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

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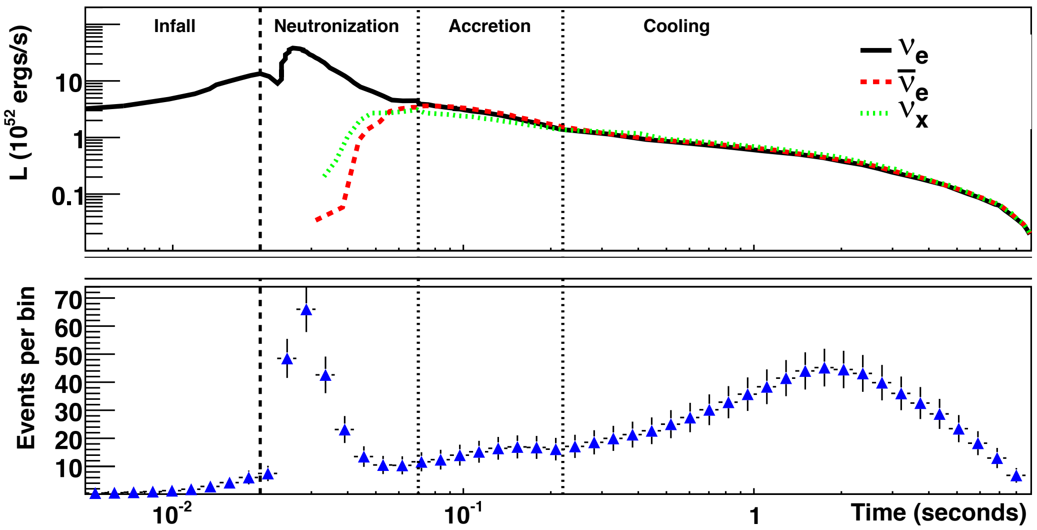
Magnificent CEvNS

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 $\nu_x \equiv \nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$

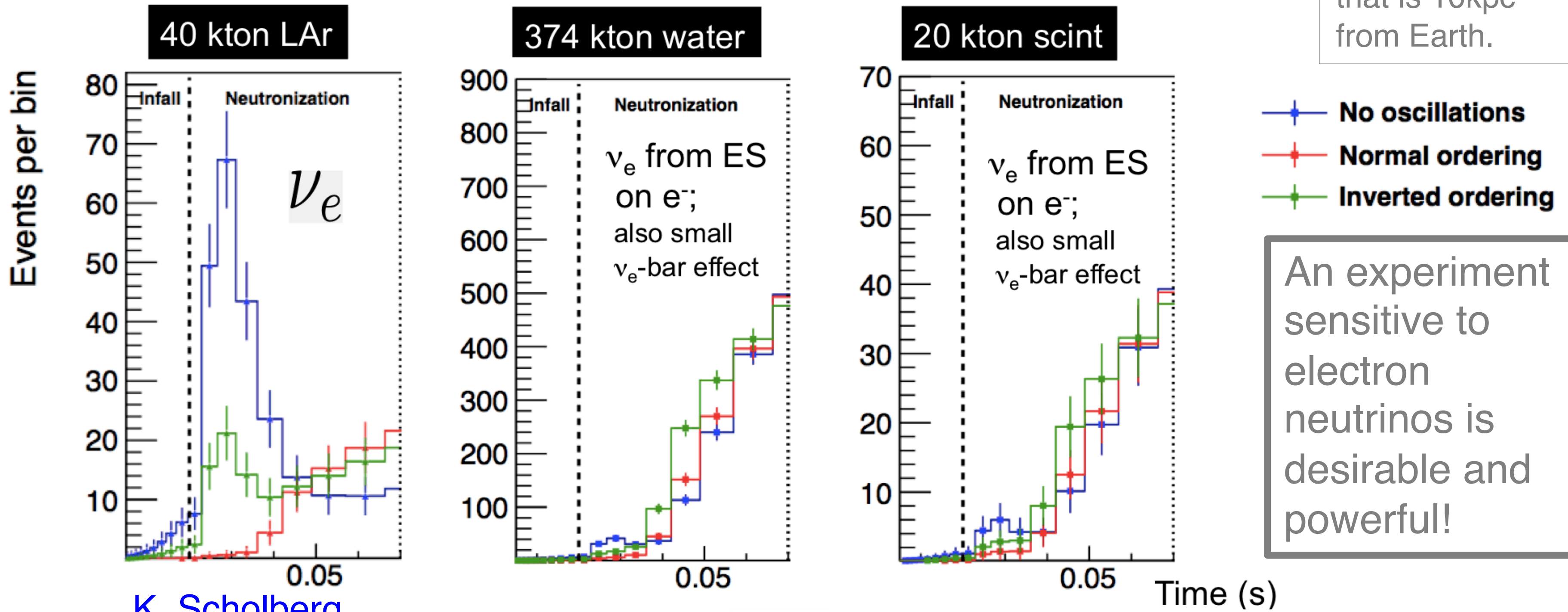


99% of potential energy from core-collapse supernova released in the form of neutrinos (tens of MeV) in a prompt burst lasting several seconds

Motivation to detect the ν_e signal

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

For a supernova that is 10kpc from Earth.

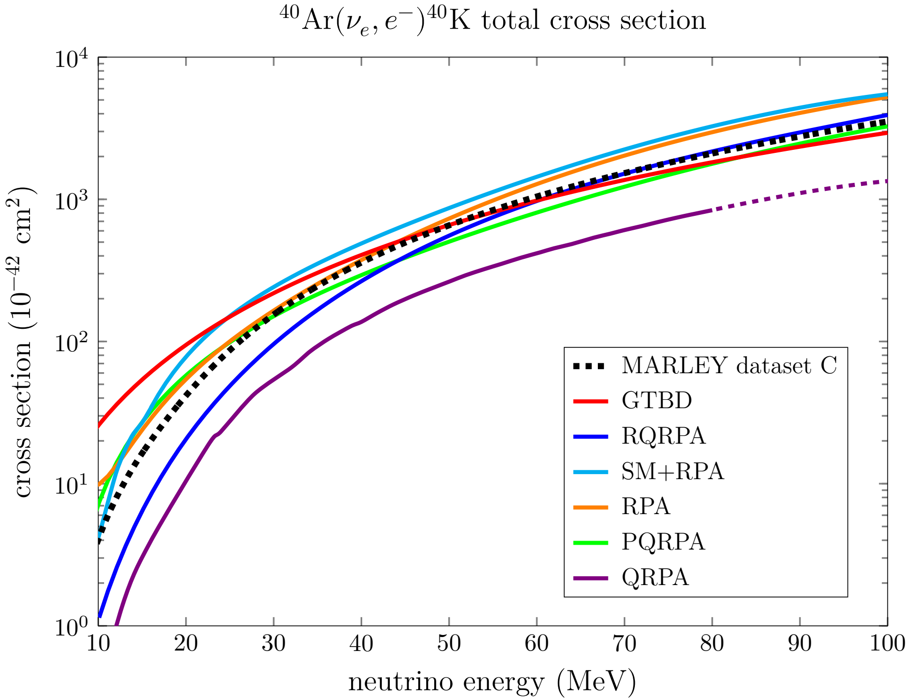


K. Scholberg

An experiment sensitive to electron neutrinos is desirable and powerful!

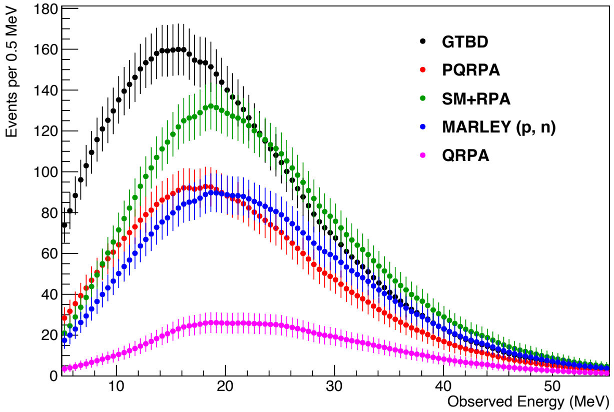
Detecting SN electron neutrinos

- 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



From S. Gardiner's thesis

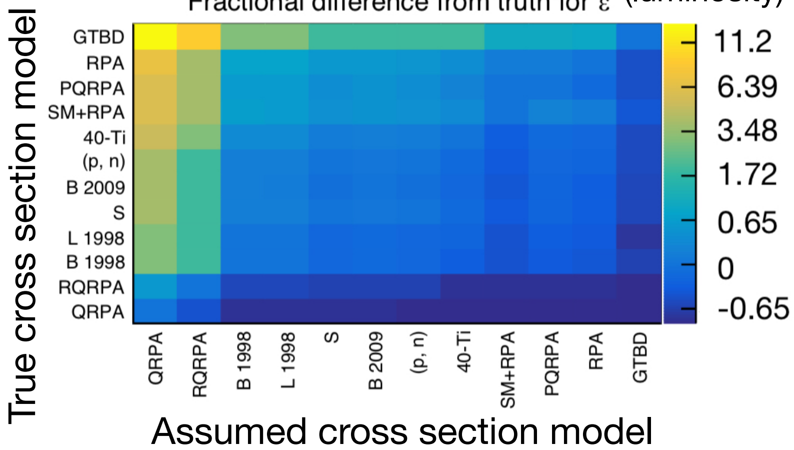
Cross section impact on SN measurements



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

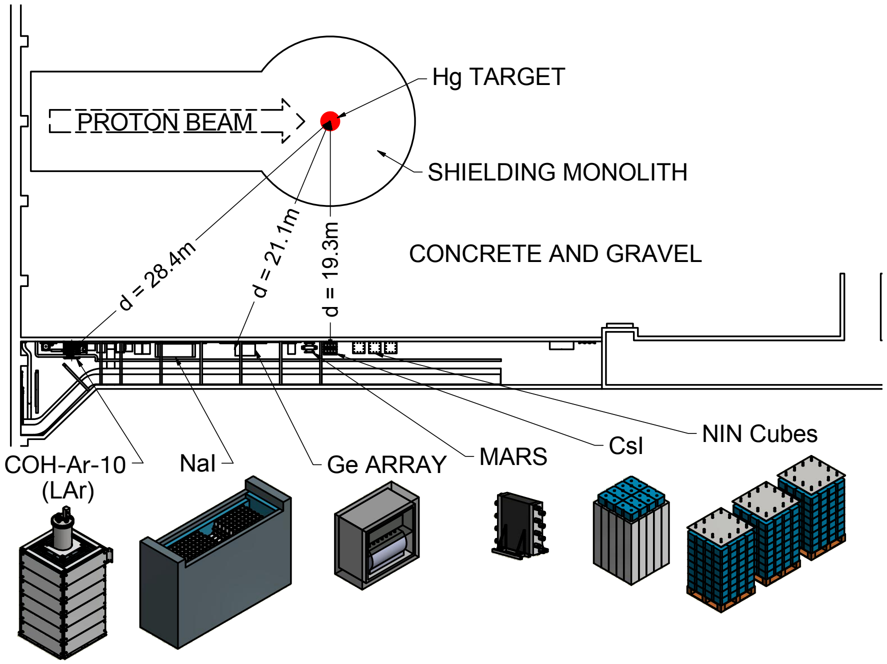
Most extreme ν_eCC cross section models yield -94% to +1400% bias on luminosity measurement → indicates that a cross section measurement would be very useful!



Best-fit parameter fractional difference from truth (bias)

COHERENT and CENNS-10

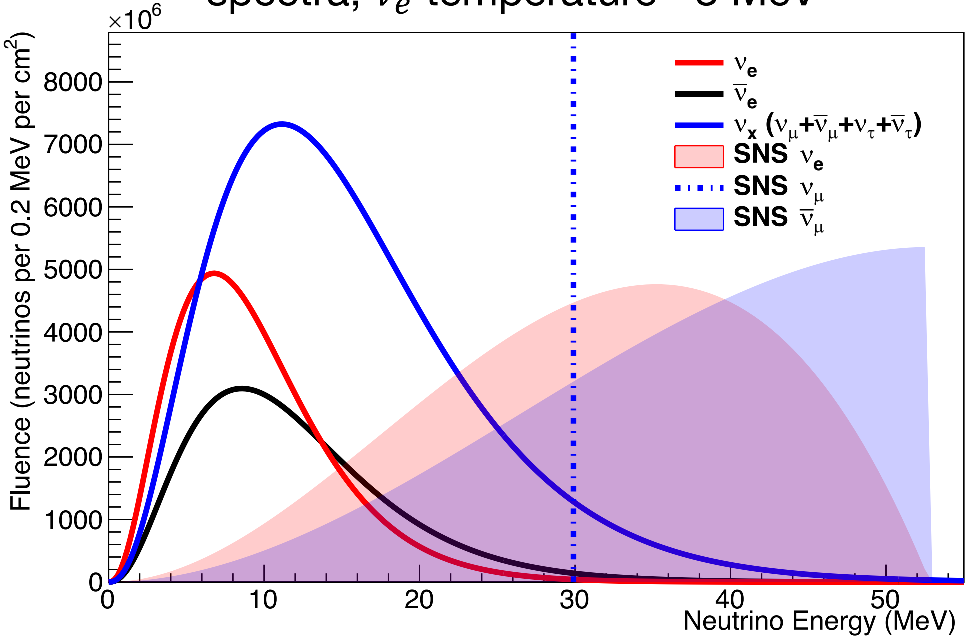
- Included in COHERENT's suite of detectors is the 24 kg liquid argon detector, CENNS-10 (or COH-Ar-10)
- Spallation Neutron Source at Oak Ridge National Laboratory (Neutrino Alley)
  - Protons on mercury target; produces prompt ν_μ flux, delayed ν_e and $\bar{\nu}_\mu$ fluxes



SNS neutrino energies

- Electron neutrinos produced at SNS in the energy region of interest for core-collapse supernova
  - Small flux shape uncertainty
- CENNS-10 provides an opportunity to detect low-energy ν_e CC interactions
  - Potentially make a cross section measurement, constrain uncertainties

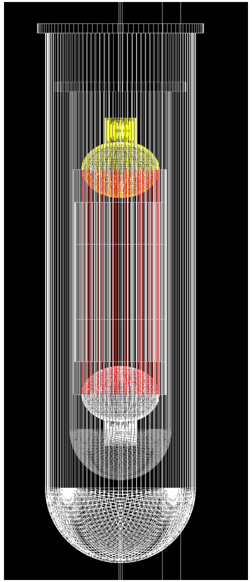
Supernova flux (10 kpc): pinched spectra; ν_e temperature ~3 MeV



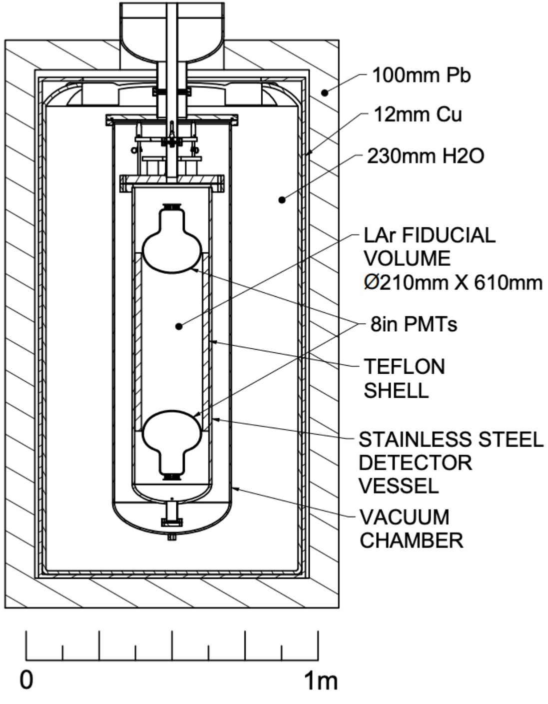
K. Scholberg; all assumptions in backup

COH-Ar-10 simulation

- Use Geant4 to model the CENNS-10 detector and response to ν_eCC interactions
  - Event generator: MARLEY
- Potential backgrounds: cosmic muons, beam-related neutrons (BRNs)
  - Cosmic-ray Shower Library (CRY) used to generate cosmic muon events

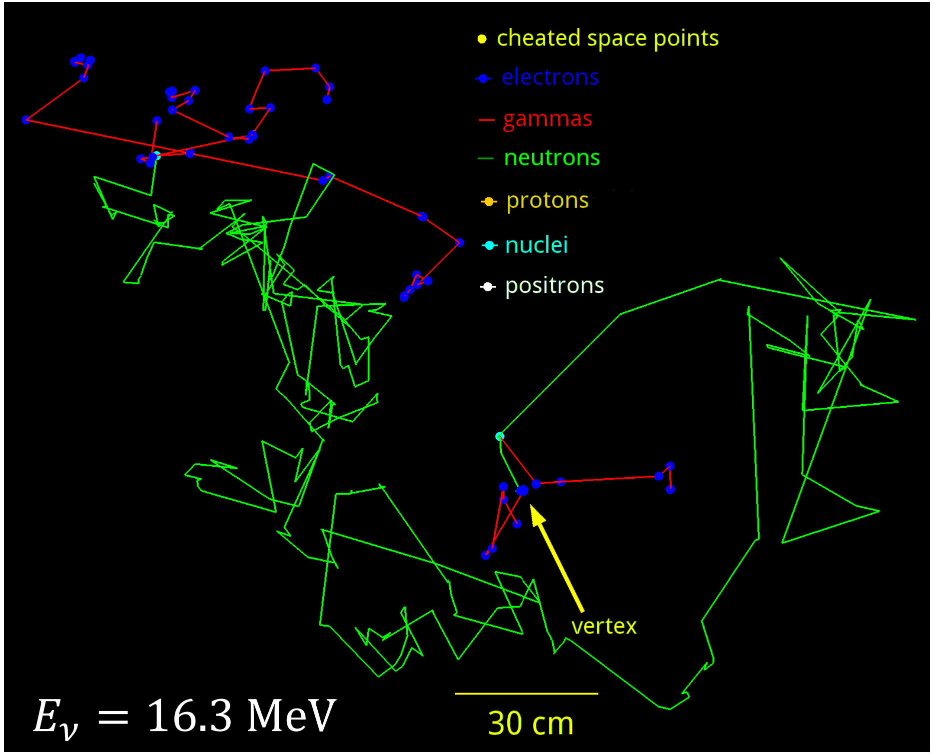


CENNS-10 in Geant4



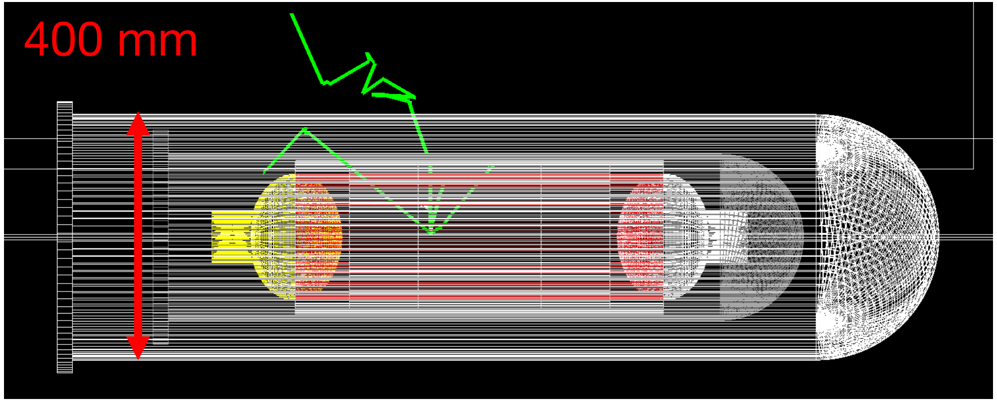
MARLEY: Model of Argon Reaction Low-Energy Yields

- Specializes in low-energy ν_eCC neutrino interactions
- More sophisticated modeling of final state particles compared to other event generators

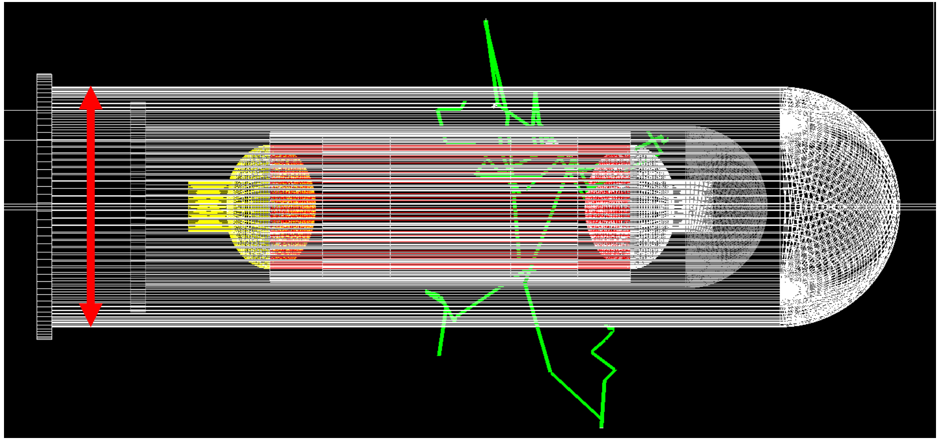


S. Gardiner (http://www.marleygen.org/)

Geant4 event displays: MARLEY

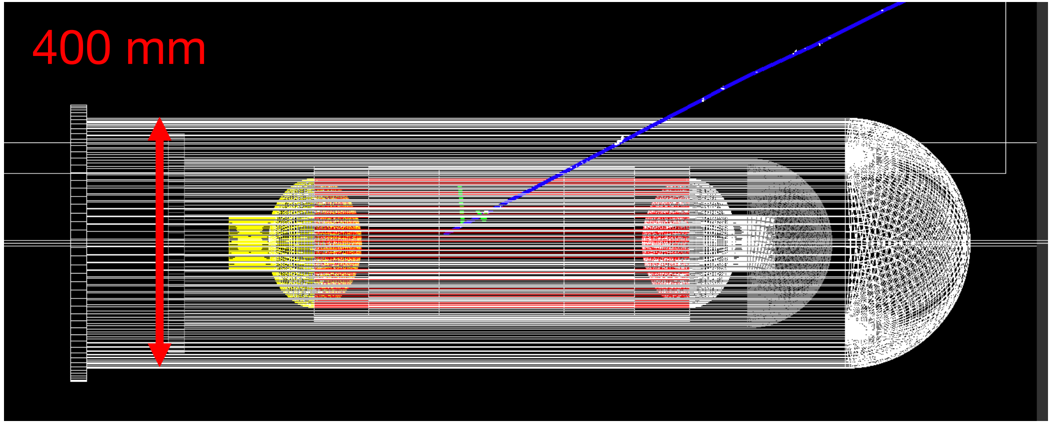


MARLEY ν_eCC event
20 MeV ν_e
White track: electron
Green tracks: gammas

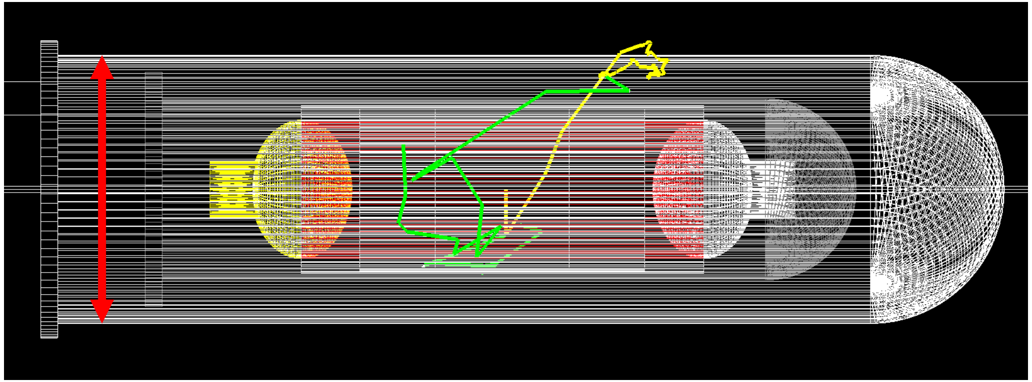


MARLEY ν_eCC event
46.9 MeV ν_e
White track: electron
Green tracks: gammas

Geant4 event displays: backgrounds

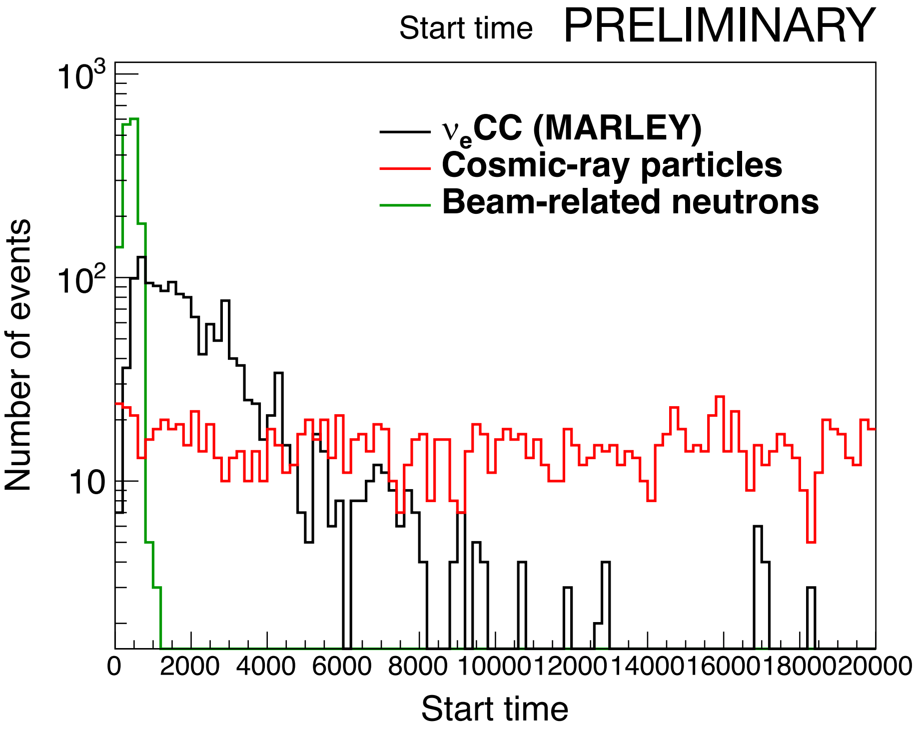


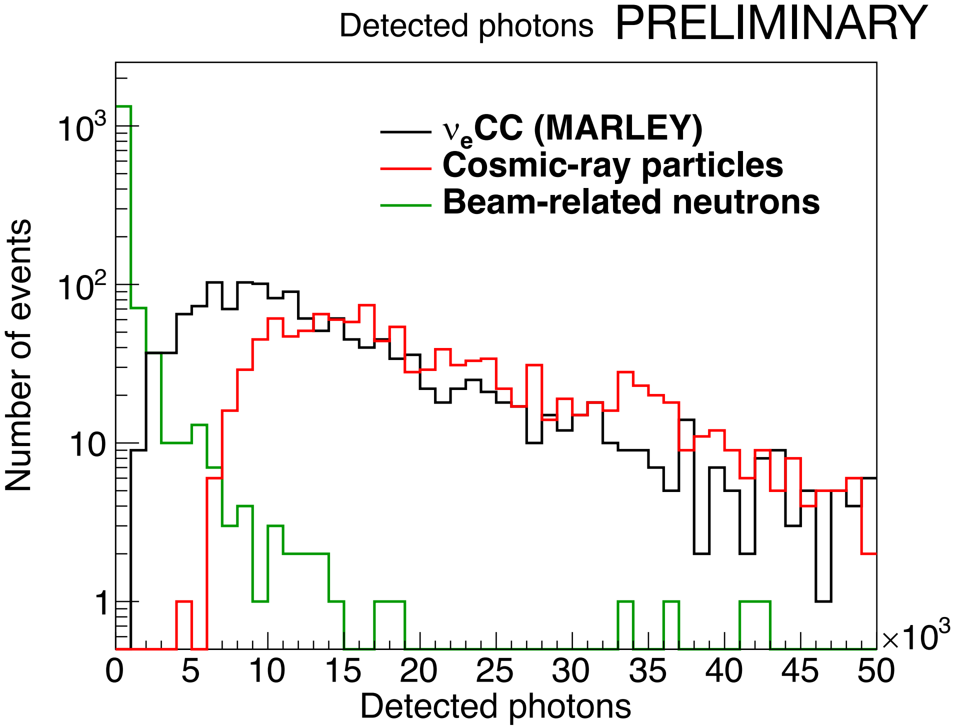
CRY cosmic muon event
835 MeV muon
White tracks: electron
Green tracks: gammas
Blue track: muon



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

Geant4 simulation output (preliminary)





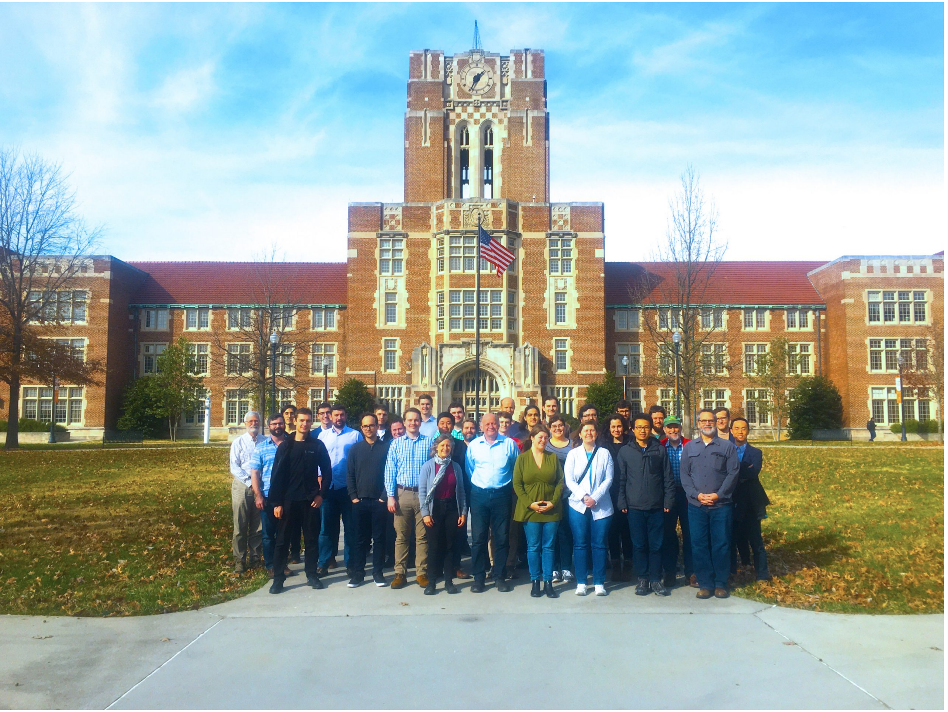
1500 events for each interaction type (not reflective of expected event rates)

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

Takeaways and next steps

- The COH-Ar-10 liquid argon detector is exposed to neutrinos with SNB-like energies; this provides us with an opportunity to observe ν_eCC interactions and potentially make a cross section measurement
- We began modeling ν_eCC interactions and its backgrounds in the COH-Ar-10 detector using Geant4
- Next steps:
  - Account for non-linear detector response for ν_eCC and cosmic events
  - Produce a smearing matrix (detected energy versus neutrino energy) to predict number of ν_eCC events in COH-Ar-10 production runs
  - Perform sensitivity and event generation studies for COH-Ar-750, the upgrade to COH-Ar-10

Thanks!



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Oak Ridge National Laboratory

Sandia National Laboratories

The University of Tennessee UT Knoxville

TUNL Triangle Universities Nuclear Laboratory

W University of Washington

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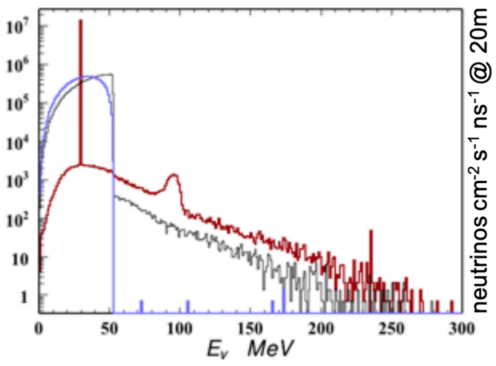
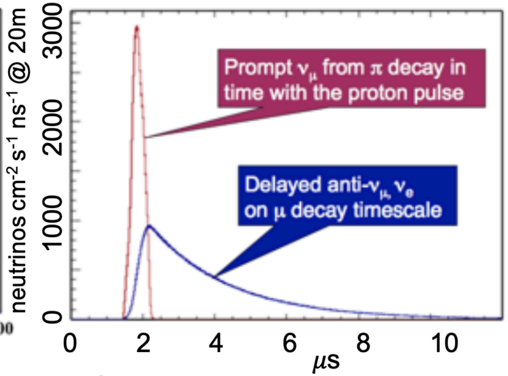
Backup

MARLEY simulation

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

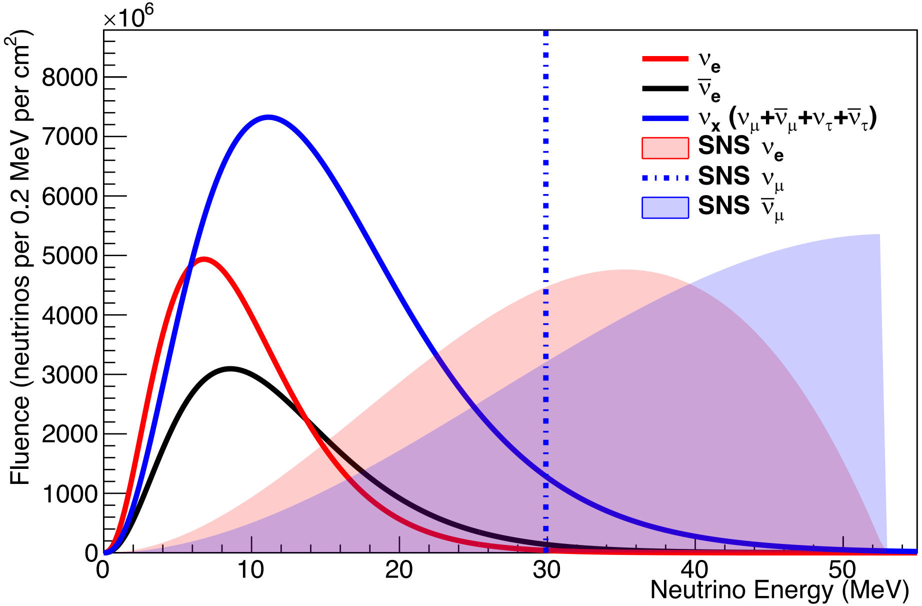




Using SNS flux from SNOwGLoBES event rate calculator (similar to the ν_e/dark blue distribution)

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

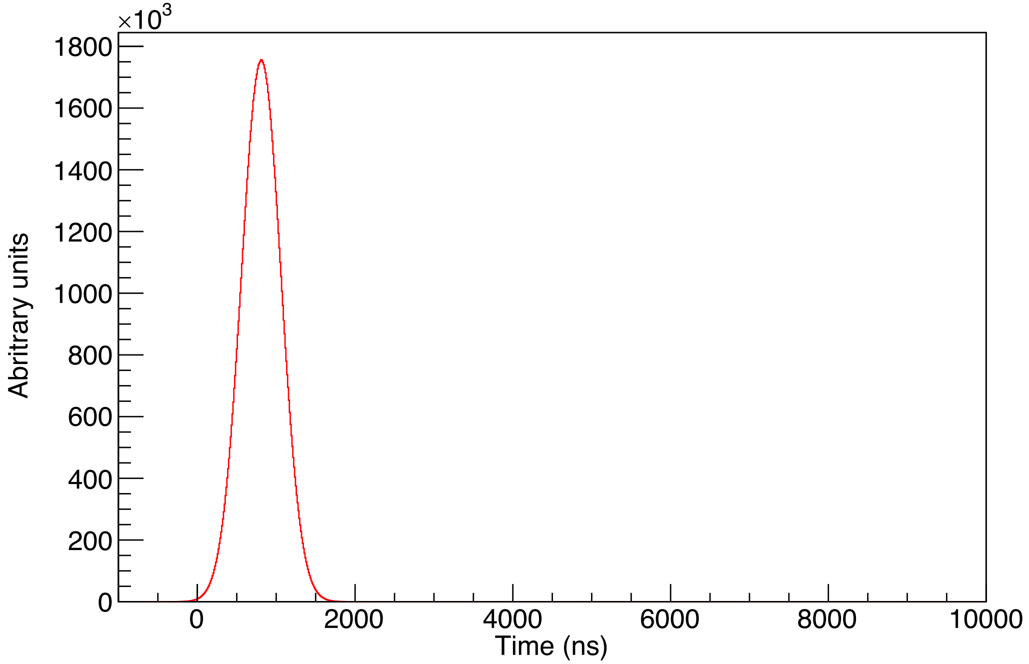


More about updated cosmic simulation

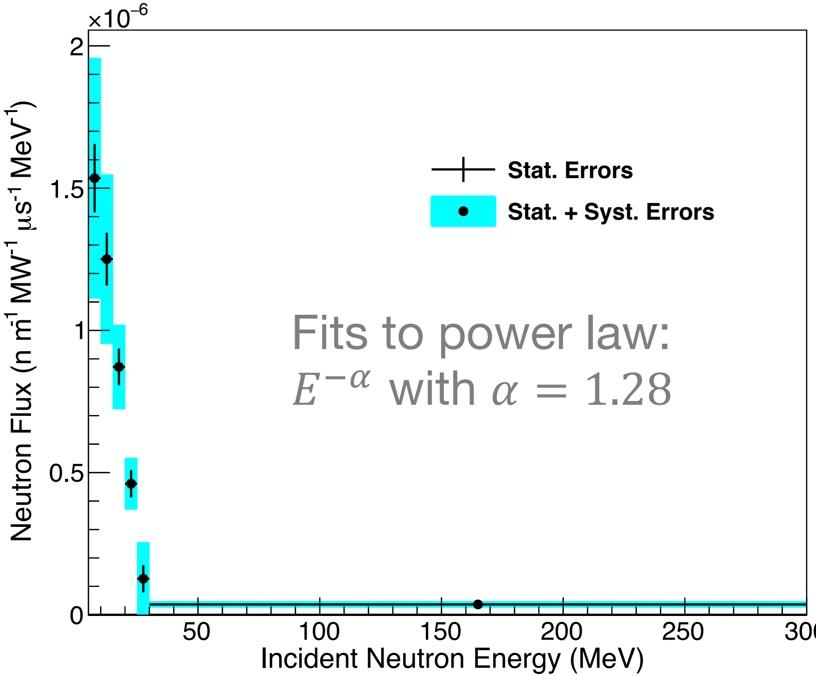
- Cosmic-ray Shower Library (CRY) from Livermore
- Correlated cosmic-ray particle shower distributions
  - Primary particle energies: 1 GeV – 100 TeV
  - Secondary particle energies: 1 MeV – 100 TeV
- Simulates particles in a specific area, time of arrival, zenith angle of secondary particles
- Defined 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?

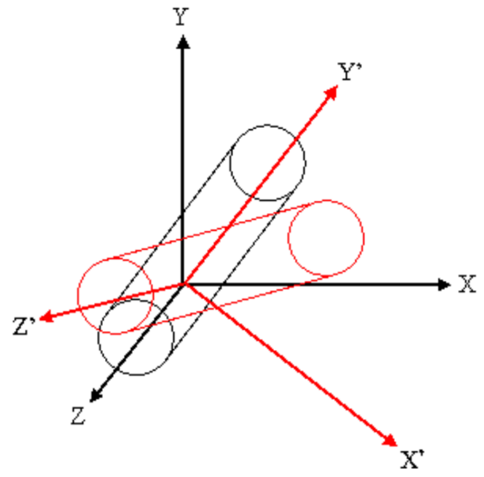


Figure 2.3. An illustration of the use of rotation matrices. A cylinder is defined with its axis parallel to the z-axis (black lines), but the definition of 2 vectors can rotate it into the frame given by x', y', z' (red lines).

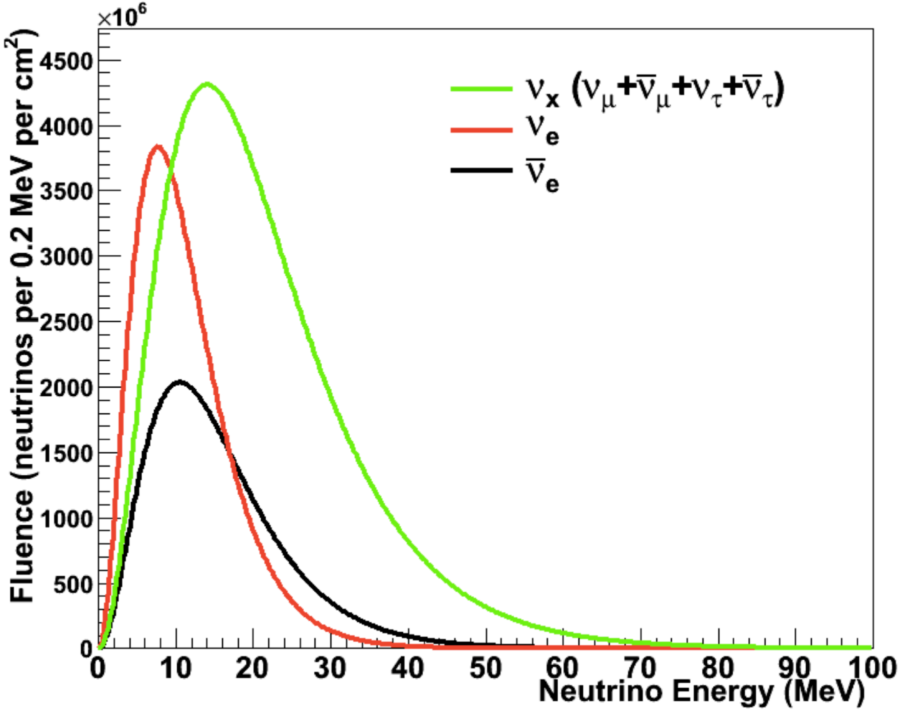
Taken from Geant4 GeneralParticleSource user document

Supernova Flux Model

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

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

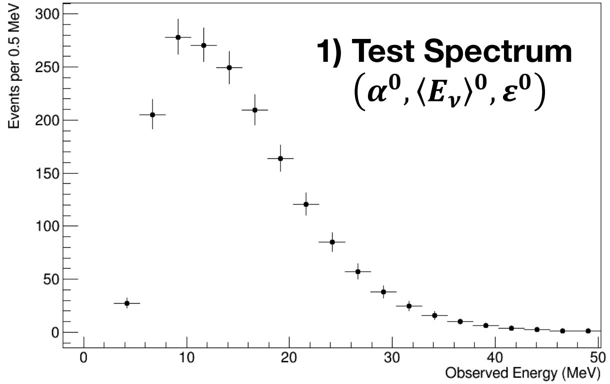
  - E_ν: Neutrino energy (MeV)
  - $\mathcal{N}$: Normalization constant (related to luminosity, ε, in ergs)
  - $\langle E_\nu\rangle$: Mean neutrino energy (MeV)
  - α: Pinching parameter; large α corresponds to more pinched spectrum (unitless)
- Parameters of interest: ε, $\langle E_\nu\rangle$, α
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



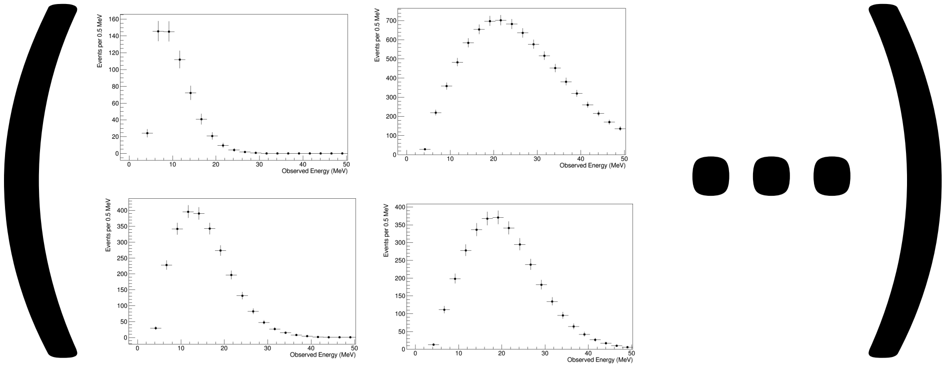
Pinched-thermal for a 10kpc supernova (K. Scholberg)
Note: Fluence refers to a time-integrated flux.

Parameter Fitting Algorithm

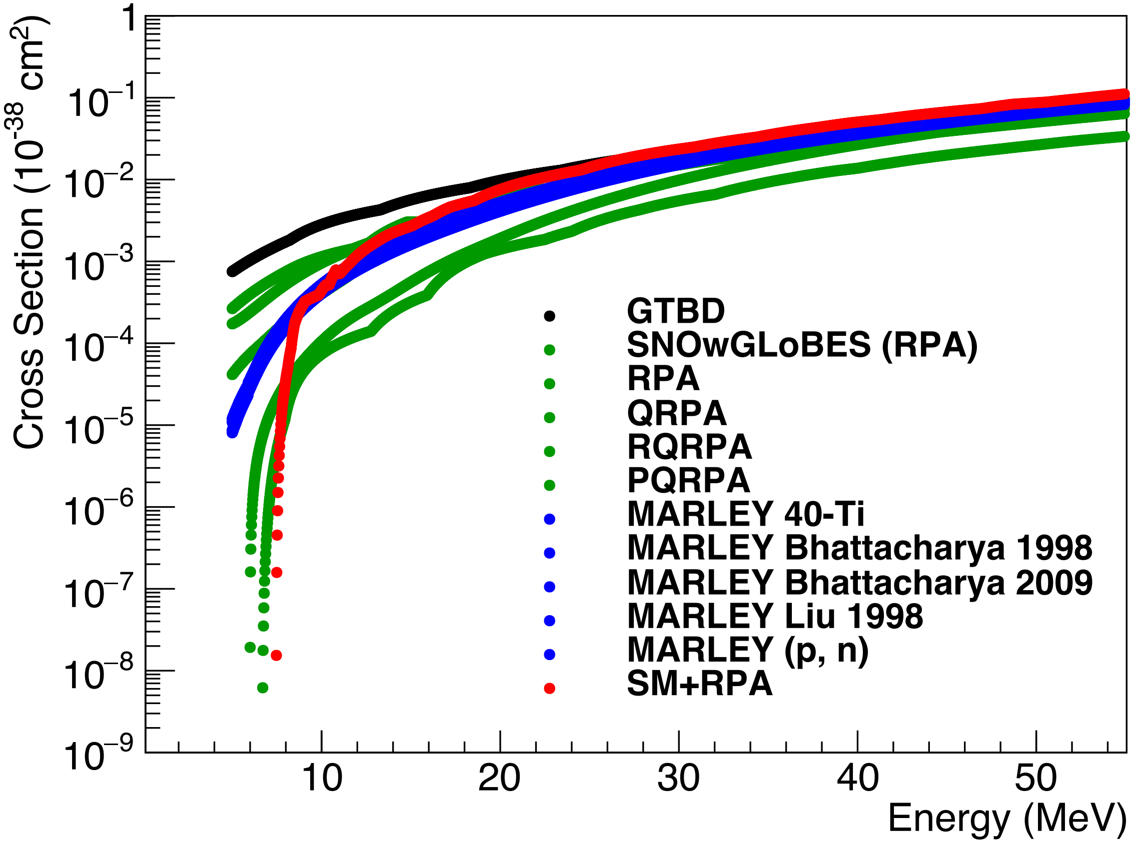
- Algorithm uses the following tools:
  - "Test spectrum" with given set of pinching parameters $(\alpha^0, \langle E_\nu \rangle^0, \varepsilon^0)$
  - Grid of energy spectra containing combinations of $(\alpha, \langle E_\nu \rangle, \varepsilon)$
- Generate spectra with cross section model, interaction 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 $(\boldsymbol{\alpha}, \langle \boldsymbol{E}_\nu \rangle, \boldsymbol{\varepsilon})$



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.

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