Prompt, Accurate Localization of Gamma-Ray Bursts in the Advanced Particle-astrophysics Telescope

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for the APT collaboration

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1 Overview

The Advanced Particle-astrophysics Telescope (APT) [1] is a mission concept aimed at prompt localization of MeV transients such as GRBs, with all-sky sensitivity and a large effective area. ADAPT (the Antarctic Demonstrator for APT), a scaled-down version of the instrument, is under construction and scheduled to fly from Antarctica during the 2024-25 season. The prompt reconstruction and integration of evidence from multiple Compton scatters raises significant computational challenges [2].

APT (not shown here) is a detector consisting of 20 layers of 3mx3m CsI:Na scintillating crystal with orthogonal 2mm wavelength-shifting (WLS) fibers bonded to the top and bottom of each layer.

ADAPT Mission
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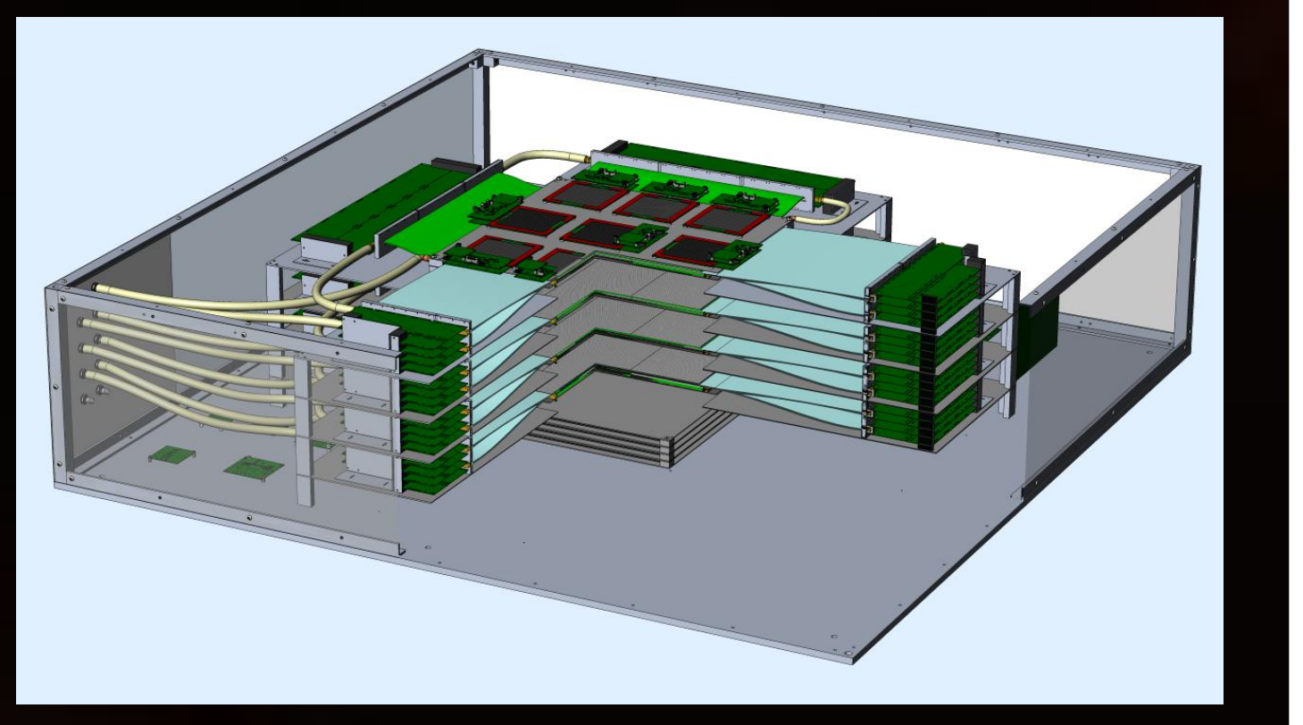

ADAPT (fig. right) is a smaller 0.5mx0.5m cross-section instrument with just four layers of crystal/WLS fibers.

Front End
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Incident gamma-ray photons scatter within the detector producing scintillations in the CsI layers. Front-end processing records the location and energy deposited by each scintillation, which we use to locate the photons' common source in the sky.

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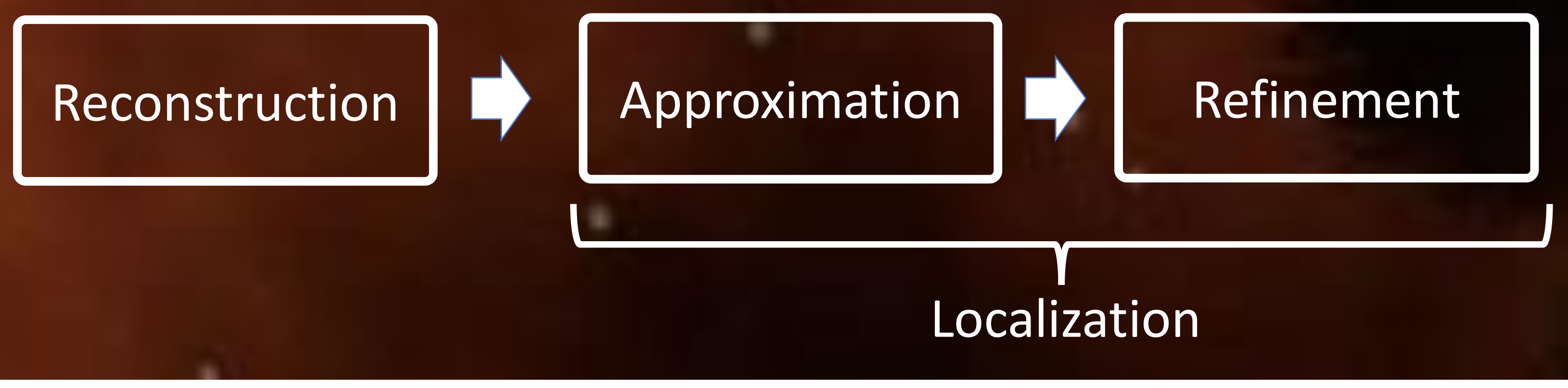
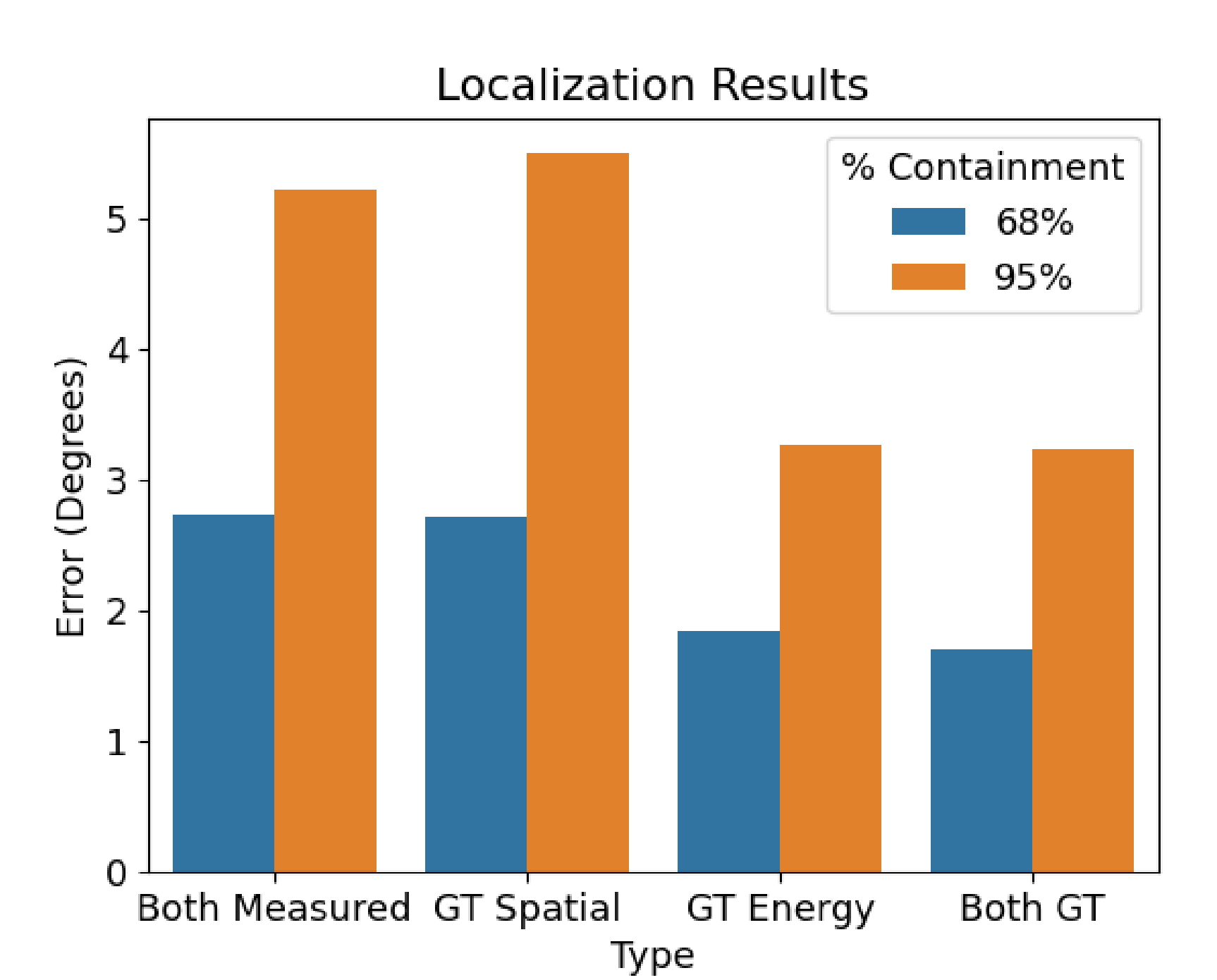


Reconstruction → Approximation → Refinement

Localization

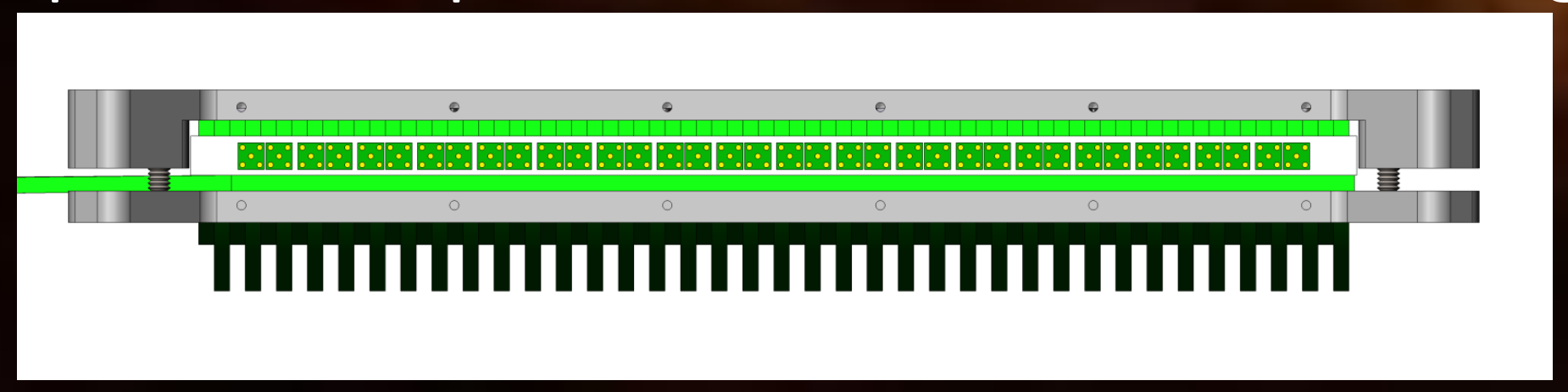
Energy Uncertainty Vs. Spatial Uncertainty



- We show that the energy estimates are more in need of improvement than the spatial estimates of the centroids.
- Generate four different datasets with permutations of measured spatial/energy and ground truth spatial/energy estimates. When running the entire pipeline with these datasets, we find that using ground truth energy alone significantly decreases the final error output.
- Hence, to improve our energy estimate we include the use of edge detectors and in ADAPT, also the calorimeter layers.

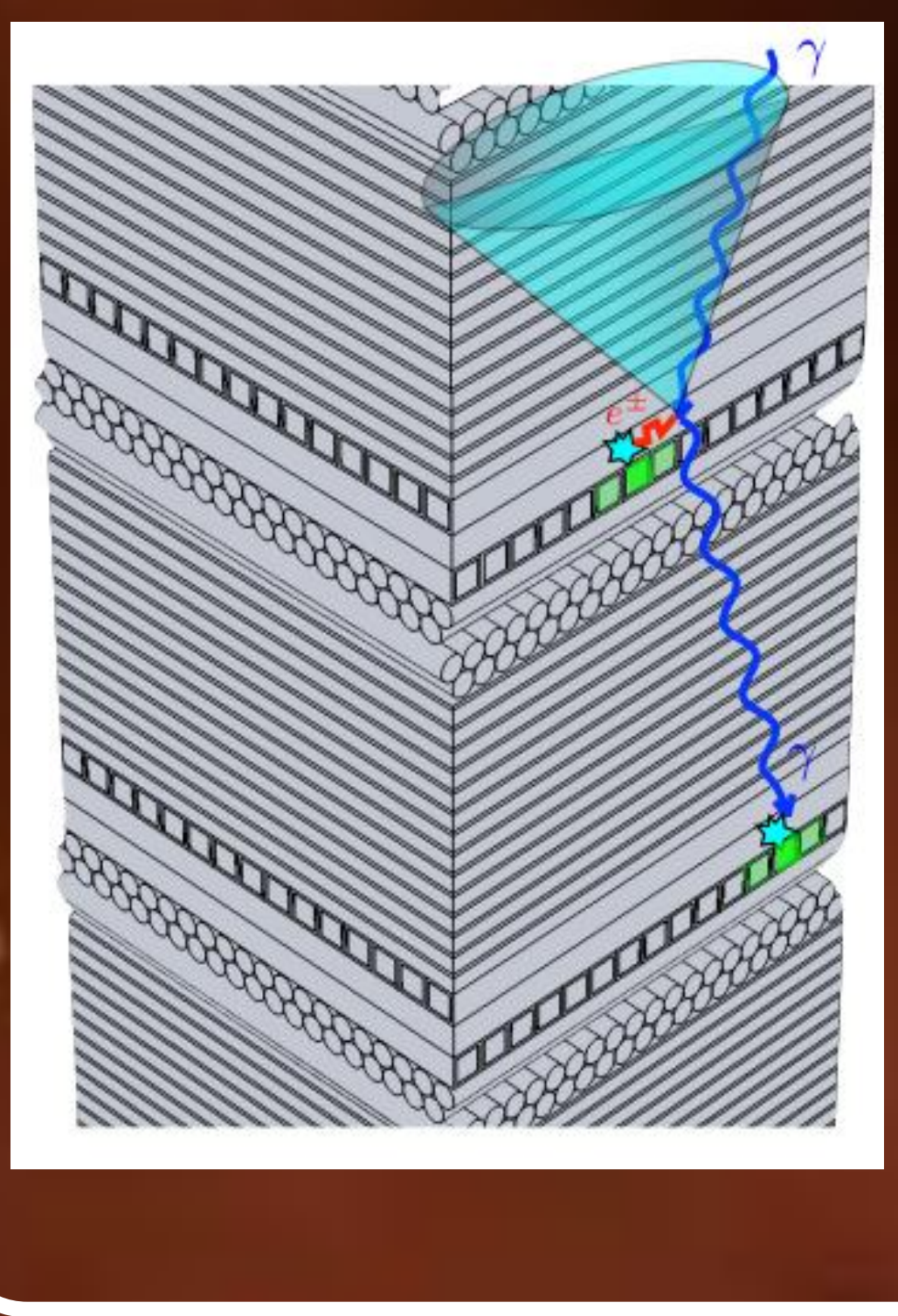
Edge Detectors & Calorimeters

- The addition of the SiPM-based edge detectors (fig. below) is a great improvement to our localization accuracy as it improves light collection and calorimetry which provides us with better energy estimates for our reconstruction algorithm.
- Furthermore, calorimeter layers (ADAPT only) at the bottom of the detector increase the chances of photoabsorption which provides us with better total energy estimates of each gamma ray.



- In this side view of a single CsI tile, the SiPMs are represented by the green squares in the middle.
- The output of all 36 edge SiPMs on a single tile is combined through a single low-gain and a single high-gain shaping preamplifier. Each output signal is then sent to an ASIC channel for time integration.

2 Reconstruction

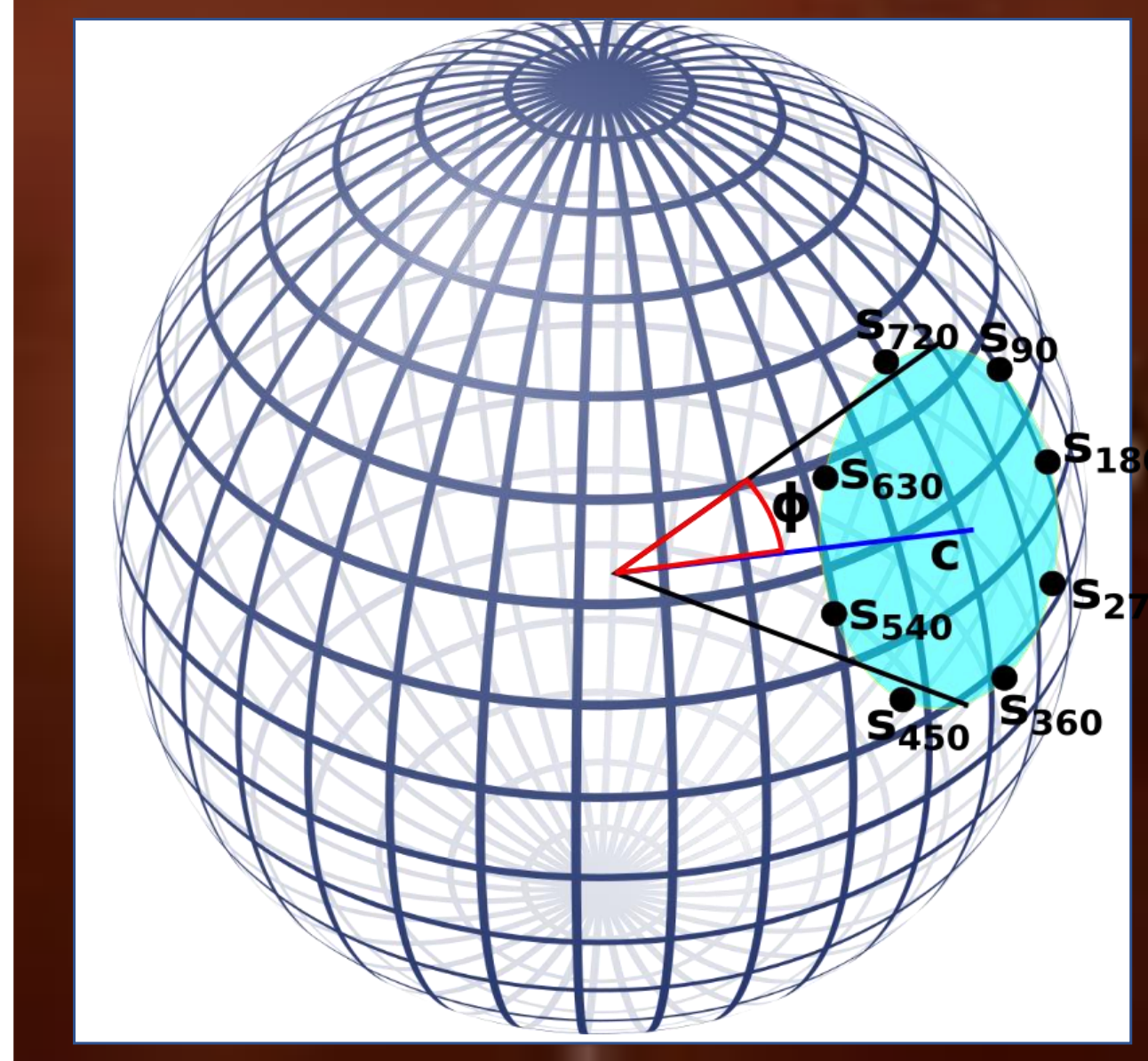


A gamma-ray photon, γ, enters the instrument from the top, then Compton-scatters (perhaps multiple times) before finally being photoabsorbed. The order of interactions must be reconstructed, as described in [2]. The first two implied scatterings define an **annulus (c, ϕ, σ)** containing an estimated source direction:

- c: The vector between the first two interactions.
- ϕ: The scattering angle implied by the photon's energy before and after the first interaction.
- σ: Propagated uncertainty based on spatial and energy measurement error.

3 Localization

Approximation

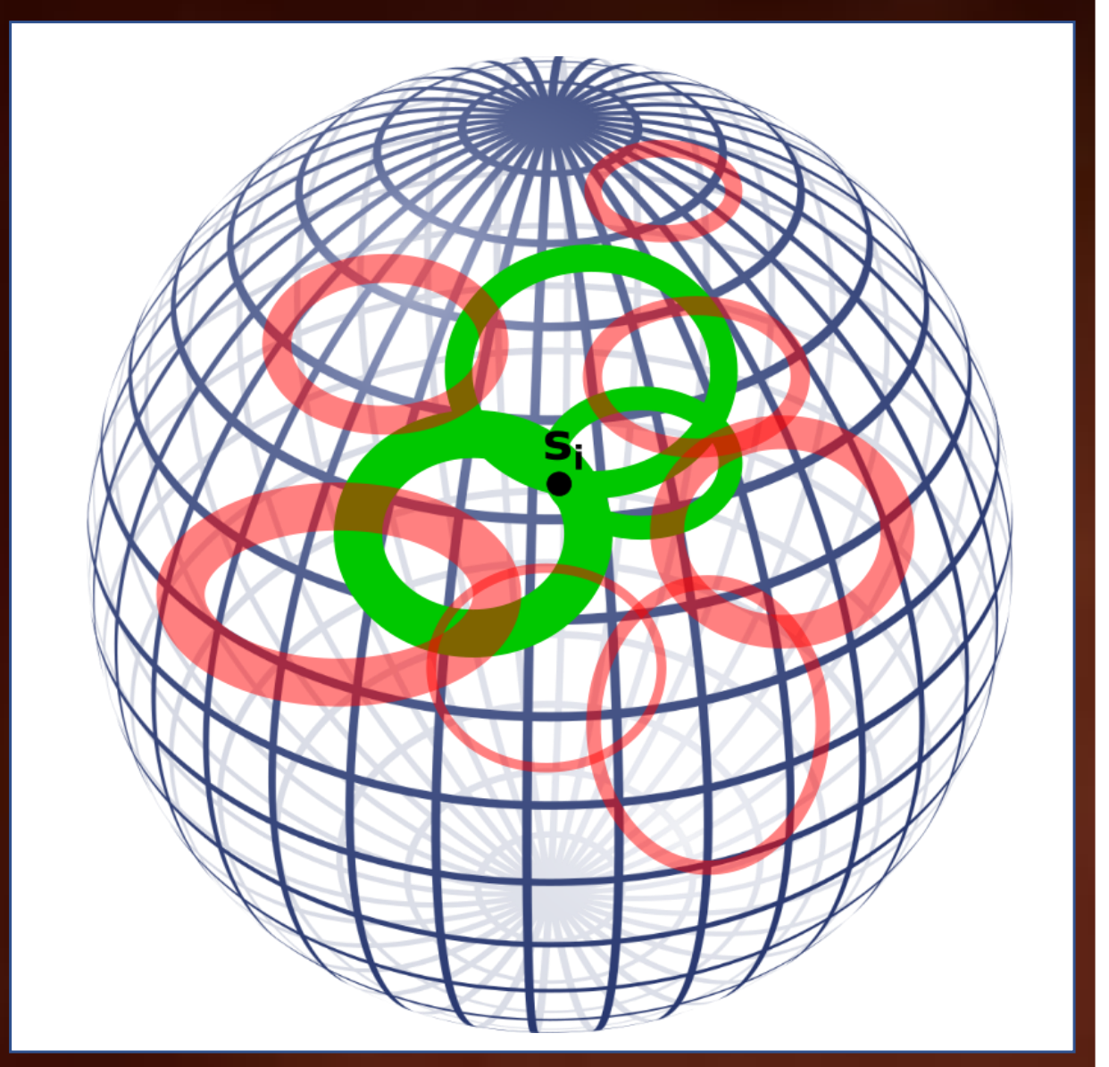


1. Preprocess the annuli to deal with background noise by removing annuli that came from events with more than two hits in the same CsI layer.

2. From N annuli, select 20 at random and for each annulus, test a set of 720 candidate source directions s_j evenly spaced on the circle (c_i, ϕ_i).
4. Calculate the joint log-likelihood for each candidate source direction with respect to all input annuli.
5. Select the candidate direction from each annulus with the highest likelihood.
6. Average over these 20 estimates, weighted by likelihood, to produce an initial approximation s_0.

Refinement (Linear Least Squares)

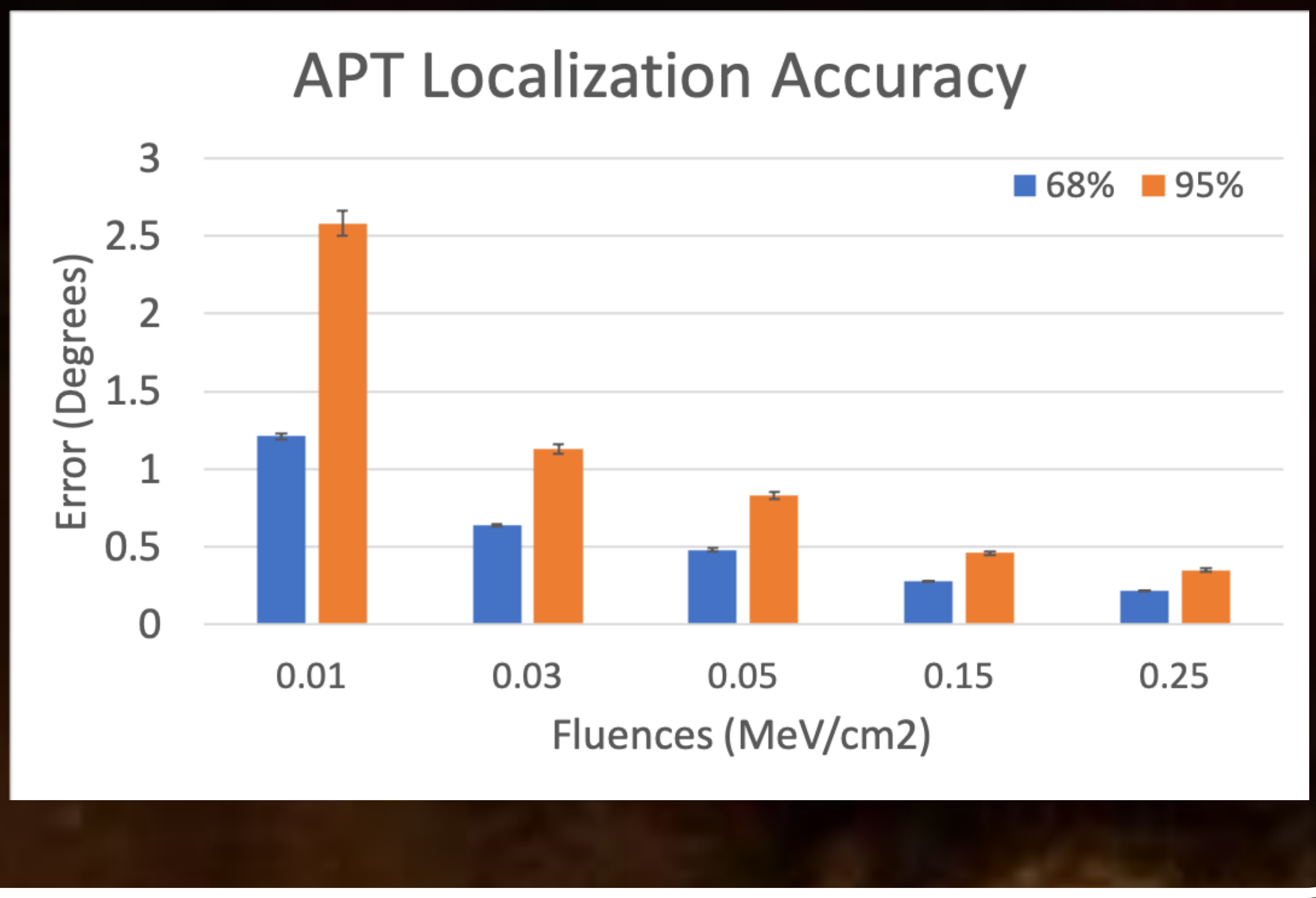
1. Begin with the estimate $s = s_0$ (from the approximation stage).
2. For each annulus i, test whether the angle $\arccos(c_i \cdot s)$ lies within $3\sigma_i$ of $\phi_{i.}$
3. For those that do, generate linear constraints $c_i \cdot s = \cos \phi_{i.}$
4. Require s to be a direction vector; this unit-norm constraint is quadratic in the coordinates of s.
5. Reduce the problem to a quadratic eigenvalue problem and solve to get a refined estimate for s.
6. Iterate 20 times, repeating steps 2-5, to get the final s, which is the estimated GRB source direction.



4 Localization Accuracy of APT

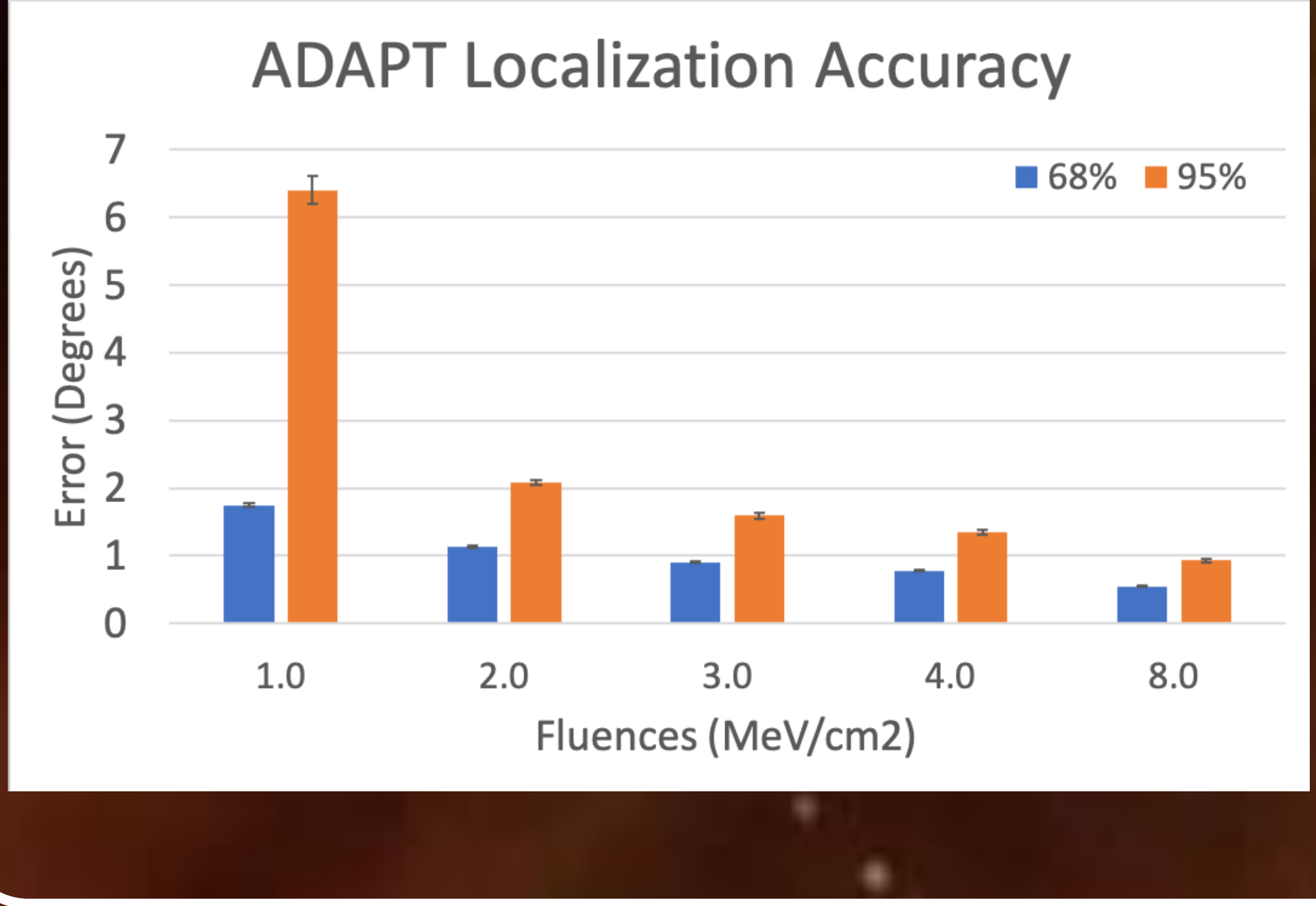
We simulate interaction of APT's detector with a typical, normally incident GRB using GEANT4. Spectral energy distribution is modeled according to a Band function with parameters: α = 0.6, β = −2.5, Epeak = 1 MeV, and energy range 300 keV to 10 MeV.

- Repeat localization for 1000 trials and sort to obtain the 68% and 95% containment values for error between actual and inferred source direction.
- Repeat each experiment 10 times with different random seeds to obtain confidence intervals.



5 Localization Accuracy of ADAPT

- We use the same GRB spectrum in this experiment but with higher fluences.
- The ADAPT device simulation includes models of impulse response, detection efficiency, and dark count uncertainty from the WLS fiber and edge detector SiPMs



- We consider the effects of simultaneously arriving photons and anisotropic at mospheric background.
- ADAPT's much smaller area means higher fluence is required to obtain a given level of localization accuracy compared to the larger APT.

References

[1] James Buckley. 2021. The Advanced Particle-astrophysics Telescope (APT) Project Status. In *Proceedings of 37th International Cosmic Ray Conference — PoS(ICRC2021)*, Vol. 395. 655.

[2] Marion Sudvarg, Jeremy Buhler, James Buckley, Wenlei Chen, et al. 2021. A Fast GRB Source Localization Pipeline for the Advanced Particle-astrophysics Telescope. In *Proc. of 37th International Cosmic Ray Conference — PoS(ICRC2021)*, Vol. 395. 588.