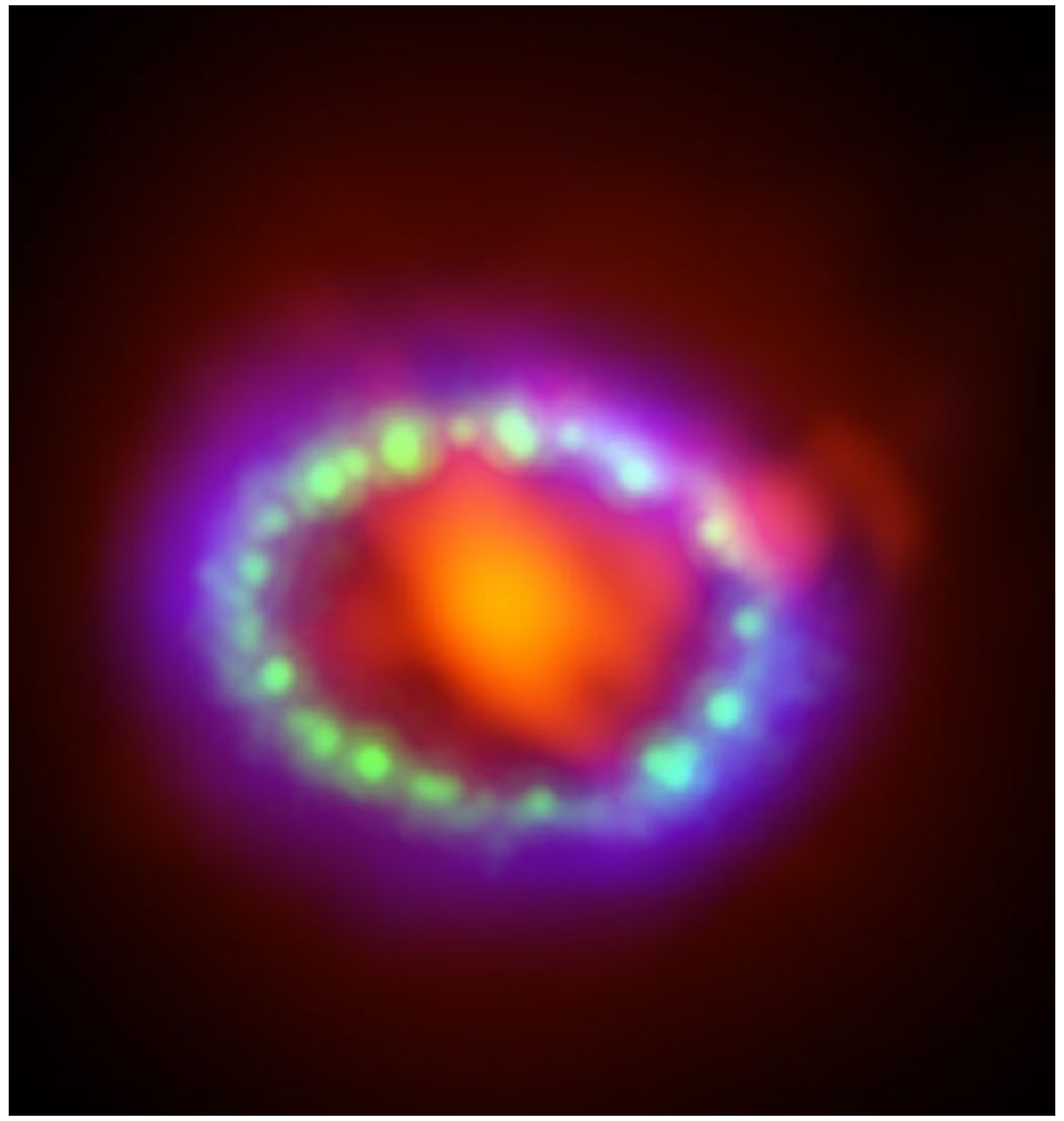
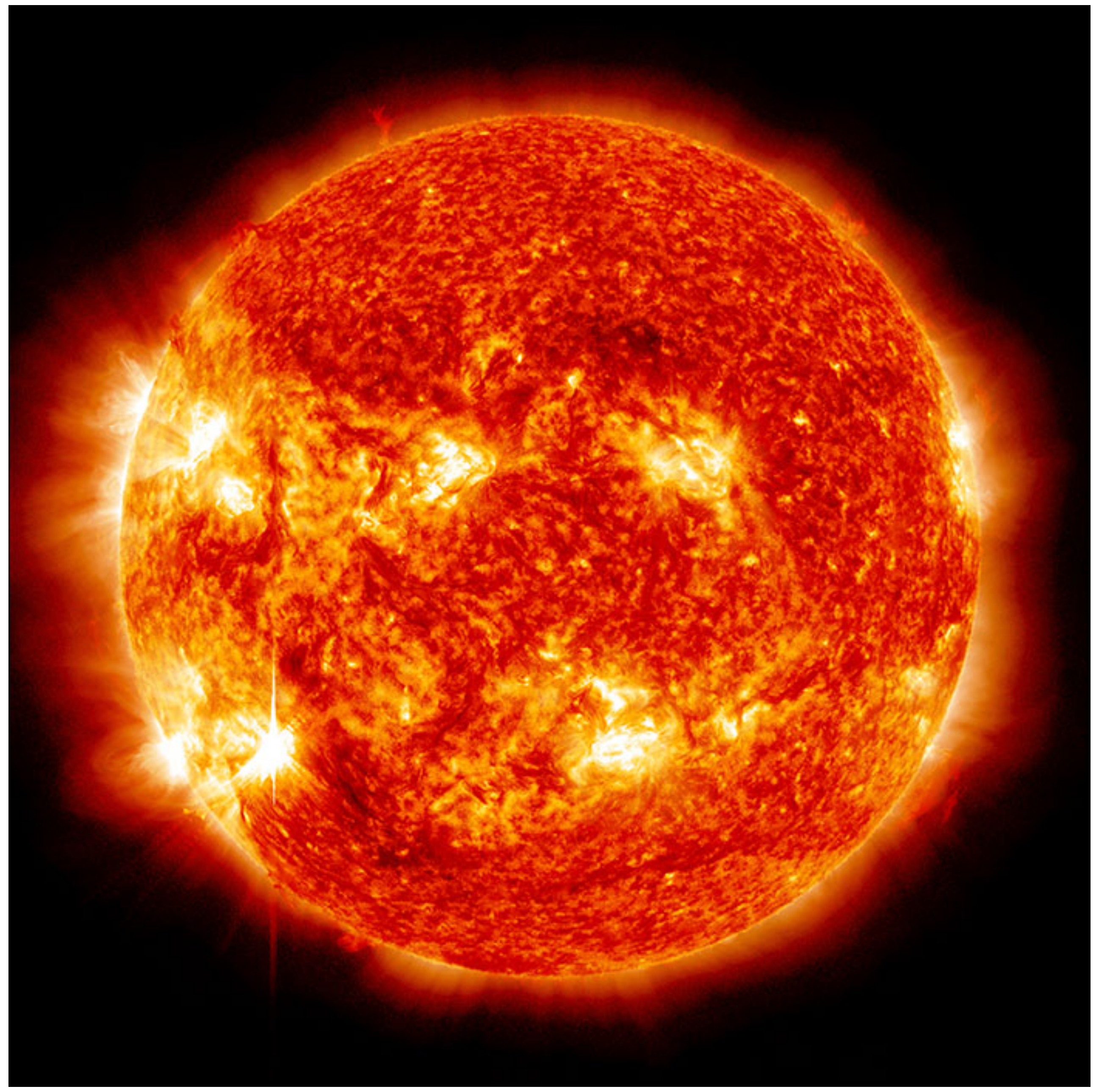
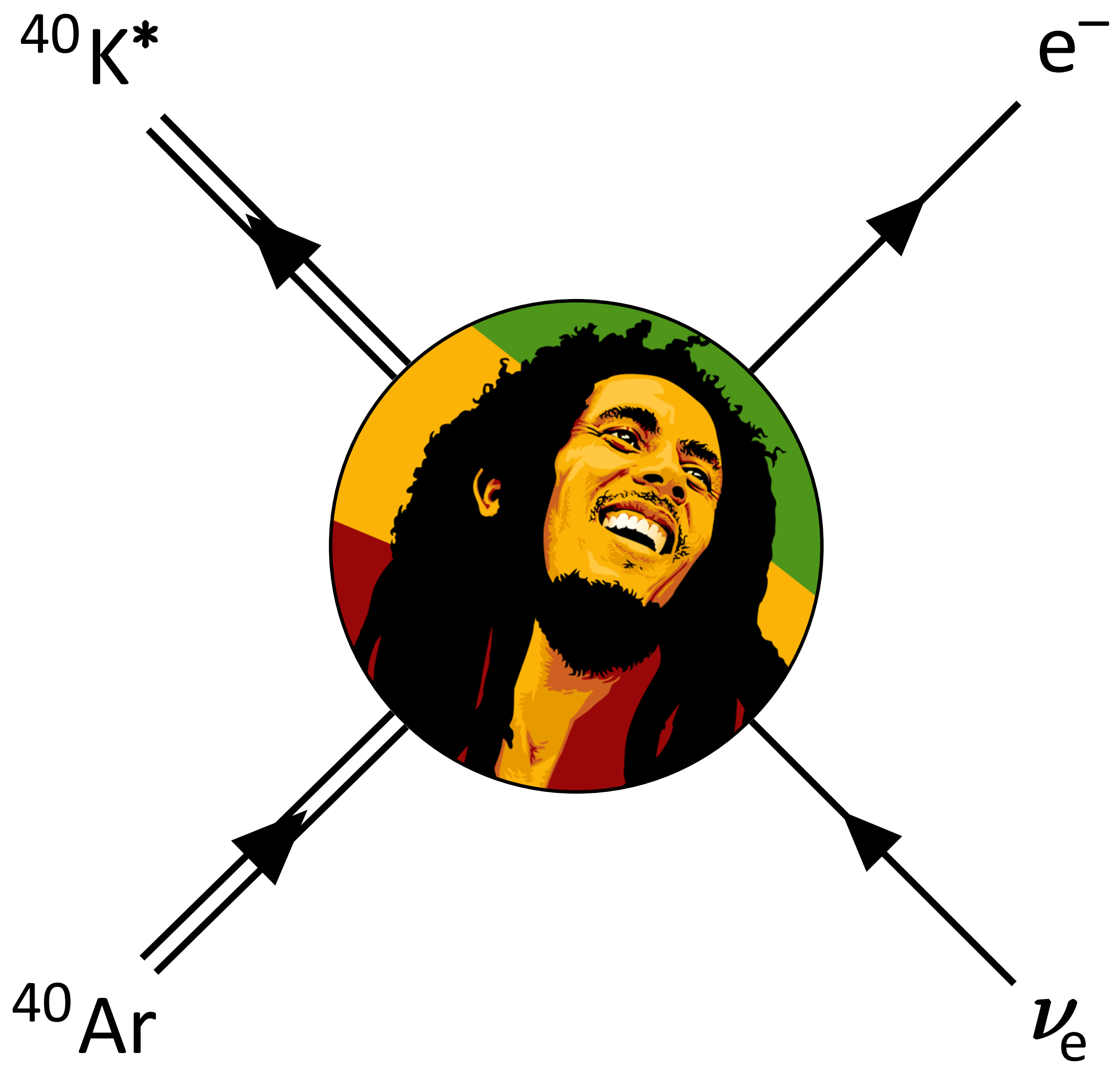
Event generators for low-energy neutrino-nucleus scattering





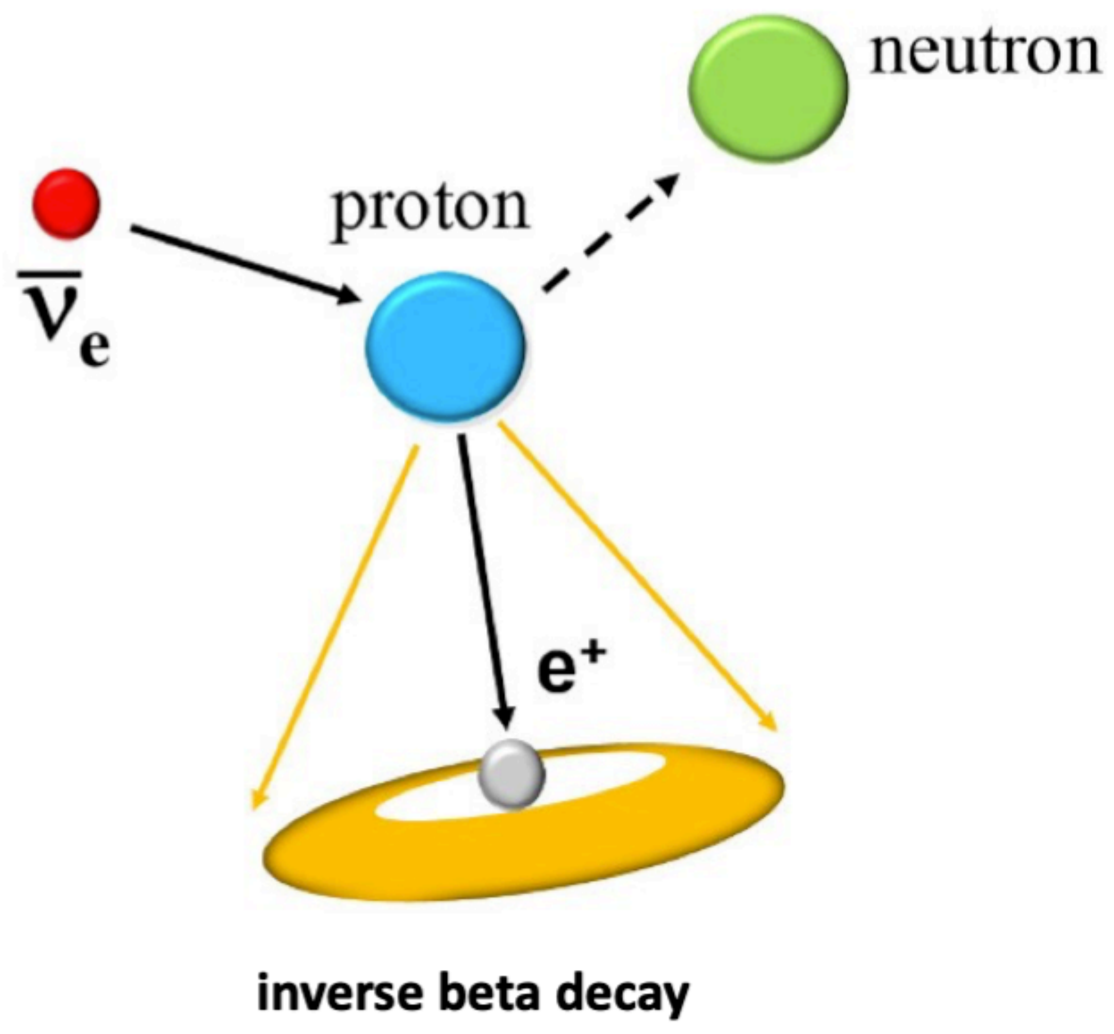


Steven Gardiner

LEPLAr Workshop
1 December 2020

Event generators for low-energy neutrino scattering

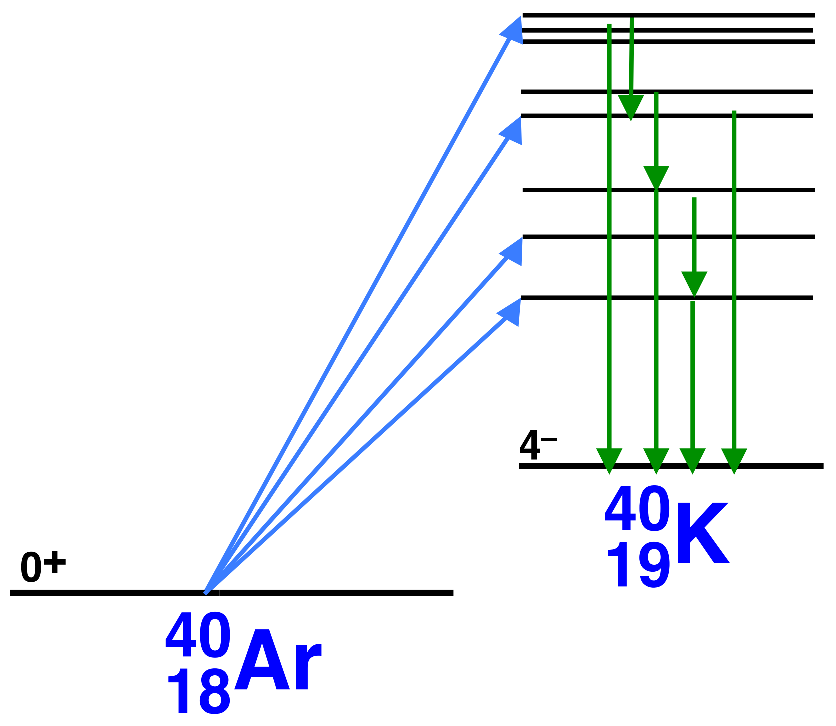
- "Bridge" between theory and experiment: model predictions are made easily usable
- Analyses lean heavily on a neutrino generator for a variety of tasks
  - **Neutrino calorimetry**
  - Efficiencies and backgrounds
  - Systematic uncertainties
- High-quality modeling critical at low energies just as it is for the GeV scale
- ~0-75 MeV neutrinos focus of this talk
  - Inelastic scattering on a complex nucleus (Ar)
  - IBD, CEvNS much simpler from a generator perspective



Outgoing e+ energy | Neutron proton mass difference | Recoil energy of neutron (negligible)

$$E_{\bar{\nu}} = E_e + \Delta + K_{\text{recoil}}$$

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



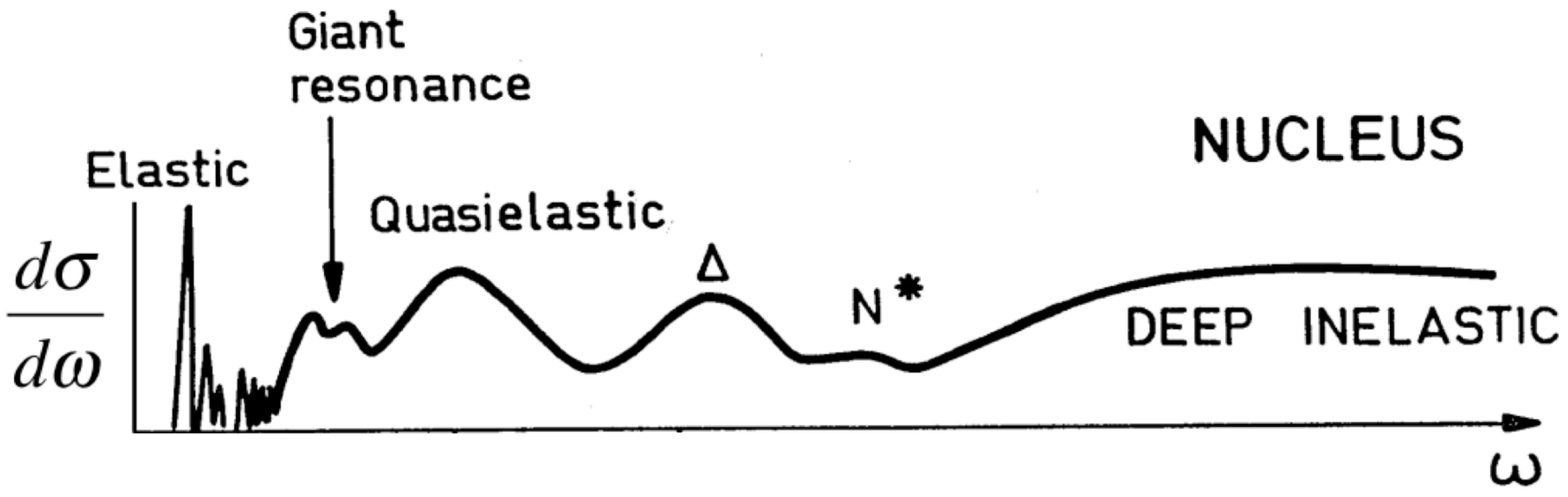
Low-energy calorimetry is challenging in DUNE due to nuclear physics

Outgoing e- Energy | Energy donated to transition | Recoil Energy of Nucleus (negligible)

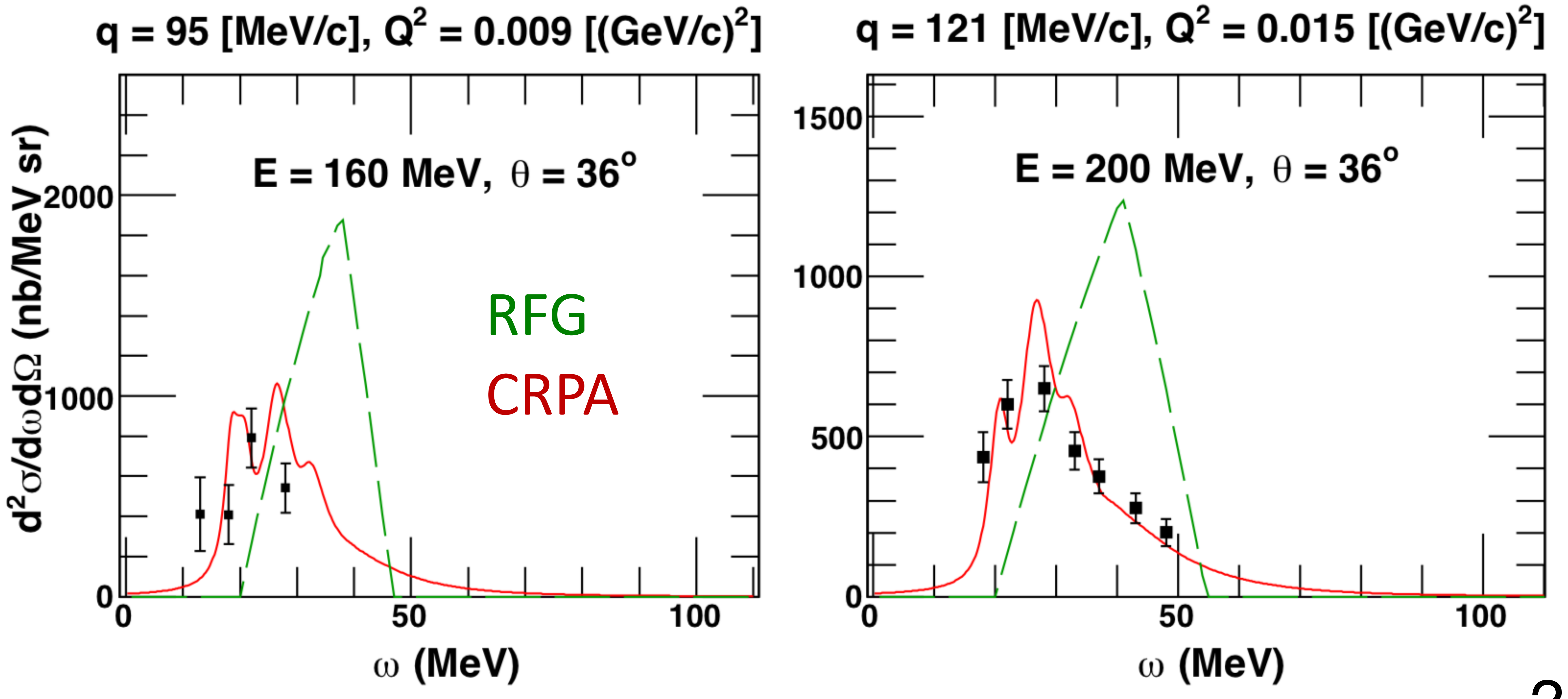
$$E_\nu = E_e + Q + K_{\text{recoil}}$$

Why not just use GENIE/GiBUU/NEUT/NuWro?

- Well-exercised tools designed for higher neutrino energies
  - Standard approximations break down as we move toward ~10 MeV
- Variants of a **Fermi gas** are the "traditional" nuclear model
  - Neglects discrete level structure, giant resonance excitations
  - Few-MeV transitions can't be neglected at 15 MeV like they can at 1 GeV
- Impact can also be seen in ~200 MeV electron data

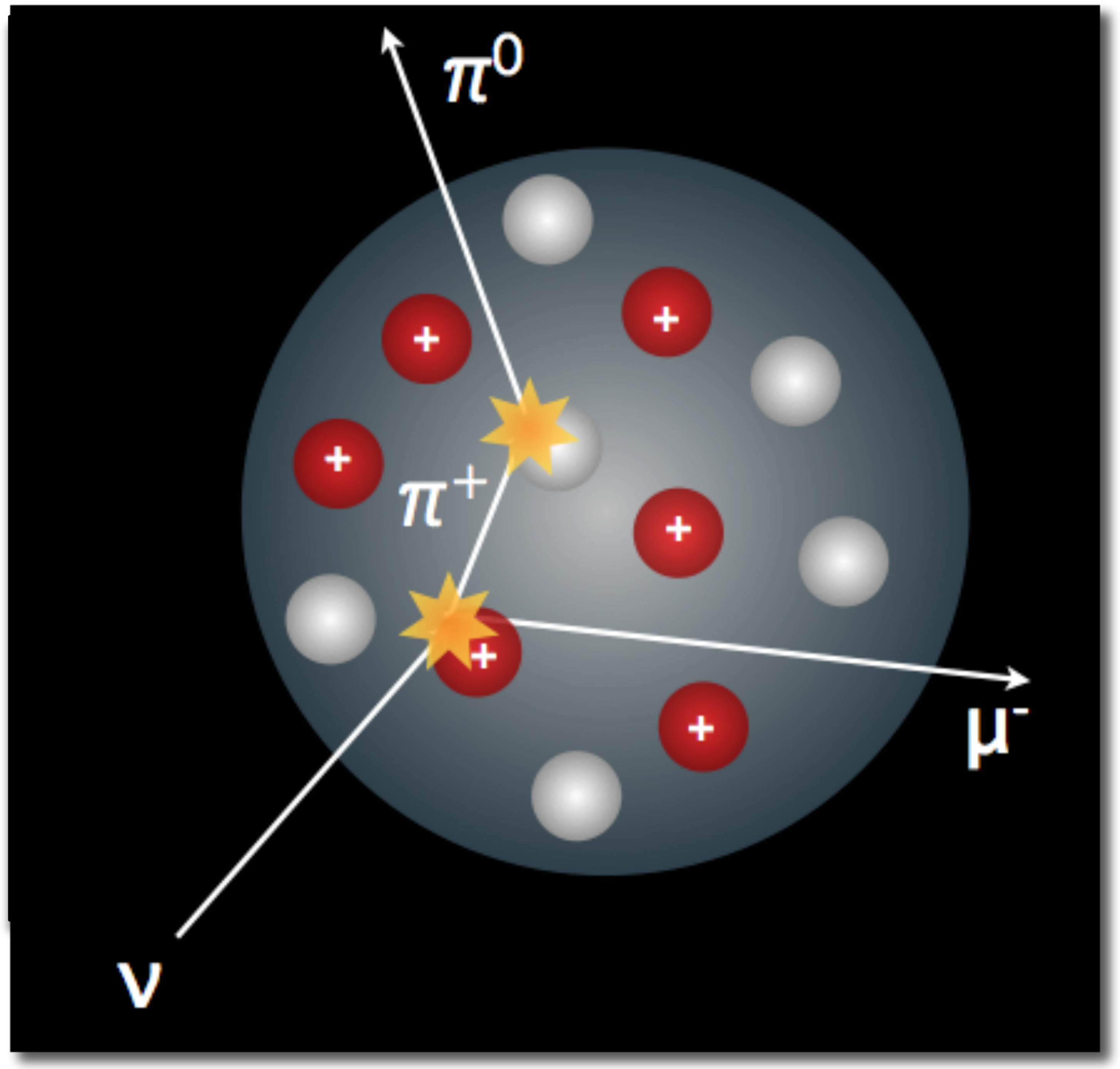


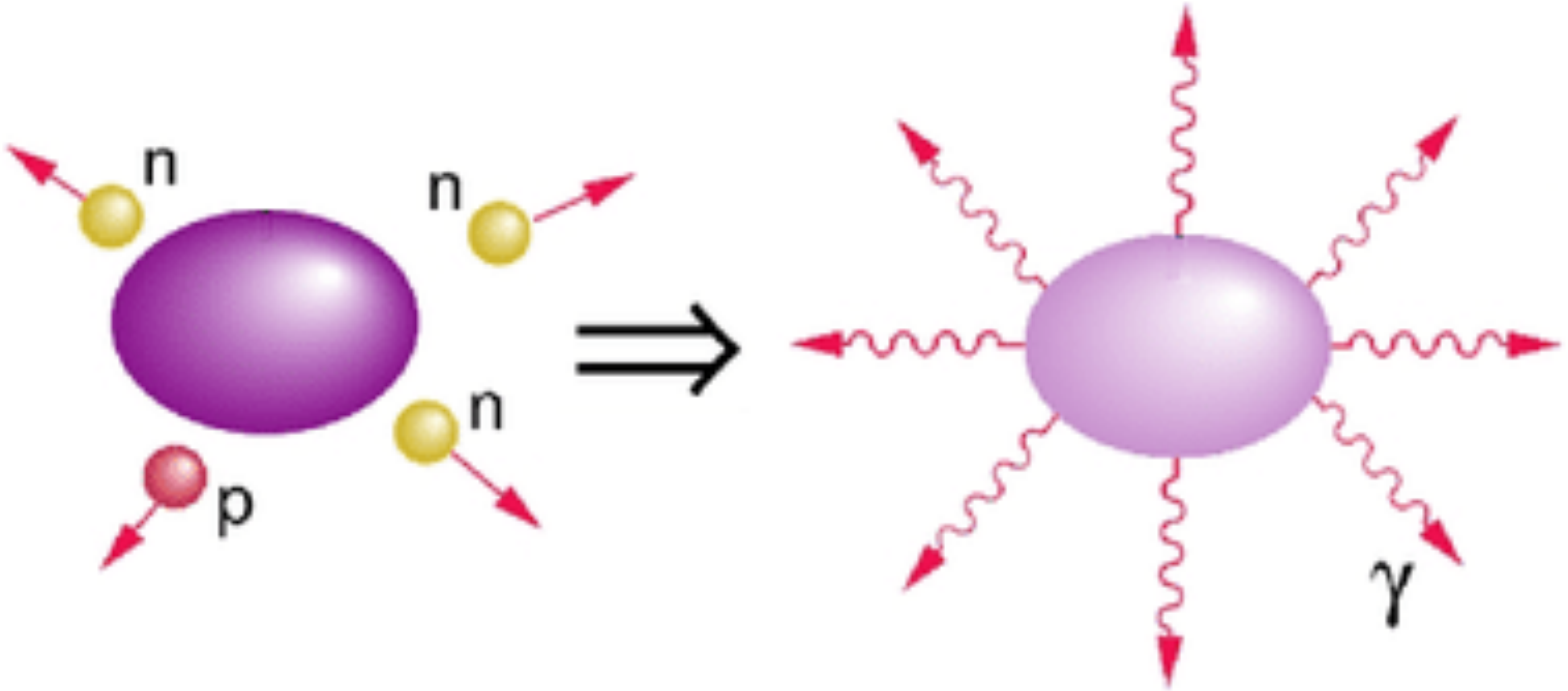
(e,e') scattering on ^{12}C, V. Pandey, NuInt 18



Why not just use GENIE/GiBUU/NEUT/NuWro?

- Treatment of final-state interactions is also different
- High-energy approaches rely primarily on a **direct knockout** picture
  - Transport outgoing hadrons through the nucleus
  - Dynamical models: intranuclear cascade (GENIE, NEUT, NuWro) or BUU transport (GiBUU)
- Low-energy literature typically uses a **compound nucleus** picture
  - Energy transfer widely shared, leading to equilibration and “boil off” of nucleons
  - Statistical models: Weisskopf-Ewing, Hauser-Feshbach
- Limited modeling of de-excitation γ-rays in high-energy generators (FLUKA most complete?)





What other generators are available for low energies?

- Emerging part of the field. I'm aware of three that attempt to handle inelastic ν-A scattering below 100 MeV:
- **sntools** (^{12}C, ^{16}O)
  - J. Migenda, arXiv:2002.01649
  - https://github.com/JostMigenda/sntools
- **newton** (^{16}O)
  - B. Bodur, K. Scholberg, talk at APS DNP 2020
  - https://github.com/itscubist/newton
- **MARLEY** (**^{40}Ar**, some others under development)
  - S. Gardiner, arXiv:2010.02393
  - https://www.marleygen.org

Nuclear de-excitations in low-energy charged-current ν_e scattering on ^{40}Ar

Steven Gardiner[1,2,*]

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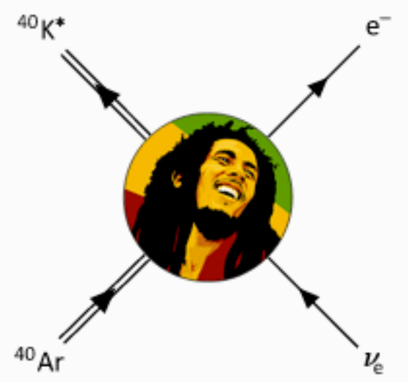
(Dated: September 15, 2020)

Background: Large argon-based neutrino detectors, such as those planned for the Deep Underground Neutrino Experiment (DUNE), have the potential to provide unique sensitivity to low-energy (~10 MeV) electron neutrinos produced by core-collapse supernovae. Despite their importance for neutrino energy reconstruction, nuclear de-excitations following charged-current ν_e absorption on ^{40}Ar have never been studied in detail at supernova energies.

Purpose: I develop a model of nuclear de-excitations that occur following the $^{40}\text{Ar}(\nu_e, e^-)^{40}\text{K}^*$ reaction. This model is applied to the calculation of exclusive cross sections.

Methods: A simple expression for the inclusive differential cross section is derived under the allowed approximation. Nuclear de-excitations are described using a combination of measured γ-ray decay schemes and the Hauser-Feshbach statistical model. All calculations are carried out using a novel Monte Carlo event generator called MARLEY (Model of Argon Reaction Low Energy Yields).

MARLEY User Guide



Model of Argon Reaction Low Energy Yields

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- Getting started
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- Bibliography
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Docs / Overview

Overview

MARLEY (Model of Argon Reaction Low Energy Yields) is a Monte Carlo event generator for neutrino-nucleus interactions at energies of tens-of-MeV and below. The current version computes inclusive neutrino-nucleus cross sections employing the *allowed approximation*: the nuclear matrix elements are evaluated while neglecting Fermi motion and applying the long-wavelength (zero momentum transfer) limit. De-excitations of the final-state nucleus emerging from the primary interaction are simulated using a combination of tabulated γ-ray decay schemes and an original implementation of the Hauser-Feshbach statistical model.

Input files are provided with the code that are suitable for simulating the charged-current process

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

coherent elastic neutrino-nucleus scattering (CEvNS) on spin-zero target nuclei, and neutrino-electron elastic scattering on any atomic target. Inclusion of additional reactions and targets is planned for the future.

The material presented here focuses on the practical aspects of MARLEY: installing the code, configuring and running simulations, and analyzing the output events. For more details on the MARLEY physics models, please see the references in the online bibliography.

MARLEY follows an open-source development model and welcomes contributions of new input files and code improvements from the community. A partial list of potential projects for future MARLEY development is available on the developer documentation webpage.

MARLEY cross section model (1)

Neutrino-nucleus reaction treated as a **two-step process**. In the first step, inclusive scattering on the nucleus is simulated.

$$\frac{d\sigma}{d\cos\theta_\ell} = \frac{G_F^2}{2\pi} \underbrace{\mathscr{F}_{CC}}_{\text{Charged current factor}} \underbrace{\left[\frac{E_i\,E_f}{s}\right]}_{\text{Recoil factor}} E_\ell\,|\mathbf{p}_\ell| \left[\left(1+\beta_\ell\cos\theta_\ell\right) B(\mathrm{F}) + \left(1-\frac{1}{3}\beta_\ell\cos\theta_\ell\right) B(\mathrm{GT})\right]$$

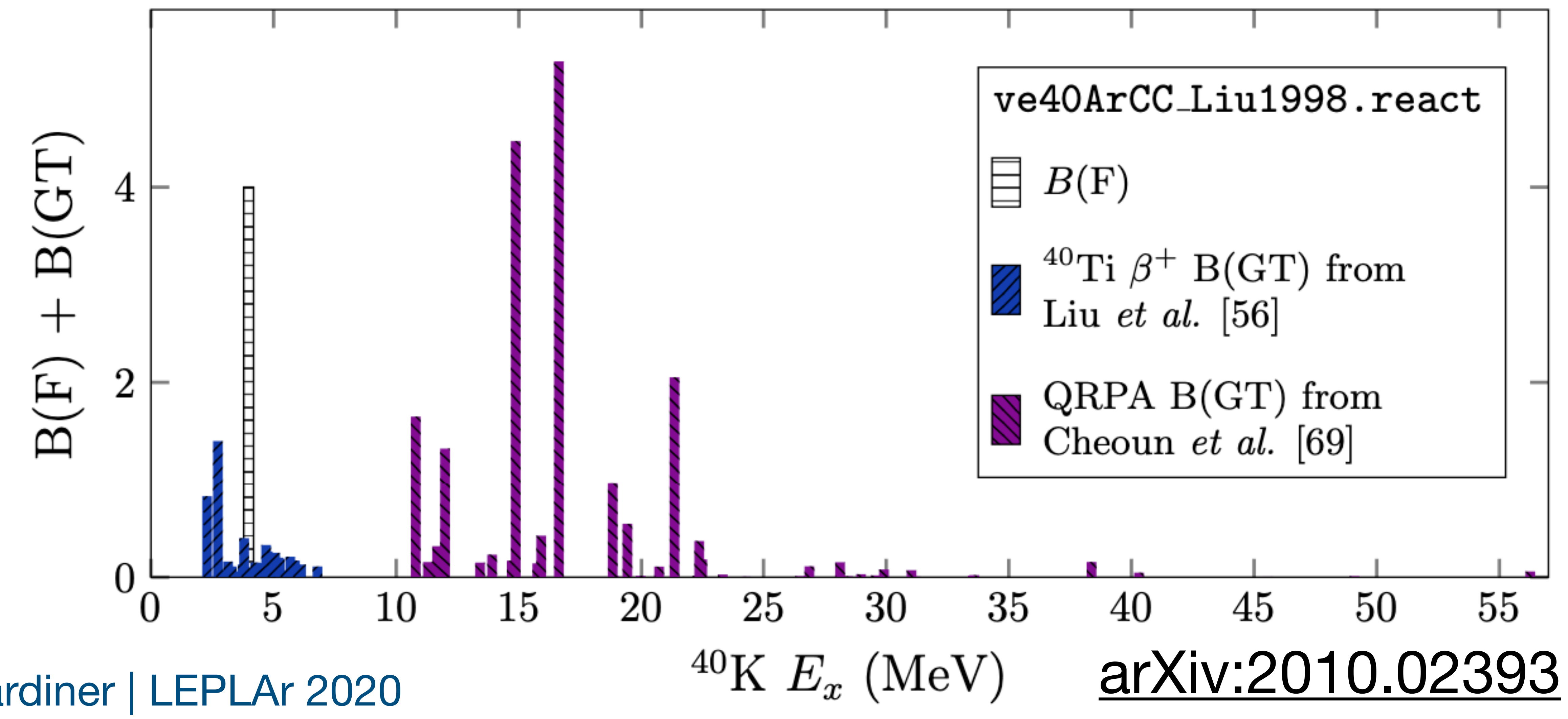
Allowed nuclear matrix elements

Expression above obtained under the impulse approximation (no 2p2h) and the **allowed approximation**

Long-wavelength limit: $q \to 0$

Slow nucleon limit: $\frac{|\mathbf{p}_{N_i}|}{m_N} \to 0$

Nuclear matrix elements must be supplied as input. For ^{40}Ar, they are based on a combination of **indirect measurements** (e.g., mirror β decay) and a **QRPA calculation**



arXiv:2010.02393

MARLEY cross section model (2)

Charged-current factor contains CKM matrix element and a Coulomb correction factor F_C. MARLEY handles Coulomb corrections using a combination of the Fermi function and the Modified Effective Momentum Approximation (MEMA).

$$\mathcal{F}_{CC} \equiv \begin{cases} |V_{ud}|^2 F_C & \text{CC} \\ 1 & \text{NC} \end{cases}$$

See J. Engel, Phys. Rev. C 57, 2004 (1998)

The code can handle **allowed matrix elements** for ν_e CC, $\bar{\nu}_e$ CC, and NC, but only inputs for ν_e CC are currently provided "out of the box"

$$\mathcal{O}_\mathrm{F} \equiv \begin{cases} \sum_{n=1}^{A} t_\pm(n) & \text{CC} \\ Q_W/2 & \text{NC} \end{cases}$$

$$B(\mathrm{F}) \equiv \frac{g_V^2}{2J_i+1} \left| \langle J_f \,\|\, \mathcal{O}_\mathrm{F} \,\|\, J_i \rangle \right|^2$$

$$B(\mathrm{GT}) \equiv \frac{g_A^2}{2J_i+1} \left| \langle J_f \,\|\, \mathcal{O}_\mathrm{GT} \,\|\, J_i \rangle \right|^2$$

$$\mathcal{O}_\mathrm{GT} \equiv \begin{cases} \sum_{n=1}^{A} \boldsymbol{\sigma}(n)\, t_\pm(n) & \text{CC} \\ \sum_{n=1}^{A} \boldsymbol{\sigma}(n)\, t_3(n) & \text{NC} \end{cases}$$

MARLEY nuclear de-excitation model

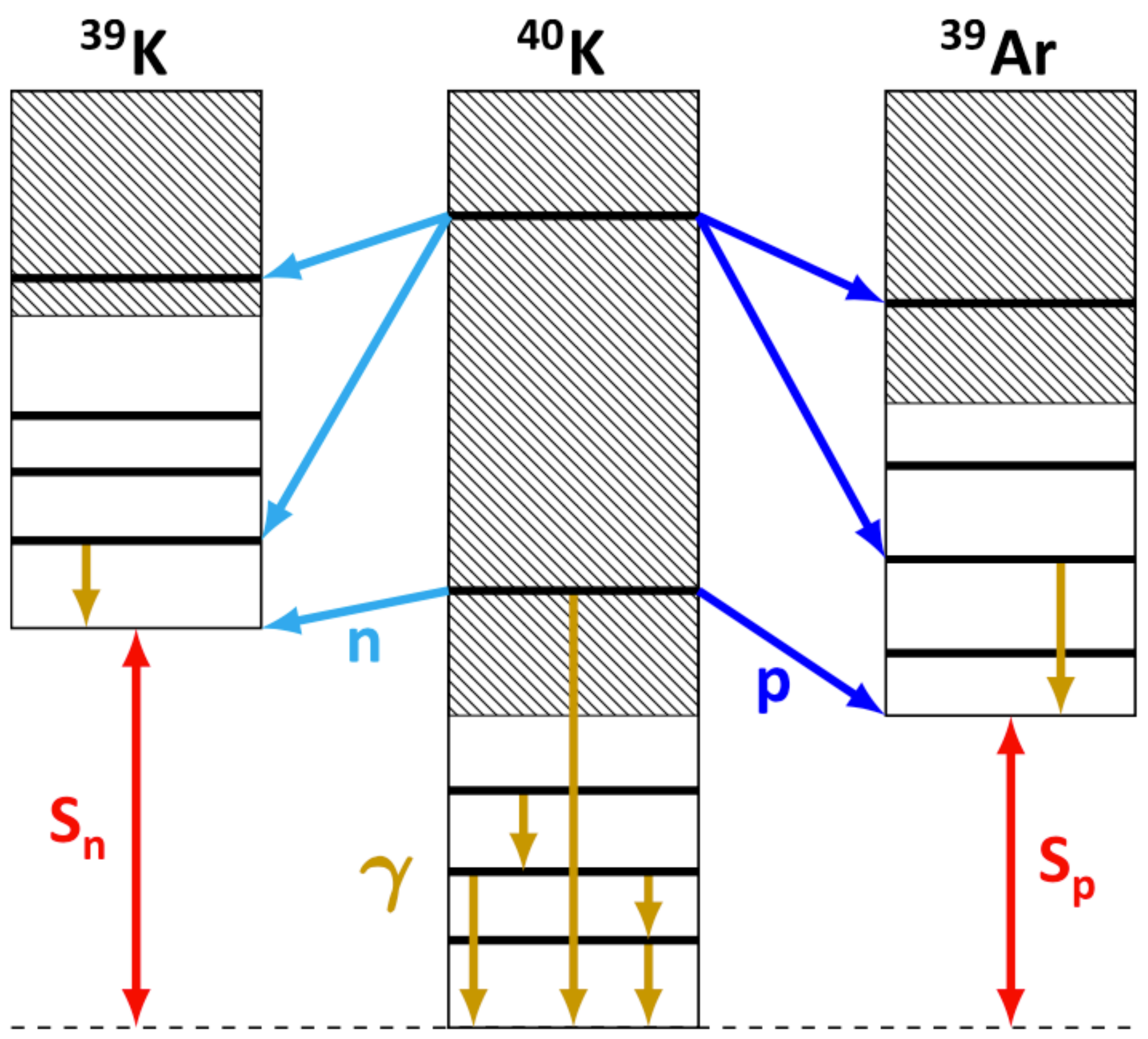
In the second step, the nucleus de-excites via a series of binary decays. Decay widths for **unbound states** are computed according to the Hauser-Feshbach formalism:

Differential decay width for emission of a nuclear fragment α (A ≤ 4 considered)

$$\frac{d\Gamma_\alpha}{dE_x'} = \frac{1}{2\pi\rho_i(E_x, J, \Pi)} \sum_{\ell=0}^{\ell_{\max}} \sum_{j=|\ell-s|}^{\ell+s} \sum_{J'=|J-j|}^{J+j} T_{\ell j}(\varepsilon)\, \rho_f(E_x', J', \Pi')$$

Differential decay width for emission of a γ-ray

$$\frac{d\Gamma_\gamma}{dE_x'} = \frac{1}{2\pi\rho_i(E_x, J, \Pi)} \sum_{\lambda=1}^{\lambda_{\max}} \sum_{J'=|J-\lambda|}^{J+\lambda} \sum_{\Pi'\in\{-1,1\}} T_{X\lambda}(E_\gamma)\, \rho_f(E_x', J', \Pi')$$



Level density model: Back-shifted Fermi gas (RIPL-3), Nucl. Data Sheets 110, 3107–3214 (2009)

Nuclear optical model: Koning & Delaroche, Nucl. Phys. A 713, 231–310 (2003)

Gamma-ray strength function model: Standard Lorentzian (RIPL-3), Nucl. Data Sheets 110, 3107–3214 (2009)

Supplemented with tabulated discrete levels and γ-rays for **bound states** (taken from TALYS 1.6). Transitions from continuum to all accessible levels are explicitly treated.

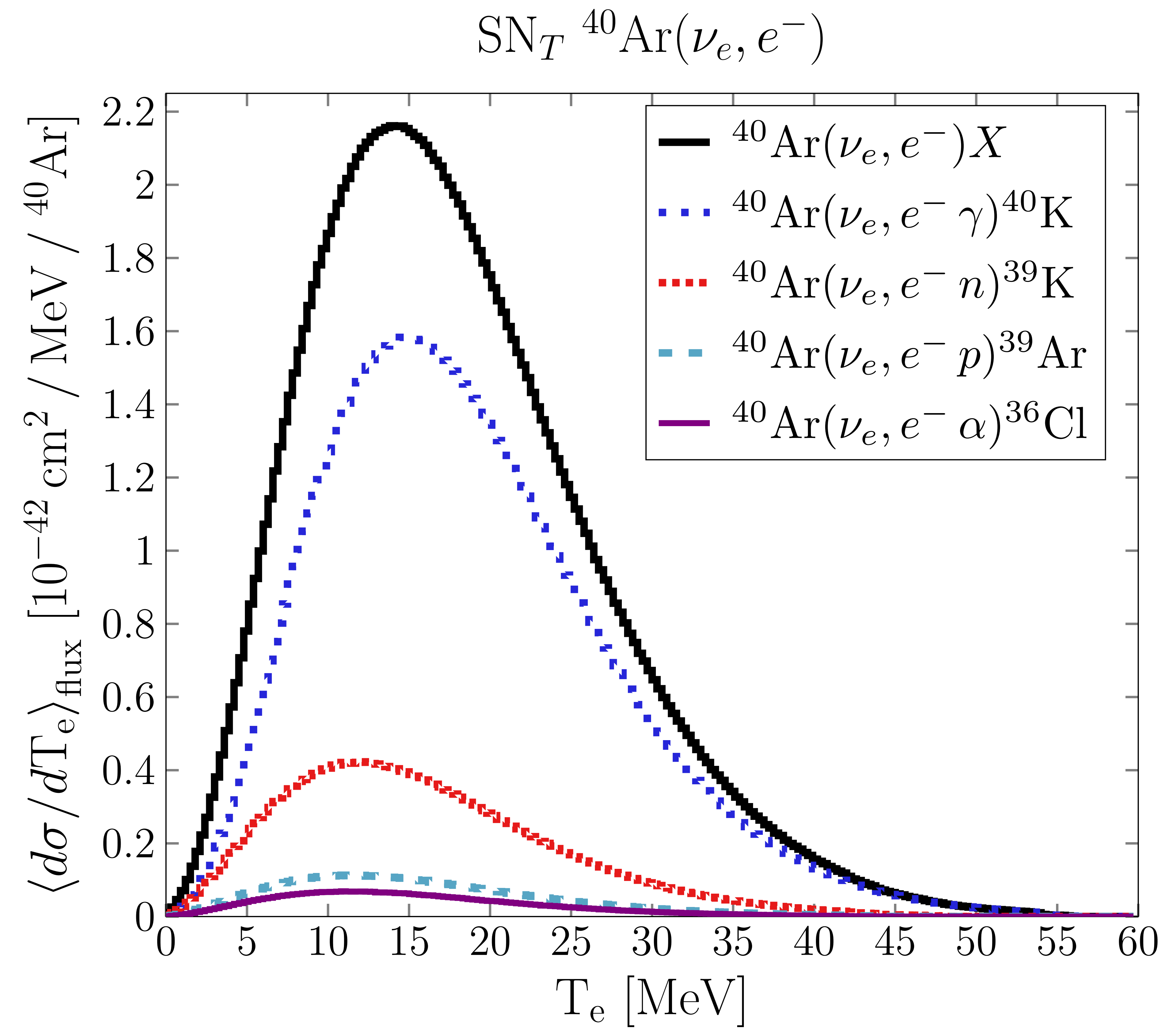
MARLEY v1.2.0 predictions for ^{40}Ar

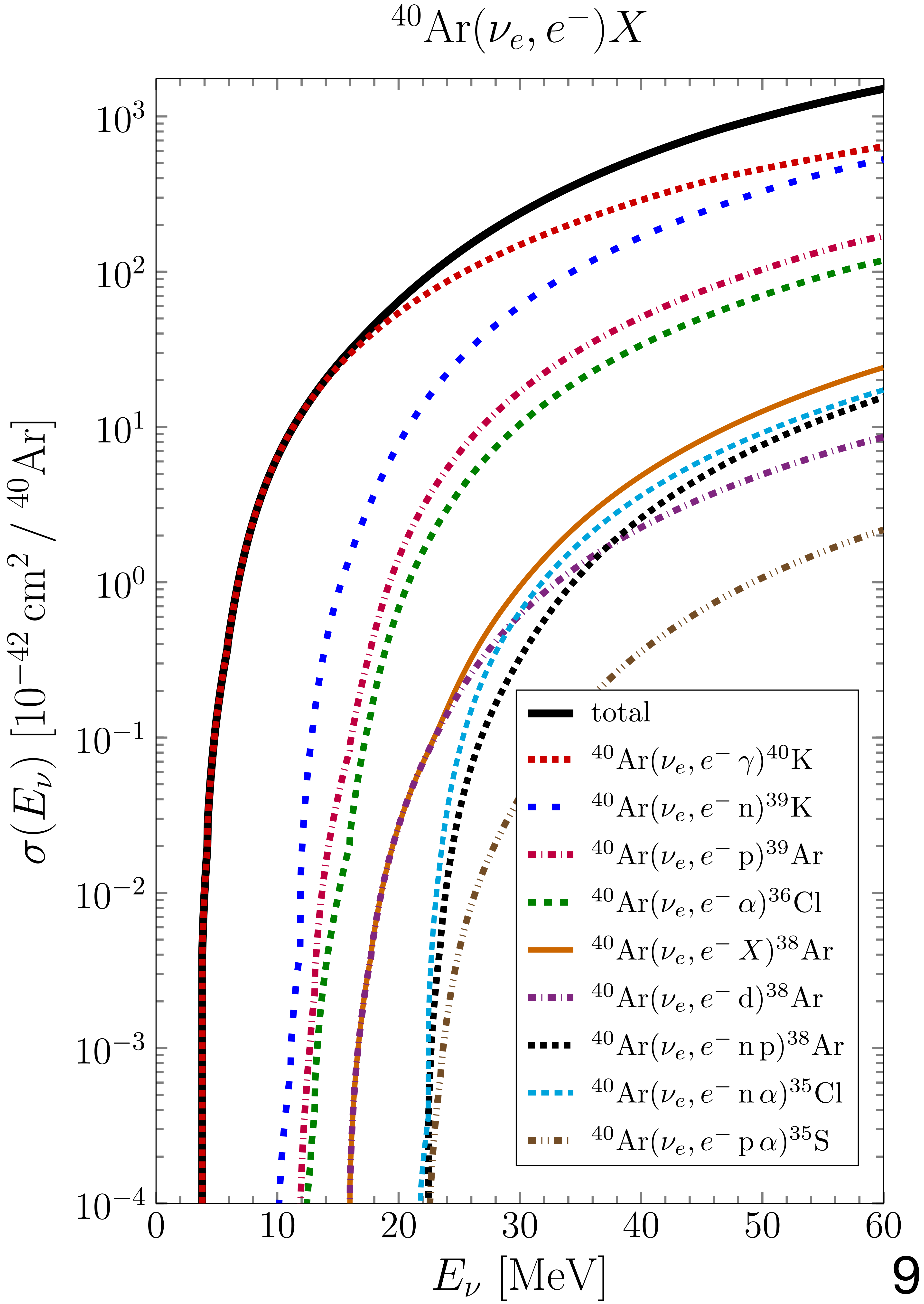
- Recent paper (arXiv:2010.02393) provides first calculation of cross sections for **exclusive final states** of the reaction

$$\nu_e \; + \; {}^{40}\mathrm{Ar} \rightarrow e^- \; + \; X$$

  at tens-of-MeV energies.

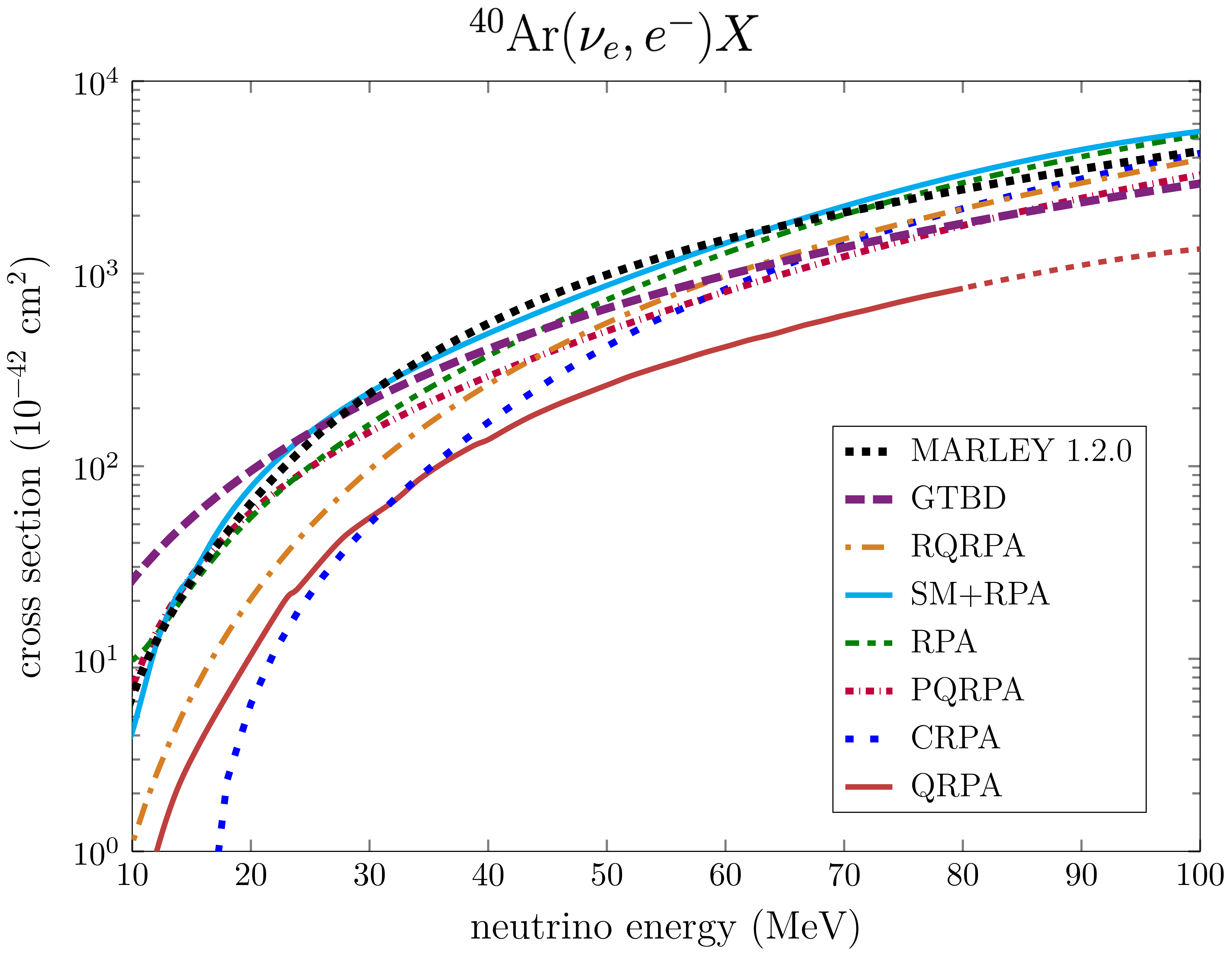
- Flux-averaged differential cross sections shown here are for the supernova model described in Phys. Rev. D 97, 023019 (2018).





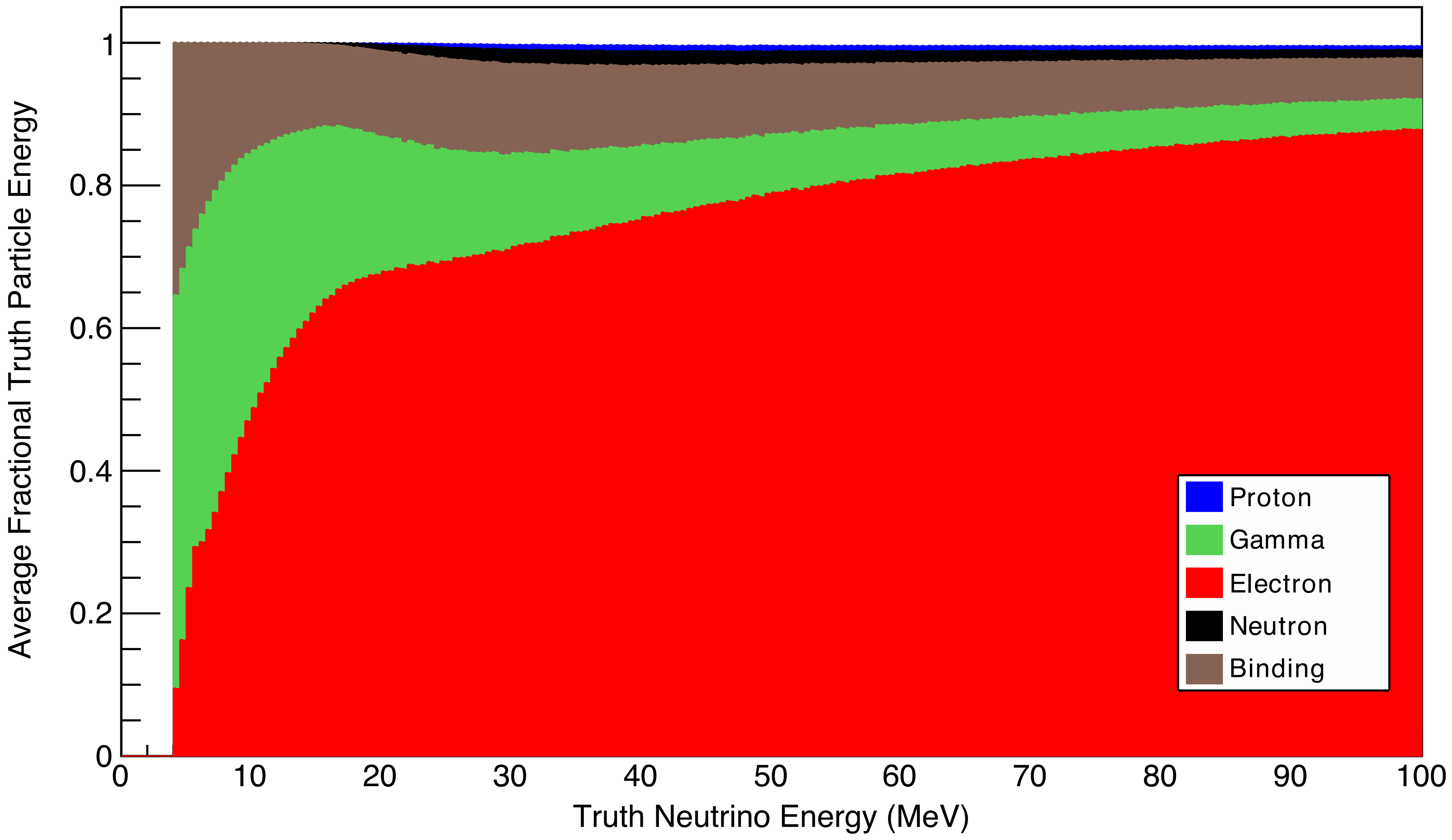
Comparison to other inclusive cross section predictions

- Allowed approximation used by MARLEY is rough, but probably pretty good ≲ 20 MeV
  - Capozzi *et al.*, Phys. Rev. Lett. 123 (2019) argue for ~10% uncertainty for solar neutrinos (see John's slides)
  - "Spread of models" is larger, but not all are expected to work well in that region
- Less clear how to choose between models at higher energies (we need data!)
- Implementing new cross section treatments will be the best way to **estimate associated uncertainties**



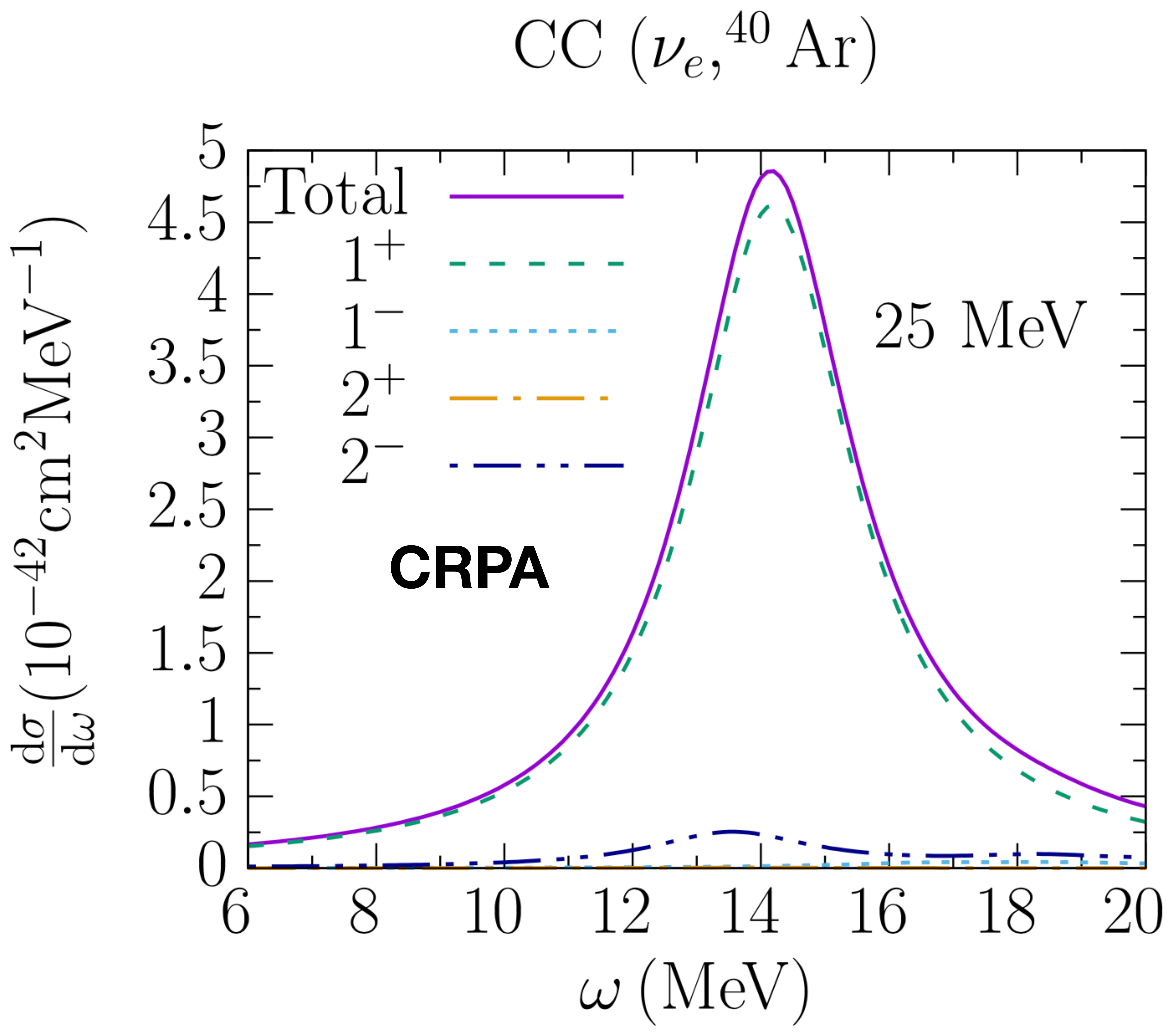
Limitations of the allowed approximation: neutron yield

DUNE Collaboration, [arXiv:2008.06647]



MARLEY thinks that neutrons have a relatively small impact on the overall “energy budget” at high energies. This is an artifact of the allowed approximation which underestimates the strength at high excitation energies.

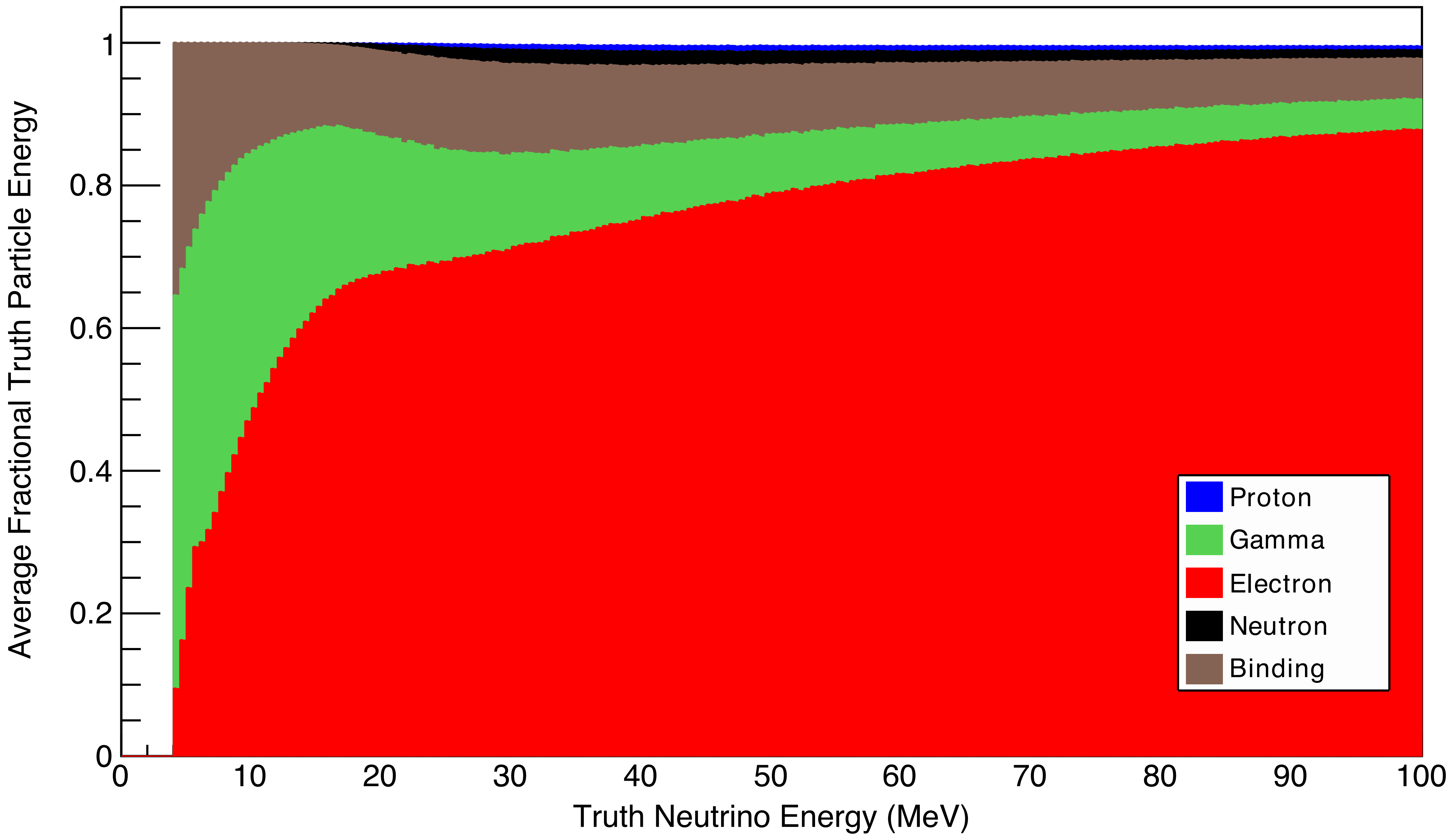
N. Van Dessel *et al.*, [Phys. Rev. C 100, 055503 (2019)]



1^+ component analogous to B(GT) strength

Limitations of the allowed approximation: neutron yield

DUNE Collaboration, arXiv:2008.06647



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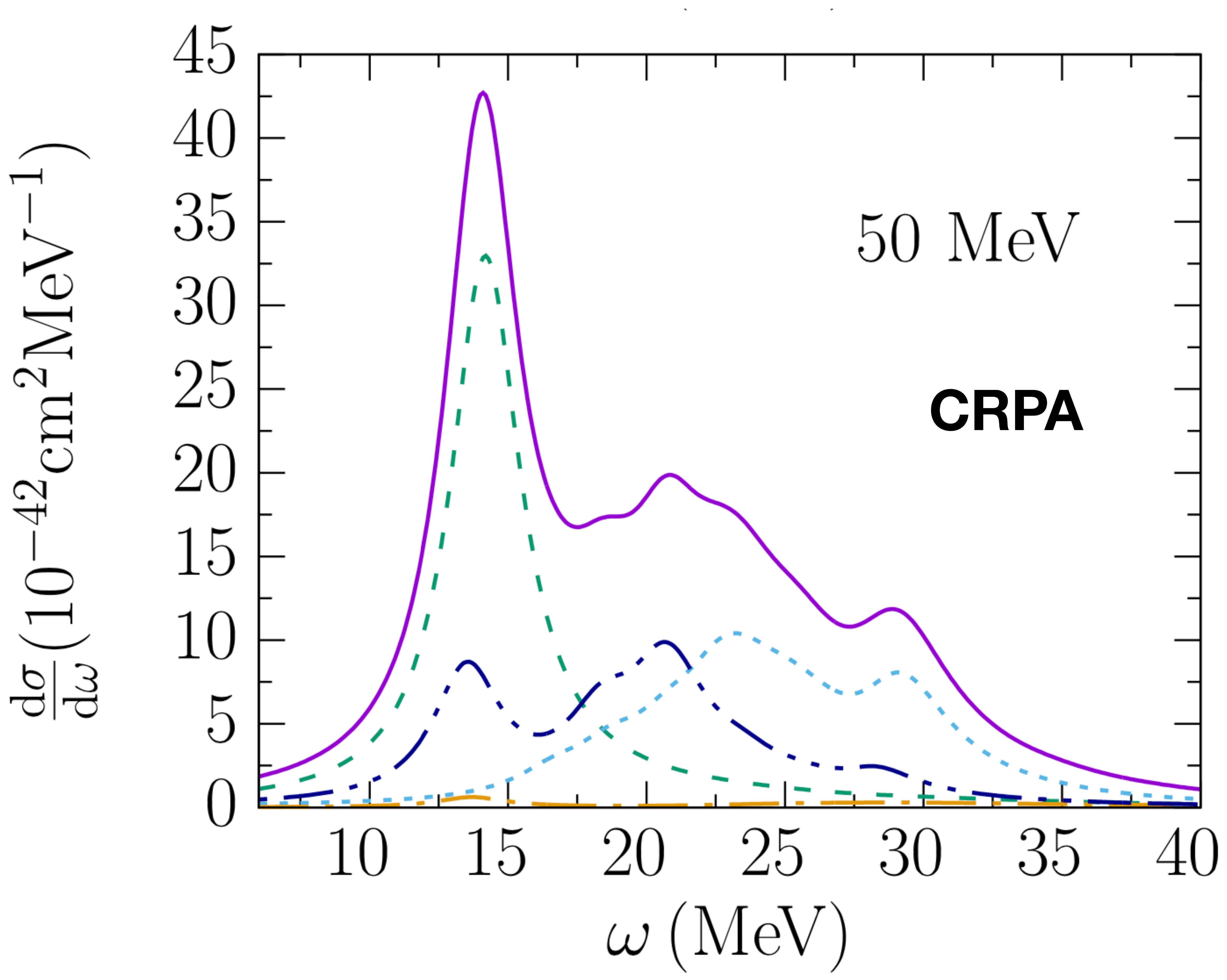

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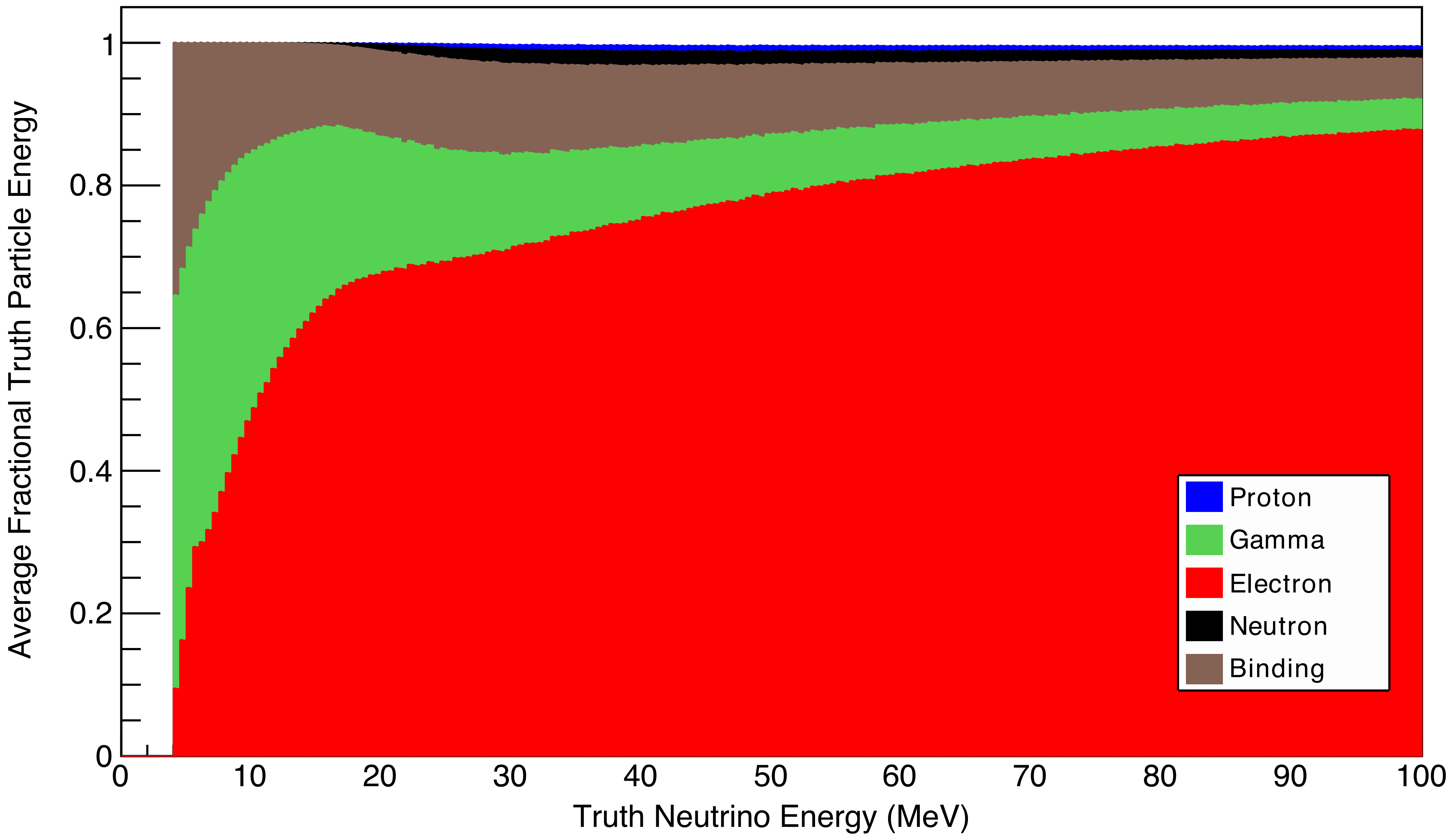

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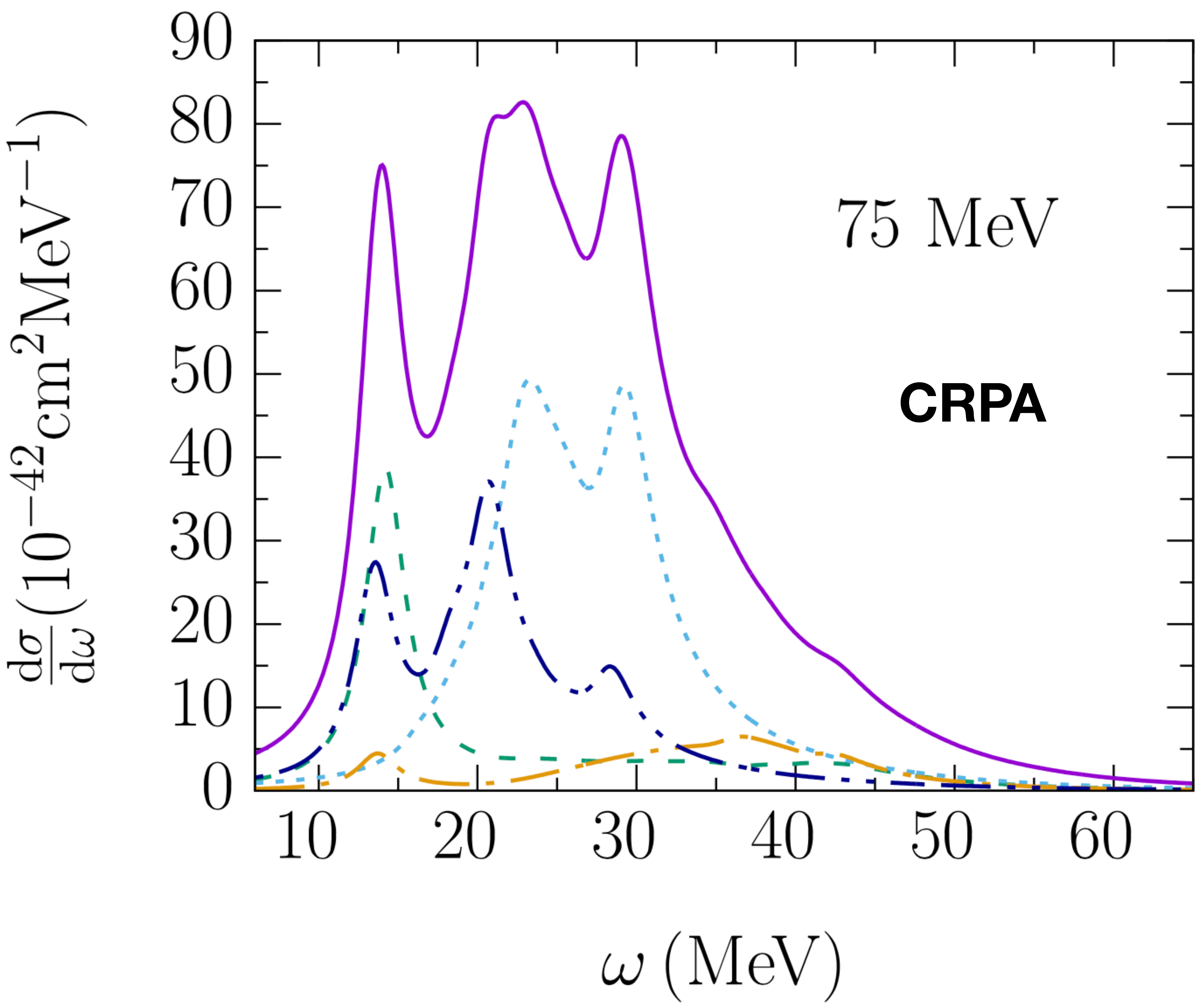
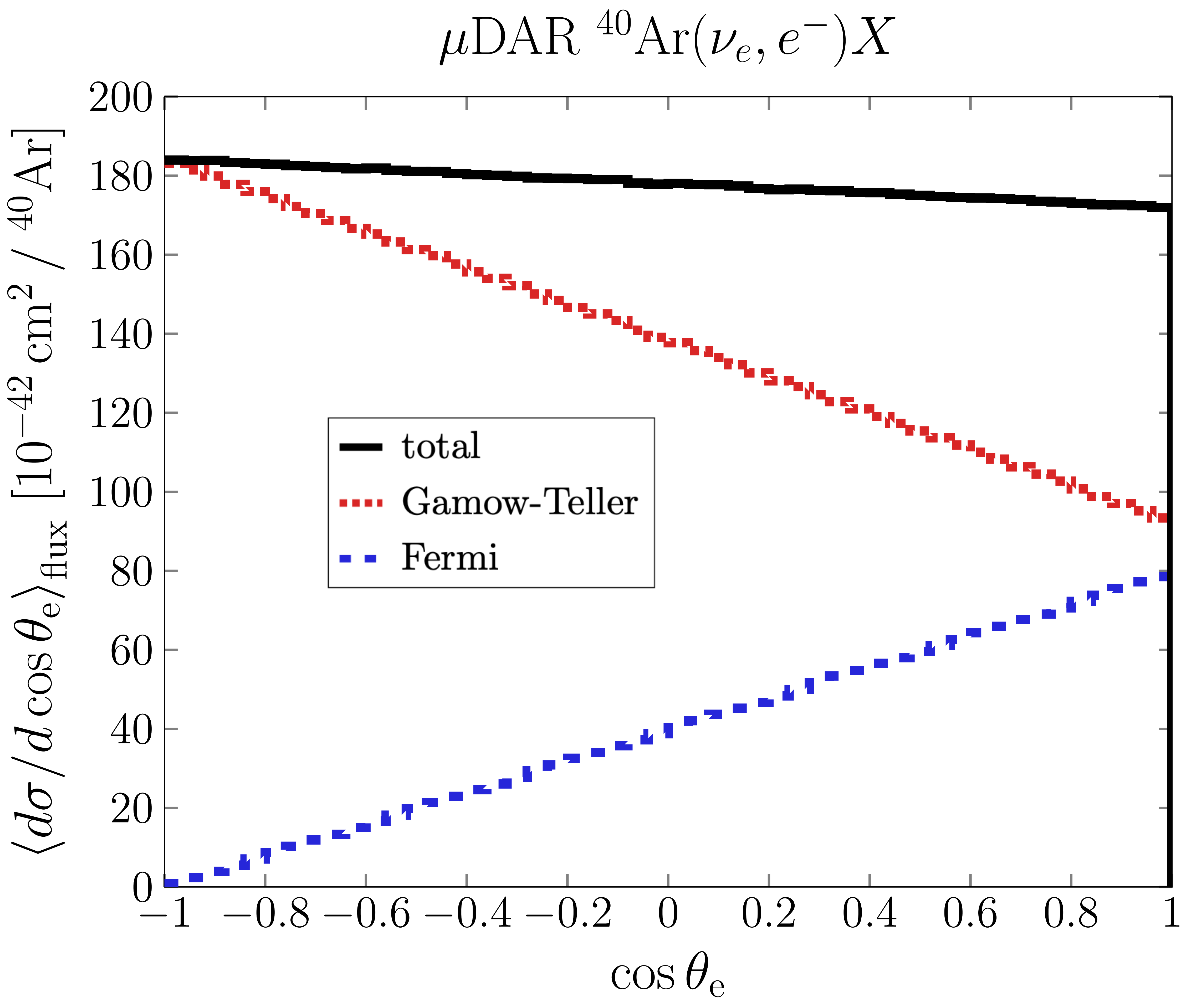
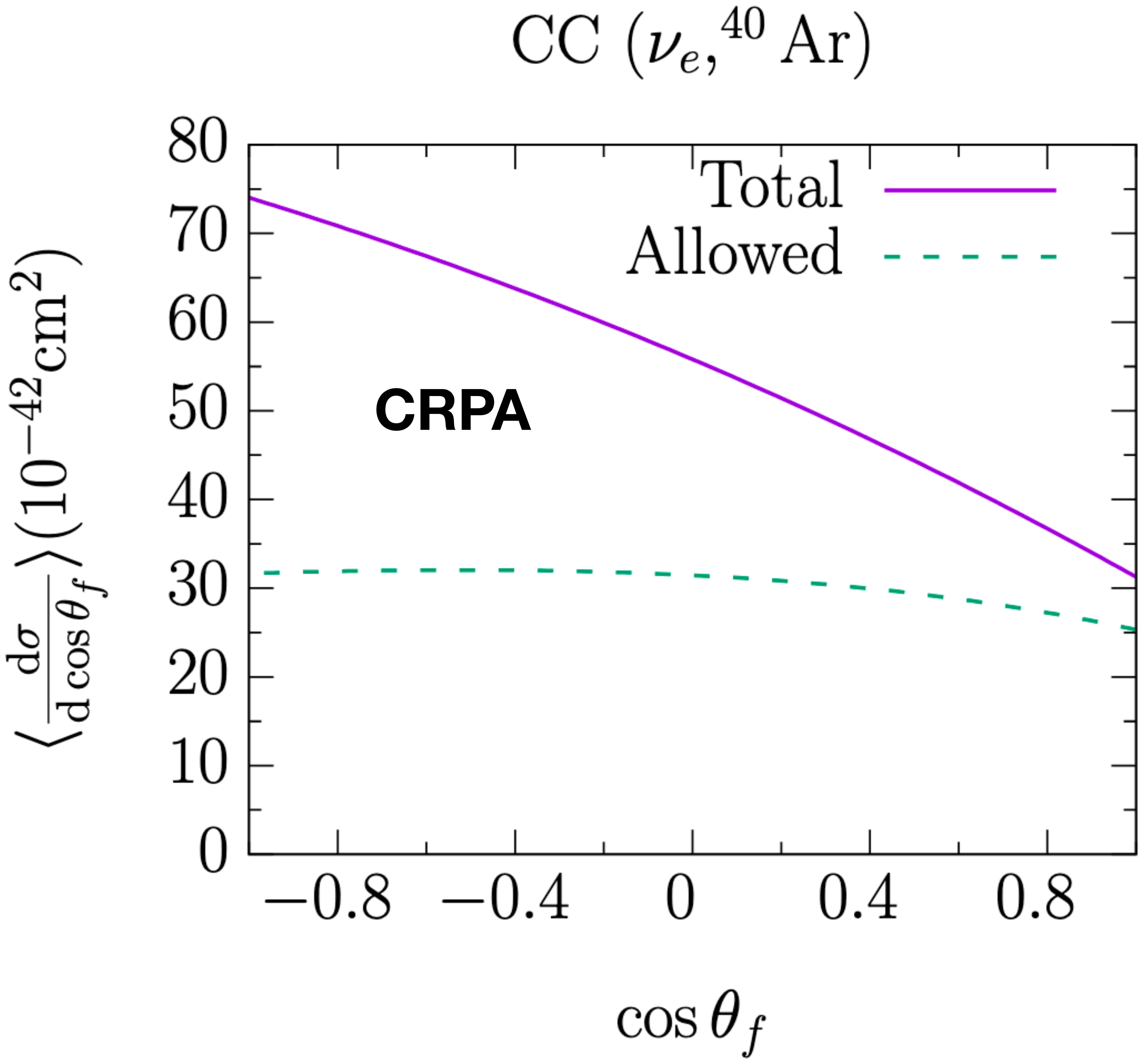


1^+ component analogous to B(GT) strength

Limitations of the allowed approximation: angular distribution

N. Van Dessel *et al.*, Phys. Rev. C 101, 045502 (2020)





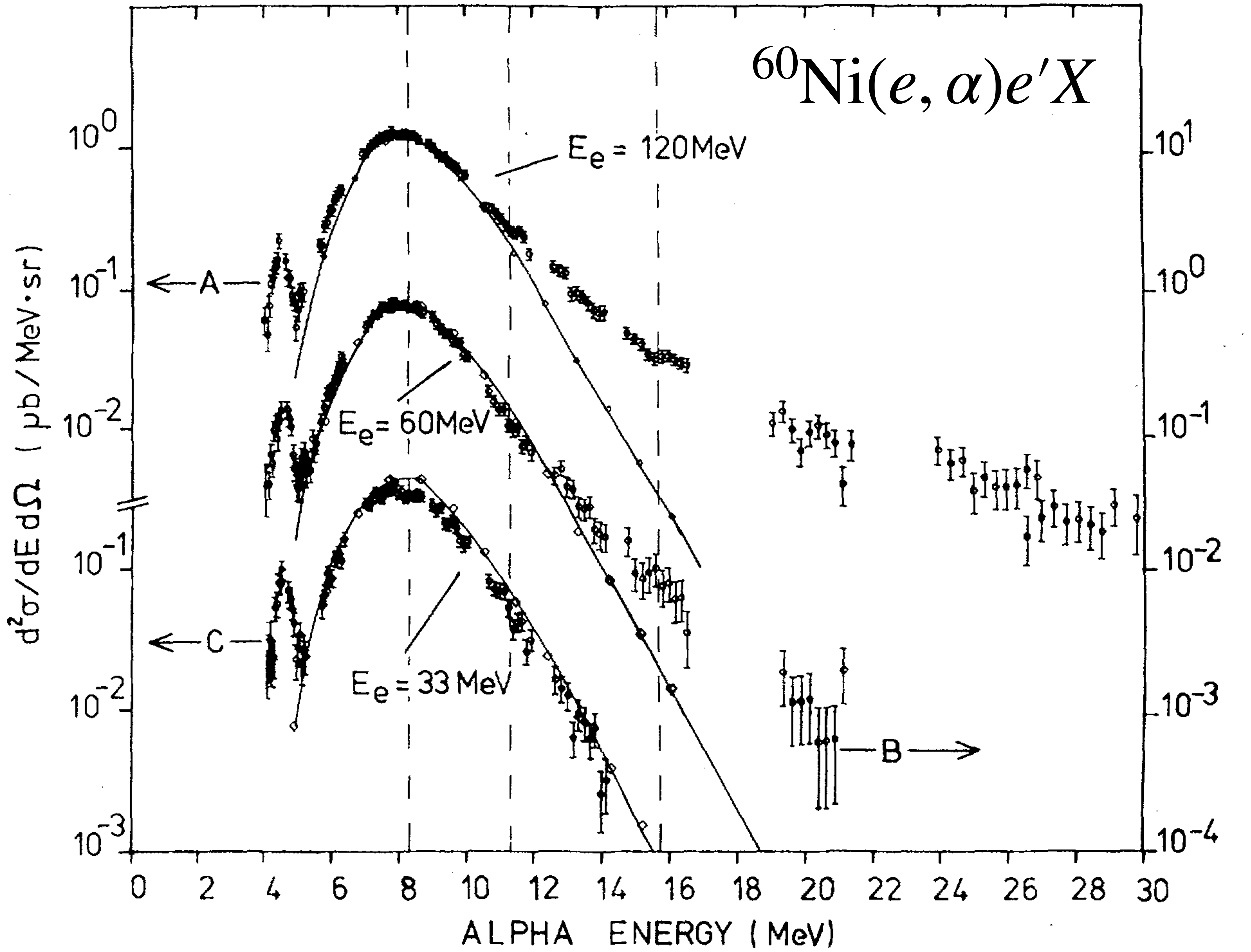
For a muon decay-at-rest source, MARLEY predicts a nearly flat angular distribution, with two linear components

Calculations which include the forbidden transitions (CRPA shown here) predict more backwards strength

Is the compound nucleus assumption adequate at tens of MeV?

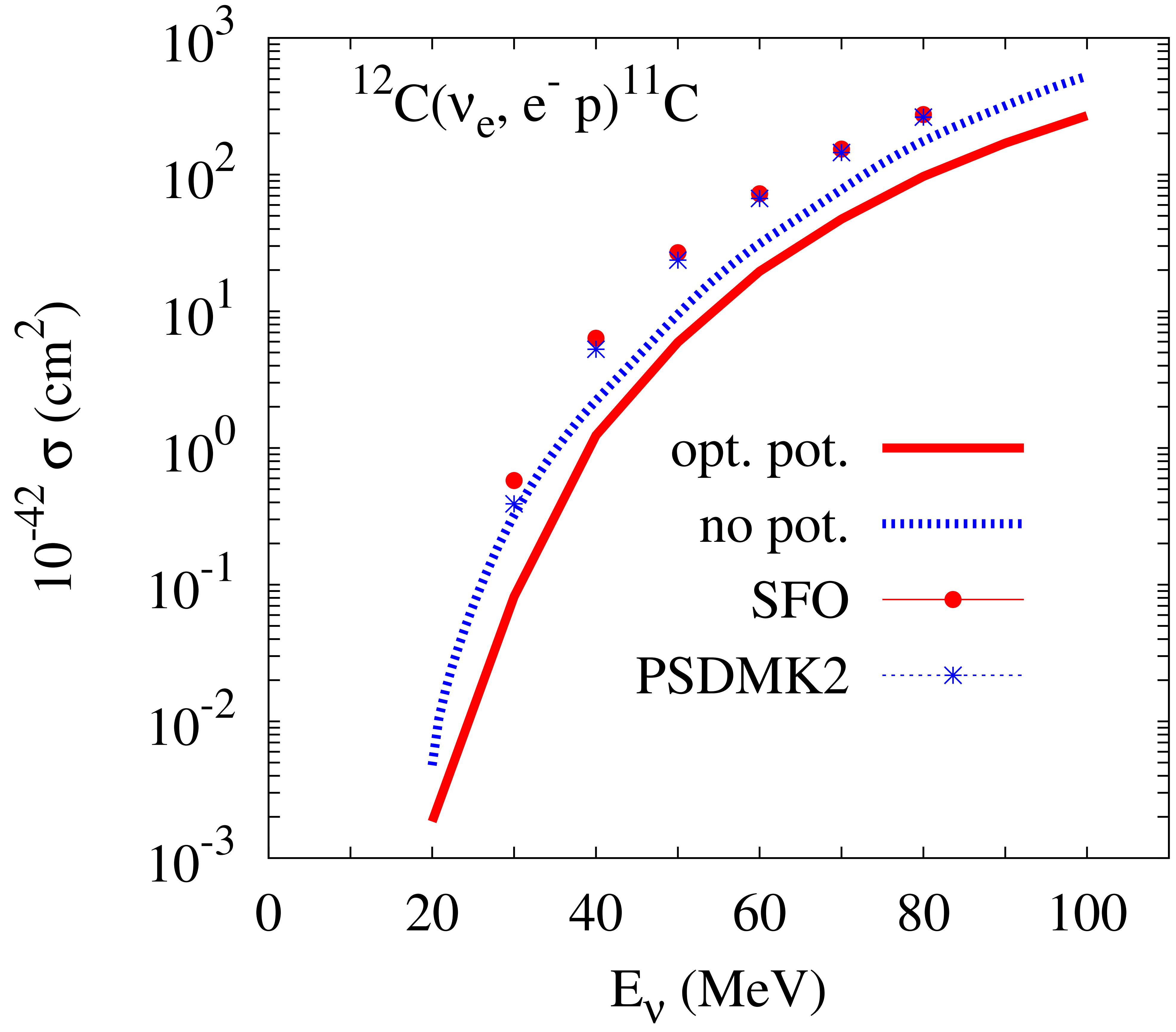
Maybe, but the available evidence is quite limited. Limited studies of any kind and no relevant neutrino data.

Flowers et al., Phys. Rev. Lett. 40 (1978)



Compound nucleus calculation shows excellent agreement at E$_e$ = 33 MeV, which worsens as the electron energy increases

Kim & Cheoun, Phys. Lett. B 679 (2009)



Two-step cross section (points, shell model + compound nucleus) dominates over direct knockout (solid red line). Turning off FSIs gets closer (dashed blue line).

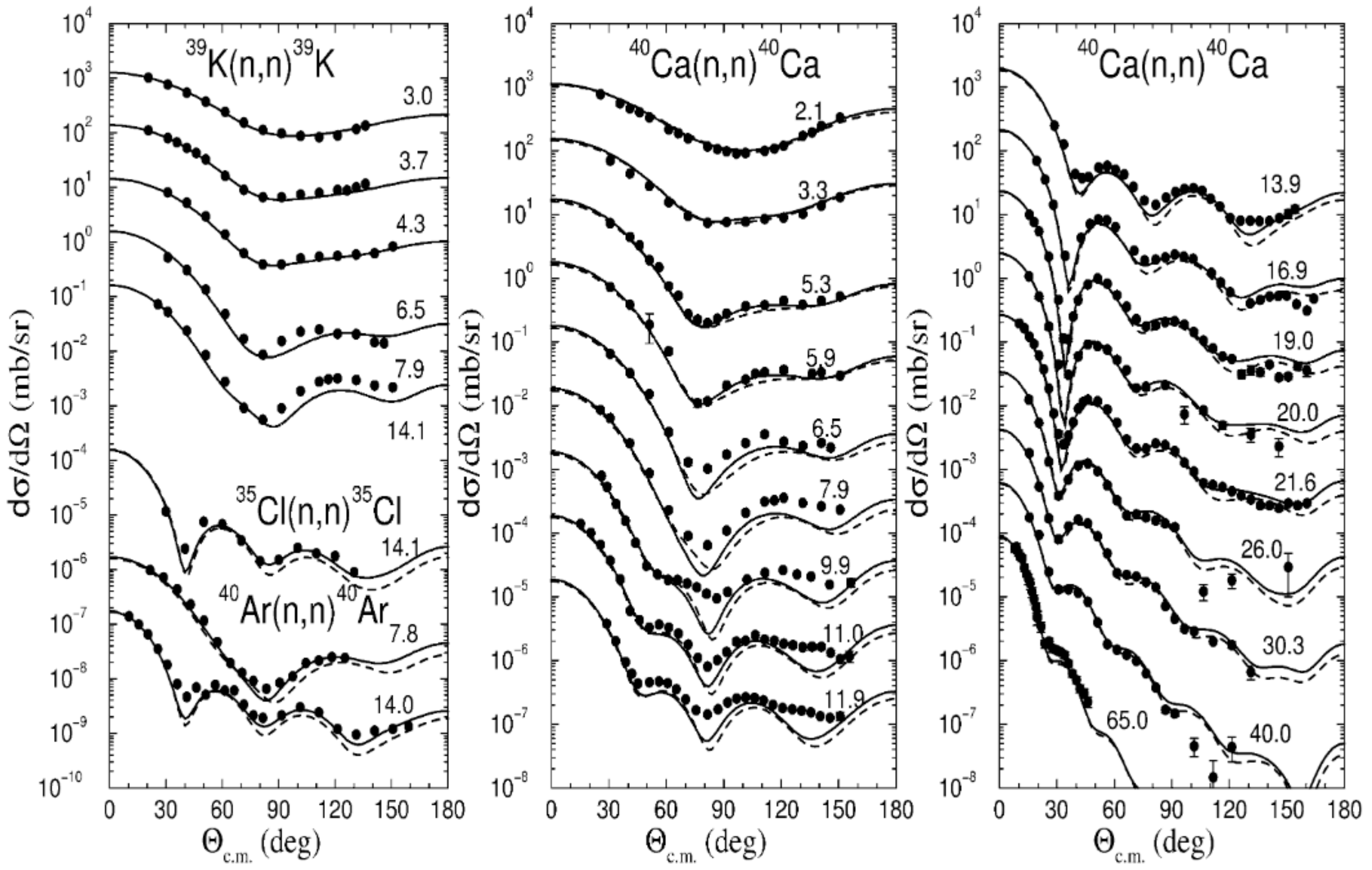
De-excitation uncertainties

- Uncertainties on the MARLEY de-excitation model should be carefully explored
  - **Neutron emission** in particular due to its importance for neutrino calorimetry
- Three classes of uncertainties can be assessed:
  1. Model parameters for “Hauser-Feshbach ingredients”
     - GENIE-style reweighting for these uncertainties is feasible
     - Requires new code, but path forward is clear
  2. Comparisons to a separate code which implements similar physics (e.g., EMPIRE, TALYS)
     - Many options on the market, interfacing will take some work
     - Most are hadron-nucleus codes, so lepton-nucleus scattering is an unexpected use case
  3. Impact of violations of compound nucleus assumption
     - Currently most difficult to quantify
     - Could be partially addressed by #2, but what new inputs from MARLEY are required?

Uncertainties on de-excitation model ingredients

- MARLEY's nuclear level densities, **optical model**, and γ-ray strength functions are all based on semi-empirical models
  - Global parameter fits across chart of nuclides
  - **No detailed fit uncertainties**
- Alternative parameterizations exist, could be implemented in code framework with some effort
- Redoing fits (just near A = 40?) also feasible, needs new infrastructure

Koning & Delaroche, Nucl. Phys. A 713, 231–310 (2003)



Dashed line is the global fit that MARLEY currently uses.
Solid lines are local fits to specific nuclei.

Other MARLEY use cases for LEPLAr

- LEPLAr physics topics are broader than just low-energy neutrinos
- Could MARLEY be coupled to GENIE to provide a statistical de-excitation treatment?
  - Yes, I can call it as an external library to make low-energy events
  - Could run only the de-excitation step in the future
- Potential applications to BSM as well, e.g., **nucleon decay**

GENIE GHEP Event Record [print level: 3]

Idx	Name	Ist	PDG	Mother		Daughter		Px	Py	Pz	E	m
0	nu_e	0	12	-1	-1	8	8	0.000	0.000	0.040	0.040	0.000
1	Ar40	0	1000180400	-1	-1	2	7	0.000	0.000	0.000	37.216	37.216
2	neutron	11	2112	1	-1	-1	-1	0.000	0.000	0.000	0.940	0.940
3	K40	1	1000190400	1	-1	-1	-1	-0.032	-0.012	0.041	37.226	*37.217
4	gamma	1	22	1	-1	-1	-1	-0.001	0.001	0.001	0.002	0.000
5	gamma	1	22	1	-1	-1	-1	0.000	-0.001	0.001	0.001	0.000
6	gamma	1	22	1	-1	-1	-1	0.001	-0.000	-0.000	0.001	0.000
7	gamma	1	22	1	-1	-1	-1	-0.000	0.000	0.000	0.000	0.000
8	e-	1	11	0	-1	-1	-1	0.033	0.012	-0.003	0.035	0.001

Snowmass2021 - Letter of Interest

Searches for proton-decay with additional signatures from nuclear deexcitations and with precise timing from photon-detectors in large LArTPCs

See related Snowmass LOI from Zelimir Djurcic *et al*.

https://tinyurl.com/y245am85

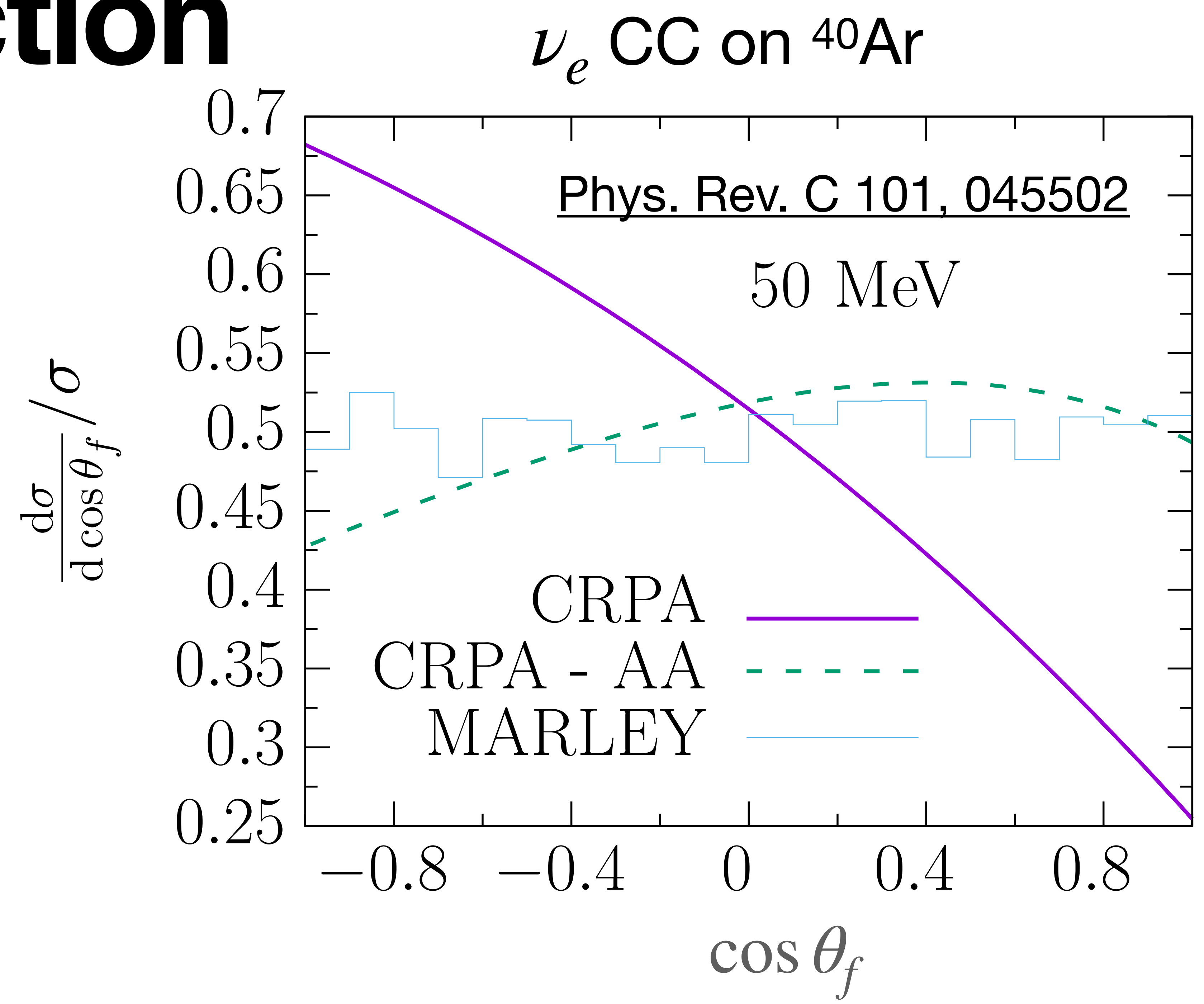
Closing thoughts

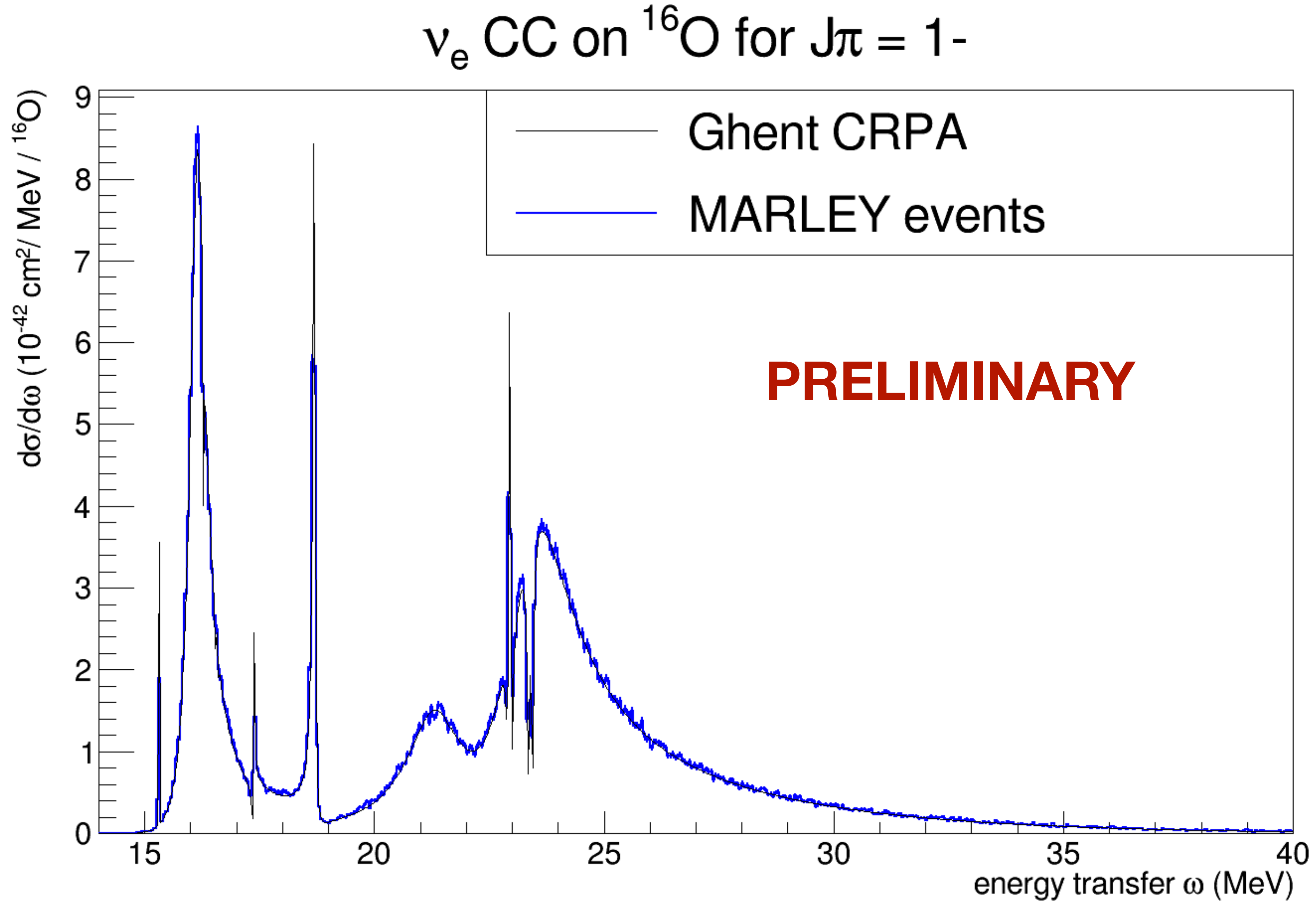
- Realistic low-energy neutrino interaction simulations are an essential part of the LEPLAr program
- Neutrino calorimetry with complex nuclei is hard at low energies as well as high energies
  - Measurements on argon below 100 MeV are **essential** to achieve our goals
  - Where would the DUNE oscillation program be without cross section data?
  - We face similar challenges but do not yet have the measurements we need
  - The alternative is to place far more trust in MARLEY than it deserves, even with new theory improvements added
- Neutrino generator developers are a small community at any energy
  - The ability to meet DUNE's needs will depend on our willingness to invest effort
  - I remain interested in this physics, but the "small fraction of one postdoc" development model will keep progress slow
- I hope MARLEY is a step in the right direction, but we should remain open to other solutions

Backup

New developments: CRPA cross section

- Allowed approximation used in existing MARLEY cross section model
  - Neglects “forbidden” contributions that become important at several tens-of-MeV
- These contributions are treated realistically via the **Continuum Random Phase Approximation** (CRPA)
  - N. Jachowicz *et al*. (Ghent)
  - Limited to excitation energies above the nucleon emission threshold
- Forbidden terms impact total cross section, **lepton kinematics**
- Work underway to make this model usable in MARLEY





New developments: extensions to other nuclei

- MARLEY continues to be actively developed as an open-source software project
- Originally conceived as an argon-specific generator for DUNE. **Recently revamped** to
  - Treat ν_e CC / $\bar{\nu}_e$ CC / NC on an equal footing
  - Include level + γ-ray data across chart of nuclides
- Nucleus-specific tables of B(F) + B(GT) values must still be prepared by the user for non-^{40}Ar targets
- Evaluation of these by the low-energy neutrino community ongoing
  - Example: ν_e CC on ^{208}**Pb** by **Sam Hedges** (Duke)
  - See his talk (http://meetings.aps.org/Meeting/DNP20/Session/RF.6) tomorrow morning for more details