COSI
Gamma-ray
Space Explorer

The Compton Spectrometer and Imager Project for MeV Astronomy

John Tomsick (COSI PI)
UC Berkeley/Space Sciences Laboratory
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Overview

- ❑ Part 1: MeV gamma-ray astronomy, scientific goals, COSI requirements
- ❑ Part 2: Compton telescope operation and COSI-balloon
- ❑ Part 3: Use of machine learning in the data pipeline
- ❑ Part 4: From balloon to satellite mission

COSI-balloon

COSI (Small Explorer satellite)

Part 1: MeV gamma-ray astronomy, scientific goals, COSI requirements

The MeV gap

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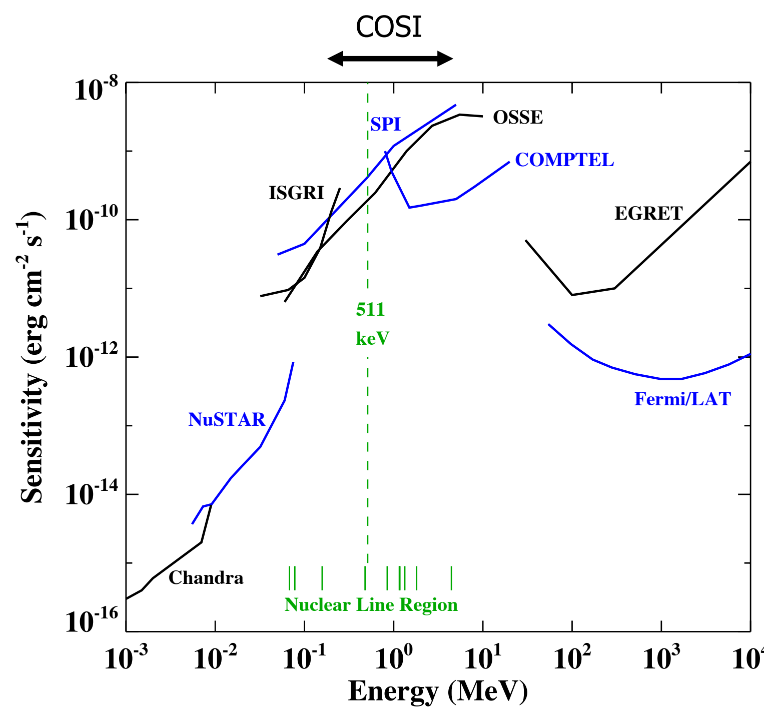
- Previous and current missions have had relatively poor sensitivity in the MeV range
- Discovery space where there is known to be interesting physics
  - Nucleosynthesis and supernovae
  - 511 keV e^-e^+ annihilation line
  - High levels of polarization
  - Multimessenger astrophysics



Missions with COSI connections:

- COMPTEL (Compton telescope)
- INTEGRAL/SPI (germanium detectors)
- Fermi/LAT (all-sky coverage every day)
- NuSTAR (nuclear line spectroscopy)

High-energy space missions with COSI connections

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Mission	Dates	Instrument	**Energy band**	**COSI connection**
CGRO	1991-2000	COMPTEL	0.8-30 MeV	Compton telescope
INTEGRAL	2002-now	SPI	0.02-8 MeV	Germanium detectors (excellent energy resolution)
Fermi	2008-now	LAT	20 MeV-300 GeV	Large field of view (FOV) giving all-sky coverage every day
NuSTAR	2012-now	CZT focal plane	3-79 keV	Nuclear line spectroscopy (science connection)
COSI	Planned for launch in 2026	Single instrument	0.2-5 MeV	All of the above (Compton telescope, germanium detectors, FOV >25%-sky)

The MeV gap

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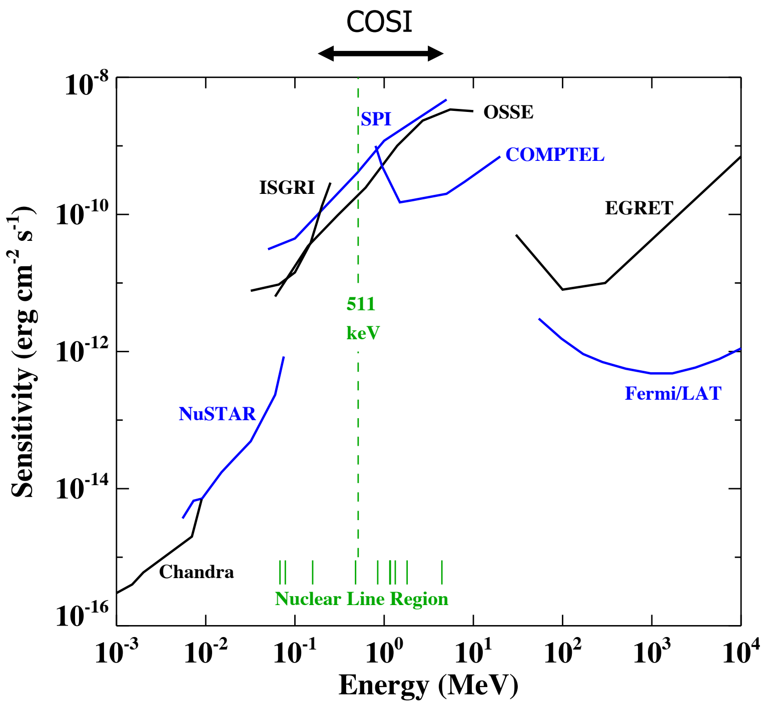

Nucleosynthesis and ^{26}Al at 1.809 MeV

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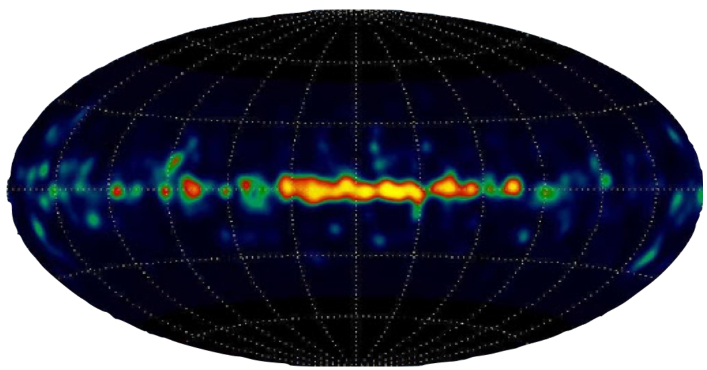
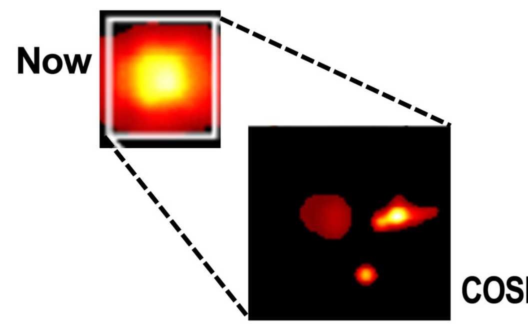
- ^{26}Al is produced in stellar processes
  - Released into the interstellar medium (ISM) in winds from massive stars and supernova explosions
- 0.7 Myr half-life for decay producing a 1.8 MeV gamma-ray
- One of the legacies of the COMPTEL mission is the mapping of ^{26}Al in the Galaxy

Element formation due to massive stars



- 1.8 MeV map of the Galaxy from COMPTEL, 3.8° angular resolution
- Oberlack+96

Cygnus region



(simulation)

COSI improvements over COMPTEL:

- 2-year baseline mission provides sensitivity improvement by 7x
- Angular resolution improvement by 2x

Nucleosynthesis and supernovae: Using ^{44}Ti to trace ejection velocities

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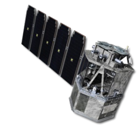
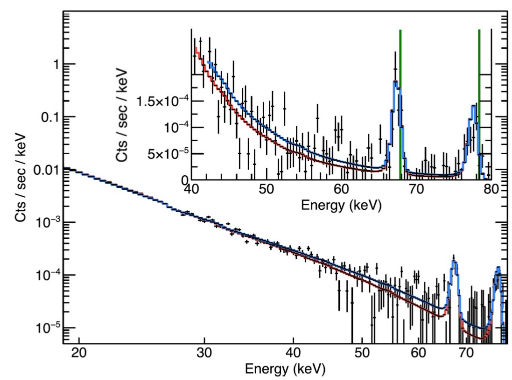
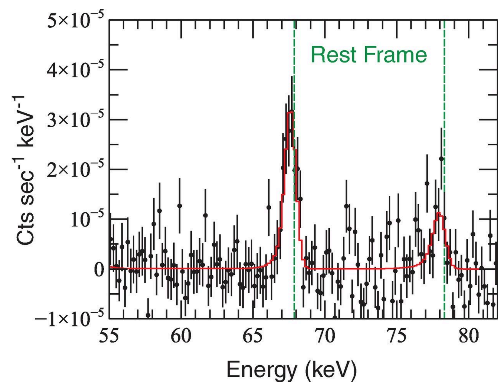


- ❑ ^{44}Ti is a tracer of young supernova remnants (60 yr half-life)
  - ^{44}Ti→^{44}Sc: 68 keV, 78 keV
  - ^{44}Sc→^{44}Ca: 1.157 MeV
- ❑ NuSTAR observations
  - Cas A: ^{44}Ti lines redshifted by 1100-3000 km/s
  - SN 1987A: ^{44}Ti line redshifted by ~700 km/s
  - Evidence for asymmetric explosions but there are only measurements for these two cases
- ❑ COSI: Search for more with a Galactic survey at 1.157 MeV

Cas A with NuSTAR (Grefenstette+14)



SN 1987A with NuSTAR (Boggs+15)



511 keV e^-e^+ annihilation line

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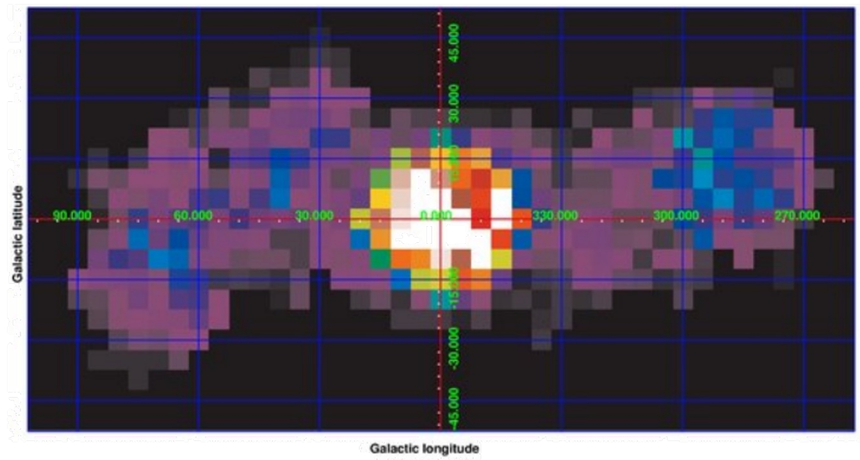
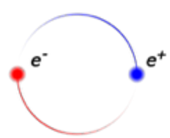
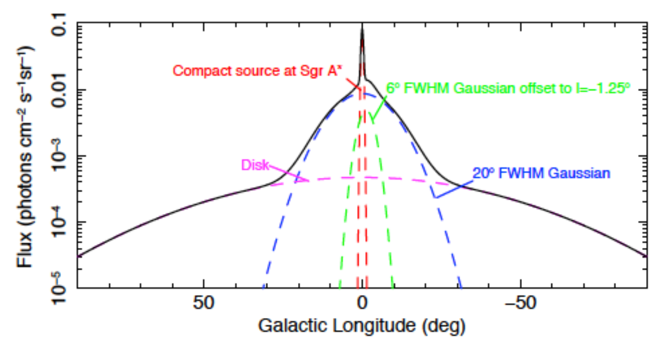
- e⁺ from massive star and core collapse SN nucleosynthesis
  - ^{26}Al: $4x10^{42}$ e^+/s
  - ^{44}Ti: ~$3x10^{42}$ e^+/s
- Strong excess coming from the Galactic bulge
  - Need $2x10^{43}$ e^+/s (bulge only)
- COSI will identify the spatial components and potentially find individual e^+ sources

INTEGRAL/SPI map of the 511 keV emission (Bouchet+10)







Skinner+14, Siegert+16

High levels of polarization at MeV energies

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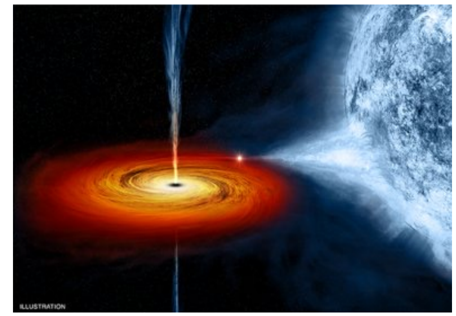
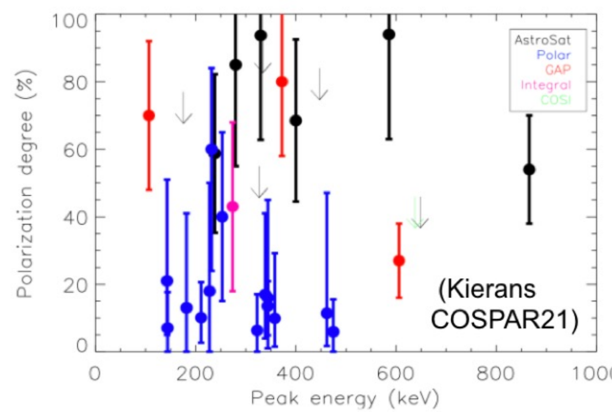
- ❑ Crab nebula and pulsar measurements at 0.1-1 MeV with INTEGRAL
  - ▪ 46-98% (Dean+08; Forot+08; Moran+16)
- ❑ Cygnus X-1 accreting black hole measurements with INTEGRAL
  - ▪ ~70% above 0.4 MeV (Laurent+11, Jourdain+12)
- ❑ Gamma-ray burst (GRB) polarization measurements
  - ▪ E.g., McConnell+17



Artist's conception of Cygnus X-1

COSI polarization measurements for:

- GRBs
- Galactic sources: BHs, Crab
- Active Galactic Nuclei



Multimessenger astrophysics

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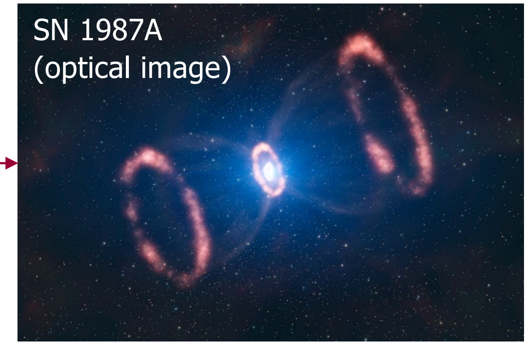
- ❑ Gamma-ray observations have played a crucial role in all multimessenger astrophysics (MMA) observations
  - ❑ Gamma-rays + neutrinos from SN1987A
  - ❑ Gamma-rays + gravitational waves from GRB 170817A/GW170817
  - ❑ Gamma-rays + high-energy neutrinos from TXS 0506+056/IceCube-170922A



Blazars:
looking down the barrel of a BH jet

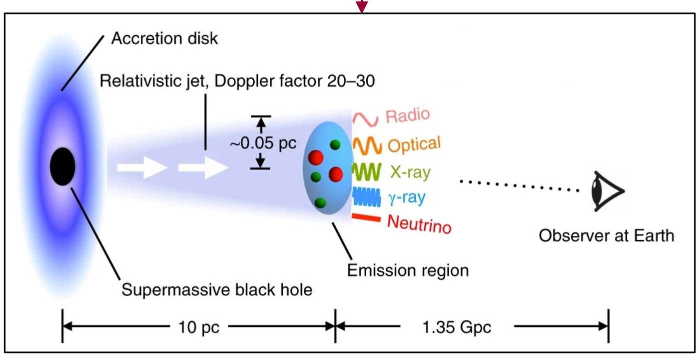


Figure from Gao+19

COSI:
- Rapid reporting of short GRB positions
- Gamma-ray counterparts to HE neutrino events
- Nearby SNe (but rare)

COSI science goals

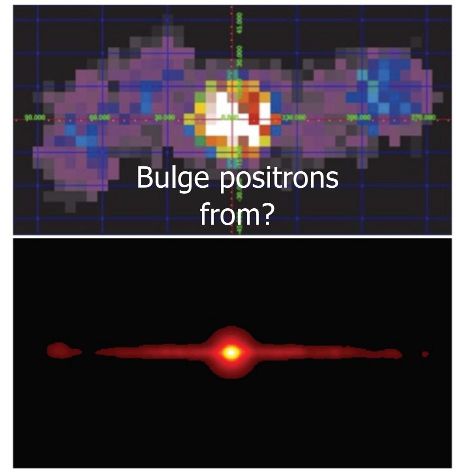
Revolutionizing our understanding of creation and destruction of matter in our Galaxy and beyond

Energy range: 0.2-5 MeV gamma-rays

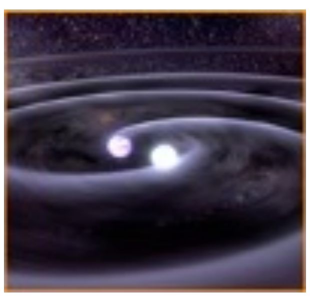
1. Uncover the origin of Galactic positrons
2. Reveal Galactic element formation
3. Gain insight into extreme environments with polarization
4. Probe the physics of multimessenger events

511 keV with INTEGRAL (Bouchet+10)

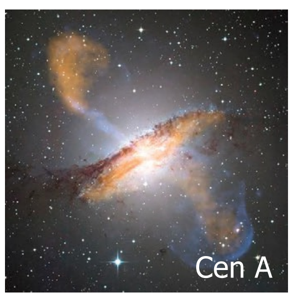
Goal 1: Positrons



Goal 4: MMA

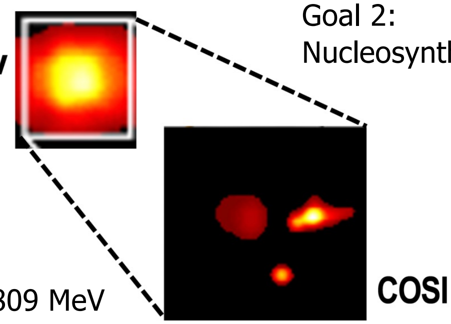


Goal 3: Polarization



Cygnus region

Goal 2: Nucleosynthesis



^{26}Al 1.809 MeV

COSI science goals with qualitative observational requirements

1. Uncover the origin of Galactic positrons
   - Imaging spectroscopy of entire Galaxy at 511 keV
2. Reveal Galactic element formation (^{44}Ti, ^{26}Al, ^{60}Fe)
   - Imaging spectroscopy of entire Galaxy at 1.157, 1.809, 1.173, 1.333 MeV
3. Gain insight into extreme environments with polarimetry
   - Polarization sensitivity
4. Probe the physics of multimessenger events
   - Large FOV to catch GRBs
   - Angular resolution for localizations

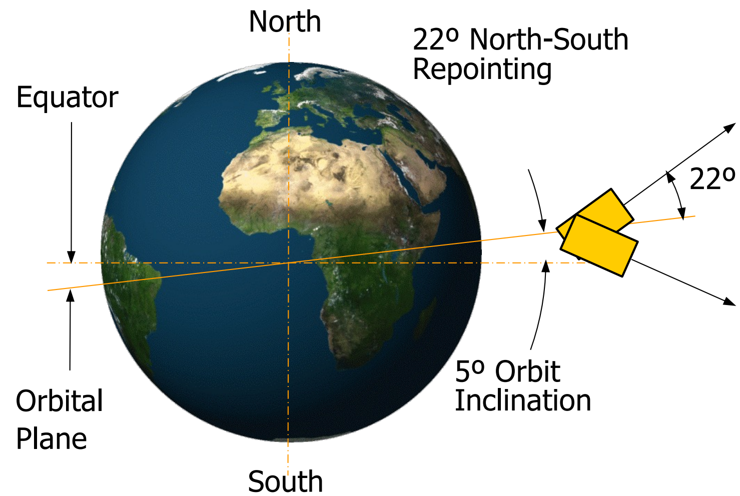
Observational requirements to do the science:

- FOV: large fraction of the sky
- High resolution spectroscopy
- Polarimetry
- Moderate angular resolution

COSI orbit and operations for daily all-sky coverage

- Instantaneous >25%-sky field of view (FOV) and North-South repointing every 12 hours to cover the whole sky every day
  - "Survey Mode"

- Near-equatorial orbit to minimize South Atlantic Anomaly passages (and background)



COSI in low-Earth orbit (LEO)

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COSI requirements

Primarily for goals 1+2

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}] • $1x10^{-5}$ (Galactic bulge is 100x brighter) • $3x10^{-6}$ (^{26}Al, ~7x better than COMPTEL)
Angular Resolution (FWHM)	• 2.0° at 1.8 MeV

Goal 3

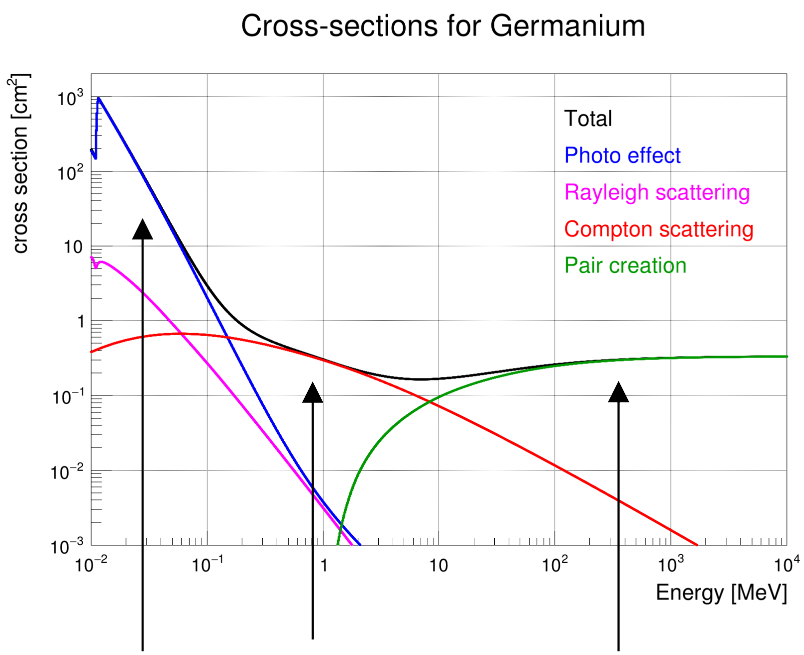
Accreting BH polarization	• Reaches bright AGN in 2 yr: Cen A, 3C 273, NGC 4151 • At least three Galactic BHs
GRB polarization	• >30 GRBs with polarization measurements

Goal 4

Short GRB detection, localization, and reporting	• >10 short GRBs (~20 detections predicted) • <1° localizations provided in <1 hr

Part 2: Compton telescope operation and COSI-balloon

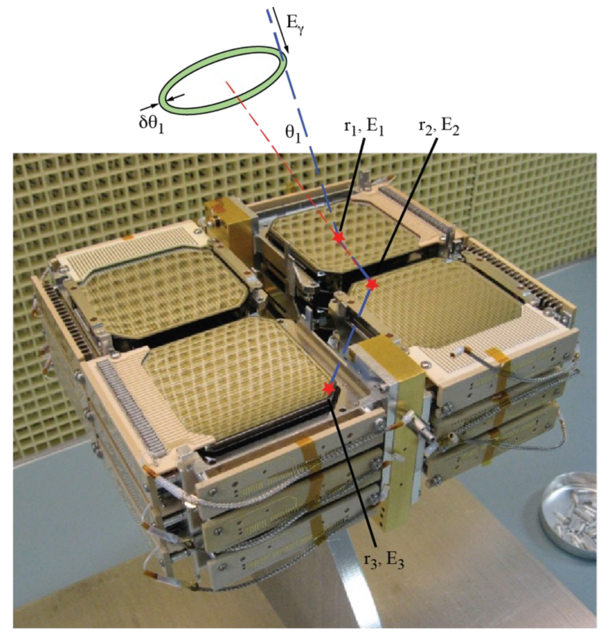
Detecting photons at ~MeV energies



Full photon absorption (NuSTAR, etc.)

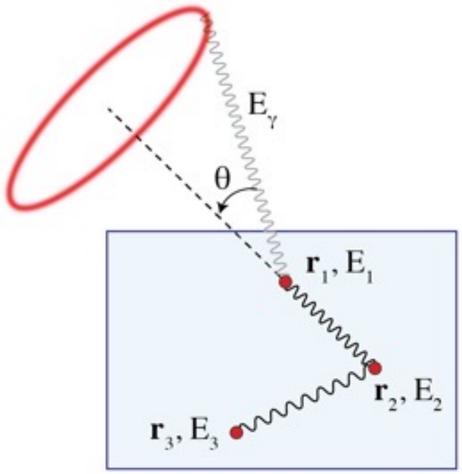
Compton telescopes (COMPTEL, **COSI**)

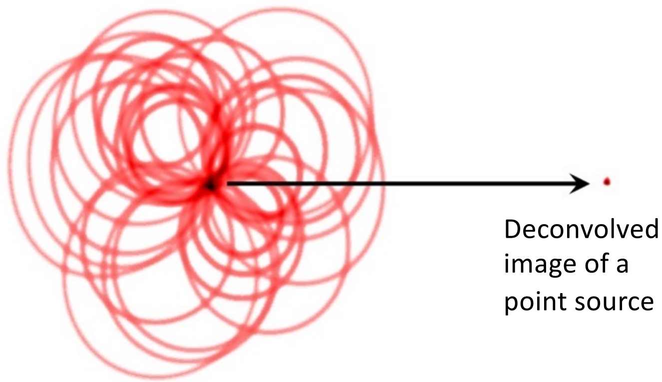
Pair creation telescopes (Fermi/LAT)



- COSI-balloon instrument
- Twelve 8x8 cm^2 detectors
- Funded under NASA's Astrophysics Research and Analysis (APRA) program

Compton telescope operating principle





- Multiple interactions in the detector
- $E_\gamma = E_1 + E_2 + E_3 + \ldots$
- The photon may have come from any point on the "event circle"

- Use iterative deconvolution techniques (e.g., maximum likelihood) to produce images

Compton telescope operating principle

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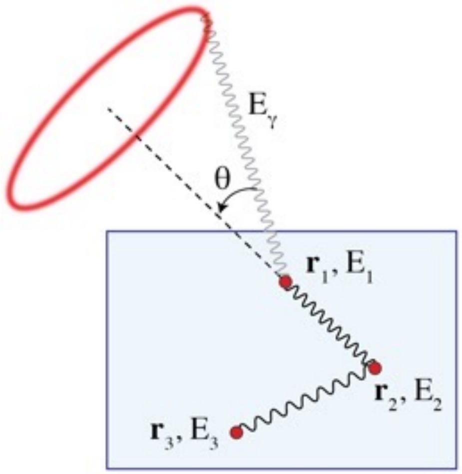

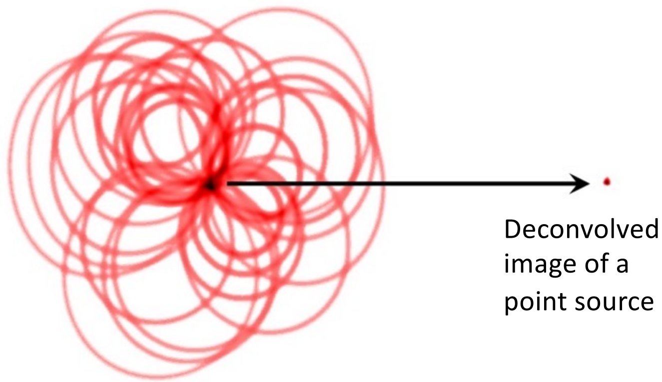

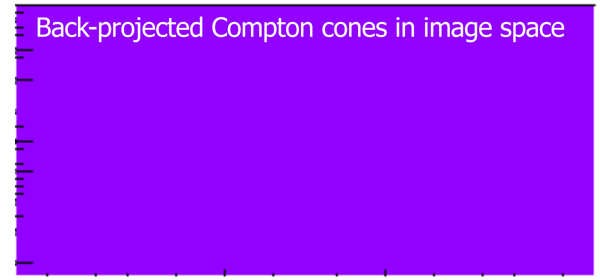

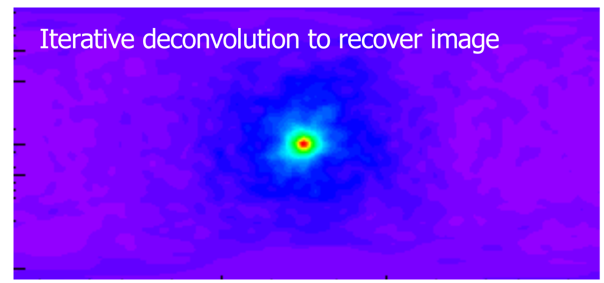

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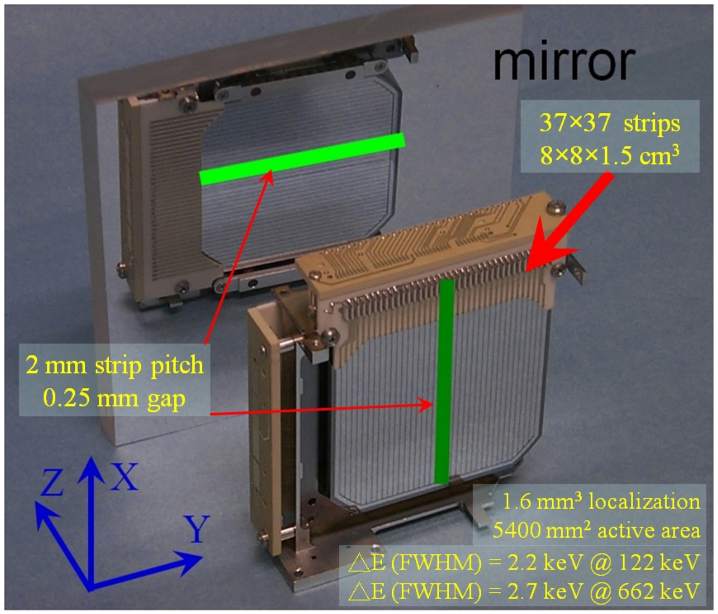
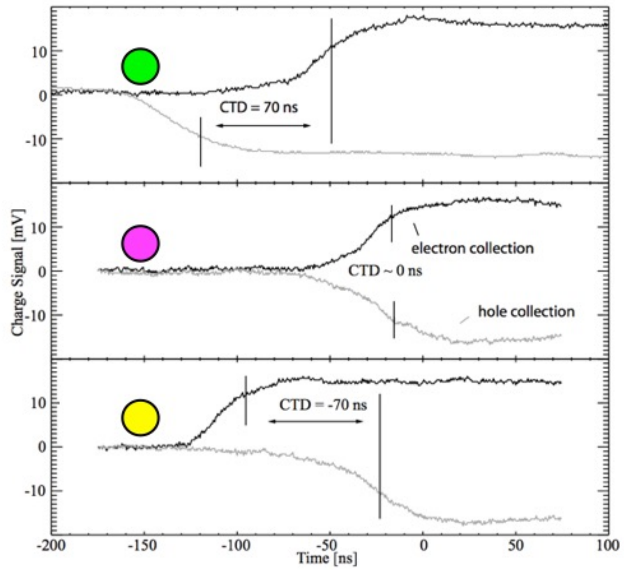
Choice of detector material

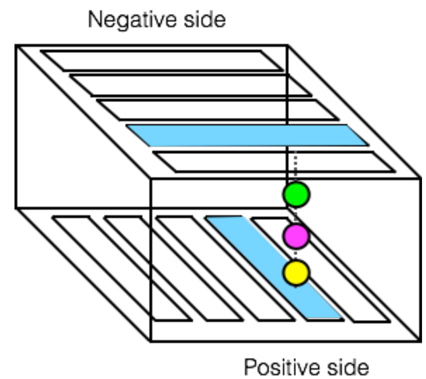
- Advantages of germanium
  - Best energy resolution: 2.96 eV per electron-hole pair
  - Moderate atomic number: Z=32
    - Lower Z does not have the stopping power for MeV energies
    - Higher Z has too much stopping power for a Compton telescope
  - High purity germanium detectors (HPGeDs) with thickness of 1.5 cm with 3-dimensional position sensitivity

- But keep in mind
  - Complex process for making the detectors (Amman+18+20)
  - Voltages of >1000 V are used for electron-hole collection
  - Detectors need to be cooled to <90 K

3-dimensional position sensitivity







- ❑ Uses orthogonal strips to measure x and y
- ❑ Uses rise-time difference to measure z

Energy spectra from calibration

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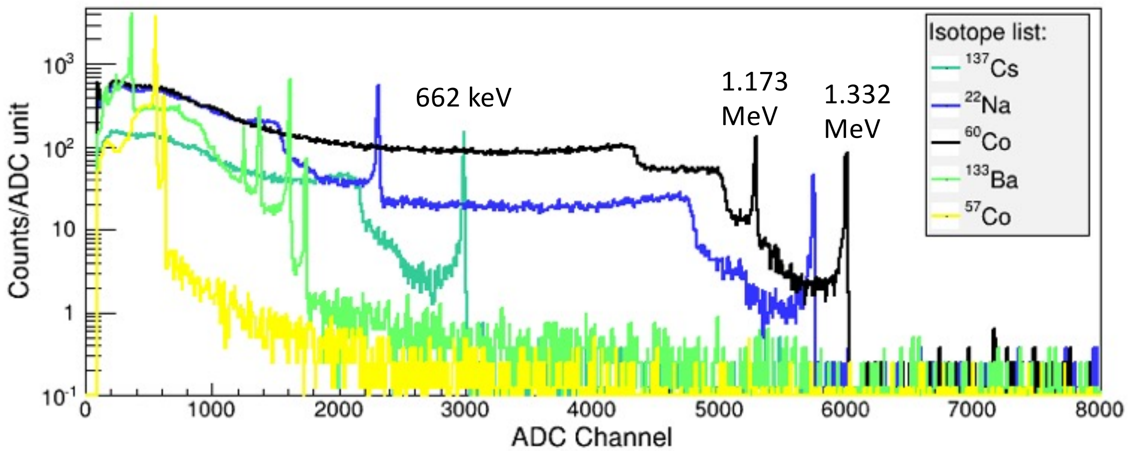

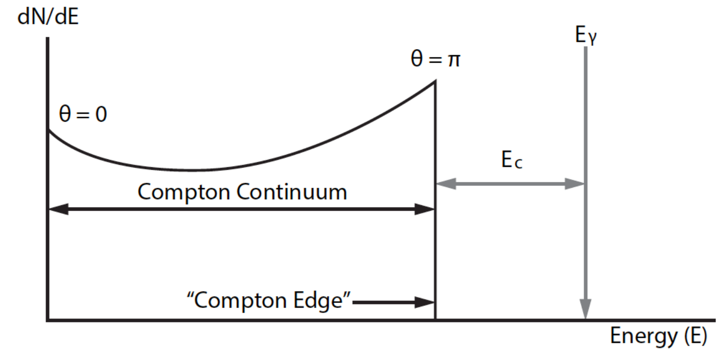

- $E_C = E_\gamma/(1+2E_\gamma/m_e c^2)$
- A Compton telescope relies on the Compton continuum photons

Cryostat, cryocooler, and shields (COSI-balloon)

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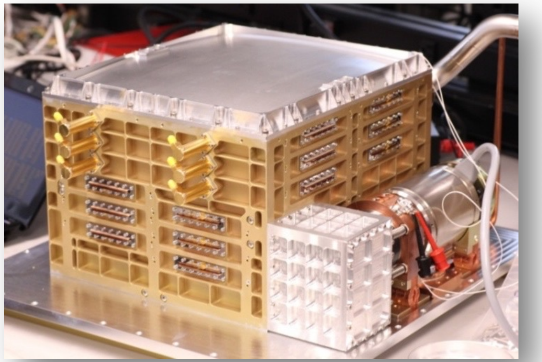
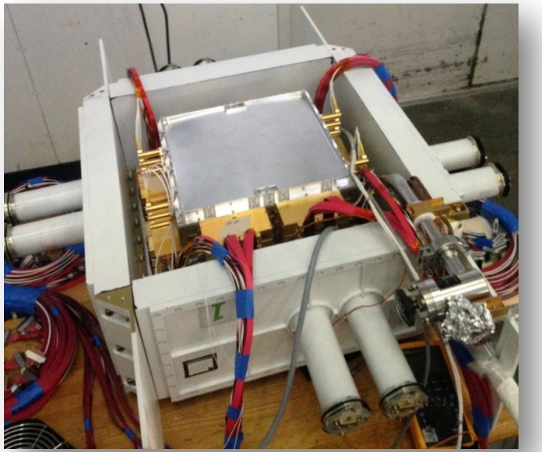
- Cryostat
  - Aluminum shell
  - HV feedthroughs
  - Preamp boxes (bottom photo)
- Cryocooler
  - Stirling cycle cooler
- CsI active shields
  - Anticoincidence



- Sunpower CryoTel
- 11 W lift for 160 W input
- Largest item in instrument power budget



- Detectors surrounded by 4cm-thick CsI shields (white) read out by photomultiplier tubes
- 4 of 6 shields shown
- Largest item in instrument mass budget

COSI balloon campaigns

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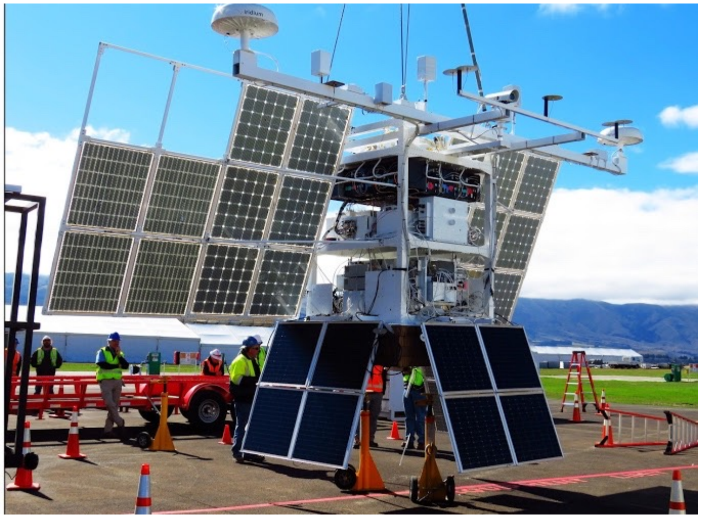
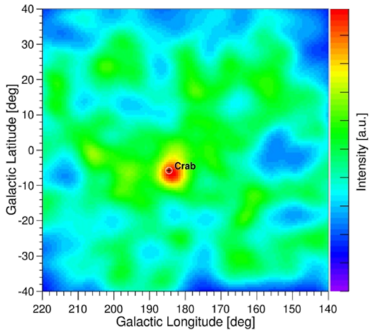
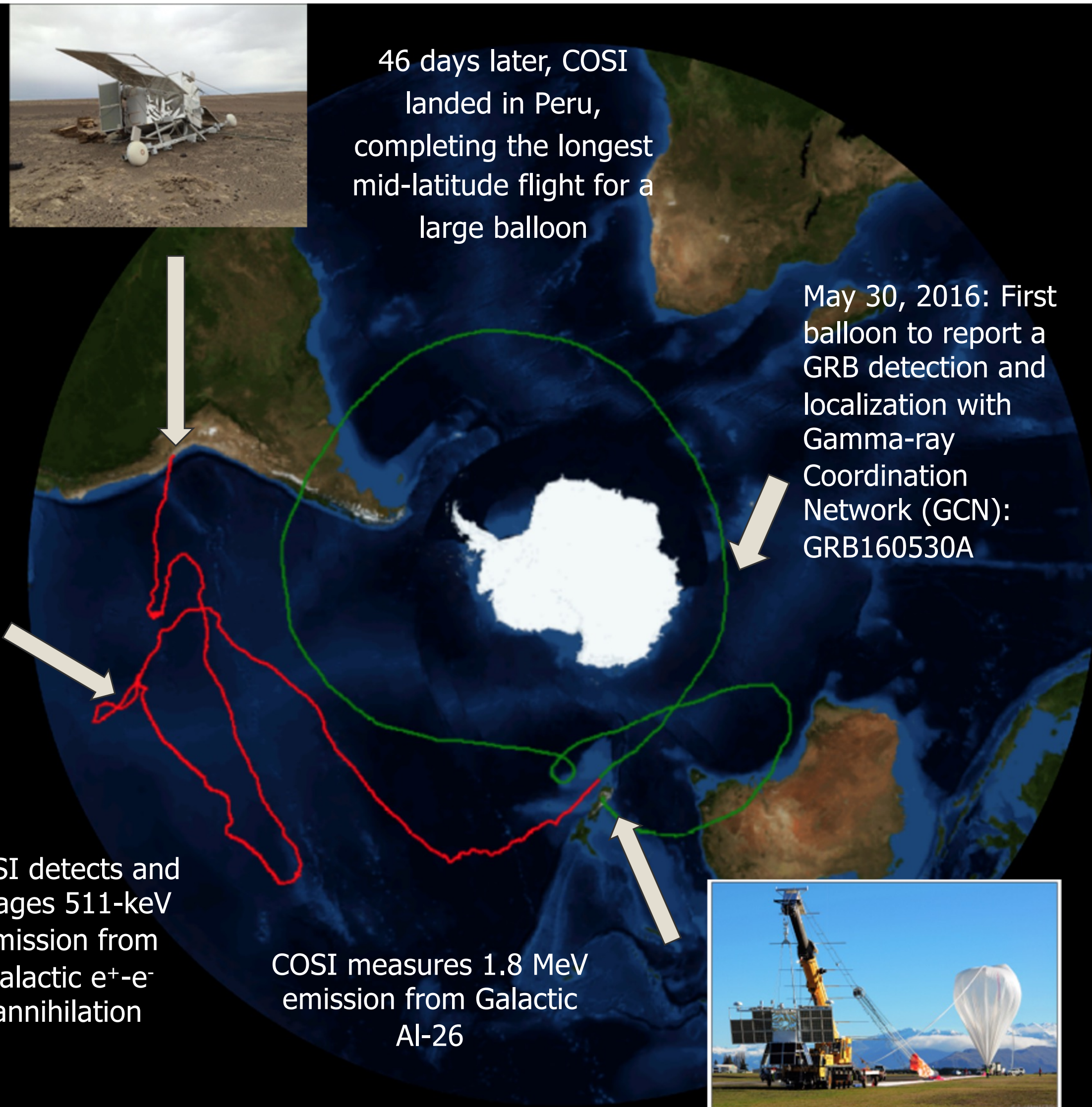
- Nuclear Compton Telescope (NCT): 2 GeD-prototype flew from Ft. Sumner, NM in 2005
- NCT: 10 GeD instrument from Ft. Sumner in 2009
- NCT: Failed launch from Australia in 2010
- COSI: 12 GeD instrument from Antarctica in 2014
- COSI: 12 GeD instrument from New Zealand in 2016
- COSI: 2020 NZ campaign cancelled due to COVID





First detection of the Crab nebula during the 2009 flight (Bandstra+11)

COSI 2016 Wanaka Flight



Slide adapted from Alex Lowell

COSI-balloon 2016 flight: GRB 160530A

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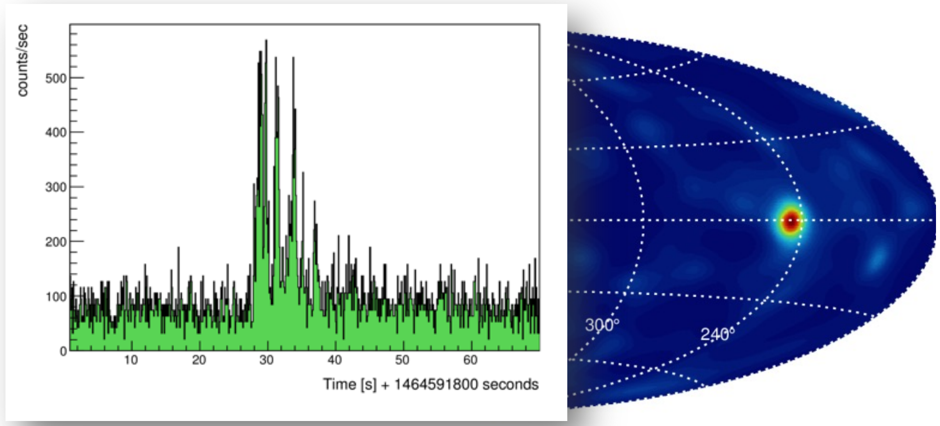
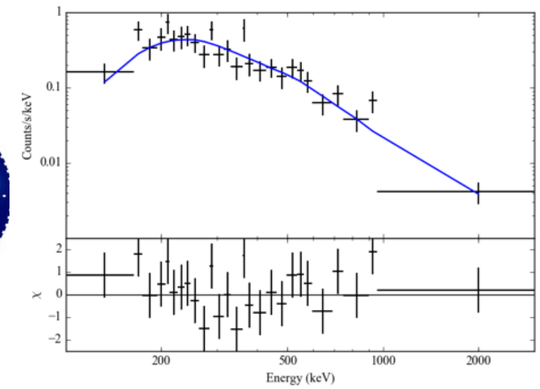
Rapid reporting:

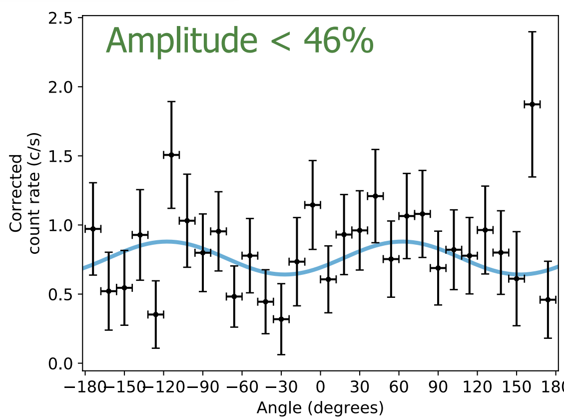
- ❑ COSI's real-time alert capabilities (a first for a balloon payload) enabled prompt notification to the observer community via GCN (GCN19473, Tomsick+16).





Polarization analysis:

- ❑ 90% confidence upper limit: <46%
- ❑ Best fit: 16% $^{+27\%}_{-16\%}$
- ❑ It was a bright burst but 44° off axis
- ❑ Lowell+17ab; Lowell+17, PhD thesis



Spectral analysis:

- ❑ Was able to compare to Konus-Wind measurements
- ❑ Sleator+19, PhD thesis

COSI-balloon summary

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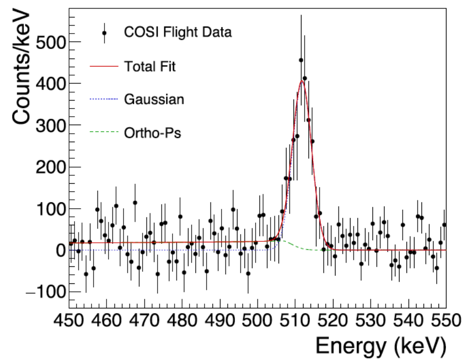
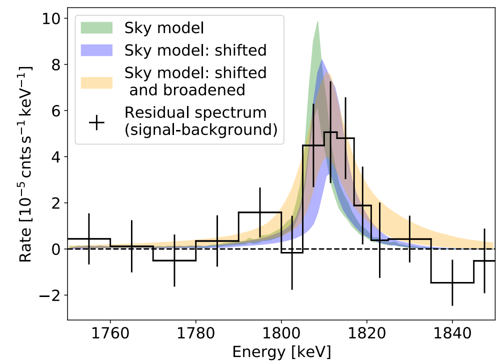
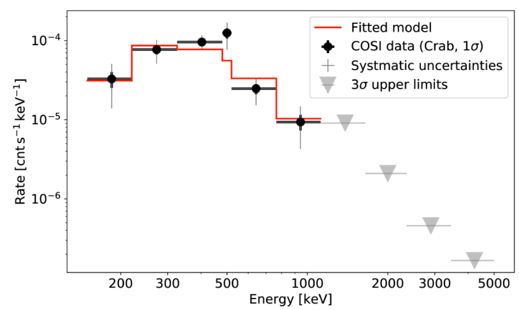
- ❑Proof of concept demonstrated with COSI-balloon
  - Instrument operation
  - Data analysis with MEGAlib (Zoglauer+06) and COSIpy (Siegert+20)
- ❑Capabilities demonstrated:
  - Real-time GRB reporting
  - Imaging
  - Spectroscopy
  - Polarization
- ❑Results
  - GRB 160530A (Lowell+17, Sleator+19)
  - 511 keV (Kierans+18+20, Siegert+20)
  - ^{26}Al (Beechert+22, ApJ)
  - Other point sources (Crab, Cyg X-1, Cen A)
    - •Zoglauer+21, Roberts et al., in prep.

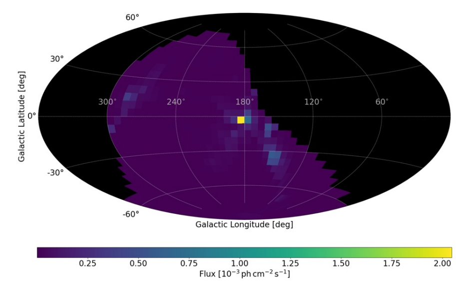
511 keV emission from the Galactic bulge



^{26}Al from the Galactic plane







Crab nebula (<2 days of exposure)
Image pixels are 5°x5°

Part 3: Use of machine learning in the data pipeline

Enhancing the data analysis pipeline with machine learning

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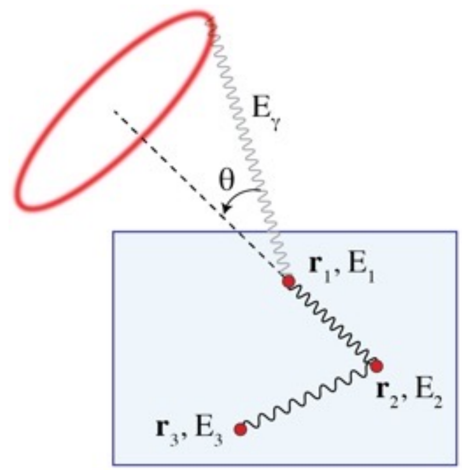
The Analysis Pipeline (simplified)

Measurements

Determine these quantities for individual interactions:
- **Energy**
- **Strip Pairing (x,y)** — ML used
- **Depth (z)**

Event reconstruction:
- **Interaction sequencing** — ML used
- **Event classification** — ML used

Data for Scientific Analysis



The Tools

MEGAlib – the Medium-Energy Gamma-ray Astronomy library

ROOT – CERN's data analysis framework

TMVA – Toolkit for Multi-Variate Analysis

The People

Andreas Zoglauer and students:
Devyn Donahue, Joan Zhu, Jasper Gan

Interaction sequencing

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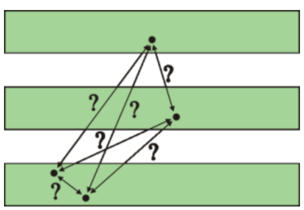
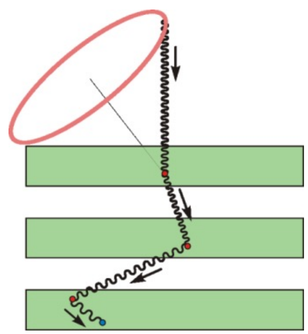
Space Explorer

Challenge:

- ❑ Determine the path of the gamma-ray in the instrument



Set of interactions with *the same measured arrival time*



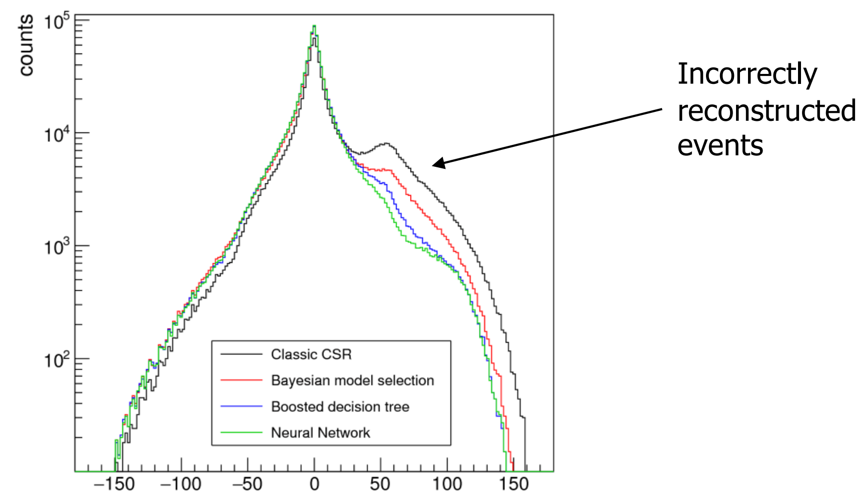
Reconstructed event

Green: Germanium detectors
Dots: Interaction locations
Lines: Possible paths

Results:

- ❑ Comparison of different machine learning approaches

Angular Resolution Measure (ARM) histogram



Smallest angular distance between the event circle and the source location (degrees)

Provides a very significant decrease in the number of incorrectly reconstructed events

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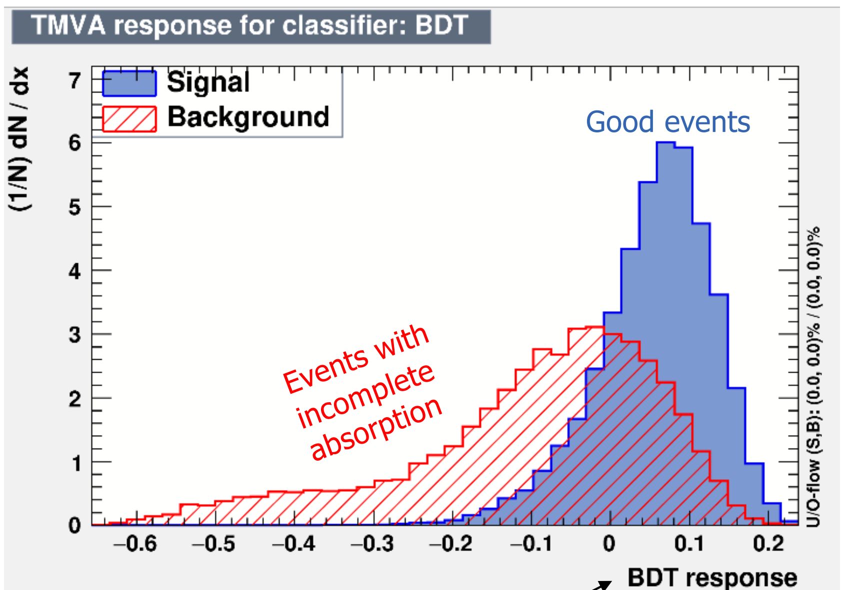
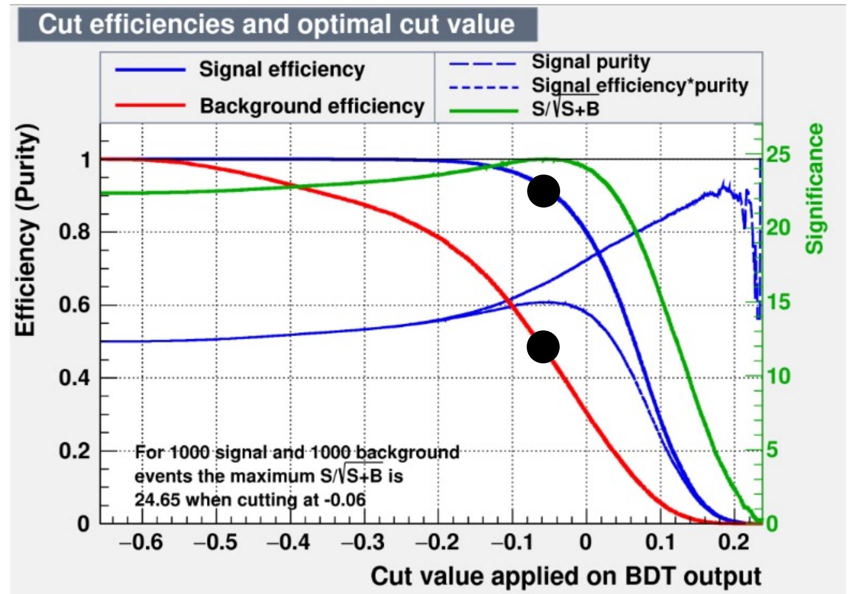
Event classification

Challenge:

- ❑ Remove events that do not deposit all of their energy in the instrument



Collapsing the multi-dimensional data space into the boosted decision tree (BDT) variable that best separates the two classes



Optimal cut:

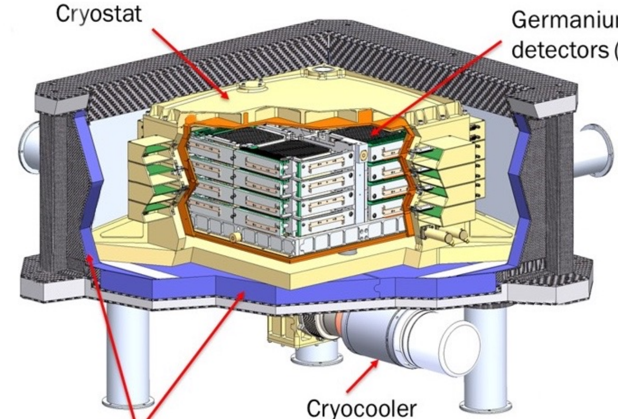
- ❑ Background reduced by half while only reducing signal efficiency by 8%

Part 4: From balloon to satellite mission

COSI advances vs. COSI-balloon

COSI
A Gamma-ray Space Explorer

- ❑ Change from 12 to 16 GeDs
- ❑ Change from 37 to 64 strips per GeD side
  - Better angular resolution
  - Better event reconstruction
- ❑ Change from CsI to BGO shield material
  - Better stopping power for BGO
- ❑ Longer exposure
  - COSI has a 2-year baseline mission (and no consumables)
- ❑ No atmosphere
  - No attenuation, lower and more stable background
- ❑ All-sky coverage



From balloon to satellite

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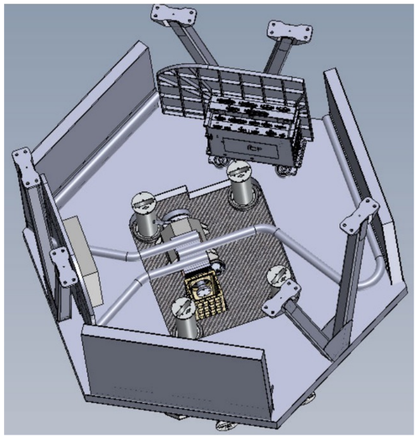
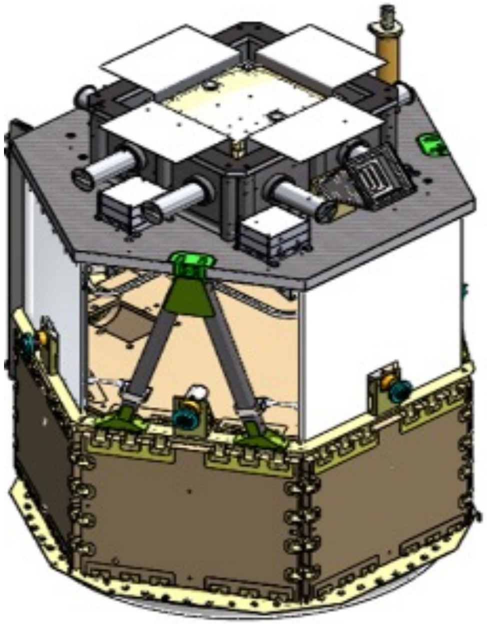
Space Explorer

- Minimize size of shields to keep mass low
- Switch to ASIC electronics
  - Needed to reduce mass while accommodating the increased number of channels
- Ruggedize detector support structure for satellite launch
  - Keep launch loads on germanium detectors at an acceptable level
  - Isolate electronics from cryocooler vibrations
- Thermal system
  - Balloon: liquid cooling system
  - Satellite: heat pipes and radiators





- Size is 1 meter across (flat-to-flat)

Considerations for keeping shield mass low

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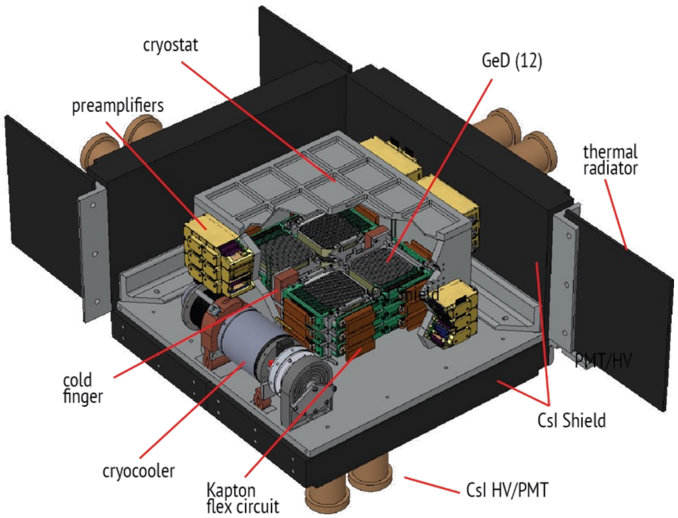
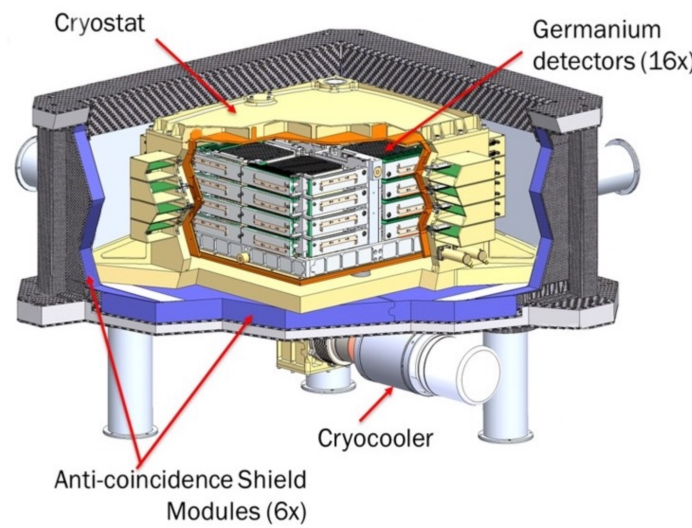
COSI-balloon



COSI



- ❑ Moving cryocooler below instrument deck
  - Allows for shield box to be smaller, shorter, and lighter
- ❑ 2cm-thick BGO instead of 4cm-thick CsI
  - better stopping power with less mass due to smaller housing

- Shields ~ 90 kg
- Total satellite mass < 365 kg (to equatorial LEO)

ASIC readout

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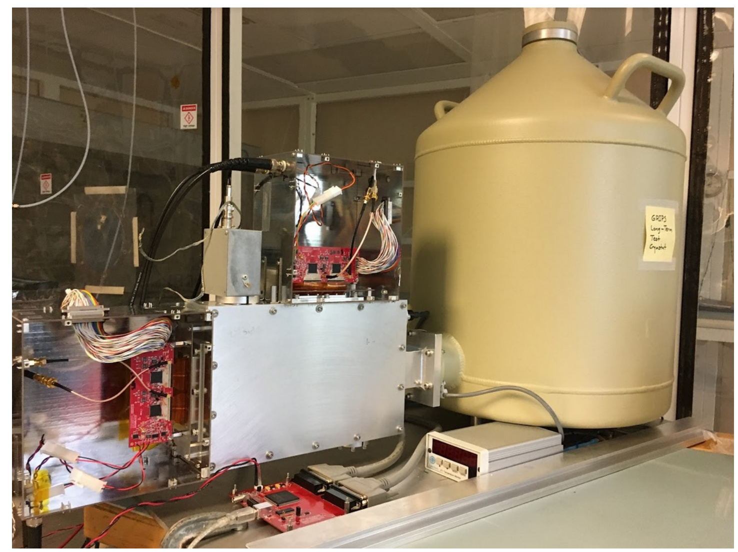
Space Explorer

- ❑ 32 channel ASICs developed by the Naval Research Laboratory (NRL)
  - Need 4 ACISs per detector
  - 2048 channels for 16 GeDs
- ❑ Heritage is NCIASIC2, which has been used for silicon strip detectors and CZT
- ❑ NRL1 added a timing circuit
  - Needed by COSI for depth measurement
  - Wulf+18, NIM A
- ❑ NRL2 separated energy and timing circuits to allow for a shorter peaking time for timing
  - Met requirements except for an instability in the track-and-hold section of the peak detect circuit
- ❑ NRL3 recently received and undergoing tests



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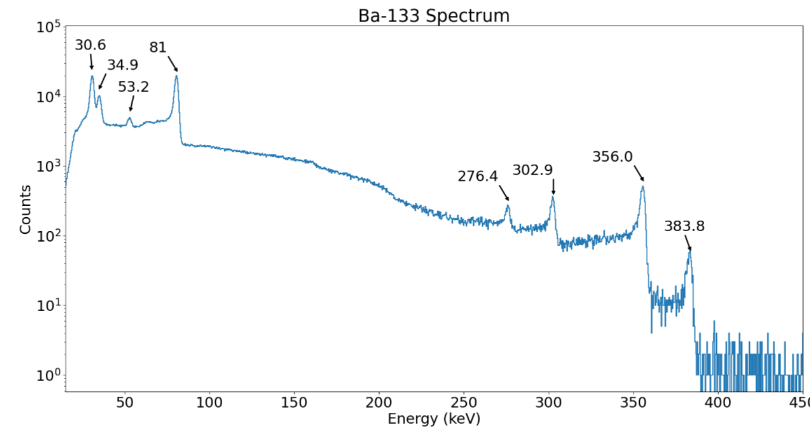
ASIC requirements and NRL2 performance

- Even though NRL2 will not be used for flight because of the “peak detect” bug, we were able to make measurements to demonstrate that NRL2 meets COSI’s requirements

- Early testing of NRL3 looks good

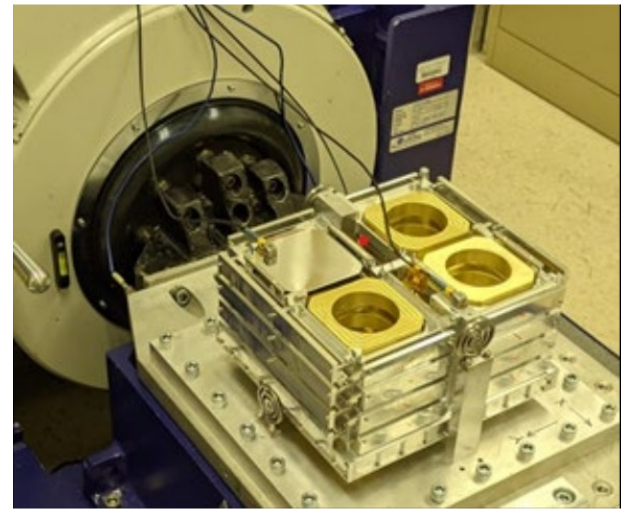


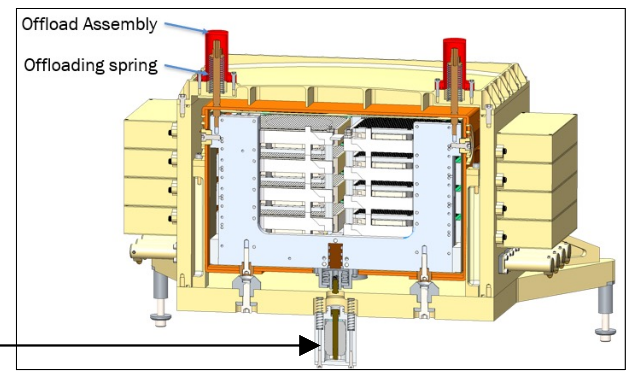
Value	Requirement	Measurement	Met
Energy Resolution	< 3.1 keV FWHM	2.4 (LV) 2.9 (HV) keV FWHM	✅
Trigger Threshold (dynamic range)	<18 keV	17.1 keV	✅
Maximum Range (dynamic range)	>1800 keV	>1850 keV	✅
Noise Threshold (nearest neighbor)	<10 keV	<9.4 keV	✅
Timing Threshold (for depth)	<50 keV	48 keV	✅
Timing Resolution (for depth)	<11.3 ns FWHM	8-10.6 ns FWHM	✅

COSI detector support structure

COSI
A Gamma-ray
Space Explorer

- The COSI detector support structure was prototyped and tested during phase A
- Use of Frangibolt™ and spring system
  - Launch configuration: Frangibolt™ locks support structure in place
  - After launch: Frangibolt™ releases and spring system provides isolation from cryocooler vibrations
- A suite of vibration tests on the structure validated the mechanical integrity of the assemblies and vibration isolation between the spacecraft and the GeD array





NASA astrophysics current and future missions

COSI

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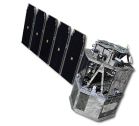
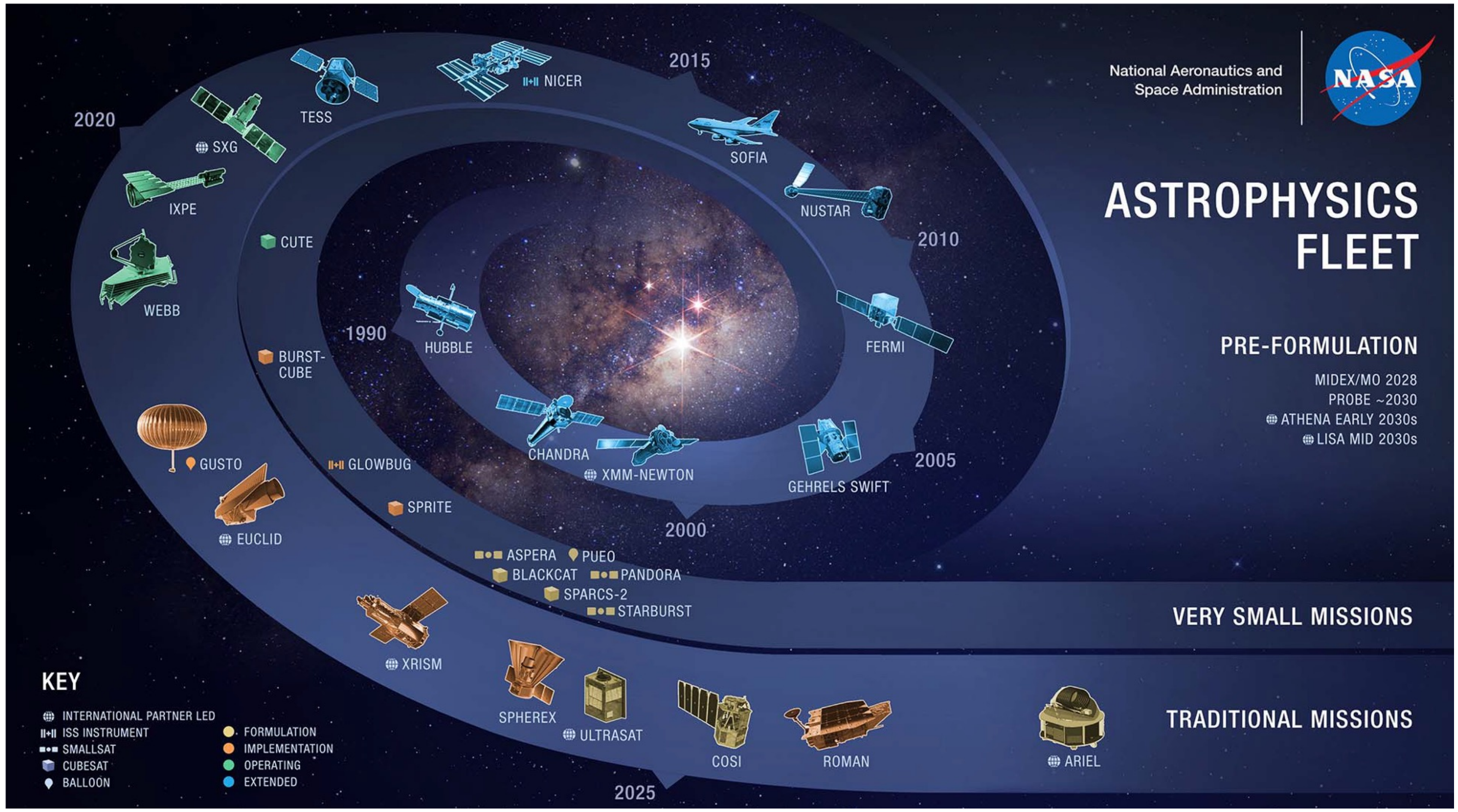


- Main Phase A deliverable is a Concept Study Report

- CSR completed in March 2021
- NASA Site Visit June 2021
- Selected to proceed to Phase B formulation in October 2021



From NASA Astrophysics Town Hall: Paul Hertz

The COSI collaboration

University of California
- John Tomsick (Principal Investigator, UCB)
- Steven Boggs (Deputy PI, UCSD)
- Andreas Zoglauer (Project Scientist, UCB)
- J. Martinez Oliveros (Student Collaboration Lead, UCB)
- P. Saint-Hilaire (SEO Lead, UCB)

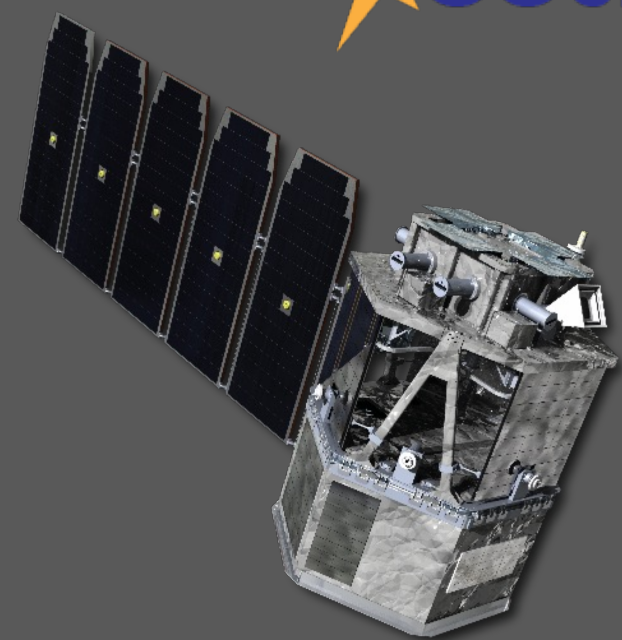
Naval Research Laboratory
- E. Wulf, C. Sleator, B. Phlips

Goddard Space Flight Center
- A. Shih, C. Kierans, A. Smale

Northrop Grumman

Institutions of Co-Is and Collaborators
- Clemson University
- Los Alamos National Laboratory
- Louisiana State University
- IRAP, France
- INAF, Italy
- Kavli IPMU and Nagoya University, Japan
- JMU, Germany
- NTHU, Taiwan

COSI



***Operation:* Every day, COSI will cover the entire sky, resulting in a sensitive all-sky map in the 0.2-5 MeV range.**

***Science:* Revolutionizing our understanding of creation and destruction of matter in our Galaxy and beyond.**

COSI required line sensitivity and grasp compared to previous and current missions

COSI
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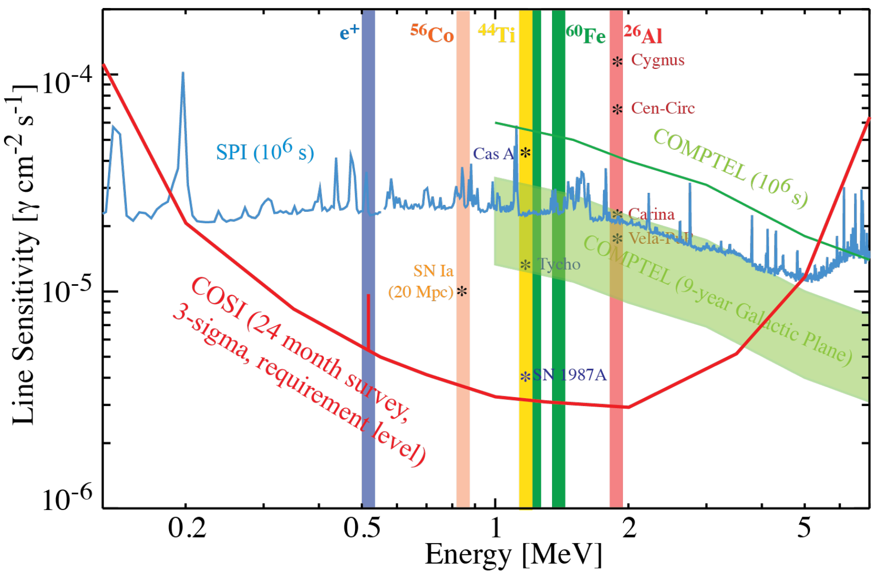

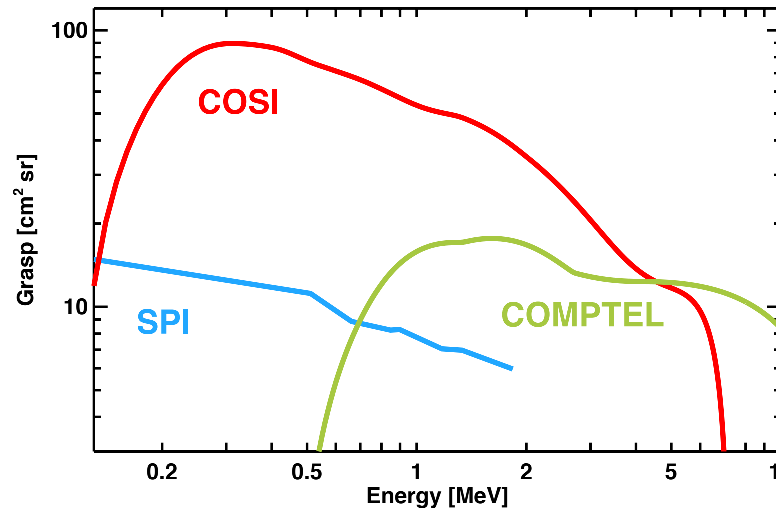

- ❑ COSI is optimized for making images of emission lines over large regions of the sky, enabling full-Galaxy and all-sky images.
- ❑ COSI's large FOV provides a substantial improvement in grasp (aka "geometric factor").

Summary and conclusions

- MeV sensitivity has lagged behind that of other energy bands, but holds large science potential
- COSI-balloon has allowed for instrument development and has provided an important proof of concept
- Engineering changes for satellite
  - Keeping shield mass low
  - ASIC readout
  - Detector support structure
  - Thermal system
- Getting involved
  - Machine learning projects (URAP program)
  - Student collaboration project (Background and Transient Observer)
  - Public data challenges starting in the Fall

Backup

Strip pairing to determine x and y

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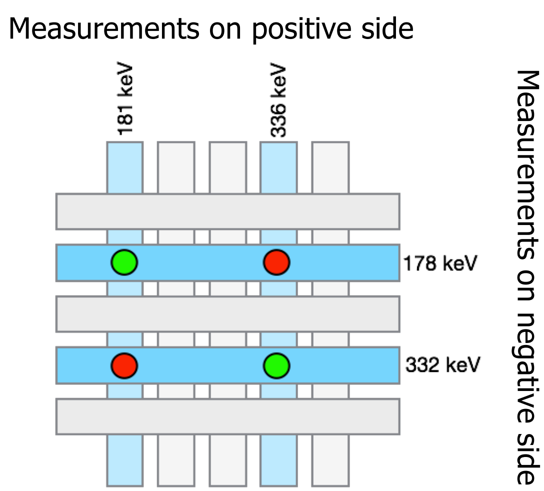
A Gamma-ray Space Explorer

Challenge:

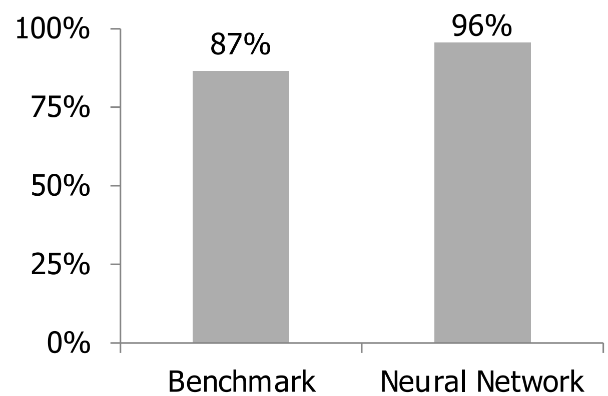
- ❑ Since all interactions from a single gamma-ray occur simultaneously, there can be x,y ambiguity when two interactions occur in the same detector

For the case shown, the energy-matching approach would work



Results:

- ❑ Benchmark (energy-matching approach) vs. 4-layer fully connected neural network:



Provides a significant increase in the reliability of the interaction location determinations

COSI observational summary

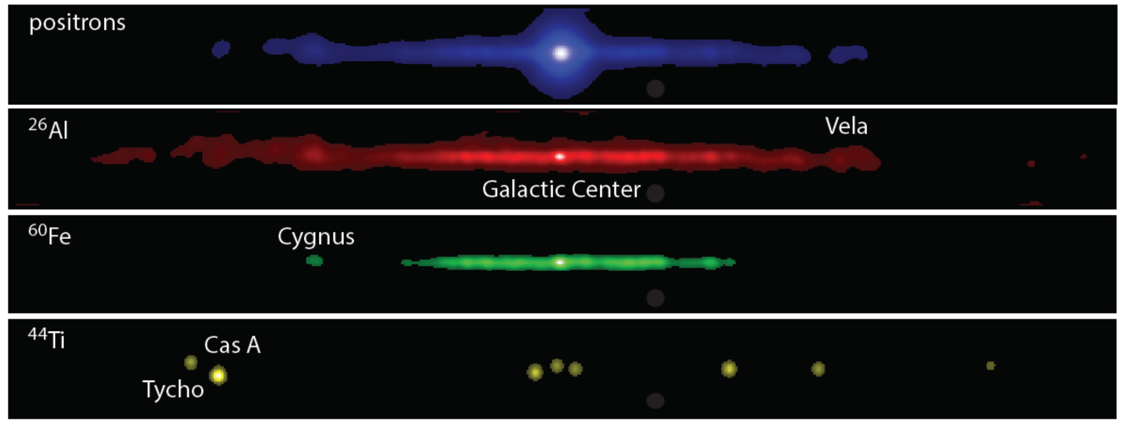
Transient science

- ❑ GRB alerts
- ❑ GRB polarization
- ❑ Correlation with HE neutrinos
- ❑ Black hole transients
- ❑ Blazars
- ❑ Classical novae
- ❑ Type Ia SNe

Expected persistent source types

- ❑ AGN (e.g., Cen A)
- ❑ X-ray binaries (e.g., Cyg X-1)
- ❑ Pulsars
- ❑ Gamma-ray binaries

The radioactive Milky Way



COSI comparisons:

- Obtains 46-day balloon 511 keV sensitivity in 1 day
- Energy resolution is >20x better than COMPTEL
- FOV is 4x larger than COMPTEL and 12x larger than INTEGRAL

COMPTEL and COSI

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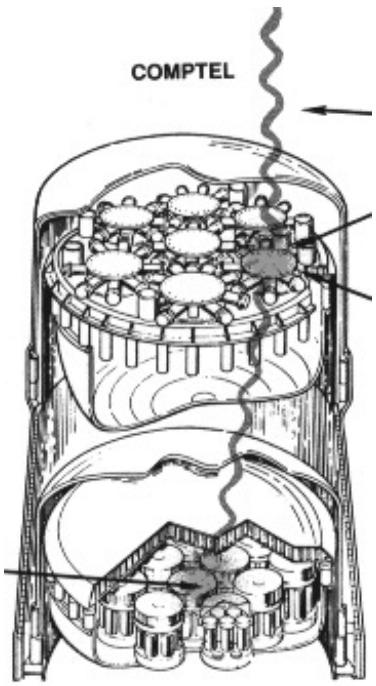
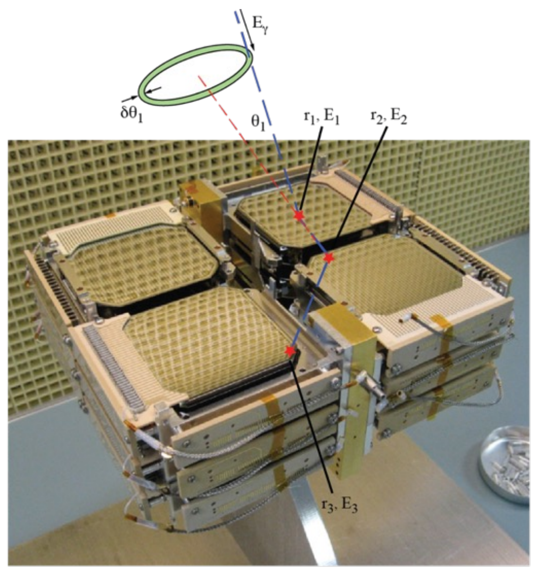
1.5 m





COSI has 16 detectors (one more layer than pictured here)

Each detector is 8cmx8cm

CGRO/COMPTEL:
- ~40 cm^3 resolution
- $\Delta E/E$ ~10%
- up to 0.4% efficiency

COSI:
- <1 mm^3 resolution
- $\Delta E/E$ ~0.2-1%
- up to 10% efficiency
- bandpass covers 511 keV
- polarization

- Vastly improved performance with a fraction of the mass and volume