Solar and Supernova Neutrino Detection for the Deep Underground Neutrino Experiment

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On behalf of the DUNE Collaboration

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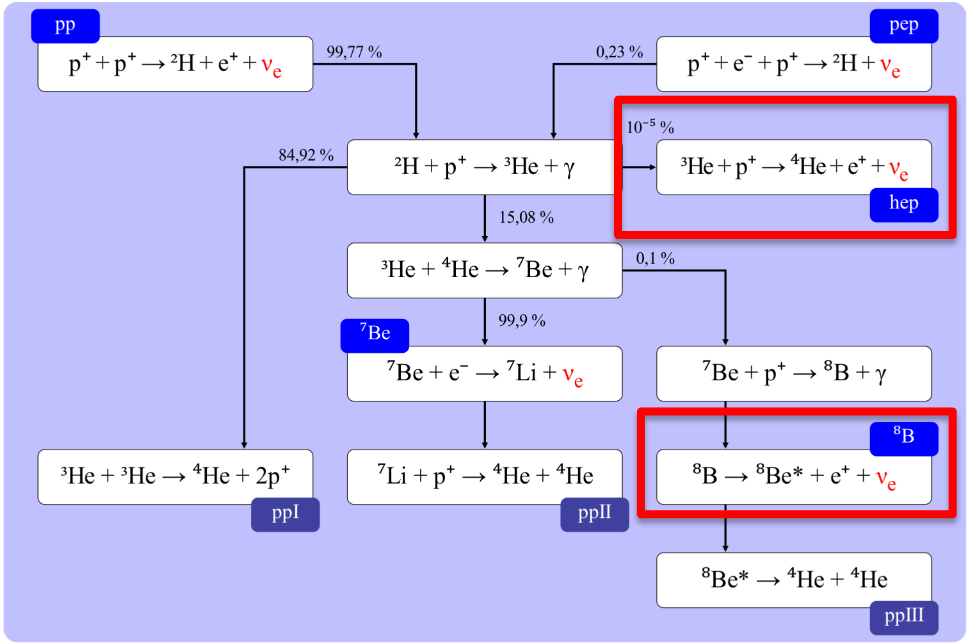
Outline

- Solar and supernova neutrinos
  - Introduction
  - Motivation
- The Deep Underground Neutrino Experiment (DUNE)
  - Liquid argon time-projection chamber
  - Where to look for supernova neutrinos
  - Challenges DUNE faces in detecting these neutrinos
- Current Work
- Summary

Solar Neutrinos: Introduction

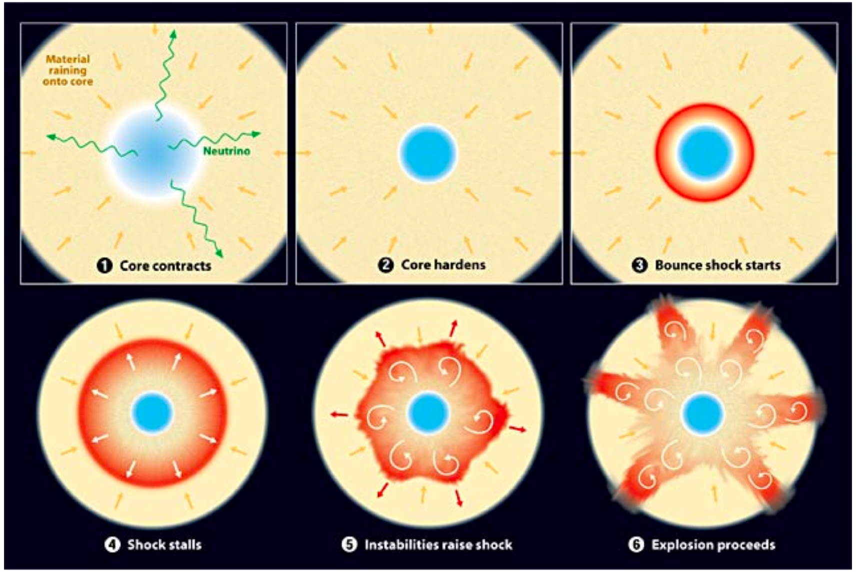
- Largest natural source of neutrinos
- Sun produces trillions of neutrinos via nuclear fusion
  - Various reactions produce solar neutrinos, e.g., proton-proton, ^{7}Be, ^{8}B, ^{15}O, etc.
- Low in energy (a few to tens of MeV)
  - For the purposes of this talk, we are interested in the ^{8}B and HEP neutrinos (outlined in red)
- Solar neutrinos are useful:
  - Help test solar models
  - Determination of neutrino parameters
  - Matter effects/oscillations



Energy generation in the sun (D. Szam)

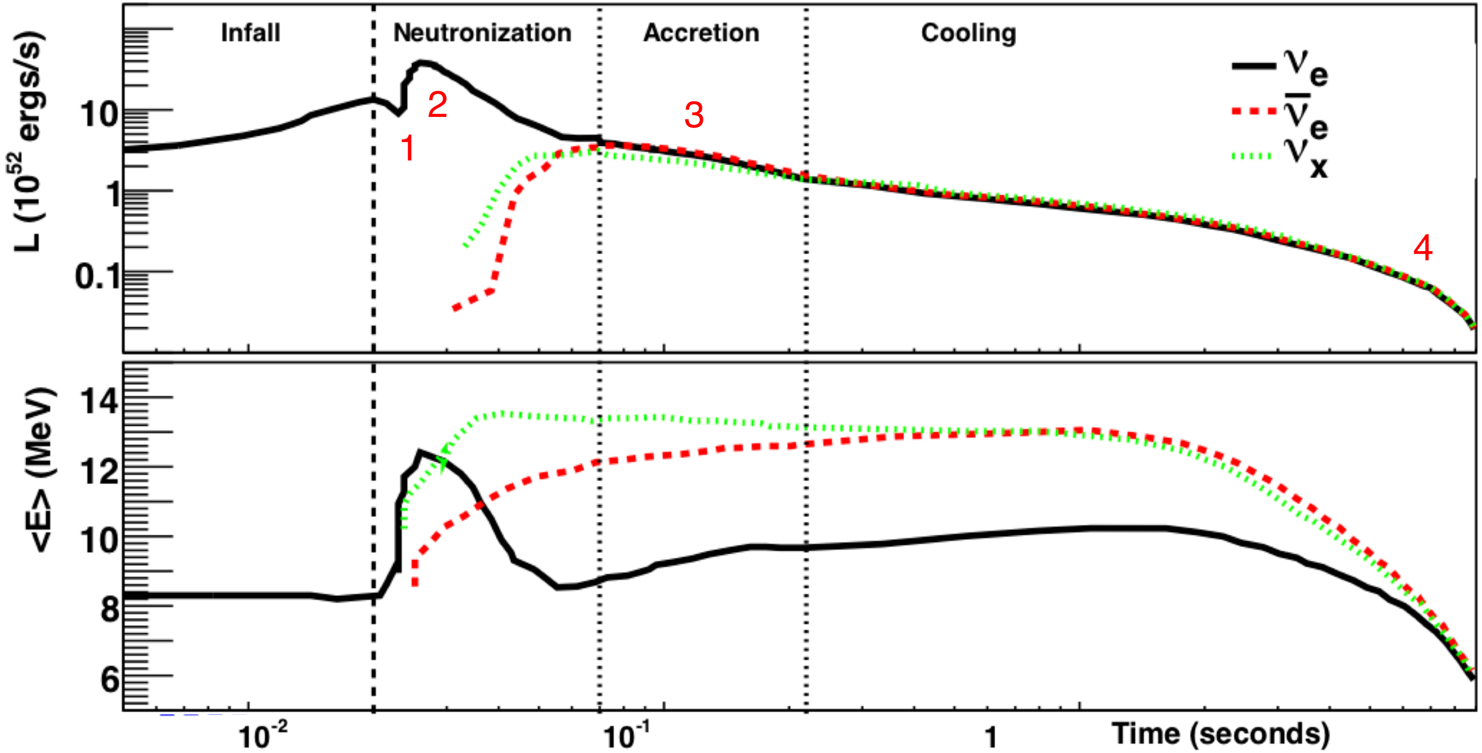
Supernova Neutrinos: Introduction

- Star at end of lifetime: core undergoes gravitational compression, collapses
- 99% of potential energy in the form of neutrinos is released (tens of MeV)
- Prompt ~10s of seconds burst
- Unknowns in supernova core collapse physics (K. Scholberg)
  - Neutrino burst contains valuable information about both the mechanism and phenomena associated with supernova bursts



Core-collapse supernova stages (S. Simpson)

Supernova Neutrino Flavor-Energy-Time Profile



1 – Neutrino trapping
2 – Neutronization burst
3 – Explosion/SASI
4 – Cooling

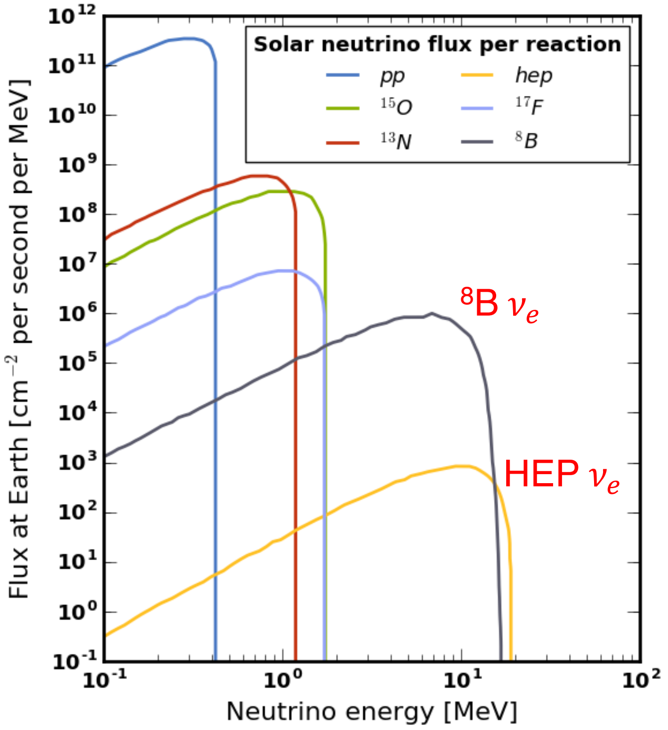
For a supernova that is 10kpc from Earth.

A lot of information about the supernova is contained in this profile!

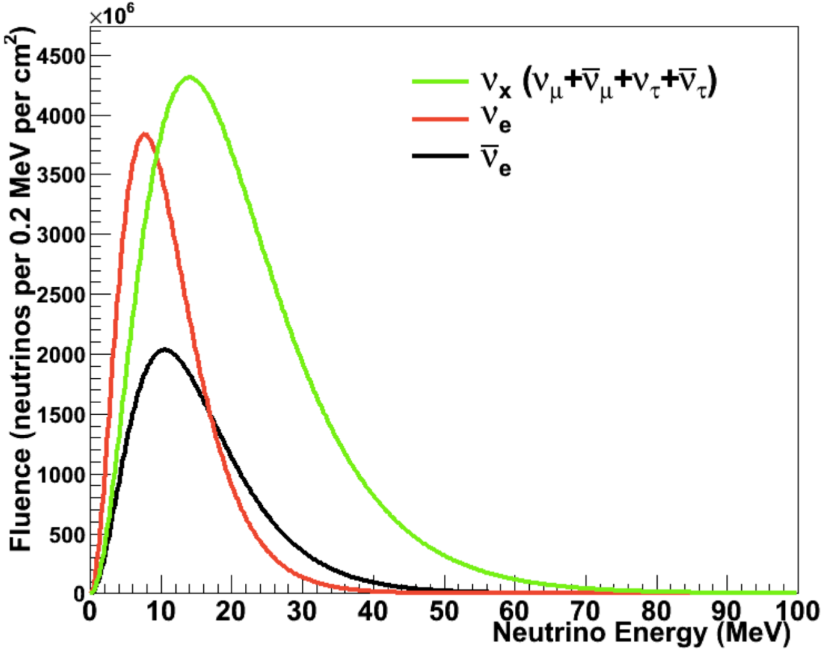
L. Huedepohl et al., PRL 104 251101

Solar/Supernova Neutrino Energy Distributions

Energy spectra for solar neutrinos (J. Bahcall)



Energy spectra for a SN 10kpc from Earth (K. Scholberg)

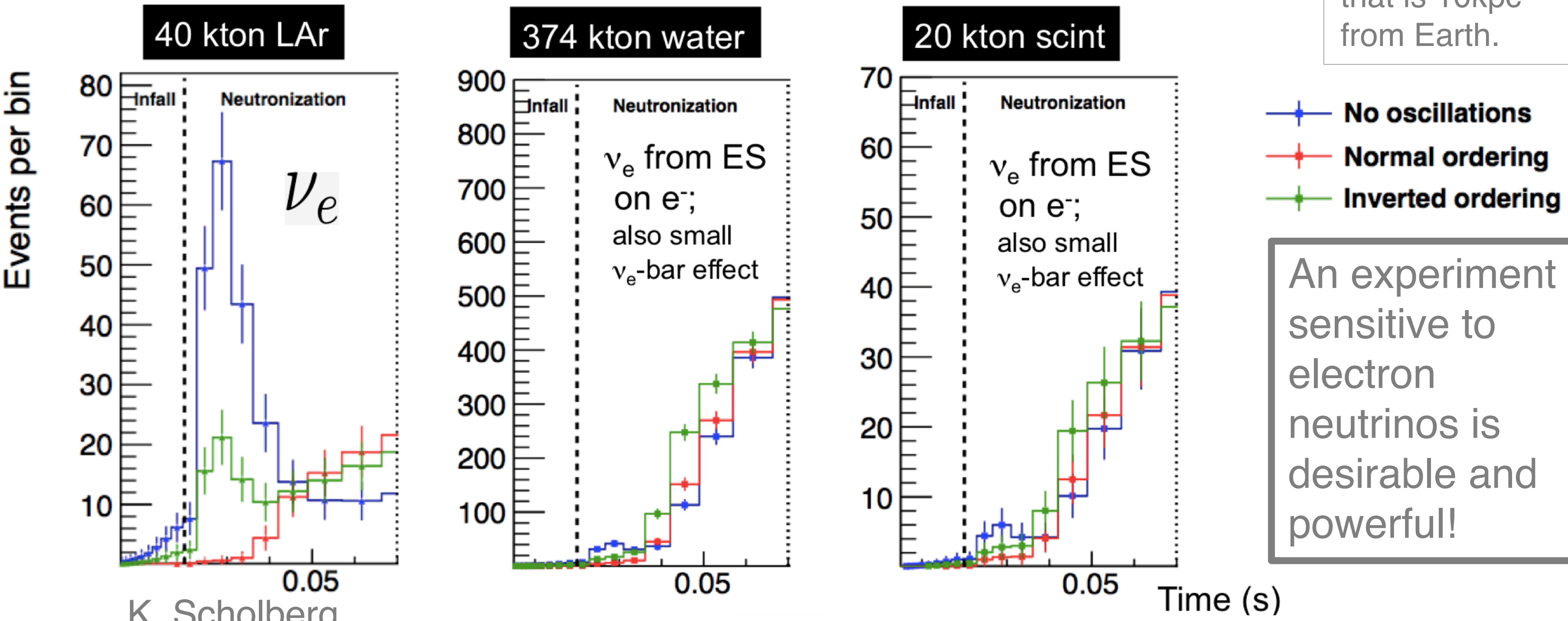


- Supernova/solar neutrinos have similar energy ranges, reconstruction issues
- Background studies underway for solar neutrinos
- This talk will focus on supernova neutrinos

Motivation to Detect Electron Neutrinos

Example of robust mass ordering signature: **the neutronization burst**

For a supernova that is 10kpc from Earth.



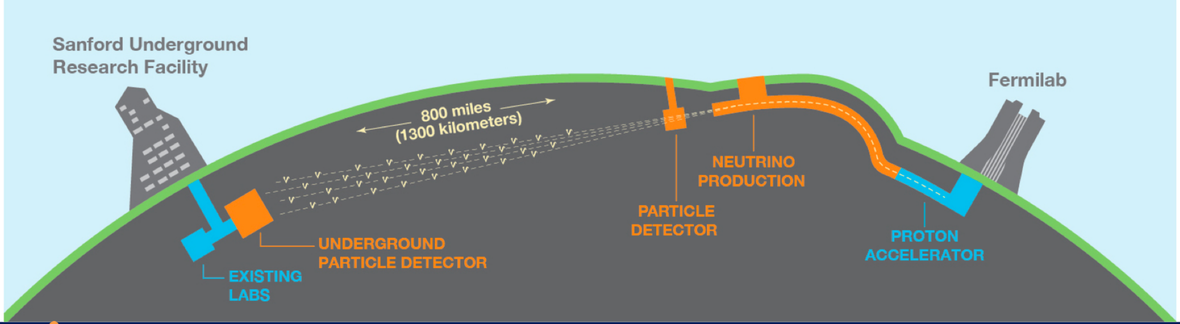
K. Scholberg

An experiment sensitive to electron neutrinos is desirable and powerful!

DEEP UNDERGROUND NEUTRINO EXPERIMENT

- International experiment for neutrino science (1000+ collaborators!)
  - Origin of matter, nucleon decay, **supernova physics**
- Two detectors:
  - Near detector on-site at Fermi National Laboratory (near Chicago, IL)
  - Far detector at Sanford Underground Research Facility (SURF) in South Dakota
    - World's largest liquid argon time-projection chamber
- Argon is sensitive to electron neutrinos, making DUNE unique with respect to other experiments (e.g., water and scintillator detectors are $\bar{\nu}_e$ sensitive)

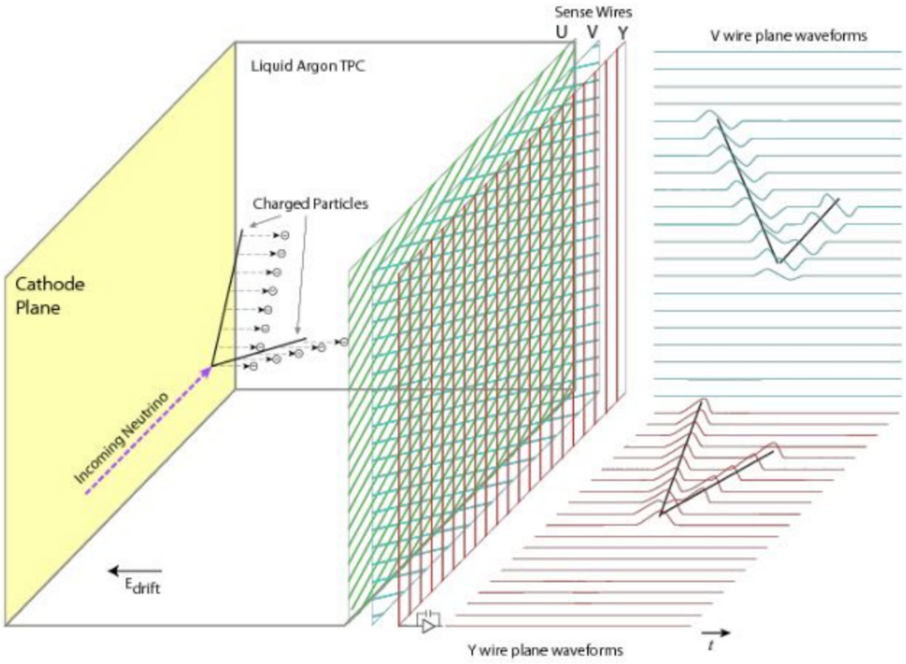
http://www.dunescience.org/



See Jiangming Bian's "Overview of DUNE" talk for more information!

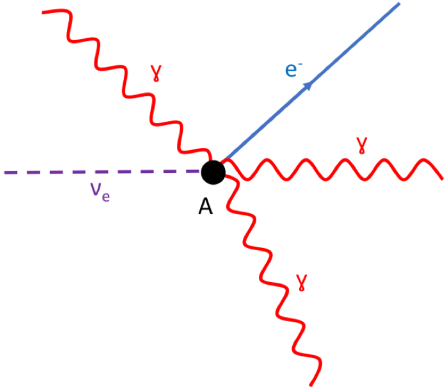
Liquid Argon Time Projection Chamber (LArTPC): Introduction

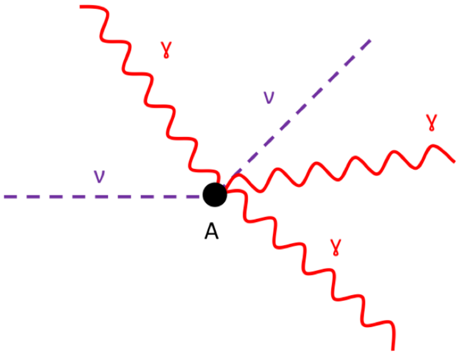
- Neutrino-argon interaction: argon is ionized by charged secondary particles
  - Scintillation light detected by PMTs gives us timing information
- Charged particles drift toward induction planes, deposit charge on collection plane wires
- Charge deposited on collection wires
  - Reconstructed wire objects (signals for specific particles)
  - Reconstructed 2D hits (single ionized particles)
  - Reconstructed 2D clusters (ionization of multiple particles)
  - Reconstructed 3D objects like tracks, showers, space points

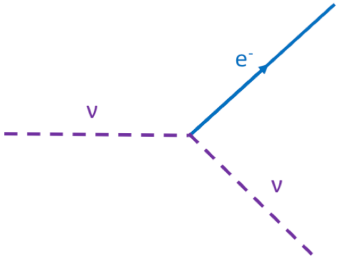


For more information

Relevant Neutrino Interactions







+ others…

Charged Current (CC):
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{K}^* + e^-$
${}^{40}\mathrm{K}^* \rightarrow \gamma + {}^{40}\mathrm{K}$

(Nucleon emission also possible)

Neutral Current (NC):
$\nu + {}^{40}\mathrm{Ar} \rightarrow \nu + {}^{40}\mathrm{Ar}^*$
${}^{40}\mathrm{Ar}^* \rightarrow \gamma + {}^{40}\mathrm{Ar}$

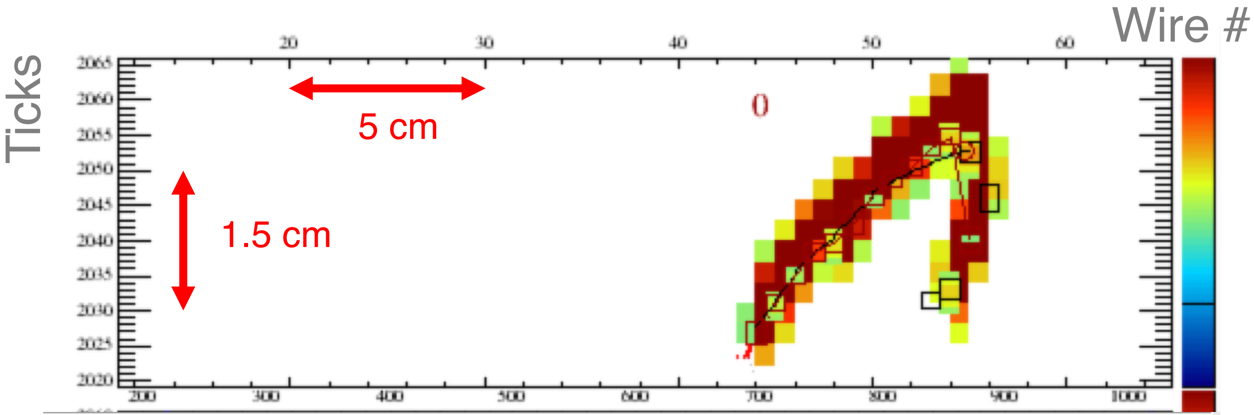
(e.g., 9.8 MeV γ)

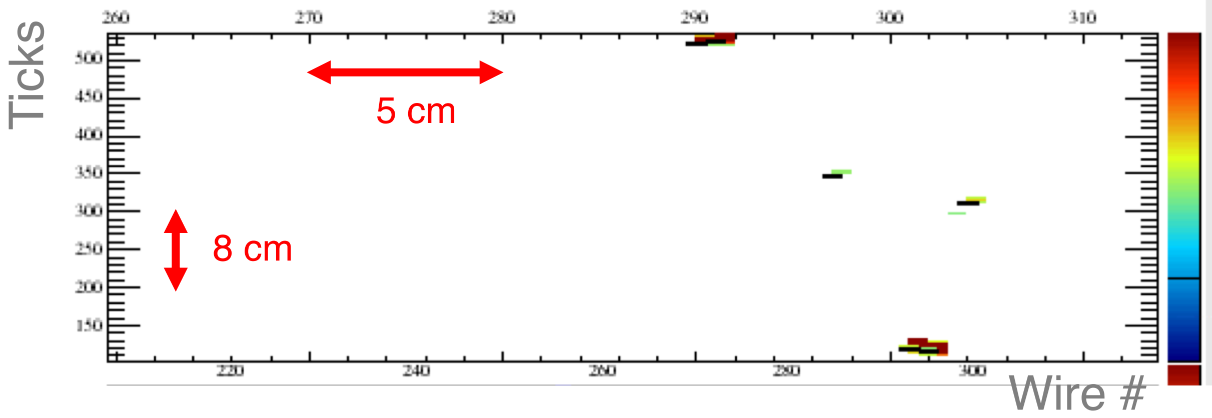
Elastic scatter on electrons (ES):
$\nu + e^- \rightarrow \nu + e^-$

Required reconstruction ability to identify interaction channels

DUNE Event Displays

- Event display: charge depositions + reconstructed objects
  - Collection plane shown here
- Top: 30.25 MeV ν_eCC event display
- Bottom: 9.8 MeV gamma NC event display



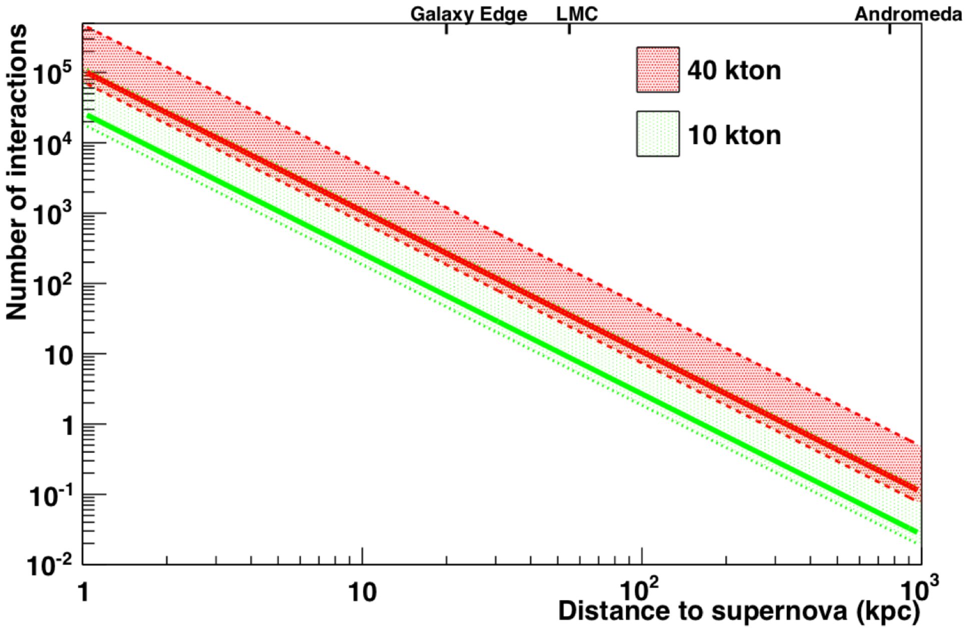


Looking for Supernova Neutrinos

- 10 kton: one DUNE module
- 40 kton: entire DUNE detector
- Error bands: range of flux models
- Places of interest:

Distance from Earth (kpc)	# CC events	# NC events	# ES events
10	3000	100	310
50 (LMC)	120	4	12
770 (Andromeda)	0.5	0.02	0.05

Number of interactions expected to be seen in DUNE detector



Challenges DUNE Faces

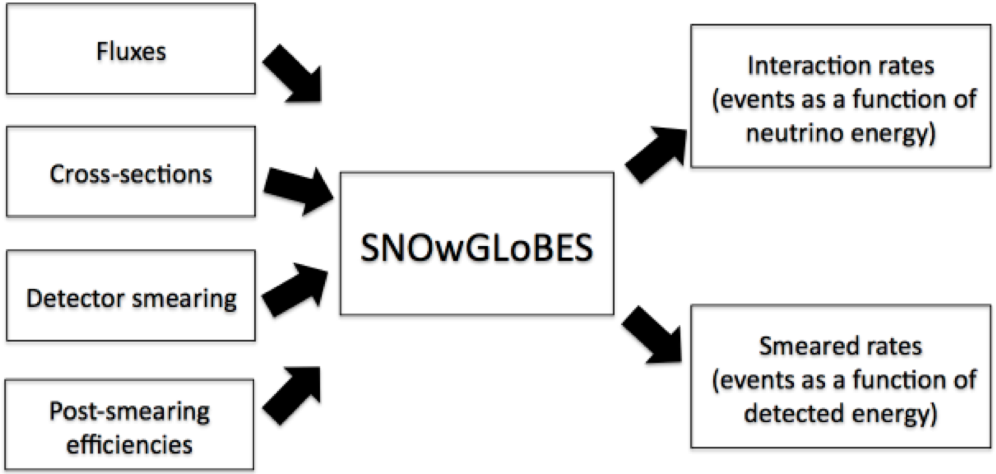
- Understanding the SN model
  - Time profile studies depend heavily on the model
- Understanding the background
  - Radiological background, electronic noise
- Reconstruction algorithms
  - Low-energy interactions (small number of hits)
- Data acquisition (DAQ) challenges
  - Trigger rates
  - Data rates
- For the purposes of this talk:
  - What predictions can we make about the supernova signal in the DUNE detector?
  - What reconstruction tools do we want for low-energy neutrino-argon events?

Work is ongoing – good progress on all these fronts!

What predictions can we make about the supernova signal in the DUNE detector?

SNOwGLoBES: Introduction

- SNOwGLoBES: SuperNova Observatories with GLoBES
  - GLoBES: General Long Baseline Experiment Simulator
- Updated default LAr smearing matrix in SNOwGLoBES using MARLEY simulations

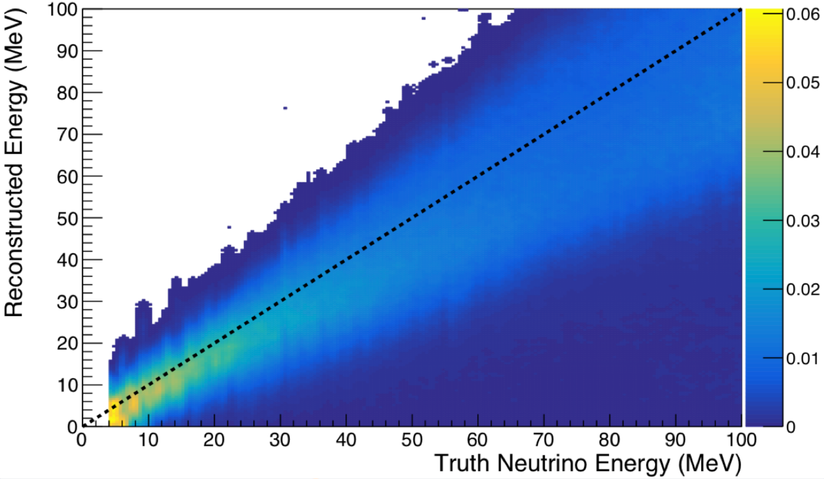


SNOwGLoBES Schematic

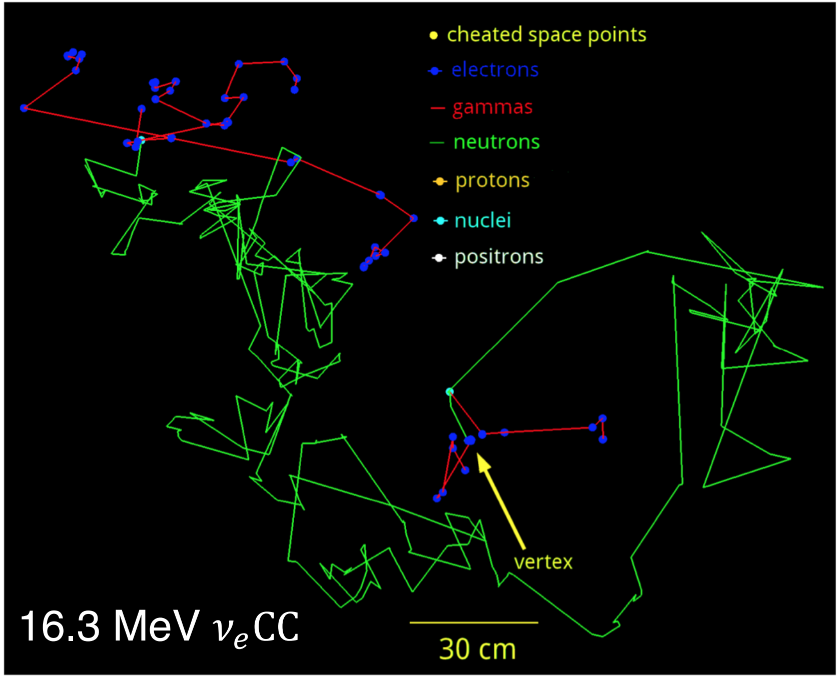
MARLEY: Model of Argon Reaction Low-Energy Yields

- MARLEY models low-energy ν_eCC neutrino interactions
  - More sophisticated modeling of final state particles
- Most sophisticated event generator available for this energy range!

MARLEY Smearing Matrix

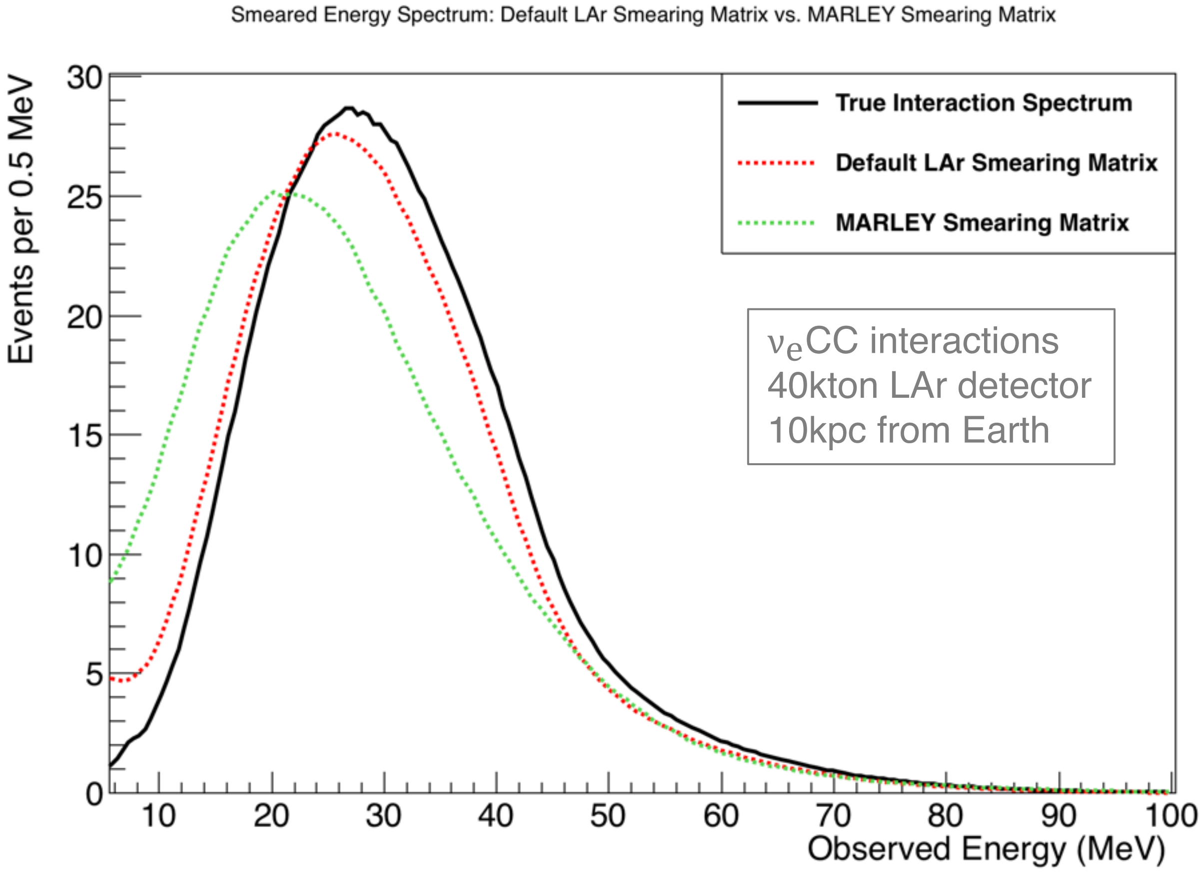


Particle trajectories from a simulated SN event in DUNE



Typical neutron emission event (S. Gardiner)

Improving the Predictions Made Using SNOwGLoBES

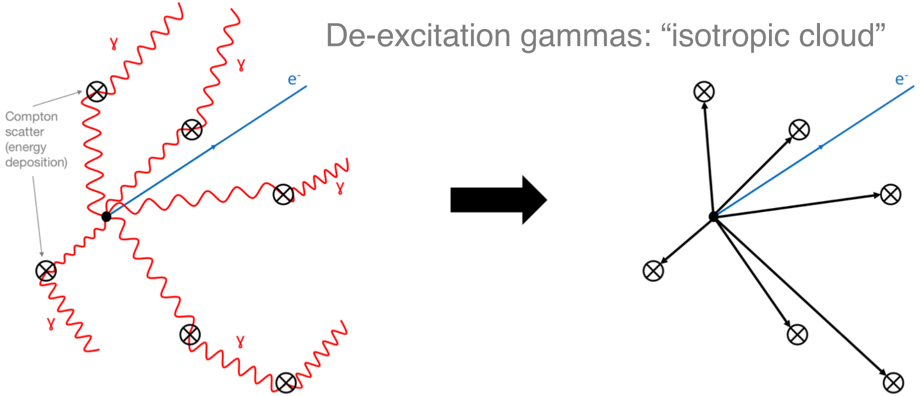


- Used GVKM flux model to make these spectra
- "True Interaction Spectrum": interaction rates before smearing
- Energy loss between the default smearing matrix, MARLEY smearing matrix
- More sophisticated MARLEY modeling generates more realistic predictions!

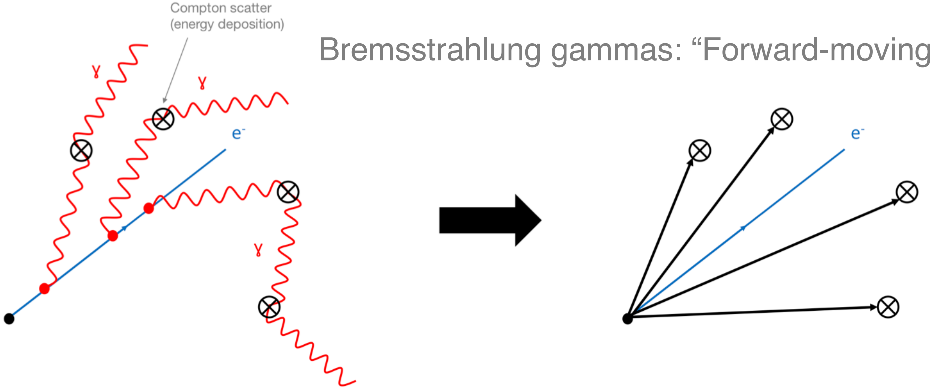
What kind of reconstruction tools do we want for low-energy, neutrino-argon events?

Finding a Gamma-Tagging Algorithm

- Motivations for a gamma-tagging algorithm:
  - Interaction channel identification
  - Energy reconstruction
  - ν_eCC, $\bar{\nu}_e$CC, ES
- Working on an algorithm to distinguish between bremsstrahlung, de-excitation gammas
  - Study differences between ν_eCC events for the two types of gammas to learn how to tag them
  - Reconstruction tool for low-energy events!
- Performed studies on MC Truth information

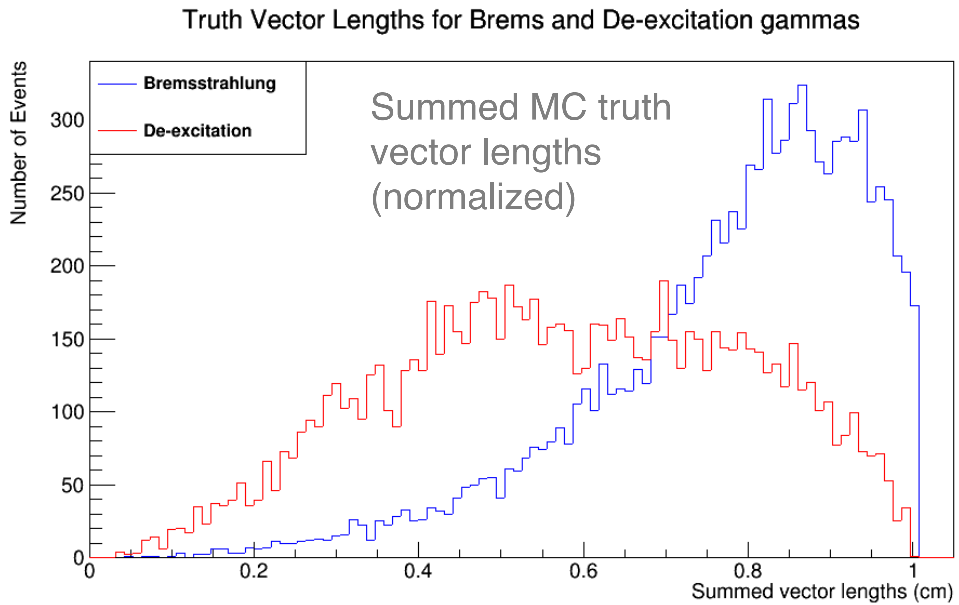


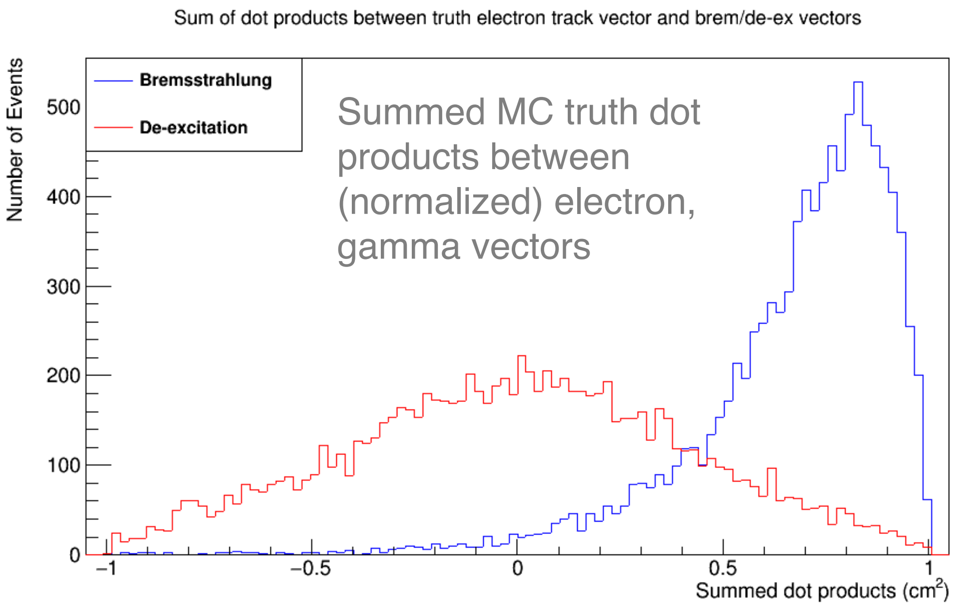
De-excitation gammas: “isotropic cloud”



Bremsstrahlung gammas: “Forward-moving jet”

MC Truth for Trial Gamma-Tagging Parameters





Bremsstrahlung distribution shows positive, more "forward-moving" behavior
De-excitation distribution shows less positive, more isotropic behavior

10k 30.25 MeV ν_eCC events

Promising information for a reconstruction algorithm!

Summary

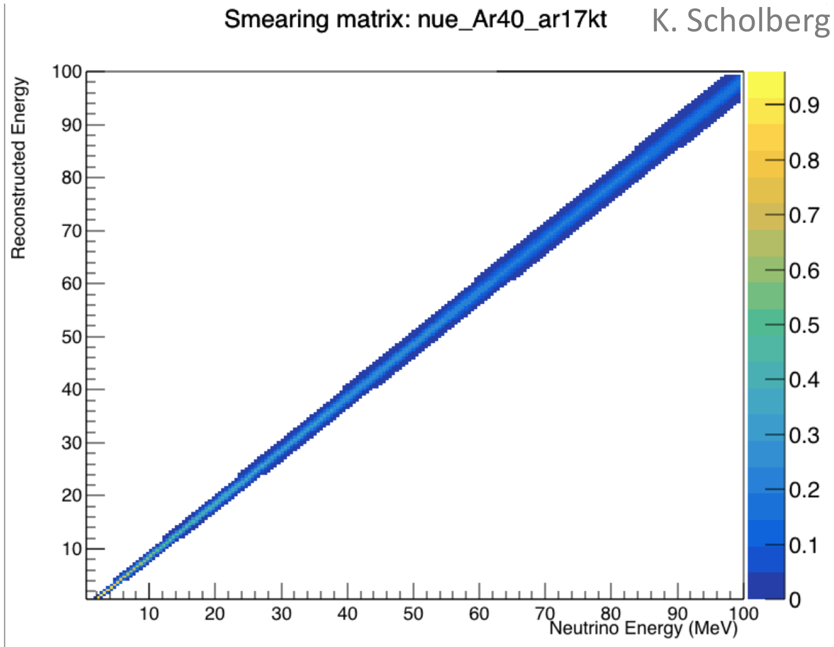
- The DUNE collaboration will be prepared for solar neutrinos and future supernovae!
  - Excellent progress made on many fronts, from DAQ to oscillation models.
  - Work ongoing with modeling solar neutrino background; stay tuned!
- Low-energy neutrino interaction modeling is more realistic with the MARLEY event generator.
  - MARLEY + SNOwGLoBES improve the reliability of supernova neutrino signal predictions in the DUNE detector.
- Supernova/solar neutrino studies improve expectations, advance the low-energy neutrino physics field, and prepare the DUNE detectors to detect these neutrinos under the most optimal circumstances!

Backup Slides

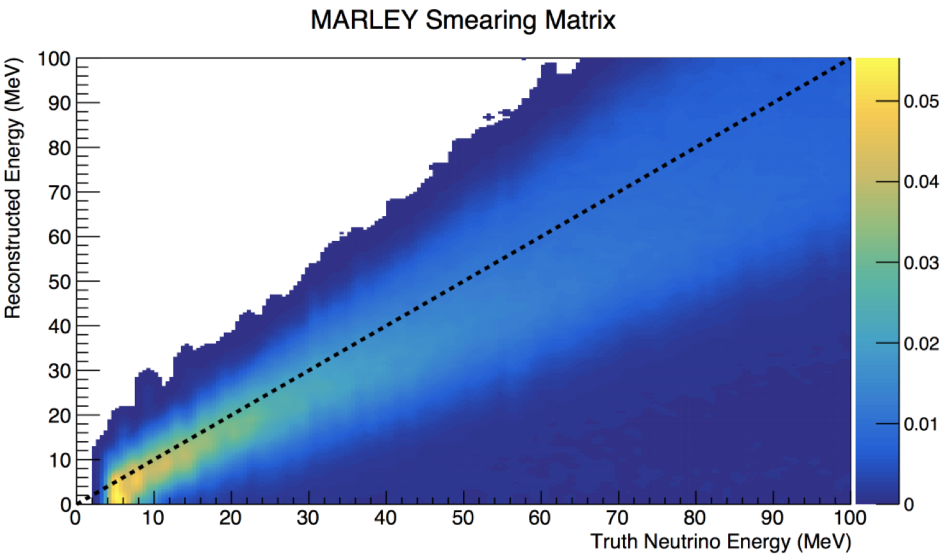
DUNE Solar Neutrino Rates

- Rate for 40kt LArTPC: 122 solar neutrinos per day
  - 4.5 MeV neutrino energy threshold, 31% ν_e survival
  - Signatures: ES, CC
- Observability will depend on backgrounds; under study
- For more information

LAr smearing matrix currently used in SNOwGLoBES



SNOwGLoBES input for MARLEY smearing



Current default in SNOwGLoBES assumes all final-state energy recovered, which is likely much too optimistic

reco energy = true ν energy – 1.5 MeV, convolved with Icarus resolution

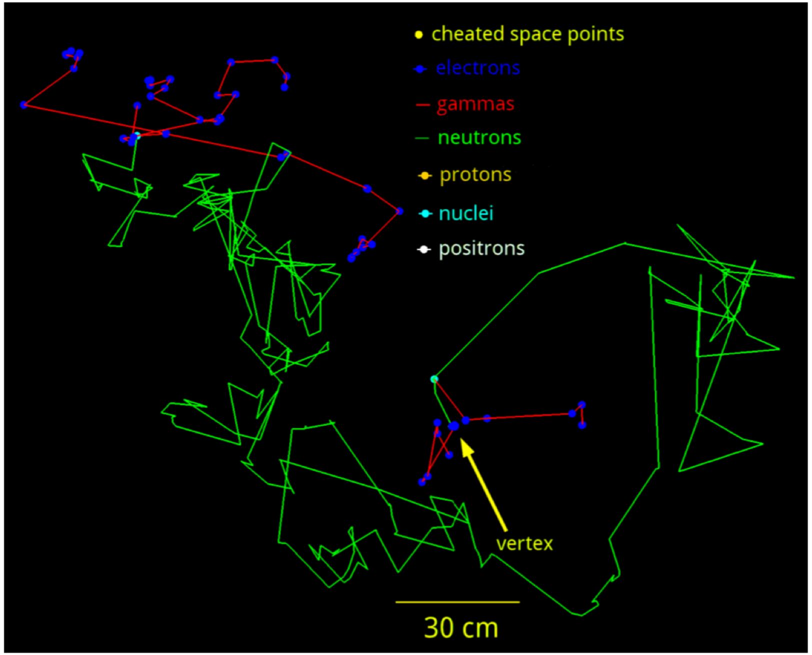
MARLEY Information (S. Gardiner)

Example neutron event (true trajectories)

- E_ν = 16.3 MeV
- e^- deposited 4.5 MeV
- No primary γs from vertex
- ^{39}K deposited 68 keV
- n deposited 7.6 MeV (mostly from capture γs)
- Total visible energy:

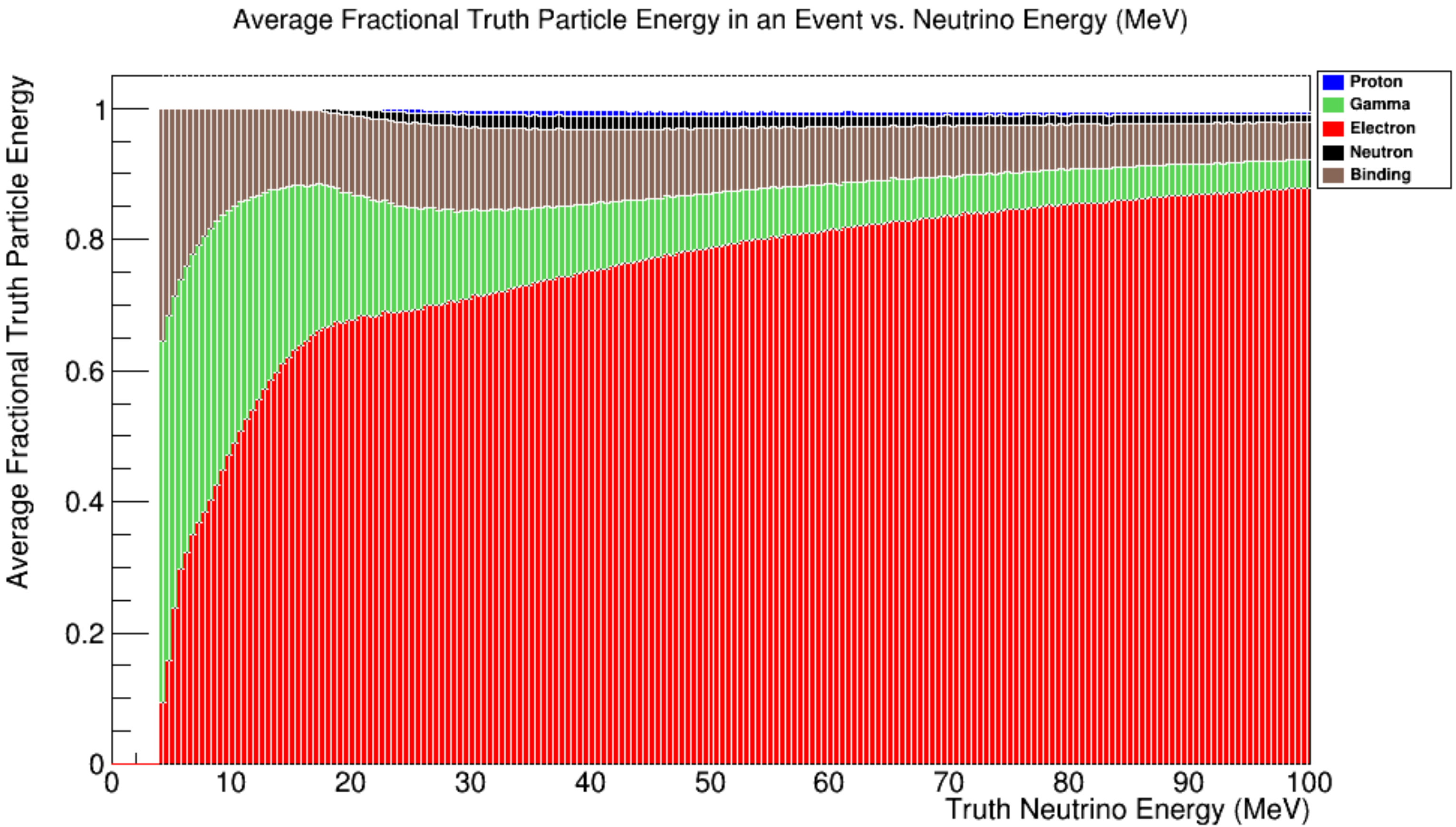
  12.2 MeV
- Visible energy sphere radius:

  1.44 m
- Neutrons bounce around for a long time!

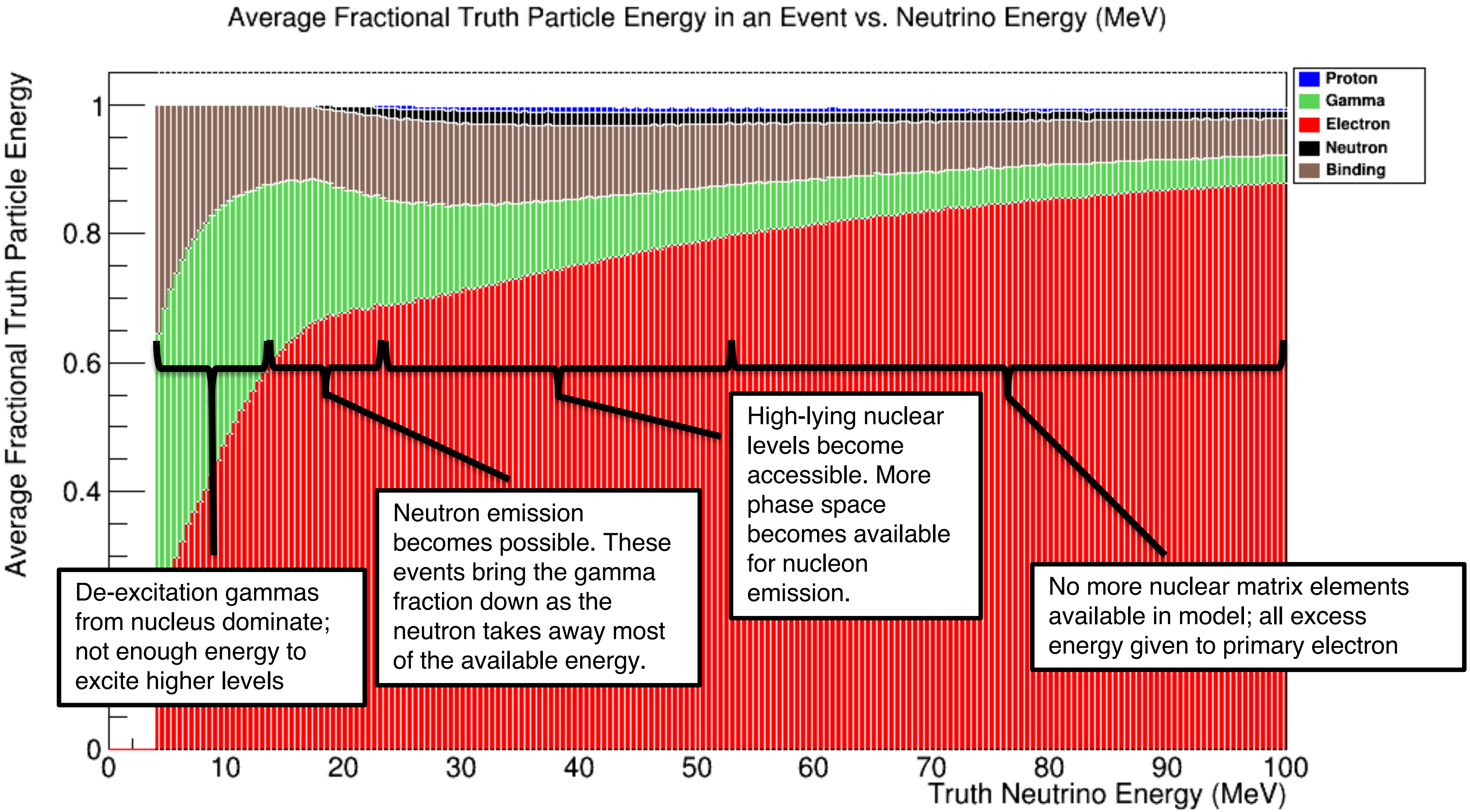


36

MARLEY Smearing Matrix Statistics



Duke UNIVERSITY DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT


Average Fractional Truth Particle Energy in an Event vs. Neutrino Energy (MeV)
Average Fractional Truth Particle Energy
Truth Neutrino Energy (MeV)
0
0.4
0.6
0.8
1
0
10
20
30
40
50
60
70
80
90
100
Proton
Gamma
Electron
Neutron
Binding
De-excitation gammas from nucleus dominate; not enough energy to excite higher levels
Neutron emission becomes possible. These events bring the gamma fraction down as the neutron takes away most of the available energy.
High-lying nuclear levels become accessible. More phase space becomes available for nucleon emission.
No more nuclear matrix elements available in model; all excess energy given to primary electron