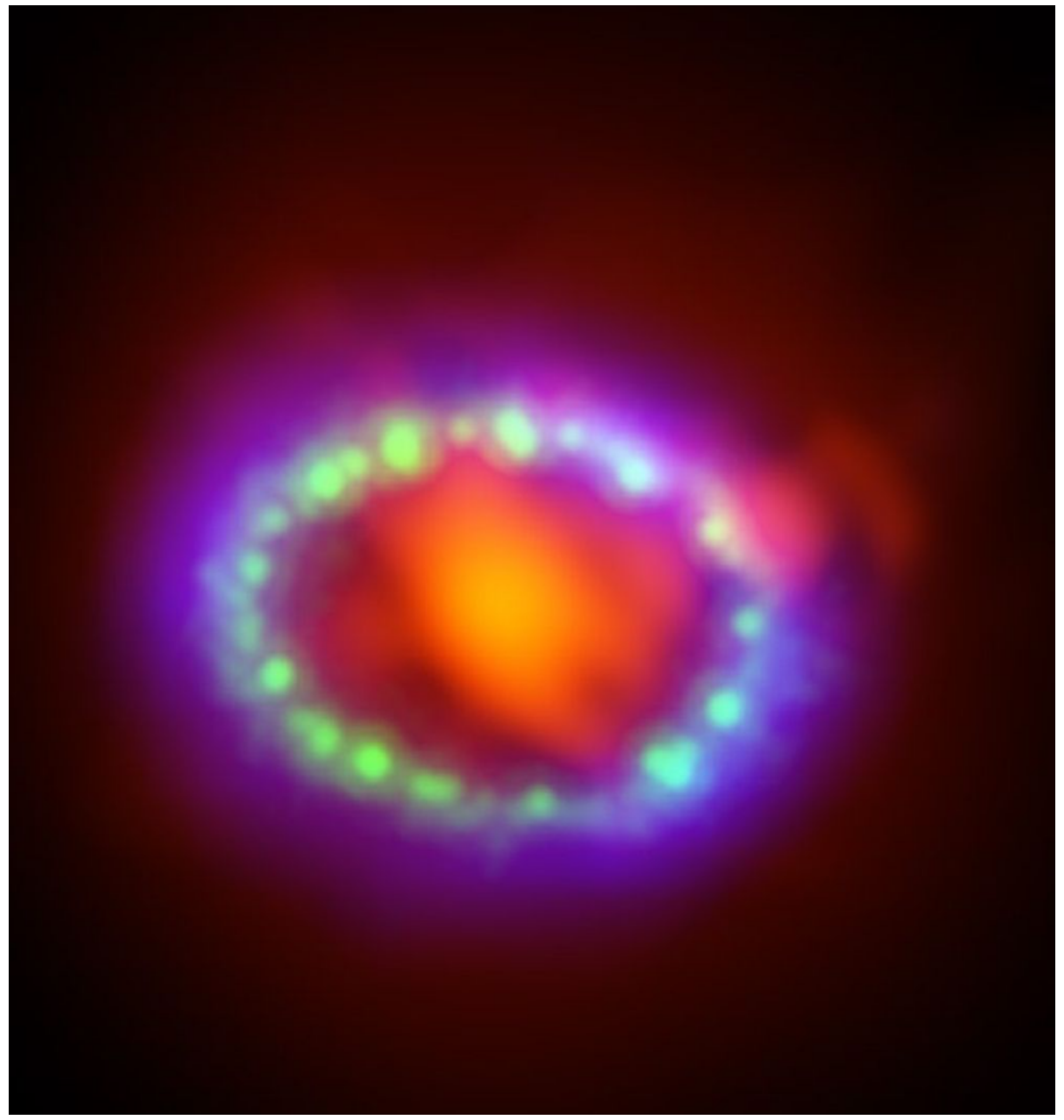
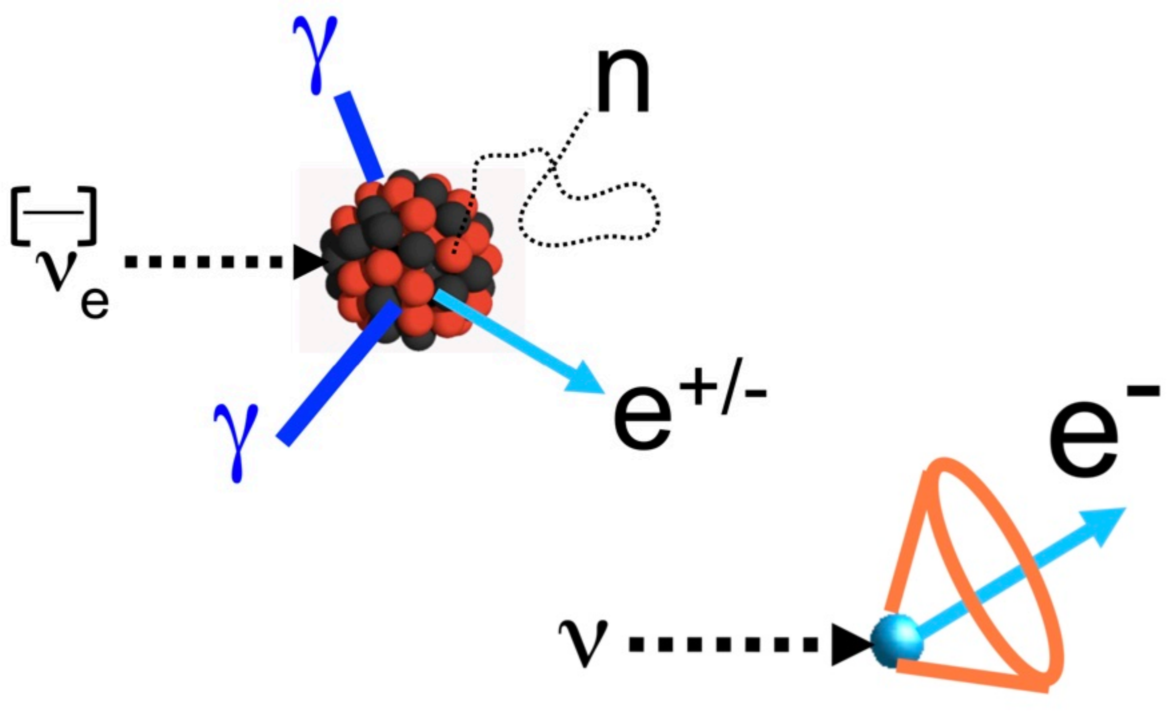
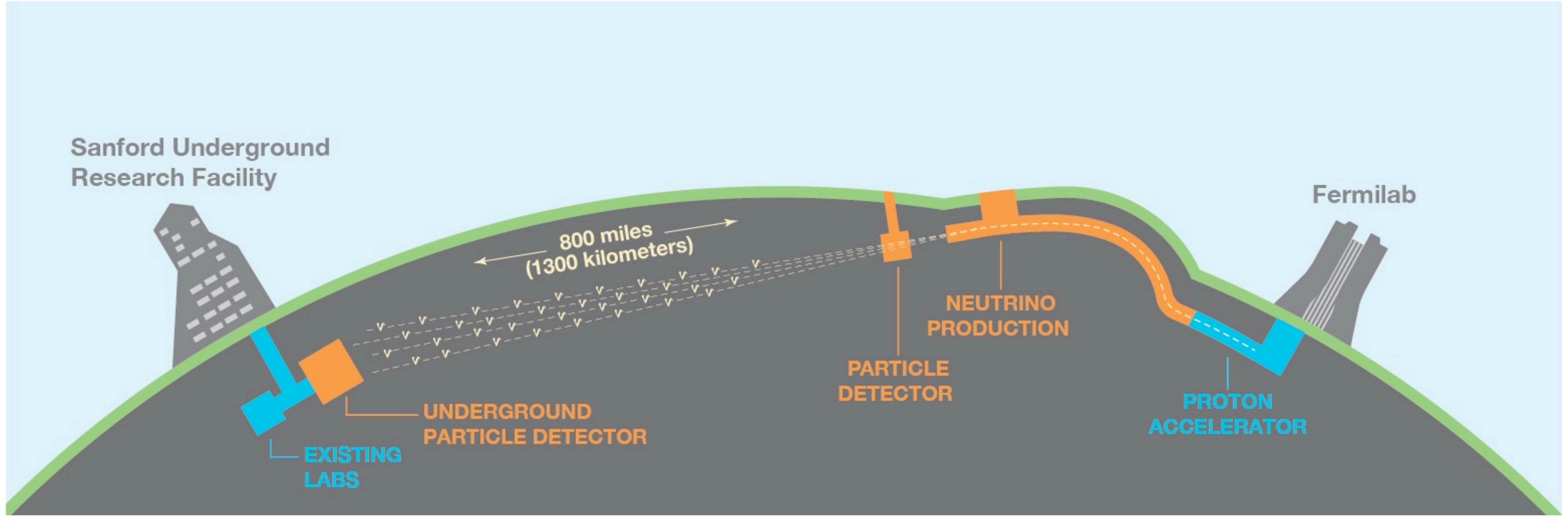
Detecting low-energy astrophysical neutrinos with DUNE







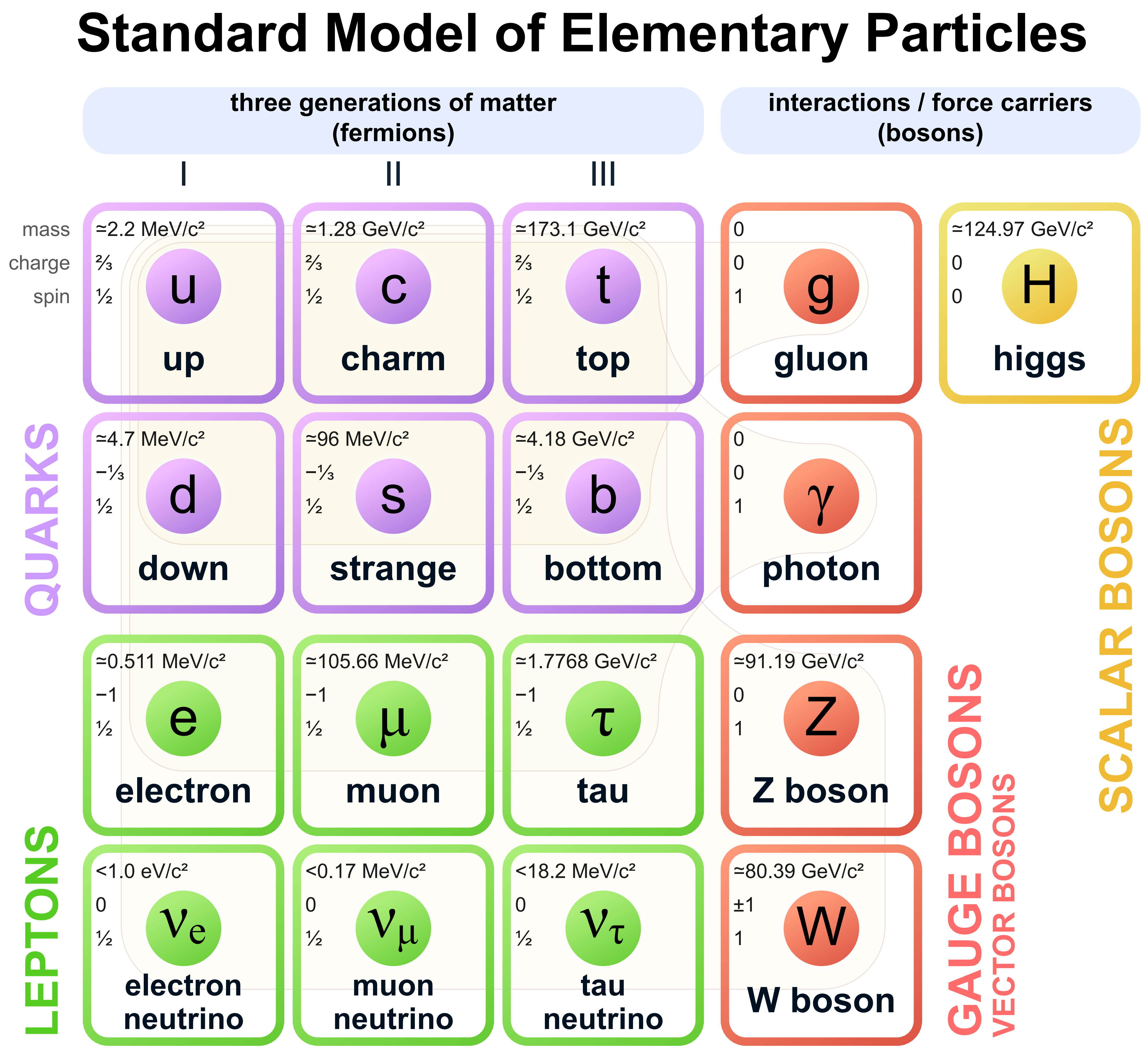
Steven Gardiner (gardiner@fnal.gov)

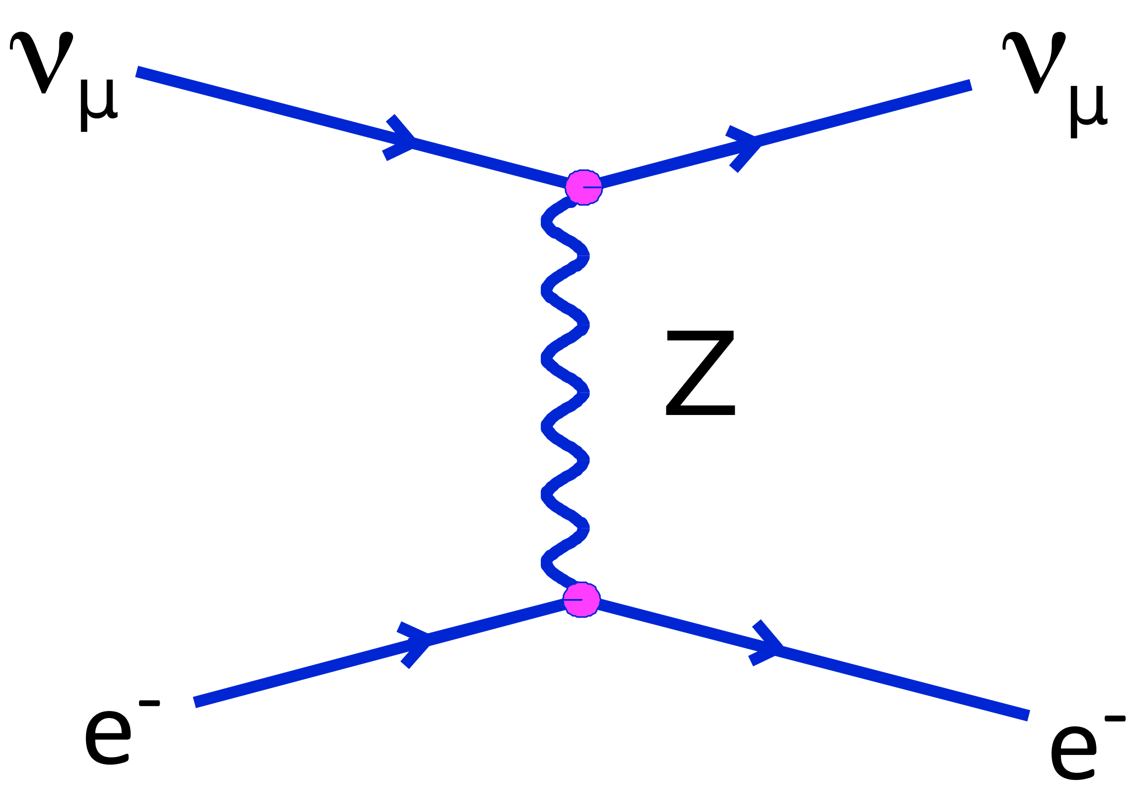
Event Generators Group, Fermilab Physics Simulation Department

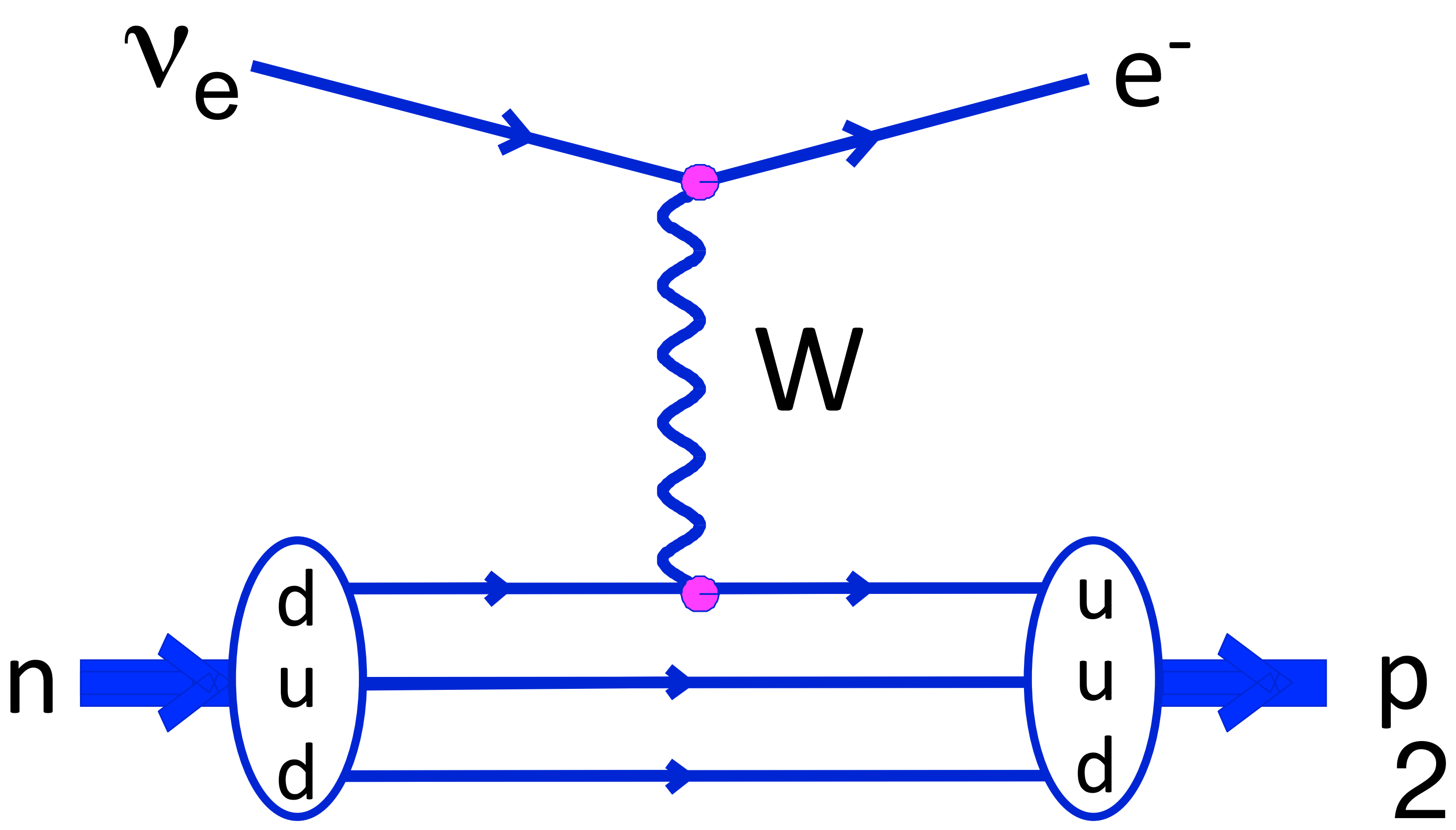
SLAC FPD Seminar, 28 November 2023

Neutrinos in the Standard Model

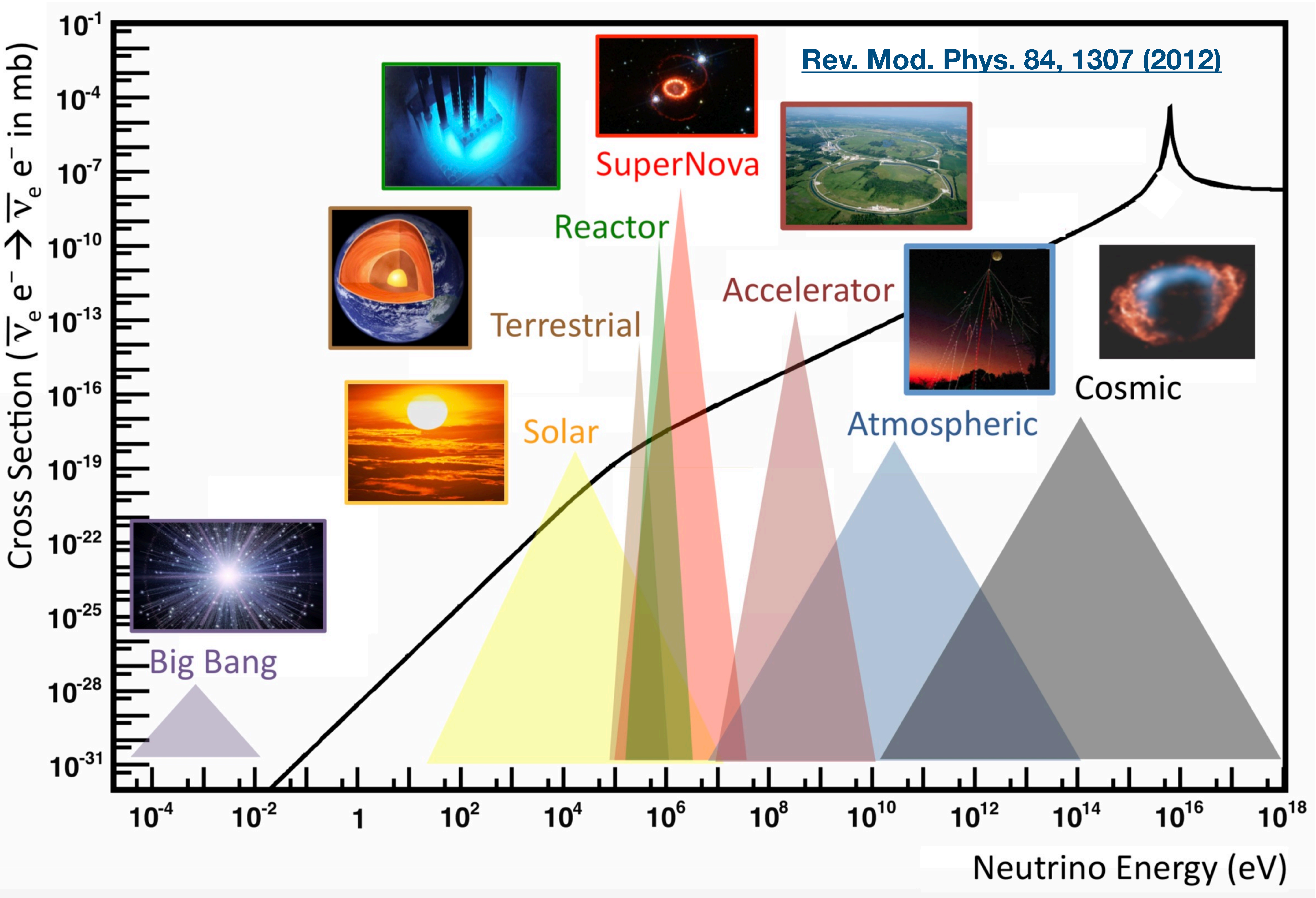
- Weakly interacting
  - W exchange = “charged current” (CC)
  - Z exchange = “neutral current” (NC)
- Detectors typically rely on **neutrino-nucleus** interactions
  - Far larger cross section than ν-e scattering
- Intense neutrino sources and massive targets still required to do the physics!





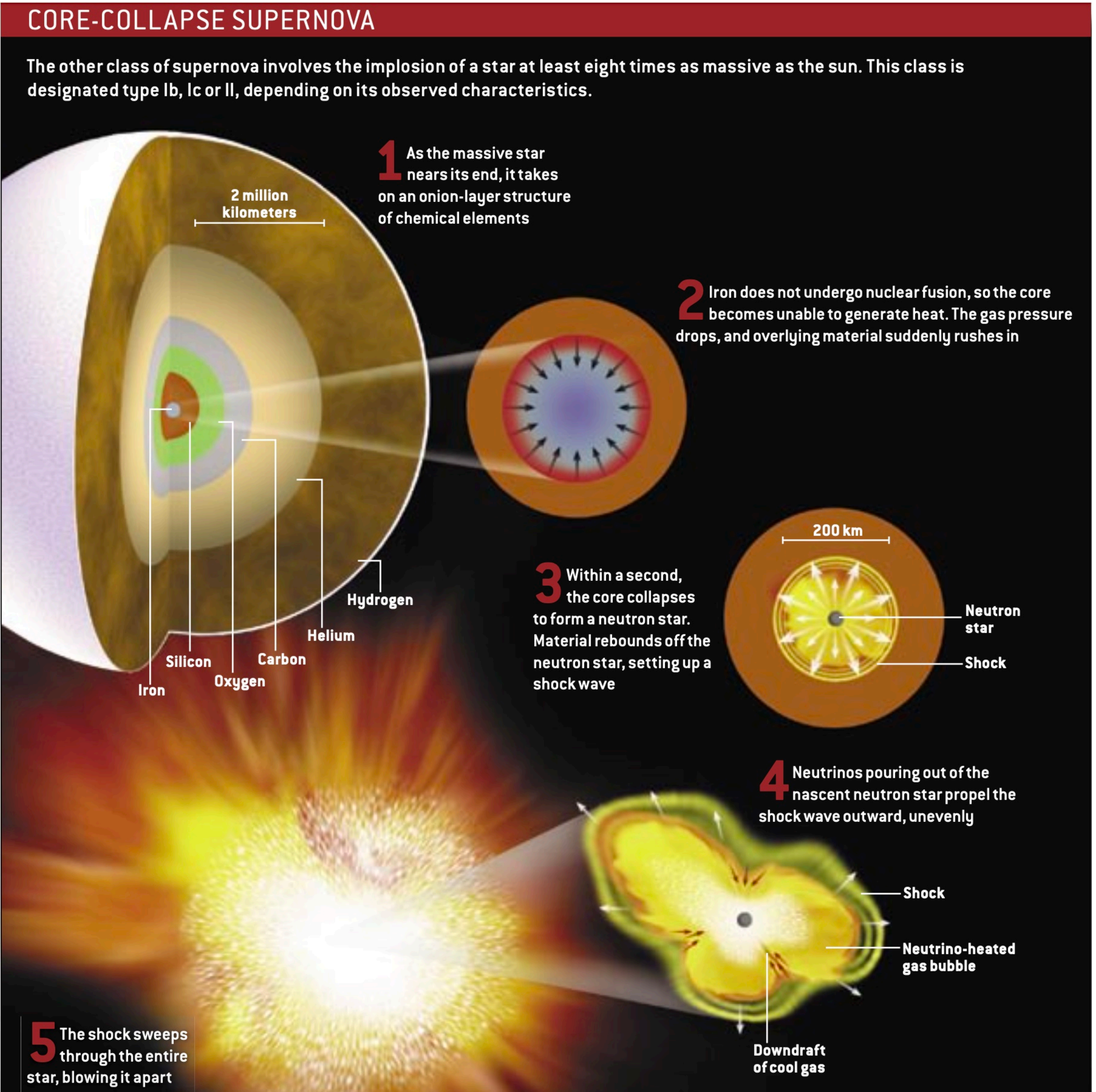


Neutrino physics across energy scales



- Many orders of magnitude in energy!
- Focus of this talk: O(1) to O(10) MeV region
- Enable exciting neutrino astrophysics by better understanding neutrino interactions

Core-collapse supernovae: nearly-perfect neutrino bombs

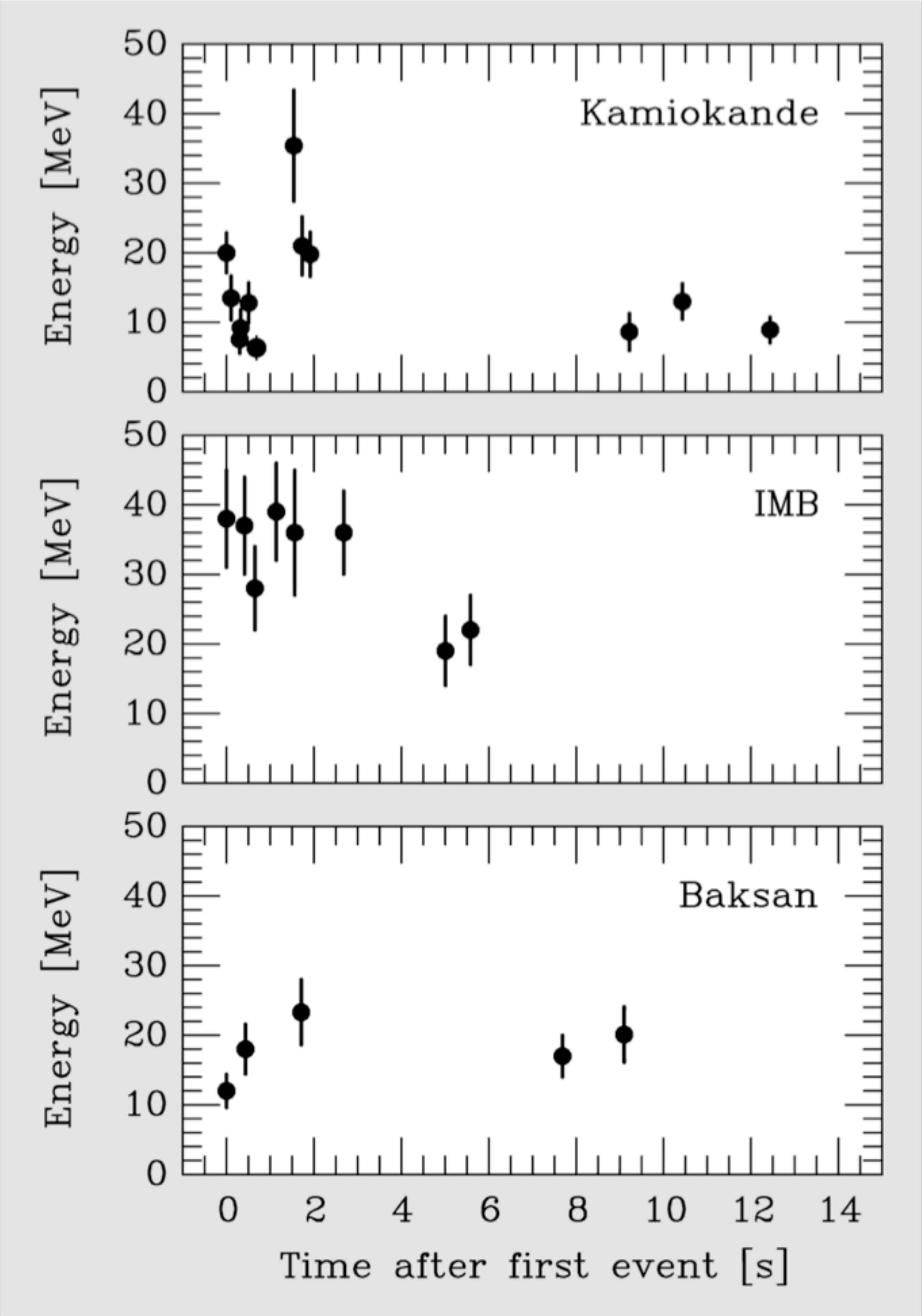


- Deaths of stars > 10 $M_\odot$
- 99% of gravitational binding energy converted to ~10^{58} neutrinos
- Many ν_e produced in initial neutronization burst (~10 ms)
- Core cools via all-flavor neutrino radiation in ~10 s
- Momentarily outshines visible universe (in neutrinos)

Sci. Am. 295, 42-49 (2006)

First and only observation so far: Supernova 1987A

- 25 antineutrino candidates detected in 13 s by 3 detectors
  - Kamiokande-II (WC)
  - IMB (WC)
  - Baksan (liquid scintillator)
- Literally hundreds of papers published scrutinizing this sparse data set
- Worldwide effort (SNEWS) to be ready for the next one
- Complementary to optical and gravitational wave observations



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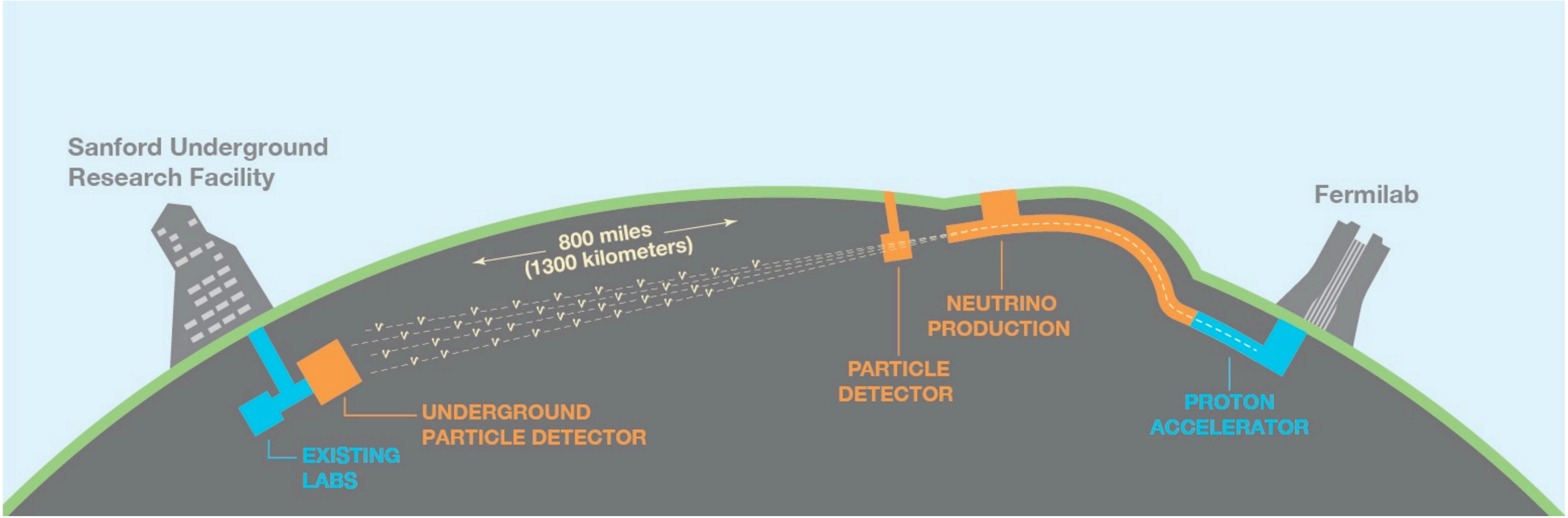
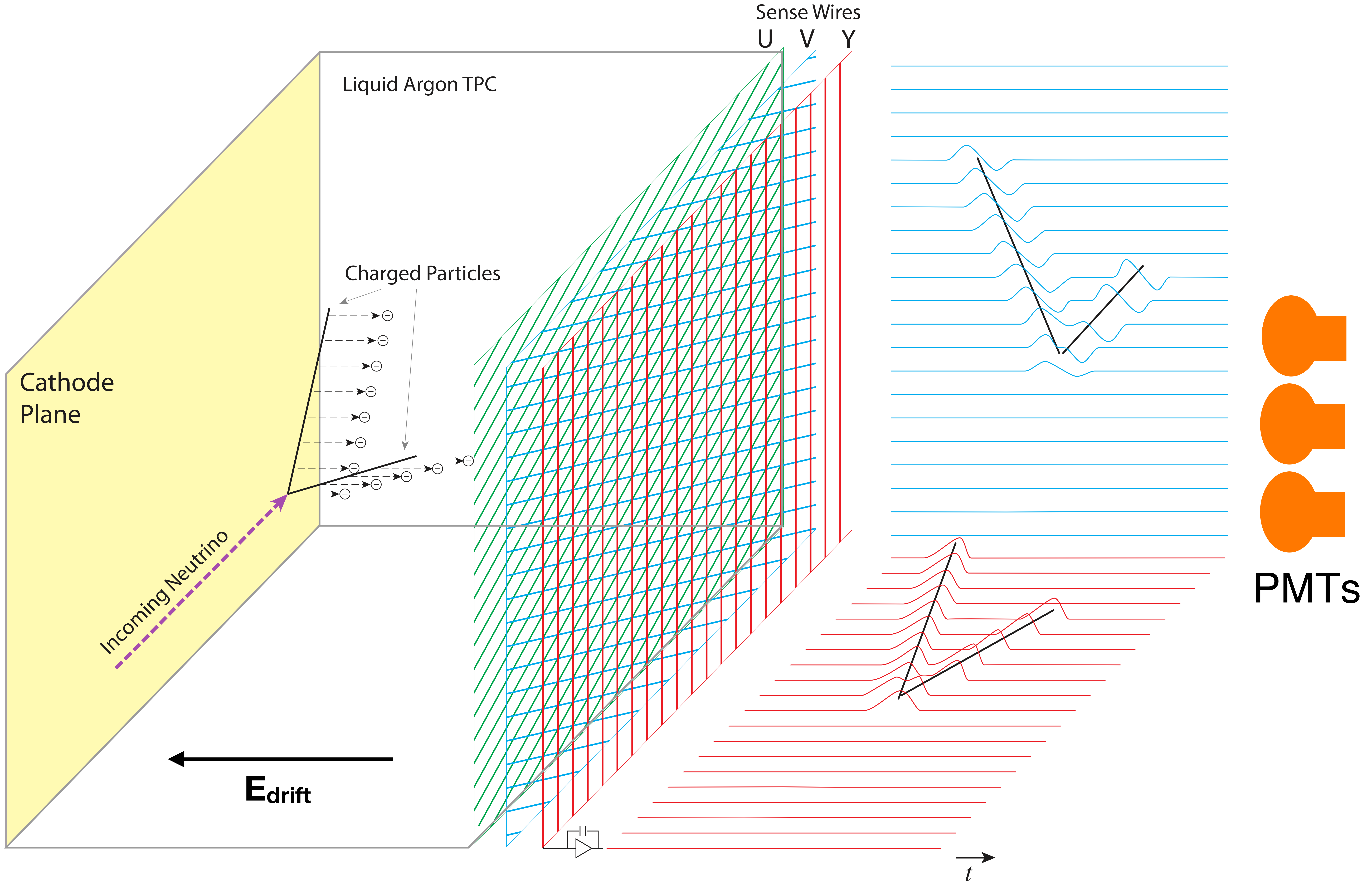
Recent JWST image of SN1987A remnant

The Deep Underground Neutrino Experiment (DUNE)



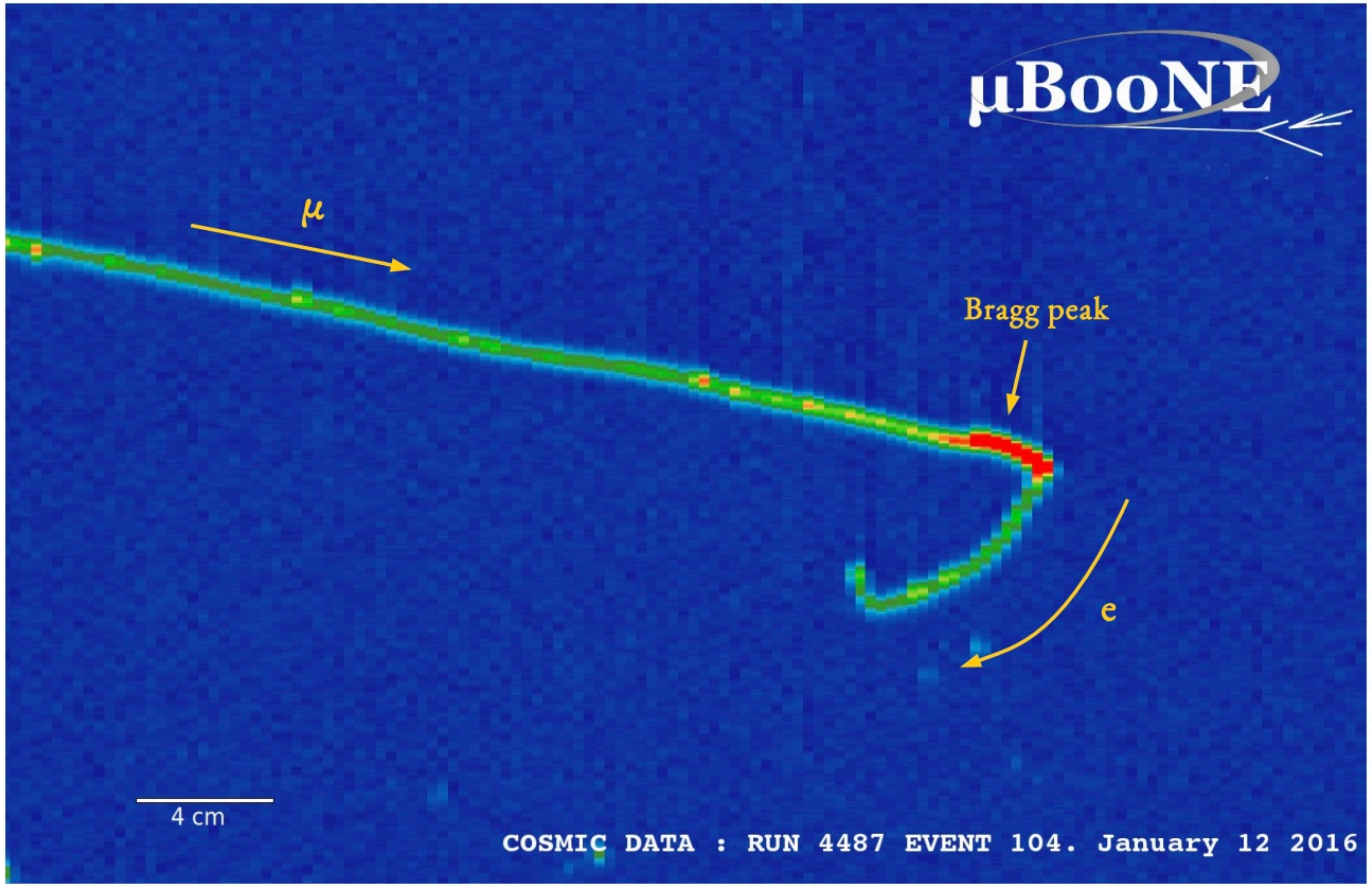
- World’s most powerful neutrino beam (1.2 MW+) and two groups of detectors
  - **Far detector**: 4 × 17 kton LArTPCs (40 kton total fiducial mass)
  - **Near detector**: Multi-component (including liquid and gaseous argon)
- Data taking to begin circa 2028

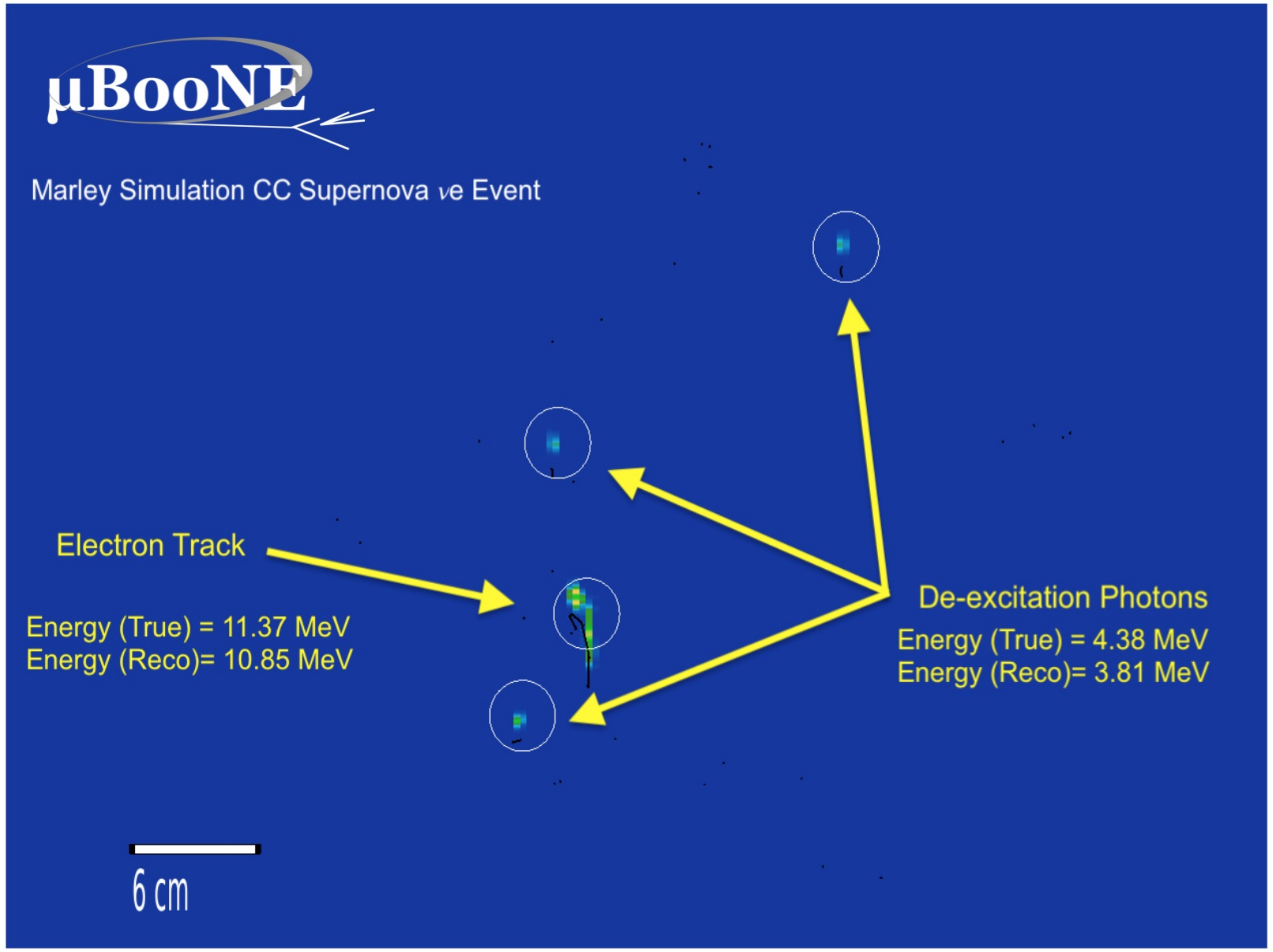
Neutrino detection in a liquid argon time projection chamber



Low-energy LArTPC event displays

- MicroBooNE: LArTPC experiment at Fermilab (2015-2021)
- MeV-scale event reconstruction under development

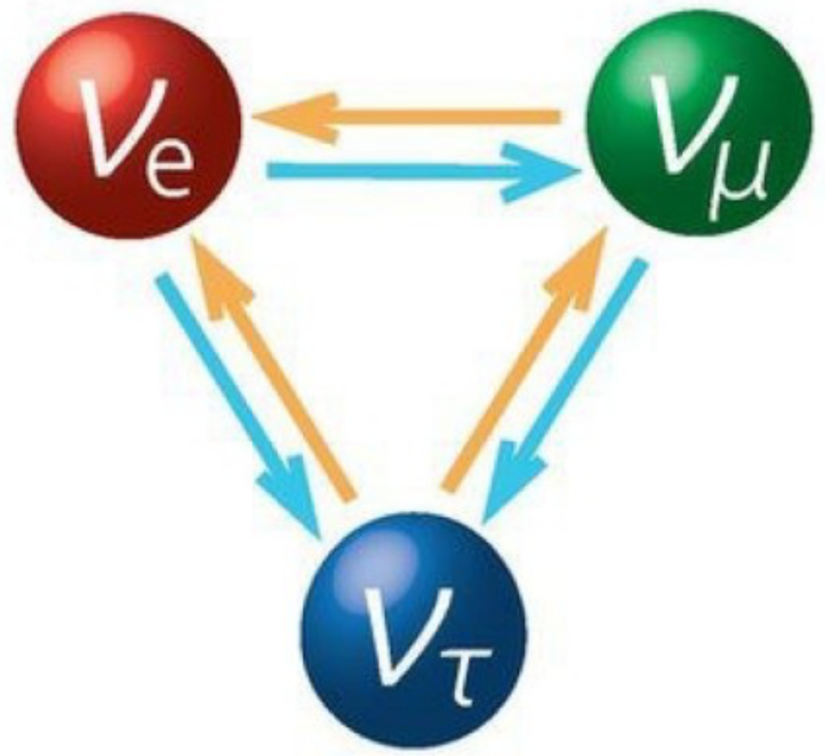




J. Instrum. 12 P09014 (2017)

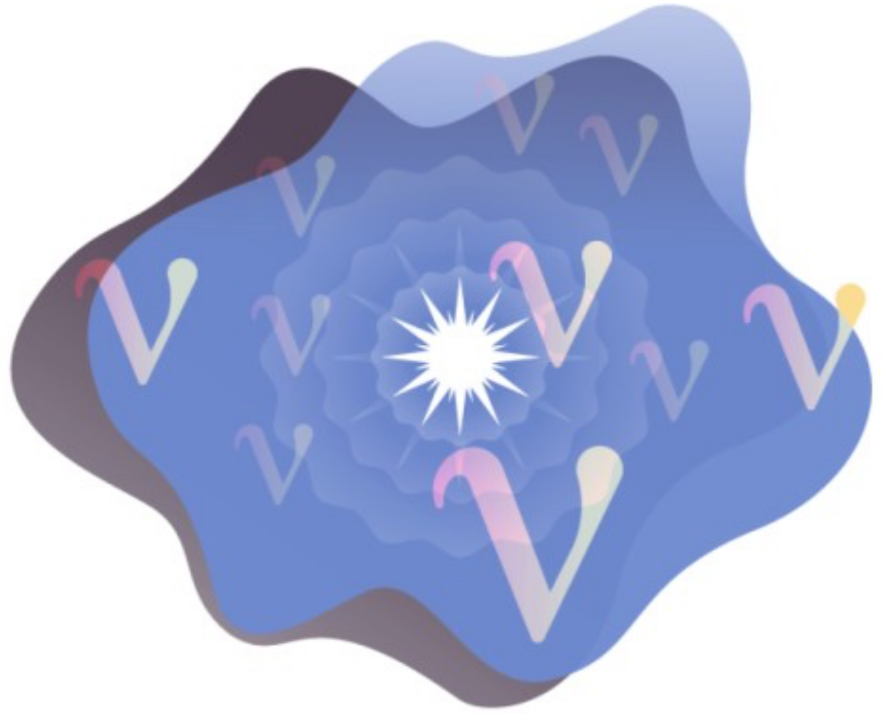
MICROBOONE-NOTE-1076-PUB

Primary science goals of DUNE



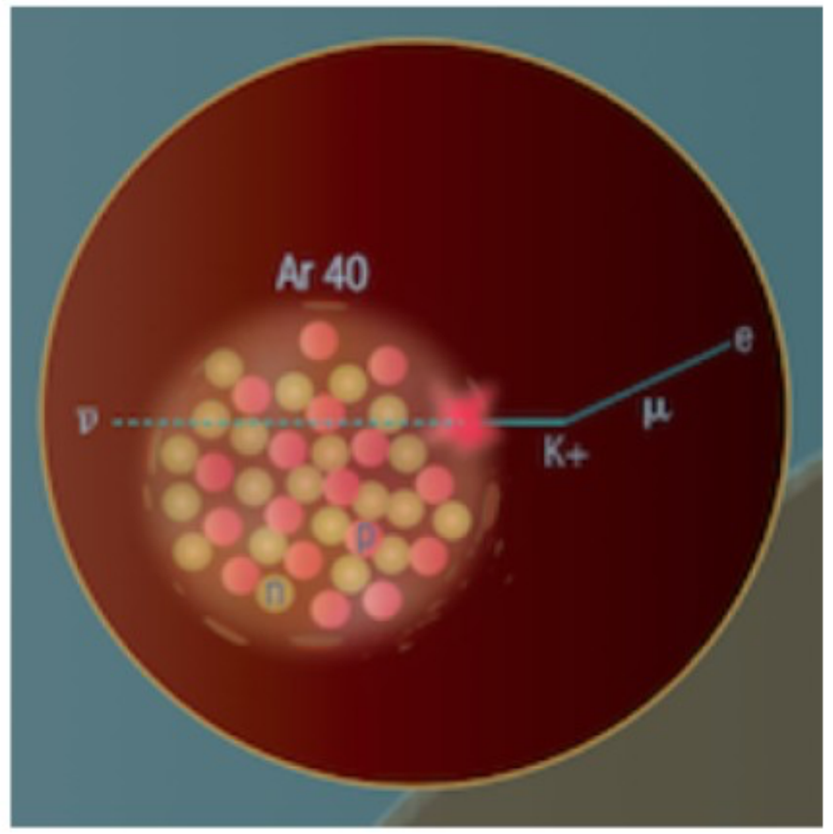
Accelerator neutrino oscillations

- Search for CP violation ($\delta^{CP} \neq 0,\pi$)
- Neutrino mass ordering
- Precision mixing parameters



Supernova physics

- Measure O(10 MeV) neutrinos from a galactic supernova
- Unique sensitivity to ν_e component, rich physics potential



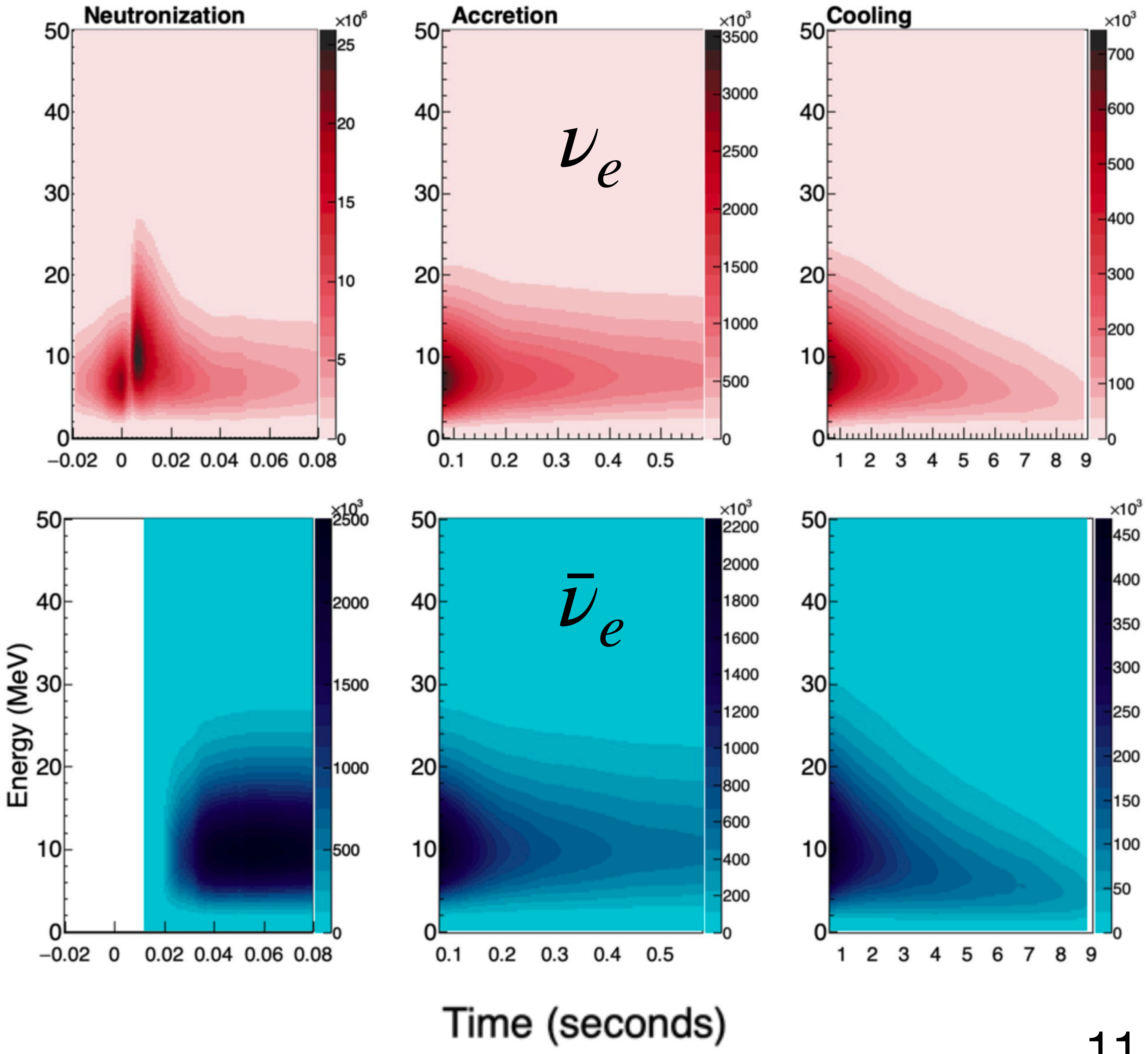
Explore physics beyond the Standard Model

- Proton decay, other baryon number violating processes
- Heavy neutral leptons, boosted dark matter
- Various other exotic physics scenarios

Observables for a supernova neutrino analysis

- Physics signatures imprinted on time-dependent flux
  - Core-collapse dynamics, mass ordering, collective oscillations, exotic physics searches, …
- Measure **energy**, flavor, and time
  - Low **tens-of-MeV** set by supernova temperature
- Distinct information from $\nu_e, \bar{\nu}_e, \nu_x$
  - Detection of all highly desirable

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



Neutrinos under extreme conditions: self-interaction effects

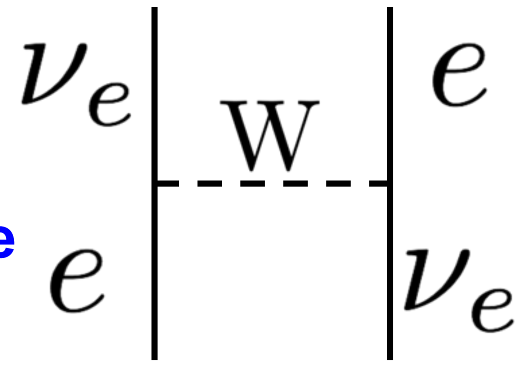
In the proto-neutron star the neutrino density is so high that ***neutrino-neutrino*** *interactions* matter

$$\psi_{\nu,i} = \begin{bmatrix} \text{amplitude to be } \nu_e \\ \text{amplitude to be } \nu_{\mu,\tau} \end{bmatrix}$$

From G. Fuller

$$i\,\frac{\partial}{\partial t}\psi_{\nu,i} = \left(\mathcal{H}_{\mathrm{vac},i} + \mathcal{H}_{\mathrm{e},i} + \mathcal{H}_{\nu\nu,i}\right)\psi_{\nu,i}$$

neutrino-electron charged current forward exchange scattering



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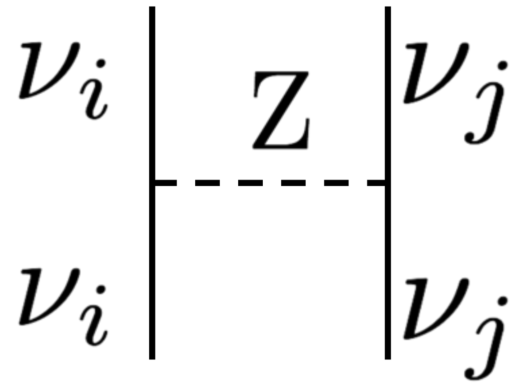
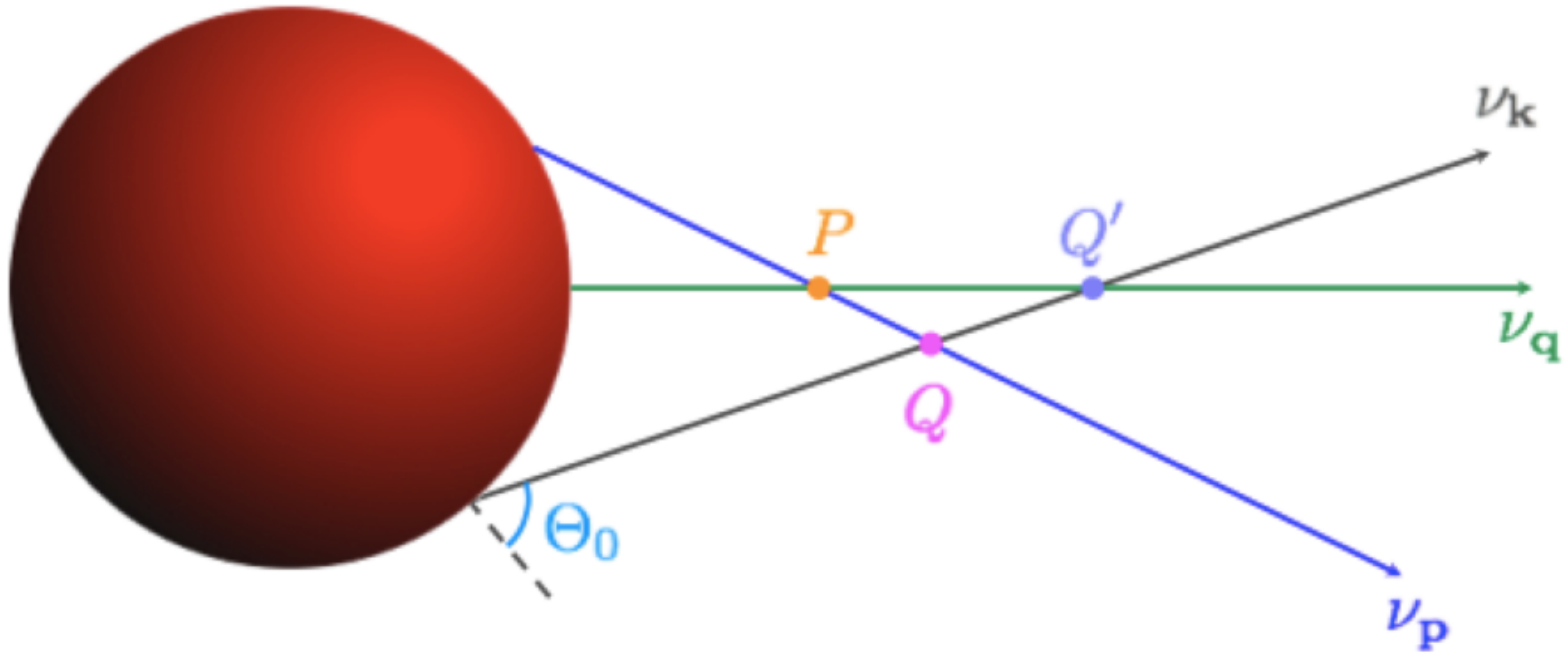
neutrino-neutrino neutral current forward scattering





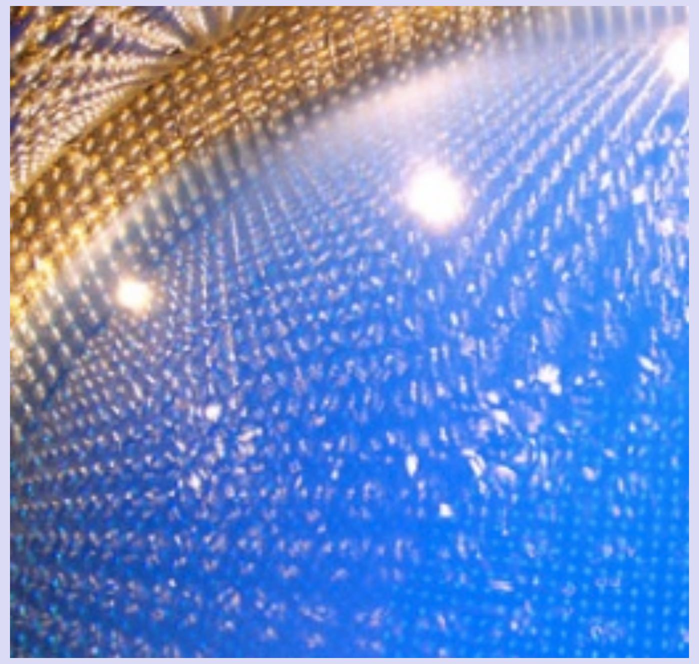
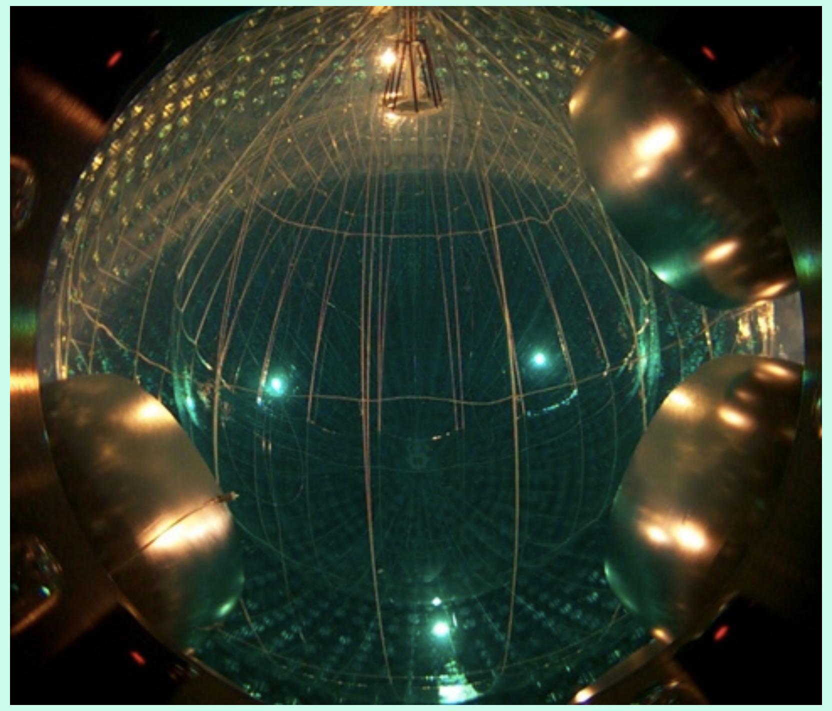
Anisotropic, nonlinear quantum coupling of all neutrino flavor evolution histories:

"collective effects"

Must solve many *millions* of coupled, nonlinear partial differential equations!!

"The physics is addictive" -- G. Raffelt

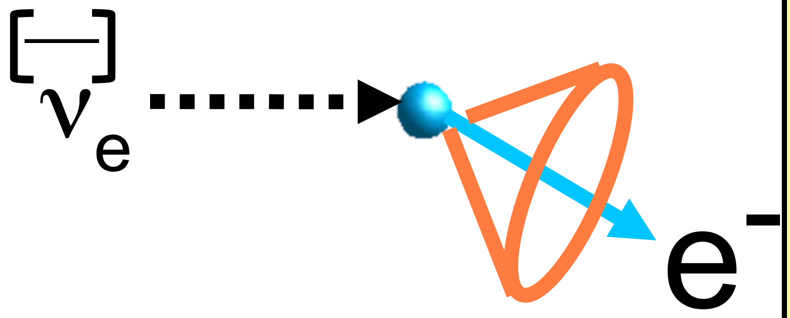
Current main supernova neutrino detector types

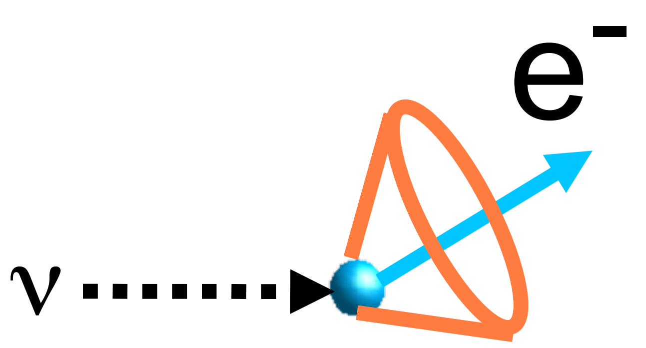
Water	**Scintillator**
 	
Argon	**Lead**
	

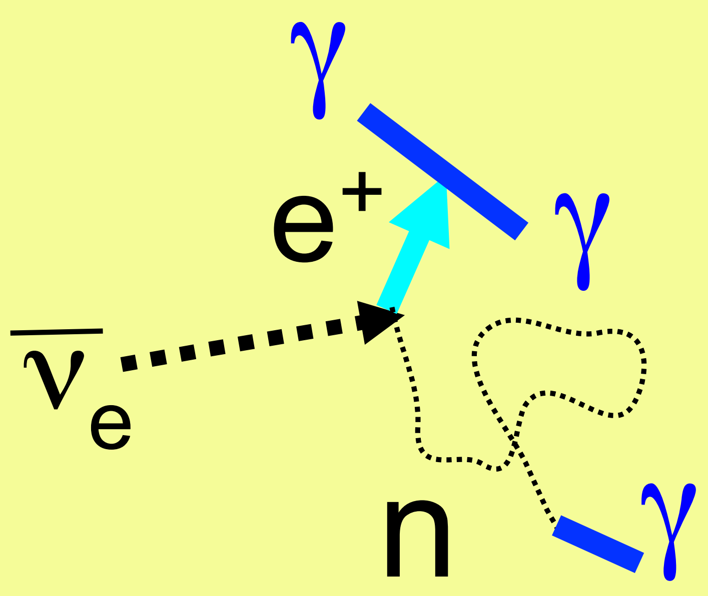
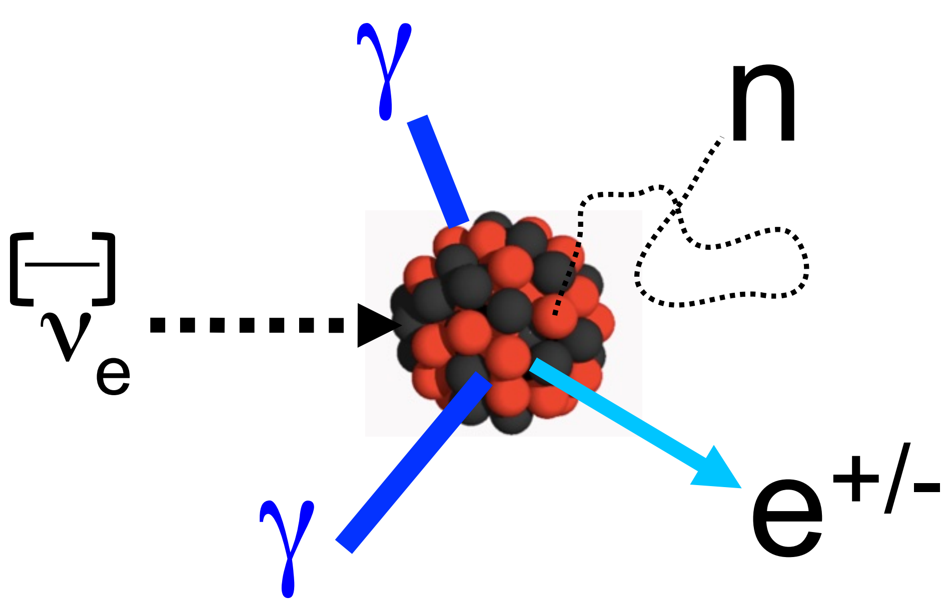
+ some others (e.g. DM detectors)

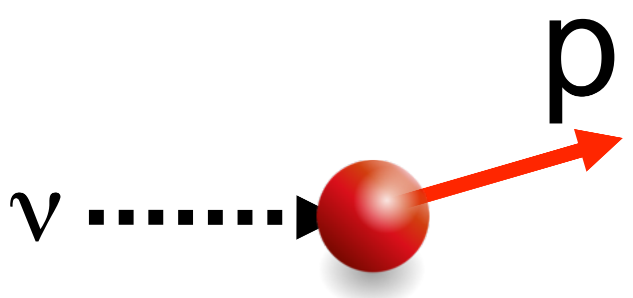
Supernova-relevant neutrino interactions

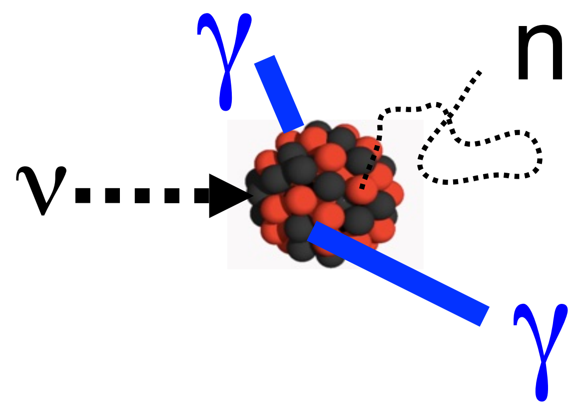
K. Scholberg

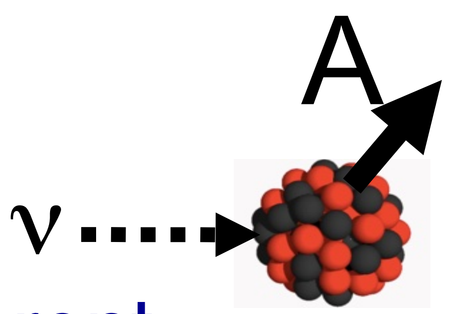
<table>
<tr><th></th><th>Electrons</th><th>Protons</th><th>Nuclei</th></tr>
<tr><td>Charged current</td>
<td rowspan="2">Elastic scattering
$\nu + e^- \to \nu + e^-$




Useful for pointing</td>
<td>Inverse beta decay
$\bar{\nu}_e + p \to e^+ + n$

</td>
<td>$\nu_e + (N, Z) \to e^- + (N-1, Z+1)$
$\bar{\nu}_e + (N, Z) \to e^+ + (N+1, Z-1)$


Various possible ejecta and deexcitation products</td></tr>
<tr><td>Neutral current</td>
<td>Elastic scattering


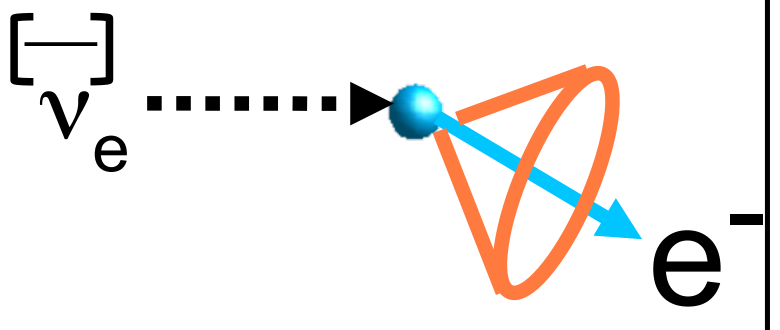
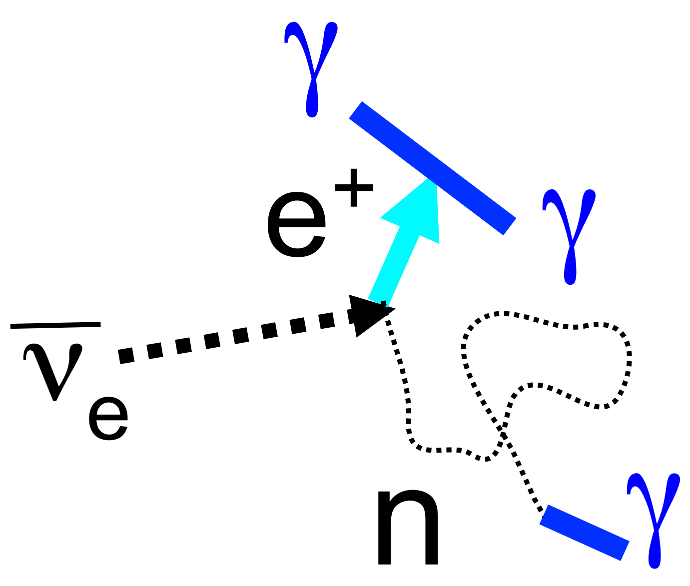
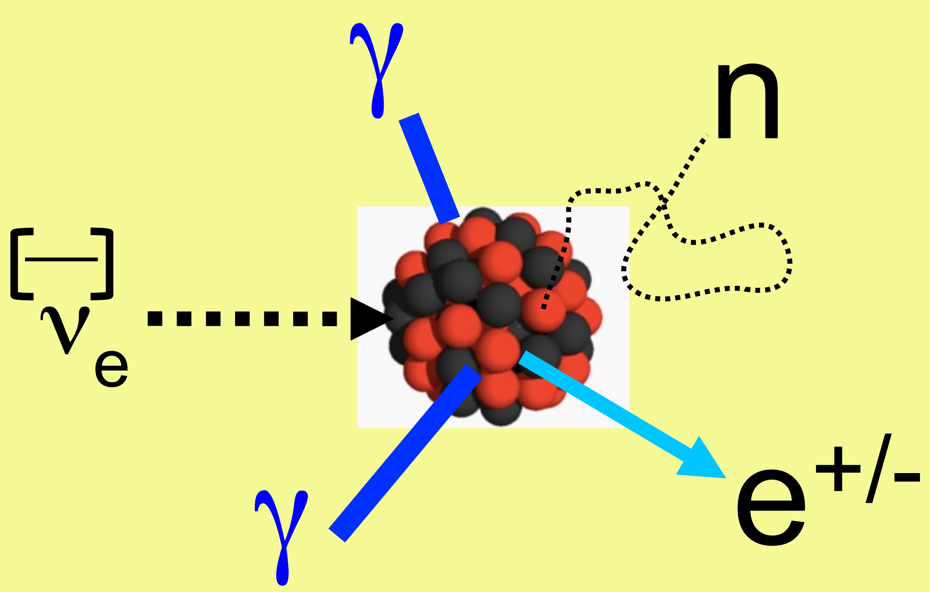
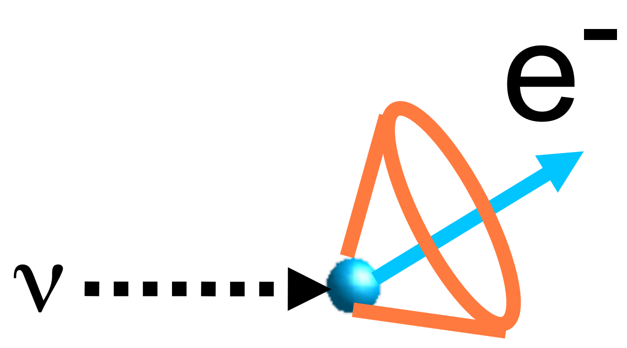
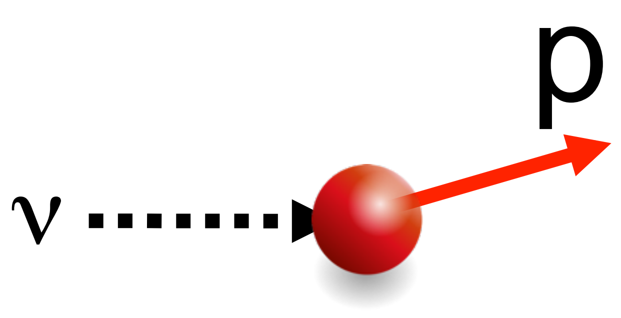
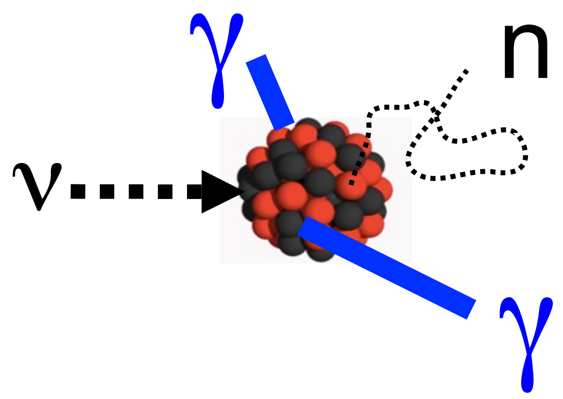
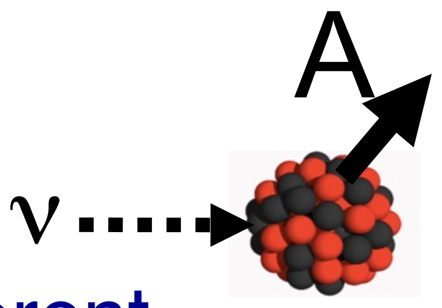
very low energy recoils</td>
<td>$\nu + A \to \nu + A^*$


$\nu + A \to \nu + A$


Coherent elastic (CEvNS)</td></tr>
</table>

IBD (electron *anti*neutrinos) dominates for current detectors

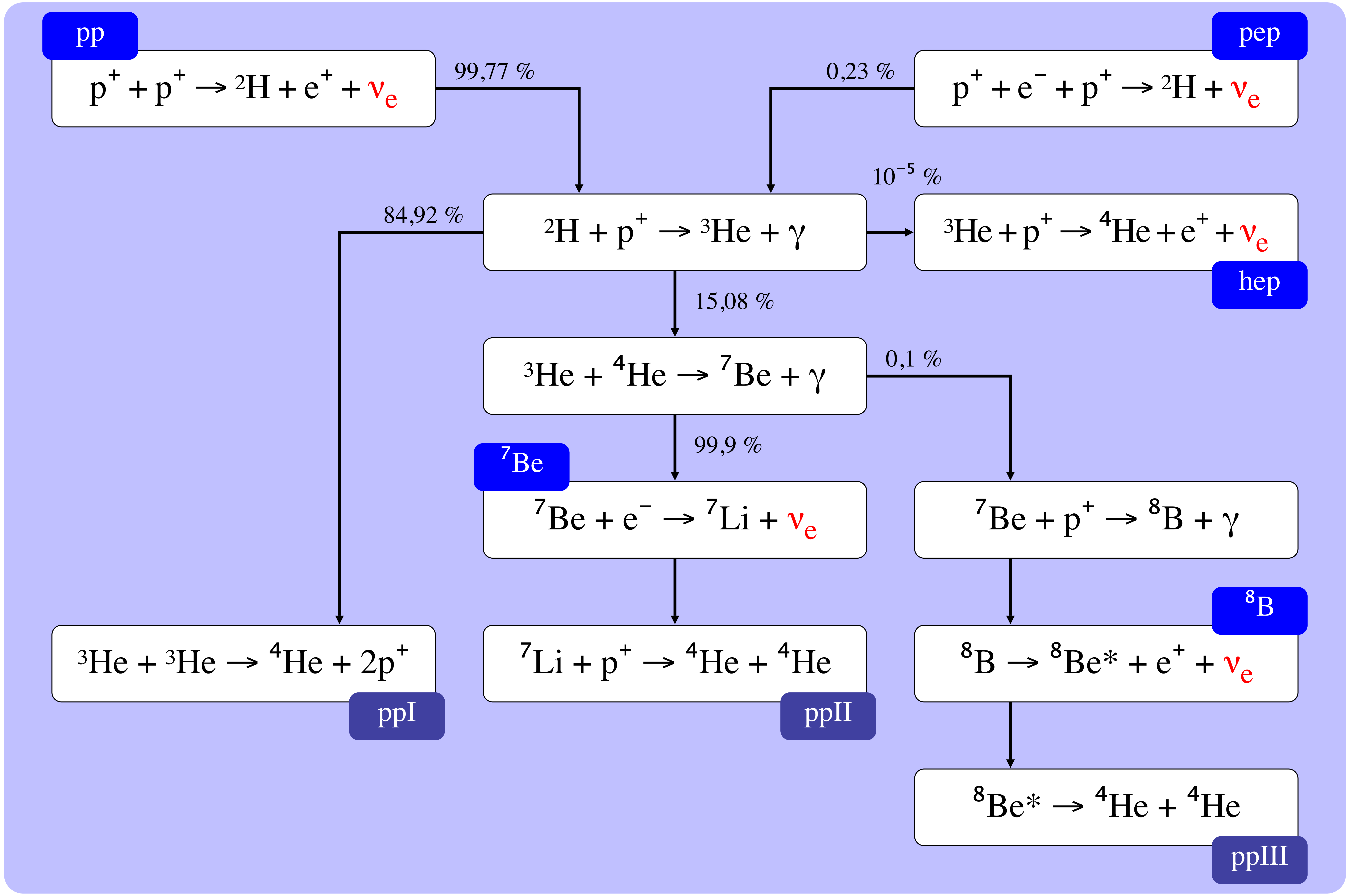
Supernova-relevant neutrino interactions

K. Scholberg	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \to \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \to e^+ + n$ 	$\nu_e + (N,Z) \to e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N,Z) \to e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \to \nu + A^*$  $\nu + A \to \nu + A$  Coherent elastic (CEvNS)

Nuclear target needed to isolate electron neutrino flux!

Solar neutrino production: proton-proton chain

- Fusion reactions in the sun generate low-energy ν_e
  - β^+ decay
  - e^- capture
- **p-p chain** dominant (~99%)
- CNO cycle (~1%)
  - Catalytic
  - Recently observed for the first time by Borexino: [**Nature 587, 577-582 (2020)**]



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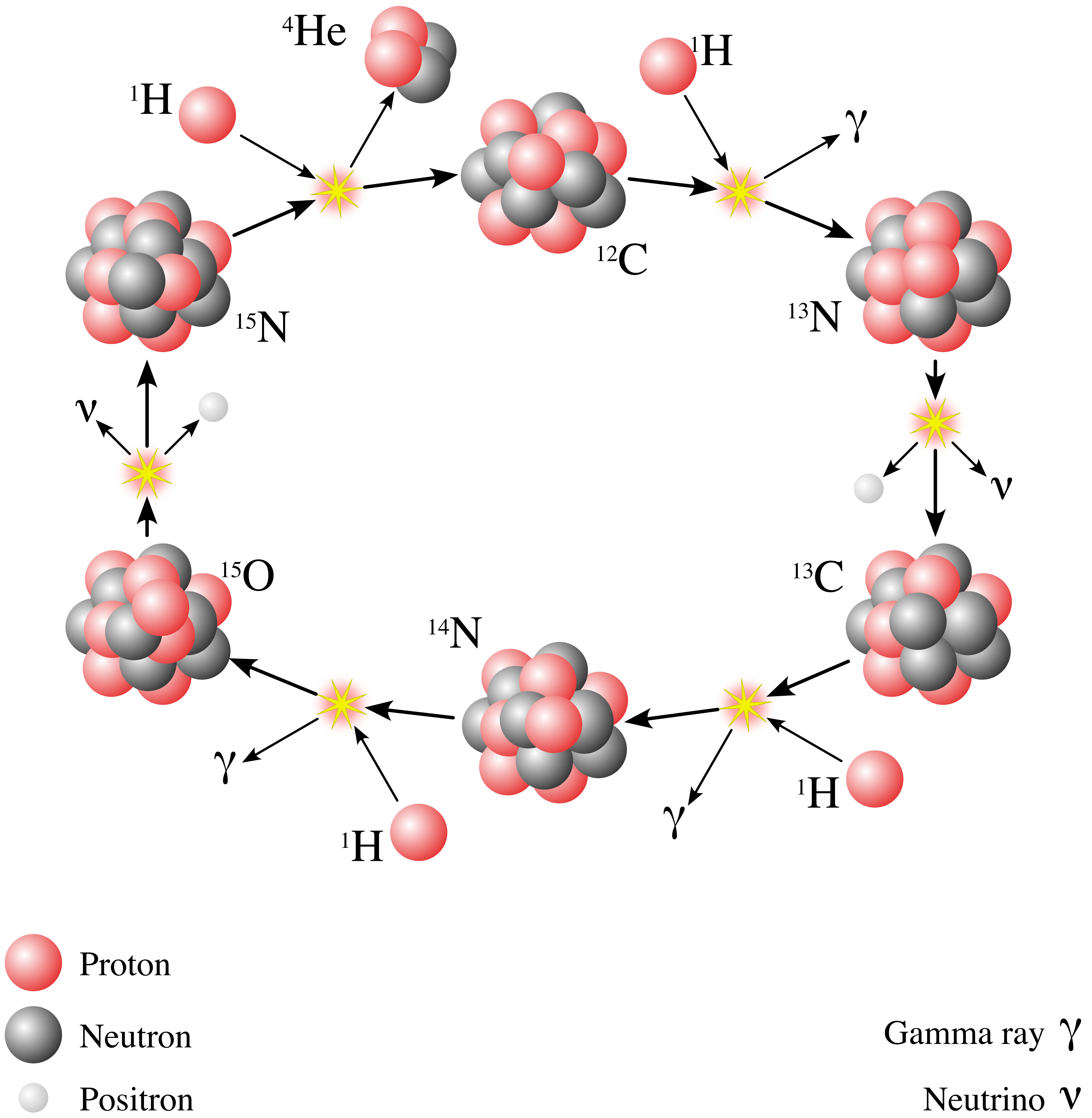
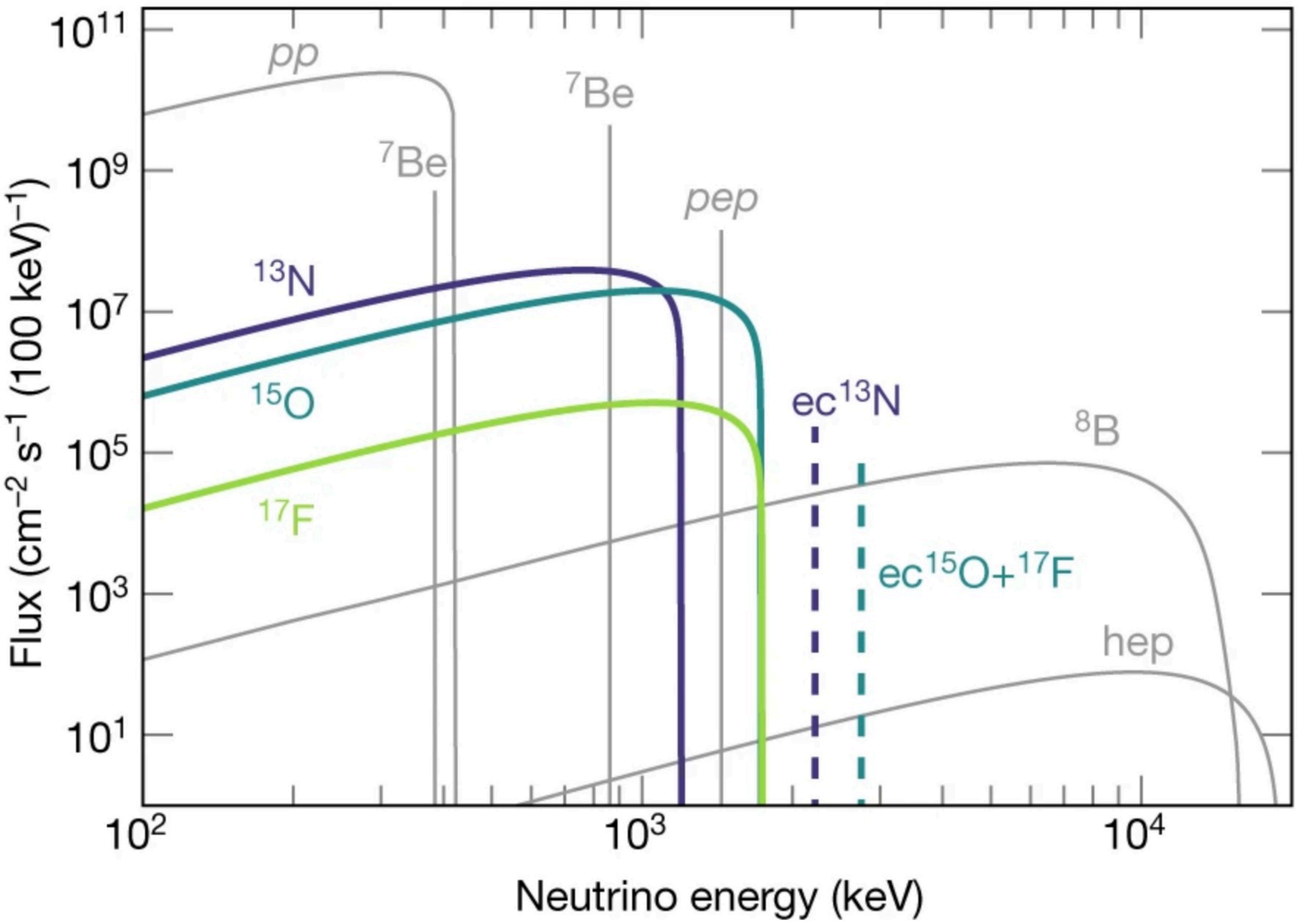


Solar neutrino fluxes

- **Gray** = p-p chain
- **Colors** = CNO cycle
- ^8B and hep fluxes extend beyond 10 MeV
  - Potentially observable in DUNE
- The **hep flux** has not yet been detected

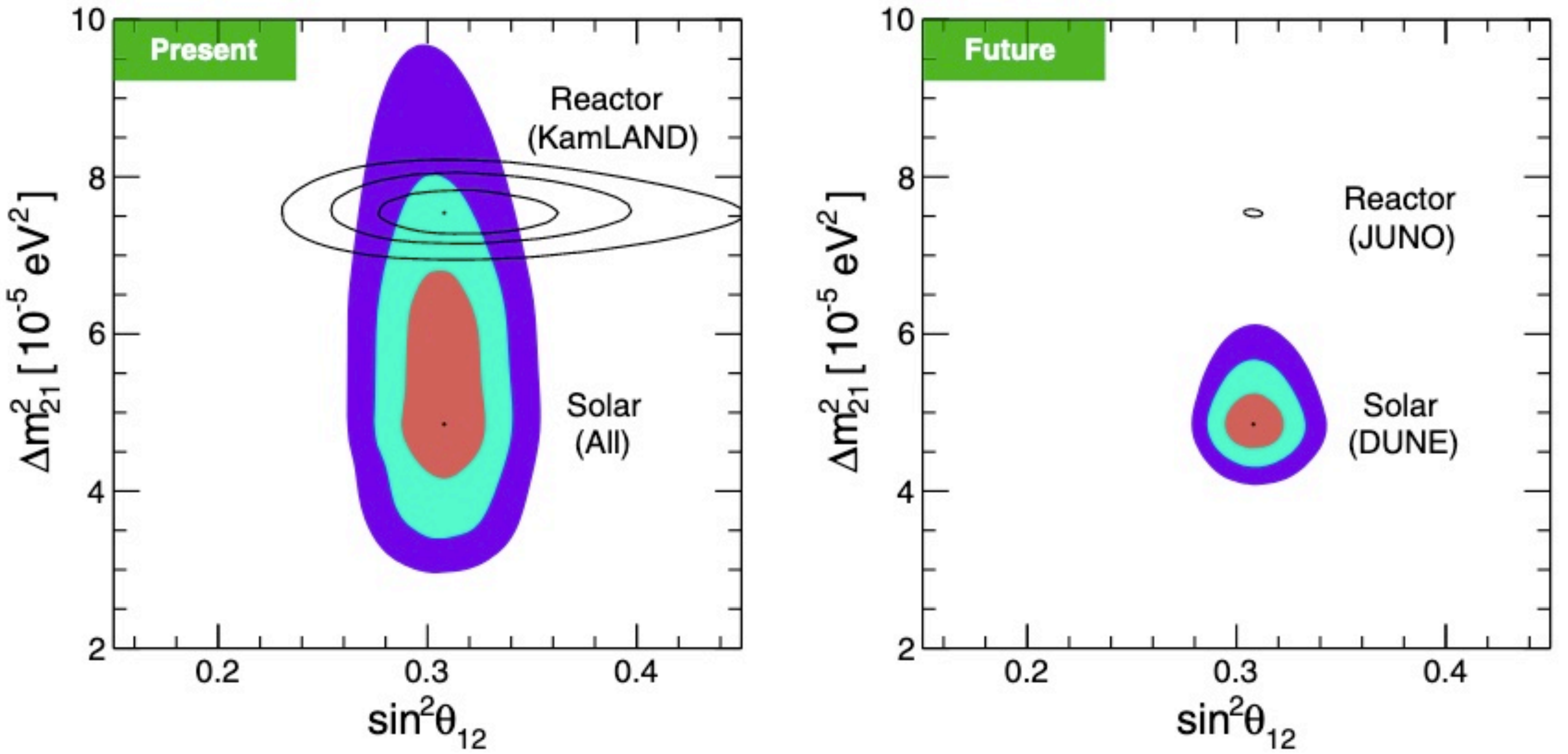
Nature 587, 577–582 (2020)

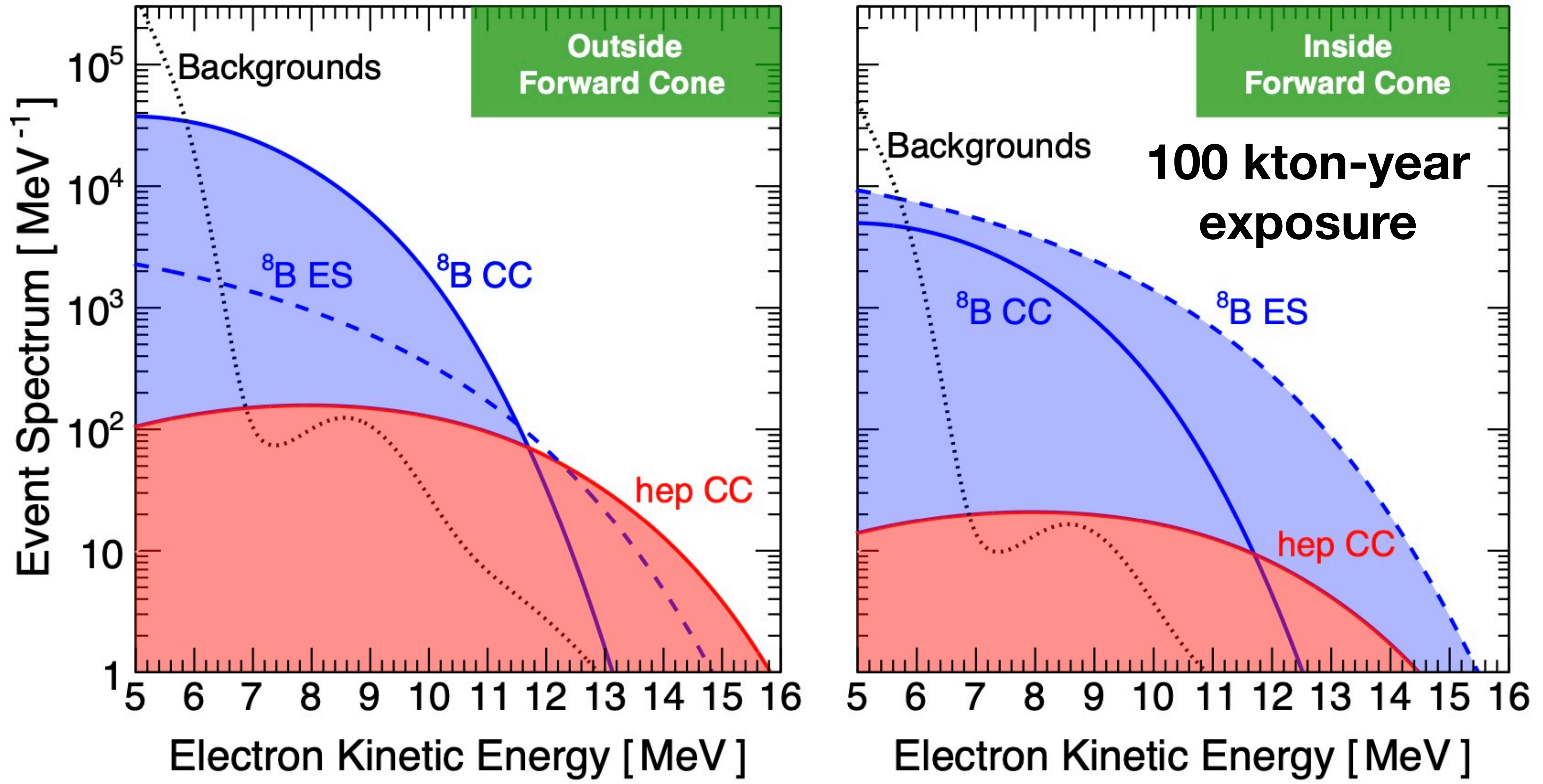


Solar neutrino physics potential of DUNE

Phys. Rev. Lett. 123, 131803

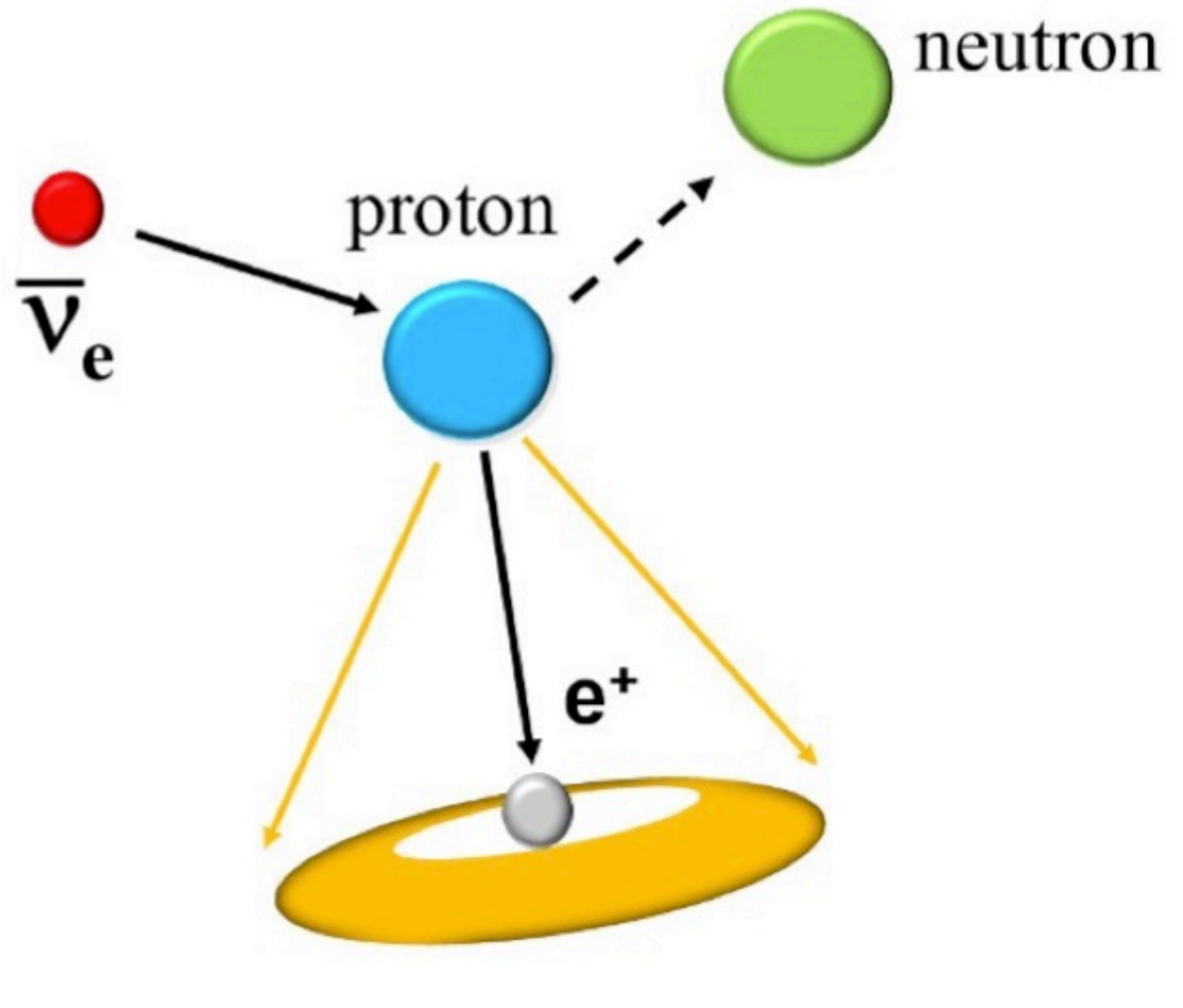
- Rate of ~100 events per day in 40 kton far detector
  - Triggering is a challenge
- 2σ tension between reactor and solar measurements of Δm^2_{21}
  - Potentially improved with DUNE
- Measure mixing parameters and $^8\mathrm{B}/\mathrm{hep}$ fluxes simultaneously
  - CC Ar and ν-e scattering





Modeling this physics is essential for neutrino calorimetry

IBD: e^+ sufficient to infer E_ν

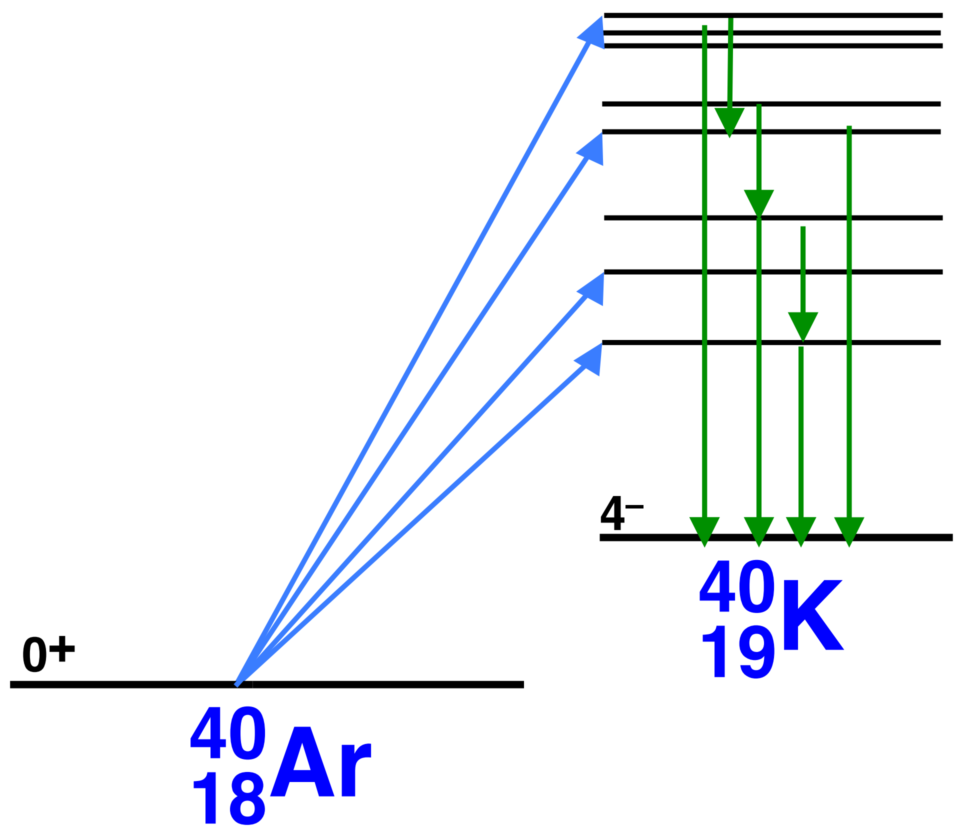


inverse beta decay

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

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

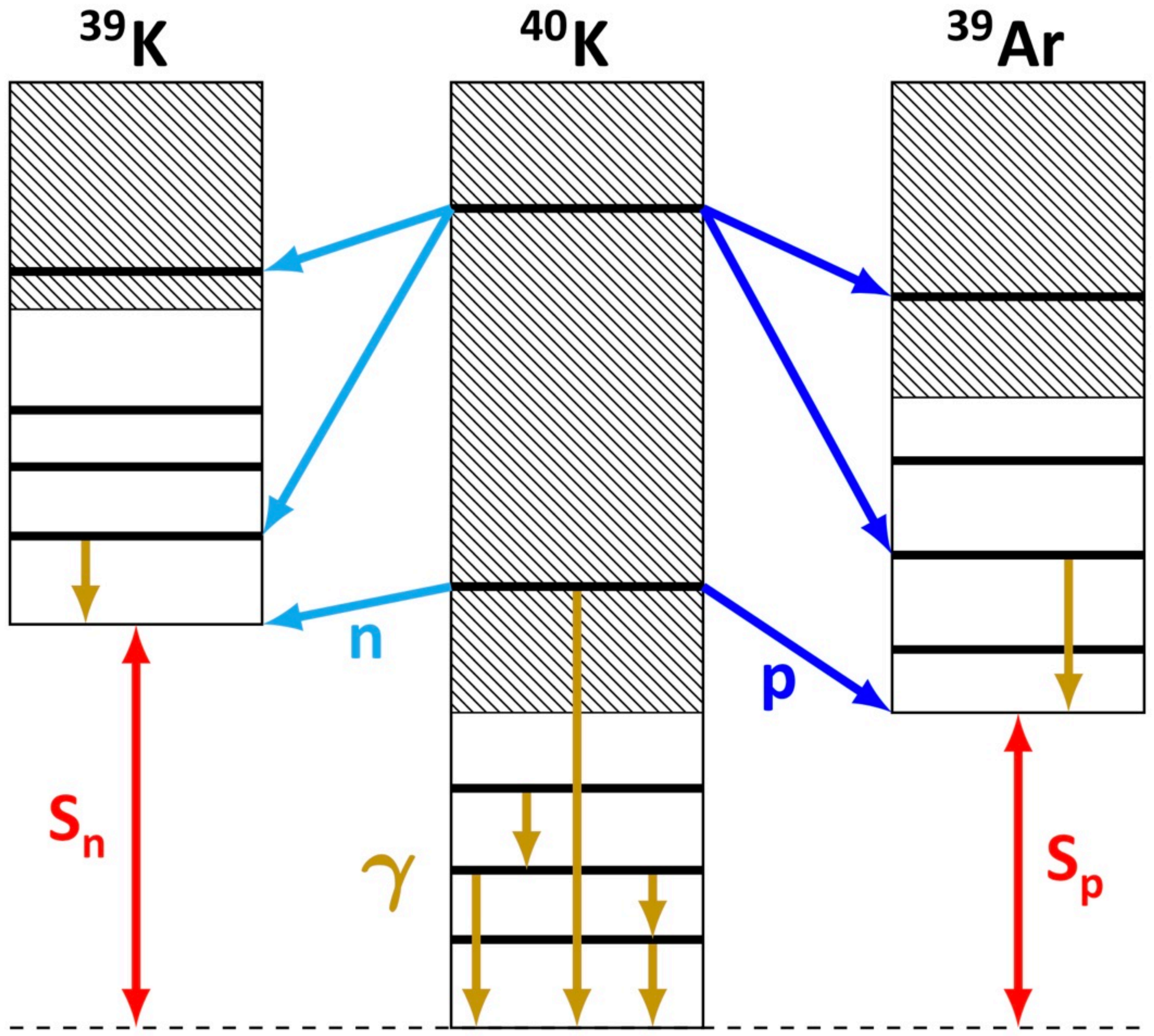
$$\nu_e + {}^{40}\text{Ar} \rightarrow {}^{40}\text{K}^* + e^-$$



ν-A is much more complex

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

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



Two-step approach

1. Nuclear transitions
2. De-excitations

MARLEY overview

- Event generator focused specifically on neutrino energies below ~100 MeV
- "Model of Argon Reaction Low Energy Yields"
  - Emphasizes ν_e CC on ^{40}Ar, extensible to other channels
- 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

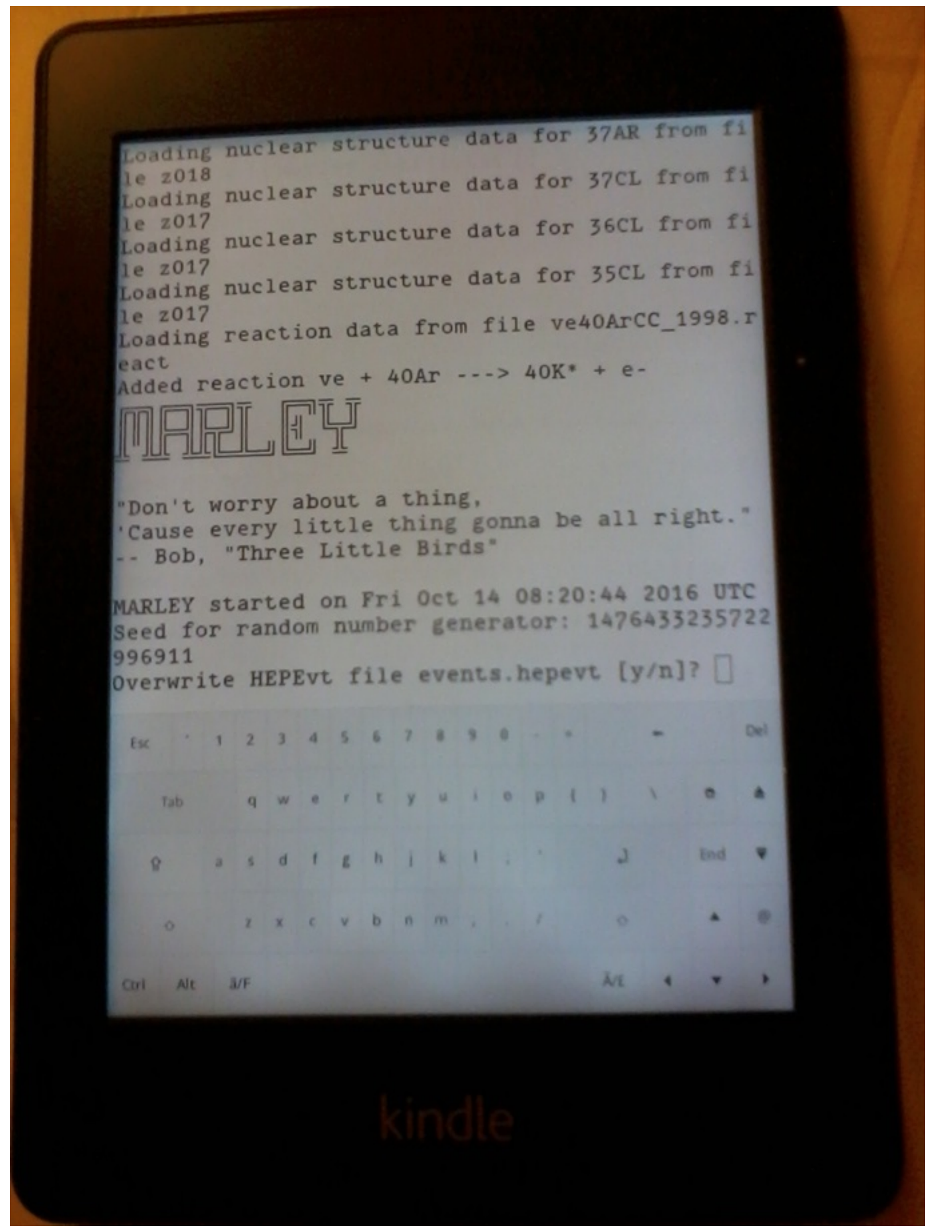
Steven Gardiner[1,2,*]
[1] Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510 USA
[2] Department of Physics, University of California, Davis, One Shields Avenue, Davis, California 95616 USA

(Dated: September 15, 2020)

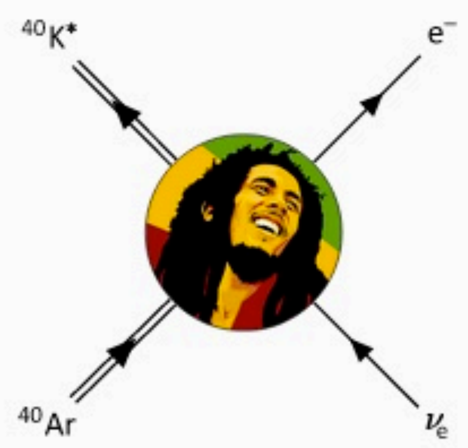
Background: Large argon-based neutrino detectors, such as those planned for the Deep Underground Neutrino Experiment (DUNE), have the potential to provide unique sensitivity to low-energy (~10 MeV) electron neutrinos produced by core-collapse supernovae. Despite their importance for neutrino energy reconstruction, 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}Ar$(\nu_e, e^-)^{40}$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

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

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

MARLEY v1.2.0 predictions for ^{40}Ar

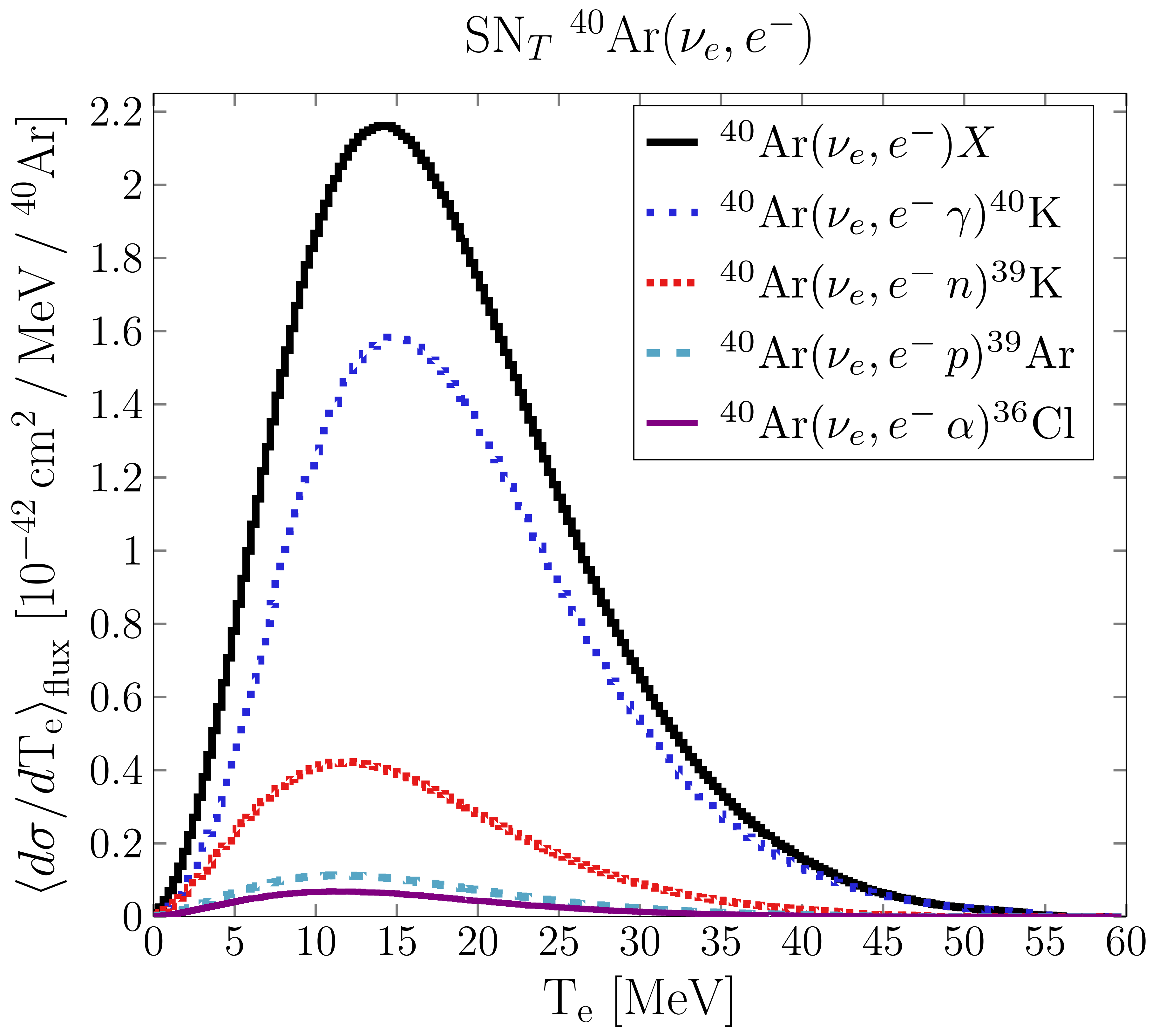
[Phys. Rev. C 103, 044604 (2021)]

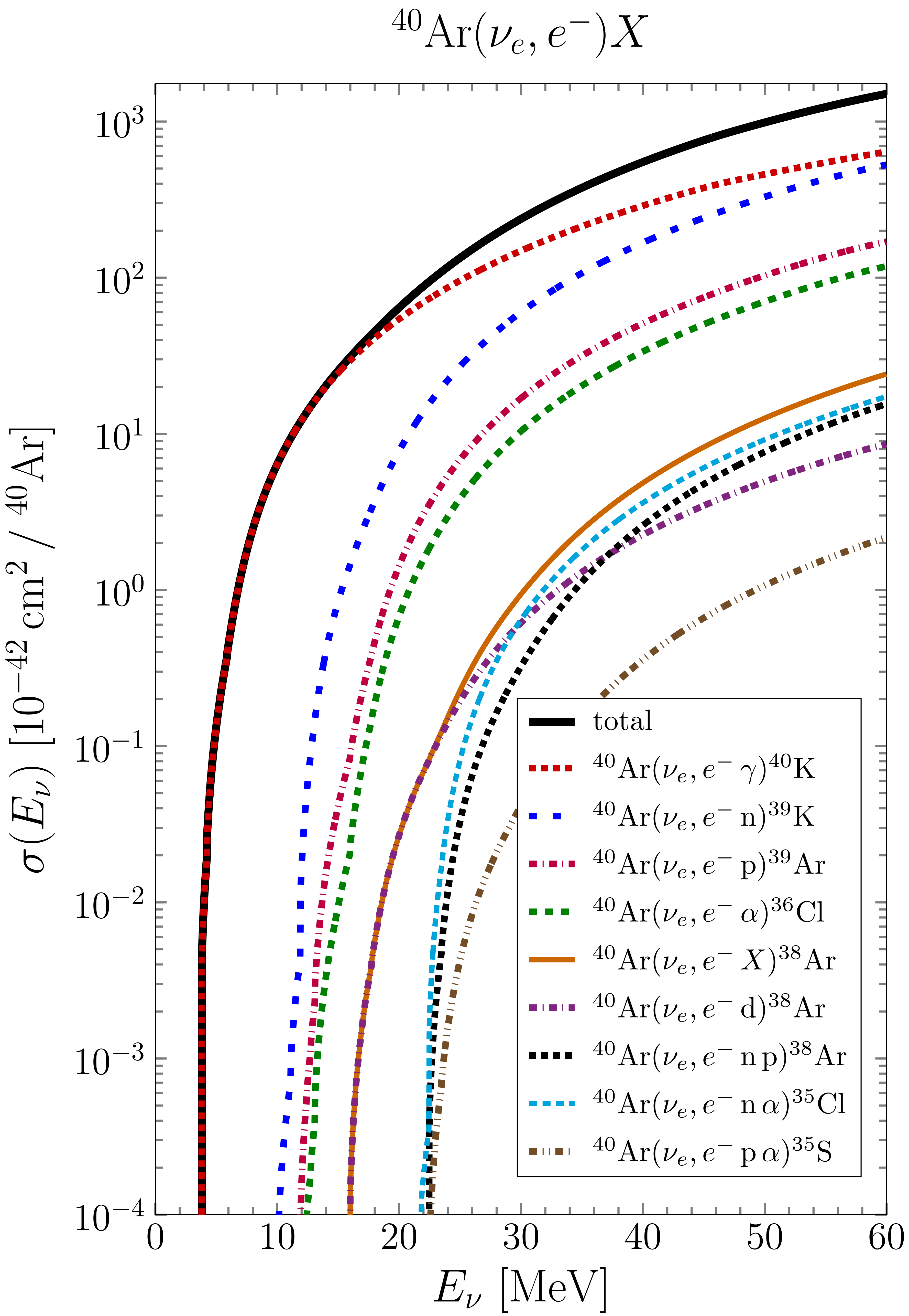
- First calculation of cross sections for **exclusive final states** of the reaction

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

at tens-of-MeV energies.

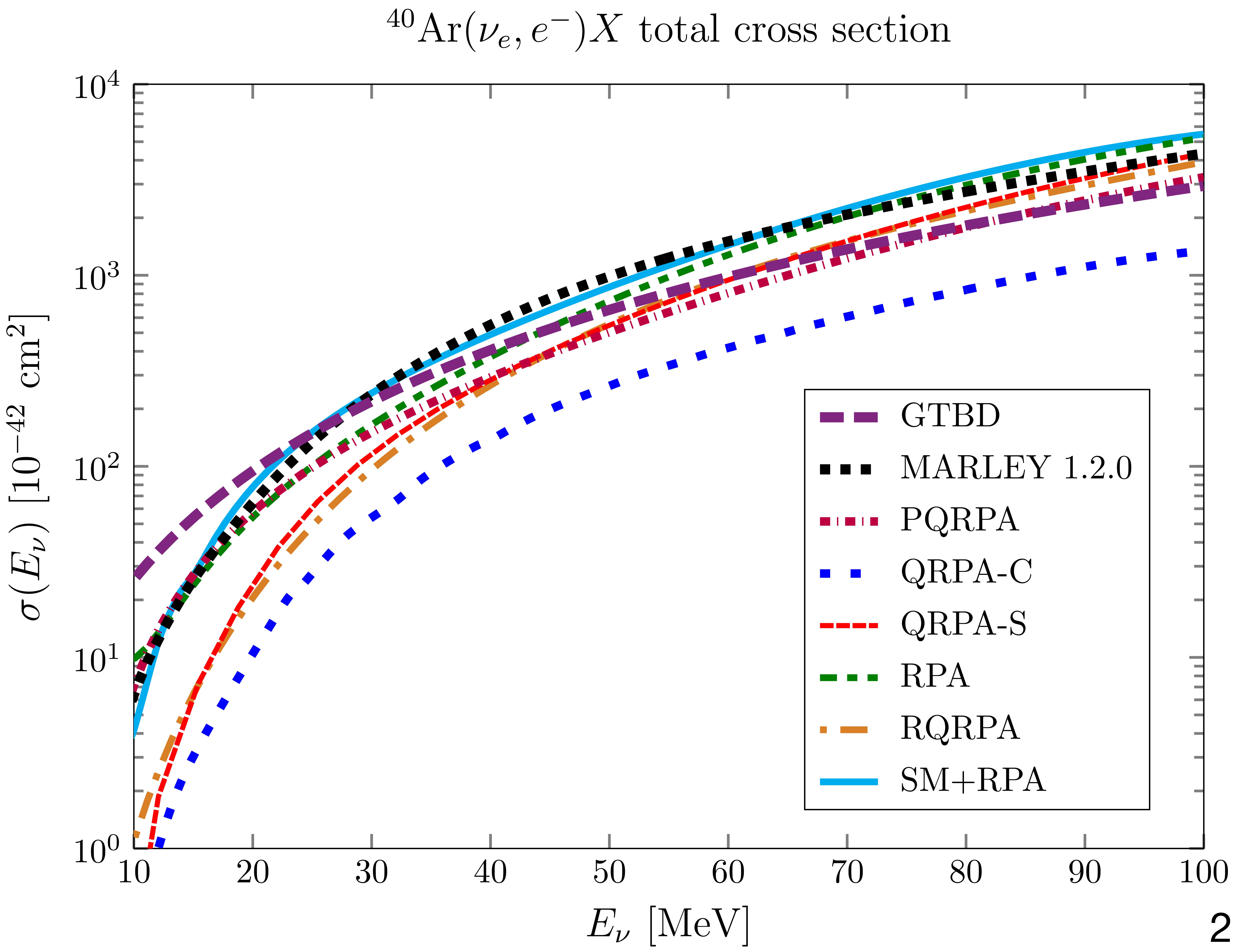
- Flux-averaged differential cross sections shown here are for the supernova model described in [Phys. Rev. D 97, 023019 (2018)].





MARLEY comparison to other calculations

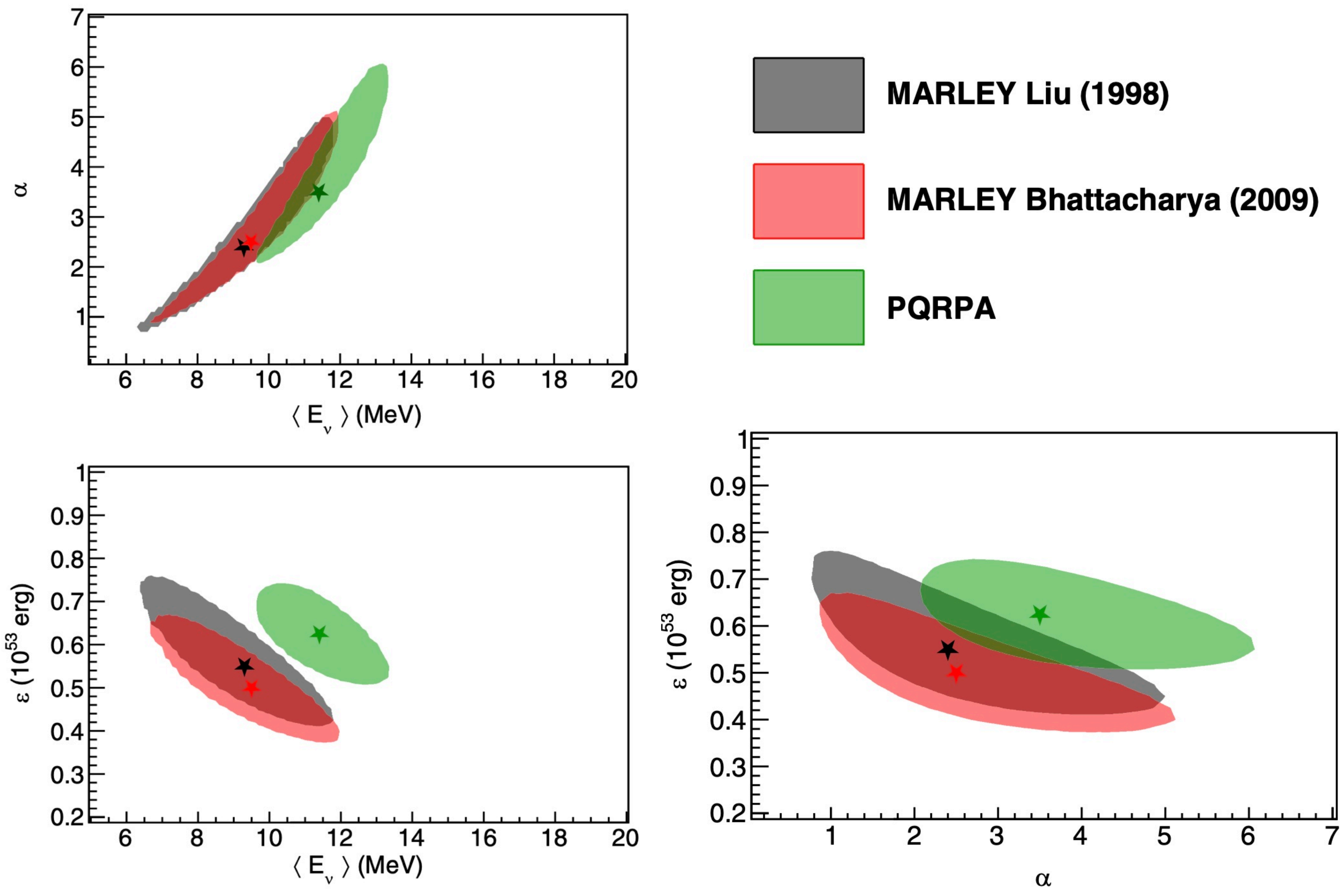
- Significant model disagreements
- No measurements of this important channel below 100 MeV
- Constraining theory uncertainty will be critical for DUNE



Low-energy cross-section uncertainties

Phys. Rev. D 107, 112012 (2023)

- **Toy analysis** seeks to extract flux parameters from simulated DUNE supernova neutrino data
- ε = energy release (erg)
- $\langle E_\nu \rangle$ = mean neutrino energy (MeV)
- α = shape parameter (dimensionless)



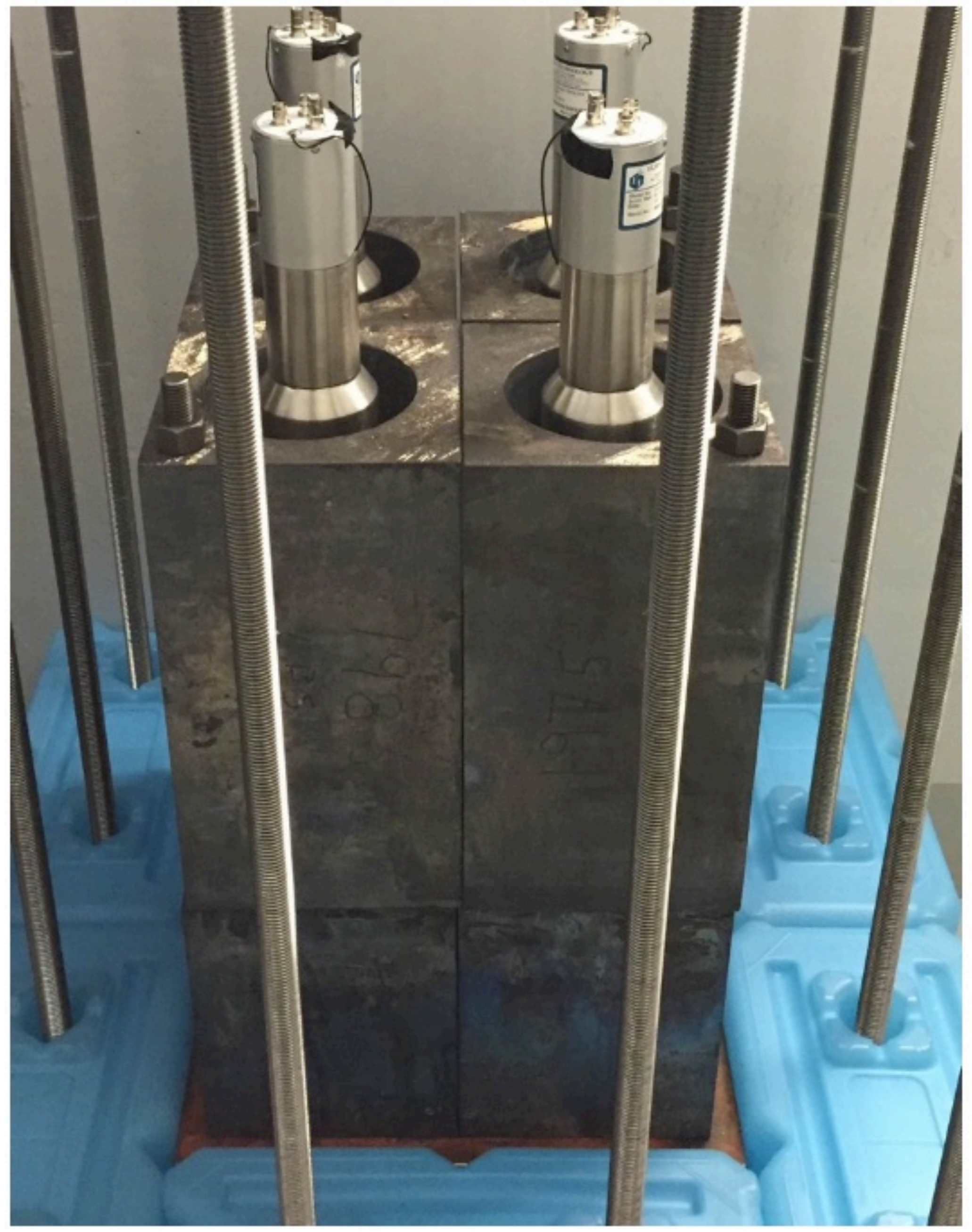
Current understanding of $\sigma(E_\nu)$ is **inadequate.**

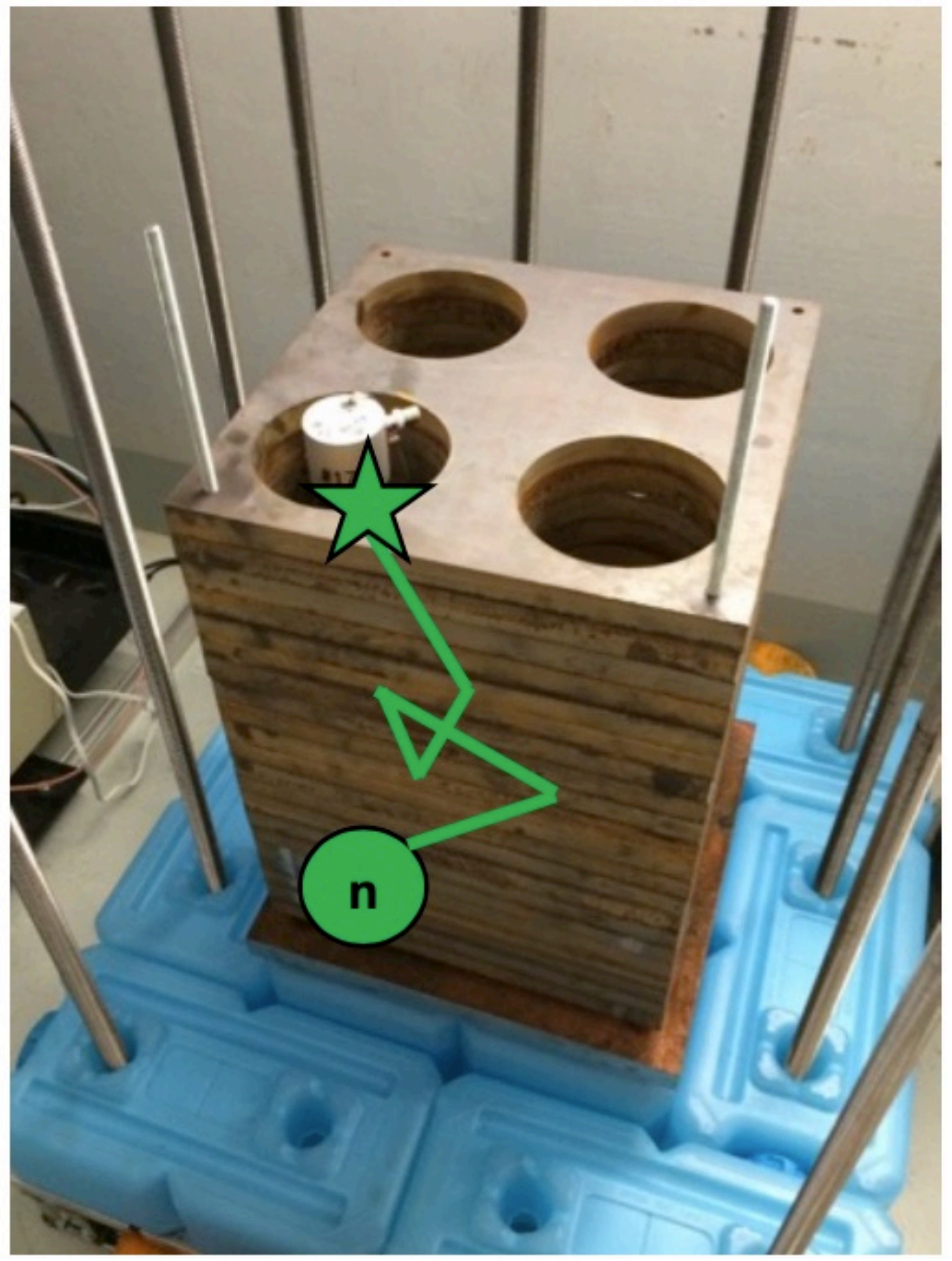
Measuring ε (other parameters) to 10% requires 5% (20%) knowledge of the cross section!

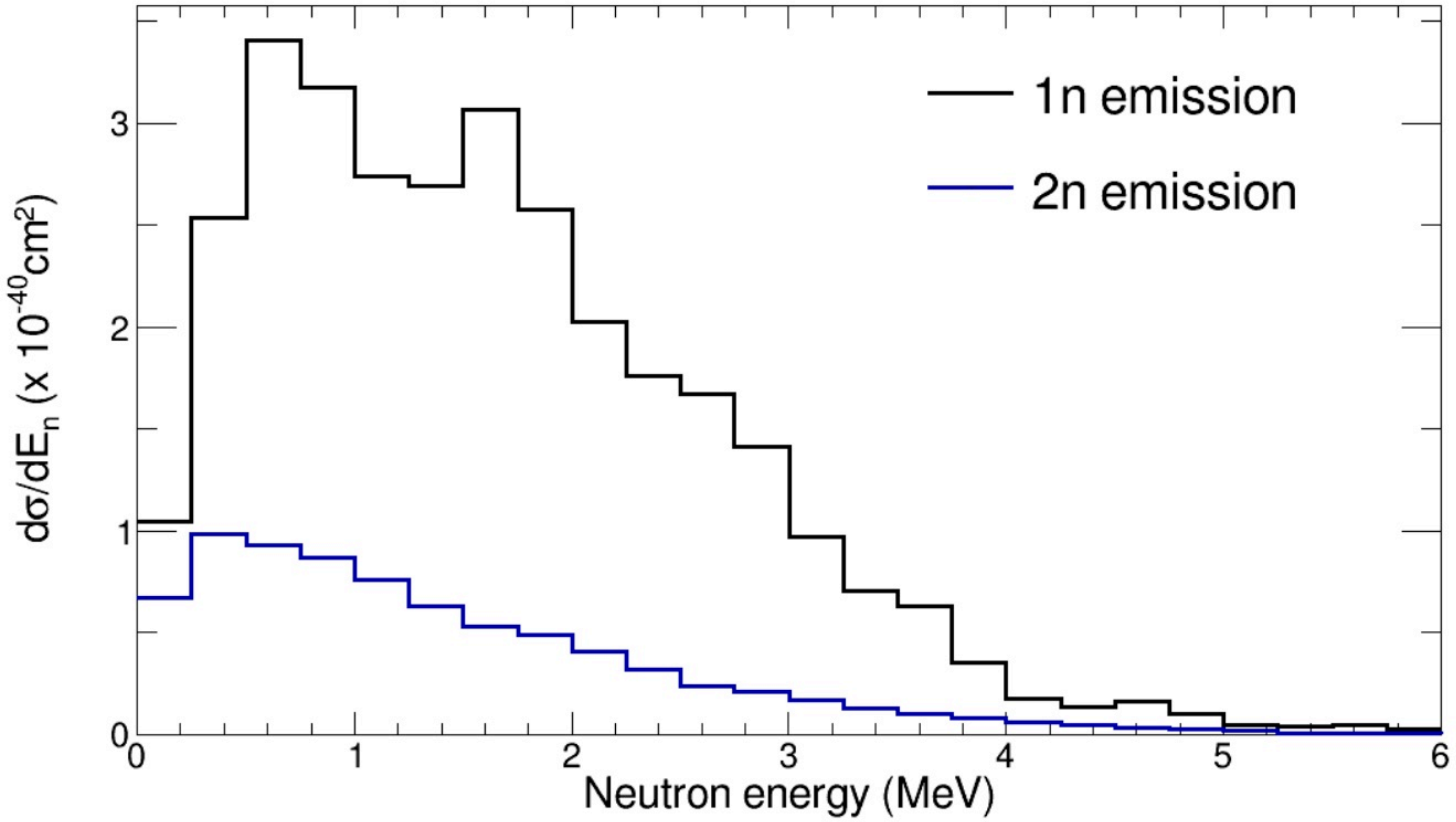
First indirect constraints from COHERENT [Phys. Rev. D 108, 072001 (2023)]

- Measurement of **neutrino-induced neutrons** at ORNL Spallation Neutron Source
  - Supernova-like neutrinos from muon decay at rest

- Lead target, neutrons detected using liquid scintillator



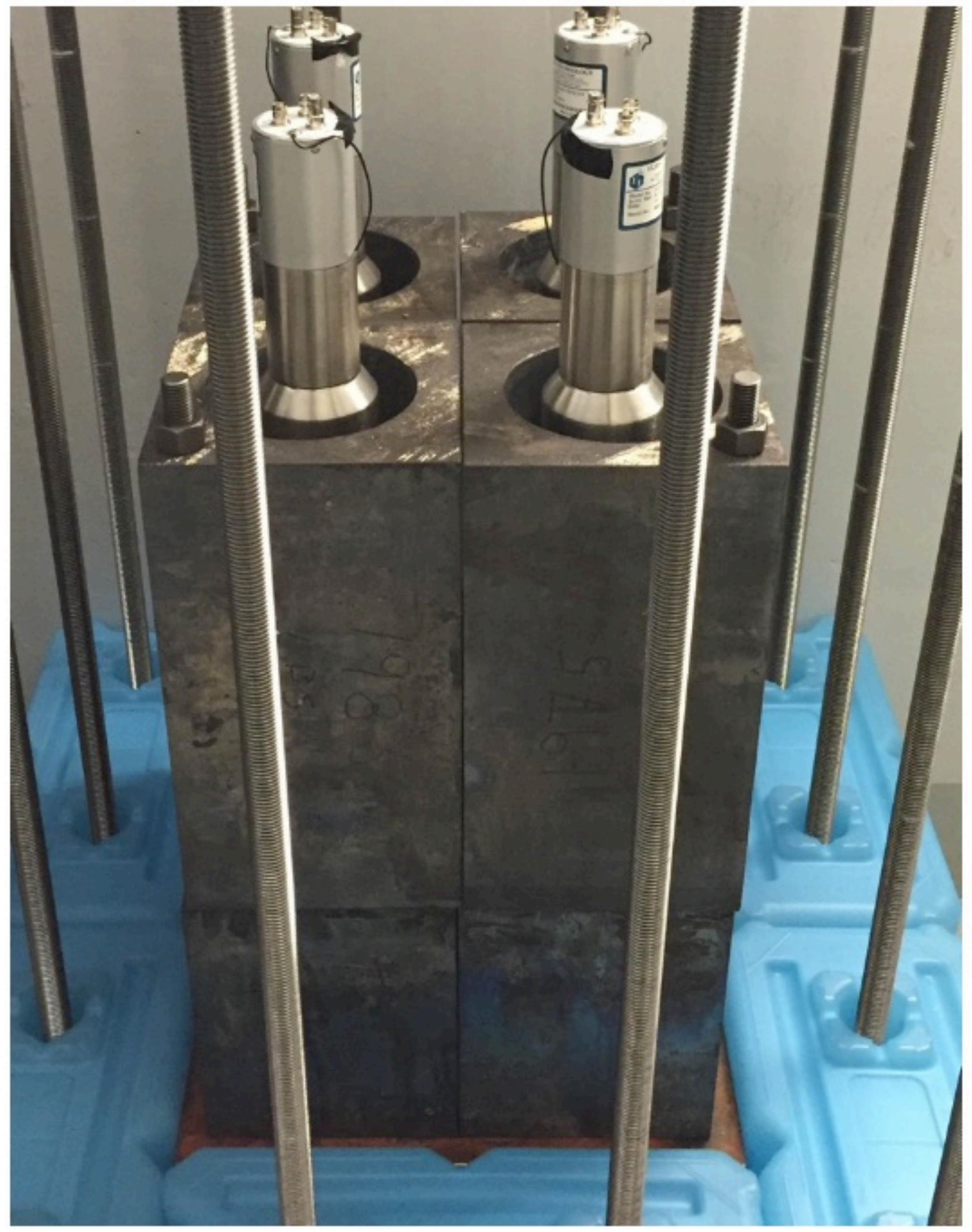


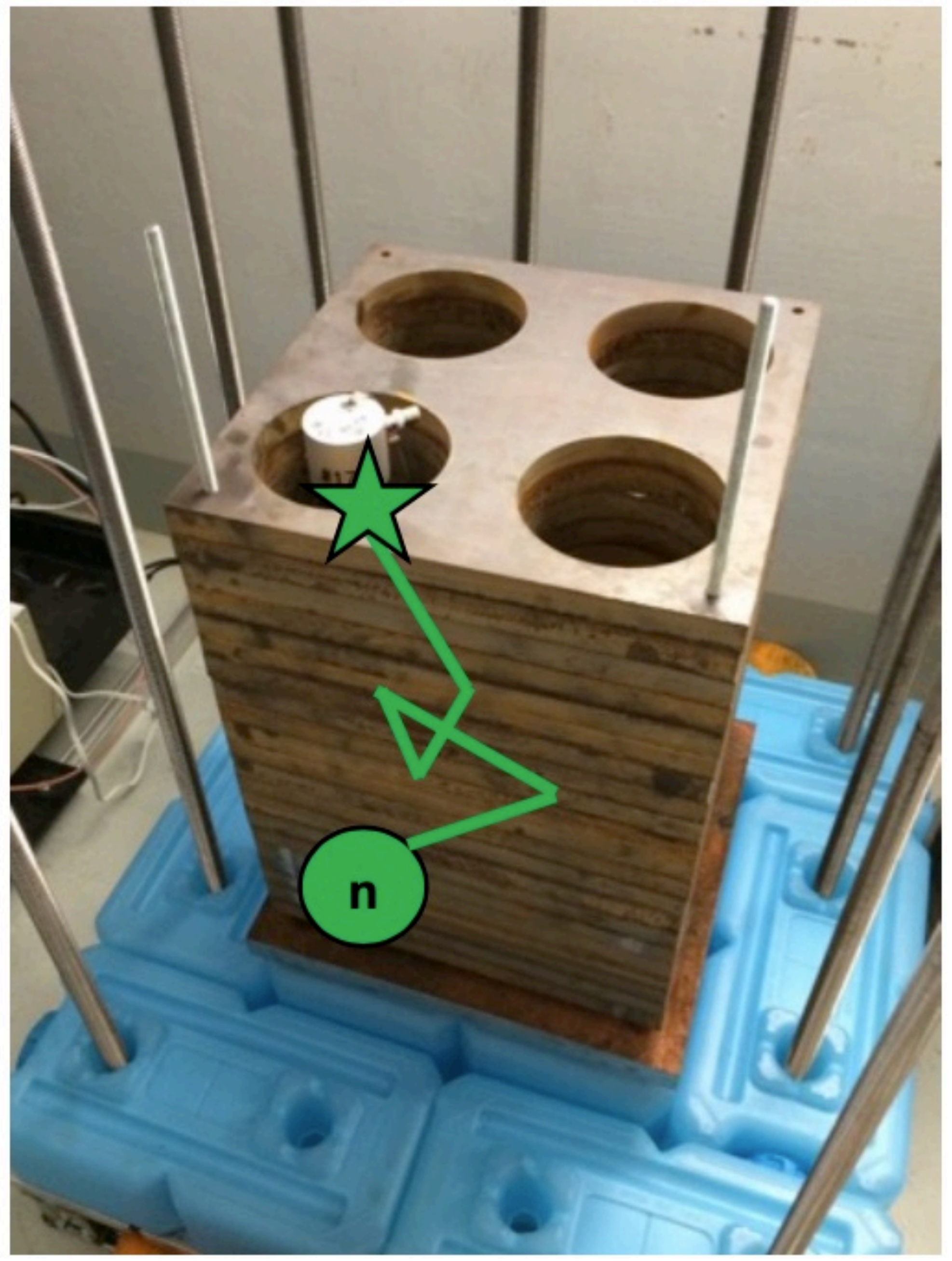


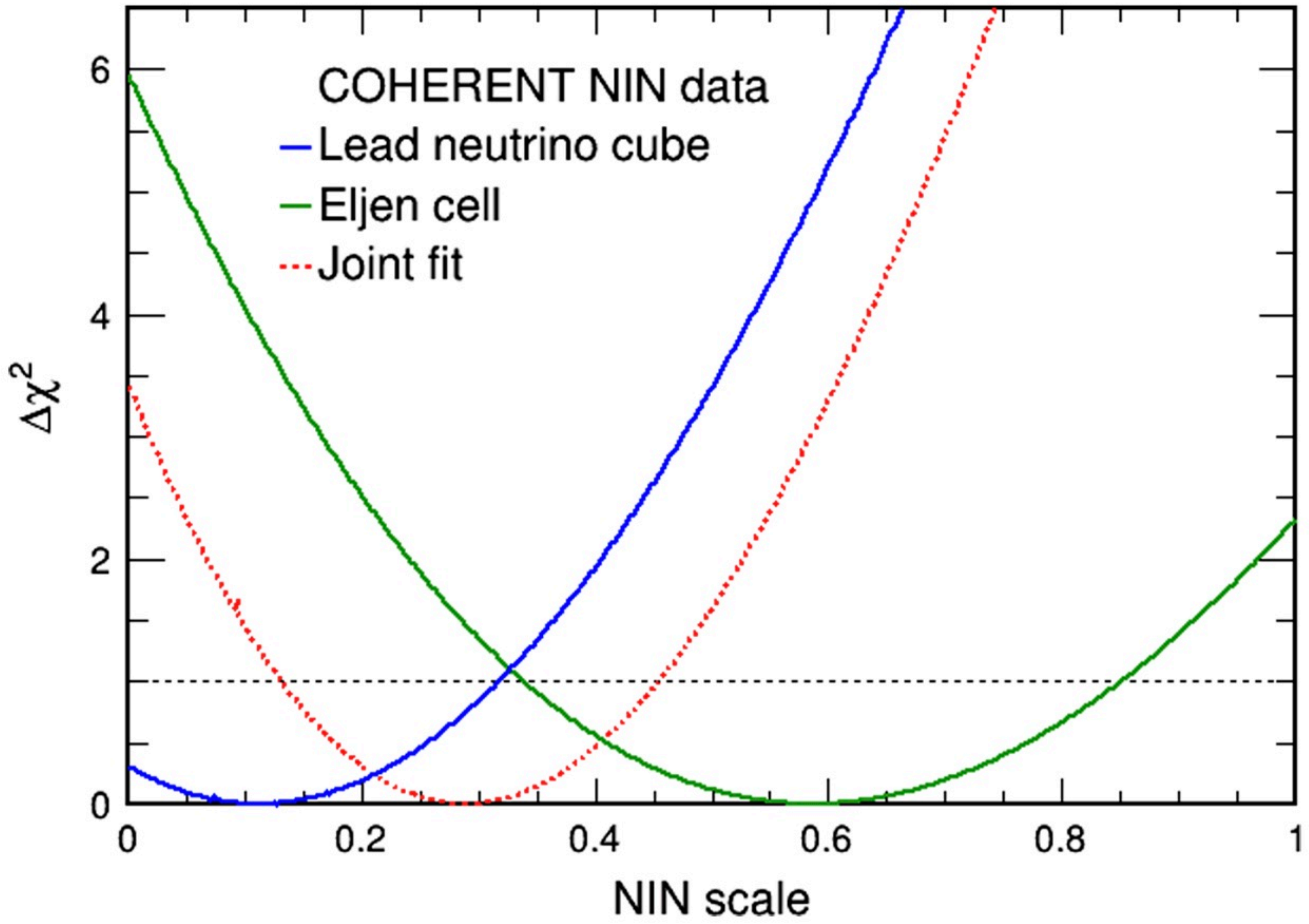
First indirect constraints from COHERENT

Phys. Rev. D 108, 072001 (2023)

- Measurement of **neutrino-induced neutrons** at ORNL Spallation Neutron Source
  - Supernova-like neutrinos from muon decay at rest
- Lead target, neutrons detected using liquid scintillator
- **Best fit to data:** $0.29^{+0.17}_{-0.16}$ times MARLEY prediction
  - 4-sigma tension!
  - Implications for DUNE **ambiguous**, worthy of further exploration!





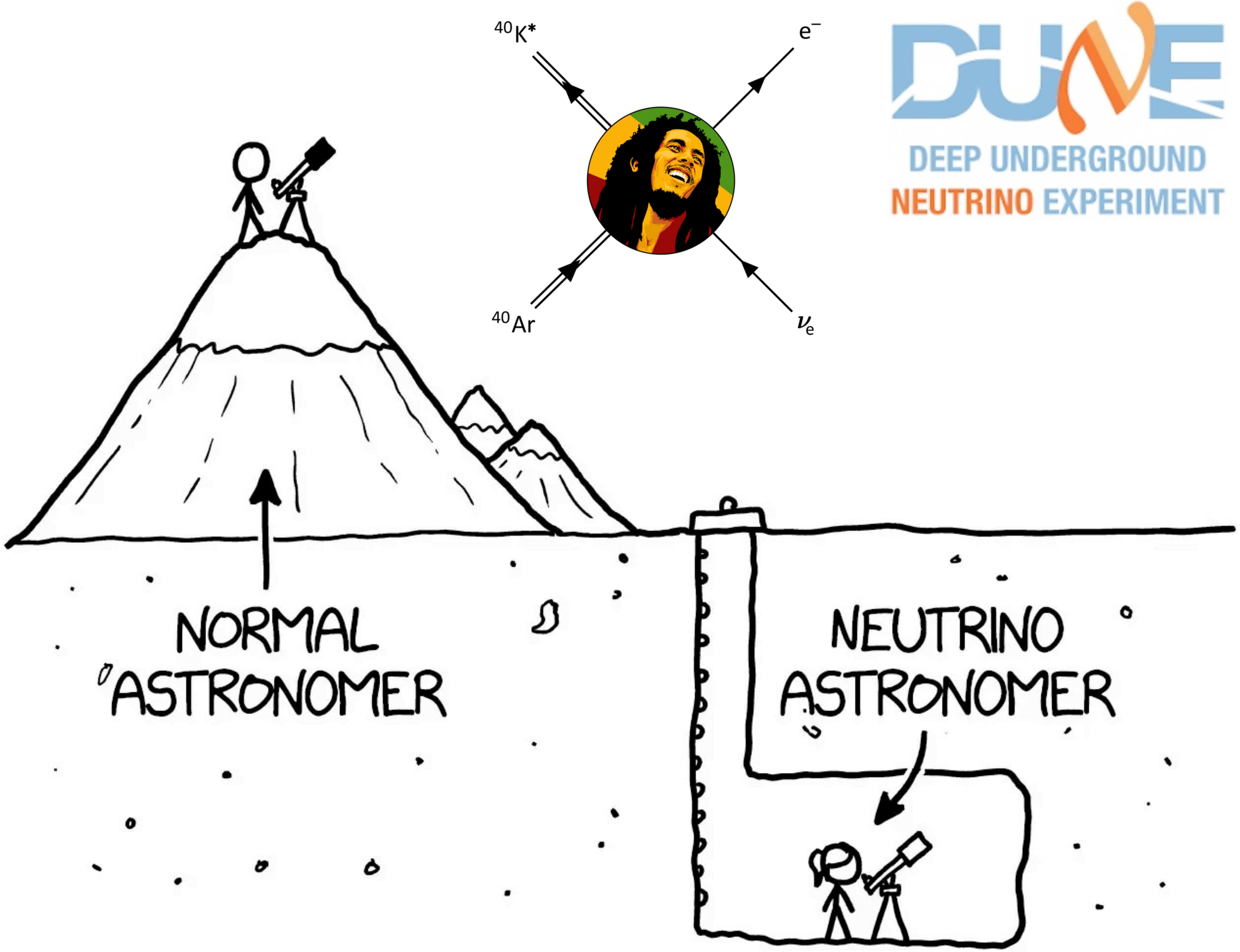


Conclusion

- DUNE has exciting potential to expand our understanding of the cosmos using supernova and solar neutrinos

- Nuclear interaction modeling is challenging but essential for robust interpretation of the data

- Work is ongoing to lay a foundation for future success of the program



Backup