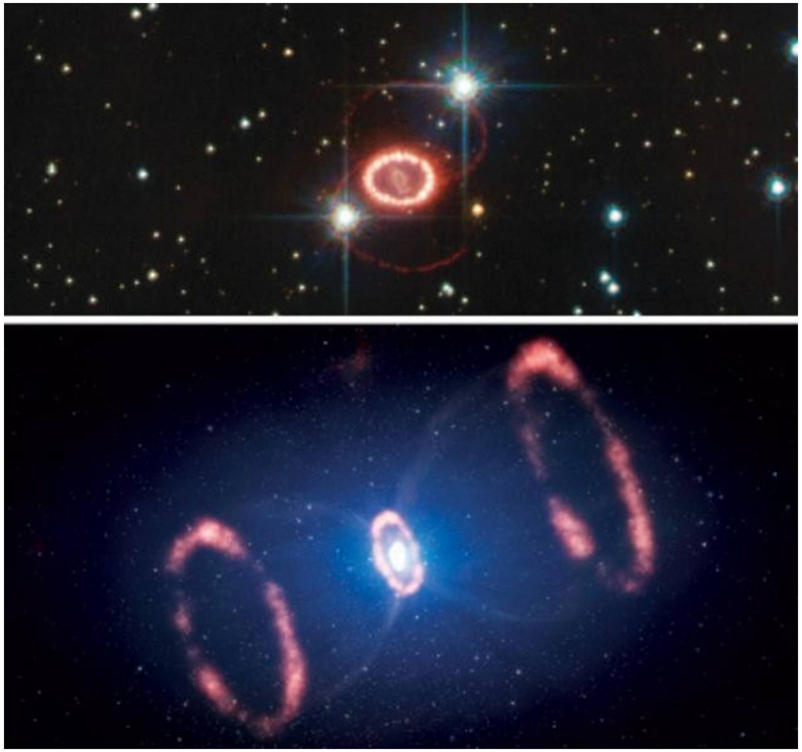
Understanding ν_e-argon cross sections with MARLEY



Steven Gardiner

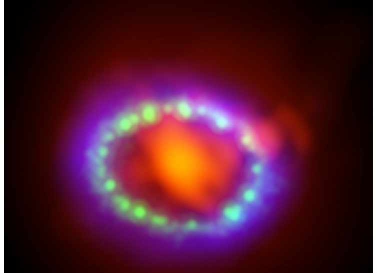
Workshop on Fundamental Physics
at the Second Target Station

Oak Ridge National Laboratory

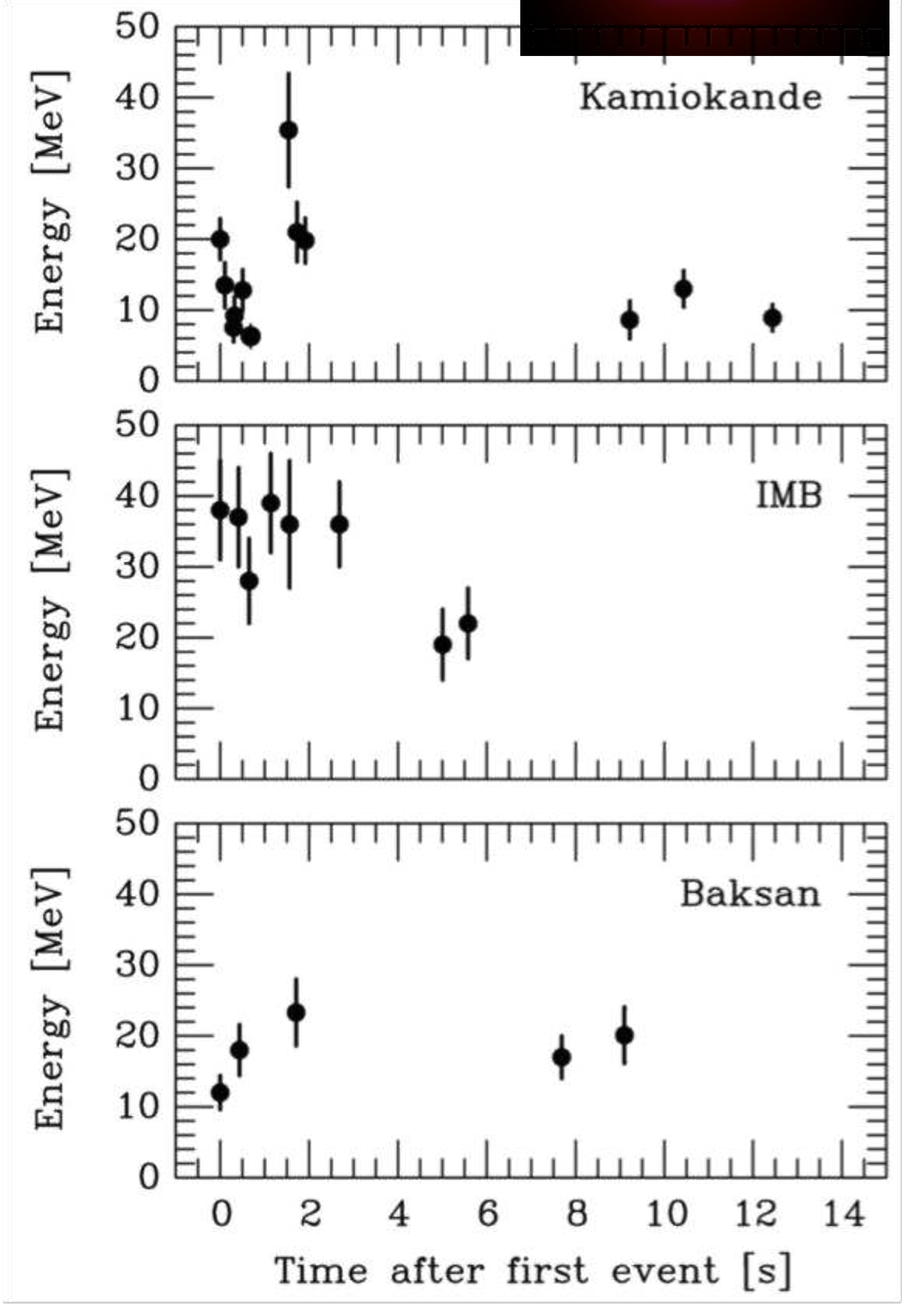
27 July 2019

Fermilab

Supernova 1987A



- 25 antineutrinos detected in 13 s
- **Only experimental observation to date**
- Three detectors involved
  - Kamiokande-II (WC)
  - Irvine-Michigan-Brookhaven (WC)
  - Baksan underground scintillation telescope (liquid scintillator)
- Confirmed basic picture of core-collapse SN
- A high-statistics SN measurement would be exciting
  - Core-collapse dynamics & nucleosynthesis
  - Neutrinos under extreme conditions
  - Exotic physics searches
- Complementary to gravitational wave and optical observations



Neutrinos provide a “window” into supernova physics

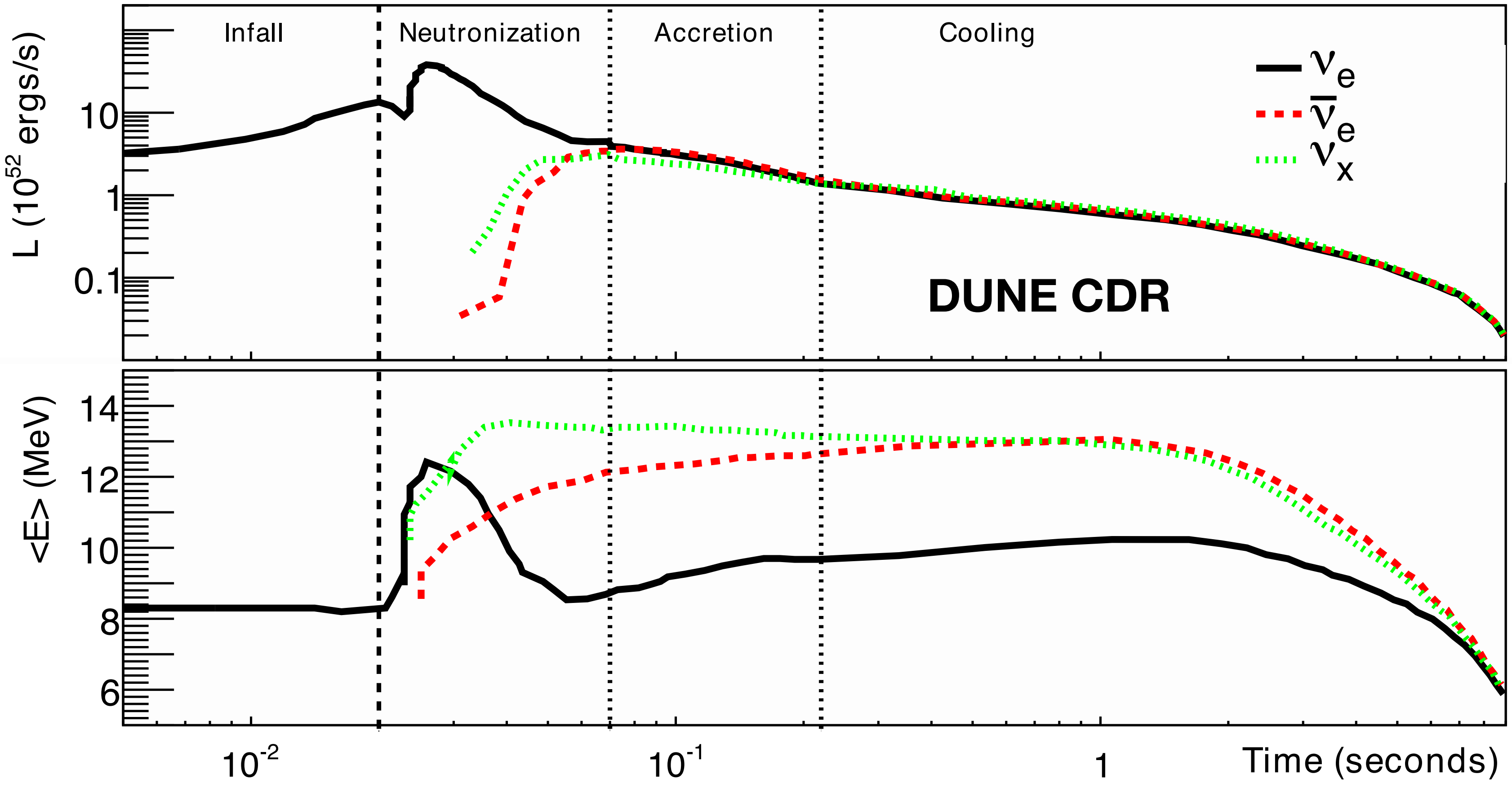
- Exciting supernova physics comes to us **encoded in the supernova ν flux**

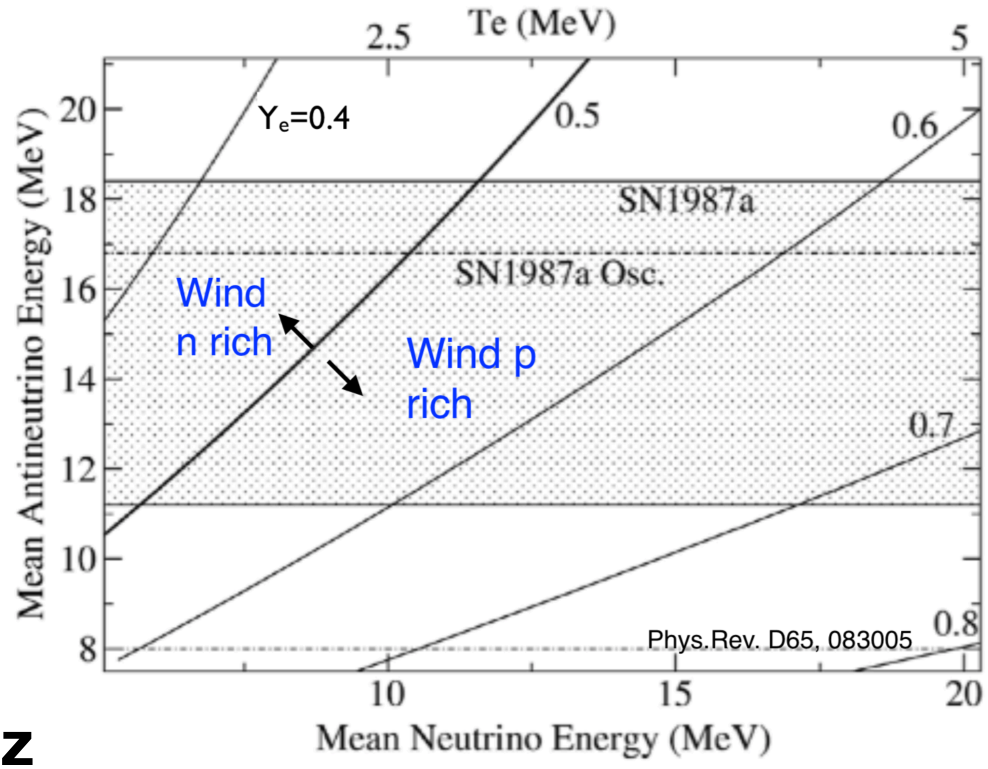
  - Nucleosynthesis
  - Collapse dynamics
  - BSM processes
  - Collective oscillations
  - Etc.

- **Key observables**:
  - Energy
  - Flavor
  - Time

- Energy is particularly tricky. It has to be **inferred** from what we see in our detector

  - We will revisit this point in a moment





Super-K

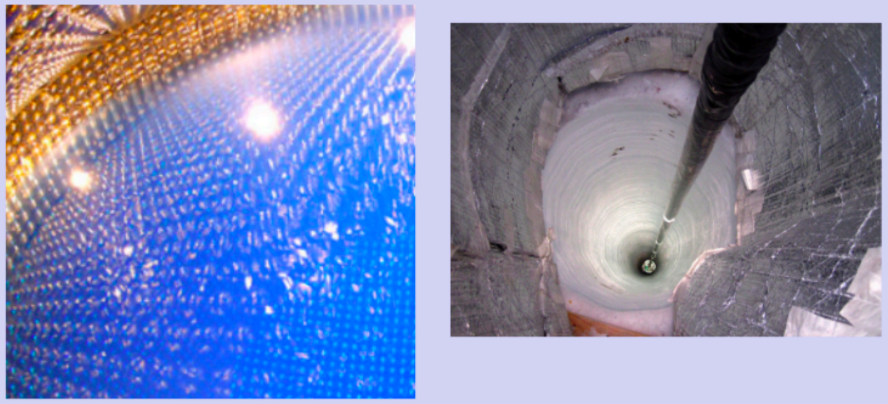
C. Horowitz

DUNE

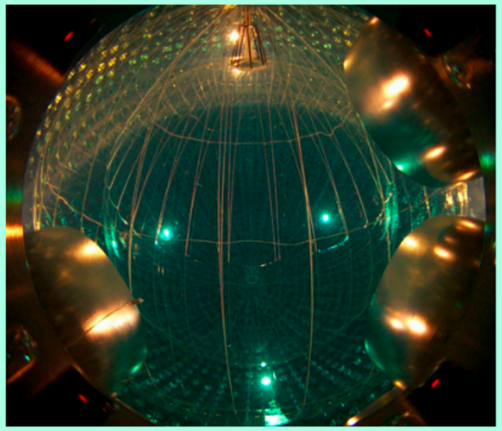
Current main supernova neutrino detector types

K. Scholberg

Water



Scintillator



Argon

Lead

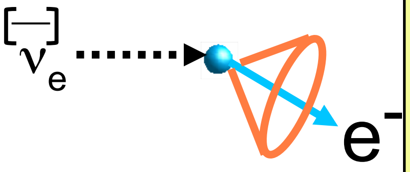
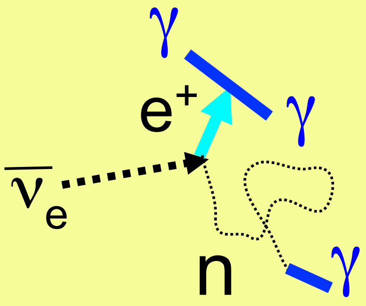
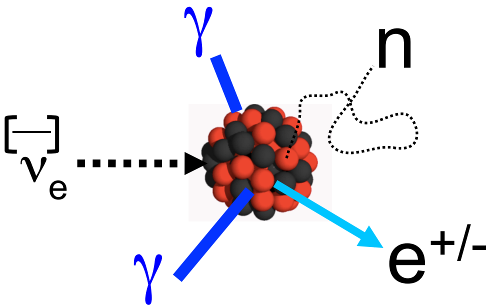
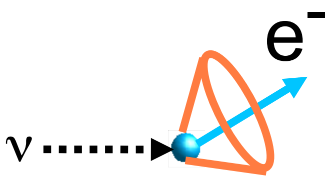
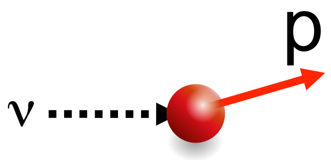
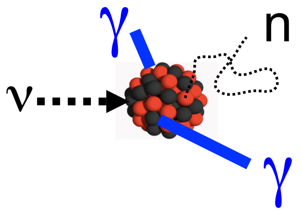
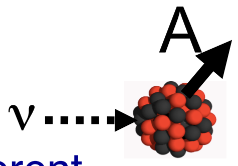
+ some others (e.g. DM detectors)

All have a role to play in maximizing the physics potential of the next supernova observation

In this talk, however, I’ll focus on argon, using water for contrast

Supernova-relevant neutrino interactions

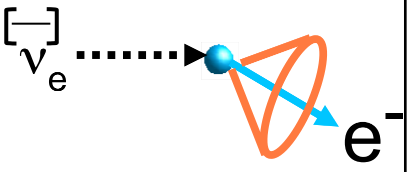
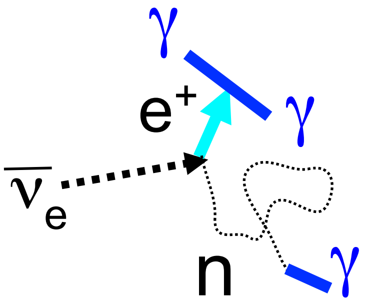
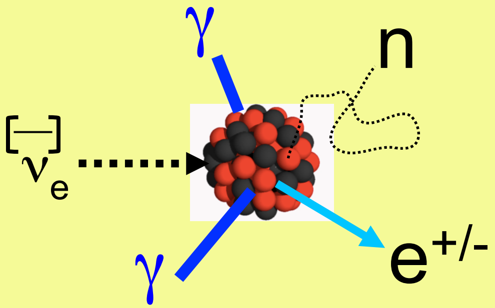
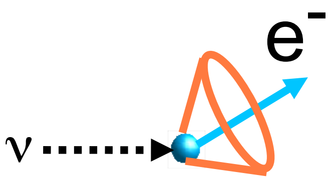
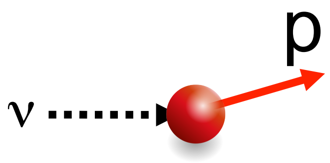
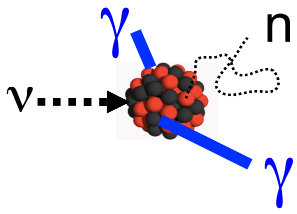
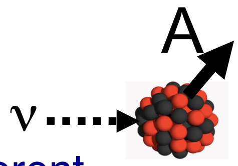
K. Scholberg

	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)

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

Supernova-relevant neutrino interactions

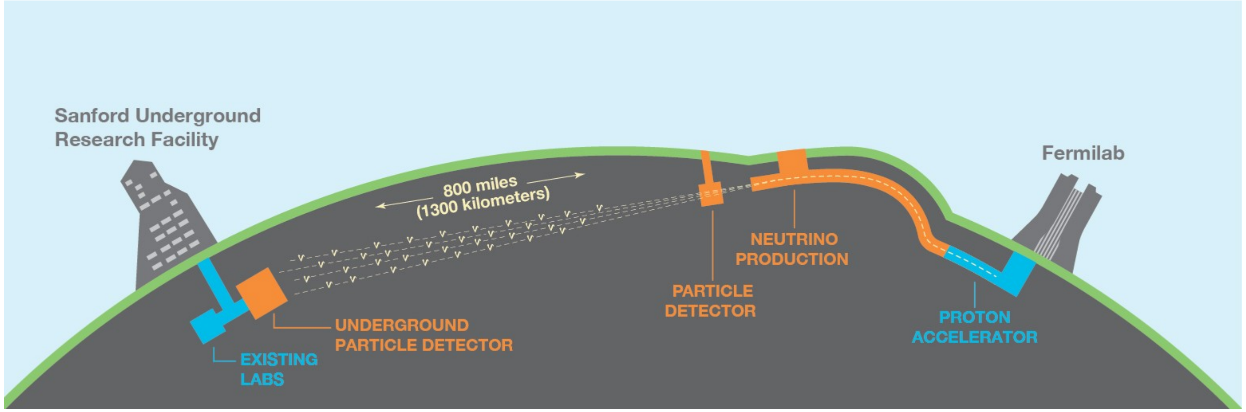
K. Scholberg

	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!

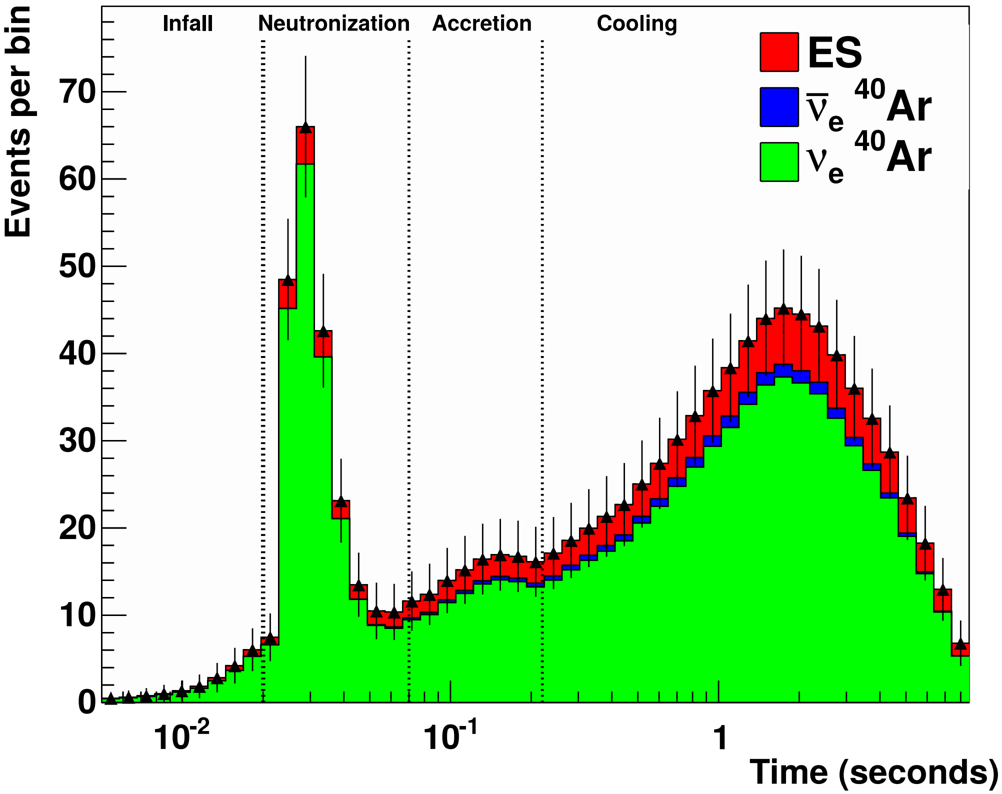
Supernova neutrinos and DUNE

One of DUNE's primary science goals is to measure "the ν_e flux from a core-collapse supernova within our galaxy, should one occur during the lifetime of the DUNE experiment" – DUNE CDR

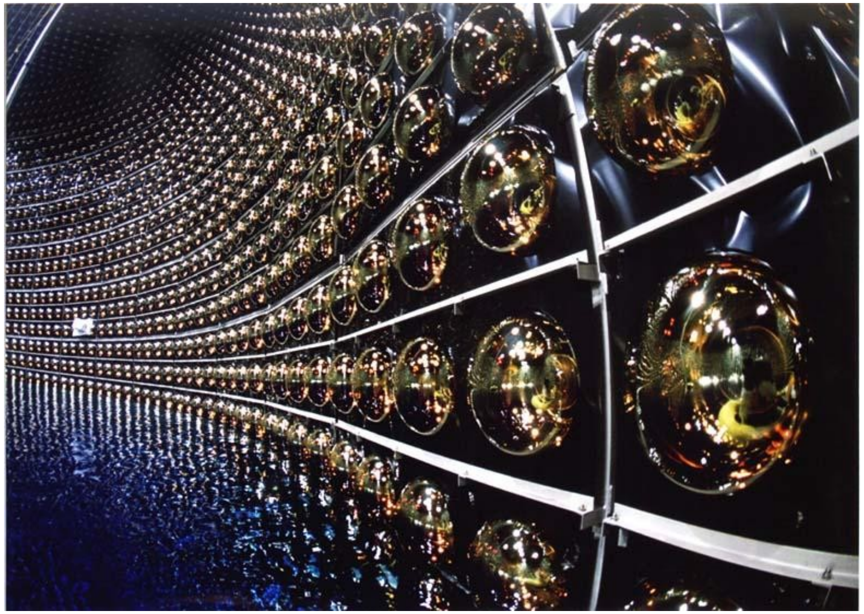


- **LArTPCs provide unique ν_e sensitivity**
  - Complementary to other SN neutrino detectors
- Other low-energy measurements may be possible (e.g., solar neutrinos)
- SN sensitivity is an important design consideration
- See talks by J. Raaf & I. Lepetic for more discussion of LArTPC technology

Time distribution of supernova neutrino events in DUNE



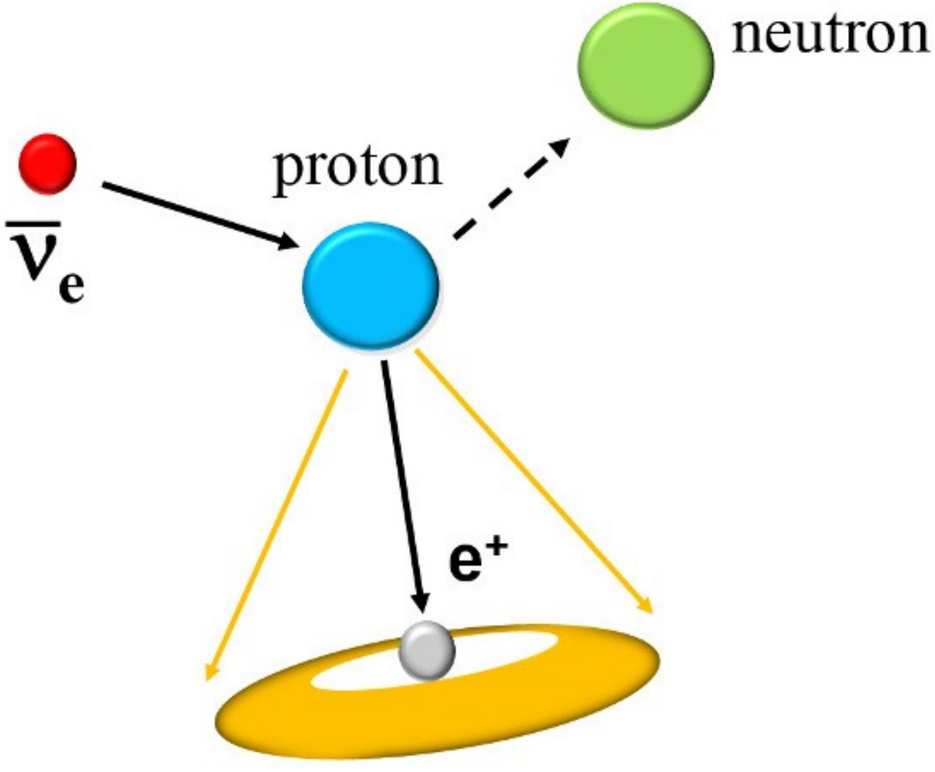
Supernova neutrino detection with water Cherenkov detectors



- Pure water instrumented with photomultipliers
- Primary reaction mode: "inverse beta decay"
- Positron detected using Cherenkov radiation
- Tag neutron to discriminate against other reaction channels
  - Loading water with Gd improves efficiency

Reconstructing true antineutrino energy:

$$E_{\bar{\nu}} = \overset{\text{Outgoing } e^+ \text{ energy}}{E_e} + \overset{\text{Neutron proton mass difference}}{\Delta} + \overset{\text{Recoil energy of neutron (negligible)}}{K_{\text{recoil}}}$$

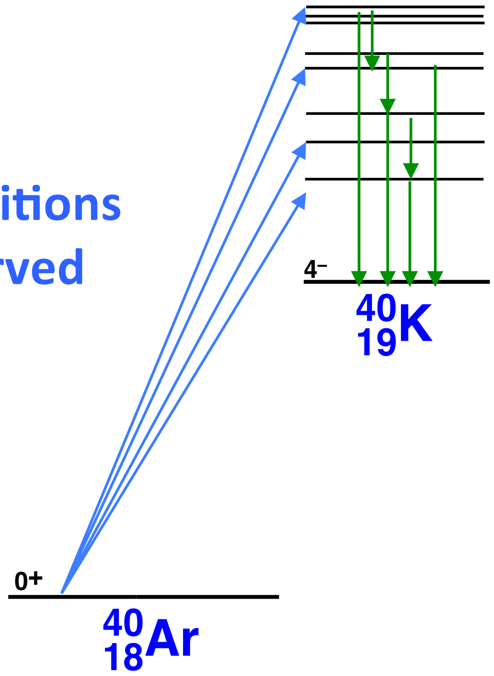


inverse beta decay

Supernova neutrino detection in liquid argon

Charged-current absorption:

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



At least 25 transitions have been observed indirectly

Transition levels are determined by observing de-excitations (γ's and nucleons)

Transitions to particle-unbound levels occur with many competing de-excitation channels

Large uncertainties in nuclear data and models complicate energy reconstruction

Reconstructing true neutrino energy:

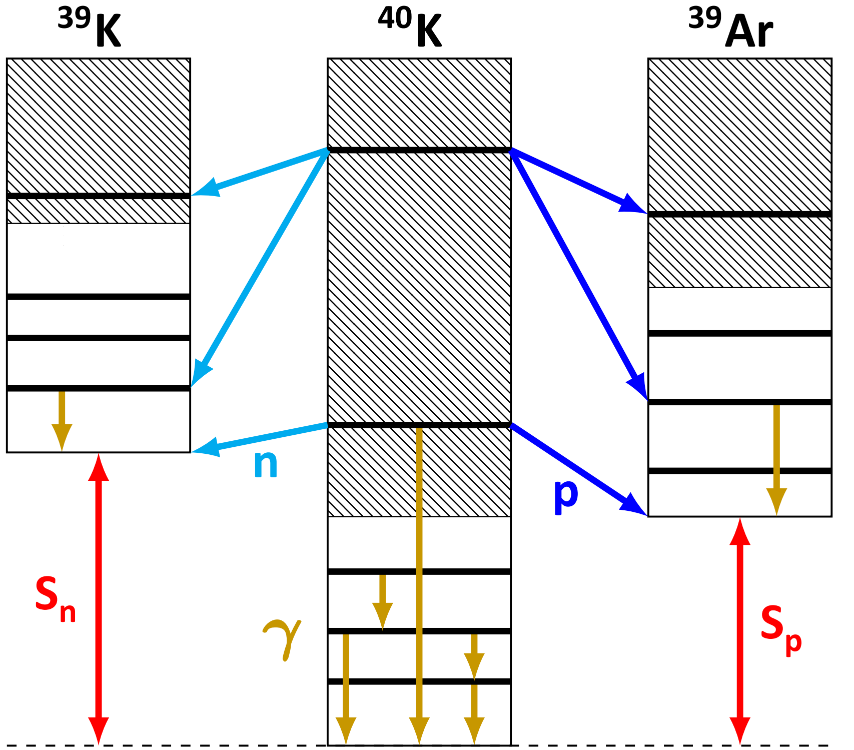
Q is determined by measuring de-excitation gammas and nucleons

Outgoing e^- Energy

Energy donated to transition

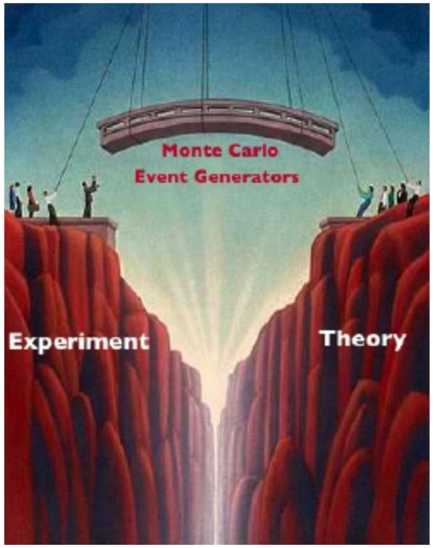
Recoil Energy of Nucleus (negligible)

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



How do oscillation experiments handle this problem?

- Generators are an essential tool to help relate observed event topologies to the neutrino energy
  - Detailed simulations provide “fake data” used to understand energy resolution, efficiencies, etc.
  - Hard work to understand systematic errors
- GENIE, GiBUU, NEUT, and NuWro typically used at accelerator energies (100s of MeV and above)
- Standard physics treatment designed for these energies: what differences might be important at tens-of-MeV?



NuWro
Wroclaw Neutrino Event Generator

GiBUU

Genie
UNIVERSAL NEUTRINO GENERATOR
& GLOBAL FIT

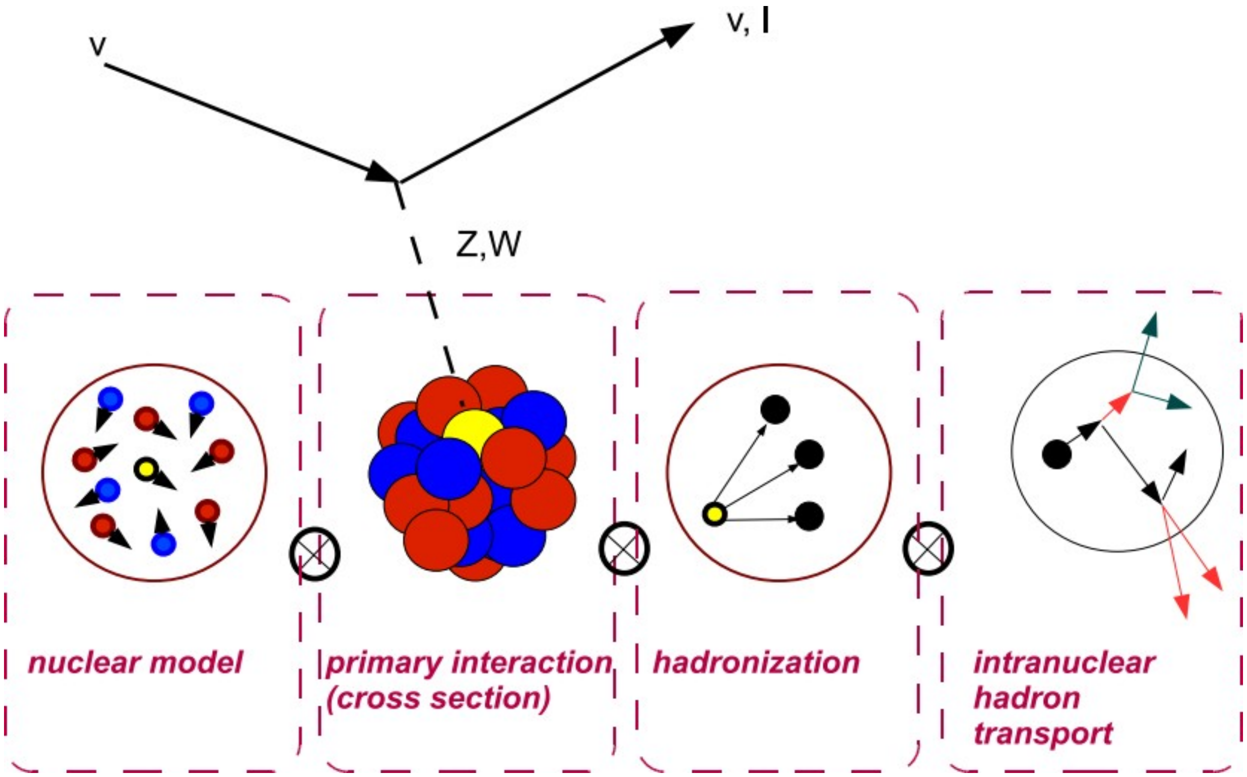
C. Andreopoulos

Can we play the same game for supernova neutrinos?

- Trouble starts when we consider how the physical picture changes for low energy neutrinos

- At high energies, neutrino-nucleus scattering is described as a **direct reaction**: the neutrino scatters on a single nucleon (or a pair of nucleons) inside the nucleus

“Traditional” factorization scheme for generators at accelerator energies



Can we play the same game for supernova neutrinos?

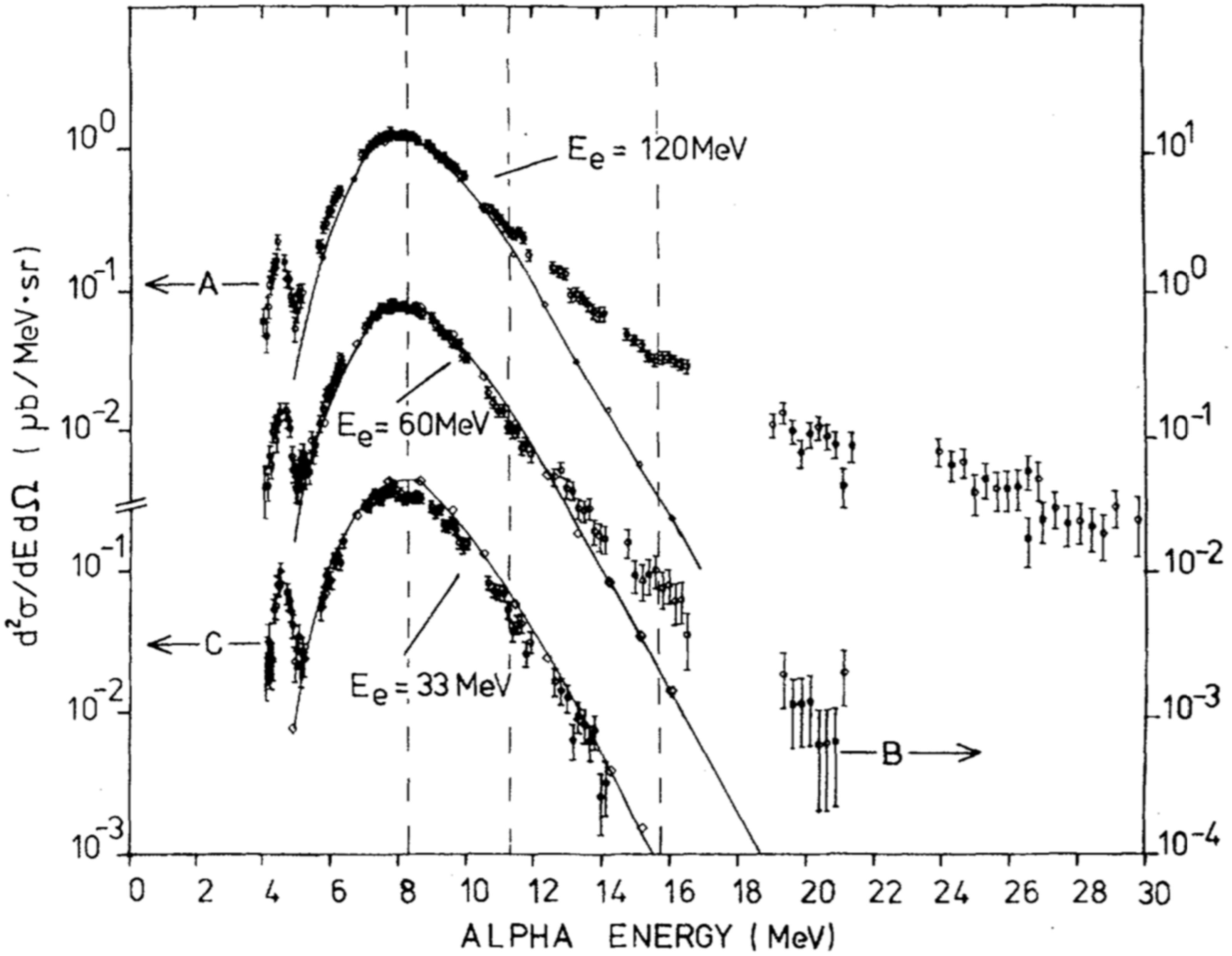
- At tens-of-MeV, on the other hand, **compound reactions** are thought to dominate
  - Kim & Cheoun, Phys. Lett. B **679**, 330 (2009)
- These proceed via the formation of a thermally equilibrated excited nucleus, which then decays
  - For a ~10 MeV neutrino, even transitions to low-lying nuclear levels become important!
- The **compound nucleus** idea goes back to Niels Bohr in the 1930s

"The first stage of [a nuclear] collision . . . consists in the formation of an intermediate semi-stable system composed of the original nucleus and the incident particle. The excess energy . . . [is] temporarily stored in some complicated motions of all the particles in the compound system."

"Its eventual disintegration must be considered as a separate event, independent of the first stage of the collision process."

Have we seen evidence of compound reactions in lepton-nucleus scattering data?

- **Yes**, with electrons
- A good example can be seen in this measurement of the $^{60}\mathrm{Ni}(e,\alpha)e'X$ reaction
- Compound nucleus model (solid line) works very well at 33 MeV
- High-energy tail attributable to direct reactions begins to appear at 60 MeV
- Obvious at 120 MeV



A. G. Flowers et al., PRL 40, 709–712 (1978)

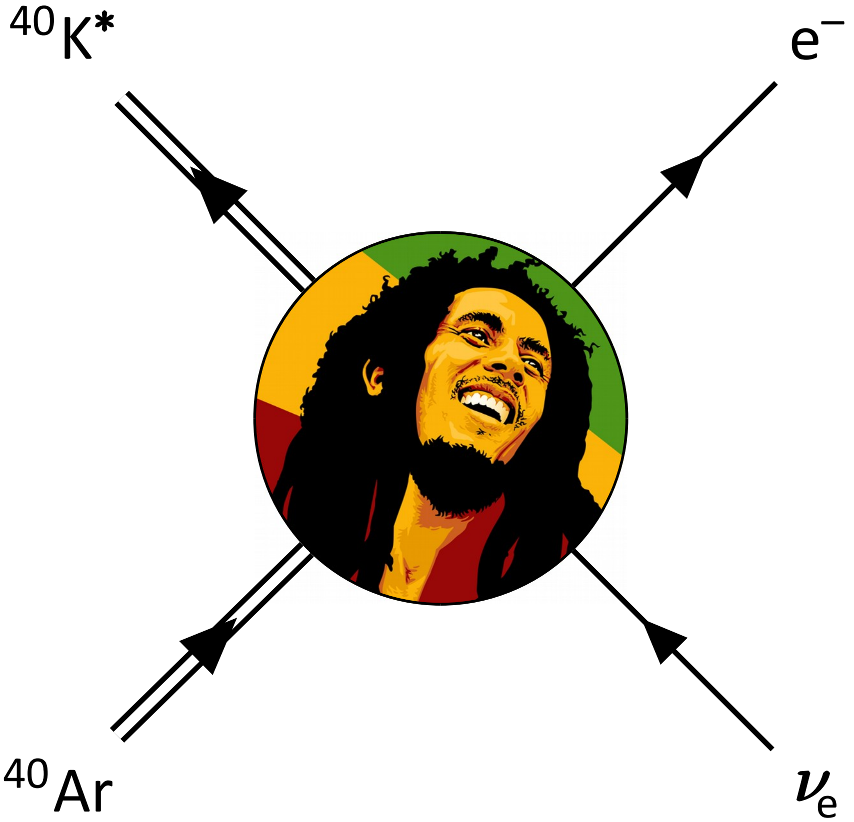
MARLEY: Model of **A**rgon **R**eaction **L**ow-**E**nergy **Y**ields

- Event generator for tens-of-MeV neutrinos on ^{40}Ar

- Current version does CC ν_e (dominant channel)

- Framework allows adding new reactions, target nuclei, etc.

- Widely used by DUNE for supernova neutrino detection studies



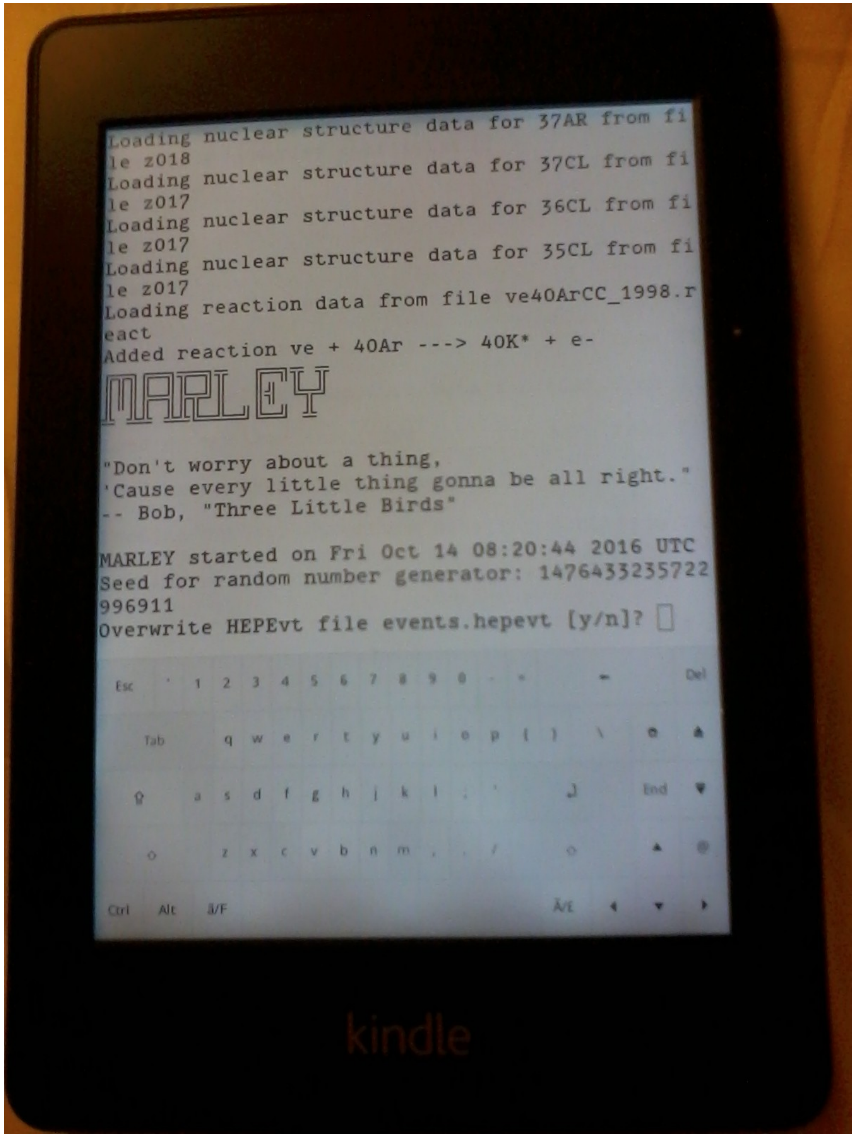
Model of **A**rgon **R**eaction **L**ow **E**nergy **Y**ields

Discussed in detail

in my **PhD thesis**

MARLEY: Model of **A**rgon **R**eaction **L**ow-**E**nergy **Y**ields

- Written in modern C++, mostly from scratch
- ~10K lines of code
- Distributed independently at www.marleygen.org
- Also part of LArSoft framework used by many liquid argon neutrino experiments
- Work underway to extend approach to a ^{127}I target for COHERENT (see D. Salvat’s talk)



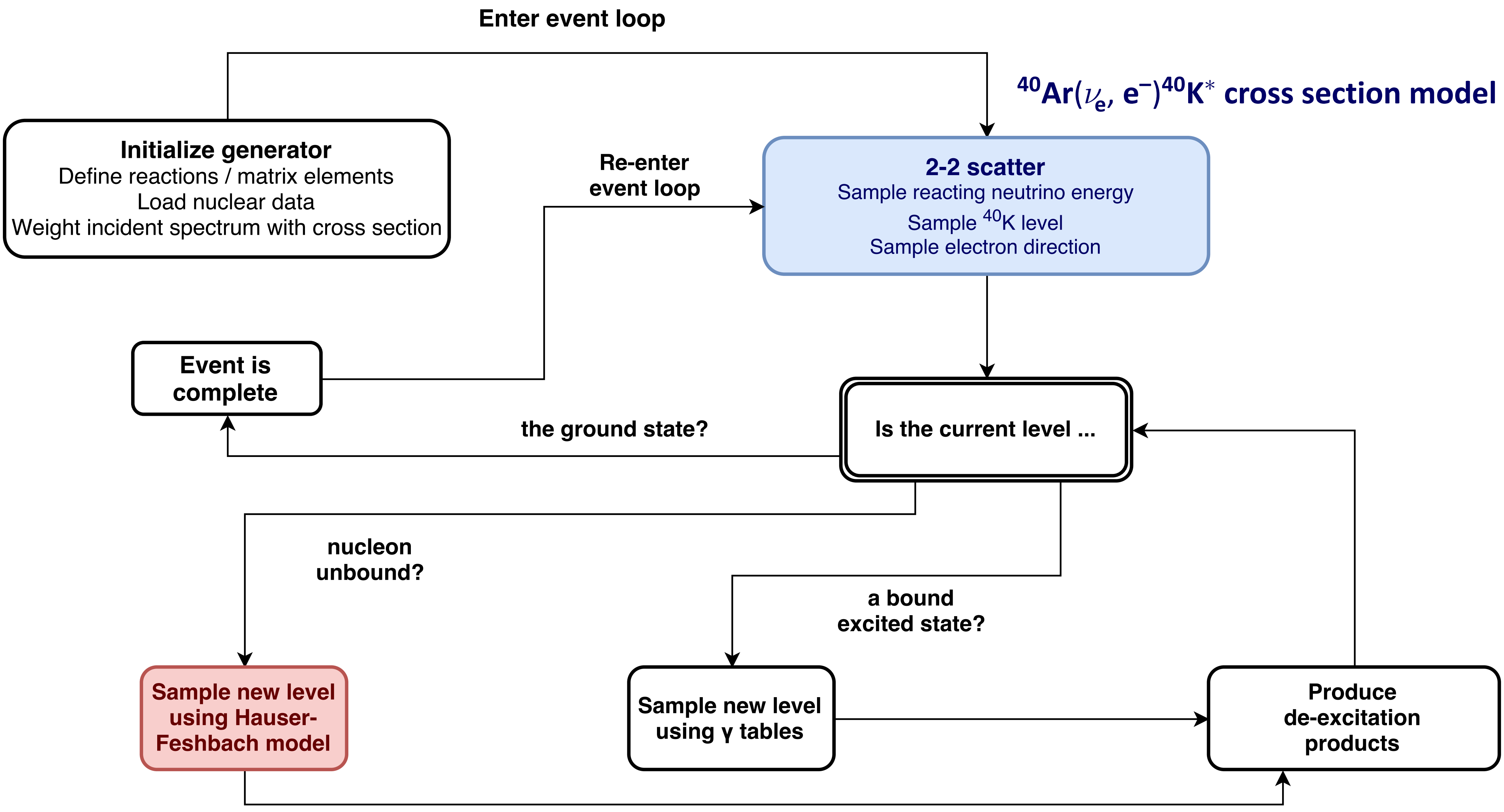
```
Loading nuclear structure data for 37AR from fi
le z018
Loading nuclear structure data for 37CL from fi
le z017
Loading nuclear structure data for 36CL from fi
le z017
Loading nuclear structure data for 35CL from fi
le z017
Loading reaction data from file ve40ArCC_1998.r
eact
Added reaction ve + 40Ar ---> 40K* + e-

"Don't worry about a thing,
'Cause every little thing gonna be all right."
-- Bob, "Three Little Birds"

MARLEY started on Fri Oct 14 08:20:44 2016 UTC
Seed for random number generator: 1476433235722
996911
Overwrite HEPEvt file events.hepevt [y/n]? 
```

MARLEY command-line executable running natively on my Kindle Paperwhite

MARLEY event generation flowchart



Enter event loop

Initialize generator
Define reactions / matrix elements
Load nuclear data
Weight incident spectrum with cross section

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

Re-enter event loop

2-2 scatter
Sample reacting neutrino energy
Sample ^{40}K level
Sample electron direction

Event is complete

Is the current level ...

the ground state?

nucleon unbound?

a bound excited state?

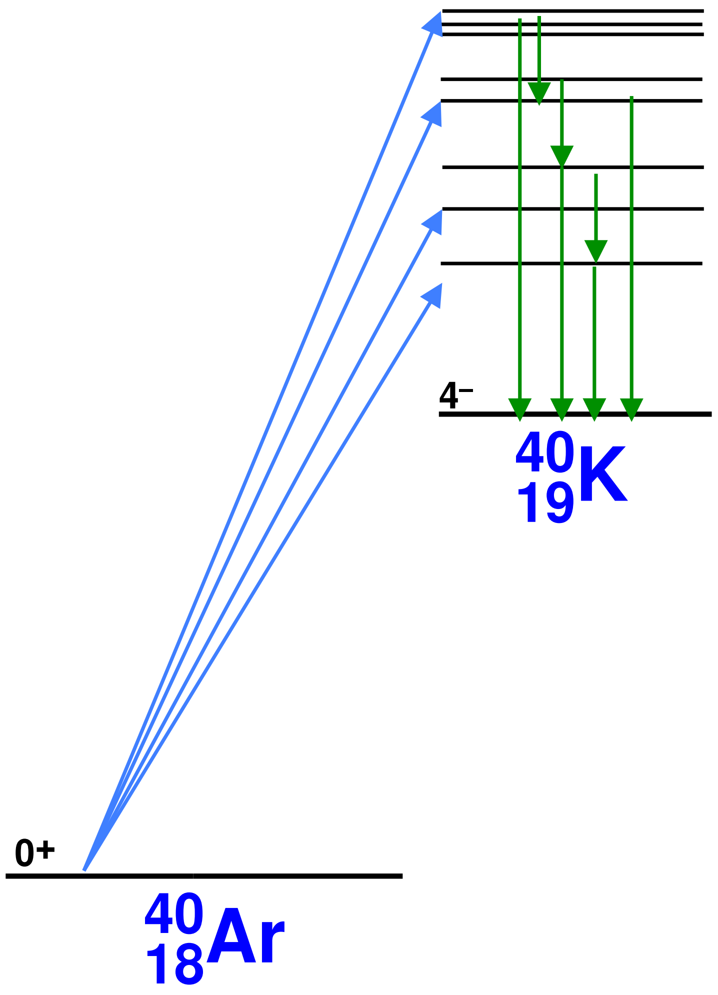
Sample new level using Hauser-Feshbach model

Sample new level using γ tables

Produce de-excitation products

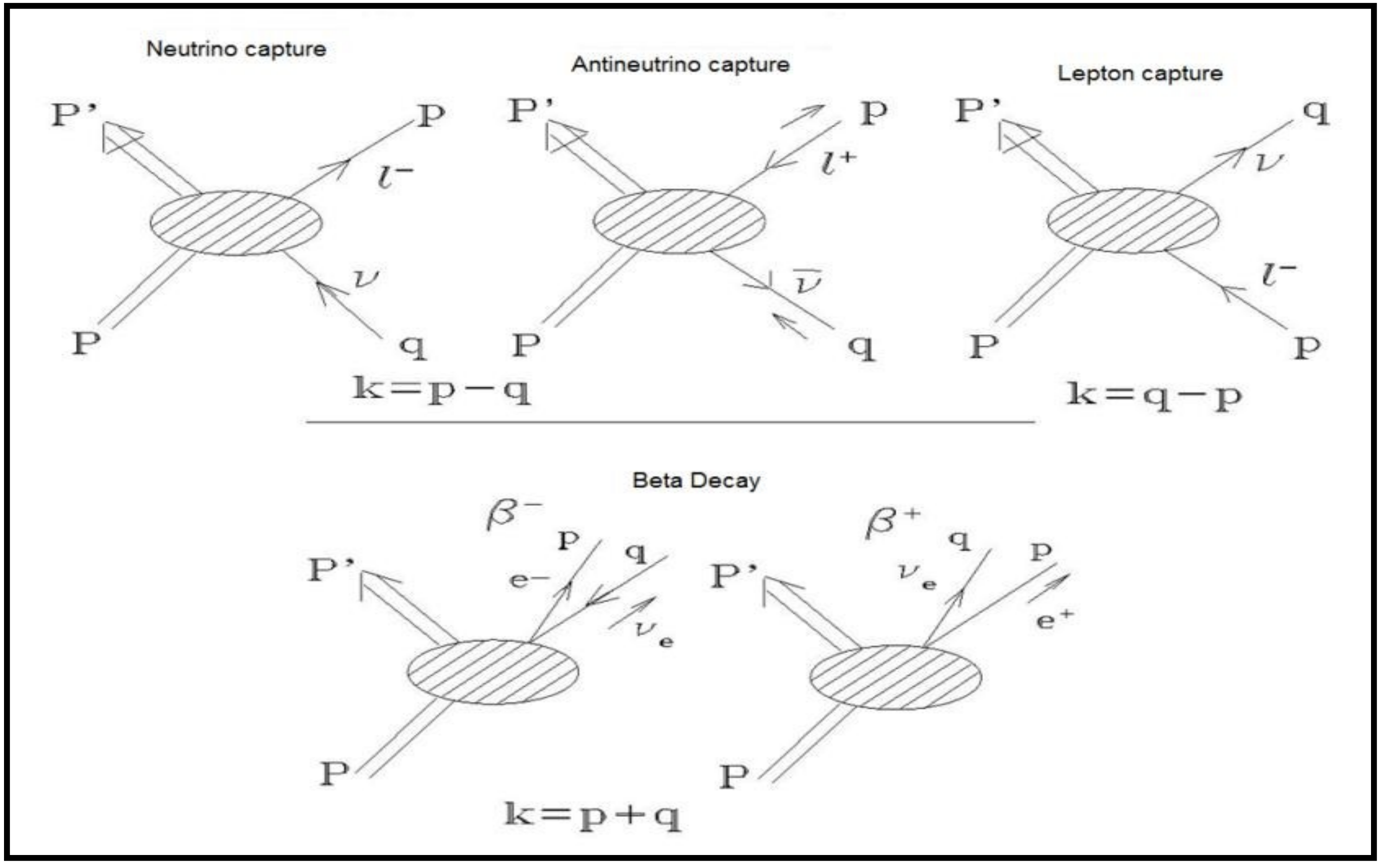
Nuclear de-excitation model

How can we calculate the loading of the nuclear levels?

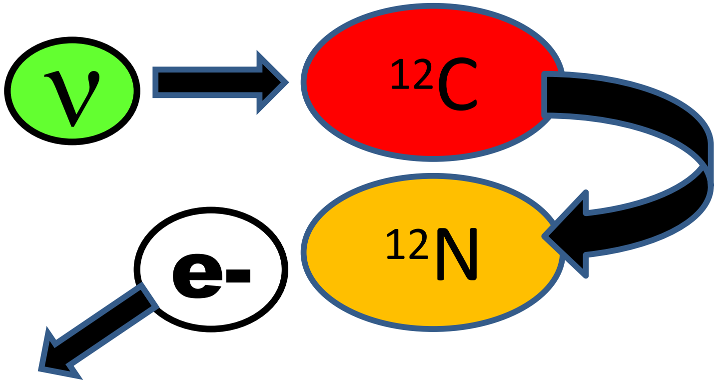


Weak–nuclear interaction

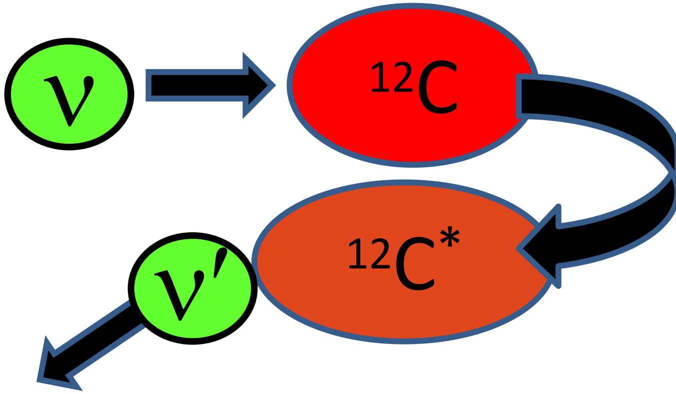
A. Samana



Charged Current



Neutral Current



$$\nu_e + A(Z,N) \Rightarrow A^*(Z+1,N-1) + e^-$$

$$\overline{\nu}_e + A(Z,N) \Rightarrow A^*(Z-1,N+1) + e^+$$

(i)O'Connell, Donelly & Walecka, PR6,719 (1972)
(ii) Kuramoto etal. NPA 512, 711 (1990)
(iii) Luyten etal. NP41,236 (1963)
(iv) Krmpotic etal. PRC71, 044319(2005).

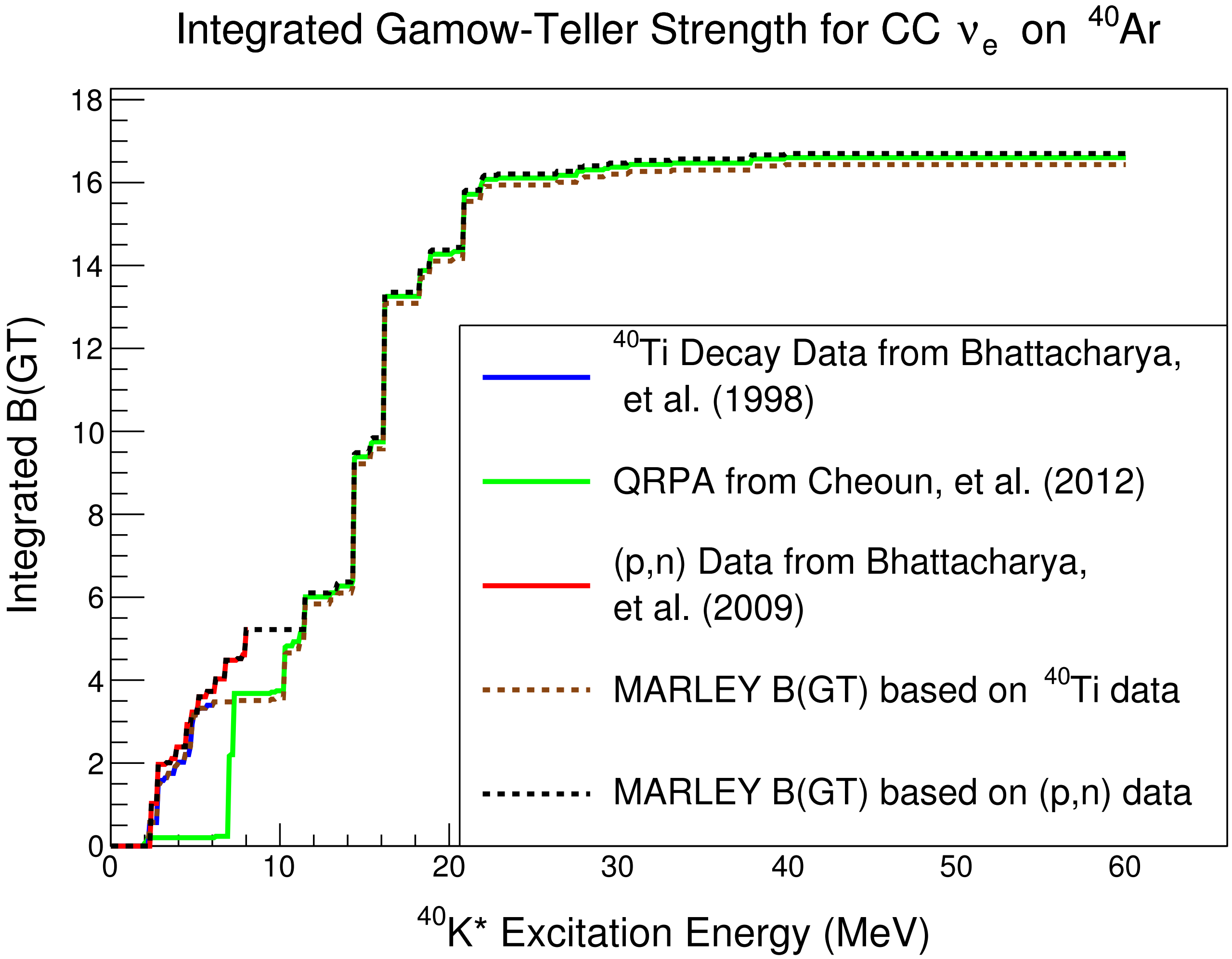
ALL ARE EQUIVALENTS.

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

- Under the allowed approximation, the differential cross section for a particular nuclear level is given by

$$\frac{d\sigma}{d\Omega} = \underset{\text{coupling constants}}{\frac{G_F^2\,|V_{ud}|^2}{4\pi^2}}\,\underset{\text{electron momentum}}{|\mathbf{p}_e|}\,\overset{\text{electron energy}}{E_e}\,\underset{\text{Coulomb correction factor}}{F(Z_f, E_e)} \times \overset{\text{Fermi and Gamow-Teller nuclear matrix elements}}{\underset{\text{electron angular distributions}}{\left[(1+\beta_e\cos\theta_e)B(F) + \left(\frac{3-\beta_e\cos\theta_e}{3}\right)B(GT)\right]}}$$

- MARLEY uses tabulated B(F) and B(GT) values to compute cross sections
- Two-two scattering final states are sampled using the differential cross section
  - 40K* excited level
  - Electron kinematics
- De-excitation of the final nucleus is simulated next



MARLEY ^{40}Ar(ν_e, e$^-$)^{40}K* cross section model

Fermi matrix element comes from time component of nuclear operator

$$\mathrm{B(F)} \equiv g_V^2 \frac{\left|\left\langle f \left\| \sum_{k=1}^{A} \tau_-(k) \right\| i \right\rangle\right|^2}{2J_i + 1}$$

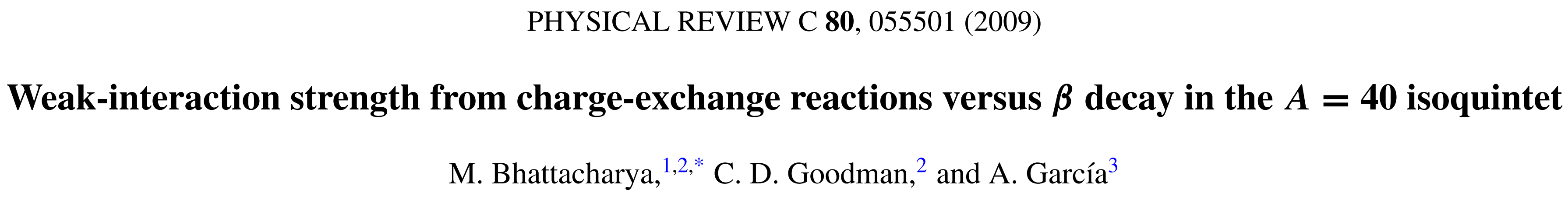
Gamow-Teller matrix element comes from spatial components

$$\mathrm{B(GT)} \equiv g_A^2 \frac{\left|\left\langle f \left\| \sum_{k=1}^{A} \boldsymbol{\sigma}(k)\, \tau_-(k) \right\| i \right\rangle\right|^2}{2J_i + 1}$$

Fermi transition is well-understood

Gamow-Teller less so…

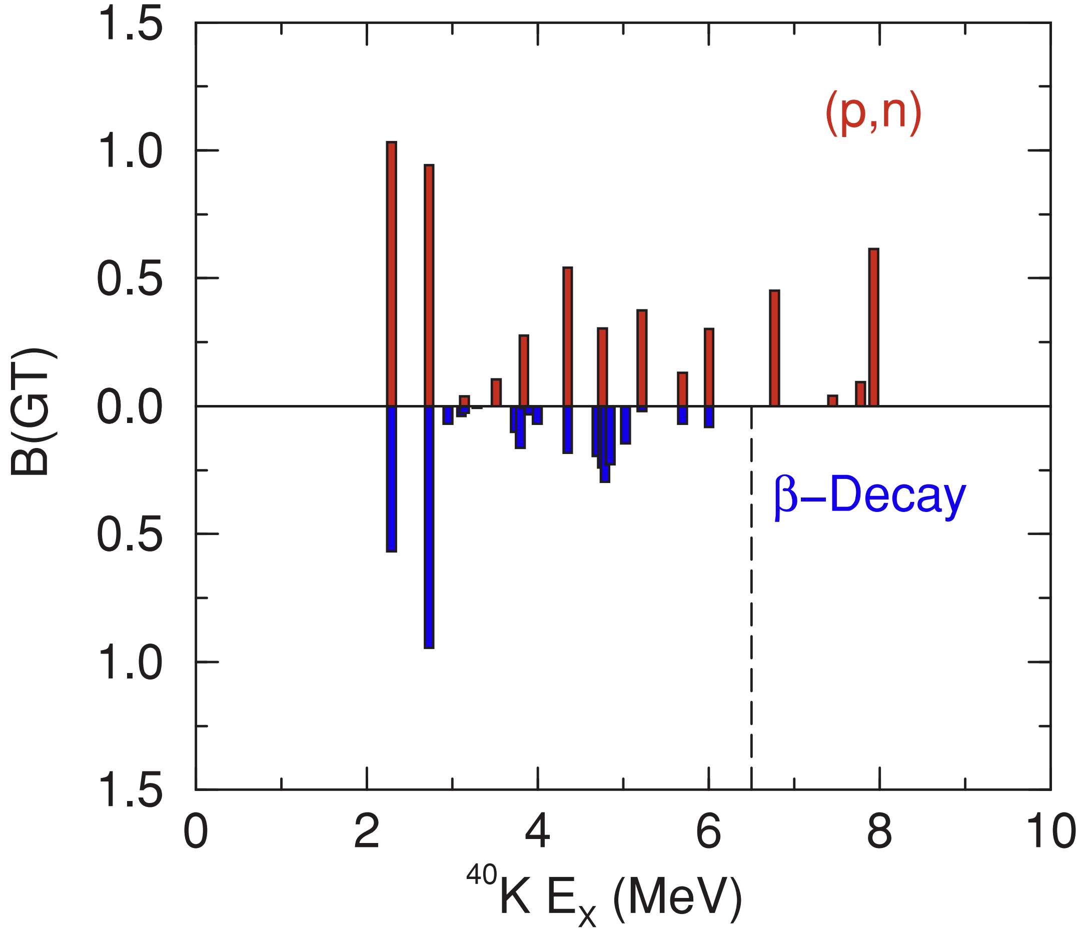
Sources of B(GT) data for ^{40}Ar



PHYSICAL REVIEW C **80**, 055501 (2009)

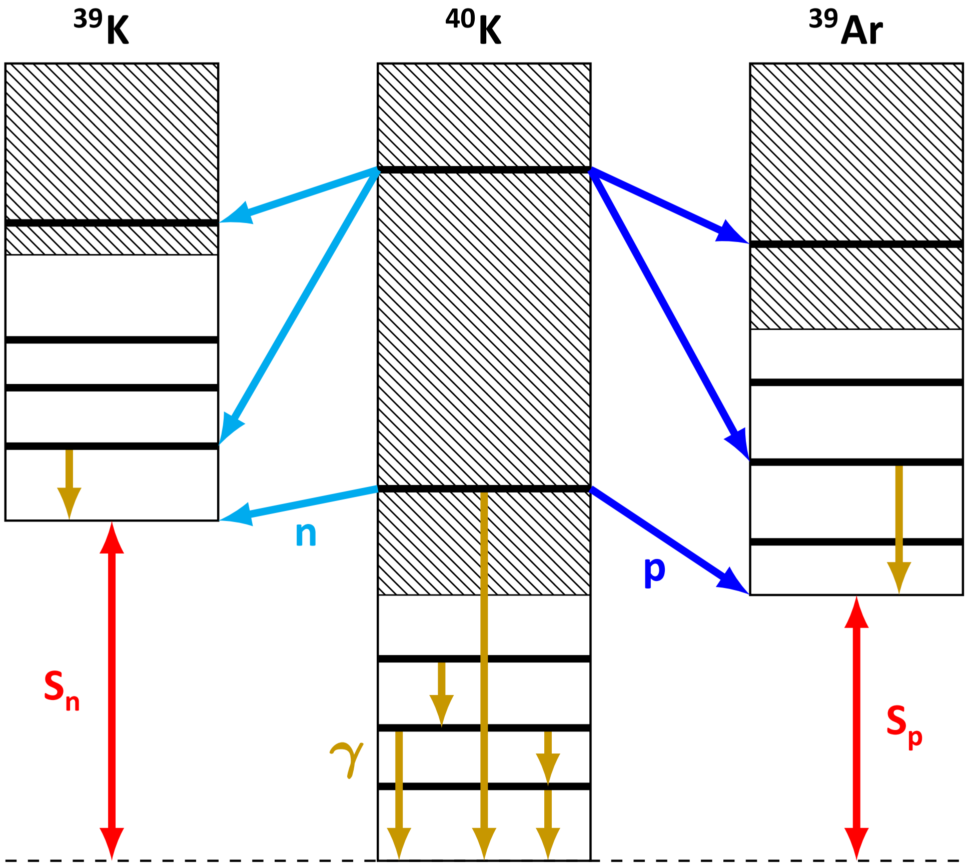
Weak-interaction strength from charge-exchange reactions versus *β* decay in the *A* = 40 isoquintet

M. Bhattacharya,[1,2,*] C. D. Goodman,[2] and A. García[3]



- Measurements using (p,n) scattering vs. ^{40}Ti beta decay show significant disagreements
- Assumptions must be made to extract B(GT) values either way
- MARLEY chooses to remain agnostic and provides 3 datasets (A, B, C)
- Must be supplemented by theory at higher energies

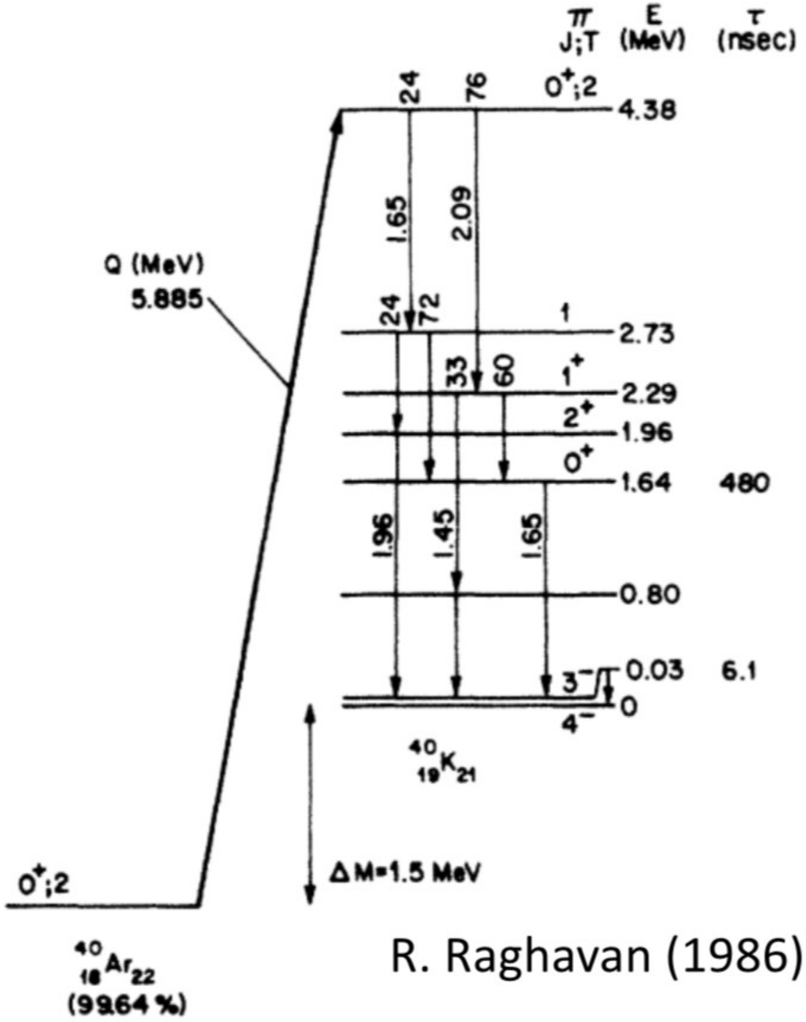
How can we simulate the nuclear de-excitations?



MARLEY de-excitation model: bound states

- If the residual nucleus is in a bound state, then tables of discrete γ-ray branching ratios are used to repeatedly sample transitions down to the ground state

- These tables are largely taken from a compilation provided with version 1.6 of the TALYS nuclear code
  - Some updates have been made to ^{40}K based on the latest (2017) ENSDF evaluation for A = 40



R. Raghavan (1986)

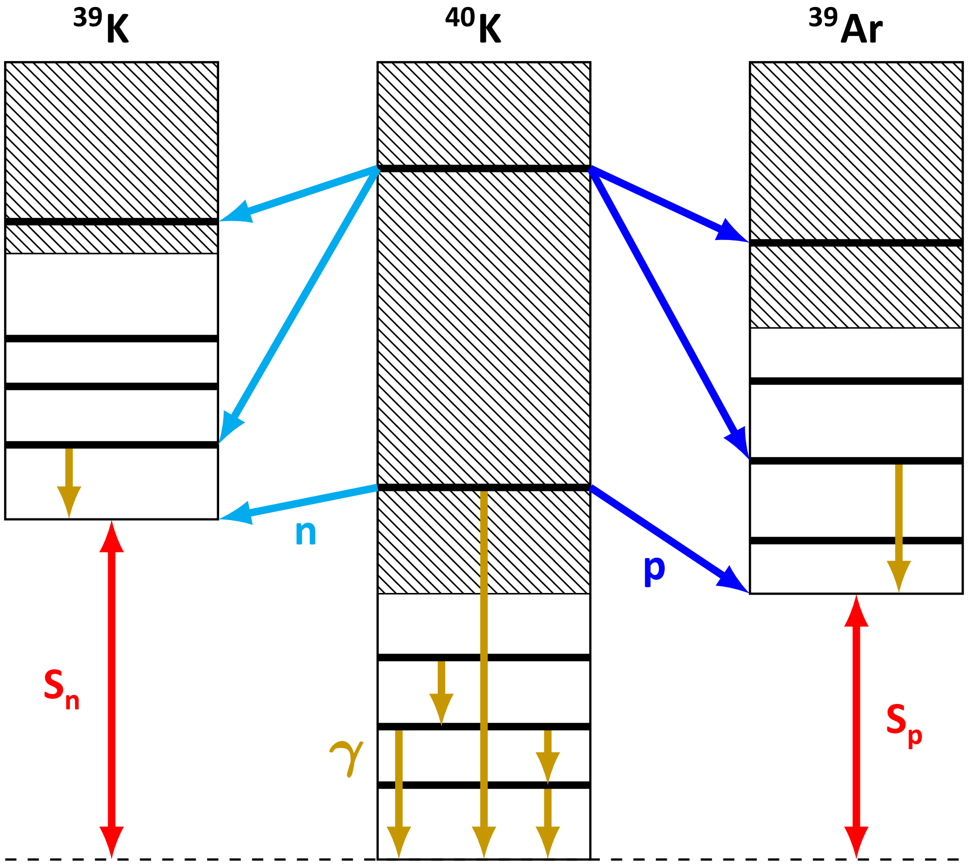
FIG. 1. Level scheme of ^{40}Ar-^{40}K relevant to ν_e capture in argon.

MARLEY de-excitation model: unbound states

- If the residual nucleus is in an unbound state, an exit channel is sampled using decay widths from the Hauser-Feshbach statistical model
  - If excitation energy remains, another de-excitation step is taken afterwards
  - Only binary decays are taken into account by the model

Hauser-Feshbach model

- Relies on the compound nucleus assumption
- Partial decay widths depend on
  - Initial level E_x and J^π
  - Discrete levels
  - Continuum level density
  - Transmission coefficients



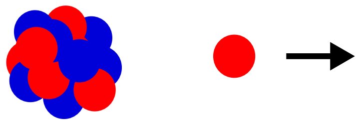
Hauser-Feshbach Model

W. Hauser and H. Feshbach, Physical Review **87**, 366 (1952)

- Commonly used for modeling low-energy nuclear cross sections
- Two key assumptions:
  1. compound nucleus
  2. reciprocity theorem (time-reversal invariance)

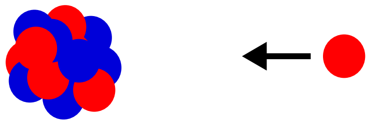
- Transmission coefficient $T_{\ell j}$ = probability for fragment to escape the nucleus
- Compound nucleus + time-reversal symmetry = $T_{\ell j}$ via “reciprocity”
- Optical model is used to compute $T_{\ell j}$ for time-reversed process
- Numerical solution of Schrödinger equation via Numerov’s method

The fragment emission width of a compound nucleus



$A \rightarrow \alpha + B$

is related to its formation cross section



$\alpha + B \rightarrow A$

Hauser-Feshbach Model

W. Hauser and H. Feshbach, Physical Review **87**, 366 (1952)

- Commonly used for modeling low-energy nuclear cross sections
- Two key assumptions:
  1. compound nucleus
  2. reciprocity theorem (time-reversal invariance)

sum over possible angular momenta

Hauser-Feshbach partial decay width

transmission coefficient

final nuclear level density

$$\Gamma_{A\to\alpha+B} = \frac{1}{2\pi\rho_A(E_x, J, \Pi)} \sum_{\ell' j'} \int \delta_\pi \, \rho_B(E'_x, I', \Pi') \, T_{\ell' j'}(\epsilon) \, d\epsilon$$

initial nuclear level density

parity conservation factor

integral over possible fragment energies

Parity conservation

$$\delta_\pi = \begin{cases} 1 & \Pi = \pi_\alpha \Pi' (-1)^{\ell'} \\ 0 & \text{otherwise} \end{cases}$$

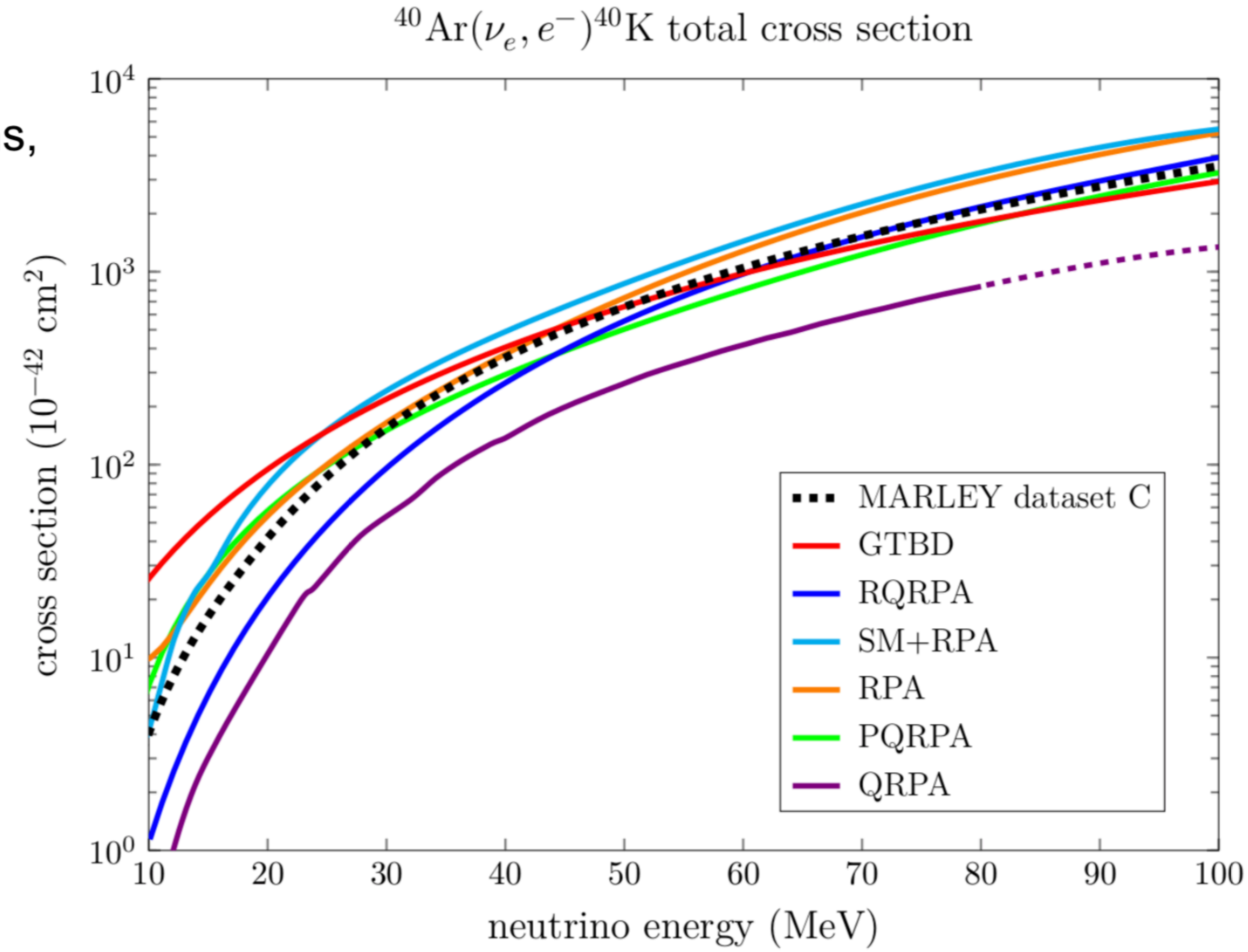
Monte Carlo implementation

$$P(A \to \alpha + B) = \frac{\Gamma_{A\to\alpha+B}}{\Gamma_A}$$

CC total cross section

- Similar to existing theoretical calculations, some much more detailed but not data-driven

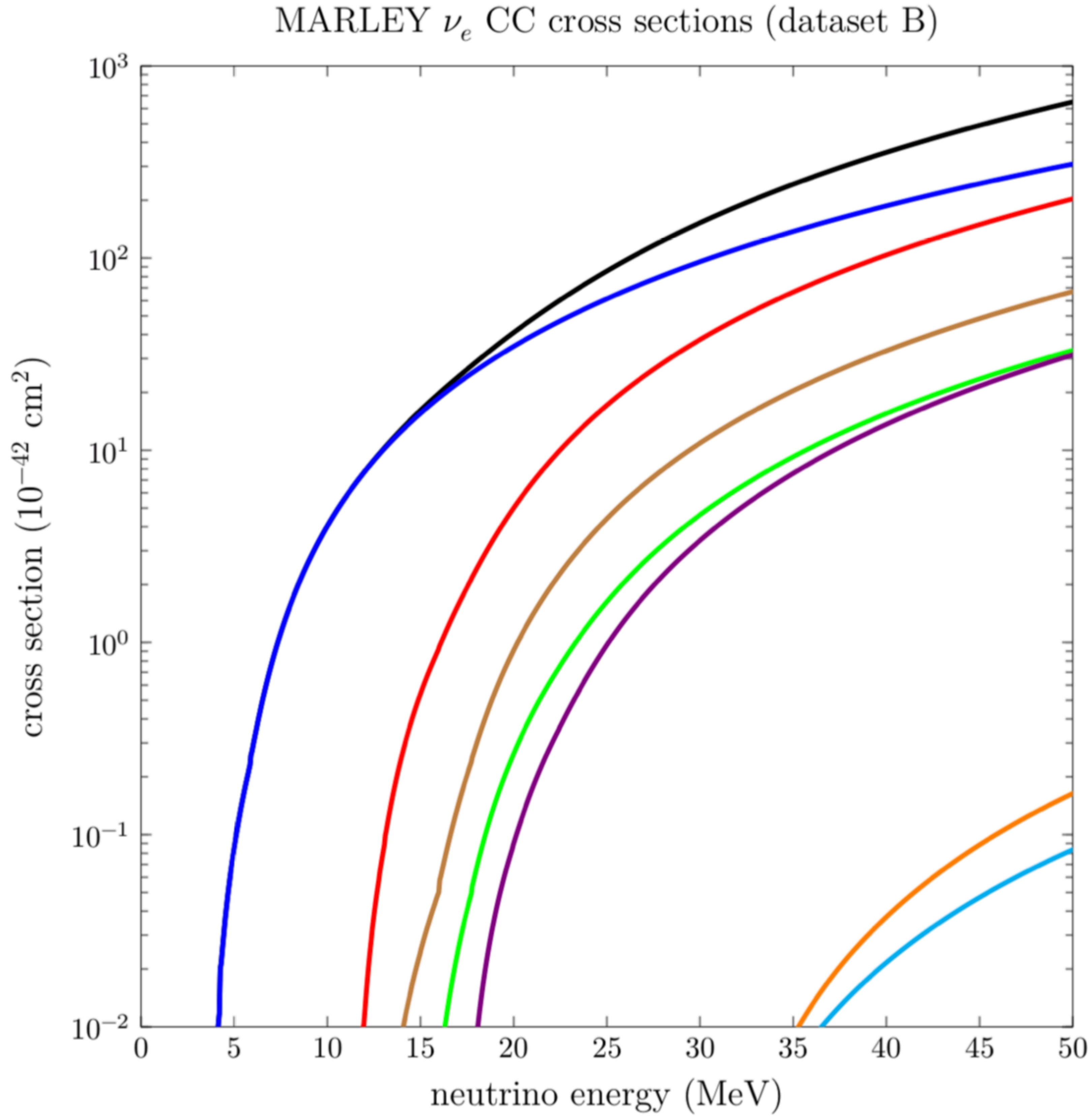
- Appears to give reasonable results even above the ~50 MeV threshold where forbidden terms become significant



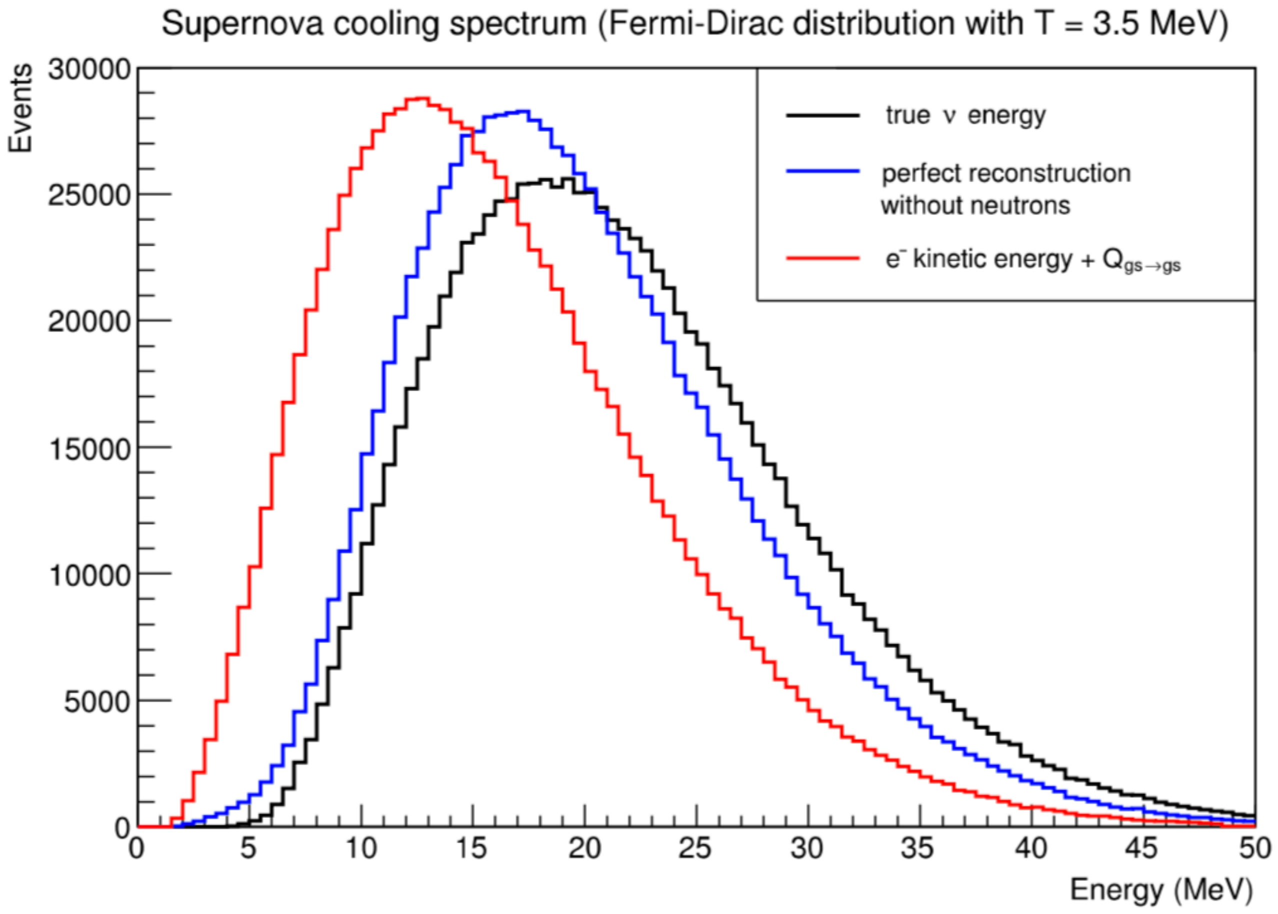
Exclusive cross sections

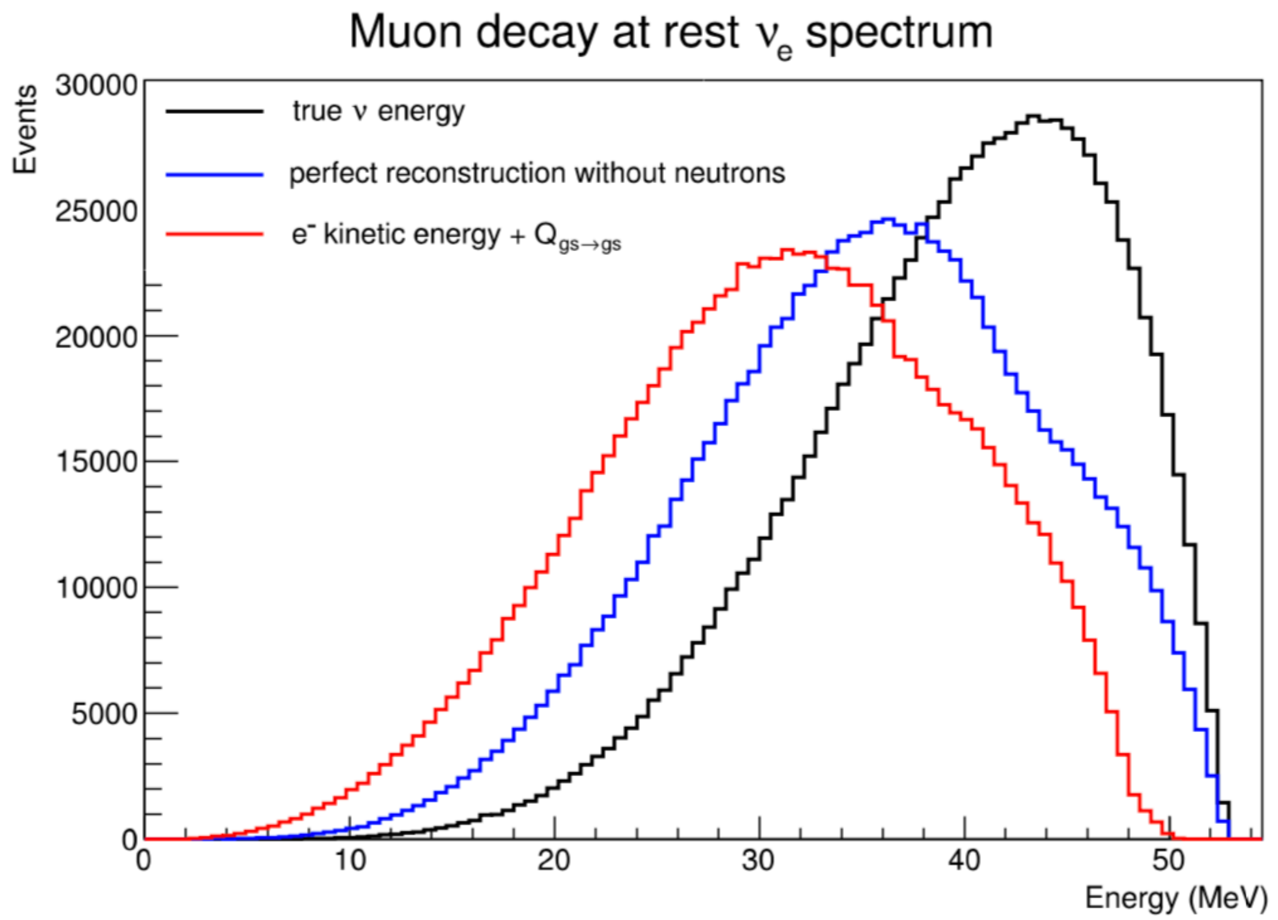
Similar treatment to that used in arXiv:nucl-th/0311022 for ^{16}O

Xγ means “any number of gammas”



MARLEY branching ratios for two different source spectra





$^{40}K^*$ de-excitations

- γs only: 82.3%
- single n + γs: 12.7%
- single p + γs: 3.3%
- other: 1.7%

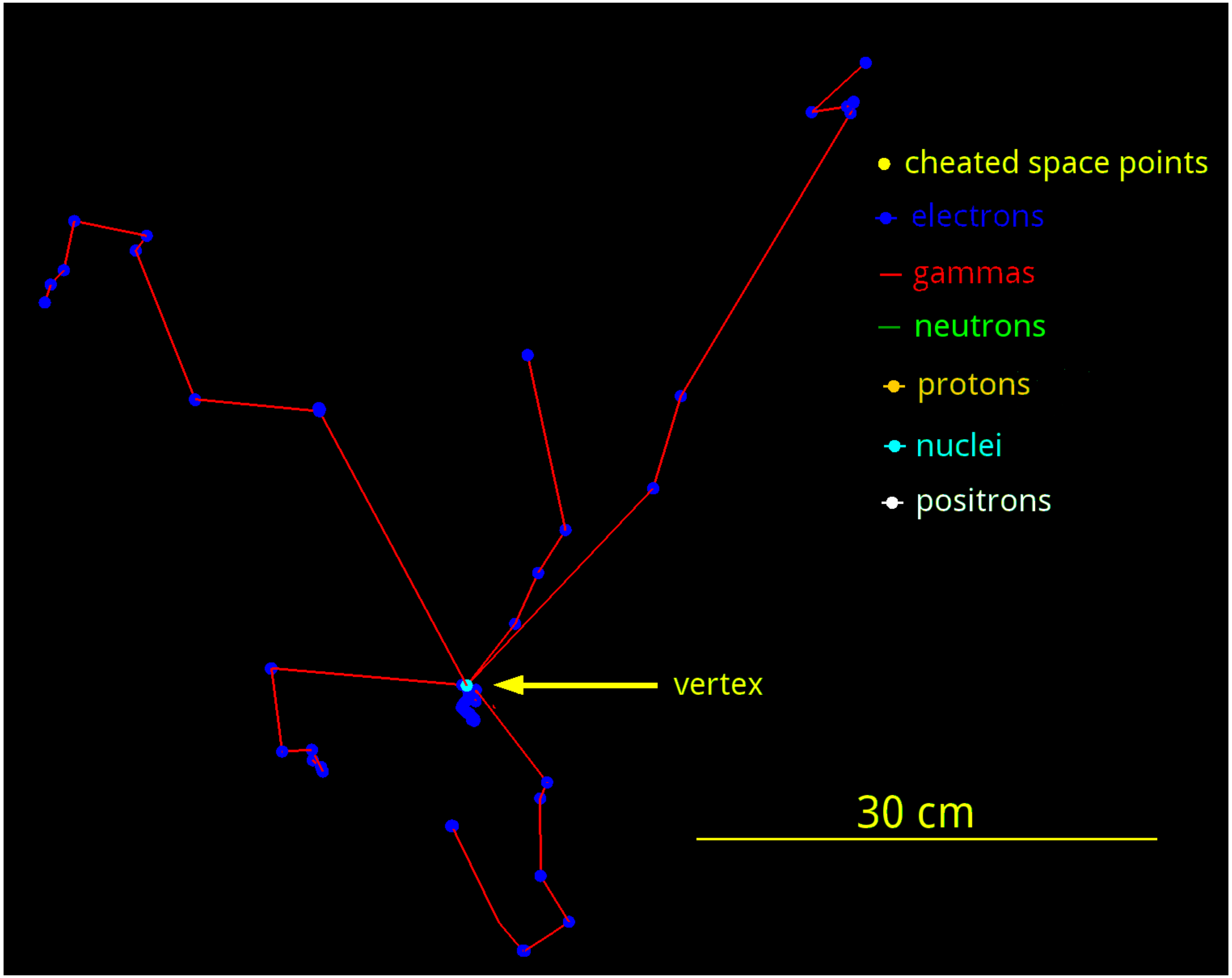
$^{40}K^*$ de-excitations

- γs only: 60.7%
- single n + γs: 25.6%
- single p + γs: 8.3%
- other: 5.3%

Higher neutron emission in particular leads to big spectral distortions!

Example e^- + γs Only Event (true trajectories)

- E_ν = 16.1 MeV
- e^- deposited 10.2 MeV
- γs deposited 4.3 MeV
- ^{40}K deposited 3.7 keV
- Total visible energy:
  14.5 MeV
- Visible energy sphere radius:
  48.4 cm



Example e^- + γs Only Event (cheated reco)

- E_ν = 16.1 MeV
- e^- deposited 10.2 MeV
- γs deposited 4.3 MeV
- ^{40}K deposited 3.7 keV
- Total visible energy:
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- Visible energy sphere radius:
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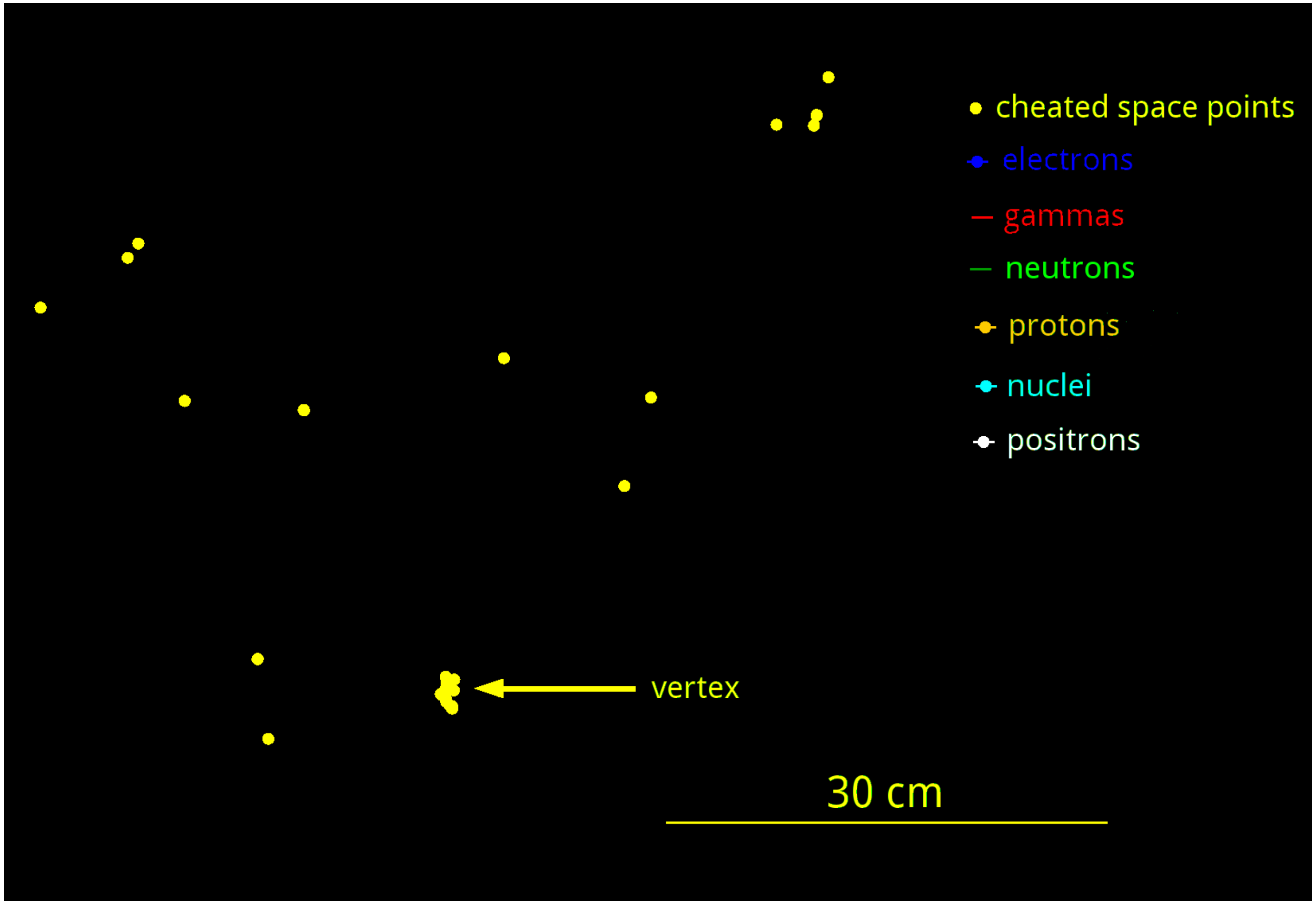
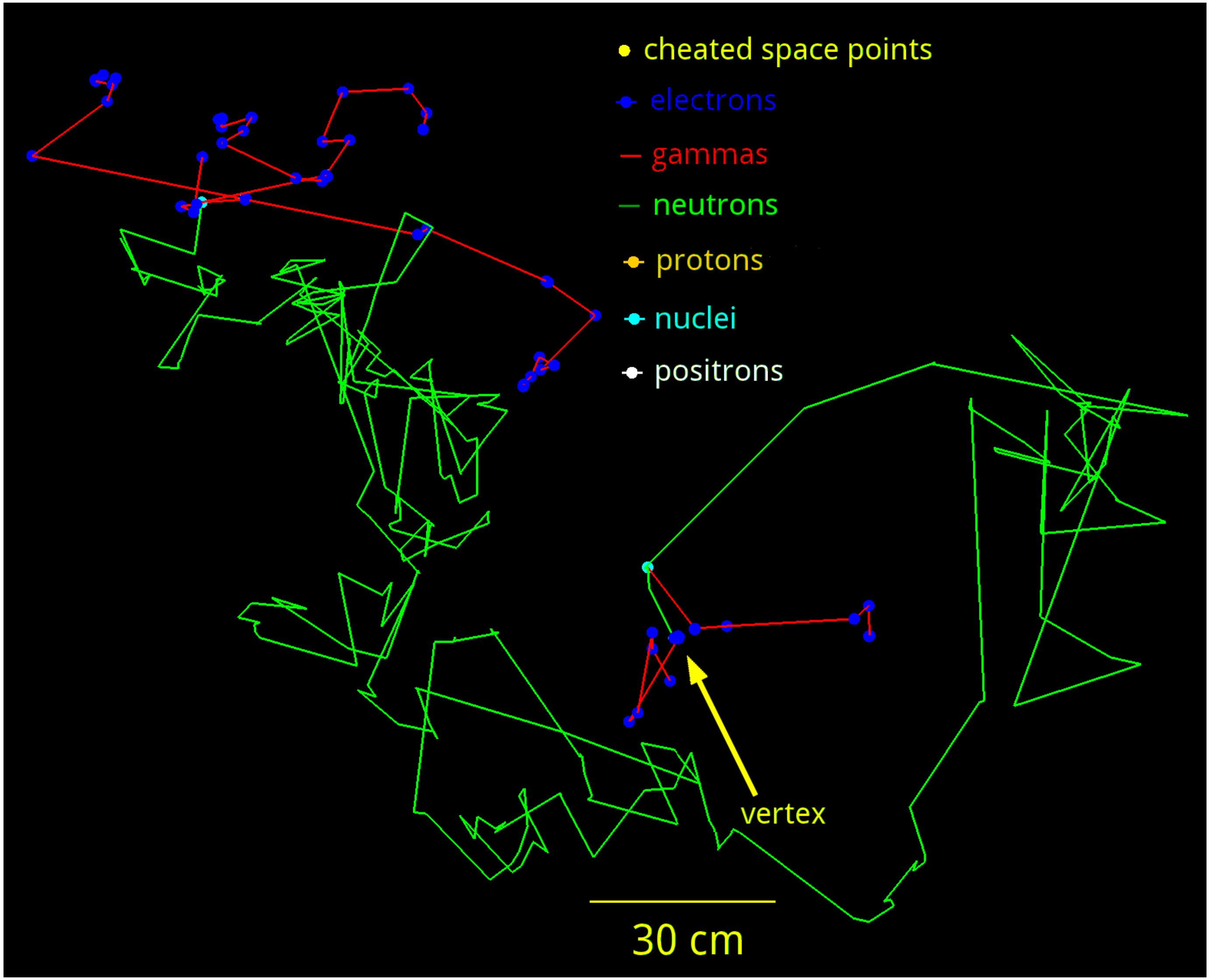


Example neutron event (true trajectories)

- $E_\nu = 16.3$ MeV
- e^- deposited 4.5 MeV
- ^{39}K deposited 68 keV
- n deposited 7.6 MeV (mostly from capture γs)
- Total visible energy:

  12.2 MeV
- Visible energy sphere radius:

  1.44 m



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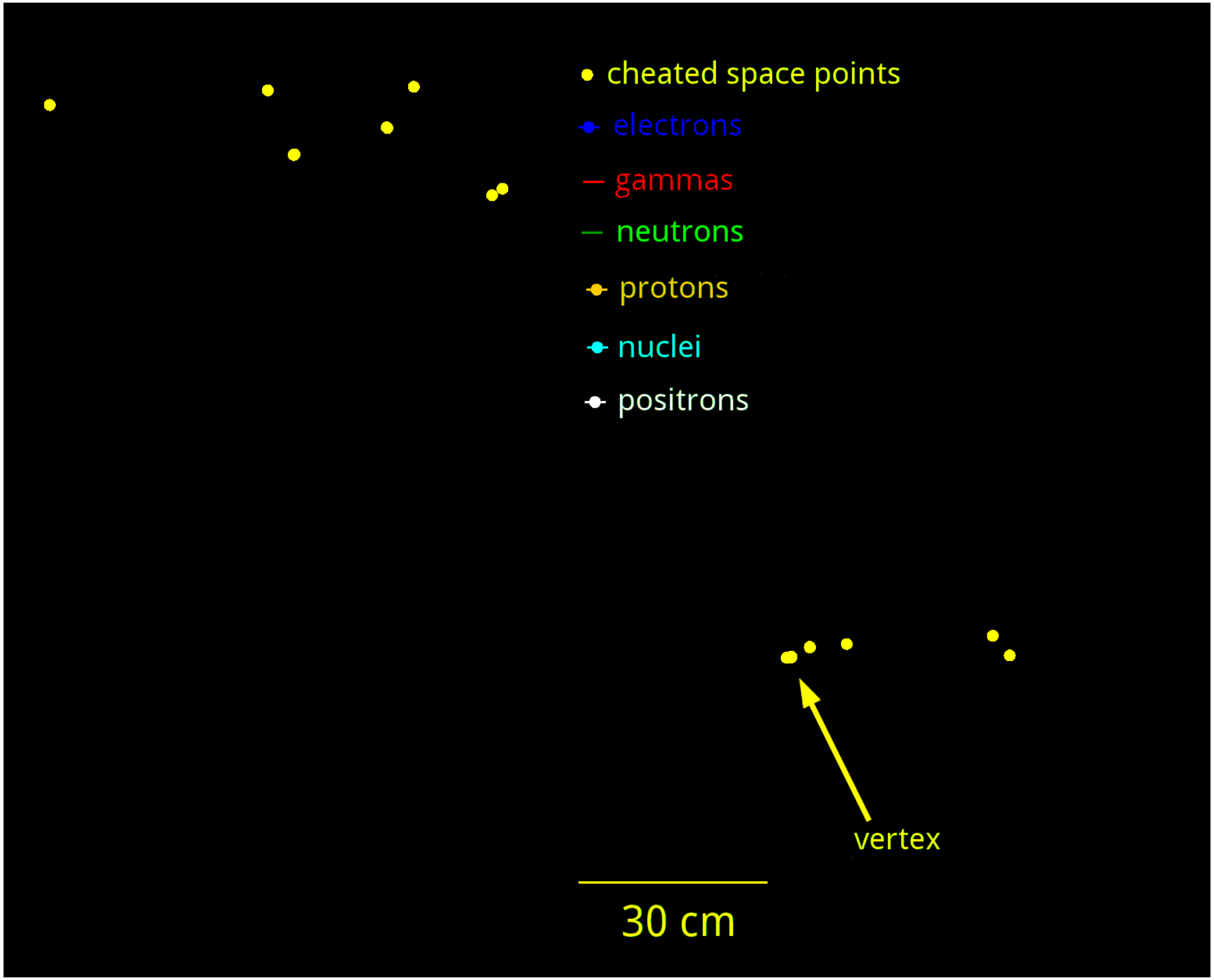


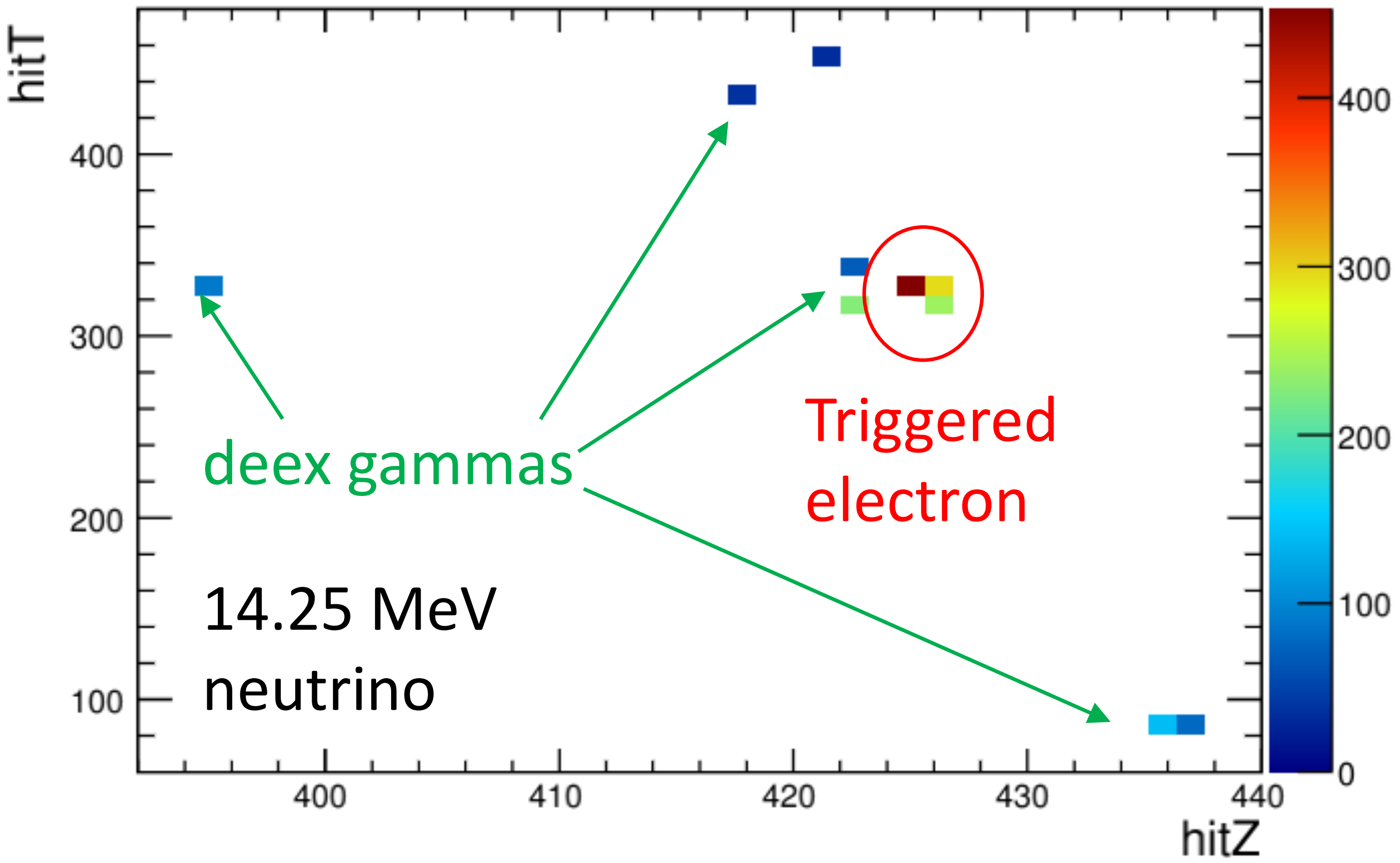
DUNE’s use of MARLEY

- A variety of low-energy studies for DUNE are underway using MARLEY

- The examples shown here are from D. Pershey’s May 2019 DUNE collaboration meeting talk

- Double peak in the bottom plot
  - Right peak: e + γ only
  - Left peak: neutron emission!

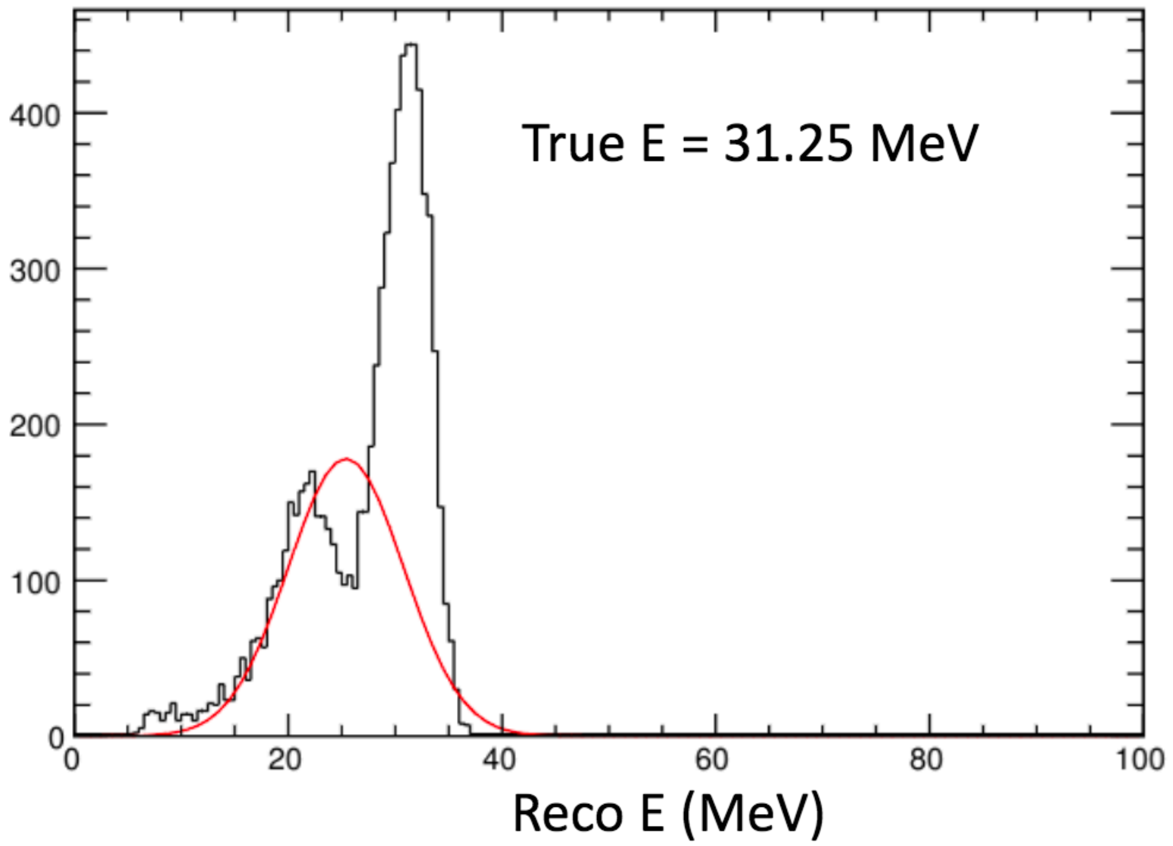
Reconstructed hits from a MARLEY event



deex gammas

Triggered electron

14.25 MeV neutrino



True E = 31.25 MeV

Revisiting MARLEY's cross section calculation

A **multipole expansion** allows one to write the full amplitude to order 1/m_N in terms of 4 nuclear matrix elements

$$\mathcal{N}_J^V(\Theta) \equiv i^J \sqrt{4\pi(2J+1)} \left\langle J_f \middle\| \sum_{k=1}^{A} j_J(\kappa r_k)\, Y_J(\hat{\mathbf{r}}_k)\, t_- \middle\| J_i \right\rangle$$

$$\kappa \equiv |\mathbf{q}|$$

$$\mathcal{N}_J^A(\Theta) \equiv i^J \sqrt{4\pi(2J+1)} \left\langle J_f \middle\| \sum_{k=1}^{A} j_J(\kappa r_k)\, Y_J(\hat{\mathbf{r}}_k)\, (\mathbf{p}_{N_i} \cdot \boldsymbol{\sigma})\, t_- \middle\| J_i \right\rangle$$

$$\mathcal{N}_{JM}^V(\Theta) \equiv \sum_L i^L \sqrt{4\pi(2L+1)}\, (L\,0\,1\,M \,|\, J\,M) \left\langle J_f \middle\| \sum_{k=1}^{A} j_J(\kappa r_k) \left[Y_L \otimes \mathbf{p}_{N_i}\right](k)_J\, t_- \middle\| J_i \right\rangle$$

$$\mathcal{N}_{JM}^A(\Theta) \equiv \sum_L i^L \sqrt{4\pi(2L+1)}\, (L\,0\,1\,M \,|\, J\,M) \left\langle J_f \middle\| \sum_{k=1}^{A} j_J(\kappa r_k) \left[Y_L \otimes \boldsymbol{\sigma}\right](k)_J\, t_- \middle\| J_i \right\rangle$$

MARLEY simplifies this calculation (drastically) by invoking the "allowed approximation"

$$q \to 0$$

$$|\mathbf{p}_{N_i}| \ll m_N$$

Can we get an idea of what we lose by doing that?

Improving MARLEY: more detailed cross section model

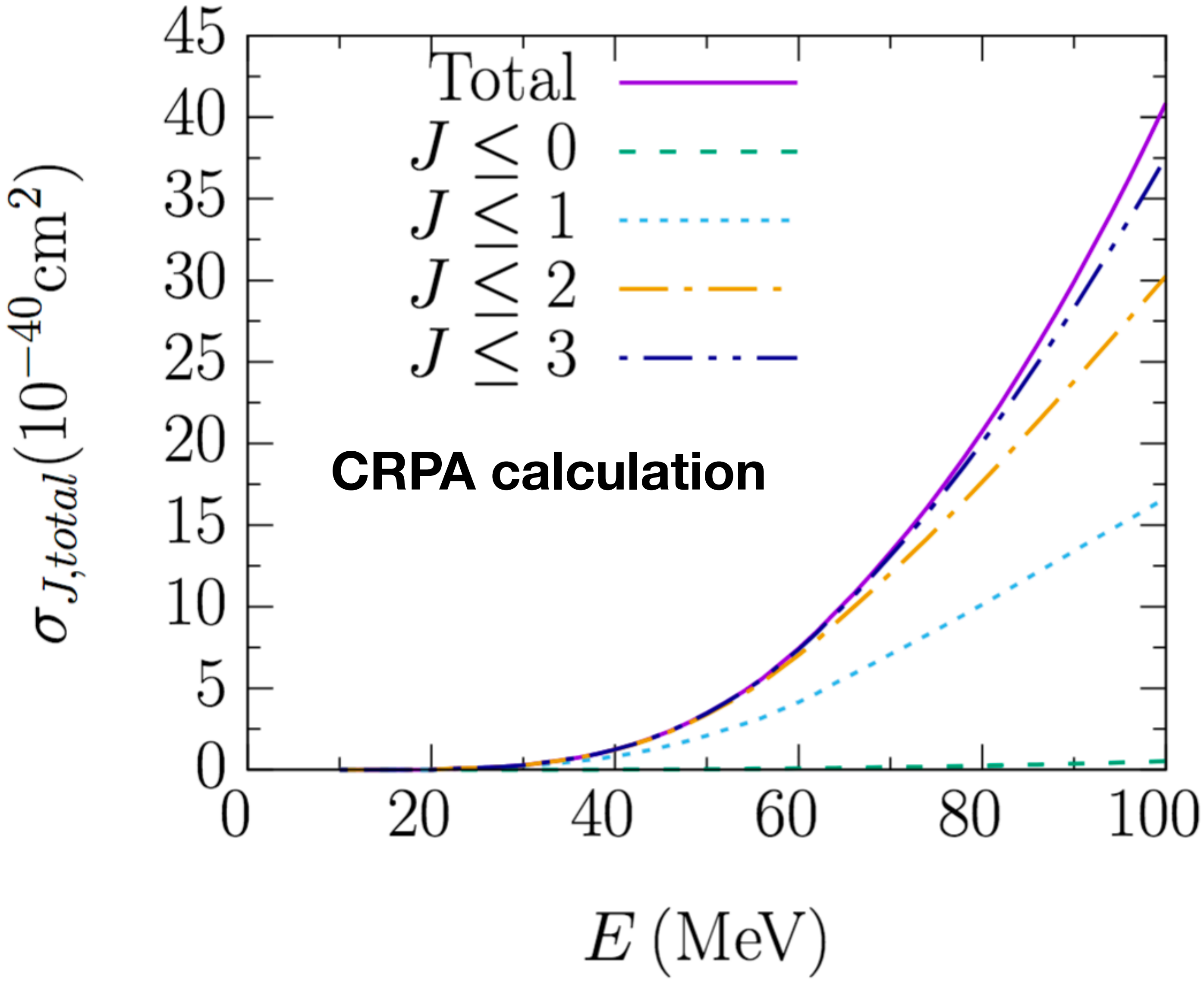
- Recent work by the U. Ghent group (**arxiv 1903.07726**) has shown the importance of higher-order multipoles to low-energy neutrino cross sections

- Contributions become important around ~40 MeV

- **They're working with me to get their calculation into MARLEY**
    - More strength to high-lying states
    - New channels (e.g., NC)

- Full impact of the physics improvements on DUNE observables remains to be seen

- Stay tuned!



Improving MARLEY: constraining the models

- **COHERENT** is pursuing a number of useful cross section measurements in this energy range

- Extending MARLEY to new targets for which data are expected soon (e.g., Pb, I) would provide sensitive test of general approach

- ^{40}Ar results also coming
  - Some CC events expected

- Other indirect methods could also be helpful
  - μ capture on ^{40}Ar
  - electron scattering

NaIvE (NaI)

NIN cubes (Pb, Fe, Cu)

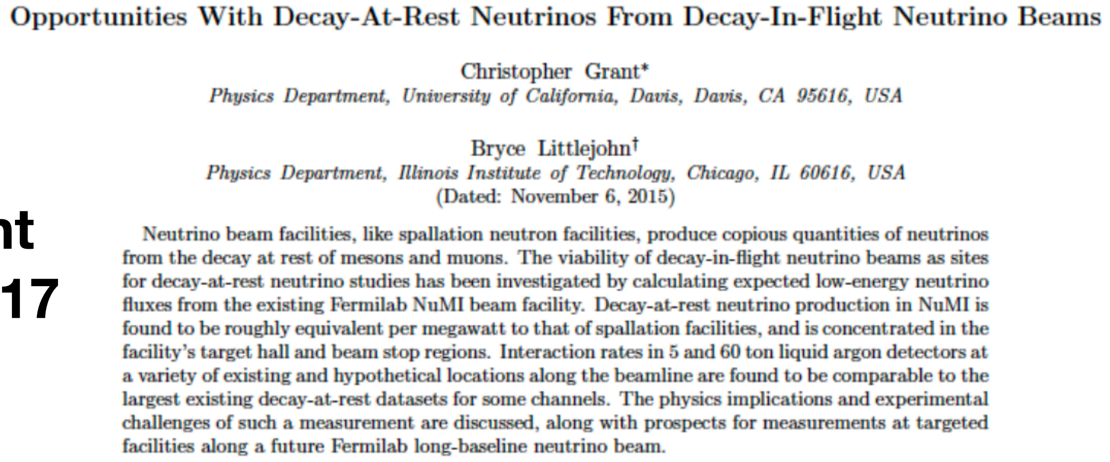
Improving MARLEY: constraining the models

- **Decay-at-rest ν_e** provide the most direct route to constraining MARLEY's cross section models
- **STS would be a great location** for such a measurement
- Another site that has been investigated: near NuMI target hall @ Fermilab

Decay-at-rest near NuMI target hall

C. Grant and B. Littlejohn, arXiv:1510.08431

C. Grant
PINS 2017

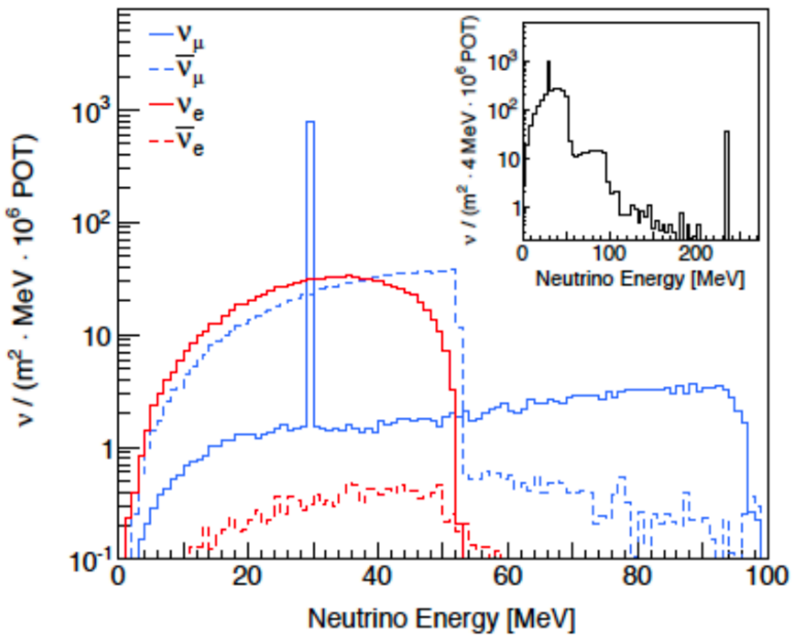


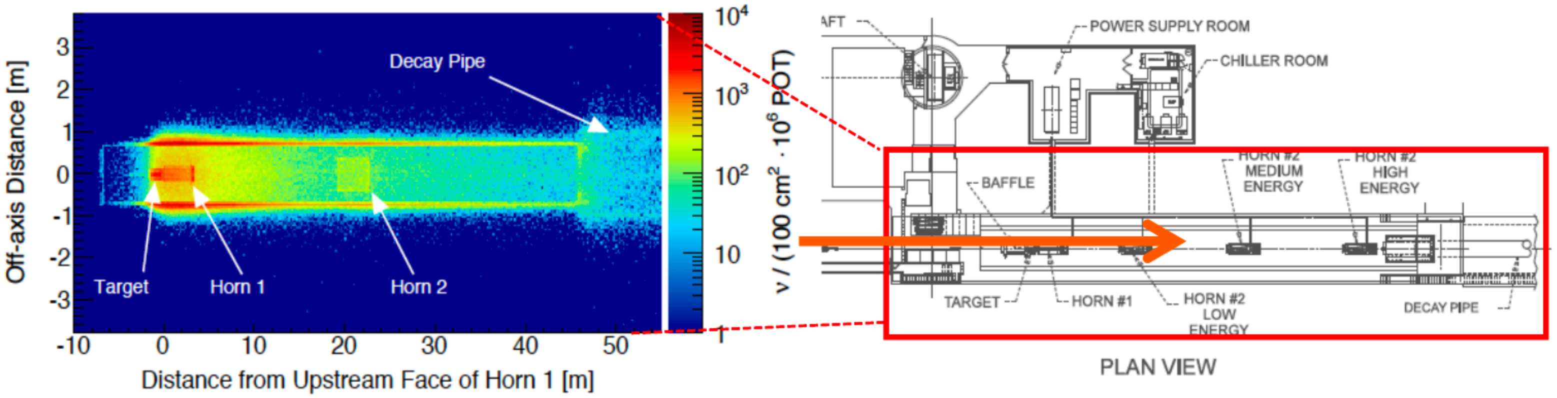
Opportunities With Decay-At-Rest Neutrinos From Decay-In-Flight Neutrino Beams

Christopher Grant*
Physics Department, University of California, Davis, Davis, CA 95616, USA

Bryce Littlejohn†
Physics Department, Illinois Institute of Technology, Chicago, IL 60616, USA
(Dated: November 6, 2015)

Neutrino beam facilities, like spallation neutron facilities, produce copious quantities of neutrinos from the decay at rest of mesons and muons. The viability of decay-in-flight neutrino beams as sites for decay-at-rest neutrino studies has been investigated by calculating expected low-energy neutrino fluxes from the existing Fermilab NuMI beam facility. Decay-at-rest neutrino production in NuMI is found to be roughly equivalent per megawatt to that of spallation facilities, and is concentrated in the facility's target hall and beam stop regions. Interaction rates in 5 and 60 ton liquid argon detectors at a variety of existing and hypothetical locations along the beamline are found to be comparable to the largest existing decay-at-rest datasets for some channels. The physics implications and experimental challenges of such a measurement are discussed, along with prospects for measurements at targeted facilities along a future Fermilab long-baseline neutrino beam.

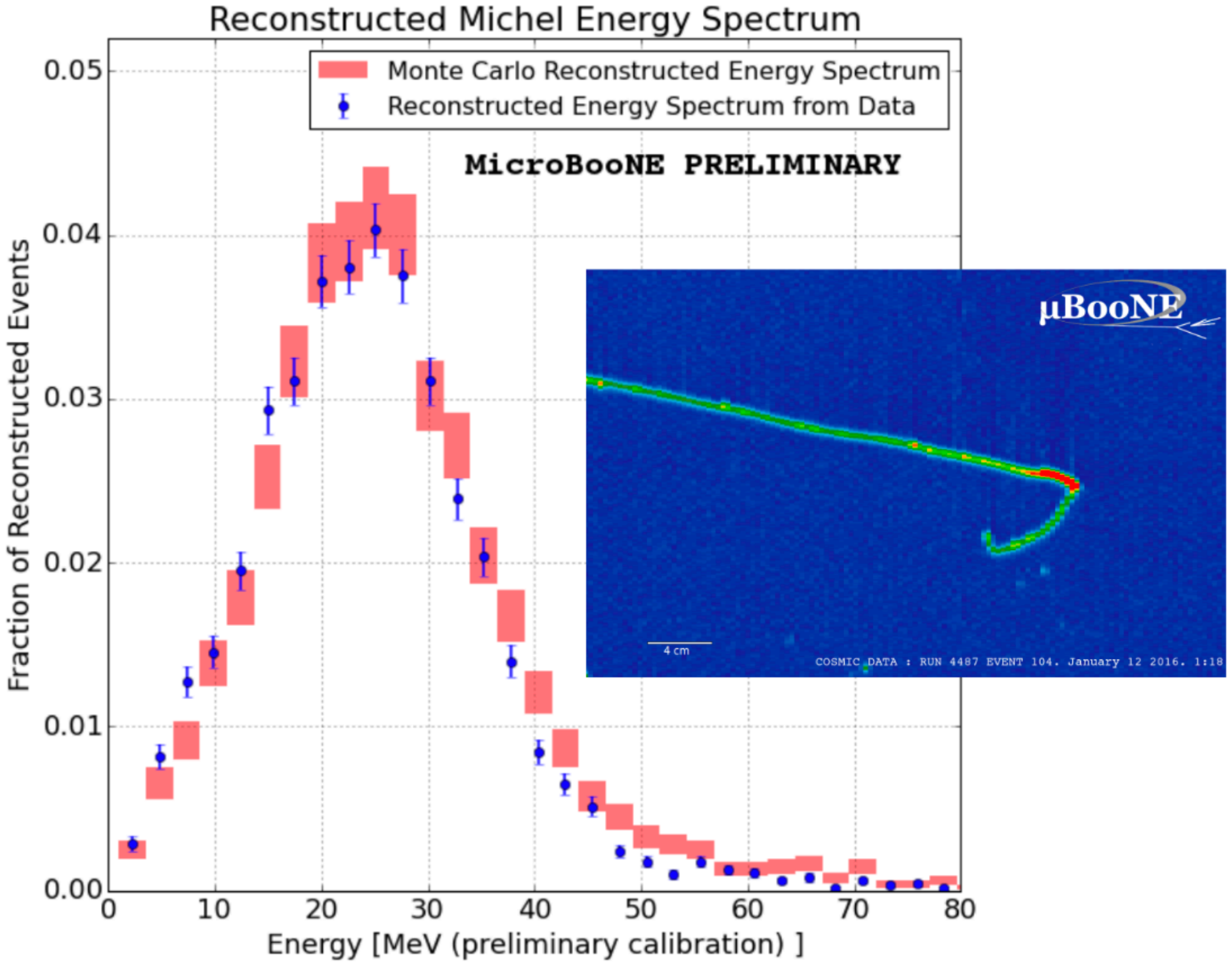




Flux is within a factor two of SNS within same detector stand-off distance. Backgrounds also need to be determined!

Could we do the measurement without a dedicated experiment?

- **MicroBooNE** has demonstrated reconstruction of electrons in the relevant energy range (from muon decays)
- Using the NuMI flux estimate from **arXiv:1510.08431**, here is the predicted event rate
  - Note the large theory uncertainty
- Limited statistics

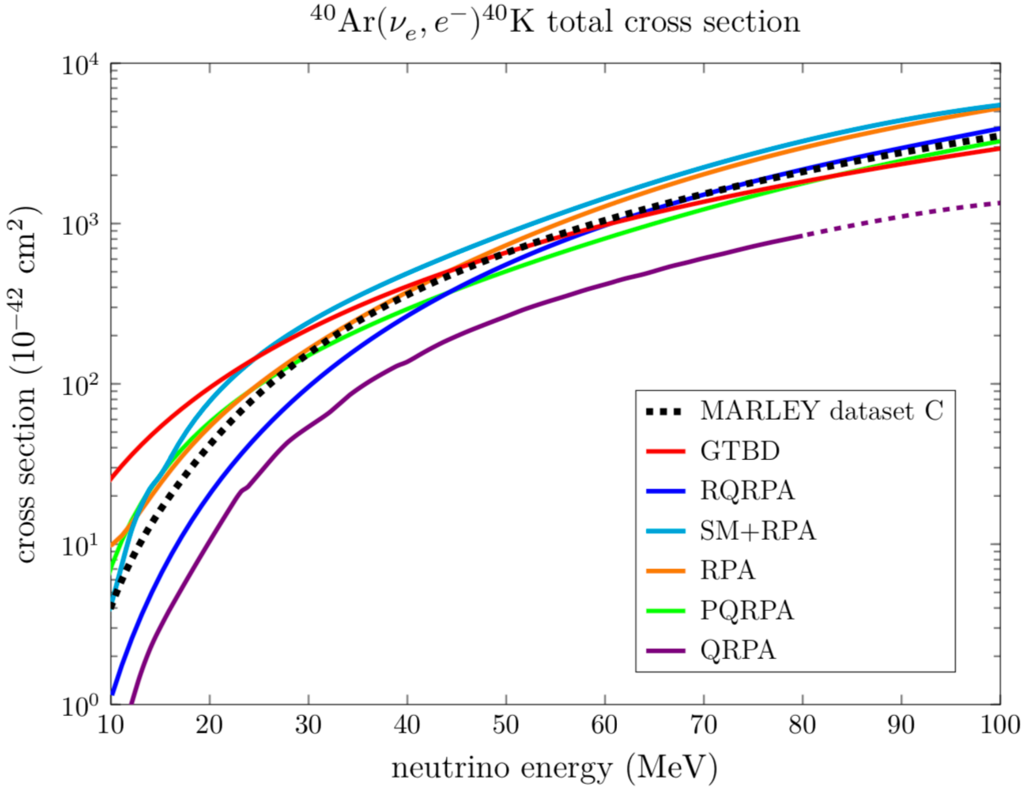


Predicted μDAR ν_e fiducial event rate (truth) in MicroBooNE for

$E_{\nu_e} \geq 10$ MeV

Model	**Fiducial events / week (10^{19} POT)**
QRPA	1.1
RQRPA	2.0
PQRPA	2.4
MARLEY v1.1.1 dataset C	2.8
RPA	3.0
GTBD	3.4
"Hybrid" shell model + RPA	4.0

Calculations used a compilation of cross sections from my PhD thesis, all but MARLEY courtesy of A. Samana



How do things look at the STS?

- A **dedicated experiment @ STS** could achieve far higher statistics and a high impact for DUNE
- Very low DIF contamination
- See E. Conley's talk for a discussion of how cross section uncertainties become a problem for DUNE supernova measurements

PRELIMINARY

Predicted μDAR ν_e event rate (truth) in LAr detector at STS (20 m from target)

$$E_{\nu_e} \geq 10 \text{ MeV}$$

Model	**Events / metric ton / day**
QRPA	1.6
RQRPA	3.2
PQRPA	3.7
MARLEY v1.1.1 dataset C	4.3
RPA	4.7
GTBD	5.2
"Hybrid" shell model + RPA	6.1

Same cross sections as in MicroBooNE calculation

ν_e flux from R. Rapp's talk

Conclusion

- Through its enhanced sensitivity to ν_e, a large liquid argon detector like DUNE can provide a valuable window into the complex physics of supernovae

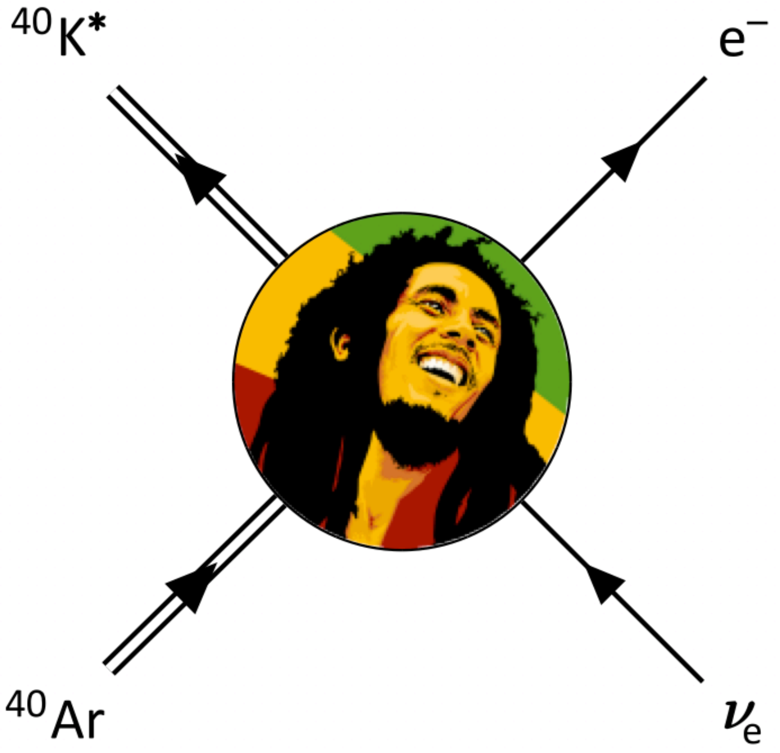
- Despite this great potential, modeling neutrino-argon scattering at tens-of-MeV is **complicated**
  - Cross section remains completely unmeasured!

- Just like oscillation measurements, interpretation of SN ν_e data in ^{40}Ar will require the use of a generator

- **MARLEY represents a first step in this direction**, with more theory engagement and constraining measurements to come!

- A **second target station** could play a world-leading role in helping us better understand ν_e-argon cross sections needed for DUNE

C. Grant

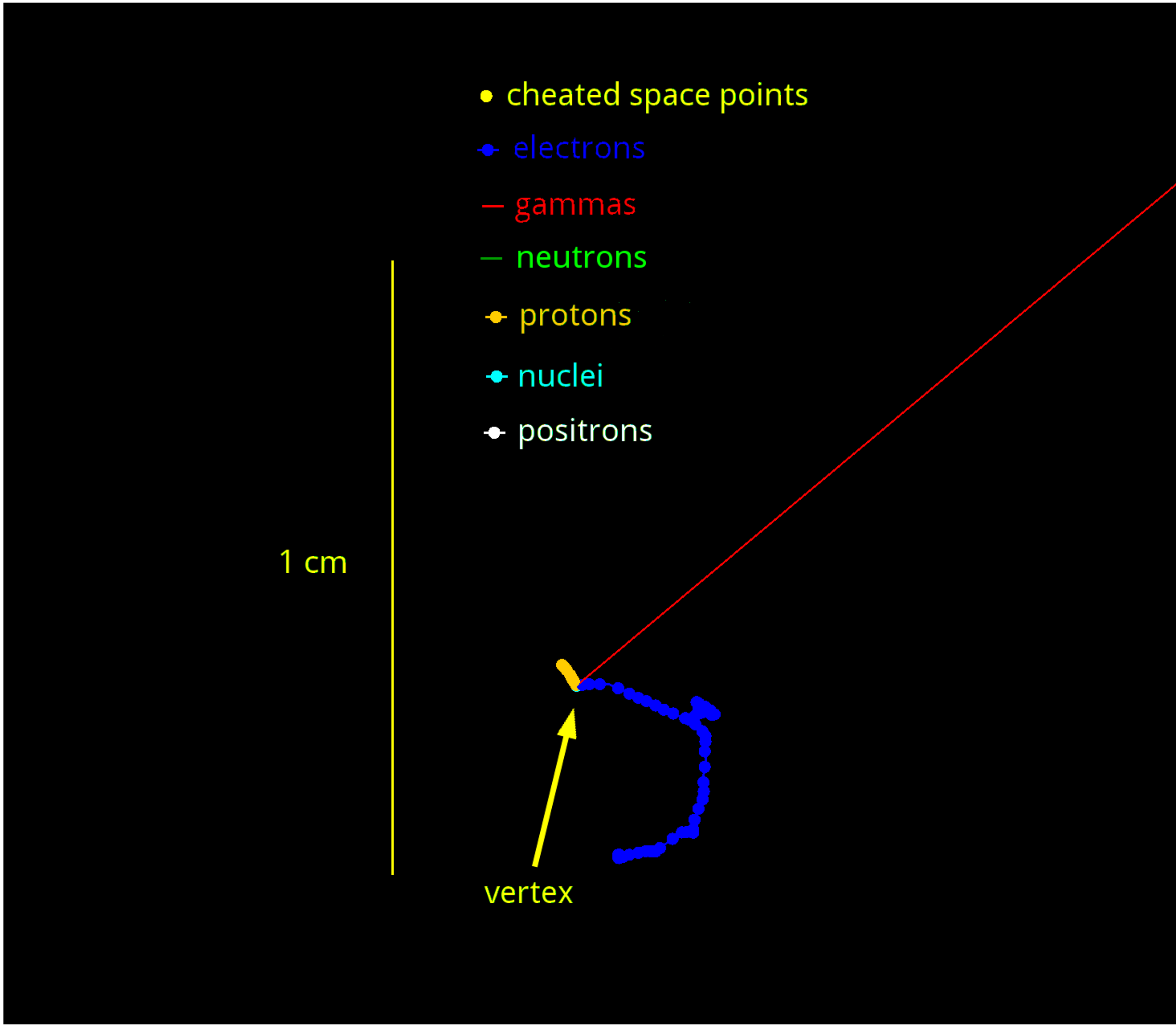


Model of **A**rgon **R**eaction **L**ow **E**nergy **Y**ields

Backup

Example proton event (true trajectories)

- E_ν = 17.8 MeV
- e^- deposited 1.9 MeV
- γ deposited 1.3 MeV
- ^{39}Ar deposited 170 keV
- p deposited 5.4 MeV
- Total visible energy:
  8.7 MeV
- Visible energy sphere radius:
  34 cm
- Protons leave a "stub" on the electron track
- Big error on E_ν if you miss them!



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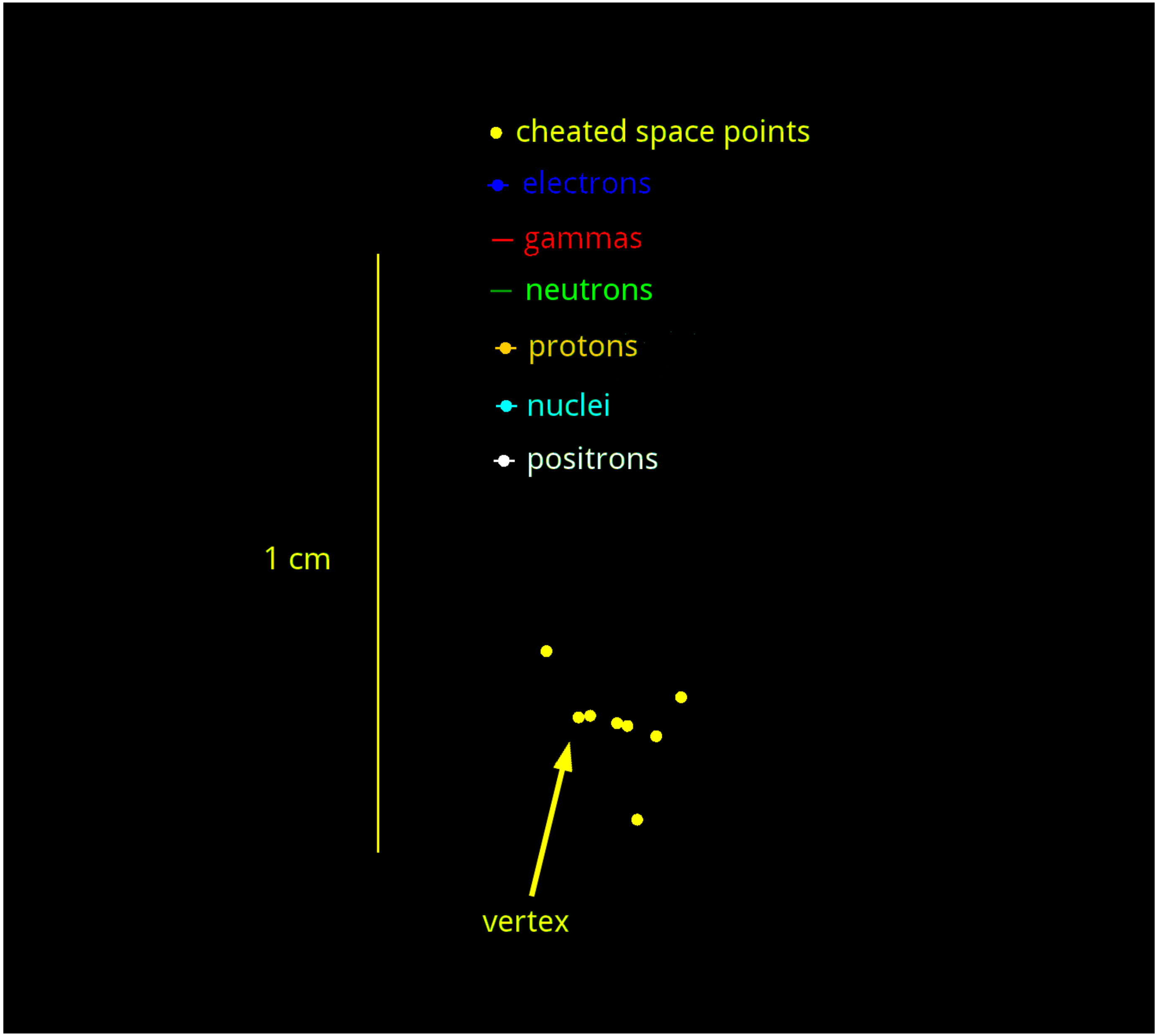
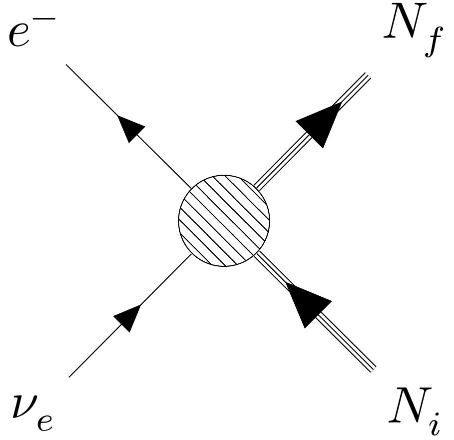


MARLEY ^{40}Ar(ν_e, e$^-$)^{40}K* cross section model

For low-energy CC scattering on a free nucleon, the amplitude may be written as

$$i\mathcal{M} =$$



$$= -i\,\frac{G_F V_{ud}}{\sqrt{2}}\,\ell_\mu \mathrm{n}^\mu$$

$$\mathrm{n}^\mu = \chi^\dagger_{N_f}\,\bar{u}_{N_f}(p_{N_f})\Big[\gamma^\mu F_1(Q^2) + \frac{i}{2m_N}\sigma^{\mu\nu}q_\nu\,F_2(Q^2)$$

$$-\gamma^\mu\gamma^5\,G_A(Q^2) - \frac{q^\mu}{m_N}\gamma^5\,G_P(Q^2)\Big]\tau_-\,u_{N_i}(p_{N_i})\,\chi_{N_i}$$

MARLEY ^{40}Ar(ν_e, e$^-$)^{40}K* cross section model

Let’s rewrite the nucleon matrix element in terms of a current operator:

$$\mathrm{n}^{\mu} = \left\langle N_f \right| \, \hat{\mathrm{j}}^{\mu} \, \left| N_i \right\rangle$$

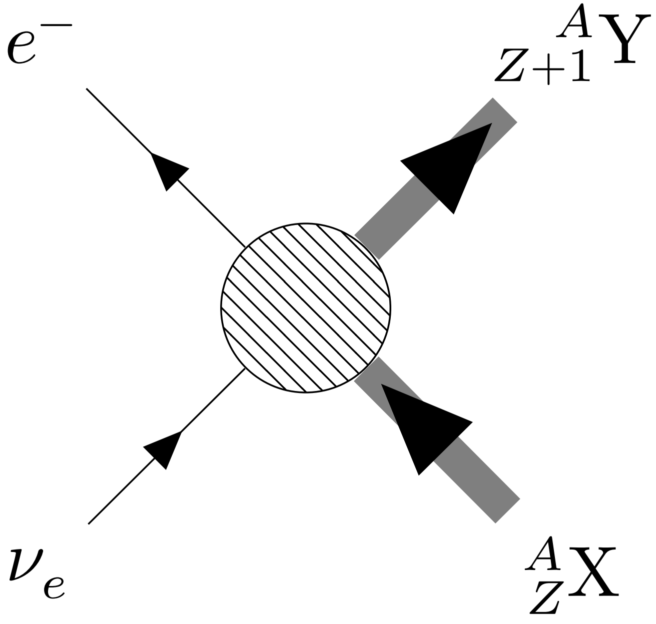
$$\begin{aligned}\hat{\mathrm{j}}^0 \propto \Bigg(& F_1(Q^2) + \frac{(\mathbf{p}_{N_i} + \mathbf{q}) \cdot \boldsymbol{\sigma}}{E_{N_i} + m_N + q^0} \left[\frac{\mathbf{q} \cdot \boldsymbol{\sigma}}{2\, m_N} F_2(Q^2) - G_A(Q^2) + \frac{q^0}{m_N} G_P(Q^2) \right] \\ & - \left[\frac{\mathbf{q} \cdot \boldsymbol{\sigma}}{2\, m_N} F_2(Q^2) - G_A(Q^2) - \frac{q^0}{m_N} G_P(Q^2) \right] \frac{\mathbf{p}_{N_i} \cdot \boldsymbol{\sigma}}{E_{N_i} + m_N} \\ & + \frac{(\mathbf{p}_{N_i} + \mathbf{q}) \cdot \boldsymbol{\sigma}}{E_{N_i} + m_N + q^0} \; F_1(Q^2) \; \frac{\mathbf{p}_{N_i} \cdot \boldsymbol{\sigma}}{E_{N_i} + m_N} \Bigg) \tau_- \end{aligned}$$

(similar long expression for spatial components)

MARLEY ^{40}Ar(ν_e, e$^-$)^{40}K* cross section model

A sum over nucleons is used to evaluate the **nuclear** operator

$$i\mathcal{M} =$$



$$= -i\,\frac{G_F V_{ud}}{\sqrt{2}}\,\ell_\mu\,\mathcal{N}^\mu$$

Exponential comes from switch to position space

$$\mathcal{N}^\mu \equiv \left\langle f \middle| \hat{\mathcal{N}}^\mu \middle| i \right\rangle \qquad \hat{\mathcal{N}}^\mu \approx \sum_{k=1}^{A} e^{i\mathbf{q}\cdot\mathbf{x}_k}\,\hat{\mathbf{j}}^\mu(k)$$

MARLEY transmission coefficient model

- Level densities are calculated using the BackshiftedFermiGasModel with global fit parameters from Koning, et al. (2008)

$$\rho_{\mathrm{BFGM}}(\mathrm{E_x}, \mathrm{J}, \Pi) = \frac{\sqrt{\pi}}{24}\left[\frac{2\mathrm{J}+1}{2\sqrt{2\pi}\sigma^3}\right]\left[\frac{\exp(2\sqrt{\mathrm{aU}})}{\mathrm{a}^{1/4}\mathrm{U}^{5/4}}\right]\exp\left[-\frac{(\mathrm{J}+\frac{1}{2})^2}{2\sigma^2}\right]$$

- Gamma transmission coefficients use the StandardLorentzianModel and global giant resonance fits from RIPL

- Nuclear fragment transmission coefficients are calculated using the global optical potential of Koning & Delaroche (KoningDelarocheOpticalModel)

A. J. Koning and J. P. Delaroche, *Nuclear Physics A* **713** 3-4 (2003)

$$\mathcal{U} = \mathcal{V}_V + i\mathcal{W}_V + i\mathcal{W}_D + \mathcal{V}_{SO} + i\mathcal{W}_{SO} + \mathcal{V}_C$$

$$\left[\frac{d^2}{dr^2} - \frac{\ell'(\ell'+1)}{r^2} + k^2 - \frac{2\mu}{\hbar^2}\mathcal{U}\right] u_{\ell' j'}(r) = 0$$

- Solve radial Schrödinger equation numerically in matching region

incoming Coulomb wavefunction

S-matrix element

outgoing Coulomb wavefunction

$$\lim_{r\to\infty} u_{\ell' j'}(r) = \frac{i}{2}\left[H^-_{\ell'}(k,r) - S_{\ell' j'} H^+_{\ell'}(k,r)\right]$$

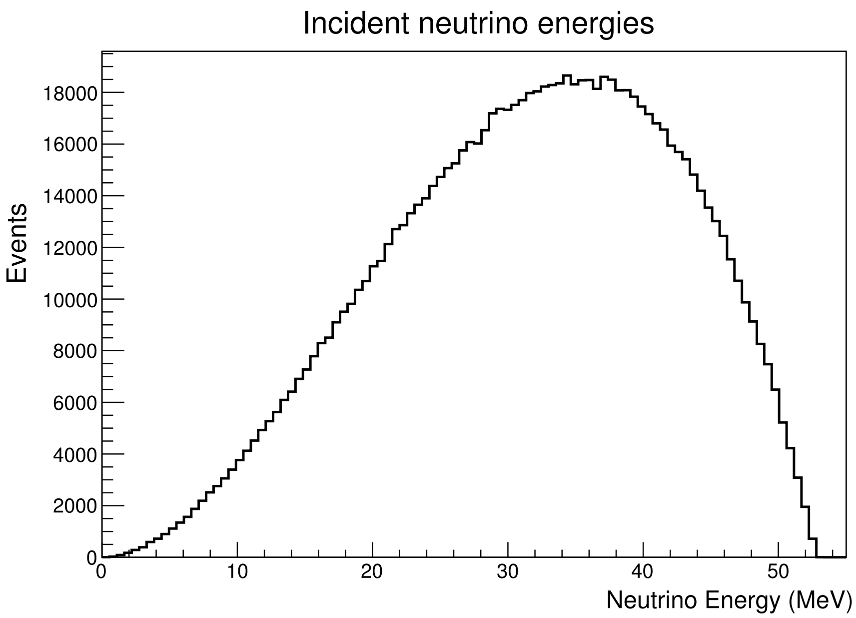
- Match to asymptotic solution, extract transmission coefficient

$$T_{\ell' j'} = 1 - |S_{\ell' j'}|^2$$

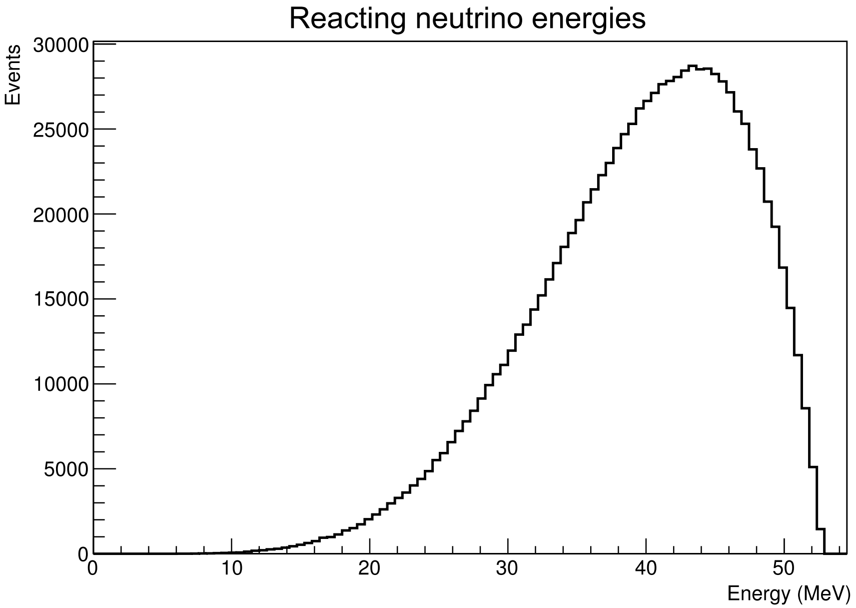
Transmission coefficient represents the probability of penetrating the nuclear surface

How does MARLEY create events?

- The user describes the incident spectrum, the reaction matrix elements, etc. in a configuration file
- Based on the incident spectrum and the reaction cross section(s), MARLEY creates a probability density function for sampling *reacting* neutrinos


Incident neutrino energies

Cross section weighting


Reacting neutrino energies

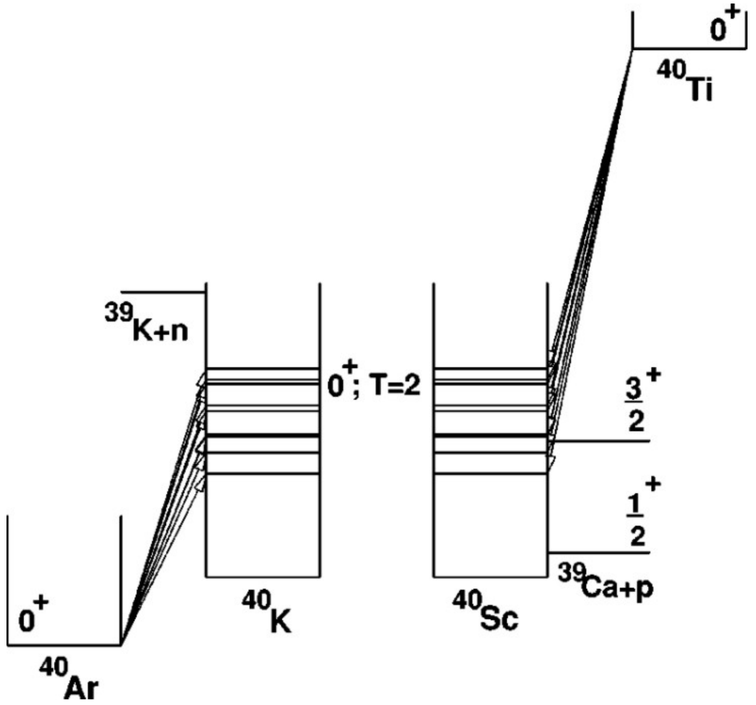
- A rejection technique is used to sample a reacting neutrino energy.
- If multiple reactions are defined, MARLEY selects one using the cross sections as weights

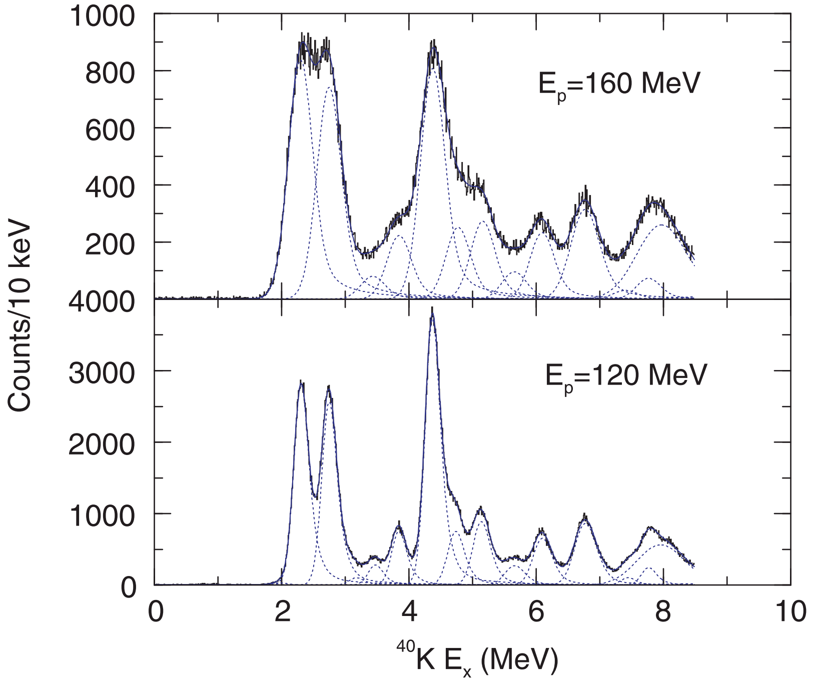
Putting all of the pieces together gives us the following differential cross section for a particular nuclear level:

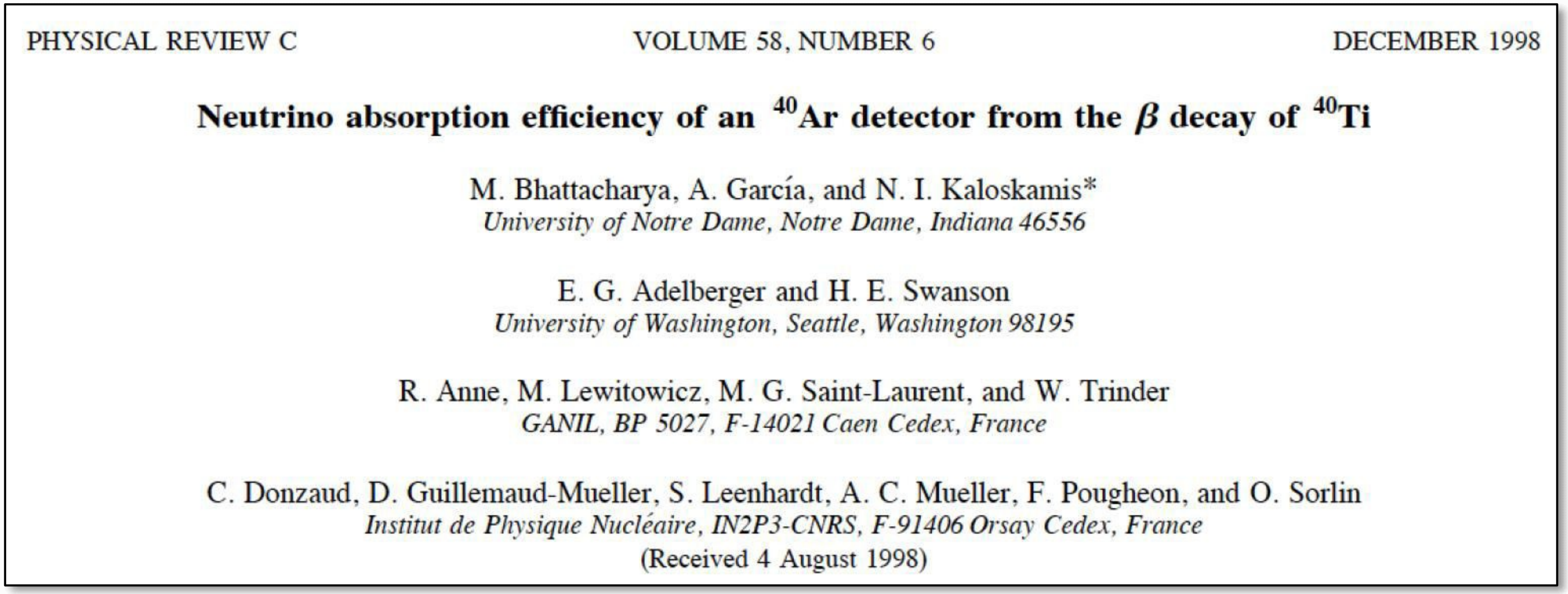
$$\frac{d\sigma}{d\Omega} = \frac{G_F{}^2 \left|V_{ud}\right|^2}{4\pi^2} \left|\mathbf{p}_e\right| E_e \, F(Z_f, E_e) \times \left[(1+\beta_e \cos\theta_e) B(F) + \left(\frac{3-\beta_e \cos\theta_e}{3}\right) B(GT)\right]$$

Calculating the cross section is straightforward if we can figure out the nuclear matrix elements B(F) and B(GT)

There are two relevant experiments in the literature. Both are indirect measurements.







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Neutrino absorption efficiency of an ^{40}Ar detector from the β decay of ^{40}Ti

M. Bhattacharya, A. García, and N. I. Kaloskamis*
University of Notre Dame, Notre Dame, Indiana 46556

E. G. Adelberger and H. E. Swanson
University of Washington, Seattle, Washington 98195

R. Anne, M. Lewitowicz, M. G. Saint-Laurent, and W. Trinder
GANIL, BP 5027, F-14021 Caen Cedex, France

C. Donzaud, D. Guillemaud-Mueller, S. Leenhardt, A. C. Mueller, F. Pougheon, and O. Sorlin
Institut de Physique Nucléaire, IN2P3-CNRS, F-91406 Orsay Cedex, France

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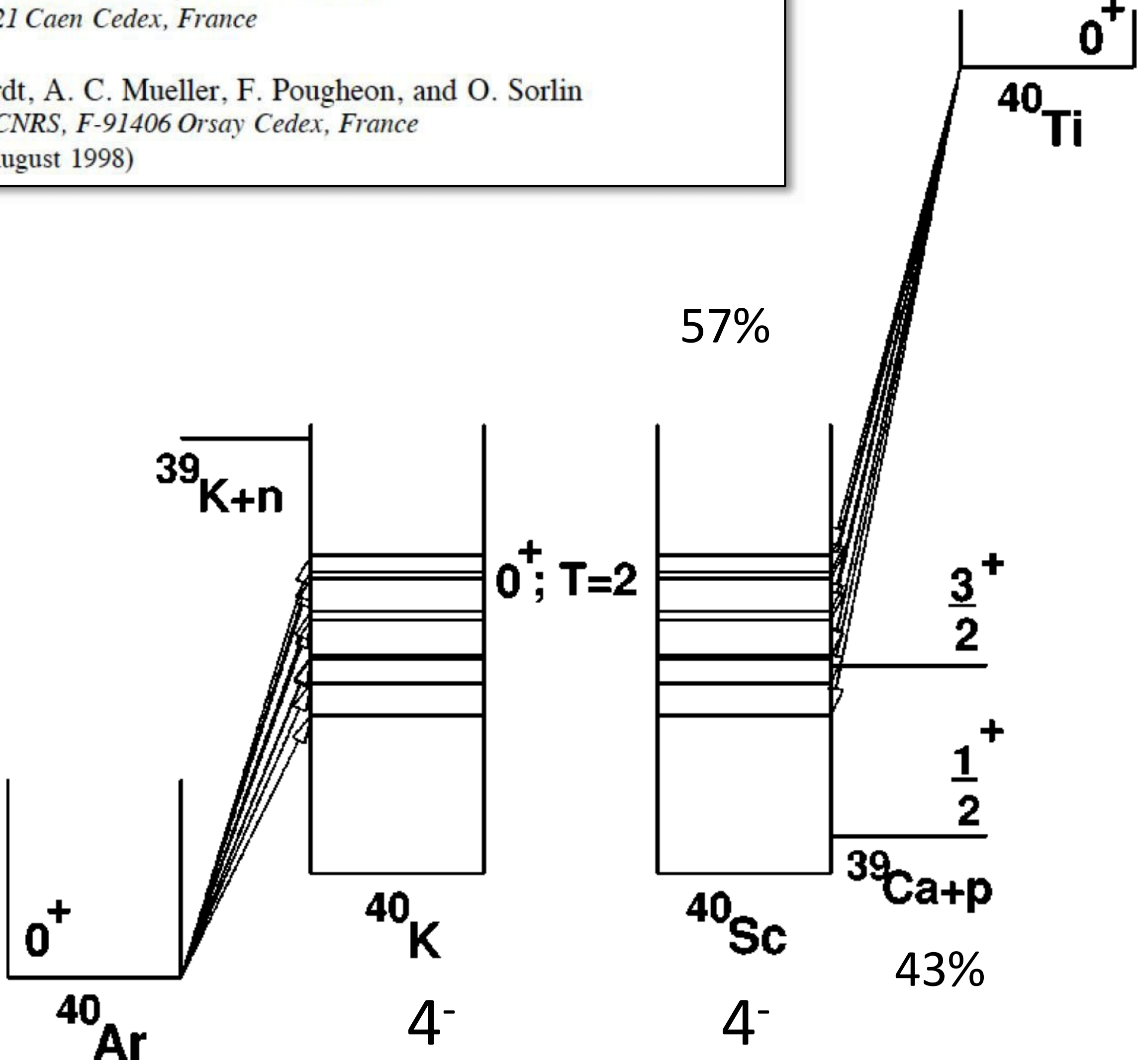
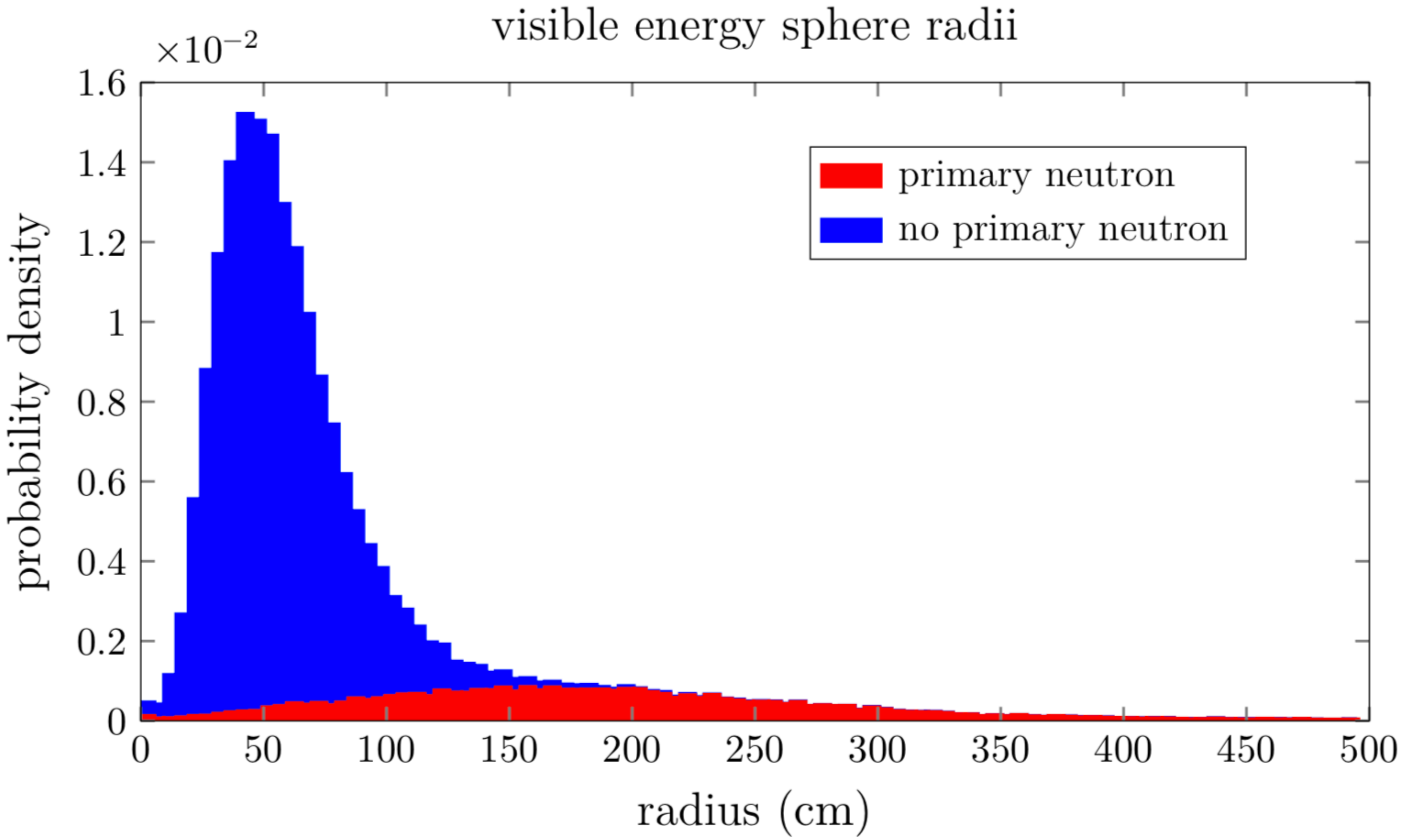
Make 40-Ti via heavy ions on a thin, heavy target (e.g. Cr on Ni). Embed ions in silicon detector.

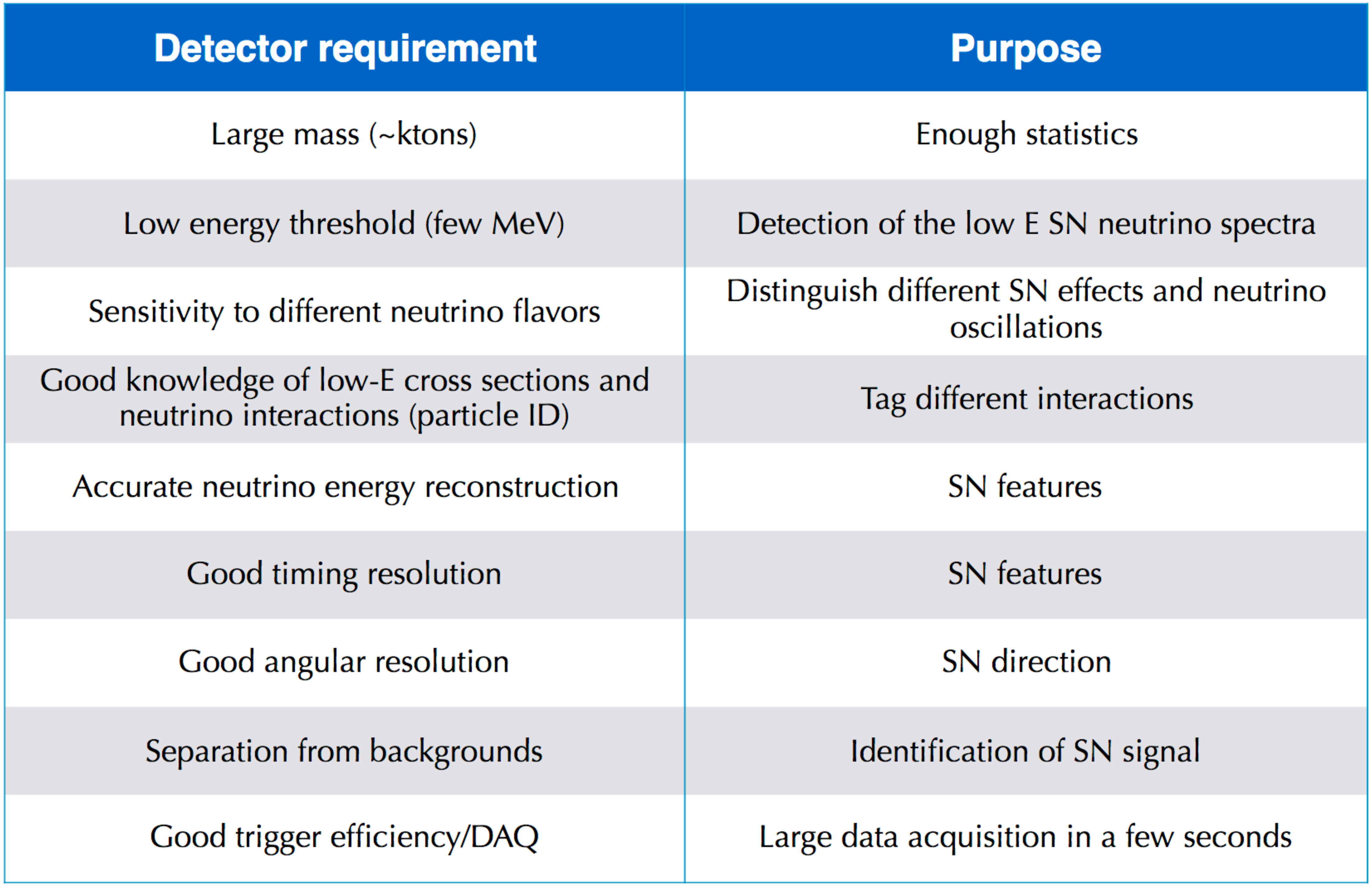
Use TOF and dE/dx to separate 40-Ti out from ion "soup"

Observe beta decay to 40-Sc excited states, which decay via delayed proton emission




visible energy sphere radii
×10⁻²
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
probability density
0
50
100
150
200
250
300
350
400
450
500
radius (cm)
🟥 primary neutron
🟦 no primary neutron

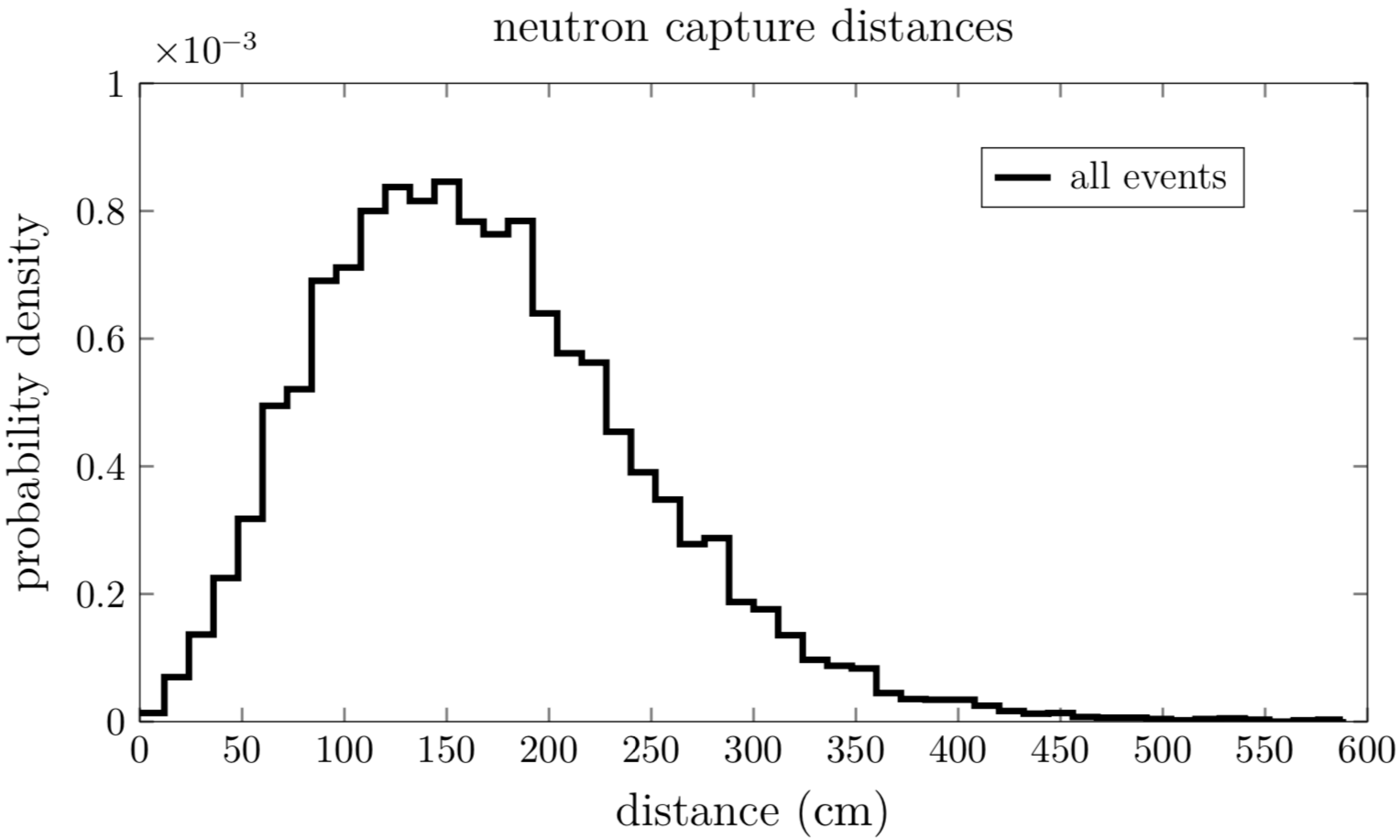
A “wish list” for a supernova neutrino detector



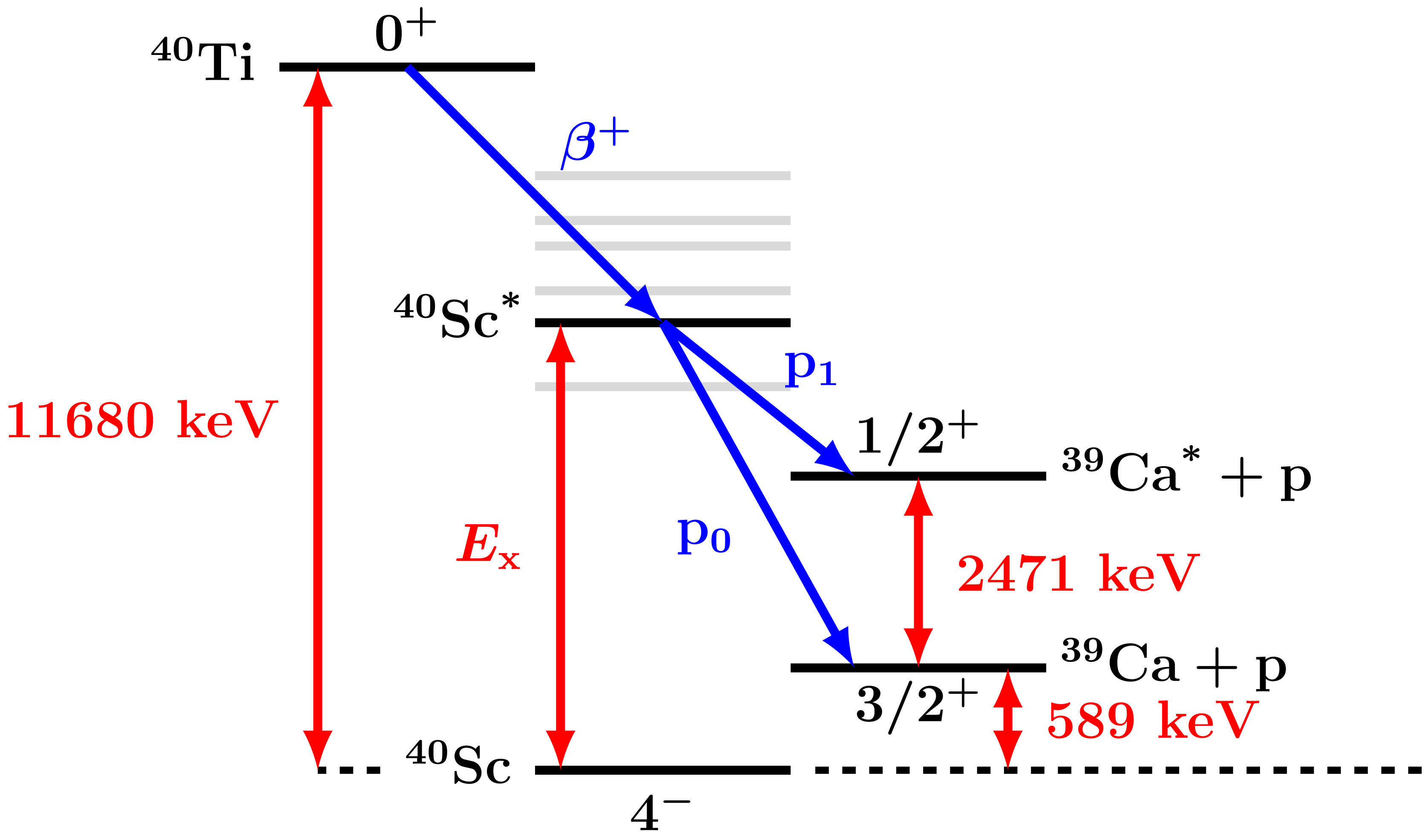
Detector requirement	Purpose
Large mass (~ktons)	Enough statistics
Low energy threshold (few MeV)	Detection of the low E SN neutrino spectra
Sensitivity to different neutrino flavors	Distinguish different SN effects and neutrino oscillations
Good knowledge of low-E cross sections and neutrino interactions (particle ID)	Tag different interactions
Accurate neutrino energy reconstruction	SN features
Good timing resolution	SN features
Good angular resolution	SN direction
Separation from backgrounds	Identification of SN signal
Good trigger efficiency/DAQ	Large data acquisition in a few seconds

I. Gil Botella

Challenging to do all of this with just one!


neutron capture distances
$\times 10^{-3}$
1
0.8
0.6
0.4
0.2
0
probability density
all events
0
50
100
150
200
250
300
350
400
450
500
550
600
distance (cm)

^{40}Sc* levels were found using the proton energy



$$E_{\mathrm{x}} = E_{\mathrm{p}}^{\mathrm{lab}} + \begin{cases} 589 \ \ \mathrm{keV} & \mathrm{p}_0 \\ 3060\ \mathrm{keV} & \mathrm{p}_1 \end{cases}$$

- 21 p_0 and 7 p_1 decays were observed