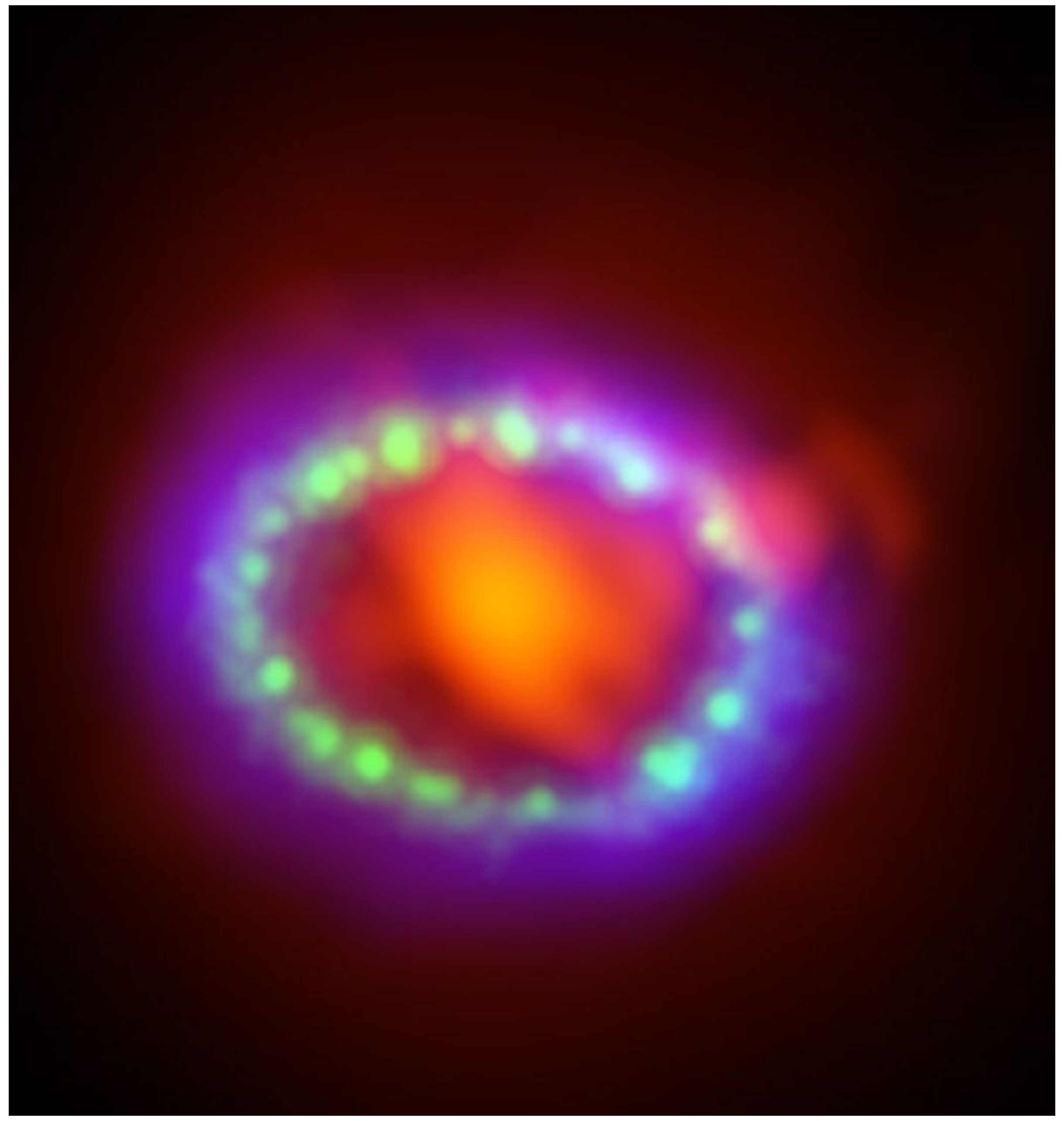
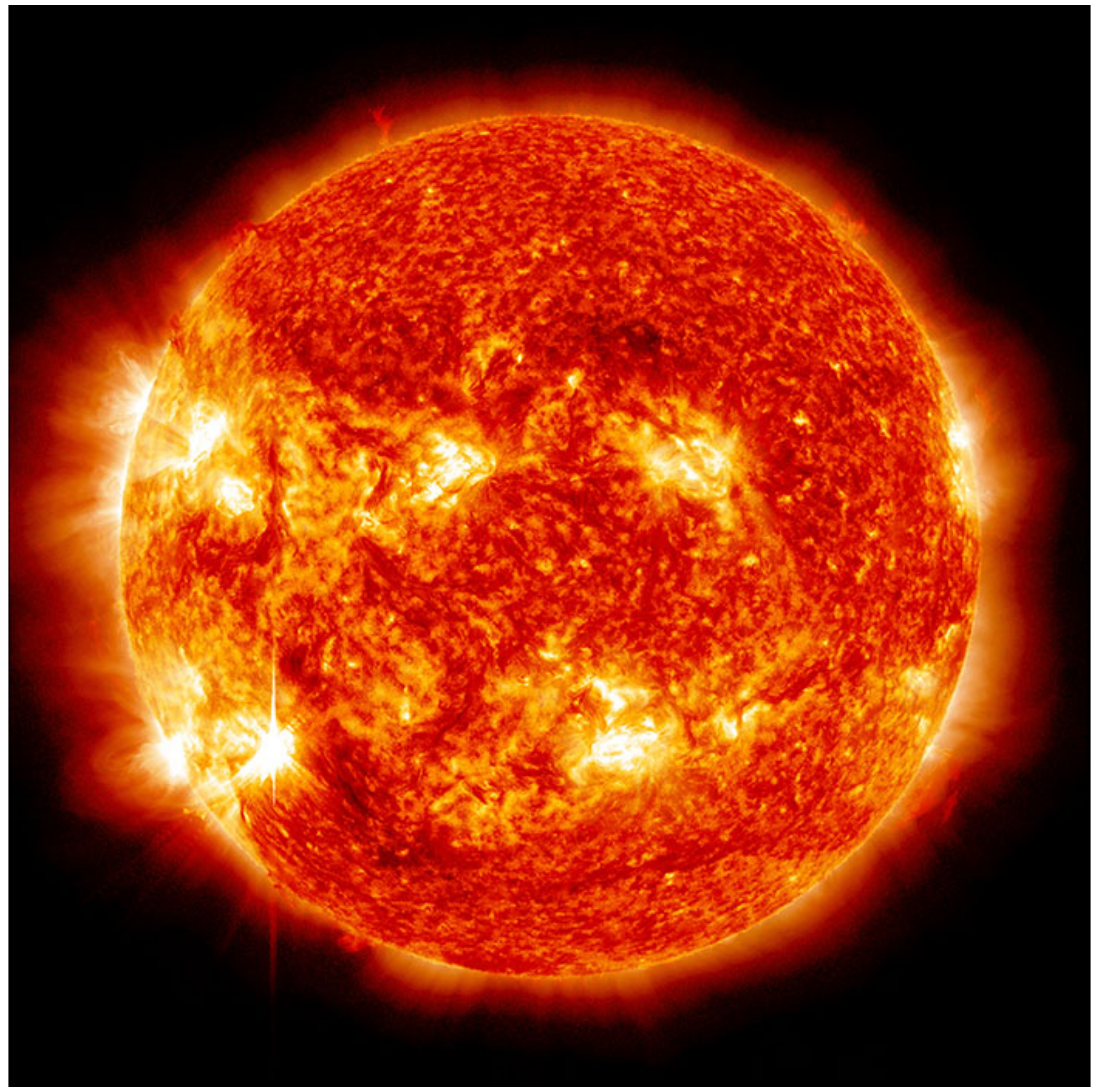
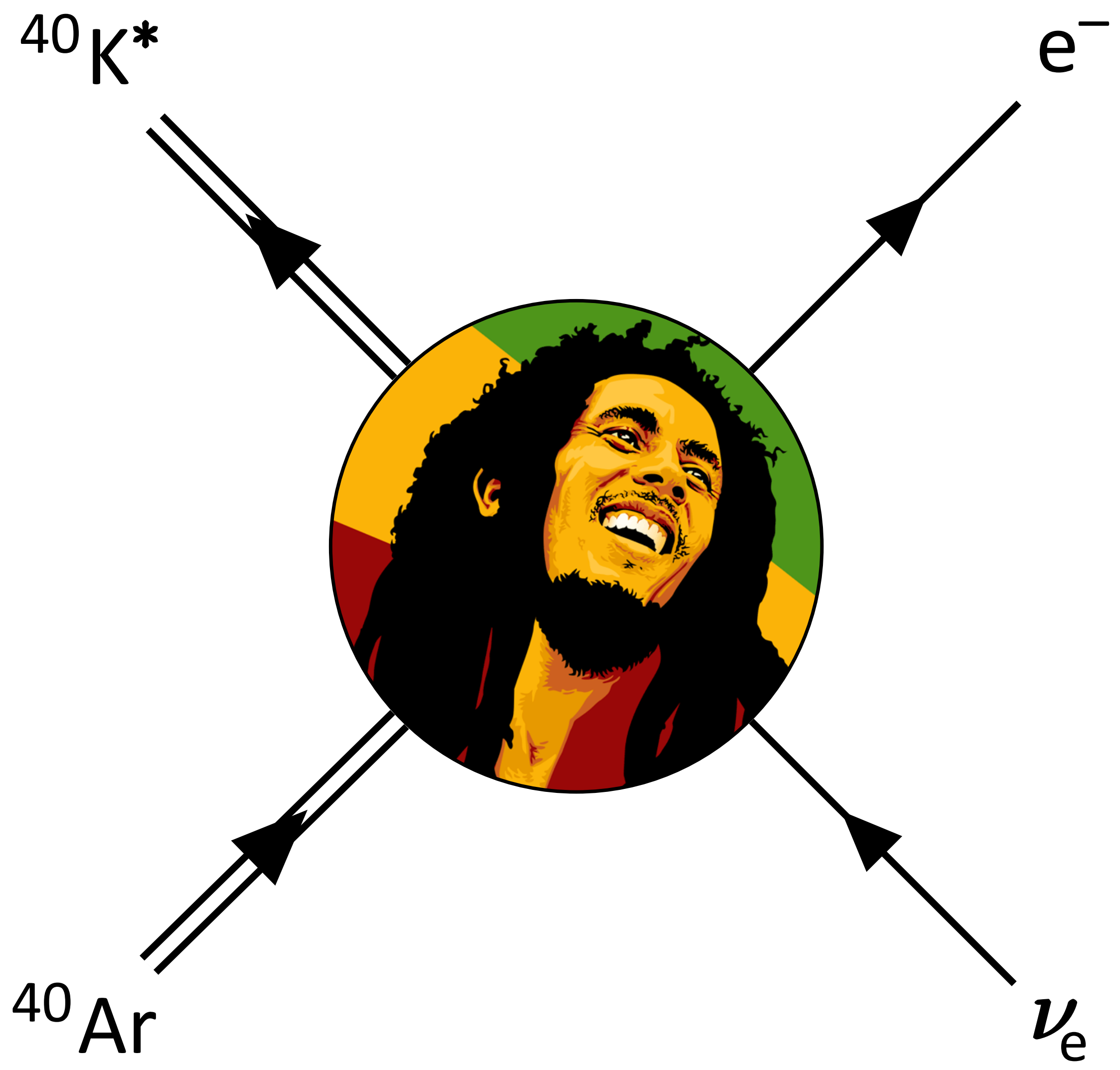
The MARLEY low-energy neutrino event generator



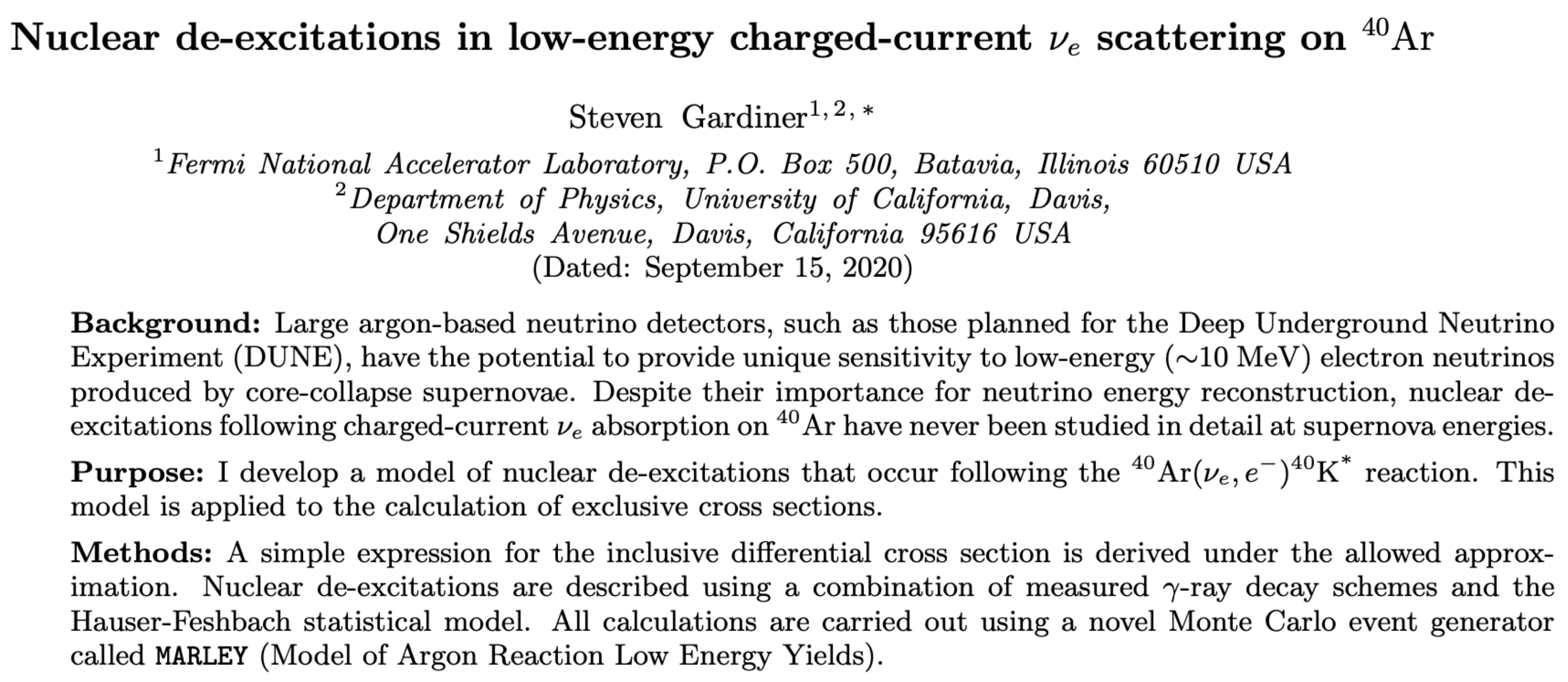




Steven Gardiner
NuSTEC Workshop on Electron Scattering
29 March 2022

MARLEY overview

- Event generator focused specifically on neutrino energies below ~100 MeV
  - ν-A inelastic scattering, some capability for ν-e, CEvNS
- "Model of Argon Reaction Low Energy Yields"
  - Emphasizes ν_e CC on ^{40}Ar, extensible
- 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



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

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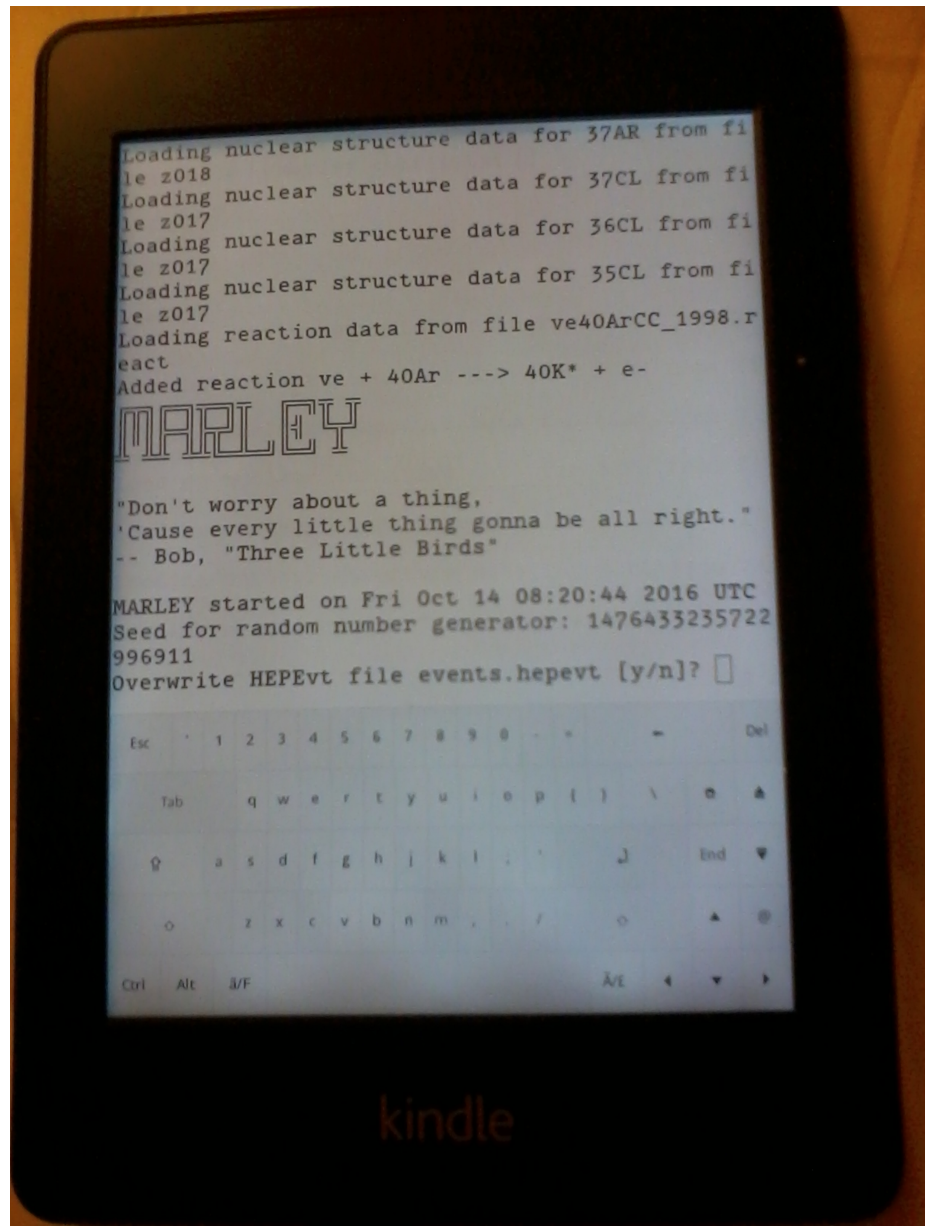
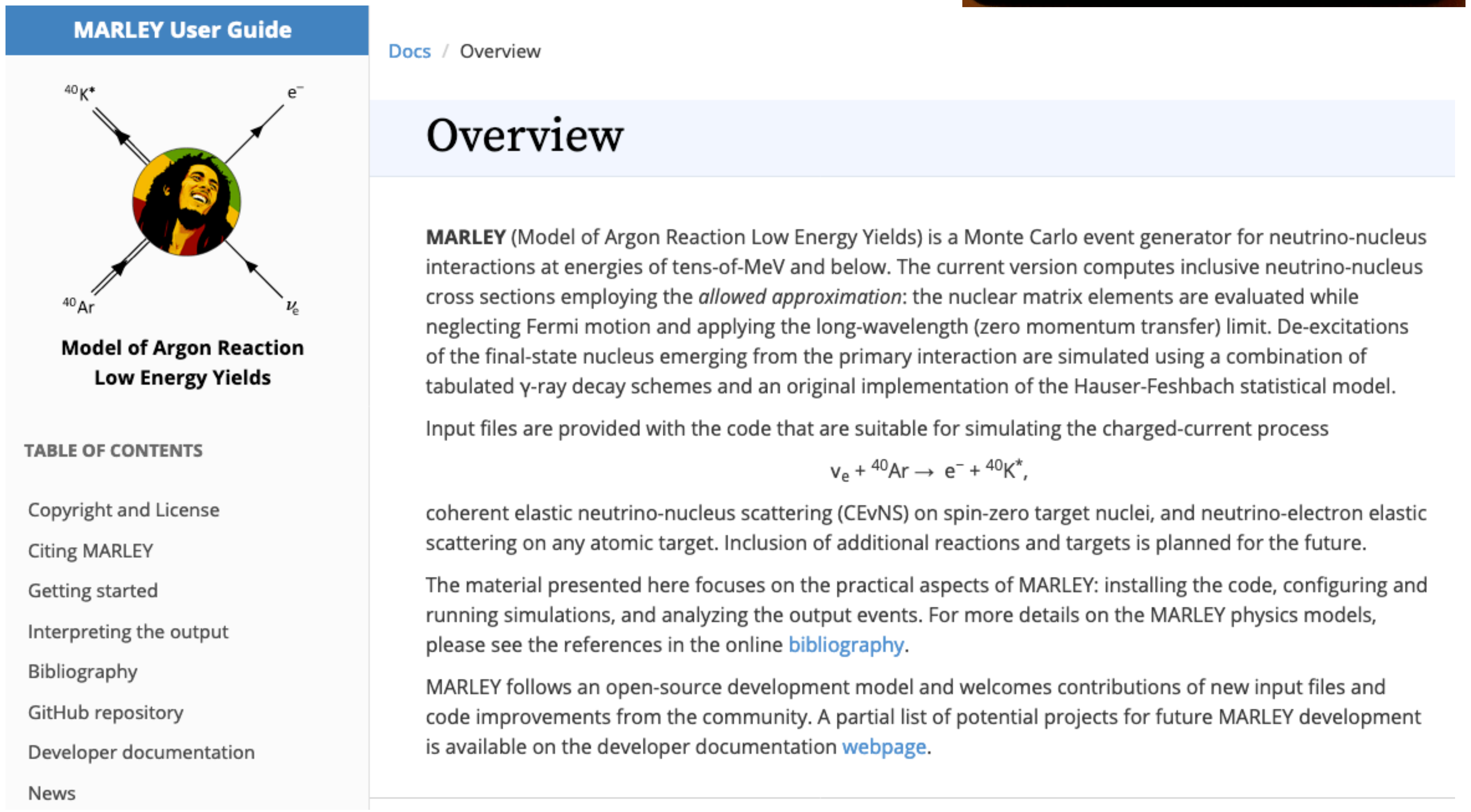
(Dated: September 15, 2020)

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).





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.

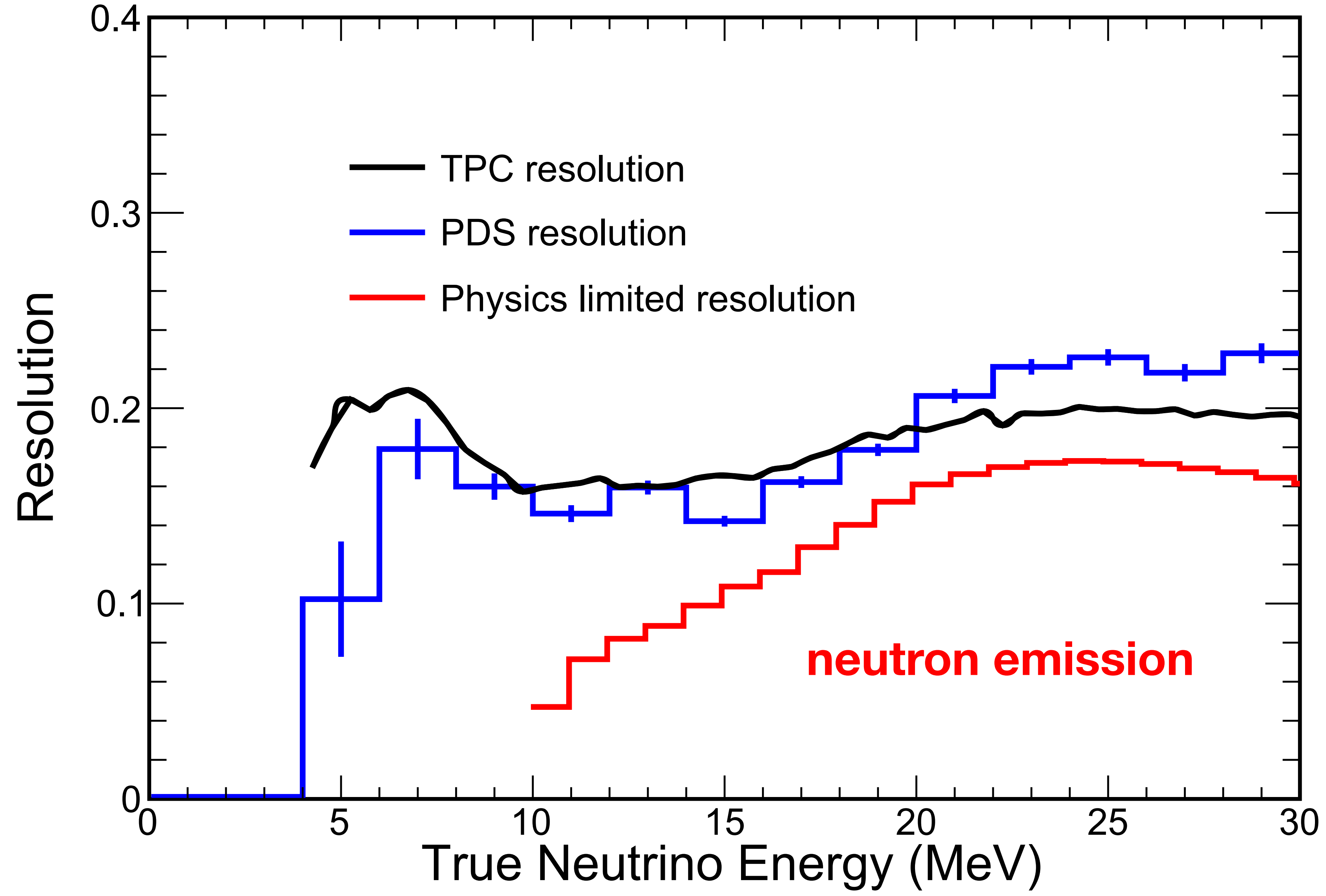
The material presented here focuses on the practical aspects of MARLEY: installing the code, configuring and running simulations, and analyzing the output events. For more details on the MARLEY physics models, please see the references in the online bibliography.

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.

https://www.marleygen.org

Example applications of MARLEY

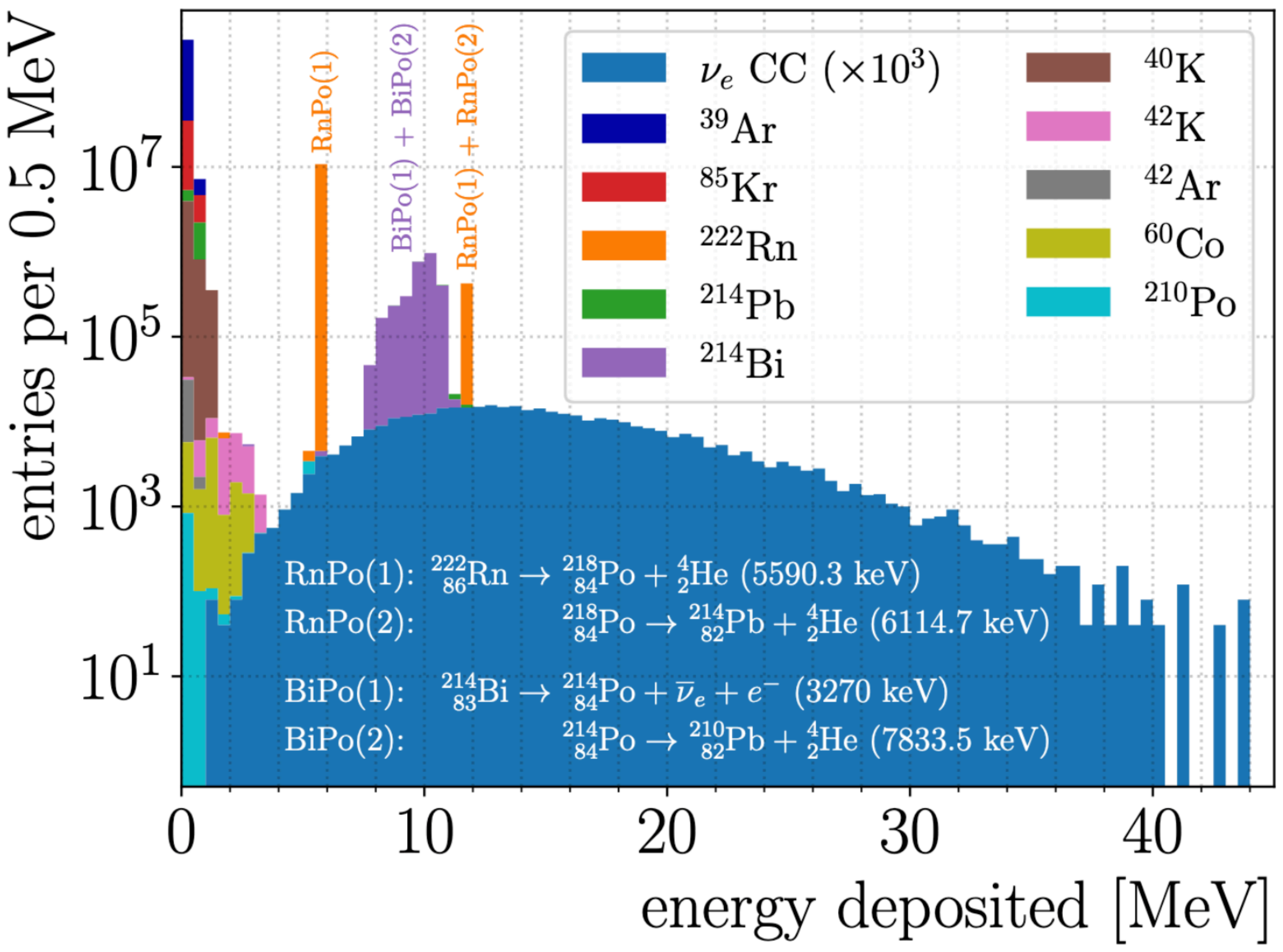
[Eur. Phys. J. C 81, 423 (2021)]

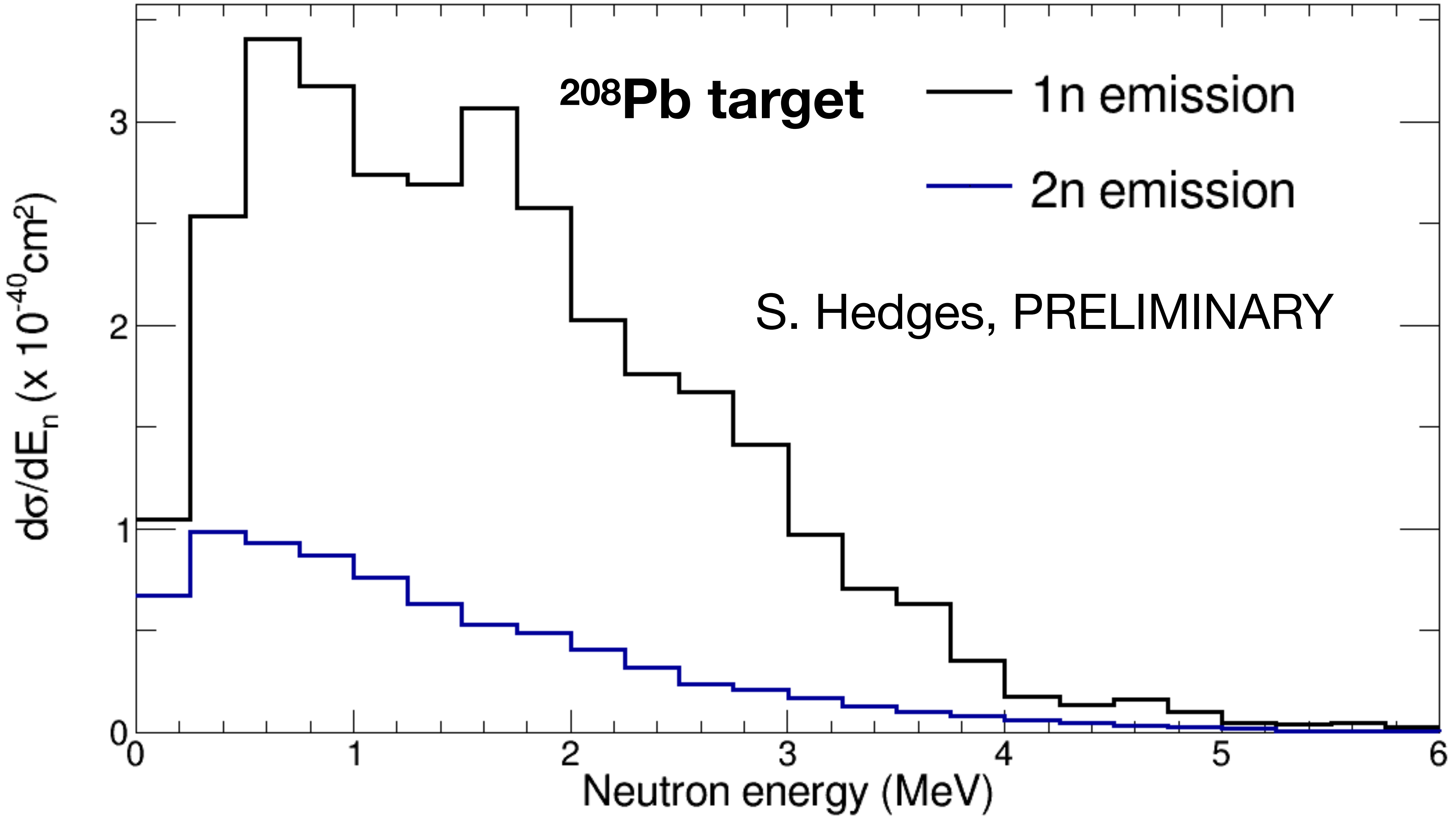


Supernova neutrino energy resolution in DUNE

[arXiv:2203.12109]

Pixelated readout (Q-Pix) performance for supernova neutrino detection in DUNE





Neutrino-induced neutron spectra for COHERENT (see [arXiv:2110.07730])

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.

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

Charged current factor

Recoil factor

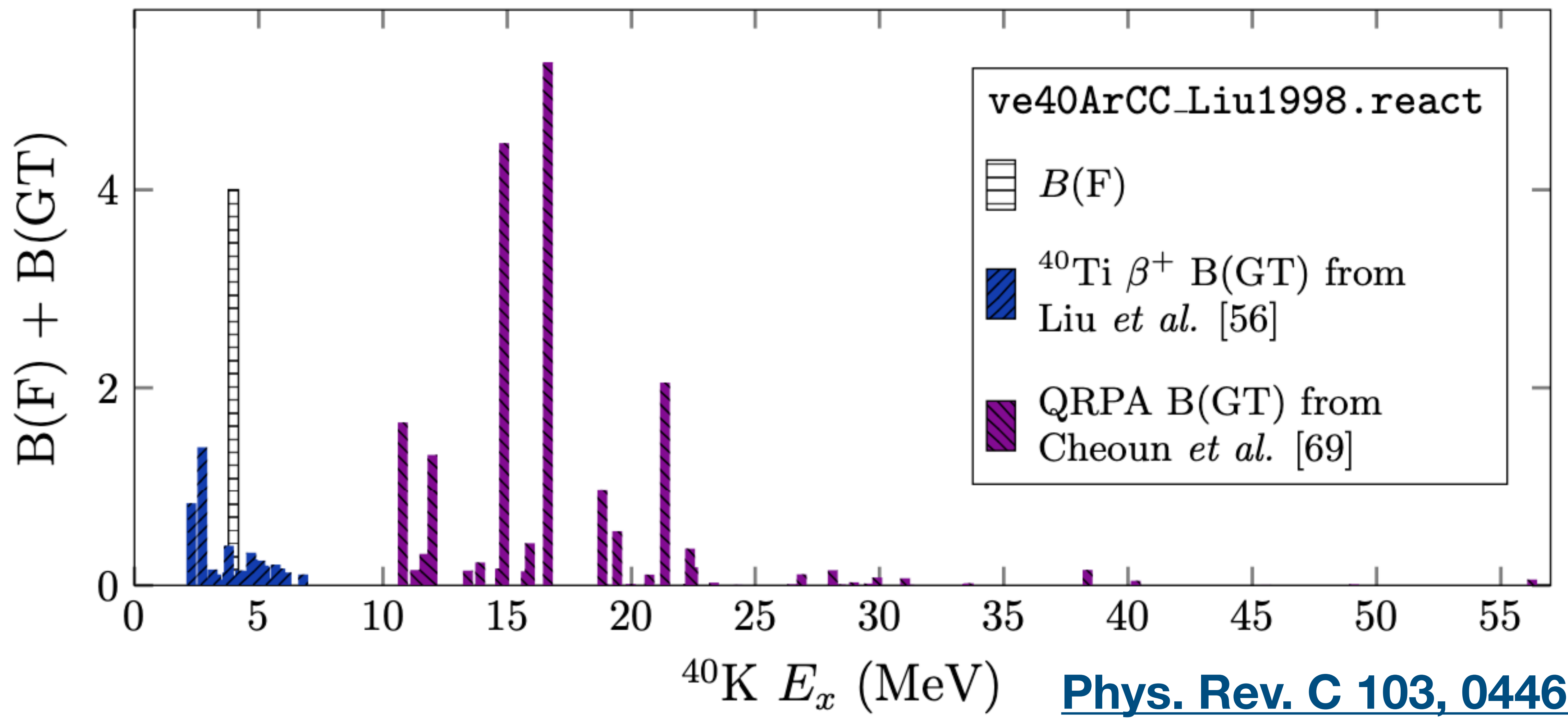
Allowed nuclear matrix elements

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).

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

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"

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

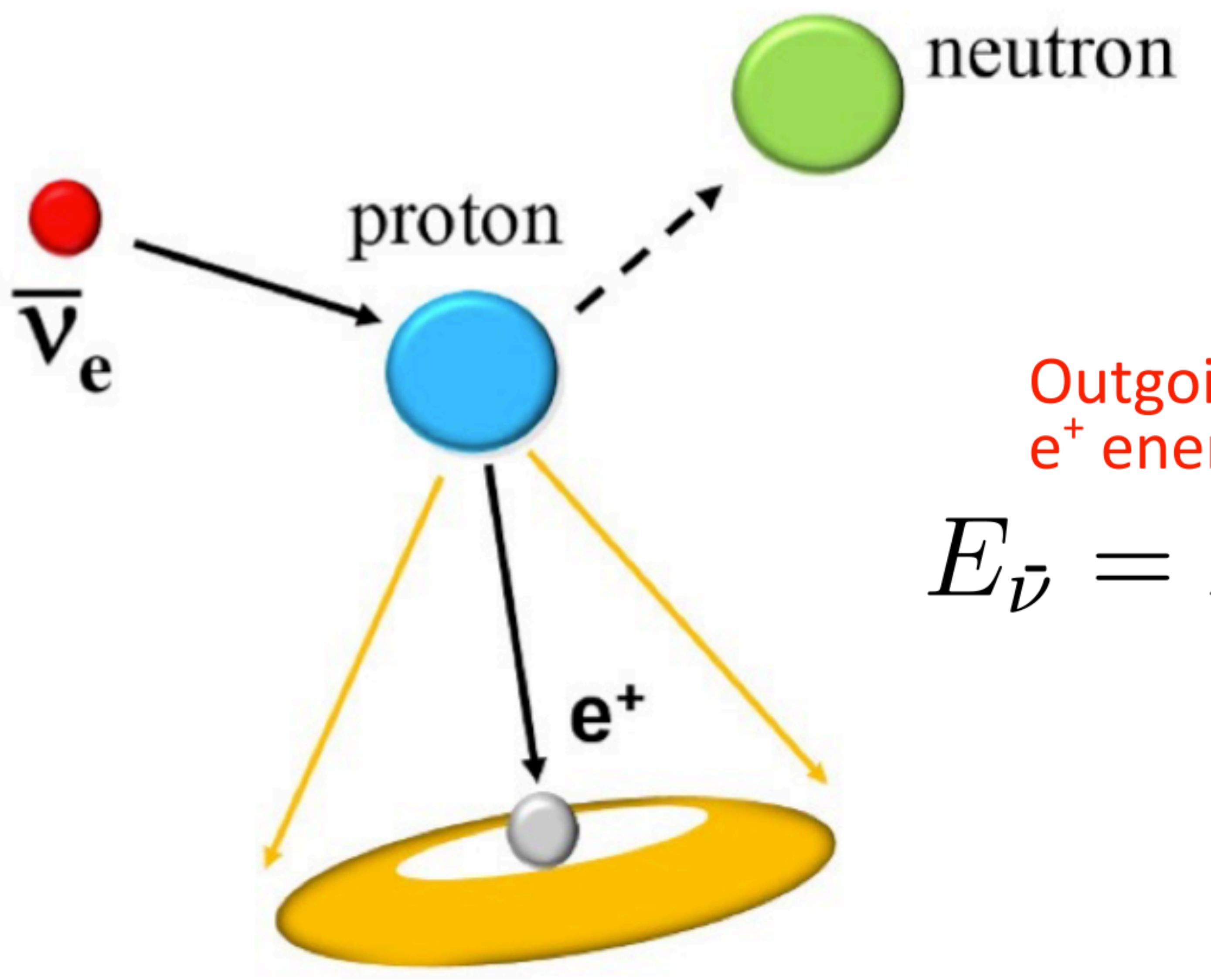
$$B(\mathrm{F}) \equiv \frac{g_V^2}{2J_i+1} \left| \langle J_f \| \mathcal{O}_\mathrm{F} \| J_i \rangle \right|^2$$

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

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

The importance of full final-state predictions

- Needs are similar to those for GeV-scale experiments
- **Example:** supernova neutrino calorimetry
- Scintillator & water Cherenkov detectors
  - Inverse beta decay
  - Positron energy sufficient
- LArTPCs (e.g., DUNE)
  - Complex nuclear target, many transitions
  - De-excitation products must be measured
  - Correct for missing energy from neutrons, etc.

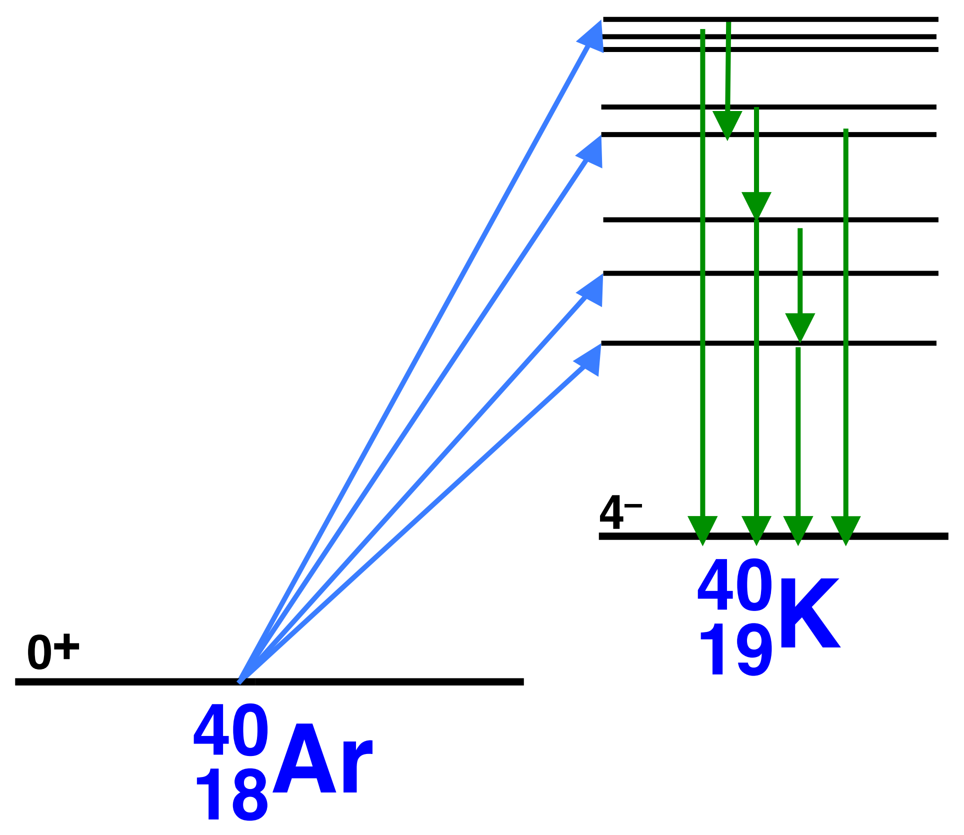


inverse beta decay

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

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

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



MARLEY seeks to provide a realistic treatment of the de-excitation physics

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

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

The importance of full final-state predictions

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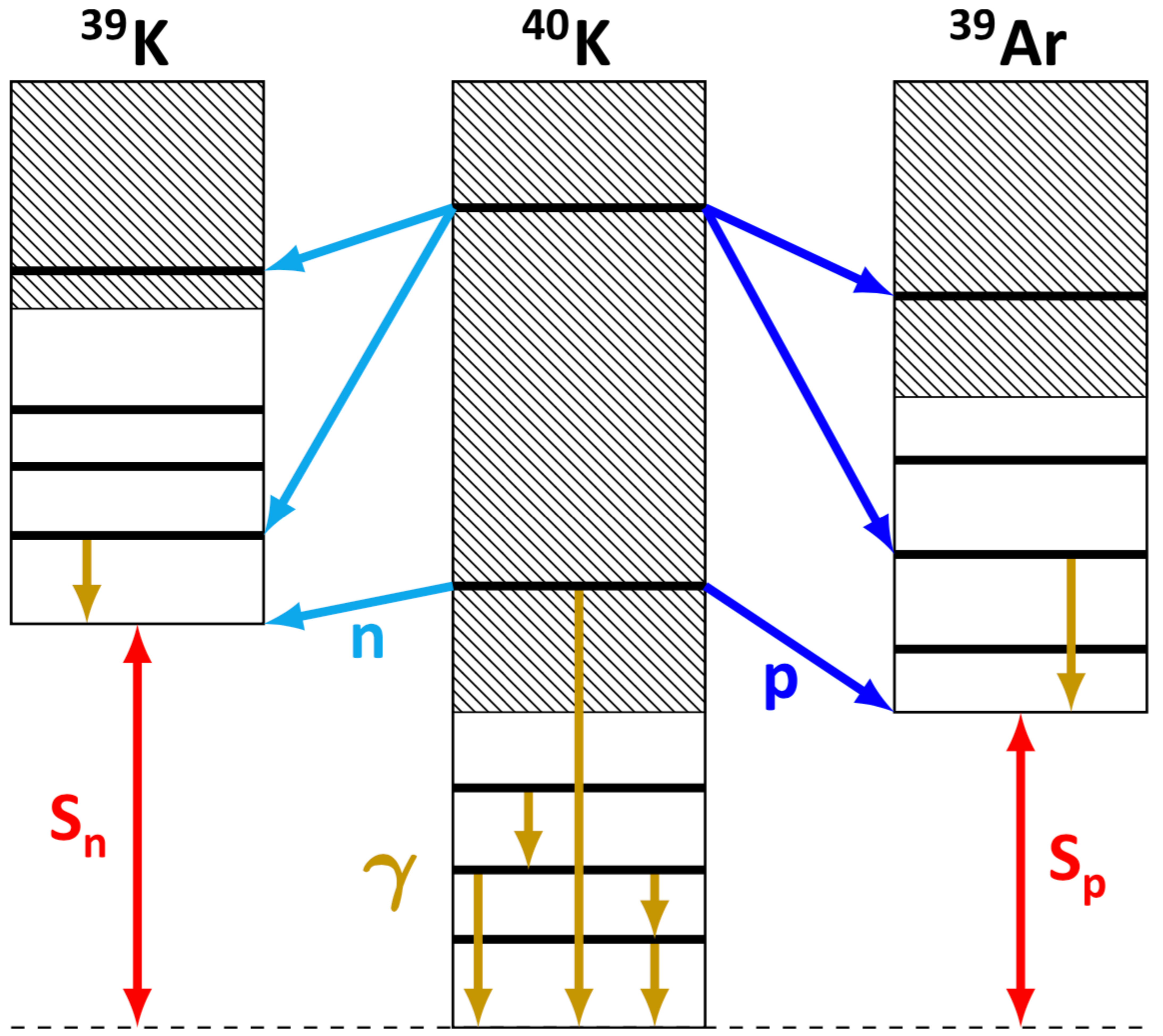
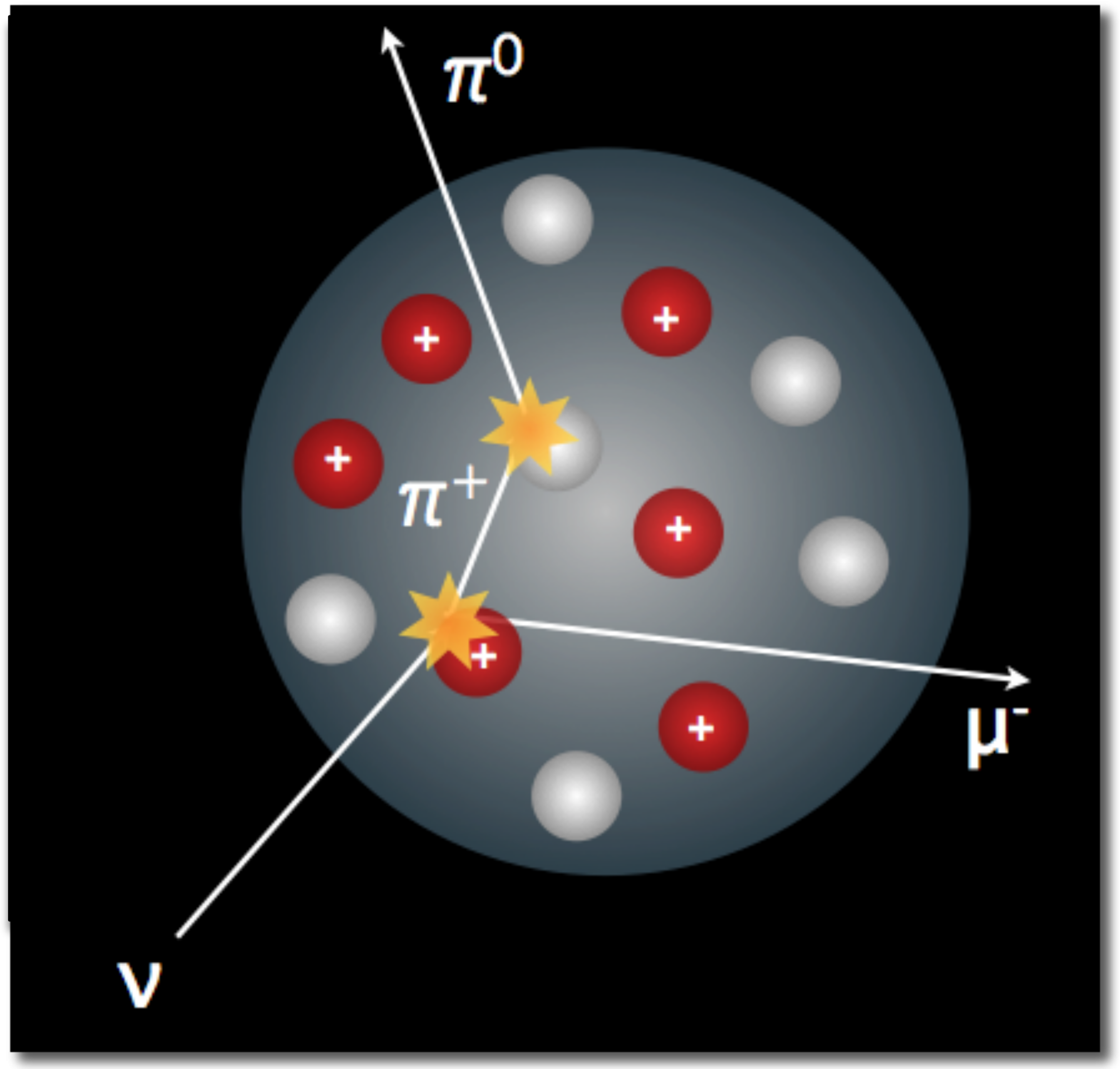
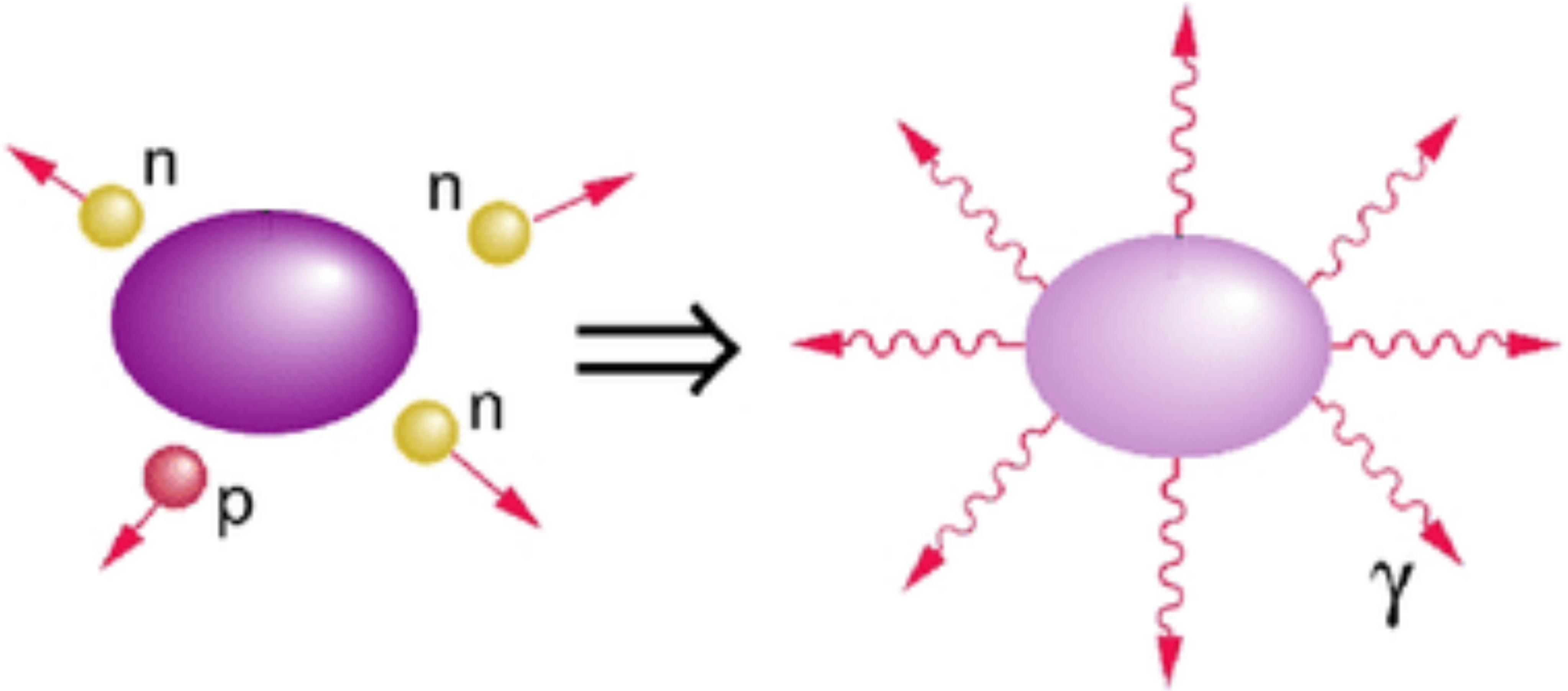


Various de-excitation channels make the problem complicated

The compound nucleus assumption

- High-energy generators rely primarily on a **direct knockout** picture
  - Transport outgoing hadrons through the nucleus
  - Dynamical models: intranuclear cascade (GENIE, NEUT, NuWro) or BUU transport (GiBUU)
- MARLEY uses a **compound nucleus** picture standard in the low-energy literature
  - Energy transfer widely shared, leading to equilibration and “boil off” of nucleons
  - Hauser-Feshbach statistical model
- Some FSI models include both (e.g., FLUKA)
  - FLUKA and MARLEY both have realistic gamma-ray emission

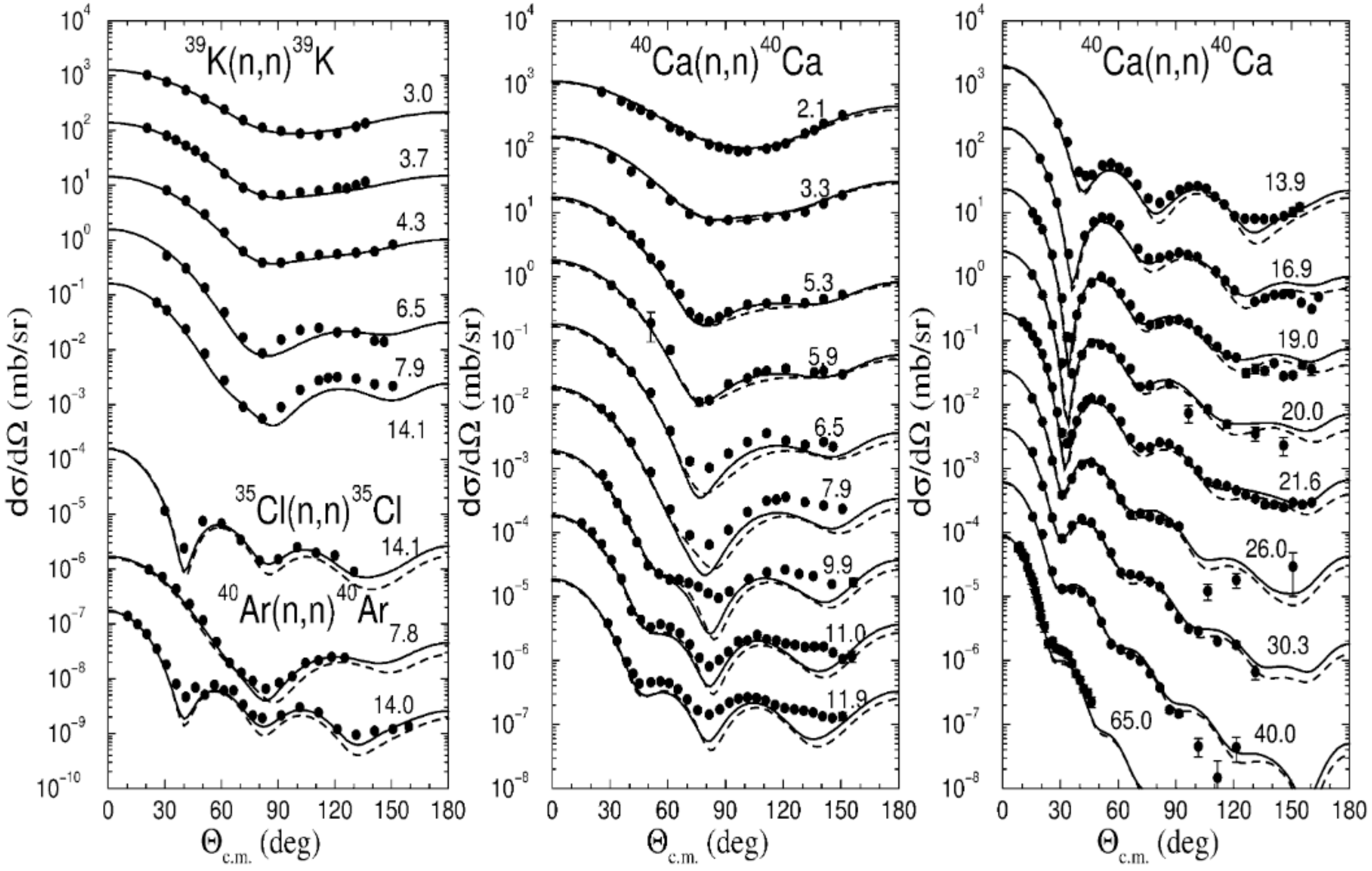




The compound nucleus assumption

- Equilibration → "amnesia"
  - Compound nucleus de-excitations independent of creation process
- Time reversal symmetry
  - Relate decay widths to compound nucleus formation cross sections
- MARLEY ingredients taken from semi-empirical fits to low-energy nuclear reaction & structure data
  - Also tabulated nuclear levels and gamma-rays

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



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

MARLEY nuclear de-excitation model

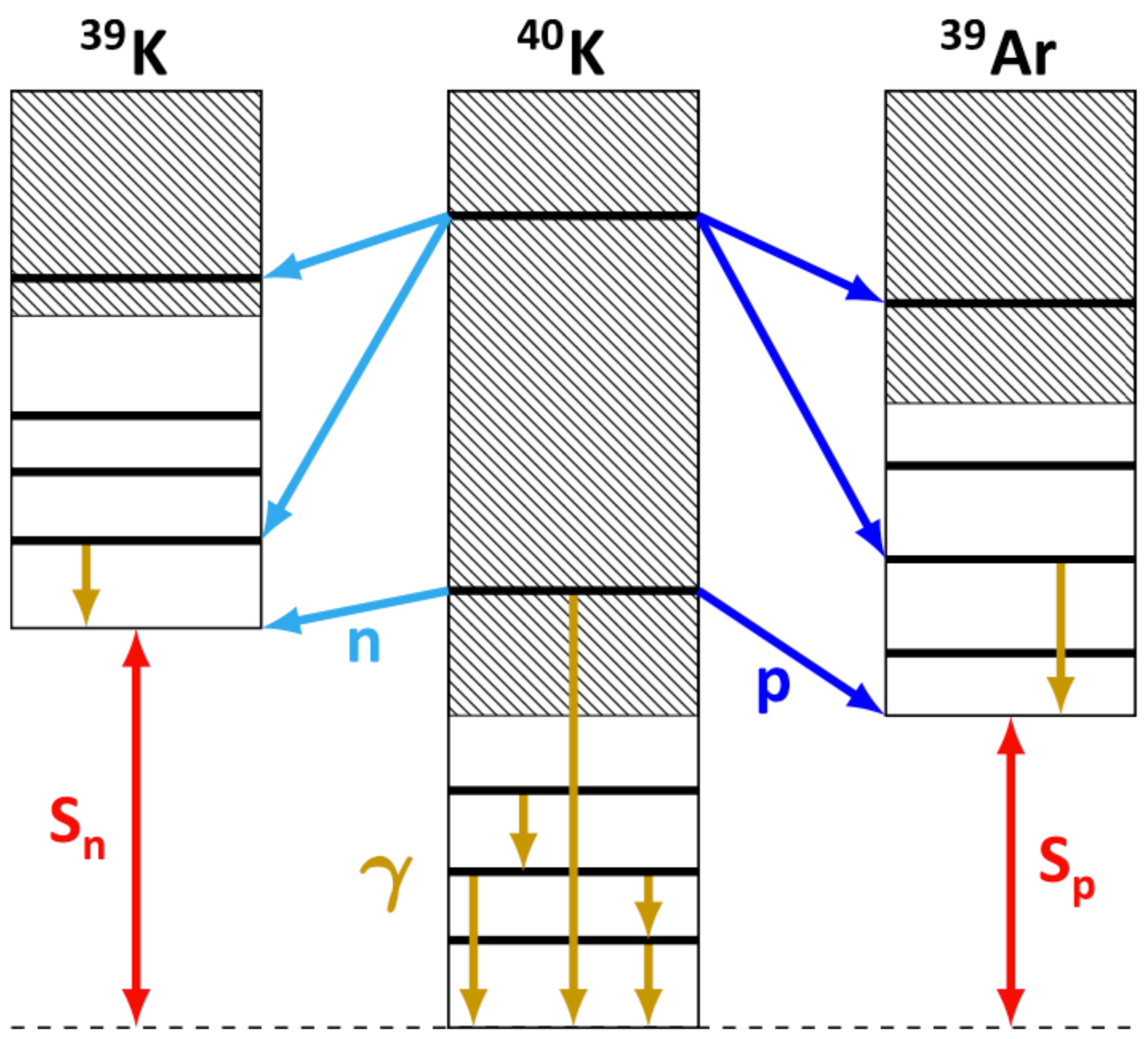
The nucleus de-excites via a series of binary decays. Decay widths for **unbound states** are computed according to the Hauser-Feshbach formalism:

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

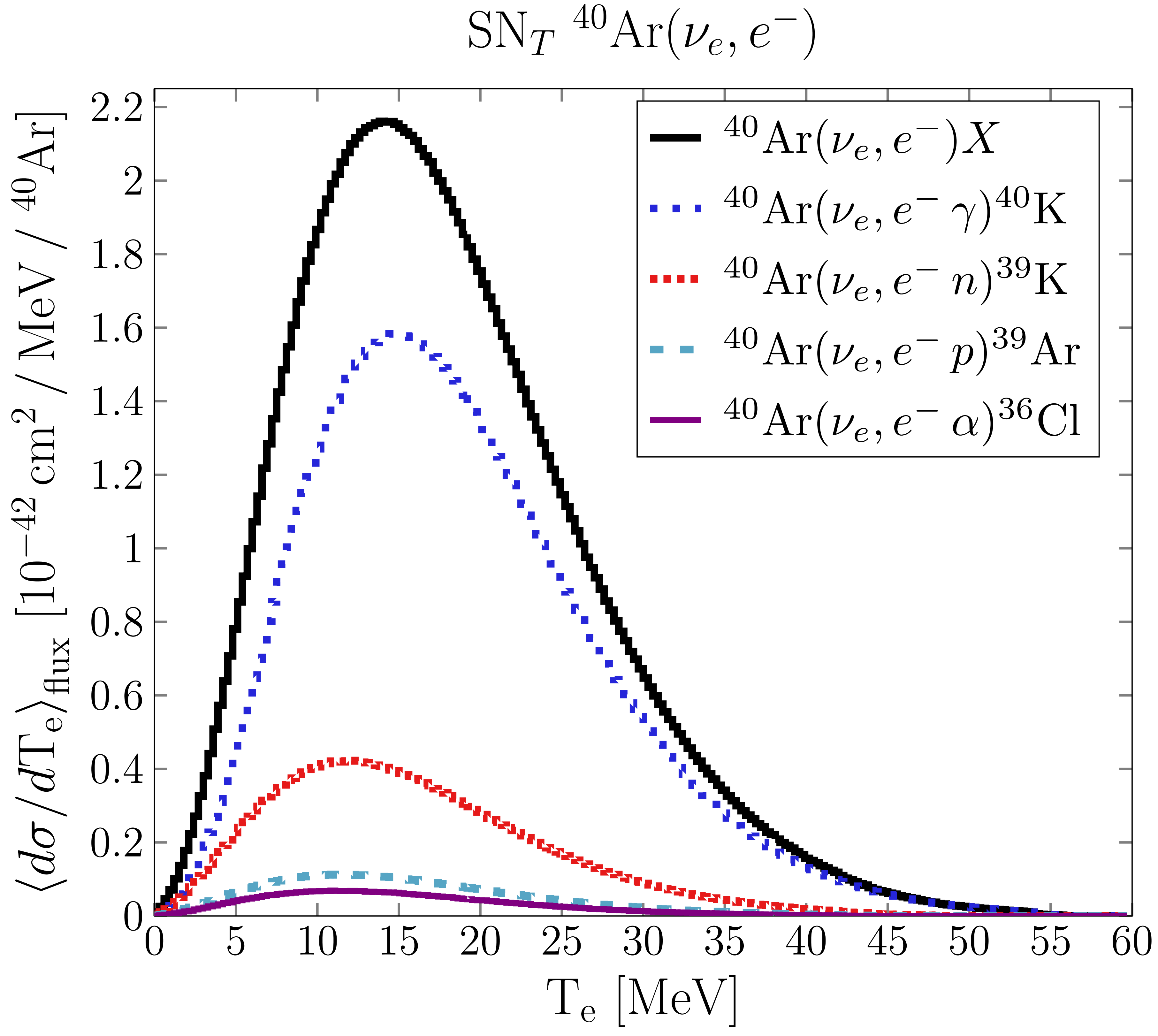
[Phys. Rev. C 103, 044604 (2021)]

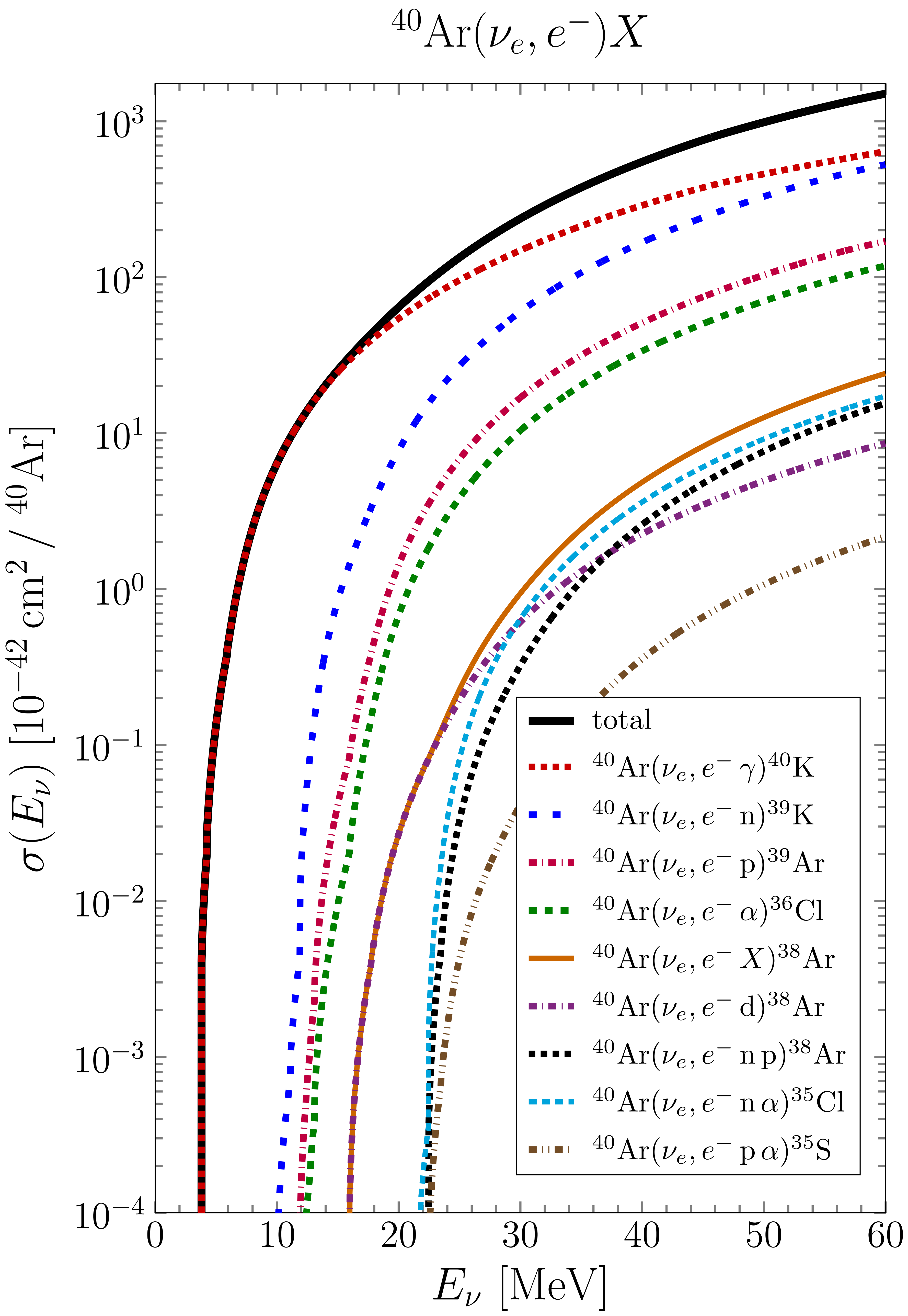
- First calculation of cross sections for **exclusive final states** of the reaction

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

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)].

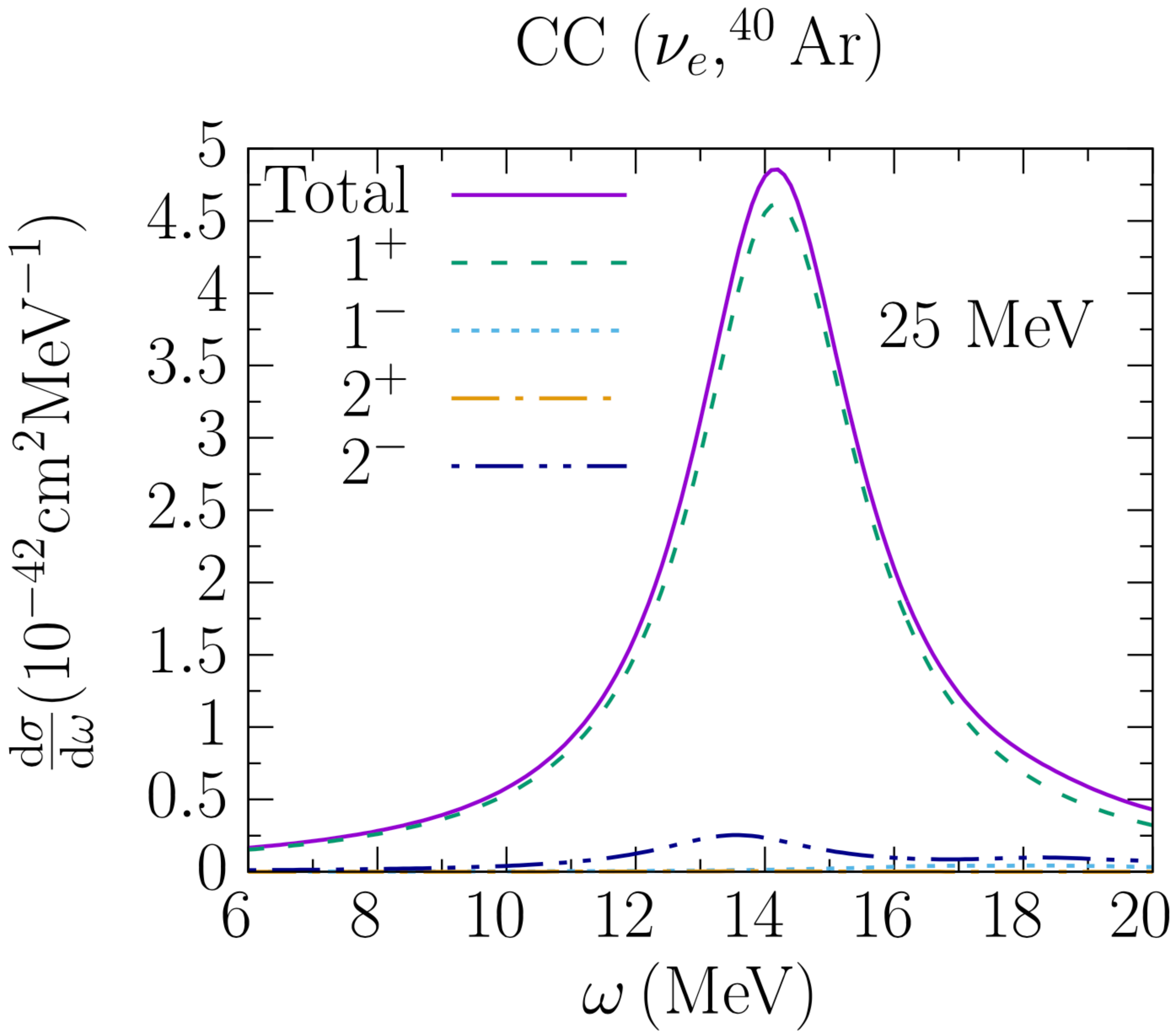




HF-CRPA model in MARLEY

- "Allowed approximation" begins to break down at several tens of MeV
  - $q \to 0$ and $p_N/m_N \to 0$, only 0^+ and 1^+ multipoles survive
- HF-CRPA includes higher multipoles ("forbidden transitions")
  - Strong impact on angular distribution
- **More strength to higher excitation energies**
  - Expected impact on neutron yield, etc.
- Implementation in progress
  - Similar to GENIE strategy (arXiv:2110.14601)
  - Responses separated by multipole order: J^π input to de-excitation model
- Opportunity to simulate electrons consistently

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



1^+ component analogous to B(GT) strength

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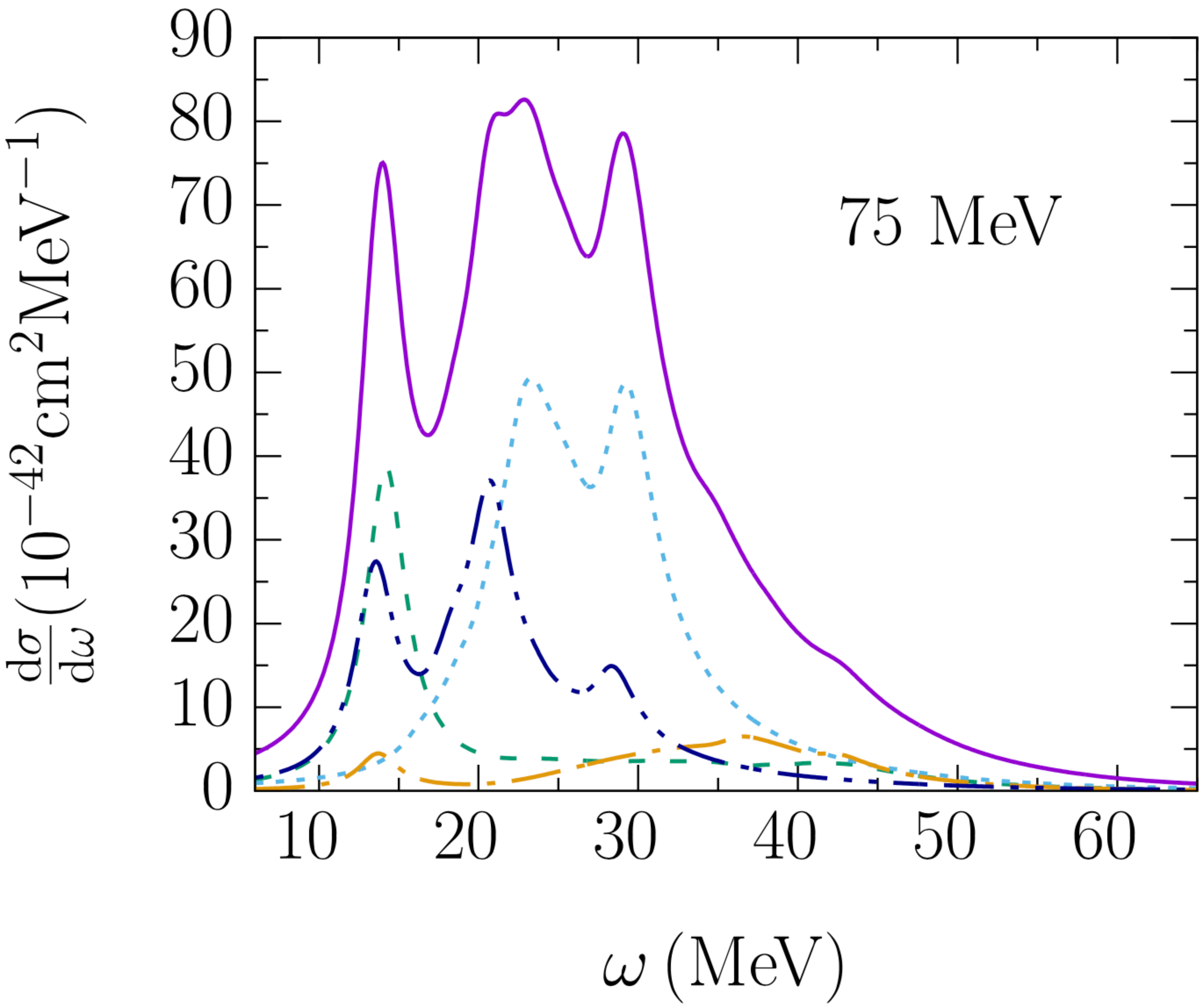
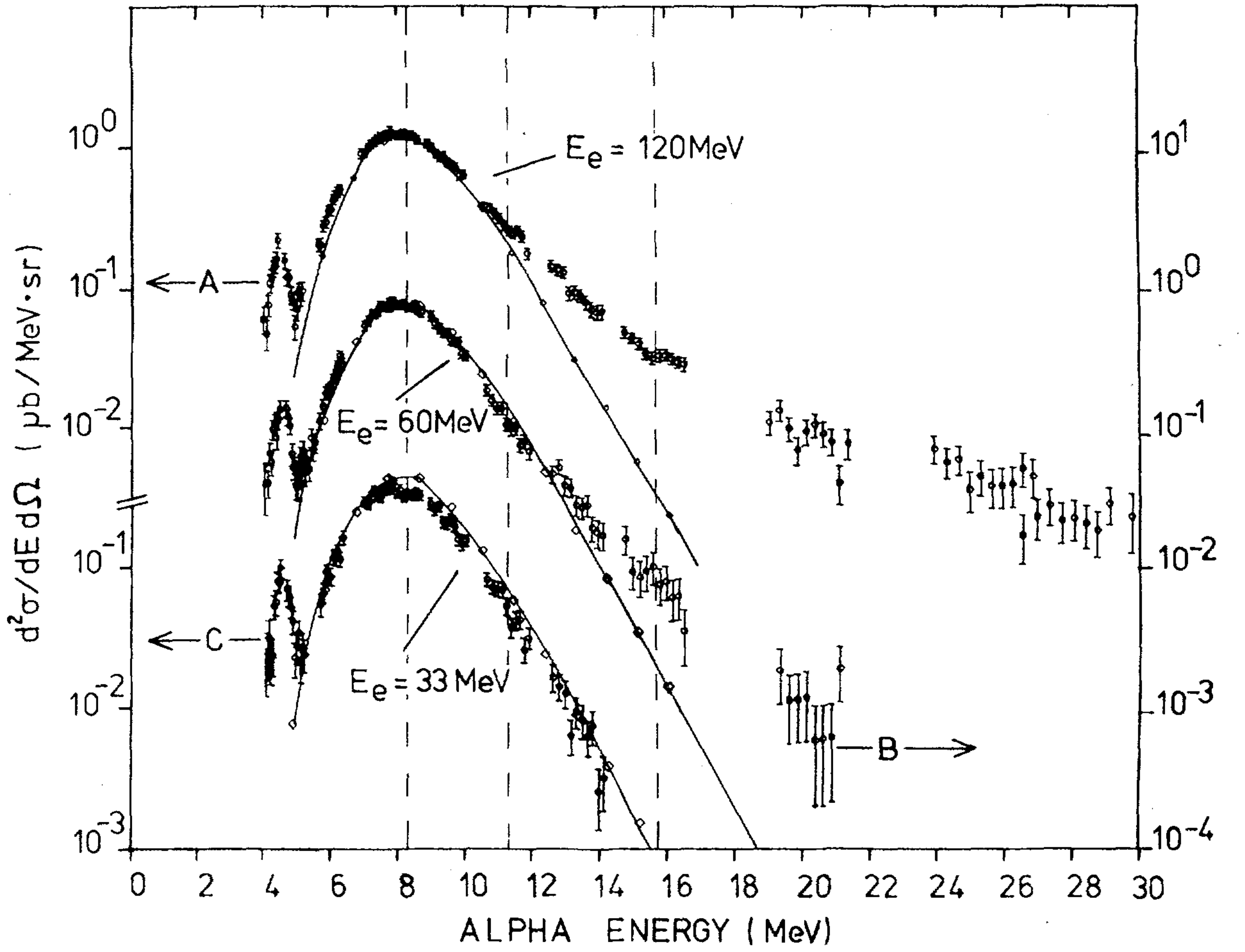


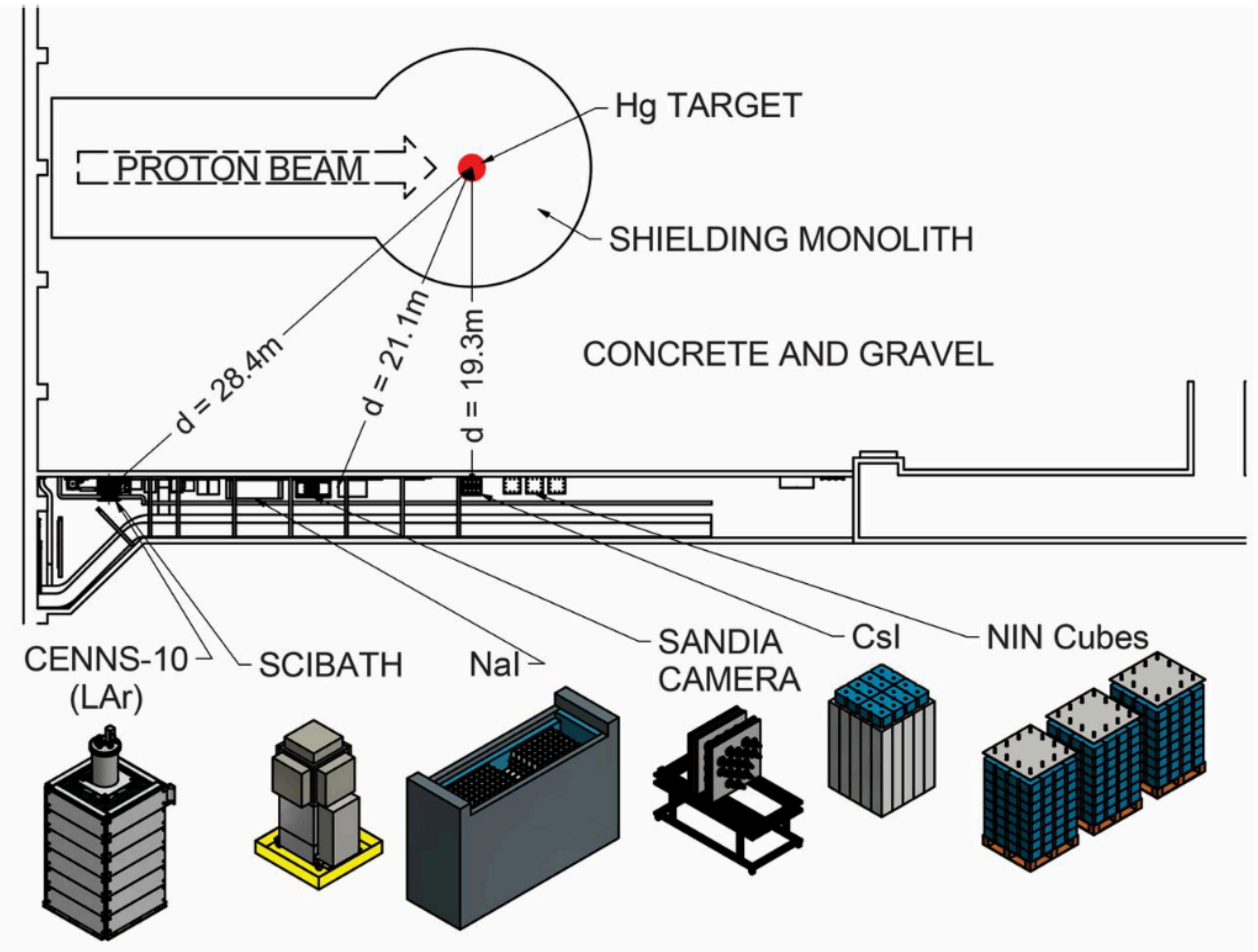
1^+ component analogous to B(GT) strength

Opportunities with electron data

- Only elastic e-A scattering under "allowed approximation"
  - Inclusive electron data can helpfully probe forbidden contributions
- (Semi-)exclusive data very powerful
  - Little direct evidence for compound nucleus assumption with leptonic probe
  - Benchmark simulations of the full final state
- Complementary to forthcoming neutrino-induced neutron data from COHERENT
  - Is any tension in the inclusive or the de-excitation model?

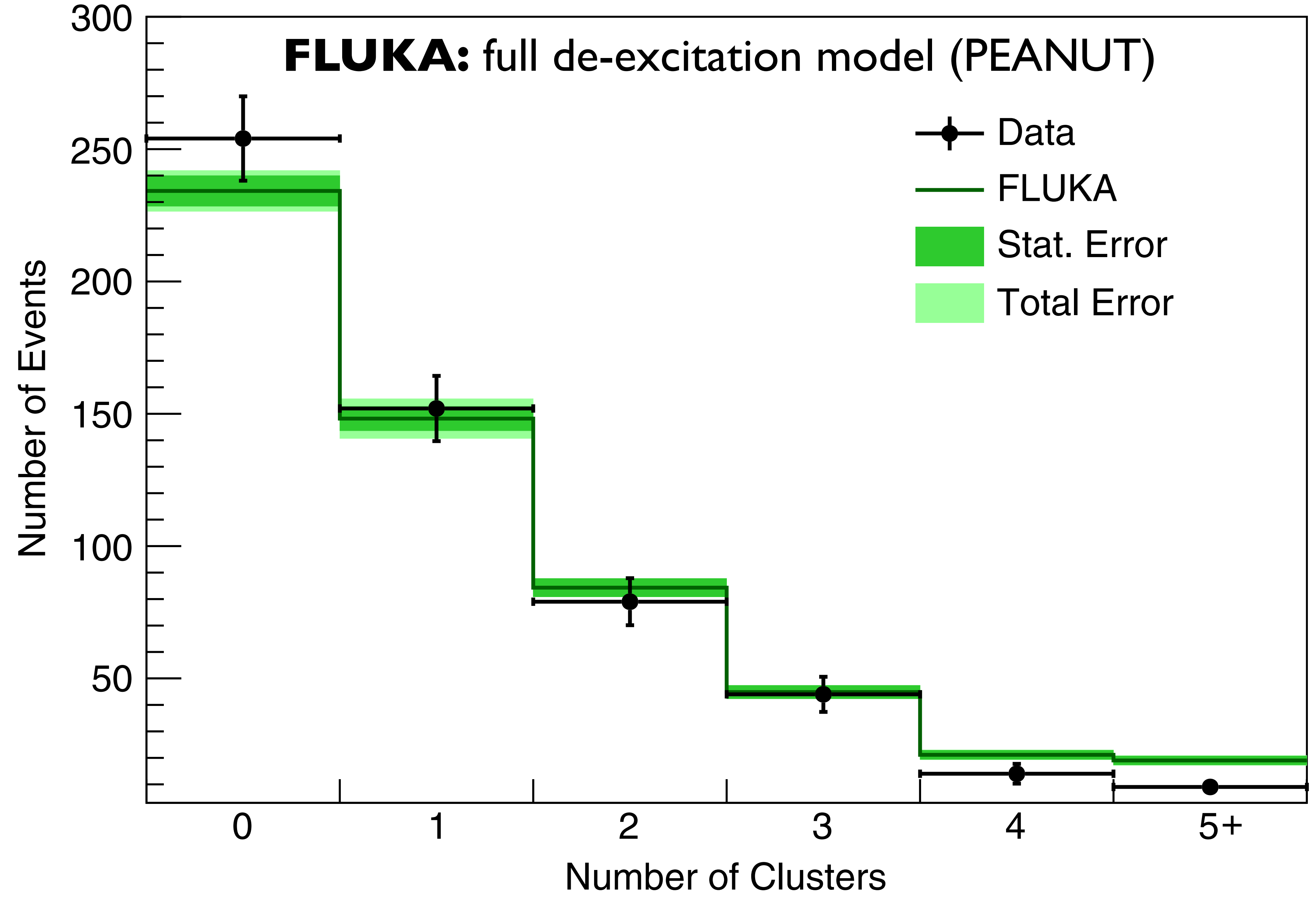
Flowers et al., Phys. Rev. Lett. 40 (1978)



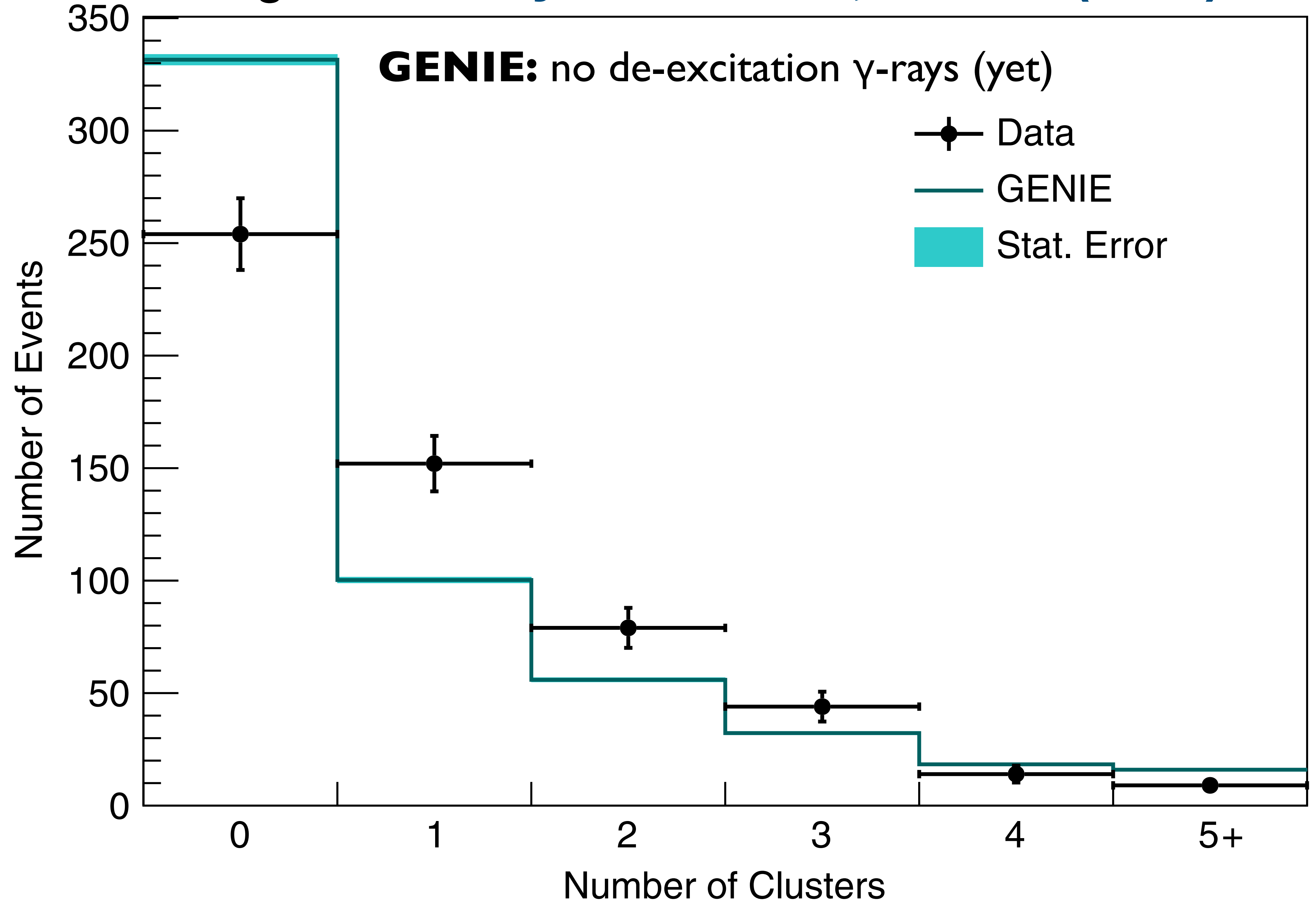


Connections to higher energies

- MARLEY-like de-excitation physics observable in LArTPCs
  - Recently demonstrated by ArgoNeuT
  - Comparisons to FLUKA, GENIE
  - Use MARLEY as an open-source “afterburner”?
- Possible means of improving reconstruction of GeV neutrinos
  - “Blip reconstruction” under active development
- De-excitations from proton decay may provide a powerful new handle for searches (see **this Snowmass LOI**)
- Snowmass white paper "Low-Energy Physics in Neutrino LArTPCs” (**arXiv:2203.00740**)

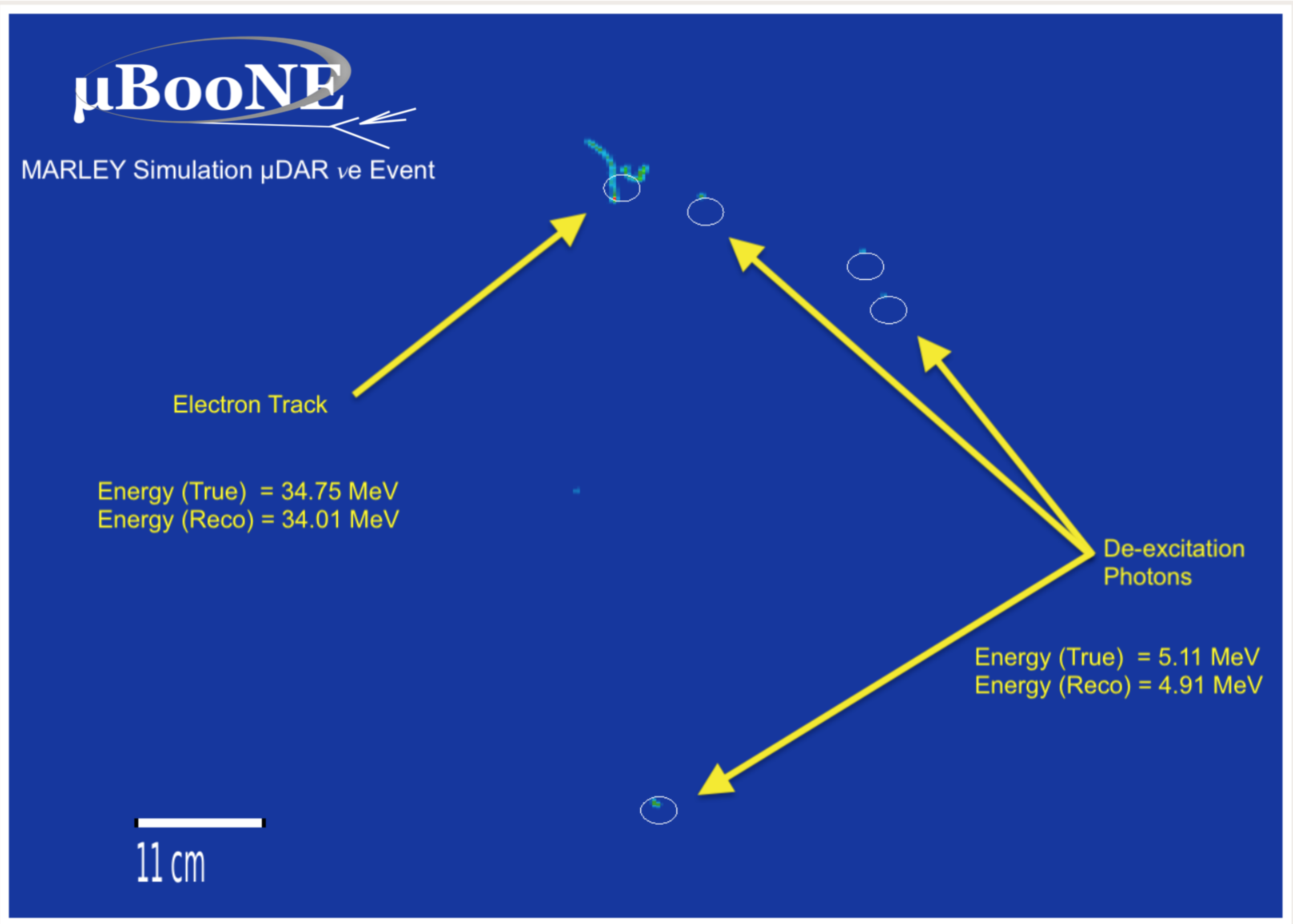


ArgoNeuT, **Phys. Rev. D 99, 012002 (2019)**



Summary

- **MARLEY** is a dedicated neutrino event generator focused on sub-100-MeV energies
  - Emphasis on ν_e CC on ^{40}Ar for DUNE
- Nuclear de-excitation modeling is key to predicting full final states
  - Some shared challenges and overlap with topics for higher energies
- HF-CRPA implementation will provide a clear path to e^- simulations
- Electron data valuable to inform low-energy interaction modeling
  - I am excited to explore related opportunities further



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