COSI
Gamma-ray
Space Explorer

The Compton Spectrometer and Imager

Science Goals and Mission Status

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COSI overview

- COSI is a NASA Small Explorer (SMEX) satellite with a planned launch in 2027
- Detects gamma-rays in the 0.2-5 MeV energy range
- Optimized for studies of nuclear and annihilation emission lines across our Galaxy
- 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

Upcoming SMEX mission operating in the energy range between NuSTAR and Fermi/LAT

The MeV gap

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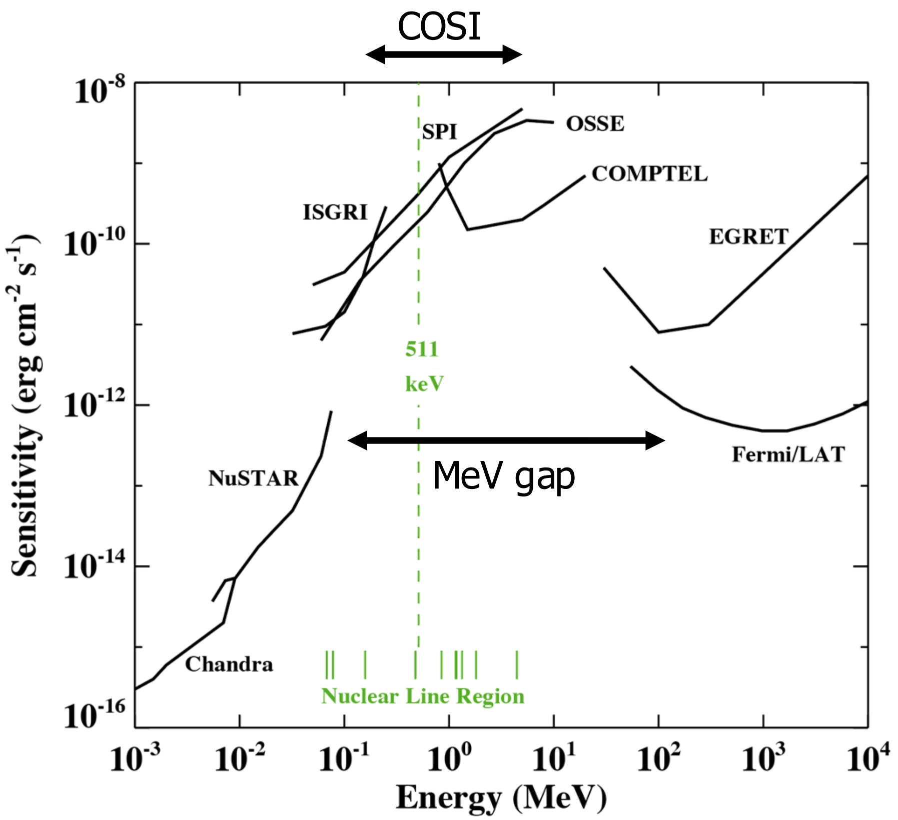
- Previous and current missions have had relatively poor sensitivity in the MeV range

- Discovery space where there is known to be interesting physics
  - Antimatter annihilation line at 511 keV
  - Nuclear lines from unstable products of element formation
  - Accreting black holes
  - Multimessenger astrophysics

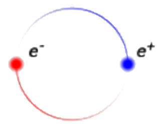


Compton telescopes:

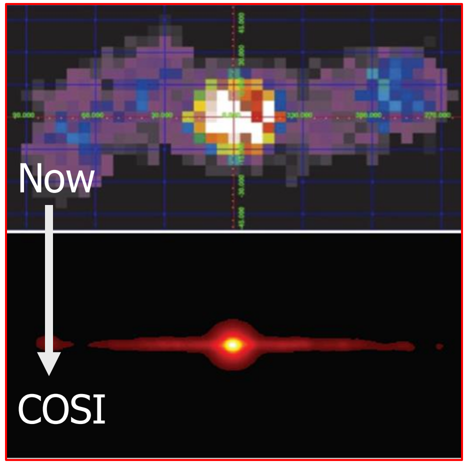
- ***COMPTEL on CGRO (1991-2000)***
- ***COSI is a new type of Compton Telescope***

Key science goals

Uncover the Origin of Galactic Positrons

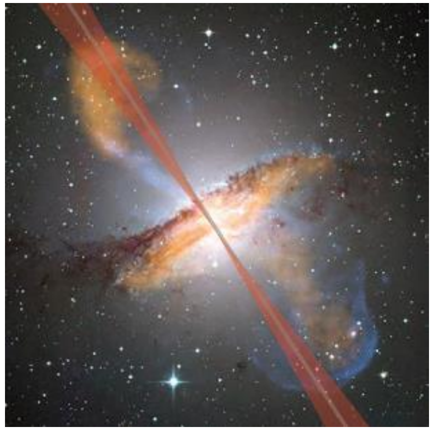


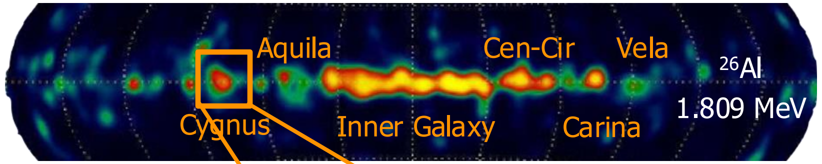
e^-e^+ @ 511 keV



Gain Insight into Extreme Environments with Polarization

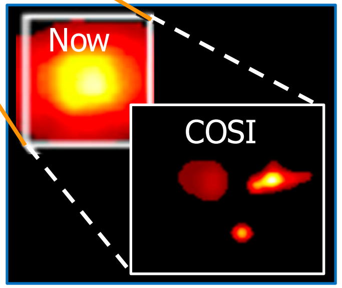
AGN and Galactic black holes @ 0.2-0.5 MeV





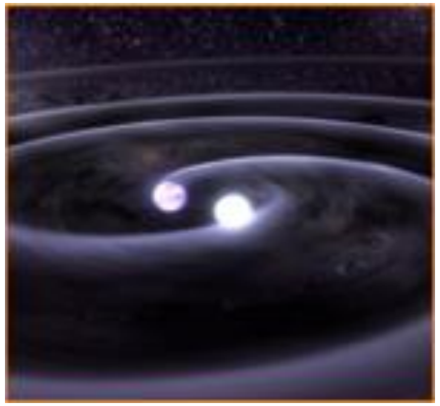
Reveal Galactic Element Formation

^{26}Al @ 1.809 MeV
^{60}Fe @ 1.173 and 1.333 MeV
^{44}Ti @ 1.157 MeV

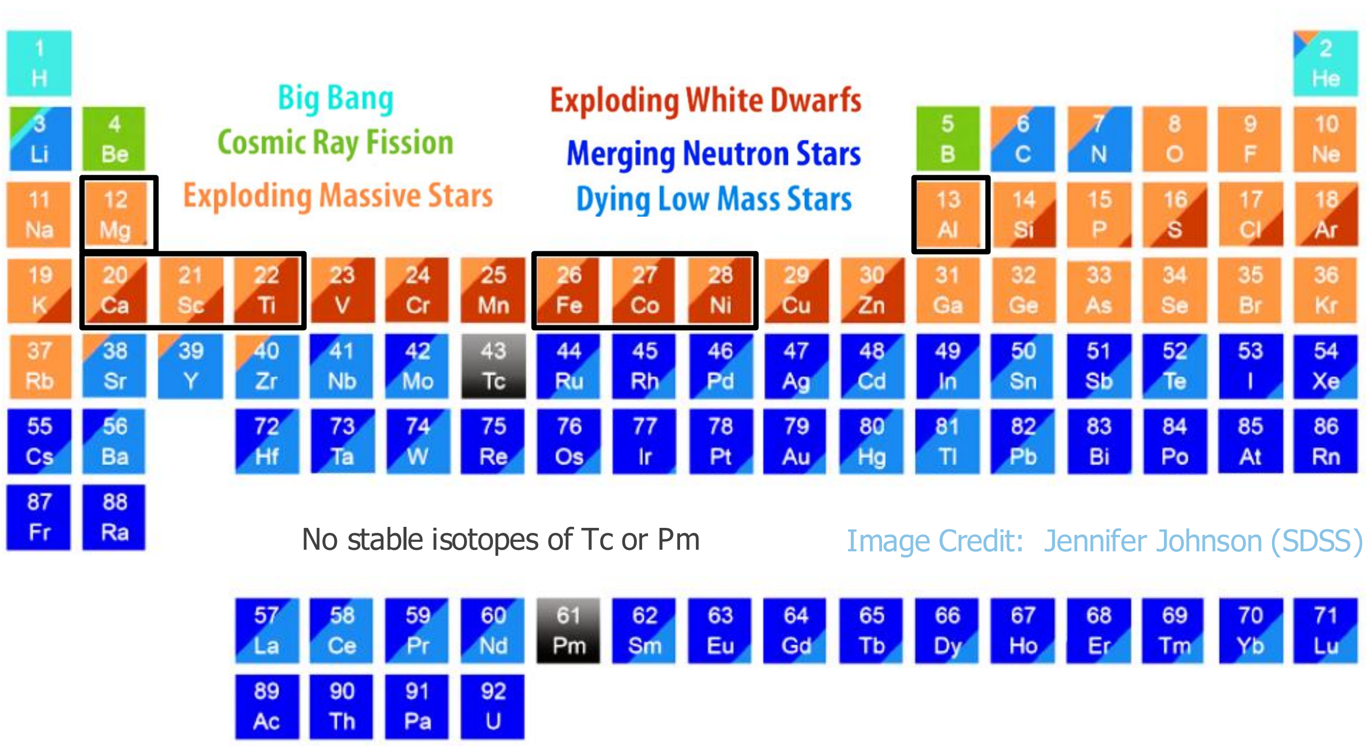


Probe the Physics of Multimessenger Events

GRB alerts



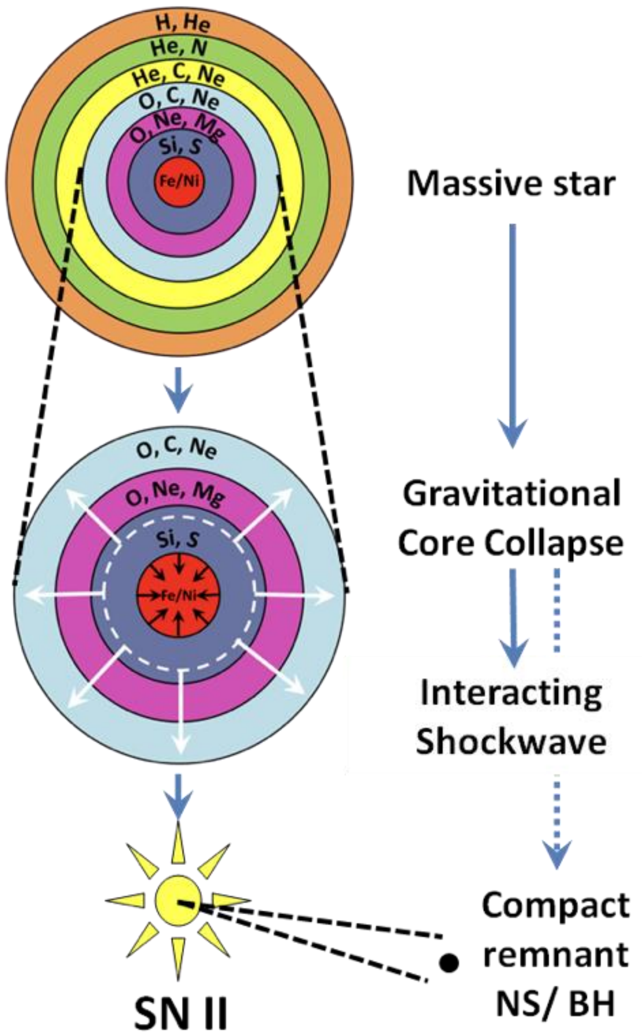
Revealing Galactic element formation



No stable isotopes of Tc or Pm

Image Credit: Jennifer Johnson (SDSS)

Core-collapse SN explosion



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

Three windows on chemical enrichment of the Galaxy

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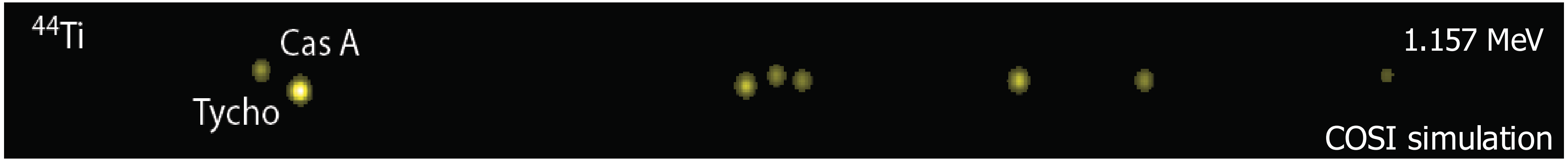
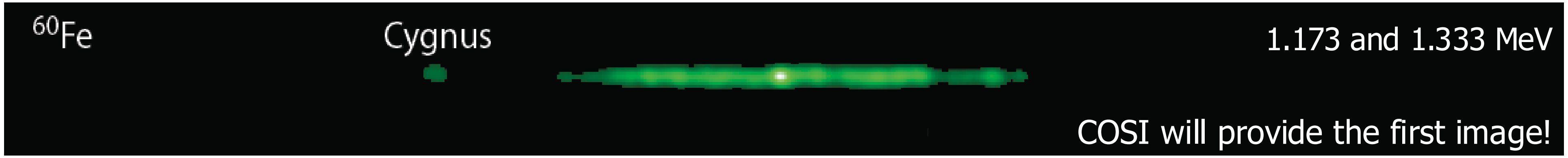
- ^{26}**Al** ($t_{1/2}$ 717 kyr) traces massive stars, providing an all-Galaxy view of **SN progenitors**

COSI provides an all-Galaxy view of SNe over the past several Myrs

- ^{44}**Ti** ($t_{1/2}$ 59 yr) survey by COSI to find **young SN remnants** (past centuries)

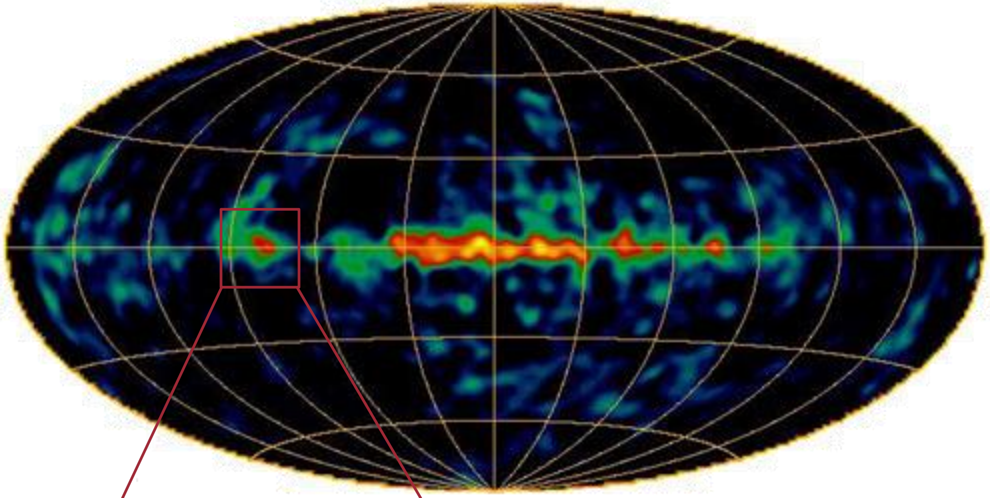


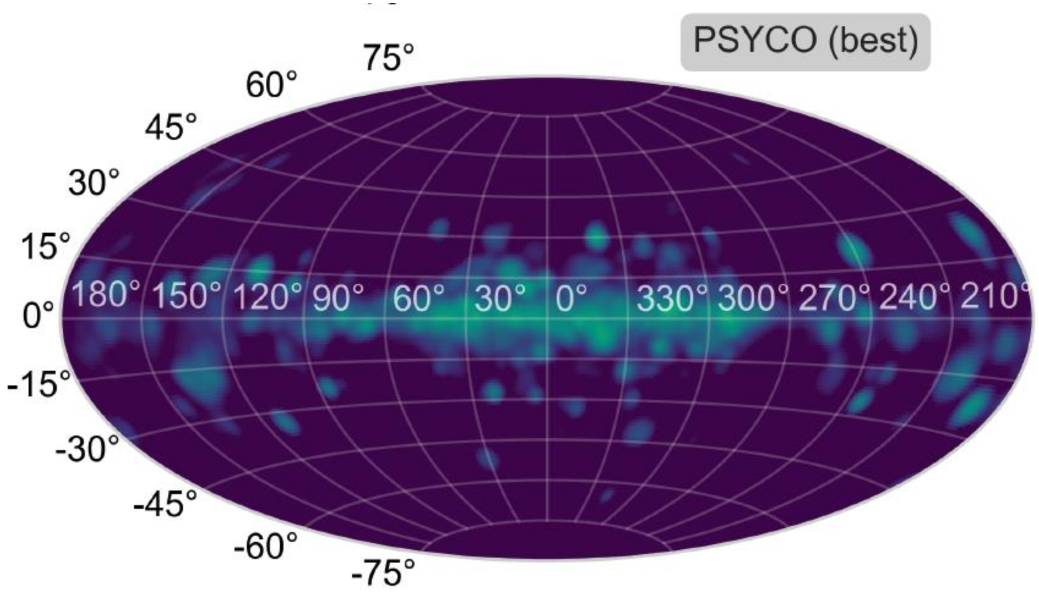
- ^{60}**Fe** ($t_{1/2}$ 2.6 Myr) is a unique tracer of **old core collapse SN remnants** (several Myr)



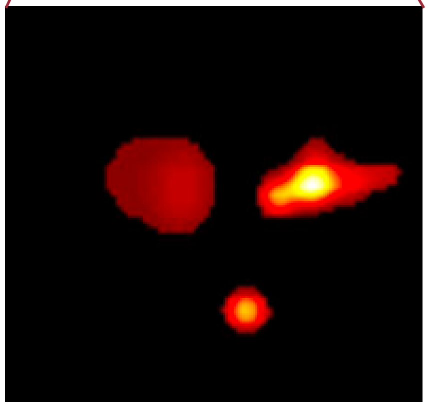
^{26}Al and ^{60}Fe

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





Modeling ^{26}Al with Population SYNthesis COde (PSYCO; Siegert+23)
Simulation includes degrading to COMPTEL's angular resolution
(SFR = 4-8 M_{sun}/yr, 1.8-2.8 SNe/century, M_{26Al} = 1.2-2.4 M_{sun}, M_{60Fe} = 1-6 M_{sun})



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

- >7x better sensitivity
- >2x better angular resolution

- ❑ Comparing COSI's ^{26}Al and ^{60}Fe images to PSYCO predictions will constrain, e.g.:
  - Nucleosynthesis yields per stellar mass
  - Mass loss in winds (related to stellar metallicity)
  - Stellar explodability (which stars produce SNe?)
  - Stellar rotation (Monday talk by Artemis Spyrou)

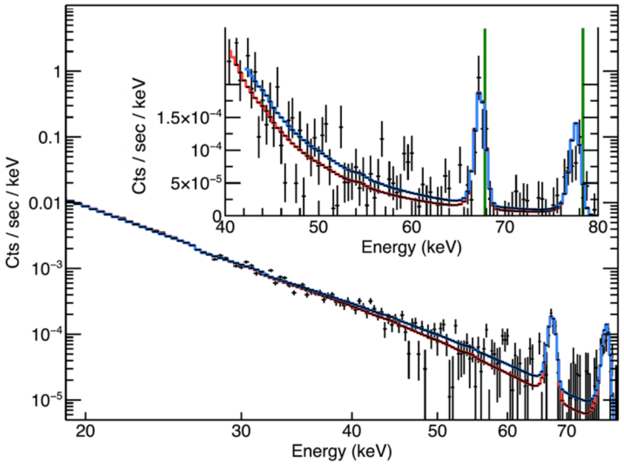
Using ^{44}Ti to trace ejection velocities

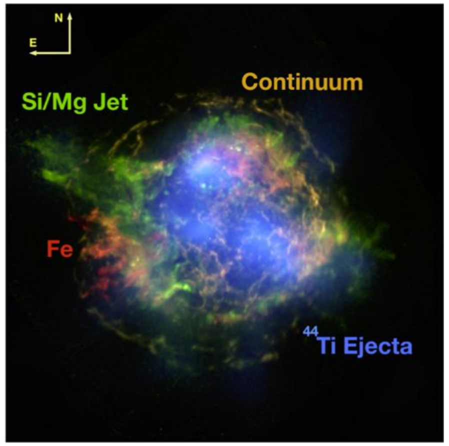
- The ^{44}Ti decay chain produces lines at 68 and 78 keV (NuSTAR) and 1.157 MeV (COSI)

- NuSTAR observations
  - Cas A: ^{44}Ti lines redshifted by 1100-3000 km/s
  - SN 1987A: ^{44}Ti line redshifted by ~700 km/s
  - Evidence for asymmetric explosions but there are only measurements for these two cases

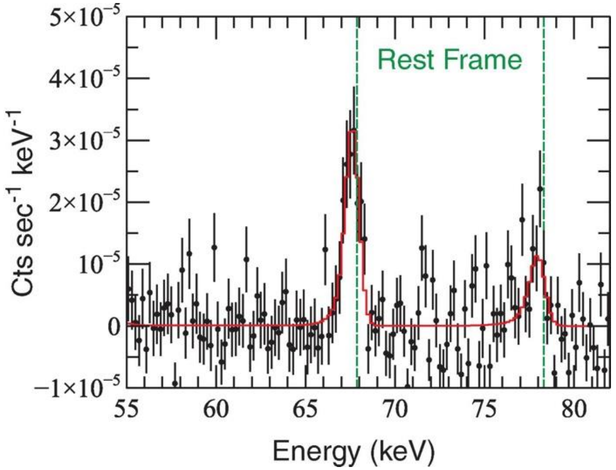
- COSI
  - Search for more with a Galactic survey at 1.157 MeV
  - Spectroscopy to measure widths of lines and Doppler shifts

Cas A with NuSTAR (Grefenstette+14+17)





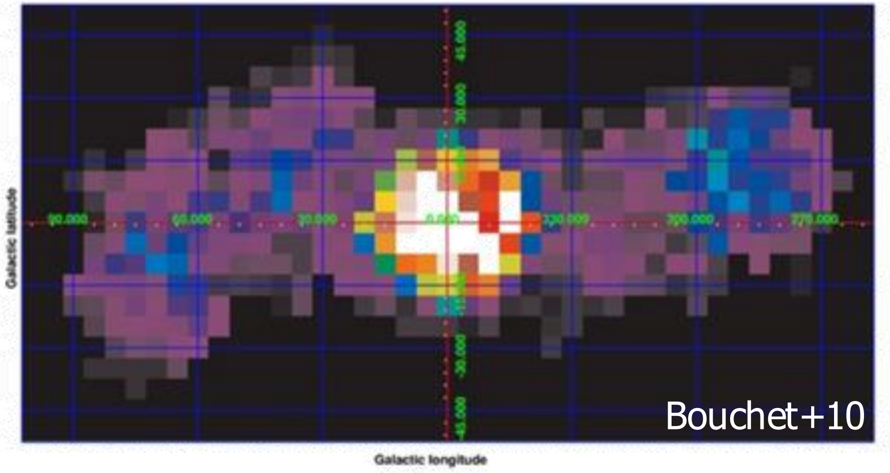
SN 1987A with NuSTAR (Boggs+15)



Uncovering the origin of Galactic positrons

- 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 map of the 511 keV emission



Positron Production Rates ($\times 10^{42}$ 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%

COSI will:
- Search for substructure in the bulge emission (individual sources?)
- Measure the disk scale-height
- Correlation with ^{26}Al

511 keV Galactic substructure

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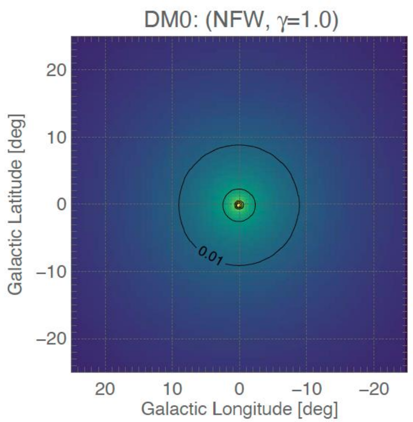
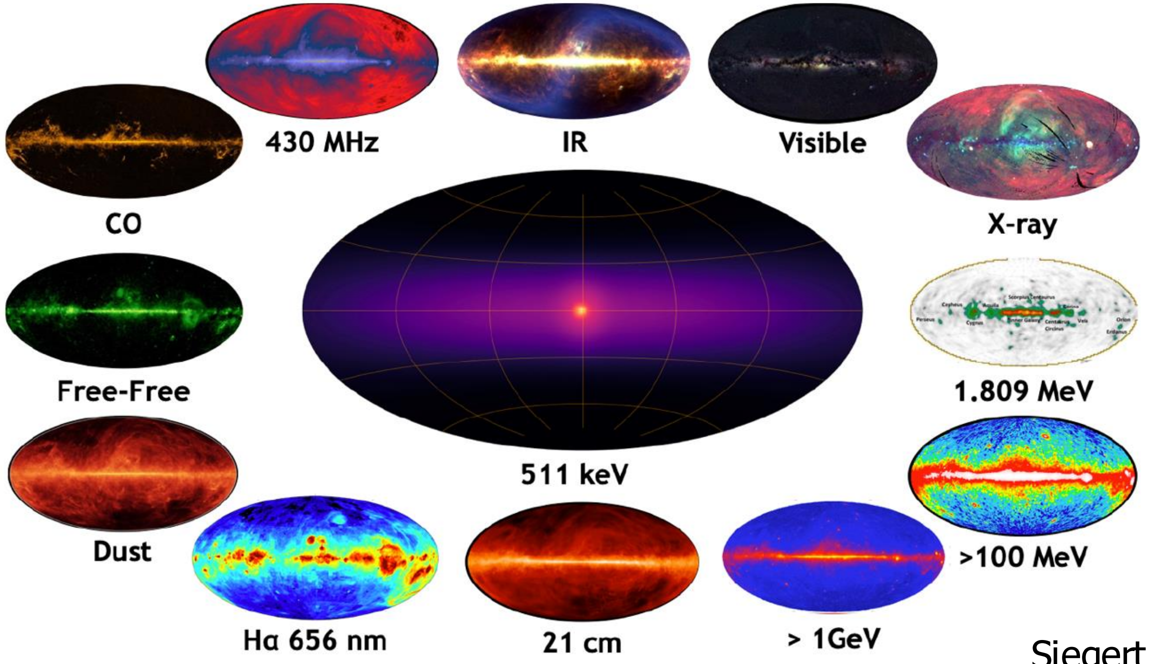
Candidate Positron Sources

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





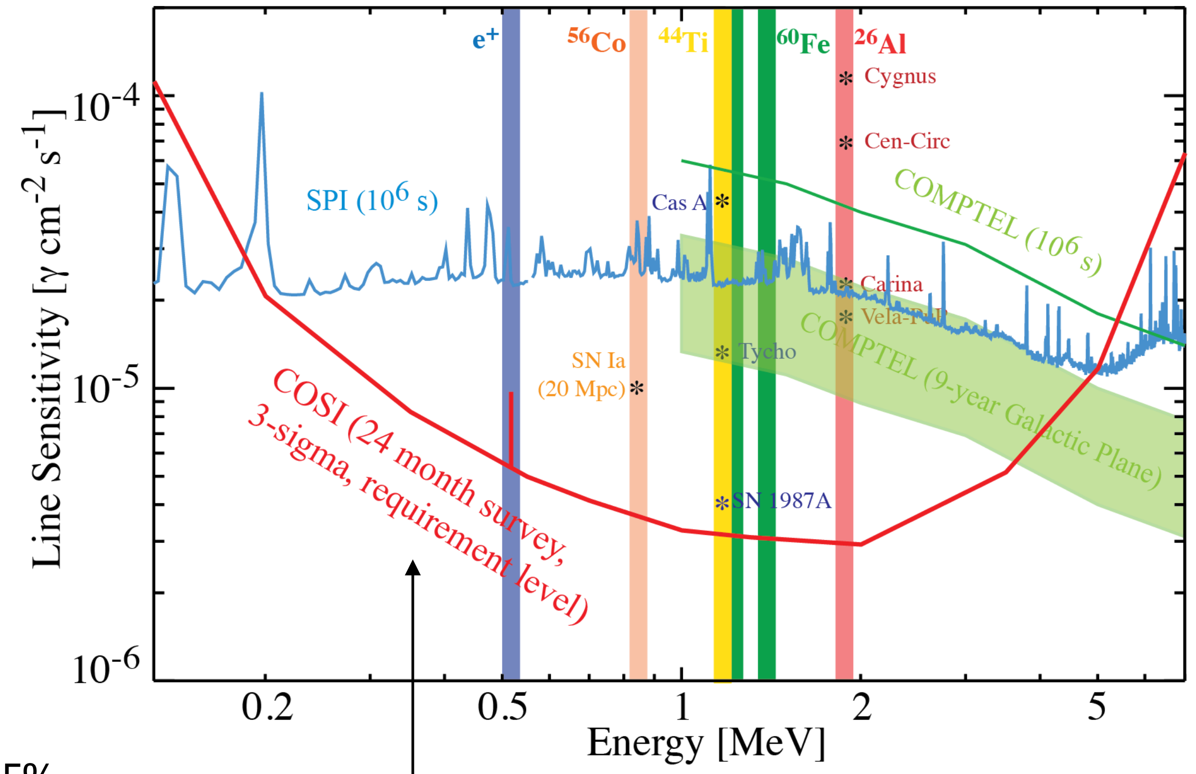
Siegert 23

Measurement requirements 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}] • 1.2×10^{-5} @ 0.511 MeV • 3.0×10^{-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%



Level that COSI is required to meet during its 2-year prime mission, but could do substantially better if mission is extended

Mission comparison

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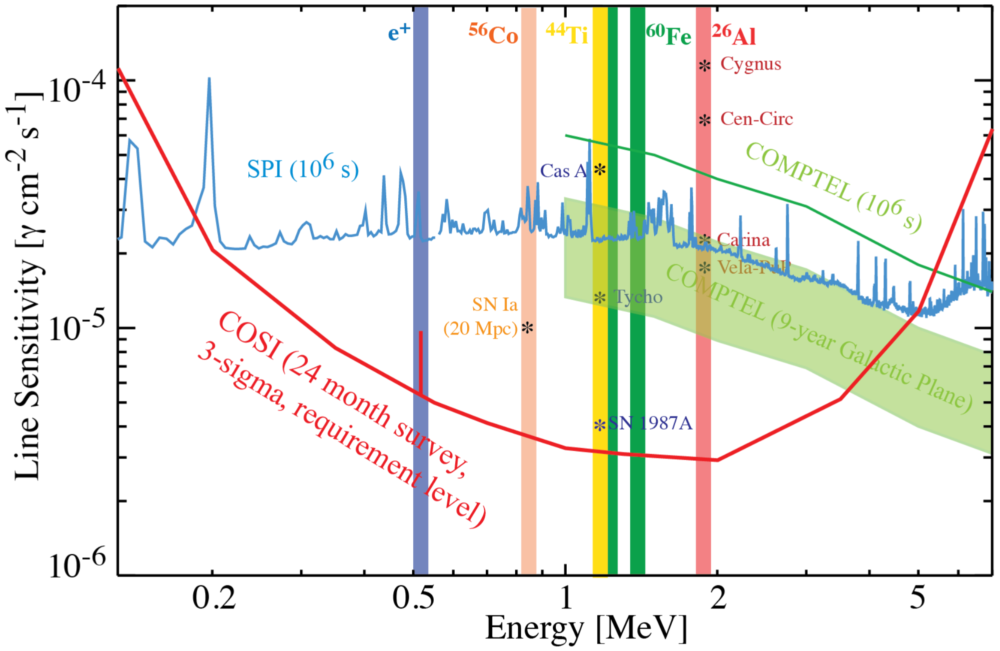
Mission (Instrument)	Operation	Energy Range	Field of View	Energy Resolution
COSI	**2027-**	**200 keV – 5 MeV**	**~10,000 deg^2**	**0.4-1.2% (>200 keV, est.)**
CGRO (COMPTEL)	**1991-2000**	**800 keV – 30 MeV**	**~3000 deg^2**	**5-10% (>1 MeV)**
INTEGRAL (SPI)	2002-	25 keV – 8 MeV	~300 deg^2	0.2-1.6% (>100 keV)
NuSTAR	2012-	3-78 keV	0.05 deg^2	1.3-4.0% (>10 keV)



- ❑ COSI will reach the sensitivities shown for every source in the sky
- ❑ COSI's extended science portfolio includes detecting the 847 keV line from Type Ia SNe out to ~20 Mpc (~two per year)

COSI operation

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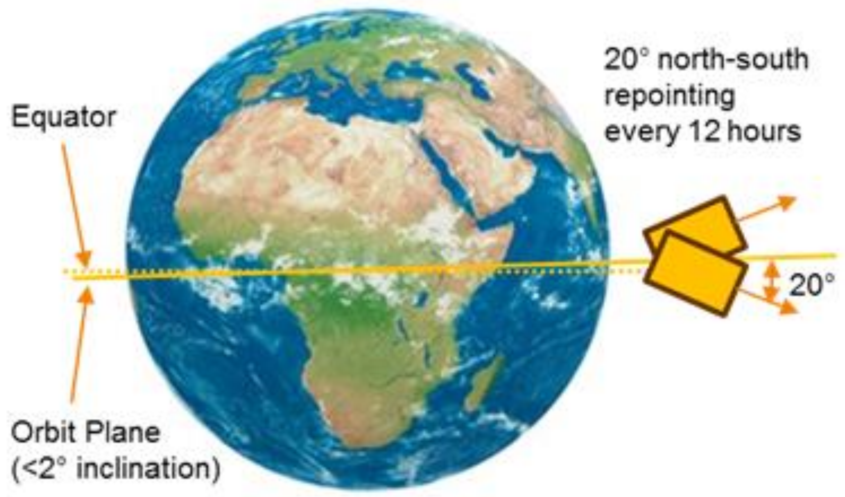
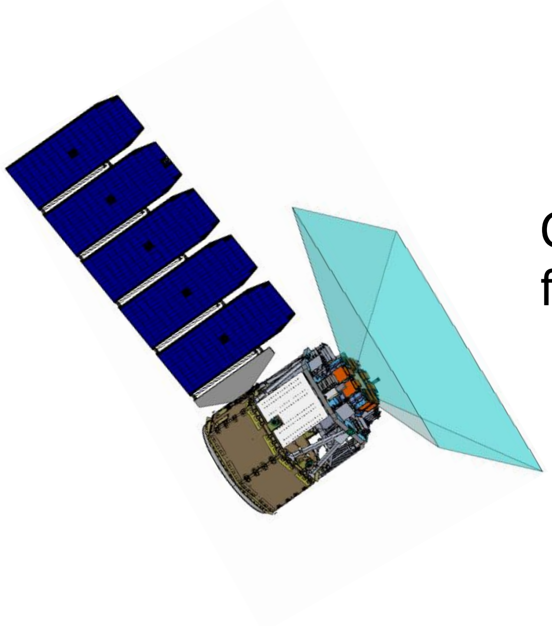
- Survey mode
  - North/South zenith offset alternating every 12 hours (8 orbits)
  - Combined with large field of view gives daily all-sky coverage



- Time to observe a transient event in survey mode
  - >25% of sources seen instantaneously
  - >50% within 90 mins
  - 100% within 13.5 hrs



COSI's >25%-sky field of view

Classical novae

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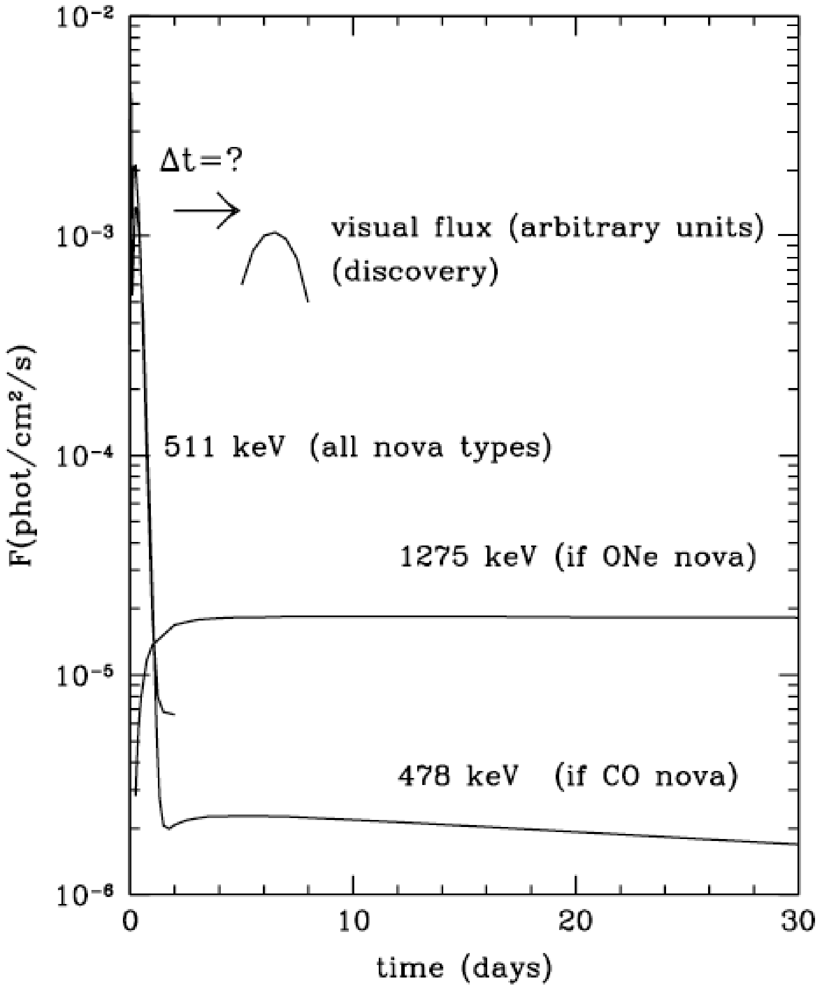
- Studying thermonuclear explosions on accreting white dwarfs combine*:
  - Laboratory measurements (nuclear lifetimes)
  - Hydrodynamic simulations (elemental yields)
  - Gamma-ray observations (^{13}N, ^{18}F, ^{22}Na, ^{7}Be)
- Predicted 511 keV line from ^{13}N and ^{18}F will be detectable by COSI out to ~2 kpc
  - Expect a nova at <2 kpc every 2 yr
- Predicted 1275 keV line from ^{22}Na will be detectable by COSI out to ~3 kpc
  - Expect an ONe nova at <3 kpc every 3-9 yr

Predicted flux levels vs. time @ 1 kpc (Hernanz 2005 and Hernanz 2014)



*See, e.g., Fougères+23, Nature, arXiv:2212.06302 (see poster 138)

Solar science

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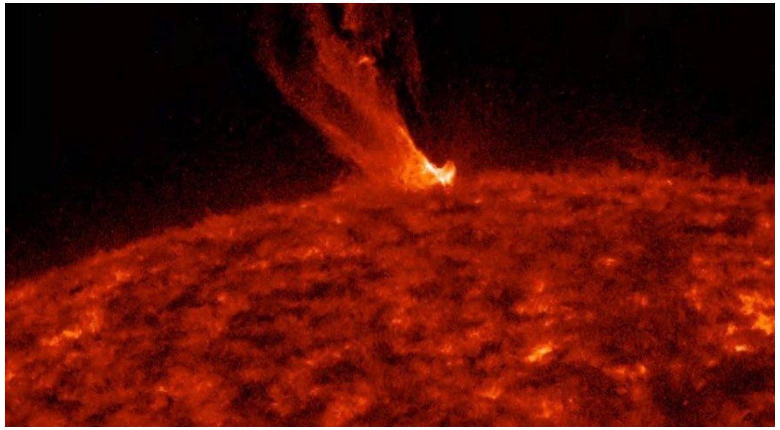
- In survey mode, COSI will obtain ~6 hrs of solar coverage per day
- Previous nuclear line detections are listed in the table below

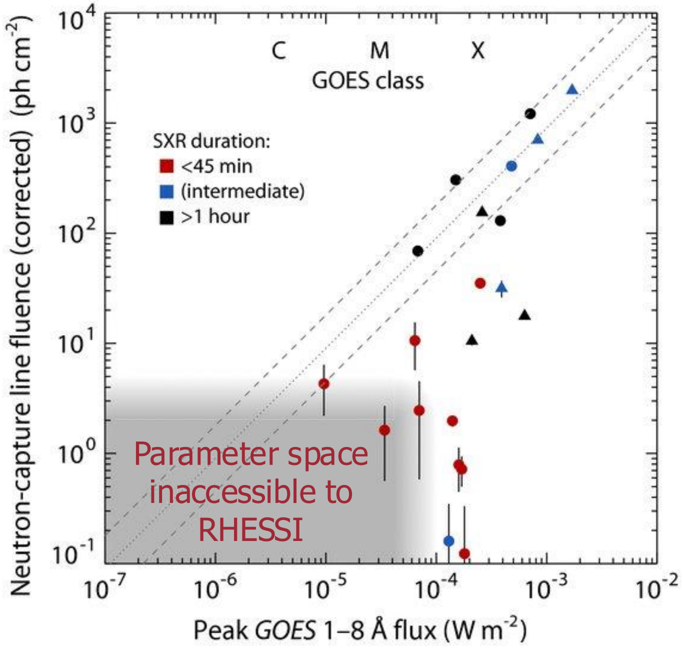


Isotope	Mechanism	Gamma-ray energies (keV)
^{2}H	Neutron capture	2223
^{12}C, ^{16}O, ^{24}Mg, ^{20}Ne, ^{28}Si	p/alpha collision and de-excitation	1369, 1634, 1779, 4438, 6129
^{7}Be, ^{7}Li	alpha-^{4}He	400-500

e^{+}/e^{-} (511 keV) and ^{56}Fe (847 keV) also detected; Shih+03, Smith+03, Share+03, Shih+09

Do small flares accelerate ions?

COSI has the line sensitivity to measure ions in much smaller flares than RHESSI (figure from Shih+09)



Nuclear lines from solar flares are a signature of ion acceleration

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

- 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 mission timeline and observatory parameters

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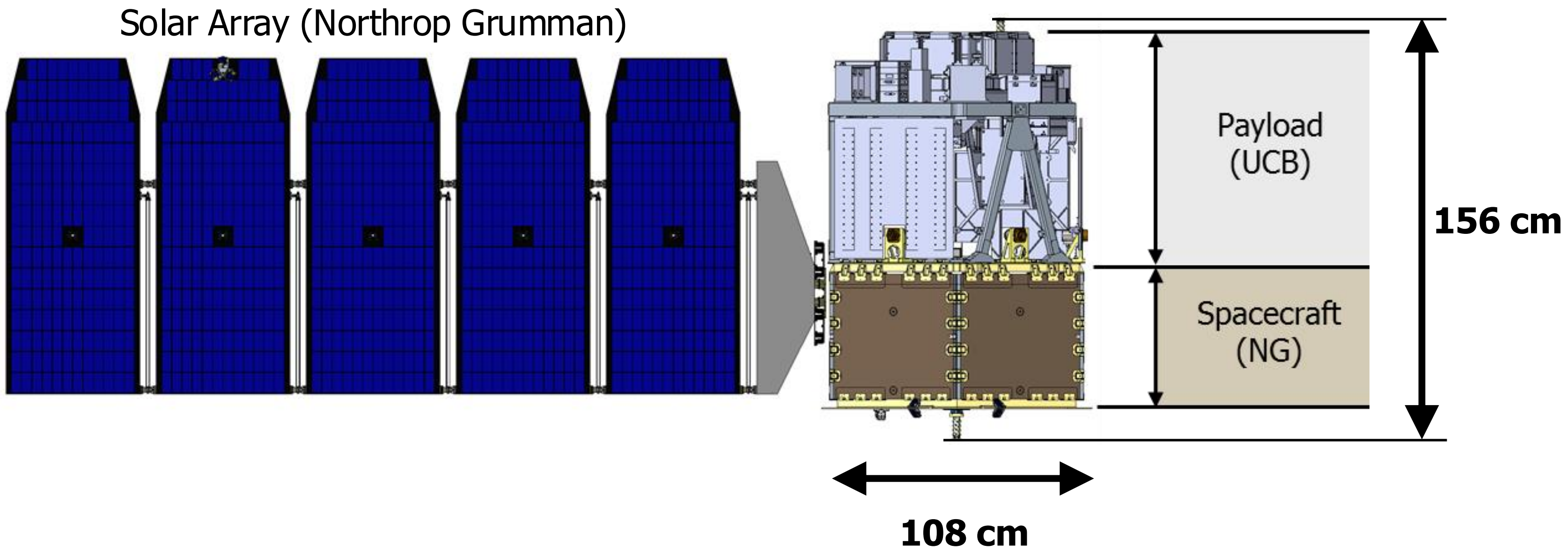
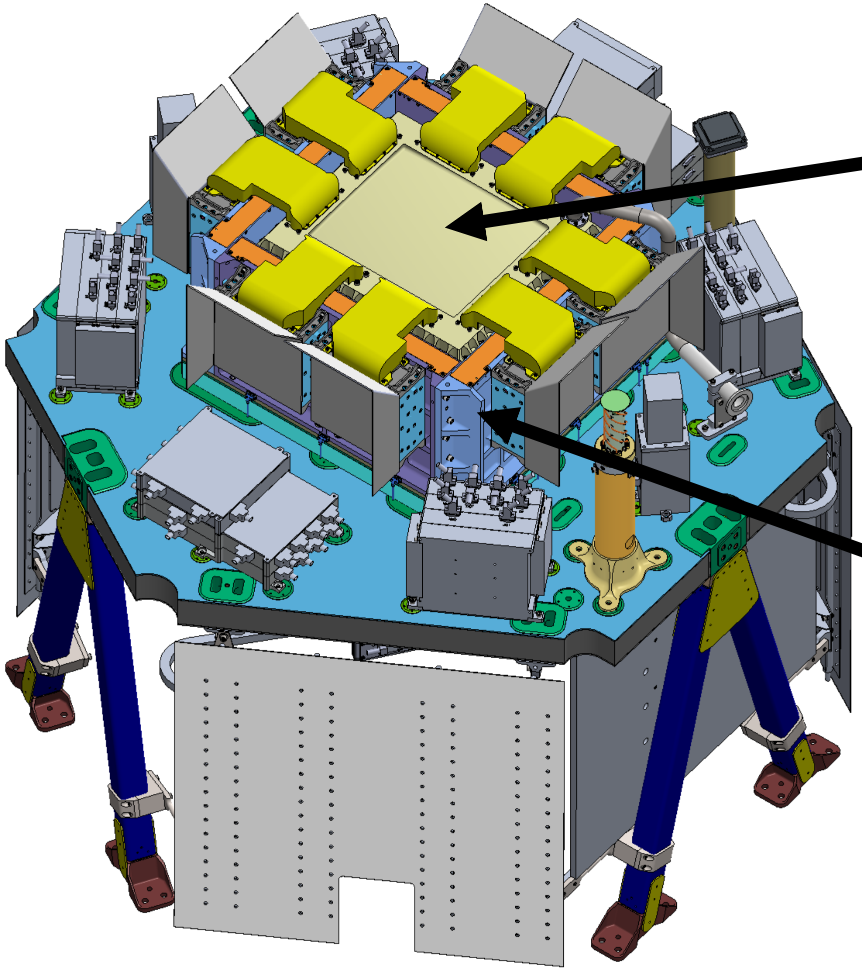
Original Proposal Opportunity	**2019 Astrophysics Small Explorer (SMEX) with $145M cost cap (FY20$), excluding launch**
Phase A start	**March 2020**
Phase B start	**January 2022**
Phase C start	**April 2024**
Planned Launch	**August 2027**
Launch Vehicle	**Space X Falcon 9**
Orbit	**530 km altitude 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

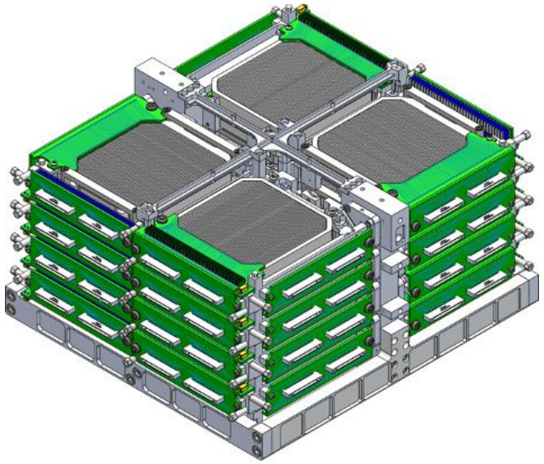


COSI Mass, Power, and Data	
Mass (372 kg Not to Exceed)	**350 kg** (Maximum Expected Value, MEV)
Power (732 W generated by Solar Array w/ battery storage)	**609 W** MEV (including battery recharge and other inefficiencies)
Data (through Malindi Ground Station, provided by ASI)	**7.7 Gb/day** S-band
Data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

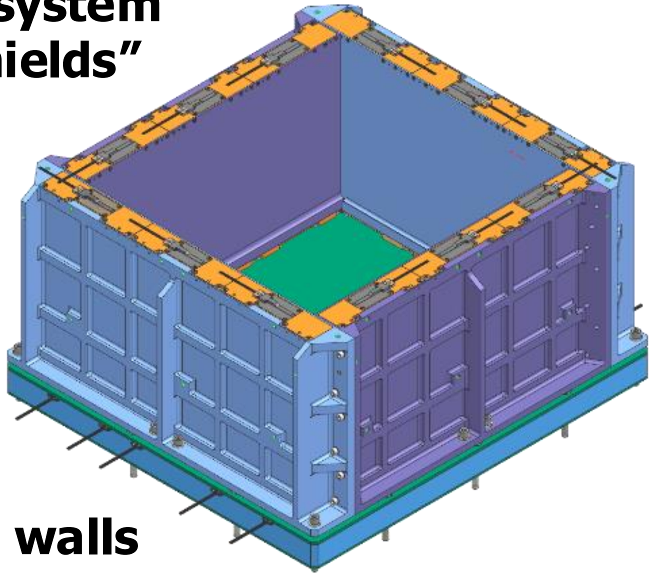
Payload design



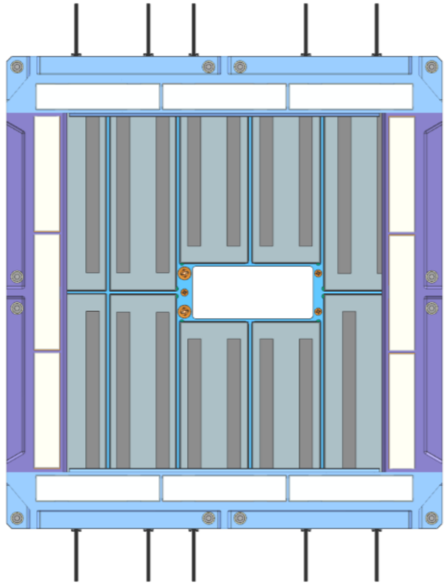
Cryostat with 16 germanium detectors



Anticoincidence subsystem "shields"



Side walls



Bottom shield

Hardware: Engineering models and testing

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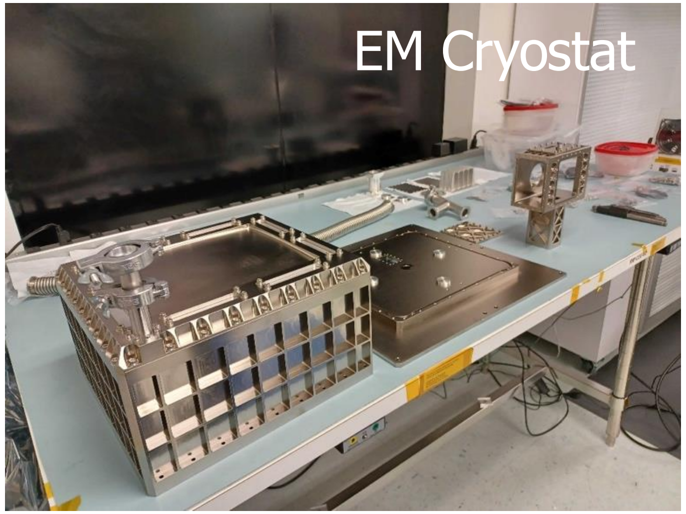
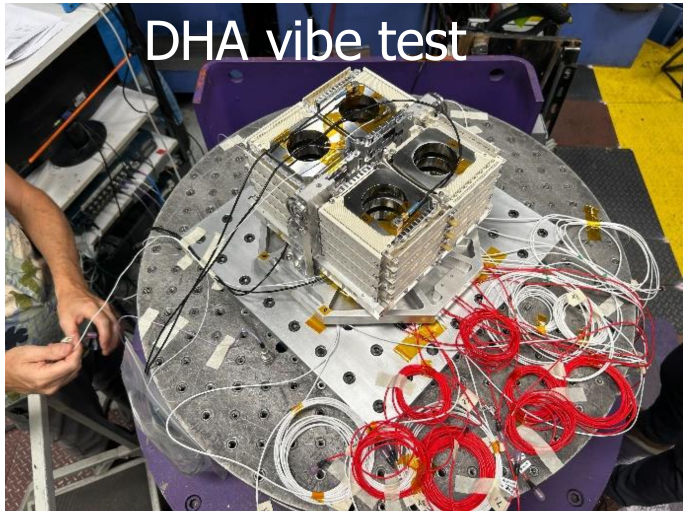
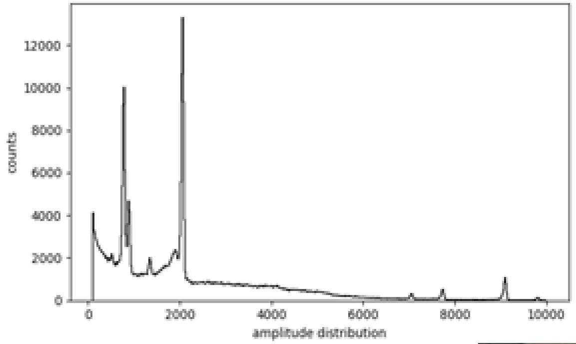
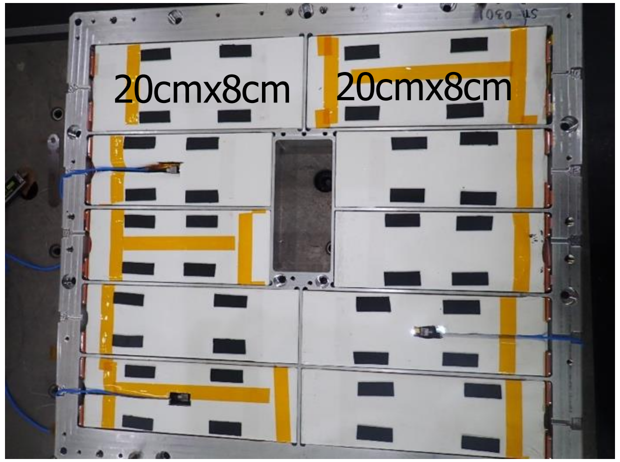
- EM (and some FM) hardware being built and tested at:
  - UCB/SSL
  - NRL
  - SDL
  - LBNL
  - GSFC
  - Northrop Grumman



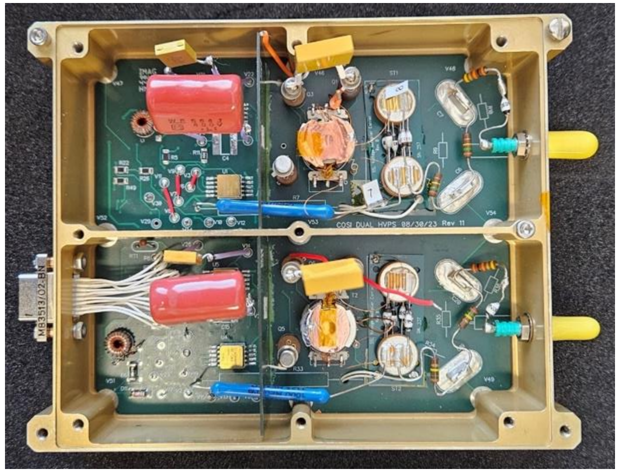




^{133}Ba spectrum measured with a COSI germanium detector



EM bottom shield (~40cmx40cm)



EM HVPS

Mission status and how you can get involved

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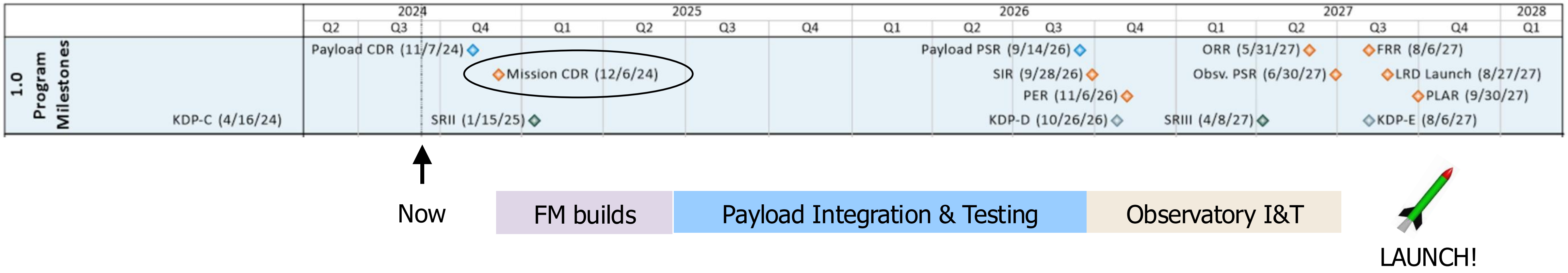
❑ Recent past and near future

- 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

cosi.ssl.berkeley.edu

❑ How you can get involved

- Yearly public "data challenges" (github.com/cositools/cosi-data-challenge-2)
- Developing ideas for additional nuclear physics investigations with COSI
  - Interested in discussing connections to lab/beamline/theory/simulations



COSI science team (99 members in total)

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Subgroup	Lead	Co-Leads
Positrons	Carolyn Kierans (GSFC)	Thomas Siegert (JMU, Germany)
Nucleosynthesis	Thomas Siegert (JMU, Germany)	Chris Fryer (LANL)
GRBs	Eric Burns (LSU)	Steve Boggs (UCSD), Dieter Hartmann (Clemson)
Galactic	Julien Malzac (IRAP, France)	Chris Karwin (GSFC)
Extragalactic	Marco Ajello (Clemson)	Fabrizio Tavecchio (INAF, Italy)
Dark Matter	Tad Takahashi (IPMU, Japan)	Fabrizio Tavecchio (INAF, Italy), Shigeki Mastumoto and Tom Melia (IPMU, Japan)

- Nucleosynthesis subgroup
  - **Lead:** Thomas Siegert (JMU, Germany)
  - **Co-lead:** Chris Fryer (LANL, USA)
  - **Members:** Hugh Bates, Jacqueline Beechert, Steve Boggs, Eric Burns, Catherine Deibel, Savitri Gallego, Dieter Hartmann, Pierre Jean, Carolyn Kierans, Jürgen Knödlseder, Martin Krause, Mark Leising, Raffaella Margutti, Saurabh Mittal, Igor Moskalenko, Katarzyna Nowak, Uwe Oberlack, David Palmore, Jacob Smith, Anaya Valluvan, Hiroki Yoneda, Andreas Zoglauer
- Authors of this presentation: Tomsick, Siegert, Hartmann, Kierans, Zoglauer, and the COSI Science Team

Backup

Goal A: Uncover the Origin of Galactic Positrons

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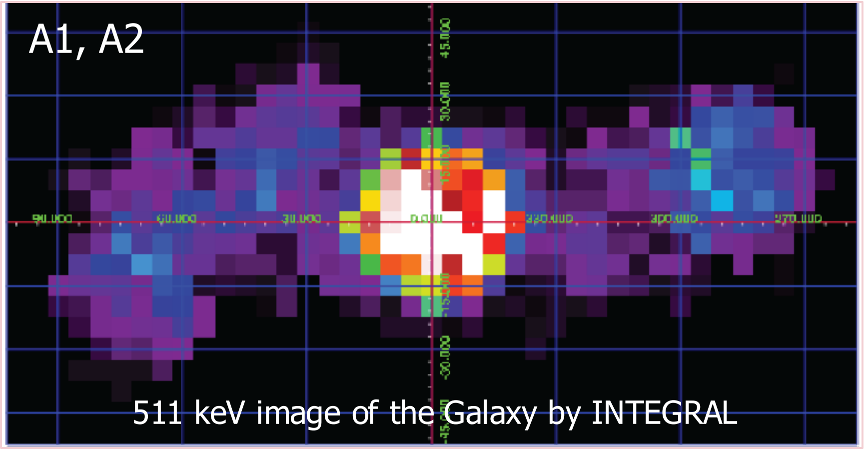

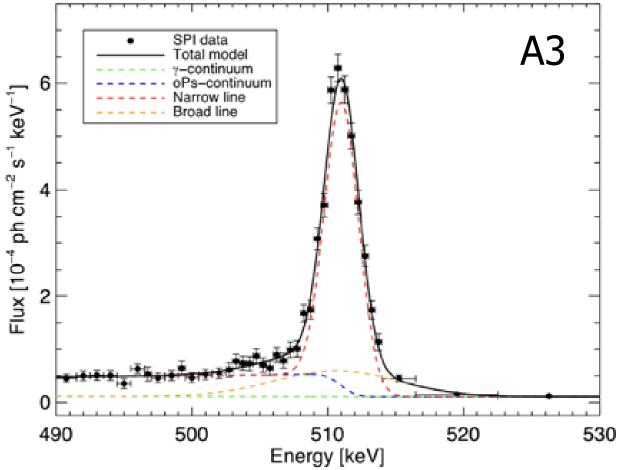

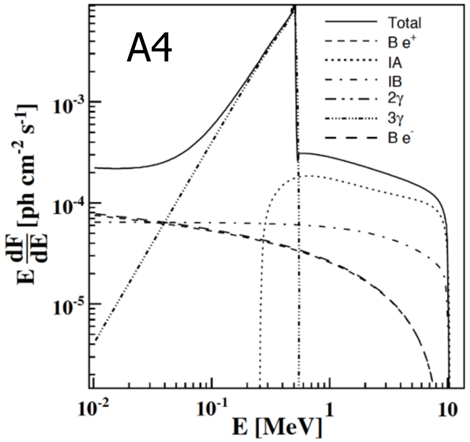

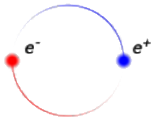

Objectives	Baseline Science Requirements (BSRs)
A1: Identify potential individual positron sources in the Galaxy	• COSI shall image the positron line emission at 0.511 MeV in the bulge at size scales of <250 pc rms (1.75° rms)
A2: Determine the scale-height of the Galactic disk	• COSI shall distinguish between a thin-disk (3.5° scale-height) and a thick-disk (10° scale-height) distribution for the 0.511 MeV Galactic positron emission
A3: Study the annihilation mechanism and the differences between the disk and bulge	• COSI shall search for variations in the annihilation mechanism by measuring the 0.511 MeV emission line profile • COSI shall determine if most of the positrons are slowed down in the interstellar medium before annihilating (0.4-0.5 MeV vs. 0.511 MeV intensity)
A4: Investigate the energy at which positrons are created	• COSI shall search for a break in the 0.5-3 MeV spectrum

Goal B: Reveal Galactic Element Formation

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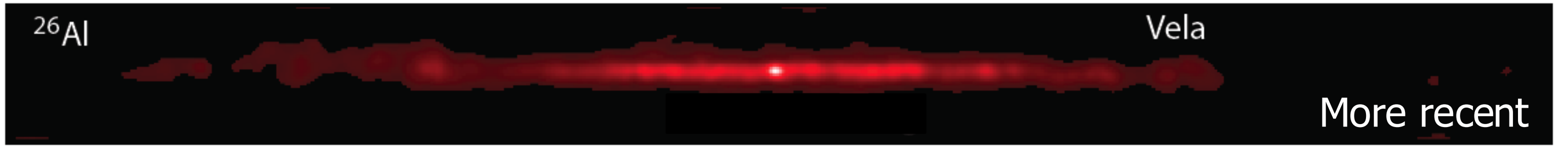
Emission line imaging and *three windows on element formation* from massive stars

B1

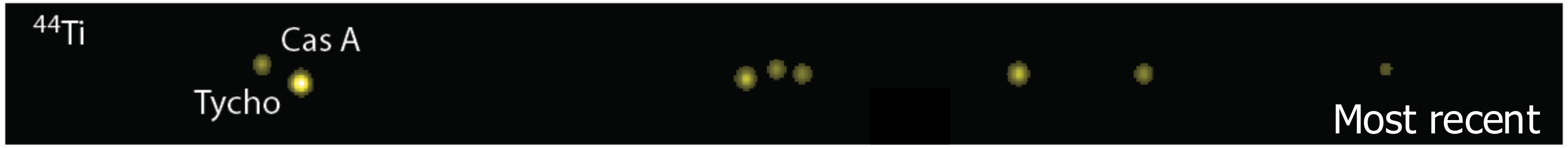
1.173/1.333 MeV
$t_{1/2}$ = 2.6 Myr

B2



1.809 MeV
$t_{1/2}$ = 700 kyr

B3/B4



1.157 MeV
$t_{1/2}$ = 60 yr

Objectives	**BSRs**
B1: Reveal the recent history of core collapse supernova activity in the Galaxy	• COSI shall image the ^{60}Fe line emission at 1.173 and 1.333 MeV (1.75° rms; SNR≥4 for 4 regions)
B2: Determine the role of massive stars in creating the elements	• COSI shall determine the stage of evolution for OB associations by imaging the ^{26}Al line emission at 1.809 MeV (0.9° rms)
B3: Detect nuclear line emission from very young supernova remnants in the Galaxy	• COSI shall search for young hidden supernova remnants by surveying the Galactic disk for ^{44}Ti at 1.157 MeV
B4: Probe explosion physics in the core of supernovae	• For any supernova remnant detected at SNR≥5, COSI shall measure the expansion rate to ±1000 km/s (drives energy resolution of 3.86 keV rms at 1.157 MeV)

^{26}Al individual sources?

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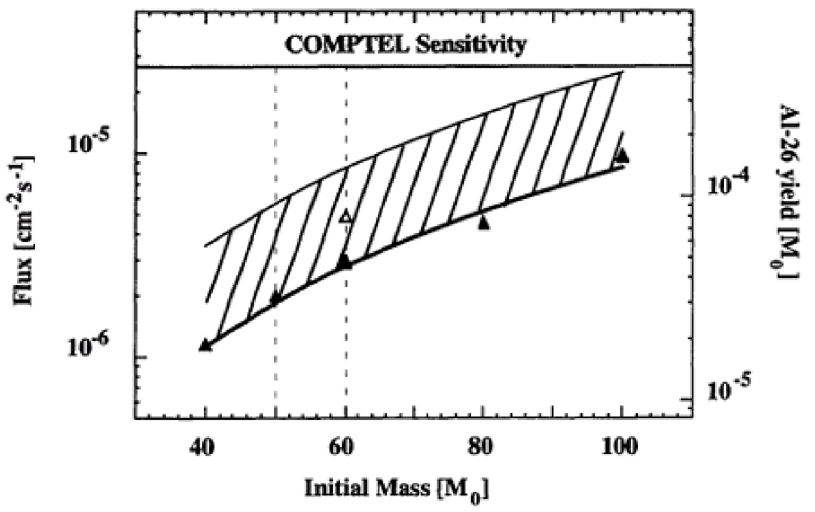
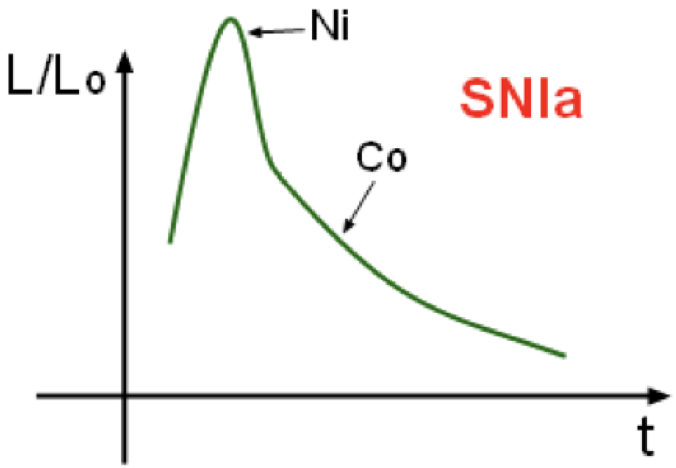
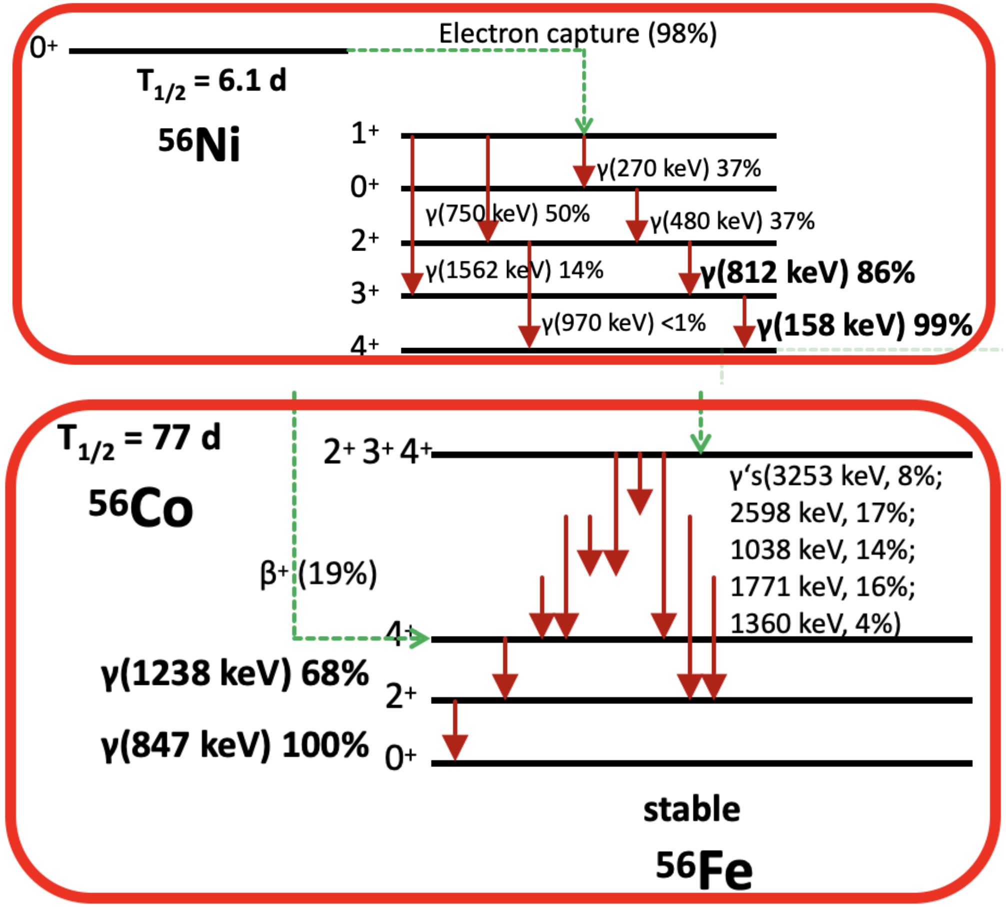
- Gamma^2 Velorum is a nearby (~345 pc) WR11/O-star binary
- Detection would calibrate the ^{26}Al ejection during the WR phase
- Not detected by COMPTEL or INTEGRAL, but what do we expect from COSI?
  - Being investigated as part of data challenge 3, considering two cases with ^{26}Al flux of $5x10^{-6}$ ph/cm^2/s
    - Point source: should be easily detectable at COSI's required 2-year sensitivity of $3x10^{-6}$ ph/cm2/s (3-sigma)
    - Extended source: investigating with the DC3 simulations

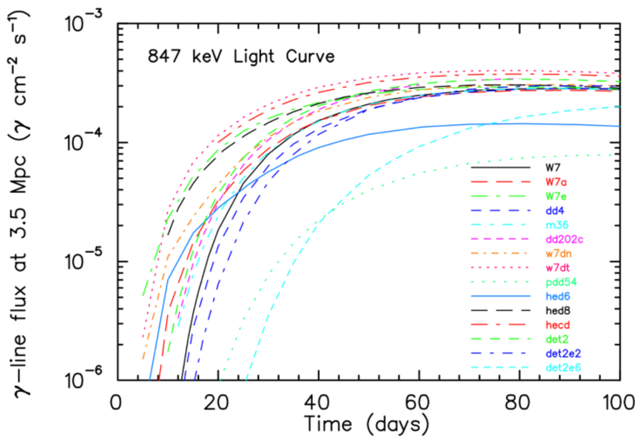


Oberlack et al. 1994

COSI and SNIa







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

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

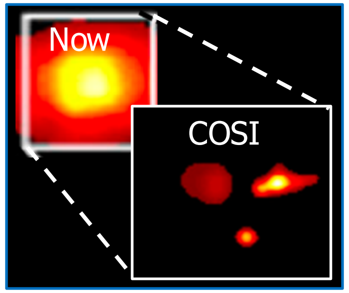
- **10^{-5} ph/cm^2/s in 100 days in survey mode**

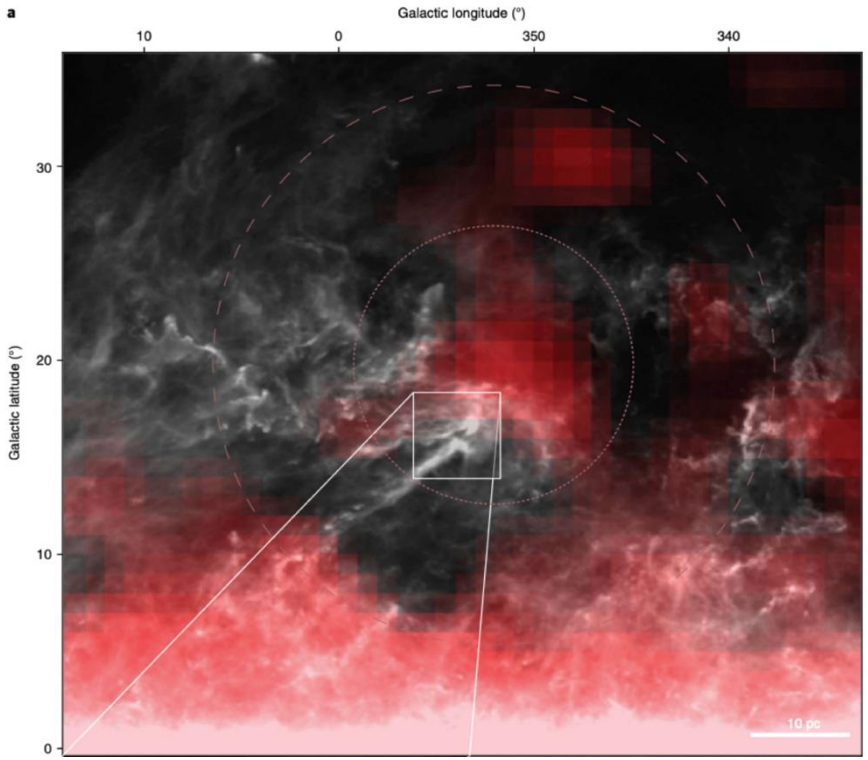
Distance	Predicted flux (median of models)
3.5 Mpc	3.0×10^{-4} ph/cm^2/s
10 Mpc	4.0×10^{-5} ph/cm^2/s
20 Mpc	1.0×10^{-5} ph/cm^2/s

Expect ~two SNIa per year within 20 Mpc ←

Planetary: star and planet formation

- ❑ Heating from radioactivity is an important parameter for planet formation
- ❑ COMPTEL 1.809 MeV image shows evidence for ^{26}Al coincident with Ophiuchus star-forming region
  - Forbes+21 Nature paper
- ❑ However, the COMPTEL detection is only ~2σ
- ❑ COSI greatly improves angular resolution and sensitivity





- Forbes+21, Nature
- Red: Distribution of ^{26}Al (COMPTEL, 3.8° ang. res.) near Ophiuchus
- Gray: Planck dust map

Supernovae: time scales

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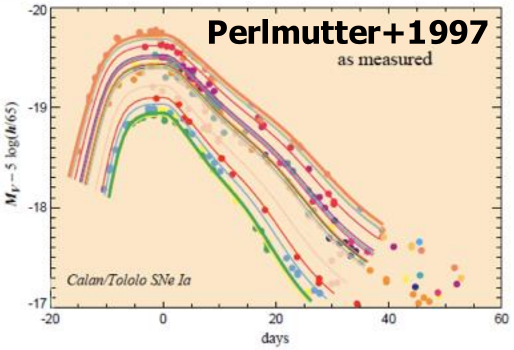
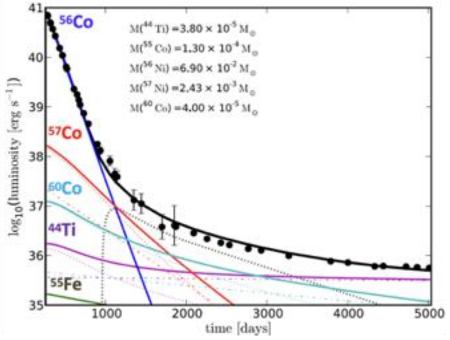
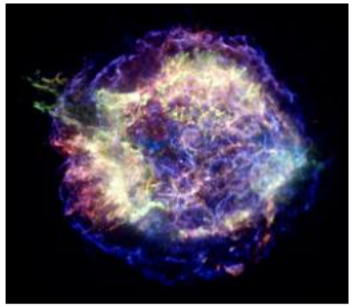
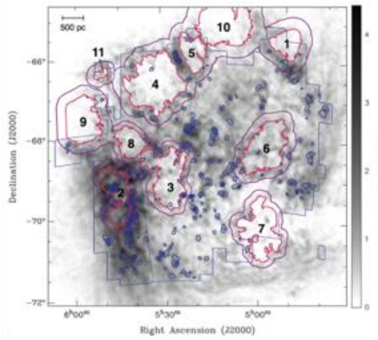
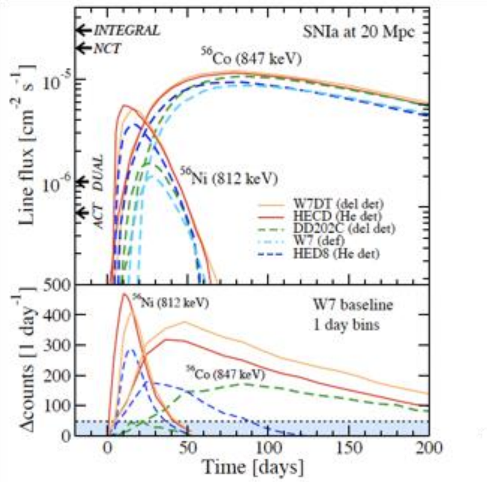
	Explosion	Lightcurve	Remnant	Superbubble
Non-gamma-ray observations				

Day -20-50 — Day <5000 — Year <1000 — Year <10^7

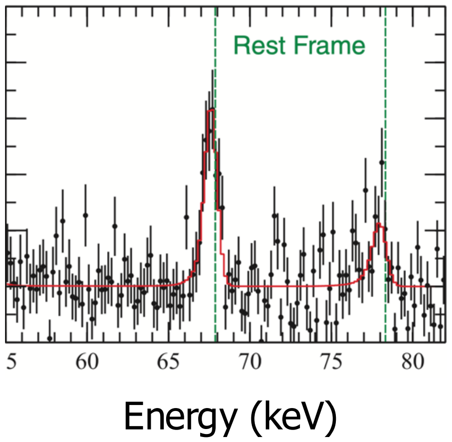
<10^7 s — <10^9 s — <10^{11} s — <10^{15} s

Gamma-ray prediction and observations

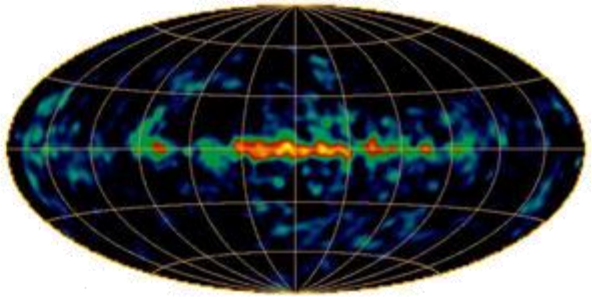
The+2014, ^{56}Ni, ^{56}Co



Boggs+2015, ^{44}Ti



Oberlack+1996, ^{26}Al



Slide credit: Thomas Siegert

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Detected gamma-ray emission lines

Beyond the Solar System

Isotope or particle	Mean Decay Time	Decay Chain	Gamma-ray energies (keV)	Detected Source(s)
^{56}Ni	8.8 d; 111 d	^{56}Ni → ^{56}Co* → ^{56}Fe*+e^{+}	158, 812, 847, 1238	SN2014J, SN1987A, SN1991T(?)
^{57}Ni	390 d	^{57}Co → ^{57}Fe*	122	SN1987A
^{44}Ti	85 yr	^{44}Ti → ^{44}Sc* → ^{44}Ca*+e^{+}	68, 78, 1157	SNRs (Cas A, 1987A, Tycho?)
^{26}Al	1.04e6 yr	^{26}Al → ^{26}Mg*+e^{+}	1809	Massive star groups (several)
^{60}Fe	3.5e6 yr	^{60}Fe → ^{60}Co* → ^{60}Ni*	1173, 1333	Milky Way Galaxy (integrated)
e^{+}	Propagation time	e^{+}/e^{-} annihilation (2 or 3 photon)	511, <511	Galactic bulge, Galactic disk

Predictions within reach for: ^{7}Be (478 keV), ^{22}Na (1275 keV), $^{229/230}$Th (many), and ^{126}Sn (many); adapted from Diehl+11

Solar

Isotope	Mechanism	Gamma-ray energies (keV)
^{2}H	Neutron capture	2223
^{12}C, ^{16}O, ^{24}Mg, ^{20}Ne, ^{28}Si	p/alpha collision and de-excitation	1369, 1634, 1779, 4438, 6129
^{7}Be, ^{7}Li	alpha-^{4}He	400-500

e^{+}/e^{-} (511 keV) and ^{56}Fe (847 keV) also detected; Shih+03, Smith+03, Share+03, Shih+09

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Element formation processes for gamma-ray lines

- **^{26}Al** is produced in core and shell H-burning via the NaMgAl-cycle in the ^{25}Mg(**p** gamma)^{26}Al reaction and will be eventually ejected in the stellar wind during the WR phase.
- **^{60}Fe** is produced by neutron captures on ^{59}Fe, and destroyed again via ^{60}Fe(**n** gamma)^{61}Fe (during the s-process)
- **^{44}Ti** is produced by ^{40}Ca(**alpha** gamma)^{44}Ti

- ^{60}Fe is entirely produced in the s-process during shell He-burning and thus is a pure product of stellar evolution

- ^{44}Ti is only made in the explosive phase of complete Si-burning with alpha-rich freeze-out from charged particle equilibrium

Table 7.1 Radioactivities with gamma-ray line emission, sorted by ascending radioactive mean lifetime (updated from Diehl et al., 2006c)

Decay chain	Lifetime(y)	γ-ray energy (keV) (branching ratio [%])	Site (detections)	Process type
^{7}Be → ^{7}Li	0.21	478 (100)	Novae	Explosive H burning
^{56}Ni ⟶ ^{56}Co ⟶ ^{56}Fe	0.31	847 (100), 1,238 (68) 2,598 (17), 1,771 (15) and 511 from e$^+$	SNe (SN1987A, SN1991T)	NSE burning
^{57}Co ⟶ ^{57}Fe	1.1	122 (86), 136 (11)	SNe (SN1987A)	NSE burning
^{22}Na ⟶ ^{22}Ne	3.8	1275 (100) and 511 from e$^+$	Novae	Explos. H burning
^{44}Ti ⟶ ^{44}Sc ⟶ ^{44}Ca	89	68 (95), 78 (96) 1,156 (100) and 511 from e$^+$	SNe (Cas A)	NSE α freeze-out
^{26}Al ⟶ ^{26}Mg	1.04 10^6	1,809 (100) and 511 from e$^+$	ccSNe, WR Novae, AGB (Galaxy) (Cygnus; Sco-Cen; Orion; Vela)	H burning (ν-proc.)
^{60}Fe ⟶ ^{60}Co ⟶ ^{60}Ni	3.8 10^6	1,173 (100), 1,332 (100) 59 (2)	SNe (Galaxy)	He,C shell burning
e$^+$ ⟶ Ps,.. ⟶ $\gamma\gamma(\gamma)$	~10^7	2·511 (~100), cont <510	Radioactivities Pulsars, μQSOs, ... (Galactic bulge; disk)	β^+ decay rel. plasma

Payload cutaway

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