COSI
Gamma-ray
Space Explorer

COSI mission status and prospects

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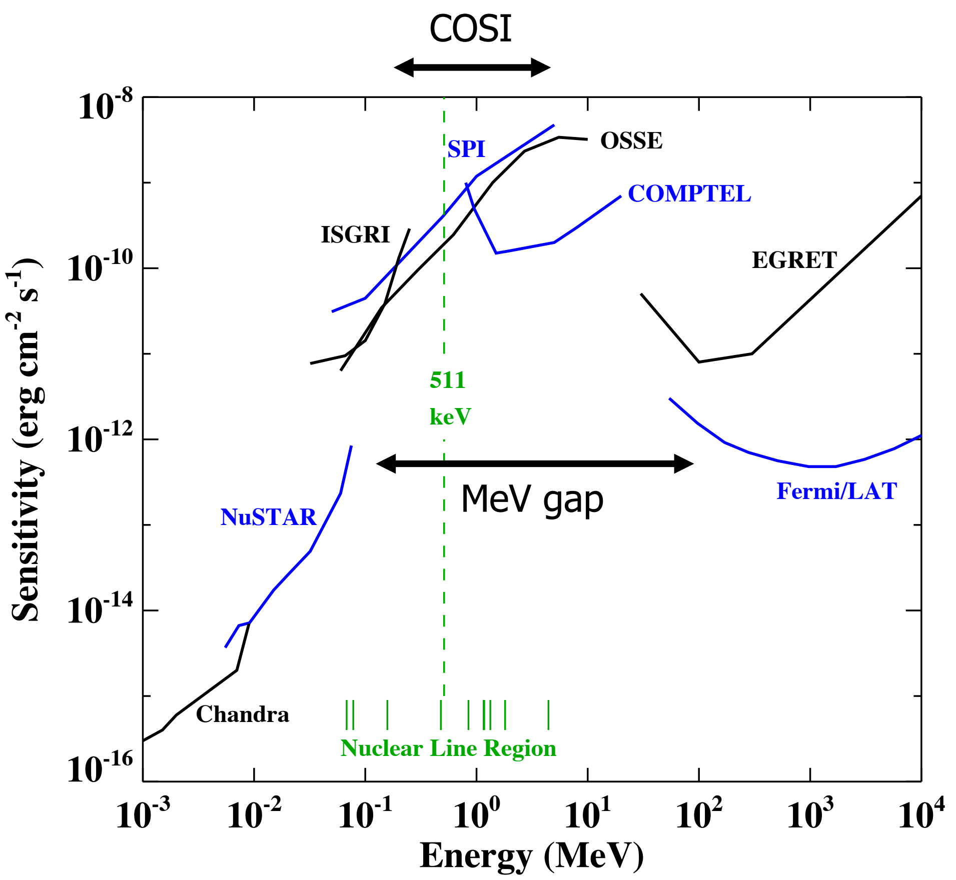
COSI overview

- 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***
  - 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

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

Why does studying MeV gamma rays call for a Compton telescope?

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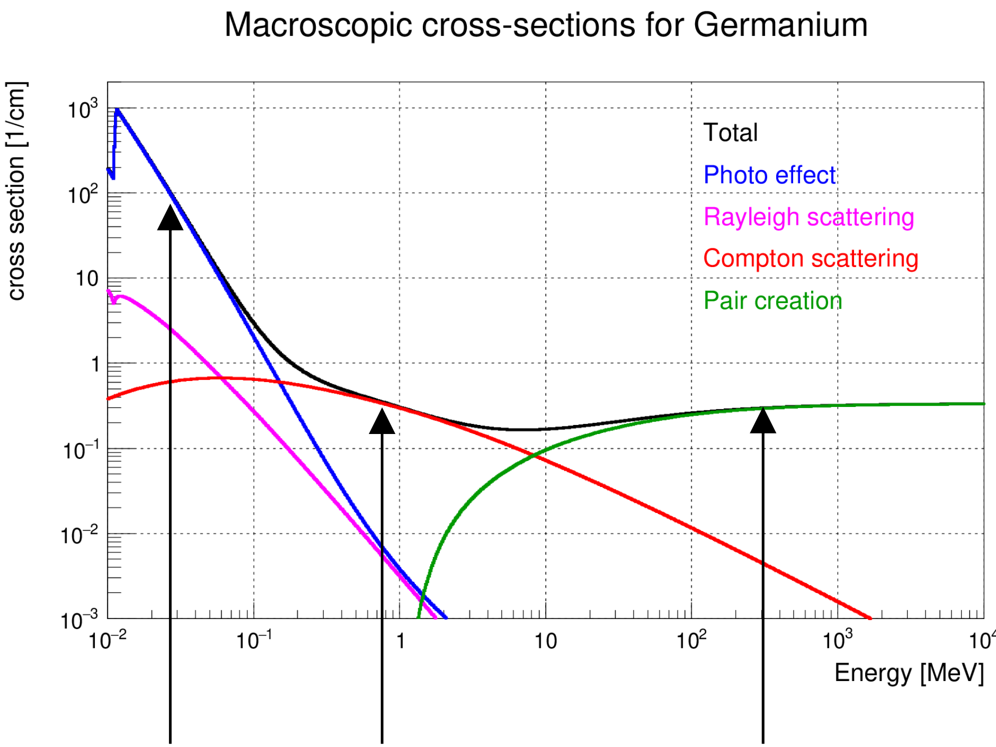
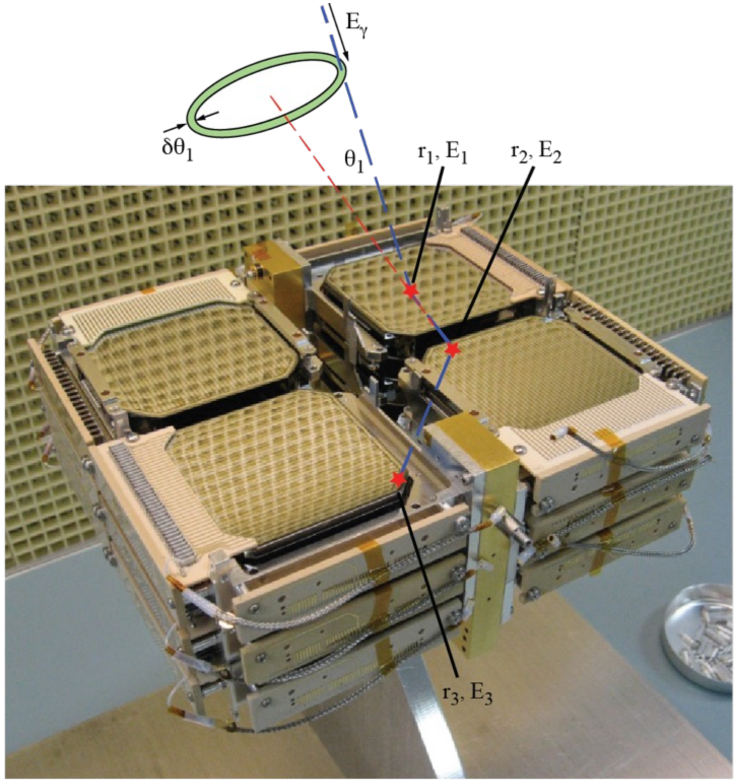


Full photon absorption (NuSTAR, etc.)

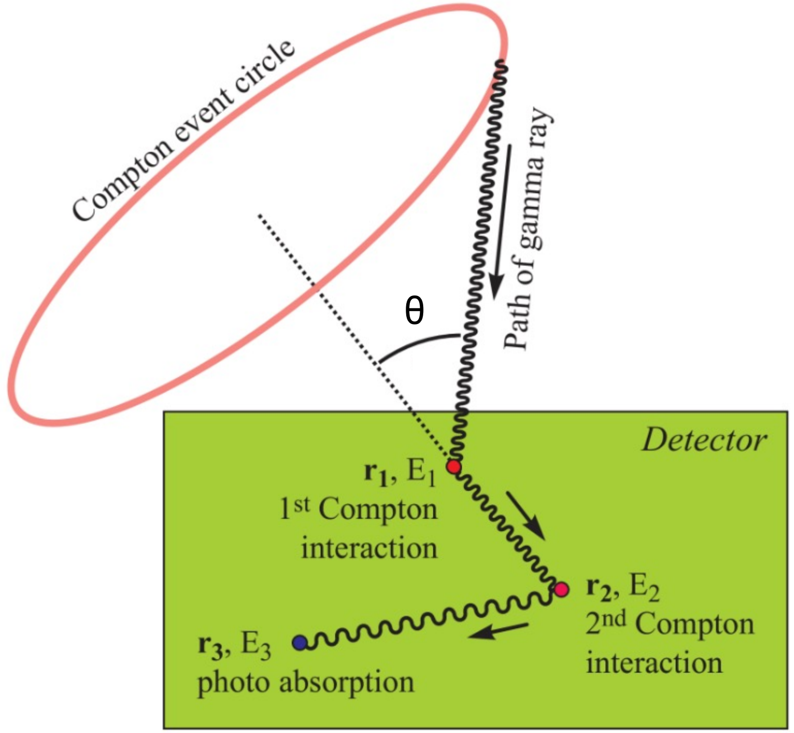
Compton telescopes (COMPTEL, **COSI**)

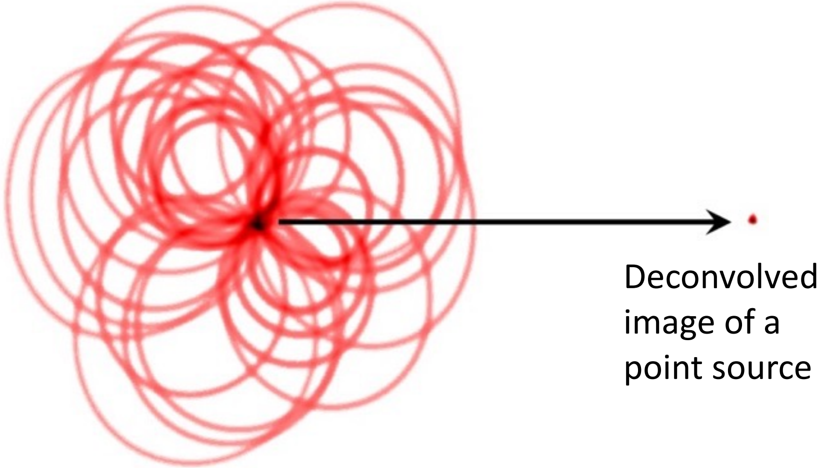
Pair creation telescopes (Fermi/LAT)



- Germanium detectors from COSI-balloon illustrating Compton telescope operation
  - 12 GeDs, 8x8x1.5 cm^3 each

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

COSI science goals

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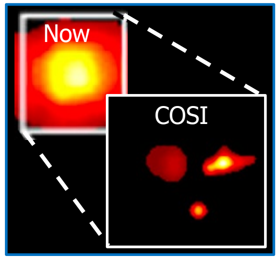
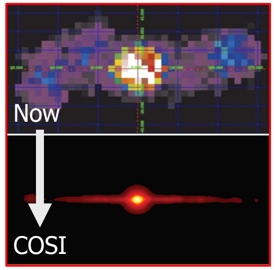
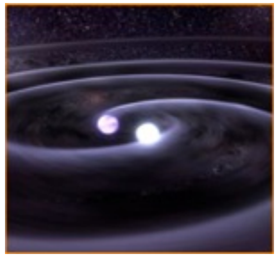


A. Reveal Galactic element formation



B. Uncover the origin of Galactic positrons

C. Gain insight into extreme environments with polarization

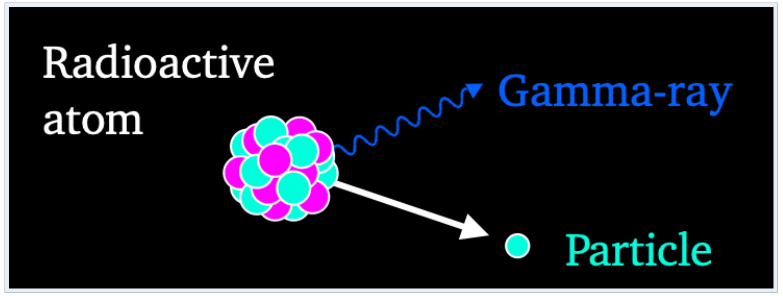


D. Probe the physics of multimessenger events

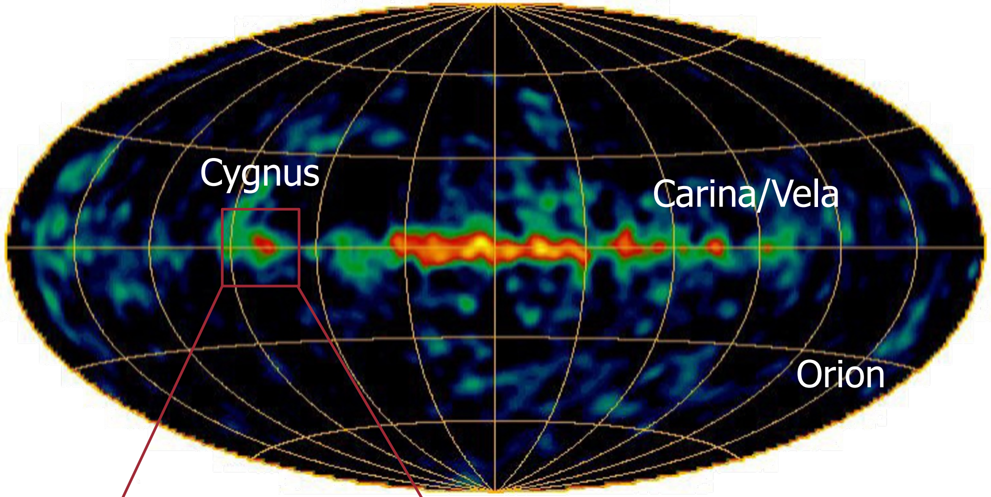
Goal A: Reveal Galactic element formation

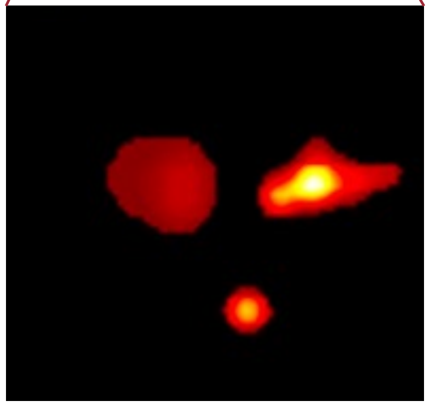
Three windows on element formation associated with massive star evolution:

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

- OOM better sensitivity
- 2x better angular resolution

Goal B: Uncover the origin of Galactic positrons

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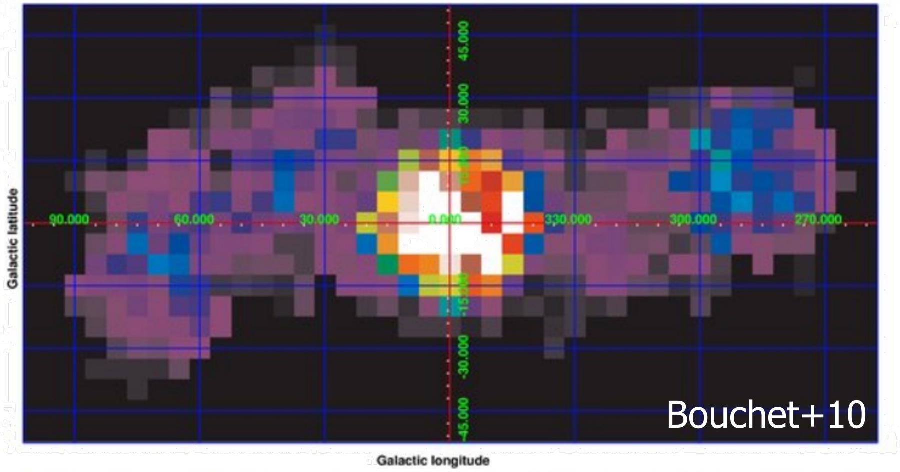
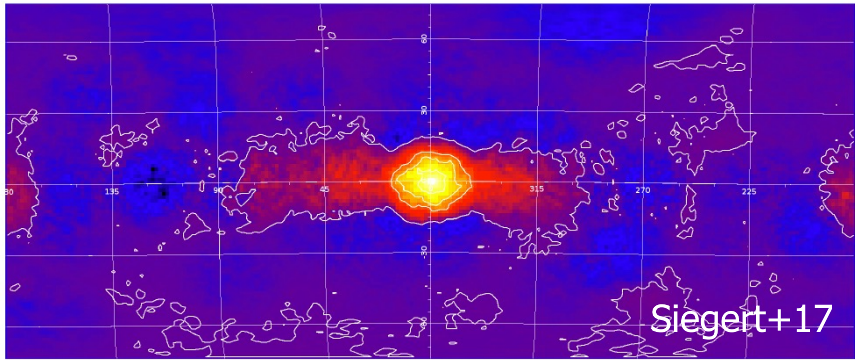
- COSI traces positrons by measuring the 511 keV e^-e^+ annihilation line
- Current questions:
  - What is producing the ~5×10^{43} e^+/s required to explain the 511 keV signal?
  - What is the reason for the strong excess coming from the Galactic bulge?

INTEGRAL/SPI maps of the 511 keV emission





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

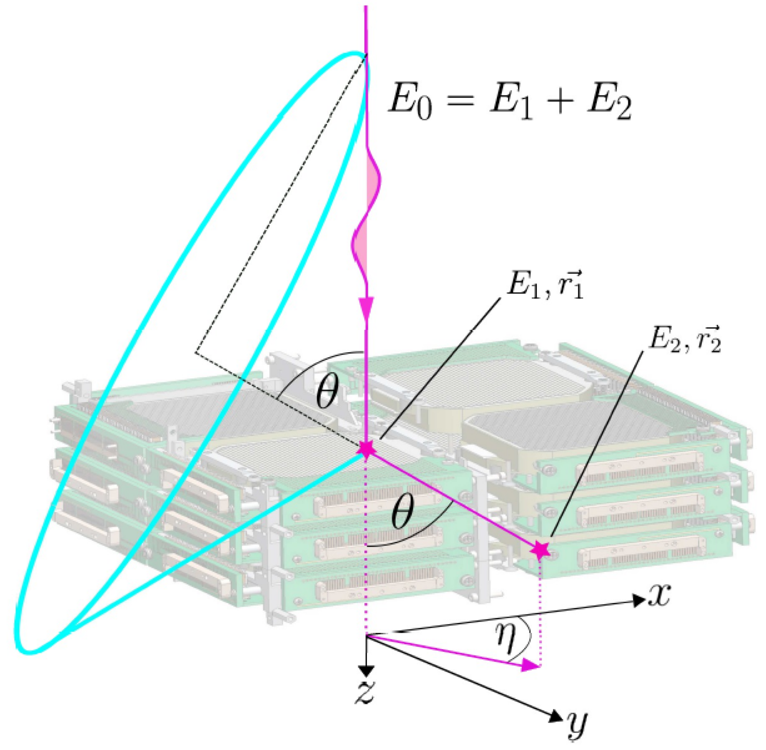
Siegert 17 and Siegert 23: "The Positron Puzzle"

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%

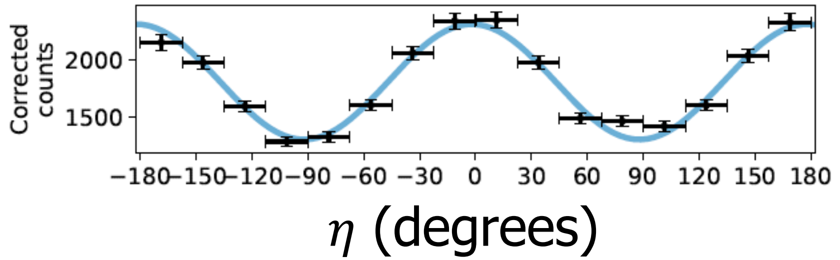
Is the 511 keV Galactic bulge excess:
- Truly diffuse?
- Made up of individual sources?
- How many sources or components?

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)
- How does COSI measure polarization?
  - The azimuthal scattering angle is polarization-dependent



COSI-balloon: partially polarized source

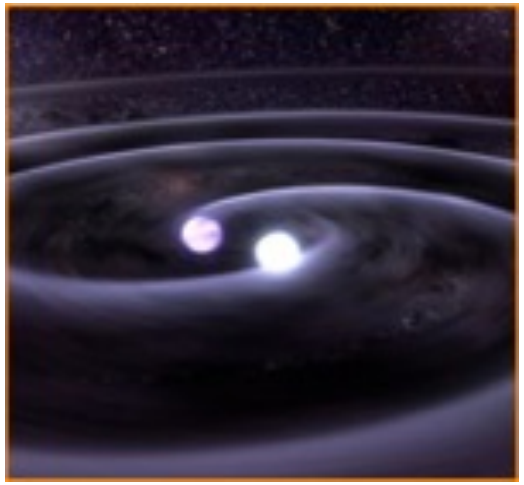


Goal D: Probe the physics of multimessenger events

- 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., Kamiokande (low-energy)
  - ***Cosmic-rays*** detected by particle detectors

- 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



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COSI requirements and measurement goals

	Characteristic	Requirement or measurement goal
Primarily for goals A+B	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}] • 1.2×10^{-5} (Galactic bulge is 100x brighter than requirement level) • 3×10^{-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)

COSI required line sensitivity compared to actual COMPTEL and INTEGRAL/SPI sensitivities

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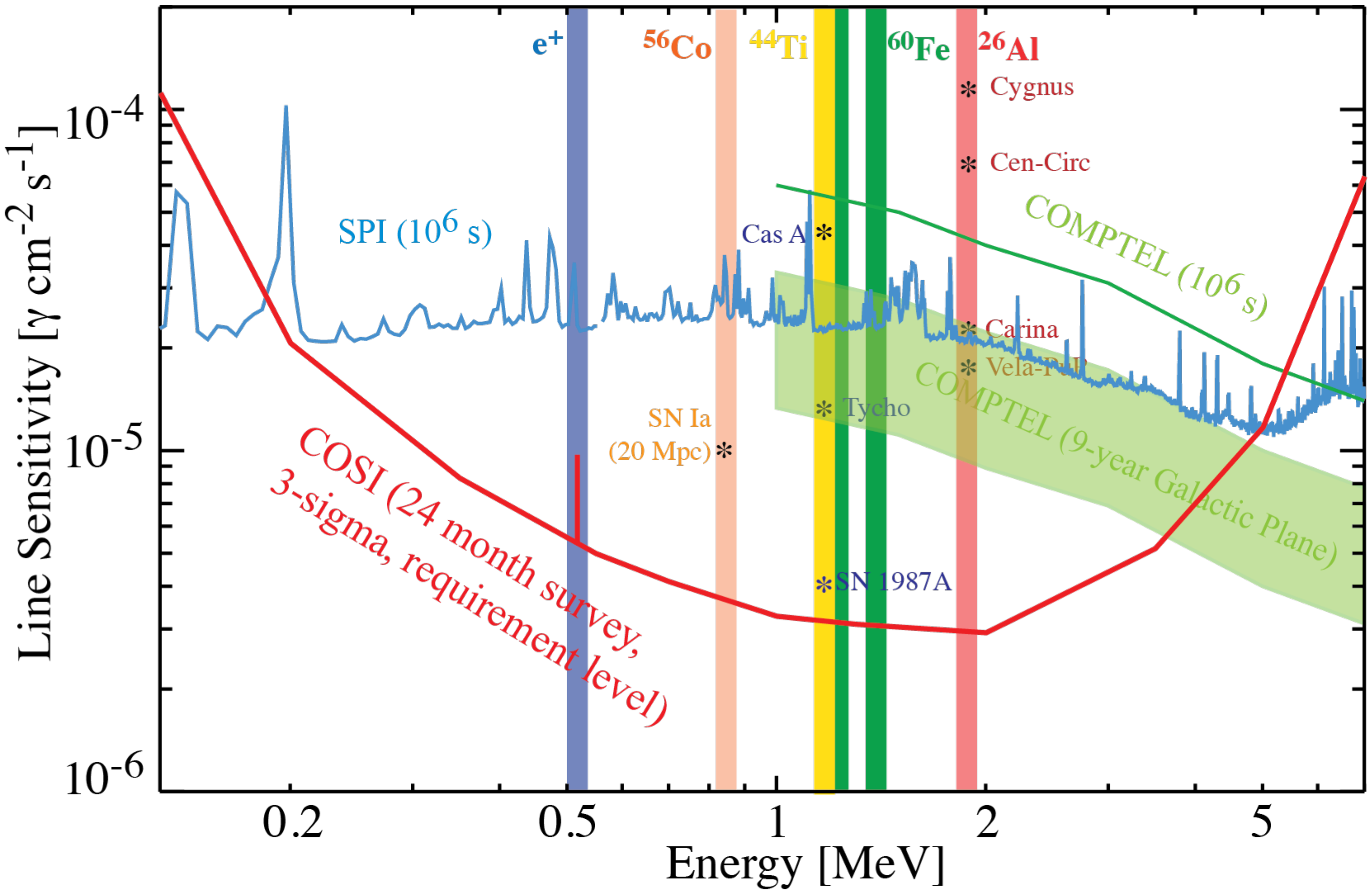
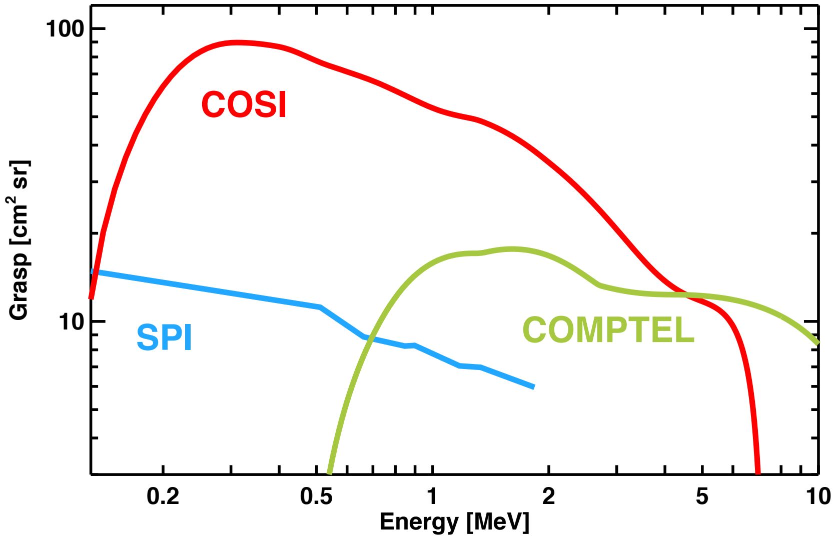


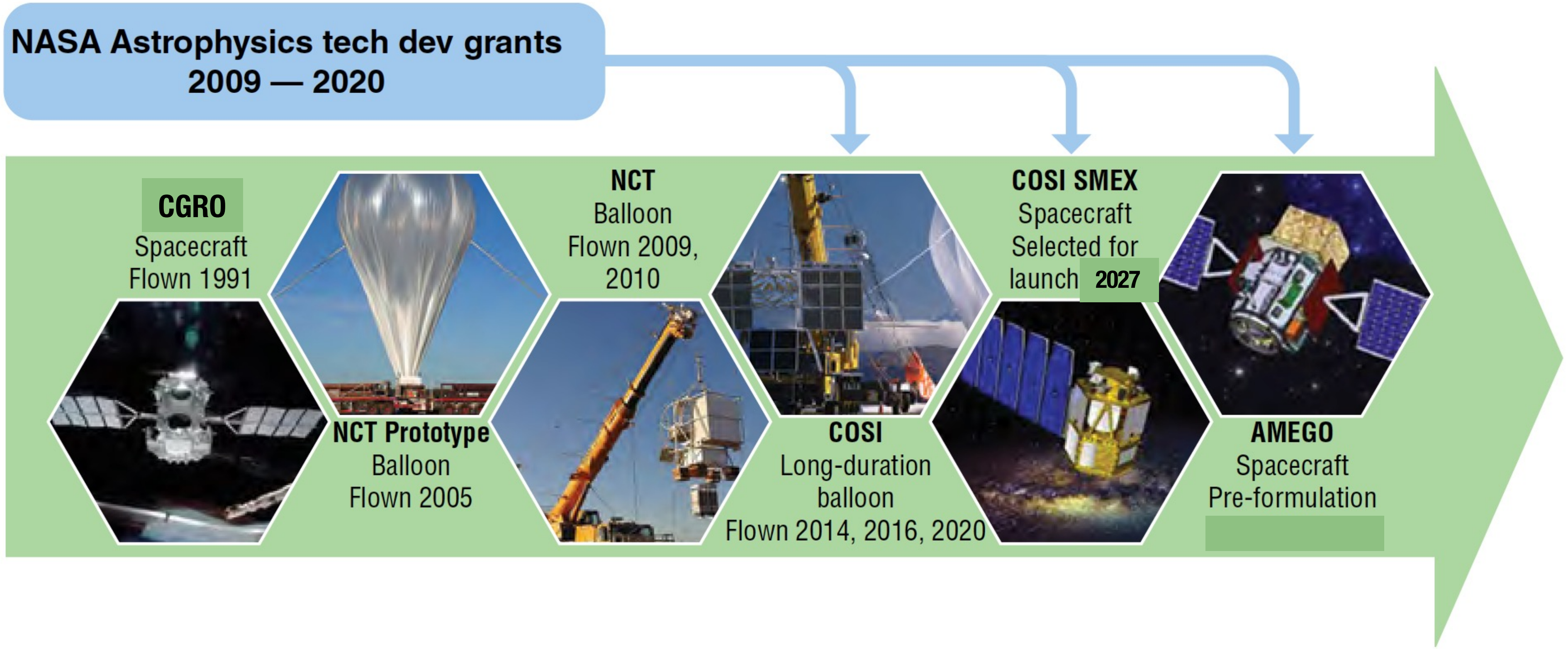


Grasp/Geometric factor (A_{eff} x FOV)

- ❑ Grasp combined with energy resolution provide the improved sensitivity

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

Compton telescope development



- ❑ NASA Astrophysics Biennial Technology Report 2022
  - ❑ Development of a compact Compton telescope
  - ❑ NCT/COSI balloon campaigns in 2005, 2009, 2010, 2014, 2016, and 2020

Germanium double-sided strip detectors (GeDs)

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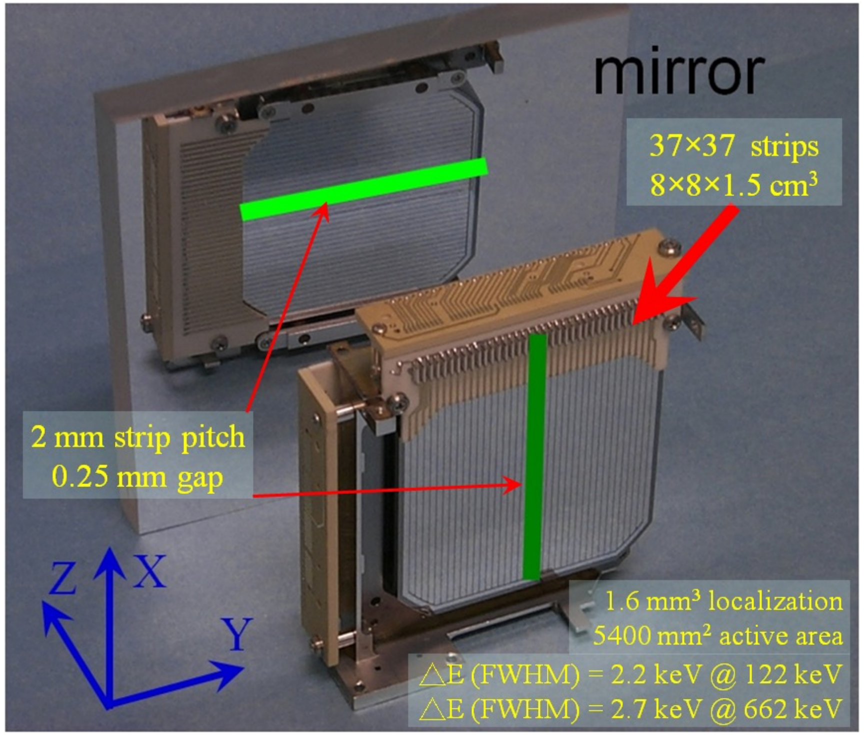
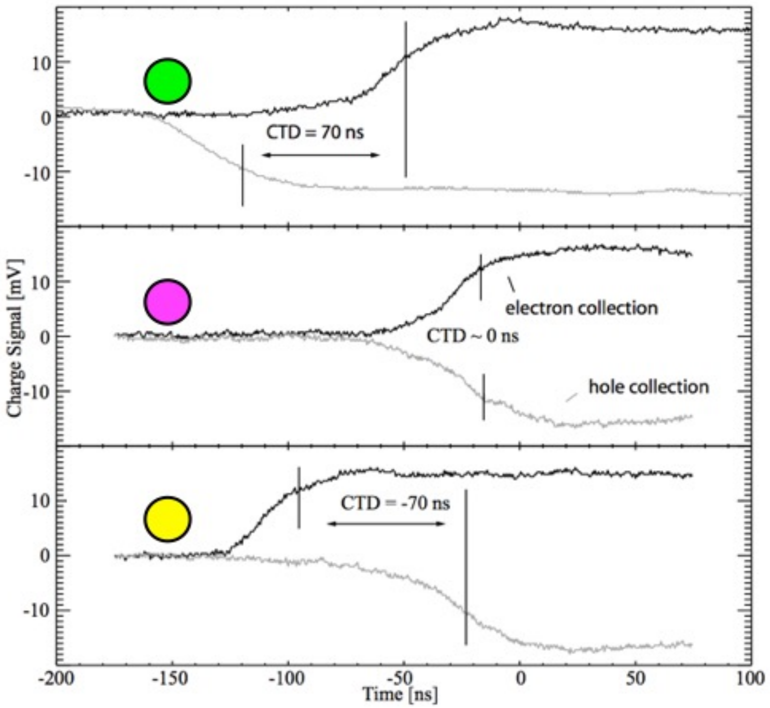
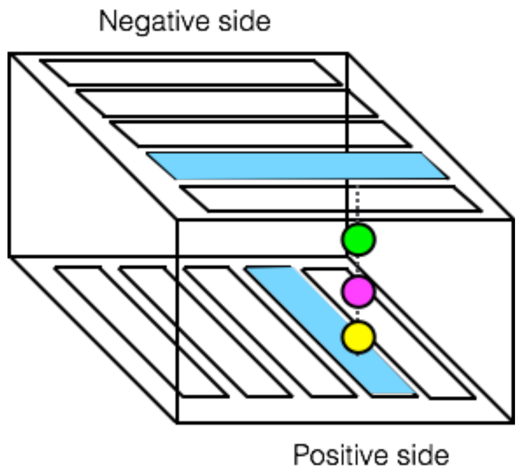
- ❑ Semiconductor detectors at cryogenic temperatures
- ❑ Voltages of 1000-1500 V across the two sides
- ❑ 3-dimensional position sensitivity







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

Cryostat, cryocooler, and shields (COSI-balloon)

❑ Cryostat

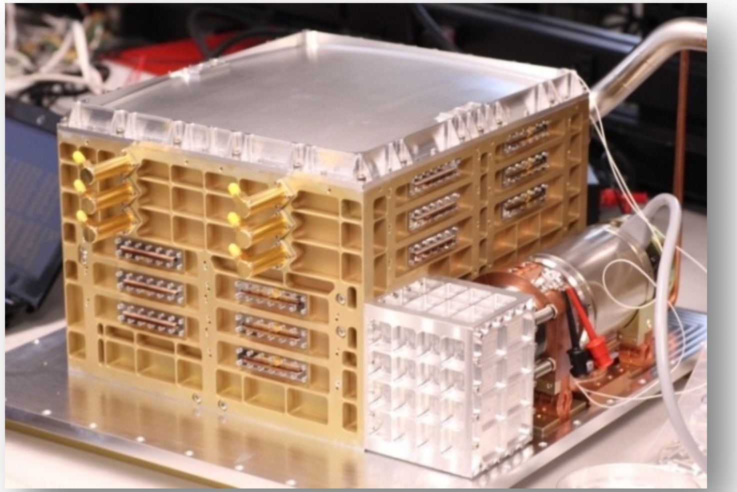
- Vacuum-sealed with the following connections to the GeDs:
  - cold finger from cryocooler
  - HV feedthroughs
  - Signals from 888 strips

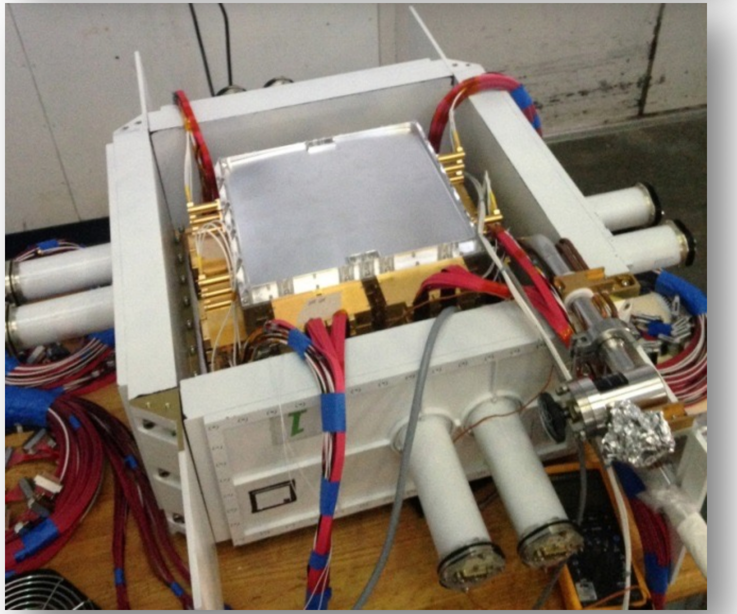
❑ Cryocooler

- Sunpower CryoTel Stirling cycle cooler
- 11 W lift for 160 W input
- Largest item in power budget

❑ Cesium iodide (CsI) anticoincidence shields

- 4 cm-thick CsI read out by photomultiplier tubes
- Germanium events coincident with shield events are vetoed
- Largest item in mass budget





COSI-balloon summary

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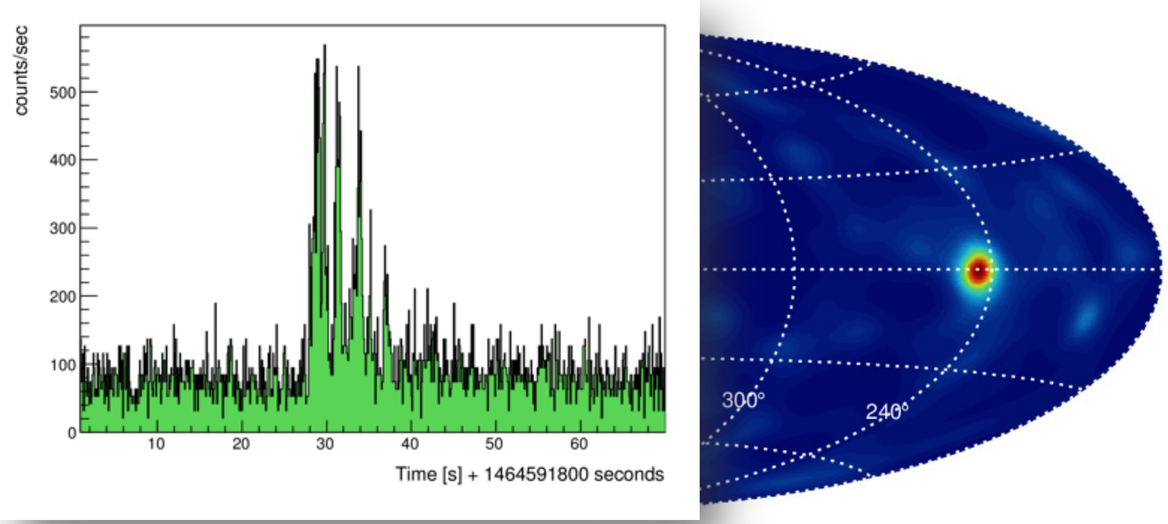
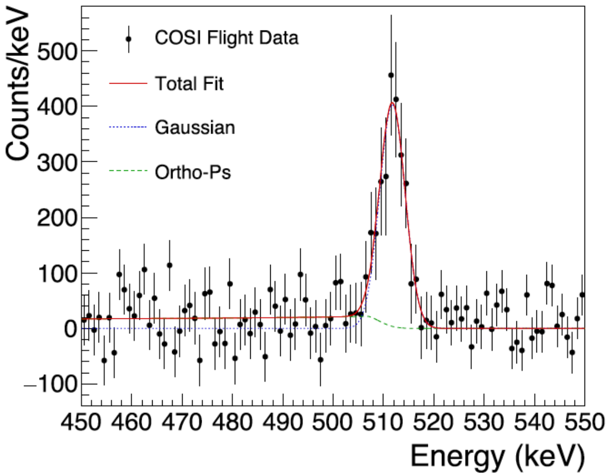
- Results from 46-day flight in 2016
  - GRB 160530A (Lowell 17, Sleator 19)
  - 511 keV (Kierans 18+20, Siegert+20)
  - ^{26}Al (Beechert+22, ApJ)
  - Crab nebula (Zoglauer+21)
- Capabilities demonstrated
  - Real-time GRB reporting
  - Imaging
  - Spectroscopy
  - Polarization measurement capabilities
- Proof of concept demonstrated with COSI-balloon
  - Instrument operation
  - Data analysis with MEGAlib (Zoglauer 06) and COSIpy (Siegert+20)

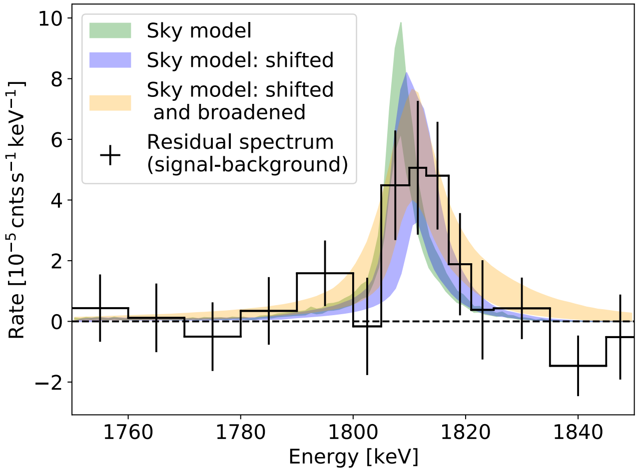
GRB 160530A: Reported in real-time in GCN 19473 (Tomsick+16)



511 keV from the Galactic bulge

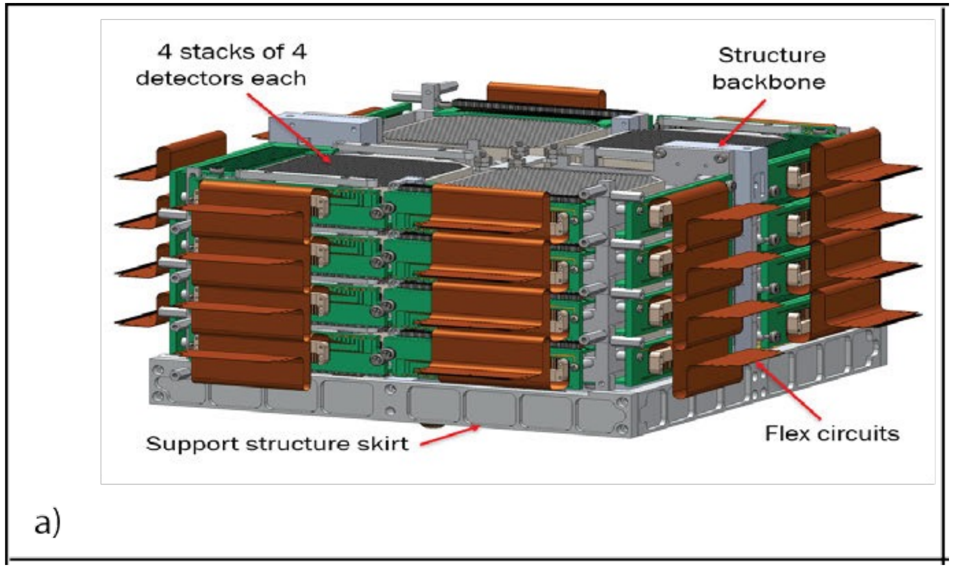


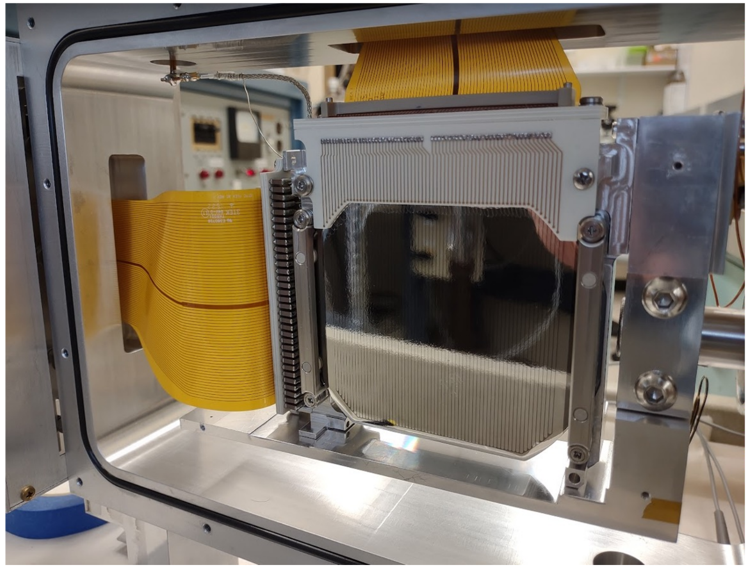
^{26}Al from the Galactic plane



COSI advances vs. COSI-balloon

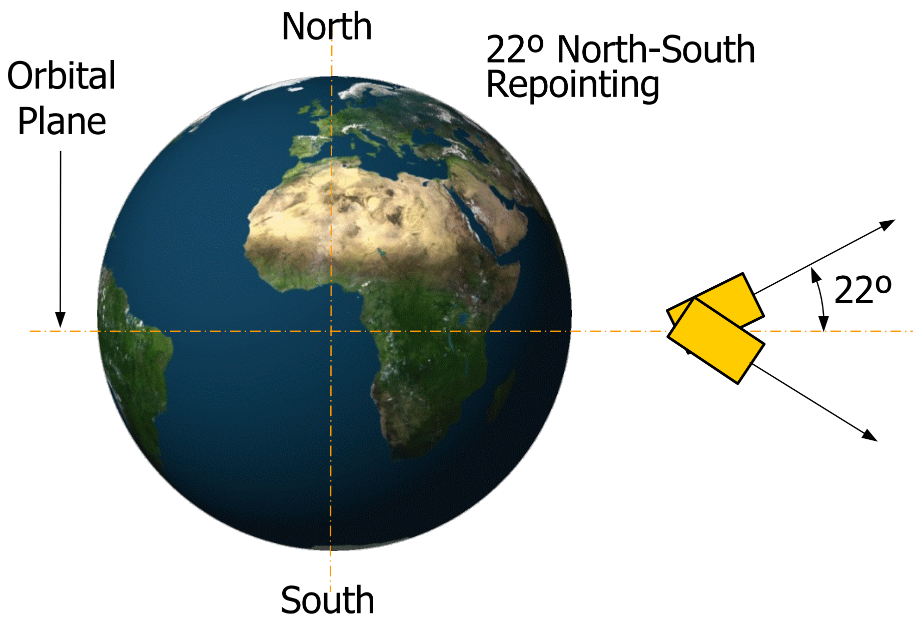
- ❑ Change from 12 to 16 GeDs
- ❑ Change from 37 to 64 strips per GeD side (2048 signals)
  - Better angular resolution
  - Better event reconstruction → A_{eff}
- ❑ Change from CsI to BGO material for active shields
- ❑ Longer exposure
  - COSI has a 2-year baseline mission
- ❑ No atmospheric attenuation
- ❑ Lower and more stable background
- ❑ All-sky coverage





64 strip GeD loaded into test cryostat

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

Mechanical overview

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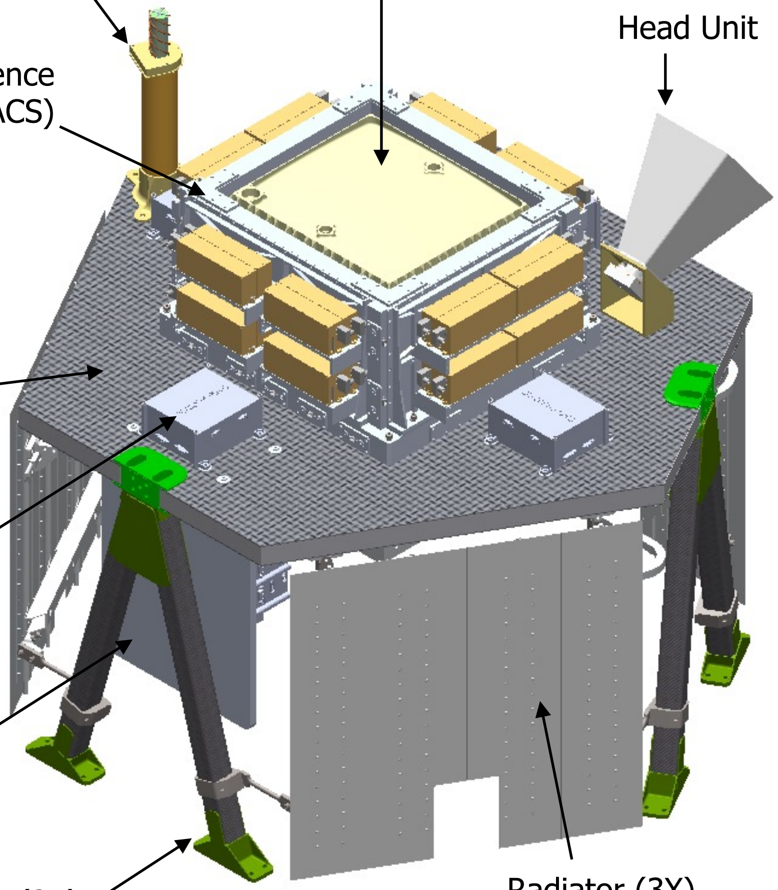

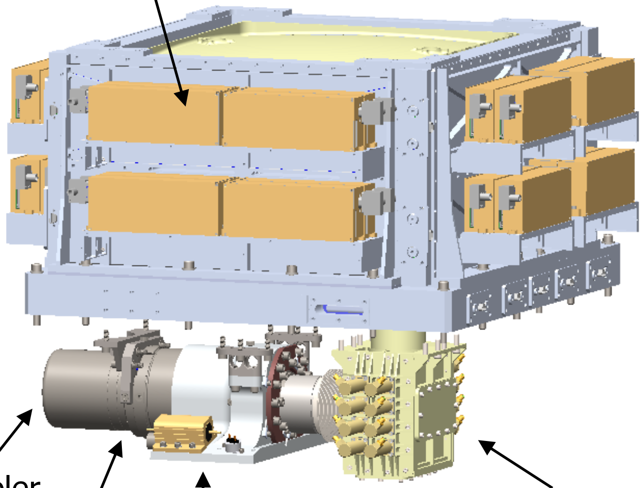

Mass Table	
COSI Payload Current Best Estimate (CBE)	188 kg
COSI total CBE	292 kg
Mass allocation	365 kg

- **Size of hexagonal PIP is ~1m flat-to-flat**

Ground communications and data link

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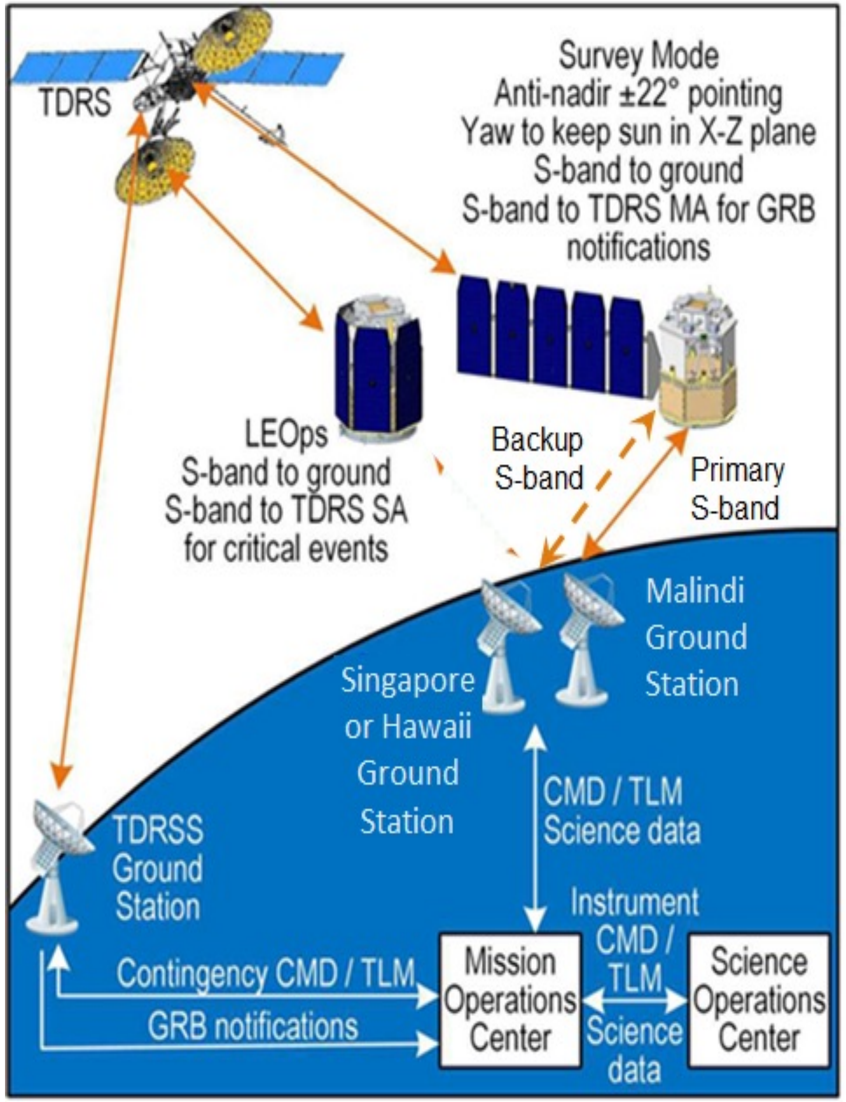
- Ground stations to accommodate 6.3 Gbits/day (59 kbps science data)
  - Primary: Malindi ground station
  - Secondary: Singapore ground station

- MOC and SOC at UC Berkeley

- Plan for transient alerts
  - Detection in BGO shields
    - ***Expect approximately one trigger per day (long and short GRBs, SGRs, TGFs, etc.)***
  - Buffered germanium data selected and sent down via Tracking and Data Relay Satellite (TDRS)
  - Automatic ground processing for classifying events, determining positions, and sending GCN notifications



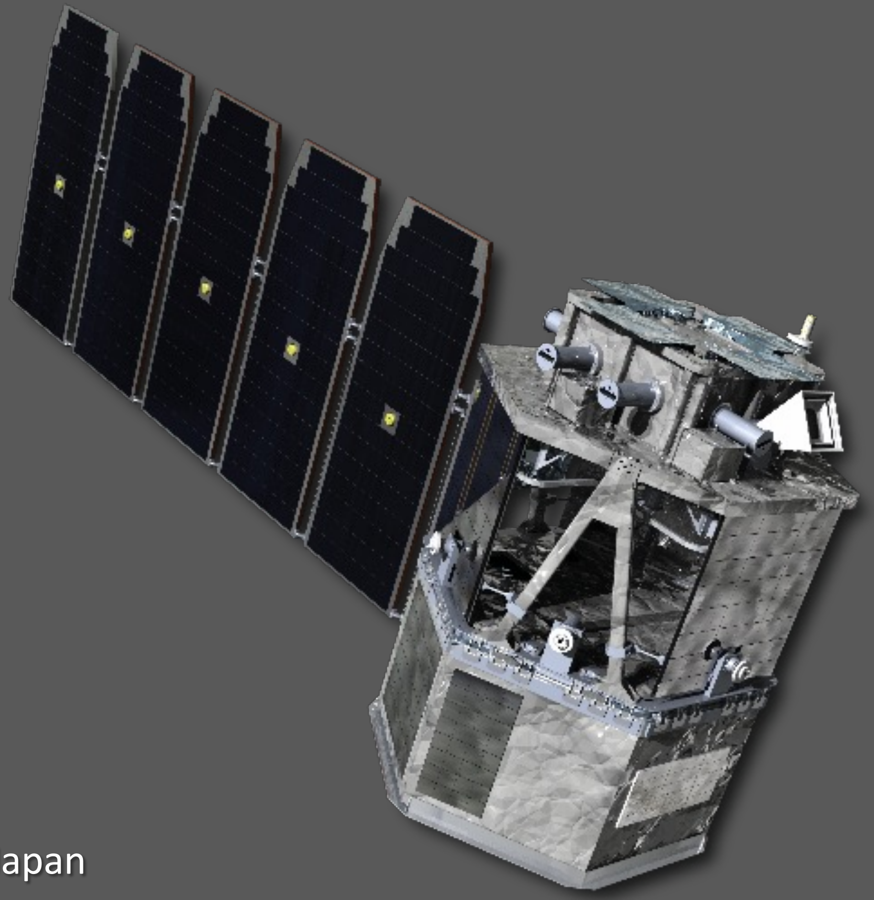
The COSI collaboration

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



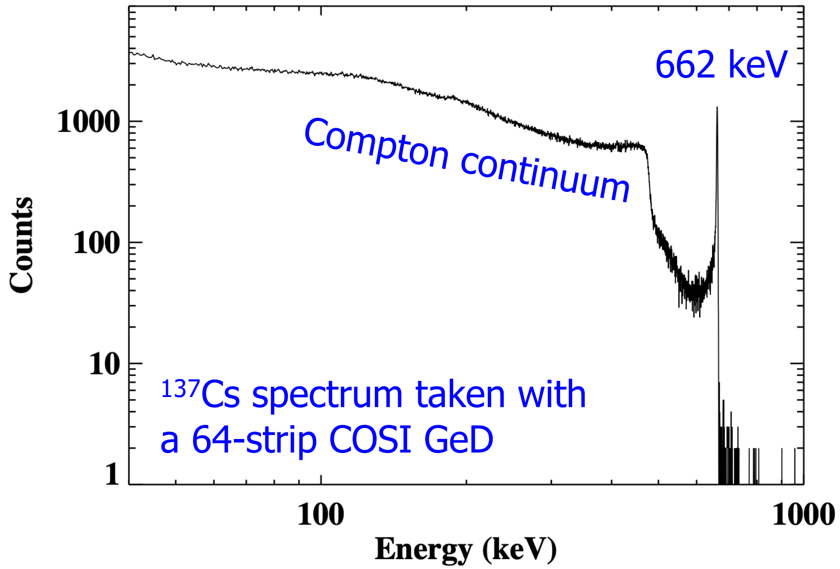
Institutions of Co-Investigators and Collaborators
- Clemson University
- Los Alamos National Laboratory
- Louisiana State University
- **INAF and ASI, Italy**

Elisabetta Cavazzuti, Luigi Costamante

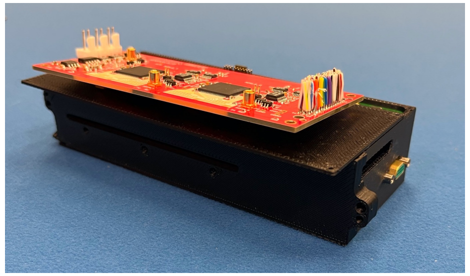
- Kavli IPMU and Nagoya University, Japan
- JMU/Wurzburg and JGU/Mainz, Germany
- IRAP, France
- Science team members at National Tsing Hua University, University of Hertfordshire, North-West University (South Africa), and Yale University

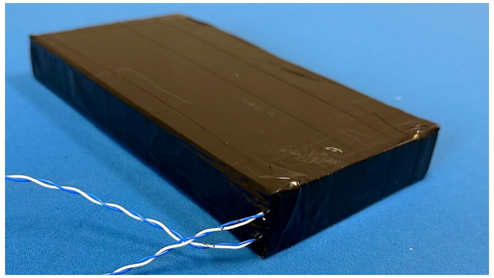
Current status and schedule

- 64-strip GeD delivered to UC Berkeley

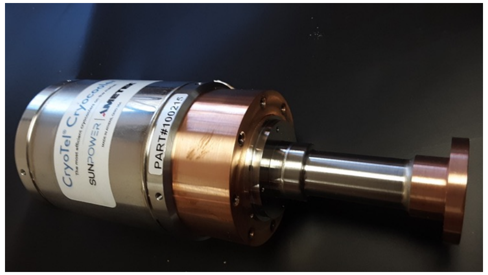


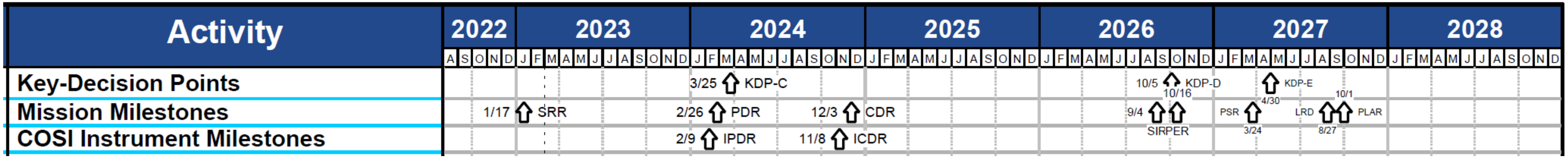
- Naval Research Lab
  - Detector Interface Board with two 32-channel ASICs (left)
  - BGO scintillators with SiPM readout (right)





- NASA/GSFC
  - Cryostat heat removal system
  - Cryocooler procurement





Currently in Phase B and passed Systems Requirements Review (SRR)

PDR in February 2024

CDR in December 2024

Payload I&T

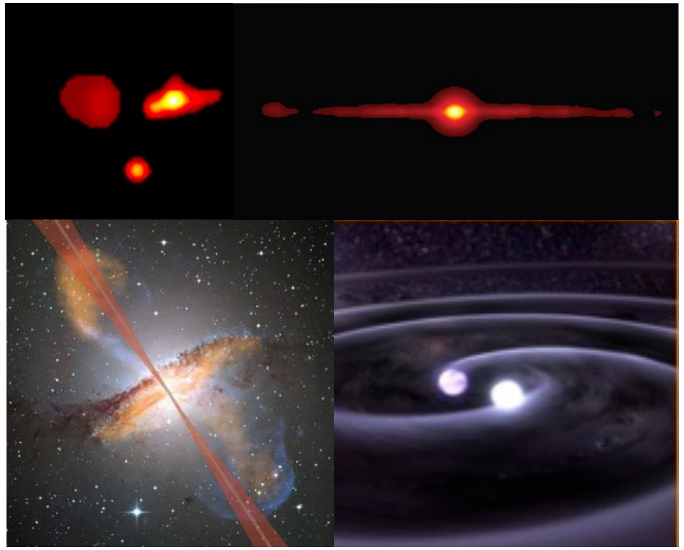
System Integration Review in Sept 2026

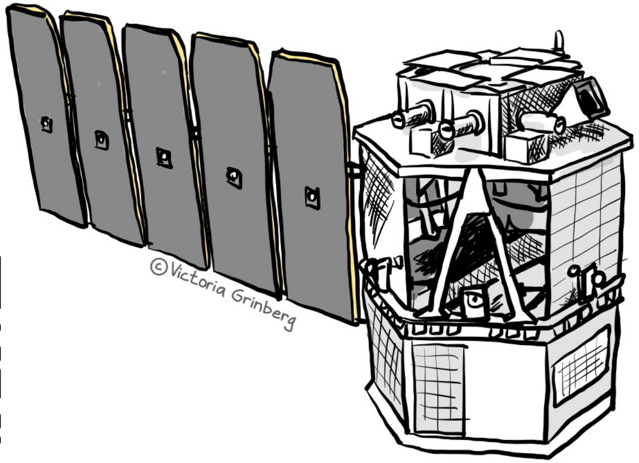
Launch!

2-year prime mission

Path forward and conclusion

- ❑ Exciting prospects for COSI's study of the MeV bandpass starting in 2027
  - Nuclear lines, positron annihilation, polarization, MMA
- ❑ COSI-balloon has allowed for instrument development and has provided an important proof of concept
- ❑ For COSI, next milestone review is Preliminary Design Review (PDR) planned for Feb 2024
- ❑ Yearly data challenges are an opportunity for community involvement and DC1 has been released
  - https://github.com/cositools/cosi-data-challenge-1



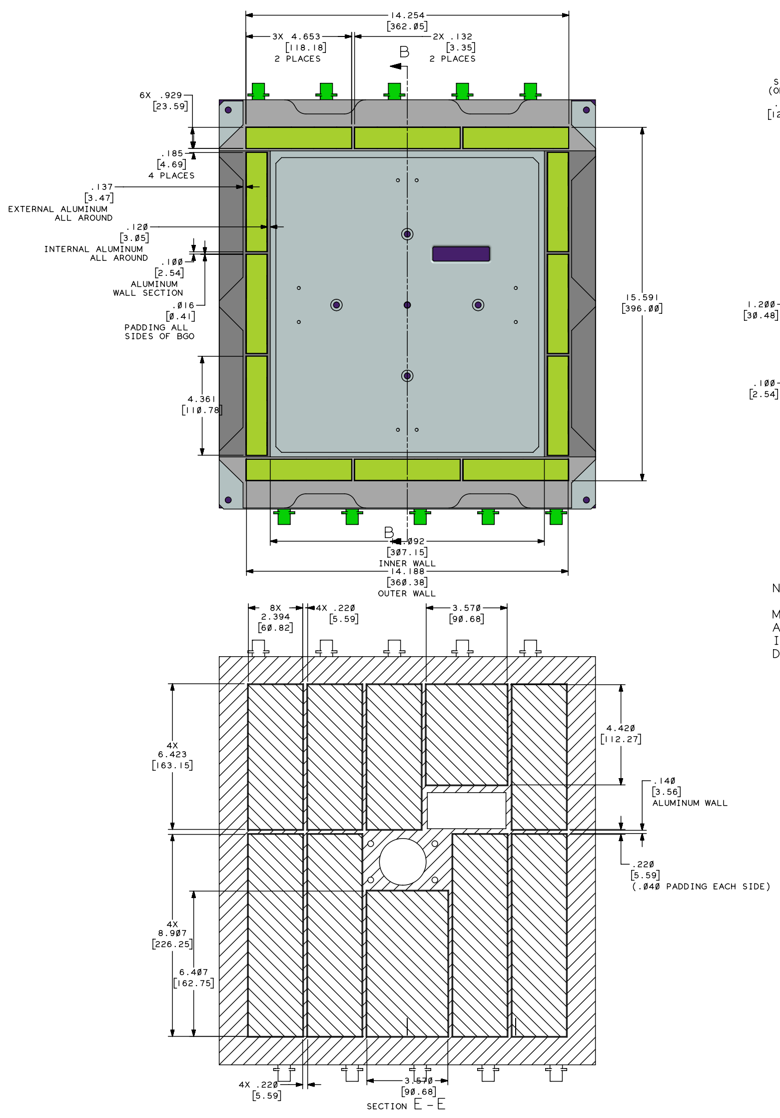


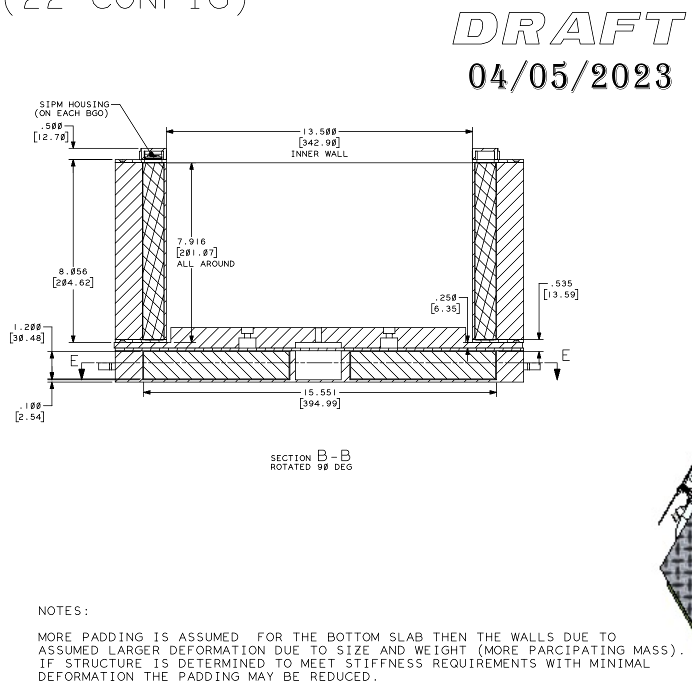
cosi.ssl.berkeley.edu

Backup

Current instrument design

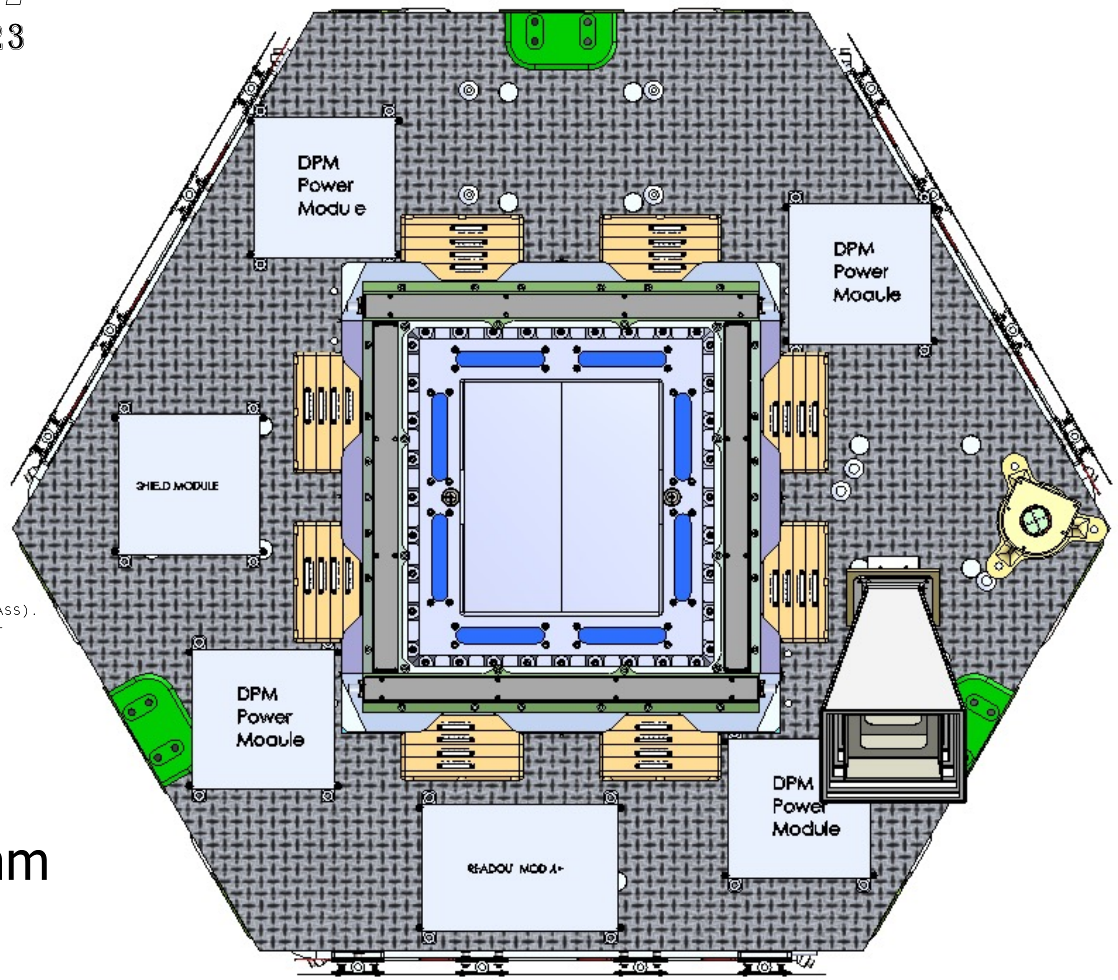
ACS BGO DIMENSIONS (22 CONFIG)





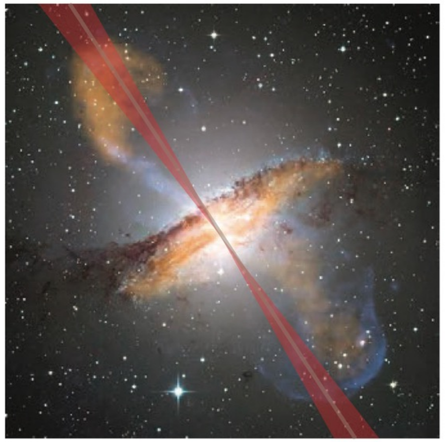
SiPMs

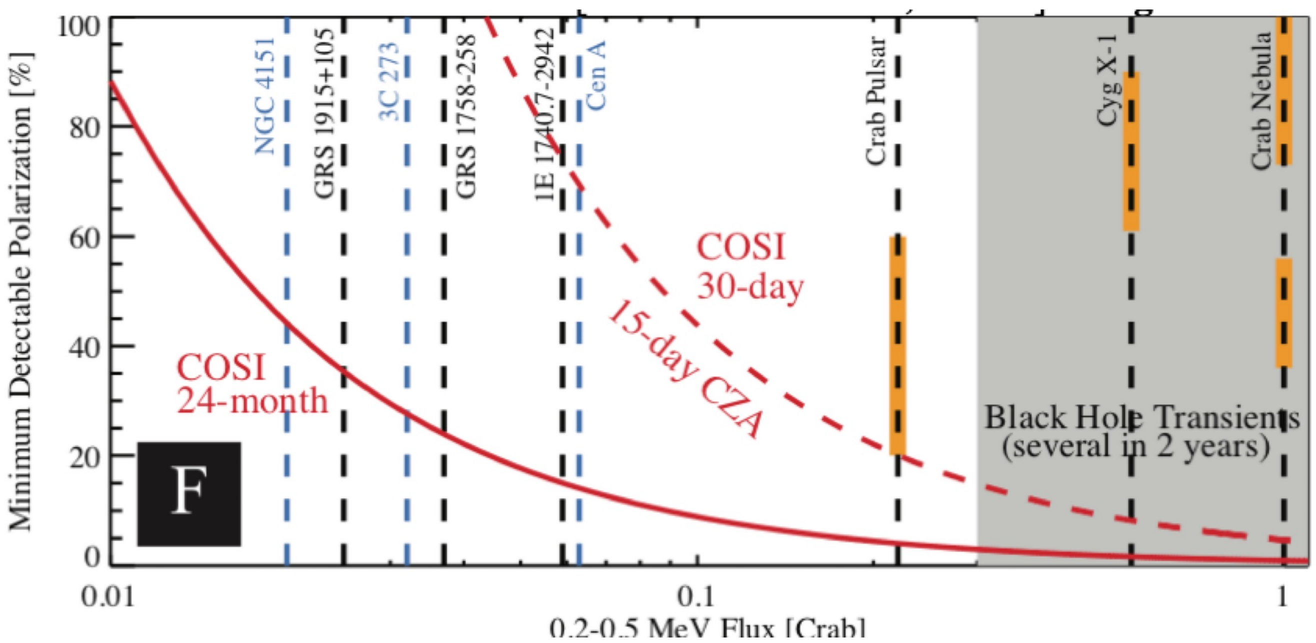
- SensL J-series, 6x6mm
- 3x3 array per crystal
- 22 crystals



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

Cosmic ray de-excitation lines

- Galactic center region (below) and Cas A (right) are considered as possibilities for detection of gamma-ray lines
  - Would constrain LECR spectrum (~10 MeV to 1 GeV)

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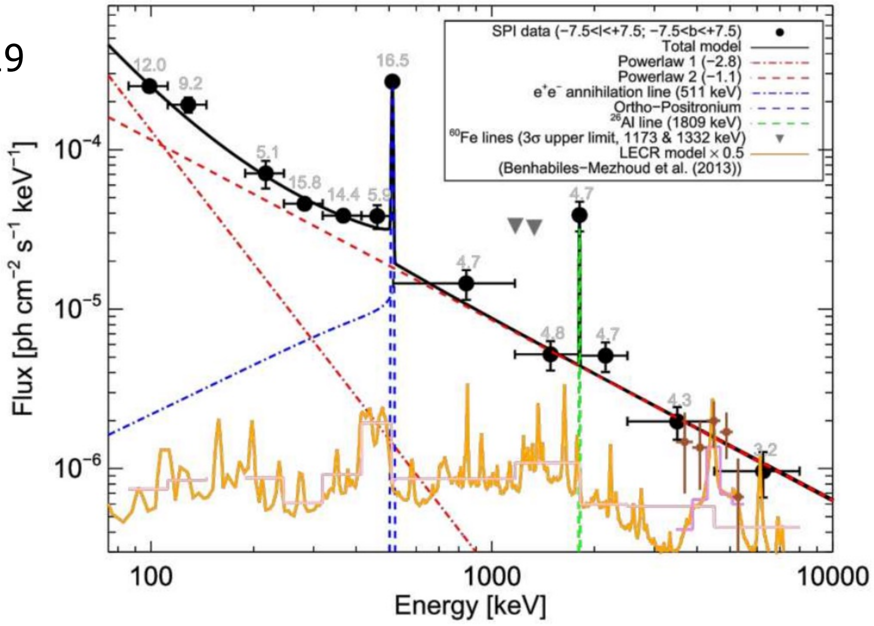
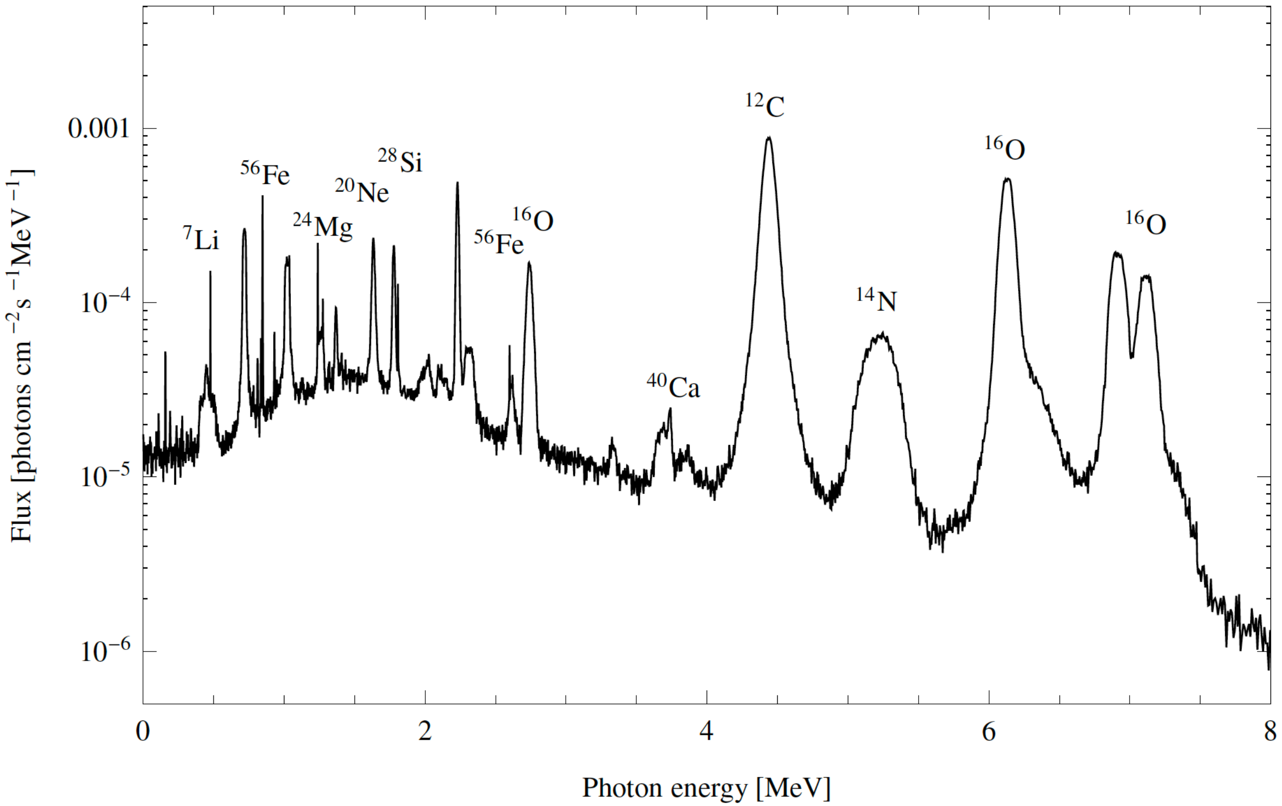


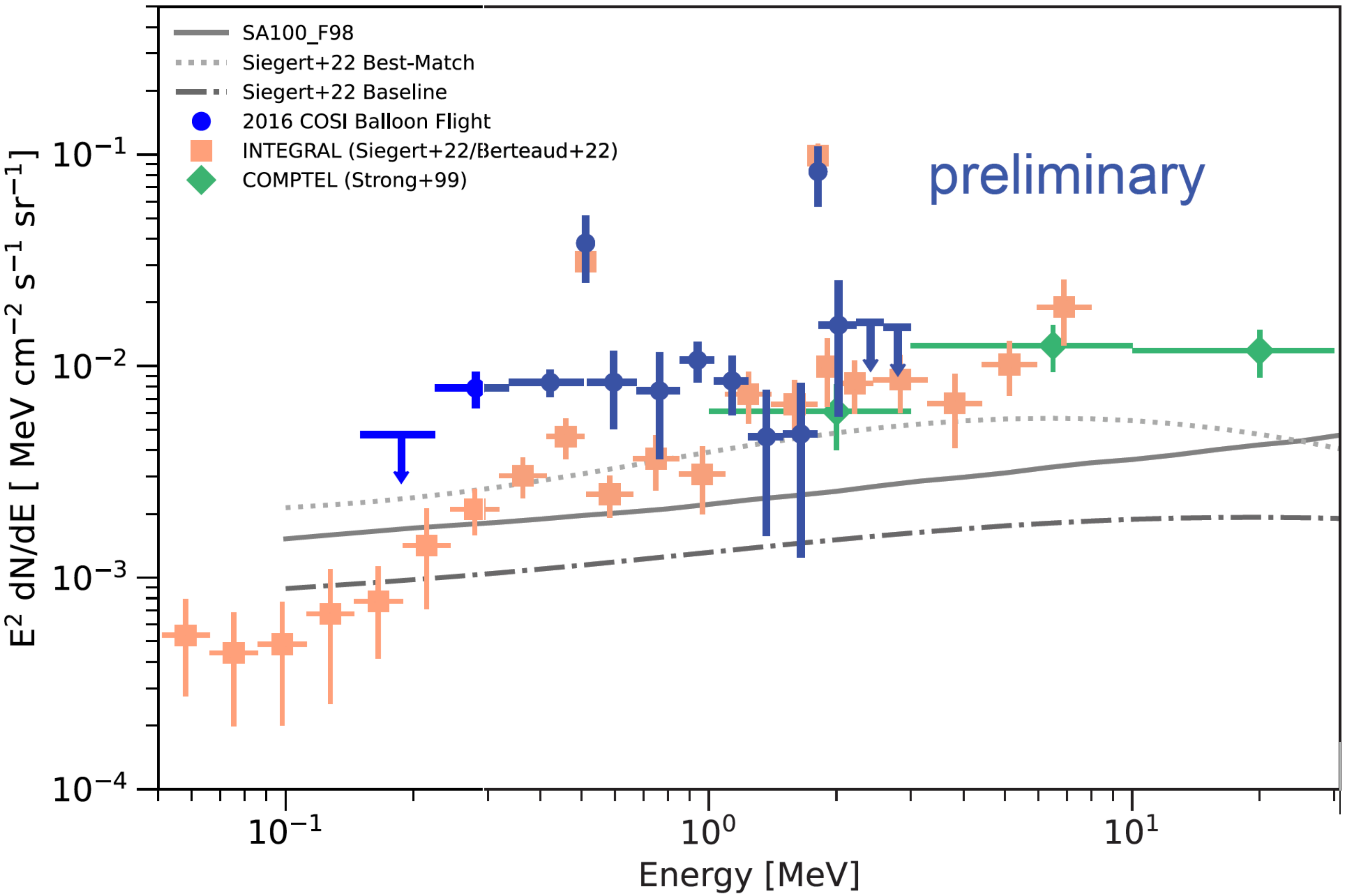
Predicted spectrum for the Cas A SNR from Summa+11



Galactic Diffuse Continuum Emission

COSI
A Gamma-ray
Space Explorer

- Most recent recent COSI-balloon data analysis has been compared to INTEGRAL
- Karwin et al., in prep.



COSI observational summary

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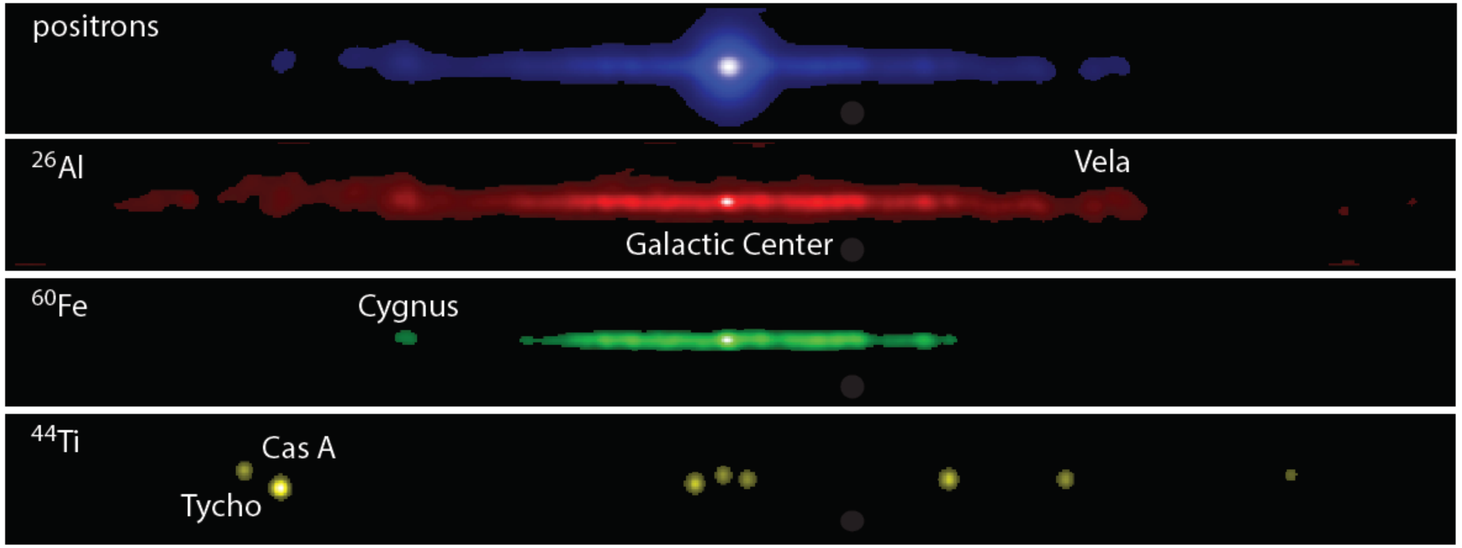
Transient science

- ❑ 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

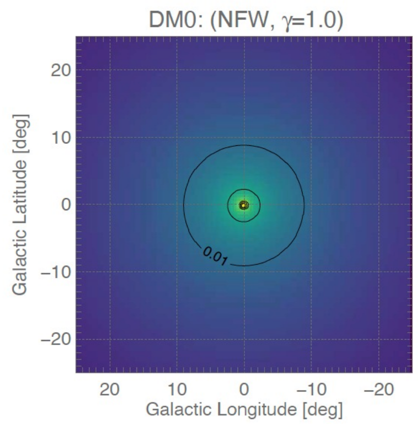
511 keV Galactic substructure

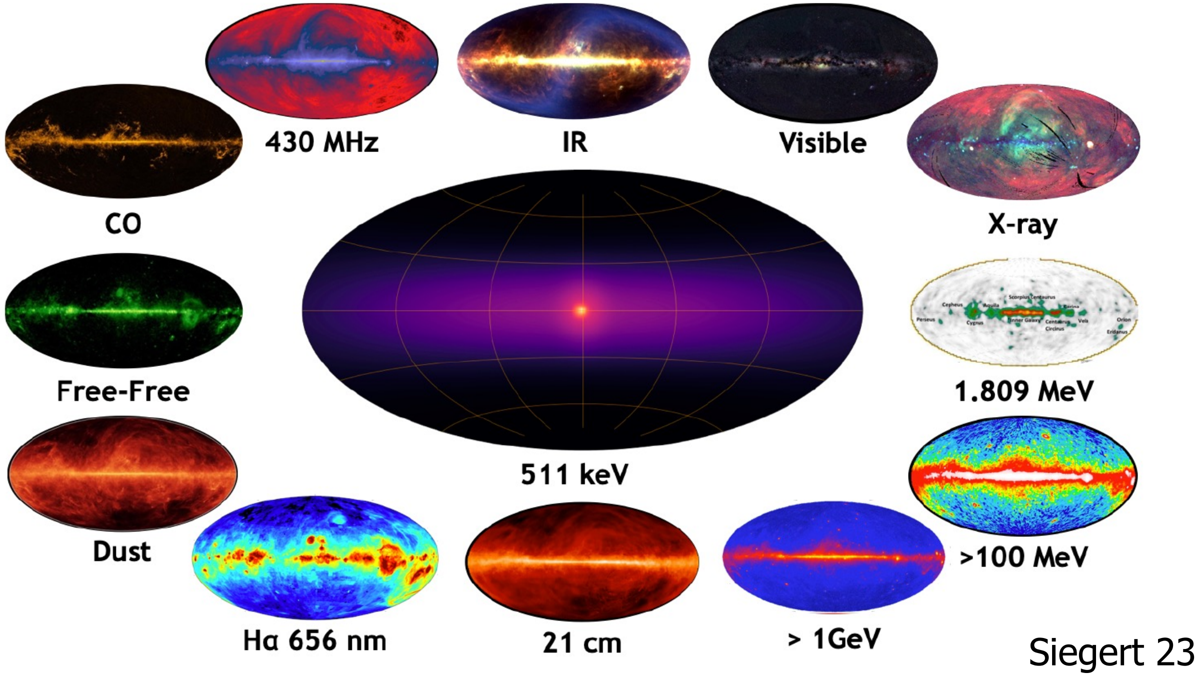
Candidate Positron Sources

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





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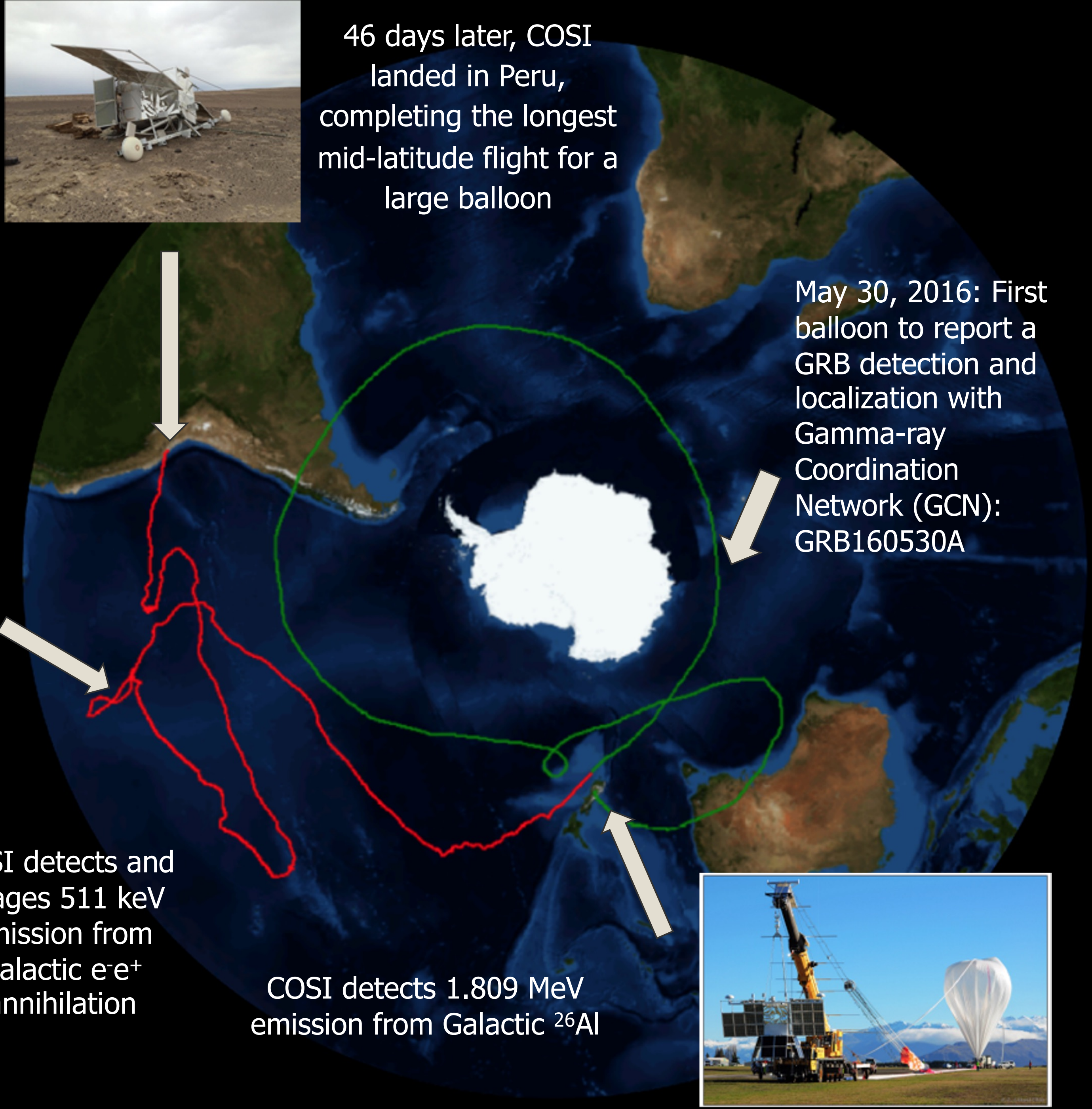
COSI 2016 Wanaka Flight



46 days later, COSI landed in Peru, completing the longest mid-latitude flight for a large balloon

May 30, 2016: First balloon to report a GRB detection and localization with Gamma-ray Coordination Network (GCN): GRB160530A

COSI detects and images the Crab nebula

COSI detects and images 511 keV emission from Galactic e^-e^+ annihilation

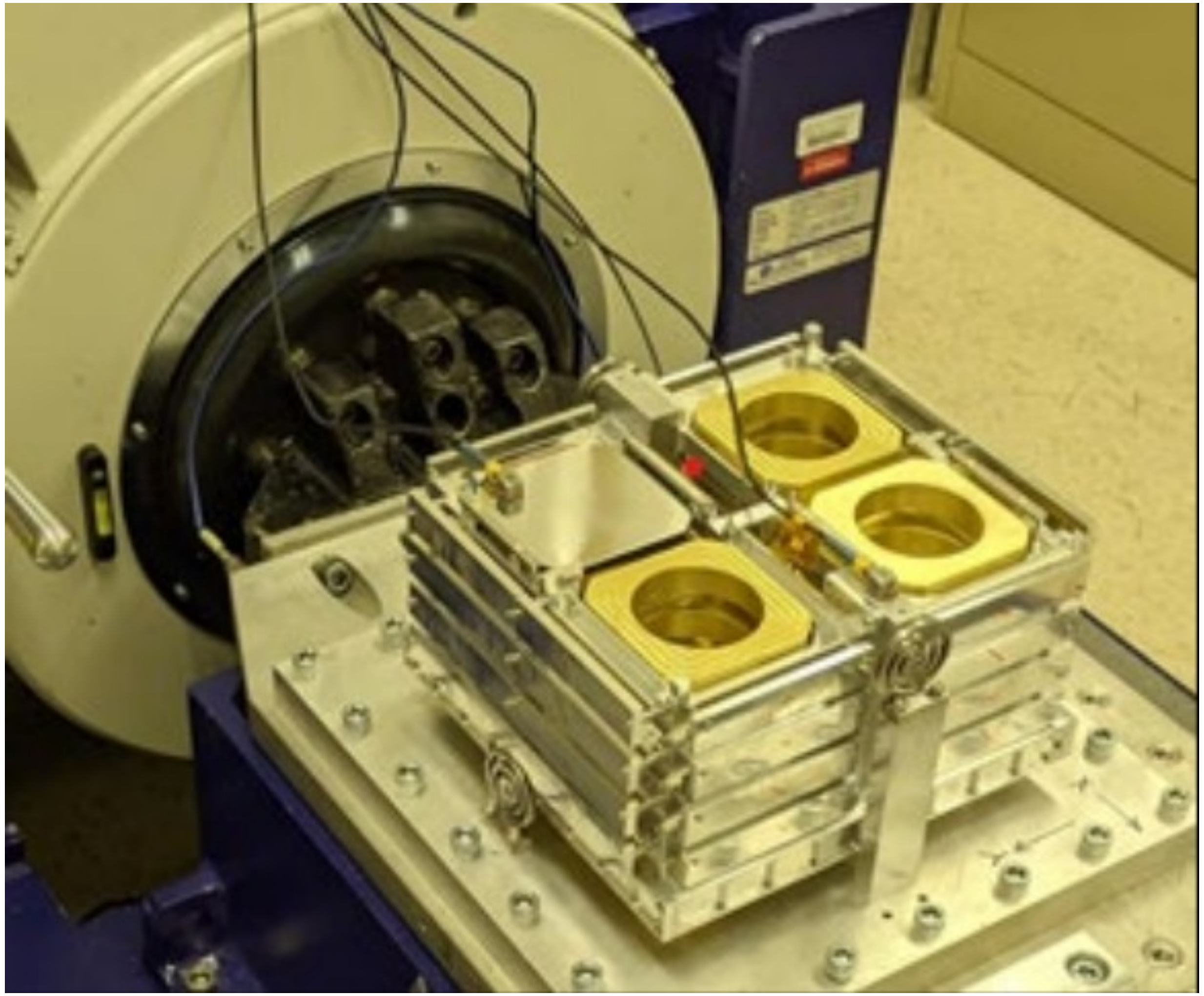
COSI detects 1.809 MeV emission from Galactic ^{26}Al

May 17, 2016: COSI launch from Wanaka, New Zealand

Slide credit: Alex Lowell

COSI detector support structure

- The COSI detector support structure was prototyped and tested during phase A
- A vibration test was carried out at SSL during Jan/Feb 2021
- Support structure design validated



COSI and SNIa

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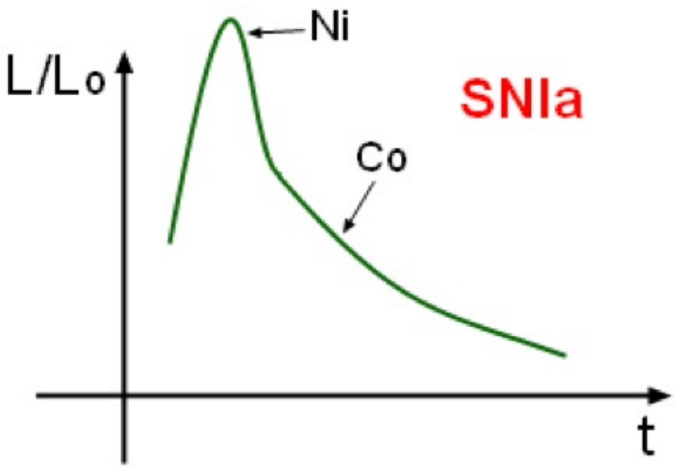
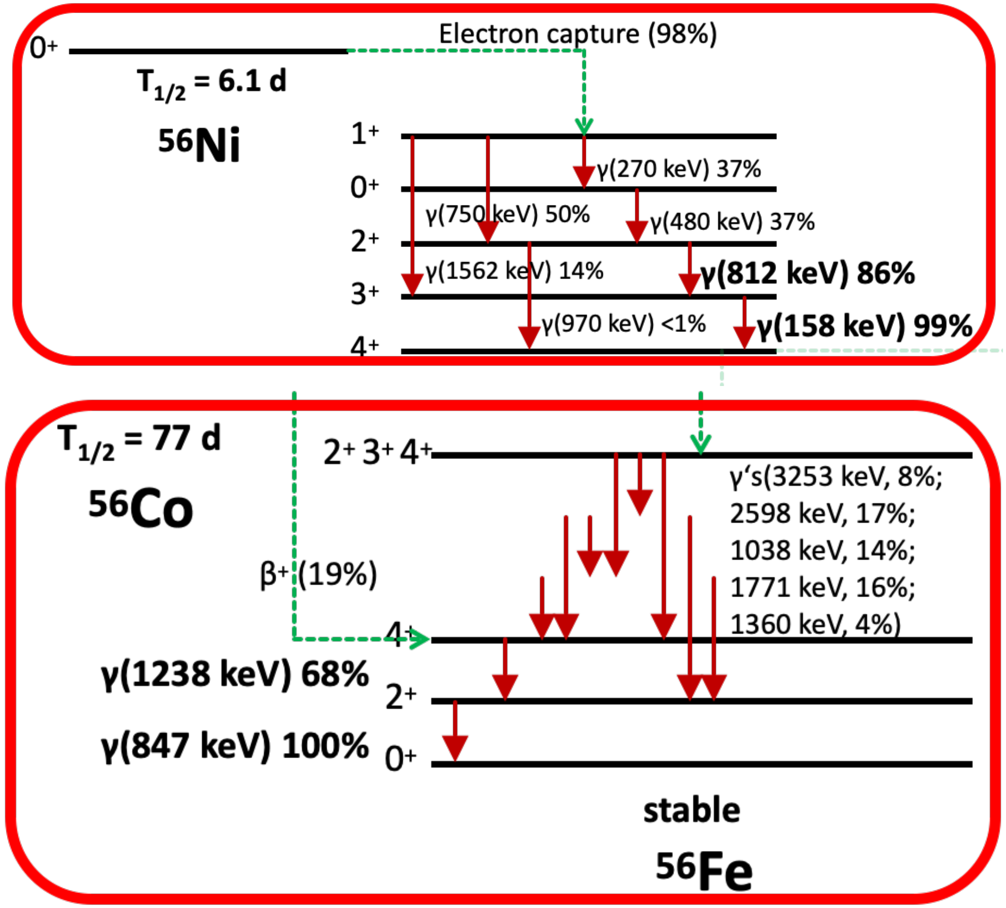
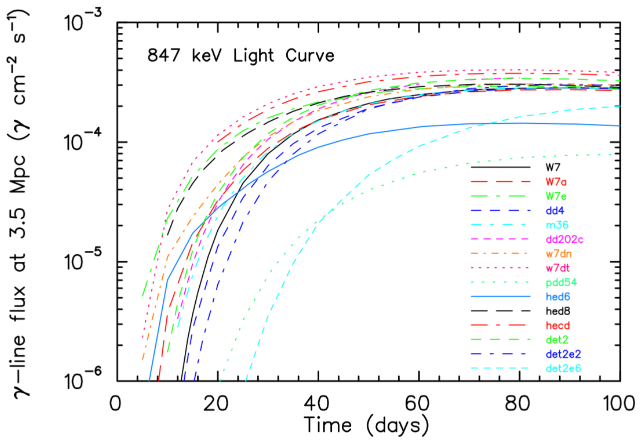


The bolometric (dominated by optical) luminosity is powered by ^{56}Ni and ^{56}Co





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

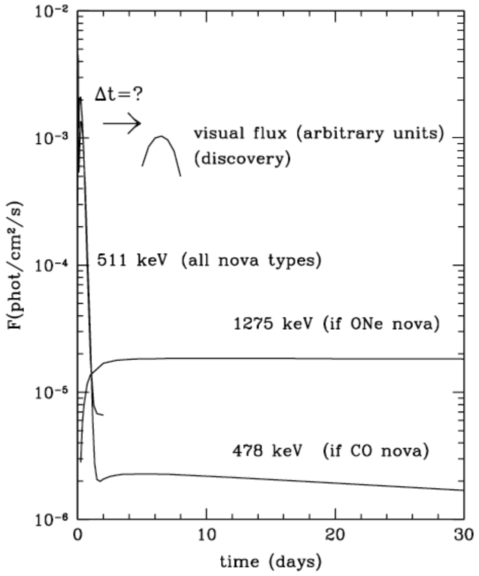
- **10^{-5} ph/cm^2/s in 100 days in survey mode**

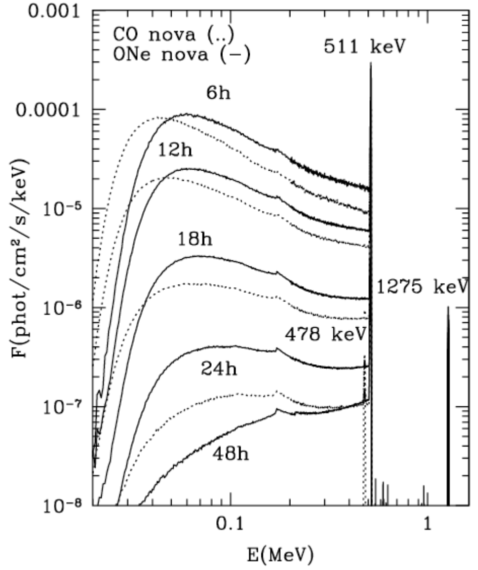
Distance	Predicted flux (median of models)
3.5 Mpc	3.0x10^{-4} ph/cm^2/s
10 Mpc	4.0x10^{-5} ph/cm^2/s
20 Mpc	1.0x10^{-5} ph/cm^2/s

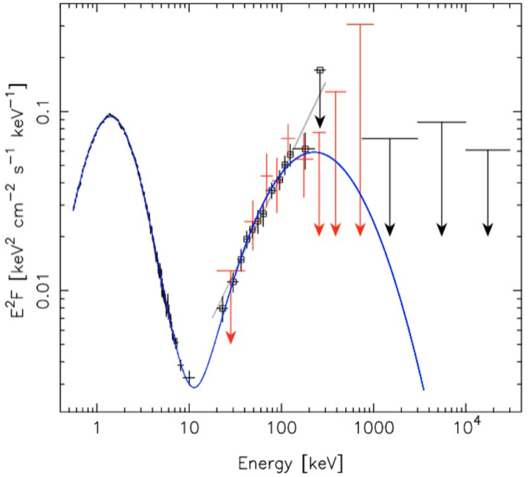
Expect ~two SNIa per year within 20 Mpc ←

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