COSI
Gamma-ray
Space
Explorer

# Closing In On the MeV Gap

## The Compton Spectrometer and Imager


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TeVPA meeting
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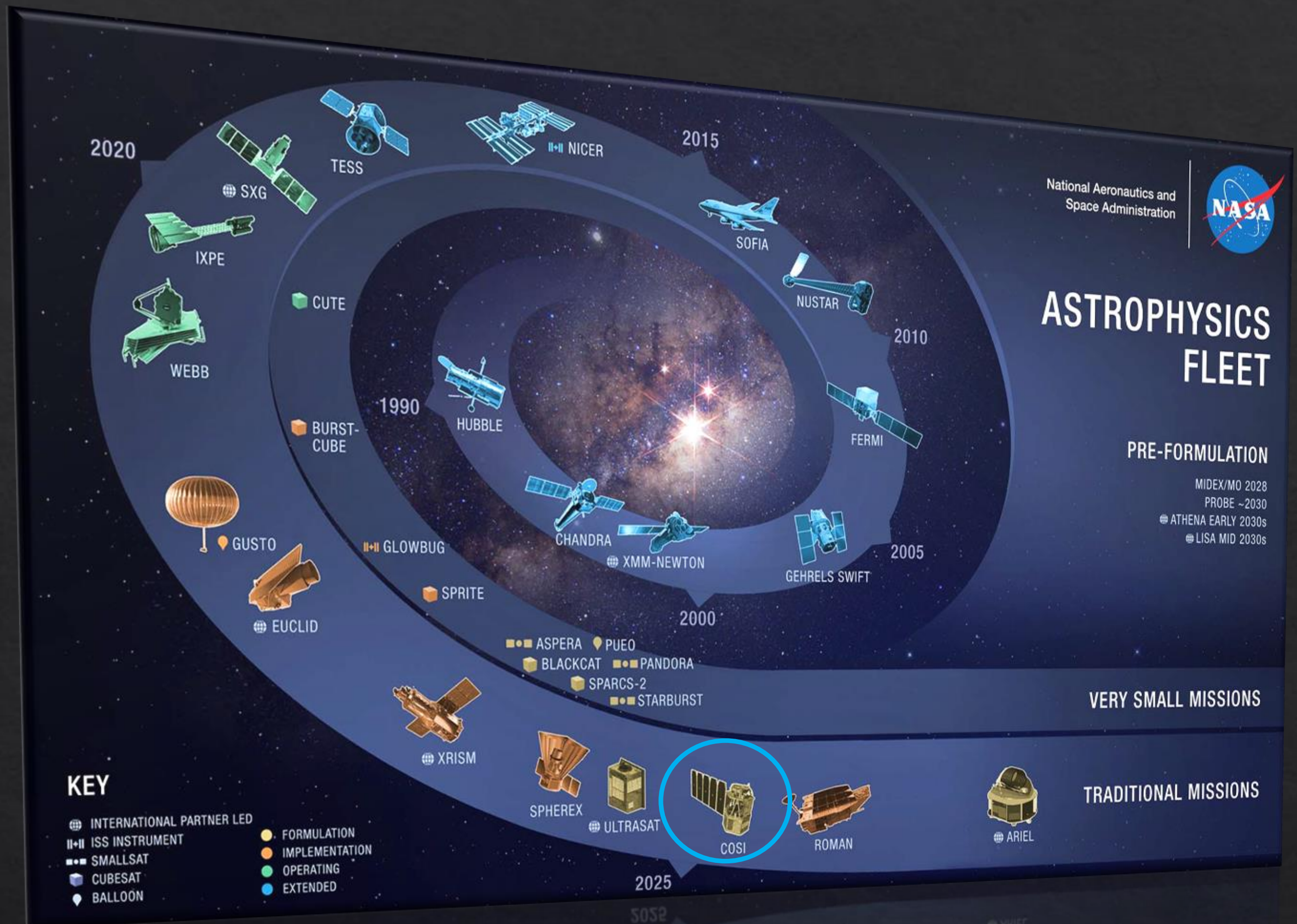
‘We need an MeV gamma-ray satellite telescope’

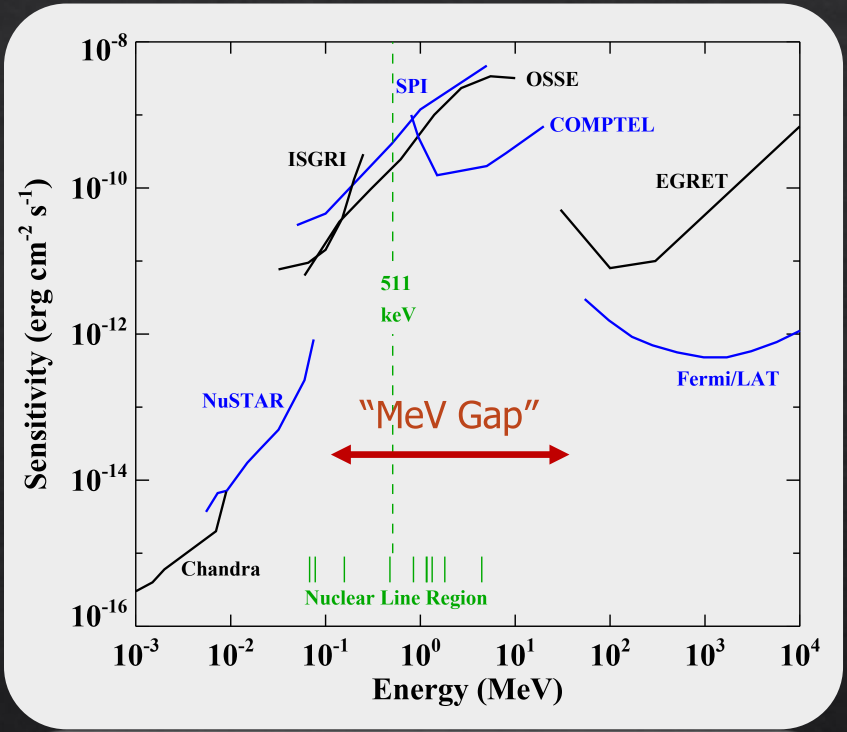




From NASA Astrophysics Town Hall: Paul Hertz

The Compton Spectrometer and Imager (COSI) was developed under NASA's APRA program as a balloon-borne telescope and has been recently selected as a NASA Small Explorer (SMEX) satellite mission for launch in 2026.

# Science opportunities in the "MeV Gap"

- Signals and sources in the COSI energy range (0.2-5 MeV)
  - $e^-e^+$ annihilation line at 511 keV
  - Gamma-ray lines from nucleosynthesis
  - Accreting black holes and gamma-ray bursts (GRBs) w/polarization
  - Multimessenger sources
    - Merging neutron stars
    - High-energy neutrinos




The "MeV gap" is one of the least explored regions of the electromagnetic spectrum

# Science opportunities in the "MeV Gap"

COSI Gamma-ray Space Explorer

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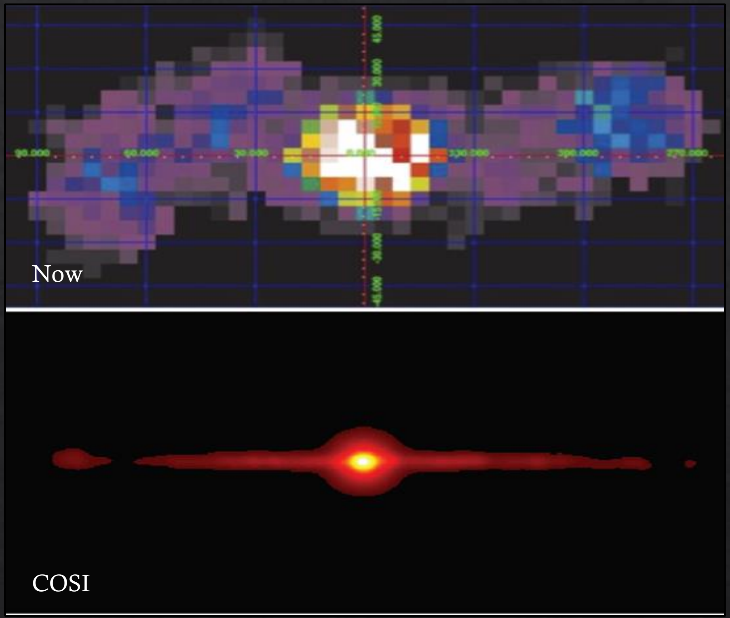
INTEGRAL/SPI (Bouchet+10)




Bulge positron excess origin?

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

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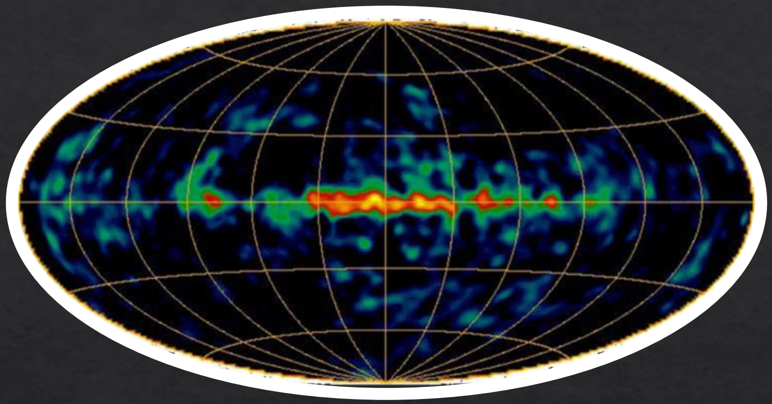

COMPTEL map of $^{26}$Al emission (Oberlack+97)

Three windows on element formation associated with massive star evolution:

- $^{26}$Al (1.809 MeV) traces massive stars, including **pre-supernova** (SN)
- $^{44}$Ti (1.157 MeV) traces **recent** SN activity
- $^{60}$Fe (1.173/1.333 MeV) traces SN activity over **the past few million years**

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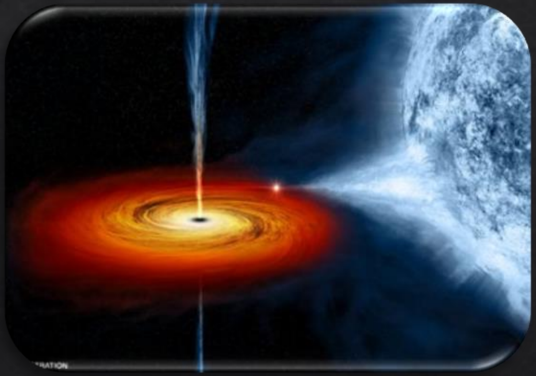
- Potential high levels of polarization
  - ~70% above 0.4 MeV for Cygnus X-1 (Laurent+11; Jourdain+12)
- What about other Galactic black holes?
- GRB distribution?
- AGN?



Cygnus X-1

AGN: Cen A

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Credit: NASA's Goddard Space Flight Center/CI Lab

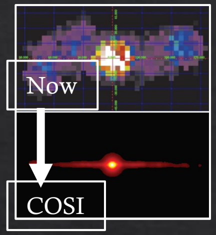
Supernovae + Gamma-rays:
SN1987A

Gravitational Waves + Gamma-rays :
GRB170817A + GW170817

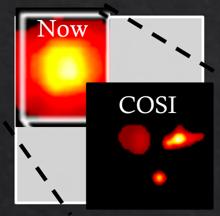
Neutrinos + Gamma-rays:
IceCube-170922A + 0506+056?
gamma-ray emitting blazar

# COSI science goals

COSI
Gamma-ray Space Explorer

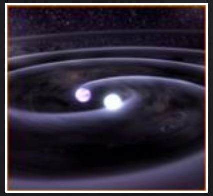



1. Uncover the origin of Galactic positrons




2. Reveal Galactic element formation

3. Gain insight into extreme environments with polarization

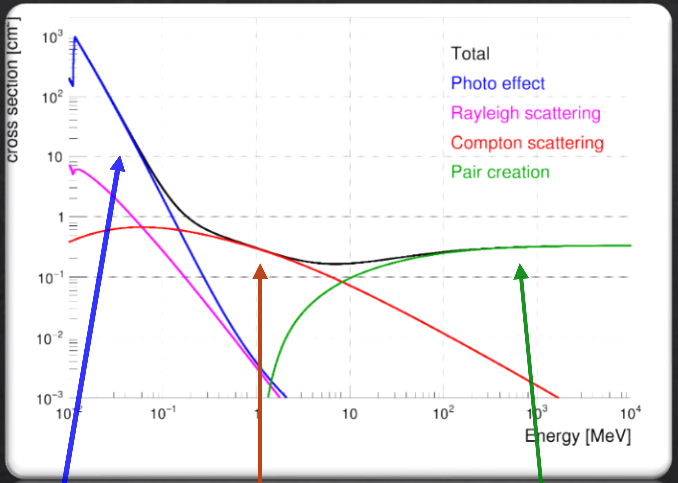


4. Probe the physics of multimessenger events

# Detecting photons at MeV energies with Compton telescopes

COSI Gamma-ray Space Explorer

Cross sections for germanium

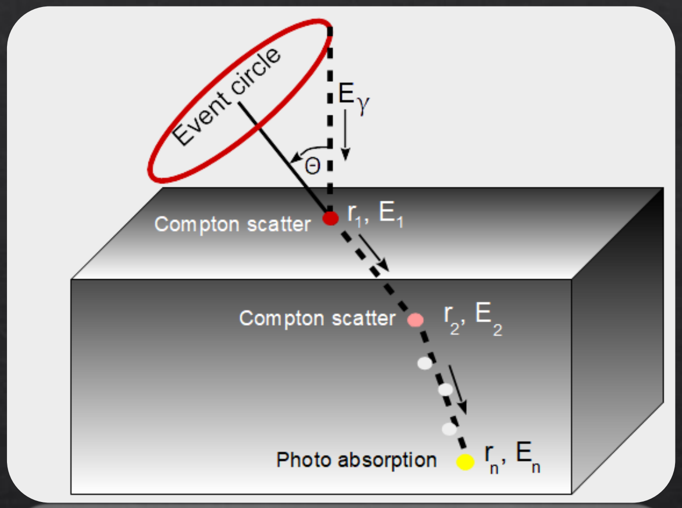



Compton telescopes (COMPTEL, **COSI**)

Full photon absorption (NuSTAR, etc.)

Pair creation telescopes (Fermi/LAT)

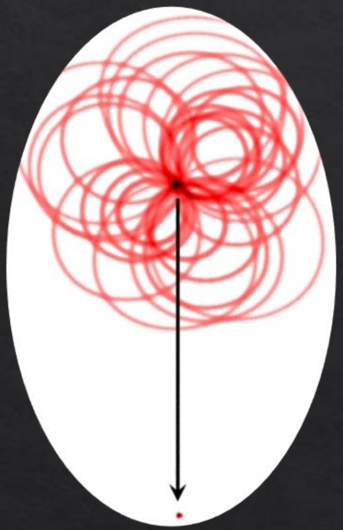
Compton event reconstruction




- Multiple interactions within detector
- $E_\gamma = E_1 + E_2 + E_3 + \ldots$
- The photon may have come from any point on the "event circle"

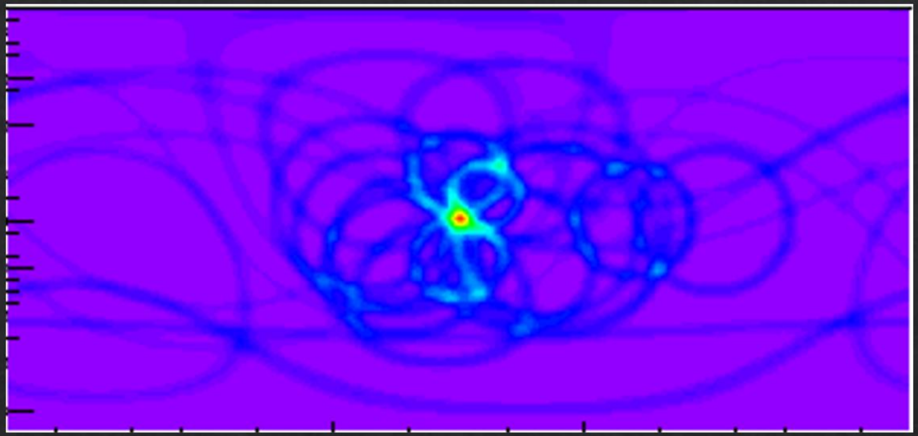
# COSI Imaging Techniques



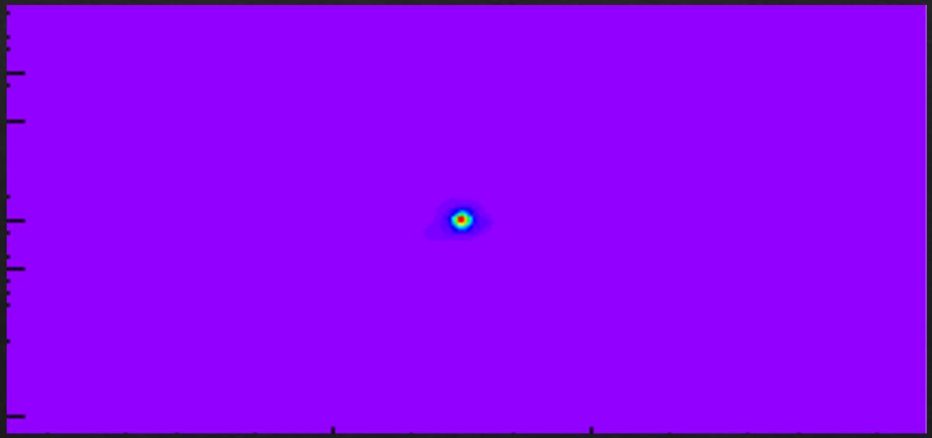


Deconvolved image
of a point source

**Back-projected Compton cones in image space**



**Iterative deconvolution to recover image**



# COSI: NASA Small Explorer satellite mission

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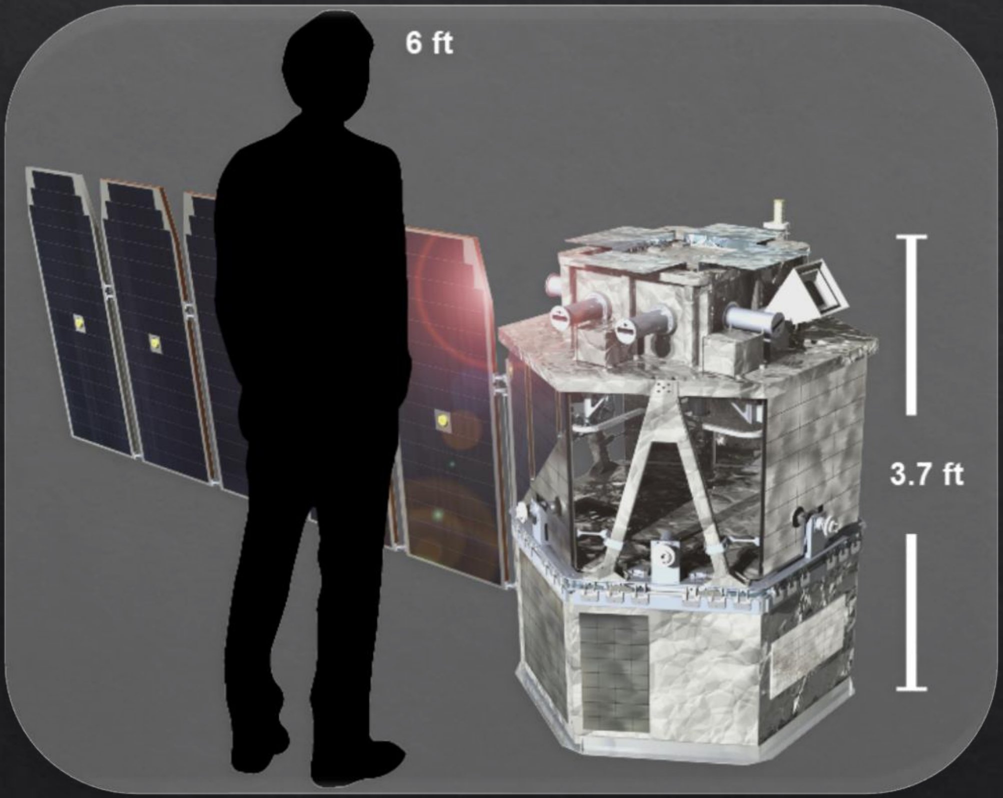
Gamma-ray Space Explorer



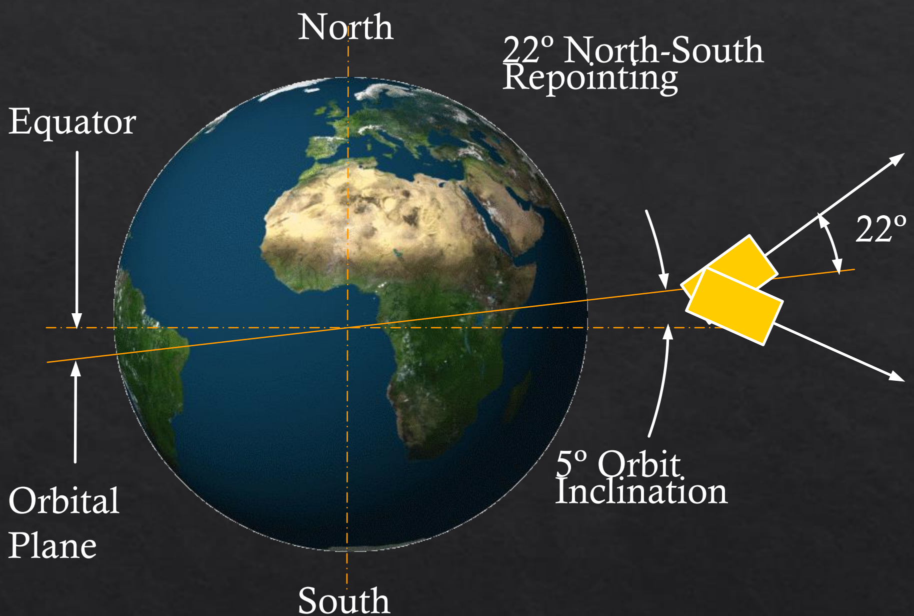

COSI instrument/spacecraft

| Parameter | Requirements |
|---|---|
| Energy range | 0.2-5 MeV |
| Sky coverage | 100%-sky each day |
| Energy resolution | 0.2-1% FWHM |
| Angular resolution | 2.1º FWHM @ 1.8 MeV ($^{26}$Al) |
| Localizations | <1.0º for GRBs |
| Polarization sensitivity | For GRBs, AGN, Galactic BHs |

# COSI orbit and operations for daily all-sky coverage

COSI Gamma-ray Space Explorer

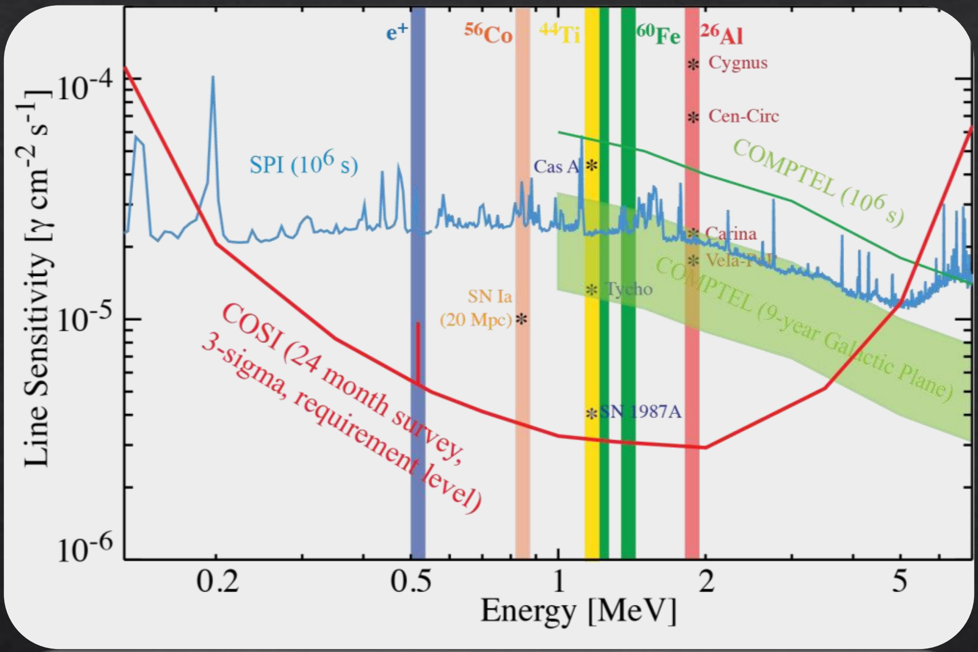
- Near-equatorial orbit to minimize South Atlantic Anomaly passages
- Instantaneous >25%-sky field of view (FOV) and North-South repointing every 12 hours to cover the whole sky every day

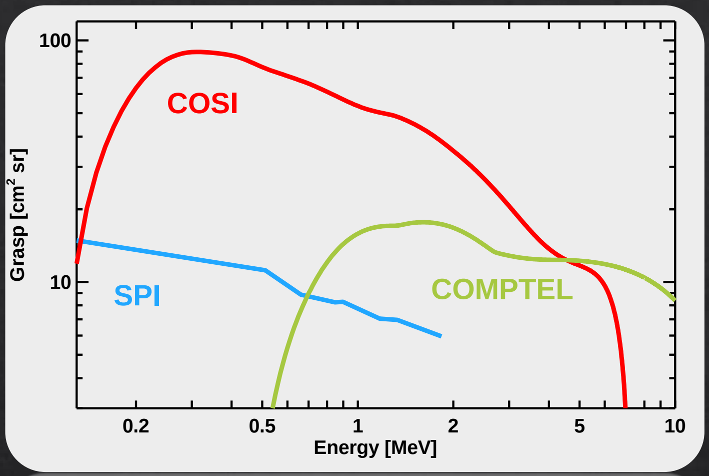



- Large FOV needed for:
  - GRBs (localizations and polarization measurements)
  - All-Galaxy images of 511 keV and nuclear lines

# COSI required line sensitivity and grasp compared to previous and current missions

COSI Gamma-ray Space Explorer



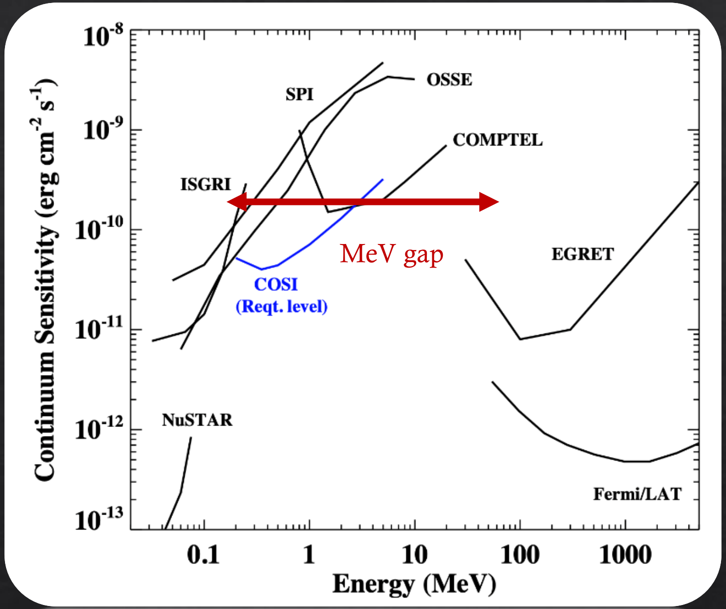




- COSI is optimized for line sensitivity to enable full-Galaxy and all-sky images.
- COSI's large FOV provides a substantial improvement in grasp.

# What COSI *doesn't* do

COSI Gamma-ray Space Explorer

- Although COSI helps, it doesn't completely close the MeV gap.
- Sub-degree but not sub-arcminute GRB localizations
- Not anticipating large number of Targets of Opportunity (TOOs).
  - Survey mode's all-sky coverage every day reduces the need
  - "Constant Zenith Angle" TOOs have some applications



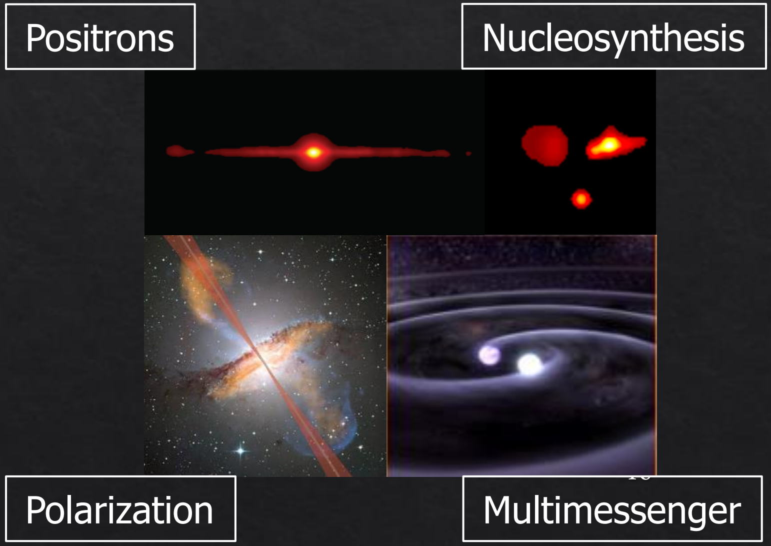
# Schedule and opportunities for involvement



## Planned Schedule

- Currently in Phase B
  - *Data Challenges in the coming months will be an opportunity for community involvement (http://cosi.ssl.berkeley.edu)*
- Additional data challenges during Phases C and D
- Launch: **2026** (start of Phase E), followed by a 2-year prime mission, but no consumables, so could be significantly longer

- In addition to the key science goals, all-sky monitor results will be provided to the community
  - *Please let us know what would be most useful for you!*



# The COSI collaboration

## University of California

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

## Naval Research Laboratory

E. Wulf, C. Sleator, B. Phlips

## Goddard Space Flight Center

A. Shih, C. Kierans, A. Smale

## Northrop Grumman

## Institutions of Co-Investigators 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

We’d be very happy to hear from you!
Contact Jarred Roberts: jmroberts@ucsd.edu

# COSI
Gamma-Ray Space Explorer

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

# COSI requirements

COSI Gamma-ray Space Explorer

Primarily for goals 1+2

| Characteristic | Requirement |
|---|---|
| Sky Coverage | • >25%-sky instantaneous FOV<br>• 100%-sky each day |
| Energy Resolution (FWHM) | • 6.0 keV at 511 keV (capability ~4.7 keV FWHM), reconstructed events<br>• 9.0 keV at 1.157 MeV ($^{44}$Ti) |
| Narrow Line Sensitivity (2 yr, 3σ, point source)<br>❖ 511 keV<br>• 1.8 MeV | [photons $cm^{-2}$ $s^{-1}$]<br><br>• $1 \times 10^{-5}$ (Galactic bulge is 100x brighter)<br>• $3 \times 10^{-6}$ (Galactic $^{26}$Al flux is 230x brighter) |
| Angular Resolution (FWHM) | • 5.1° at 511keV (capability ~3.6° FWHM)<br>• 2.0° at 1.8 MeV ($^{26}$Al) |

Goal 3

| | |
|---|---|
| Accreting BH polarization | • Reaches bright AGN: Cen A, 3C 273, NGC 4151<br>• Reaches several Galactic BHs (plus transients) |
| GRB polarization | • >30 GRBs with polarization measurements |

Goal 4

| | |
|---|---|
| Short GRB detection, localization, and reporting | • >10 short GRBs (~20 detections predicted)<br>• <1° localizations provided in <1 hr |

# Radioactive Milky Way

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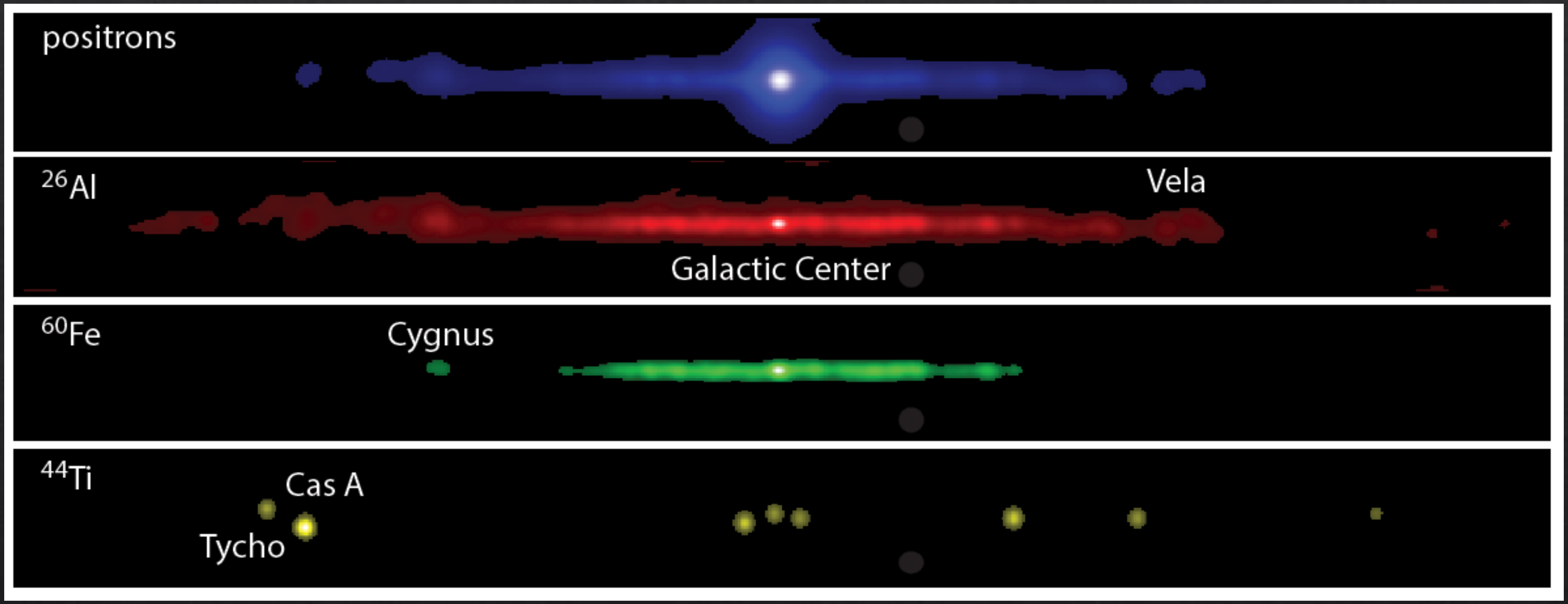



Simulated COSI emission line images

# Accreting Black Holes Polarization Measurements

COSI Gamma-ray Space Explorer

Cyg X-1 polarization:

- 0.25-0.4 MeV: <20% (low polarization)
  - thermal corona of hot electrons
  - photons Compton upscattered off corona
- 0.4-2 MeV: 67±30% (high polarization)
  - points to nonthermal jet contribution
  - synchrotron self-Compton (SSC)

COSI will measure polarization (50% MDP, 99% confidence, 0.2-0.5 MeV) with flux limits:

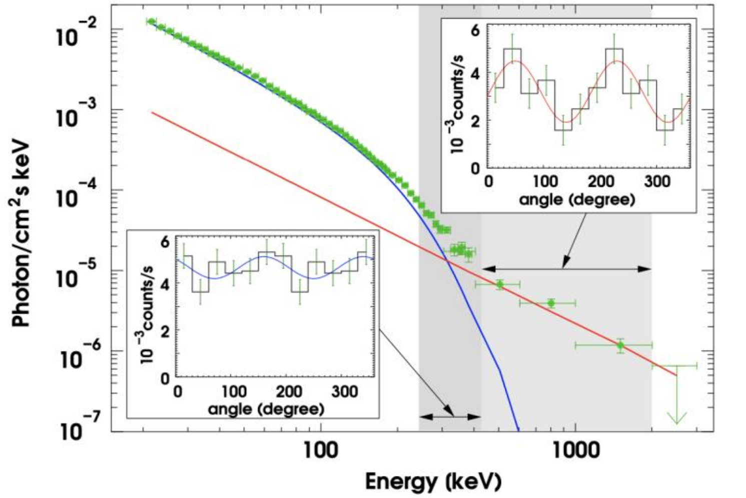
- $6.9 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$

(Galactic black hole transients, 1 month)

- $1.4 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ (AGNs, 2 years)

COSI will measure Cyg X-1 polarization within a few weeks of launch

(Laurent et al. 2011, Nature)




Cyg X-1 spectrum and modulation curves (from ESA press release)

# Nearby SNe and Classical Novae

COSI Gamma-ray Space Explorer

- Nearby SNe
  - $^{56}$Co lines at 0.847 and 1.238 MeV detected from Type Ia SNe to a distance of ~20 Mpc
    - COSI detections for ~1.7 per year
- 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
- Classical novae
  - Predicted 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 large FOV gives a good chance to see this, and we would expect to see about 1 event per year

# Production and decay chain of key isotopes

COSI Gamma-ray Space Explorer

| Isotope | Production | Decay chain |
|---|---|---|
| $^{26}Al$ | Hydrostatic burning, proton capture by $^{25}Mg$ | • $^{26}Al \rightarrow {}^{26}Mg^* \rightarrow {}^{26}Mg$<br>• Beta+ ($p \rightarrow n+e^+$) and 1.809 MeV gamma-ray |
| $^{60}Fe$<br>(neutron rich) | He and C shell burning, explosive burning, neutron capture | • $^{60}Fe \rightarrow {}^{60}Co \rightarrow {}^{60}Ni$<br>• Both beta- ($n \rightarrow p+e-$) |
| $^{44}Ti$ | Si burning in the inner regions of the material ejected by CCSNe | • $^{44}Ti \rightarrow {}^{44}Sc \rightarrow {}^{44}Ca$<br>• EC and beta+<br>• 1.157 MeV and 68/78, respectively |

# COSI Imaging Techniques

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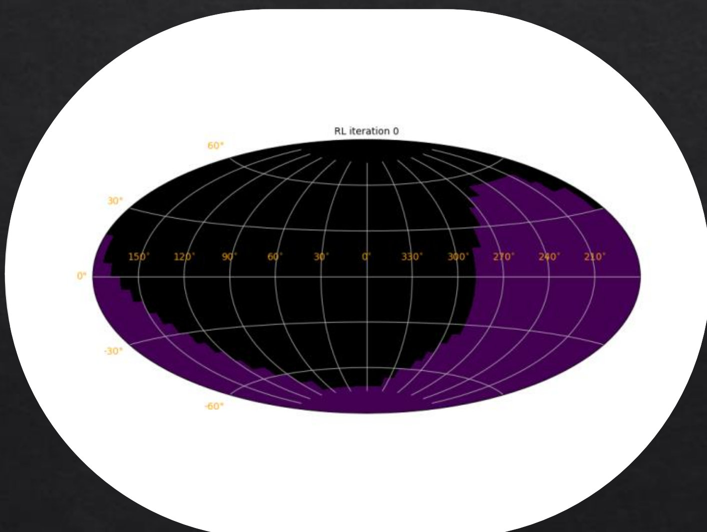
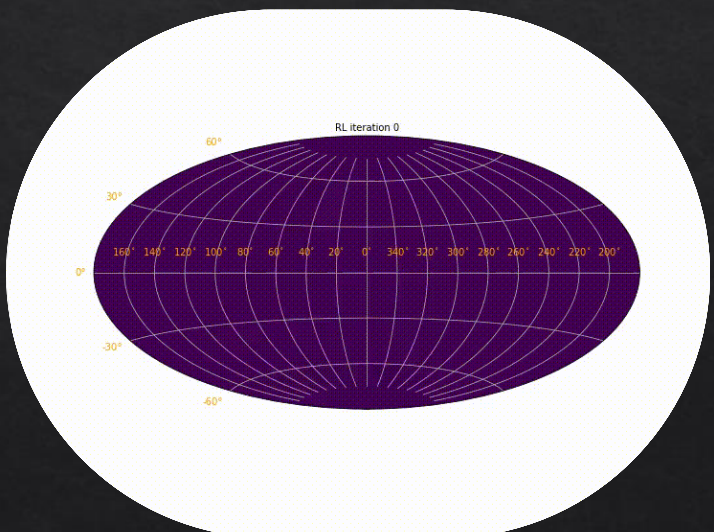
Modified Richardson-Lucy algorithmic techniques:
- Background fitting
- Data energy and time binning tunable full-sky imaging




Crab
(2016 Balloon Flight)

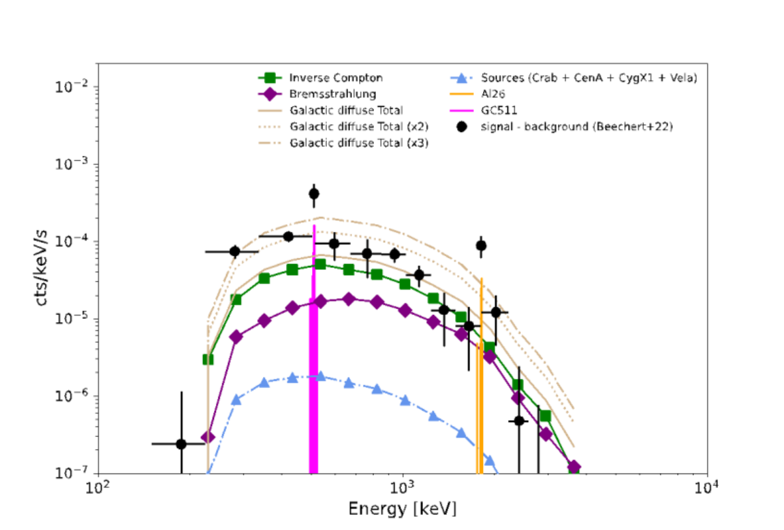



Cygnus X-1
(2016 Balloon Flight)

# COSI continuum emissions



- Preliminary analysis shows that the continuum emission level is between 1x and 3x (depending on the energy) of the GALPROP prediction for GDCE
- Spectrum below 0.511 MeV shows the largest excess
  - Orthopositronium continuum?
  - Unresolved point sources?




Spectrum from the source region
(Karwin et al., in prep.)