The Compton Spectrometer and Imager

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IRAP

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COSI overview

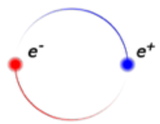
- COSI is:
  - a NASA Small Explorer satellite with a planned launch in 2027
  - a Compton telescope for observing gamma-rays in the 0.2-5 MeV energy range

- Optimized for studies of nuclear and annihilation emission lines across the Milky Way Galaxy

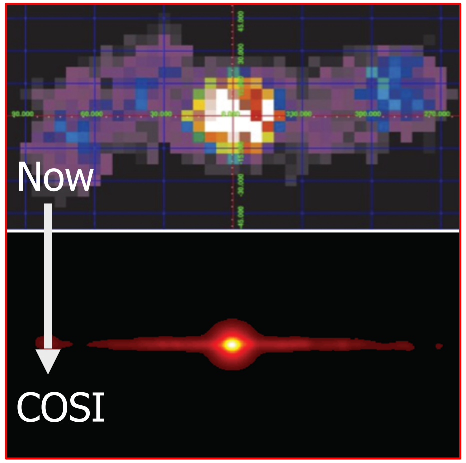
- It is the combination of two capabilities that makes COSI unique
  - Uses germanium detectors cooled to cryogenic temperatures to provide **excellent energy resolution**
  - Instantaneous field of view is **>25%-sky** and covers the whole sky every day

Key Science Goals

A. Uncover the Origin of Galactic Positrons

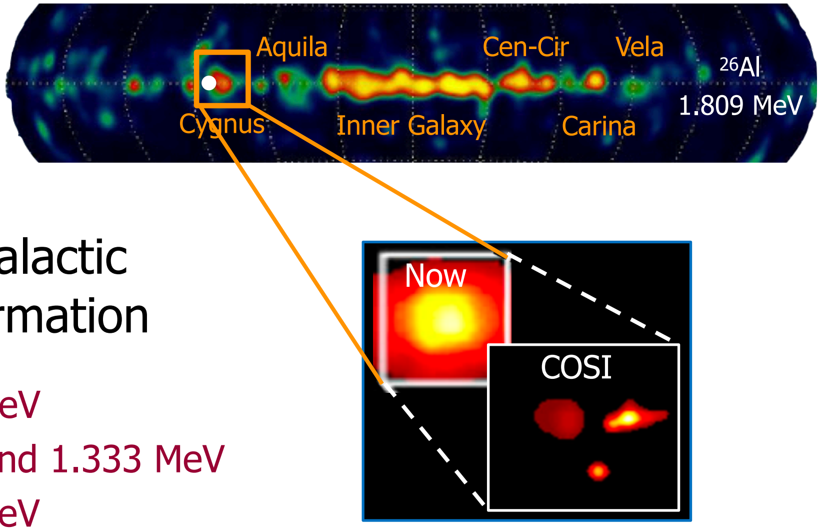


e^-e^+ @ 511 keV



C. Gain Insight into Extreme Environments with Polarization

AGN and Galactic black holes @ 0.2-0.5 MeV



B. Reveal Galactic Element Formation

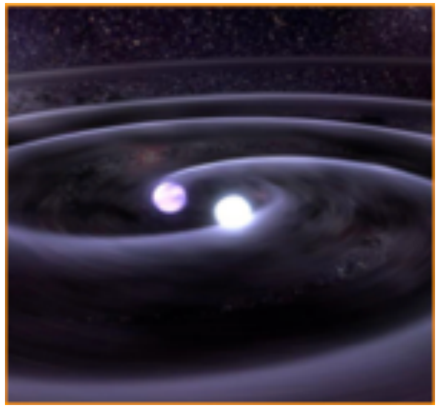
^{26}Al @ 1.809 MeV

^{60}Fe @ 1.173 and 1.333 MeV

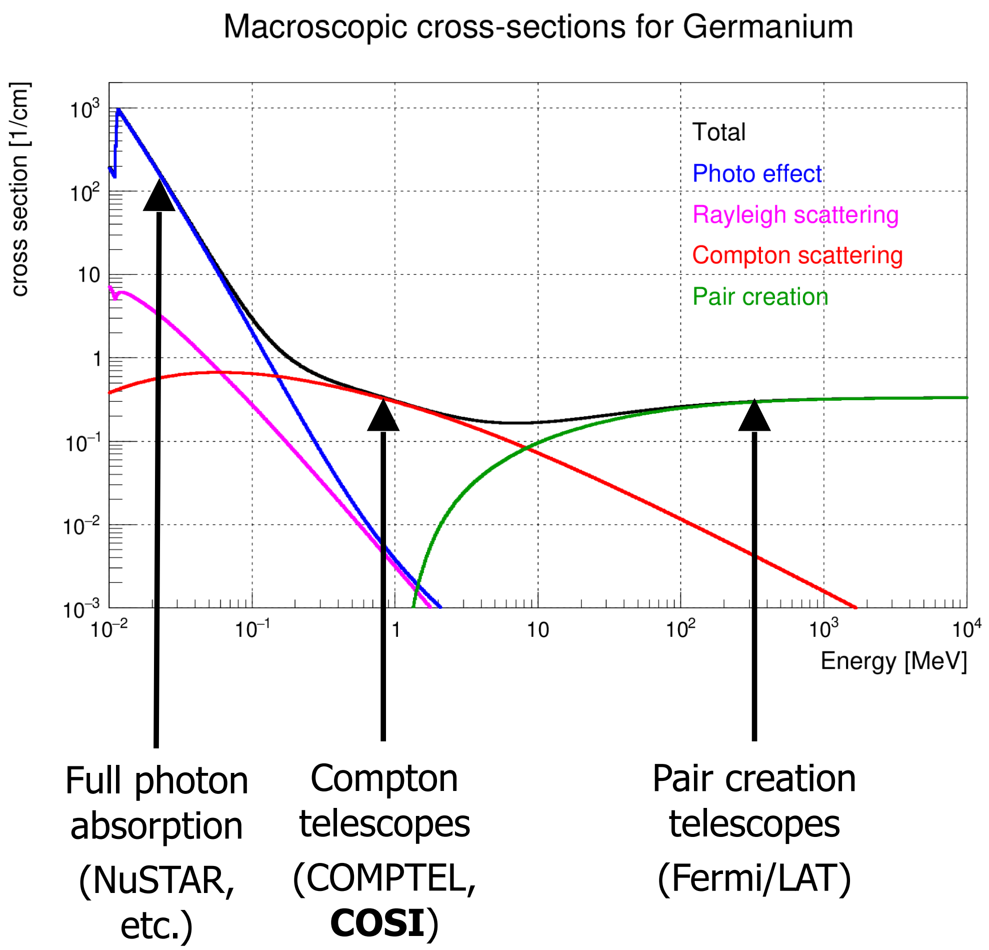
^{44}Ti @ 1.157 MeV

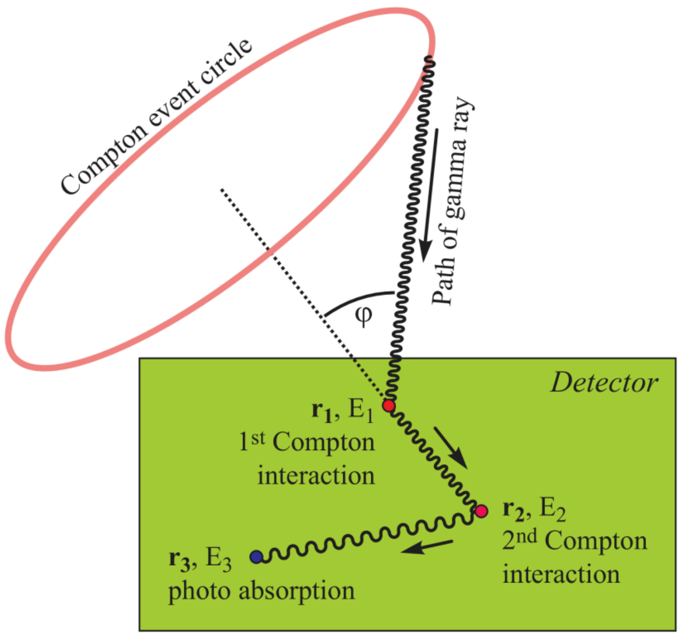
D. Probe the Physics of Multimessenger Events

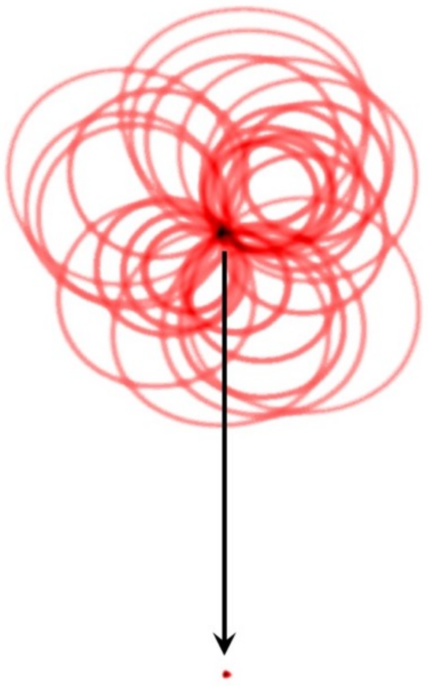
GRB alerts



Why use a Compton telescope to study the MeV bandpass?







- ❑ 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"

- ❑ Use iterative deconvolution techniques to produce images (point source example)

COSI's germanium detectors

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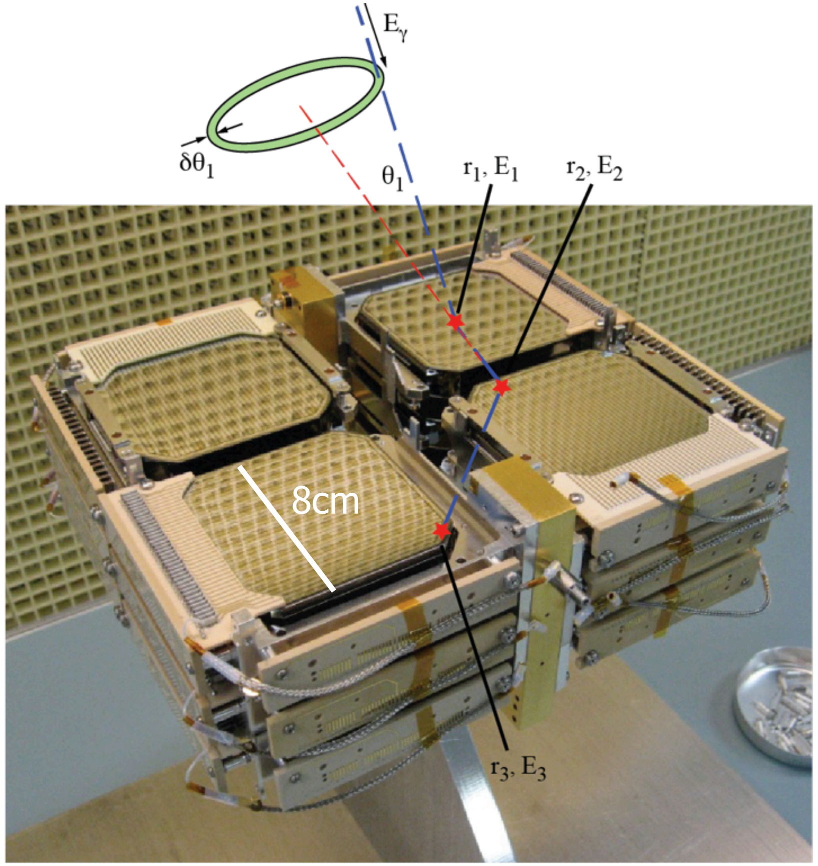

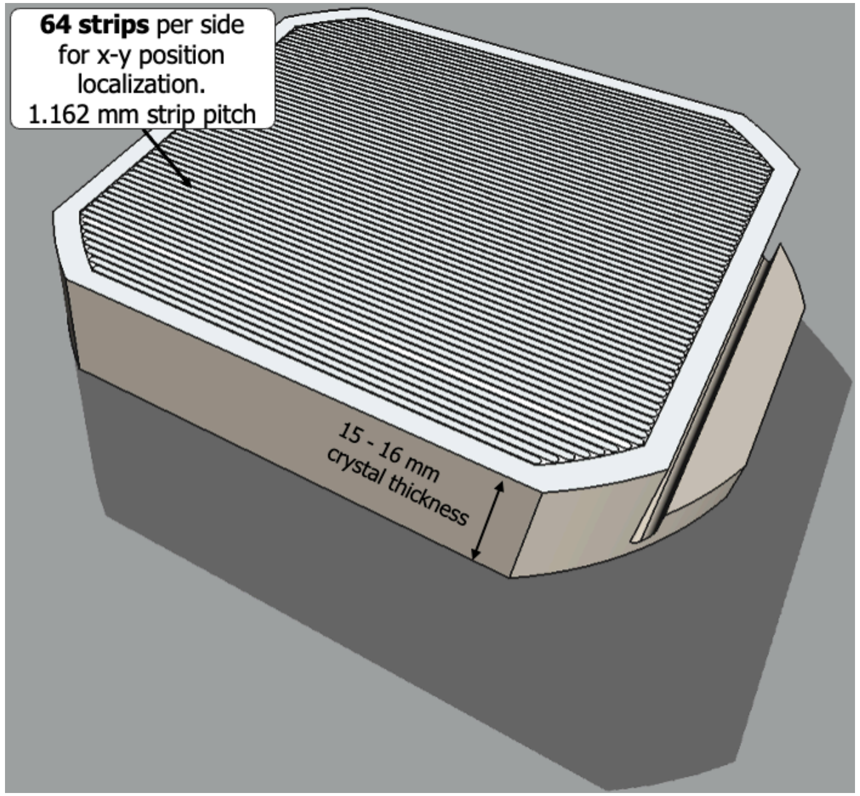

- ❑ COSI-balloon instrument with 12 germanium detectors
- ❑ Satellite will have 16 detectors (4 stacks of 4)

Double-sided strip detectors give 3D Compton interaction positions

COSI payload design and instrument concept

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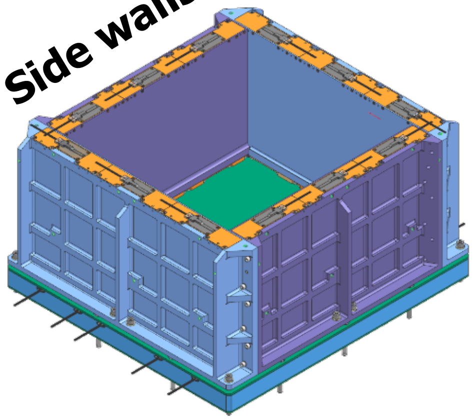
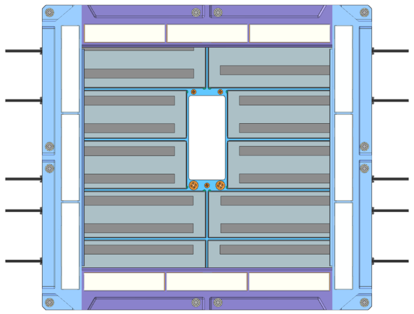
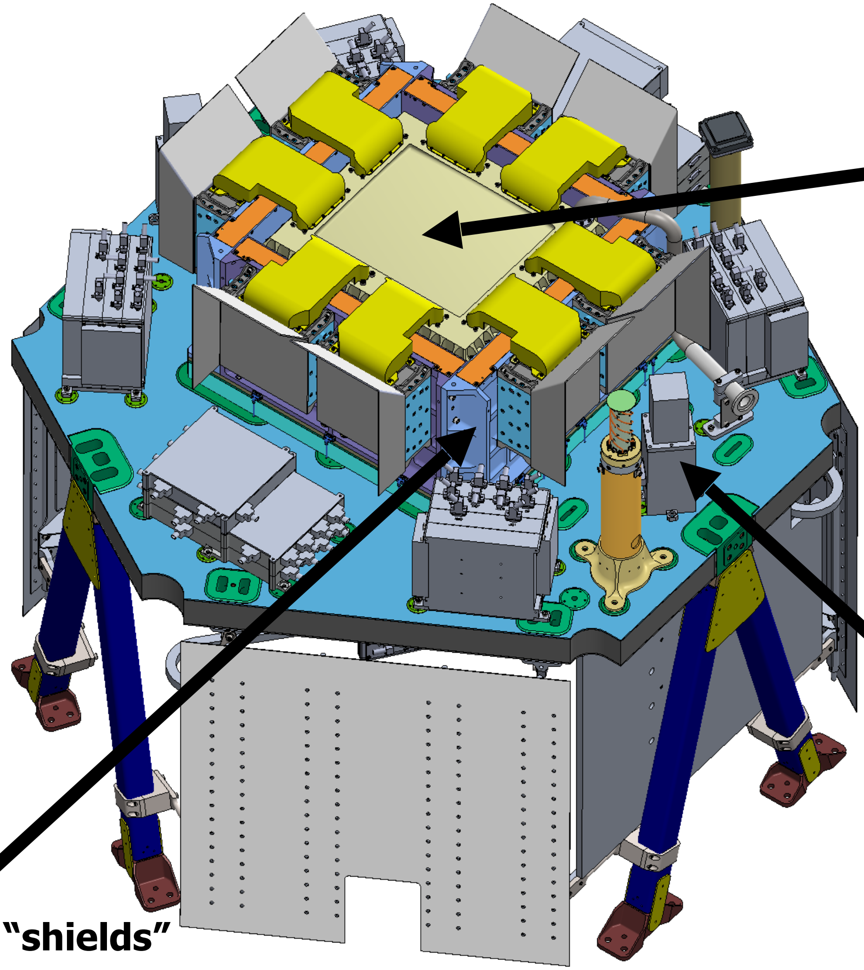
Side walls

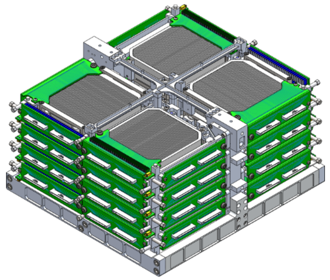


Bottom shield





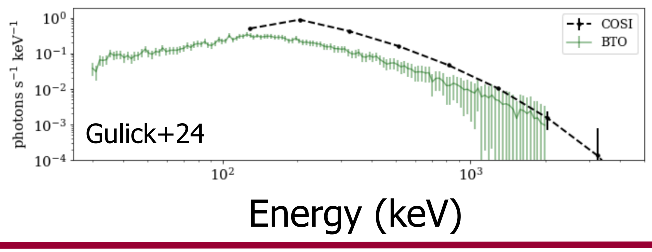
Germanium detector array



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

Background and Transient Observer (BTO) Student Collaboration instrument

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



Anticoincidence subsystem (ACS)

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

COSI mission timeline and observatory parameters

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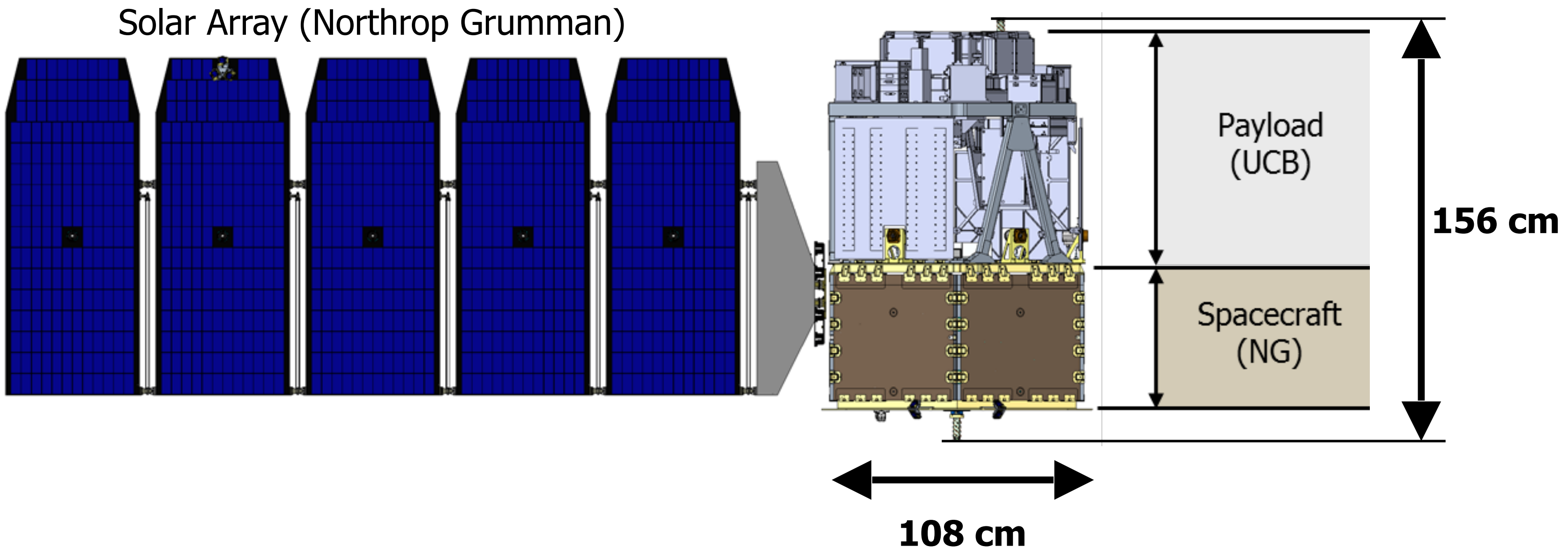
A Gamma-ray Space Explorer

Original Proposal Opportunity	**2019 Astrophysics Small Explorer (SMEX) with $145M cost cap (FY20$), excluding launch**
Phase A start	**March 2020**
Phase B start	**January 2022**
Phase C start	**April 2024**
Planned Launch	**August 2027**
Launch Vehicle	**Space X Falcon 9**
Orbit	**530 km altitude <2 deg inclination (for low background)**
Prime Mission Duration	**2 years (extensions are anticipated)**



COSI Mass, Power, and Data	
Mass (372 kg Not to Exceed)	**350 kg** (Maximum Expected Value, MEV)
Power (732 W generated by Solar Array w/ battery storage)	**609 W** MEV (including battery recharge and other inefficiencies)
Data (through Malindi Ground Station, provided by ASI)	**7.7 Gb/day** S-band
Data (through Tracking and Data Relay Satellite System, TDRSS)	4 kbps S-band GRB Data: **500 kb per alert**

The COSI collaboration

University of California, Berkeley

PI: John Tomsick

University of California, San Diego

Deputy PI: Steven Boggs

Naval Research Laboratory

Goddard Space Flight Center

Space Dynamics Laboratory

Northrop Grumman

Italian Space Agency (ASI)

German Aerospace Center (DLR)

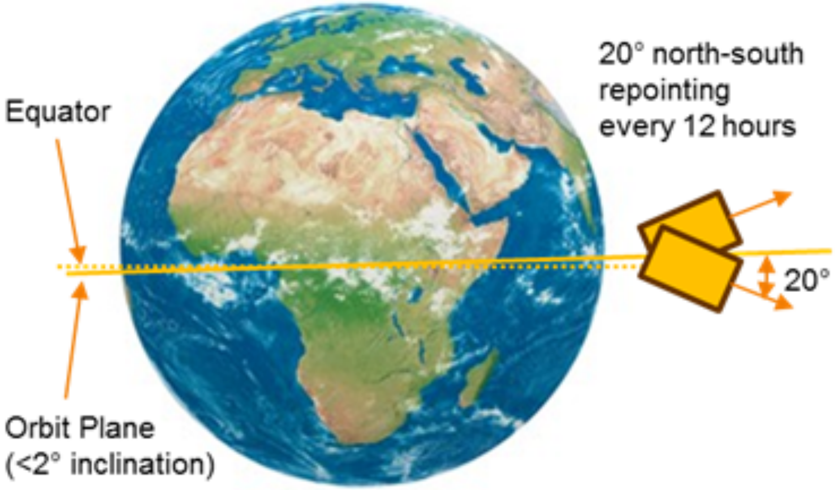
French National Space Agency (CNES)

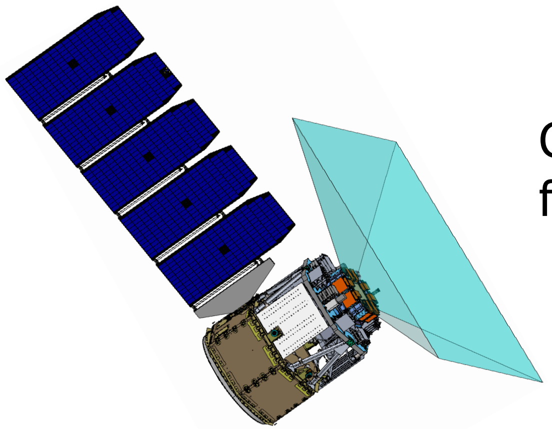
Institutions of Co-Investigators and Collaborators

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

COSI science modes

- ❑ Survey mode
  - ▪ North/South zenith offset alternating every 12 hours
  - ▪ Combined with large field of view gives daily all-sky coverage
- ❑ Constant Zenith Angle (CZA) mode
  - ▪ Targets of Opportunity for up to 15 days, commanded within 2 days





COSI's >25%-sky field of view

Goal A: Uncover the origin of Galactic positrons

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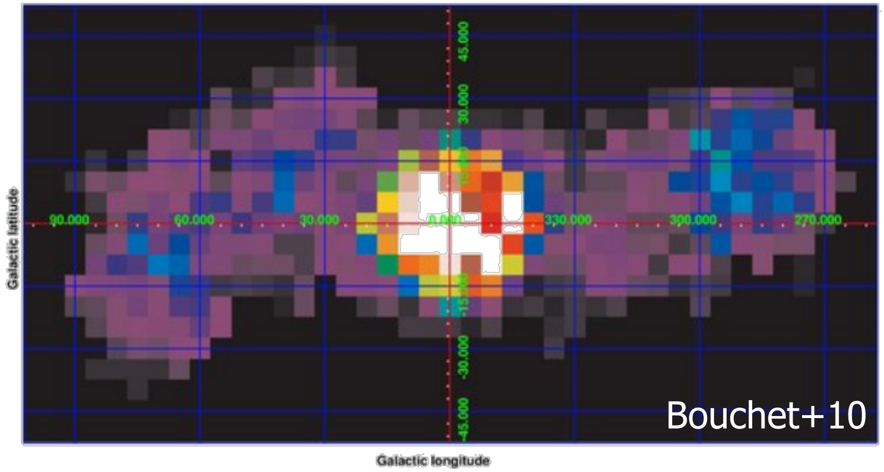
- ❑ COSI traces positrons by measuring the 511 keV e^-e^+ annihilation line
- ❑ Current questions:
  - What is producing the ~$5x10^{43}$ e^+/s required to explain the 511 keV signal?
  - What is the reason for the strong excess coming from the Galactic bulge?

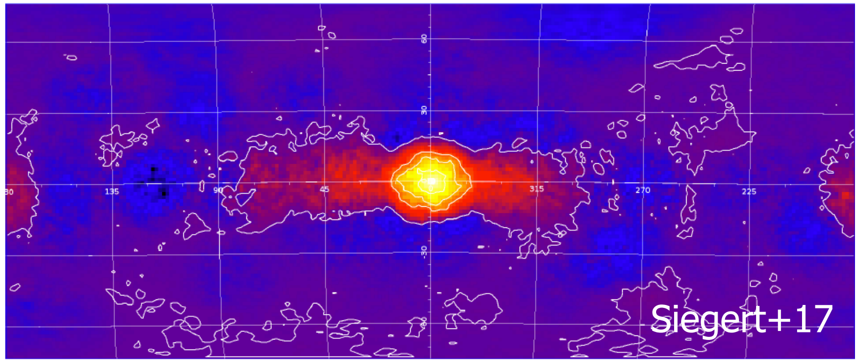
Positron Production Rates ($x10^{42}$ e^+/s)

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%

INTEGRAL/SPI maps of the 511 keV emission





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

511 keV Galactic substructure

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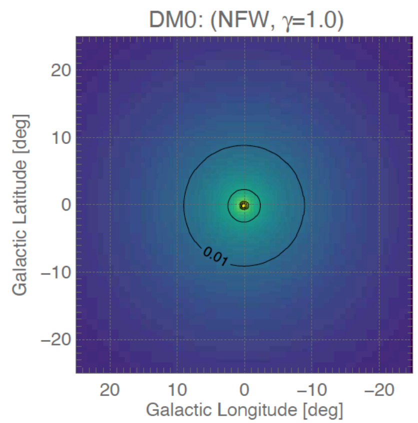
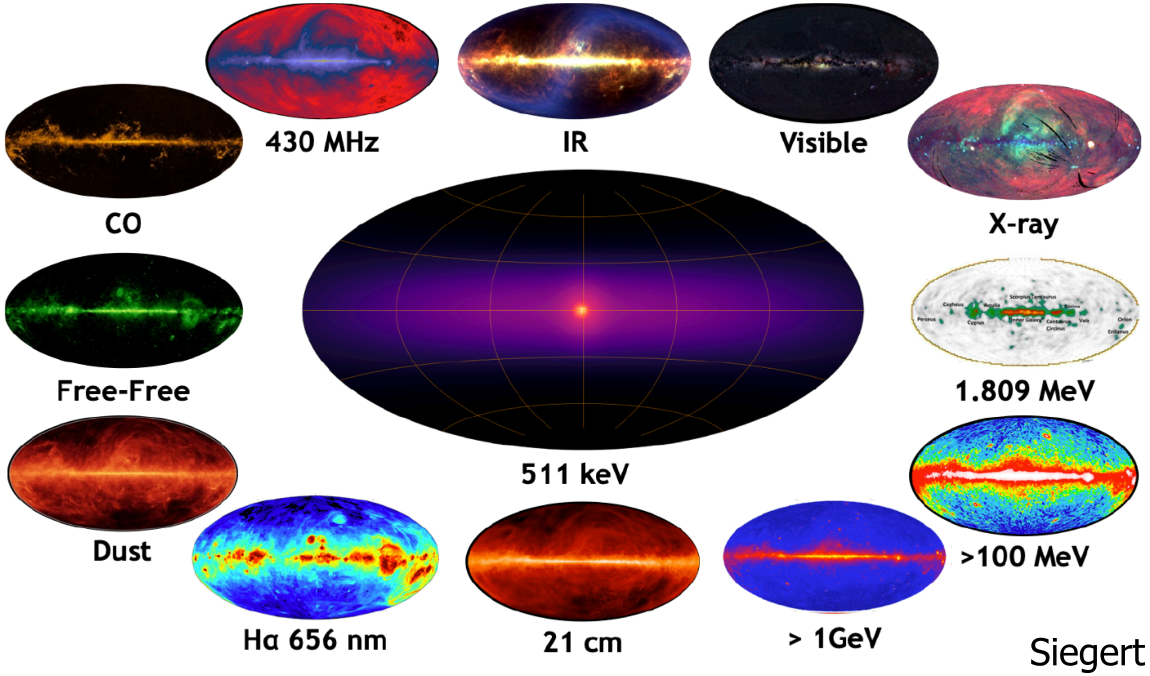
Candidate Positron Sources

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





Siegert 23

Goal B: Reveal Galactic element formation

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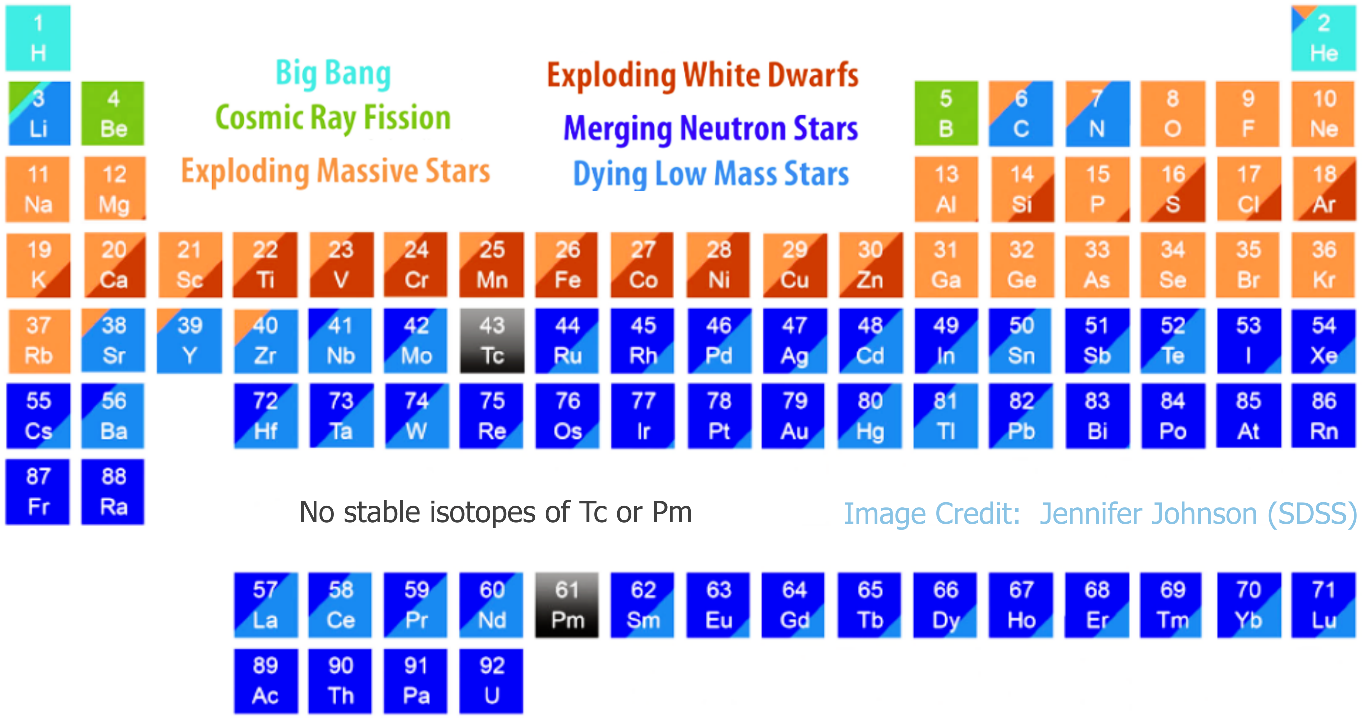
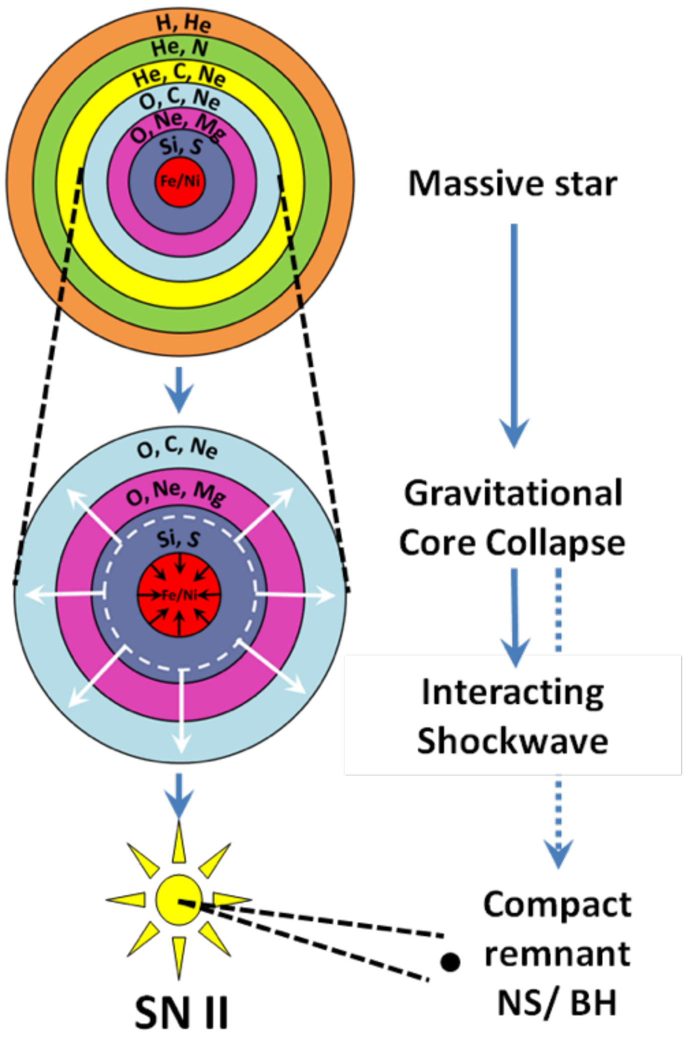
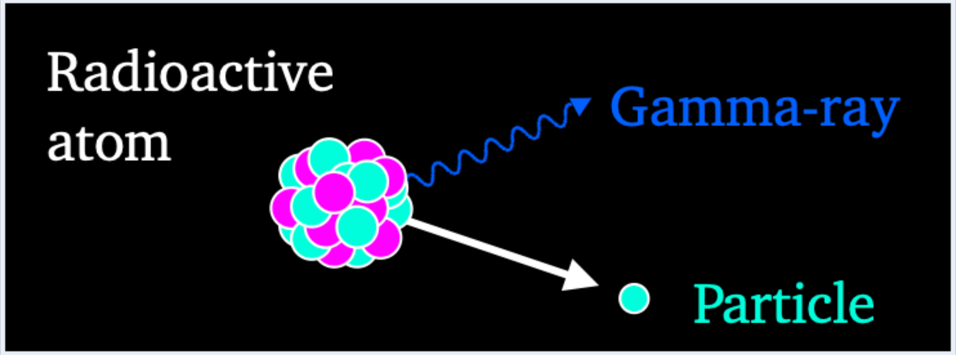


Core-collapse SN explosion

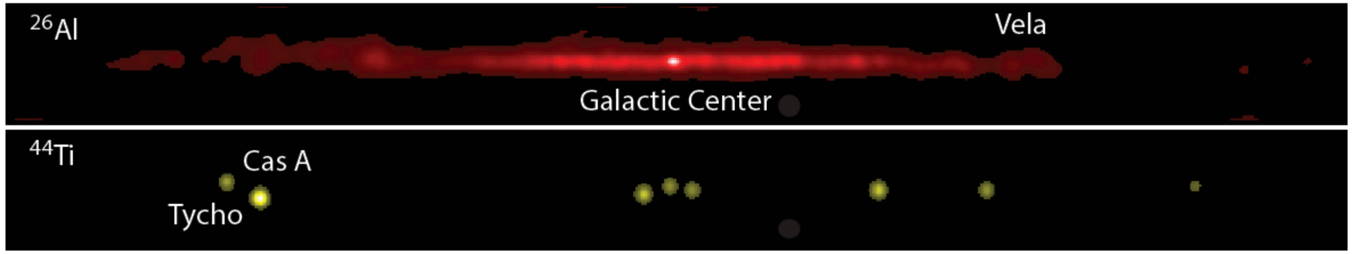


- COSI investigates element creation related to massive stars
  - Stellar-interior nucleosynthesis
  - Stellar-explosion nucleosynthesis in supernovae (SN)

Element formation



Isotope	Half-life	Energies (MeV)
^{56}Co	77 days	0.847, 1.238
^{44}Ti	60 years	1.157
^{26}Al	0.7 Myr	1.809
^{60}Fe	2.6 Myr	1.173, 1.333

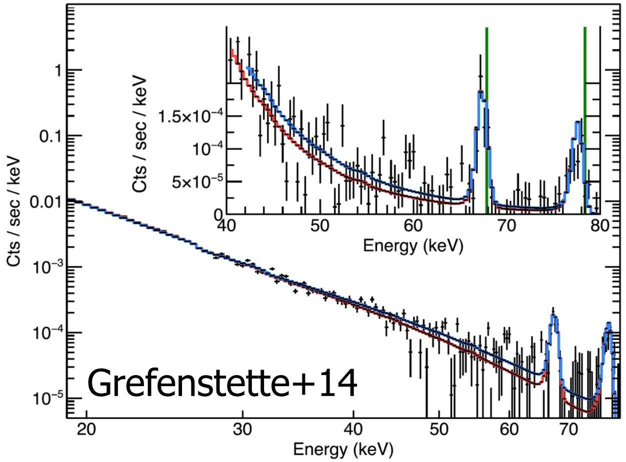


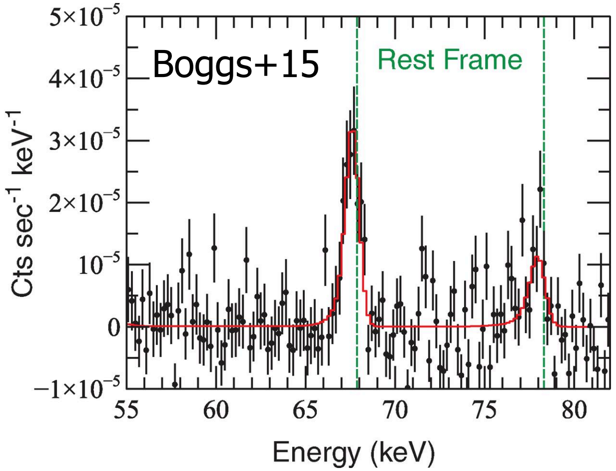
^{26}Al: mapping element formation from massive stars over the last few Myrs

vs.

^{44}Ti: observing the most recent supernova explosions in the Galaxy

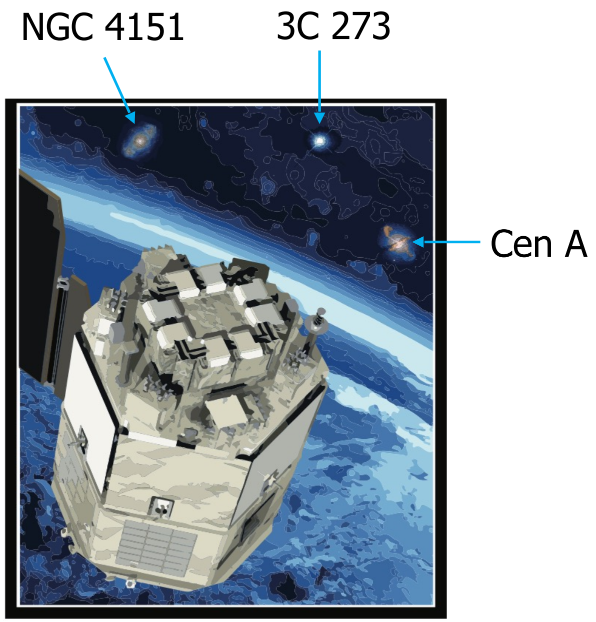
(below: spectral measurements constrain supernova dynamics)

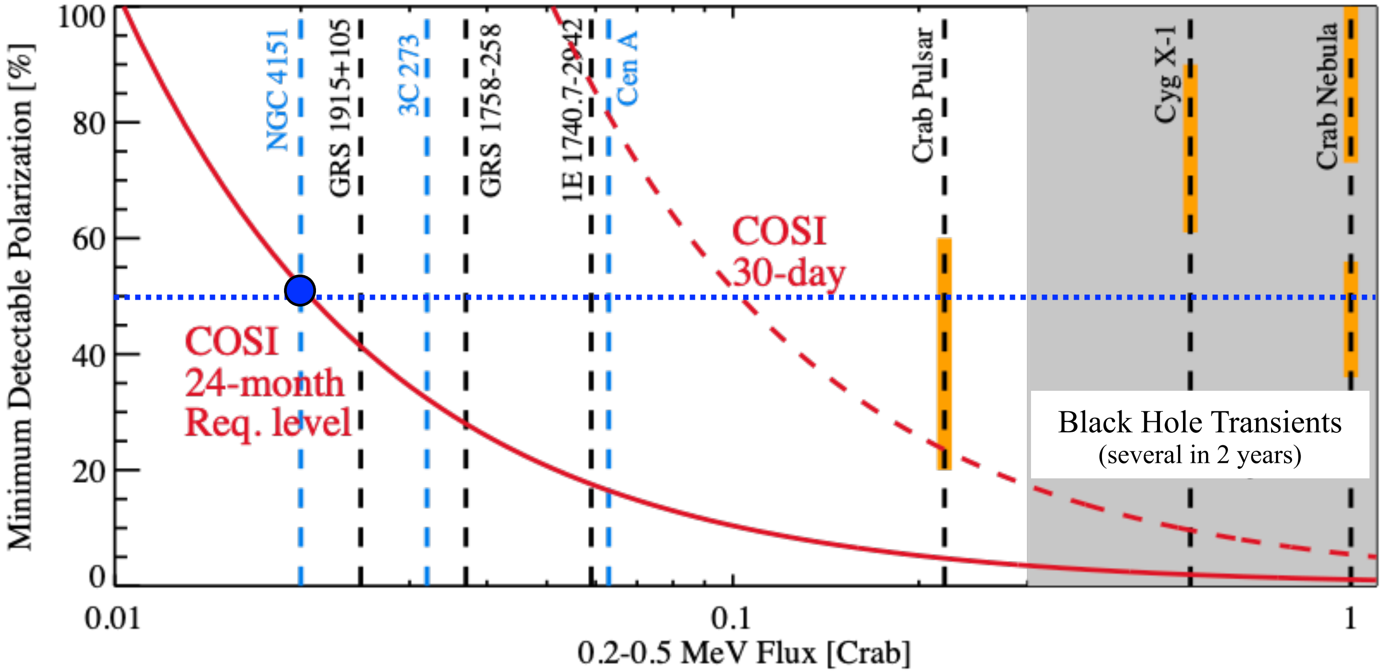




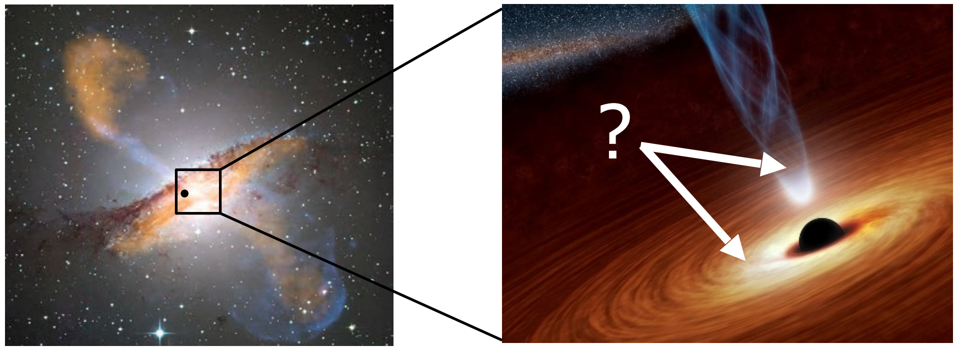
- How do massive stars make elements? (all isotopes)
- What happens when stars explode? (especially ^{44}Ti and ^{56}Co)

Goal C: Gain Insight into Extreme Environments with Polarization





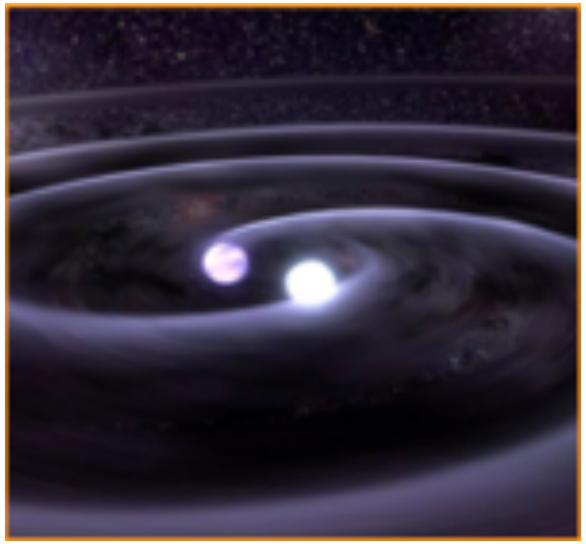
Orange bars show existing measurements by INTEGRAL



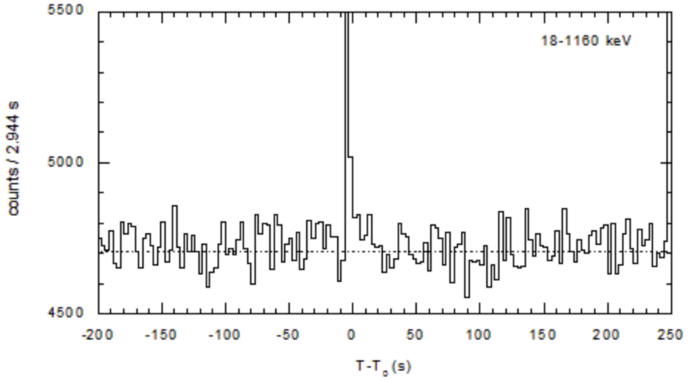
- ❑ COSI will measure the polarization of 0.2-0.5 MeV emission from at least 3 AGN and at least 3 Galactic BHs to constrain geometries and emission processes

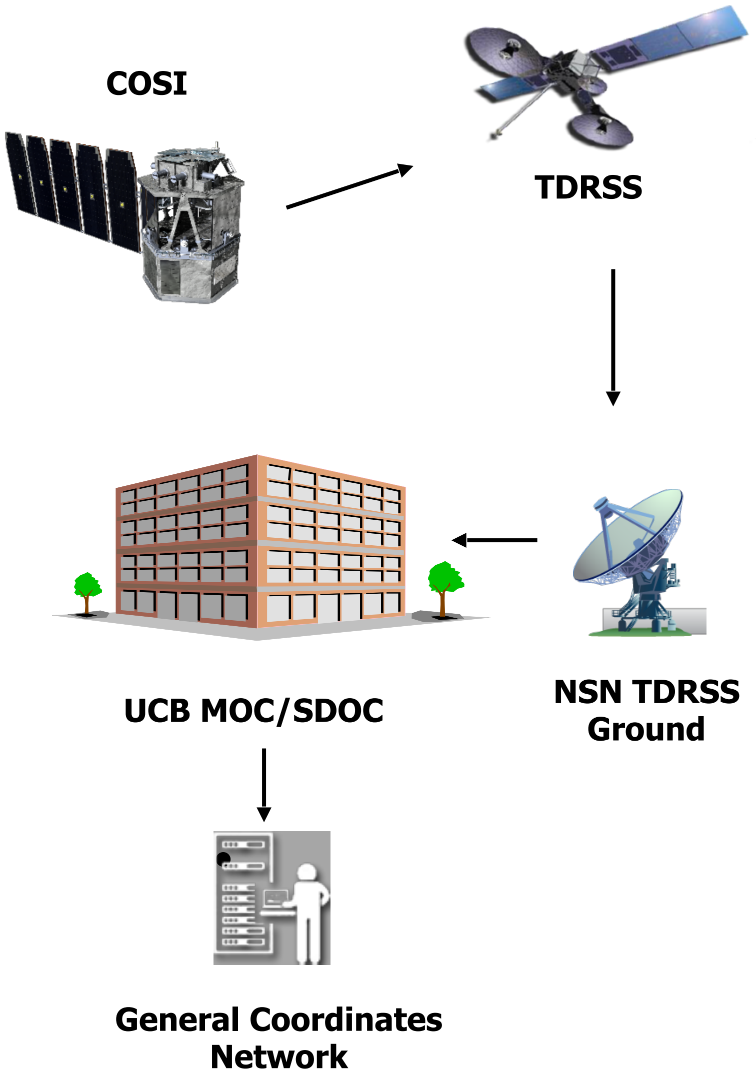
Goal D: Probe the Physics of Multimessenger Events

Merging neutron stars



Short gamma-ray burst (GRB)





- ❑ COSI will rapidly (<1 hr) report the positions of GRBs from merging neutron stars to allow for follow-up by other observatories
- ❑ For the one previously detected (GW170817), the gamma-ray signal arrived 1.7 seconds after the gravitational wave signal, and COSI's detections will help test possible theories for this delay (Collapse to a black hole? Shock formation? Other?)

Measurement requirements

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For emission line goals

Characteristic	Requirement
Sky Coverage	• >25%-sky instantaneous FOV • 100%-sky each day
Energy Resolution* (FWHM)	• <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)

*Notes on energy resolution:

- For fully reconstructed Compton events (average of 2.5 interactions)
- 1.157 MeV requirement is <0.8% FWHM; capability estimate ~0.4-0.5%

For polarization and multimessenger goals

Characteristic	Requirement
Polarization	• >1.4x10^{-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) • Arrival times to an absolute accuracy of <100 ms • Reporting in <1 hr

Hardware: Engineering models and testing

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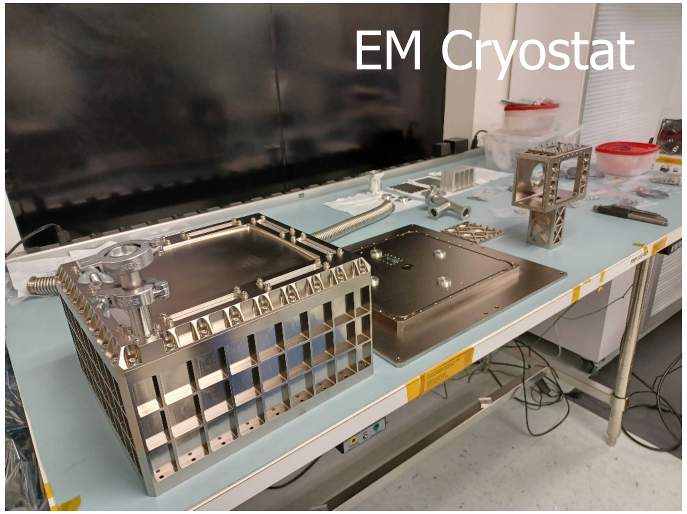
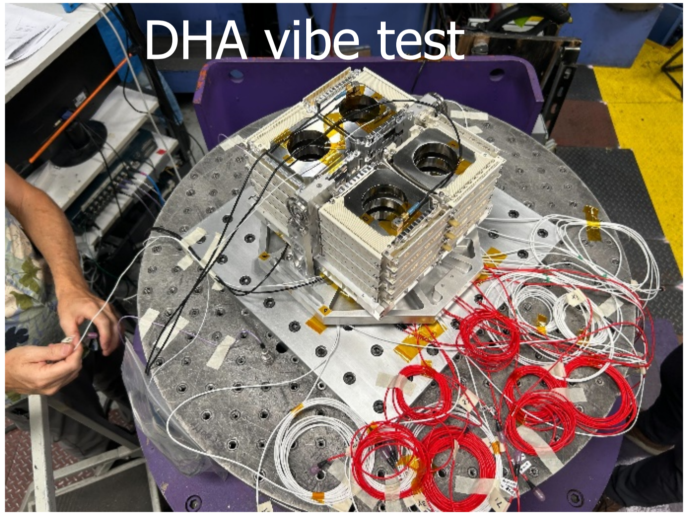
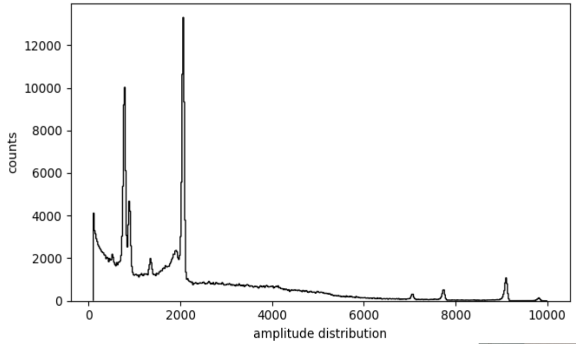
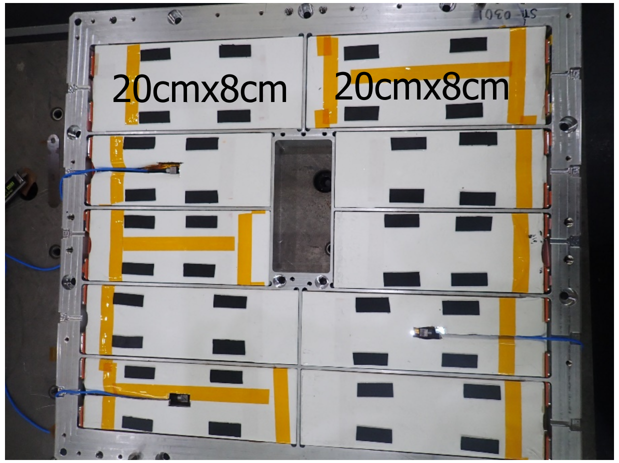
- EM (and some FM) hardware being built and tested at:
  - UCB/SSL
  - NRL
  - SDL
  - LBNL
  - GSFC
  - Northrop Grumman



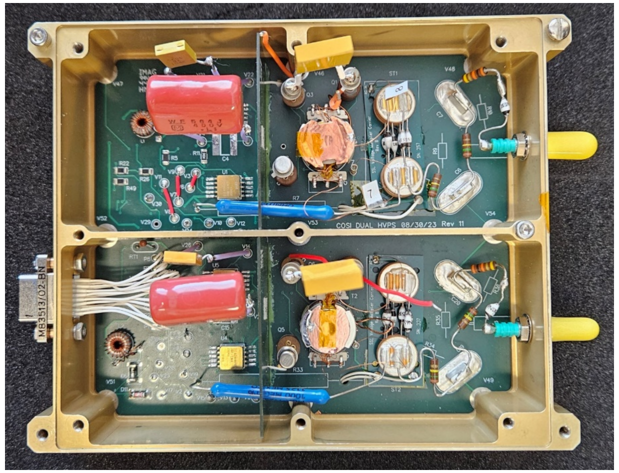




^{133}Ba spectrum measured with a COSI germanium detector



EM bottom shield (~40cmx40cm)



EM HVPS

Mission status and how you can get involved

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- Recent past and near future
  - Completed Preliminary Design Review (PDR) in February 2024
  - Launch vehicle selected (SpaceX Falcon 9) in July 2024
  - **Next:** Critical Design Review (CDR) coming up in Nov/Dec 2024
- How you can get involved
  - Yearly public “data challenges” (github.com/cositools/cosi-data-challenge-2)

cosi.ssl.berkeley.edu