Research Strategy Report

Steven Gardiner

SCD Postdoc Meeting

7 January 2020

Introduction

- **Neutrino experimentalist, but "theory-minded"**
  - Primary focus on neutrino-nucleus interactions
  - Software & analysis, no big hardware projects (at least so far)

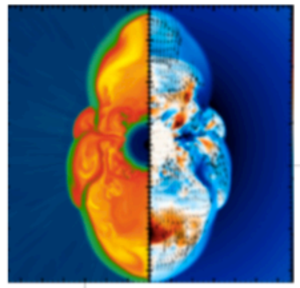
- **PhD in 2018 from UC Davis**
  - Thesis committee: Bob Svoboda (advisor, neutrino experiment), Ramona Vogt (nuclear theory, LLNL), Mike Mulhearn (particle experiment)

- **Background in low-energy nuclear data and neutron detectors**
  - One-year "post-bac" at LANL working with nuclear data team (XCP-5)

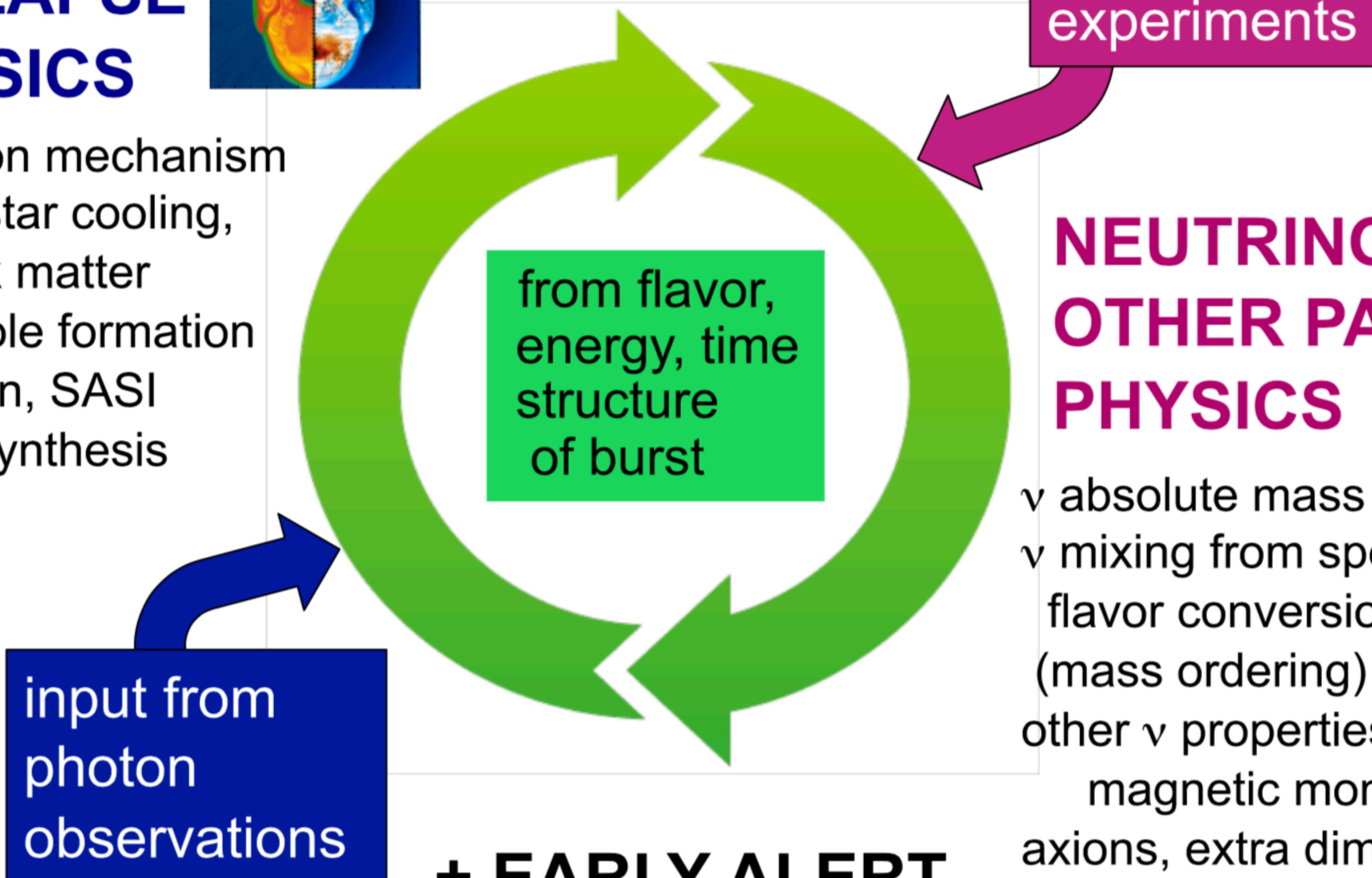
- Beyond thesis topics, also involved during grad study in neutron cross section measurements by CAPTAIN (**arXiv:1903.05276**) and ACED (**arXiv:1902.00596**)

What can we learn from observing supernova neutrinos?

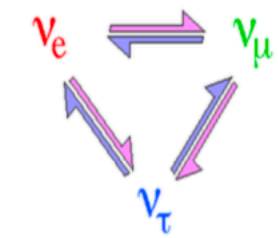
CORE COLLAPSE PHYSICS



explosion mechanism
proto nstar cooling,
quark matter
black hole formation
accretion, SASI
nucleosynthesis
....



+ EARLY ALERT



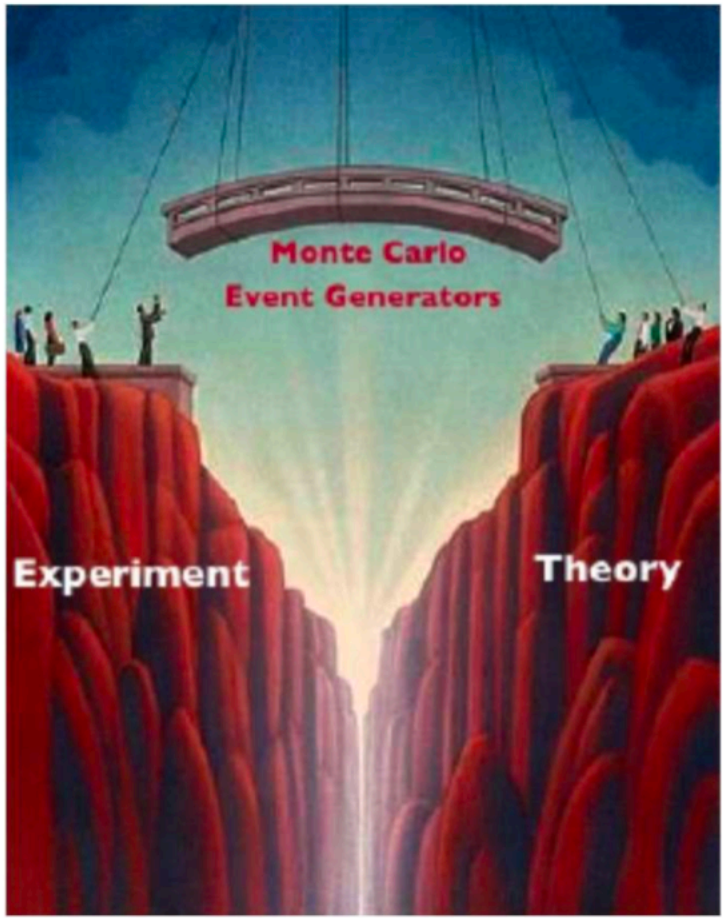
NEUTRINO and OTHER PARTICLE PHYSICS

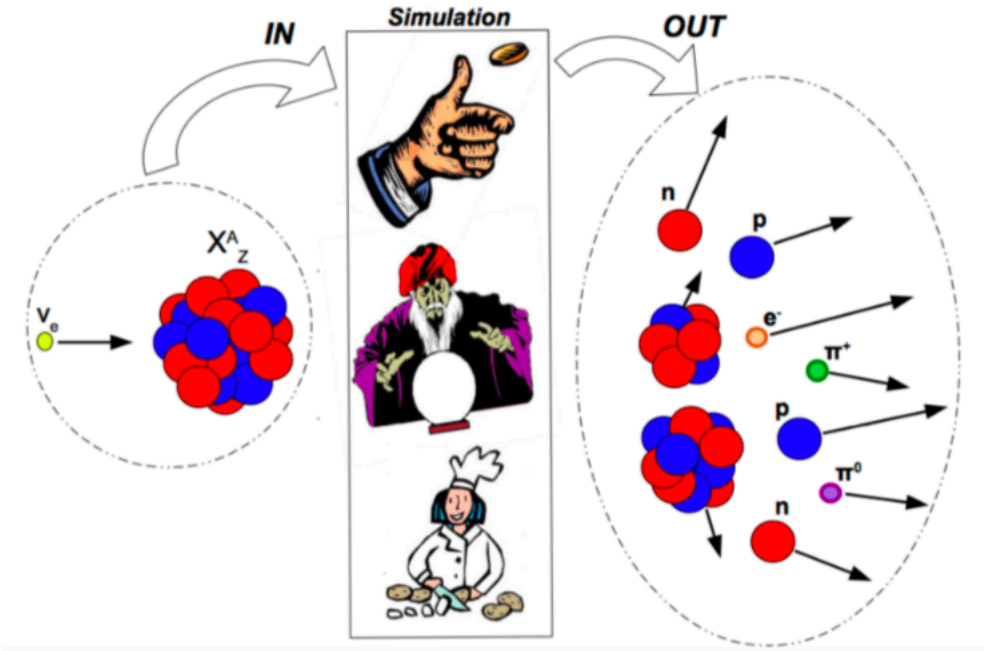
ν absolute mass (not competitive)
ν mixing from spectra:
flavor conversion in SN/Earth
(mass ordering)
other ν properties: sterile ν's,
magnetic moment,...
axions, extra dimensions,
FCNC, ...

K. Scholberg **Determining the neutrino energy is tricky . . .**

Event Generators

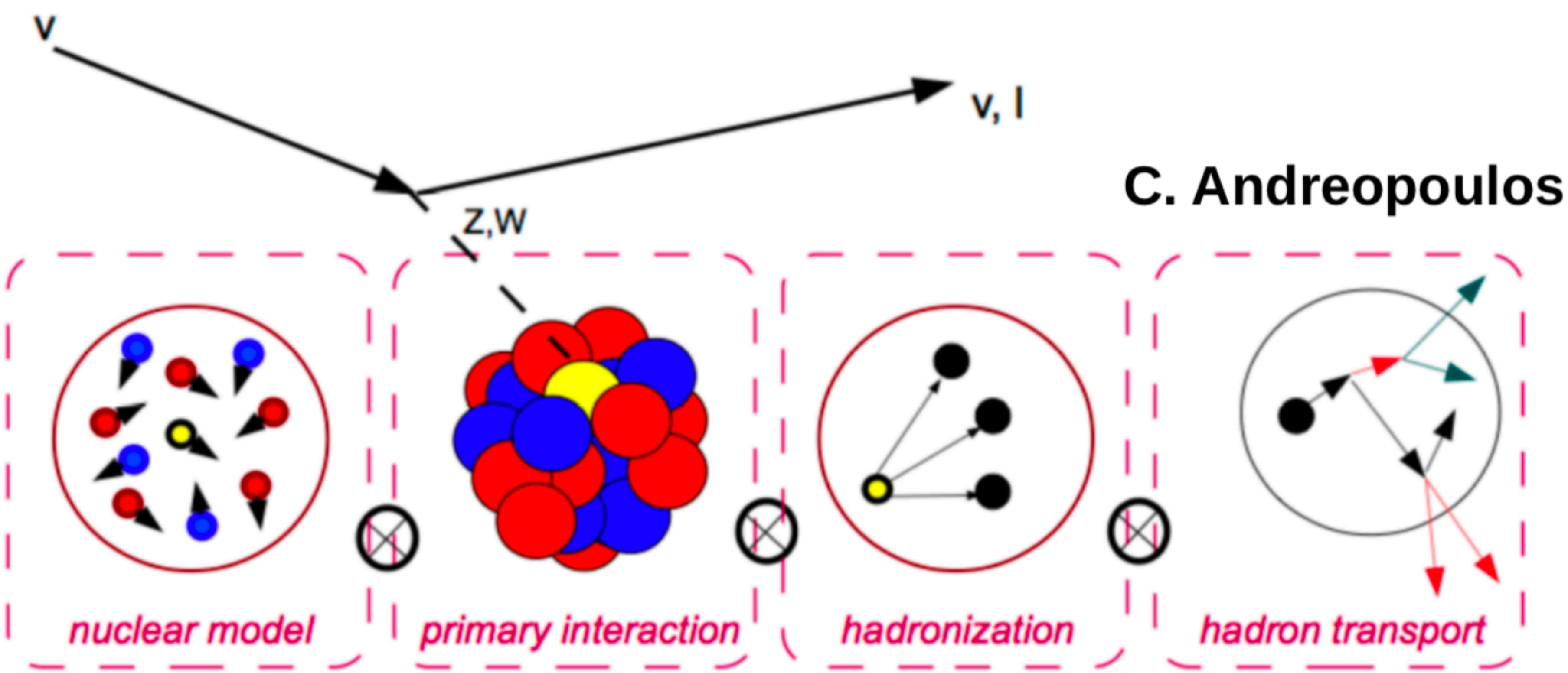
- "Bridge" between theory and experiment
  - Translate a theorist's model into the particles observed in a detector
  - Theories of neutrino-nucleus interactions are currently incomplete. Generators have to rely on approximations & empirical models to fill in the gaps.
  - **GENIE** (**G**enerates **E**vents for **N**eutrino **I**nteraction **E**xperiments) is the most widely-used neutrino event generator
  - Others on the market as well (NuWro, GiBUU, NEUT, MARLEY, etc.)





C. Andreopoulos

“Traditional” factorization of reactions in neutrino event generators

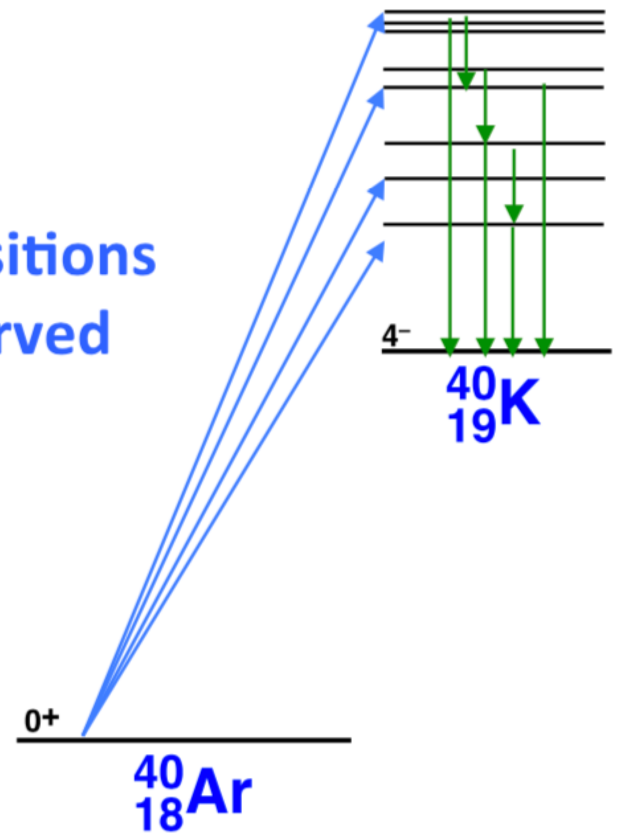


- At accelerator energies (~200 MeV and above), simple description of the nucleus is typically used (Fermi gas)
- Products tracked through the nuclear medium
- At very low energies, things like discrete nuclear level structure start to matter!

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:

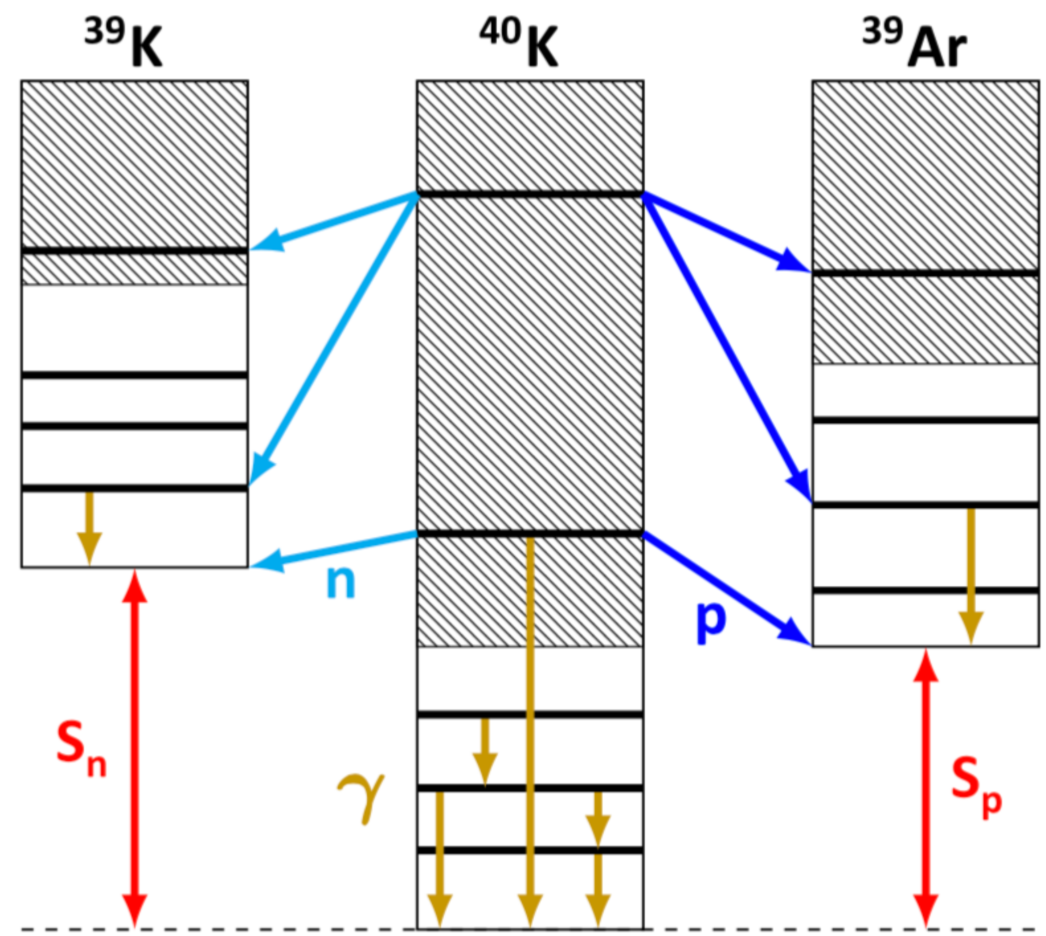
Q is determined by measuring de-excitation gammas and nucleons

Outgoing e⁻ Energy

Energy donated to transition

Recoil Energy of Nucleus (negligible)

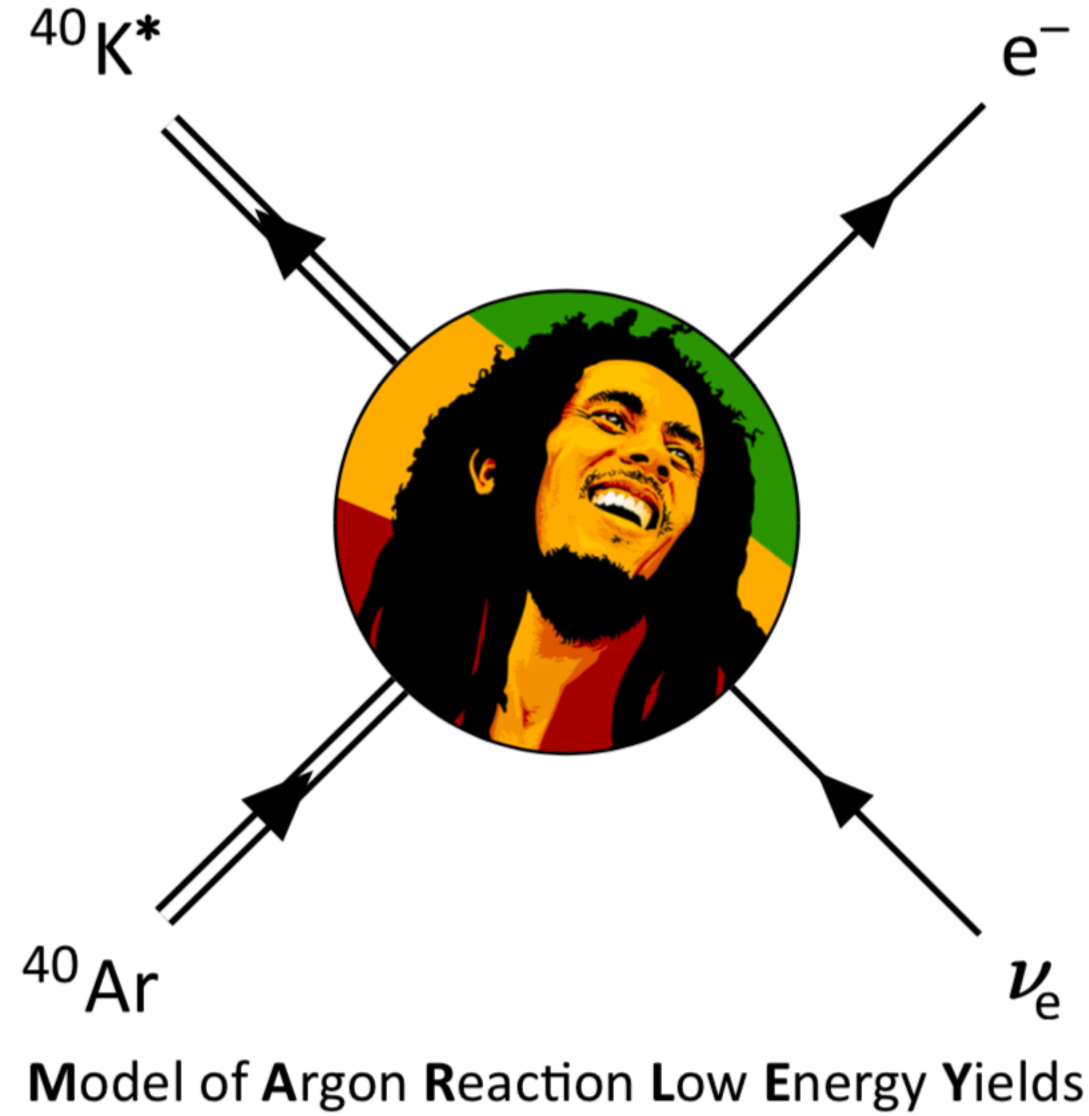
$$E_\nu = E_e + Q + K_{\text{recoil}}$$



Fermilab

MARLEY: Model of Argon Reaction Low-Energy Yields

- Event generator for neutrino-nucleus reactions at supernova energies (tens-of-MeV)
  - First of its kind
  - C++14 (for now)
  - ~20K lines of code
- Simulates ν_e CC channel on ^{40}Ar
  - Ready for other channels (NC, $\bar{\nu}_e$ CC) and targets, but preparation of input data non-trivial
  - Widely used by DUNE for supernova studies
  - Some activity from other experiments (e.g., COHERENT)



Two single-author manuscripts in prep.

Physics modeling → PRD

Implementation → Comput. Phys. Commun.

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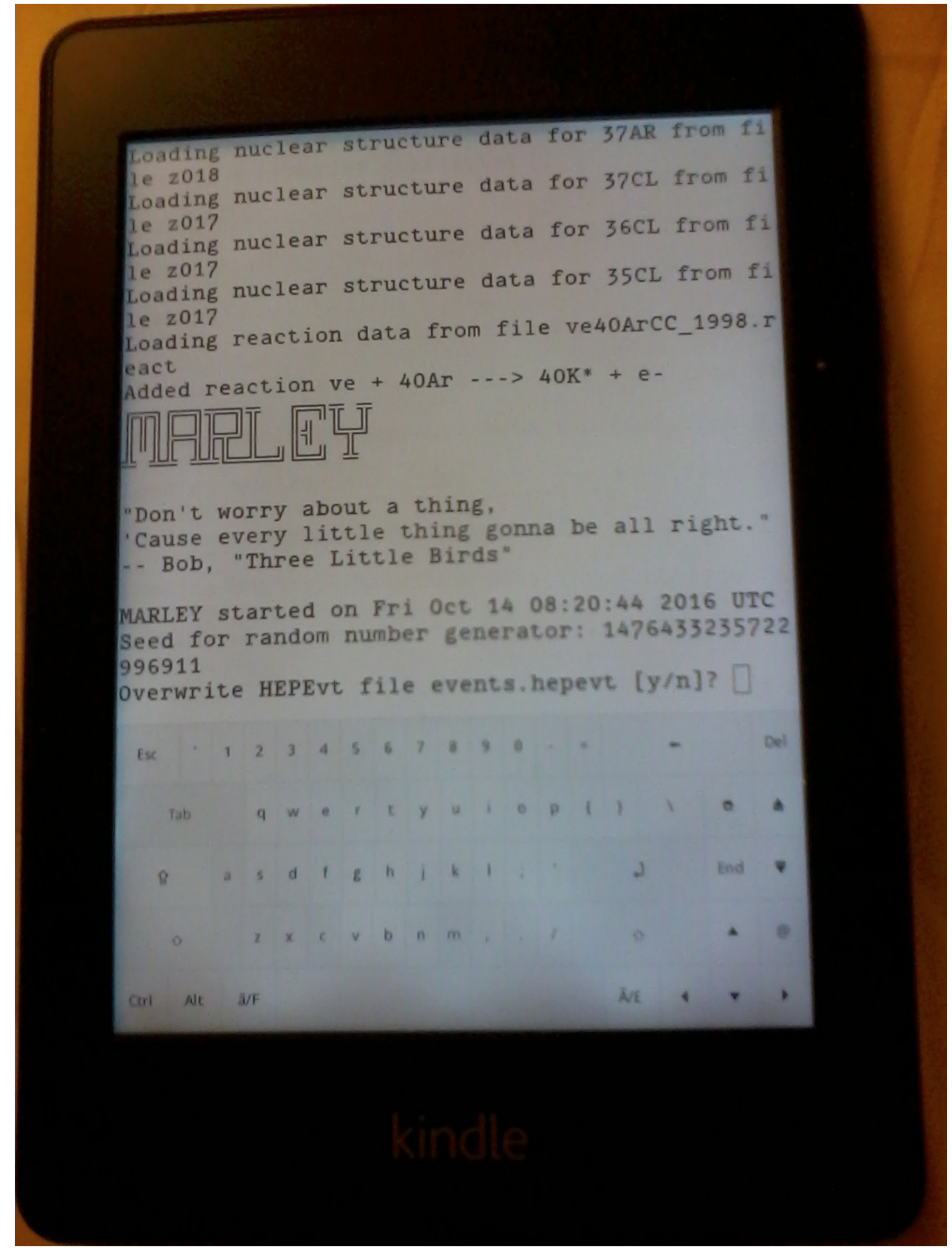
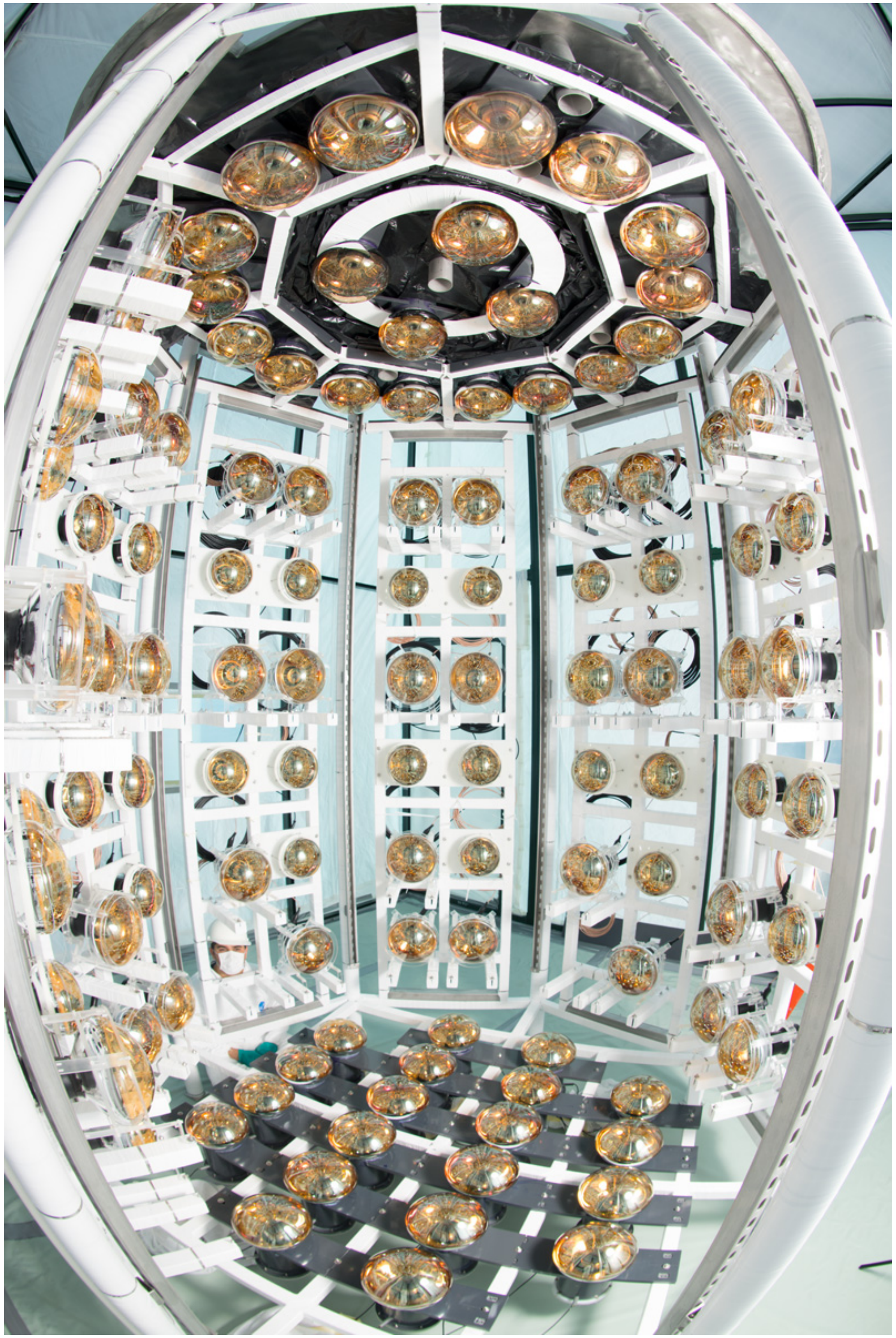


MARLEY command-line executable running natively on my Kindle Paperwhite

The Accelerator Neutrino Neutron Interaction Experiment (ANNIE)

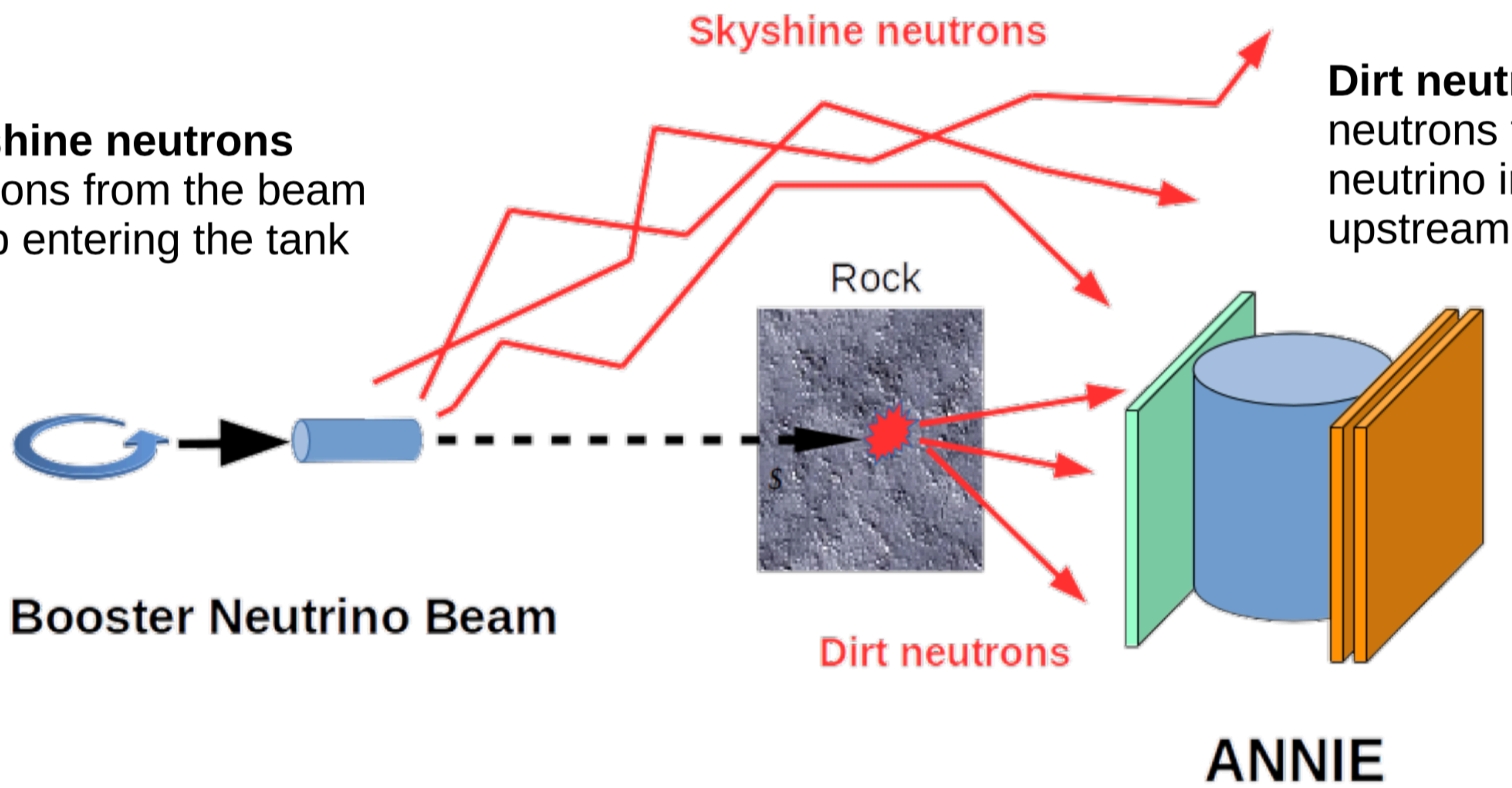


- Gadolinium-loaded water Cherenkov neutrino experiment on the Booster Neutrino Beam
- Measure the multiplicity of final-state neutrons from neutrino-nucleus interactions in water
- Demonstrate new detection technologies (fast photosensors, detection media)
- **Neutron background measurements** (Phase-I) proved feasibility
- Fully loaded with Gd 24 December. It's time for physics data!

ANNIE Phase-I: neutron background measurement

“measure and understand beam-induced neutron backgrounds to the physics measurement to be conducted in Phase II”

Skyshine neutrons
neutrons from the beam dump entering the tank



Dirt neutrons
neutrons from neutrino interactions upstream of ANNIE

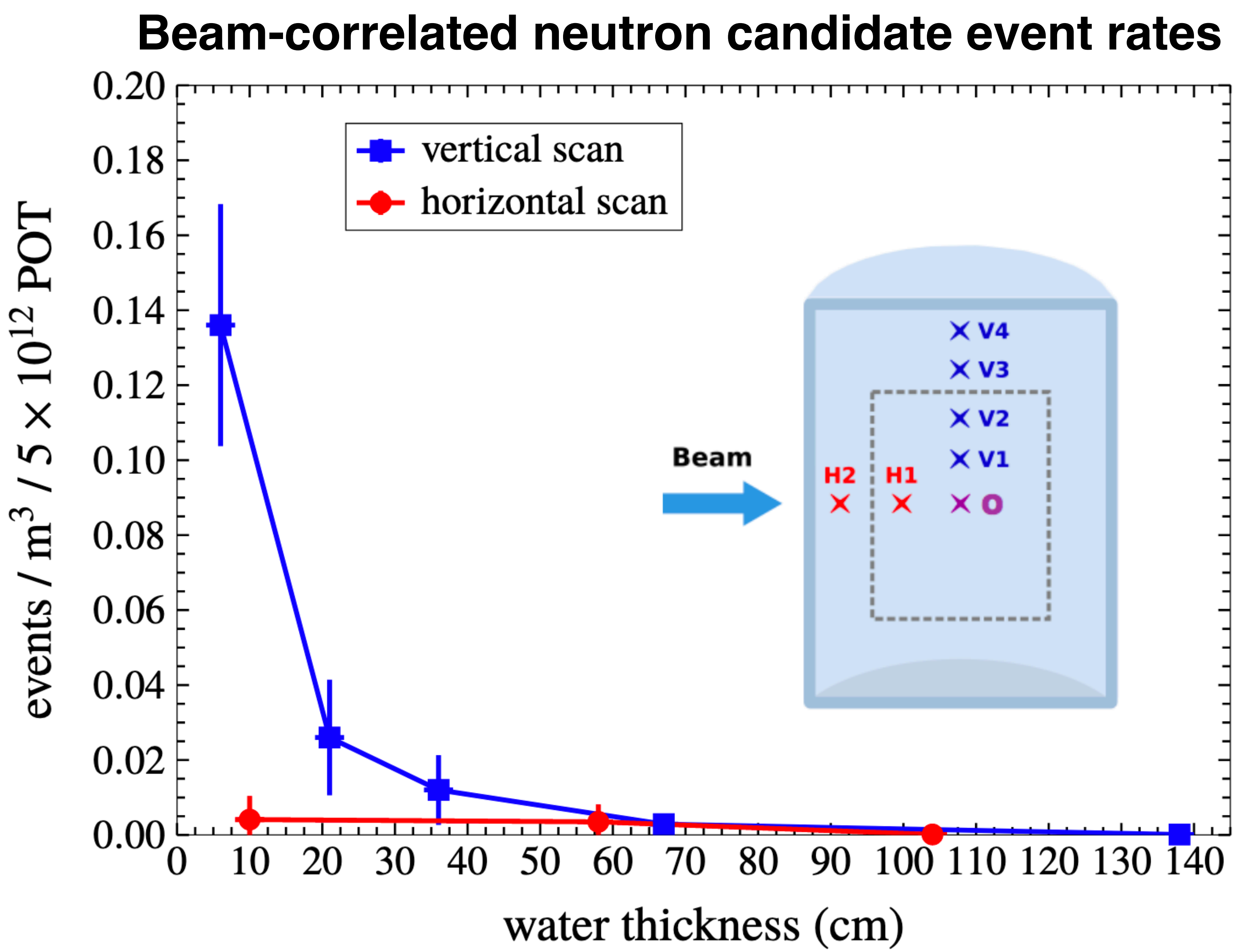
- Installation in former SciBooNE hall: March – May 2016
- Data taking: June 2016 – September 2017
- **Paper: arXiv:1912.03186**

ANNIE Phase-I Results

- ~5% contamination of Phase-II signal events by beam-correlated background neutrons

- Small experiment, so I got to do a little of everything
  - Wrote code for all stages of the analysis (signal processing to final plots)
  - Minor hardware work
  - Etc.

- I produced all plots and tables in the paper



Fermilab

Activities at Fermilab

- **I started my postdoc at Fermilab in early August 2018**
  - Sam Zeller & Gabe Perdue are my advisors
  - Initially in Neutrino Division, switched to SCD (as planned) in October 2019
  - Laura Fields is my SCD supervisor
- Much like my PhD, I've tried to strike a balance between generator and experimental work
- **Three focus areas during my time here so far:**
  - Development of the GENIE event generator
  - Systematic uncertainties for MicroBooNE
  - Transverse variables analysis for MicroBooNE

GENIE development work

- A few months after I joined GENIE, the collaboration finalized the first major release (v3) in a decade
  - **Change in philosophy:** multiple comprehensive model sets ("tunes") co-exist instead of a single "GENIE model" used historically
  - Made available many physics improvements, albeit with some growing pains

- Since then, I've worked to **add new models** to the generator and **fix problems**
  - I work most closely with Steve Dytman (U. Pittsburgh)

GENIE Collaboration

Luis Alvarez Ruso[8], Costas Andreopoulos[2,5], Christopher Barry[2], Francis Bench[2], Steve Dennis[2], Steve Dytman[3], Hugh Gallagher[7], Steven Gardiner[1], Walter Giele[1], Robert Hatcher[1], Libo Jiang[3], Rhiannon Jones[2], Igor Kakorin[4], Konstantin Kuzmin[4], Anselmo Meregaglia[6], Donna Naples[3], Vadim Naumov[4] Gabriel Perdue[1], Marco Roda[2], Jeremy Wolcott[7], Júlia Tena Vidal[2], Julia Yarba[1]

[Faculty, Postdocs, PhD students]

1 - Fermi National Accelerator Laboratory, 2 - University of Liverpool, 3 - University of Pittsburgh, 4 - JINR Dubna, 5 - STFC Rutherford Appleton Laboratory, 6 - CENBG Université de Bordeaux, 7 - Tufts University, 8 - Valencia University

Core GENIE mission - from GENIE by-law

Framework	"... provide a state-of-the-art neutrino MC generator for the world experimental neutrino community ..."
Universality	"... simulate all processes for all neutrino species and nuclear targets, from MeV to PeV energy scales ..."
Global fit	"... perform global fits to neutrino, charged-lepton and hadron scattering data and provide global neutrino interaction model tunes ..."

R-3_00_02
ee1f86a

R-3_00_02
sjgardiner tagged this on Dec 9, 2018 · 512 commits to master since this tag

v3.0.2

R-3_00_04
15f2956

R-3_00_04
sjgardiner tagged this on Apr 10, 2019 · 441 commits to master since this tag

v3.0.4

R-3_00_06
b1c78c5

R-3_00_06
sjgardiner tagged this on Jul 23, 2019 · 318 commits to master since this tag

v3.0.6

New model example: SuSAv2 via a new "hadron tensor" framework

$$\frac{d^2\sigma}{dE'_\ell \, d\cos(\theta'_\ell)} = \frac{|\boldsymbol{k}'|}{|\boldsymbol{k}|} \frac{G_F^2}{2\pi} L_{\mu\nu} W^{\mu\nu}$$

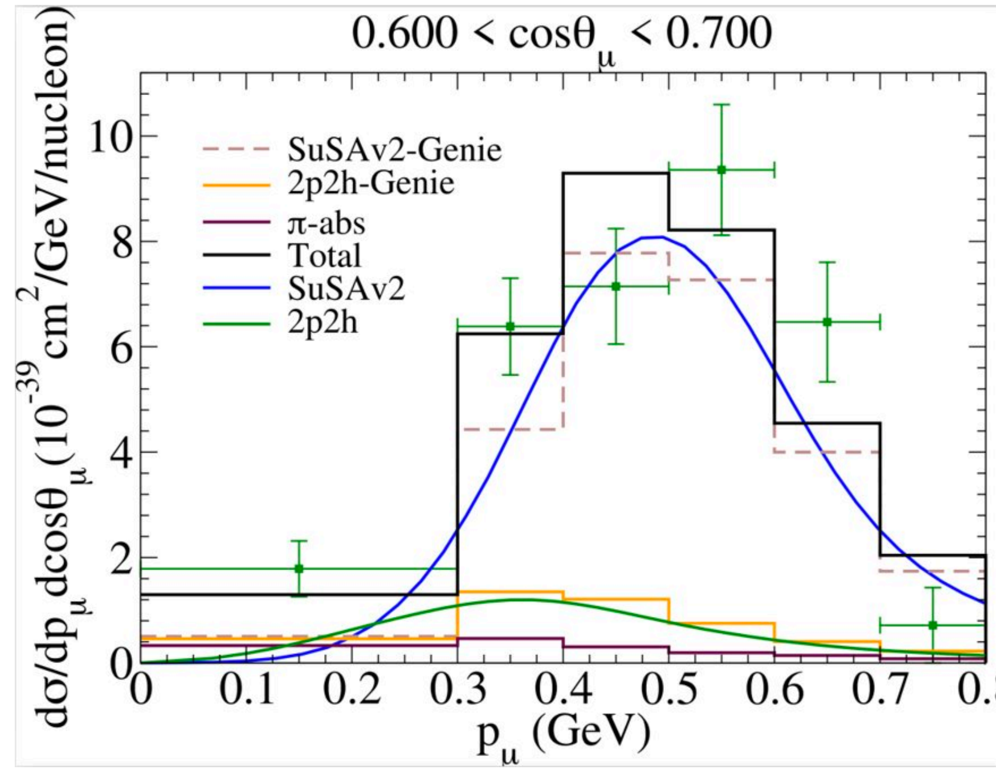
- Use a very general form to provide differential prediction for lepton kinematics
  - Hadronic tensor pre-calculated and tabulated for efficient evaluation in GENIE
  - Elements expressed as a function of

$$\omega = E_\ell - E_{\ell'}$$

$$q = |\mathbf{p}_\ell - \mathbf{p}_{\ell'}|$$

- First new GENIE model that uses these: SuSAv2 (G. Megias et al.)
  - Approved for next public GENIE release (v3.2)

SuSAv2 prediction compared to T2K data



SuSAv2 implementation note

- Productive collaboration with S. Dolan & G. Megias as the first "customers" for the framework
  - Pros and cons discussed in detail at **ECT* workshop** in June 2019

- Other new model implementations with Noemi Rocco (**spectral functions**) and Saori Pastore (**"short time approximation"**)

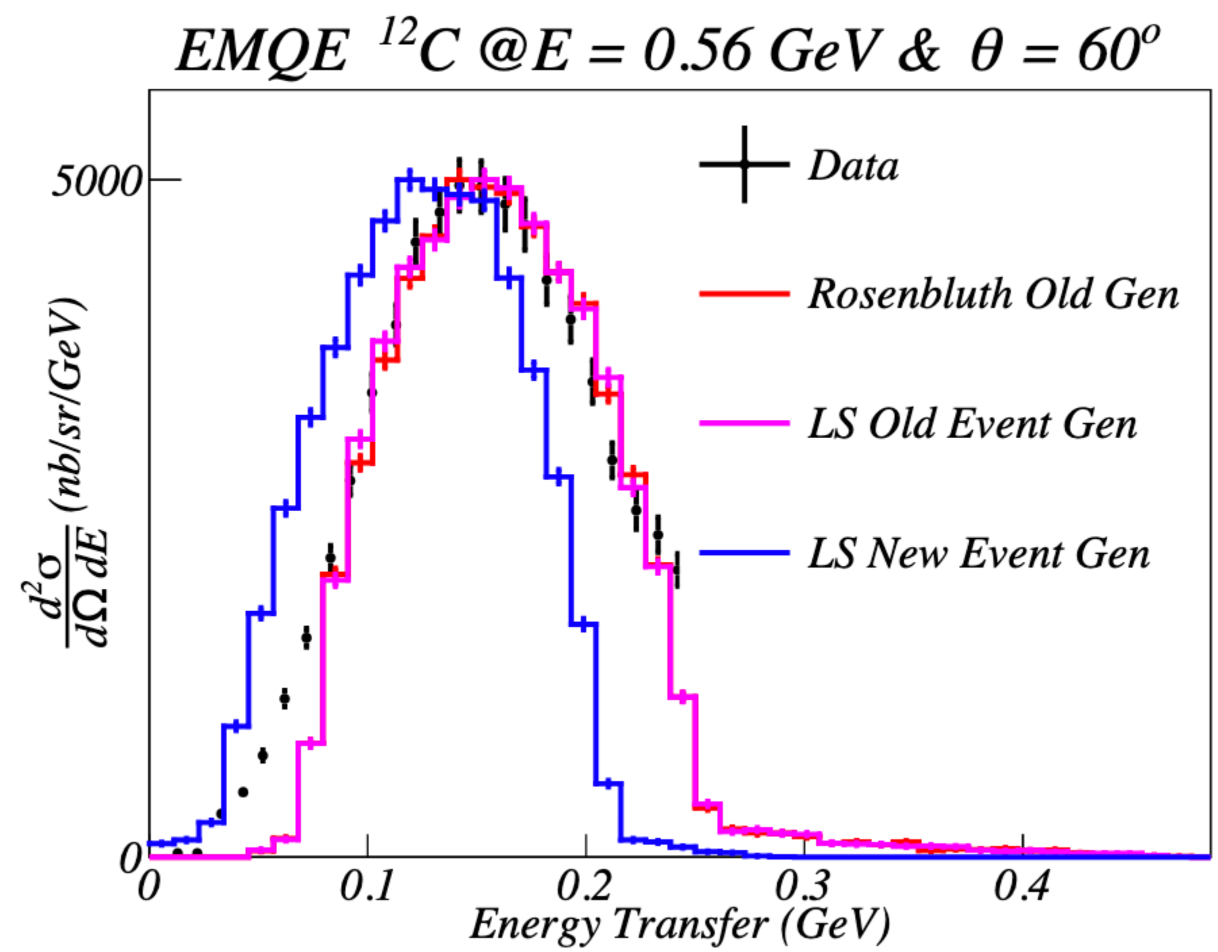
Fermilab

Fixing problems: GENIE v3.0.x patch releases

- Alongside my development of new models, I've contributed crucial fixes to GENIE

- **Three recent patch releases** (v3.0.2 → v3.0.6) resolve issues discovered after v3 roll-out

- Most important one (months-long effort) was a bug in the treatment of nucleon binding energy
  - Obvious in electron scattering plots, symptoms for neutrinos were more subtle
  - Diagnosing the problem, fixing it, and dealing with knock-on effects took a lot of my effort for a few months last year



MicroBooNE

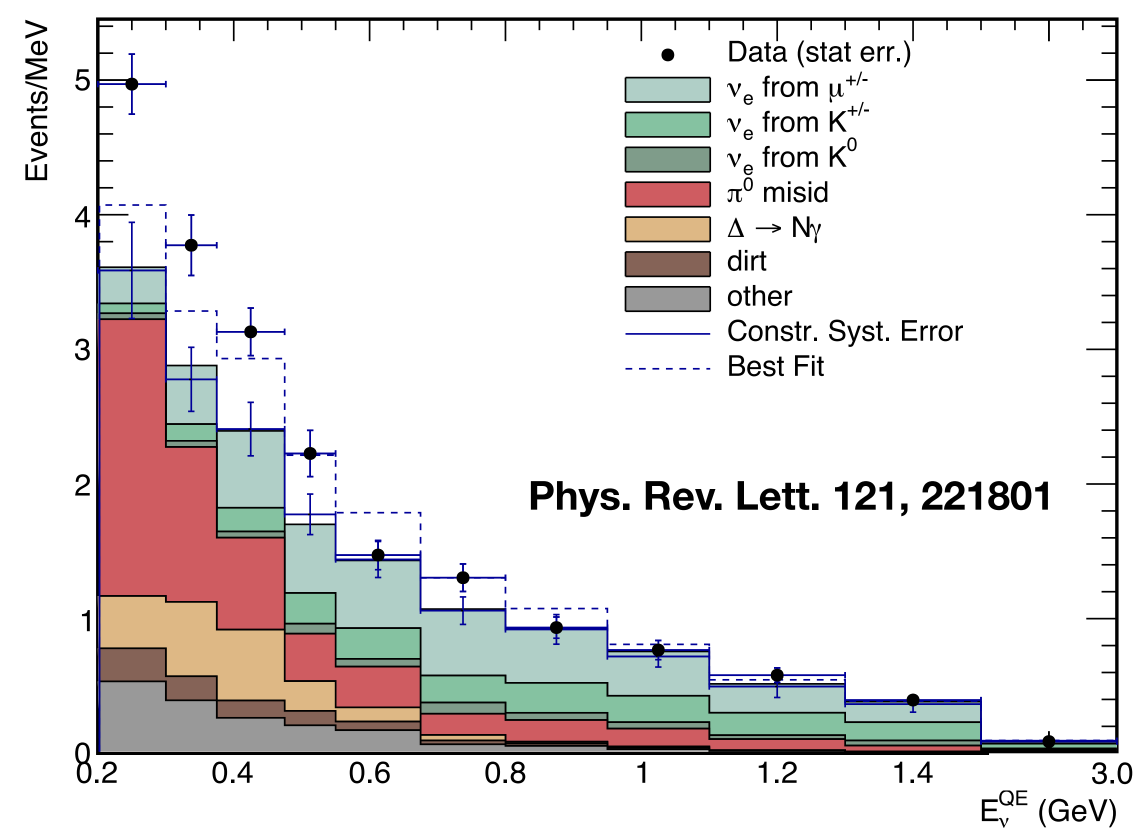
- Liquid argon time projection chamber in the Booster Neutrino Beam at Fermilab (60-ton fiducial mass) with two primary physics goals

- Investigate the origin of the low energy excess (LEE) of electron-like events seen by MiniBooNE

- Measurements of neutrino-argon cross sections

- With Adi Ashkenazi, I serve as co-convener of the **systematics working group**

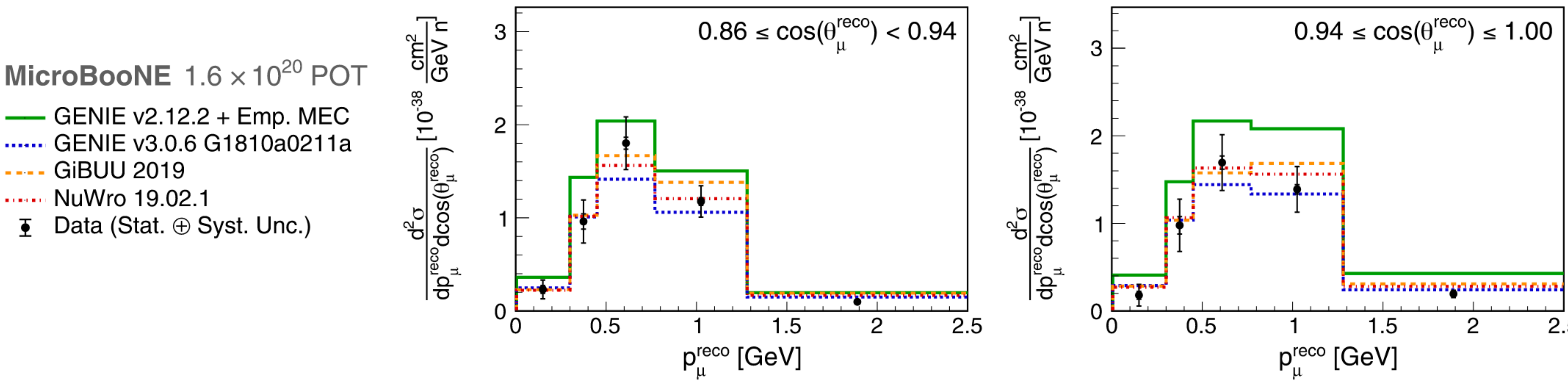
- I am also pursuing a **cross section analysis** (transverse variables)



GENIE v3 for MicroBooNE

- Beyond working on GENIE itself, I've also been a major player in the effort to update MicroBooNE's simulation tools
- MicroBooNE's recently-published **CC inclusive cross section** data strongly favor the v3 improvements over v2
- Together with Lynn Garren & Robert Hatcher, I produced the first test release of LArSoft built against GENIE v3

Model	42 bins χ^2
GENIE v2 + MEC	245.9
GENIE v3	103.9
GiBUU	172.9
NuWro	126.5



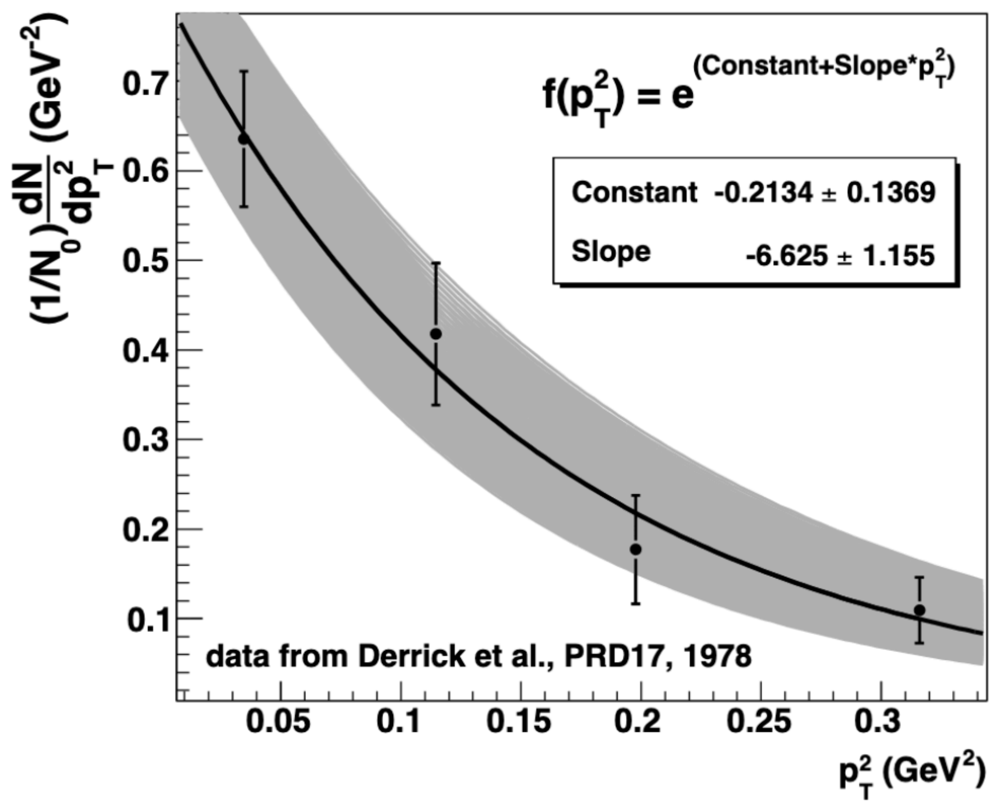
Reweighting for cross section systematic uncertainties

- **Production of Monte Carlo samples for neutrino experiments is an expensive process**
  - Need to simulate the beam, neutrino scattering, outgoing particle transport, and detector electronics response

$$\text{weight}_{\alpha \to \alpha'} = \frac{d\sigma(\alpha')/dX}{d\sigma(\alpha)/dX}$$

- **Variations needed to assess cross section uncertainties**
  - Brute-force too time-consuming

- Generators have a standard way of dealing with this called **reweighting**:
  - For a simulated event, how does the probability of producing it change with a model parameter?
  - Weighting events by the likelihood ratio is equivalent* to regenerating and a lot faster

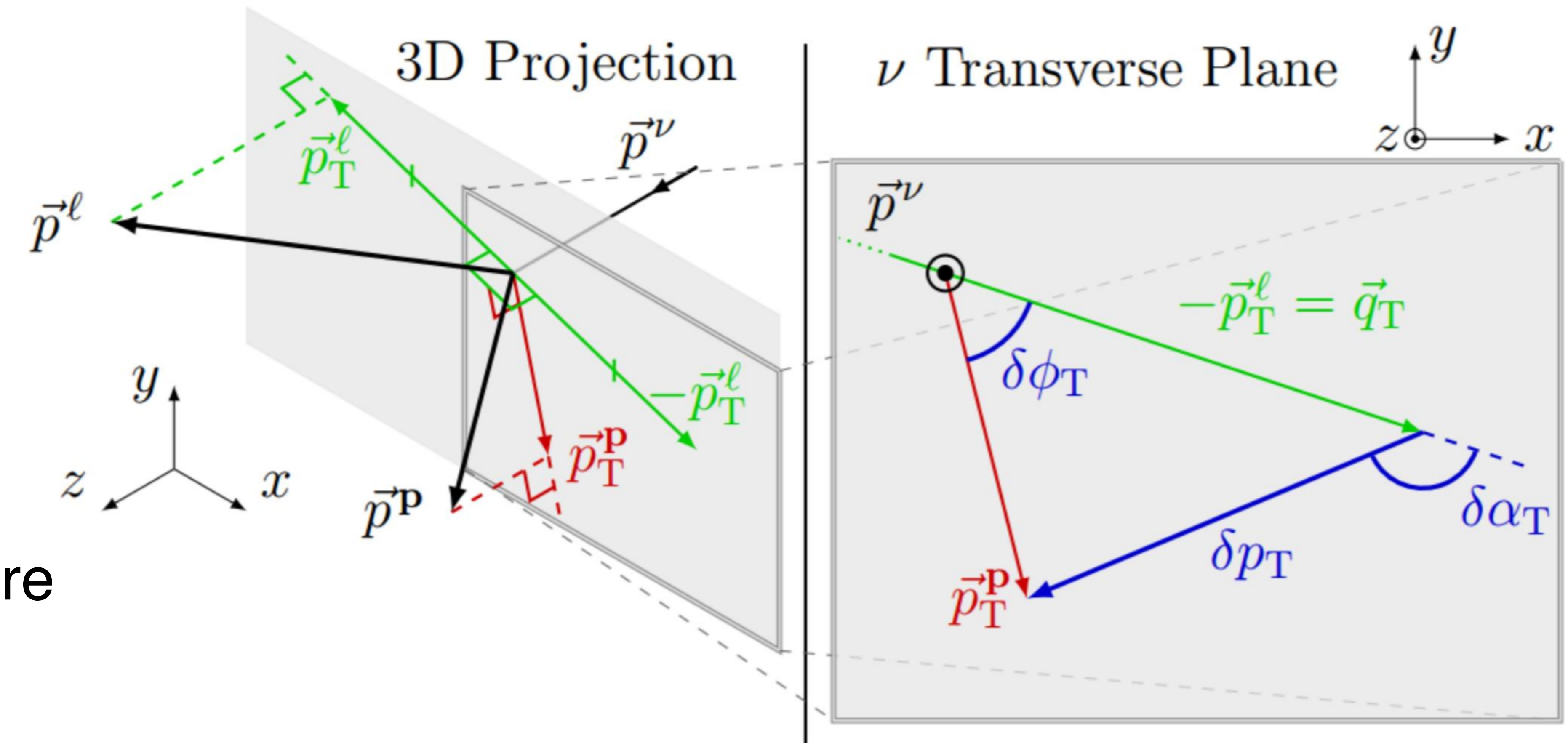


Cross section uncertainties for MicroBooNE

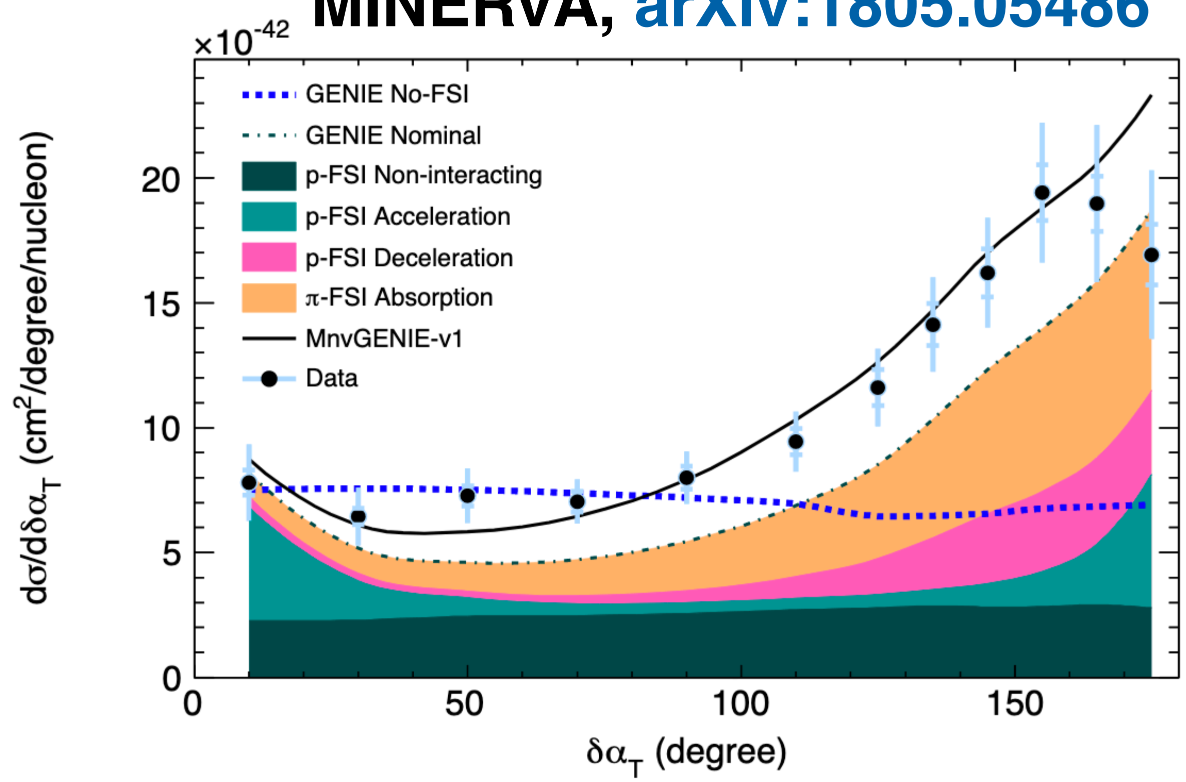
- Major focus in recent months: reweighting tools needed a thorough overhaul
  - Many **hard-coded assumptions** of the historical default model invalidated in the move to v3
  - **Missing reweighting capabilities** for uncertainties important to MicroBooNE
- Deliverables from my efforts (with Kirsty Duffy, Steve Dytman)
  - **GENIE v3.0.4 μBooNE patch 01** = adds the fixes and extra features needed for MicroBooNE to carry out its systematics strategy for the flagship LEE analyses
  - Lengthy **internal note** providing a full cross section systematics strategy
  - **μBooNE GENIE tune** = parameter adjustments to external neutrino data (T2K) to achieve better data/MC agreement

Single Transverse Variables (STVs)

- Observables based on kinematic imbalance along the direction transverse to the incoming neutrino
- For a free nucleon at rest, the distributions are trivial
- Opportunity to probe nuclear effects in neutrino cross section data
- Measurements by MINERvA, T2K. **No argon . . . yet!**



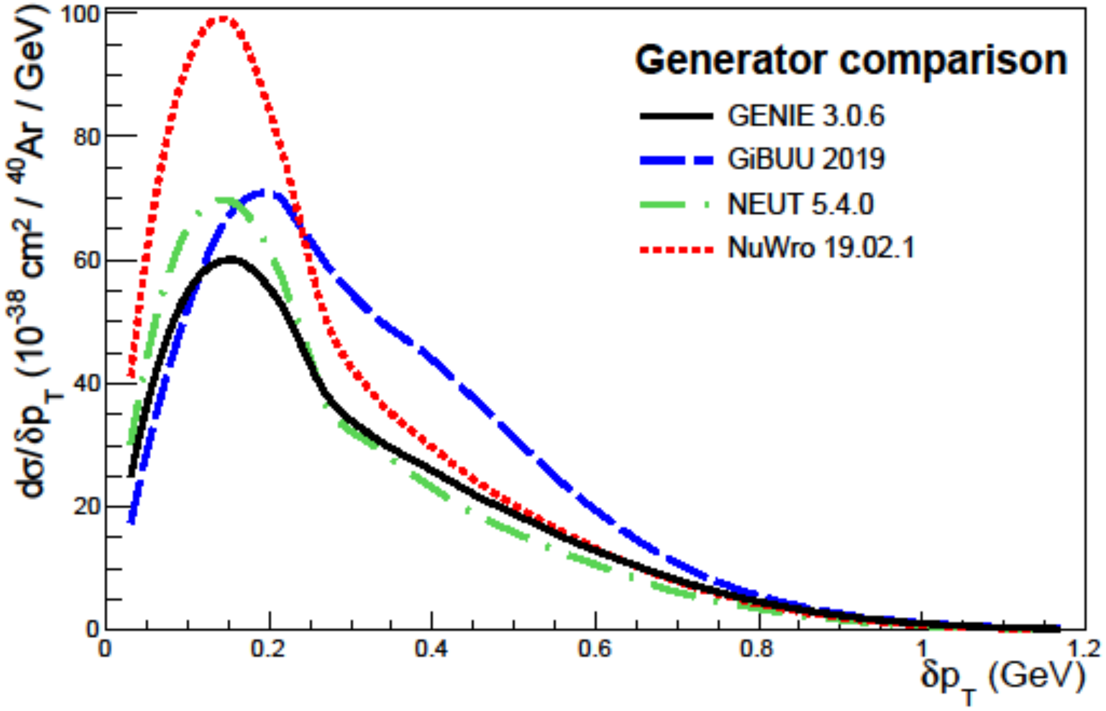
MINERvA, arXiv:1805.05486

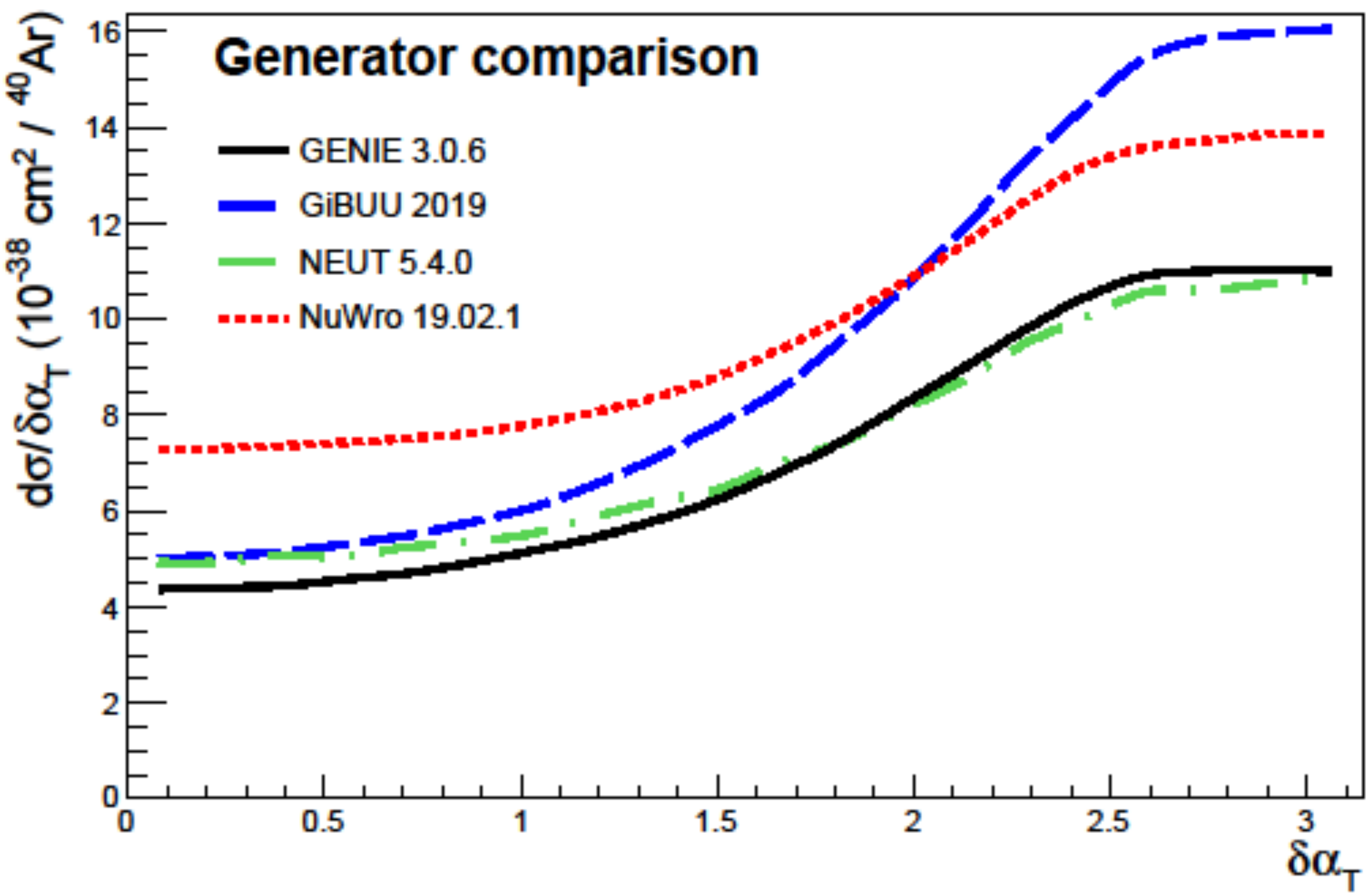


Studying transverse variables in MicroBooNE

- Collaboration with **Lars Bathe-Peters** (M.S. student), Roxanne Guenette (both at Harvard)

- Working on **both generator comparisons and an associated analysis** for MicroBooNE
  - First detailed MC study of these for argon, and with all 4 standard generators
  - Poster at NuPhys last month





- Basis for upcoming publication and Lars' M.S. thesis

Future plans: Wrap up nearly-finished projects

- Finish and submit MARLEY papers

- Finalize MicroBooNE GENIE and detector systematics for LEE analyses
  - To be presented at Neutrino 2020 (June)

- Merge new models (SuSAv2, spectral functions) into GENIE v3.2
  - Release expected within a few weeks

- **Goal**: Have all these tasks done within the next few months

  - I see this as clearing the way for my main priorities for the year

Future plans: Transverse variable data analysis

- Preliminary event selection in place, based on combination of tools used previously for other measurements

- Full assessment of systematics is the rate-limiting step right now

  - As co-convener of the relevant WG, I'm pushing hard to get that done

- **Goal 1**: Show kinematic distributions in MC vs. data at NuInt conference (June 2020) with full systematics

- **Goal 2**: Draft publication with differential cross section results by end of 2020

- **Finishing this analysis is my highest priority in 2020.**

Future plans: “short time approximation”

- Collaboration with Saori Pastore (WUSTL), Minerba Betancourt (FNAL), **Josh Barrow** (UTK)
  - GENIE implementation & comparison to electron scattering data = Josh’s PhD thesis
- Solve Schrödinger equation via quantum Monte Carlo techniques (on supercomputers)
- Limited to very light nuclei (^{4}He) right now, but pushing toward ^{12}C and beyond. Our work is “proof of principle.”
- Includes **exciting physics not currently available in generators**
  - Kinematic predictions for two-nucleon final states
  - Proper treatment of interference between one- and two-nucleon processes
- **Goal**: Finish code and publication by late summer 2020.

Future plans: next steps

- I intend to mostly avoid taking on other tasks for a while so I can **focus on delivering the transverse variables analysis**
  - Nevertheless, existing commitments will be respected (e.g., leadership of systematics WG)
- **Josh will soon spend nearly all of his time on STA**, I will assist as needed in a supporting role
- As the STV work converges, I have a few possible next steps in mind that I will revisit and evaluate
  - DUNE / SBN systematics involvement
  - CRPA (MARLEY-like, but good to high energies) modeling in GENIE
  - Joint ANNIE + μBooNE analysis (can one model explain neutron yield and proton observables?)
  - Low-energy nuclear de-excitation modeling in GENIE
  - Cross sections with muon decay-at-rest neutrinos

Future plans: next year

- I intend to remain open to many ideas for how to move forward, then choose carefully when the time is right

- As the end of 2021 approaches, I intend to compete for a faculty or lab staff position

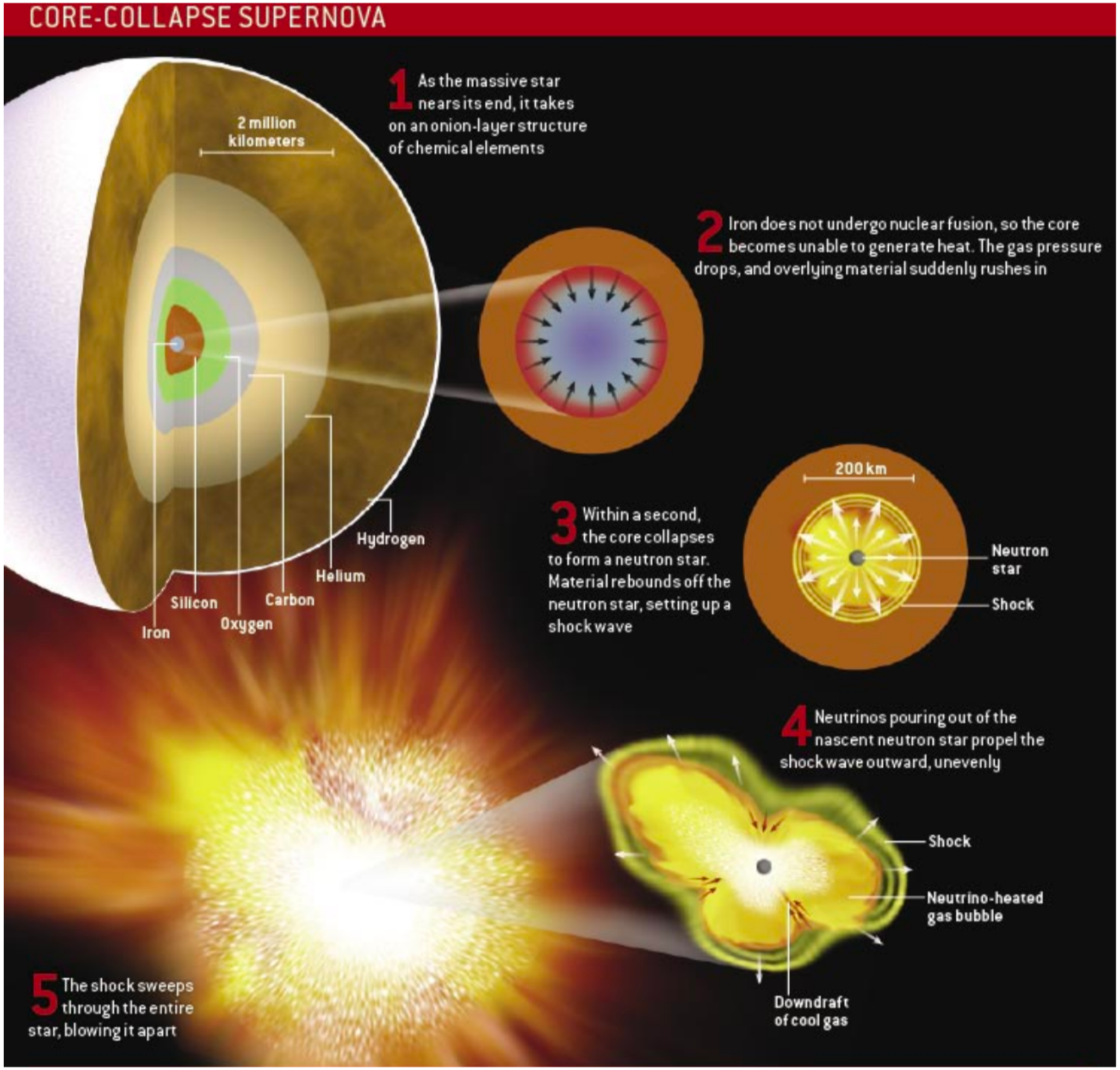
- Establishing a clear path for a transition into DUNE will become increasingly important

- I see at least three possible “on-ramps" for making that happen, each connected to past or present activities

  - Cross section systematics for oscillation analyses (current work, some of the first data with an **argon target**)
  - Low-energy / supernova program (MARLEY)
  - Backgrounds & calibrations (nuclear data & neutron physics)

Backup

Core-collapse supernovae: near-perfect neutrino bombs

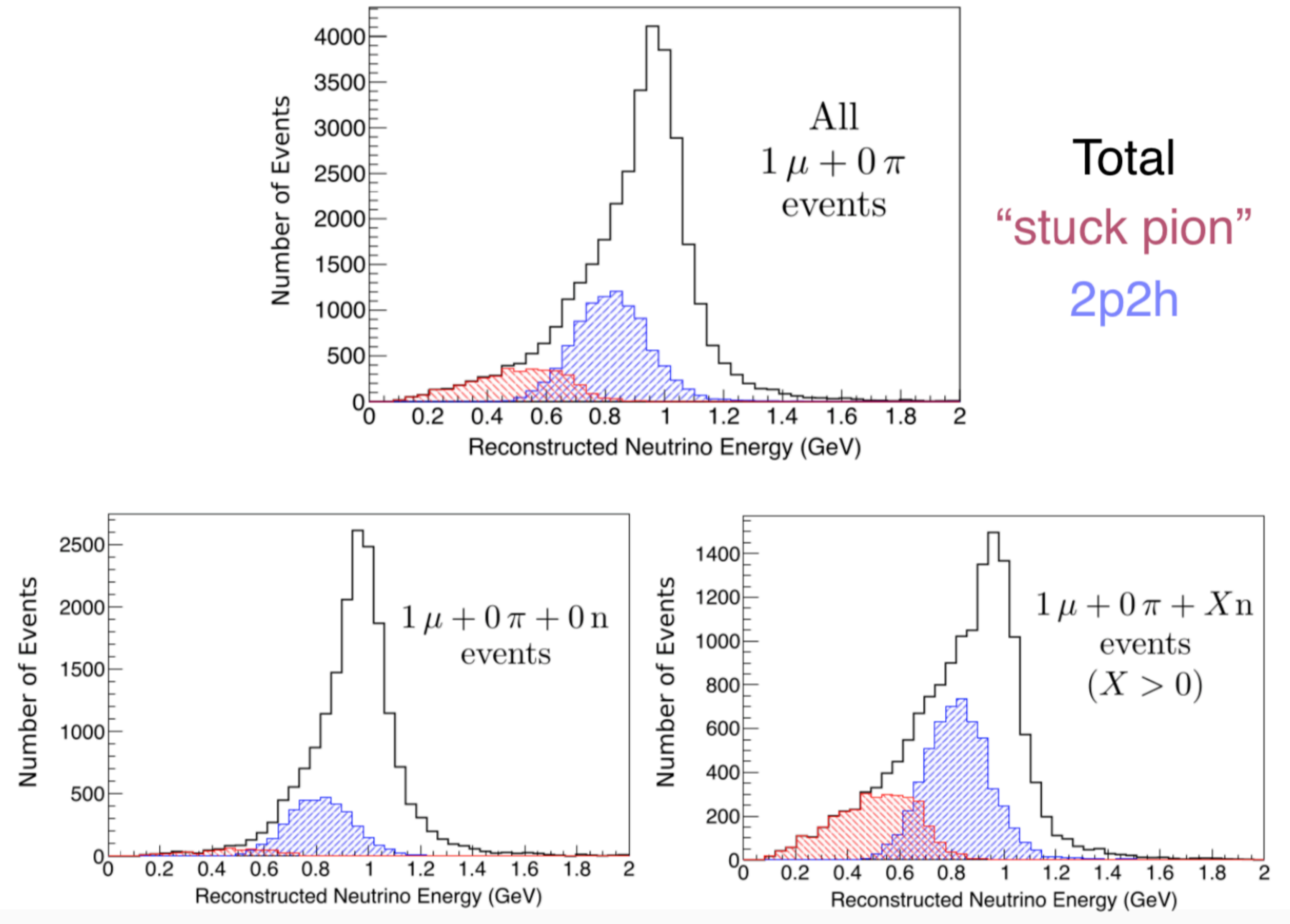


- Deaths of stars > $10M_\odot$
- 99% of gravitational binding energy emitted as neutrinos
- Many ν_e produced as core collapses (burst lasting few tens of ms)
- Core cools via all-flavor radiation in ~10 seconds
- Momentarily outshines visible universe (in neutrinos)

Neutrino energy reconstruction

- Event generators are routinely used to correct for biases in the reconstructed neutrino energy
- Stuck pion and two-particle two-hole (2p2h) events significantly contaminate a CCQE-like $1\mu + 0\pi$ sample
- GENIE simulations suggest that neutron tagging can help improve the energy reconstruction

GENIE simulations of 1 GeV ν_μ scattering in water



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