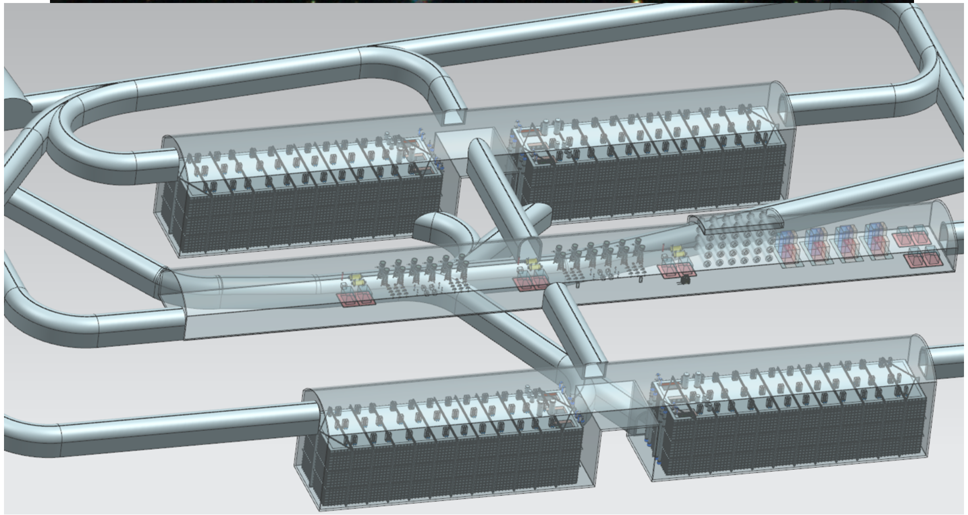
# Simulating supernova neutrino events in liquid argon



Steven Gardiner

University of California, Davis

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Toronto, Canada

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# Outline

- Motivation for argon-based supernova neutrino detectors

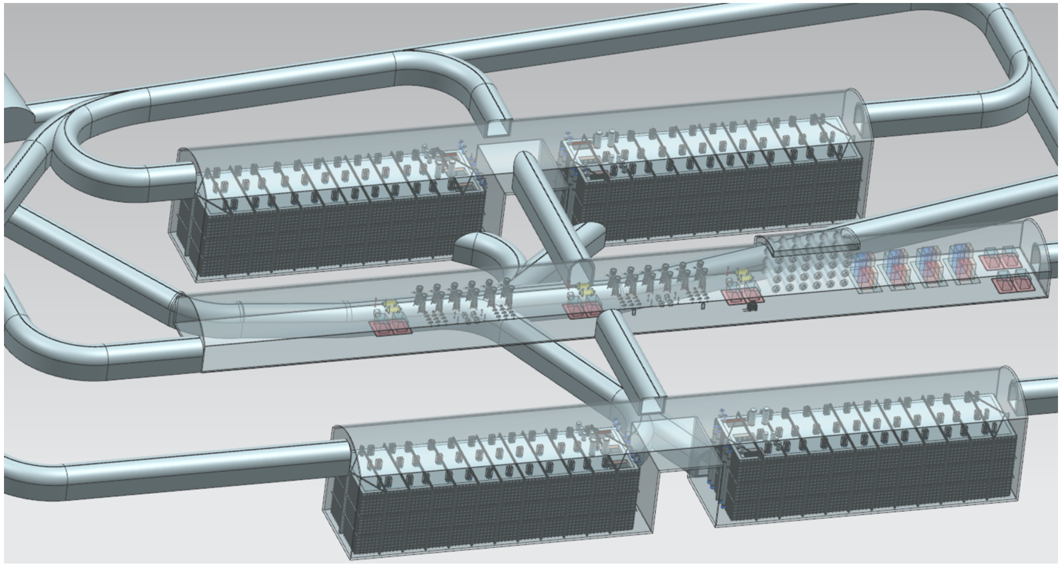
- Event reconstruction challenges (why is this hard?)

- **MARLEY**: **M**odel of **A**rgon **R**eaction **L**ow **E**nergy **Y**ields
  - Ingredients in our model
  - Example simulation results

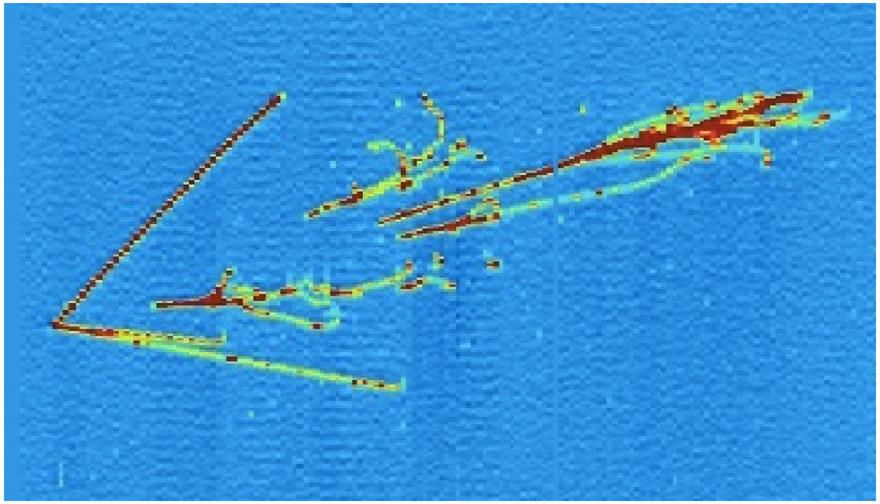
- Current studies and future prospects

# Why argon?

- Large water and liquid scintillator supernova neutrino detectors already exist
- Key statement from Evan O'Connor's talk this morning:
    - **"Each species carries important and complementary info, so we need to measure them all"**
- Argon can help us obtain complementary information



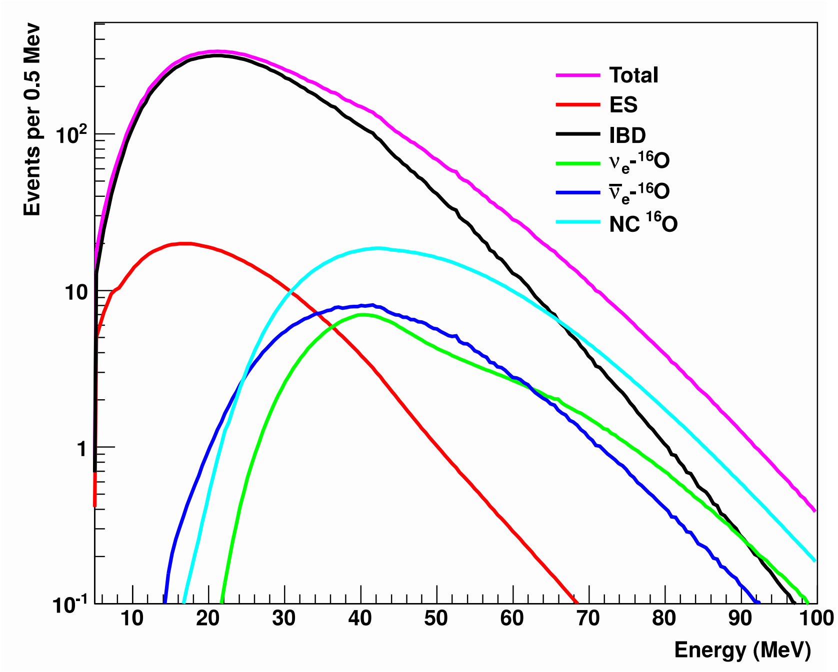
DUNE far detector



ArgoNeuT event display

# Water- and argon-based neutrino detectors have complementary sensitivities to SN neutrinos

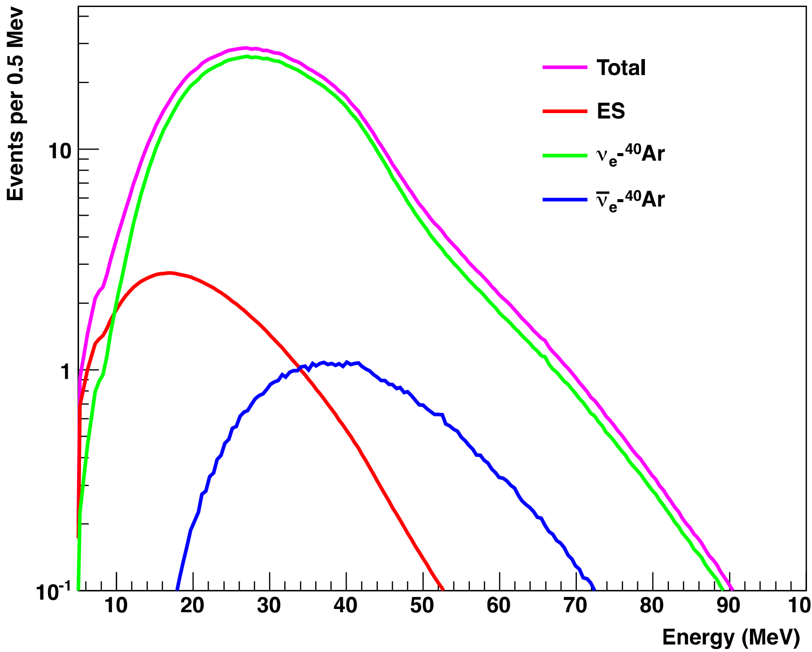
## 100 kt Water Cherenkov Detector



| Reaction | | Events / 10 kt |
|---|---|---|
| **(CC)** | $\bar{\nu}_e + p \rightarrow e^+ + n$ | **~2,000** |
| (CC) | $\nu_e + {}^{16}O \rightarrow e^- + {}^{16}F^*$ | ~20 |
| (CC) | $\bar{\nu}_e + {}^{16}O \rightarrow e^+ + {}^{16}N^*$ | ~60 |
| (NC) | $\nu_x + {}^{16}O \rightarrow \nu_x + {}^{16}O^*$ | ~50 |
| (ES) | $\nu_x + e^- \rightarrow \nu_x + e^-$ | ~70 |

Estimates for SN at 10 kpc based on work by K. Scholberg

## 17 kt Liquid Argon Time Projection Chamber (LArTPC)

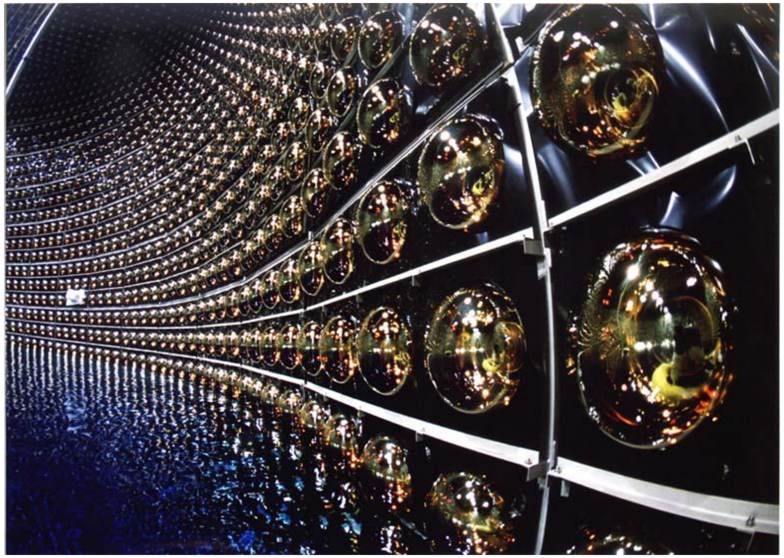


| Reaction | | Events / 10 kt |
|---|---|---|
| **(CC)** | $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$ | **~700** |
| (CC) | $\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$ | ~60 |
| (NC) | $\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$ | ~90 |
| (ES) | $\nu_x + e^- \rightarrow \nu_x + e^-$ | ~85 |

Estimates for SN at 10 kpc based on work by K. Scholberg and A. Hayes

# Supernova neutrino detection with water Cherenkov detectors

- Inverse beta decay is the dominant reaction
- Number of detected photons gives a positron energy measurement
- From there, reconstructing the antineutrino energy is straightforward



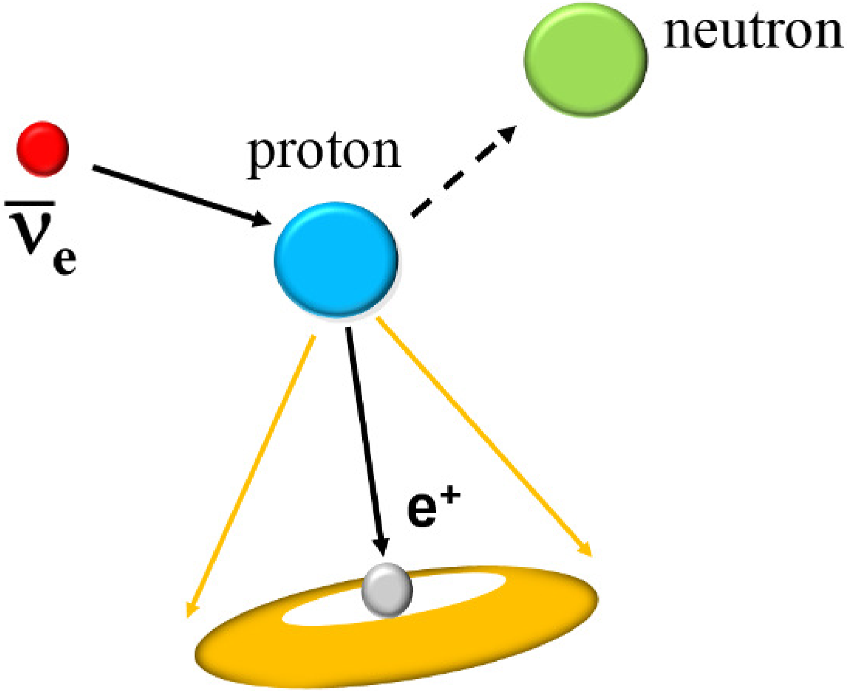
**Reconstructing true antineutrino energy:**

Outgoing $e^+$ energy

Neutron proton mass difference

Recoil energy of neutron (negligible)

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

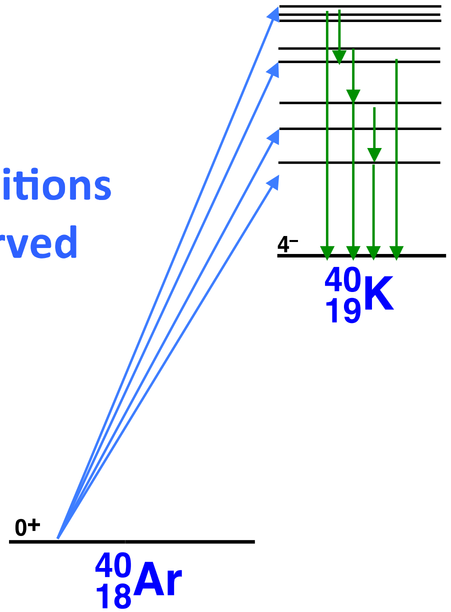


**inverse beta decay**

# 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:**

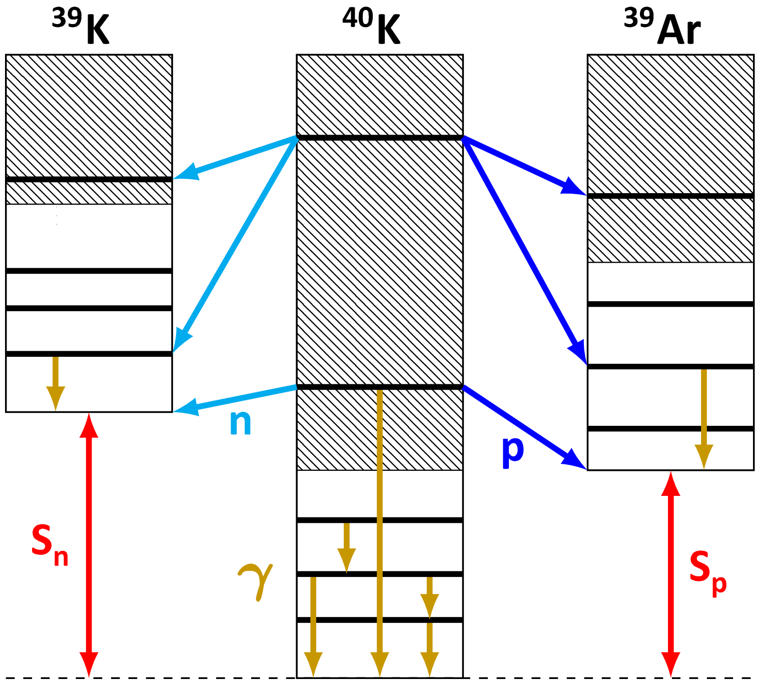
$Q$ is determined by measuring de-excitation gammas and nucleons

Outgoing $e^-$ Energy

Energy donated to transition

Recoil Energy of Nucleus (negligible)

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



# The need for a supernova neutrino simulation tool

- Simulations are needed to understand LArTPC response to SN neutrinos

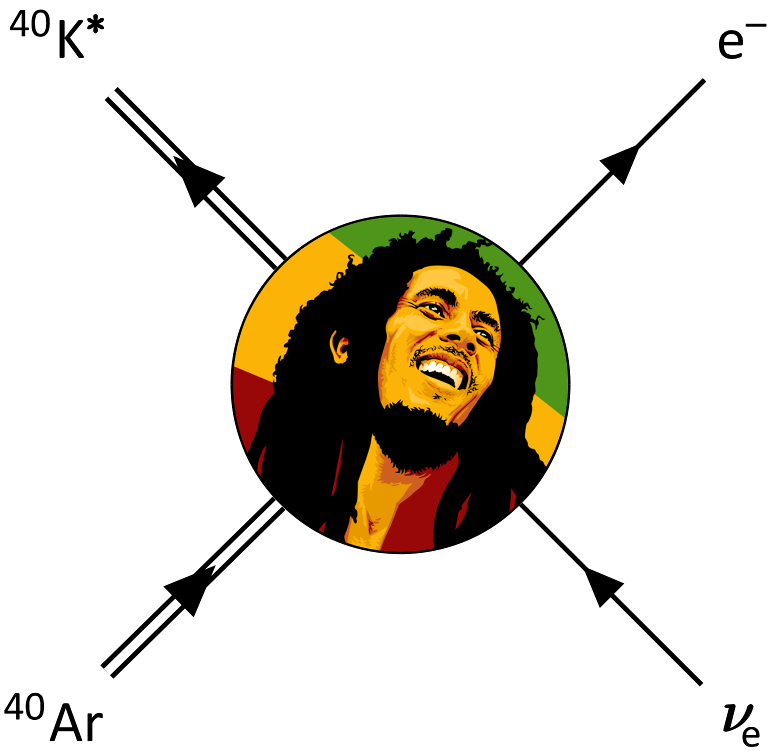
- A number of neutrino event generators exist, but the emphasis is on high-energy physics

- In the low tens-of-MeV regime, nuclear structure details become quite important!

- We have developed a new generator to help us understand the response of $^{40}$Ar to SN neutrinos
  - Nuclear data measurements (levels, gammas, matrix elements) can help us

# MARLEY: Model of Argon Reaction Low-Energy Yields

- Event generator for supernova neutrinos on $^{40}$Ar
- Current version does CC $\nu_e$ (dominant channel)
- Framework allows adding new reactions, target nuclei, etc.
- In use by DUNE for SN simulations
- Also has users from several other liquid argon experiments



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

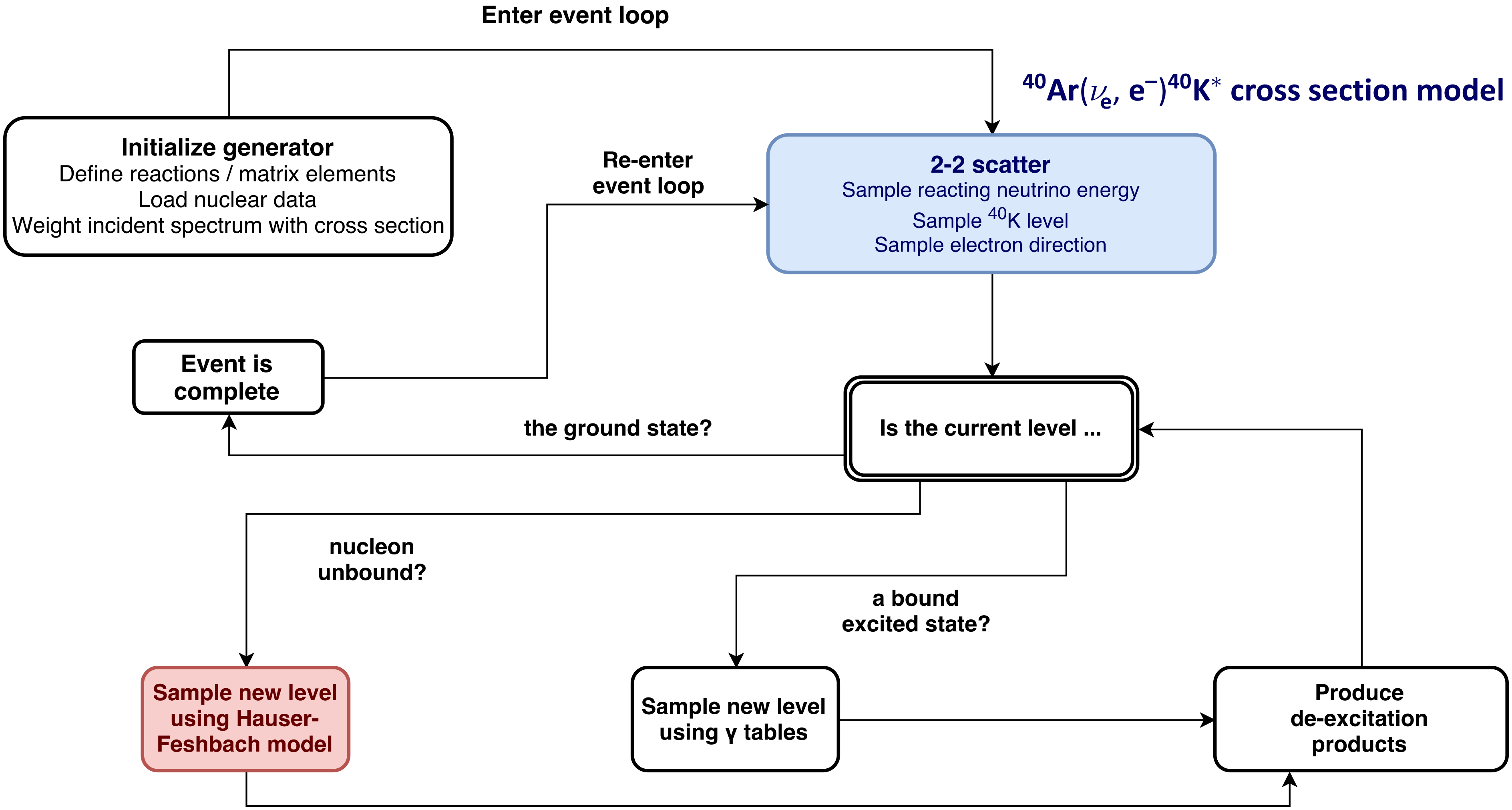
Bob Marley illustration by Zero Anixter

Collaborators:

S. Gardiner, C. Grant,

E. Pantic, R. Svoboda

# MARLEY event generation flowchart



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

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

Enter event loop

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

Re-enter event loop

**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**

Transmission coefficient model

# MARLEY $^{40}\mathrm{Ar}(\nu_e, e^-)^{40}\mathrm{K}^*$ Cross Section Model

$2 \to 2$ scattering differential cross section (in general)

$$\left.\frac{d\sigma}{d\Omega}\right|_{\mathrm{CM}} = \frac{1}{4\pi^2}\left[\frac{E_a E_b E_c E_d}{s}\right]\frac{|\mathbf{p}_\mathrm{f}|}{|\mathbf{p}_\mathrm{i}|}\left|\langle f|\, H_\mathrm{int}\, |i\rangle\right|^2$$

Low-energy CC interaction Hamiltonian

$$H_\mathrm{int}(\mathbf{r}) = \frac{\mathrm{G_F}}{\sqrt{2}}\,|\mathrm{V_{ud}}|\, J_\mu^\dagger L^\mu(\mathbf{r})$$

Leptonic matrix element

$$L^\mu(\mathbf{r}) = \bar{u}_{s_e}\gamma^\mu(1-\gamma_5)u_{s_{\nu_e}} e^{-i\mathbf{r}\cdot\mathbf{k}} = \ell^\mu\, e^{-i\mathbf{r}\cdot\mathbf{k}}$$

Nuclear current operator

$$J_\mu = \gamma_0\left[g_\mathrm{V}\gamma_\mu + \frac{g_\mathrm{M}}{2\mathrm{m_N}} i\sigma_{\mu\nu}k_\nu - g_\mathrm{A}\gamma_\mu\gamma_5 + \frac{g_\mathrm{P}}{\mathrm{m_e}}k_\mu\gamma_5\right]$$

Momentum Transfer

$$k \equiv p_e - p_{\nu_e} = P_i - P_f$$

See Krmpotić, et al., Phys. Rev. C **71**, 044319 (2005) for a full calculation.

# MARLEY $^{40}\mathrm{Ar}(\nu_\mathrm{e}, \mathrm{e}^-)^{40}\mathrm{K}^*$ Cross Section Model

So far, we've been working with the **allowed approximation**
(low momentum transfer limit keeps the leading order terms)

Measurements are available for the surviving terms, facilitating use with nuclear data.
For supernova neutrinos, this should be a decent approximation.

$$|\langle f|\, H_\mathrm{int}\, |i\rangle|^2 \approx \mathrm{G_F}\, |\mathrm{V_{ud}}|^2 \left[(1 + \beta_\mathrm{e}\cos\theta_\mathrm{e})\, \mathrm{B(F)} + \left(\frac{3 - \beta_\mathrm{e}\cos\theta_\mathrm{e}}{3}\right) \mathrm{B(GT)}\right]$$

where the Fermi and Gamow-Teller nuclear matrix elements are given by

$$\mathrm{B(F)} \equiv g_\mathrm{V}^2 \frac{\left|\langle J_f\, T_f \,\|\, \tau_- \,\|\, J_i\, T_i\rangle\right|^2}{2J_i + 1} \qquad \mathrm{B(GT)} \equiv g_\mathrm{A}^2 \frac{\left|\langle J_f\, T_f \,\|\, \boldsymbol{\sigma}\tau_- \,\|\, J_i\, T_i\rangle\right|^2}{2J_i + 1}$$

**Fermi transition is well-understood**

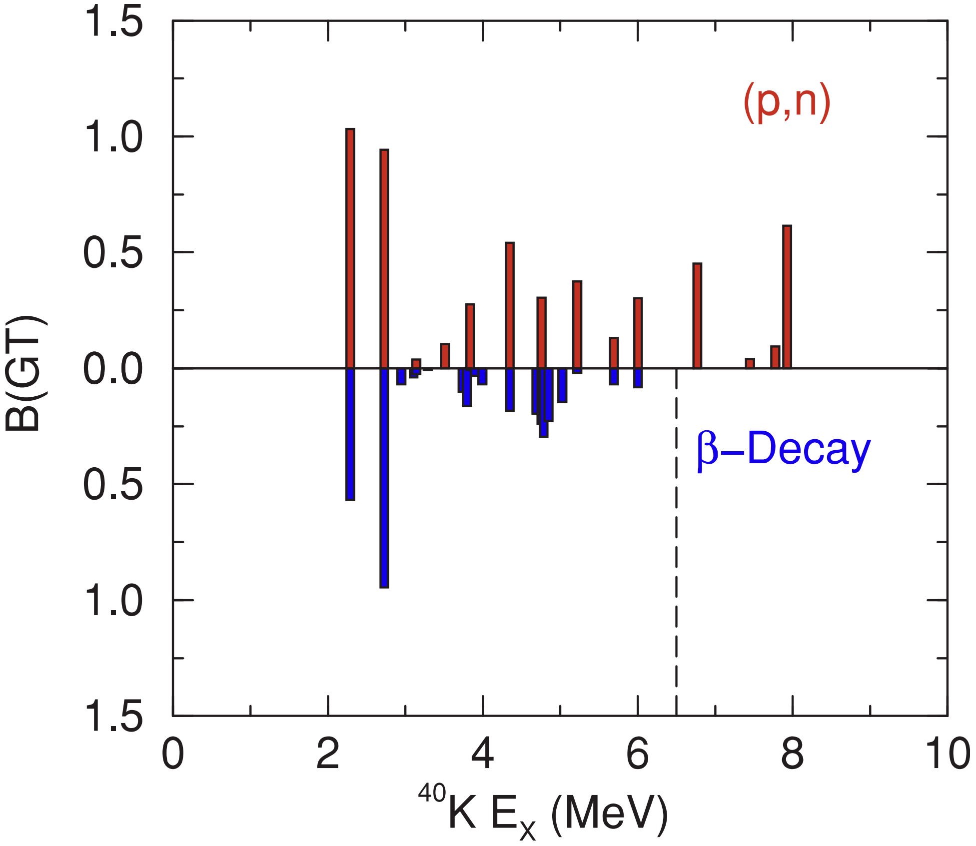
**Gamow-Teller less so…**

# World’s B(GT) data for $^{40}$Ar

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

**Weak-interaction strength from charge-exchange reactions versus $\beta$ 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
- Hard to calculate and hard to measure!
- Karakoç, et al. Phys. Rev. C 89, 064313 (2014) refers to a third measurement that remains unpublished
- Must be supplemented by theory at higher energies

# 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

Fermi and Gamow-Teller nuclear matrix elements

electron energy

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

coupling constants

electron momentum

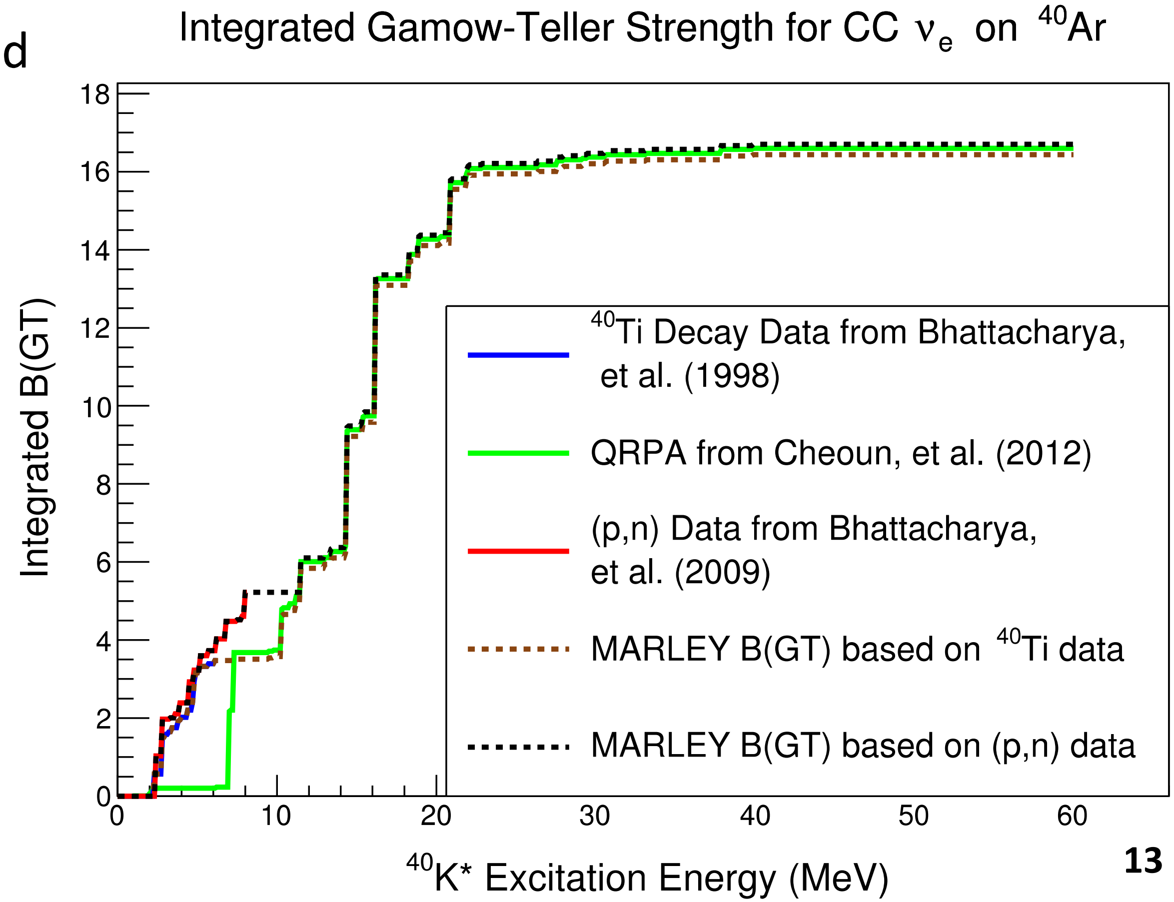
Fermi function

electron angular distributions

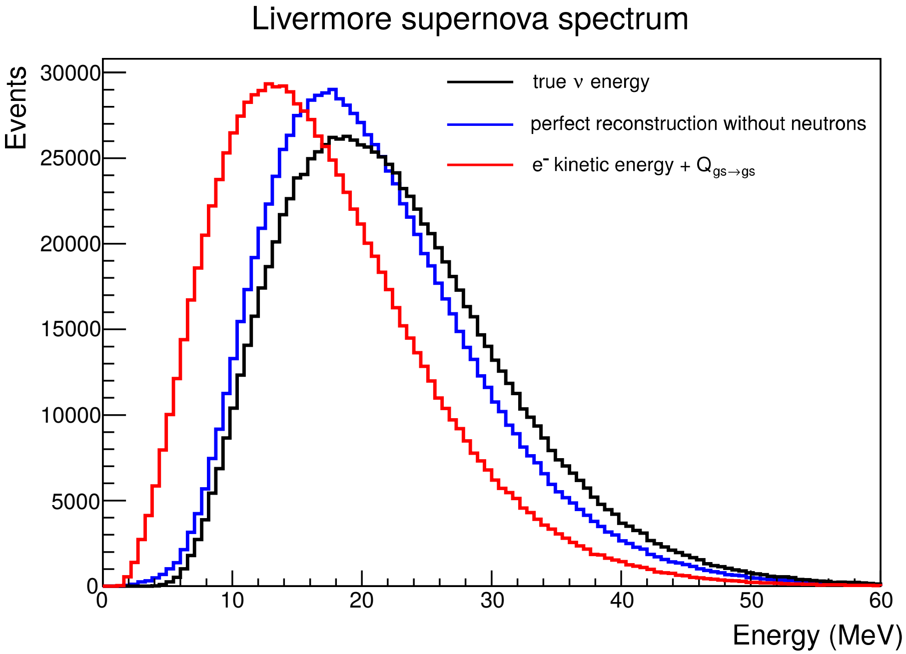
- MARLEY uses tabulated B(F) and B(GT) values to compute cross sections

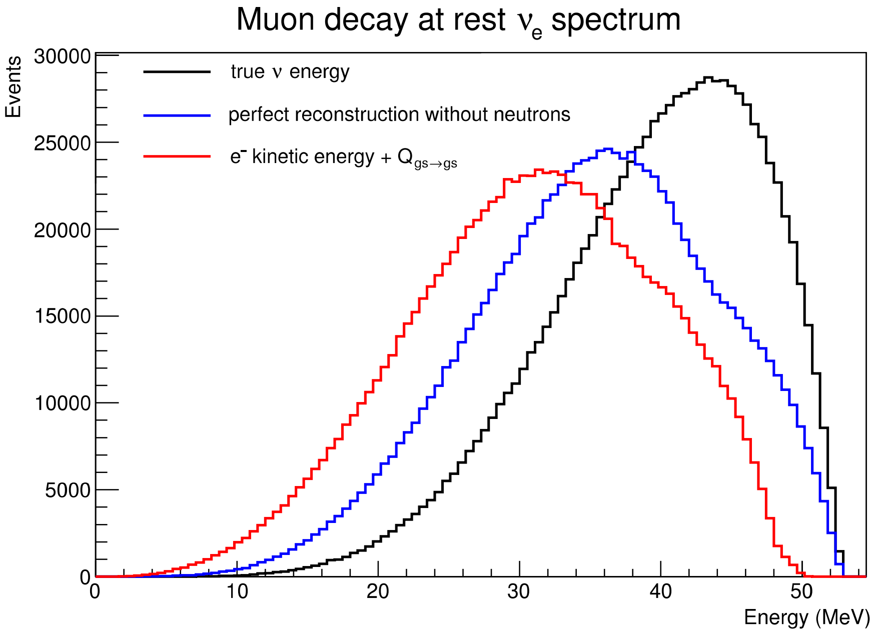
- Two-two scattering final states are sampled using this cross section
  1. $^{40}\mathrm{K}^*$ excited level
  2. $e^-$ energy
  3. $e^-$ direction

- De-excitation of the final nucleus is simulated next



# MARLEY branching ratios for two different source spectra





$^{40}$K* de-excitations

- $\gamma$s only: 83.7%
- single n + $\gamma$s: 14.6%
- single p + $\gamma$s: 1.5%
- other: 0.2%

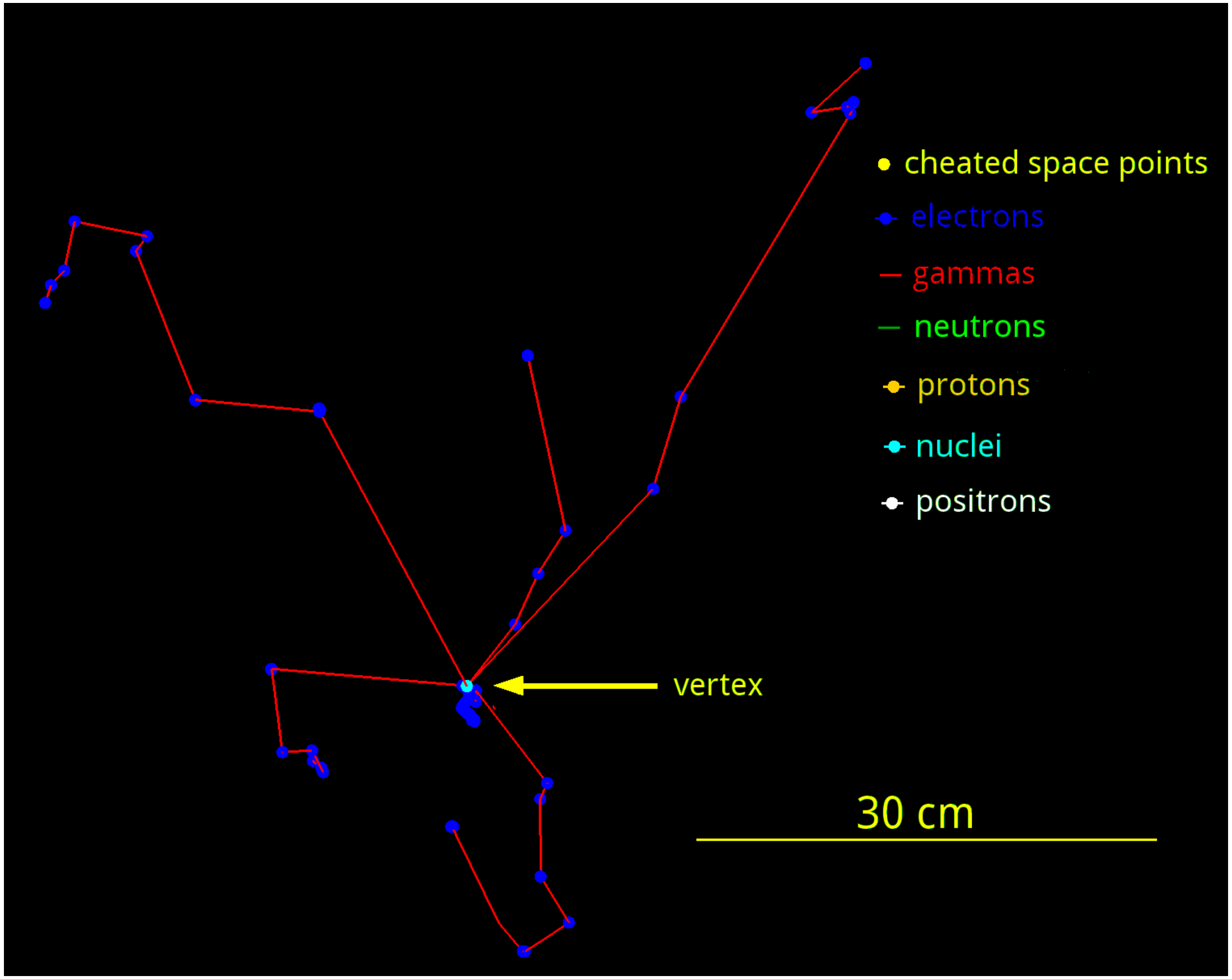
$^{40}$K* de-excitations

- $\gamma$s only: 58.0%
- single n + $\gamma$s: 36.3%
- single p + $\gamma$s: 4.6%
- other: 1.1%

A simple table of branching ratios is inadequate due to this energy dependence

# Example e⁻ + $\gamma$s Only Event (true trajectories)

- $E_\nu$ = 16.1 MeV
- e⁻ deposited 10.2 MeV
- $\gamma$s deposited 4.3 MeV
- $^{40}$K deposited 3.7 keV
- Total visible energy:
  14.5 MeV
- Visible energy sphere radius:
  48.4 cm



# Example $e^-$ + $\gamma$s Only Event (cheated reco)

- $E_\nu$ = 16.1 MeV
- $e^-$ deposited 10.2 MeV
- $\gamma$s 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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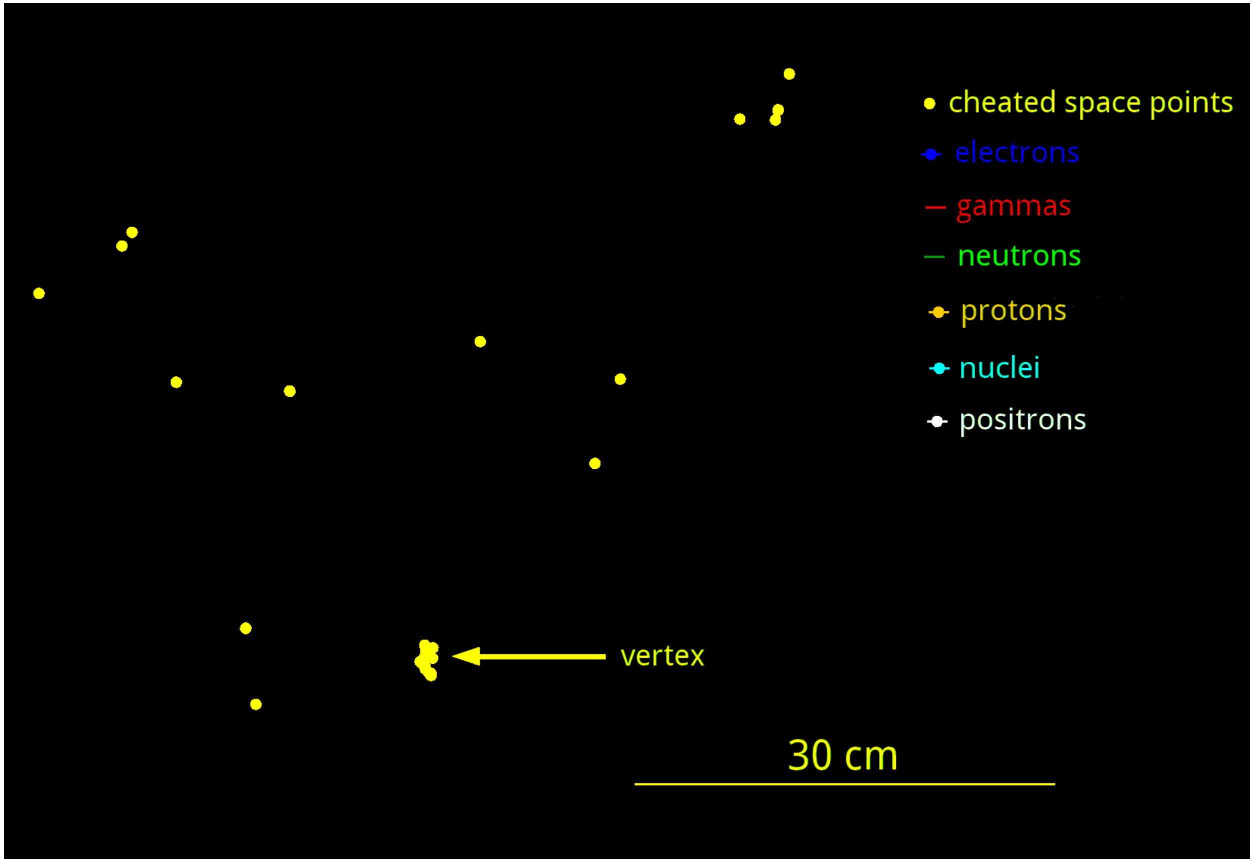
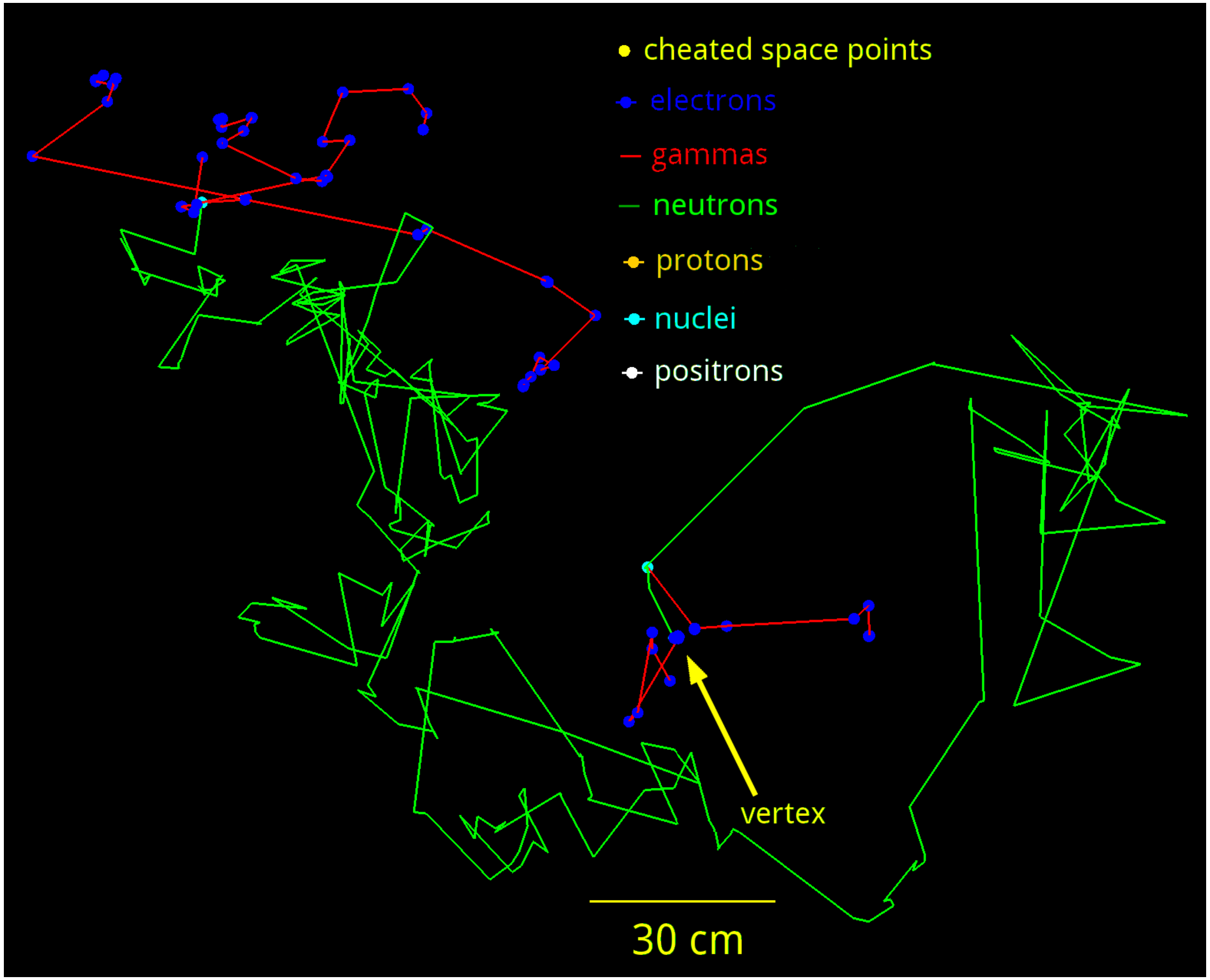


# Example neutron event (true trajectories)

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

  12.2 MeV
- Visible energy sphere radius:

  1.44 m
- Neutrons bounce around for a long time!



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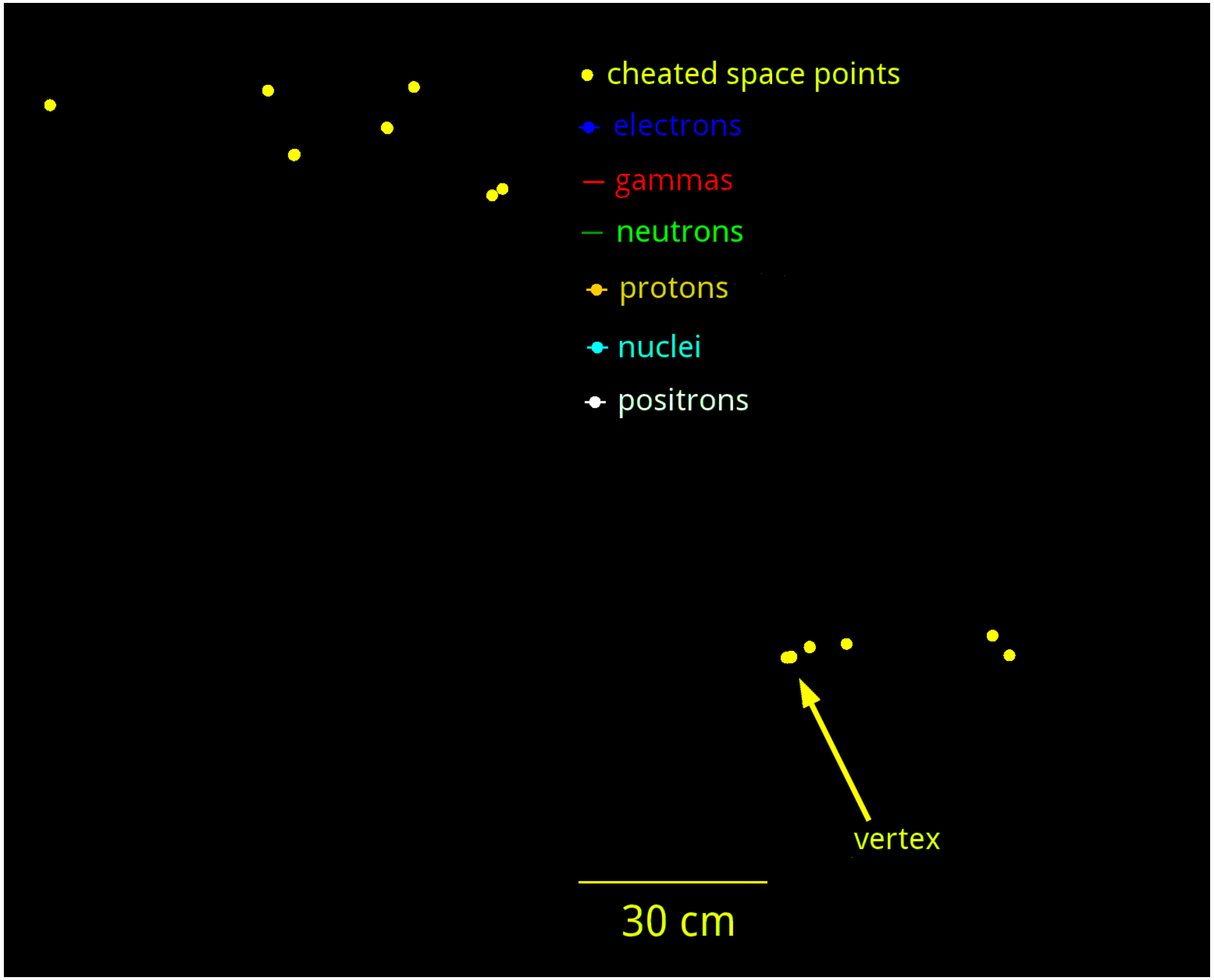
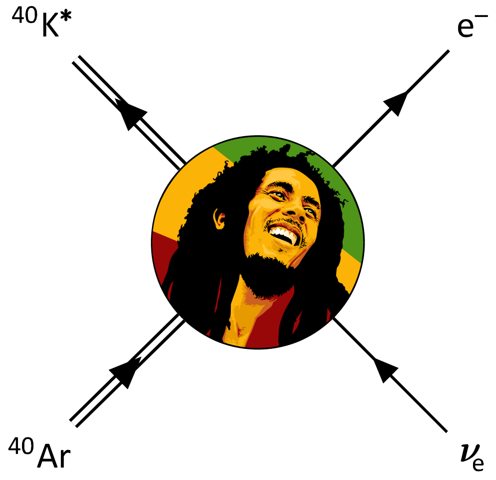
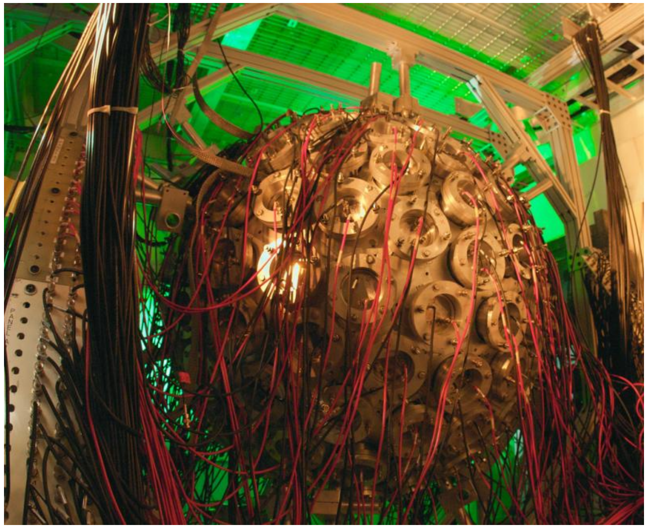


# Current studies and future prospects



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

- MARLEY development is ongoing
  - Interfaces to other codes (e.g., LArSoft)
  - Physics improvements (your calculation could be here!)
  - Preparation of data for other reaction channels
- A variety of reconstruction topics are beginning to be addressed using MARLEY events
  - De-excitation vs. bremsstrahlung γ
  - Nucleon emission tagging
  - Event t0 determination
  - SN triggering
  - MC-based smearing matrix for SNOwGLoBES
- **ACED**: **A**rgon **C**apture **E**xperiment at **D**ANCE
  - Measurement of $^{40}$Ar thermal neutron capture cross section and event-by-event gammas
  - Addresses key uncertainties in liquid argon response to low energy neutrons
  - First data this fall



The **D**etector for **A**dvanced **N**eutron **C**apture **E**xperiments at Los Alamos

# Conclusion

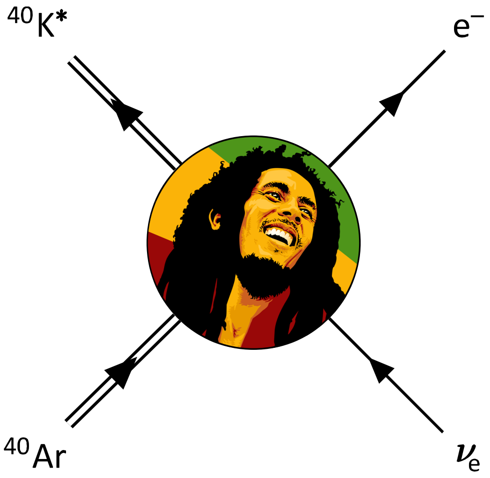
- LArTPCs provide complementary SN information to existing large detectors

- Nuclear effects in argon present a significant challenge for SN event reconstruction

- MARLEY is a new generator specifically targeting supernova neutrinos in $^{40}$Ar
  - More input from the theory community can help us move beyond our simplified models

- A direct measurement of these cross sections would be very valuable!
  - **See Robert Cooper's talk (up next) for one proposed experiment**

- Want to become a MARLEY user or developer? Email me at support@marleygen.org for more information



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

# Backup

# MARLEY transmission coefficient model

- Unbound states in MARLEY de-excite according to the Hauser-Feshbach model
  - W. Hauser and H. Feshbach, *Physical Review* **87**, 366 (1952)
  - Successfully used for many years to describe nuclear cross sections
  - Work continues to refine the input parameters (e.g., RIPL-3)
  - Used in many SN neutrino theory papers (in combination with RPA, QRPA, etc.)
  - Two key assumptions: 1. compound nucleus 2. reciprocity theorem (time-reversal invariance)
- Final states are sampled using decay widths

Hauser-Feshbach partial decay width

sum over possible angular momenta

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

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

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

# MARLEY transmission coefficient model

- Nuclear potential from Koning & Delaroche global optical model

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

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

- Solve radial Schrödinger equation numerically in matching region

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

- Match to asymptotic solution, extract transmission coefficient

incoming Coulomb wavefunction

S-matrix element

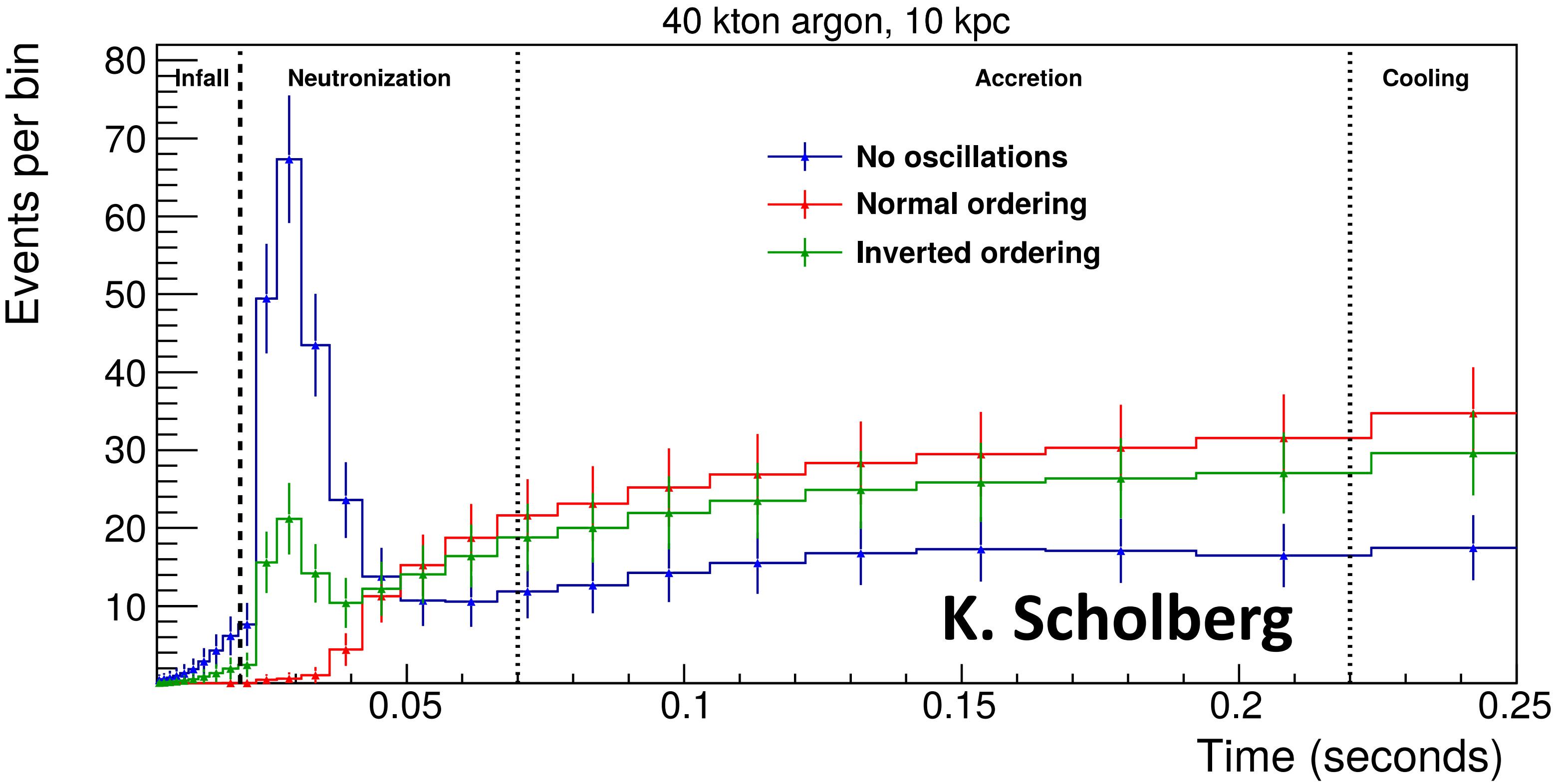
outgoing Coulomb wavefunction

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

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

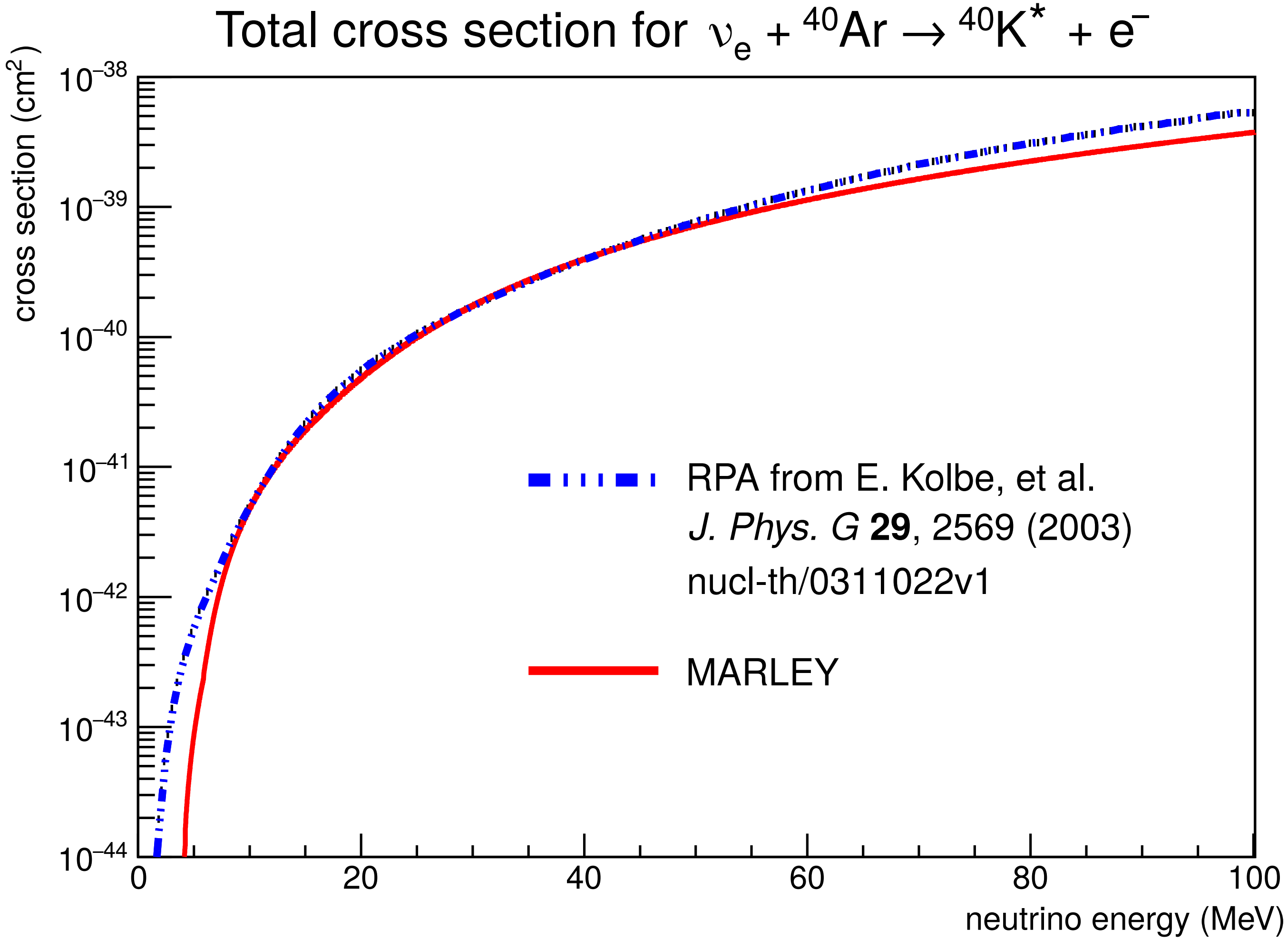
Transmission coefficient represents the probability of penetrating the nuclear surface

# An example: mass ordering from the neutronization burst



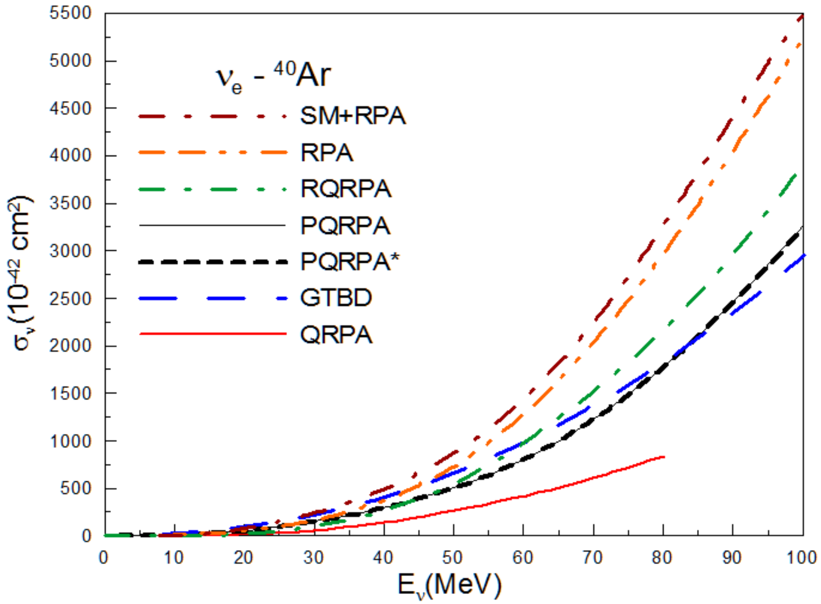
**K. Scholberg**

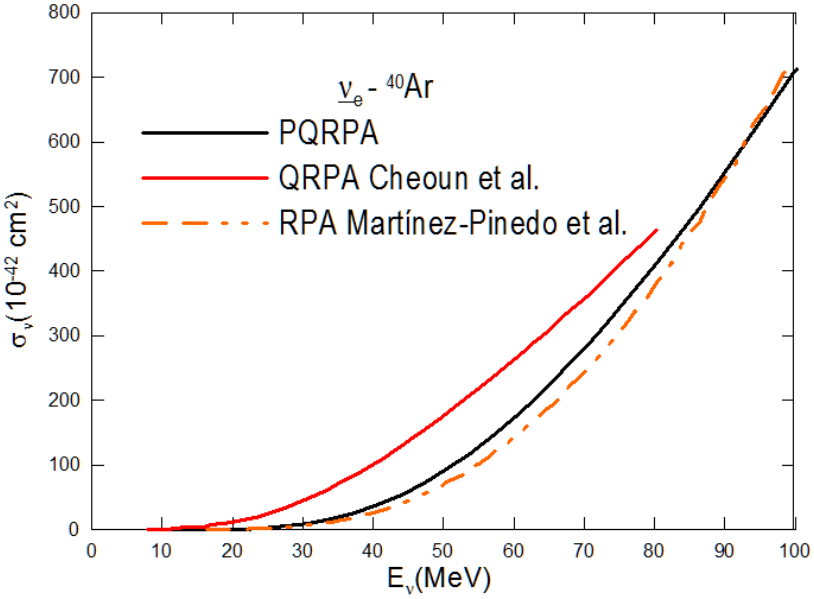
# MARLEY's cross section agrees with similar calculations over much of the relevant energy range

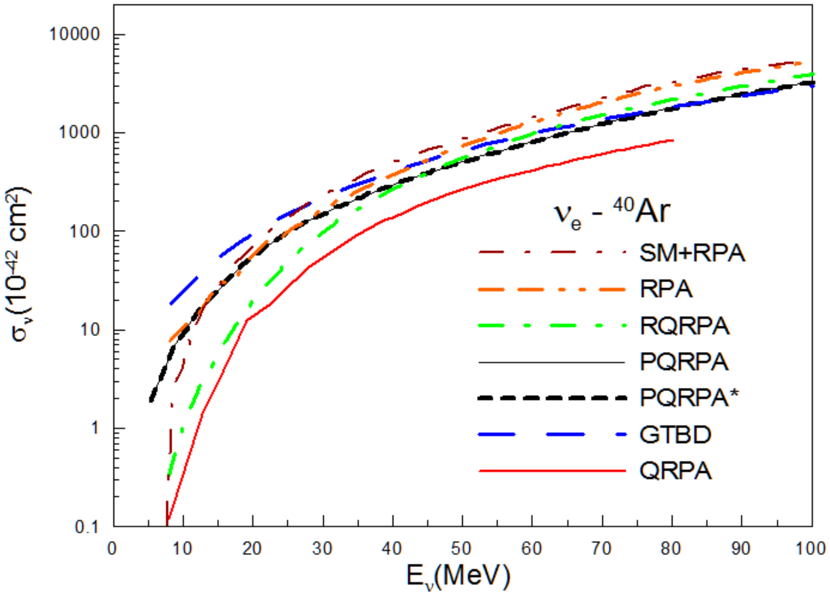


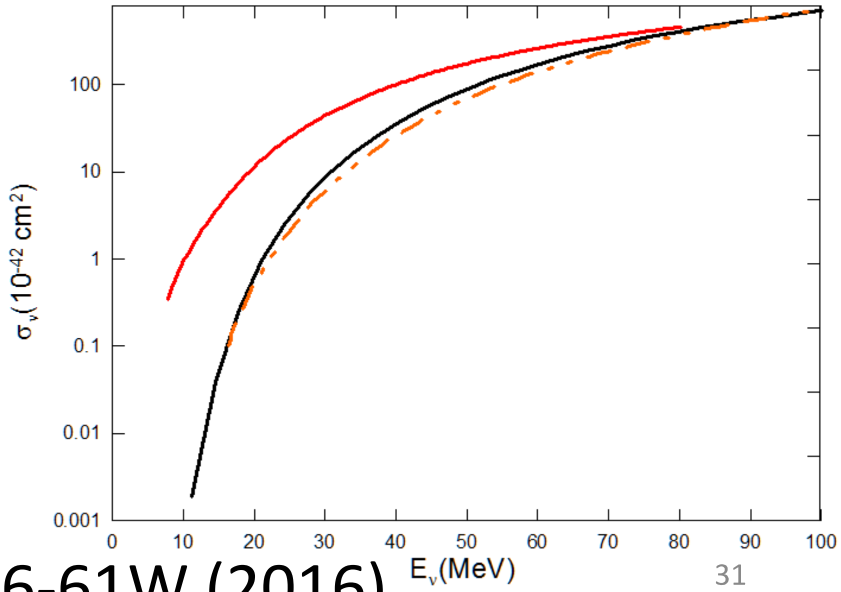
- Low energies = forbidden transitions make a small contribution below MARLEY's hard cutoff
- High energies = forbidden transitions start to dominate near 100 MeV

# Neutrino/antineutrino cross sections $^{40}$Ar





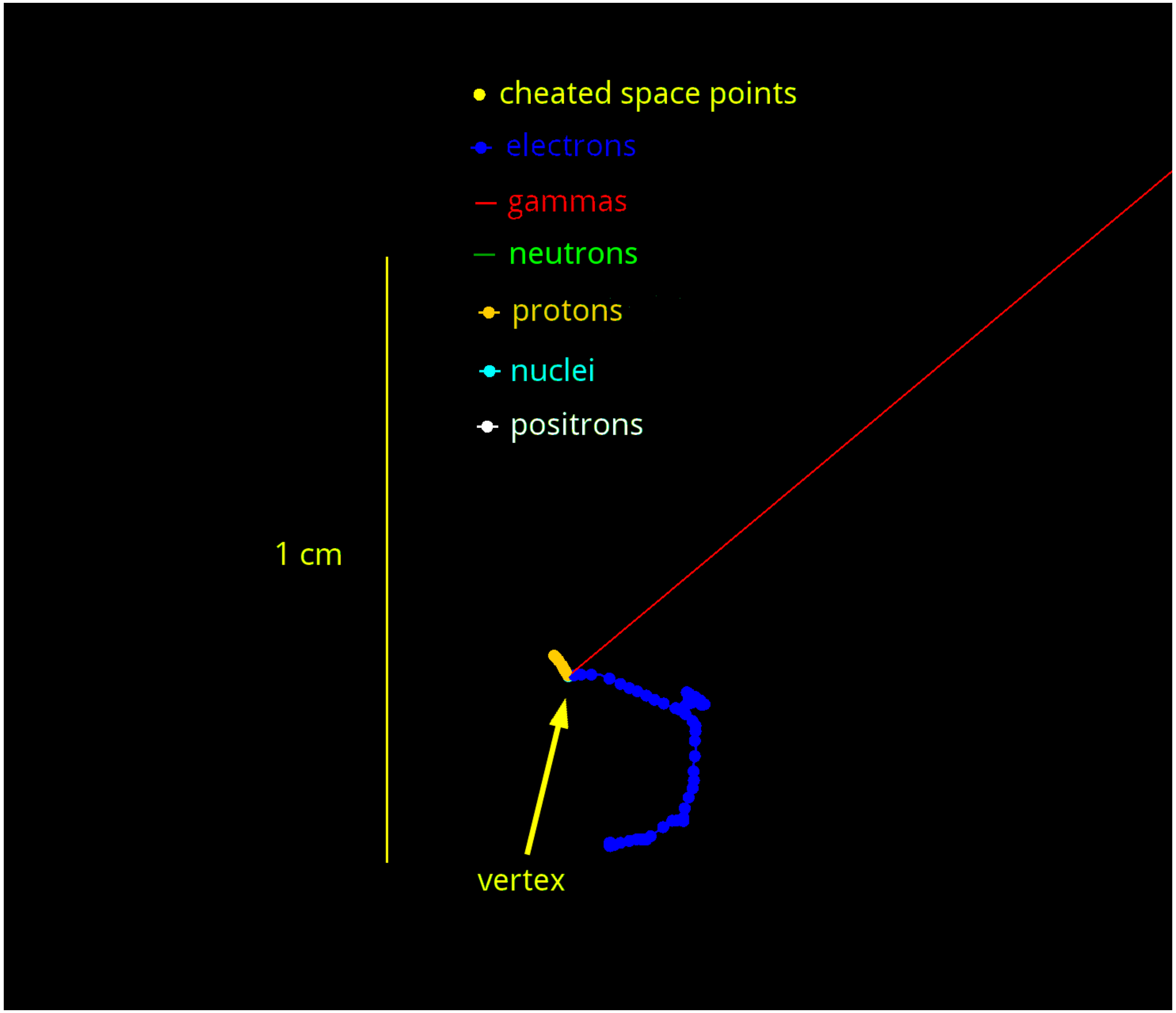




A. R. Samana, INT-16-61W (2016)

# Example proton event (true trajectories)

- $E_{\nu}$ = 17.8 MeV
- $e^{-}$ deposited 1.9 MeV
- $\gamma$ 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 $E_{\nu}$ if you miss them!



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