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

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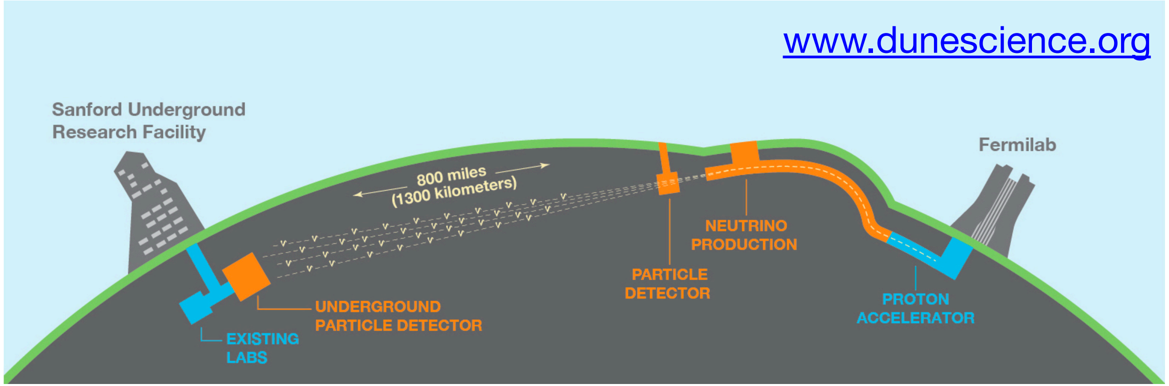
Workshop on Fundamental Physics at the Second Target Station

Outline

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

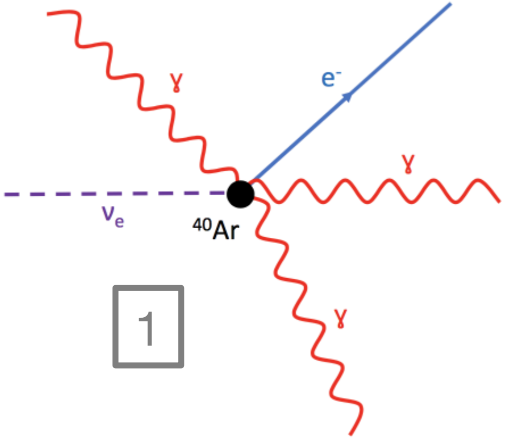
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

- International experiment for neutrino science (1100+ collaborators!)
  - 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



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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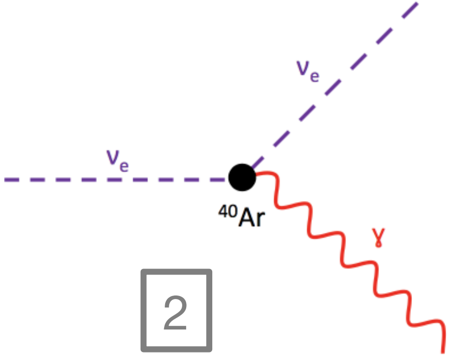

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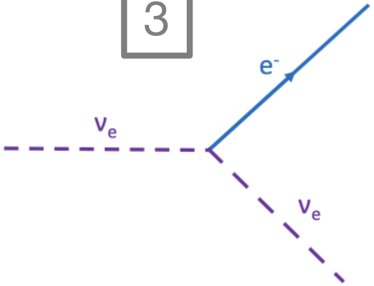


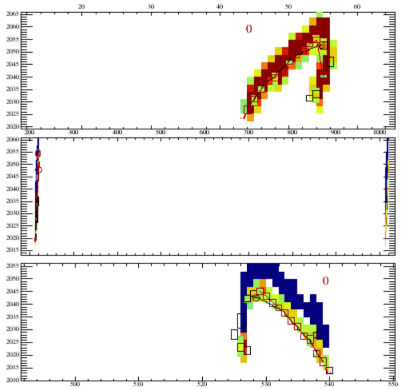
1 $$\nu_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{K}^* + e^-$$
$$^{40}\mathrm{K}^* \rightarrow \gamma + {}^{40}\mathrm{K}$$

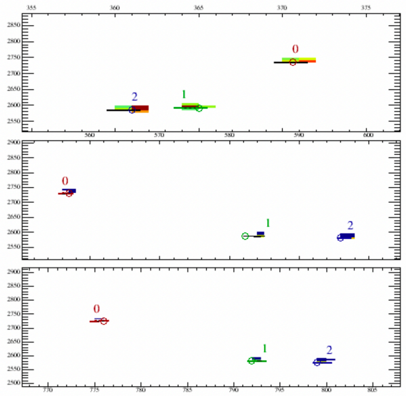
2 $$\nu_e + {}^{40}\mathrm{Ar} \rightarrow \nu_e + {}^{40}\mathrm{Ar}^*$$
$$^{40}\mathrm{Ar}^* \rightarrow \gamma + {}^{40}\mathrm{Ar}$$

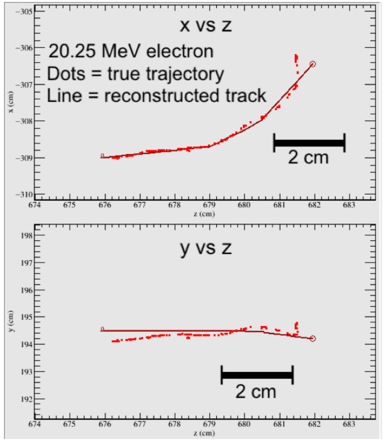
3 $$\nu_e + e^- \rightarrow \nu_e + e^-$$

Supernova Neutrinos in DUNE

- Expect ~3000 neutrino interaction events in DUNE detector for a 10 kpc supernova
  - Neutrinos of all flavors carry 99% of core collapse energy
  - LAr is sensitive to ν_e (versus water/scintillator which are sensitive to $\bar{\nu}_e$)
- Assume we can separate different interaction channels; select ν_eCC







Top: 2D time (ticks) vs Wire #; color scale indicates charge

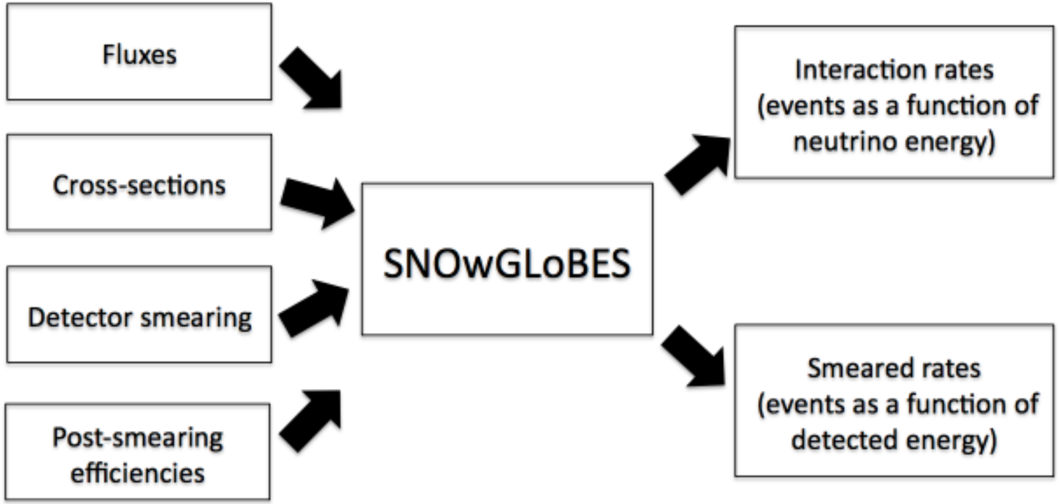
Left: 30.25 MeV ν_eCC interaction

Right: 15 MeV ν_eNC interaction

Bottom: 20.25 MeV ES interaction (3D view)

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/

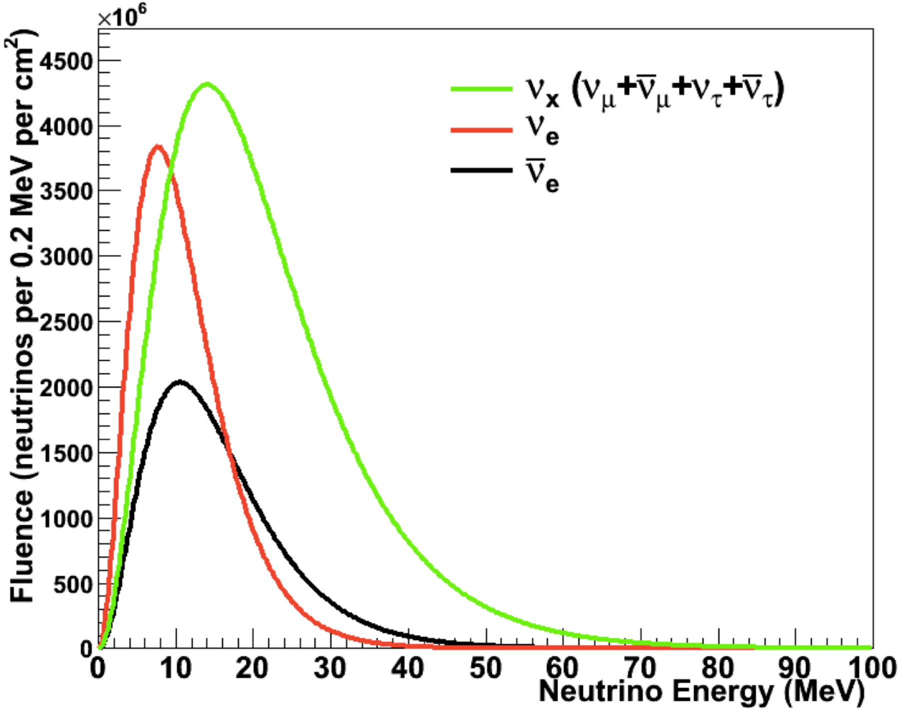
GLoBES: General Long Baseline Experiment Simulator

Supernova Flux Model

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

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

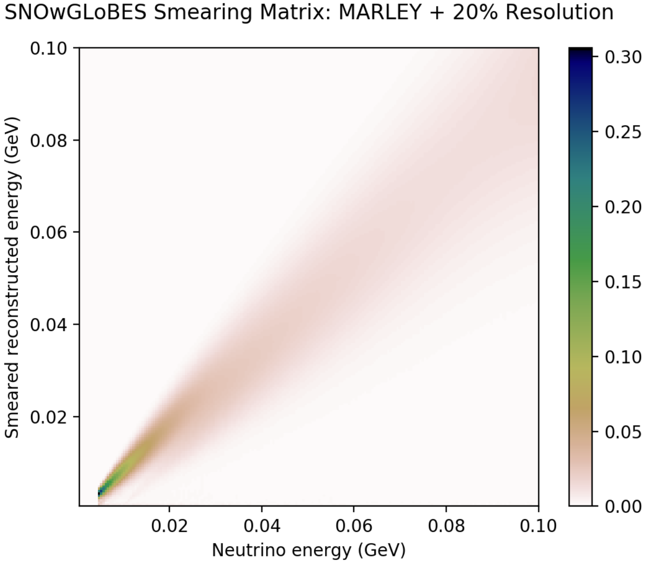
  - E_ν: Neutrino energy (MeV)
  - $\mathcal{N}$: Normalization constant (related to luminosity, ε, in ergs)
  - $\langle E_\nu \rangle$: Mean neutrino energy (MeV)
  - α: Pinching parameter; large α corresponds to more pinched spectrum (unitless)
- Parameters of interest: ε, $\langle E_\nu \rangle$, α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

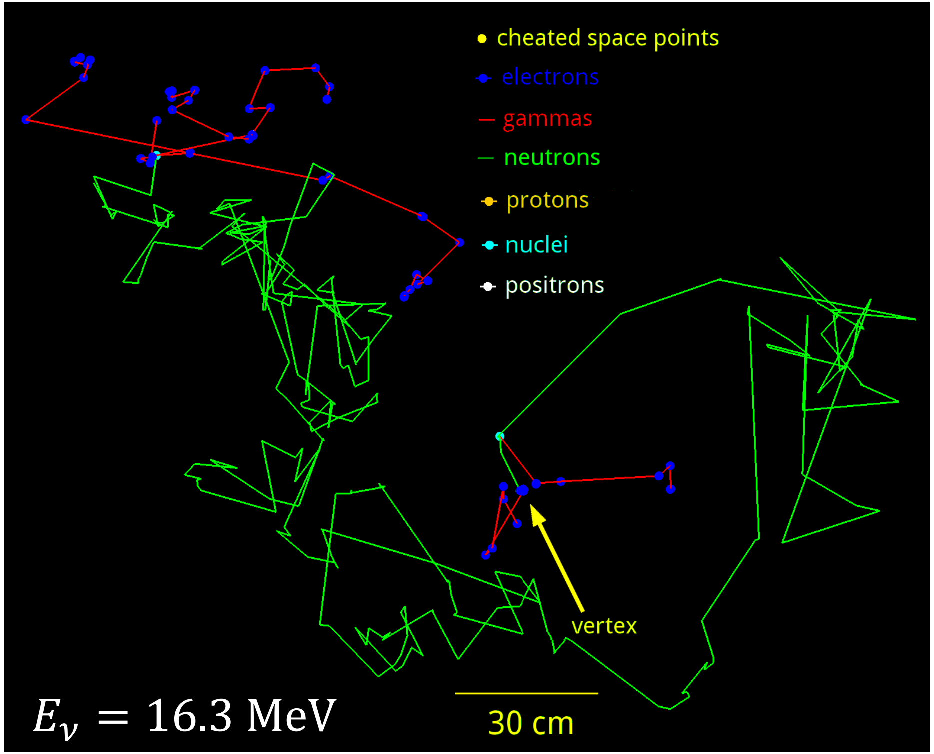


Pinched-thermal for a 10kpc supernova (K. Scholberg)
Note: Fluence refers to a time-integrated flux.

MARLEY: Model of Argon Reaction Low-Energy Yields

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

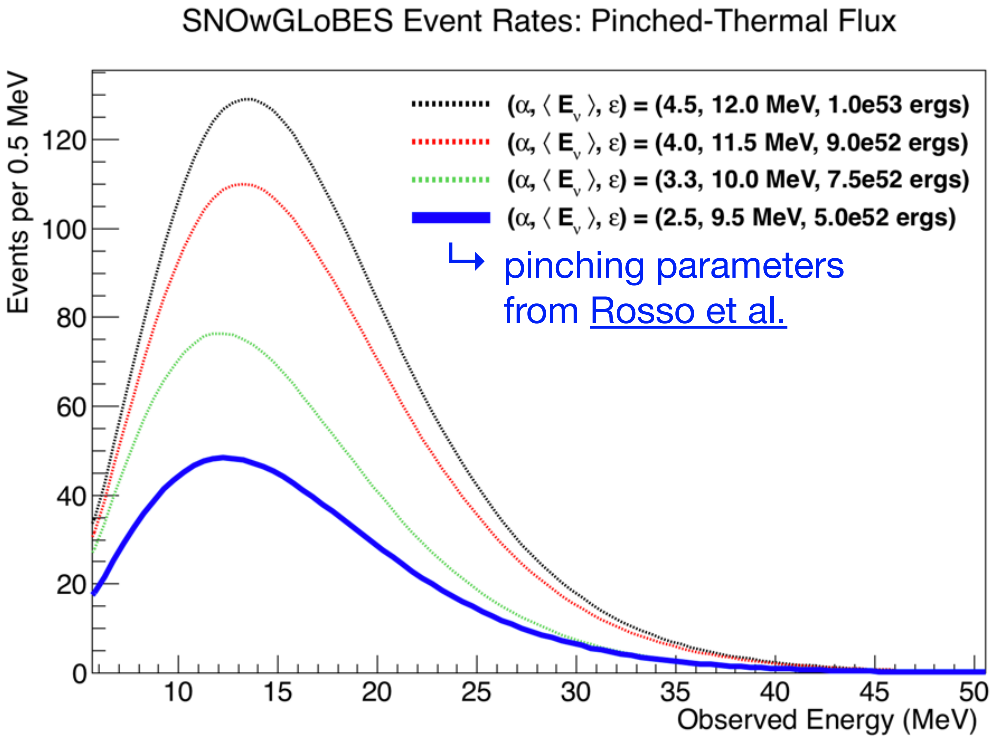




S. Gardiner (http://www.marleygen.org/)

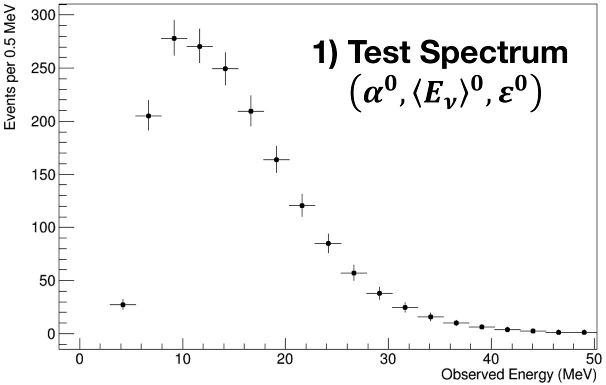
Measuring the Flux Parameters

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

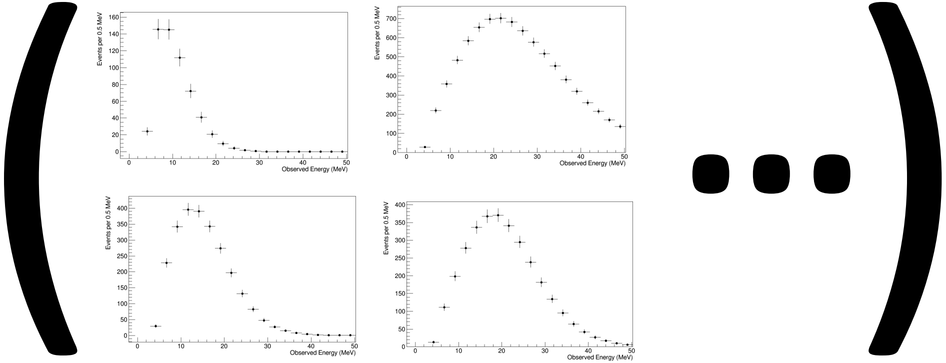


Parameter Fitting Algorithm

- 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

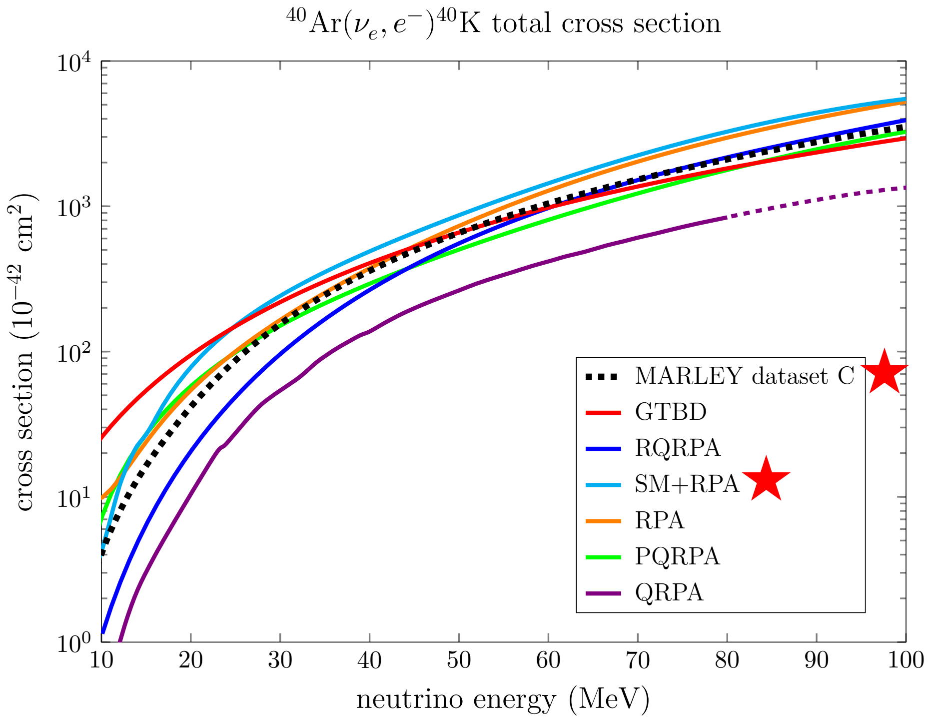


2) Grid with many different combinations of $(\alpha, \langle E_\nu \rangle, \varepsilon)$



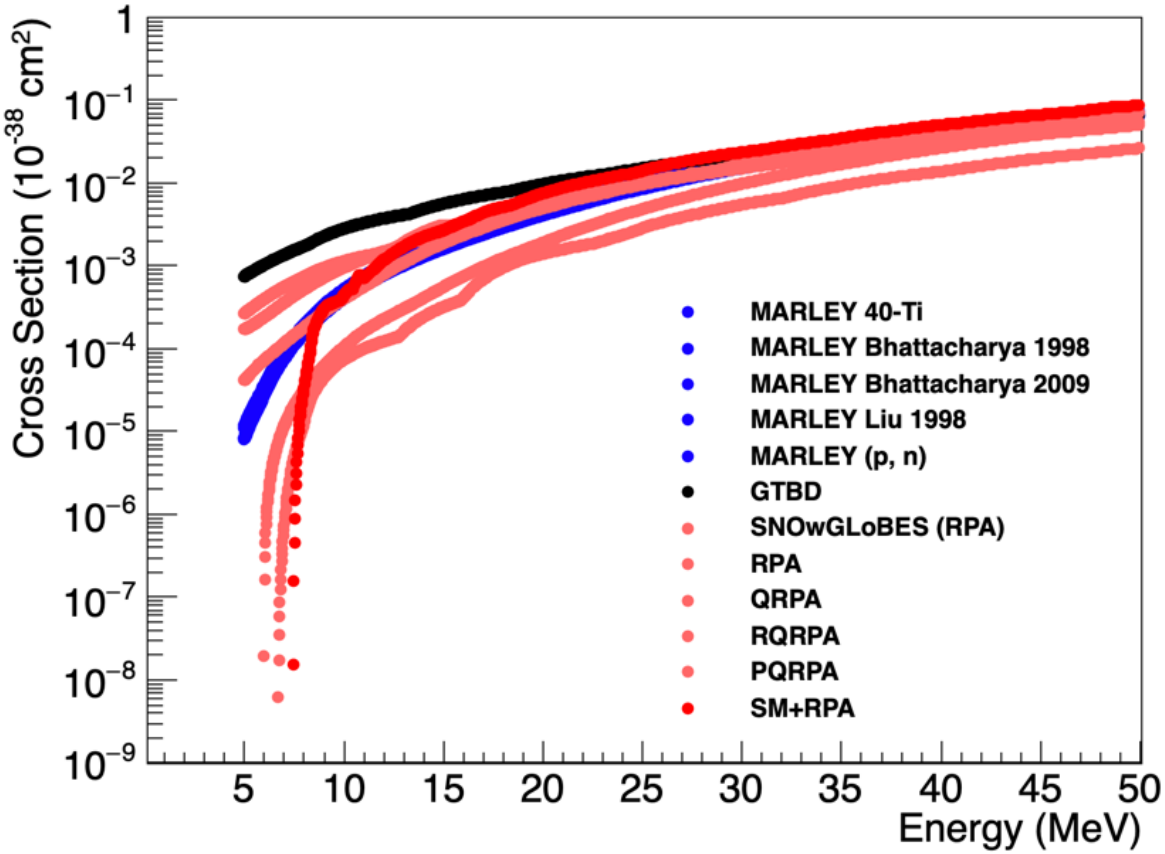
Studying ν_e-^{40}Ar Cross Section Models

- Understand impact of cross section model on parameter fitting algorithm and results
- Considered 12 cross section models calculated using different methods
  – Because these cross section models cover a wide range of values, multiple grids were generated for reasonable fits for all combinations



★ Most reliable models From S. Gardiner's thesis

SNOwGLoBES-Formatted Cross Sections



Reliability of these models:

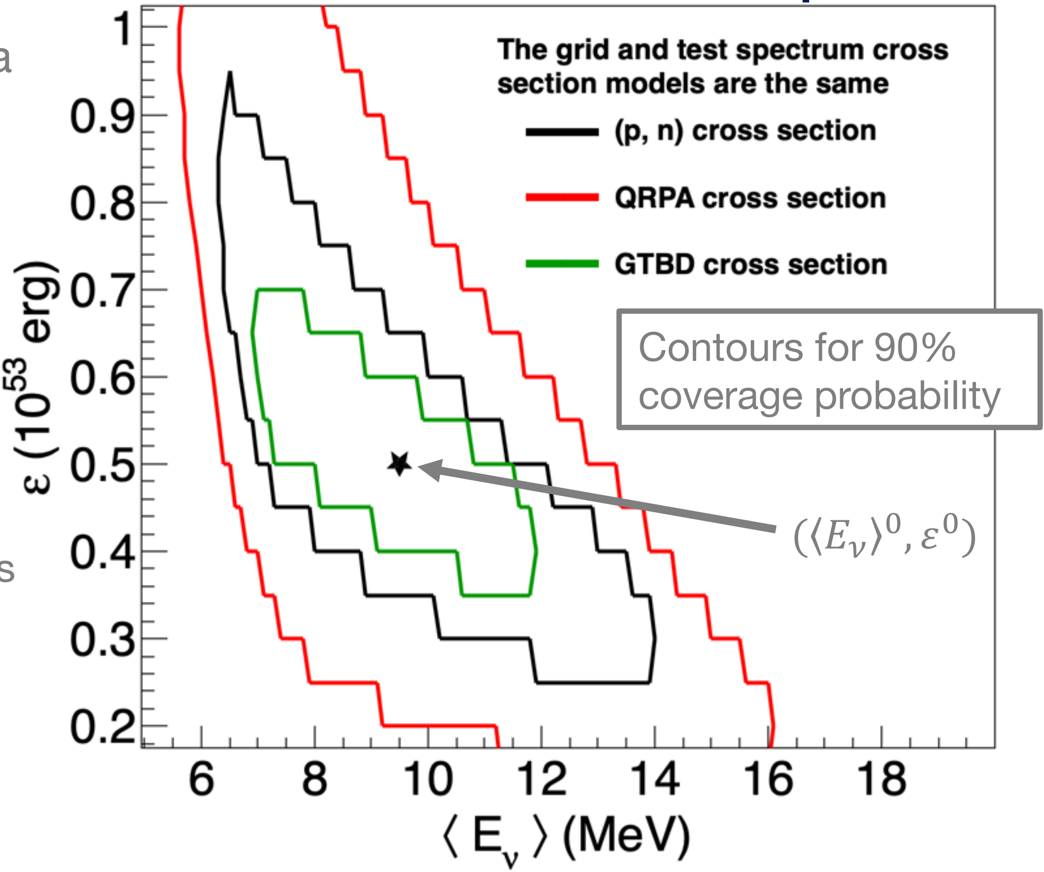
1. Blue curves: MARLEY partially data-driven filled in with QRPA, probably most reliable at low energies
2. Red curve: SM+RPA (hybrid approach with RPA) is considered most theoretically motivated
    1. Pink curves: RPA is preferred for the high energies (not explicitly defined) of SN ν_e according to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

See backup for references.

Studying Biases due to Incorrect Detector Assumptions

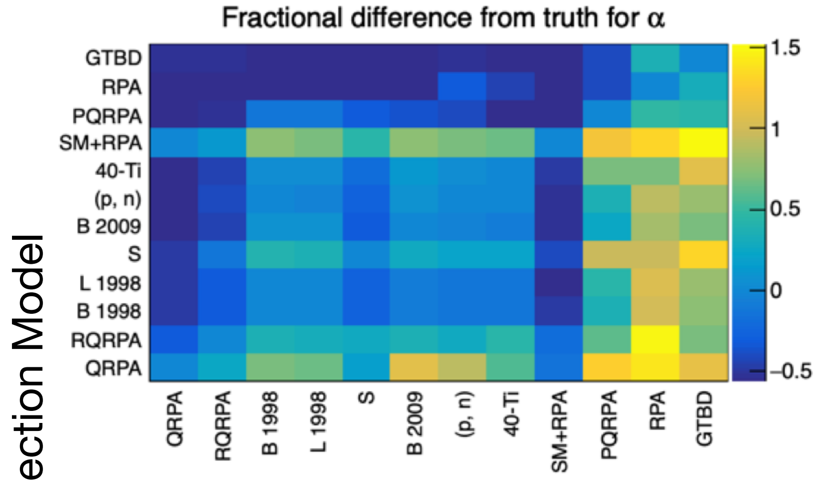
- Test spectrum: data from supernova as observed by DUNE
- Grids: different DUNE detector performance assumptions
- Change assumptions for test spectrum, and for grids, to study effect of mismatched assumptions about ν_e-^{40}Ar cross section
  - Study amount of parameter phase space enclosed in sensitivity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

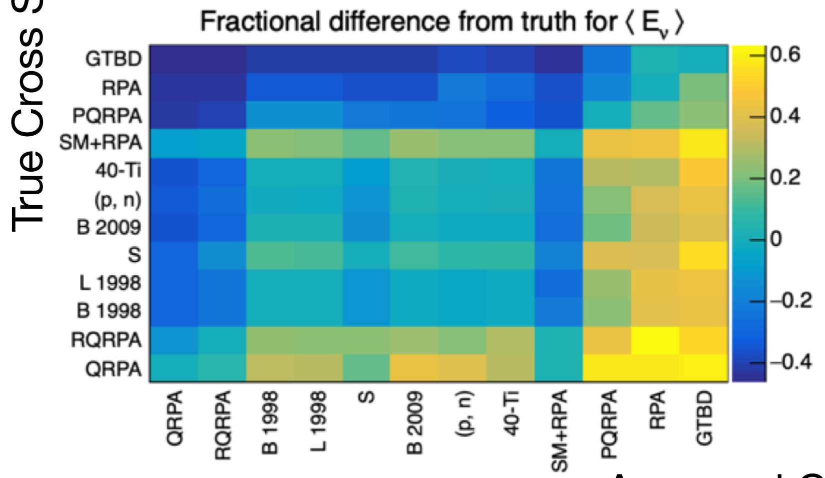
$$\text{Frac. Diff.} = \frac{x - x^0}{x^0}$$

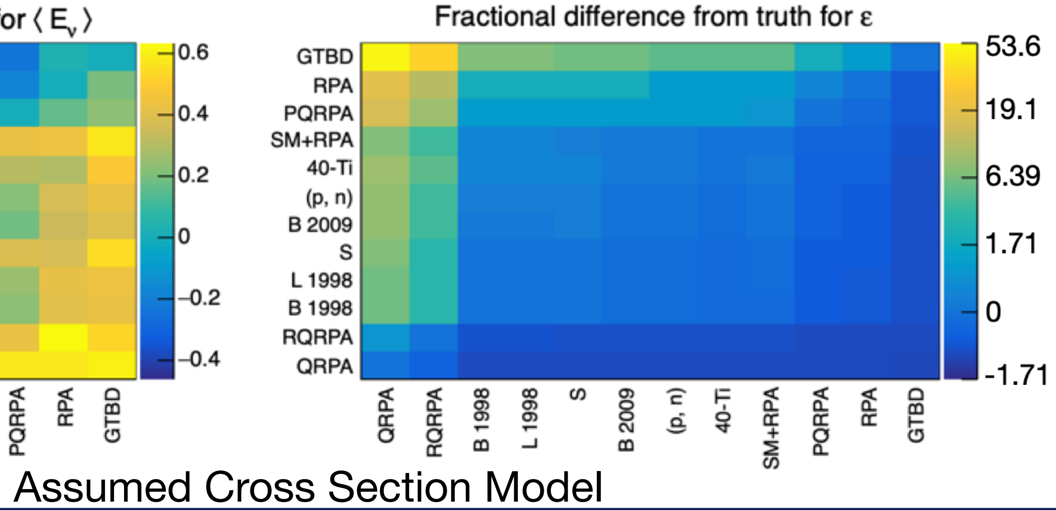


Studying fractional difference for incorrect assumptions about cross section models:

- Included ν_eCC interactions only
- Color scale for α and $\langle E_\nu \rangle$ are fractional difference from true parameter value
- ε range from $\mathcal{O}(10^{51}\ \text{ergs})$ to $\mathcal{O}(10^{54}\ \text{ergs})$; biases extend from -94% to $+5000\%$
  - Unrealistic range for ε chosen to account for wide range in cross section models







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

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; most extreme cross section models yield most extreme biases:
  - α: -52% to $+112\%$
  - $\langle E_\nu \rangle$: -46.3% to $+60\%$
  - ε: -94% to $+5000\%$
- DUNE technical note for parameter fitting: 14068-v2; paper for publication currently in progress

Backup Slides

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

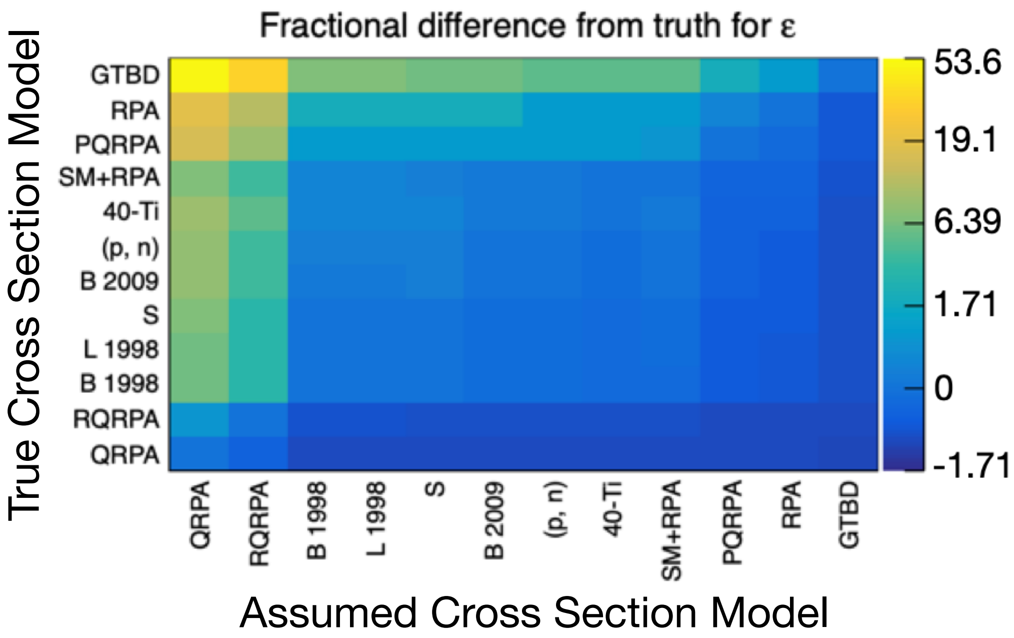
- From S Gardiner's thesis and MARLEY:
  - Bhattacharya 1998
  - Liu 1998
  - Bhattacharya 2009
  - (p, n) and 40-Ti
- GTBD: gross theory of beta decay

"Log scale" for ε

- Color scale:

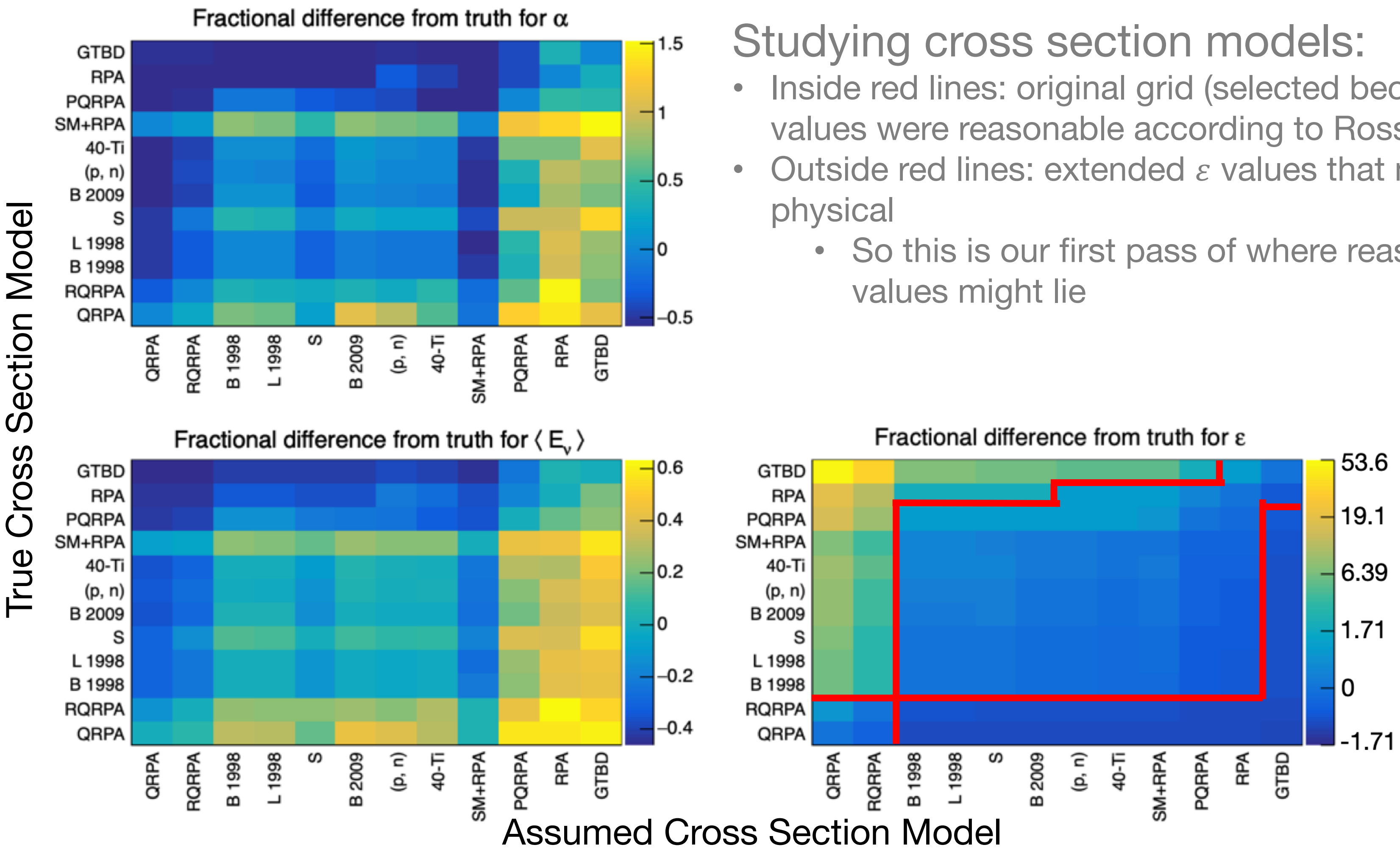
  $$\pm \log(1 + |\text{fracDiff}|\ )$$

  - 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 $[-1.0, 4.0]$



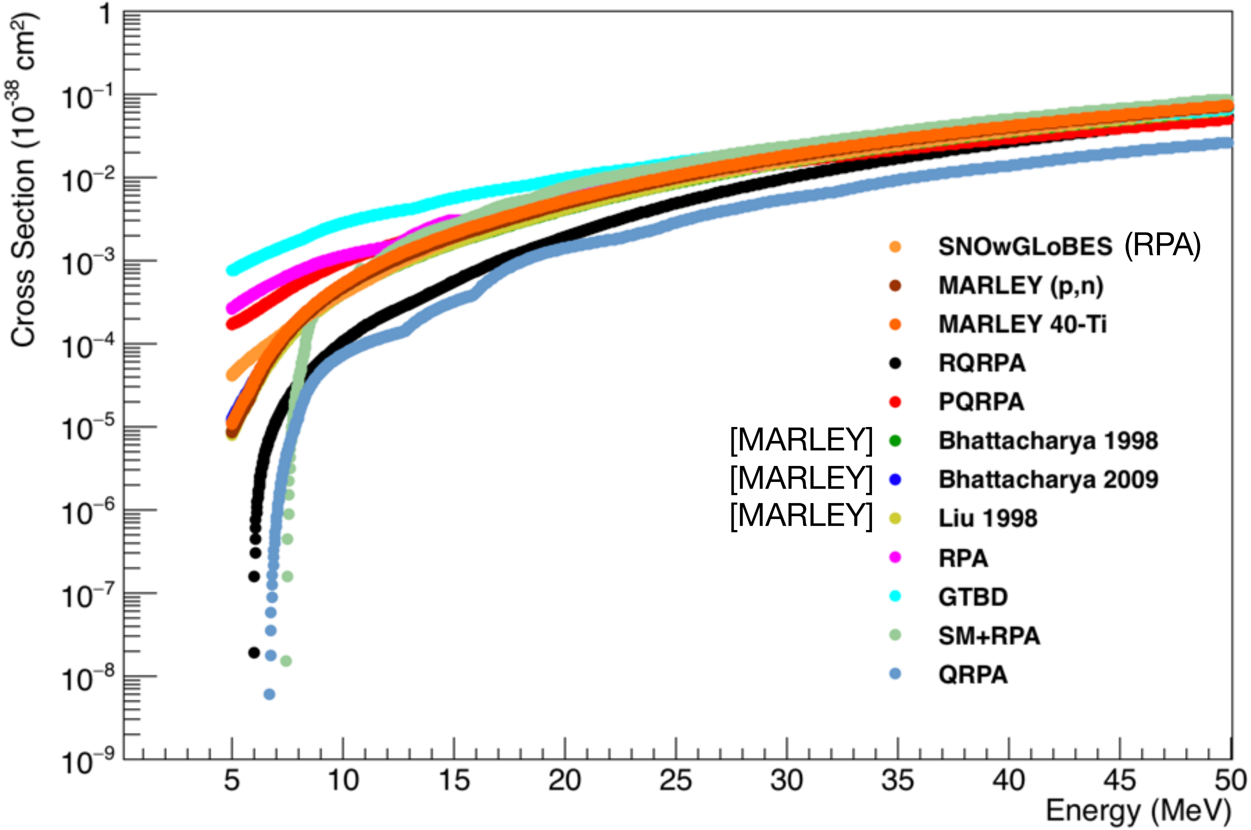
Studying cross section models:

- Inside red lines: original grid (selected because the ε values were reasonable according to Rosso et al.)
- Outside red lines: extended ε values that might not be physical
    - So this is our first pass of where reasonable ε values might lie



These values are NOT log!

SNOwGLoBES-Formatted Cross Sections



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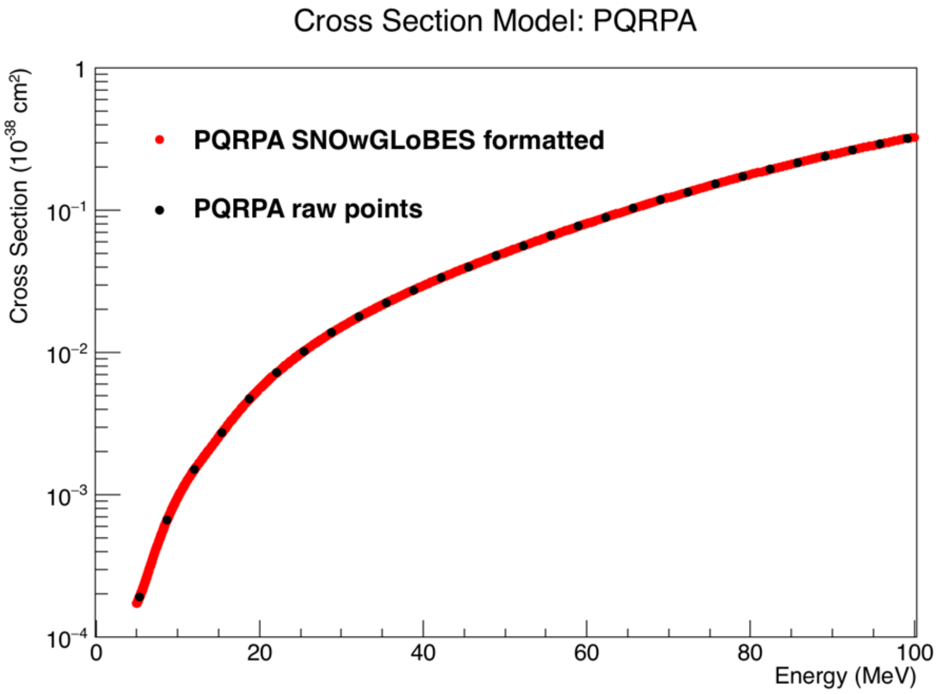
See backup for references.

Formatting for SNOwGLoBES

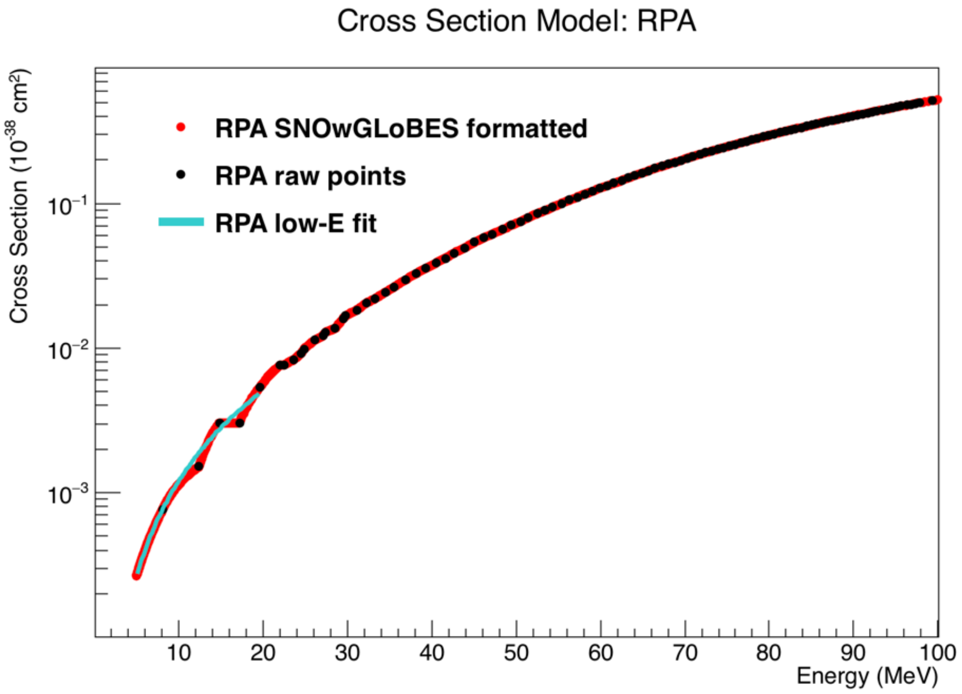
- Used interpolation, extrapolation to format cross section models for usage in SNOwGLoBES
  - Interpolation using ROOT Eval function (uses TSpline)
  - Quadratic fit for extrapolation: $\sigma = p_0(E - p_1)^2$
    - Remove discontinuities by forcing fit through first data point
- See backup for more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

Examples of Extrapolation/Interpolation

PQRPA Model (Interpolation Only)



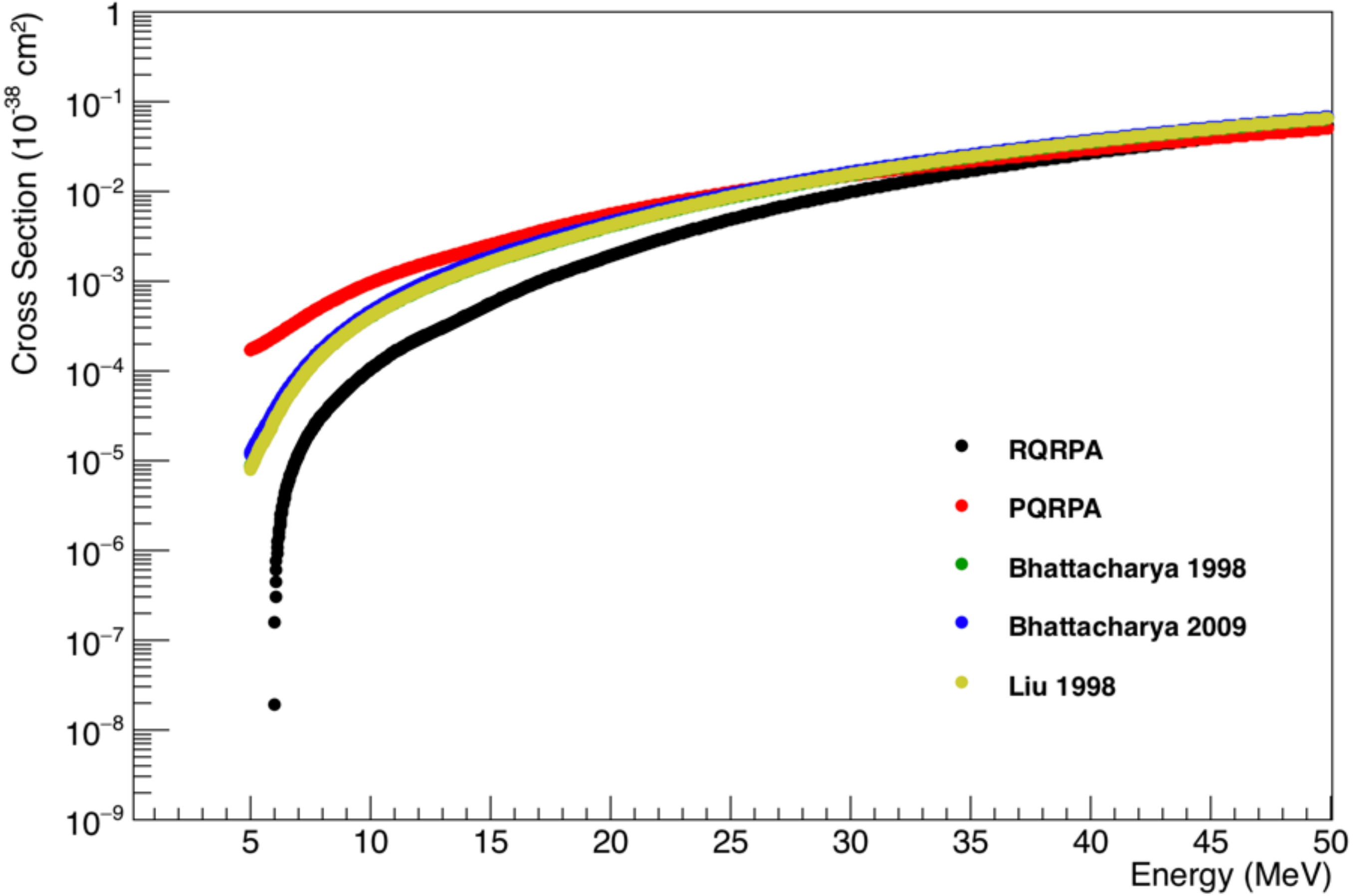
RPA Model (Extrapolation Required)



Cross section models: no extrapolation

- Models:
  - RQRPA (Paar 2013)
  - PQRPA (Samana, unpublished)
  - Bhattacharya 1998
  - Bhattacharya 2009
  - Liu 1998
- Used cubic spline (TSpline3) to perform interpolation
  - Smoother interpolation compared to linear spline; see page 6

Cross Section Models



Notes:

- Models extend to 100 MeV; only showing up to 50 MeV here
- RQRPA goes to zero at 6 MeV in the original text file and the interpolation reflects that
- The two Bhattacharya models are very similar and nearly overlap

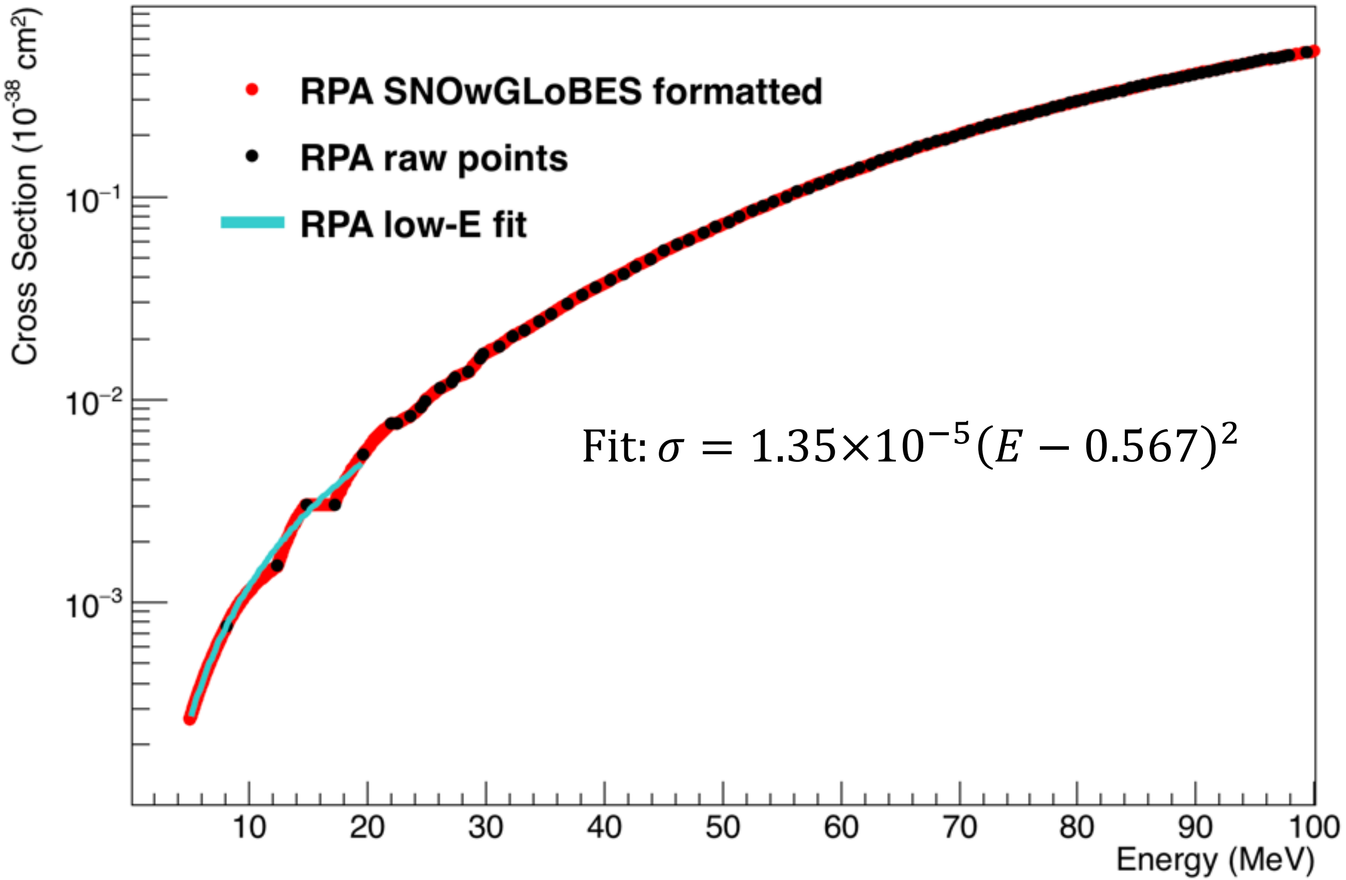
Cross section models: extrapolation required

- Models:
  - RPA (Botella 2004)
    - Modified original text file by removing duplicate points (to test higher-degree TSpline that requires completely unique points)
  - QRPA (Cheoun 2011)
  - GTBD (Samana 2008)
    - Modified original text file by removing “duplicate” points above 1000 MeV (most likely a result of truncation; should not impact interpolation)
  - SM+RPA (Suzuki 2014)

Cross section models: extrapolation required

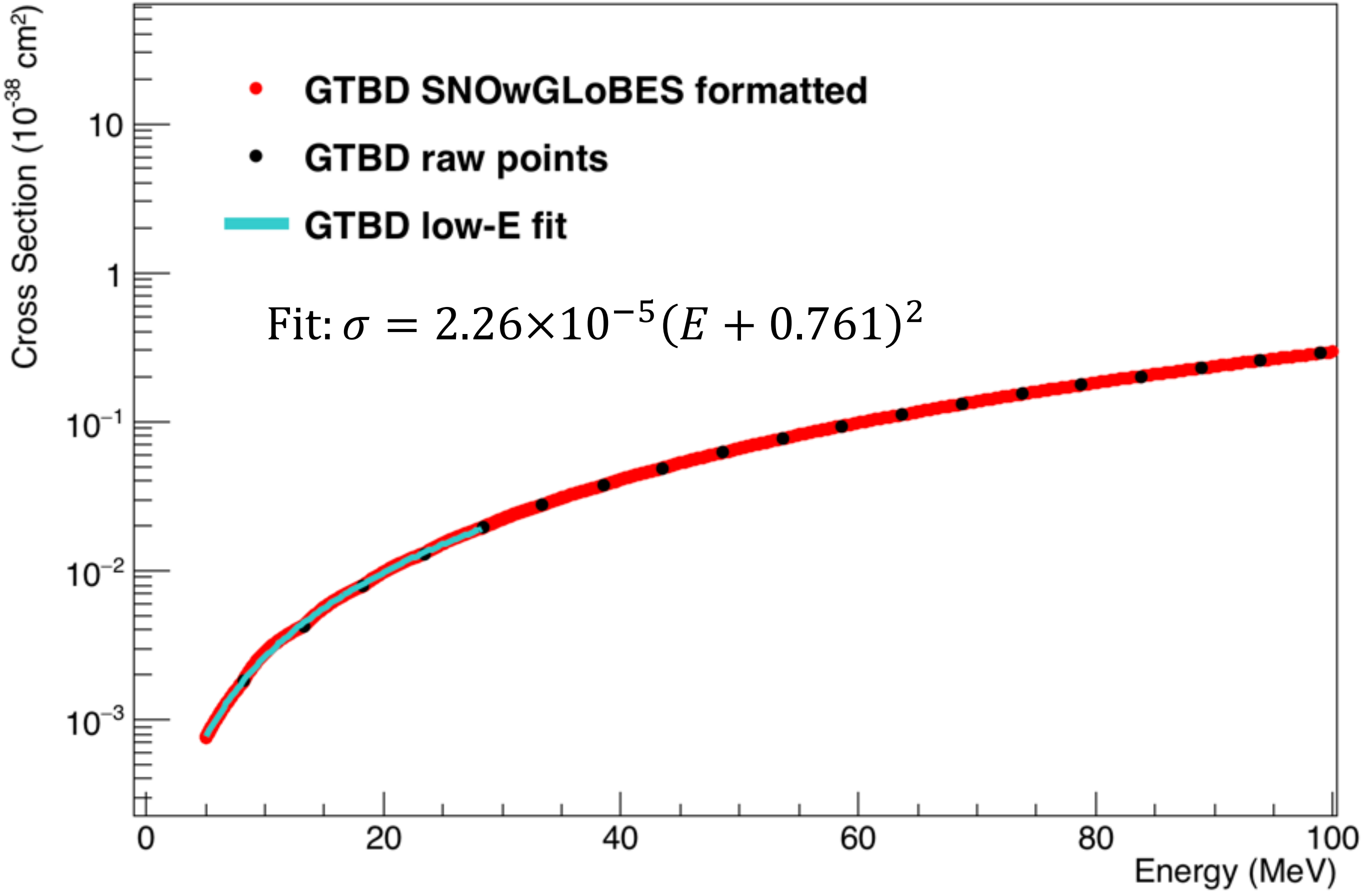
- Use quadratic fit $\sigma = p_0(E - p_1)^2$ for extrapolation
  - Fit a quadratic to 5 points
  - Fixed function to go through first point using weights (weighted the first point heavily compared to all other points, which got smaller but equal weights)
  - Used function to extrapolate beyond model range (e.g., to 5 MeV)
  - QRPA model has points up to 80 MeV; repeat this process (fixing function to go through last point) to extrapolate to 100 MeV
  - p_1 is not constrained and can be any value; if $p_1 > 5\ \mathrm{MeV}$ then I set $\sigma = 0$ for energies lower than p_1; this happens for SMRPA and QRPA
- Used linear spline (TSpline) to perform interpolation
  - Smoother compared to cubic spline

Cross Section Model: RPA

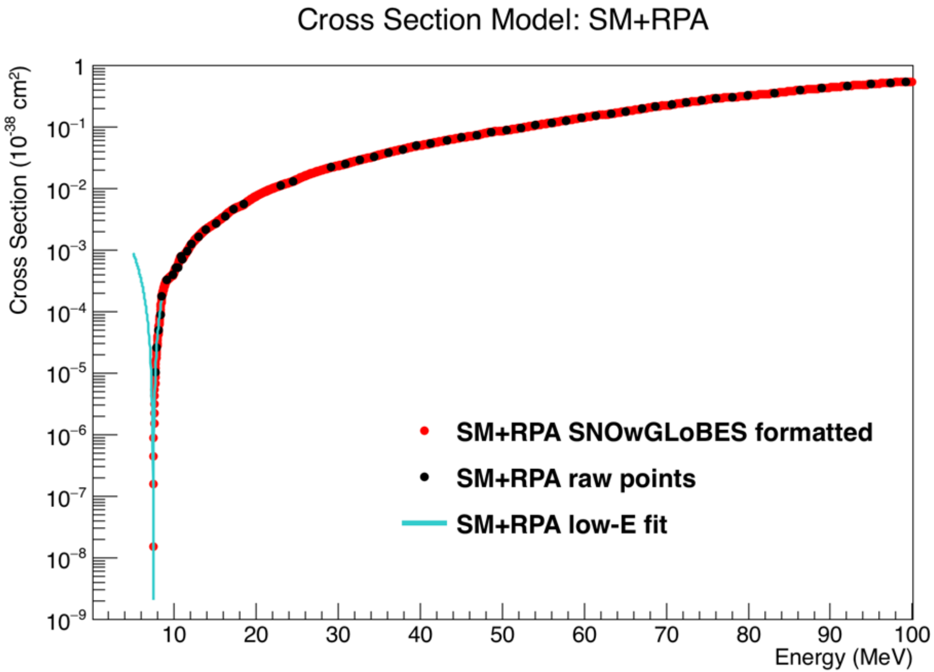


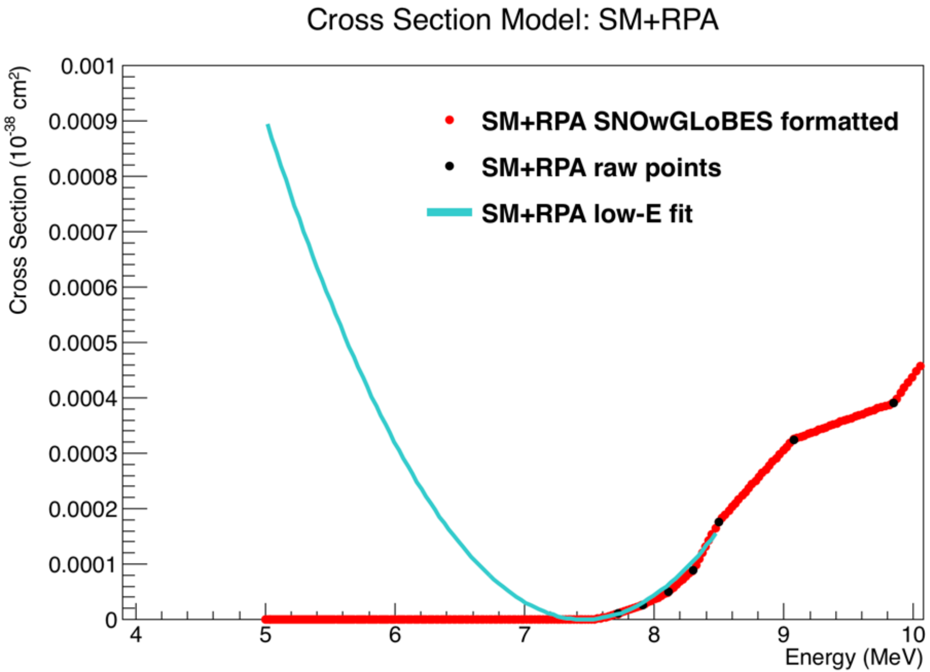
Fit: $\sigma = 1.35\times10^{-5}(E - 0.567)^2$

Cross Section Model: GTBD

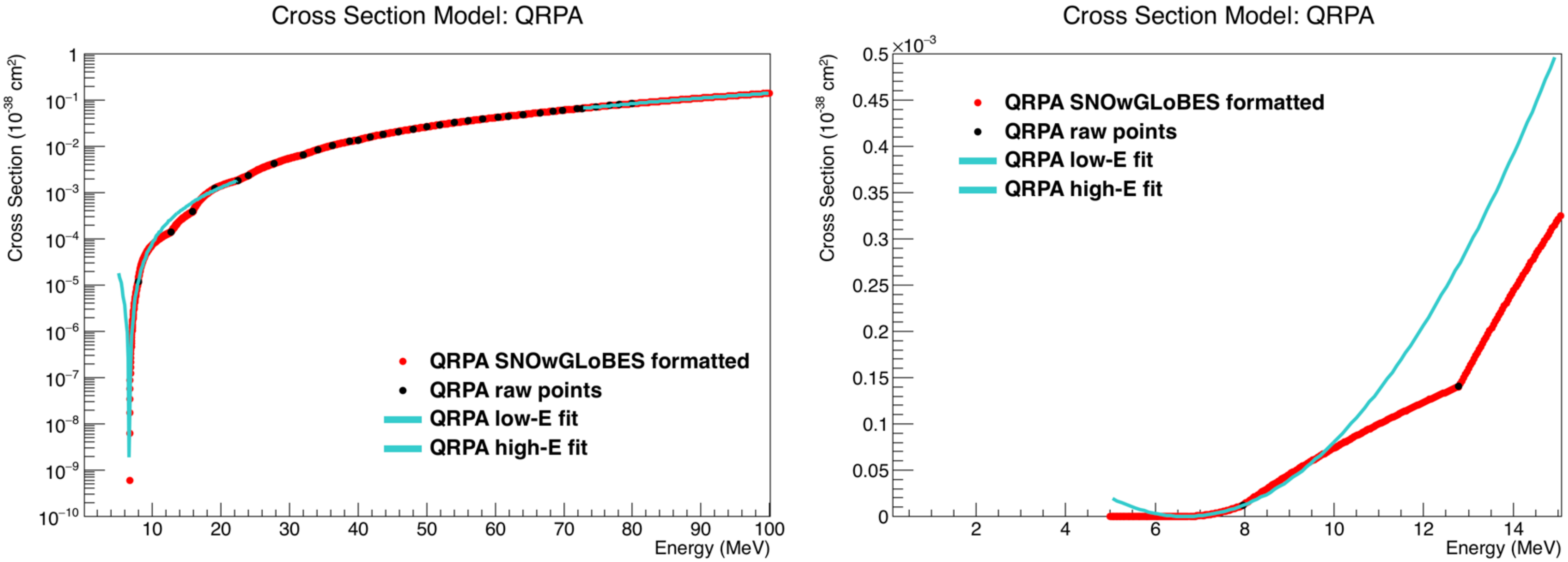


Fit: $\sigma = 2.26\times10^{-5}(E + 0.761)^2$





- SM+RPA quadratic fit matches points well: $\sigma = 1.50\times10^{-4}(E - 7.46)^2$
  - Since $p_1 = 7.46\ \mathrm{MeV}$, I set all values below p_1 to be zero (so the cross section is more realistic)



- QRPA quadratic fit matches points well:
  - Low energy: $\sigma = 7.30\times10^{-6}(E - 6.68)^2$; since $p_1 = 6.68$ MeV, I set all values below p_1 to be zero
  - High energy: $\sigma = 1.83\times10^{-5}(E - 12.4)^2$