COSI – the Compton Spectrometer and Imager

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On behalf of the COSI Team

Part 1: COSI overview

COSI overview

COSI is:

- ***a NASA Small Explorer satellite with a planned launch in 2027***
- a Compton telescope for observing ***0.2-5 MeV gamma-rays***

Key capabilities:

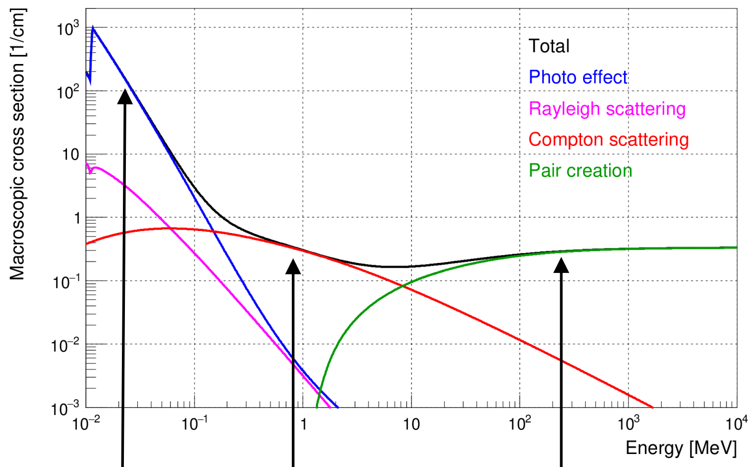
- Uses cryogenically-cooled ***germanium*** cross-strip detectors to provide ***excellent energy resolution***
- Instantaneous field of view is ***>25%-sky*** and covers the whole sky every day

Core science:

- The COSI science goals ***advance our understanding of creation and destruction of matter*** in our Galaxy and beyond

COSI's operating principle

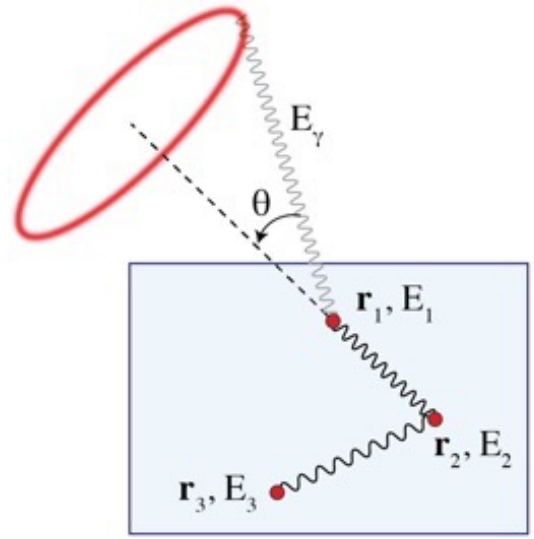
Cross sections for germanium

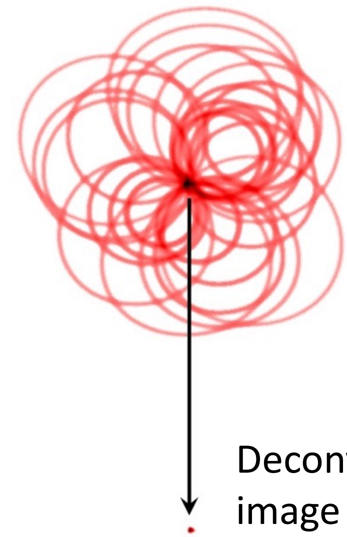


Full photon absorption (NuSTAR, etc.)

Pair creation telescopes (Fermi/LAT, AGILE, etc.)

Compton scattering telescopes (COMPTEL, **COSI**)





Deconvolved image of a point source

- Multiple interactions in the detector
- $E_\gamma = E_1 + E_2 + E_3 + \ldots$
- The photon is localized to an "event circle"

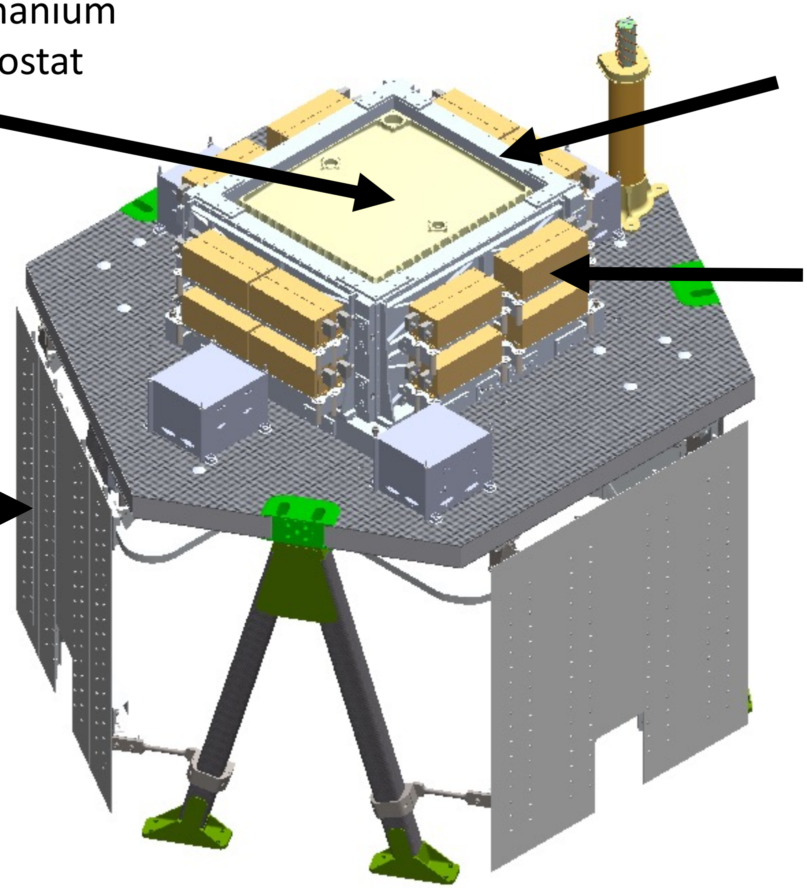
COSI instrument and payload overview

Cryogenically cooled germanium detectors in a vacuum cryostat

Active BGO shields for background reduction

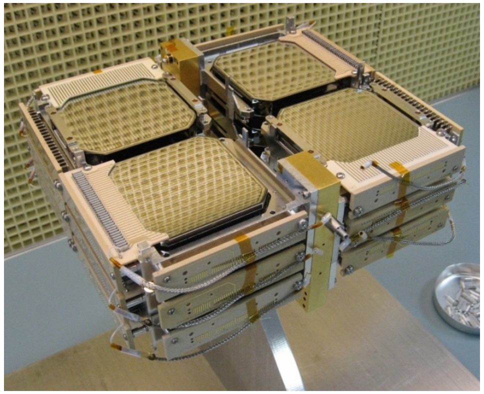
Front-end electronics with ASIC readout

Heat removed by system of heat pipes and radiators



COSI instrument/payload

Scale: payload interface plate is 1 meter flat-to-flat

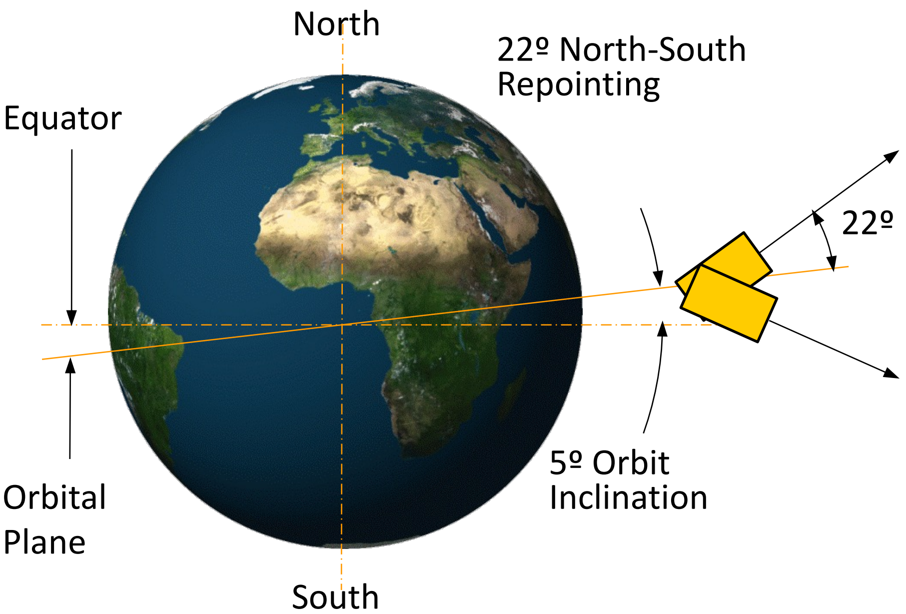


COSI sensors and readout were developed under NASA's APRA program.

For more details on the COSI mission, see Tomsick et al. 2021 (arXiv:2109.10403)

COSI orbit and operations for daily all-sky coverage

- ❑ Near-equatorial orbit to minimize South Atlantic Anomaly (SAA) passages



- ❑ Instantaneous >25%-sky field of view (FOV) and North-South repointing every 12 hours to cover the whole sky every day
- ❑ Large FOV needed for:
  - Generating all-sky images with an as even exposure as possible
  - Catching GRBs (localizations and polarization measurements)

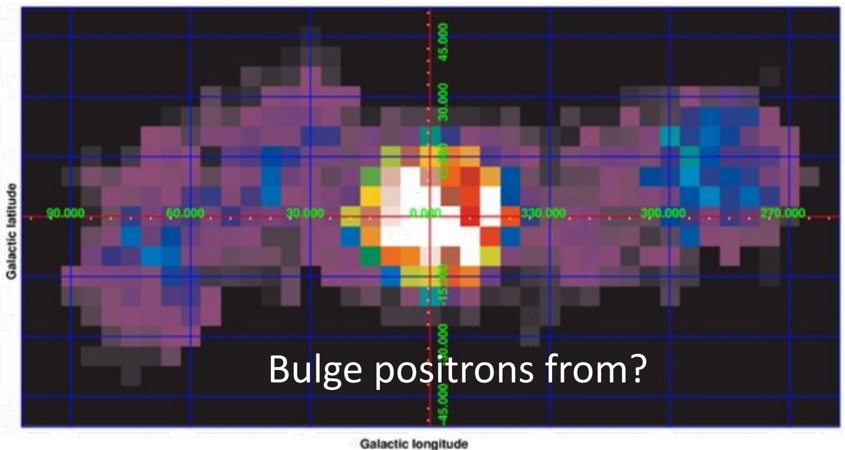
Science opportunities in the MeV bandpass

COSI
Gamma-ray Space Explorer

Signals and sources in the COSI energy range (0.2-5 MeV):

- e^-e^+ annihilation line at 511 keV →
- Gamma-ray lines from nucleosynthesis
- Accreting black holes and gamma-ray bursts (GRBs)
- Multi-messenger sources
  - Merging neutron stars
  - High-energy neutrino sources

INTEGRAL/SPI (Bouchet+10)



Is the 511 keV Galactic bulge excess:

- Truly diffuse?
- Made up of individual sources?
- How many sources or components?

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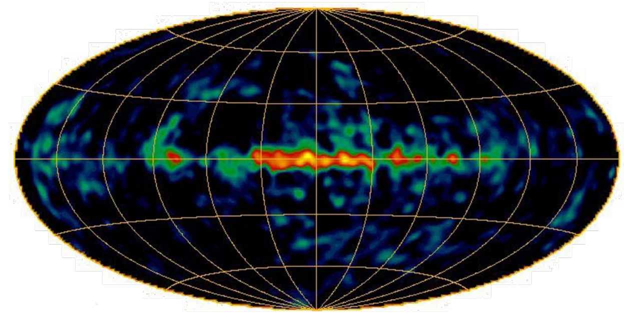

COMPTEL map of ^{26}Al emission (Oberlack+97)

Three windows on element formation associated with massive star evolution:

- ❑ ^{26}Al (1.809 MeV) traces massive stars, including **pre-supernova** (SN)
- ❑ ^{44}Ti (1.157 MeV) traces **recent** SN activity
- ❑ ^{60}Fe (1.173/1.333 MeV) traces SN activity over **the past few million years**

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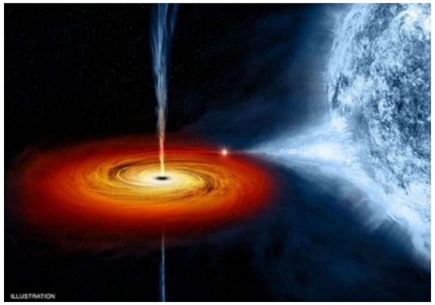
Potential high levels of polarization:

- ~70% above 0.4 MeV for Cygnus X-1 (Laurent+11; Jourdain+12)
- Similar for other Galactic black holes?
- GRB emission mechanisms and geometries?
- AGN?



Cygnus X-1

AGN: Cen A

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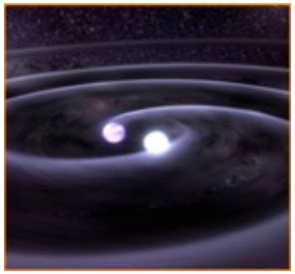


- Coincidence:
  - GW signature (GW170817)
  - Short GRB
- More please

- Coincidence:
  - IceCube-170922A
  - TXS 0506+056 (gamma-ray-flaring blazar)
- What fraction of HE neutrinos can be explained by blazars?

Part 2: Calibration overview

COSI calibration overview

Ultimate calibration goal:

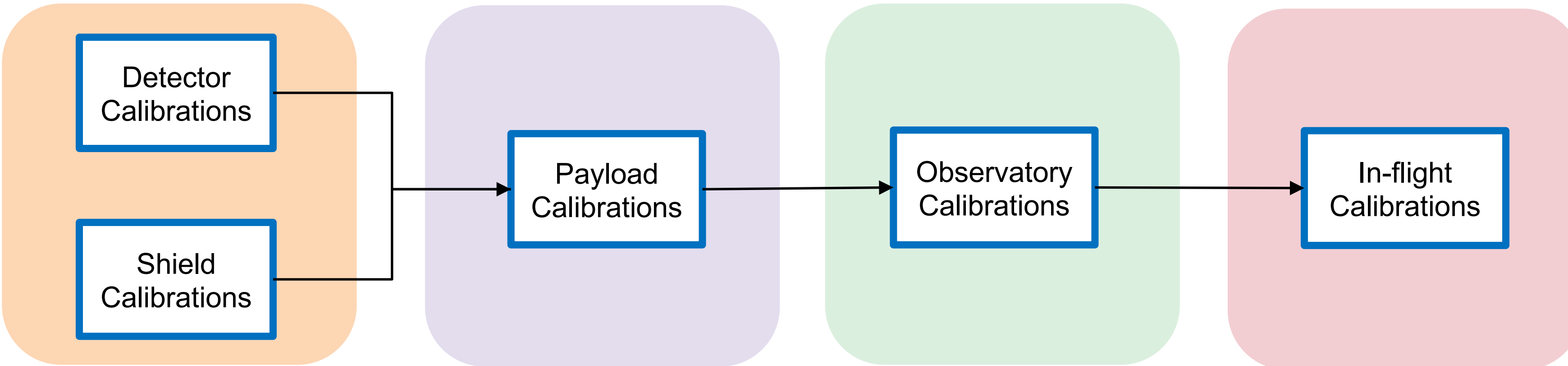
- Use calibrations to benchmark simulations (cosima/Geant4)
- Use simulations to create the instrument response
- Use response for science analysis

Key challenges:

- Complex, not-separable data space requires a combined spatial-spectral-polarization response (reason: Compton scattering)
  - Response can only be created with simulations (using NASA's supercomputer) which are well-benchmarked against calibrations
- Need to be able to combine 2+ years of mission data
  - Constant monitoring of instrument response in space and handling of any changes in the analysis pipeline
- Each event has its individual angular resolution
  - Influenced by energy and position uncertainty, number of interactions, distance between interactions, Compton scatter angle, Doppler broadening, etc.
  - Requires detailed knowledge of instrument response as a function of many parameters and several very long calibrations: $O(10^7)$ photo peak events

COSI's 4 phases of calibration

COSI
Gamma-ray
Space Explorer



- **Step 1: Sensor Calibrations:** Calibrate all effects intrinsic to individual detectors
- **Step 2: Payload Calibrations:** Calibrate the performance parameters of the telescope in Compton mode (energy & angular resolution, efficiency)
- **Step 3: Observatory Calibratiions:** Calibrate the effects the whole space craft has on performance parameters (shield leakage, scatters, etc.)
- **Step 4: In-flight Calibrations:** Use the Crab and activation lines to monitor/correct instrument response

- The calibrations in the different phases of the integration allow us to fully understand the instrument effects introduced at each phase.

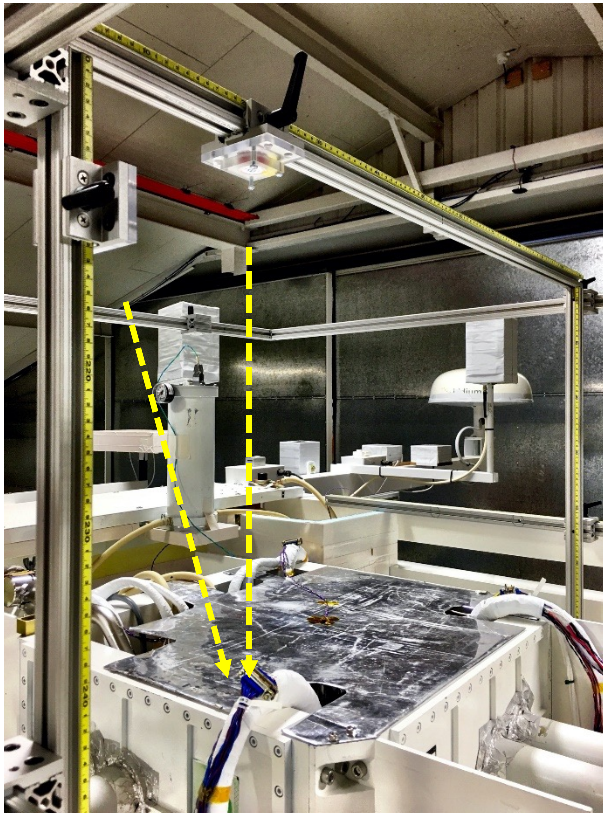
COSI ground calibrations (steps 1-3)

- Sensor, payload & observatory calibrations use sealed radioactive sources (~0.1 mCi)
- Use well-known and reproducible source positions covering 4π
- All ground calibrations are based on COSI-balloon experience (Beechert+ 2022)

7 sources sample single strip dynamic range

^{241}Am/Be measures upper-end of Compton response

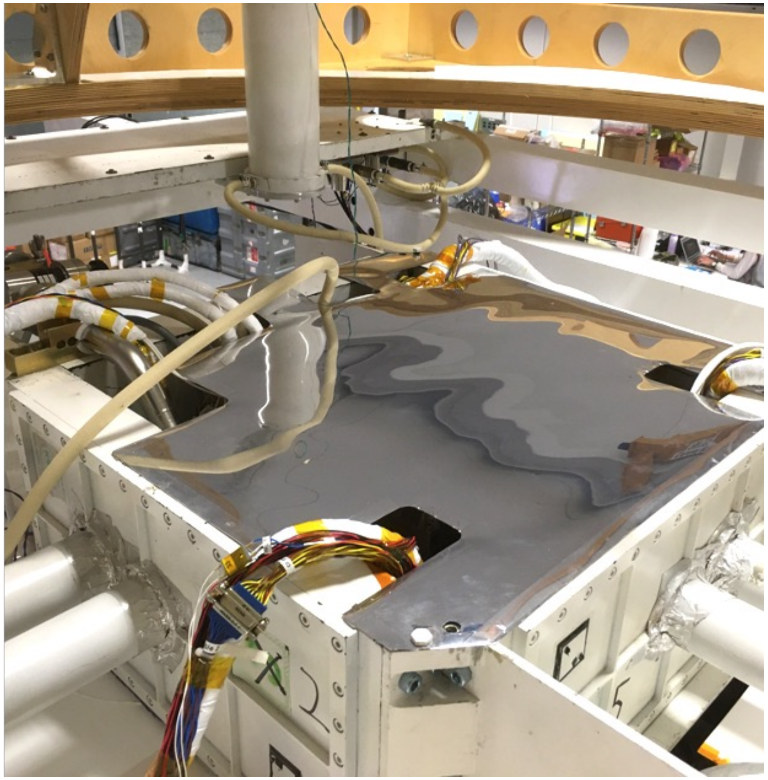
Source	Line energy (keV)
^{241}Am	60
^{57}Co	122, 136
^{133}Ba	81, 276, 303, 356, 384
^{22}Na	511, 1274
^{137}Cs	662
^{88}Y	898, 1836
^{60}Co	1173, 1333
^{241}Am/Be	4400



COSI-balloon calibration

COSI sensor level calibrations (step 1/4)

- Measurements for calibration-parameter generation for individual detector and shield modules
  - Germanium: Energy calibration, depth calibration, cross talk, charge loss, charge trapping, etc.
  - BGO shield: Trigger efficiency as a function location
- Confirm detector performance meets mission requirements
  - Select best detectors for space mission
- First data sets to benchmark simulations to calibrations


COSI-balloon calibration

COSI payload level calibration (step 2/4)

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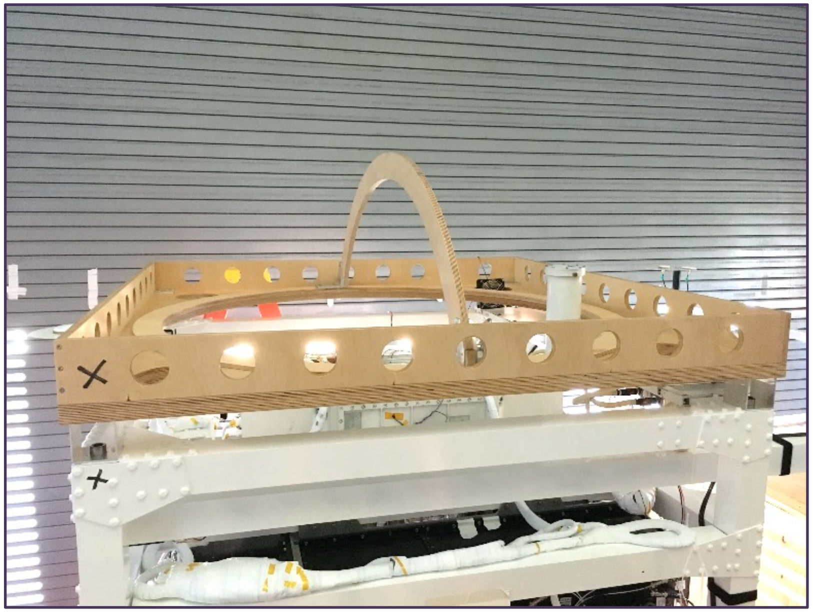
Gamma-ray
Space Explorer

- Repeat step 1: calibration-parameter generation
- Measurements to determine performance
  - Effective area, energy resolution of Compton events, angular resolution, polarization, trigger rates, thresholds, etc.
- Repeatable source placement relative to payload
  - Measuring Compton performance across the full FOV with several tens of source positions and energies from 60 keV to 4.4 MeV
  - Partially-polarized source created via scattering (see Lowell+ 2017)
- Data is again used to benchmark simulations

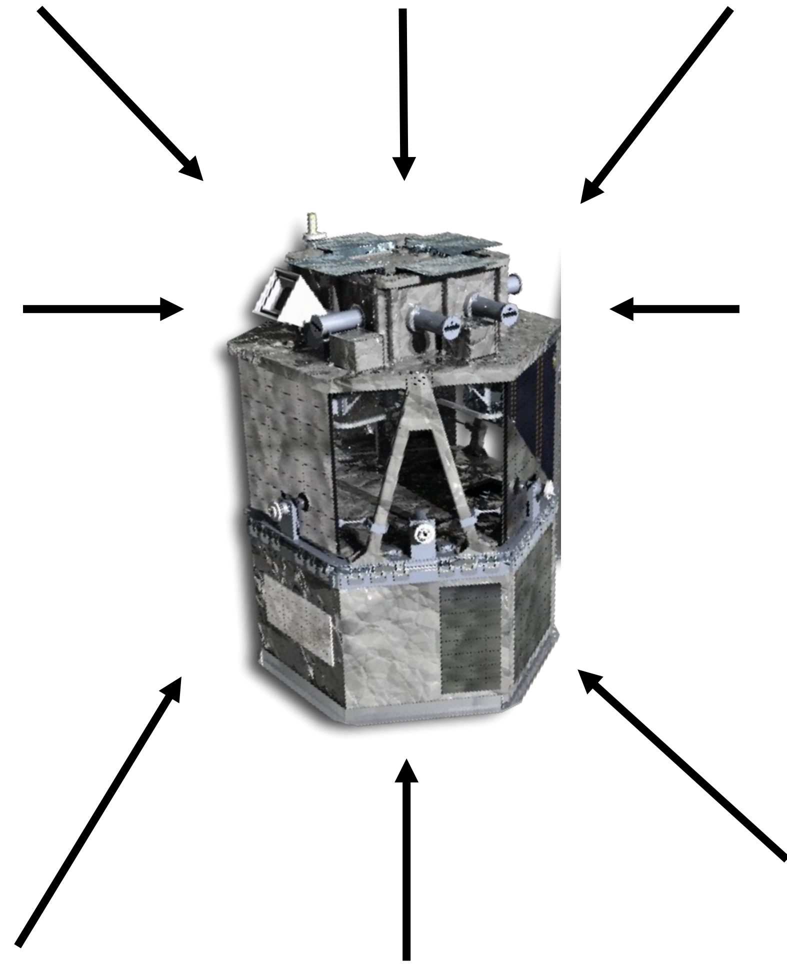


COSI-APRA Calibration:

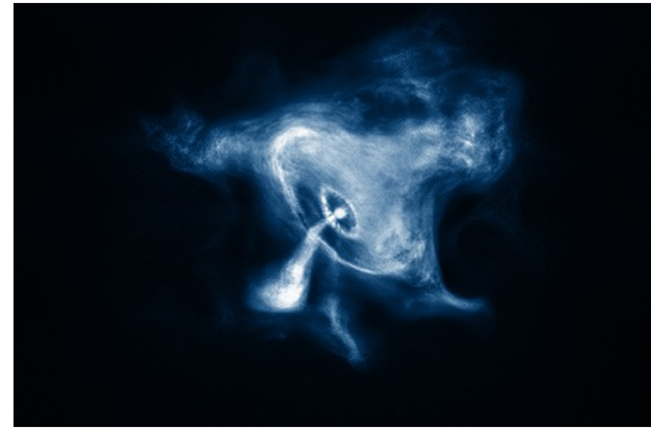
Wooden half-circle structure for COSI 2020 calibration

COSI observatory level calibration (step 3/4)

- Repeat step 1: calibration-parameter generation
- Measurements to determine observatory performance
  - Subset of payload calibration for a direct comparison of the effects of the spacecraft
  - In addition, select source paths through spacecraft and shield to evaluate shield-leakage, space craft scatters & absorption, etc.
- Data is again used to benchmark simulations
- Benchmarked simulations used to create pre-flight response



COSI in-flight calibration (step 4/4)



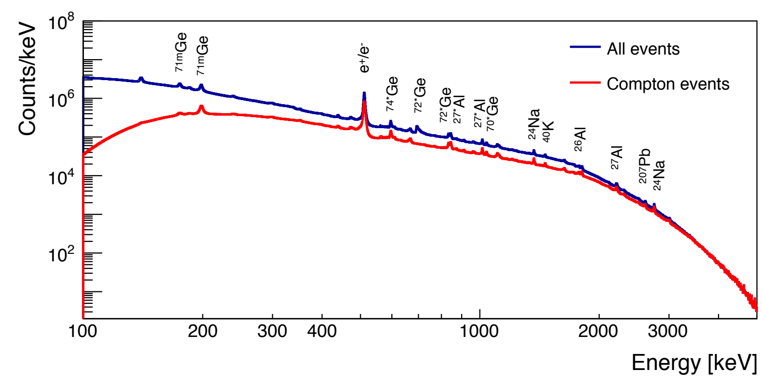
Crab - Chandra

❑ Crab observations

- Initially 6 Crab pointings at different off-axis angles during the first 6 months to check angular resolution and efficiency as a function of field-of-view
  - Each pointing is 12 hours to provide required SNR (>20) at multiple energies
- In addition, Crab is in the field-of-view every day for further calibration stability checks

❑ Activation lines

- 511 keV and other instrumental background lines can be used to monitor spectral response for gain shifts and radiation damage



COSI-balloon measured spectrum with identified nuclear lines (Kierans 2018)

➢ Any changes in the measured energy or position resolutions during flight can be monitored and included in the response

COSI
Gamma-ray
Space Explorer

COSI yearly data challenges

Goal:

Perform yearly data challenges with increasingly realistic source and background models analyzed with increasingly complete & matured analysis tools. Culminating in Data Challenge 5 in 2026 before launch.

Data Challenge 1:

https://github.com/cositools/cosi-data-challenge-1

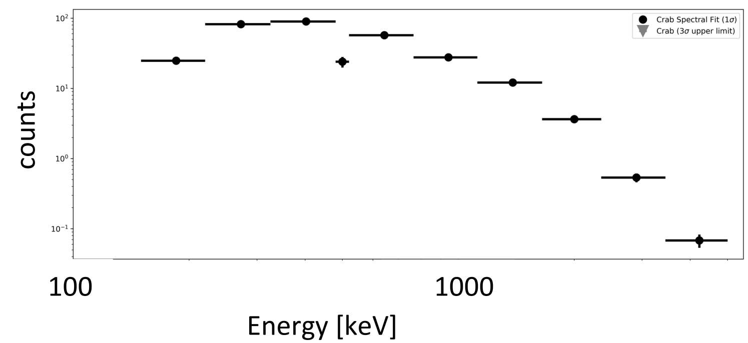
- ❑ Snapshot of current development
- ❑ COSI-balloon using balloon background & atmosphere

Data Challenge 2 (Fall 2023):

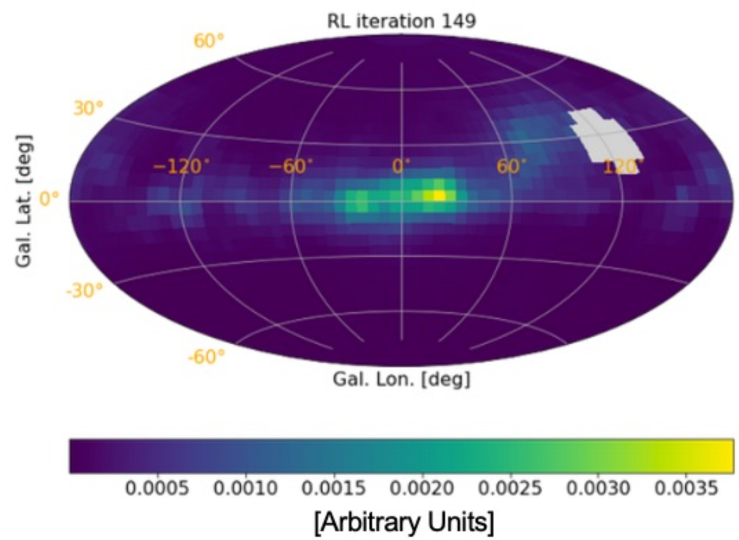
- ❑ 3-6 months of simulated satellite observations
- ❑ Updated analysis tools, simplified mass model and detector effects

Data Challenge 1:

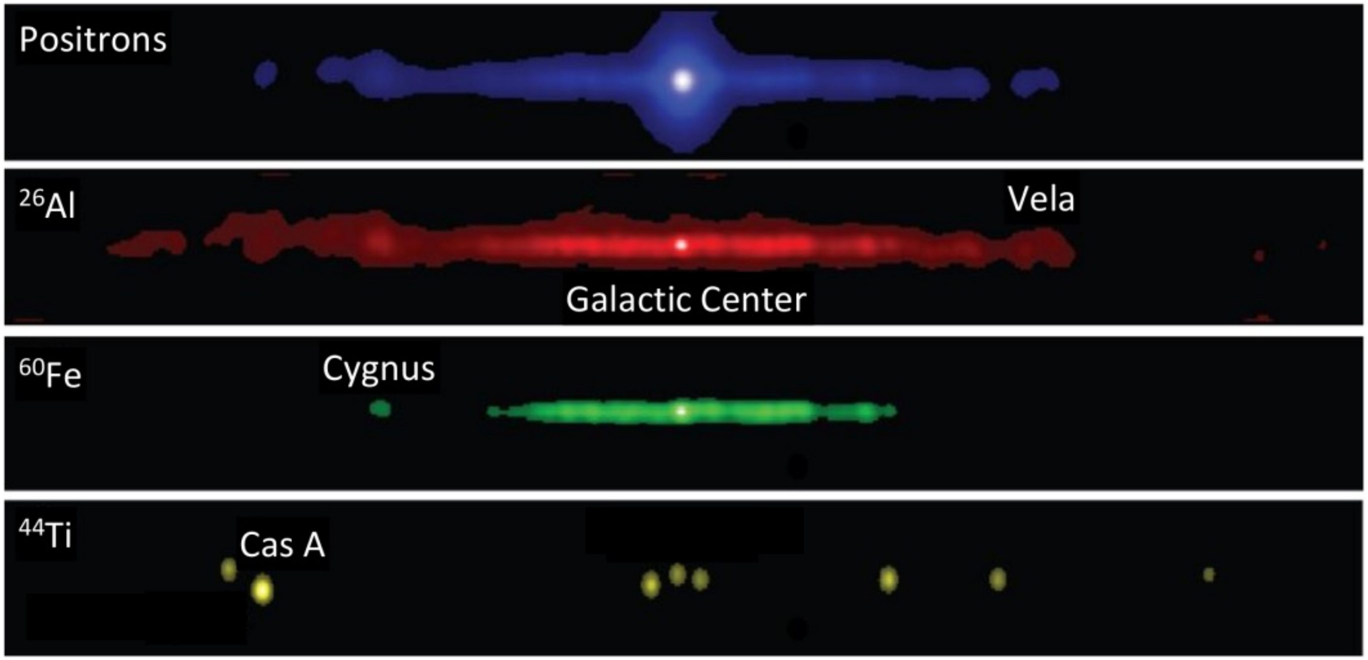
Crab spectral analysis



Data Challenge 1: ^{26}Al imaging



And finally … the expected panorama of our Galaxy



The Galactic disk as seen in the light of different nuclear lines
(COSI simulation)

Thank You!

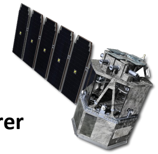
Backup slides

COSI design requirements

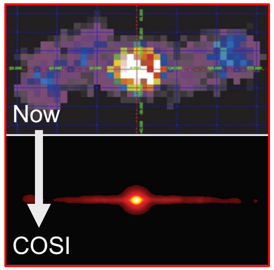
Characteristic	Requirement
Sky Coverage	• >25%-sky instantaneous FOV • 100%-sky each day
Energy Resolution (FWHM)	• 6.0 keV at 511 keV • 9.0 keV at 1.157 MeV (^{44}Ti)
Narrow Line Sensitivity (2 yr, 3σ, point source) 511 keV 1.8 MeV	[photons cm^{-2} s^{-1}] • 1.2×10^{-5} (Galactic bulge is 100x brighter) • 3.0×10^{-6} (Galactic ^{26}Al flux is 230x brighter)
Angular Resolution (FWHM)	• 2.1° at 1.8 MeV (^{26}Al)

Accreting BH polarization	• Reaches bright AGN: Cen A, 3C 273, NGC 4151 • Reaches several Galactic BHs (plus transients)
GRB polarization	• ≥30 GRBs with polarization constraints

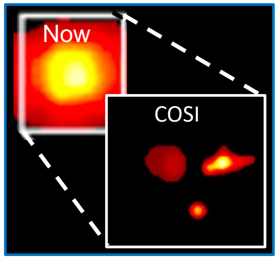
Short GRB detection, localization, and reporting	• ≥10 short GRBs • <1° localizations provided in <1 hr if TDRS available



COSI science goals

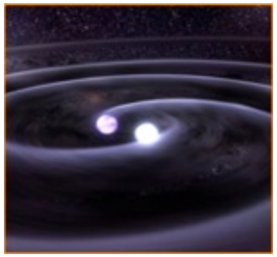


A. Uncover the origin of Galactic positrons



B. Reveal Galactic element formation

C. Gain insight into extreme environments with polarization



D. Probe the physics of multi-messenger events

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 (CHRS lead)
- Carolyn Kierans (Data pipeline co-lead)
- Alan Smale (HEASARC/archiving lead)

Northrop Grumman

Institutions of Co-Investigators and Collaborators

- Clemson University
- Los Alamos National Laboratory
- Louisiana State University
- Yale University
- IRAP, France
- INAF, Italy
- Kavli IPMU and Nagoya University, Japan
- JMU/Wurzburg and JGU/Mainz, Germany
- NTHU, Taiwan
- University of Hertfordshire, UK
- Centre for Space Research, North-West University, South Africa