The Compton Spectrometer and Imager

Dr. Savitri Gallego
Johannes Gutenberg University Mainz
On behalf of the COSI Team

IV Gravi-Gamma-Nu Workshop
3-6 October 2023

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

DLR

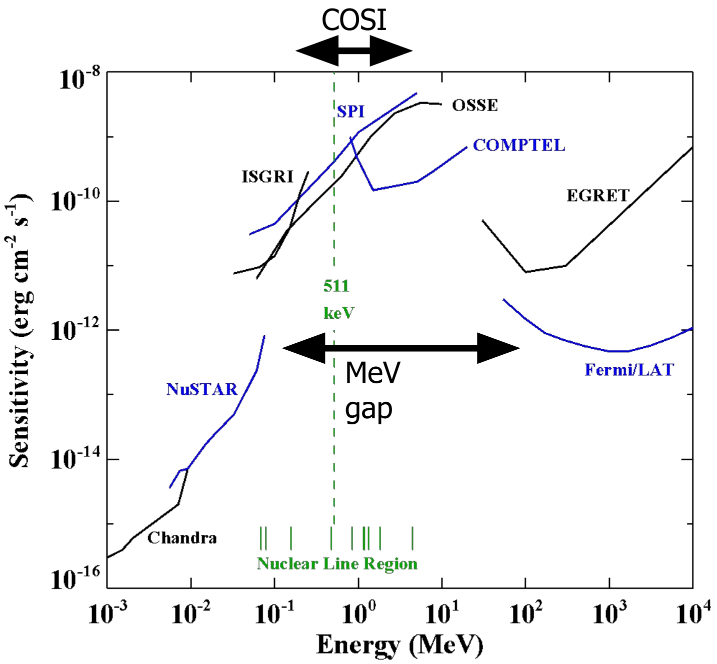
COSI overview

- COSI is:
  - a Compton telescope for observing ***0.2-5 MeV gamma-rays***
  - ***a NASA Small Explorer satellite with a planned launch in 2027***
- Key capabilities
  - Uses cryogenically-cooled germanium detectors (GeDs) to provide ***excellent energy resolution (~1%)***
  - Instantaneous field of view is ***>25%-sky*** and covers the whole sky every day
- Optimized to make all-Galaxy/all-sky emission line images in the MeV bandpass
- Advances our understanding of creation and destruction of matter in our Galaxy

The MeV gap

COSI
A Gamma-ray Space Explorer

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



Missions/instruments with COSI connections:

- CGRO/COMPTEL (1991-2000): Compton telescope
- INTEGRAL/SPI (2002-now): germanium detectors
- Fermi/LAT (2008-now): all-sky coverage every day
- NuSTAR (2012-now): nuclear line spectroscopy

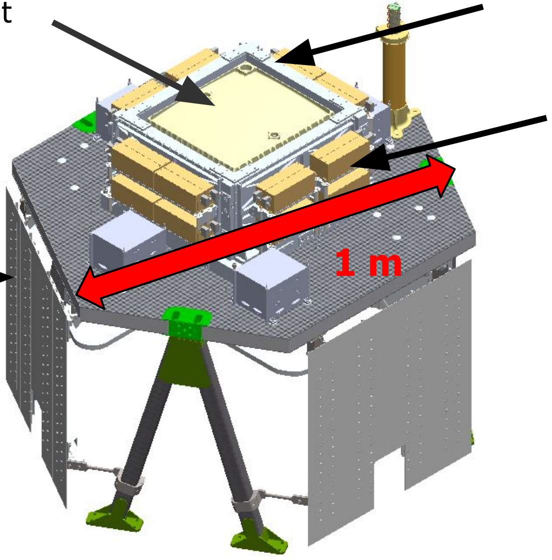
COSI: NASA Small Explorer satellite mission

Cryogenically cooled germanium detectors in a vacuum cryostat

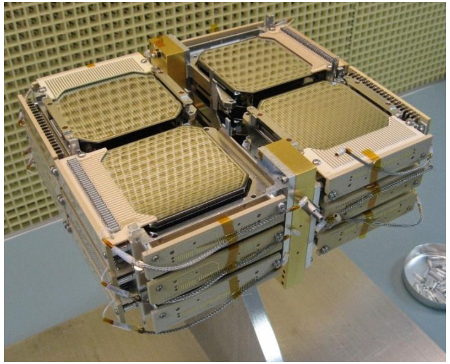
BGO shields for background reduction

Front-end electronics with ASIC readout

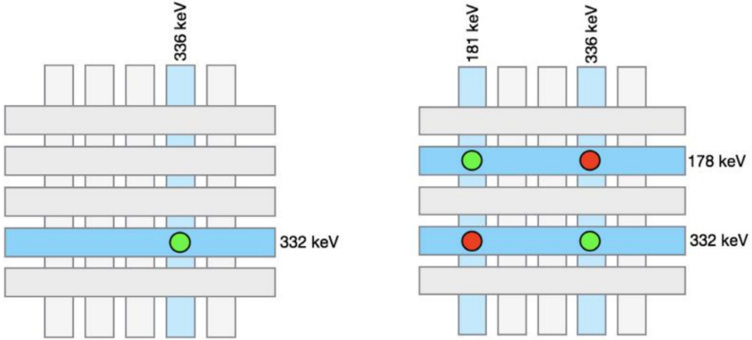
Heat removed by system of heat pipes and radiators



COSI instrument/payload



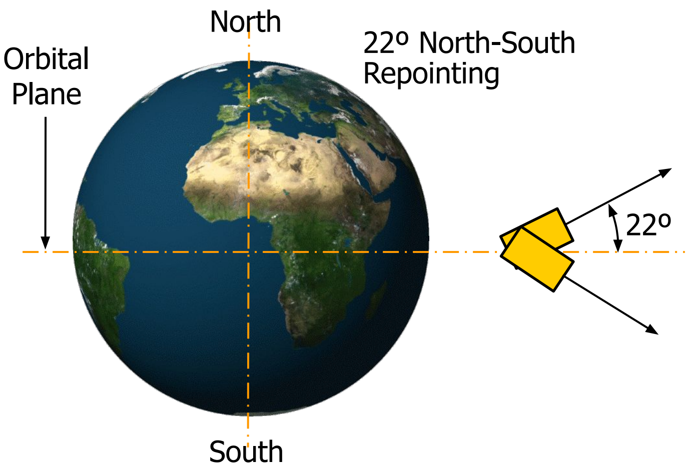
12 germanium detectors from COSI-balloon: 8x8x1.5 cm^3 each



For more details on the COSI mission, see Tomsick et al. (arXiv:1908.04334 and arXiv:2109.10403)

COSI orbit and observing modes

- Low-Earth equatorial orbit to minimize background
  - Targeting
    - 0° orbital inclination
    - 550 km altitude (trade-off between background and orbit lifetime)

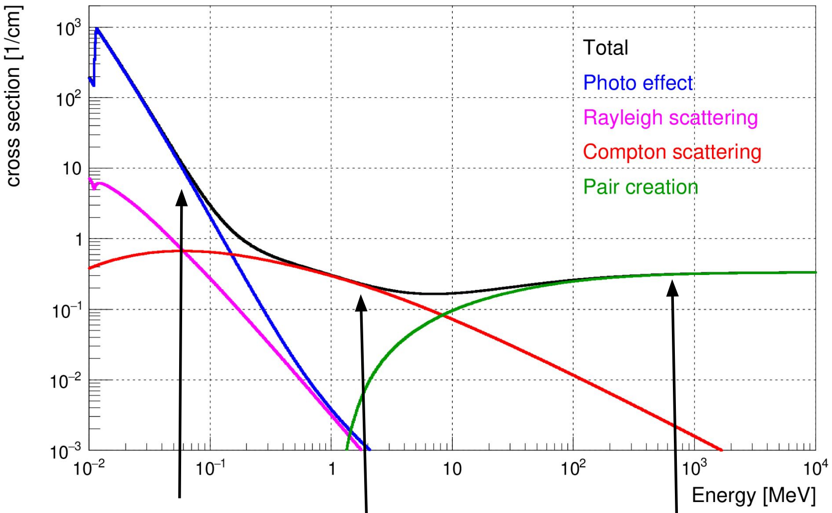


- Survey mode
  - North-South repointing (±22°) every 12 hours to cover the whole sky every day
- Constant Zenith Angle (CZA) mode
  - CZA mode will be used to maximize coverage of interesting events
  - Plan to respond to targets of opportunity (TOOs) with CZA mode

Detecting photons at MeV energies with Compton telescopes

COSI
A Gamma-ray Space Explorer

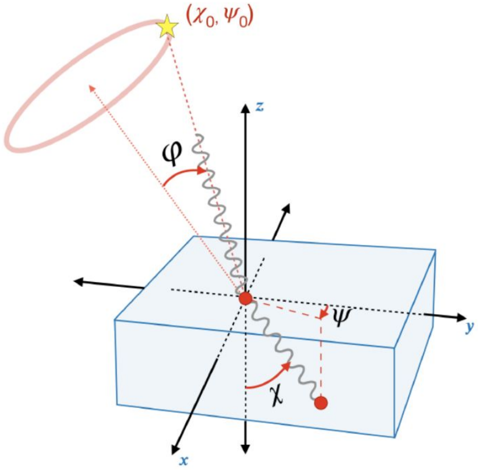
Photon cross section



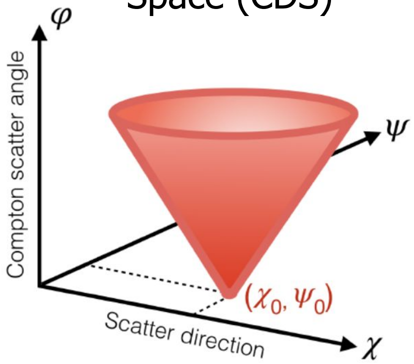
Full photon absorption (NuSTAR, etc.)

Compton telescopes (COMPTEL, **COSI**)

Pair creation telescopes (Fermi/LAT)

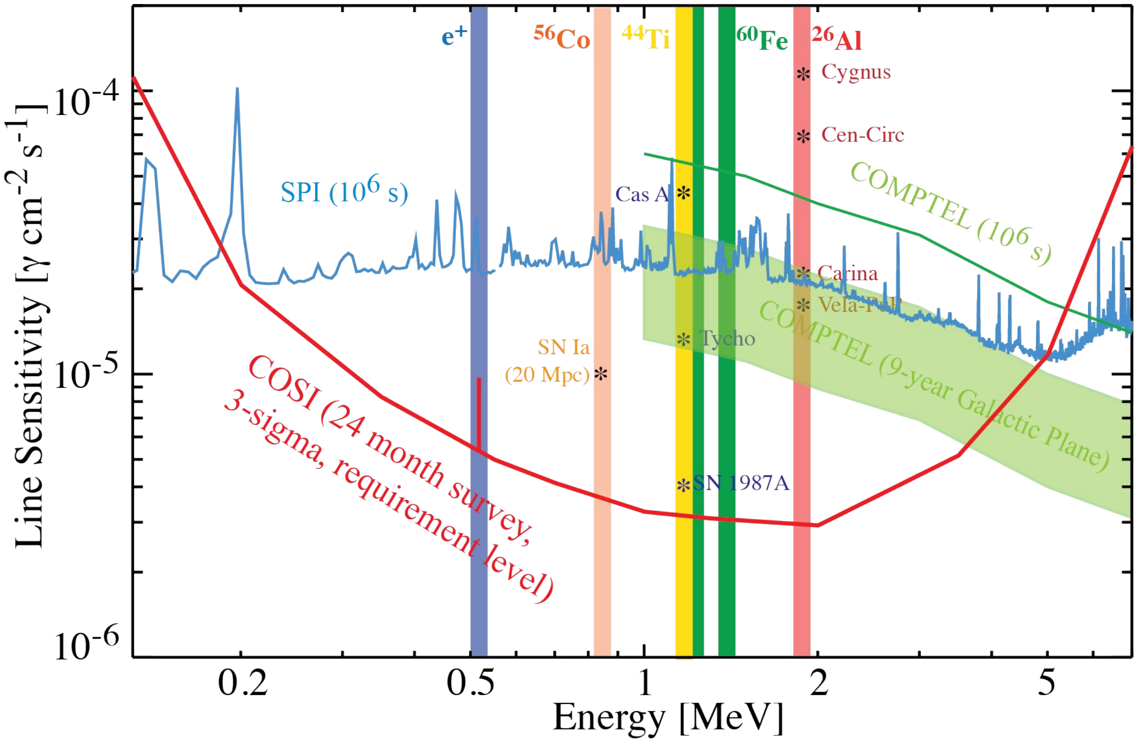


Compton Data Space (CDS)



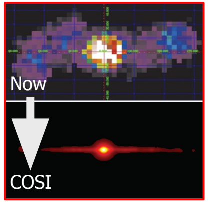
- As photons from a point source at location scatter in the detector, the CDS is populated in the shape of a cone whose apex lies at the source location
- point spread function of a Compton telescope
- extended source will appear as a broadened cone

COSI required line sensitivity

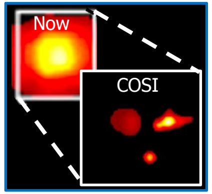


- ❑ COSI will reach the required sensitivity for every source on the sky

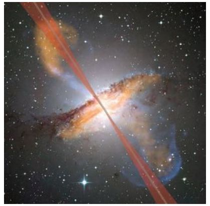
COSI science goals



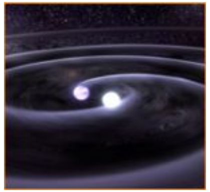
A. Uncover the origin of Galactic positrons



B. Reveal Galactic element formation

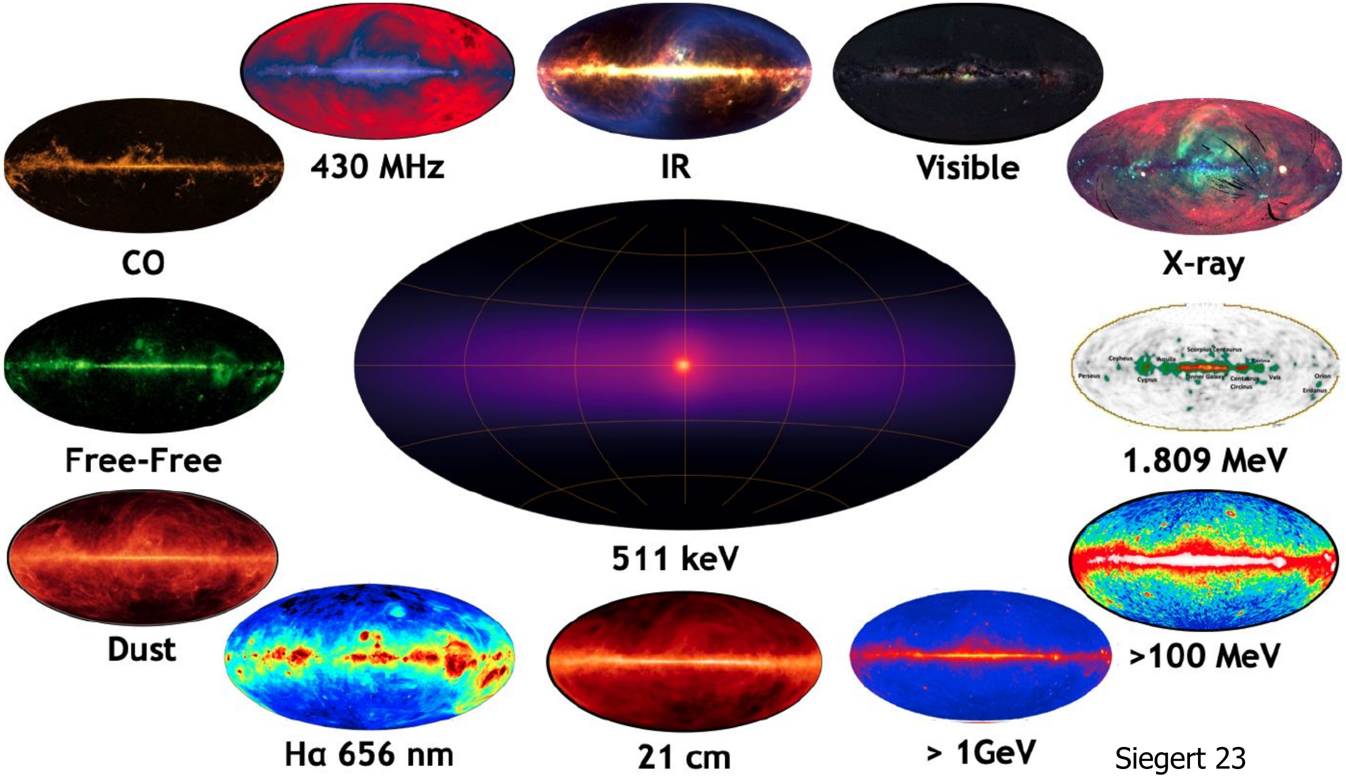


C. Gain insight into extreme environments with polarization



D. Probe the physics of multimessenger events

Goal A: Uncover the origin of Galactic positrons



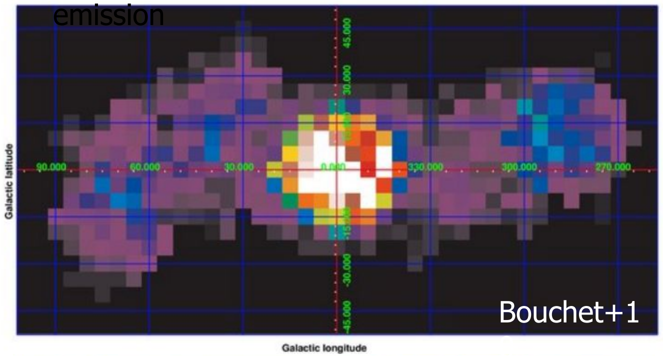
Siegert 23

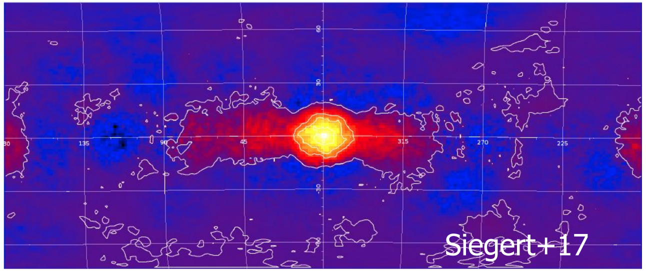
Goal A: Uncover the origin of Galactic positrons

COSI
A Gamma-ray Space Explorer

- COSI traces positrons by measuring the 511 keV e^-e^+ annihilation line
- Current questions:
  - What is producing the ~5×10^{43} e^+/s required to explain the 511 keV signal?
  - What is the reason for the strong excess coming from the Galactic bulge?

INTEGRAL/SPI maps of the 511 keV emission





Positron Production Rates ($\times10^{42}$ e^+/s)

Siegert 17 and Siegert 23: "The Positron Puzzle"

Source	Galaxy	Bulge	Disk
$^{26}Al+^{44}Ti$	5.6±0.3	0.57±0.03	4.9±0.3
Observed	49±15	18.0±0.2	31±15
% explained by $^{26}Al+^{44}Ti$	11%±3%	3.2%±0.3%	16%±6%

Is the 511 keV Galactic bulge excess:
- Truly diffuse?
- Made up of individual sources?
- How many sources or components?

511 keV Galactic substructure

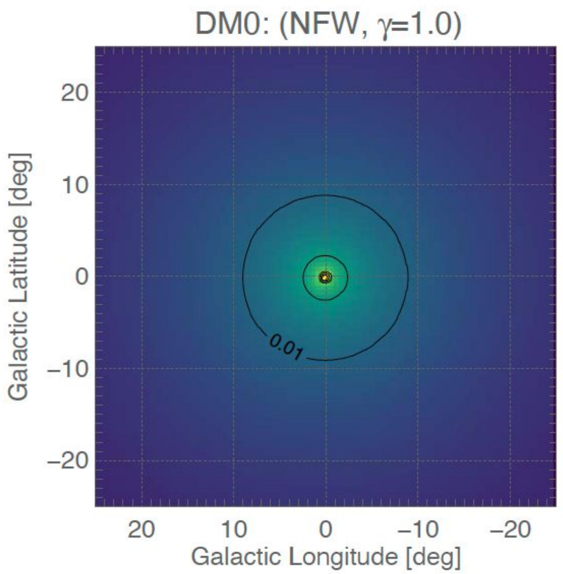
COSI
A Gamma-ray Space Explorer

Candidate Positron Sources

Type of Source	Source
Nucleosynthesis products	^{26}Al from stellar winds
	^{26}Al & ^{44}Ti from CCSNe
	^{56}Ni/^{56}Co from Type Ia SNe
	^{13}N, ^{18}F, ^{22}Na from novae
Individual sources	Low-mass X-ray binaries
	Microquasars
	Sgr A*
	Active stars
	Pulsar winds
	Gamma-ray bursts
	Neutron star mergers
Dark matter	Annihilating MeV DM
	Decaying heavy DM
	Primordial black holes

Contributions are highly uncertain

- 511 keV imaging of the Galaxy with COSI
  - Compare to observed distributions
  - Compare to theoretical distributions
  - Look for individual sources



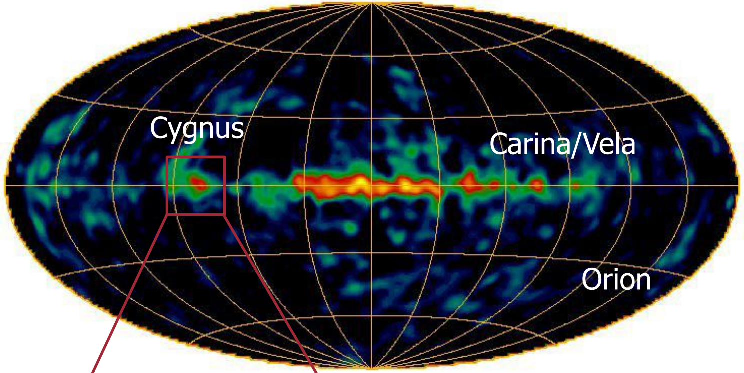
Goal B: Reveal Galactic element formation

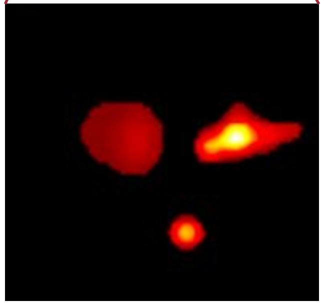
COSI
A Gamma-ray
Space Explorer

Three windows on element formation associated with massive star evolution:

Isotope	Line energies	Half-life	Phase of evolution
^{26}Al	1.809 MeV	0.7 Myr	Includes pre-supernovae (SNe)
^{44}Ti	1.157 MeV	59 yr	Recent core collapse SNe
^{60}Fe	1.173 and 1.333 MeV	2.6 Myr	CCSNe over the past millions of years

COMPTEL ^{26}Al map (Oberlack+96)



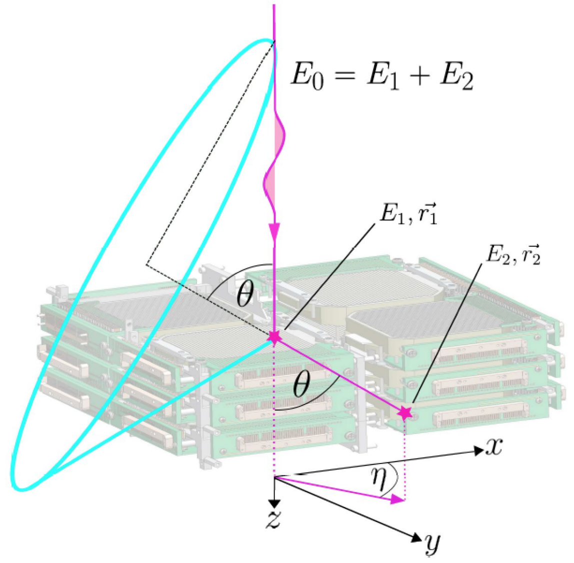


COSI simulation of the Cygnus region at 1.809 MeV after 2 yr

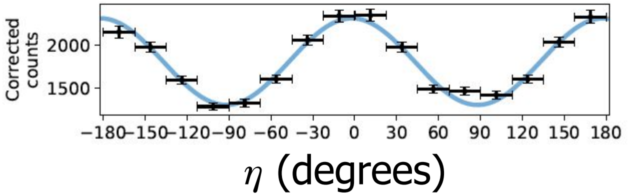
- 10 times better sensitivity
- 2x better angular resolution

Goal C: Gain insight into extreme environments with polarization

- Polarization measurements constrain high-energy emission mechanisms and source geometries
  - Imaging X-ray Polarimetry Experiment (IXPE) making great advances in X-rays (2-8 keV)
- In the MeV band, >50% polarization levels have been measured for:
  - The Crab pulsar (Dean+08; Forot+08)
  - Cygnus X-1 (Laurent+11; Jourdain+12)
  - Some gamma-ray bursts (e.g., McConnell 17)
  - Black hole binary system MAXI J1348-630 (Cangemi, Rodriguez, Belloni, et al.)
- How does COSI measure polarization?
  - The azimuthal scattering angle is polarization-dependent



COSI-balloon: partially polarized source

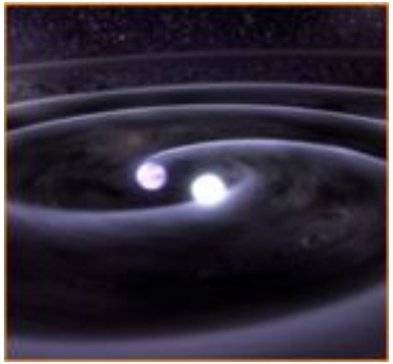


Goal D: Probe the physics of multimessenger events

- Four messengers
  - ***Gamma-rays*** detected by Fermi and INTEGRAL (and COSI starting in 2027)
  - ***Gravitational waves*** detected by LIGO and Virgo facilities
  - ***Neutrinos*** detected by the IceCube facility in Antarctica (high-energy) and, e.g., SuperKamiokande (low-energy)
  - ***Cosmic-rays*** detected by Pierre-Auger, MAGIC, H.E.S.S

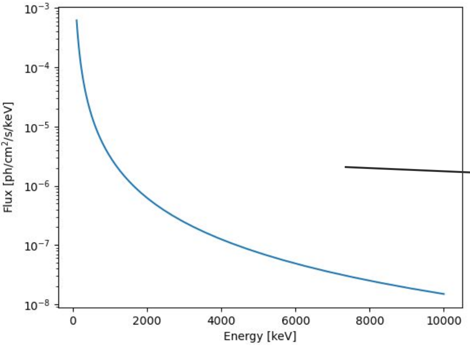
- COSI has connections to all messengers

- Goal D emphasizes the connection to ***gravitational waves***
  - Detects short gamma-ray bursts (GRBs) from merging neutron stars
  - Localizations to ~1° accuracy
  - Public alerts in <1 hour

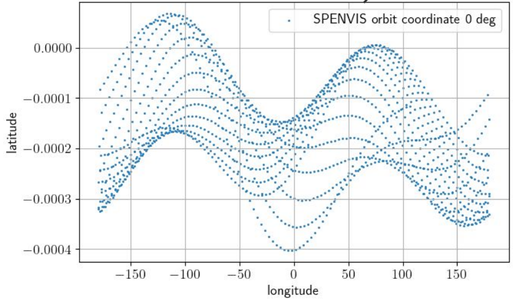


COSItools and Status

COSI
A Gamma-ray
Space Explorer



low-level data analysis



COSItools

MEGAlib
The Medium-Energy Gamma-ray Astronomy library

- general purpose tools not tailored to COSI
- C/C++ based

Pipeline Tools:
- event reconstruction
- response file generation
- source and background simulations

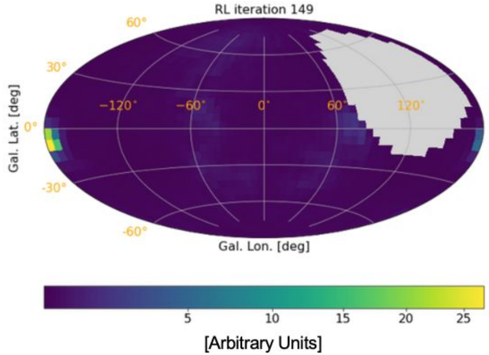
Nuclearizer Calibration
- applies calibration and creates housekeeping files

COSIpy

- user-facing
- python-based

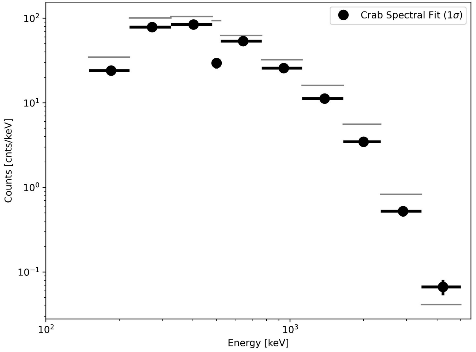
Pipeline Tools:
- background-model generation
- exposure correction

High-level Analysis Tools:
- spectral extraction & fitting
- various imaging tools
- spatial model fitting
- source localization
- transient analysis
- polarization analysis



high-level data analysis

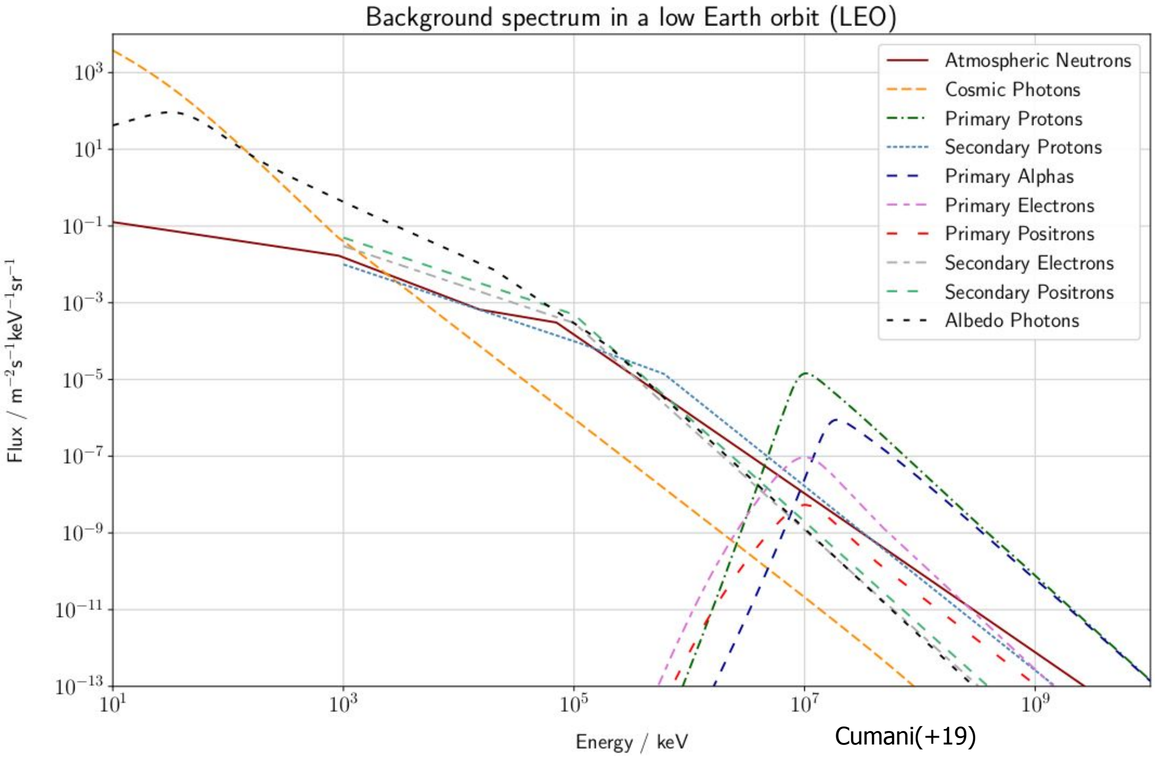
- ❑ Data Challenges released every year until 2026
- ❑ Data Challenge 1 (COSI Balloon) : [GitHub - cositools/cosi-data-challenge-1]
- ❑ Data Challenge 2 (end 2023) : 3-6 month of simulated satellite observations (Signal +background)



[GitHub - cositools/cosi-data-challenge-1]

Background model

- For the current data challenge, a full bottom-up approach will be used for the background model
- 2 categories : Primary particles and secondary particles produced in the atmosphere
- Depend on the Geomagnetic cutoff, solar modulation,passage in the SAA, ect.

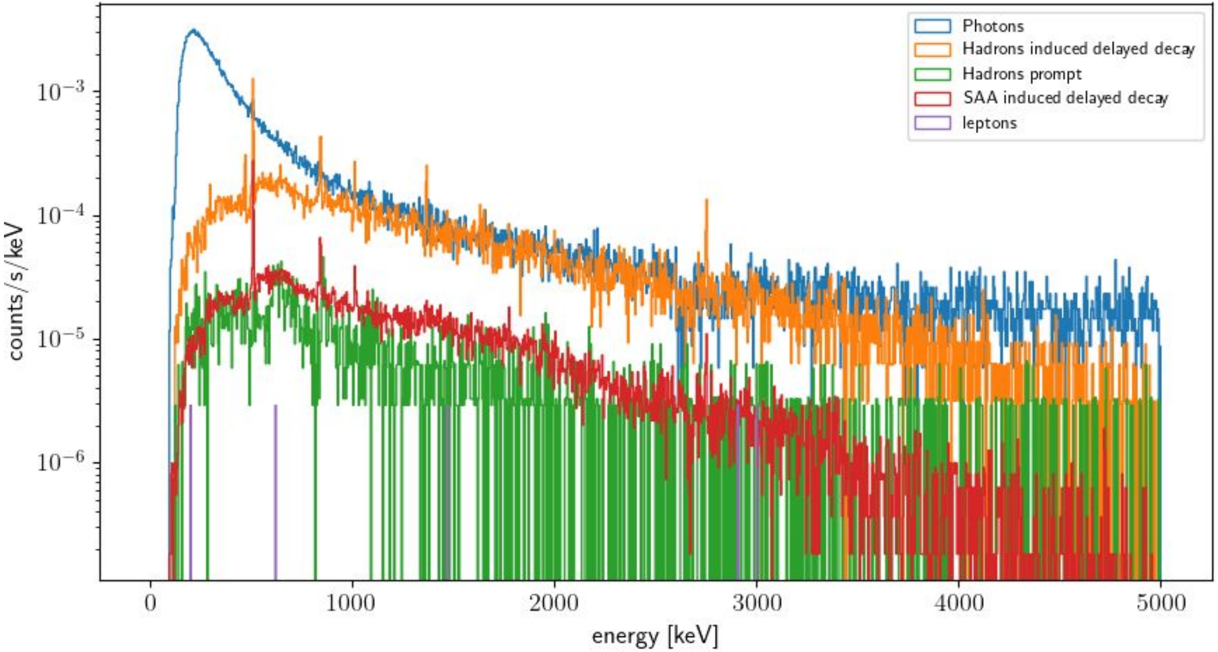


Cumani(+19)

Background model

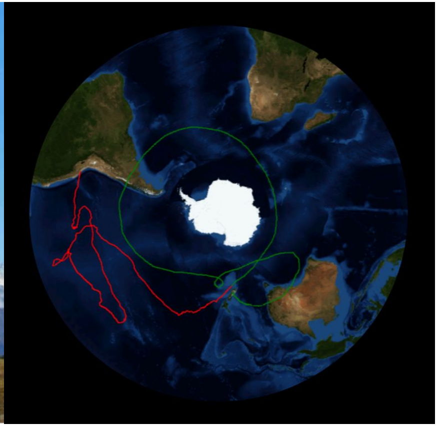
- Allow to see the contribution from each component as function of time, GC, solar modulation , etc…

- Study the background induced by activation (lines)



reconstructed and selected Compton events after 24 hours of exposure time

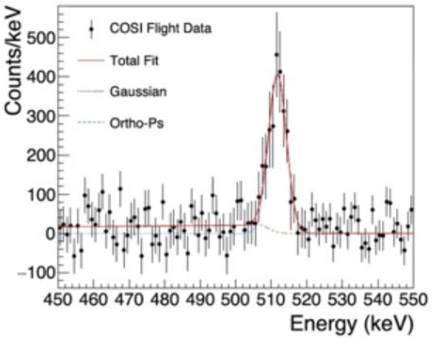
COSI Balloon flight 2016



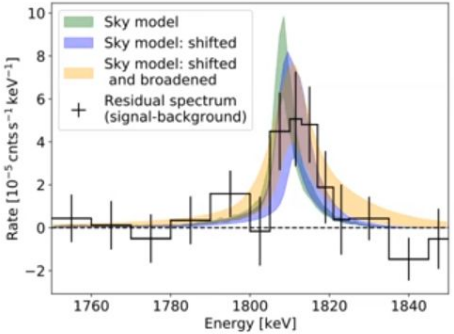
- launched from Wanaka, New Zealand on NASA's Super Pressure Balloon on May 16th, 2016
- 46 days of flight

- Results :
    - GRB 160530A (Lowell+17,Sleator+19)
    - 511 KeV (Kierans+18+20,Siegert+20)
    - ^{26}Al (Beechert+22, ApJ)
    - Crab nebula (Zoglauer+21)
    - Cyg X-1, Cen A (Roberts et al., in prep.)
    - Galactic Diffuse (Karwin et al., submitted)

511 keV from the Galactic bulge

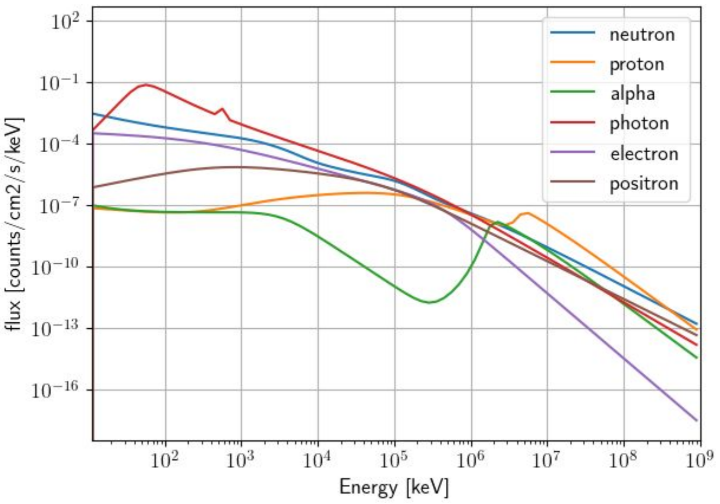


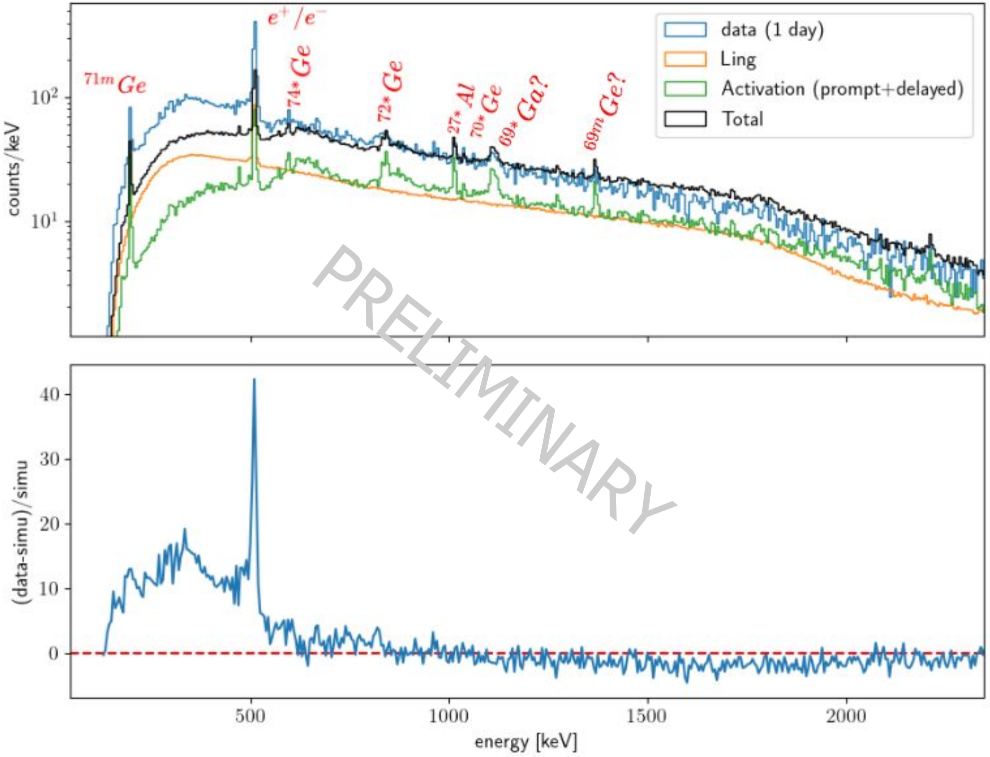
^{26}Al from the Galactic plane



COSI Balloon : Background model test

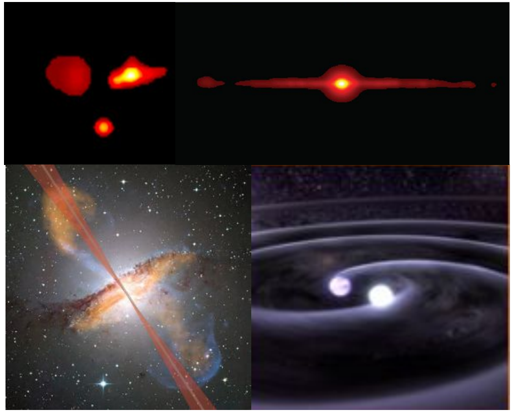
- one day : 6/06/2016
- simulate all background components

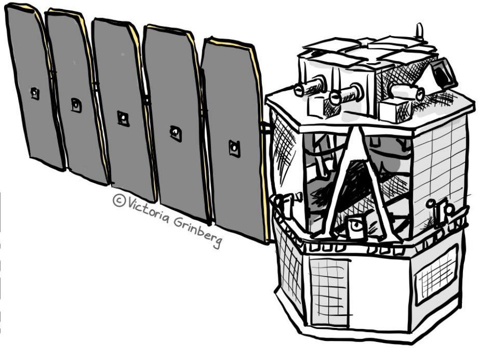




Conclusion

- Exciting prospects for COSI's study of the MeV bandpass starting in 2027
  - Nuclear lines, positron annihilation, polarization, MMA
- Yearly data challenges are an opportunity for community involvement





cosi.ssl.berkeley.edu

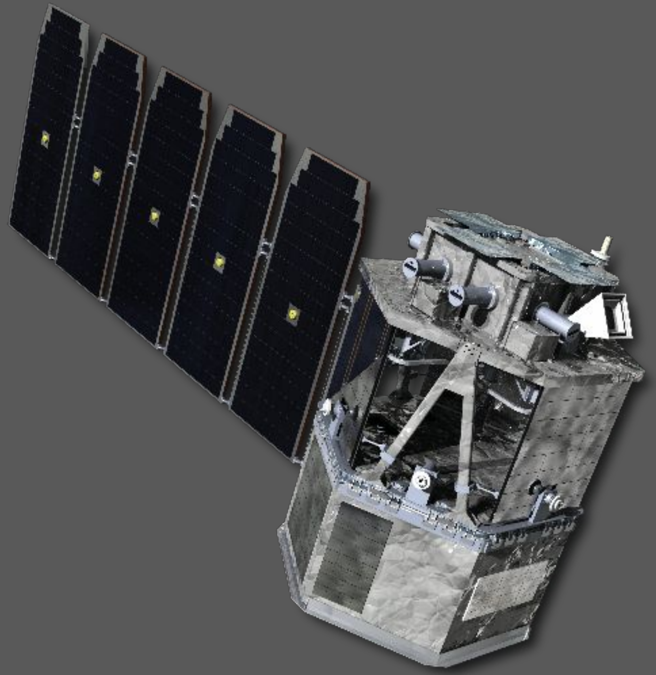
The COSI collaboration

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 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
- INAF, Italy
- IRAP, France
- Kavli IPMU and Nagoya University, Japan
- JMU/Würzburg and JGU/Mainz, Germany
- Science team members as National Tsing Hua University, University of Hertfordshire, North-West University (South Africa), and Yale University

Backup

COSI requirements and measurement goals

COSI
A Gamma-ray Space Explorer

Primarily for goals A+B

Characteristic	Requirement or measurement goal
Sky Coverage	• >25%-sky instantaneous FOV • 100%-sky each day (in survey mode)
Energy Resolution (FWHM)	• 6 keV at 511 keV (FWHM/E = 1.2%) • 9 keV at 1.157 MeV (^{44}Ti) (FWHM/E = 0.8%)
Narrow Line Sensitivity (2 yr, 3σ, point source) 0.511 MeV 1.8 MeV	[photons cm^{-2} s^{-1}] • 1.2x10^{-5} (Galactic bulge is 100x brighter than requirement level) • 3x10^{-6} (Galactic ^{26}Al flux is 230x brighter than requirement level)
Angular Resolution (FWHM)	• ~2° at 1.8 MeV (^{26}Al, ~2x better than COMPTEL)

Goal C

Accreting BH polarization	• Reaches bright AGN in 2 yr: Cen A, 3C 273, NGC 4151 • Reaches several persistent Galactic BHs (plus transients)
GRB polarization	• ≥30 GRBs with polarization measurements (goal in 2 yr)

Goal D

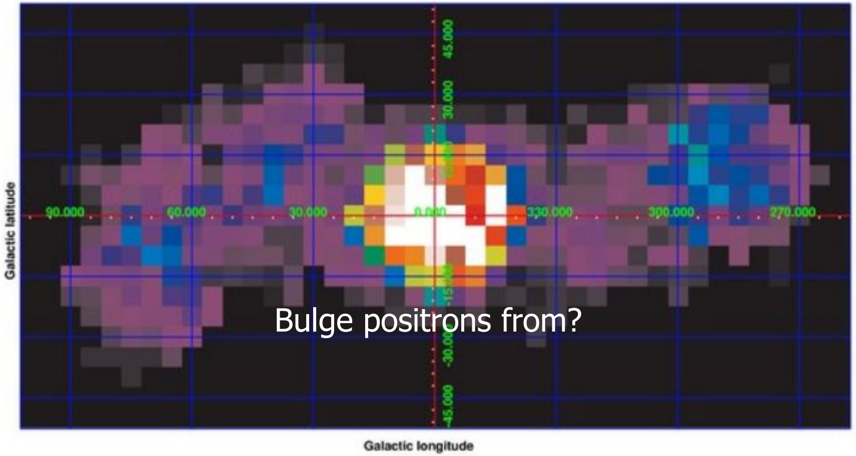
Short GRB detection, localization, and reporting	• ≥10 short GRBs (goal in 2 yr) • Reporting localizations in <1 hr

Science opportunities in the MeV bandpass

COSI
A 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)
  - Multimessenger sources

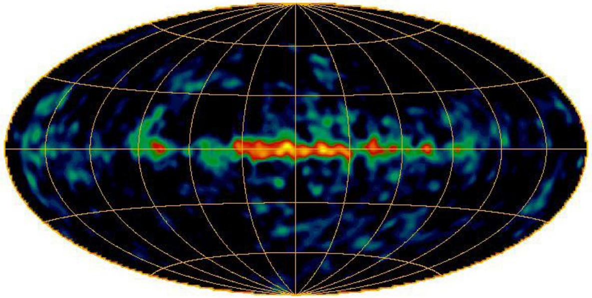
INTEGRAL/SPI (Bouchet+10)



Is the 511 keV Galactic bulge excess:
- Truly diffuse?
- Made up of individual sources?
- How many sources or components?

Science opportunities in the MeV bandpass

- 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)
  - Multimessenger sources



COMPTEL map of ^{26}Al emission (Oberlack+97, Pluschke+01)

Three windows on element formation associated with massive star evolution:

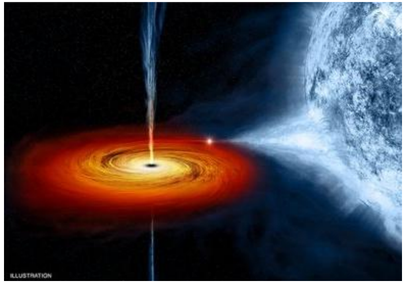
- ^{26}Al (1.809 MeV) traces massive stars, including **pre-supernova** (SN)
- ^{44}Ti (1.157 MeV) traces **recent** SN activity
- ^{60}Fe (1.173/1.333 MeV) traces SN activity over **the past few million years**

Science opportunities in the MeV bandpass

- 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)
  - Multimessenger sources

Potential high levels of polarization

- ~70% above 0.4 MeV for Cygnus X-1 (Laurent+11; Jourdain+12)
- What about other Galactic black holes?
- GRB distribution?
- AGN?

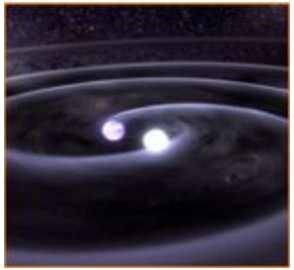


Cygnus X-1

AGN: Cen A

Science opportunities in the MeV bandpass

- ❑ 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)
  - ❑ Multimessenger sources →



- GW signature (GW170817)
- Short GRB

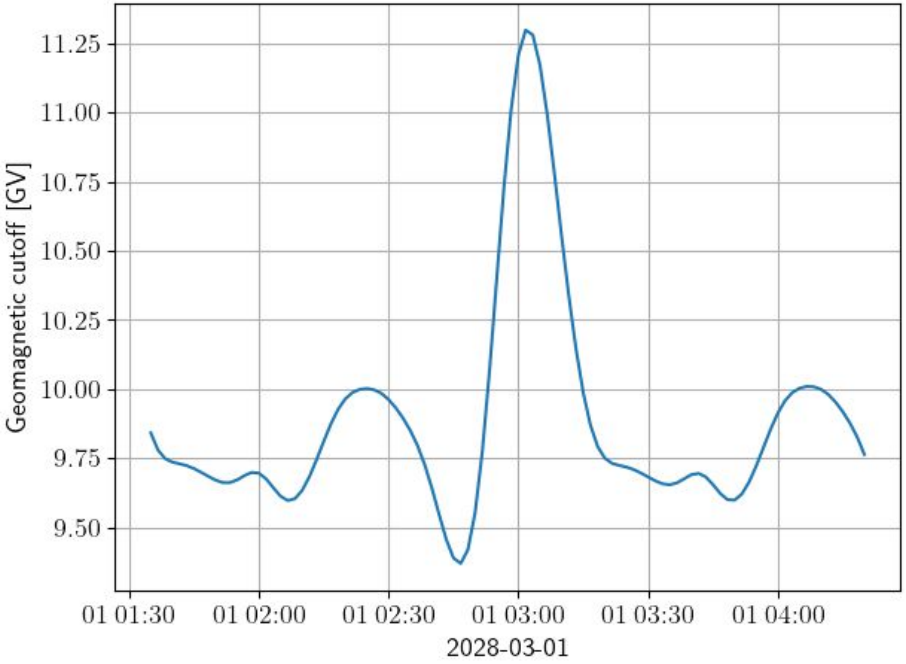
- COSI provides gamma-ray measurements that has potential connections to all messengers (gravitational waves, neutrinos, and cosmic rays)

Geomagnetic cutoff (GC)

- GC will vary in the range [9-11.5] GV for a equatorial orbit at 550km of altitude

- Dipole approximation (Smart et al. 2005) using IGRF value for g10

$$GC = \frac{g_0^1 \cdot R_{Earth}}{4} \cdot \left(1 + \frac{h}{R_{Earth}}\right)^{-2} \cos^4(\lambda)$$

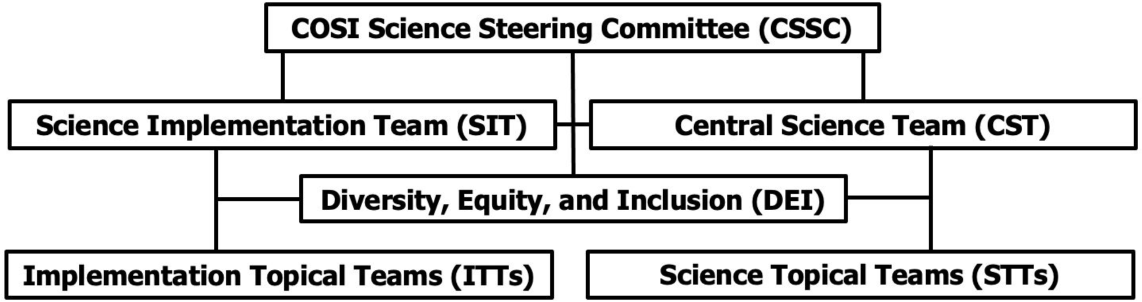


Science team structure

COSI
A Gamma-ray
Space Explorer

Subgroup	Lead	Co-Leads	Technical Expert(s)
Positrons	Carolyn Kierans (GSFC)	Thomas Siegert (JMU, Germany)	Thomas Siegert (JMU, Germany)
Nucleo-synthesis	Thomas Siegert (JMU, Germany)	Chris Fryer (LANL)	Hiroki Yoneda (JMU, Germany)
GRBs	Eric Burns (LSU)	Steve Boggs (UCSD), Dieter Hartmann (Clemson)	Alyson Joens (UCB) Eliza Neights (GSFC)
Galactic	Julien Malzac (IRAP, France)	Chris Karwin (GSFC)	Chris Karwin (GSFC)
Extragalactic	Marco Ajello (Clemson)	Fabrizio Tavecchio (INAF, Italy)	Jarred Roberts (UCSD)
Dark Matter	Tad Takahashi (IPMU, Japan)	Fabrizio Tavecchio (INAF, Italy), Shigeki Mastumoto (IPMU, Japan), Tom Melia (IPMU, Japan)	Thomas Siegert (JMU, Germany)

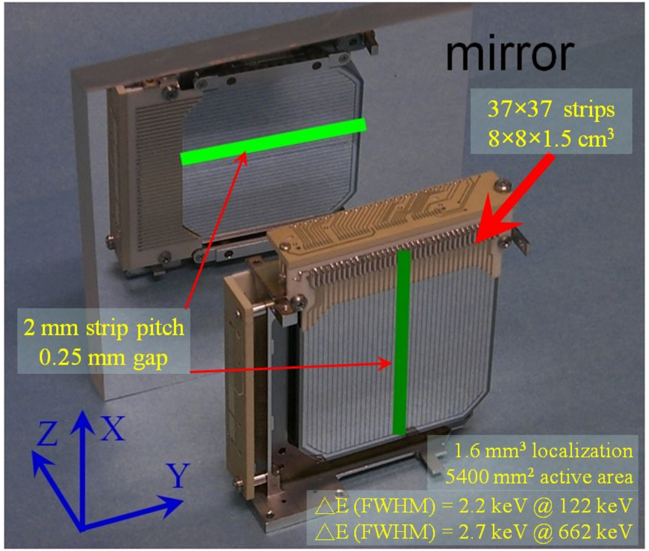
- CSSC:
  - John Tomsick
  - Andreas Zoglauer
  - Dieter Hartmann

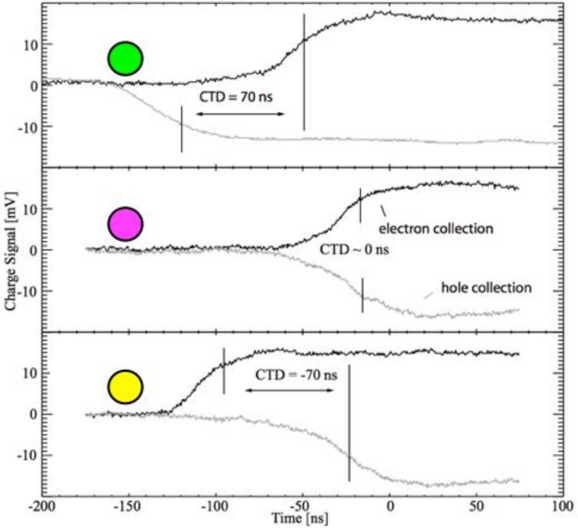


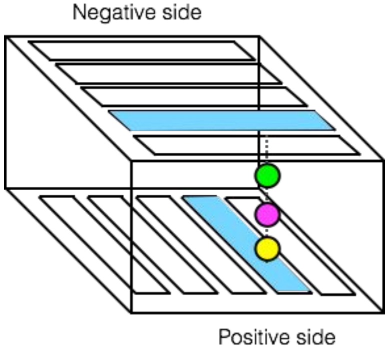
Germanium double-sided strip detectors (GeDs)

COSI
A Gamma-ray
Space Explorer

- ❑ Semiconductor detectors at cryogenic temperatures
- ❑ Voltages of 1000-1500 V across the two sides
- ❑ 3-dimensional position sensitivity



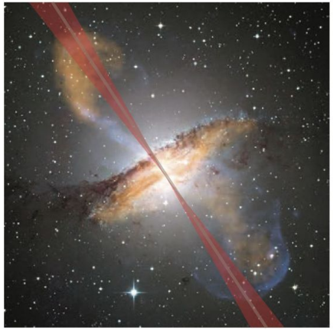


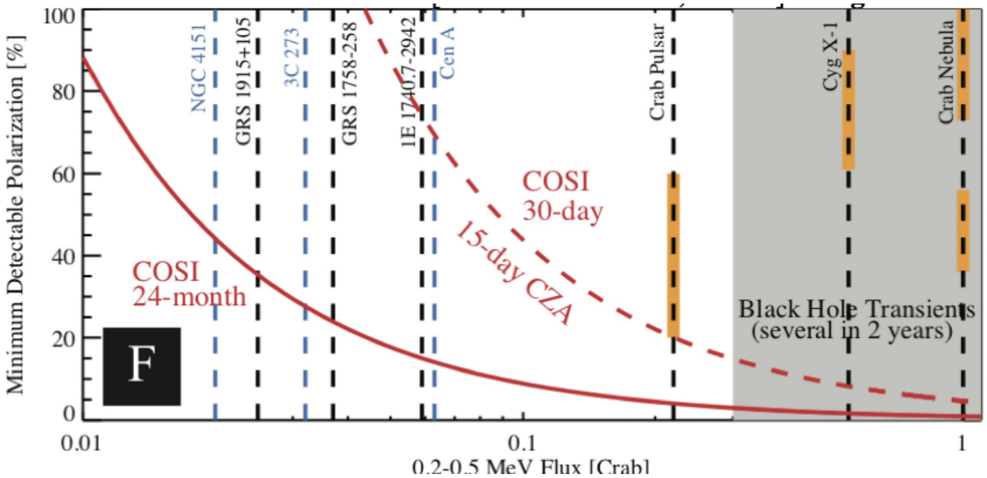


- ❑ Uses orthogonal strips to measure x and y
- ❑ Uses collection time difference (CTD) to measure z

COSI AGN Science: Polarization

- Polarization measurements provide unique diagnostics for determining emission mechanisms and source geometries (e.g., magnetic field, accretion disk, and jet)





- AGN like Cen-A, 3C 279, 3C 454.3, etc. bright enough to be detected in steady state
- Several other flaring blazars will also be detected on the 1-2 week timescale

COSI observational summary

COSI
A Gamma-ray
Space Explorer

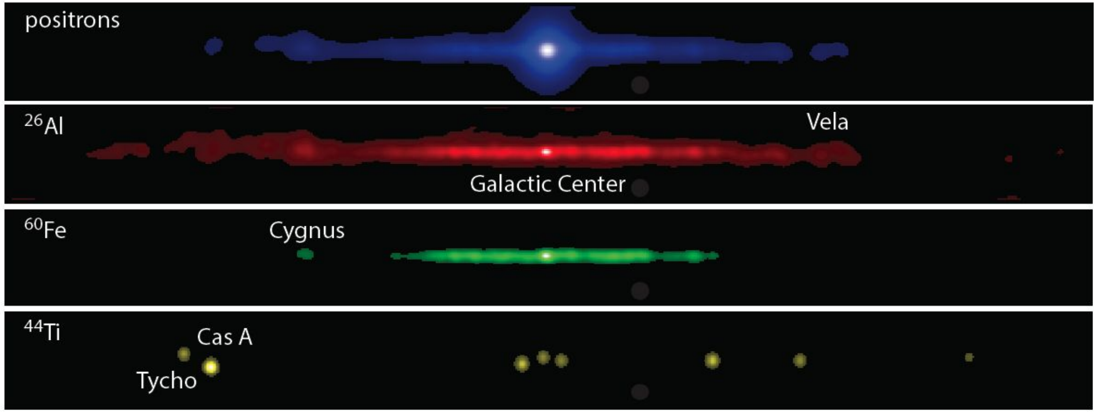
Transient science

- ❑ 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

Emission line science

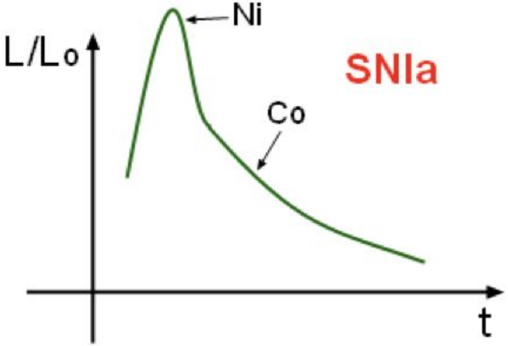


COSI comparisons:

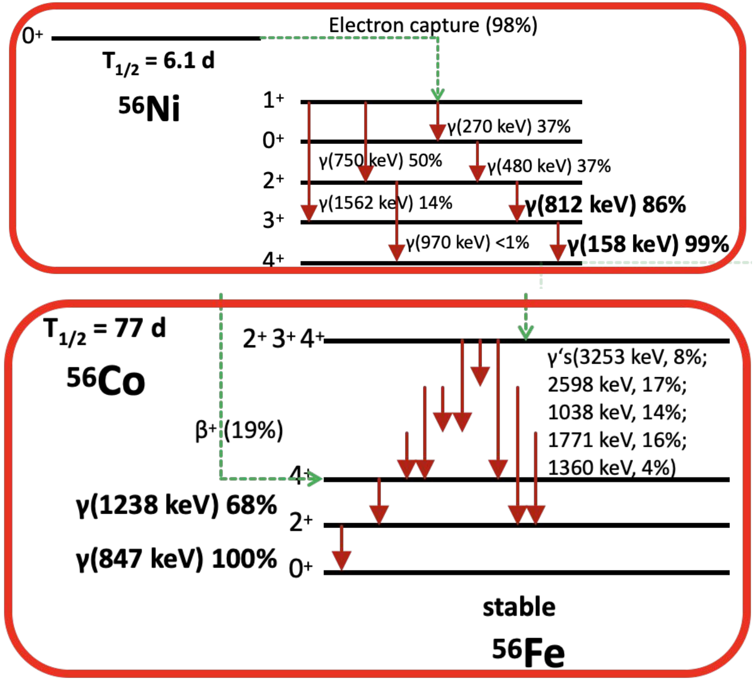
- Obtains 46-day balloon 511 keV sensitivity in ~1 day
- Energy resolution is >20x better than COMPTEL
- FOV is 4x larger than COMPTEL and 12x larger than INTEGRAL

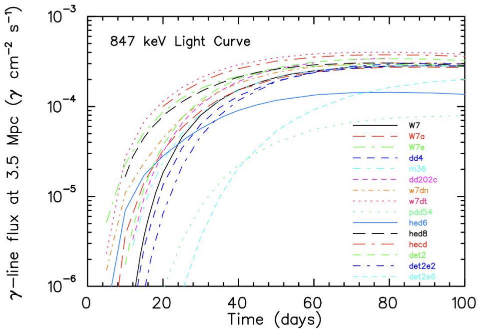
COSI and SNIa

COSI
A Gamma-ray
Space Explorer



The bolometric (dominated by optical) luminosity is powered by ^{56}Ni and ^{56}Co





COSI's 3σ sensitivity at 847 keV (at requirement levels):

- **10^{-5} ph/cm^2/s in 100 days in survey mode**

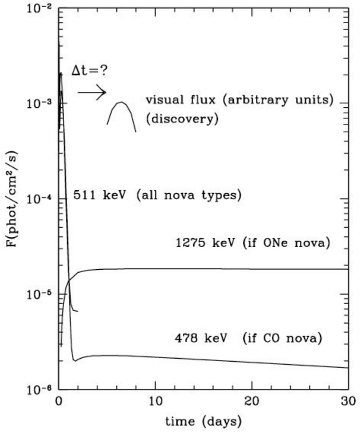
Distance	Predicted flux (median of models)
3.5 Mpc	3.0×10^{-4} ph/cm^2/s
10 Mpc	4.0×10^{-5} ph/cm^2/s
20 Mpc	1.0×10^{-5} ph/cm^2/s

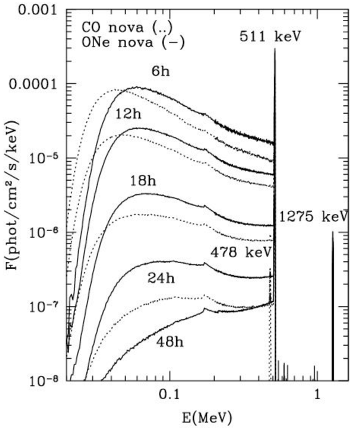
Expect ~two SNIa per year within 20 Mpc

Classical novae, magnetars, Galactic SNe

❑ Classical novae

- Predicted (Hernanz+05) 511 keV line and gamma-ray continuum have not been seen *because the explosion and gamma-ray emission occur several days before the optical nova*
  - COSI's all-sky-every-day coverage is the right strategy
  - ~1 event per year <2 kpc

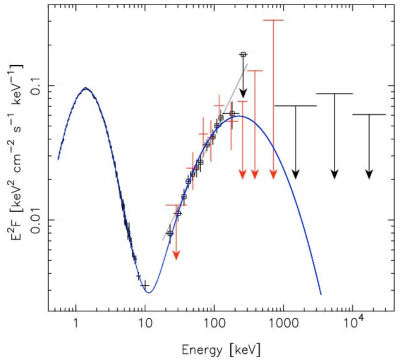




❑ Magnetars

❑ Galactic CCSNe

- Nuclear lines from more than ten different radioactive nuclei in the SN ejecta to probe asymmetries in the SN engine and details of the burning layers in the progenitor star
- Shock breakout (Margutti+12)
- Collision with binary (Kasen+10)



- 4U 0142+61 is one of nine magnetars detected at >20 keV in quiescence
- COSI will be capable of measuring outburst emission and bursts