# Scintillation and Cherenkov Light Separation in a Liquid Argon Detector

## New results from the Coherent CAPTAIN-Mills Experiment

- Presenting new results!
  arXiv:2507.08886 and
  arXiv:2507.08887

**SLAC Fundamental Physics Directorate Seminar**
**19 August 2025**

**Darcy Newmark** ***on behalf of the CCM Collaboration***

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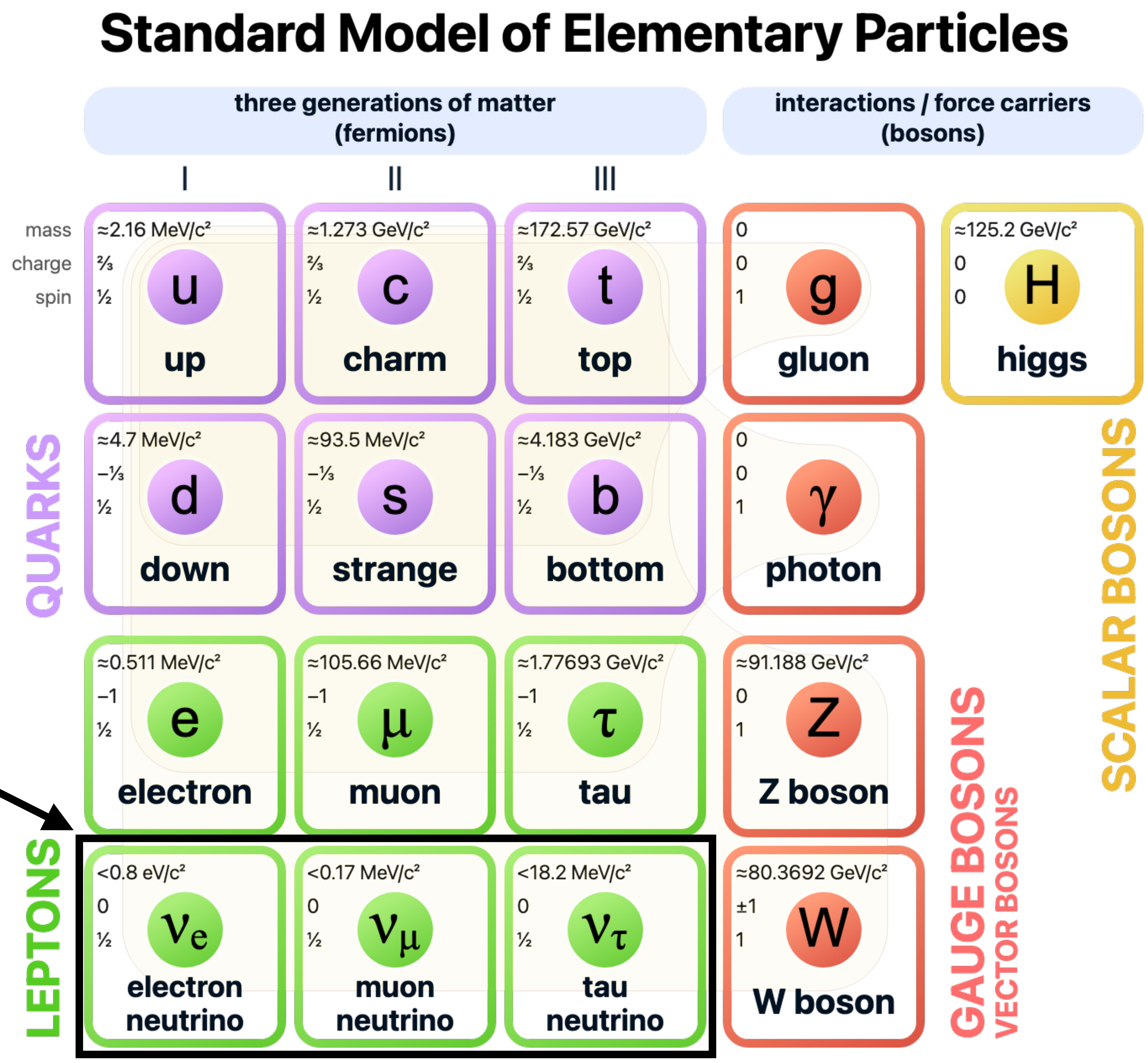
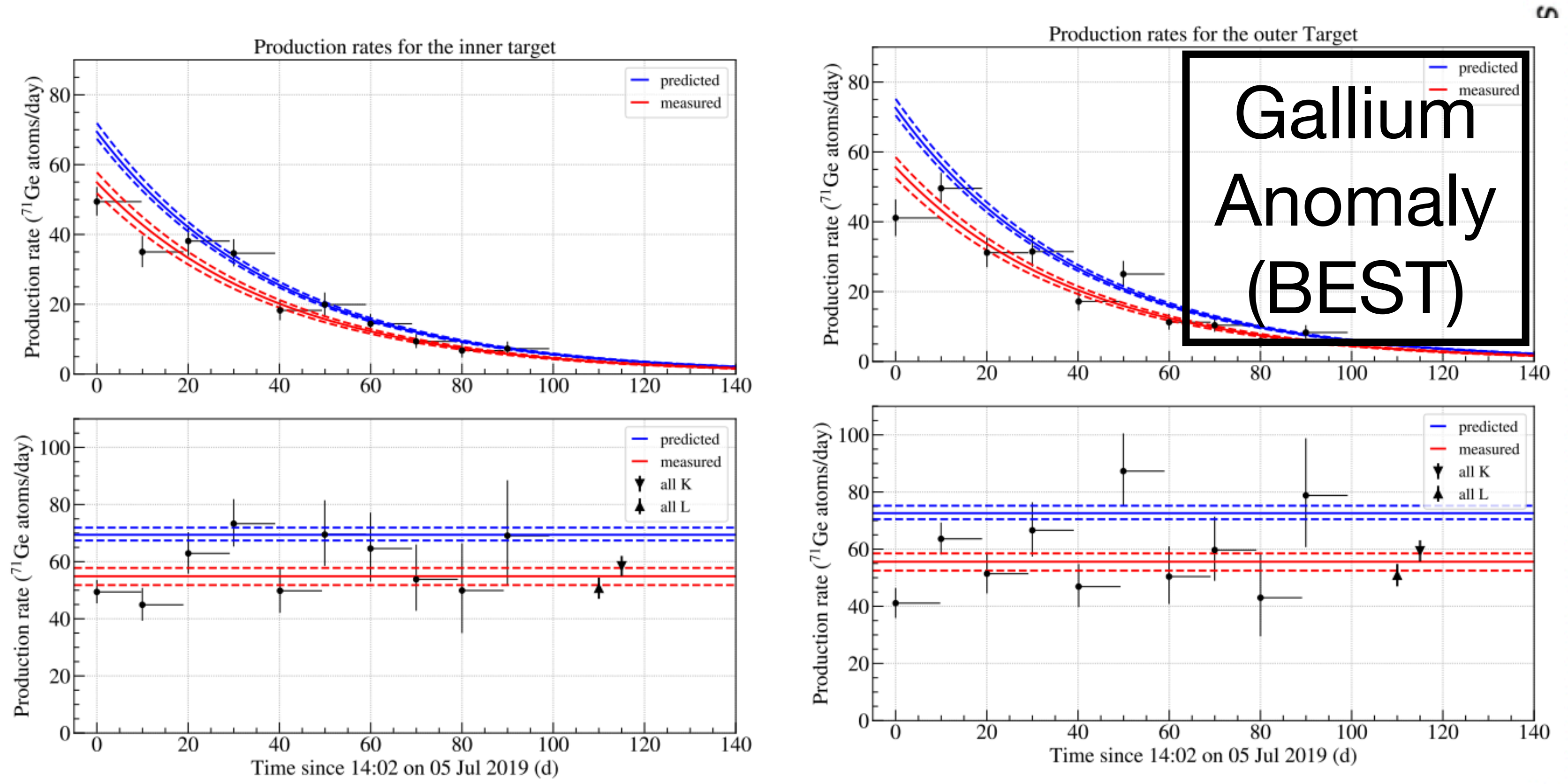
1. Open Questions In Neutrino Physics
2. Light Collection Detectors
3. Coherent CAPTAIN-Mills Experiment
4. CCM as a Hybrid Detector
5. *New results* — Cherenkov light
6. *New results* — photon simulation calibration
7. Physics program

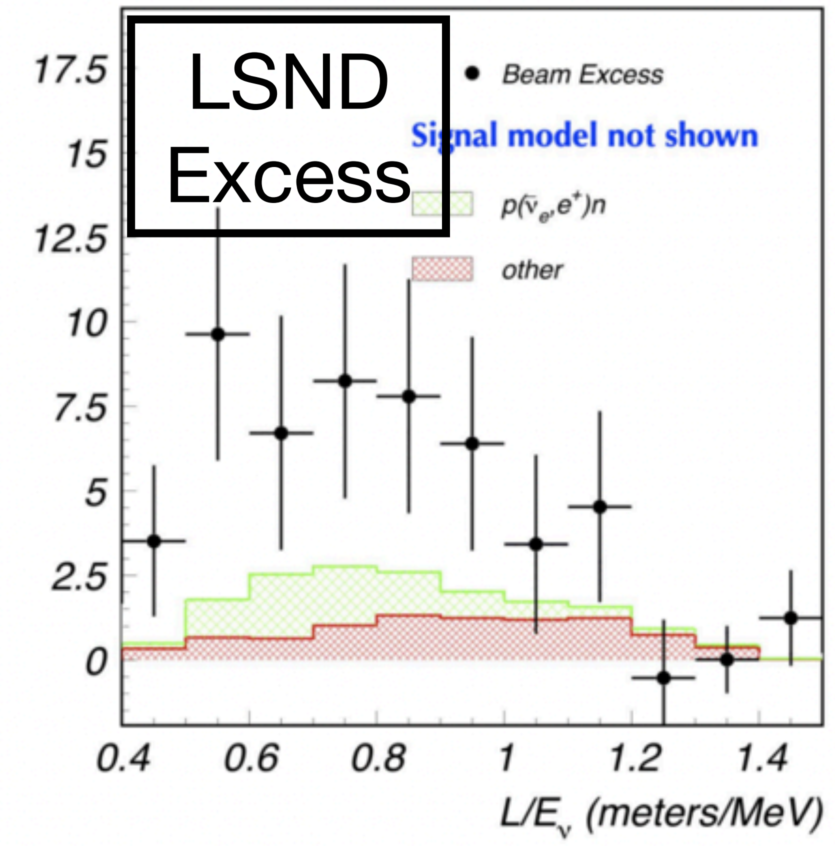
# Standard Model

- Standard Model describes how particles interact
- Excellent description overall, ***but*** does not explain neutrinos!
- Observation of neutrino oscillations prove they have mass, which is not predicted by the SM

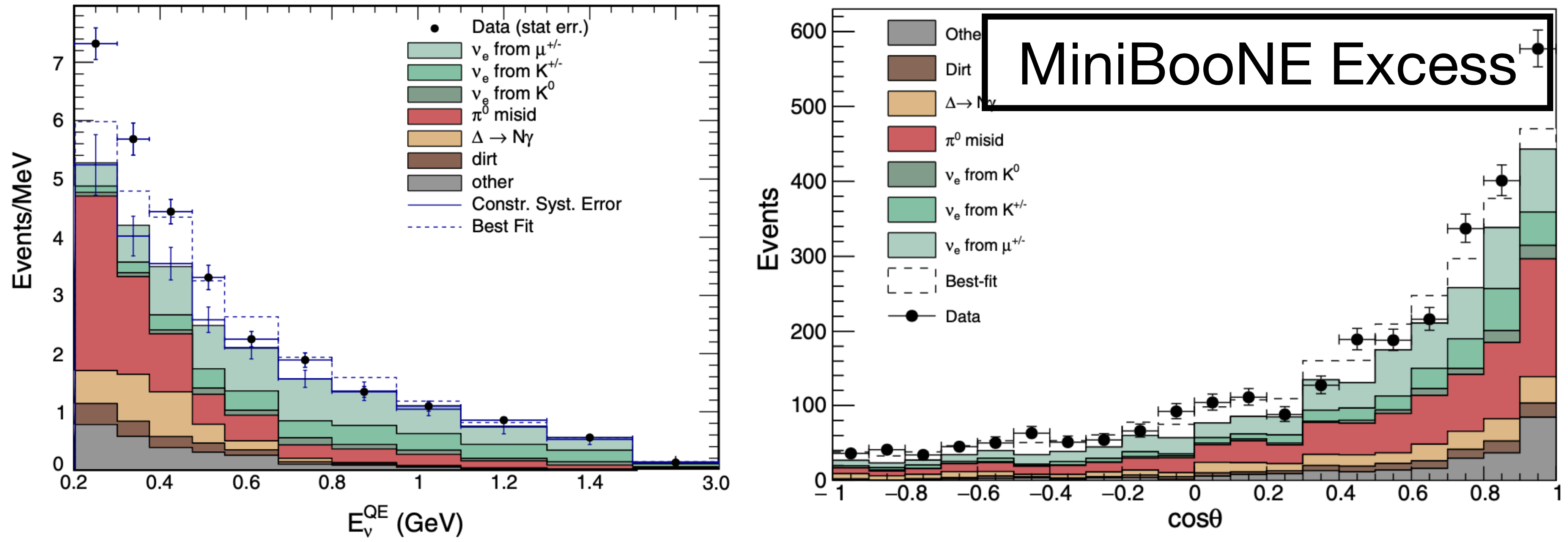


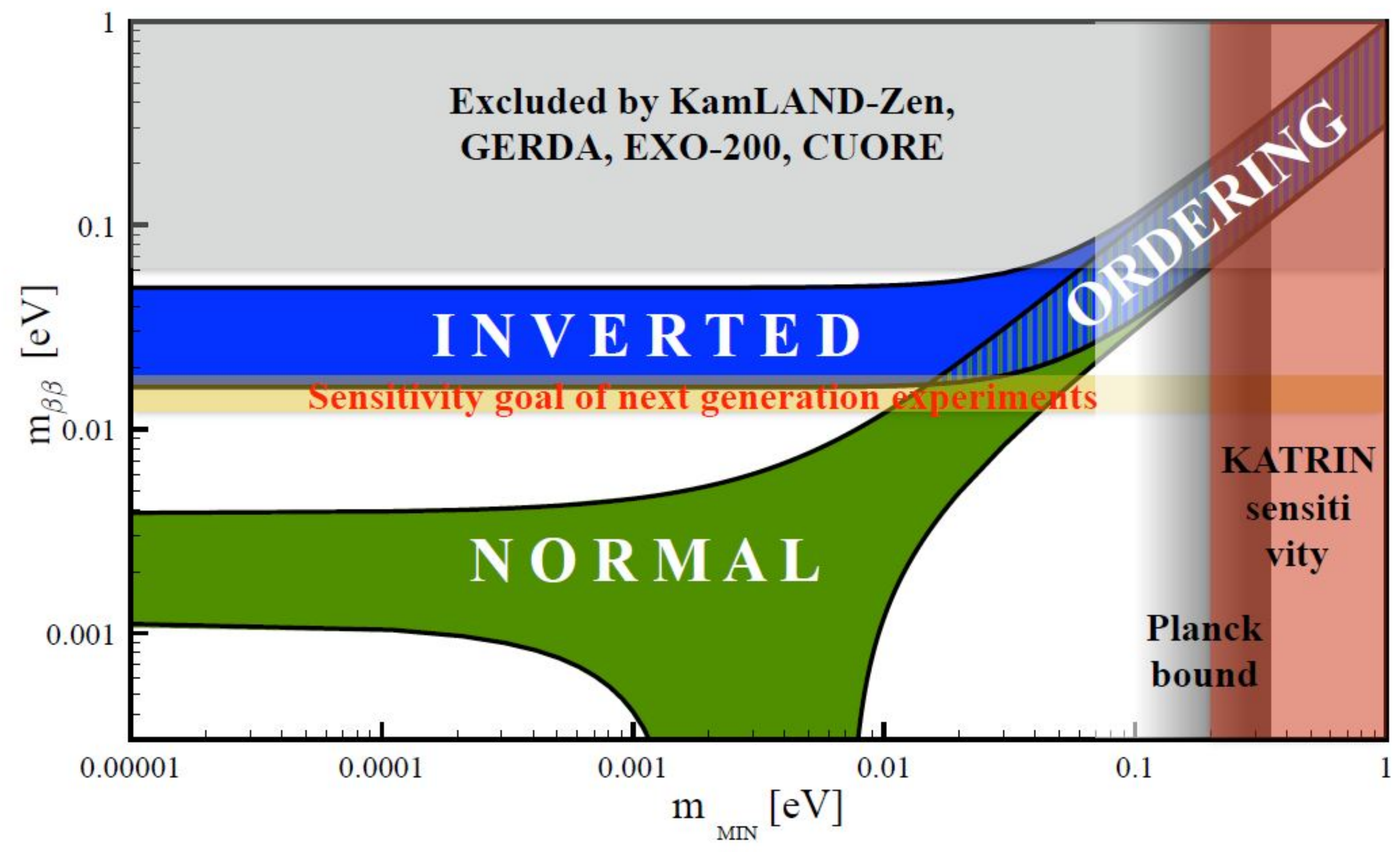
# Open Questions




- What mass are neutrinos? How do they get their mass?
- Are neutrinos their own anti-particle?
- Do neutrinos violate fundamental symmetries?
- Why are there so many experimental anomalies in neutrino physics?



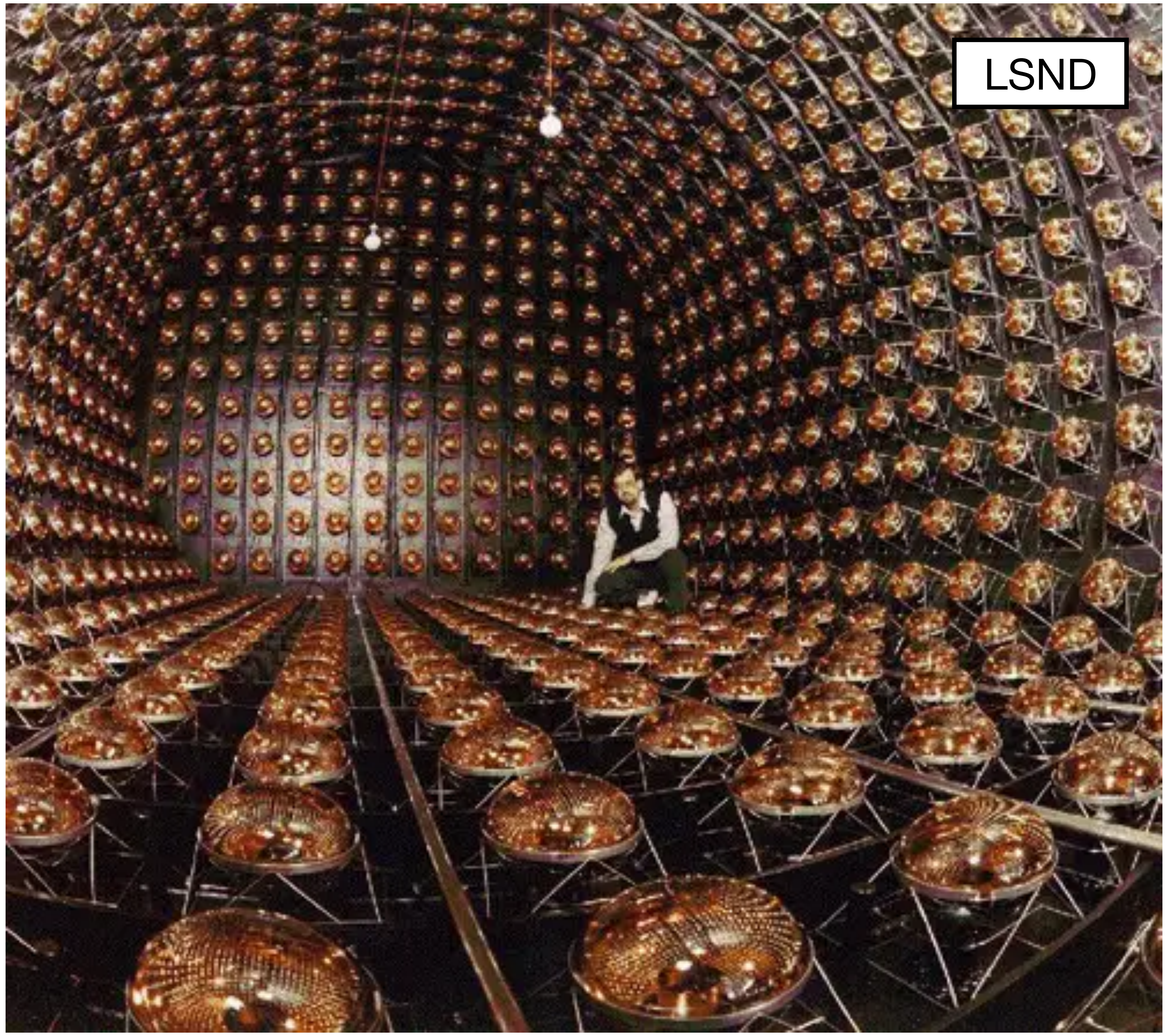




**<u>Need to keep studying neutrinos!</u>**

# 2. 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

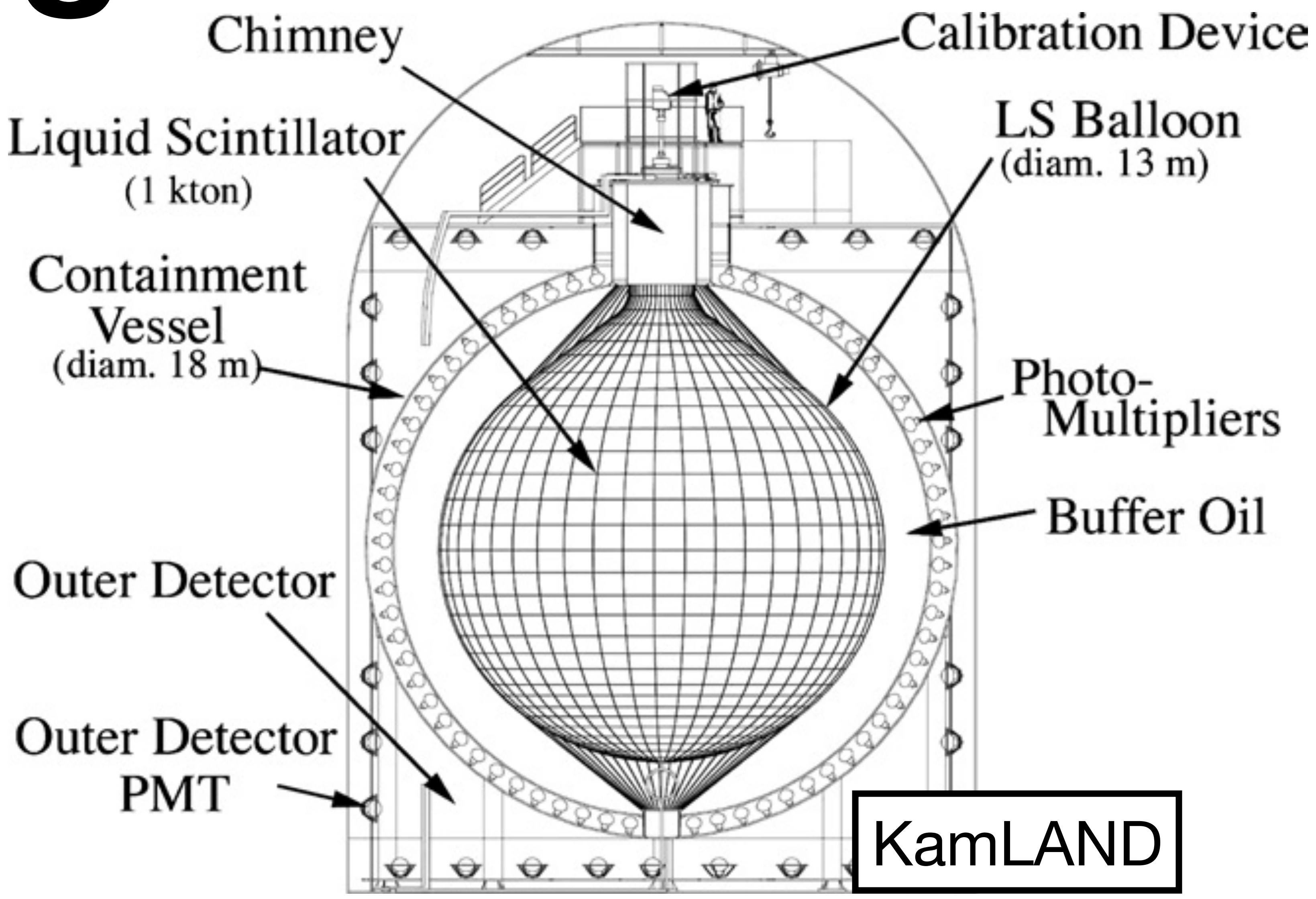


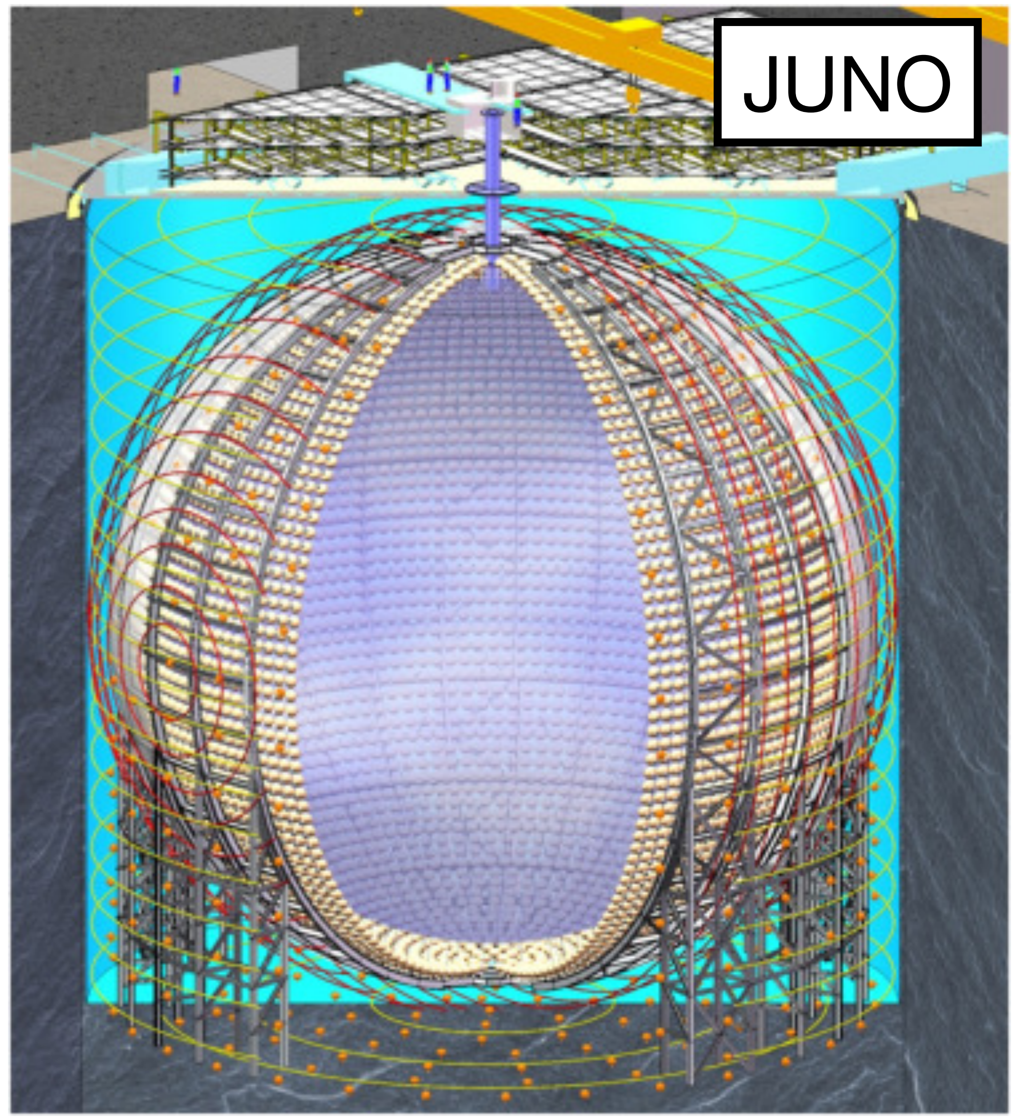
# Scintillation vs Cherenkov Light

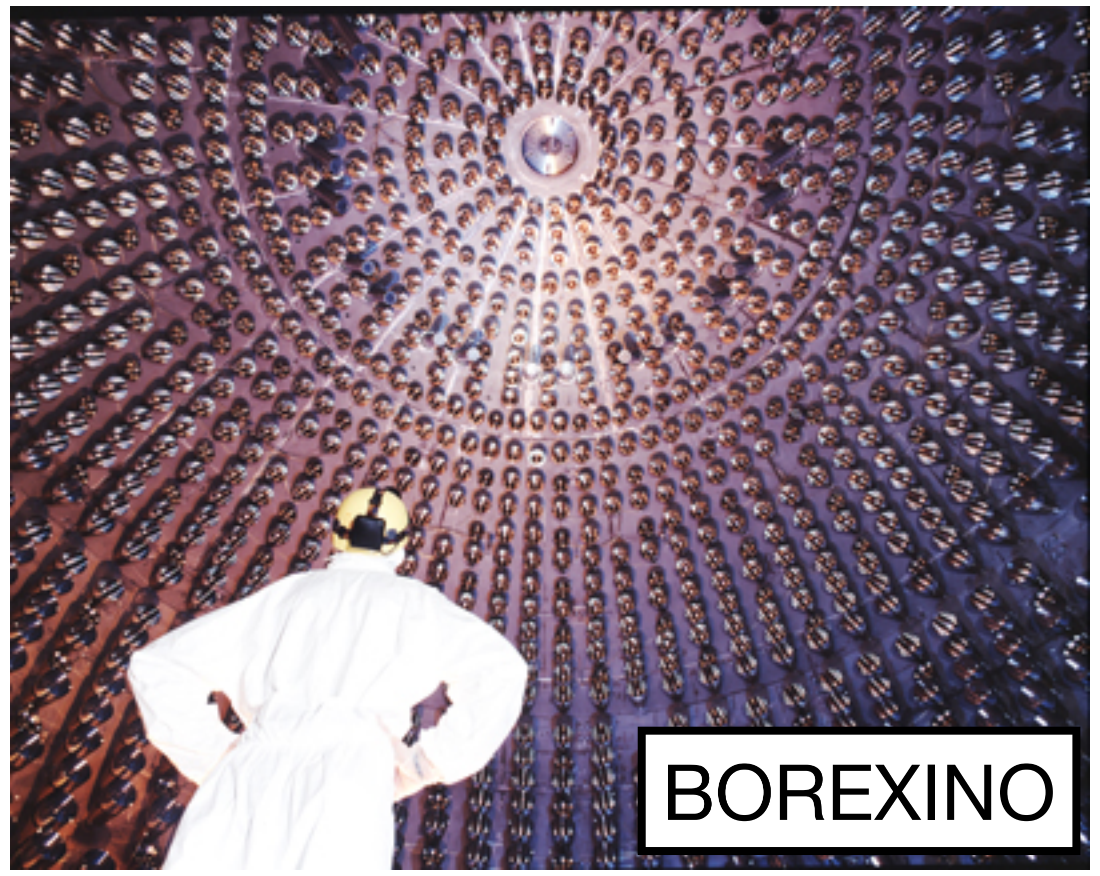
| Quality | Scintillation Light | Cherenkov Light |
|---|---|---|
| Intensity | ~$10^4$ photons/MeV | ~ $10^2$ photons/MeV |
| Direction | Isotropic | Directional |
| Timing | Typically ~nsec | Prompt (psec start) |
| Photon Wavelength | Narrow emission spectrum | $dN/d\lambda \propto \lambda^{-2}$ |

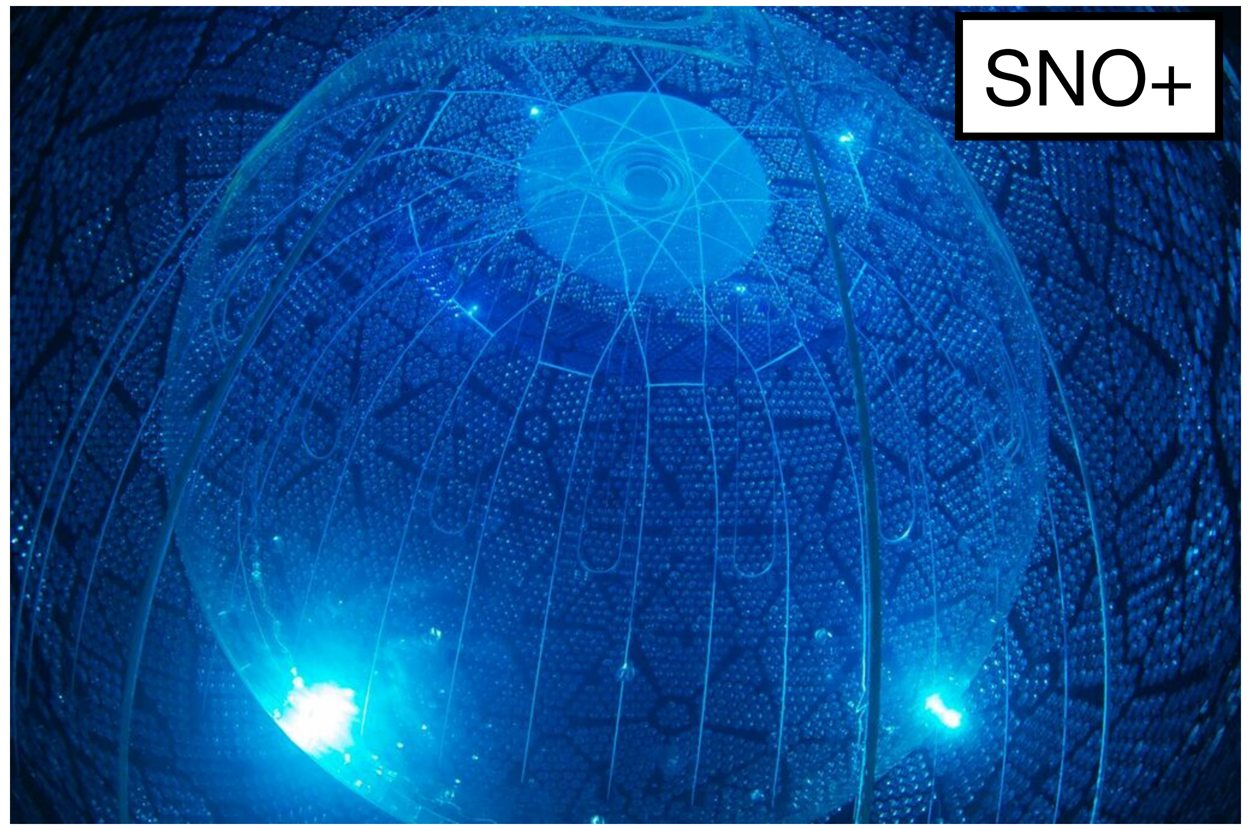
# Scintillation Detectors

- 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



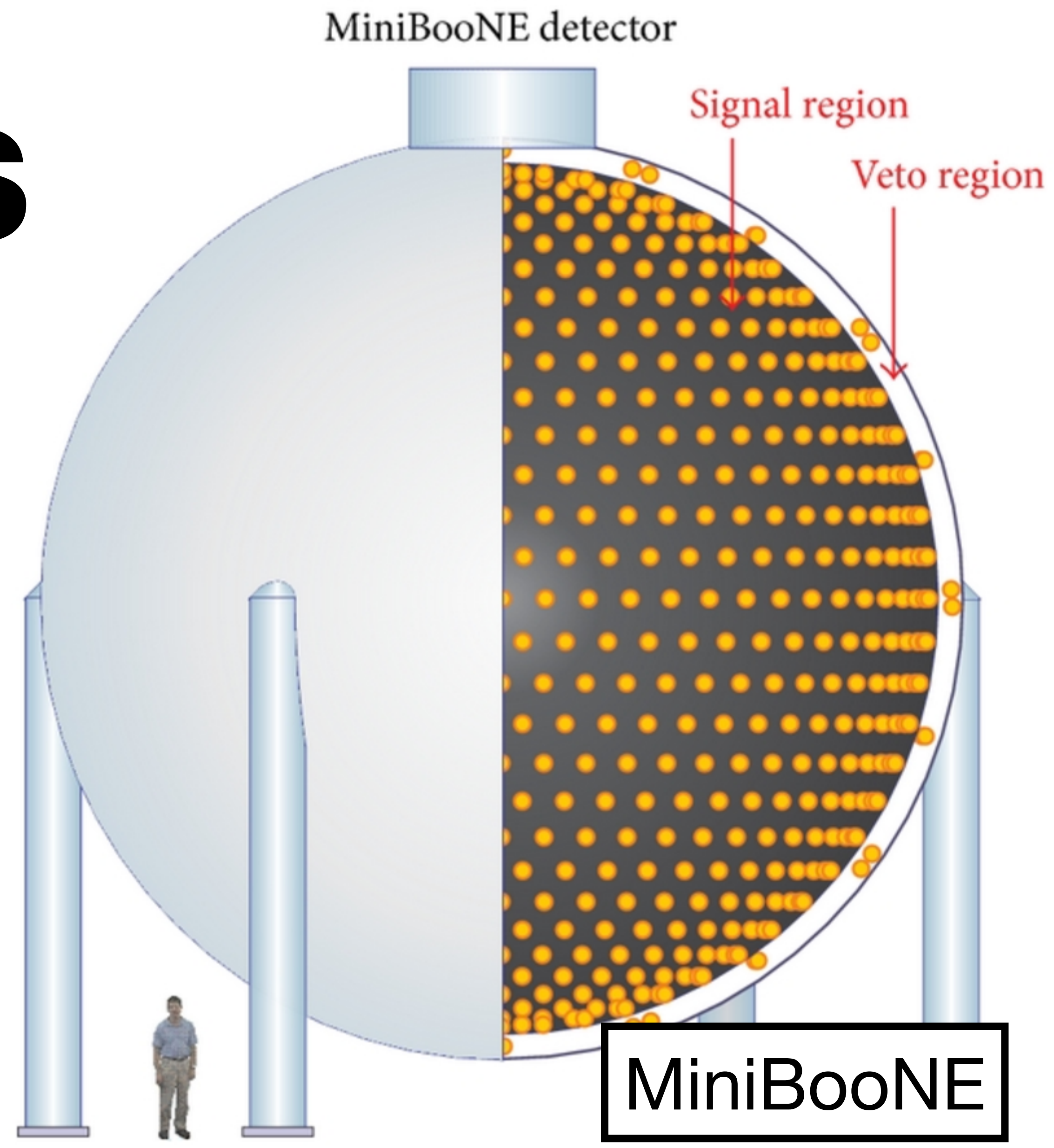



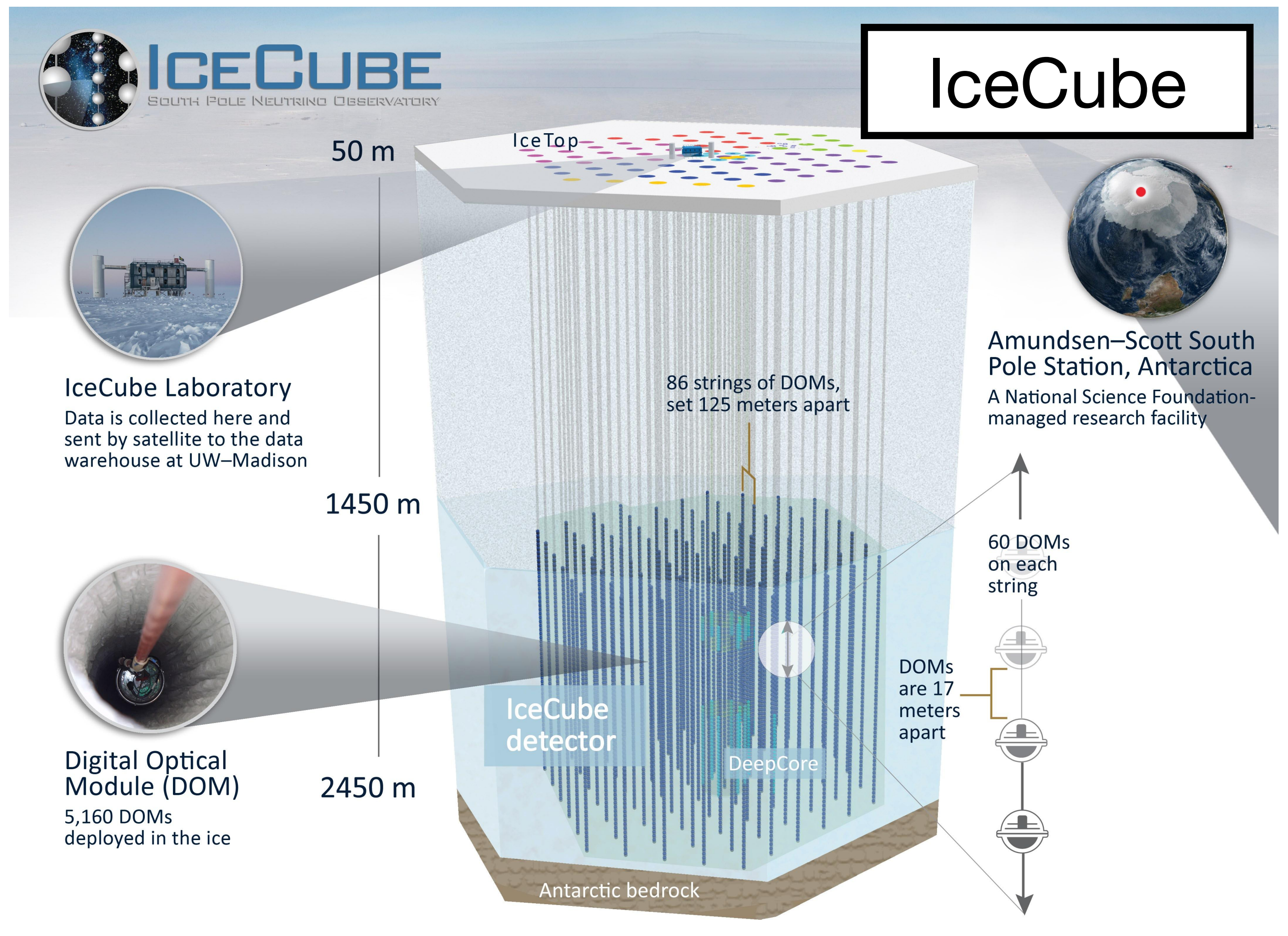



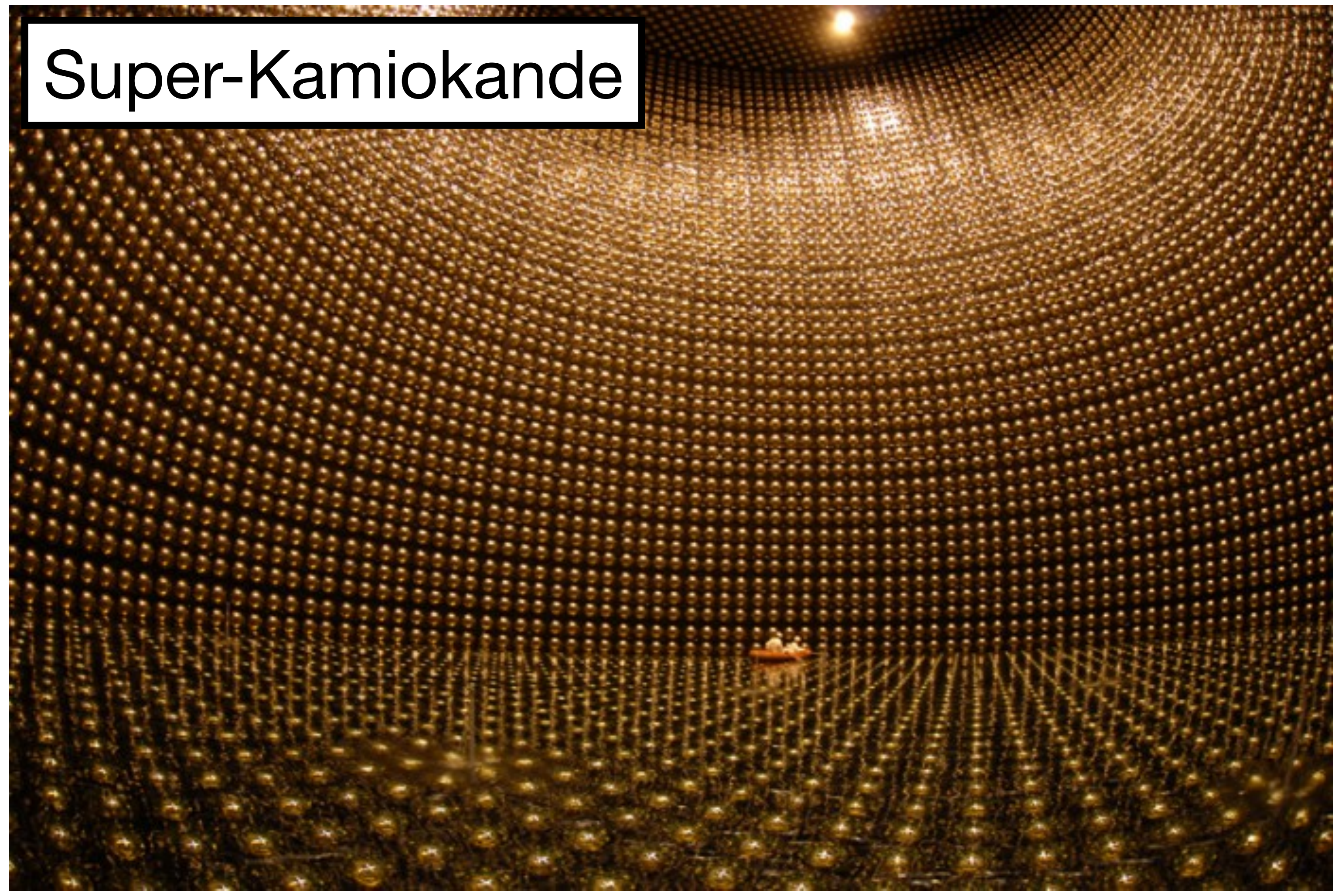



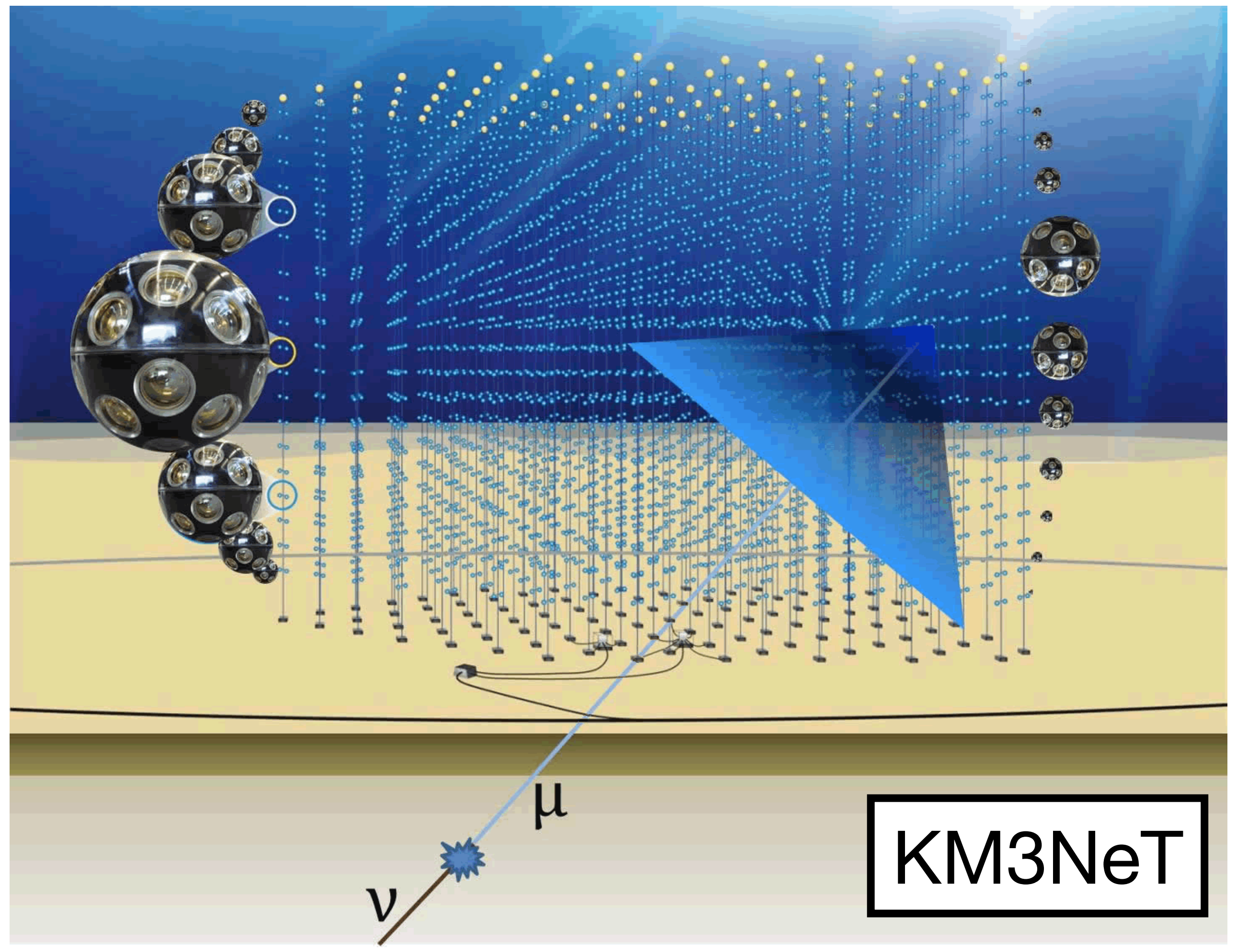
# Cherenkov Detectors

- 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





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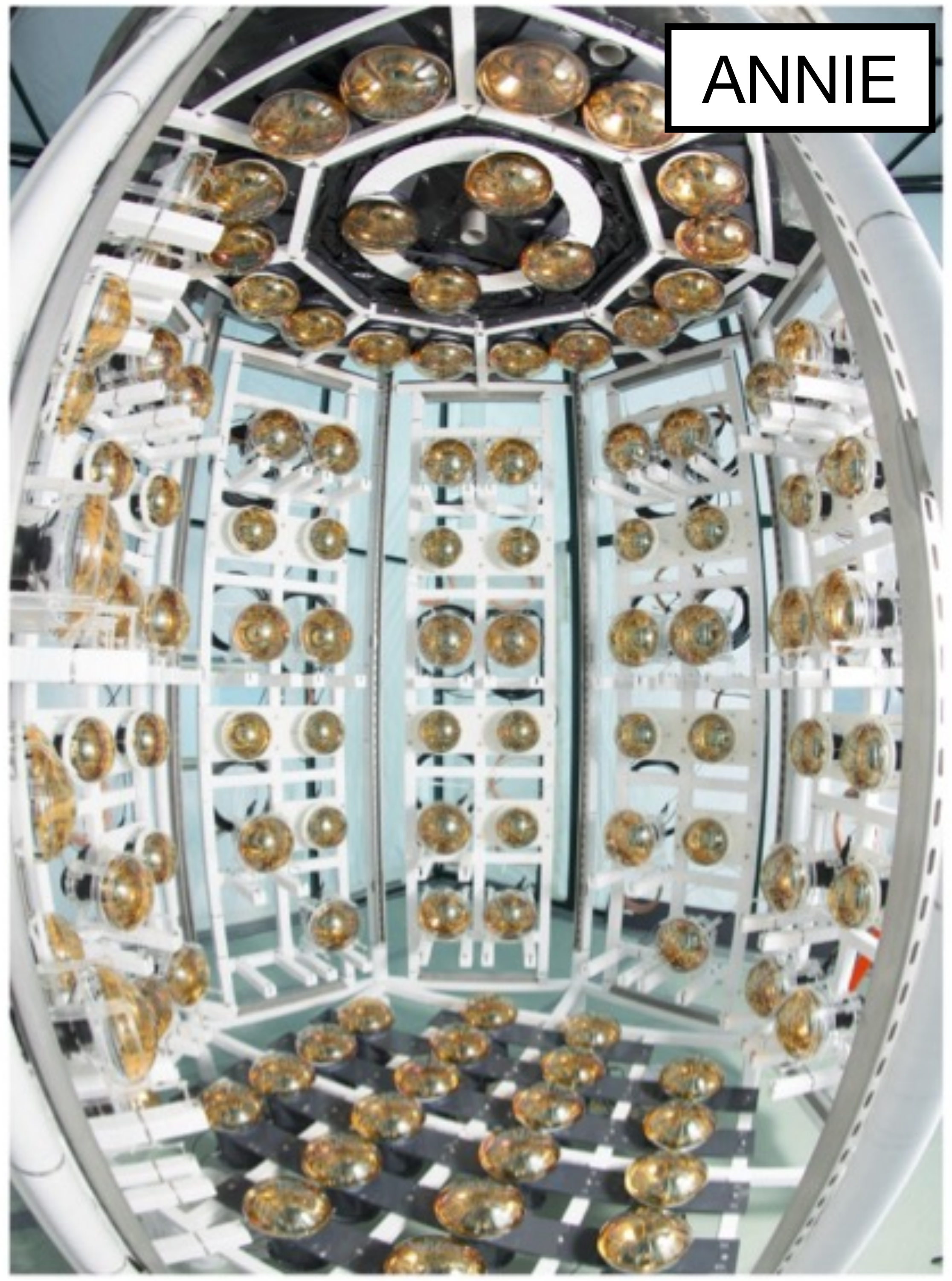
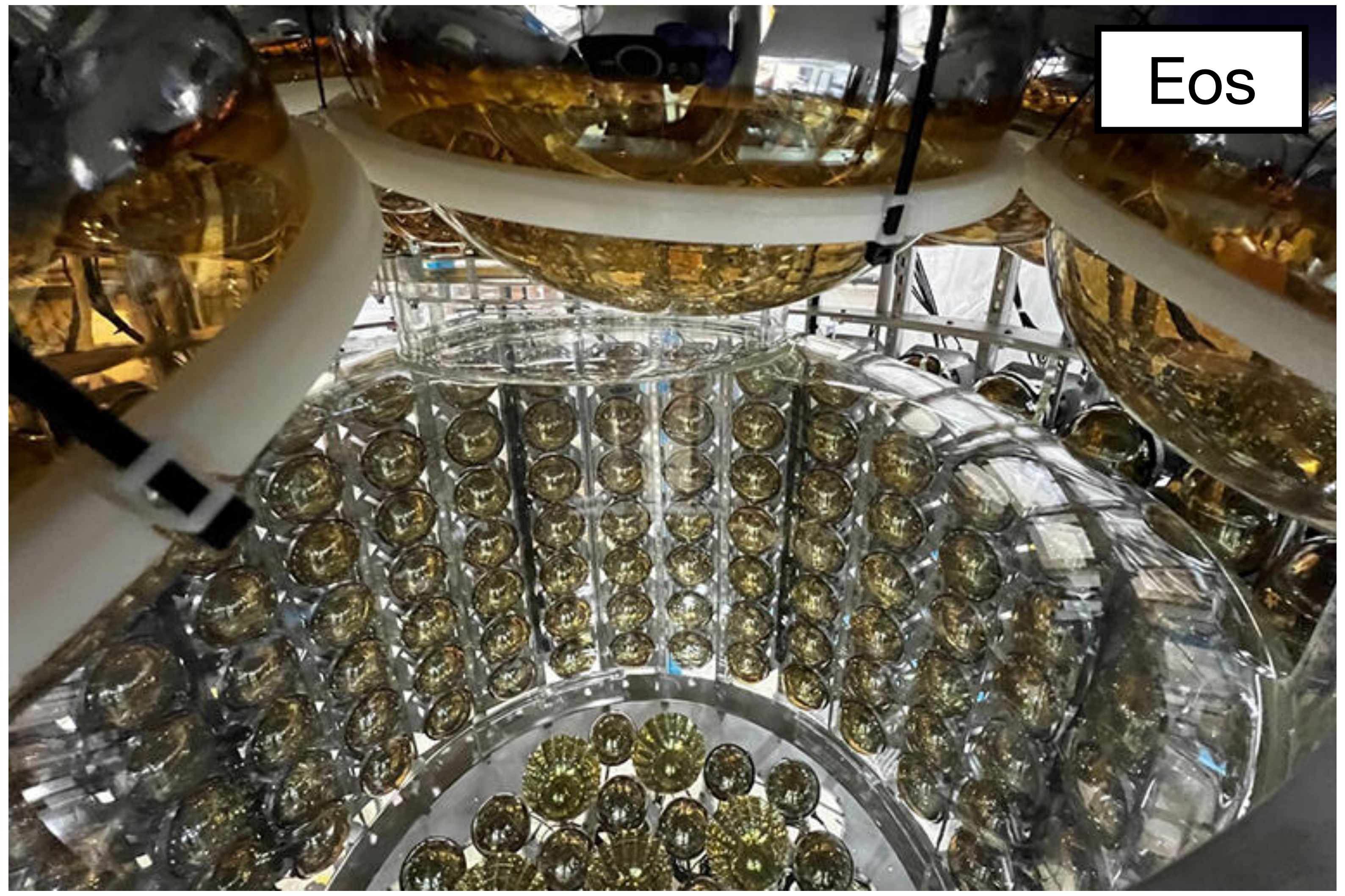
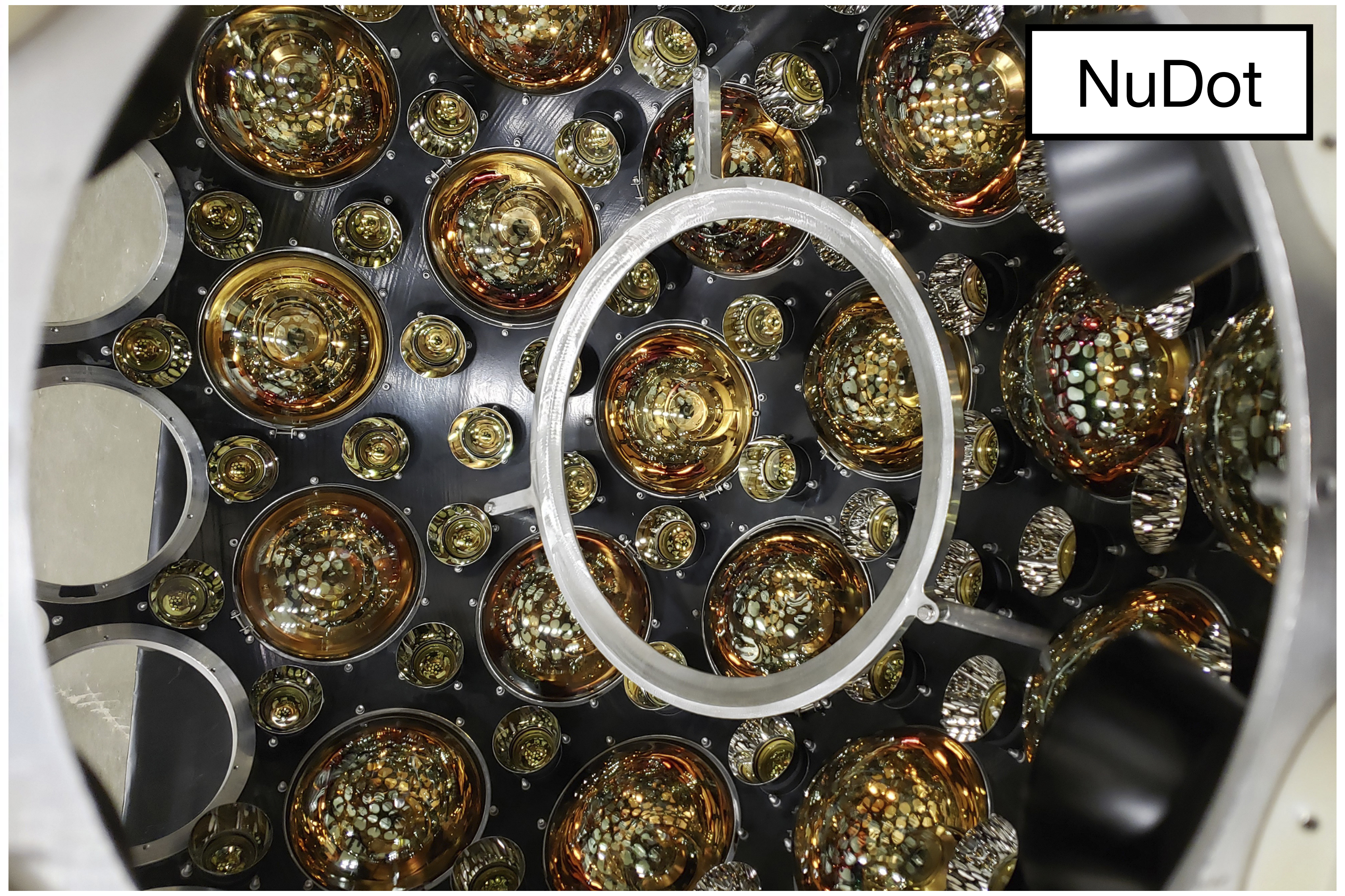
# Hybrid Detectors

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

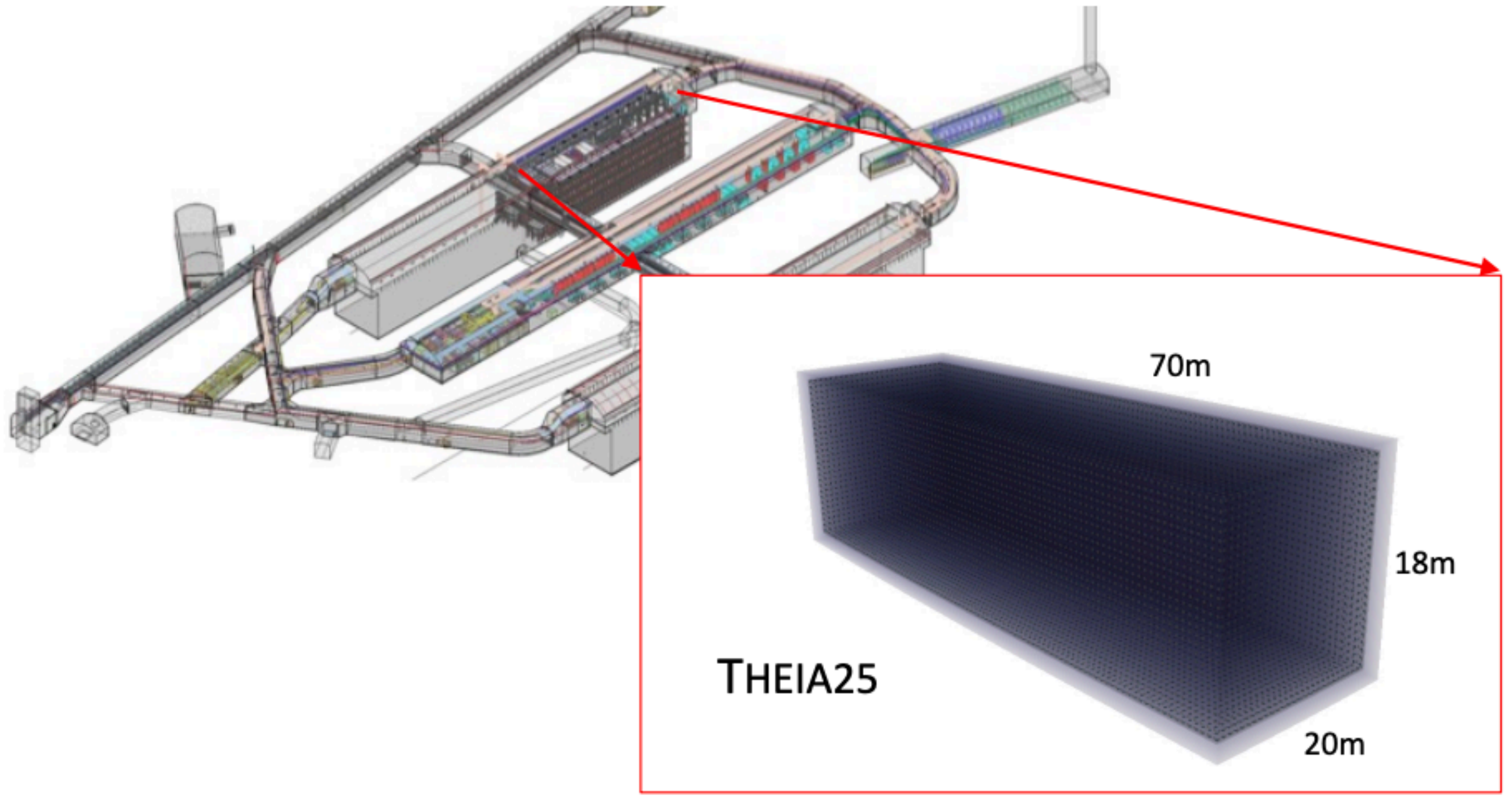


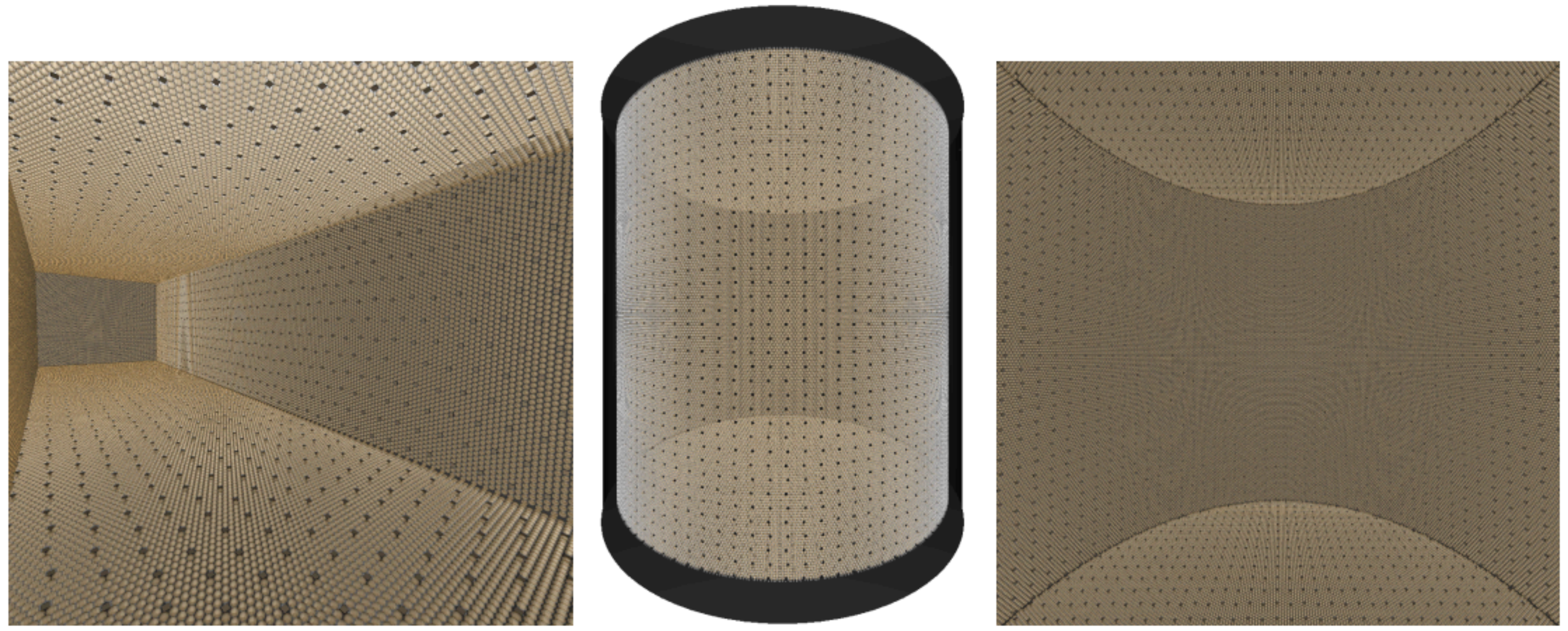



# Theia Detector

- 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

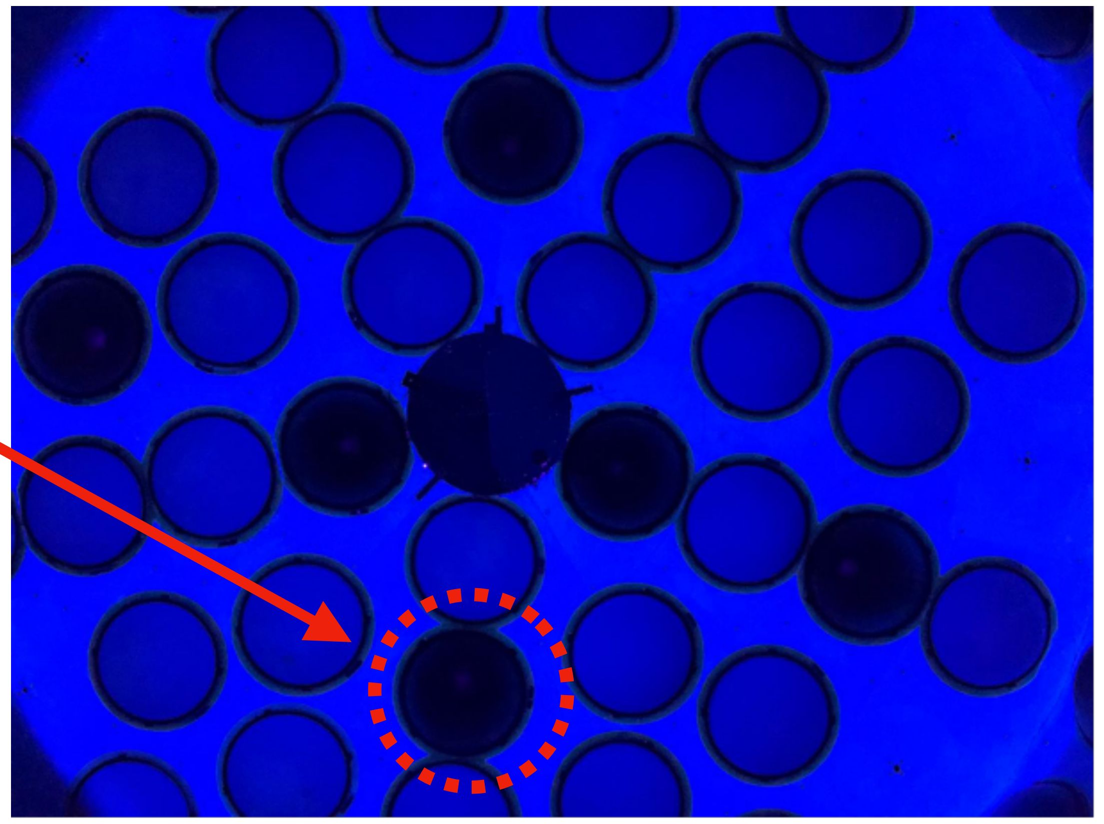


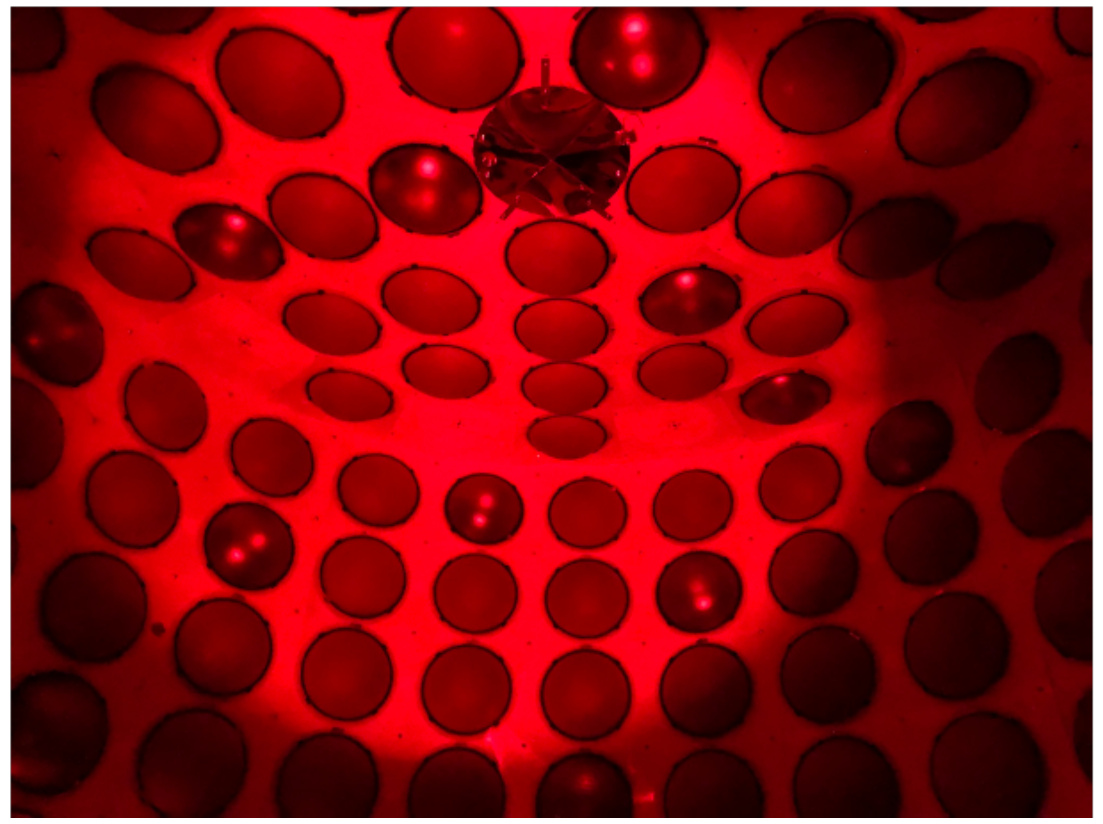



# 3. Coherent CAPTAIN-Mills Experiment

# Coherent CAPTAIN-Mills Overview

- ***Running*** 10 ton LAr light collection detector at Los Alamos National Lab ($\pi$DAR 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







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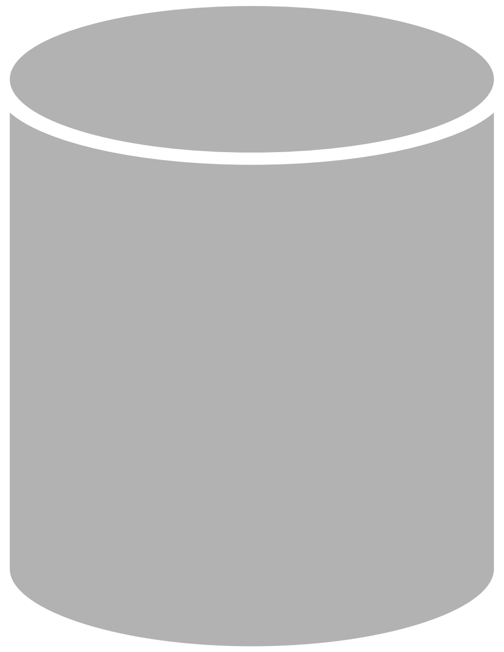
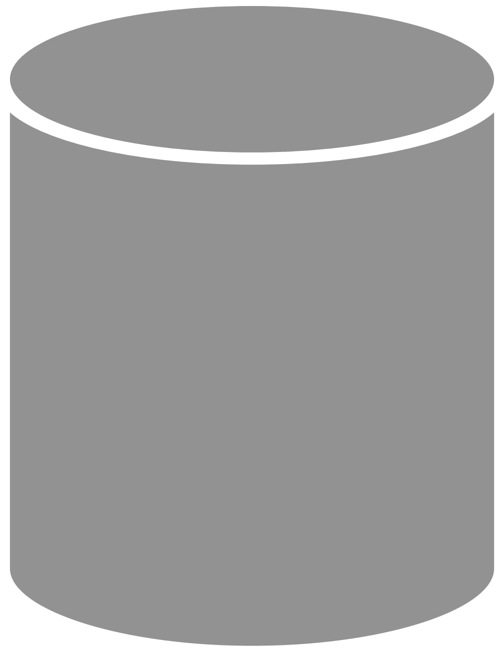
# Timeline



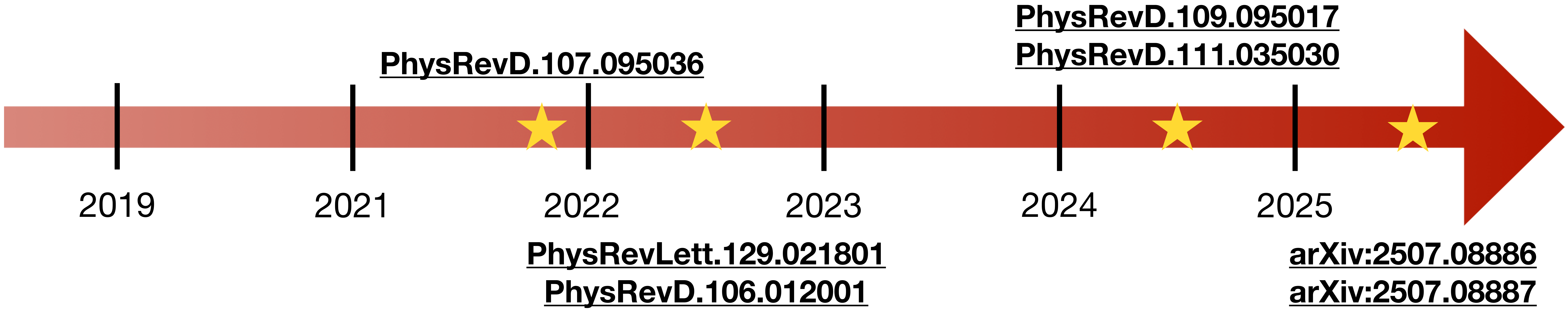




**CCM120 Engineering Run (2019)**
- Prototype detector
- Testing 120 8" PMTs for SBND
- Produced physics results

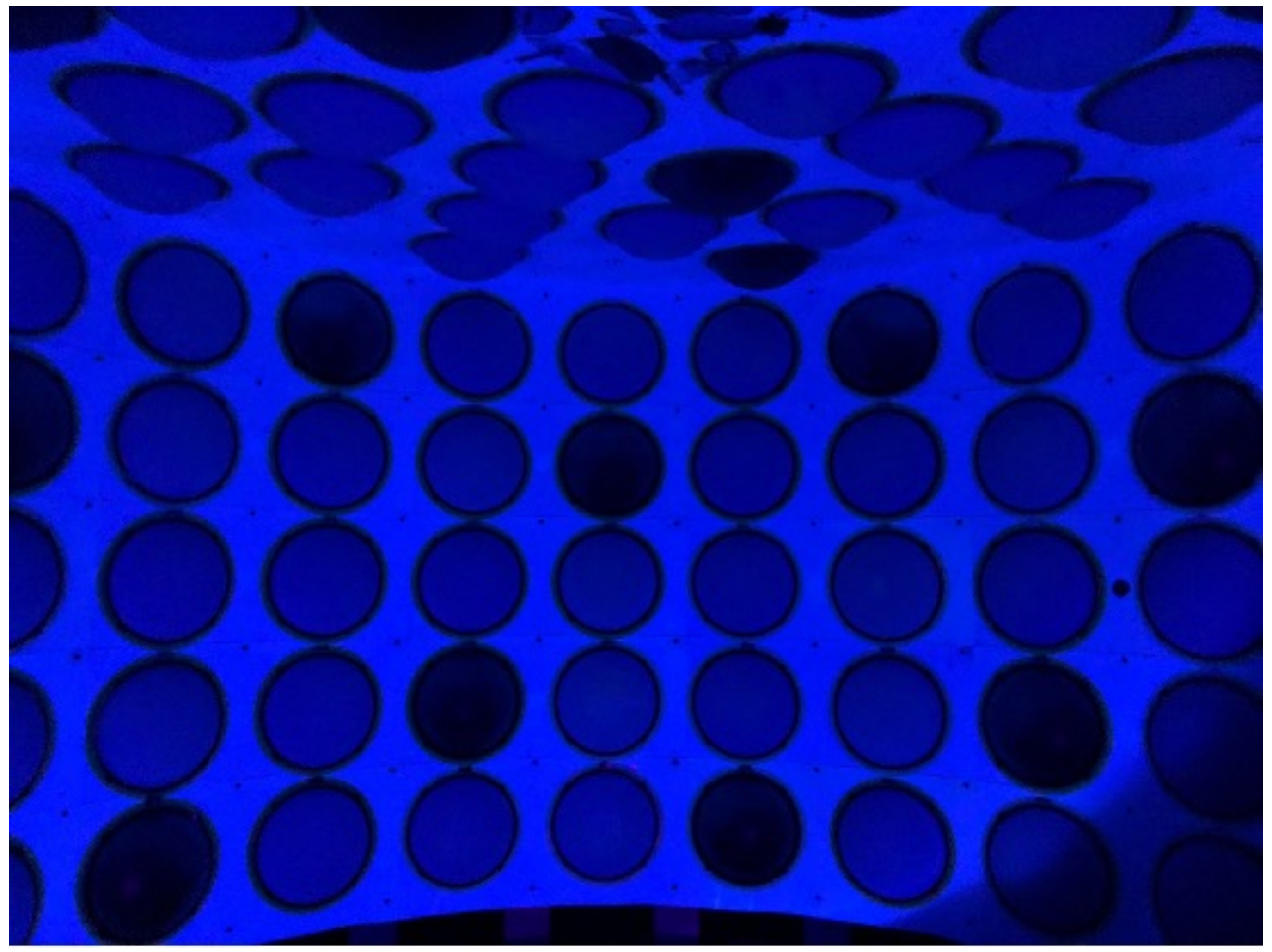
**CCM200 Engineering Run (2021)**
- Upgraded detector to 200 8" PMTs
- Doubled veto PMT coverage
- Increased forward shielding

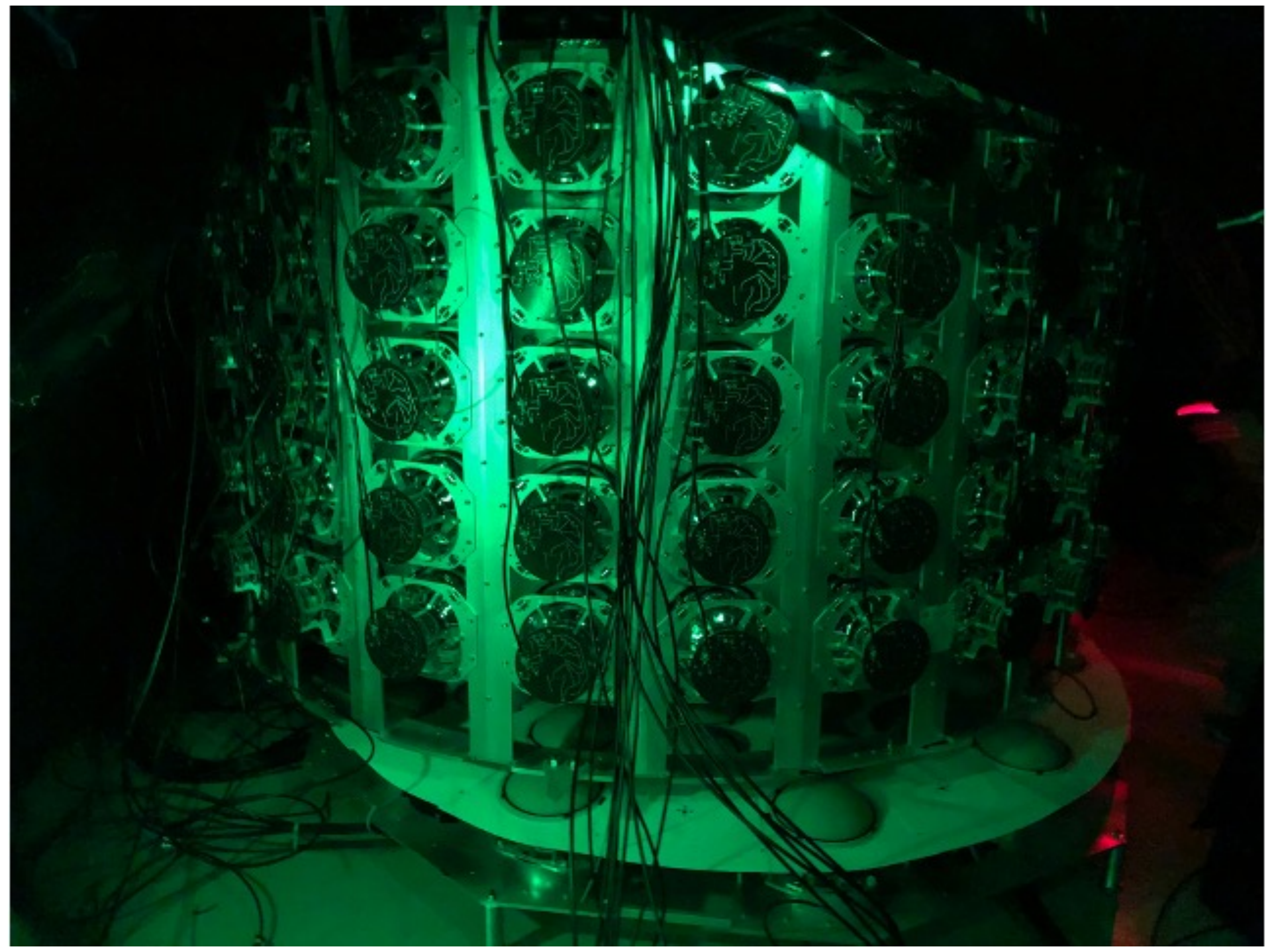
**CCM200 Physics Run (2022-2025)**
- Improved DAQ
- Installed additional top-shielding
- New data processing for Cherenkov light separation



# Detector Specifics

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



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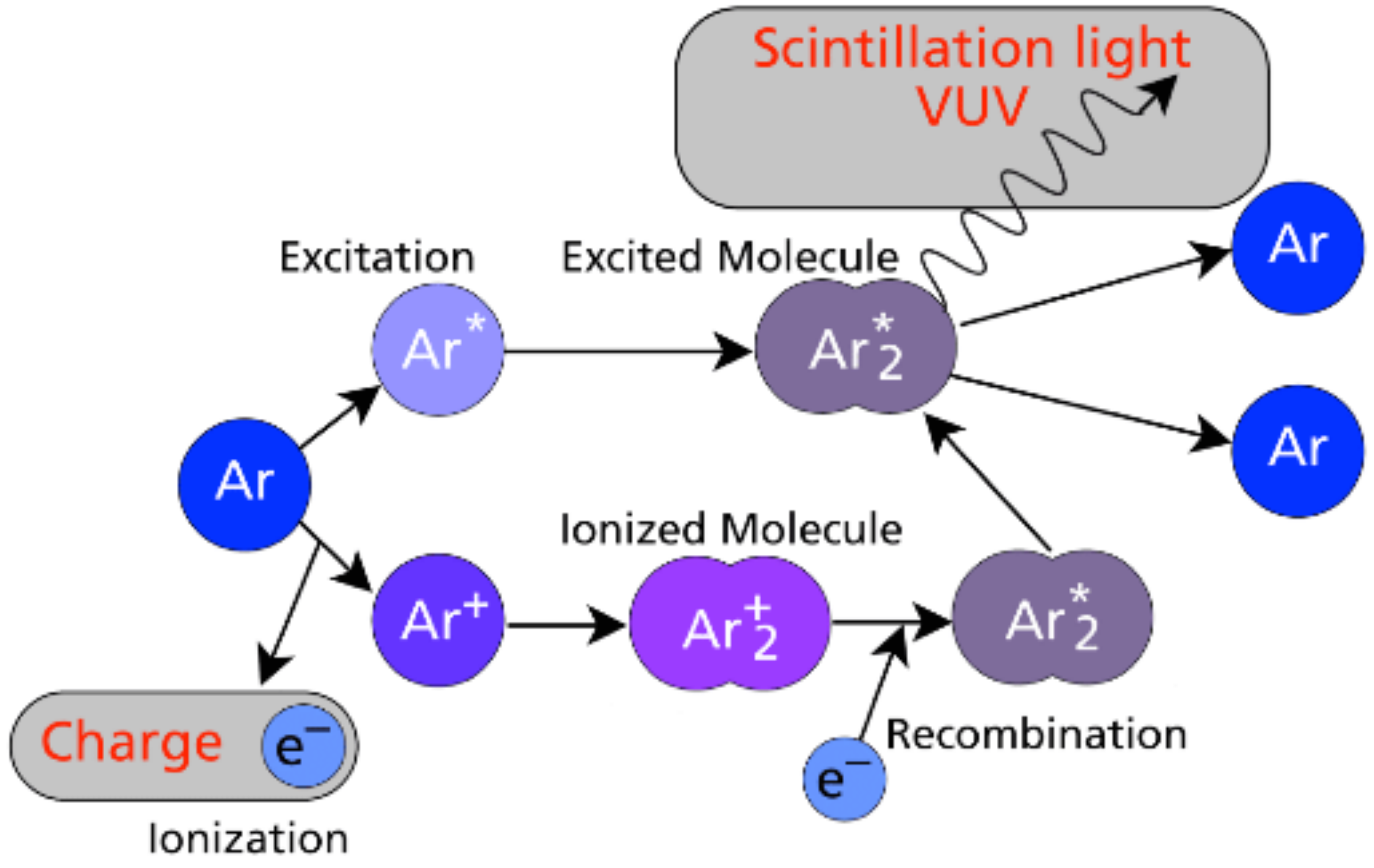
# Light Production in Liquid Argon

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





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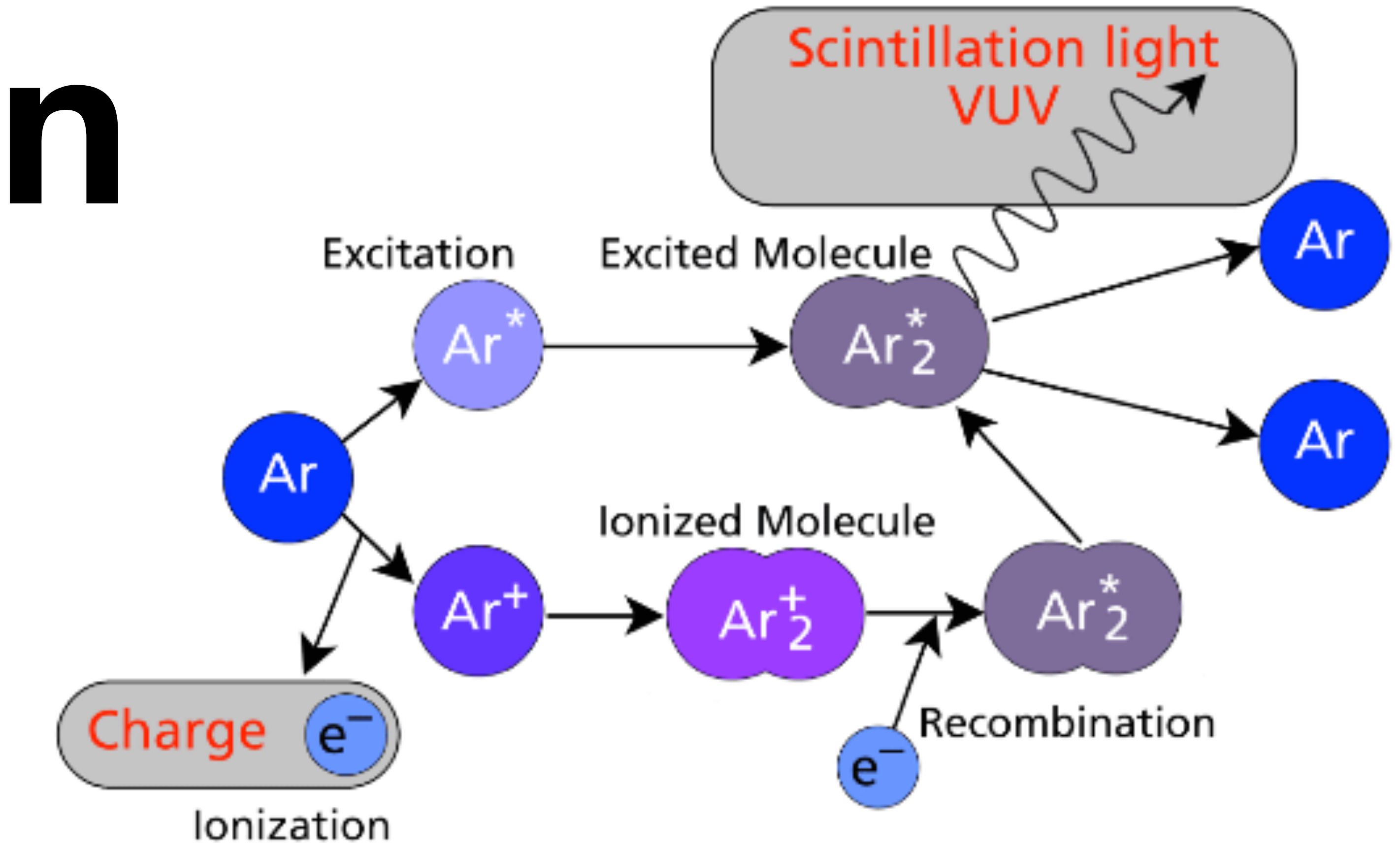
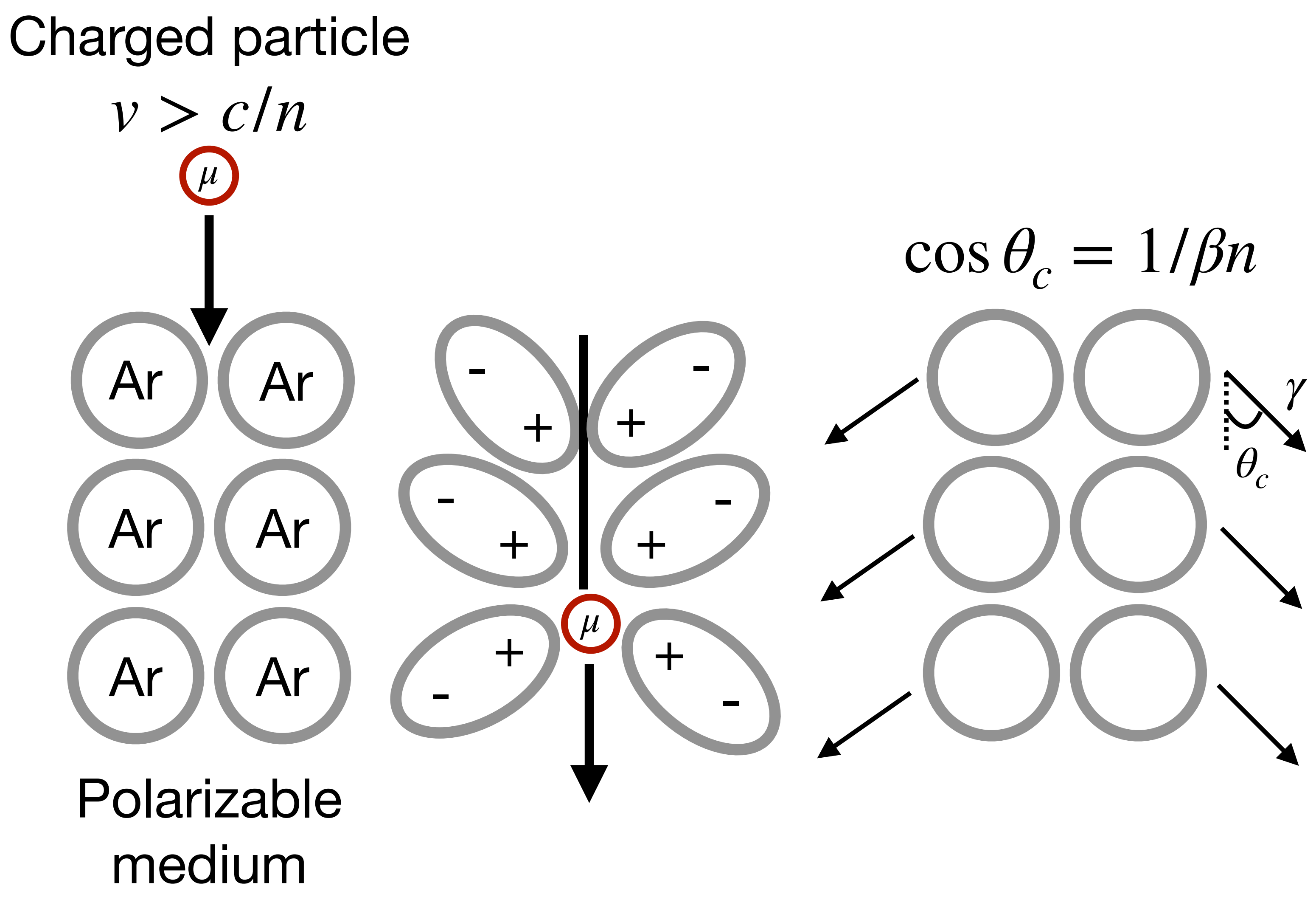
# Light Production in Liquid Argon

| 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 | $dN/d\lambda \propto \lambda^{-2}$ |



# 4. 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

# 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 advanta… with low-energy PID…* Snowmass 2021

- Relevant ex…

**This work** — ***event-by-event*** observation of Cherenkov light from ***sub-MeV*** particles using liquid argon

First use of liquid argon for hybrid detector!

  - 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

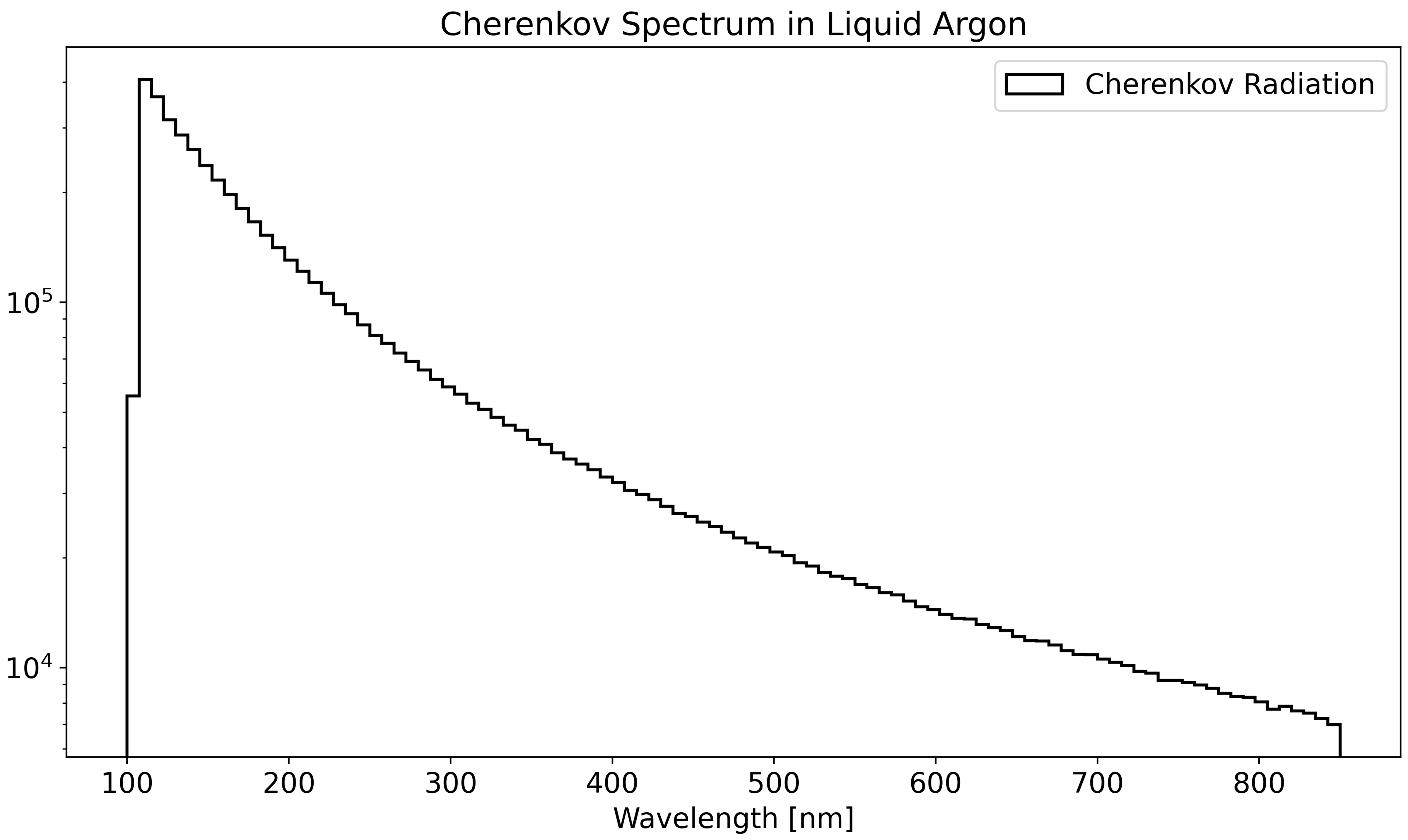
# Liquid Argon for Hybrid Detectors

- 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

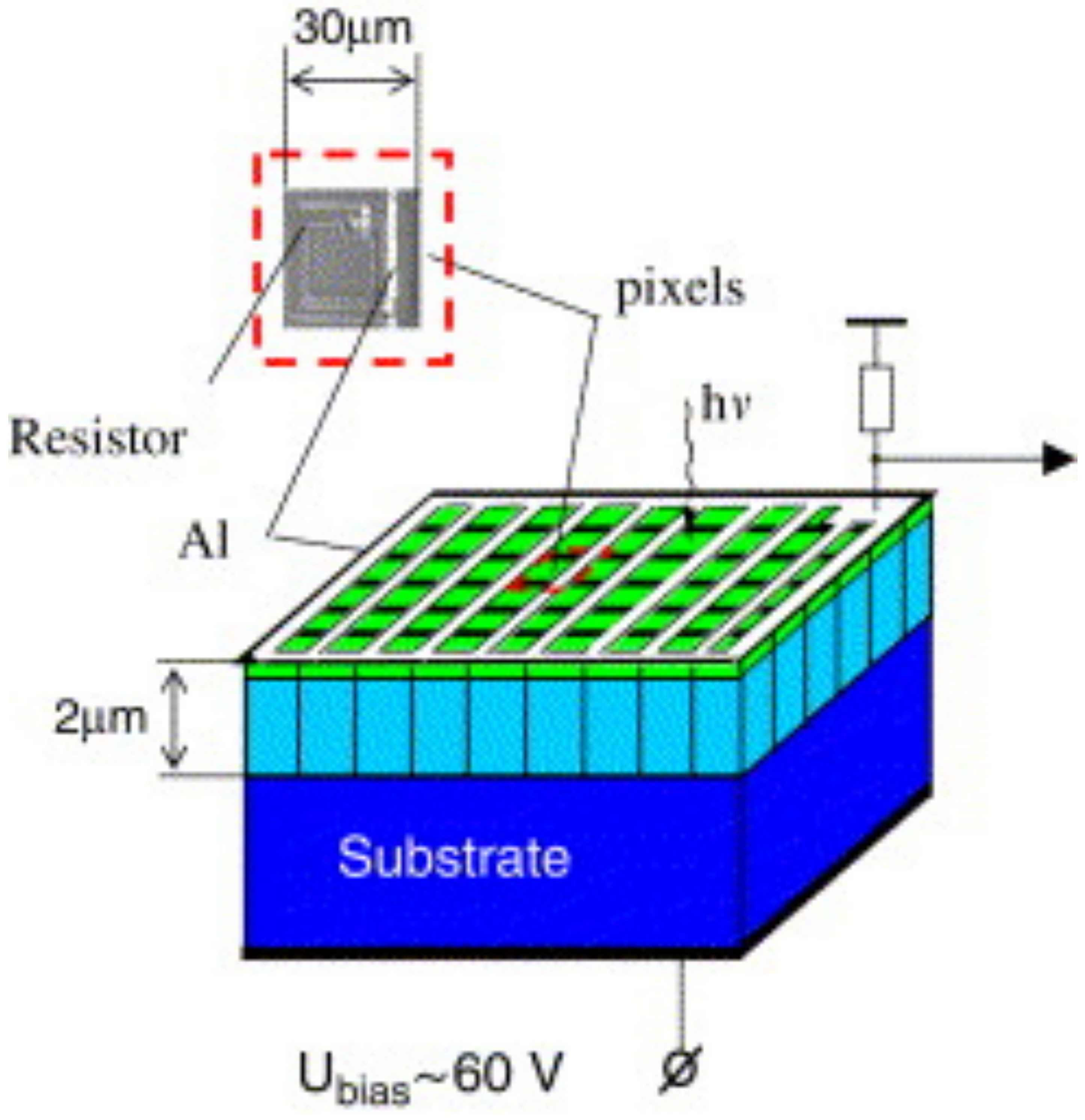
2. Time delay between prompt Cherenkov and scintillation signals

    - 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
        - This allows CCM to separate Cherenkov from scintillation light with 2ns timing resolution

# Liquid Argon for Hybrid Detectors

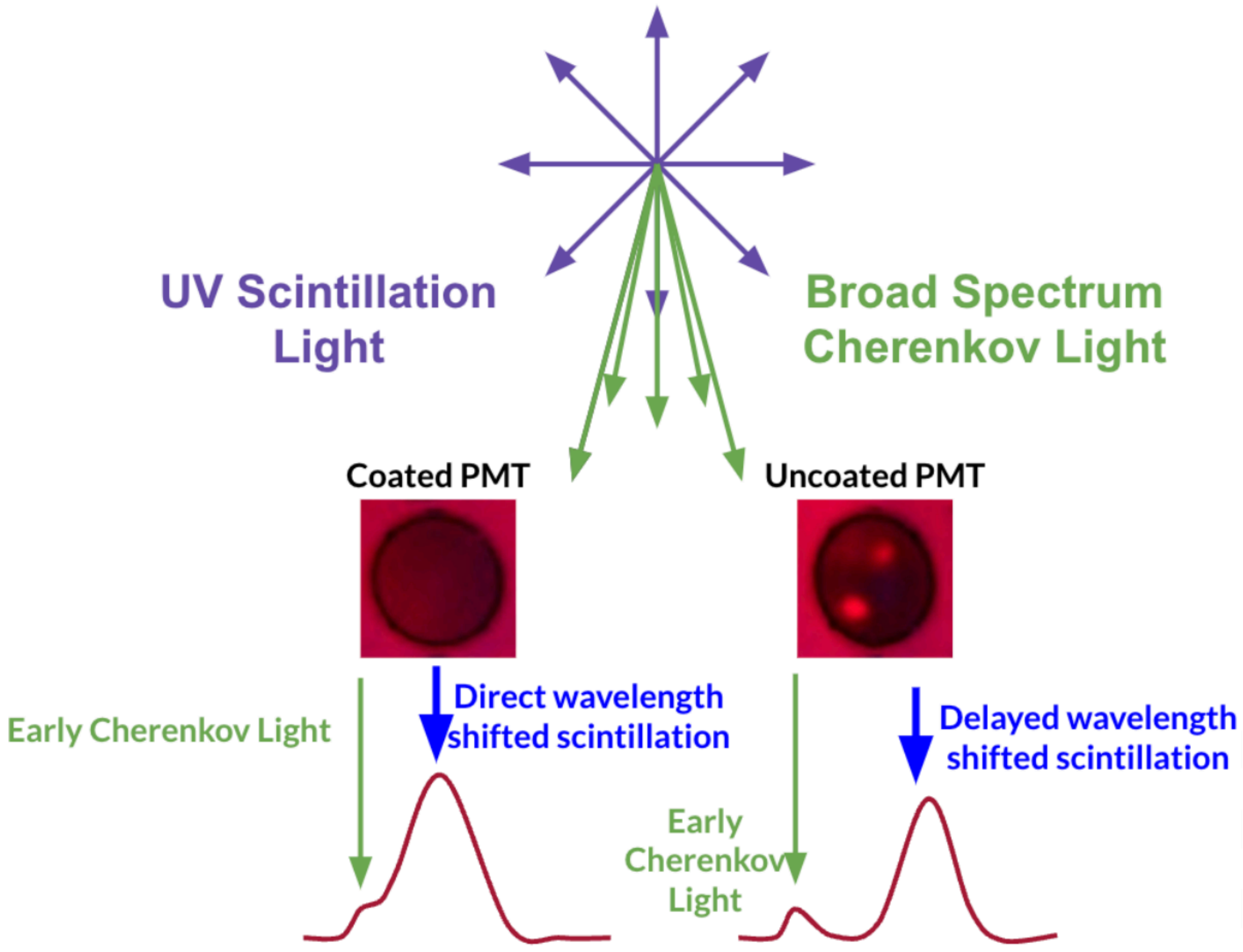
- Liquid argon offers key advantages over oil-based liquid scintillators

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

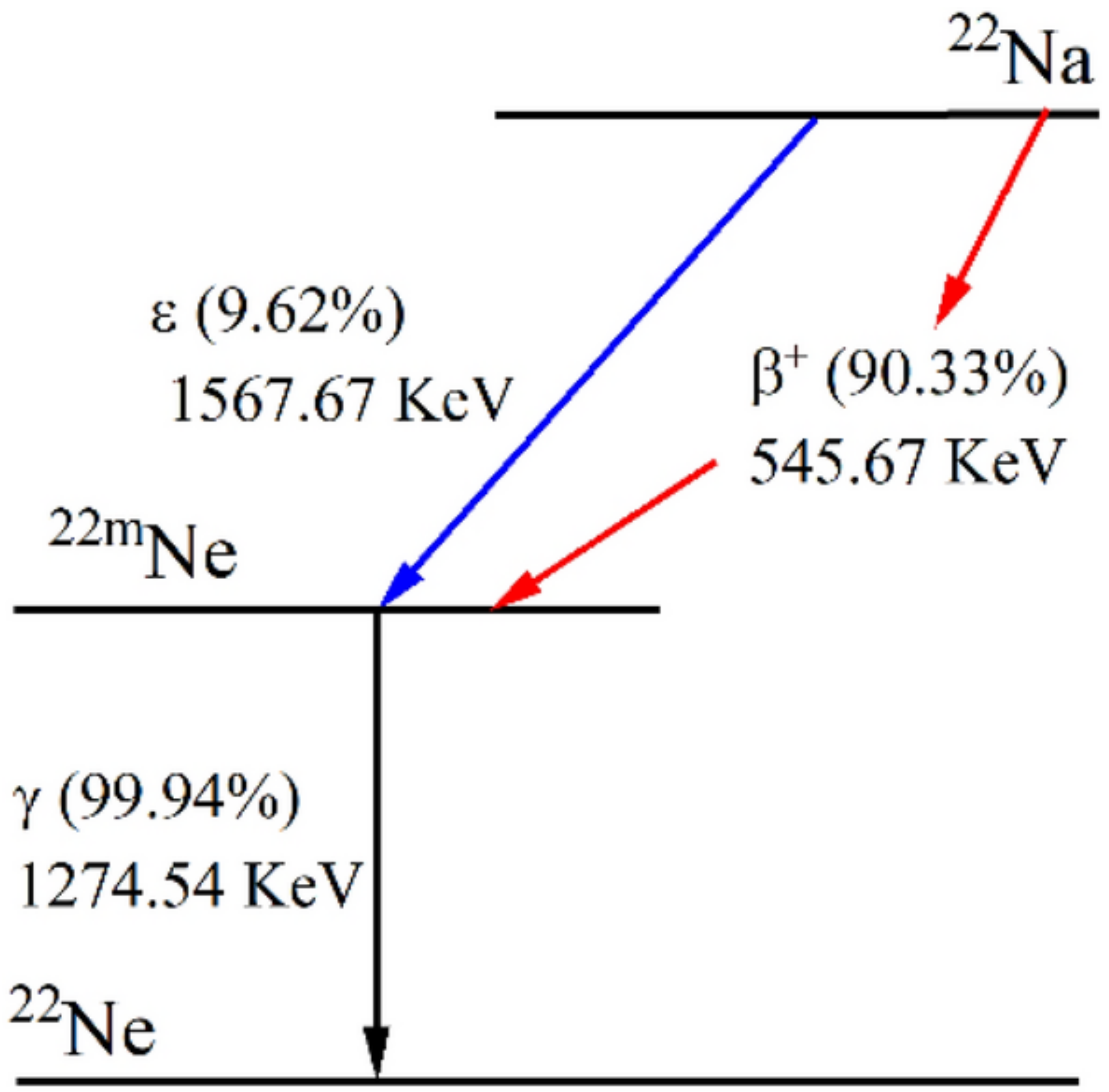
- ***Uncoated PMTs*** allow for wavelength discrimination between UV scintillation light and broad spectrum Cherenkov light
- Visible Cherenkov photons detected by uncoated tubes ***before*** wavelength shifted scintillation light
- Combined with 2ns timing resolution, able to ***isolate early Cherenkov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

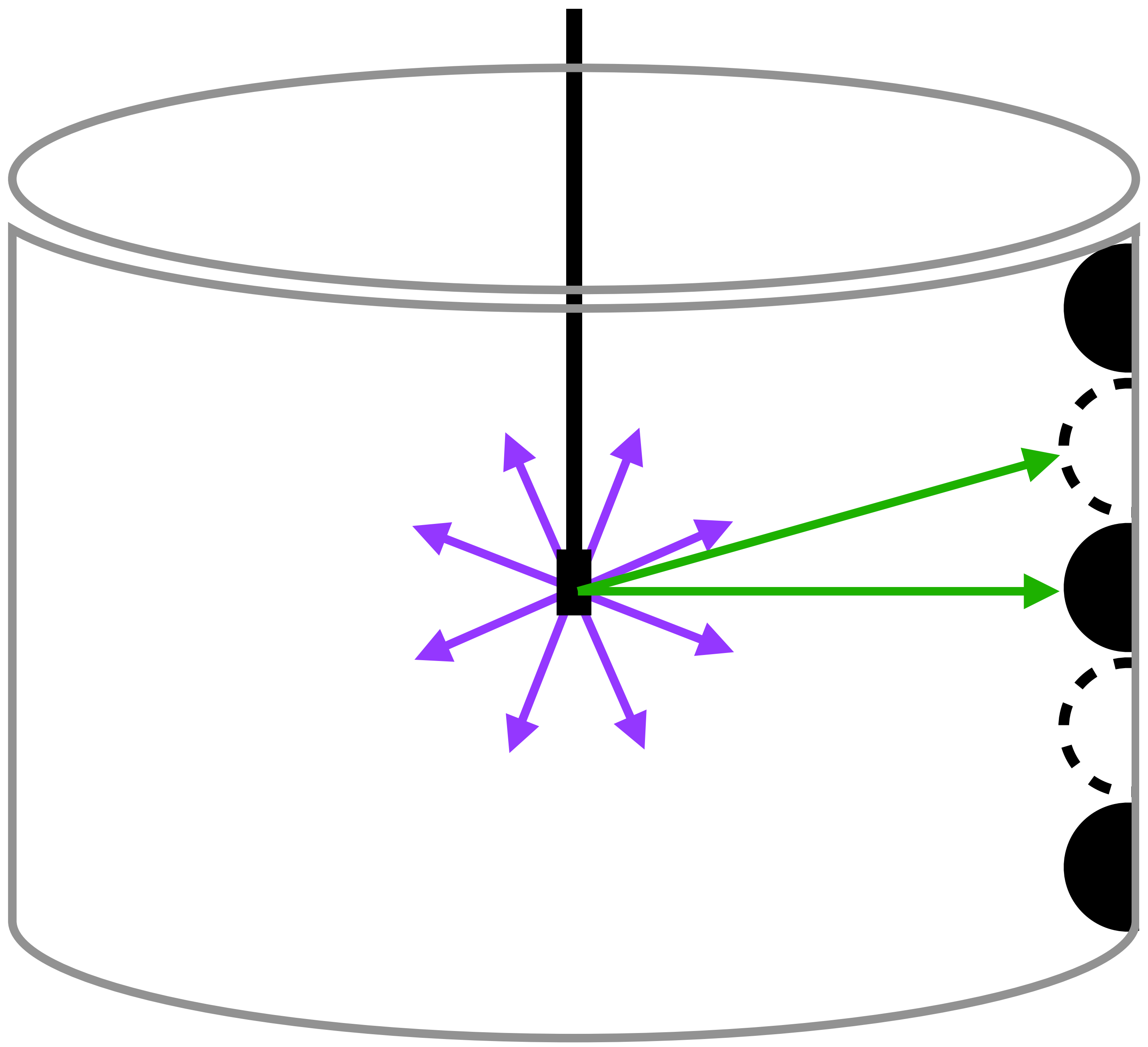


5. First Event-by-Event Identification of Cherenkov Radiation from Sub-MeV Particles in Liquid Argon
arXiv:2507.08886

# Calibration Source

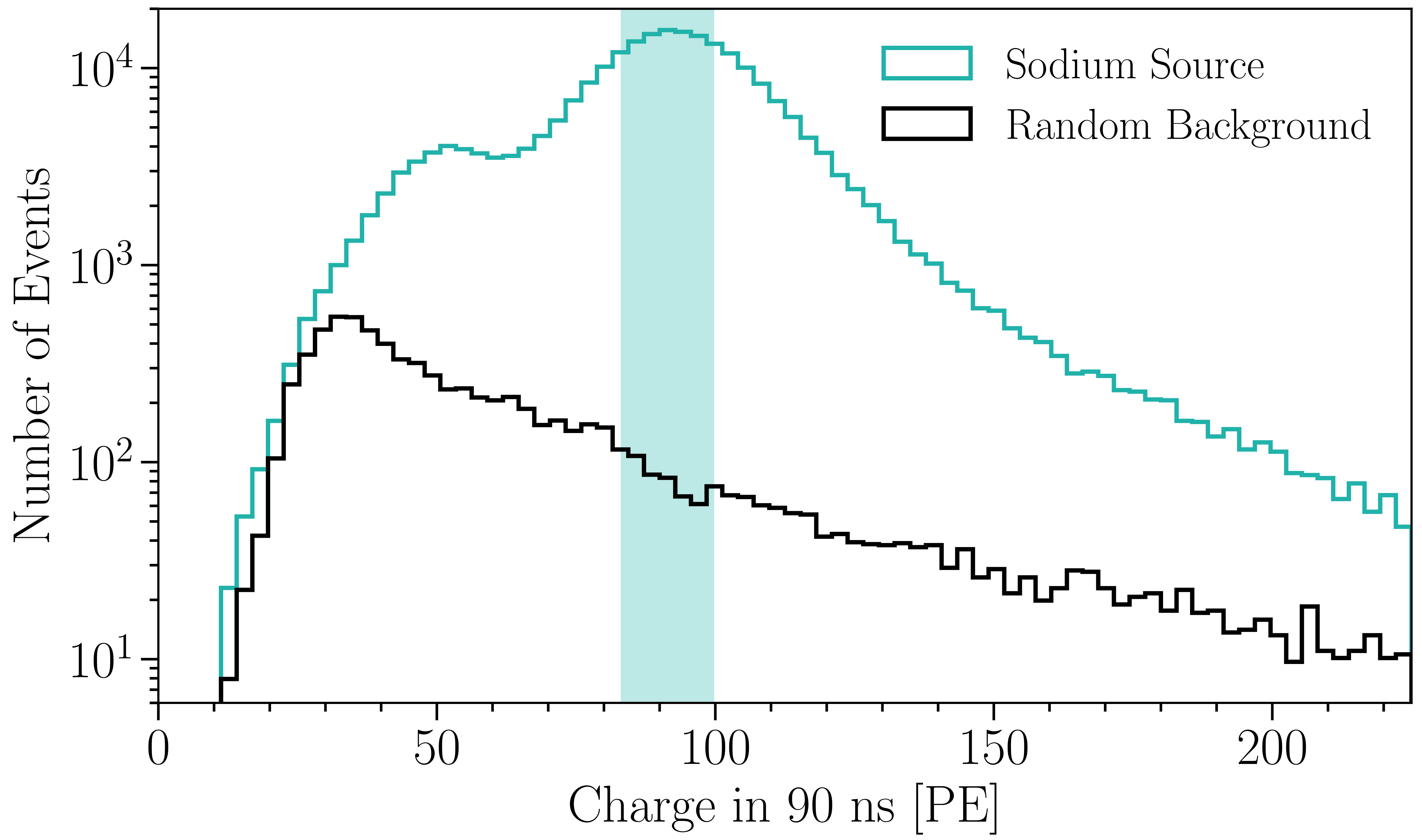
- $^{22}$Na calibration source at origin of the detector
    - Source is enclosed in stainless steel
    - Decays produce 1.275 MeV $\gamma$ and 0.546 MeV $e^+$ (promptly annihilates)
    - Decay produces a ***single*** gamma-ray or ***three*** gamma-rays



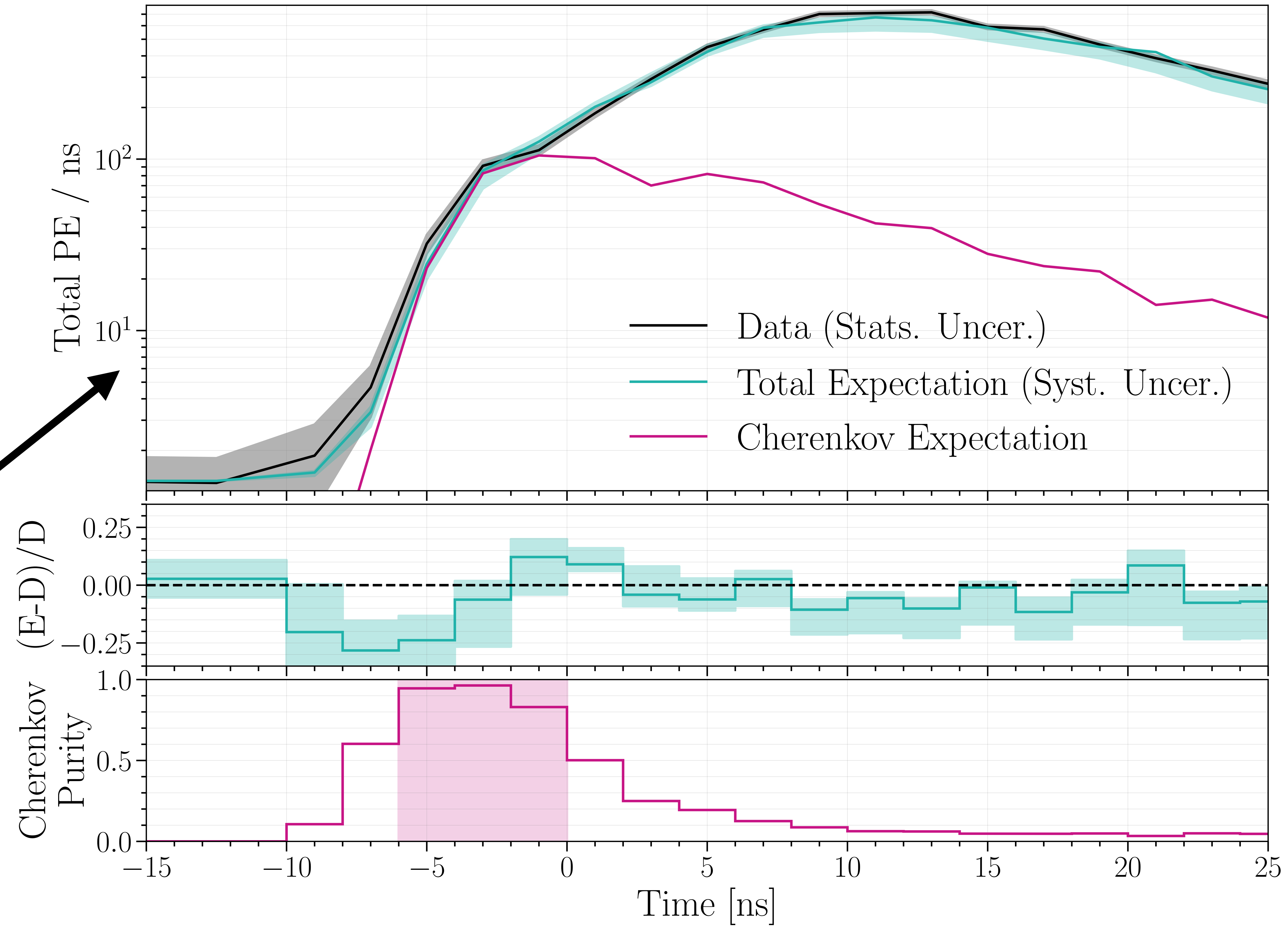
# Calibration Source

- 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 $\beta^+$ decay)



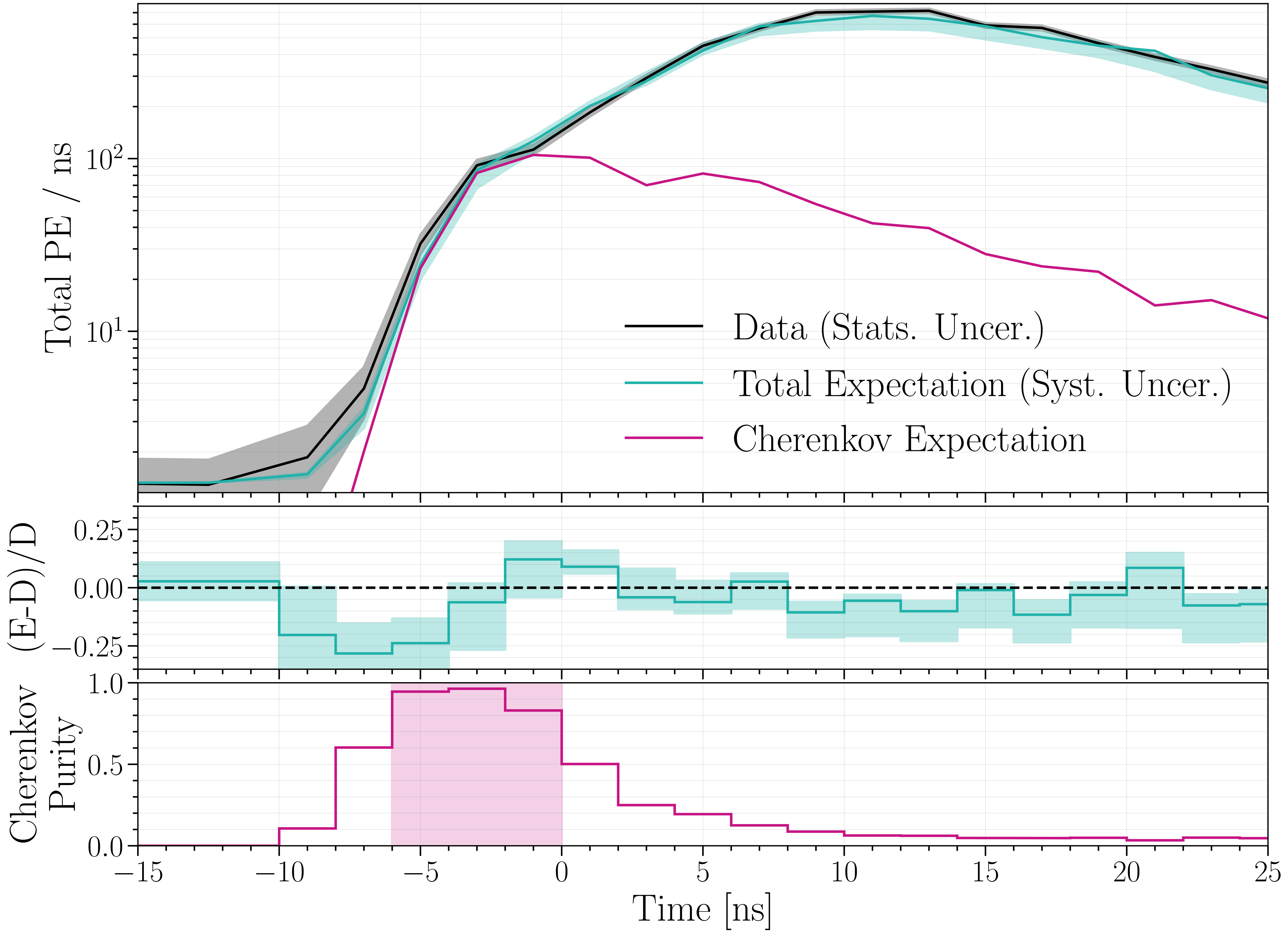
# Typical Uncoated PMT Response

- 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 $1\sigma$ uncertainties
    - Total expectation combines scintillation, Cherenkov, and random backgrounds



# 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***
- ***Middle plot —*** residual between expectation and data, $\pm 15\ \%$ agreement at $1\sigma$ level



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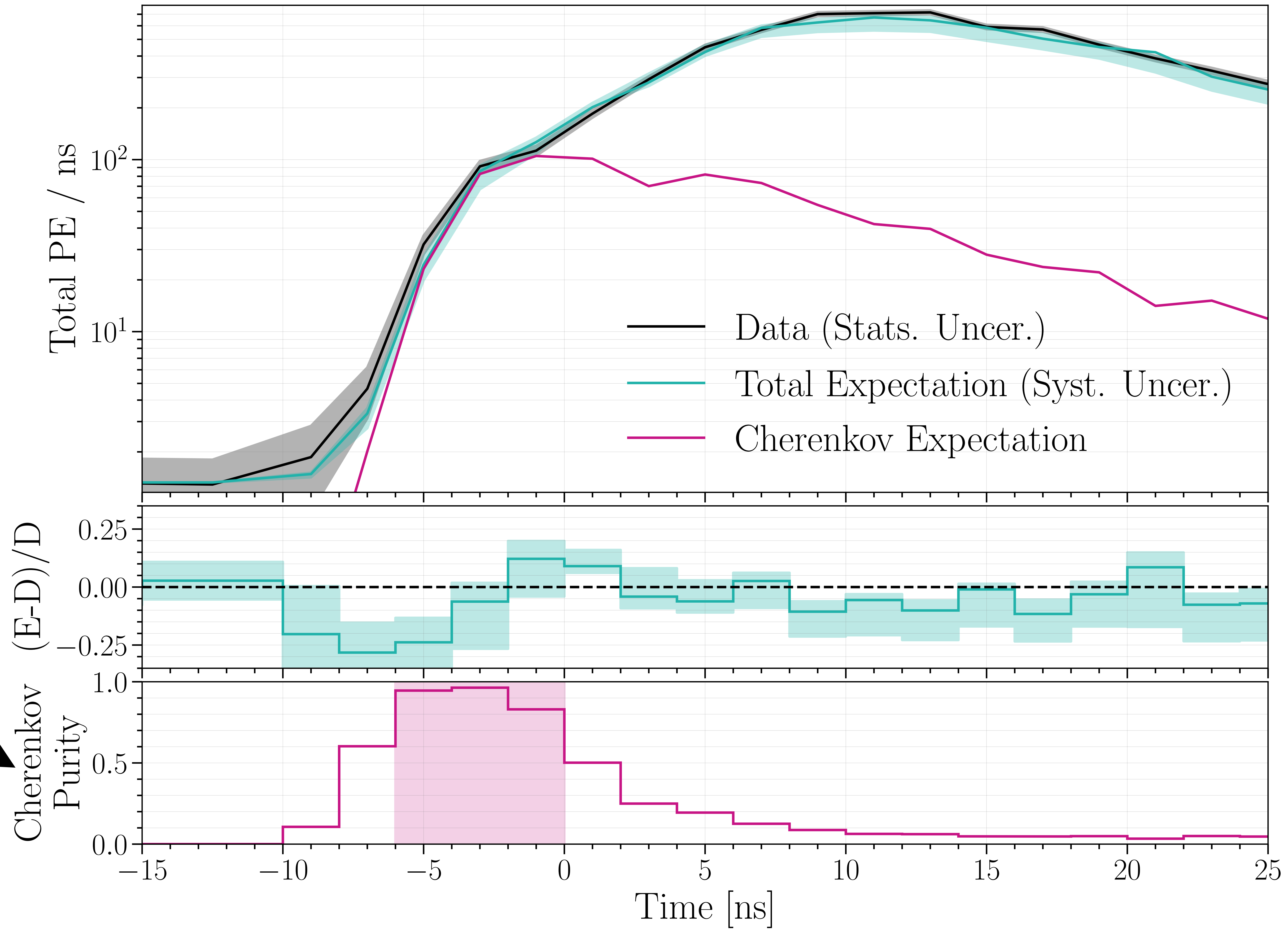
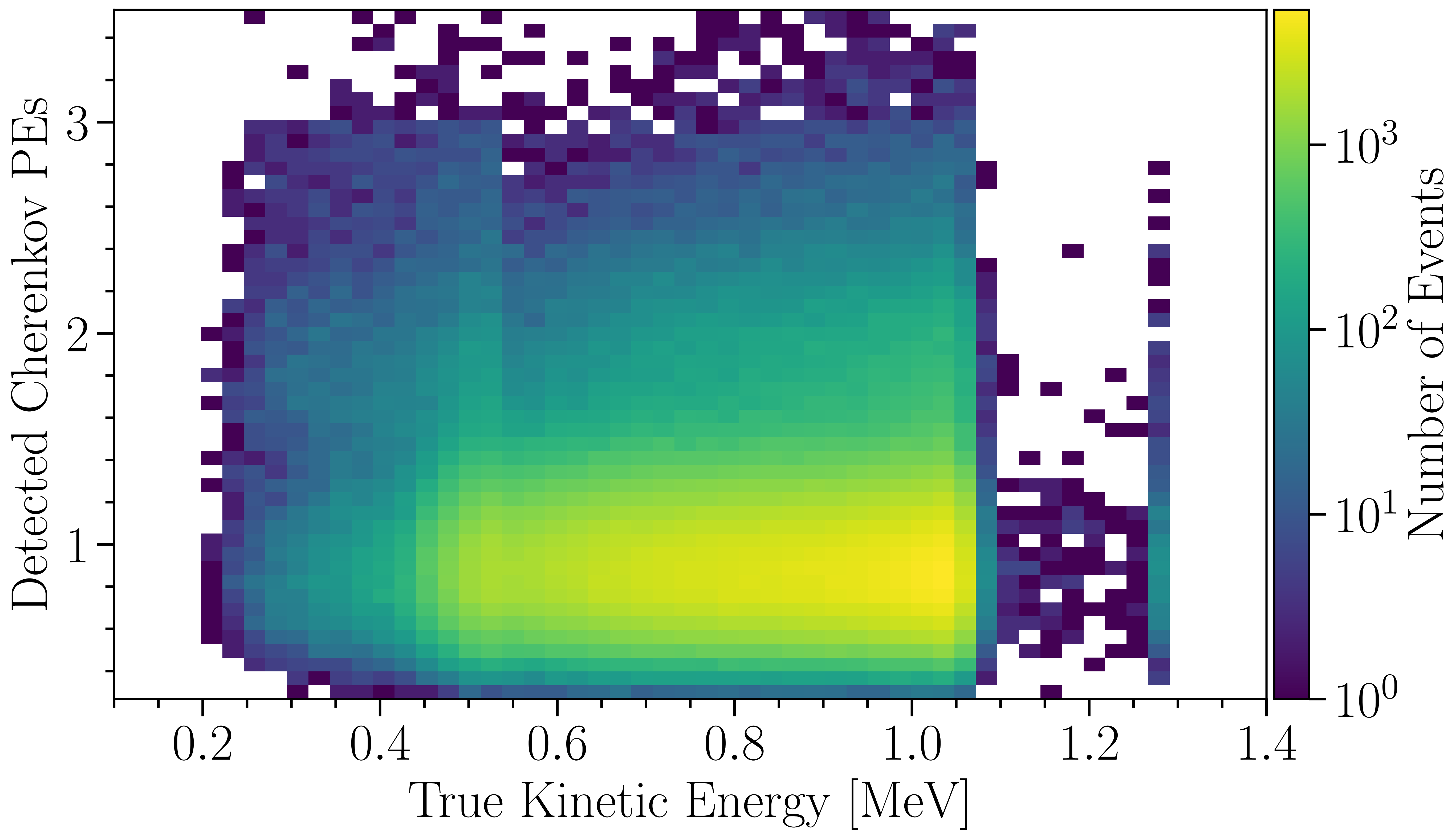
# Typical Uncoated PMT Response

- 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***
- ***Bottom plot —*** Cherenkov purity as a function of time, $-6 \leq t \leq 0$ ns is "Cherenkov enhanced" time region



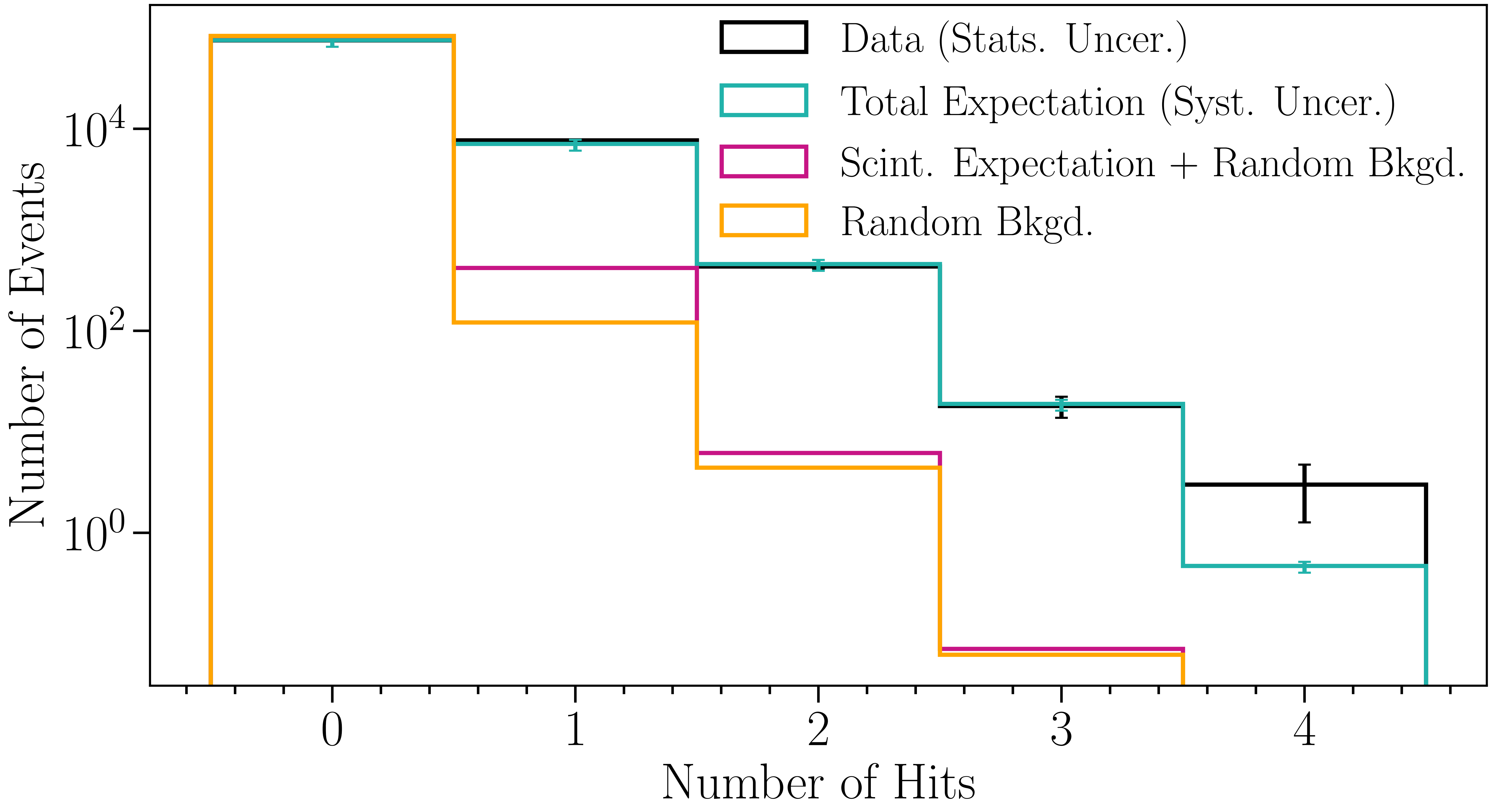
# Expected Cherenkov Photons per Event

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



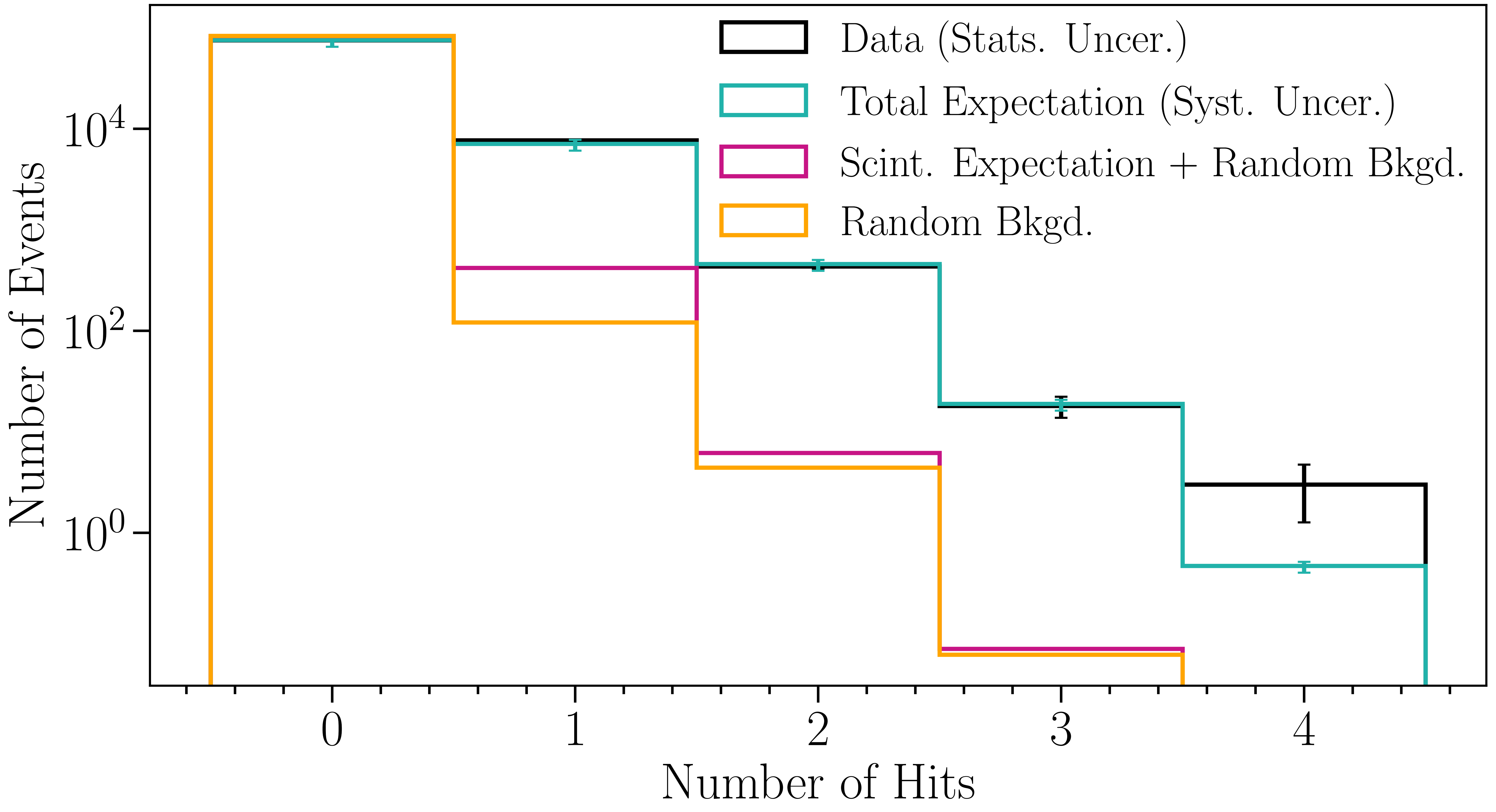
# Number of Hits in Sodium Events

- 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)



# Number of Hits in Sodium Events

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





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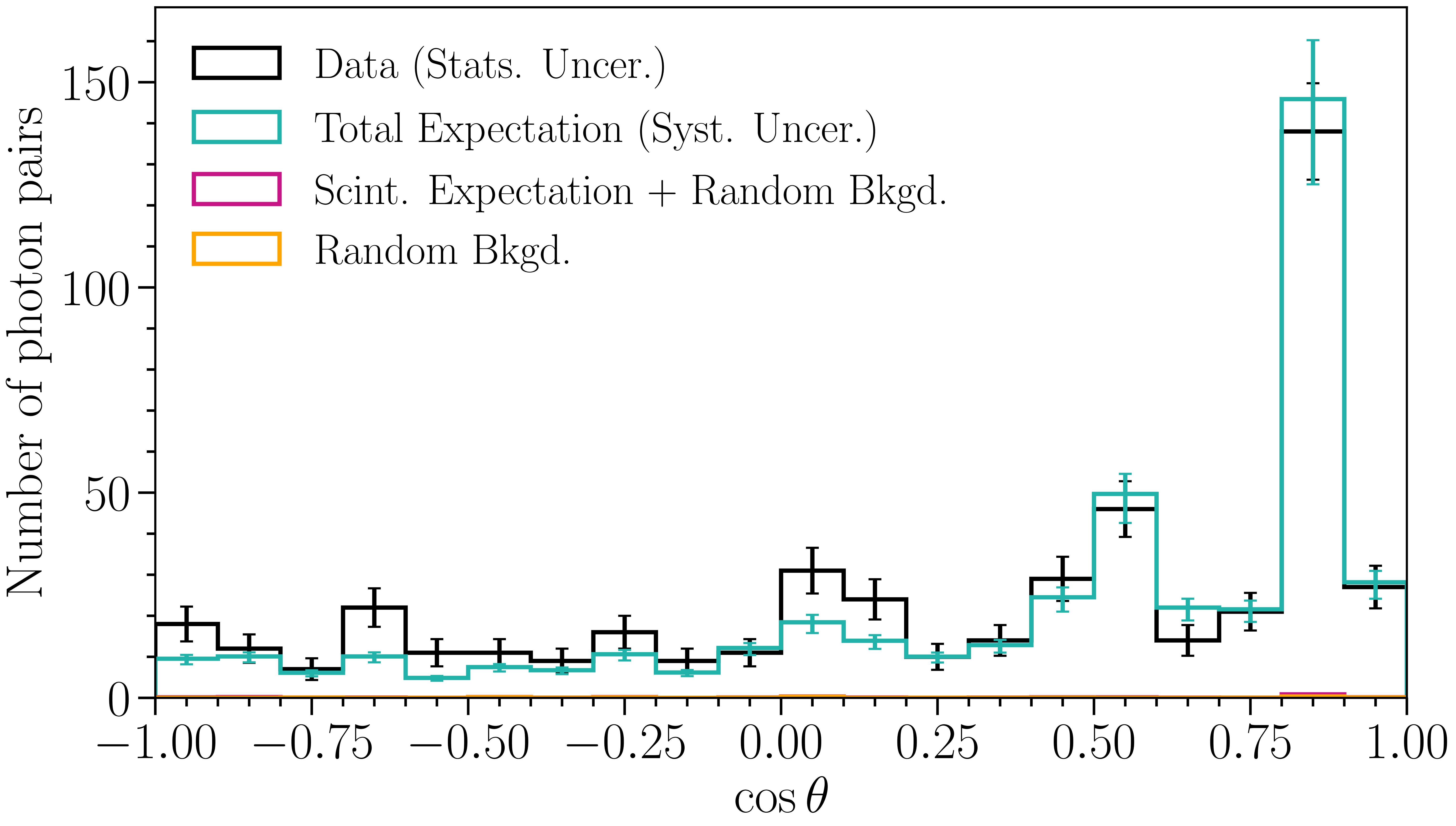
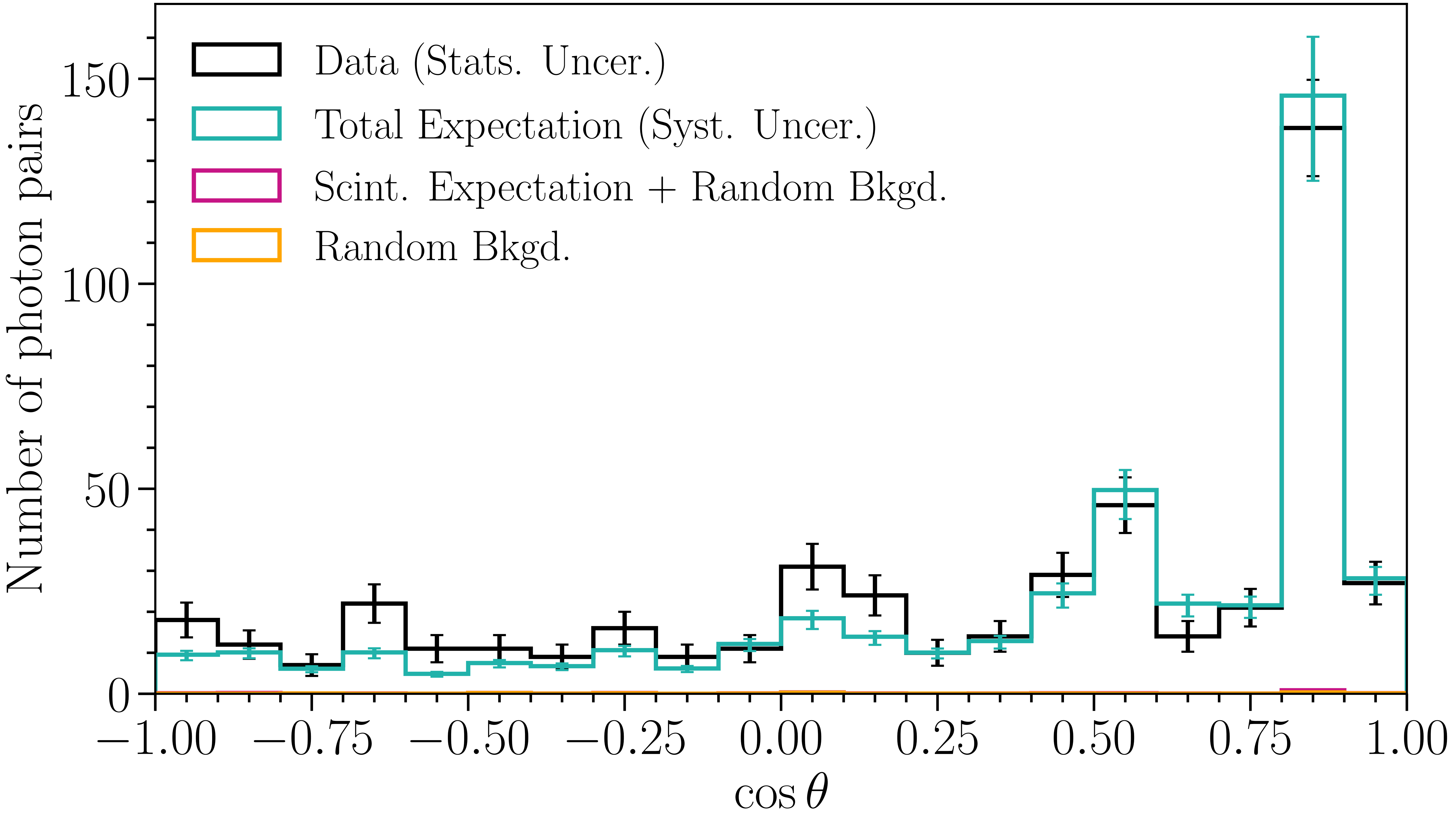
# Angle Between Photon Hits

- Require $\geq 2$ 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 $2\sigma$ across all angles



# 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
- $\chi^2$ = 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



6. Measurement of the Liquid Argon Scintillation Pulse Shape Using Differentiable Simulation in the Coherent-CAPTAIN Mills Experiment
arXiv:2507.08887

# Overview

- CCM has the ***largest volume and highest photo-coverage*** for LAr light collection only detectors, making it uniquely suited to characterize light in LAr
- This work characterizes light production and propagation in LAr using a differentiable simulation and —

★ Is the ***first*** description of both scintillation and Cherenkov light in a large LAr detector

★ Uses a ***new model for the index of refraction*** that describes absorption near UV resonance

★ ***Finds evidence for Mie scattering*** off of the impurities in the bulk LAr

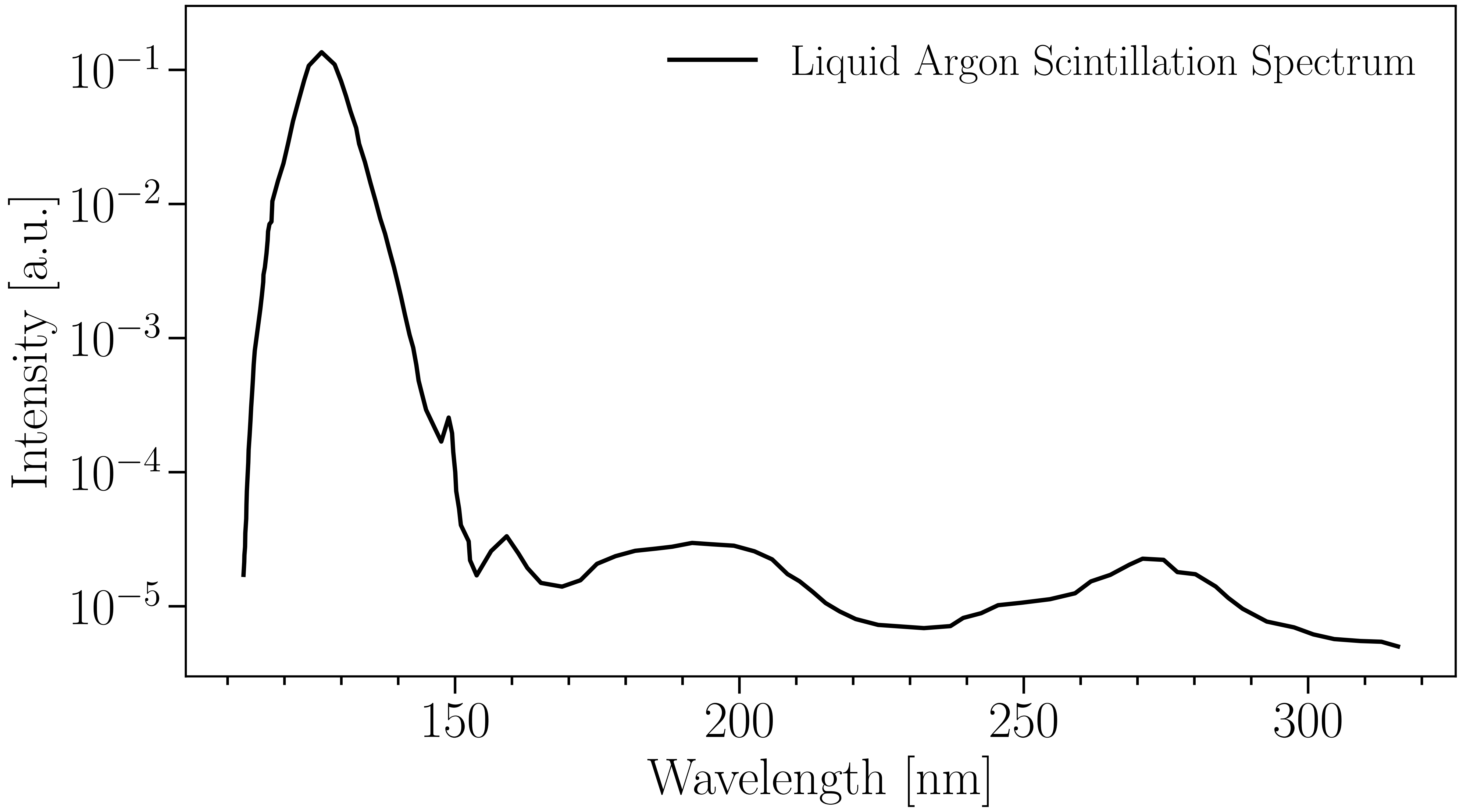
# Differentiable Simulation

- Differentiable simulation ascribes gradient with respect to a physics parameter on the unit of measure
- Through tracking photon wavelength, distance travelled, and time (both before and after WLS), can ***re-weight the probability of PE observation under a different physics scenario***
- ***Reduces computation time and allows for efficient gradient based optimization, which allows for simultaneous constraint of 20+ parameters in binned likelihood optimization***

# Scintillation Light Profile

- LAr scintillation light is produced from decay of excited argon dimers
- Argon dimer has two spin configurations: singlet (fast time constant decay) and triplet states (slower time constant decay)
- Experimental evidence for “intermediate” time constant due to electron recombination physics
- Time profile can be altered by impurities quenching the triplet state

$$I(t) = \frac{R_s}{\tau_s} e^{-t/\tau_s} + \frac{R_t}{\tau_t} e^{-t/\tau_t} + \frac{1 - R_s - R_t}{(1 + t/\tau_{rec})^2 \ \tau_{rec}} \quad (1)$$

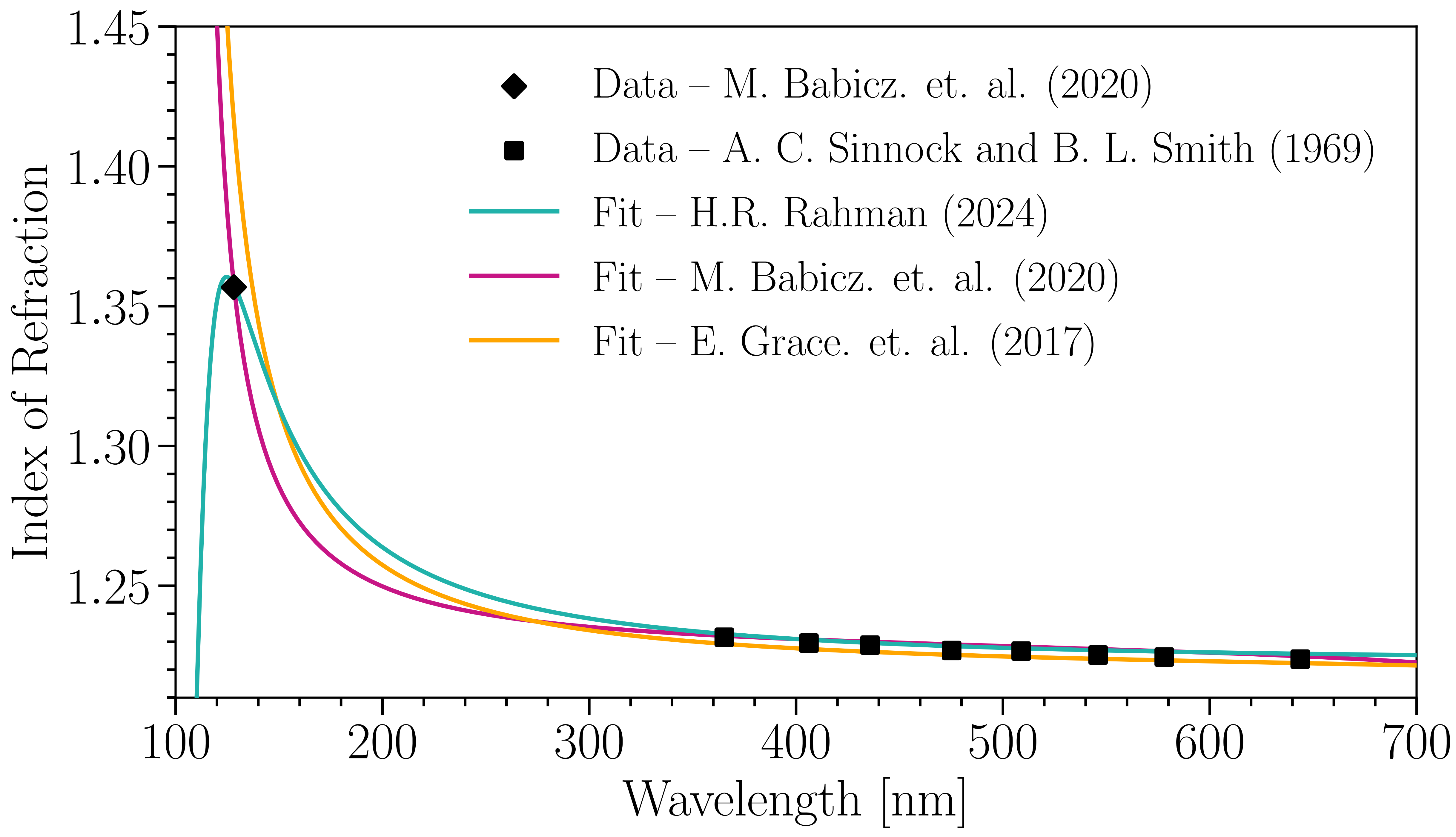


# Index of Refraction

- Index of refraction governs Cherenkov light production
- Previous treatments of the index of refraction fit data using the Sellmeier dispersion relationship (M.Babicz, E. Grace)

$$n^2(\lambda) = a_0 + \Sigma_i \frac{a_i \lambda^2}{\lambda^2 - \lambda_i}$$

  - Diverges to infinity near the resonances $\lambda_i$ (problematic for LAr with a UV resonance at 106nm)





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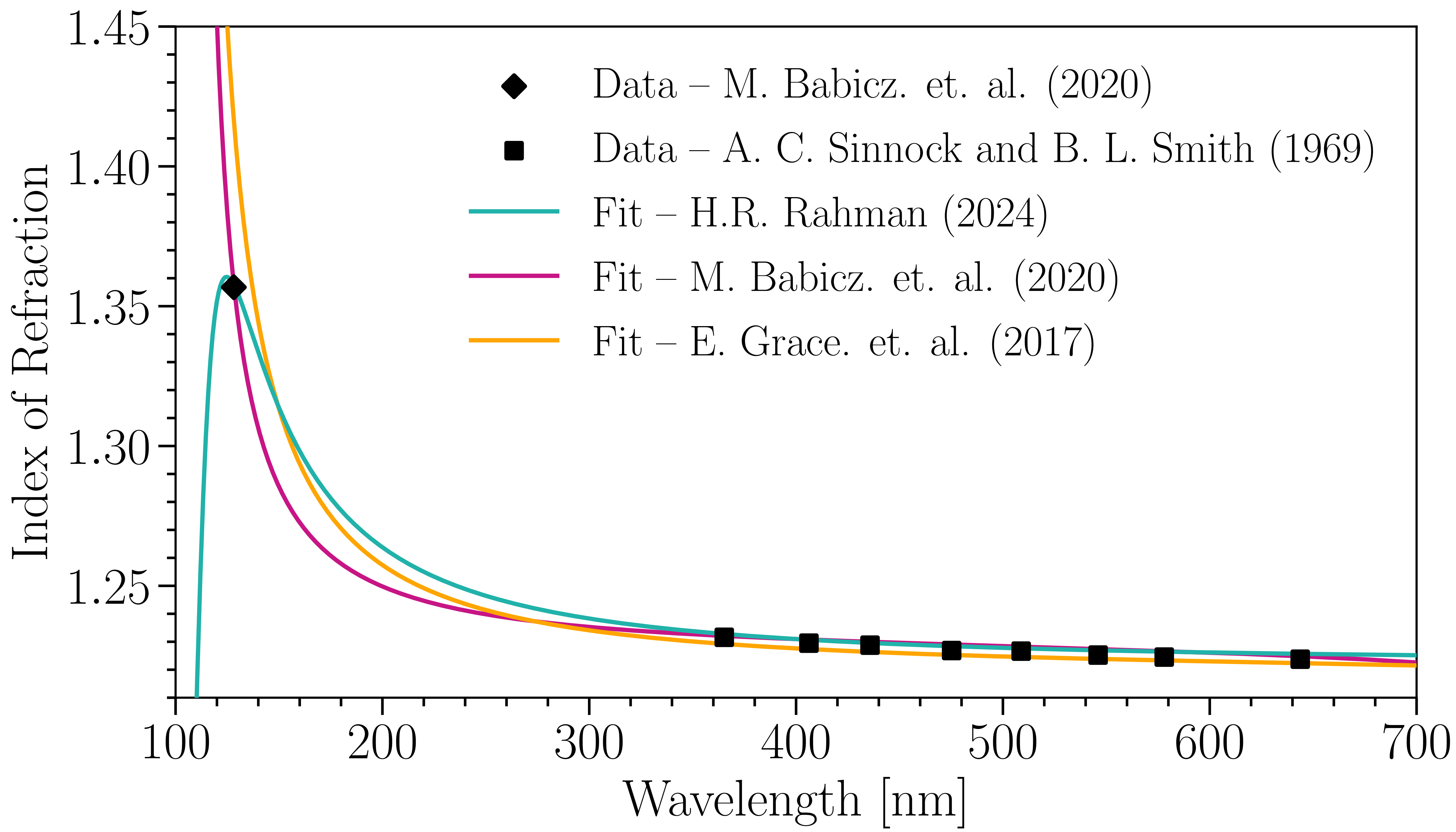
# Index of Refraction

- This work uses a damped harmonic oscillator model for the index of refraction that accounts for both the real and imaginary (absorptive) effects near the resonances (H.R. Rahman)

$$n(\lambda) = a_0 + a_{UV}\left(\frac{\lambda_{UV}^{-2} - \lambda^{-2}}{(\lambda_{UV}^{-2} - \lambda^{-2})^2 + \gamma_{UV}^2\lambda^{-2}}\right)$$

- Fit for $\gamma_{UV}$ parameter



# Fitting Strategy

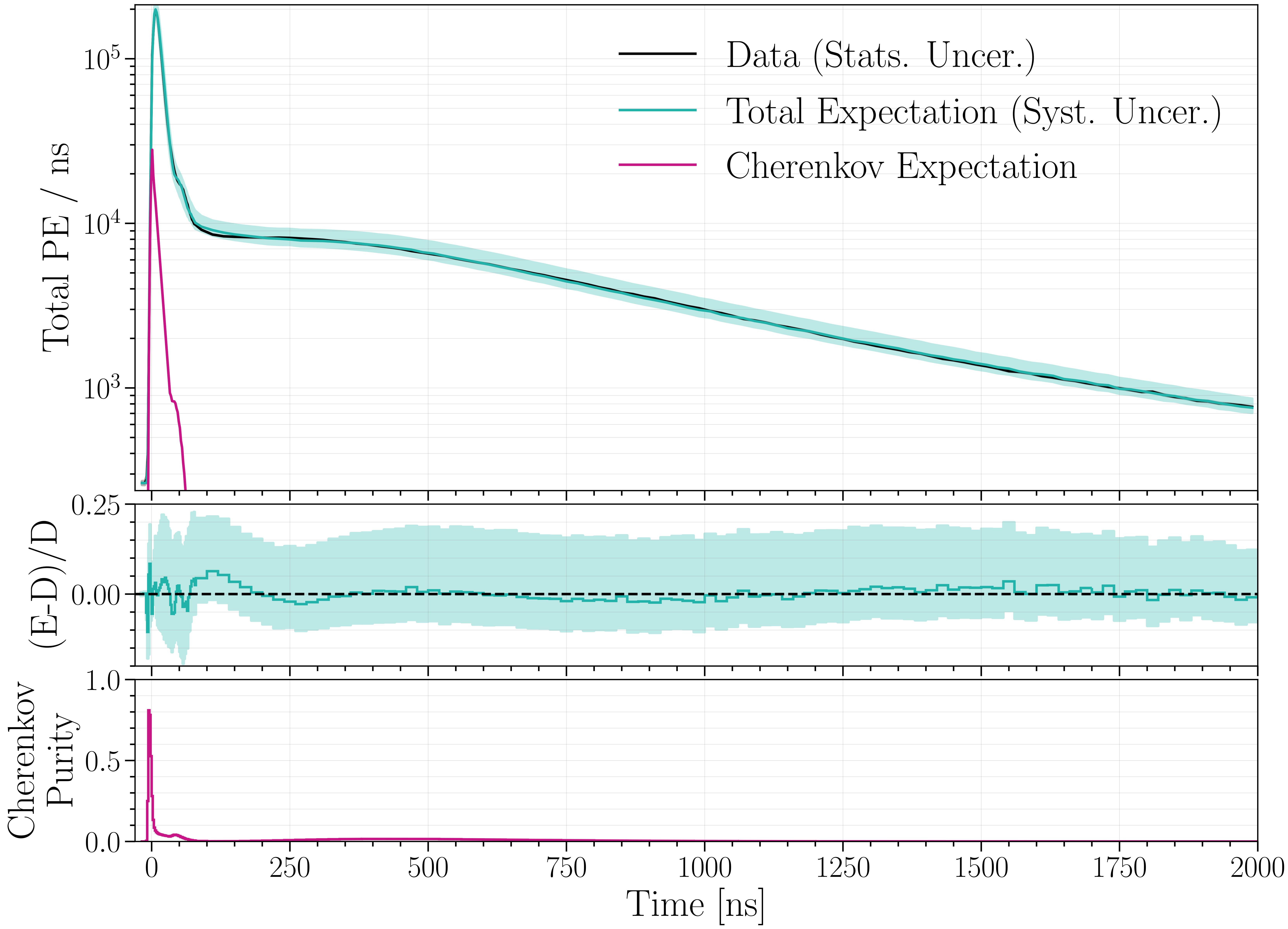
- Using Geant4 to simulate sodium decay events, accumulate events, and fit time series data across PMTs
  - Simulate at nominal set of parameters and implement extensive photon tracking in Geant4
  - Same selection and accumulation procedure as in data
- To calculate expectation at another point in the parameter space, every simulated PE is individually reweighted according to a ratio of probability distribution functions evaluated at the nominal and new parameter values using forward automatic differentiation
- Reweight for scintillation pulse shape, photon absorption, and PMT timing response analytically
- Reweight for scattering lengths and index of refraction through interpolation of simulation sets

# Systematic Uncertainty Estimation

- First experimental measurement of photon production and propagation in large liquid argon detector ***with uncertainties***
- Developed a procedure of fitting to each PMT individually to understand uncertainties from fitting to all PMTs simultaneously
  - Use the distribution preferred fit parameters to estimate uncertainties on parameters as $1\sigma$ highest posterior density region and similarly for the expectation

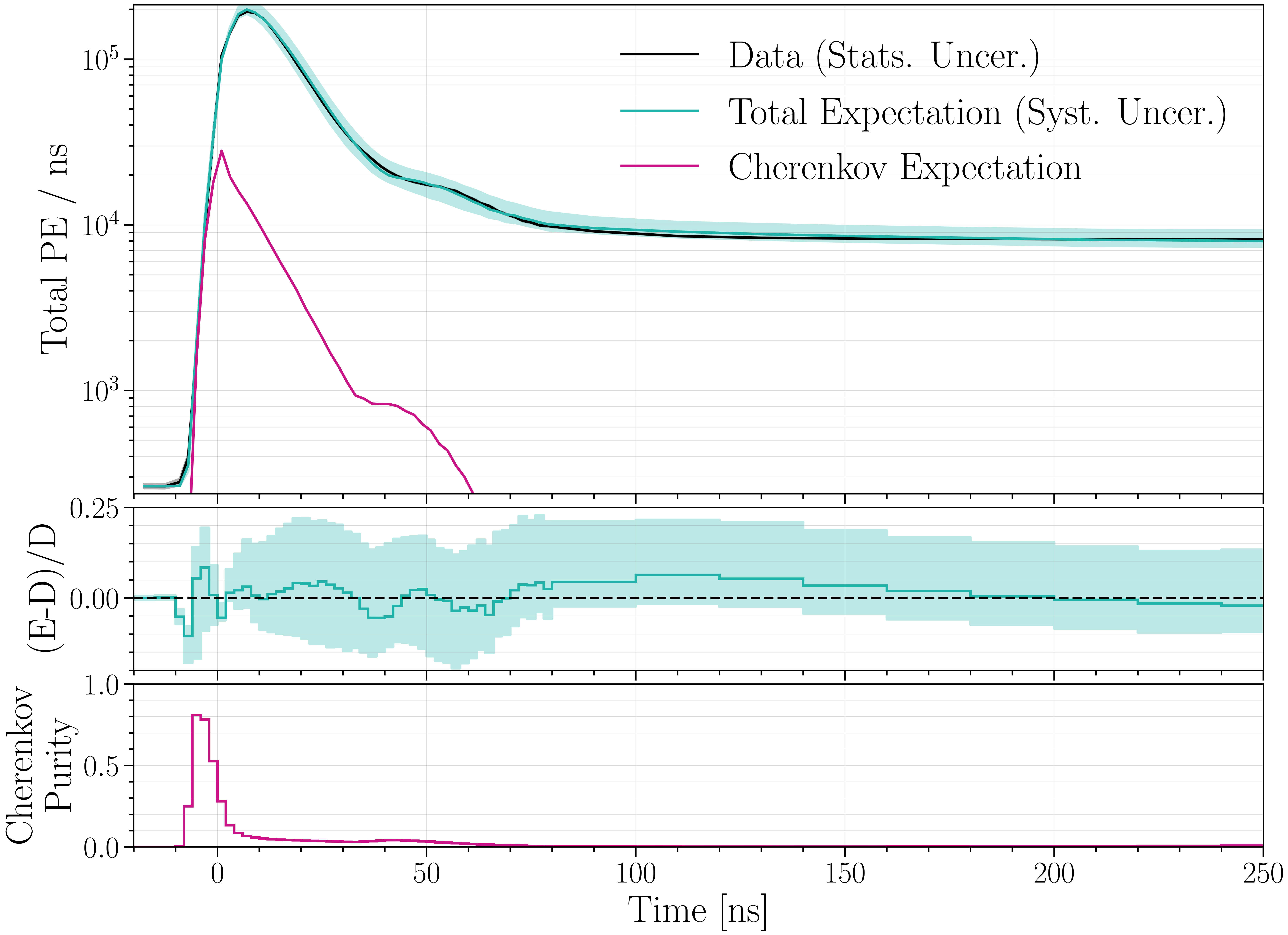
# Fit Results — Overall Time Structure

- Data (black) and total expectation (blue) ***summed across all PMTs***
- Data and predicted values agree within 10% across entire time region
- Bottom plot shows Cherenkov purity as a function of time



# Fit Results — Overall Time Structure

- Data (black) and total expectation (blue) ***summed across all PMTs***
- Medium time scale
- PMT post-pulsing evident around 50ns



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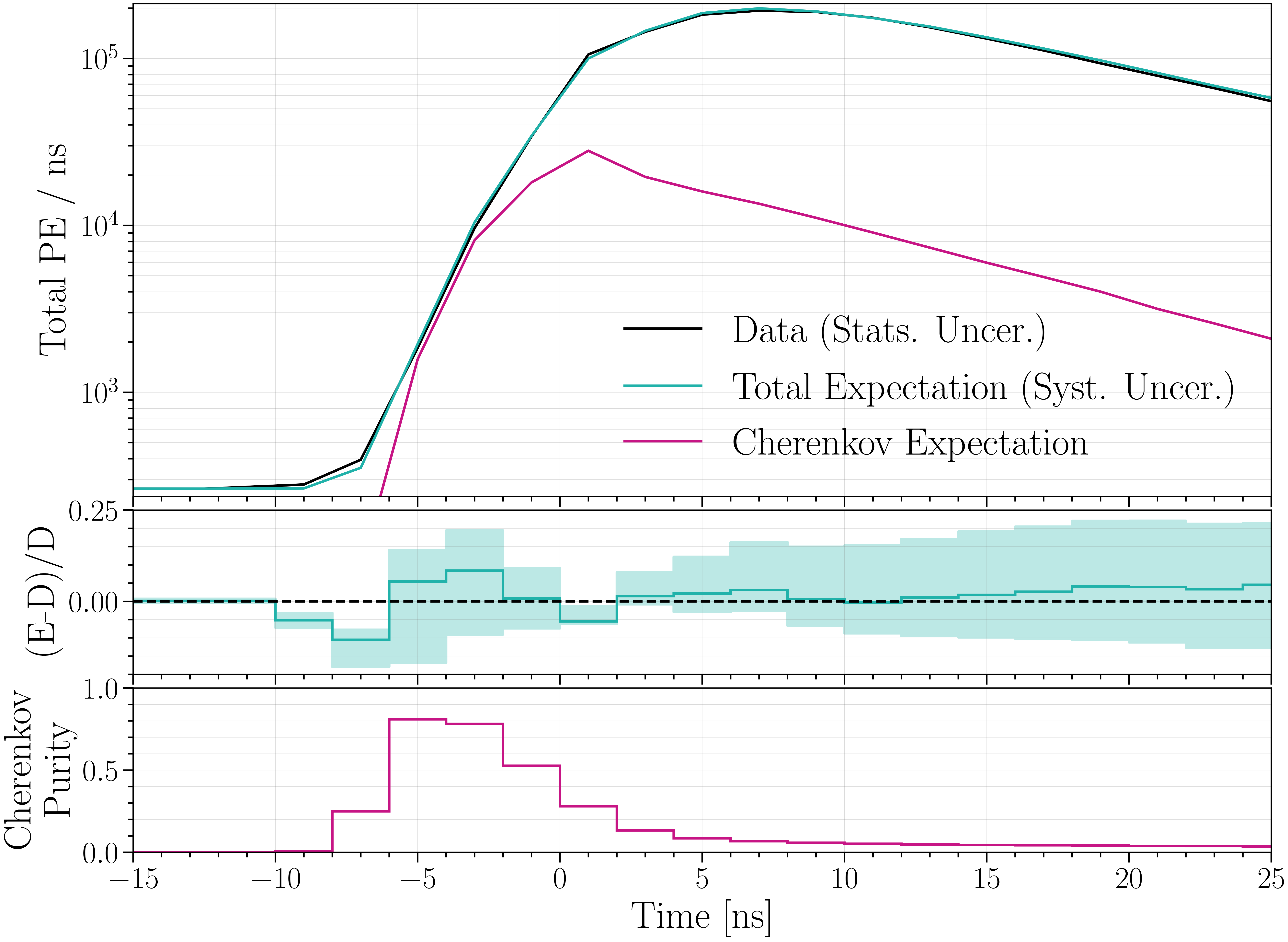
# Fit Results — Overall Time Structure

- Data (black) and total expectation (blue) ***summed across all PMTs***
- Short time scale
- Cherenkov light is > 10% contribution until ~5ns, necessitating characterization of both scintillation and Cherenkov light simultaneously



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# Fit Results — Scintillation Parameters

- This work finds $\tau_s \sim 4$ ns and $\tau_t \sim 580$ ns
  - Impurities quench triplet light, leading to reduced $\tau_t$ compared to the nominal value of ~1.5 $\mu$s
- Do not find preference for intermediate time component

TABLE II. Scintillation pulse shape fit parameters with uncertainties. See Eq. 1 for full description of the scintillation time dependence.

| Parameter | Central Value | Uncertainties |
|---|---|---|
| $R_s$ | 0.367 | $-0.015, +0.017$ |
| $R_t$ | 0.633 | $-0.015, +0.017$ |
| $\tau_s$ | 4.28 ns | $-0.42$ ns, $+1.20$ ns |
| $\tau_t$ | 588.80 ns | $-3.30$ ns, $+3.65$ ns |



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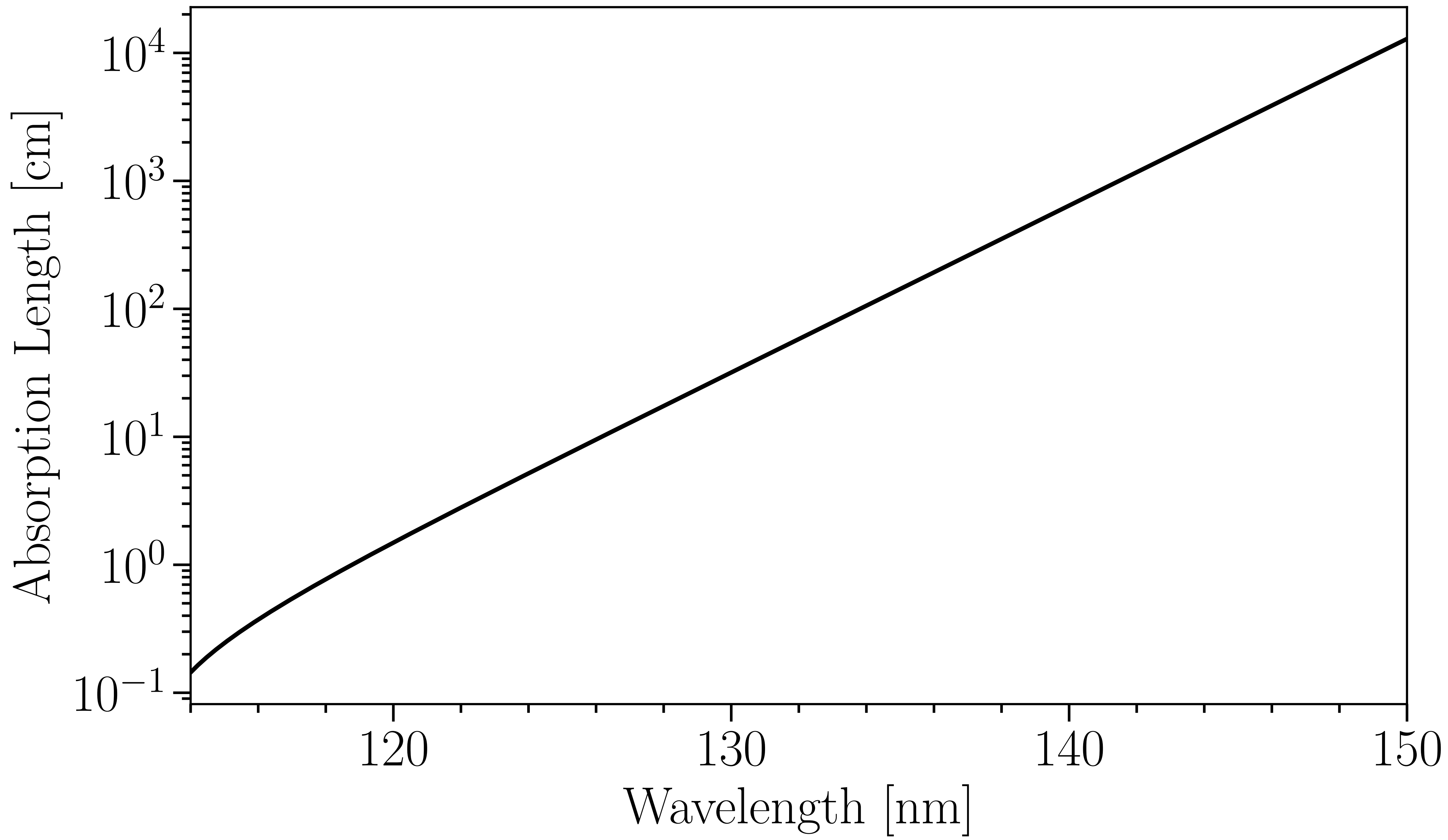
# Fit Results — Photon Absorption

- Fit for ***wavelength resolved absorption*** from 113nm to 150nm
- Based on work from Eur.Phys.J.C 72 (2012) 2190
- Allow $a$ parameter (controls shape) and $d$ parameter (controls scale) to vary
    - Fix $b$ parameter to literature value of 113nm (corresponds to resonant absorption due to first excimer continuum)

$$l(\lambda) = \frac{d}{\ln\left(\frac{1}{1 - e^{-a(\lambda - b)}}\right)}$$

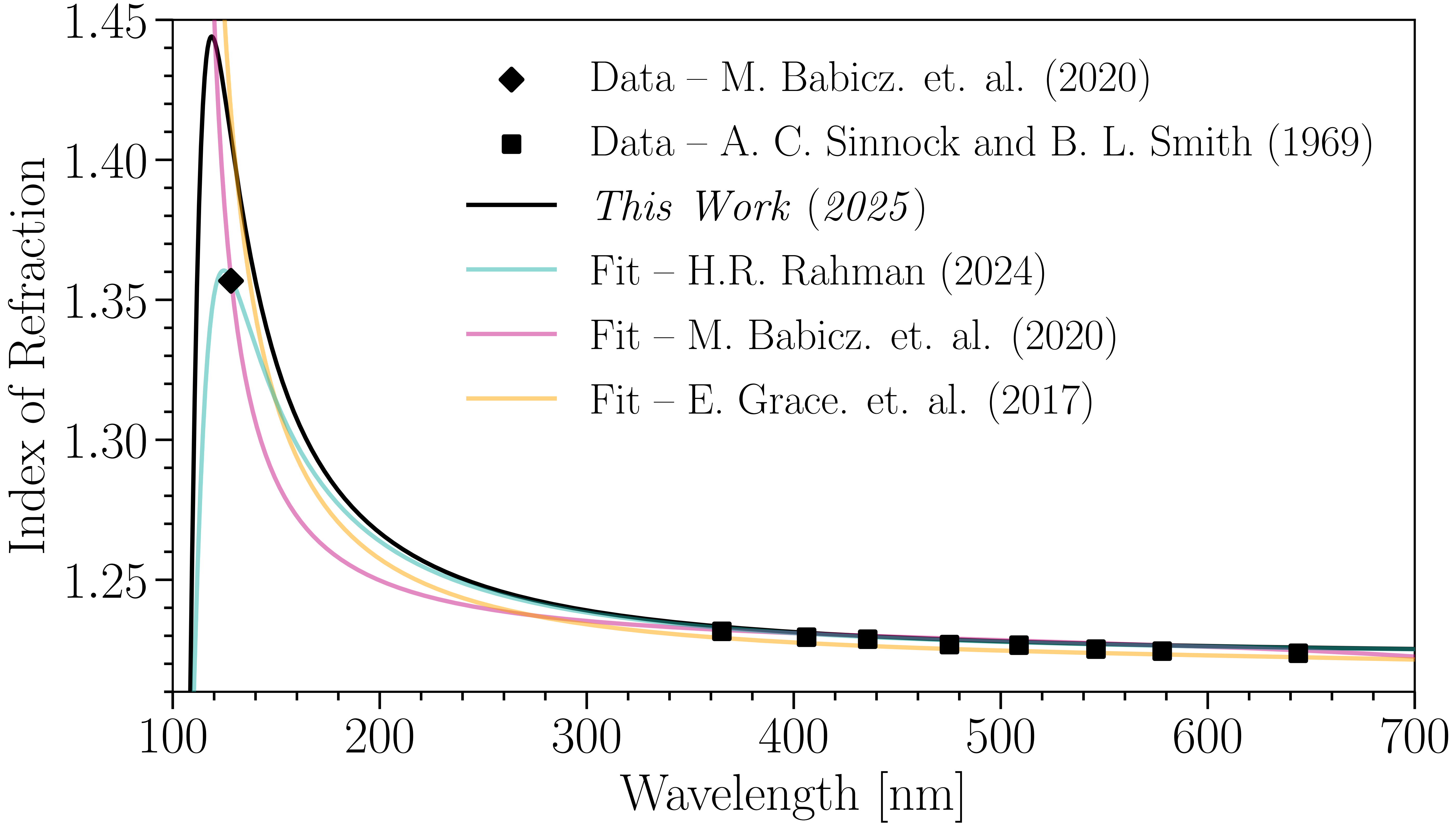
# Fit Results — Photon Absorption

- Find absorption length of **17.42cm at 128nm**, which then increases exponentially
- Additionally, allow for absorption in near-UV range due to impurities
    - Prefer 98.25cm absorption length from 300nm to 400nm

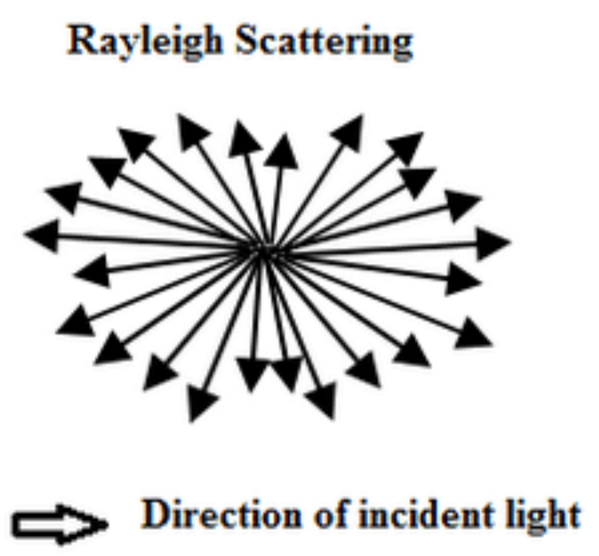


# Fit Results — Index of Refraction

- Allowed parameter $\gamma_{UV}$ that controls behavior around UV resonance to vary
- Original fit by H.R. Rahman found $\gamma_{UV} = 0.0025$, this work prefers $\gamma_{UV} = 0.0018$
- Measurements between 200nm and 300nm would be useful in constraining index of refraction

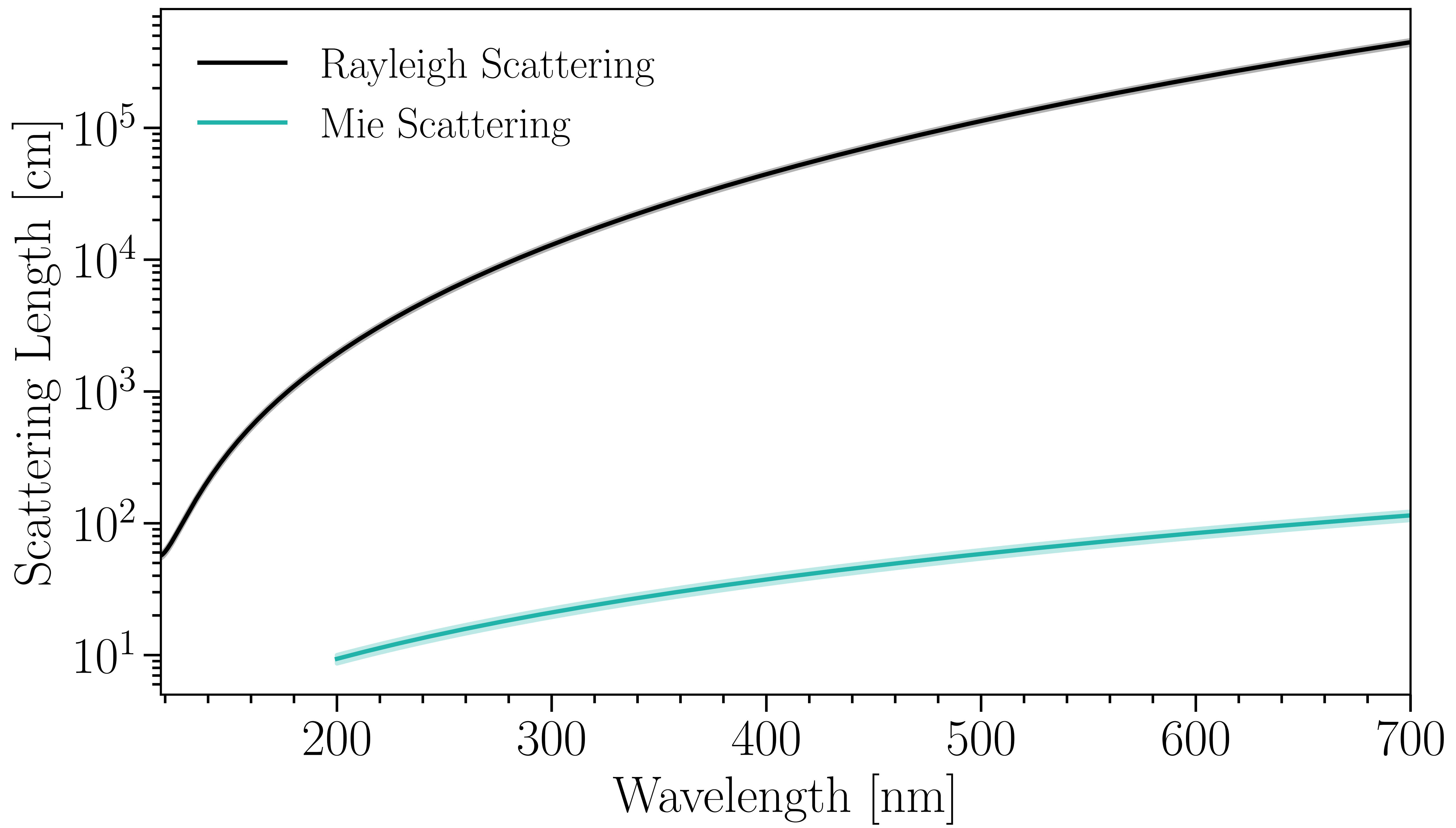


# Fit Results — Rayleigh Scattering

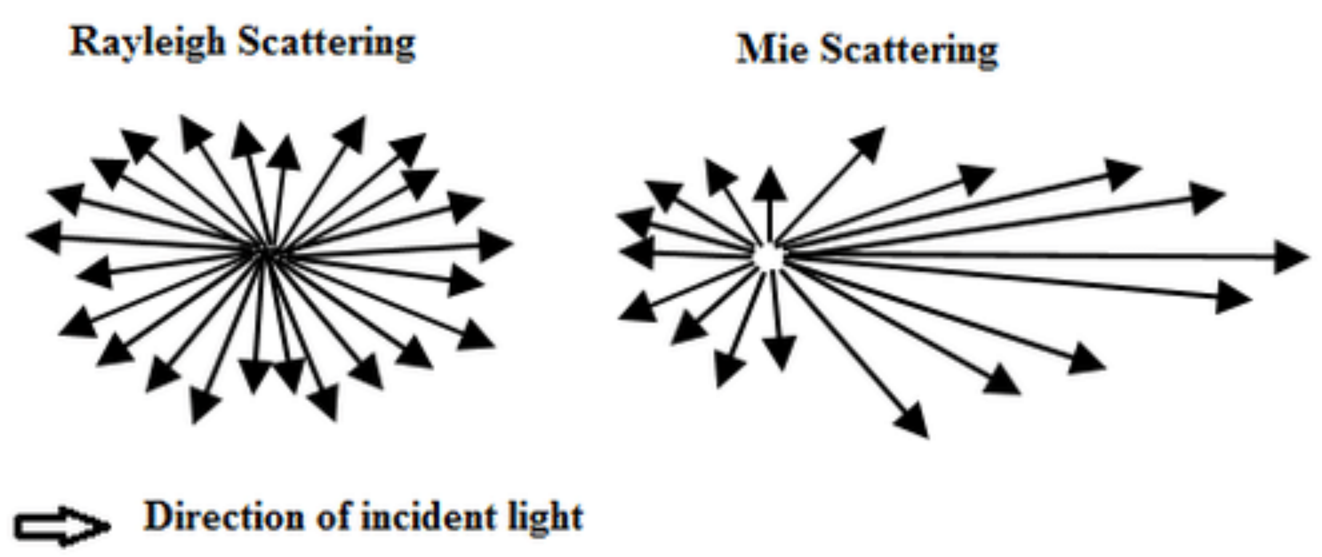



- Short wavelength photons can Rayleigh scatter off of argon atoms due to their small size
- Outgoing angular profile is relatively isotropic
- Fit for Rayleigh scattering length parameterized as Eq. 10
  - Prefer $l = 99.98^{+3.56}_{-4.52}$ cm at 128nm

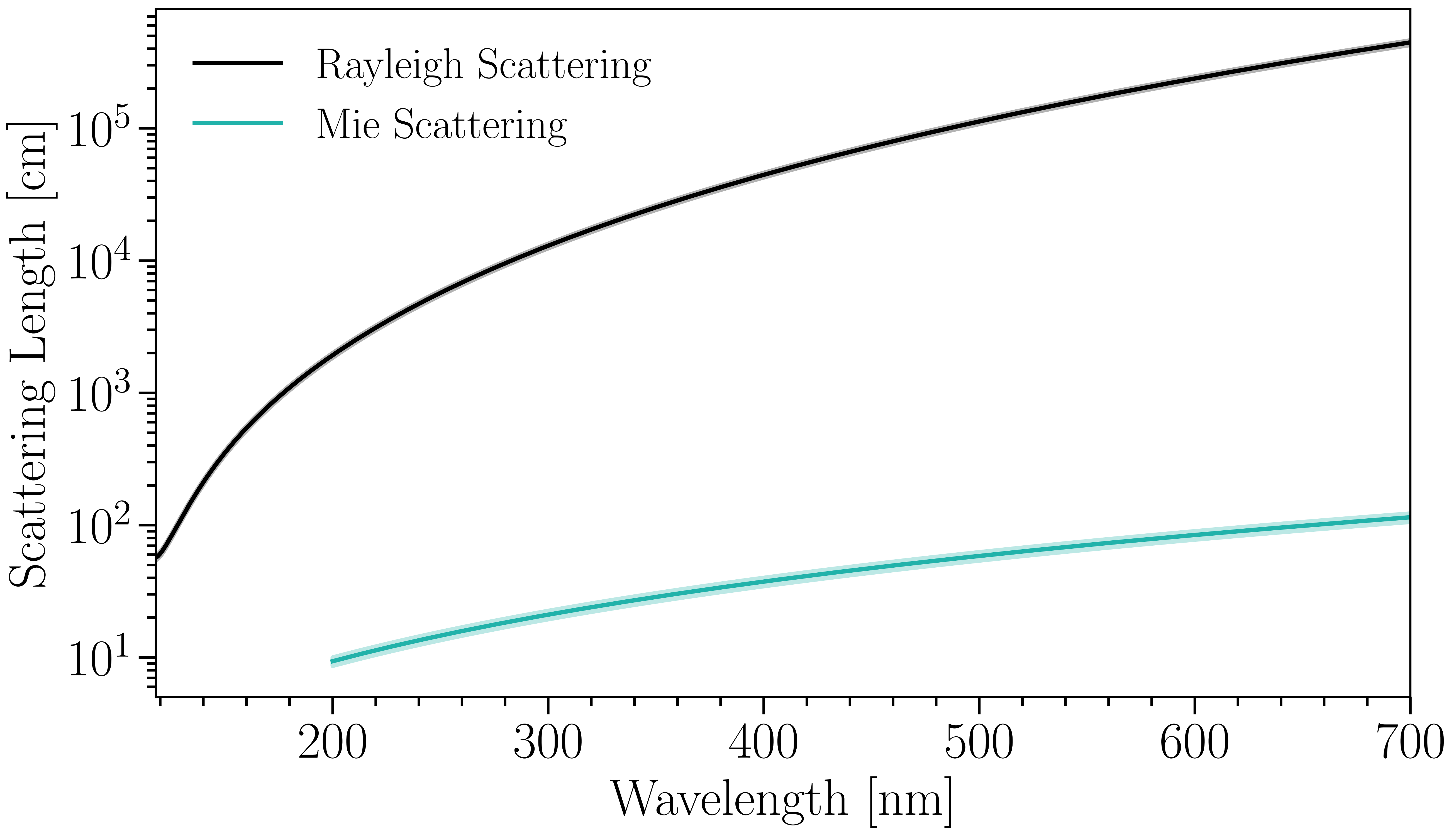
$$l^{-1} = \frac{16\pi^3}{6\lambda^4}\left[kT\rho^2\kappa_T\left(\frac{(n^2-1)(n^2+2)}{3}\right)^2\right] \quad (10)$$



# Fit Results — Mie Scattering




- Mie scattering is predominantly forward and relevant when photon wavelength approaches size of target
- Possible sources of Mie scattering in CCM include:
  - TPB degradation in LAr (as found by other experiments)
  - Known manufacturer quoted water impurity
  - Possible dust contamination during construction / LAr bubbles as it boils off
- Use $1/\lambda^2$ scaling to fit for effective Mie scattering length of $l = 9.37^{+0.63}_{-0.73}$ cm at 200nm



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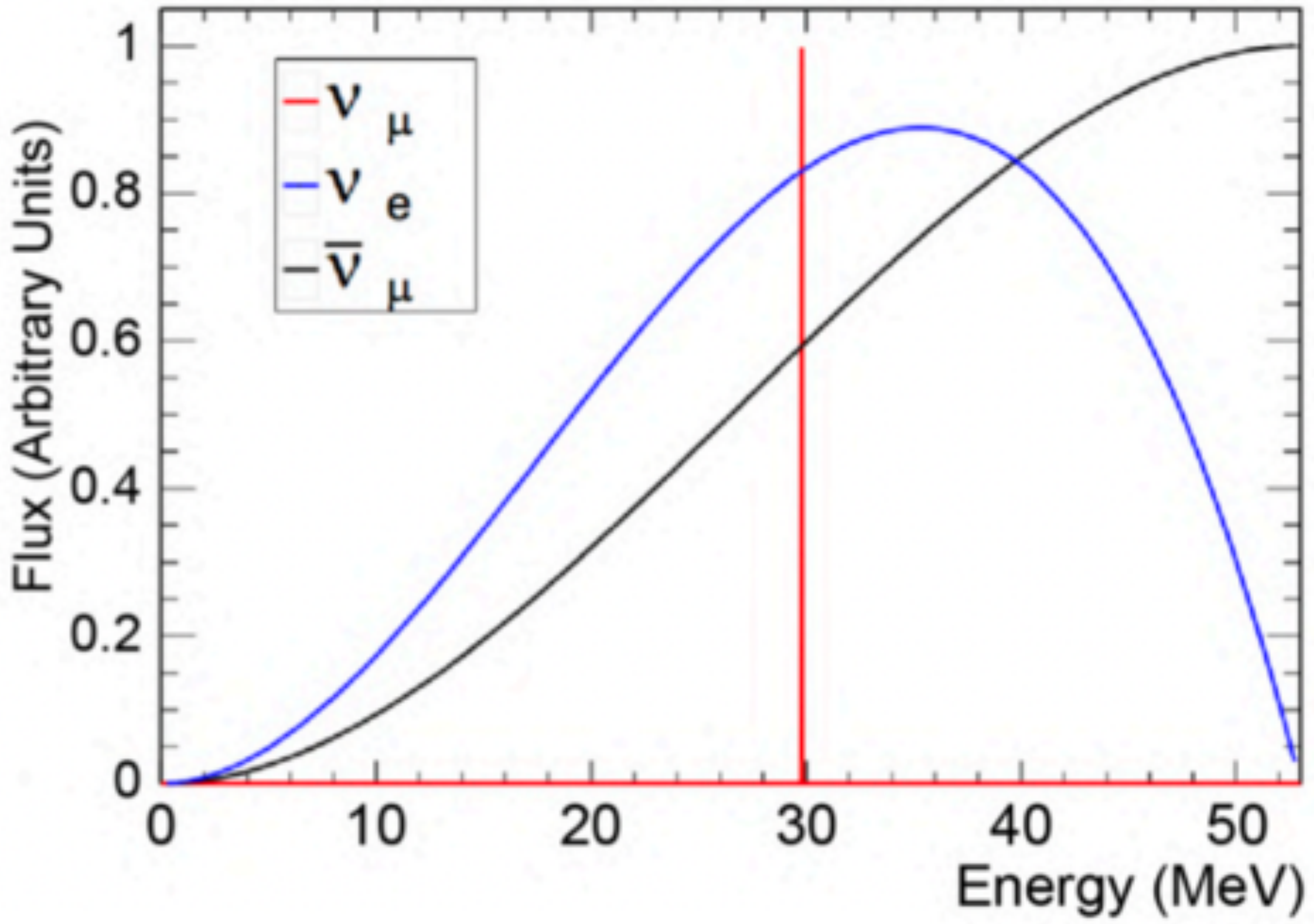
# Applications of This Work

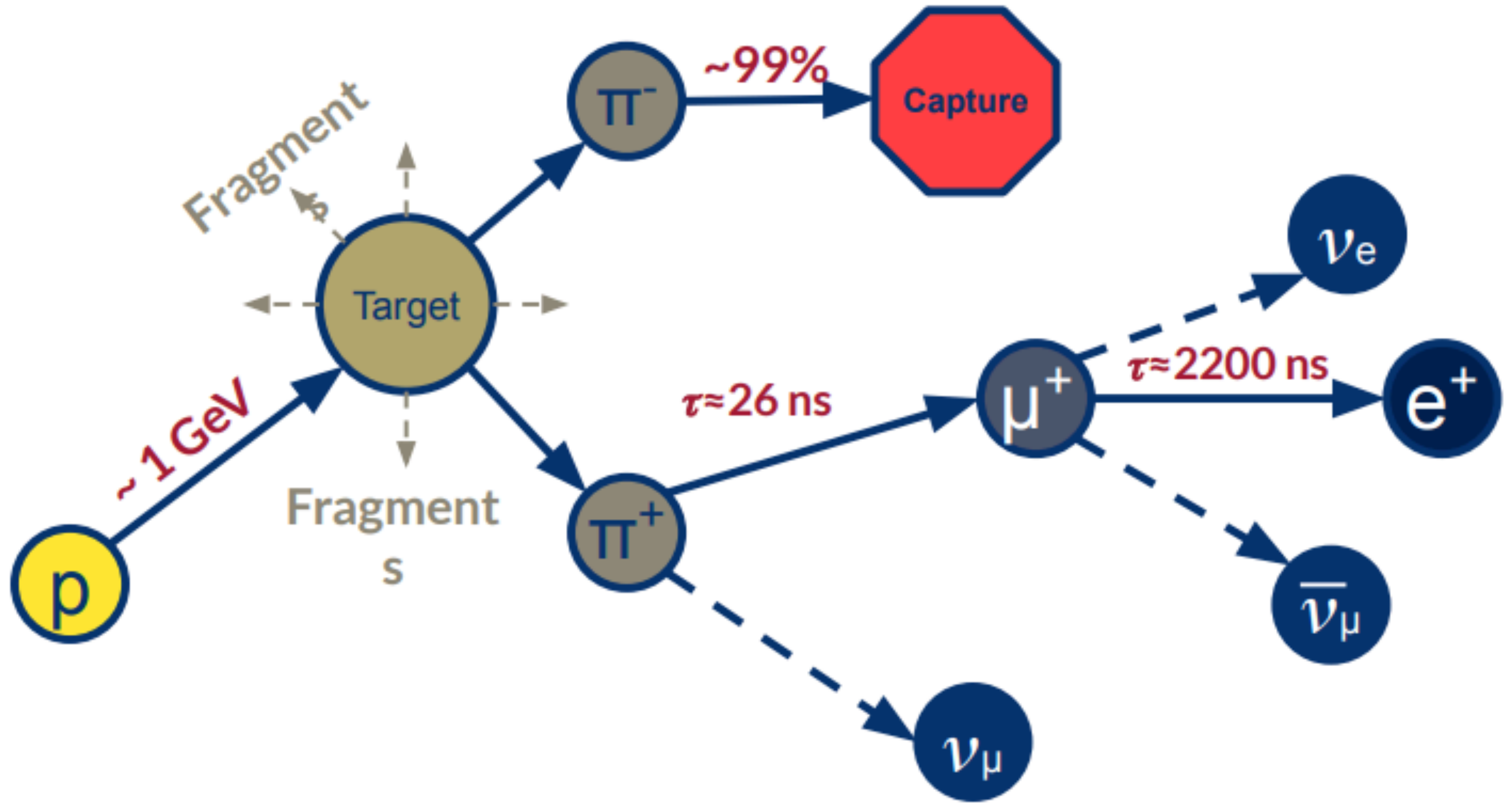
- Immediate application are for the ongoing physics searches in CCM
    - Essential for Cherenkov light separation ***(presented in arXiv:2507.08886)***
- ***Template for efficient optimization of many parameter optical models***
    - New method of characterizing uncertainty in large detector optical model calibration fits
- This work can also be used to explore future detector designs, especially considering need-vs-cost for purification systems

# 7. Physics Program

# Neutrino production at Lujan Facility

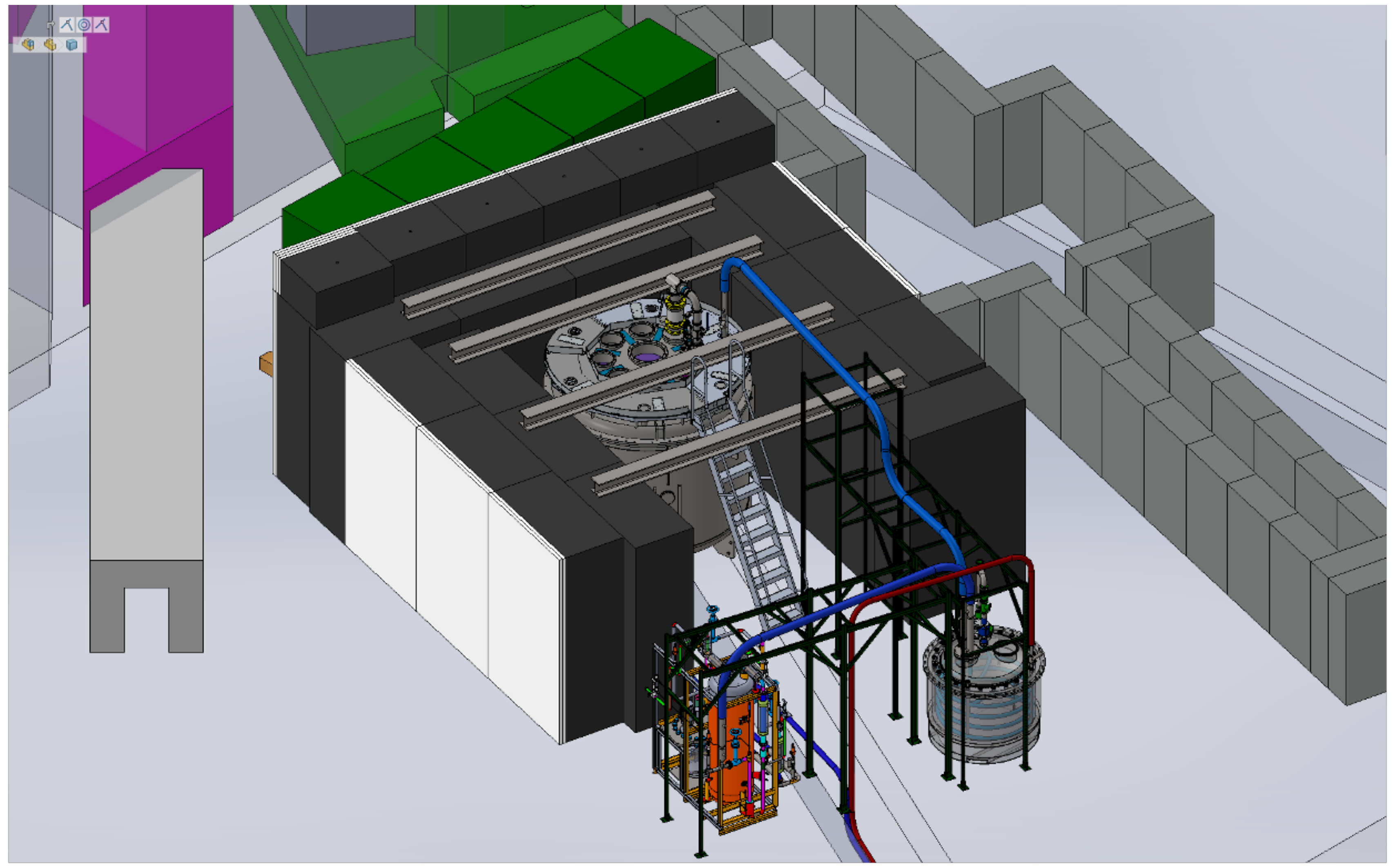
- **800 MeV pulsed proton beam** incident on **tungsten target**
    - 20 Hz, 100 $\mu$Amp current, and 290ns beam spill (145ns FWHM)
- Prolific source of neutrinos from $\pi^+$DAR (flux of $4.74 \times 10^5\ \nu/\text{cm}^2/\text{s}$ per $\nu$-species at 23m from target)
- Above ground facility —> short beam spill window is necessary to reduce backgrounds from comic rays

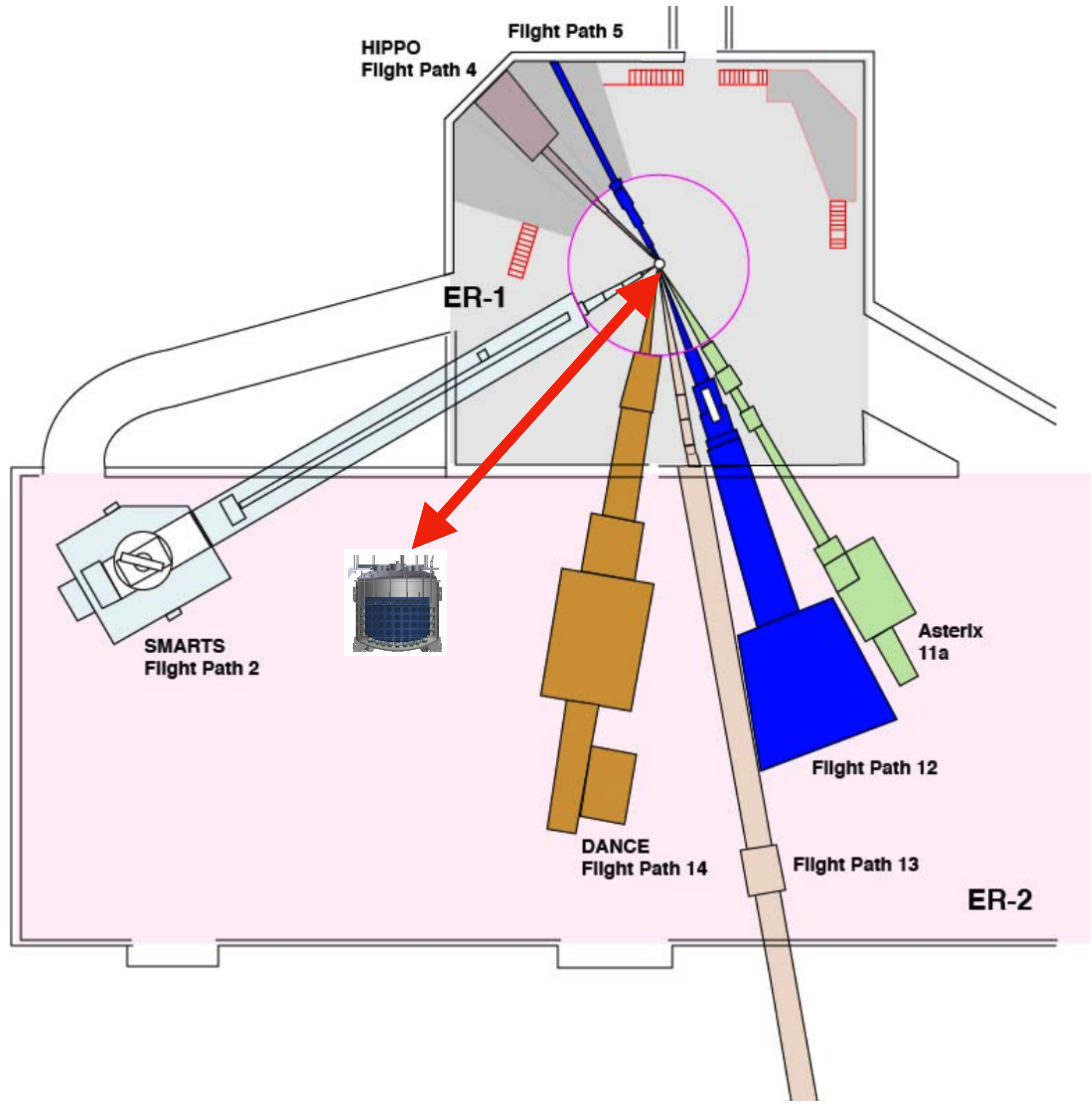


# CCM at Lujan

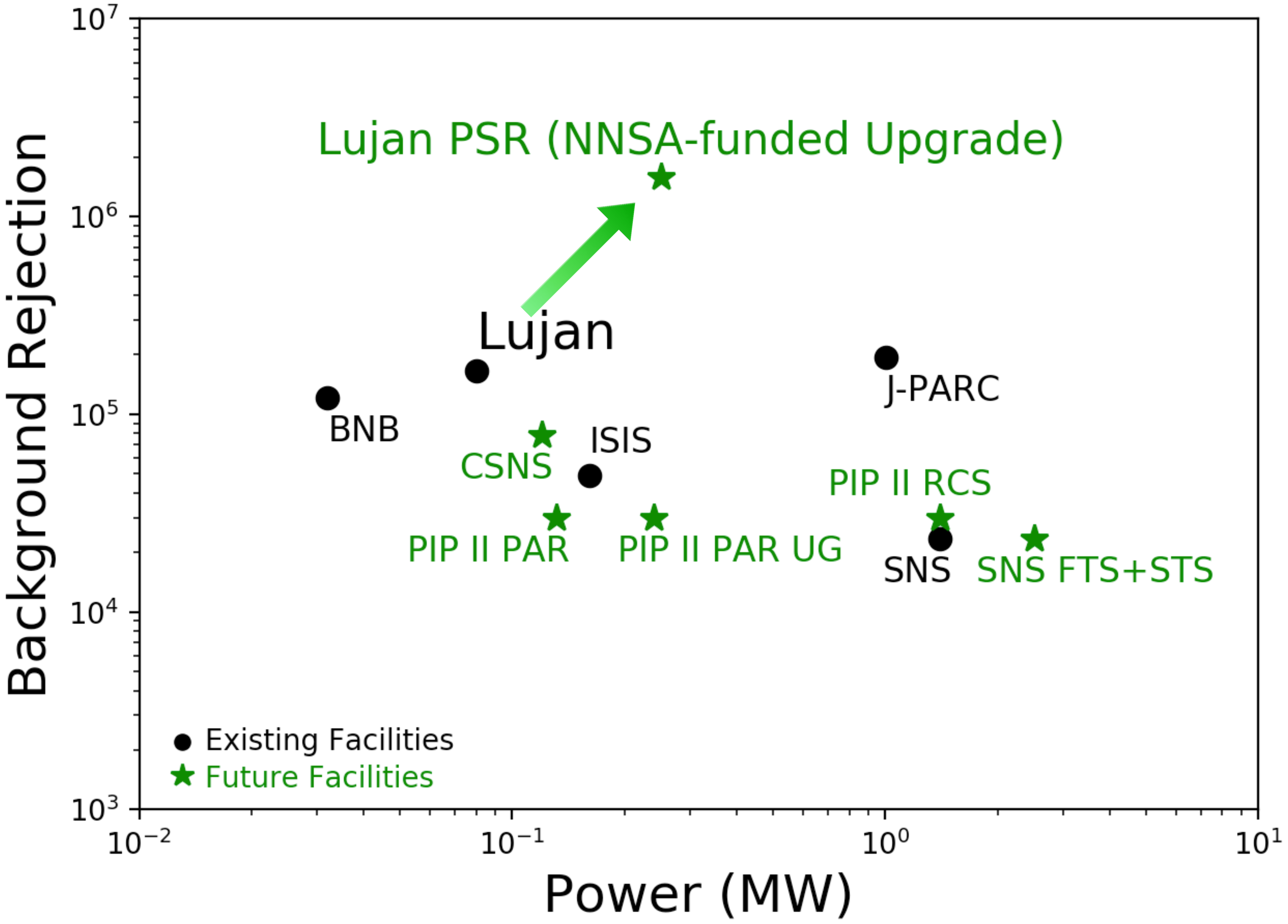
- Detector positioned **90˚ off axis** from the proton beam and **23m** from tungsten target
- 6m of steel, 3.5m of concrete, and 5cm of borated polyethylene of total shielding between the target and the detector
- CCM has received $0.9 \cdot 10^{22}$ POT in the ongoing 3 year run cycle, potential to increase to $1.5 \cdot 10^{22}$ POT





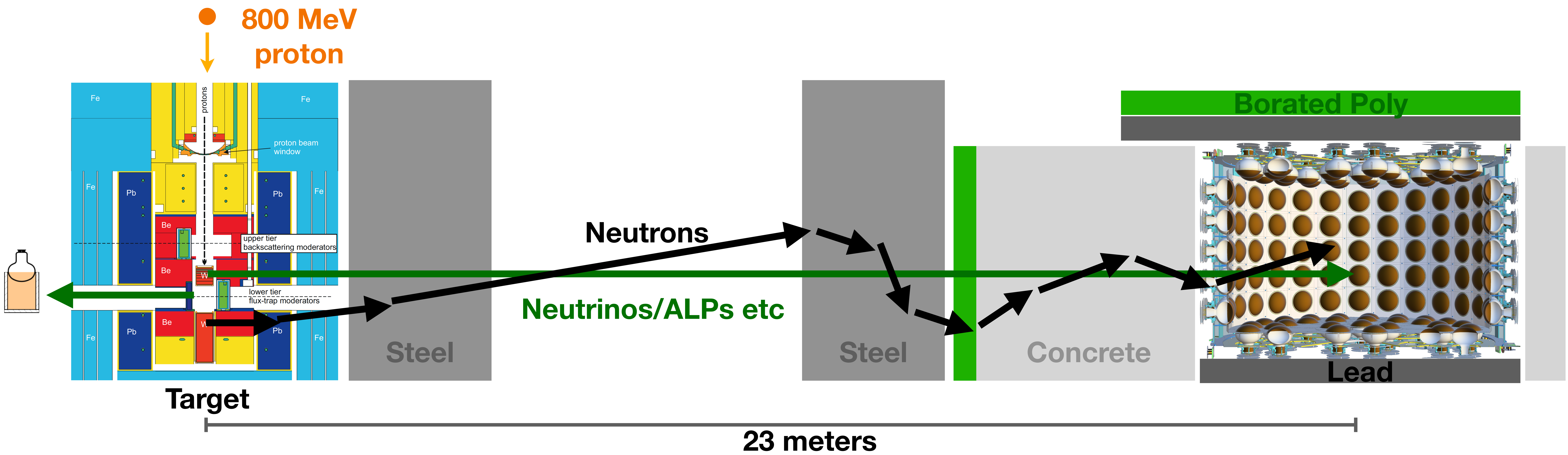

# Lujan Facility Capabilities

- Lujan Facility upgrades focusing on **background rejection**, lower power can be compensated with larger detector
- 10 year upgrade to increase background rejection by an order of magnitude through shortening beam spill window from 290 ns to 30 ns



# Backgrounds

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





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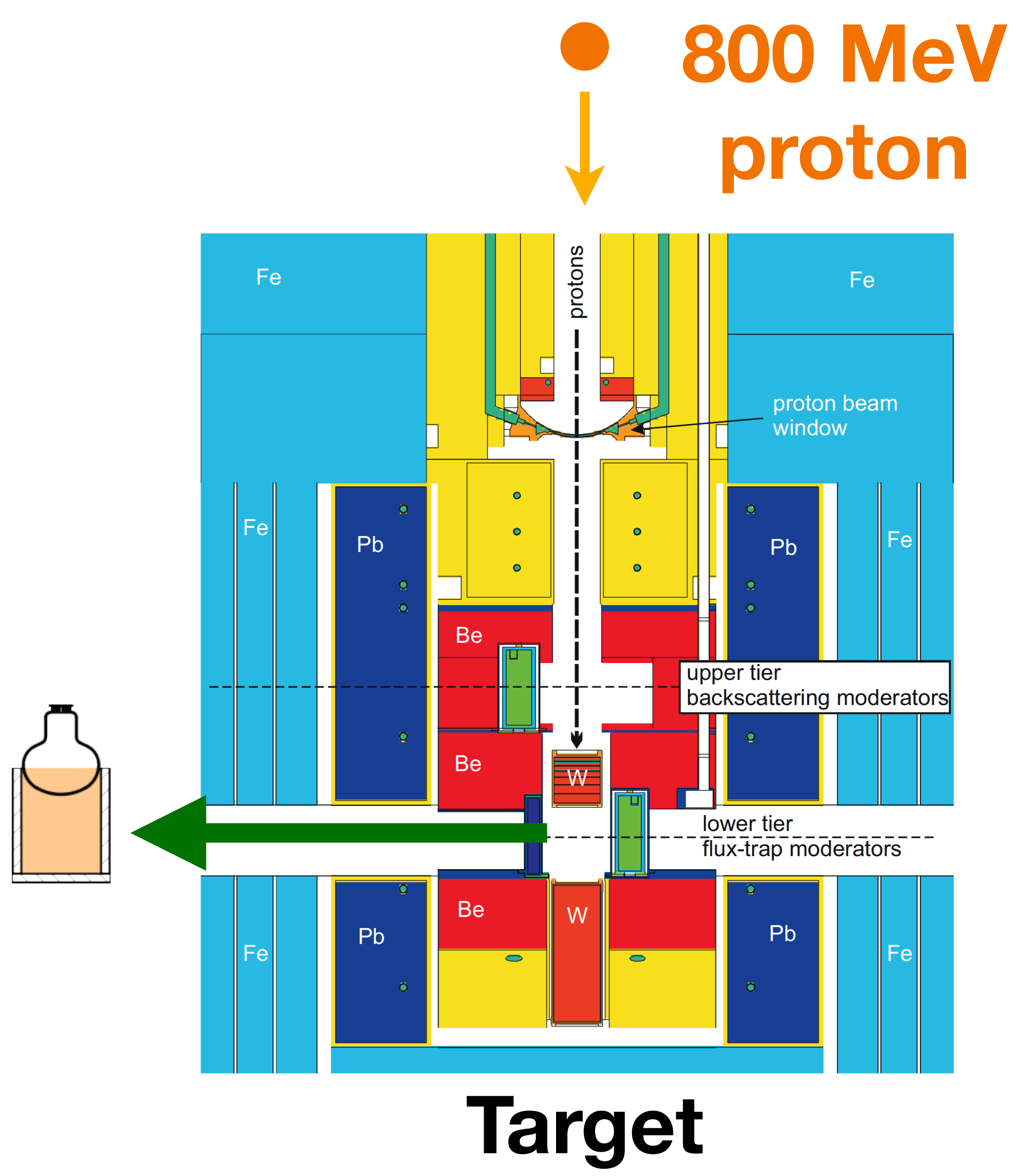
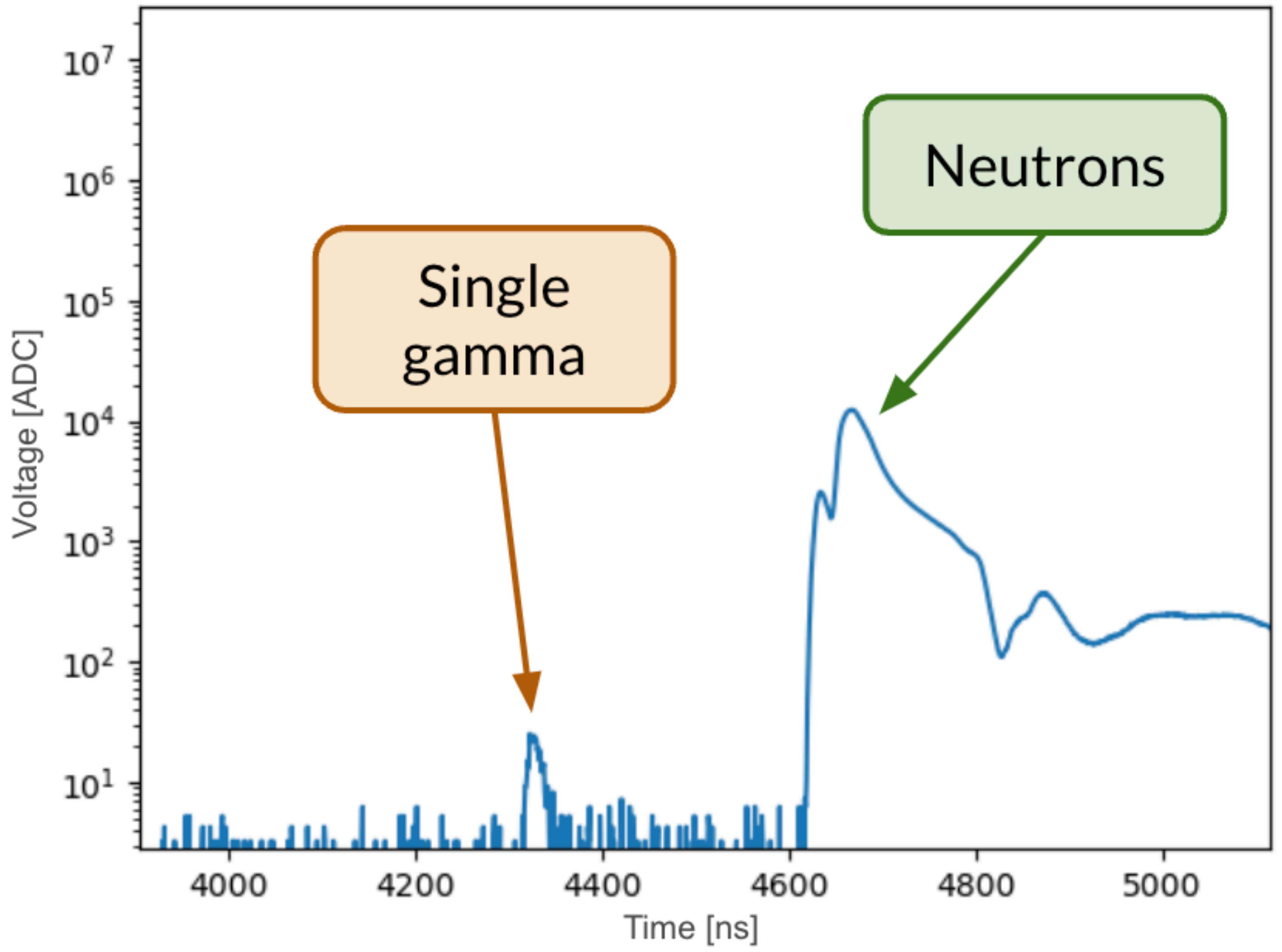
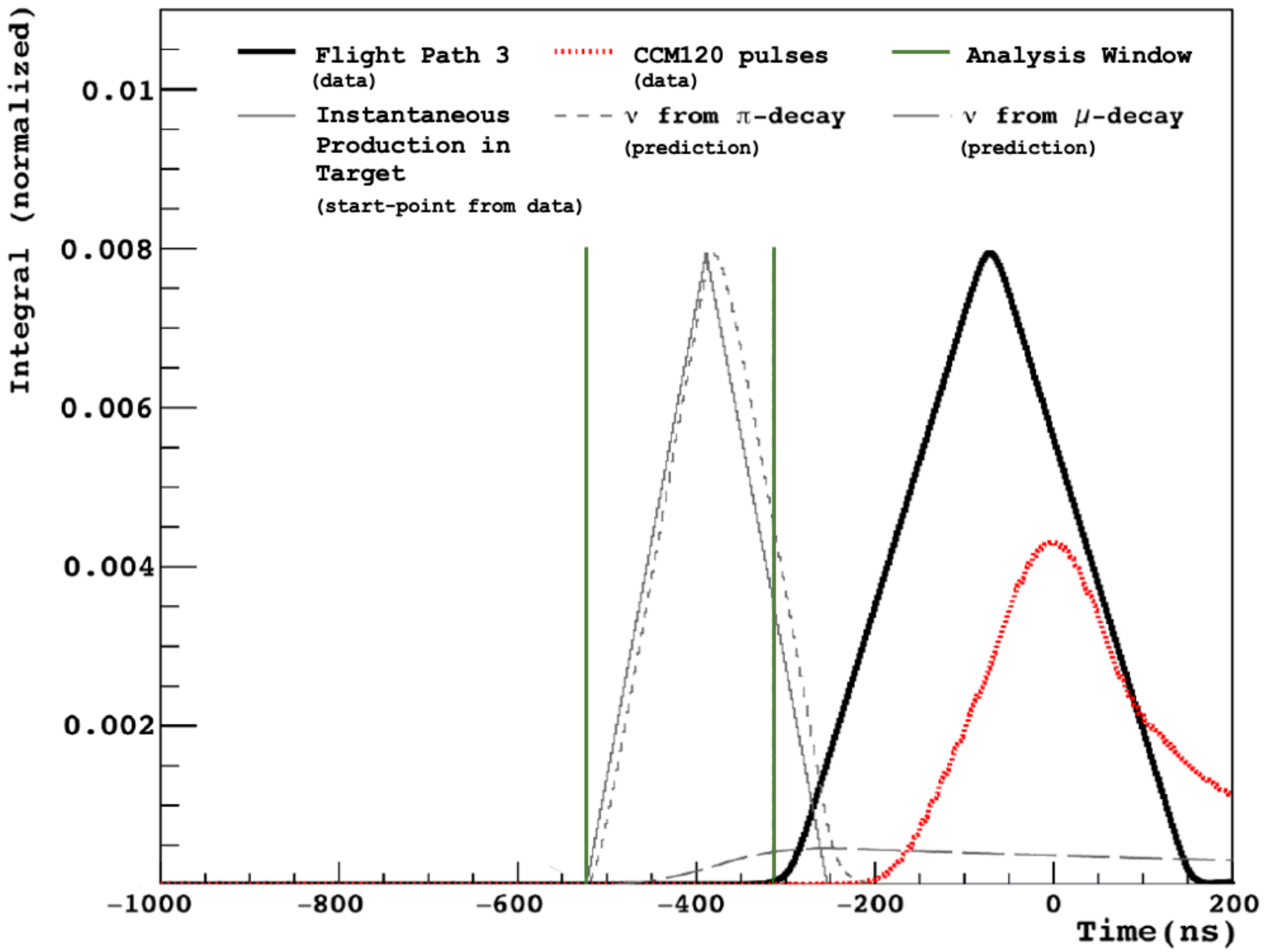
# Backgrounds

- 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



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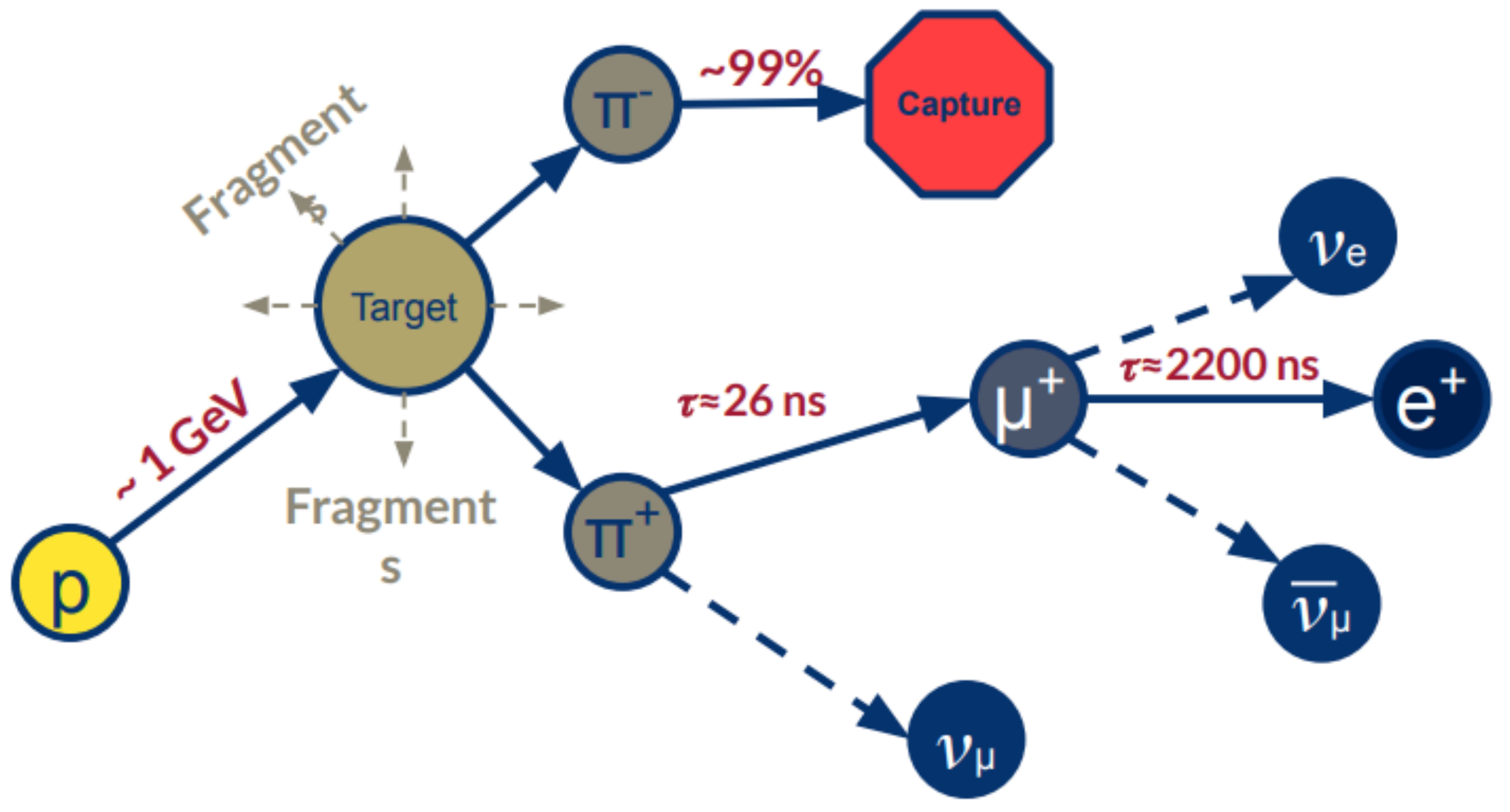
# Physics Searches Overview

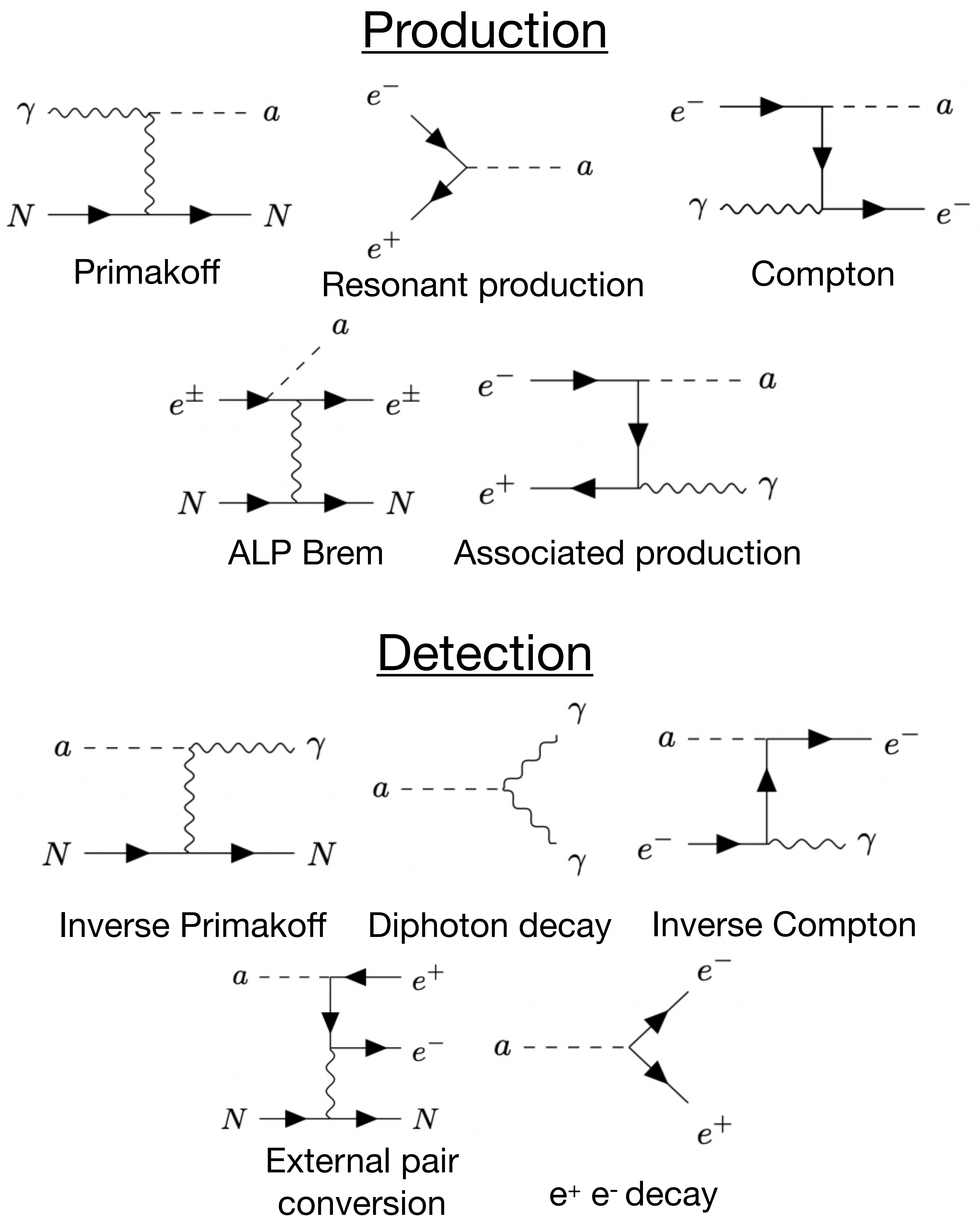



- Looking for physics from:
  1. Intense flux of neutrinos from $\pi$DAR
     - Charged current $\nu_e$ cross section measurement ***(relevant to DUNE supernovae physics)***, BSM neutrino physics (ex: heavy neutral leptons)
  2. Intense flux of $\gamma/e^{\pm}/\pi^{0,\pm}$ produced in the beam stop
     - Axion like particle coupling to EM particles, BSM particles coupling to pions, leptophobic/vector portal dark matter

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

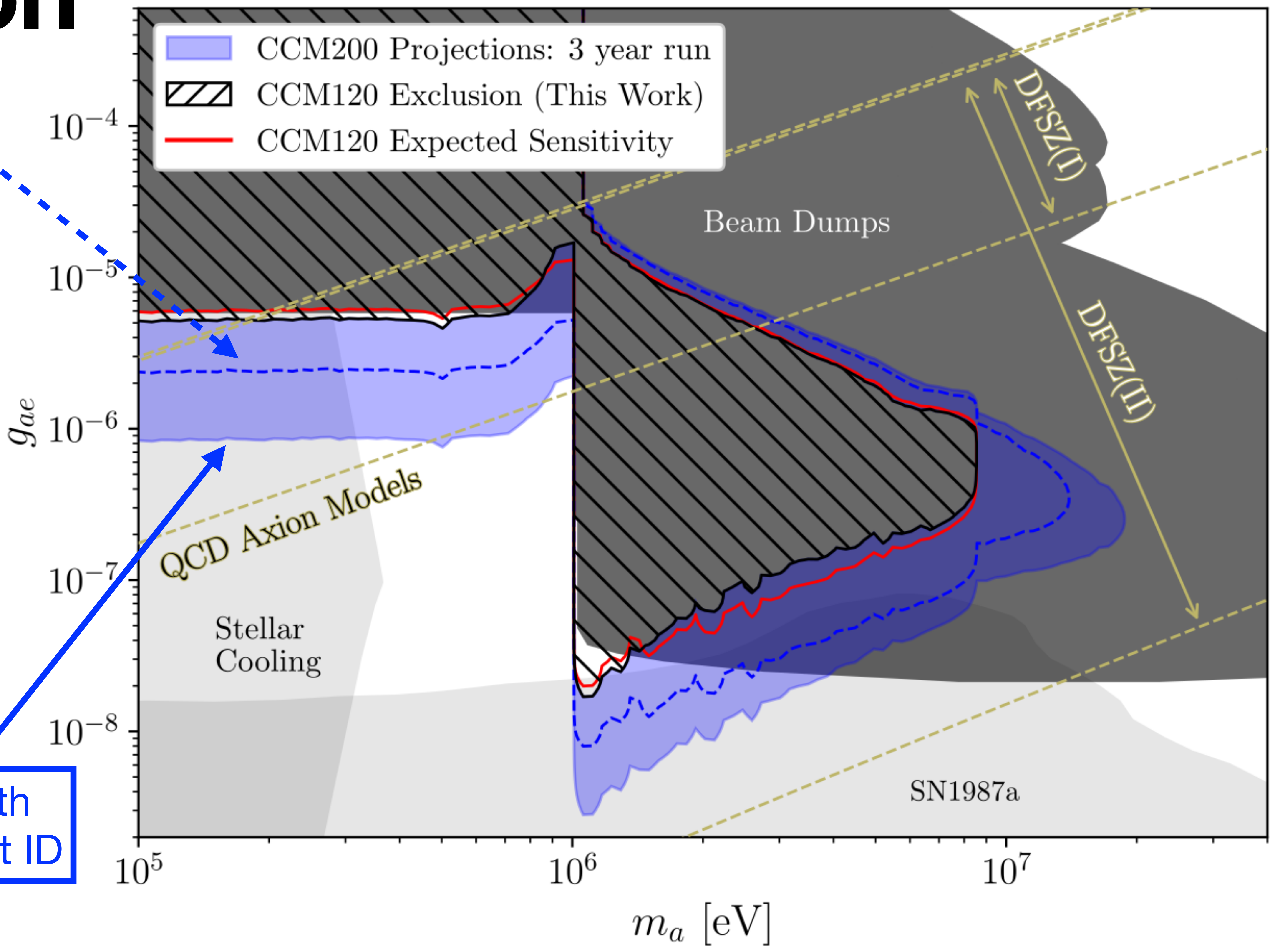
# ALPs and QCD Axion

- Axion like particles and MeV scale QCD axion [PhysRevD.107.095036]
- Production via Primakoff, resonant, Compton, bremsstrahlung, and associated processes
- Detection via inverse Primakoff, diphoton decay, inverse Compton, external pair conversion, and $e^+e^-$ decay



# ALPs and QCD Axion

Sensitivity without Cherenkov light ID




Sensitivity with Cherenkov light ID

- Mass of axion vs **axion-electron** coupling constant
- Probe open parameter in DFSZ(I) region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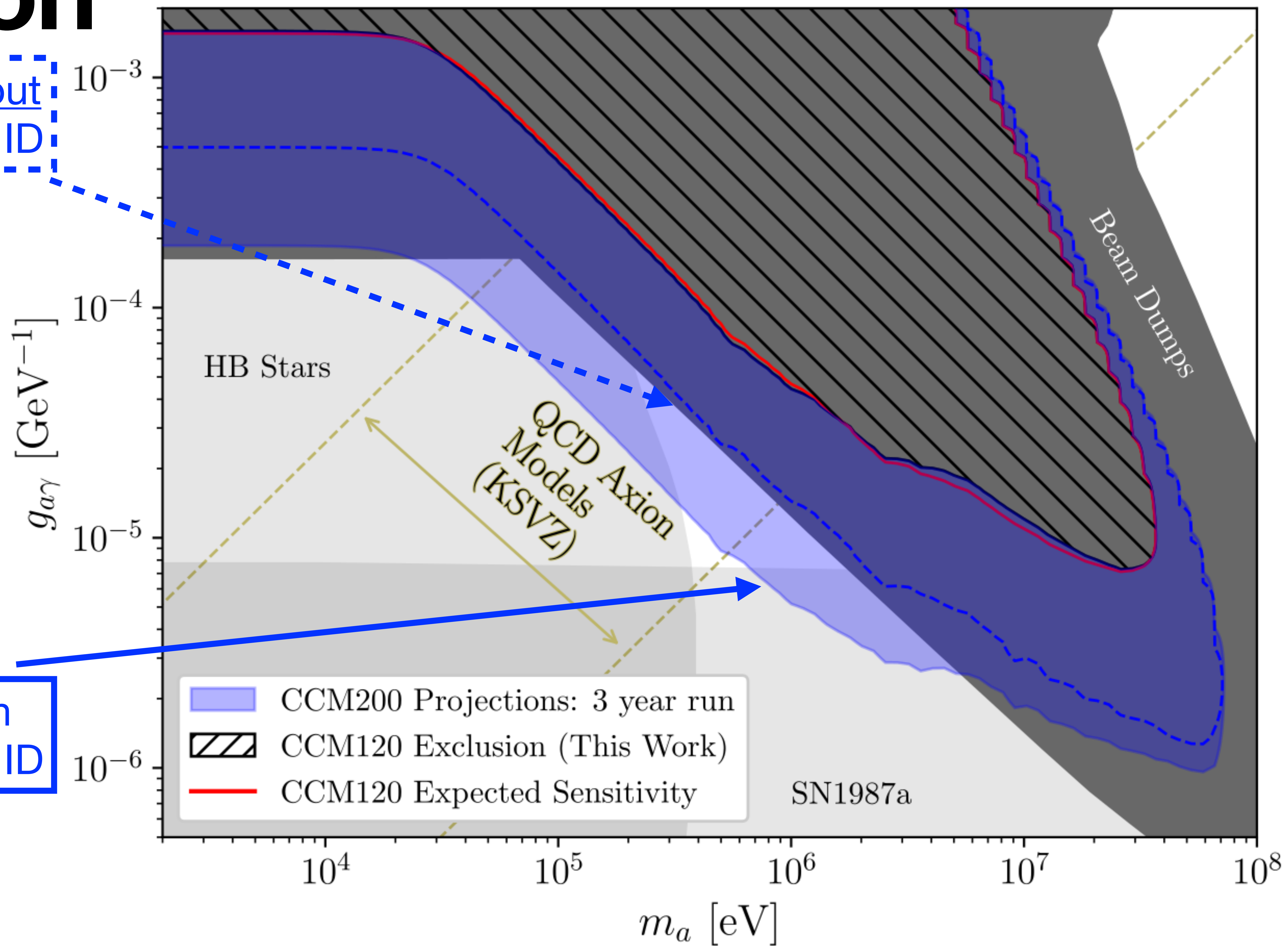
# ALPs and QCD Axion

- Mass of axion vs **axion-photon** coupling constant
- ***Probe "cosmological triangle" with Cherenkov light ID for background reduction***

Sensitivity without Cherenkov light ID

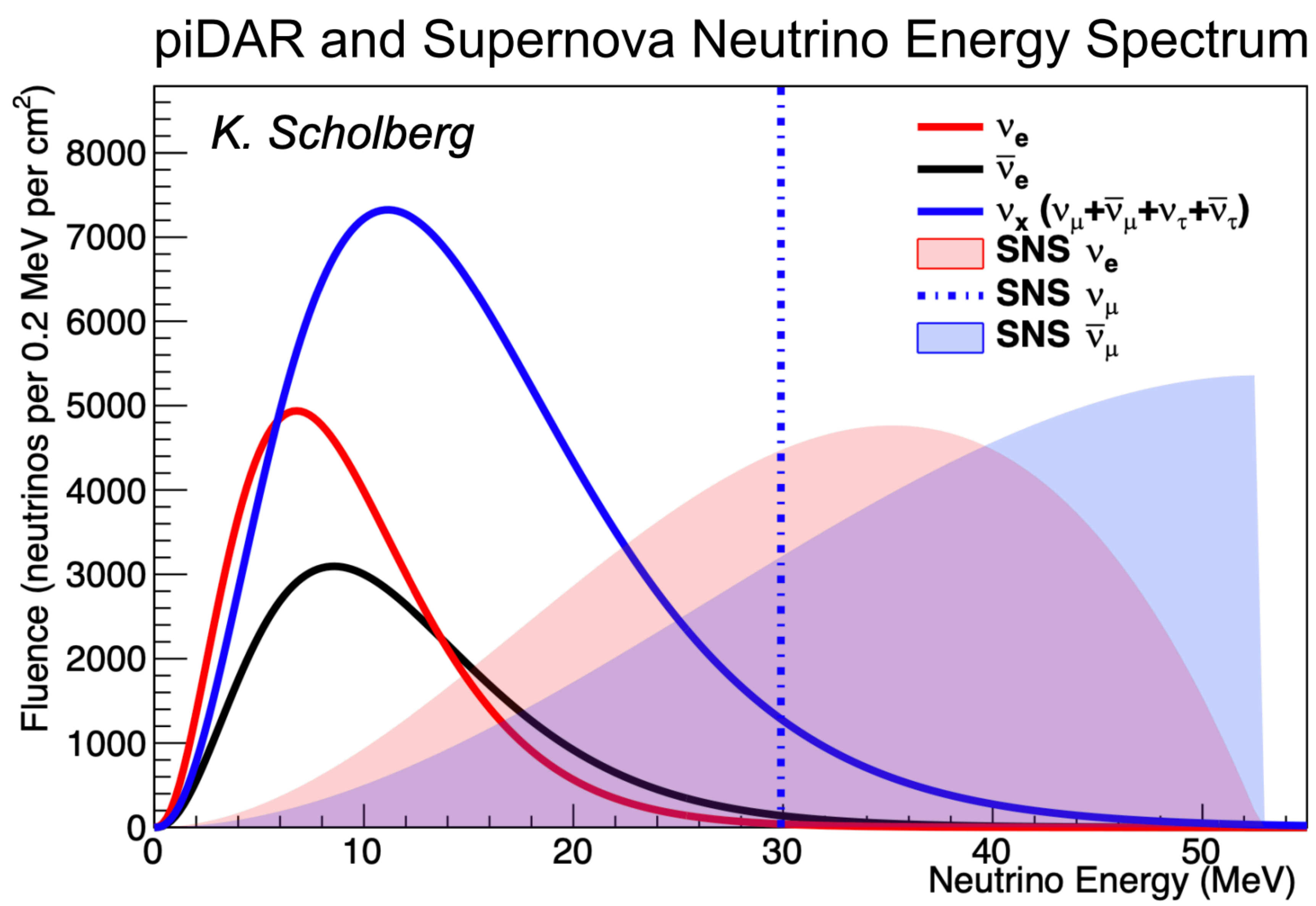


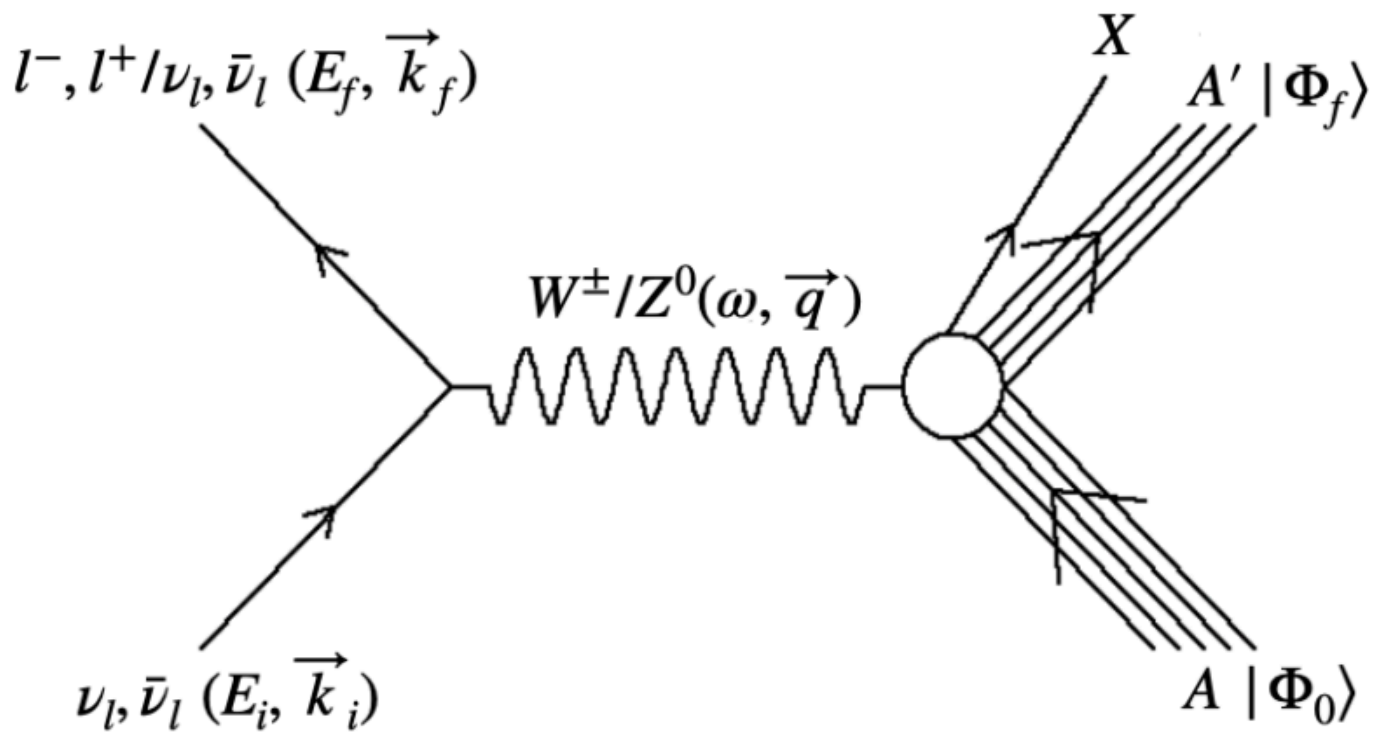

Sensitivity with Cherenkov light ID

```
> pip install siren
```

# Charged Current Cross Section

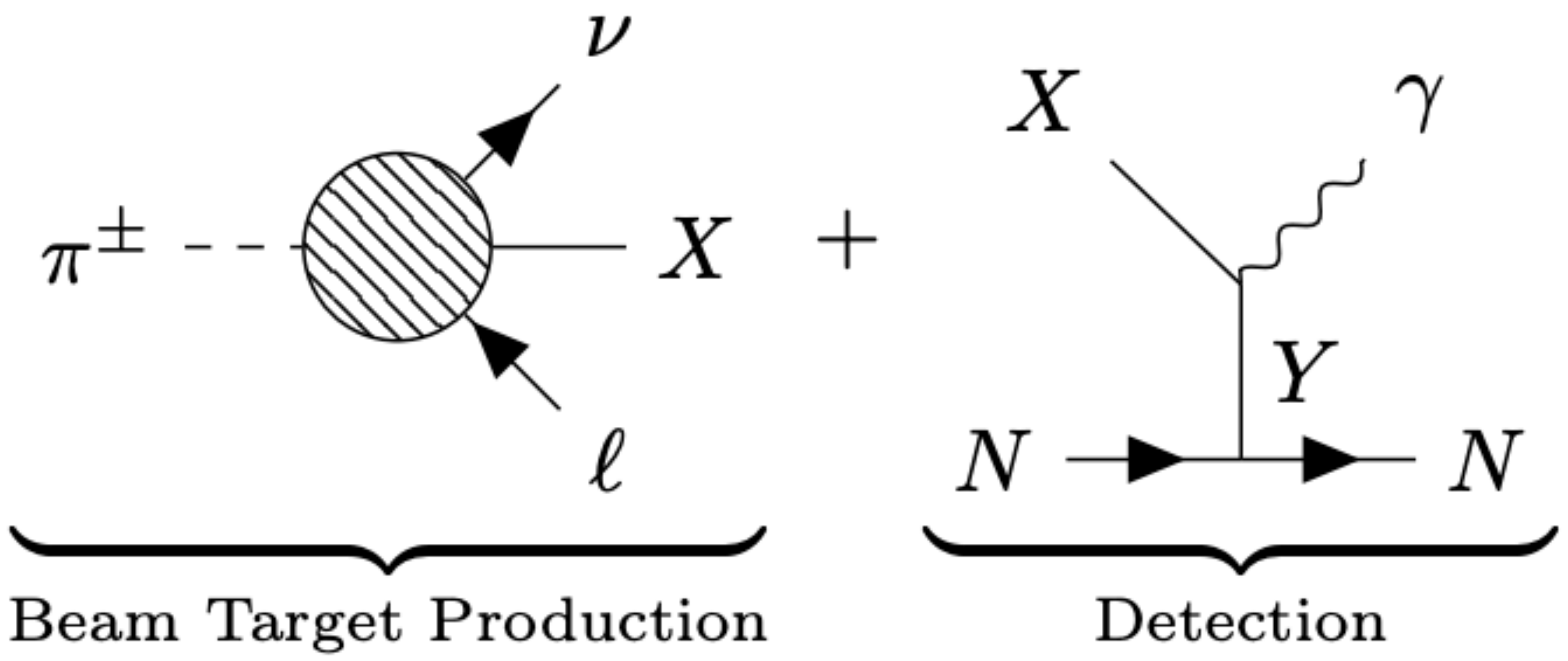
- First measurement (currently ongoing) of CC in argon for $E_\nu < 50\ \mathrm{MeV}$
    - $\pi\mathrm{DAR}$ energy spectrum overlaps with expected supernovae Fermi-Dirac spectrum
    - ***Primary channel for DUNE supernovae physics***
- Physics modeled with SIREN and MARLEY before input to Geant4 based detector simulation
- With the data already on tape, expect ~70 events at 75% efficiency and ~20% total uncertainty

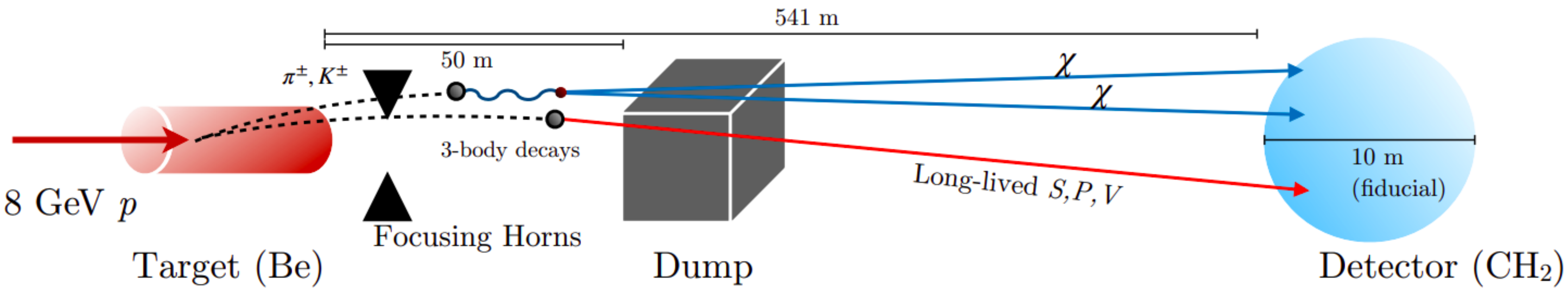



# Solution to MiniBooNE Anomaly

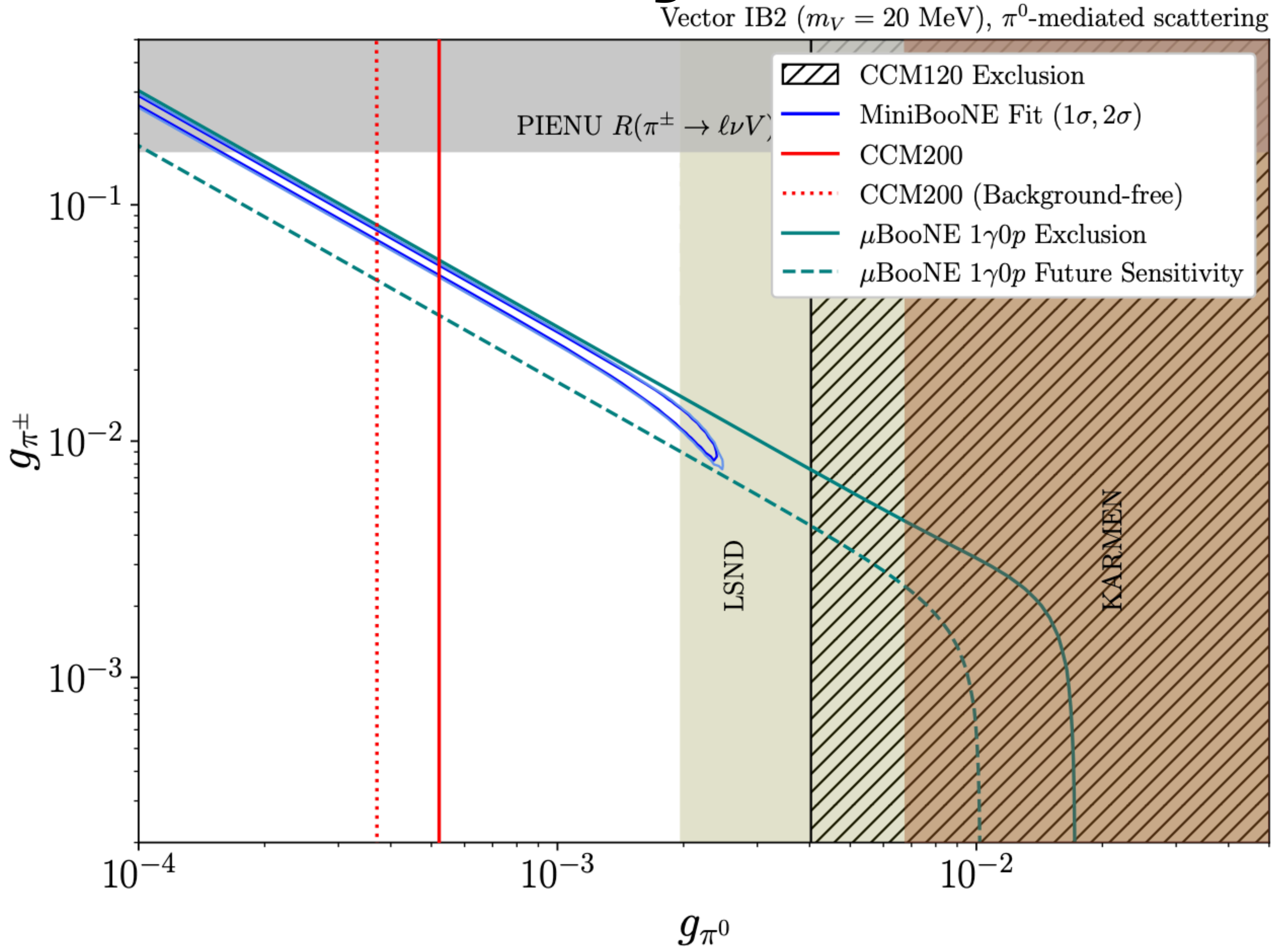
- Dark sector coupling to meson decays [PhysRevLett.129.111803, PhysRevD.109.095017, PhysRevD.111.035030]
- MiniBooNE excess in target mode only
- Excess could be caused by long-lived particles or light dark matter produced in charged meson decays



# Solution to MiniBooNE Anomaly

- Coupling to $\pi^0$ vs coupling to $\pi^\pm$
- CCM primarily sensitive to long-lived particles coupling to $\pi^0$



# Takeaways

# Summary

- CCM has demonstrated first ***event-by-event*** observation of Cherenkov radiation from ***sub-MeV*** particles in LAr
    - Novel result and novel technique of using LAr for hybrid detection medium
- Companion paper describes simulation calibration using differentiable simulation
    - ***Across all PMTs, <10% agreement between data and simulation for >2$\mu$s of data***
    - This work serves as a template for other light-based detectors to characterize photon production and propagation
- Ongoing physics searches will leverage scintillation and Cherenkov light for CC$\nu_e$ measurement, axion like particle search, and additional BSM physics scenarios

# Thank you for listening!

# Additional Slides

# Fit Results — PMT Timing Response

- Well known effect of post-pulsing for many models of PMTs
  - Caused by PE backscattering off of dynode stage
- Use a Gumbel distribution to characterize PMT post-pulsing
- Fix main pulse based on PMT transit time spread and find preference for 3 additional pulse shapes
- Find that post-pulsing is a 19.7% effect compared to the main PMT pulse

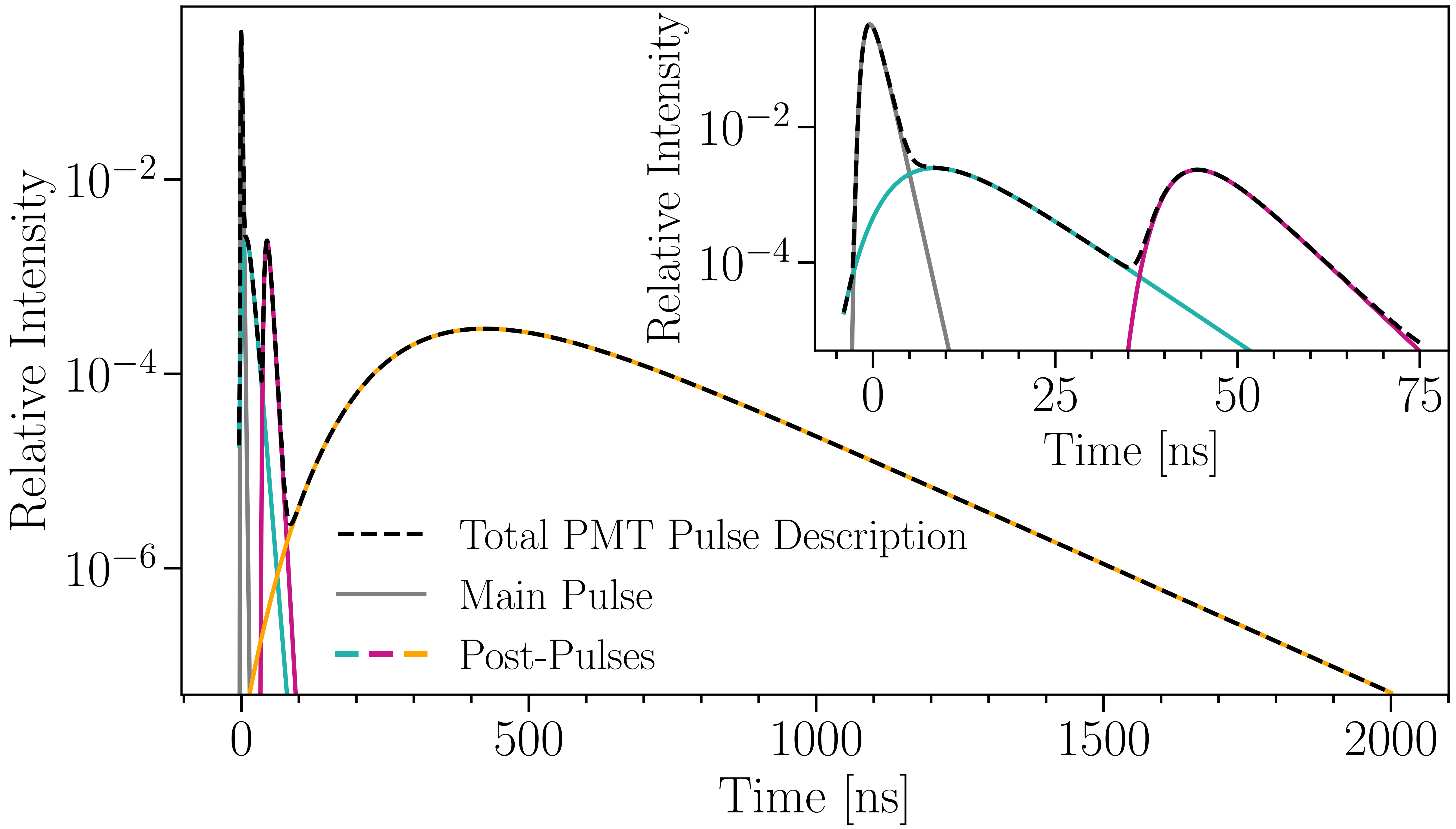



TABLE III. PMT timing response fit parameters and uncertainties. We allowed up to four PMT post-pulses but found preference for only three, plotted in Fig. 12 along with the main PMT pulse to show the total PMT timing distribution. Main PMT pulse parameters are derived from the spread in electron transit times for R5912-Y002 PMTs and were fixed in this work.

| Pulse | Location [ns] | Shape [ns] | Probability |
|---|---|---|---|
| Main Pulse | −0.45 | 0.9 | 0.803 |
| Post-Pulse 1 | 8.47 [+2.42, −1.20] | 6.00 [+2.12, −1.52] | 0.040 [+0.038, −0.040] |
| Post-Pulse 2 | 44.51 [+1.00, −7.21] | 4.26 [+4.77, −0.21] | 0.027 [+0.017, −0.008] |
| Post-Pulse 3 | 423.24 [+0.63, −1.22] | 163.84 [+1.71, −1.49] | 0.13 [+0.028, −0.001] |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