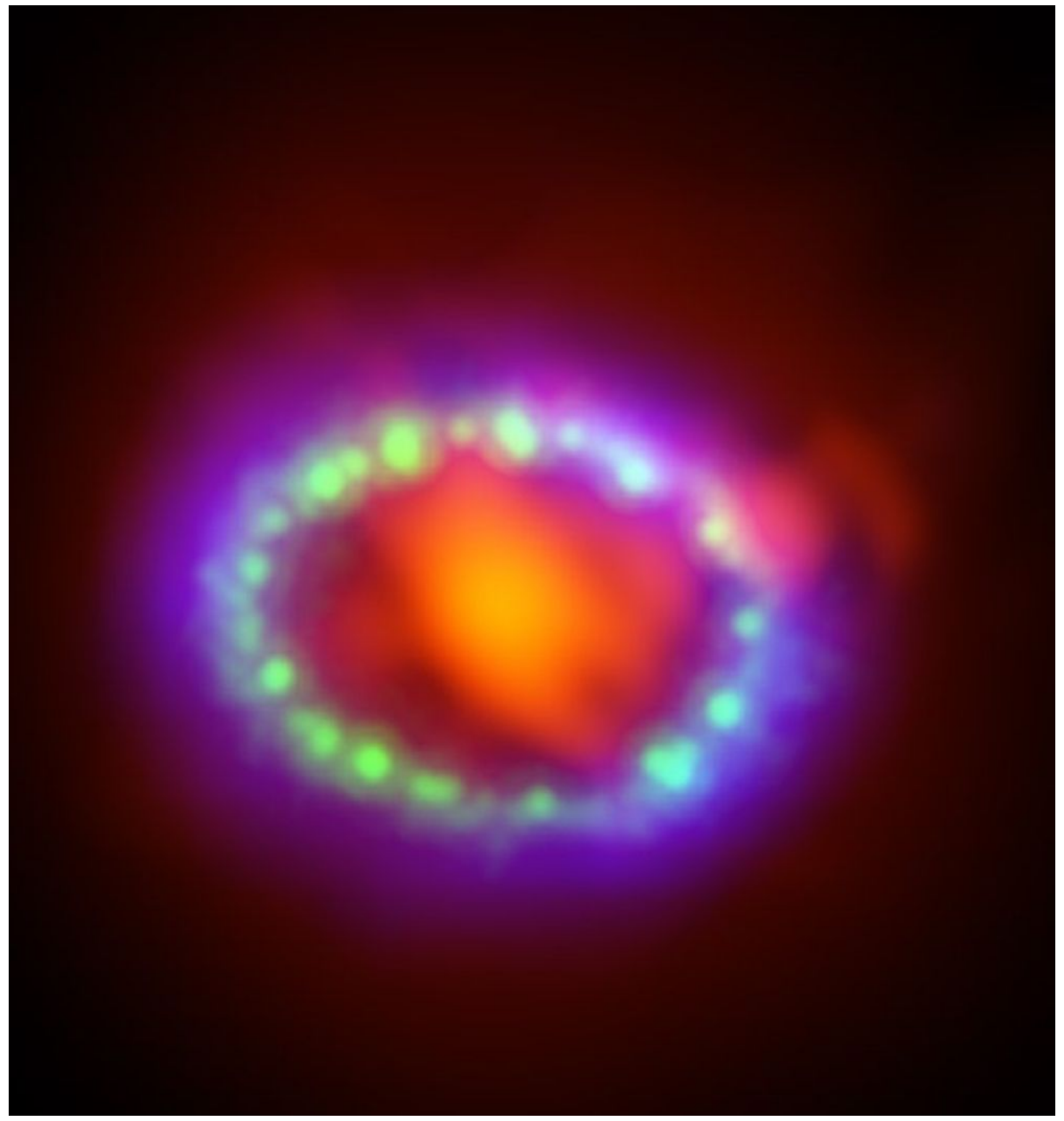
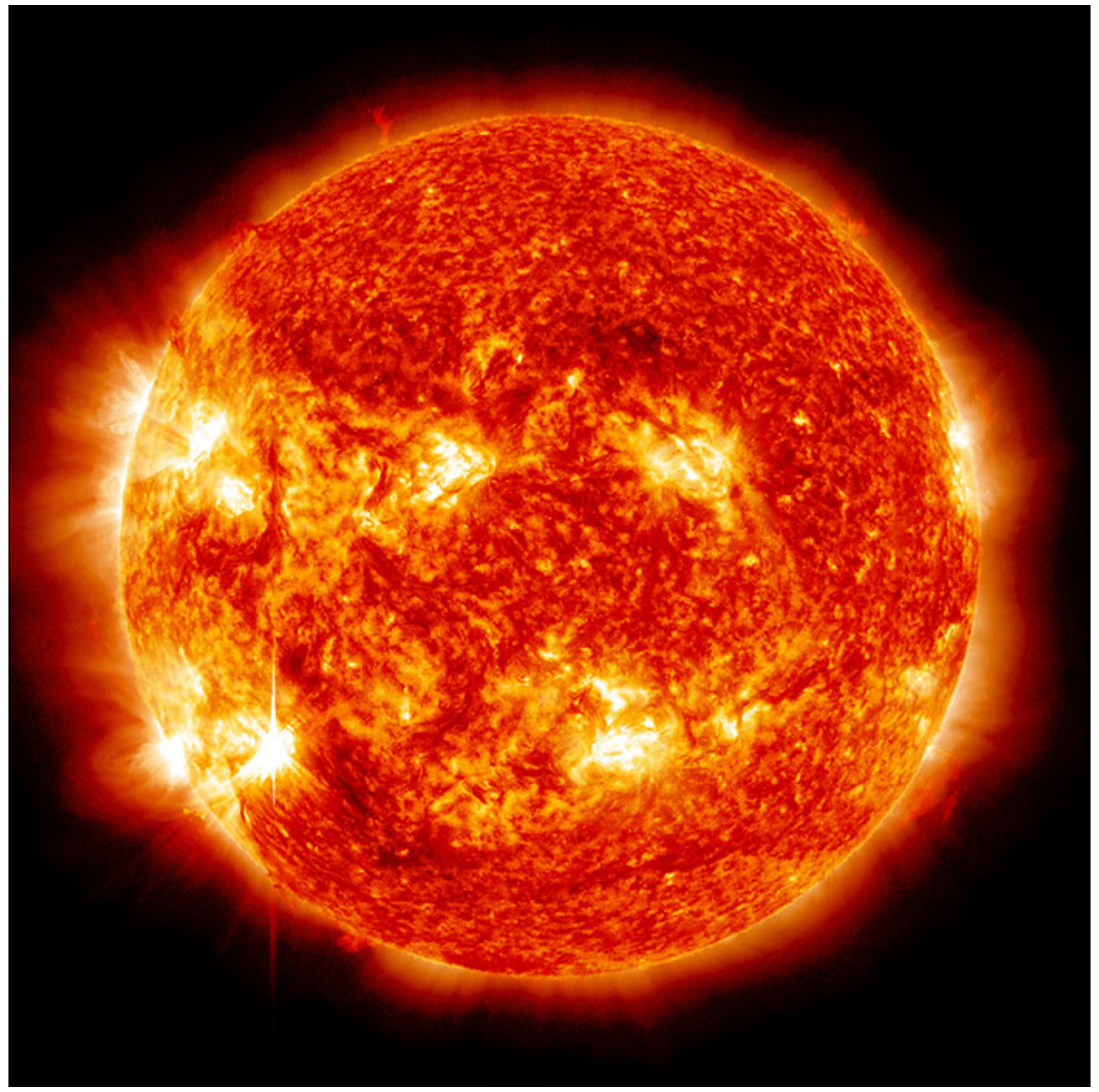
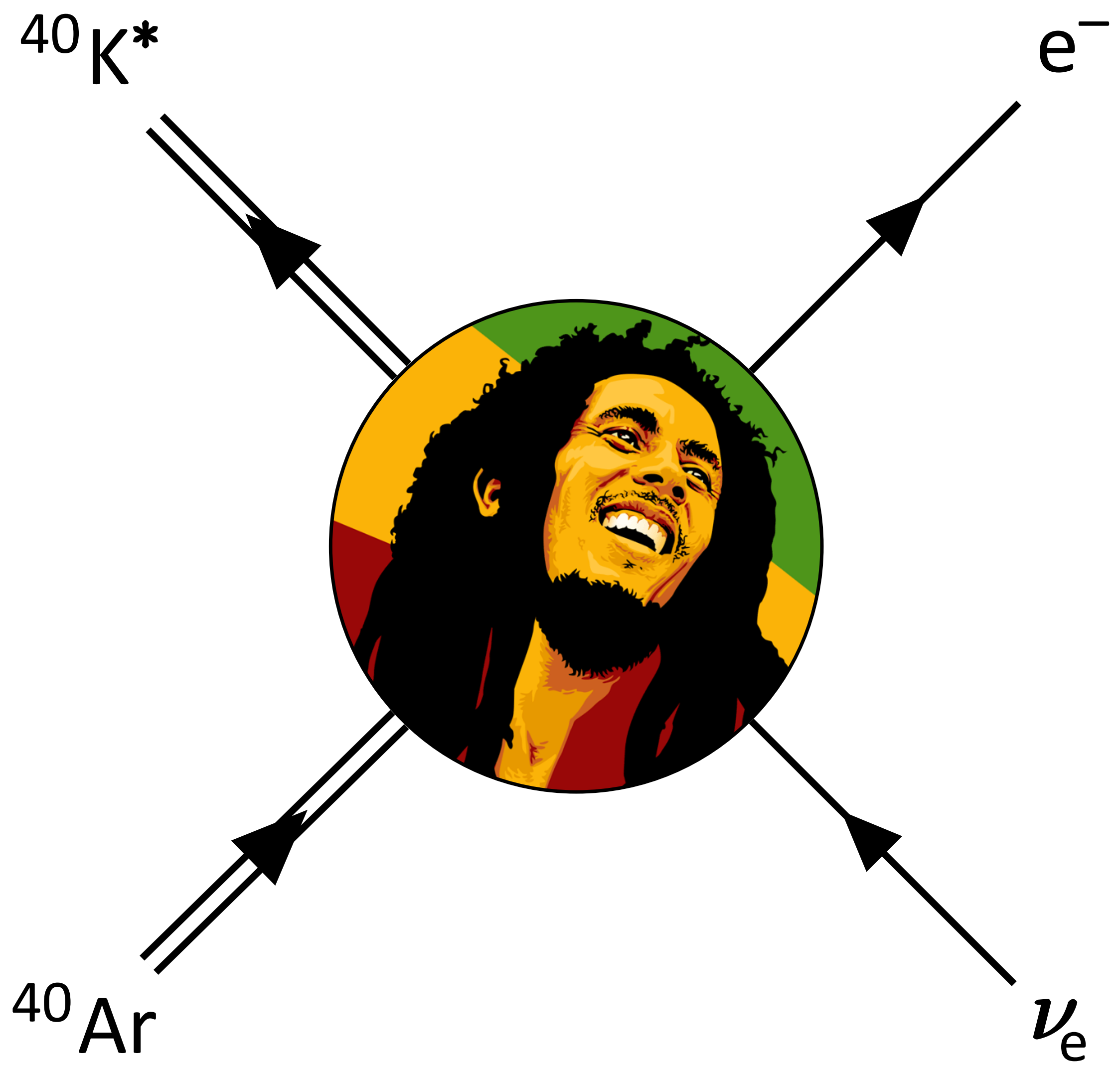
MARLEY and low energy physics

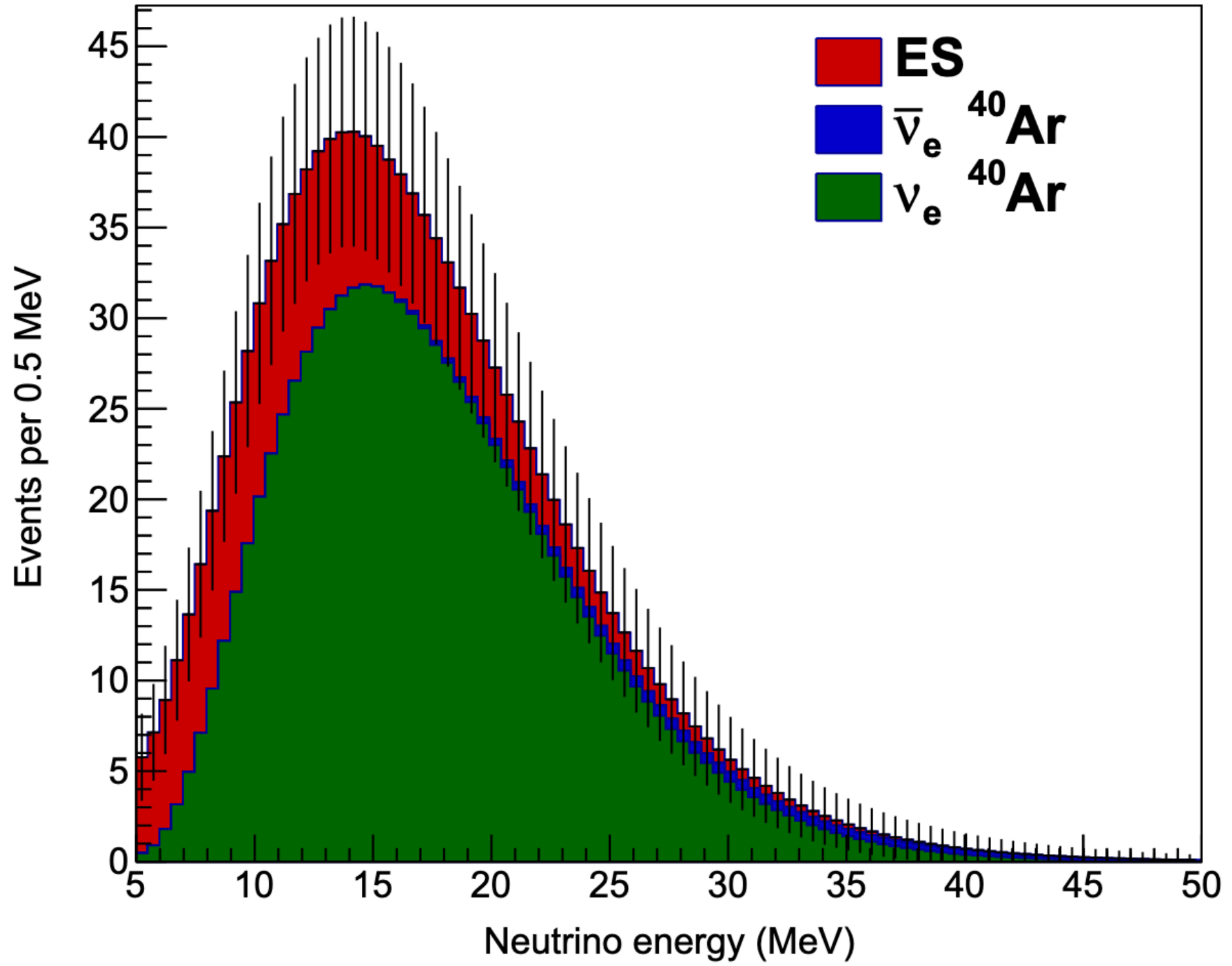



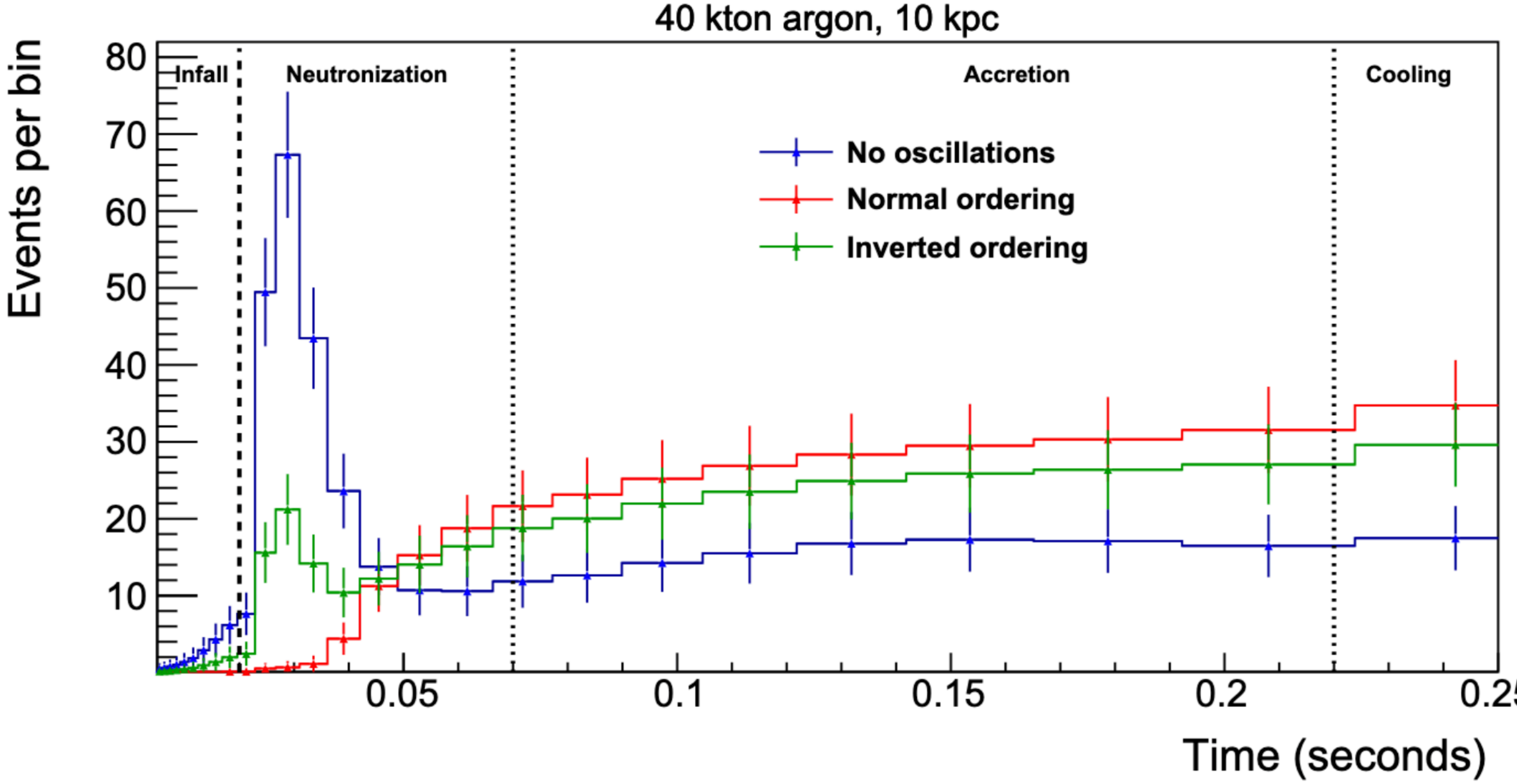


Steven Gardiner
NuSTEC Board Meeting
6 December 2021

Low-energy applications

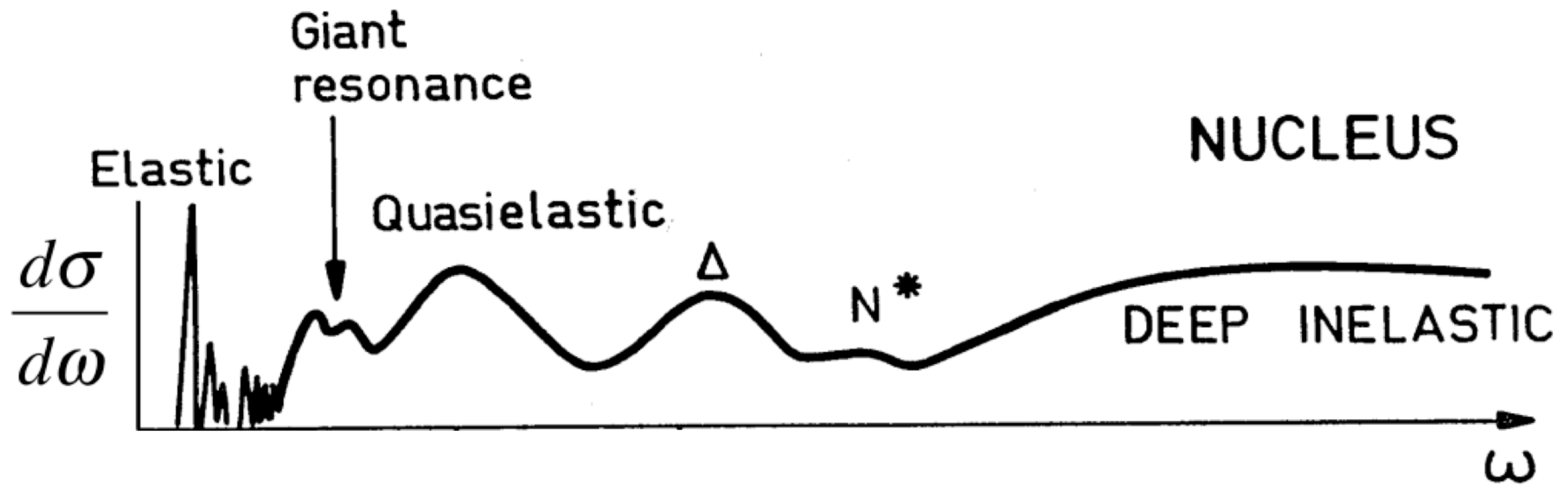
- **Supernova neutrino detection in DUNE**
  - Primary goal of the experiment
  - Also solar neutrinos, low-energy BSM scenarios, etc.
  - Dominated by **ν_e CC channel**
- HALO supernova neutrinos
  - Via neutrino-induced neutrons
- Clarify role of neutrino interactions in nucleosynthesis
- Oscillations with pion decay-at-rest sources
- Spin-off: improvements to reconstruction of GeV-scale neutrino interactions



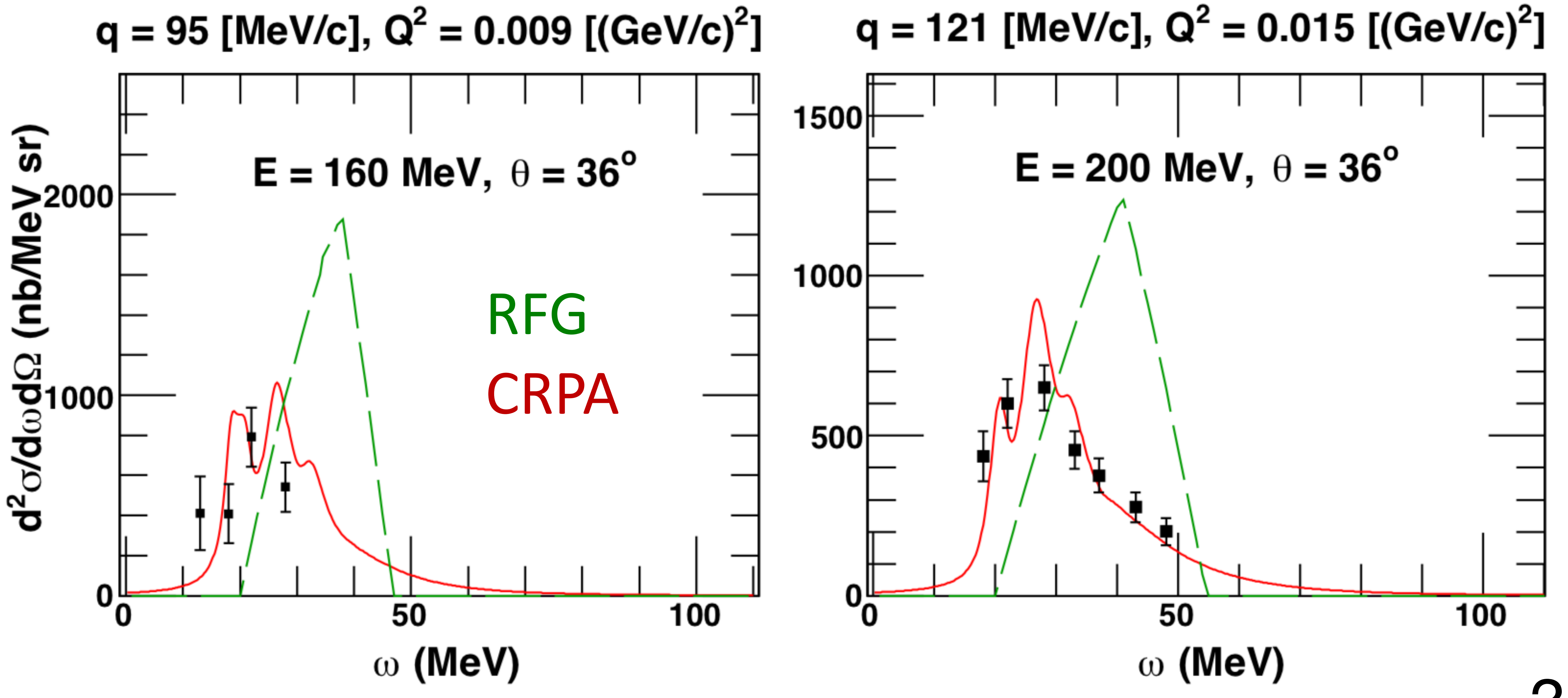


Why not just use GENIE/GiBUU/NEUT/NuWro?

- 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

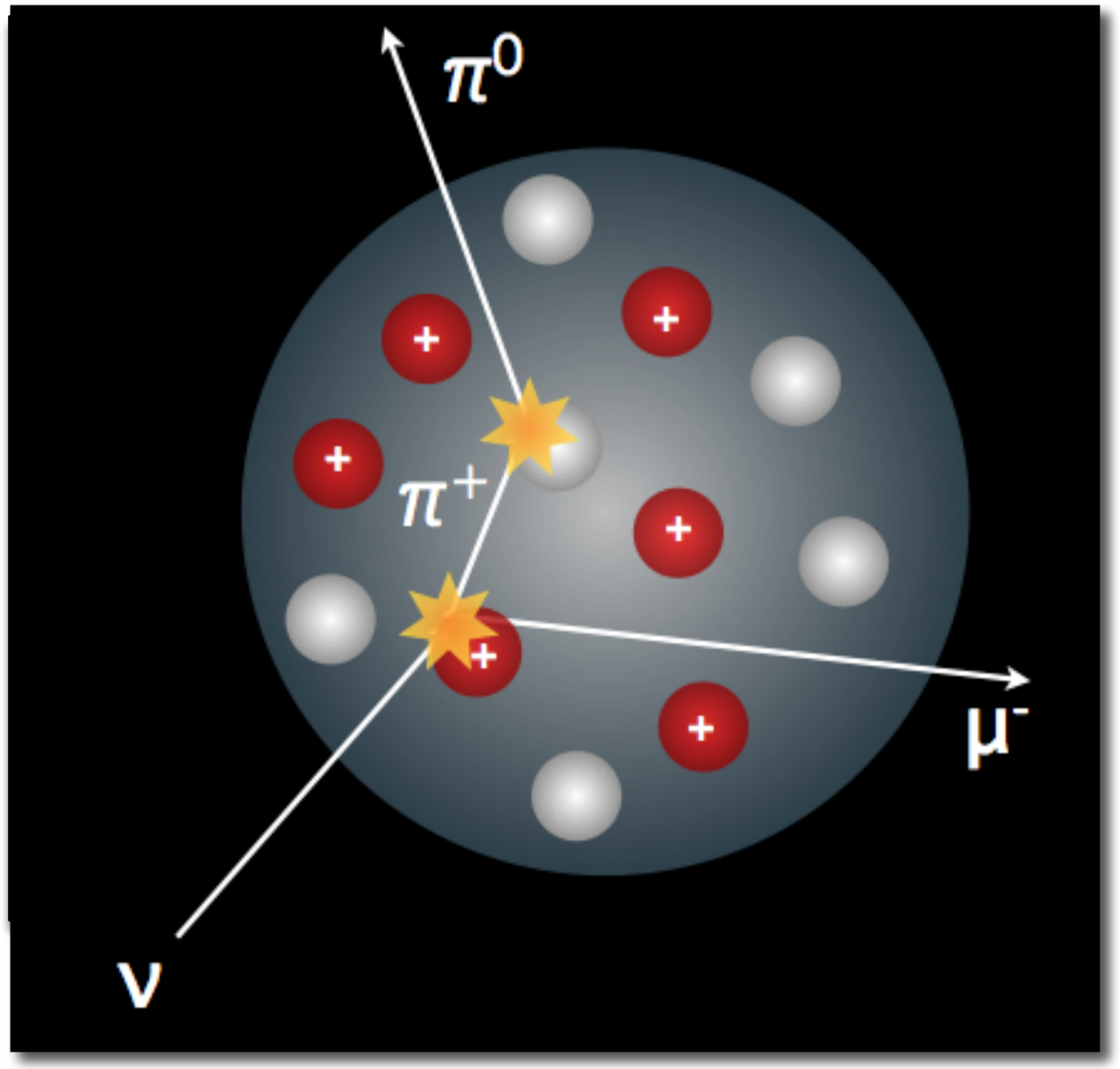


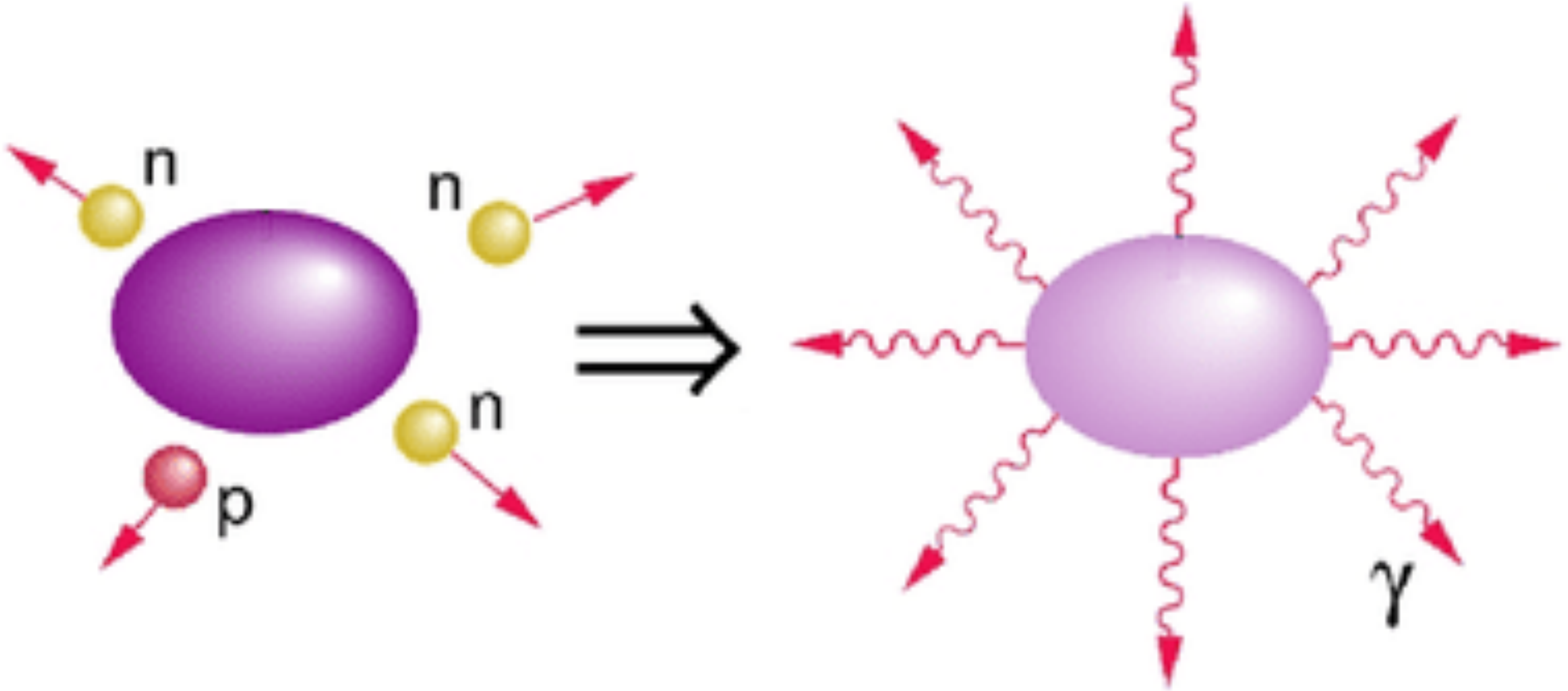
(e,e') scattering on ¹²C, V. Pandey, NuInt 18



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

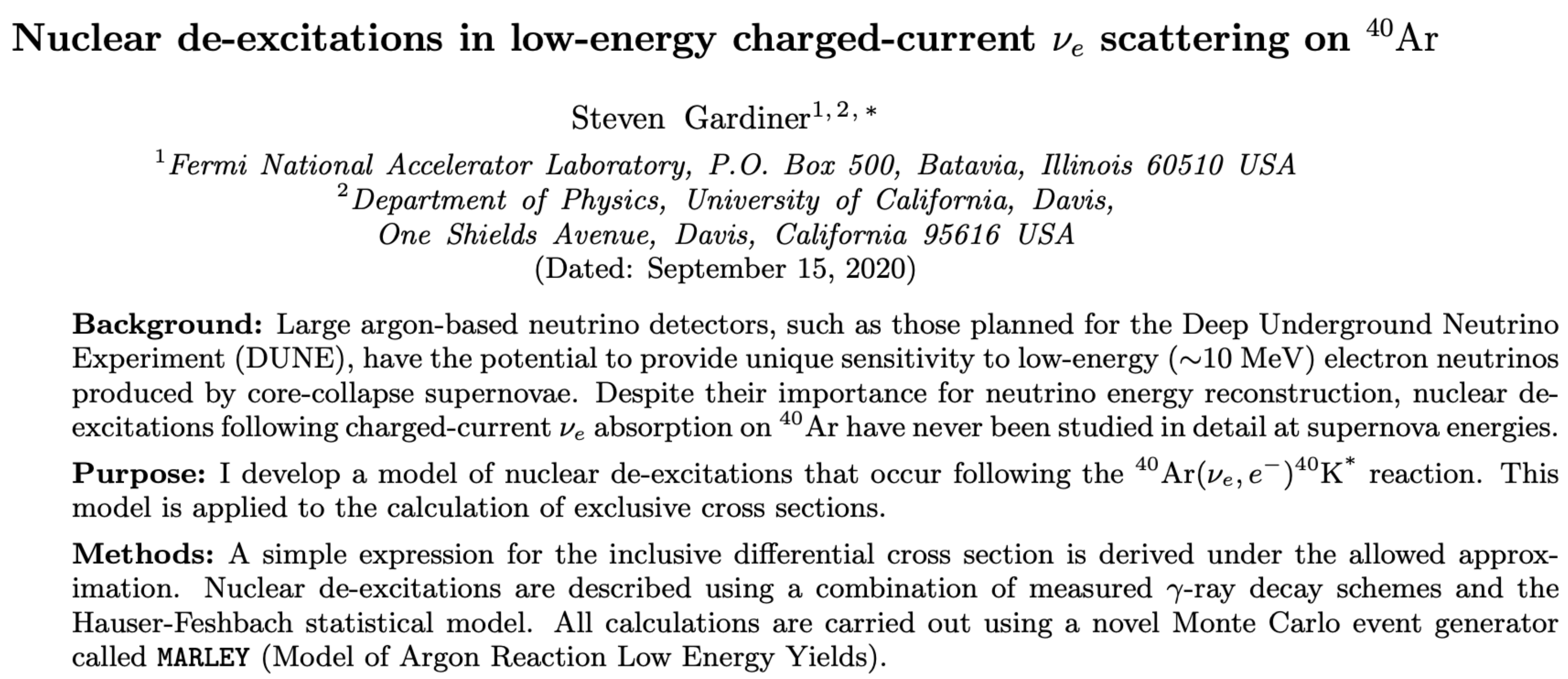
- Treatment of final-state interactions is also different
- High-energy approaches rely primarily on a **direct knockout** picture
  - Transport outgoing hadrons through the nucleus
  - Dynamical models: intranuclear cascade (GENIE, NEUT, NuWro) or BUU transport (GiBUU)
- Low-energy literature typically 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?)





MARLEY overview

- Event generator focused specifically on neutrino energies below ~100 MeV
- **http://www.marleygen.org/**
- Two dedicated publications so far:
  - Physics models: **Phys. Rev. C 103, 044604 (2021)**
  - Numerical implementation: **Comput. Phys. Commun. 269, 108123 (2021)**
- Written in C++14, few dependencies
- Emphasis on ν_e CC on ^{40}Ar, extensible
  - Some capability for CEvNS, ν-e
- Nuclear reactions treated in **two steps**
  - Justified via compound nucleus assumption



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

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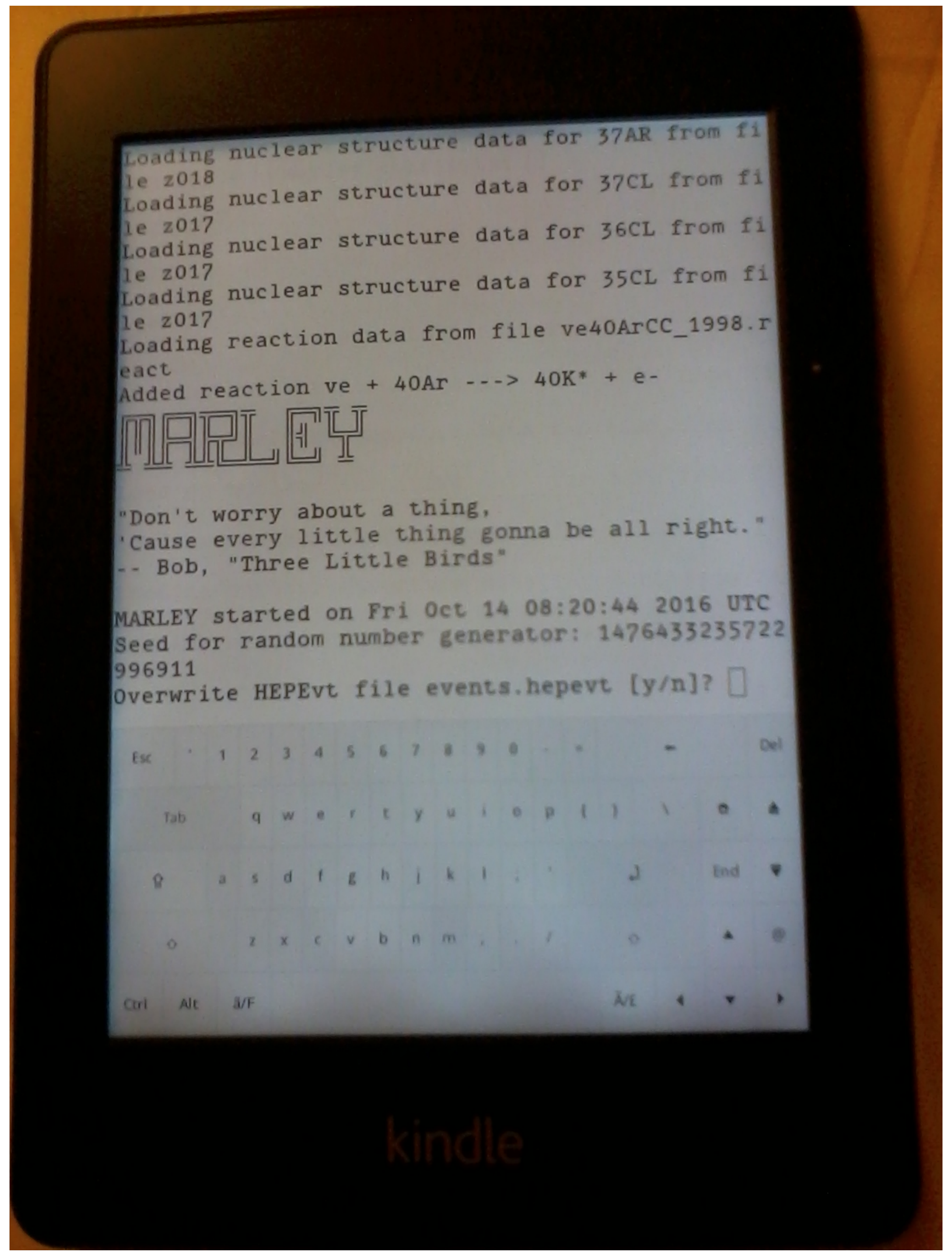
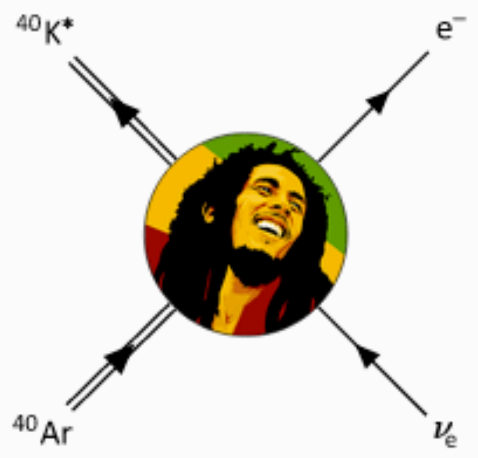
(Dated: September 15, 2020)

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 $^{40}\mathrm{Ar}(\nu_e, e^-)^{40}\mathrm{K}^*$ 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

TABLE OF CONTENTS

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

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

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 inclusive cross section model

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

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

Charged current factor

Recoil factor

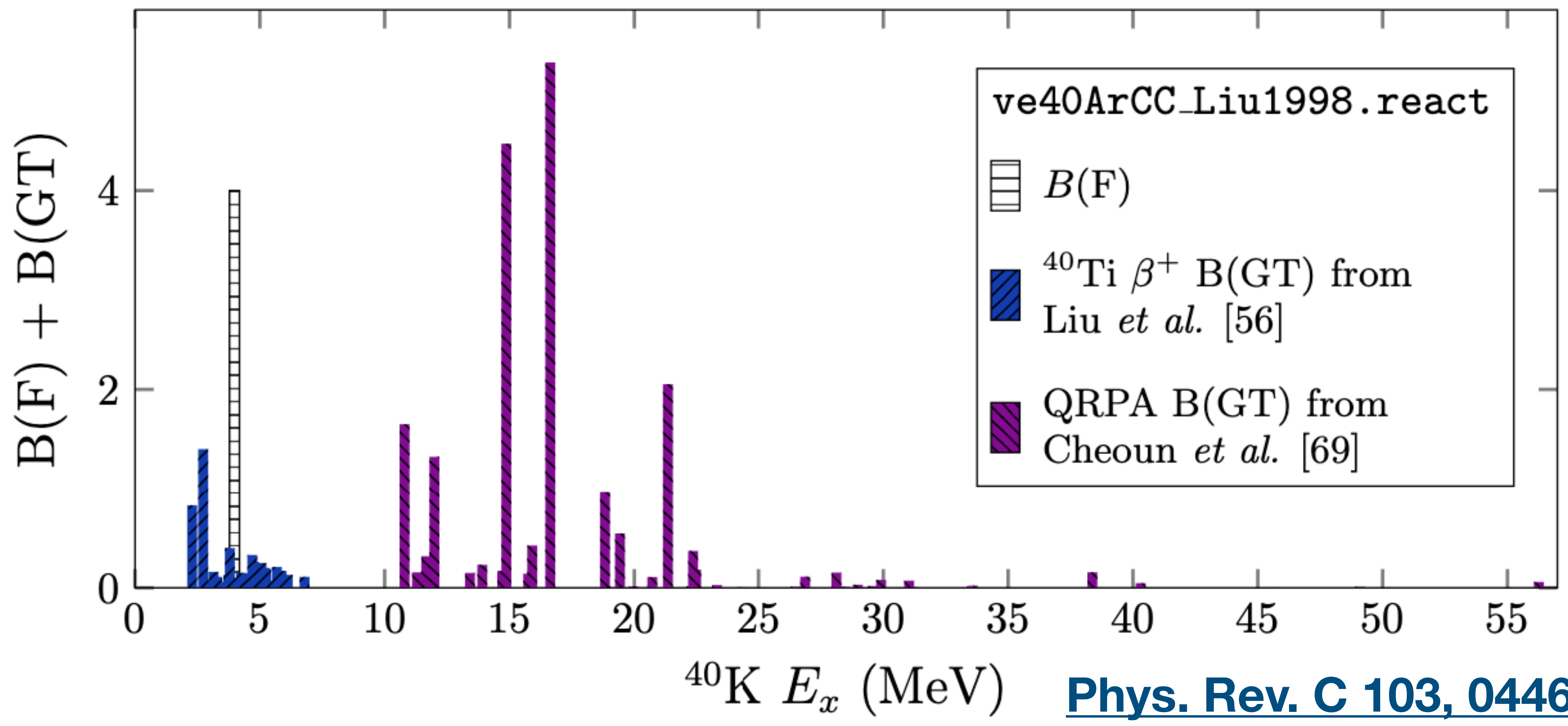
Allowed nuclear matrix elements

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**



Phys. Rev. C 103, 044604 (2021)

MARLEY inclusive cross section model

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).

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

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"

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

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

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

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

MARLEY nuclear de-excitation model

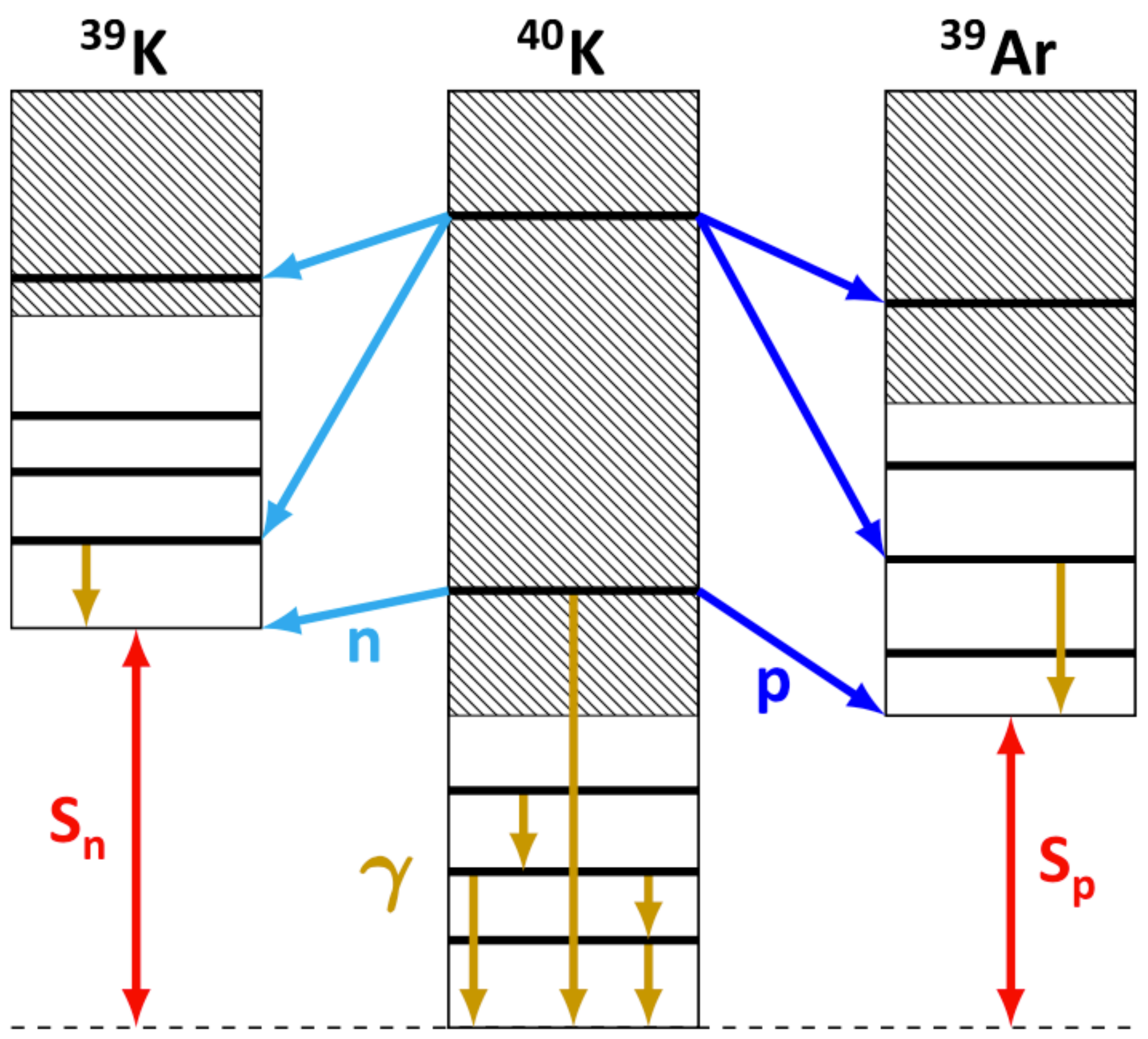
In the second step, the nucleus de-excites via a series of binary decays. Decay widths for **unbound states** are computed according to the Hauser-Feshbach formalism:

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

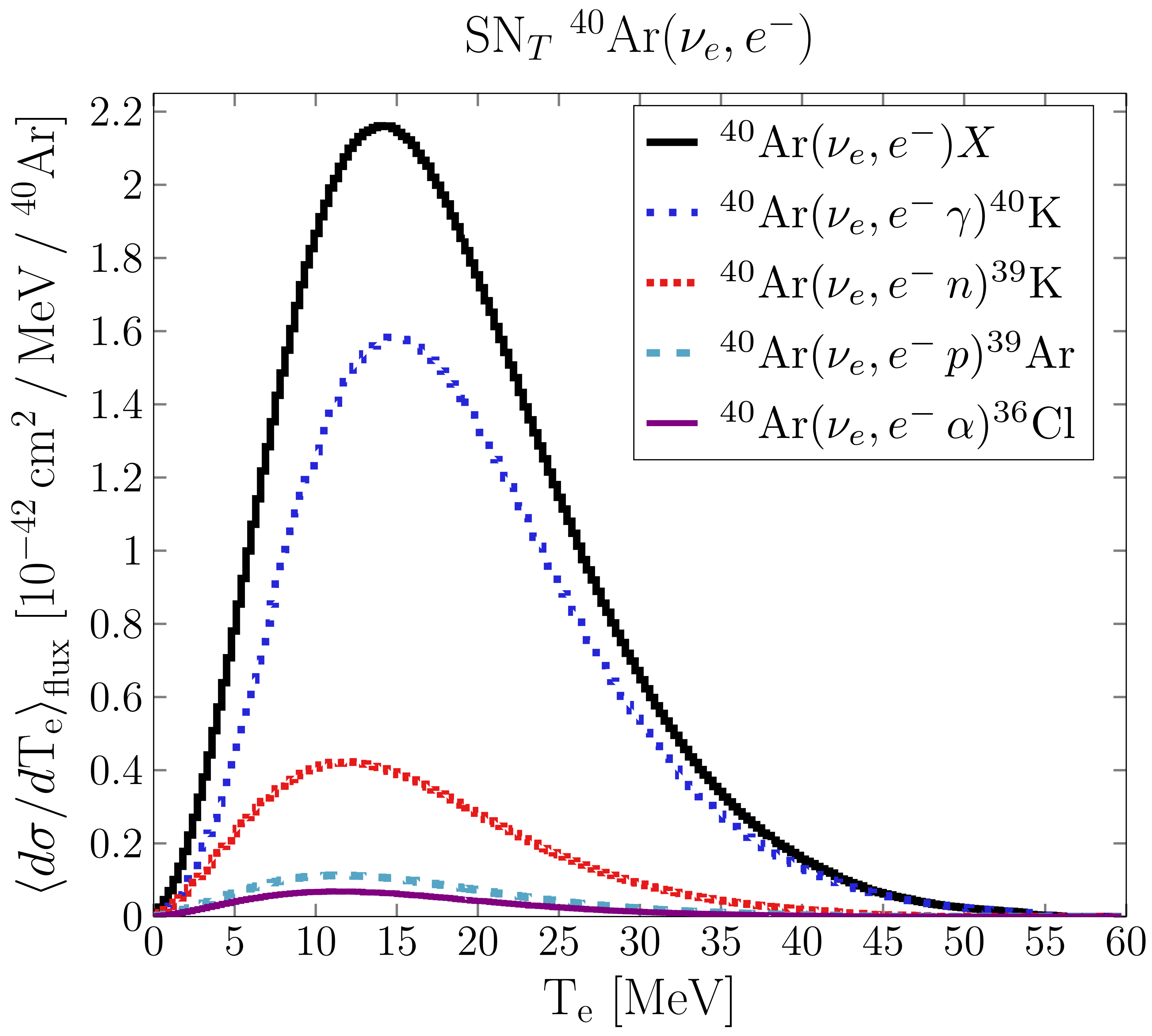
Phys. Rev. C 103, 044604 (2021)

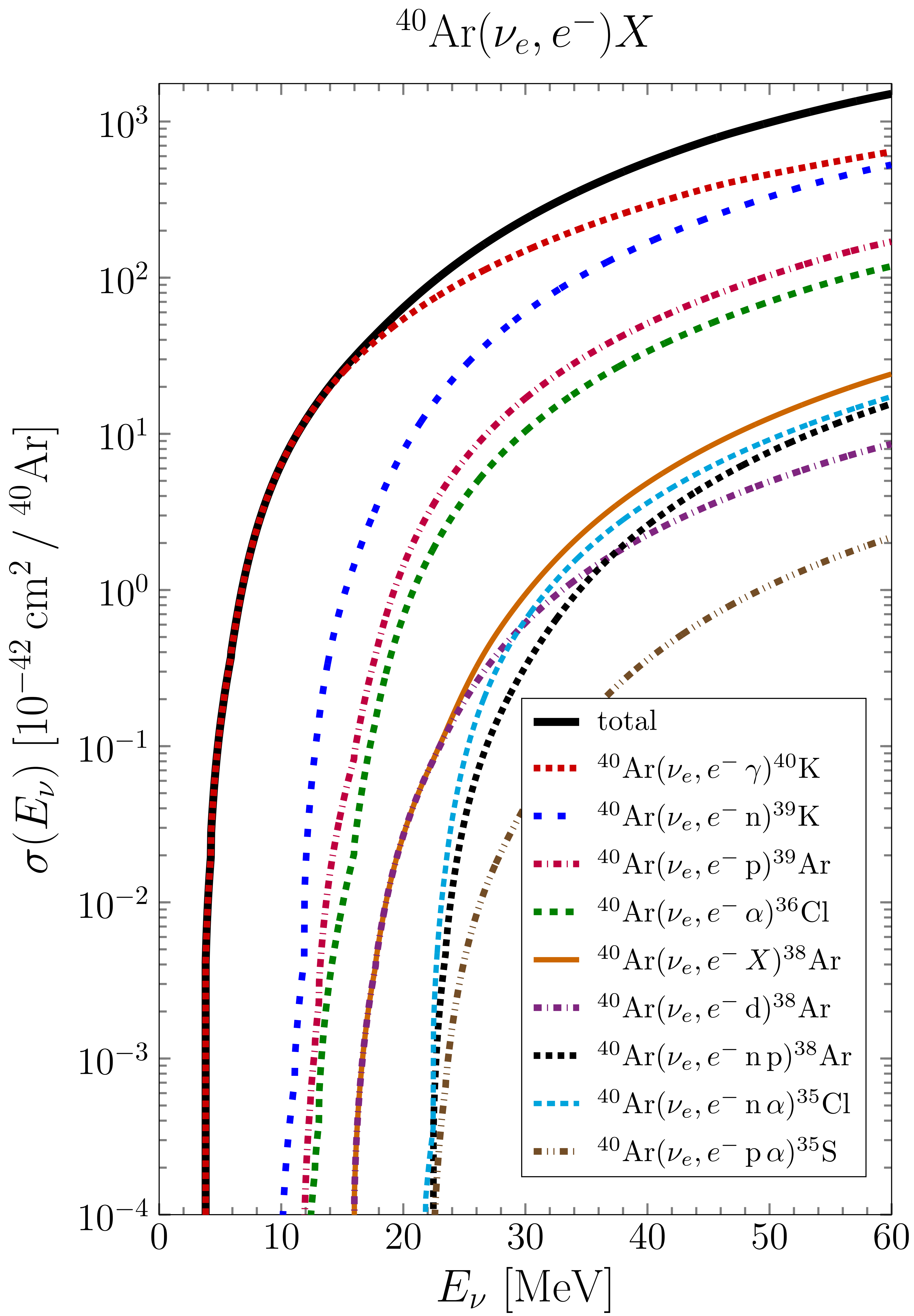
- First calculation of cross sections for **exclusive final states** of the reaction

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

at tens-of-MeV energies.

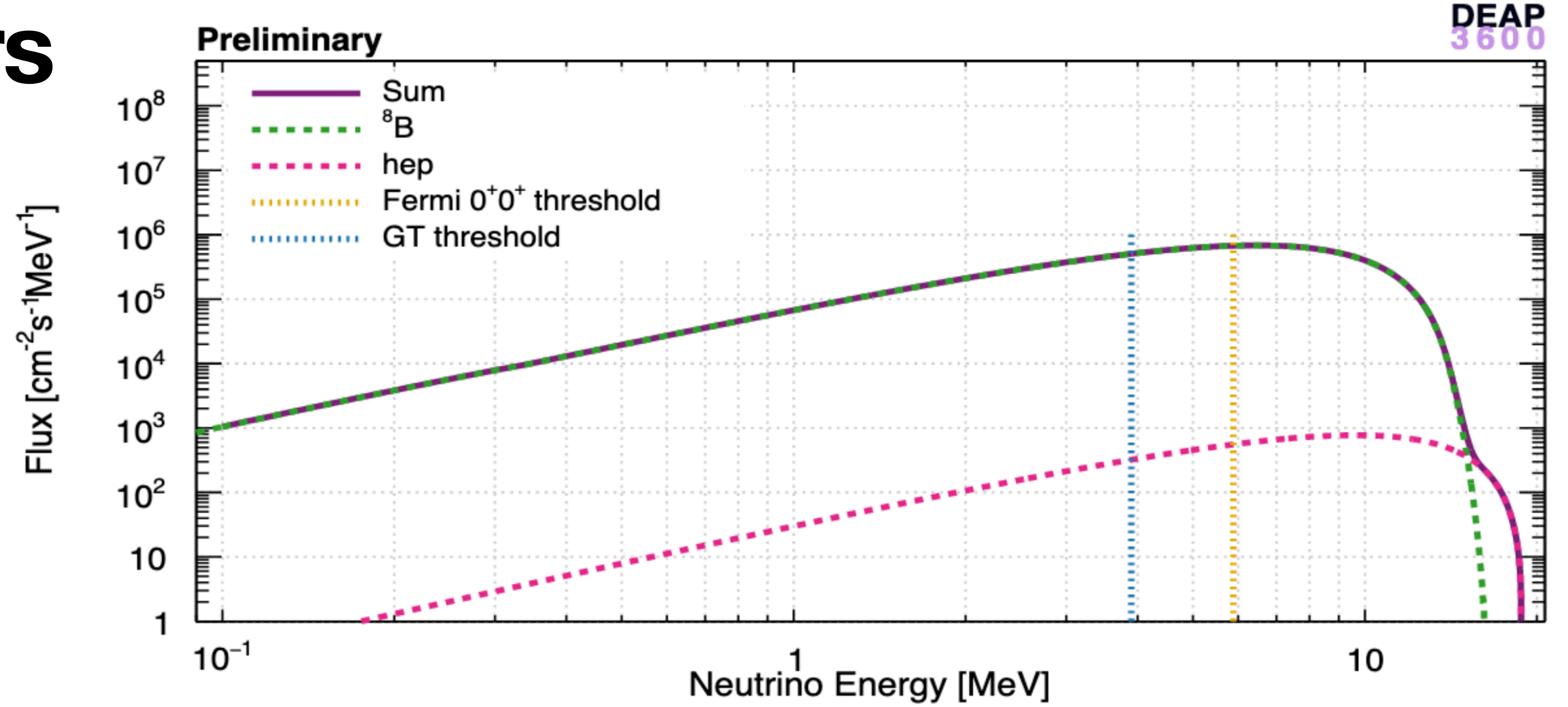
- Flux-averaged differential cross sections shown here are for the supernova model described in **Phys. Rev. D 97, 023019 (2018)**.

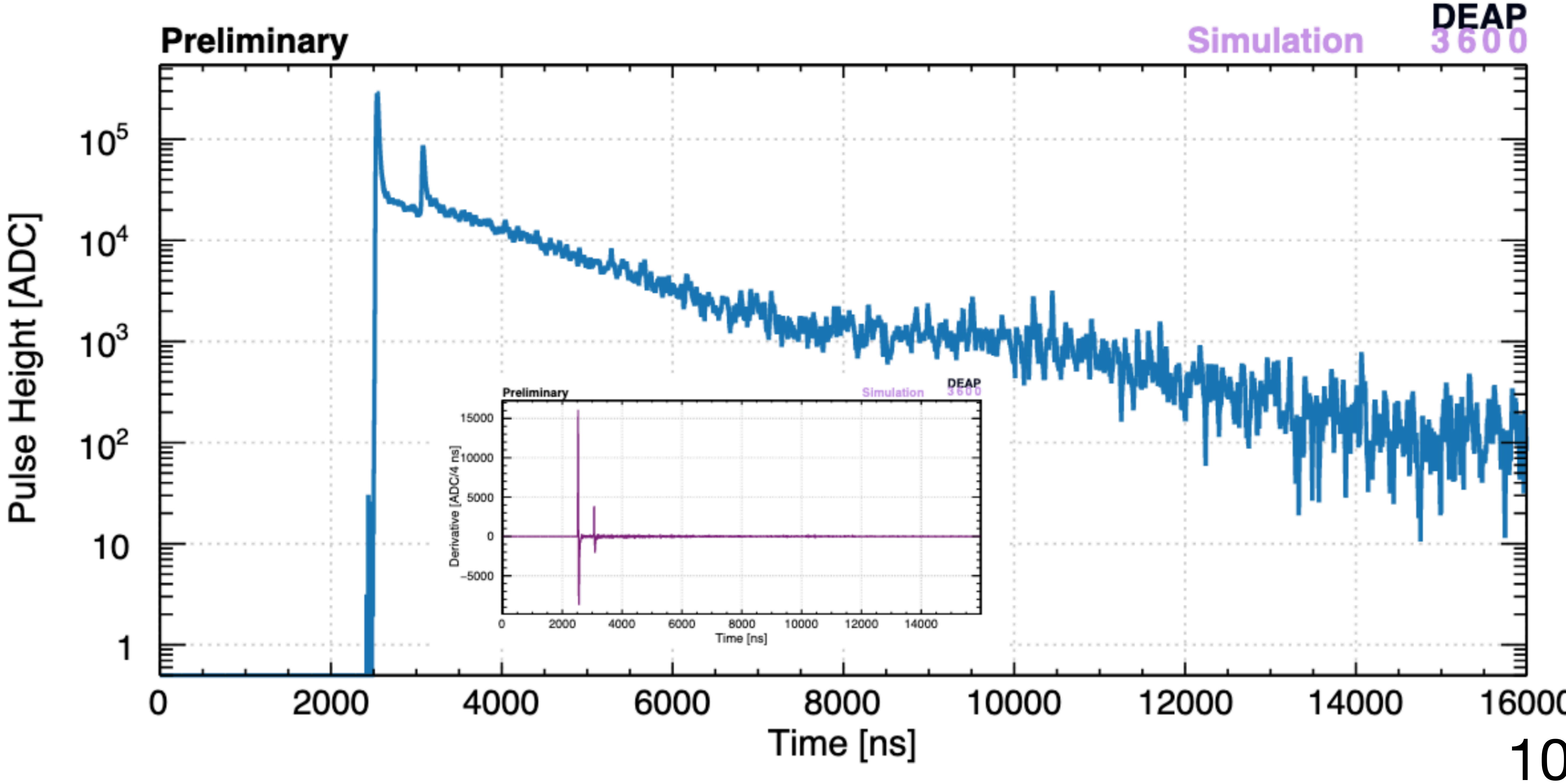




Results from external users

- **DEAP-3600 detector @ SNOLAB**
  - Argon-based dark matter search
- **LIDINE 2021 poster** about solar neutrino sensitivity
  - Realistic selection based on delayed coincidence
  - Signal MC computed using MARLEY
- 7.34 ± 0.66 events / 7.2 tonne-years
- COHERENT @ Oak Ridge
  - CEvNS and inelastic measurements
- MARLEY used to calculate spectrum of neutrino-induced neutrons on Pb target
  - See **arXiv:2110.07730**





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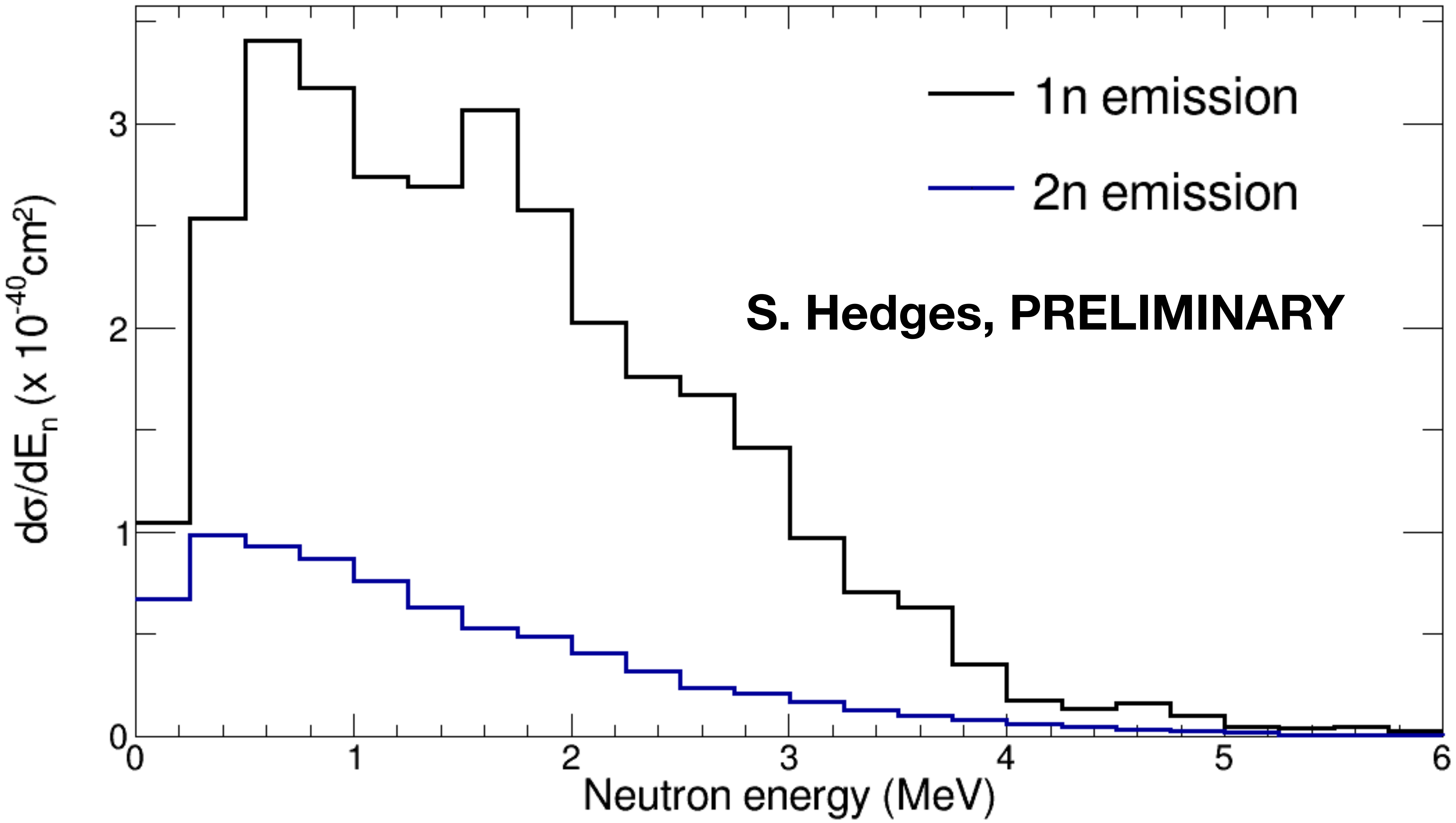
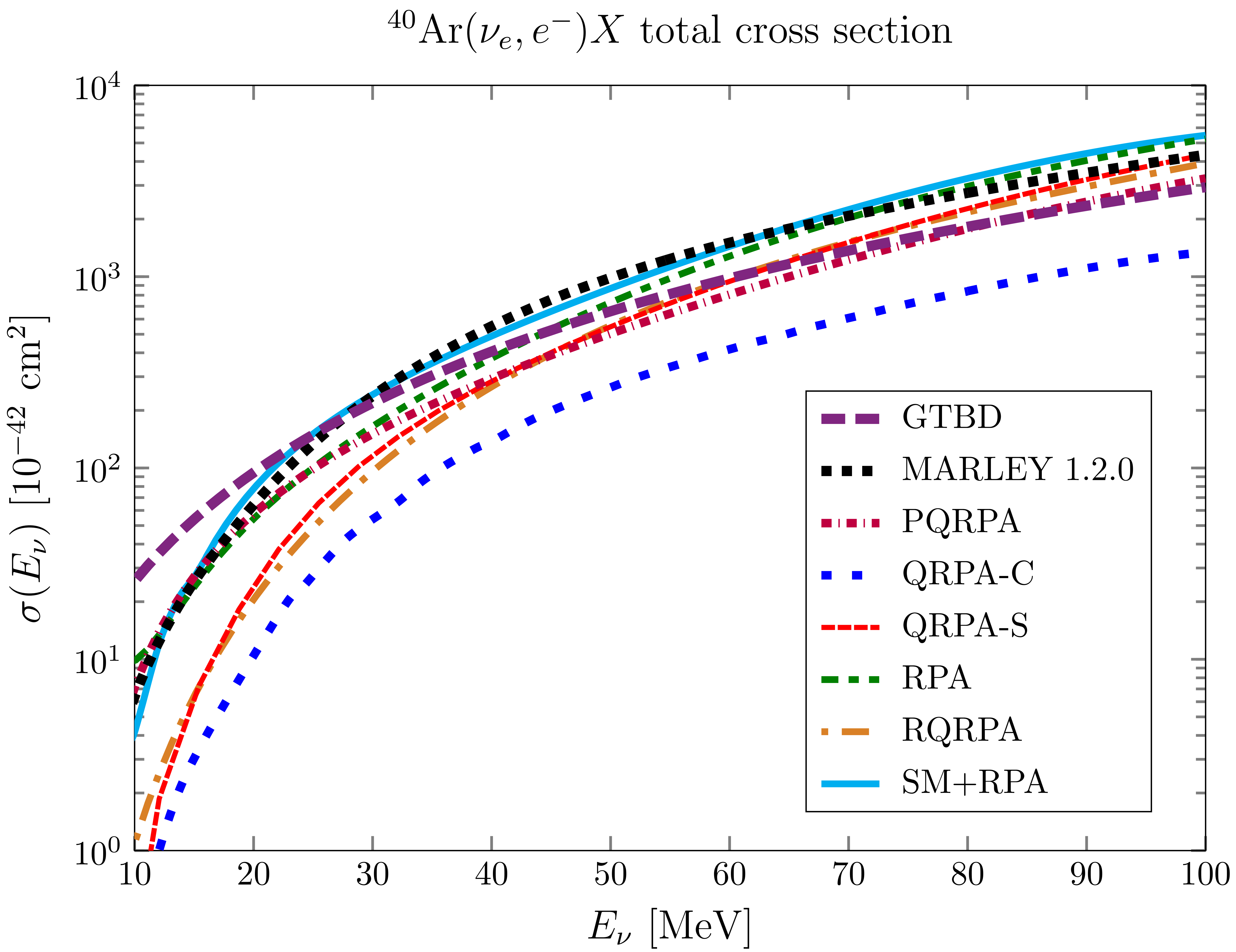


Connections to higher energies

- **Cross-section uncertainties** expected to be important for DUNE supernova effort
  - Even less understood than at the GeV-scale (e.g., no data for CC channel!)
- MARLEY-like de-excitation physics observable in LArTPCs
  - Recently demonstrated by ArgoNeuT
  - Comparisons to FLUKA, GENIE
- Possible means of improving reconstruction of GeV neutrinos
- De-excitations from proton decay may provide a powerful new handle for searches
  - See [this Snowmass LOI]



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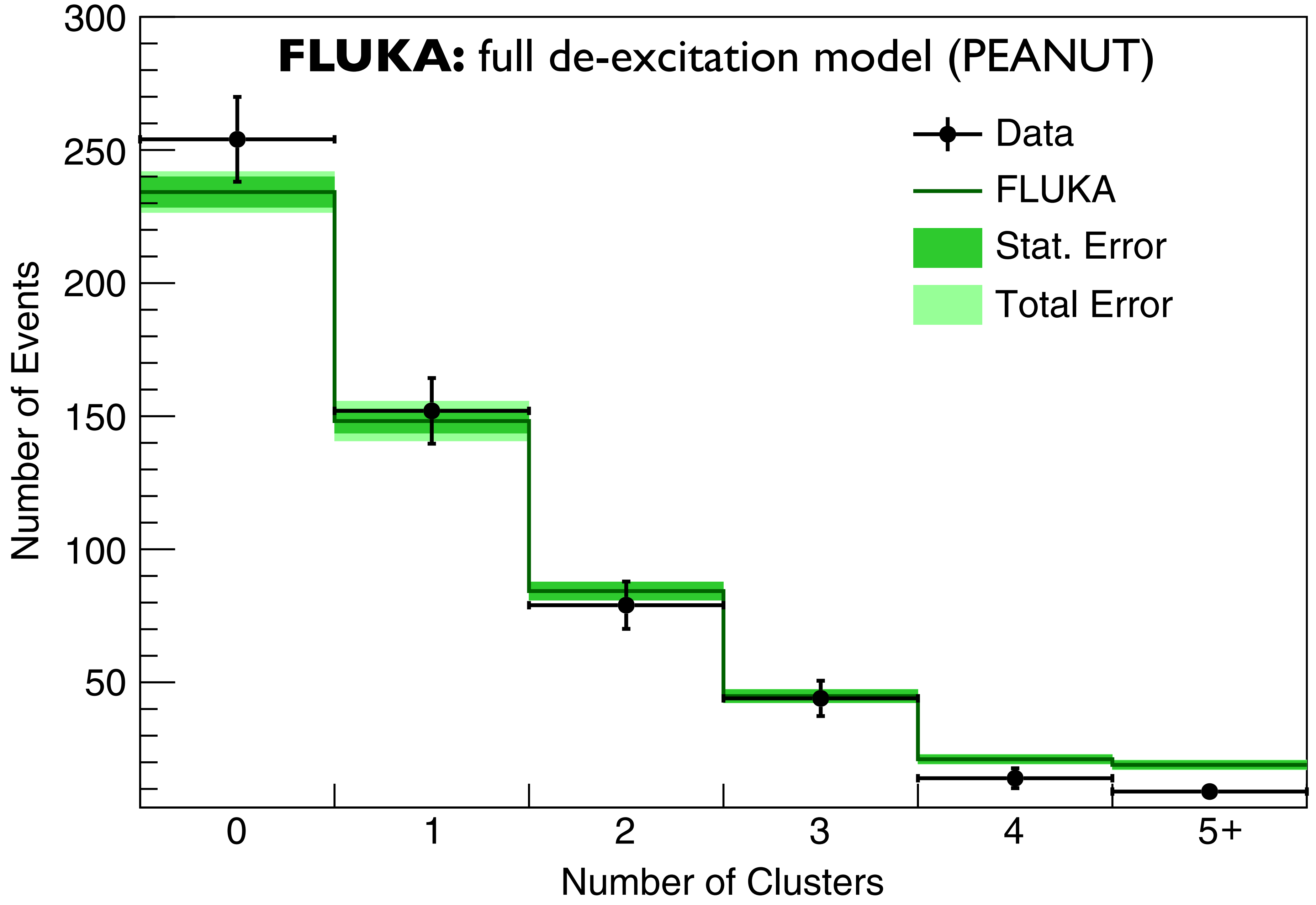
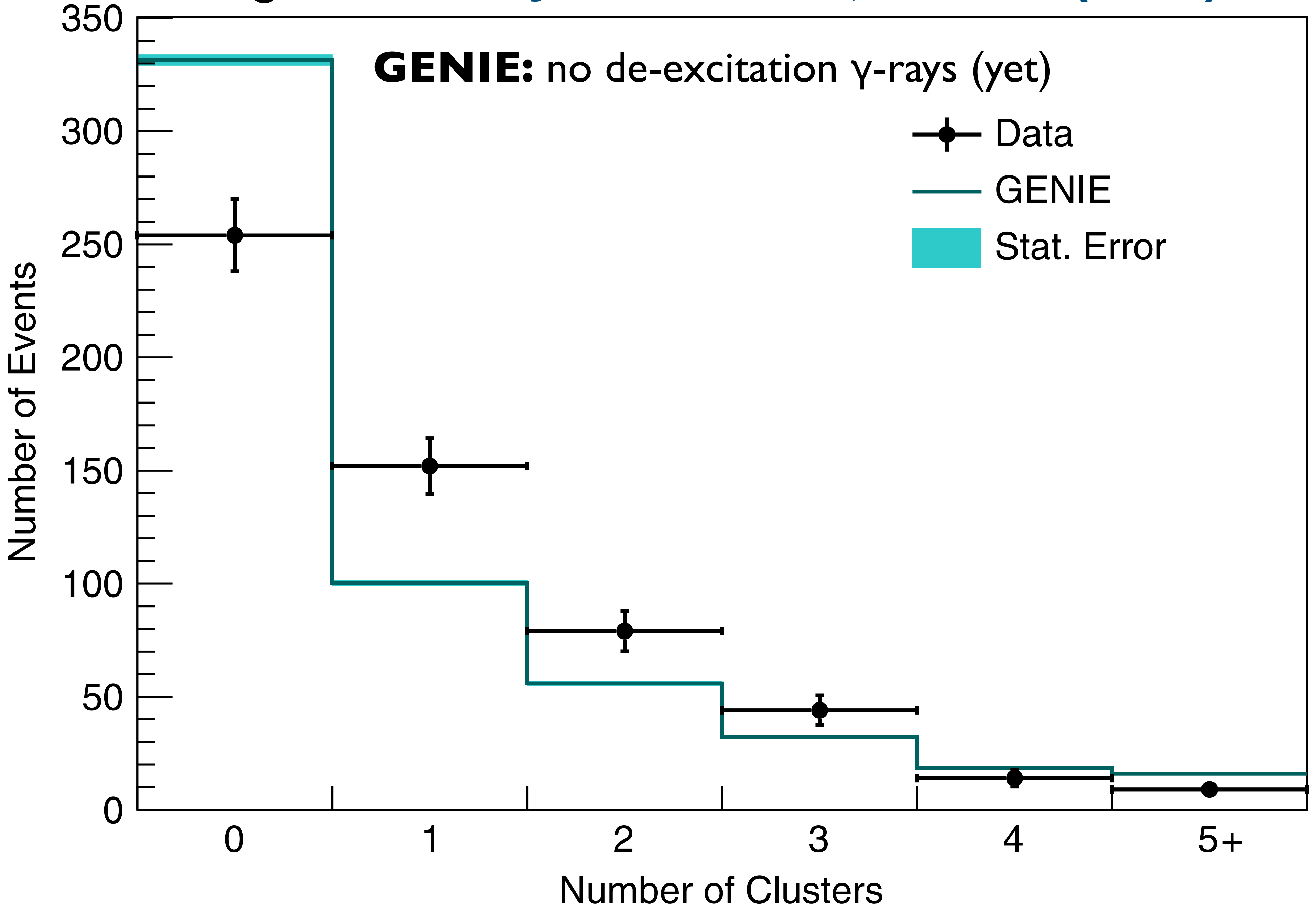
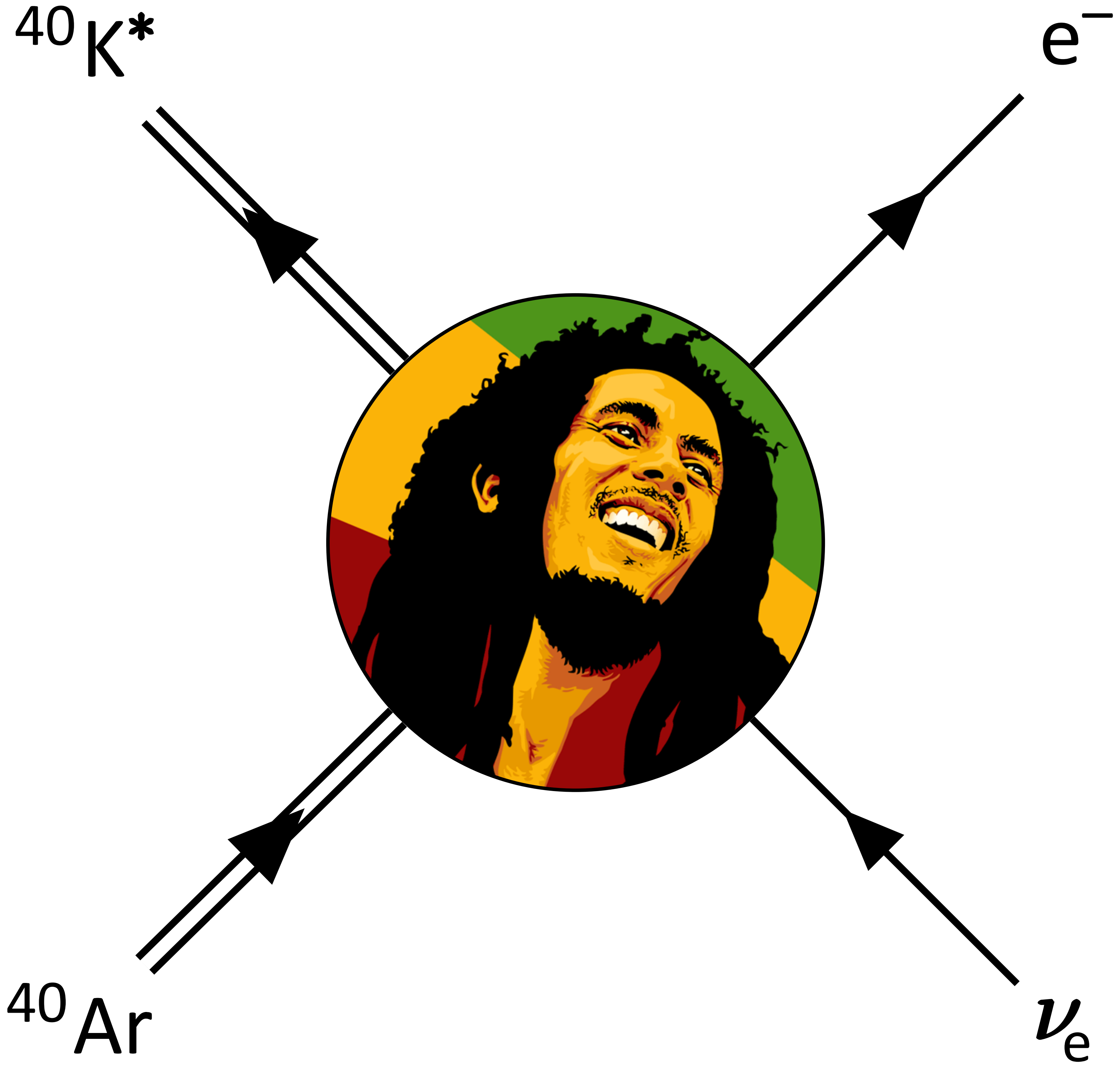


ArgoNeuT, **Phys. Rev. D 99, 012002 (2019)**



Summary

- **MARLEY** is a dedicated neutrino event generator focused on sub-100-MeV energies
  - Emphasis on ν_e CC on ^{40}Ar for DUNE
- First formal publications this year
  - In use by multiple external groups
- Low-energy inelastic neutrino-nucleus scattering has some unique simulation needs
  - Future measurements needed in this regime to test model assumptions
- I look forward to exploring this physics further with you in NuSTEC!



Model of Argon Reaction Low Energy Yields

Phys. Rev. C 103, 044604 (2021)

Comput. Phys. Commun. 269, 108123 (2021)

Backup