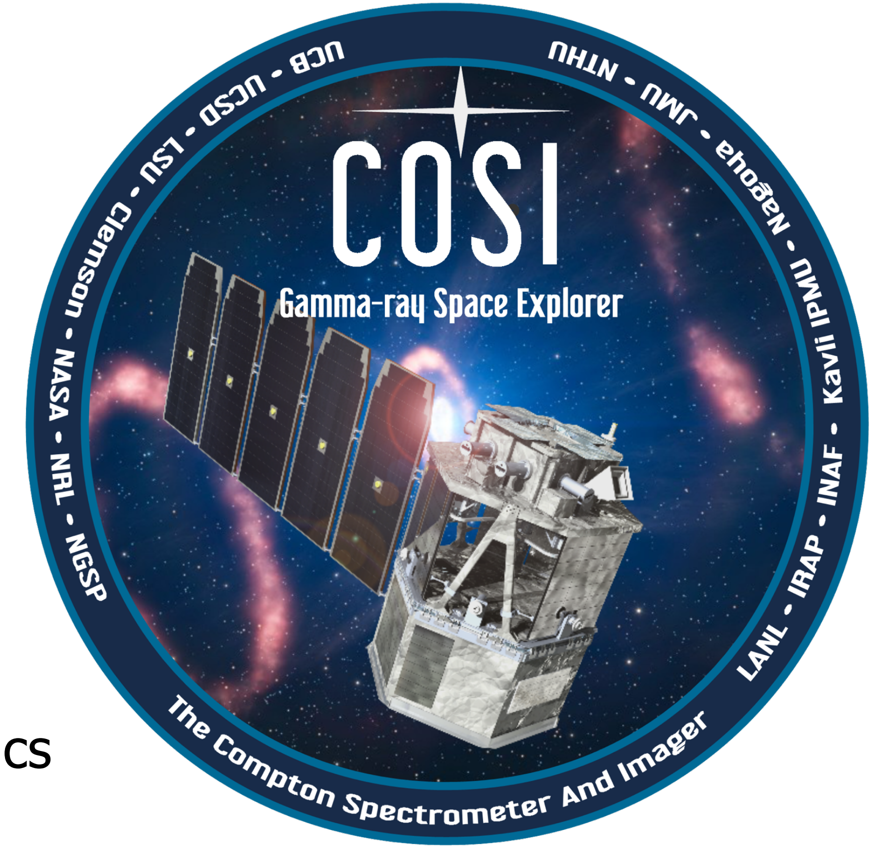
Gamma-ray astronomy with the Compton Spectrometer and Imager



Jacqueline Beechert (COSI PhD Candidate)
UC Berkeley/Space Sciences Laboratory
14th Conference on the Intersections of Particle and Nuclear Physics
August 30, 2022

Particle and Nuclear Astrophysics

- ☐ Positrons
  - 511 keV annihilation signature in the Milky Way

- ☐ Nuclear emission lines from stellar/explosive nucleosynthesis
  - ^{26}Al
  - ^{60}Fe
  - ^{44}Ti

- ☐ Multimessenger events
  - Neutron star mergers
  - High energy neutrinos
  - Nearby supernovae

Today, we’ll focus on the
MeV energy range

COSI: 0.2-5 MeV

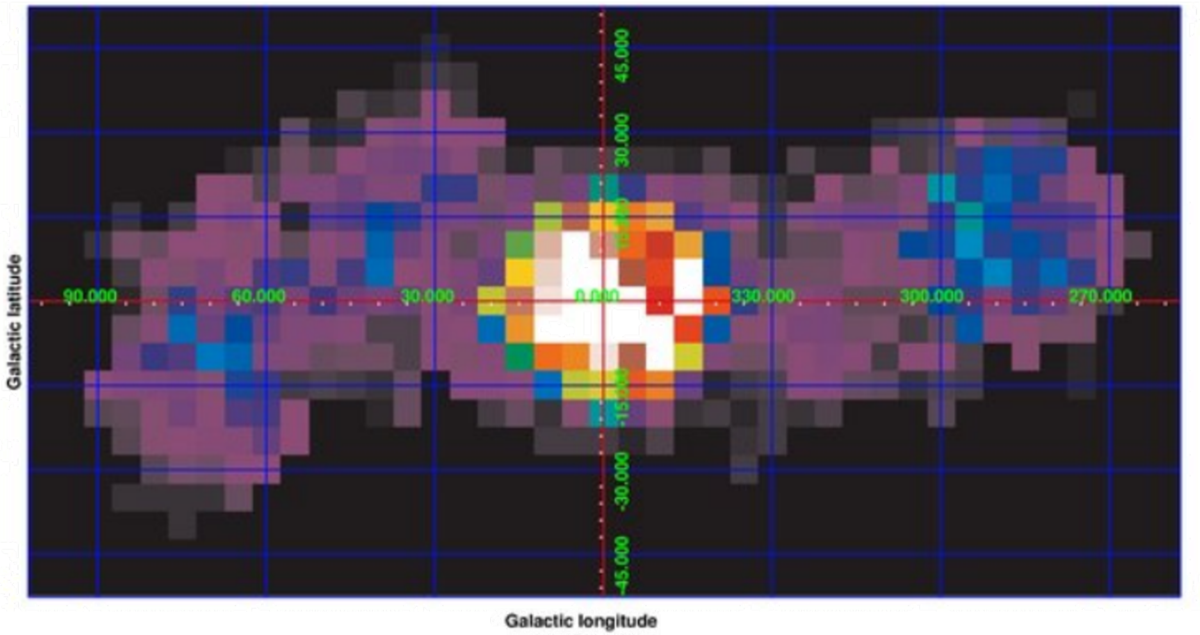
The Milky Way’s “Positron Puzzle”

❑ Strong 511 keV signature at the center of the Milky Way (10^{-3} ph cm^{-2} s^{-1})

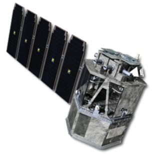
❑ Diffuse nature:
- Truly diffuse? Annihilation after propagation from production sites
- Effectively diffuse? Annihilation in situ from many point-like sources
- Bright central bulge vs. extended, fainter disk emission

→ Need imaging with fine angular resolution to constrain the spatial morphology of the emission.

511 keV with INTEGRAL SPI
Bouchet et al. 2010



The Milky Way’s “Positron Puzzle”

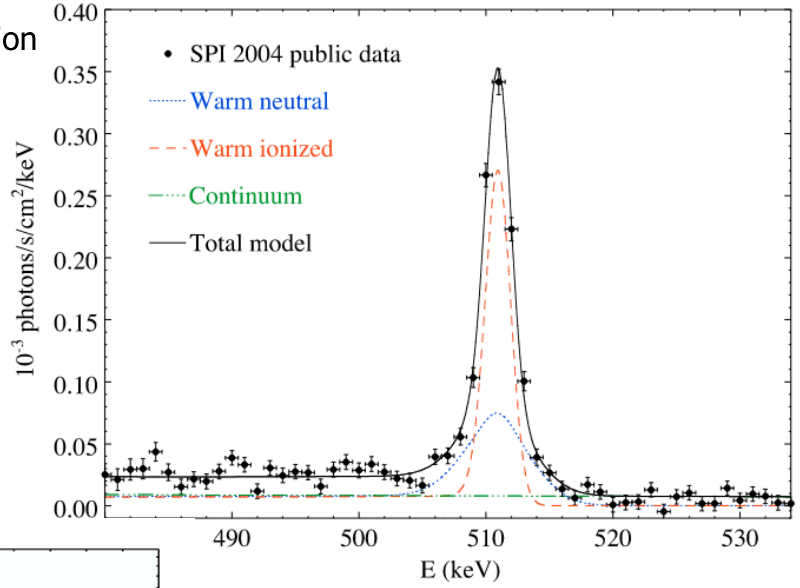


- Source of the positrons:
  - Disk emission: possibly explained by e⁺ from stellar and explosive nucleosynthesis products (β^+ decay; e.g. ^{26}Al, ^{44}Ti ~10^{42} e⁺ s^{-1})
  - Origin of the bulge positrons is unknown:
    - Bulge emission: 2 x 10^{43} e⁺ s^{-1}
    - Nucleosynthesis products account for ~10%
    - Other candidates: ^{56}Co, DM, LMXRB, GRBs, SgrA*, …

→ Need high-resolution spectroscopy to characterize the annihilation spectrum.

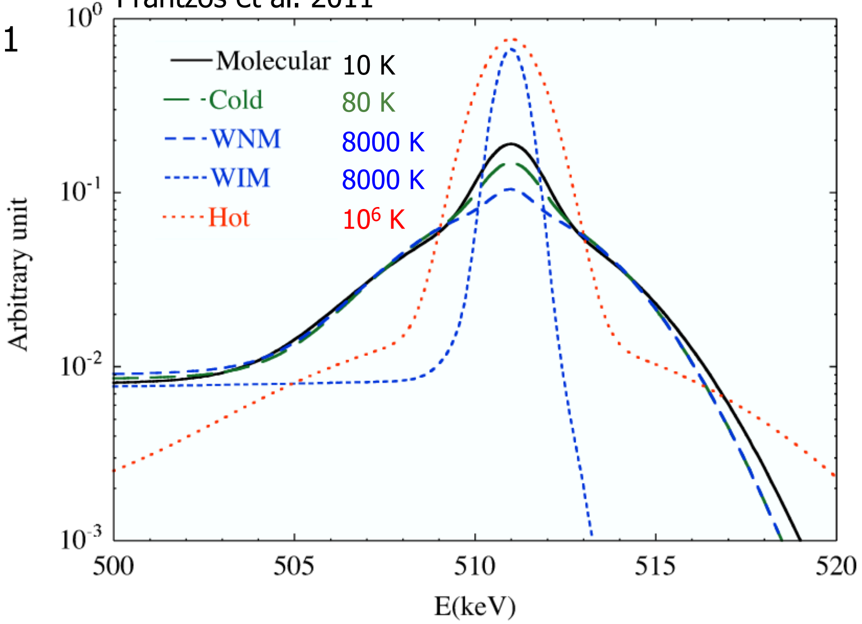
Fit of SPI data to annihilation models

Jean et al. 2006



Models of annihilation in the ISM

Prantzos et al. 2011



Annihilation line (2γ) vs. ortho-positronium (3γ) continuum?

$$f_{\mathrm{Ps}} = \frac{8I_{3\gamma}/I_{2\gamma}}{9 + 6I_{3\gamma}/I_{2\gamma}}$$

Nuclear emission lines

- ❑ Radioactive isotopes produced by stars emit MeV γ-rays upon decay

Trace SNe history

soon after SNe events →

integrated over ~10^2 years →

integrated over ~10^6 years →

Isotope	**Half-life**	**Energies [MeV]**
^{56}Co	77 days	0.847, 1.238
^{44}Ti	60 years	0.068, 0.078, 1.157
^{26}Al	0.7 Myr	1.809
^{60}Fe	2.6 Myr	1.173, 1.333

Nuclear emission lines

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Trace star formation history

integrated over ~10^6 years → ^{26}Al

integrated over ~10^6 years → ^{60}Fe

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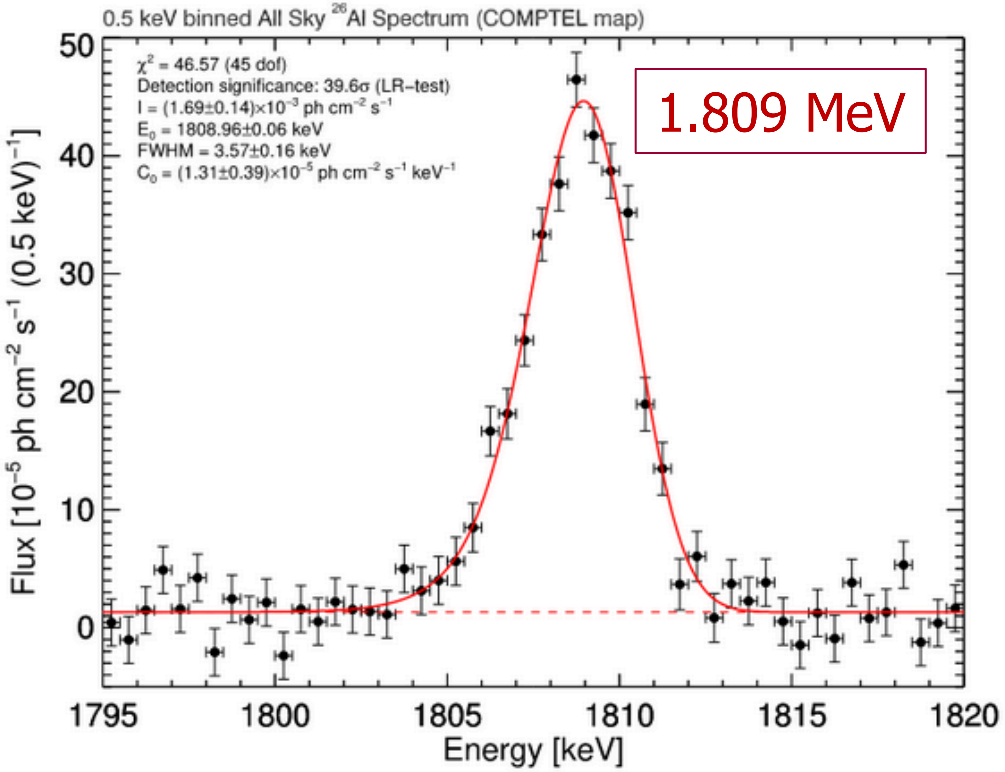
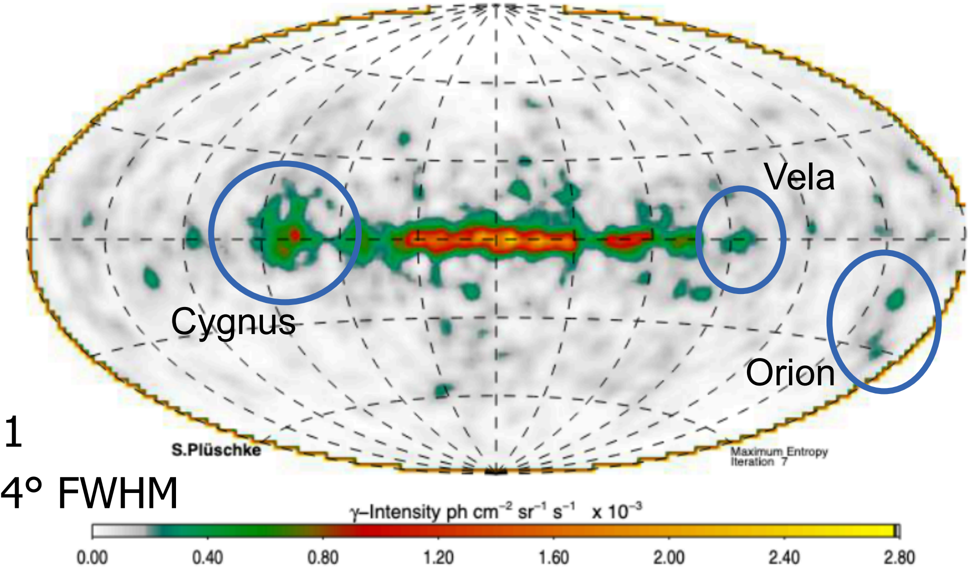
Nucleosynthesis and ^{26}Al

- ❑ ^{26}Al is produced in massive stellar processes
  - Released into the interstellar medium (ISM) in winds from massive stars and supernova explosions



SPI, Siegert 2017

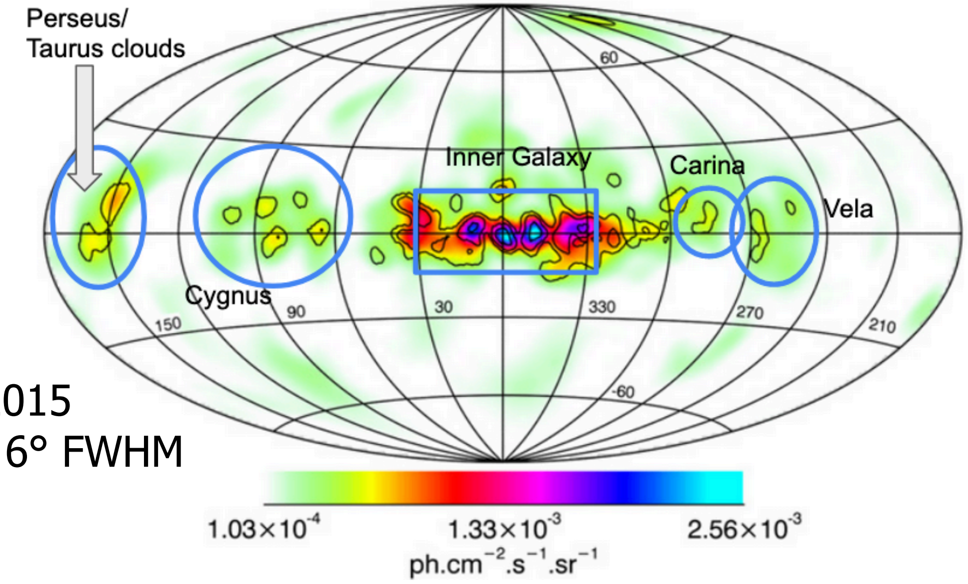
Energy resolution ~ 3 keV



COMPTEL

Plüschke 2001

Angular resolution ~ 4° FWHM



SPI

Bouchet et al. 2015

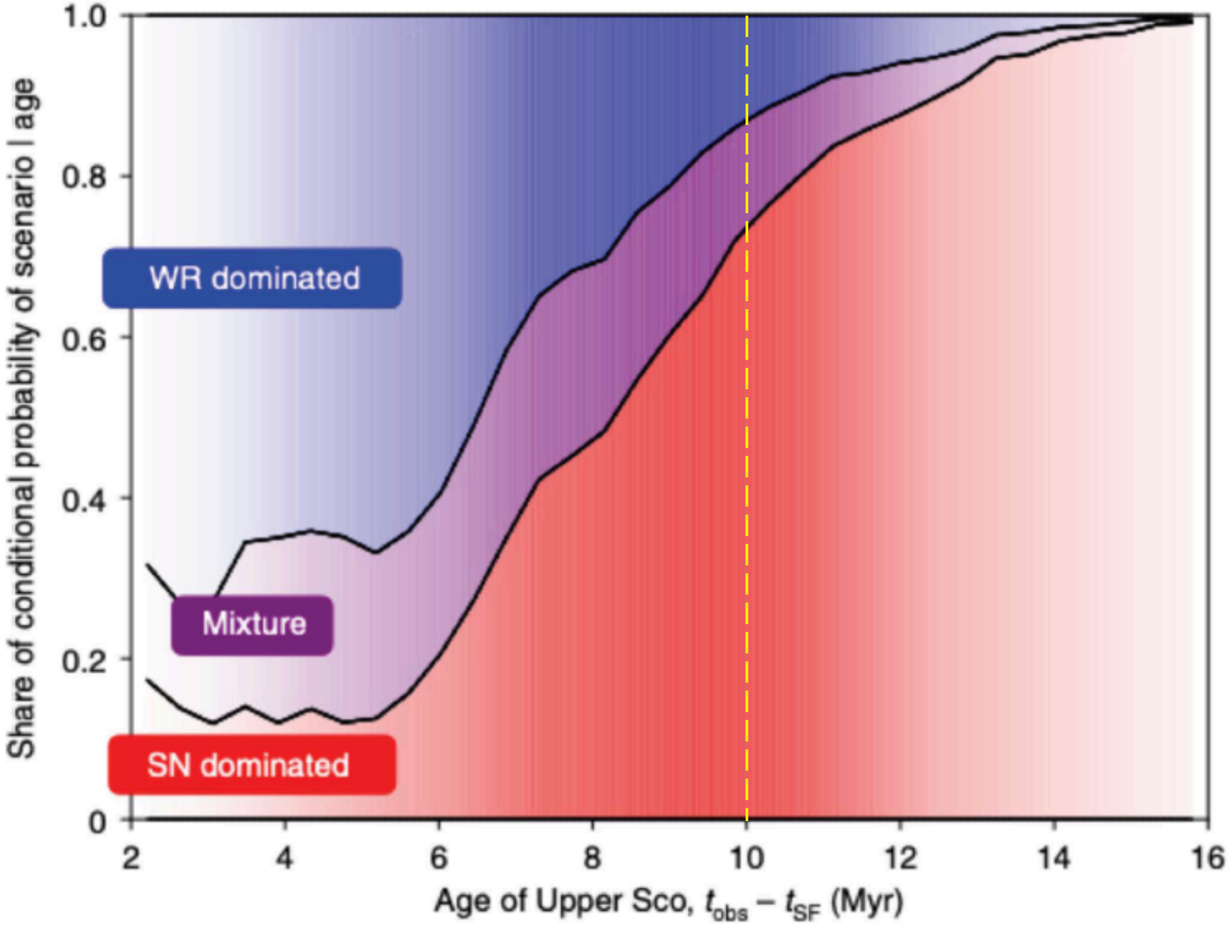
Angular resolution ~ 6° FWHM

Nucleosynthesis and ^{26}Al

- ☐ Wolf-Rayet star vs. CCSNe contribution? Contribution from novae?
- ☐ Help constrain stellar evolution models and models of explosive nucleosynthesis in SNe (metallicity, rotation, etc.)
  - e.g. Solar metallicity rotating and non-rotating (Brinkman 2019, 2021)

HEAO-3: ^{26}Al/^{27}Al ~ 10^{-5} → Likely origin from novae (Mahoney et al. 1984)

COMPTEL: strong correlation of ^{26}Al with ionizing stars → excludes novae; only CCSNe and W-R stars coexist with the ionizing population of the Galaxy (Knödlseder 1999)



Forbes et al. 2021: SNe-dominated case is the most probable, but WR-dominated is still possible

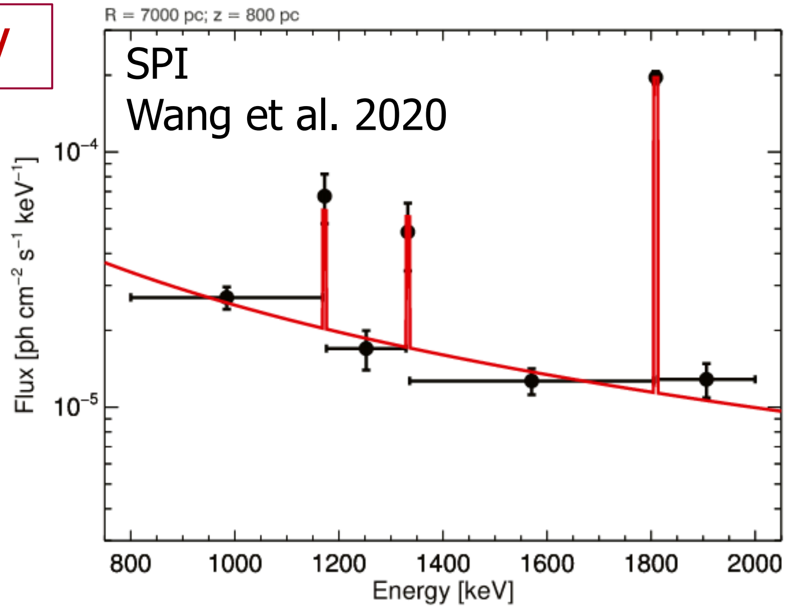
Nucleosynthesis and ^{60}Fe

COSI
A Gamma-ray
Space Explorer

- ☐ ^{60}Fe is thought to be released *only* in CCSNe explosions
  - Produced deeper in the stellar interior with slow neutron capture (s-process)
    → Not released into ISM in winds from massive stars, as with ^{26}Al
  - Study C/He shell burning. Uncertainties in neutron capture rates → uncertainties in estimations of ^{60}Fe yields from explosions
- ☐ Ratio of ^{60}Fe/^{26}Al: determine the evolutionary stages of different regions of the Galaxy

1.173, 1.332 MeV

- ☐ INTEGRAL SPI:
  - Difficult to detect ^{60}Fe (instrumental BG lines: ^{60}Co)
  - Longer lifetime than ^{26}Al → more diffuse emission. No map of ^{60}Fe emission to date.
  - ^{60}Fe/^{26}Al ~ 0.2 – 0.4 (Galaxy-wide average)



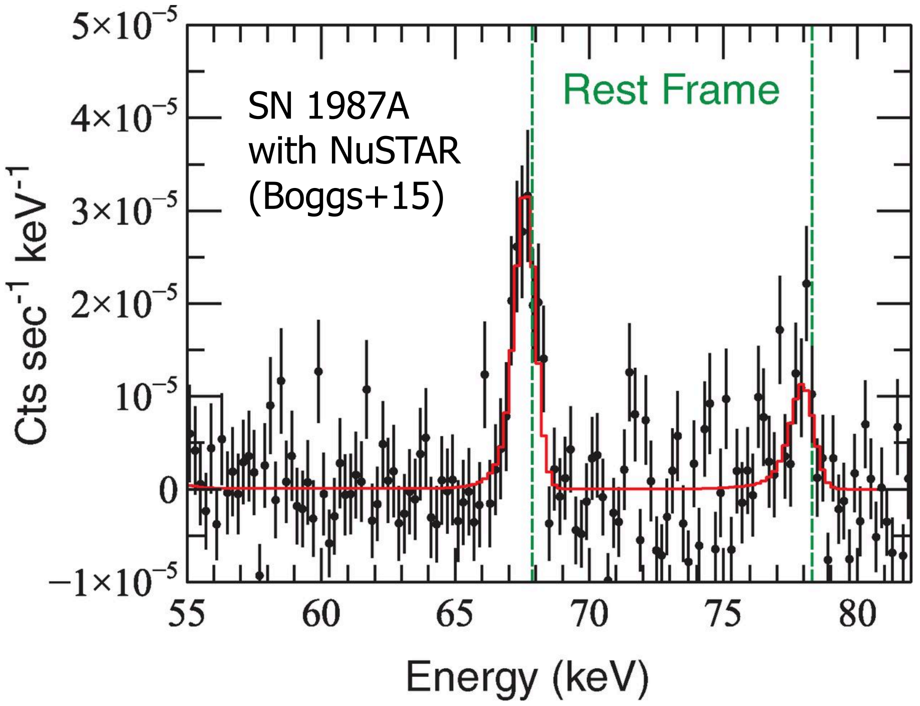
Nucleosynthesis and ^{44}Ti

- ❑ ^{44}Ti traces young supernova remnants
  - ^{44}Ti→^{44}Sc: 68, 78 keV
  - ^{44}Sc→^{44}Ca: 1.157 MeV

  Probes the innermost ejecta → study the properties of the explosion itself

- ❑ NuSTAR observations (68, 78 keV):
  - Cassiopeia A: bulk motion ~1100-3000 km s^{-1} (Grefenstette et al. 2014)
  - SN 1987A: bulk motion ~700 km s^{-1} (Boggs et al. 2015)

- ❑ Evidence for asymmetric explosions, but we only have these two sources



Doppler shift: probe bulk motion

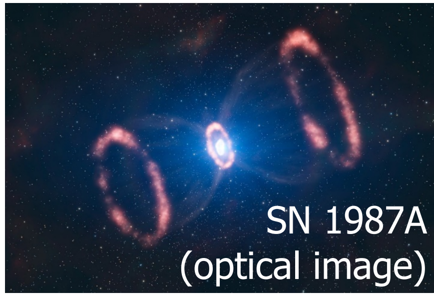
Doppler broadening: probe temperature, expansion velocity, opacity effects

Both: probe asymmetries

Multimessenger events

- ☐ Neutron star mergers:
  - GW signature (GW170817; Abbott et al. 2017)
  - Associated **short GRB** (GRB170817A; Goldstein et al. 2017)
  - Source of **positrons** and heavy **elements** (e.g. ^{126}Sn, 666.3 keV)

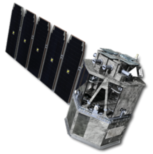

Neutron star merger


SN 1987A
(optical image)

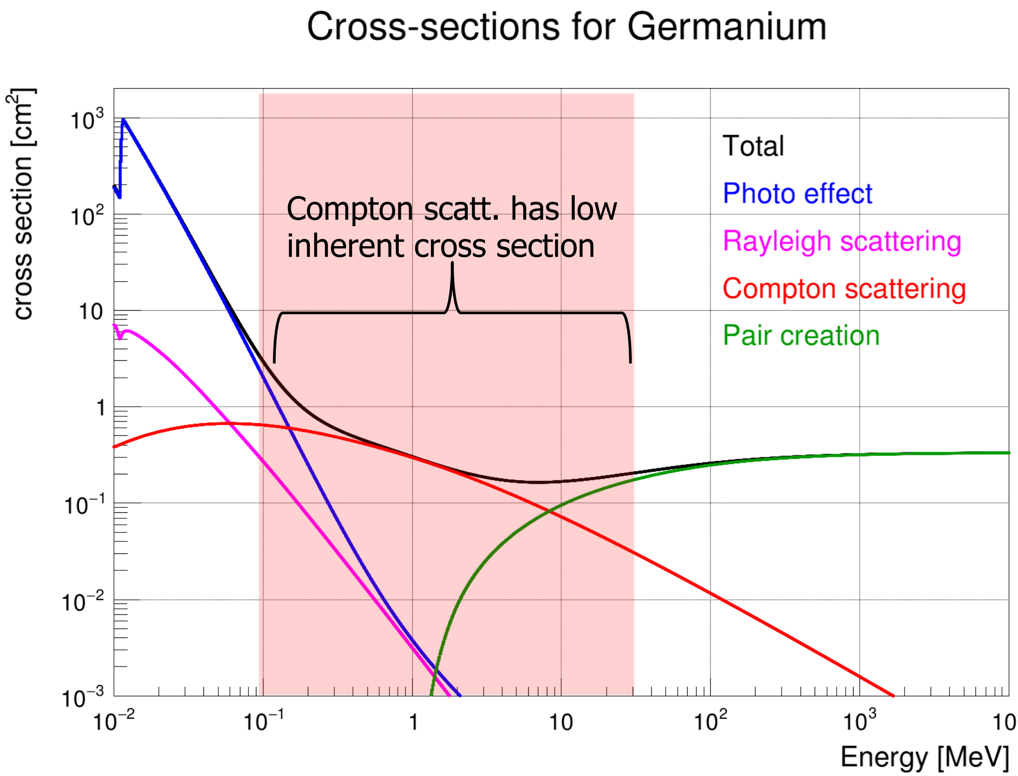
- ☐ High-energy neutrinos
  - Fermi LAT γ-ray activity (Aartsen et al. 2018) coincident with high energy neutrino (IceCube-170922A, ~290 TeV; IceCube Collaboration et al. 2018)
  - Neutrino likely associated with blazar TXS 0506+056
  - Enhanced **γ-ray emission** from TXS 0506+056 weeks **after the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

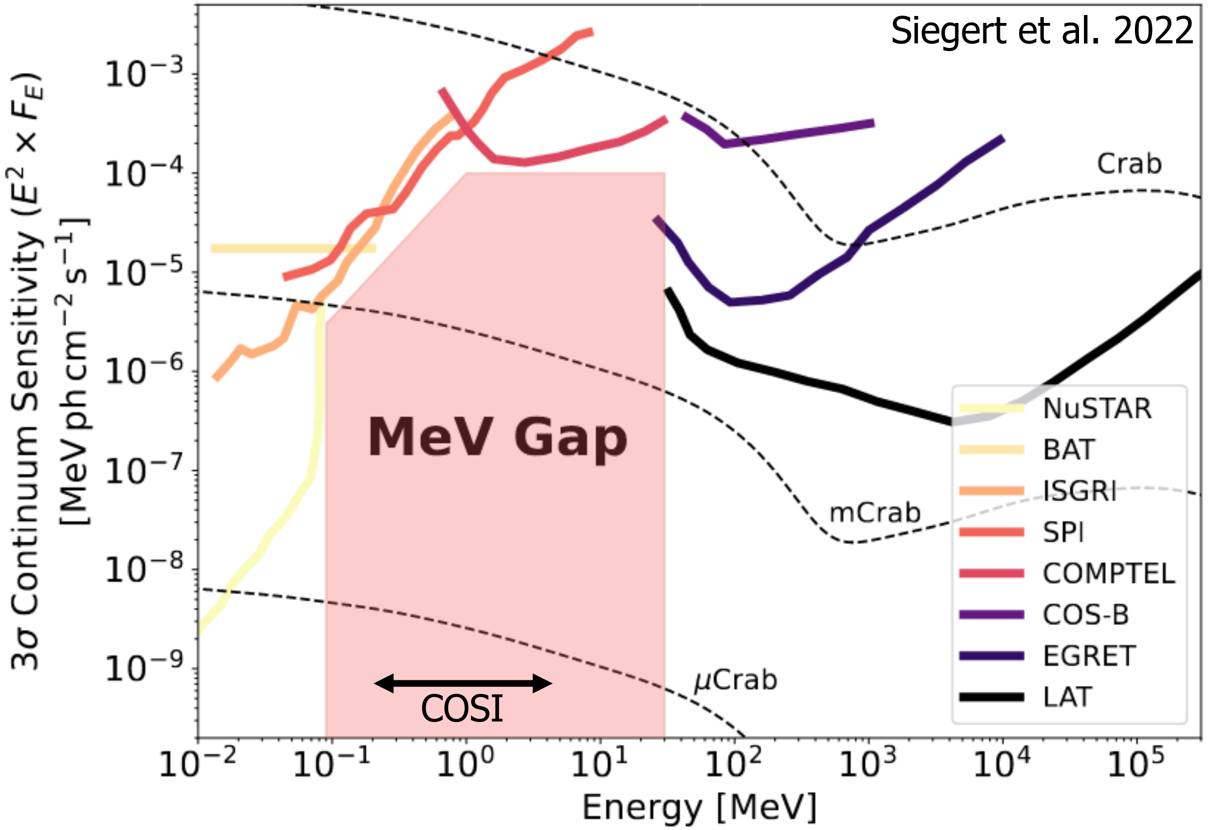
- ☐ Nearby SNe
  - e.g. SN 1987A, the first multimessenger transient (Type II, LMC, ~51 kpc). ~Two dozen neutrinos.
  - Understand just before/after core collapse with neutrino and GW emission (Kalogera et al. 2019)
  - Study **γ-ray lines** from radioactive isotopes (Palmer et al. 1993, Tueller et al. 1990)

The MeV gap (~0.1-30 MeV)



- ☐ Historically poorer sensitivity in the MeV range because of low interaction cross-sections, high instrumental background, and instrumental constraints





→ Important to explore this space: it's an historical gap in instrument sensitivity, not scientific potential!

How do we fill the MeV gap?

How do we fill the MeV gap?

We need an instrument which has:

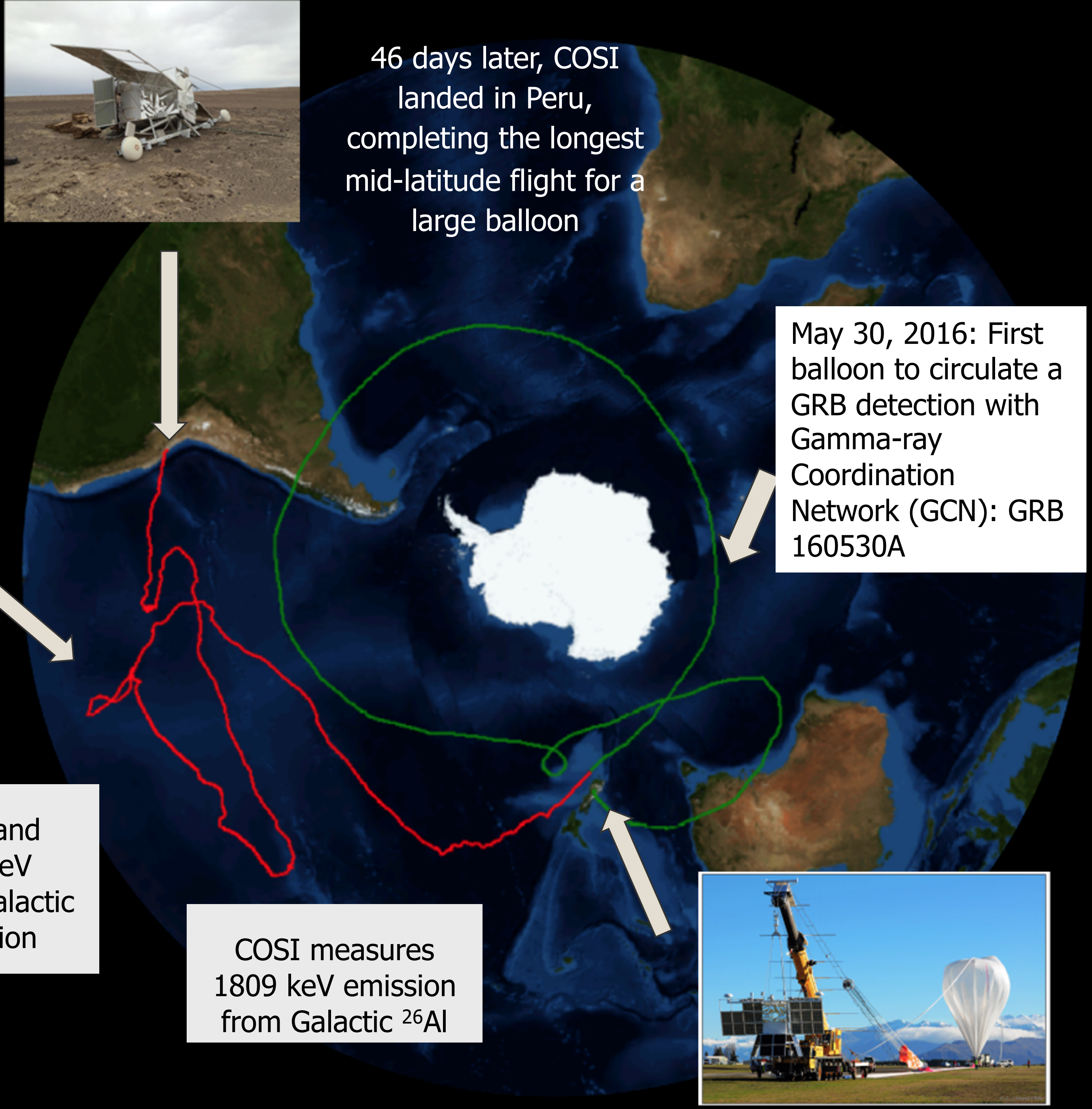
- ☐ Excellent energy resolution across the MeV bandpass:
  - Study annihilation and nuclear lines with high resolution → examine line widths and shapes
- ☐ Wide field of view
  - Map nuclear line emission throughout the Galaxy
  - Detect transients (e.g. GRBs) across the sky

COSI-balloon overview

Balloon-borne MeV γ-ray telescope

- ❑ Energy range: 0.2 - 5 MeV
- ❑ Energy resolution: ~0.7% FWHM at 511 keV, ~0.2% FWHM at 1809 keV
- ❑ Angular resolution: ~6° at 511 keV, ~4° at 1809 keV
- ❑ Instantaneous FOV: 25% of the sky

COSI 2016 balloon flight: Launch from Wanaka, NZ



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 ^{26}Al

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

Slide adapted from Alex Lowell

COSI 2016 balloon flight: Lau Wa

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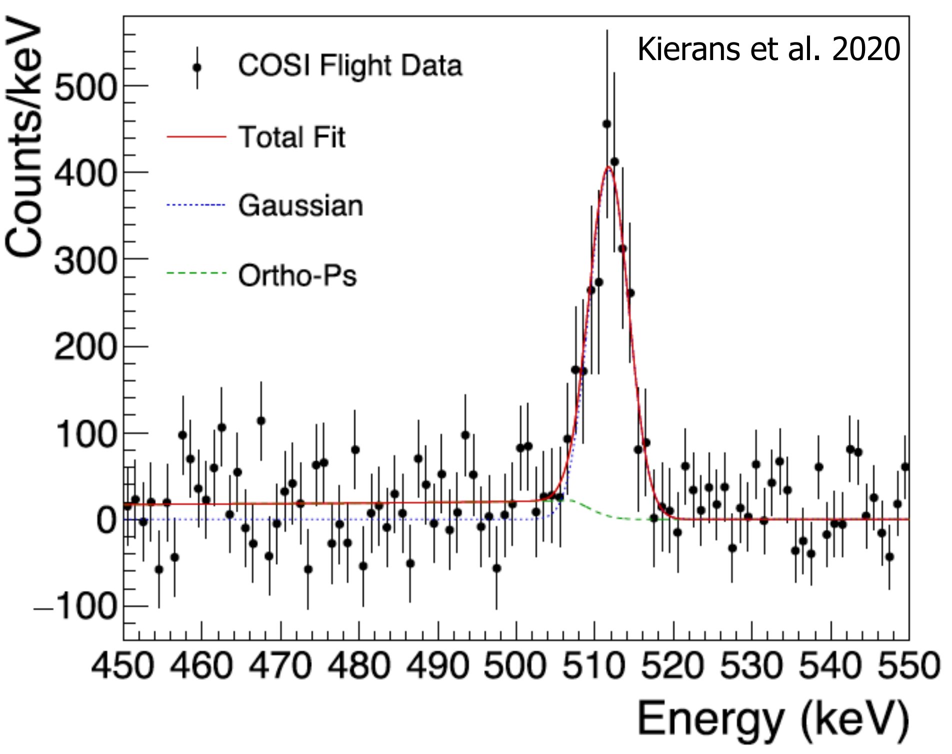
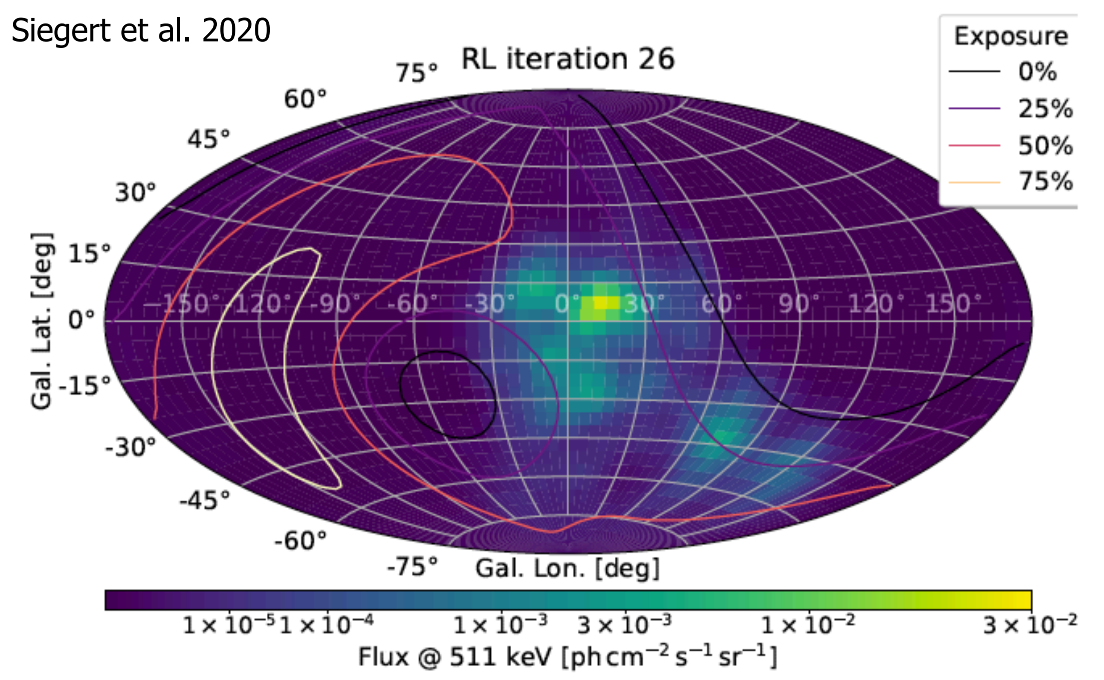
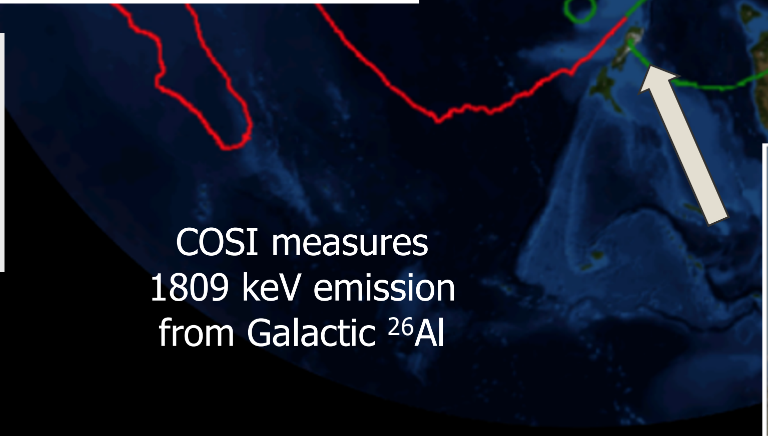




COSI detects and images 511-keV emission from Galactic e^+-e^- annihilation



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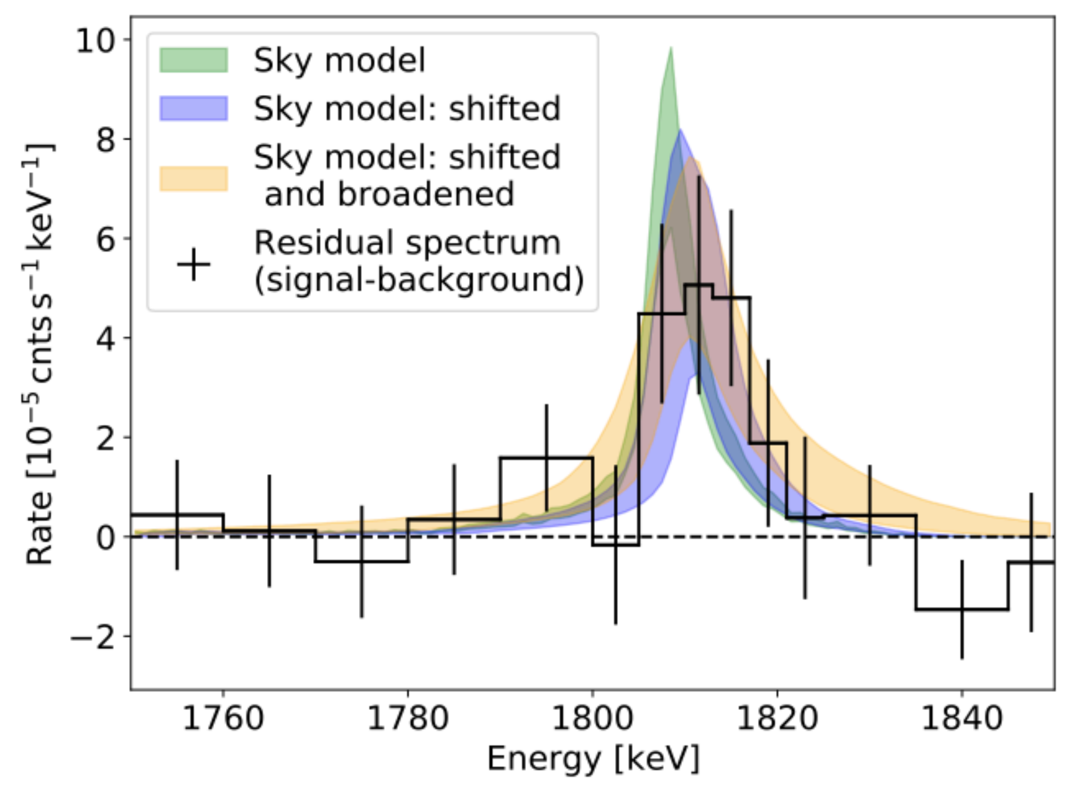

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images
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Slide adapted from Alex Lowell

What about ^{60}Fe, ^{44}Ti, and multimessenger events?

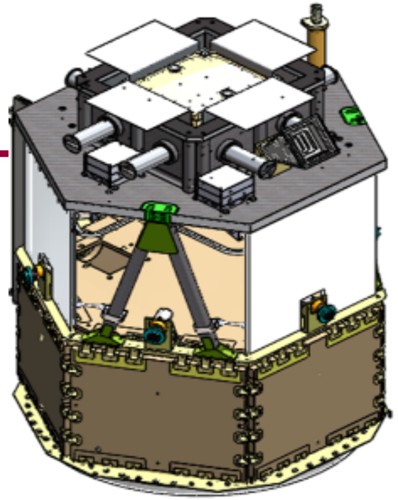
COSI: A Gamma-ray Space Explorer

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



Rendering of the satellite instrument

COSI-balloon

COSI

(Small Explorer satellite, launch ~ 2026)

University of California

- John Tomsick (Principal Investigator, UCB)
- Bryce Unruh (Project Manager, UCB)
- Steven Boggs (Deputy PI, UCSD)
- Andreas Zoglauer (Project Scientist, UCB)
- J. Roberts, J. Martinez Oliveros (Student Collaboration Lead), P. Saint-Hilaire (SEO Lead)

Naval Research Laboratory: E. Wulf, C. Sleator, B. Phlips

Goddard Space Flight Center: A. Shih, C. Kierans, A. Smale

Northrop Grumman

Institutions of Co-Is and Collaborators:

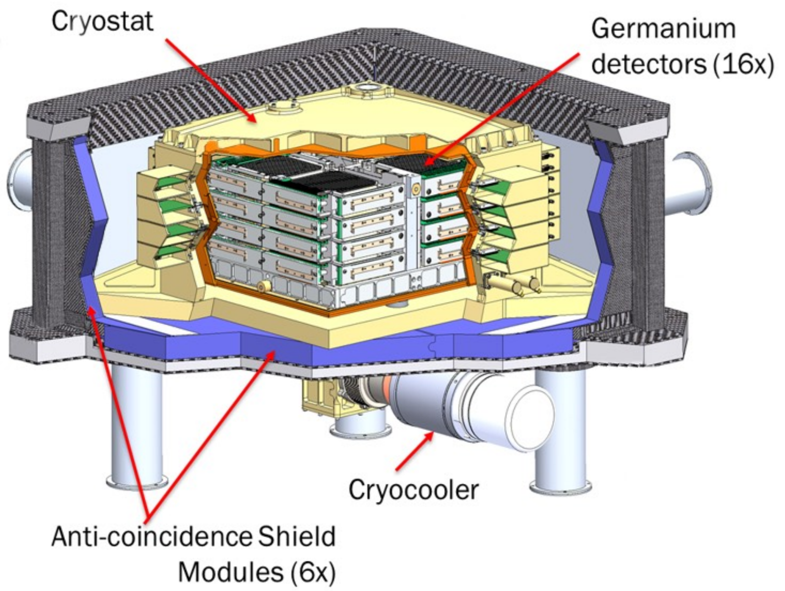
Clemson University, Los Alamos National Laboratory, Louisiana State University, IRAP (France), INAF (Italy), Kavli IPMU and Nagoya University (Japan), JMU (Germany), NTHU (Taiwan)

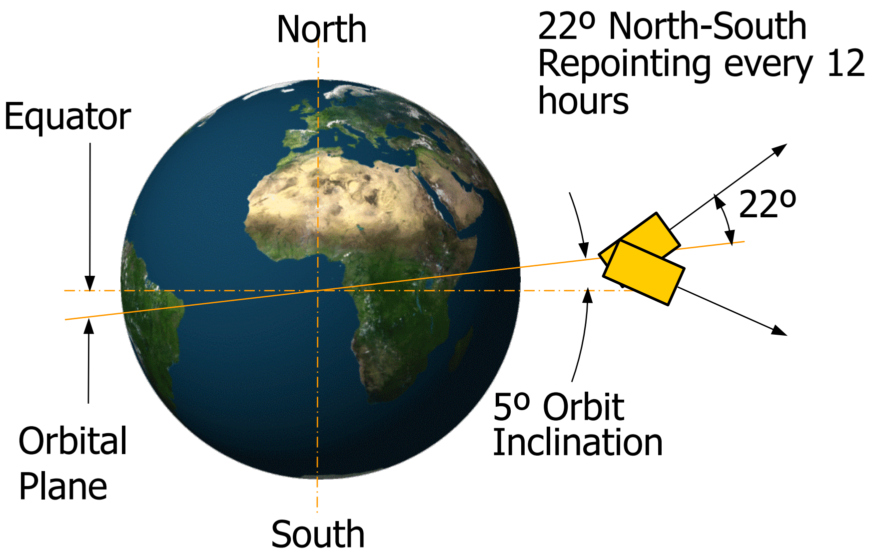
COSI: A Gamma-ray Space Explorer

Improvements:

- ☐ Low-Earth orbit → no atmospheric background
- ☐ 2-year prime mission → huge increase in observation time
- ☐ Survey the entire sky every 24 hours → more sensitive to emission across the Galaxy and to transients (GRBs, NSM, etc.)
- ☐ 16 GeDs (12 in COSI-balloon) → greater effective area
- ☐ 2x finer strip pitch → finer angular resolution

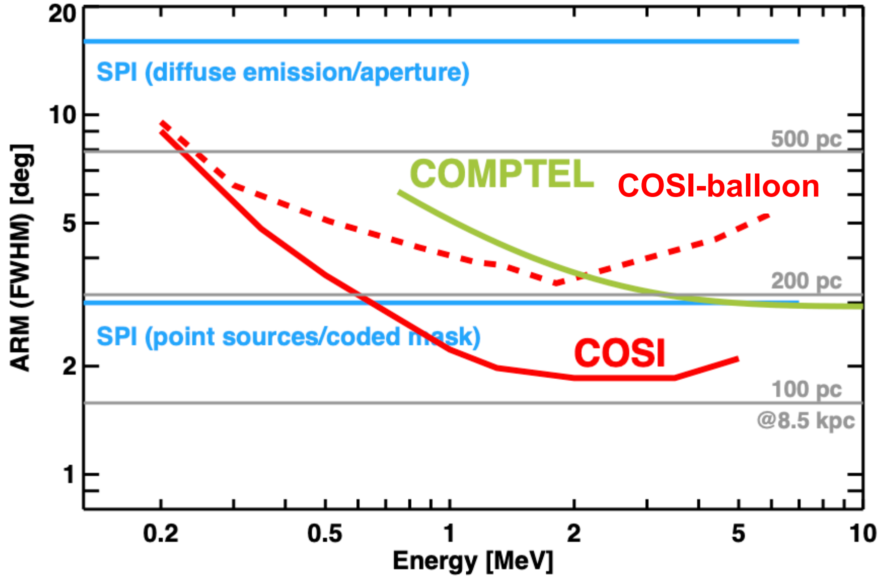
Will reach the COSI-balloon flight's 511 keV sensitivity in 1 day with excellent energy resolution and wider FOV than previous satellite missions

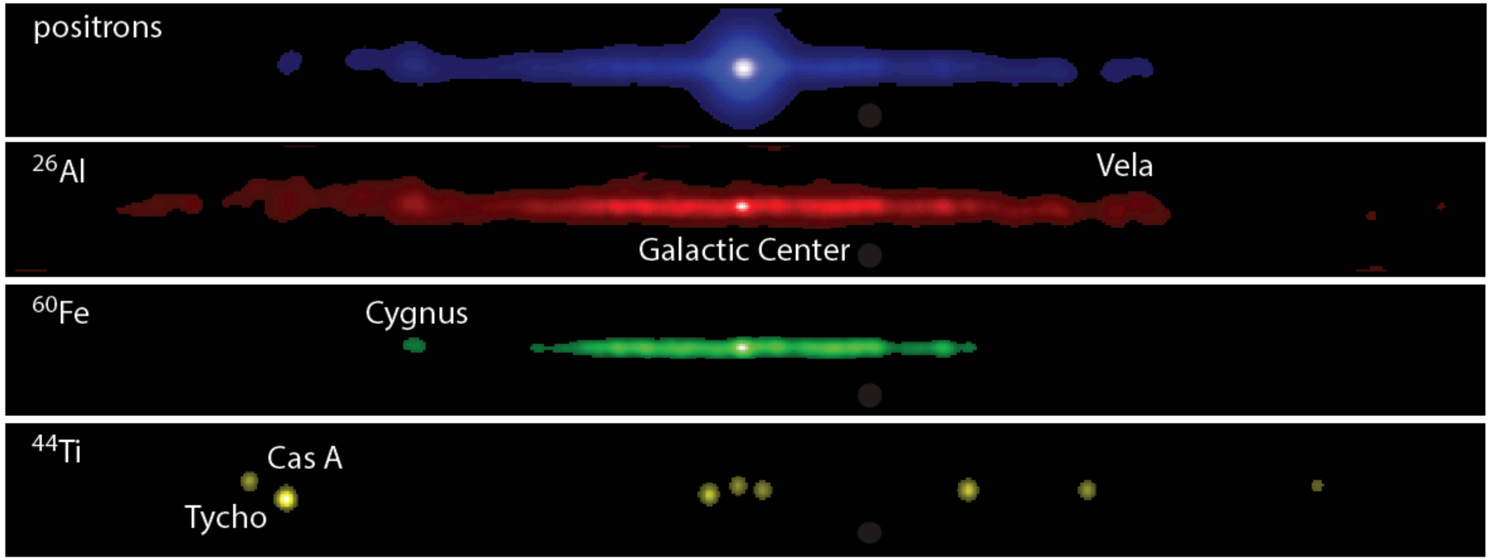


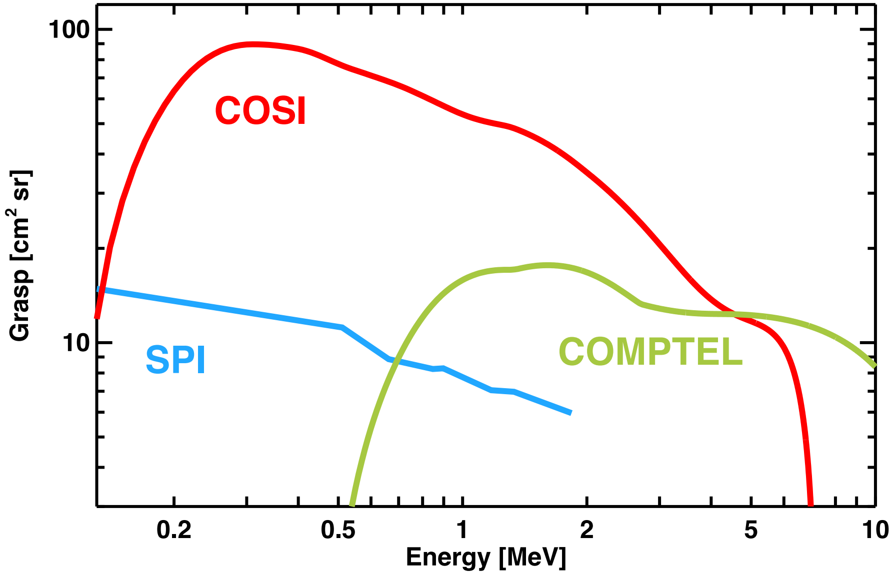


COSI: Expected contributions

- ☐ Probe true morphology of 511 keV emission in the Galactic bulge and disk
- ☐ Most precise map of ^{26}Al to date, including individual OB associations
- ☐ First map of ^{60}Fe
- ☐ First all-sky survey of ^{44}Ti

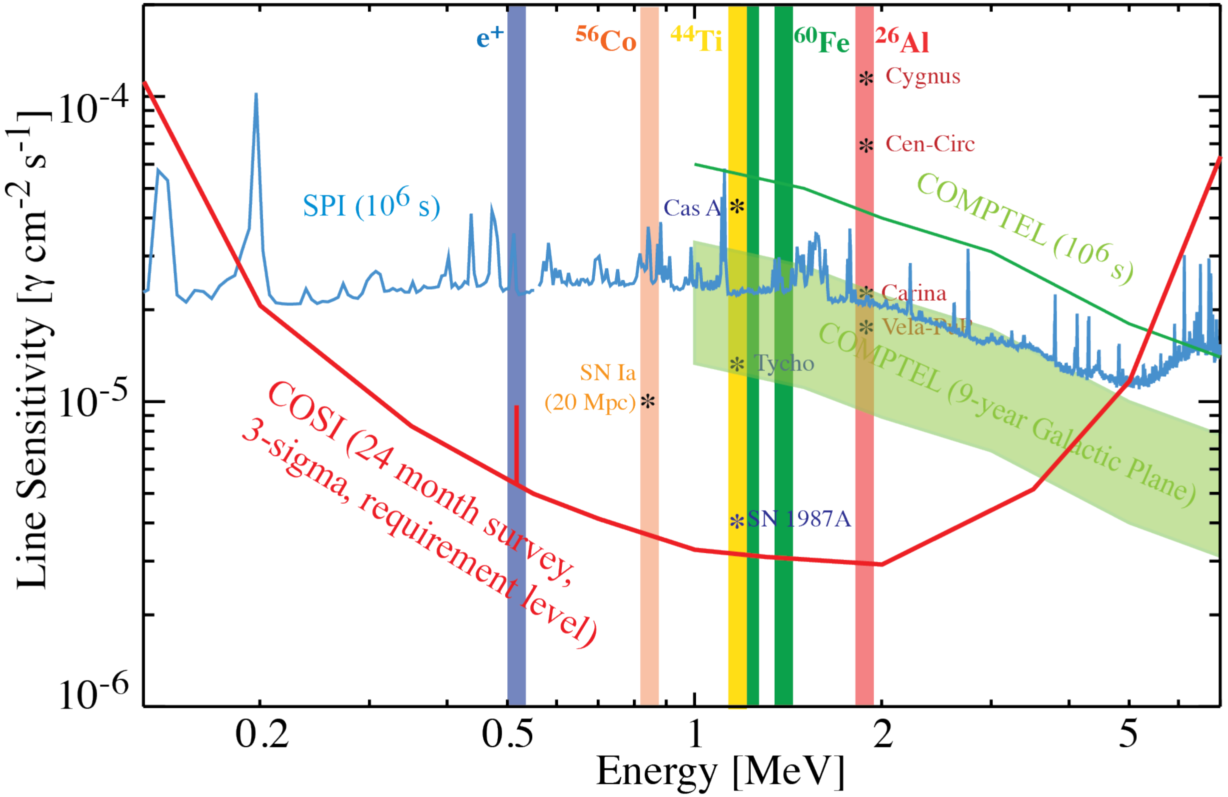






COSI: Expected contributions

- High-resolution spectroscopy of gamma-ray lines:
  - Positronium fraction in 511 keV emission
  - Dynamics of ^{26}Al ejecta → trace formation and incorporation, feedback into ISM
  - More stringent constraints on ^{60}Fe/^{26}Al flux ratio, search for variations across the Galaxy
  - Dynamics of ^{44}Ti → asymmetries in SN ejecta



COSI: Potential contributions

☐ Gamma-ray counterpart to multimessenger events

NSM:

- map positrons, γ-ray lines to study Galactic NSM history
- **detect ~15-20 short GRBs in Ge with sub-degree localization** in $\sim\pi$ sr 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)

Coincident high-energy neutrino and γ -ray activity:

- **observe all high-energy neutrino events within 12 hours**
- detect blazar γ-ray flares (which typically last ~weeks, months)
- serve as key γ-ray counterpart to IceCube Upgrade[a], due online by 2025

Nearby SNe (low probability of occurrence)

- reveal nucleosynthesis (e.g. map ^{44}Ti, 1.157 MeV) and SN asymmetries
- γ-ray counterpart to Advanced LIGO+ and HyperKamiokande[b] (MeV ν detection, starting ~2027)
- ^{56}Co (0.847 and 1.238 MeV) from Type Ia SNe (detect ~1.7 per year up to ~20 Mpc away)

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[a] Ishihara, Aya. arXiv preprint arXiv:1908.09441 (2019)

[b] J-PARC. (2020, February 12). http://www.j-parc.jp/c/en/topics/2020/02/12000416.html

Summary

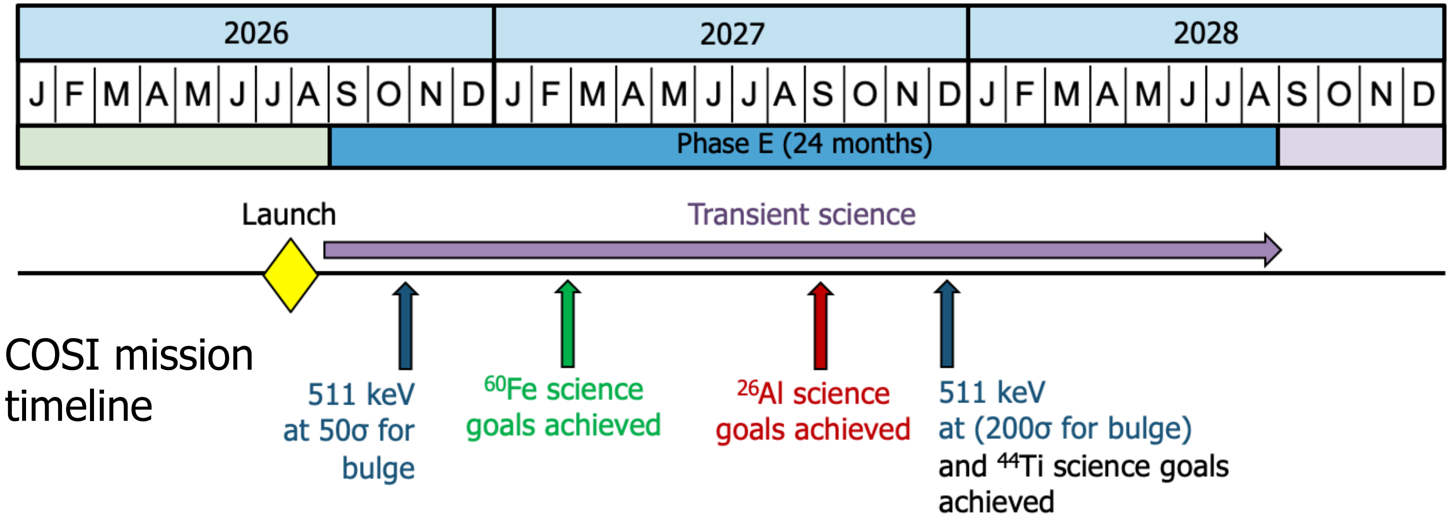
- ❑ MeV gamma-ray instruments are uniquely equipped to observe particle and nuclear processes in the universe
  - Important constraints on models of positron production and stellar/explosive nucleosynthesis
  - Gamma-ray observations of multimessenger events

- ❑ COSI-balloon was key proof-of-concept for the instrument design

- ❑ COSI satellite mission has great potential to help fill the MeV gap

Thank you and stay tuned for the COSI launch in 2026!

https://cosi.ssl.berkeley.edu



COSI mission timeline

511 keV at 50σ for bulge

^{60}Fe science goals achieved

^{26}Al science goals achieved

511 keV at (200σ for bulge) and ^{44}Ti science goals achieved

Backup

Production mechanisms, decay chains

Isotope	Production	Decay chain
^{26}Al	Stellar nucleosynthesis: • Primarily produced in H burning of massive stars ($\gtrsim 8\ M_\odot$, $\sim 10^7$ K) • Proton capture ^{25}Mg(p, γ)^{26}Al • Is dredged up and ejected in strong winds	• ^{26}Al → ^{26}Mg* → ^{26}Mg • β^+ (p → n + e^+), then 1.809 MeV γ-ray
^{60}Fe	Explosive nucleosynthesis: • Produced in He and C shell burning of massive stars ($\gtrsim 8\ M_\odot$, $\sim 10^8$ K) • s-process: Neutron capture ^{58}Fe(n, γ)^{59}Fe(n, γ)^{60}Fe • Is *not* dredged up in stars and is only ejected in CCSNe	• ^{60}Fe → ^{60}Co → ^{60}Ni • Both steps: β^- (n → p + e^-)
^{44}Ti	Explosive nucleosynthesis: • Produced during alpha-rich freezeout in CCSNe explosion ($\sim 10^9$ K) • Asymmetries in CCSNe ejecta can probe inner supernova engine (deep Si core)	• ^{44}Ti → ^{44}Sc → ^{44}Ca • EC (p + e^- → n + ν_e), then β^+ • 1.157 MeV, then 68/78 keV

^{56}Co

- ☐ Type 1a SNe: ^{56}Ni is formed when the white dwarf ignites
  - Emission from ^{56}Ni → ^{56}Co → ^{56}Fe escapes the opaque SN cloud after a few weeks
  - Max γ-ray emission brightness from ^{56}Co → ^{56}Fe occurs 60-100 days after the explosion
  - Brightness and temporal appearance of ^{56}Co lines reveal initial quantity of ^{56}Ni and explosion mechanism/structure

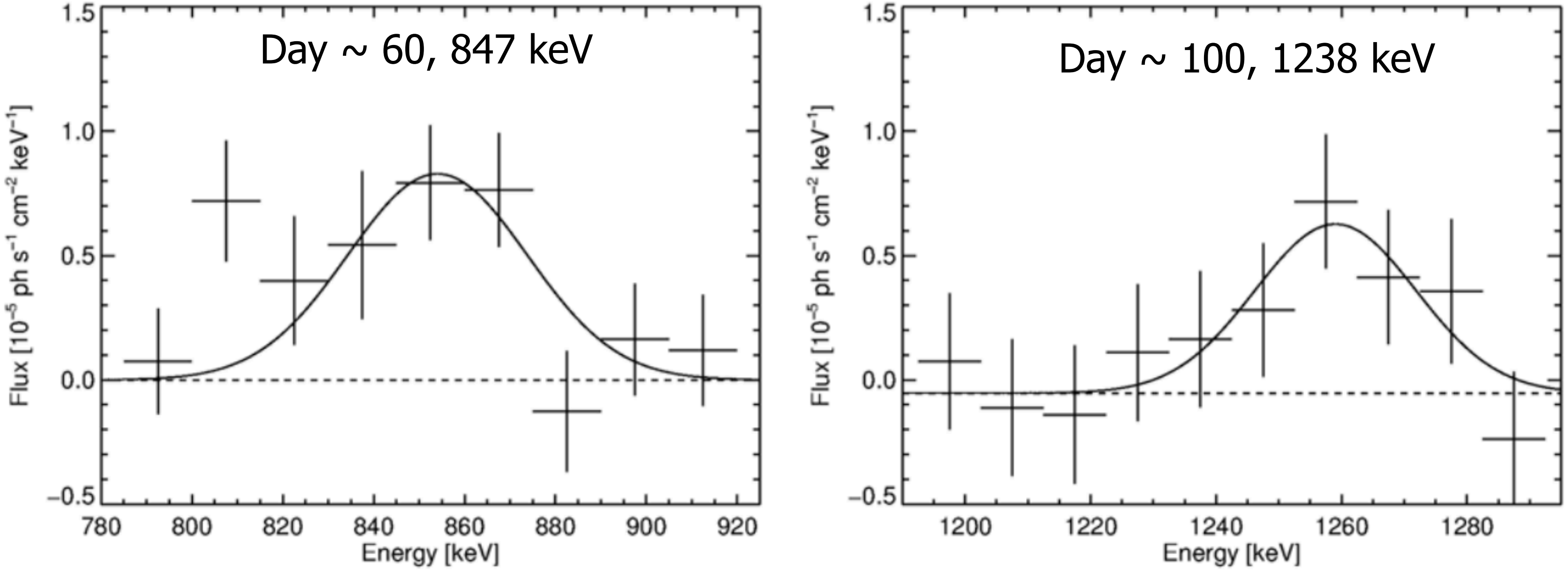
SN2014J:

Messier 82, closest supernova in last 4 decades (11.5 million light-years ~ 3 Mpc)

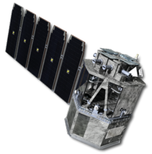
INTEGRAL:

Broadened lines → velocity spread ~3000-8000 km s^{-1}

^{56}Ni mass: (0.50 ± 0.12) $M_\odot$



Siegert et al. 2015



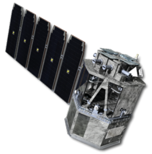
r-process kilonovae

- Kilonova: transient event associated with NS-NS or NS-BH merger. Triggers short GRB and strong EM emission from the **decay of r-process elements** produced during the merger

→ Can use γ-rays to study **nucleosynthetic yields and nuclear physics in NSMs**

→ Useful because γ-rays appear on the timescale of their decay, unlike optical/infrared measurements which are cumulative, i.e. γ-rays show evolution of the kilonova in real time

r-process kilonovae



Need robust simulations:

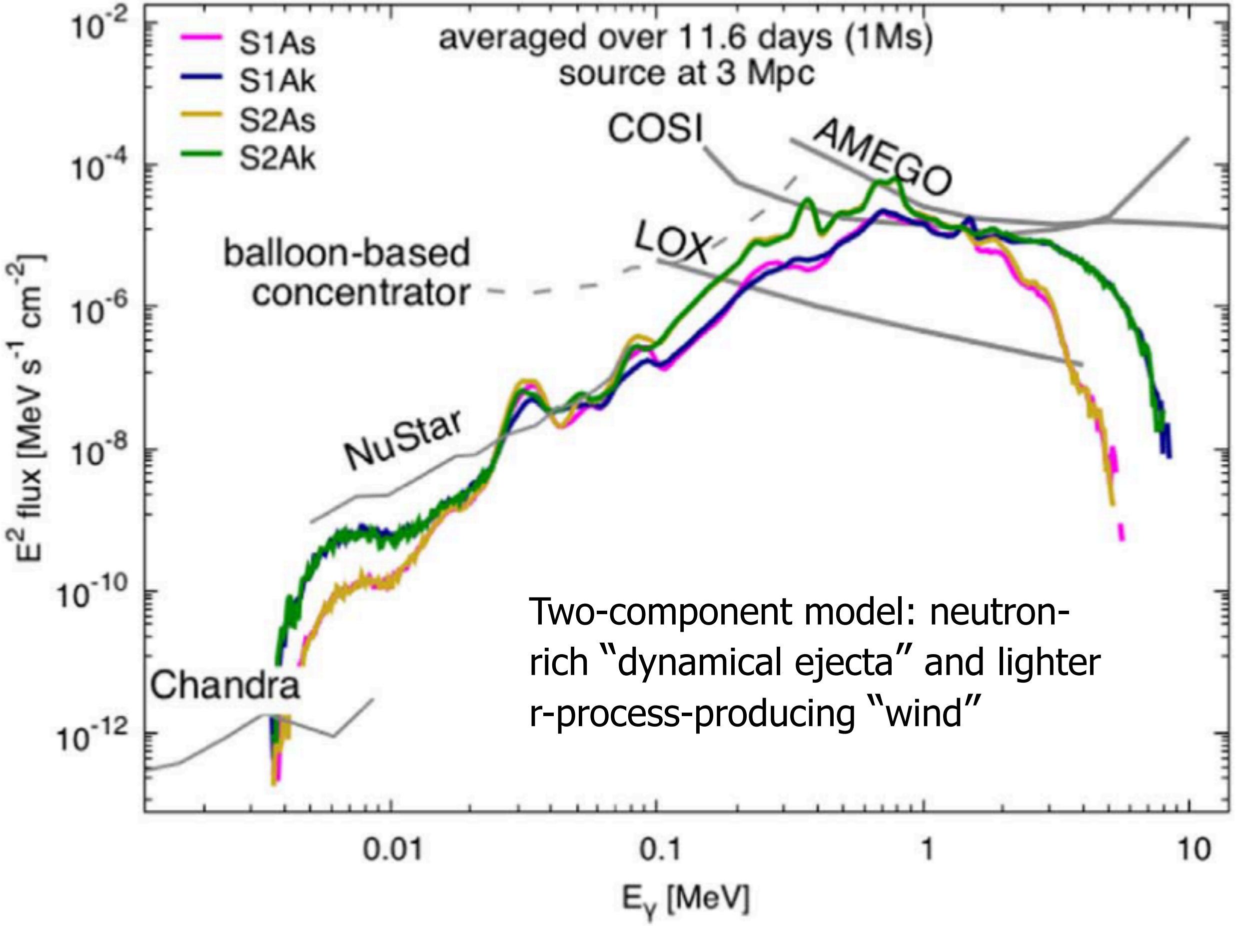
- ❑ Simulate nucleosynthetic yields of kilonovae using key nuclear physics inputs
    - e.g. capture rates, neutron-induced and β-delayed fission, nuclear densities, beta decay rates, etc.
    - e.g. Portable Routines for Integrated nucleoSynthesis Modeling (PRISM) reaction network (used in Korobkin et al. 2020)

- ❑ Proper treatment of γ-ray transport
    - Most are trapped in the initial flow of the explosion, broadening the lines in the γ-ray spectrum
    - e.g. Monte Carlo γ-ray transport code "Maverick" (used in Korobkin et al. 2020)

r-process kilonovae

- First 10 days after merger: peak γ-ray flux, “kilonova epoch”
  - Dynamical ejecta have many isotopes which blend to form a ~continuum
  - Must occur within ~10 Mpc to be observed

- ~10^4-10^5 years after merger: weaker emission, “kilonova remant”
  - Lines from **long-lived r-process nuclides**
    - Dominant isotopes: ^{126}Sb, ^{128}Sb, ^{214}Bi, ^{214}Pb, ^{243}Am, ^{246}Am, ^{245}Cm, and ^{250}Bk
  - Decelerating remnant → easier to resolve individual lines from radioactive decay → can discriminate between r-process models
  - Must occur within ~3 Mpc to be observed



Two-component model: neutron-rich “dynamical ejecta” and lighter r-process-producing “wind”

Korobkin et al. 2020

Classical novae

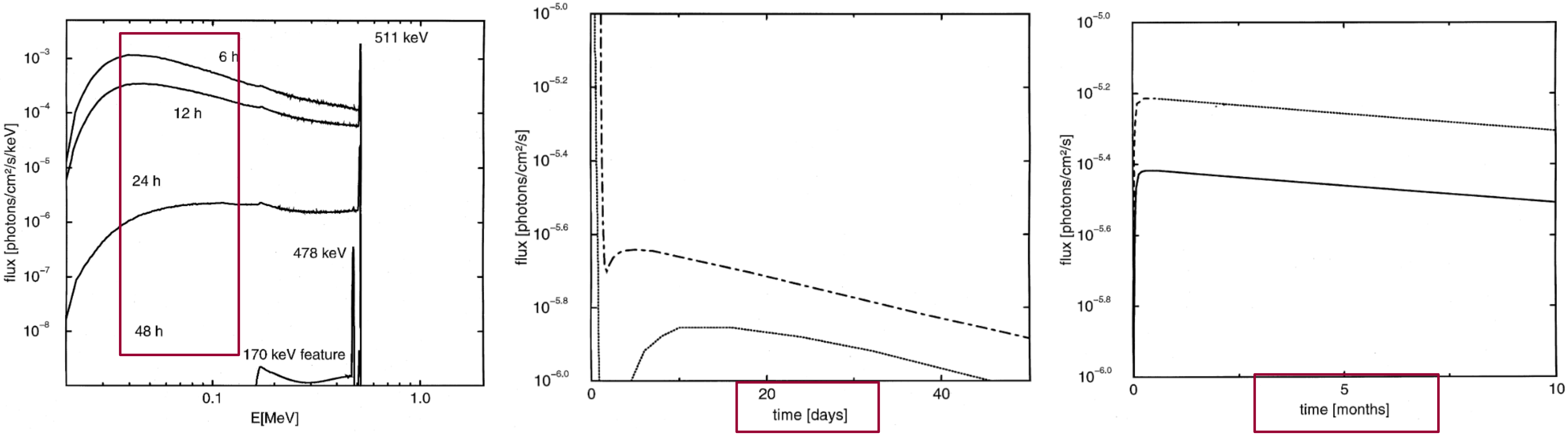
- Nova: explosive H-burning of accreted material on top of a white dwarf
- Galactic rate ~ 30 novae/year
- Emission lines:
  - ^{13}N, ^{18}F: e$^-$/e$^+$ annihilation; Continuum: o-Ps from Compton scattering. Line: 511 keV. Quick (~hours) lifetime.
  - ^{7}Be: 478 keV. ~10s of days
  - ^{22}Na: 1275 keV. ~5 months

- Emission is not yet detected (BATSE, OSSE, COMPTEL, SPI/INTEGRAL)
  - Gamma-ray emission occurs several days before the optical nova
  - Secondary science goal for COSI:
    - Large FOV → potential to observe ~1 event per year out to 2 kpc distance
    - Study secondary particles and their interaction with the nova environment

Classical novae

COSI
A Gamma-ray Space Explorer

Gómez-Gomar et al. 1998



^{13}N, ^{18}F

^{7}Be

^{22}Na

Gamma-ray emission from novae in the hours, days/weeks, and months after the explosion (Gómez-Gomar et al. 1998)

Compact Compton Telescope (CCT)

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

Cross-sections for Germanium

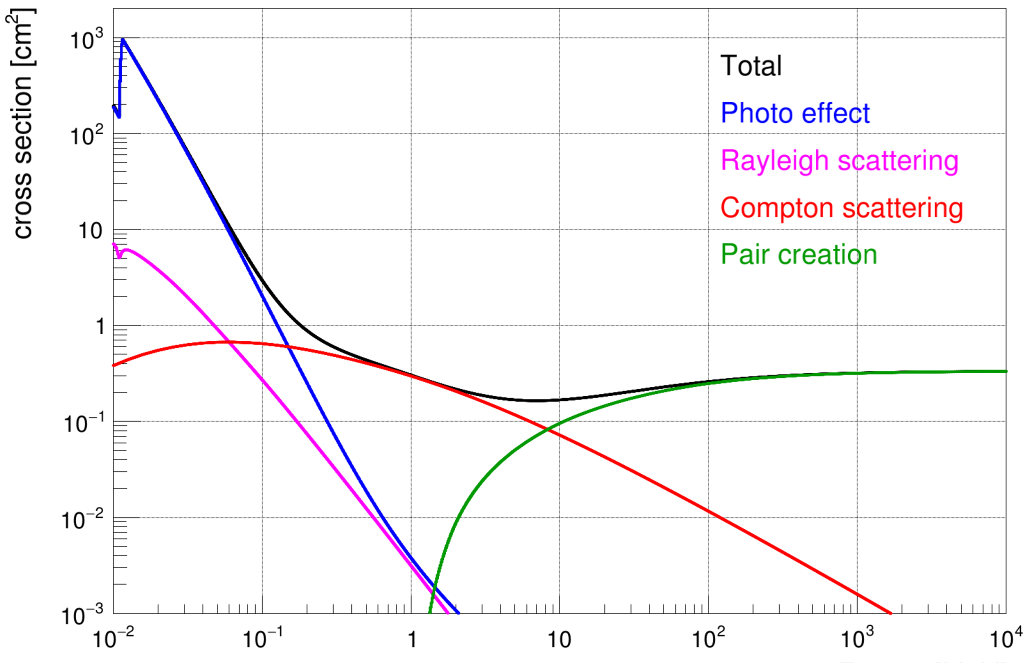


Image credit: MEGAlib

Constrain γ to event circle defined by ϕ:

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

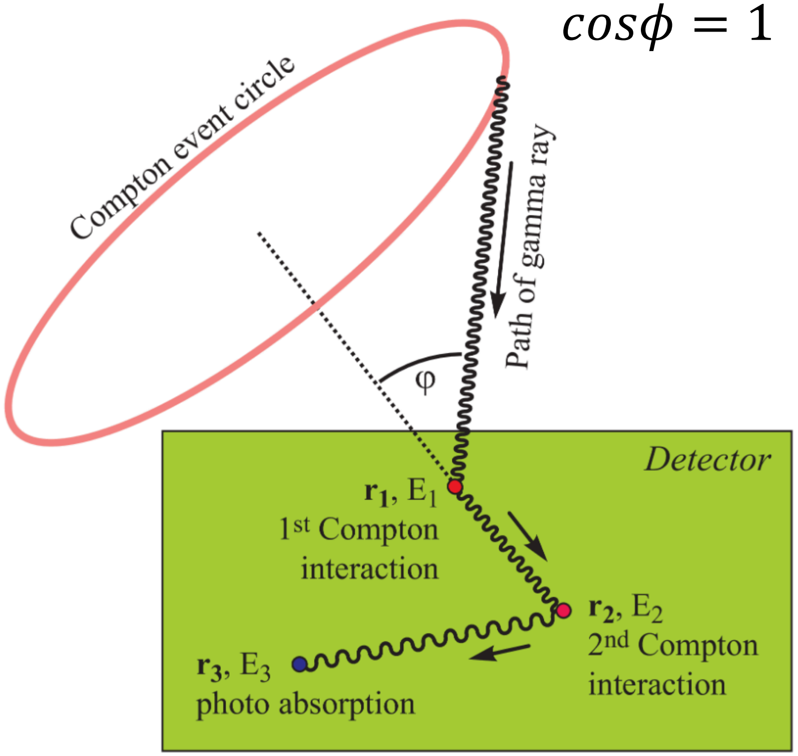
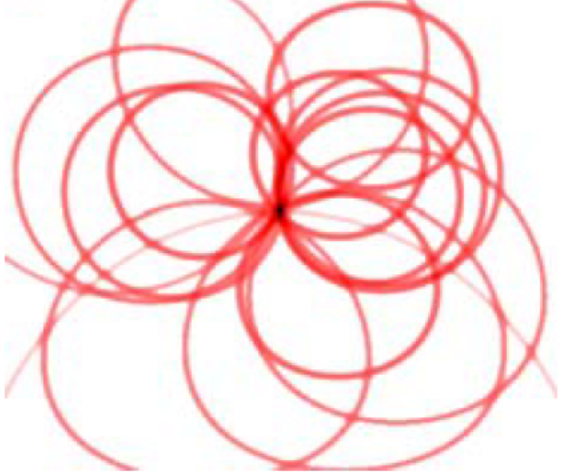


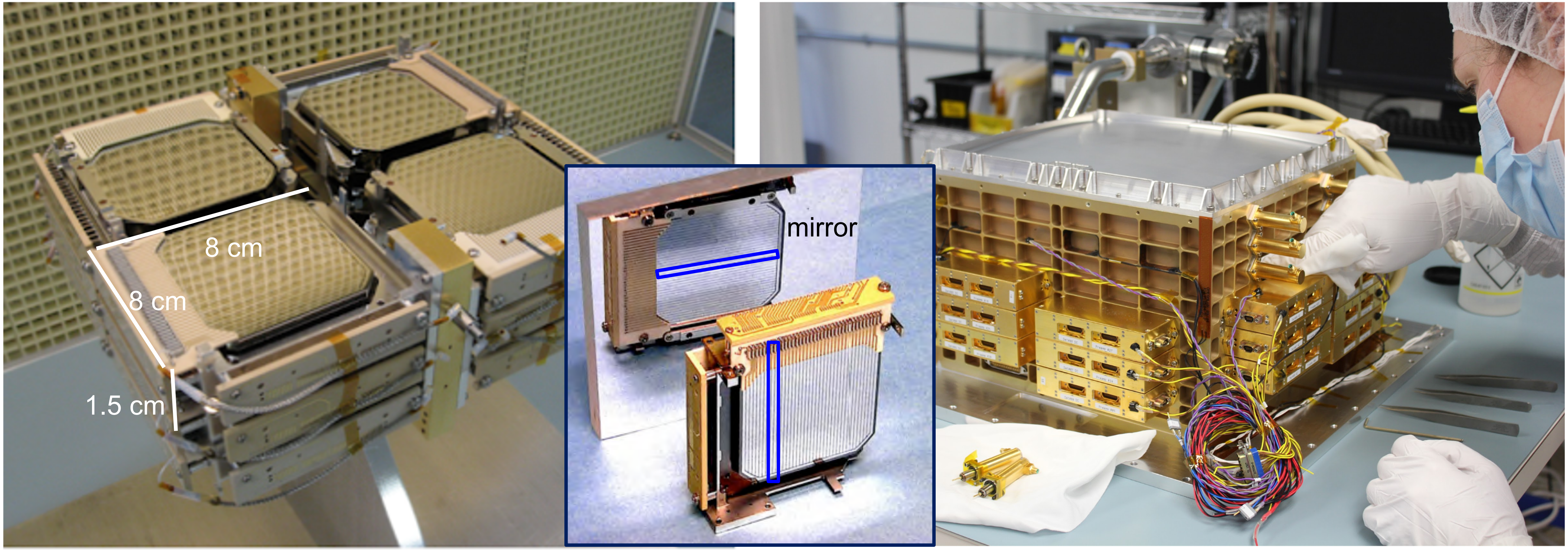
Image credit: Zoglauer et al. 2021

Image credit:
Zoglauer 2006



Overlapping event circles constrain the source location

COSI-balloon’s GeD Array



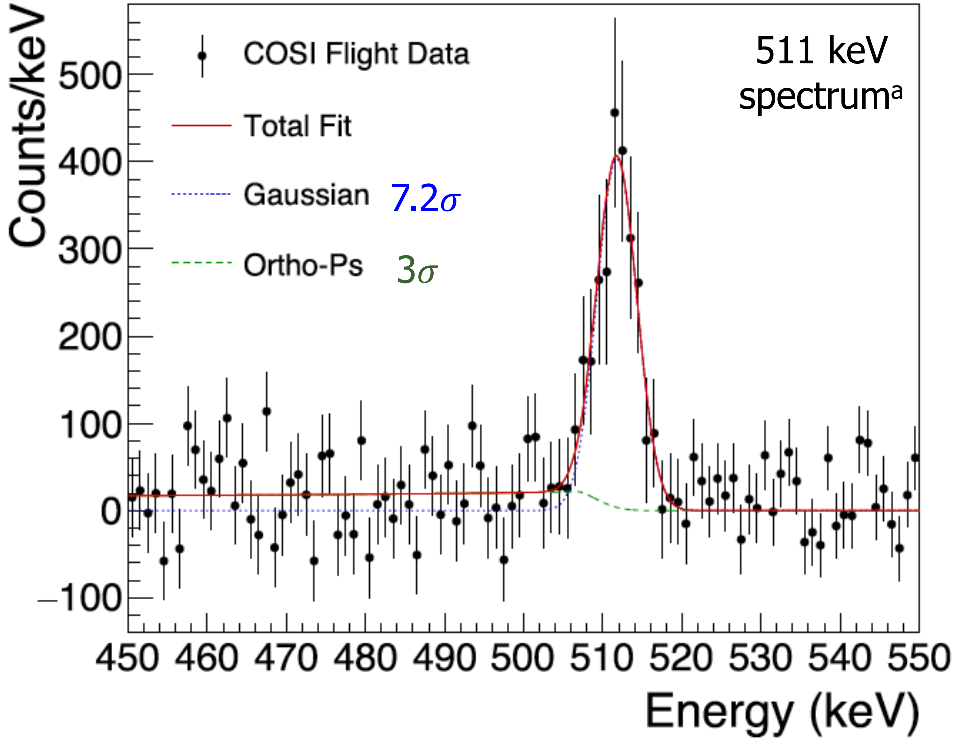
- 12 high-purity germanium cross-strip detectors (GeDs)
  - 12 x 37 strips x 2 sides = 888 strips of 2 mm pitch
    - 3D position resolution of 2 x 2 x 0.5 mm^3

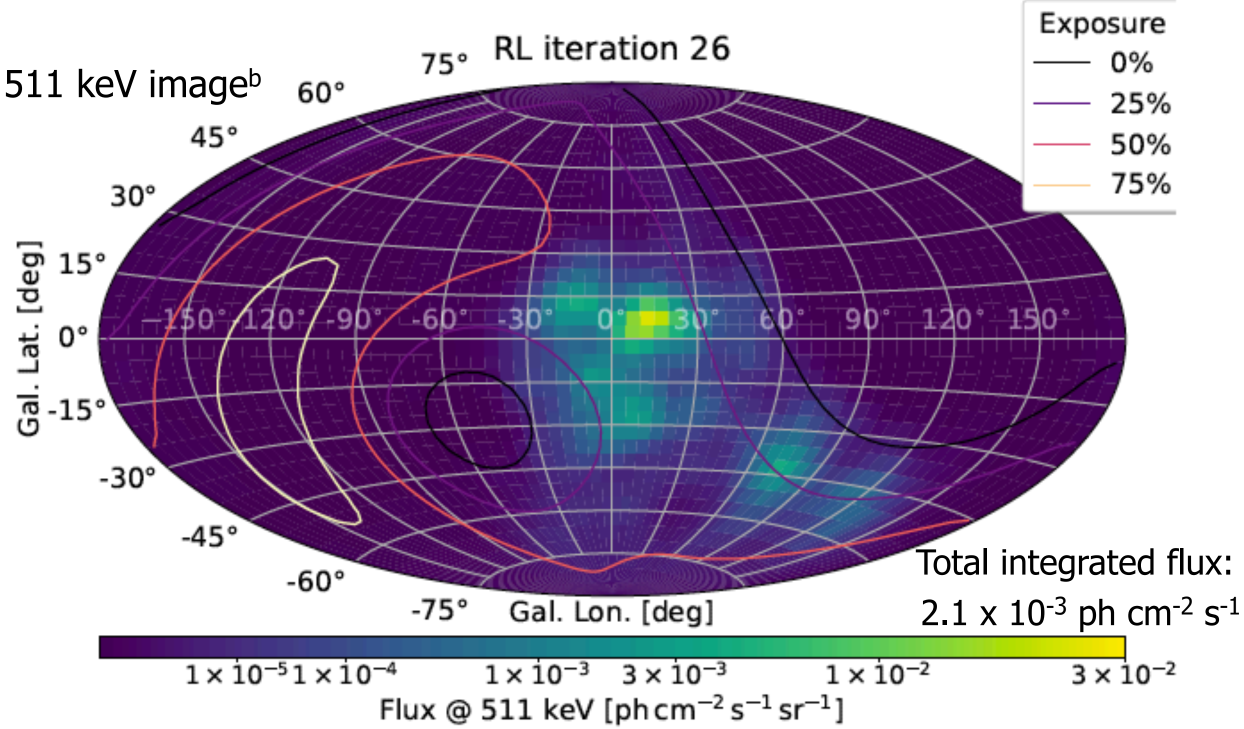
- Detectors housed in aluminum cryostat

- Operating conditions: ~84 K, 10^{-6} Torr

COSI 2016 flight: Science resume

1. Uncover the origin of Galactic positrons





Total integrated flux:
2.1×10^{-3} ph cm^{-2} s^{-1}

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

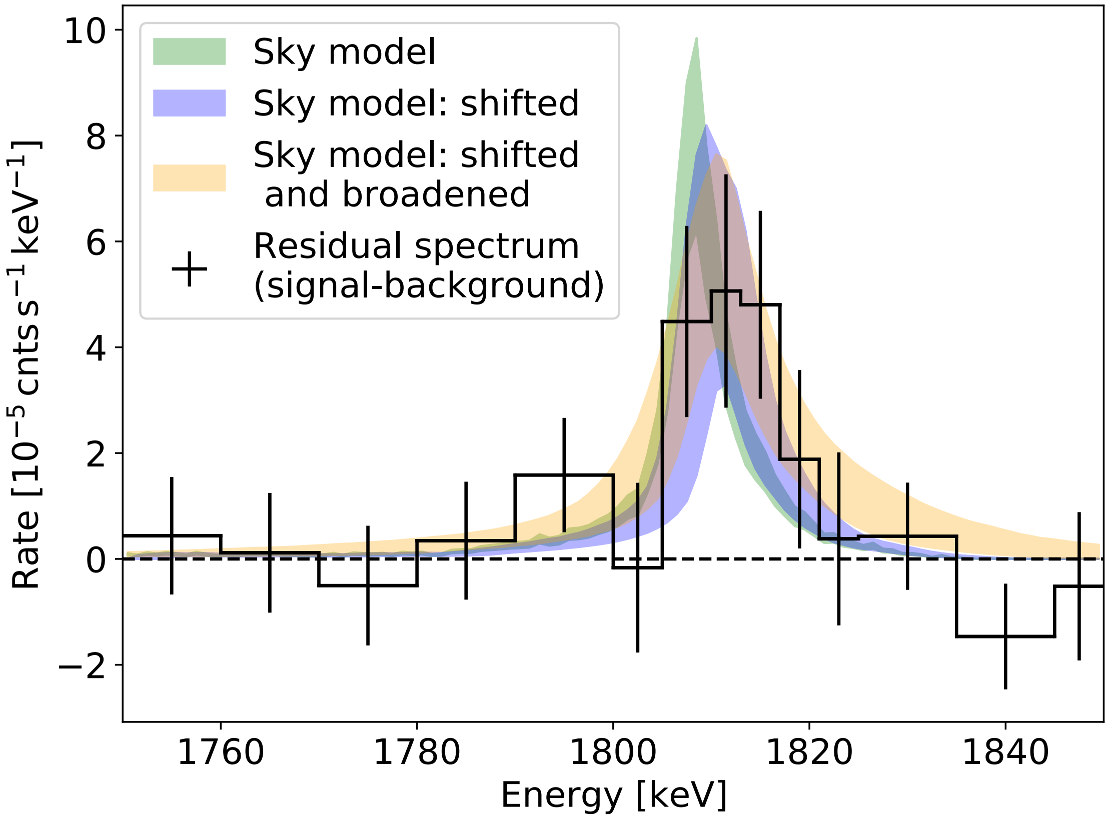
- 7.2σ detection at 511 keV
- Confirmed bulge emission

[a] Kierans et al. 2020

[b] Siegert et al. 2020

COSI 2016 flight: Science resume

2. Reveal Galactic element formation



Measurement of Galactic ^{26}Al

	Centroid [keV]	Inner Galaxy flux [10^{-4} ph cm^{-2} 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 ^{26}Al in the Inner Galaxy

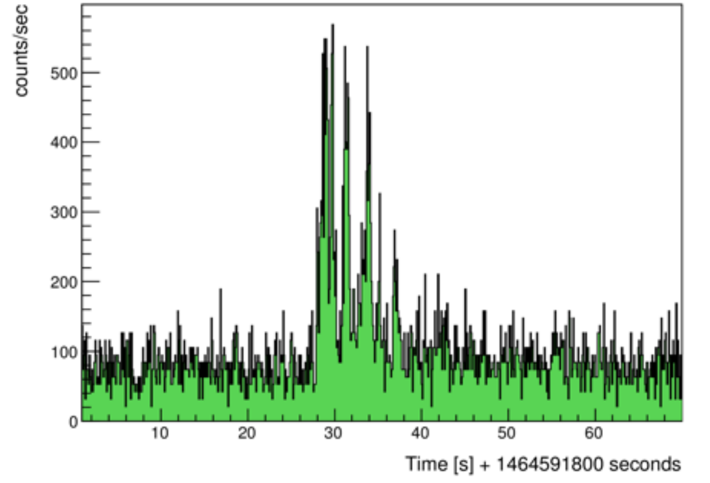
Beechert et al. 2022

COSI 2016 flight: Science resume

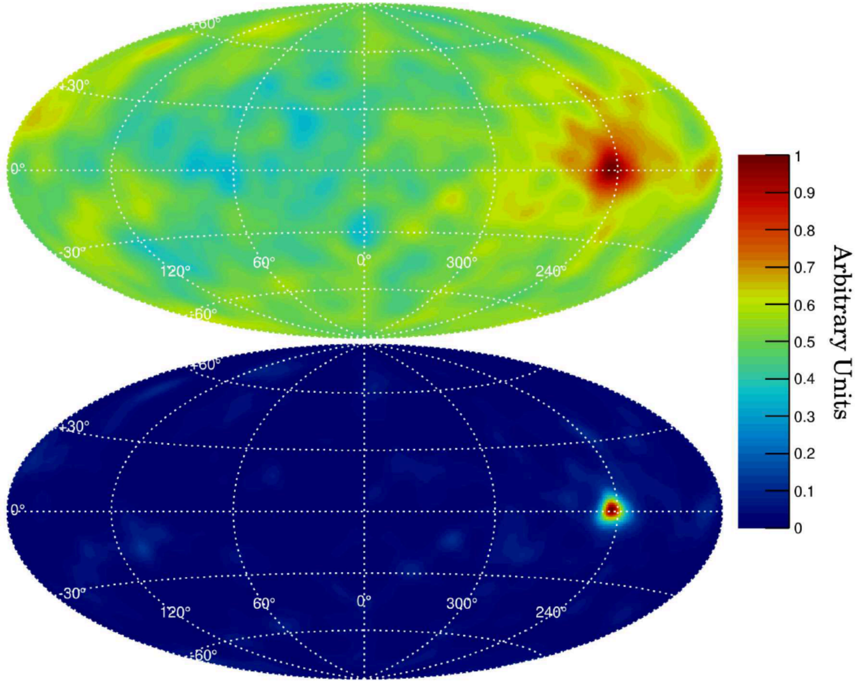
3. Gain insight into extreme environments with polarization

Real-time detection of GRB160530A

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



Lightcurve of GRB160530A



COSI images of GRB160530A
(ℓ = 243.4°, b = 0.4°)

Top: zero iterations (back-projection of Compton cones)
Bottom: ten iterations of MLEM deconvolution algorithm
Lowell 2017

4. Probe the physics of multi-messenger events

→ For this and other improvements, go to space with the COSI satellite

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