December 17, 2025 @ Kavli IPMU
MeV–PeV Frontiers: New Perspectives in
Gamma-Ray Astronomy and Particle Acceleration

Opening the MeV Window: From Today's Constraints to COSI and Beyond

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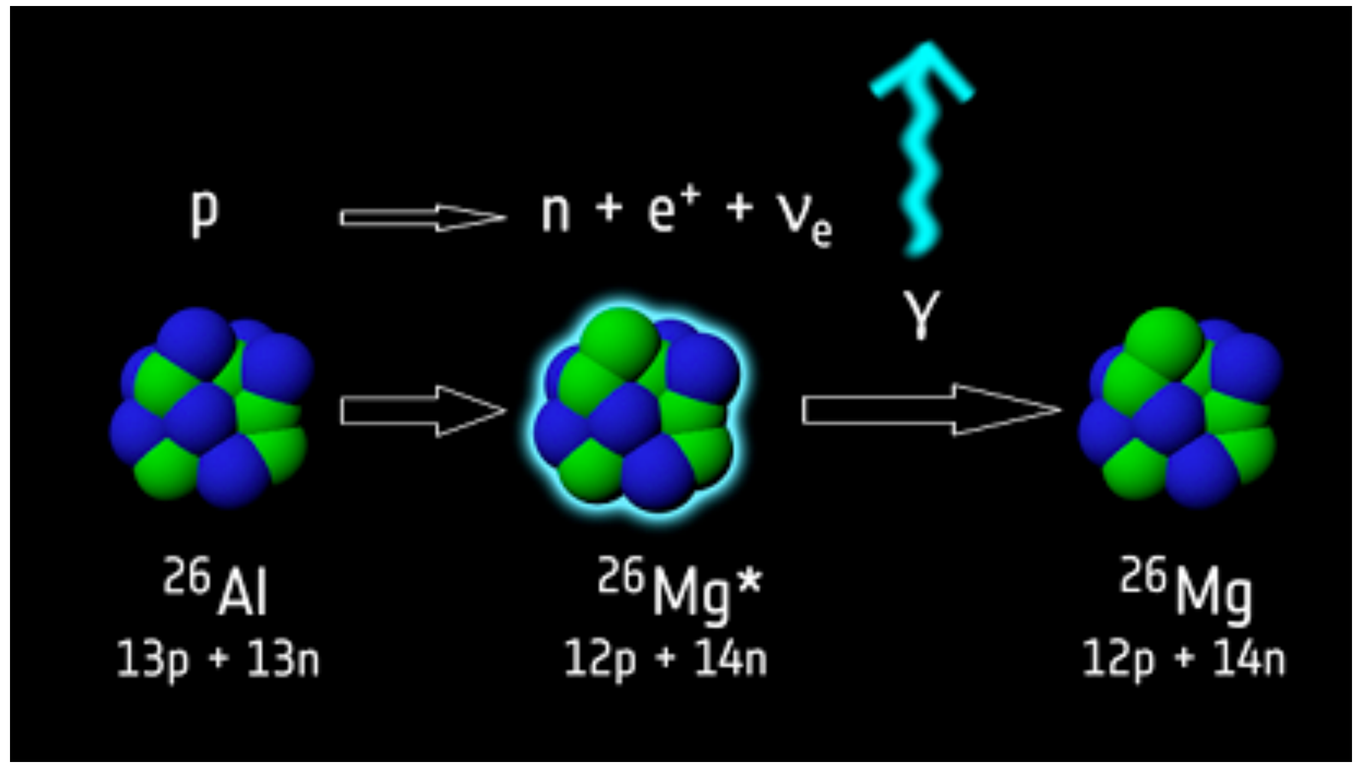
Astrophysics with MeV gamma rays

Nucleosynthesis

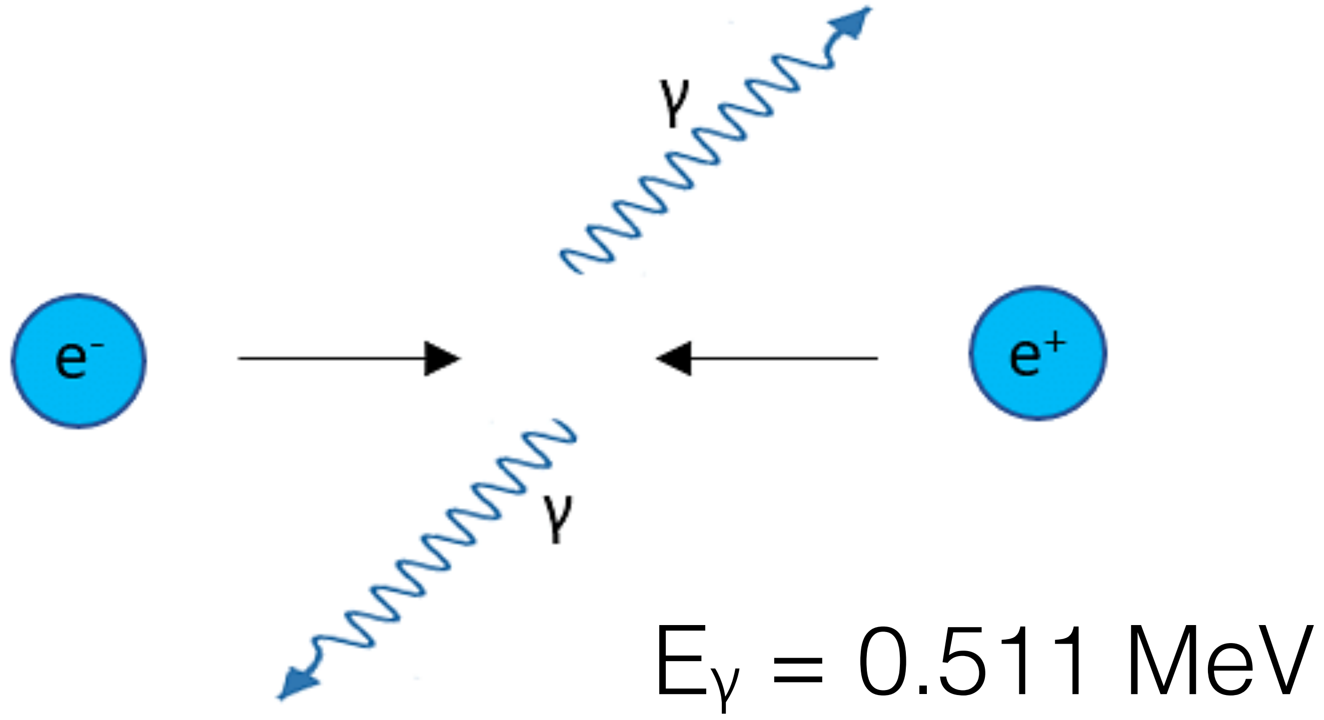
e.g. supernovae, merging neutron stars



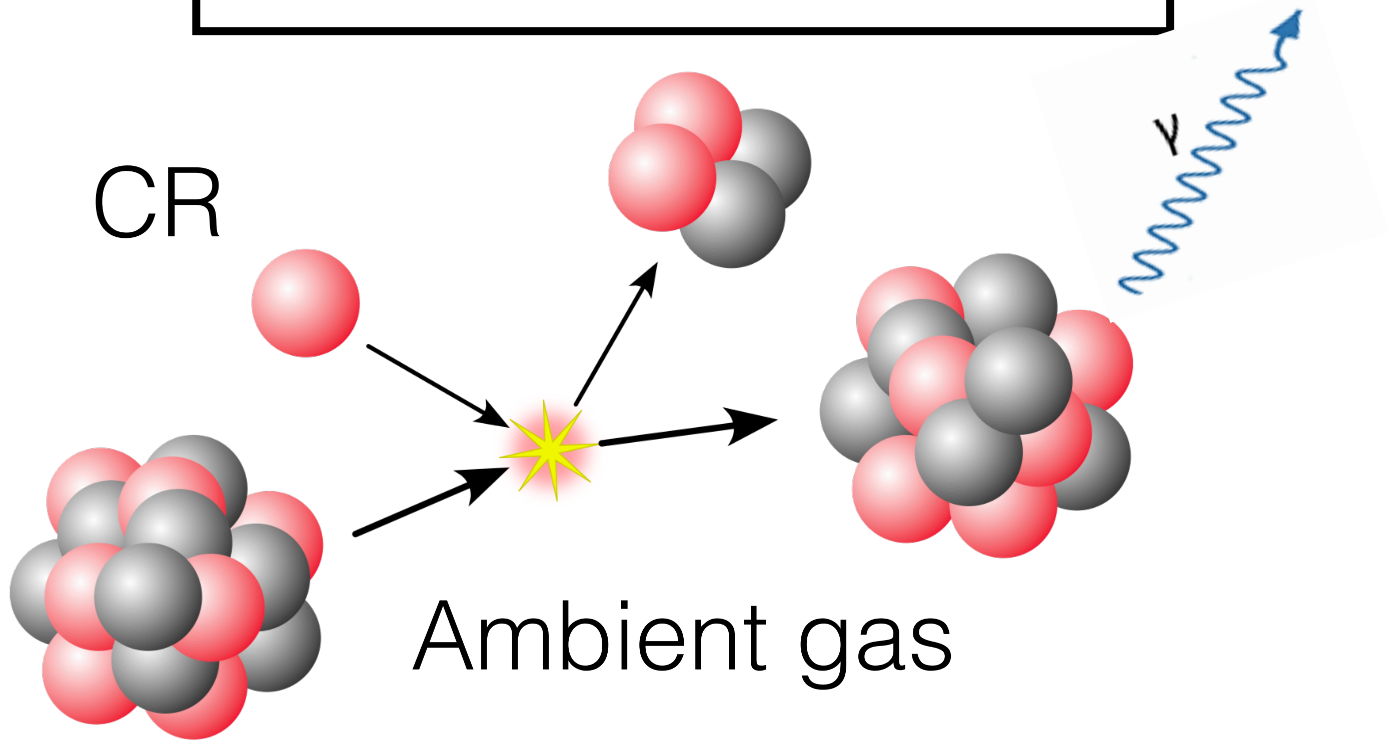
Nucleus	E_γ
^{60}Fe	1.17, 1.33 MeV
^{44}Ti	1.15 MeV
^{26}Al	1.81 MeV
^{56}Co	0.85 MeV

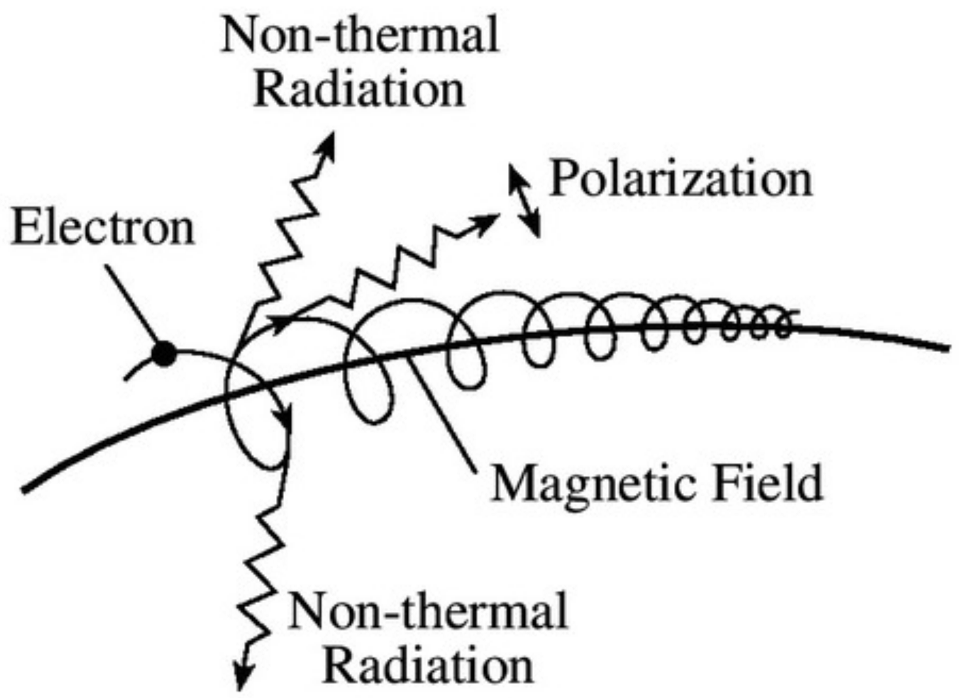
Anti-matter

e.g. supernovae, star flares, pulsars
dark matter annihilation, etc



Particle Acceleration



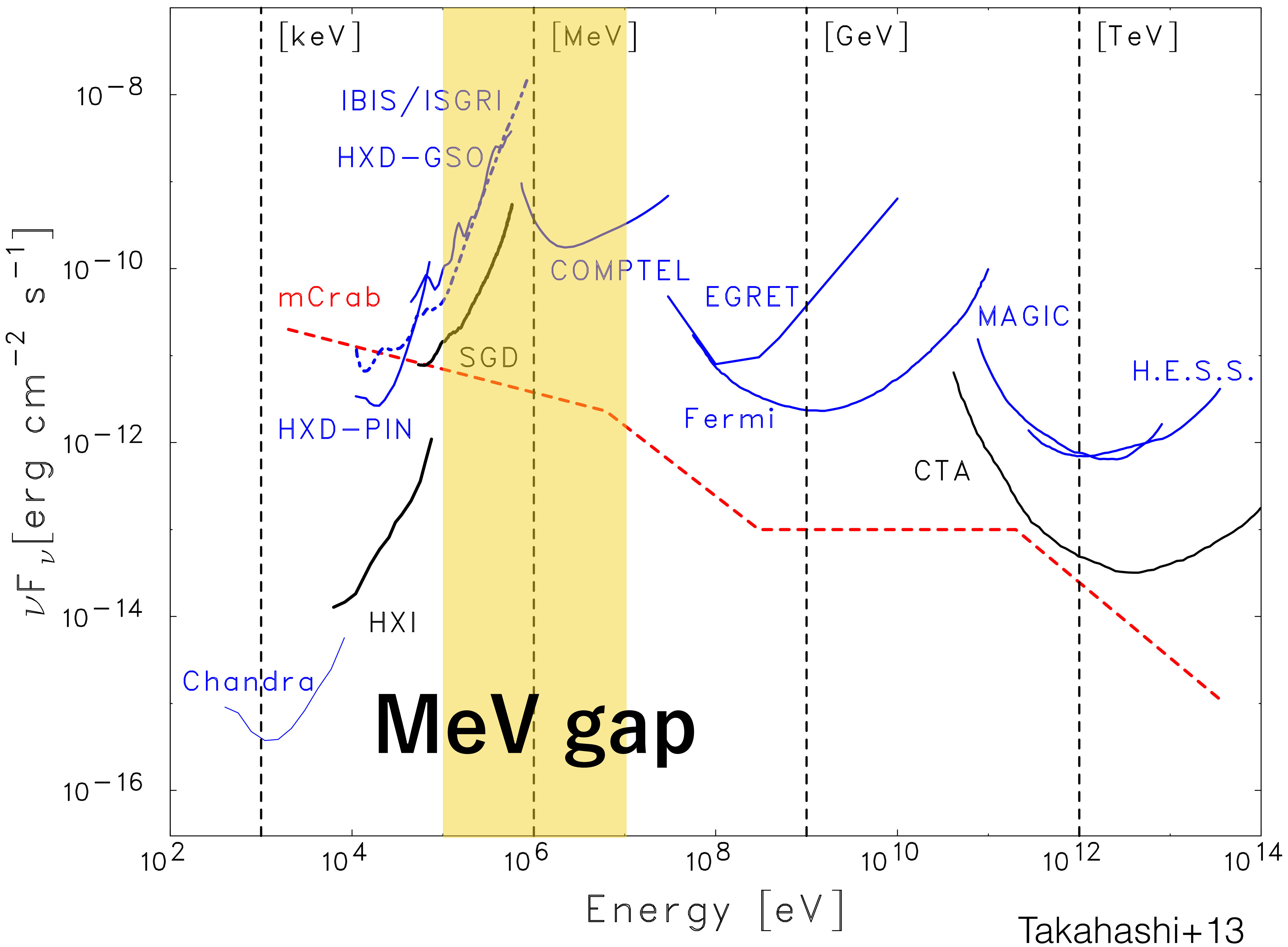


Gamma-rays with specific energies are emitted from radioisotopes, anti-matter, and high-energy particles

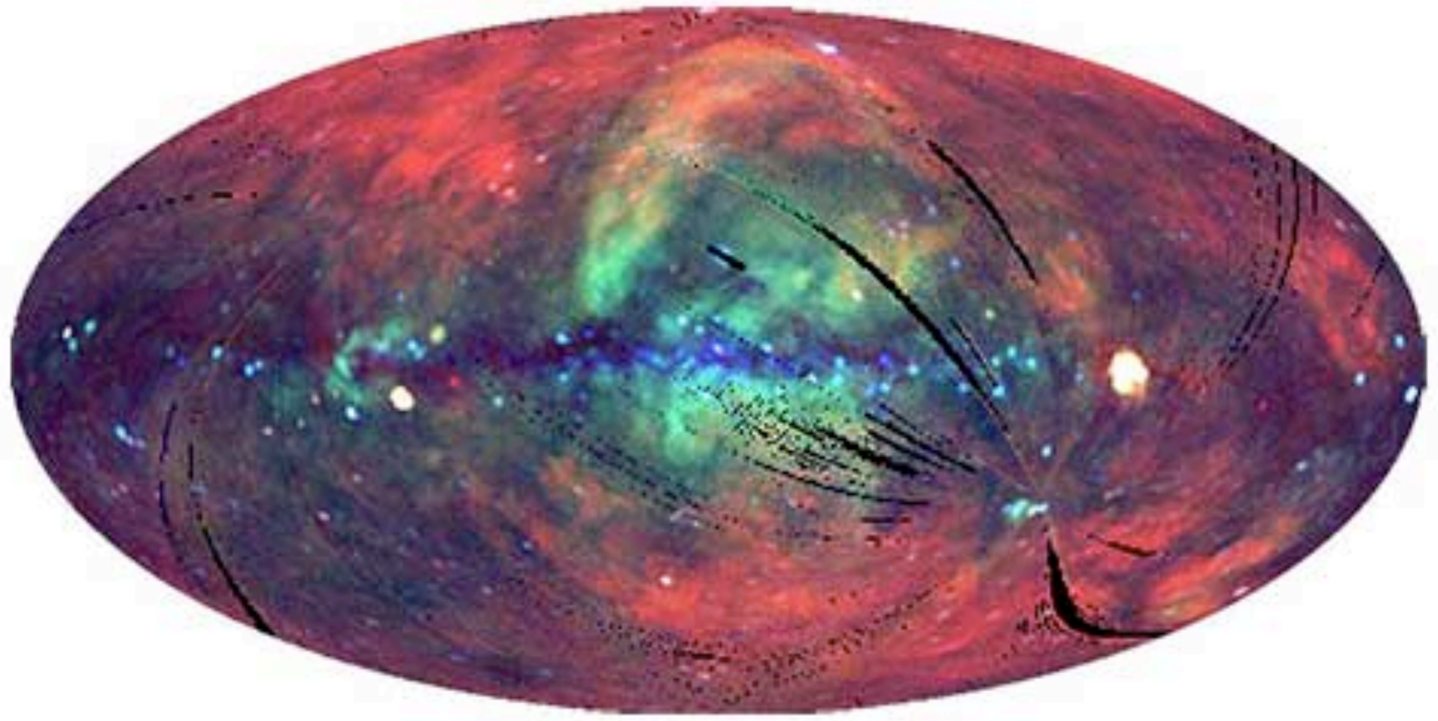
MeV photons are a direct tracer of the cosmic matter production

The MeV Gap in Gamma-ray Astronomy

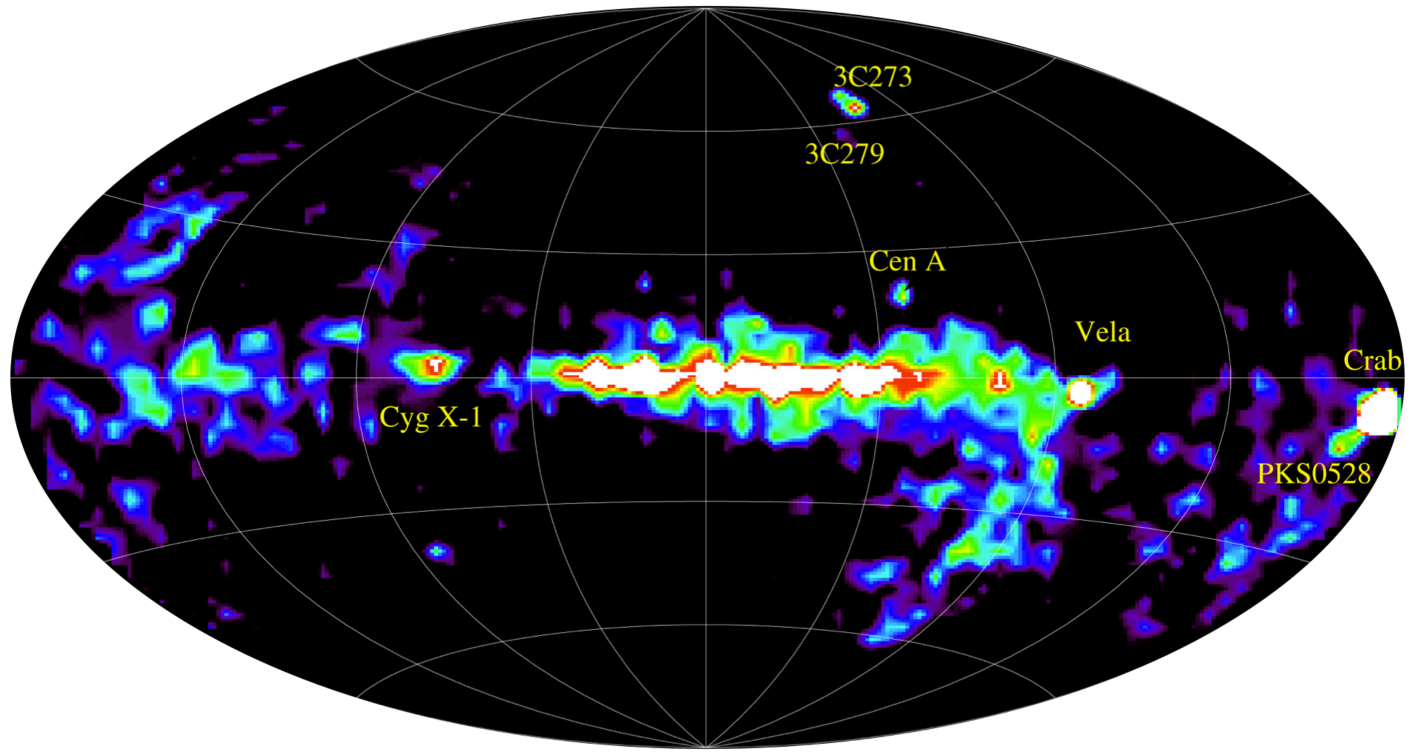
Achieved sensitivity from X-rays to the TeV band



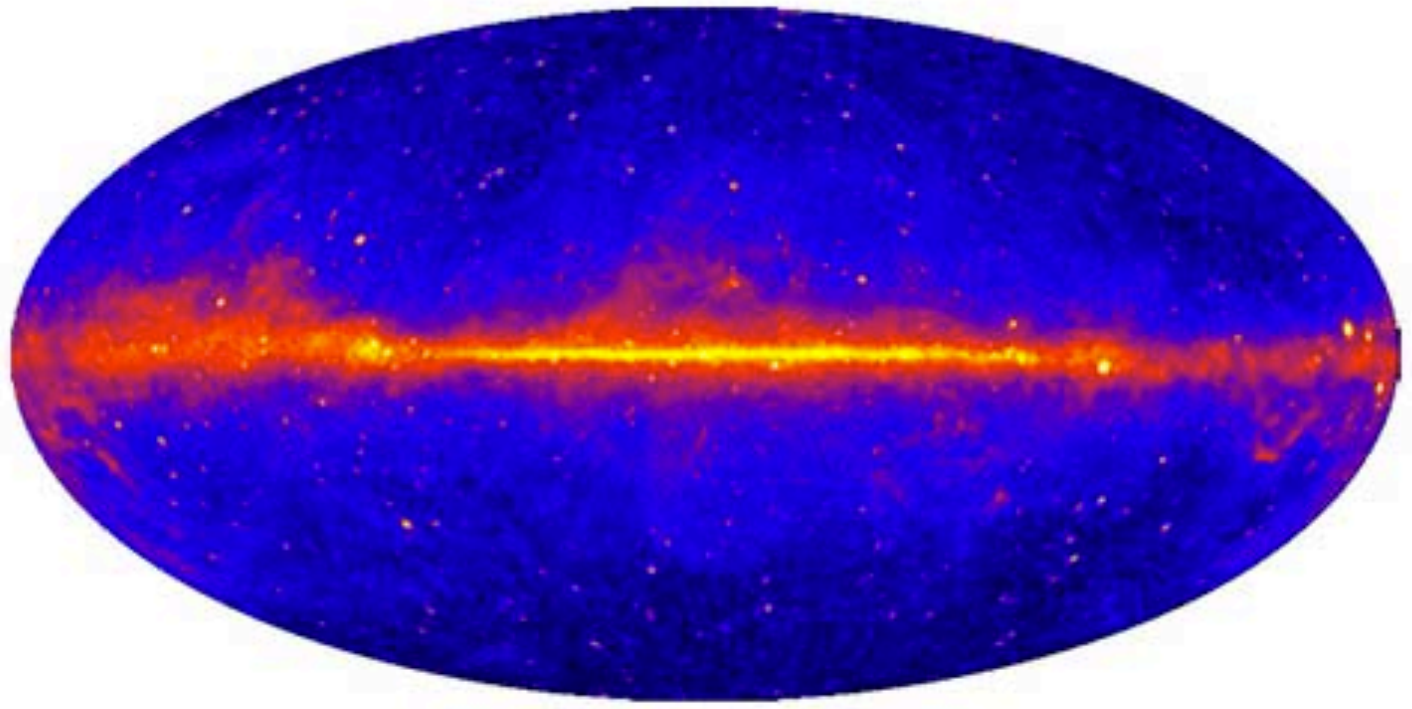
Takahashi+13



X-ray
~10^6 sources



MeV gamma-ray
(COMPTEL/CGRO, 1991-2000)
~30 sources

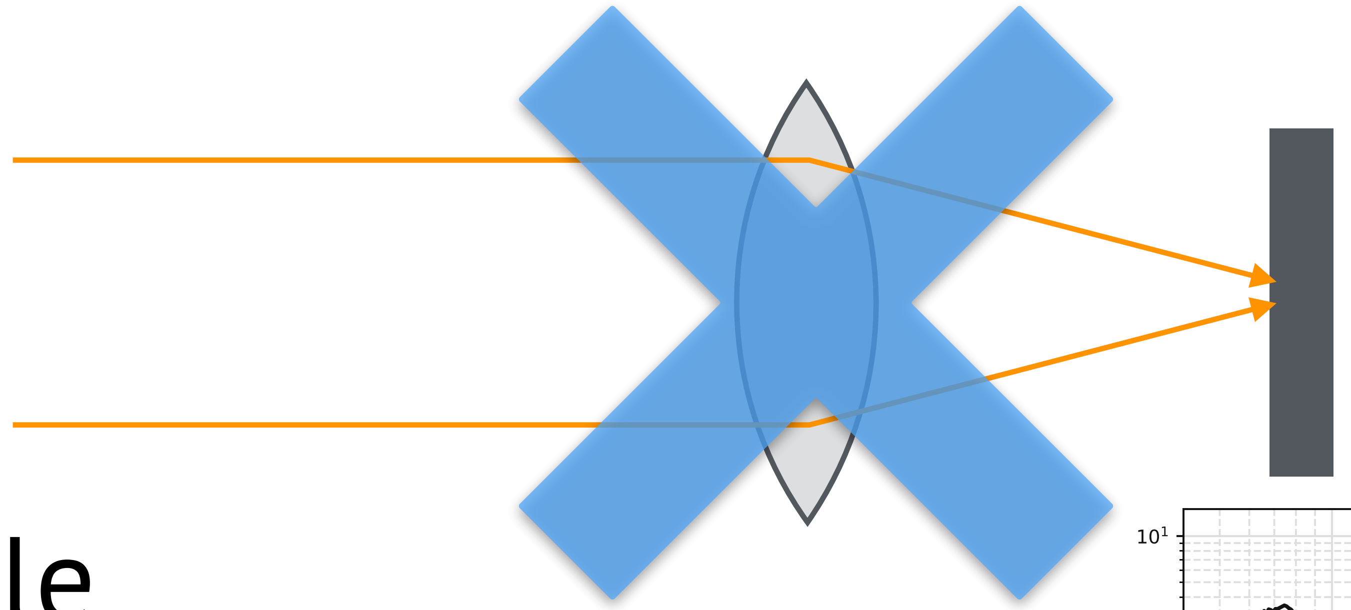


GeV gamma-ray
~5000 sources

Challenges in MeV gamma-ray observations

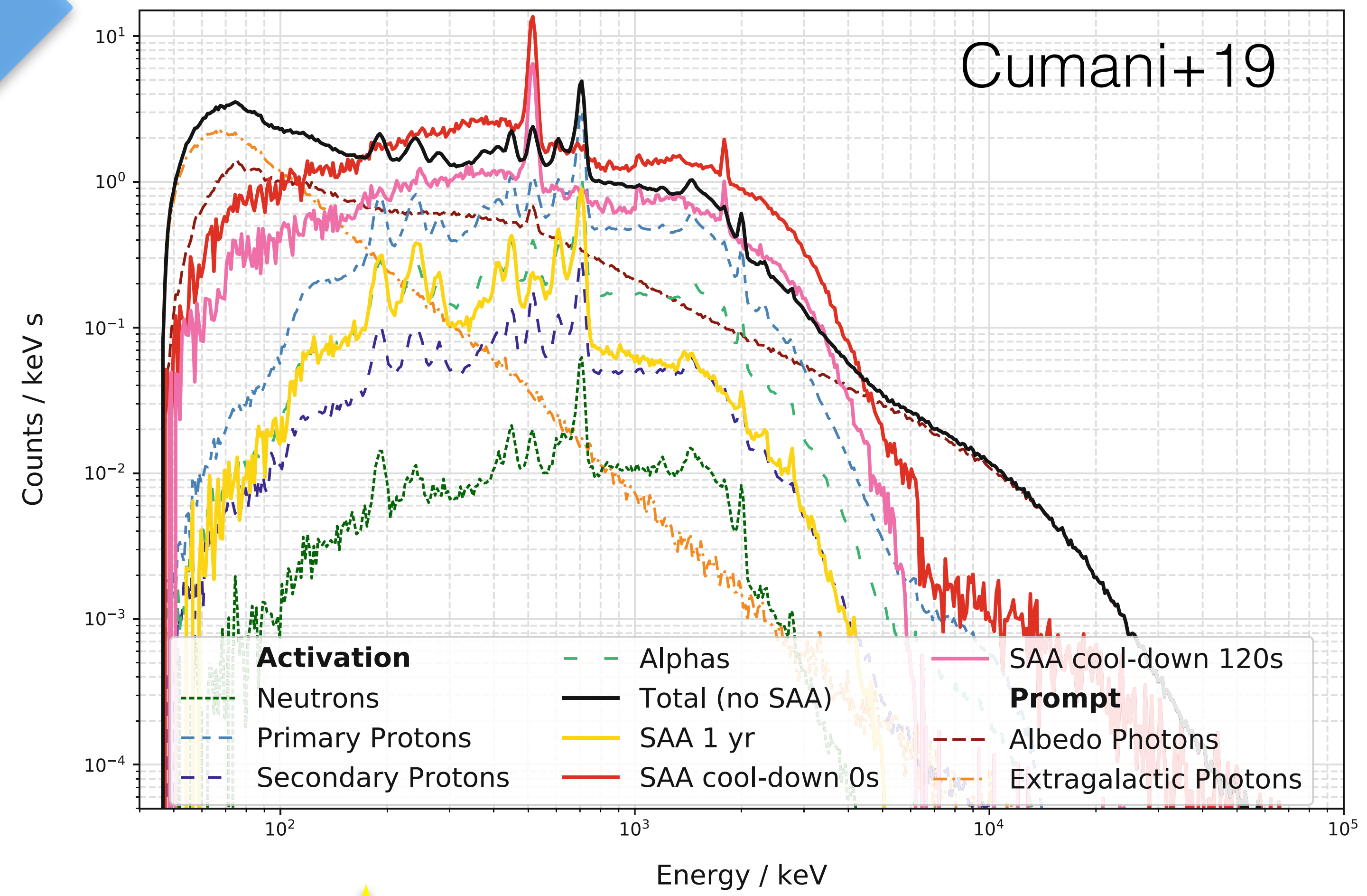
Limited Imaging Capabilities

- ✦ X-rays: focusing mirrors work well
- ✦ GeV gamma-rays: pair conversion tracking
- ✦ MeV: no efficient focusing currently possible



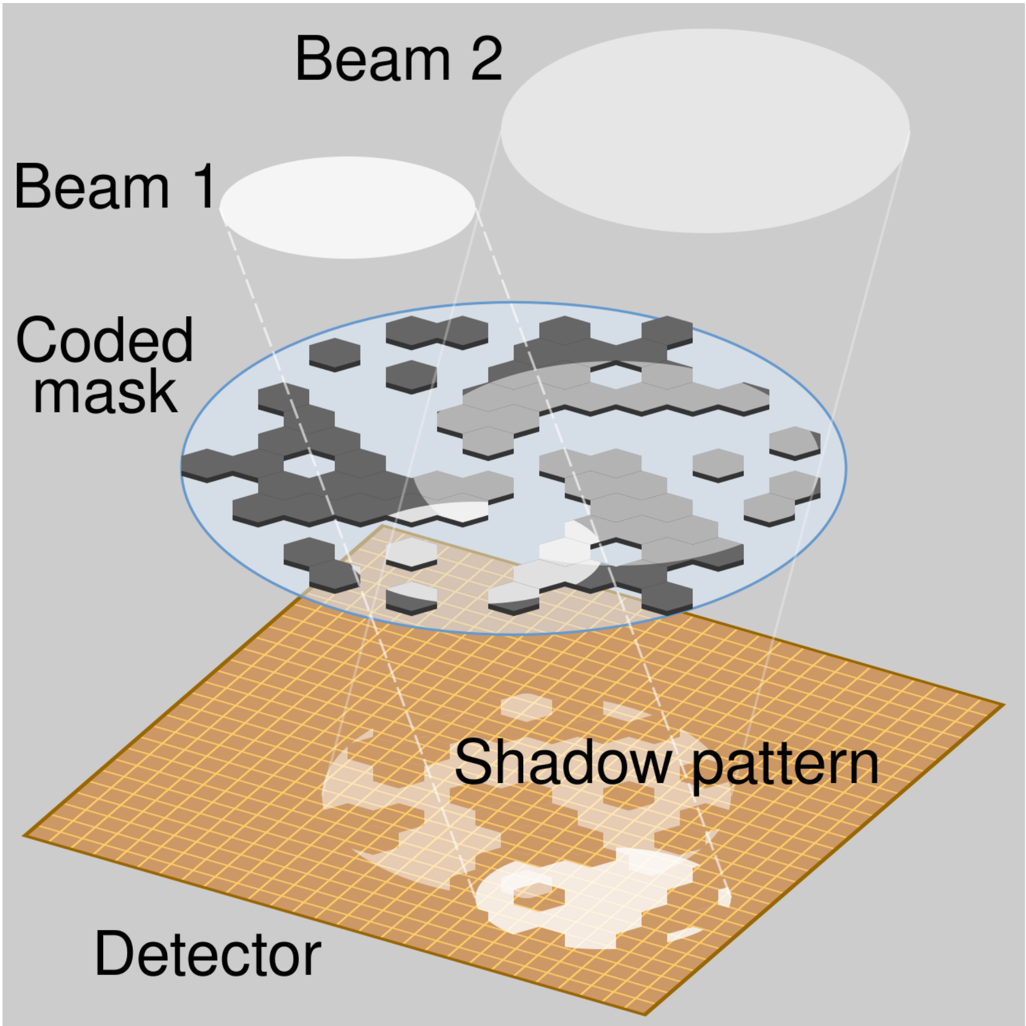
High Background Environment (S/B < a few %)

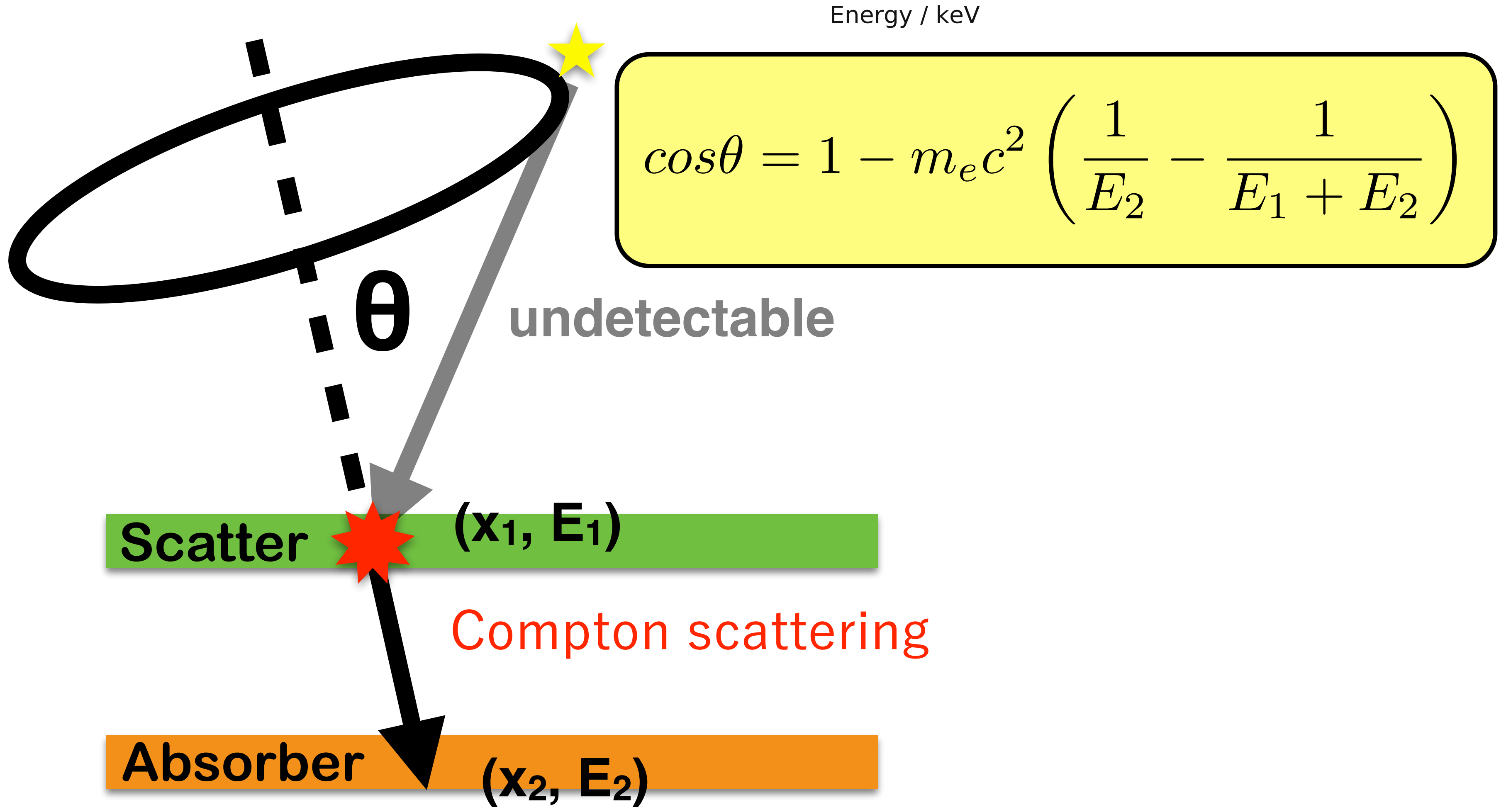
- ✦ Cosmic ray interactions in spacecraft/atmosphere
- ✦ Satellites themselves are bright in MeV gamma rays



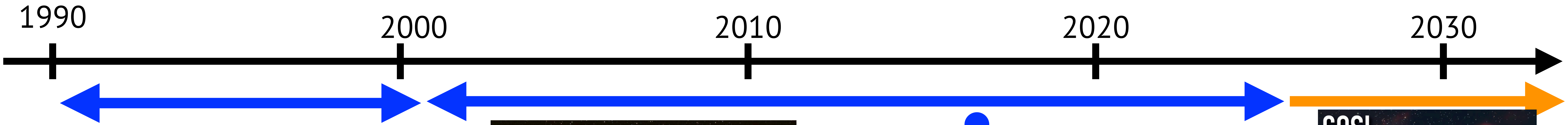
Indirect imaging methods

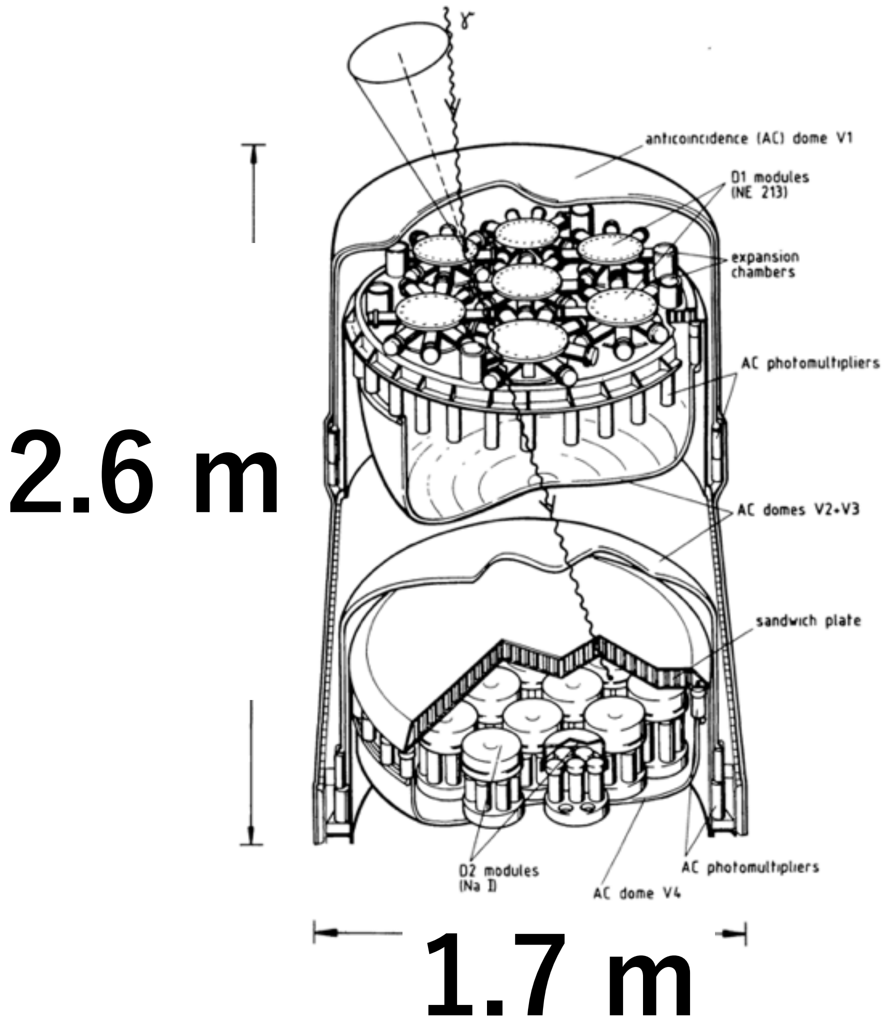
- ✦ **Coded masks**
- ✦ **Compton telescopes**





Current Status achieved by COMPTEL, INTEGRAL and Hitomi/SGD





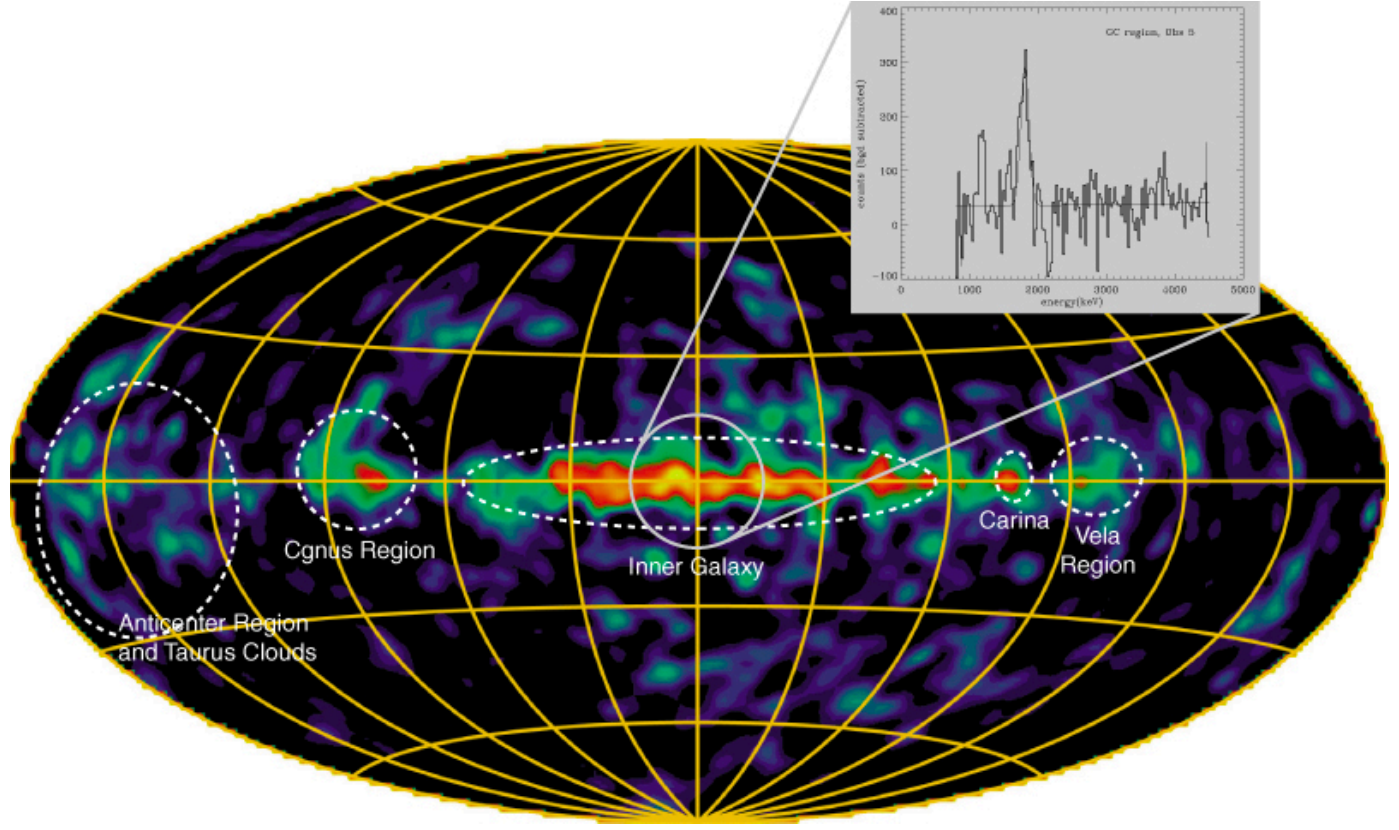
COMPTEL, NASA
(Compton telescope)
(1991-2000)

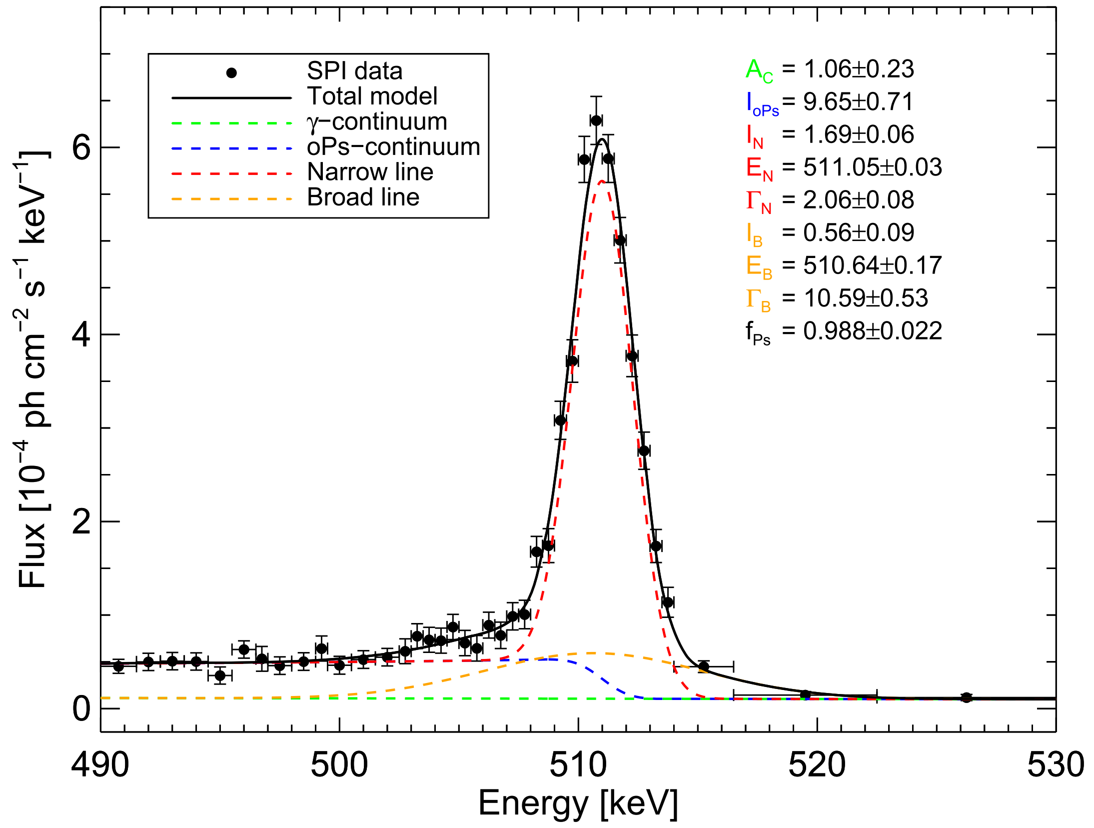
INTEGRAL/SPI, ESA (coded-mask)
(2002-2025)

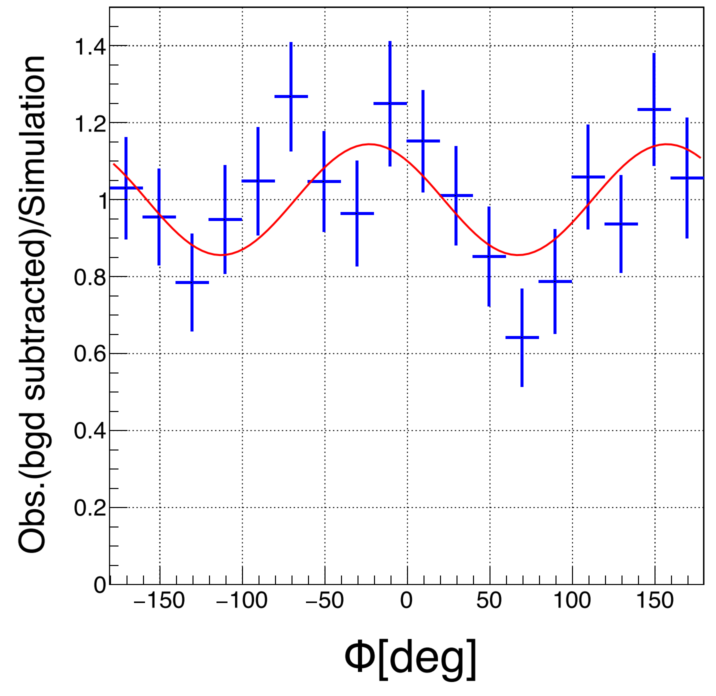
SGD/Hitomi, JAXA
(Compton telescope) (2016)

COSI, NASA
(Compton telescope)
(2027-)

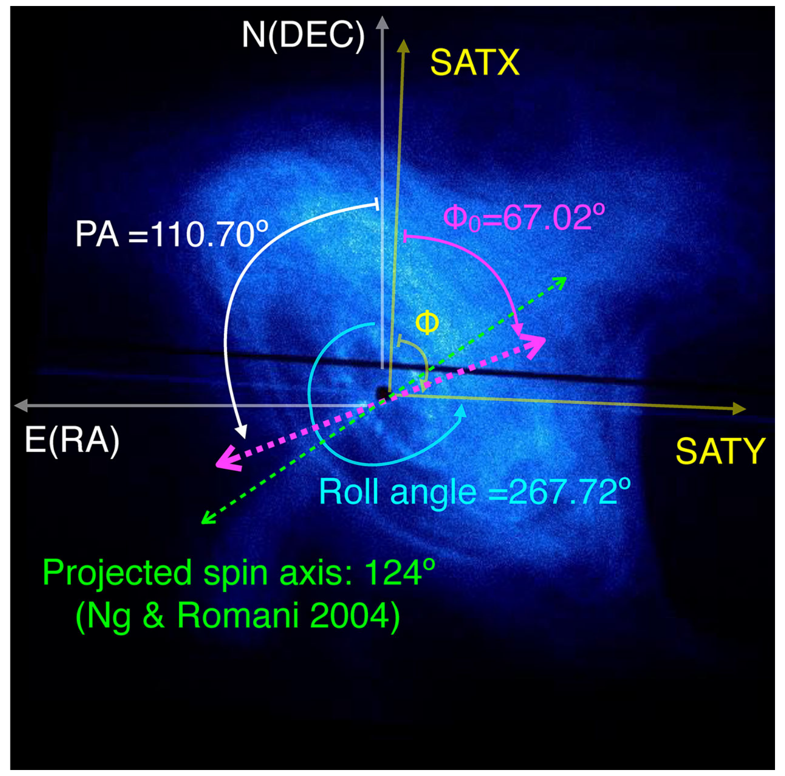
- Excellent energy resolution with semi-conductor detectors
- Compact and efficient detectors with stacking detectors







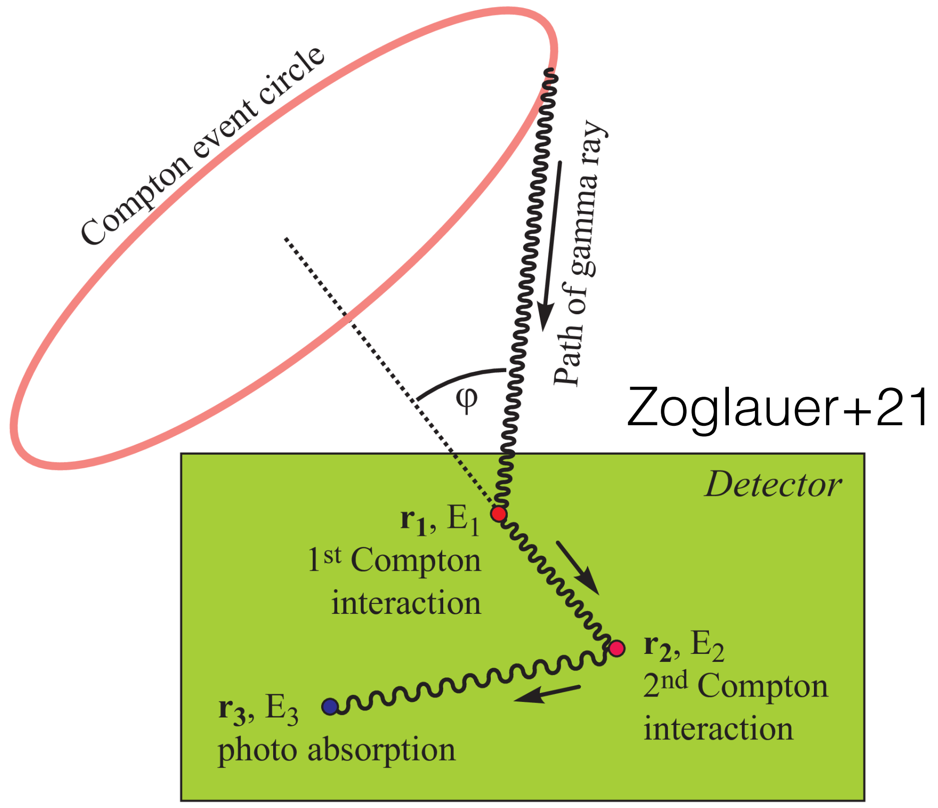
17. Modulation curve of the Crab nebula observed with SGD. The

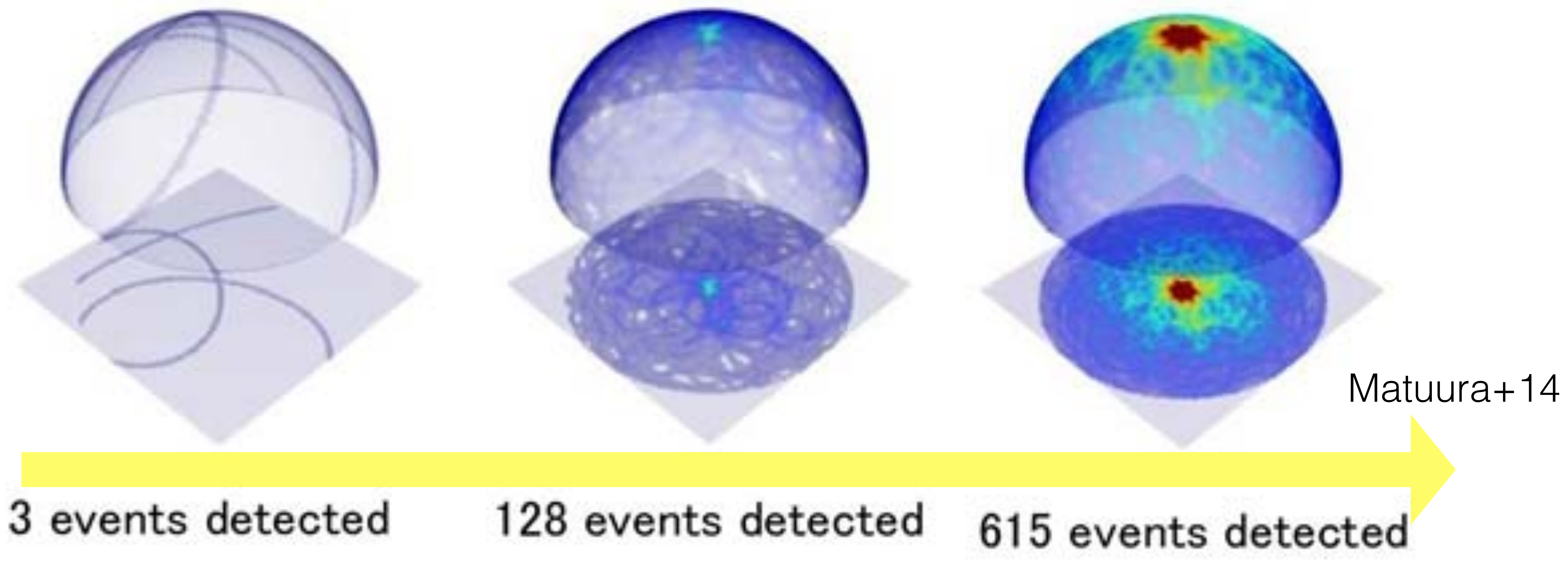


COSI: The Compton Spectrometer and Imager

Core Institutes (PI: John Tomsick)
Univ. of California (UCB, UCSD)
Naval Research Laboratory
Goddard Space Flight Center
Northrop Grumman

- An all-sky survey Compton telescope covering 0.2 - 5 MeV
- Selected as a NASA SMEX satellite
- The Critical Design Review (CDR) was successfully passed
- To be launched by SpaceX Falcon 9 in the summer of 2027



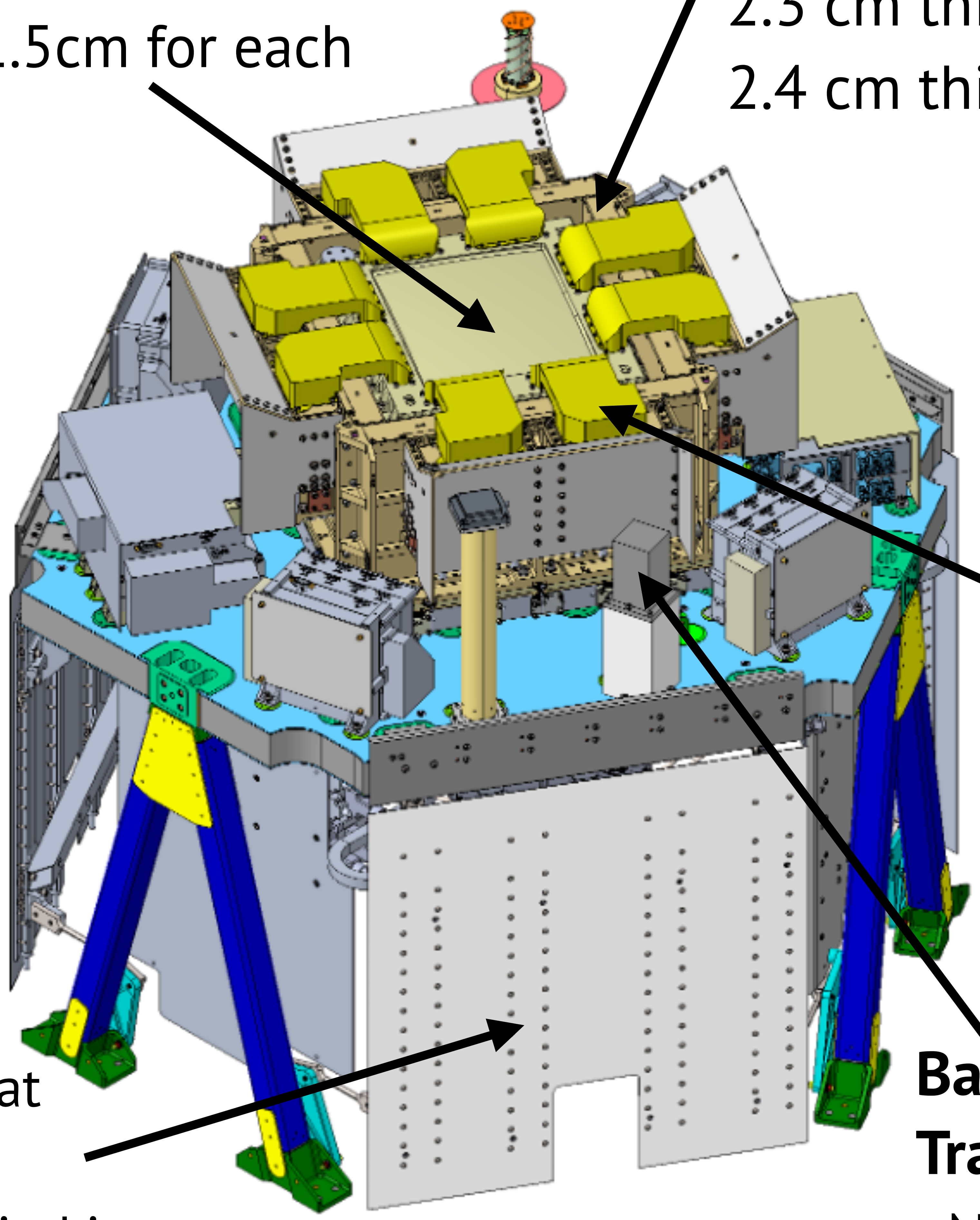


- Uses a double-sided strip germanium semiconductor detector array
  ➔ **MeV gamma-ray observations with an energy resolution of ~1%**
- Instantaneous field-of-view is ~25% of the sky
  ➔ **All-sky monitoring with a uniform exposure**

Detector Configuration and Requirement Performance

Germanium double-side strip detectors in a vacuum cryostat
2x2 x 4layer configuration
8cmx8cmx1.5cm for each

Active BGO shields
2.3 cm thickness (side)
2.4 cm thickness (bottom)



Front-end electronics with ASIC readout

Radiator for heat removal
Cryocooler behind it

Background and Transient Observer
NaI(Tl) scintillator

Germanium Compton telescope

Energy Range	0.2 - 5 MeV
Energy Resolution	6 keV @ 0.511 MeV 9 keV @ 1.157 MeV
Angular Resolution	4.1 deg @ 0.511 MeV 2.1 deg @ 1.809 MeV
FoV	25% of the sky

Background and Transient Observer

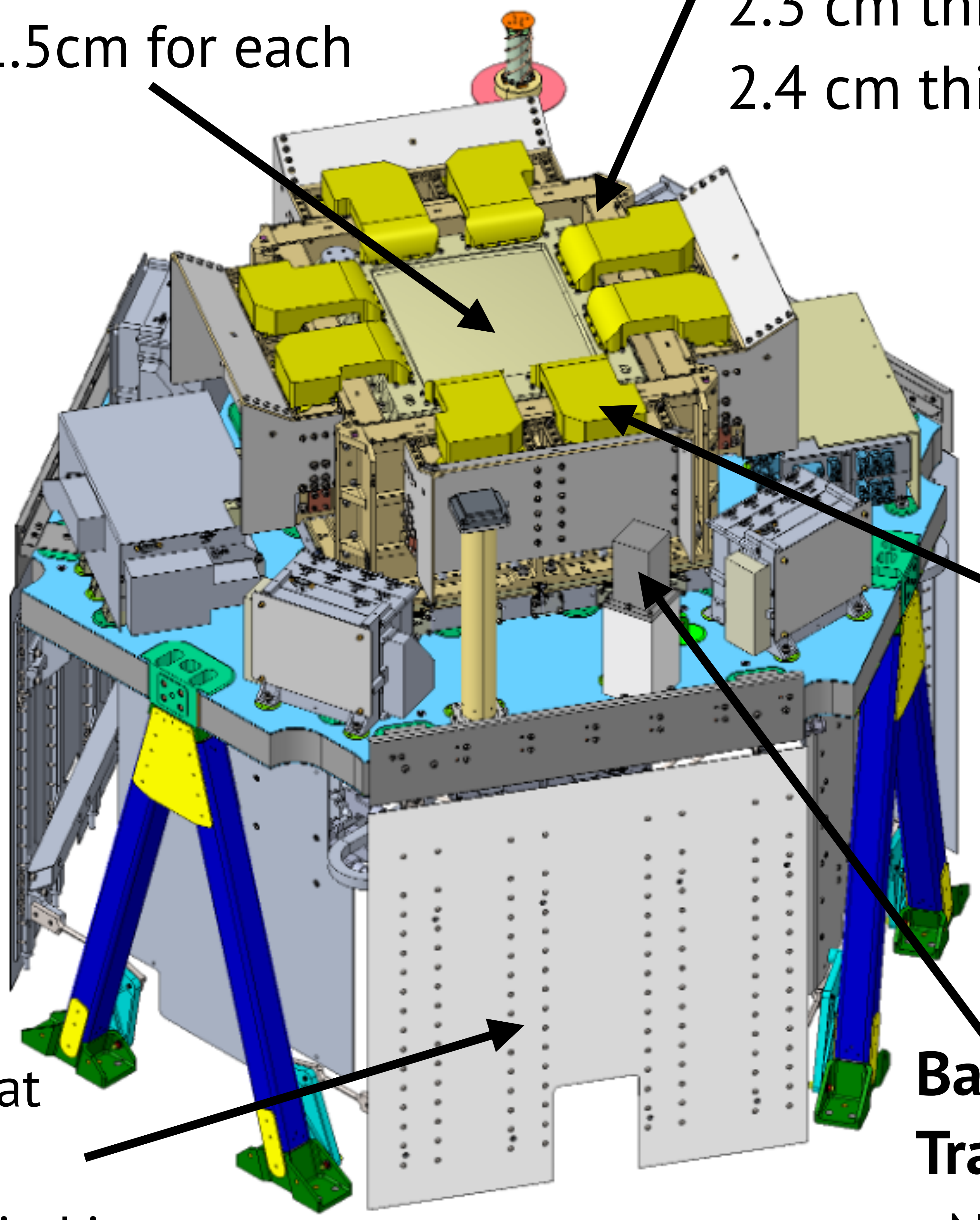
Energy Range	30 keV - 2 MeV
Energy Resolution	15% @ 662 keV
FoV	>60% of the Sky

arXiv:2308.12362

Detector Configuration and Requirement Performance

Germanium double-side strip detectors in a vacuum cryostat
2x2 x 4layer configuration
8cmx8cmx1.5cm for each

Active BGO shields
2.3 cm thickness (side)
2.4 cm thickness (bottom)

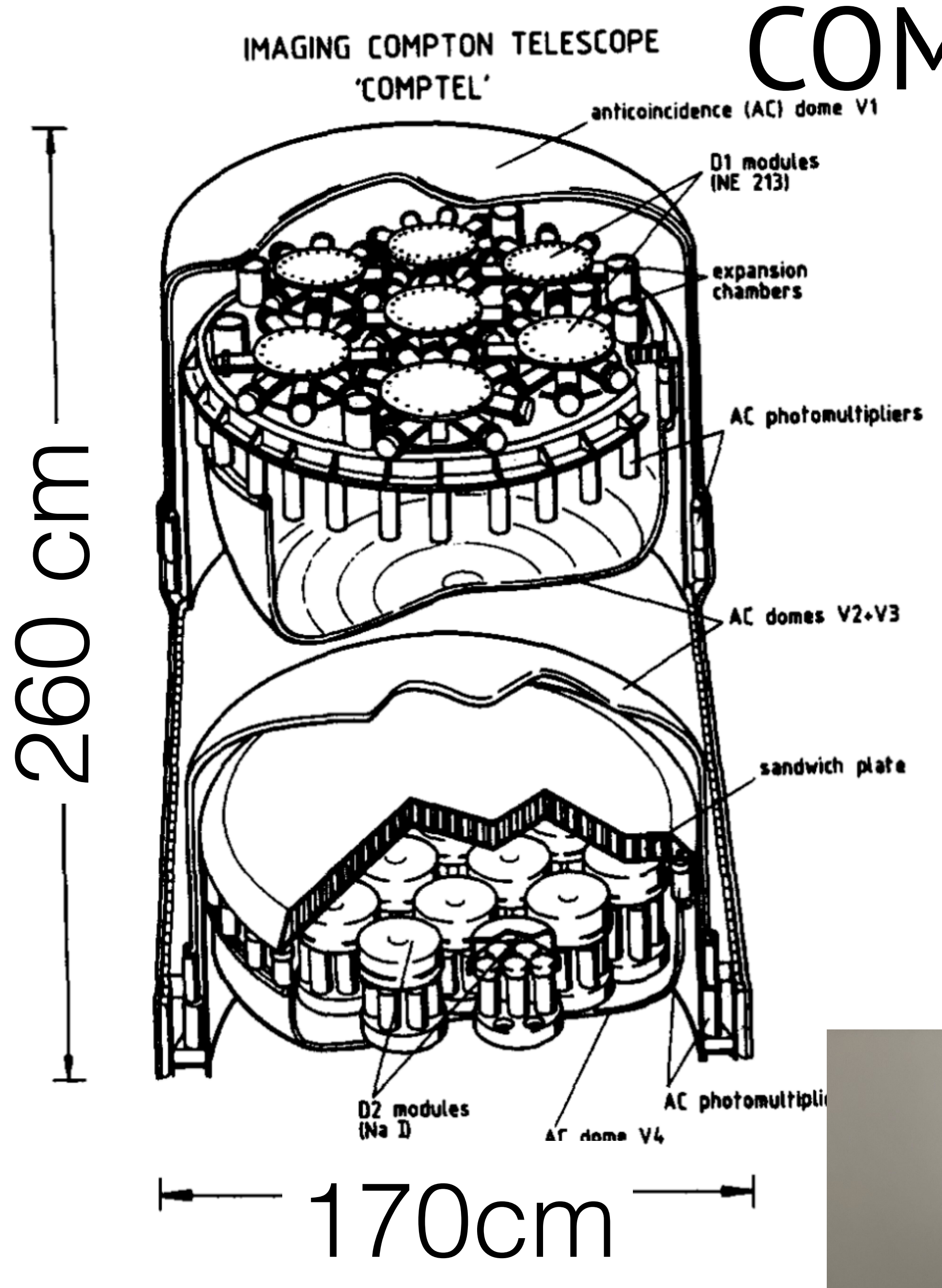


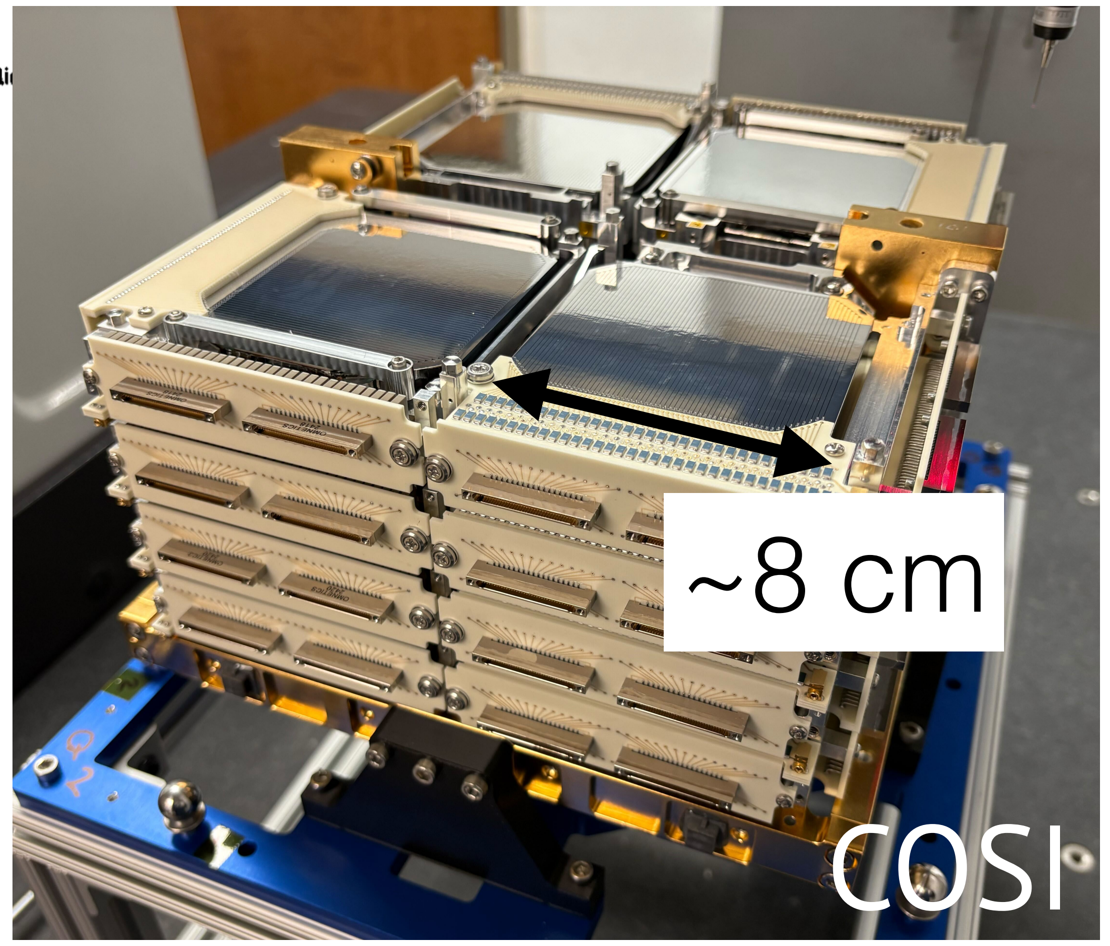
Front-end electronics with ASIC readout

Radiator for heat removal
Cryocooler behind it

Background and Transient Observer
NaI(Tl) scintillator

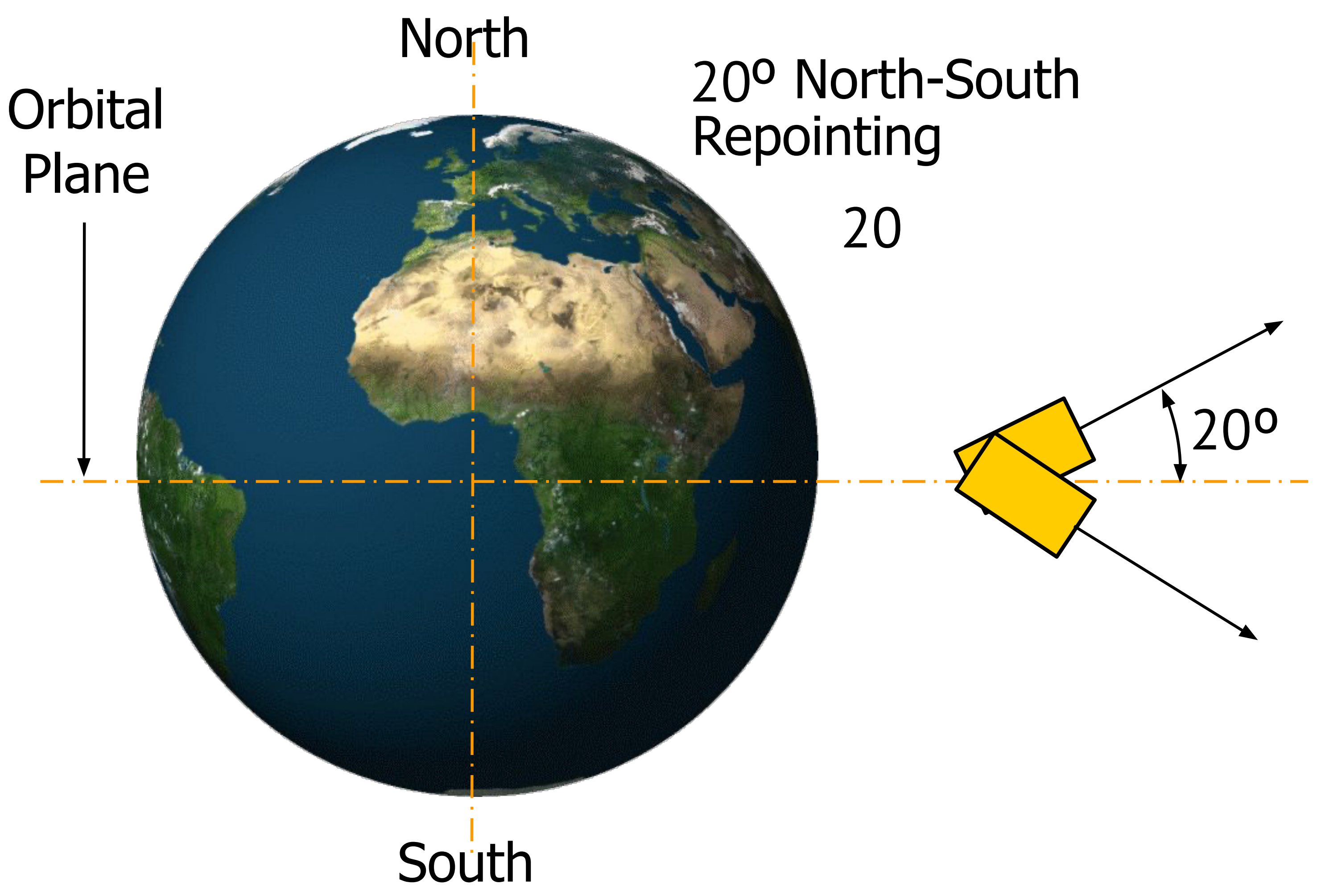
COMPTEL





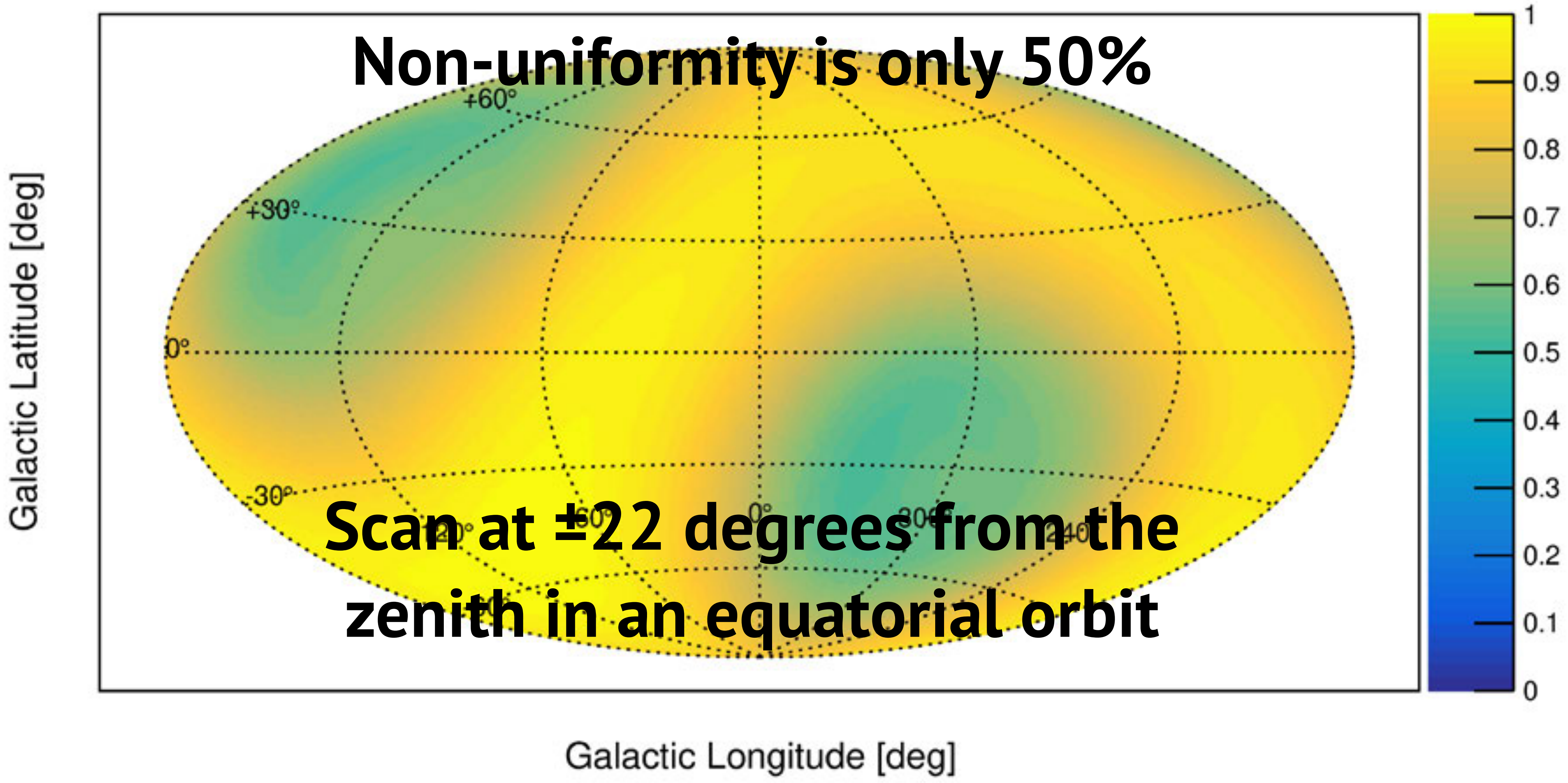
From a giant but only two layers to a compact and stacked detector

Operation and sky coverage

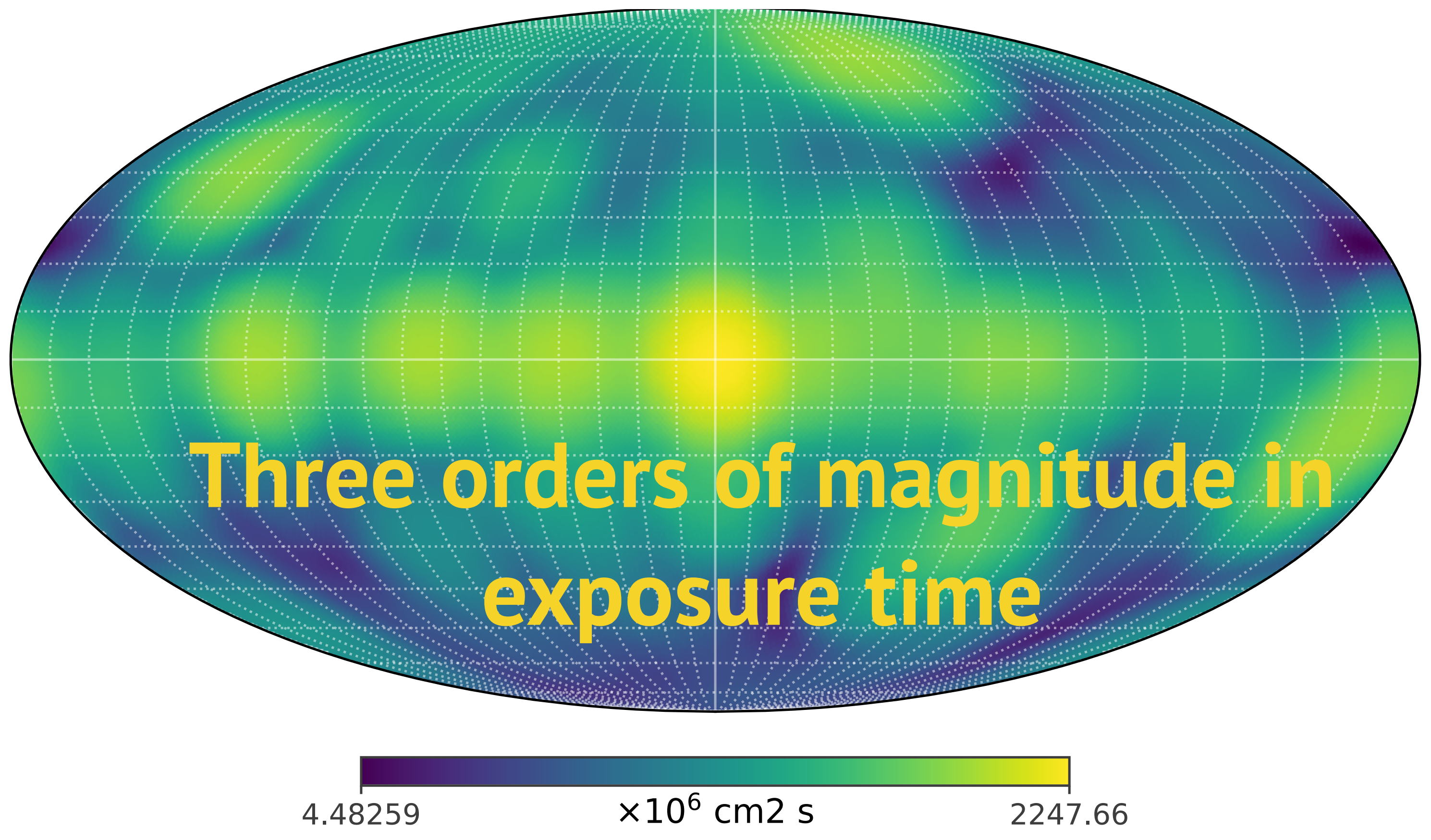


- A low-earth and near-equatorial orbit (to minimize SAA passages)
- The satellite changes its pointing from 20 deg. North to 20 deg. South with 12-hour cycle
- 25% sky coverage in a single shot

1-day exposure map



INTEGRAL/SPI 20-year exposure map



INTEGRAL→COSI

- Line sensitivity improved by up to a factor of 10
- Nearly uniform all-sky exposure

Observation Performance

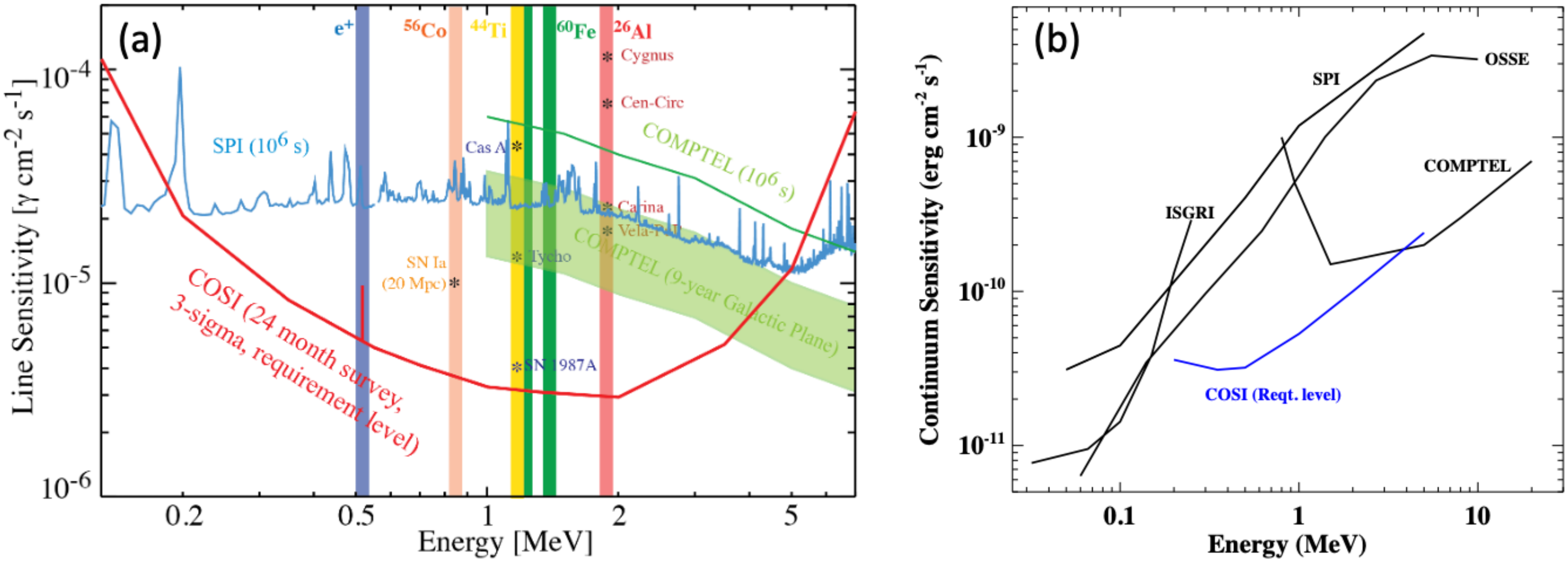
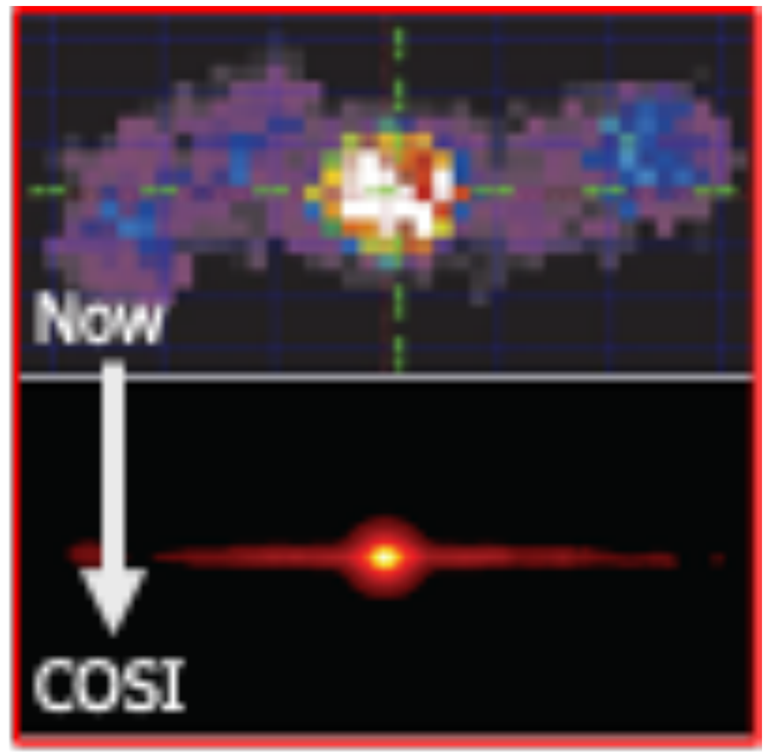


Figure 2: Narrow-line (a) and continuum (b) sensitivities based on COSI's requirements compared to current and previous instruments. The sensitivity curves are for point sources at the 3-σ level during 2 years of COSI survey time. Due to the all-sky coverage that COSI obtains, these sensitivities will be reached for every source in the sky.

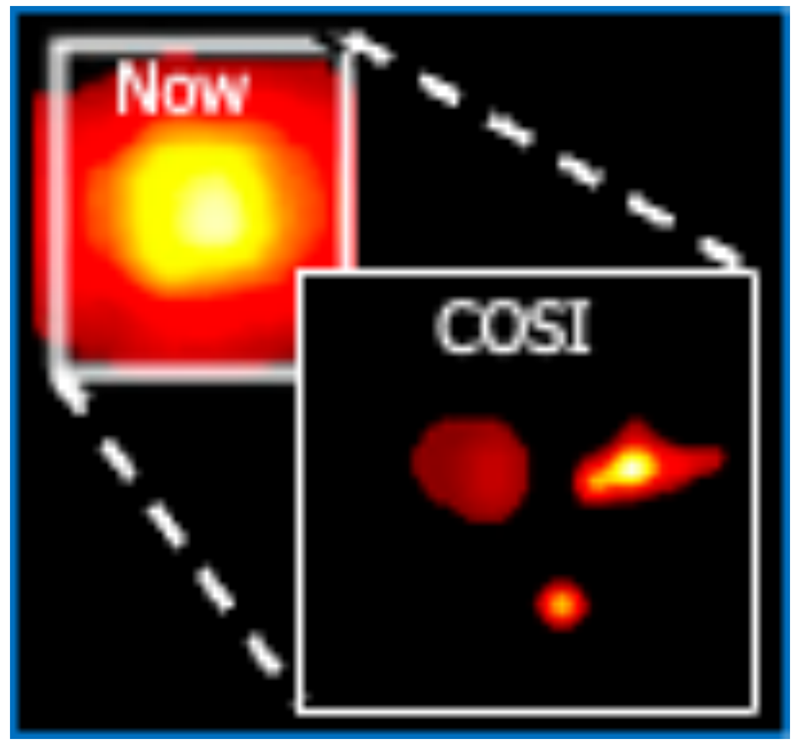
arXiv:2308.12362

Primary Science Goals of COSI



① Uncover the origin of Galactic positrons

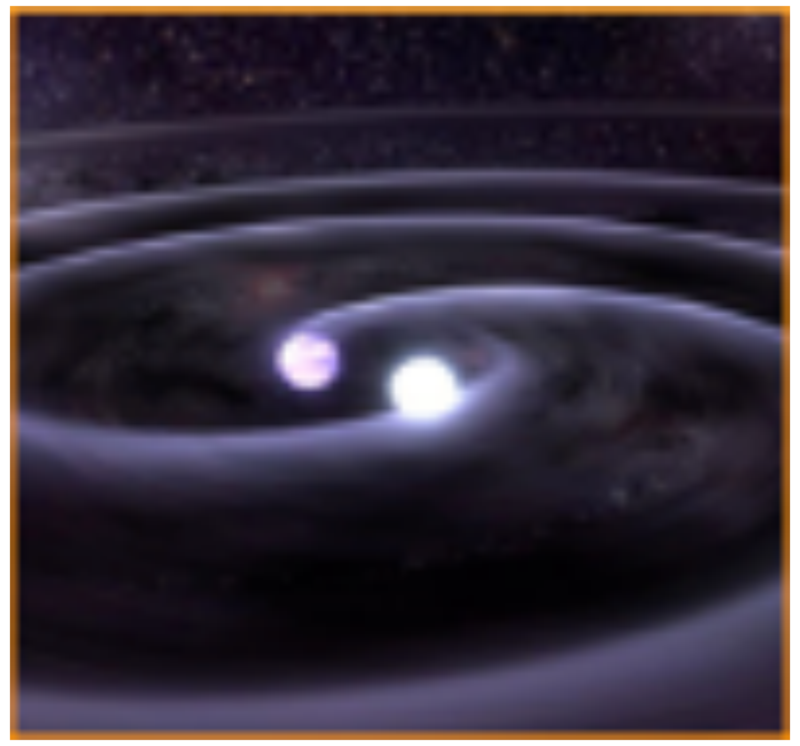
- Imaging 511 keV emission from the Galactic disk and bulge / scale-height measurement
- Constraints on positron initial energy combining o-Ps and continuum emission
- identify potential individual positron sources in the Galaxy



② Reveal Galactic element formation

- Fe-60 (1.17, 1.33 MeV), Al-26 (1.81 MeV), Ti-44 (1.16 MeV)

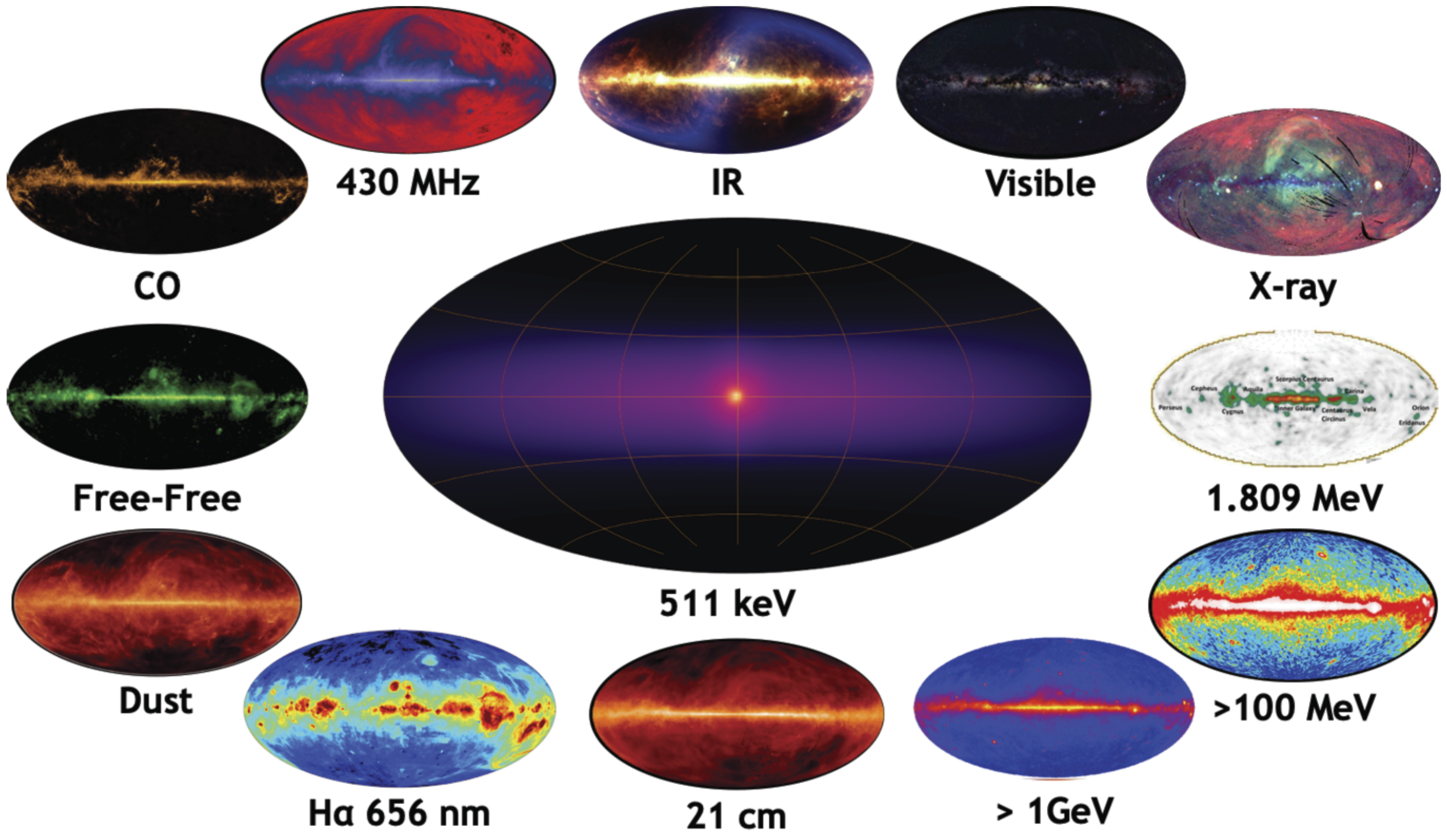
③ Gain insight into extreme environments with polarization



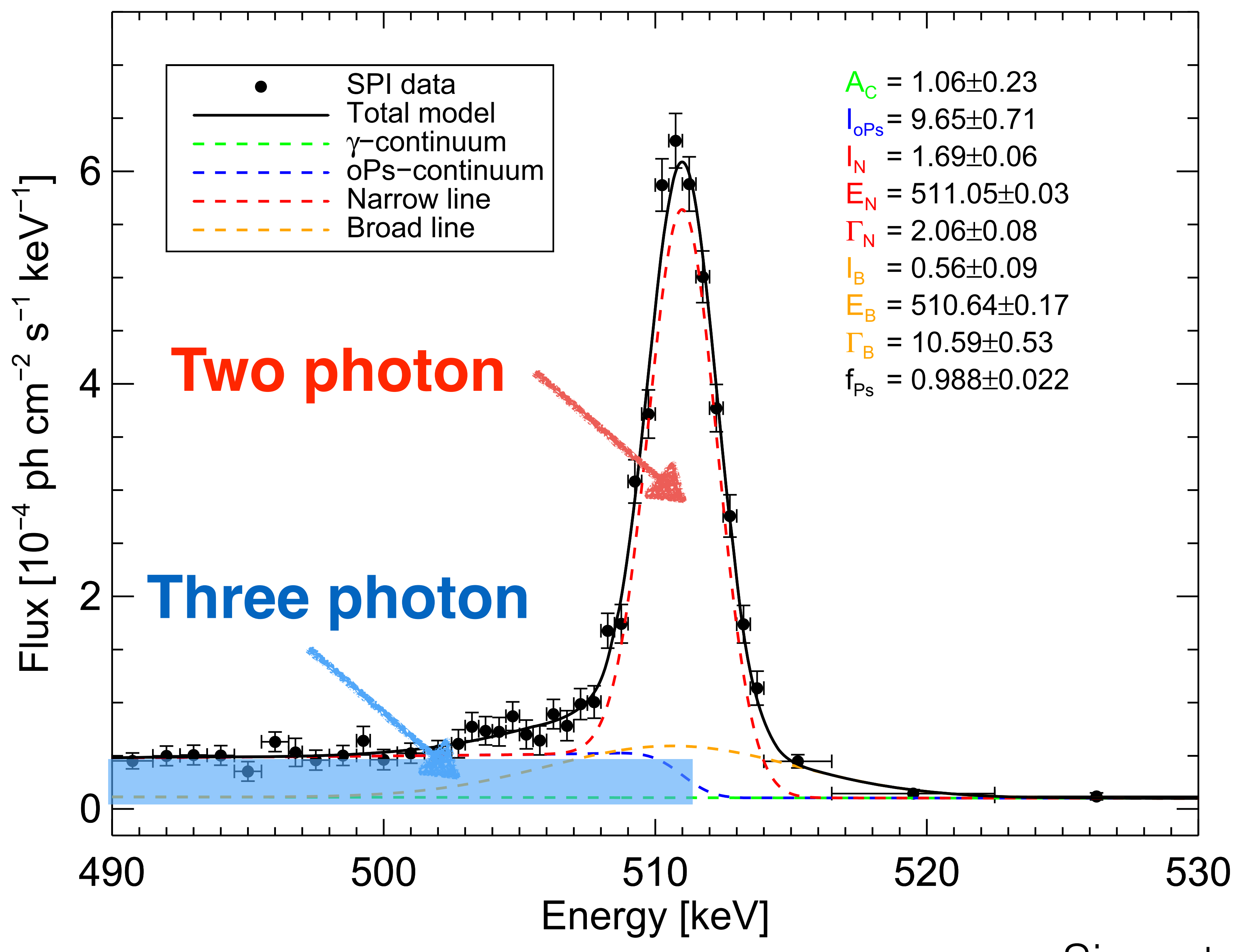
④ Probe the physics of multimessenger events

- To maximize observation time for critical transient events, constant zenith angle (CZA) observations are scheduled.

A. Uncover the origin of Galactic positrons



Line shape of the entire Galaxy



Siegert+19

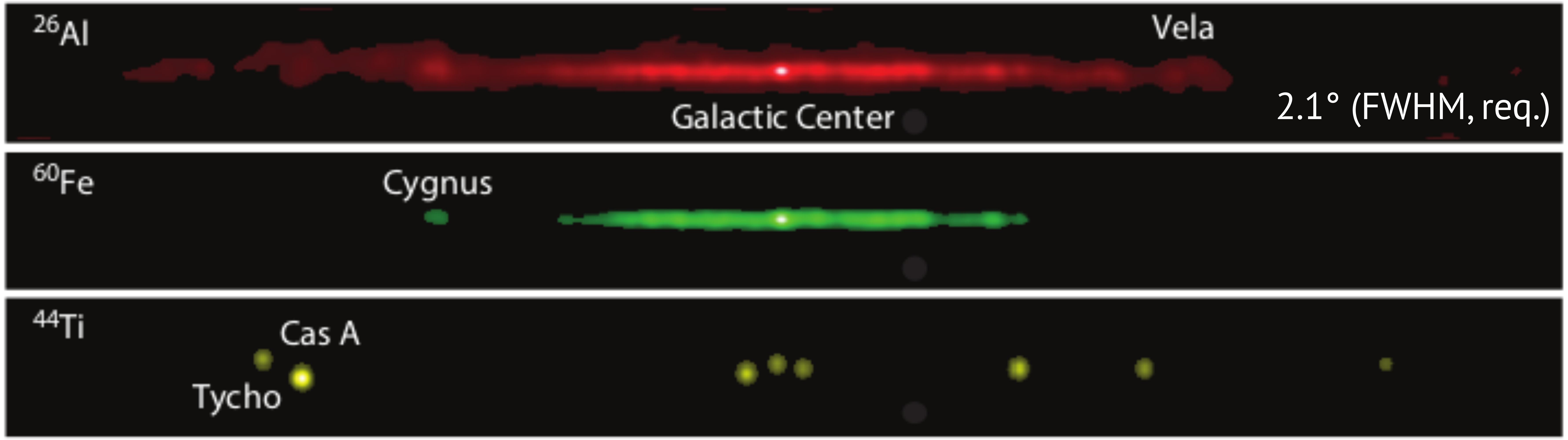
What is the positron source (β+ decaying radio isotopes, X-ray binaries, pulsars, etc.)?

- Cannot be explained by a single source

Why is the galactic center bright?, bulge/disk luminosity ratio ≈ 1.0

- Past activity of the galactic center black hole (Totani06, Cheng+07)
- Positron production from annihilation/decay of dark matter (e.g., Finkbeiner+07)

B. Reveal Galactic element formation



The tracer of the nucleosynthesis in the universe

Fe-60 (1.173&1.333 MeV, $\tau = 2.6 \times 10^6$ yr)

- Core-collapsed supernovae (CCSNe)

Al-26 (1.809 MeV, $\tau = 7.2 \times 10^5$ yr)

- massive star wind & CCSNe

Ti-44 (1.157 MeV, τ = 60 yr)

- Young SNe

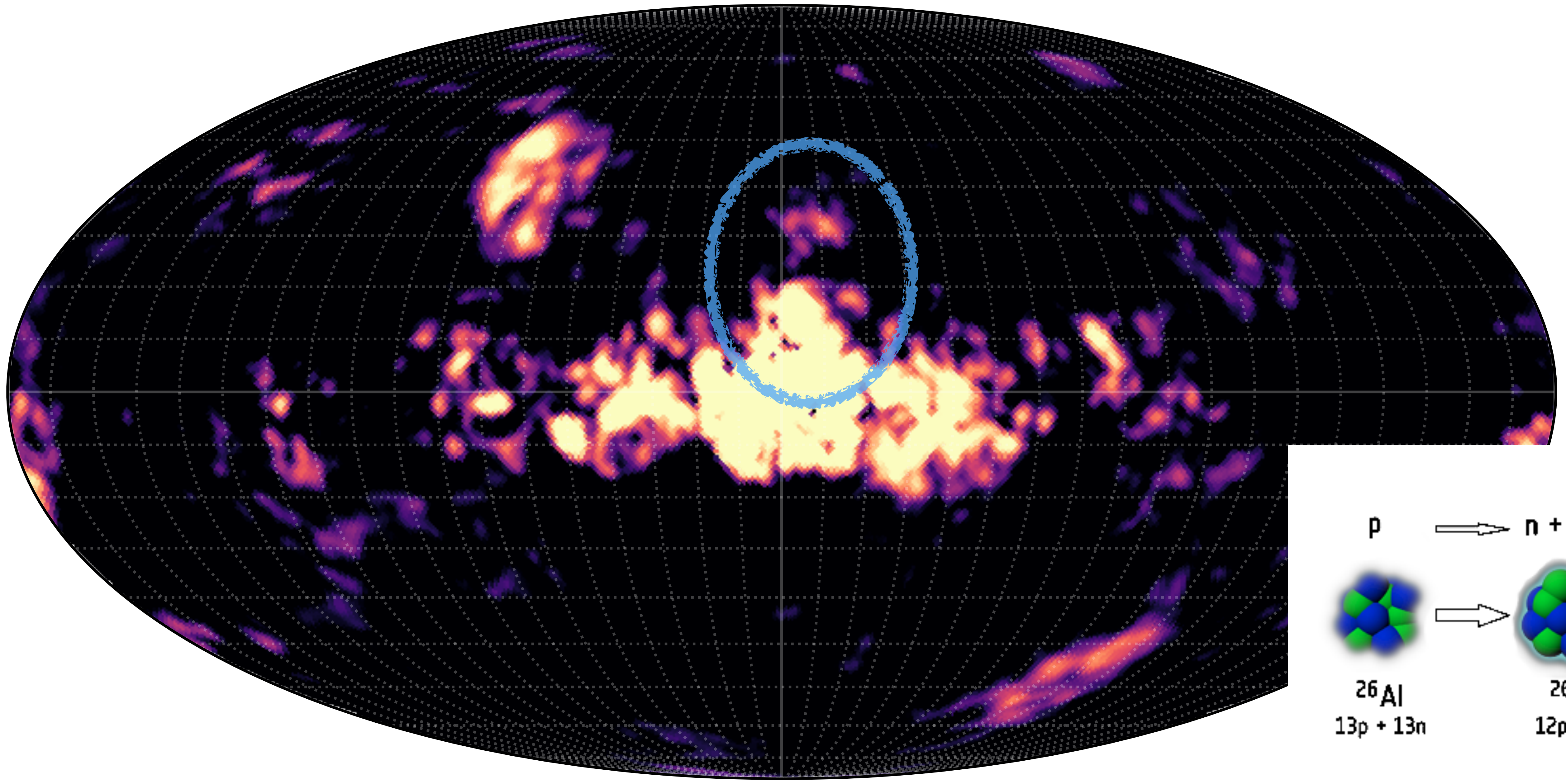
Line gamma-ray imaging with COSI

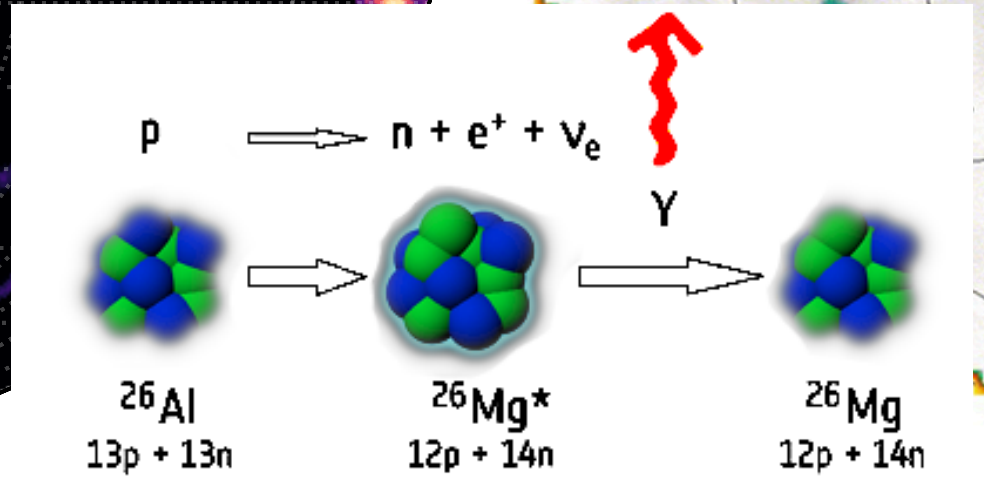
- First all-sky image of Fe-60
- Improved Al-26 image, and correlation with Fe-60
- Search for Ti-44 sources (Cas A, Tycho, SN1897A, etc.)

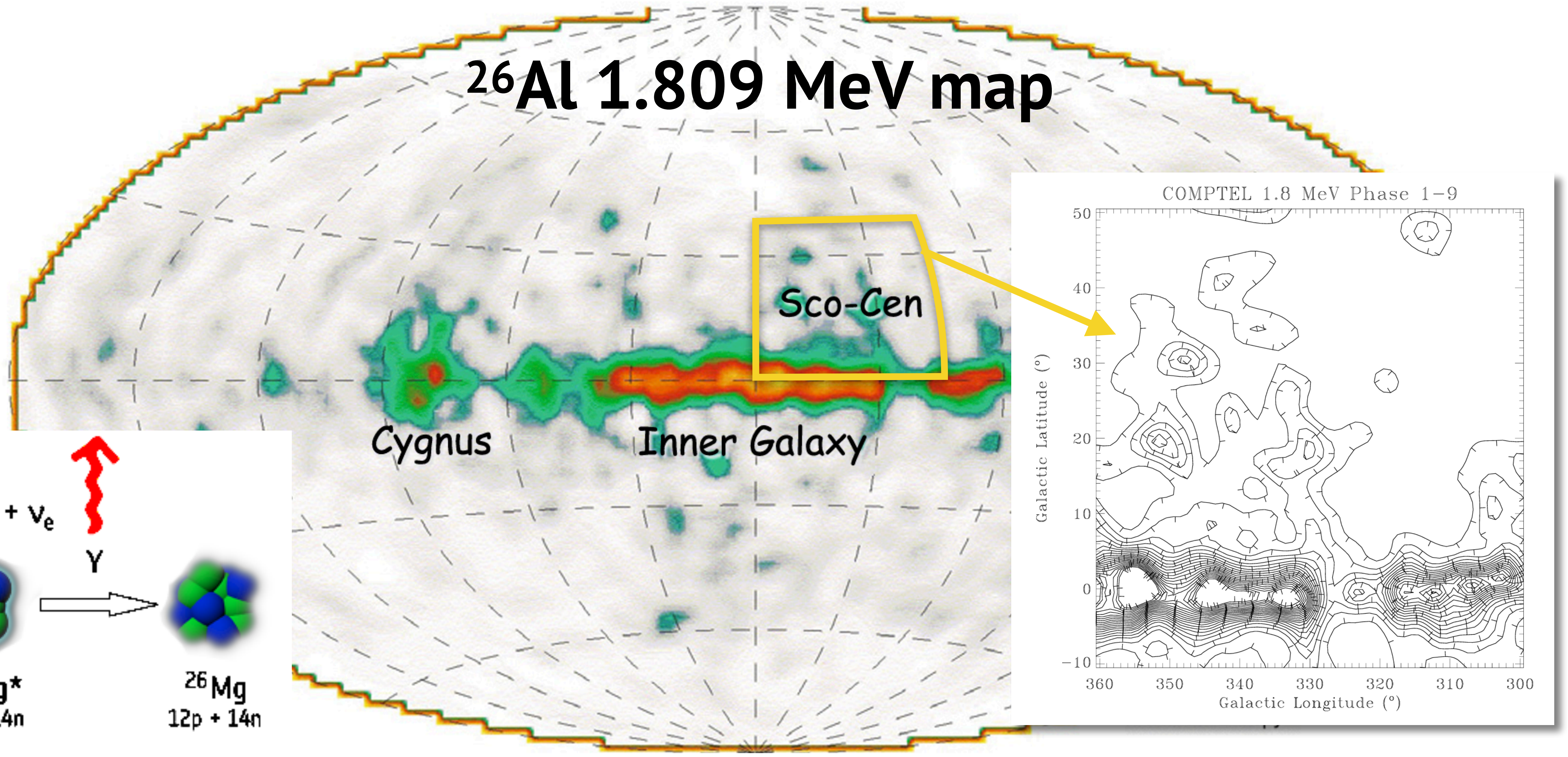
Connecting Positrons and Nucleosynthesis

- 511 keV map was updated using 20-yr INTEGRAL SPI observations (HY+25)
- 2-sigma excess of 511 keV emission detected above GC (1.4±0.8±0.5 × 10^-5 ph cm^-2 s^-1)
- Associated with ScoCen OB association (distance ~100 pc, ~100 massive stars)?
- ^{26}Al → e$^+$ → 511 keV chain?
- COSI will test this connection with better sensitivity and uniform exposure

Connecting Positrons and Nucleosynthesis







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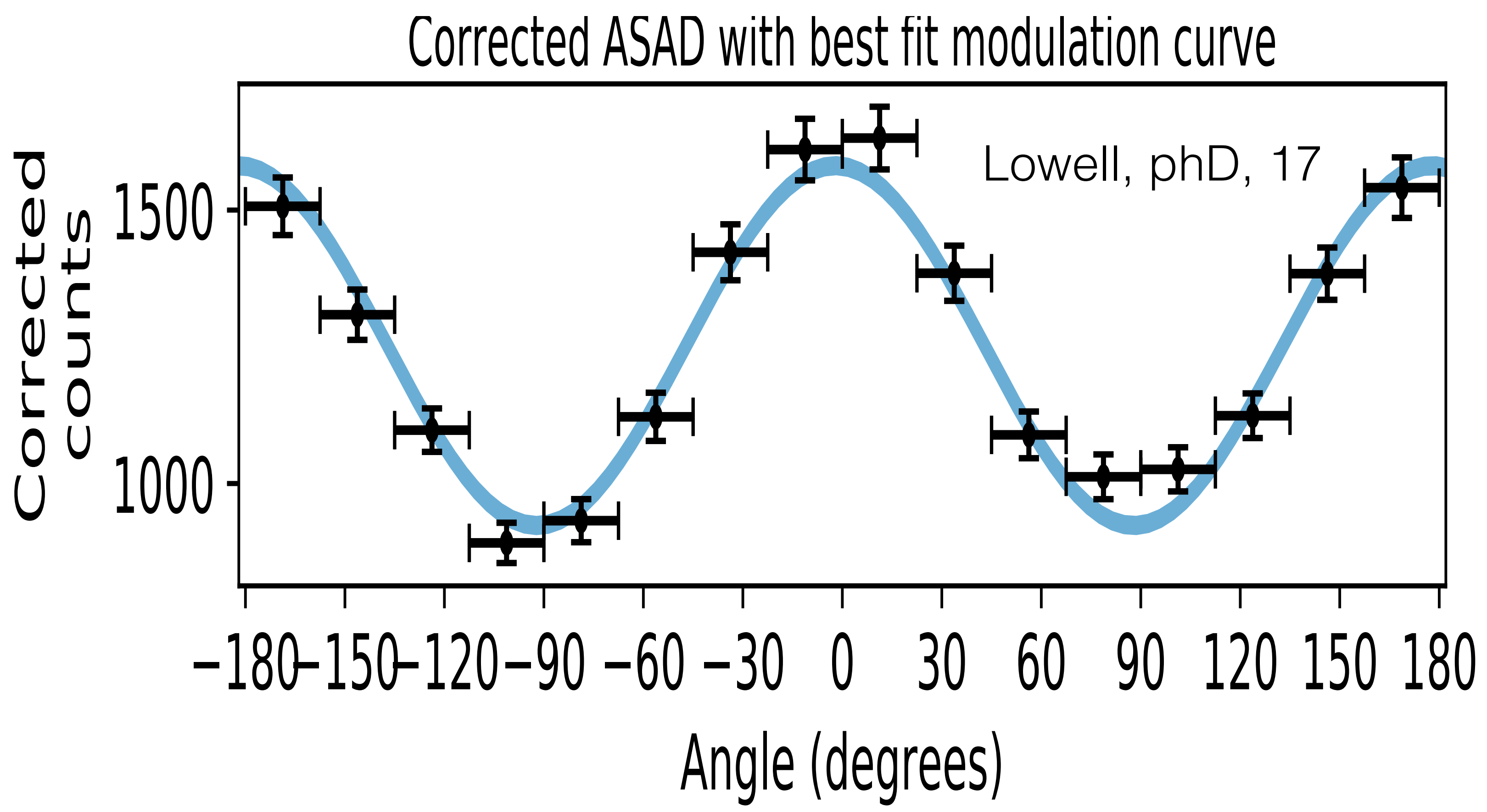
- ✦ ^{26}Al → e^+ → 511 keV chain?
- ✦ COSI will test this connection with better sensitivity and uniform exposure

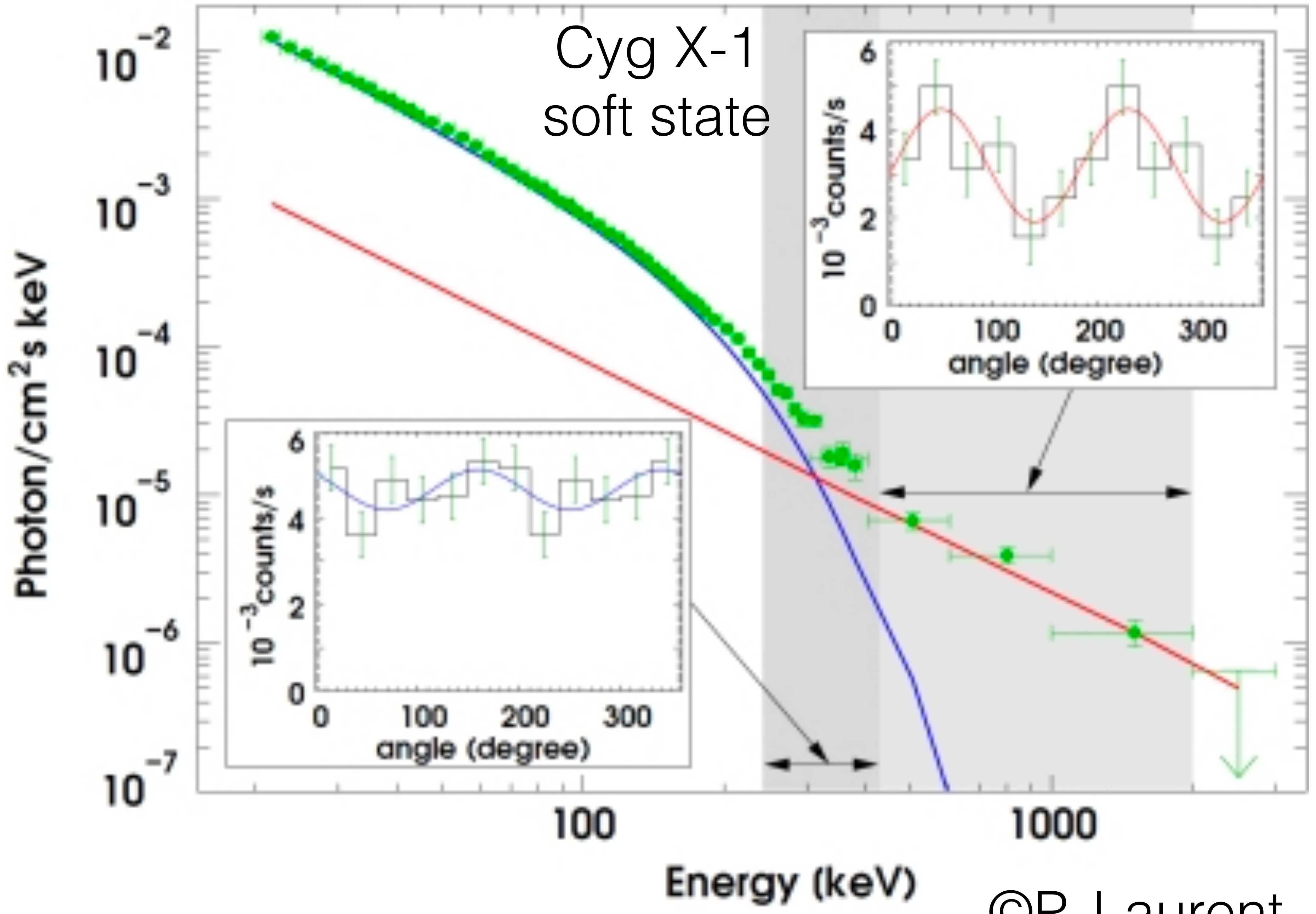
C. Polarization & D. Multi-messenger events

Polarization measurements with COSI

Azimuthal angle distribution of scattered gamma rays provides the polarization degree/angle

Measure the polarization of galactic black holes and AGNs with ~20 mCrab, and constrain the emission models (e.g., corona, jet)





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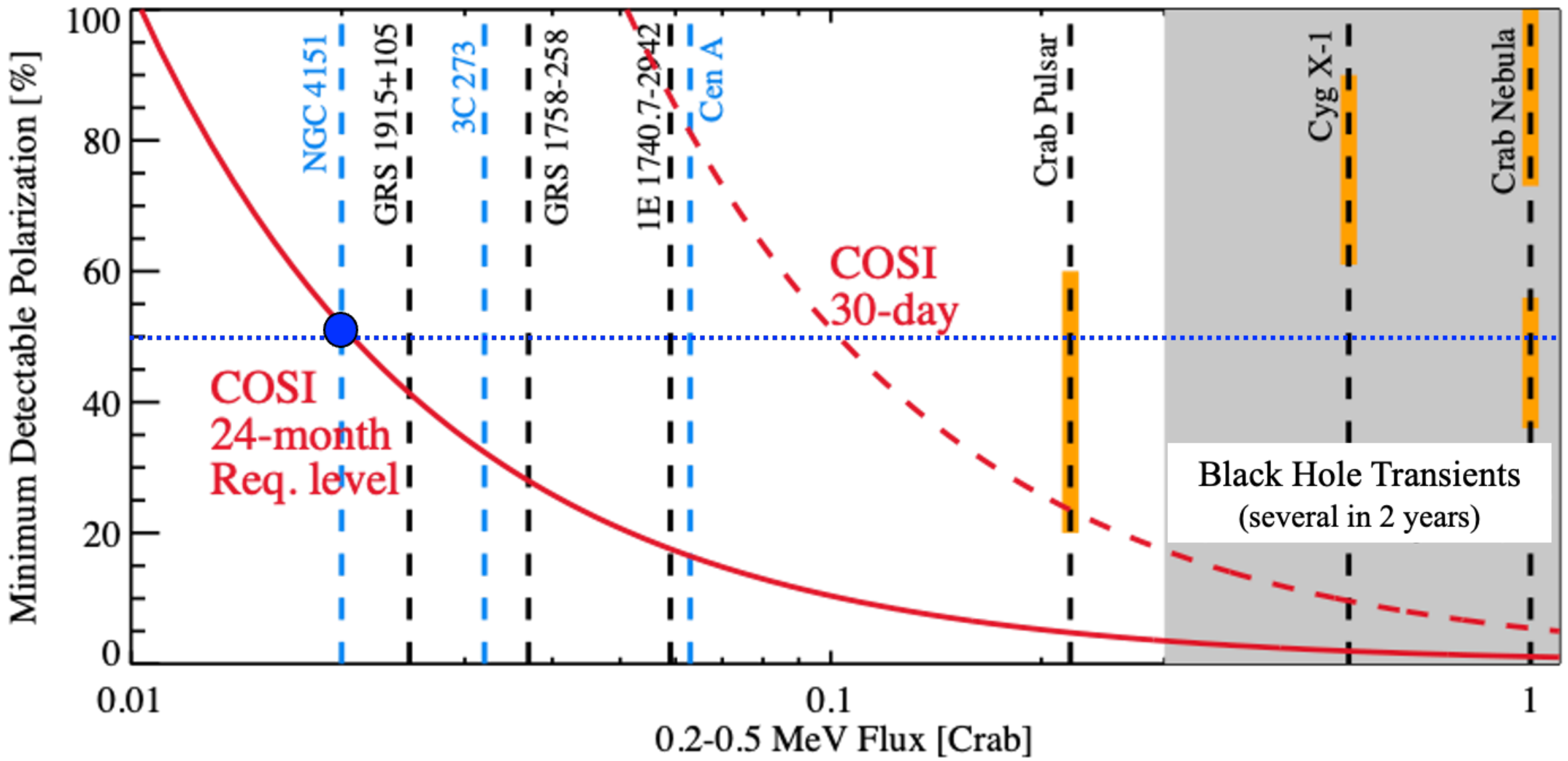
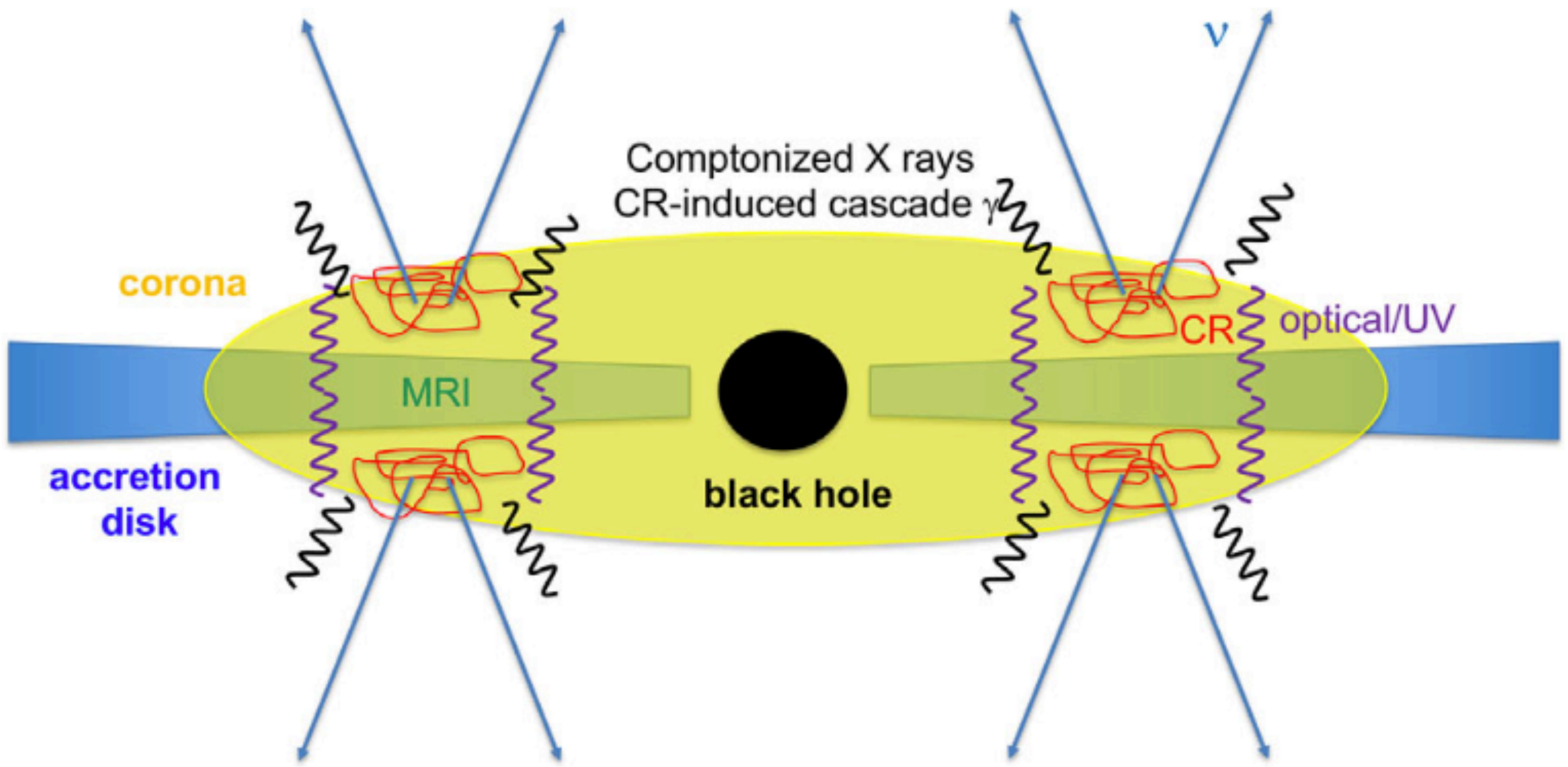


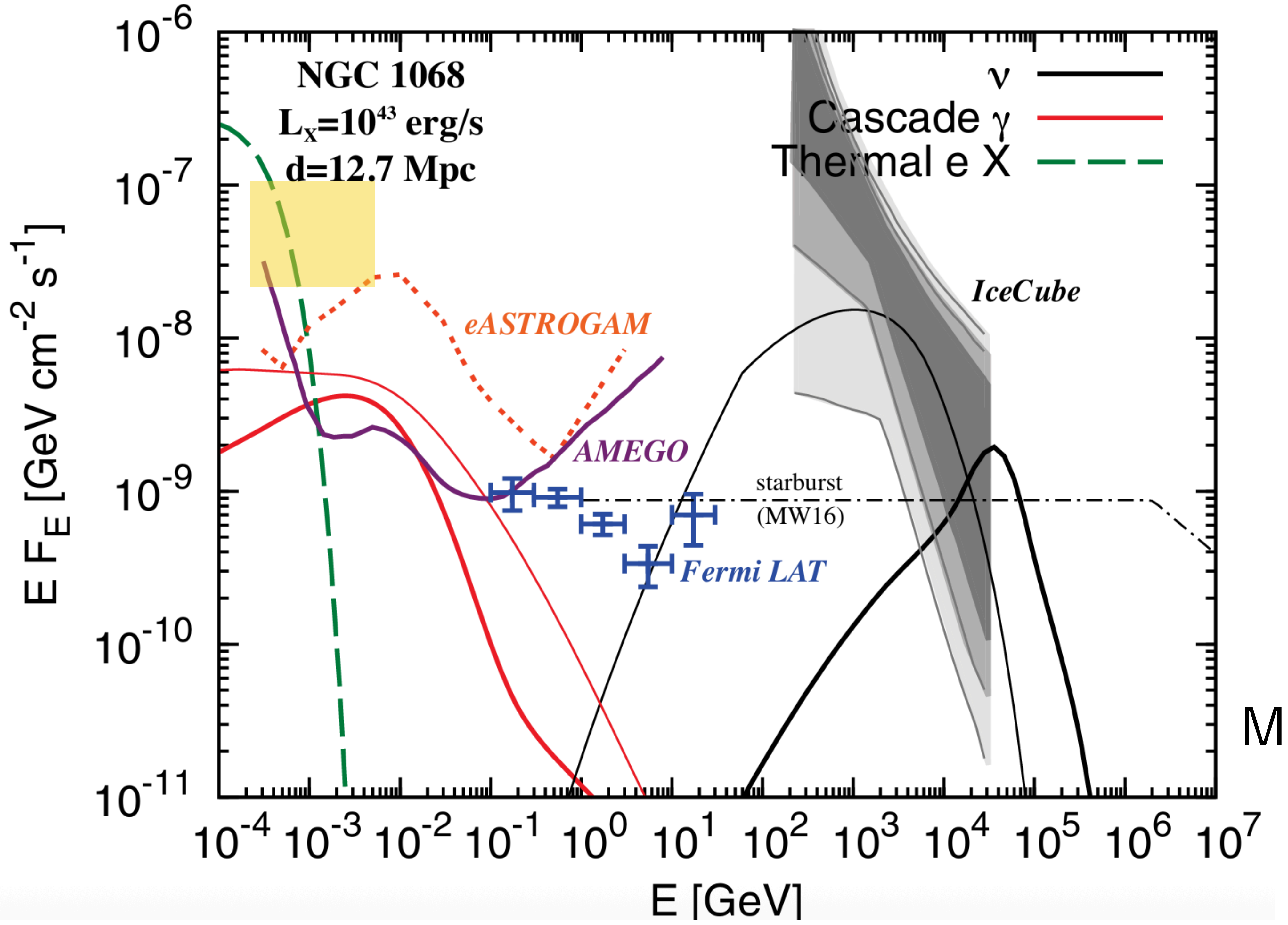
C. Polarization & D. Multi-messenger events

GRB events

- For a short GRB, its localization <2.5 deg will be reported within 1 hour
- Constrain GRB models using polarization measurements
- Goal in 2 years: > 10 short GRBs, > 30 GRB polarization measurements

Cosmic-ray accelerators - neutrino





Murase+20

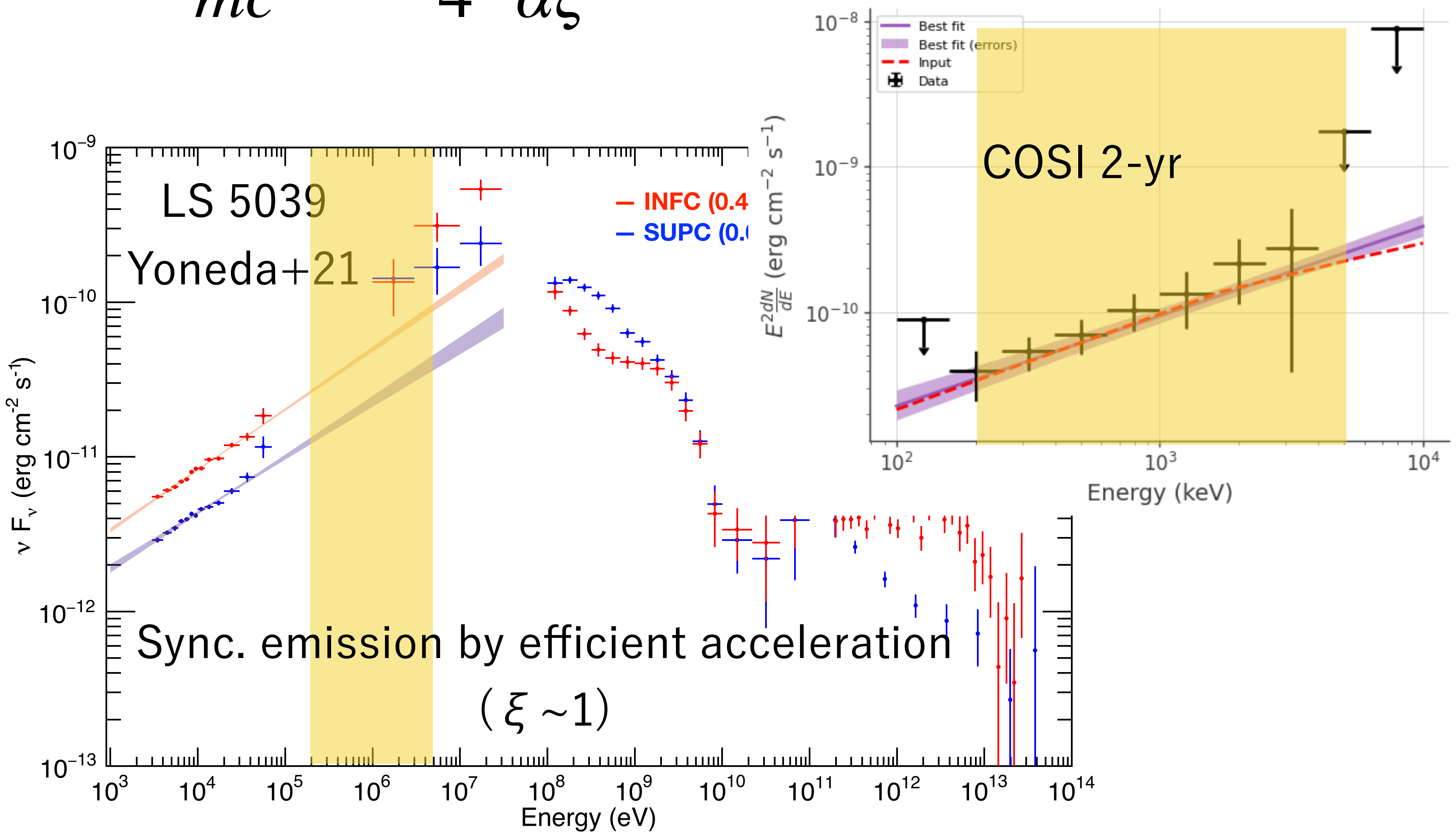
Search for MeV gamma rays from potential neutrino sources

C. Polarization & D. Multi-messenger events

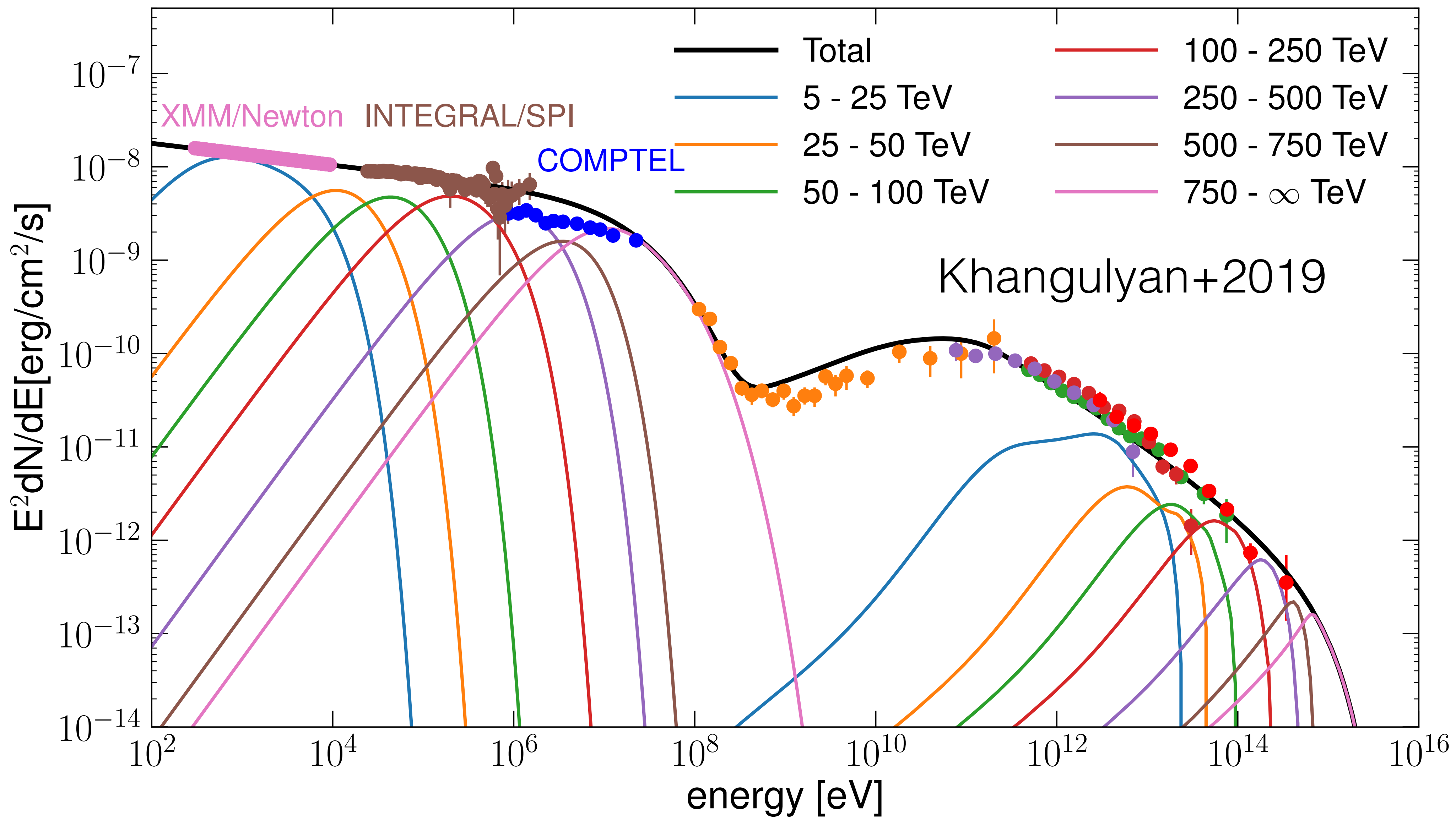
Cosmic-ray accelerators - efficient particle acceleration

The characteristic energy of synchrotron radiation is:

$$E_\gamma = \hbar \frac{qB}{mc}\gamma^2 = \frac{9}{4}\frac{mc^2}{\alpha\xi} \sim 160\ \mathrm{MeV} \times \xi^{-1} \text{ under } \dot{E} = \frac{q_e B c}{\xi}$$



Non-thermal emission peaking at MeV in gamma-ray binaries



Two leptonic components in the Crab Nebula

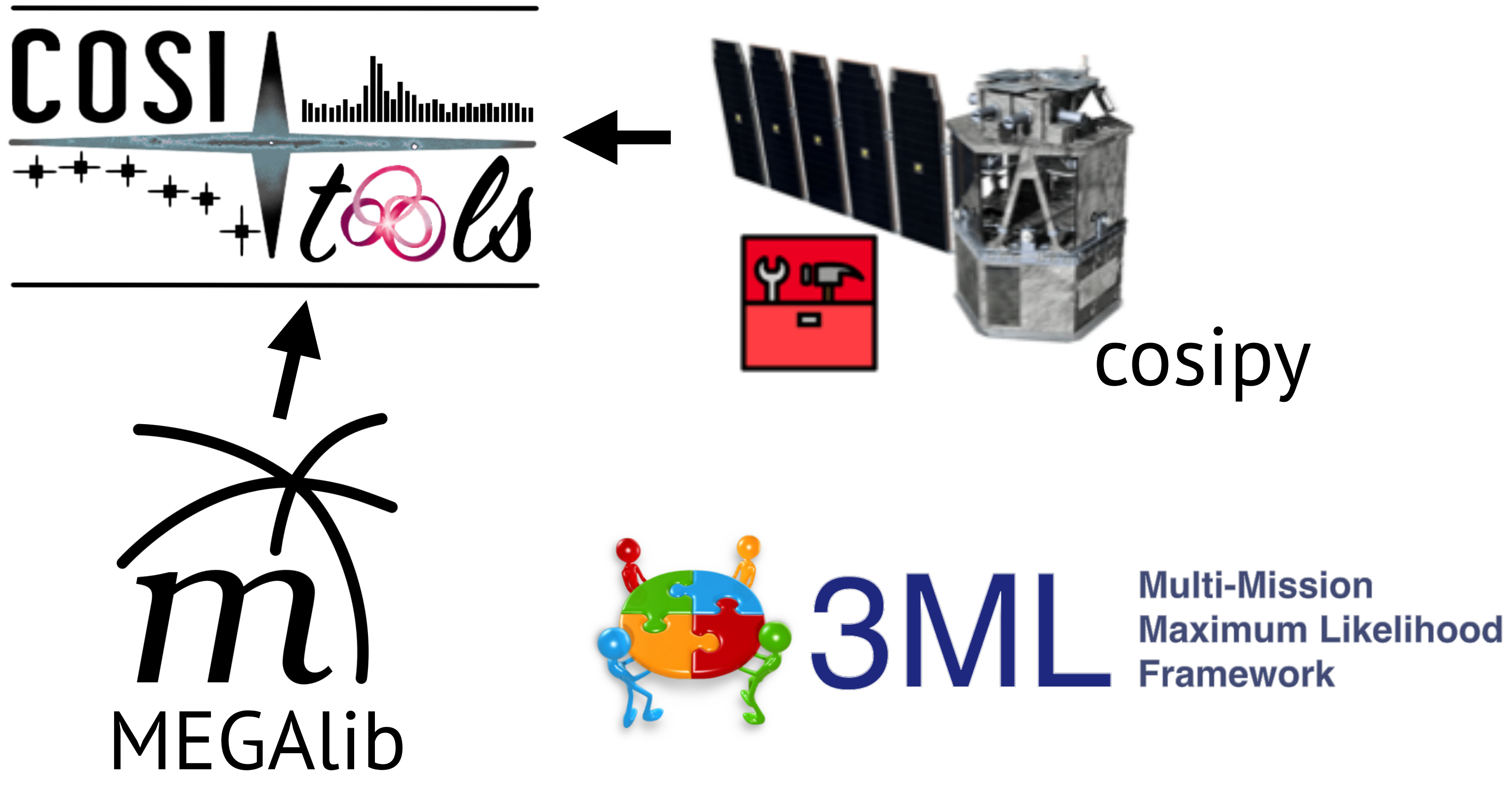
Data analysis framework for COSI

No de facto standard software in MeV astronomy as for now

→ Need to establish data analysis framework even for future MeV astronomy

COSItools: a collection of COSI data-analysis tools, documentation, and verification data sets

- **MEGAlib**: Detector simulation & raw data processing
- **cosipy**: Python-based high-level data analysis
  - Fitting based on the threeML library
  - All-sky image reconstruction



The COSI Data Challenge (DC) is currently released annually

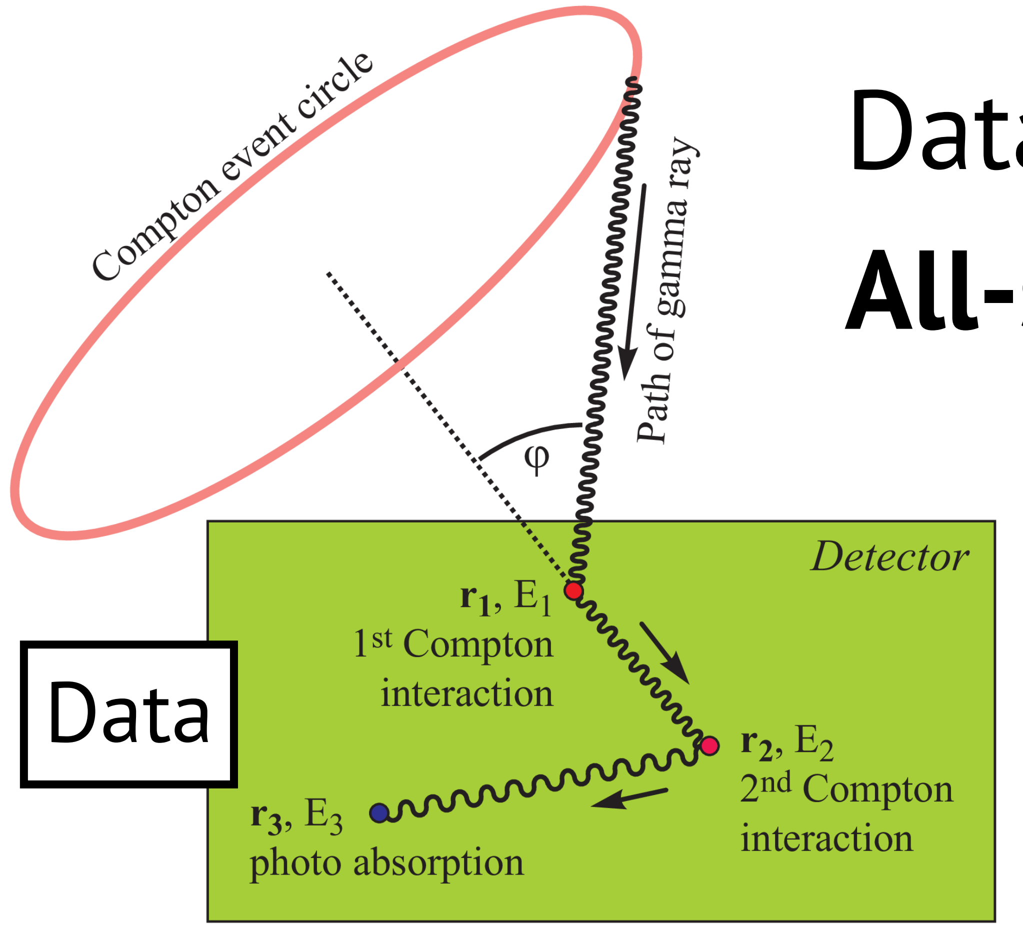
- Softwares under development are publicly available with simulation datasets
  - Balloon data in 2016 (DC1), 3-month observation simulations (DC2, DC3).
- Provide a broader community with opportunities to get familiar with COSI data
- https://github.com/cositools/cosi-data-challenges

COSI data challenge

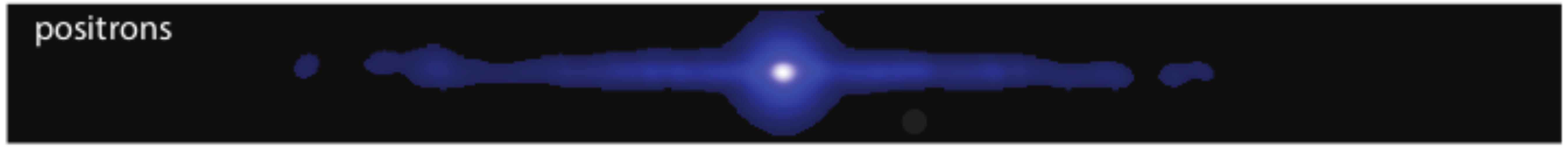
All-sky Image Reconstruction Framework

Data = Compton scattering patterns of gamma rays in a detector

All-sky images need to be reconstructed by solving an inverse problem statistically



Multi-dimensional response matrix



All-sky image (model)

Image Deconvolution with Richardson-Lucy Algorithm

- A type of maximum likelihood estimation that estimates the flux of each pixel in an image
- Iteratively updates the image to obtain an image that maximizes the likelihood

Generic data format compatibility: Applicable to other MeV gamma-ray missions, e.g., INTEGRAL/SPI

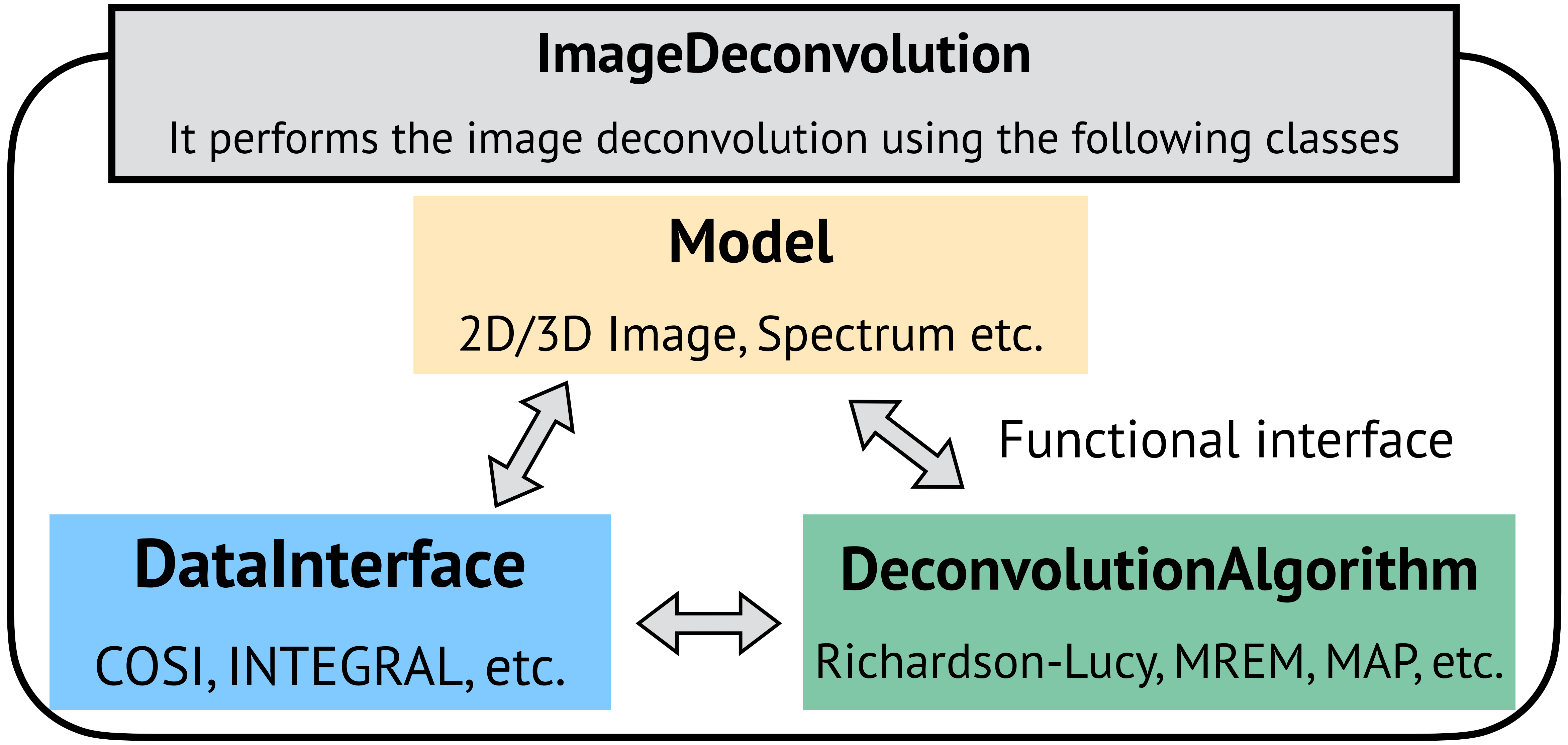


Image Deconvolution using Bayesian approach

Maximizing the posterior probability

$$P(\text{image \& bkg} \,|\, \text{data}) \propto P(\text{data} \,|\, \text{image \& bkg}) \times P(\text{image \& bkg})$$

Likelihood

Prior probability, e.g.,
- image features (smooth, sparse, flat etc.)
- bkg. normalization with uncertainties

Ex.) Imaging of the black hole shadow with EHT (EHT collab. 19)

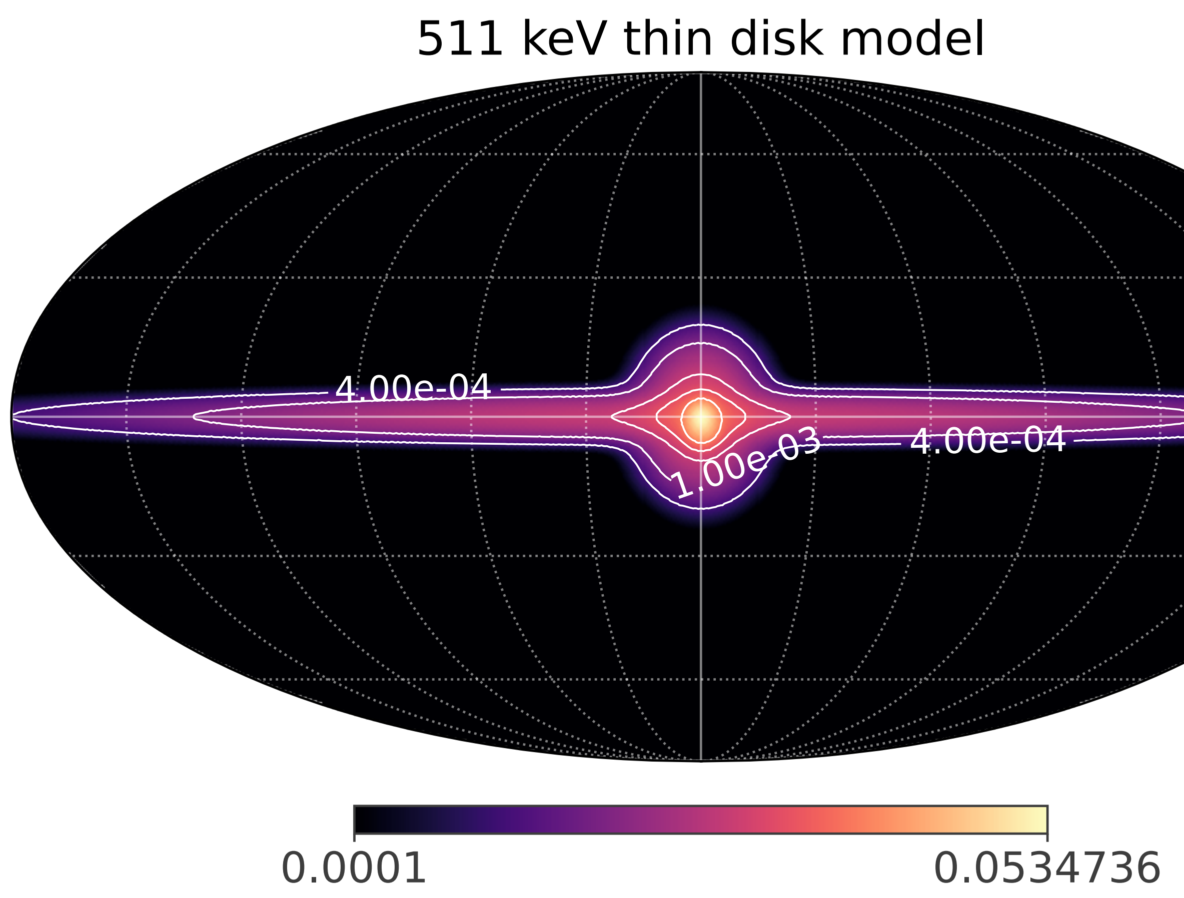
Implement modern image reconstruction techniques adopted in other fields into COSI

- Maximize the posterior rather than the likelihood using the RL algorithm (MAP estimation)

$$\sum_i D_i \log \epsilon_i - \sum_i \epsilon_i - c^{\mathrm{TSV}} \sum_j \sum_{k \in \sigma_j} (\lambda_j - \lambda_k)^2 - c^{\mathrm{SP}} \sum_j \log \lambda_j$$

Likelihood — **Total Squared Variation (smoothness)** — **sparseness prior (Ikeda+14)**

Validation with 3-month COSI Simulation of 511 keV



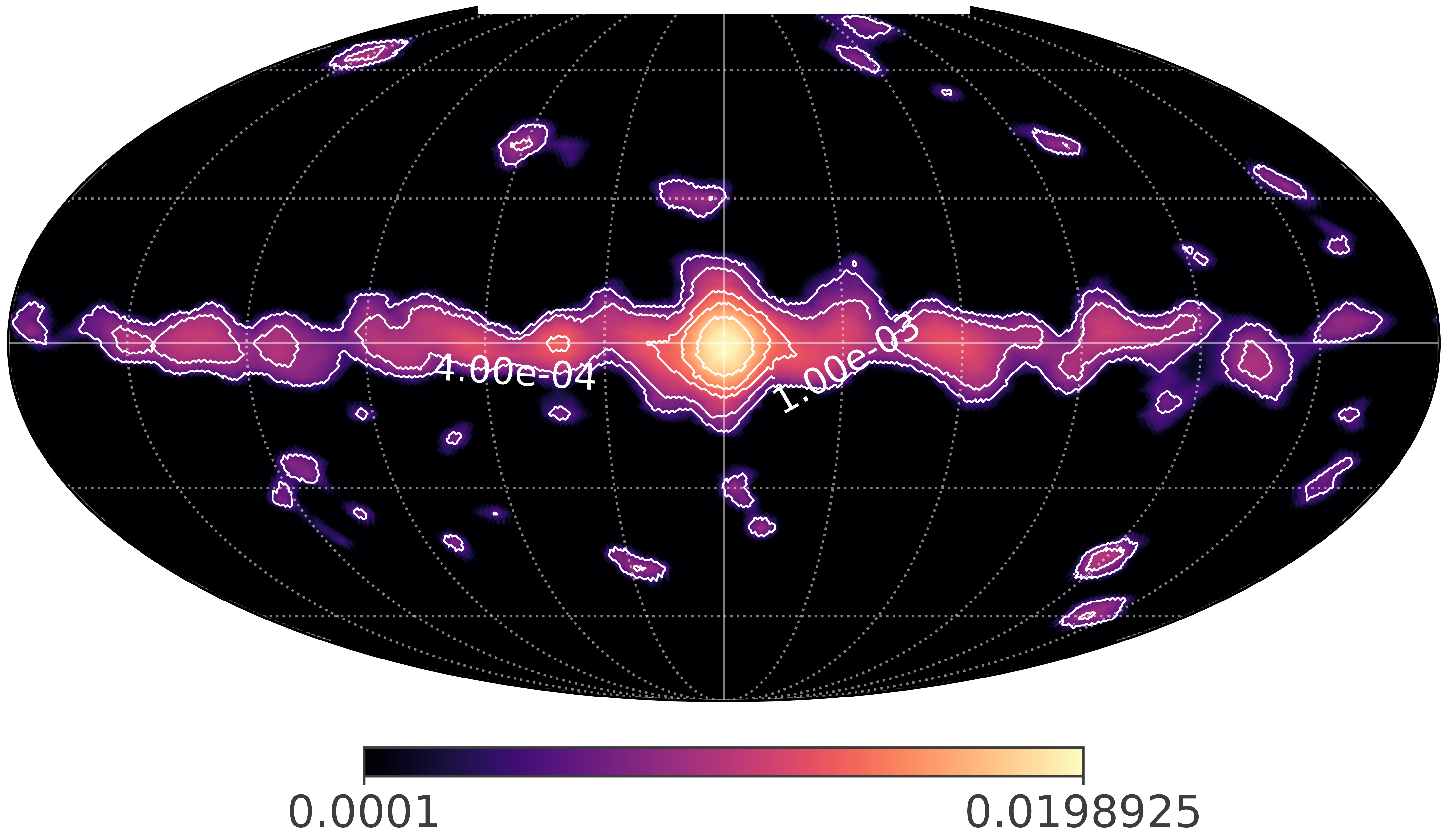
Simulating the 3-month observations including in-orbit background components

Sparse modeling suppresses high-latitude noise

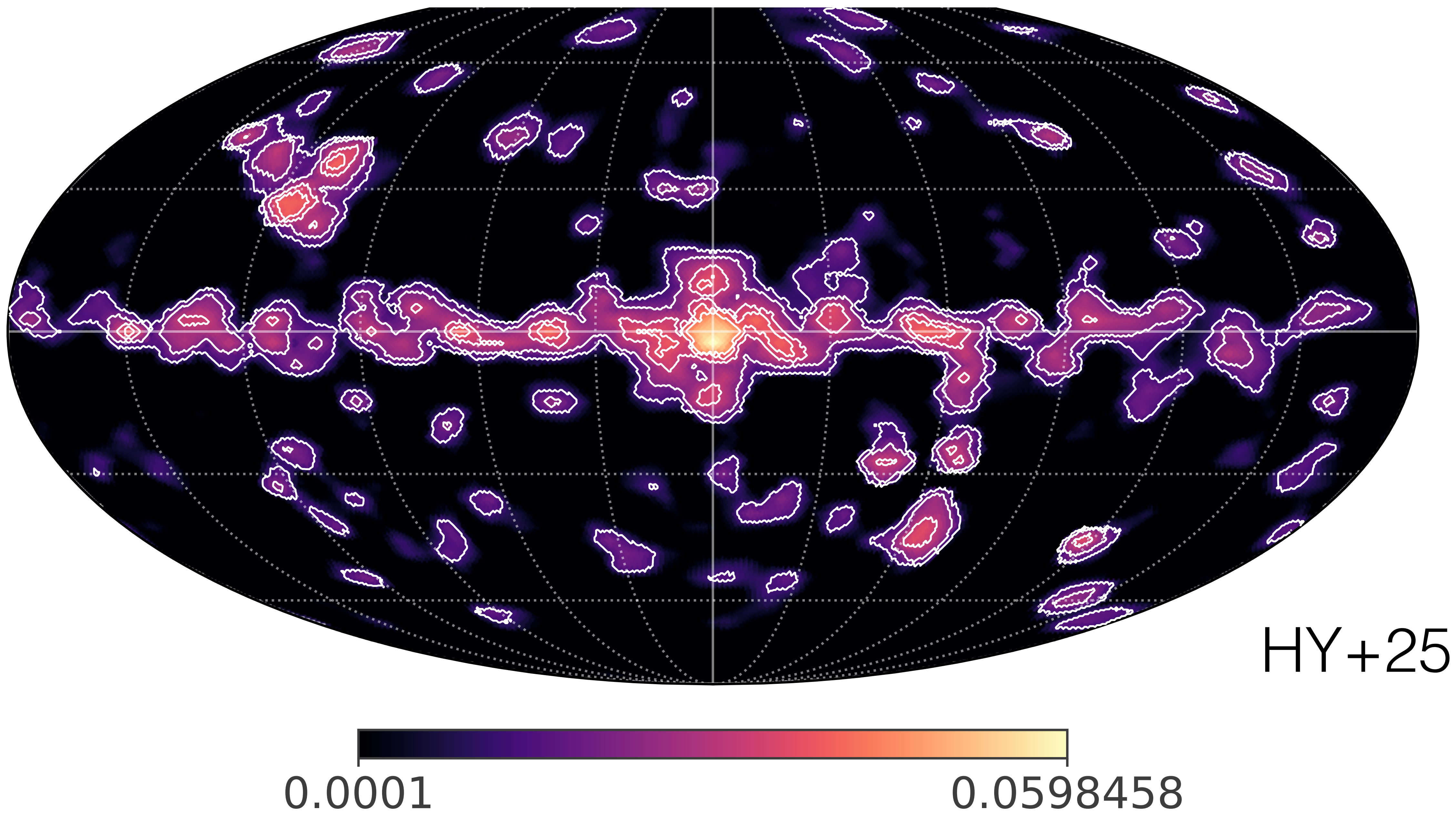
Smoothness prior preserves the galactic plane structure

Within 3 months, global structures across the sky can be identified

MAP estimation



Conventional algorithm

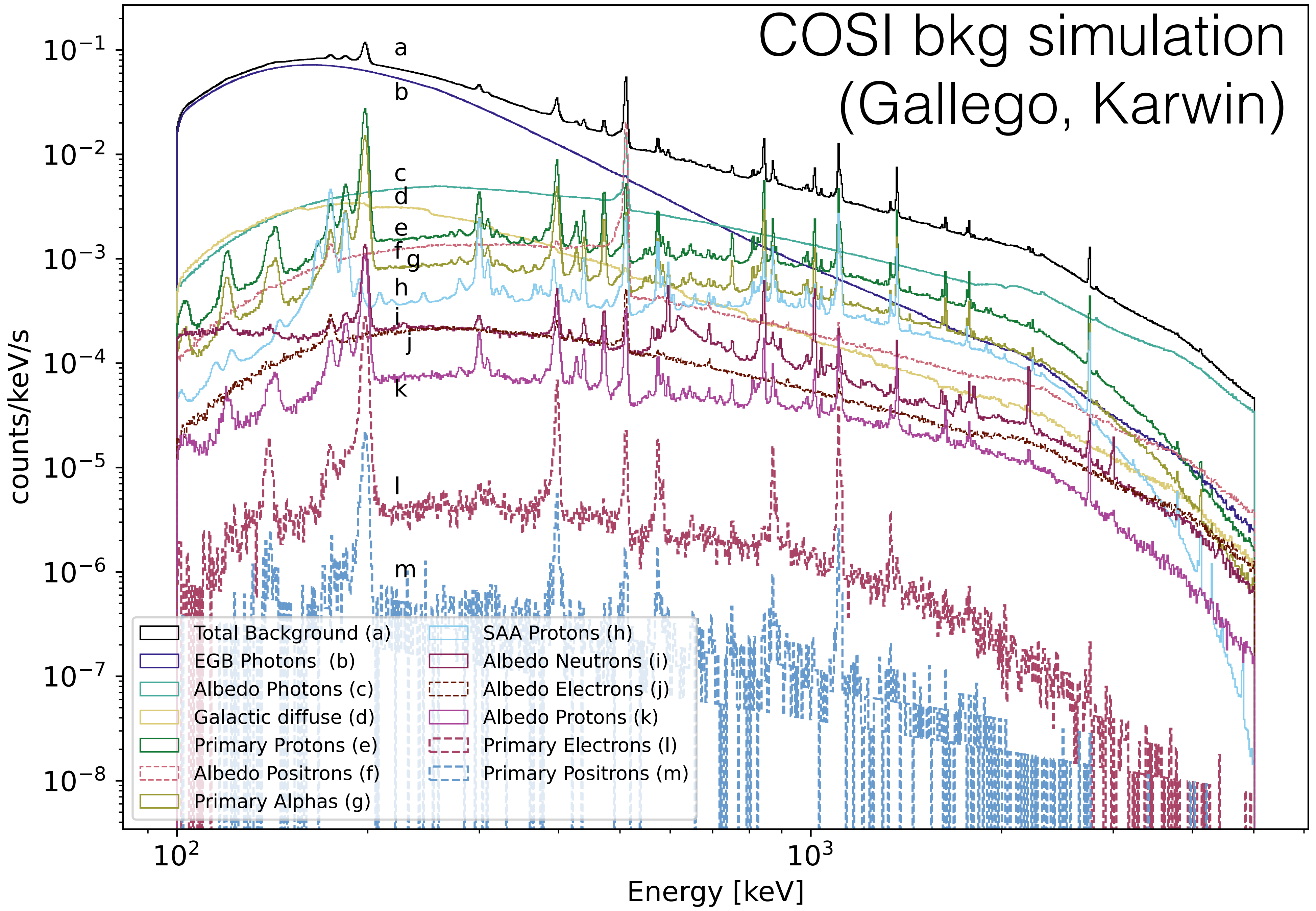


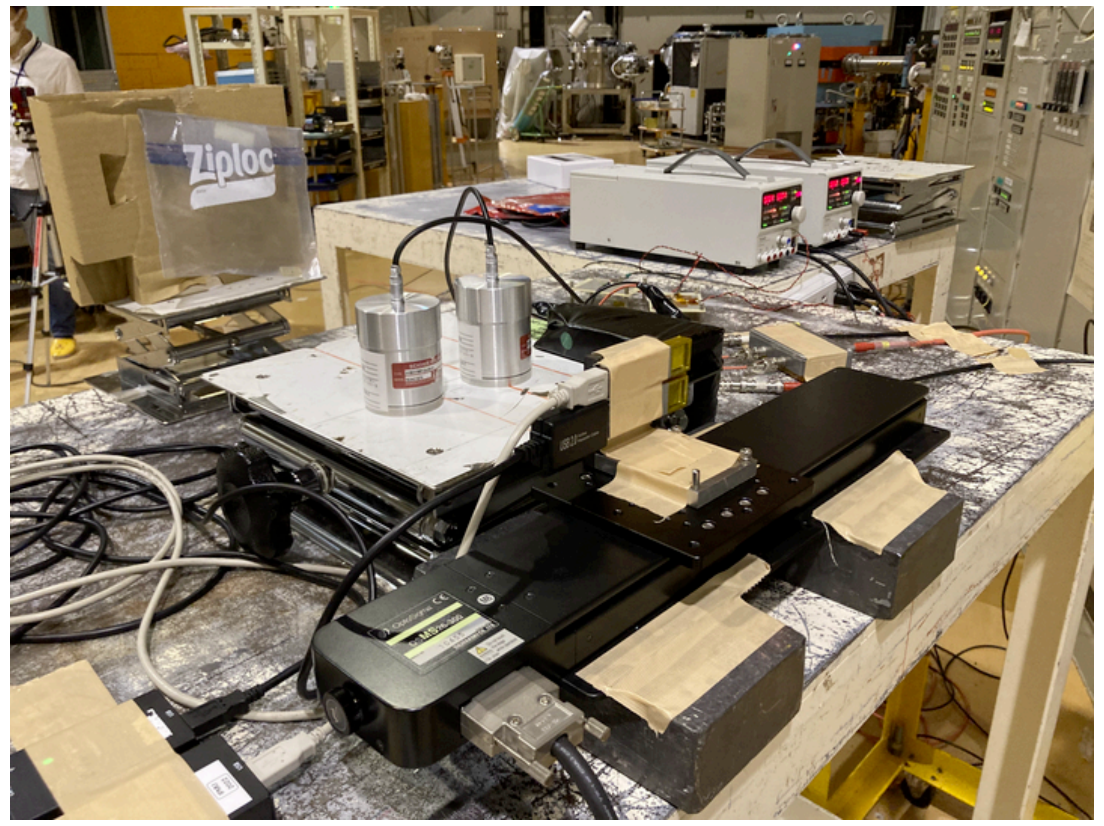
HY+25

Towards better background modeling

The low S/B ratio requires detailed understanding of background components

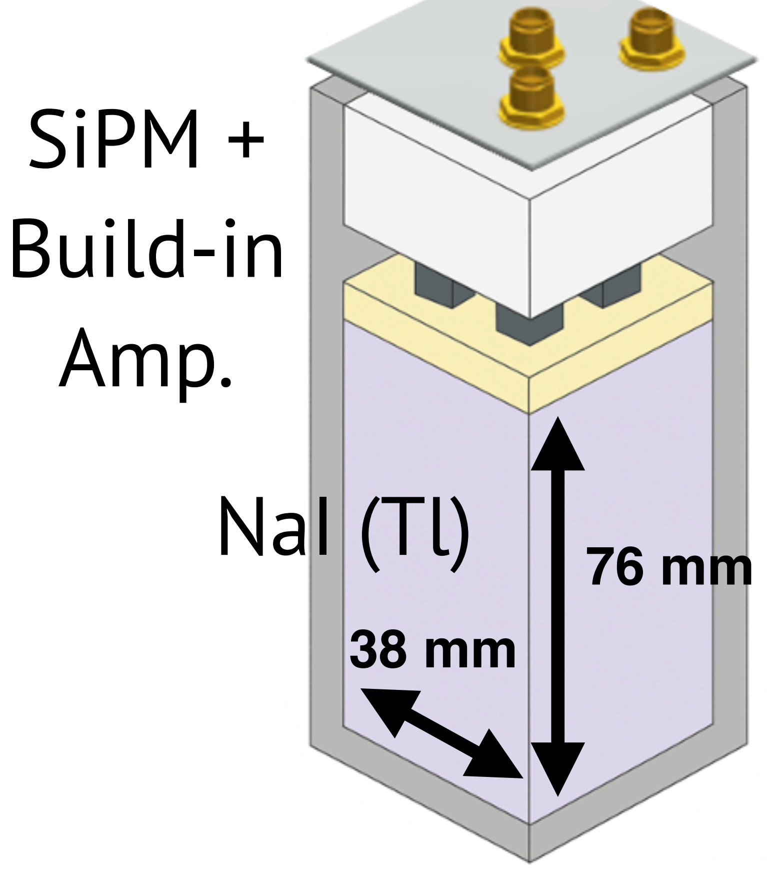
- ✦ Full background simulation compared with 2016 balloon data (Gallego+25)
- ✦ In addition to the main detectors, scintillation detectors (NaI) will be onboard as a student collaboration project (Gulick+24,25, Nagasawa+2025)
- ✦ BTO will be used as a tracer of background components, which will be incorporated in the data analysis (ongoing effect)





Afterglow study (CsI, NaI) at the beamline facility HIMAC in Japan

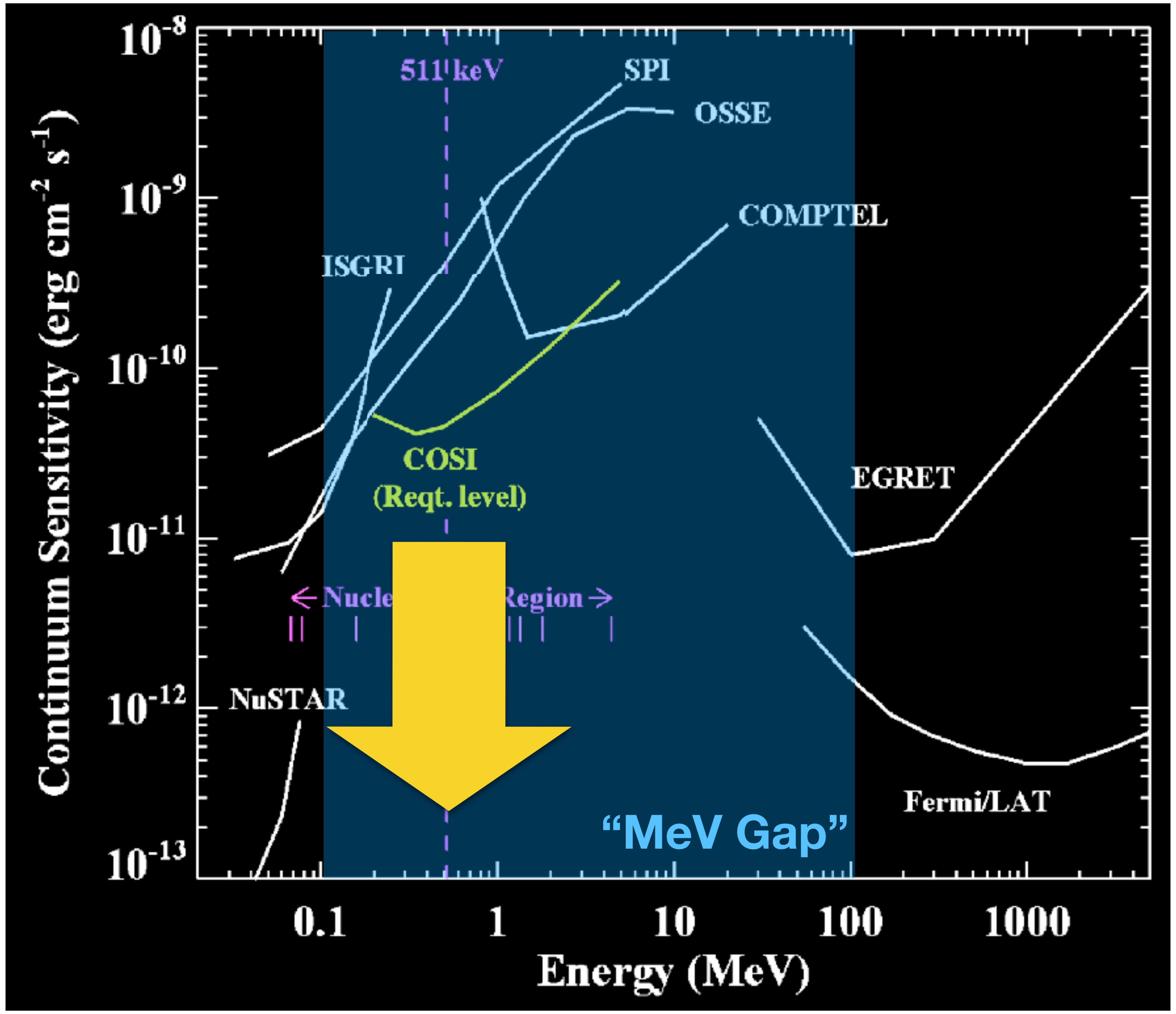
Scionix module



Beyond COSI

Present
Future

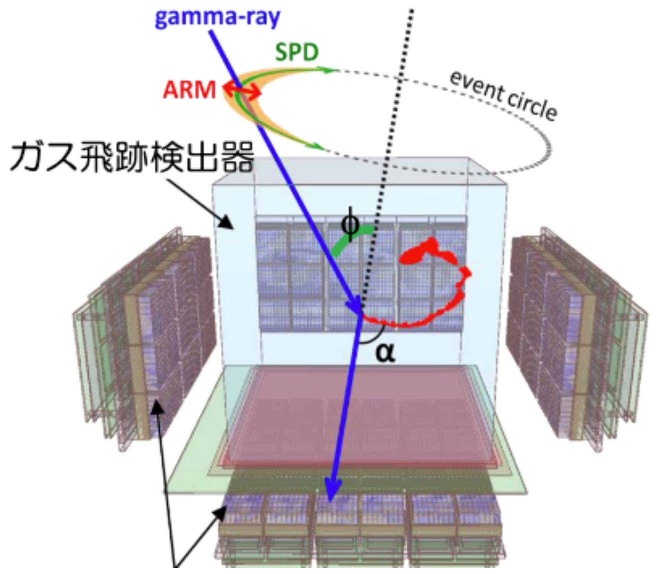
2020 2030 2040



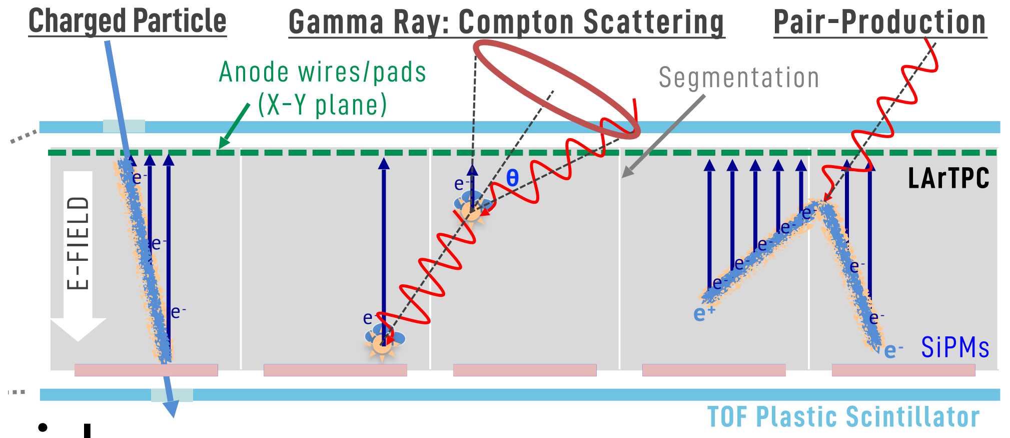
COSI, NASA (CC)
(2027-)

A large-scale mission in 2030s? 2040s?

SMILE, AMEGO, GRAMS, MASS, MeGaT, MeVCube (CC), GECCO (CC+coded mask) …



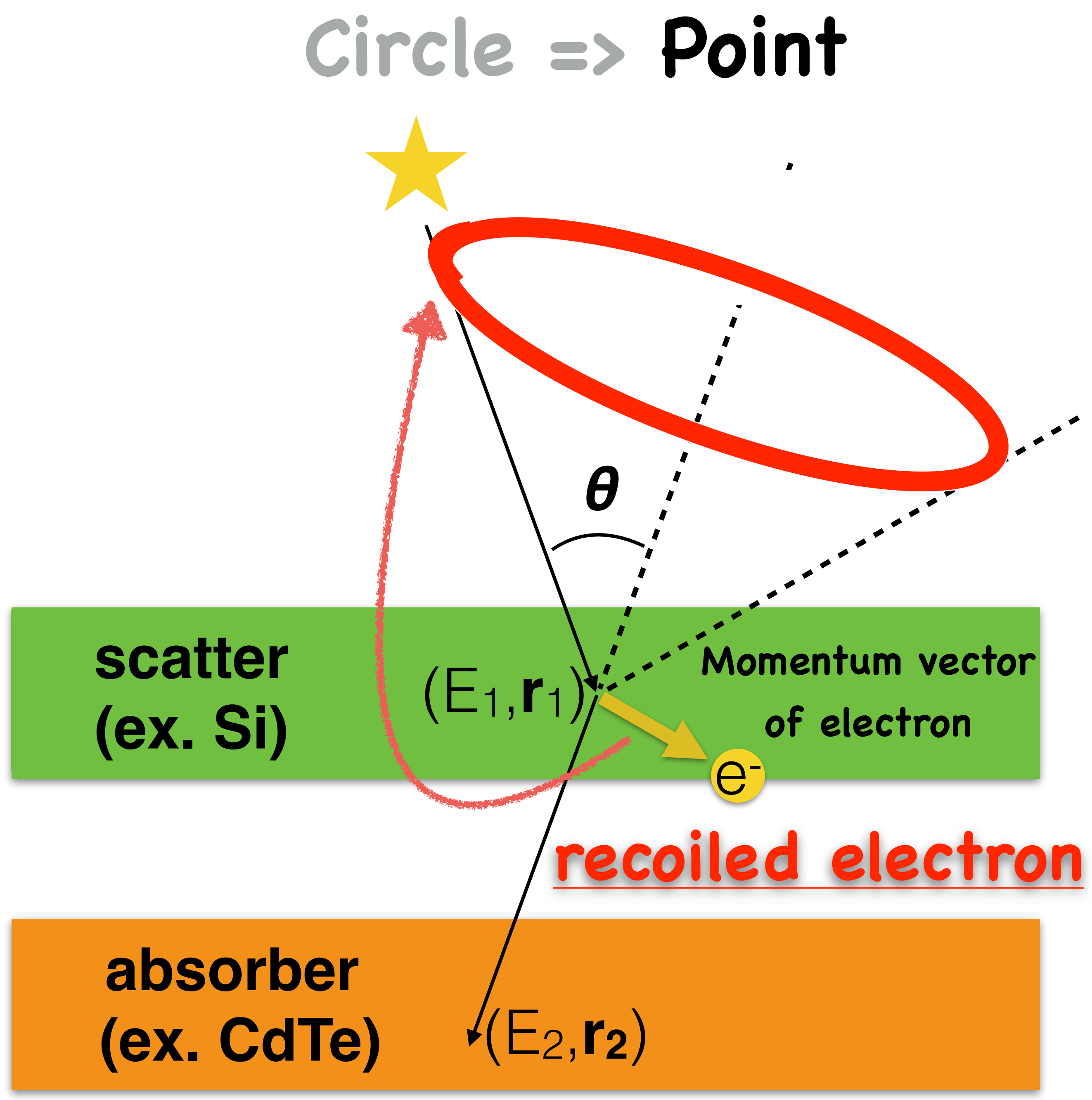
SMILE-3 (CC)
- Kyoto University, CR group
- Science balloon flight in 2027



GRAMS, Japan+US (CC)
- A large-scale mission with liquid argon
- Engineer balloon flight in US in 2026

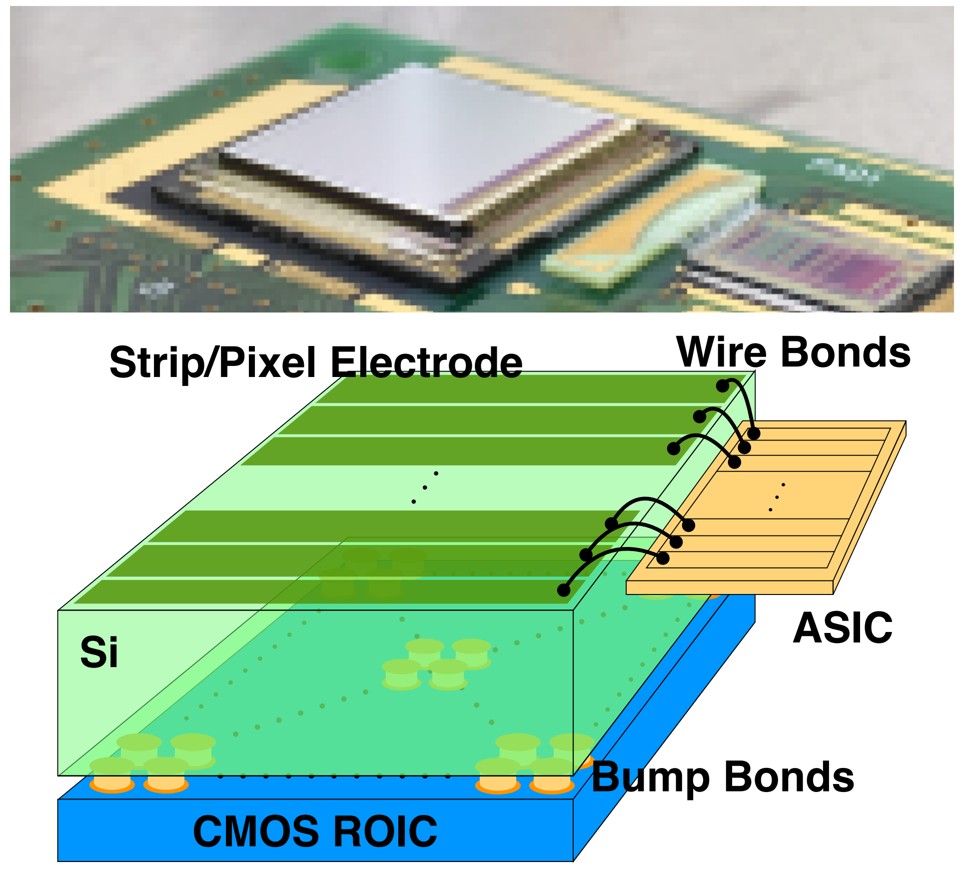
Sub-GeV/GeV Gamma Rays with Balloon-borne Emulsion Telescopes GRAINE project

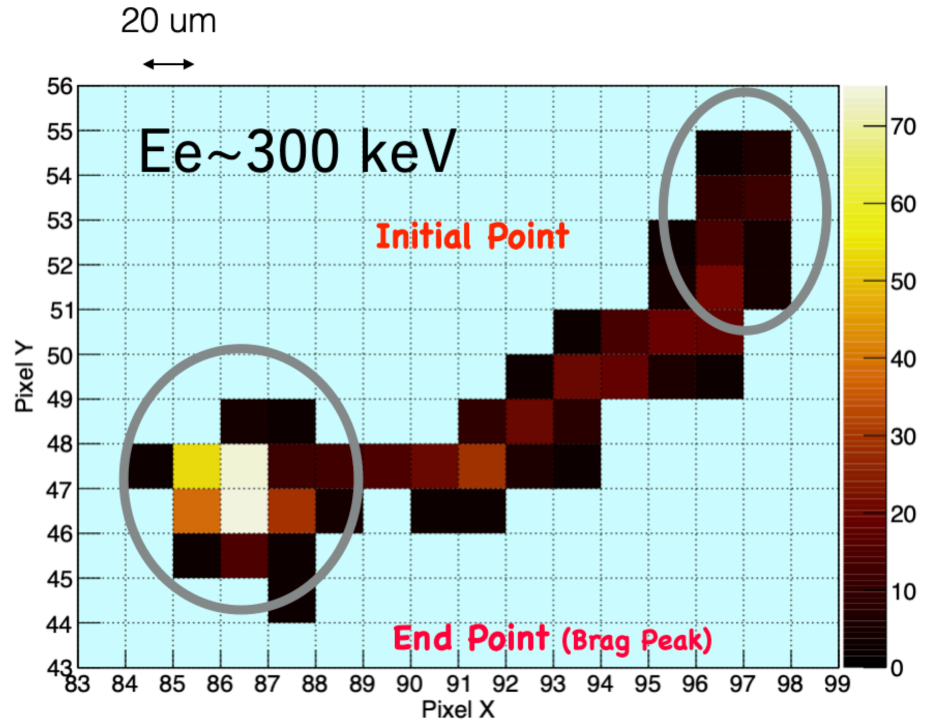
Electron-tracking semiconductor Compton telescopes

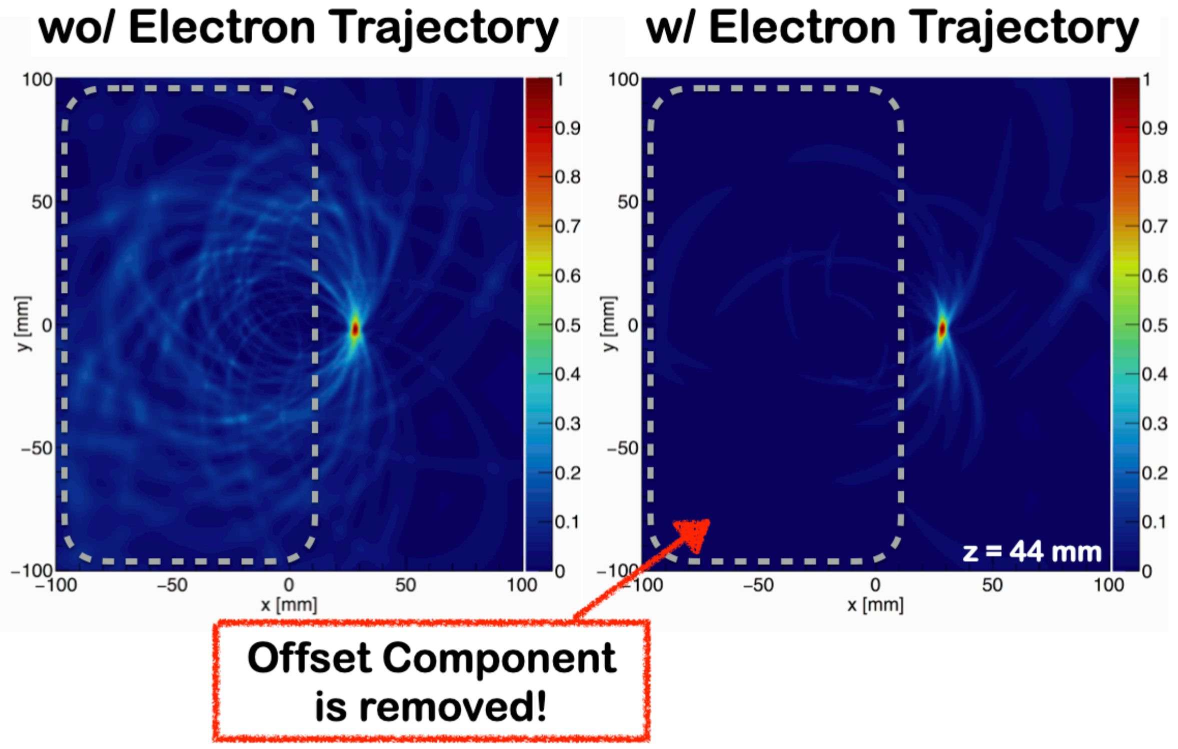


"Electron-tracking based Compton imaging" (e.g. Vetter et al. 2011)

Semi-conductor detector

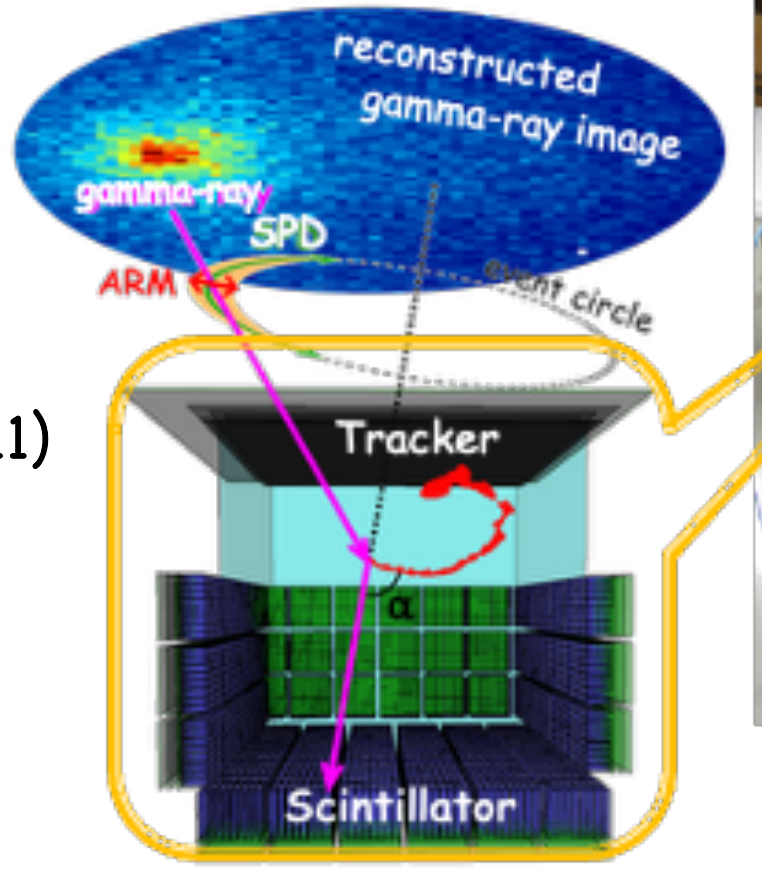




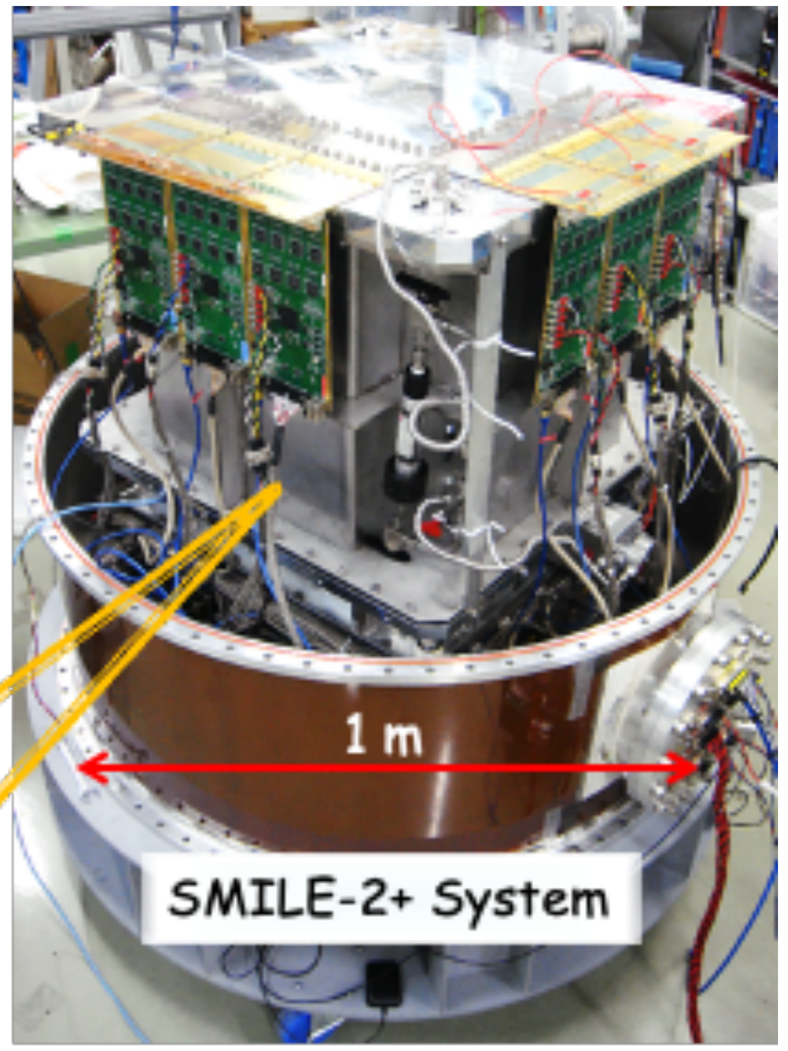


in collaboration with **Hamamatsu Photonics** (**Yoneda et al. 2018**)

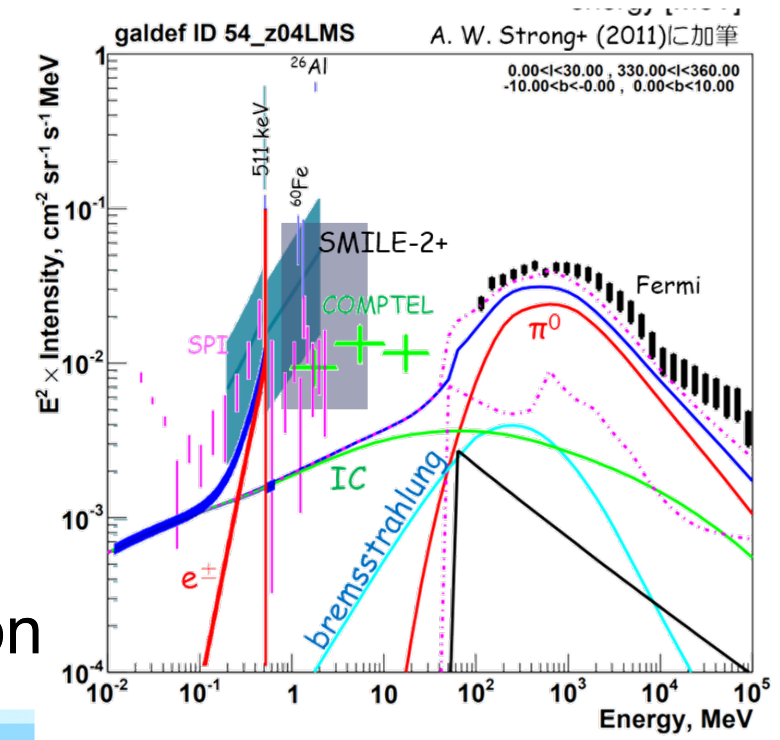
Gaseous TPC + Pixel Scintillator Arrays



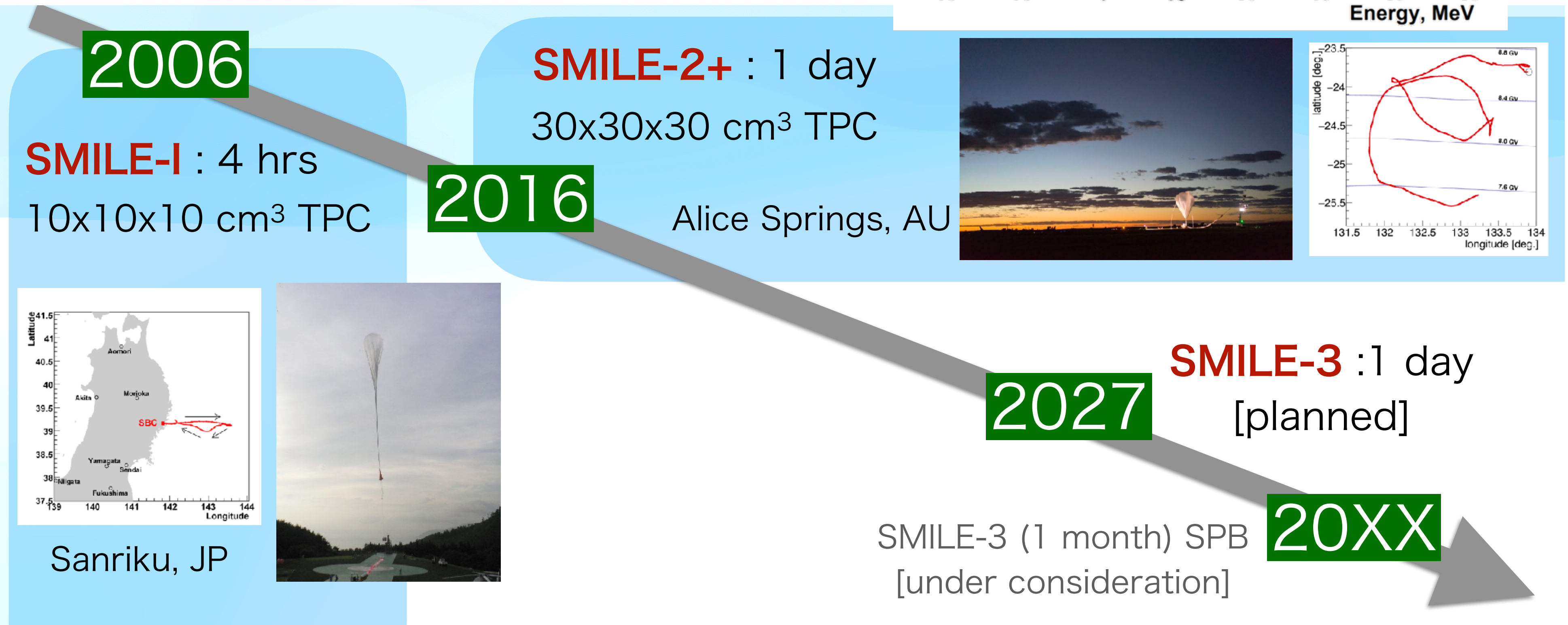
Electron-Tracking Compton Camera



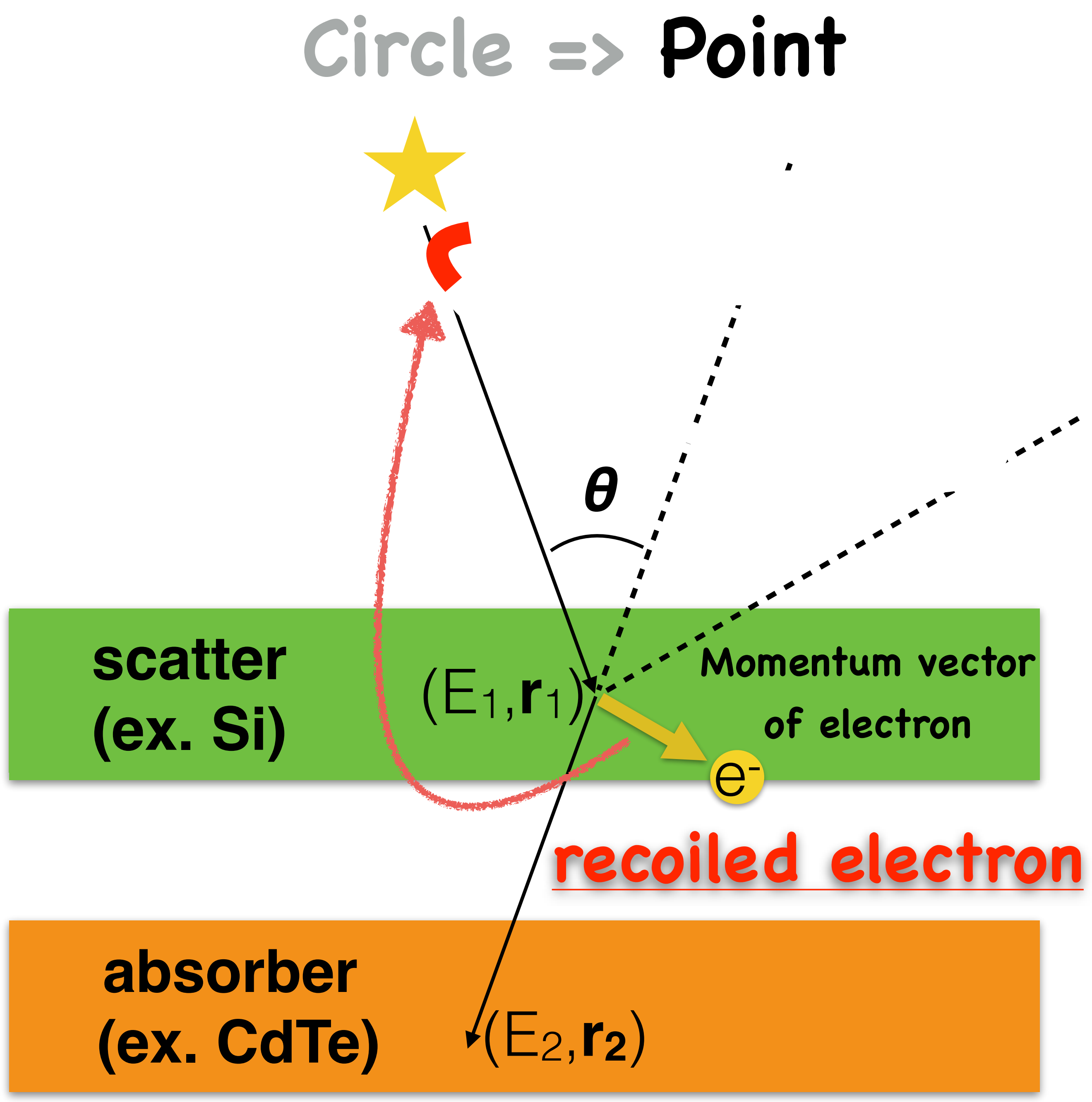
(**SMILE project**, PI: A. Takada, Kyoto university)



Galactic diffuse emission

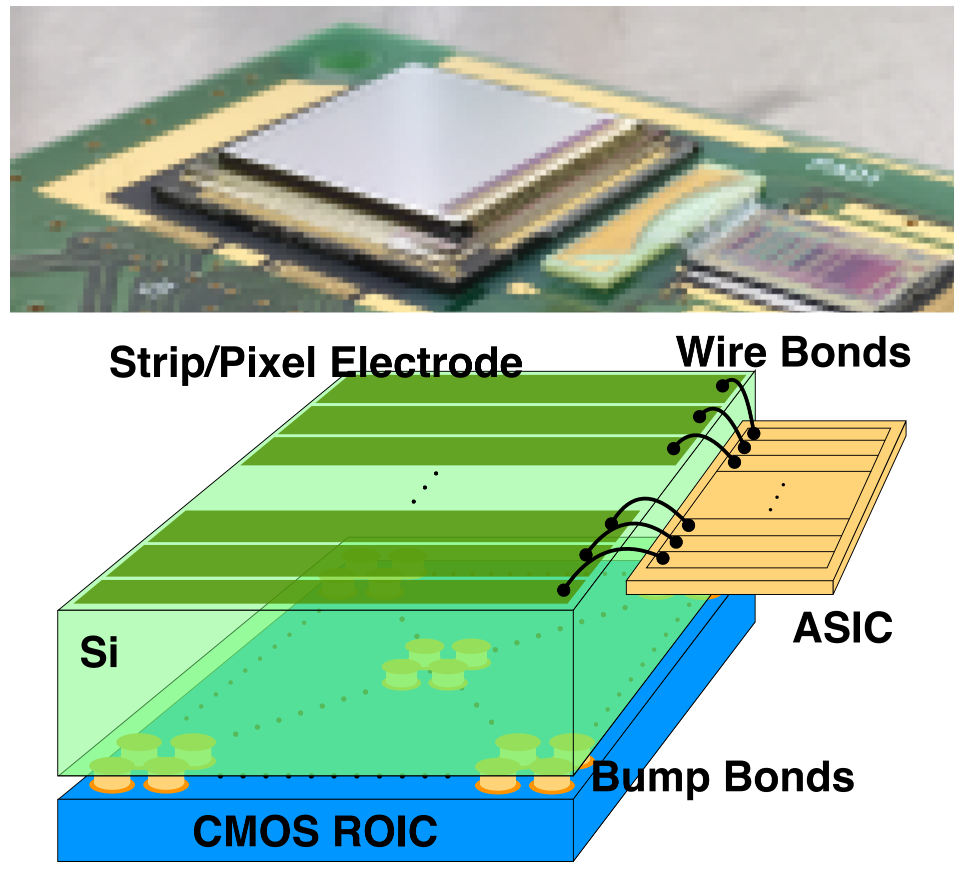


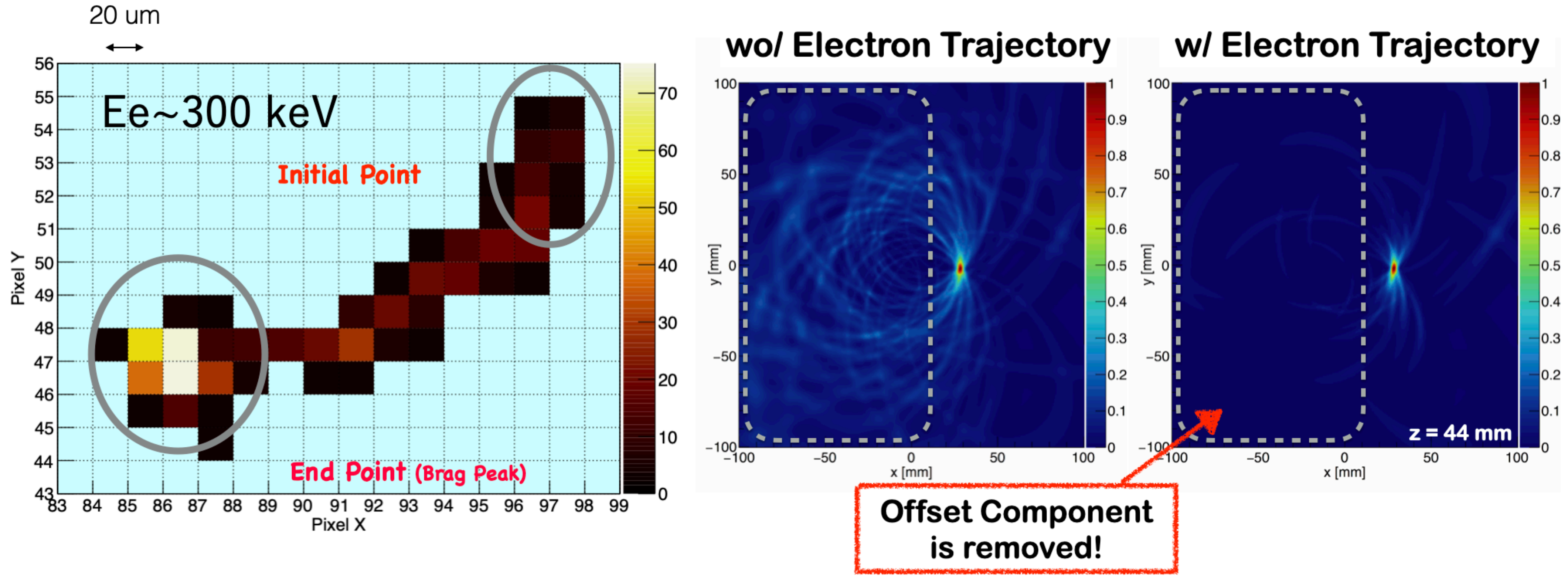
Electron-tracking semiconductor Compton telescopes



"Electron-tracking based Compton imaging" (e.g. Vetter et al. 2011)

Semi-conductor detector





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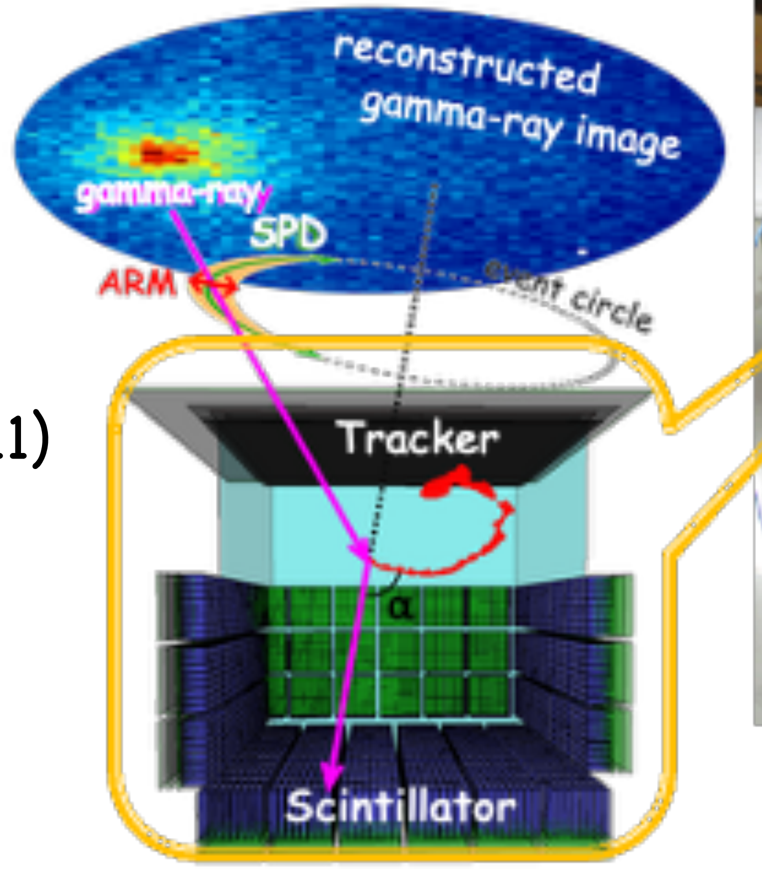
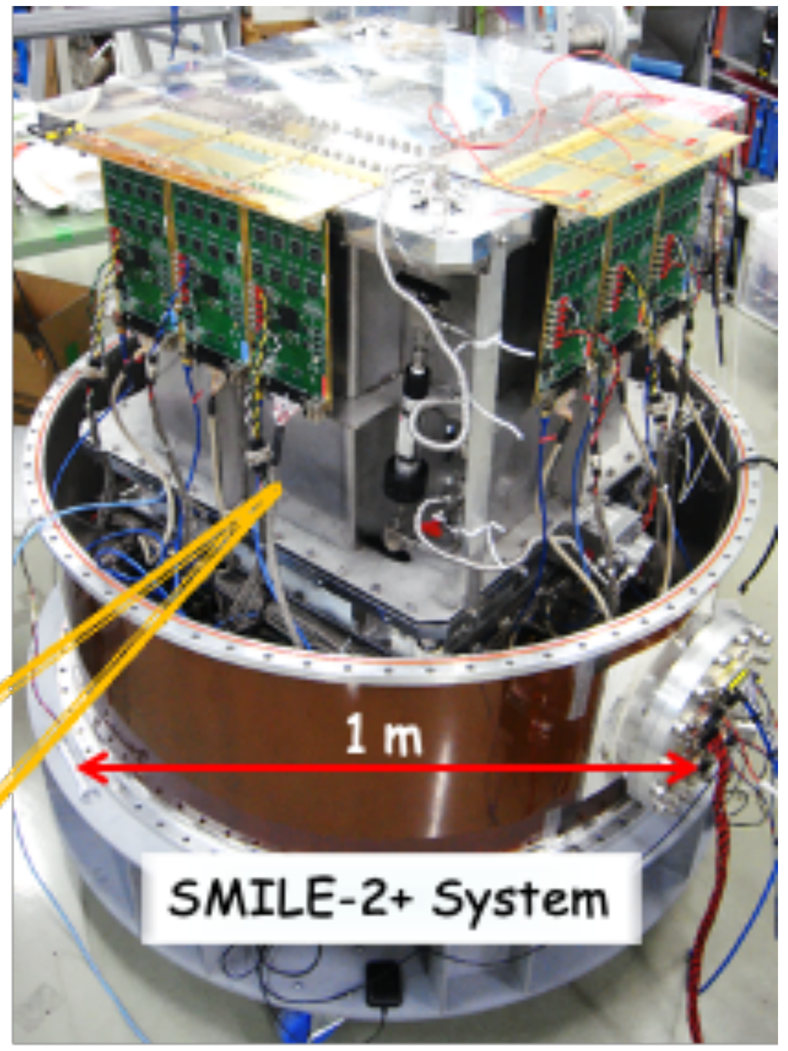
Gaseous TPC + Pixel Scintillator Arrays



Electron-Tracking Compton Camera



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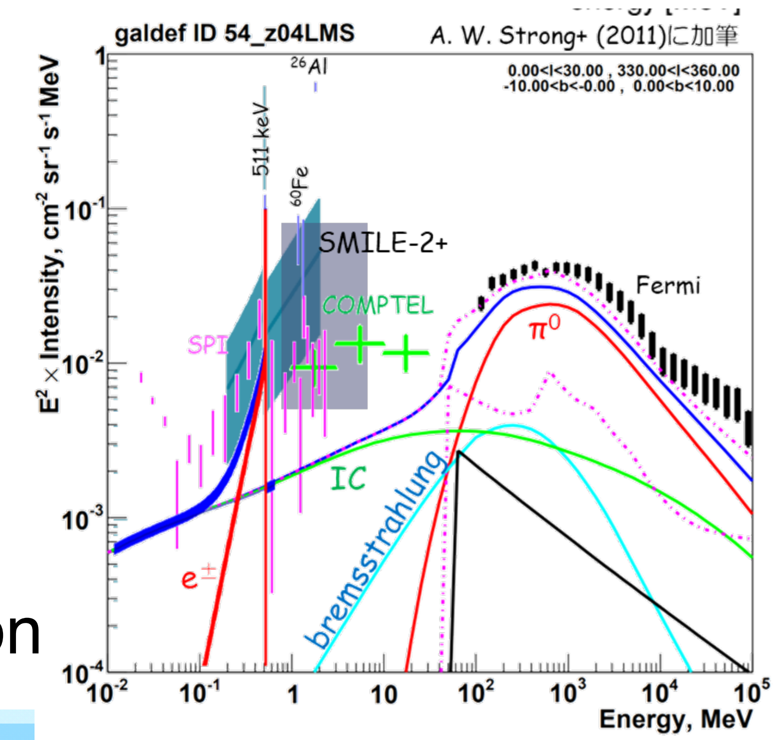
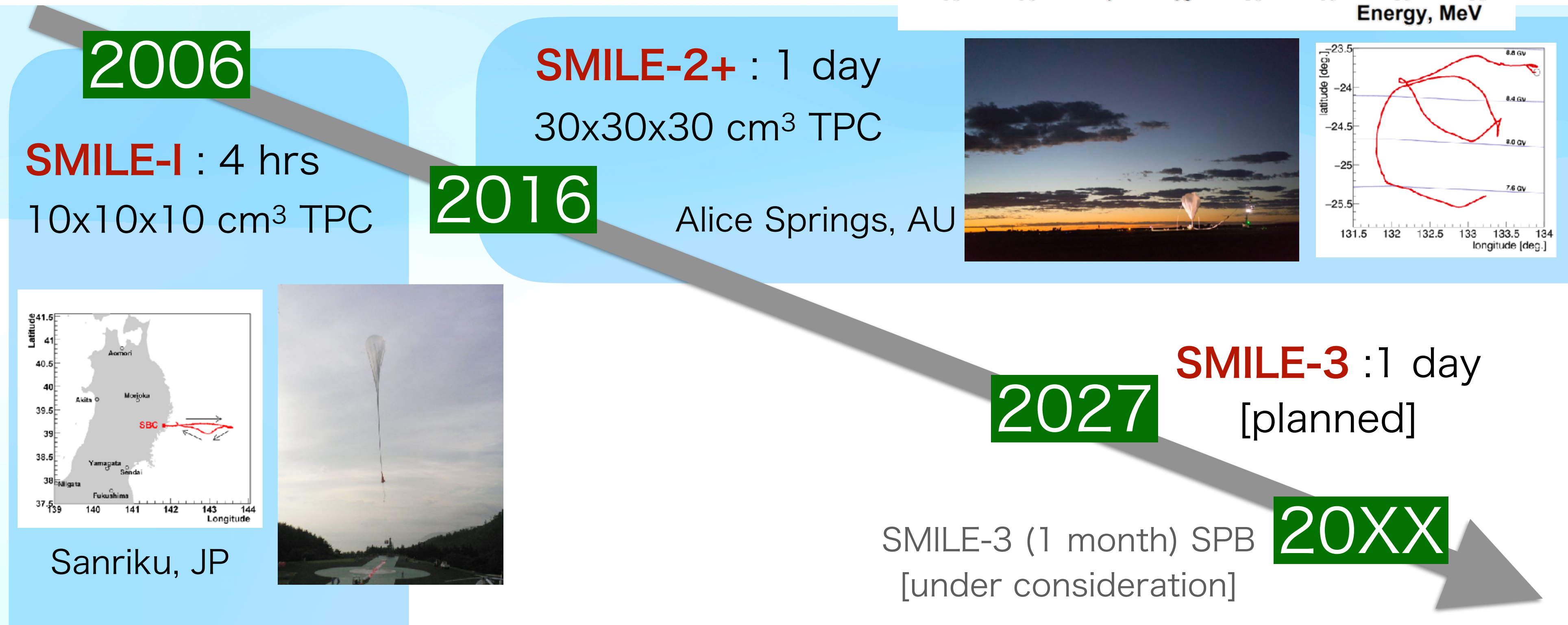


Galactic diffuse emission



Conclusions

NASA's SMEX mission COSI will be the first dedicated MeV mission in over 20 years, filling the gap left by COMPTEL and INTEGRAL.

Utilizing a germanium Compton telescope, it achieves both high spectral resolution and a wide field of view (25% of the sky) in 0.2-5 MeV.
It improves MeV sensitivity by ~10x and opens the window for gamma-ray polarimetry.

With uniform exposure and large FoV, it provides all-sky maps of key nuclear lines and 511 keV and capabilities to observe transient events like GRBs and multimessenger events.

Characterizing the in-orbit background and establishing statistical analysis methods for non-direct imaging systems will set the standard for MeV astronomy.
COSI's scientific results and technical verification pave the way for future large-scale missions.