Effect of cross section uncertainties on extraction of supernova neutrino information in DUNE

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Neutrinos at ORNL Workshop

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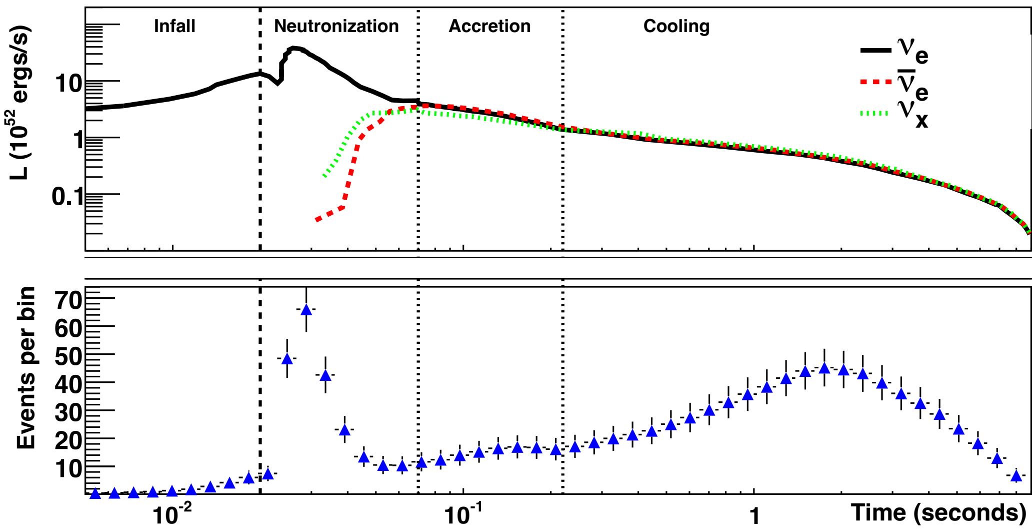
Outline

- Introduction
  - The Deep Underground Neutrino Experiment (DUNE)
  - Supernova neutrinos
- Modeling supernova neutrinos in DUNE
  - SNOwGLoBES
  - Pinched-thermal flux model
  - MARLEY
- Parameter fitting algorithm
  - Study assumptions
  - Studying ν_e-^{40}Ar cross section models
- Takeaways

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

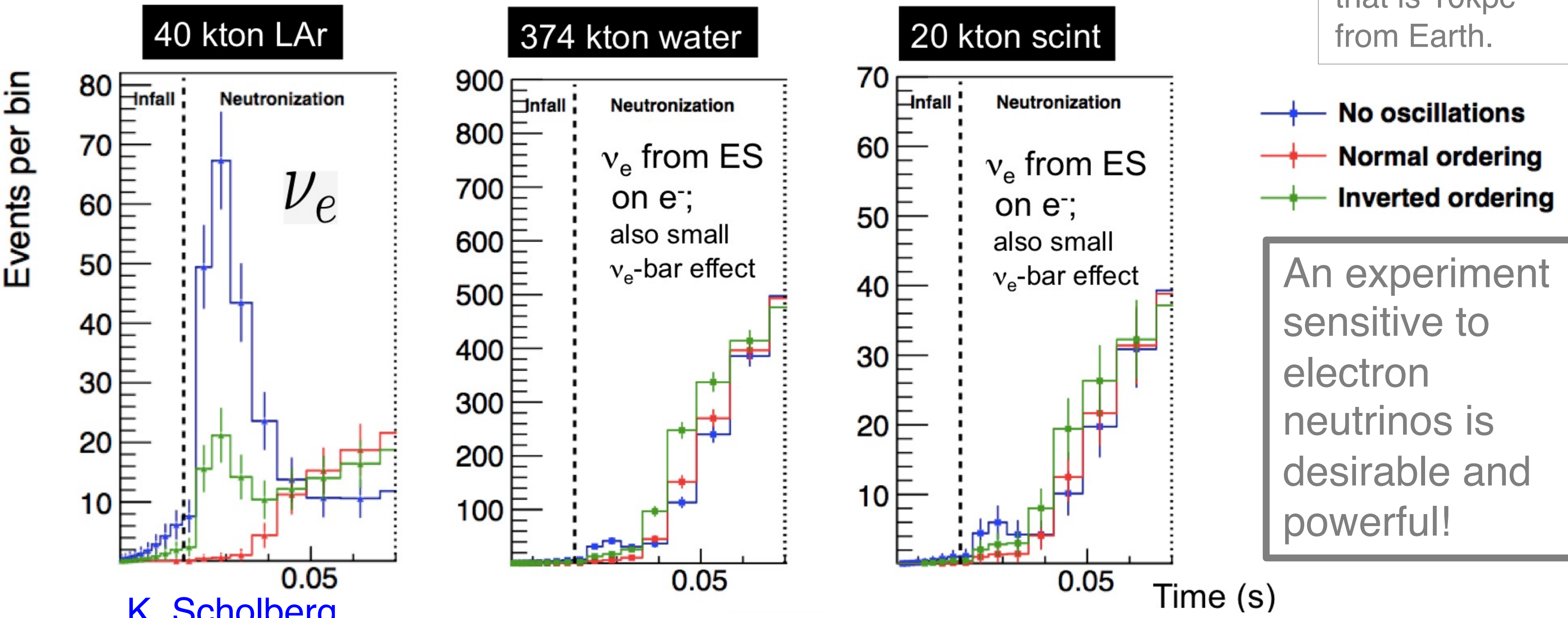


99% of potential energy from core-collapse supernova released in the form of neutrinos (tens of MeV) in a prompt burst lasting several seconds

Motivation to detect the ν_e signal

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

For a supernova that is 10kpc from Earth.



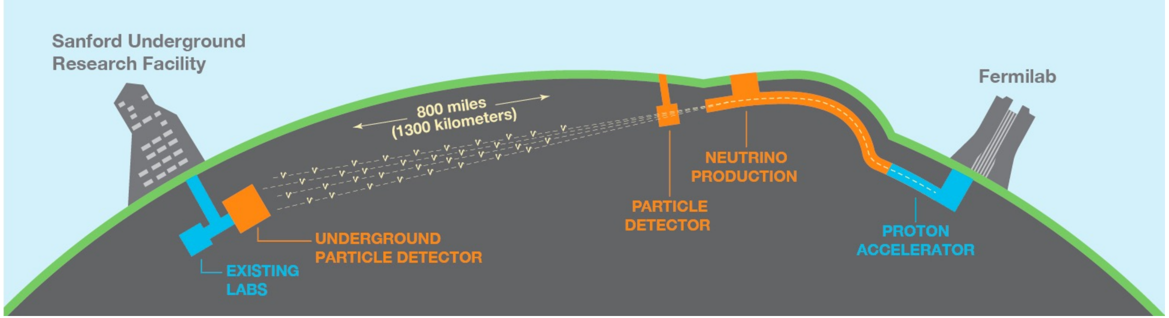
K. Scholberg

An experiment sensitive to electron neutrinos is desirable and powerful!

DEEP UNDERGROUND NEUTRINO EXPERIMENT

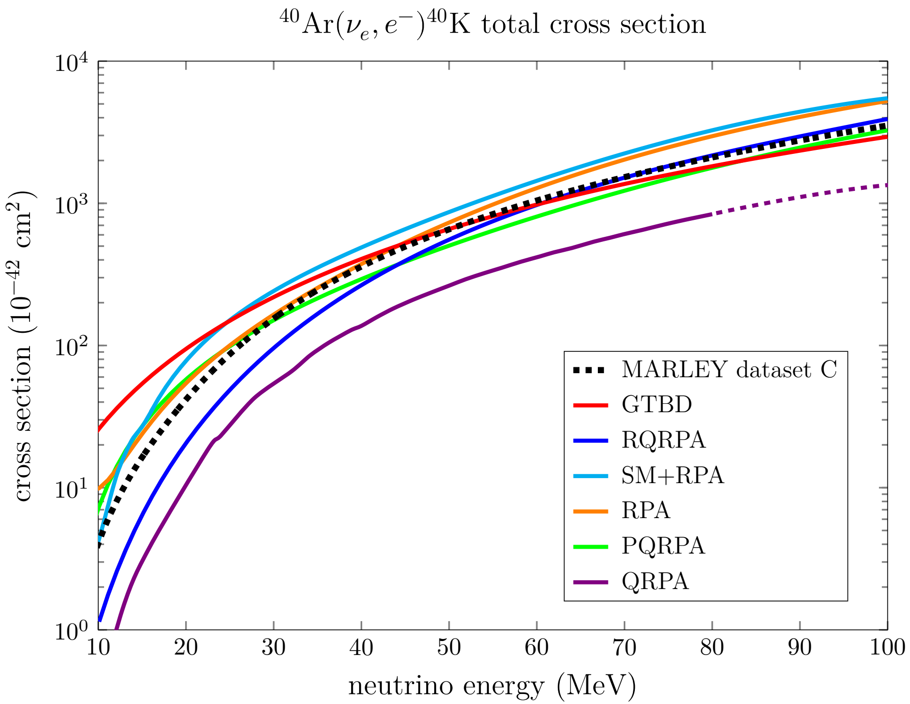
- International experiment for neutrino science: Neutrino oscillation physics, **supernova physics**, nucleon decay
- Two detectors:
  - Near detector on-site at Fermilab
  - Far detector at Sanford Underground Research Facility (SURF) in South Dakota
- Far detector: world's largest liquid argon time-projection chamber (40 kton fiducial mass)
  - Ionization electrons drift due to high-voltage electric field
  - Parallel wire planes create 3D images of particle tracks

www.dunescience.org



Detecting SN electron neutrinos

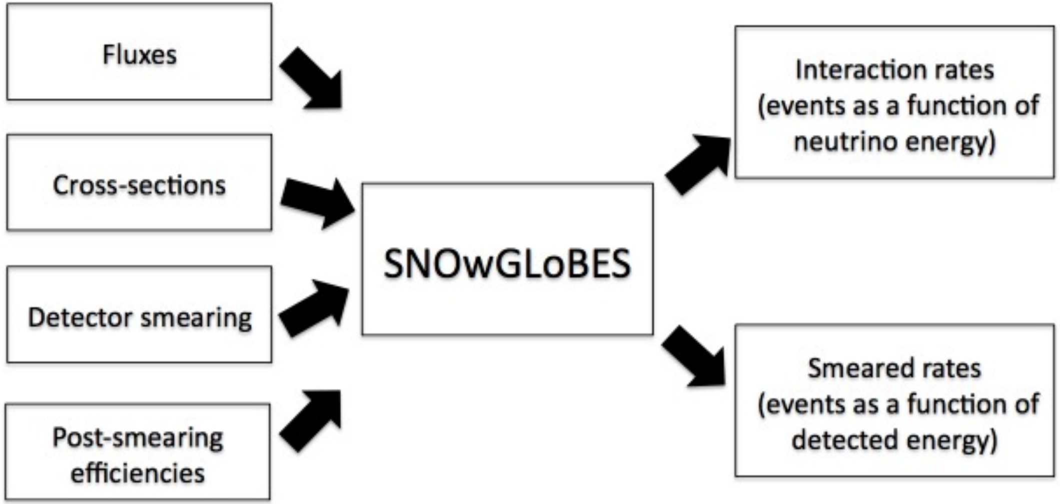
- Charged current interaction (ν_eCC): $\nu_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{K}^* + e^-$
- Low-energy neutrino-argon cross sections contain loosely constrained uncertainties; models cover wide range of phase space
- Incorrect assumptions can introduce biases in SN neutrino measurements



From S. Gardiner's thesis

Simulating Supernova Neutrino Signals

- SNOwGLoBES: SuperNova Observatories with GLoBES
- Open source event rate calculation tool
  - Simple folding with generalized detector response



http://phy.duke.edu/~schol/snowglobes/

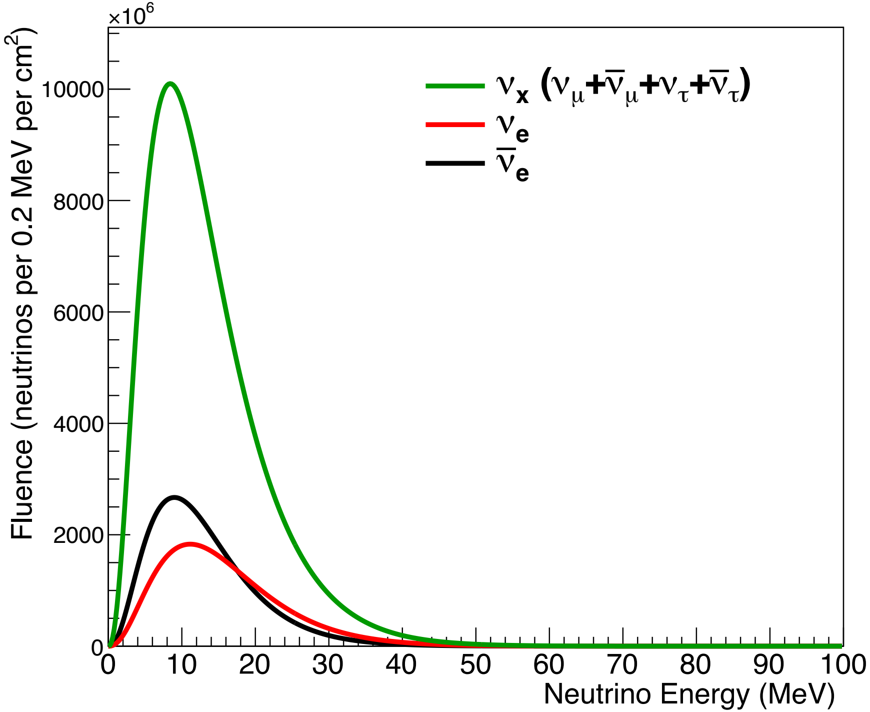
GLoBES: General Long Baseline Experiment Simulator

Supernova Flux Model

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

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

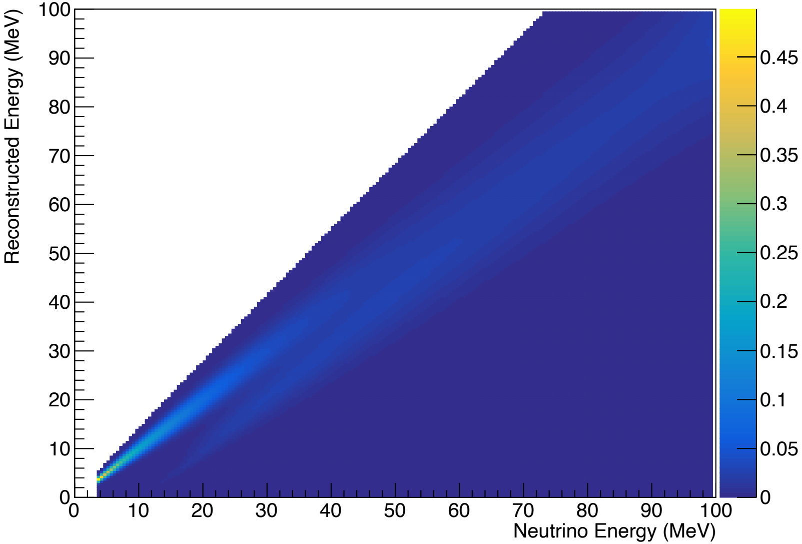
  - E_ν: Neutrino energy (MeV)
  - $\mathcal{N}$: Normalization constant (related to luminosity, ε, in ergs)
  - $\langle E_\nu\rangle$: Mean neutrino energy (MeV)
  - α: Pinching parameter; large α corresponds to more pinched spectrum (unitless)
- Parameters of interest: ε, $\langle E_\nu\rangle$, α
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

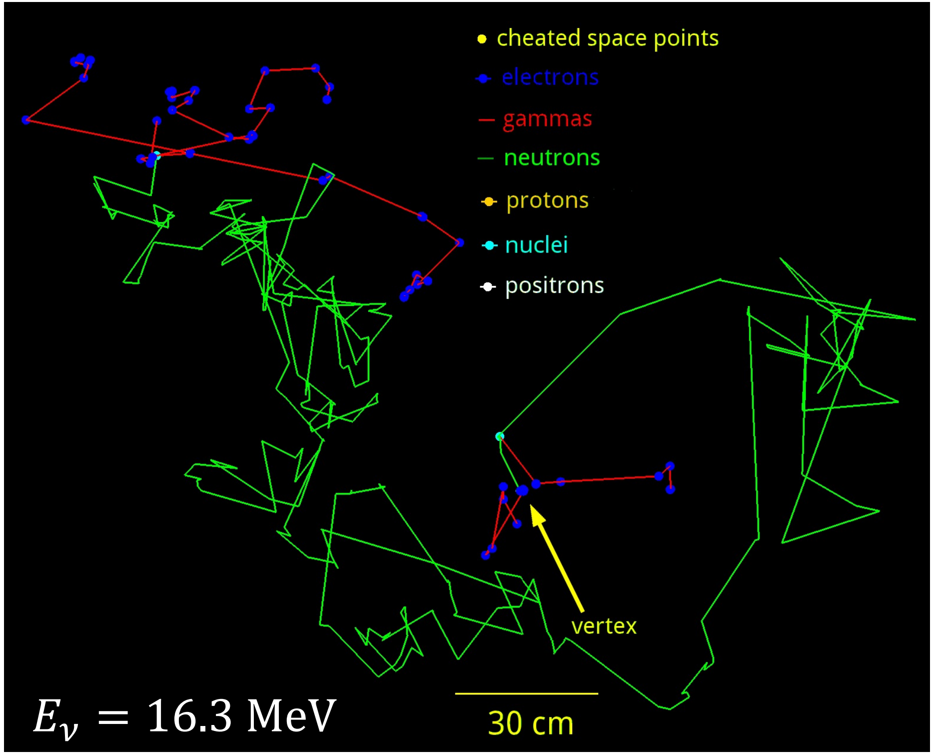


Pinched-thermal for a 10kpc supernova (K. Scholberg)
Note: Fluence refers to a time-integrated flux.

MARLEY: Model of Argon Reaction Low-Energy Yields

- MARLEY models low-energy ν_eCC neutrino interactions
- More sophisticated modeling of final state particles

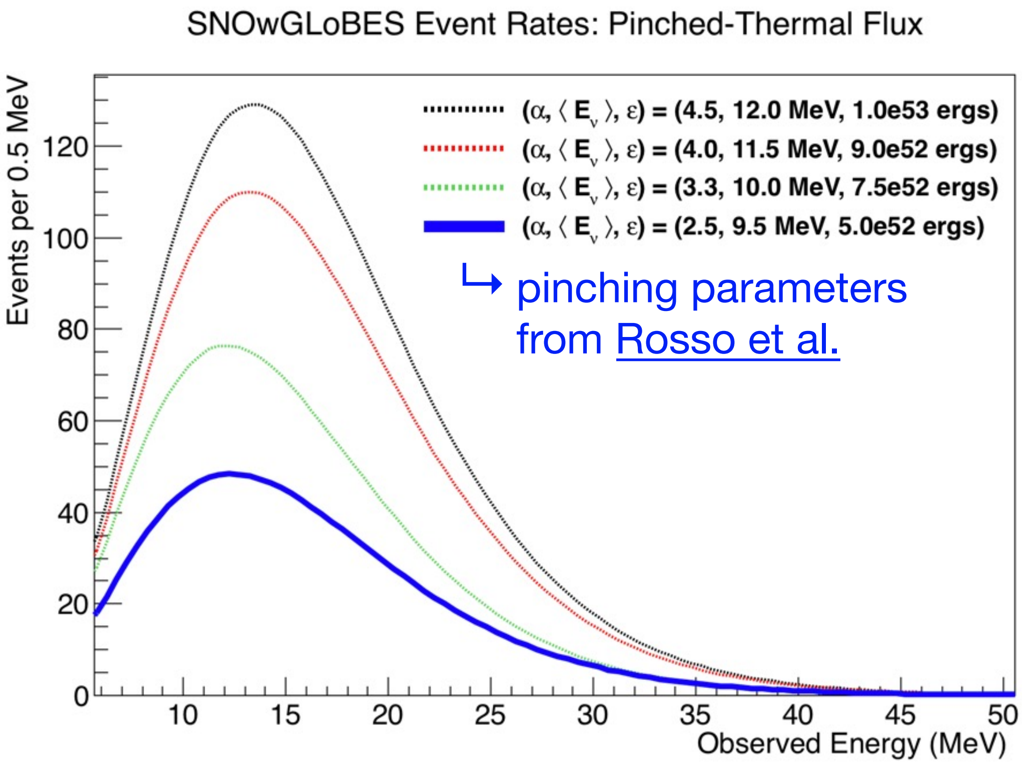




S. Gardiner (http://www.marleygen.org/)

Measuring the Flux Parameters

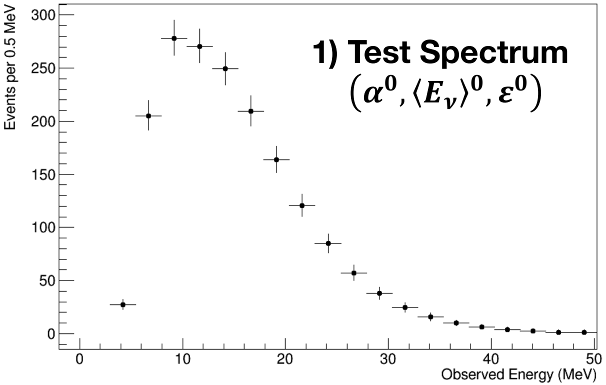
- Use pinched-thermal flux with pinching parameters $(\alpha, \langle E_\nu \rangle, \varepsilon)$ + cross section + interaction modeling to simulate event rates in DUNE detector
- Flux parameters play significant role in ν_e event rates (shape, statistics, etc.)
- Develop algorithm to measure, constrain flux pinching parameters based on SNOwGLoBES event rates



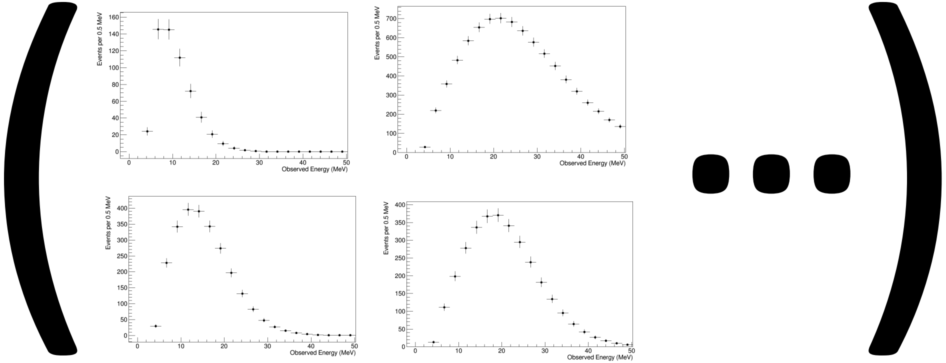
↳ pinching parameters from Rosso et al.

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 $(\boldsymbol{\alpha}, \langle \boldsymbol{E_\nu} \rangle, \boldsymbol{\varepsilon})$

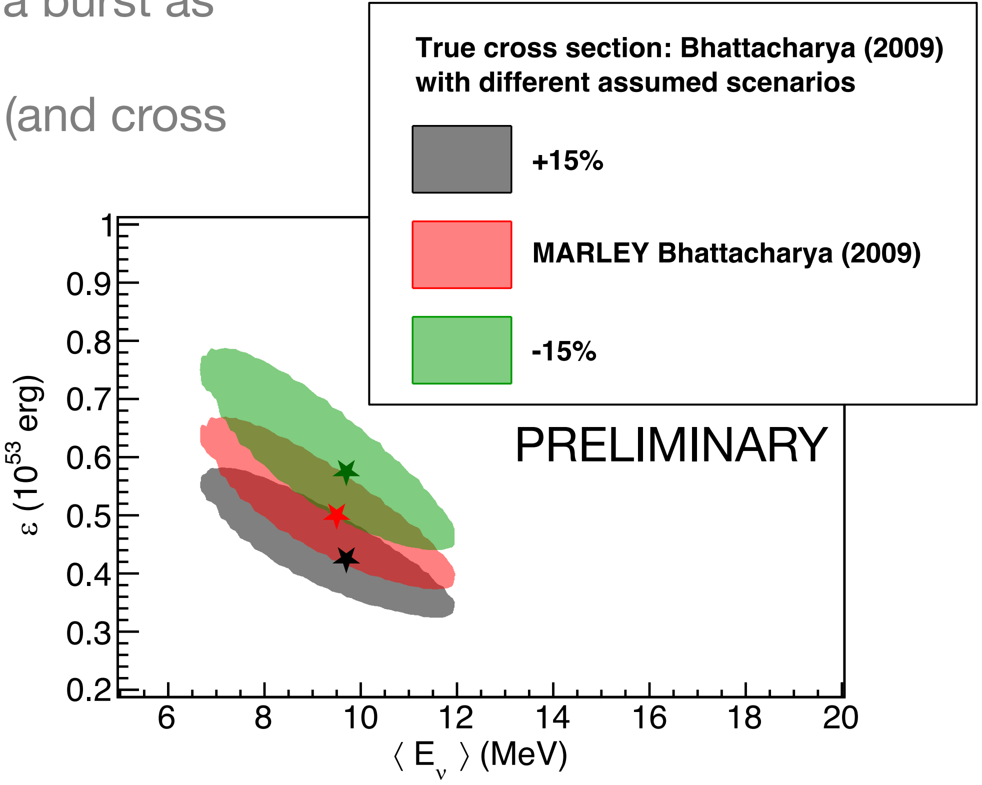


Studying Biases due to Incorrect Detector Assumptions

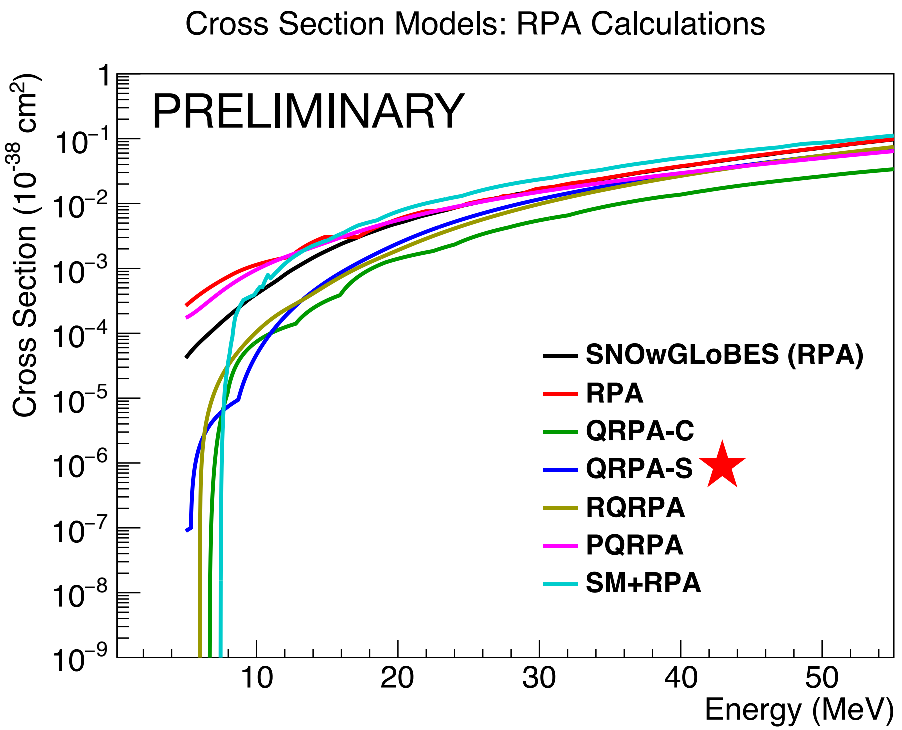
Test spectrum: data from supernova burst as observed by DUNE
Grids: DUNE detector performance (and cross section) assumptions

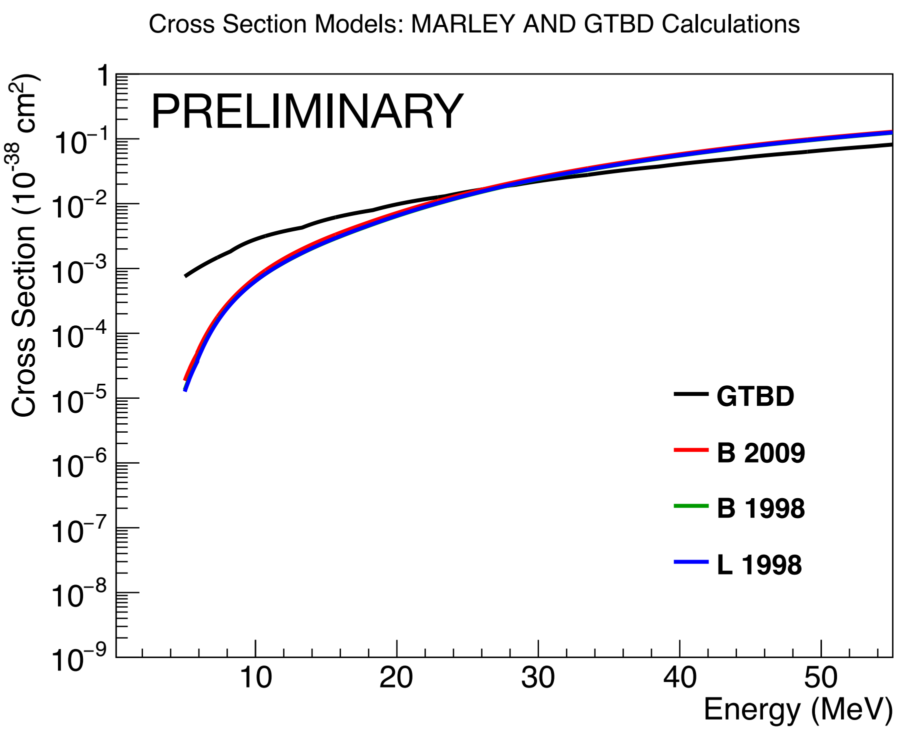
- Change assumptions for test spectrum, and for grids, to study effect of mismatched assumptions about ν_e-^{40}Ar cross section
  - Study amount of parameter phase space enclosed in sensitivity regions
  - Study parameter biases introduced by incorrect assumptions using fractional difference from truth:

$$\text{Frac. Diff.} = \frac{x - x^0}{x^0}$$



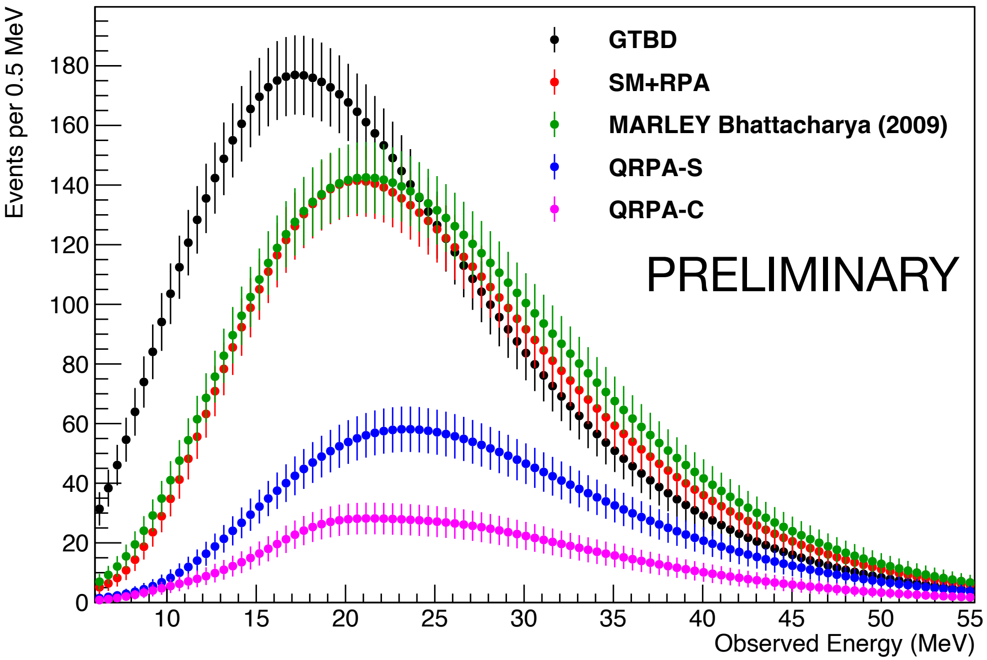
ν_eCC cross section calculations

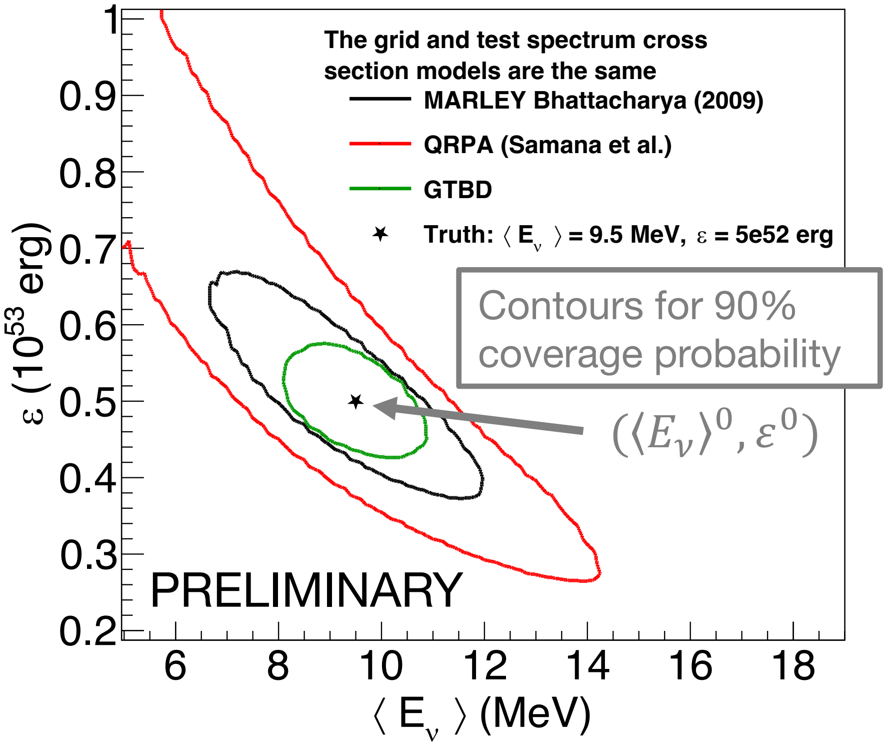




Studying ν_e-^{40}Ar Cross Section Models

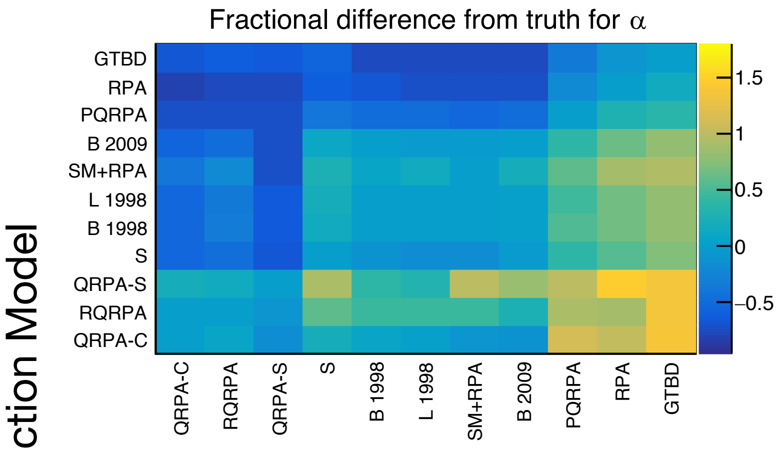
Test spectra for different cross section calculations

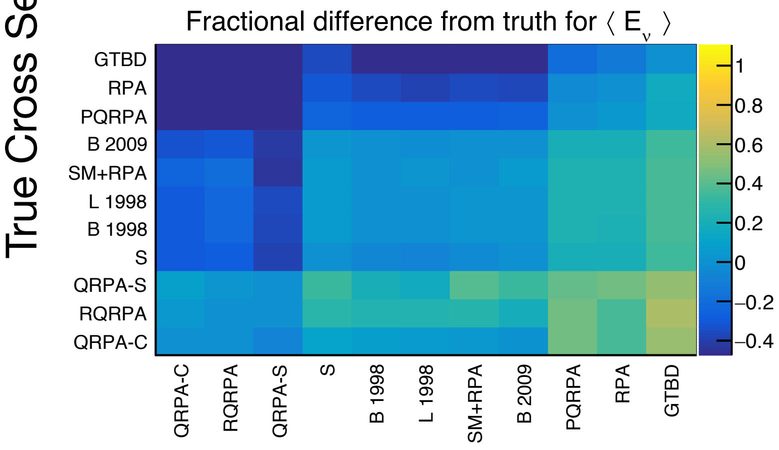


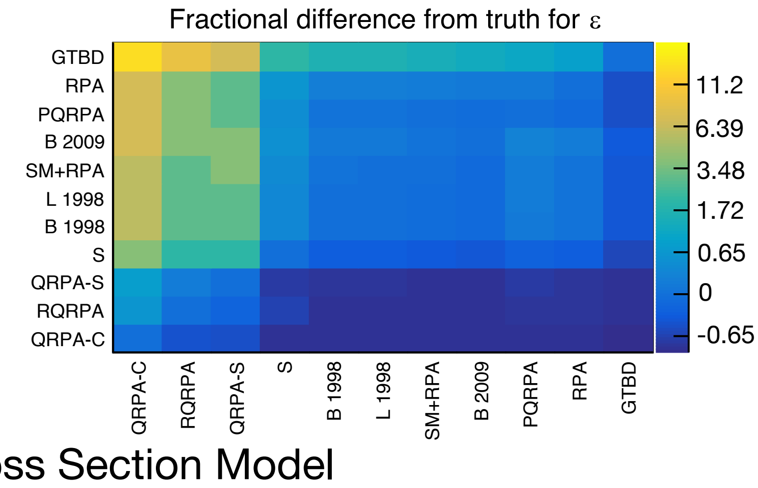


Studying fractional difference for incorrect assumptions about cross section models:

- Color scale for α and $\langle E_\nu \rangle$ are fractional difference from true parameter value
- ε range from $\mathcal{O}(10^{51}\ \mathrm{ergs})$ to $\mathcal{O}(10^{54}\ \mathrm{ergs})$; biases extend from -100% to $+1400\%$
  - Unrealistic range for ε chosen to account for wide range in cross section models





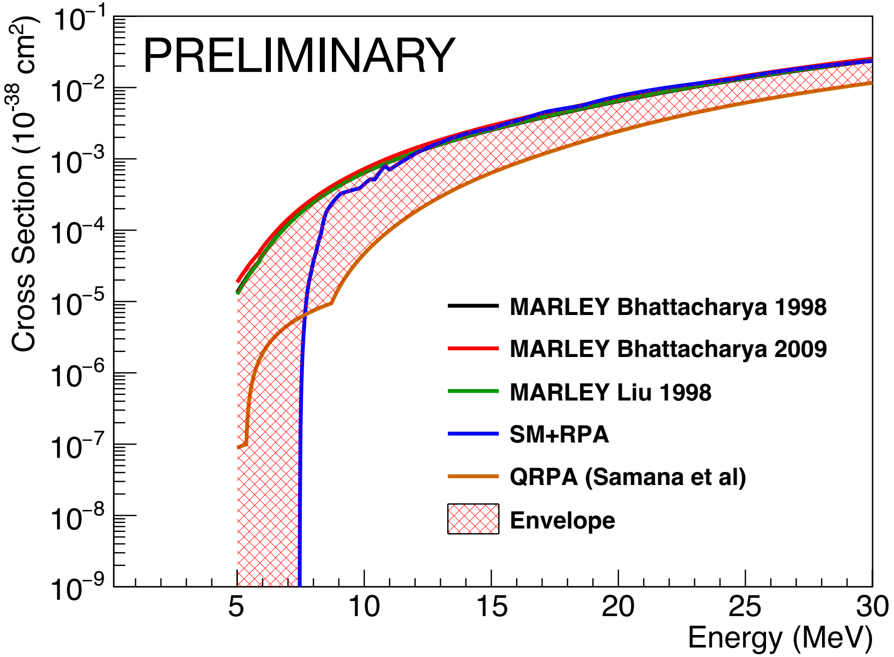


Color scale: $\pm\log(1 + |\mathrm{fracDiff}|)$, see backup for more info.
While the color scale is log, the values listed here are not!

PRELIMINARY

Reliability of cross section calculations

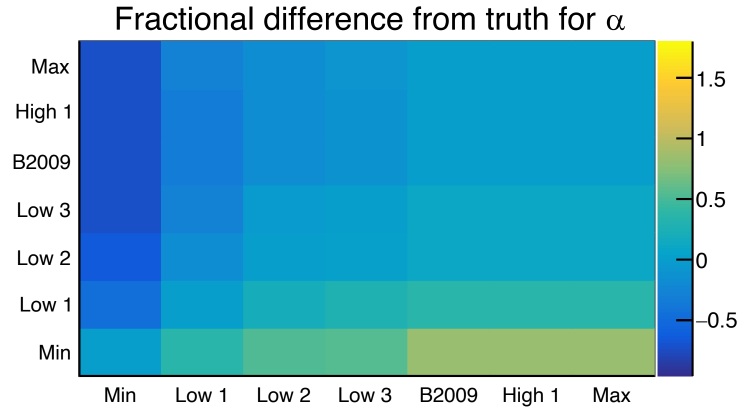
- Not all cross section calculations are built equally!
  - RPA is preferred for the high energies (not explicitly defined) of SN ν_e according to paper from [Capozzi et al.]
  - MARLEY partially data-driven filled in with QRPA, probably most reliable at low energies
  - SM+RPA (hybrid approach with RPA) is considered most theoretically motivated
- Define "uncertainty envelope" using reasonable calculations to constrain ε biases

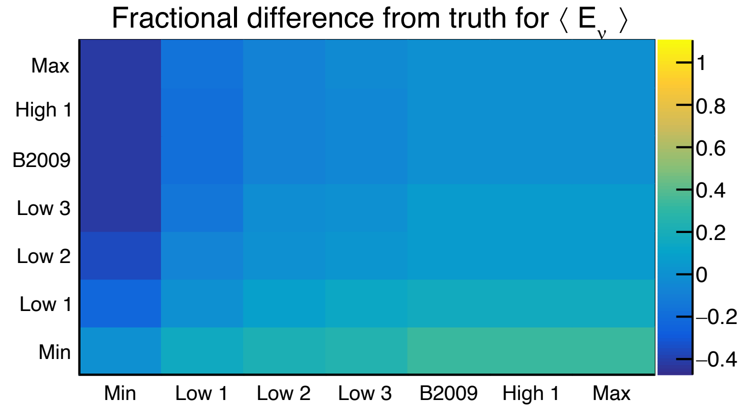


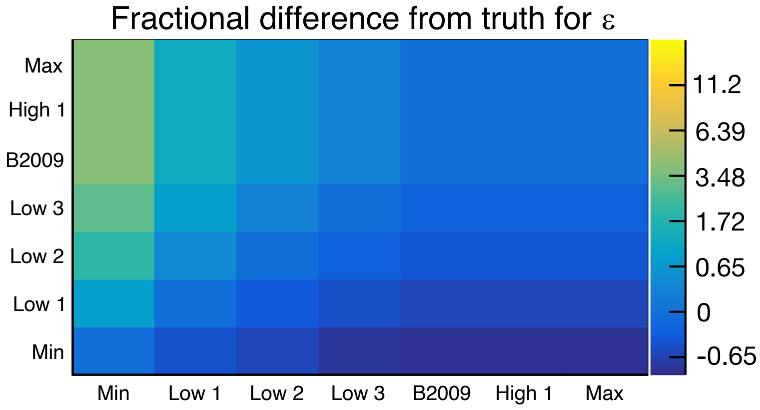
Studying fractional difference for incorrect assumptions about cross section models (uncertainty envelope):

- Color scale for α and $\langle E_\nu \rangle$ are fractional difference from true parameter value; ε is a log-like scale
- ε biases now extend from -86% to $+400\%$
  - Previously: -100% to $+1400\%$

True Cross Section Model







While the color scale is log, the values listed here are not!

Assumed Cross Section Model

PRELIMINARY

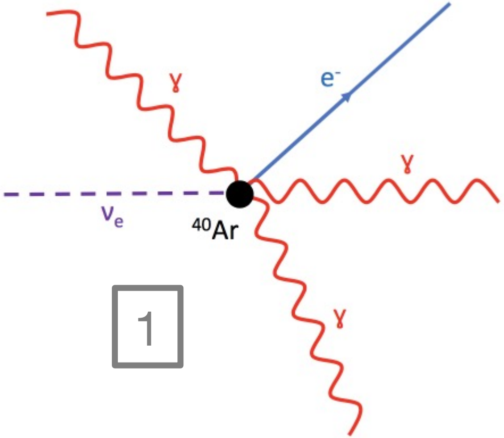
Takeaways

- ν_eCC cross section model greatly influences DUNE measurements of supernova flux
  - We need better information about the cross section – a measurement would be very useful!
- Study biases introduced by diverse set of cross section models; combination of most extreme cross section models yield most extreme biases, although those models might not be reliable at SN neutrino energies
- Paper in progress – stay tuned!

Backup Slides

Supernova Neutrinos + Their Interactions

- Neutrinos carry 99% of core collapse energy
- Electron neutrinos interact with particles in detector:
  - CC: Argon nuclei, electrons (ionization + bremsstrahlung), de-excitation gammas
  - NC: Argon nuclei, 9.8 MeV de-excitation gammas
  - Elastic scatter on electrons: electrons (ionization + bremsstrahlung)



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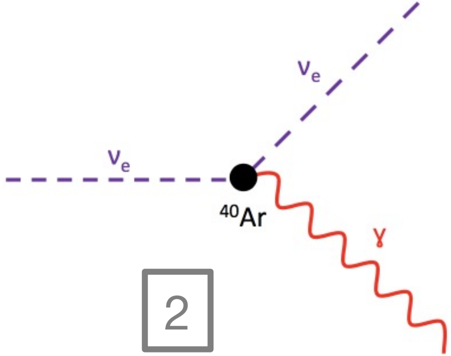


2

1 $\nu_e + {}^{40}\text{Ar} \rightarrow {}^{40}\text{K}^* + e^-$

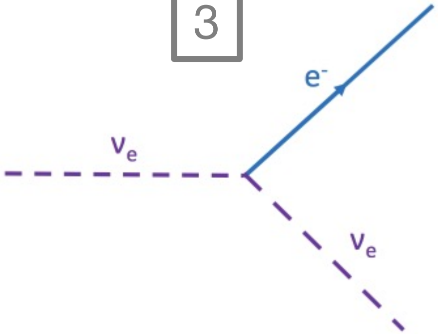
$${}^{40}\text{K}^* \rightarrow \gamma + {}^{40}\text{K}$$

2 $\nu_e + {}^{40}\text{Ar} \rightarrow \nu_e + {}^{40}\text{Ar}^*$

$${}^{40}\text{Ar}^* \rightarrow \gamma + {}^{40}\text{Ar}$$

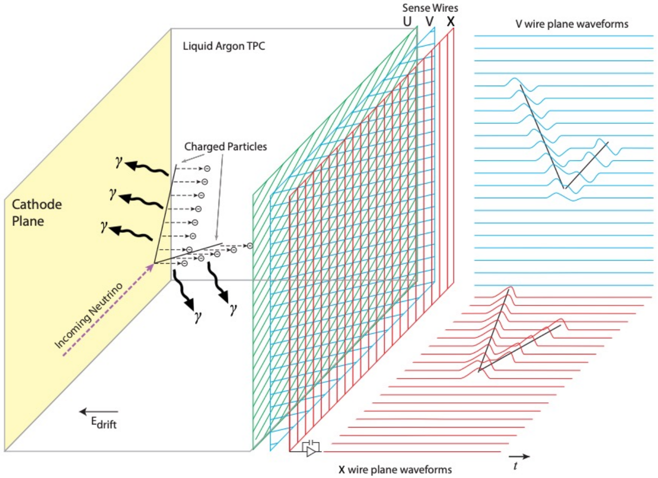
3 $\nu_e + e^- \rightarrow \nu_e + e^-$

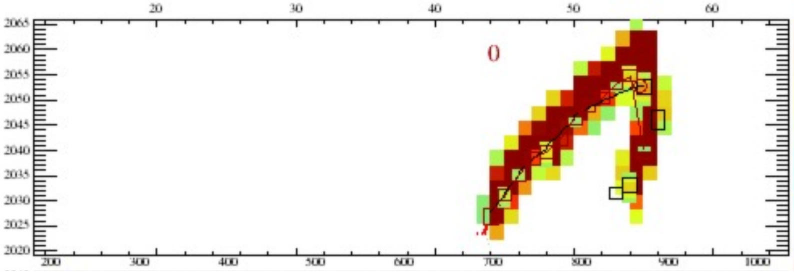
3



Supernova Neutrinos in DUNE

- Expect ~3000 neutrino interaction events in DUNE detector for a 10 kpc supernova
- Event display in time (ticks) vs wire number; color scale indicates charge deposition
- Right: electron from 30.25 MeV ν_eCC interaction





Study Assumptions

- Pure pinched-thermal ν_e flux
- 10 kpc supernova with no distance uncertainty
- Event rates integrated over 10 seconds
- Pure ν_eCC signal (i.e., channel tagging capability)
- ν_e flavor only; normal mass ordering assumed
  - "True" ν_e flux parameters: $(\alpha, \langle E_\nu \rangle, \varepsilon) = (2.5, 9.5\ \text{MeV}, 5\times 10^{52}\ \text{ergs})$ from Rosso et al.

SNOwGLoBES flux calculation

- SNOwGLoBES calculates fluxes from $(\alpha, \langle E_\nu \rangle, \varepsilon)$ using:

$$F(E_\nu) = \frac{1}{4\pi d^2} \frac{\varepsilon}{\langle E_\nu \rangle} \phi(E_\nu, \langle E_\nu \rangle, \alpha) \times (\text{binning factor})$$

  - ε converted from erg/sec to GeV/sec

- Here, $\phi(E_\nu, \langle E_\nu \rangle, \alpha)$ is defined as

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

where N is defined as

$$N = \frac{(\alpha + 1)^{\alpha+1}}{\langle E_\nu \rangle \, \alpha!}$$

SNOwGLoBES fluence calculation

- In order to get the integrated flux (fluence), you must integrate $\phi(E_\nu, \langle E_\nu \rangle, \alpha)$ over E_ν
  - $\mathcal{N}$ linearly related to ε, no dependence on α or $\langle E_\nu \rangle$
- Fluence from Rosso et al.:

$$F_i^0(E_\nu) = \frac{\varepsilon_i}{4\pi d^2} \frac{E_\nu^{\alpha_i} \exp[-E_\nu/T_i]}{T_i^{\alpha_i+2}\Gamma(\alpha_i + 2)}$$

  - $T_i = \langle E_i \rangle / (\alpha_i + 1)$ is the "temperature"

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

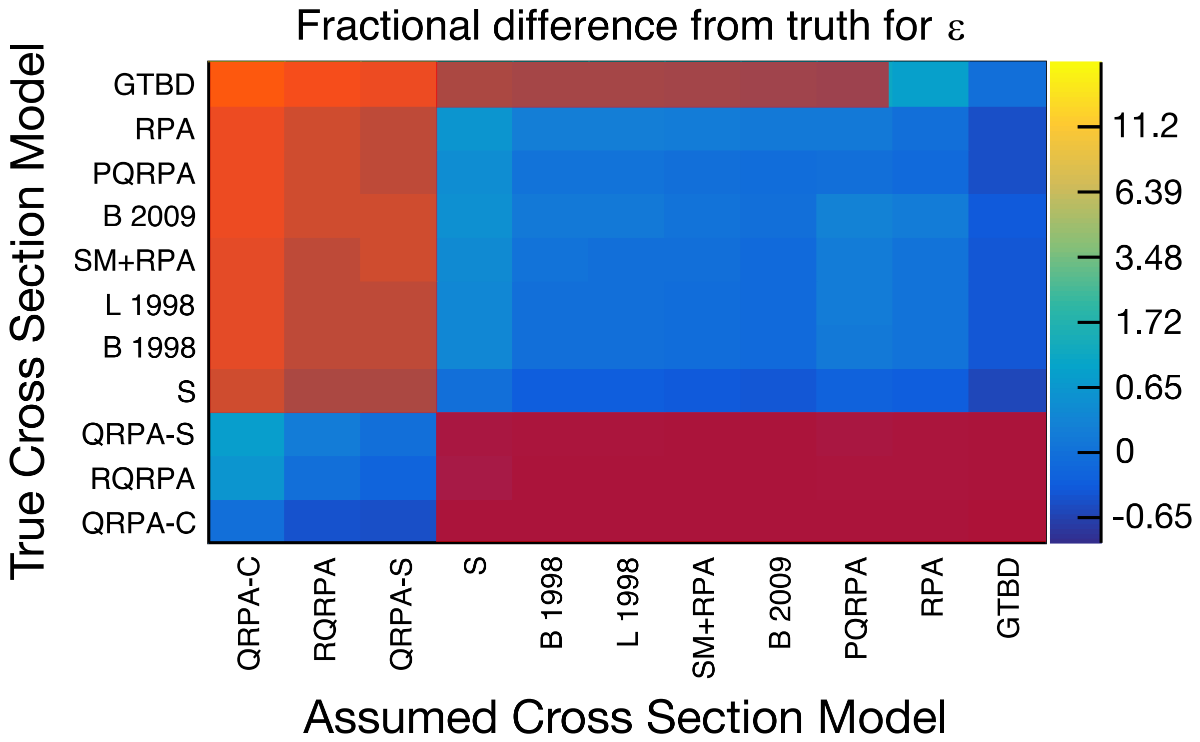
“Log scale” for ε

- Color scale:

$$\pm \log(1 + |\text{fracDiff}|)$$

  - Accounts for the wide range of biases
  - Includes scenarios where there is no bias introduced into measurement
- The z-axis numerical values shown in right-hand plot are NOT log! The corresponding log scale here is $[-1.0, 4.0]$

Reasonable ε values (preliminary)

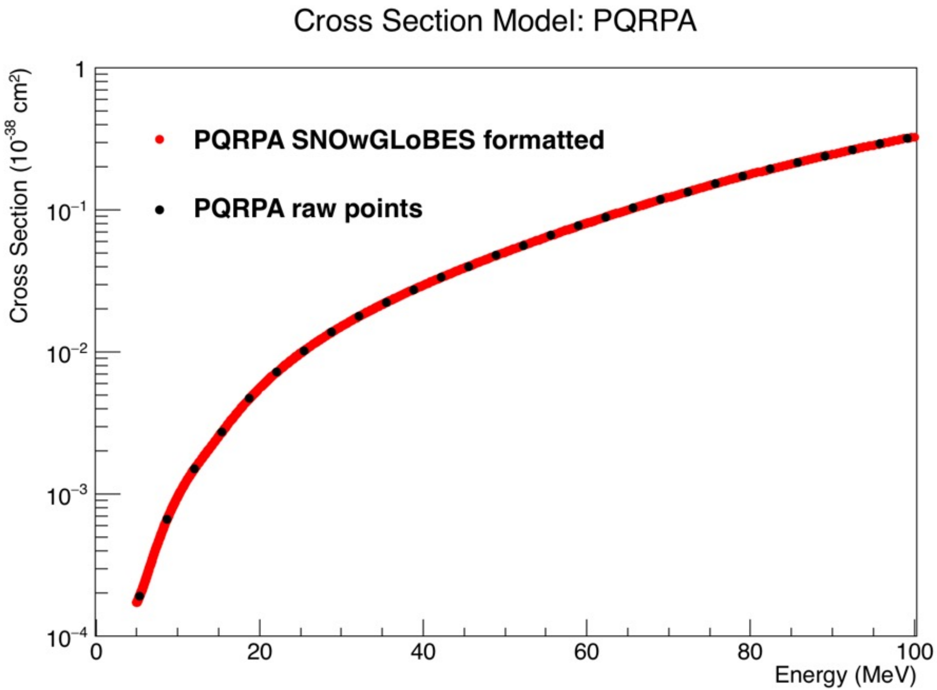


Formatting for SNOwGLoBES

- Used interpolation, extrapolation to format cross section models for usage in SNOwGLoBES
  - Interpolation using ROOT Eval function (uses TSpline)
  - Quadratic fit for extrapolation: $\sigma = p_0(E - p_1)^2$
    - Remove discontinuities by forcing fit through first data point

Examples of Extrapolation/Interpolation

PQRPA Model (Interpolation Only)



RPA Model (Extrapolation Required)