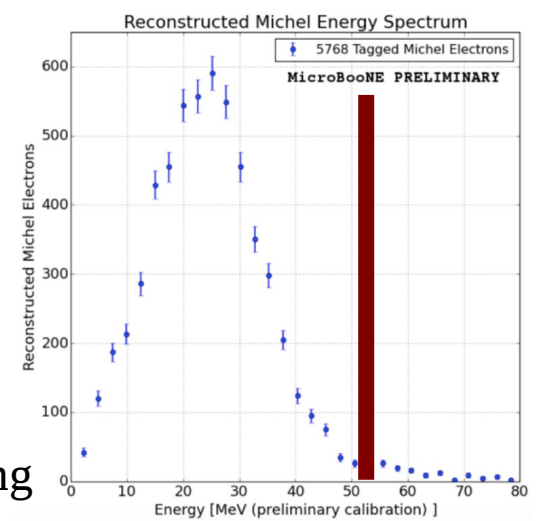
What (might be) measured in LAr





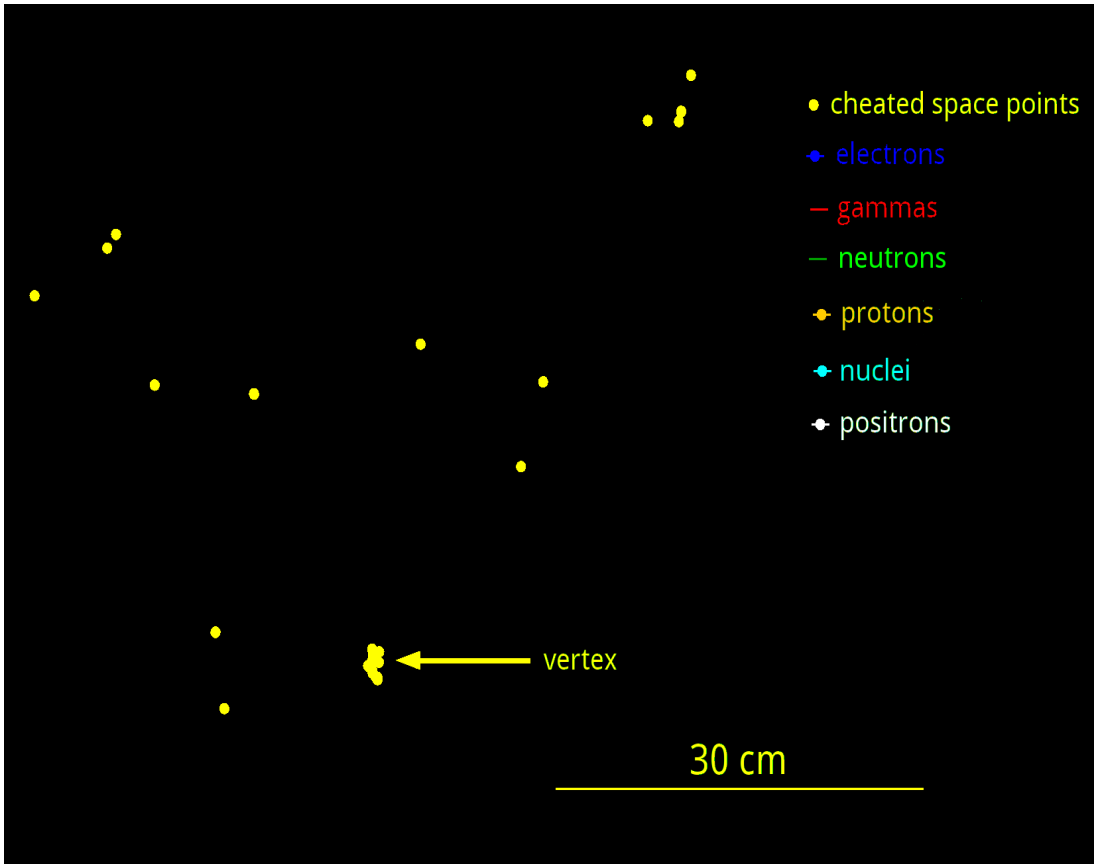
- Where does the energy go?
  - $^{40}K^*$ deexcitation
    - 58% photons
    - 36% single n + photons
    - 4% single proton + photons
    - 1% everything else



Electron energy also challenging

"Typical" SN ν_e interaction in LAr

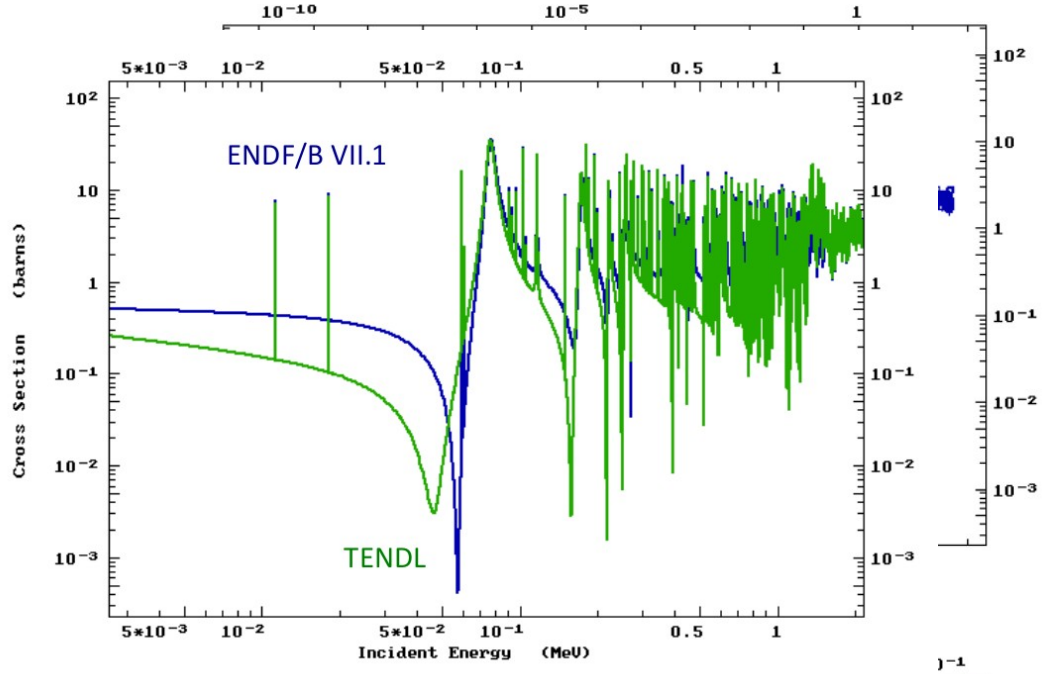
- Neutrino interaction predicted by MARLEY
- Detector simulation vs LArSoft
  - Hit reconstruction via "cheated analysis"
- Typical event radius will be several 10's of cm
  - Determined by argon radiation length
- Neutrons not visible in this plot
  - GEANT4 says event radius is meters

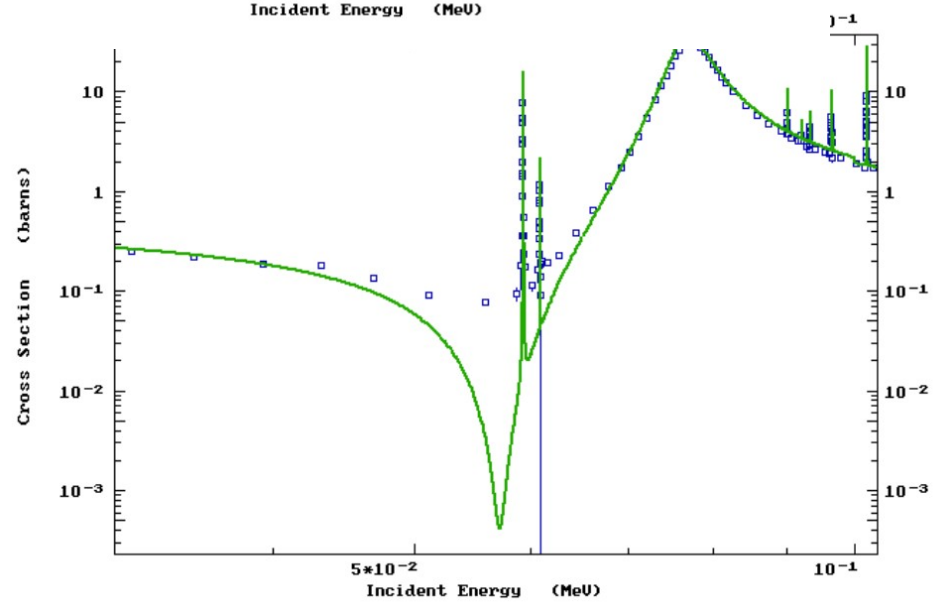


Steven Gardiner (UCD)

Neutrons in Argon

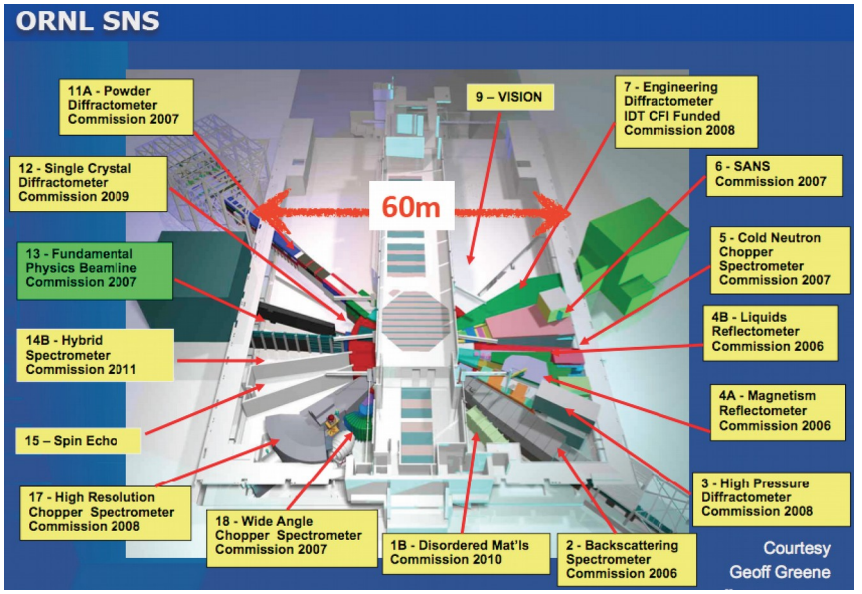
- A negative resonance makes argon transparent at 55 keV
- Neutron above the resonance should survive 100's μs or longer
  - according to GEANT4 using ENDF
- Large discrepancy between data and ENDF
- Also a discrepancy between different calculations
  - Neither match data very well.
    - miniCAPTAIN data may help discriminate between experiment and calculation.

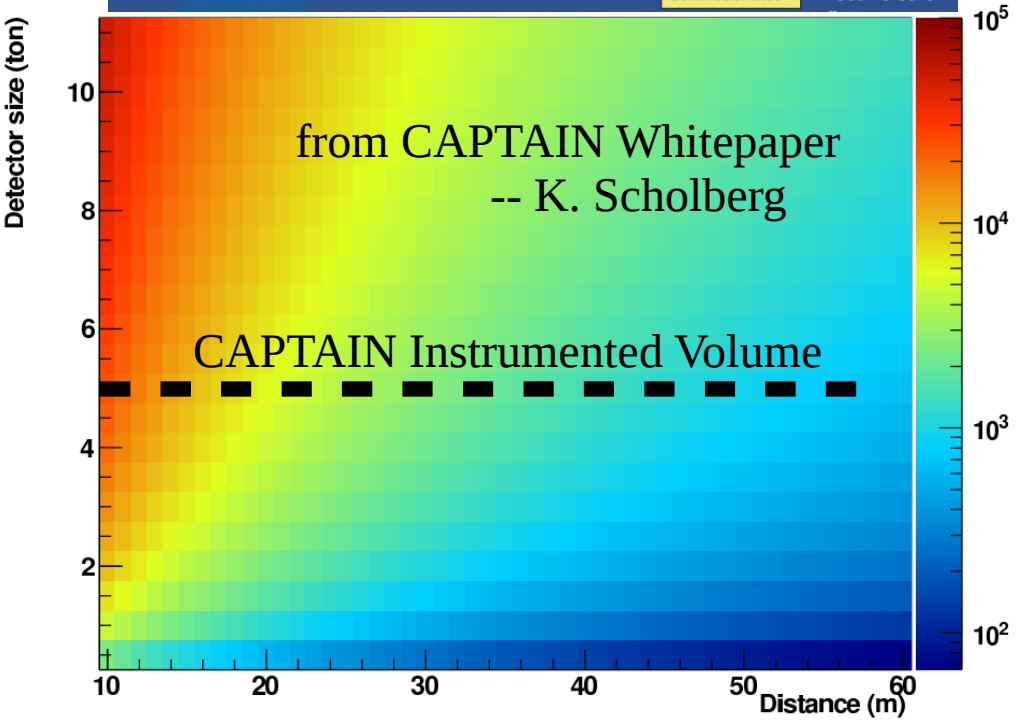




SNS as a D.A.R. ν Source

- 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
- Lujan is also possible, but not evaluated after upgrade.
  - Nominally 800 MeV @ 100 kW

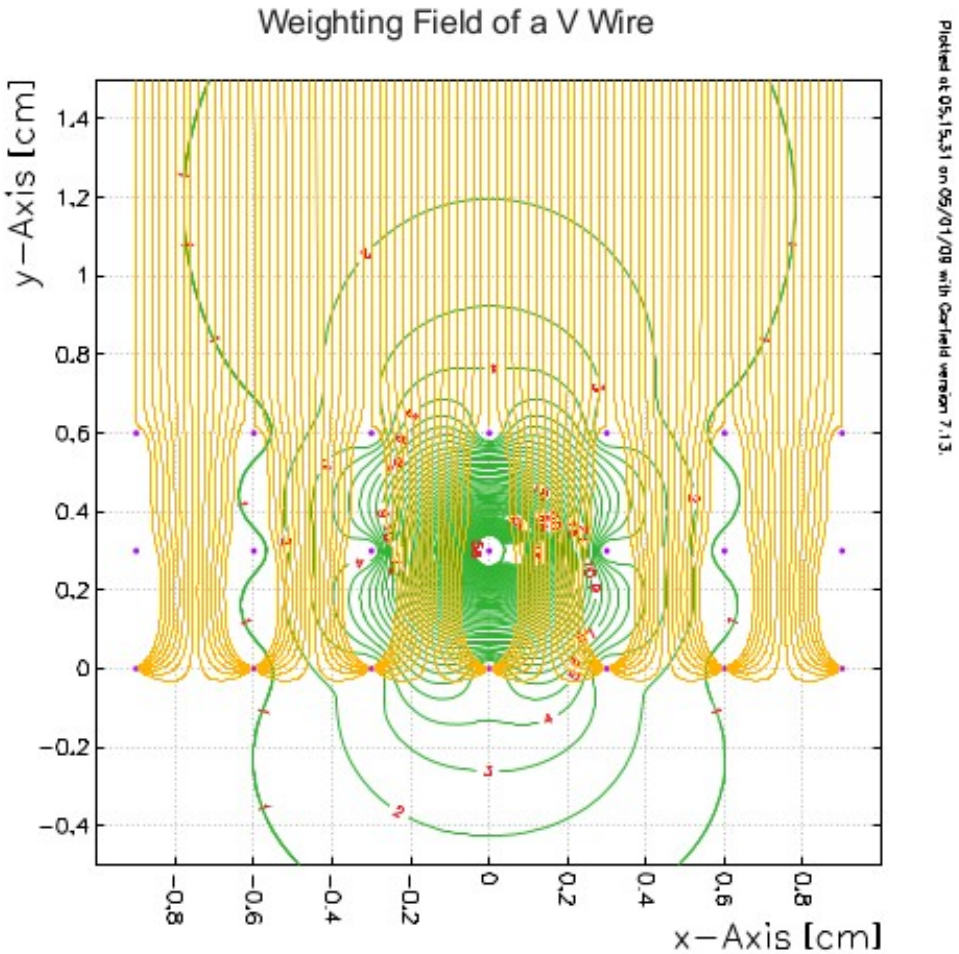




Final Thoughts

- 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.
- CAPTAIN run plan includes several measurements
  - Neutrons on argon
    - Data at WNR next Summer
  - Low energy neutrino cross sections
    - Measured at a stopped pion neutrino source
  - Medium energy neutrino cross sections
    - Proposed for NuMI (CAPTAIN-MINERvA), but tabled due to overstretched resources at FNAL
- There are opportunities with CAPTAIN for new collaborators

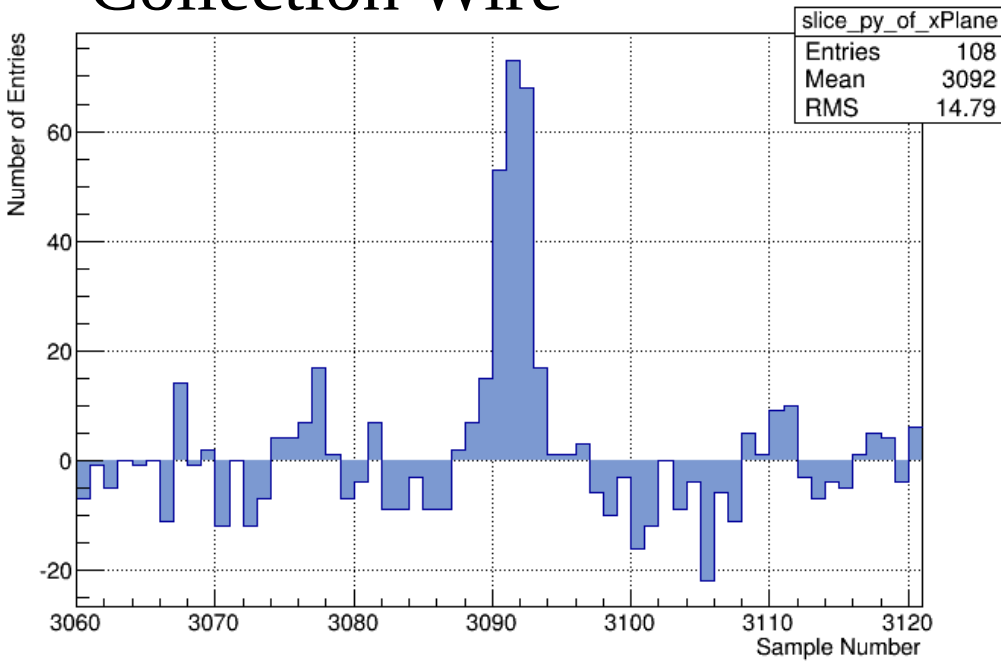
Backup Slides



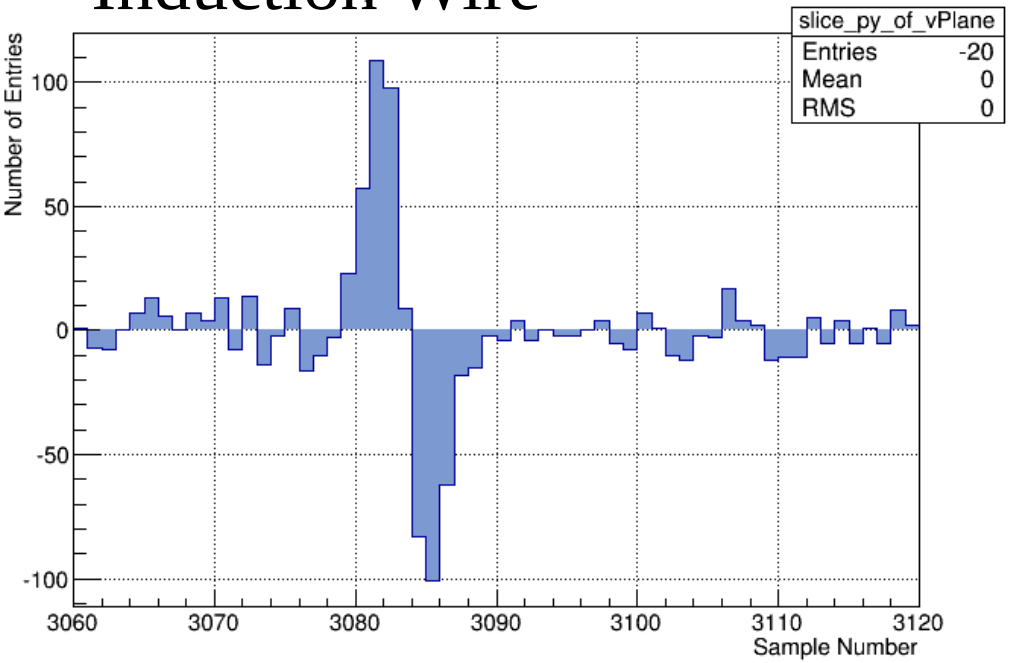
Induced Current: $i = - q\, v_d \circ E_w$

Signals in CAPTAIN

Collection Wire

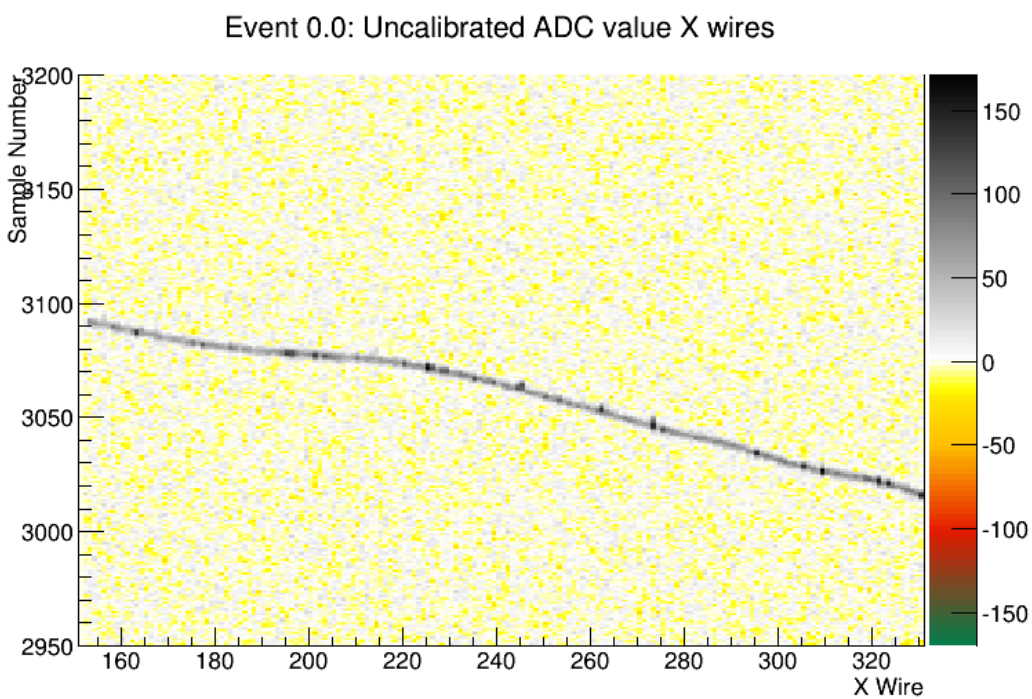


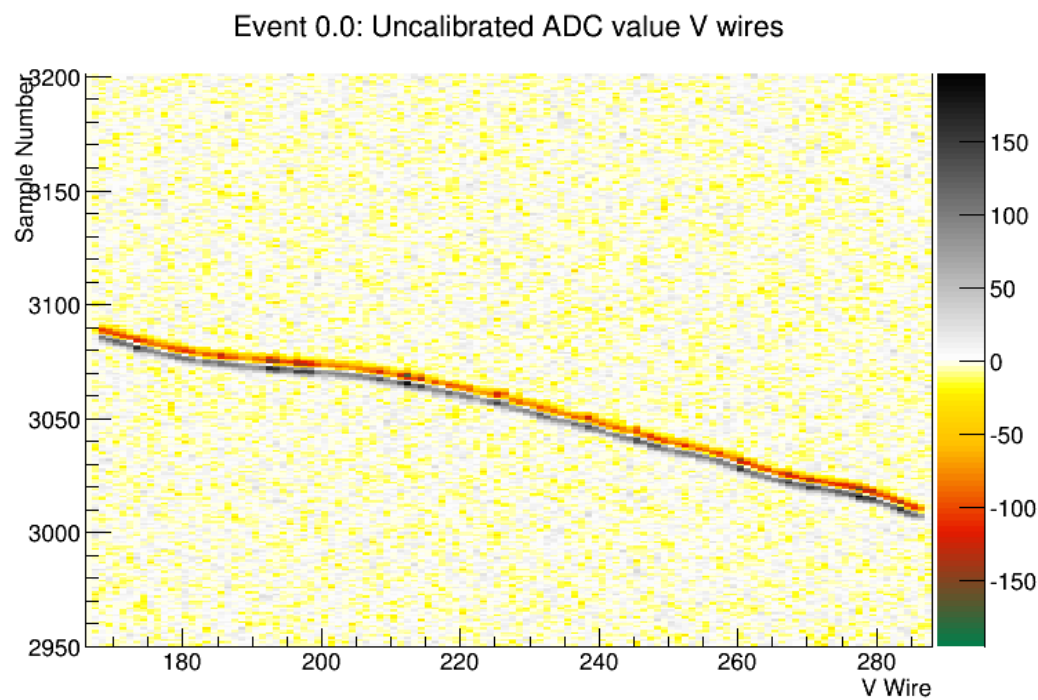
Induction Wire



- Signals in the CAPTAIN LAr TPC (these are simulated)
- Expect ~3 fC of ionization per wire in ~2 μs (~nA)
  - Unlike typical gas TPC, there isn't any amplification

Simulated Event





Horizontal, 300 MeV muon, initial direction is (1,0,0.1), and starting 10 cm from U wires.

Electron lifetime is set to 1.3 ms

Electronics Settings: 14 mV/fC, 2 ADC/mV, 1 μs peaking time, 2 μs pulse length

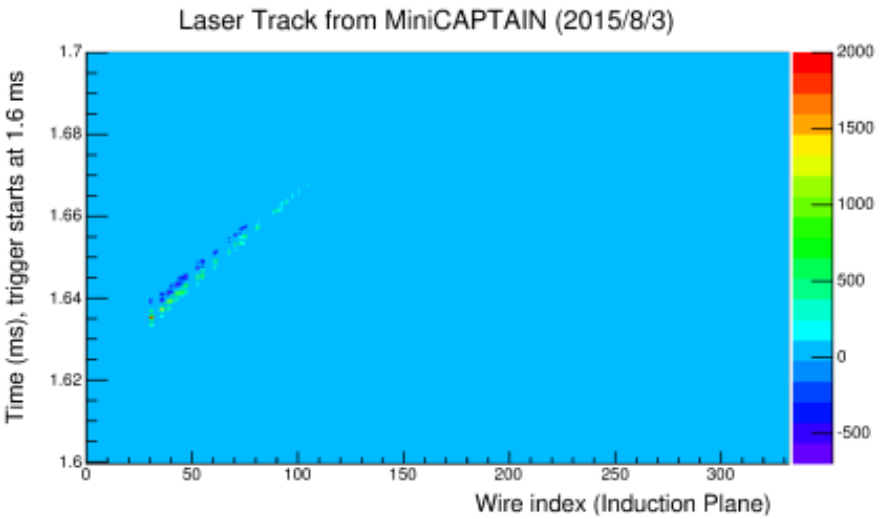
- settings based on results from pulser runs.

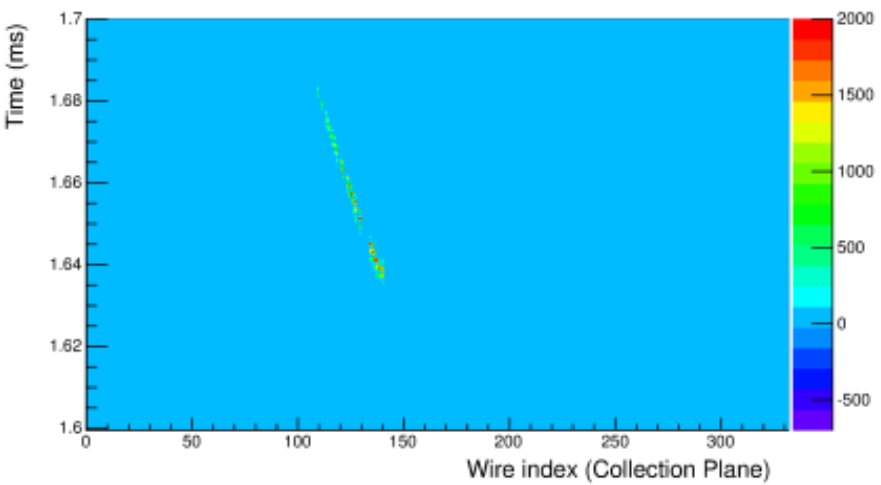
Nominal noise: 6.4 ADC noise total (fitted to pulser run)

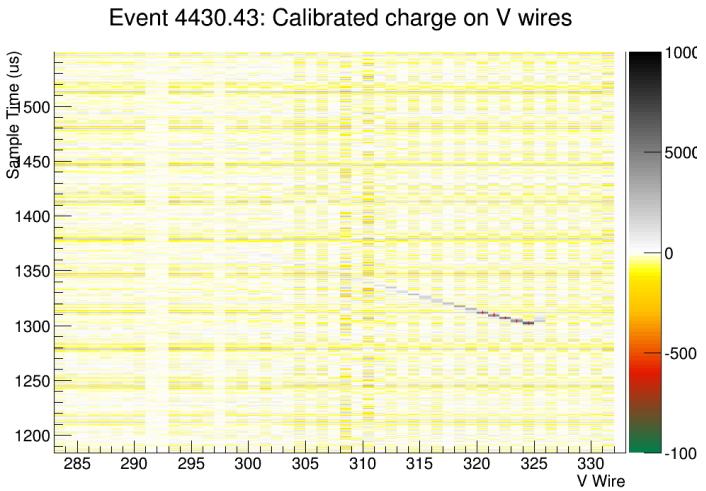
1300 electron “wire noise” (before shaping)

6 ADC digitizer noise (after shaping)

First signals in miniCAPTAIN







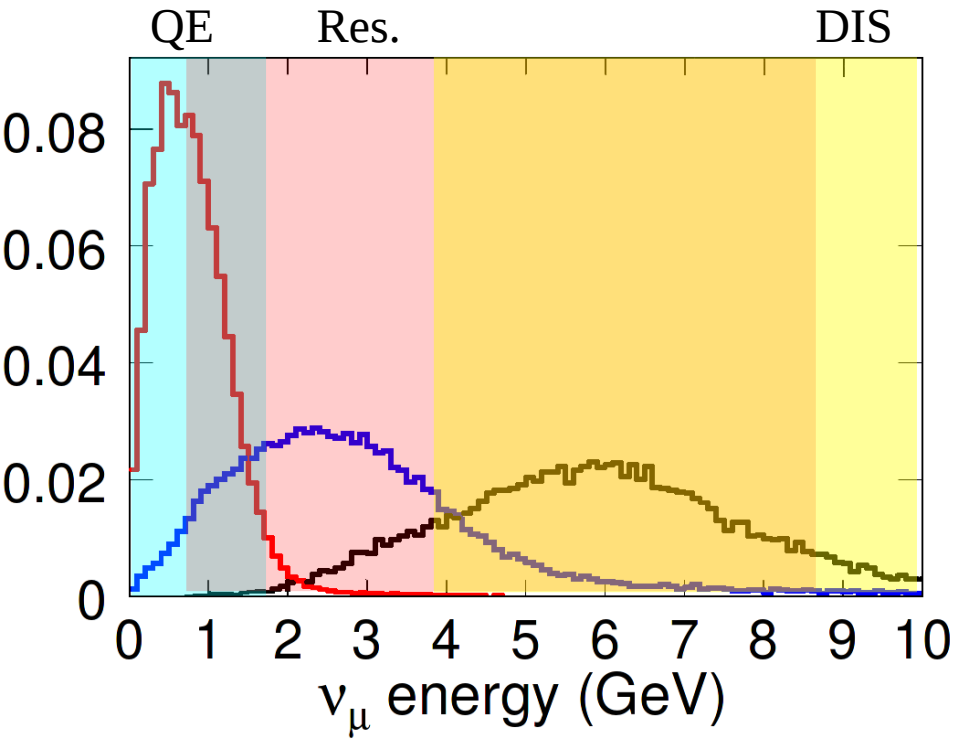
- First drift signals collected during summer 2015 commissioning
  - Electron lifetime was ~20μs w/o indium seal to ease access to TPC (will add for physics run)

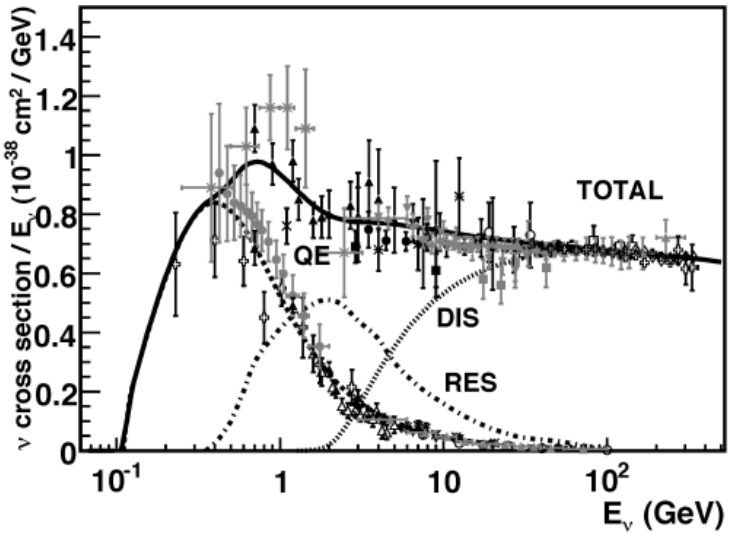
DUNE Physics Challenges

- Observation of Supernova Neutrinos
  - SN1987a
    - 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_{13}?
    - See recent tension between NOvA and T2K
  - Observation/Measurement of CP violation in neutrino oscillations
    - Maximal CP Violation? (see hints from DayaBay/NOvA/T2K)

DUNE E_ν Reconstruction

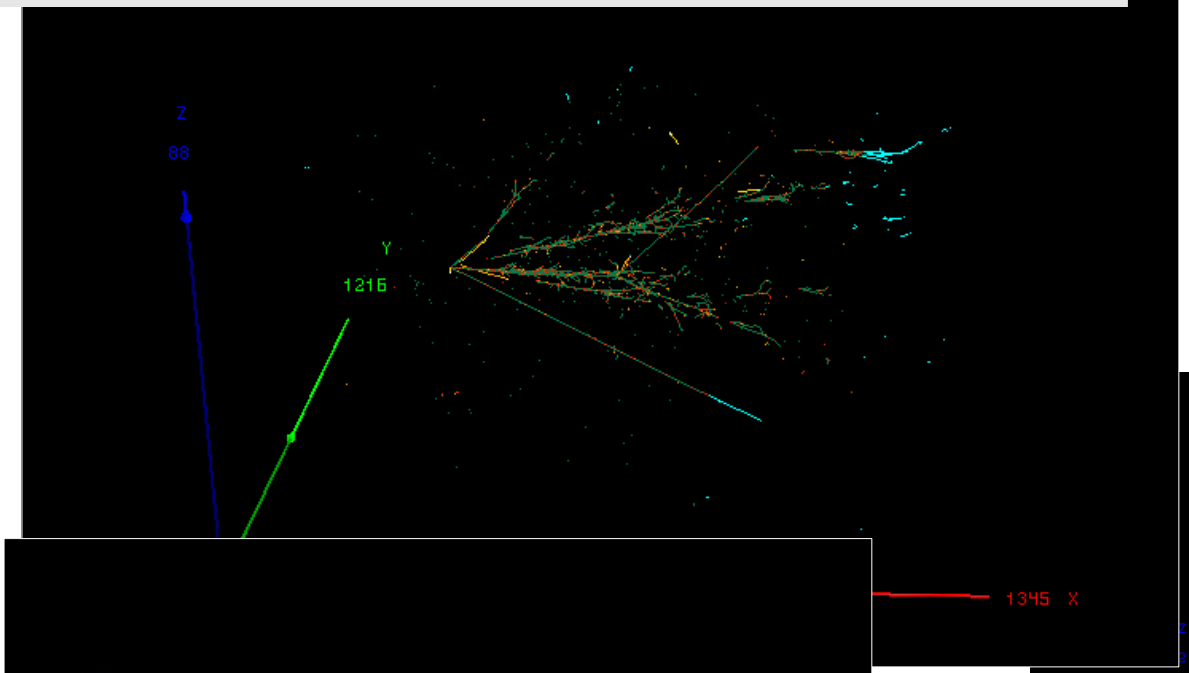
- The LBNF wide band beam spans an "interesting" range of neutrino cross sections
  - High energy measured using DIS (provides overall normalization)
  - First oscillation measured using resonant scattering
  - Second oscillation at transition between QE and resonant scattering.
- Few existing argon neutrino cross section measurements
  - Expect significant FSI and nuclear corrections
- Will need to tie many effects together to predict E_ν response





Reconstructing CAPTAIN Events

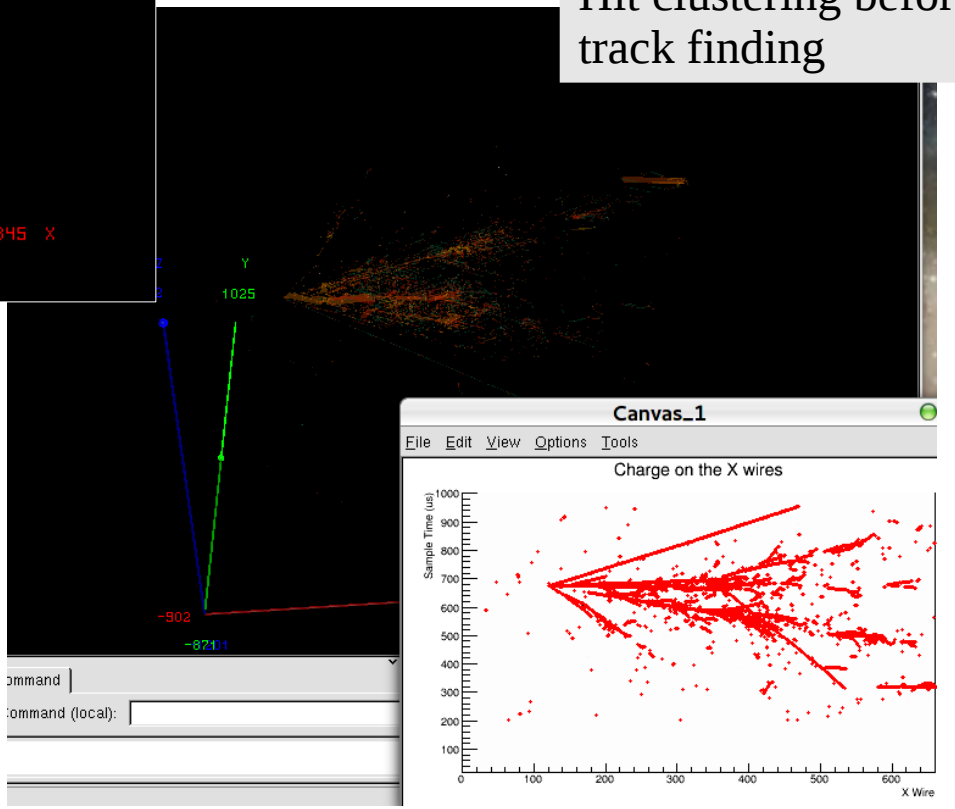
The true energy deposition information (from GEANT)

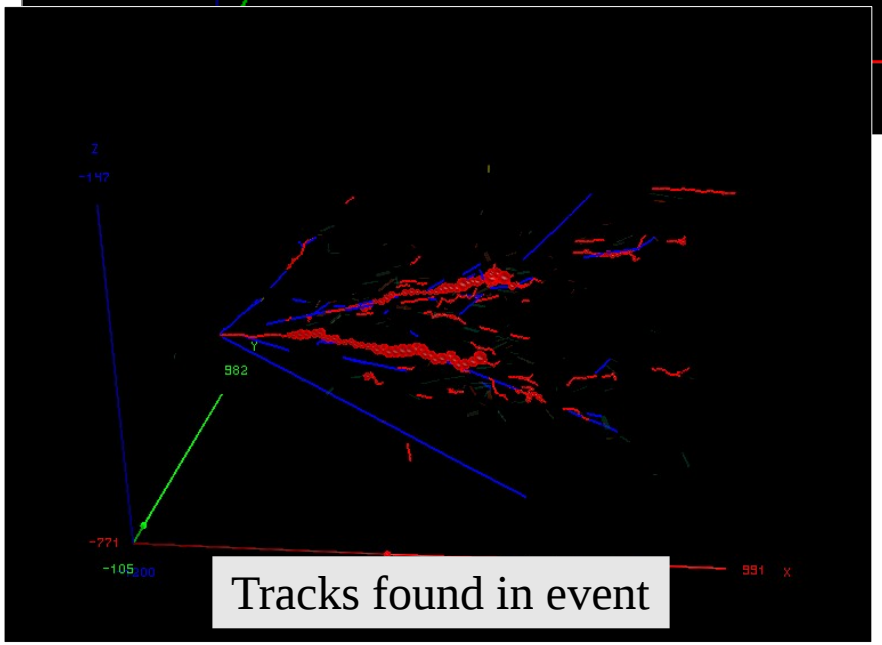


12 GeV muon neutrino producing:

- 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^{--}

Hit clustering before track finding





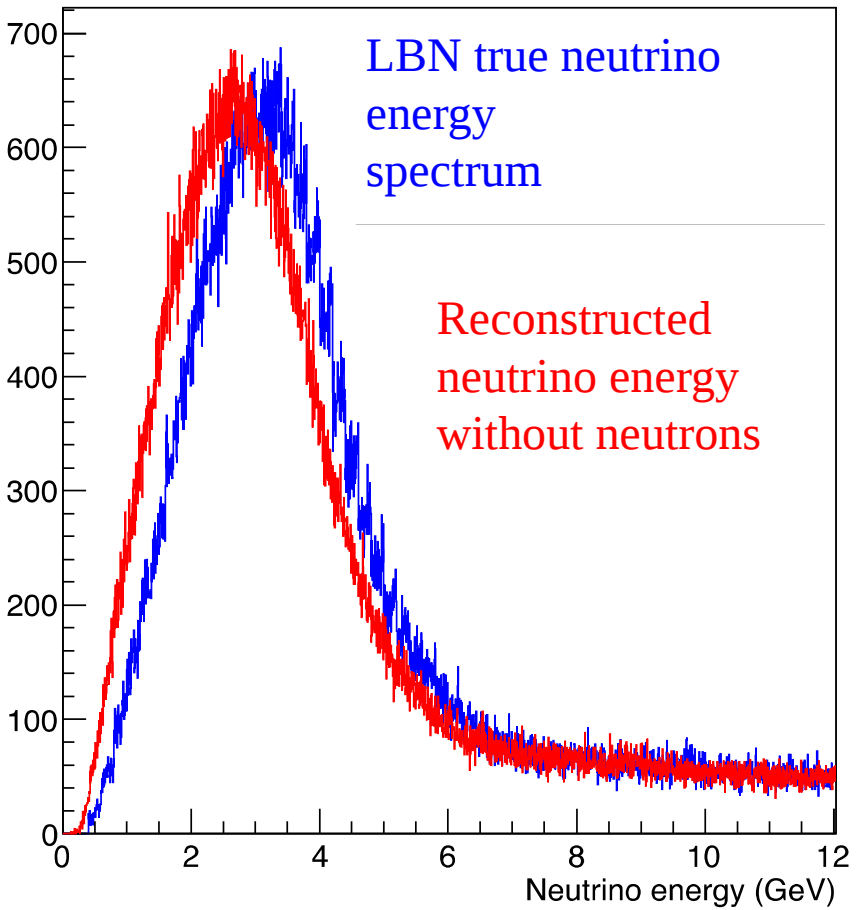
Tracks found in event

Reconstructing E_ν

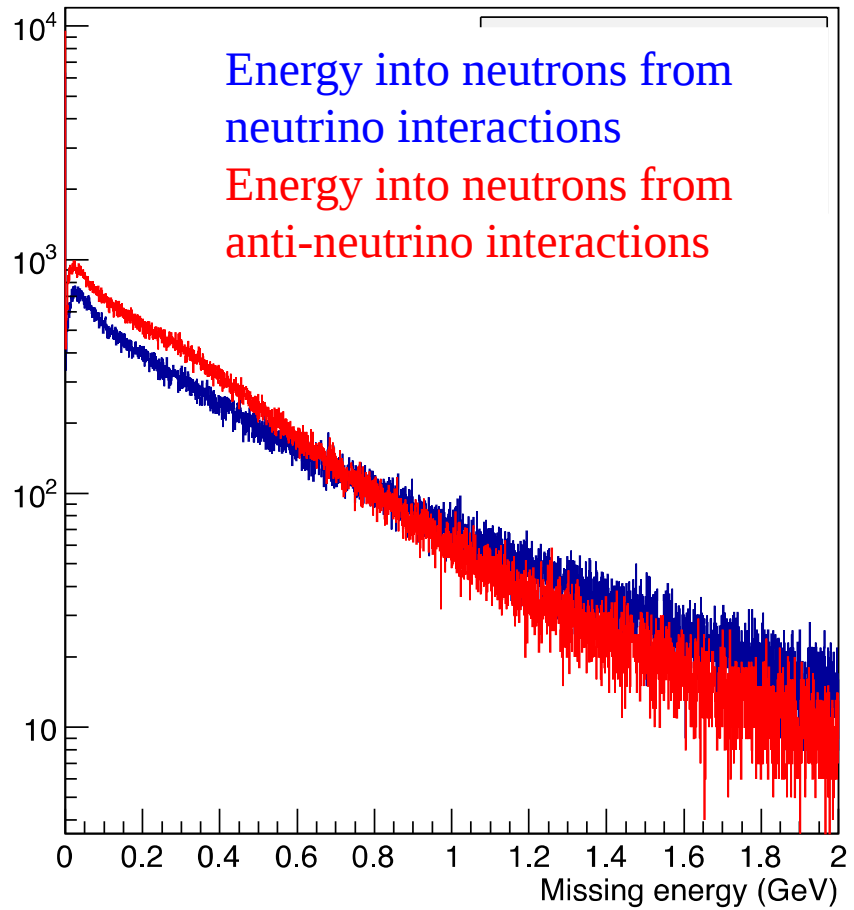
- Neutrino physics is based on "nothing in, something out"
  - The problem is to find the energy of "nothing" (the neutrino)
    - without knowing the initial state of the target (needs a model).
    - without knowing if all final state particles are observable (needs a model).
    - without knowing if the final state particles scatter before being observed (needs a model).
- Kinematic Reconstruction
  - e.g. Neutrino Energy assuming CCQE
- Calorimetric Reconstruction
  - Neutrino Energy from E_{vis}.
  - Inverse Beta Decay (low energies)
  - $E_\nu = E_l + E_{had}$ (high energies)

Reconstructed E_ν w/o Neutrons

LBNF Neutrino Energy Spectrum



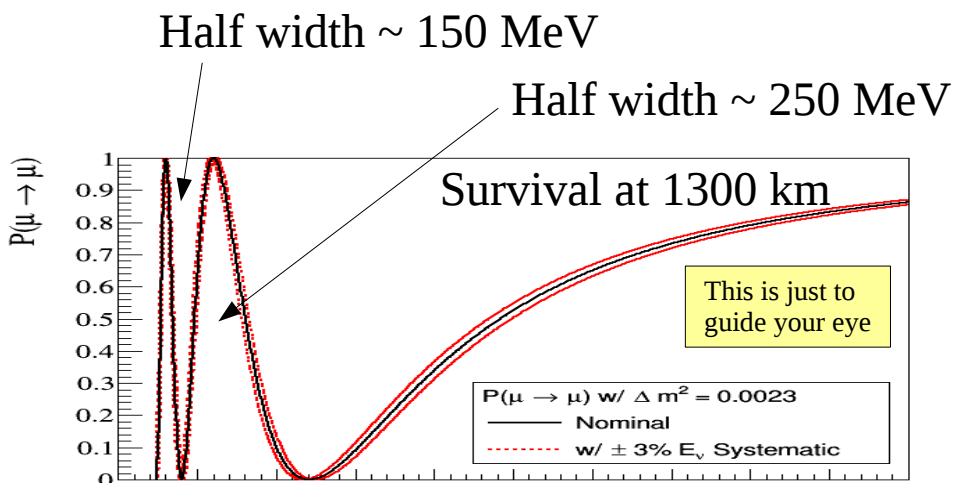
Outgoing energy in neutrons

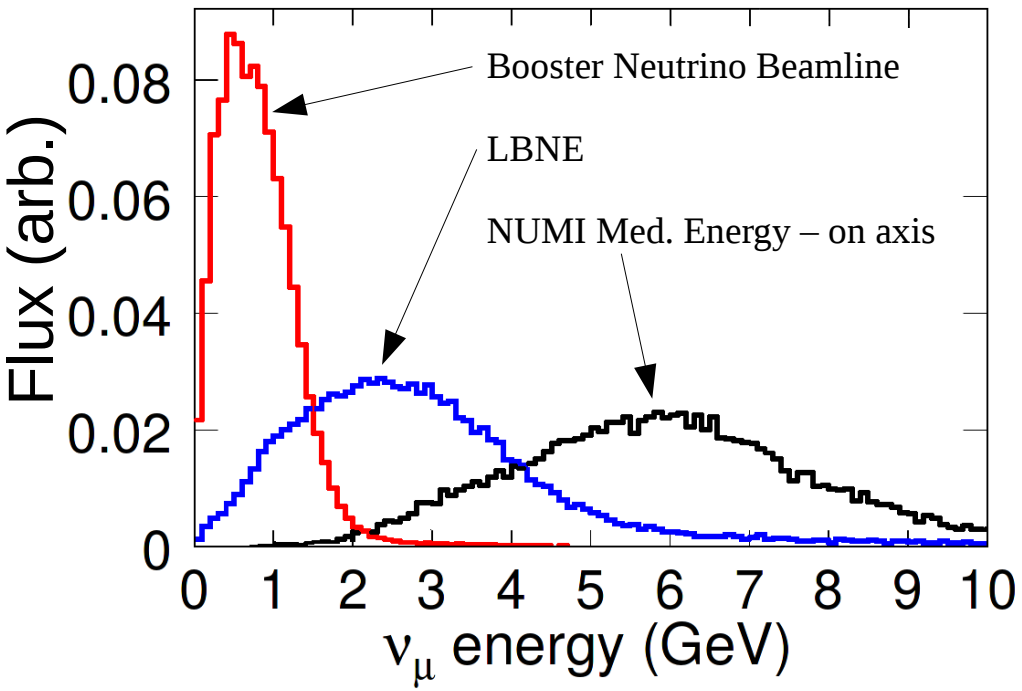


Elena Guardincerri

Typical LBNE Neutrino Flux

- Need to observe multiple nodes to break degeneracies
  - 1st osc. is 2 GeV to 3 GeV
  - 2nd osc. is 500 MeV to 1 GeV
- E_ν resolution gives ability to find features
  - Half widths of osc. features
    - First Max: 20%
    - Second Min: 18%
- E_ν scale gives ability to locate features
  - For $\delta(\Delta m^2) \sim <1 \times 10^{-4}\ eV^2$
    - $\delta(E_\nu) << 5\%$
      - for ν_e and ν_μ
    - Absolute energy << 5%
      - for all particles

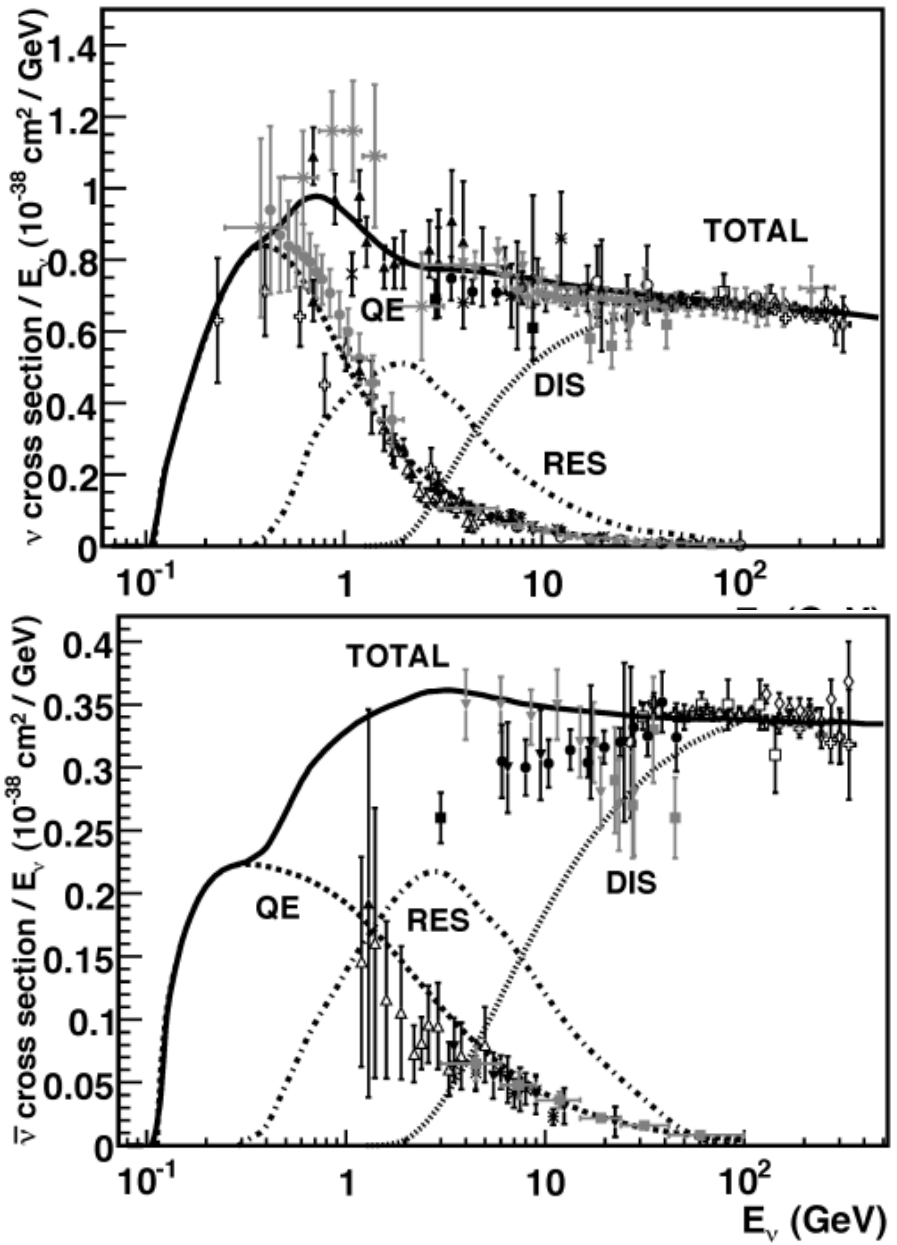




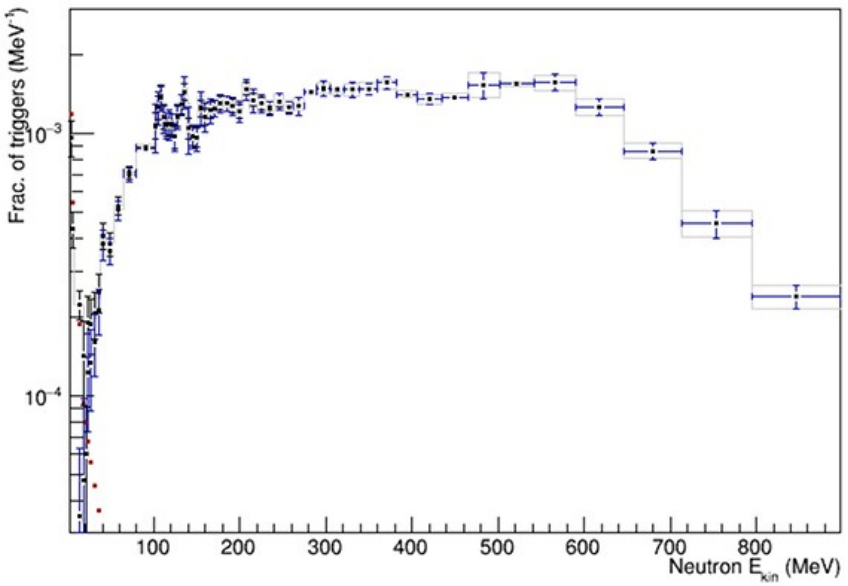
Neutrino CC Cross Sections

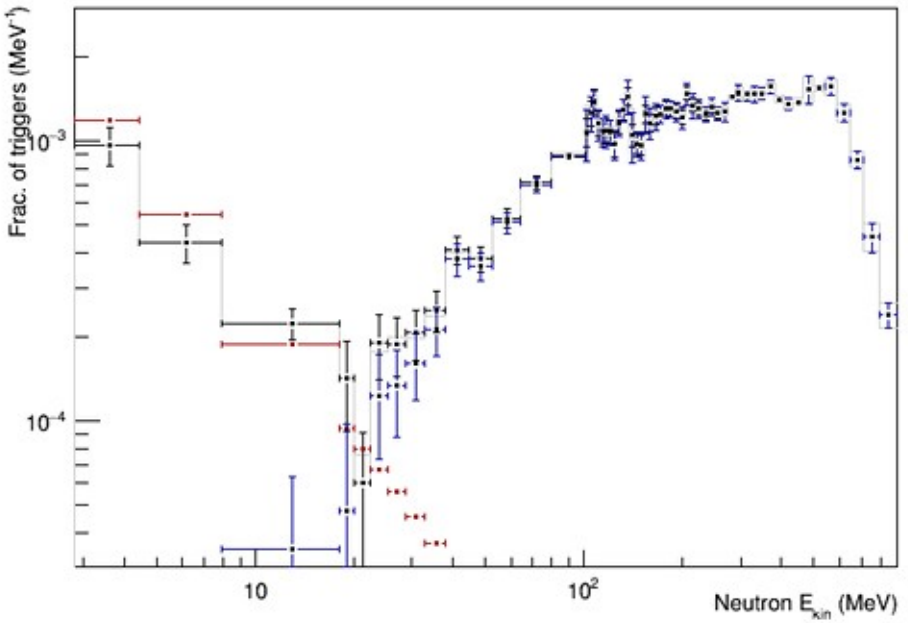
1305.7513

- Above 10 GeV: Dominated by DIS
  - Simple cross-section to calculate
  - Very little dependence on nucleus
- Below 10 GeV: Interesting...
  - Interplay between several different branches
    - QE (below 1 GeV)
    - Several Resonant scattering modes
- Care must be taken to define the neutrino measurements in terms of observables, not cross section models
  - e.g. Charged current w/o pions vs CC quasi-elastic scattering



Neutron Kinetic Energy Spectrum

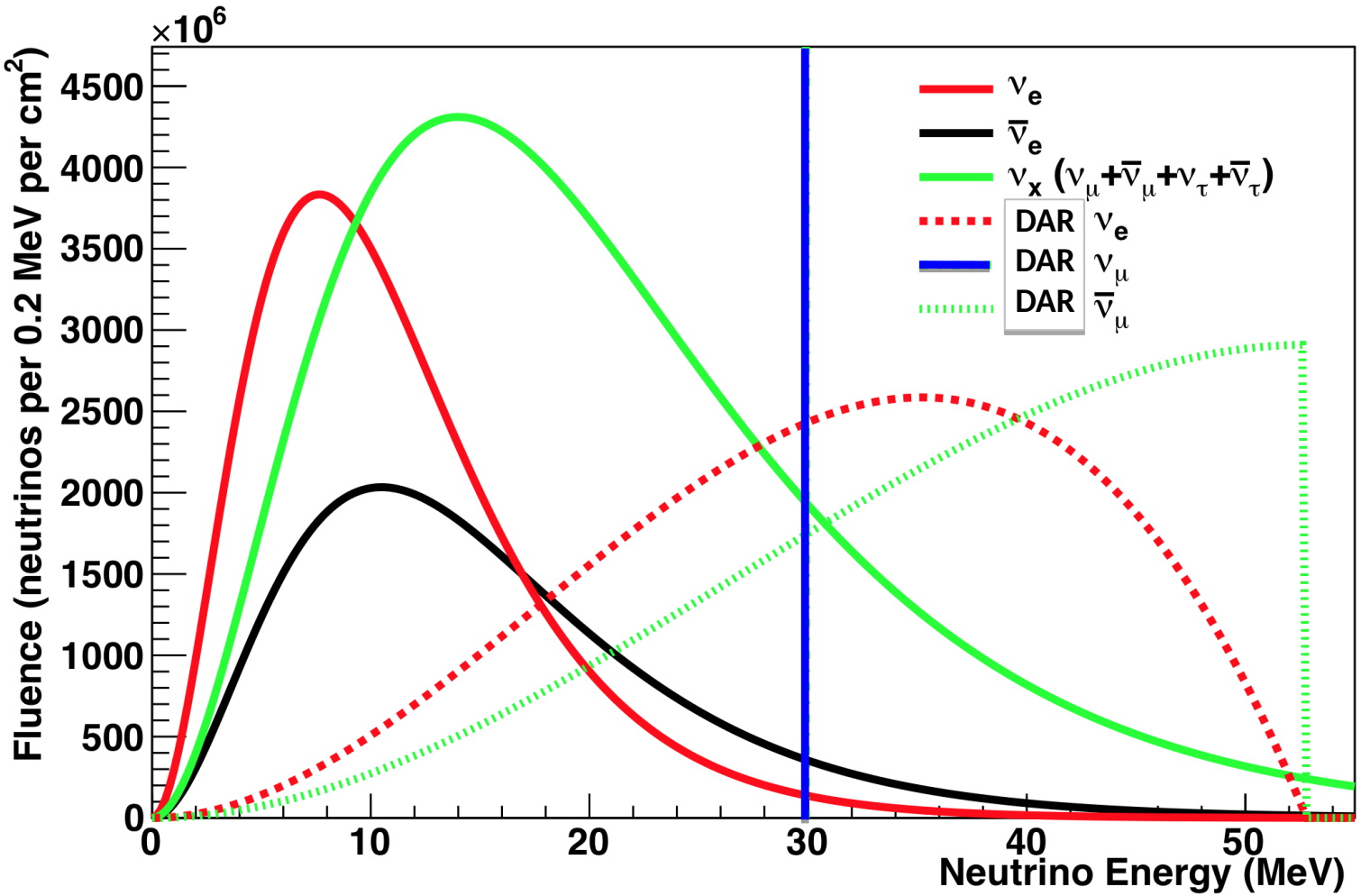




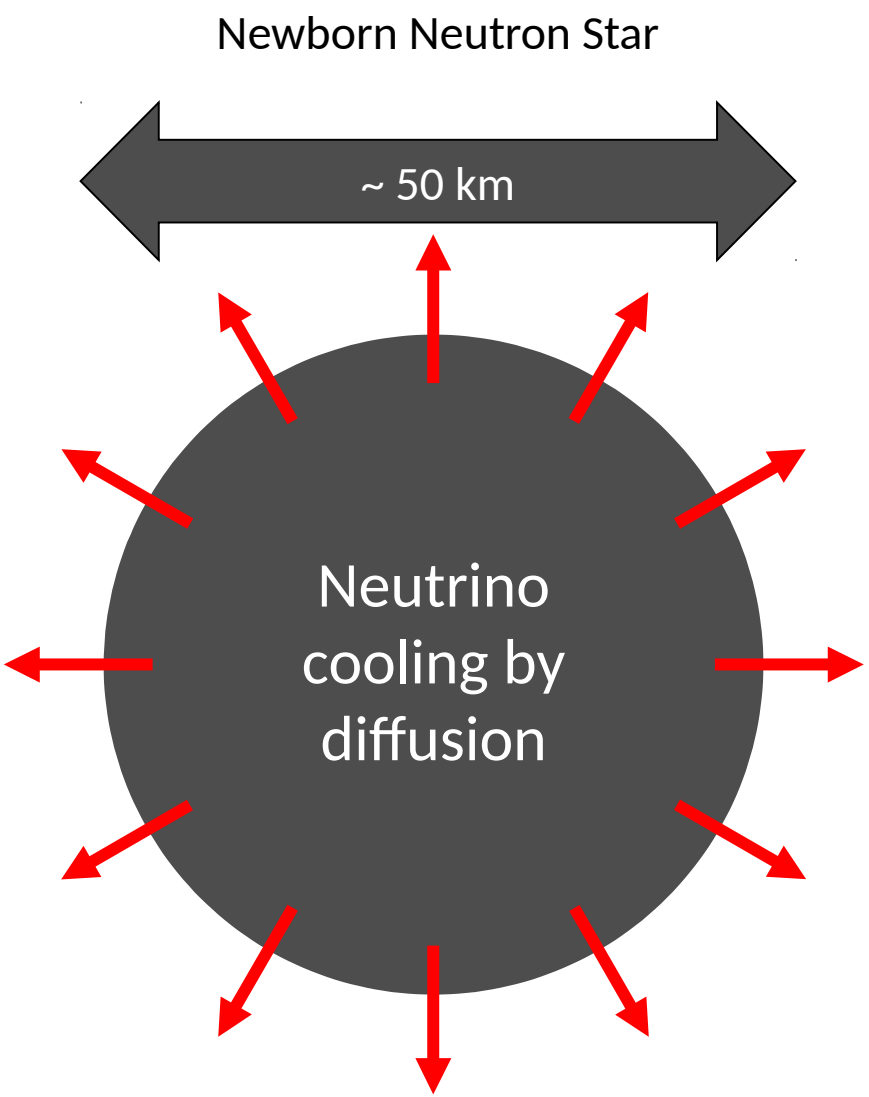
O(10 MeV) Neutrino Source: Stopped Pion Facilities

DAR flux: very well understood (analytic):

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



Physics Motivation: Stellar Collapse & SN Explosion



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

Alex Friedland at DUNE Meeting

Evolution of the explosion is reflected in neutrinos

- Neutronization burst, accretion and cooling phases can all be seen in neutrinos. All stages are extremely important!!
- Signal depends on the progenitor star

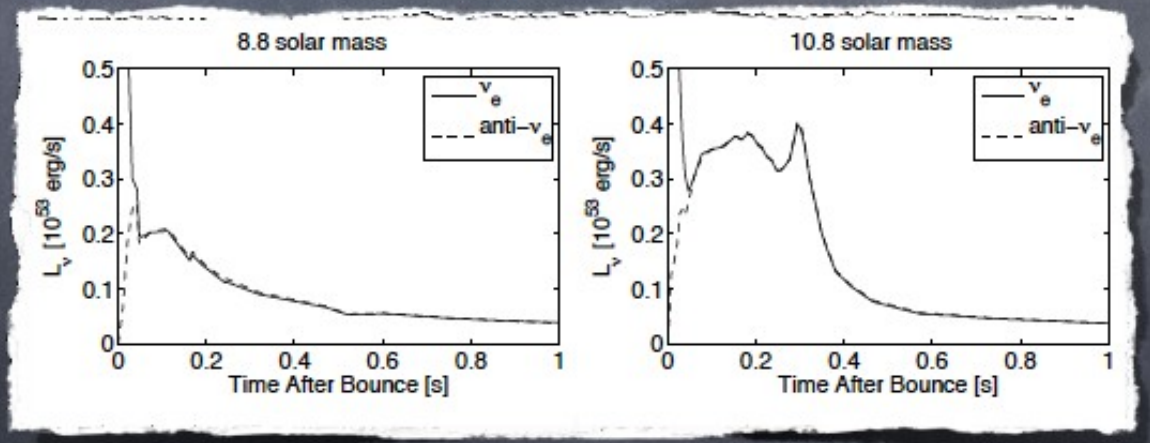
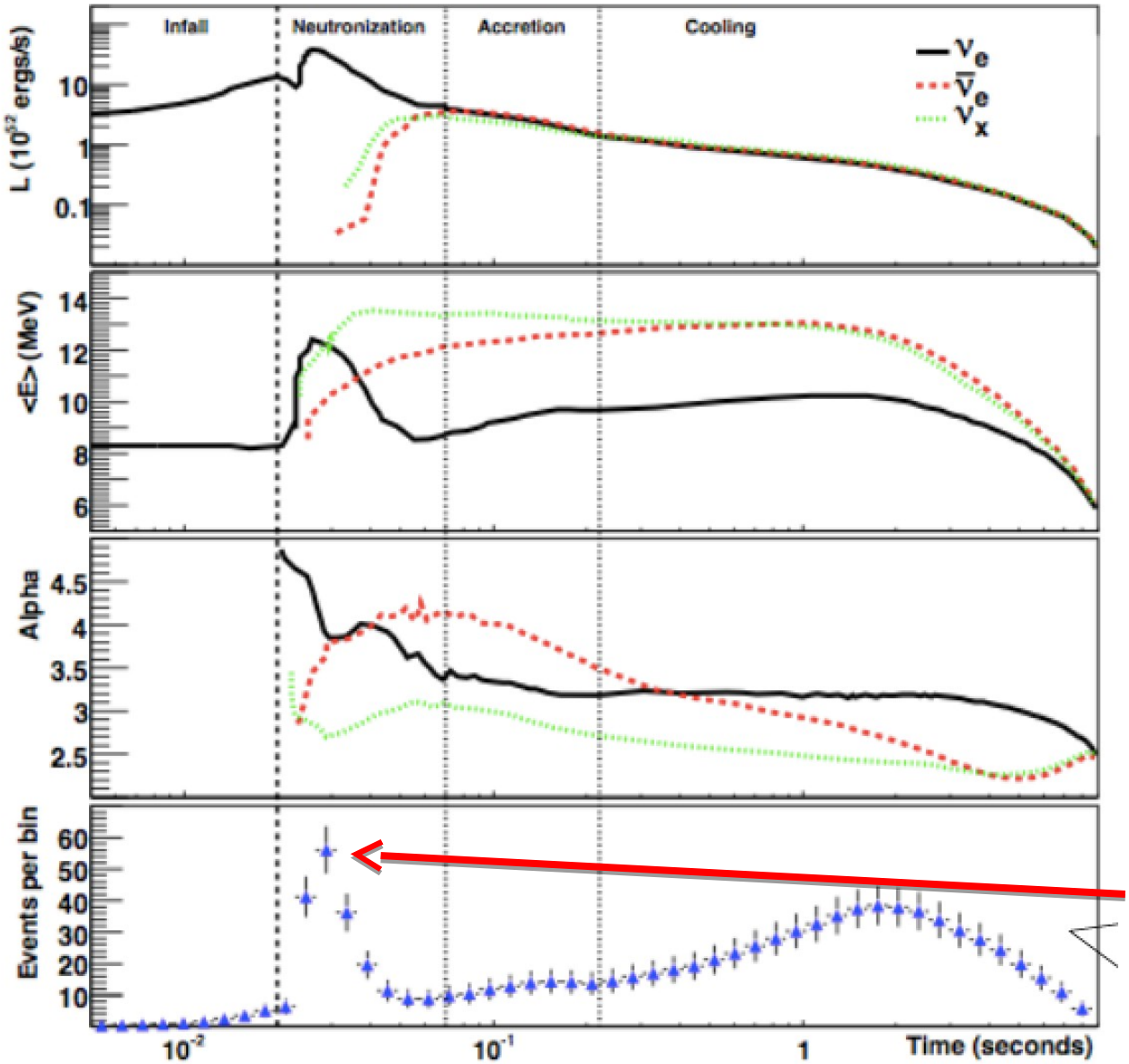


Fig from Fischer, Whitehouse, Mezzacappa, Thielemann, Liebendörfer, arXiv: 0908.1871

Detection of the SN Neutronization Burst: ν_e Sensitivity!

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



Burst is only 20 ms long and is essentially all ν_e

Mean energy of events is low, 10–12 MeV

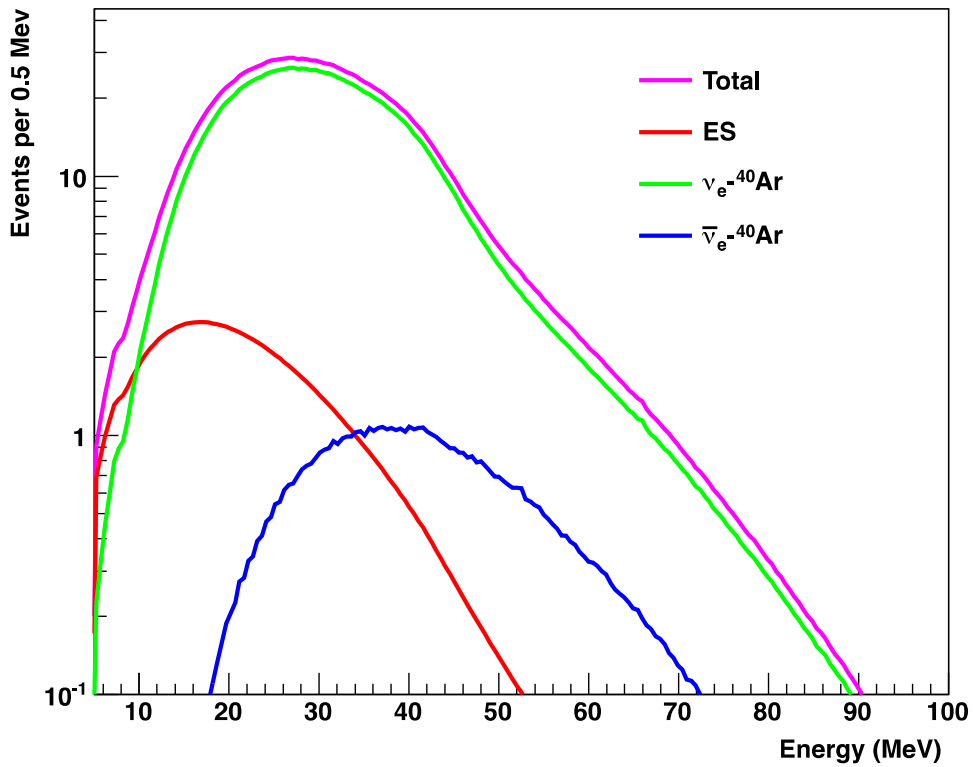
IMB/Kamiokande detected higher energy cooling neutrinos, not neutrinos from the neutronization process

Potential for ν_e detection in liquid argon by ELBNF

10 kpc SN Event Rates

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

17 kton LAr detector



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)

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

Critical items for supernova physics with a LAr TPC:

- Accurate measurements of the CC and NC cross-sections
- Ability to clearly tag excited states $^{40}K^*$ and $^{40}Ar^*$ using de-excitation γ's
- Ability to reject backgrounds such as neutron spallation
- Adequate energy resolution in a LAr TPC
- Reasonable event timing