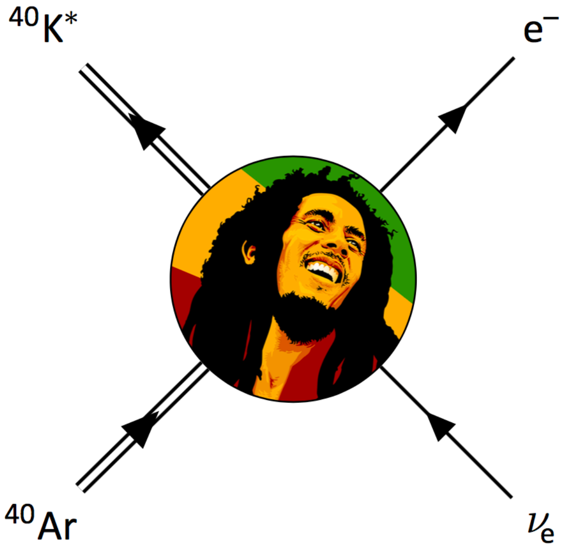


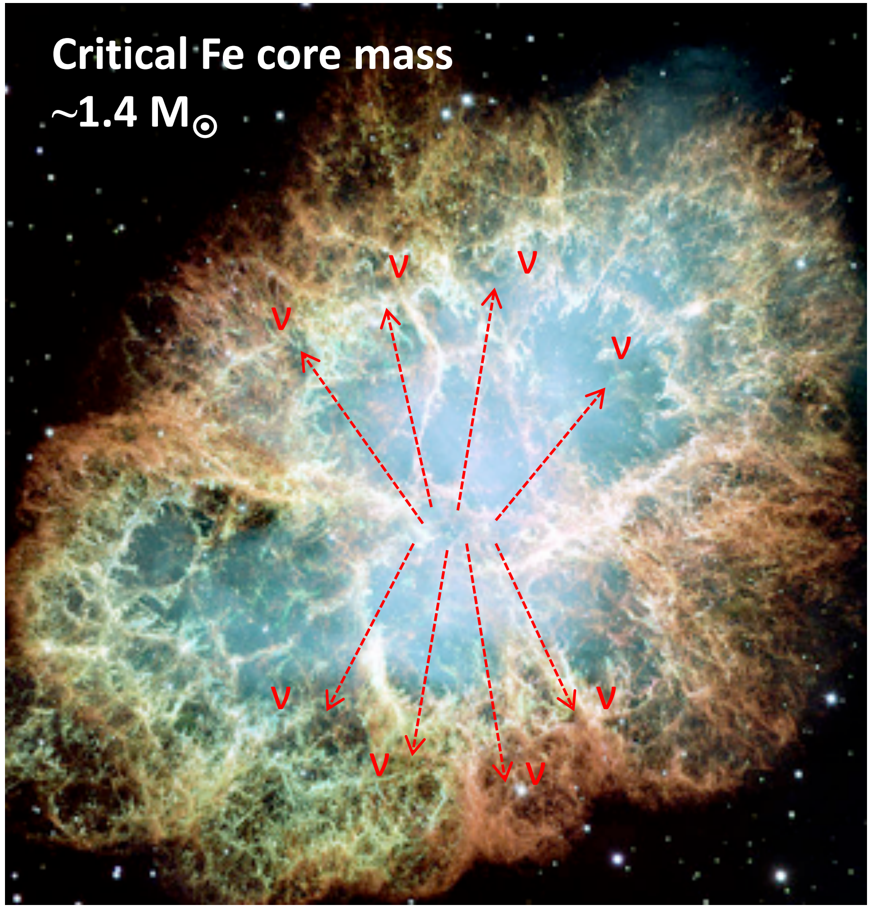
Low-Energy Neutrino-Argon Interactions: A Window into Stellar Collapse

Christopher Grant

VECLIPSE 2017

BOSTON UNIVERSITY

Neutrino "bombs" in outer space



For core-collapse supernovae (SN)…

Gravitational binding energy (~ 3 x 10^{53} ergs) is liberated in the form of

- 0.01% photons
- 1% kinetic energy of explosion
- 99% in the form of neutrinos – order of 10^{58} neutrinos!

Below ~**20 $M_{\odot}$** – left with a **neutron star**
Above this – left with a **black hole**

Dissecting the neutrino explosion

Neutronization burst made of electron neutrinos

Other neutrino species grow in during accretion and cooling phases

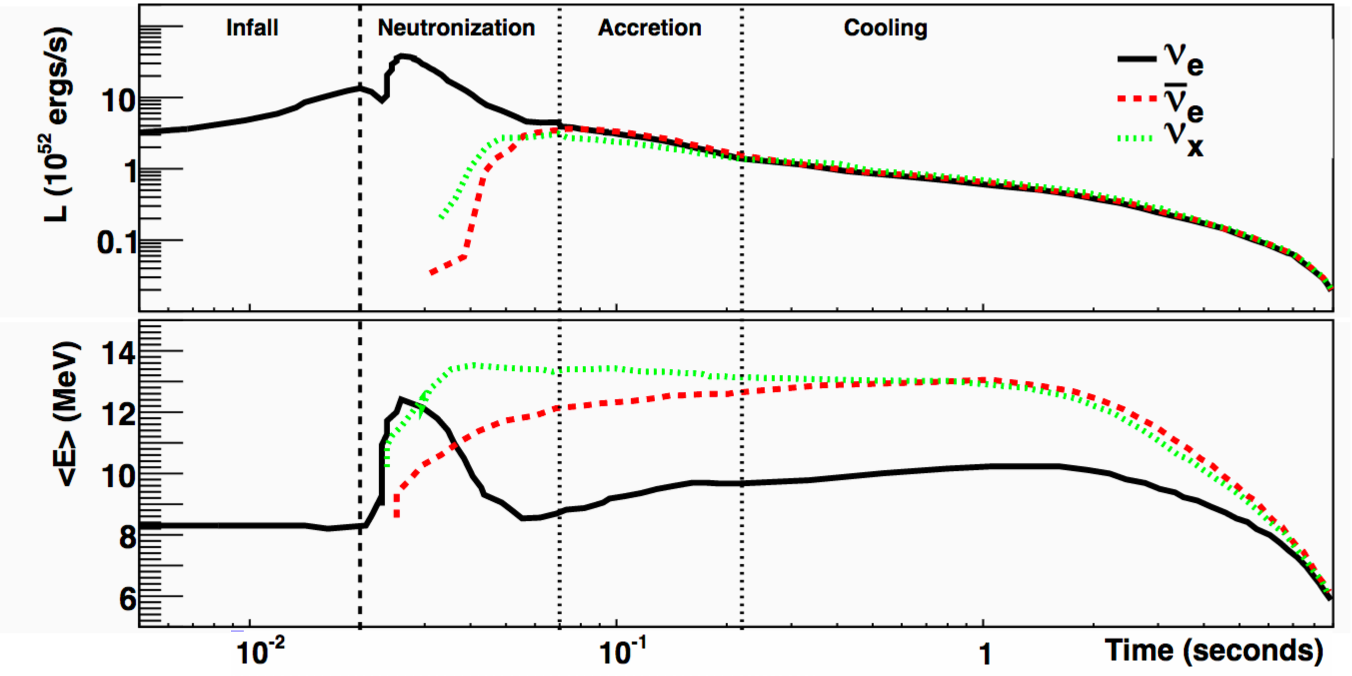
Expect the unexpected!

Collective oscillations, shock waves, sterile oscillations, dark photons, dark matter, axions…

Many of these surprises reveal themselves in the electron neutrino energy distribution

Garching Model

K. Scholberg, DUNE CDR



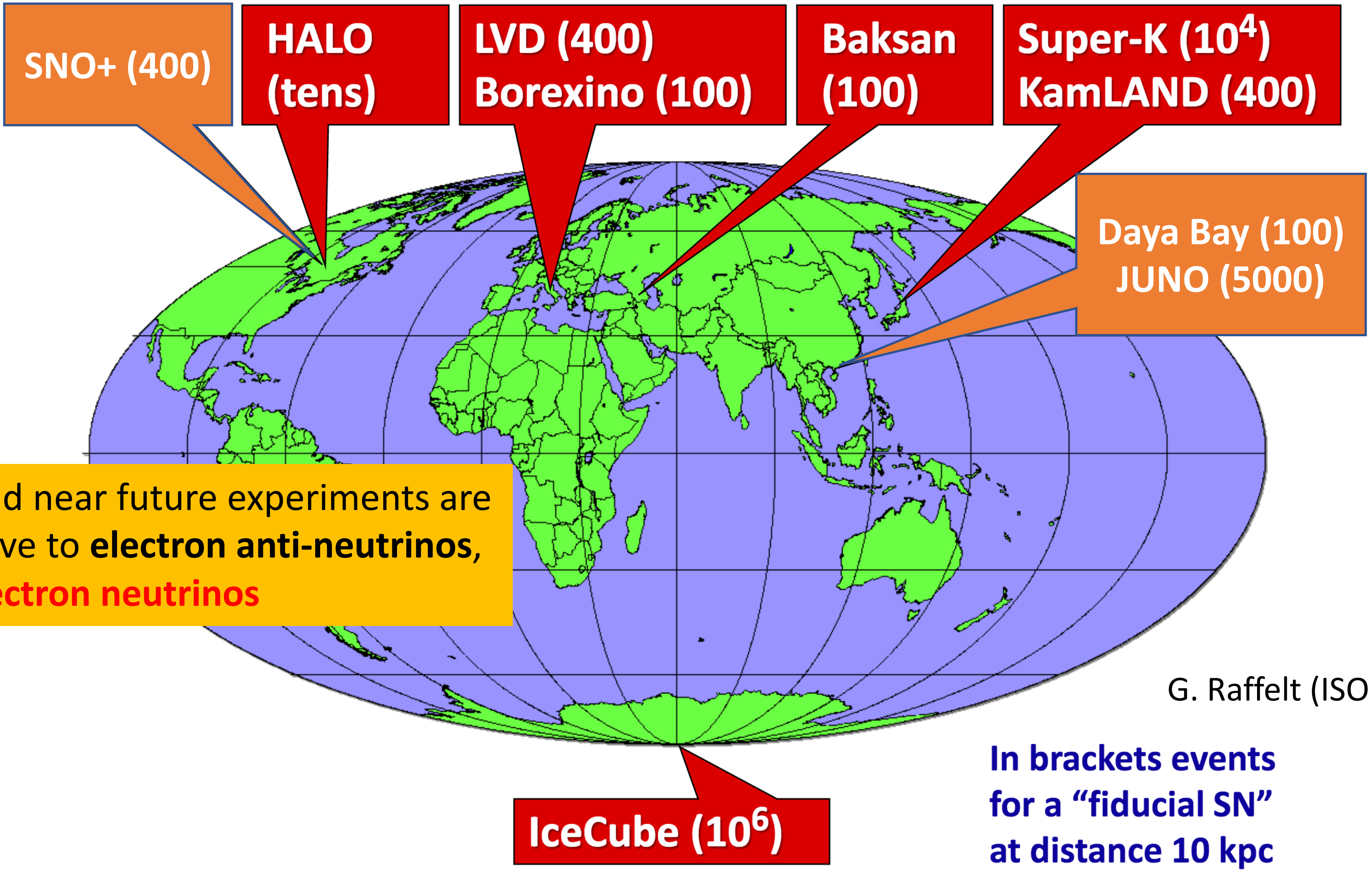
What are we trying to measure?

Tens of seconds worth of neutrino interactions containing the following information:

- Flavor (unique tags)
- Neutrino energy (10% resolution or better?)
- Time (ms resolution)
- Total flux (detection efficiency known)

Need as much information as possible to disentangle the physics inside a supernova

World’s available neutrino detectors

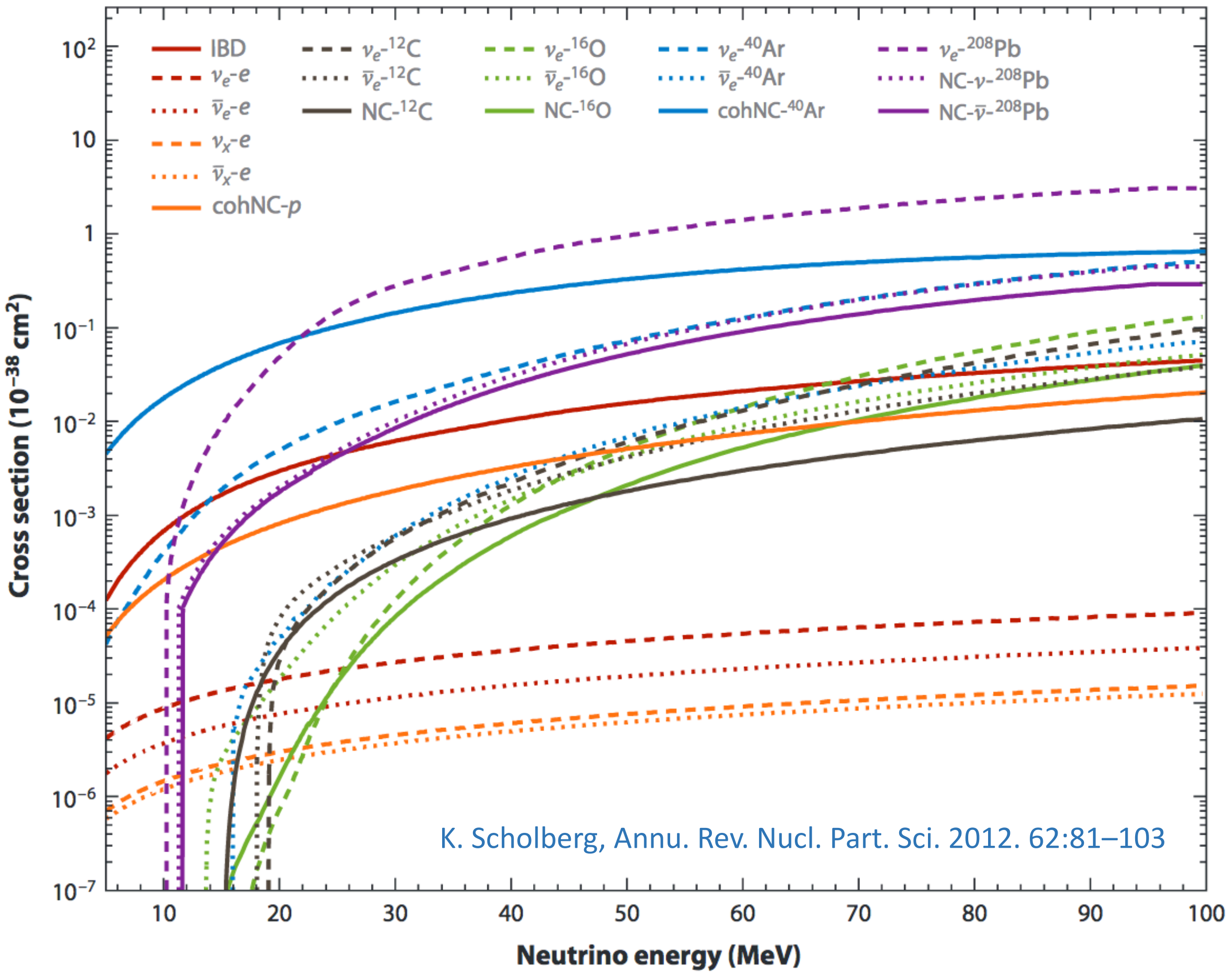


Most current and near future experiments are primarily sensitive to **electron anti-neutrinos**, **not so much electron neutrinos**

G. Raffelt (ISOUPS 2013)

In brackets events for a “fiducial SN” at distance 10 kpc

Why use Argon?



Argon has a large electron neutrino cross-section

Can be used as a scintillator or a medium to drift ionized charge in a Time Projection Chamber. Technologies could be scaled to very large volumes to increase event rates (**Deep Underground Neutrino Experiment – DUNE = 40 kt**).

First, something more familiar…

Inverse beta decay:

$$\bar{\nu}_e + p \rightarrow n + e^+$$

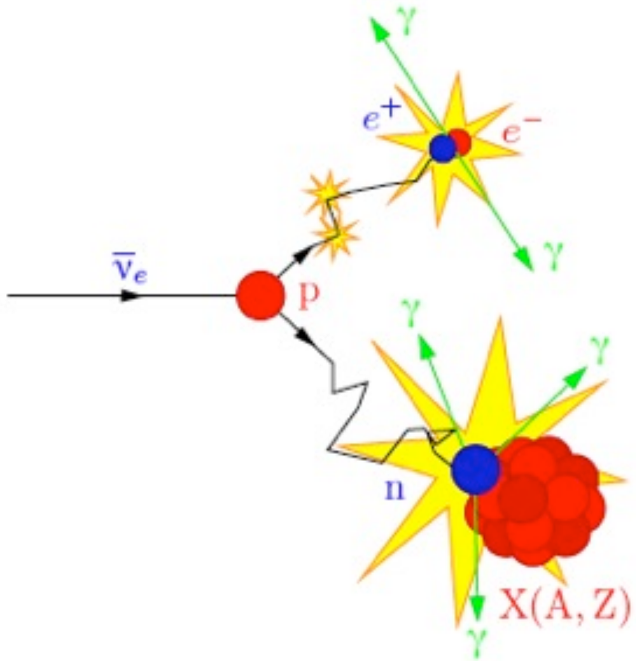
Reaction threshold of 1.8 MeV

Cross-section known to the percent level

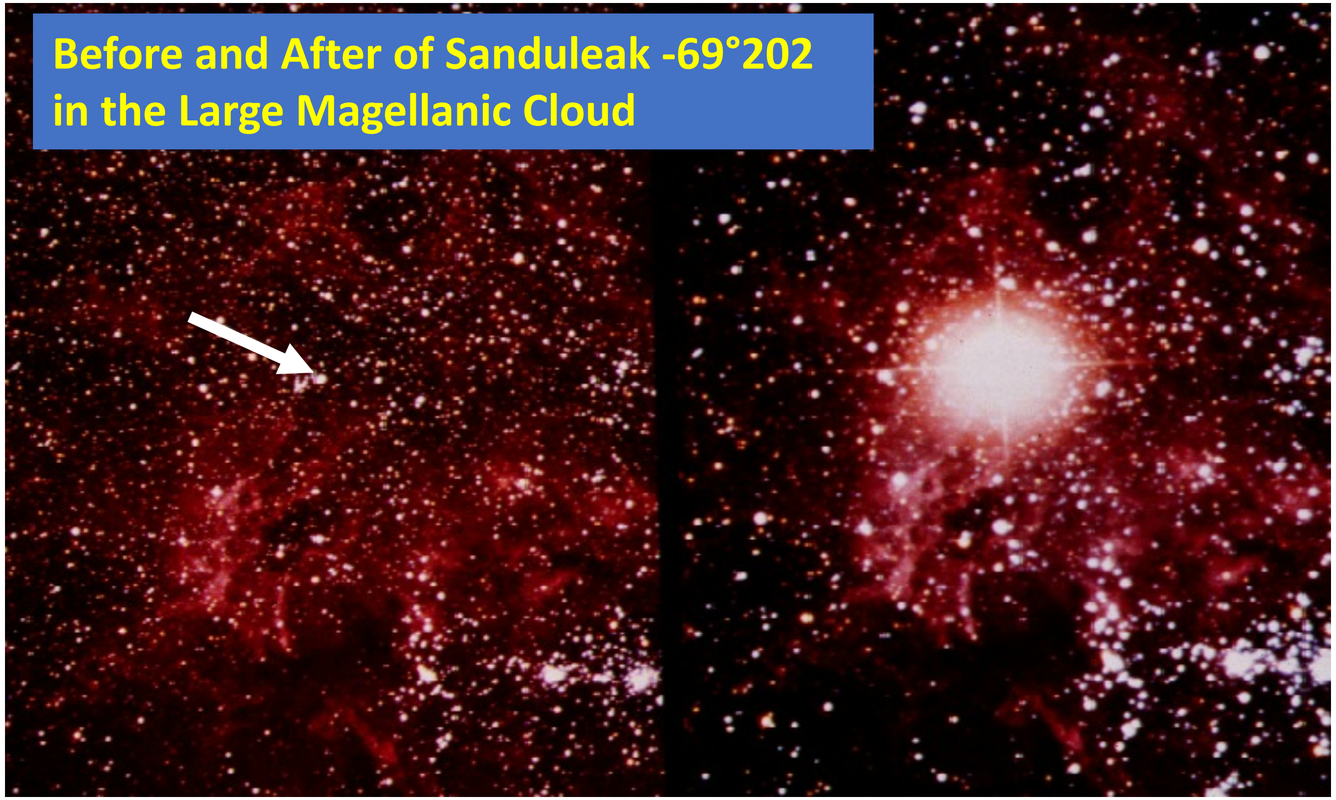
Neutrino energy is directly obtained from the energy of the outgoing positron:

$$E_\nu = E_e + 1.3\ \mathrm{MeV}$$

Prompt e^+ and delayed n-capture suppresses backgrounds

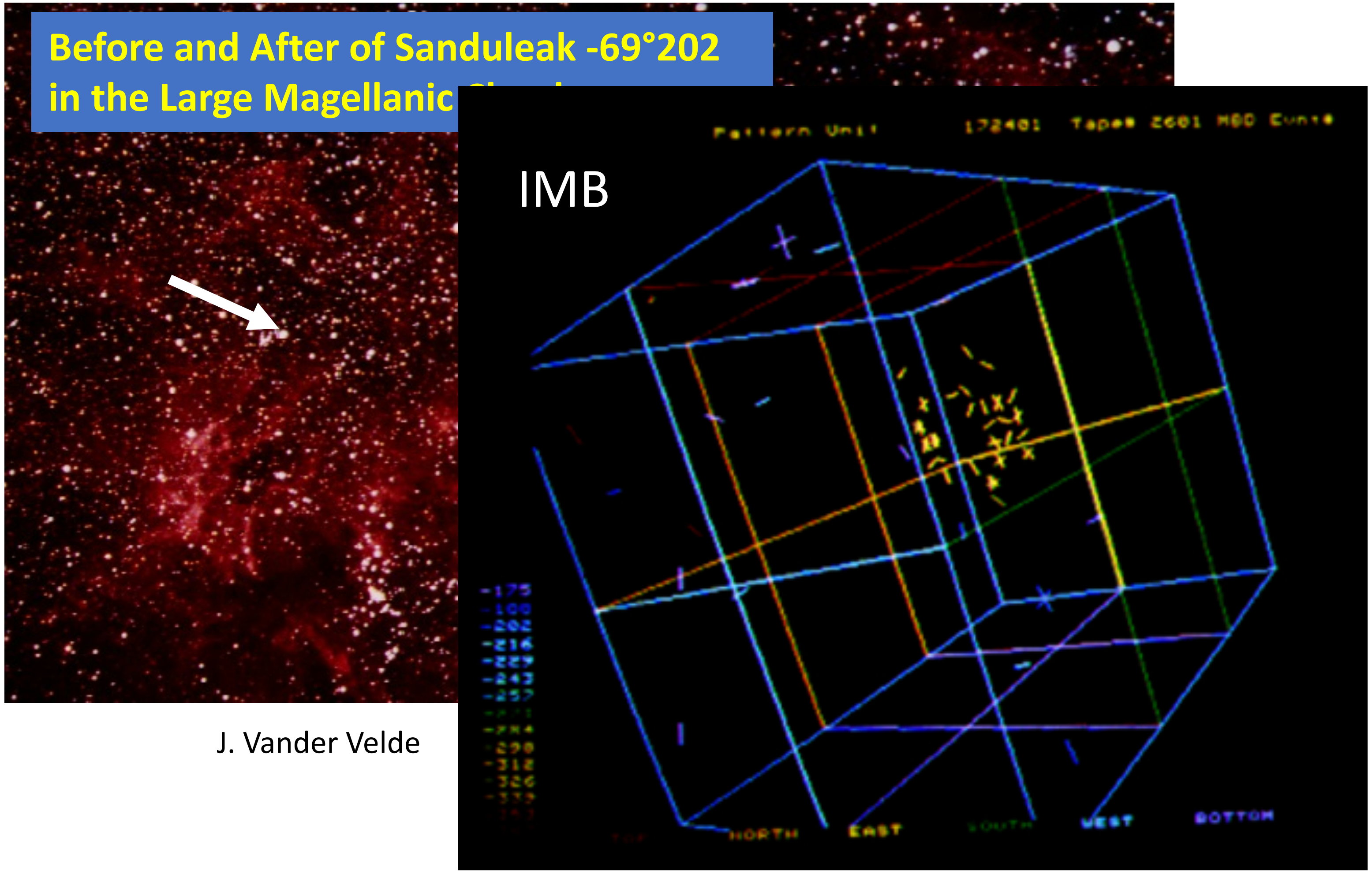


SN 1987A neutrino detection



J. Vander Velde

SN 1987A neutrino detection



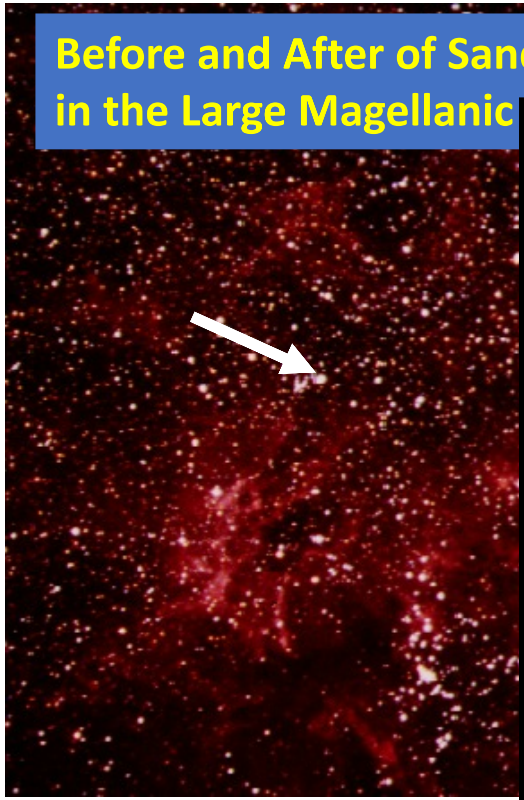
J. Vander Velde

IBD events observed around the world:

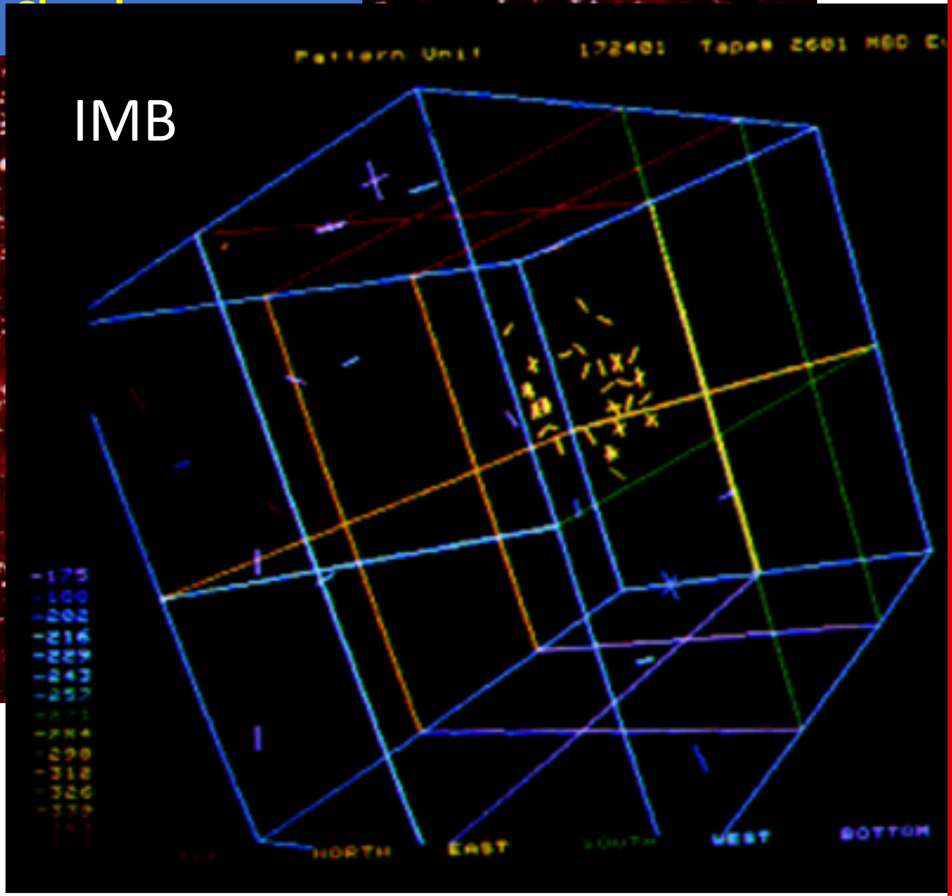
Kamiokande = 11 events
IMB experiment = 8 events
Baskan = 5 events

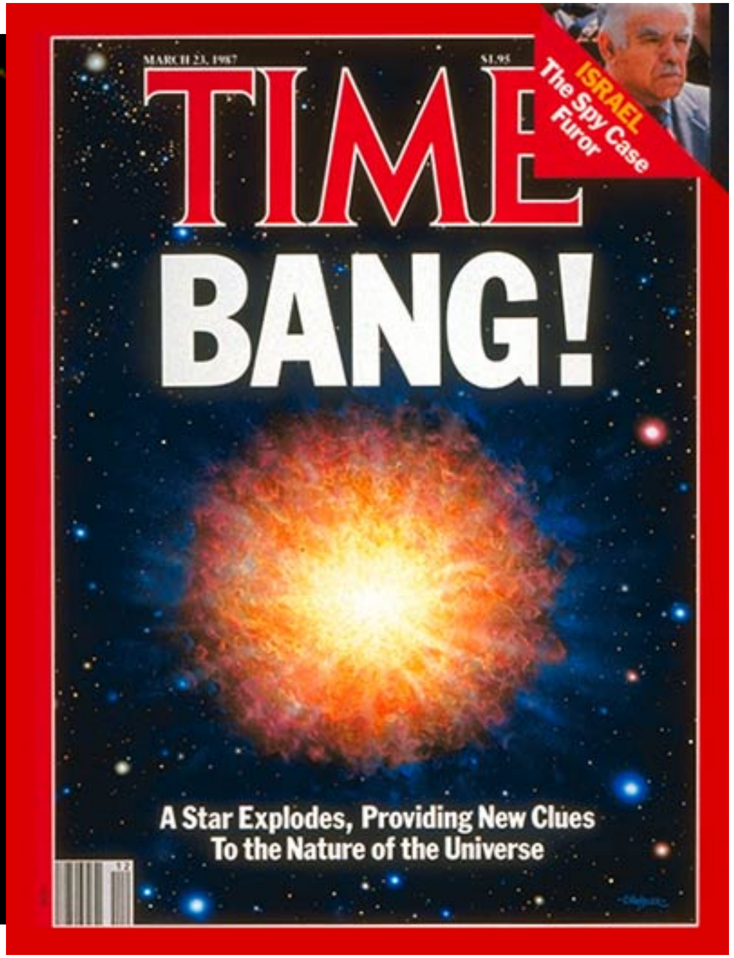
Total of 24 events

SN 1987A neutrino detection



J. Vander Velde





Advantages of knowing the cross-section

Example from the IMB experiment

VOLUME 58, NUMBER 14 PHYSICAL REVIEW LETTERS 6 APRIL 1987

Observation of a Neutrino Burst in Coincidence with Supernova 1987A in the Large Magellanic Cloud

R. M. Bionta,[12] G. Blewitt,[4] C. B. Bratton,[5] D. Casper,[2,14] A. Ciocio,[14] R. Claus,[14] B. Cortez,[16] M. Crouch,[9] S. T. Dye,[6] S. Errede,[10] G. W. Foster,[15] W. Gajewski,[1] K. S. Ganezer,[1] M. Goldhaber,[3] T. J. Haines,[1] T. W. Jones,[7] D. Kielczewska,[1,8] W. R. Kropp,[1] J. G. Learned,[6] J. M. LoSecco,[13] J. Matthews,[2] R. Miller,[1] M. S. Mudan,[7] H. S. Park,[11] L. R. Price,[1] F. Reines,[1] J. Schultz,[1] S. Seidel,[2,14] E. Shumard,[16] D. Sinclair,[2] H. W. Sobel,[1] J. L. Stone,[14] L. R. Sulak,[14] R. Svoboda,[1] G. Thornton,[2] J. C. van der Velde,[2] and C. Wuest[12]

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What was the energy, flavor, and kinematics of the SN neutrinos?

TABLE III. Characteristics of the contained neutrino events recorded on 23 February.

Event No.[a]	Time (UT)	No. of PMT's	Energy[b] (MeV)	Angular distribution[c] (degrees)
33162	7:35:41.37	47	38	74
33164	7:35:41.79	61	37	52
33167	7:35:42.02	49	40	56
33168	7:35:42.52	60	35	63
33170	7:35:42.94	52	29	40
33173	7:35:44.06	61	37	52
33179	7:35:46.38	44	20	39
33184	7:35:46.96	45	24	102

Advantages of knowing the cross-section

Example from the IMB experiment

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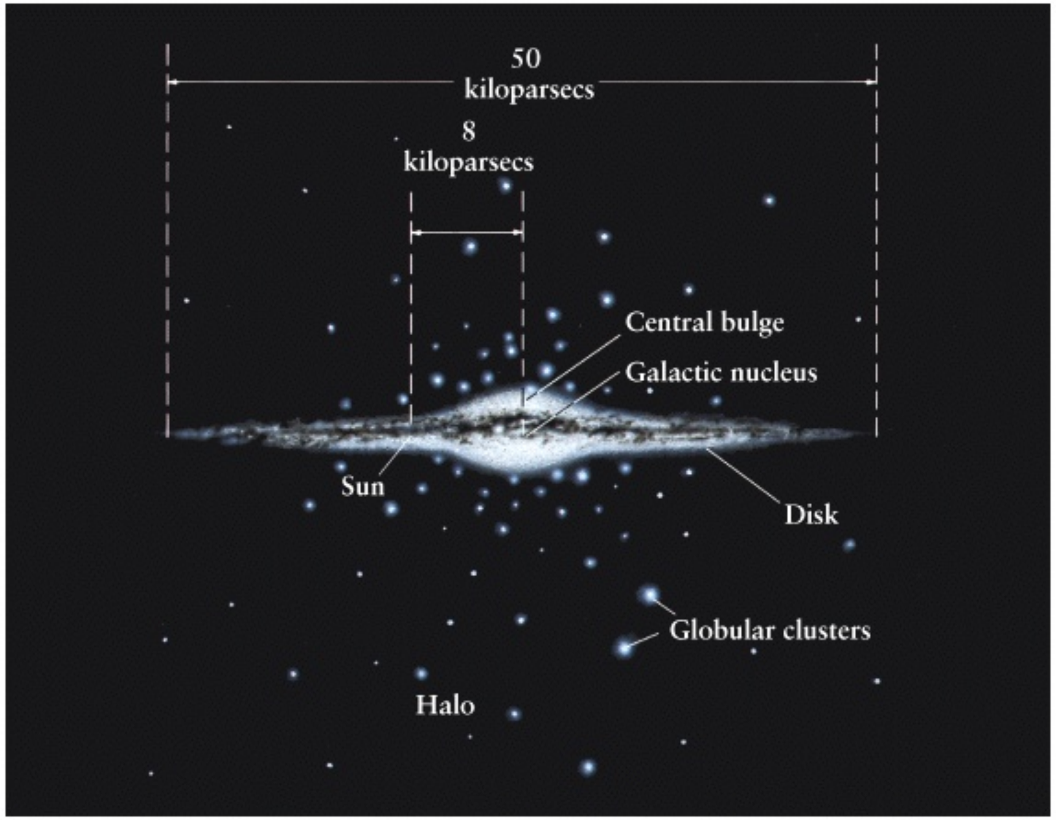
33179	7:35:46.38	44	20	39
33184	7:35:46.96	45	24	102

Detection efficiency – what was the SN neutrino flux?

TABLE I. The estimated trigger efficiency for the detector with the loss of one high-voltage power supply as a function of visible energy.

Visible energy (MeV)	Trigger efficiency
20	0.14
30	0.56
40	0.76
50	0.89
60	0.92

Breakdown of neutrino-Argon reactions



https://sites.ualberta.ca/~pogosyan/teaching/ASTRO_122/lect22/lecture22.html

Expected Events for Supernova at 10 kpc

Reaction Type		Events / 40 kt
(CC)	$\nu_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{K}^* + e^-$	~3300
(CC)	$\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{Cl}^* + e^+$	~160
(ES)	$\nu + e^- \rightarrow \nu + e^-$	~260
(NC)	$\nu + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{Ar}^* + \nu$	Several 100 ???

Elastic scattering off electrons is the only cross-section we know reasonably well

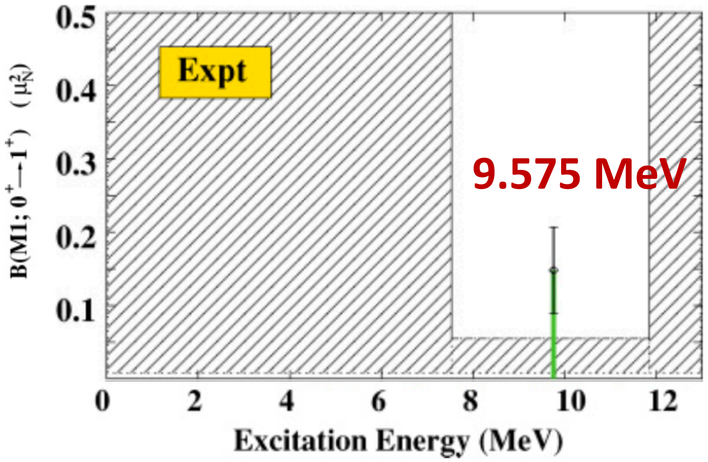
Evidence for neutral current reactions

Photon scattering on Argon

PHYSICAL REVIEW C **73**, 054306 (2006)

First evidence for spin-flip $M1$ strength in ^{40}Ar

T. C. Li,[1] N. Pietralla,[1,2] A. P. Tonchev,[3] M. W. Ahmed,[3] T. Ahn,[1,2] C. Angell,[4] M. A. Blackston,[3] A. Costin,[1,2] K. J. Keeter,[5] J. Li,[6] A. Lisetskiy,[7,*] S. Mikhailov,[6] Y. Parpottas,[3] B. A. Perdue,[3] G. Rainovski,[1] W. Tornow,[3] H. R. Weller,[3] and Y. K. Wu[6]
[1]*Nuclear Structure Laboratory, SUNY at Stony Brook, Stony Brook, New York 11794-3800, USA*
[2]*Institut für Kernphysik, Universität zu Köln, D-50937 Köln, Germany*
[3]*Triangle Universities Nuclear Laboratory, Duke University, Durham, North Carolina 27708, USA*
[4]*Triangle Universities Nuclear Laboratory, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina 27599, USA*
[5]*Department of Physics, Idaho State University, Pocatello, Idaho 83209, USA*
[6]*Duke Free Electron Laser Laboratory, Duke University, Durham, North Carolina 27708, USA*
[7]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
(Received 15 February 2006; published 5 May 2006)



$$\nu + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{Ar}^{*} + \nu$$

Cross-section estimate using this state in the following reference:

A. Hayes, D. Ibeling, J. Friar

http://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-14-25081

Lower lying states are predicted (**4.473 MeV**) and could confuse the detection of other reactions!

For higher neutrino energies - nuclear breakup with **neutron emission** still under investigation

Charged-current (IBD) reactions

Dominant cross-section

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

Energy Threshold = 1.5 MeV

$$\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{Cl}^* + e^+$$

Energy Threshold = 7.48 MeV

Is it possible to separate these two types of events in a liquid argon detector?

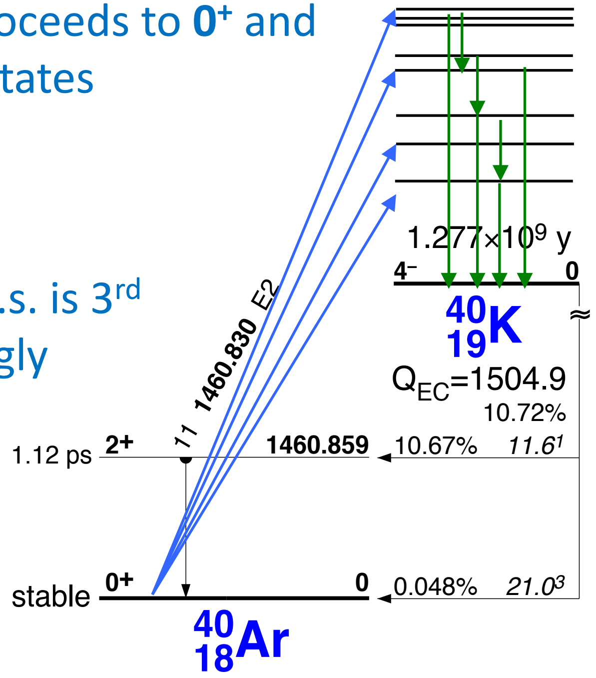
Will require e-/e+ tagging at low energies – maybe use additional de-excitation tags?

Focusing on the dominant CC reaction

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

reaction proceeds to **0⁺** and **1⁺** excited states

transition to ^{40}K g.s. is 3rd forbidden – strongly suppressed



At least 25 transitions have been observed indirectly

Focusing on the dominant CC reaction

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

reaction proceeds to **0^+** and **1^+** excited states

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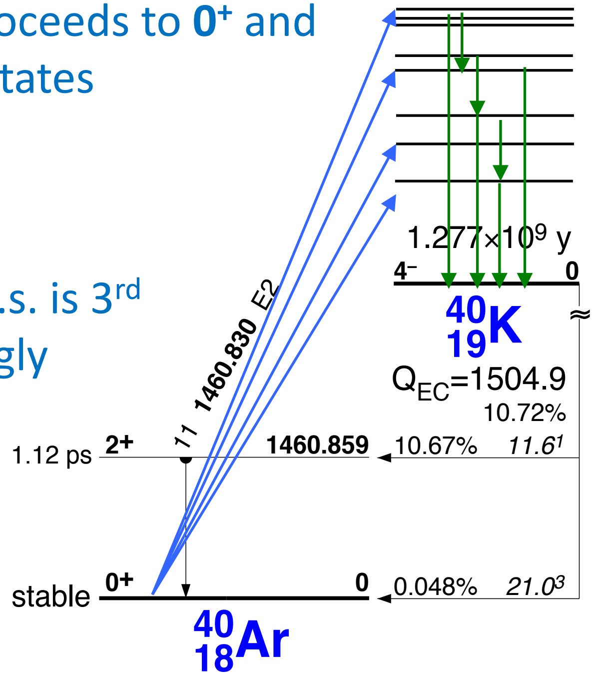

At least 25 transitions have been observed indirectly

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

Reconstructing true neutrino energy:

Q is determined from de-excitation gammas and nucleons

Outgoing e⁻ Energy — Energy donated to transition — Recoil Energy of Nucleus (negligible)

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

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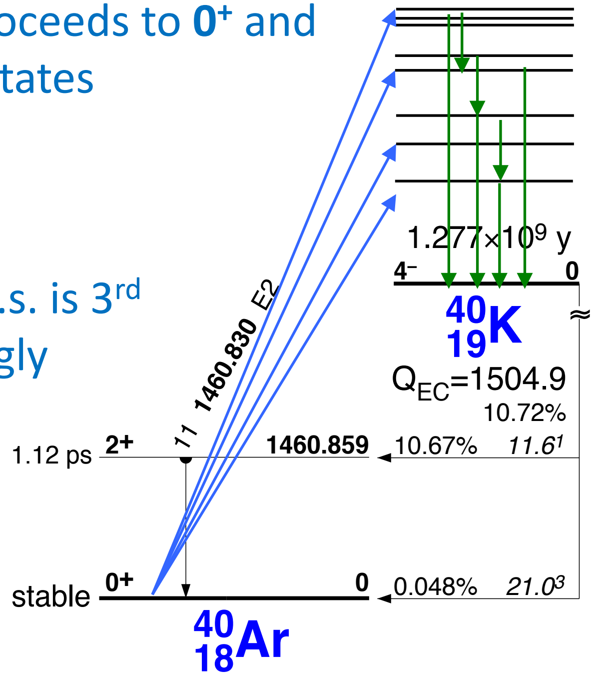

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Outgoing e⁻ Energy | Energy donated to transition | Recoil Energy of Nucleus (negligible)

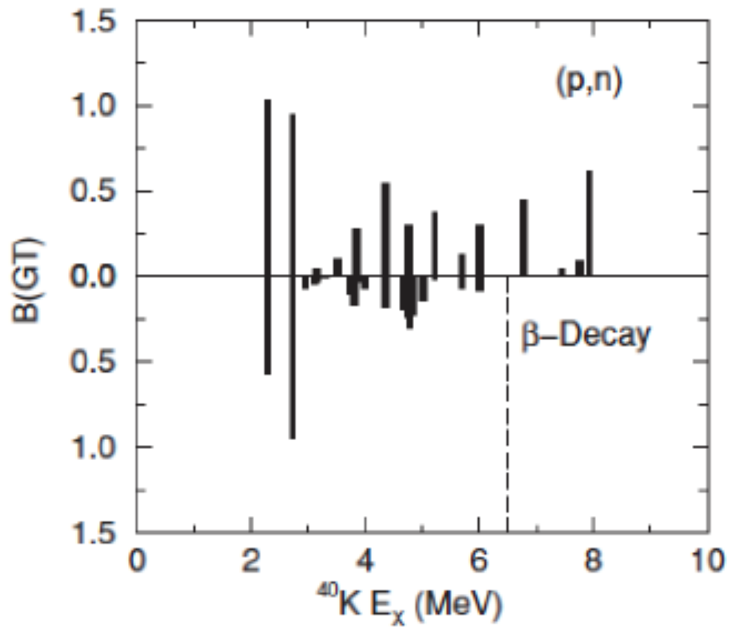
$$E_\nu = E_e + Q + K_{\text{recoil}}$$

Need to measure the transition intensities

Under allowed approximation: $\sigma = \sum_{\text{levels}} \frac{G_F^2 |V_{ud}|^2}{\pi} |\boldsymbol{p}_e| E_e \; F(Z_f, E_e) \left[B(F) + B(GT) \right]$

World's data for ^{40}K excitation

A comparison of two methods for measuring the ^{40}K excited states – experimental strengths are available up to ~ 8 MeV

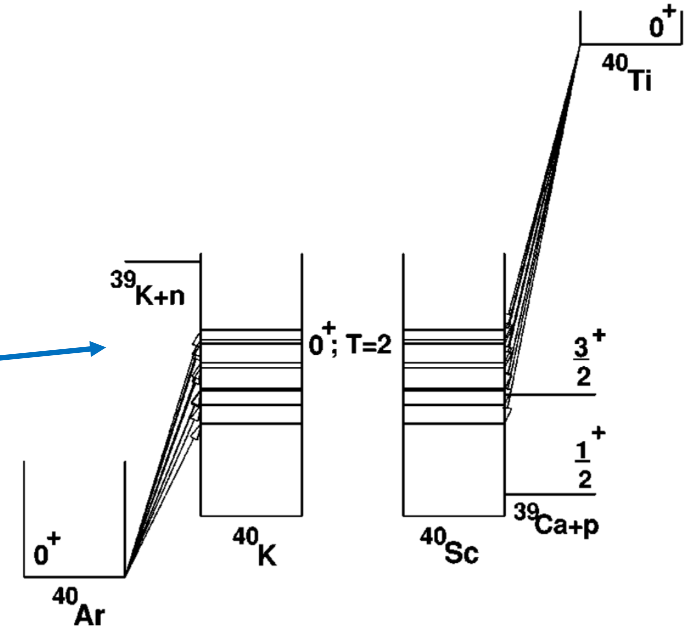


(p,n) forward scattering on ^{40}Ar

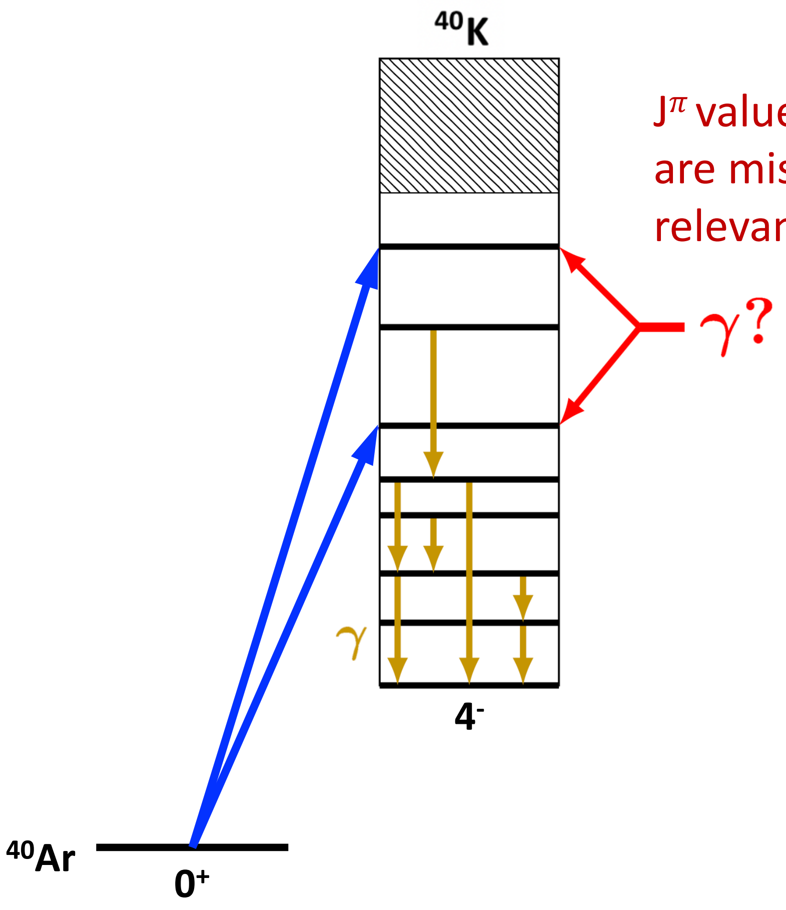
M. Bhattacharya, et al. PRC 80, 055501 (2009)

Analog decay of ^{40}Ti to ^{40}Sc (isospin mirror nucleus)

M. Bhattacharya, et al. PRC 58, 6 (1998)



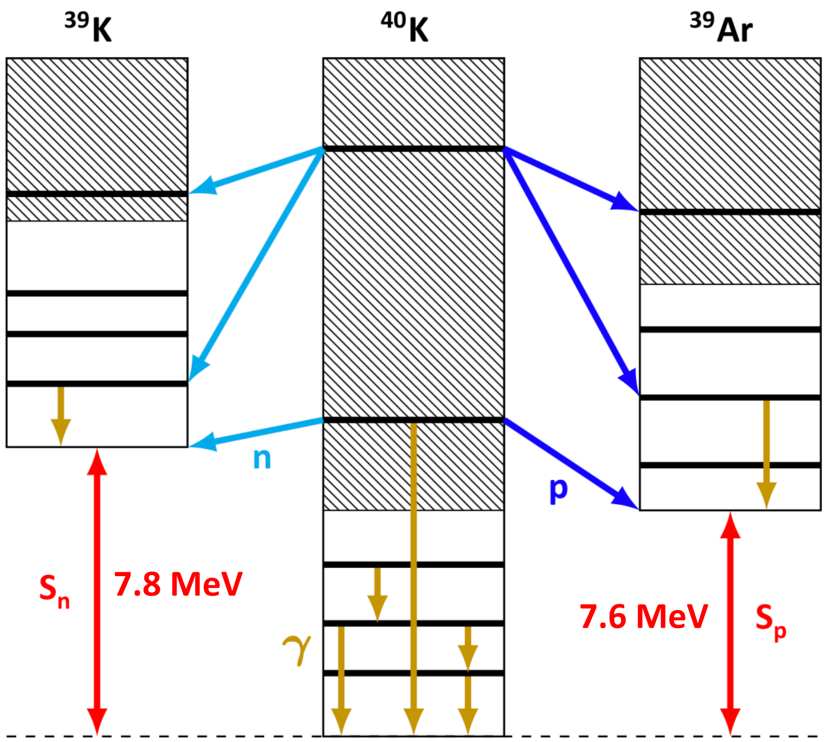
Additional challenges with CC cross-section



J^{π} values and γ-decay data are missing for many relevant ^{40}K* levels

Significant loading of unbound nuclear levels occurs

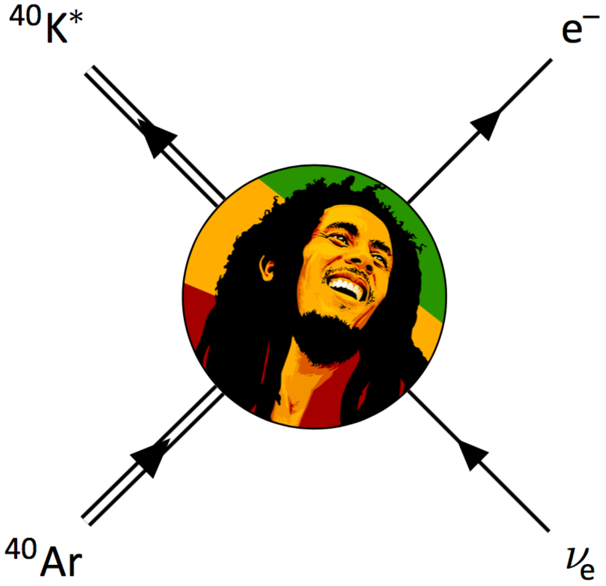
Large number of de-excitation channels complicates energy reconstruction



MARLEY: Model of Argon Reaction Low-Energy Yields

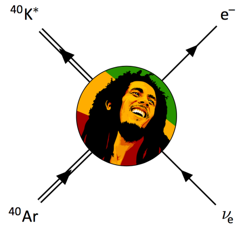
MARLEY attempts to combine all the available reaction data into a model of neutrino-argon reactions in the energy range of stellar collapse.

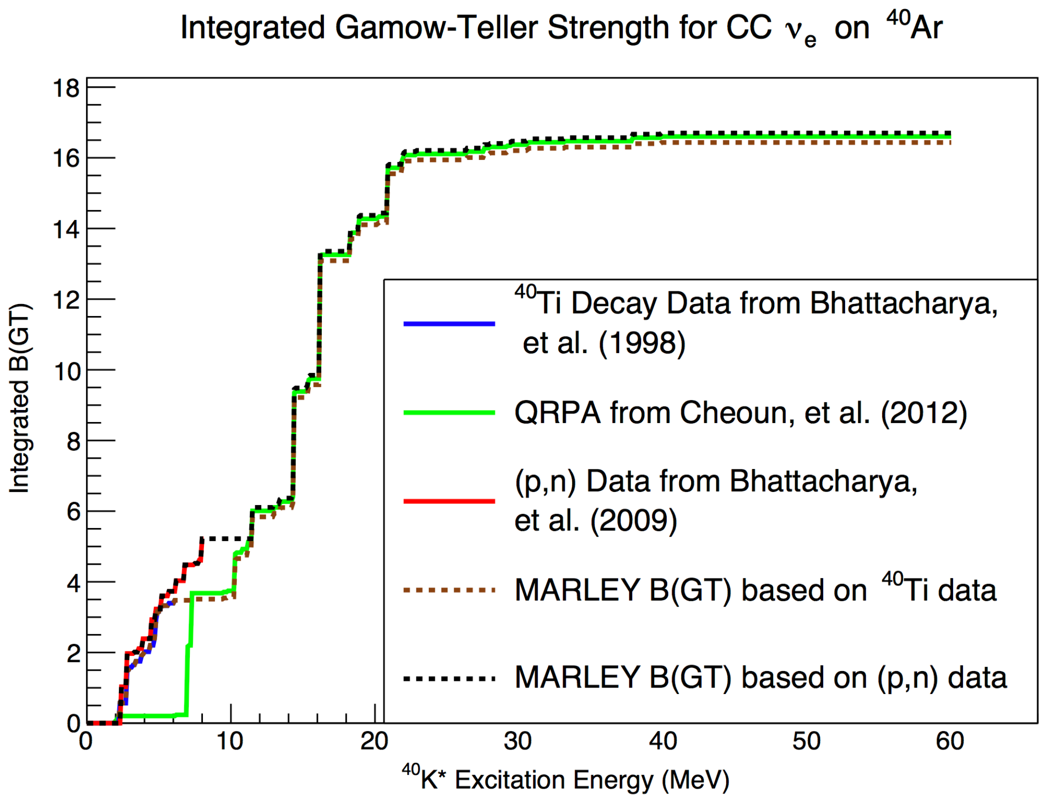
- Modern C++, mostly from scratch
- No required external dependencies
- Current focus is on ν_e CC event generation
- Additional reactions ($\overline{\nu}_e$ CC and NC) will be added in the near future
- Implemented in “LArSoft” simulation of the DUNE neutrino detector



Steven Gardiner
Christopher Grant
Emilija Pantic
Robert Svoboda

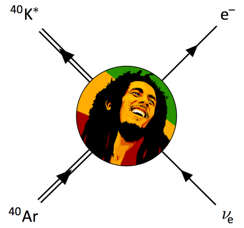
MARLEY tabulated results for GT strengths

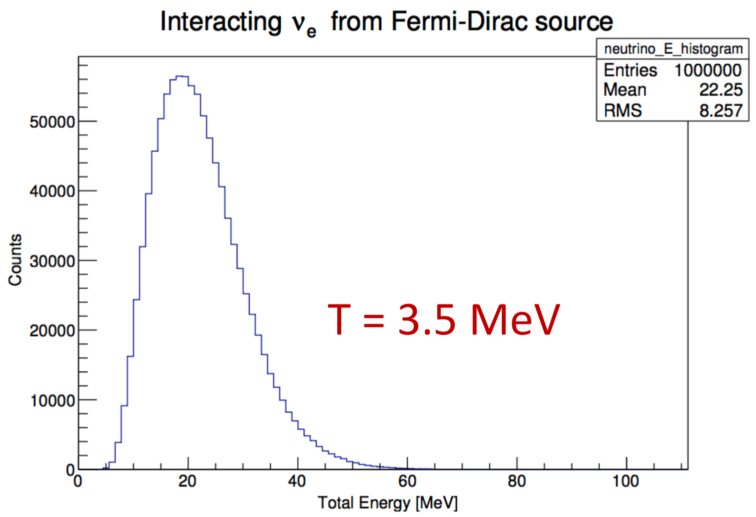


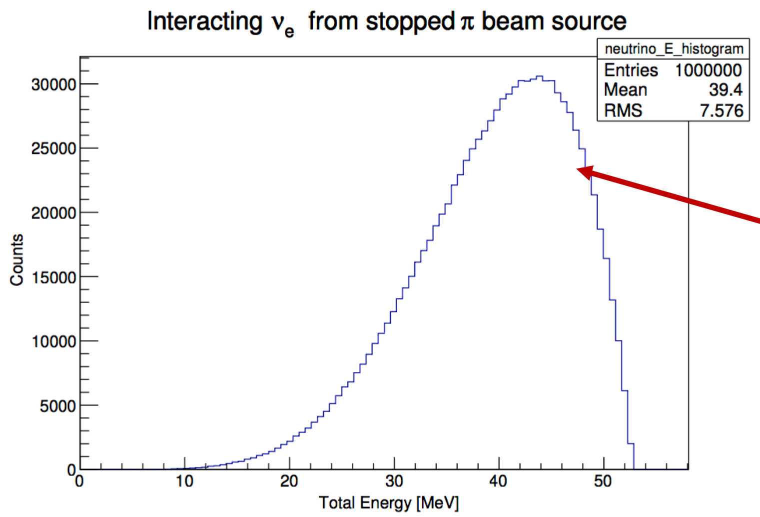


- User can choose which experimental strengths to use:
  - ^{40}Ti analog decay data
  - (p,n) scattering data
- QRPA calculation (Cheoun, et al.) is used for higher energies
- Experimental GT strengths have significant disagreement with strengths from QRPA calculation. We naively “stitch” them together with a linear interpolation.

MARLEY output for different neutrino spectra







$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\downarrow$$
$$e^+ + \bar{\nu}_\mu + \nu_e$$

^{40}K* de-excitations

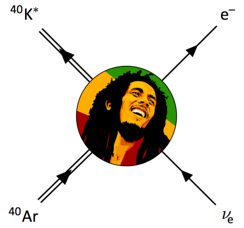
- γs only: 82.5%
- single n + γs: 15.9%
- single p + γs: 1.4%
- other: 0.2%

^{40}K* de-excitations

- γs only: 58.0%
- single n + γs: 36.3%
- single p + γs: 4.6%
- other: 1.1%

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

Electron + gammas event



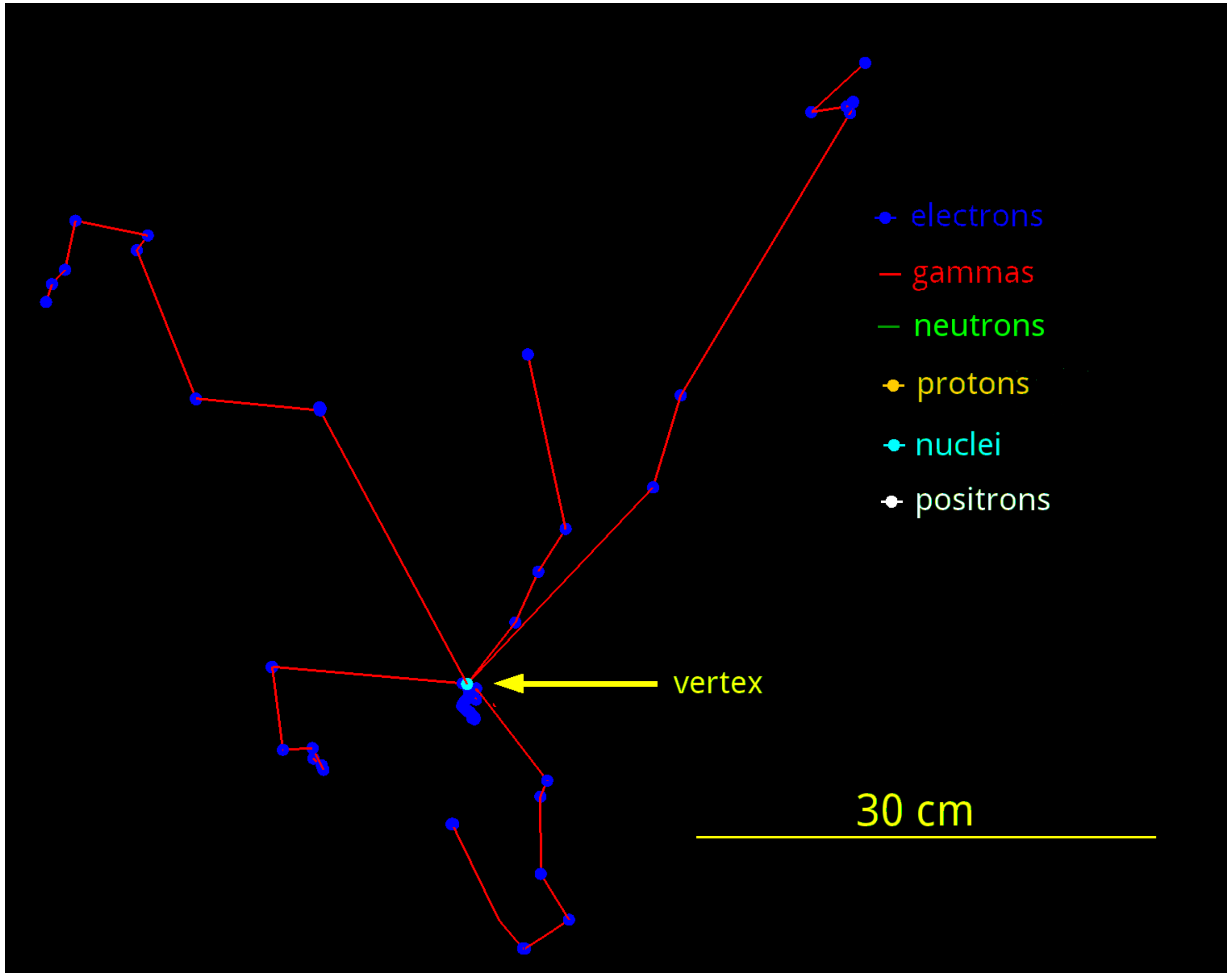
E_ν = 16.1 MeV

e^- deposited 10.2 MeV

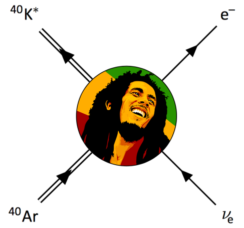
γ's deposited 4.3 MeV

Total visible
Energy = 14.5 MeV

Visible event
radius = 48.4 cm



Example neutron event



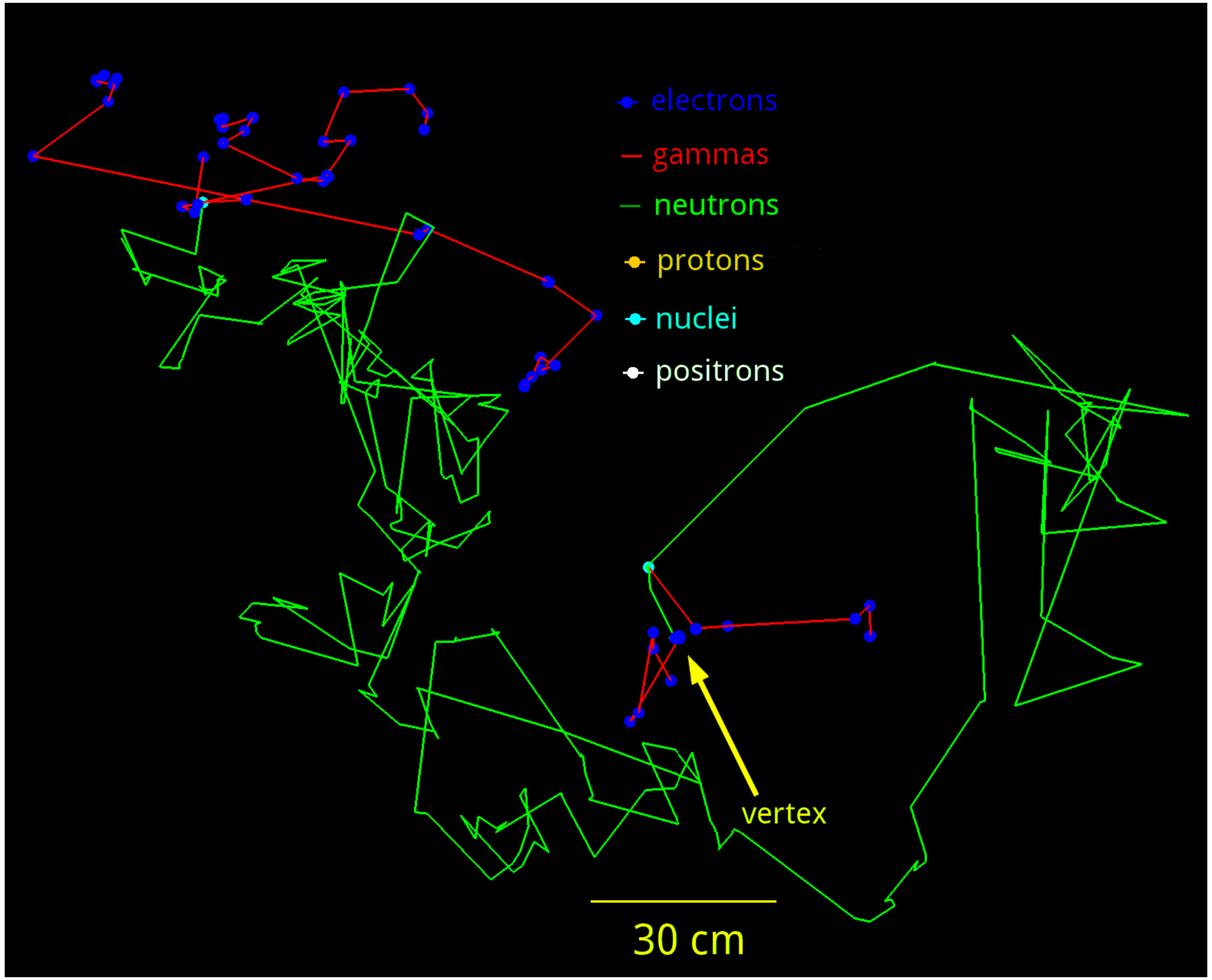
E_ν = 16.3 MeV

e^- deposited 4.5 MeV

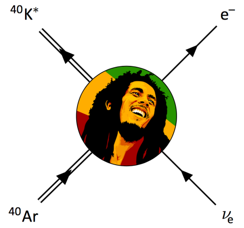
γ's from n-capture 7.6 MeV

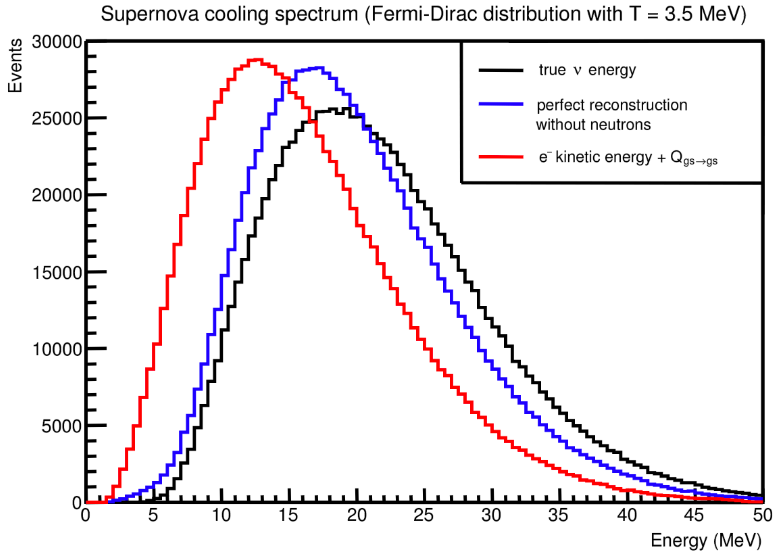
Total visible Energy = 12.2 MeV

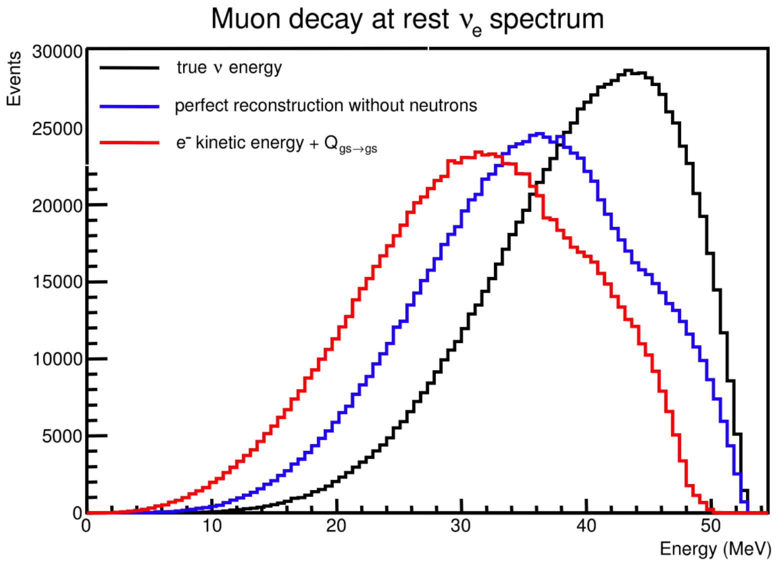
Visible event radius = 144 cm



Where does the neutrino energy go?







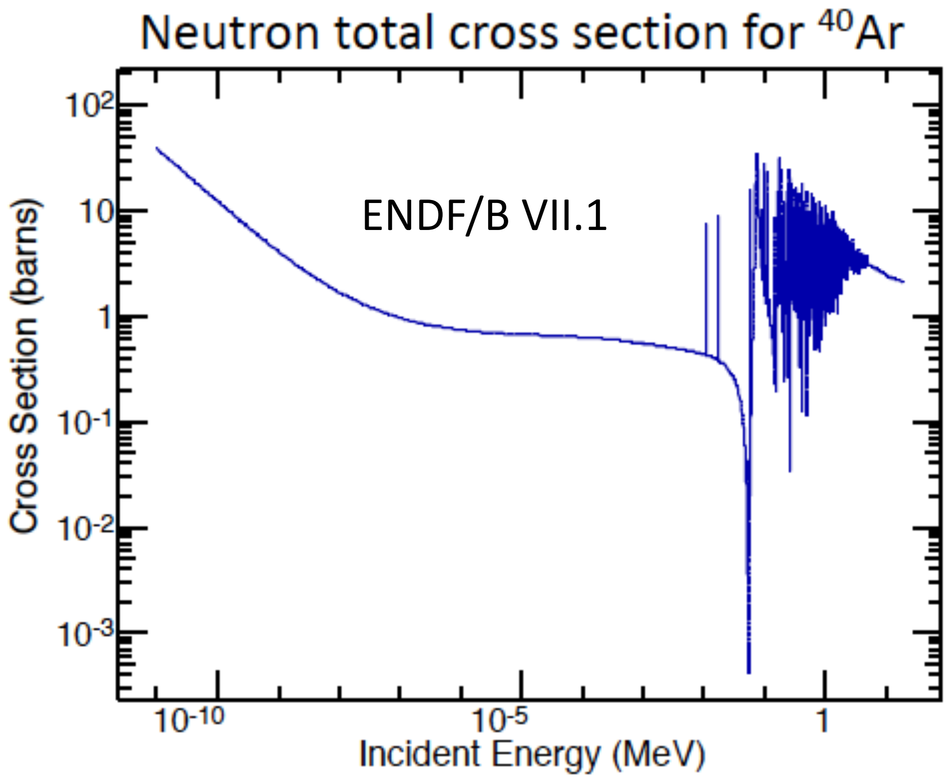
Black = incoming neutrino energy

Red = energy donated to electron (+ Q-value g.s. to g.s.)

Blue = energy donated to electron + gammas (overall effect due to neutron emission)

Large spectral distortion may exist due to neutron emission!

Neutrons in argon



Can breakup neutrons be detected in a LArTPC?

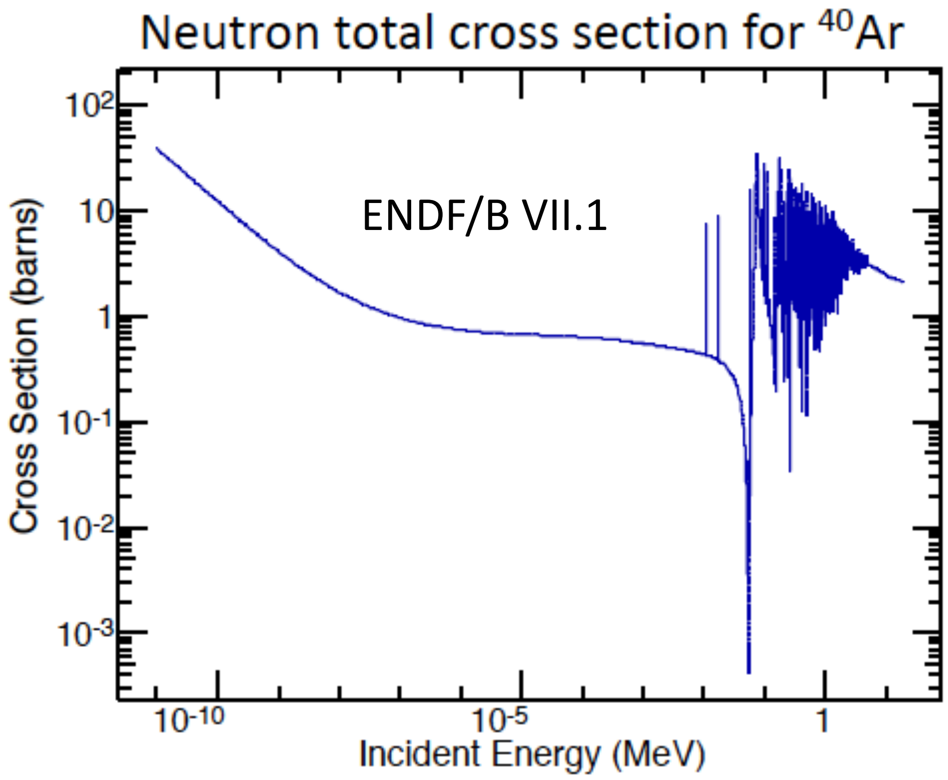
Can we recover missing energy?

Negative resonance make ^{40}Ar almost transparent to neutrons of ~50 keV

Neutrons produced above the resonance will lose only small amounts of energy per scatter until they “fall in the well” – occasionally they meet one of the other stable isotopes of argon and get “knocked out of the well”

Capture times are long (order 100s microseconds) and many neutrons will not be contained, even by a DUNE-size detector

Neutrons in argon



Can breakup neutrons be detected in a LArTPC?

Can we recover missing energy?

If a capture does occur:

$$n + {}^{40}\mathrm{Ar} \rightarrow {}^{41}\mathrm{Ar} + 6.209\ \mathrm{MeV}$$

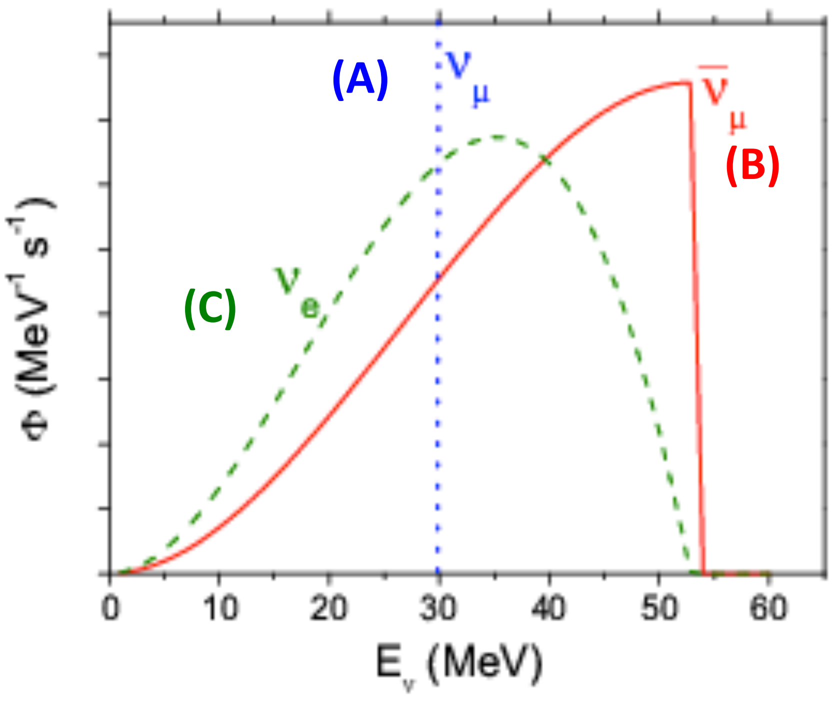
Up to ~6.2 MeV of gammas are released during de-excitation of ^{41}Ar

Low-threshold photon detection may reveal this signature

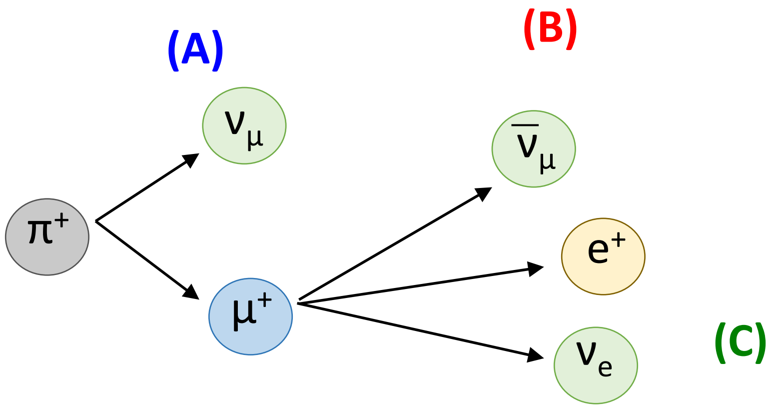
The consequence of missing a neutron? Neutrino energy is miss-reconstructed by at least 7.8 MeV!

Can’t we just measure the cross-section?

Shoot a beam of protons onto a target and create lots of stopped pions:



The Michel spectrum is a great standard candle for low-energy neutrino studies (SN neutrinos and coherent scattering)

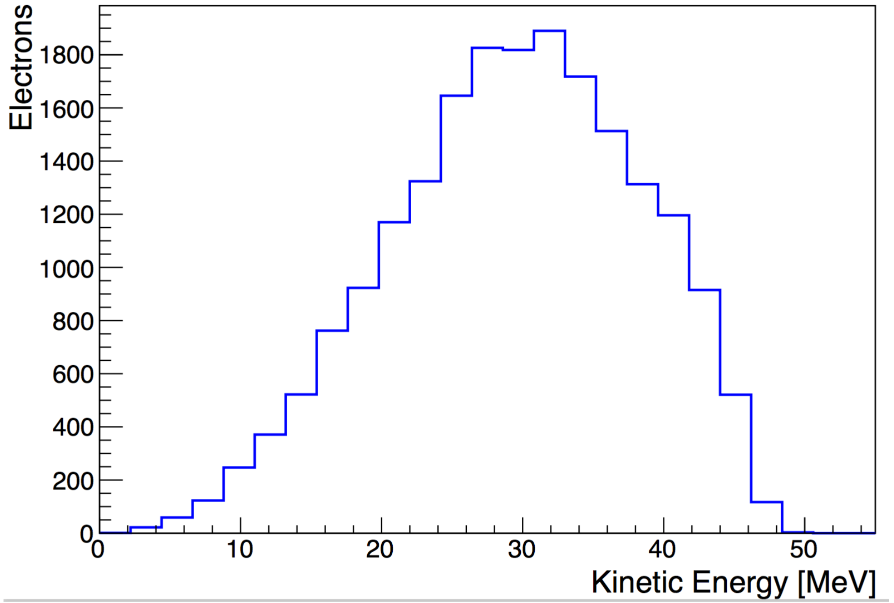


Decay-at-rest CC output from MARLEY

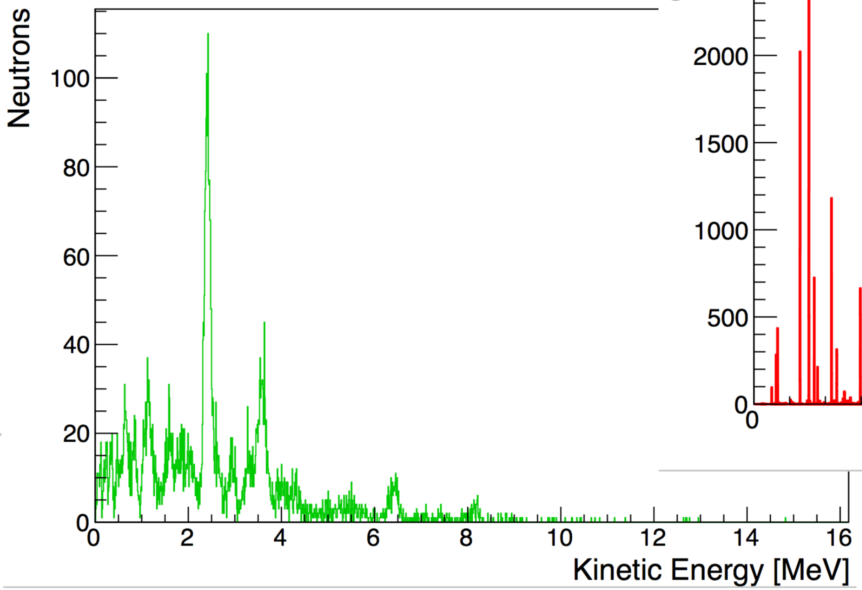
$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

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

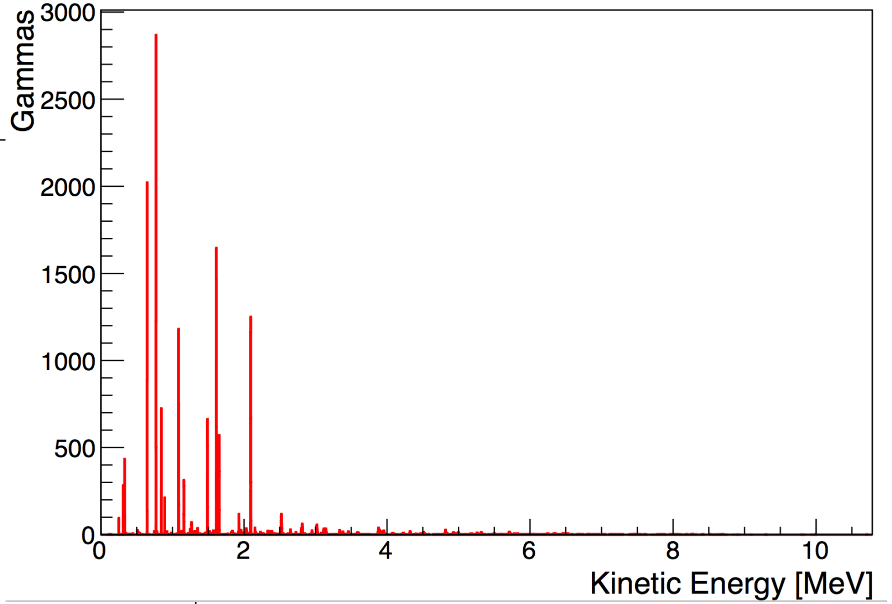
Outgoing electrons analogous to Michel electrons



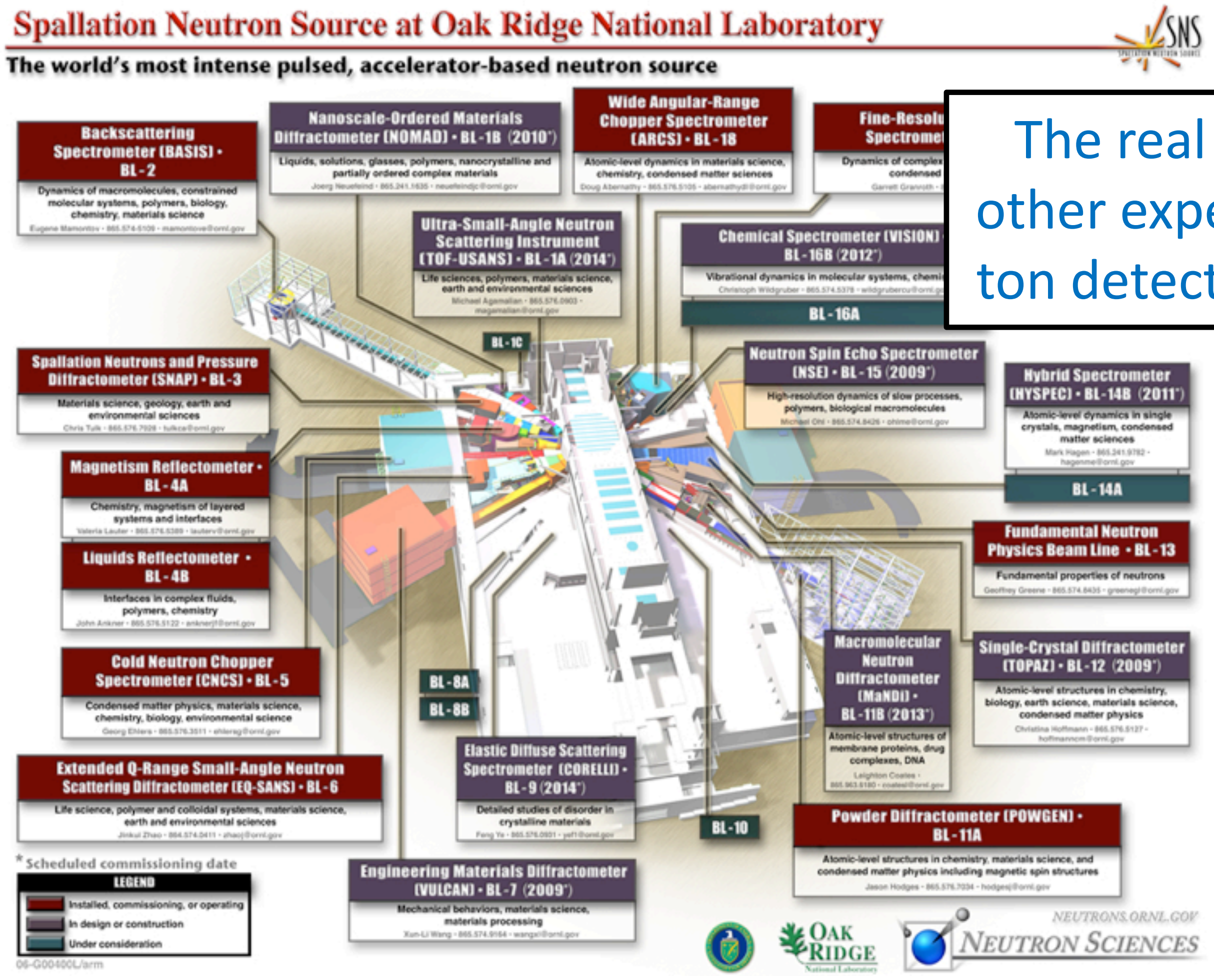
Neutrons below 10 MeV



Gammas primarily below 4 MeV



Spallation Neutron Source

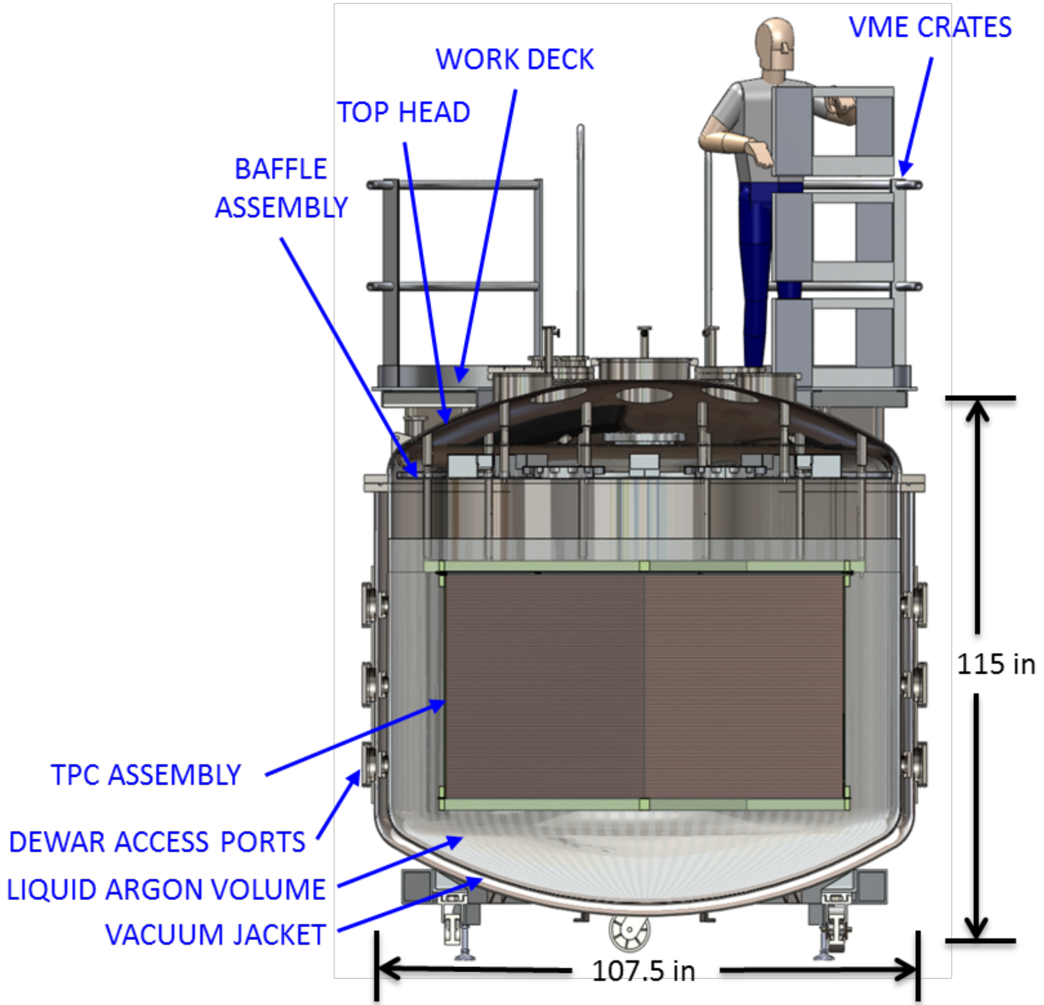


The real estate near the source is taken up by other experiments. Closest proximity for a multi-ton detector ~ 35 - 40 meters away from source.

Expect about 1000 CC ν_e events per year for 5-tons liquid argon ~35 meter stand-off distance

How to mitigate cosmic-ray and beam-related neutron backgrounds? How much shielding material is required?

CAPTAIN (next talk by C. Mauger)

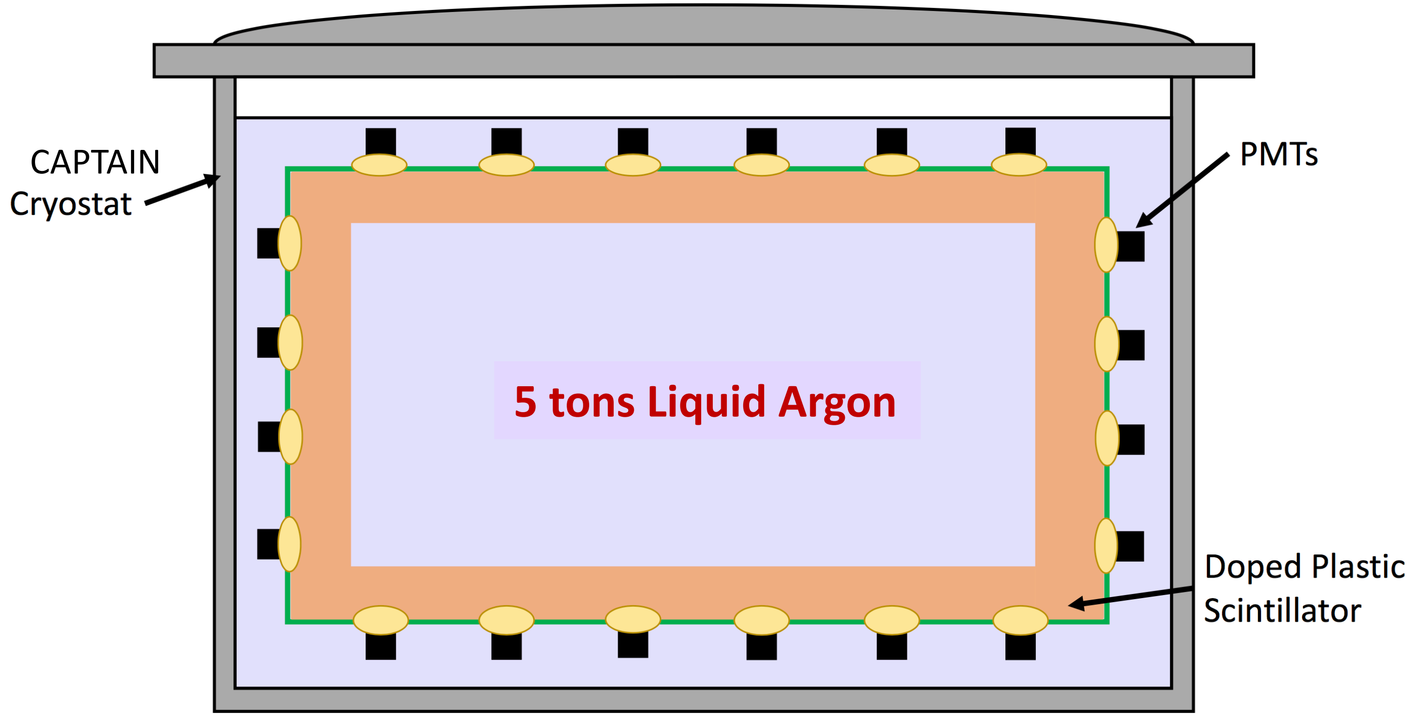


- Liquid argon TPC detector:
  - Portable and evacuable cryostat
  - 5 tons of instrumented liquid argon
- TPC:
  - Hexagonal prism, vertical upward drift ($E = 500$ V/cm, $v_d = 1.6$ mm/μs)
  - 2001 channels (667/plane)
  - 3 mm pitch and wire spacing
- Laser calibration system
- Photon detection system
- Electronics chain is the same as MicroBooNE
- Purification system is a scaled version of MicroBooNE's, similar to LArIAT, based on LAPD experience
- Mini-CAPTAIN: a smaller prototype detector (400 kg of instrumented liquid argon)

Measuring SN neutrino-argon reactions

“Magellan”

(named after the Large Magellanic Cloud)



Measuring SN neutrino-argon reactions

Goals:

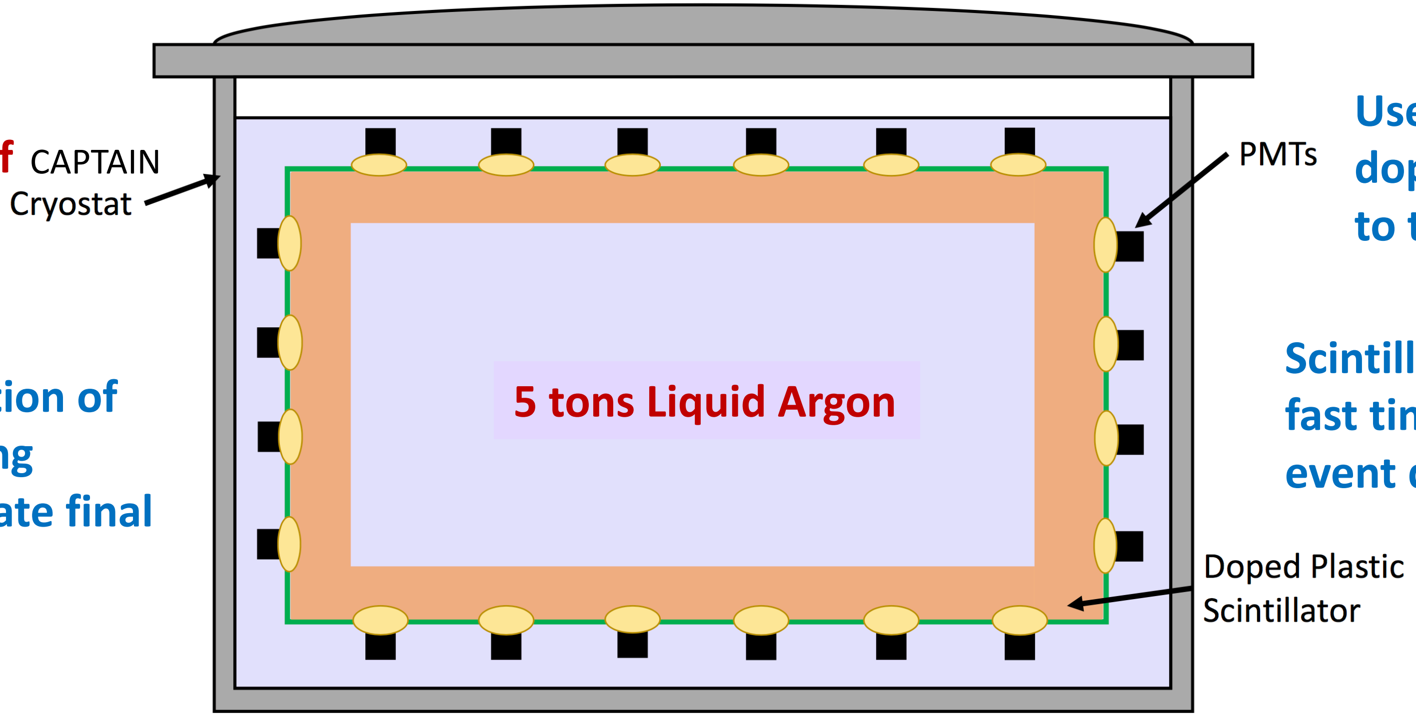
1) **Combine with CAPTAIN to measure CC and NC total cross-sections**

2) **Determine number of neutrons vs. incoming neutrino energy**

Additionally, segmentation of the inner volume is being studied – used to separate final state electron from de-excitation gammas

"Magellan"

(named after the Large Magellanic Cloud)



Use Boron or Gadolinium doped plastic scintillators to tag final state neutrons

Scintillation detection yields fast timing and low-threshold event detection

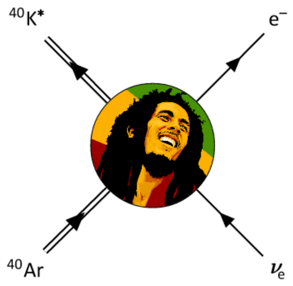
Summary

- Argon gives us a mechanism for extracting the **electron neutrino** information from a supernova burst
- Nuclear physics of the neutrino-argon interaction in the energy range of stellar collapse is ***complicated:***
  - **No direct measurements of these reactions exist**
  - **Indirect measurements of transitions to excited states are in mediocre agreement at best**
  - **No experimental data to compare to predictions for nucleon evaporation**
- **MARLEY** attempts to compute these reactions to the best of our ability. **The CC $\bar{\nu}_e$ and NC neutrino reactions will be added soon.**

Summary

- We are in **dire** need of direct measurements of these reactions – there several facilities where this could happen (**neutrinos are now a big deal at the SNS**)
- **Magellan** is a detector concept that would deploy neutron capture material (in-situ with PMTs) inside **CAPTAIN** cryostat:
  - **Measure the total cross-section (CC and NC) from decay-at-rest neutrinos**
  - **Measure number of neutrons vs neutrino energy**

Summary



MARLEY (Model of Argon Reaction Low Energy Yields)

v0.9.5

A Monte Carlo event generator for tens-of-MeV neutrino-nucleus interactions in liquid argon

Main Page | Related Pages | Classes | Search

MARLEY documentation

The source code for MARLEY v0.9.5 is available here. Build requirements: g++ >= 4.9 (or a recent version of clang) and GNU make

The nuclear structure data that we recommend for use with MARLEY are taken from TALYS-1.6 and are available in the source code tar.gz file under the structure/ subdirectory.

The beginning of a draft user manual is available here.

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http://www.marleygen.org/