COSI: Optimization of Compton Event & Image Reconstruction for the 511-keV Annihilation Line

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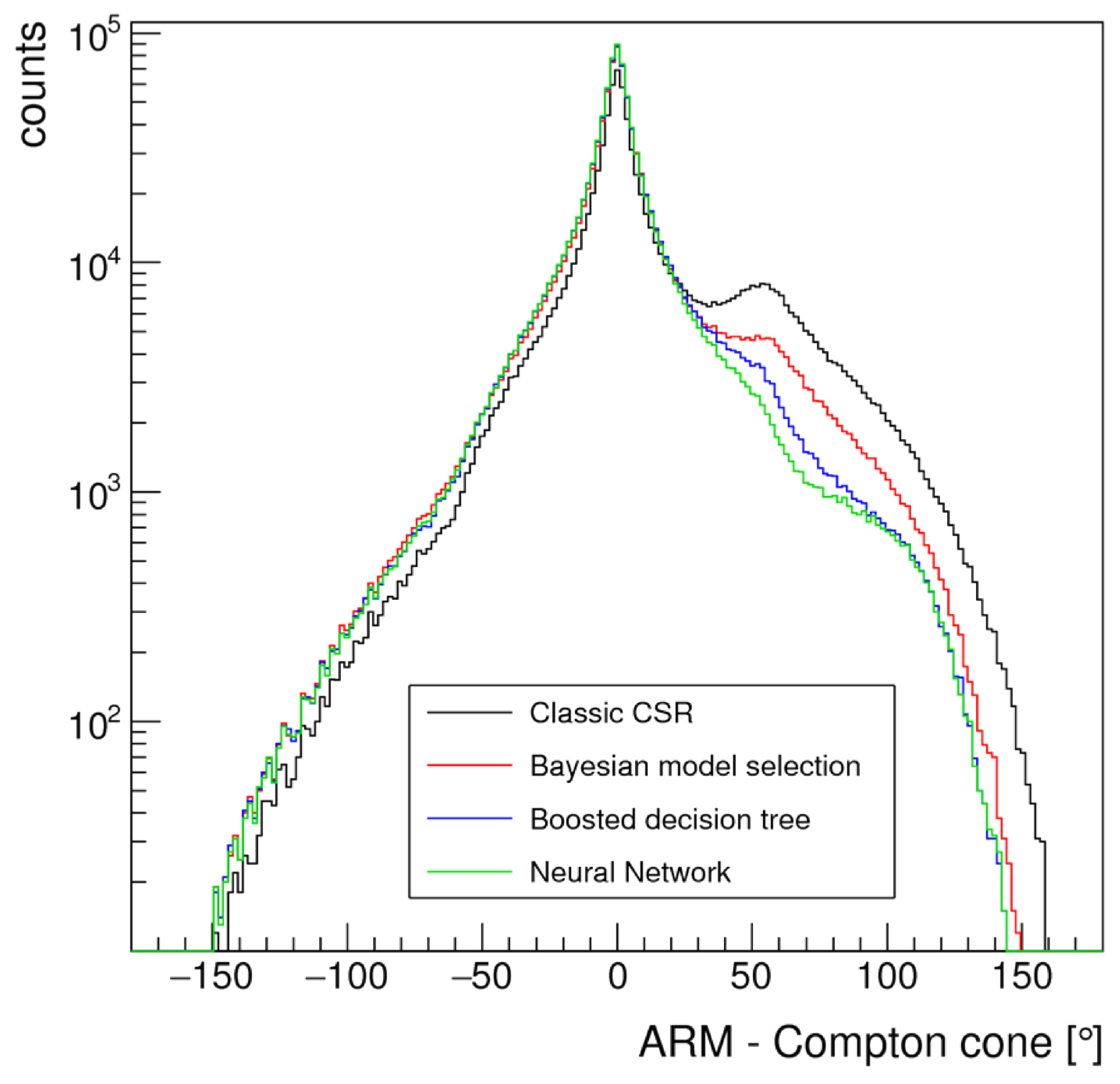
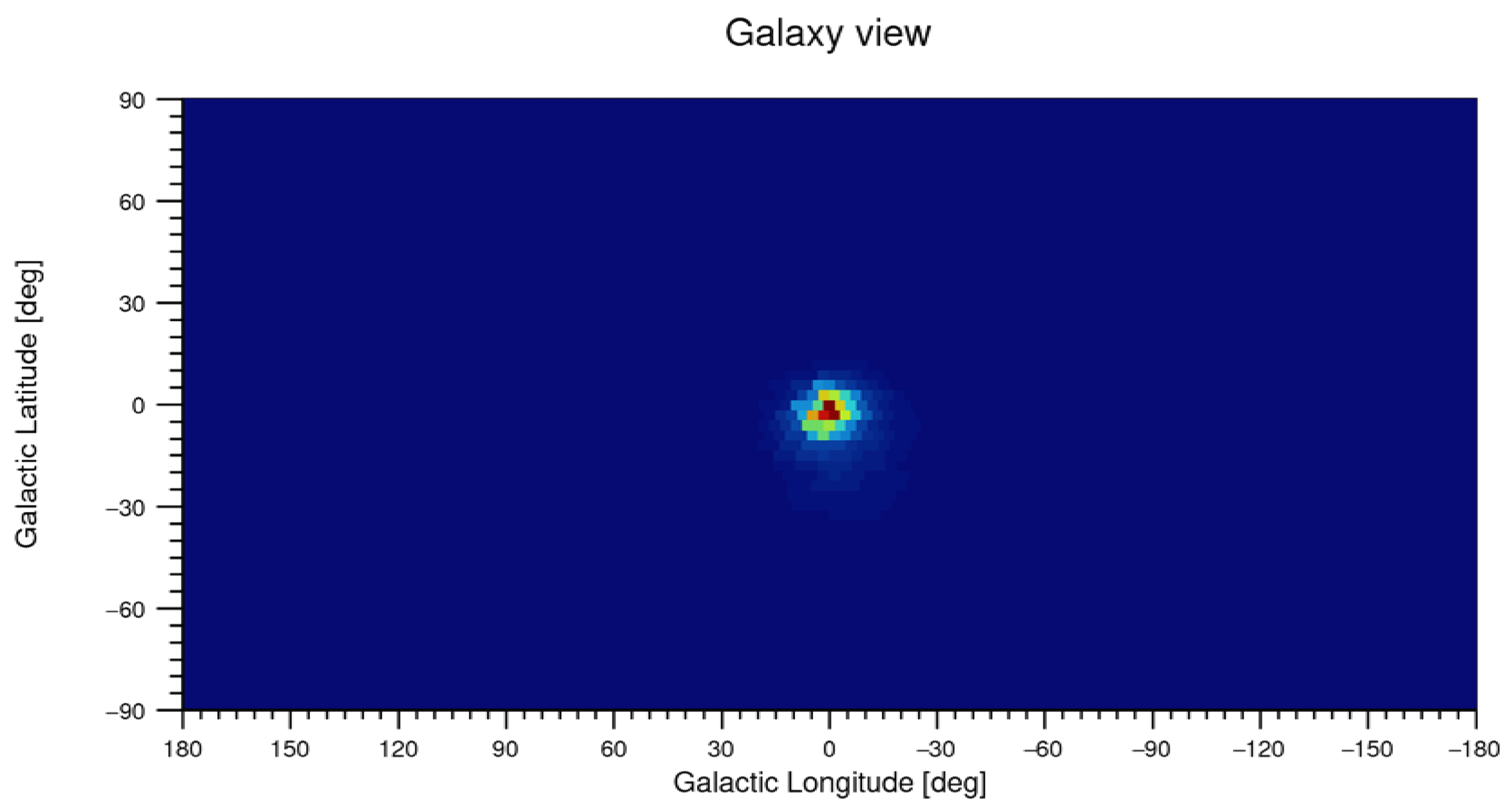


Comparison of different Compton event reconstruction approaches using COSI's 511-keV calibration data: The narrowest (ARM) distribution shows the best event reconstruction approach (here: neural network).



Reconstructed image of a COSI simulation of the Galactic Center seen in the 511-keV line using the newly developed COSI binned-imaging response generator, background model generator, background estimator, and utilizing a binned-mode Maximum-Entropy image deconvolution approach.

COSI: The Compton Spectrometer and Imager

COSI is a balloon-borne, gamma-ray telescope (0.2-5 MeV) with inherent sensitivity to polarization utilizing Compton scattering for imaging. COSI's key science goals are:

- Observe gamma-ray bursts (GRBs) and their polarization,
- Detect Galactic nucleosynthesis (e.g. ^{26}Al), and
- Map the Galactic 511 keV annihilation emission.

COSI minutes before launch with a 18 million cubic feet super-pressure helium balloon in Wanaka, New Zealand.

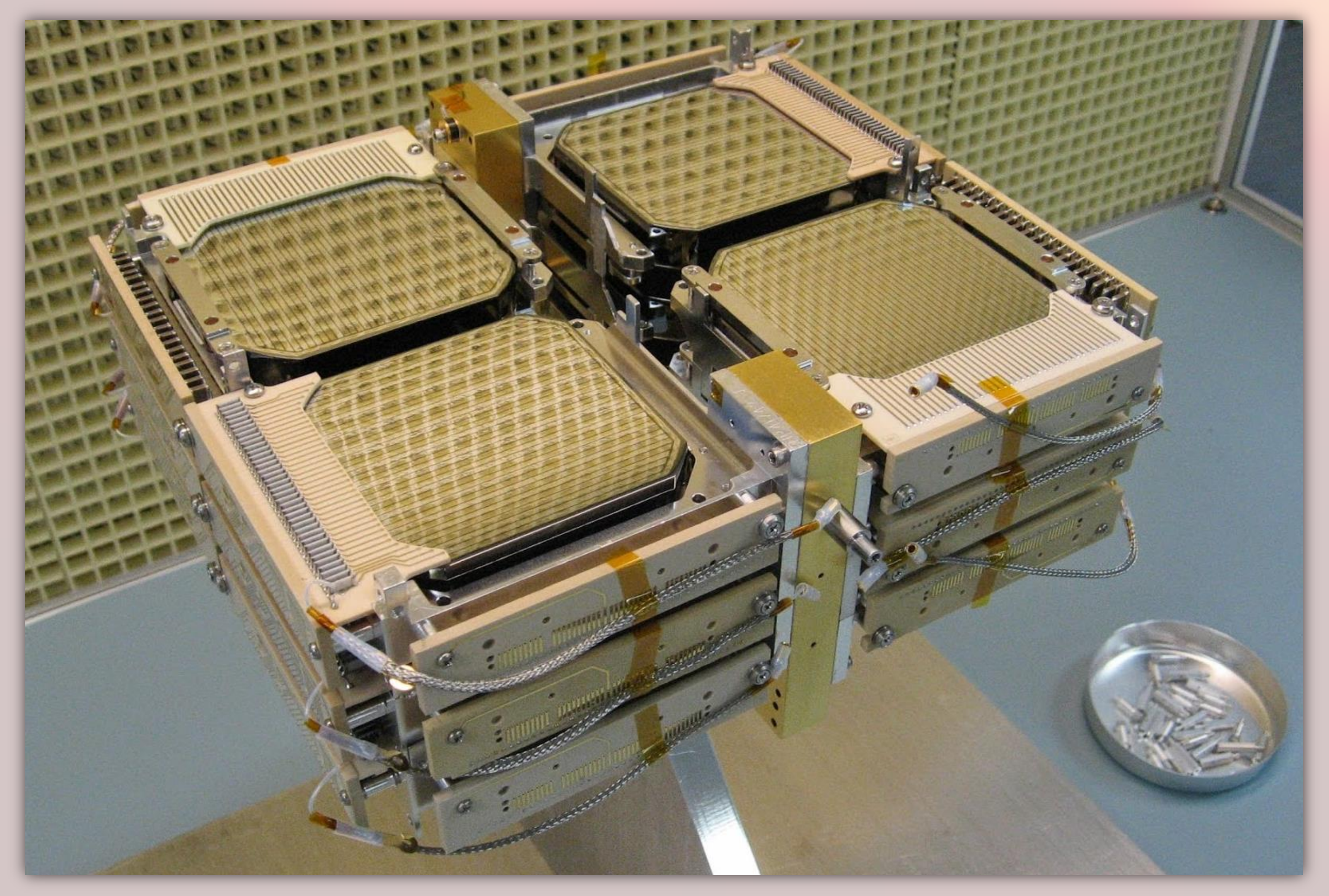
All data analysis was performed with

MEGAlib

An open-source toolkit for the simulation, calibration, reconstruction, and data analysis of gamma-ray telescopes on ground and in space.

See https://megalibtoolkit.com

COSI consists of 12 high-purity double-sided Germanium strip detectors (8x8x1.5 cm3, 2 mm pitch) with an energy resolution of 2-3 keV and 0.5 mm depth resolution (FWHM).



Launched from Wanaka, New Zealand, COSI circled the Earth 1.5 times before landing in the Atacama desert, Peru.

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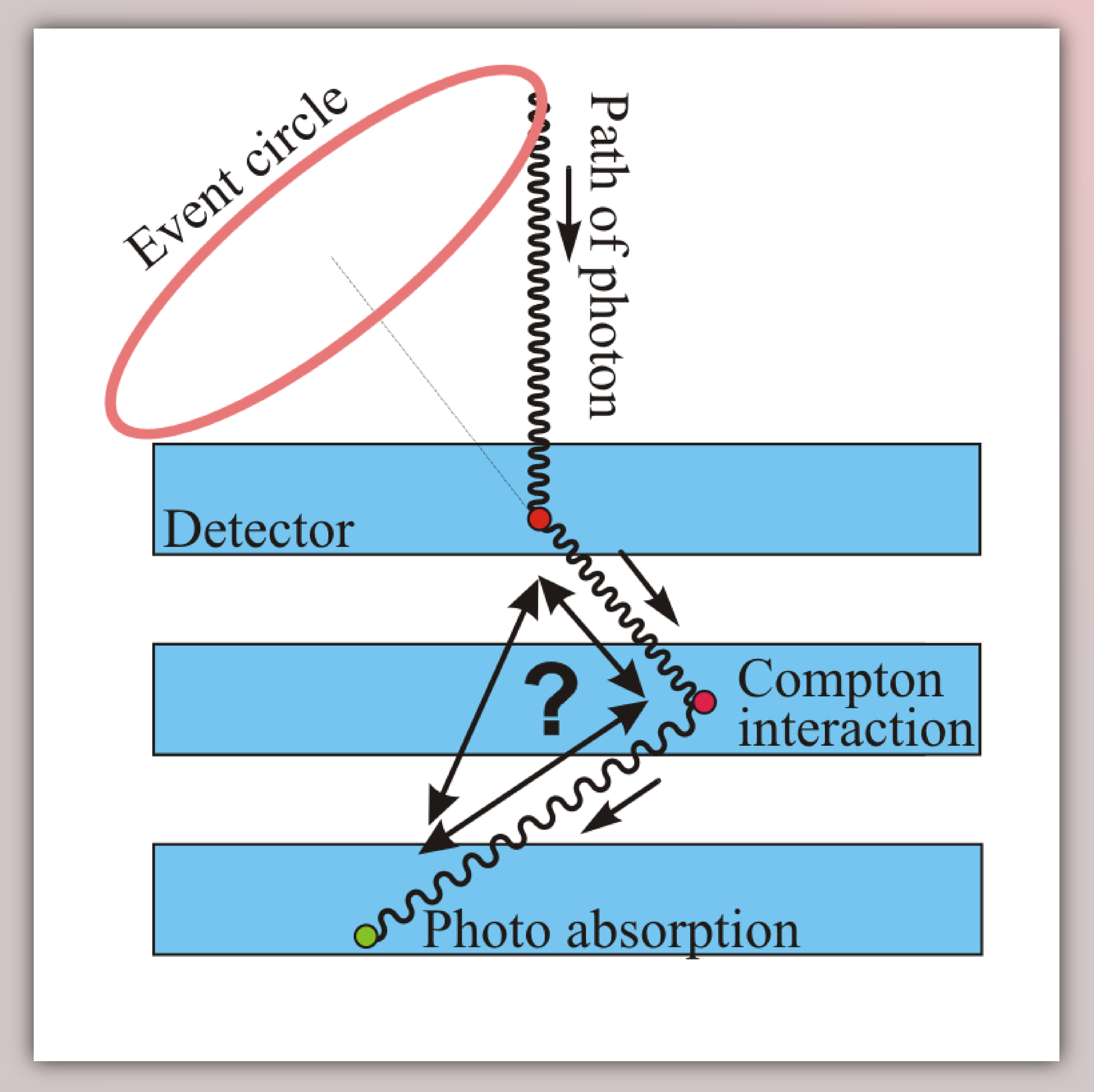
Compton Event Reconstruction

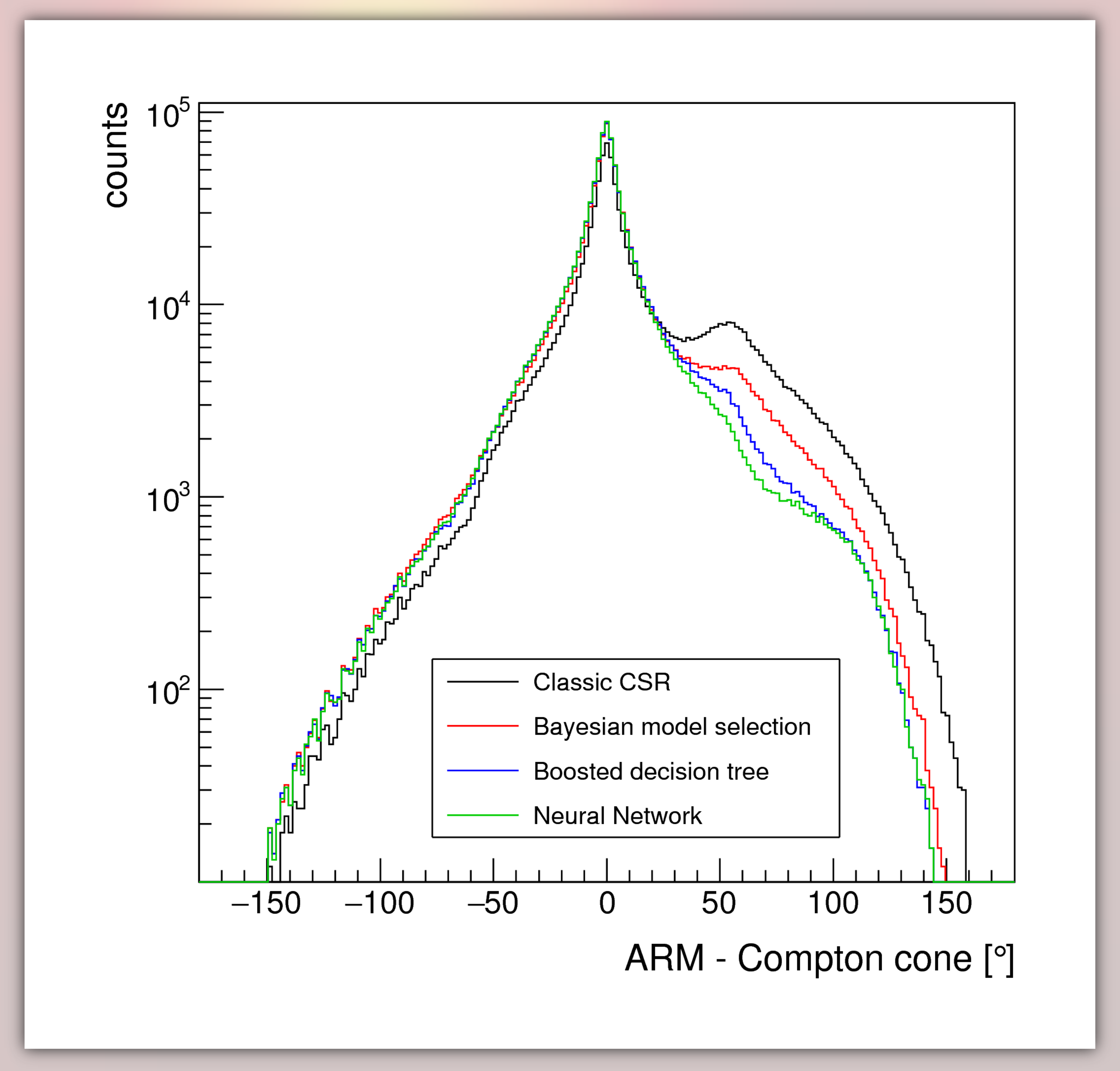
Event Classification

Modern Compton telescopes are not able to measure the time between the measured hits. Therefore, reconstruction approaches have to be applied to determine the path of photon in the detector, and ultimately determine the parameters of the first Compton interactions for image reconstruction. The reconstruction algorithms have to consider all possible paths of the photon, and for each of them look at redundant information, such as the second Compton scatter angle for 3-site events, absorption probabilities, scatter angles and probabilities, the measured energies and locations in the detector, etc.

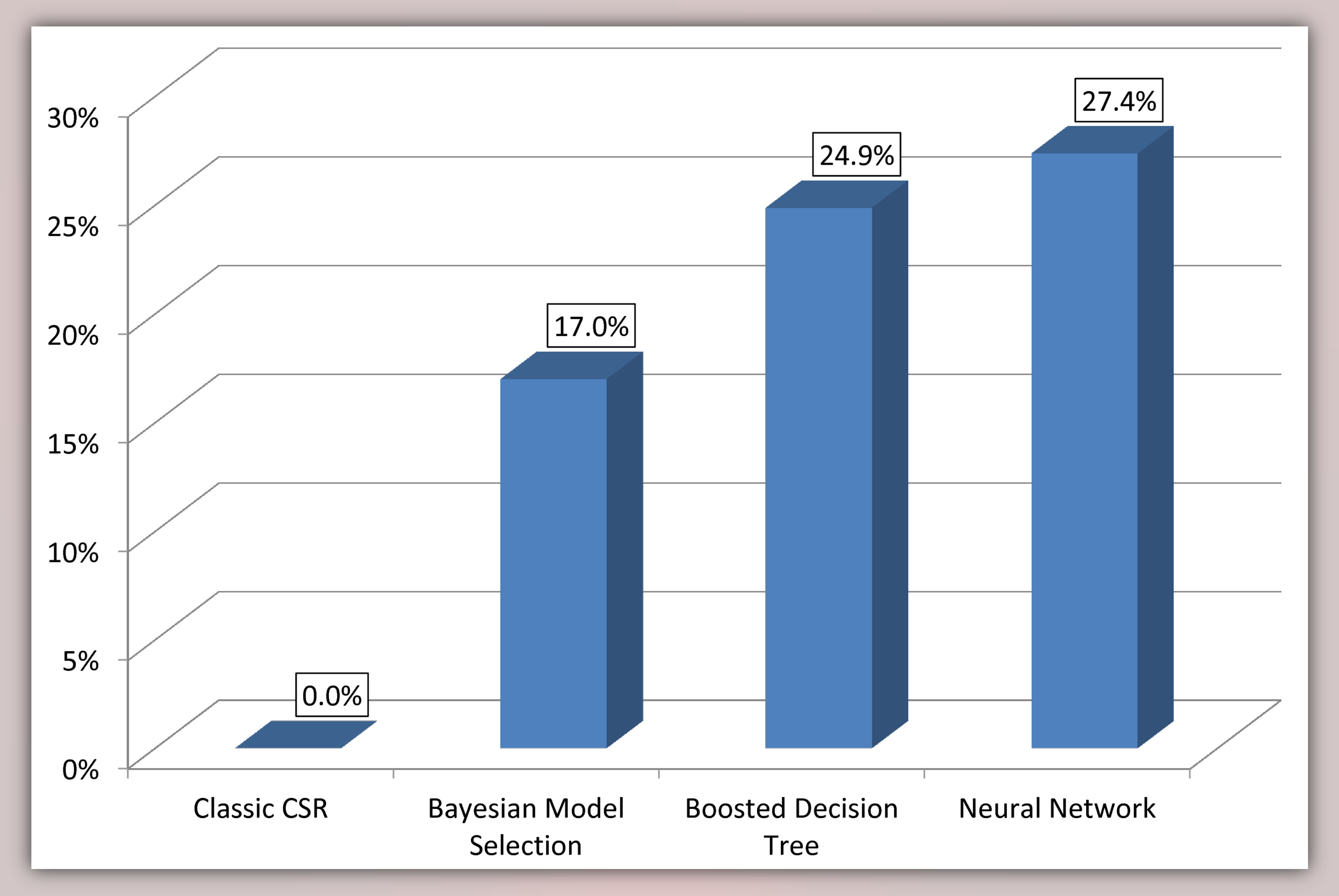


Application to the 511-keV ^{22}Na calibration line

The best metric to describe the performance of an event reconstruction algorithm is the angular resolution measure, the ARM. It is defined as the smallest angular distance between the Compton cone and the known origin of the gamma ray. The left figure shows an ARM distribution of a 511-keV ^{22}Na calibration line using different event reconstruction approaches. The good events assemble close to zero, bad event are off axis, in COSI's case mostly to the right. The ideal ARM distribution is narrowly concentrate near zero, only broadened by Doppler broadening, energy and position resolution.



The right figure shows the improvement of the RMS of the ARM distribution relative to the Classic Compton sequence reconstruction. The currently best approach are neural networks, followed by boosted decision trees, and the Bayesian approach.



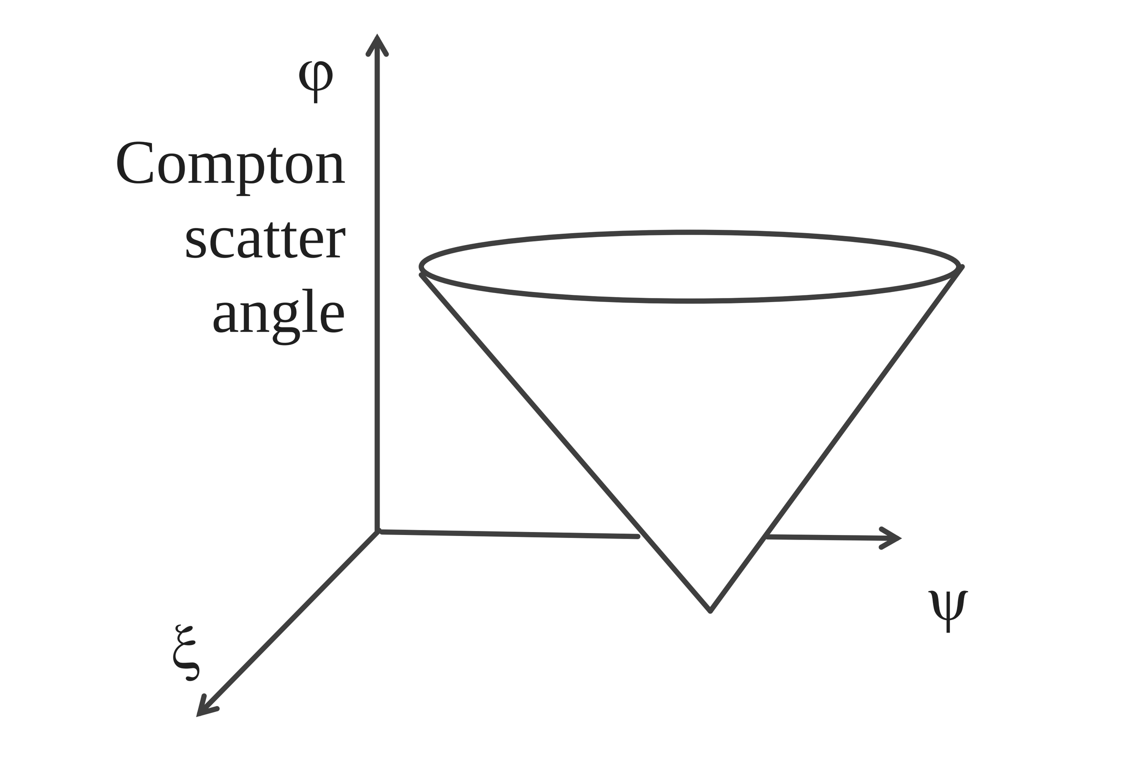
BINNED-MODE COMPTON IMAGE RECONSTRUCTION

Image, Data, and Response Space

During the measurement process of a Compton telescope, photons emitted from a sky distribution I undergo the measurement process R and together with background events B are measured in the data space D:

$$D = RI + B$$

Ideally, the image space spans the sky, energy, and polarization dimensions. The data space spans the original 3 COMPTEL dimensions, Compton scatter angle and the direction of the scattered gamma ray (ξ, ψ), for tracking Compton telescopes the direction of the recoil electron, the energy, the distance between interactions, and, for multiple Compton scatters, the direction of the second scattered gamma-ray, etc. The response is a large matrix with spans both image and data space. Image reconstruction inverts this measurement process utilizing iterative deconvolution methods such as Richardson-Lucy and Maximum-Entropy.



ξ, ψ: Scattered gamma-ray direction

The point spread function of a point source in the COMPTEL data space is a cone with an opening angle of 90 degrees pointing at the direction of origin of the gamma rays in the plane of the direction of the scattered gamma ray.

511-keV GC simulations with COSI

For the COSI 511-keV data analysis we have developed a toolset to create an optimized multi-dimensional binned-mode response from benchmarked simulations, a background model generator, and implemented a Maximum-Entropy image deconvolution and background estimation approach.

The approach is evaluated with simulations of the 511-keV emission from the Galactic center (Skinner+ 2014) and COSI background. The response is restricted to 5 dimensions (image dimensions & classic COMPTEL data space) to achieve sufficient statistics. The response has been determined using ~100.000 core hours on a collection of computers with (mostly) Intel i7 4770 CPUs simulating 2.6 10^{13} 511-keV photons. The background has been simulated as internal decays as well as isotropic 511-keV emission. From this, a background model has been created. The resulting image can be seen in the figure below. The final application to COSI flight data is work in process as the required 511-keV background model is developed.