MeV gamma-ray astronomy and COSI

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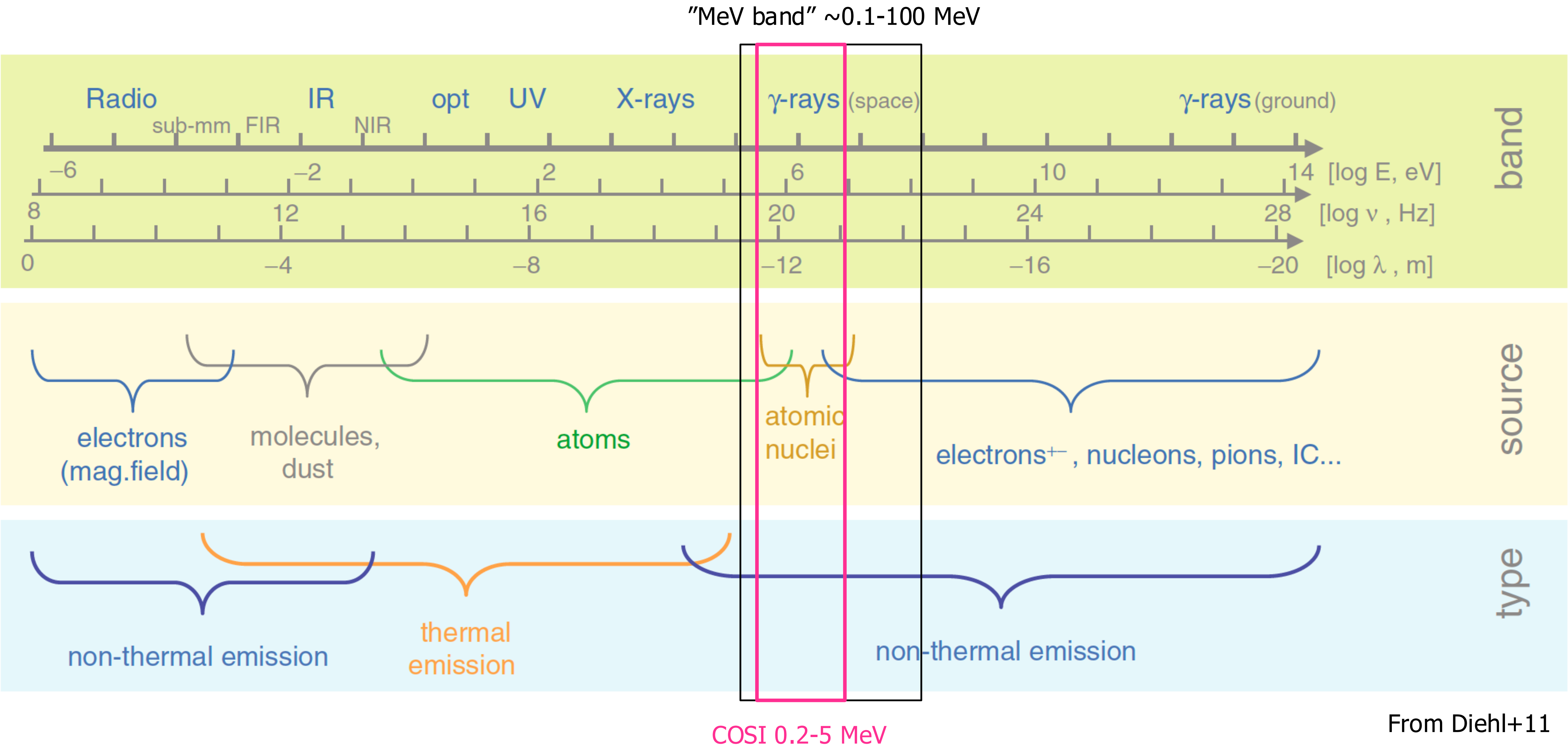
Overview

- The MeV gamma-ray landscape
  - Sources and types of emission
  - Scientific objectives
  - Detecting MeV gamma rays
  - What did past observations show? COMPTEL and INTEGRAL
- COSI
  - Upcoming (Aug 2027 launch) NASA Small Explorer for MeV gamma rays
- Beyond COSI
  - Next generation wish list and current concepts

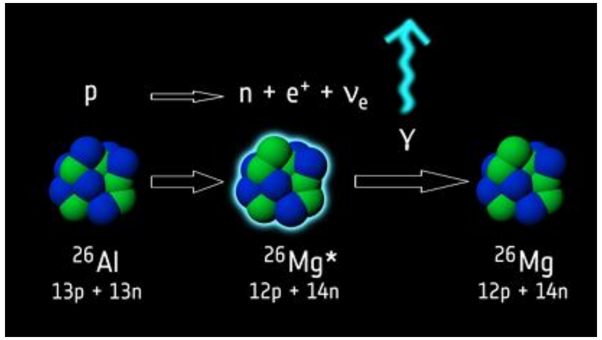
Sources and types of emission – MeV definition



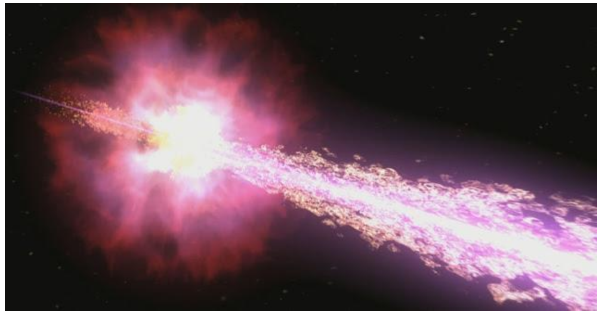
From Diehl+11

Scientific objectives and measurement capabilities needed

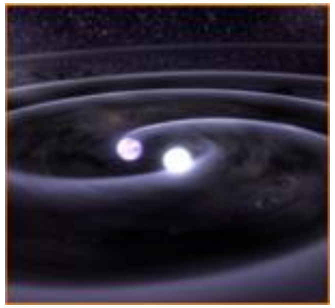
- Understanding element formation
  - Capability: ***50 keV – 10 MeV spectroscopy with <1% energy resolution*** for nuclear line detection



- Understanding relativistic jets (e.g., hadronic vs. leptonic)
  - Capability: ***100 keV – 10 GeV polarimetry***



- Revealing the origins and mechanisms of cosmic explosions
  - Capability: ***Large FOV keV/MeV/GeV coverage for detection and localization of transients***
  - Along with gravitational waves, high-energy neutrinos, and new optical capabilities (Rubin, Roman – launched on Sunday!)

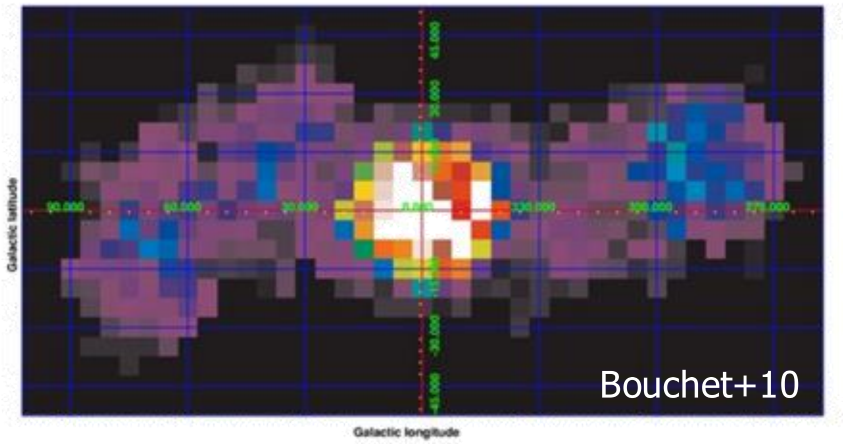


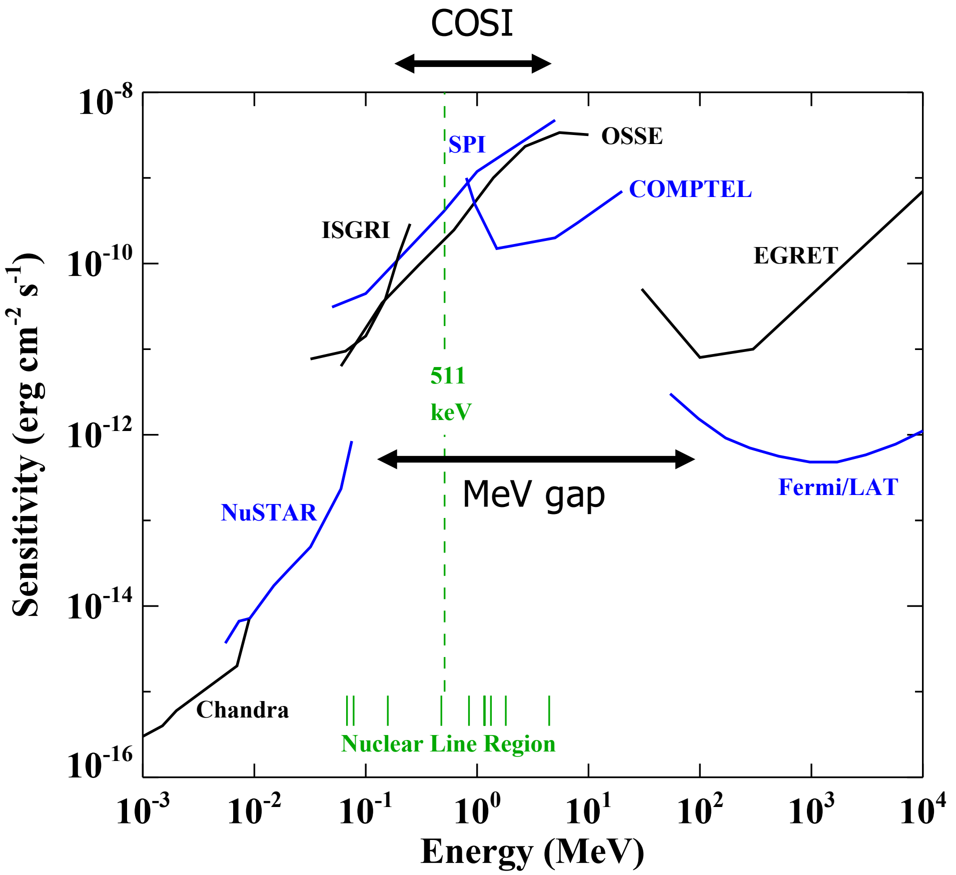
- Extreme environments and fundamental physics
  - Indirect dark matter searches (***MeV/GeV/TeV sensitivity***)

List based on recent (2026) Gamma ray Science Interest Group (GammaSIG) white paper (4/5 include MeV coverage)

The MeV gap

- Previous missions have had relatively poor sensitivity in the MeV range
- Discovery space where there is known to be interesting physics
  - Element formation and gamma-ray emission lines from nucleosynthesis
  - Accreting black holes and relativistic jets
  - Multimessenger sources
  - e^-e^+ annihilation line at 511 keV

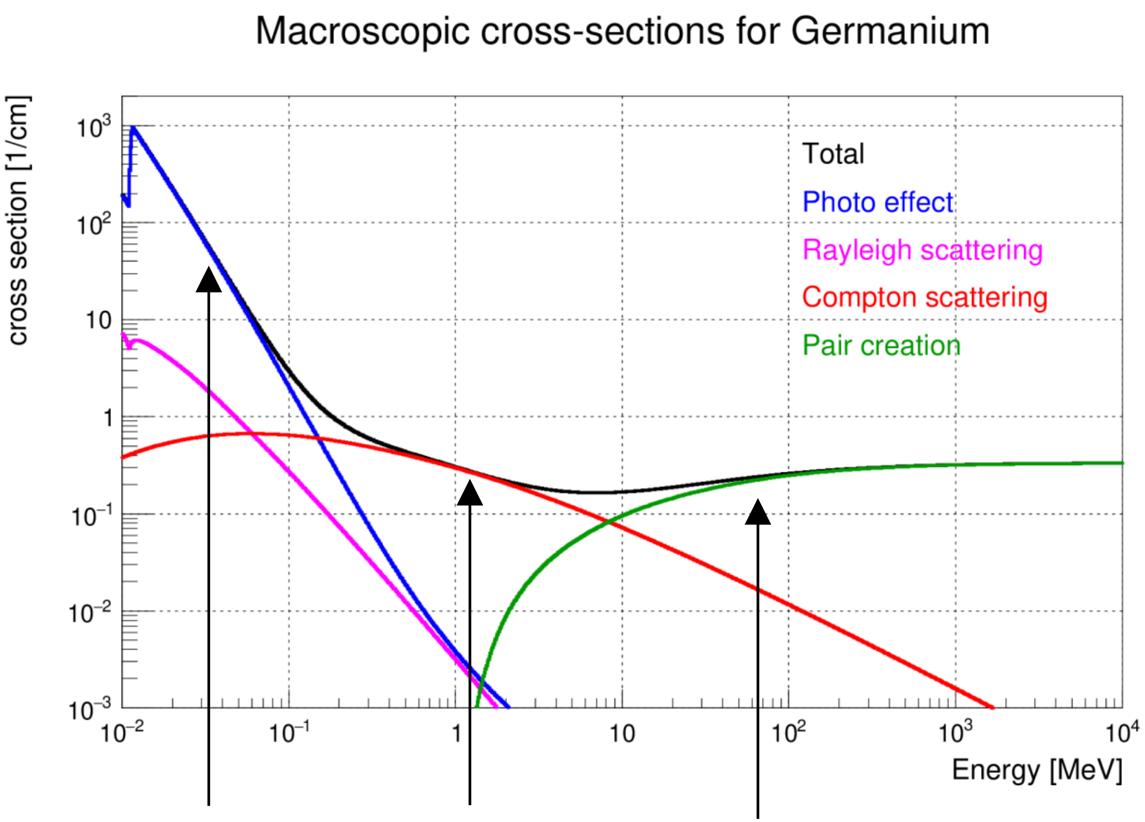




Missions/instruments with COSI connections:

- CGRO/COMPTEL (1991-2000): Compton telescope
- INTEGRAL/SPI (2002-2025): germanium detectors
- Fermi/LAT (2008-now): all-sky coverage every day
- NuSTAR (2012-now): nuclear line spectroscopy

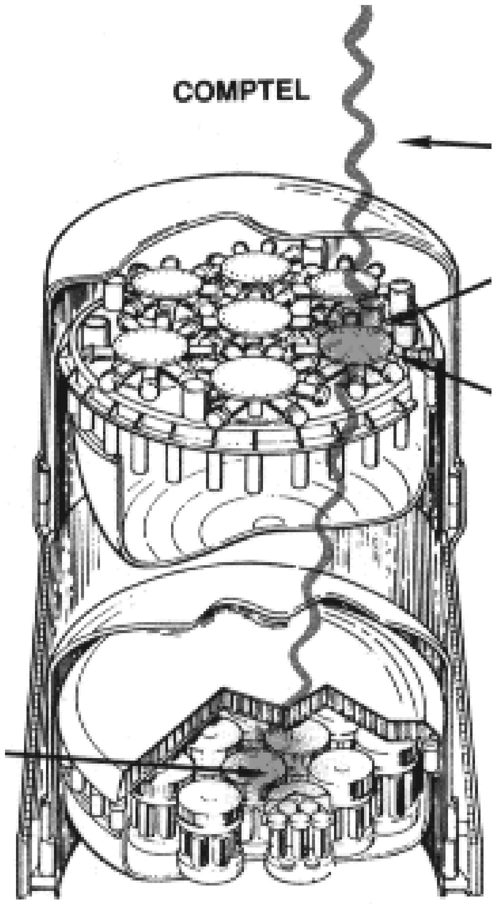
Detecting MeV gamma rays and COMPTEL/CGRO



Full photon absorption (NuSTAR, etc.)

Compton telescopes (COMPTEL, COSI)

Pair creation telescopes (Fermi/LAT)

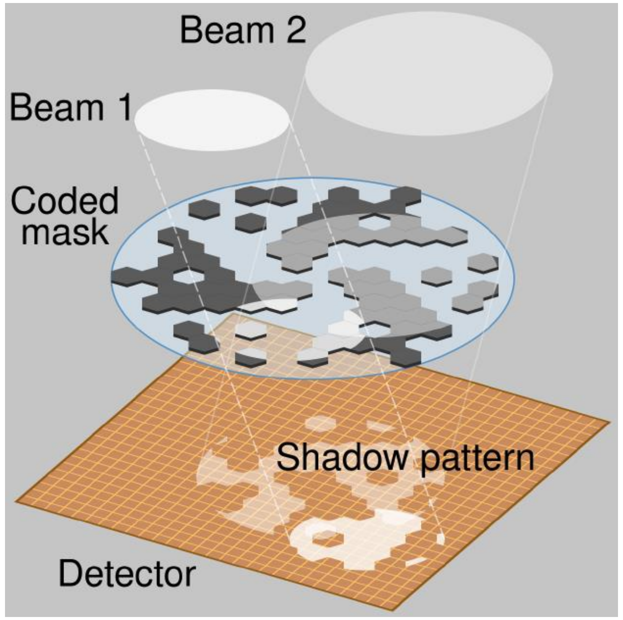


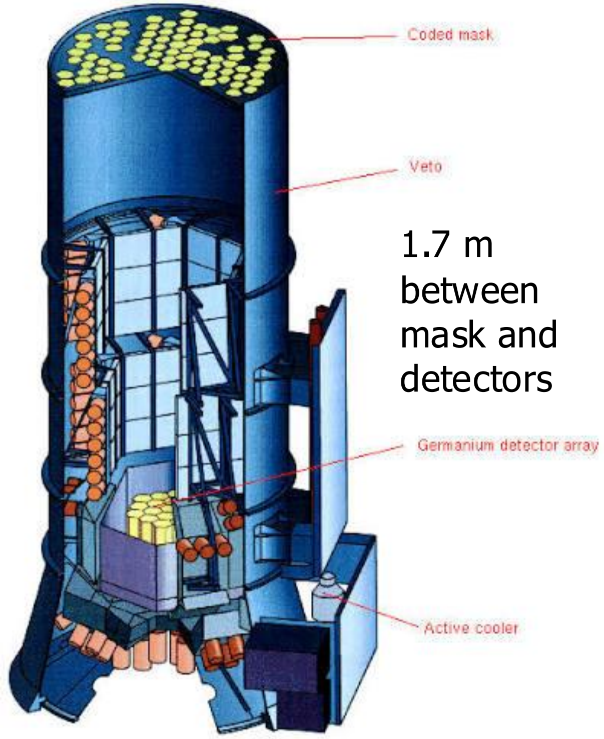
1.5 m between detector planes

COMPTEL instrument on the Compton Gamma-ray Observatory (CGRO)
1991-2000, 1-30 MeV

INTEGRAL

- Three instruments that all used the coded aperture mask technique
  - JEM-X 3-20 keV
  - IBIS 15 keV – 10 MeV
  - SPI 20 keV – 8 MeV





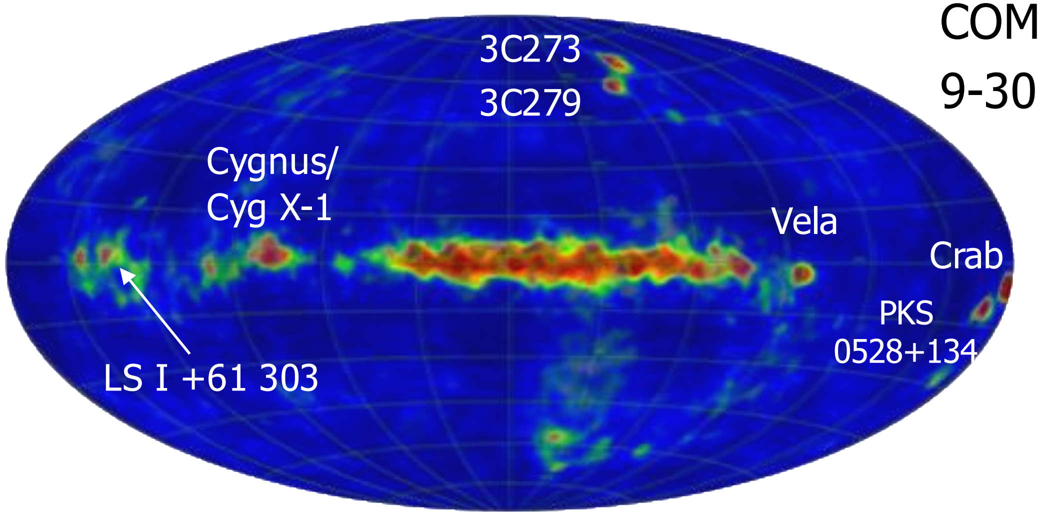
1.7 m between mask and detectors

SPI - Spectrometer on-board the INTEGRAL satellite
2002-2025, 20 keV – 8 MeV

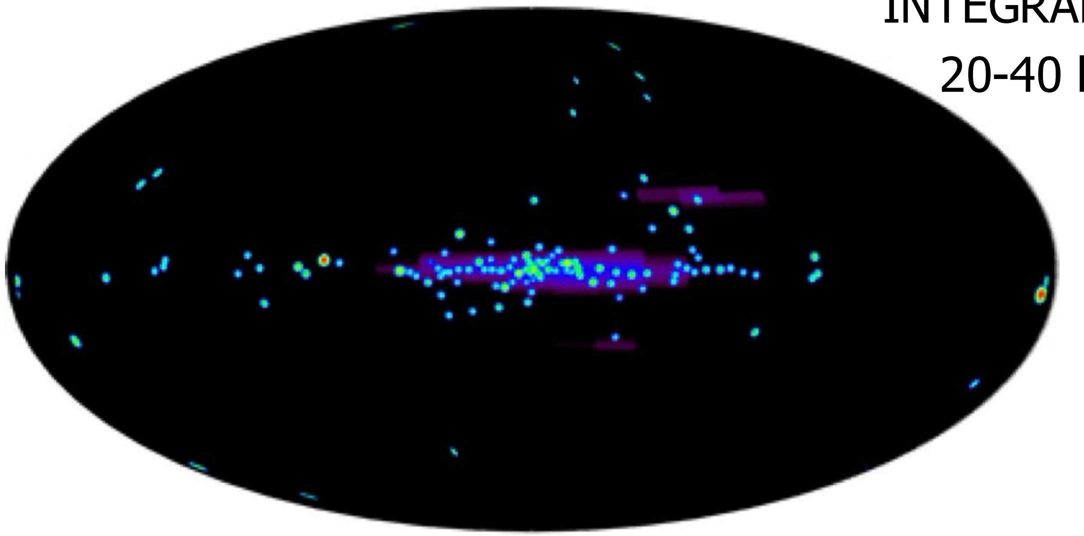
COMPTEL and INTEGRAL – broadband images and source detection

COSI Gamma-ray Space Explorer

- COMPTEL detected 63 sources during its mission (Schönfelder+00, Strong & Colmar 2019)
  - 32 steady (e.g., AGN, pulsars, gamma-ray binaries)
  - 31 GRBs
- INTEGRAL detected hundreds of point sources (e.g., HMXBs, Intermediate Polars), but primarily at <100 keV
  - Several source catalogs using IBIS by Bird+ and Krivonos+



COMPTEL
9-30 MeV



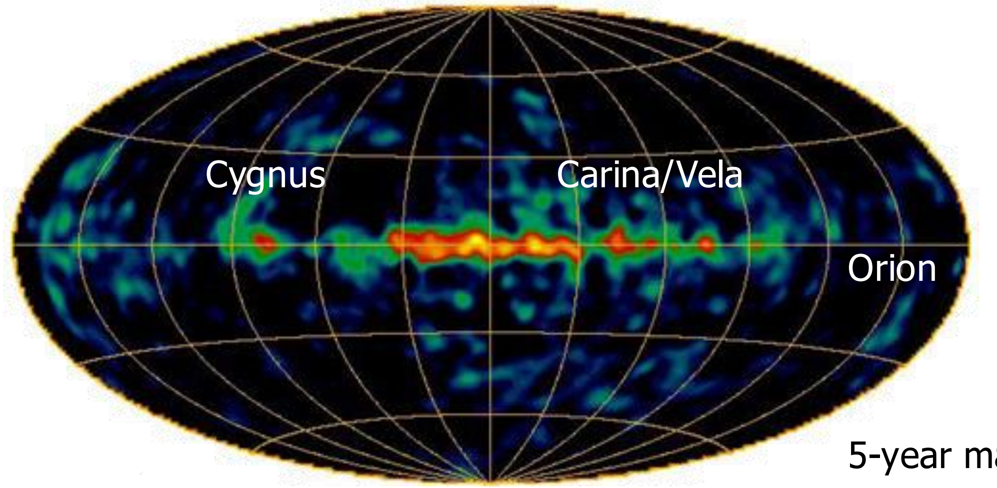
INTEGRAL/IBIS
20-40 keV

COMPTEL and INTEGRAL - emission line maps

- COMPTEL mapped the 1.8 MeV emission line
  - Detection of massive star regions, showing that they generate ^{26}Al and release it into the ISM (likely in winds and in supernova explosions)
- INTEGRAL mapped the 511 keV line
  - Galactic Bulge excess detected at very high significance
  - Other identified Galactic features have chance detection probabilities in the 2%-8% range
  - Possible extragalactic detections

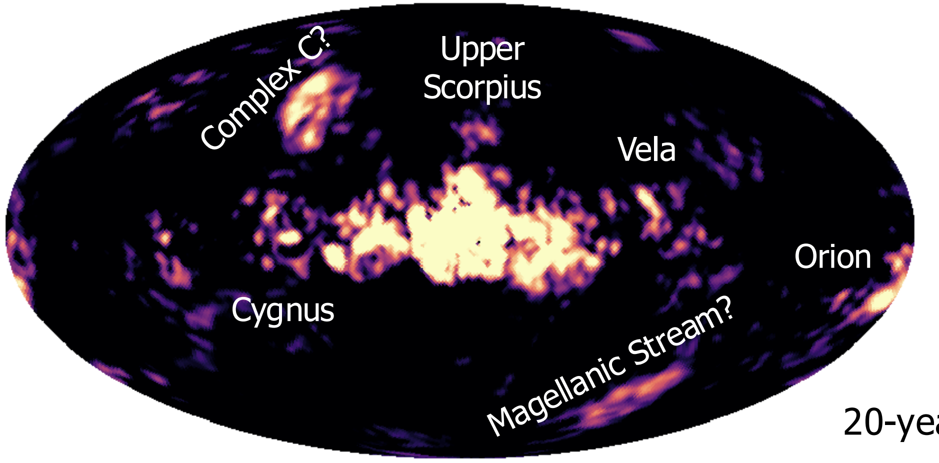
  (see Knödlseder+05, Weidenspointner+08, Bouchet+10, Siegert+17, Yoneda+25, Siegert & Yoneda 2025)
- Great advances, but better line sensitivity is needed

COMPTEL ^{26}Al map at 1.8 MeV (Oberlack+96)



5-year map

INTEGRAL/SPI 511 keV map (Yoneda+25)



20-year map

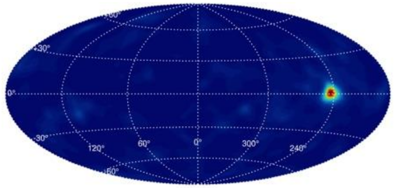
Compton Spectrometer and Imager

- COSI is a NASA Small Explorer (SMEX) satellite with a planned launch on a SpaceX Falcon 9 from Cape Canaveral, Florida in Aug 2027

- Compton telescope operating in the 0.2-5 MeV gamma-ray bandpass

- Unique combination of capabilities
  - Uses germanium detectors (GeDs) for ***excellent energy resolution (FWHM/E ≲ 1%)***
  - Instantaneous field of view is ***>25%-sky*** and covers the whole sky every day

- History/Status
  - COSI-balloon flights: 2005, 2009, 2014, 2016
  - COSI-SMEX proposed in 2019 and started in 2020
  - Current Status
    - Payload Flight Model at Space Sciences Laboratory (Berkeley, California)
    - Spacecraft Bus at Northrop Grumman (Stirling, Virginia)



Ballooning heritage, including 46-day flight around the World in 2016

The COSI collaboration

University of California, Berkeley

University of California, San Diego

Naval Research Laboratory

Goddard Space Flight Center

Space Dynamics Laboratory

Northrop Grumman

Italian Space Agency (ASI)

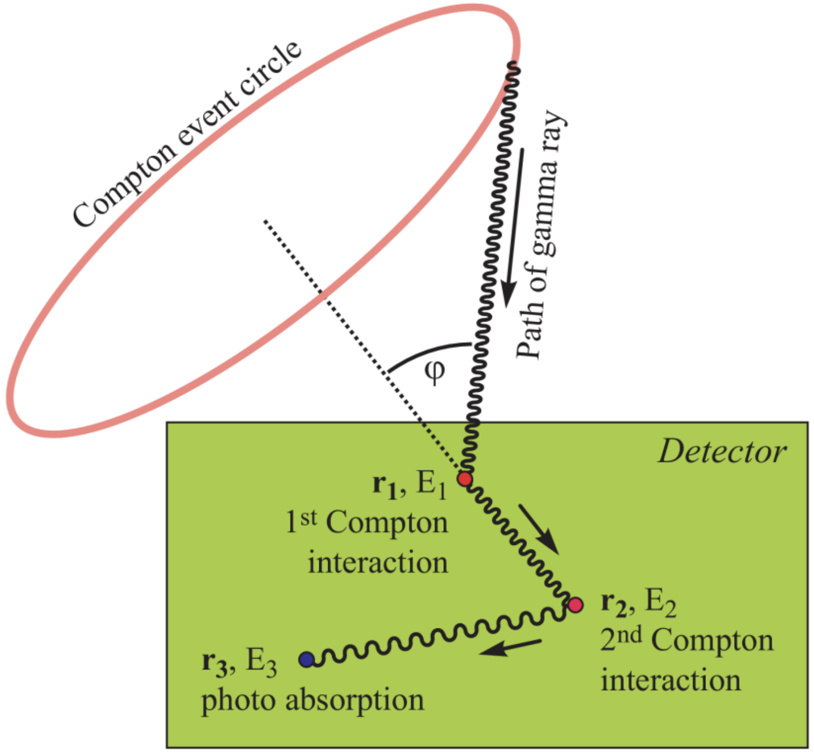
German Aerospace Center (DLR)

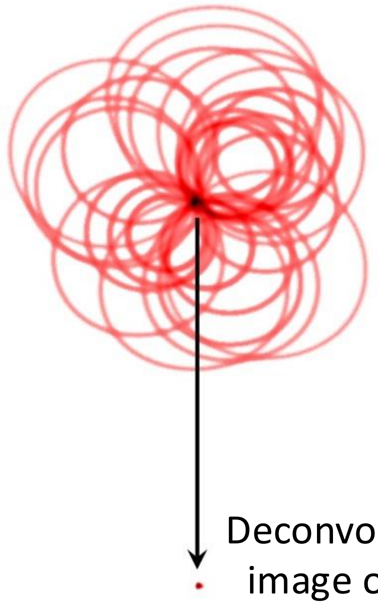
French National Space Agency (CNES)

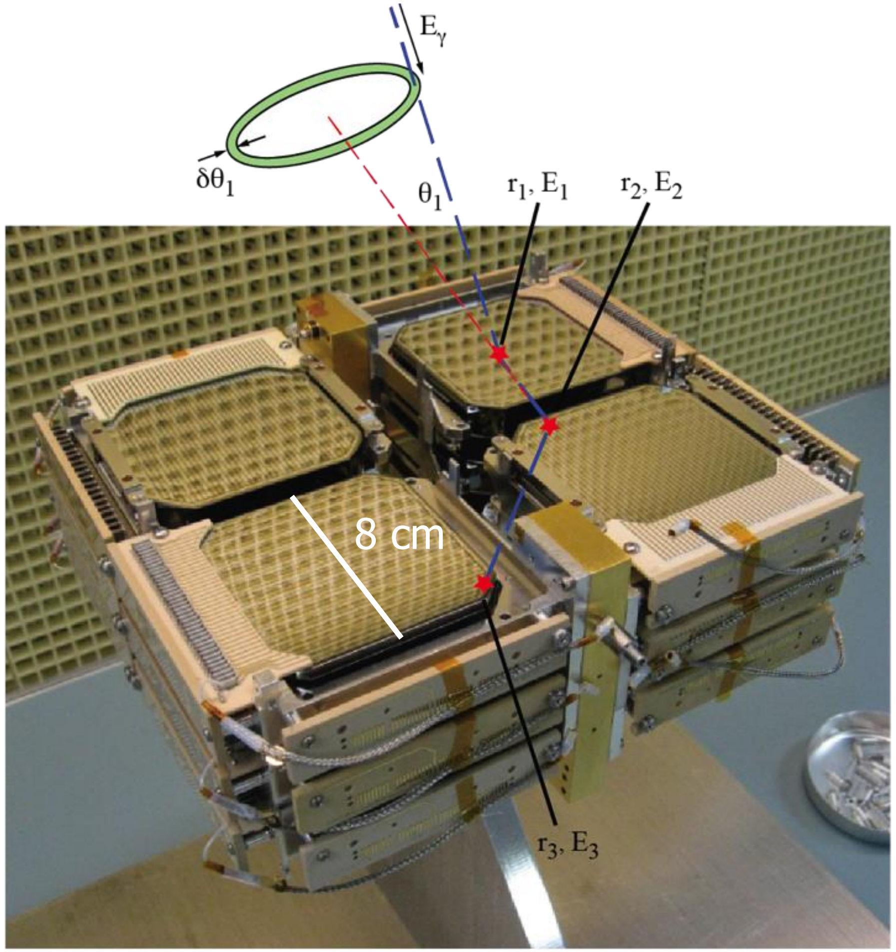
Institutions of Co-Investigators and Collaborators

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

COSI operation as a compact Compton telescope





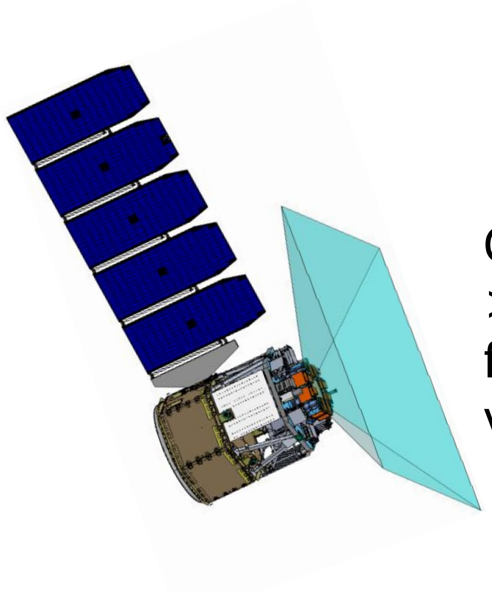


Double-sided strip GeDs to measure 3D interaction positions (12 GeDs for the balloon and 16 GeDs for the satellite)

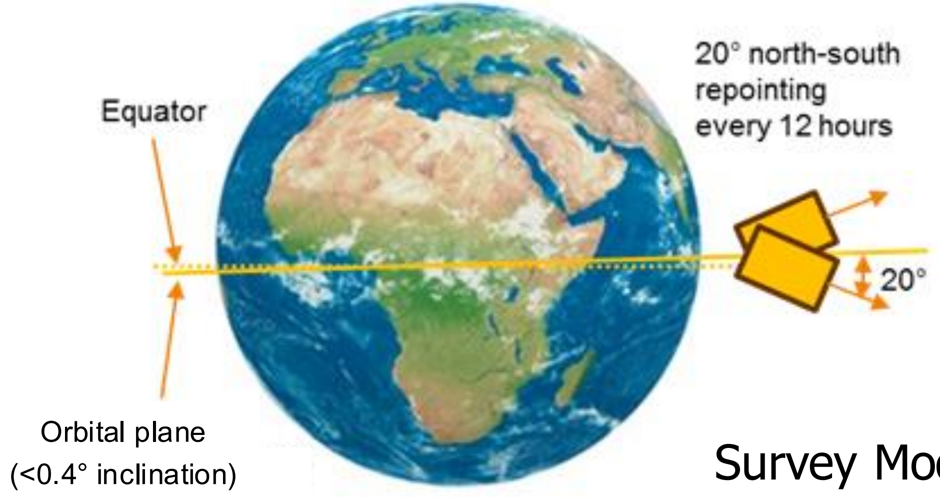
- ❑ Multiple interactions in the instrument
- ❑ $E_\gamma = E_1 + E_2 + E_3 + \ldots$
- ❑ The gamma-ray origin can be restricted to the "event circle"

COSI orbit and operations

- Equatorial low-Earth orbit, targeting:
  - 530 km altitude
  - <0.4° inclination
- COSI will spend most of its time in "survey mode"
  - North/South zenith offset alternating every 12 hours



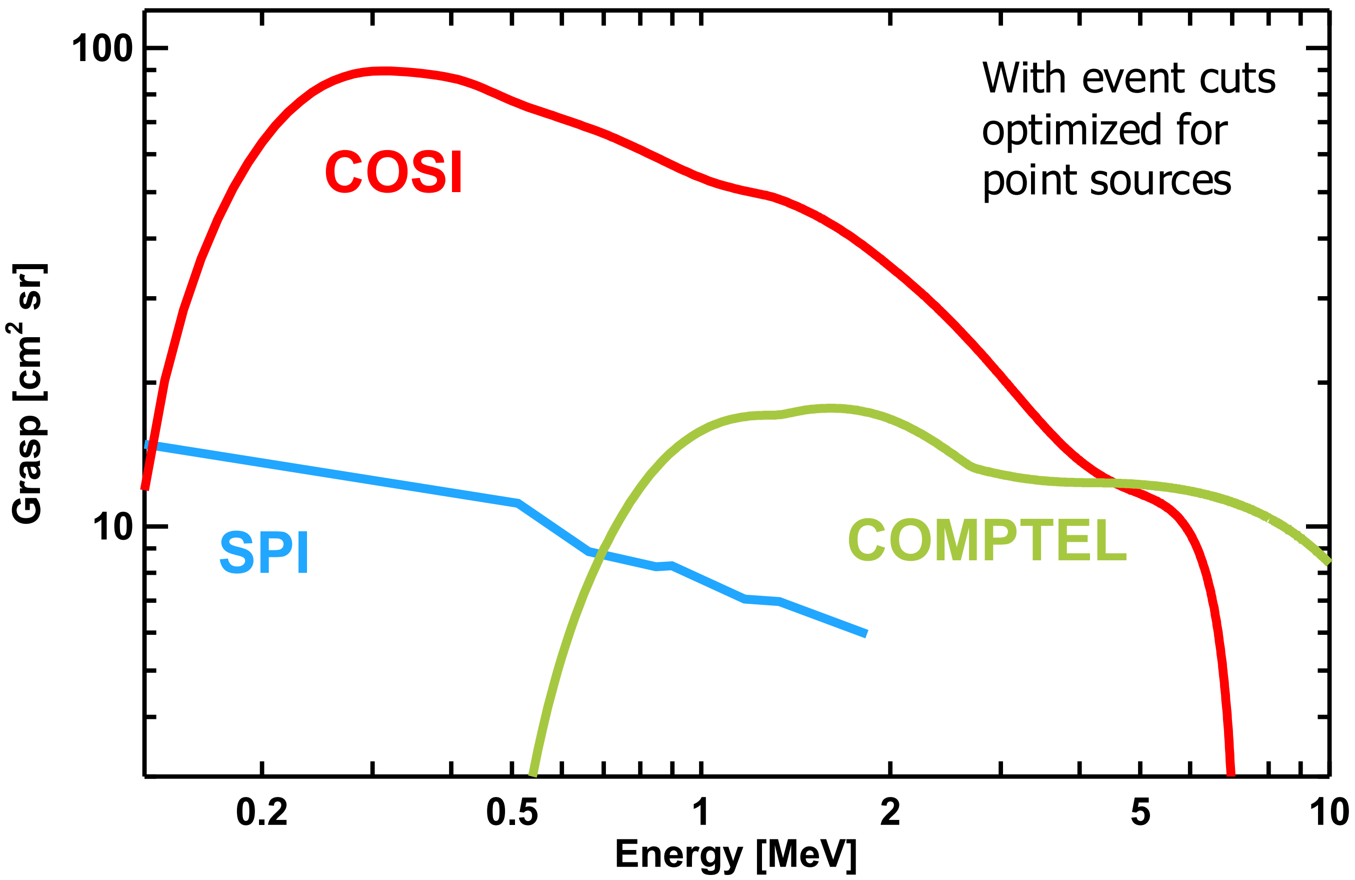
COSI's >25%-sky field of view



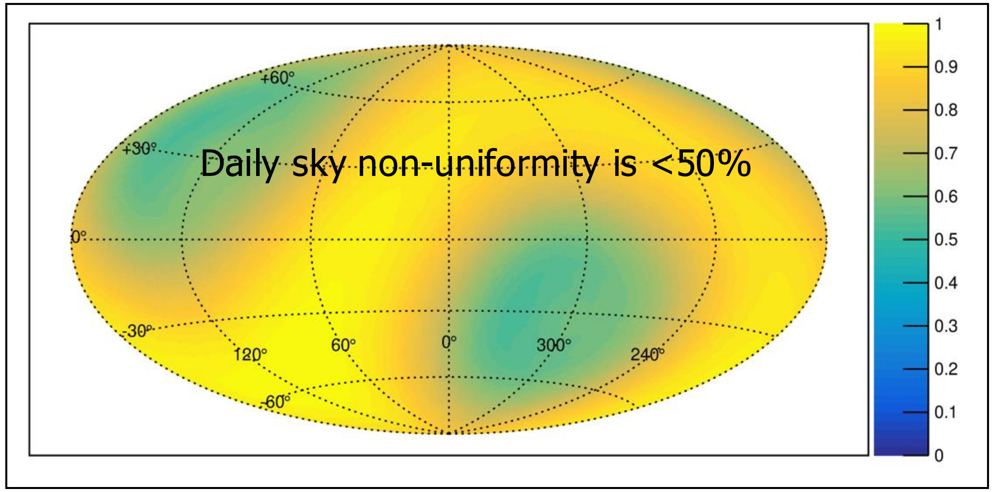
Survey Mode

Three key COSI advances

1. COSI's grasp (A_{eff} x FOV) is ~10x previous missions



2. Complete and relatively uniform sky coverage

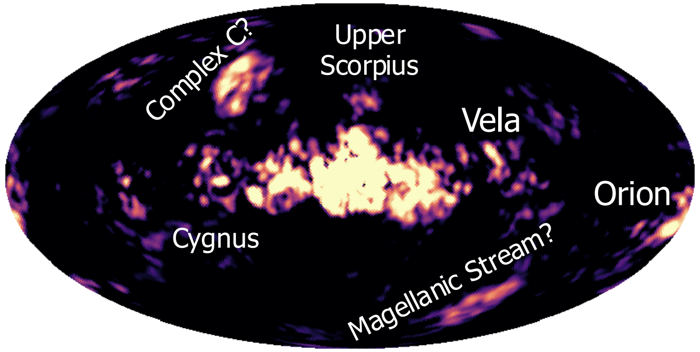


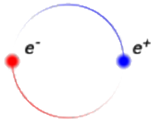
3. Background reduction due to equatorial orbit and Compton event selections

- Pre-launch background paper: Gallego+26

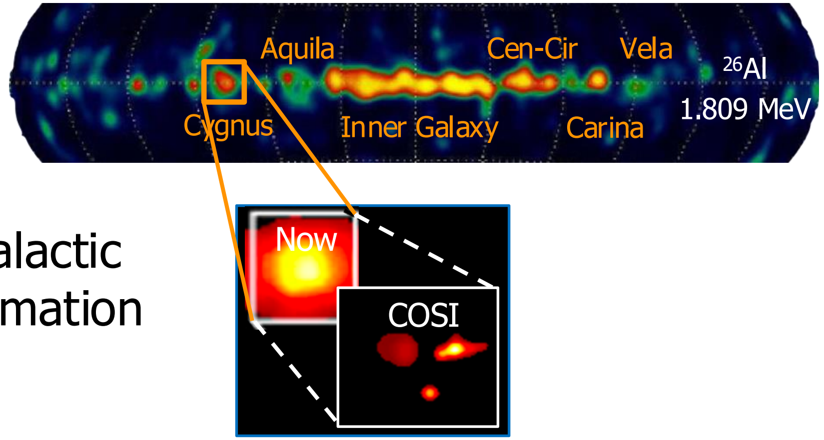
COSI Science Goals

A. Uncover the Origin of Galactic Positrons

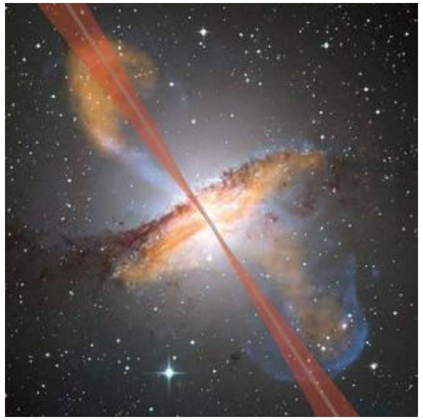




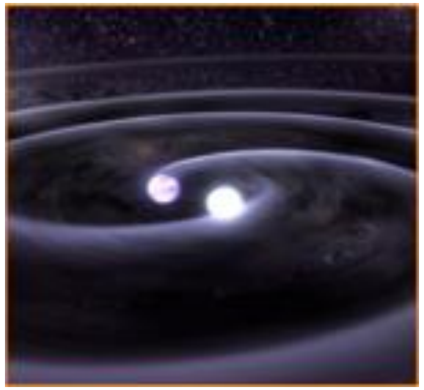
B. Reveal Galactic Element Formation



C. Gain Insight into Extreme Environments with Polarization



D. Probe the Physics of Multimessenger Events



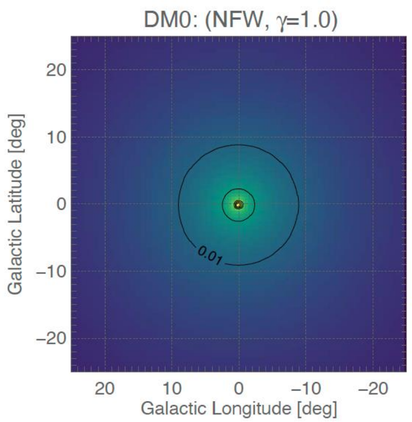
Goal A: Uncover the origin of positrons – 511 keV

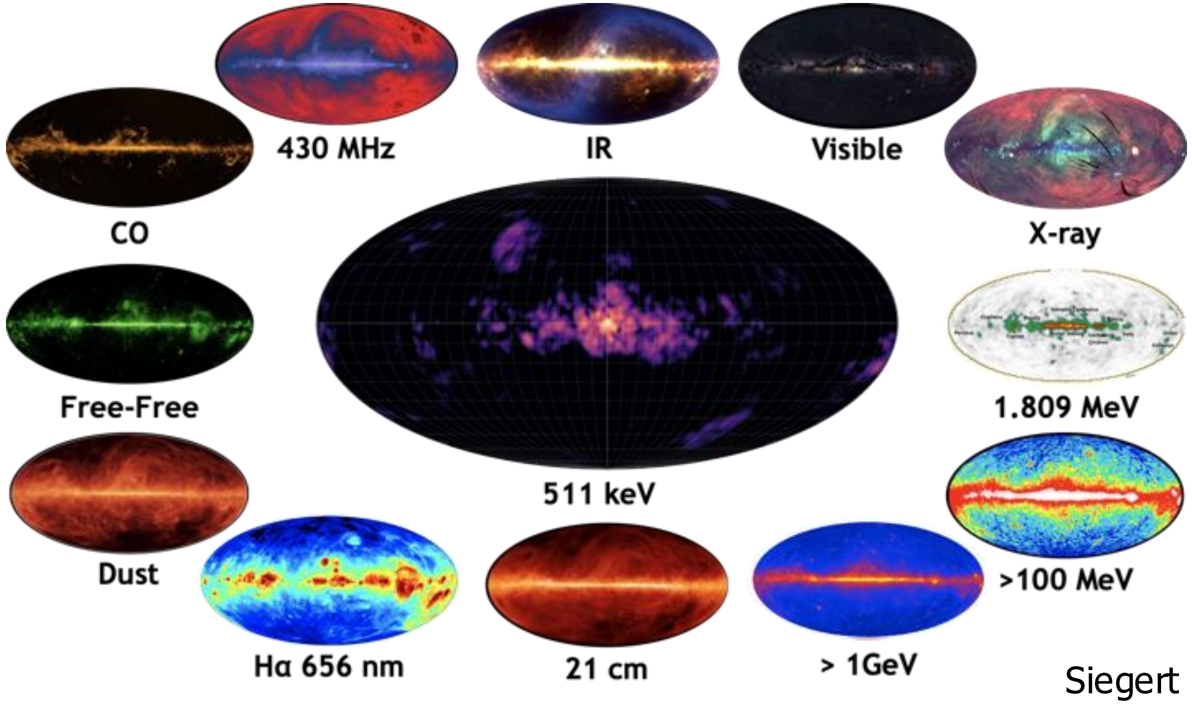
Candidate Positron Sources

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
  - Check on regions with possible INTEGRAL detections





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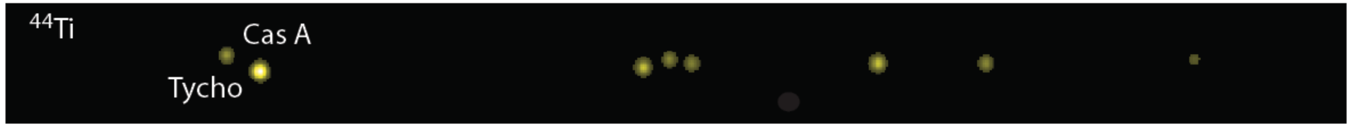
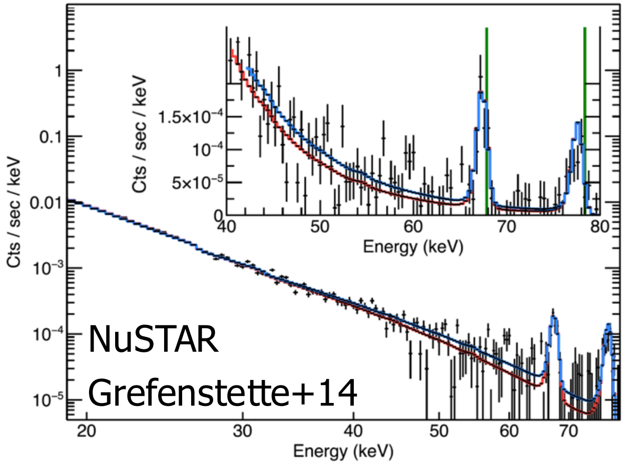
Goal B: Element formation

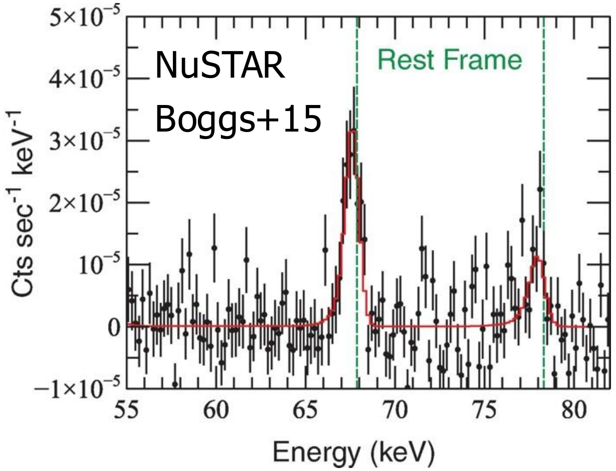
Isotope	Half-life	Energies (MeV)
^{60}Fe	2.6 Myr	1.173, 1.333
^{26}Al	0.7 Myr	1.809
^{44}Ti	60 years	1.157 (also 68 and 78 keV)

^{26}Al: mapping element formation from massive stars over the last few Myrs

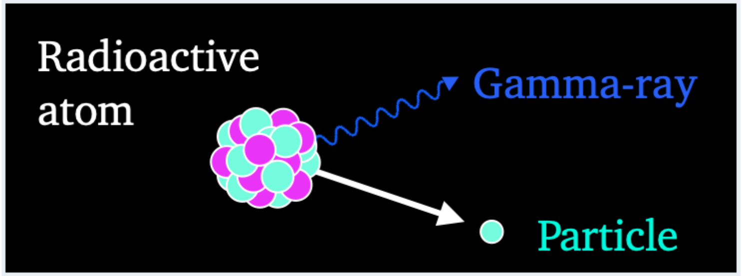


^{44}Ti: observing the most recent supernova explosions in the Galaxy (below: spectral measurements constrain supernova dynamics)





^{60}Fe: COSI will provide the first image, showing where core-collapse SNe have happened over the last ~10 Myr

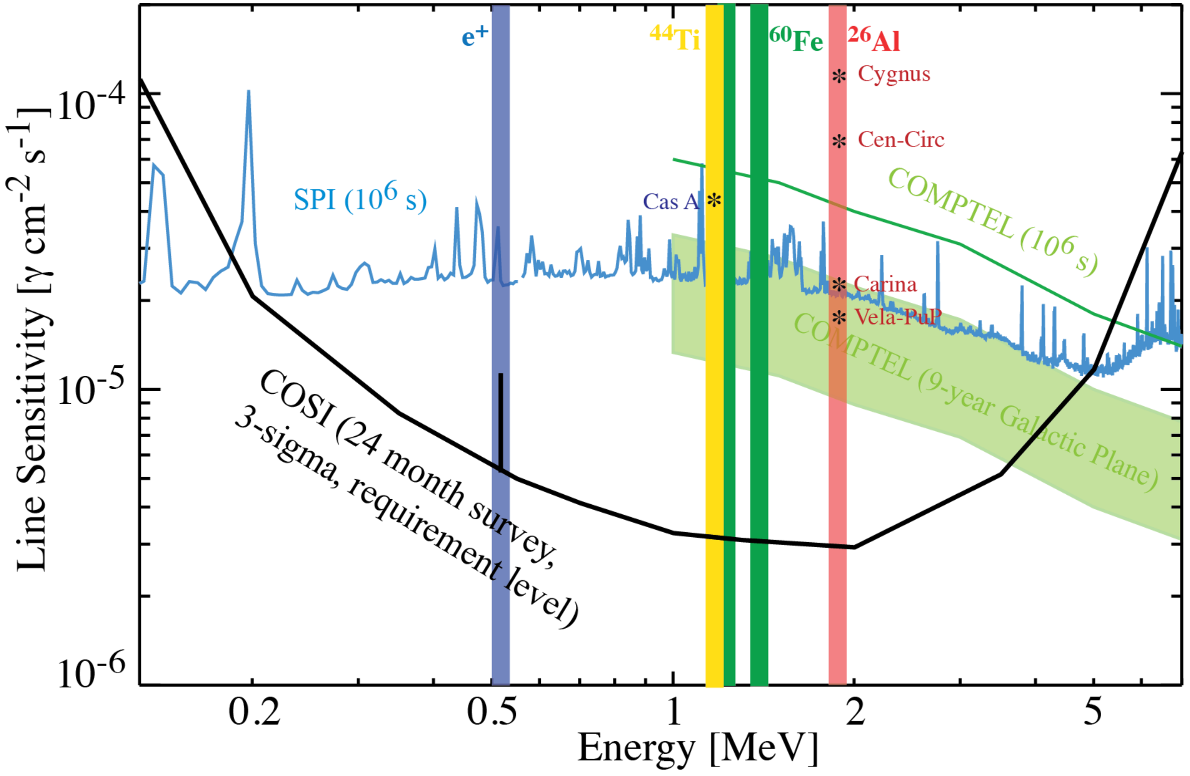


- How do massive stars make elements?
- What happens when stars explode?

Measurement requirements for emission line goals

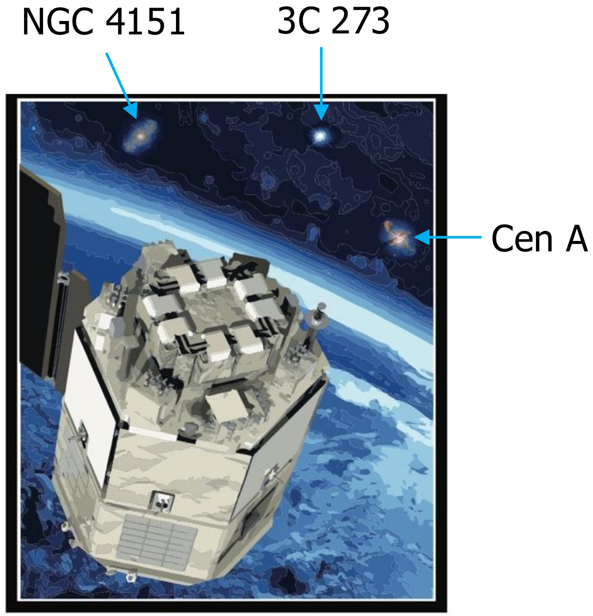
Characteristic	Requirement
Sky Coverage	• >25%-sky instantaneous FOV • 100%-sky each day
Energy Resolution* (FWHM/E)	• <1.2% @ 0.511 MeV • <0.8% at 1.157 MeV (^{44}Ti)
Narrow Line Sensitivity (2 yr, 3σ, point source)	[photons cm^{-2} s^{-1}] • 1.2x10^{-5} @ 0.511 MeV • 3.0x10^{-6} @ ^{26}Al, ^{60}Fe, and ^{44}Ti
Angular Resolution (FWHM)	• <4.1° @ 0.511 MeV • <2.1° @ 1.8 MeV (^{26}Al)

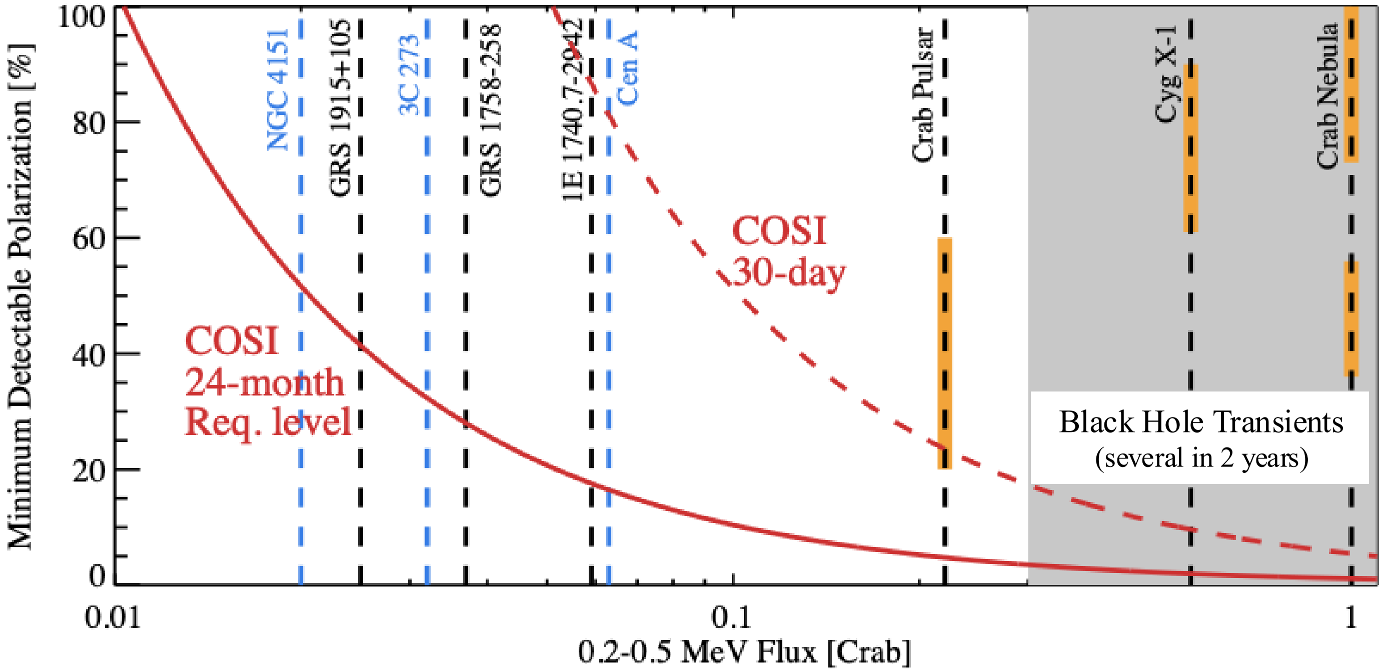
*For fully reconstructed Compton events (average of 2.5 interactions)



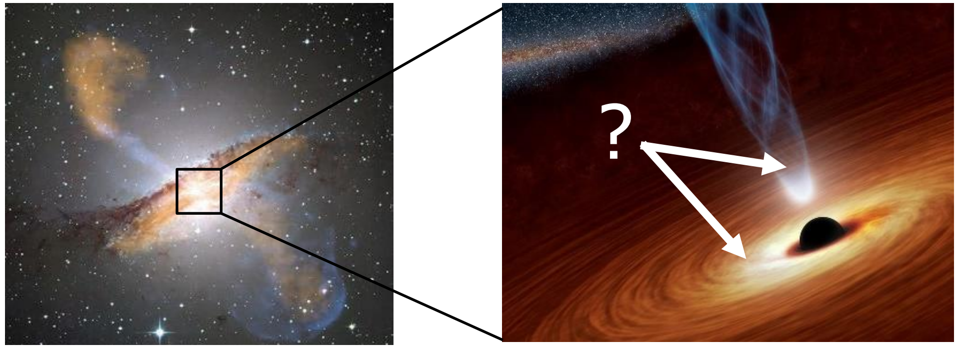
COSI will reach the sensitivities shown for every source in the sky (Tomsick+24)

Goal C: Gain Insight into Extreme Environments with Polarization





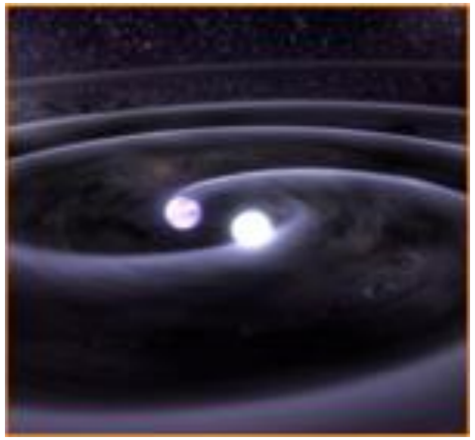
Orange bars show existing measurements by INTEGRAL



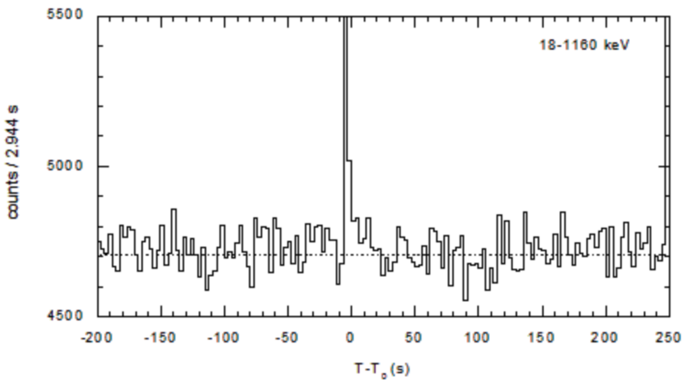
- COSI will measure the polarization of 0.2-0.5 MeV emission from at least 3 AGN and at least 3 Galactic BHs to constrain geometries and emission processes
- Related COSI publication: Latiolais+26 (predictions for blazar polarization detections)

Goal D: Probe the Physics of Multimessenger Events

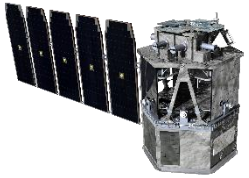
Merging neutron stars
(or other gamma-ray transients)



Gamma-ray burst (GRB) detection
and automatic data downlink

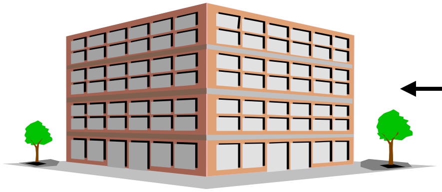


COSI



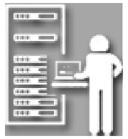
Tracking and Data Relay Satellite System (TDRSS)

Automatic GRB position determination



UCB MOC/SDOC

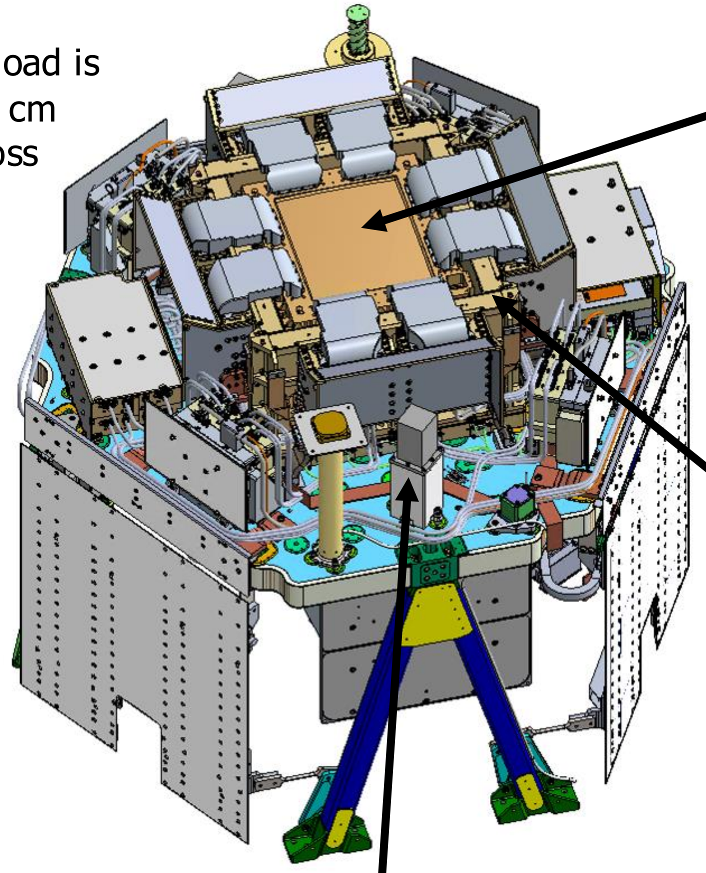
NSN TDRSS Ground



General Coordinates Network

- COSI will report the positions of GRBs and other transients in <1 hr to allow for follow-up by other observatories
- Positions to <2.5° (90% confidence error radius)
- Related COSI publications: Parmiggiani+26; Gulick+24
- Also, we plan to do studies to look for correlations between gamma rays and high-energy neutrinos (e.g., COSI/IceCube)

Payload design and instrument concept

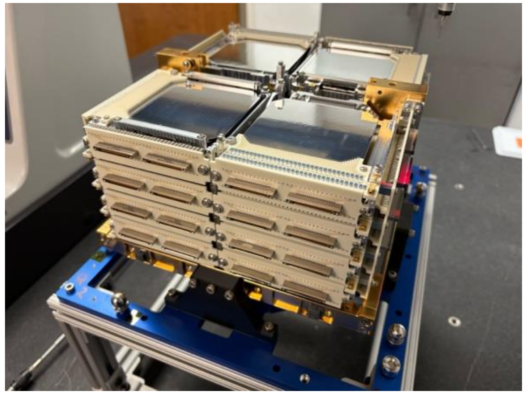


Payload is 108 cm across

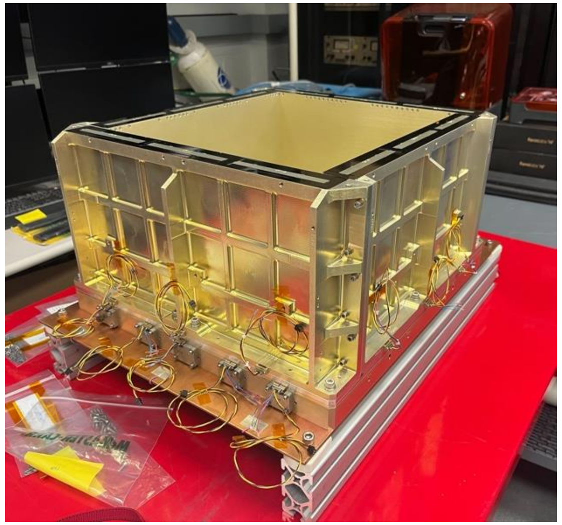
Germanium Compton Telescope (GCT)

16 GeDs cover 0.2-5 MeV for:

- **High-resolution spectroscopy**
- **Compton imaging**
- **Compton polarimetry**



COSI Flight Model (FM) hardware



Anticoincidence Subsystem (ACS)

Bismuth germanium oxide (BGO) scintillator "shields" for:

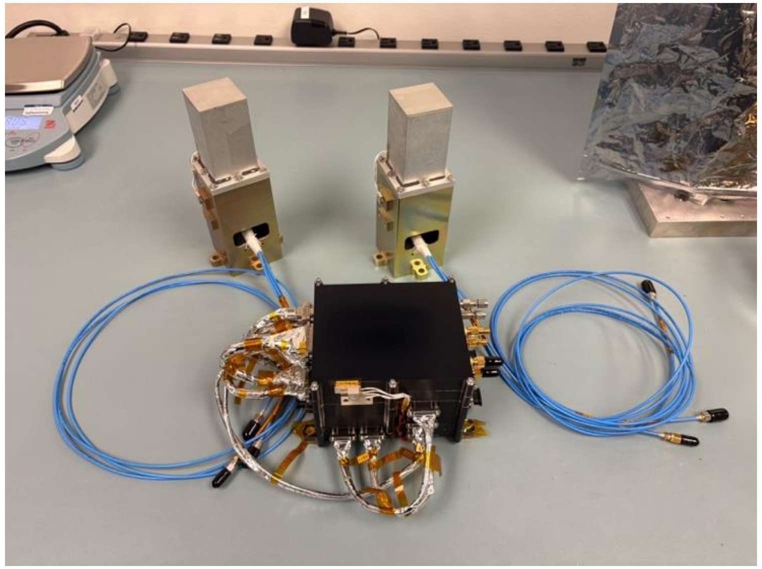
- **Reducing external background**
- **Rejecting escaping events**
- **50 ms light curves at 80 keV - 2 MeV (for GRB alerts)**
- **Light curves at >2 MeV (for proton background monitoring)**

Background and Transient Observer (BTO)

- **Student Collaboration instrument**
- **2 NaI(Tl) scintillator detectors (30 keV – 2 MeV)**

Background and Transient Observer

- >20 UC Berkeley undergraduates worked on this project over the past several years
- Effort led by Dr. Hannah Gulick (recently completed her PhD)
- Collaboration with Japan
  - Prof. Tad Takahashi (Kavli IPMU)
  - Prof. Kazu Nakazawa (Nagoya University)
  - Dr. Shunsaku Nagasawa (was a postdoc at SSL and now at Kavli IPMU)
- BTO helps and complements COSI:
  - Measurements will improve the COSI ***background*** model
  - Extend spectral coverage of ***transients*** down to 30 keV



BTO flight model hardware ready for integration

Schedule for COSI and Data Challenges (DCs)

2025		2026				2027			
Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4

DC4

Calibration Sept 26

System Integration Review (SIR)

DC5

ORR

Pre-launch release

Calibration

2-year prime mission, but extended mission possible

Payload Integration & Testing (I&T) @ SSL

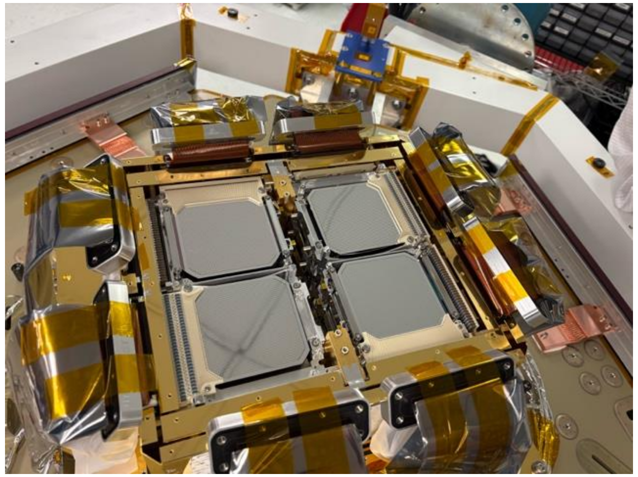
Observatory I&T in Stirling, VA

LAUNCH!

Now

Dec 2026

Aug 2027



Last look at the germanium detectors before they were enclosed in the cryostat shell

Doing electrical checks after adding cryostat shell and ACS

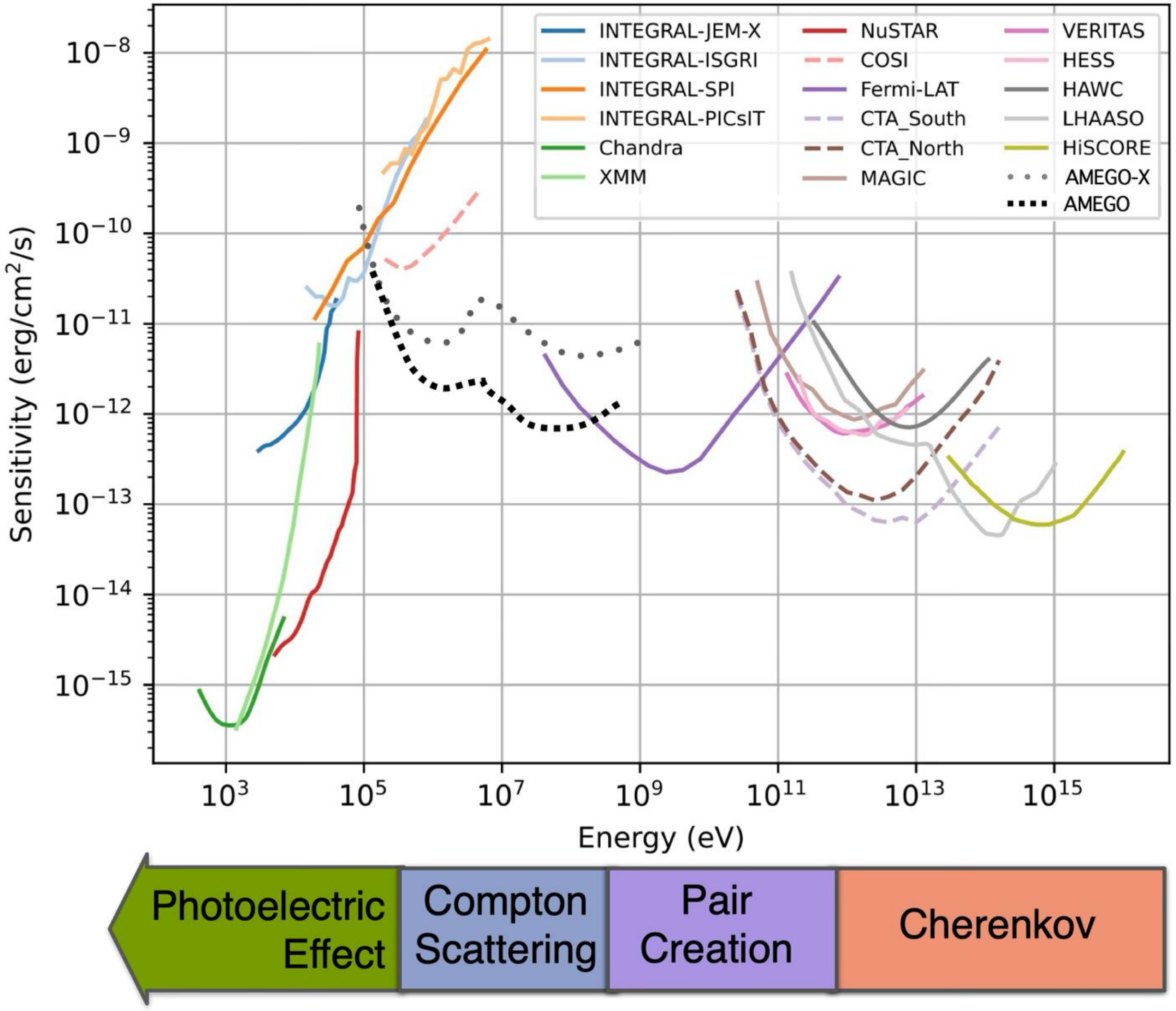
Welcome to COSI Data Challenge 4!

A great way to get involved in COSI!

Beyond COSI

- Next generation wish list
  - Closing the MeV gap to 100 MeV
  - Further sensitivity improvements
    - Needs to go along with angular resolution improvements to avoid source confusion
  - Maintain ~COSI-level energy resolution

- Many excellent concepts
  - AMEGO/AMEGO-X (silicon tracker and calorimeter)
  - APT (fiber and scintillator tracker)
  - GRAMS/GammaTPC (Liquid Ar)
  - ARCTIS (pixelated Ge)
  - TANGO (lunar occultation technique)



Adapted by T. Lewis from the AMEGO Team

MeV outlook and COSI leadership

COSI Gamma-ray Space Explorer

- There are very exciting science opportunities via MeV improvements
- COSI will be the next step with its planned launch in August 2027
- Please try out the data challenges and talk to the leadership if you are interested in getting involved

cosi.ssl.berkeley.edu

COSI Science Steering Committee:

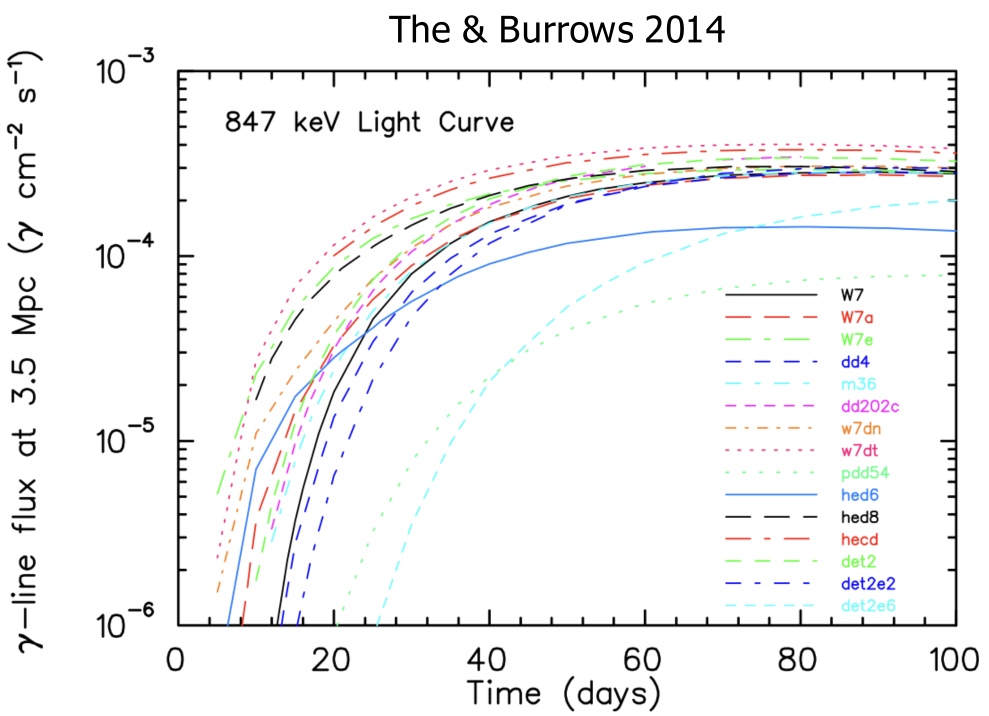
John Tomsick (UCB), Andreas Zoglauer (UCB), Carolyn Kierans (GSFC), Steve Boggs (UCSD), Dieter Hartmann (Clemson)

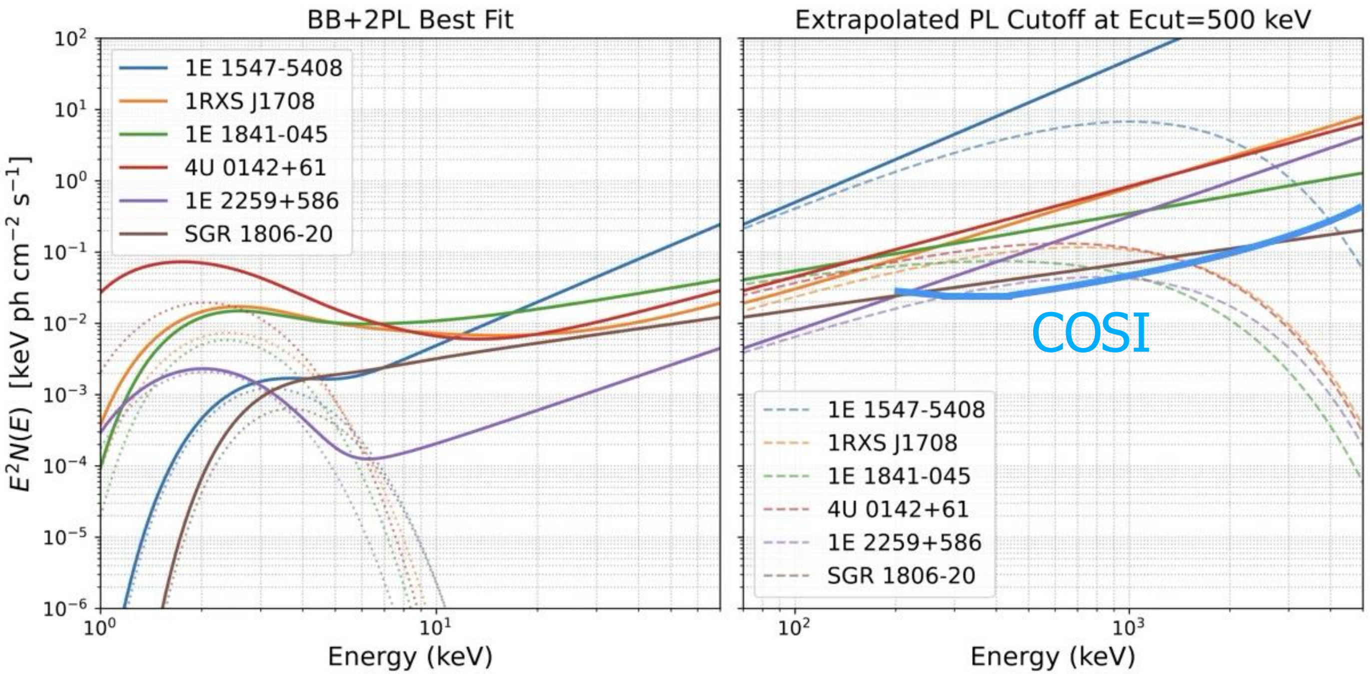
Science Group	Lead	Co-Leads
Positrons	Carolyn Kierans (GSFC)	Thomas Siegert, Pierre Jean
Nucleosynthesis	Thomas Siegert (JMU, Germany)	Chris Fryer, Hiroki Yoneda, Anaya Valluvan
GRBs	Eric Burns (LSU)	Steve Boggs, Dieter Hartmann, Eliza Neights
Galactic	Julien Malzac (IRAP, France)	Chris Karwin, Michela Negro, Koothodil Abhijith Augustine
Extragalactic	Marco Ajello (Clemson)	Fabrizio Tavecchio, Jarred Roberts
Dark Matter	Tad Takahashi (Kavli IPMU)	Shigeki Matsumoto, Tom Melia, Maíra Dutra, Yu Watanabe

Backup

COSI's extended science portfolio – bonus science

- ❑ Type Ia supernovae and the 847 keV ^{56}Co line out to 20 Mpc
  - 77-day half-life
  - COSI expected to detect ~2 per year
  - Line shape diagnostic of type of progenitor (accreting WD or merging WDs) – Leising 22



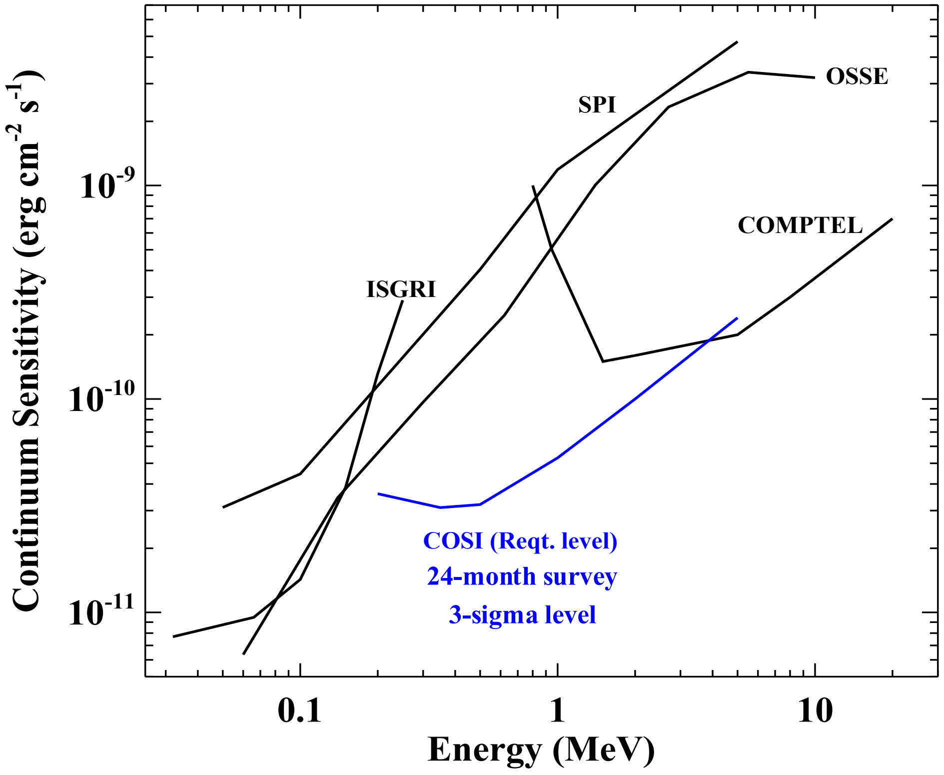


- ❑ Magnetar spectral cutoffs
  - B-field geometry and plasma properties (Baring & Harding 2027; Beloborodov 2013, Sautron+25)
  - COSI expected to detect 3 or more

Measurement requirements for goals C and D

Characteristic	Requirement
Polarization	• $>1.4\times10^{-10}$ erg/cm^2/s (0.2-0.5 MeV) to reach <50% MDP for NGC 4151 (3rd brightest AGN)
GRB alerts	• Locations to <2.5° (90% confidence error radius) • Reporting in <1 hr (potentially as fast as ~15 min) • Arrival times to an absolute accuracy of <100 ms (goal <500 μs with GPS)

Continuum sensitivity required for AGN polarization measurements



Tomsick+24