COSI
Gamma-ray
Space Explorer

The COSI gamma-ray telescope: Data management challenges

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on behalf of the COSI Science Team

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COSI overview

COSI
A Gamma-ray
Space Explorer

- COSI is:
  - a NASA Small Explorer satellite with a planned launch in 2027
  - a Compton telescope for observing gamma-rays in the 0.2-5 MeV energy range
- Optimized for studies of nuclear and annihilation emission lines across the Milky Way Galaxy
- Uses germanium detectors cooled to cryogenic temperatures to provide ***excellent energy resolution***
- Instantaneous field of view is ***>25%-sky*** and covers the whole sky every day

Upcoming SMEX mission operating in the energy range between NuSTAR and Fermi/LAT

Key Science Goals

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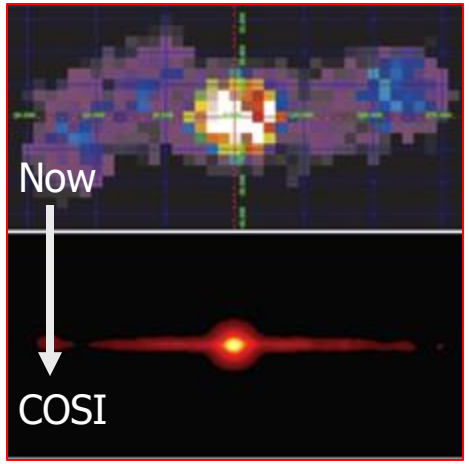
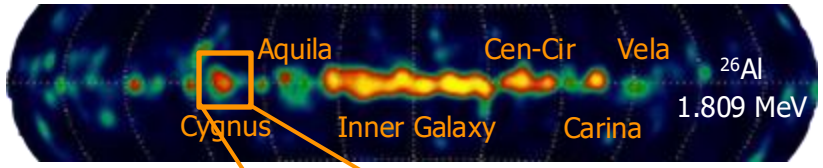
A. Uncover the Origin of Galactic Positrons

e^-e^+ @ 511 keV



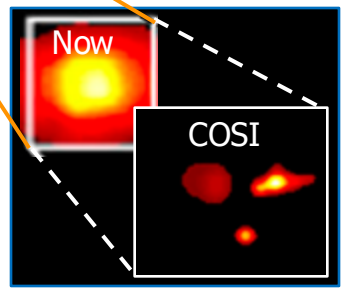
C. Gain Insight into Extreme Environments with Polarization

AGN and Galactic black holes @ 0.2-0.5 MeV



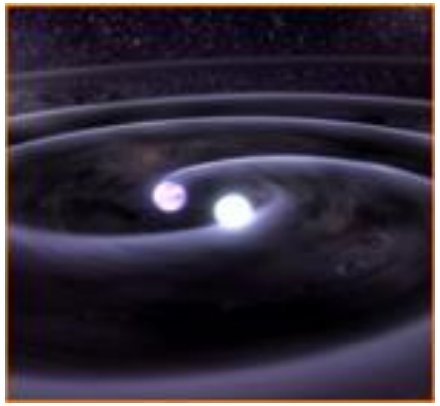
B. Reveal Galactic Element Formation

^{26}Al @ 1.809 MeV
^{60}Fe @ 1.173 and 1.333 MeV
^{44}Ti @ 1.157 MeV



D. Probe the Physics of Multimessenger Events

GRB alerts



COSI payload design and instrument concept

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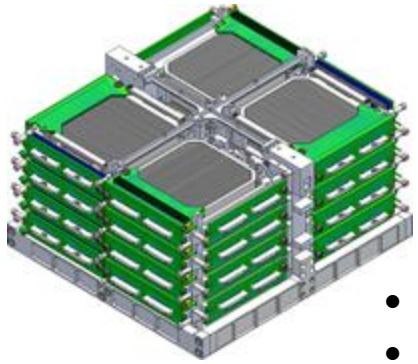
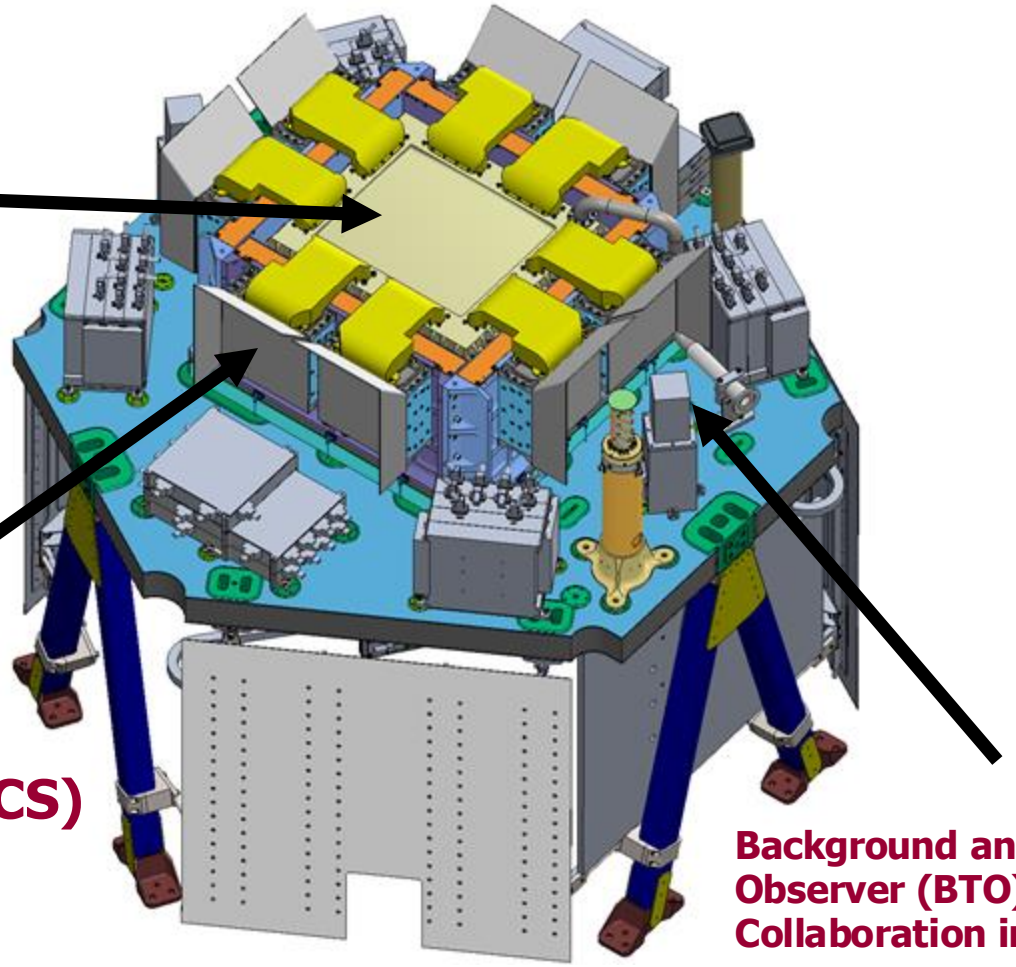
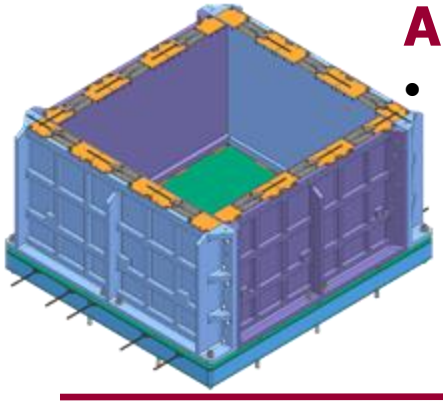


Germanium detector array

- 16 germanium detectors in a cryostat
- 0.2 - 5 MeV
- High-resolution spectroscopy
- Compton imaging
- Compton polarimetry





Anticoincidence subsystem (ACS)

- Bismuth germinate (BGO) scintillators
  - Vetoing escaping events
  - Reducing external background
  - 50 ms light curves at 80 keV - 2 MeV (for GRB alerts)
  - Light curves at >2 MeV (for monitoring background)

Background and Transient Observer (BTO) Student Collaboration instrument

- NaI scintillators
- 30 keV - 2 MeV light curves and energy spectra

COSI science modes

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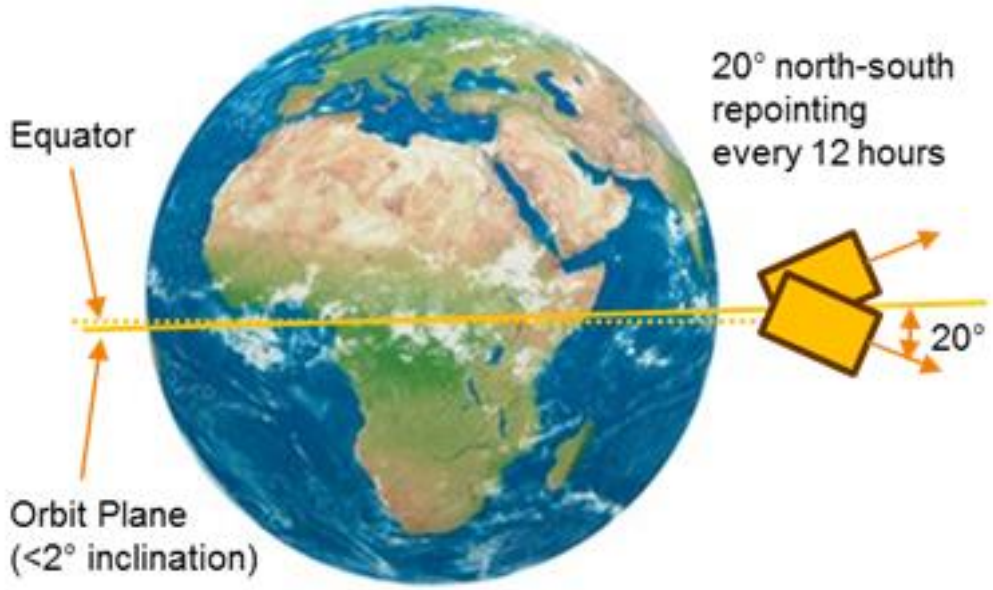
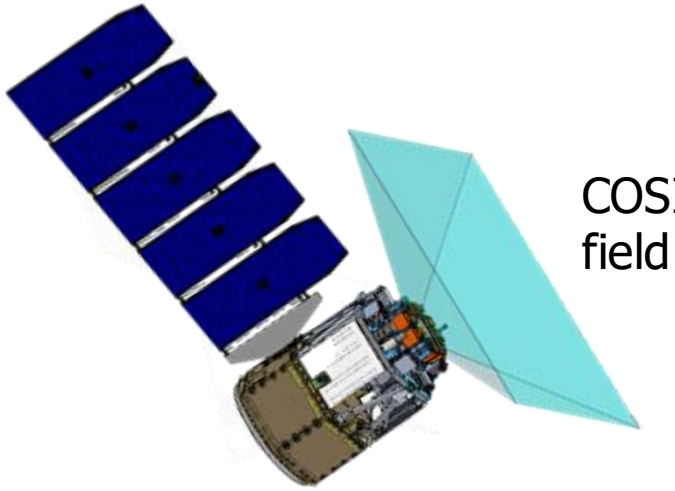
- Survey mode
  - North/South zenith offset alternating every 12 hours
  - Combined with large field of view gives daily all-sky coverage



- Constant Zenith Angle (CZA) mode
  - Targets of Opportunity for up to 15 days, commanded within 2 days



COSI's >25%-sky field of view

COSI's Science Products

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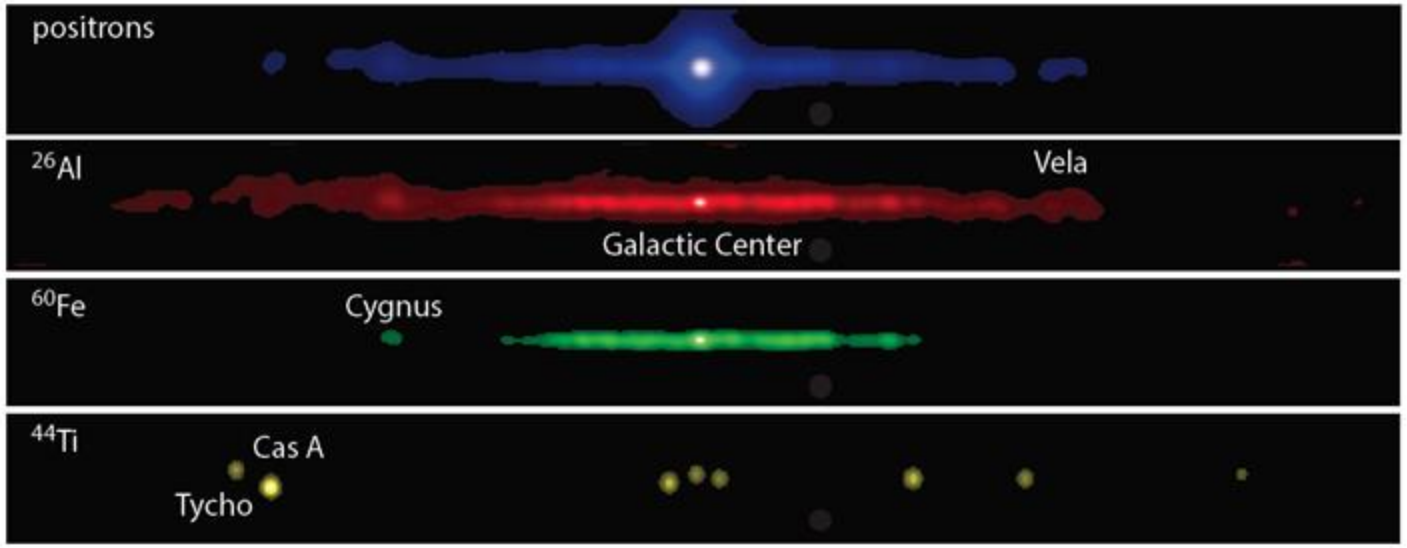
❑ All-sky emission line images

- 5 gamma-ray lines, and
  5 continuum energy bands
- Bkg-subtracted, exposure corrected
- Spectral model

Simulated COSI images of "The Radioactive Milky Way"



❑ Gamma-ray bursts and transients

- Light curves (50 ms bins) and
  event data from BGO and BTO
- Spectra, image and gamma-ray polarization from GeD data
- Reported through GCN

❑ Source studies in an underexplored energy band

- Extragalactic and Galactic persistent/flaring sources
- Spectra, light curves, images, gamma-ray polarization

COSI will host all data at HEASARC in FITS format

Why use a Compton telescope to study the MeV bandpass?

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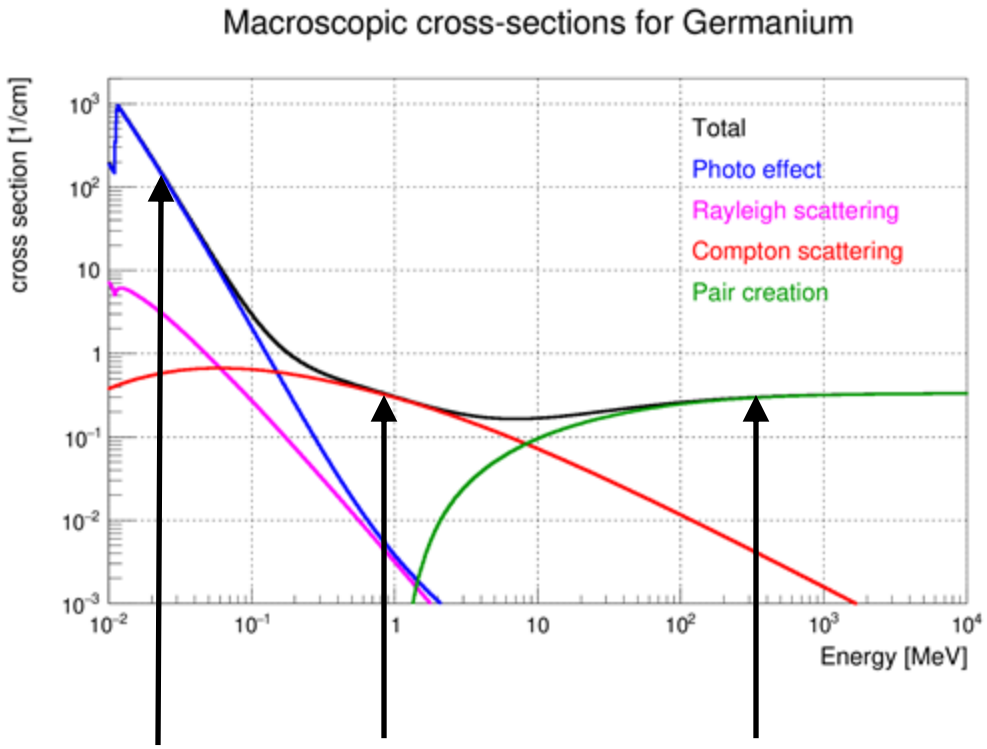
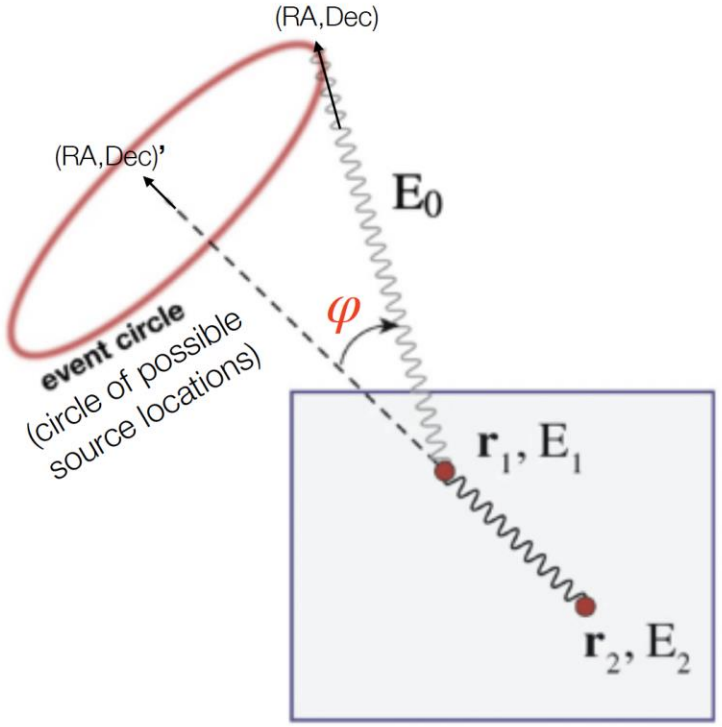


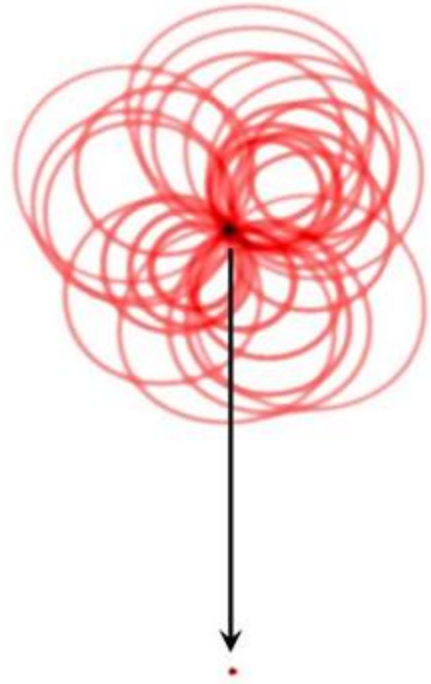
Full photon absorption (NuSTAR, etc.)

Compton telescopes (COMPTEL, **COSI**)

Pair creation telescopes (Fermi/LAT)



- Multiple interactions in the instrument
- $E_\gamma = E_1 + E_2 + \ldots$
- The gamma-ray origin is restricted to the "event circle"



Iterative deconvolution techniques produce images

The Compton Data Space

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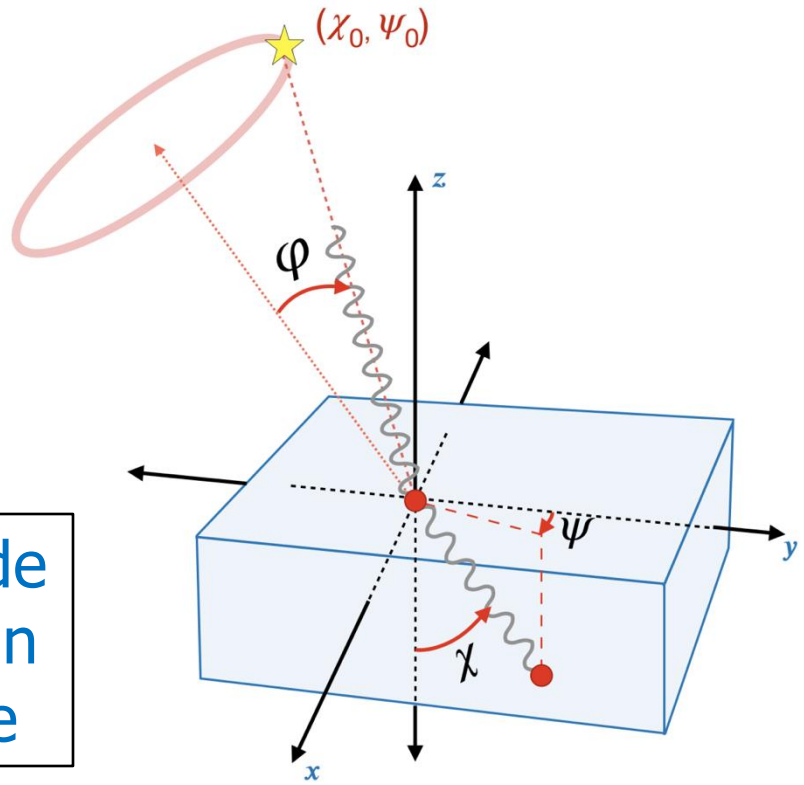
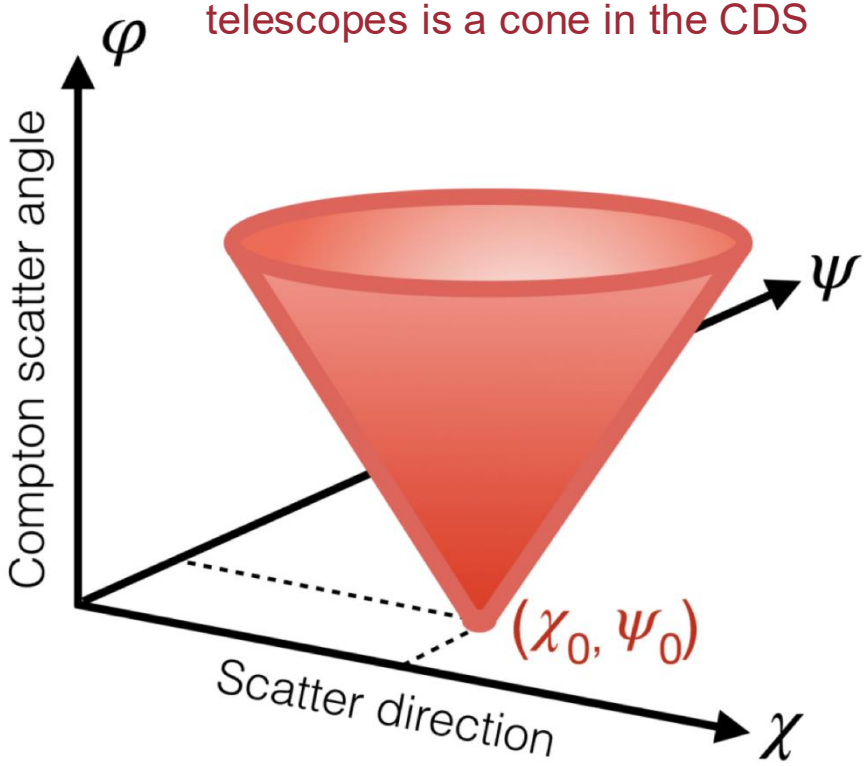
Each event measured by COSI is described by a minimum of 5 parameters:

- Measured energy (E)
- Compton scattering angle (ϕ) of first interaction
- Polar (χ) and Azimuthal (ψ) angles of scattered photon
- Event time (t)



The point spread function for Compton telescopes is a cone in the CDS



COSI is the first wide FOV, high-resolution Compton telescope

Compton Telescope Point Spread Function

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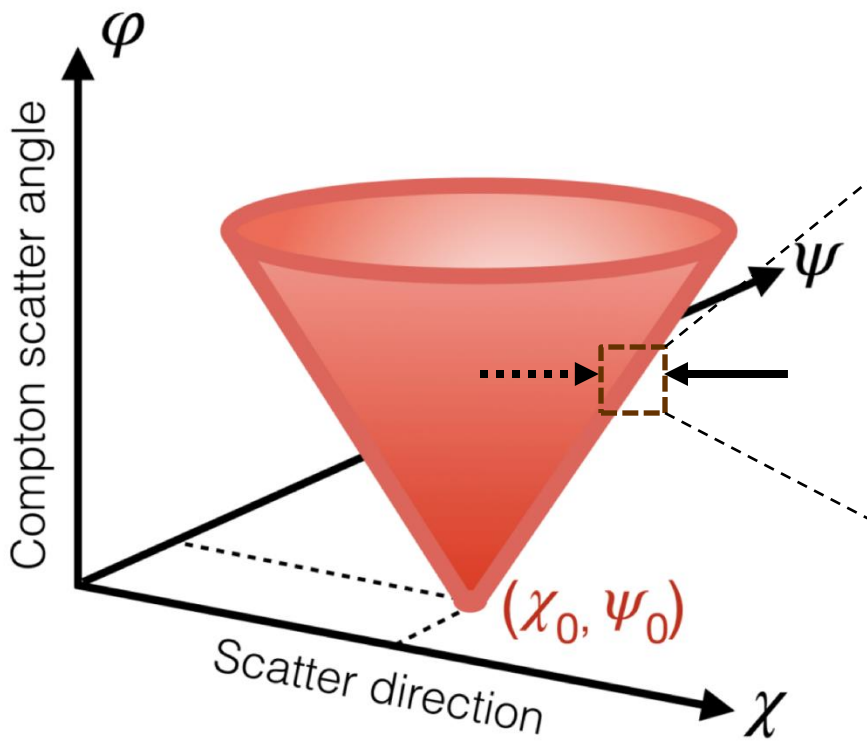
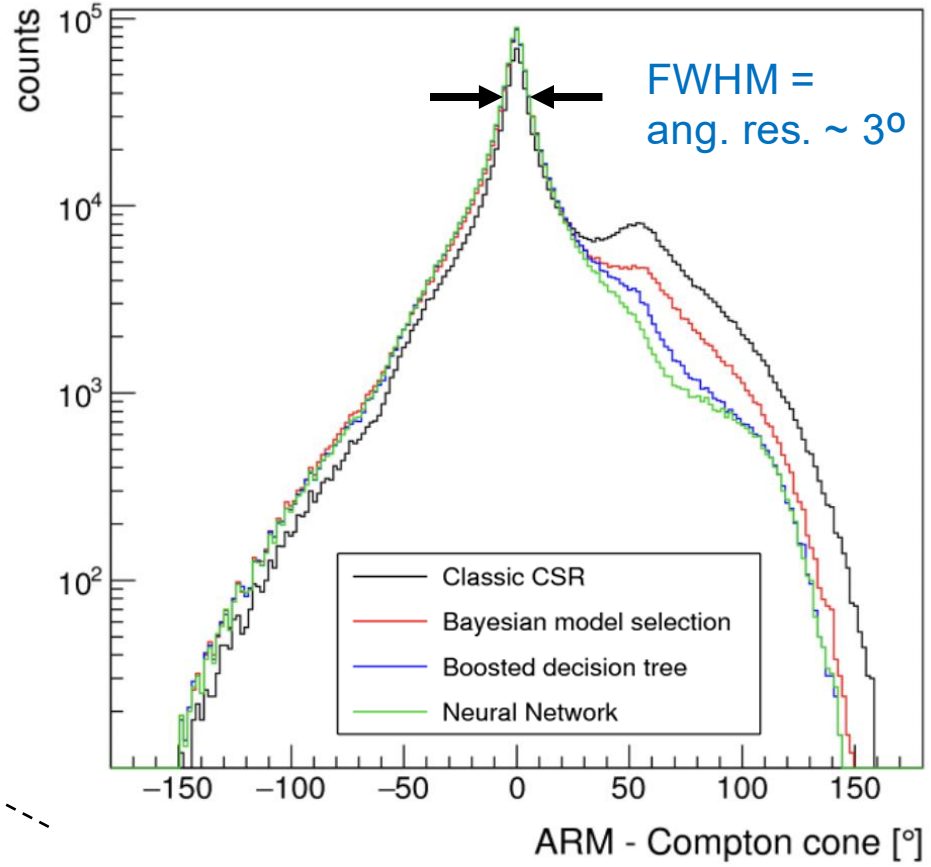
- 1D projection of the width of the cone is the ARM distribution, where the FWHM is the common definition of the angular resolution of a Compton telescope
- The ARM distribution shows significant tailing from poorly reconstructed events





The Instrument Response Function and Forward folding

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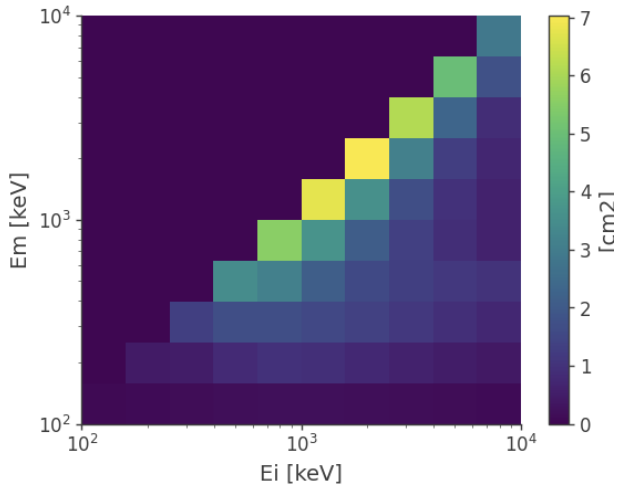
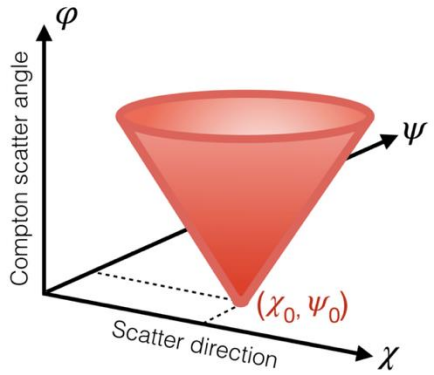
- Instrument response function
  - 7D matrix containing the effective area at given energy for given direction
  - effective area, energy dispersion, directional response, and polarization response are all coupled

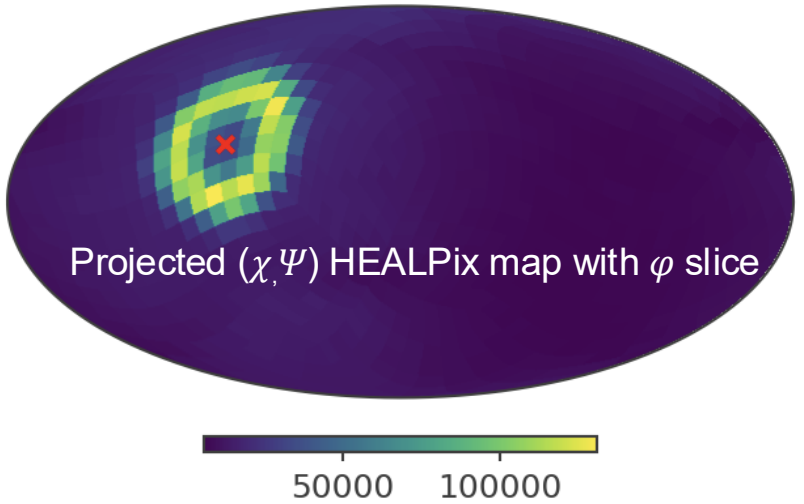
$$\left[E_{true}\ (\mathrm{RA,DEC})\right] \Leftrightarrow \left[E_{meas}\ \varphi\ (\chi, \Psi)\right]$$

Projected Energy dispersion matrix



IRF convolved with source position gives point spread function





- Poisson likelihood-based forward folding analysis

COSItools

A collection of COSI data-analysis tools, documentation, and verification data sets

25 followers Berkeley http://cosi.ssl.berkeley.edu

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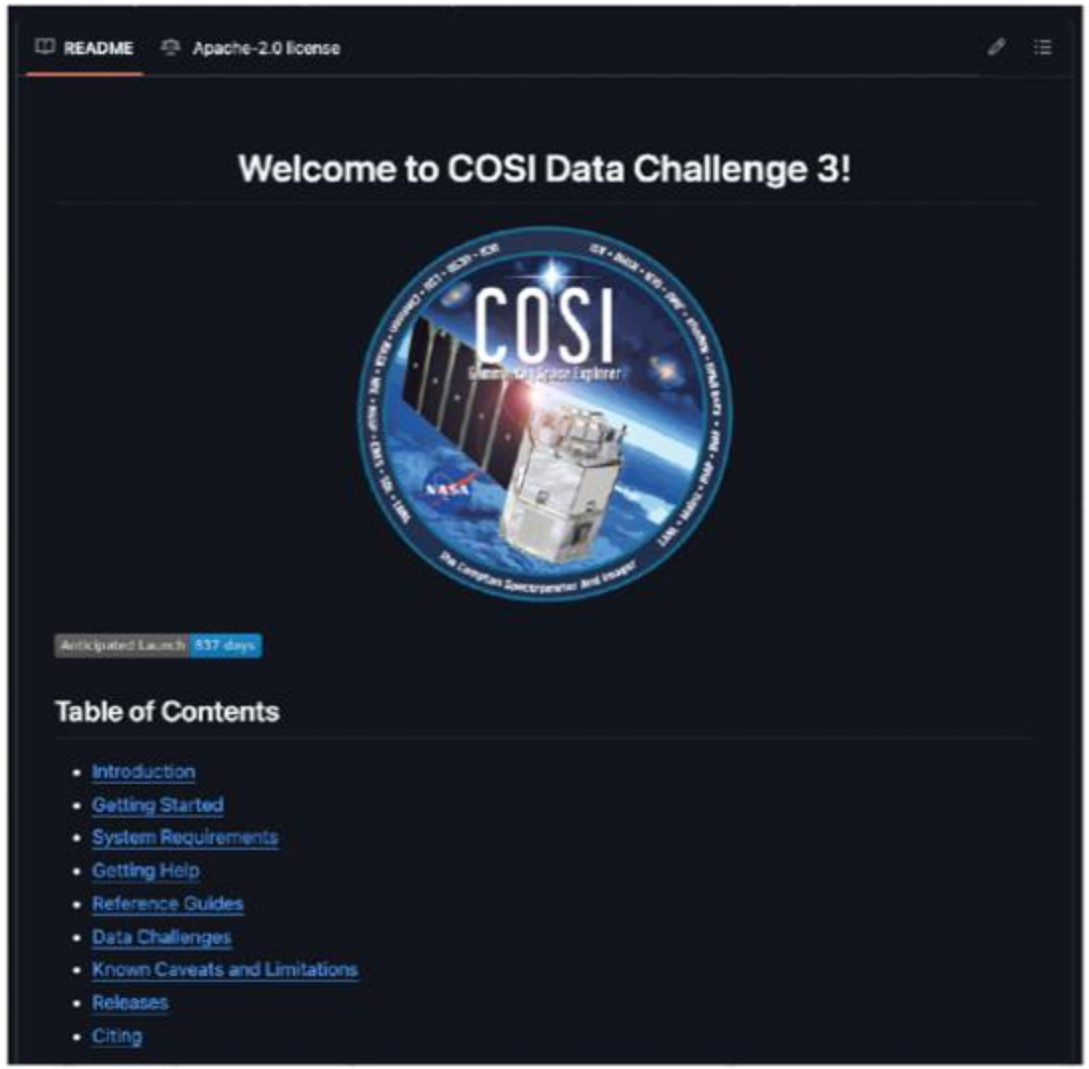
- Currently developing high-level python analysis tool **cosipy**
  - handle instrument response, bin and manipulate data, forward-folding analysis, and modeling fitting
- Dependencies:
  - Astropy
  - Astromodels to build models for likelihood analysis
  - 3ML plug-in for model fitting
  - HDF5 format for data and response files
  - mheapy for multi-resolution HEALPix images and maps
- Planning for compatibility with Gamma-ray Data Tools (GDT)

COSI Data Challenges

https://github.com/cositools/cosi-data-challenges



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- **Publicly released April 2**:
  - USA: HEAD and GR-SIG
  - Japan: Kouuren (X-ray/MeV astronomers) and Tennet (all astronomers)
  - Europe: ASTROGAM
- **Published on zenodo**
  - giving citable DOI
- **Data products**: Simulated 45 unique sources, running 75 different source simulations in total (using multiple models), 12 background components.
- **Analysis tools**: Coincides with updated alpha release of cosipy.

Are you considering data standards and aligning with IVOA?

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- I didn't know about IVOA until last May when Francesa invited me to give this presentation!

- COSI will archive flight and calibration data at HEASARC
  - Currently working with HEASARC to define L1, L2, and L3 data formats

- Will use GCN for GRB/transient alerts, as is standard in HE Astro

Virtual Observatory and High Energy Astrophysics IVOA Note (2024-11-12) doesn't have representation from MeV missions

The COSI collaboration

University of California
John Tomsick (Principal Investigator, UCB)
Steven Boggs (Deputy PI, UCSD)
Andreas Zoglauer (Project Scientist, UCB)

Naval Research Laboratory
Eric Wulf (Electronics and BGO shield lead)

Goddard Space Flight Center
Albert Shih (Cryostat Heat Removal Subsystem lead)
Carolyn Kierans (Data pipeline co-lead)

Space Dynamics Laboratory

Northrop Grumman

Institutions of Co-Investigators and Collaborators

Clemson University
Louisiana State University
Los Alamos National Laboratory
Lawrence Berkeley National Laboratory
IRAP, France
INAF and ASI, Italy
Kavli IPMU and Nagoya University, Japan
JMU/Wuerzburg and JGU/Mainz, Germany
NTHU, Taiwan
University of Hertfordshire, UK
Centre for Space Research, North-West University, South Africa
Deutsches Elektronen Synchrotron (DESY), Germany
LAPTh-CNRS, France
Yale University
Michigan Technical University
Washington University, St. Louis
Marshall Space Flight Center
Boston University
IAA-CSIC, Spain
Stanford University

Conclusions

COSI, launching in 2027, will be the first high-resolution Compton telescope

Currently working with HEASARC to define L1 and L2 data formats

Planning to coordinate with IVOA HE and Time Domain WGs going forward!

Data Formats

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- L1a – Raw data with interactions defined by triggered strip numbers, detector ID, timing, ADC:

  [Time, Event Type, NumStripHits, Hit Type, Det ID, Side ID, Strip ID, DT, ADC, TAC]

- L1b – Calibrated hits, with events defined by location (x,y,z) of interactions and energy deposits, in an ordered sequence:

  [Time, Event Type, Event Classification, NumInter, Hit_X, Hit_Y, Hit_Z, Hit_x_err, Hit_y_err, Hit_z_err, Hit_E, Hit_E_err, Sequence, TestStat, RecoilDir, RecoilDir_err]

- L2 – Filtered L1b data for science analysis

The COSI Analysis Pipeline - COSItools

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Calibration:
- convert instrument parameters (ADC, timing) to physical parameters (energy and position)

➔ Level 2: event lists

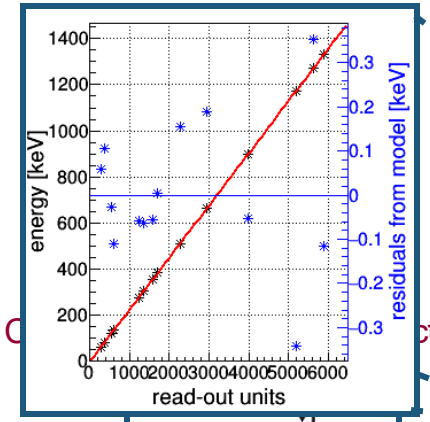
Reconstruction:
- determine sequence of interactions and calculate initial photon energy and direction

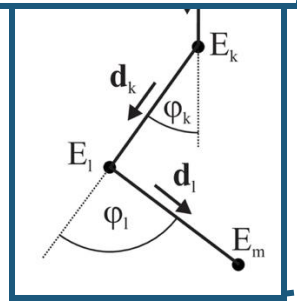
➔ Level 3: photon lists

High-level Analysis:
- image reconstruction, spectral fitting, polarization

➔ Level 4: science results!

ADC -> Energy Calibration





Spectral analysis of Crab