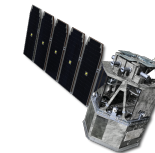


Gamma-ray science with the Compton Spectrometer and Imager (COSI)

COSI

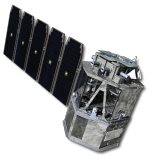
A Gamma-ray
Space Explorer



Jacqueline Beechert
UC Berkeley/Space Sciences Laboratory
Gamma-Ray Science Interest Group (GR SIG)
January 28, 2022
<https://cosi.ssl.berkeley.edu>

COSI Science Goals

COSI
A Gamma-ray
Space Explorer

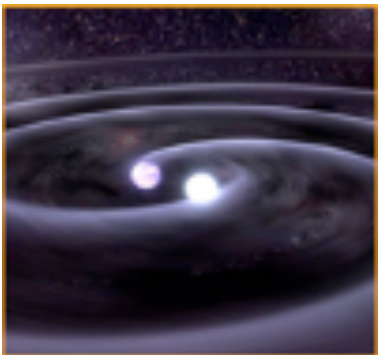


Revolutionizing our understanding of creation and destruction of matter in our Galaxy and beyond

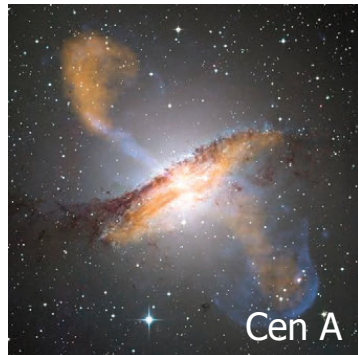
Energy range: 0.2-5 MeV γ -rays

1. Uncover the origin of Galactic positrons
2. Reveal Galactic element formation
3. Gain insight into extreme environments with polarization
4. Probe the physics of multi-messenger events

Goal 4: MMA



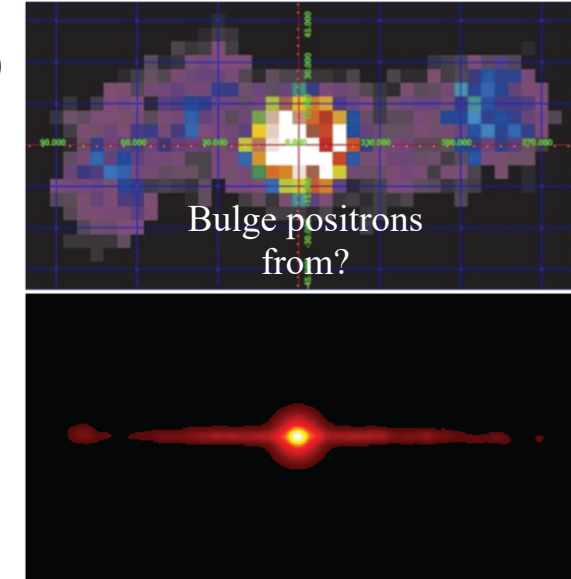
Goal 3: Polarization



Cen A

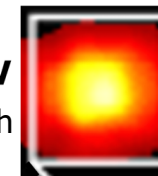
511 keV with
INTEGRAL
(Bouchet+10)

Goal 1: Positrons



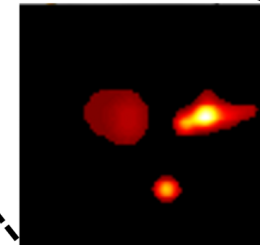
Cygnus region

Now
Simulation with
COMPTEL

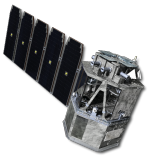


Goal 2:
Nucleosynthesis

^{26}Al 1.809 MeV



COSI



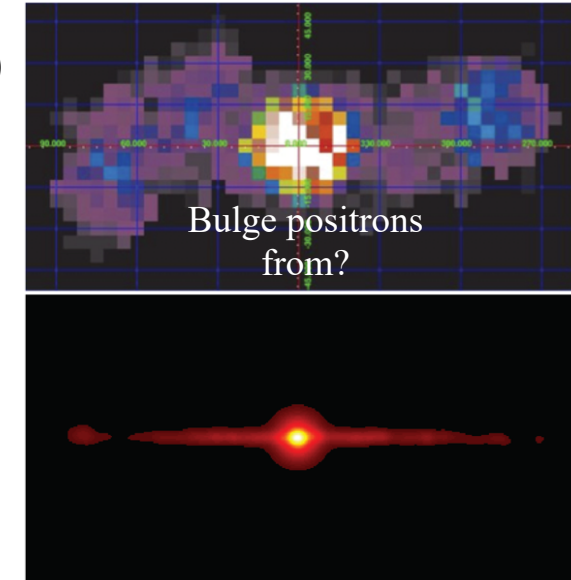
Revolutionizing our understanding of creation and destruction of matter in our Galaxy and beyond

1. Uncover the origin of Galactic positrons

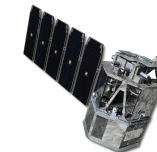
- Strong 511 keV signature at the center of the Milky Way (10^{-3} ph cm $^{-2}$ s $^{-1}$)
- Diffuse nature:
 - Truly diffuse? Annihilation after propagation from production sites
 - Effectively diffuse? Annihilation in situ from many point-like sources
 - Bright central bulge vs. extended, fainter disk emission
- Source of the positrons:
 - Disk emission may be explained by positrons from β^+ decay of stellar nucleosynthesis products (e.g. Al-26, Ti-44)
 - Origin of bulge positrons is unknown
 - Other candidates: Co-56, DM, LMXRB, GRBs, SgrA*, ...

511 keV with
INTEGRAL
(Bouchet+10)

Goal 1: Positrons



- Need to characterize the 511 keV spectrum and its o-Ps continuum component
- Need to constrain the spatial morphology of the emission



Revolutionizing our understanding of creation and destruction of matter in our Galaxy and beyond

2. Reveal Galactic element formation

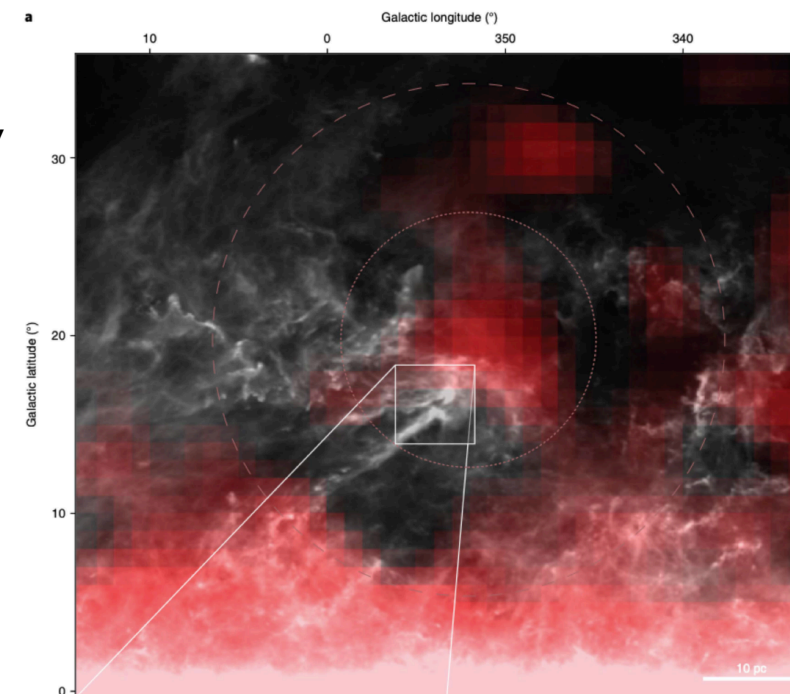
- Study Galactic chemical evolution through products of SNe nucleosynthesis
- Integrated history over $\sim$ Myr
 - Al-26 (1809 keV; half-life: 0.7 Myr)
 - Fe-60 (1173 keV, 1332 keV; half-life: 2.6 Myr)
- Young SN remnants in last $\sim$ 100 years
 - Ti-44 (1157 keV; half-life: 60 years)

- Need high-resolution spectroscopy to study nucleosynthetic line emission and isotopic yields
- Need to constrain the spatial distribution of these isotopes throughout the Galaxy

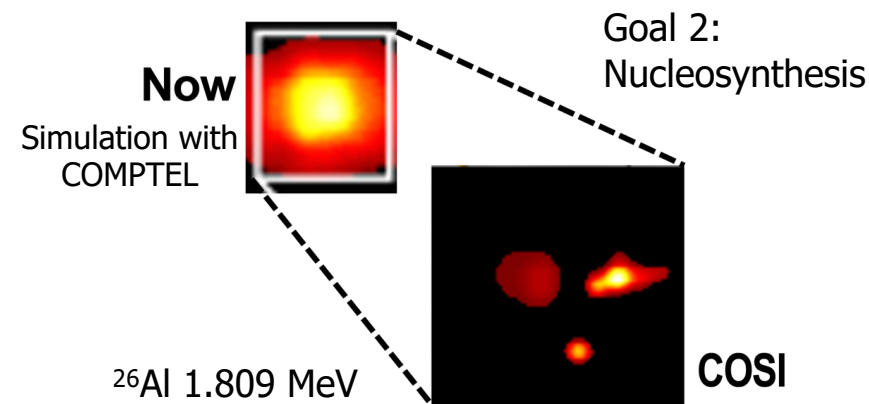
Forbes et al. 2021,
Figure 1

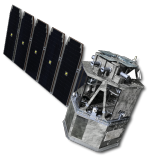
Red: Distribution
of Al-26
(COMPTEL, 3.8°
ang. res.) near
Ophiuchus

Gray: Planck dust
map



Cygnus region



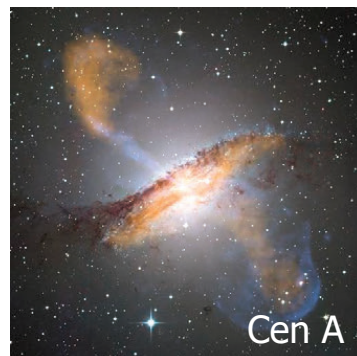


Revolutionizing our understanding of creation and destruction of matter in our Galaxy and beyond

3. Gain insight into extreme environments with polarization

- Probe emission mechanisms and source geometries (magnetic field orientation, accretion disks, jets)
- Reconcile differences in polarization levels and time variability across GRBs
 - RHESSI: GRB021206 polarization $80 \pm 20\%$ $\rightarrow$ synchrotron origin, strong mag. field (Coburn and Boggs 2003)
 - INTEGRAL GRB041219A: high polarization, time variability in polarization amplitude and angle (Gotz et al. 2009)
 - POLAR: 14 GRBs of lower polarization, time variability (Kole et al. 2020)
 - COSI-APRA: GRB160530A: upper limit on polarization of 46% (Lowell 2017)
- Study polarization of pulsars (e.g. Crab), accreting BHs (e.g. Cygnus X-1), and AGN (e.g. Cen A)

Goal 3: Polarization

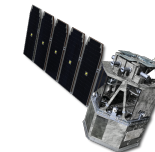


➤ Need more polarization measurements with enhanced sensitivity to understand emission mechanisms and time evolution of these events

Compact Compton Telescope (CCT)

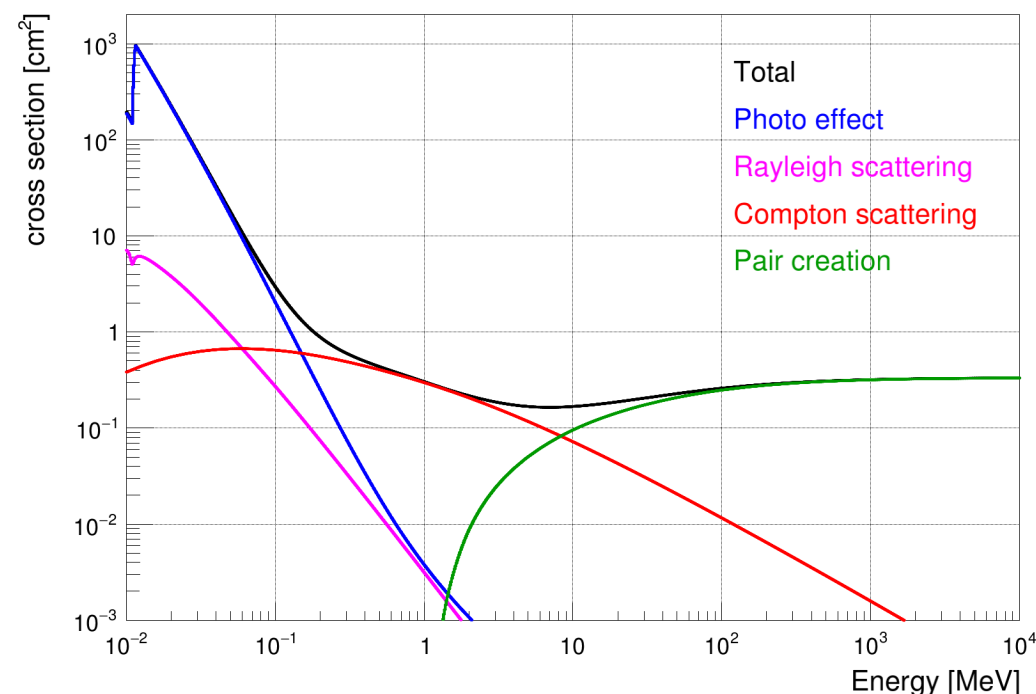
COSI

A Gamma-ray
Space Explorer



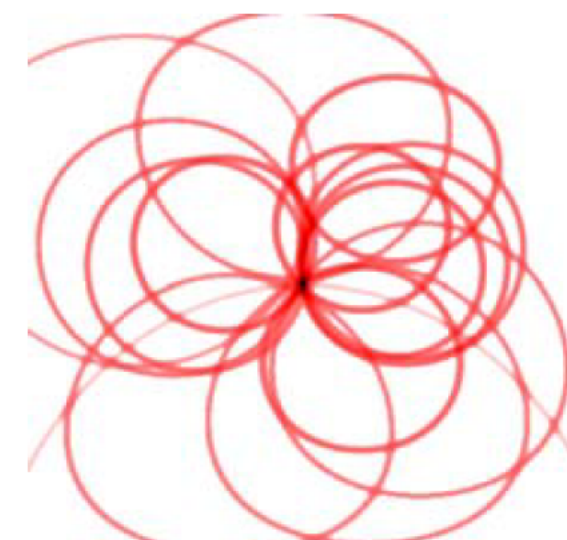
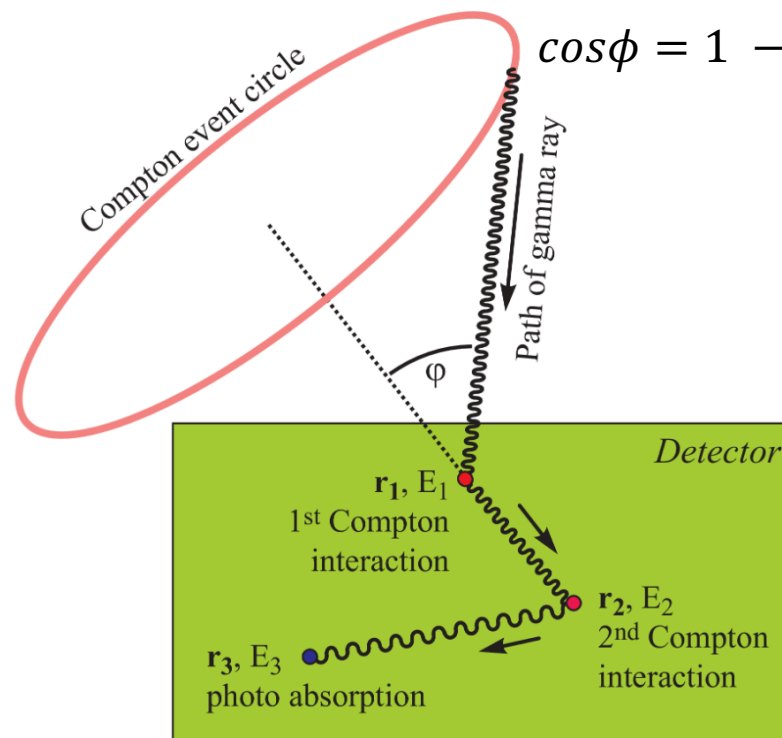
Principle: Compton scattering dominates
the 0.2-10 MeV energy range

Cross-sections for Germanium



Constrain γ to event circle defined by ϕ :

$$\cos\phi = 1 - \frac{m_e c^2}{E_2 + E_3} + \frac{m_e c^2}{E_1 + E_2 + E_3}$$

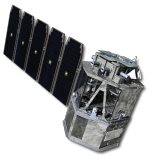


Overlapping event
circles constrain the
source location

Images Left: MEGAlib; Middle: Zoglauer, Andreas, et al. "COSI: From Calibrations and Observations to All-sky Images." arXiv preprint arXiv:2102.13158 (2021), Right: Zoglauer (2006)

CCT: COSI-APRA (balloon) overview

COSI
A Gamma-ray
Space Explorer



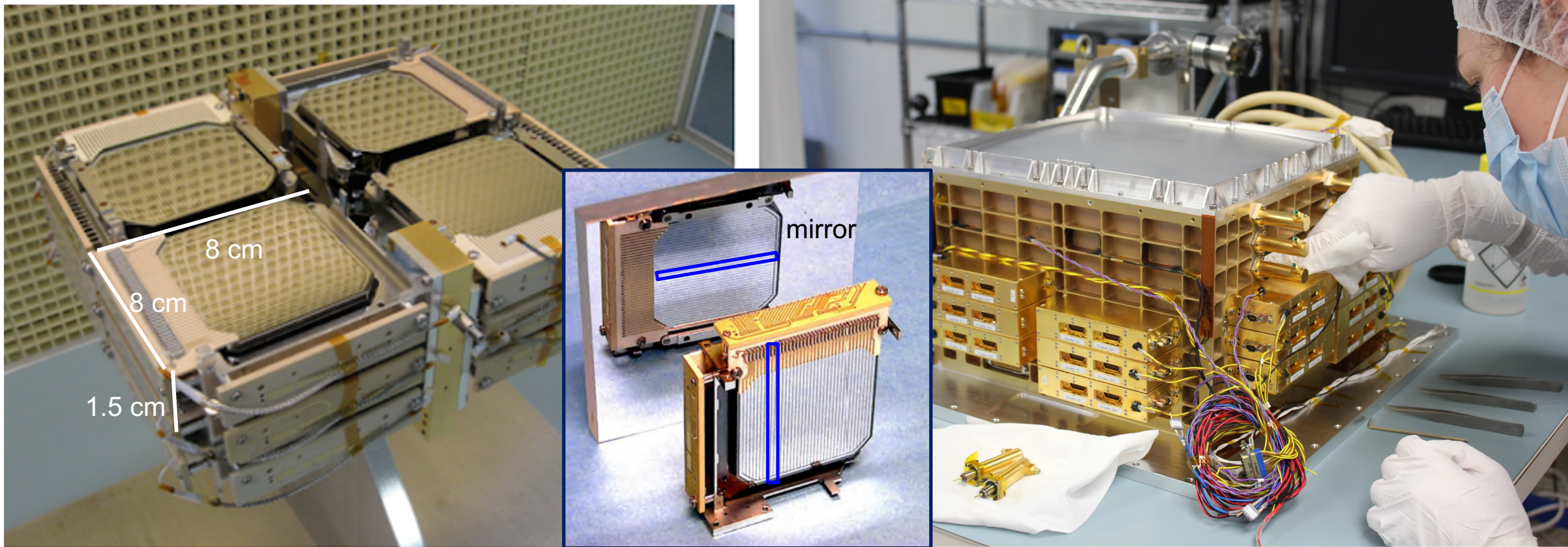
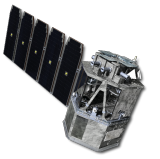
Balloon-borne compact Compton telescope

- Energy range: 0.2 - 5 MeV
- Energy resolution: $\sim 0.7\%$ FWHM at 511 keV, $\sim 0.2\%$ FWHM at 1809 keV
- Angular resolution: $\sim 6^\circ$ at 511 keV, $\sim 4^\circ$ at 1809 keV
- FOV: 25% of the sky ($\sim \pi$ steradian)



COSI's GeD Array

COSI
A Gamma-ray
Space Explorer



- 12 **HPGe** cross-strip detectors
 - 12 x 37 strips x 2 sides = 888 strips of 2 mm pitch
 - 3D position resolution of $2 \times 2 \times 0.5 \text{ mm}^3$
- Detectors housed in aluminum **cryostat**
- Operating conditions: $\sim 84 \text{ K}$, 10^{-6} Torr

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 circulate a
GRB detection with
Gamma-ray
Coordination
Network (GCN): GRB
160530A

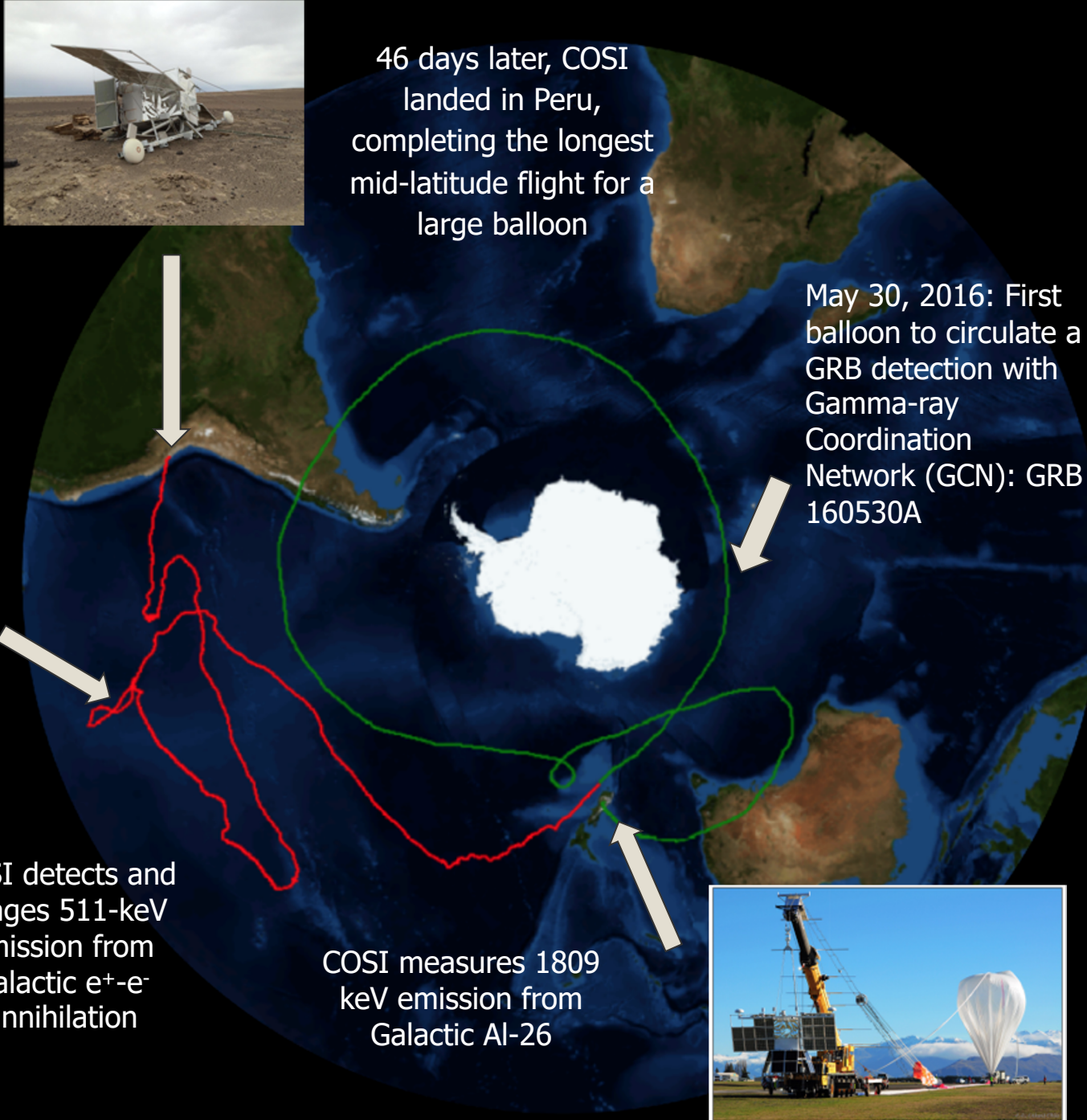
COSI
detects and
images the
Crab nebula

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

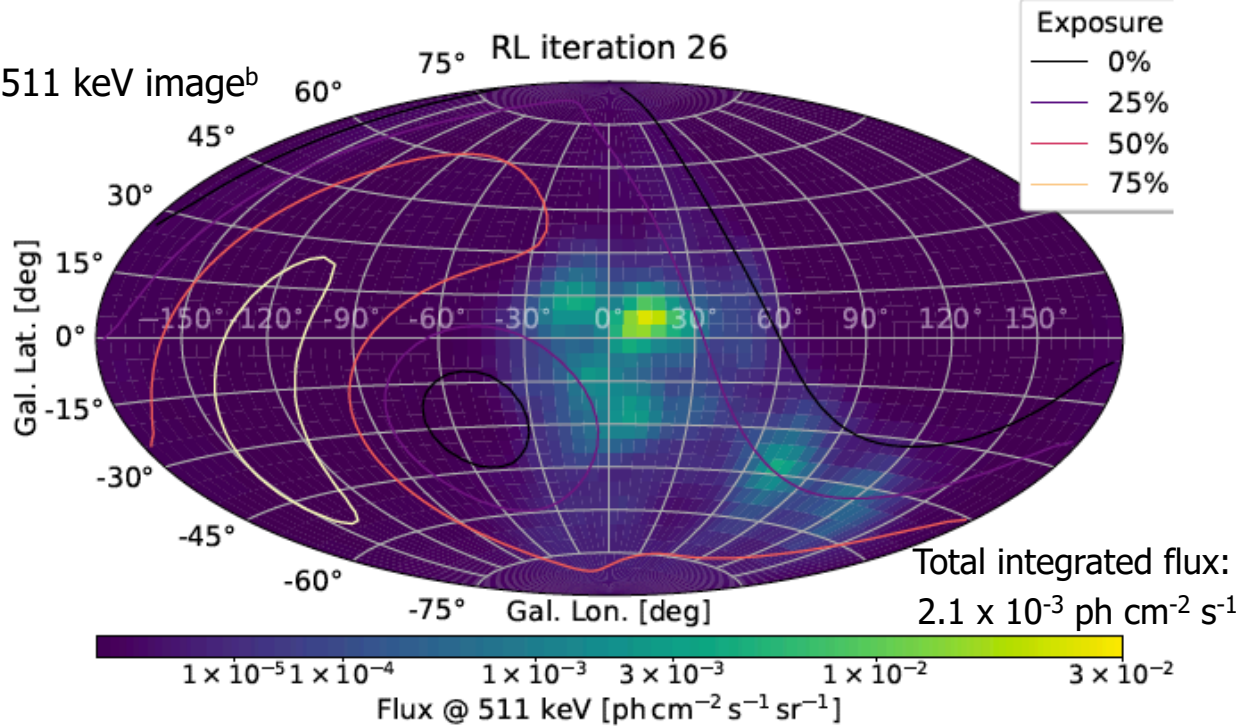
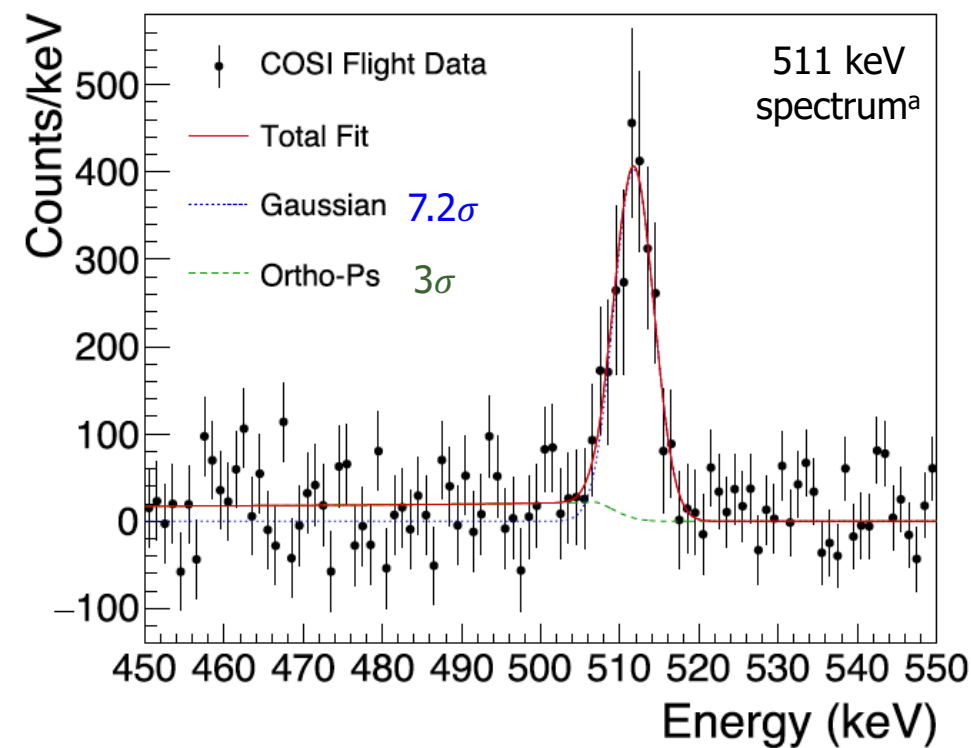
COSI measures 1809
keV emission from
Galactic Al-26



May 17, 2016: COSI
launch is the first
mid-latitude science
flight with NASA's
Super Pressure
Balloon (SPB)
technology



1. Uncover the origin of Galactic positrons

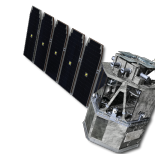


The Bulge	Centroid [keV]	Line flux [$10^{-3} \text{ ph cm}^{-2} \text{ s}^{-1}$]	Radial distribution [°]
COSI 2016	511.8 ± 0.3^a	1.90 ± 0.45^b	$28^{+19}_{-12}^b$

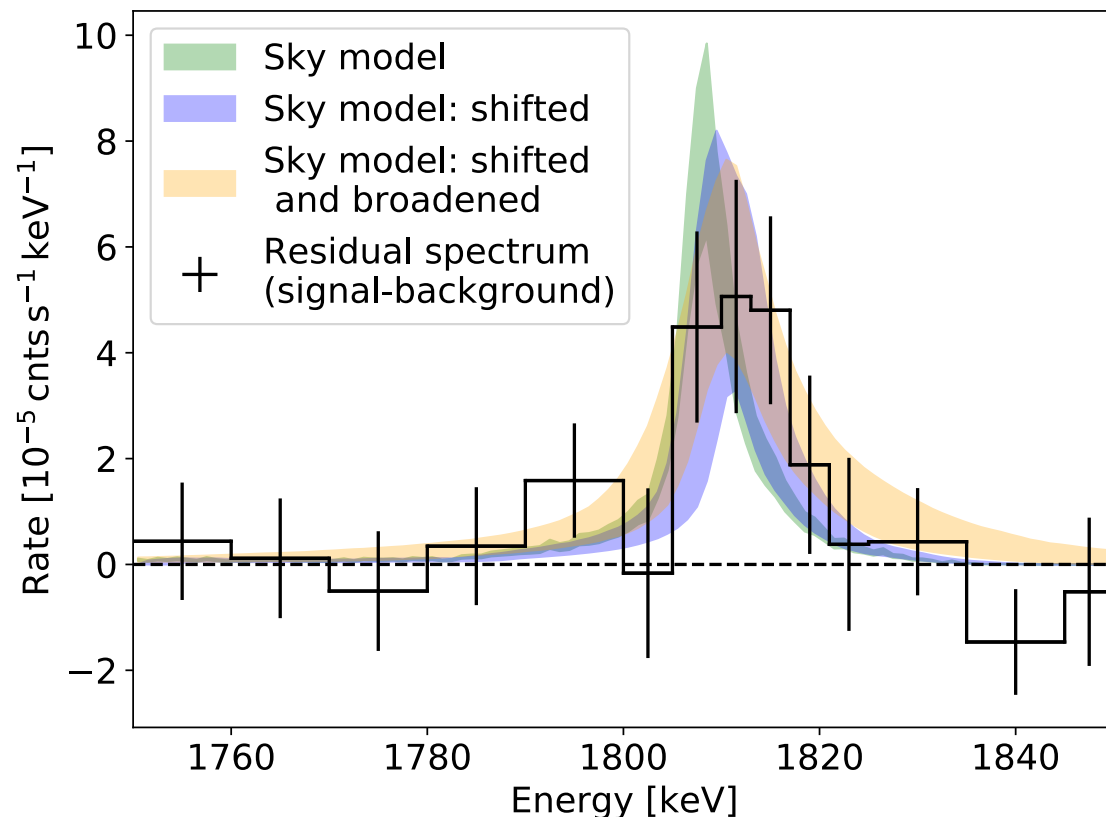
- 7.2σ detection at 511 keV
- Confirmed bulge emission

^aKierans et al. 2020, The Astrophysical Journal, 895, 44

^bSiegert et al. 2020, The Astrophysical Journal, 897, 45



2. Reveal Galactic element formation



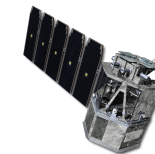
Measurement of Galactic Al-26

The Bulge	Centroid [keV]	Inner Galaxy flux [$10^{-4} \text{ ph cm}^{-2} \text{ s}^{-1}$]	Significance [σ]
COSI 2016	1811.2 ± 1.8	8.6 ± 2.5	3.7

- 3.7σ measurement at 1809 keV
- Demonstration of ability to measure Al-26 in the Inner Galaxy

Beechert (2021) ICRC 2021 proceedings: <https://arxiv.org/abs/2109.10365>

Beechert et al. (2021), submitted to ApJ



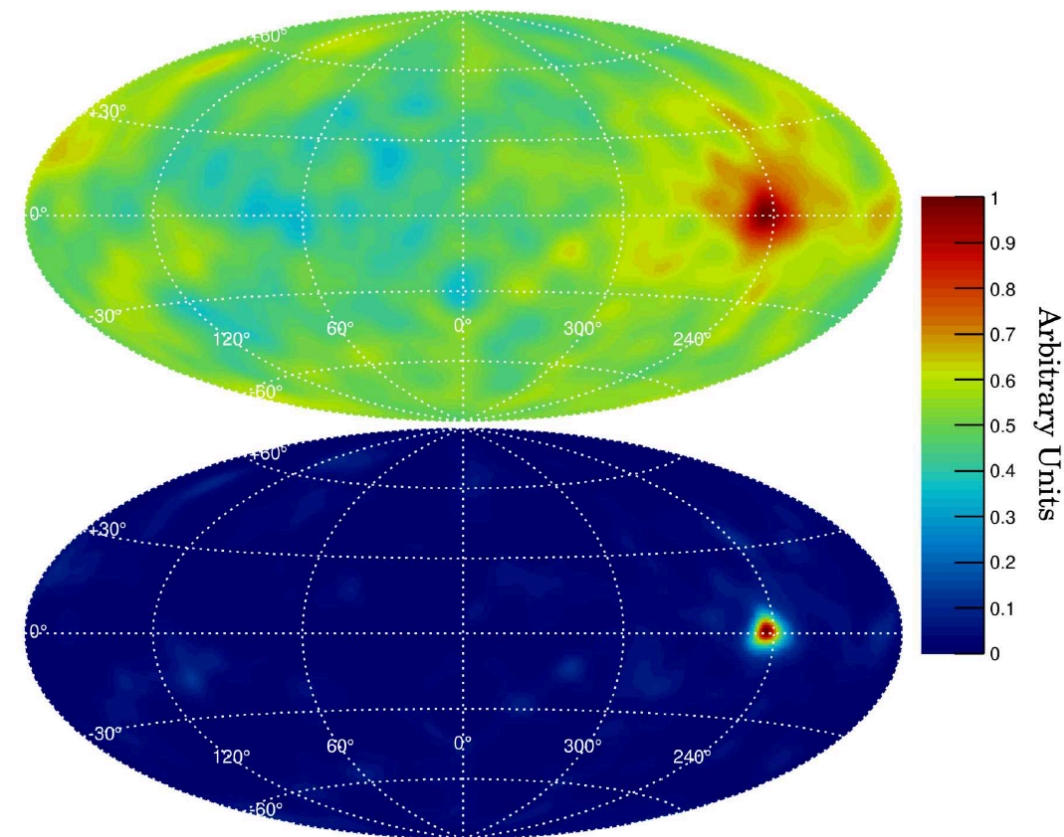
3. Gain insight into extreme environments with polarization

Real-time detection of GRB160530A

- GCN notification: first balloon payload to do so
- $< 46\%$ polarization level (90% confidence upper limit)^a

4. Probe the physics of multi-messenger events

→ For this and other improvements, let's go to space



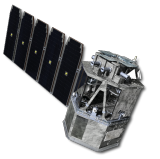
COSI images^a of GRB160530A ($\ell = 243.4^\circ$, $b = 0.4^\circ$)
Top: zero iterations (back-projection of Compton cones),
Bottom: ten iterations of LM-MLEM deconvolution algorithm.

^aLowell (2017), University of California, Berkeley

COSI: A Gamma-ray Space Explorer

COSI

A Gamma-ray
Space Explorer



Tomsick (2021) ICRC 2021 proceedings: <https://arxiv.org/abs/2109.10403>

Astro2020 APC White Paper: <https://arxiv.org/pdf/1908.04334.pdf>

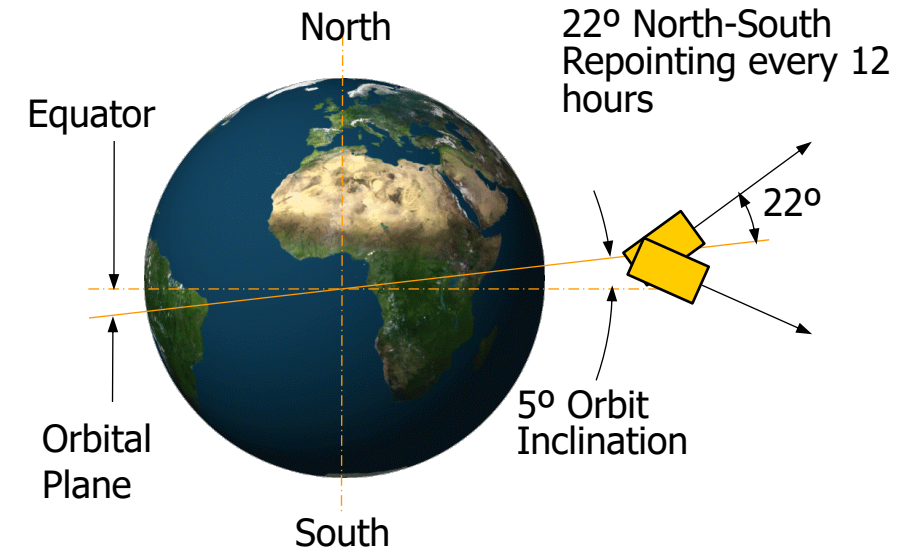
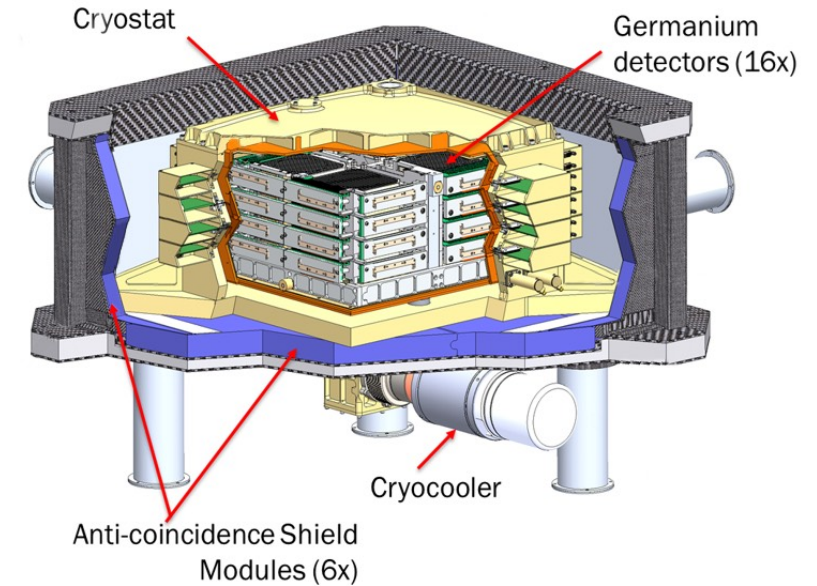
Oct 18, 2021

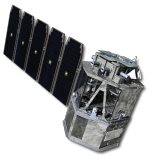
RELEASE 21-134

NASA Selects Gamma-ray Telescope to Chart Milky Way Evolution

<https://www.nasa.gov/press-release/nasa-selects-gamma-ray-telescope-to-chart-milky-way-evolution>

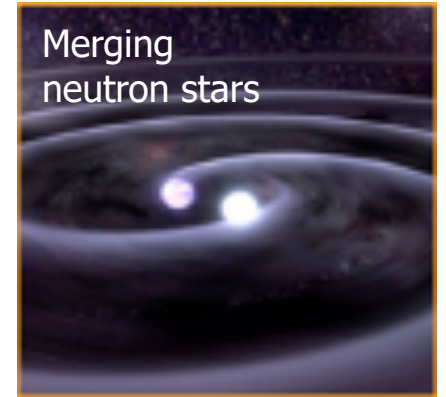
- Low-Earth orbit
- 4 more germanium detectors than COSI-APRA
- COSI constantly points away from Earth and alternates between North and South to cover the whole sky in 24 hours
 - Instantaneous FOV >4x larger than COMPTEL and >12x larger than INTEGRAL/SPI





I. Neutron star merger (NSM)

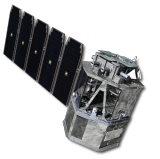
- GW signature (GW170817; Abbott et al. 2017)
- Associated short GRB (GRB170817A; Goldstein et al. 2017)
- Source of positrons and heavy elements



→ We need observatories in EM and GW ready for these events!

→ Over its 2-year prime mission, COSI will

- map positrons and γ -ray lines to study Galactic NSM history
- detect ~ 15 -20 short GRBs in Ge with sub-degree localization in $\sim \pi$ str FOV
- detect ~ 15 -20 short GRBs in BGO shields (compare γ -ray and GW arrival times)
- alerts to community < 1 hour
- detect **~ 4 -6 events in COSI coincident with GWs** (LIGO A+ sensitivity; Burns 2020)



II. High-energy neutrino

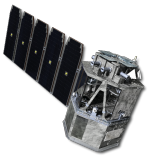
- Fermi LAT γ -ray activity (Aartsen et al. 2018) coincident with high energy neutrino (IceCube-170922A, ~ 290 TeV; IceCube Collaboration et al. 2018)
- Neutrino likely associated with blazar TXS 0506+056
- Enhanced γ -ray emission from TXS 0506+056 weeks after the neutrino event



- We need MeV observations of high-energy neutrino events! COSI will
- **observe all high-energy neutrino events within 12 hours**
 - detect blazar γ -ray flares (which typically last $\sim$ weeks, months)
 - serve as key γ -ray counterpart to IceCube Upgrade^a, due online by 2025

COSI can also trigger a Constant Zenith Angle/Target of Opportunity observation for special events of interest, e.g. if there is a blazar near IceCube neutrino position

^aIshihara, Aya. arXiv preprint arXiv:1908.09441 (2019)



III. Nearby SNe

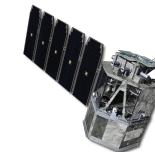
- e.g. SN1987A, the first multi-messenger transient
- Understand moments before and after core collapse with neutrino and GW emission (Kalogera et al. 2019)
- Study γ -ray lines from radioactive isotopes (Palmer et al. 1993, Tueller et al. 1990)
- Low probability of occurrence (not a primary COSI requirement)



- We need GW, neutrino, and γ -ray observations! COSI will
- reveal nucleosynthesis (e.g. map Ti-44, 1.157 MeV) and **SN asymmetries**
 - serve as key γ -ray counterpart to Advanced LIGO+ and HyperKamiokande^a (MeV neutrino detection, starting ~2027)

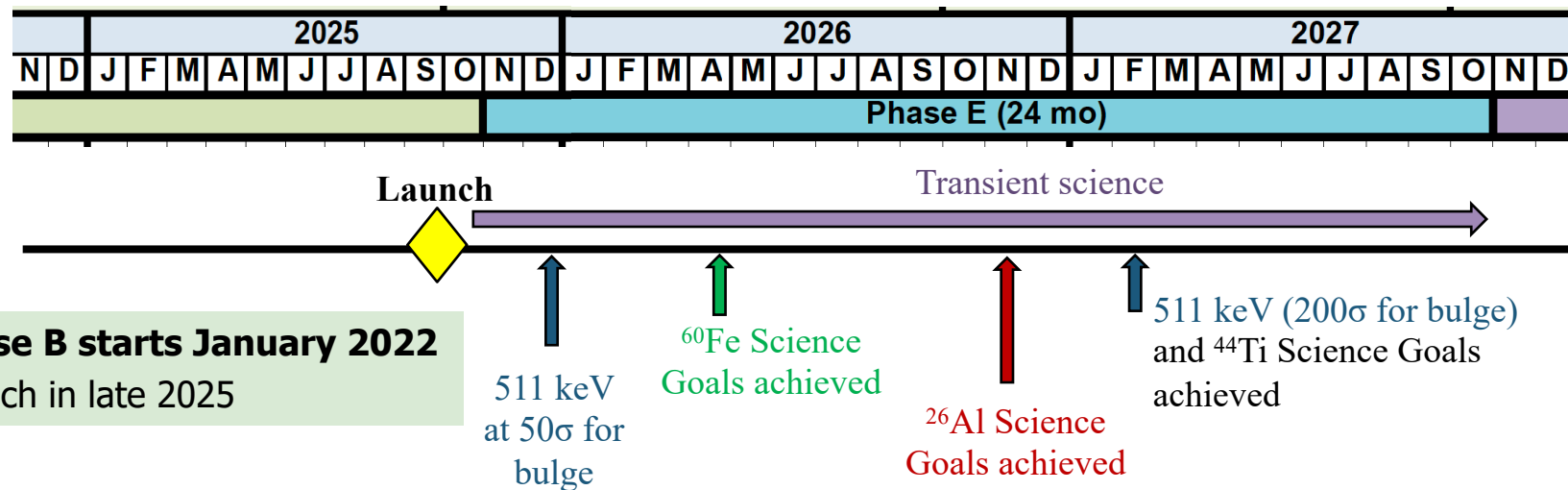
^aJ-PARC. (2020, February 12). <http://www.j-parc.jp/c/en/topics/2020/02/12000416.html>

Summary



COSI-APRA: CCT in MeV regime

- Emission line science:
 - 511 keV detection and imaging, 1809 keV measurement
- Transient science:
 - Detection of GRB160530A with polarization U.L.



Phase B starts January 2022
Launch in late 2025

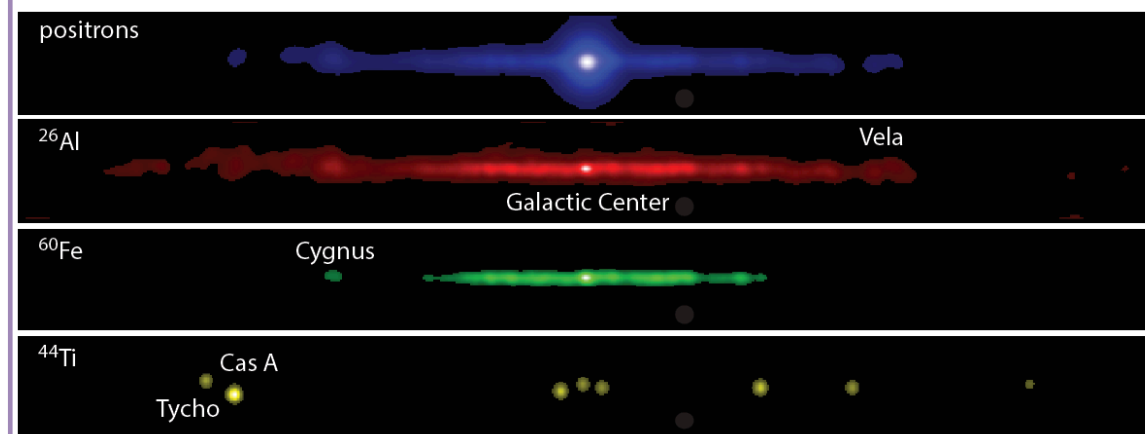
COSI: COSI-APRA instrument upgraded to NASA SMEX

- Obtain total balloon 511 keV sensitivity in 1 day
- More Al-26 observation time, including at high latitudes
- Survey GW/short GRB and high-energy neutrino events in γ -ray regime

Transient science

- ☐ GRB alerts
- ☐ GRB polarization
- ☐ Correlation with HE neutrinos
- ☐ Black hole transients

Emission line science



Where do we come from?

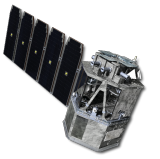
Questions?



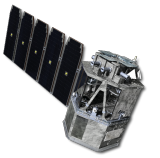
COSI

A Gamma-Ray
Space Explorer

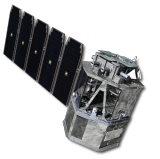
Revolutionizing our
understanding of the
creation and destruction
of matter in our galaxy
and beyond



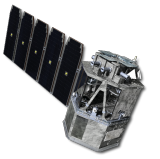
- Abbott, B. P., et al., 2017, GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral, *Physical Review Letters*, 119, 161101
- Aartsen, M. G., Ackermann, M., Adams, J., et al. (2018), Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert, *Science*, 361(6398), 147-+, doi:10.1126/science.aat2890.
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Backup



I. GRBs

Use **polarization** measurements to probe emission mechanisms and source geometries.

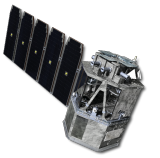
- RHESSI: GRB021206 polarization $80 \pm 20\%$ → synchrotron origin of prompt emission with strong magnetic field (Coburn and Boggs 2003)
- INTEGRAL GRB041219A: high polarization, time variability in polarization amplitude and angle (Gotz et al. 2009)
- POLAR: several GRBs of lower polarization, time variability (Zhang et al. 2019)
- COSI-APRA: GRB160530A: upper limit on polarization of 46% (Lowell et al. 2017)

→ We need more measurements! COSI will measure

~40 GRBs (minimum detectable polarization <50%)

>12 GRBs (with polarization measurements to $\pm 5-10\%$)

with public GRB notifications < 1 hr.



II. Galactic BHs

Origins of thermal X-ray and non-thermal γ -ray components of emission?

- Cygnus X-1
 - Persistently bright in X-rays
 - INTEGRAL: high polarization > 0.4 MeV (Jourdain et al., 2012; Laurent et al., 2011), lower polarization < 0.4 MeV (Chauvin et al., 2018). $\rightarrow$ possible jet origin of γ -ray emission different from X-ray emission

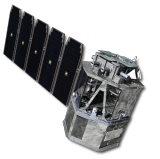
$\rightarrow$ We need more measurements! COSI will

- make **γ -ray observations** that complement soft X-ray observations by IXPE
- measure **polarization** of BH transient outbursts
- conduct CZA/TOO observations when triggered by a BH transient (start within ~ 2 days of trigger, last for ~ 15 days)

Similarly, study AGN, blazars. Use polarization to resolve emission mechanisms, jet compositions, etc.

The COSI Collaboration

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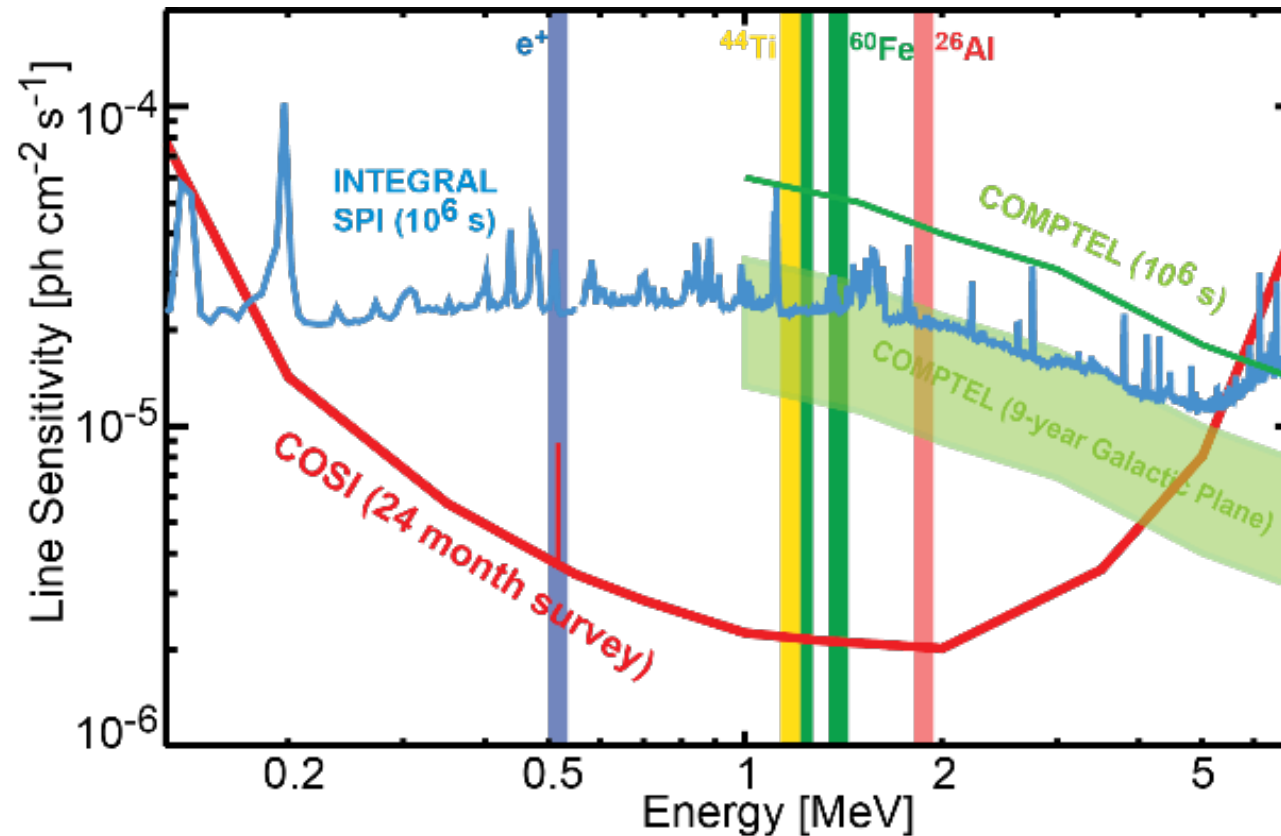
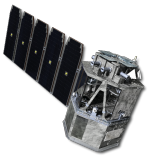
IRAP, France

INAF, Italy

Kavli IPMU and Nagoya University, Japan

NTHU, Taiwan

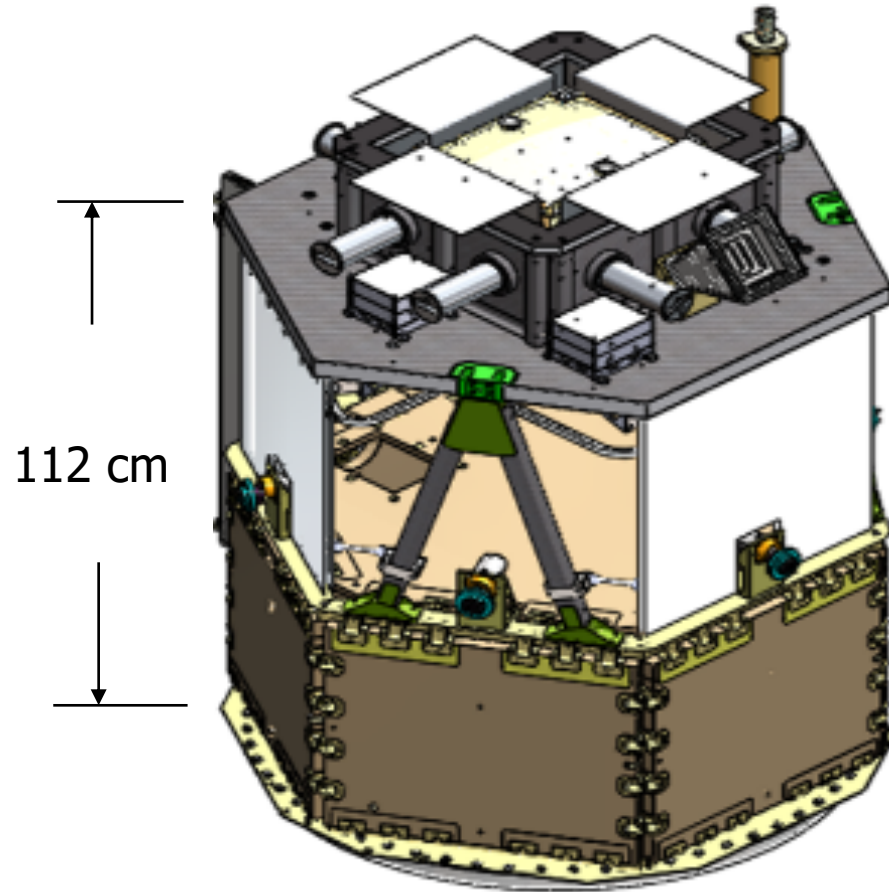
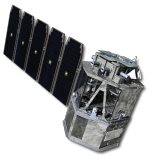
Improvement over previous and current missions



3 σ line sensitivities for the 2-year COSI prime mission compared to INTEGRAL/SPI and COMPTEL

Overview of Instrument and Requirements

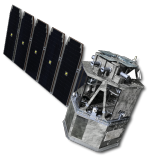
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COSI instrument/payload and spacecraft

Parameter	Requirements
Energy range	0.2-5 MeV
Sky coverage	100% per day
Energy resolution	0.4% FWHM @ 1.8 MeV
Angular resolution	2.0° FWHM @ 1.8 MeV
Localizations	<1.0° for GRBs

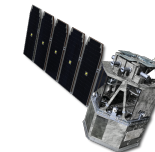
COSI requirements



Characteristic	Requirement	Rationale
Energy Range	0.2-5 MeV	Polarization; 511-1809 keV lines; cont.
Sky Coverage	25% sky FoV	GRBs; Full Galaxy coverage
Energy Resolution	2.6 keV (rms) 511 keV 3.9 keV (rms) 1.157	Line shapes and line sensitivity
Narrow Line Sensitivity (2 years, 3σ , point source) 511 keV 1.809 MeV	[photons $\text{cm}^{-2} \text{s}^{-1}$] 1x10 ⁻⁵ 3x10 ⁻⁶	Galactic bulge $\sim 1 \times 10^{-3} \text{ cm}^{-2} \text{s}^{-1}$ Galactic ²⁶ Al flux $\sim 7 \times 10^{-4} \text{ cm}^{-2} \text{s}^{-1}$
Angular Resolution	3.8° (FWHM) 511 keV 2.0° (FWHM) 1.809 <1.0°	Substructure in the Galactic bulge Individual massive star clusters GRB localizations
Flux limit for polarization	1.4x10 ⁻¹⁰ erg $\text{cm}^{-2} \text{s}^{-1}$ 6.9x10 ⁻¹⁰ erg $\text{cm}^{-2} \text{s}^{-1}$	Reaches bright AGN (2 yr) Galactic black hole transients (30 days)
Fluence limit for GRB polarization (50% MDP)	5x10 ⁻⁶ erg cm^{-2} (<20°) 2x10 ⁻⁶ erg cm^{-2} (<60°)	For COSI to obtain polarization measurements for >40 GRBs in 2 yr
Fluence limit for short GRBs	5x10 ⁻⁷ erg cm^{-2}	For COSI to detect >10 short GRBs

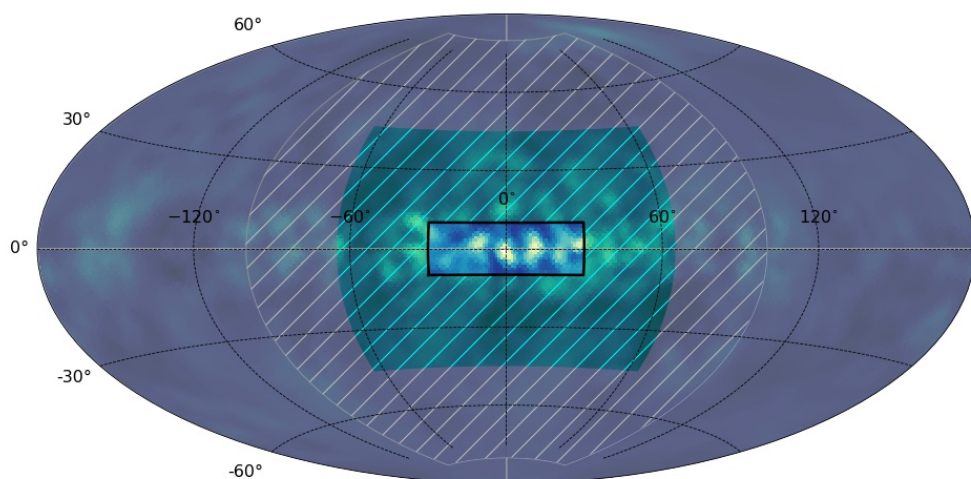
Measurement of Galactic Al-26 in the COSI 2016 Flight

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Beechert (2021) ICRC 2021 proceedings: <https://arxiv.org/abs/2109.10365>; Beechert et al. (2021), submitted to ApJ

Pointing cuts over the SPI 1.8 MeV image
(Bouchet et al. 2015)

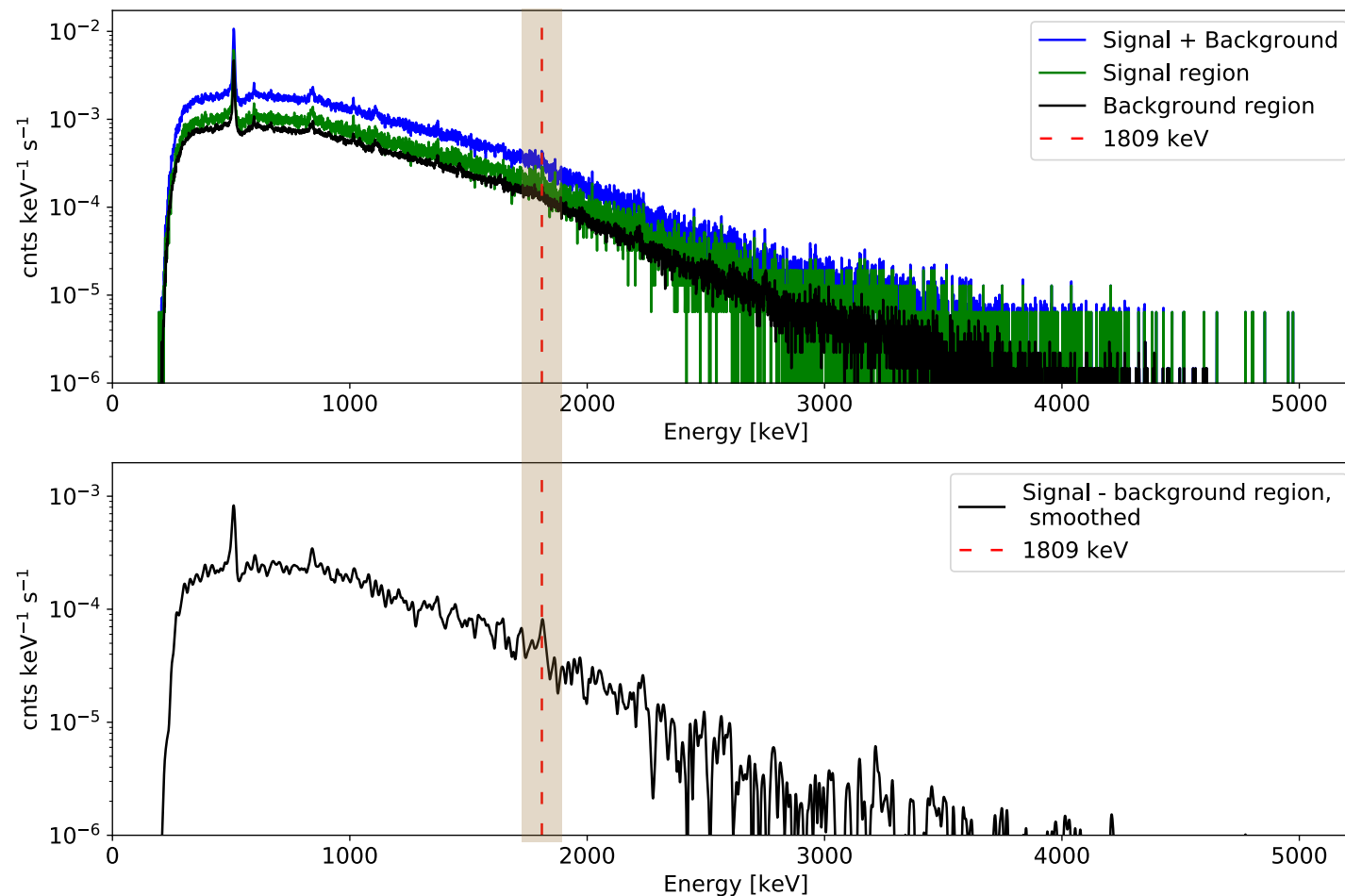


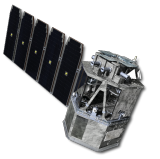
Region	(ℓ, b) [°]
Signal	$(0 \pm 30, 0 \pm 10)$
Background Region 1	$(-180 \pm 80, 0 \pm 90)$
Background Region 2	$(0 \pm 30, 85 \pm 5)$
Background Region 3	$(0 \pm 30, -85 \pm 5)$

Signal region exposure time ~ 156 ks

BG region exposure time ~ 1356 ks

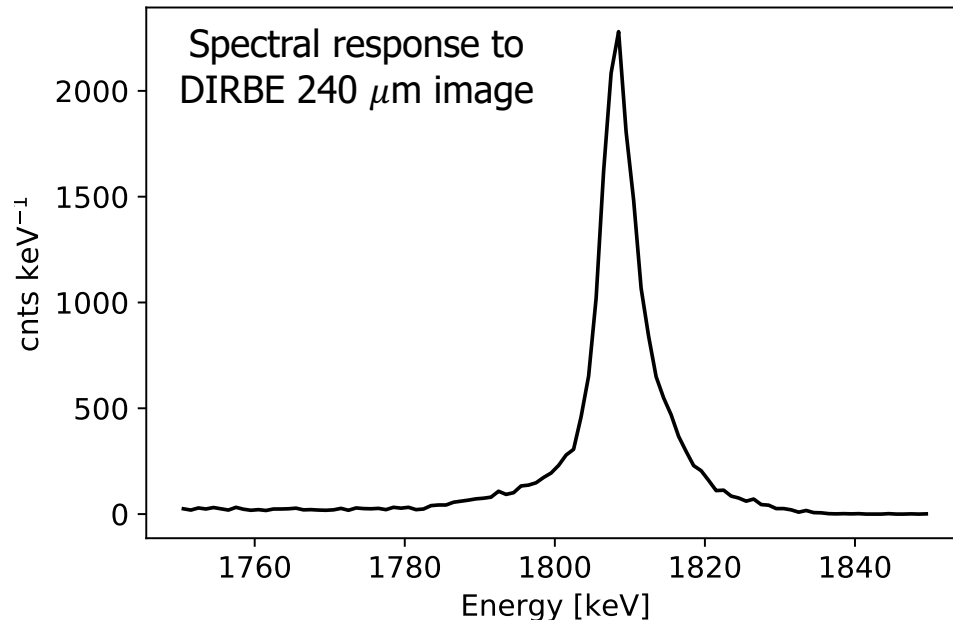
Flight spectra





Maximum likelihood framework:
For 1-keV energy bins i spanning 1750-1850 keV:

$$C(d|m) := - \sum_{i=1}^{N=100} [m_i - d_i \ln(m_i)] \quad (\text{Cash 1979})$$

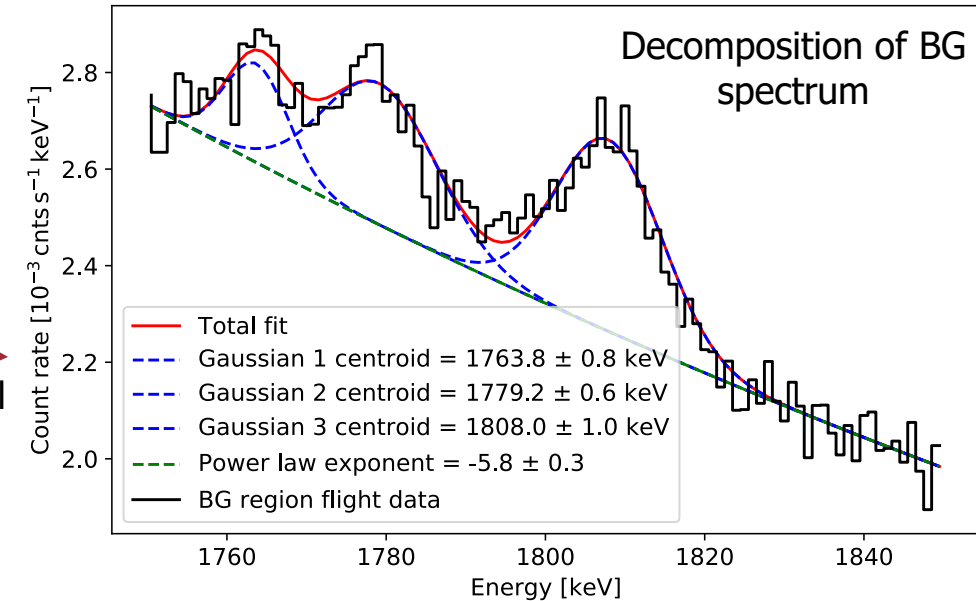
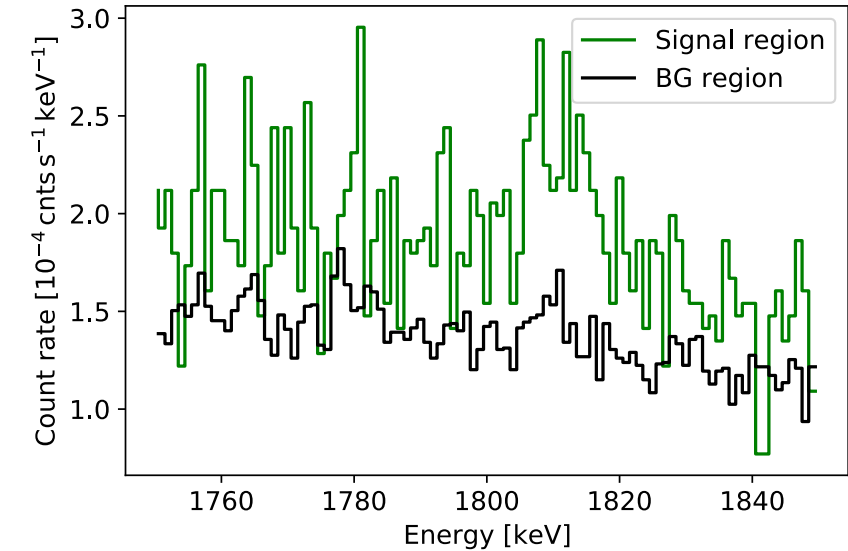


Model:

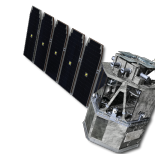
$$m_i = \alpha s_i + \beta b_i$$

Sky model

BG model

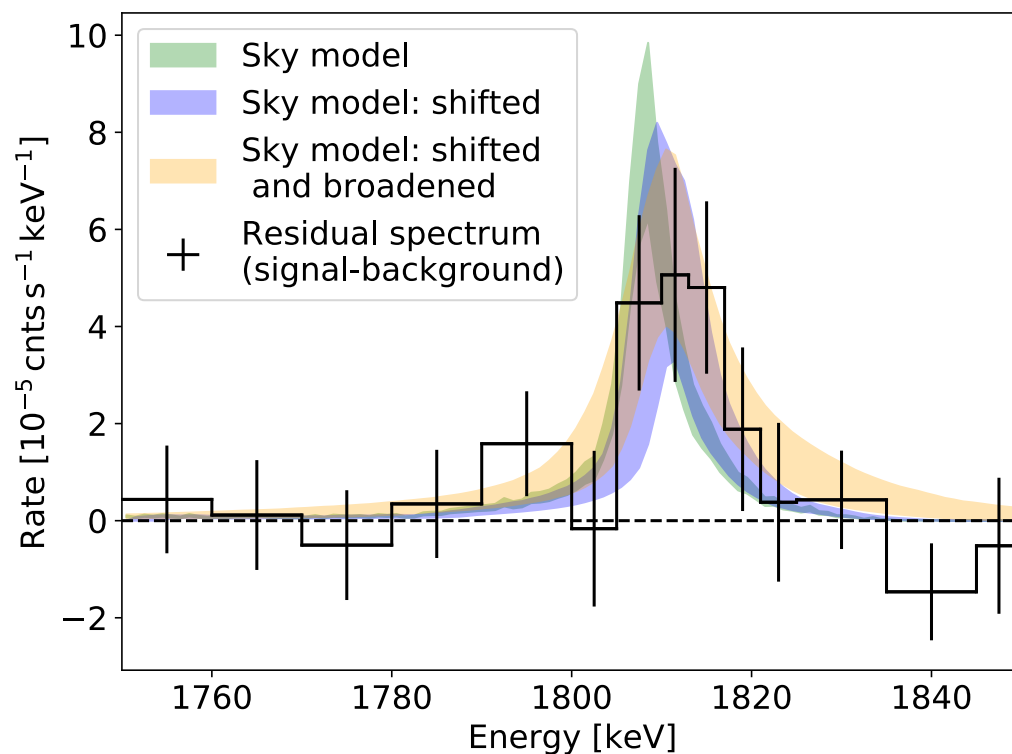


Measurement of Galactic Al-26 in the COSI 2016 Flight



Beechert (2021) ICRC 2021 proceedings: <https://arxiv.org/abs/2109.10365>

Beechert et al. (2021), submitted to ApJ



Likelihood ratio test: 3.7σ significance over background

Inner Galaxy flux: $(8.6 \pm 2.5) \times 10^{-4} \text{ ph cm}^{-2} \text{ s}^{-1}$

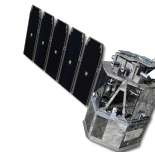
Rate: $6.8 \times 10^{-4} \text{ cnts s}^{-1} \cdot 156 \text{ ks} \rightarrow \sim 106 \text{ Al-26 photons}$

$\Delta E = 2.5 \pm 1.8 \text{ keV} \rightarrow E_{sky} = 1811.2 \pm 1.8 \text{ keV}$

Intrinsic sky broadening: $< 9.7 \text{ keV } (2\sigma)$

Turbulent velocity of Al-26 ejecta: $< 2800 \text{ km s}^{-1} (2\sigma)$

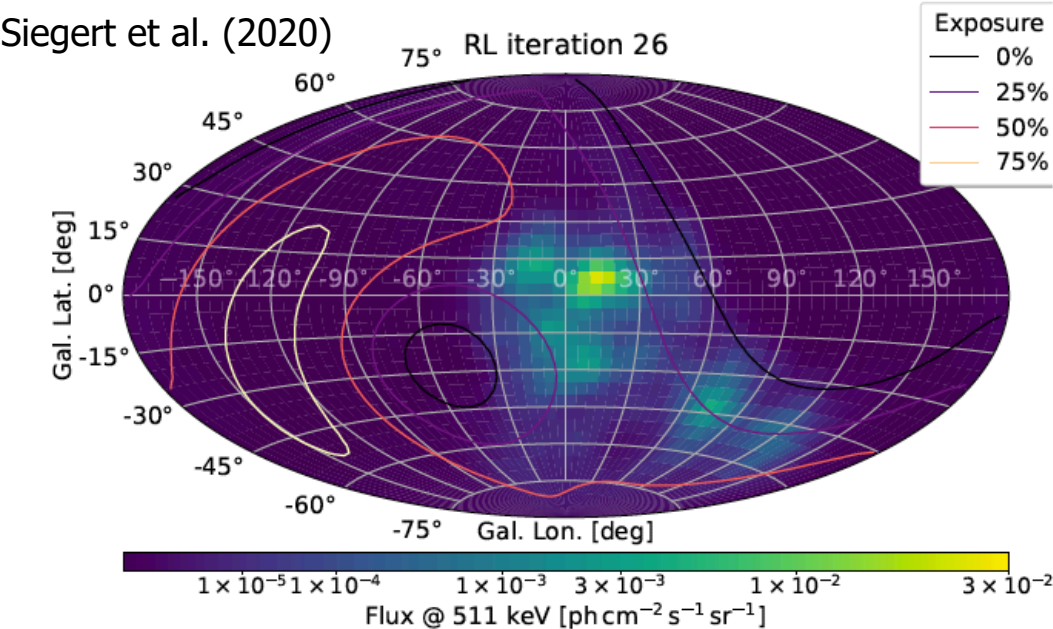
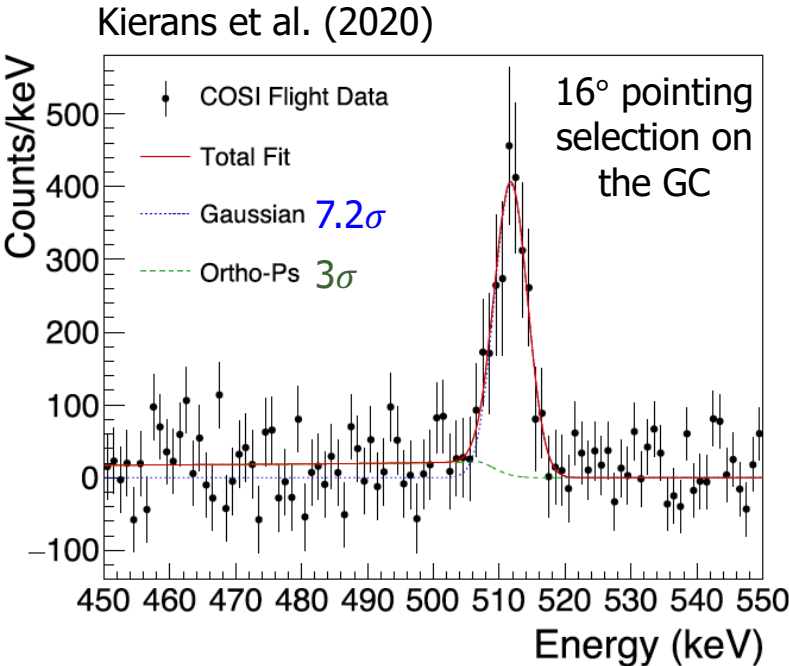
Measurement of Galactic Al-26 in the COSI 2016 Flight



	Significance [σ]	Line energy [keV]	Inner Galaxy flux [10^{-4} ph cm $^{-2}$ s $^{-1}$]
COSI 2016	3.7	1811.2 ± 1.8	8.6 ± 2.5
SPI	58 (Pleintinger 2020)	1809.83 ± 0.04 (Pleintinger 2020)	2.9 ± 0.1 (Siegert 2017)
COMPTEL	>20 (Knödseder 1996)	---	3.3

- All line values consistent within 2σ
- Systematics:
 - ~50% uncertainty in effective area
 - High-latitude ~10-30% of total signal
 - Weak massive star groups in BG region
- Work to image the emission is underway (response is now ready)

Detection of Galactic 511 keV in the COSI 2016 flight



The Bulge	Centroid [keV]	FWHM celestial line [keV]	Line flux [$10^{-3} \text{ ph cm}^{-2} \text{ s}^{-1}$]	f_{Ps}	Radial distribution [°]
COSI 2016	511.8 ± 0.3	4.0 ± 0.9	1.90 ± 0.45^a	0.76 ± 0.12^a	$28^{+19}_-12^a$
SPI ^b	511.09 ± 0.08	2.59 ± 0.17	0.96 ± 0.07	1.08 ± 0.03	15^c

^a Siegert et al. (2020)

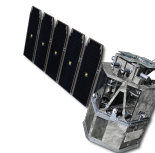
^b Siegert et al. (2016)

^c Skinner et al. (2014) and Siegert et al. (2016) model (3 components, maximally 20°)

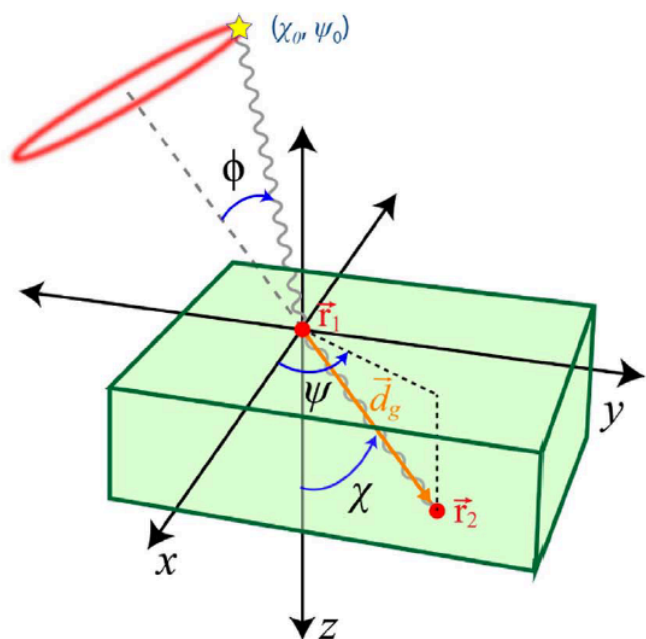
Detection of Galactic 511 keV in the COSI 2016 Flight

Kierans et al. (2020)

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- First detection of annihilation signature with a Compton telescope
- Extract signal and background estimation within the Compton Data Space (CDS)



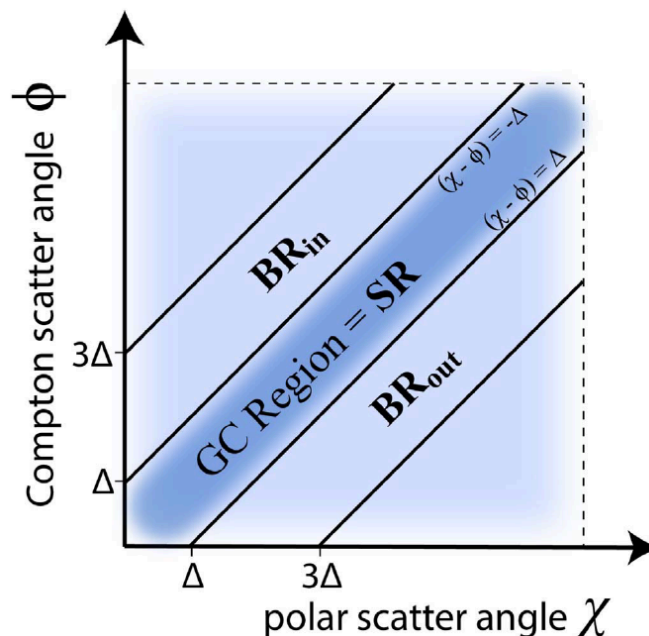
CDS coordinates:

Polar scatter angle χ

Azimuthal scatter angle ψ

Compton scatter angle ϕ

(Energy is fourth dimension)



GC is on-axis $\rightarrow \phi = \chi$

$\Delta = 16^\circ \rightarrow$ highest S/N

Use BR_{out} for BG estimation (smaller ϕ
 $\rightarrow$ more accurate event reconstruction)

Spectrum estimation

For each 1° bin i in ϕ :

χ is energy independent $\rightarrow$ scale BG by adjacent energy band

$$B^{SR}(\phi_i, E) = \frac{N^{SR}(\phi_i, E | 520 < E < 720)}{N^{BR}(\phi_i, E | 520 < E < 720)} N^{BR}(\phi_i, E)$$

Then, the source spectrum is

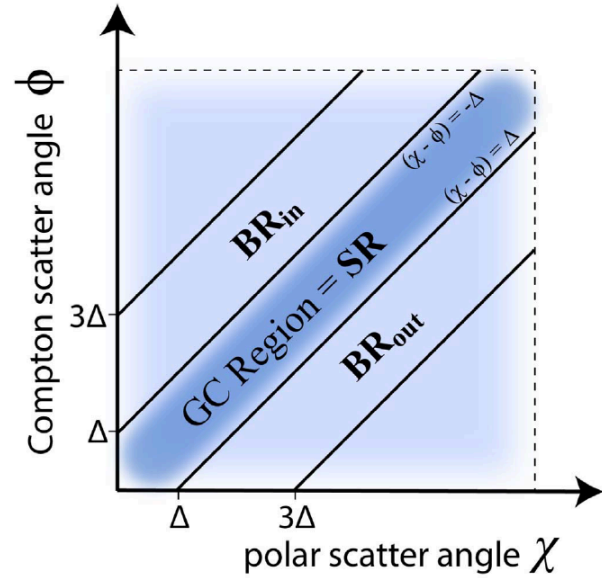
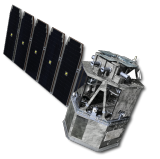
$$S(E) = \sum_i [N^{SR}(\phi_i, E) - B^{SR}(\phi_i, E)]$$

Detection of Galactic 511 keV in the COSI 2016 Flight

Kierans et al. (2020)

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Radial distribution: histogram of $\chi - \phi$

Energy dependence in $\phi \rightarrow$ find distributions in signal (506-516 keV) and background (520-720 keV) energy bands

Radial distribution estimation

For each 1° bin i in ϕ :

Source measurement (506-516 keV):

$$N^{511}(\phi_i, \chi - \phi) \text{ for each } \phi \text{ in bin } i$$

High energy measurement (520-720 keV):

$$N^{HE}(\phi_i, \chi - \phi)$$

Normalize $N^{HE}(\phi_i, \chi - \phi)$ s.t.

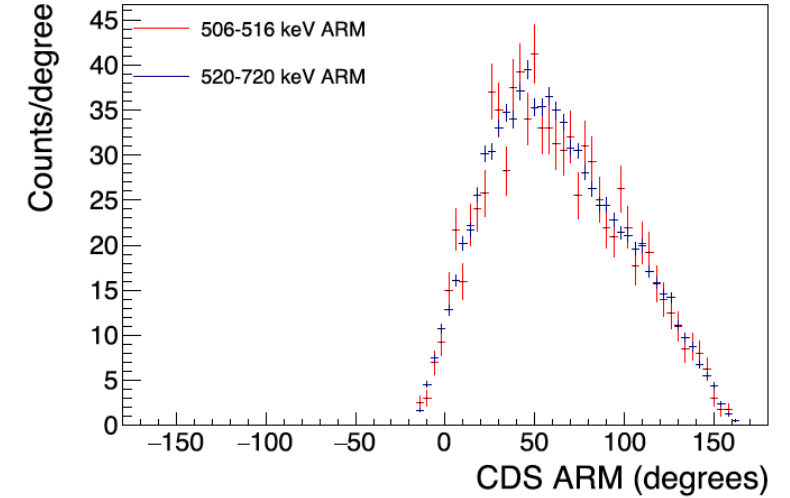
$$B^{511}(\phi_i, \chi - \phi) = A_{\phi_i} N^{HE}(\phi_i, \chi - \phi)$$

$$A_{\phi_i} = \frac{B^{SR}(\phi_i, E|506 < E < 516)}{B^{SR}(\phi_i, E|520 < E < 720)}, \text{ where}$$

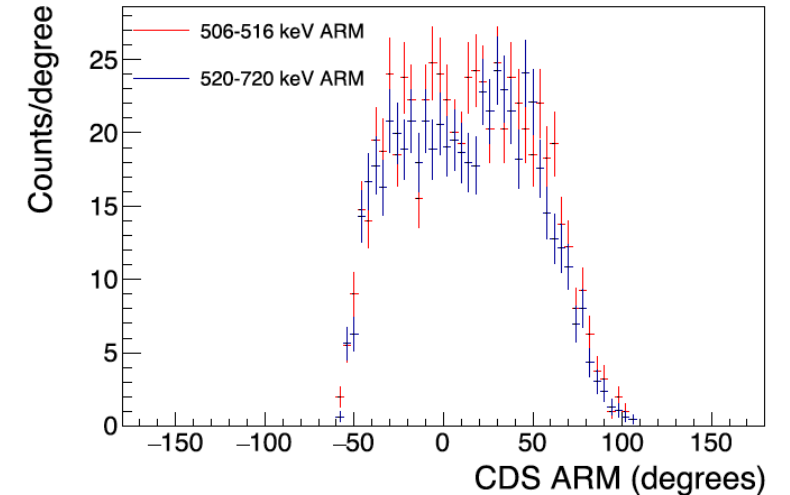
$$B^{SR}(\phi_i, E) = \frac{N^{SR}(\phi_i, E|520 < E < 720)}{N^{BR}(\phi_i, E|520 < E < 720)} N^{BR}(\phi_i, E)$$

Then, the radial distribution of the source is

$$S(\chi - \phi) = \sum_i [N^{511}(\phi_i, \chi - \phi) - B^{511}(\phi_i, \chi - \phi)]$$



(a) CDS-ARM for $\phi = [16^\circ, 17^\circ]$.



(b) CDS-ARM for $\phi = [59^\circ, 60^\circ]$.