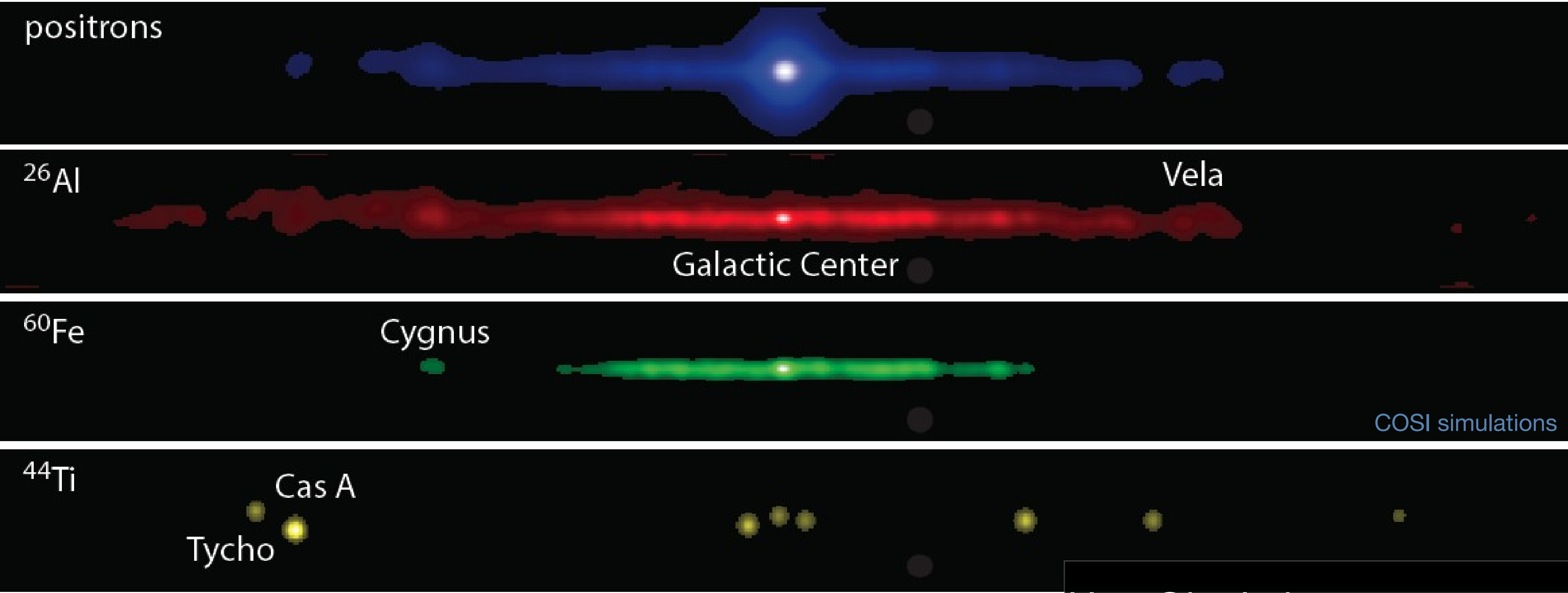
MeV Astronomy
Status and Prospects

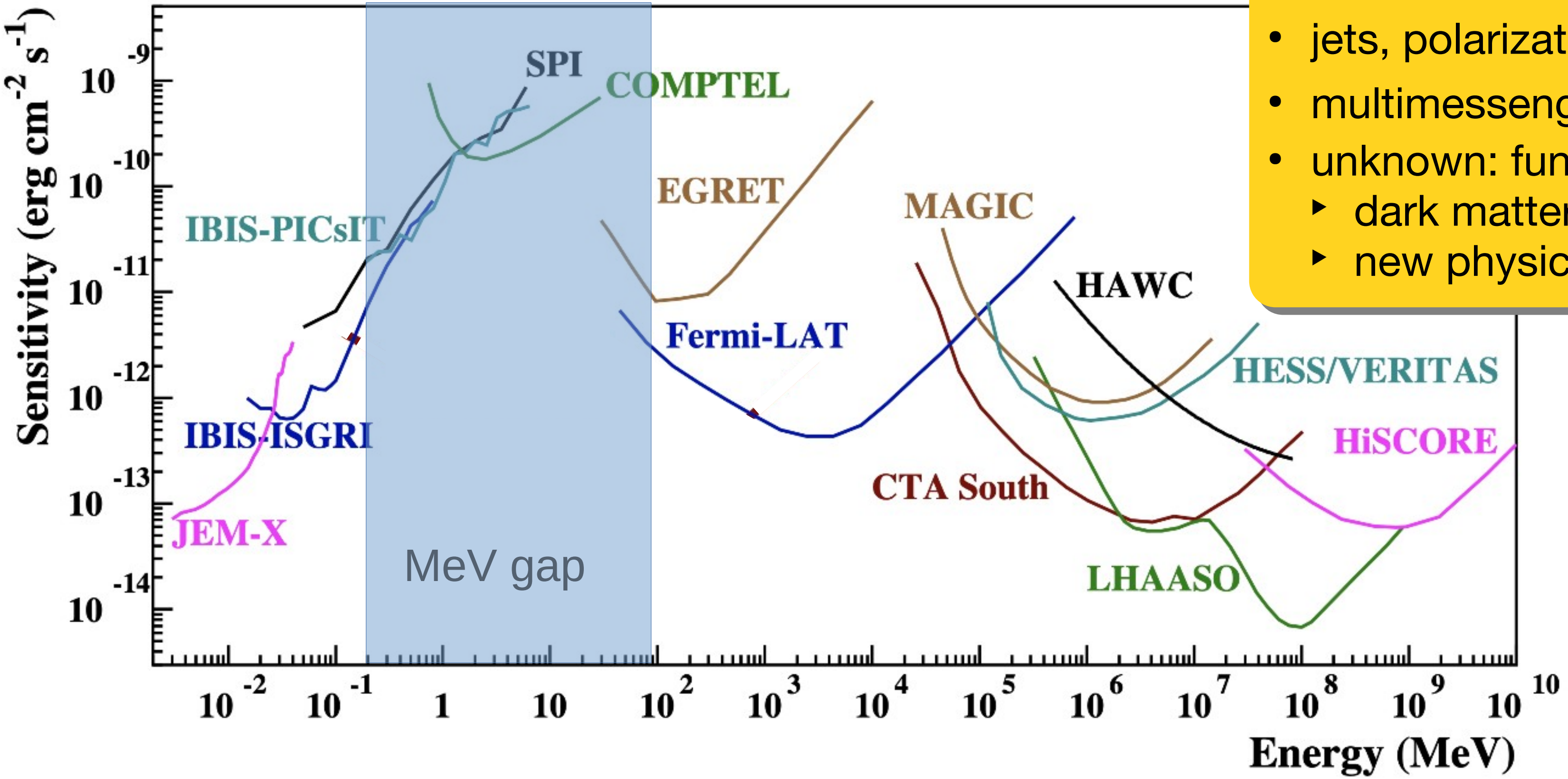


Marcel Grossmann Meeting
Pescara
2024-07-11

Uwe Oberlack
Institute of Physics &
PRISMA+ Excellence Cluster
Johannes Gutenberg University Mainz

The MeV Sensitivity Gap

Continuum sensitivity



Discovery space where there is known to be exciting or unique physics

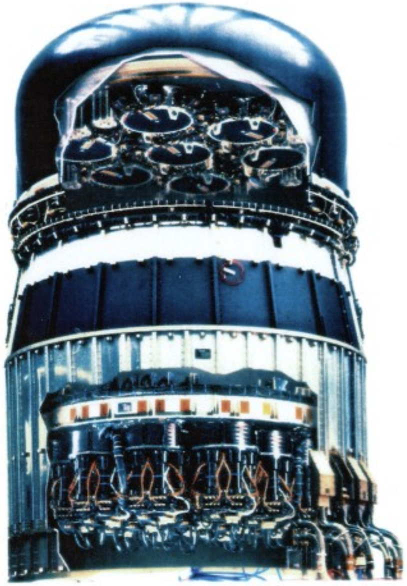
- e^+e^- annihilation line & continuum
- nucleosynthesis & supernovae
- jets, polarization
- multimessenger astrophysics
- unknown: fundamental physics
  - dark matter searches
  - new physics searches

Outline

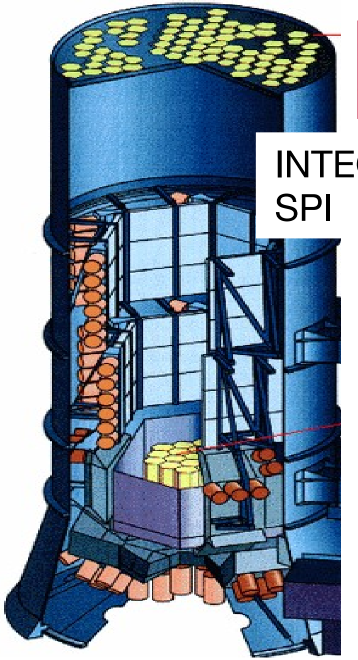
- ✔ MeV sensitivity gap
- Science drivers
- Spectral imaging at MeV energies
- Past, present, and future in MeV astronomy

I will skip INTEGRAL, as there was already a very nice talk by Sandro Mereghetti on Tueday.

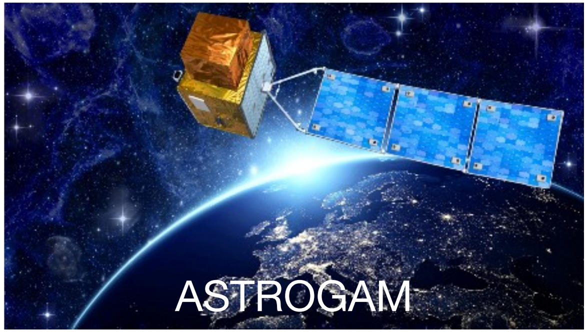
Future: see also following talks by P. Coppi & I. de Vitri

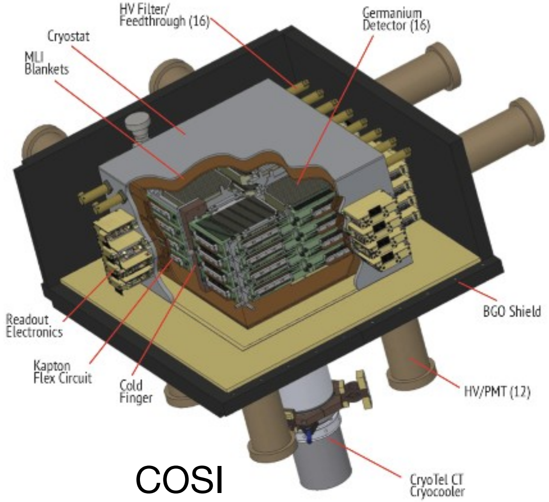


COMPTEL



INTEGRAL SPI





COSI

Science Topics (overview)

- Nucleosynthesis & galactic chemical evolution
- Positrons (MW and beyond)
- Supernovae:
  core-collapse, thermonuclear
- Cosmic accelerators
  AGN, galactic X-ray binaries (polarization)
- Low-energy cosmic rays
- “Multi-messenger” science
  - GW + γ (NS merger, kilonovae)
  - $\nu + \gamma$ (AGN, ...)
- Galactic diffuse emission
- Extragalactic background
- Gamma-ray bursts (polarization)
- Dark matter and new physics
- Pulsars
- Expect the unexpected!

Outline

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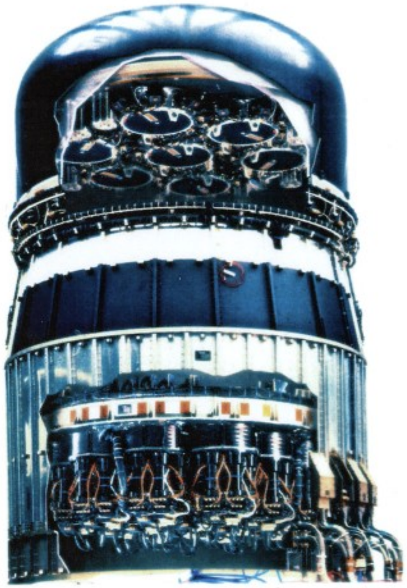

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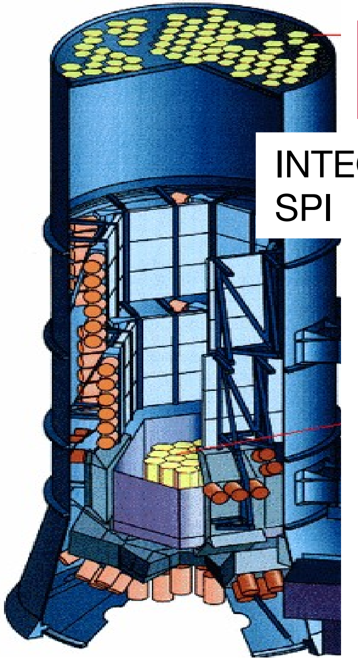

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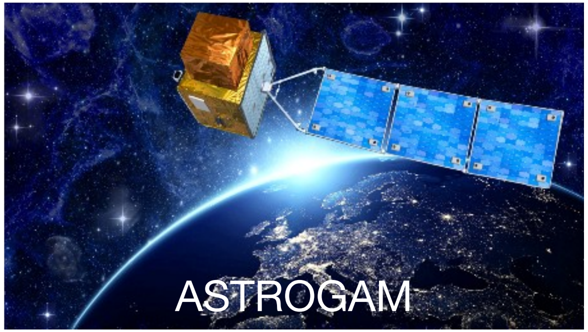
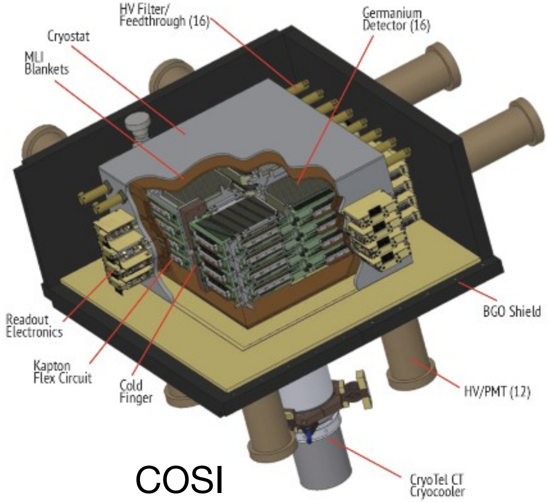
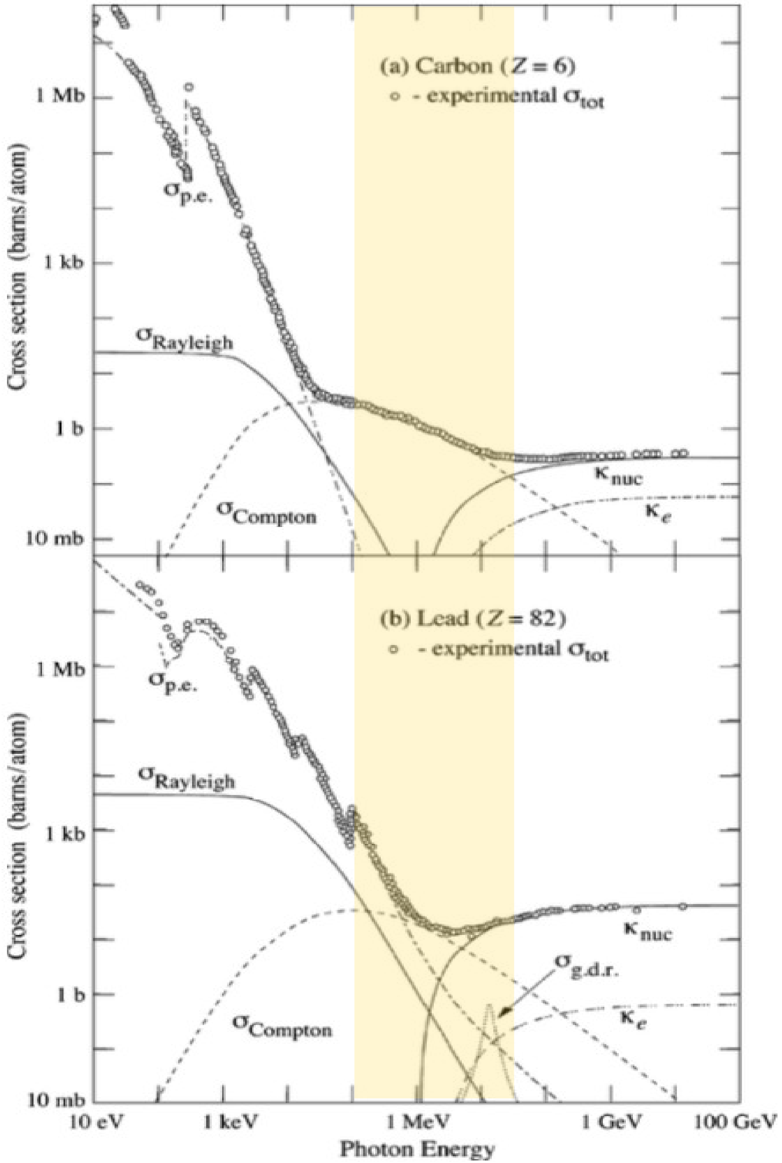




COSI

The problem of imaging MeV gammas

- High energy / short wavelength: focusing lenses hardly# feasible.
  ⇒ light collection area = detector area
- High detector background due to
  - cosmic particle radiation
  - secondary radiation (prompt or delayed)
  - atmospheric gamma radiation
- Interaction cross-section of photons with matter has a minimum in the MeV range
  ⇒ large mass required for absorption of photons.
- Compton scattering (incoherent) dominates.

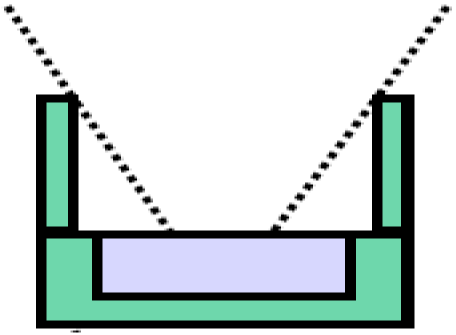


#detailed caveats skipped

Imaging Gamma-ray Telescopes: Geometric Imaging

Collimators

- Simple gamma detector with a collimator
- Limited field of view, determined by choice of collimator
- "Mapping" by "on/off" observations
- Example: Compton GRO / OSSE

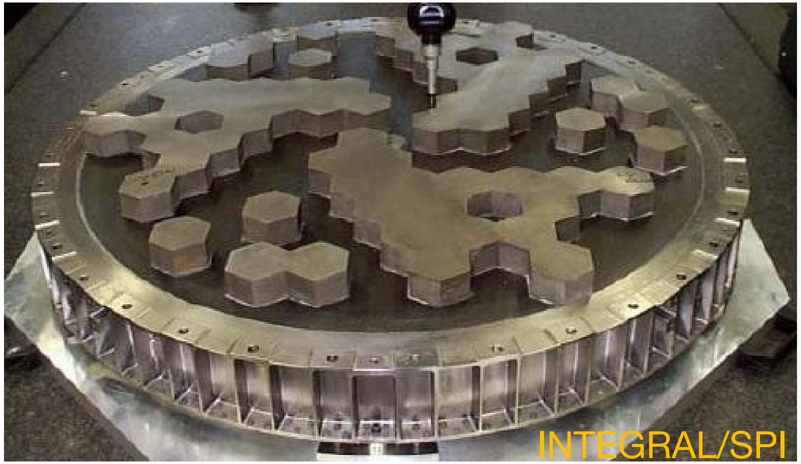


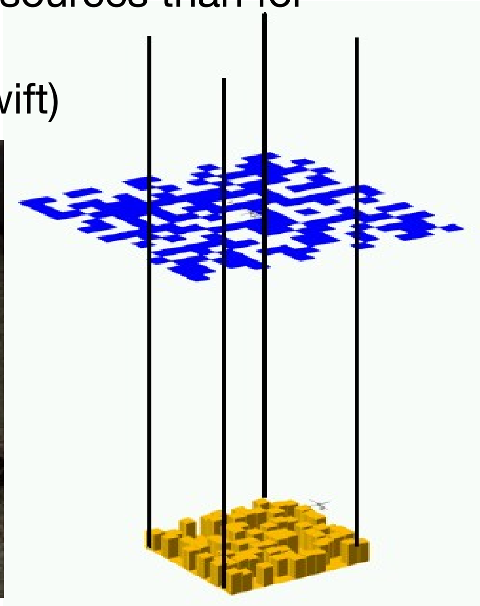
Coded masks

- Good angular resolution possible in principle.
- But: PSF (point spread function) distributed over the entire detector.
- Mask radiates.

} ⇒ high background

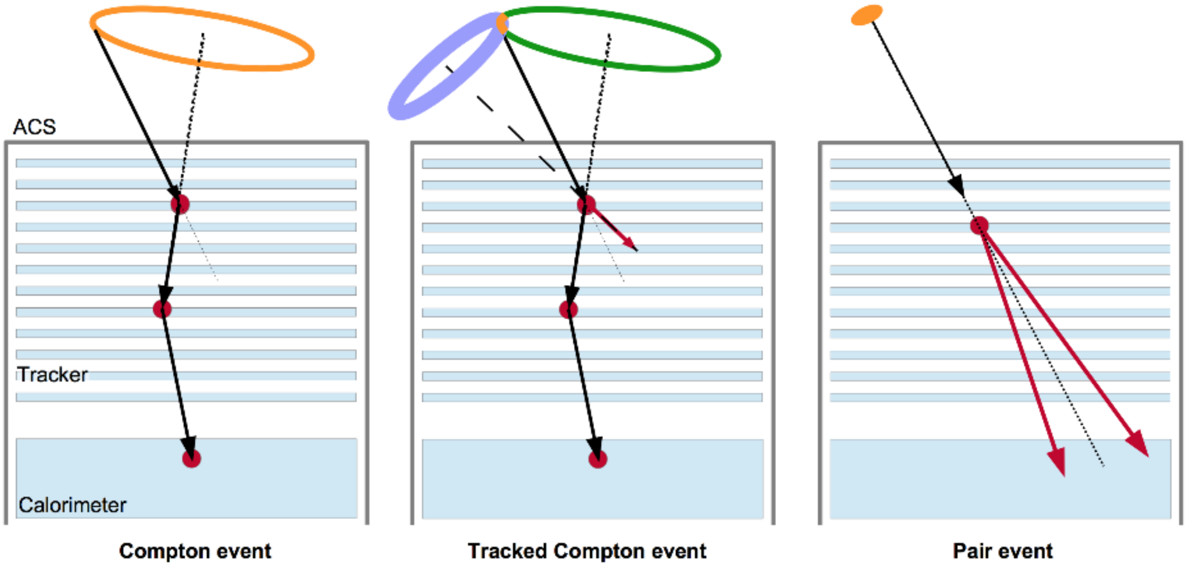
- Generally better for point sources than for diffuse emission.
- Example: INTEGRAL (, Swift)





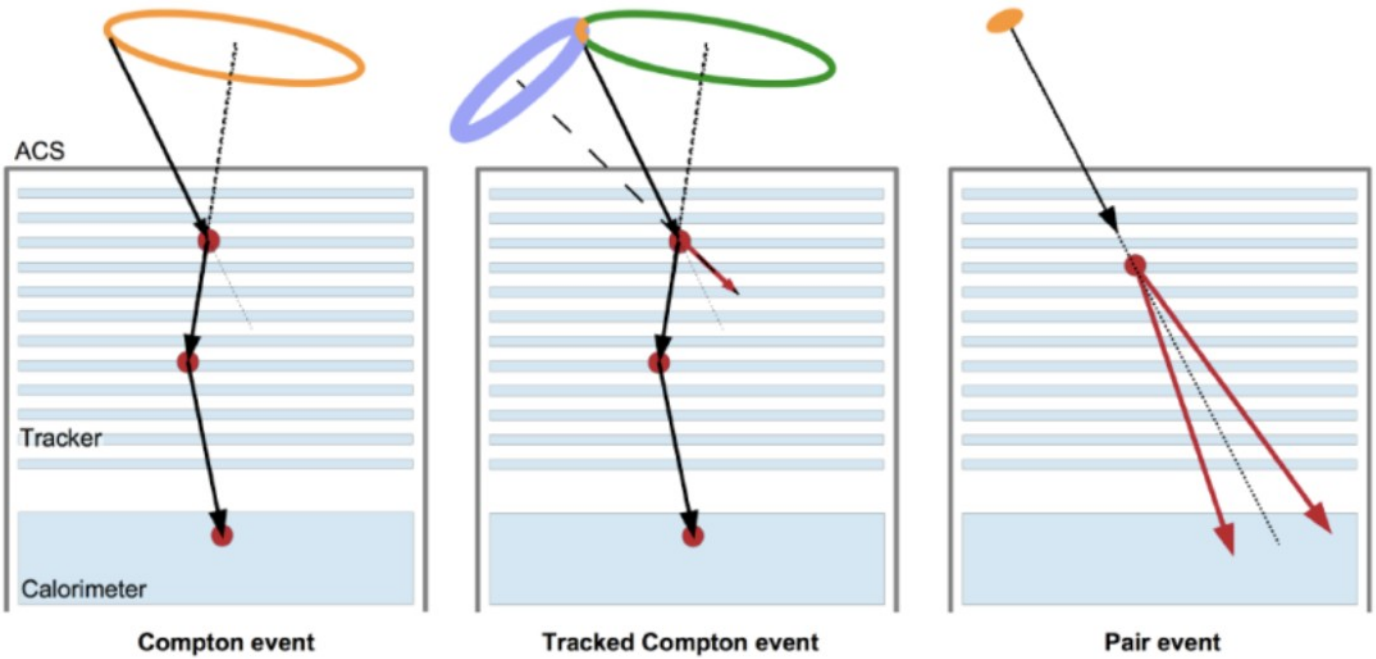
Imaging Gamma-ray Telescopes

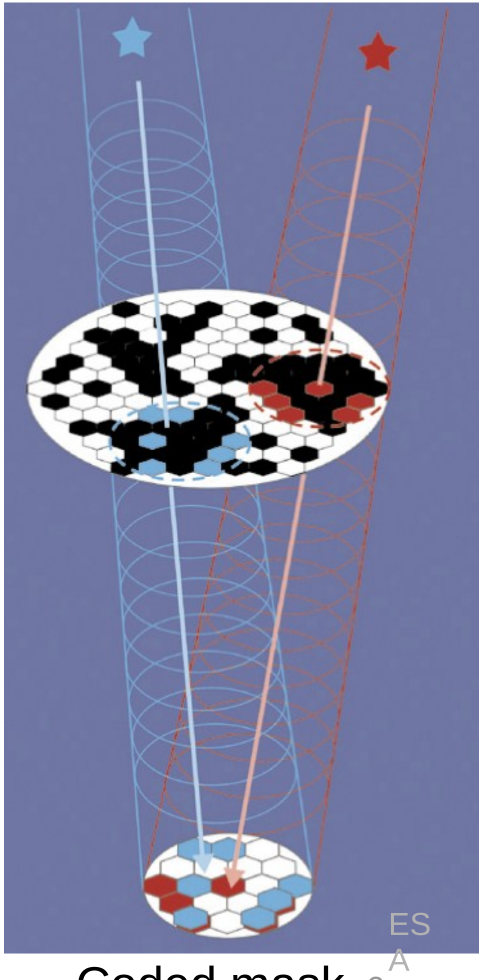
- Dominant interaction of photons with matter in
  - ~0.1–10 MeV: Compton scattering → Compton telescope
  - E_γ >~ 10 MeV: pair production (nucleus) → Pair telescope
- Both: very large field-of-view
- Good sensitivity to diffuse emission
- Survey instrument
- Background suppression techniques
- Moderate angular resolution



Imaging the Gamma-Ray Sky from 0.1 MeV to GeV

- photo effect: coded mask - INTEGRAL
- Compton telescope: COMPTEL, COSI
- Pair telescope: Fermi





Coded mask

Compton Imaging

Compton imaging requires the measurement of:

- Gamma energy E_γ
- Energy transfer to electron E_e
- Direction of scattered gamma-ray $\vec{n}_1$

Compton kinematics:

$$\cos\bar{\varphi} \;= 1 - \frac{m_e c^2}{E_{tot} - E_1} + \frac{m_e c^2}{E_{tot}}$$

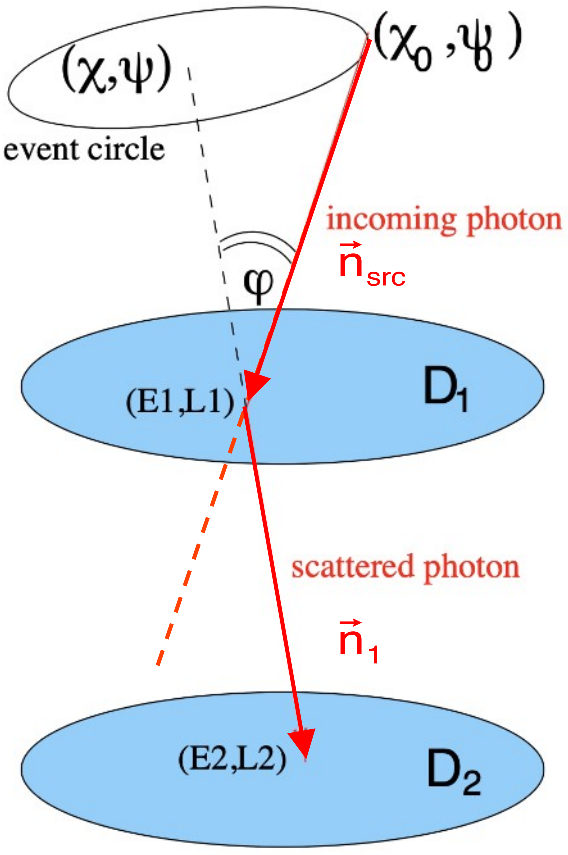
$$\cos\varphi_{geo} = \vec{n}_{src} \cdot \vec{n}_1$$

$\varphi_{geo} = \bar{\varphi}$ defines an event circle about $\vec{n}_1$ for one photon.

Imaging principle: maximize likelihood

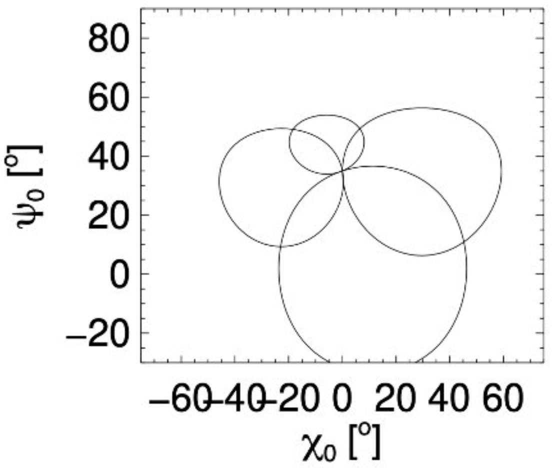
$$\prod_i \prod_j \, p\left(\cos\varphi_{geo,ij}, \cos\bar{\varphi}_i, E_{tot,i} \mid E_{\gamma,ij}, \vec{n}_{src,j}\right)$$

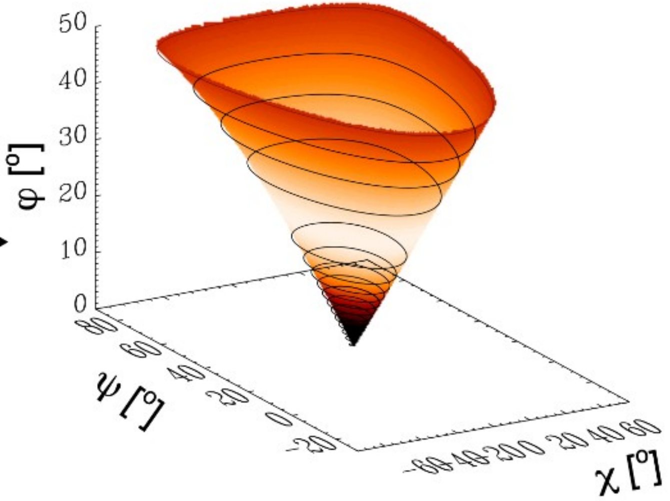
for multiple photons i and sources j.
+ regularisation

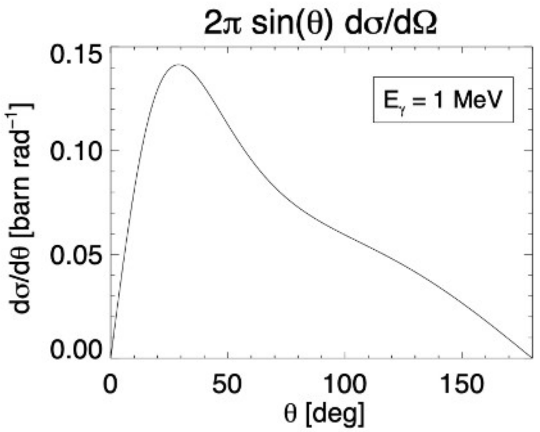


$$\bar{\varphi} = \arccos\left(1 - \frac{m_0 c^2}{E_2} + \frac{m_0 c^2}{E_1 + E_2}\right)$$

Principle of the Double-Scatter Compton Telescope COMPTEL (II)







Compton scatter (Klein-Nishina) cross-section

- Since the direction of the scattered electron is not measured, the arrival direction of a γ-ray is ambiguous to within an "event circle" around the measured direction of the scattered photon. Many γ-rays from a celestial source generate event circles that intersect (within the measurement uncertainties) in one position.

- In practice, imaging data are collected in a 3D data-space, consisting of the angles of the scattered photons (χ, ψ) and the calculated scatter angles $\bar{\varphi}$, for a fixed energy window. For image reconstruction, the dominating background is modelled and fitted together with assumed source positions in an iterative scheme, that allows to find the image which is most consistent with the data.

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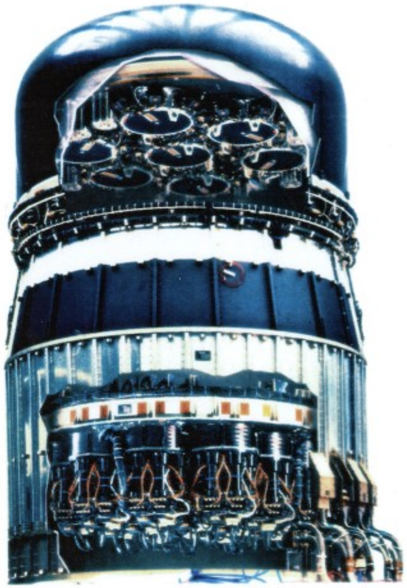
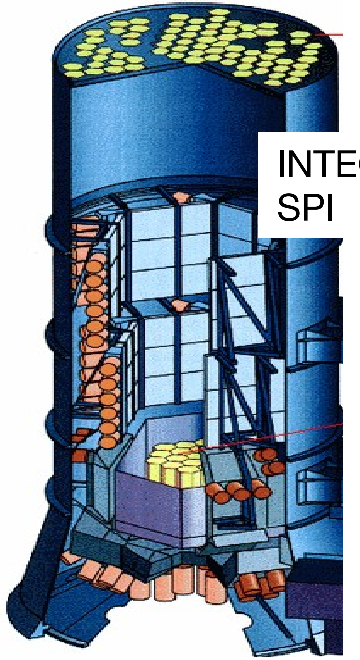
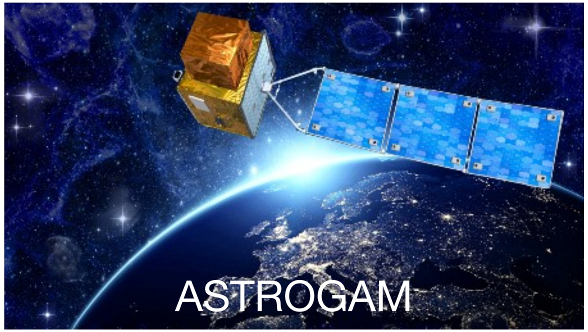
Future: see also following talks by P. Coppi & I. de Vitri

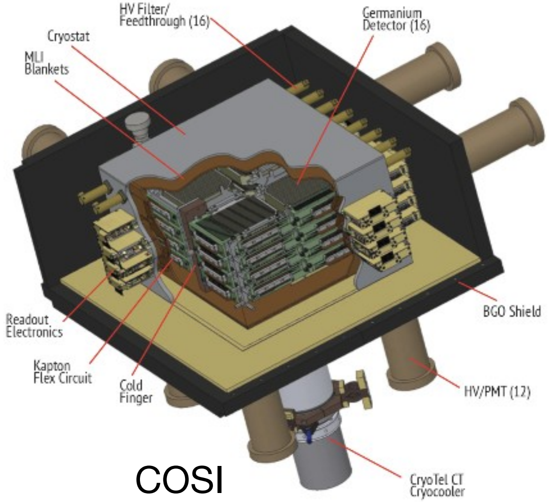


COMPTEL



INTEGRAL SPI



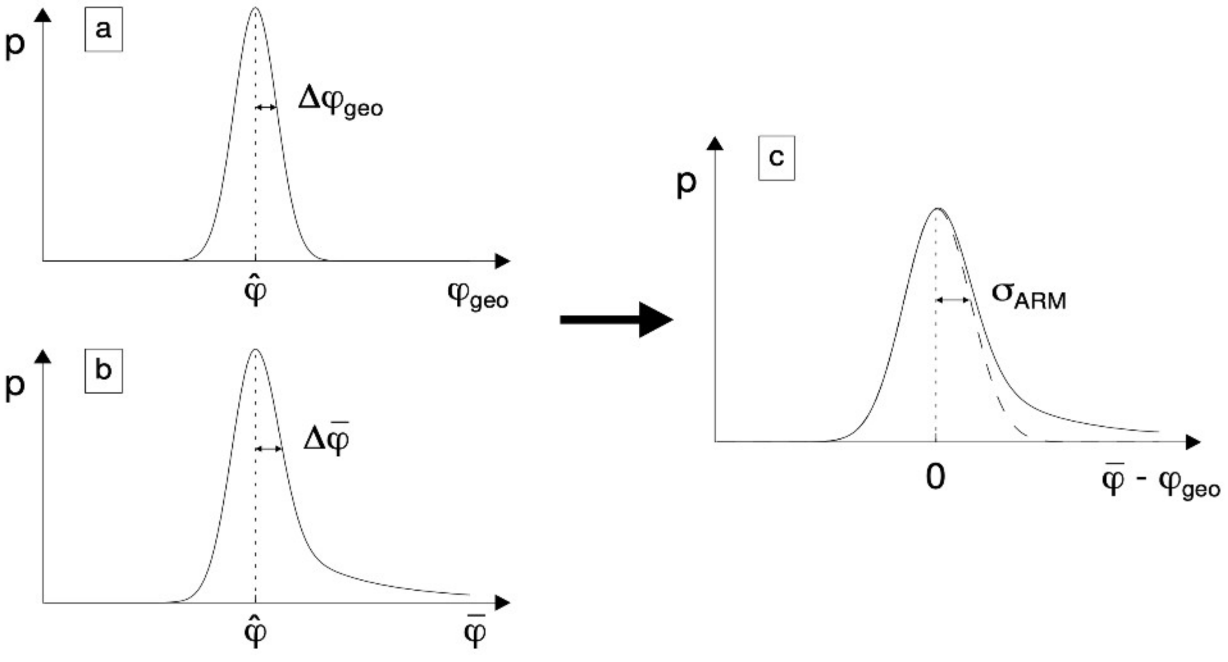


COSI

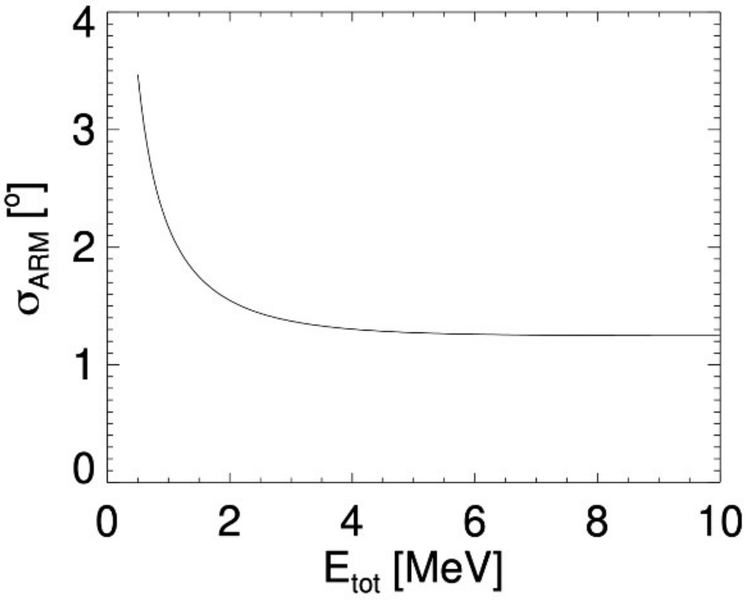
Aspects of Compton telescope performance

- sensitivity
- energy resolution
- angular resolution
- Doppler broadening
- backgrounds
  - reduction: e.g., 0° inclination low-Earth orbit (LEO), material selection
  - suppression: example COMPTEL – ToF, PSD; event classification, reconstruction, selection
- efficiency
  - COMPTEL vs. compact CTs
- field of view (usually very large)

Energy and angular resolution



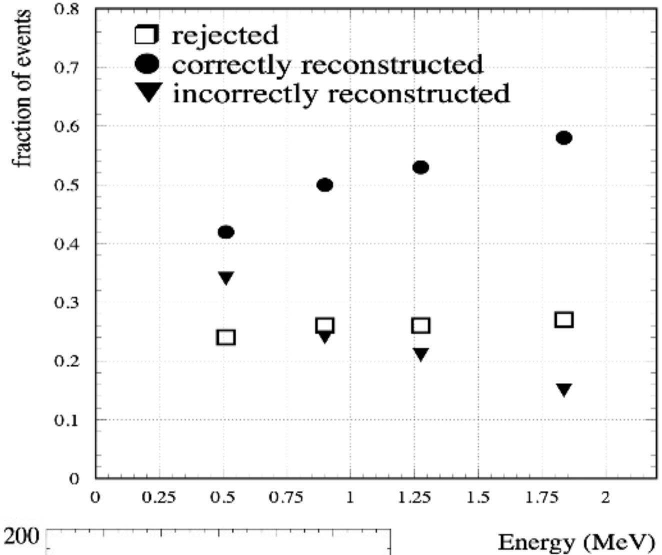
PhD thesis UO '97

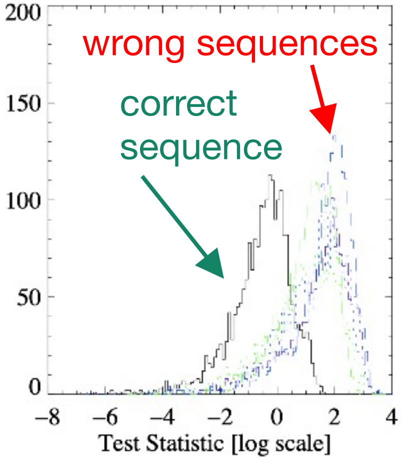


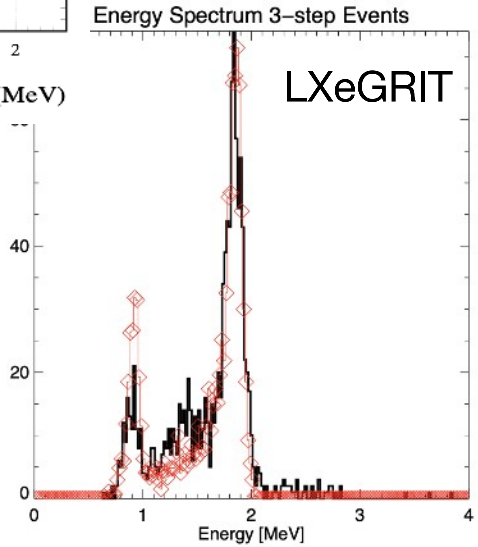
after
PhD thesis R. Much '94

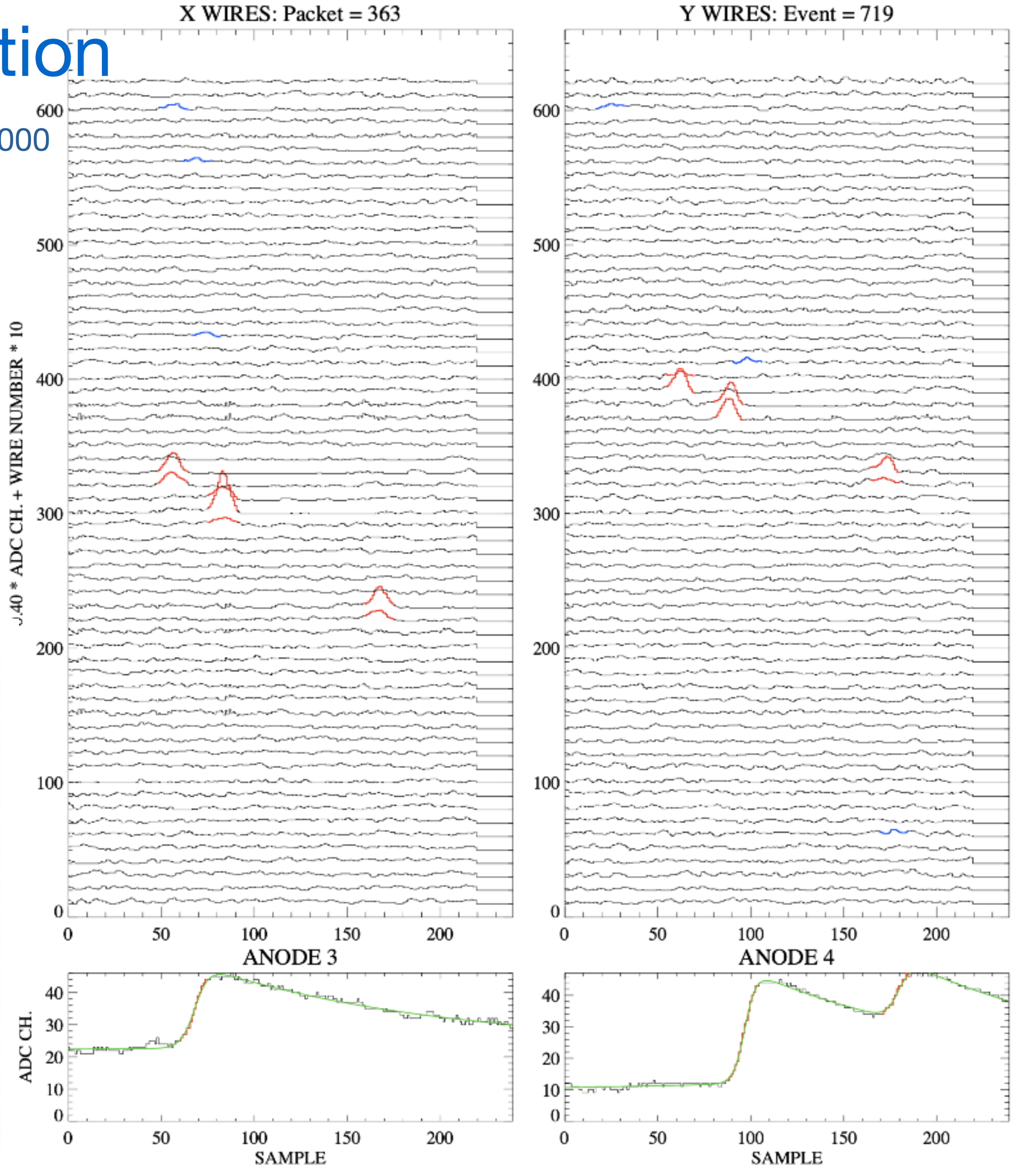
Compton sequence reconstruction
Event reconstruction

UO+ SPIE 2000

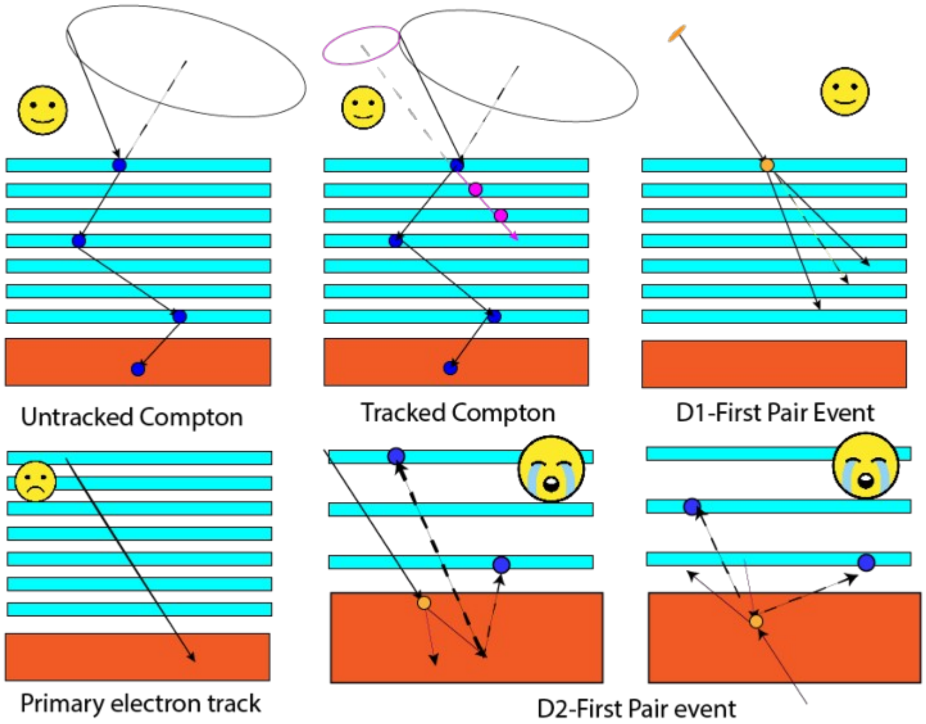








Event Topologies in Compton-Pair Telescopes

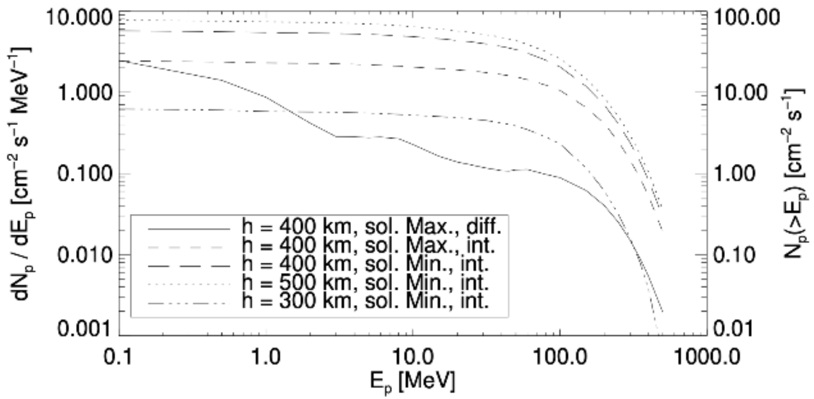


- Compton-Pair telescopes have two detection channels for imaging.
- Compton events can occur either with or without measurable recoil electron track.
- Pair creation can occur in the tracker (desired) or in the calorimeter (“lost photon”)
- Charged particles can enter the detector and create non-reconstructable events
- Apply machine learning to event classification before reconstruction

PhD thesis Jan Lommler (JGU Mainz)

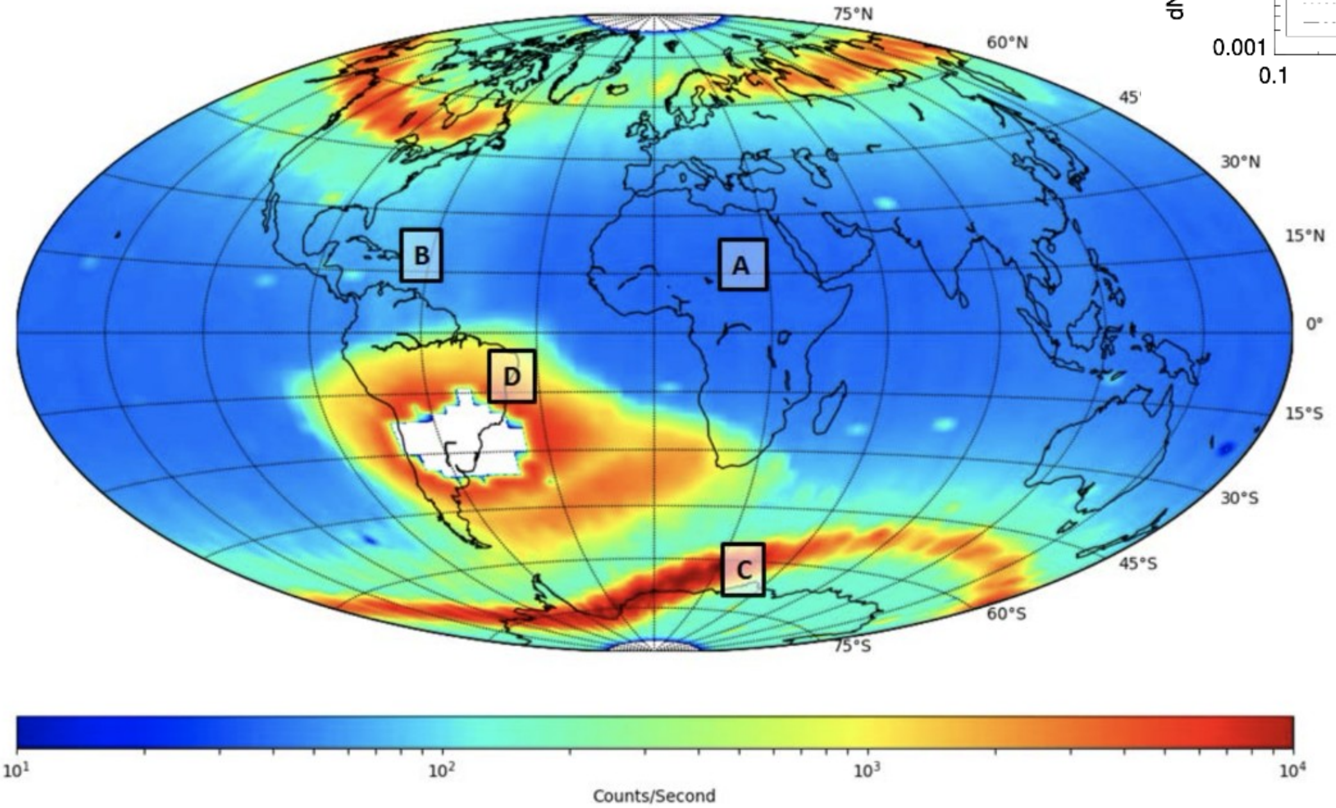
Backgrounds

Strontium Iodide Radiation Instrument (SIRI)



trapped proton fluxes vs. altitude in 28.5° inclination orbit

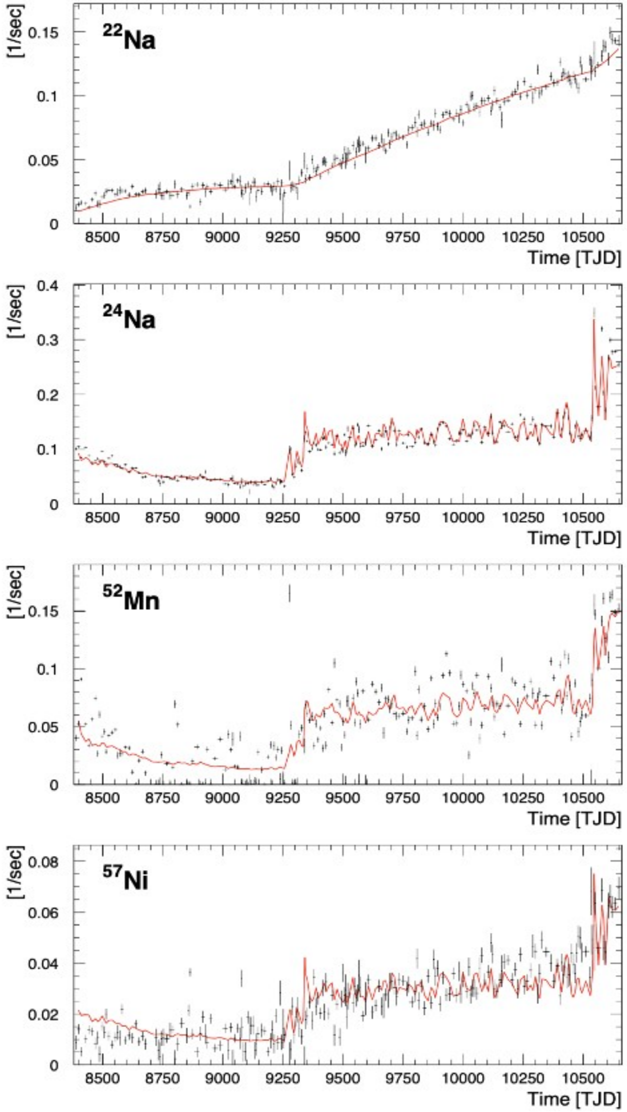
(UO PhD thesis '97)

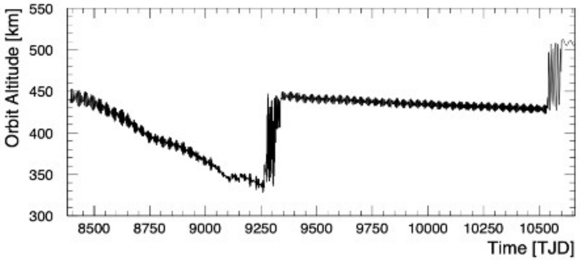


Mitchell+19

Gross gamma-ray count rate showing the elevated background as the instrument transitions through the various trapped particle regions. The four zones A, B, C and D were used generate the spectra shown in Figure 5. No data is indicated by the white areas of the plot.

COMPTEL
Background from activation





Nuclear line background is due to **activation** by protons and neutrons, and to **primordial radioactivity**. For the time-coincidence measurement of COMPTEL, **gamma-ray cascades** are particularly harmful, and have to be modeled carefully. Physical background models are developed iteratively by **identification of background generating isotopes** in the data, fitting **simulated templates**, and testing the temporal behavior with a **neural network model**, which predicts activation as a function of orbit parameters.

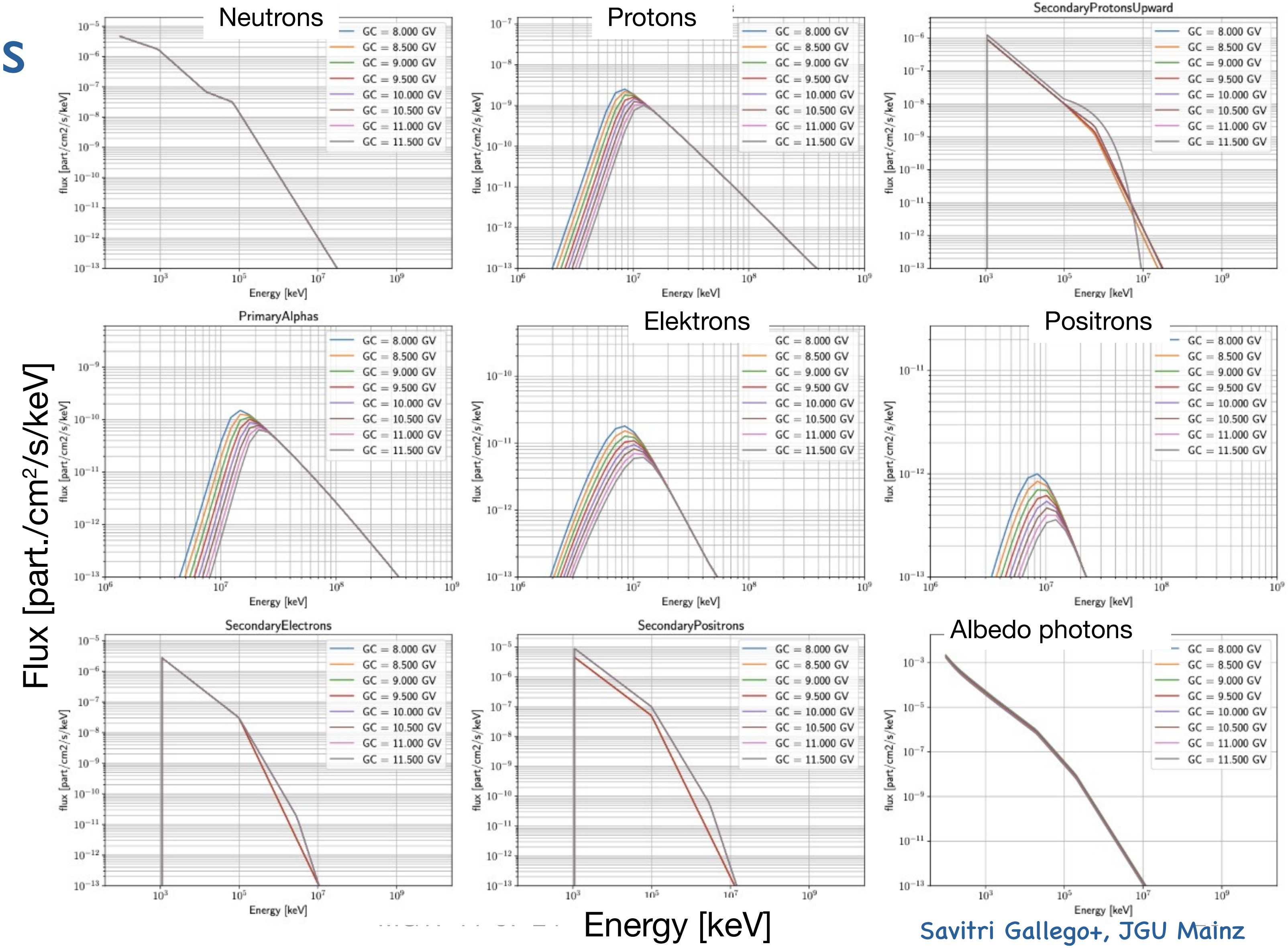
Weidenspointner, Varendorff, Oberlack, et al. A&A 2001

Backgrounds

input spectra

Simulations of the physical backgrounds for COSI.
Test case: COSI balloon flight.

Setup:
MEGAlib (Zoglauer+06) based on current GEANT4 version (Agostinelli+03, Allison+06, Allison+16) and input models (Cumani+19 etc.)



Savitri Gallego+, JGU Mainz

Backgrounds: Example COSI Balloon flight

Simulations of the physical backgrounds for COSI.
Test case: COSI balloon flight.

Setup:
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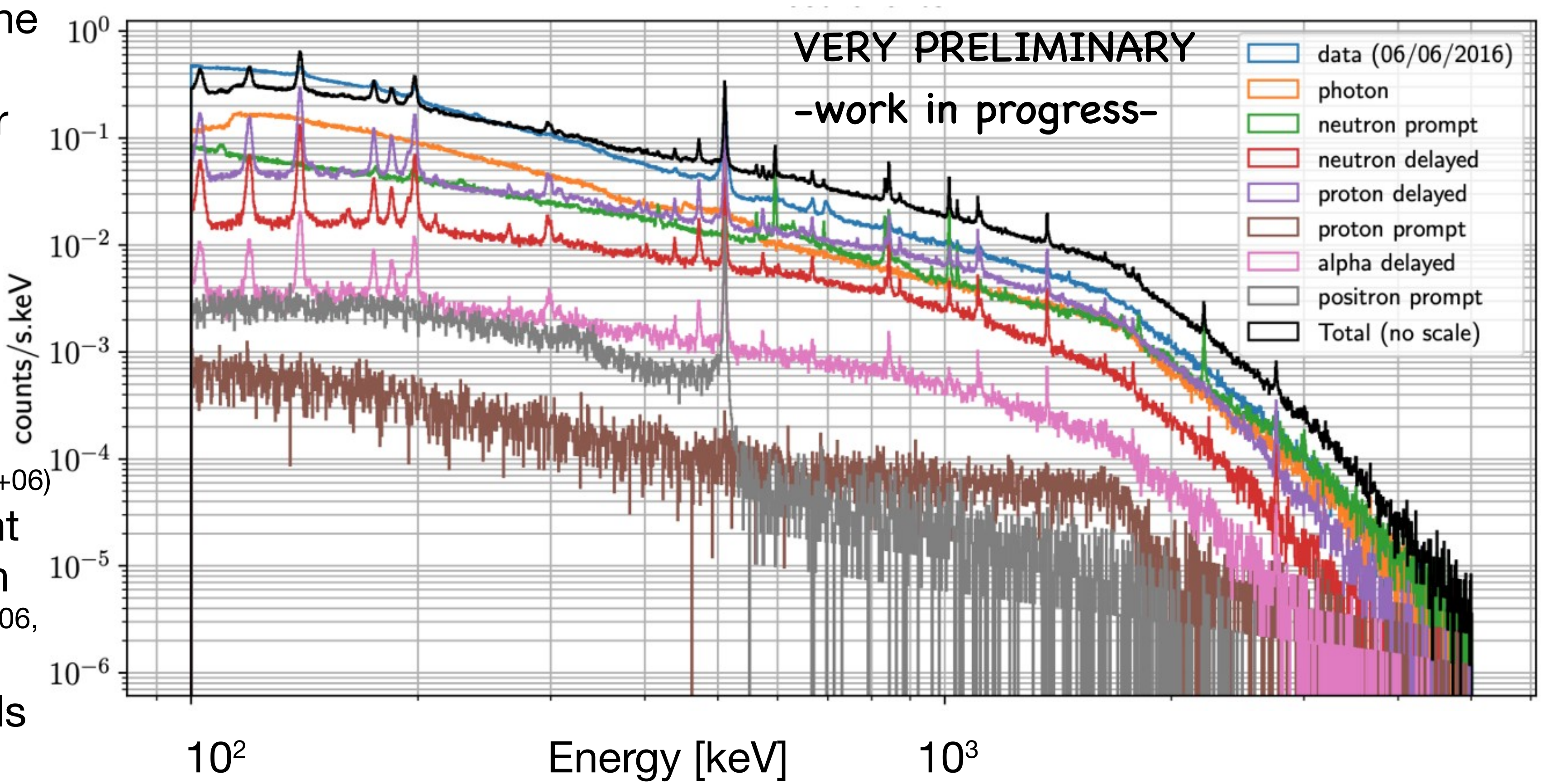


Savitri Gallego+, JGU Mainz

Sensitivity: from COMPTEL to future CTs

What does it take to reach a sensitivity of $f_{3\sigma} \sim 10^{-7}$ ph cm^{-2} s^{-1} (narrow-line point source) – improvement of a factor 100 over COMPTEL (after 9 yr of operation)?

$$f_{3\sigma} \propto \left[\frac{f_b V_{psf}}{X_{eff}} \right]^{0.5}$$

- equivalent background flux f_b
- effective exposure $X_{eff} = A_{eff} * t_{obs}$
  (geometric area * efficiency * observing time on source)
  Scanning mode:
  observing time on source ≈ (FoV/4π) * total observing time
- V_{psf} volume of PSF in Compton data space ⊗ energy
  $V_{psf} \propto$ angular resolution, energy resolution
  → optimizes signal / background

Requirements:

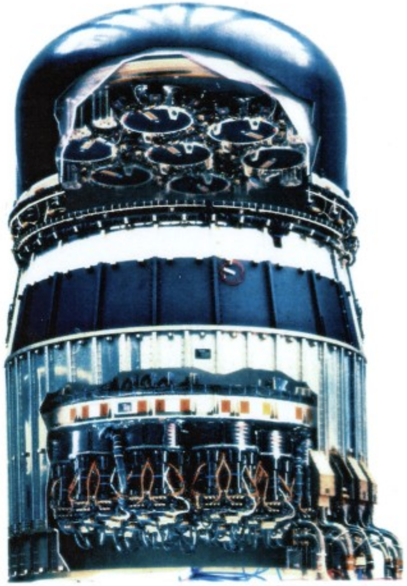
- Much lower background
- Much higher efficiency and larger area
- Better position and energy resolution, larger FoV

Status & Prospects of MeV Gamma-ray Astronomy

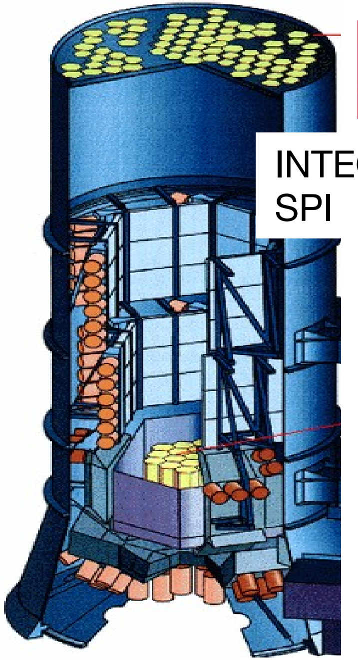
- COMPTEL (pioneering, PI: MPE)
- INTEGRAL/SPI (ending 2024, Co-PIs: MPE, CESR/IRAP)

  → Tuesday Sandro Mereghetti
- COSI (launch 2027, PI: UCB)
- Plans for bigger future missions
  - ESA ASTROGAM (M7, launch 2037) Italy, France, Germany + partners → proposal ‘22 rejected.
  - Plans in US to put a large gamma-ray mission on the NASA roadmap.

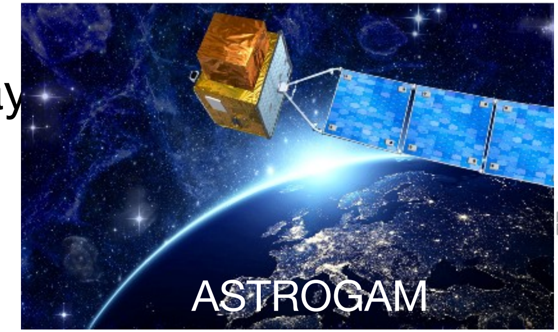
    → next talk by Paolo Coppi
  - Other international plans

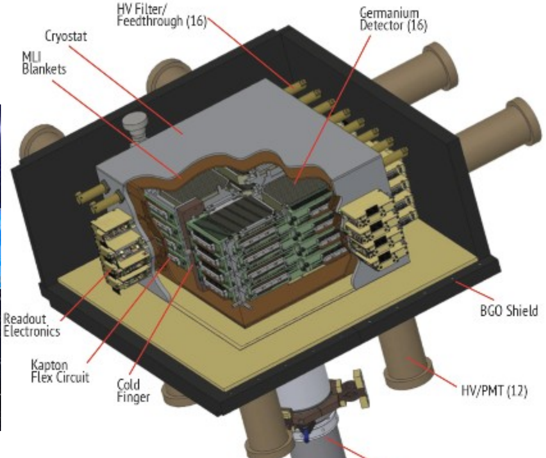


COMPTEL



INTEGRAL SPI



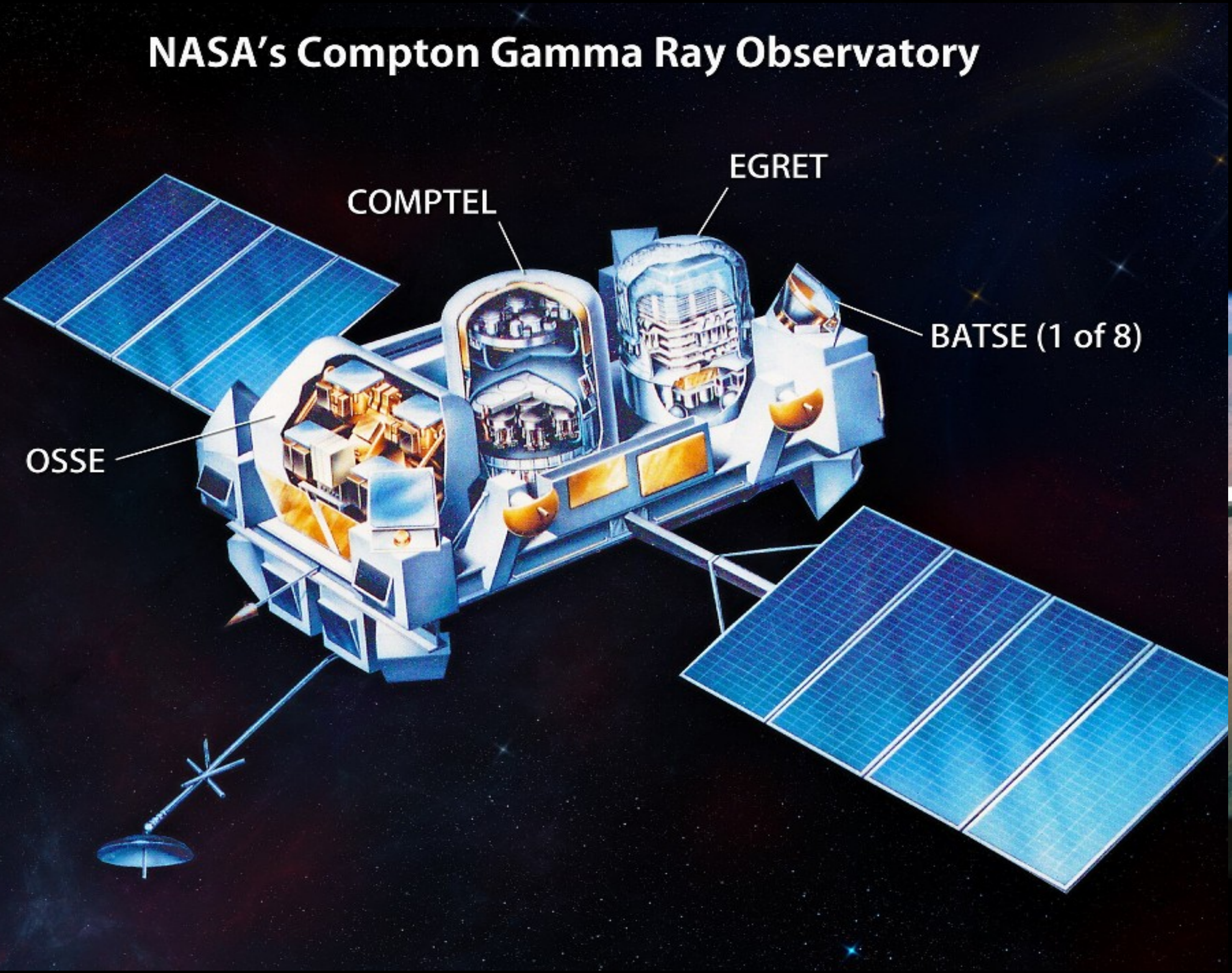


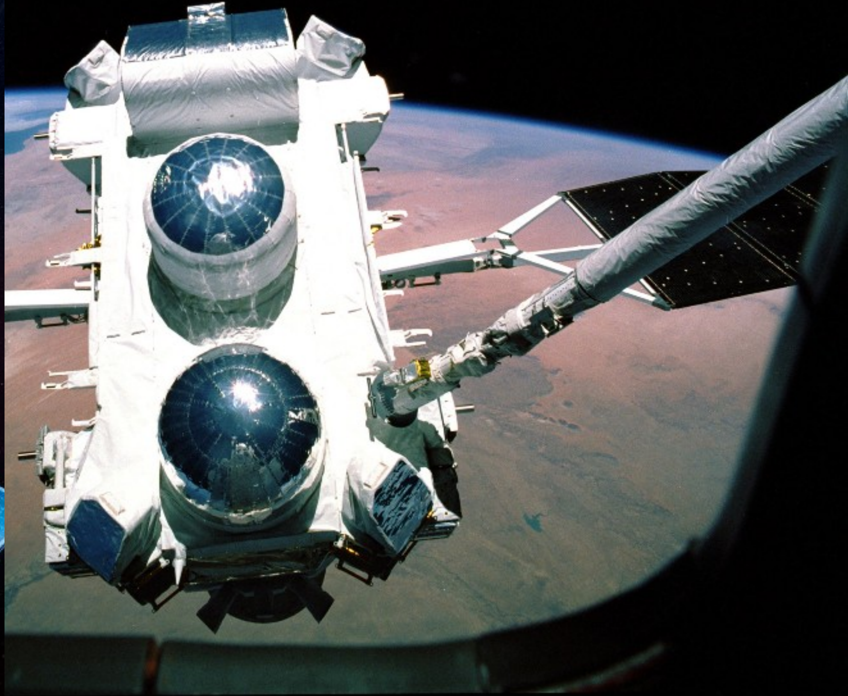
COSI

The 1990s: the “Golden Age” of Gamma-ray Astronomy

- Compton Gamma-ray Observatory (CGRO) 1991-2000

- simultaneous observation of cosmic gamma rays from 20 keV to 30 GeV

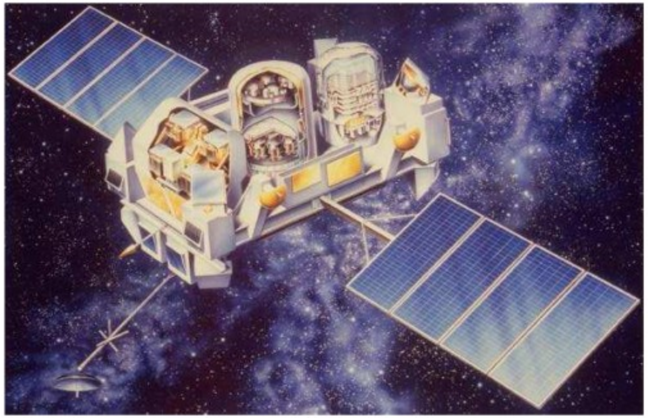




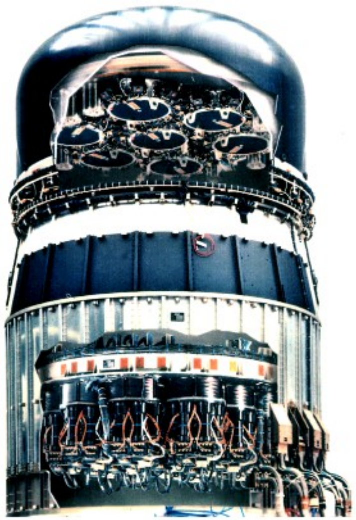
Uwe Oberlack

COMPTEL
Characteristics

Volker Schönfelder
1939 - 2024

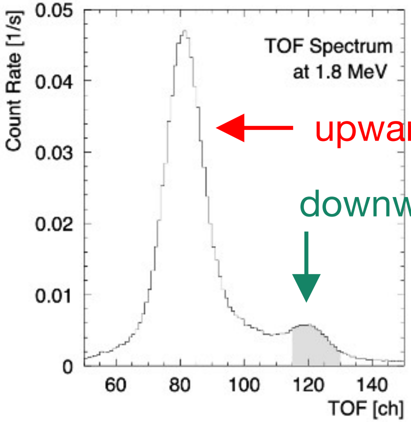


detectors	liquid scintillator (D1), NaI (D2)
geometrical area	D1: 4188 cm^2, D2: 8620 cm^2
spatial resolution	D1: 5.4 cm, D2: 3.5 cm (FWHM)
distance D1 – D2	$\sim$ 1.5 m
field-of-view	$\sim$ 1 sr
angular resolution	3.6° @ 1.8 MeV (FWHM, $\bar{\varphi} < 50°$)
energy resolution	$\sim$ 8% @ 1.8 MeV (FWHM)
energy threshold	$\lesssim$ 70 keV (D1)
energy range	0.75 – 30 MeV
effective area	5 – 10 cm^2 @ 1.8 MeV after cuts
line sensitivity	$\lesssim 10^{-5}\ \gamma\, cm^{-2} s^{-1}$ after 9 yr mission
exposure maximum	$X_{eff} \approx 1.5\ 10^8\ cm^2\ s$ (estim.)



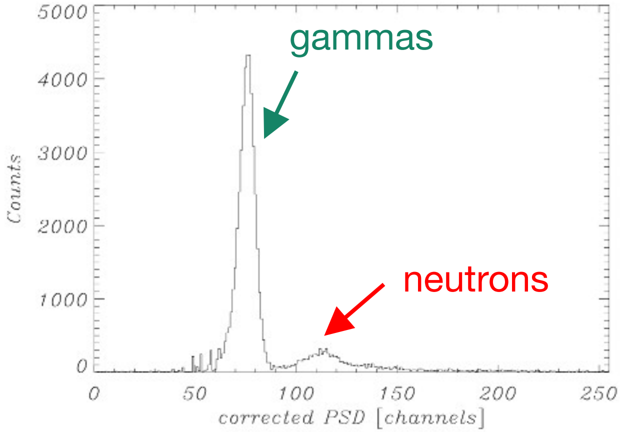
Background reduction techniques:

Time-of-flight (TOF)



U. Oberlack, PhD thesis, 1997

Pulse-shape discrimination (PSD)

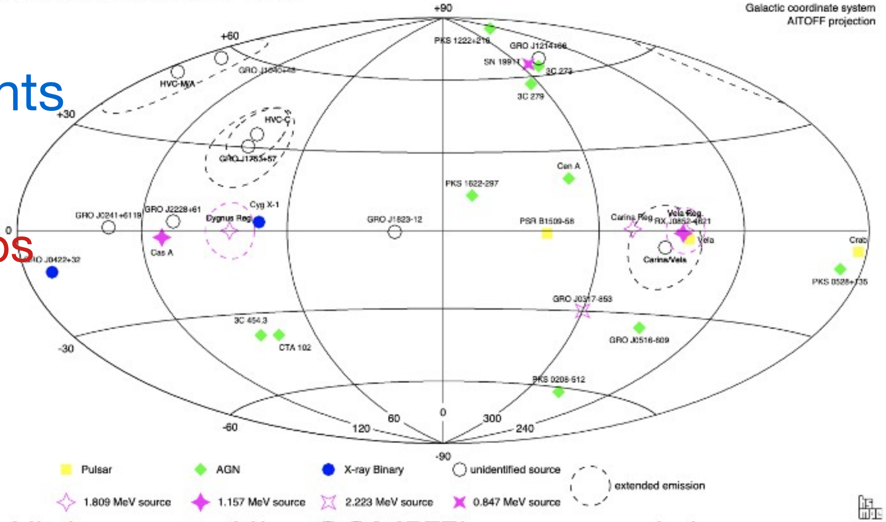


R. van Dijk, PhD thesis, 1996

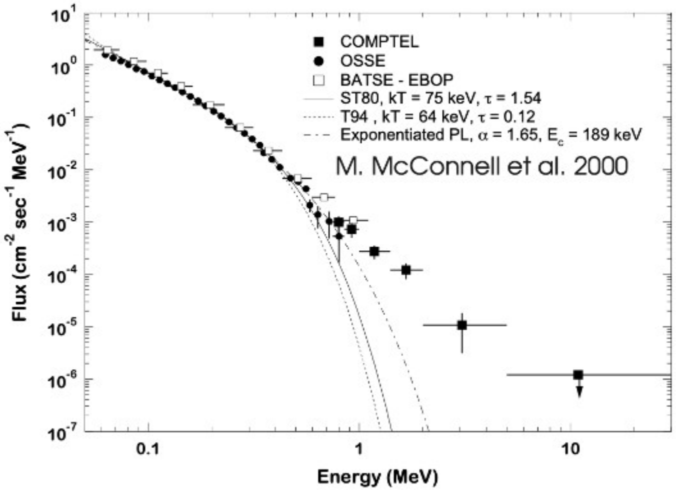
COMPTEL
Science Highlights

First all-sky coverage and maps @ MeV energies!

V. Schönfelder et al. 2000

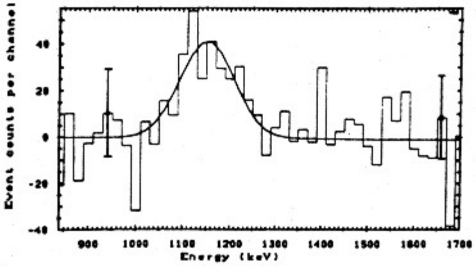


All-sky map of the COMPTEL source catalogue.

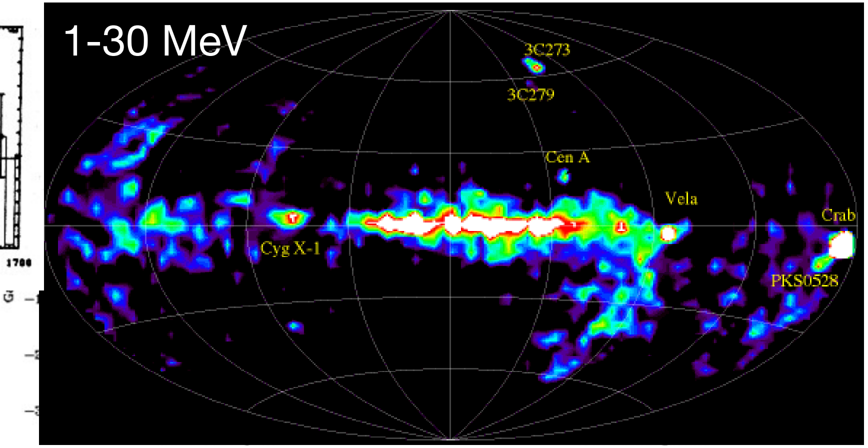


High-energy spectrum of the high-mass X-ray binary system Cyg-X1.

^{44}Ti Cas A



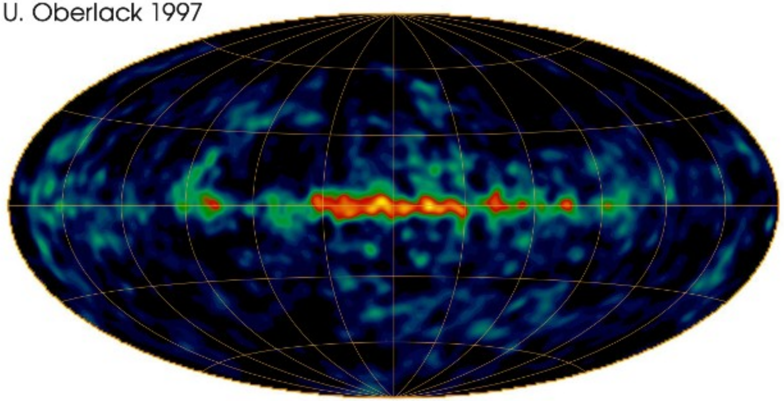
A. Iyudin et al. 1994



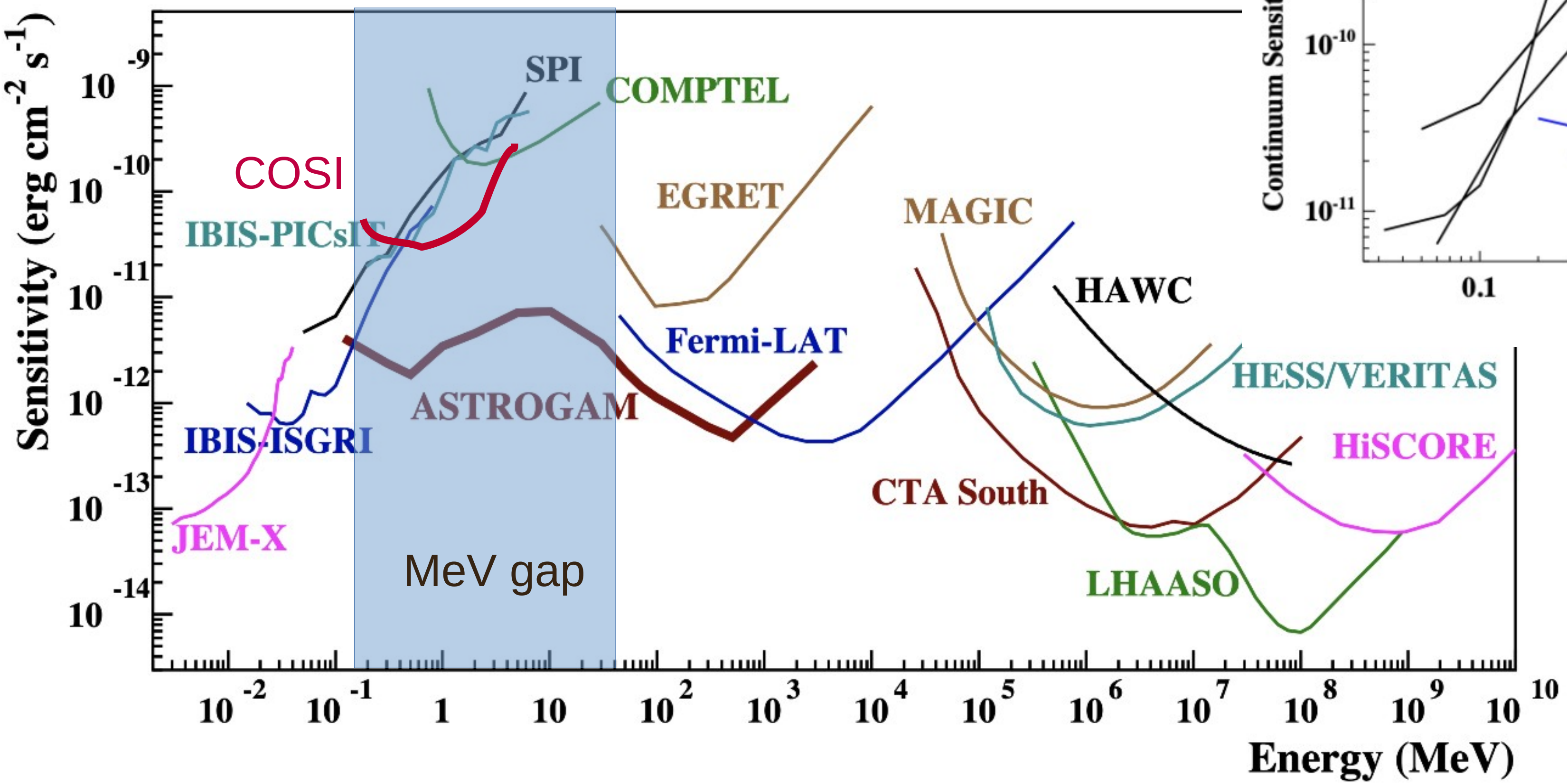
A. Strong et al. 1997, 1999

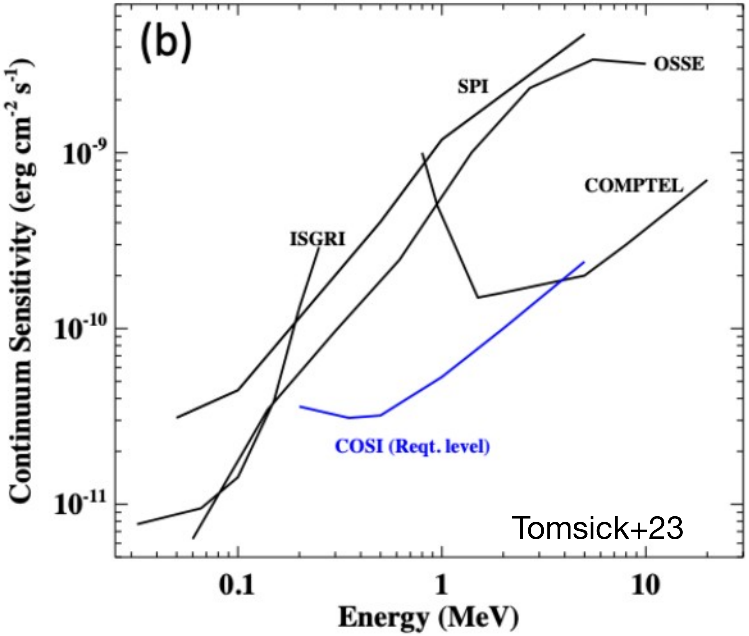
COMPTEL ^{26}Al Map at 1.8 MeV

U. Oberlack 1997



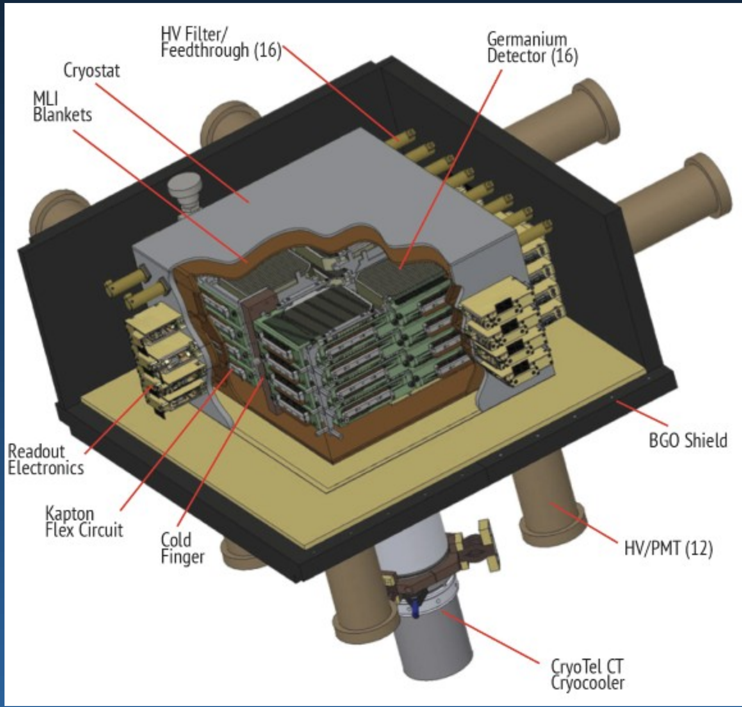
Outlook to COSI and beyond





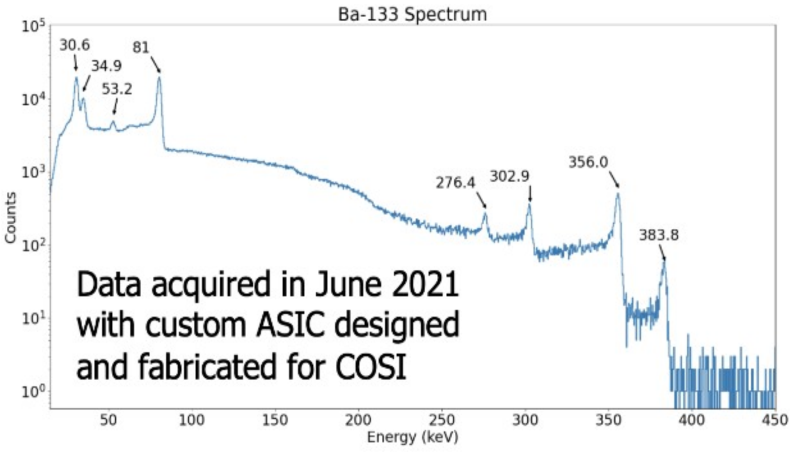
COSI: Compton Spectrometer and Imager

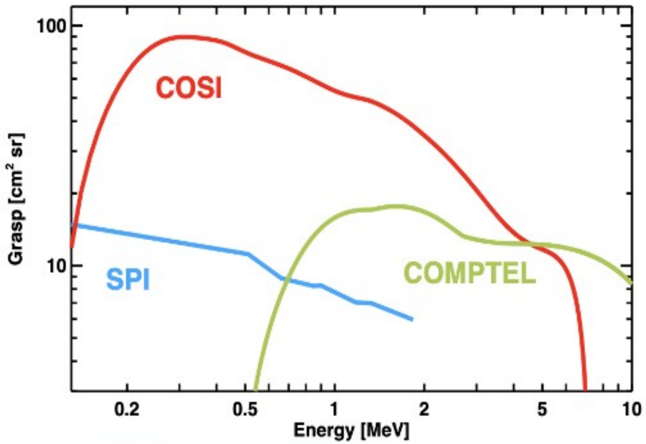
- NASA small explorer (SMEX) mission.
  Launch: 2027, 2 year mission (extensions possible)
  PI: John Tomsick, UC Berkeley / SSL
- Energy: 0.2 – 5 MeV.
  Ge Compton telescope
- Wide field-of-view. Instantaneous: >25%-sky and covers the whole sky every day.
- Great energy resolution but small instrument with limited energy range.
- **All-sky maps** of **511 keV** line and continuum, and **^{26}Al** and **^{60}Fe** nuclear lines.
- Search for Galactic SNR in **^{44}Ti.**



Excellent energy resolution & field of view

- COSI uses germanium detectors for excellent energy resolution
  - ΔE/E more than an order of magnitude better than the previous Compton telescope (COMPTEL on CGRO)
- COSI's instantaneous FOV is >25%-sky:
  - Large improvement in grasp (= product of effective area and FOV) over INTEGRAL/SPI and COMPTEL





COSI science objectives

1. Pinpoint the sources of Galactic positrons
2. Reveal sites of past supernovae and recent element formation (^{44}Ti, ^{26}Al, ^{60}Fe)
3. Probe the physics in extreme environments with polarimetry
4. Find counterparts to merging neutron stars and high-energy neutrino events

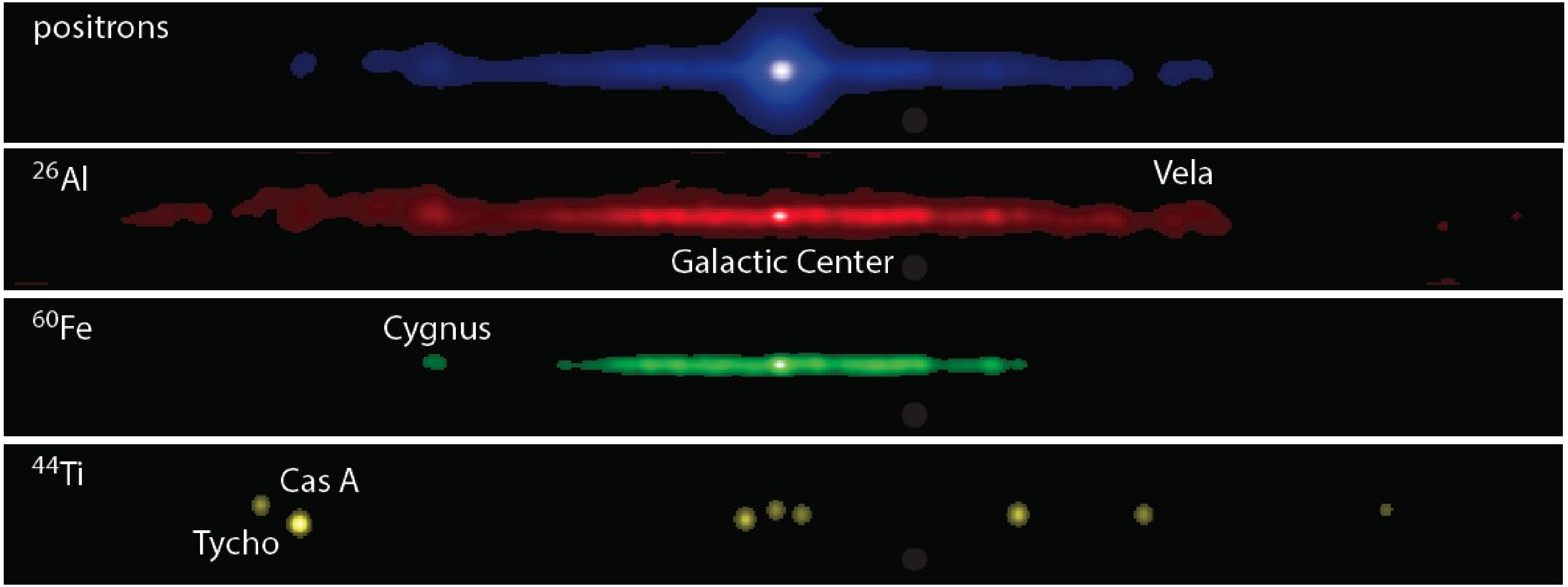
COSI simulations (related to objectives 1,2 above)

0.511 MeV + cont.

1.809 MeV

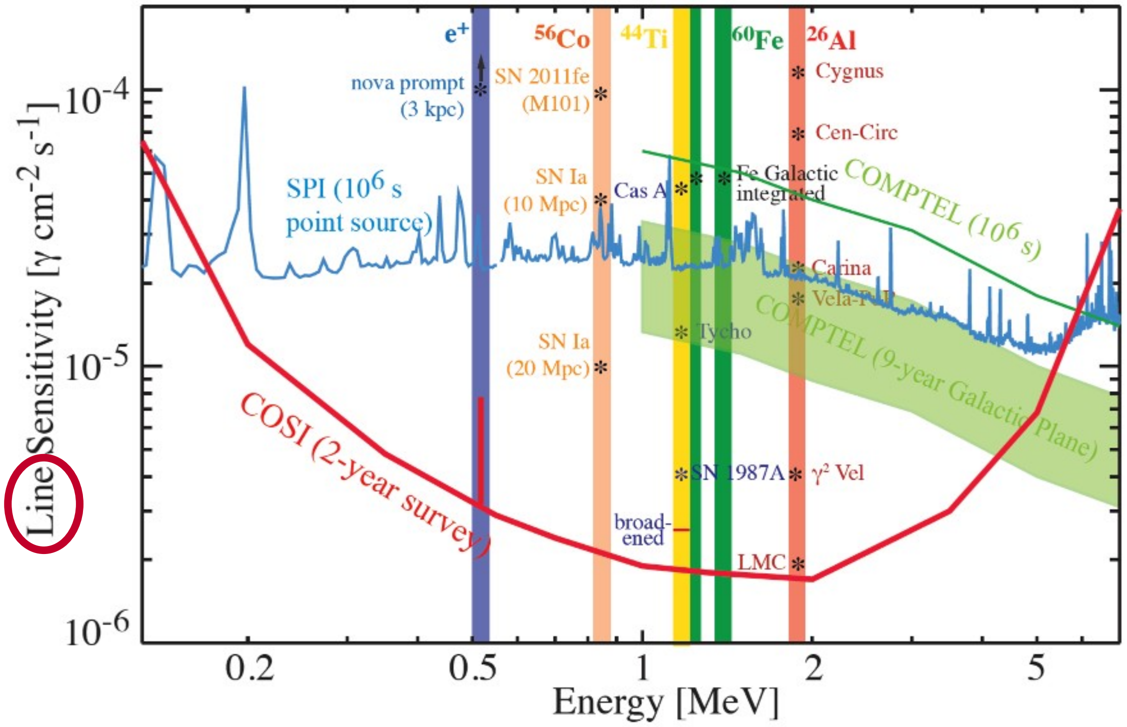
1.173, 1.332 MeV

1.157 MeV + 68, 78 keV



Gamma-ray Lines – revealing element formation

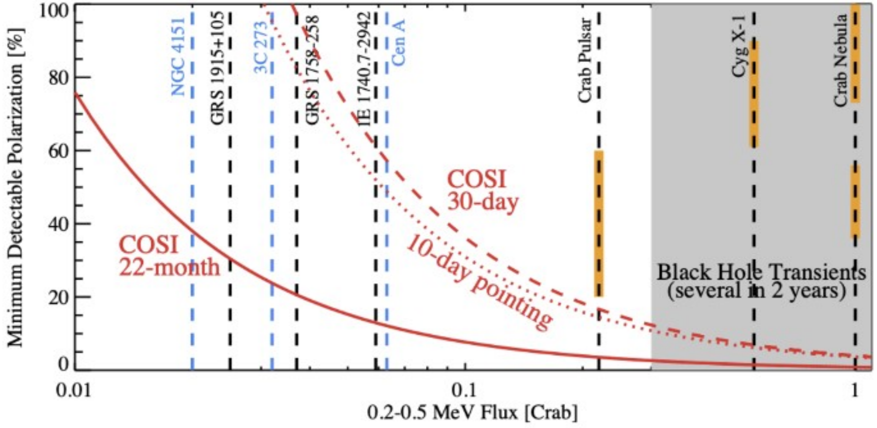
- Positron annihilation
  - 511 keV + ortho-pos. continuum
  - bulge, disk, globular clusters
  - dark matter component?
- ^{56}Co study SNIa
- ^{44}Ti SNRs of the last few centuries
- ^{26}Al: galactic diffuse.
  OB associations / superbubbles, spiral arms, individual sources
- ^{60}Fe: only integrated flux measured.
  COSI: first all-sky map.
  Produced only in core-collapse SNe.
  Together w/ ^{26}Al:
  → Galactic star formation rate over the last few million years.

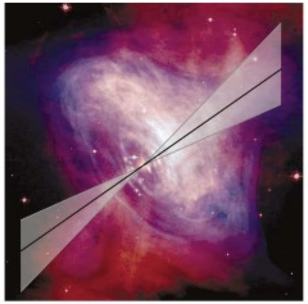


- Nuclear de-excitation lines
  - study low-energy cosmic-ray component
- …

Polarization: AGN and Galactic X-ray Binaries

- Improve over previous high-energy polarization measurements of the Crab and Cyg X-1
  - INTEGRAL (both)
  - AstroSat (Crab)
  - POGO+ (both, but at lower energy)
  - Hitomi/SGD (Crab)
- AGN: Cen A, 3C 273, NGC 4151
- Black hole binaries
  - Several persistent
  - Several transient





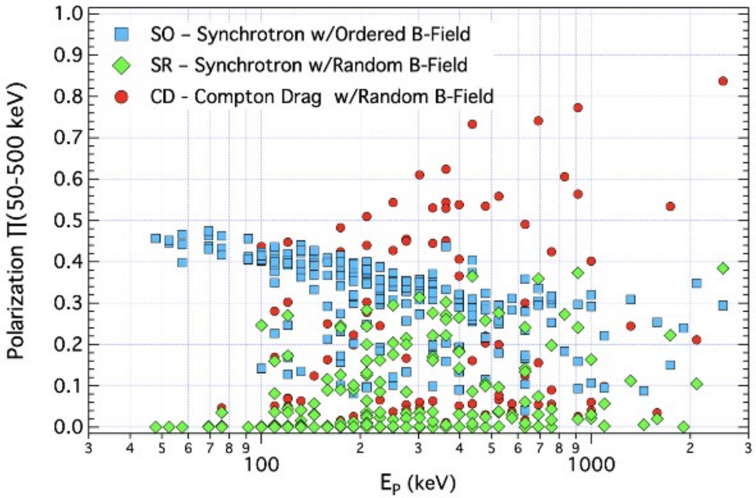
Crab pulsar and nebula (Dean+08)

AGN (e.g., Cen A)
- High polarization (~60%) for Synchrotron Self-Compton from a jet
- Lower polarization for Compton scattering from a hot tenuous accretion disk corona

J. Tomsick

Polarization: Gamma-ray Bursts

- Polarization measurements provide unique diagnostics for determining emission mechanisms and source geometries
- Most recent progress on GRB polarization by POLAR mission (Zhang+19)
- COSI will measure the polarization of ~40 GRBs in a 2-year mission
- ~a dozen GRBs with polarization measurements to ±5-10%



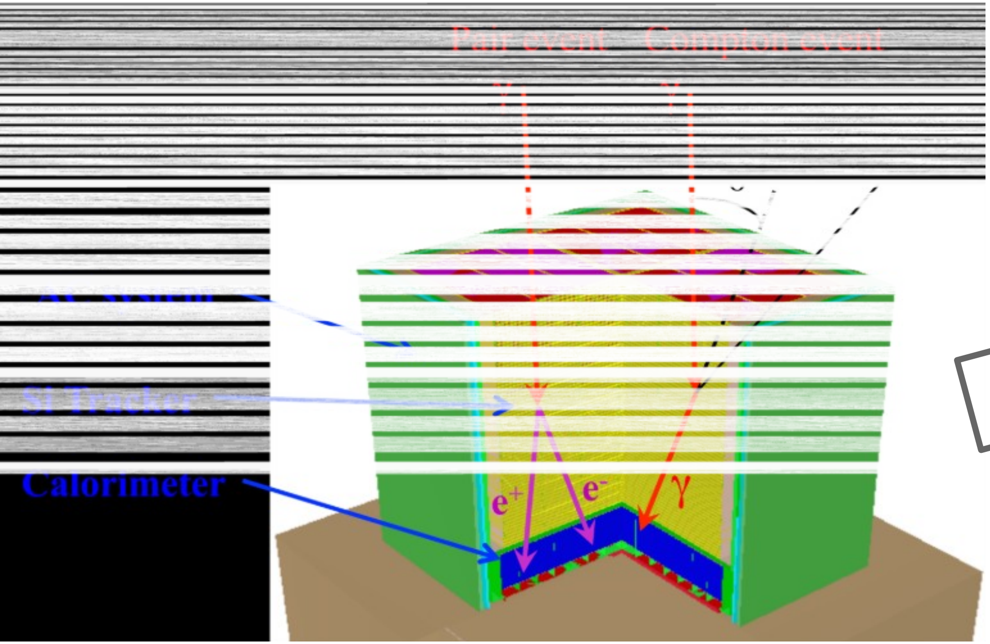
Toma+09; McConnell+16

J. Tomsick

ASTROGAM Proposal for ESA M7 Mission Opportunity Call

medium-size

PI: A.De Angelis (INFN, INAF), Co-PI: V.Tatischeff (CNRS), Co-PI: D.Berge (DESY)



Design concept

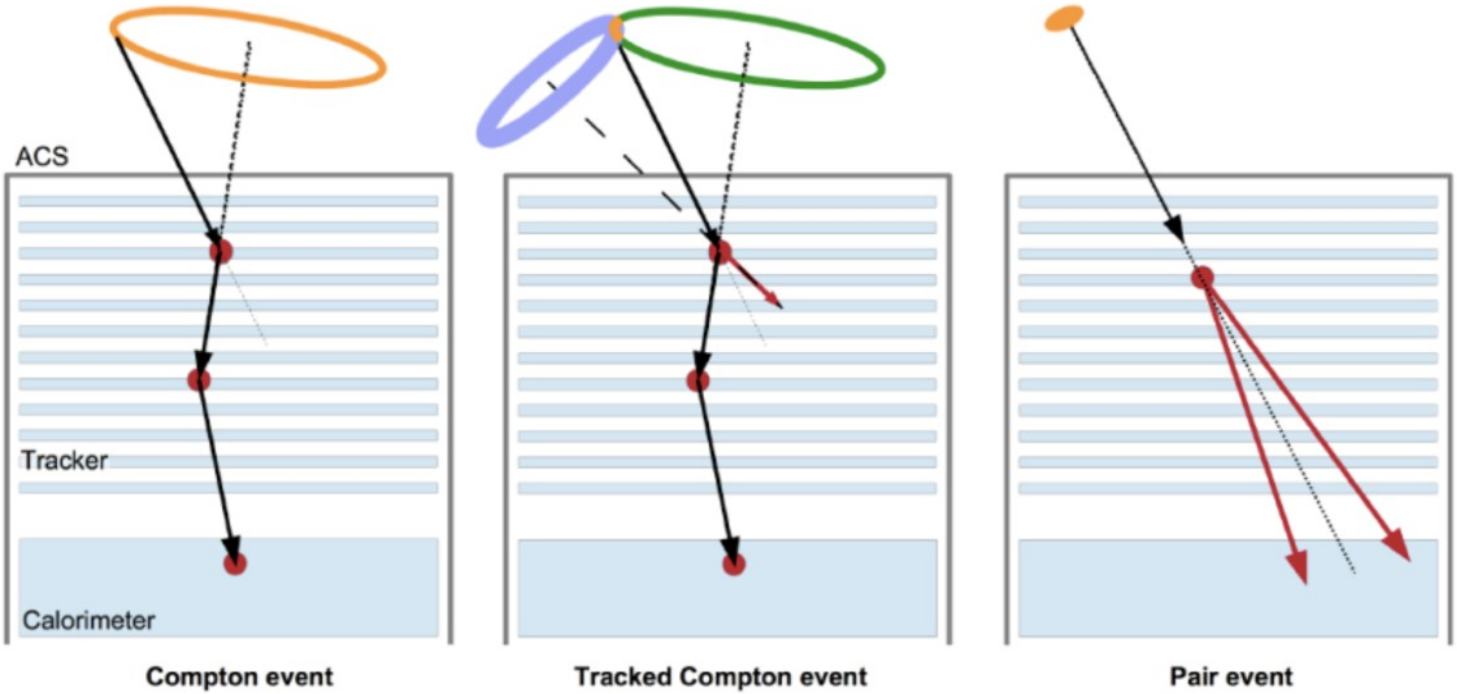
- Gamma-ray satellite concept with unprecedented energy coverage (100 keV – 3 GeV), sensitivity, and angular resolution
- Silicon tracker + pixelated scintillation detector
- Proposal
  - Submitted by scientists from 16 ESA member states: Croatia, Czech Republic, Denmark, Finland, Ireland, Italy, France, Germany, Netherlands, Norway, Poland, Portugal, Spain, Sweden, Switzerland, UK
  - Launch circa 2037, min. 3 years planned mission time

rejected

- Diverse and unique astrophysics science cases, e.g.
  - Multi-messenger science: Neutrino and GW sources
  - Unique MeV blazar population studies reaching z=6 and beyond
  - Galactic and extragalactic cosmic ray accelerators
  - Explosive nucleosynthesis & chemical evolution
  - Dark matter and new physics
  - See White Paper at https://arxiv.org/abs/2102.02460

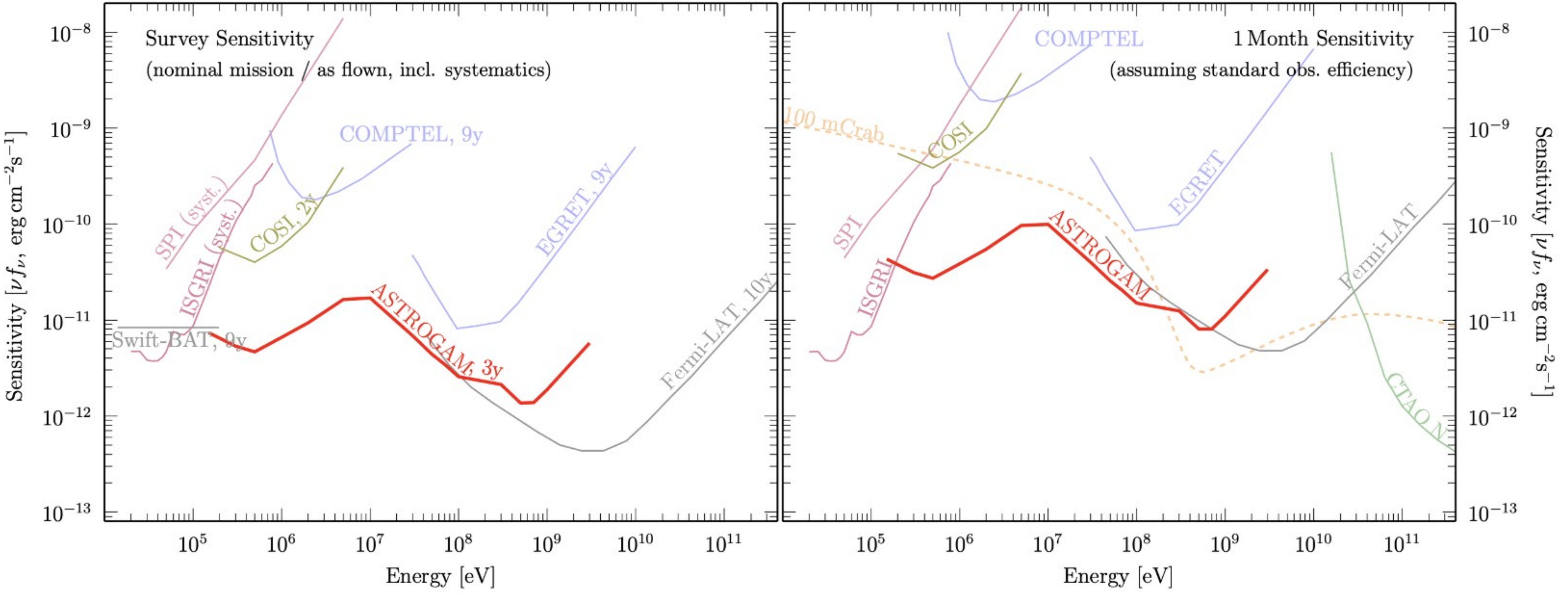
ASTROGAM (ESA M7 Mission)
Exploring the Gamma-Ray Sky from MeV to GeV

- Compton **and** pair telescope
- M7 proposal based on former work (eASTROGAM M5, ...)



ASTROGAM Sensitivity

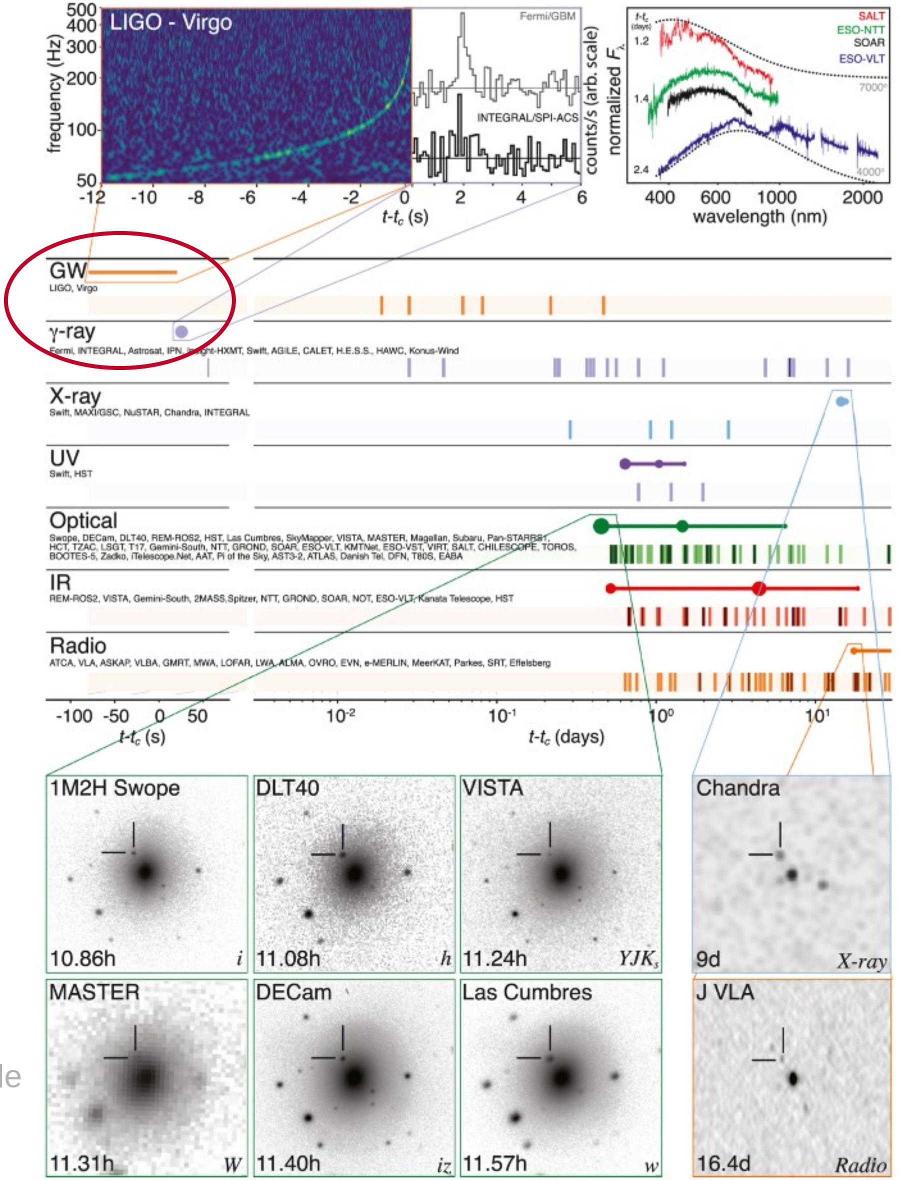
Coverage of MeV-GeV gap in the 2030's



Multimessenger Astronomy

Electromagnetic counterparts to gravitational wave transients

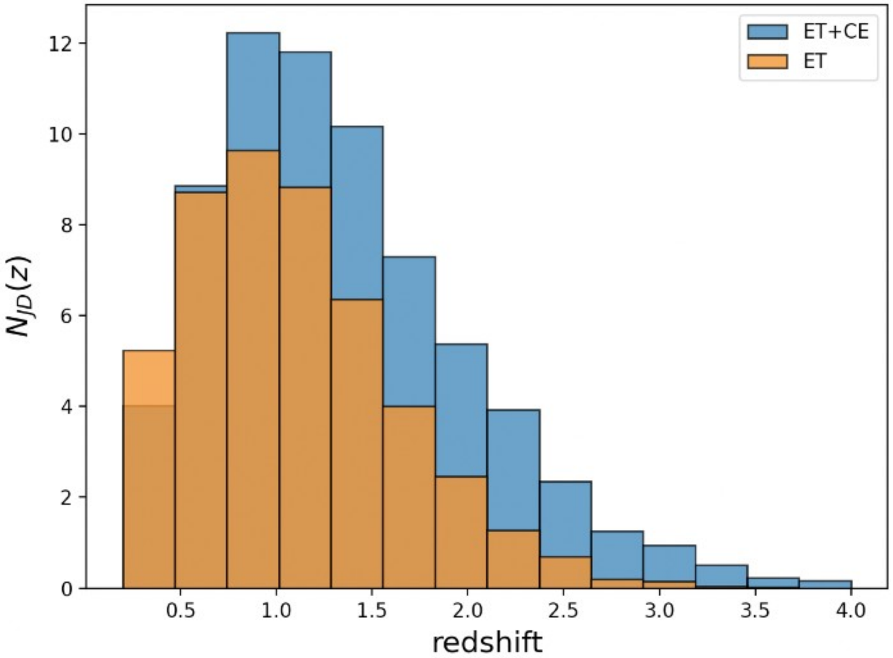
- Detect sGRBs from NS-NS merging (0.2-6 during 2 years) with sensitivity to their likely energy cutoff (~20 MeV)
- and maybe BH-NS
- Particularly interesting energy region to estimate the energetics of these processes
- Use large field of view and imaging to refine localisation for follow-up observations



Stratta & Pannarale

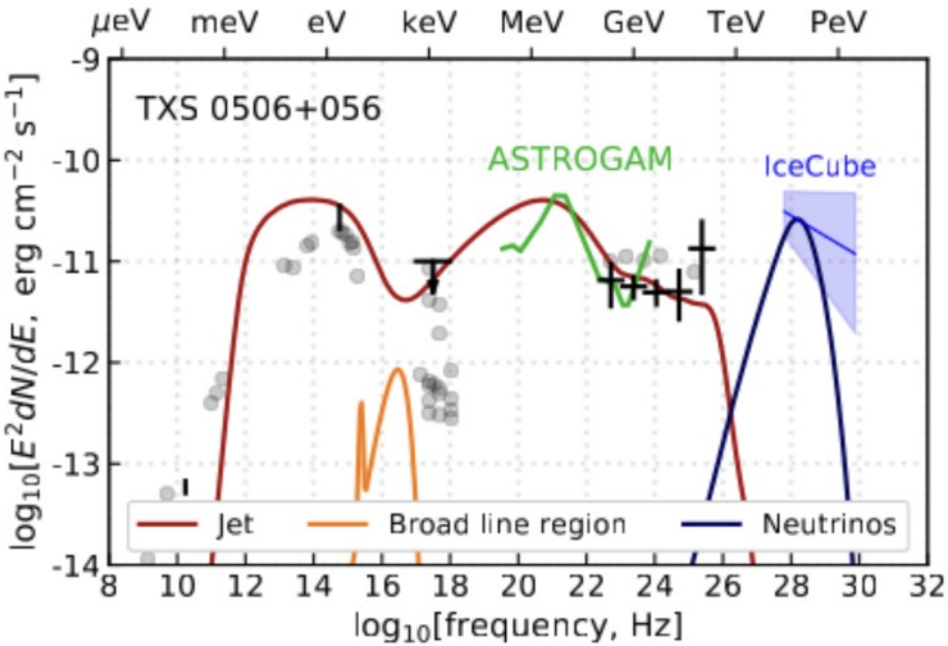
Multimessenger Astronomy: GRB γ+GW, blazars γ+ν

Ronchini et al (2022), arXiv:2204.01746



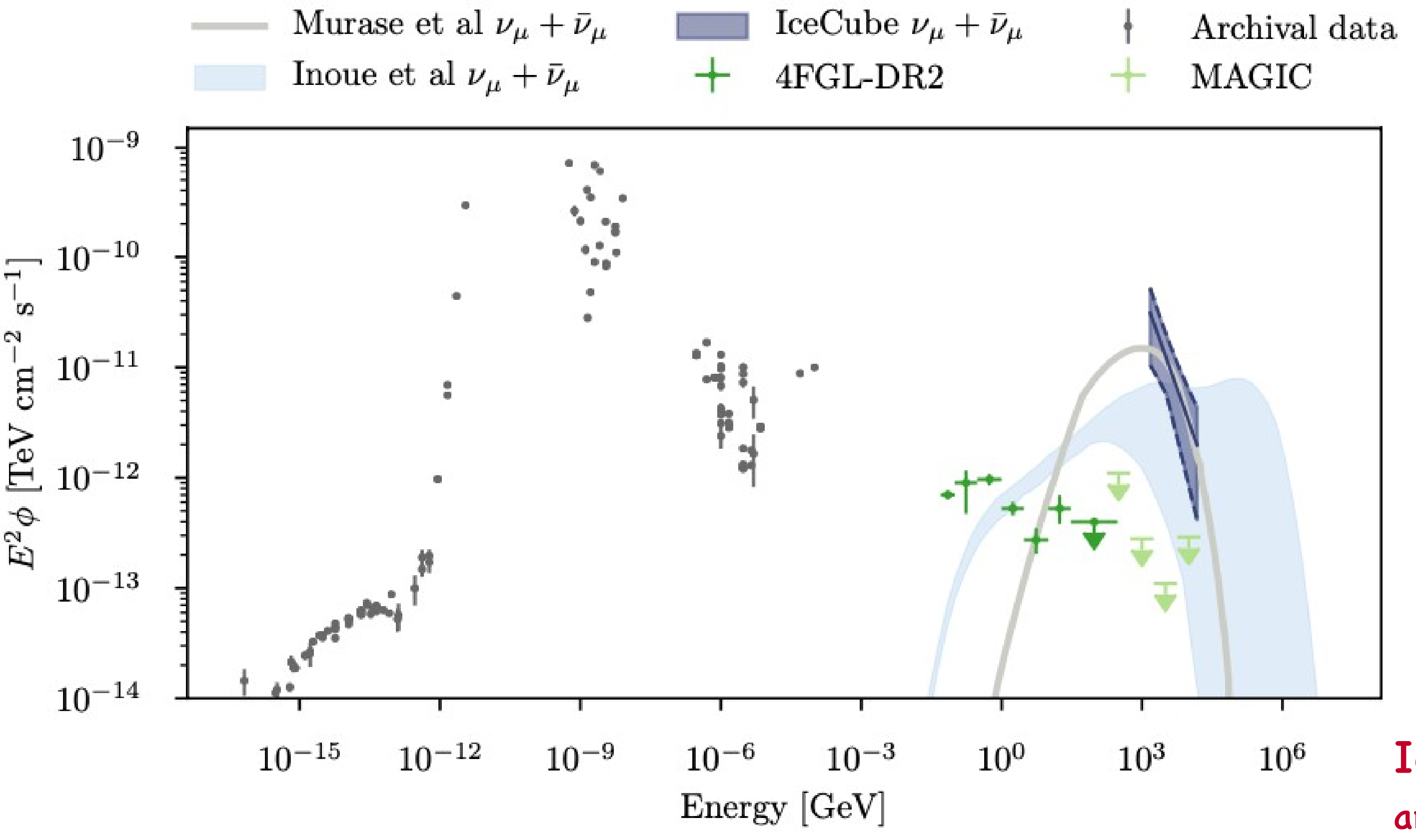
Joint GW + ASTROGAM detections of short GRBs in 1 yr
(50 sGRBs/yr with ET, 70 sGRBs with ET + Cosmic Explorer
300 long + short GRBs measurable per year in total)

Rodrigues et al (2019), ApJ Letters, arXiv:1812.05939



Photon and neutrino emission of blazar TXS 0506+056 and 6-month ASTROGAM sensitivity. MeV band essential to constrain models and identify hadronic accelerators.

ASTROGAM $\gamma+\nu$



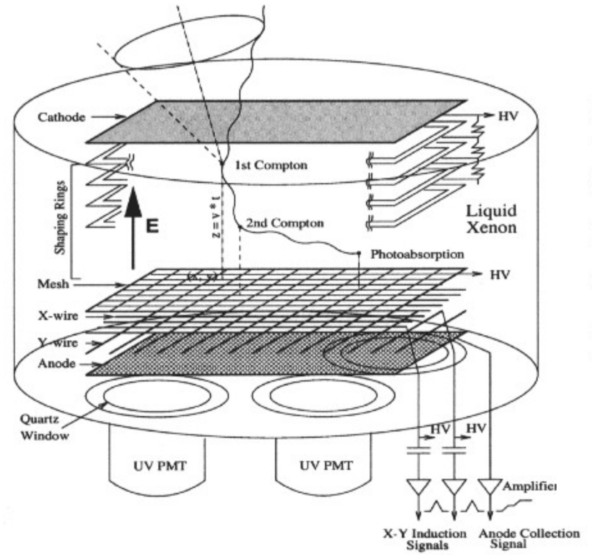
Photon and neutrino emission of active galaxy NGC 1068 and 6-month ASTROGAM sensitivity. MeV band essential to constrain models and identify hadronic accelerators.

Icecube results on NGC 1068

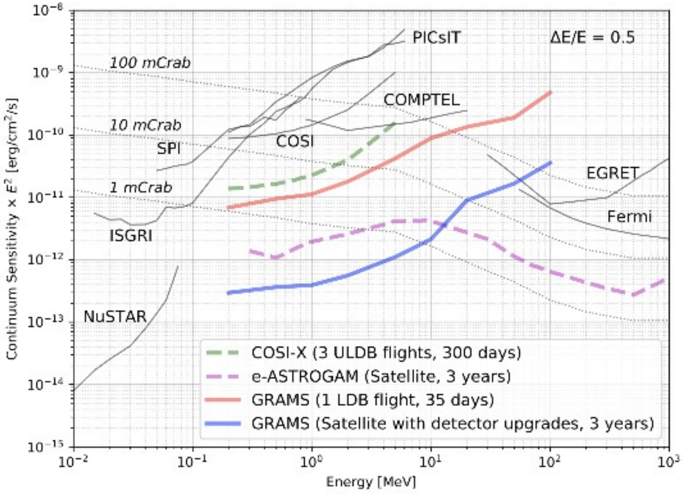
arXiv:2211.09972

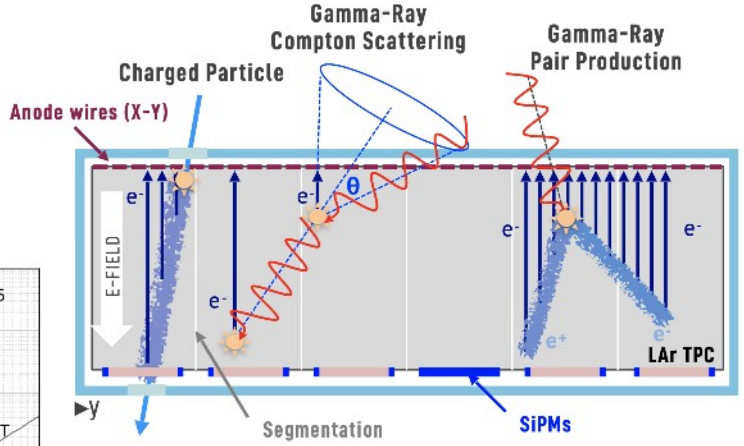
Other technologies

- Liquid noble gas TPC: Liquid Ar: GRAMS, GammaTPC
- Liquid Xe: former LXeGRIT, new attempt?
- Pixelated Si tracker
- Super-COMPTEL: Scintillator w/ time-of-flight



E. Aprile et al. 2008, Nucl.Instrum.Meth.A593:414-425





T. Aramaki et al. 2020 Astropart. Phys., 114, 107-114

Conclusions and Outlook

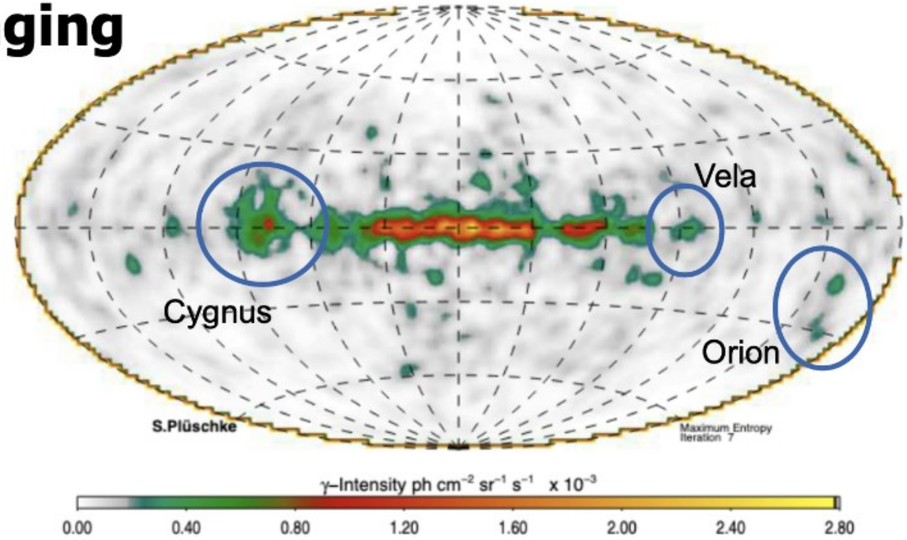
- **Unveiling the MeV Universe is an exciting (and challenging) goal!**
- COSI: a major step in nuclear lines and positron annihilation radiation.
  but only a small step in filling the continuum sensitivity "MeV gap".
  → a next big mission is needed.
- We have the tools: simulation, event reconstruction, imaging.
  … and advancing further with COSI!
- We have a set of technologies available.
  … but we need to keep advancing them and explore others.
  The going is tough: improvements enter sensitivity only with the square-root!
- Improving greatly over the status quo and beyond COSI requires
  - much better efficiency over COMPTEL
  - much lower background
  - increase in size (much over COSI, moderately over COMPTEL)
  - improve moderately in angular resolution
  - improve moderately in energy resolution over COMPTEL

Thank you!

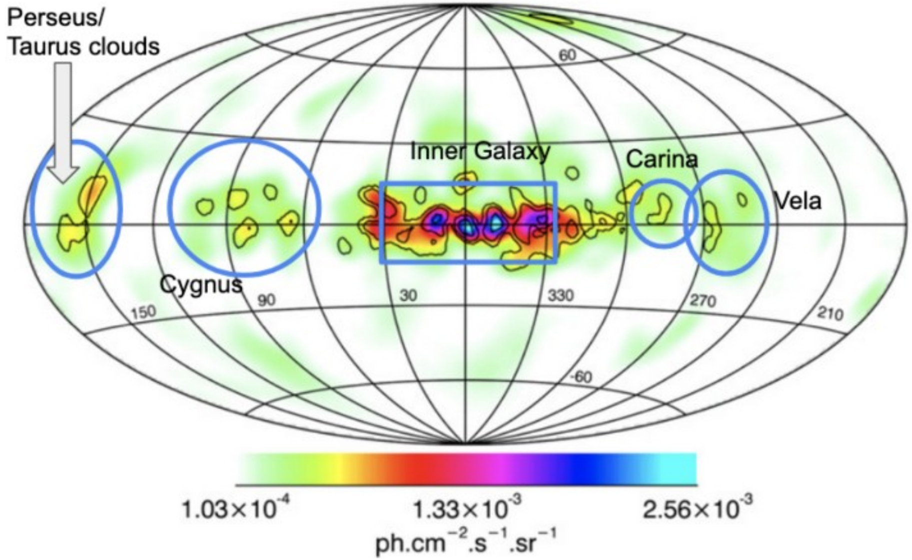
BACKUP

Gamma-ray Lines - ^{26}Al

Imaging



COMPTEL
Plüschke et al. 2001
Angular resolution ~ 4° FWHM

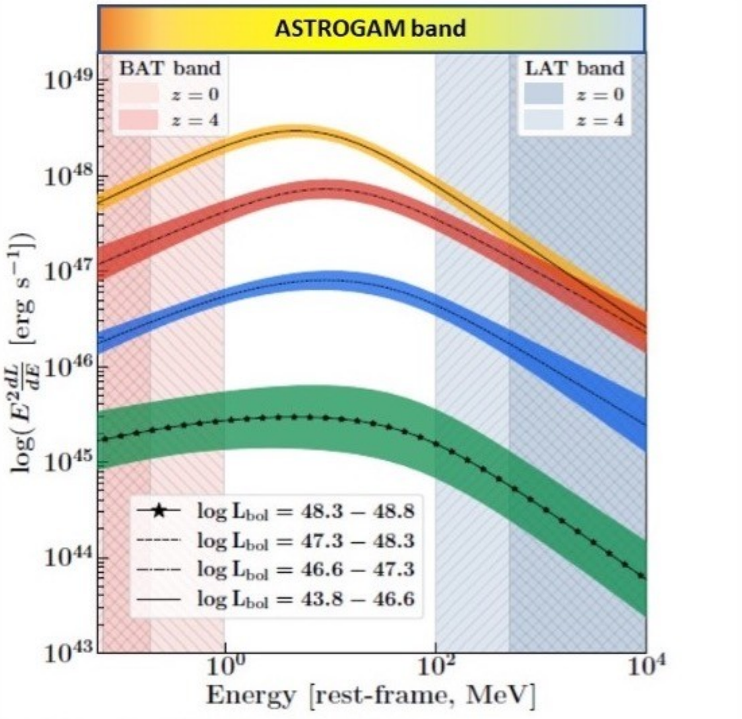


INTEGRAL /
SPI
Angular resolution ~ 6° FWHM

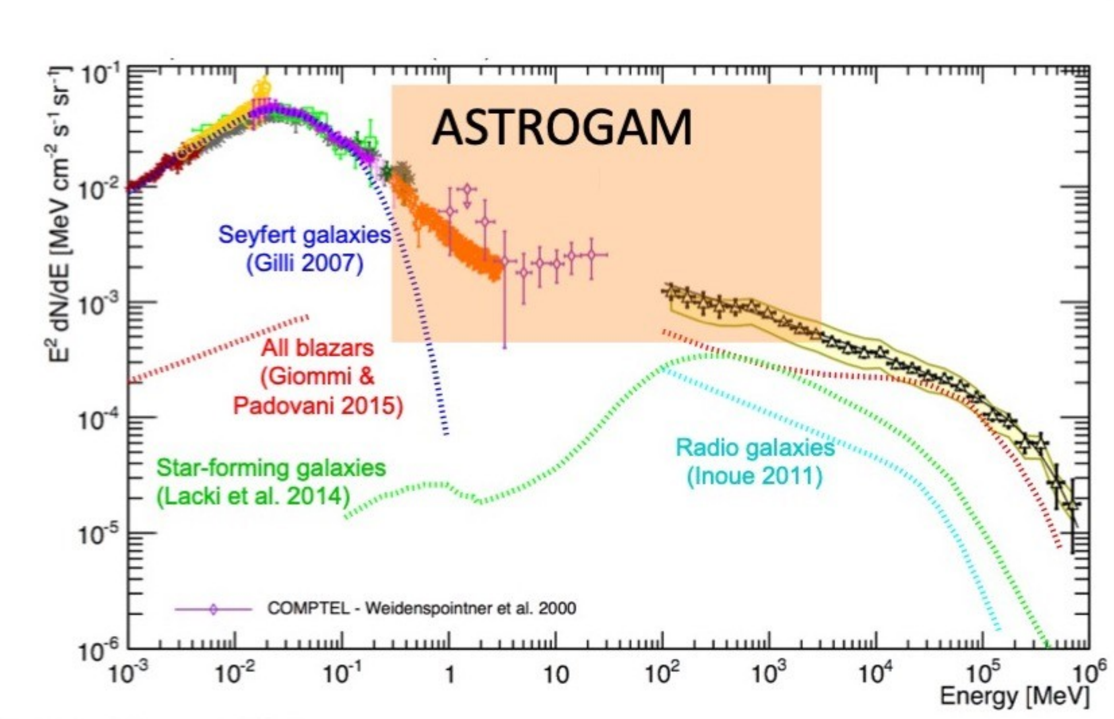
Images from COMPTEL and SPI indicate concentrated emission in the **Inner Galaxy** ($|l| \leq 30°$, $|b| \leq 10°$) and enhanced emission in regions of massive star activity (e.g. Cygnus, Carina, and Vela).

ASTROGAM

Black hole activity at Cosmic Dawn, γ-ray background



Adapted from Marcotulli & Ajello (2022), AAS HEAD



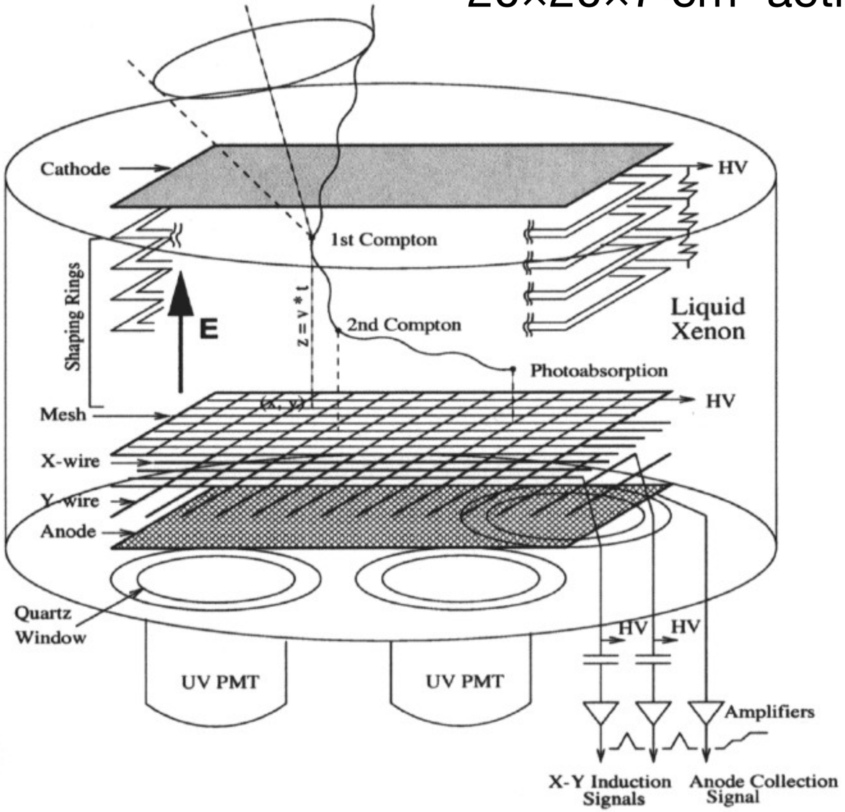
Adapted from Ackermann et al (2015)

Average SEDs MeV blazars; discovery potential z>6 blazars

Extra-galactic γ-ray background; MeV contribution largely unknown, expect dramatic improvement

LXeGRIT

- liquid xenon TPC: dense liquid (2.85 g/cm^3 @ -95°C)
- Z=54
- uniform medium
- excellent UV scintillation and ionization medium
- 20×20×7 cm^3 active volume



E. Aprile+ Columbia University