Cross section uncertainty paper: Status and plans

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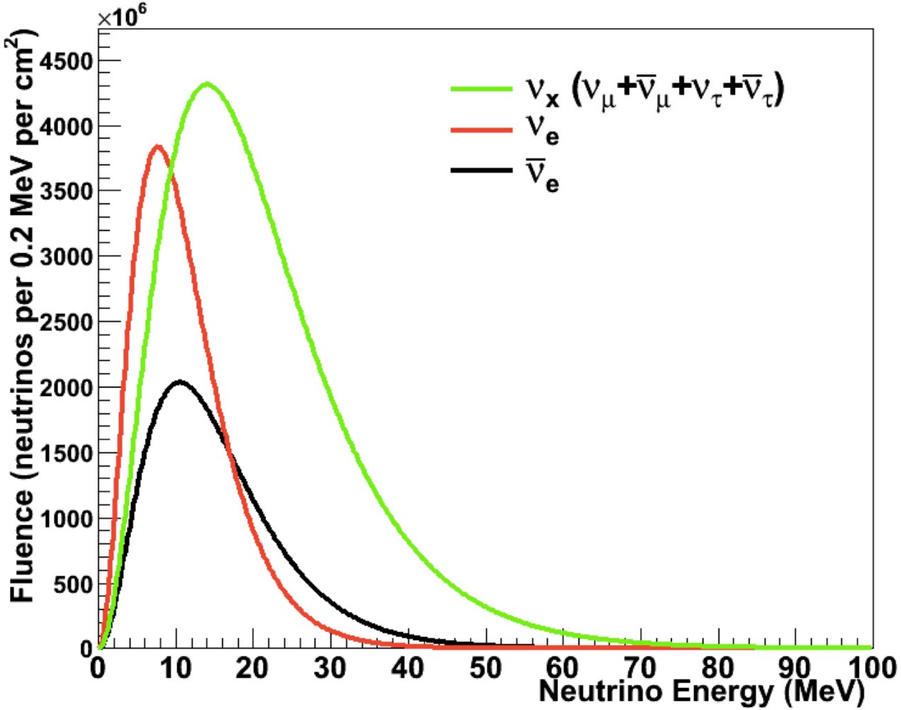
DUNE Low-Energy Working Group Meeting

Supernova Flux Model

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

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

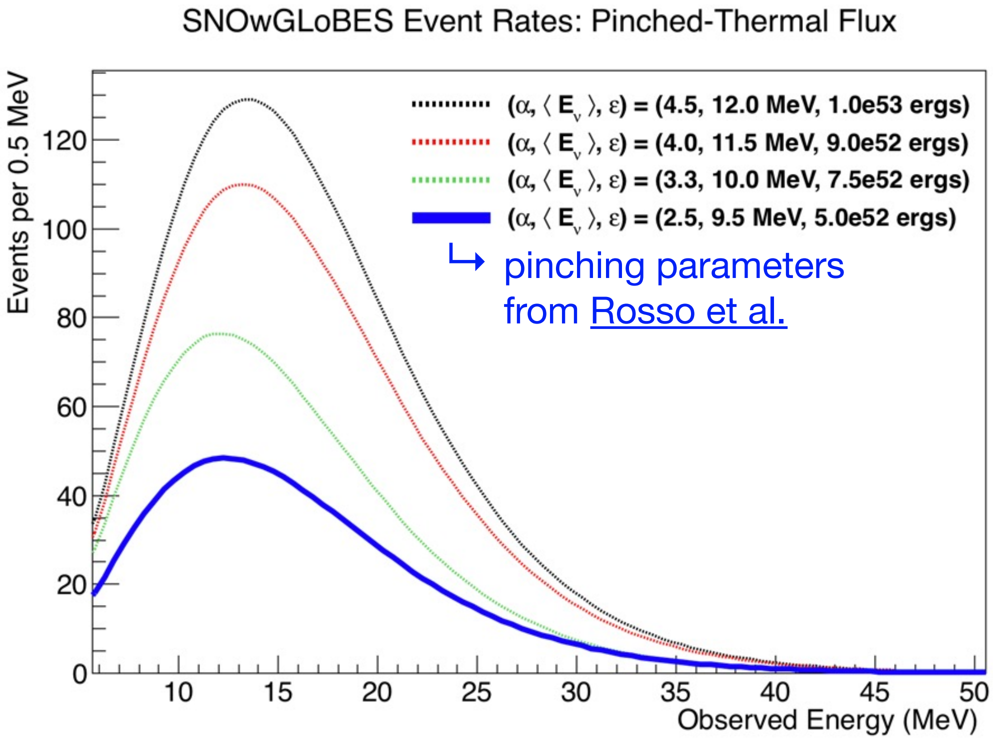
  - E_ν: Neutrino energy (MeV)
  - $\mathcal{N}$: Normalization constant (related to luminosity, ε, in ergs)
  - $\langle E_\nu \rangle$: Mean neutrino energy (MeV)
  - α: Pinching parameter; large α corresponds to more pinched spectrum (unitless)
- Parameters of interest: ε, $\langle E_\nu \rangle$, α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



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

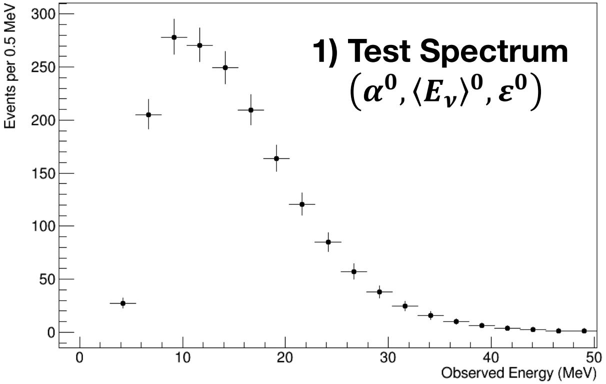
Measuring the Flux Parameters

- 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
- Parameter fitting algorithm: measure, constrain flux pinching parameters based on SNOwGLoBES event rates

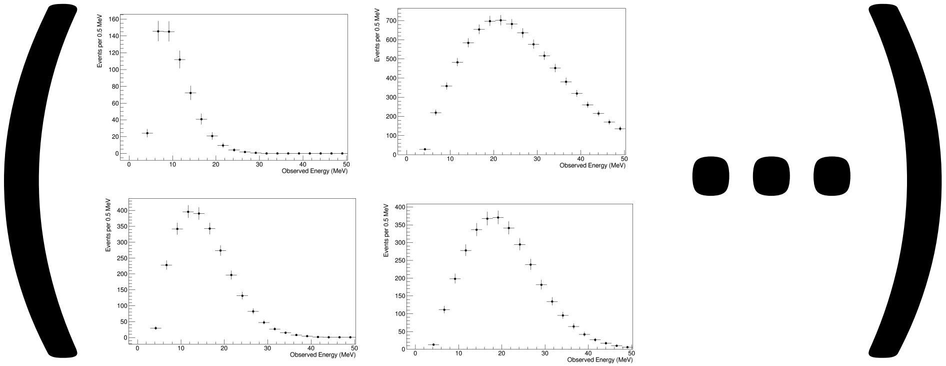


Parameter Fitting Algorithm

- 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

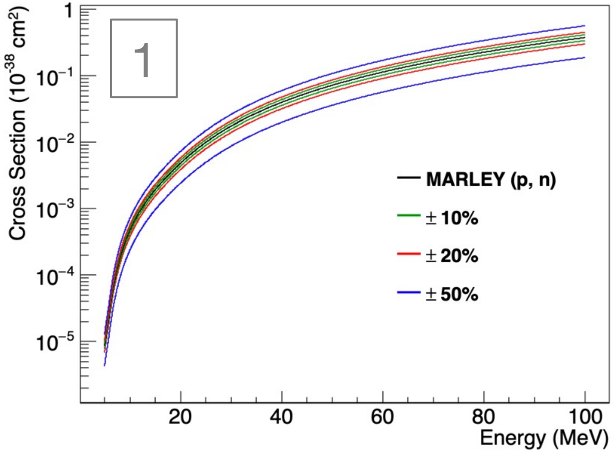


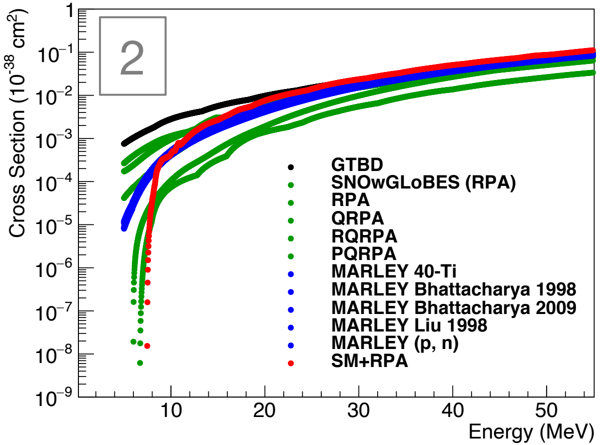
2) Grid with many different combinations of $(\alpha, \langle E_\nu \rangle, \varepsilon)$

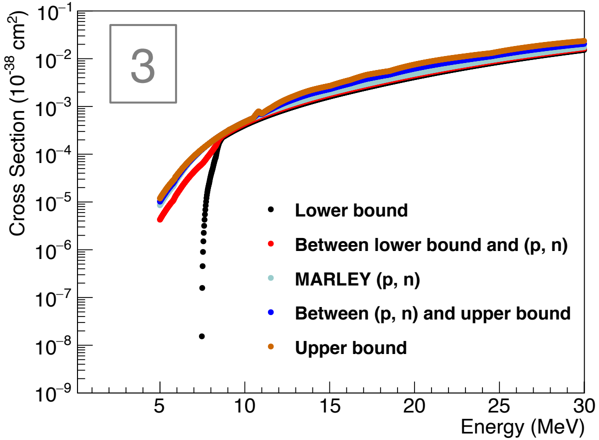


Summary of previous studies

1. Constant in energy scaling factor on one specific model
2. Different theoretical models
3. “Uncertainty envelope” for range of more reliable models







Results (see backup for more)

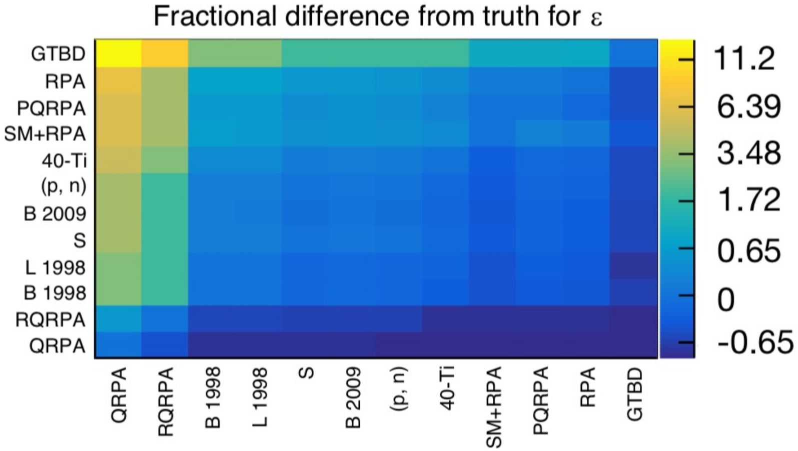


TABLE II. Parameter biases caused by uncertainties on the total cross section.

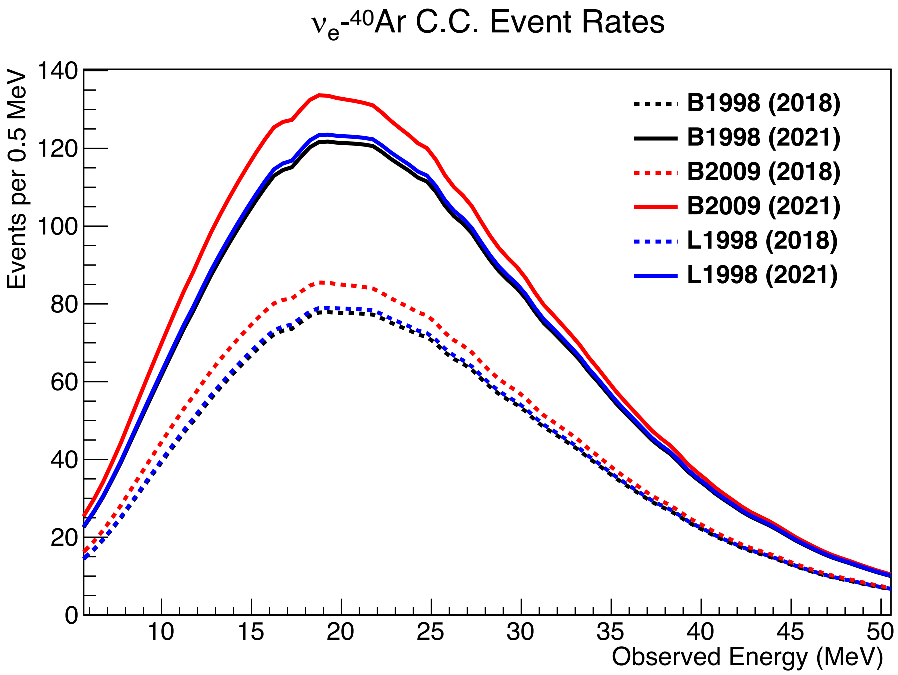
Parameter	Total cross section uncertainty shift	Parameter measurement bias
α	$\pm 20\%$	0% to $+8\%$
α	$-50/+100\%$	-80% to $+172\%$
$\langle E_\nu \rangle$	$\pm 20\%$	0% to $+2\%$
$\langle E_\nu \rangle$	$-50/+100\%$	-41.1% to $+47.4\%$
ε	$\pm 20\%$	-35% to $+50\%$
ε	$-50/+100\%$	-60% to $+100\%$

- 2D bias plots for fitting parameters
- Example: cross section models; most extreme cross section models yields -94% to +1400% bias on ε

- Ranges of biases in parameter measurements
- Example: Constant scaling factor on MARLEY (p, n) model

Status of paper

- Draft in Overleaf (similar to DUNE-doc-14068-v8)
- Received updated MARLEY cross-section files from S. Gardiner
- To do: reproduce plots, finalize draft



Backup slides

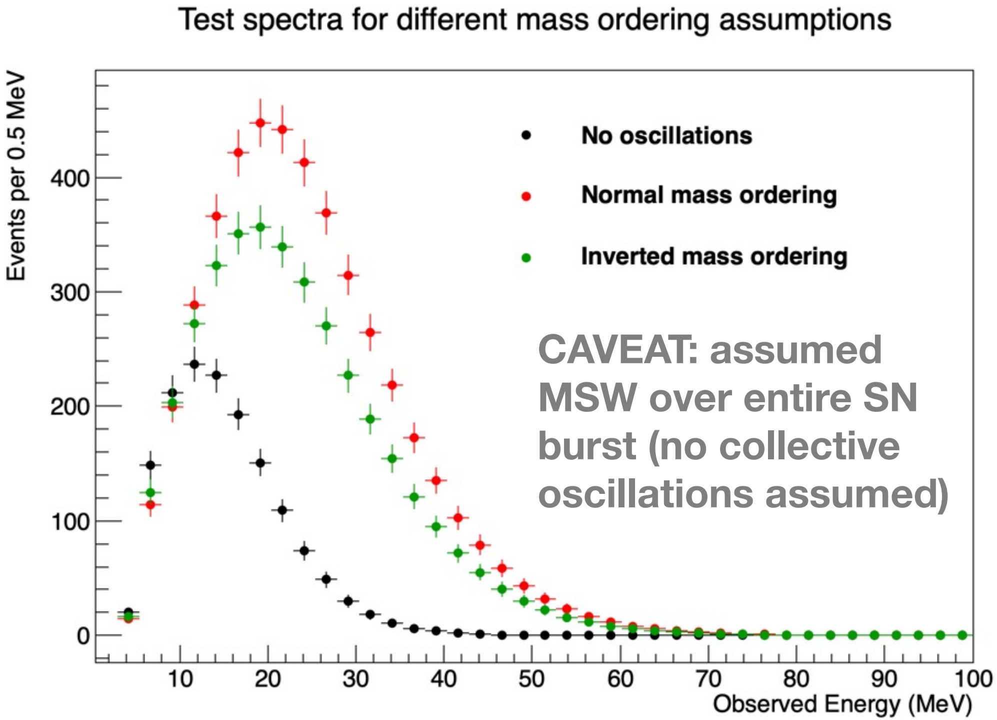
Study Assumptions

- Pure pinched-thermal flux
- 10 kpc supernova with no distance uncertainty
- Event rates integrated over 10 seconds
- Pure ν_eCC signal (i.e., channel tagging capability)
- Simple MSW effects, normal mass ordering, all neutrino flavors included

Introducing Mass Ordering Assumptions

- Used the following assumptions to build grids, test spectra:
  - $\alpha_{\nu_e} = \alpha_{\overline{\nu}_e} = \alpha_{\nu_x}$
  - $\langle E_\nu \rangle_{\nu_x} = 1.3 \langle E_\nu \rangle_{\overline{\nu}_e}$

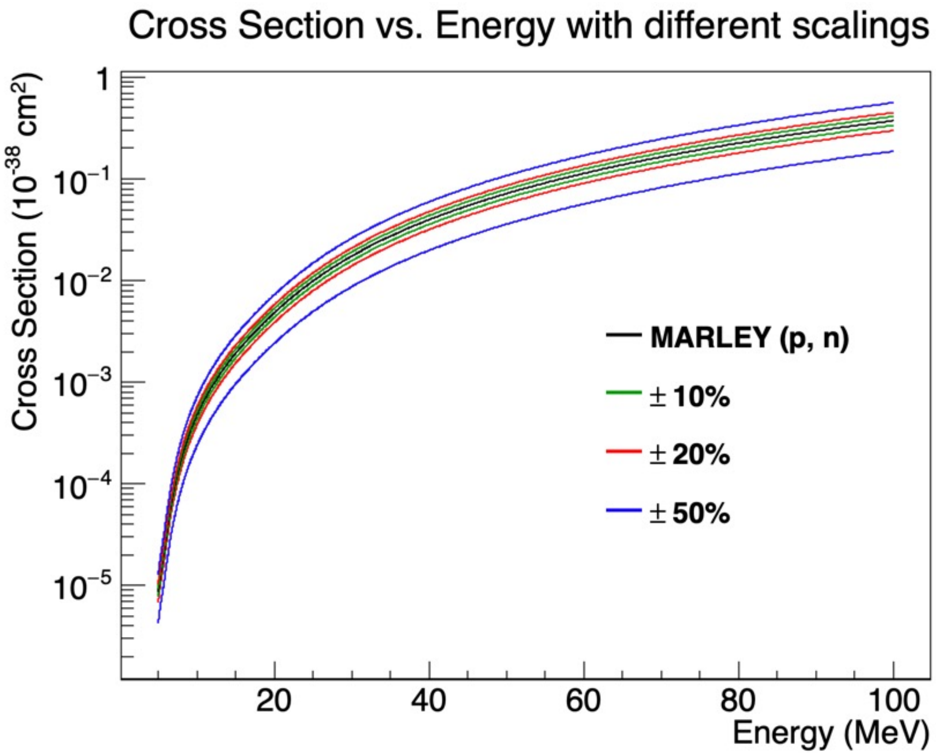
    $\langle E_\nu \rangle_{\overline{\nu}_e} = \frac{12.0}{9.5} \langle E_\nu \rangle_{\nu_e}$
  - $\varepsilon_{\nu_e} = \varepsilon_{\overline{\nu}_e} = \varepsilon_{\nu_x}$
- NMO swaps ν_e and ν_x fluxes (IMO does a partial swap), which is why the event rates increase when we introduce MO



CAVEAT: assumed MSW over entire SN burst (no collective oscillations assumed)

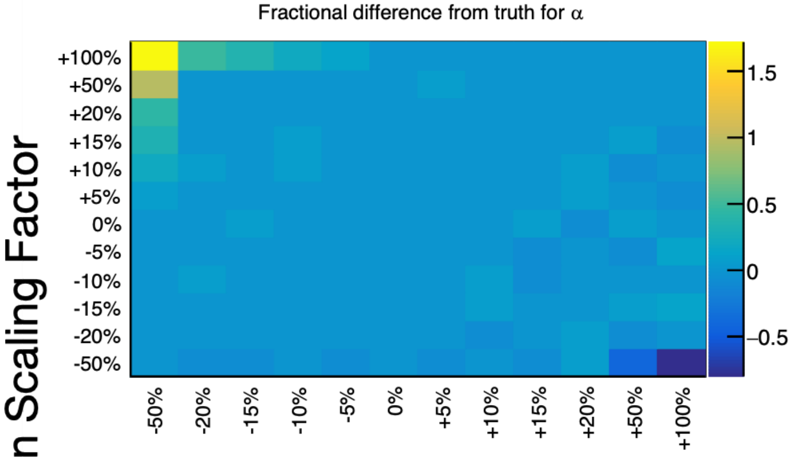
Cross Section Uncertainty: Introduction

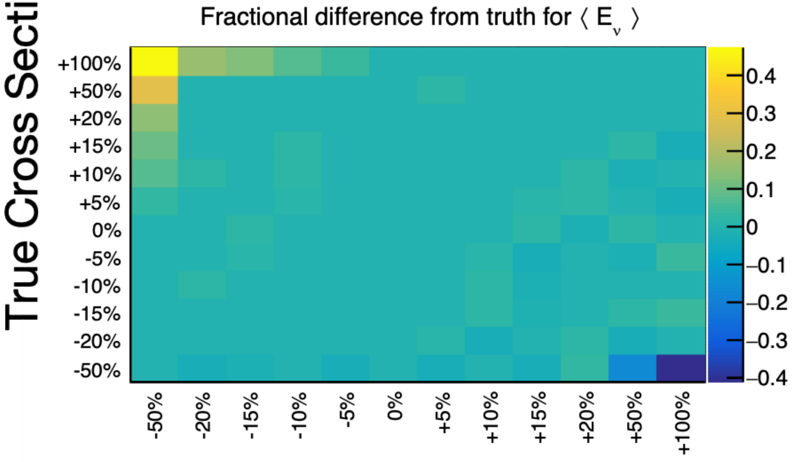
- Determine how uncertainties in the ν_e-^{40}Ar cross section affects parameter measurements – what if our assumptions are incorrect?
- Scale the cross section by $\pm 5\%, 10\%, 15\%, 20\%, 50\%, +100\% \rightarrow$ 12 different cross section "models"
  - Take every combination of test spectra (true) + grid (assumed) and determine the sensitivity regions, best-fit parameters

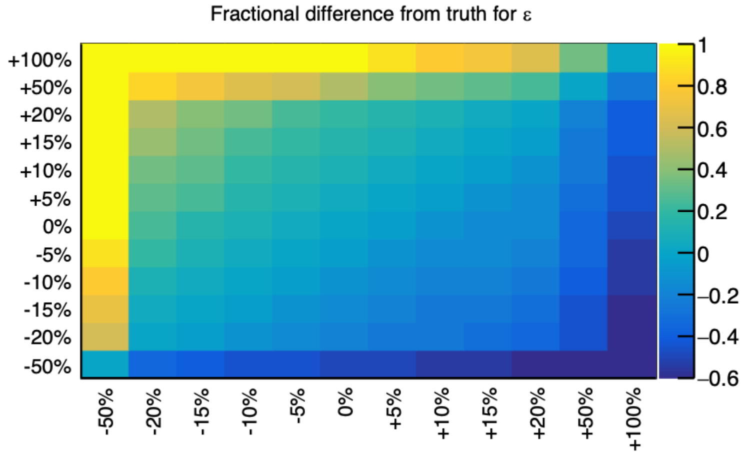


Fractional Difference Plot: Cross Section Uncertainty

- Color scale indicates best-fit parameter fractional difference from truth
- Relatively small bias on $\alpha, \langle E_\nu \rangle$
- $-50\%/+100\%$ shift in cross section yields:
  - -80% to +172% bias on α
  - -41.4% to +47.4 bias on $\langle E_\nu \rangle$
  - -60% to +100% bias on ε



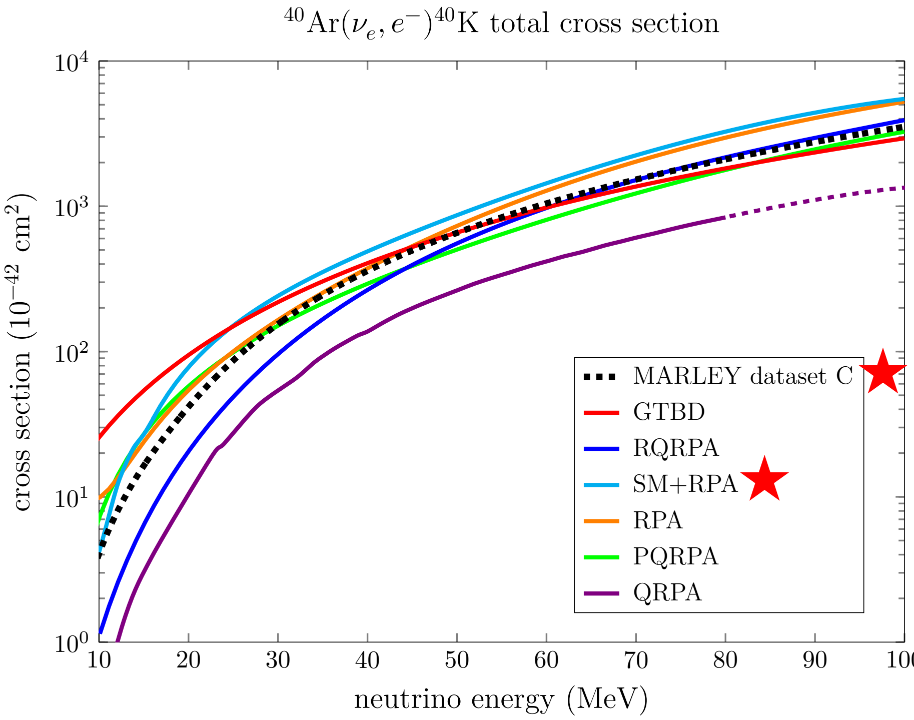




Assumed Cross Section Scaling Factor

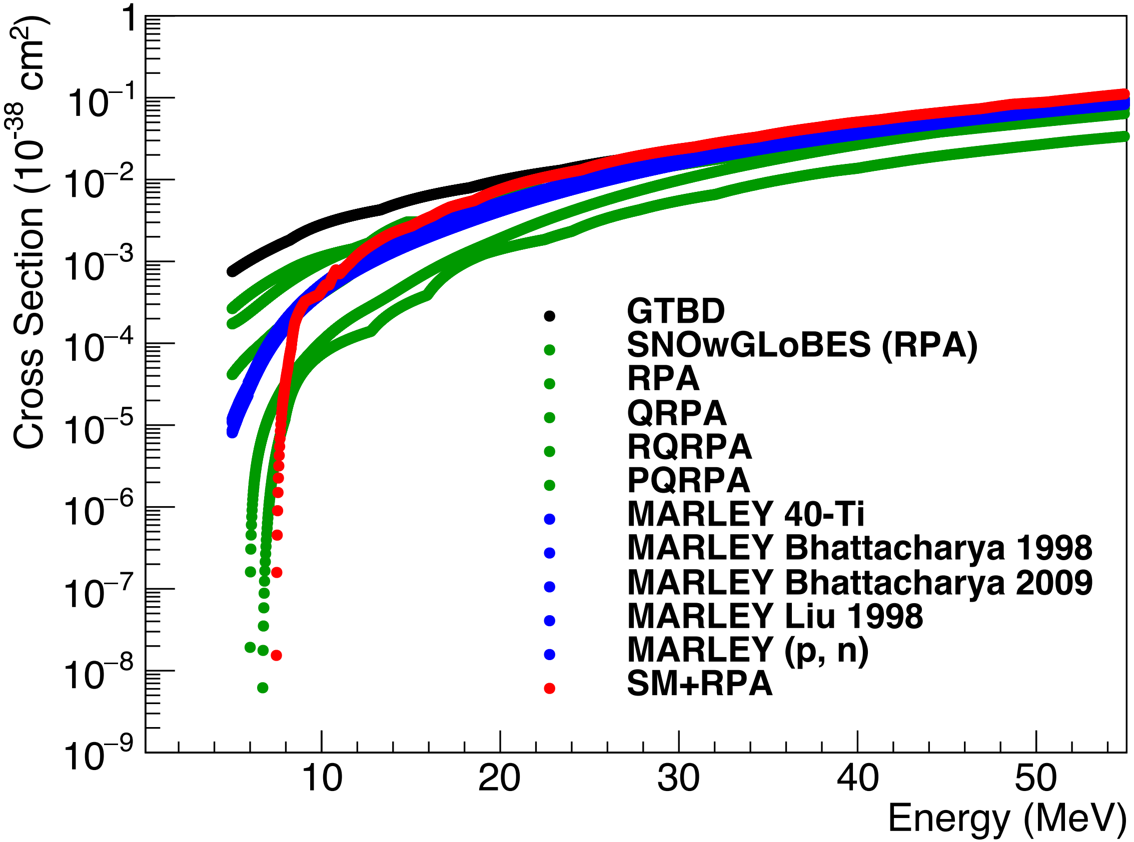
Studying ν_e-^{40}Ar Cross Section Models

- Understand impact of cross section model on parameter fitting algorithm and results
- Considered 12 cross section models calculated using different methods
  - Because these 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



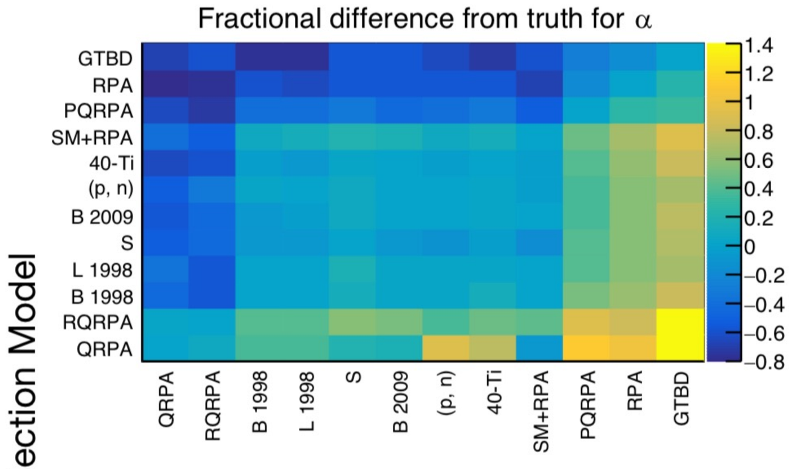
Reliability of these models:

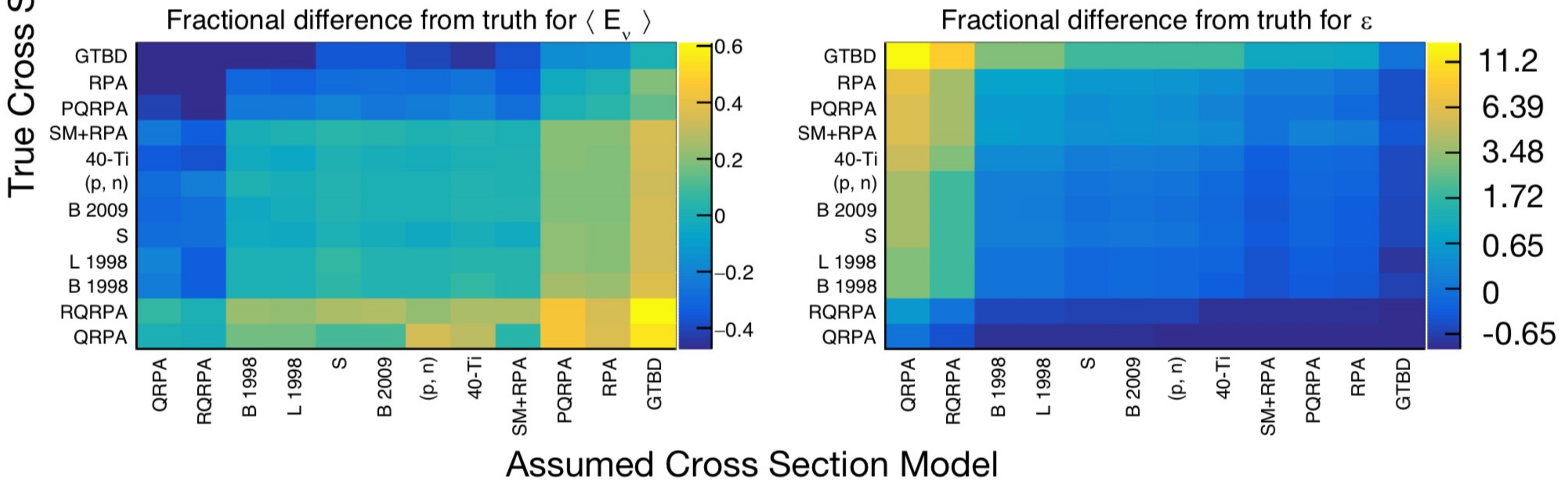
1. Blue curves: MARLEY partially data-driven filled in with QRPA, probably most reliable at low energies
2. Red curve: SM+RPA (hybrid approach with RPA) is considered most theoretically motivated
3. Green curves: RPA is preferred for the high energies (not explicitly defined) of SN ν_e according to paper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

See backup for references.

Fractional Difference Plot: Cross Section Models

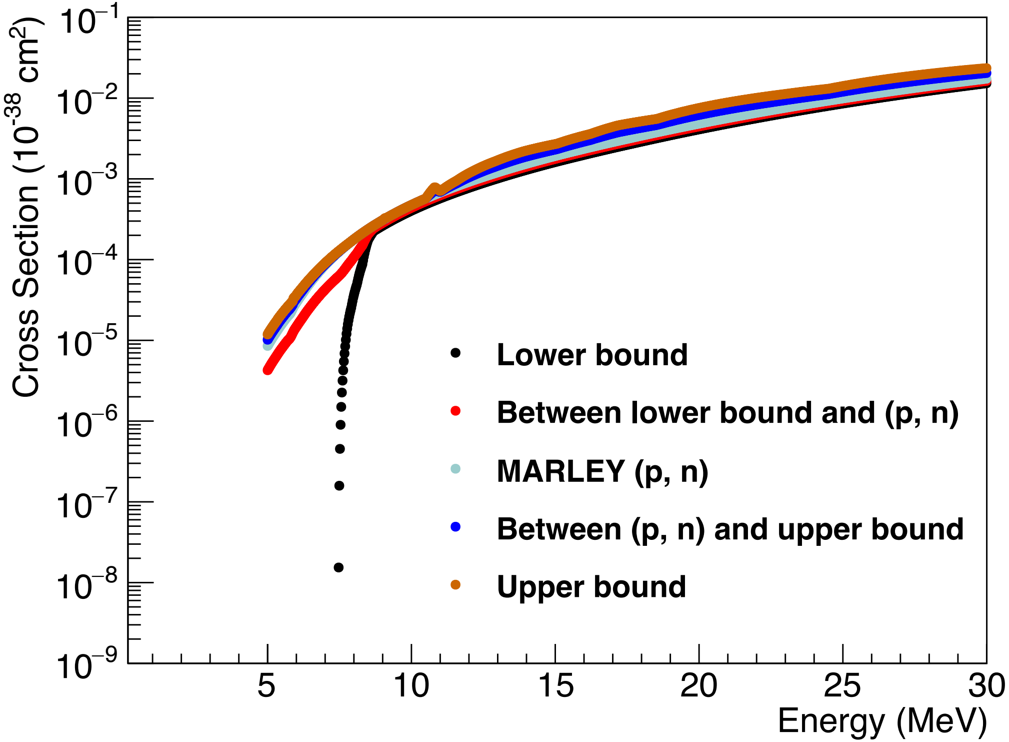
- Color scale indicates best-fit parameter fractional difference from truth
- Log for ε color scale; values are not log!
- Most extreme cross section models yields -94% to +1400% bias on ε, an improvement from no osc. (-94% to +5000%); still indicates that a cross section measurement would be very useful!

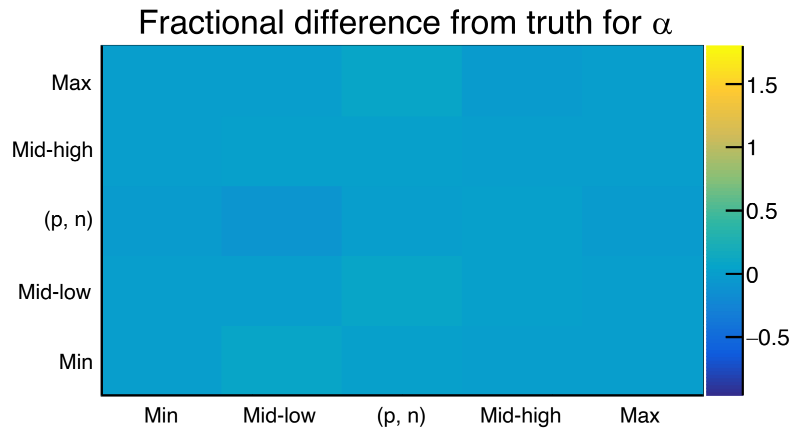




Cross section uncertainty envelope

- "Maximum" model used the largest cross section values between the reliable models; "minimum" models used the smallest values
  - Took averages between MARLEY (p, n) model and min/max values
  - Any weird behavior attributed to interpolation methods for SNOwGLoBES formatting
- Use these 5 models to study biases introduced by reasonable uncertainty range

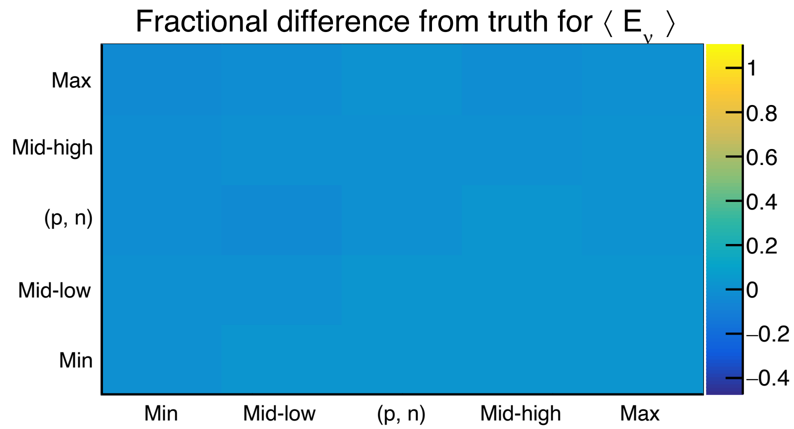


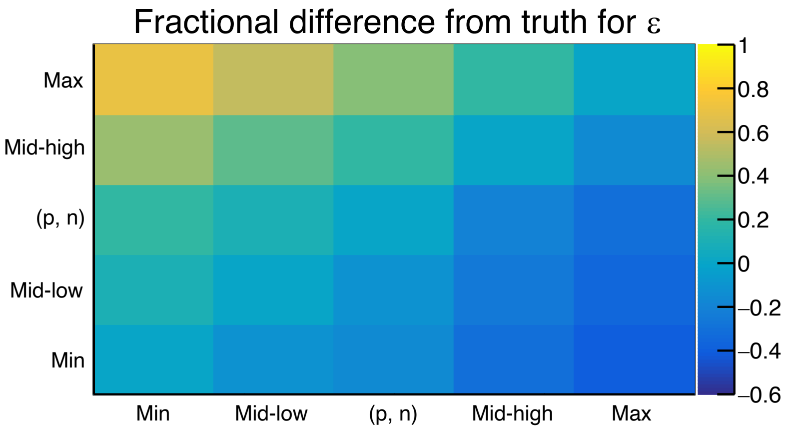


Studying cross section uncertainty envelope

- For pinched-thermal flux, NMO assumptions, 10 kpc supernova
- Color-scale hopefully useful in showing that ε impacted more than α, $\langle E_\nu \rangle$ in this study
- Largest shift (between min/max) in cross section model yields:
  - 0% bias in α (maximum bias: $\pm 8\%$)
  - $\pm 3.16\%$ bias in $\langle E_\nu \rangle$
  - -40% to $+70\%$ bias in ε

True Cross Section Model





Assumed Cross Section Model

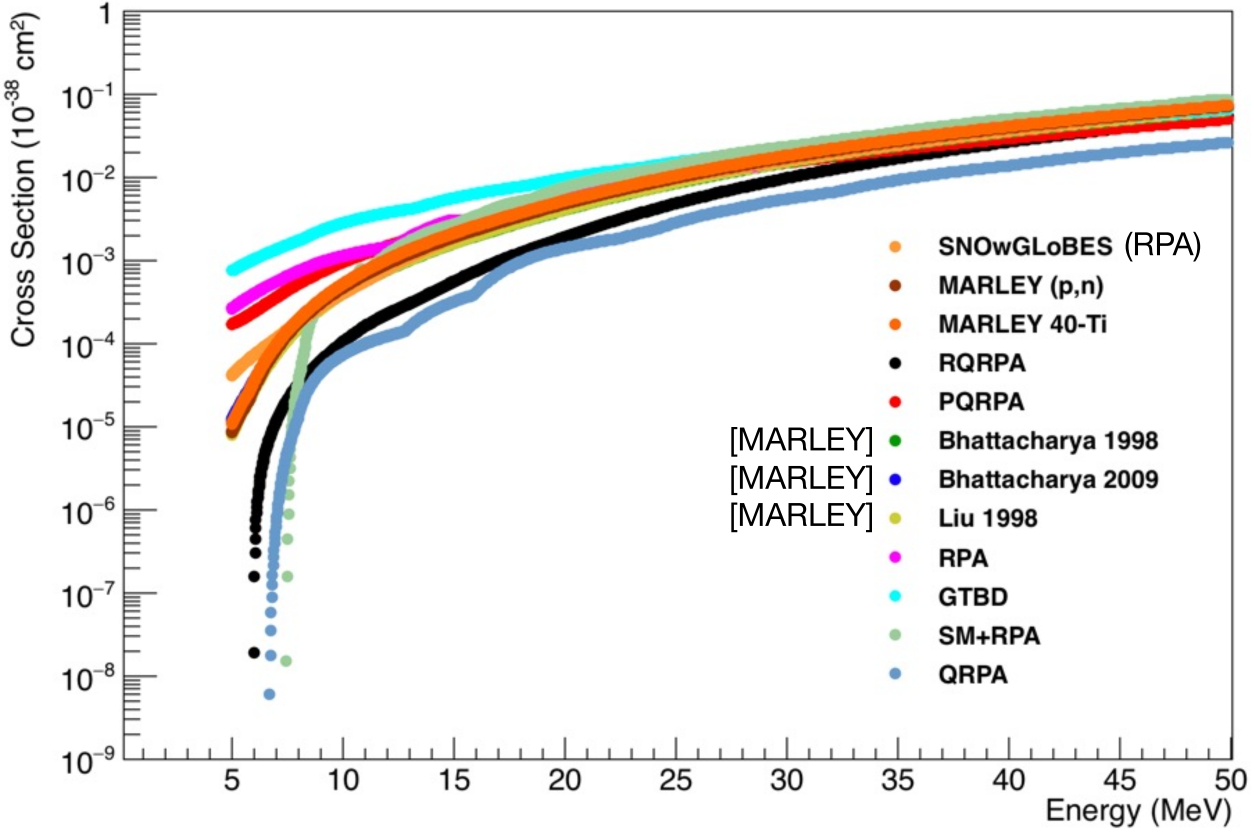
RPA References

- 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

SNOwGLoBES-Formatted Cross Sections



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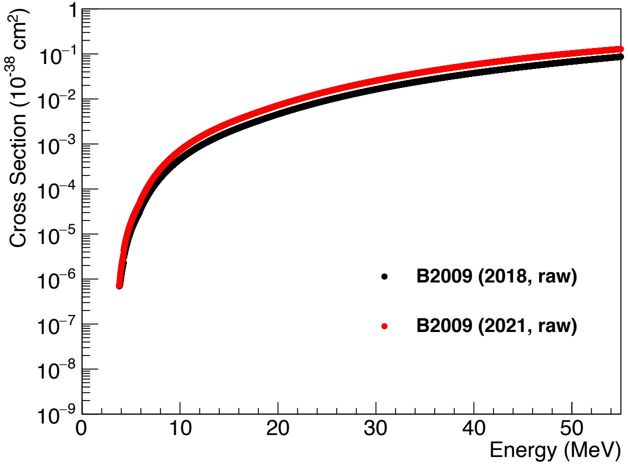
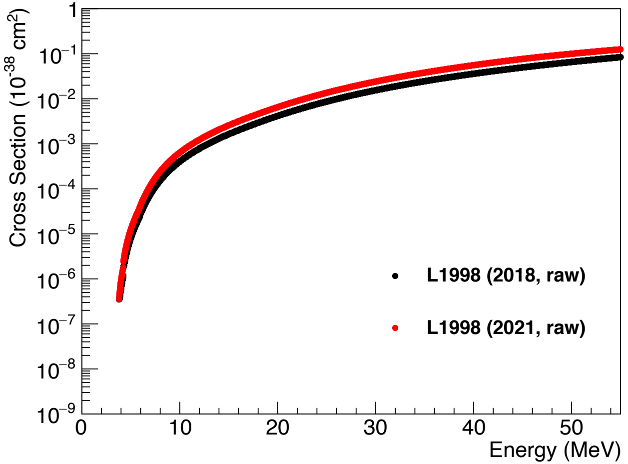
Formatting for SNOwGLoBES

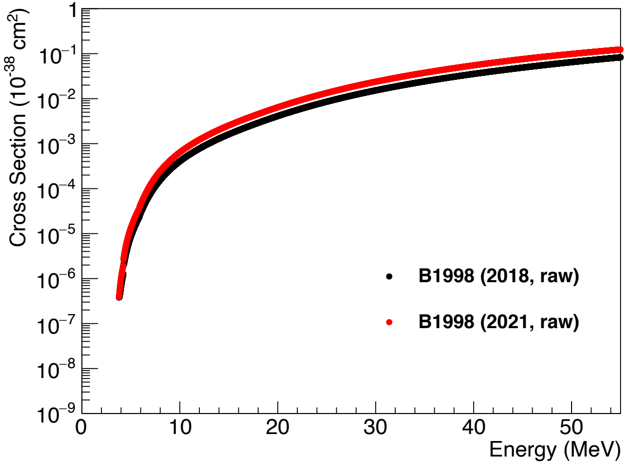
- Used interpolation, extrapolation to format cross section models for usage in SNOwGLoBES
  - Interpolation using ROOT Eval function (uses TSpline)
  - Quadratic fit for extrapolation: $\sigma = p_0(E - p_1)^2$
    - Remove discontinuities by forcing fit through first data point
- See technical note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

Raw xscn files

Calculations done by Bhattacharya (1998, 2009), Liu (1998)







Files obtained in 2021 contain larger values than files obtained in 2018…likely due to bug that incorrectly applied Coulomb corrections

Event rates

Cross section model	SNOwGLoBES ν_eCC event rates
Bhattacharya 1998 (obtained 2018)	4017.16
Bhattacharya 1998 (obtained 2021)	6251.91
Bhattacharya 2009 (obtained 2018)	4363.28
Bhattacharya 2009 (obtained 2021)	6789.67
Liu 1998 (obtained 2018)	4070.26
Liu 1998 (obtained 2021)	6334.59