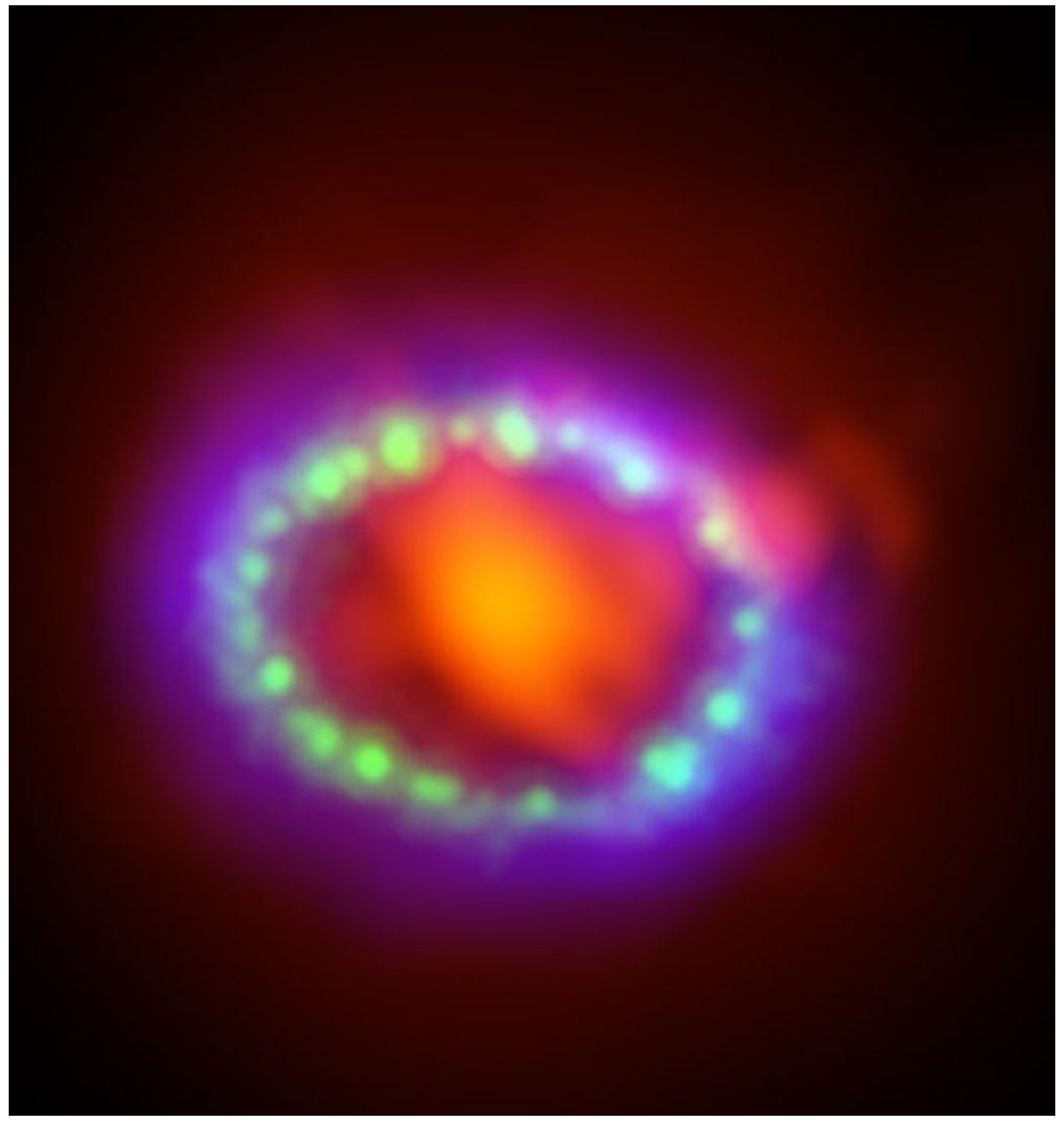
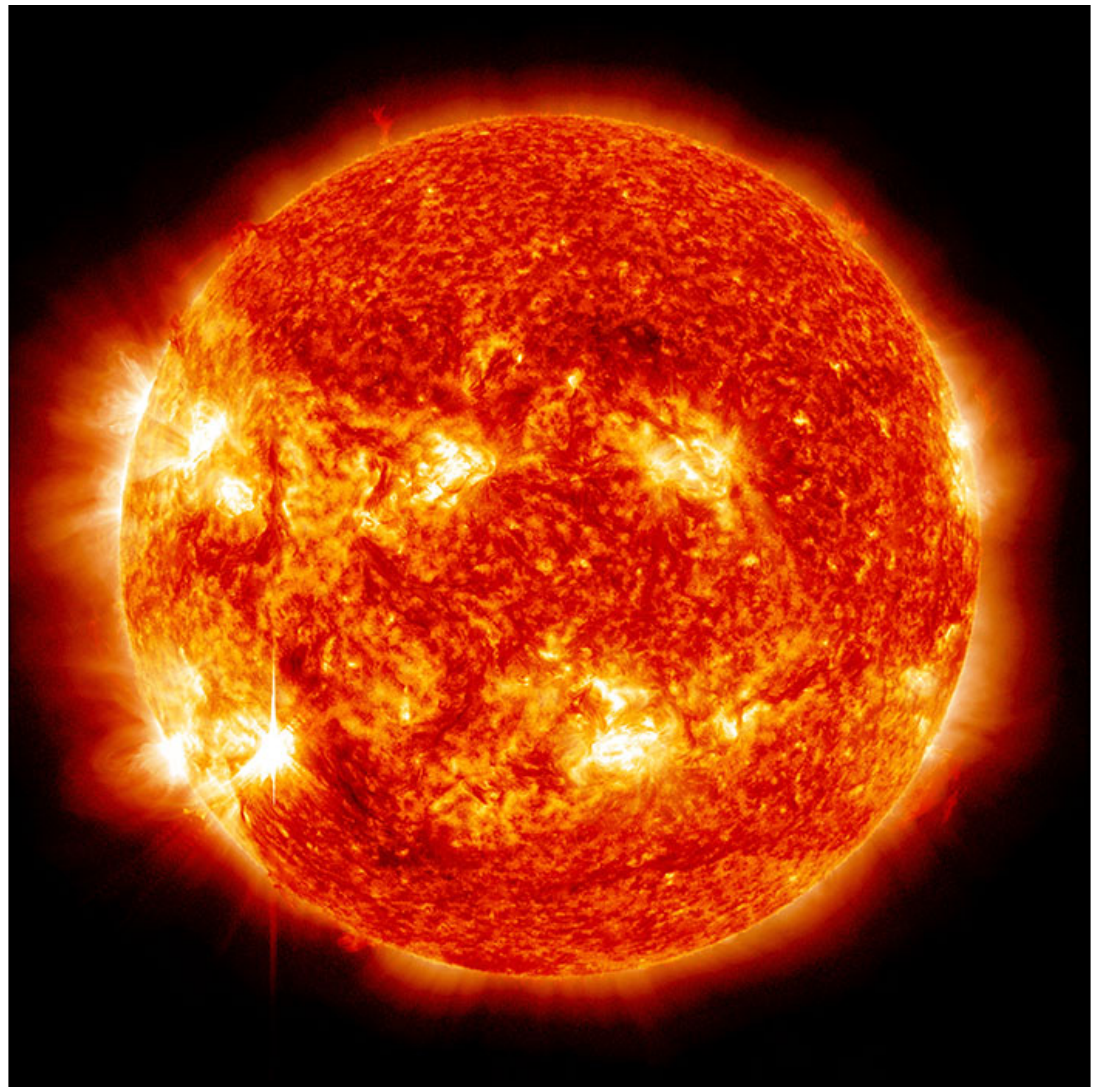
Low-energy inelastic neutrino cross sections





Steven Gardiner

SEC-NF Meeting

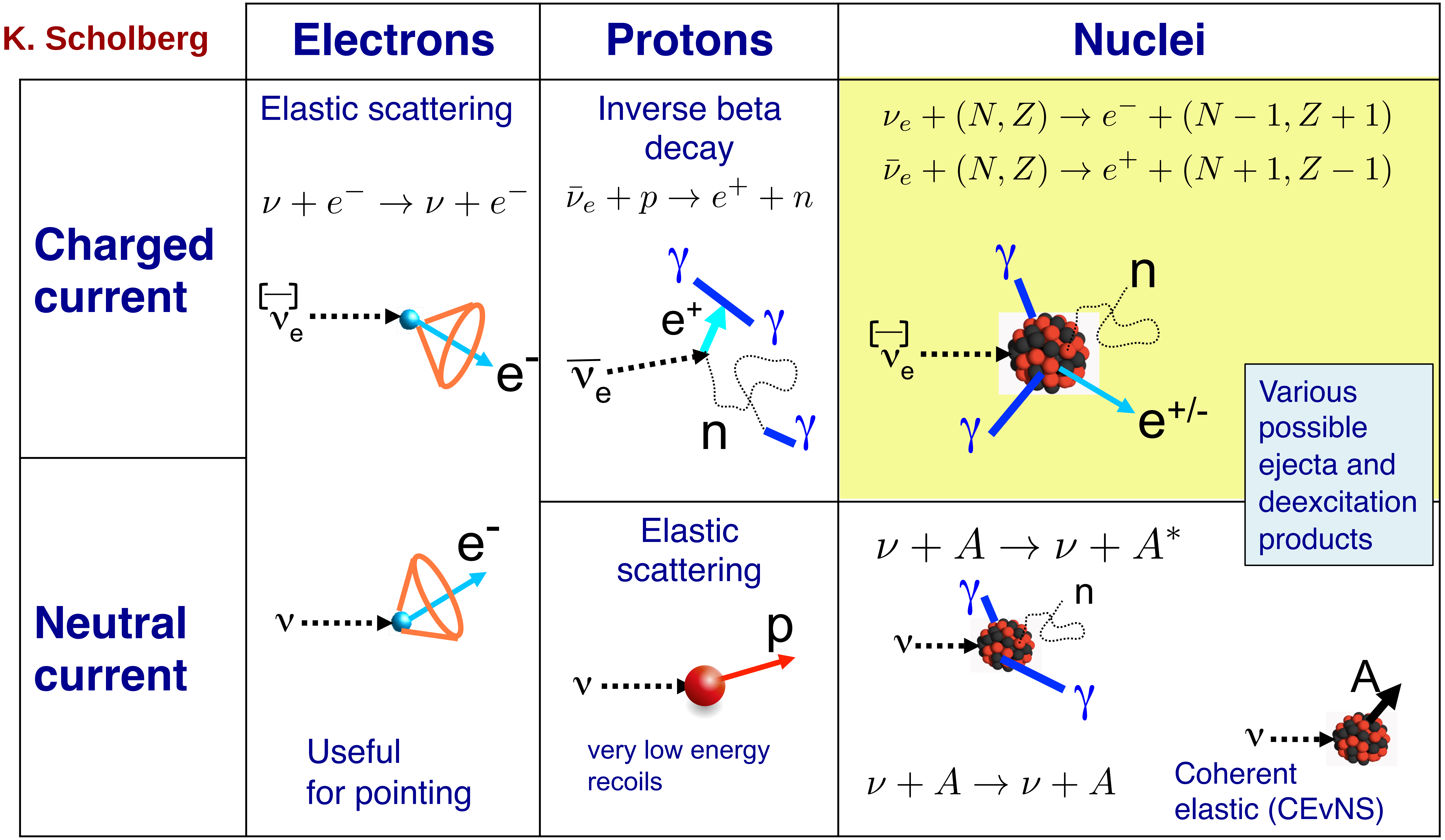
2 December 2020

Based on this Snowmass LOI:
https://tinyurl.com/lowE-inelastic-nu-xsec

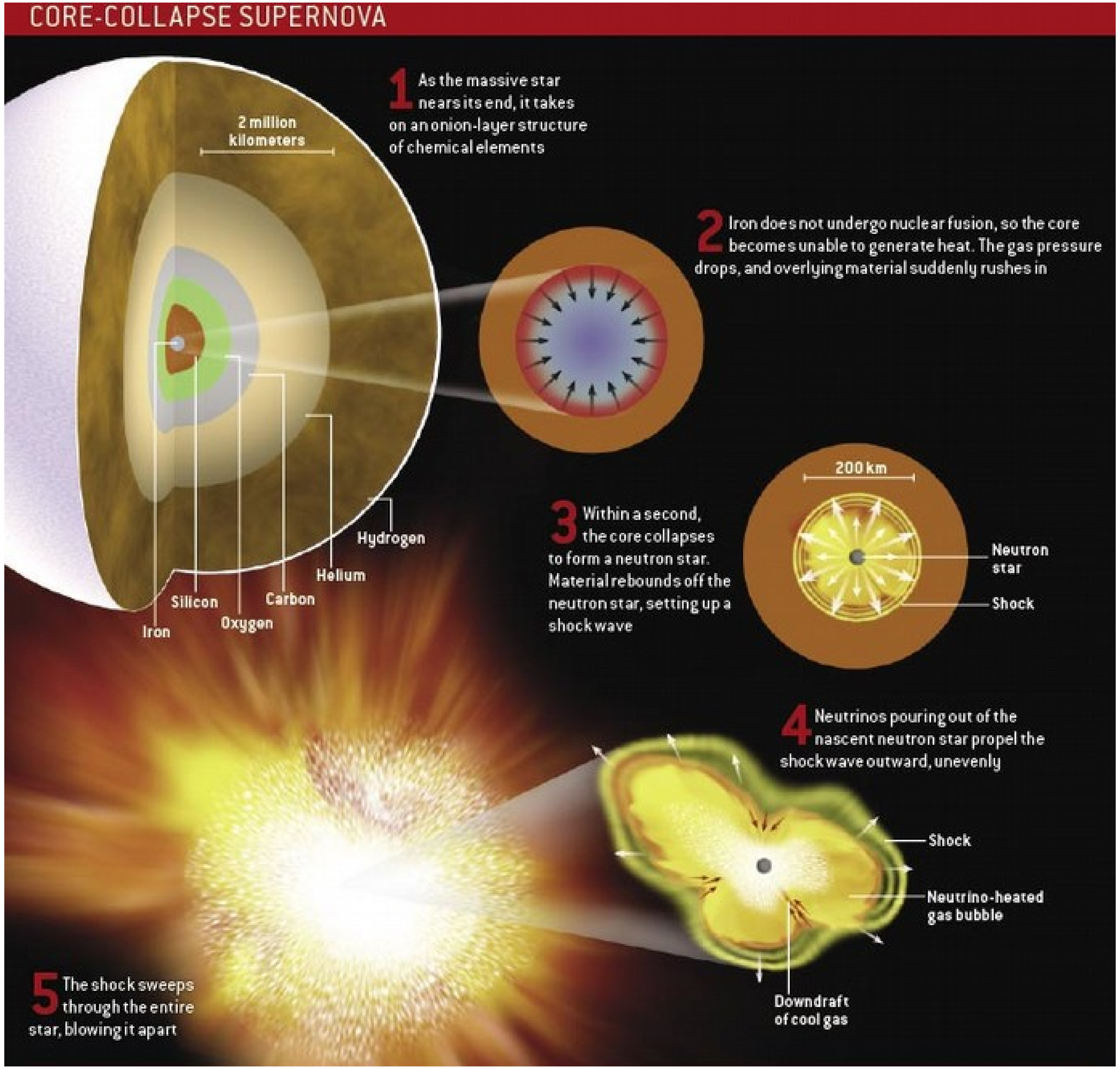
Low-energy (< 100 MeV) neutrino interactions

- CEvNS has largest cross-section, but also challenging to detect
- Small ν-e cross-section, but kinematics highly useful
  - Also very well-understood
- Inelastic reactions on nuclei hold lots of promise for a number of applications
  - **Supernovae**
  - Solar neutrinos
  - BSM searches
  - Low-energy oscillation measurements
  - Improving interaction modeling

K. Scholberg



Core-collapse supernovae: near-perfect neutrino bombs

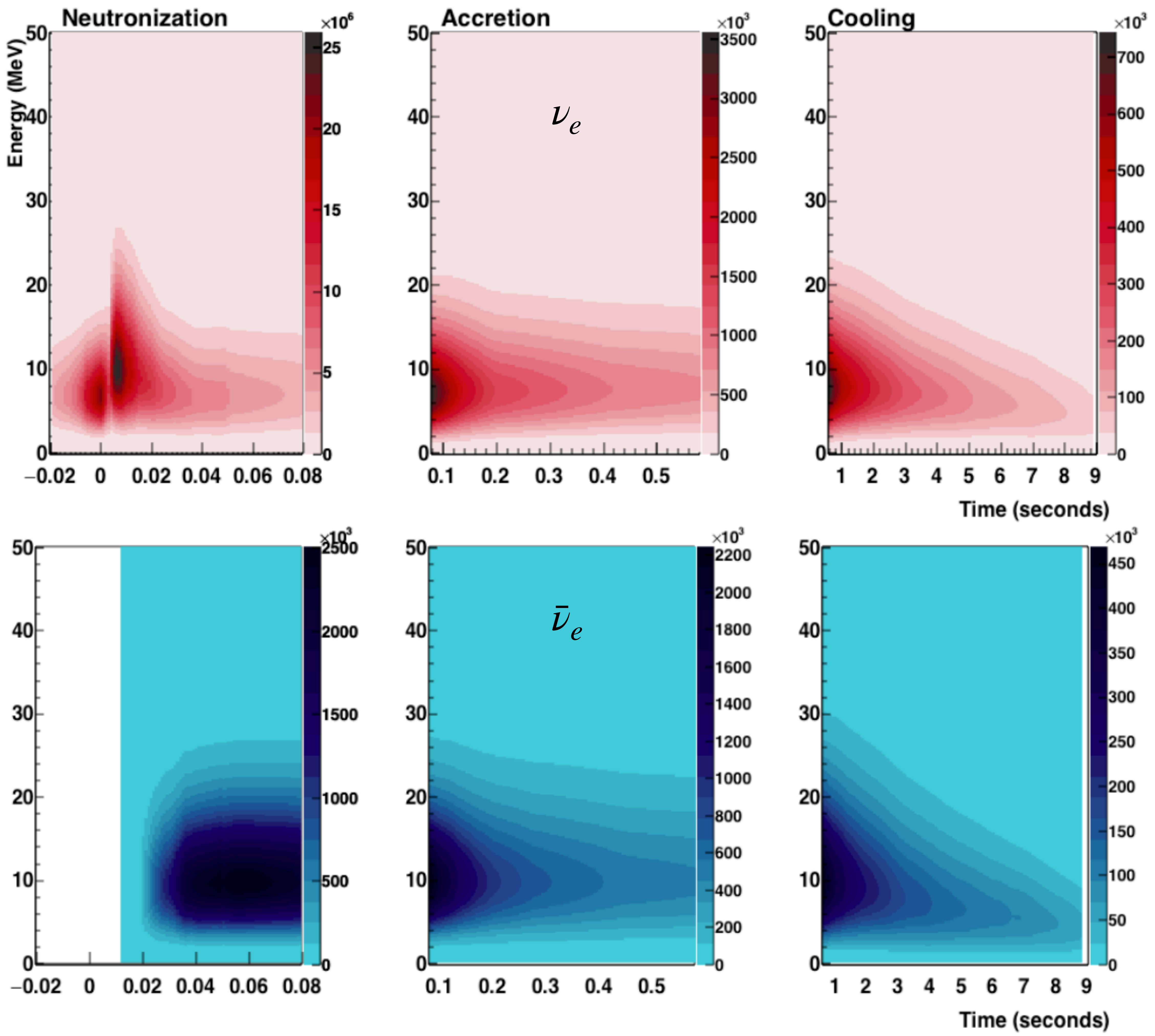


- Deaths of stars > $8M_\odot$
- 99% of gravitational binding energy emitted as neutrinos
- Many ν_e produced as core collapses (few-ms burst)
- Core cools via all-flavor radiation in ~10 seconds
- Momentarily outshines visible universe (in neutrinos)

Supernova Neutrinos

- Tens-of-MeV neutrinos from a galactic supernova are a promising window into a variety of physics topics
  - Core-collapse dynamics
  - Collective oscillations
  - Beyond the Standard Model searches
- Key observables are the **energy**, flavor, and arrival time of the neutrinos
  - 3 distinct species: $\nu_e, \bar{\nu}_e, \nu_x$
- **Physics signatures imprinted on the time-dependent fluxes**
- Galactic supernovae are rare (~1-2 per century). We need to be prepared when the opportunity comes!

Time evolution of neutrino spectra, electron-capture supernova model, arXiv:2002.03005

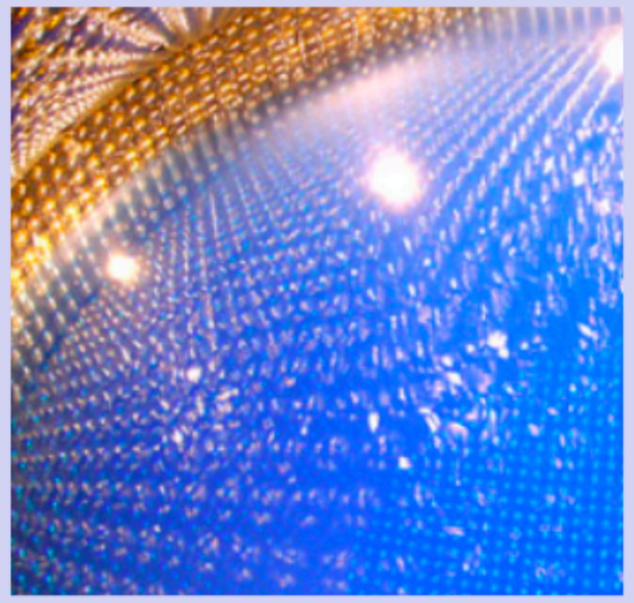


Each species provides distinct information, detection of all highly desirable

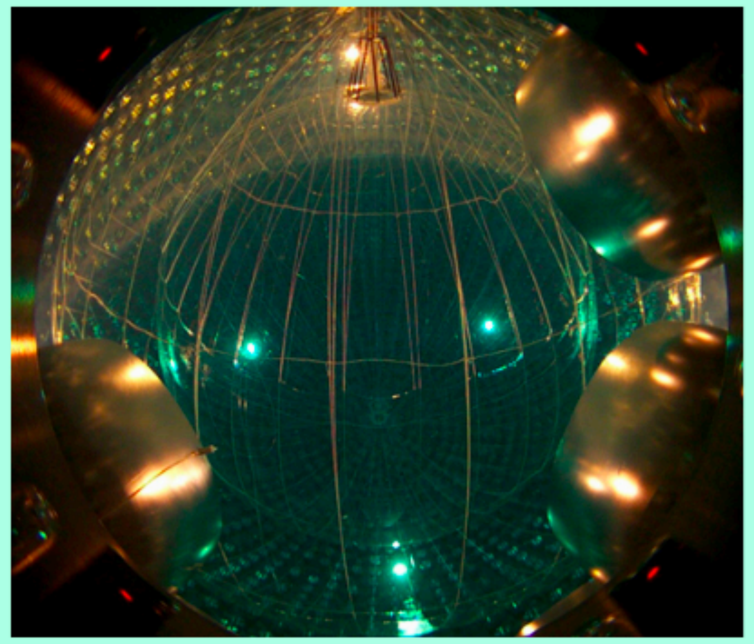
Current main supernova neutrino detector types

- Water & scintillator dominated by inverse beta decay on hydrogen
  - Excellent $\bar{\nu}_e$ sensitivity
- Argon and lead targets contain only neutron-rich complex nuclei
  - CC ν_e dominant (apart from CEvNS)
  - **DUNE** (argon) and HALO (lead) can help us investigate ν_e component of supernova flux in detail

Water



Scintillator



Argon

Lead

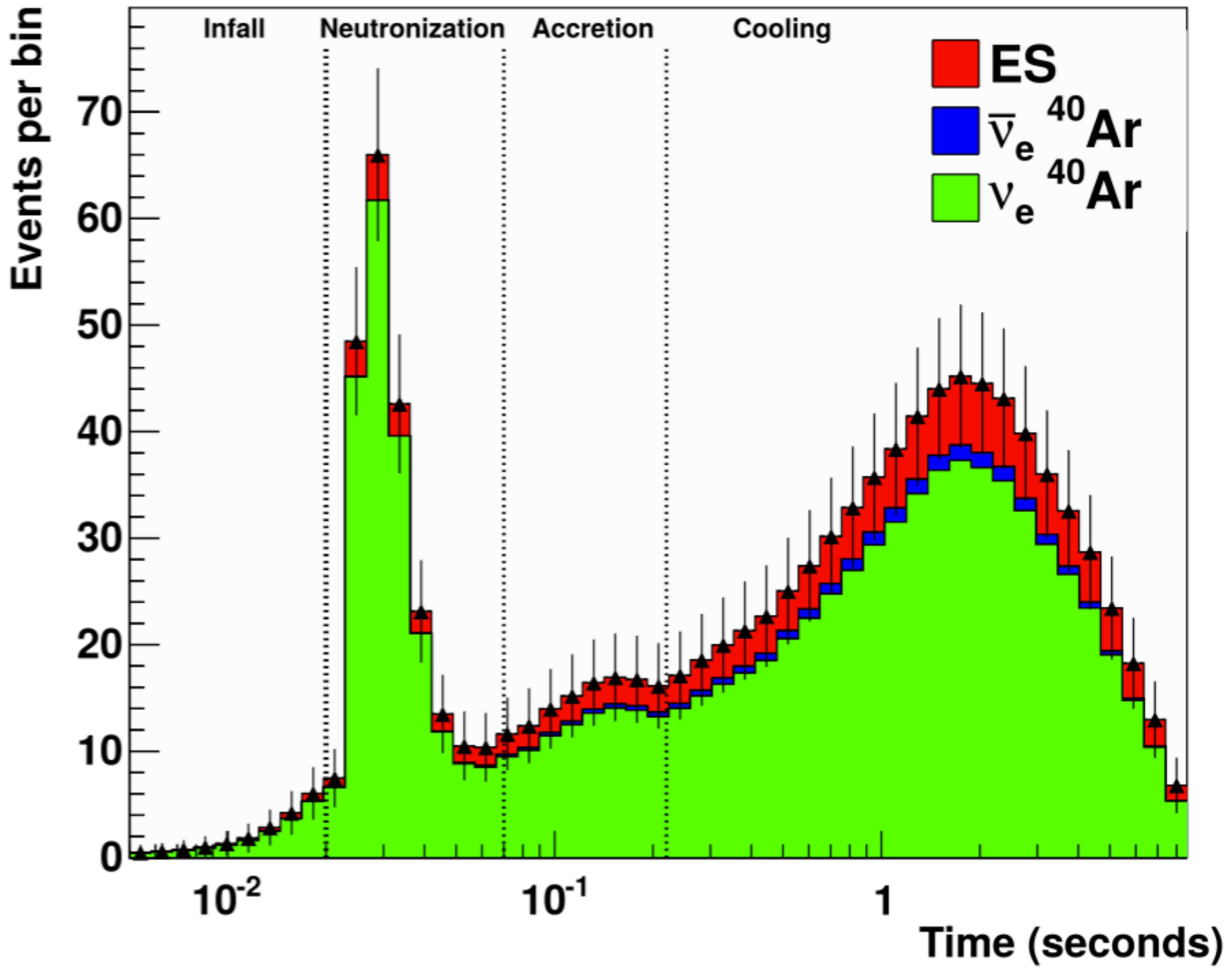
+ some others (e.g. DM detectors)

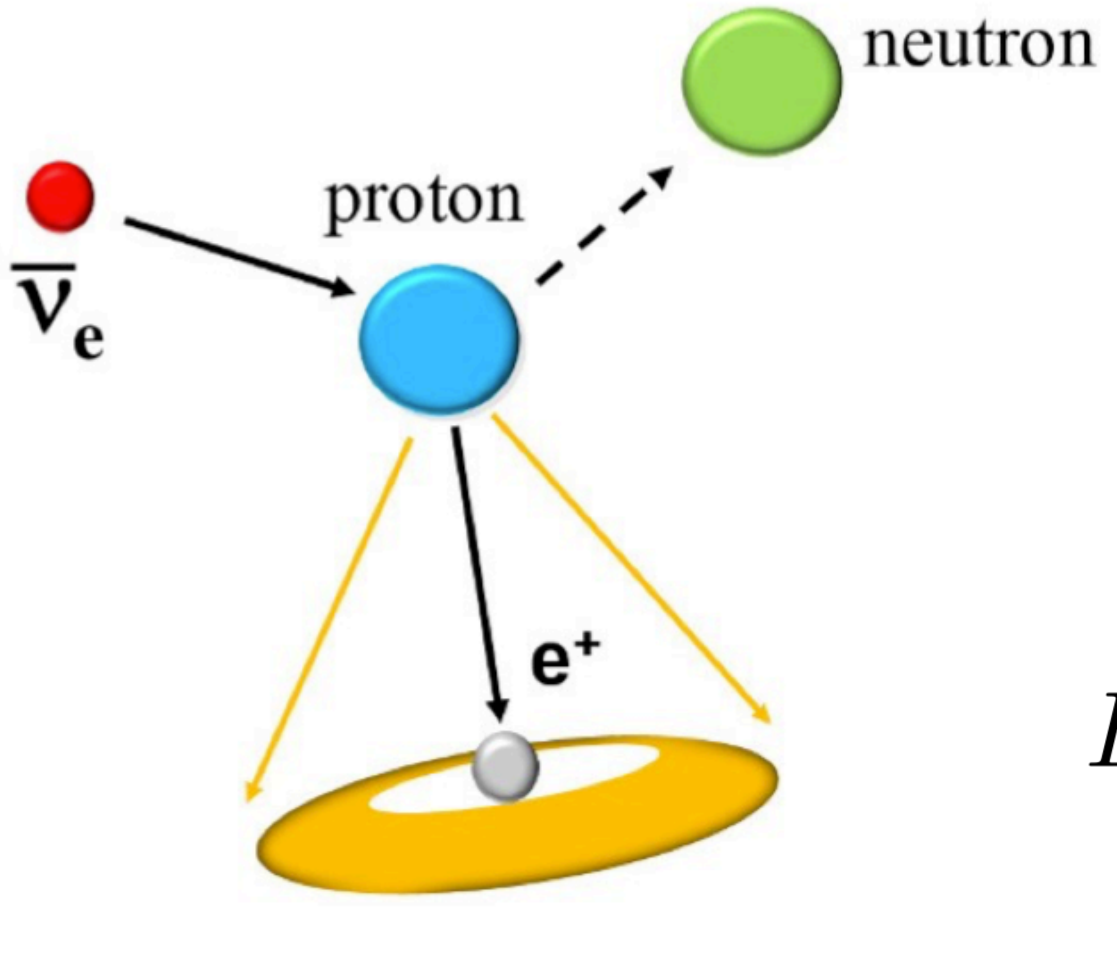
K. Scholberg

Supernova neutrino calorimetry

- Opportunity for a clean, high-statistics measurement of supernova ν_e in DUNE
- Reconstructing the **neutrino energy** is the tricky part
  - Much easier in water and scintillator for the $\bar{\nu}_e$
  - Nevertheless, highly interesting for supernova physics
- Higher-energy (~1 GeV) neutrino oscillation experiments face a similar problem
  - Solved using models implemented in event generators
- What simulation capabilities do we have at low energy?

Time distribution of supernova neutrino events in DUNE





inverse beta decay

$\bar{\nu}_e$ energy reconstruction in water or scintillator

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

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

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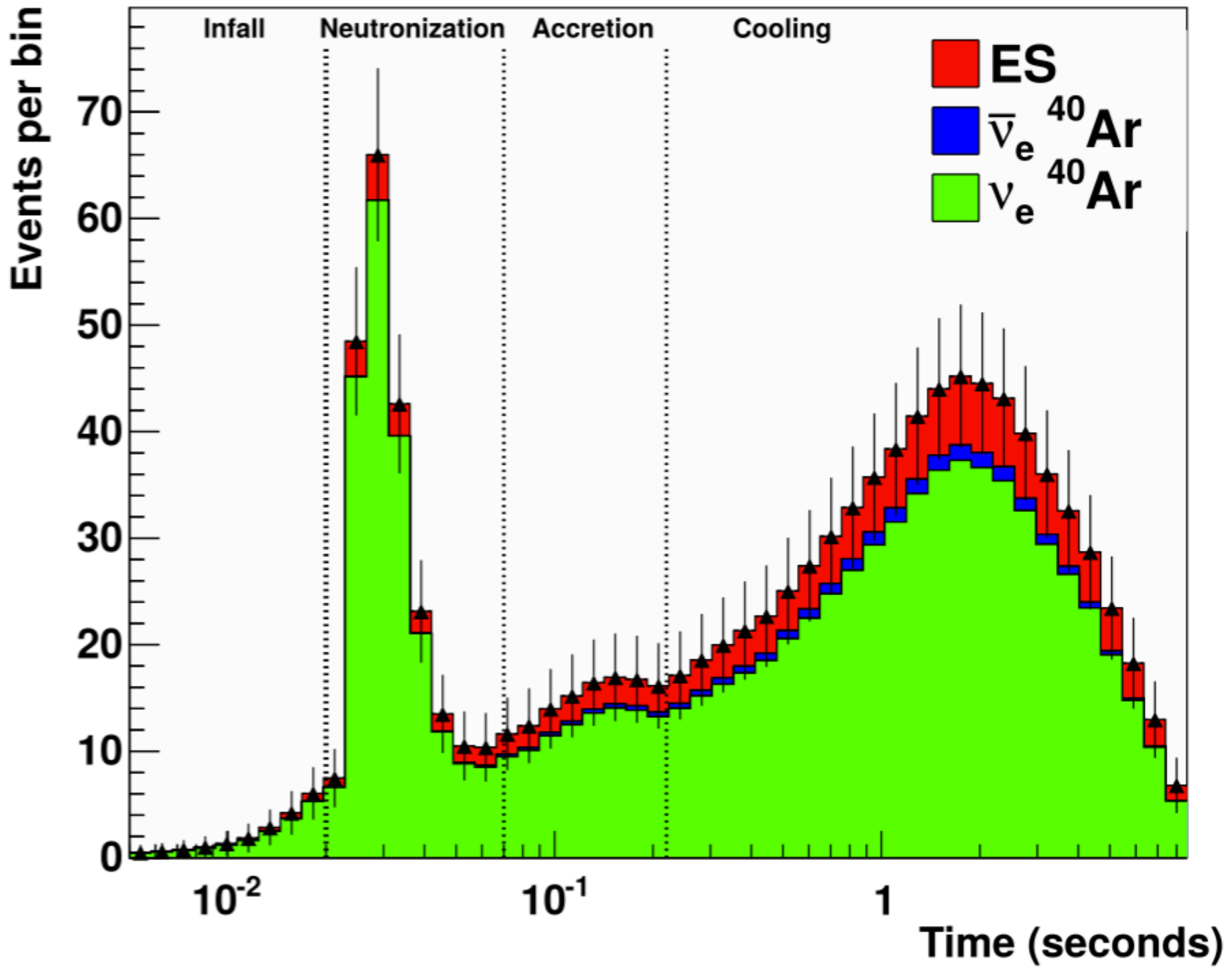
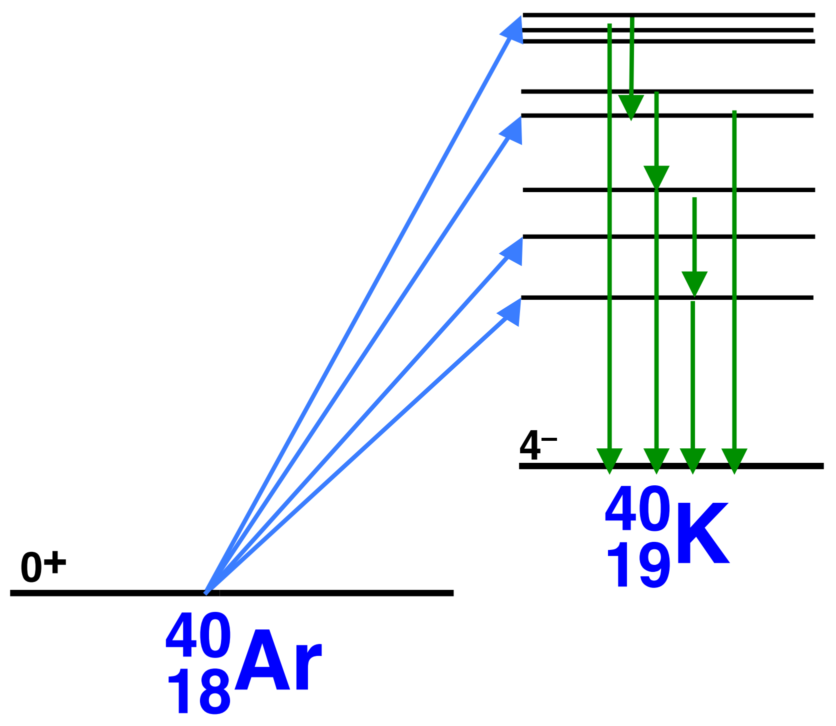


$$\nu_e + {}^{40}\text{Ar} \rightarrow {}^{40}\text{K}^* + e^-$$



For DUNE, this is harder because of nuclear physics effects

Outgoing e⁻ Energy

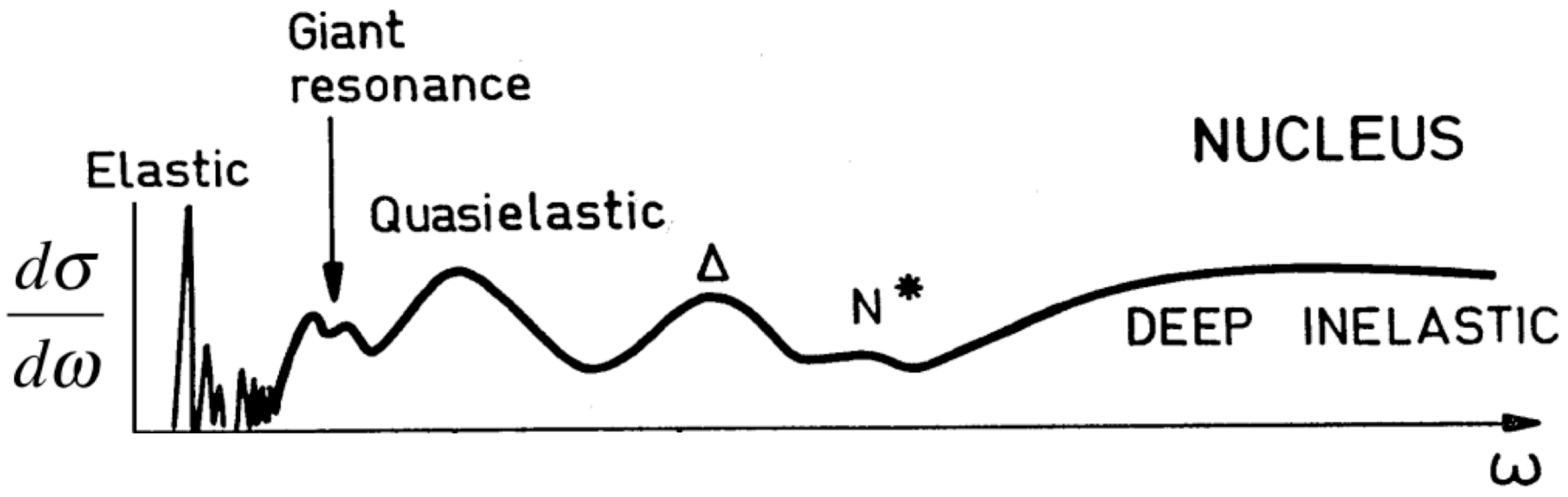
Energy donated to transition

Recoil Energy of Nucleus (negligible)

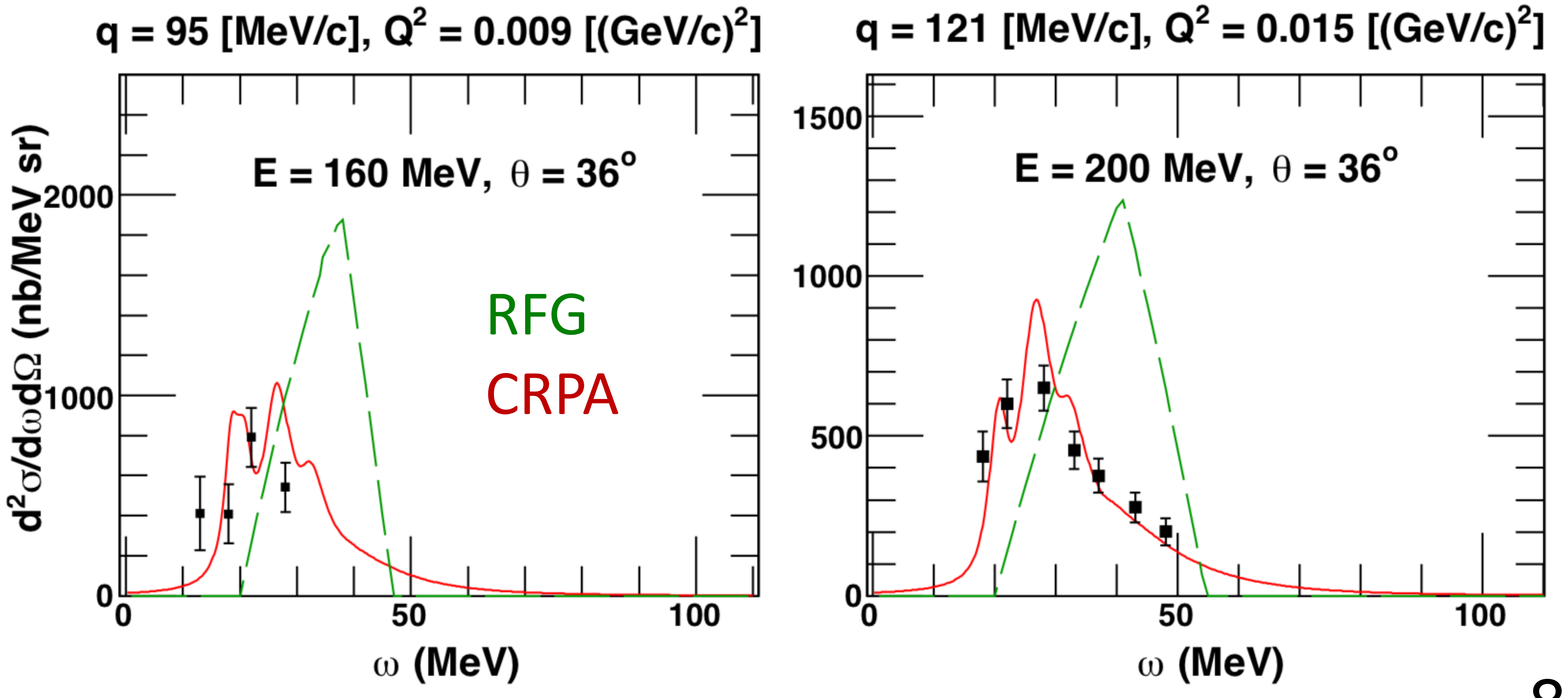
$$E_\nu = E_e + Q + K_{\text{recoil}}$$

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

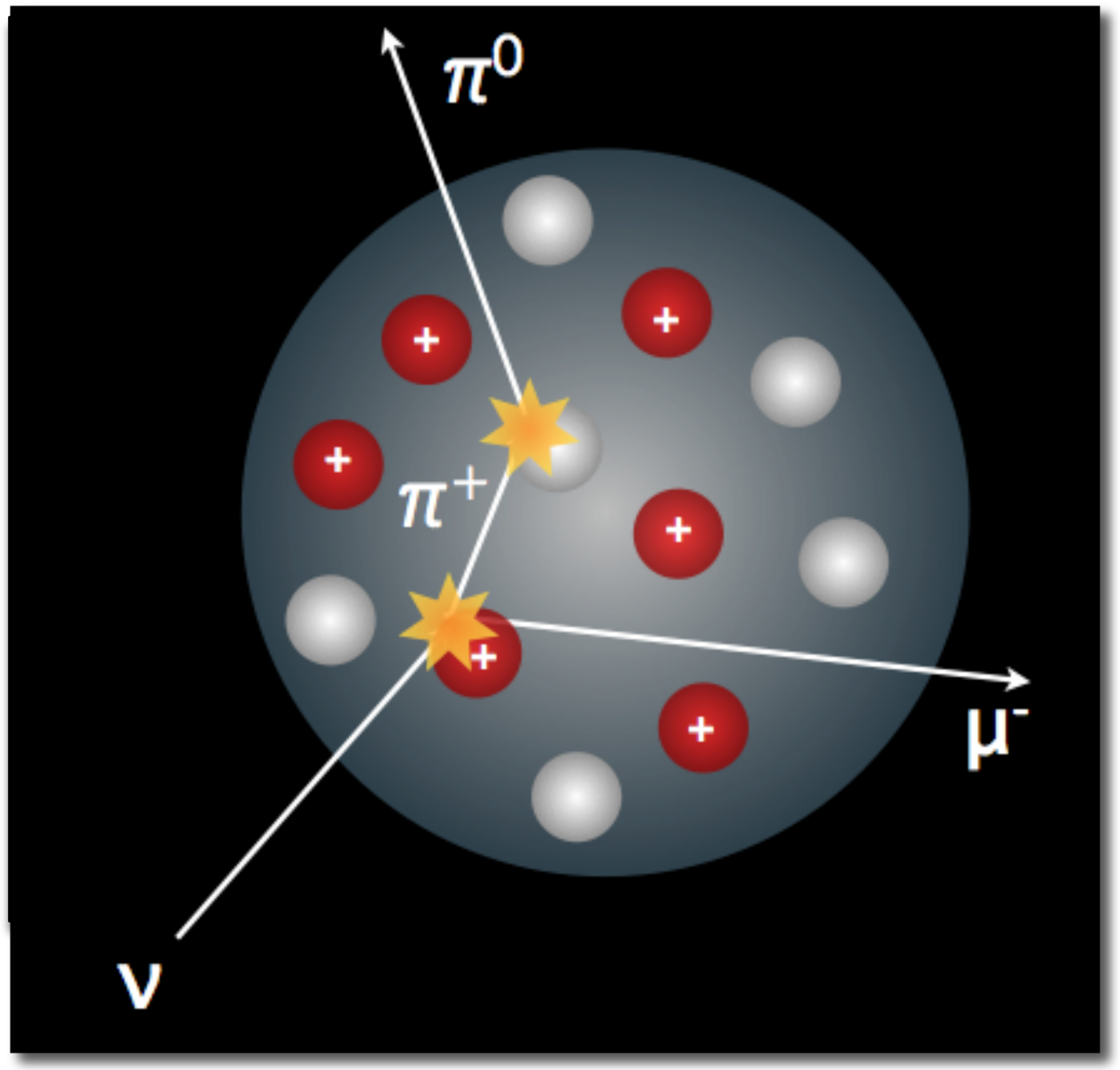


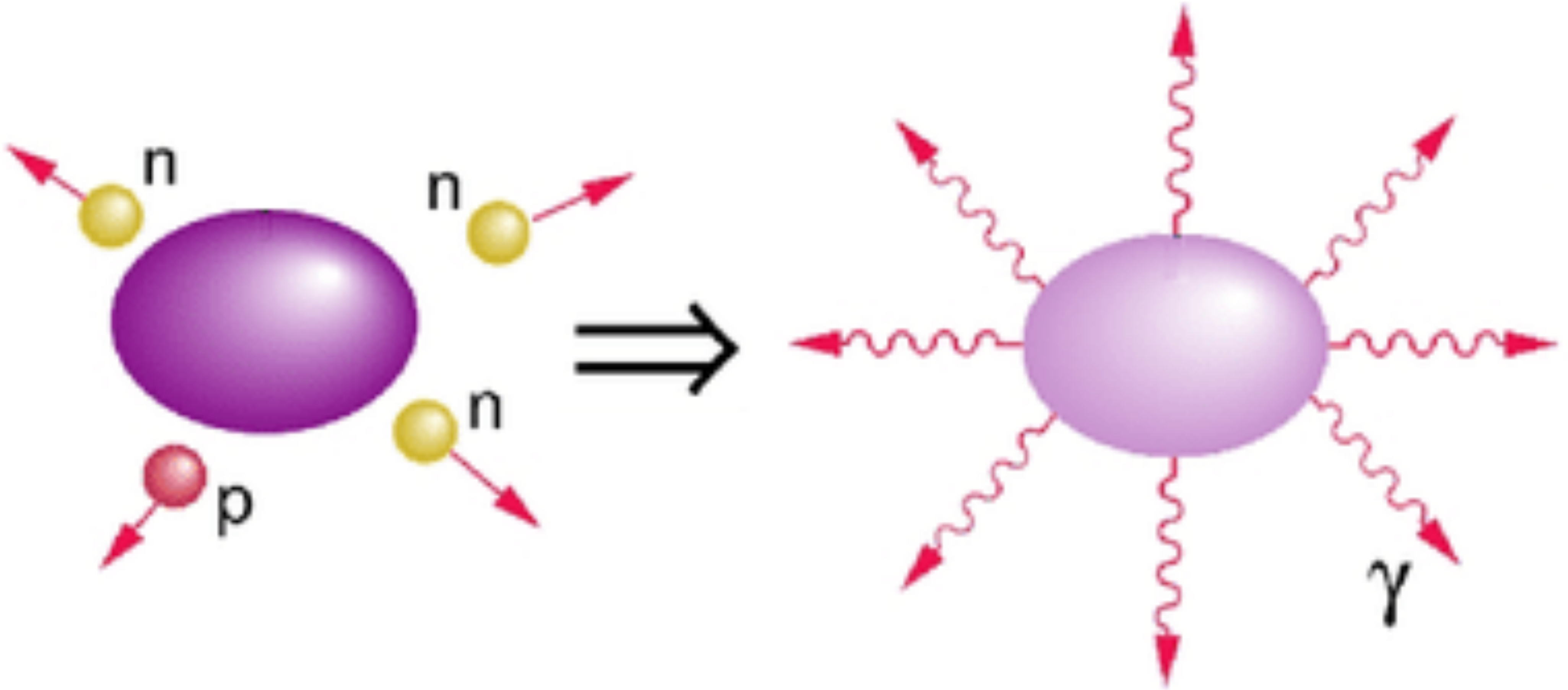
(e,e') scattering on ¹²C, V. Pandey, NuInt 18



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?)





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
- The LOI advocates for further effort to develop low-energy generators. The generator community is very small, especially for low energy.

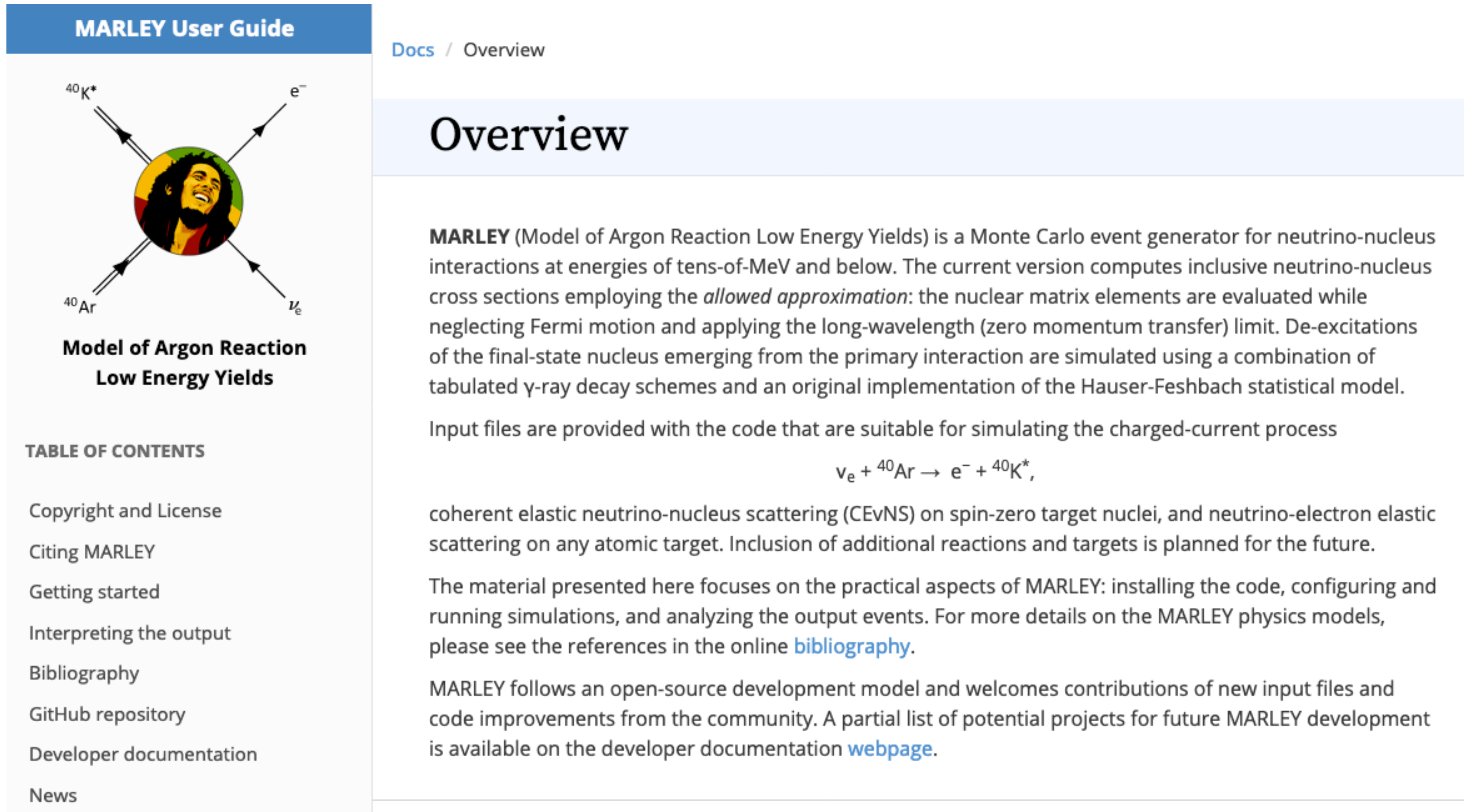
Nuclear de-excitations in low-energy charged-current ν_e scattering on ^{40}Ar

Steven Gardiner[1,2,*]
[1] Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510 USA
[2] Department of Physics, University of California, Davis, One Shields Avenue, Davis, California 95616 USA
(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

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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

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

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.

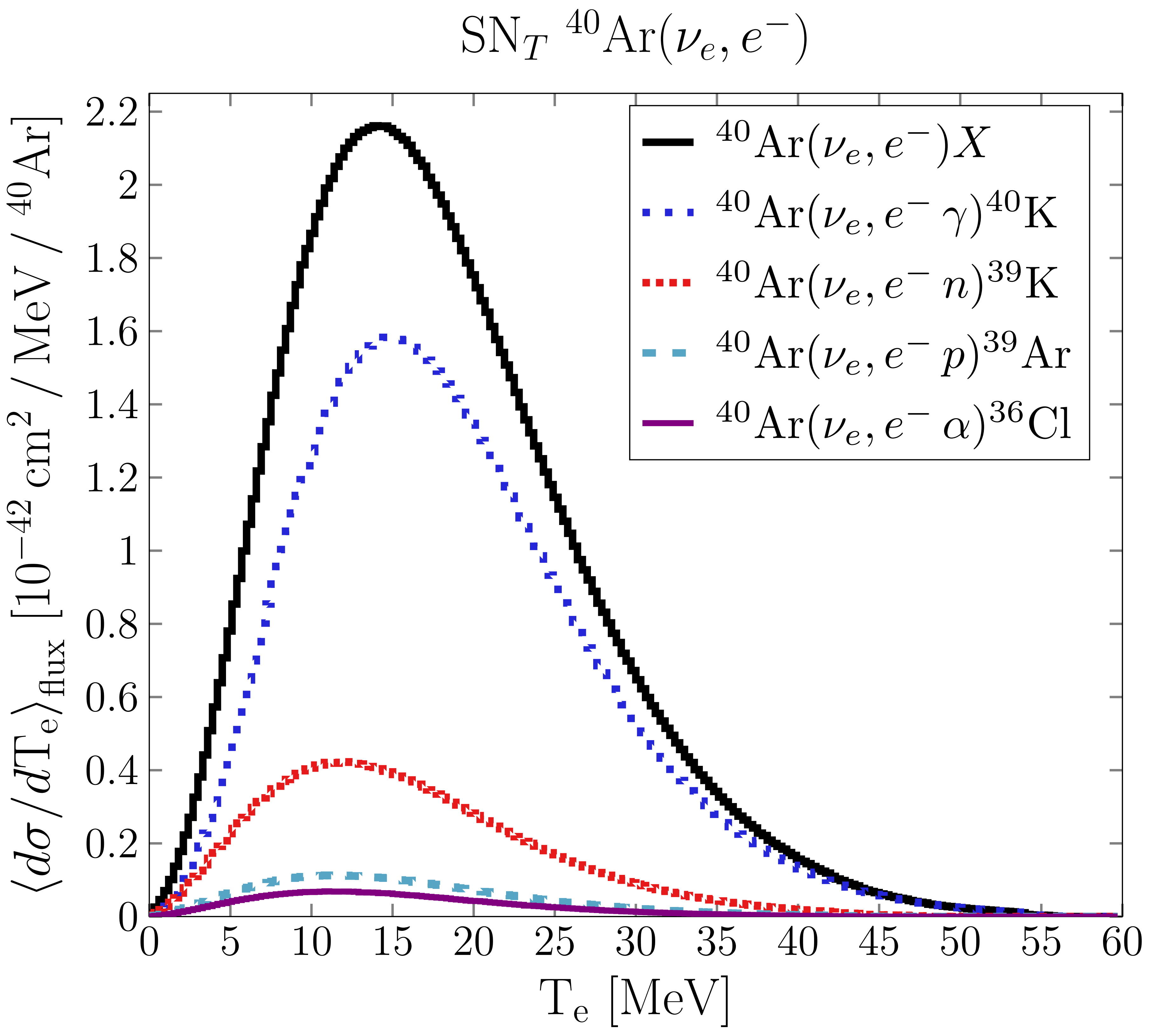
MARLEY v1.2.0 predictions for ^{40}Ar

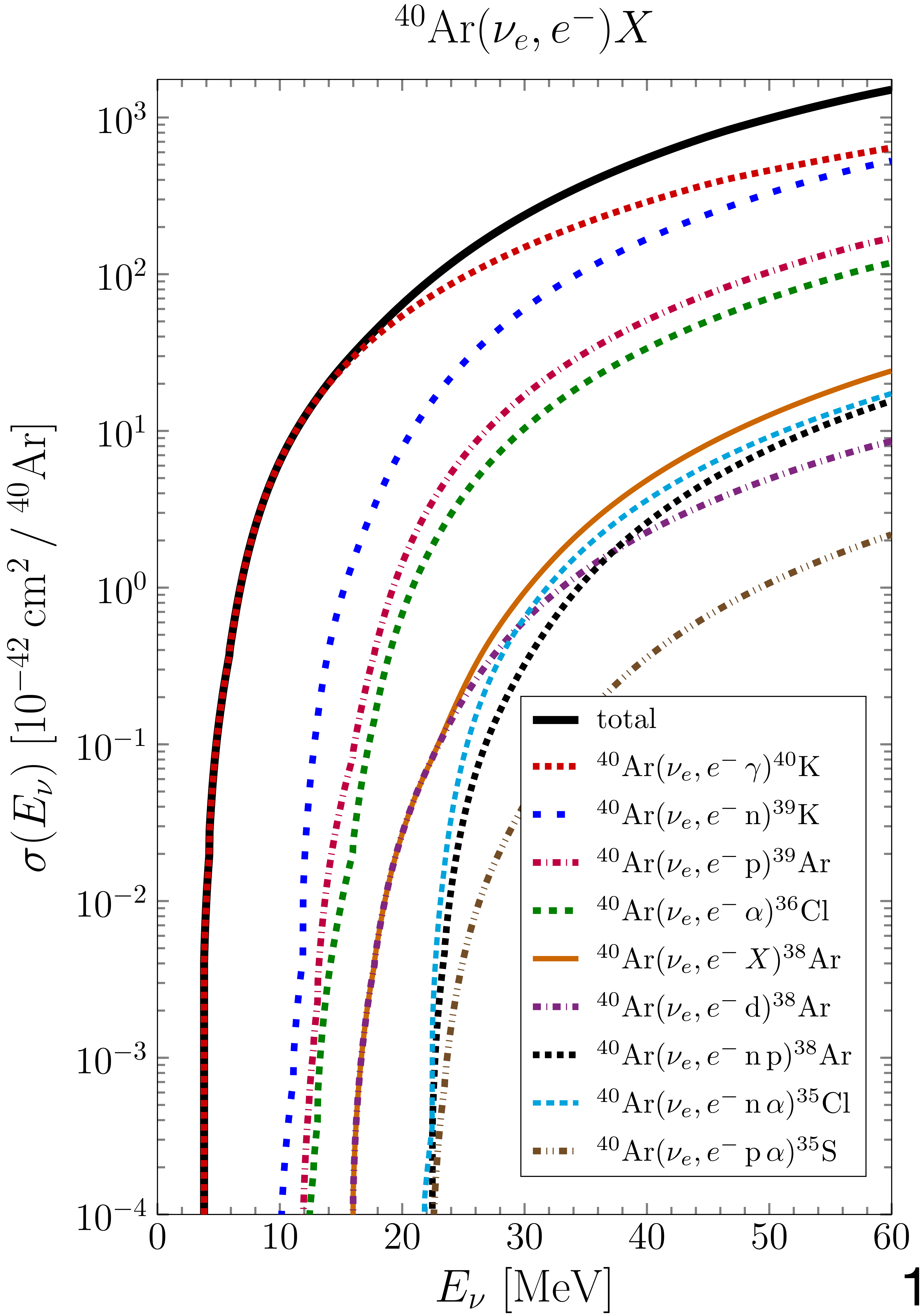
- Recent paper (arXiv:2010.02393) provides first calculation of cross sections for **exclusive final states** of the reaction

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

at tens-of-MeV energies.

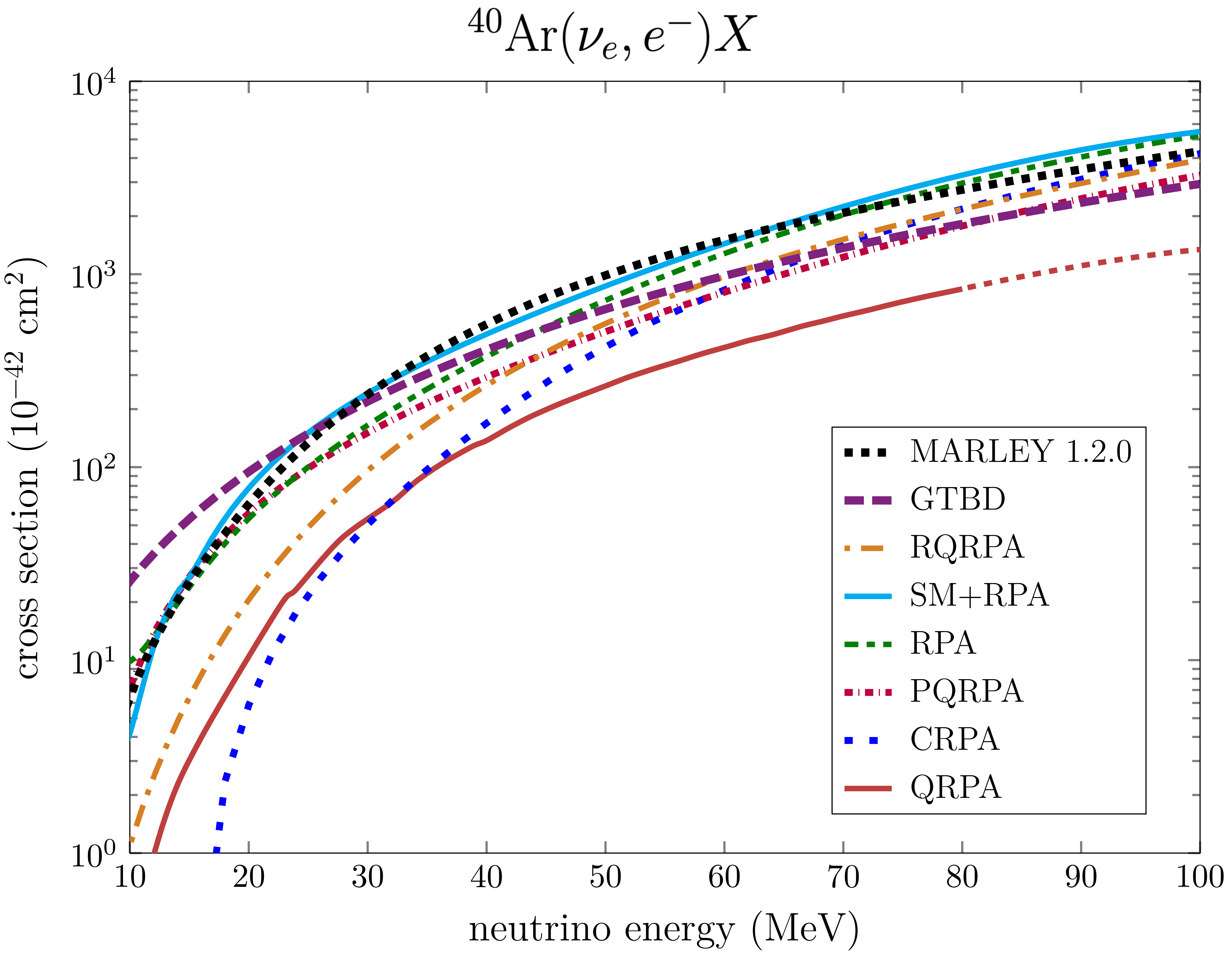
- Flux-averaged differential cross sections shown here are for the supernova model described in Phys. Rev. D 97, 023019 (2018).





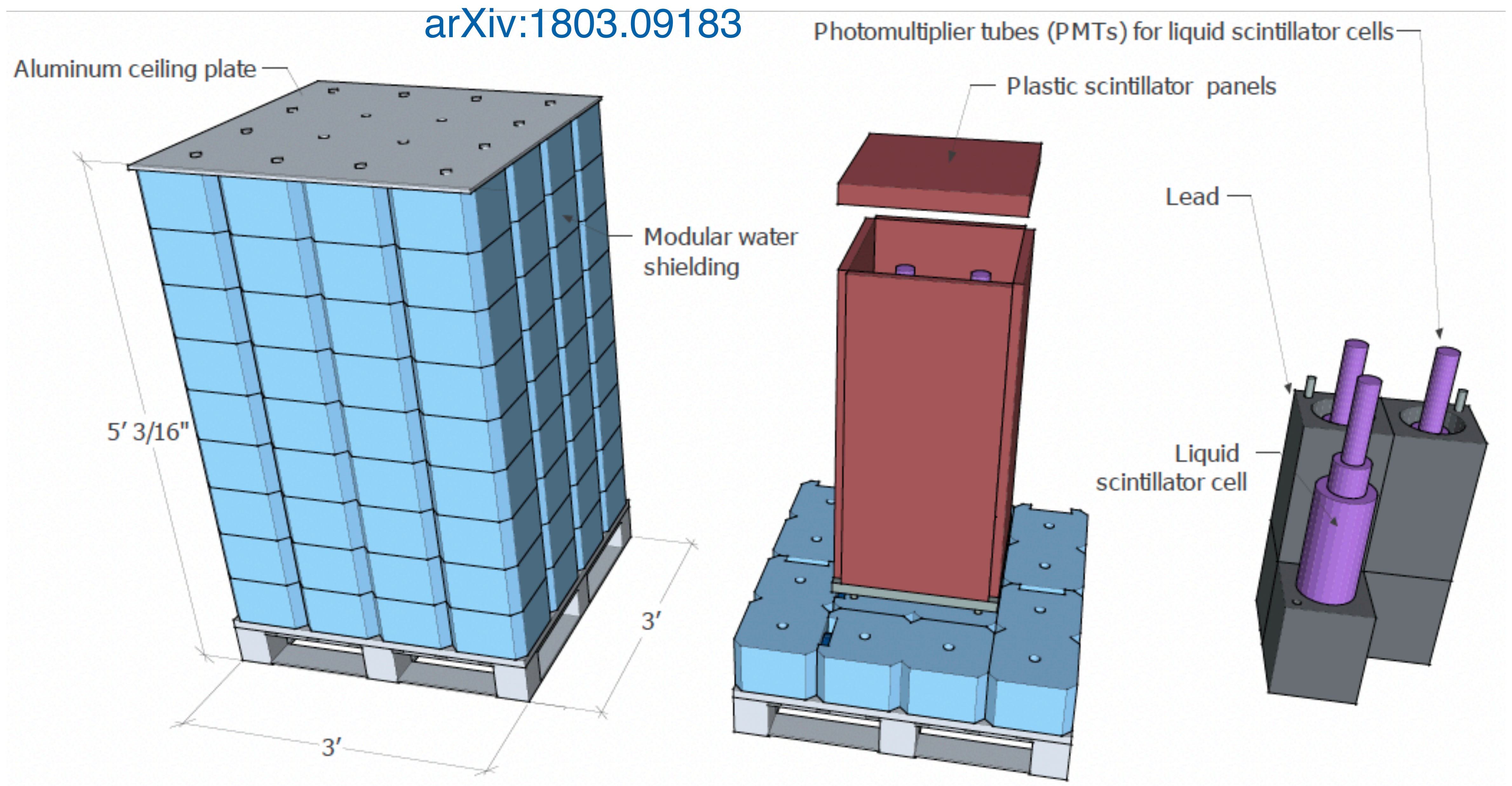
What about cross section data?

- Theoretical uncertainties related to these interactions are **large**
  - Here's an example for argon, note the log scale of the y-axis
- Little data below 100 MeV, none for argon yet
- Critical input for generators
  - Cross section measurements are crucial at higher energies as well
  - Much effort from MINERvA, MicroBooNE, etc. to provide this for DUNE's accelerator neutrino program



Facilities and detectors for future measurements

- Near-future
  - **COHERENT**: Iodine (NaIvE) and Pb, Fe, Cu (NIN cubes)
  - JSNS[2]: carbon
- Other possibilities
  - SBN detectors (MicroBooNE, SBND, ICARUS)
    - Challenging, but progress has been made on low-energy reconstruction
  - Dedicated experiment at Fermilab or Oak Ridge?
  - Coherent Captain-Mills @ LANSCE
  - Reactor or “beta beam” sources



NaIvE (I)

NIN cubes (Pb, Fe, Cu)

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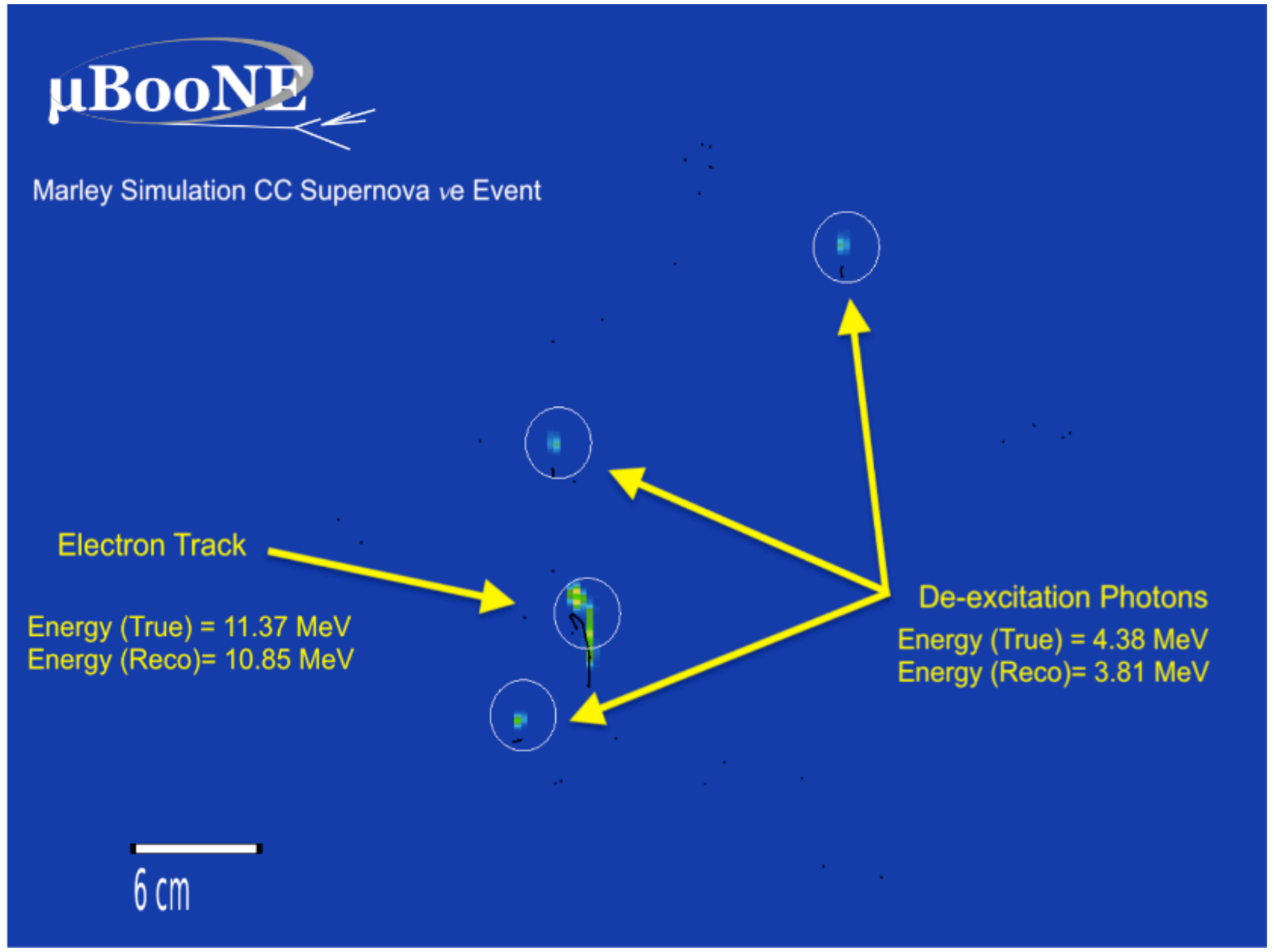

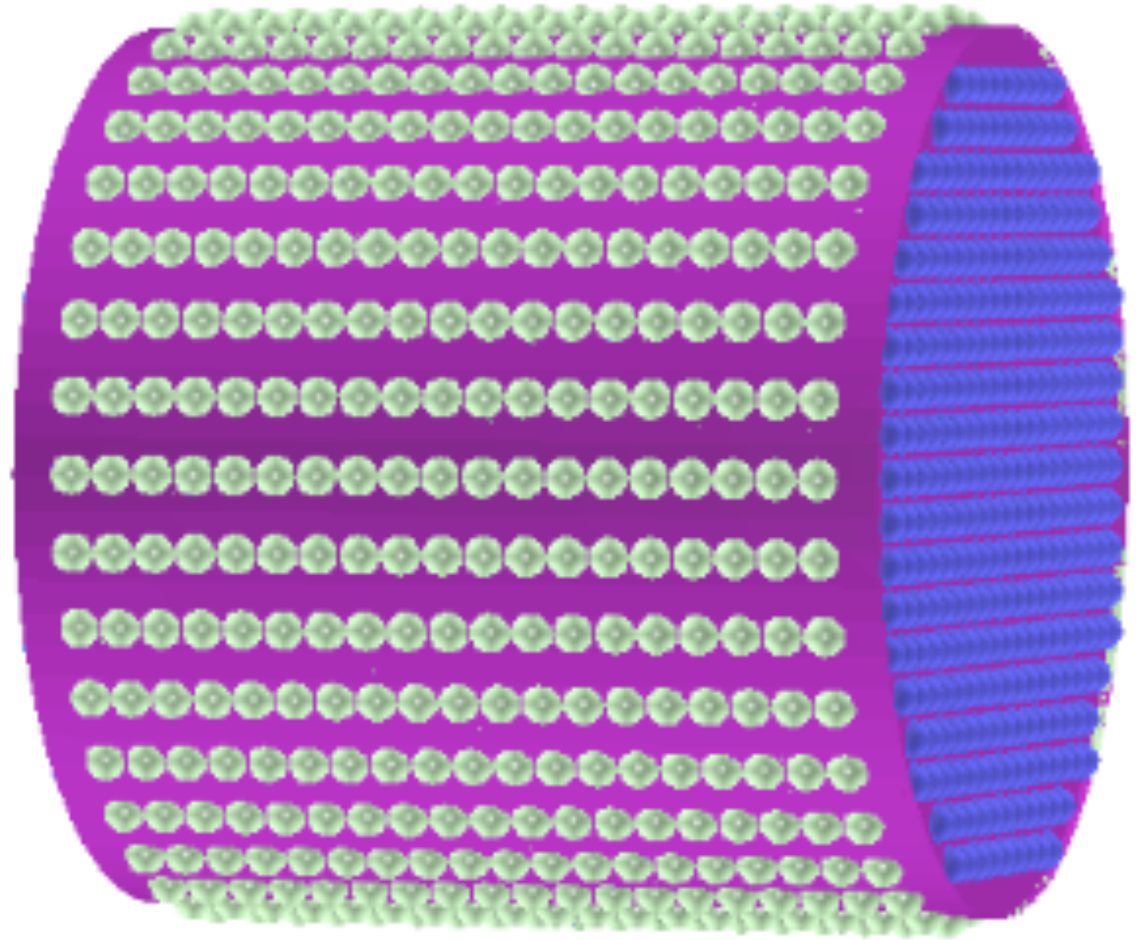

Concept for a Fermilab stopped-pion source and scintillation-only argon-based detector

J. Zettlemoyer, Magnificent CEvNS 2020