Scintillation and Cherenkov Light Separation in a Liquid Argon Detector

New results from the Coherent CAPTAIN-Mills Experiment

* Presenting new results! arXiv:2507.08886
(accepted in *Physical Review Letters*)

Next Generation Nucleon Decay and Neutrino Detectors Workshop
3 October 2025

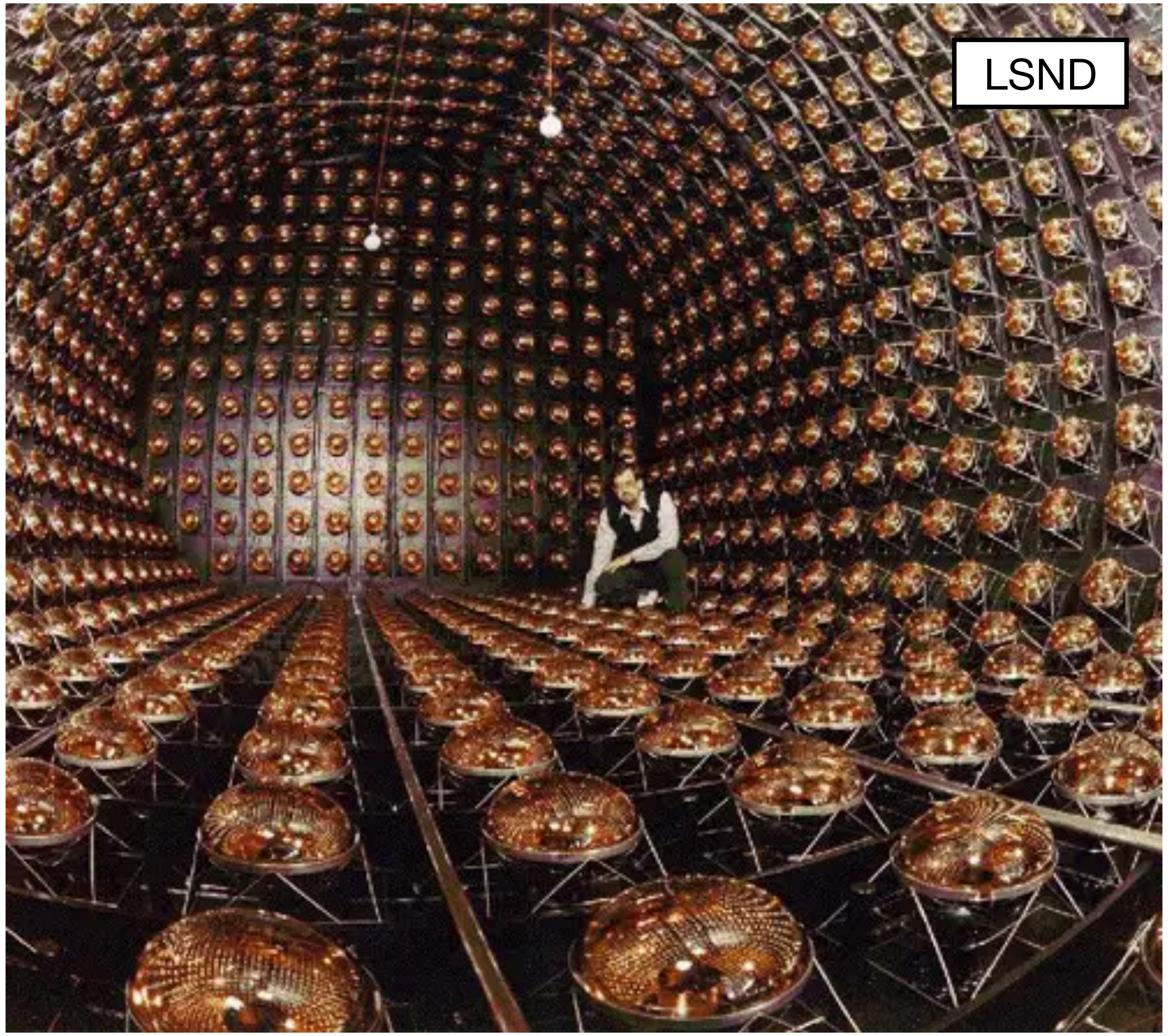
Darcy Newmark ***on behalf of the CCM Collaboration***
dnewmark@mit.edu

1. Light Collection Detectors
2. Coherent CAPTAIN-Mills Experiment
3. CCM as a Hybrid Detector
4. *New results* — Cherenkov light

1. Light Collection Detectors

Light Collection Detectors

- Neutrinos ***rarely interact***, requires detectors with large target masses
- One of the easiest ways to make a very large and sensitive detector is to instrument a ***large volume of optically-transparent material with photo-sensors***
- Typically — bulk material dictates if it's a scintillation or Cherenkov detector

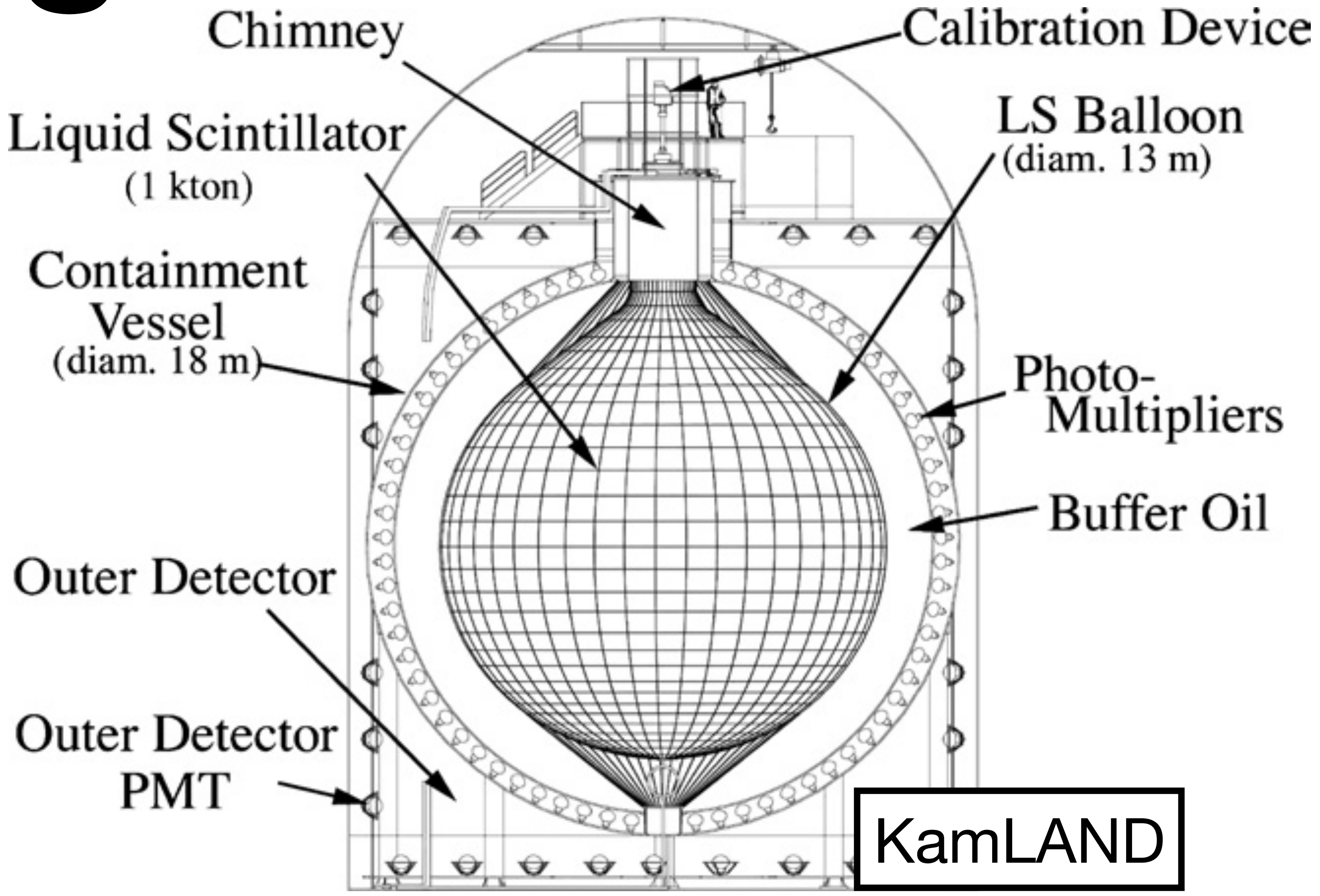


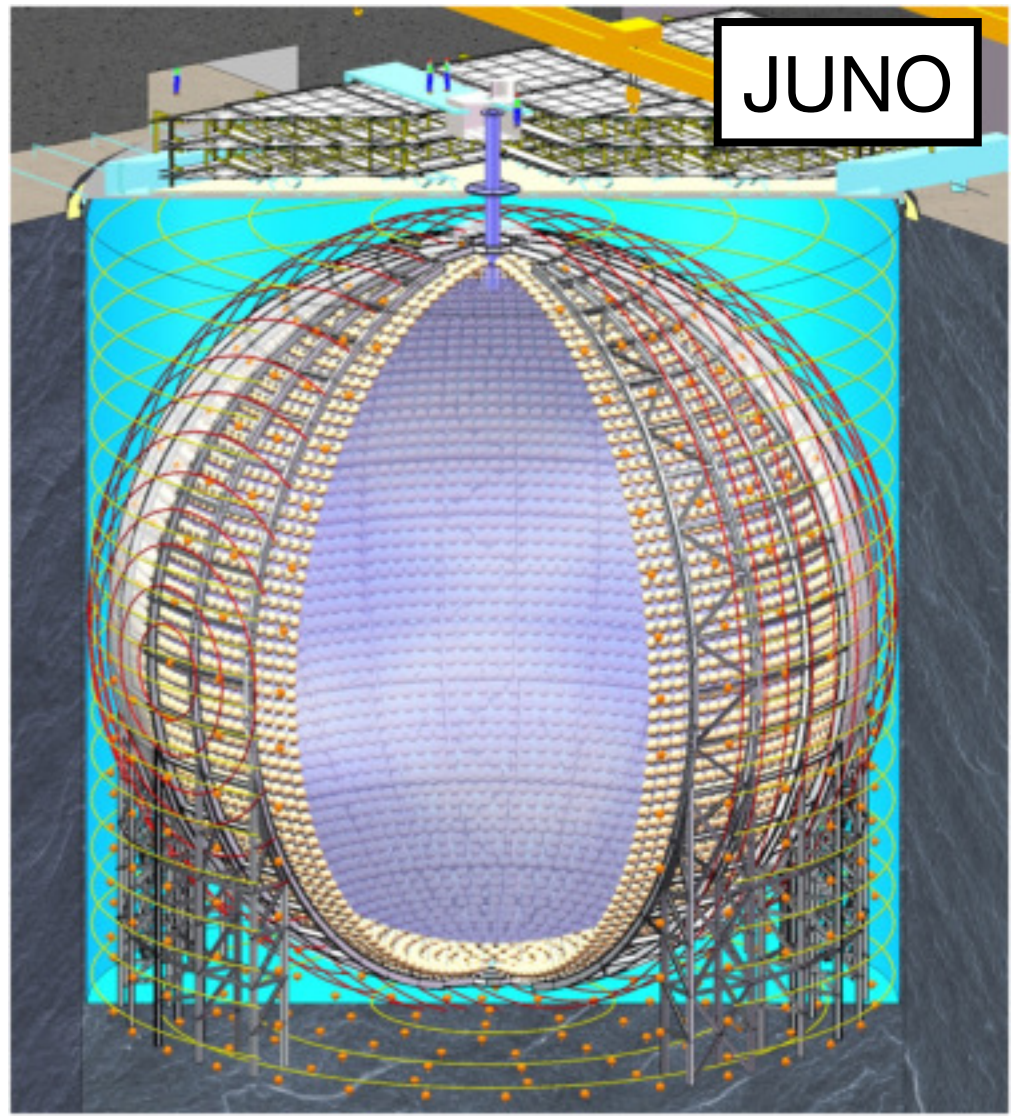
Scintillation vs Cherenkov Light

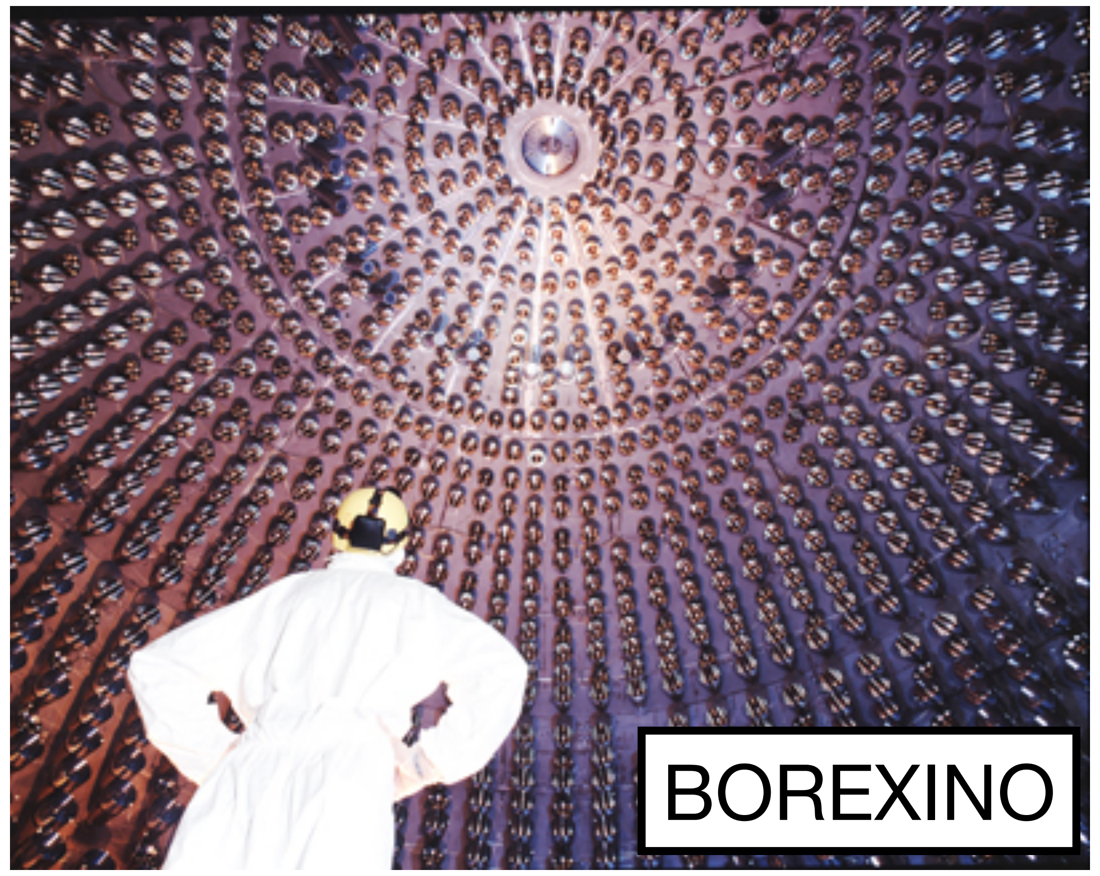
Quality	Scintillation Light	Cherenkov Light
Intensity	~10^4 photons/MeV	~ 10^2 photons/MeV
Direction	Isotropic	Directional
Timing	Typically ~nsec	Prompt (psec start)
Photon Wavelength	Narrow emission spectrum	$dN/d\lambda \propto \lambda^{-2}$

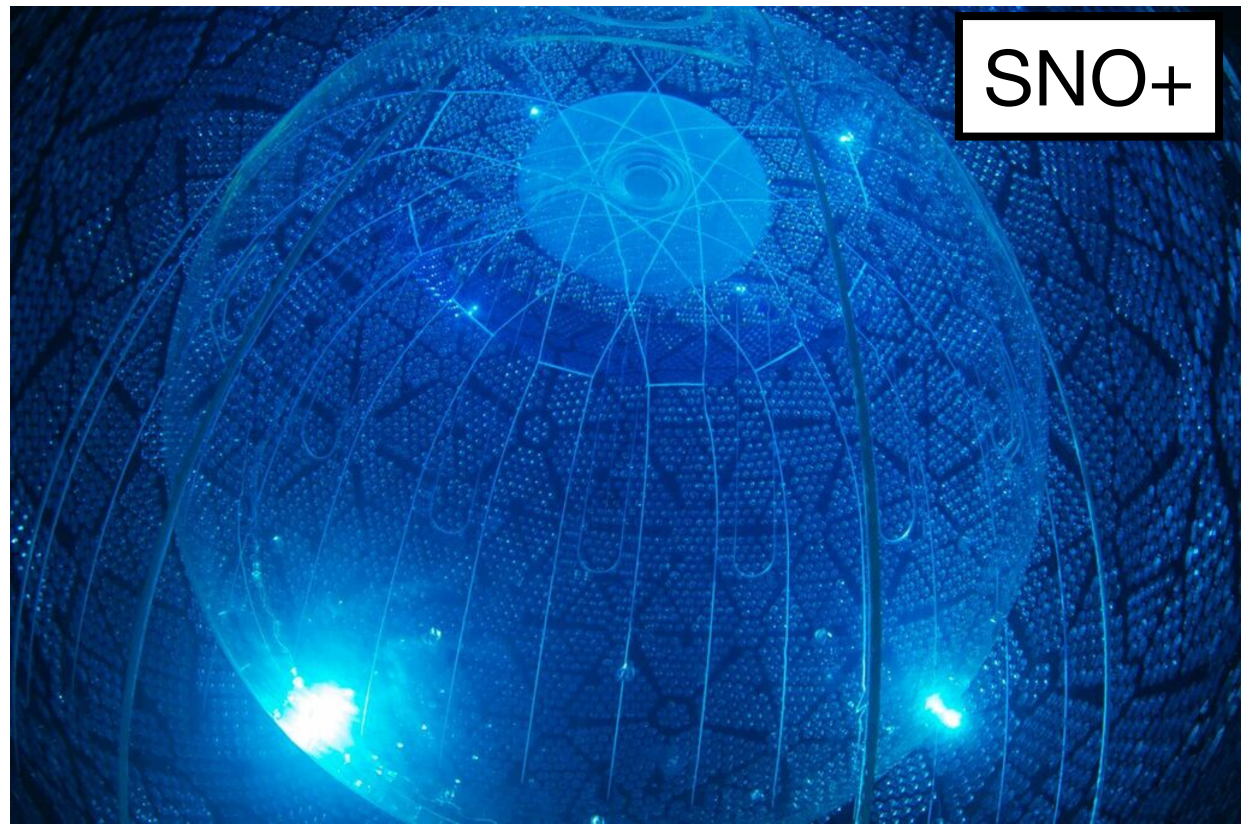
Scintillation Detectors

- Utilize high-yield scintillators and wavelength shifter
- Examples: KamLAND, JUNO, SNO+*, BOREXINO*
- Pros: high light yields allow for very good energy resolution, low energy thresholds
- Cons: no directional information, limited PID



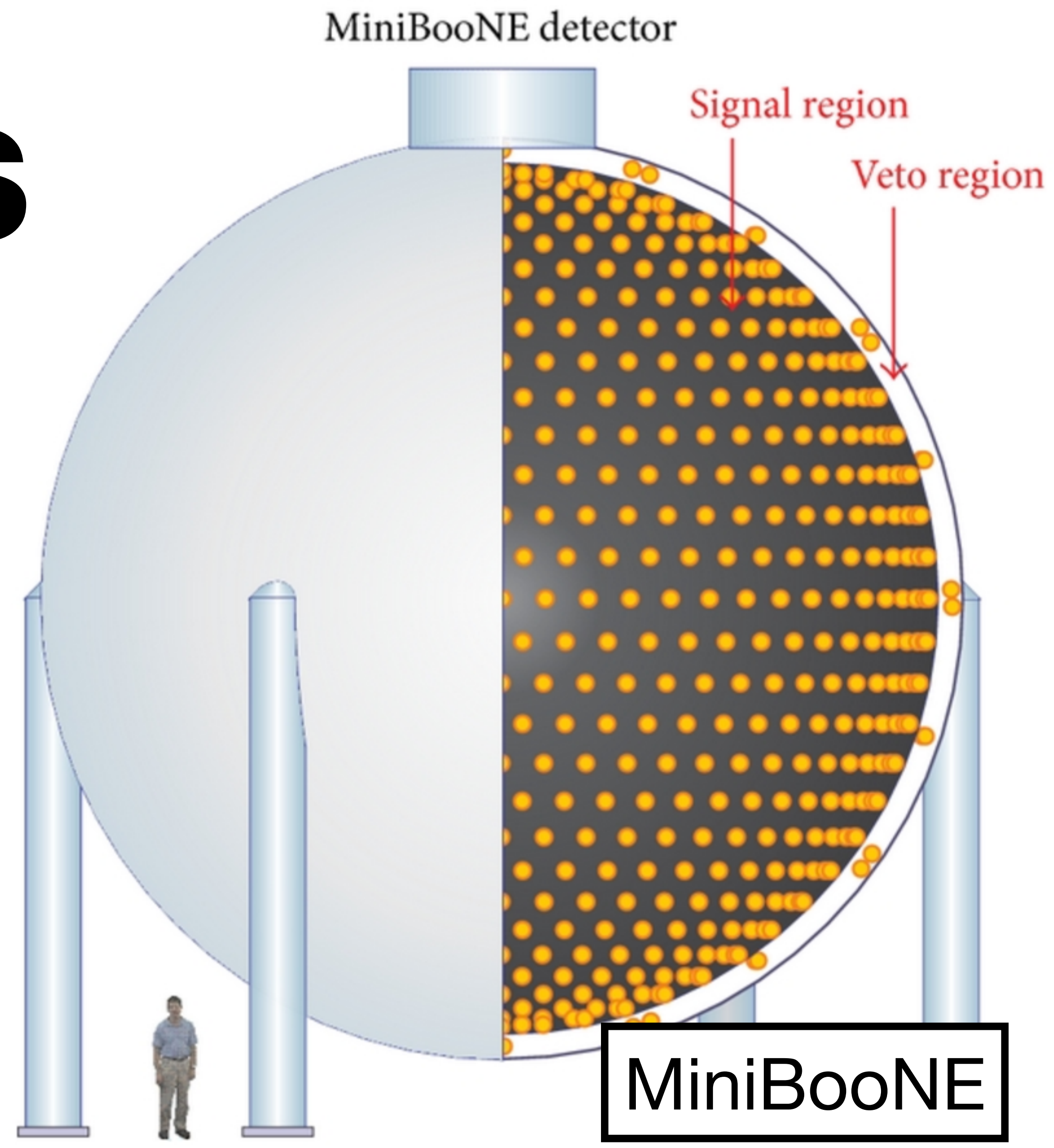


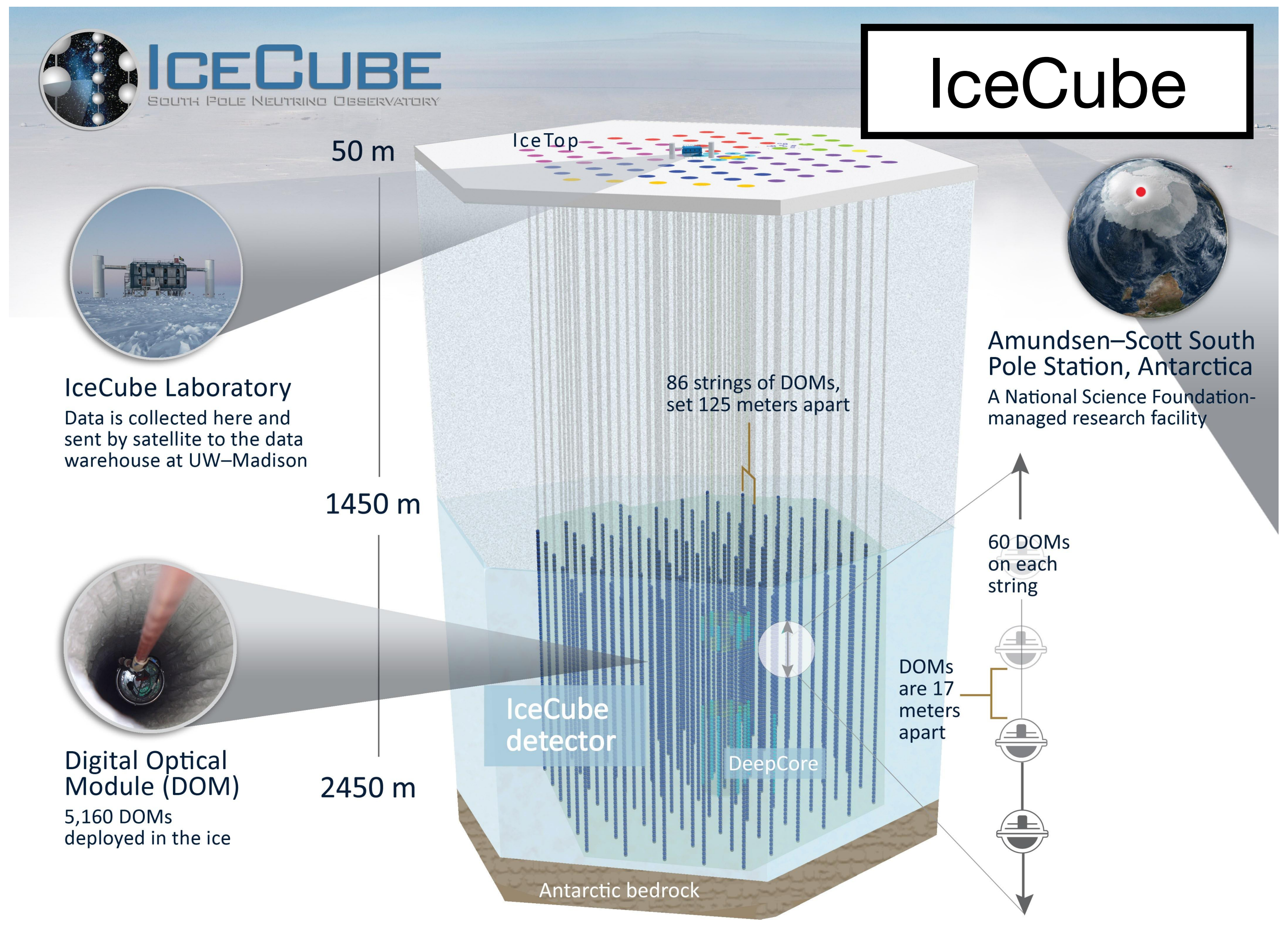


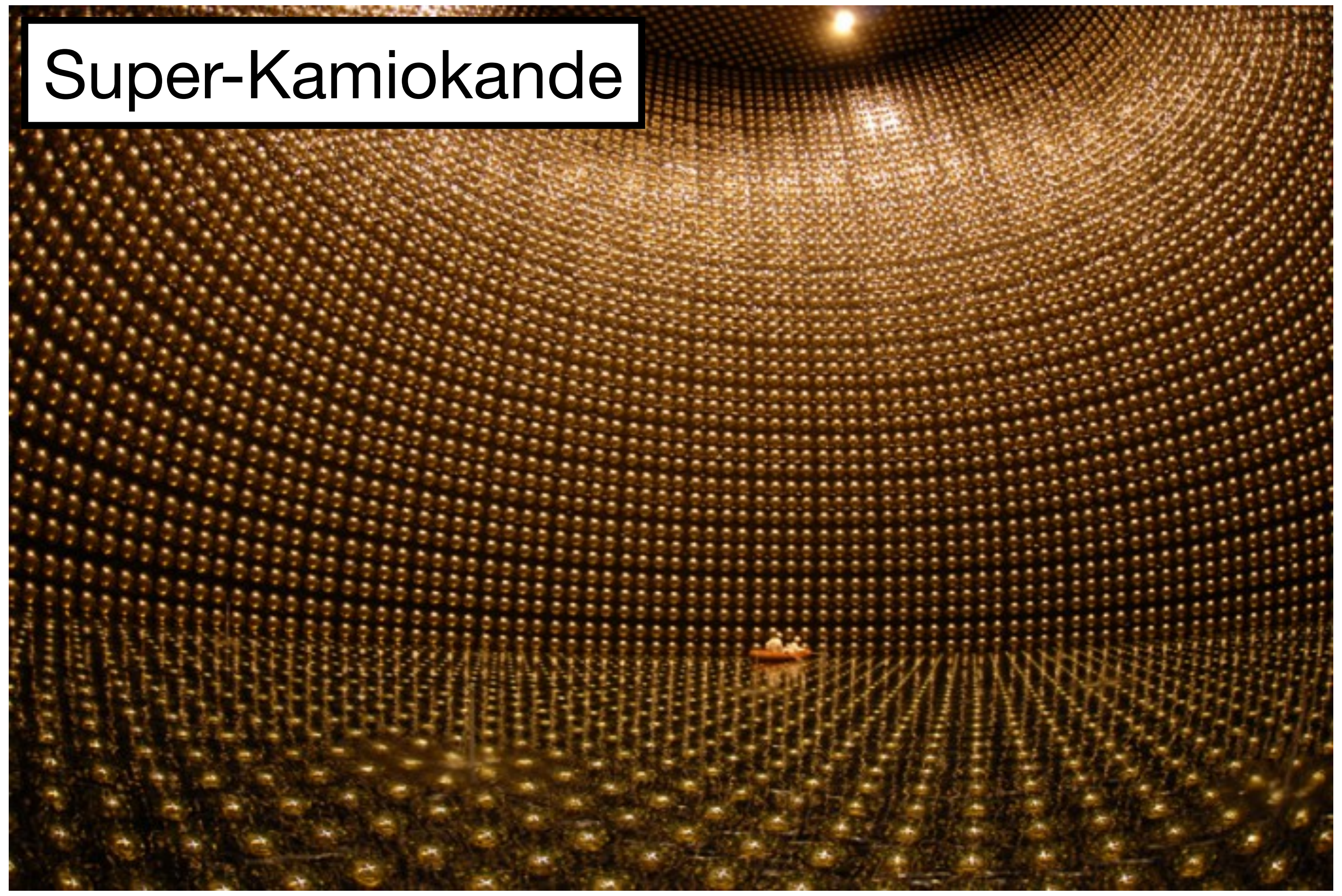


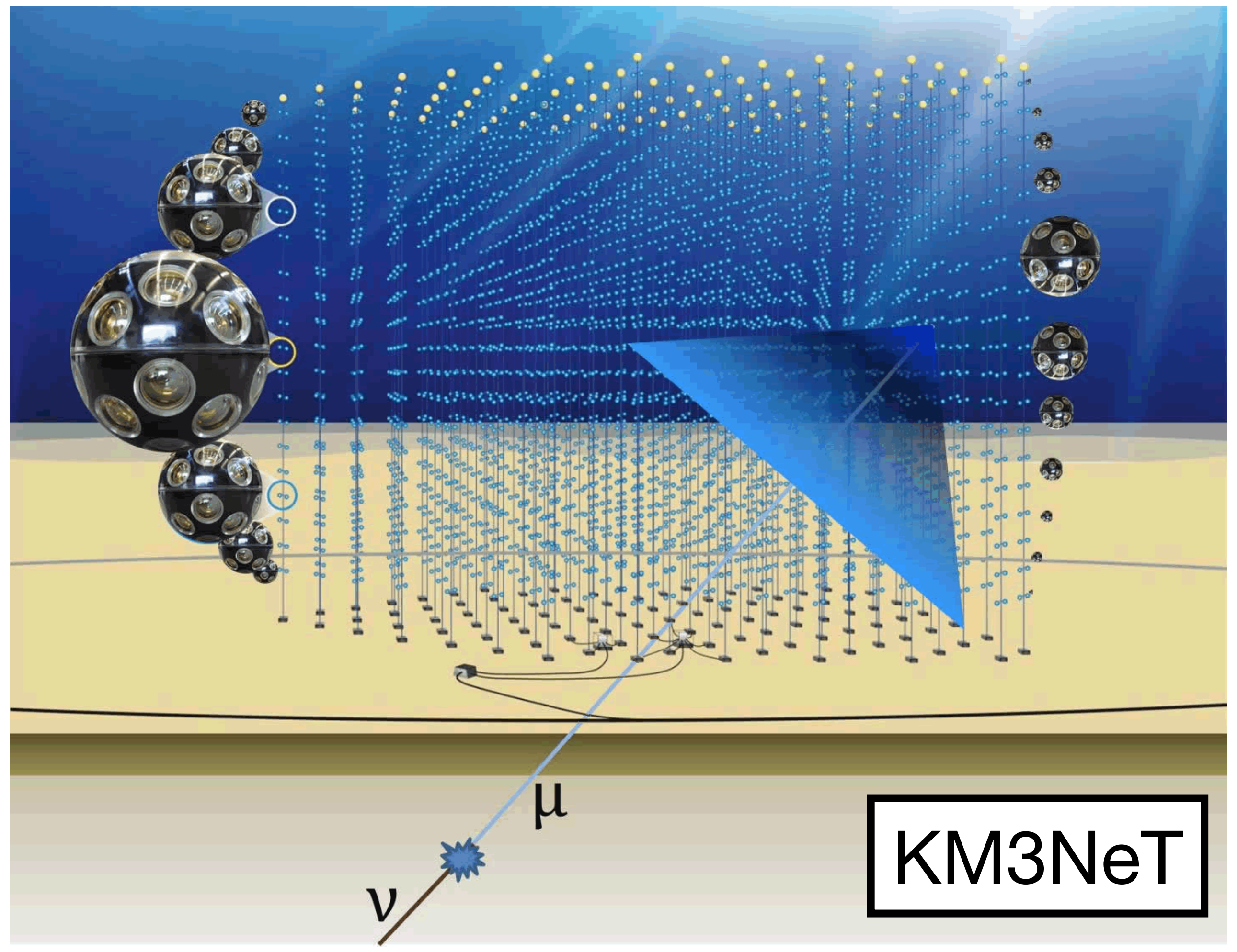
Cherenkov Detectors

- Typically use water (opaque to it’s own scintillation light) to reconstruct only Cherenkov radiation
- Examples: MiniBooNE, IceCube, KM3NeT, Super-Kamiokande
- <u>Pros:</u> can reconstruct particle direction, PID through event topology
- <u>Cons:</u> worse energy resolution, higher energy threshold



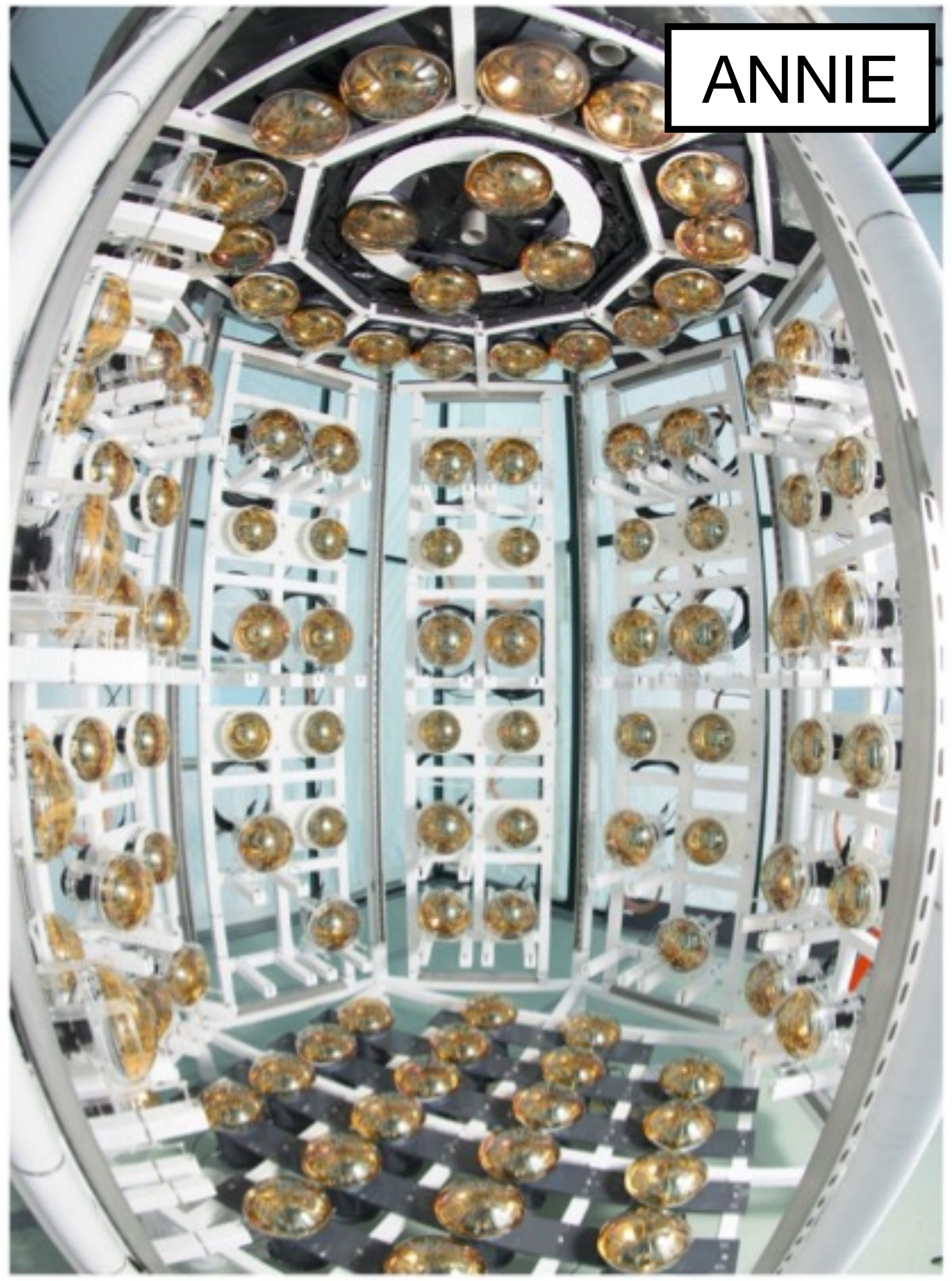


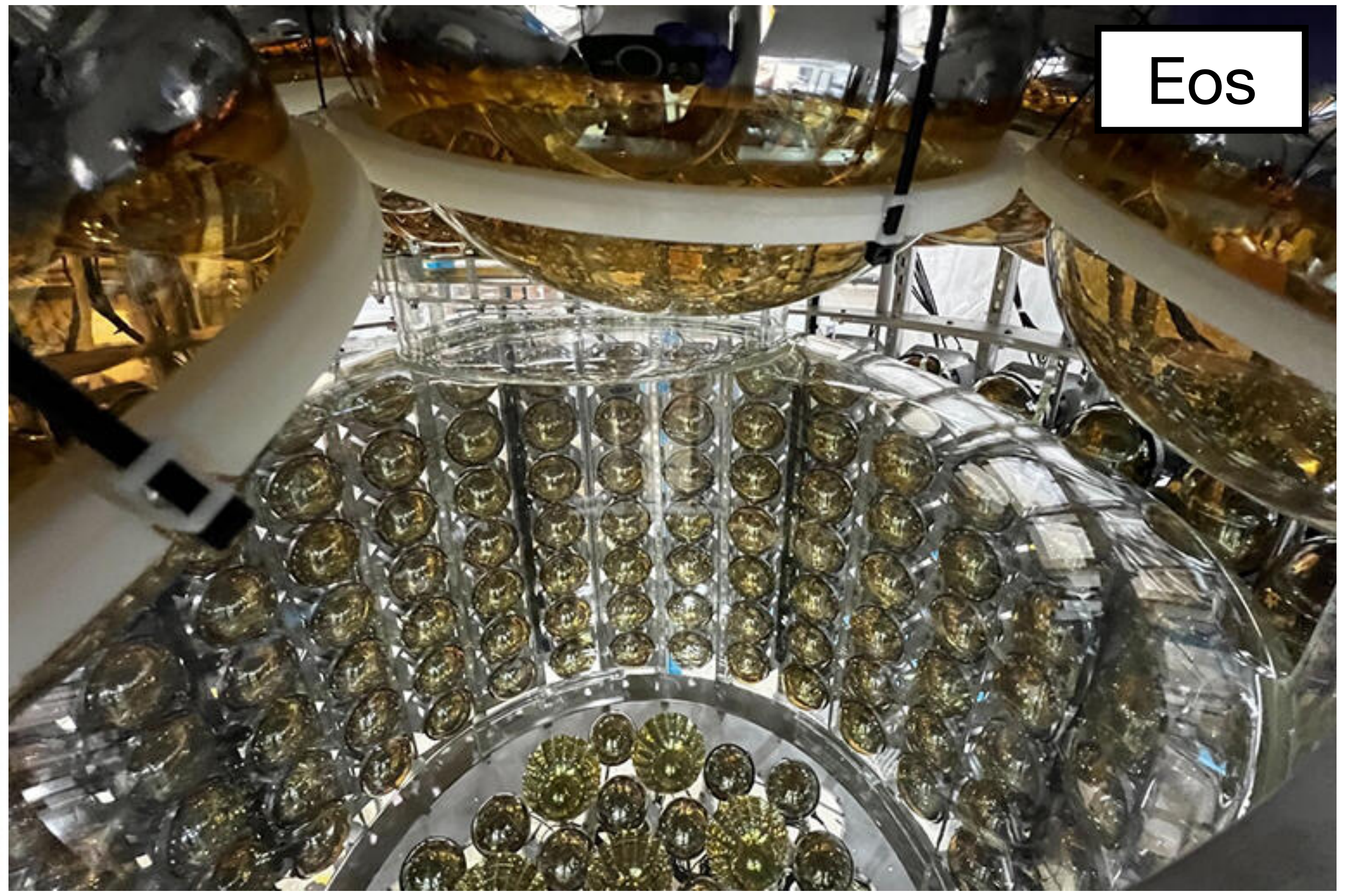


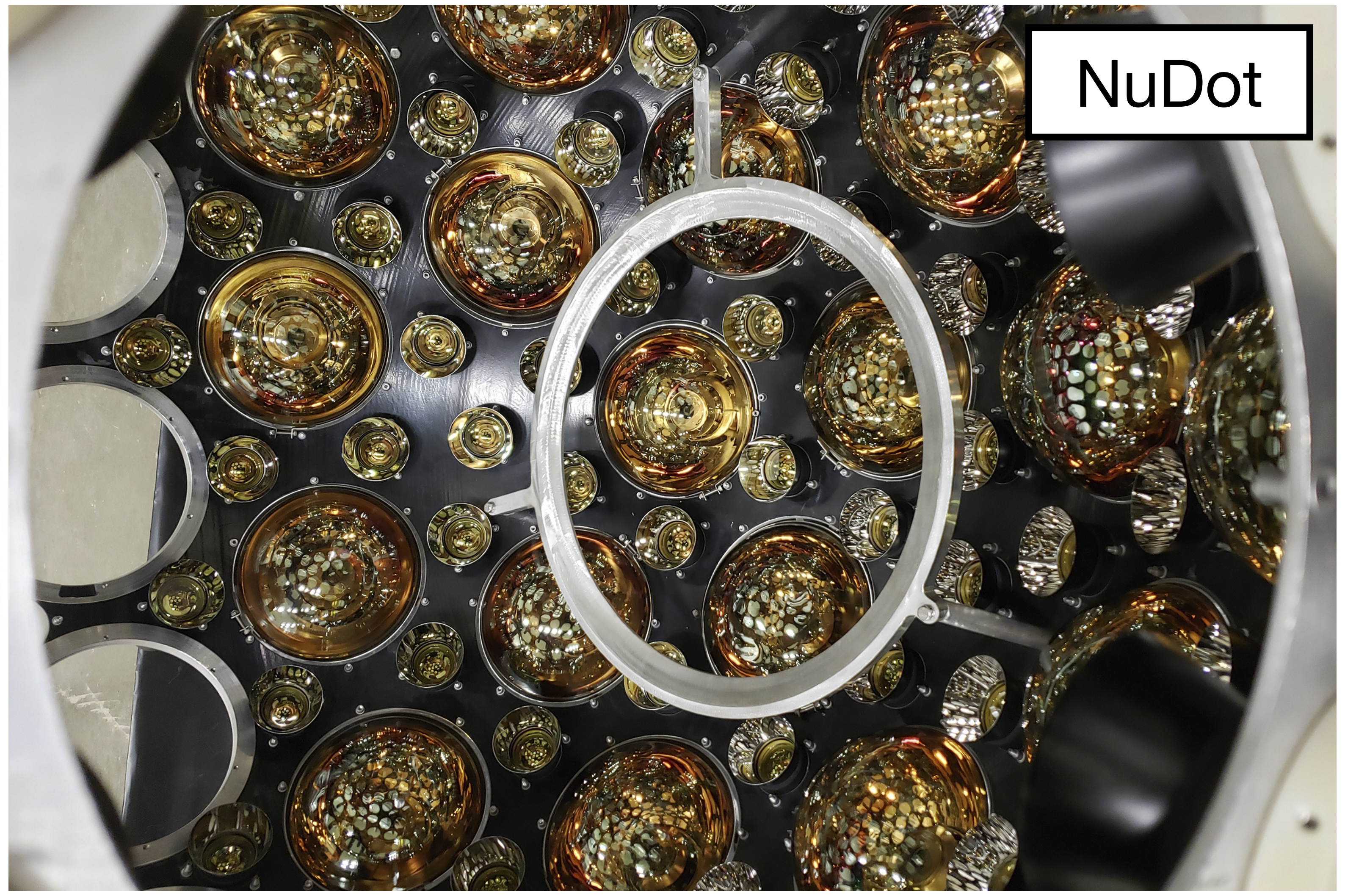


Hybrid Detectors

- Hybrid detectors can resolve ***both*** scintillation and Cherenkov signals
- Examples: Eos, SNO+, Borexino, ANNIE, NuDot, CCM
- Pros: excellent energy resolution/ low threshold ***and*** can reconstruct particle direction/PID
- Cons: need very fast timing and/or wavelength discrimination —> ***experimentally difficult***



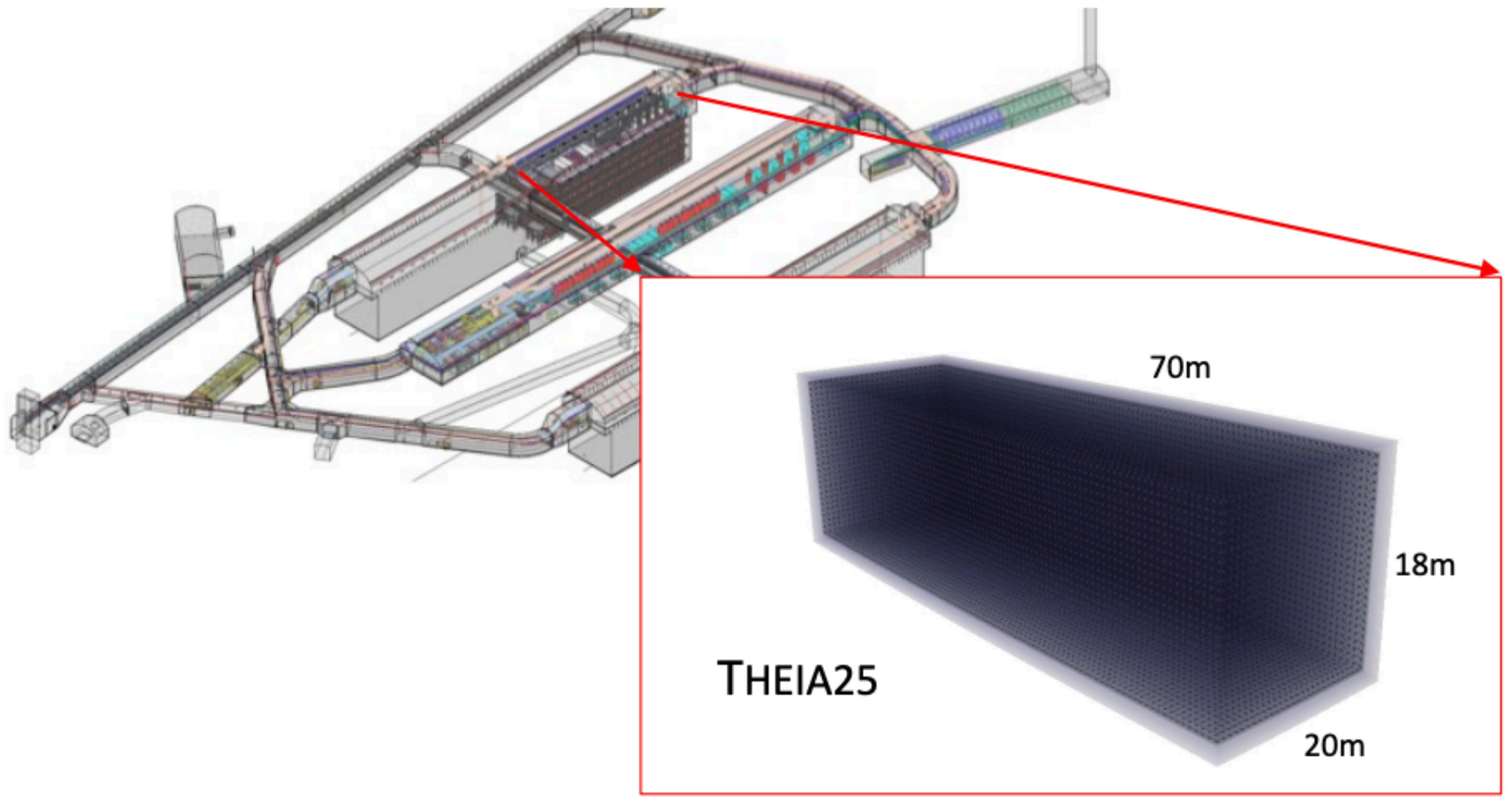


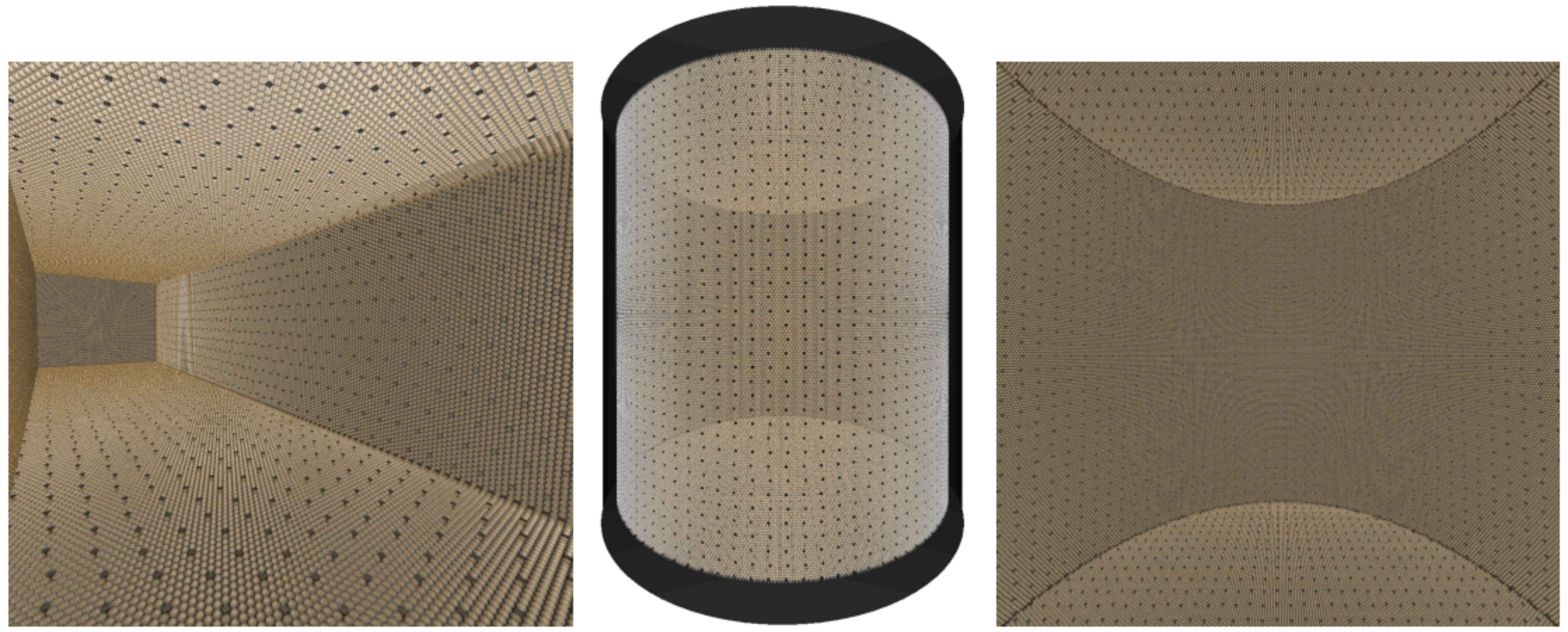


THEIA Detector

Checkout Logan's talk "The Theia physics program and the Eos demonstrator" Friday @ 2pm for more details!

- Combines developments in liquid scintillators, fast photo-detection, and spectral sorting to create an ***ultra-large hybrid optical detector***
- Physics program includes:
  - Solar neutrinos (CNO + ^{8}B)
  - Geoneutrinos
  - Supernovae neutrinos
  - Neutrinoless double beta decay
  - Long-baseline physics

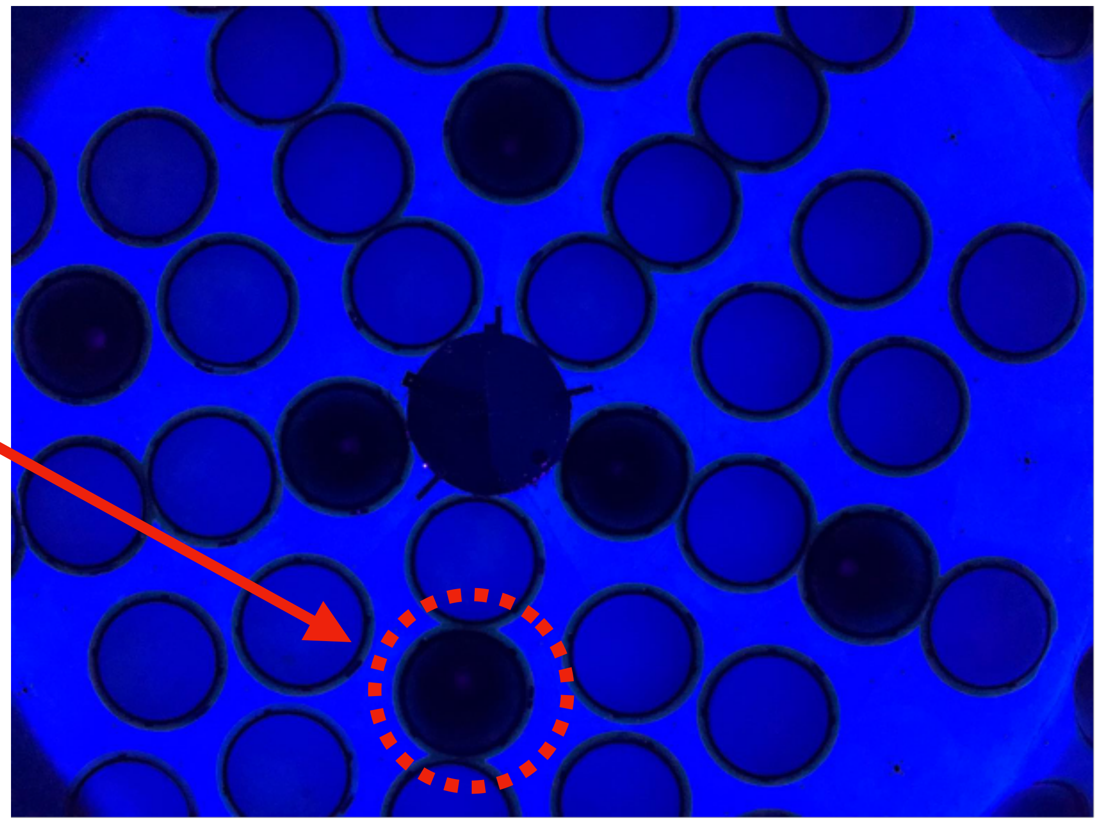


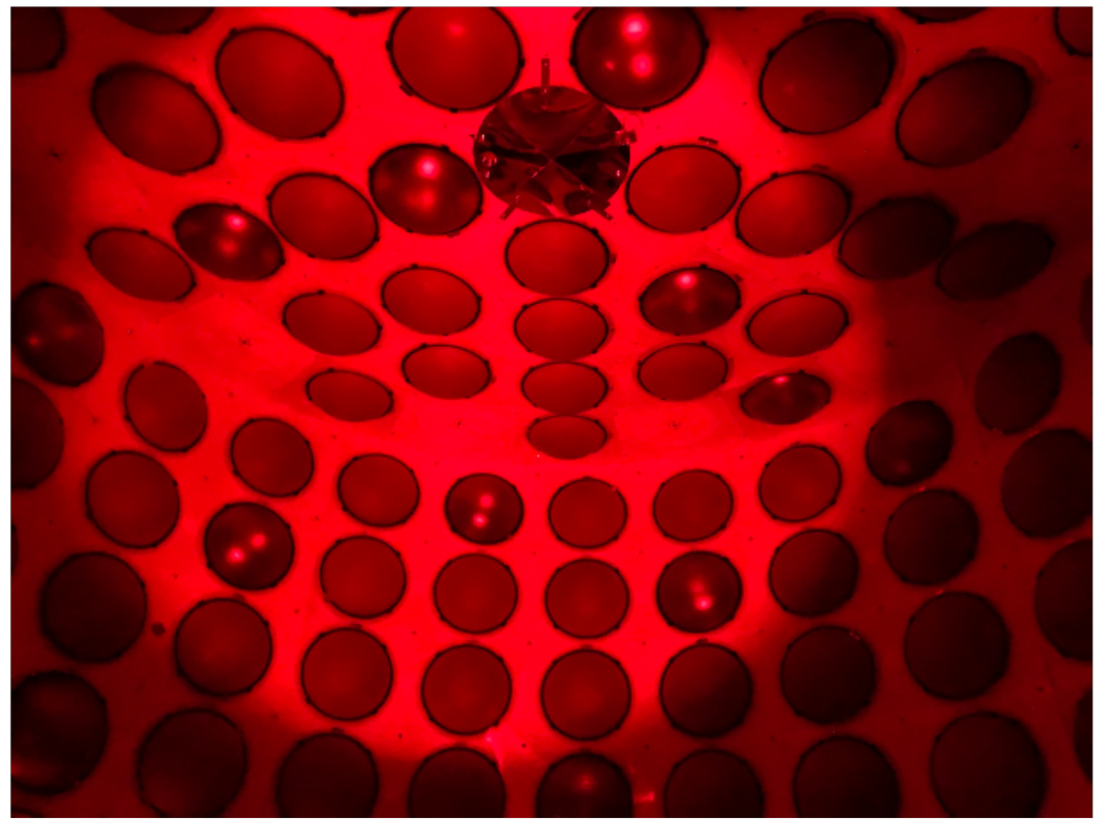


2. Coherent CAPTAIN-Mills Experiment

Coherent CAPTAIN-Mills Overview

- ***Running*** 10 ton LAr light collection detector at Los Alamos National Lab (πDAR source)
- **7 ton active LAr volume, 200 8” PMTs, 50% photocoverage**
- 160 PMTs are coated in tetraphenyl butadiene (TPB) ***(40 uncoated tubes)***
- TPB coated foils lining walls of detector





Timeline

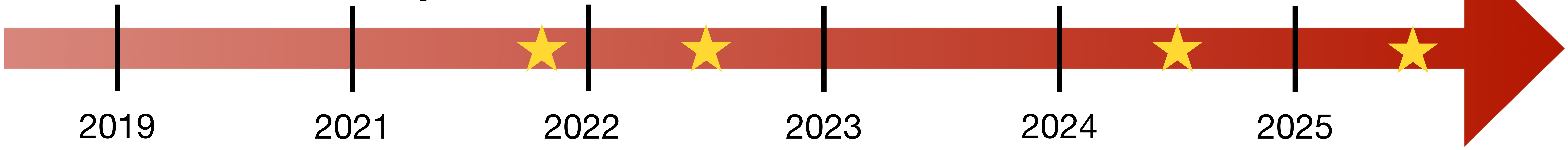
CCM120 Engineering Run (2019)
- Prototype detector
- Testing 120 8” PMTs for SBND
- Produced physics results

CCM200 Engineering Run (2021)
- Upgraded detector to 200 8” PMTs
- Doubled veto PMT coverage
- Increased forward shielding

CCM200 Physics Run (2022-2025)
- Improved DAQ
- Installed additional top-shielding
- New data processing for Cherenkov light separation

PhysRevD.109.095017
PhysRevD.111.035030

PhysRevD.107.095036

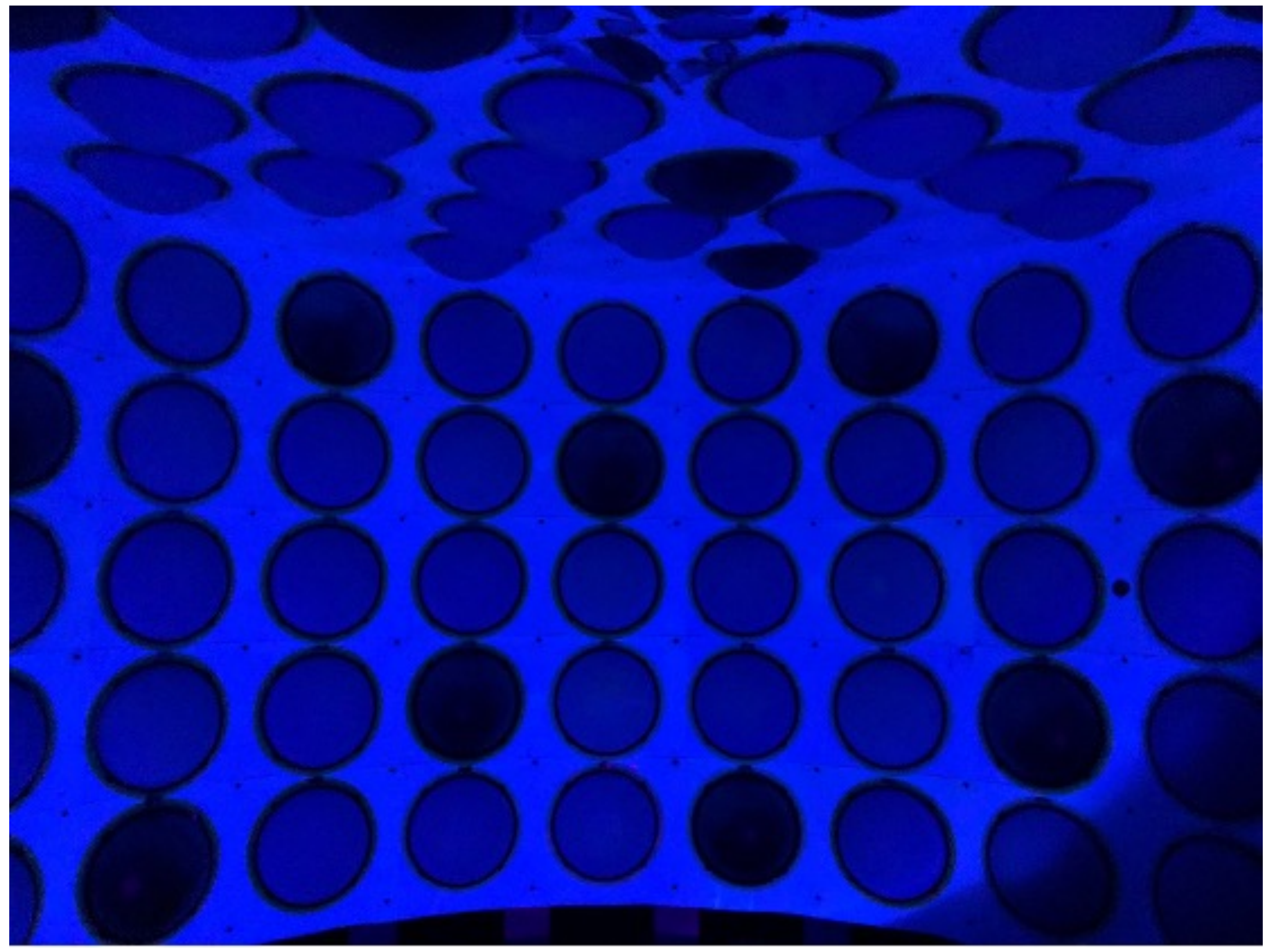


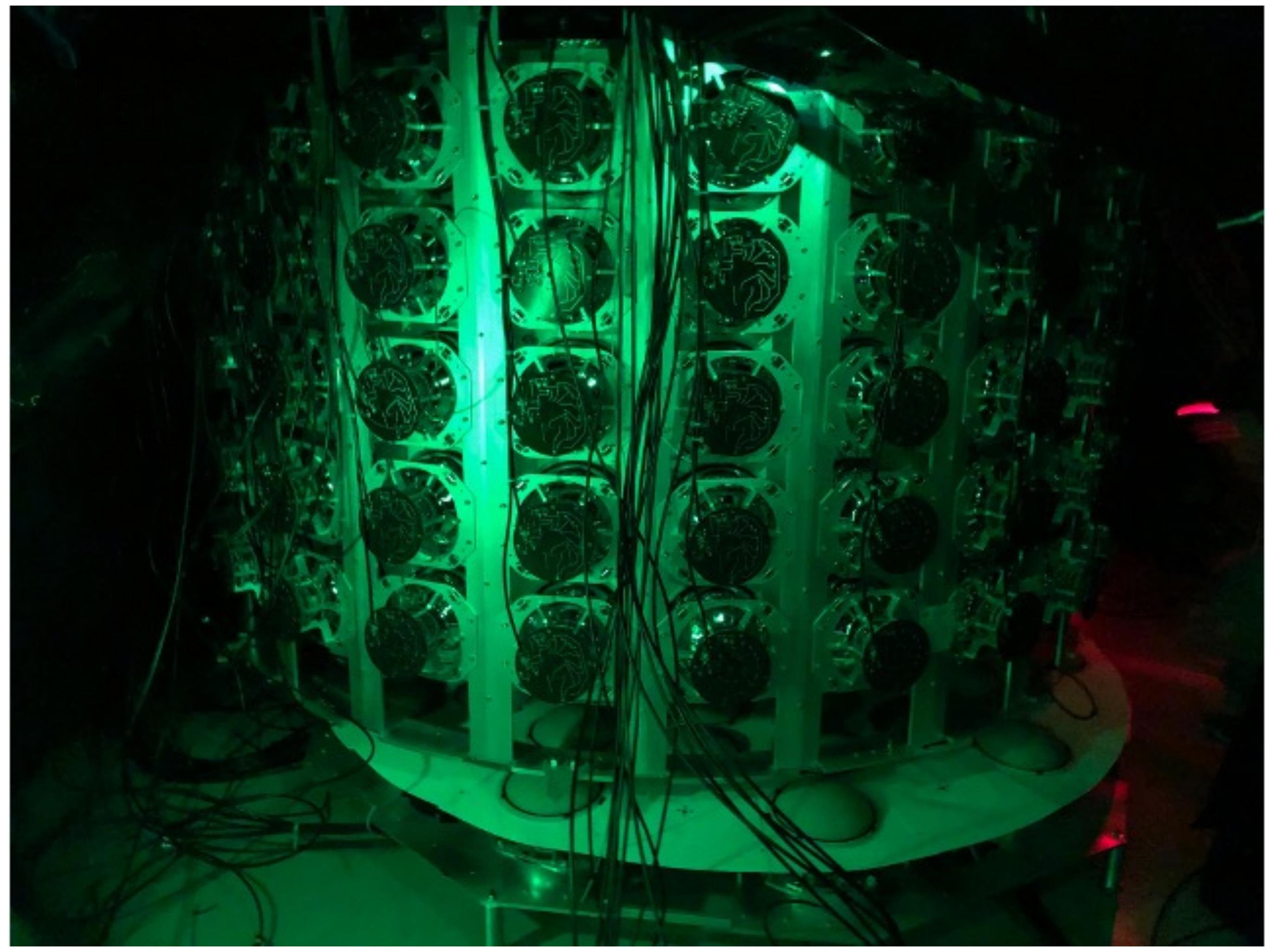
PhysRevLett.129.021801
PhysRevD.106.012001

arXiv:2507.08886
arXiv:2507.08887

Detector Specifics

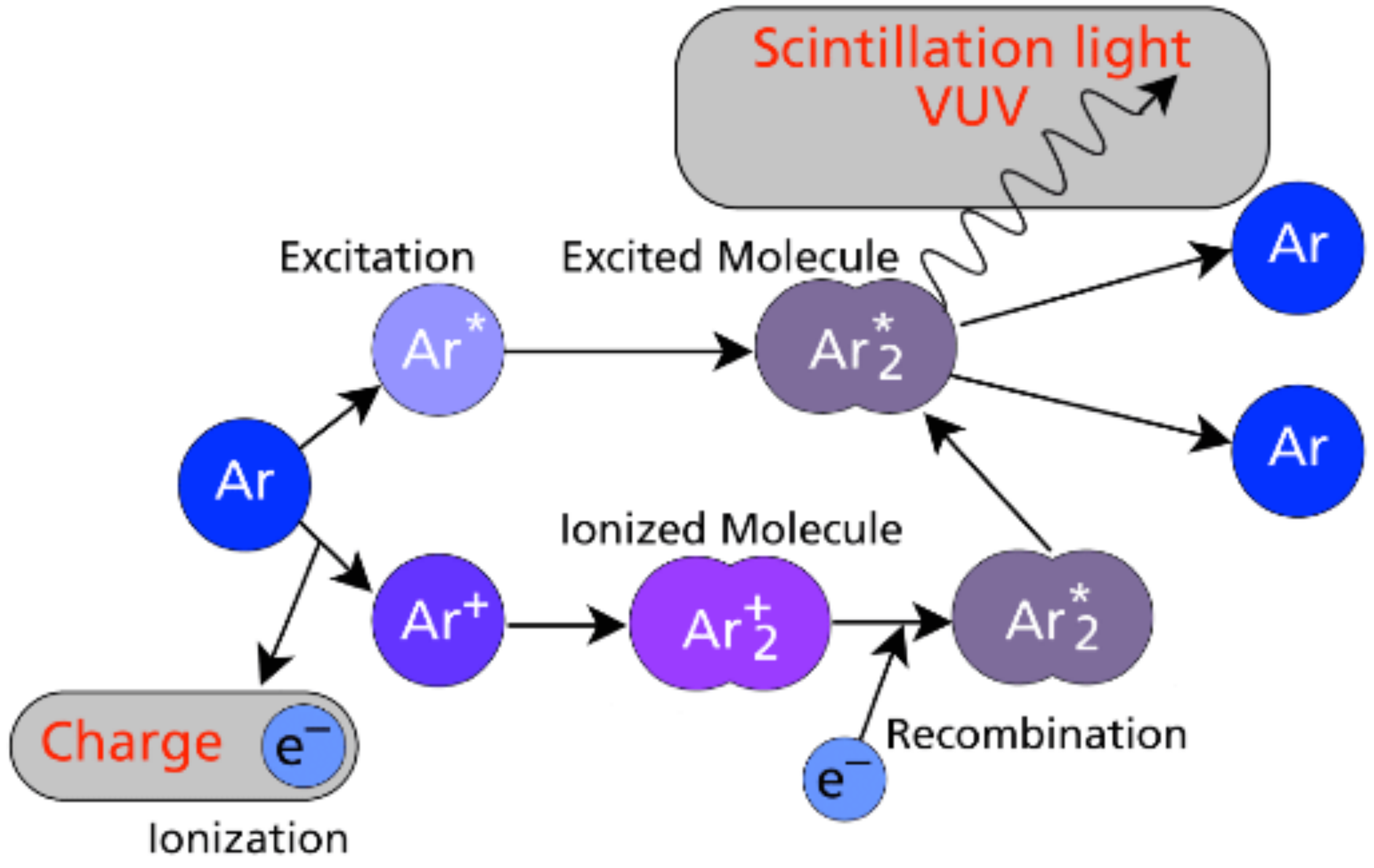
- **2 ns** timing resolution from CAEN V1730 digitizer sampling rate
- CCM does ***not*** filter LAr
    - Measure around 2.2 ± 0.5 ppm of oxygen and 0.1 ± 0.1 ppm of nitrogen impurities during run conditions
    - Manufacturer specifications quote 0.01 ppm of water





Light Production in Liquid Argon

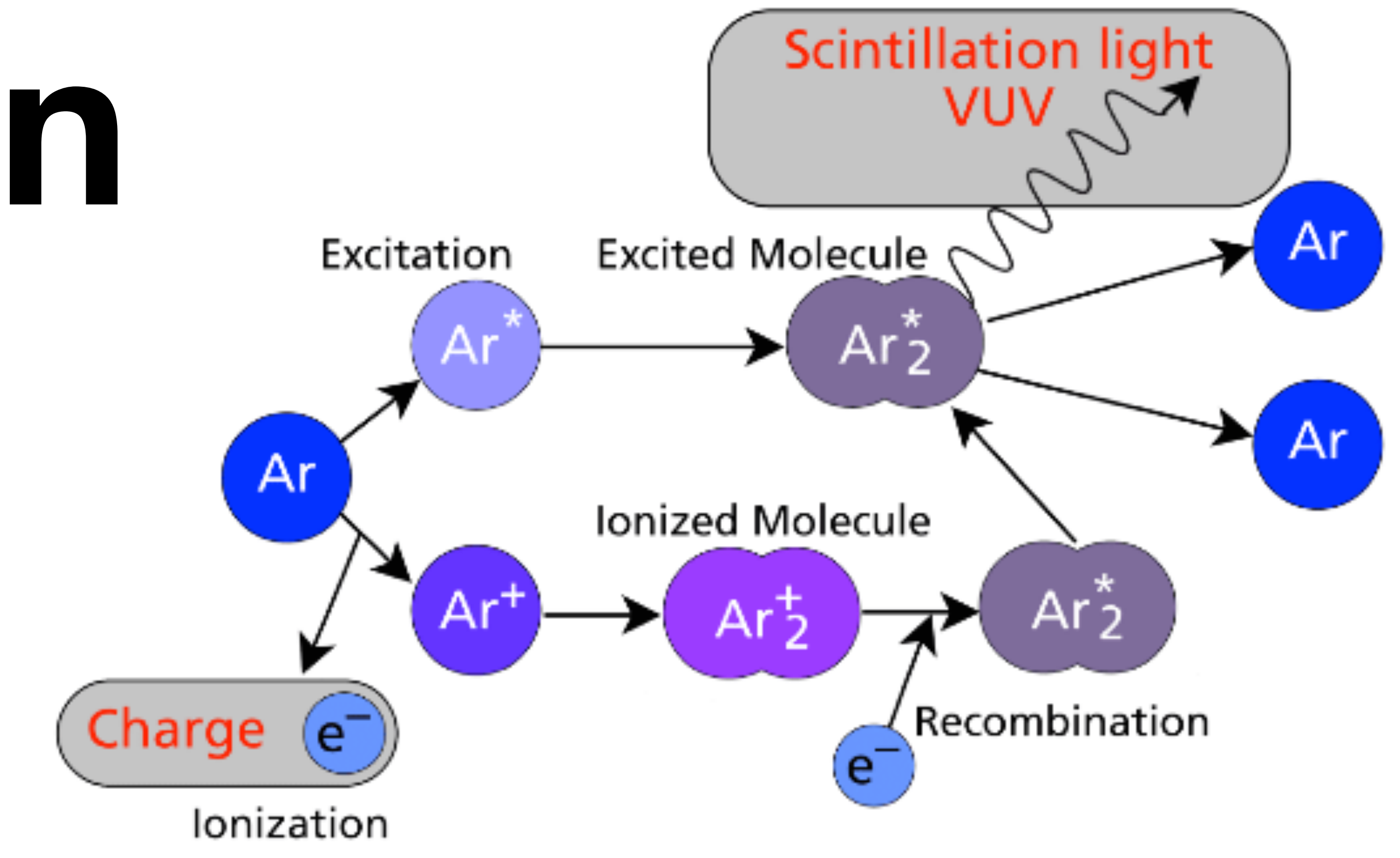
Quality	Scintillation Light
Intensity (for a MIP)	~40,000 photons/MeV
Direction	Isotropic
Timing	Fast component (nsec) and slow component (usec) measured by DEAP collaboration
Photon Wavelength	Spectrum peaks at 128 nm

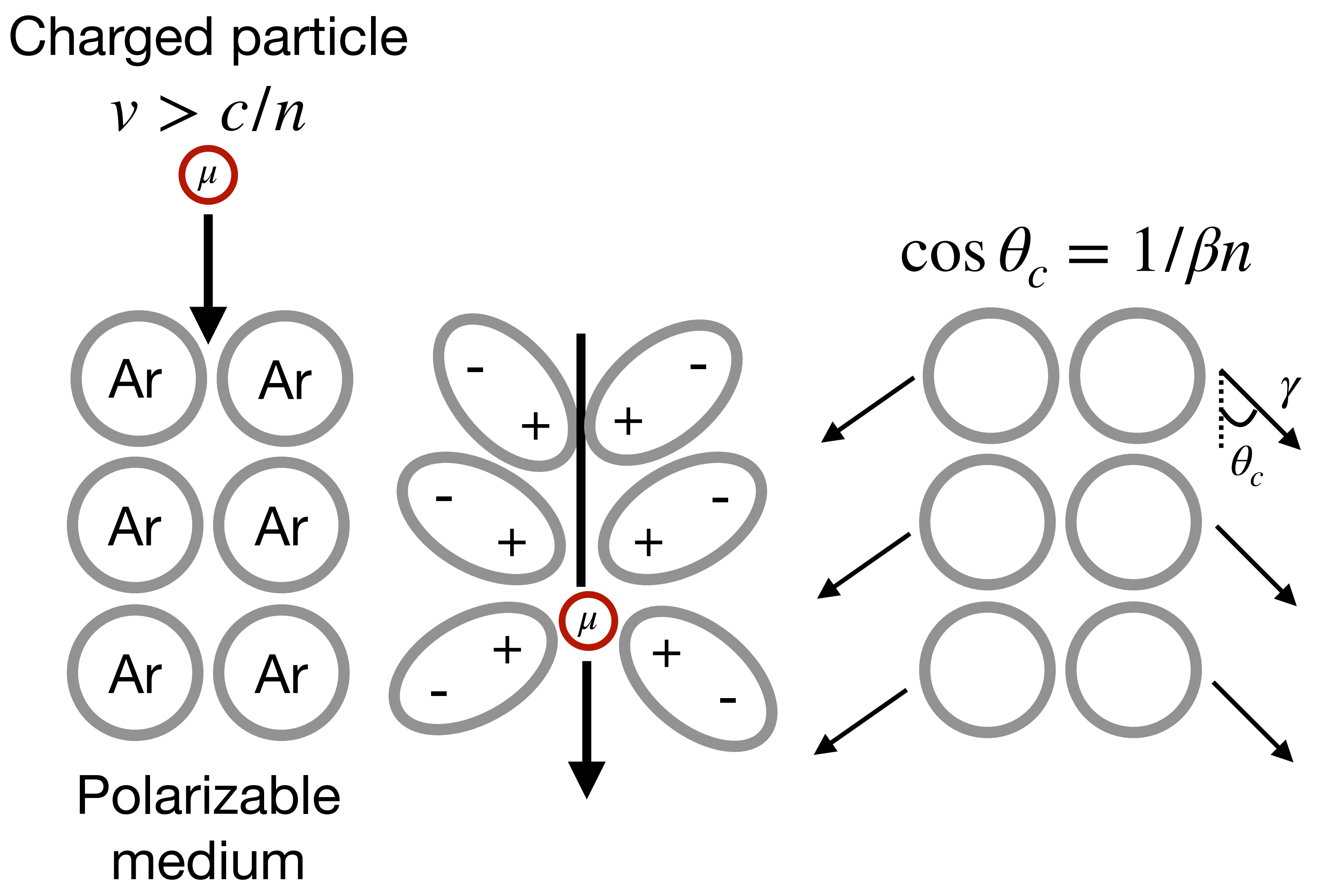


D. A. Newmark, dnewmark@mit.edu

Light Production in Liquid Argon

Quality	Scintillation Light	Cherenkov Light
Intensity (for a MIP)	~40,000 photons/MeV	~ 700 photons/MeV (wavelength > 100nm)
Direction	Isotropic	Directional
Timing	Fast component (nsec) and slow component (usec) measured by DEAP collaboration	Prompt (psec start)
Photon Wavelength	Spectrum peaks at 128 nm	$dN/d\lambda \propto \lambda^{-2}$





D. A. Newmark, dnewmark@mit.edu

3. CCM as a Hybrid Detector

Hybrid Detectors

- *"Of particular community interest is the development of **hybrid Cherenkov-scintillation detectors**, which can simultaneously exploit the advantages of Cherenkov light's reconstruction of direction and related high energy particle identification (PID) and the advantages of scintillation light, high light-yield, low-threshold detection with low-energy PID."* — Report of the Instrumentation Frontier Working Group for Snowmass 2021

- Relevant experimental results:

    - Borexino (PhysRevLett.128.091803, 2022)— ***statistical*** observation of Cherenkov radiation from sub-MeV particles using liquid scintillator

    - SNO+ (PhysRevD.109.072002, 2024) — event-by-event observation of Cherenkov radiation from ***>5 MeV*** particles using liquid scintillator

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This work — **_event-by-event_** observation of Cherenkov light from **_sub-MeV_** particles using liquid argon

First use of liquid argon for hybrid detector!

- Relevant ex...
  - Borexino (PhysRevLett.128.091803, 2022)— ***statistical*** observation of Cherenkov radiation from sub-MeV particles using liquid scintillator
  - SNO+ (PhysRevD.109.072002, 2024) — event-by-event observation of Cherenkov radiation from ***>5 MeV*** particles using liquid scintillator

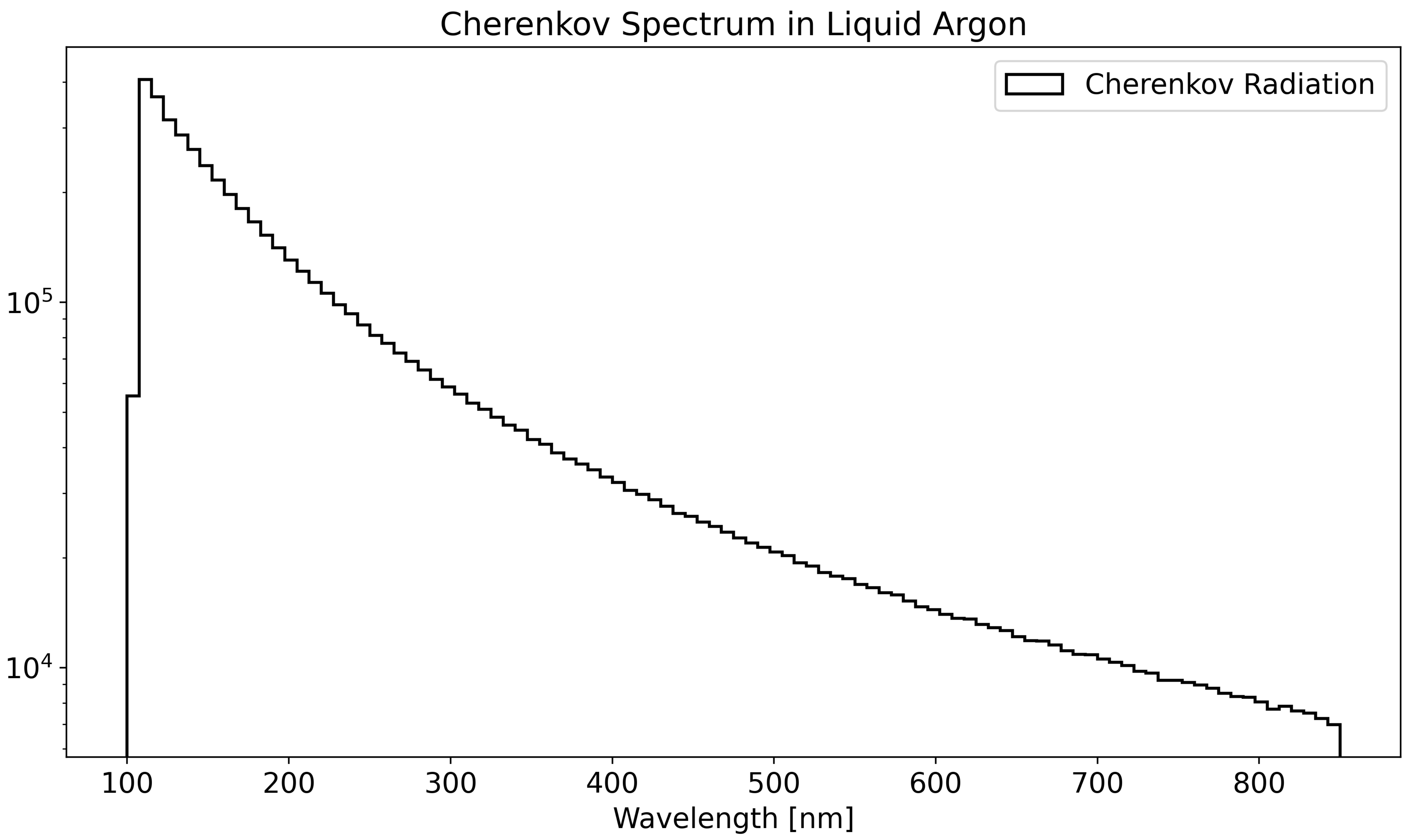
Liquid Argon for Hybrid Detectors

- Liquid argon offers key advantages over oil-based liquid scintillators

1. Pure LAr does not intrinsically absorb optical photons ($\lambda \gtrsim 113$ nm)

    - Do ***not*** need bulk WLS dopants → UV Cherenkov photons maintain directionality in LAr as they travel to detection plane

    - Cherenkov emission ~ $1/\lambda^2$, capturing that short wavelength portion of Cherenkov emission ***significantly increases*** photon statistics

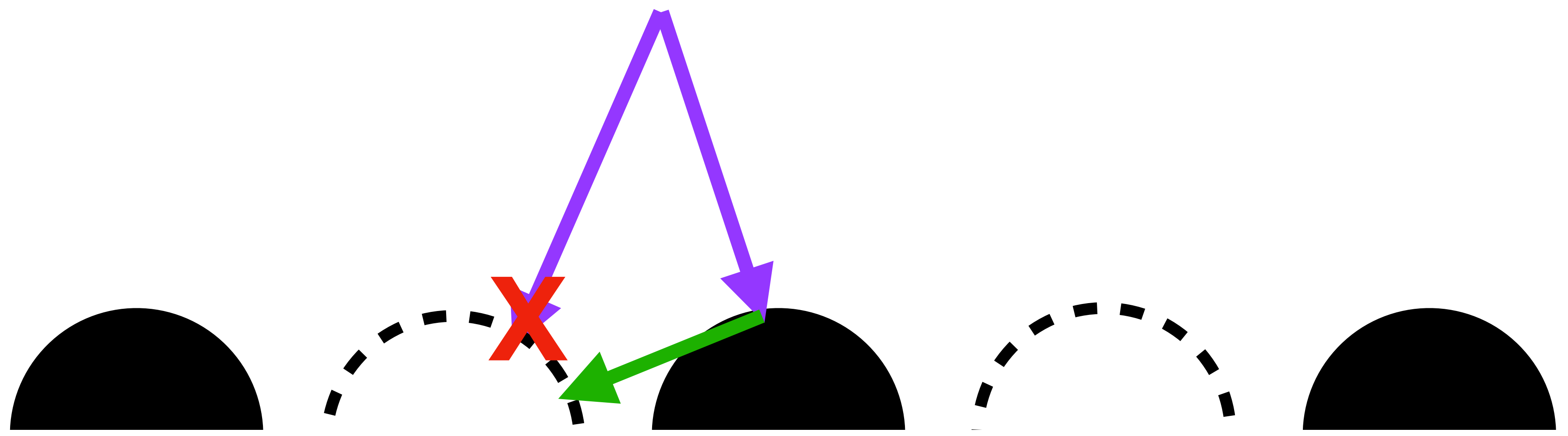


Liquid Argon for Hybrid Detectors

- Liquid argon offers key advantages over oil-based liquid scintillators

2. Time delay between prompt Cherenkov and scintillation signals

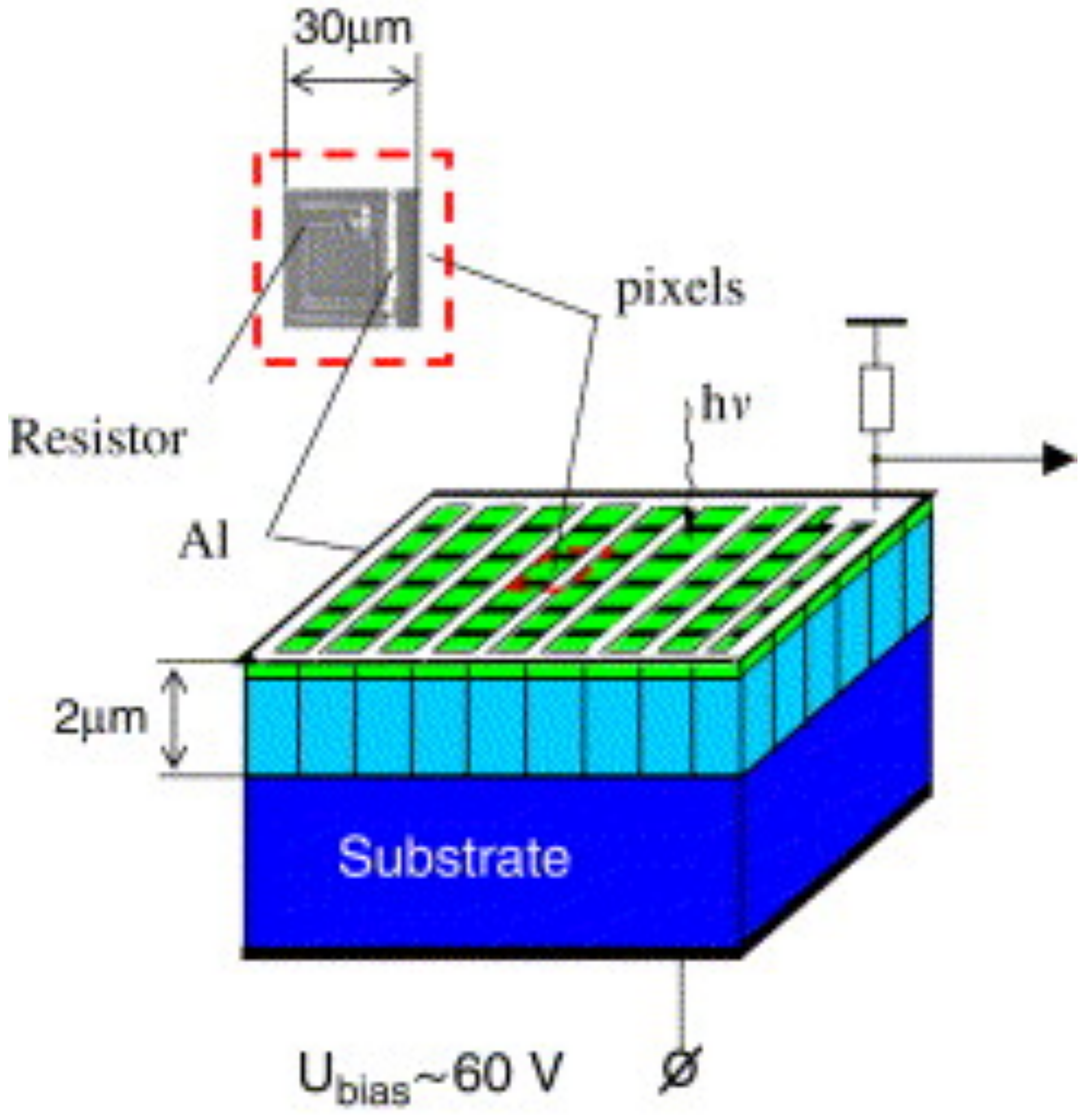
    - LAr ($\tau_s \sim \mathcal{O}(5\ \mathrm{ns})$) is a slightly slower scintillator than LS ($\tau \sim \mathcal{O}(3\ \mathrm{ns})$)
    - WLS on edges of detector introduces ***additional propagation time delays*** between the prompt visible Cherenkov signal and delayed WLS scintillation light



Liquid Argon for Hybrid Detectors

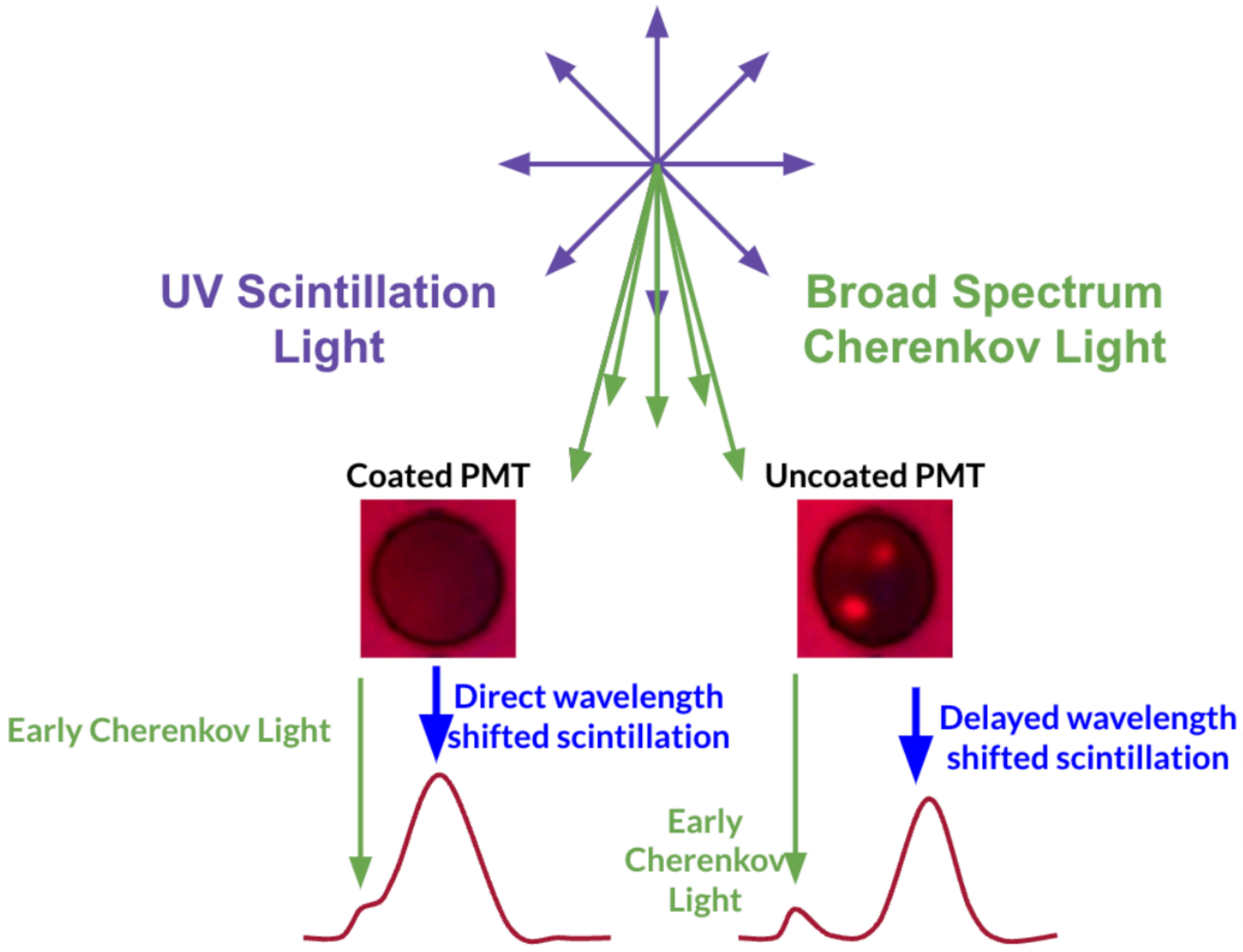
- Liquid argon offers key advantages over oil-based liquid scintillators

3. Cryogenic nature can be advantageous
    - Lot of interest in silicon photomultipliers (SiPMs)
        - Lower operating voltage, cost, and radioactive backgrounds and high QE compared to PMTs and ***faster timing***
    - But SiPMs have very large dark rate current at room temperature
        - Drops by two orders of magnitude at cryogenic temperatures
    - Active research into red-sensitive SiPMs —> spectral sorting of broad spectrum Cherenkov light vs narrowly peak scintillation light



CCM's Approach for Cherenkov Light Separation

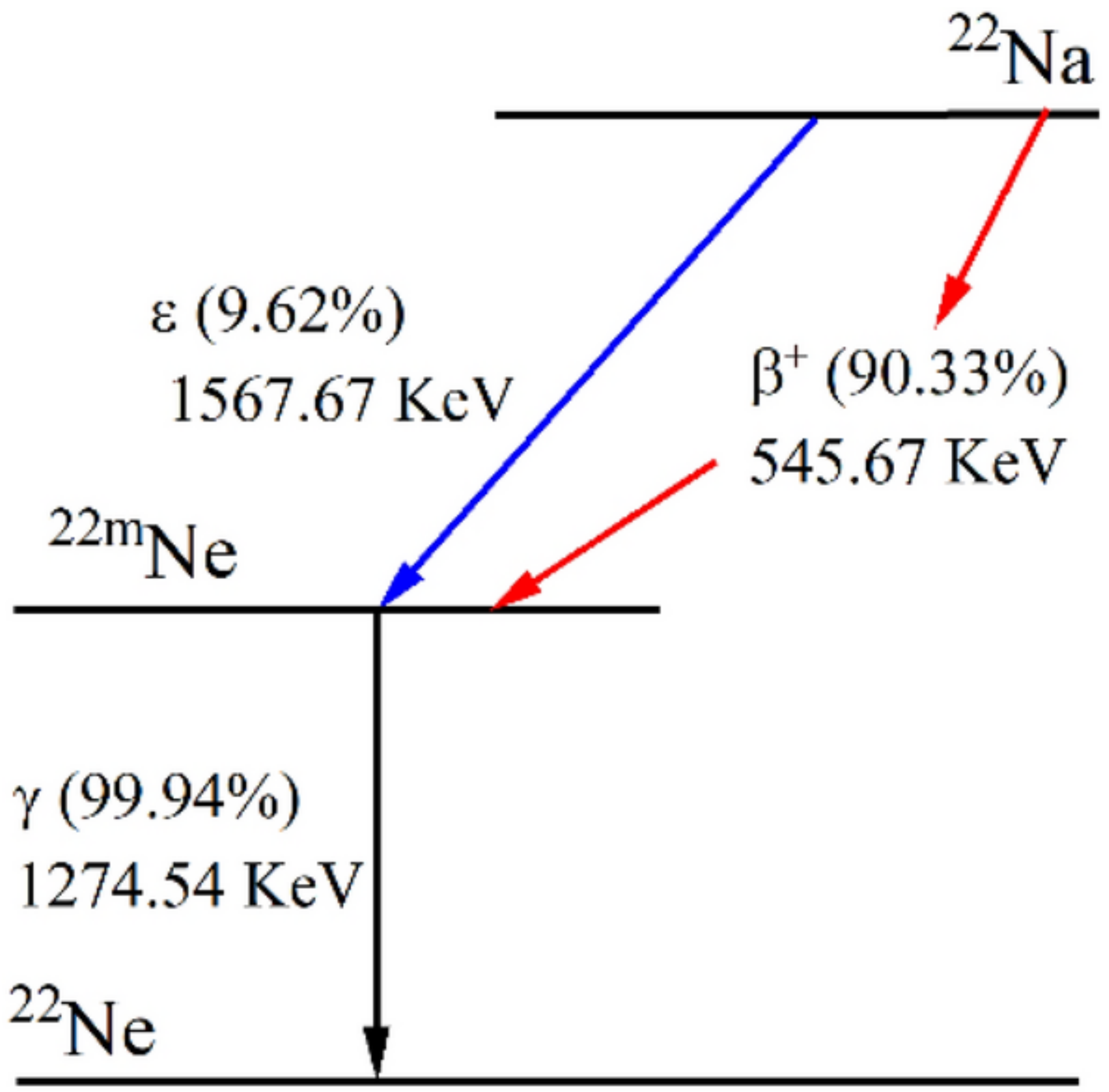
- ***Uncoated PMTs*** allow for wavelength discrimination between UV scintillation light and broad spectrum Cherenkov light
- Visible Cherenkov photons detected by uncoated tubes ***before*** wavelength shifted scintillation light
- Combined with 2ns timing resolution, able to ***isolate early Cherenkov signal in uncoated PMTs***

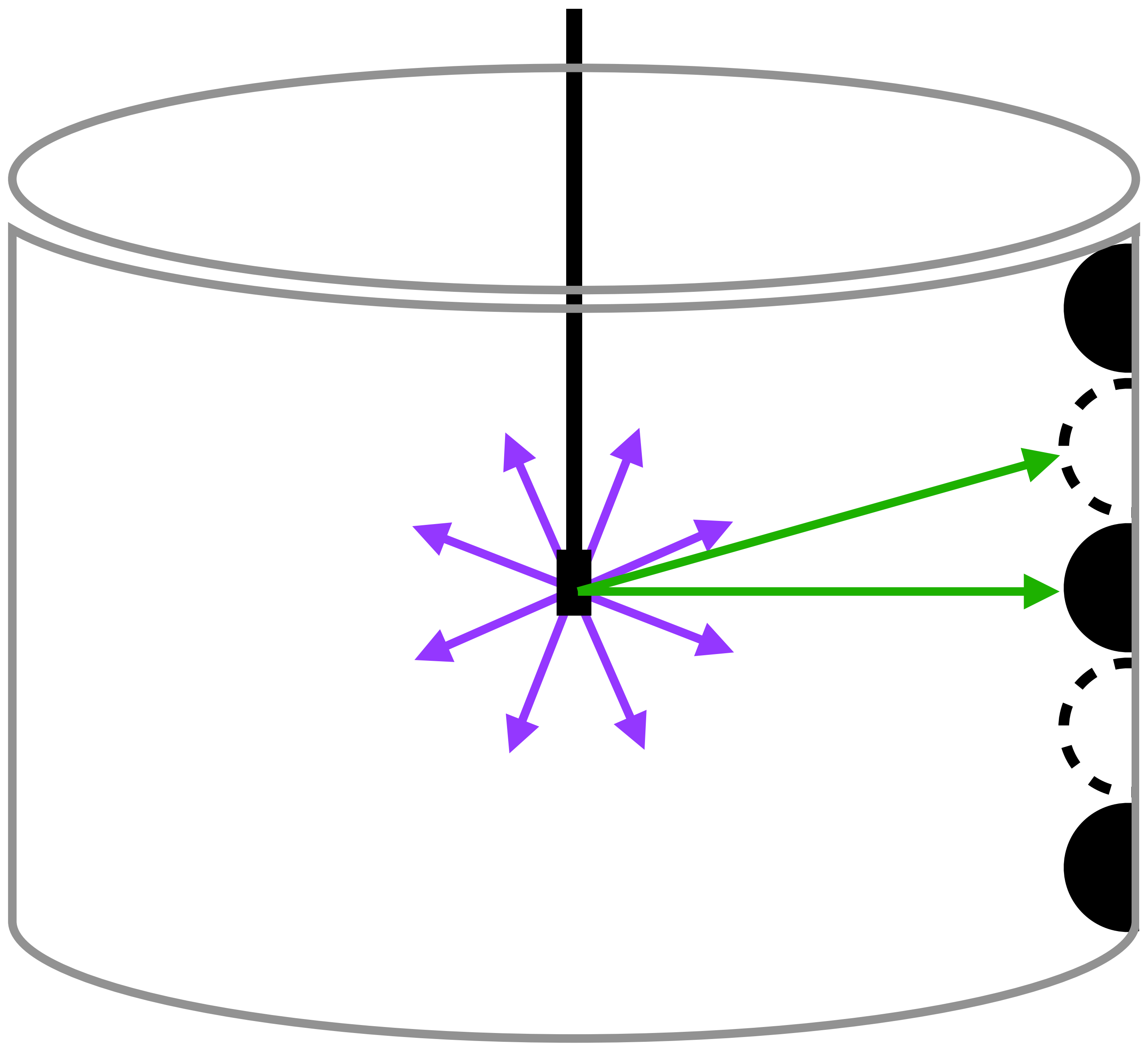


4. First Event-by-Event Identification of Cherenkov Radiation from Sub-MeV Particles in Liquid Argon
arXiv:2507.08886

Calibration Source

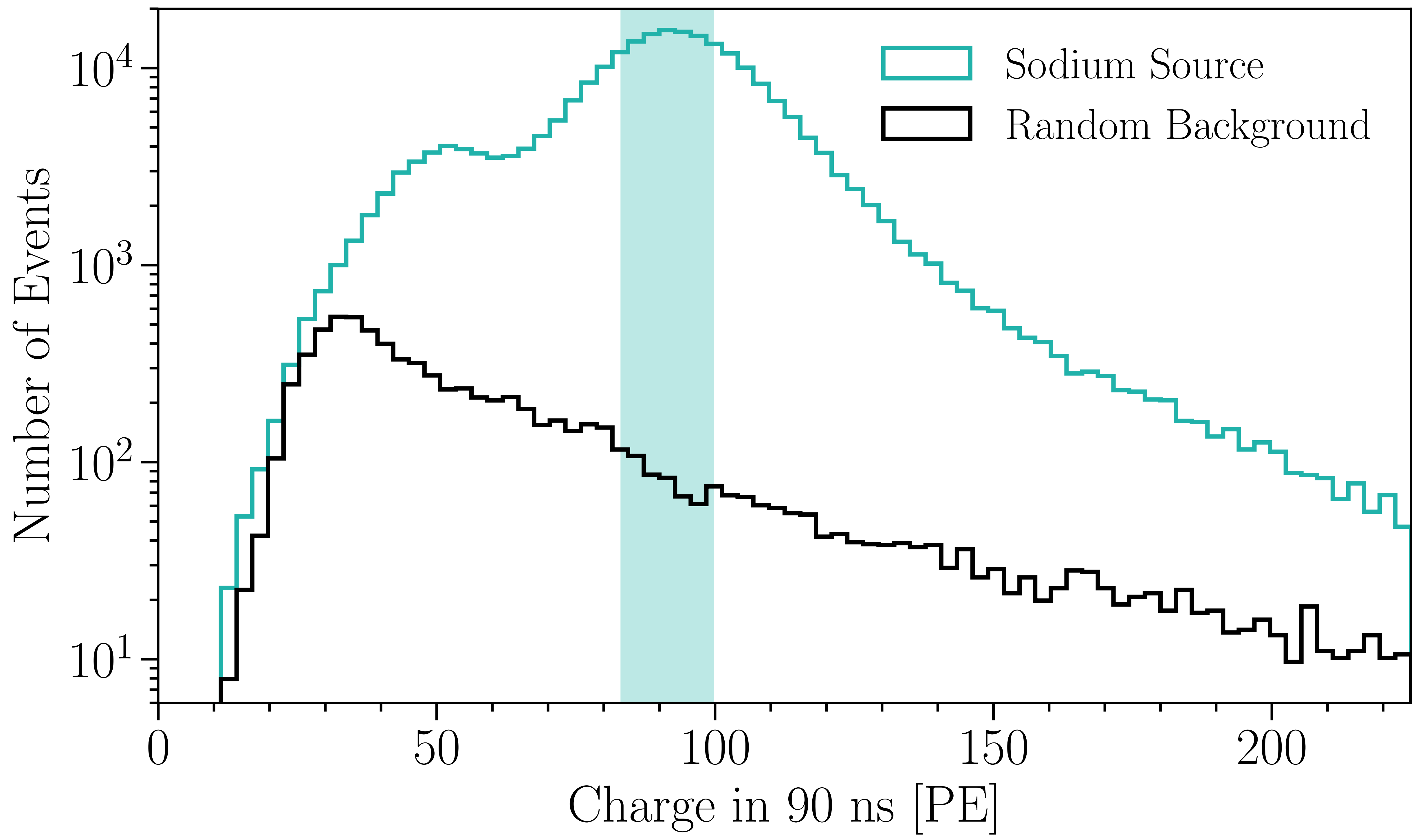
- ^{22}Na calibration source at origin of the detector
  - Source is enclosed in stainless steel
  - Decays produce 1.275 MeV γ and 0.546 MeV e^+ (promptly annihilates)
  - Decay produces a ***single*** gamma-ray or ***three*** gamma-rays





Calibration Source

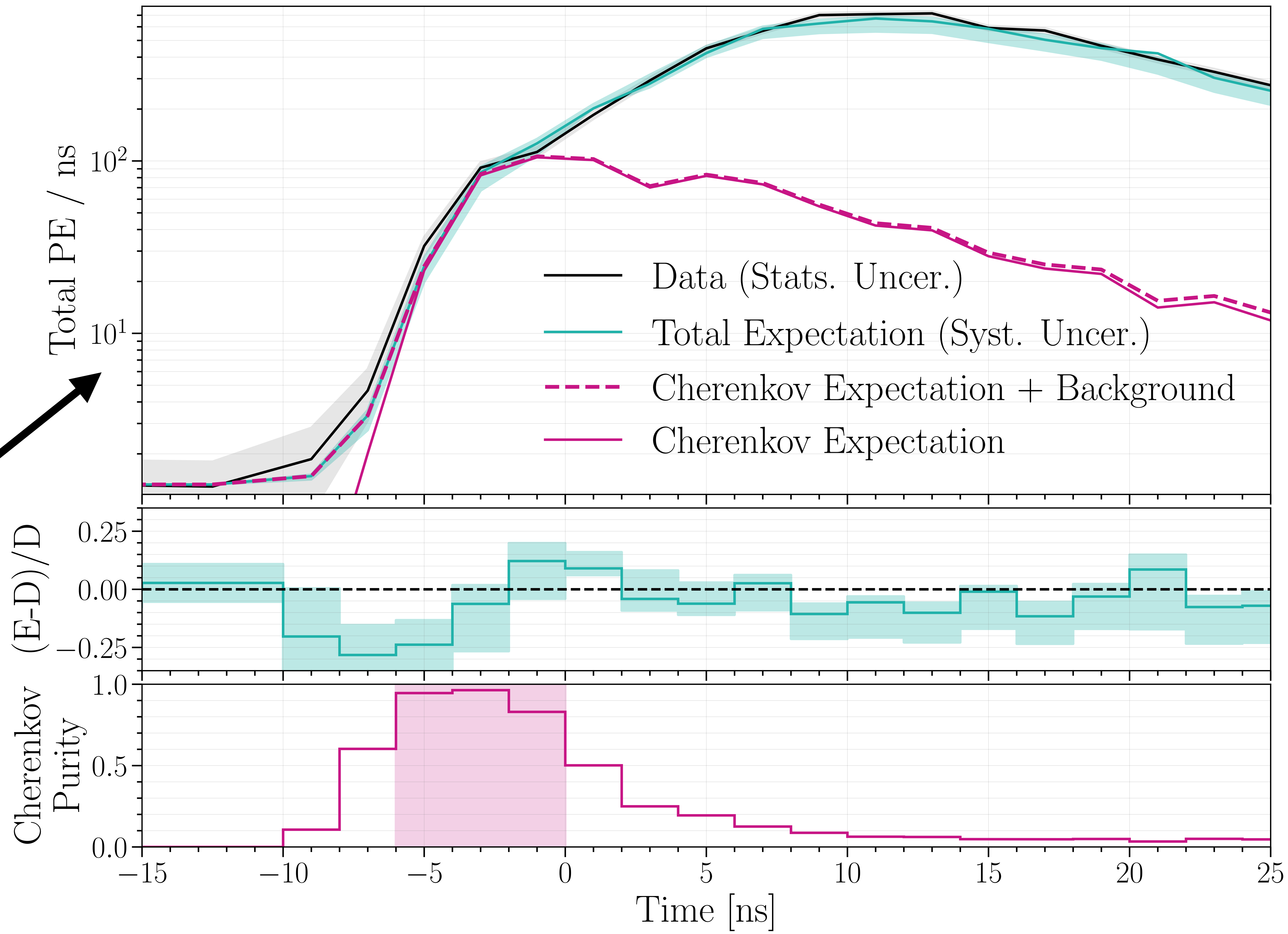
- Reconstruct event start times using charge threshold of 3 PE in 2 ns time window
- Use charge in first 90ns of each event as a proxy for energy
- Compare sodium data (blue) to background spectrum (black)
- Select events in high energy peak (corresponding to β^+ decay)



D. A. Newmark, dnewmark@mit.edu

Typical Uncoated PMT Response

- Accumulate ^{22}Na data to characterize detector response using Geant4 simulation ***(focus of arXiv:2507.08887)***
- Example accumulated events in data and Monte Carlo for a ***typical uncoated PMT***
- ***Top plot —*** accumulated data and expectation with 1σ uncertainties
    - Total expectation combines scintillation, Cherenkov, and random backgrounds



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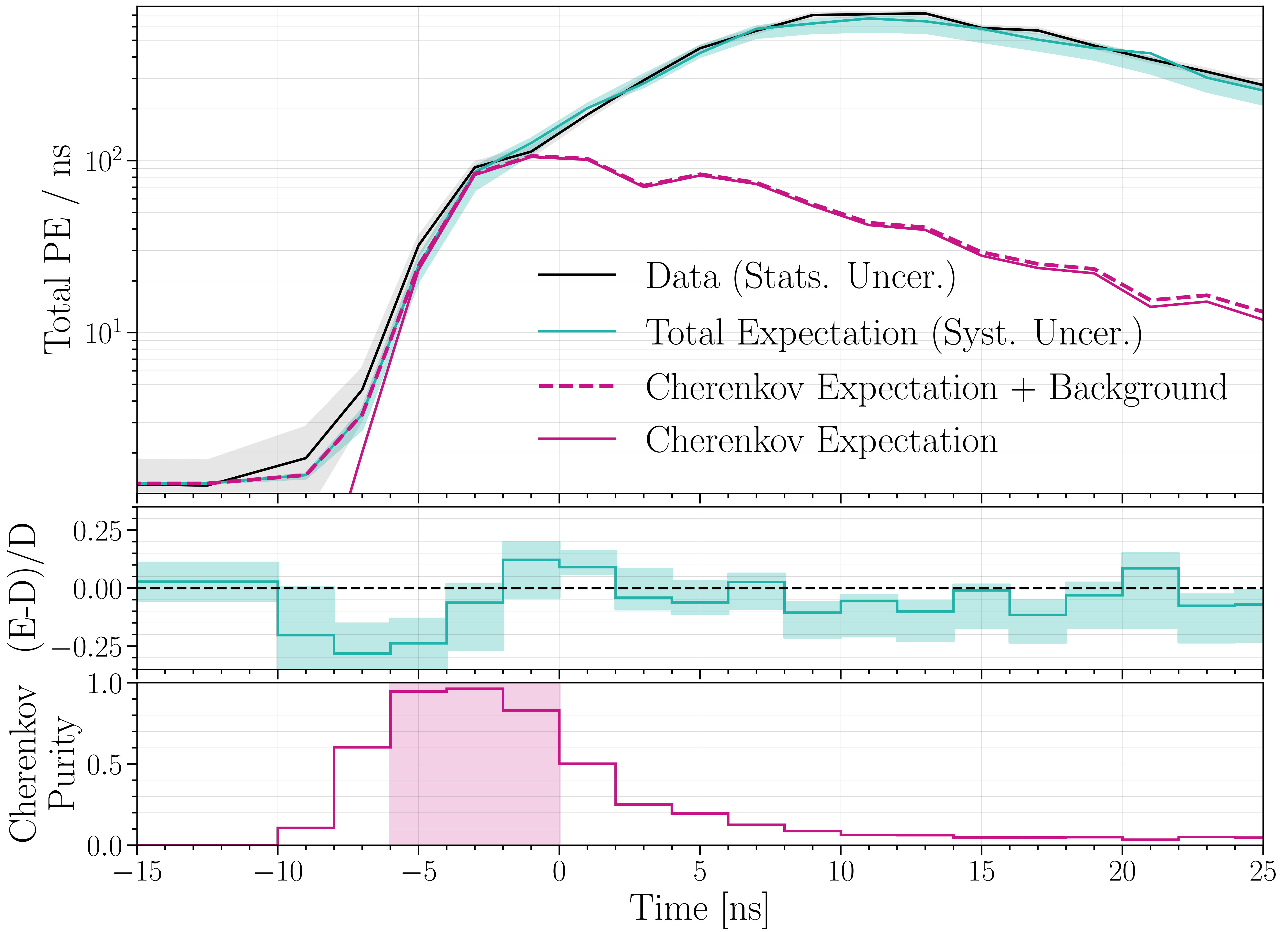
- Example accumulated events in data and Monte Carlo for a ***typical uncoated PMT***
- ***Middle plot —*** residual between expectation and data, $\pm 15\,\%$ agreement at 1σ level



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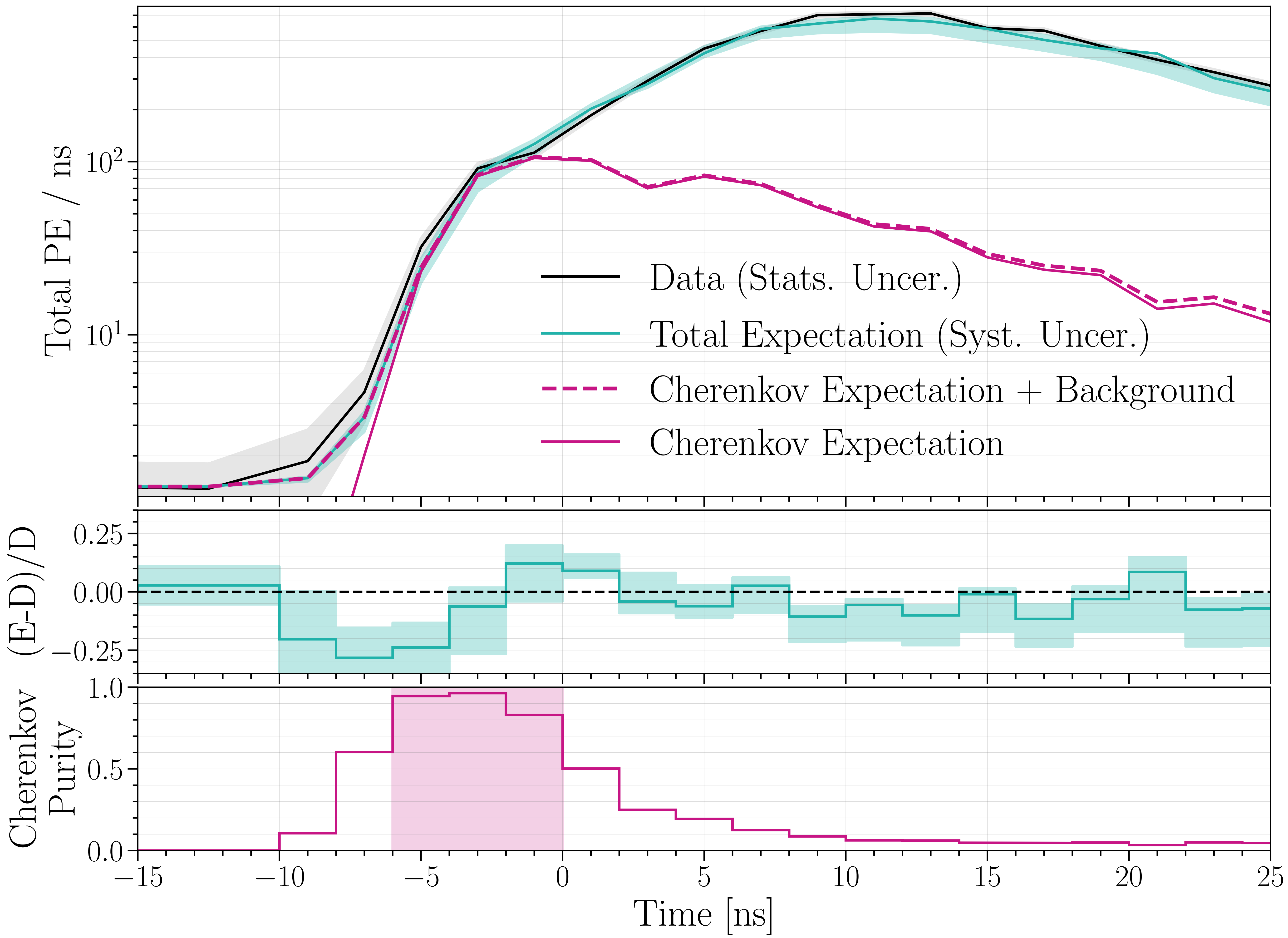
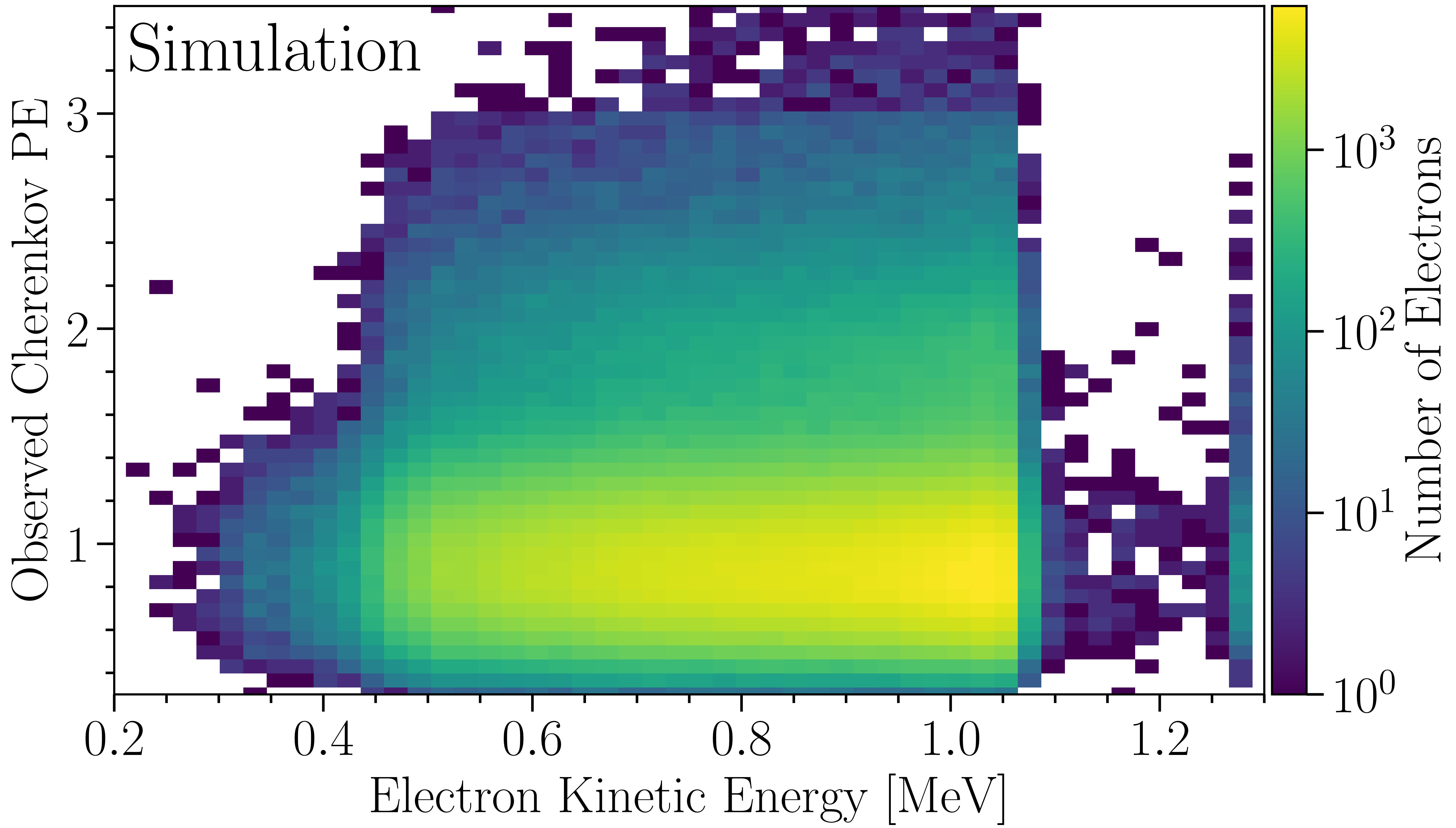
- Accumulate ^{22}Na data to characterize detector response using Geant4 simulation ***(focus of arXiv:2507.08887)***
- Example accumulated events in data and Monte Carlo for a ***typical uncoated PMT***
- ***Bottom plot —*** Cherenkov purity as a function of time, $-6 \le t < 0$ ns is "Cherenkov enhanced" time region



D. A. Newmark, dnewmark@mit.edu

Expected Cherenkov Photons per Event

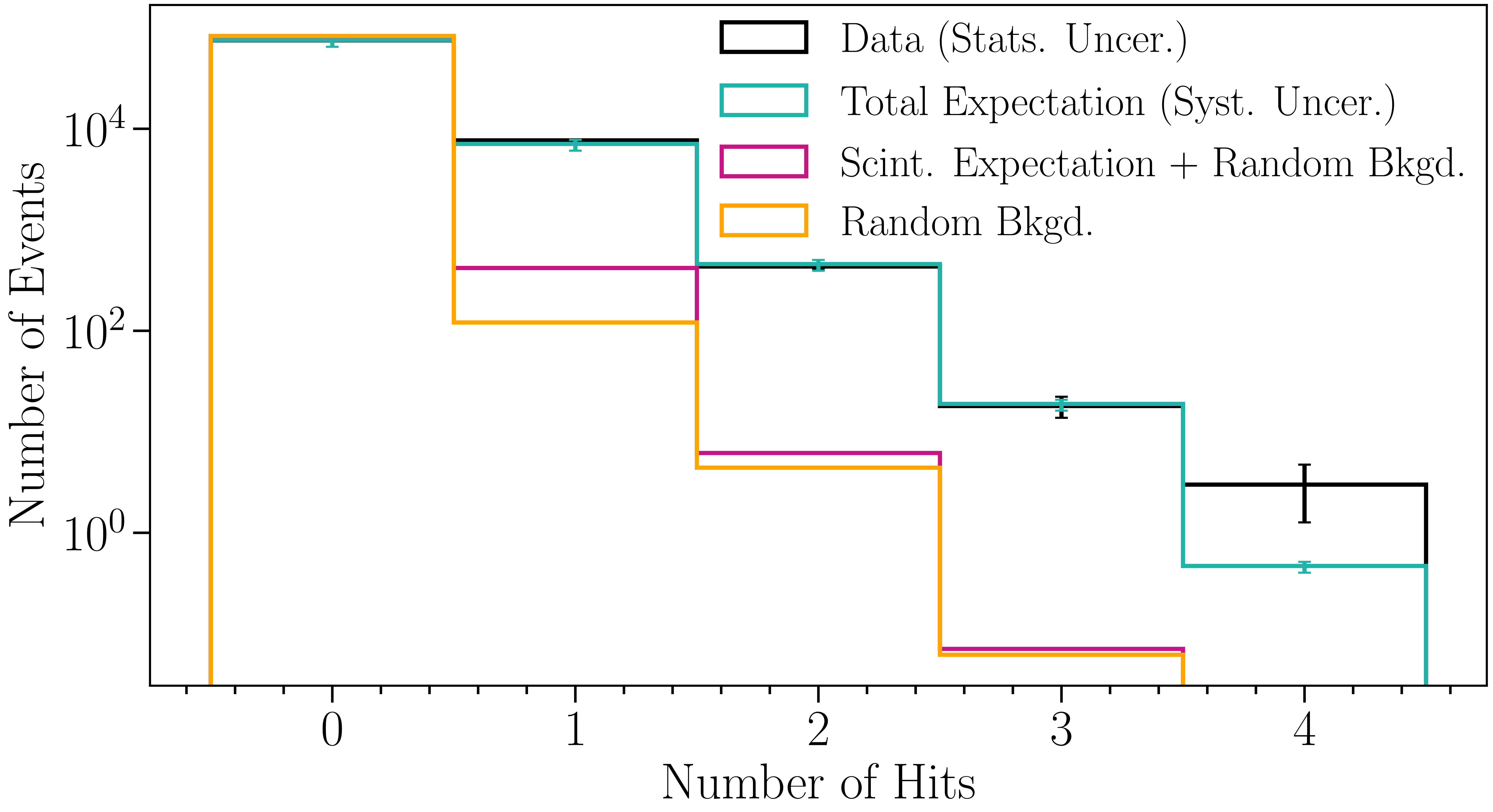
- In ***individual*** Monte Carlo sodium decay events, compare true electron energy vs observed Cherenkov photons
    - ***Only using uncoated PMTs***
    - ***Selecting Cherenkov enhanced time region***
- Detecting Cherenkov photons produced from sub-MeV electrons



D. A. Newmark, dnewmark@mit.edu

Number of Hits in Sodium Events

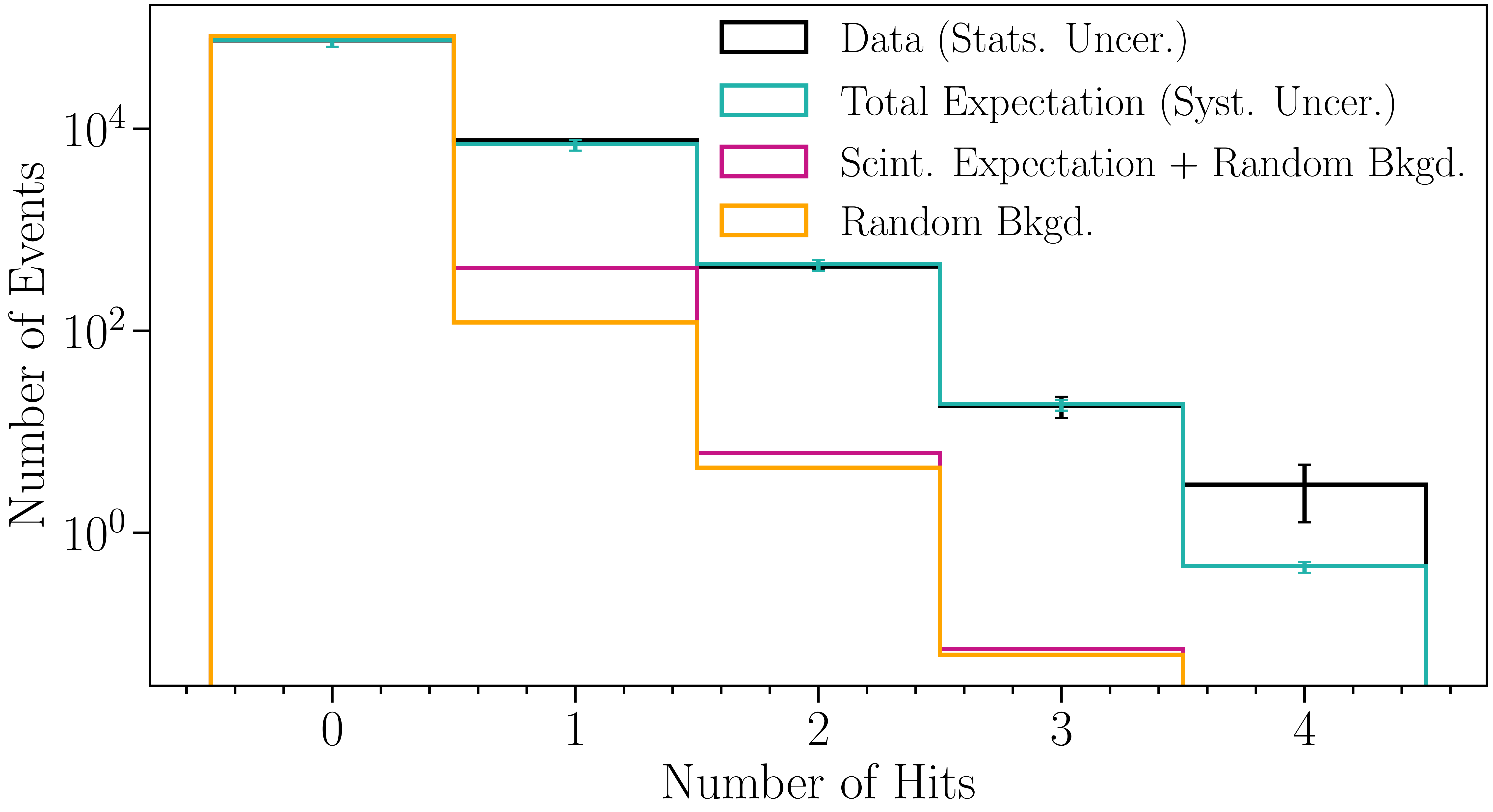
- Examine number of hits per event in sodium data
  - ***Only using uncoated PMTs***
  - ***Selecting Cherenkov enhanced time region***
- Stacked histogram for expectation, data (black) agrees with total expectation (blue)



D. A. Newmark, dnewmark@mit.edu

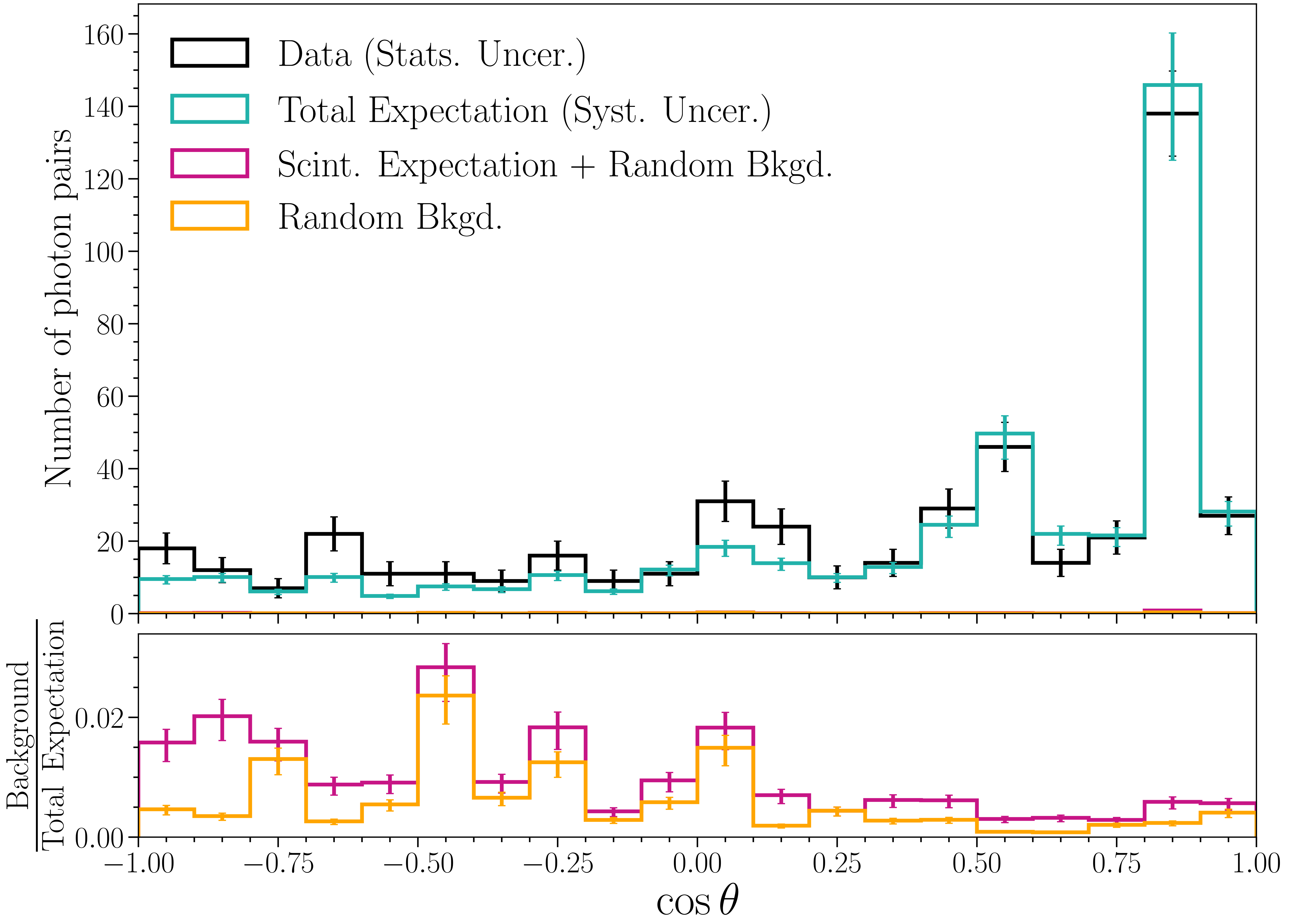
Number of Hits in Sodium Events

- ***94.8%*** purity of Cherenkov light for ≥ 1 hit
- ***~10%*** selection efficiency requiring ≥ 1 hit
    - This is for sub-MeV events and using only uncoated PMTs (total of 10% photocoverage)!



Angle Between Photon Hits

- Require ≥ 2 hits in the early time region
- Calculate angle between sodium source location (origin of detector) and center of hit PMTs
- Data (black) and total expectation (blue) agree within 2σ across all angles



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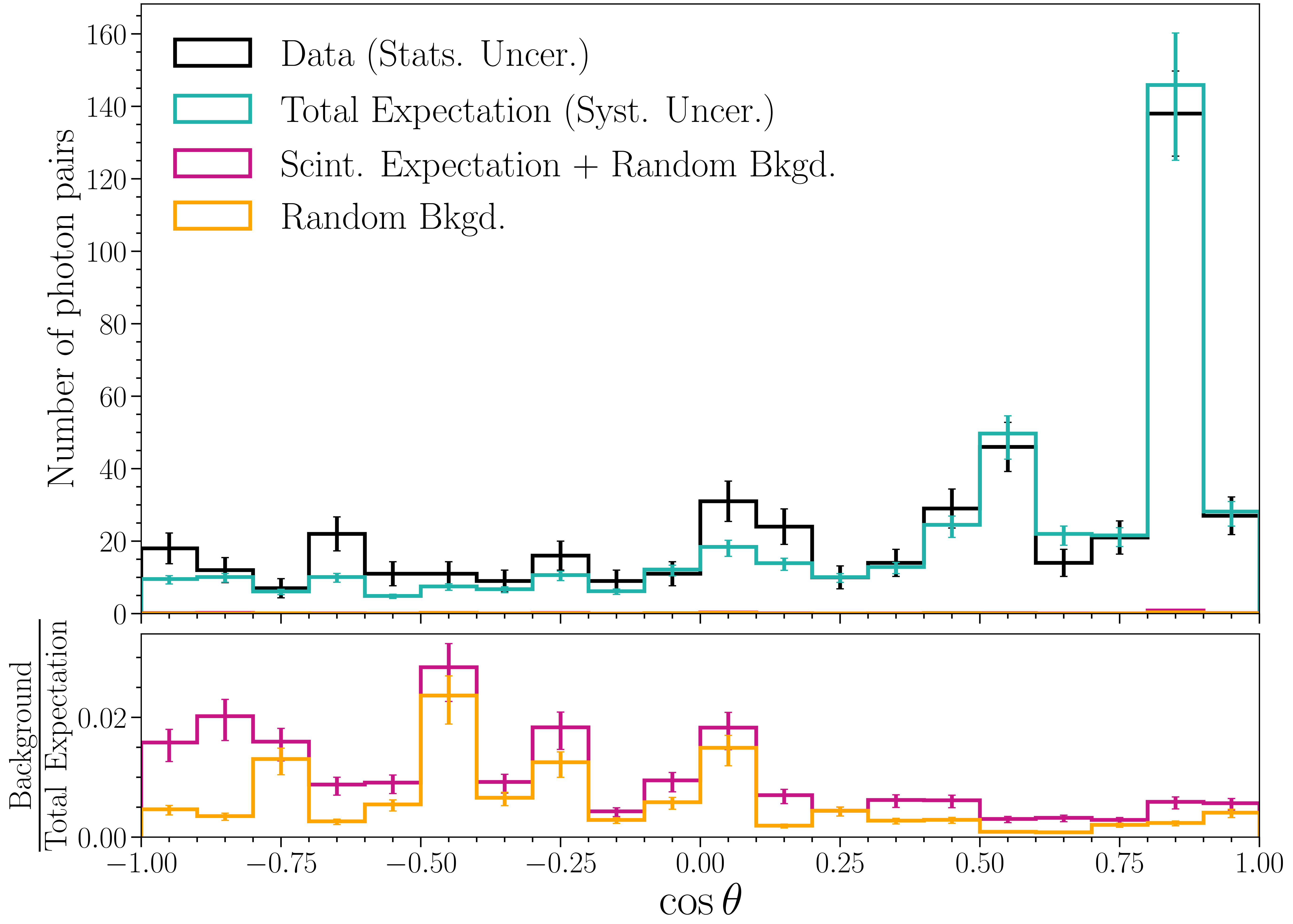
Angle Between Photon Hits

- Preference for $0.8 < \cos\theta < 0.9$ as expected for $0.7 \lesssim KE \lesssim 1.0$ MeV electrons given visible light index of refraction is 1.22 in LAr

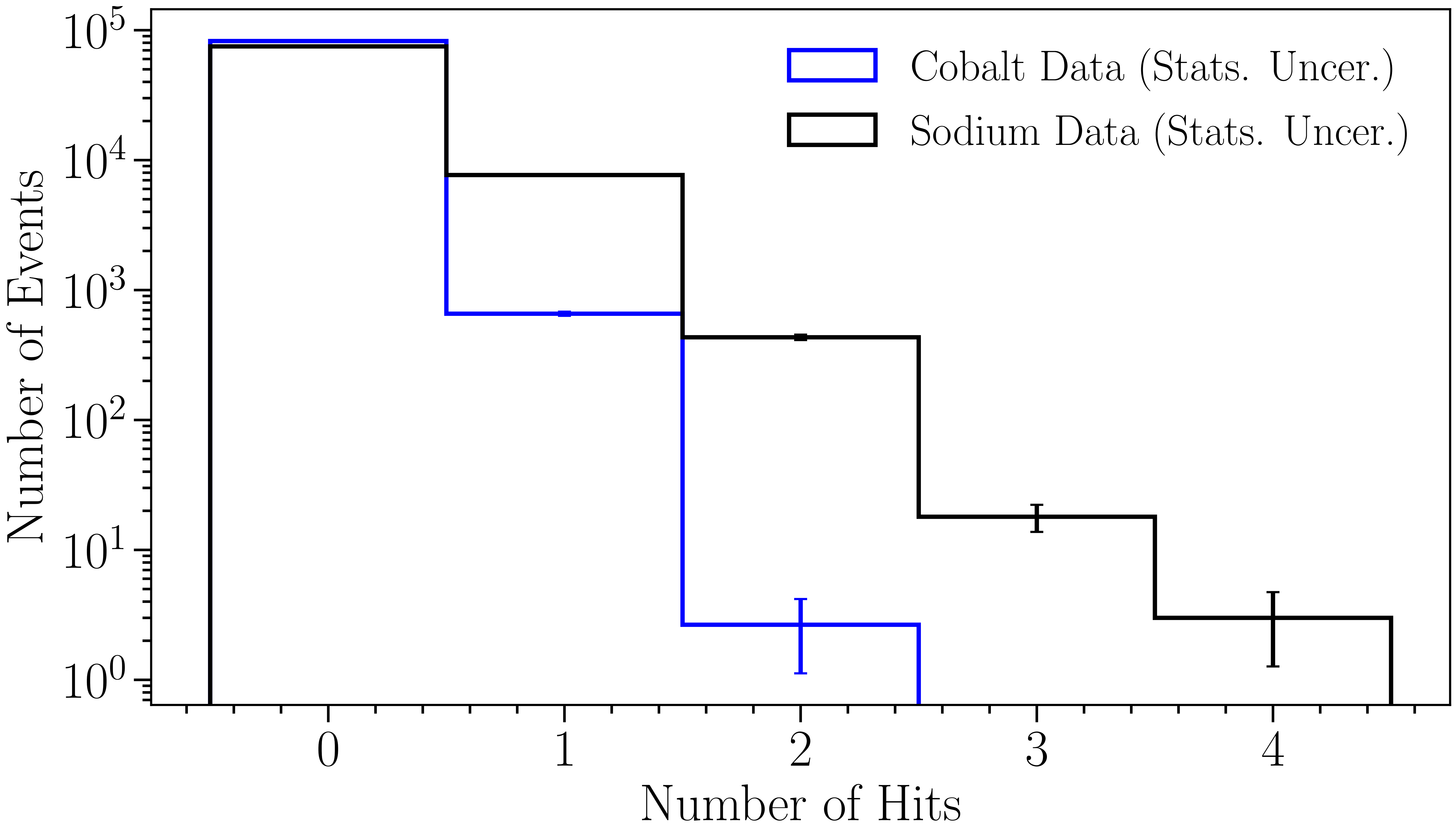
- χ^2 = 30.12 / 20 degrees of freedom between data and total expectation

- Reject scintillation and background only hypothesis using $\Delta\chi^2$ test with $> 5\sigma$ confidence



Null Example

- Apply this analysis procedure to a data sample ***without*** any expected Cherenkov light
- ^{57}Co decays via electron capture emitting < 136 keV gamma-rays (below Cherenkov threshold)
- Reproduce NHits distribution with sodium vs cobalt



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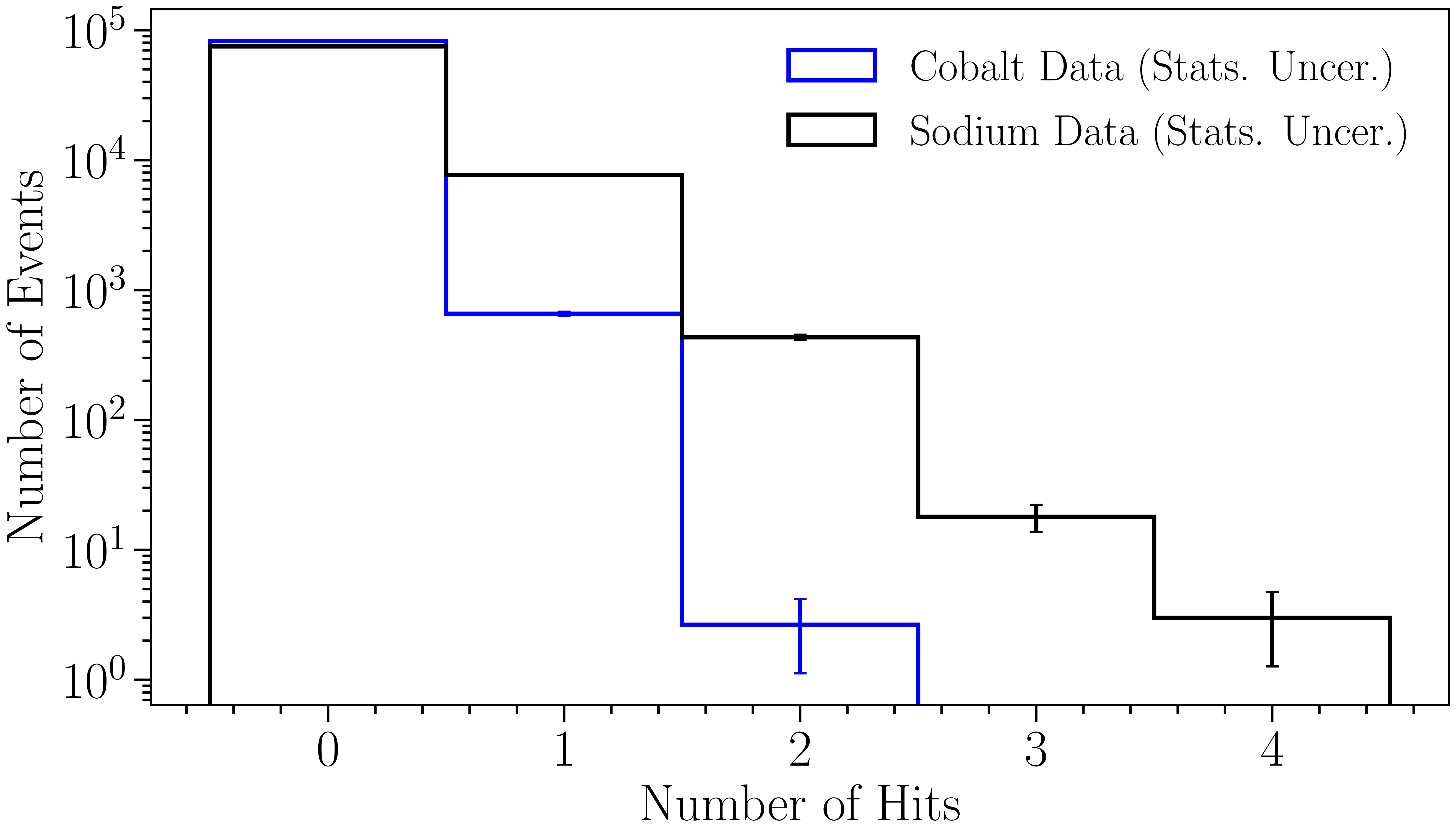
Null Example

- In sodium (with Cherenkov radiation), 9.78% of events have >= 1 hit

- In cobalt (below Cherenkov threshold), 0.79% of events have >= 1 hit

- Smaller rate of hits in the early time region in cobalt is in-line with expected scintillation and random backgrounds



Takeaways

Summary

- Community has emphasized the need for hybrid detector technologies to advance neutrino and rare event searches
- CCM has demonstrated first ***event-by-event*** observation of Cherenkov radiation from ***sub-MeV*** particles in liquid argon
    - Novel result and novel technique of using LAr for hybrid detection medium
    - Can inform future hybrid + liquid argon detector developments
- Ongoing physics searches will leverage scintillation and Cherenkov light for CCν_e measurement, axion like particle search, and additional BSM physics scenarios

Thank you for listening!

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