Cherenkov Light Identification at Coherent CAPTAIN-Mills Experiment

10 ton liquid Argon light collection detector studying neutrino and beyond Standard Model physics at Los Alamos National Lab

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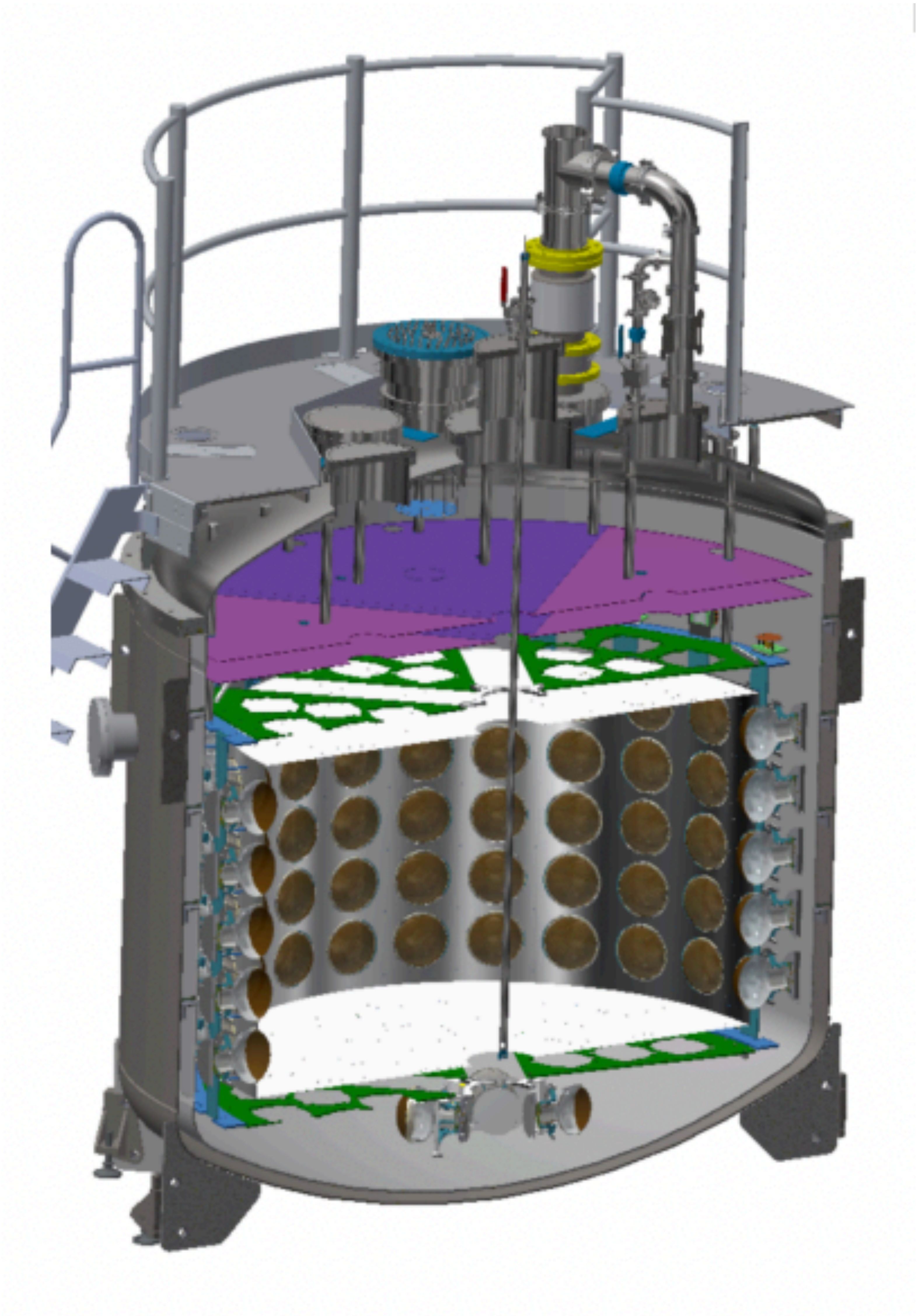
Outline

1. CCM Experiment
2. Cherenkov Light Identification
3. Physics Program

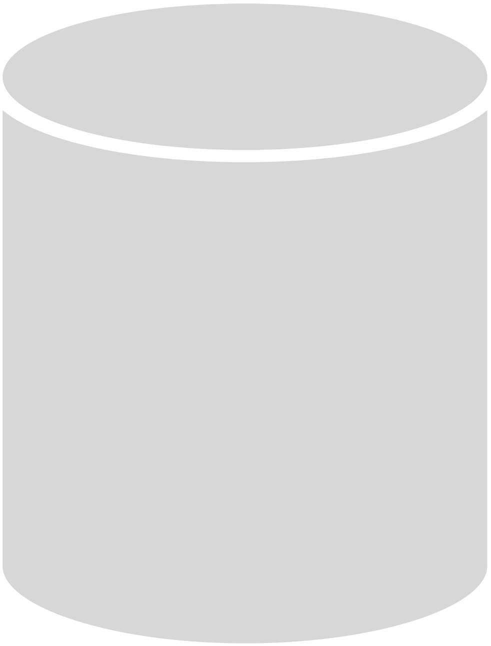


CCM Experiment

- Introduction to CCM
- Neutrino production
- Detector design

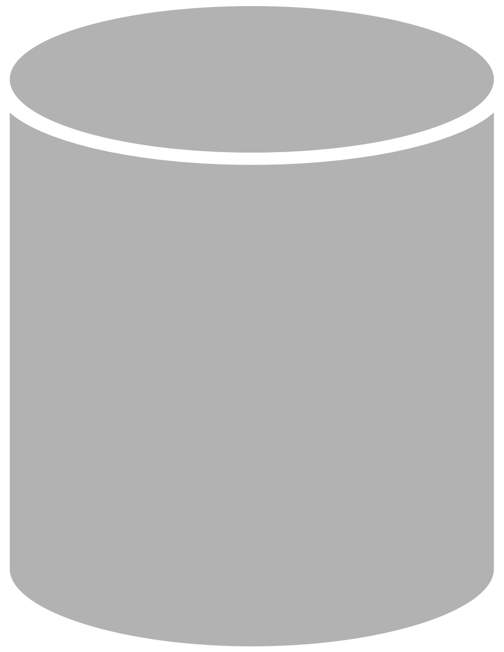
Timeline

Recently completed first year of data collection!



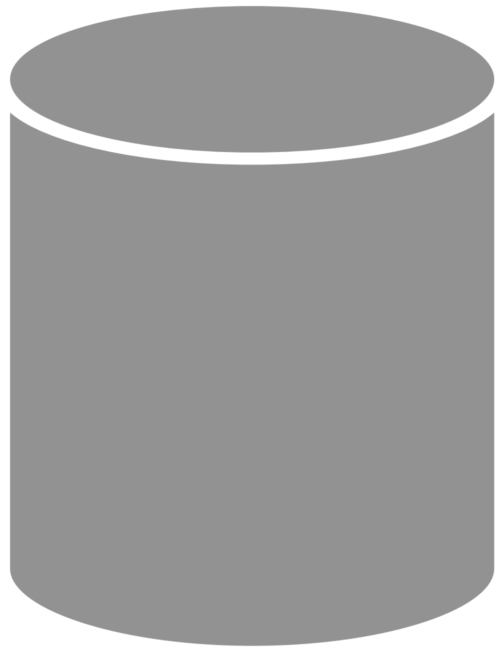
CCM120 Engineering Run

- Prototype detector
- Testing 120 PMTs for SBND
- Produced physics results



CCM200 Engineering Run

- Upgraded detector to 200 8” PMTs
- Doubled veto PMT coverage
- Increased forward shielding



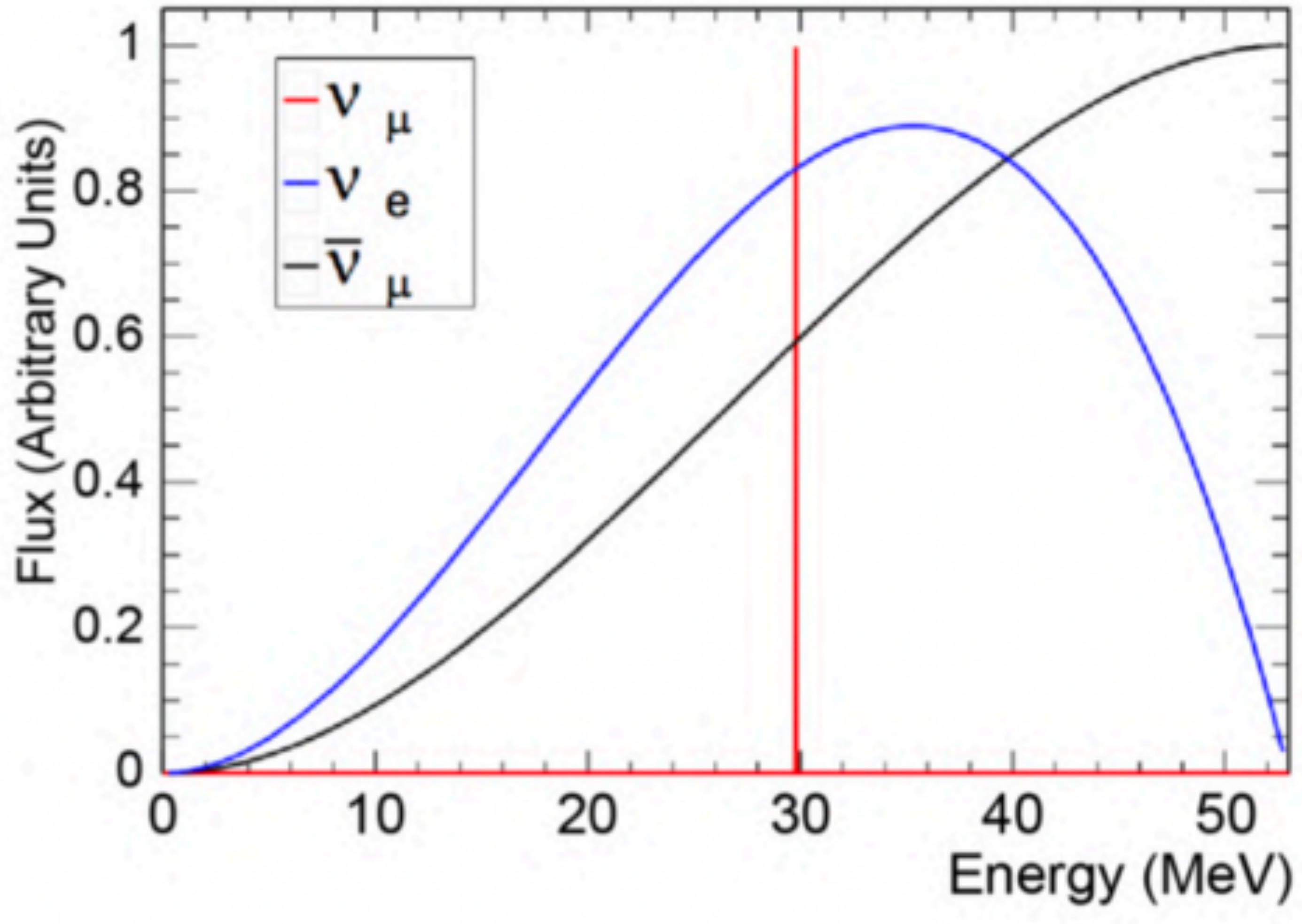
CCM200 Physics Run (2023-2025)

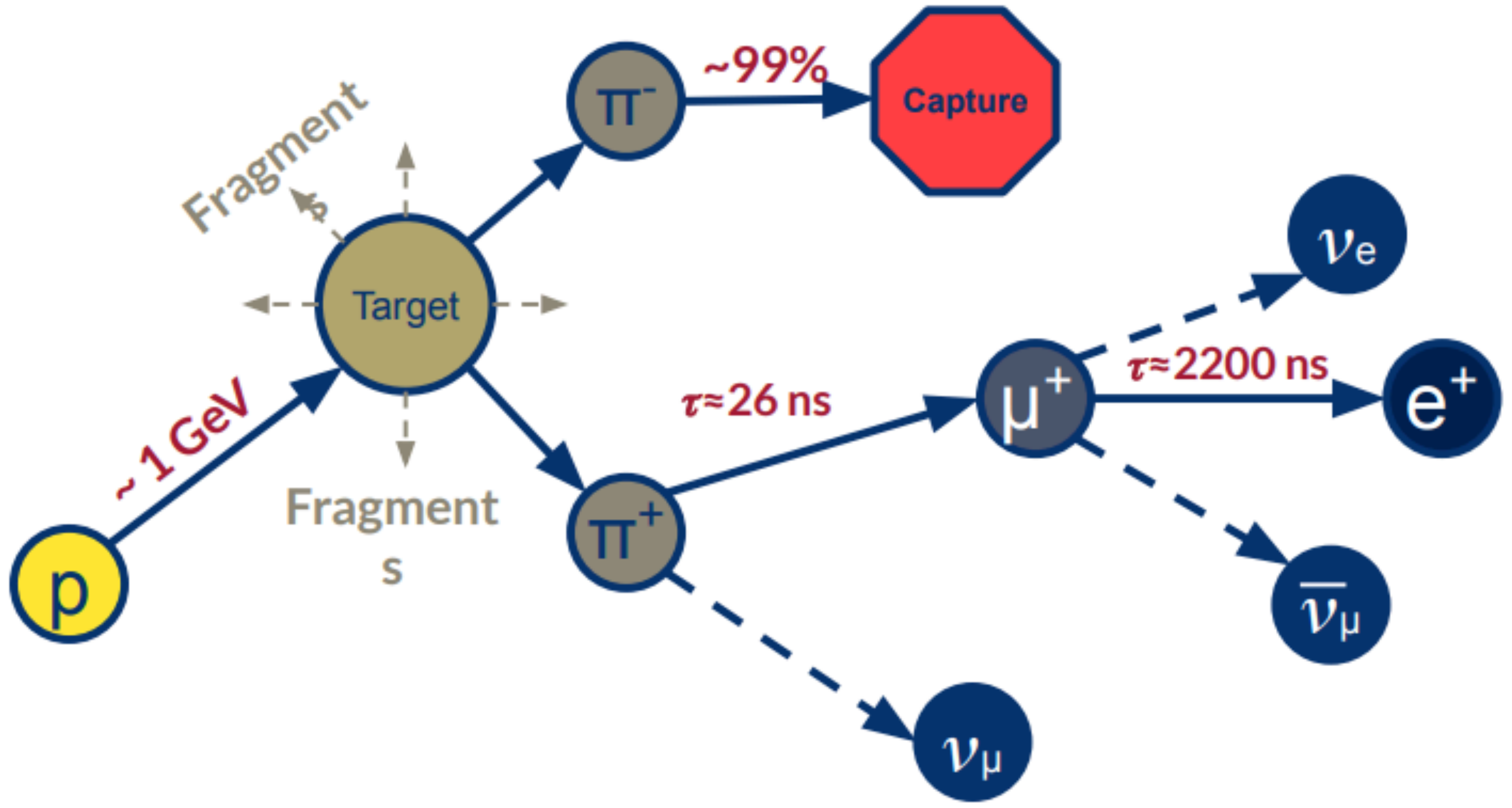
- Improved DAQ
- Installed additional top-shielding
- Pursing higher energy calibration

CCM120 physics results published here and here!

Neutrino production at LANSCE

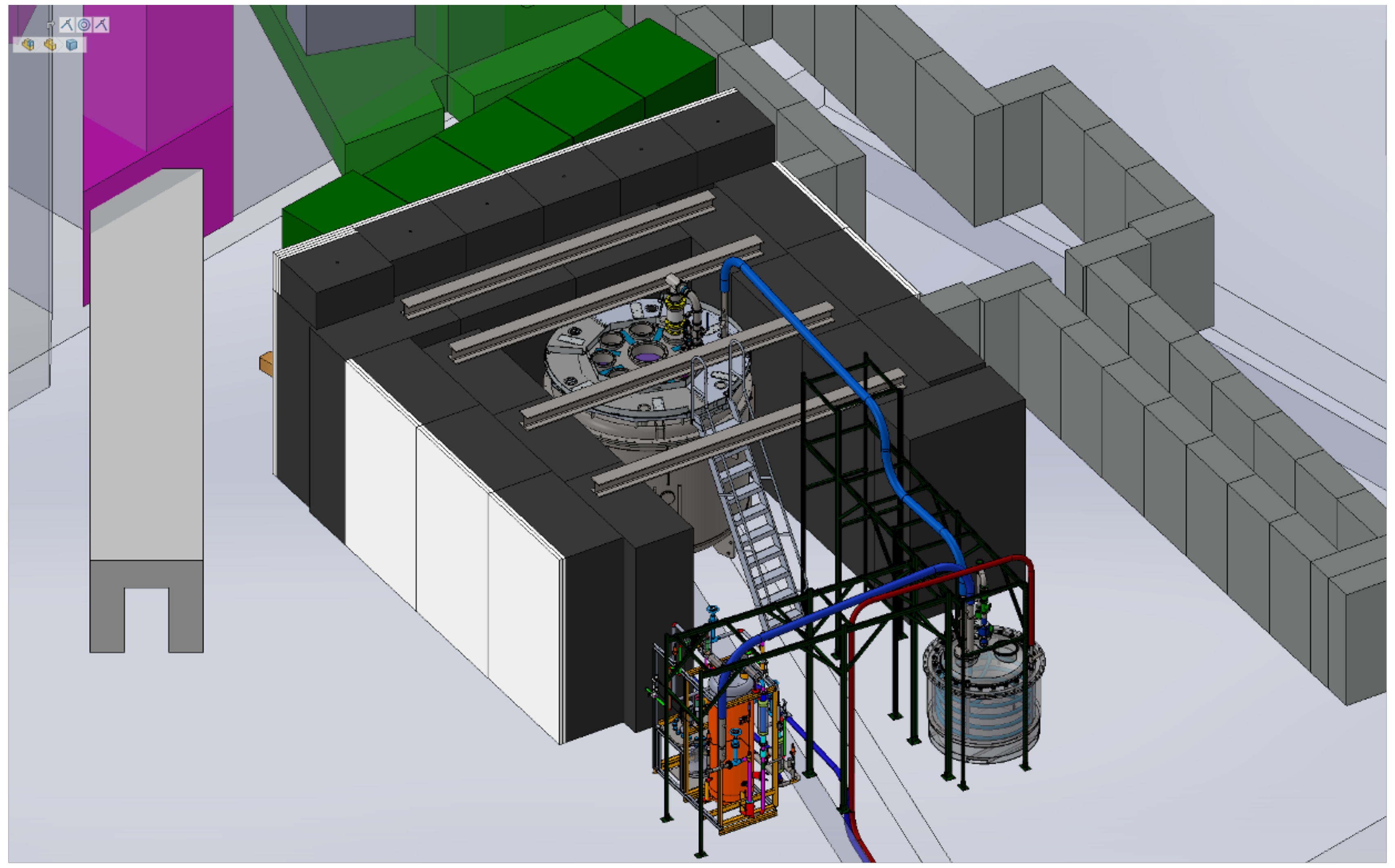
- **800 MeV pulsed proton beam** (20 Hz, 100 μAmp current, and 290 nsec beam spill) incident on **tungsten target**
- Prolific source of neutrinos from π^+ DAR (flux of $5.28 \cdot 10^5$ ν /cm²/s at 23m from target)
- Above ground facility —> short beam spill window is necessary to reduce backgrounds from comic rays

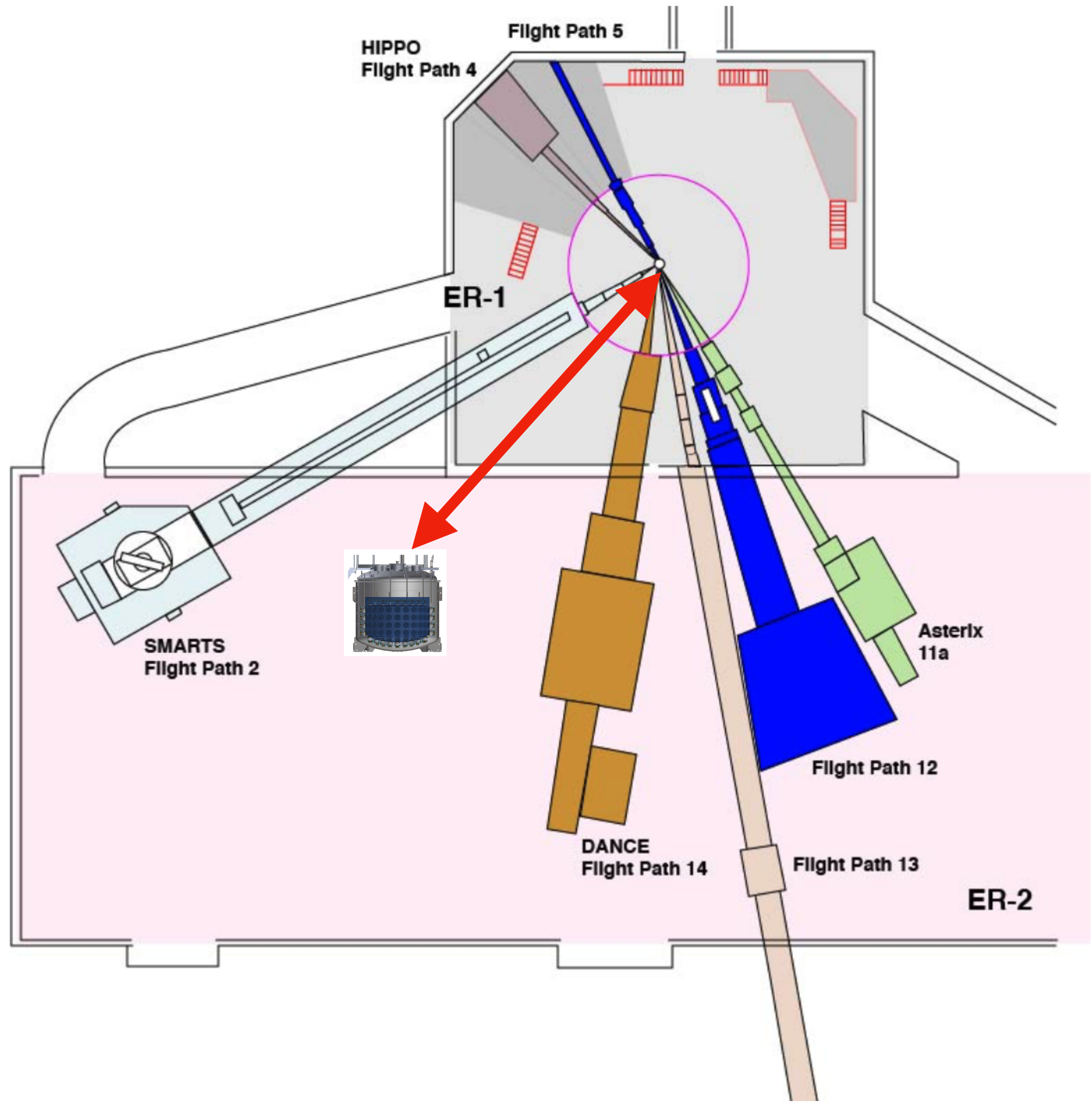




CCM at Lujan

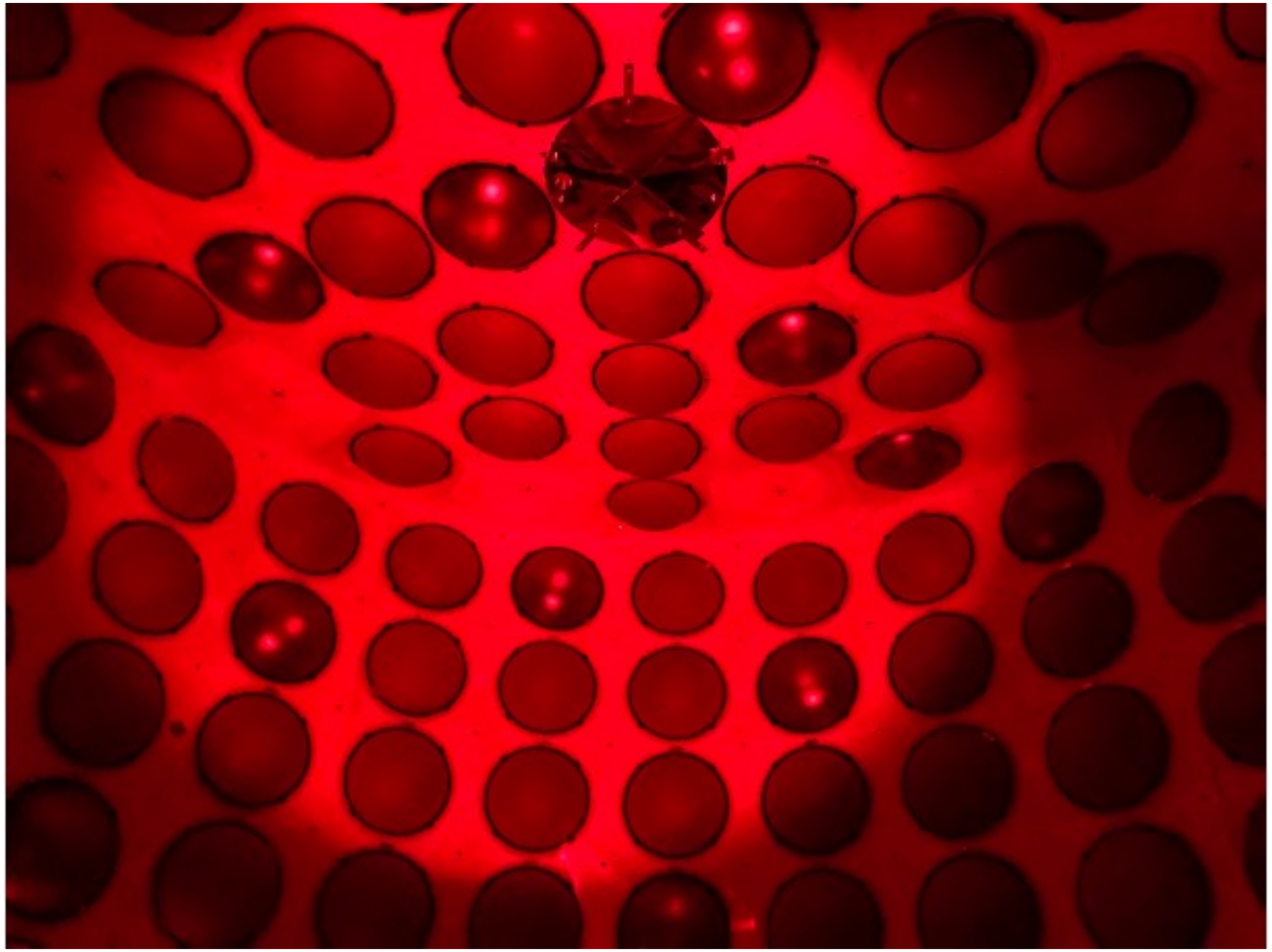
- Detector positioned **90° off axis** from the proton beam and **23m** from tungsten target
- **7 ton fiducial LAr volume, 50% photocoverage from 200 8” PMTs**
- **3 ton optically isolated active veto region** surrounding fiducial volume with 40 1” PMTs
- The Lujan facility will receive $2.25 \cdot 10^{22}$ POT in the ongoing 3 year run cycle





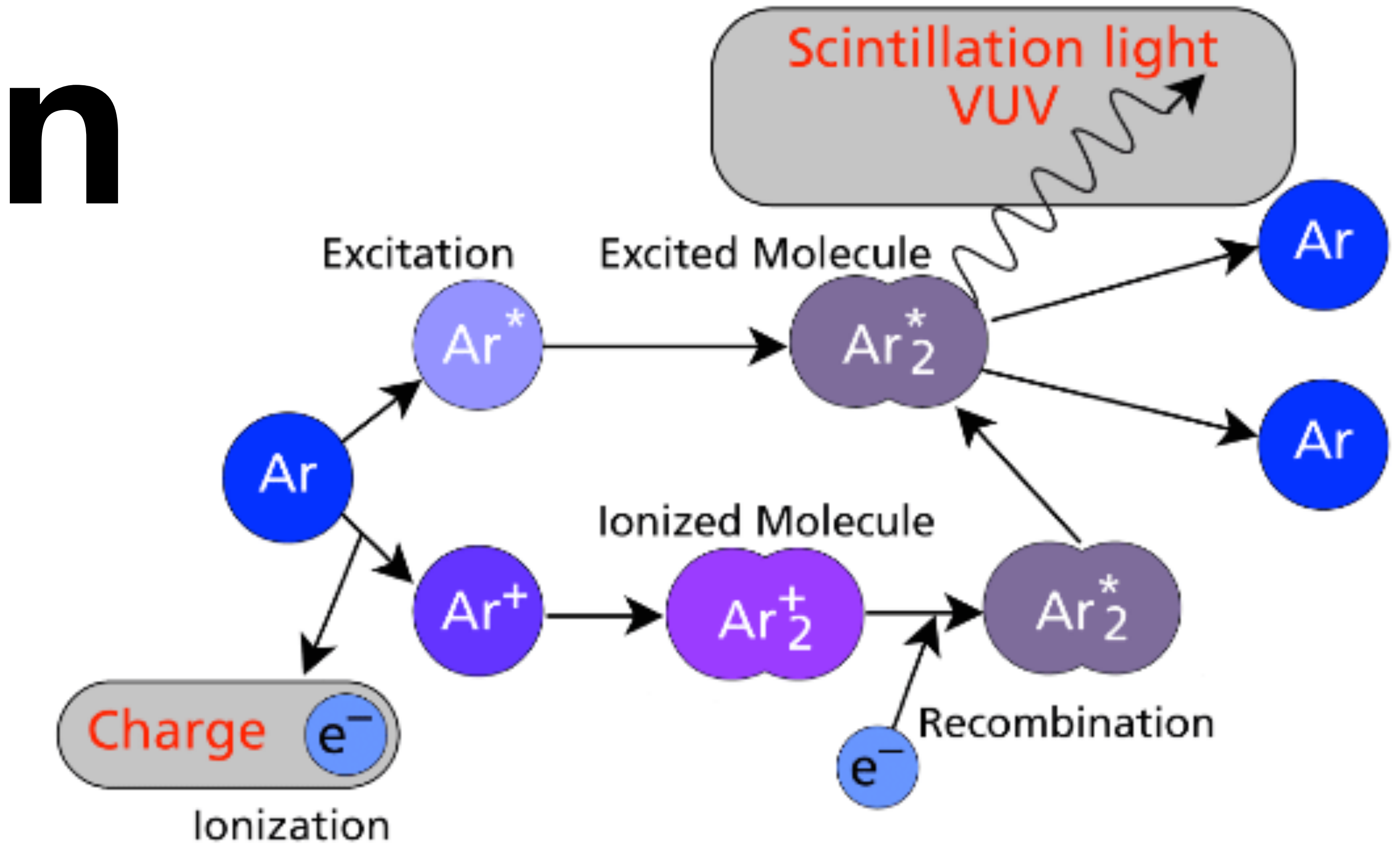
CCM200 Detector

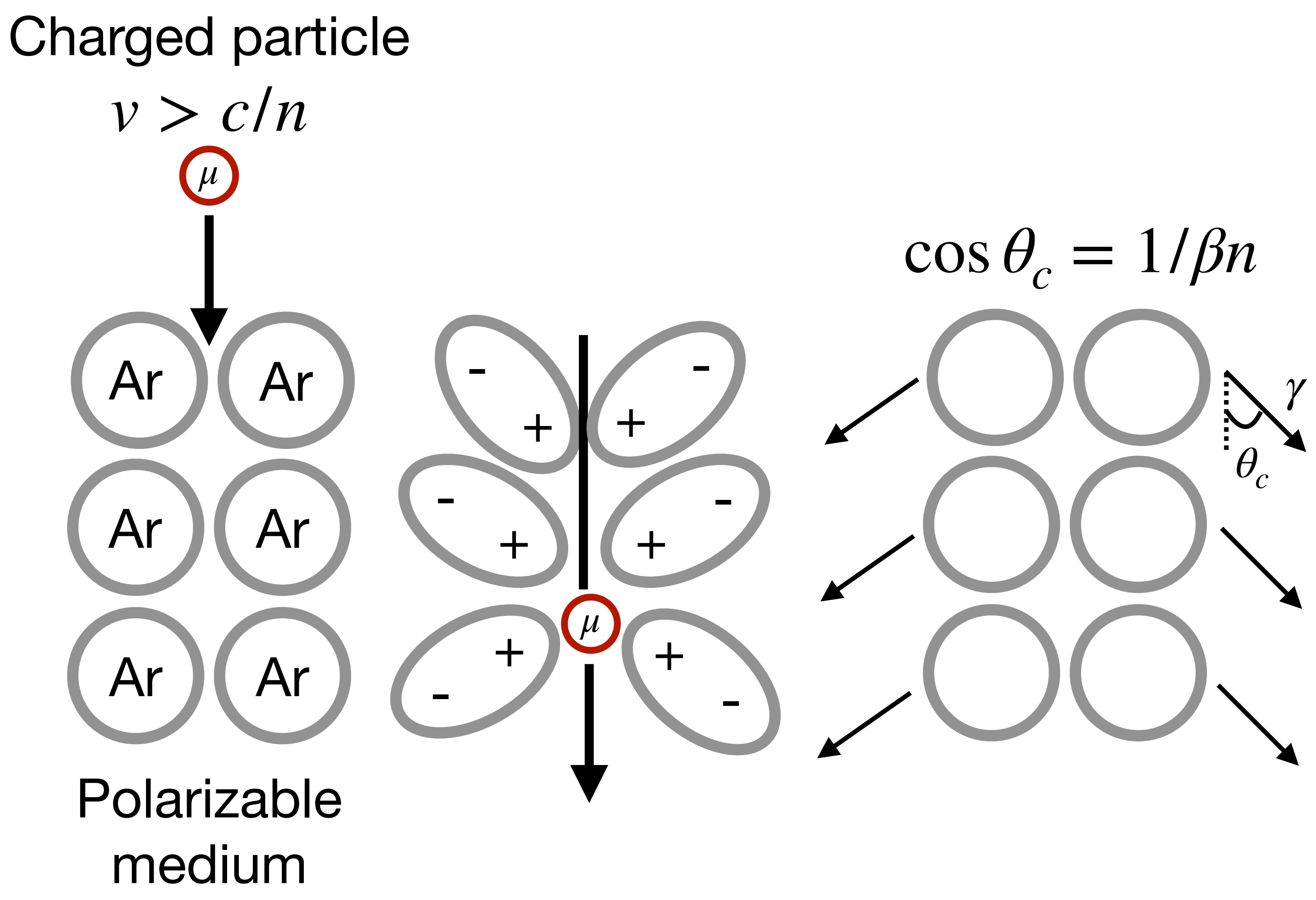
- 80% of PMTs coated in 1,1,4,4-Tetraphenyl-1,3-butadiene (TPB) to **wavelength shift LAr scintillation light**
- TPB foils on walls of the detector
- Fast timing — **2nsec** resolution from digitizers
- Energy detection range from ~100 keV to ~2 GeV



Light Production in Liquid Argon

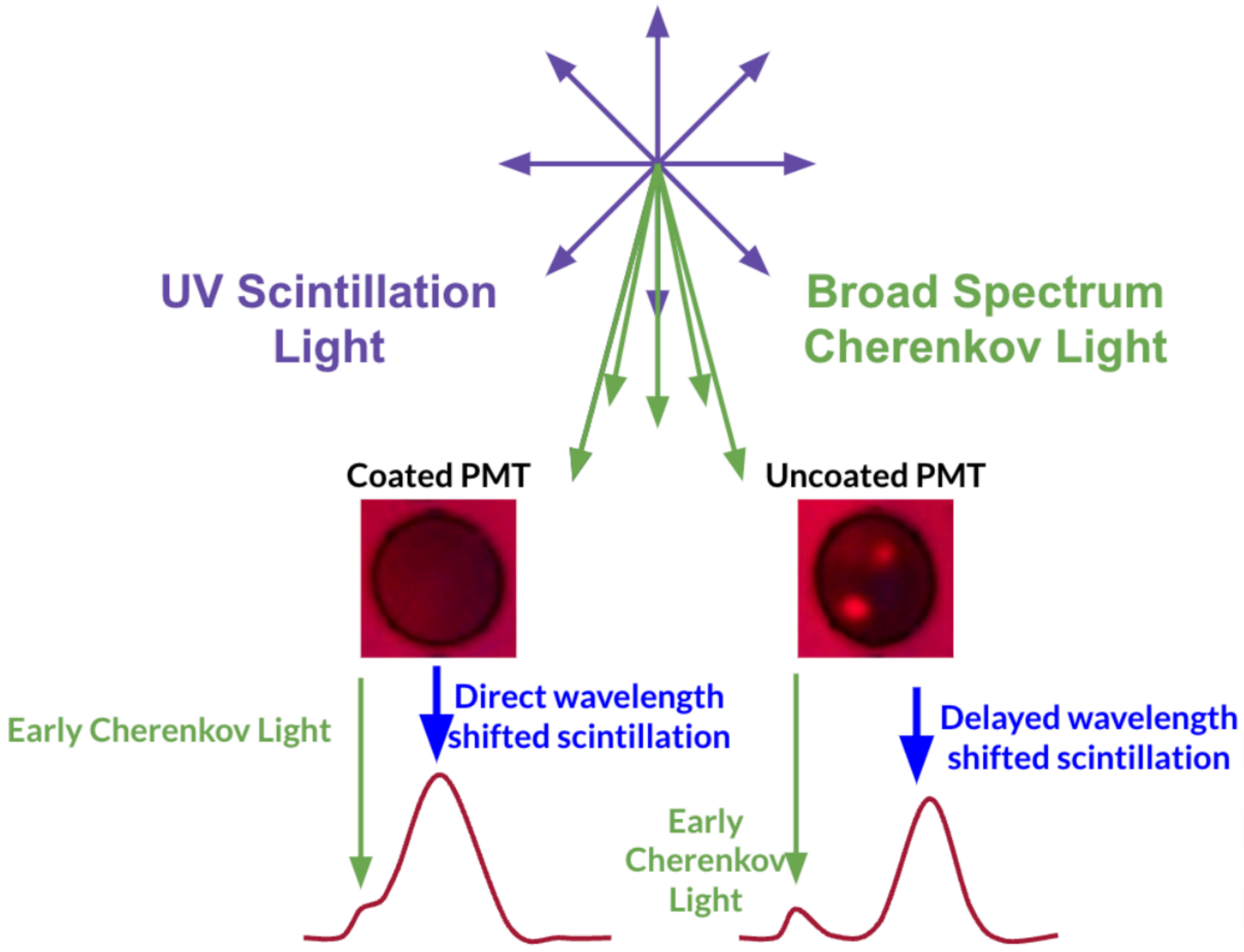
Quality	Scintillation Light	Cherenkov Light
Intensity (for a MIP)	~40,000 photons/MeV	~ 700 photons/MeV (wavelength > 100nm)
Direction	Isotropic	Directional
Timing	Fast component (nsec) and slow component (usec) measured by DEAP collaboration	Prompt (psec start)
Photon Wavelength	Spectrum peaks at 128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





Light Collection in CCM

- UV scintillation light can be directly detected by **only coated PMTs**
- Broad spectrum Cherenkov light can be directly detected by **coated AND uncoated PMTs**
- Wavelength shifted light from TPB re-emission can be detected by all PMTs
- Use 2nsec timing resolution to isolate early direct Cherenkov light hits in uncoated PMTs



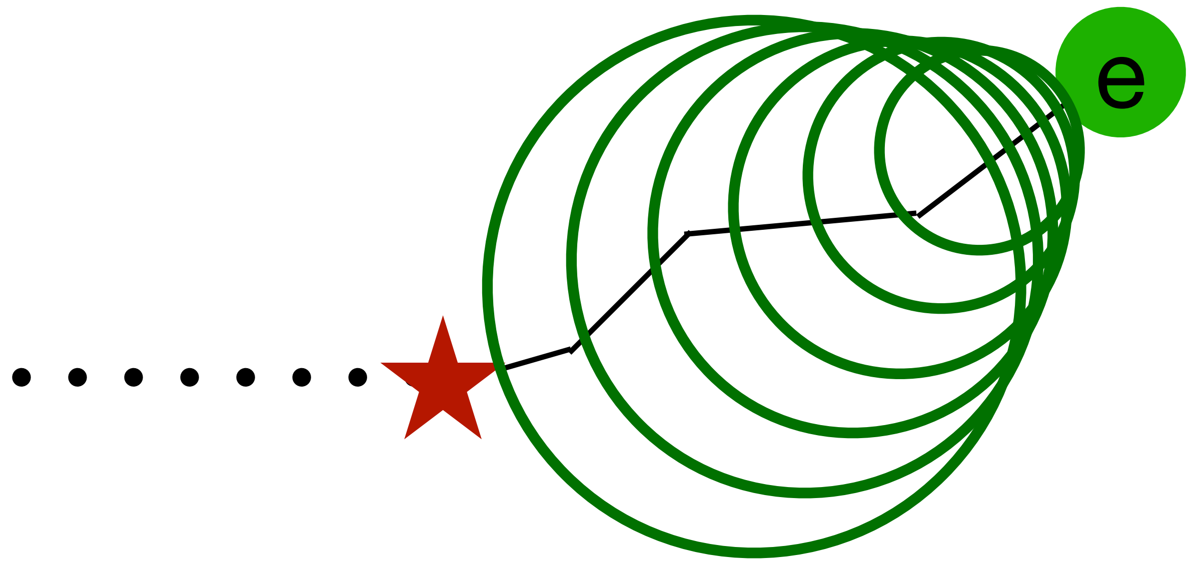
Cherenkov Light Identification

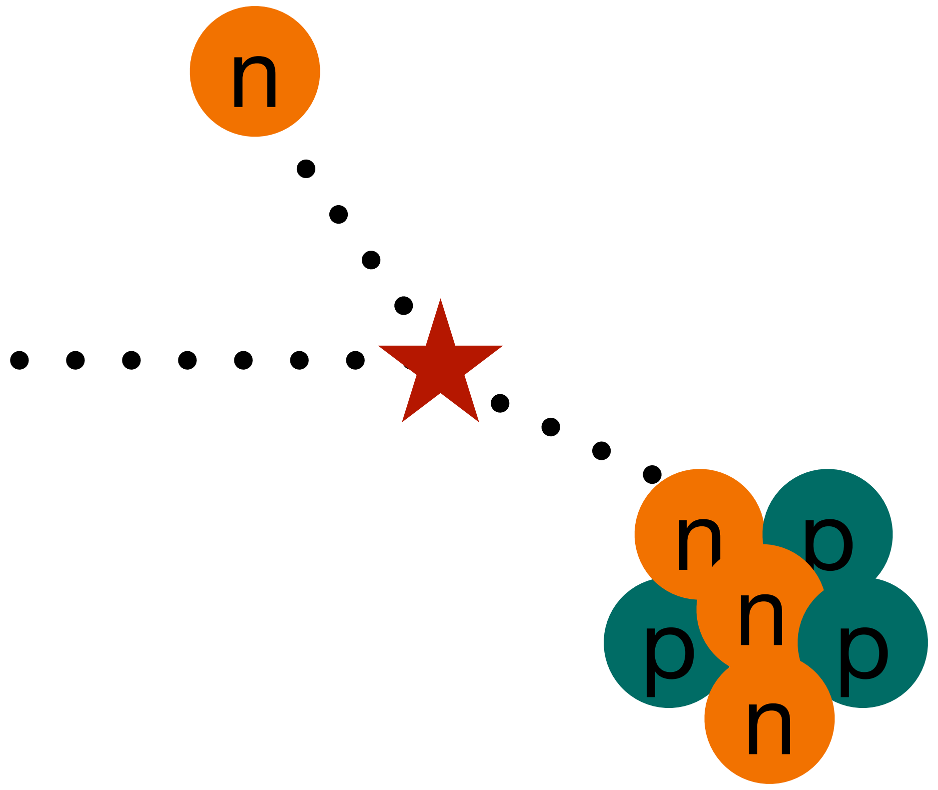
- Motivations
- Data driven approach

Cherenkov Light for Particle Discrimination

- At the most basic level Cherenkov light identification isolates **neutral from charged particles**

- Combining scintillation detectors — which have low energy thresholds and good energy resolution — with Cherenkov light detection for PID enables a broad physics program and powerful background rejection





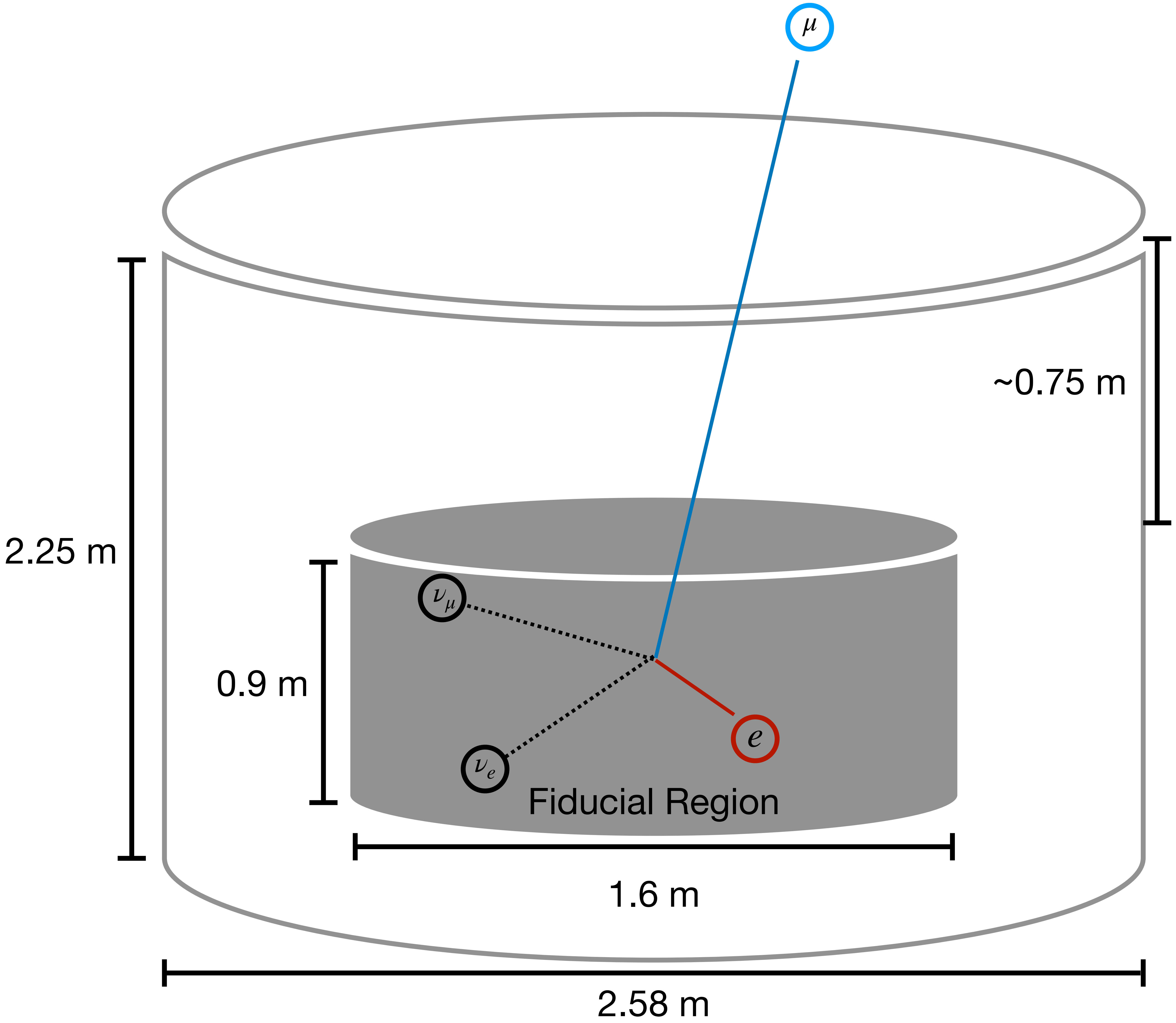
Experimental Efforts

1. Reduce scintillation light
   - Lightly dope liquid scintillator — most straightforward experimental technique
   - “Tuning” scintillation light yield to Cherenkov light yield
   - Drawback — reduces energy resolution and increases energy threshold
   - Example : LSND

2. Smarter light collection
   - Exploit differences in time spectrum though slower scintillator
   - Exploit differences in wavelength spectrum though light collection mechanism
   - Drawback — experimentally difficult
   - Examples : CCM, nuDOT, Borexino, THEIA

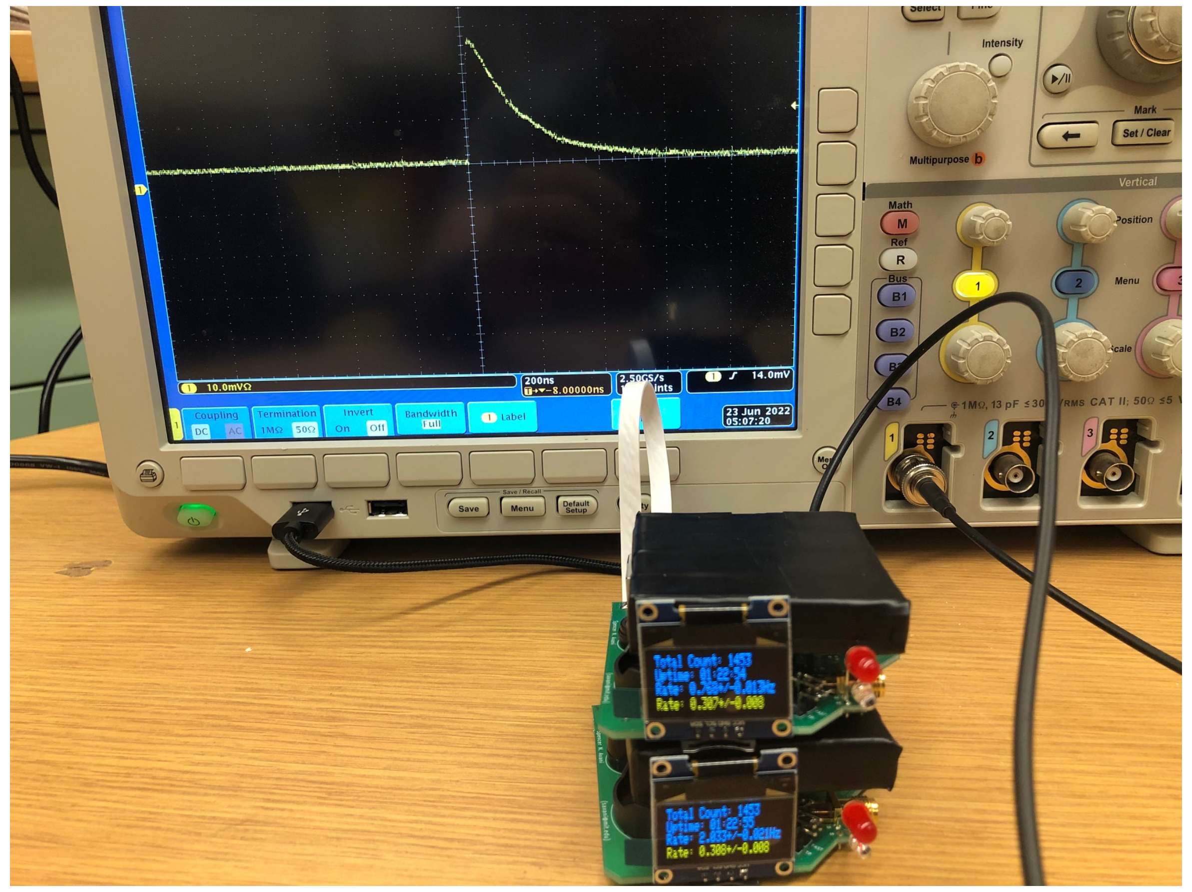
Our Approach

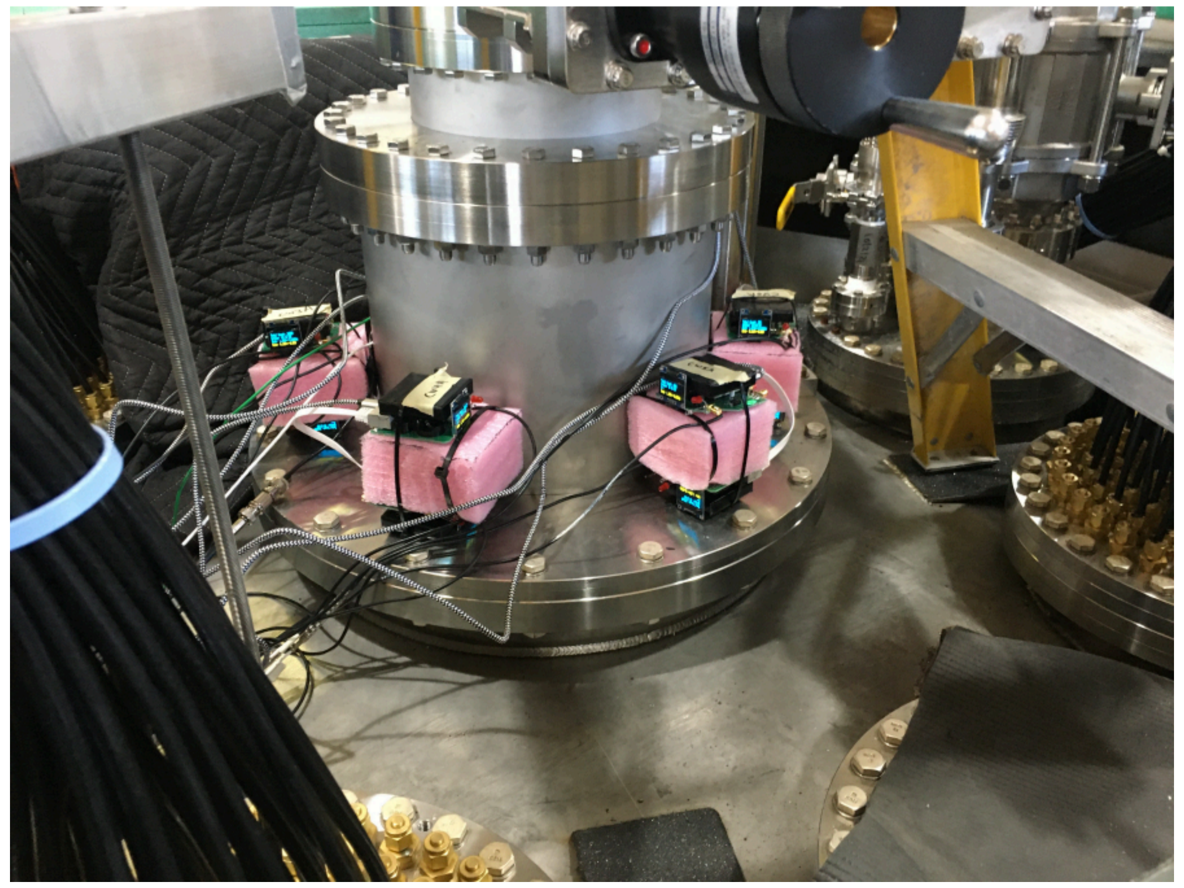
- Need a well known, bright source of Cherenkov light for developing identification procedure
- Cosmic ray muons that decay at rest produce Michel electrons with well known energy spectrum and energies up to ~50 MeV electrons
- Select cosmic muons entering CCM with a **dedicated cosmic muon trigger using CosmicWatch Detectors**



CosmicWatch

- Developed by Spencer Axani while graduate student at MIT
- Table top muon counters using plastic scintillator optically coupled to a SiPM
- Trigger on coincidence signal from pair of cosmic watch detectors located on top of CCM

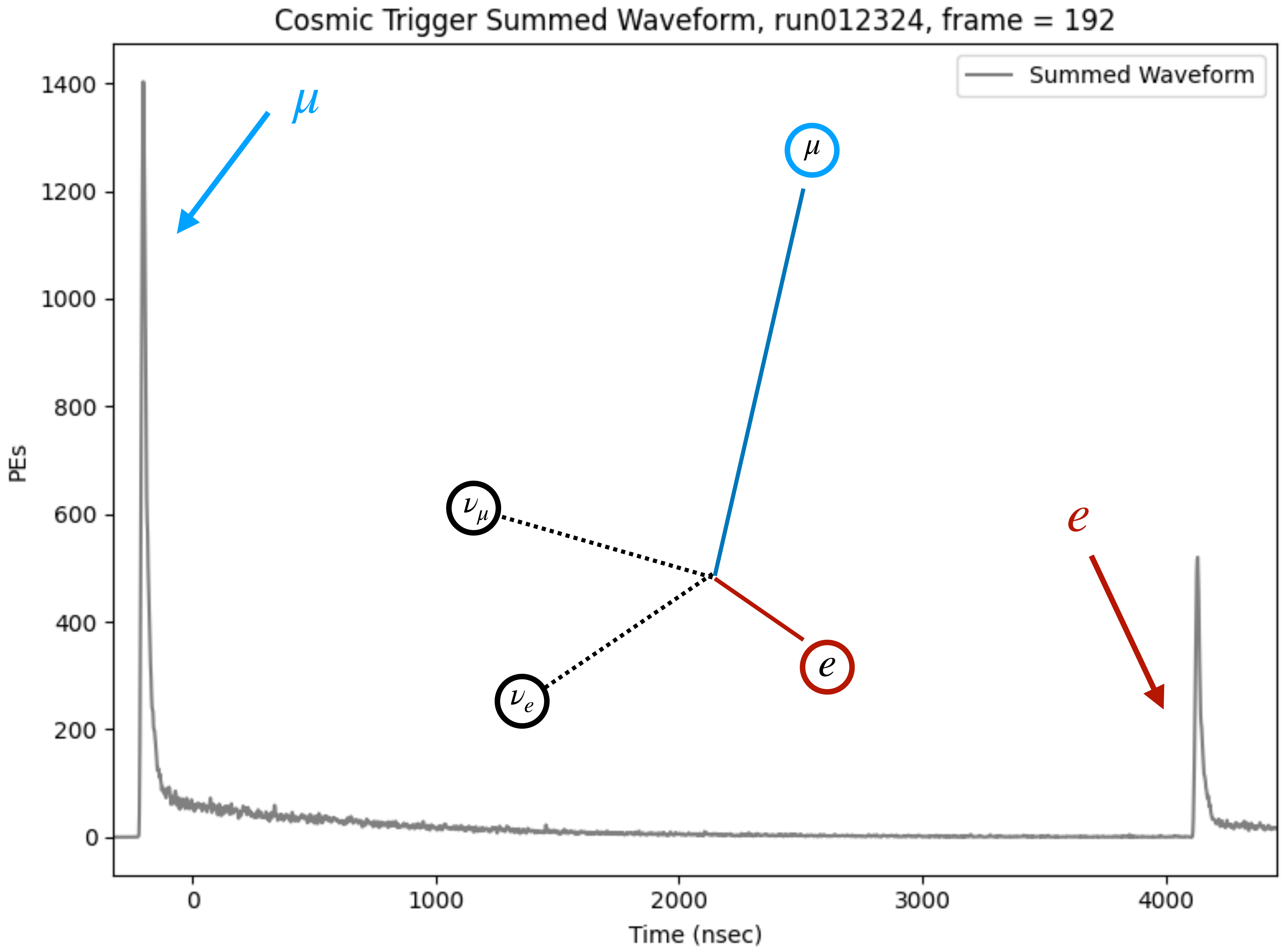




http://www.cosmicwatch.lns.mit.edu/

Example Cosmic Muon Decay

- Plot showing photoelectrons summed across all PMTs as a function of time for one cosmic trigger
- Muon deposits energy around trigger at t = 0 nsec
- About 4μsec later, additional energy deposit from Michel electron
- Dedicated cosmic trigger has rate of around 0.41 Hz

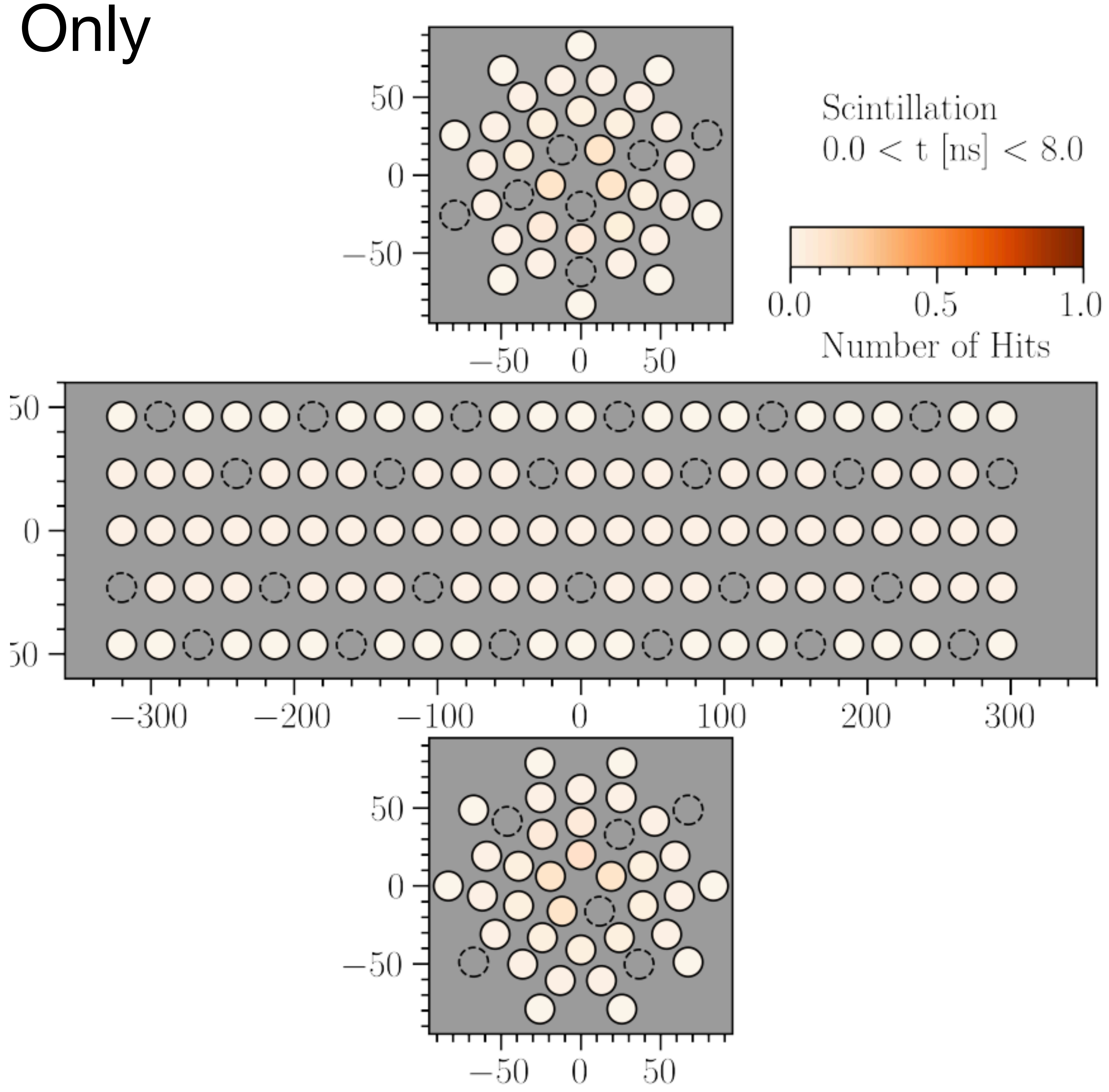


Simulation of 5 MeV Electron in CCM

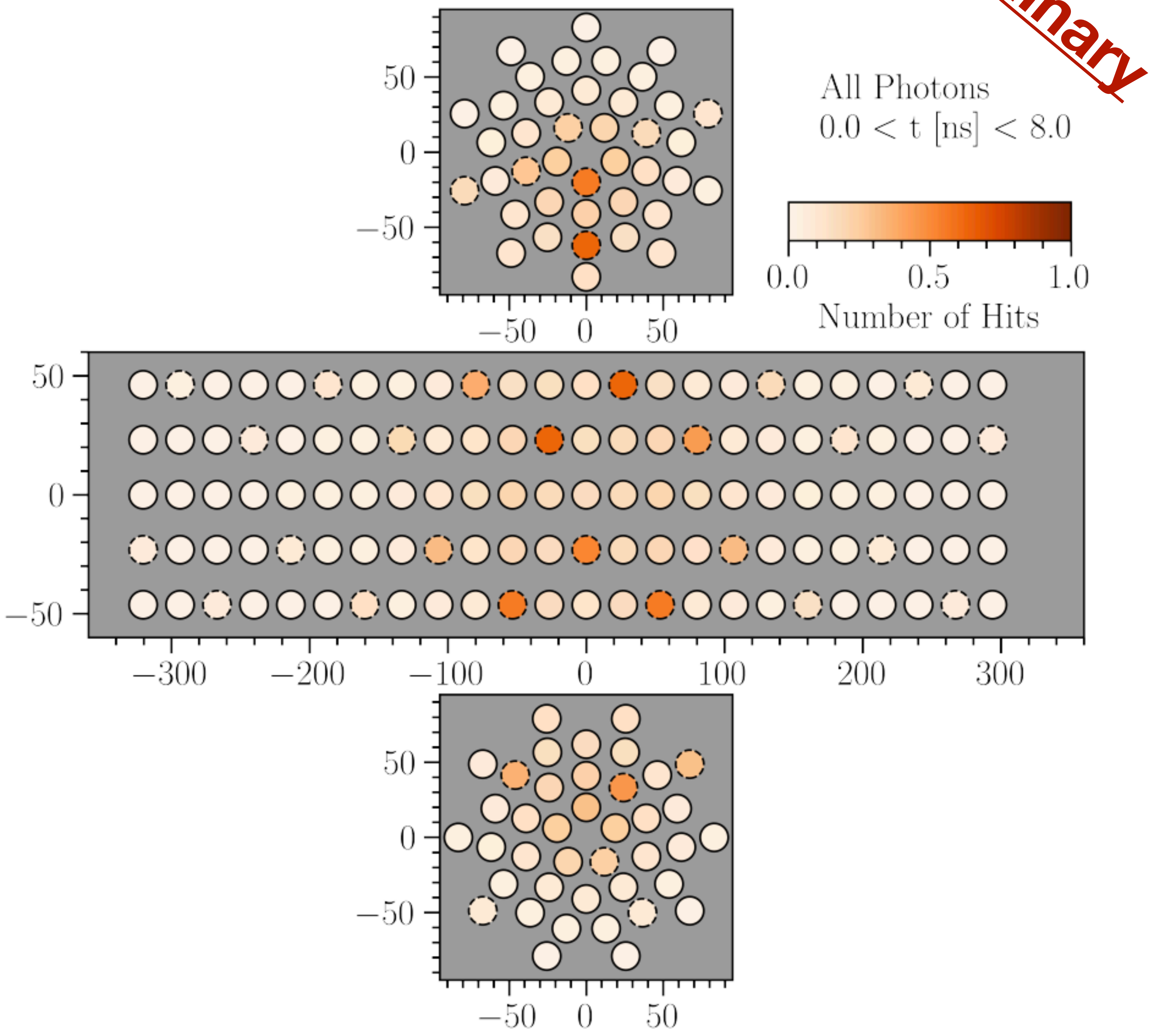
★ Direct Scintillation Hits Only

Preliminary

Scintillation Photons Only (No Cherenkov Light)

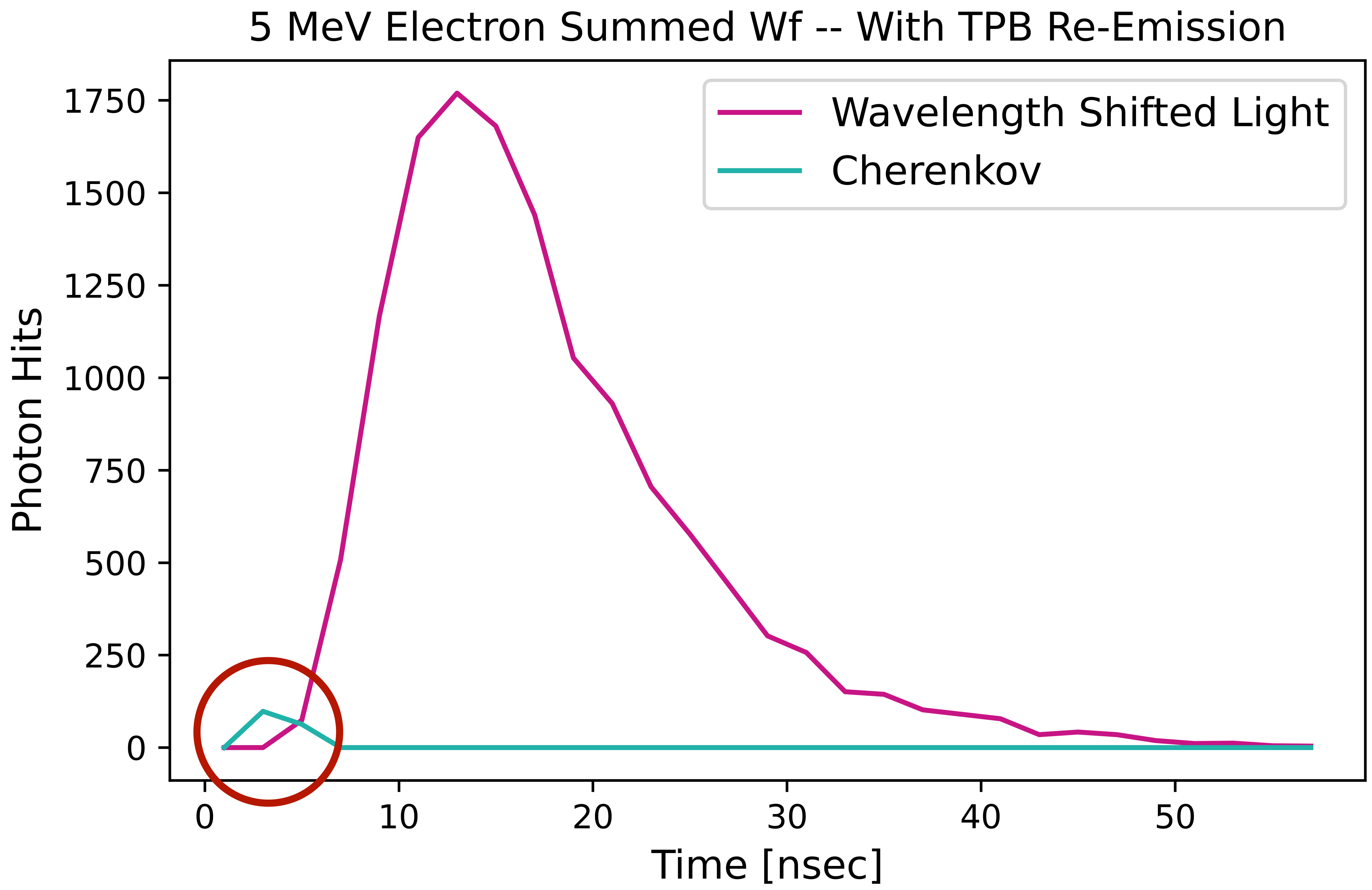


All Photons (With Cherenkov Light)

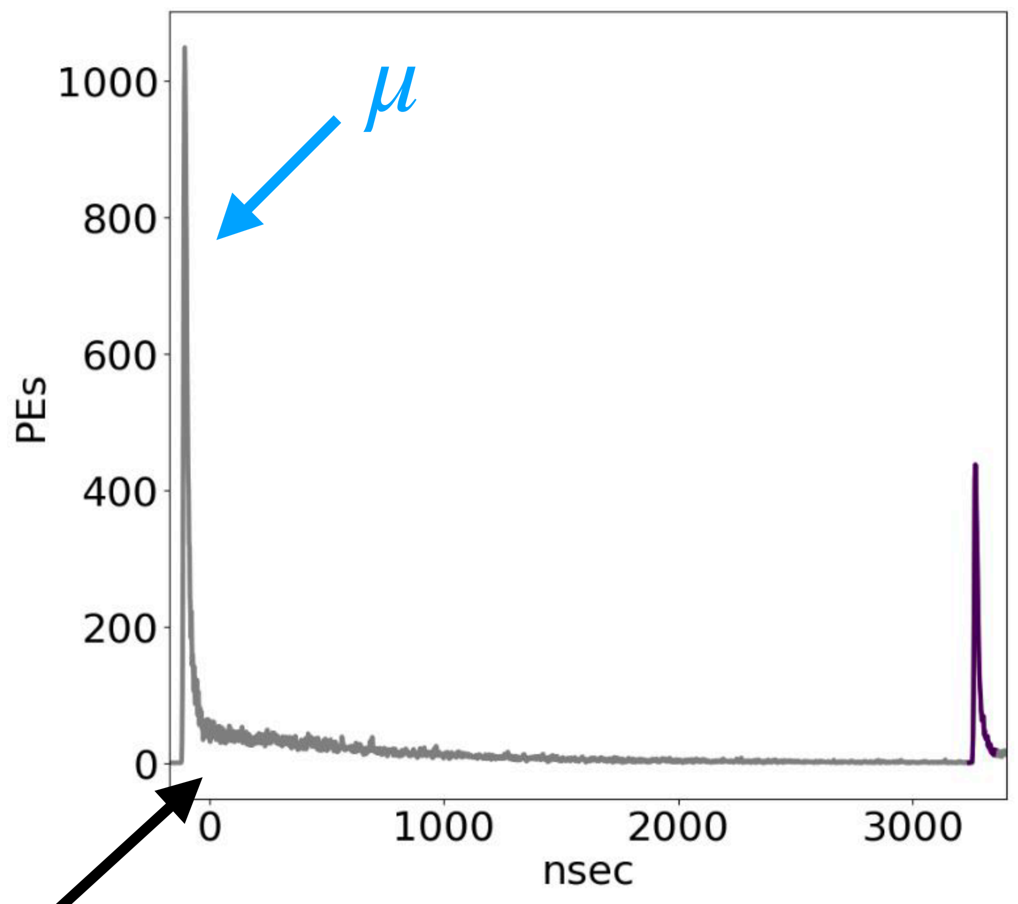


Time Structure from Simulation

- Injected 5 MeV electron at the origin of detector
- Plot showing photoelectrons summed across all PMTs as a function of time
- Cherenkov light is earlier and dimmer than scintillation light
- About 8 nsec after event start, TPB WLS light re-emissions become significant
- **Need excellent reconstruction of time structure to isolate Cherenkov light**



Cosmic Event

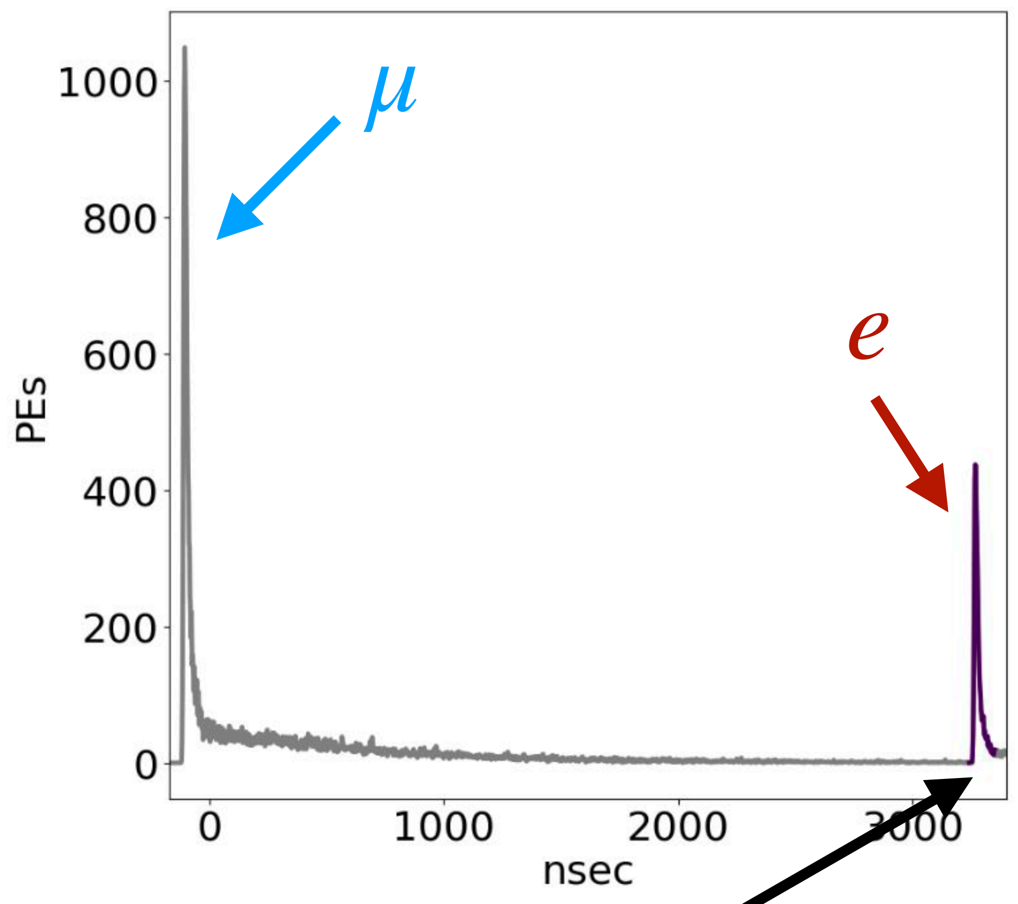


- Using cosmic triggers, we can look at data

- Muon enters detector, deposits scintillation light

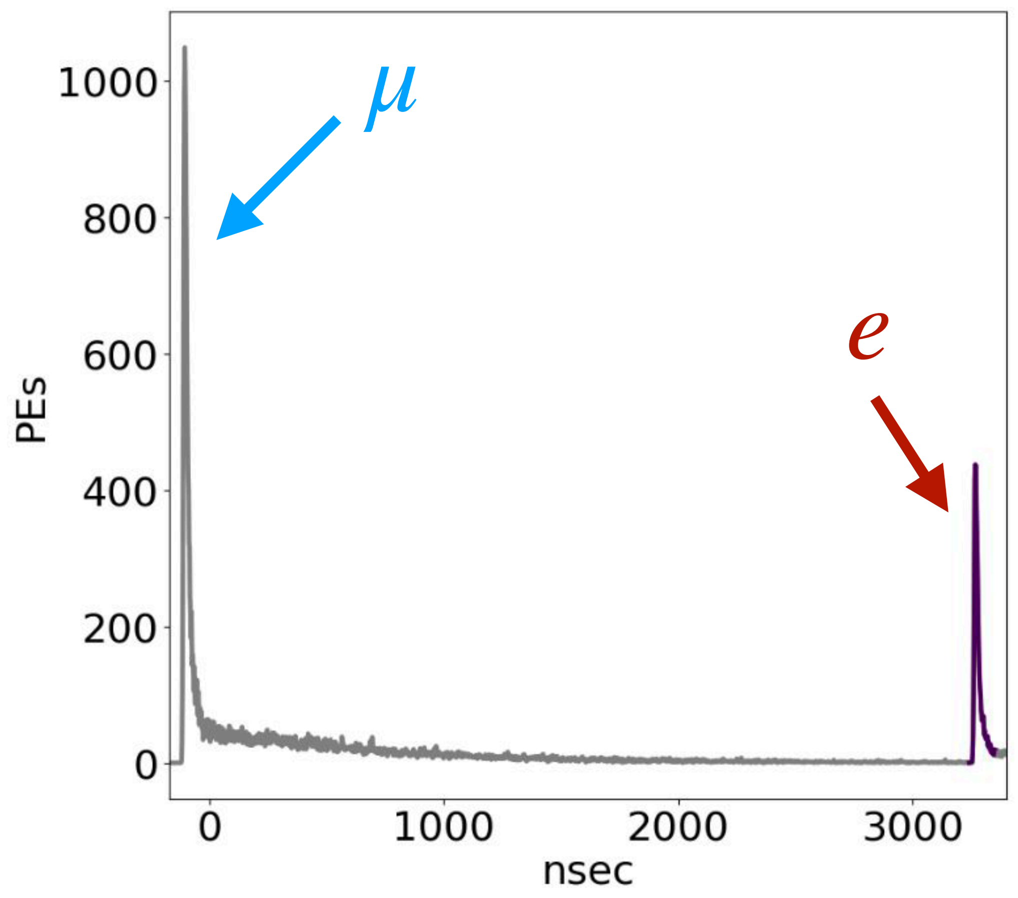
Cosmic Event

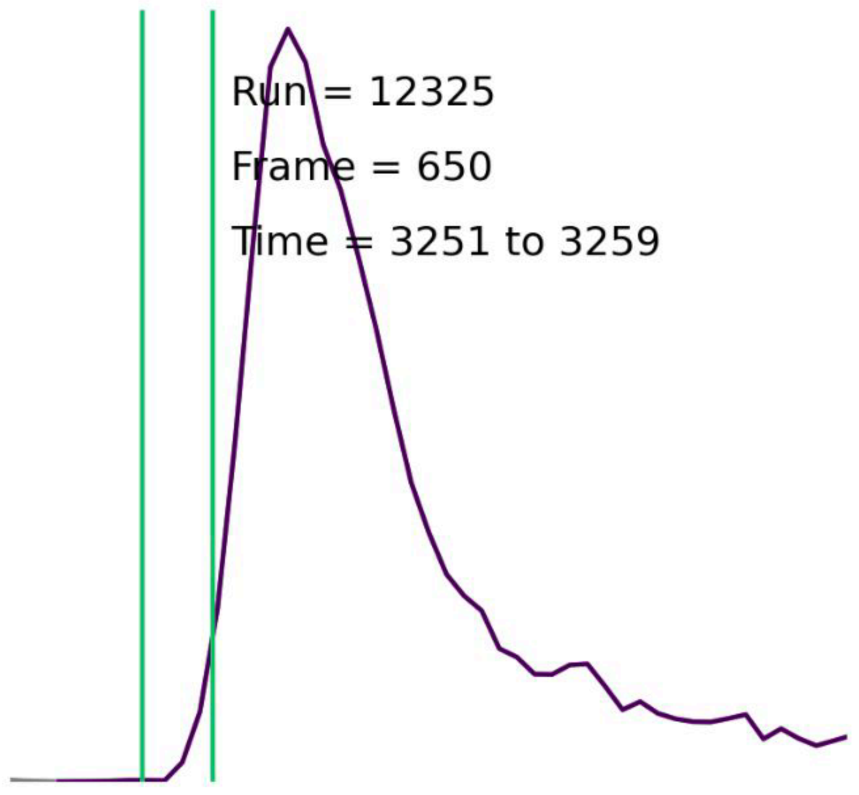
- Using cosmic triggers, we can look at data
- Muon enters detector, deposits scintillation light
- Stopped muon decays, emitting Michel electron about 3 μsec later



Cosmic Event

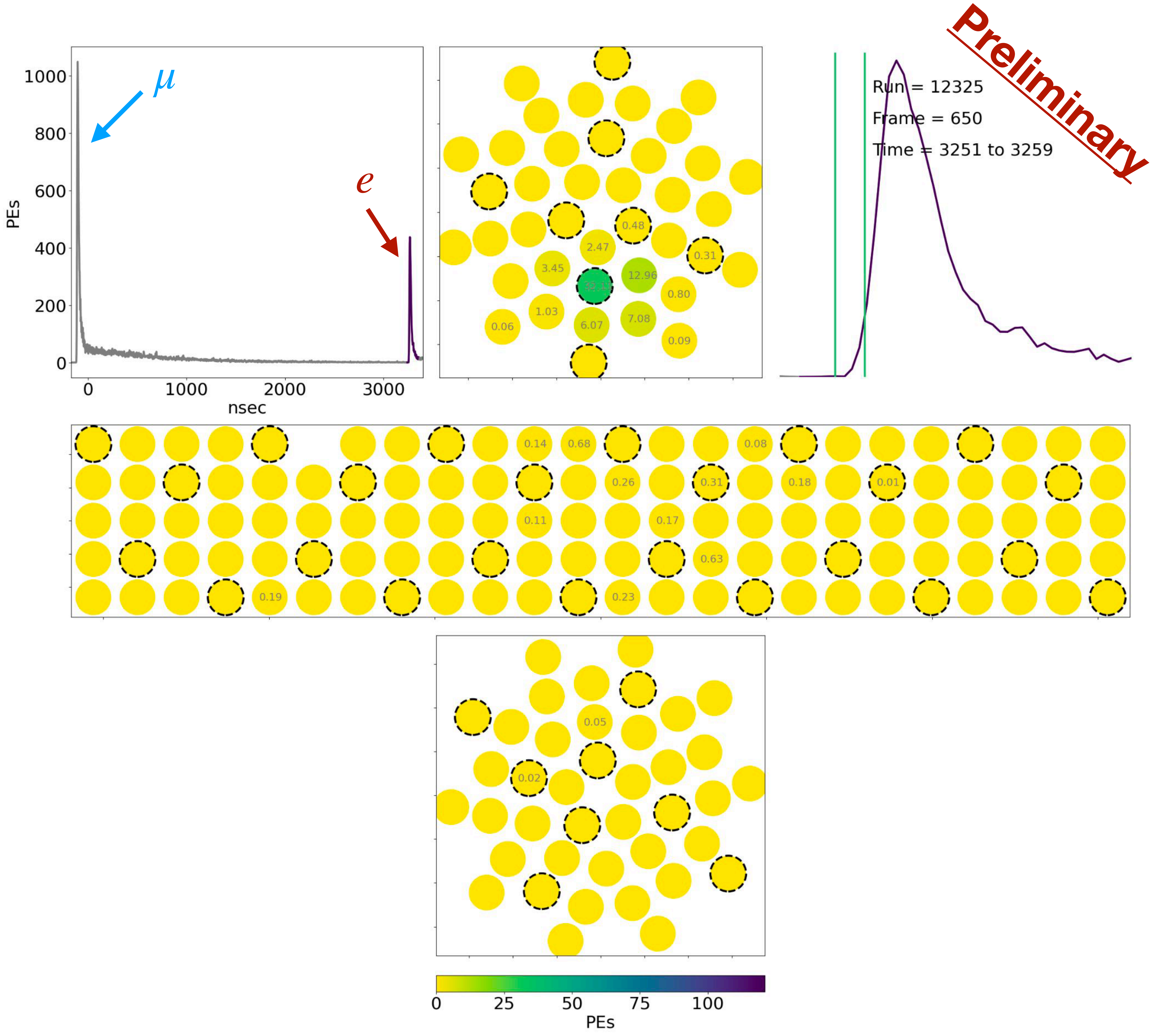
- Using cosmic triggers, we can look at data
- Muon enters detector, deposits scintillation light
- Stopped muon decays, emitting Michel electron about 3 μsec later
- Zoom in on first 8 nsec of Michel electron waveform





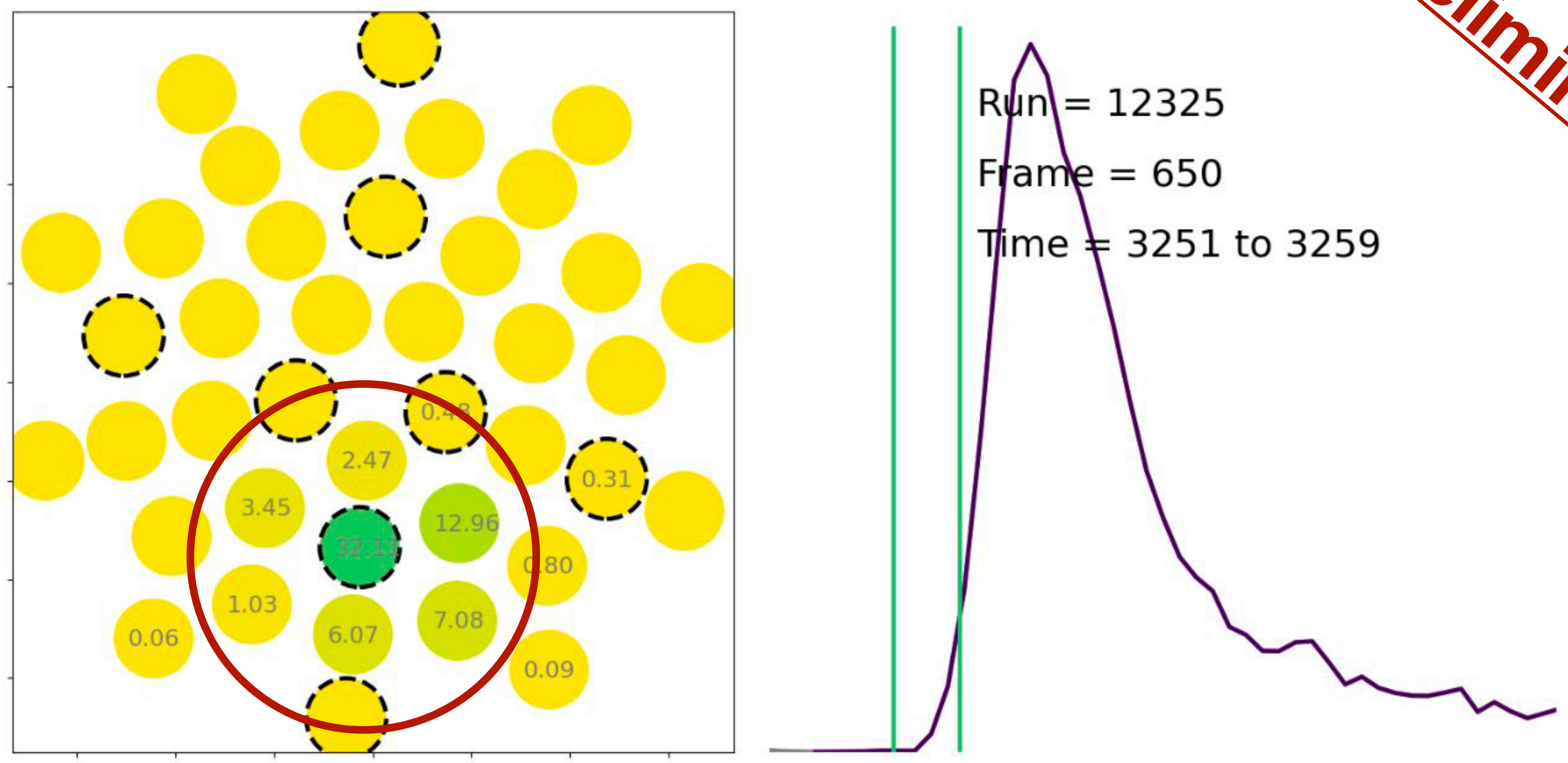
Cosmic Event

- Using cosmic triggers, we can look at data
- Muon enters detector, deposits scintillation light
- Stopped muon decays, emitting Michel electron about 3 μsec later
- Zoom in on first 8 nsec of Michel electron waveform — plotting spatial distribution of charge



Cosmic Event

- Uncoated PMTs are efficient at picking up initial direct Cherenkov photons in the visible spectrum
- Promising first demonstration of event by event identification of Cherenkov light in liquid argon
- Will provide an important reference point for developing **Cherenkov light based particle discrimination**



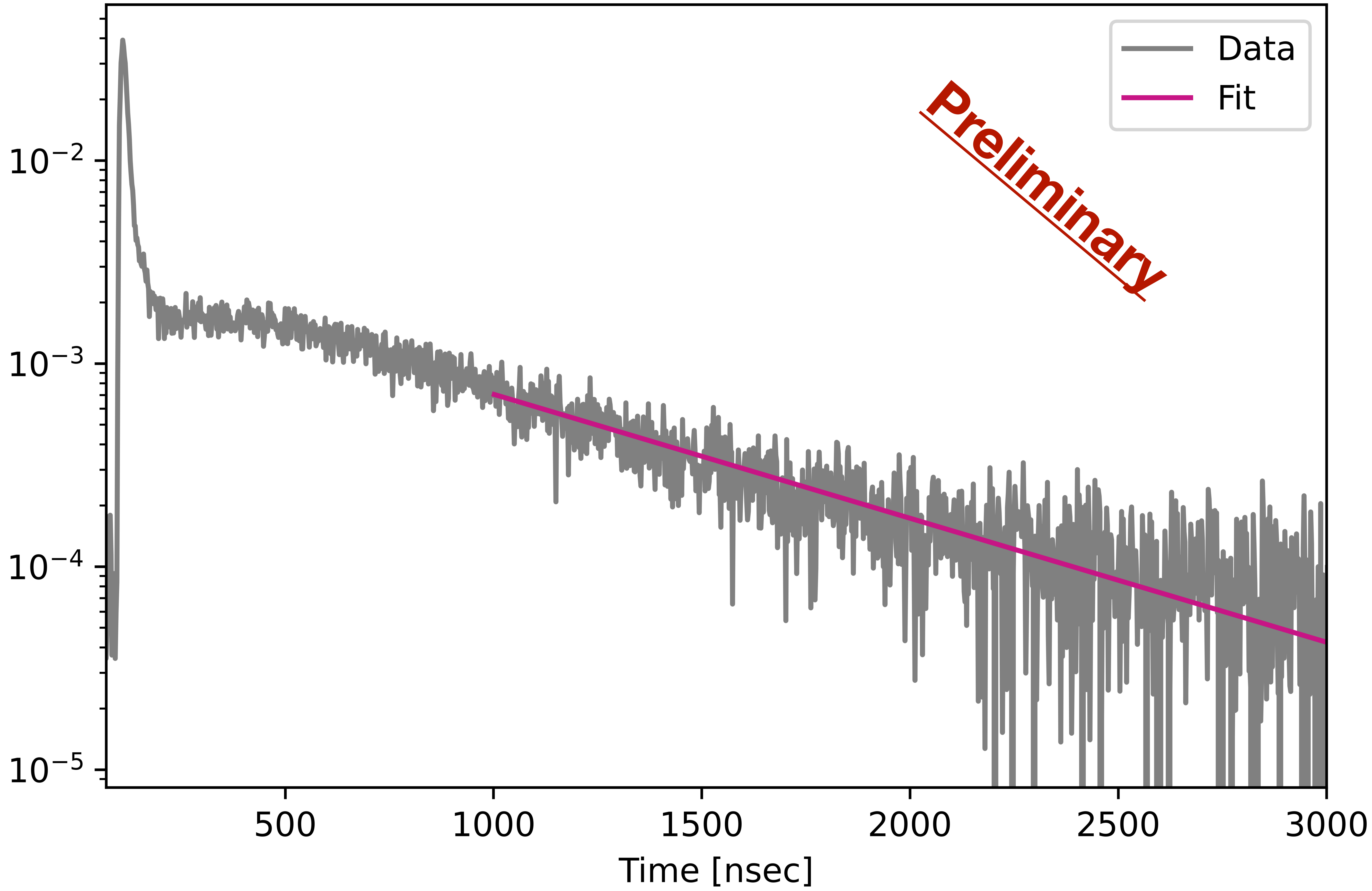
Preliminary

Ongoing Work

- Vertex reconstruction algorithm that leverages timing information
    - Fitting for LAr scintillation light profile
    - Derive template for scintillation light
- Simulation of Cherenkov rings
    - Using Geant4 based simulation
    - Derive template for Cherenkov light

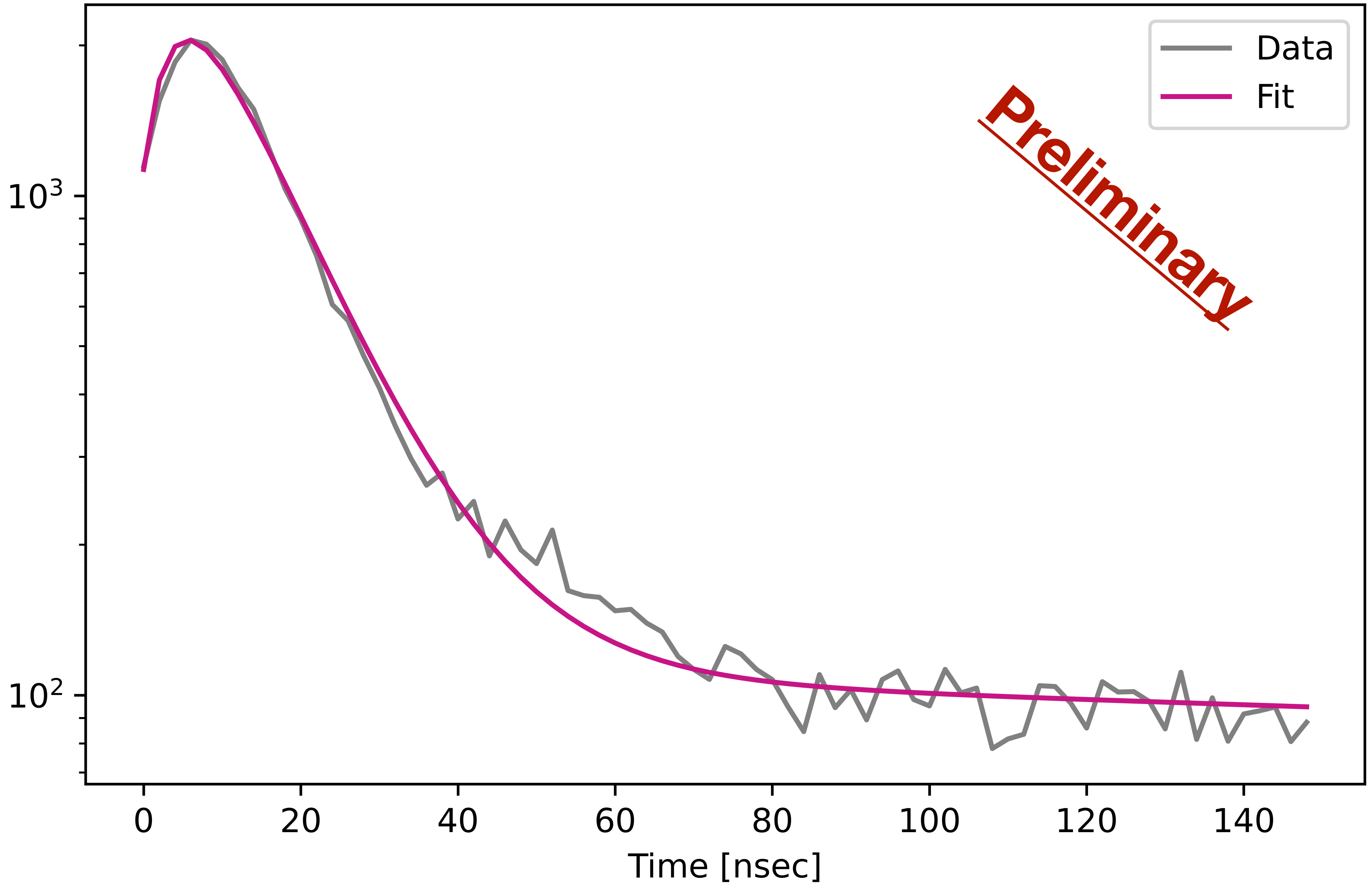
LAr Light Profile — Long Time Scale

- Using ^{22}Na calibration source, accumulate many events from β^+ decay
- Fit for long time constant decay from 1 - 3 μs from event start
- Measure long scale time constant τ ~ 743 nsec *(preliminary)*



LAr Light Profile — Short Time Scale

- For the prompt component, we model geometric effects analytically
- Fit for prompt decay constant and ratio of singlet to triplet light to early portion of the waveform
- Measure short scale time constant τ ~ 9 nsec *(preliminary)*



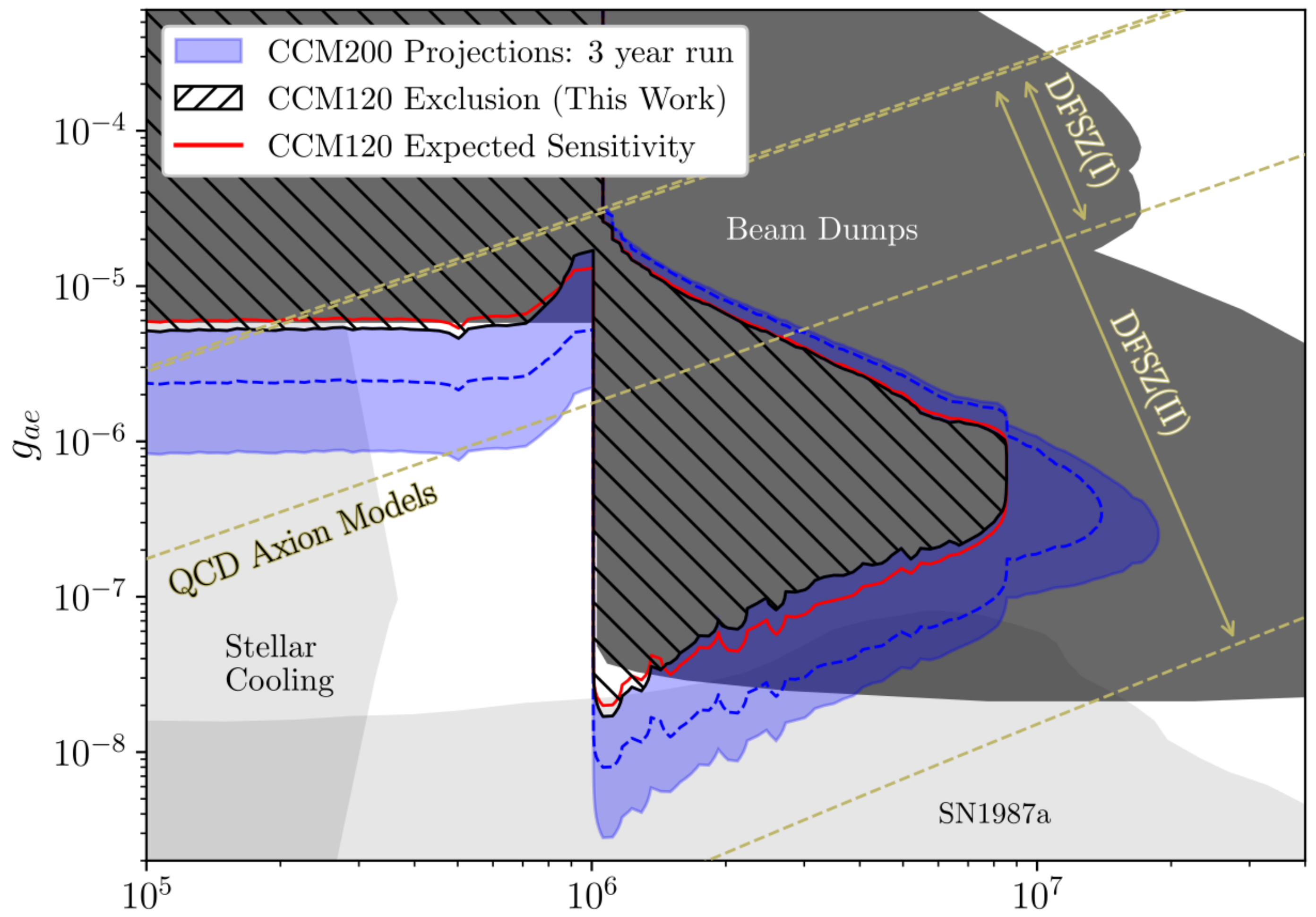
Physics Program

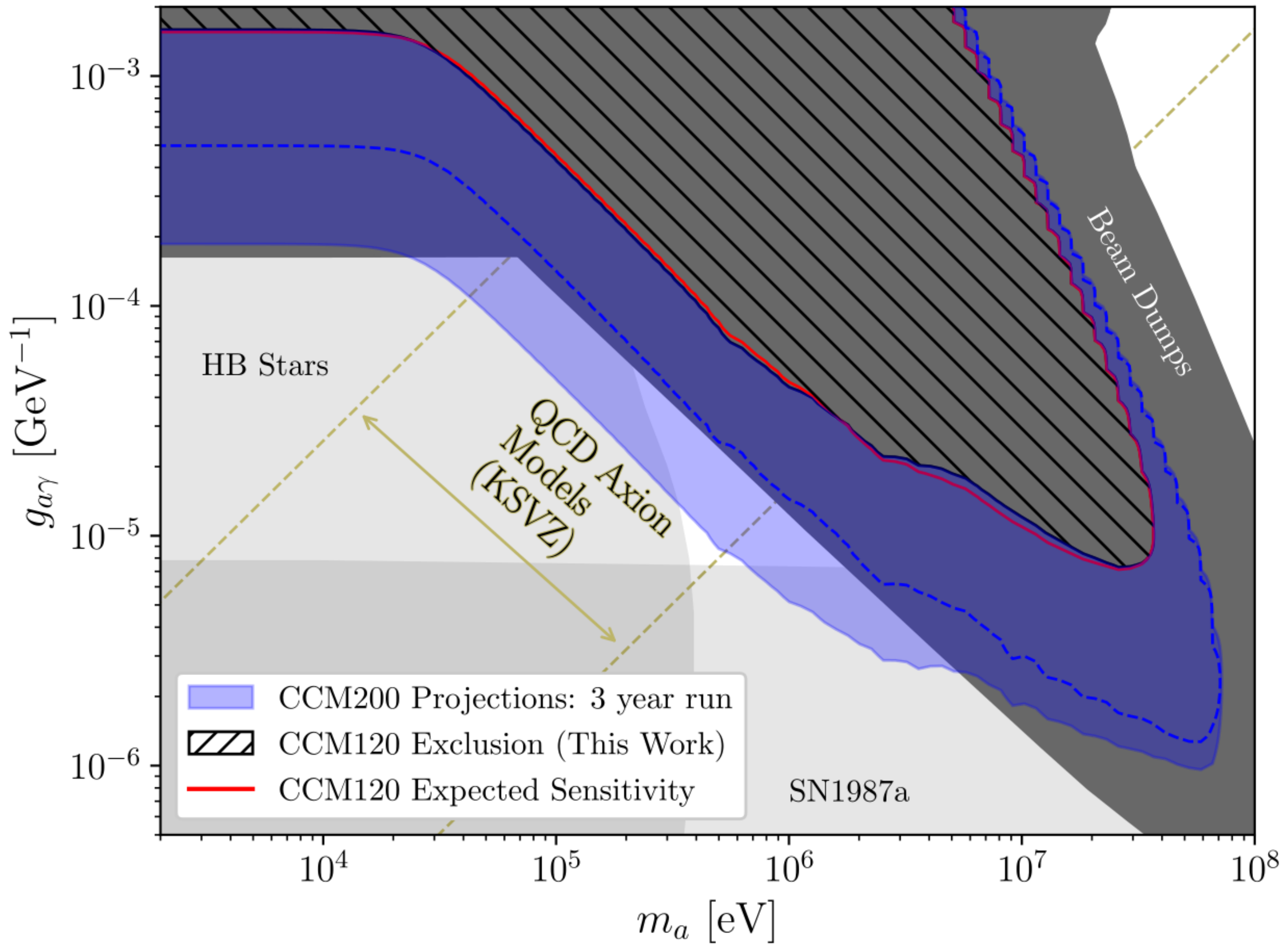
- Cherenkov light for background reduction
- Published physics searches

Final State Signals	**Electron/Photon**	**Nuclear Recoil**
Energy Range	~1 - 15 MeV	~100 keV
Scintillation Light	Yes	Yes
Cherenkov Light	Yes	No
Primary background	Neutron scatters	Low energy beta decays (^{39}Ar)
Background signal	Scintillation light only	Scintillation and cherenkov light

Physics Results Summary Plots

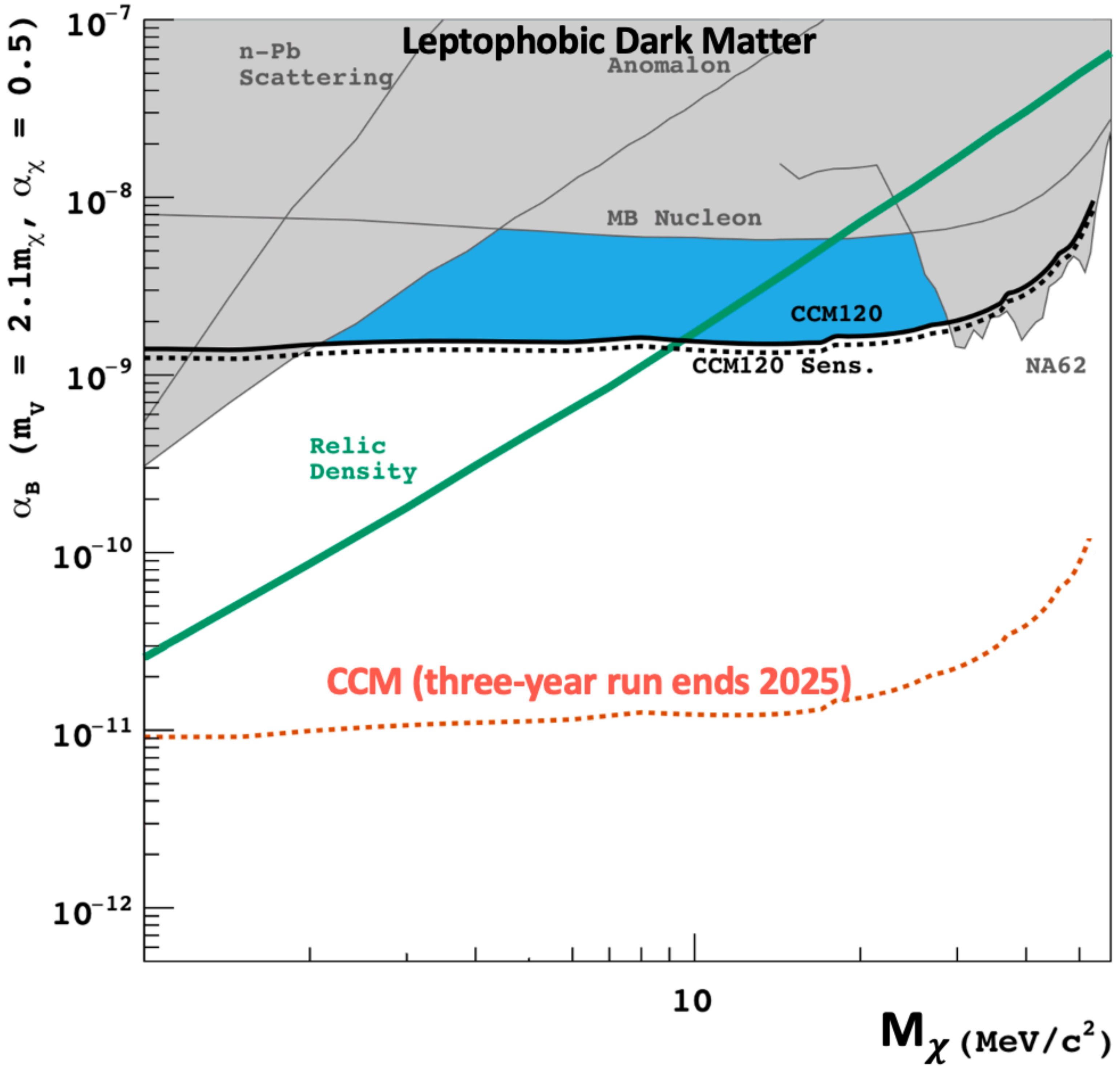
ALPs and QCD Axion





https://doi.org/10.1103/PhysRevD.107.095036

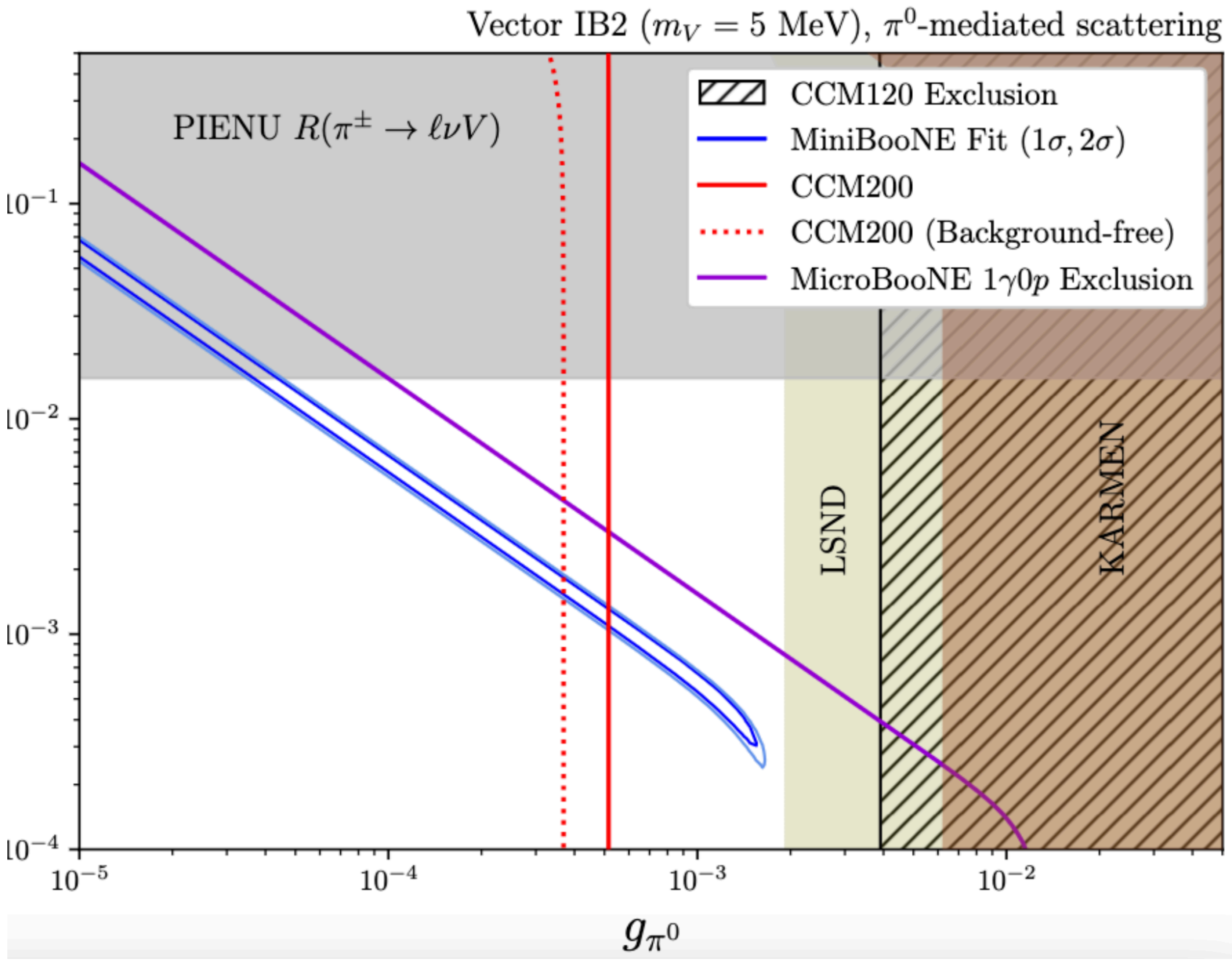
Light Dark Matter



https://doi.org/10.1103/PhysRevLett.129.021801

https://doi.org/10.1103/PhysRevD.106.012001

Dark Sector Coupling to Meson Decay



https://doi.org/10.1103/PhysRevLett.129.111803

https://doi/org/10.1103/PhysRevD.109.095017

Conclusion

Summary

- CCM200 has completed the first of a three year run cycle and will probe many new models/parameter space in the dark sector
- Cherenkov light separation in CCM is possible because of precision timing and combination of coated and uncoated PMTs
- Event by event identification of Cherenkov light program is ongoing

Thank you for listening!

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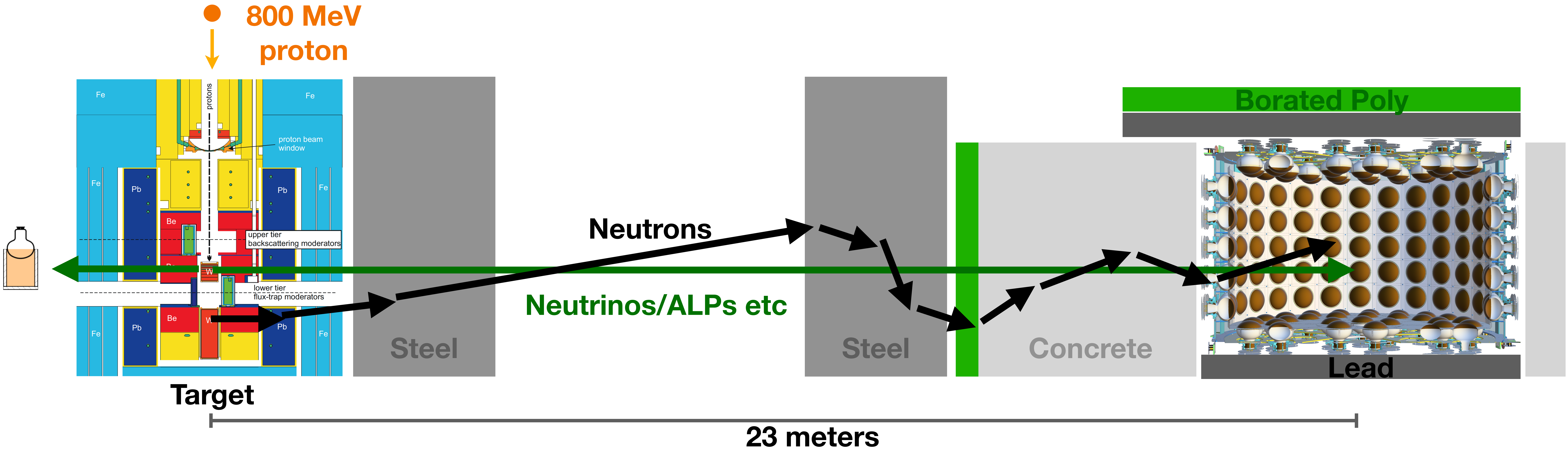
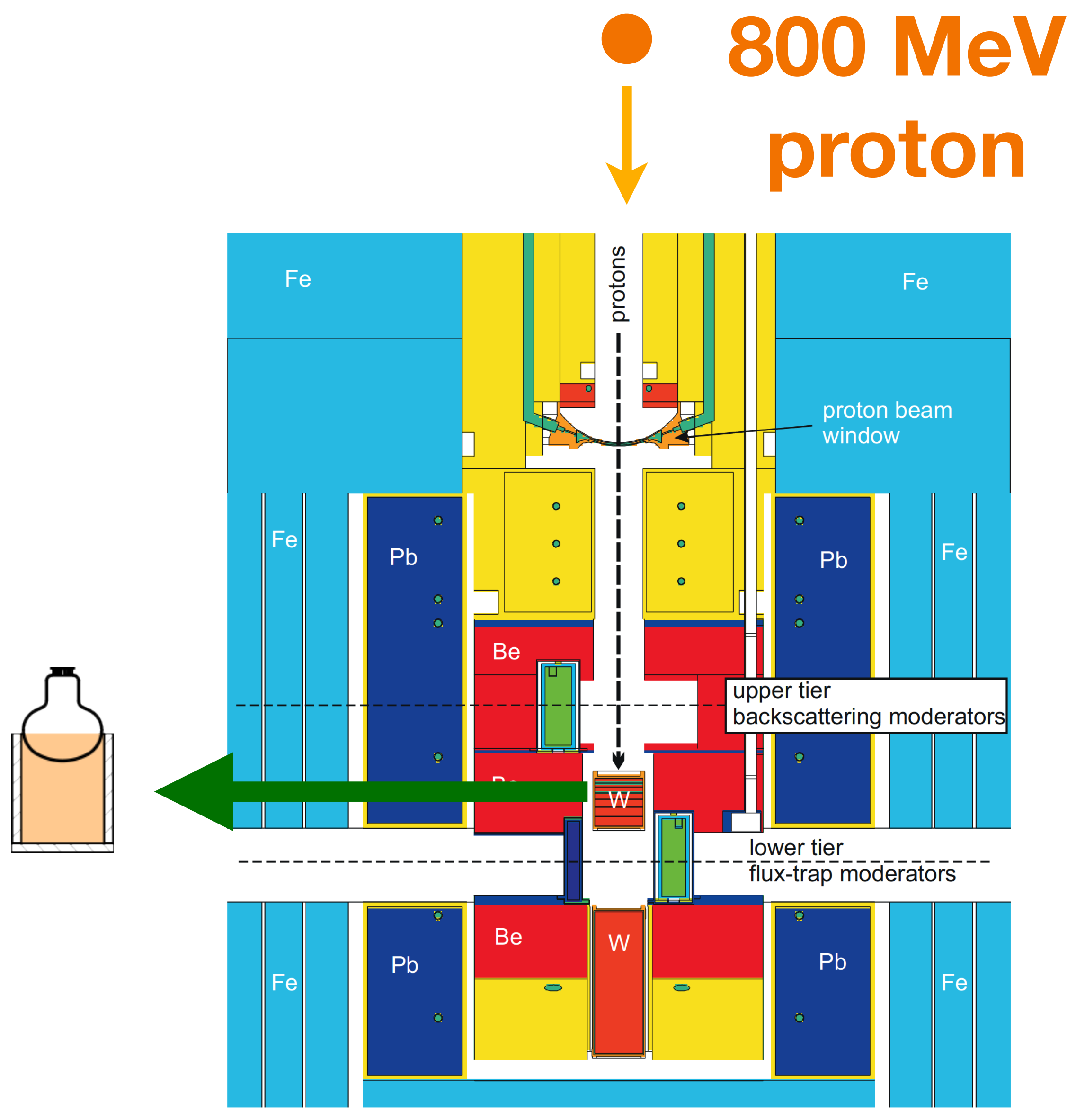
Backgrounds

- 90 degrees off axis —> no DIF contamination
- Primary backgrounds are fast neutrons
- Shielding attenuates neutrons, active veto allows us to tag neutrons entering our detector

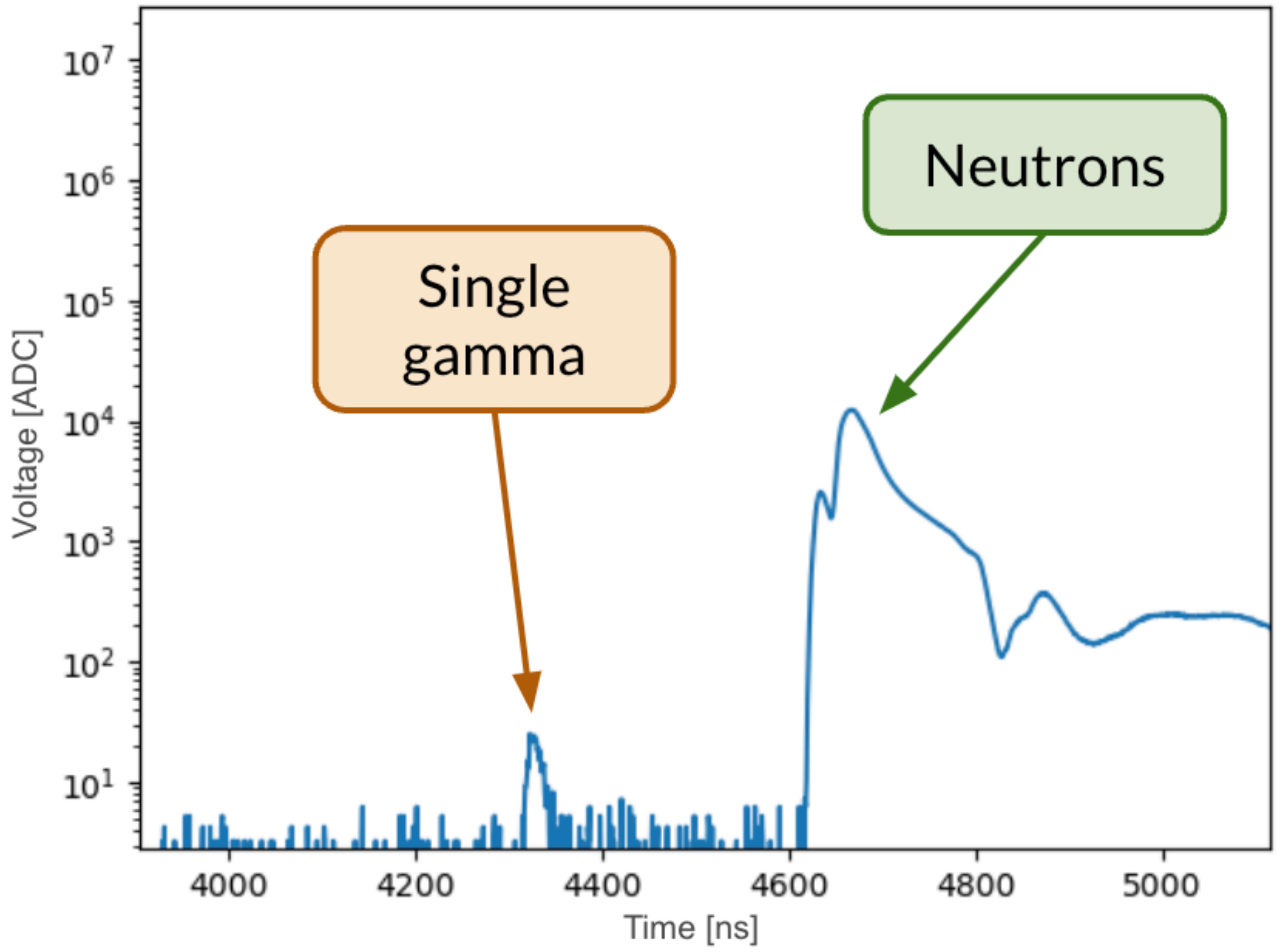


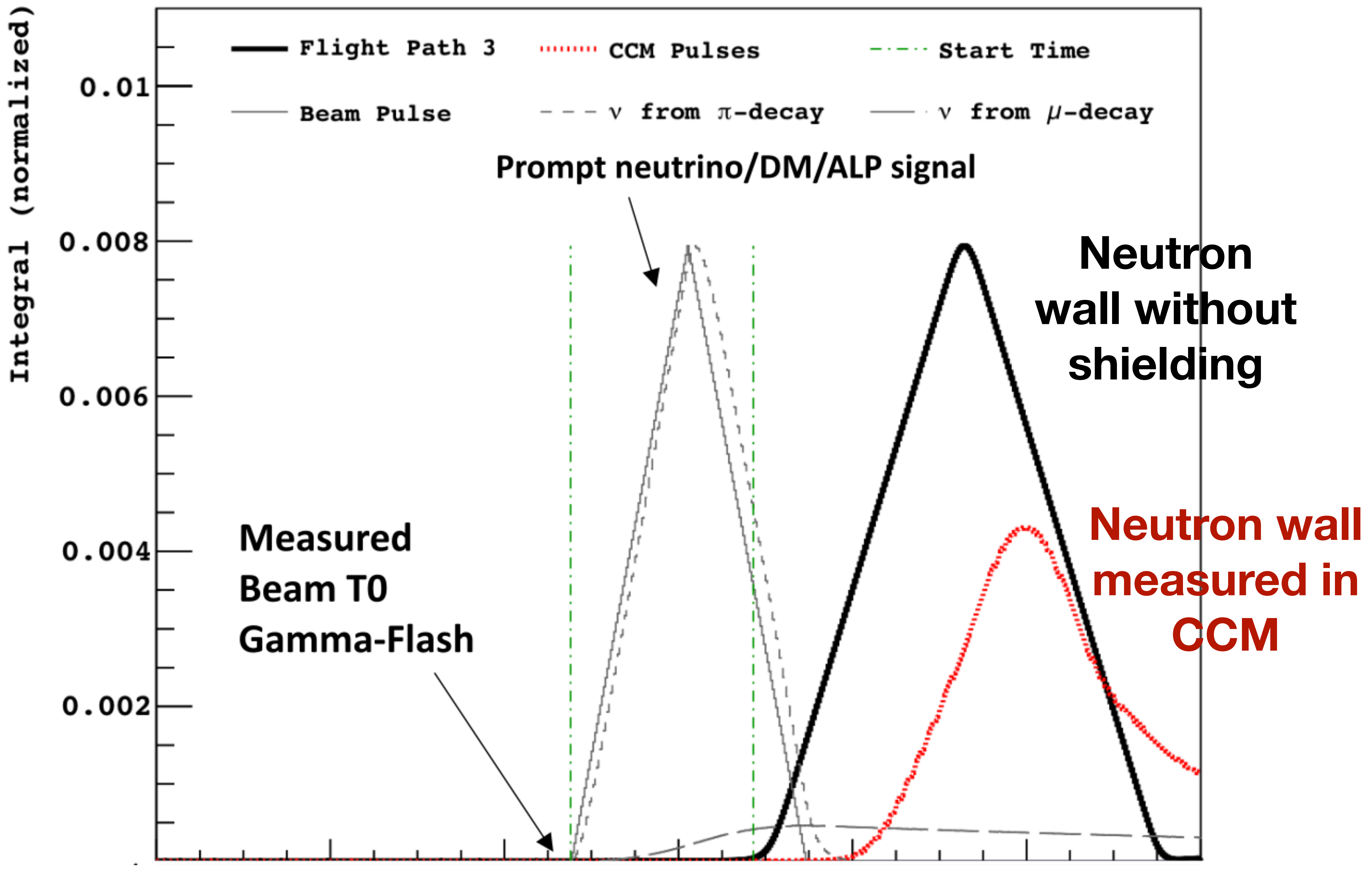
Backgrounds

- Precise timing using measured gamma flash allows us to isolate speed of light particles
- Can measure steady state backgrounds using pre-beam region of data collection



Target

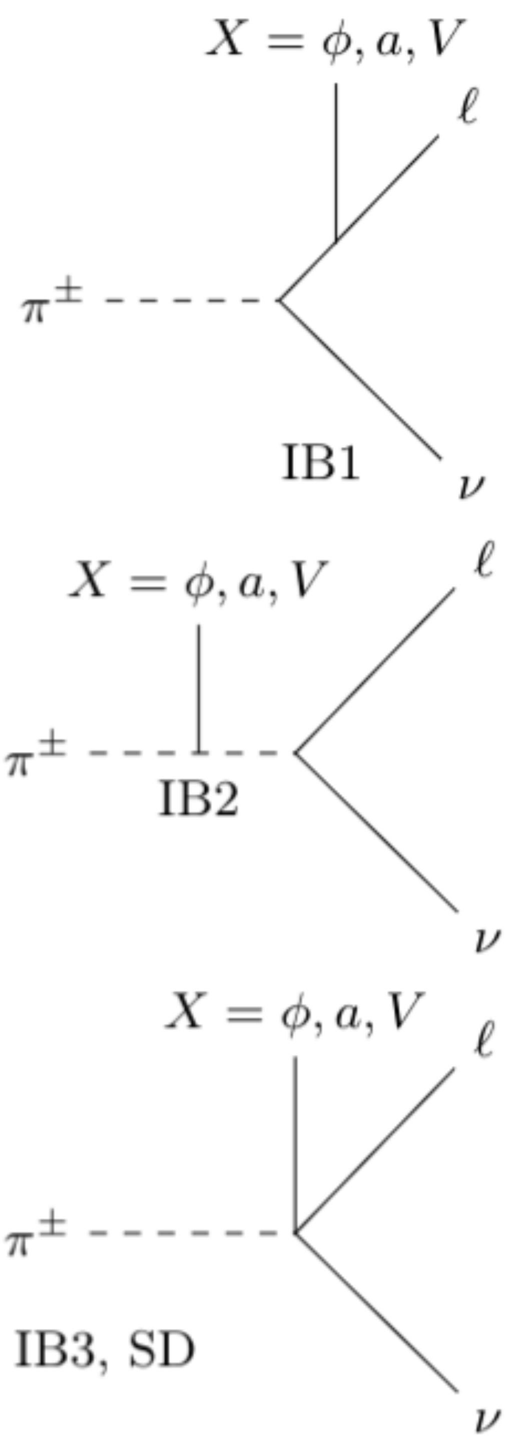




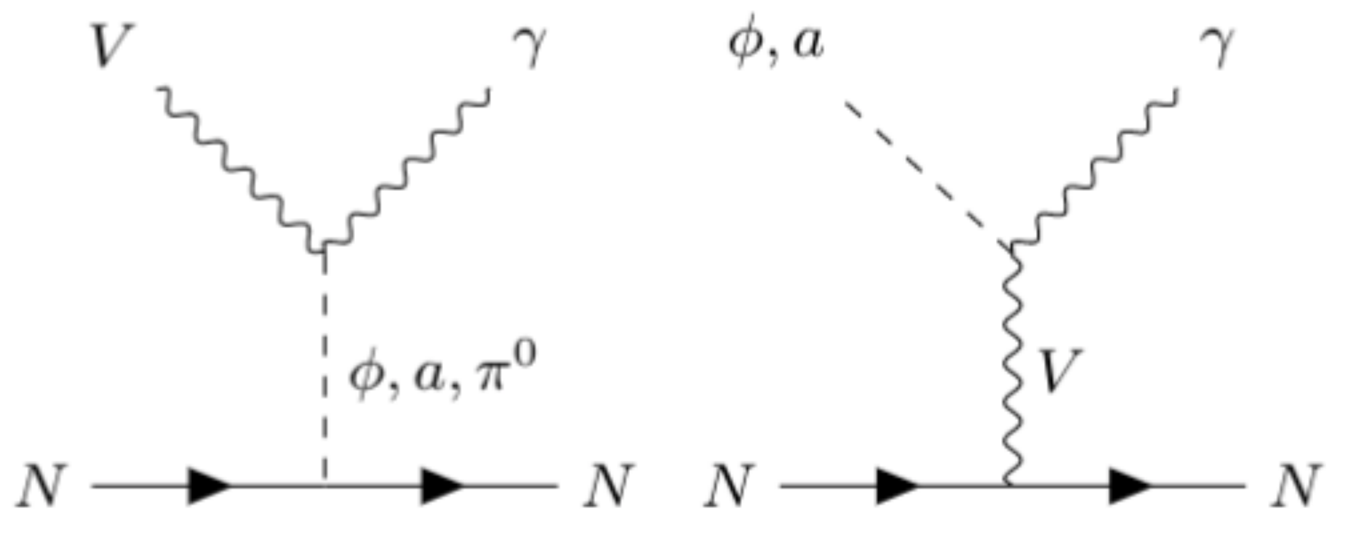
Search for Solution to MB Anomaly

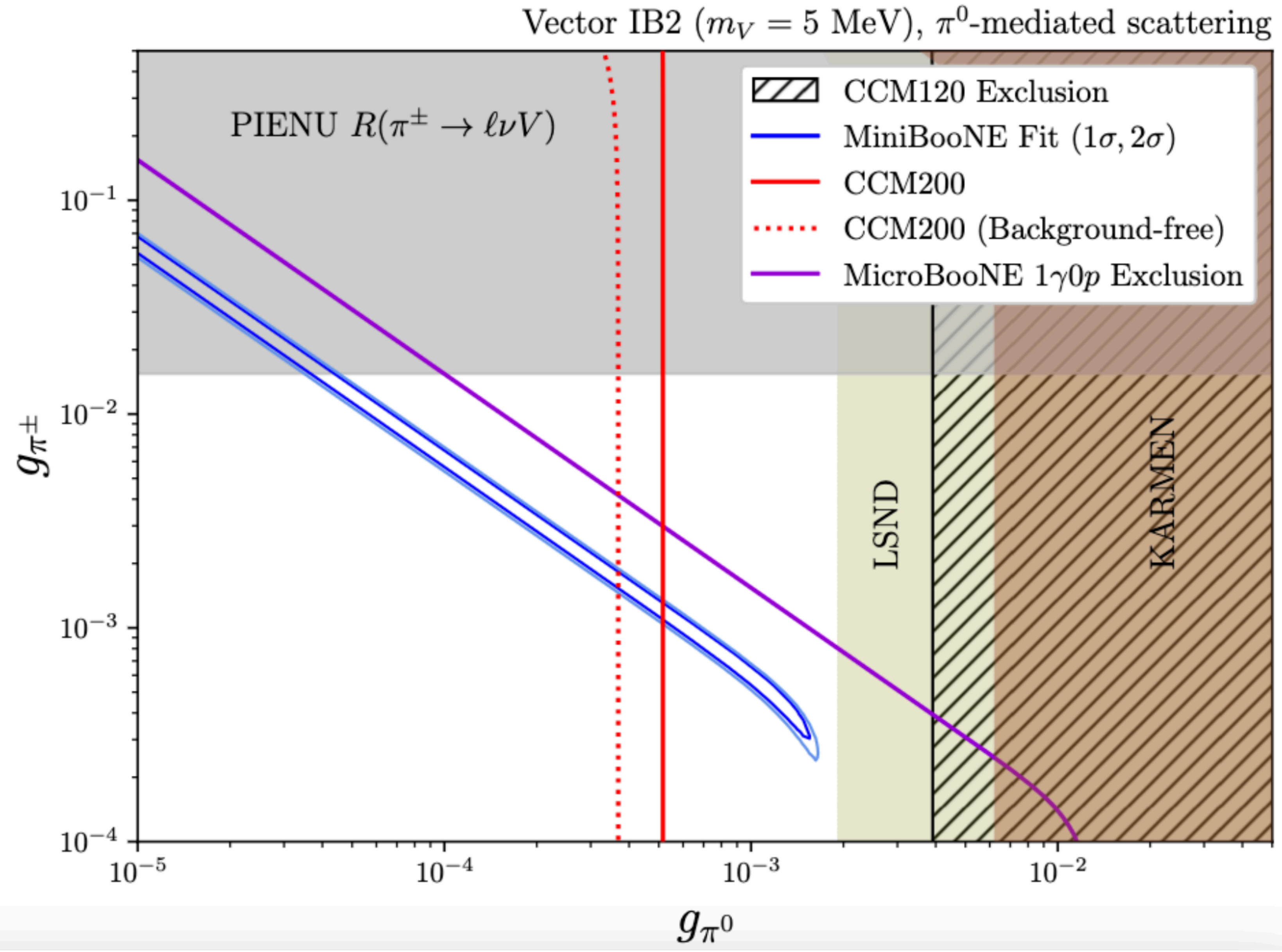
- Dark sector coupling to meson decays [https://doi.org/10.1103/PhysRevLett.129.111803]
- MiniBooNE excess in target mode only
- Excess could be caused by long-lived particles or light dark matter produced in charged meson decays
- Can study through charged and neutral pion decays at CCM

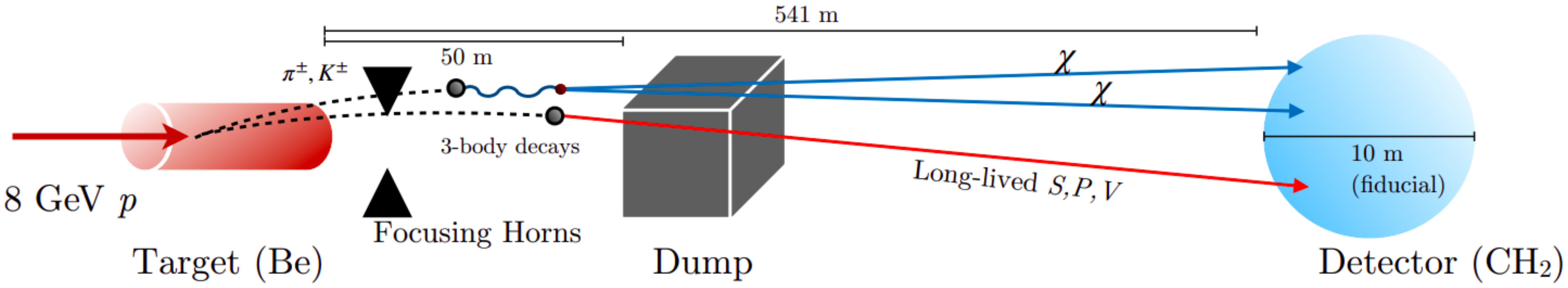
Production



Detection

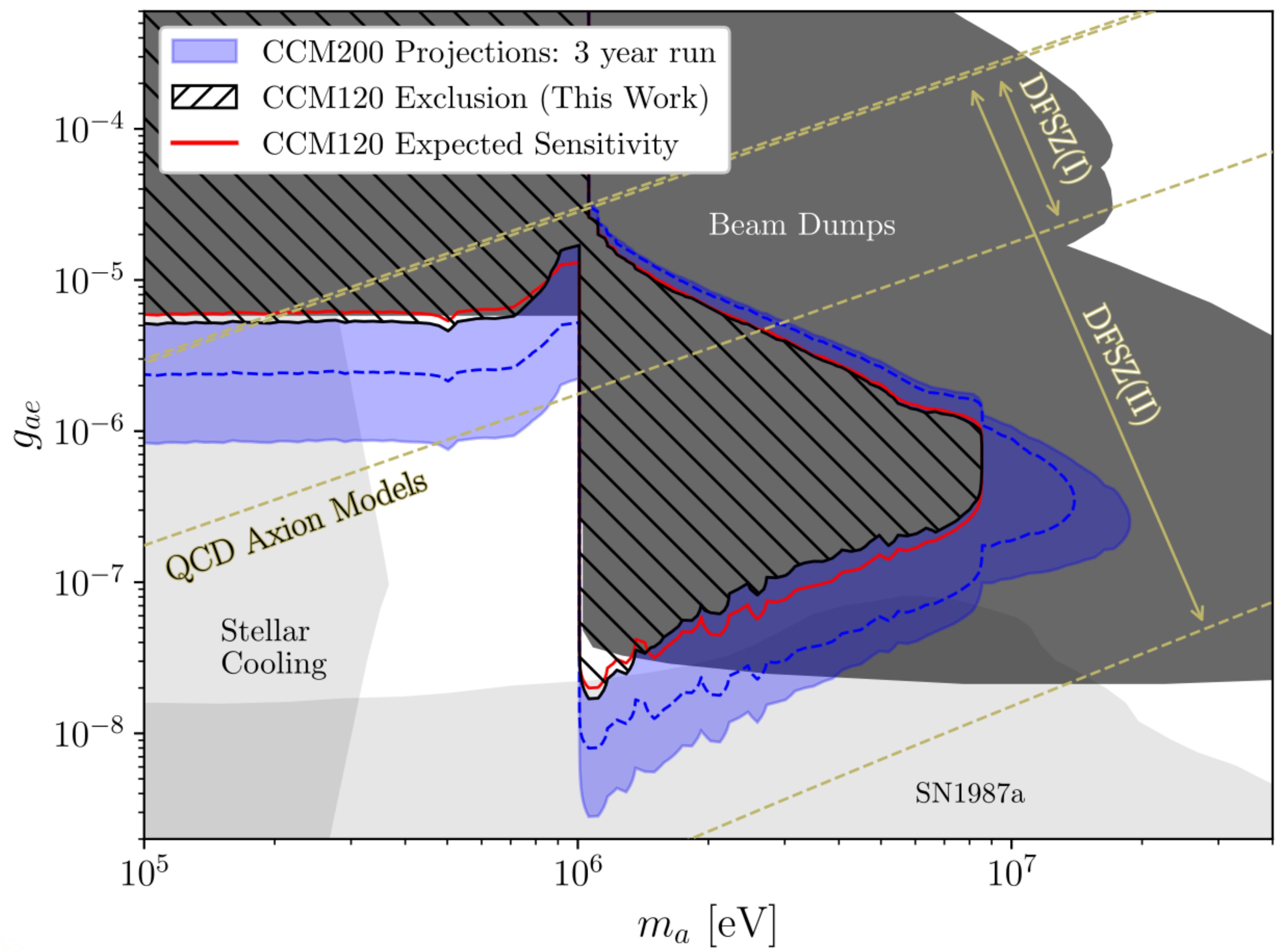




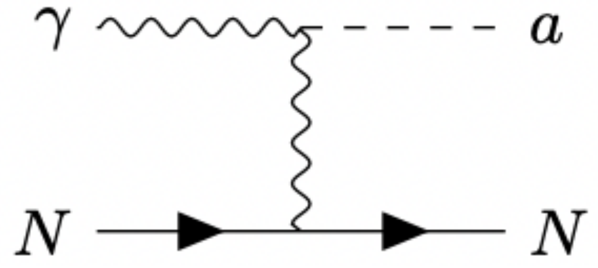


ALPs and QCD Axion

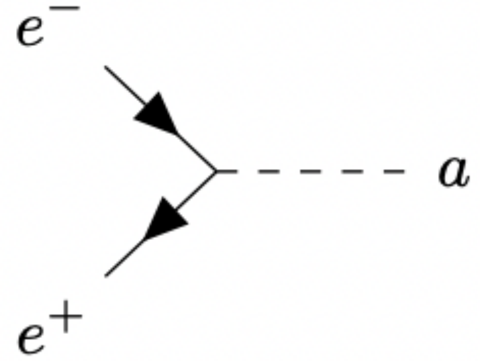
- Axion like particles and MeV scale QCD axion [https://doi.org/10.1103/PhysRevD.107.095036]
- Probe “cosmological triangle” with terrestrial measurements



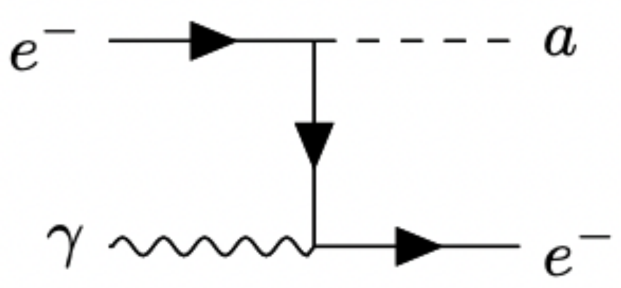
Production



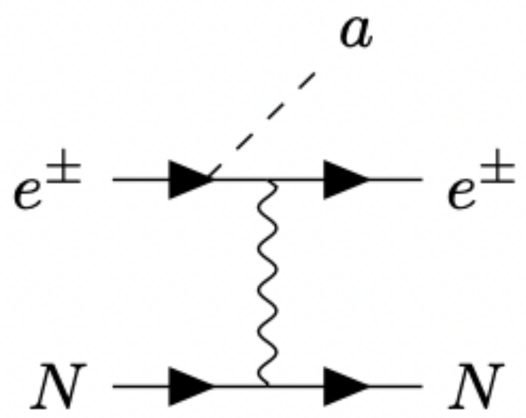
Primakoff



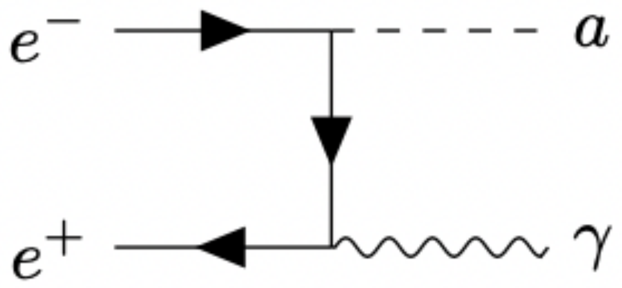
Resonant production



Compton

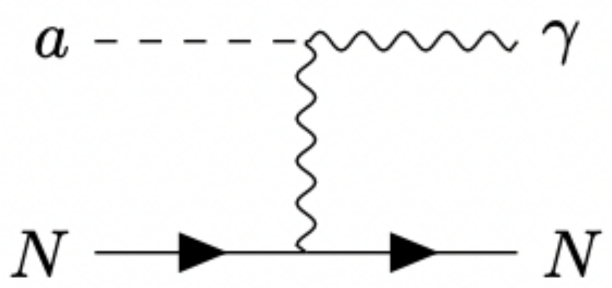


ALP Brem

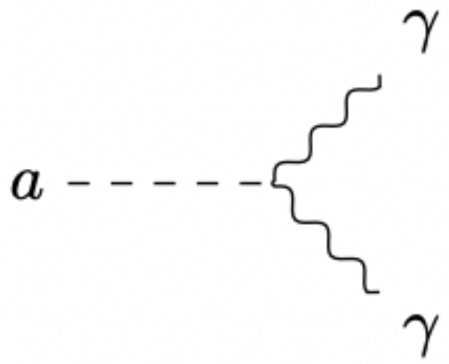


Associated production

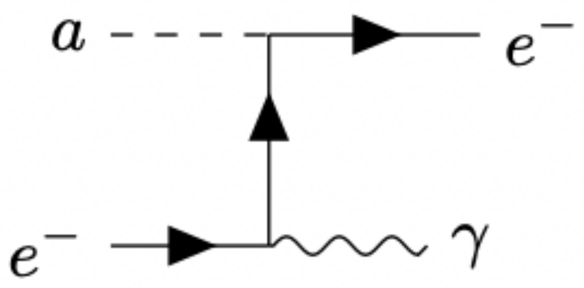
Detection



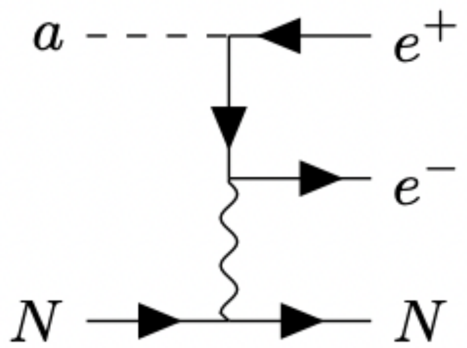
Inverse Primakoff



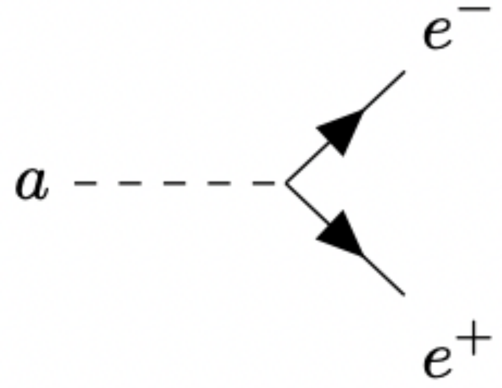
Diphoton decay



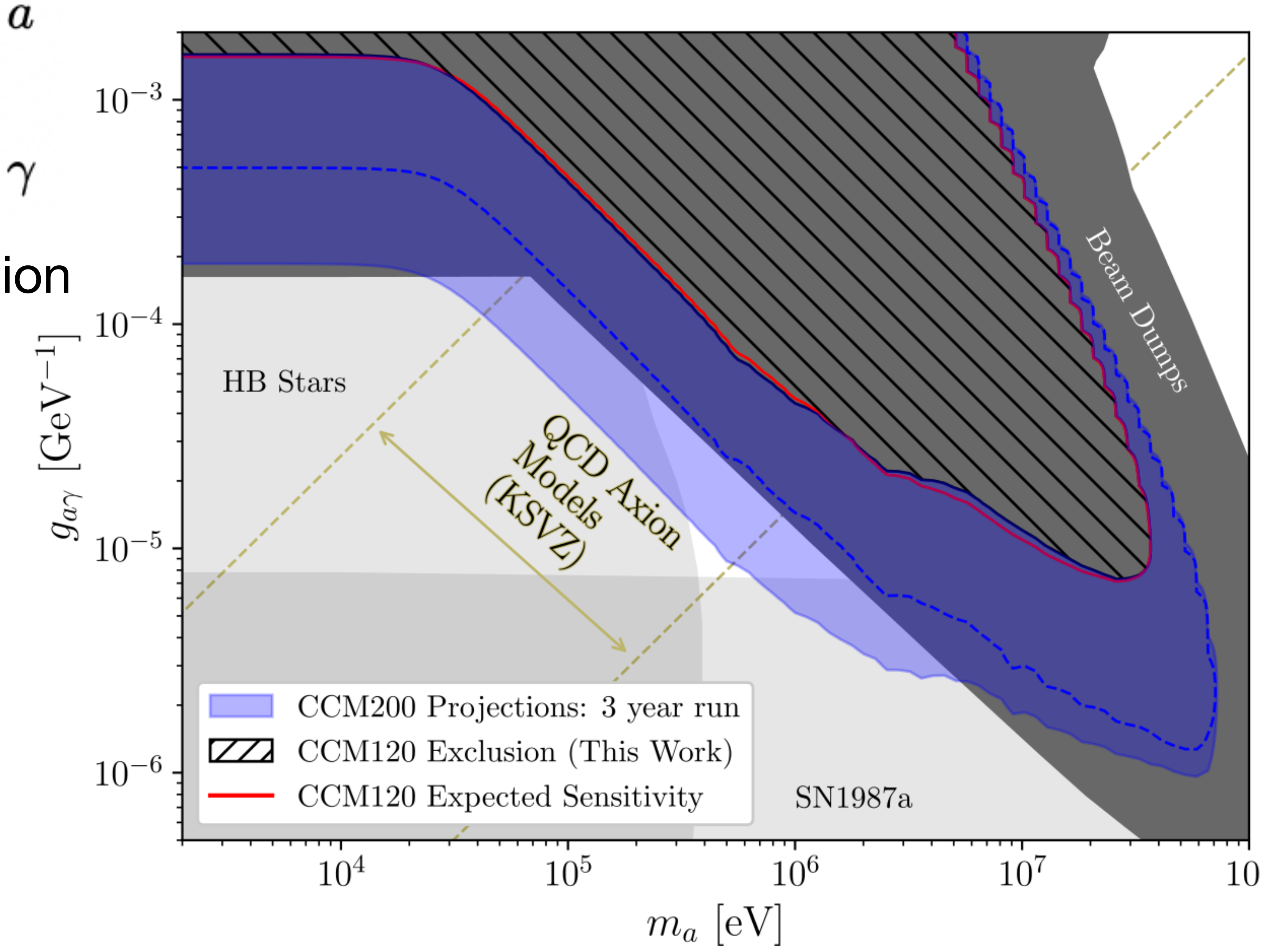
Inverse Compton



External pair conversion

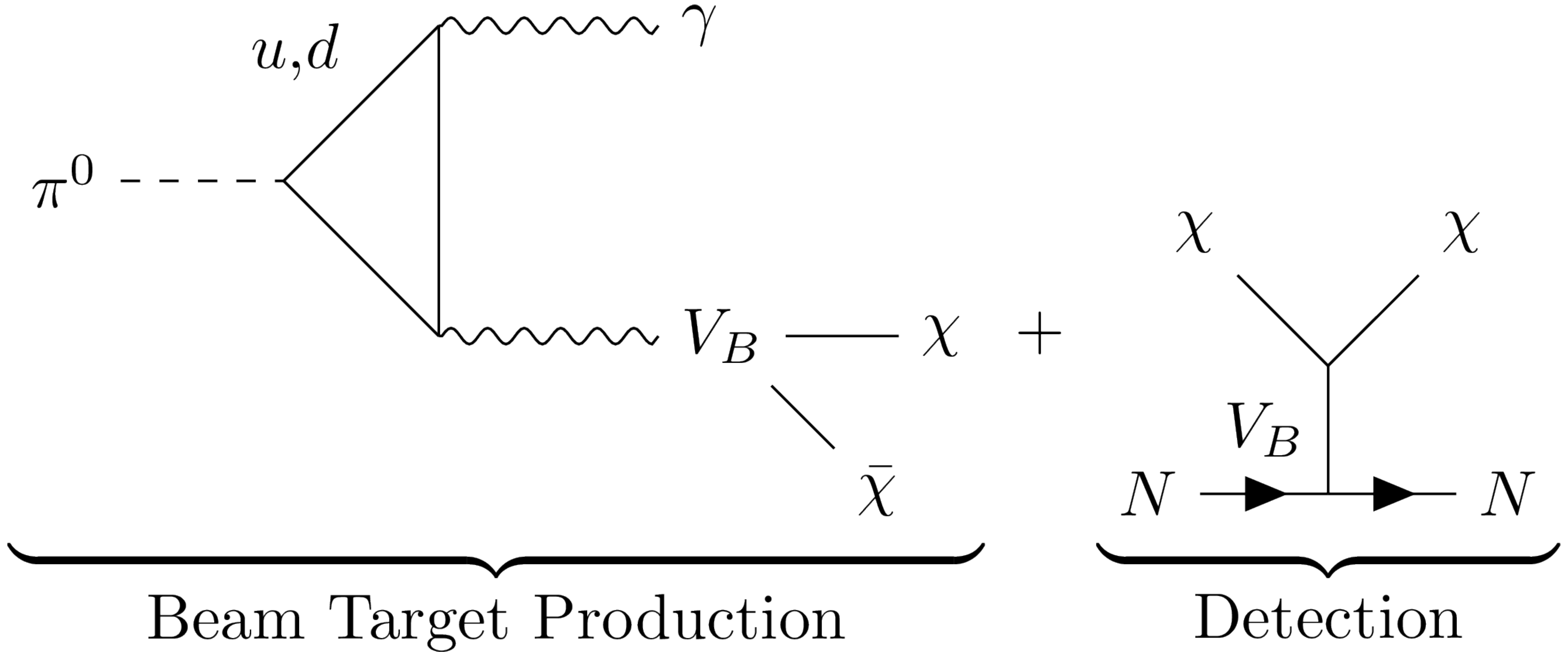


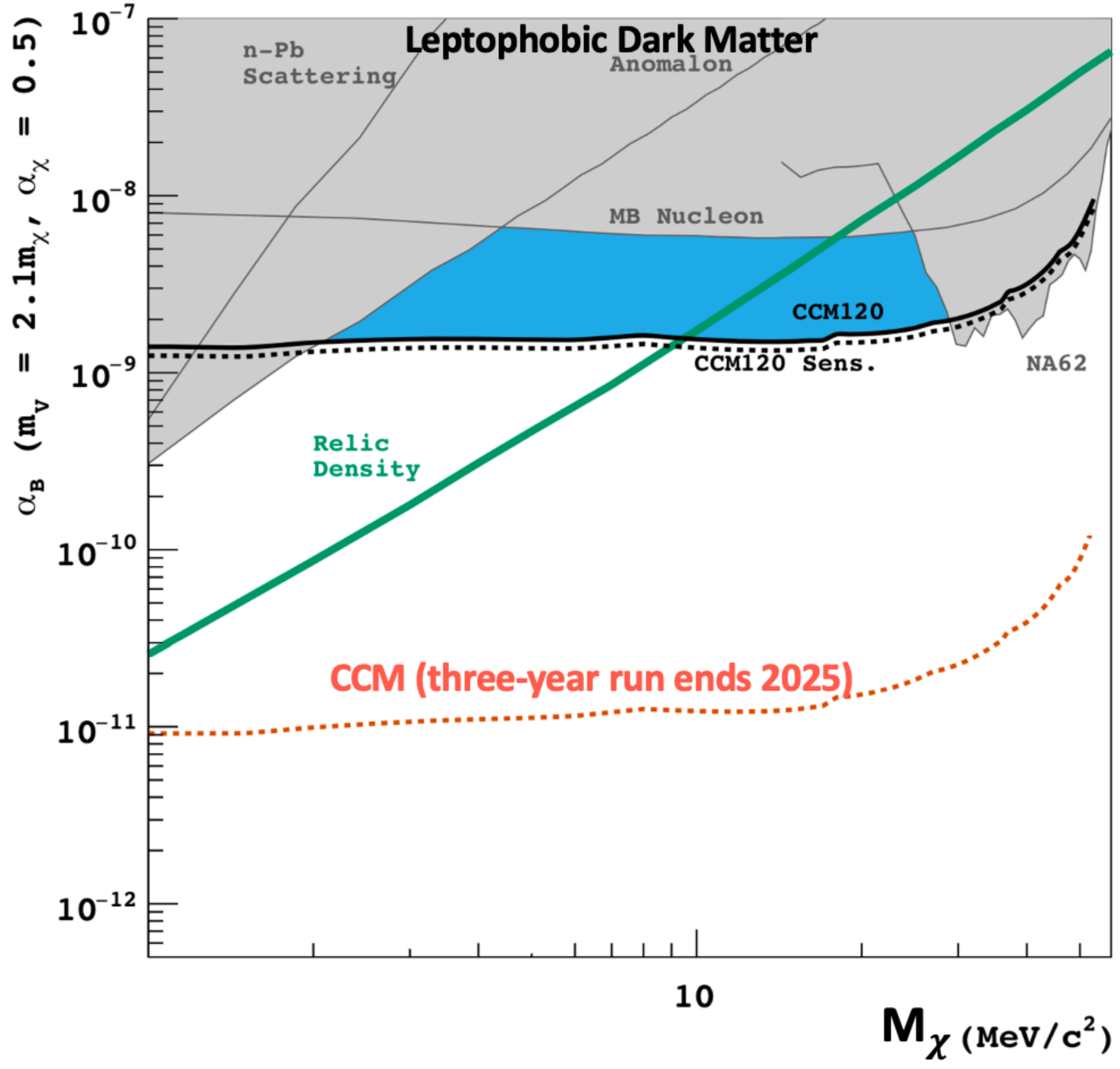
e+ e- decay



Leptophobic DM

- Leptophobic dark matter [https://doi.org/10.1103/PhysRevLett.129.021801]
- Explore ~10 MeV mediator masses
- Scalar DM χ produced from π^0 decay in target
- Detected through coherent interaction in CCM (low energy nuclear recoil)
- Results from CCM120 engineering run in blue, CCM200 expected results in dashed red





Heavy Neutral Leptons

- Heavy neutral leptons
- Using dipole portal transition model [https://doi.org/10.1103/PhysRevD.107.055009]
- Considering HNL production from upscattering in shielding and detector materials
- Detection from ~10 MeV photon