The Advanced Particle-astrophysics Telescope: Reconstruction of the MeV gamma-ray sky and estimation of point-source sensitivity in the presence of the background

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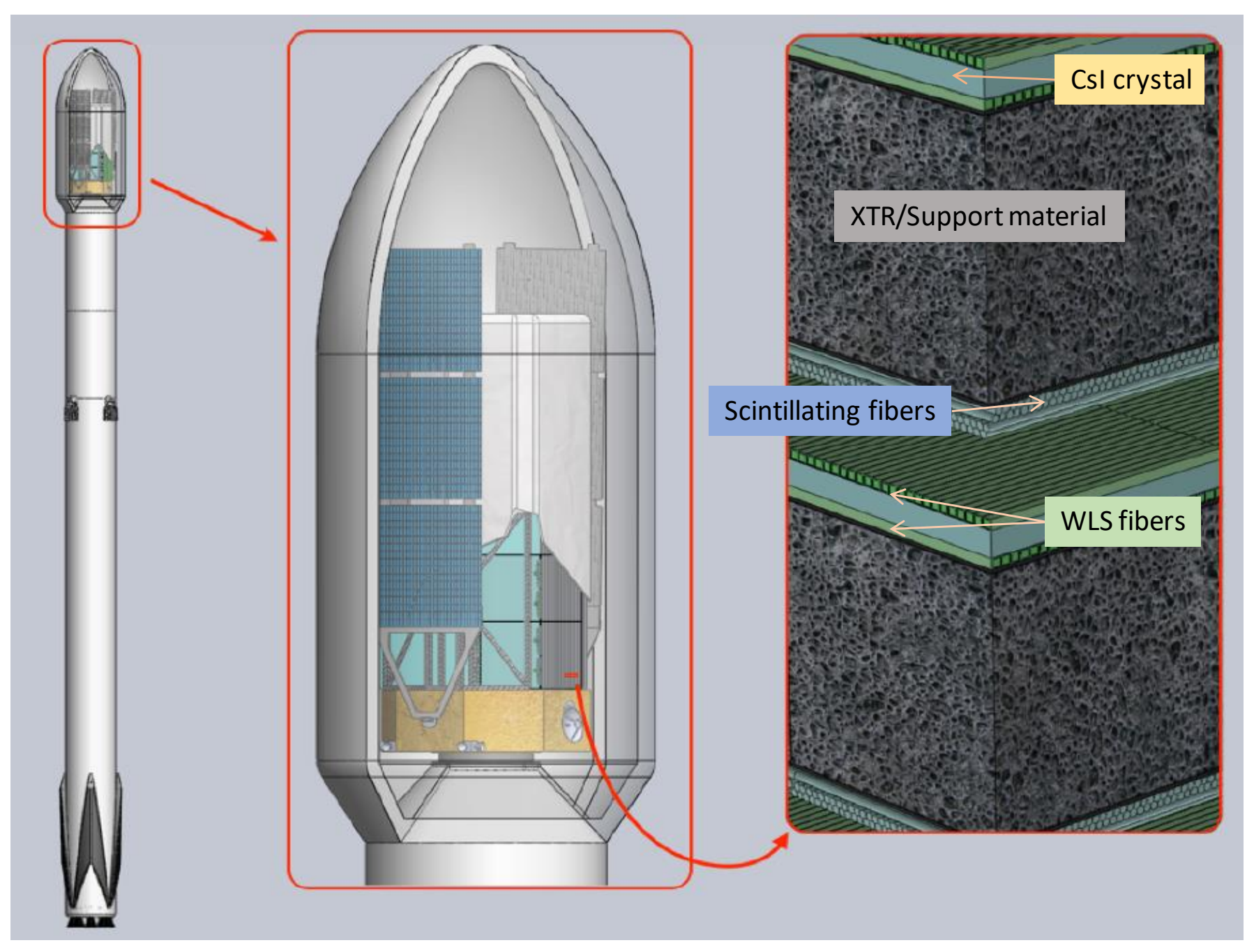
The Advanced Particle-astrophysics Telescope (APT)

Detector Design

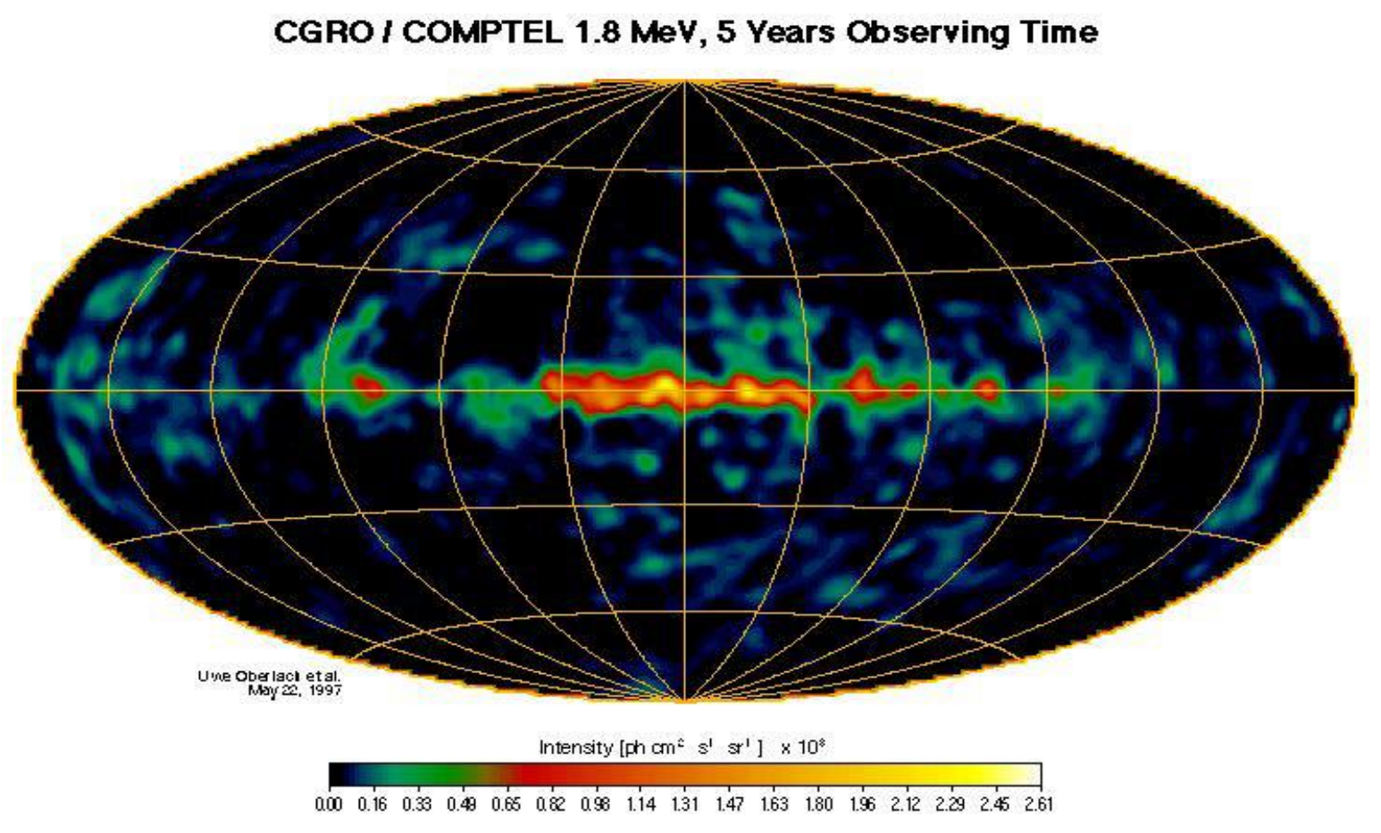
- The APT is a mission concept of a gamma-ray and cosmic-ray observatory in an orbit around the second sun-Earth Lagrange point (L2). With a multiple-layer tracker and an imaging calorimeter, APT is designed to observe gamma-rays at energies from hundreds of keV up to a few TeV.
- The instrument design is aimed at maximizing effective area and field of view for MeV-TeV gamma-ray and cosmic-ray measurements. The current detector design is based on 3-meter scintillating fibers read out by Silicon photomultipliers (SiPMs). The APT detector includes a multiple-layer tracker composed of scintillating fibers and an imaging calorimeter composed of thin layers of sodium-doped CsI (CsI:Na) scintillators and wavelength-shifting (WLS) fibers. The CsI:Na crystals are coupled to crossed planes of wavelength shifting fibers to localize energy deposition to ~mm accuracy.

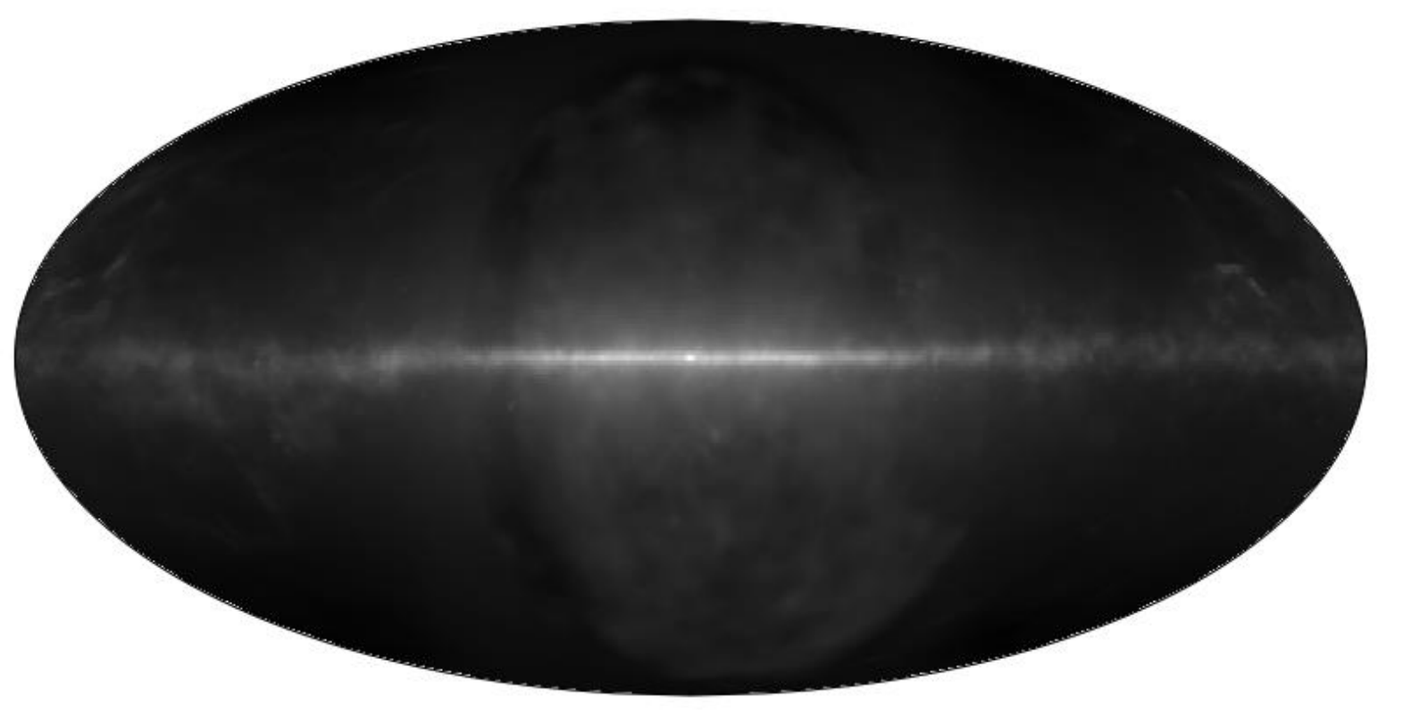


- At energies above 30 MeV, pair production is the dominant photon interaction in most materials, by which an electron-positron pair is created as the cosmic gamma-ray interacts in the electric fields of atoms in the detector. At lower energies (< 10 MeV), incident gamma-rays experience multiple Compton scatterings. The APT instrument will function both as a pair telescope for 30 MeV to 1 TeV gamma-rays and as a Compton telescope with excellent sensitivity down to ~ 0.3 MeV.

Observing the MeV Gamma-Ray Sky

Generating a MeV gamma-ray background model



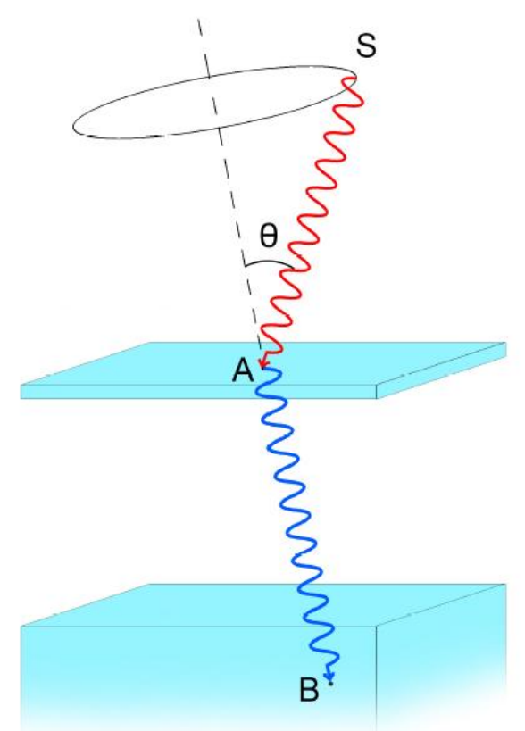


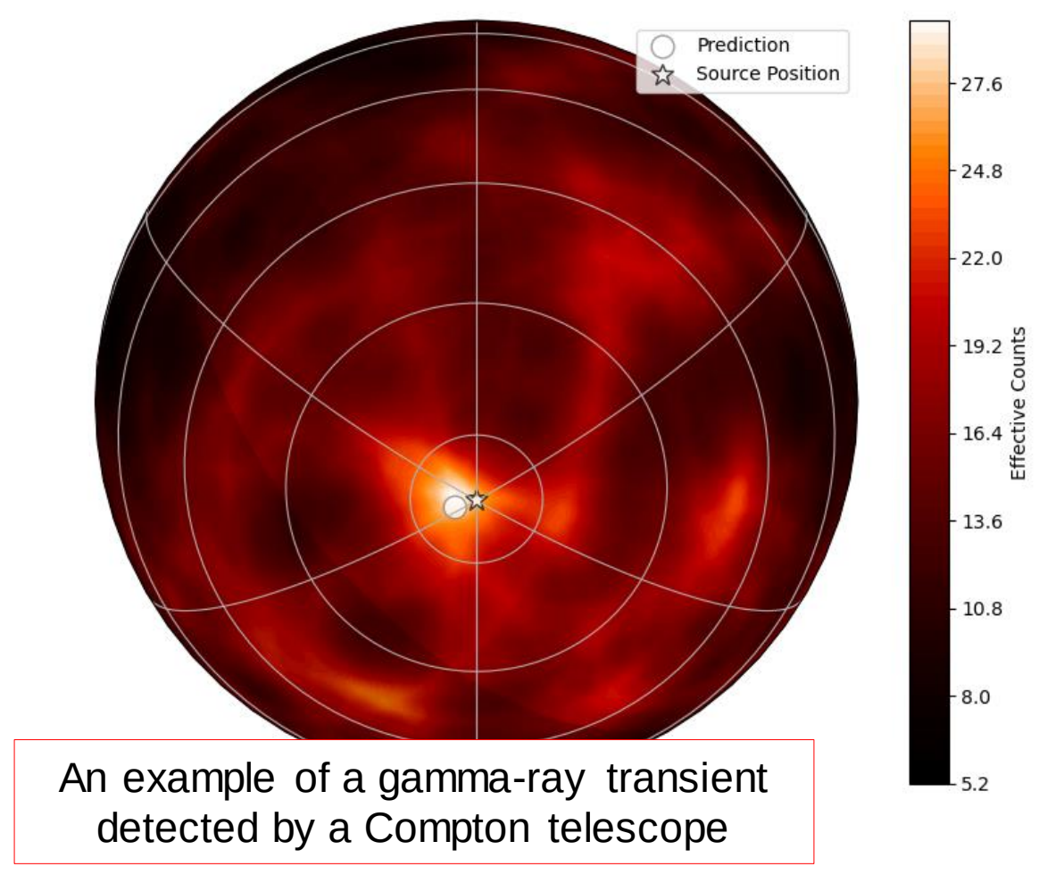
Gamma-ray Background at 1 MeV

- There is no detailed observation of the MeV gamma-ray sky with a degree-level resolution.
- We generate an MeV background model based on the photo distribution in the 30 MeV sky from the Fermi background model[1]. The model is matched to the Milky Way emission observed by the CGRO/COMPTEL and extrapolated to different MeV energies based on power-law spectra for galactic and extragalactic emissions.

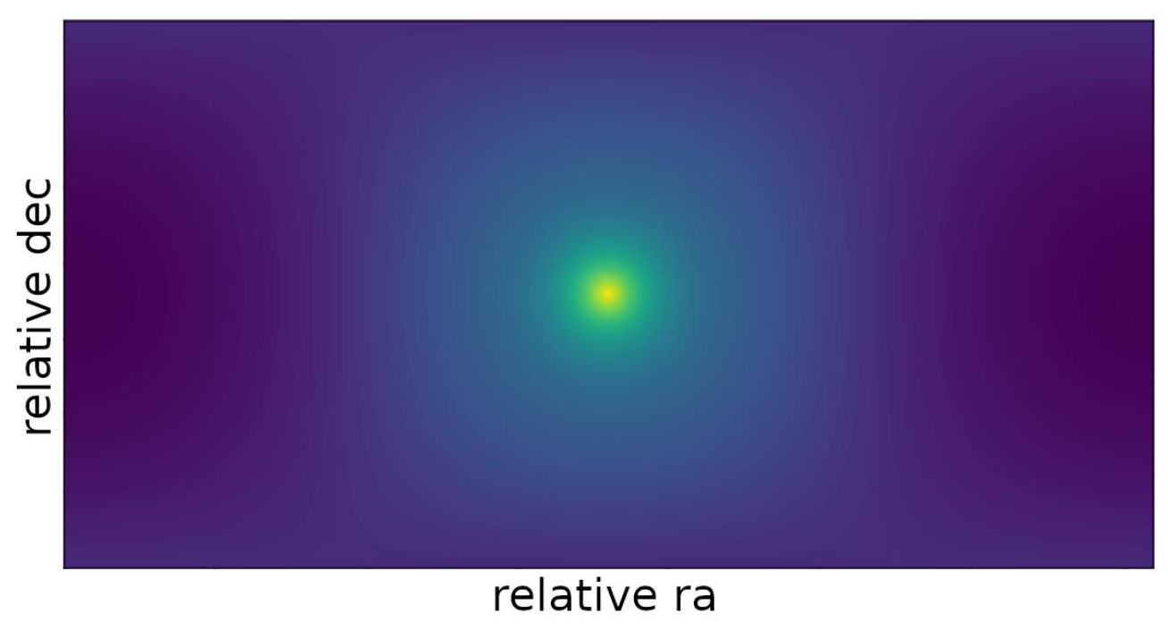
[1] https://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html

Observing the MeV gamma-ray sky with APT



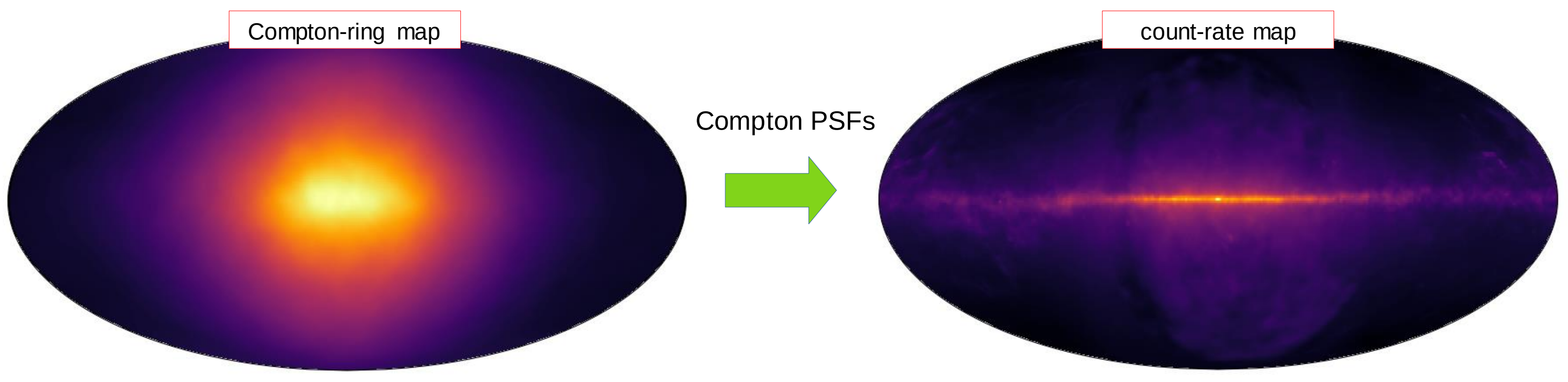


An example of a gamma-ray transient detected by a Compton telescope

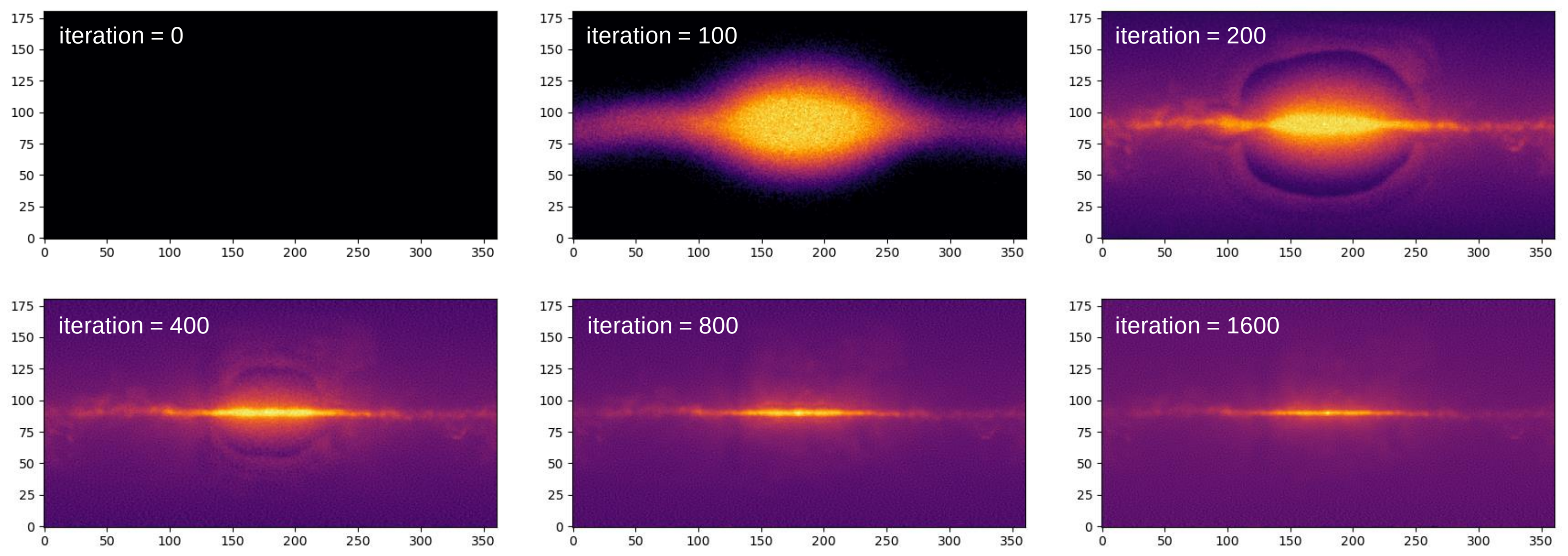


PSF in the Compton regime is global

- A single MeV gamma-ray will be detected as a Compton ring by a Compton telescope. A sky map of gamma-rays observed by a Compton telescope is a stack of many Compton rings.
- The task of reconstructing the MeV sky from APT observations is to restore the gamma-ray count rate map from the map of Compton rings, based on globally distributed point-spread functions (PSFs).



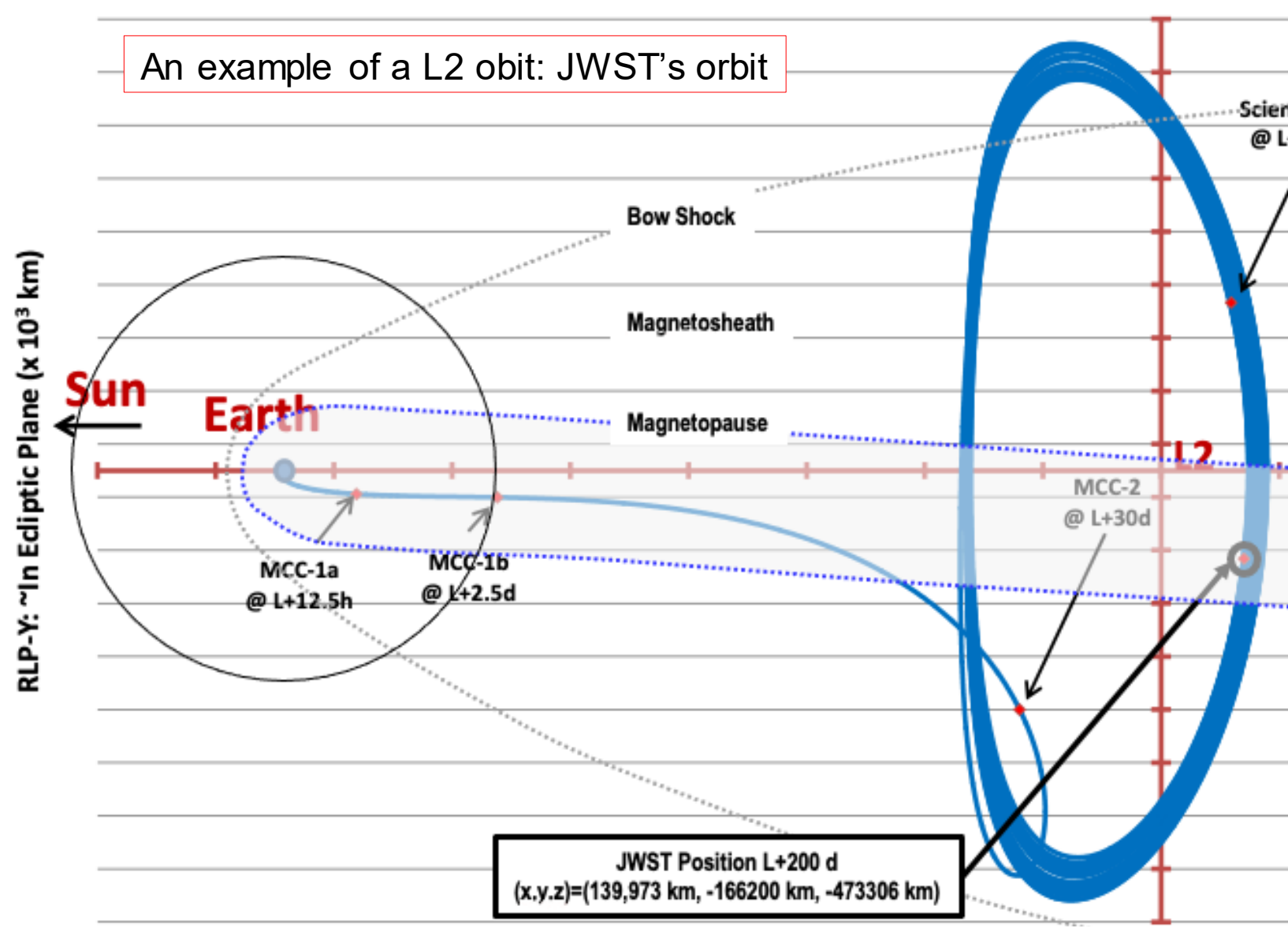
- Here we develop an iteration algorithm to restore the count rate from a Compton map. We generate a Monte Carlo sample of point-source perturbations located based on the Compton map. The perturbations, convolved with the APT PSF, will be removed from the Compton map. The residual map will serve as the probability for the new-step Monte Carlo sampling. After a large number of iteration steps, the residual map will approach a featureless noise map, while the integration of these point-source perturbations (source map) will give the predicted count-rate map. This method can reconstruct the MeV sky with a degree-level resolution.
- The example of the MeV sky reconstruction below shows the source maps at different iteration steps. The calculation is based on a simulated APT obviation with a 2-year exposure.

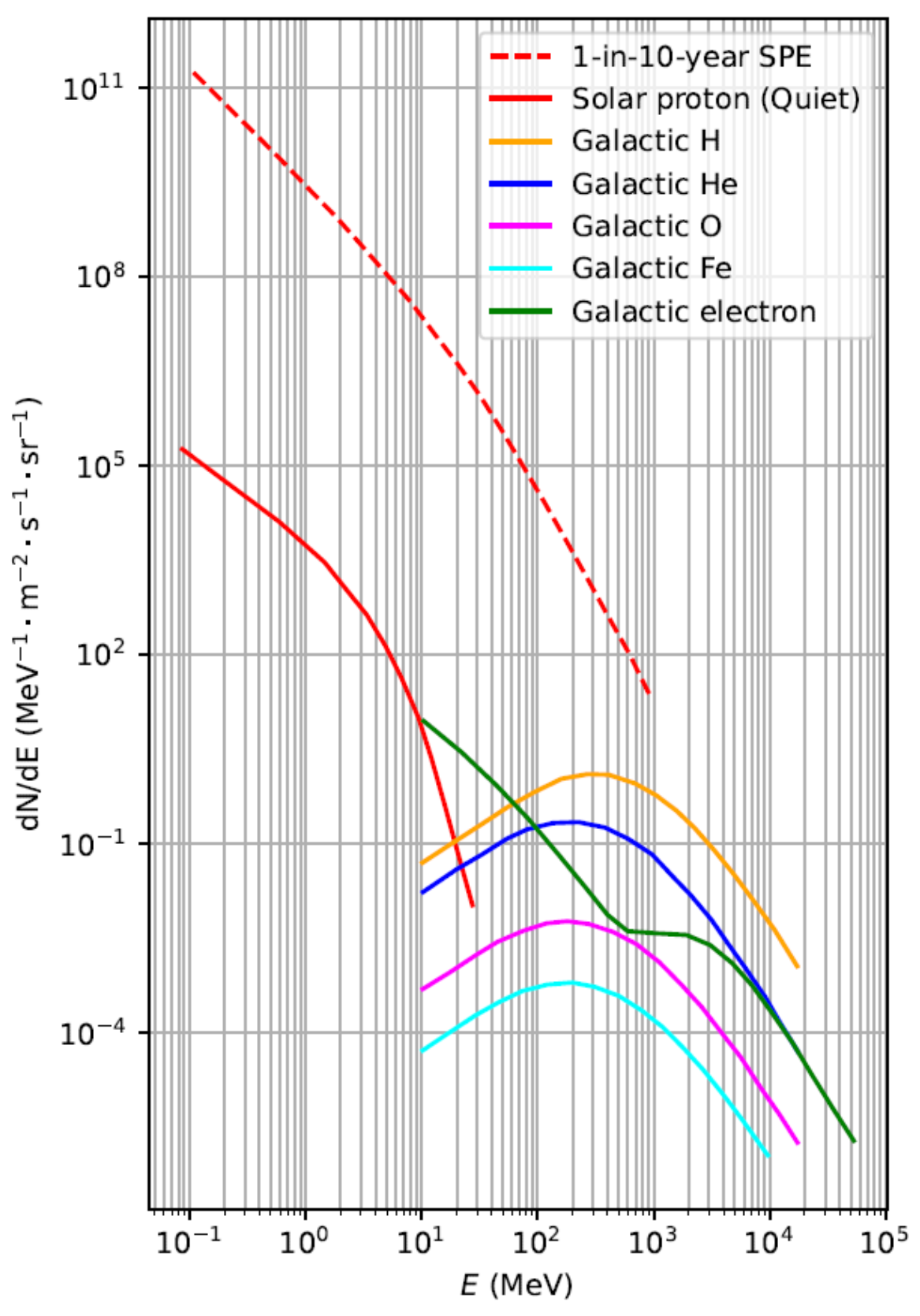


The Astro-particle Background at L2 Orbits

Background particles

- Although the sun-earth L2 point can be enclosed by the magnetotail where the particle density is much lower than that in the solar wind, L2 orbits are in general outside the magnetopause, and the MeV/GeV astro-particle background is dominated by solar particles and galactic cosmic rays (GCRs).



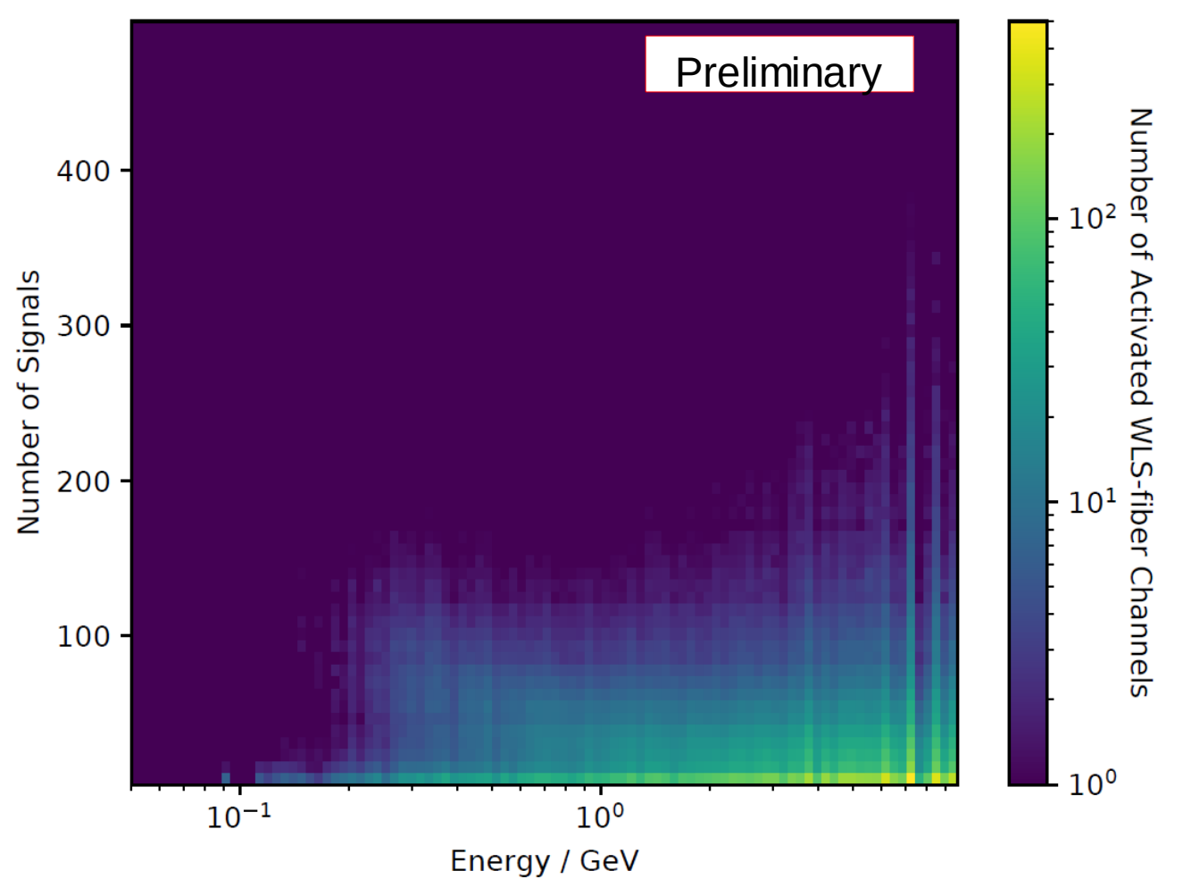


- Solar proton is the major contributor to the solar high-energy flux. Solar particle flux is sensitive to the solar activity. During a solar proton event (SPE), the high-energy particle flux at L2 will be dominated by solar protons.
- The major element of the GCR components is hydrogen, while electrons, helium, oxygen, iron and other heavy ions also contribute to the GCR flux. GCR flux at 1 AU is also dependent on the solar activity, because the solar-wind particles and fields attenuate the GCR flux in the solar system.
- The figure on the left shows the spectra of solar protons and GCRs we expect to see at L2 orbits. In this work, the ion spectra of the GCR are given by the Badhwar-O'Neill model in the solar minimum. The galactic electron and the solar quiet-time proton spectra are given by models fitted using the Ulysses and ACE data, respectively.

- **For APT observations, the advantage of L2 orbits is that it will get rid of the bright earth limb from the gamma-ray albedo. However, the L2 orbit will be heavily influenced by solar protons.**
- **To simplify the calculations, here we adopted the Fermi background model to estimate the gamma-ray emissions from Milky Way and the extragalactic sky, which is based on the Fermi-LAT detector and its low-earth-orbit observations of the gamma-ray sky. We note that the gamma-ray background observed at L2 orbits (in the presence of solar protons and GCRs) has not been modeled for the APT detector yet in this work.**

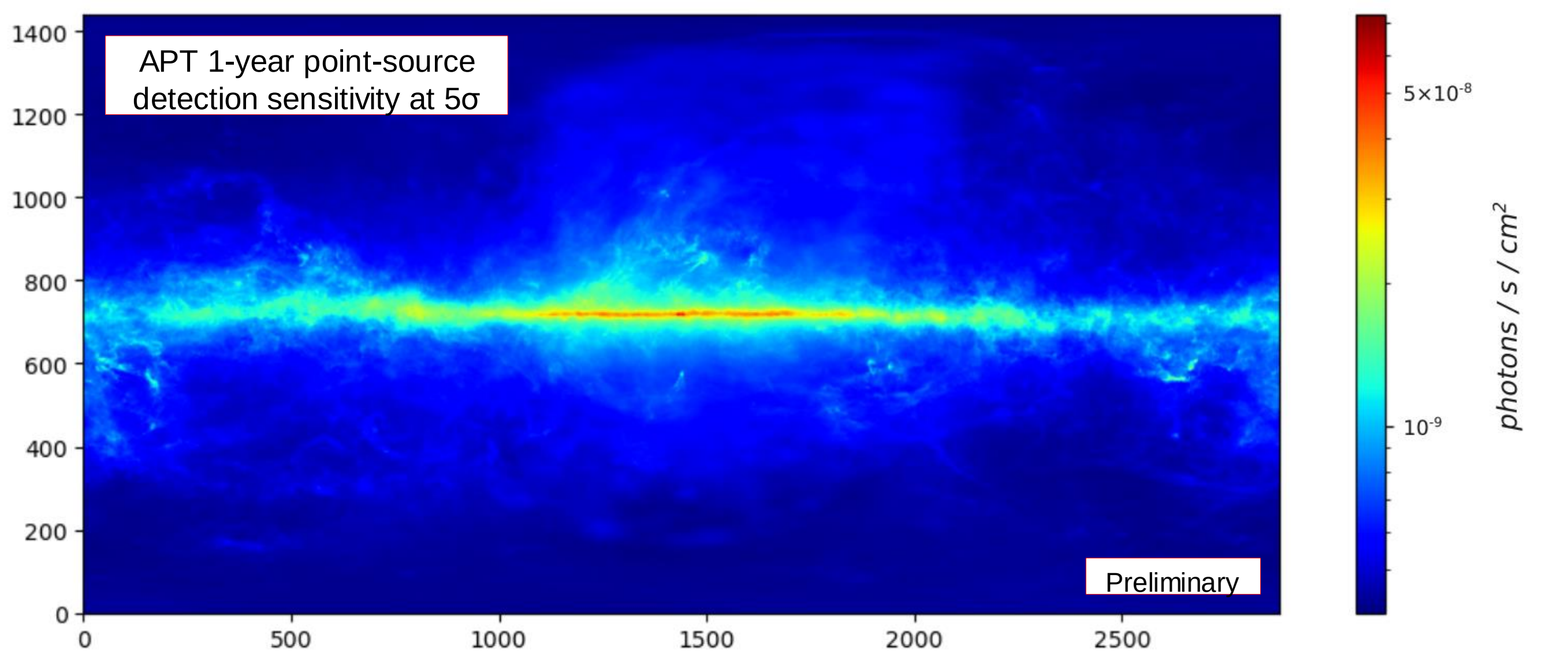
APT background rate and channel occupancy

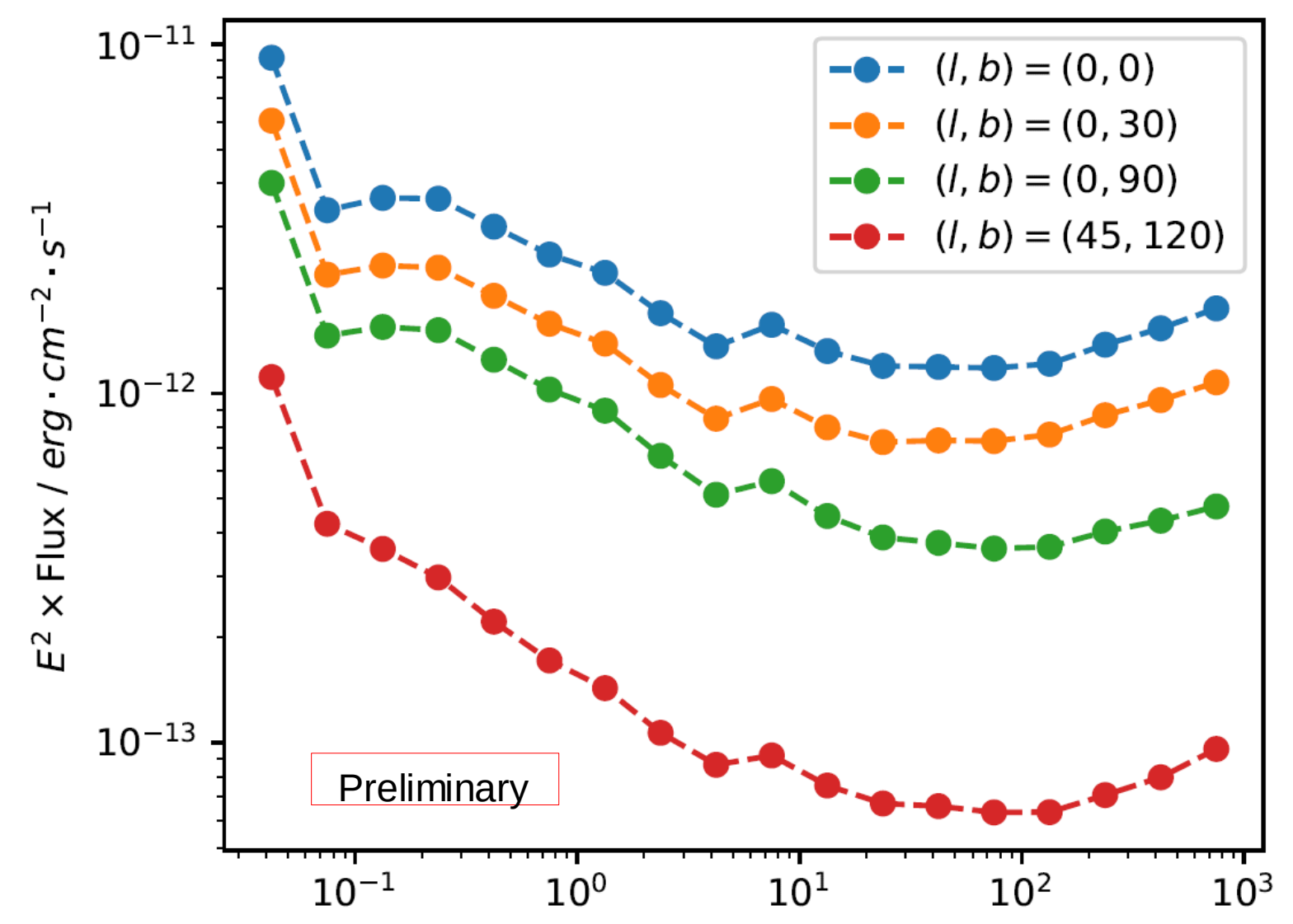
- The figure on the right shows the APT channel occupancy (averaged number of activated channels) as a function of the particle energy and the channel's signal intensity.
- The APT high-energy background count rate is dominated by the solar proton in the MeV regime. However, as shown in the figure, the detector is only sensitive to protons with energies above 10 MeV. In this energy range, GCR is the most important background source.
- Our APT background simulation gives a background event rate of 26 kHz. The background astro-particles occupied about 13% of the readout capacity.



Point-Source Detection in the Presence of the Background

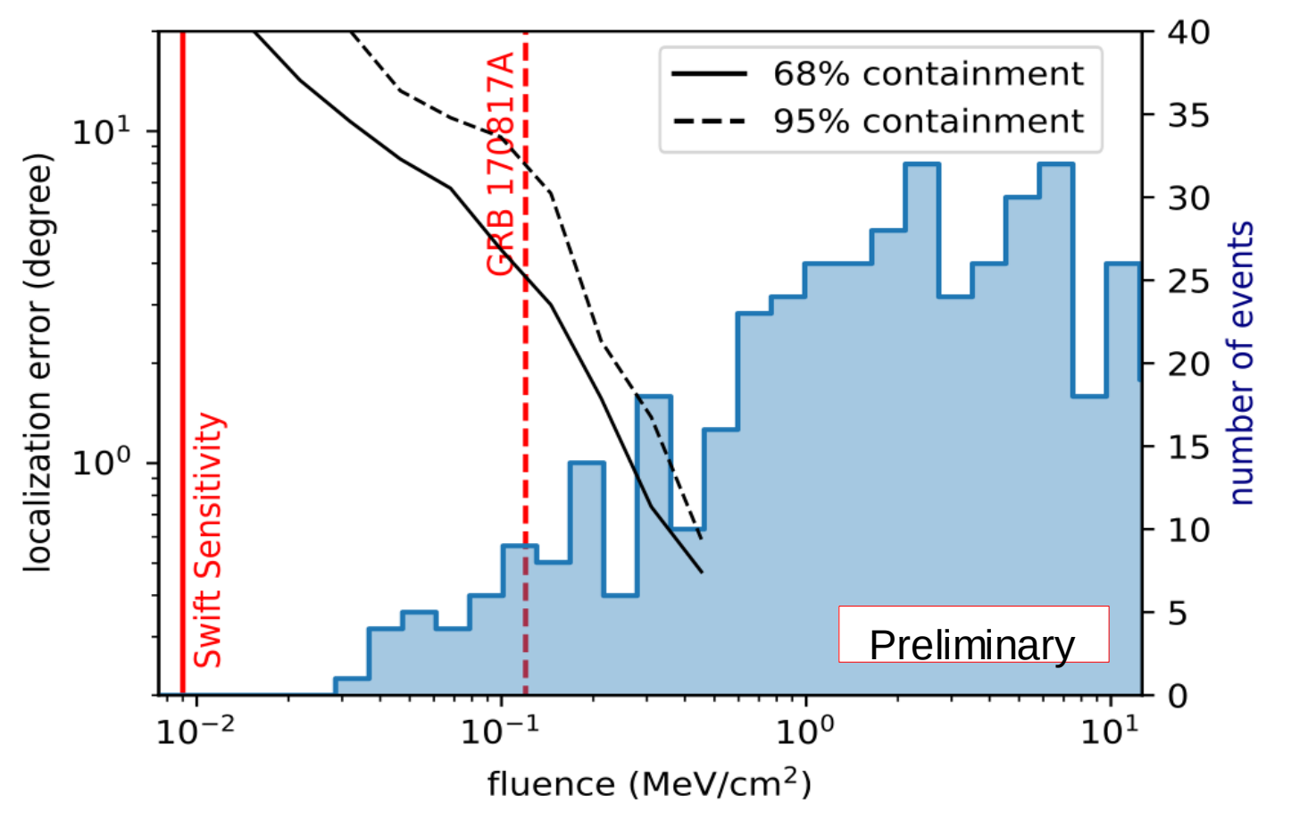
> 30 MeV Point-source sensitivity





- We estimate the point-source detection sensitivity for > 30 MeV gamma-ray sources. The calculation is based on the Fermi background model, the APT's geometric factor, and the channel occupancy from the astro-particle background.
- For the calculation, we assume the background rate is known (or can be accurately measured), and the signal-to-noise ratio of the point source is measured based on an aperture that can fully cover the APT's PSF of the source. We note that APT's geometric factor is larger than Fermi-LAT's by an order of magnitude, this is consistent with our estimated APT sensitivity.

Localization of gamma-ray bursts (GRBs)



- We simulated a number of normal-incident GRBs with spectral energy distribution based on the Band's function for a range of fluence values. As we can see, the APT can achieve a degree-level to sub-degree-level localization accuracy for gamma-ray transients down to ~ 0.1 MeV/cm^2 in the presence of the gamma-ray and astro-particle background. In the figure, the histogram shows the count rate of GRBs from the first Fermi-GBM catalog in the energy range from 10 keV to 1 MeV.

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