Studying neutrino charged-current interactions in the COHERENT liquid argon detector

Erin Conley

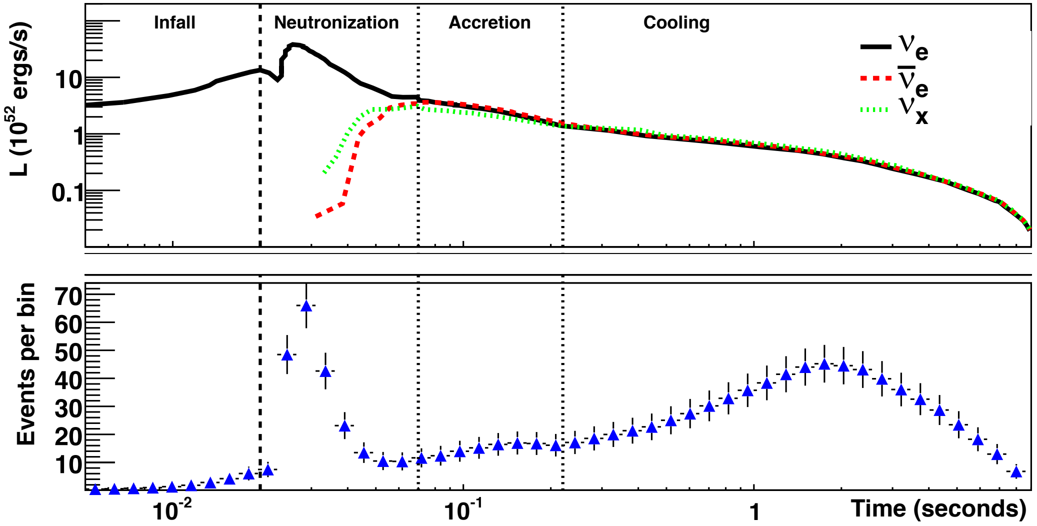
March 16, 2021

New Directions in Neutrino-Nucleus Scattering Workshop

Core-collapse supernova neutrinos

- Massive star at end of lifetime: core undergoes gravitational compression and collapses until halted by neutron degeneracy; shock wave propagates outward and expels stellar material
- Neutrino burst contains valuable information about both the mechanism and phenomena associated with supernova bursts

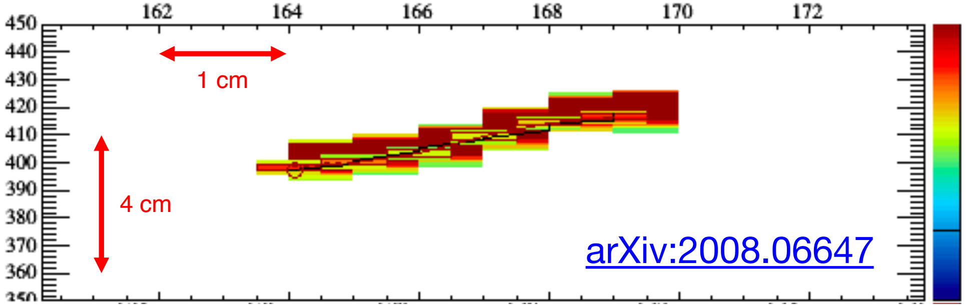
40kton LAr detector, 10kpc supernova, no oscillations $\nu_x \equiv \nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$

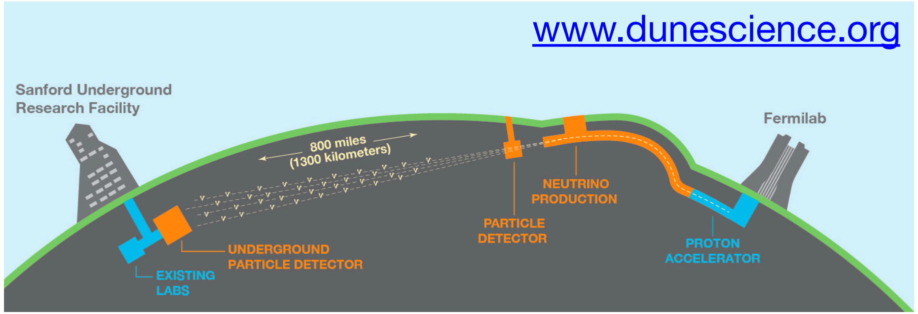


99% of potential energy from core-collapse supernova released in the form of neutrinos (tens of MeV) in a prompt burst lasting several seconds

Detecting the SN signal: DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

- Large international experiment for neutrino science: Neutrino oscillation physics, **supernova physics**, nucleon decay
- Far detector at Sanford Underground Research Facility (SURF) in South Dakota will be world's largest liquid argon time-projection chamber (including a 10 kton single-phase TPC)



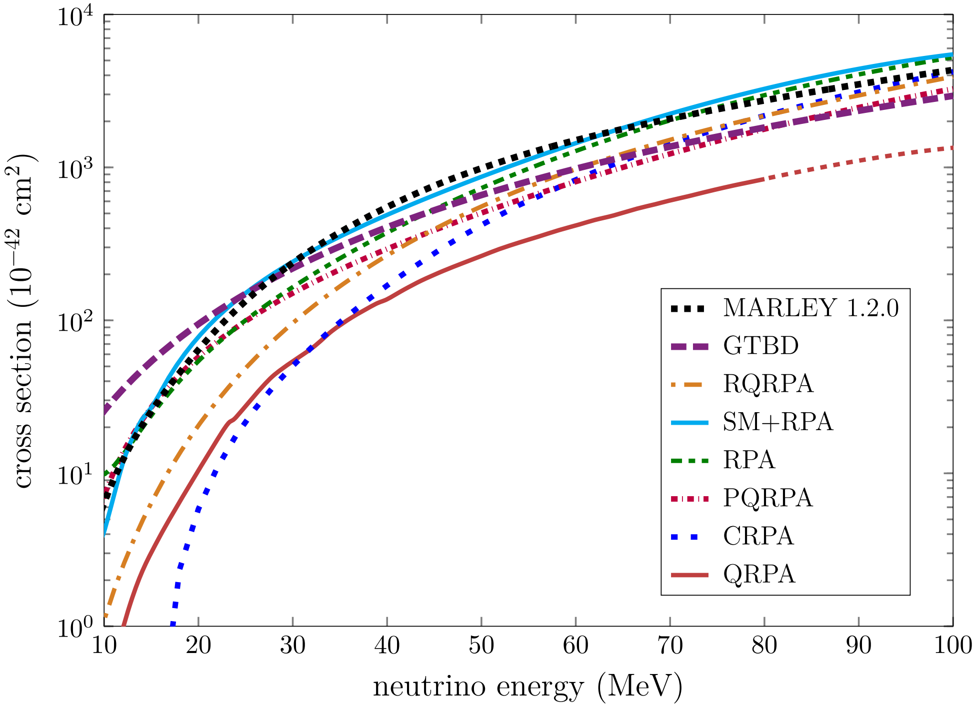


Event display for 10.25 MeV electron track (time vs wire number, charge color-scale)

Detecting electron neutrinos

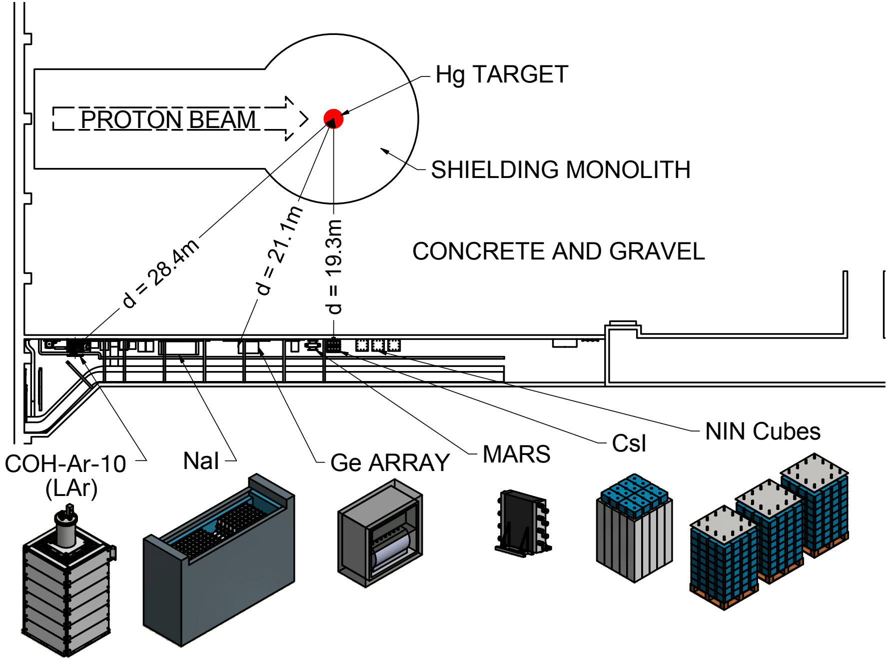
- Charged current interaction (ν_eCC): $\nu_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{K}^* + e^-$
- Low-energy neutrino-argon cross sections contain loosely constrained uncertainties; models cover wide range of phase space
- Incorrect assumptions can introduce biases in SN neutrino measurements (see backup)

S. Gardiner



COHERENT and CENNS-10

- Included in COHERENT's suite of detectors is the 24 kg liquid argon detector, CENNS-10 (or COH-Ar-10)
- Spallation Neutron Source at Oak Ridge National Laboratory (Neutrino Alley)
  - Protons on mercury target; produces prompt ν_μ flux, delayed ν_e and $\bar{\nu}_\mu$ fluxes



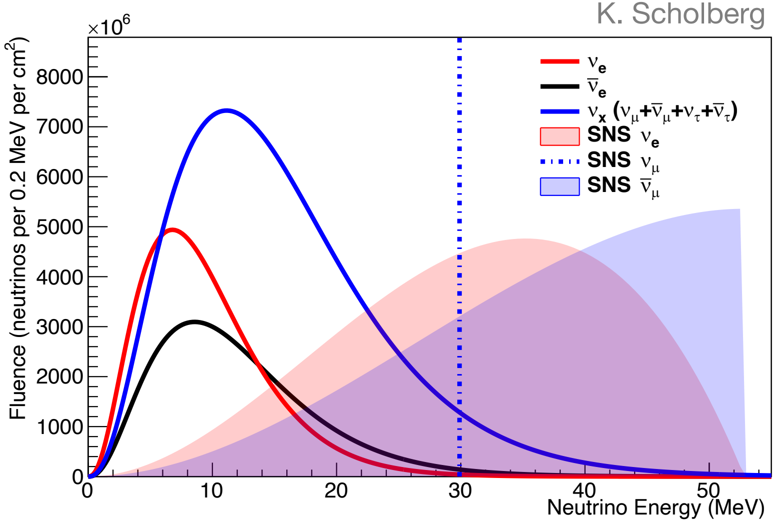
See M. Heath's talk on Friday

Studying neutrinos at ORNL

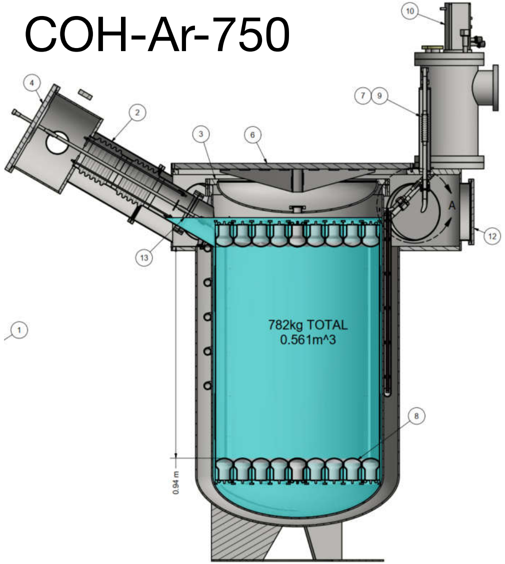
- Electron neutrinos produced at SNS in the energy region of interest for core-collapse supernova – opportunity to study ν_eCC interaction!
- Further high-precision measurements possible with COH-Ar-750 or at Second Target Station

Supernova flux (10 kpc) with pinched spectra, ~3 MeV ν_e temperature; all assumptions in backup

K. Scholberg

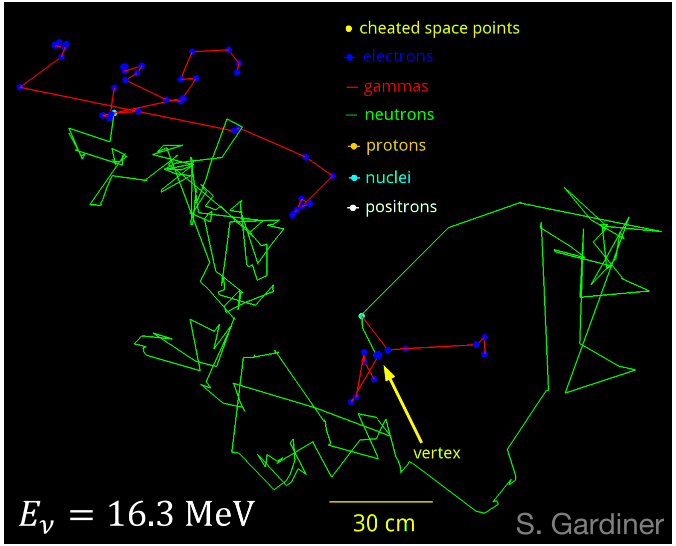


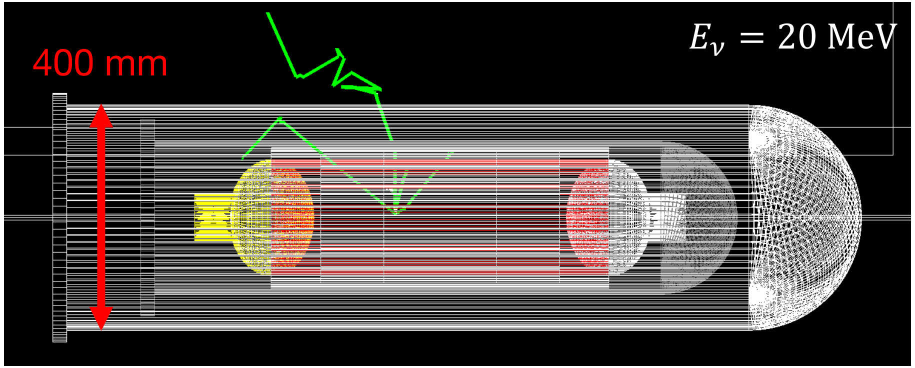
COH-Ar-750



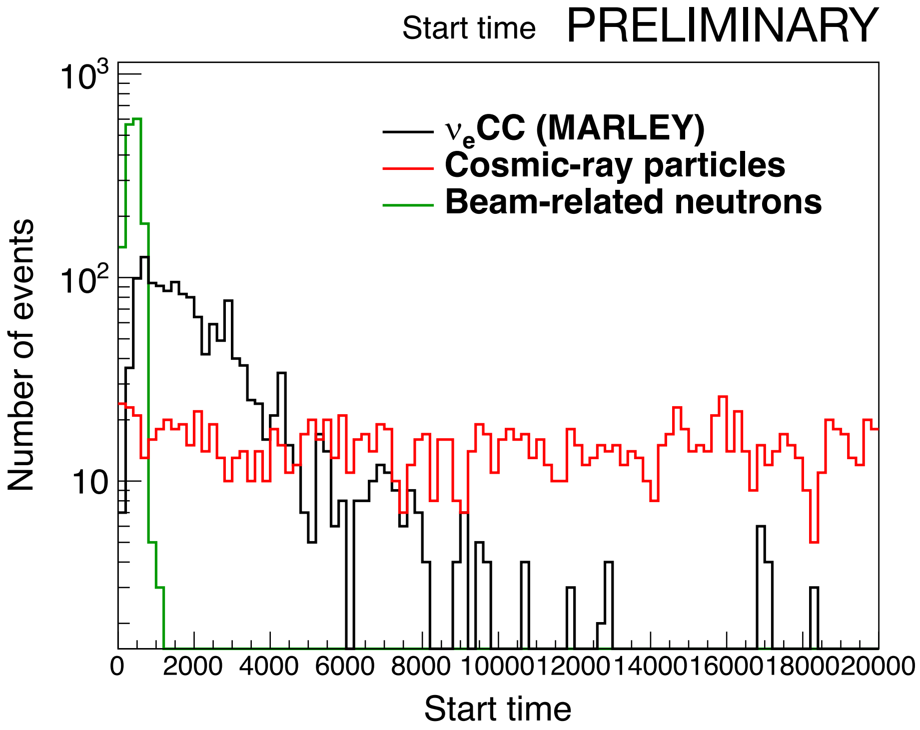
CENNS-10 simulation

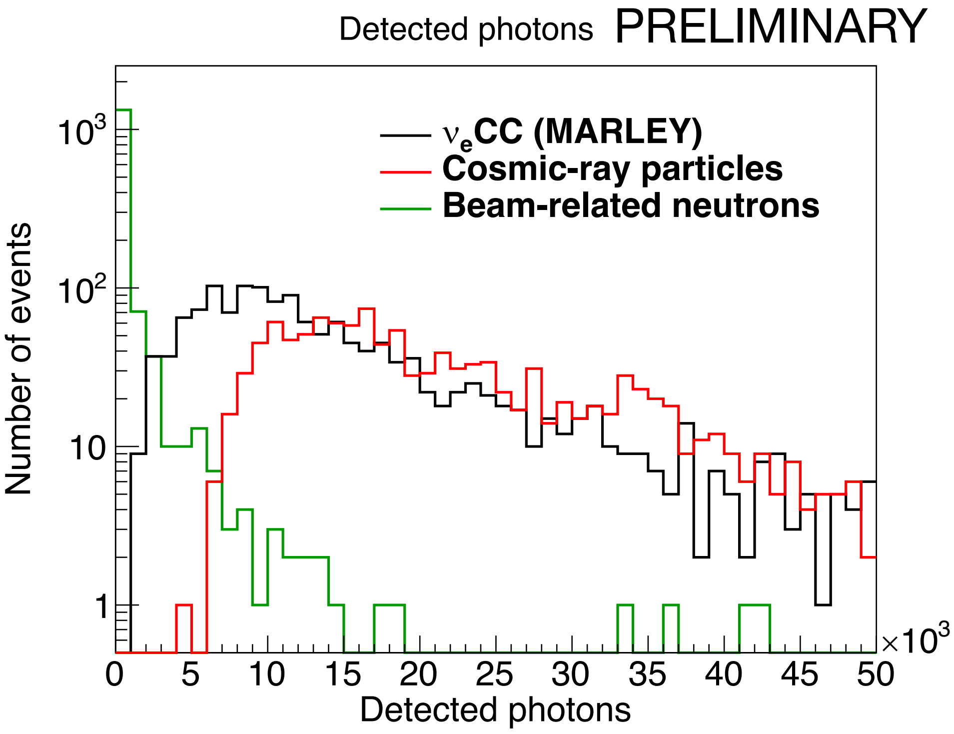
- Use Geant4 to model the CENNS-10 detector and response to ν_eCC interactions
- ν_eCC event generator: MARLEY (arXiv:2101.11867)
  - Provides sophisticated modeling of final state particles compared to other event generators
- Potential backgrounds: cosmic muons, beam-related neutrons (BRNs)





Geant4 simulation output (preliminary)





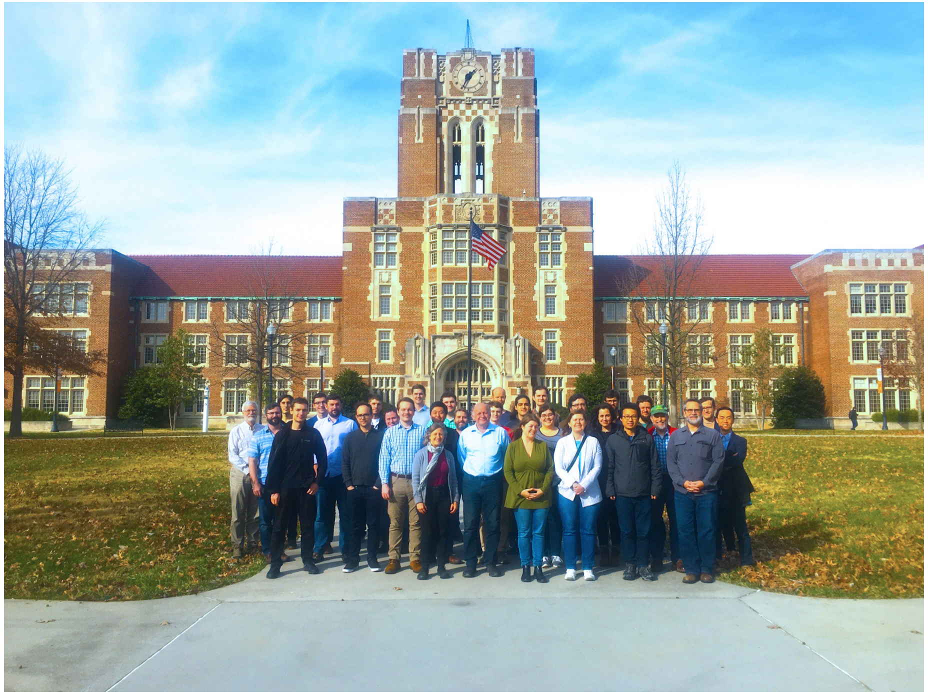
1500 events for each interaction type (not reflective of expected event rates)

We expect a saturated/non-linear detector response for ν_eCC and cosmic events

Takeaways and next steps

- The CENNS-10 liquid argon detector is exposed to neutrinos with SNB-like energies; this provides us with an opportunity to observe ν_eCC interactions, potentially constrain cross section uncertainties
- We began modeling ν_eCC interactions and its backgrounds in the CENNS-10 detector using Geant4
- Long-term precision measurements at the SNS will be possible for both TPC and single-phase designs (COH-Ar-750, STS)
- Next steps:
  - Account for non-linear detector response for ν_eCC and cosmic events
  - Perform sensitivity and event generation studies for COH-Ar-750

Thanks!



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Sandia National Laboratories
THE UNIVERSITY of TENNESSEE UT KNOXVILLE

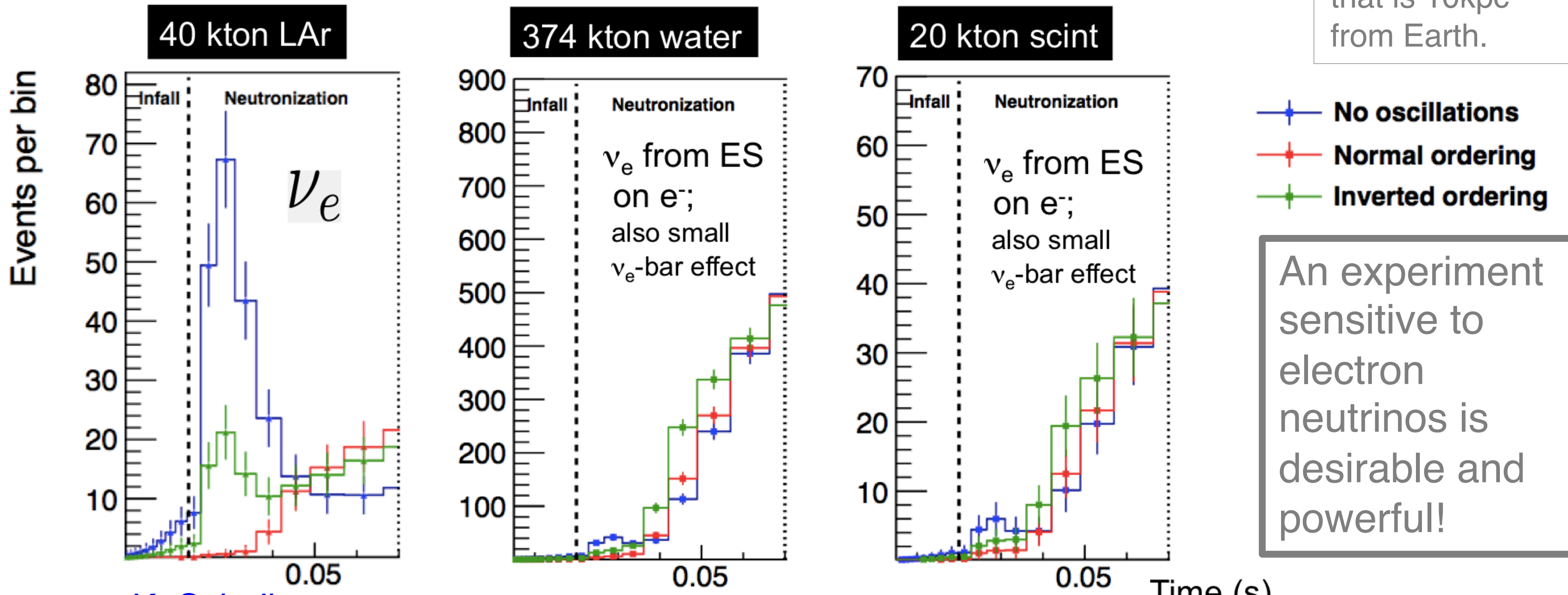
TUNL TRIANGLE UNIVERSITIES NUCLEAR LABORATORY
W UNIVERSITY of WASHINGTON
SD UNIVERSITY OF SOUTH DAKOTA

Backup

Motivation to detect the ν_e signal

Example of robust mass ordering signature: **the neutronization burst**

For a supernova that is 10kpc from Earth.

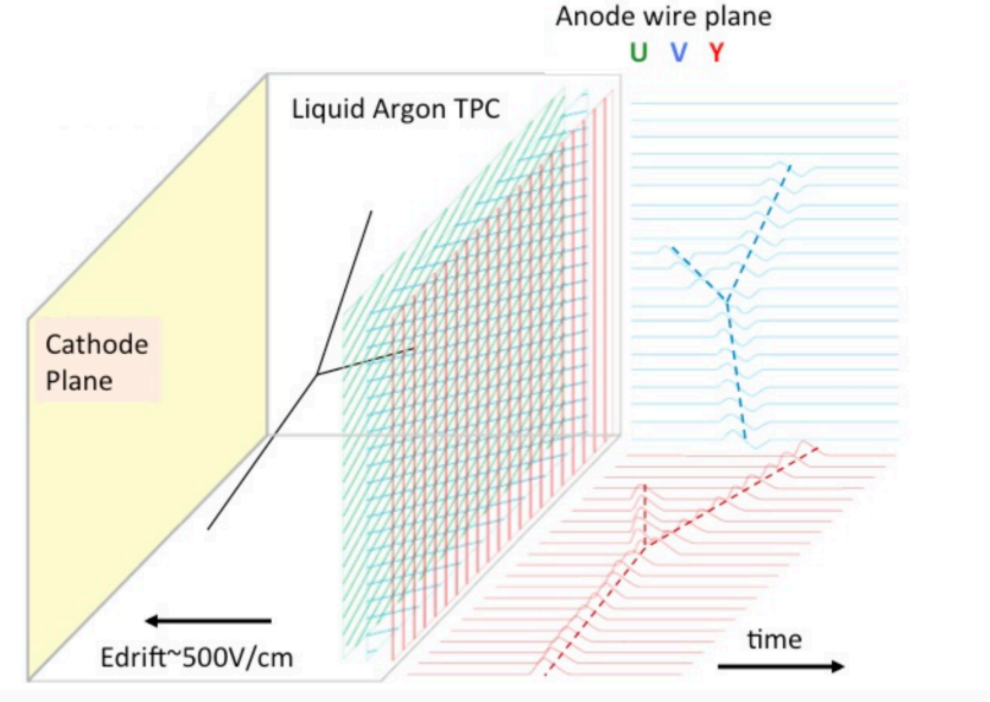


[K. Scholberg]()

An experiment sensitive to electron neutrinos is desirable and powerful!

Liquid Argon Time Projection Chamber

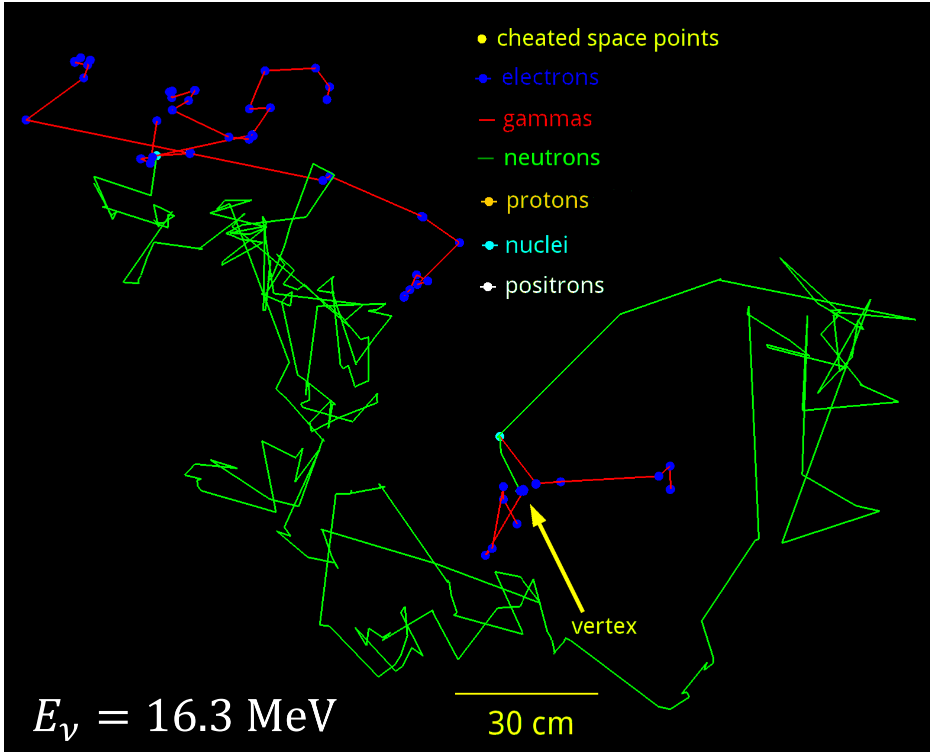
- Neutrino-argon interaction: argon is ionized by charged secondary particles
  - Scintillation light detected by photon detectors provides timing information
- Charged particles drift toward induction planes, deposit charge on collection plane wires
- Charge deposited on wire planes:
  - Wire objects (signals for specific particles)
  - 2D hits (single ionized particles) and clusters (ionization of multiple particles)
  - 3D tracks, showers, space points



LArTPC Schematic

MARLEY: Model of Argon Reaction Low-Energy Yields

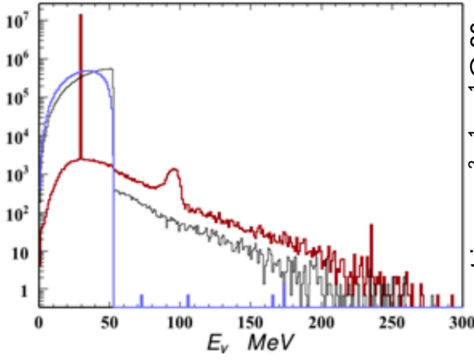
- Specializes in low-energy ν_eCC neutrino interactions
- Provides sophisticated modeling of final state particles compared to other event generators
- For more information: arXiv:2101.11867

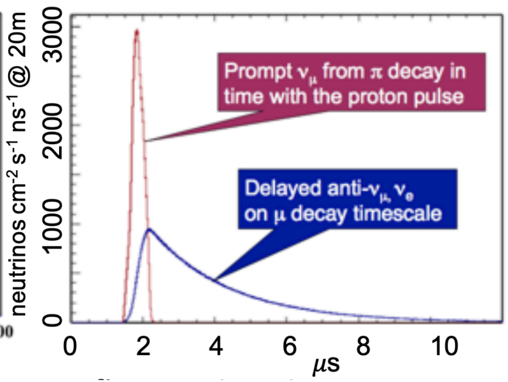


S. Gardiner (http://www.marleygen.org/)

MARLEY simulation

- Using MARLEY event generator, input final-state particles into COH-Ar-10 G4 simulation
- Randomly generated positions, timing sampled from blue histogram

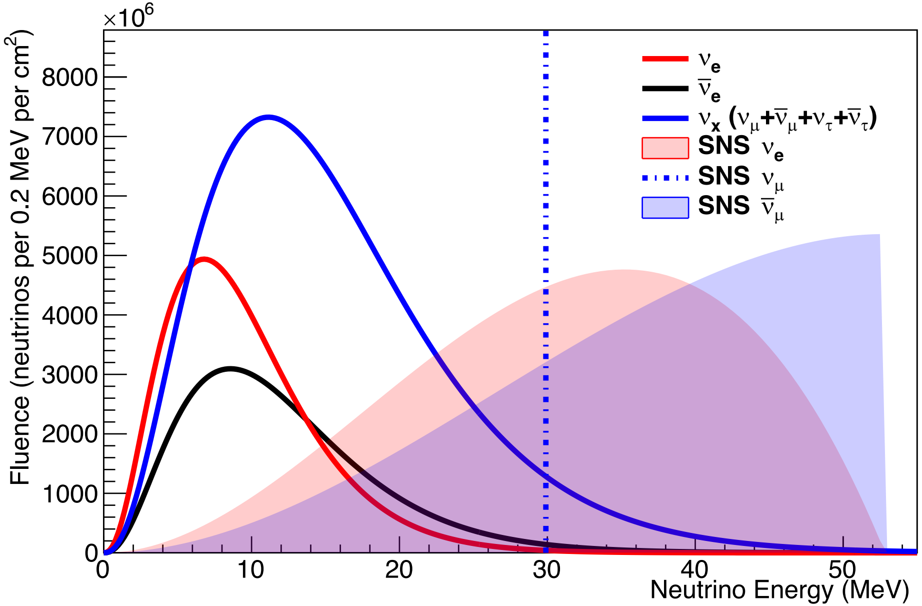




Using SNS flux from SNOwGLoBES event rate calculator (similar to the ν_e/dark blue distribution)

SNS flux plot assumptions

- SNS fluence: 1 day at 27.5 m, 1.4 MW
- 10 kpc supernova
- Flux parameters from Andrea GR papers:
  - Luminosity: 5e52 ergs
  - “Pinching”: 2.5
  - Average energies: 9.5 MeV for ν_e, 12 MeV for $\bar{\nu}_e$, 15.6 MeV for ν_x
  - “Temperature” ~3 MeV for ν_e

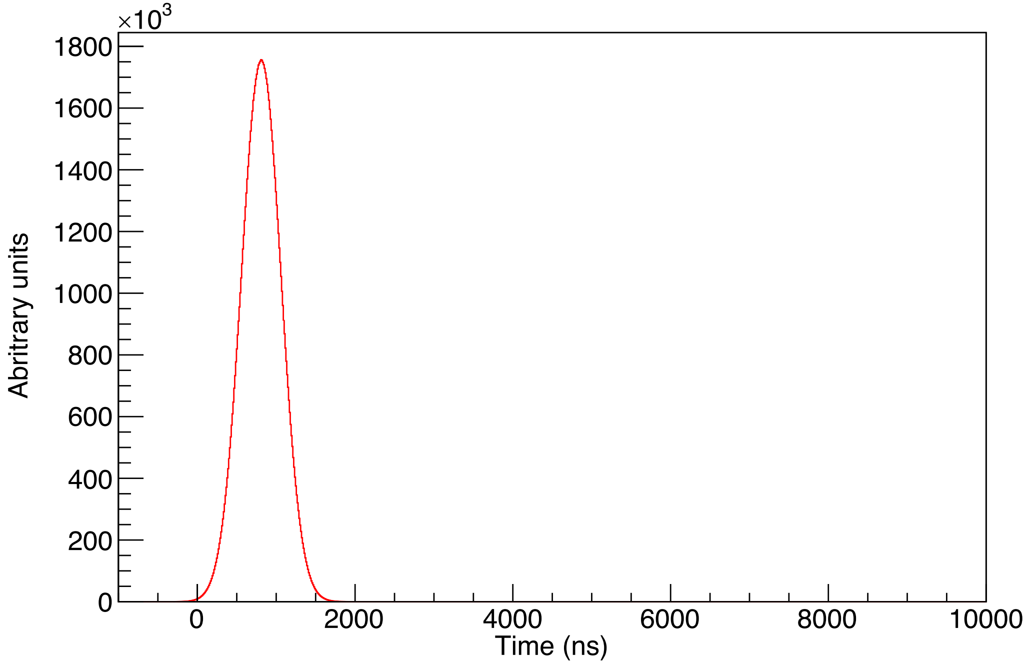


More about updated cosmic simulation

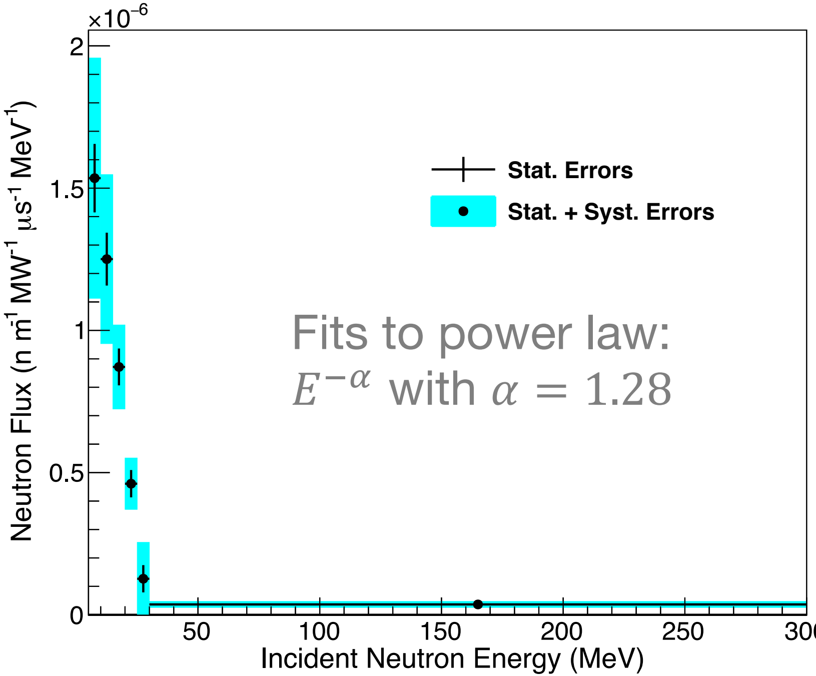
- Cosmic-ray Shower Library (CRY) from Livermore
- Correlated cosmic-ray particle shower distributions
  - Primary particle energies: 1 GeV – 100 TeV
  - Secondary particle energies: 1 MeV – 100 TeV
- Simulates particles in a specific area, time of arrival, zenith angle of secondary particles
- Defined initial x, y positions as random; z position = 100 cm (defined in other COHERENT CRY code)
- Read more here

Beam related neutron simulation

Time distribution



Energy distribution



Fits to power law:
$E^{-\alpha}$ with $\alpha = 1.28$

More information about BRN sim.

- Define square plane 0.7 m from detector with 1 meter half-length
- Rotation matrix defined using (0, 0, 1) and (0, 1, 0)
- Cosine-law angular distribution
- Initial position [cm] is always (0.7, 0, 0) – perhaps could be more realistic?

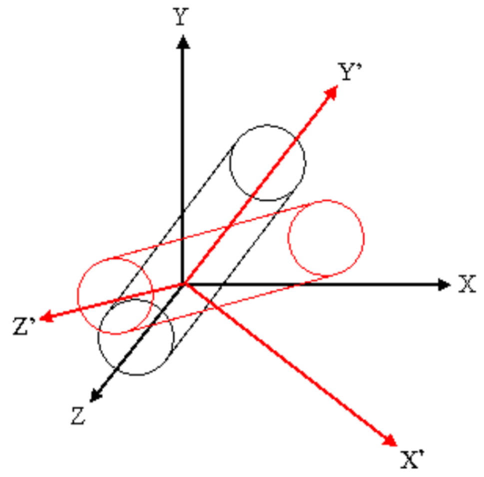
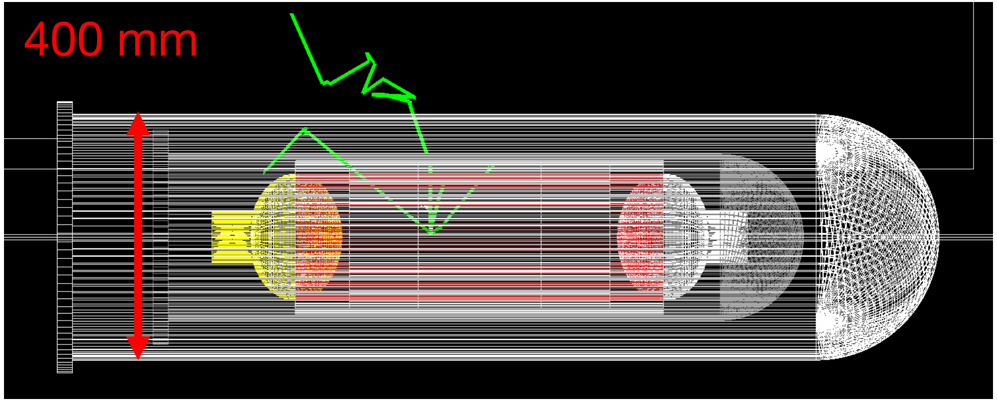


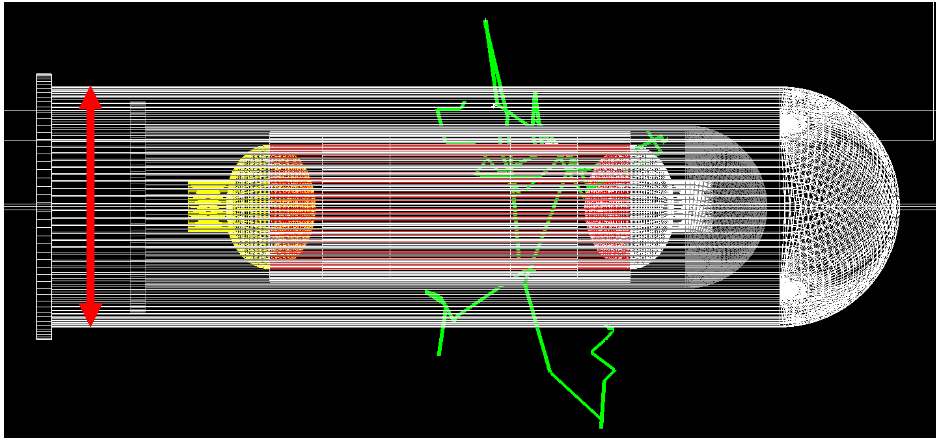
Figure 2.3. An illustration of the use of rotation matrices. A cylinder is defined with its axis parallel to the z-axis (black lines), but the definition of 2 vectors can rotate it into the frame given by x', y', z' (red lines).

Taken from [Geant4 GeneralParticleSource user document]()

Geant4 event displays: MARLEY

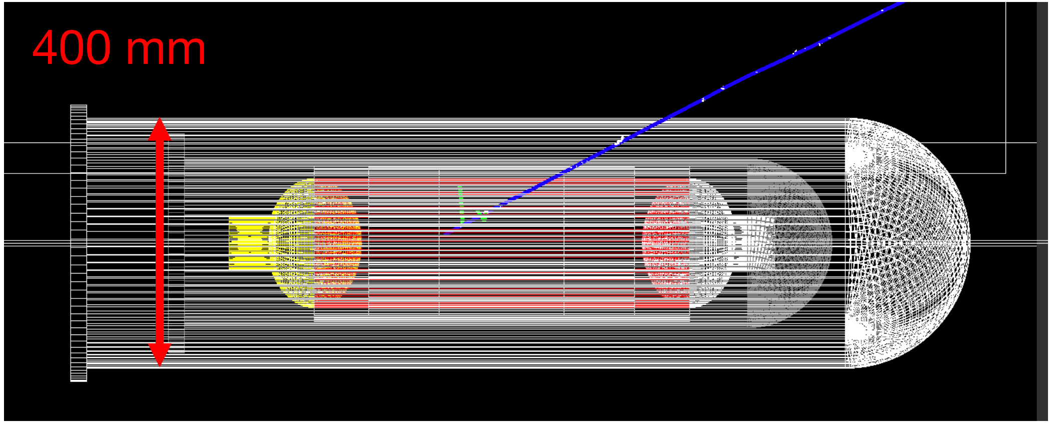


MARLEY ν_eCC event
20 MeV ν_e
White track: electron
Green tracks: gammas

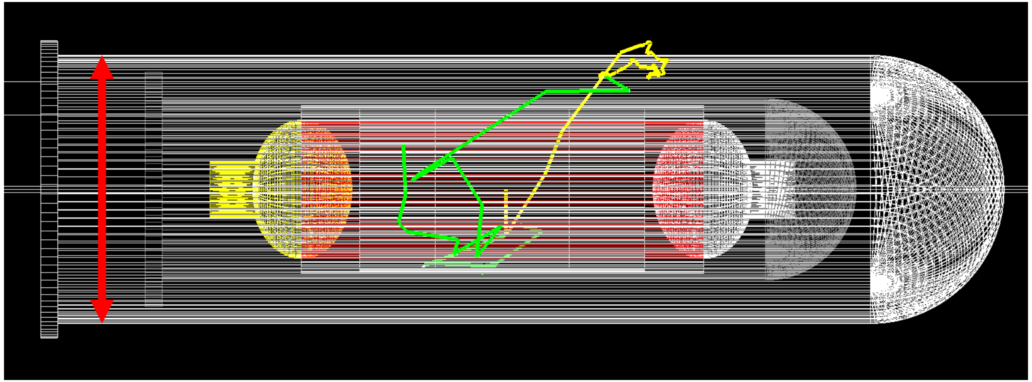


MARLEY ν_eCC event
46.9 MeV ν_e
White track: electron
Green tracks: gammas

Geant4 event displays: backgrounds



CRY cosmic muon event
835 MeV muon
White tracks: electron
Green tracks: gammas
Blue track: muon



Beam-related neutron
5.62 MeV G4 neutron
Yellow track: neutron
Green tracks: gammas

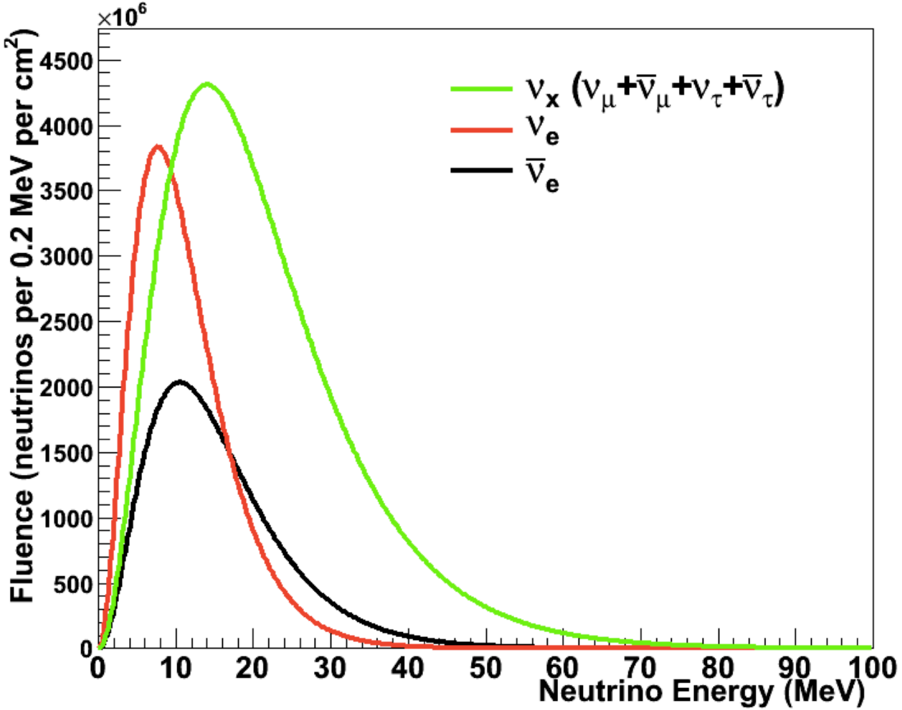
How might the cross section impact SN measurements?

Supernova Flux Model

- Supernova neutrino spectrum AKA "pinched-thermal form":

$$\phi(E_\nu) = \mathcal{N}\left(\frac{E_\nu}{\langle E_\nu \rangle}\right)^\alpha \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu \rangle}\right]$$

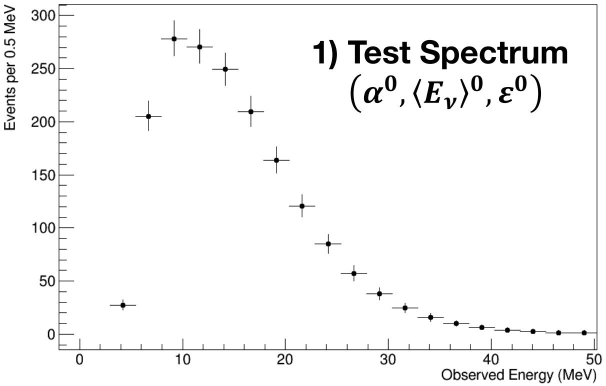
  - E_ν: Neutrino energy (MeV)
  - $\mathcal{N}$: Normalization constant (related to luminosity, ε, in ergs)
  - $\langle E_\nu \rangle$: Mean neutrino energy (MeV)
  - α: Pinching parameter; large α corresponds to more pinched spectrum (unitless)
- Parameters of interest: ε, $\langle E_\nu \rangle$, α
  - ε physical parameter of interest to theorists



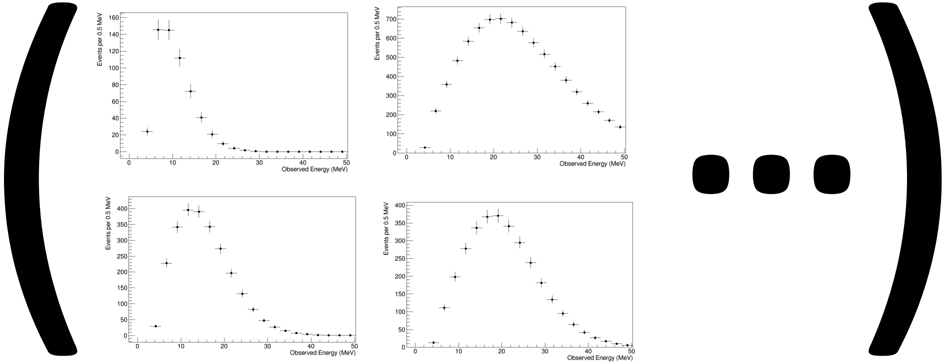
Pinched-thermal for a 10kpc supernova (K. Scholberg)
Note: Fluence refers to a time-integrated flux.

Parameter Fitting Algorithm

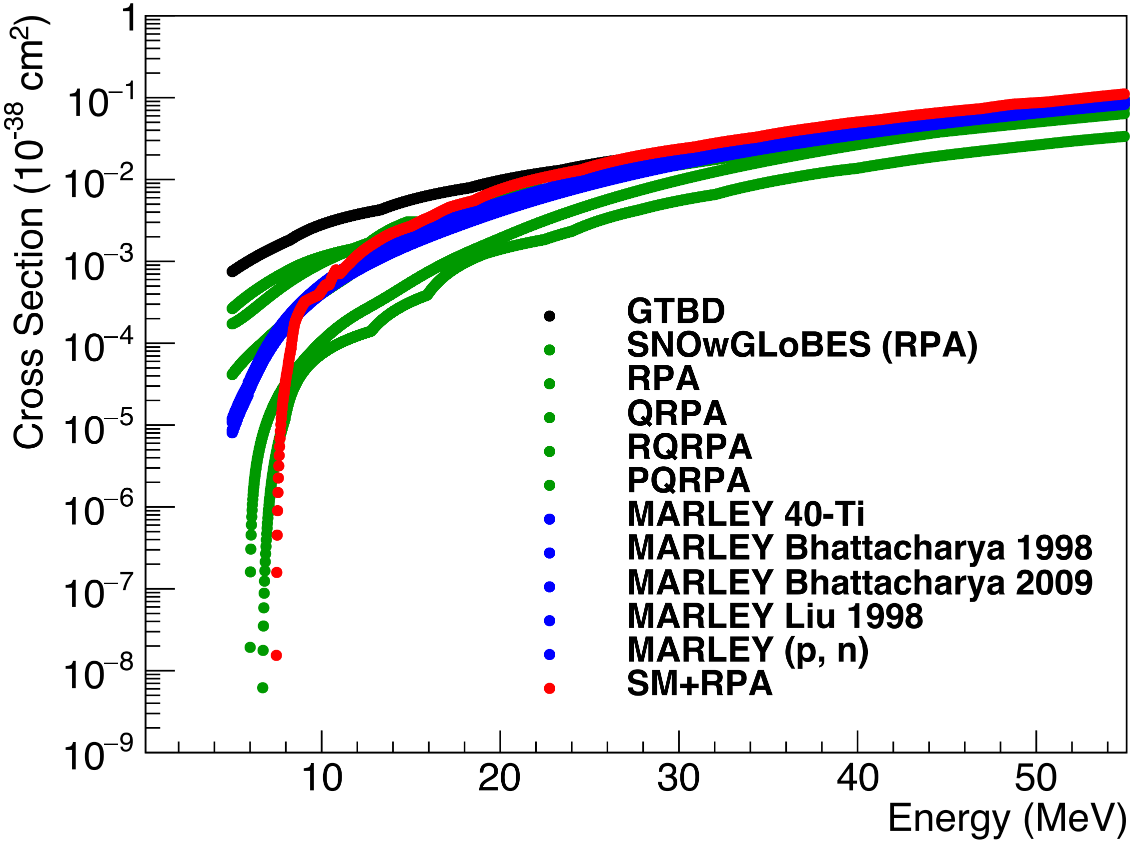
- Algorithm uses the following tools:
  - "Test spectrum" with given set of pinching parameters $(\alpha^0, \langle E_\nu \rangle^0, \varepsilon^0)$
  - Grid of energy spectra containing combinations of $(\alpha, \langle E_\nu \rangle, \varepsilon)$
- Generate spectra with cross section model, interaction modeling, efficiencies (not necessarily the same!)
- Compute χ^2 value between test spectrum and all grid spectra; determine best-fit grid element, "sensitivity regions" that constrain parameters



2) Grid with many different combinations of $(\alpha, \langle E_\nu \rangle, \varepsilon)$



Cross Section Models

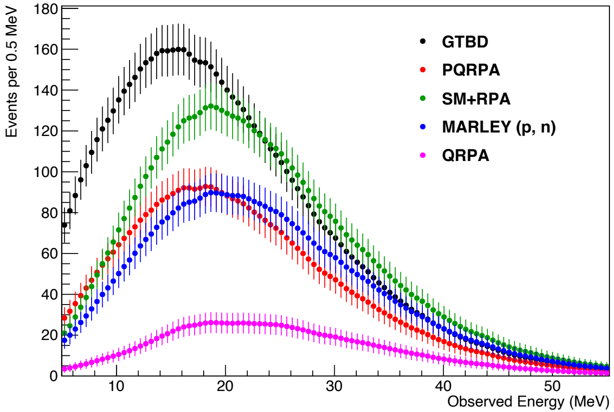


Reliability of these models:

1. Blue curves: MARLEY partially data-driven filled in with QRPA, probably most reliable at low energies
2. Red curve: SM+RPA (hybrid approach with RPA) is considered most theoretically motivated
3. Green curves: RPA is preferred for the high energies (not explicitly defined) of SN ν_e according to paper from Capozzi et al.

See backup for references.

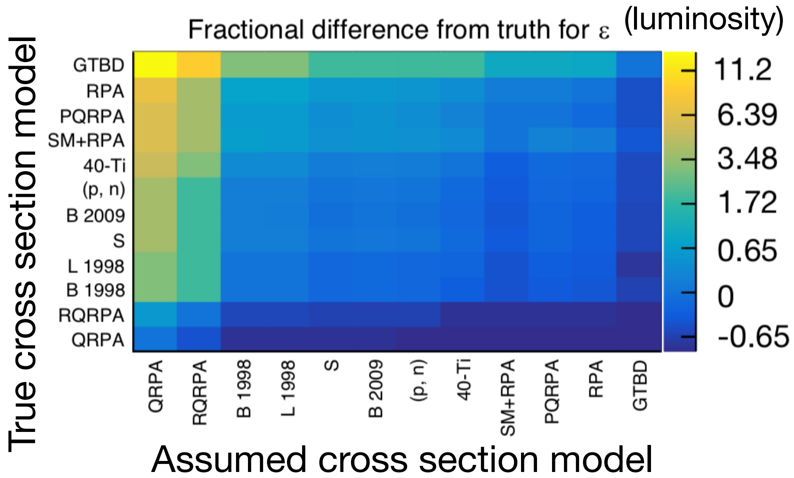
Cross section impact on SN measurements



Study for DUNE: "forward fit" simulated SN signals to measure SN flux parameters (more information in backup)

- Right: predicted 10 kpc SN signals for DUNE + same flux assumptions + different ν_eCC cross section models
- Study biases introduced for incorrect ν_eCC cross section assumptions, since the choice of xscn model has significant effects on DUNE's predicted SN signal

Most extreme ν_eCC cross section models yield -94% to +1400% bias on luminosity measurement → indicates that a cross section measurement would be very useful!



Best-fit parameter fractional difference from truth (bias)

RPA References

- RPA (SNOwGLoBES): random phase approximation
  - Note that RPA and SNOwGLoBES are different papers by the same authors
  - QRPA: quasiparticle RPA
    - RQRPA: relativistic QRPA
    - PQRPA: projected QRPA (the xscn is unpublished; the paper outlines the computer code)
- SM+RPA: shell model + RPA
  - Cappozi et al. cites a different paper by the same authors

Other cross section models

- From S Gardiner's thesis and MARLEY:
  - Bhattacharya 1998
  - Liu 1998
  - Bhattacharya 2009
  - (p, n) and 40-Ti
- GTBD: gross theory of beta decay