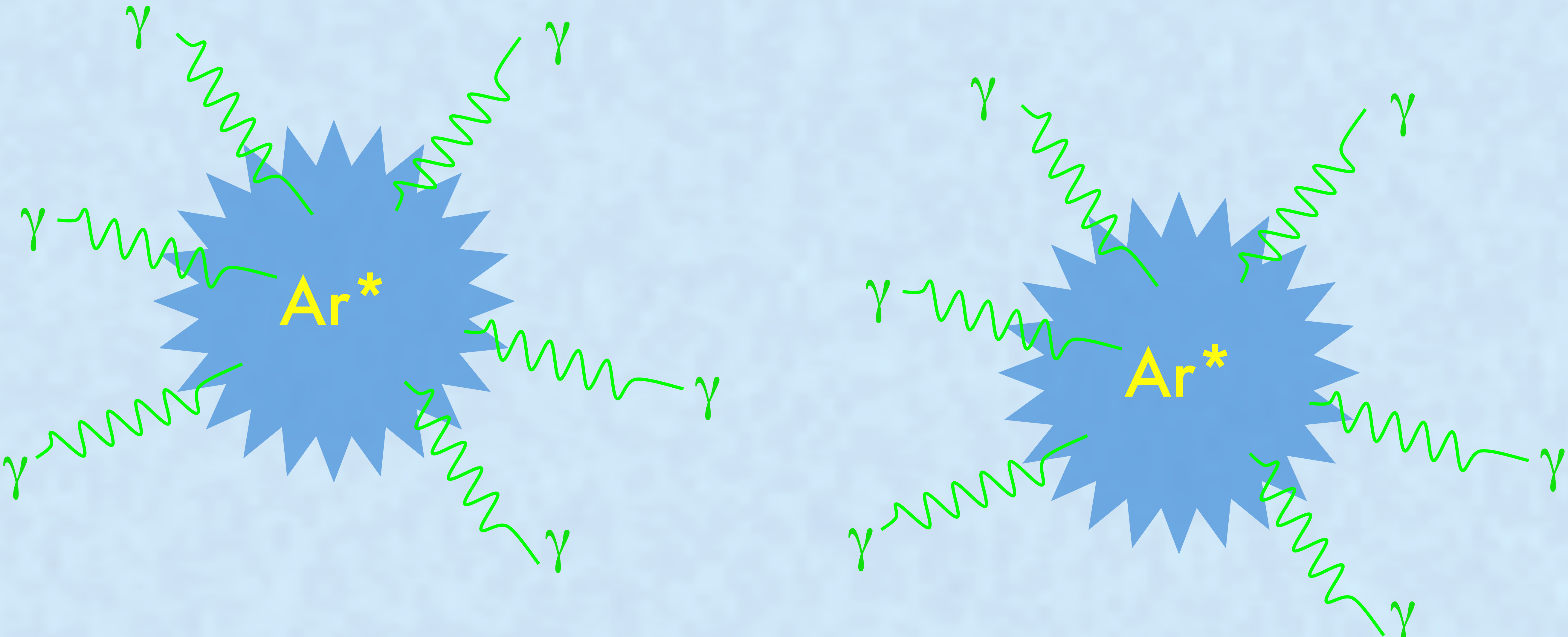


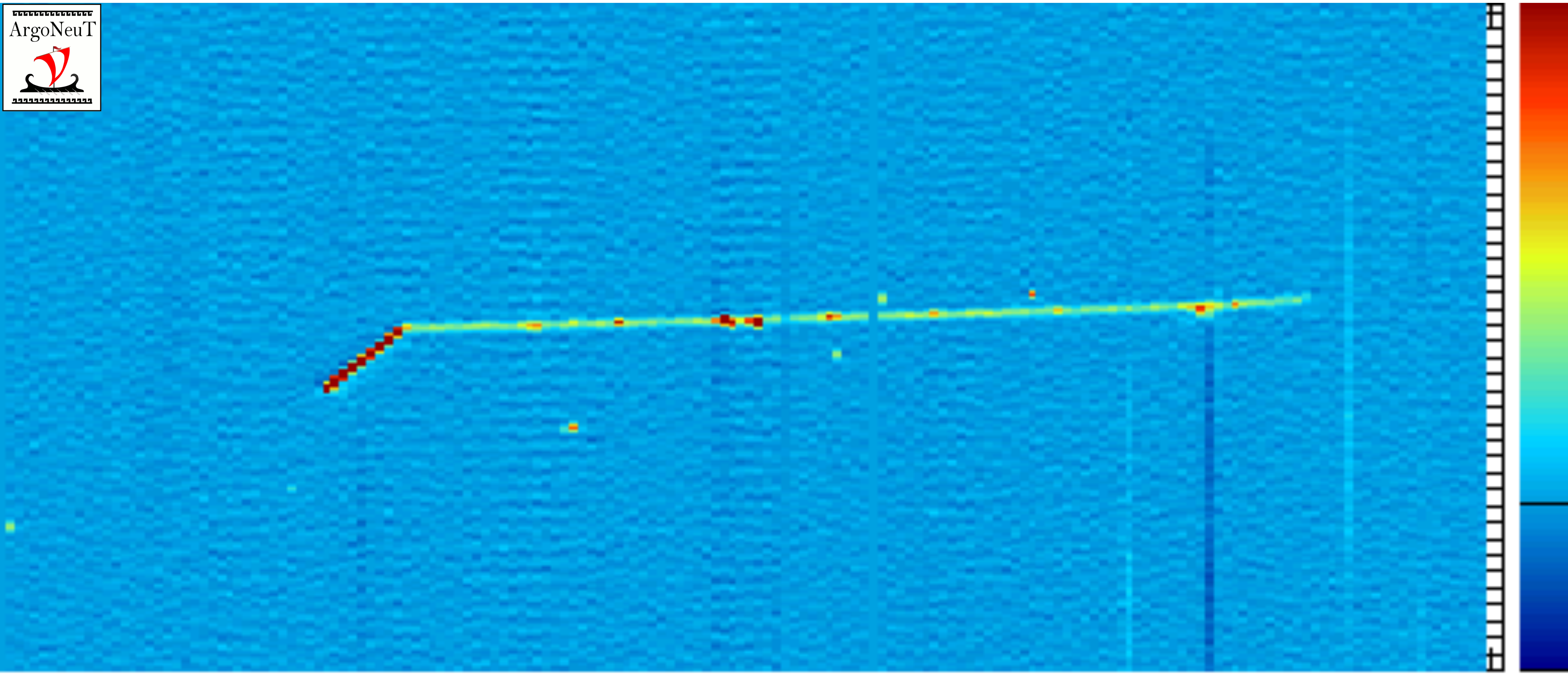
Demonstration of MeV-Scale Physics in Liquid Argon Time Projection Chambers Using ArgoNeuT

"Physics Opportunities in the Near DUNE Detector Hall: PONDD" Workshop

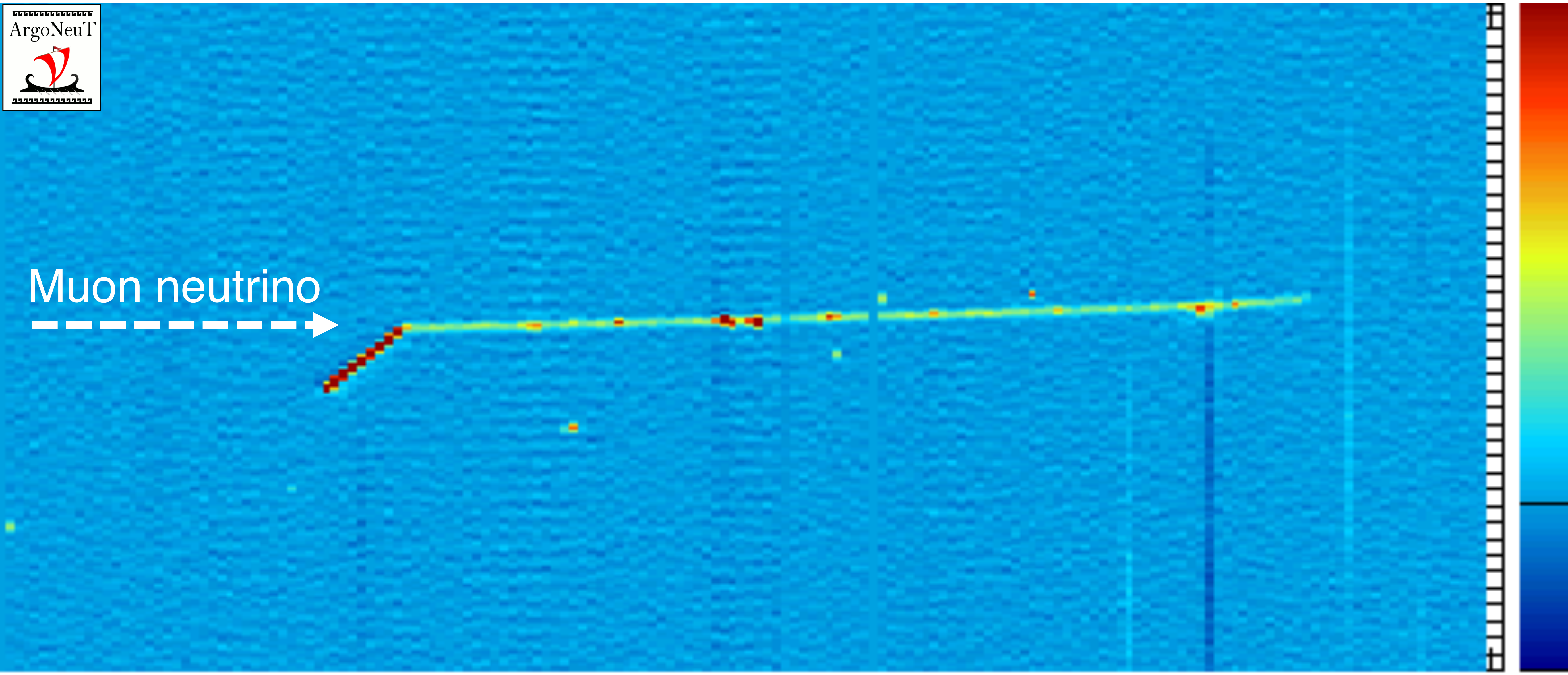
Fermilab, December 7th 2018

Ornella Palamara
Fermilab & Yale University

Preview



Preview



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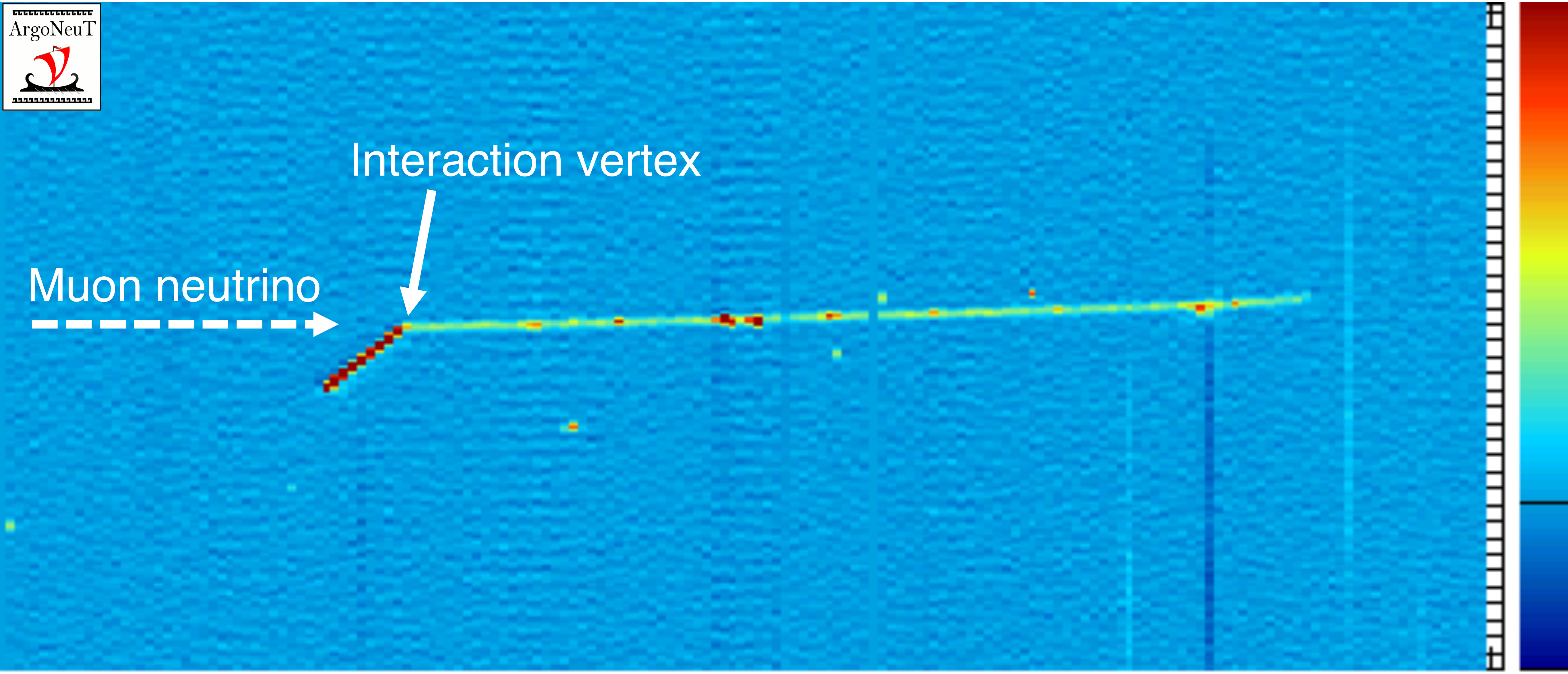

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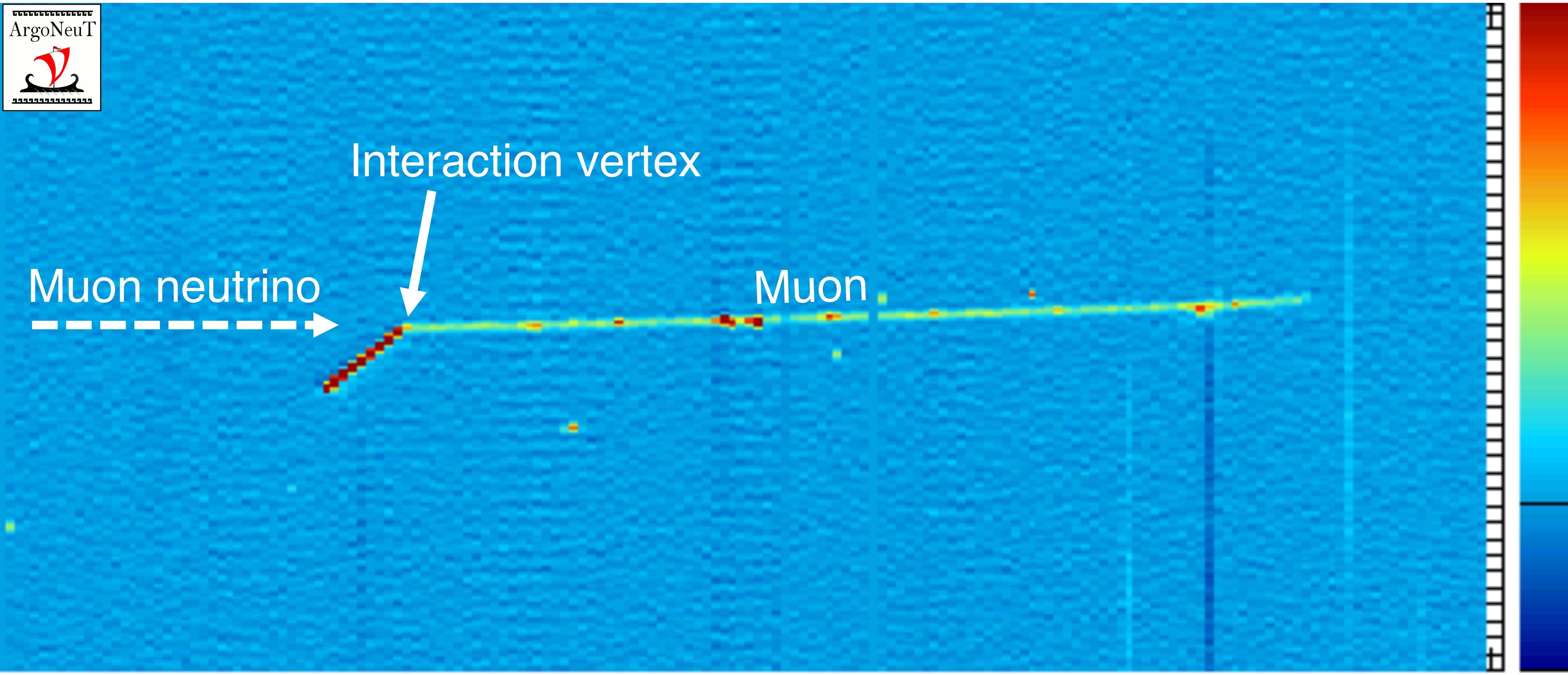

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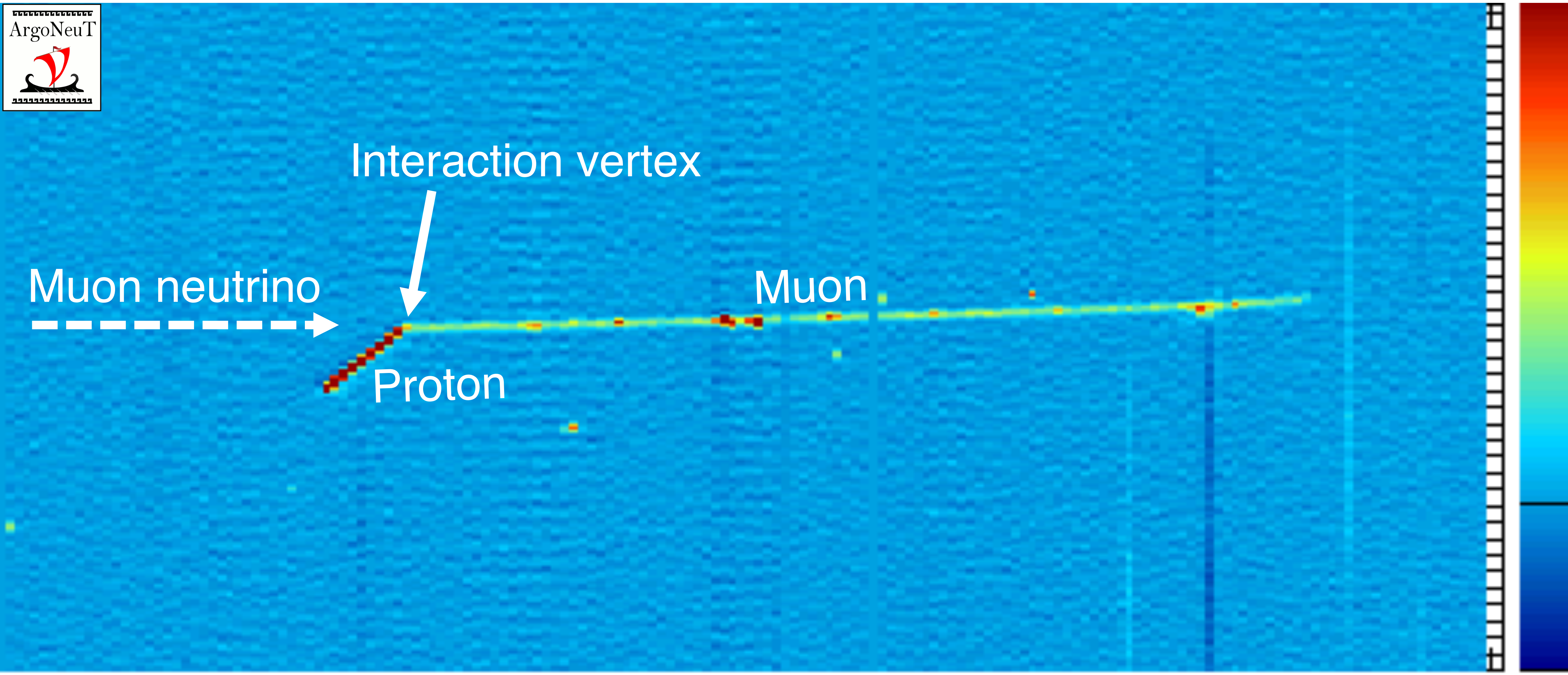

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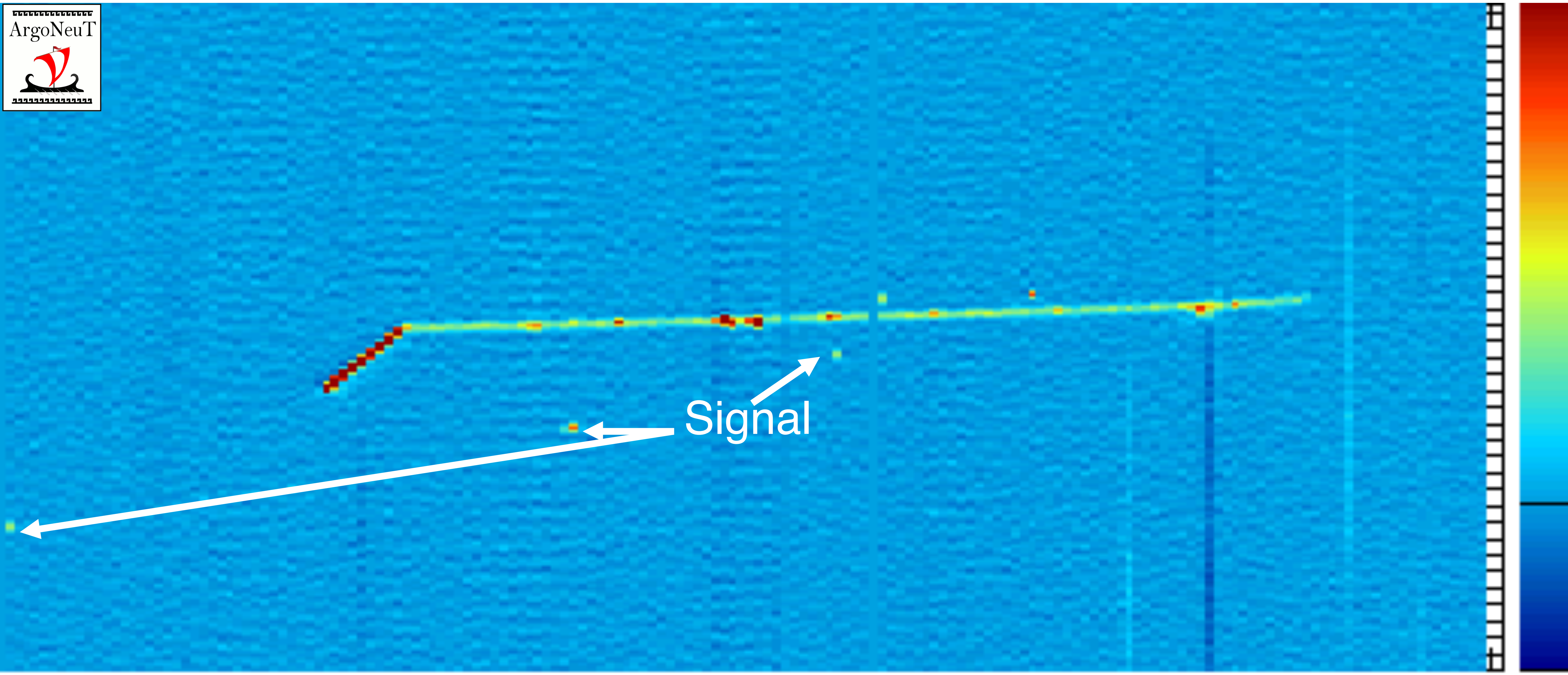

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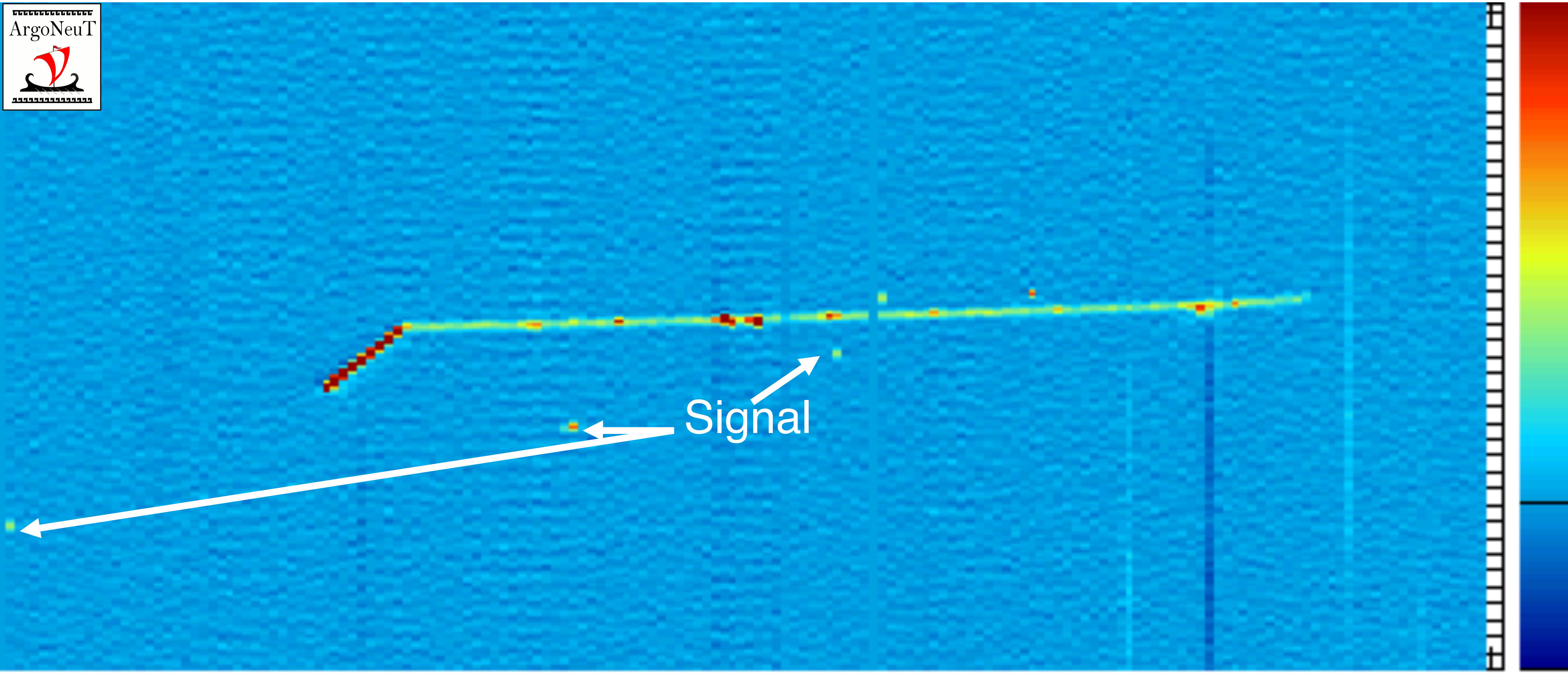


We're going to show that we can identify the source and reconstruct this activity (signals)

Outline

- Production of low energy photons in GeV neutrino-argon interactions.
- The ArgoNeuT study of MeV activity in neutrino interactions
    - FLUKA MC simulation
    - Signal section & reconstruction
    - Data-MC comparison
- Benefits to future LArTPC studies.

ArgoNeuT in the NUMI Beam line

First LAr TPC in a neutrino beam in the US

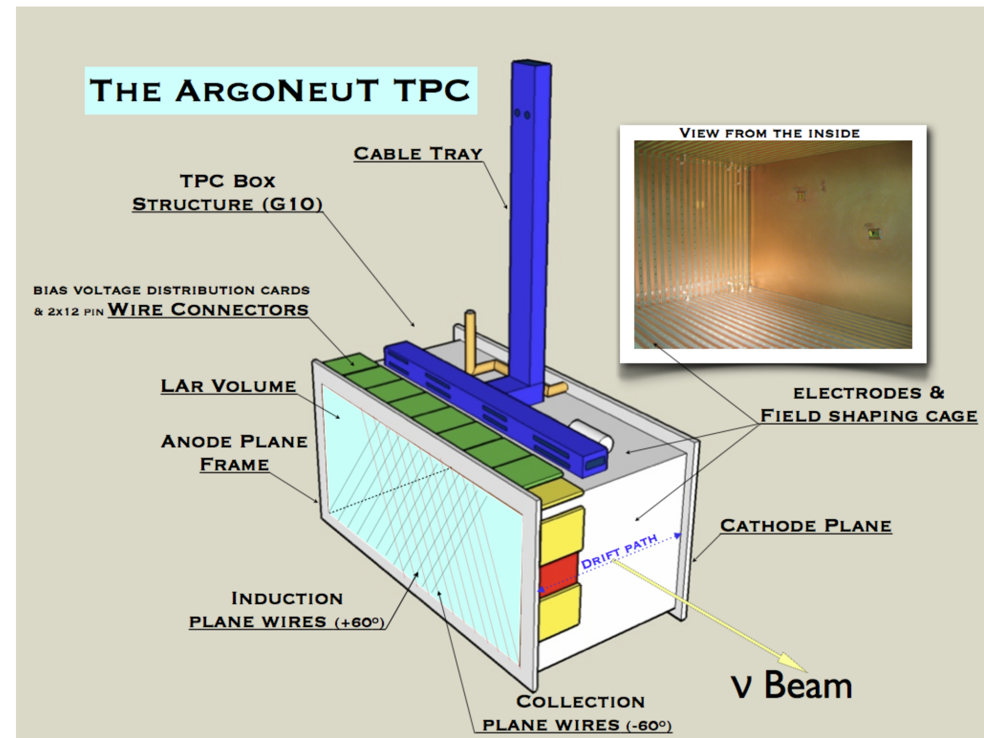
Acquired 1.35 × 10^{20} POT, mainly in $\overline{\nu}_\mu$ mode (4.5 months run)

0.24 tons active volume

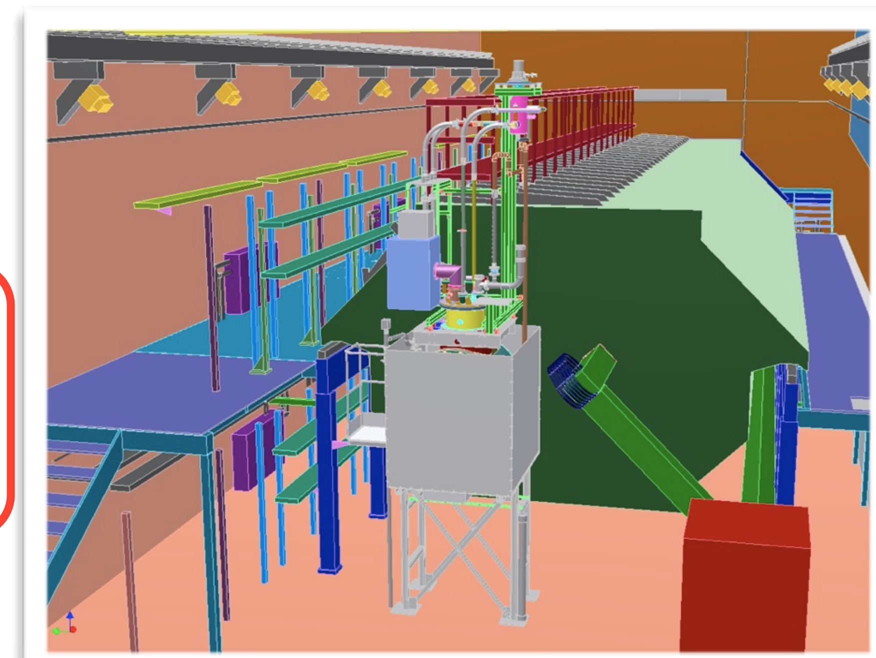
LAr TPC

47×40×90 cm^3, 2 readout planes,
480 wires, 4 mm spacing,
no light detection system

JINST 7 (2012) P10019



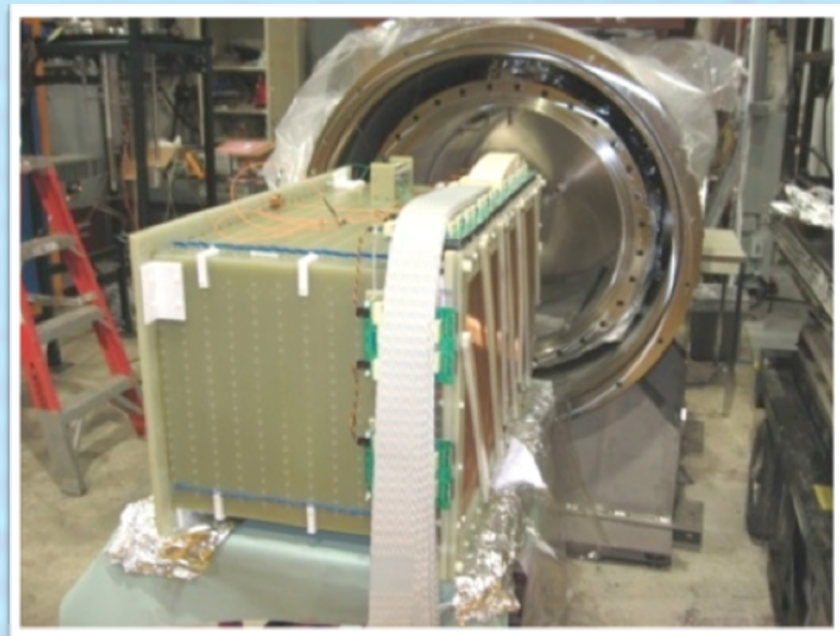
100 m underground
MINOS ND as muon spectrometer
for ArgoNeuT events*

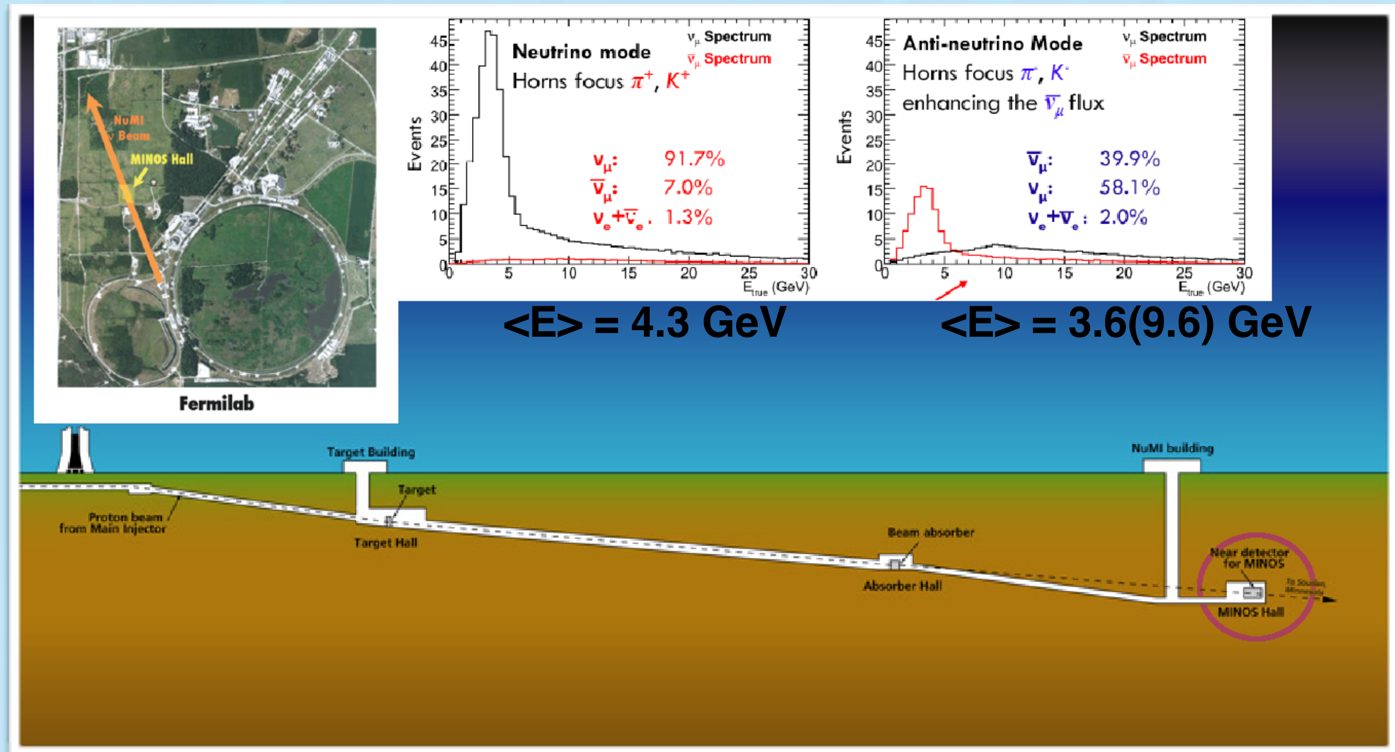


ArgoNeuT

*ArgoNeuT Coll. is grateful to MINOS Coll. for providing the muon reconstruction

ArgoNeuT in the NuMI Beam line





~7000 CC
neutrino events collected

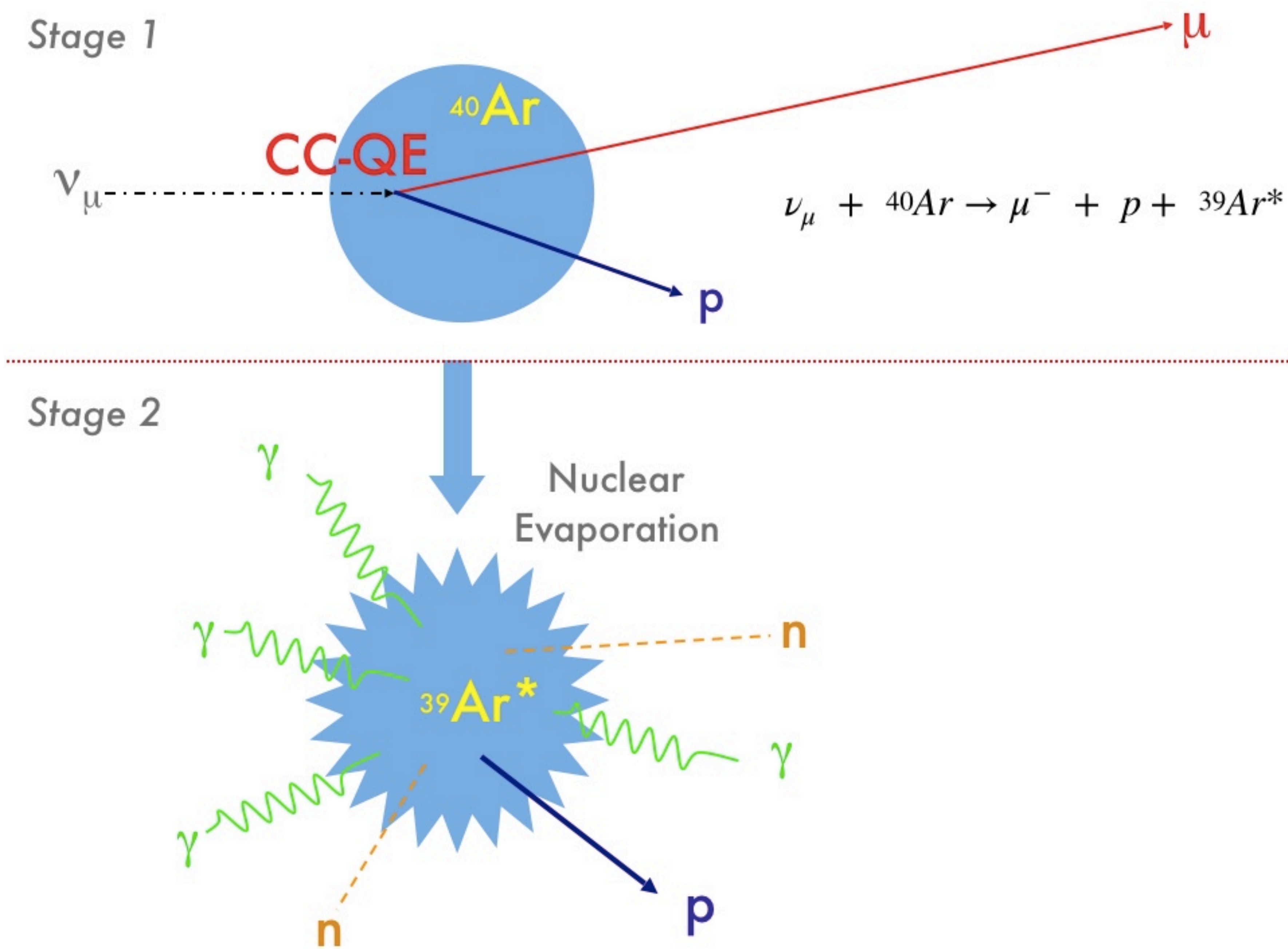
Designed as a test experiment,
but produced physics results!

First to demonstrate electron-gamma separation in LAr
Developed LAr TPC calibration techniques
Several first ν-Ar cross sections measurements
Studies of nuclear effects in ν-argon interactions

Low Energy Photon Production

Low Energy (MeV) Photons can be produced in GeV neutrino-argon interactions by two possible mechanisms:

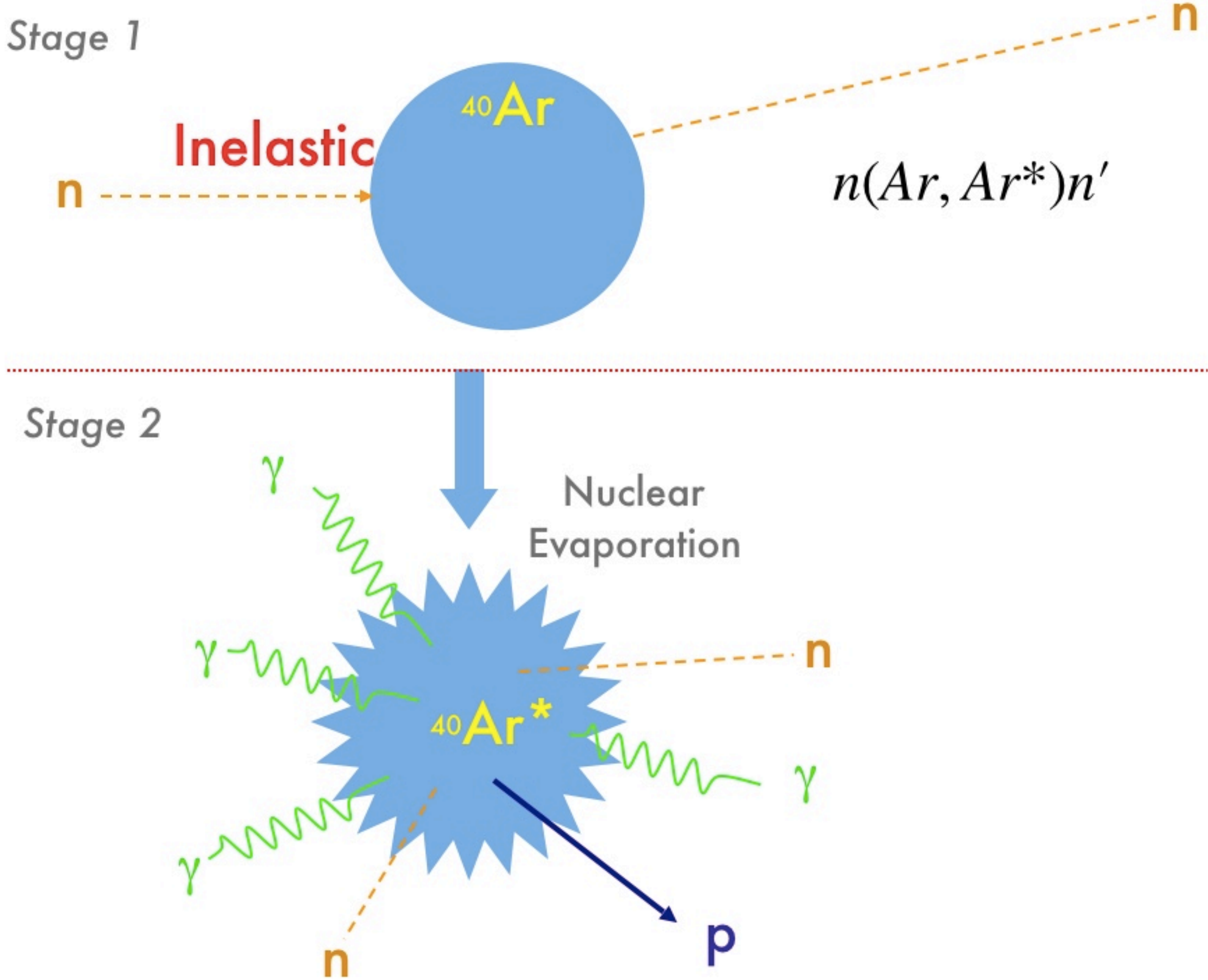
1. De-excitation of the target nucleus



Low Energy Photon Production

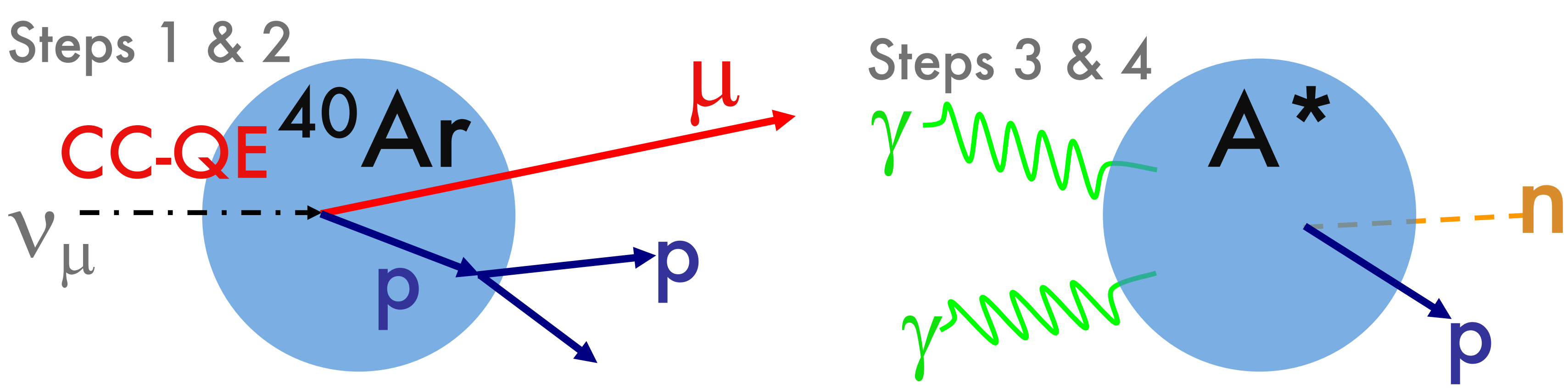
Low Energy (MeV) Photons can be produced in GeV neutrino-argon interactions by two possible mechanisms:

1. De-excitation of the target nucleus
2. Inelastic scattering of neutrons



Neutrino Interactions in FLUKA

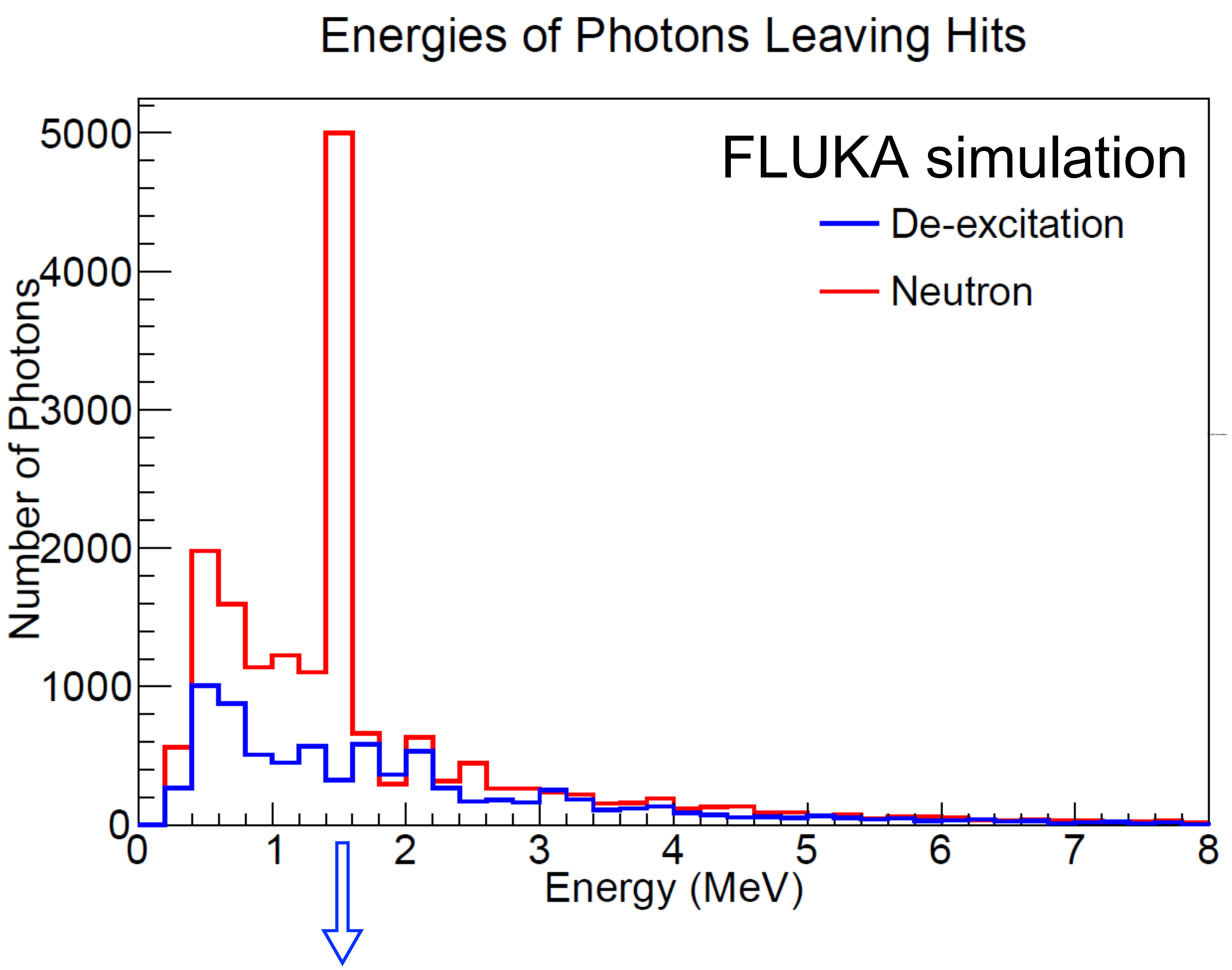
- FLUKA* is a multi-particle transport and interaction code.
- Also a neutrino interaction generator.
- **Only** GeV-neutrino MC generator that simulates the **physics of the final-state nucleus**, resulting in the production of final-state de-excitation photons.
- Steps (e.g. CCQE ν_μ interaction):
    1. Neutrino interaction
    2. Proton tries to escape → Intranuclear cascade
    3. Pre-equilibrium stage → Evaporation of nucleons
    4. Photon emission
    5. Ground state



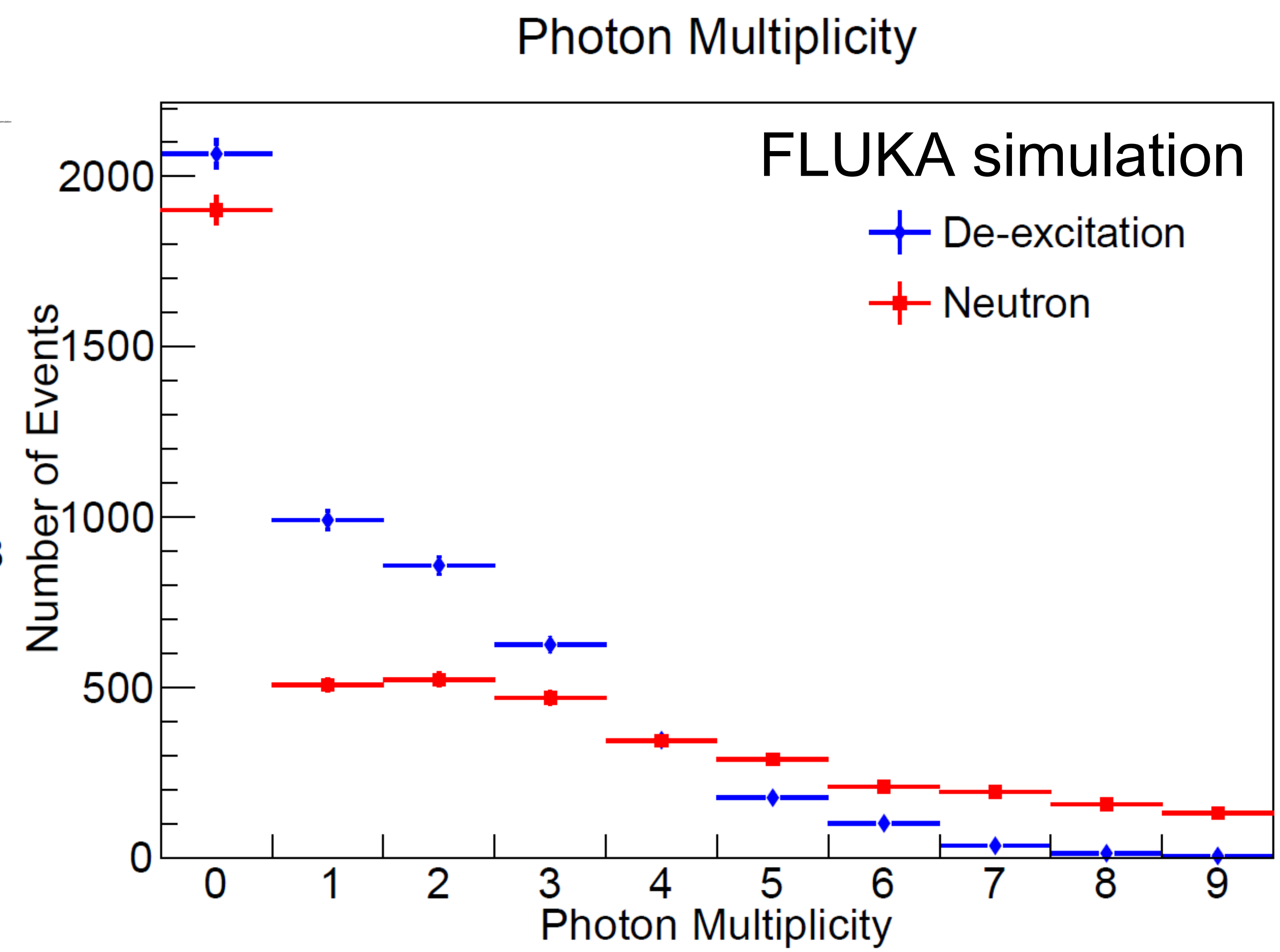
* "FLUKA: A Multi-Particle Transport Code" (CERN-2005-010 INFN/TC_05/11, SLAC-R-773)

Production of Low-Energy Photons

Photons from simulated neutrino interactions in ArgoNeuT using FLUKA and the energy spectrum of the NuMI beam

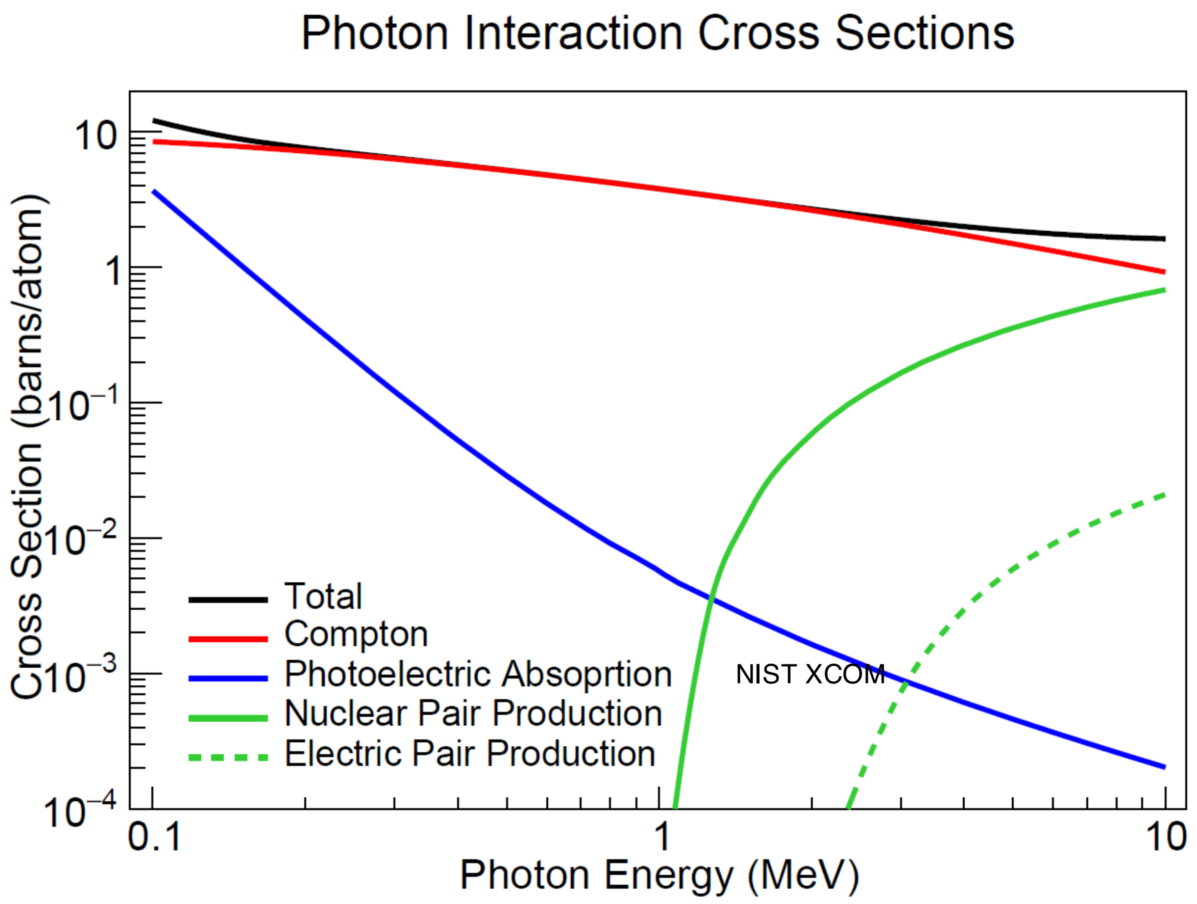


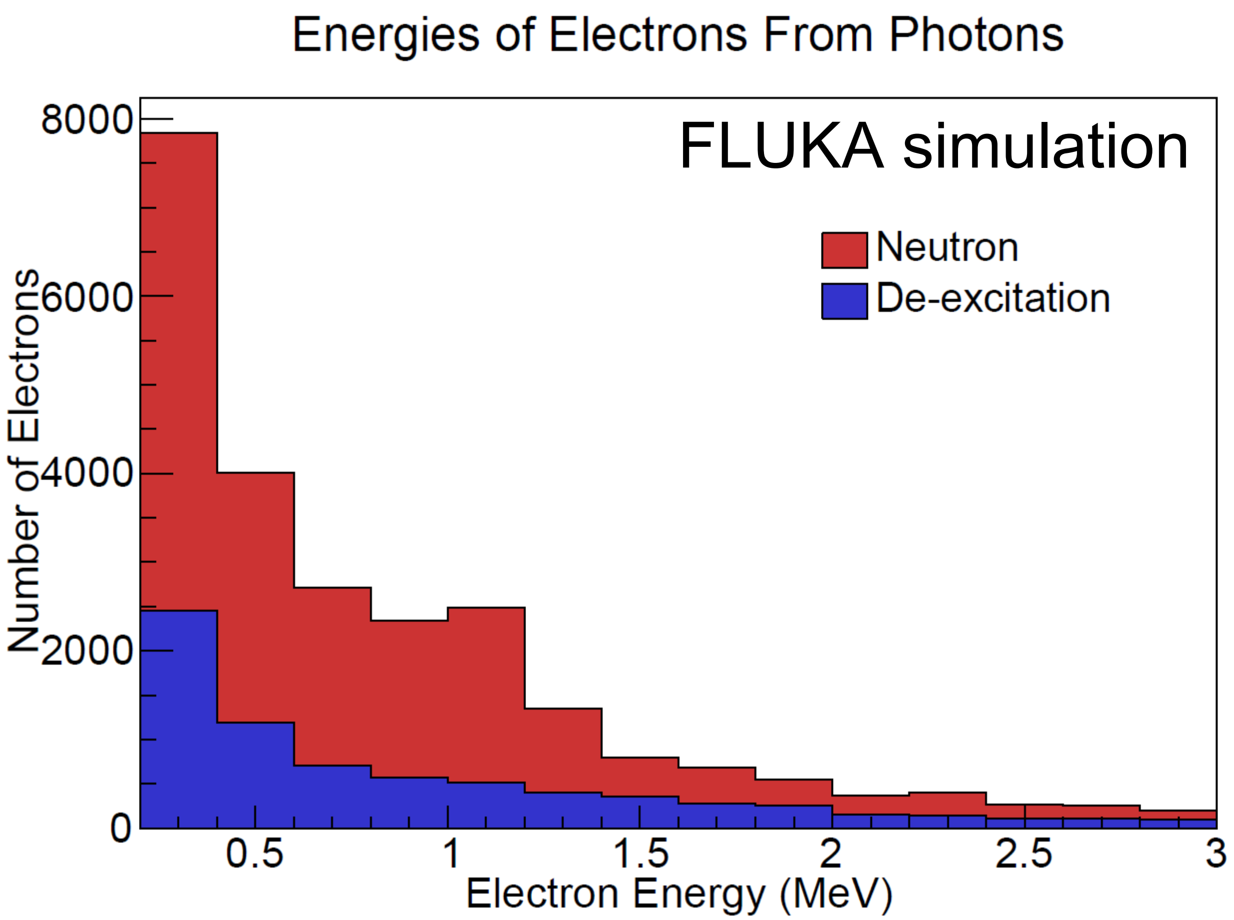
The peak at 1.46 MeV corresponds to the 1st excited state of ^{40}Ar



Interaction of Low-Energy Photons

- Detection via electrons from Compton scattering
- Radiation length: 14 cm in LAr
- Result: **topologically separated low-energy depositions**





Advantages of ArgoNeuT for This Analysis

- 100 m underground →No cosmics
- Well understood dataset
- Muon ID from MINOS ND
- Minimal ^{39}Ar activity
  - 1 decay in every 10 events
- Minimal space charge

Advantages of ArgoNeuT for This Analysis

- 100 m underground →No cosmics
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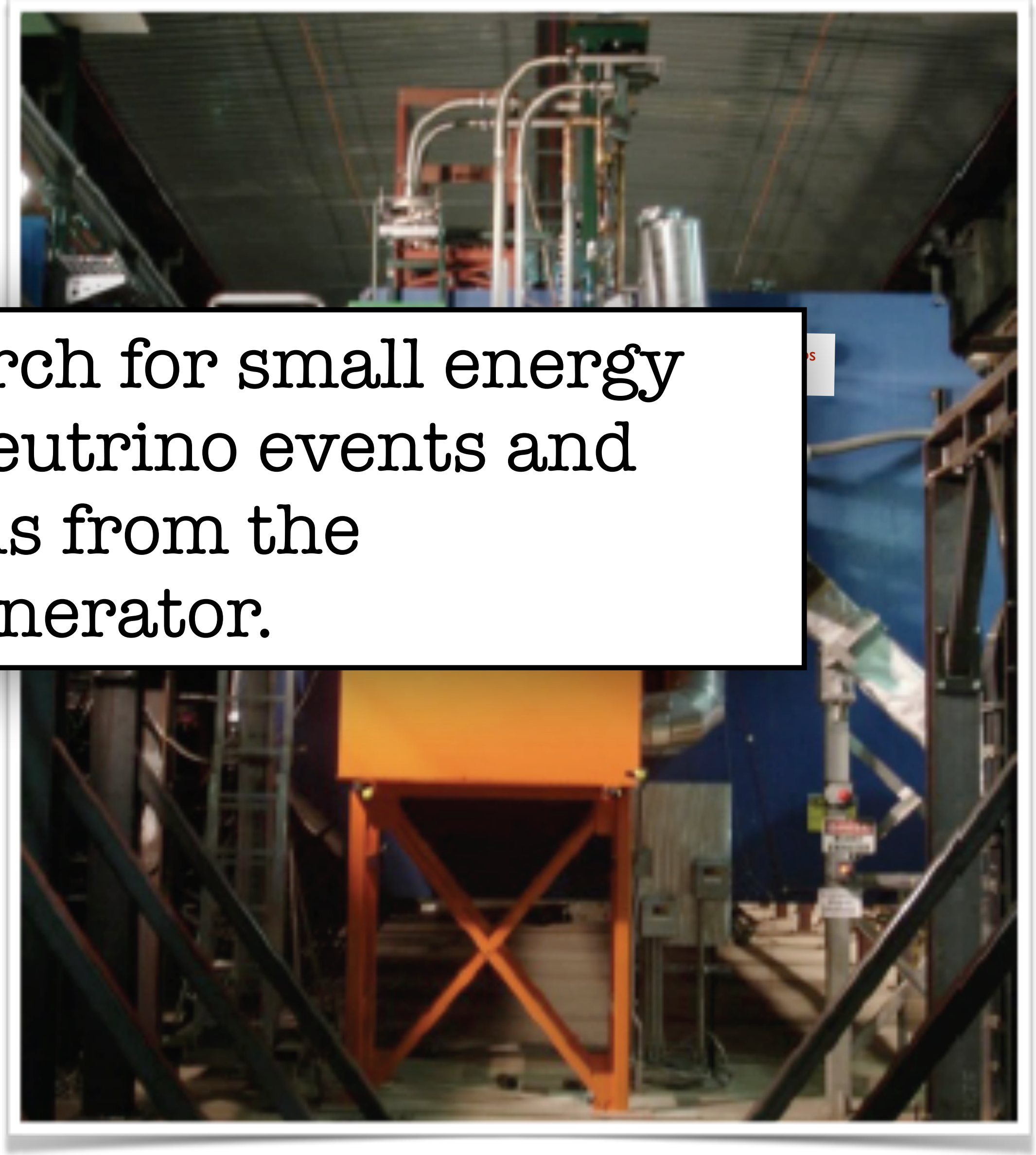
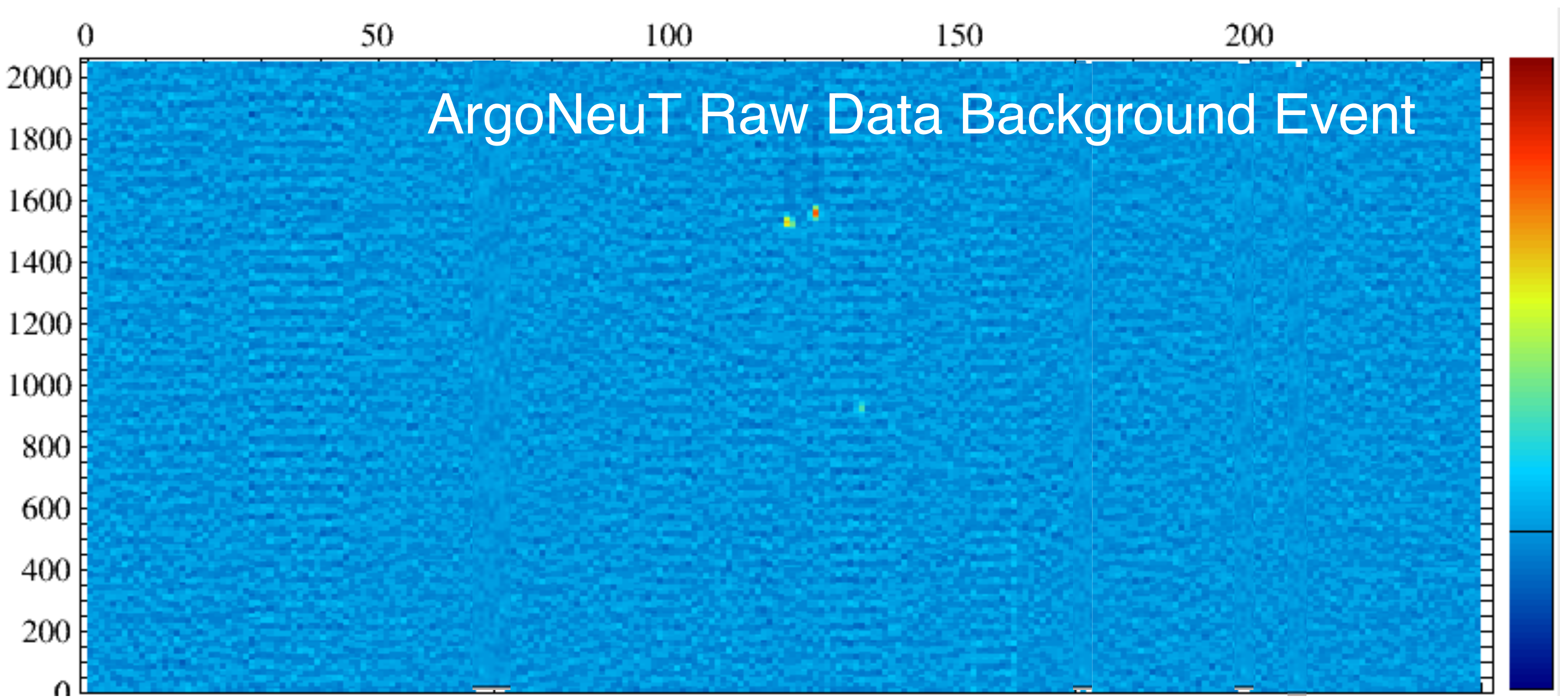
    - 1 de
- Minim



We'll use ArgoNeuT data to search for small energy depositions associated with neutrino events and compare to predictions from the FLUKA neutrino generator.

Data and Simulation

- **ArgoNeuT** Data: **552 CC 0π events**
  - Events with one muon and up to one proton
  - No pions, EM showers
- **MC dataset**: neutrino interactions in ArgoNeuT using **FLUKA** and the NUMI energy spectrum.
- **Background sample**
  - Spills without a visible neutrino interaction.
  - Contain electronic noise, ambient and internal radioactivity, photons from "dirt" neutrons, ^{39}Ar decays.
  - Added to simulation on an event-by-event basis



Data-driven modeling of the Background

Data and Simulation

- **ArgoNeuT** Data: **552 CC 0π events**
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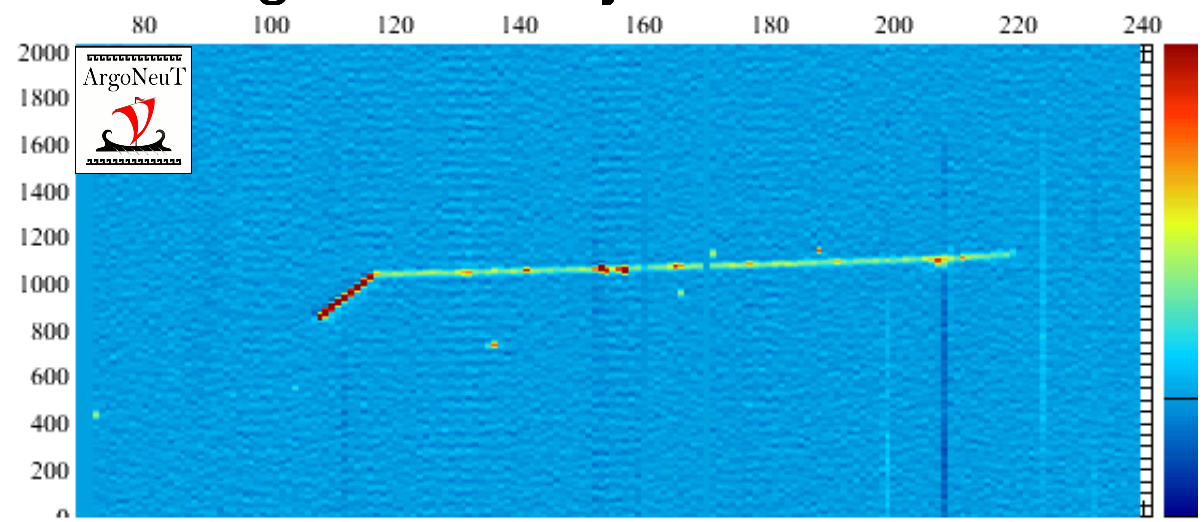
  - Added to simulation on an event-by-event basis

Data-driven modeling of the Background

The same reconstruction procedure has been applied to all the selected neutrino data, MC and background samples.

Reconstructing Low (MeV) Energy Depositions in LAr

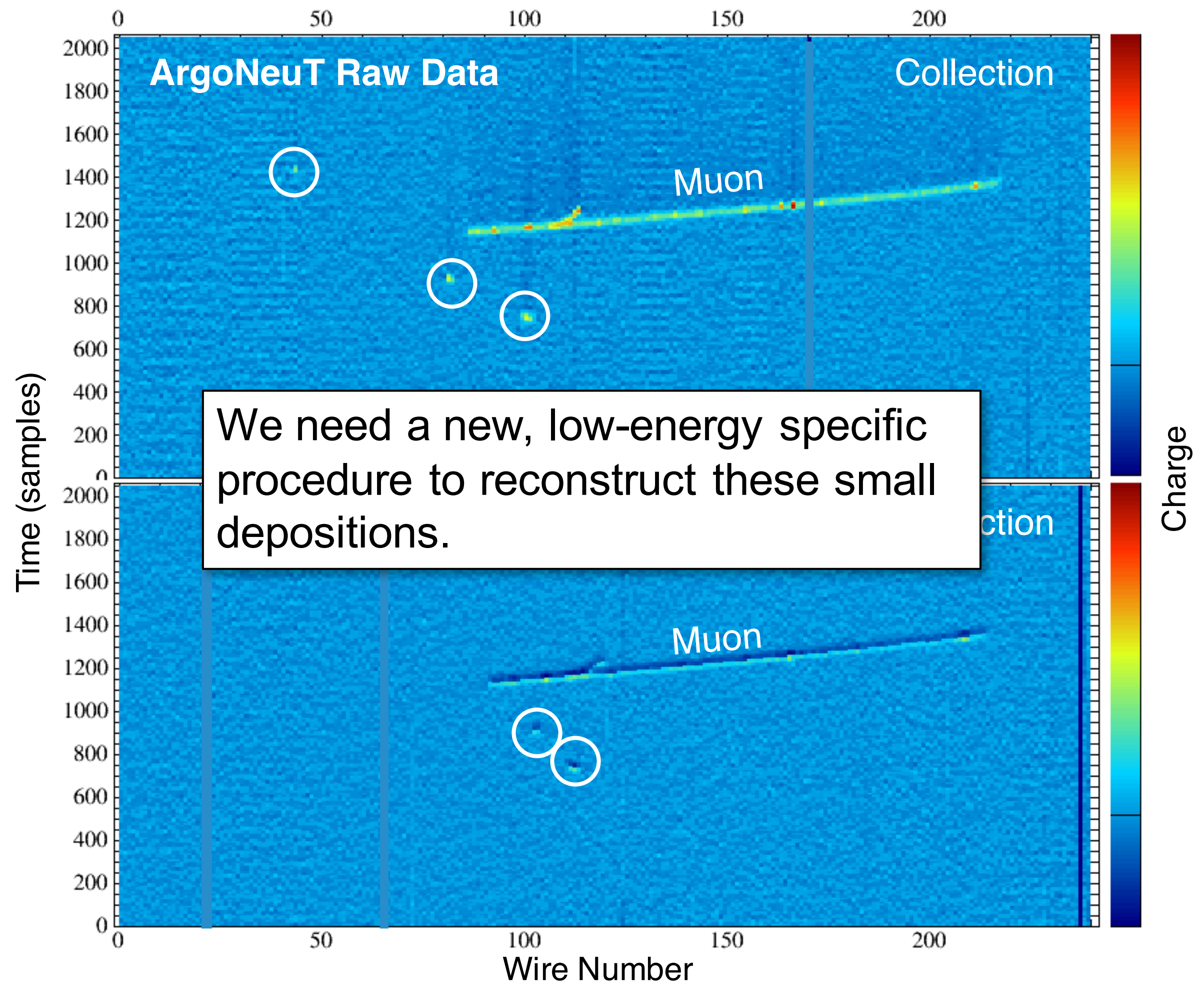
- It is a difficult task.
- At high energies (>100 MeV), charged particles travel several centimeters to meters.
    - Signals on tens to hundreds of wires.
    - Methods for reconstructing the identity and kinematics of the particle already exist.



- Particles at MeV energies travel much shorter distances.
    - Sometimes less than the wire spacing (3-5 mm) → Signals on just one or two wires
    - Current reconstruction methods are ineffective for these energies.
    - There is a need for new, **low-energy specific method**.

Event Reconstruction

- Two steps:
  - First, the standard automated reconstruction is performed.
    - Wires are scanned for signals.
    - Hits and tracks are found.
    - High energy particles (muons, protons, pions) are identified.
    - Neutrino interaction vertex is located.
  - Then comes a **low-energy specific** reconstruction.



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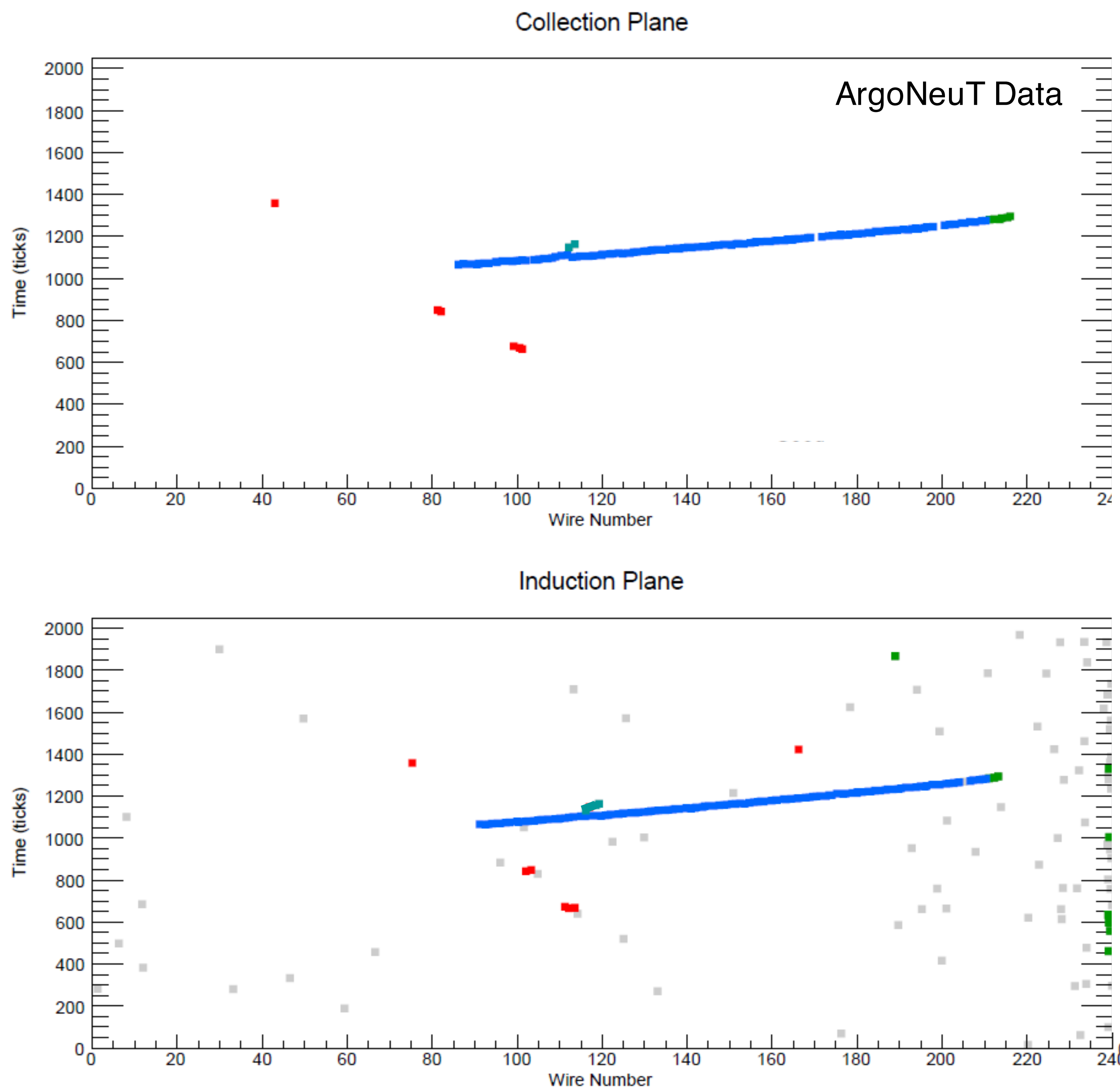
Signal Selection



Each dot is a reconstructed hit.

Cuts

Below Threshold (0.2 MeV)

Upper limit of 1.2 MeV (no hits)

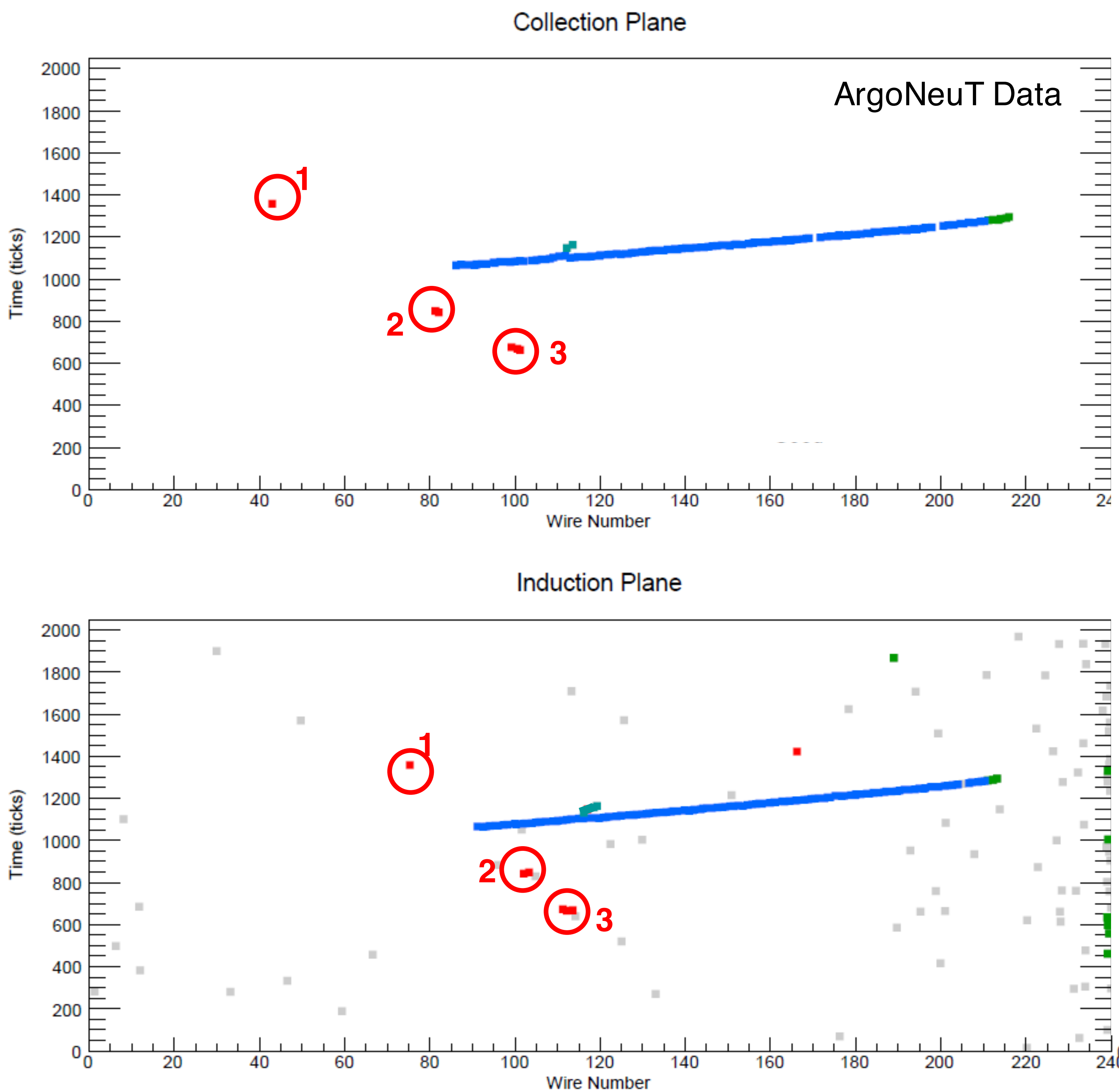
Fiducial

Track

Cone

Good hits

Signal Selection



Each dot is a reconstructed hit.

Cuts

Below Threshold (0.2 MeV)

Upper limit of 1.2 MeV (no hits)

Fiducial

Track

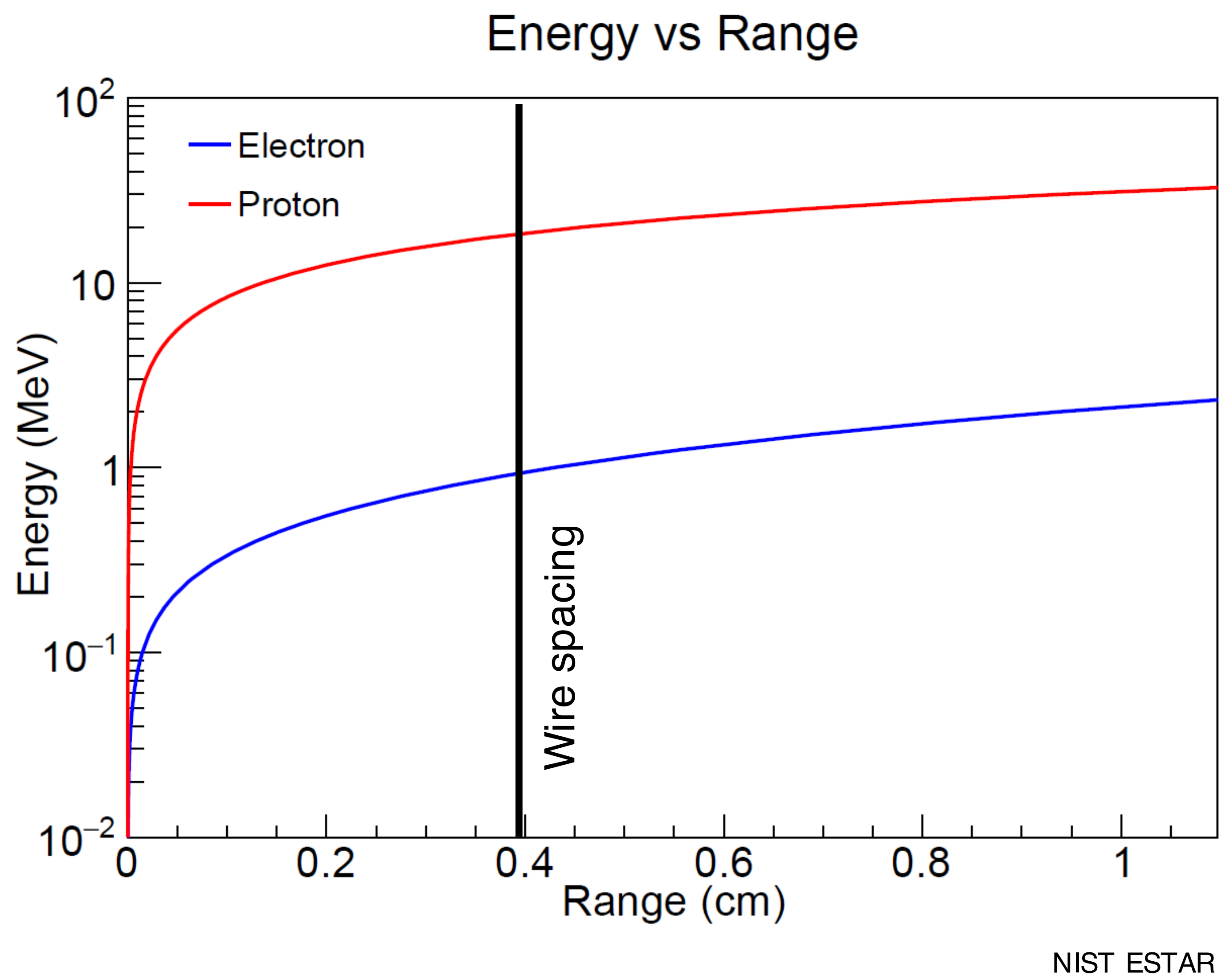
Cone

Good hits

Circles denote plane matched clusters.

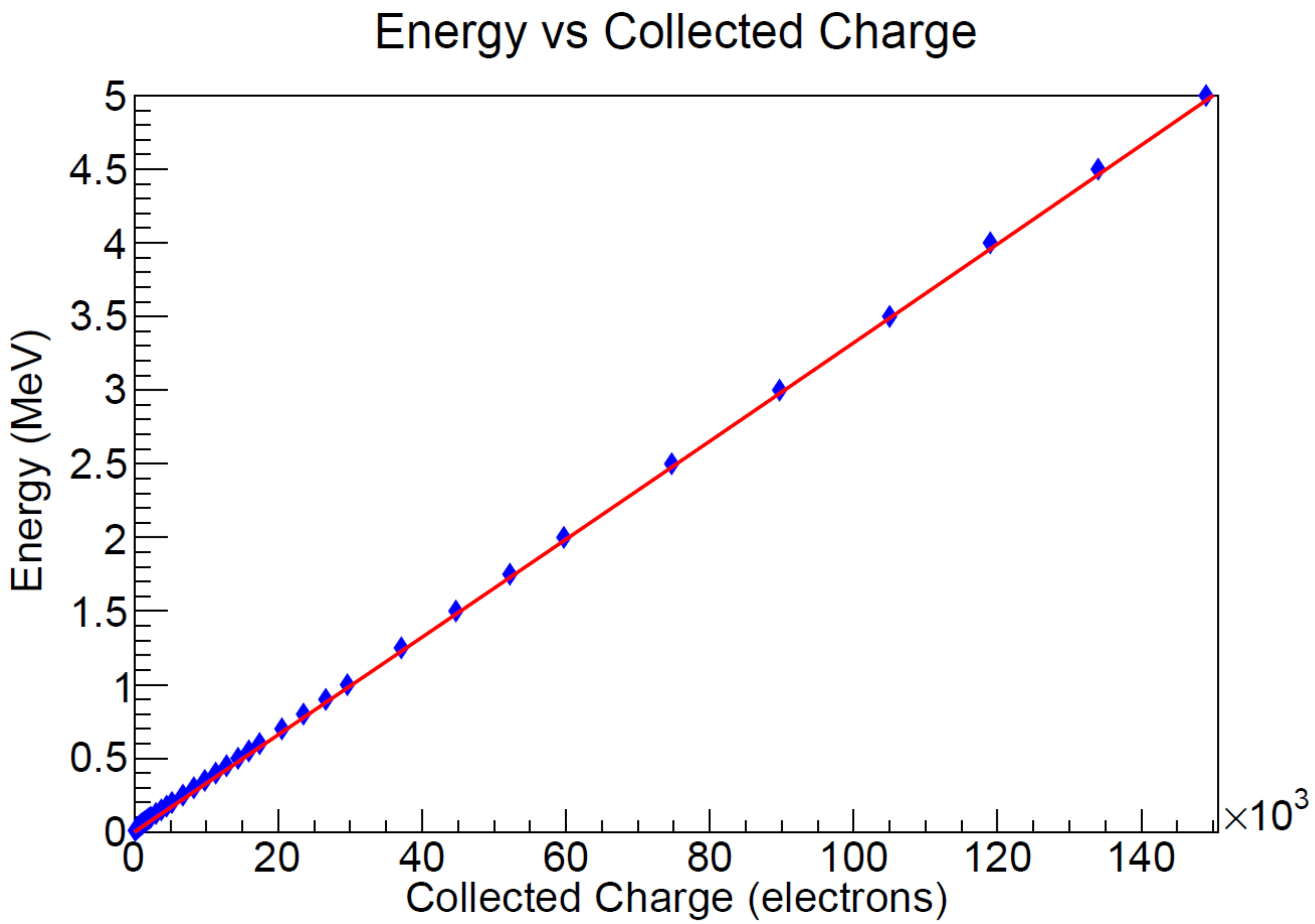
Charge to Energy conversion

- Assume that all hits passing cuts are due to electrons.
  - From simulation only 1% of the hits are due to proton.



Charge to Energy conversion

- Method uses the National Institute of Standards and Technology (NIST) table of electron energy vs range for electrons*:
  - NIST Table (range and energy for electrons in argon) → dE/dx
  - Applying Recombination Effect → Collected Charge

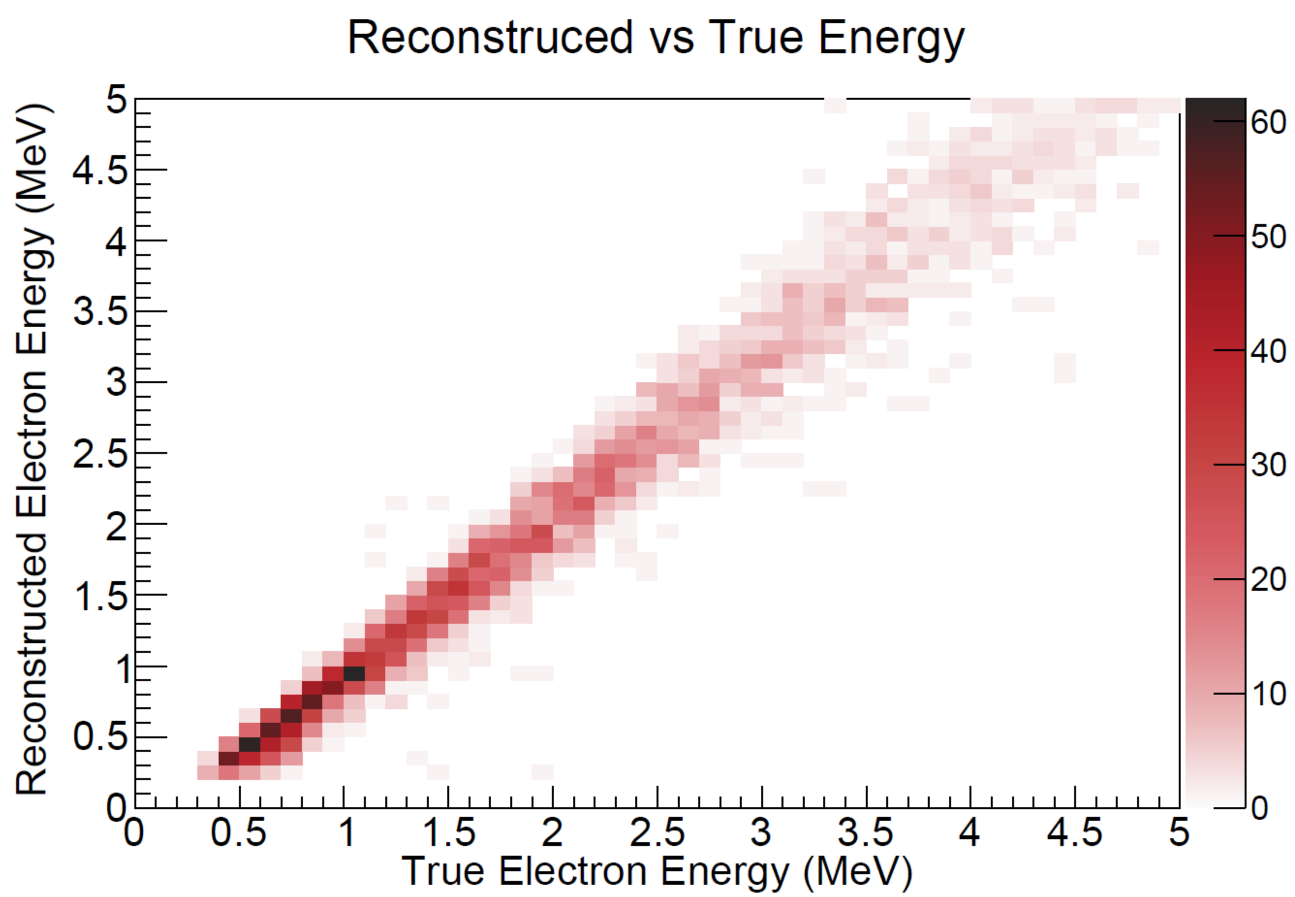


- **Reconstruction**: Measured Charge → Track Length → Deposited Energy

*https://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html

Charge to Energy conversion

Test of the method on a sample of simulated electrons propagating in liquid argon



- At 0.5 MeV, detection efficiency = 50%, energy resolution = 24%
- At 0.8 MeV, efficiency almost 100%, energy resolution = 14%

Comparison of neutrino and Background Datasets

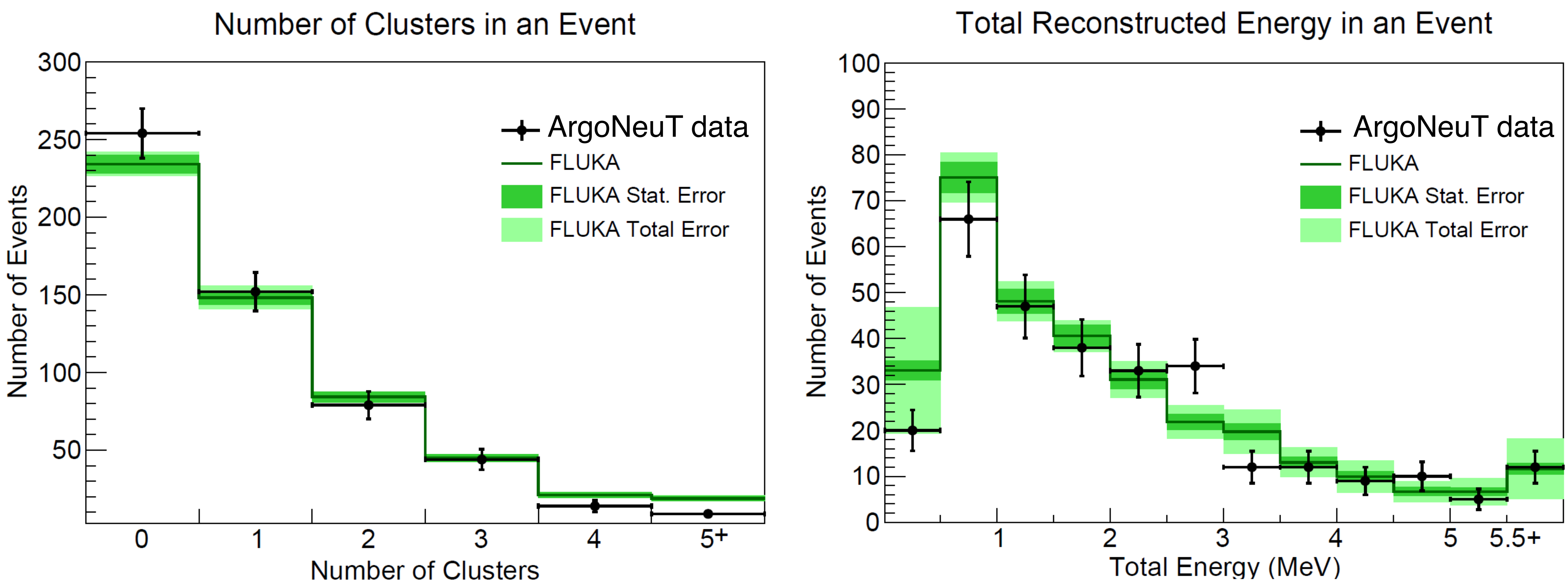
- Background: spills without neutrino interactions.
- "Blips" due to electronic noise, intrinsic radioactivity, "dirt" neutrons, ^{39}Ar decays.

Metric	Neutrino Data	Background
Number of signal hits per event	1.30	0.21
Average total signal energy in an event (MeV)	1.11	0.19
Percent of events with at least one signal hit	54%	12%

This can be interpreted as evidence of neutrino induced MeV-scale energy depositions in the neutrino event sample

Comparison with FLUKA MC

FLUKA generate photons from de-excitation of the target nucleus.

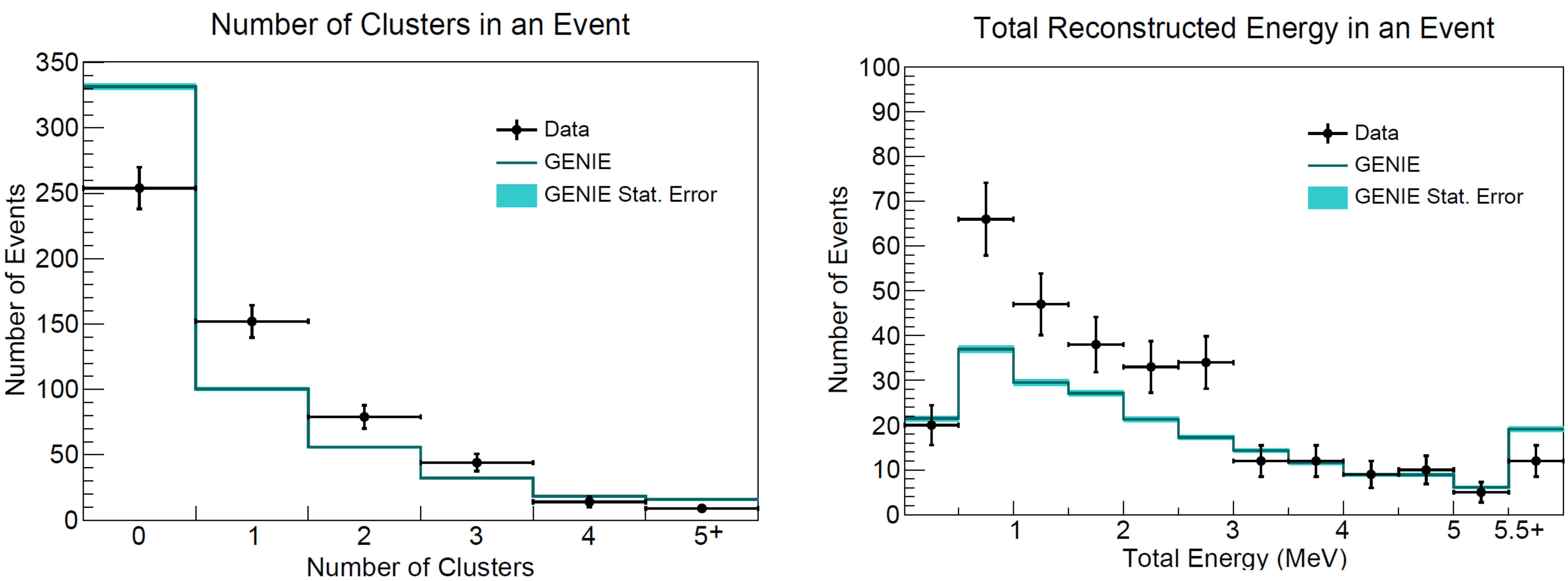


FLUKA agrees very well with our data!

Both components, de-excitation photons from the target nucleus and photon produced by neutron inelastic interactions are necessary for data-MC agreement.

Comparison with GENIE

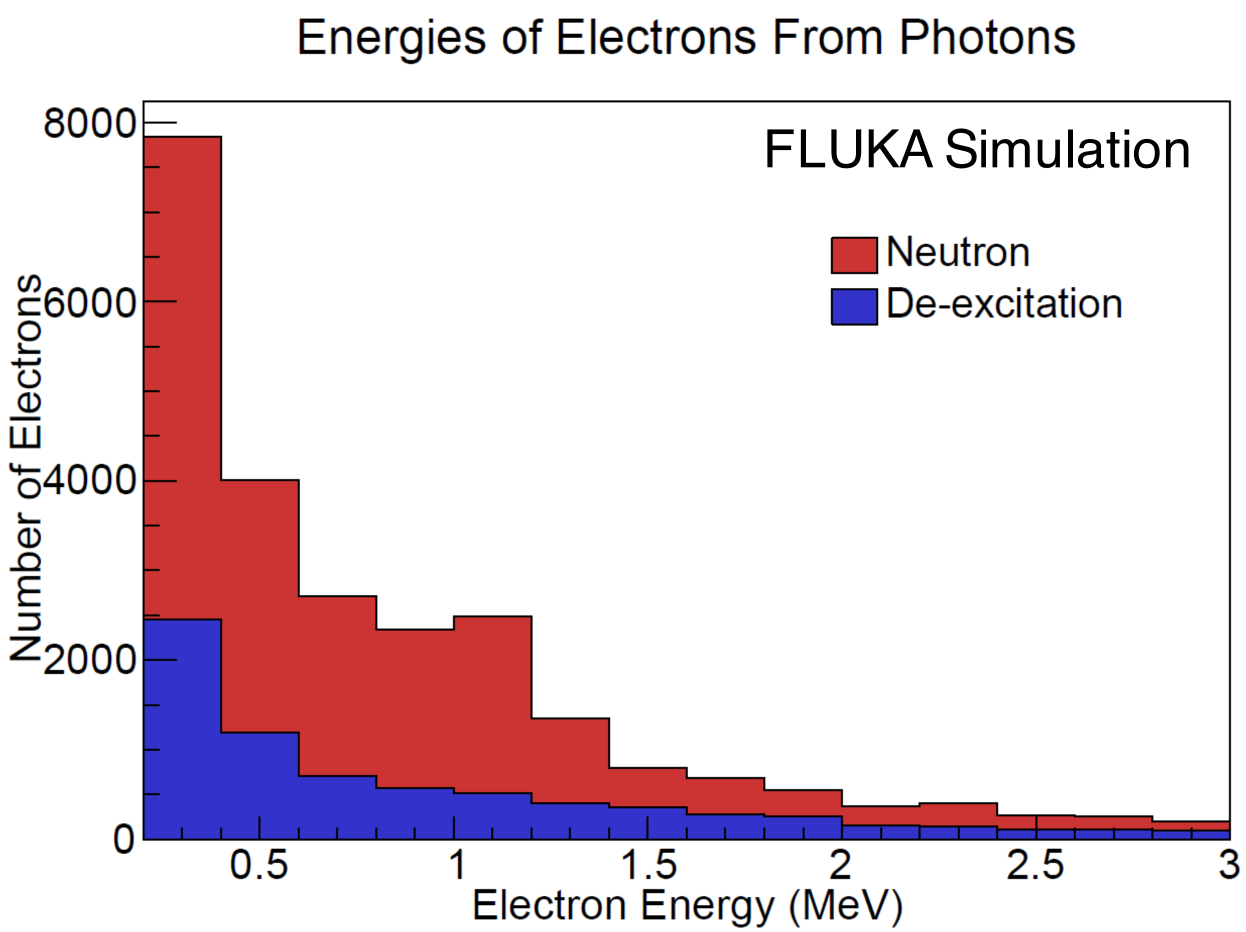
- GENIE simulation contains only neutron-produced photons.
- Disagreement with data, attributed to the lack of de-excitation photons in GENIE



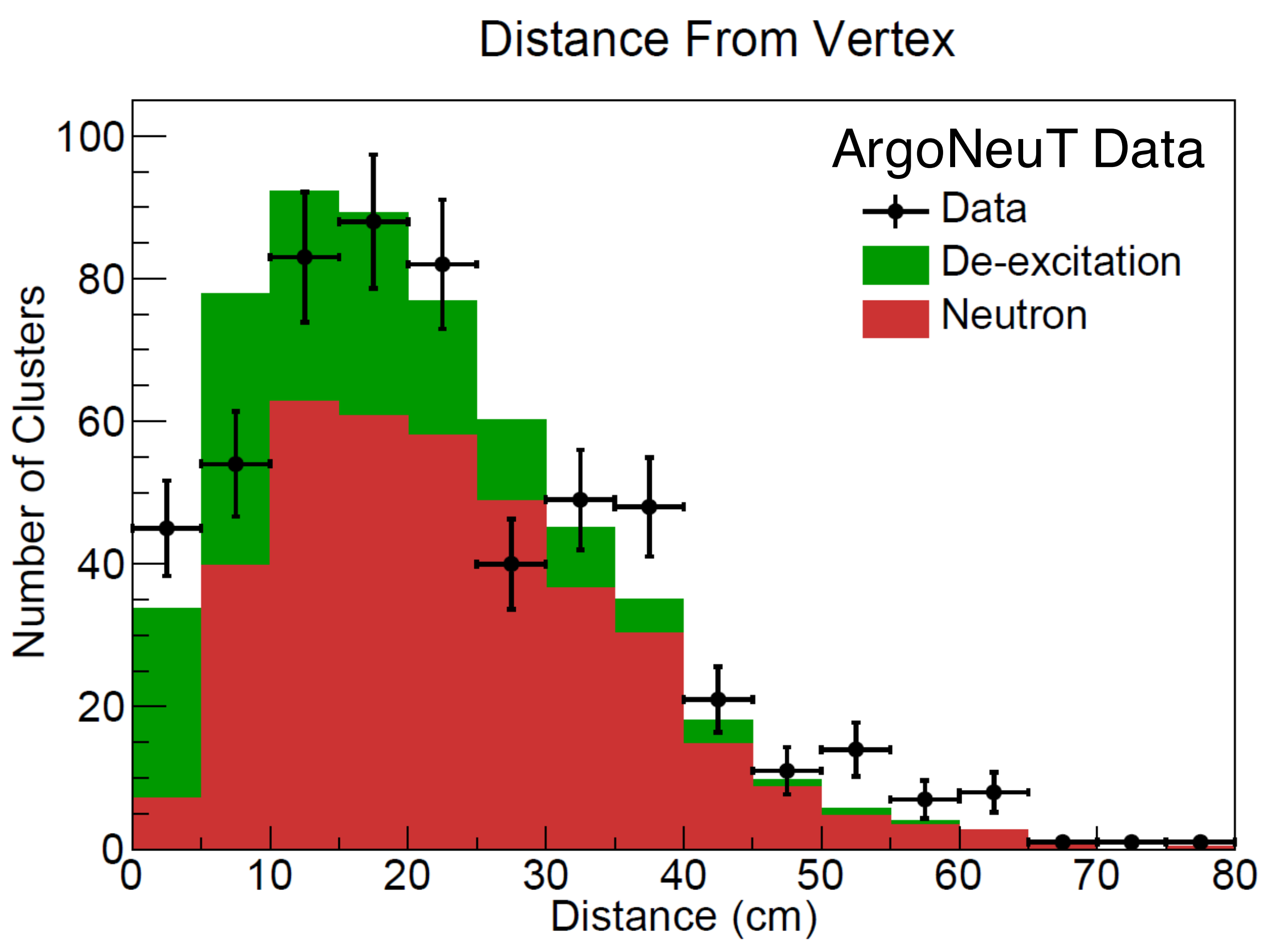
These results indicate that the observed MeV-scale signals in ArgoNeuT contain both de-excitation and neutron-produced photons.

"The GENIE Neutrino Monte Carlo Generator" (Nucl. Instrum. Meth. A614 (2010))

Separating the Sources



We can't distinguish between the two sources of photons using energy.



How about using distance from the neutrino interaction vertex?

From FLUKA simulation:
<distance de-excitation photon clusters>=15.7 cm
<distance neutron-produced photon clusters>=23.4 cm

Benefits to Future LArTPC Studies

- Future large LArTPCs could provide additional understanding of the value of these MeV-scale features.
  - Advantages: larger, better electronics, higher statistics
  - Disadvantages: (cosmics), space charge, ^{39}Ar decays
- Detection of de-excitation photons adds additional insight into reconstructing **supernova** and **solar neutrinos**.

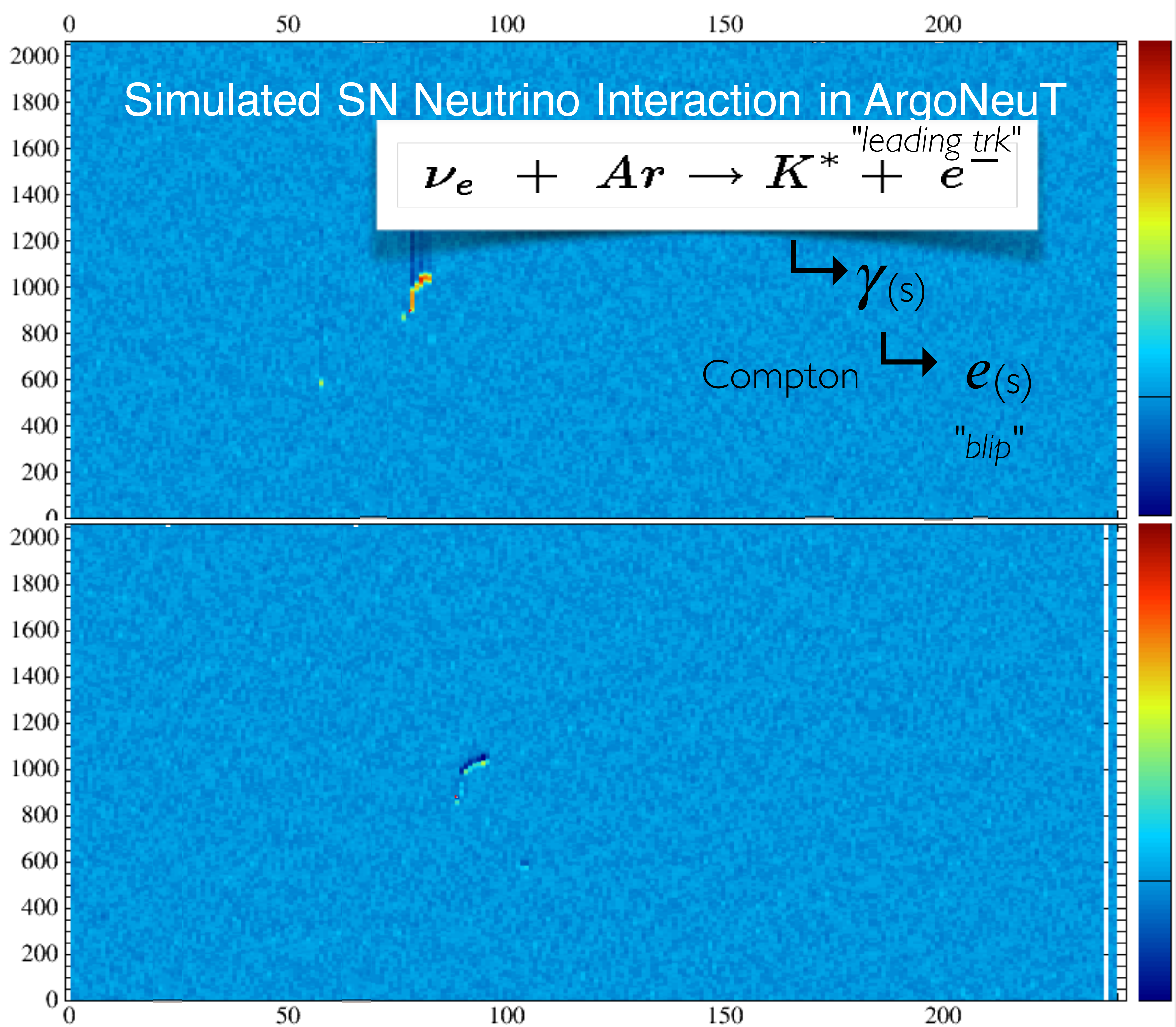
"A precise gamma-ray energy reconstruction would aid neutrino energy reconstruction, and help signal and background separation."

arXiv: 1811.07912

- Studies of low scale new physics scenarios
  - Millicharged particles *(see Roni Harnik's talk on Wednesday)*
  - Light mediators
  - Inelastic scattering with small splittings

An ArgoNeuT analysis is underway.

Supernova Neutrinos Revisited



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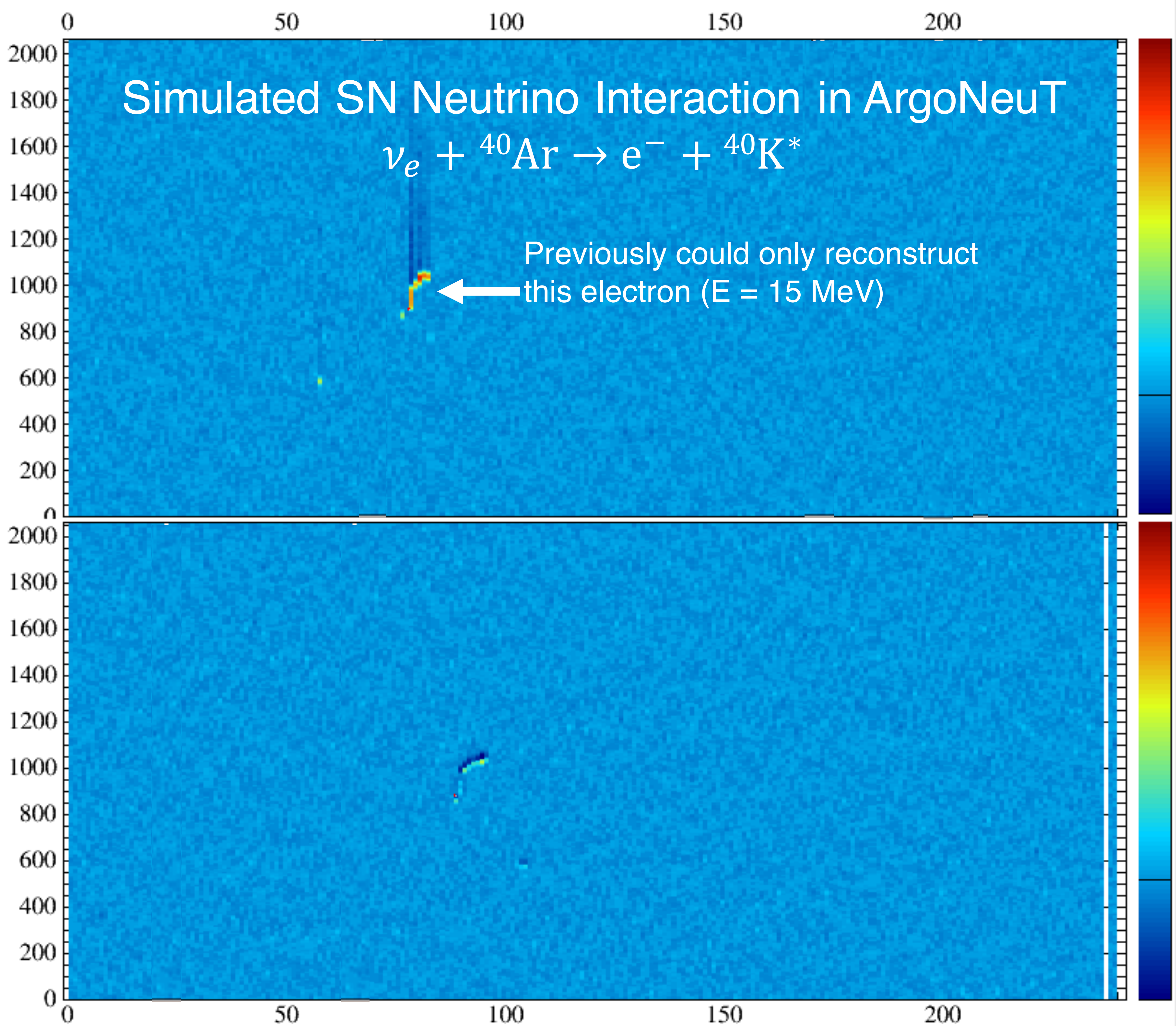
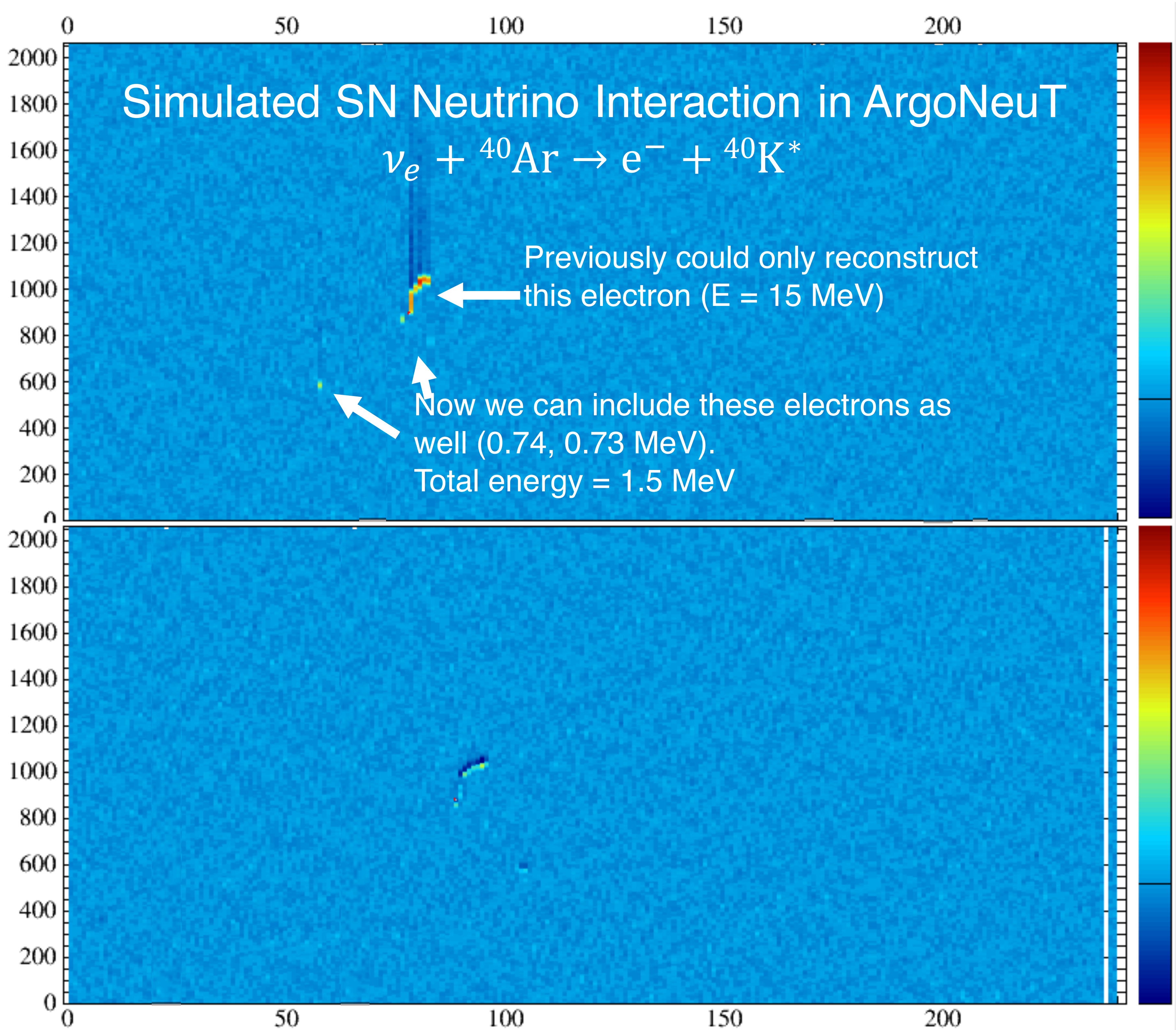
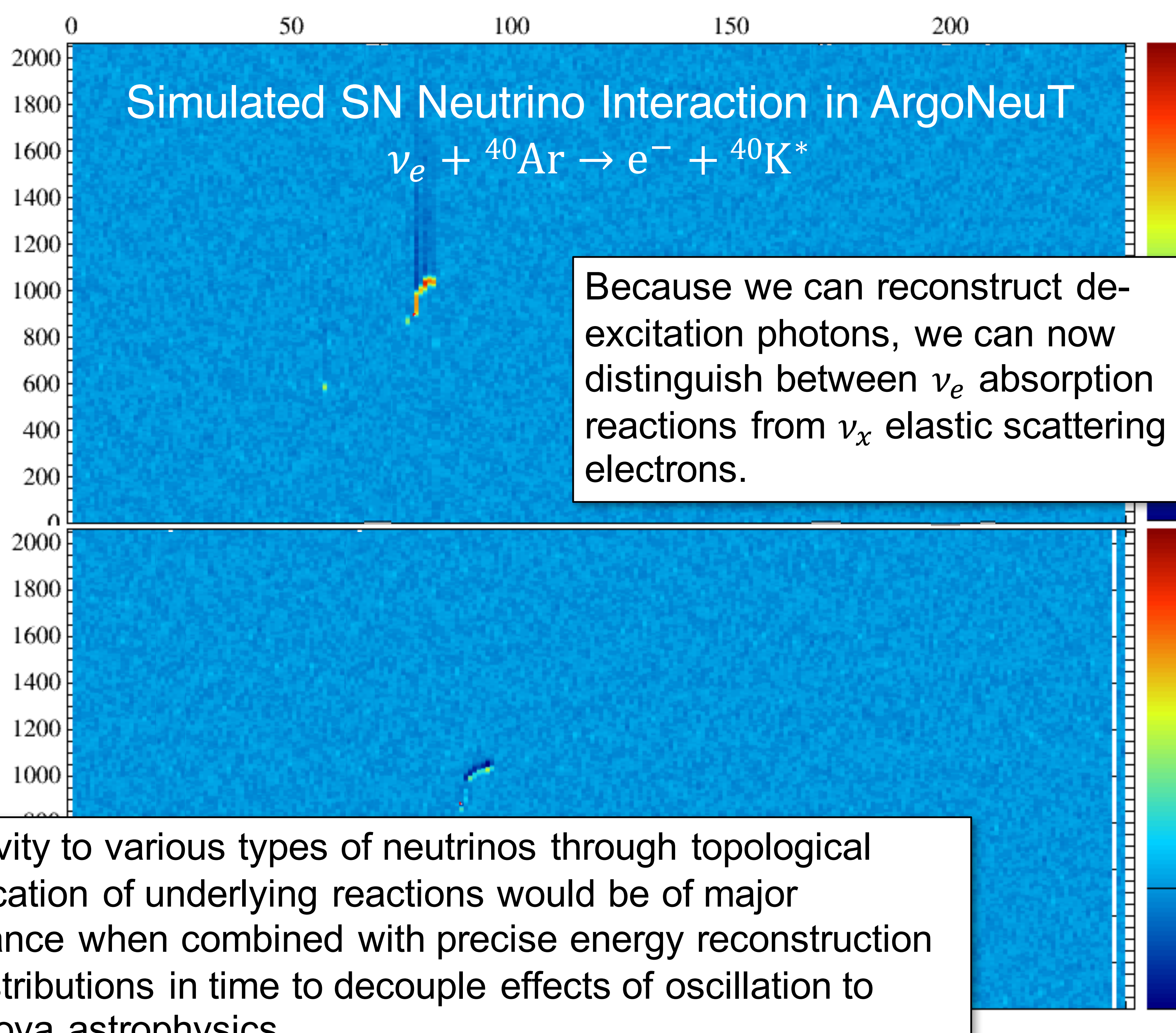


Supernova Neutrinos Revisited



Supernova Neutrinos Revisited



Because we can reconstruct de-excitation photons, we can now distinguish between ν_e absorption reactions from ν_x elastic scattering off electrons.

Sensitivity to various types of neutrinos through topological identification of underlying reactions would be of major importance when combined with precise energy reconstruction and distributions in time to decouple effects of oscillation to supernova astrophysics.

Summary

- This analysis represents the first-ever reported detection of **de-excitation photons** produced by beam neutrino interactions in argon.

- Using new reconstruction tools we found evidence of activity due to de-excitation of the neutrino's target nucleus and inelastic scattering of neutrons in the detector.

- We have extended the LArTPC's range of physics sensitivities down to the sub-MeV level, reaching a **threshold of 300 keV** in this analysis.

- Precise reconstruction of de-excitation photon multiplicities and energies will improve the overall reconstruction of neutrino energies, particularly for those at lower energies, such as **supernova and solar neutrinos**.

If you want to know more…

arXiv:1810.06502

Accepted by Phys. Rev. D

FERMILAB-PUB-18-559-ND

Demonstration of MeV-Scale Physics in Liquid Argon Time Projection Chambers Using ArgoNeuT

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(The ArgoNeuT Collaboration)

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[15]*University of Manchester, Manchester M13 9PL, United Kingdom*

MeV-scale energy depositions by low-energy photons produced in neutrino-argon interactions have been identified and reconstructed in ArgoNeuT liquid argon time projection chamber (LArTPC) data. ArgoNeuT data collected on the NuMI beam at Fermilab were analyzed to select isolated low-energy depositions in the TPC volume. The total number, reconstructed energies and positions of these depositions have been compared to those from simulations of neutrino-argon interactions using the FLUKA Monte Carlo generator. Measured features are consistent with energy depositions from photons produced by de-excitation of the neutrino's target nucleus and by inelastic scattering of primary neutrons produced by neutrino-argon interactions. This study represents a successful reconstruction of physics at the MeV-scale in a LArTPC, a capability of crucial importance for detection and reconstruction of supernova and solar neutrino interactions in future large LArTPCs.

I. INTRODUCTION

The Liquid Argon Time Projection Chamber (LArTPC) is a powerful detection technology for neutrino experiments, as it allows for millimeter spatial resolution, provides excellent calorimetric information for particle identification, and can be scaled to large, fully active, detector volumes. LArTPCs have been used to measure neutrino-argon interaction cross sections and final-state particle production rates in the case of ArgoNeuT [1–7] and MicroBooNE [8], neutrino oscillations in the case of ICARUS [9], and charged particle interaction mechanisms on argon in the case of LArIAT [10].

LArTPCs are being employed to make important measurements, e.g. understanding the neutrino-induced low-energy excess of electromagnetic events with MicroBooNE [11] and will be used to search for sterile neutrinos in the Fermilab SBN program [12] and for CP-violation in the leptonic sector with DUNE [13]. Precise measurements of neutrino-argon cross sections will be performed with SBN [12] and of charged hadron interactions with ProtoDUNE [14]. In most of the existing measurements, LArTPCs were placed in high energy neutrino beams to study GeV-scale muon and electron neutrinos as well as final-state products, generally with energies greater than 100 MeV. A smaller number of measurements have investigated particles or energy depositions in the $<$ 100 MeV range [6, 15, 16], some using scintillation light [17].

Few existing measurements have demonstrated LArTPC capabilities at the MeV scale for neutrino experiments, despite the wealth of physics studies that have been proposed for future large LArTPCs in this energy range. A number of studies have investigated expected supernova and solar neutrino interaction rates

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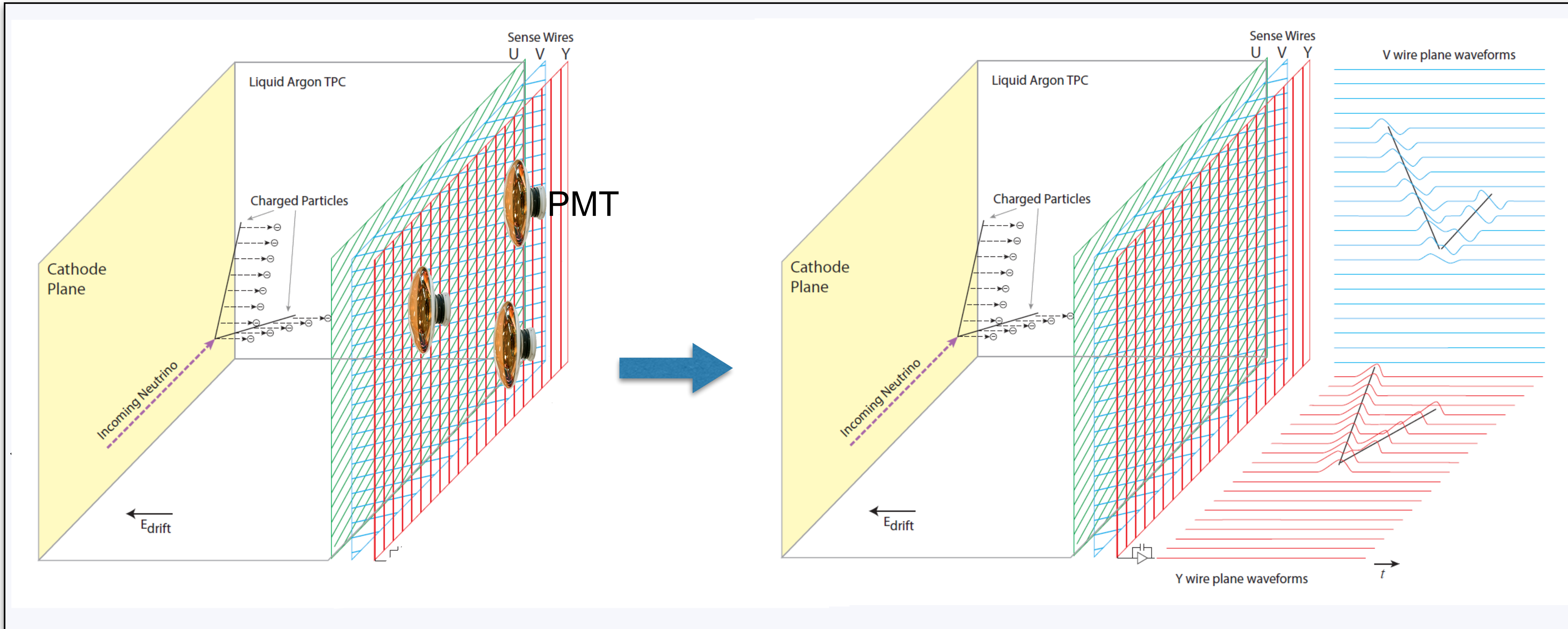
Overflow

LArTPC at work



Charged particles in LAr produce free ionization electrons and scintillation light

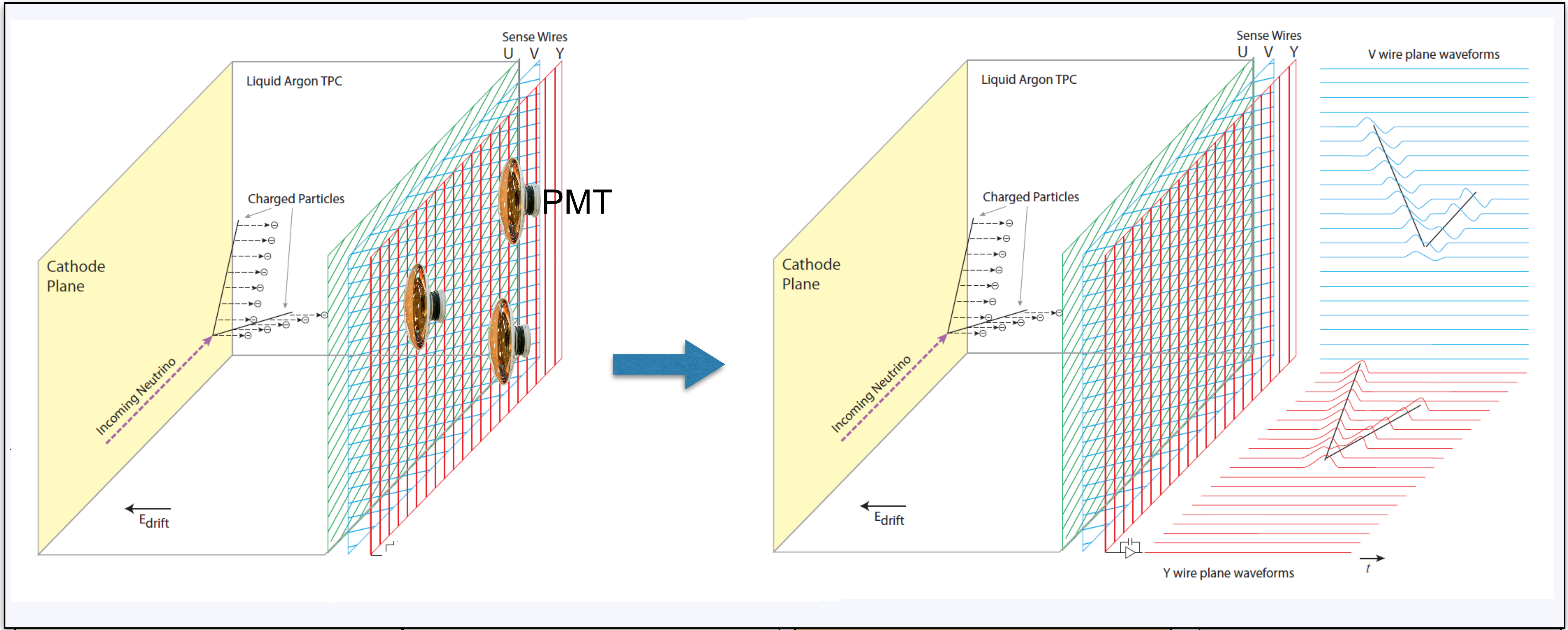
Ionization charge drifts in a uniform electric field towards the readout wire-planes

VUV photons propagate and are shifted into VIS photons

Digitized signals from the wires are collected [time of the wire pulses gives the drift coordinate of the track and amplitude gives the deposited charge].

Scintillation light signals from PMTs give event timing (t_0)

LArTPC at work



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VUV photons propagate and are shifted into VIS photons

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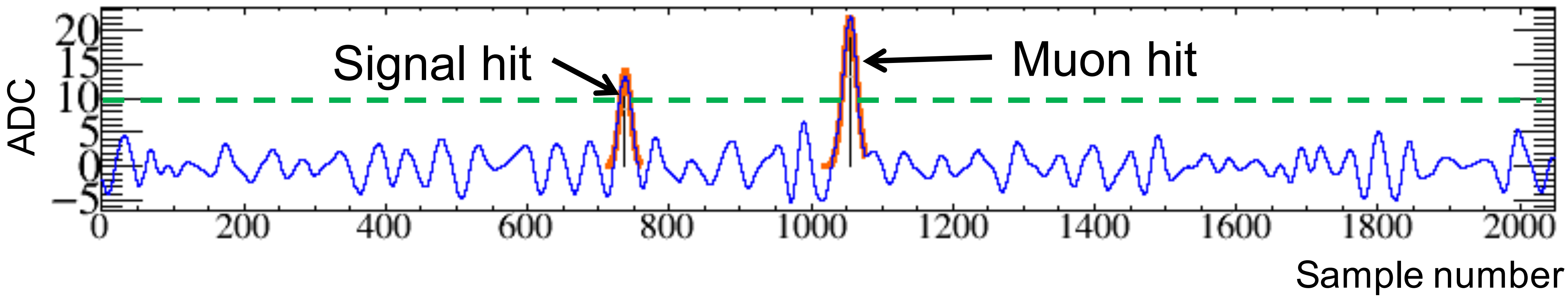
- Multiple 2D and the 3D reconstruction of charged particles tracks ⇒ **imaging**
- Total charge proportional to the deposited Energy ⇒ **calorimetry**
- dE/dx along the track ⇒ **Particle Identification**

Scintillation light signals from PMTs give event timing (t_0)

Hit Reconstruction Cuts

- Threshold = 10 ADC = 8500 electrons = **200 keV**



- Upper limit cut (~1.2 MeV = 60 ADC) removes hits possibly due to protons.
- Fiducial cut removes activity near corners (short wires) and cathode and anode (6 cm).
- Track cut removes high energy activity (e.g. muon)
- “Cone cut” removes activity near tracks (e.g. delta rays)

Supernova Neutrinos

Interactions in argon

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

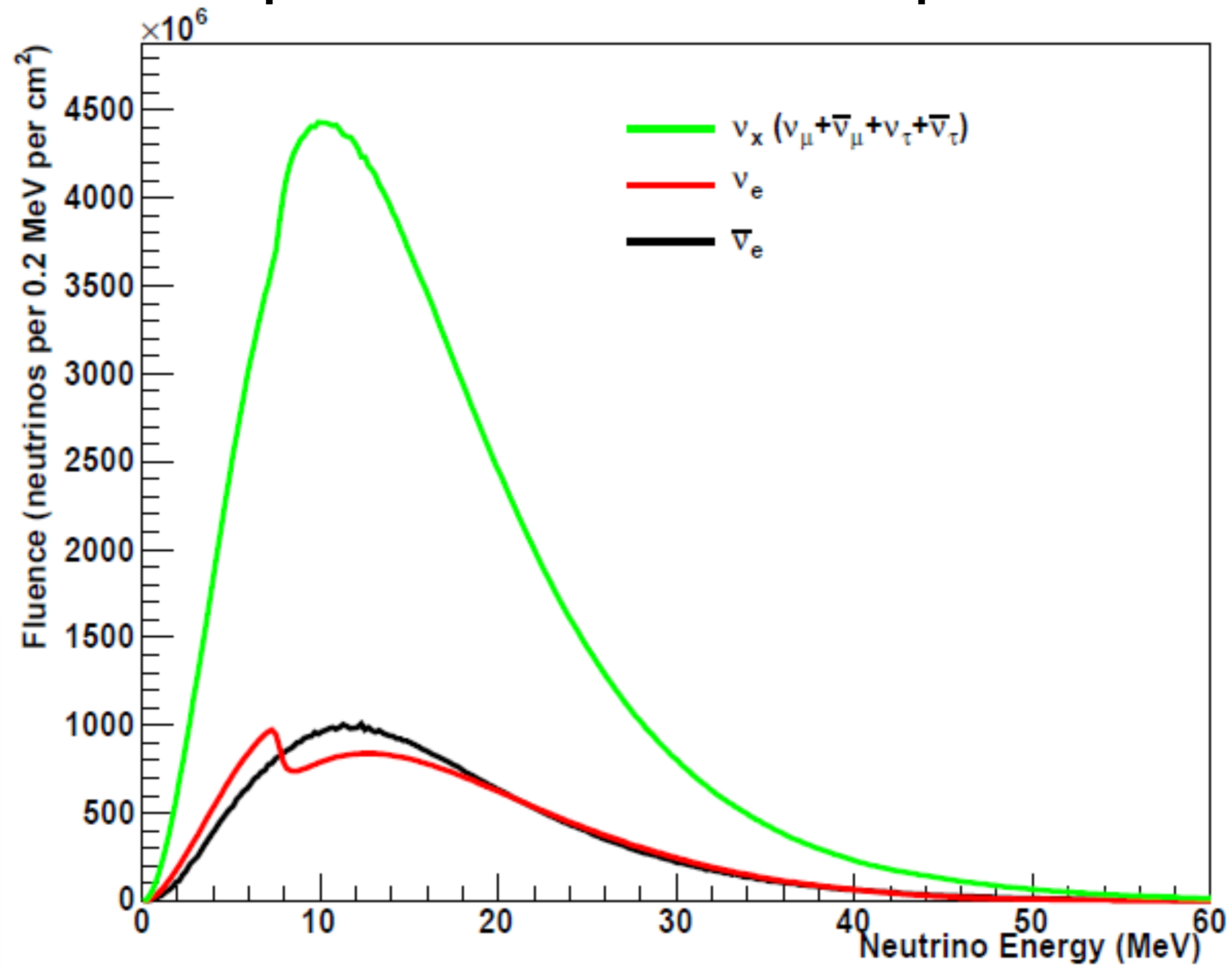
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

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

$\rightarrow \gamma$'s

LArTPCs are sensitive to these reactions, which will tell us more about what's happening inside a supernova.

Supernova Neutrino Spectrum



Nucl. Phys. Proc. Suppl., 91:331-337, 2001

The detection and study of supernova neutrinos is one of the main goals of the DUNE (LArTPC) experiment.

Solar Neutrinos

Interactions in argon

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

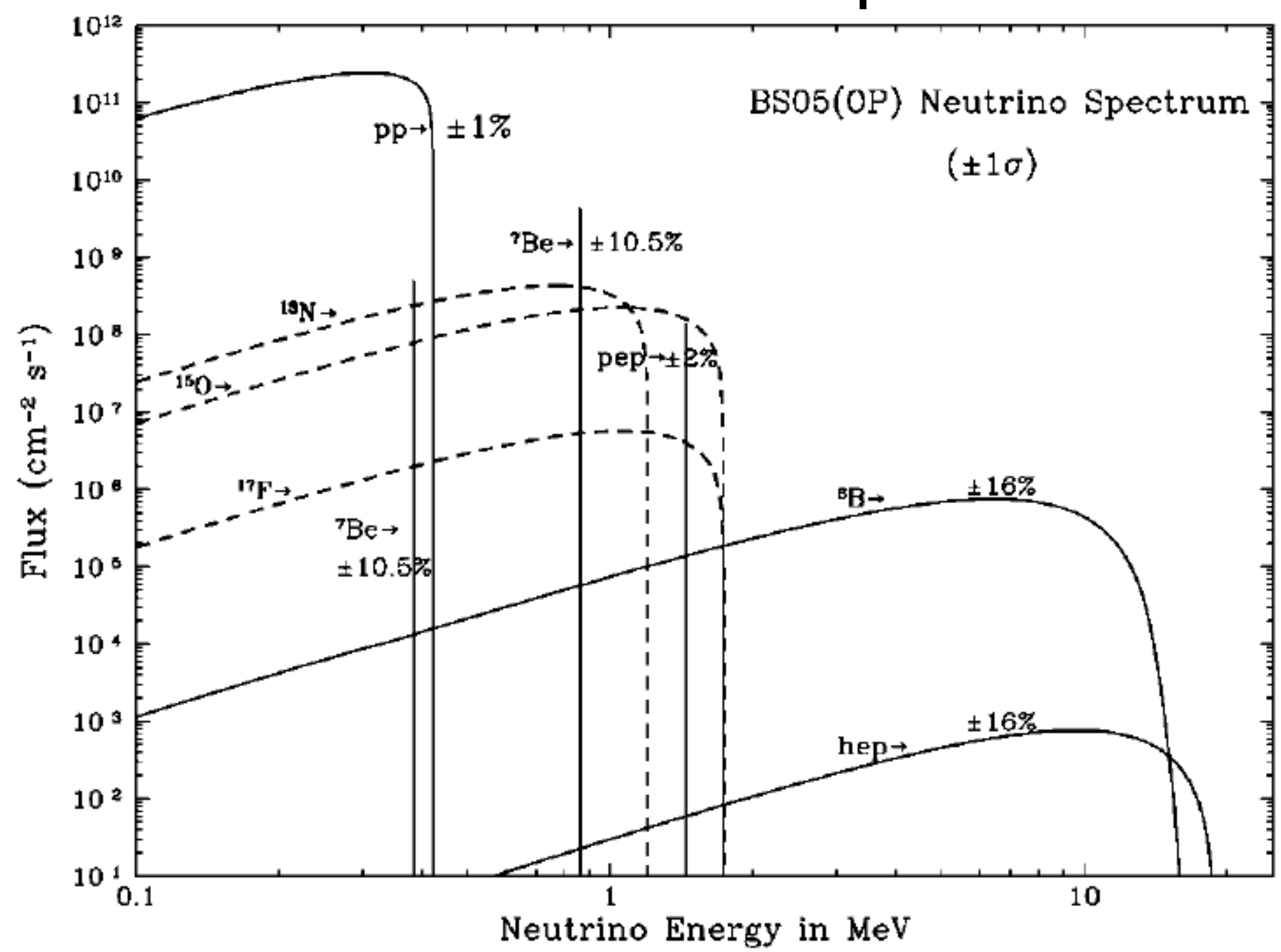
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

$\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad \llcorner\!\!\rightarrow \gamma$'s

"A precise gamma-ray energy reconstruction would aid neutrino energy reconstruction, and help signal and background separation."

arXiv: 1811.07912

Solar Neutrino Spectrum



Astrophys. J., 621:L85-L88, 2005

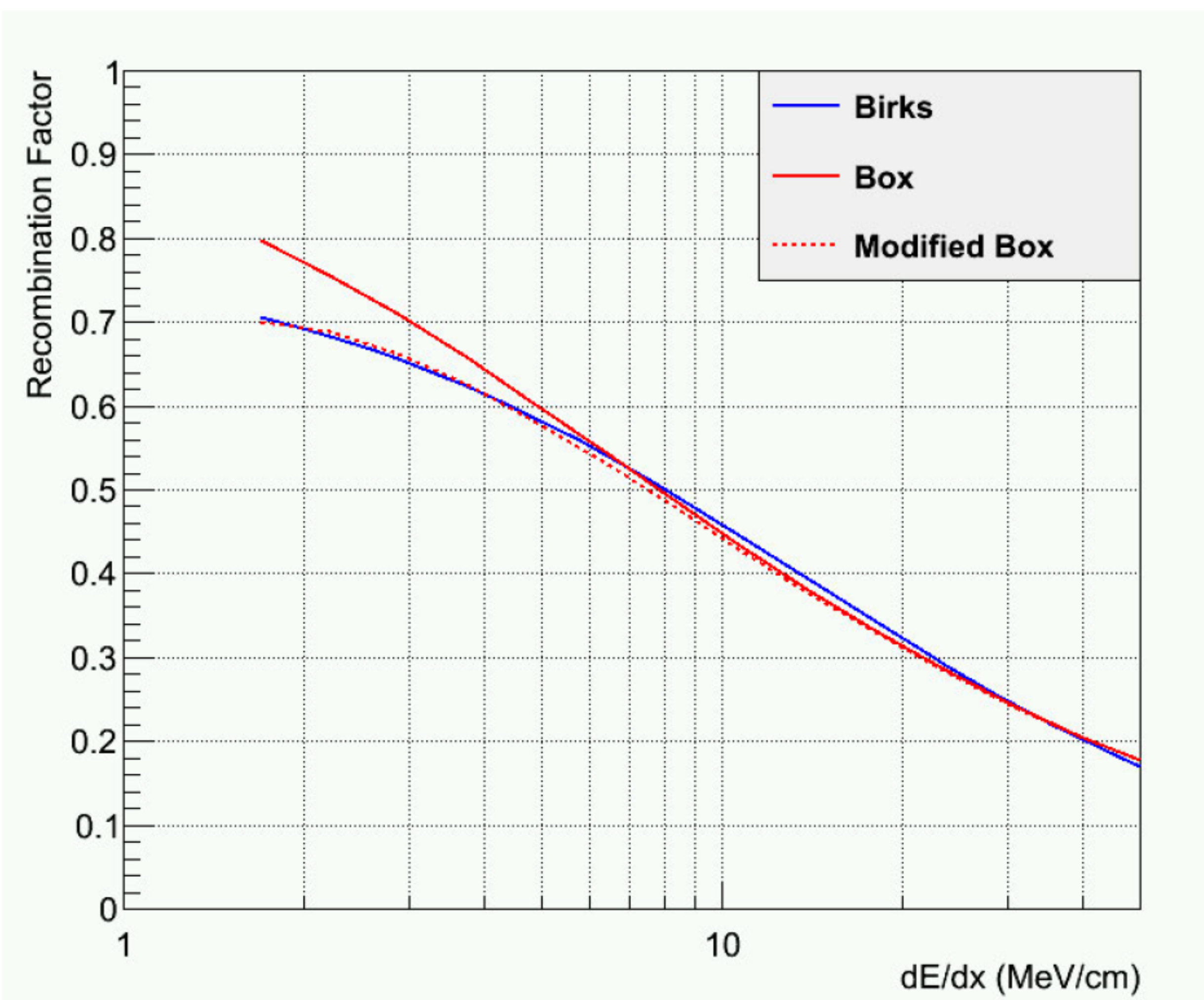
Expanding the DUNE physics program to the detection and study of solar neutrinos is currently being considered.

Calorimetric Reconstruction

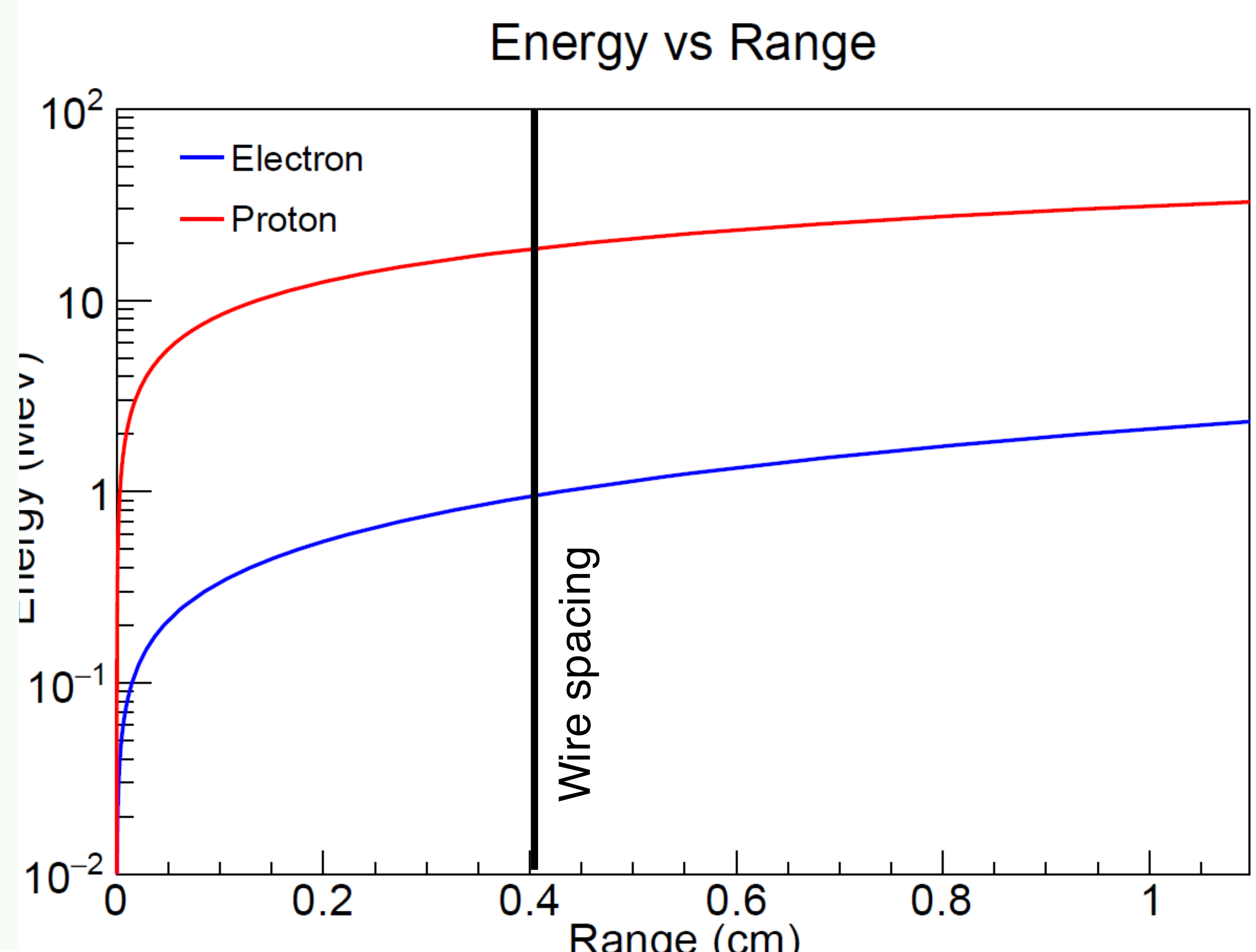
1. Electronic calibration factor (ADC → number of electrons)
2. Lifetime correction (electron attachment to impurities in LAr)
3. Recombination of ionized electrons to Ar^+

   Depends on dE/dx (amount of energy deposited per unit length)

   Low-energy electrons travel short distances.



JINST **8** P08005 (2013)



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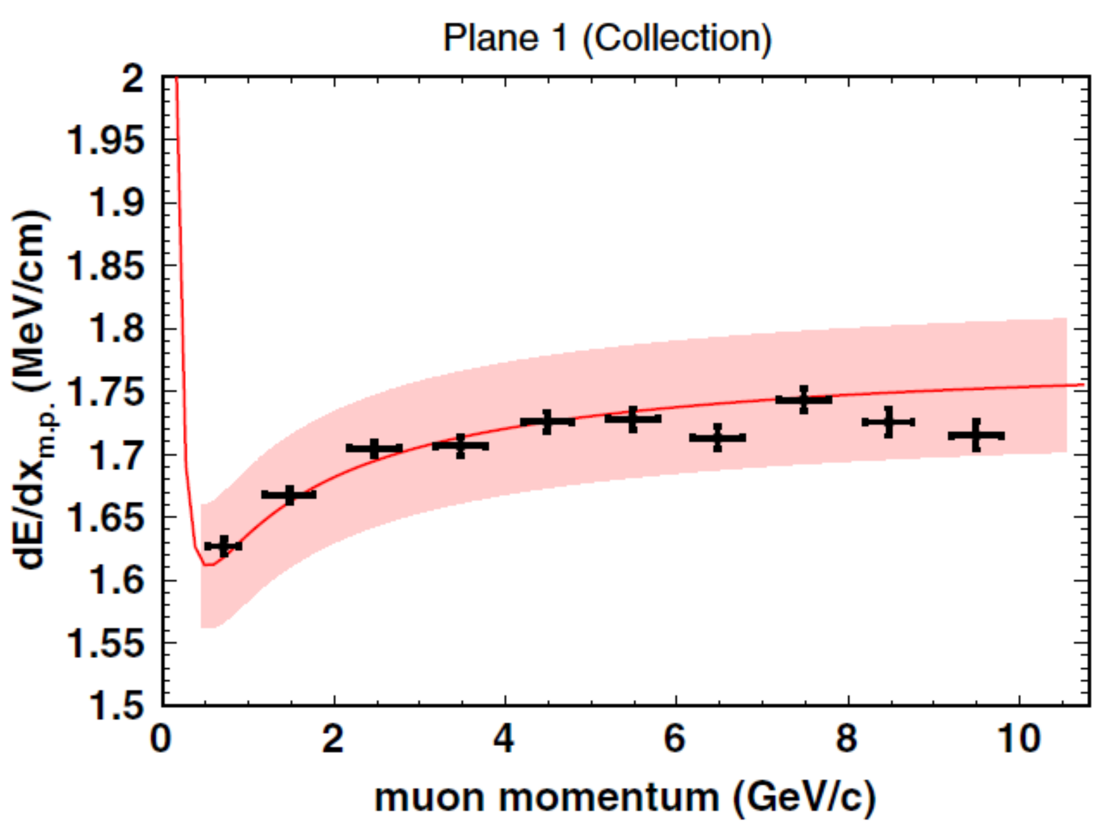
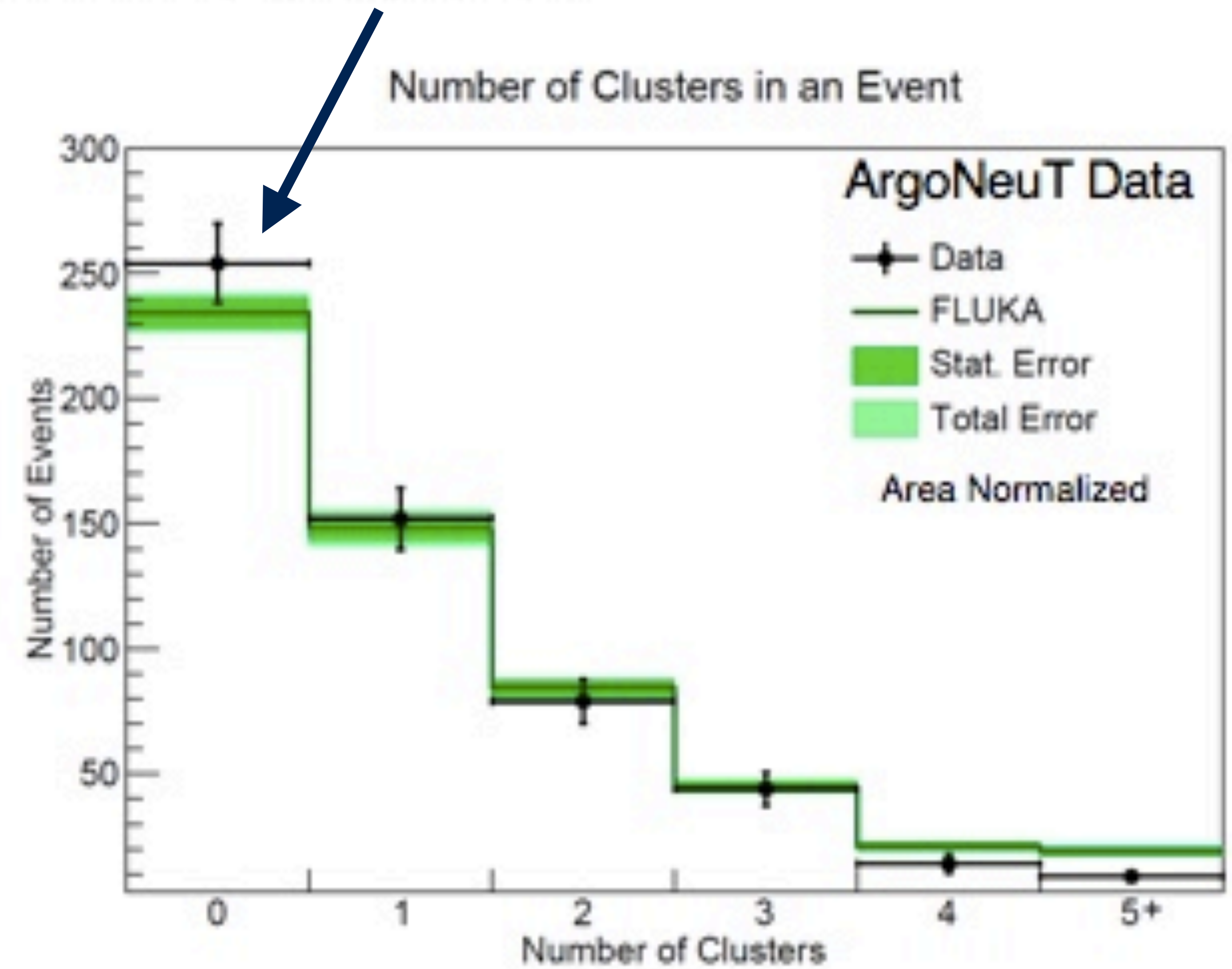
Systematic Uncertainties

- Calorimetric calibration constants: 3% uncertainty.
- Electron lifetime correction
  - Variation from run to run in data.
  - Accounted for by simulating with ±25%change in electron lifetimes. Actual variation is smaller.
- Recombination corrections
  - accounted for by using different models (modified vs unmodified Box model)



Events Without Low Energy Activity

- Why are there so many events with no clusters?
- 24% of final-state nuclei are in the ground state.
  - No de-excitation photons
- ArgoNeuT is small.
  - 90 cm at its longest dimension
  - Radiation length = 14 cm
  - Neutron interaction length: 90 cm
- A larger detector will catch more photons.



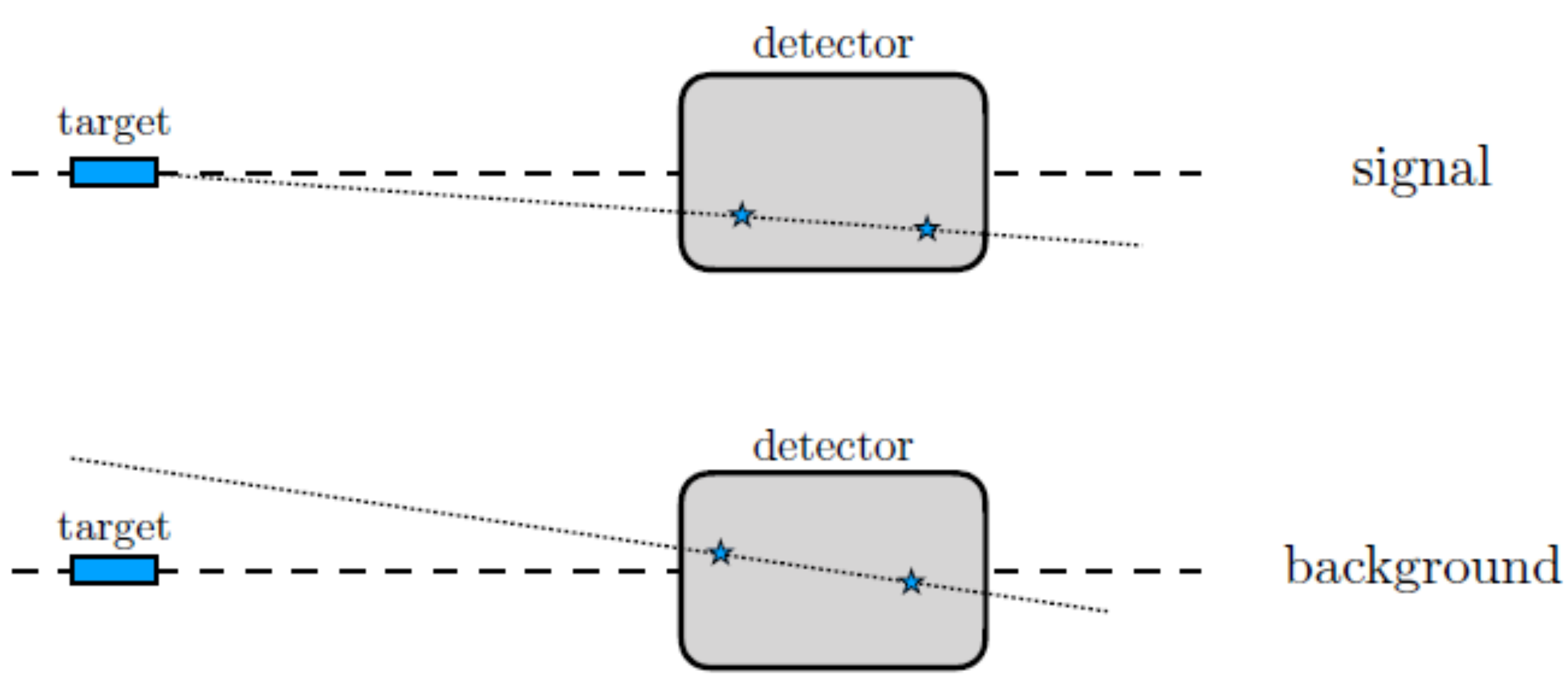
Contributions by Photon Source

Metric	De-excitation	Neutron	Total
Number of hits per event	0.48	0.98	1.46
Number of clusters per event	0.35	0.77	1.12
Average event energy (MeV)	0.41	0.76	1.17
Average cluster energy (MeV)	1.18	0.98	1.04
Average hit energy (MeV)	0.86	0.77	0.80
Average cluster distance from	15.7	23.4	21.0

Millicharged Particles in ArgoNeuT

- The demonstrated capability to detect MeV scale electron recoils enables a search for new physics.
- Millicharged particles: particles with charges 1/10th to 1/10000th of an electron.
- Millicharged particles tend to scatter at low recoil $\frac{\partial \sigma}{\partial E_r} \propto E_r^{-2}$
- Having a low threshold allows us to create a good measurement.

to reduce backgrounds: search for "double-hit events" that are aligned with the proton target.



Millicharged Particles in ArgoNeuT

Expected reach with existing ArgoNeuT data:

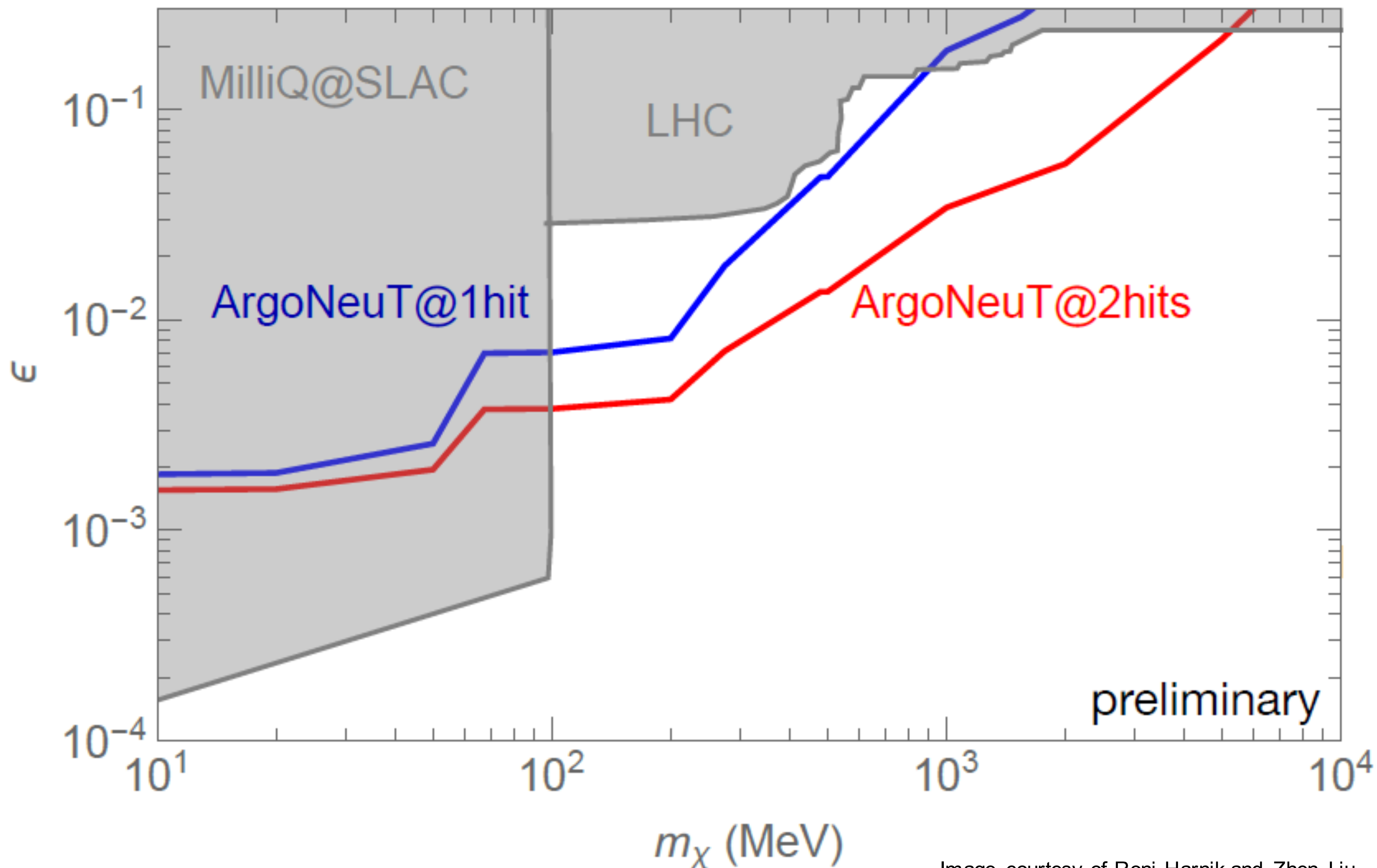
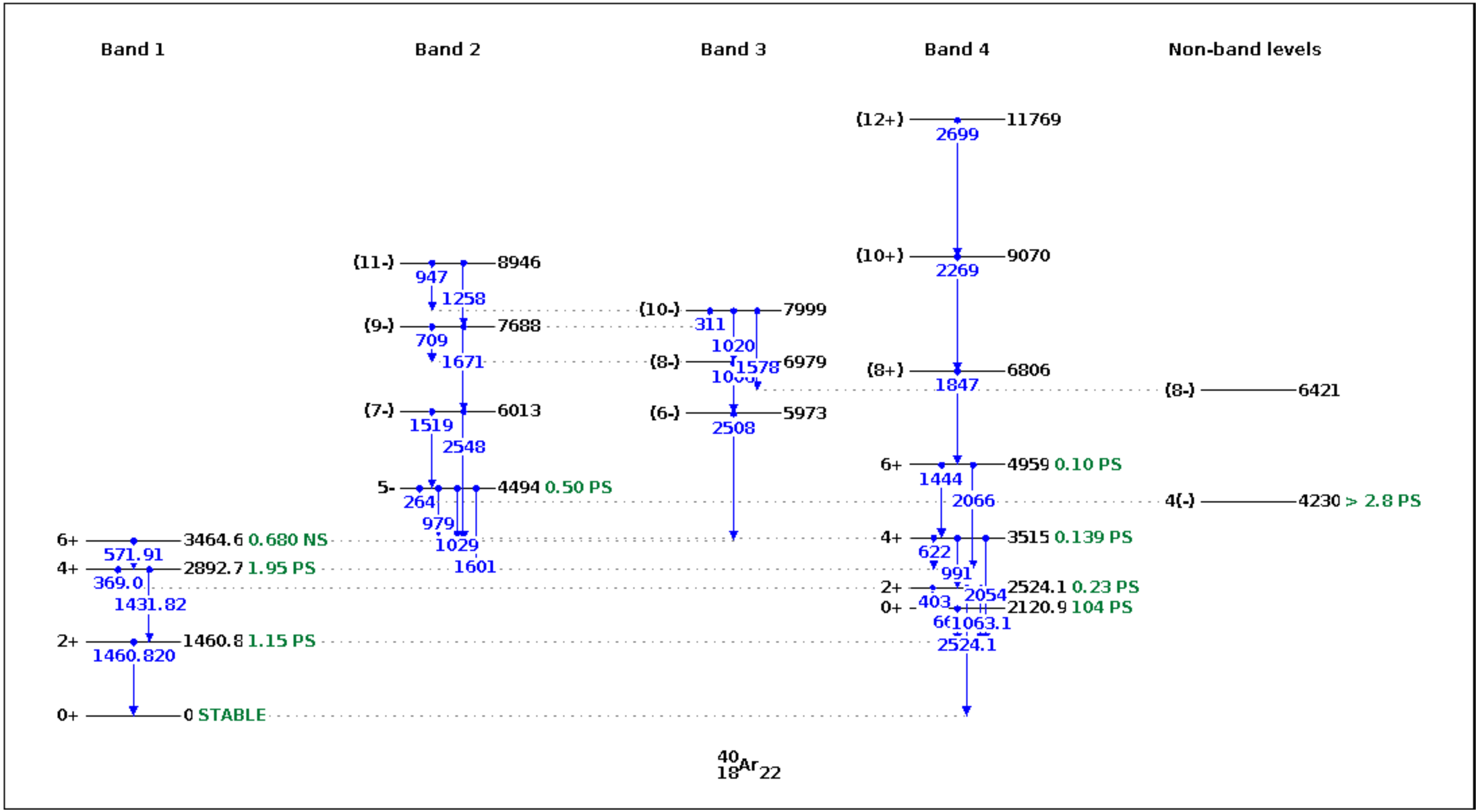


Image courtesy of Roni Harnik and Zhen Liu

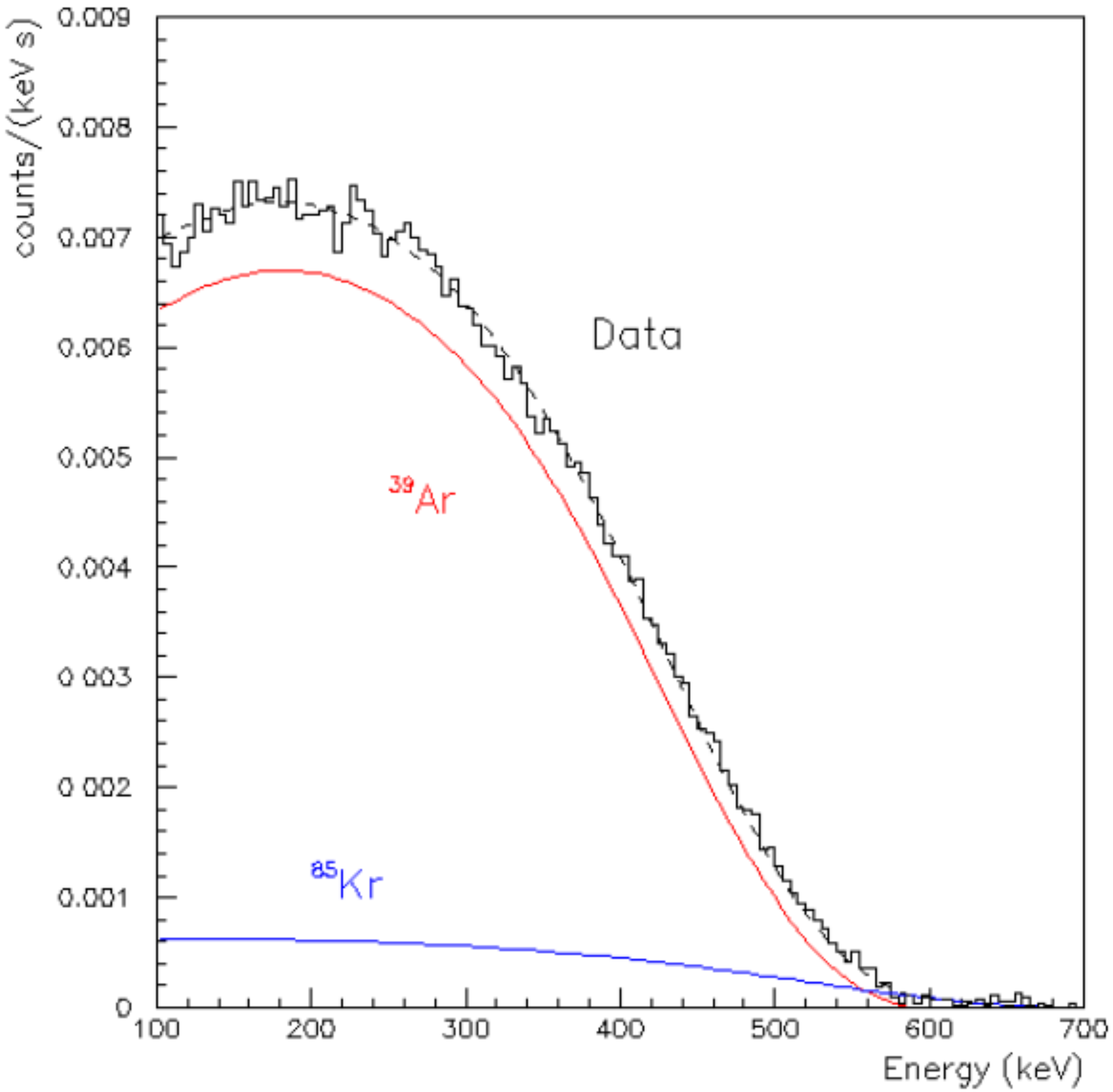
An ArgoNeuT analysis is underway.

Energy Levels for ^{40}Ar



Source: NNDC. For more levels, see https://www.nndc.bnl.gov/chart/chartNuc.jsp

^{39}Ar decay spectrum



arXiv:astro-ph/0603131

^{39}Ar specific activity:
1.01±0.08 Bq/kg of natural Ar