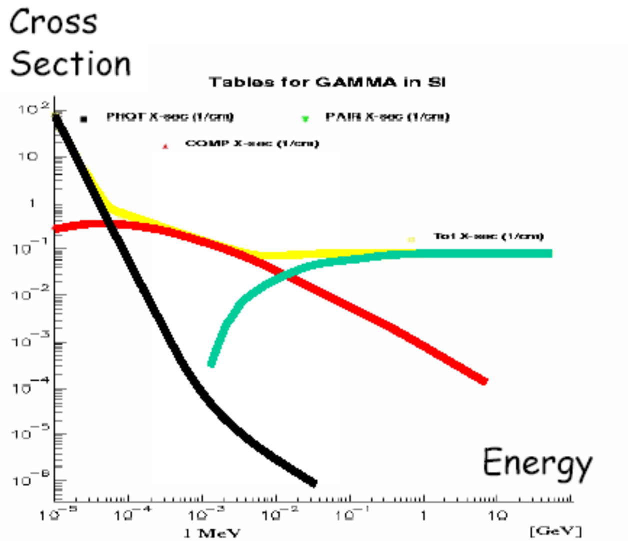
Astrofisica Nucleare e Subnucleare

“MeV” Astrophysics

MeV astrophysics techniques

Detection of Gamma Radiation



Pair Creation (> 10 MeV)
Photons completely converted to e^+e^-

Telescope:
Tracking chambers to visualize the pairs

Photoeffect(< 100 keV)

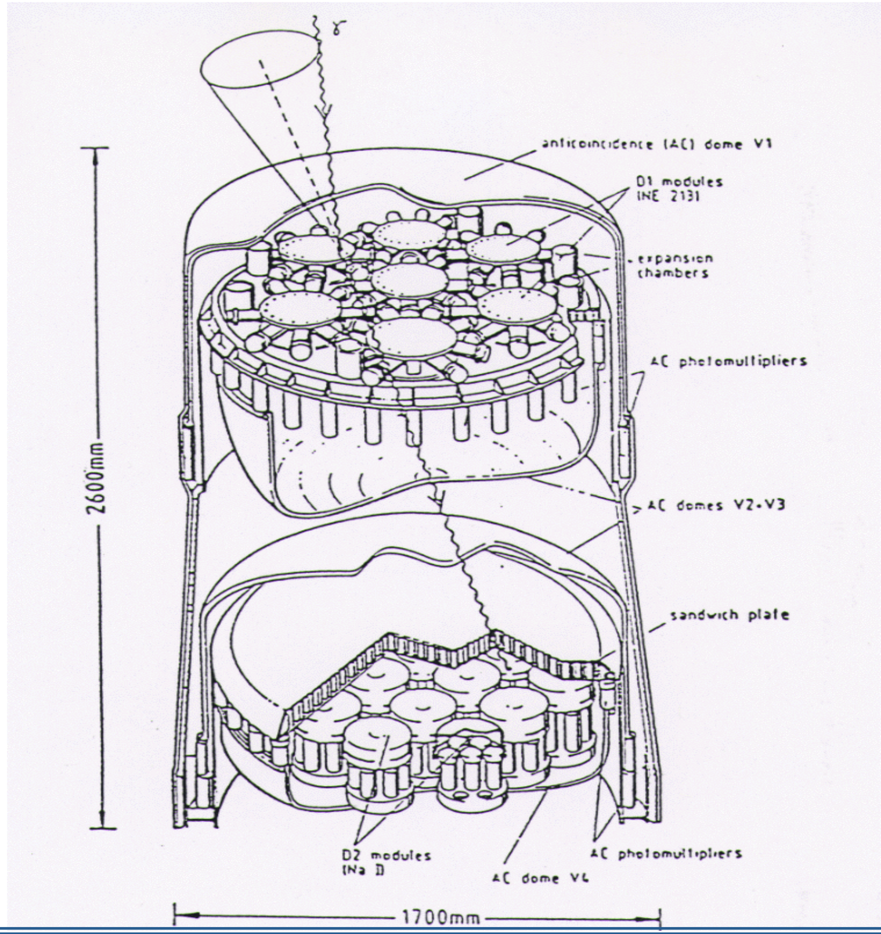
Photons effectively blocked and stopped

Telescopes:

Collimators
Coded Mask Systems

Compton Scattering (0.2-10 MeV)
Photon Crossection Minimum
Scattered photons with long range
Telescope:
Compton Camera Coincidence System

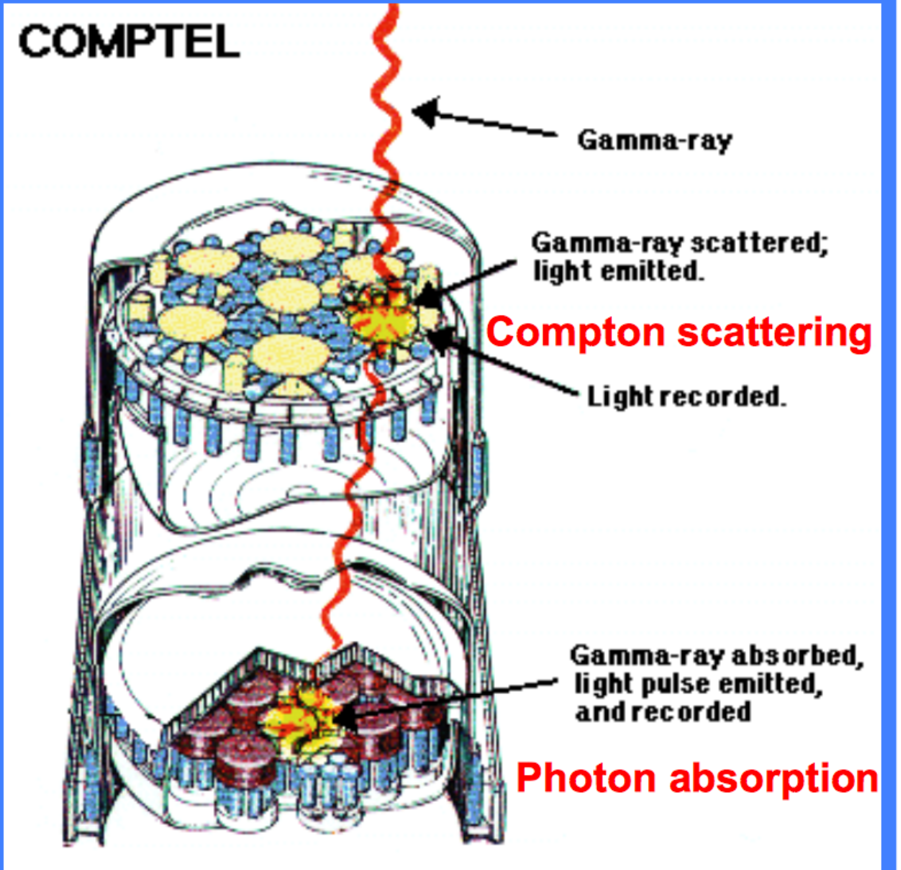
The Compton Gamma Ray Observatory



COMPTEL

- 0.05-30 MeV
- Radioactive elements map, pulsars, a flaring black hole candidates, blazars, solar flares

Telescopi Compton



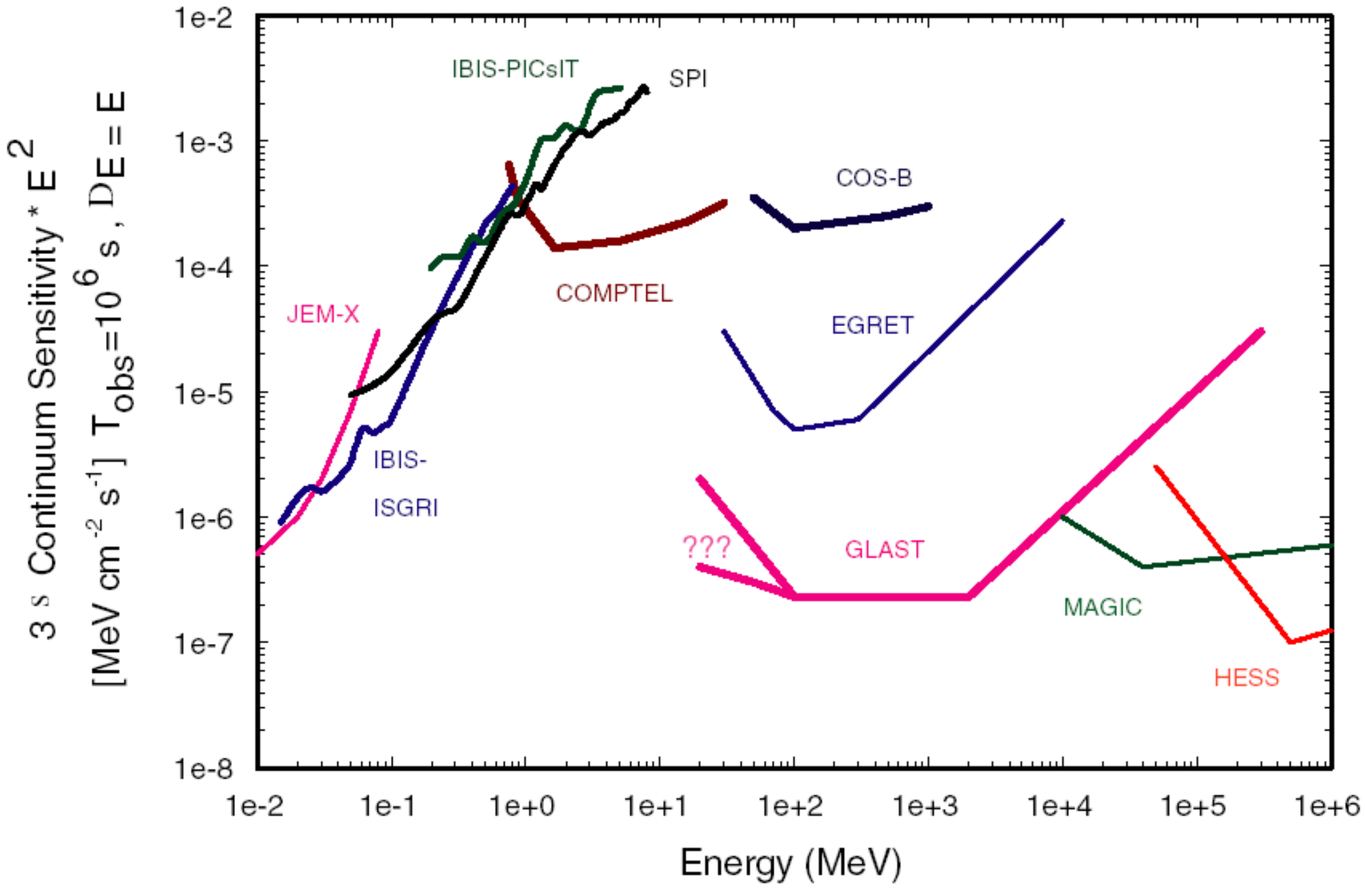
Two-level instruments:
1st level: the γ-ray Compton scatters off an electron in a **liquid scintillator**. The scattered photon enters into a **2nd level scintillator** (NaI) and is absorbed. Phototubes can determine the interaction points at the two layers and record the amount of energy deposited in each layer.

It is possible to reconstruct the angle of incidence the photon made wrt the original direction using the Compton scattering law, linking this angle and the energy of the scattered photon
(2nd level) and the scattering electron (1st level).

“Event circle” (ring on the sky), poor angular resolution (but multiple photons can help to reconstruct the position)

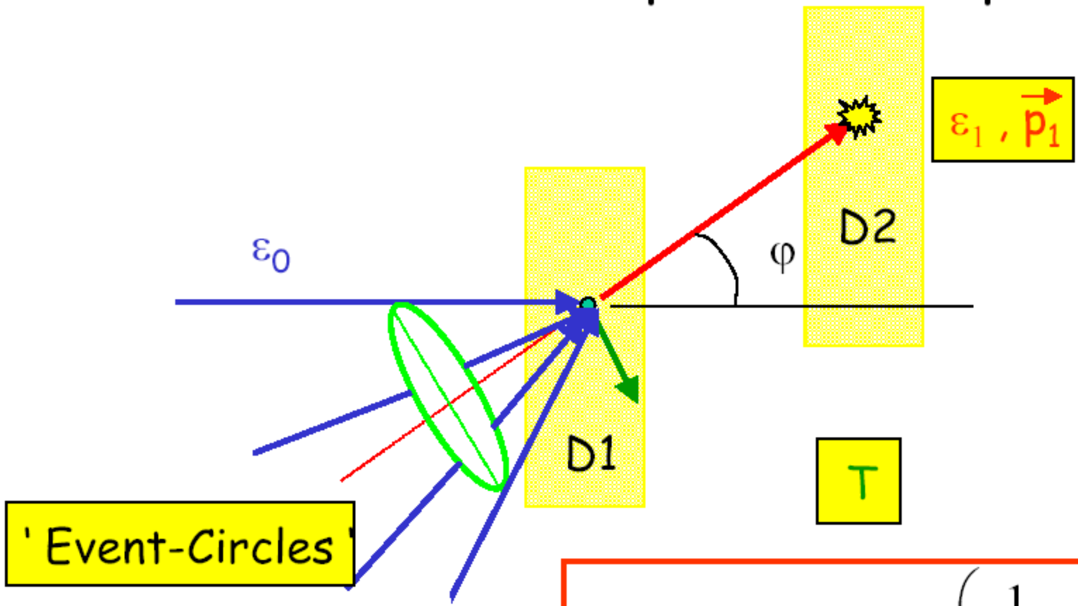
Sensitivity

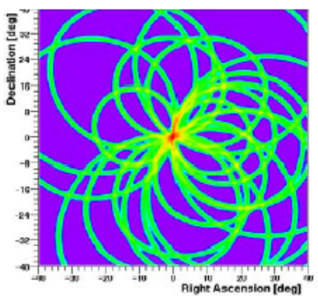
G. Kanbach et al. / New Astronomy Reviews 48 (2004) 275–280



Compton Imaging

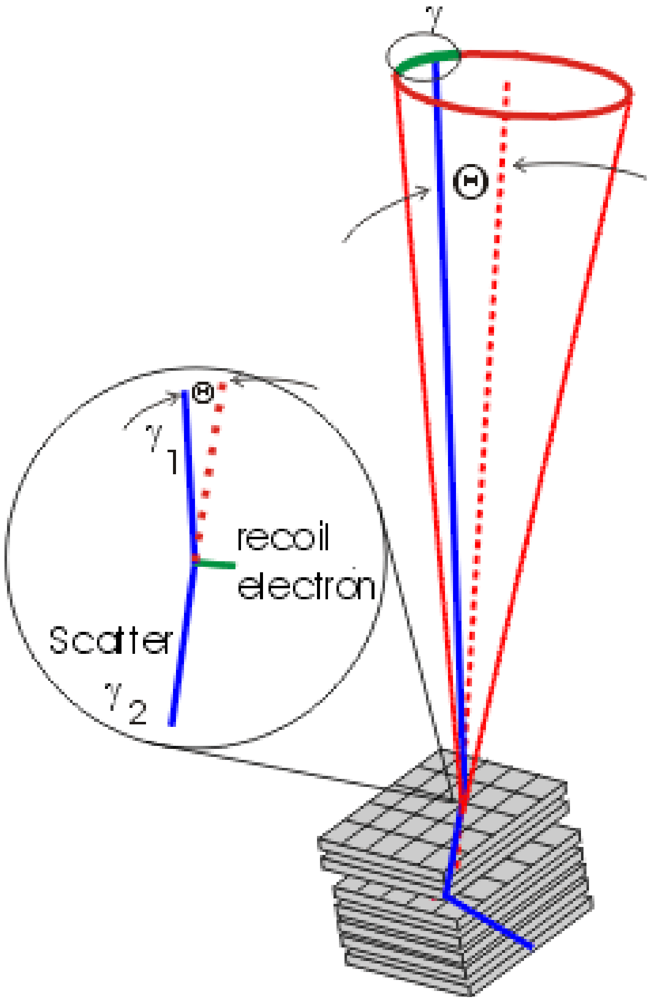
The ,classical' Compton telescope

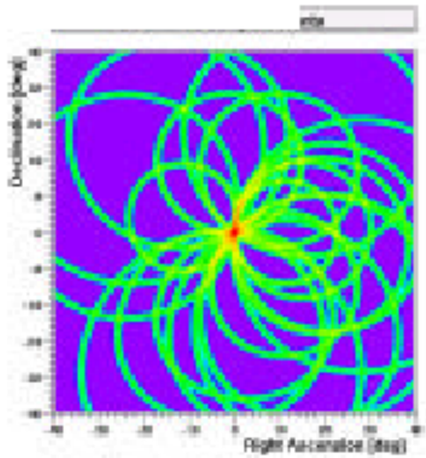


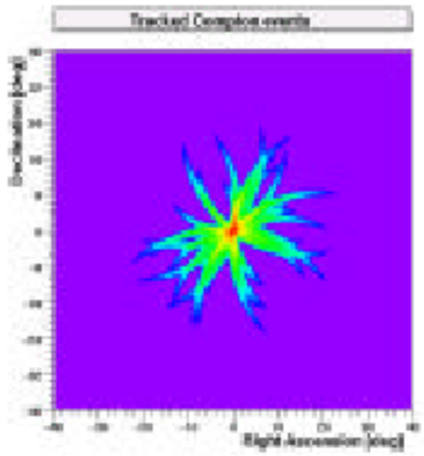


$$\cos\varphi = 1 - m_0 c^2 \left(\frac{1}{\varepsilon_1} - \frac{1}{\varepsilon_0} \right)$$

Compton Imaging



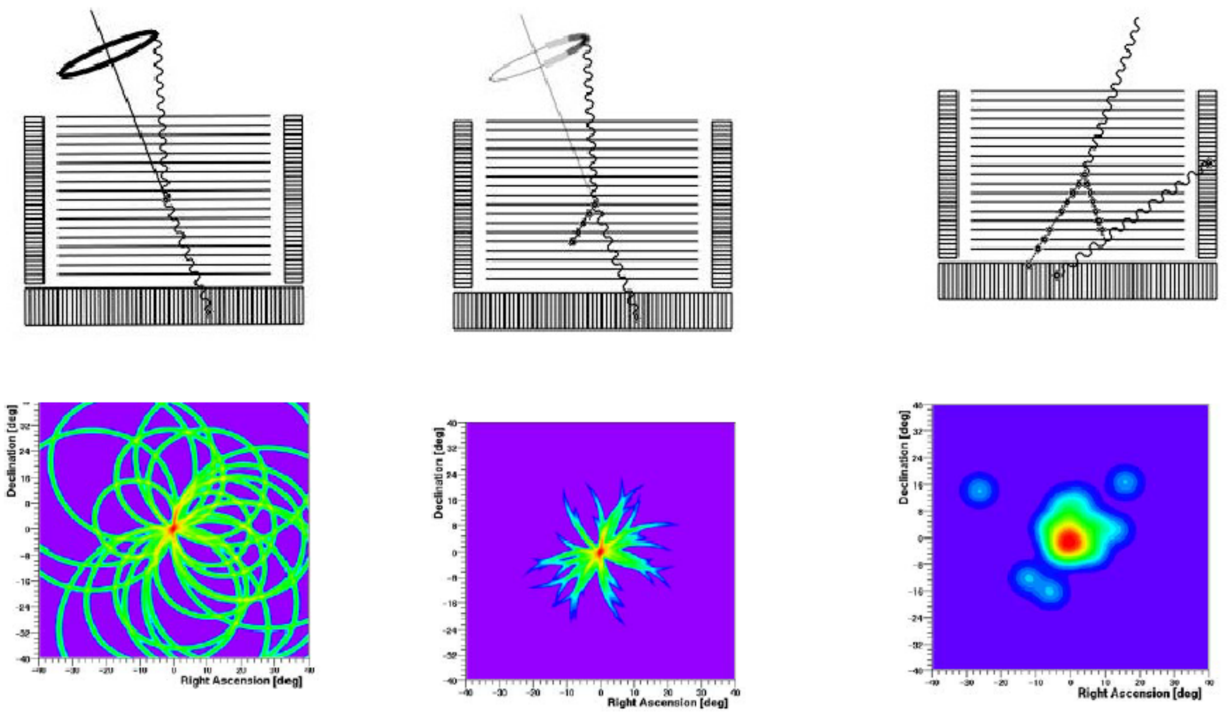




Compton Imaging

Coincidence Detector Schematics

Classical Compton Event Circles (no electron tracking)	Reduced Compton circles of events with electron track	Direct imaging of pair-creation events

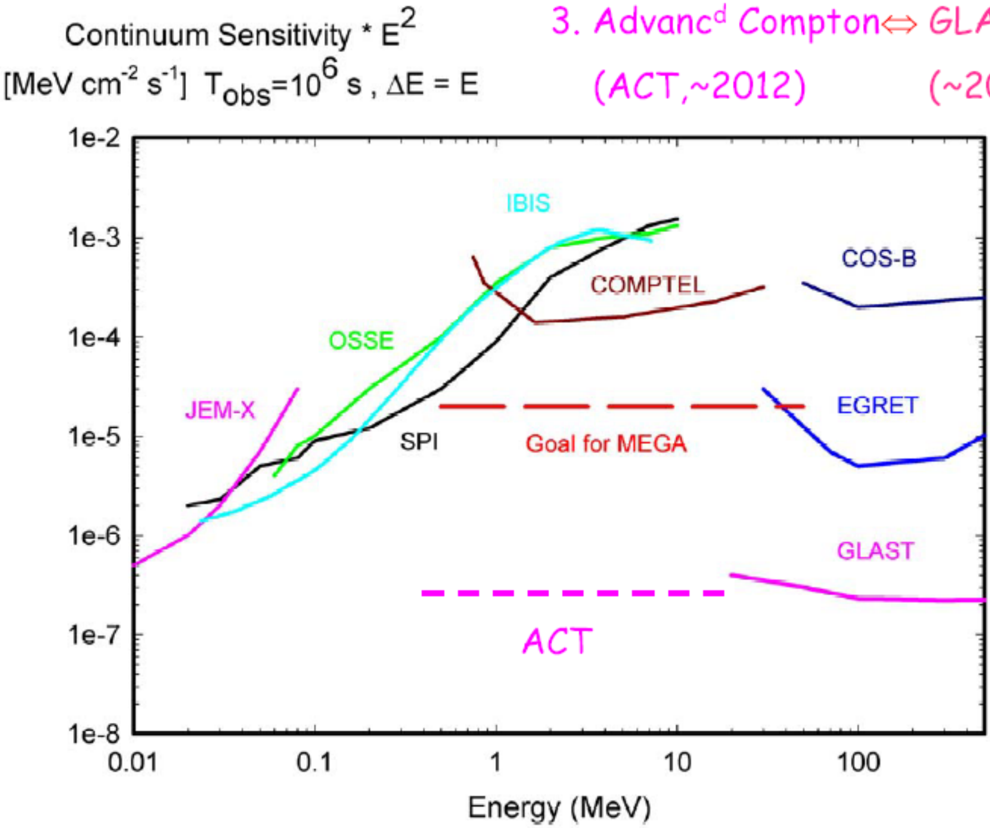


Compton Imaging

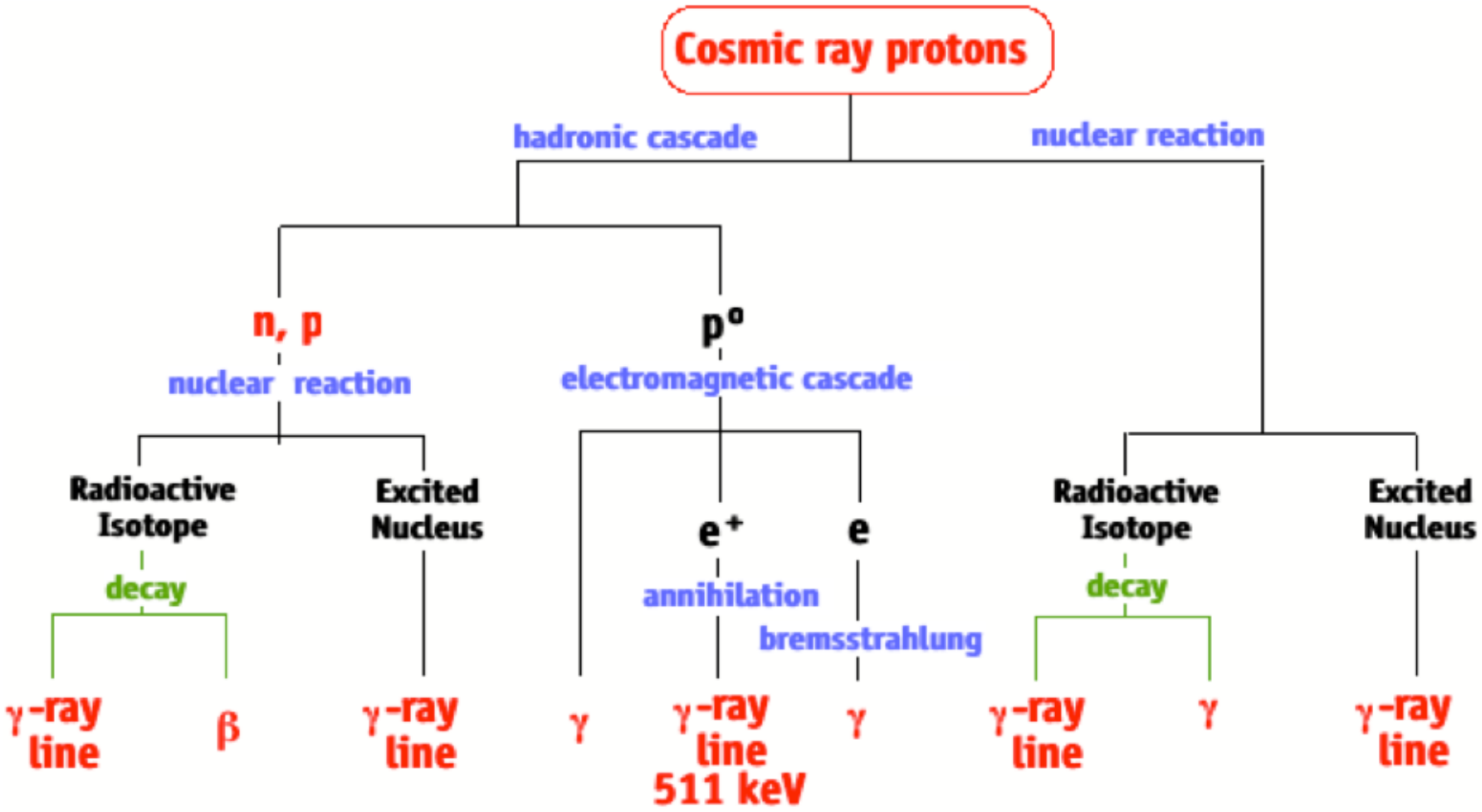
Sensitivities

Generations of γ-ray Missions:

1. COMPTEL ⇔ COS-B
2. MEGA (~2006) ⇔ EGRET
3. Advanc[d] Compton⇔ GLAST
   (ACT,~2012) (~2006)



Cosmic Ray interactions and γ-ray background



Compton Astrophysics

Astrophysics of low/medium Energy γ - rays

The energy range from a few 100 keV to several 10 MeV is scaled by the electron rest mass $m_o c^2 = 0.511$ MeV

- continuous γ-ray spectra from sites of high-energy particle acceleration are mostly produced in e-m interactions:
  Bremsstrahlung, inverse Compton scattering, Synchrotron
  Many of these sources have their maximum Luminosity at MeV energies

and by the nuclear energy levels

- Signatures of cosmic radioactivity through γ-ray lines: the direct observation of nucleosynthesis, i.e. the creation of the elements,

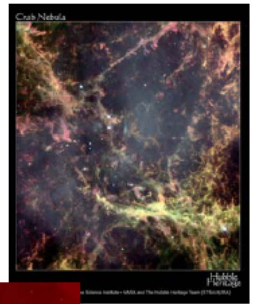
Compton Astrophysics

Cosmic Accelerators:

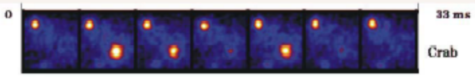
- Accretion on compact objects (relativistic jets):

  AGN, μBlazars, Binaries

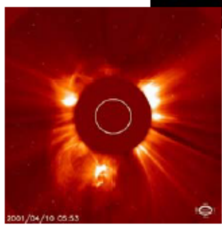
- Explosions and Shocks: GRBs, SNRs, mass. stellar winds, ISM
  Novae, Supernovae



- Rotation of NS: pulsars



- electro-magnetic dissipation: solar flares



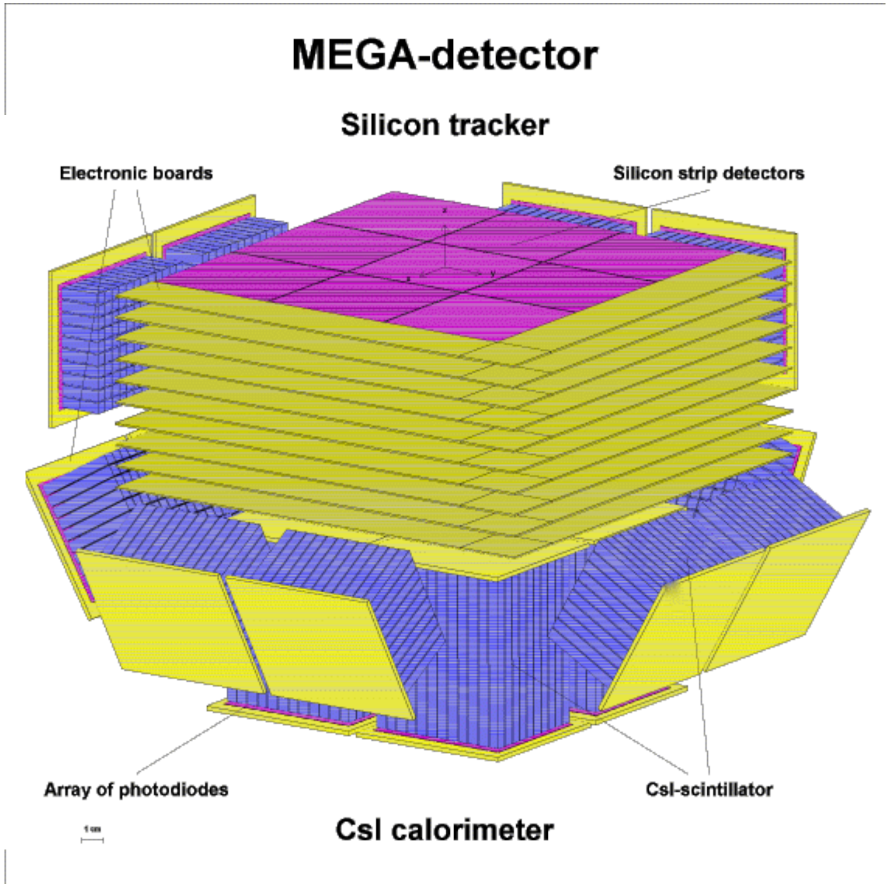
Compton Astrophysics

Origin and characteristics of astrophysically important γ-ray lines

Isotope	Energy	$t_{1/2}$	origin
^{57}Ni	1378 keV	2.14 d	SN
^{56}Ni	812 keV	8.5 d	SN
^{56}Co	847 keV 1238 keV	111.5d	SN
^{22}Na	1275 keV	3.8 yr	Novae
^{44}Ti	1157 keV	79 yr	SNR
^{26}Al	1809 keV	1Myr	AGB and massive stars (O & WR), Novae, core-collapse SNe
^{12}C* ^{16}O*	4.4 MeV 6.1 MeV	prompt	cosmic ray induced ISM lines, flares
e^+, e^-	511 keV		β^+ activity, jet sources, PSR, Novae, flares etc.
n+p $\rightarrow$ d	2.21 MeV		flares, flare stars?

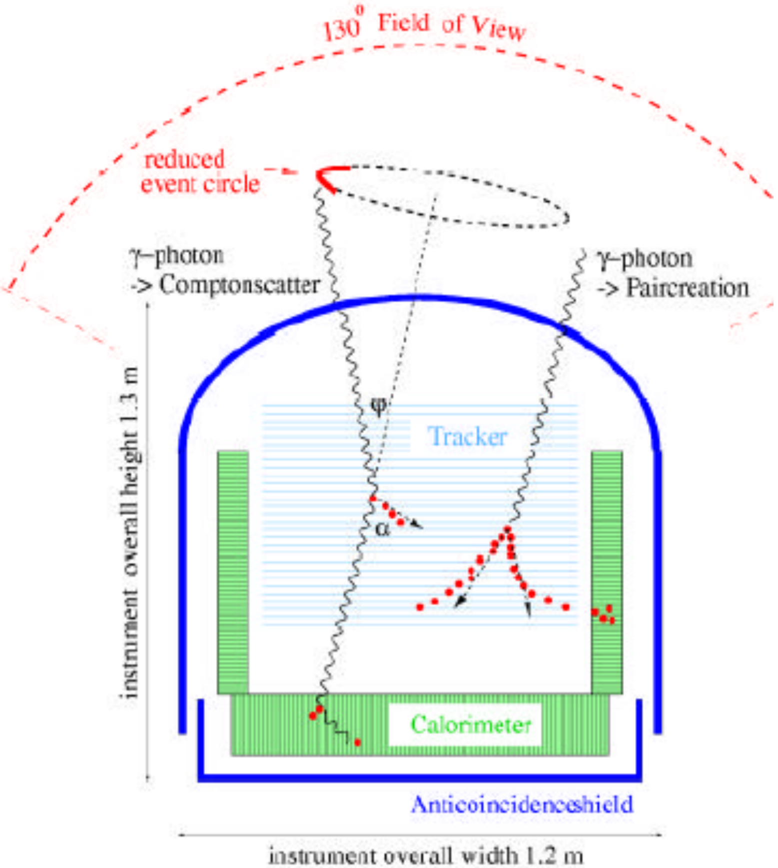
MEGA

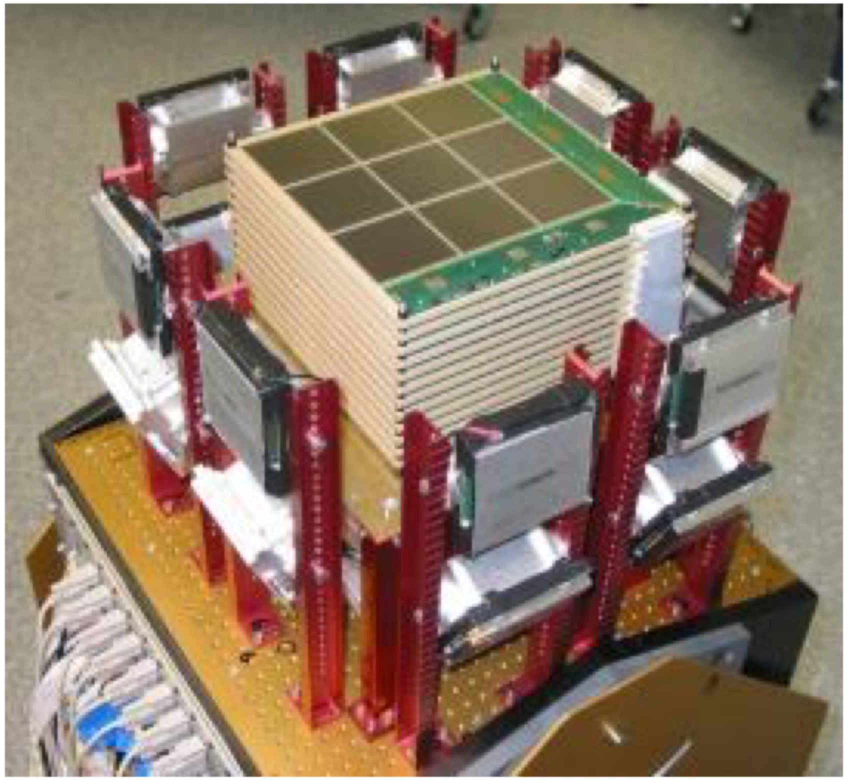
MEGA is planned as a telescope for
Medium **E**nergy **G**amma-Ray **A**stronomy
in the energy range between 400 keV and 50 MeV.
In this energy range MEGA exploits the two dominating interaction mechanisms for gamma rays:
Compton scattering and Pair creation.
MEGA has two detectors: A tracker, consisting of double-sided silicon strip detectors,
and a calorimeter, consisting of highly segmented CsI(Tl) bars. In the tracker the Compton and Pair interactions take place and the direction and energy of the participating electrons and positrons is measured.
In the calorimeters the Compton scattered gamma rays are stopped and thus their energy and direction is determined.



http://www.gamma.mpe-garching.mpg.de/MEGA/mega.html

MEGA





http://www.gamma.mpe-garching.mpg.de/MEGA/mega.html

ACT project

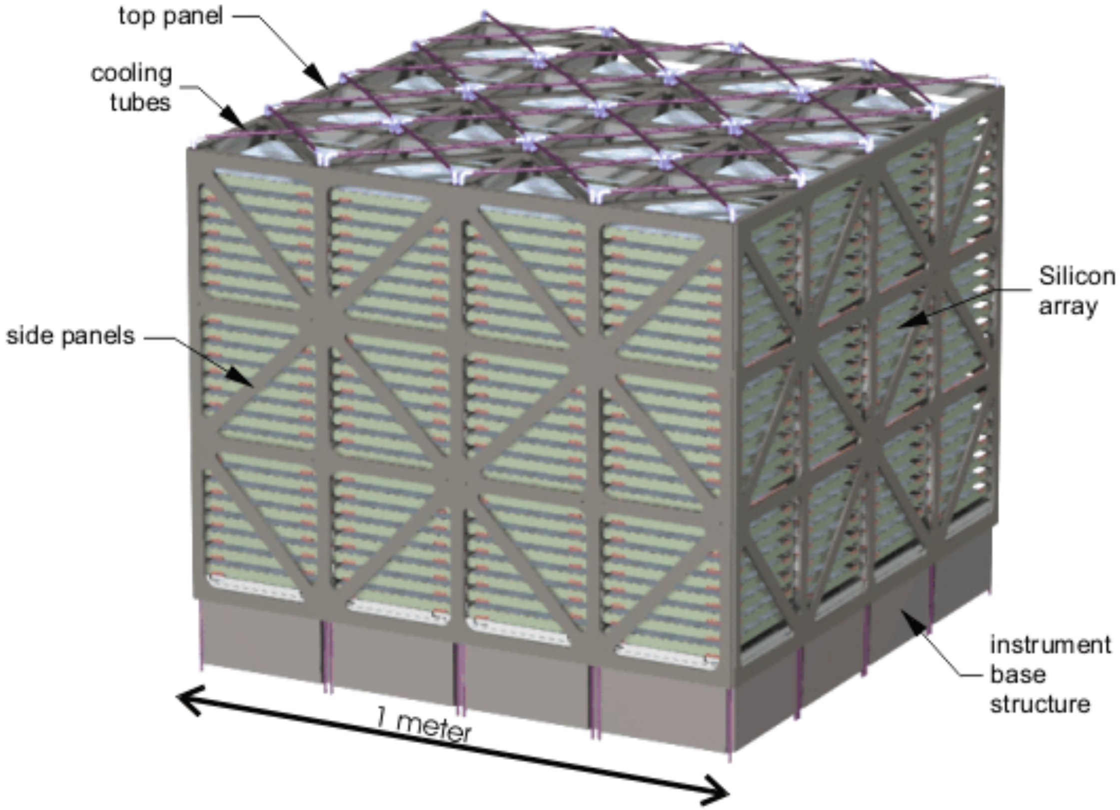
ACT Science Requirements

Energy Range	0.2 - 30 MeV Compton mode
Energy Resolution	< 10keV FWHM @ 1 MeV
Field of View	> 4 steradian
Angular Resolution	1 deg
Source Localization	5 arcmin for bright sources
Line Sensitivity in 1.0E6 sec	1.0E-7 ph/(cm2s) (narrow) 5.0E-7 ph/(cm2s) (broad)
Continuum Sensitivity	1.0E-5 ph/(cm2sMeV) @ 0.5 MeV
Polarization Sensitivity	1%, 2.0E-3 ph/(cm2sMeV) 10%, 2.0E-4 ph/(cm2sMeV)

These science requirements are expected to translate to an instrument with effective area on the order of 1000-3000 cm2, a position resolution in the detectors of 1mm3, energy resolution of 1% (0.5-2.0 MeV) or better, and possibly recoil electron tracking capabilities for electron energies < 0.5 MeV. The concept study will look at a variety of possible detector technologies for implementing such a Compton telescope. Candidate detectors include, but are not limited to, CZT strip detectors, Si strip detectors, Ge strip detectors, liquid Xe, and gaseous Xe (or Ar) microwell detectors.

https://arxiv.org/abs/astro-ph/0608532

ACT project



The baseline instrument (pictured above) is built from thick Silicon(Li) detectors, and measures roughly 1 m x 1 m in frontal area. The individual detectors are ~7 mm thick, and measure 10 x 10 cm in area using technology in crystal growth and lithium drifted silicon, or Si(Li). Detectors are assembled in tower structures, each containing a small 4x4 array of detectors and stacked 24 layers deep. Readout electronics for the detectors are distributed along the four side walls of each tower.

New MeV concepts

National Aeronautics and Space Administration
Goddard Space Flight Center

Astrophysics Science Division • Sciences and Exploration

Home | Registration | Directions/Hotel | Program | Participants

Future Space-based Gamma-ray Observatories

March 24-25, 2016
Goddard Space Flight Center
Building 34, Rooms W150 & W120A/B

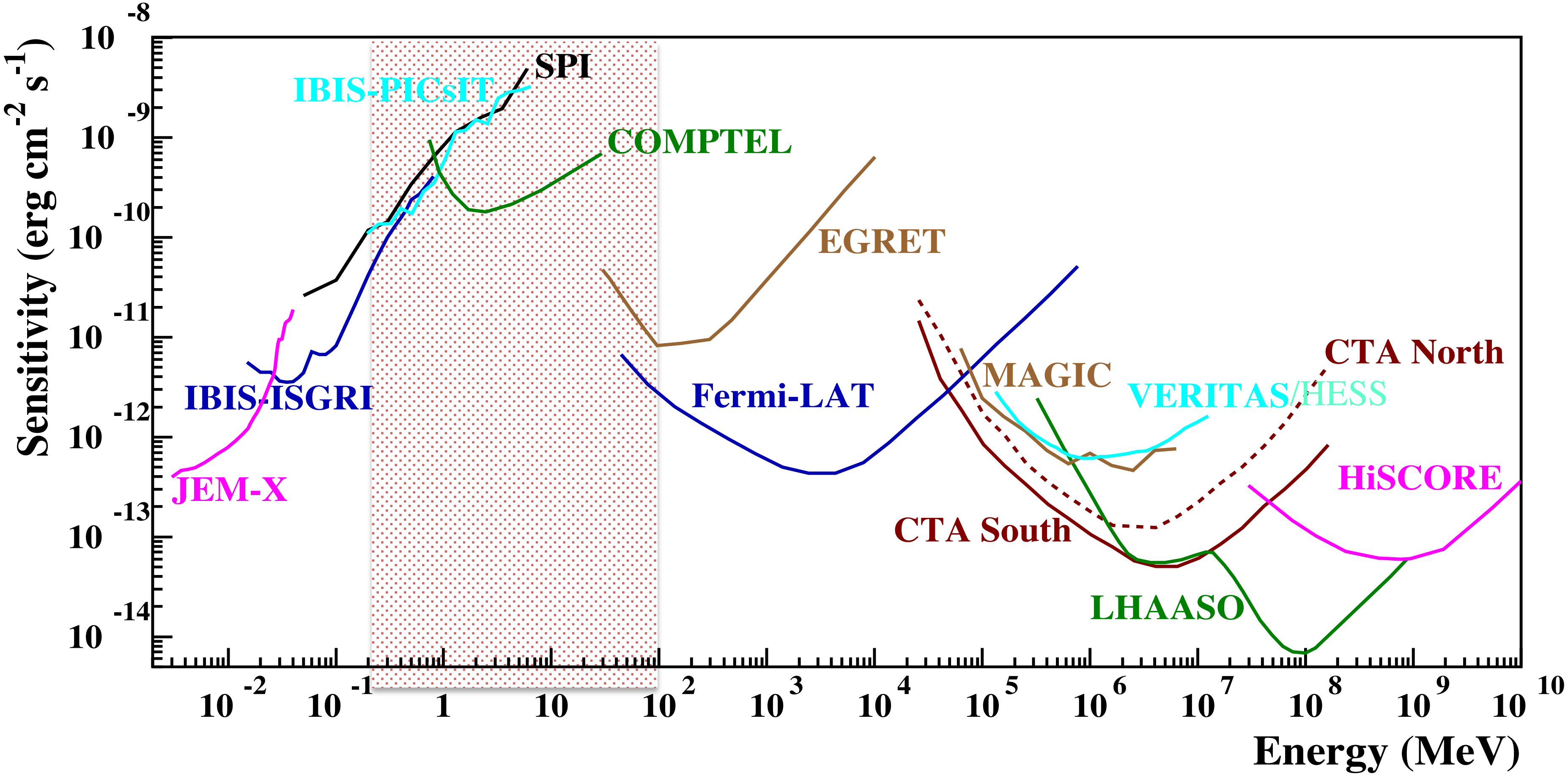
The medium energy γ-ray band accessible from space contains a wealth of scientific promise from the study of γ-ray bursts and active galaxies, dark matter annihilation and decay, particle acceleration and cosmic ray production in Galactic and extragalactic sources, cosmic ray interactions in the Milky Way, rotation powered pulsars and magnetars, acceleration processes in the Sun and more. Our appetite for this science has been whetted by many recent exciting results from Fermi (at higher energies) and NuSTAR (at lower energies) and is based on studies of the MeV sky by CGRO/COMPTEL and INTEGRAL. Progress in this exciting field has been limited largely by the challenges of building sufficiently capable instruments to detect these γ rays as they interact by Compton scattering and pair production. The detailed scientific questions within these areas are addressed by a range of different performance optimizations such as flux and polarization sensitivity, angular and energy resolution, photon counting statistics, background rejection, and field of view. Different technical and hardware approaches result in different optimization of these performance parameters.

We will meet March 24-25 at Goddard Space Flight Center in Greenbelt, MD to discuss the Science Drivers for new space-based gamma-ray missions, as well as technologies and instruments concepts for new gamma-ray experiments. This workshop is a continuation of the discussions from the previous Future Gamma-ray workshop.

http://asd.gsfc.nasa.gov/conferences/fgo2/

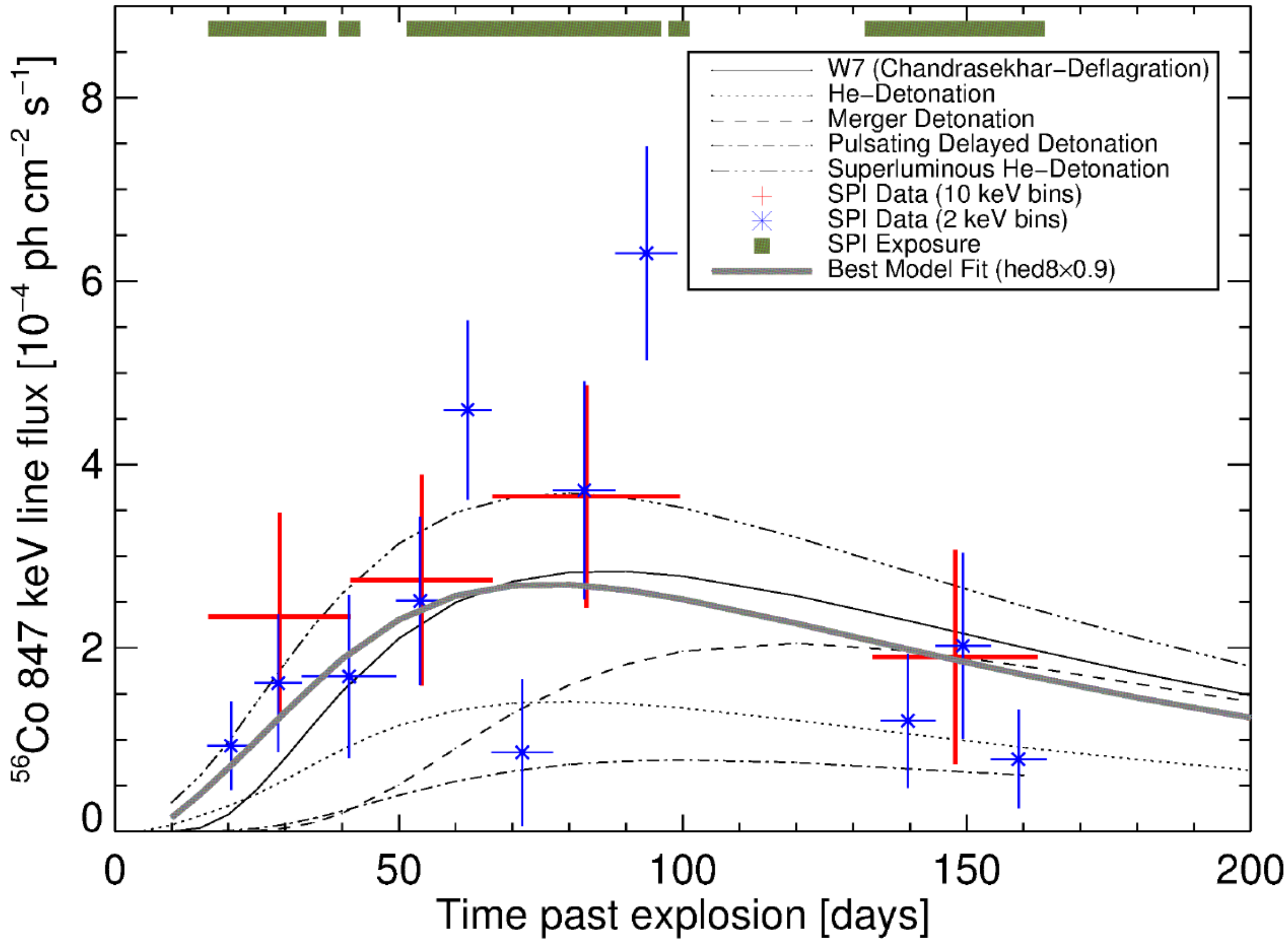
e-ASTROGAM
at the heart of the extreme Universe
http://eastrogam.iaps.inaf.it
An observatory for gamma rays
In the MeV/GeV domain
Lead proposer: A. De Angelis
Co-lead proposer: V. Tatischeff

The MeV/GeV domain



- Worst covered part of the electromagnetic spectrum (only a few tens of steady sources detected so far between 0.2 and 30 MeV)
- Many objects have their peak emissivity in this range (GRBs, blazars, pulsars...)
- Binding energies of atomic nuclei fall in this range, which therefore is as important for HE astronomy as optical astronomy is for phenomena related to atomic physics

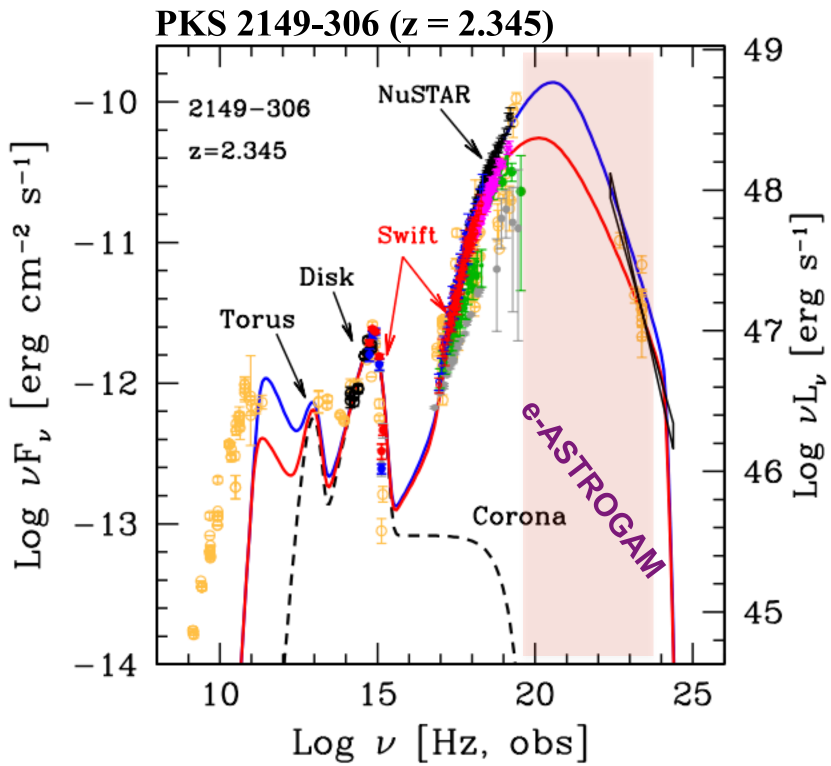
SPI gamma-ray observations of SN2014 J

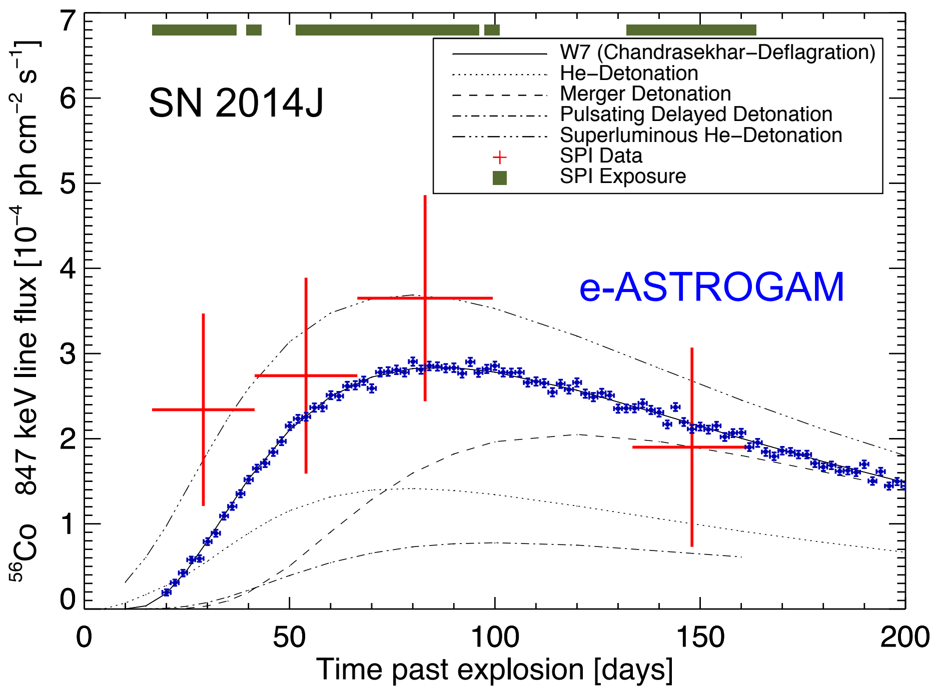


Core science motivations for a γ-ray mission in the MeV/GeV

1. **Processes at the heart of the extreme Universe (AGNs, GRBs, microquasars): prospects for the Astronomy of the 2030s**

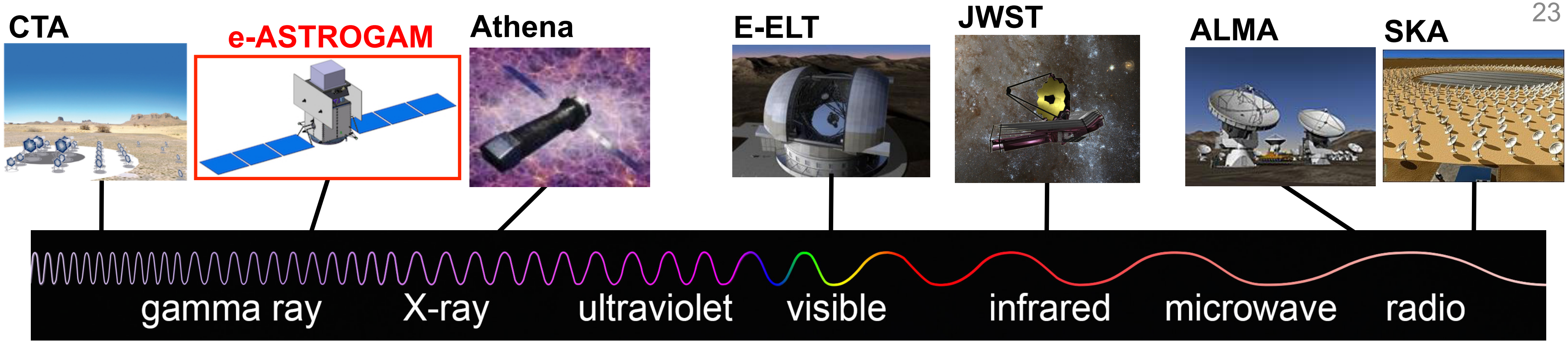
2. **The origin and impact of high-energy particles on galaxy evolution, from cosmic rays to antimatter**





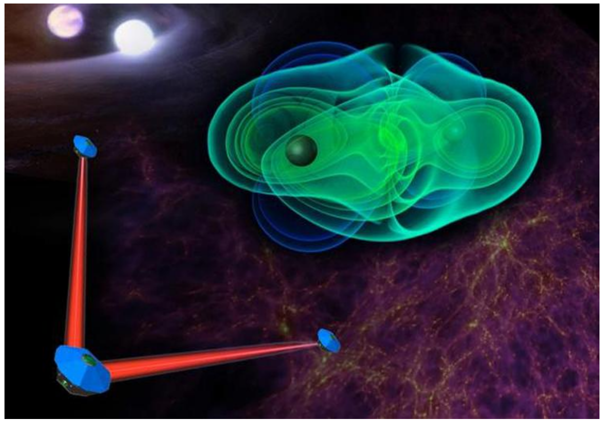
3. **Nucleosynthesis and the chemical enrichment of our Galaxy**

e-ASTROGAM: γ-ray astronomy in context

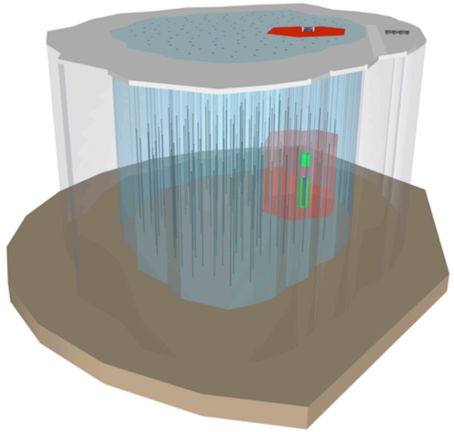


New Astronomies:
gravitational waves
neutrinos

eLISA – Gravitational waves



Km3Net/IceCube-Gen2 - ν

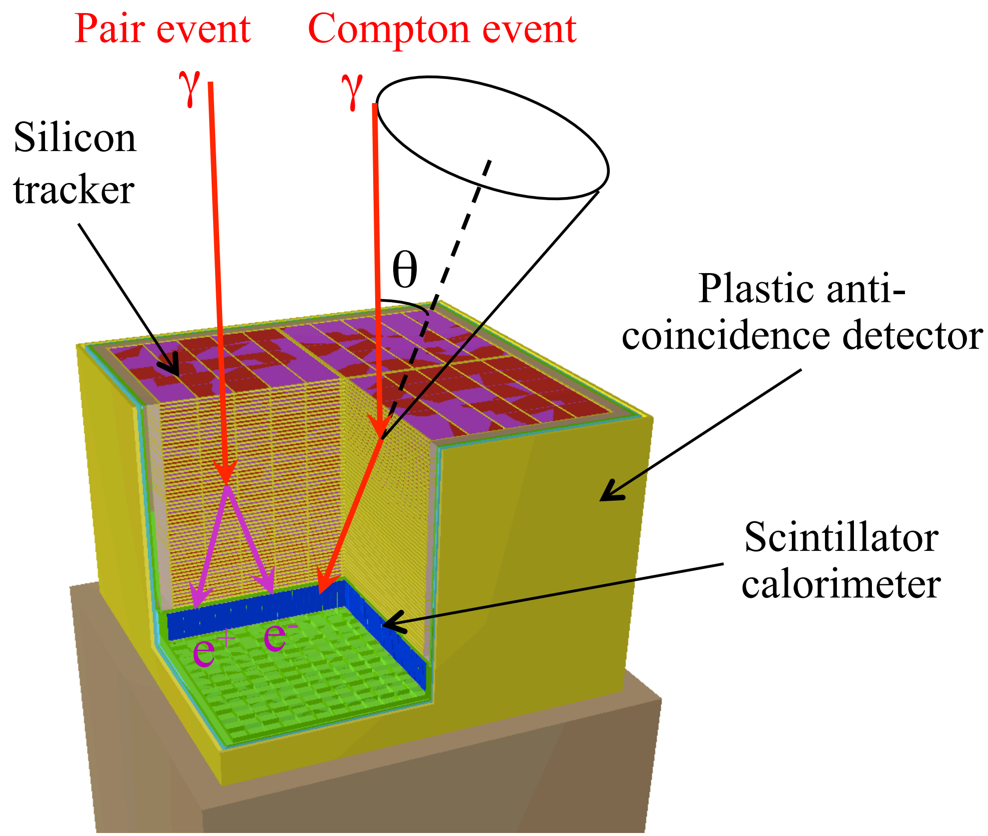


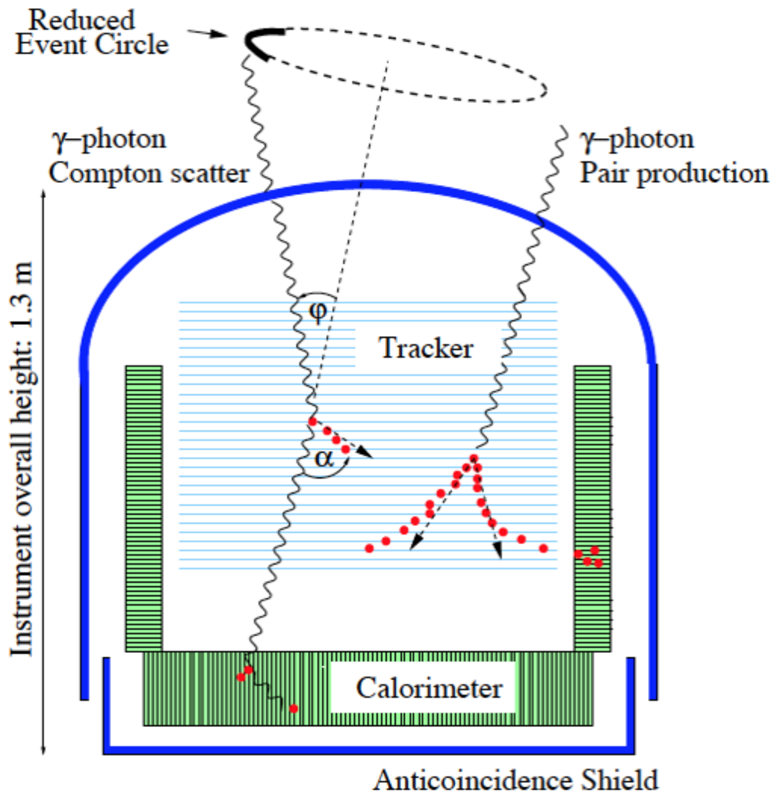
- e-ASTROGAM will be a sensitive, wide-field γ-ray space observatory operating at the same time as facilities like SKA and CTA, as well as eLISA and neutrino detectors, to get a coherent picture of the transient sky and the sources of gravitational waves and high-energy neutrinos

e-ASTROGAM scientific requirements

1. Achieve a sensitivity better than that of INTEGRAL/CGRO/COMPTEL by a factor of 20 - 50 – 100 in the range 0.2 – 30 MeV
2. Fully exploit gamma-ray polarization for both transient and steady sources
3. Improve significantly the angular resolution (to reach, e.g., ~ 10’ at 1 GeV)
4. Achieve a very large field of view (~ 2.5 sr) ⇒ efficient monitoring of the γ-ray sky
5. Enable sub-milisecond trigger and alert capability for transients

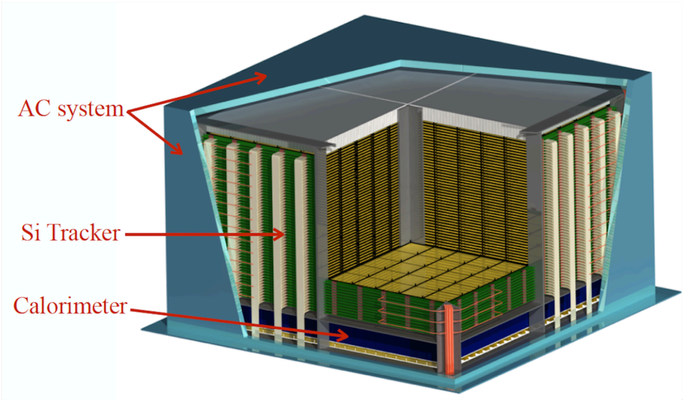
How to measure gamma rays in the MeV-GeV?



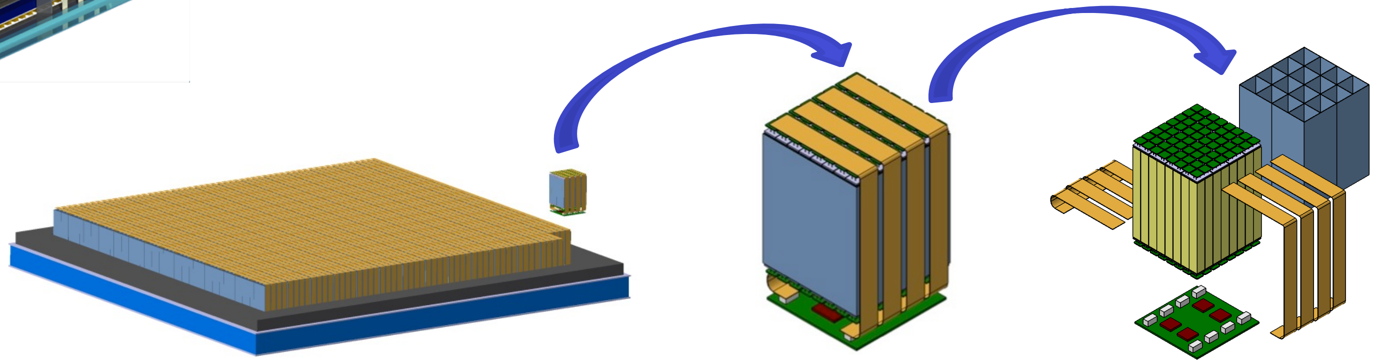


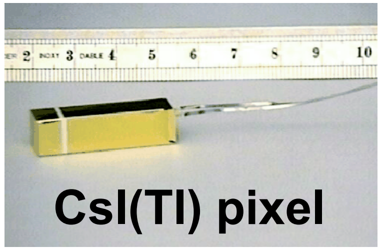
- **Tracker** – Double sided Si strip detectors (DSSDs) for excellent spectral resolution and fine 3-D position resolution ($1 m^2$, 500 μm thick, 0.3 Xo in total)
- **Calorimeter** – High-Z material for an efficient absorption of the scattered photon ⇒ CsI(Tl) scintillation crystals readout by Si drift detectors or photomultipliers for best energy resolution. 8 cm (4.3 Xo)
- **Anticoincidence detector** to veto charged-particle induced background ⇒ plastic scintillators readout by Si photomultipliers

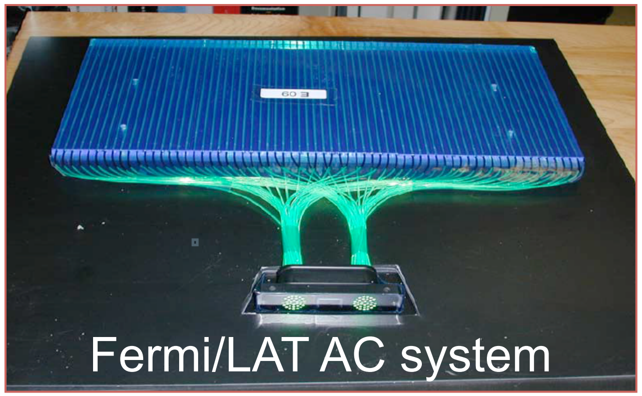
e-ASTROGAM: the payload



- **Tracker**: 56 layers of 4 times 5×5 DSSDs (5 600 in total) of 500 μm thickness and 240 μm pitch
- DSSDs bonded strip to strip to form 5×5 ladders
- Light and stiff mechanical structure
- Ultra low-noise front end electronics



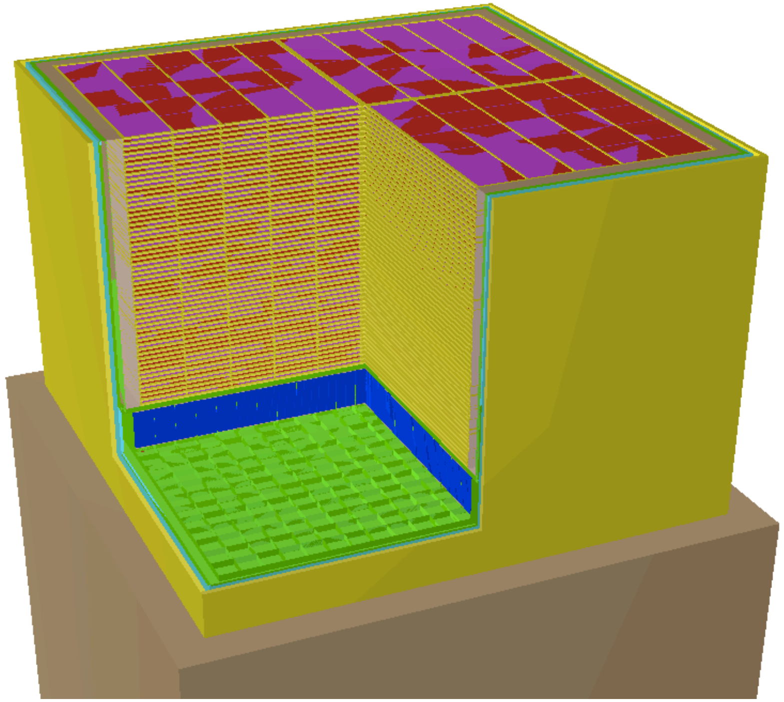


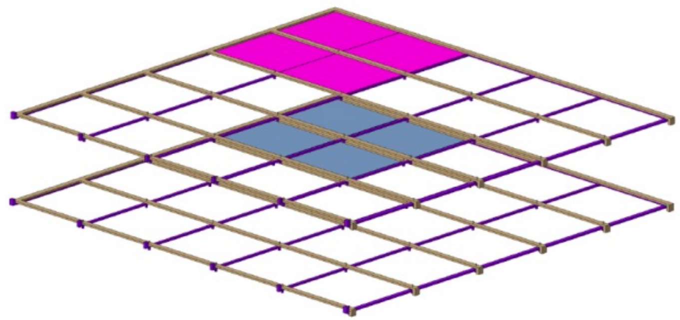


- **Calorimeter**: 33 856 CsI(Tl) bars coupled at both ends to low-noise Silicon Drift Detectors
- **ACD**: segmented plastic scintillators coupled to SiPM by optical fibers
- **Heritage**: AGILE, Fermi/LAT, AMS-02, INTEGRAL, LHC/ALICE…

e-ASTROGAM: silicon tracker

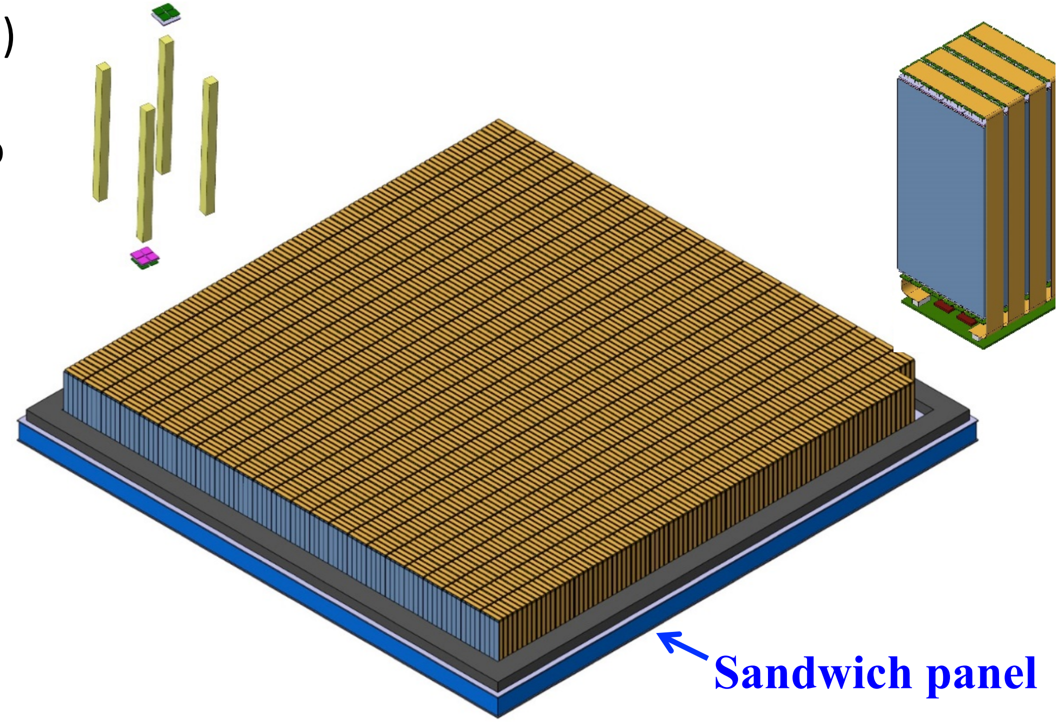
- 4 towers, 56 layers of 5×5 double sided Si strip detectors each (5600 DSSDs)
  - Each DSSD has a total area of 9.5×9.5 cm^2, a thickness of 500 μm and pitch of 240 μm (384 strips per side)
  - The DSSDs are wire bonded strip to strip to form 5×5 2-D ladders
- Spacing of the Si layers: 10 mm
  - Each layer held by a very light mechanical
    - two frames sandwiching the Si detectors
- DSSD strips connected to ASICs through a pitch adapter
  - 26 880 IDeF-X ASICs (32 channels each)
    - 860160 electronic channels
    - 12 IDeF-X ASICs each side
  - The analog output signals of IDeF-X will be converted to digital signals with the OWB-1 ADC
    - 5 OWB-1 ADCs each side
- Power budget = 688 W (800 mW/channel)

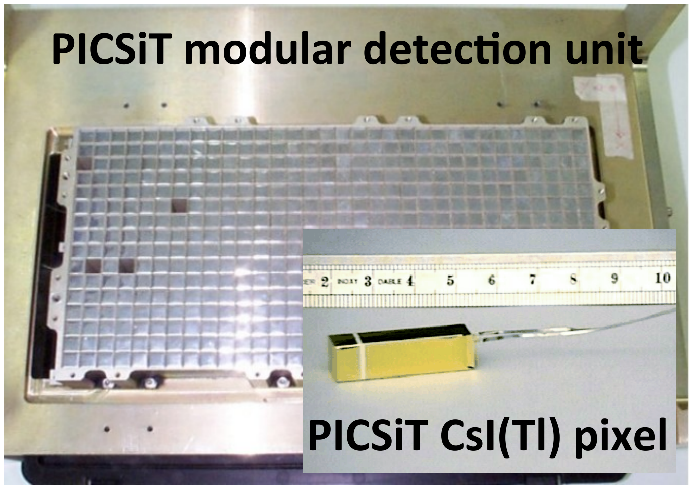


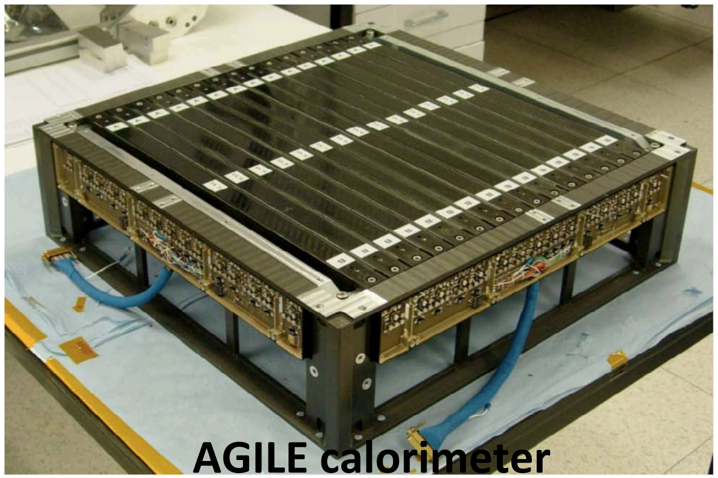


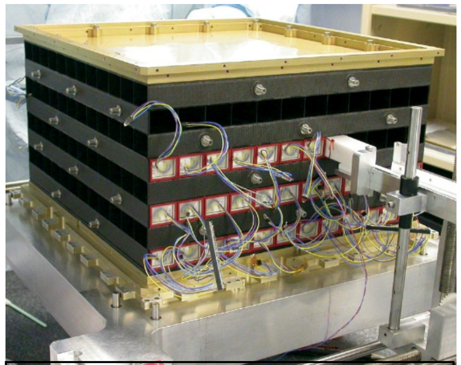
e-ASTROGAM: calorimeter

- Pixelated detector made of 33 856 CsI(Tl) scintillator bars of 8 cm length and 5×5 mm^2 cross section, glued at both ends to low-noise Silicon Drift Detectors (SDDs)
- Calorimeter formed by the assembly of 529 (23×23) modules
- **Heritage**: INTEGRAL/PICsIT, AGILE, Fermi/LAT, LHC/ALICE
    - FEE ASIC: modified version of the ultra low-noise VEGA ASIC (INFN)





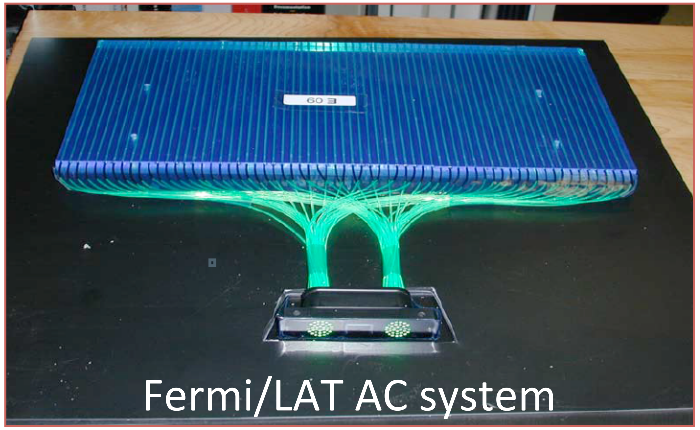


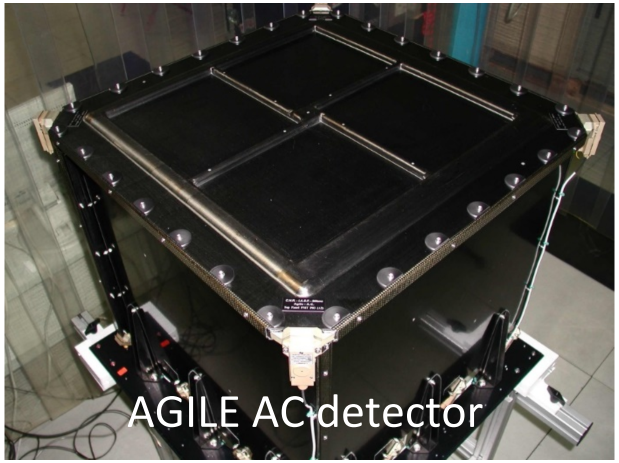


Fermi cal. module

e-ASTROGAM: anticoincidence system

- **Upper-AC** system formed by large panels of plastic scintillators covering 5 faces of the instrument (6 plastic tiles per lateral side and 9 tiles for the top = 33 tiles total)
- Wavelength shifting optical fibers buried in trenches convey the scintillation light to Si photomultipliers
- The SiPM signals are readout by the space-qualified VATA64 ASICs from Ideas©
- **Heritage**: Fermi/LAT, AGILE

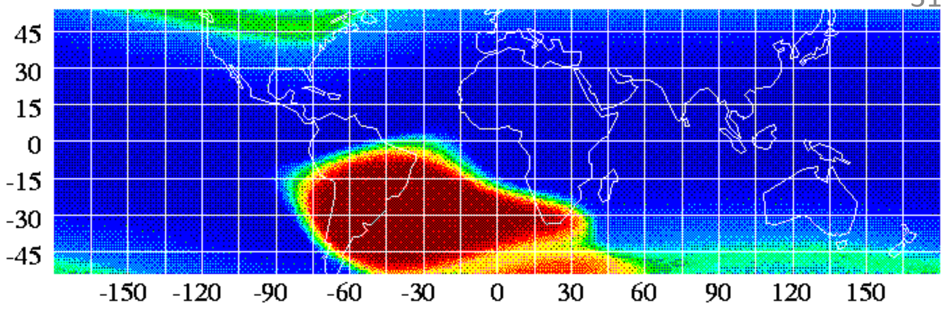

Fermi/LAT AC system

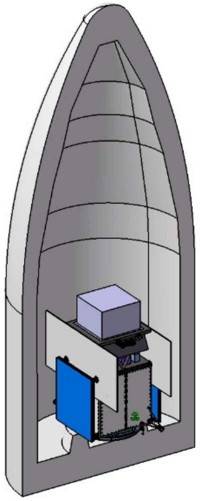

AGILE AC detector

- **Time-of-Flight** system formed by two scintillator layers separated by 50 cm below the instrument to reject the particle background from the platform
- **Heritage**: AMS, PAMELA

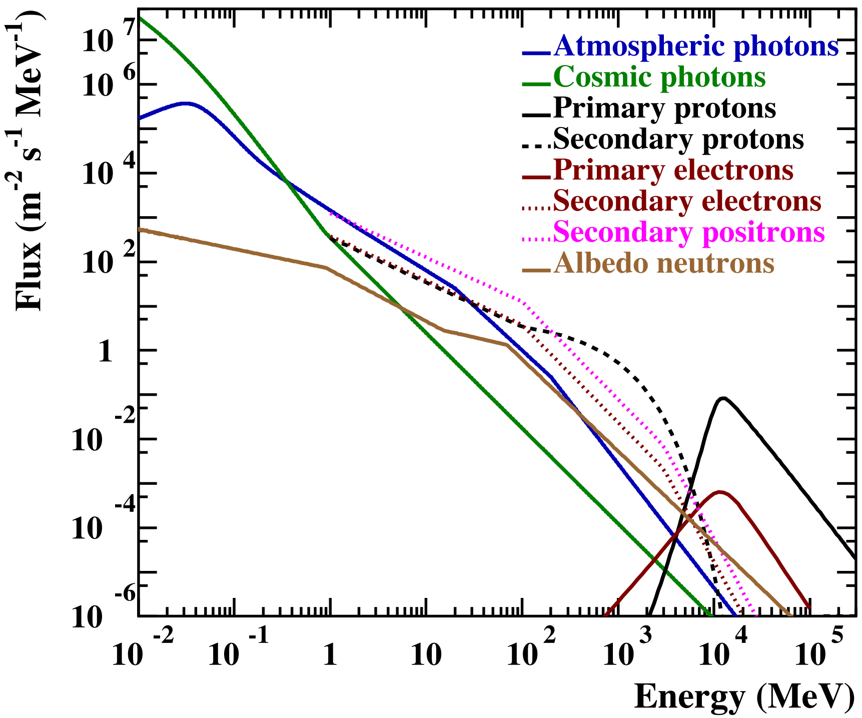
e-ASTROGAM mission profile

- **Orbit** – Equatorial (inclination $i < 2.5°$, eccentricity $e < 0.01$) low-Earth orbit (altitude in the range 550 - 600 km)
- **Launcher** – Ariane 6.2
- **Satellite communication**
    - ESA ground station at Kourou
    - + ASI Malindi station (Kenya)
- **Data transmission** – via X-band (available downlink of 8.5 MHz)
- **Observation modes** – (i) zenith-pointing sky-scanning mode, (ii) nearly inertial pointing, and (iii) fast repointing to avoid the Earth in the field of view
- **In-orbit operation** – 3 years duration + provisions for a 2+ year extension





Background environment in an ELEO



The e-ASTROGAM Collaboration

Principal investigator: Alessandro De Angelis, INFN/INAF Padova, U. Udine, Italy; LIP/IST, Portugal

Co-PI: Vincent Tatischeff – CSNSM Paris, France

INFN, INAF, U. Padova, U. & Polit. Bari, U. Roma Tor Vergata, U. Siena, U. Udine, U. Trieste

CSNSM, APC, CEA/Irfu, IPNO, LLR, CENBG, LUPM, IRAP

U. Mainz, KIT/IPE, U. Tübingen, U. Erlangen, RWTH Aachen, U. Potsdam, U. Würzburg, MPE

DPNC UniGe, ISDC, Univ. Geneva, PSI

ICE (CSIC-IEEC), IMB-CNM (CSIC), IFAE-BIST, Univ. Barcelona, CLPU & Univ. Salamanca

KTH and Univ. Stockholm

Czech Technical Univ., Prague; University of Coimbra, LIP and IST Lisboa, Univ.Sofia

DTU Copenhagen

Univ. College Dublin, Dublin City Univ.

Space Research Center of PAS Warsaw

NASA GSFC, NRL, Clemson Univ., Washington Univ., Yale Univ., Univ. Maryland, UC Berkeley

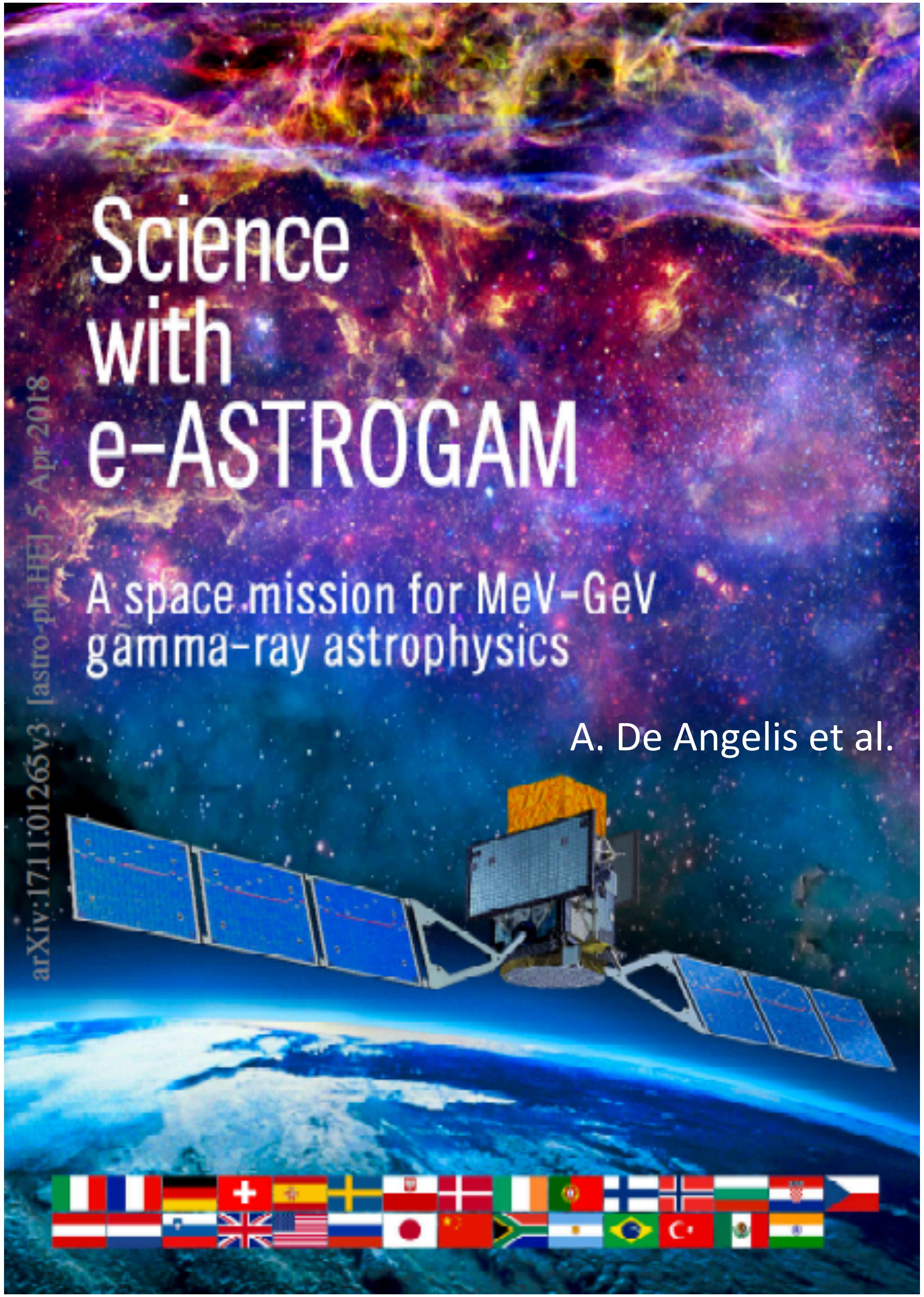
Ioffe Institute, St. Petersburg

University of Tokyo

CBPF Rio de Janeiro

Science with e-ASTROGAM

See https://arxiv.org/abs/1611.02232
(Exp. Astronomy)
and https://arxiv.org/abs/1711.01265
(JHEAP)



A. De Angelis*,[1,2,3,4] V. Tatischeff*,[5] I. A. Grenier*,[6] J. McEnery*,[7] M. Mallamaci*,[1] M. Tavani,[8,9,10]
U. Oberlack,[11] L. Hanlon,[12] R. Walter,[13] A. Argan,[14] P. Von Ballmoos,[15] A. Bulgarelli,[16] A. Bykov,[17] M. Hernanz,[18]
G. Kanbach,[19] I. Kuvvetli,[20] M. Pearce,[21] A. Zdziarski,[22] J. Conrad,[23] G. Ghisellini,[24] A. Harding,[7] J. Isern,[25]
M. Leising,[26] F. Longo,[27,28] G. Madejski,[29] M. Martinez,[30] M. N. Mazziotta,[31] J. M. Paredes,[32] M. Pohl,[33]
R. Rando,[1,34] M. Razzano,[35,36] A. Aboudan,[34,2] M. Ackermann,[37] A. Addazi,[38] M. Ajello,[26] C. Albertus,[39]
J. M. Álvarez,[40] G. Ambrosi,[41] S. Antón,[42,43] L. A. Antonelli,[44] A. Babic,[45] B. Baibussinov,[1] M. Balbo,[13]
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M. Boettcher,[58] V. Bonvicini,[28] V. Bosch-Ramon,[32] E. Bottacini,[1,34] V. Bozhilov,[59] T. Bretz,[60] M. Branchesi,[61,62]
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B. De Lotto,[81] D. de Martino,[82] A. De Rosa,[8] M. Del Santo,[83] L. Delgado,[18] R. Diehl,[77] S. Dietrich,[84]
A. D. Dolgov,[85,86] A. Domínguez,[49] D. Dominis Prester,[87] I. Donnarumma,[8] D. Dorner,[88] M. Doro,[1,34]
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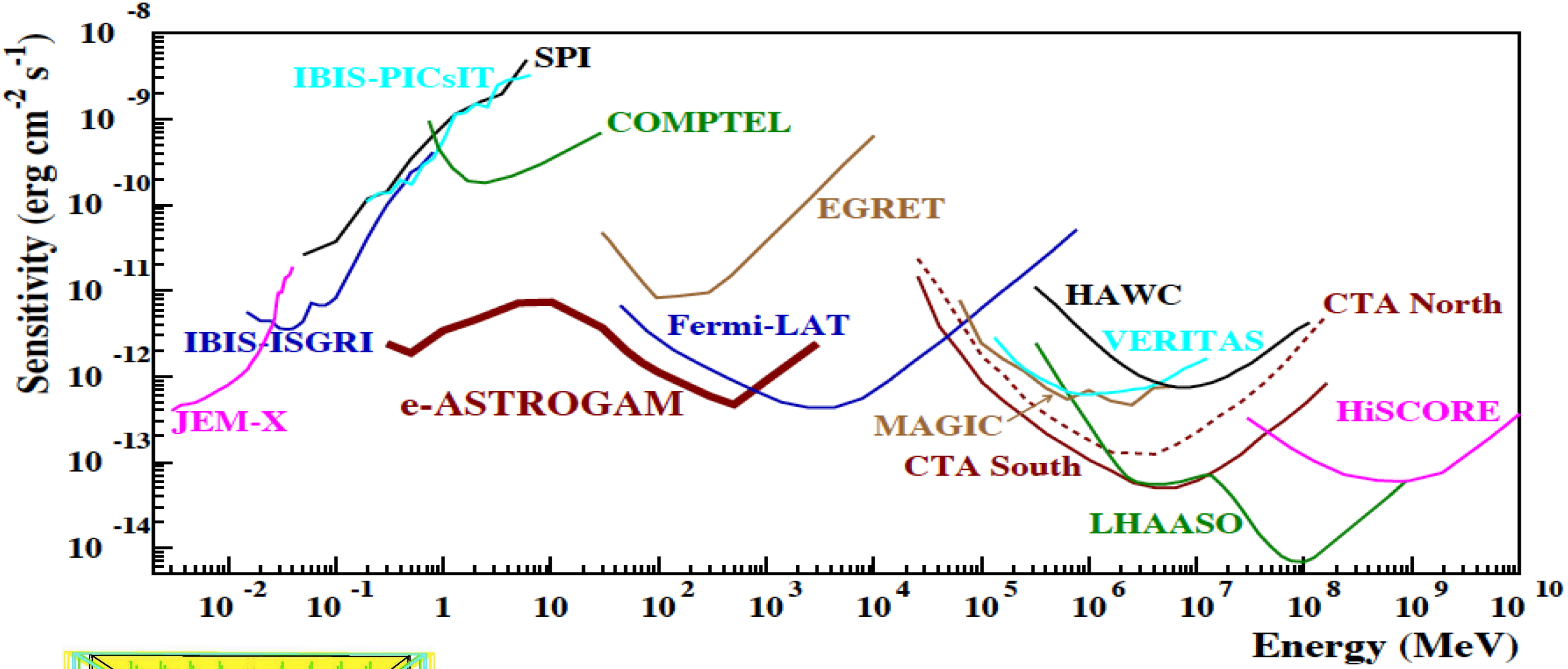
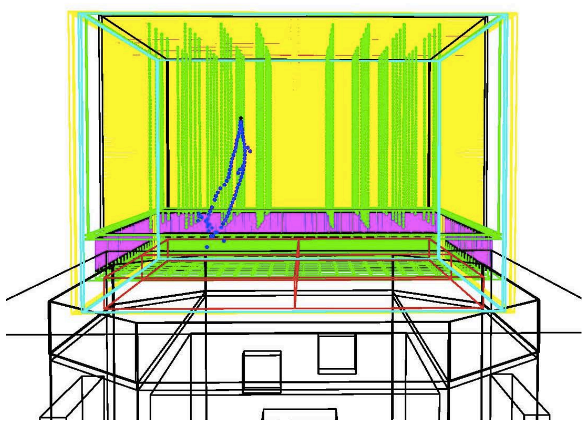
G. Zaharijaš,[148] L. Zampieri,[2] S. Zane,[149] S. Zimmer,[150,13] A. Zoglauer,[151] and the e-ASTROGAM collaboration

White Book published in arXiv/JHEAP
Wide interest from the scientific community

e-ASTROGAM: performance assessment

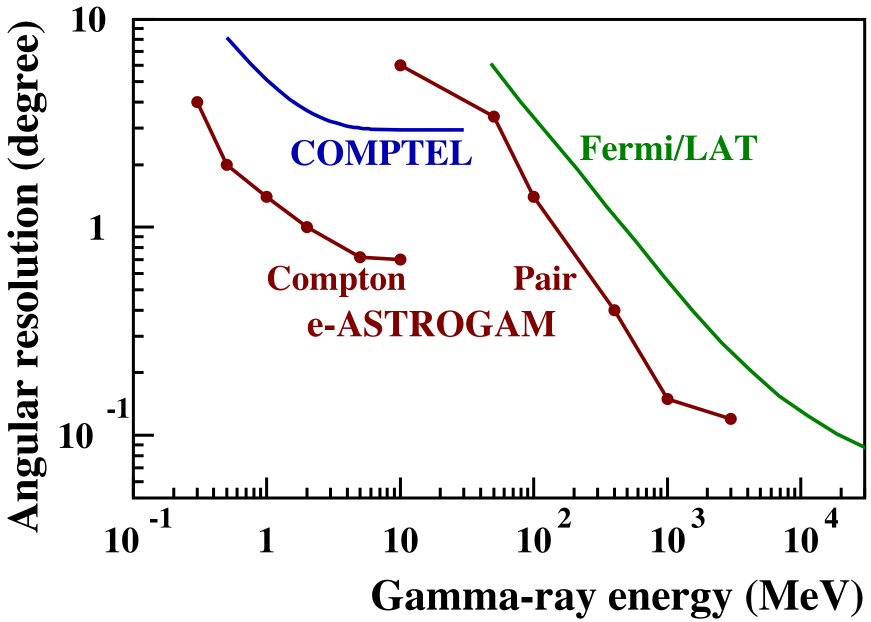




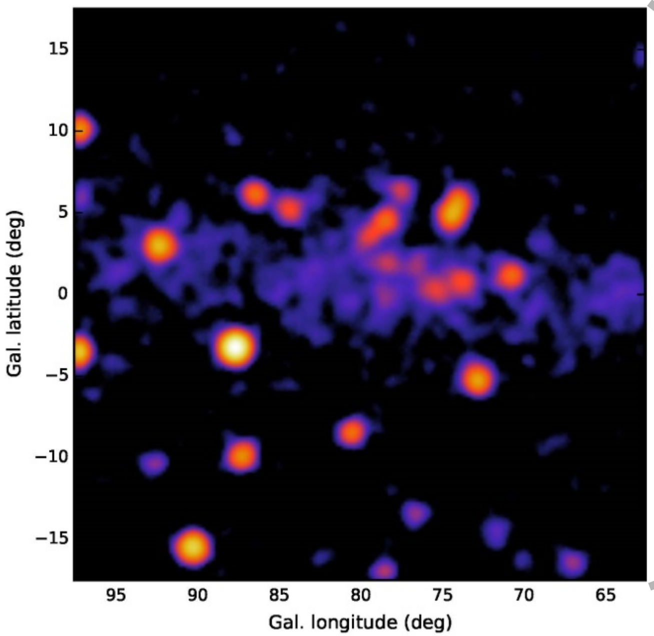
- e-ASTROGAM performance evaluated with **MEGAlib** (Zoglauer et al. 2006) and **Bogemms** (Bulgarelli et al. 2012) − both tools based on Geant4 − and a detailed numerical mass model of the gamma-ray instrument

Angular resolution

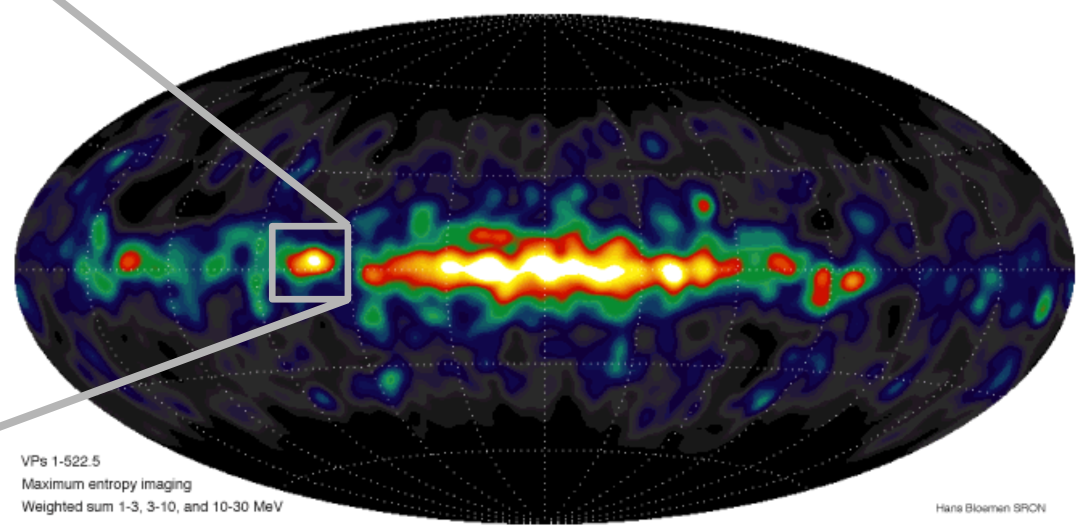
- Angular resolution improved close to the physical limits

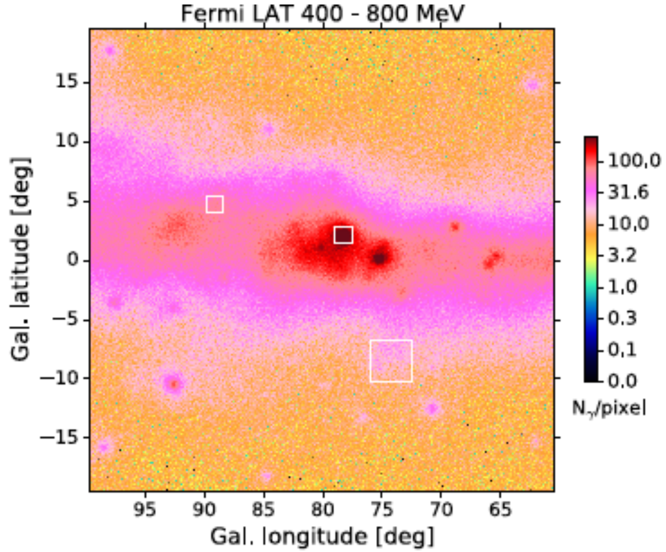


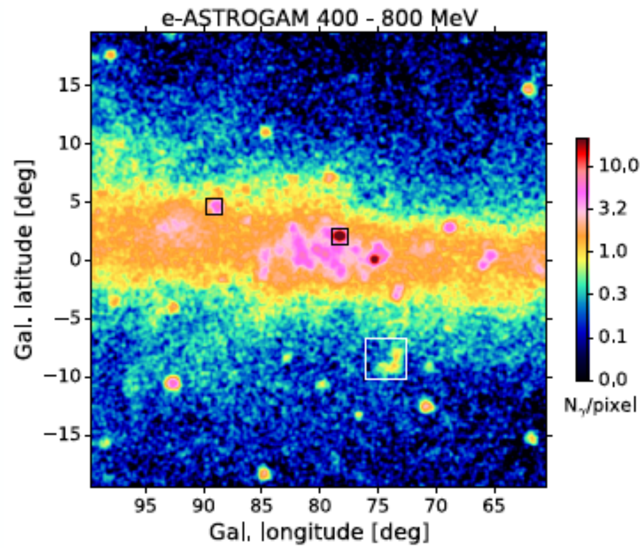
Cygnus region in the 1 - 3 MeV energy band with the e-ASTROGAM PSF (extrapolation of the 3FGL source spectra to low energies)



COMPTEL 1-30 MeV

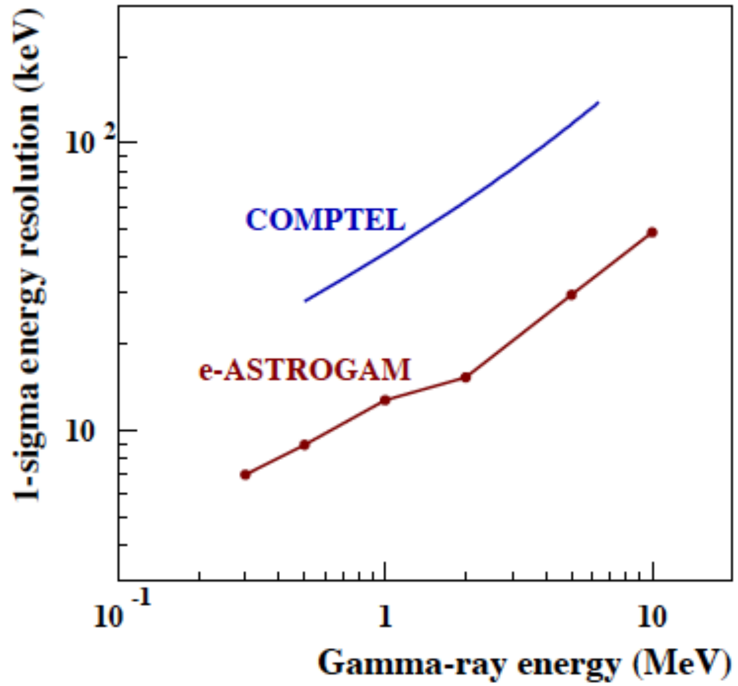






Energy resolution

$\Delta E/E$ (Gamma-ray imager)	2.5% at 1 MeV 30% at 100 MeV
$\Delta E/E$ (Calorimeter burst)	< 25% FWHM at 0.3 MeV < 10% FWHM at 1 MeV < 5% FWHM at 10 MeV



Key instrument characteristics: a summary

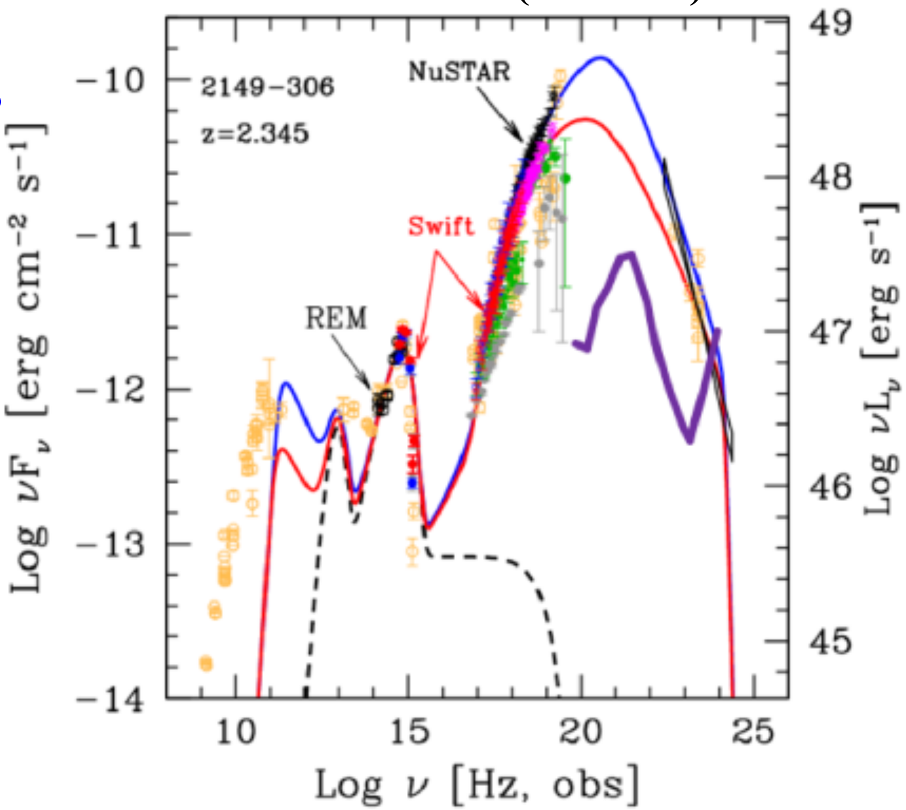
- Best PSF in MeV-GeV
  - Resolve sources
- Calorimetric measurements of MeV lines with high resolution:
  - Positron detection (511 keV line)
  - Measurements of isotopic contents, with highest sensitivity
  - Hadronic collisions of LECR with molecular clouds
- Capability of measuring polarization (marks Compton interactions at the sources and magnetic fields)
- SED resolution in the GeV range: allows to reconstruct the “pion bump”, characteristic of the decay $\pi^o \rightarrow \gamma\gamma$ and thus an indicator of hadronic processes

e-ASTROGAM core science topic #1

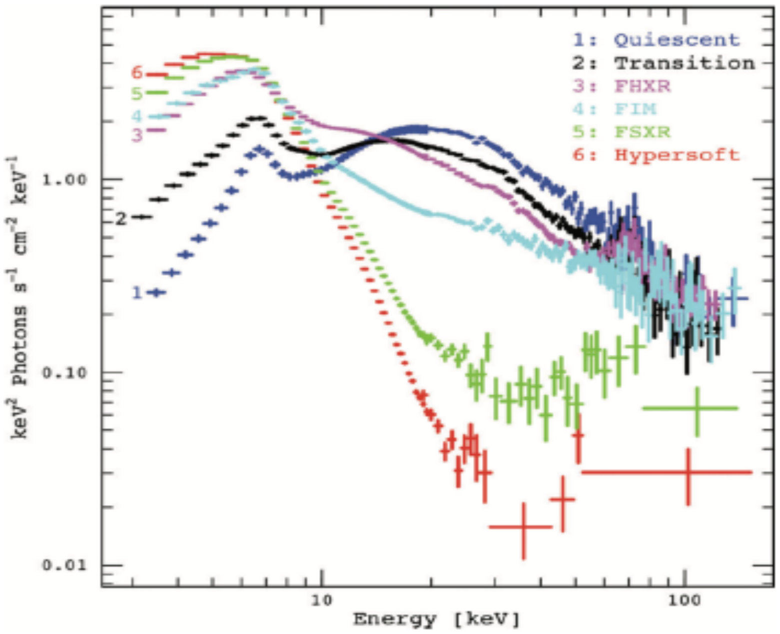
At the heart of the extreme Universe

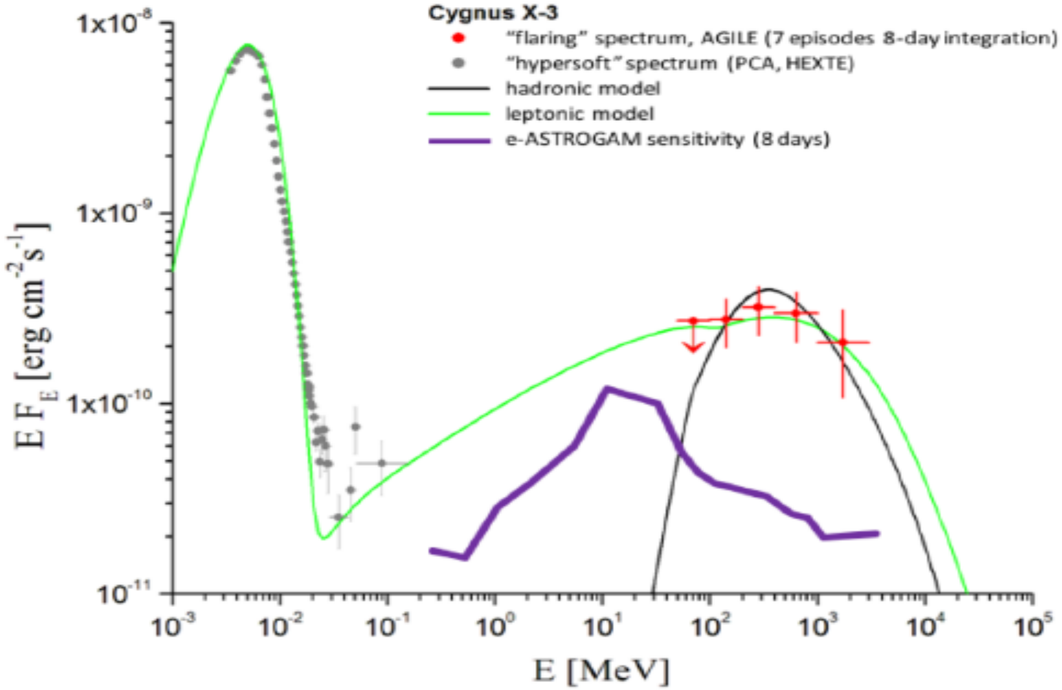
- *Launch of ultra-relativistic jets in **GRBs**? Ejecta composition, energy dissipation site, radiation processes?*
- *Can short-duration GRBs be unequivocally associated to **gravitational wave** signals?*
- *How does the accretion disk/jet transition occur around supermassive black holes in **AGN**?*
- *Are BL Lac blazars sources of **UHECRs** and high-energy **neutrinos**?*

PKS 2149-306 (z = 2.345)



✓ With its wide **field of view**, unprecedented **sensitivity** over a large spectral band, and exceptional capacity for **polarimetry**, **e-ASTROGAM** will give access to a variety of extreme **transient** phenomena





Relativistic jets; flares

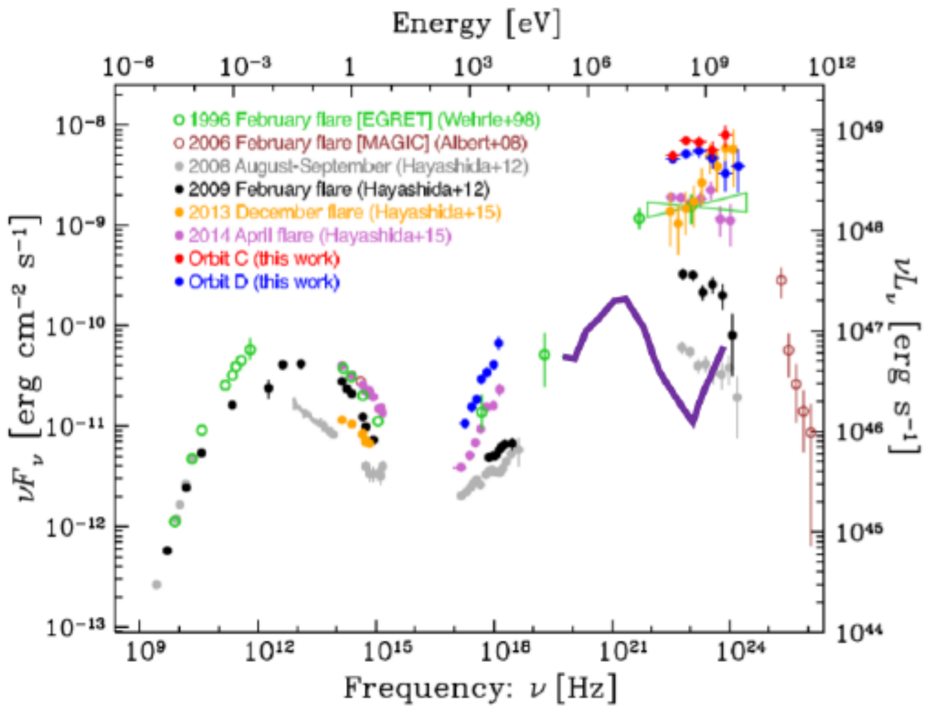
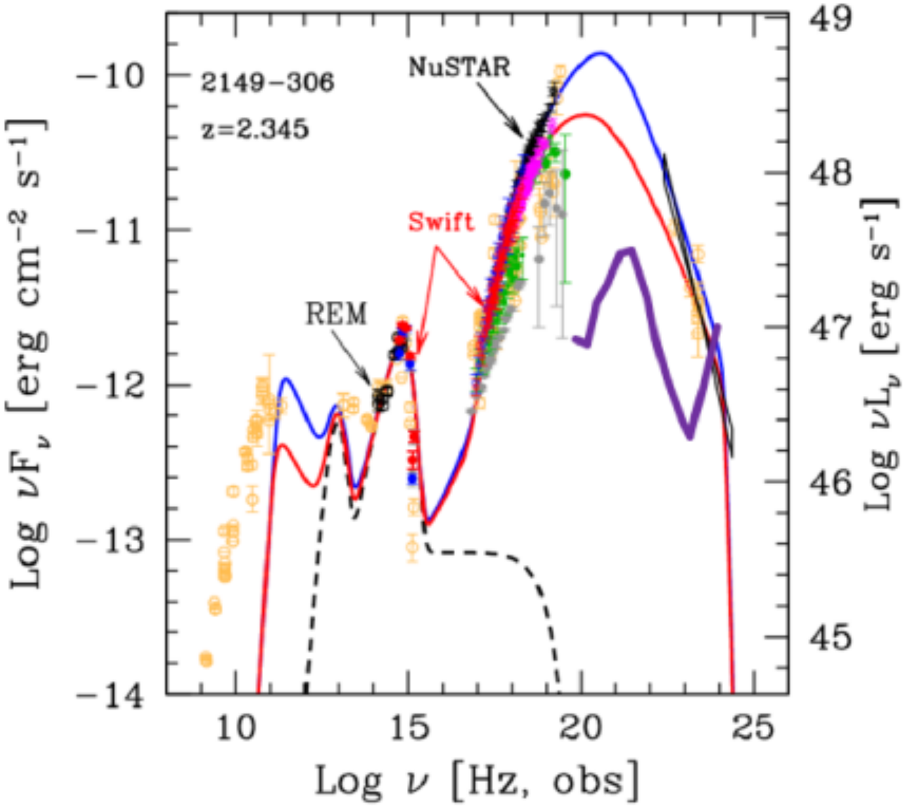
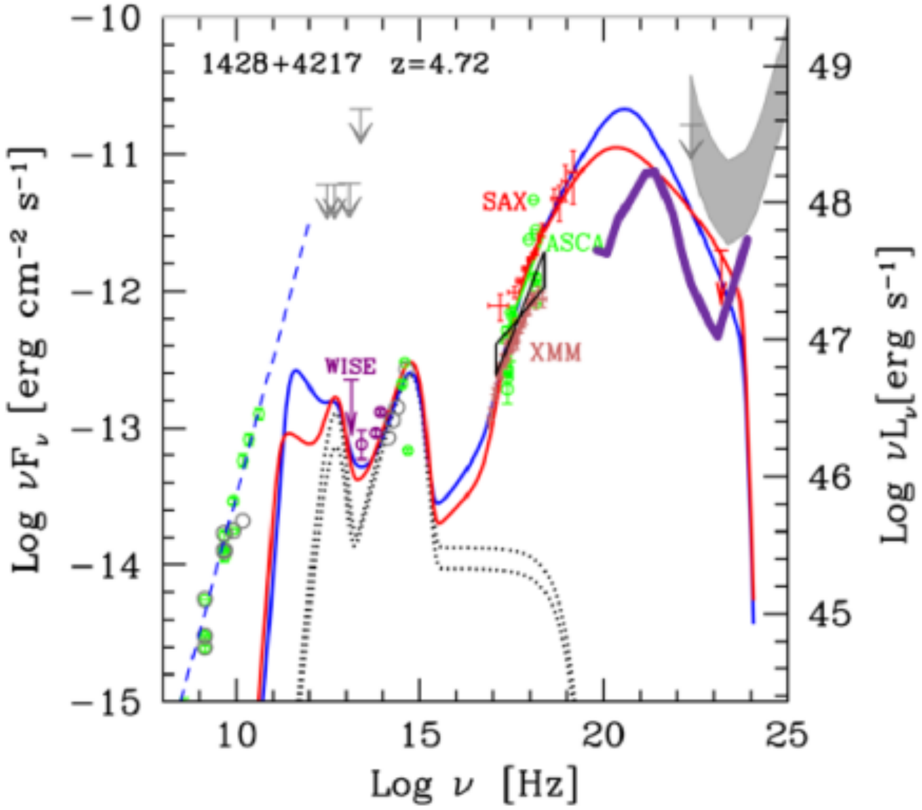


Figure 5: SED from a collection of different spectral states of the FSRQ 3C 279 showing a dramatic gamma-ray flaring activity, including the minute-timescale episode detected by Fermi in June 2015 [13]. The purple solid line is the 3σ e-ASTROGAM sensitivity calculated for a 50 ks exposure.

MeV blazars; cosmology at z up to 4.5





Gamma-ray bursts; the new Astronomy

- Threshold at 30 keV using the Calorimeter
- 200 GRB/year detected
  - Localized within 0.1-1 deg, and the information can be processed onboard
  - 42 GRBs/year with a detectable polarization fraction of 20%;
- Possible detection of electromagnetic counterparts of impulsive GW events
  - MeV likely to be the threshold (Patricelli et al. 2016)
  - Possible associations GRB/GW
- MeV good target also for the counterparts of neutrino bursts

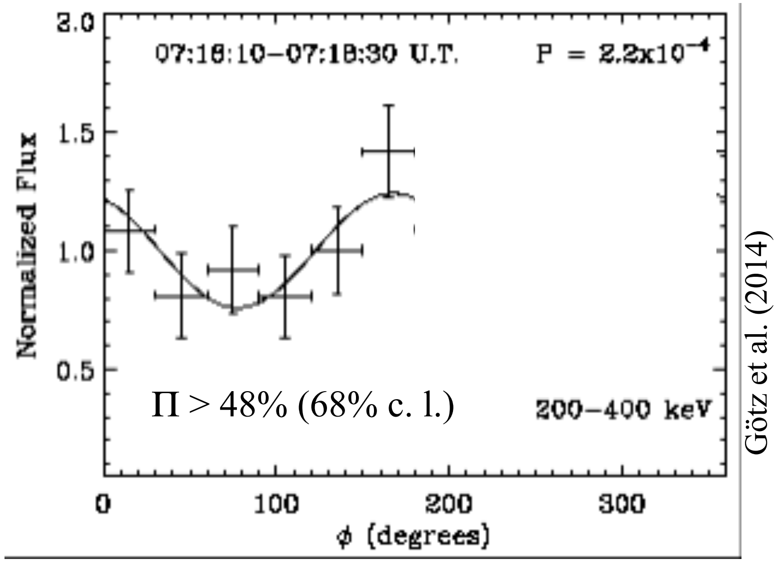
Gamma-ray polarization

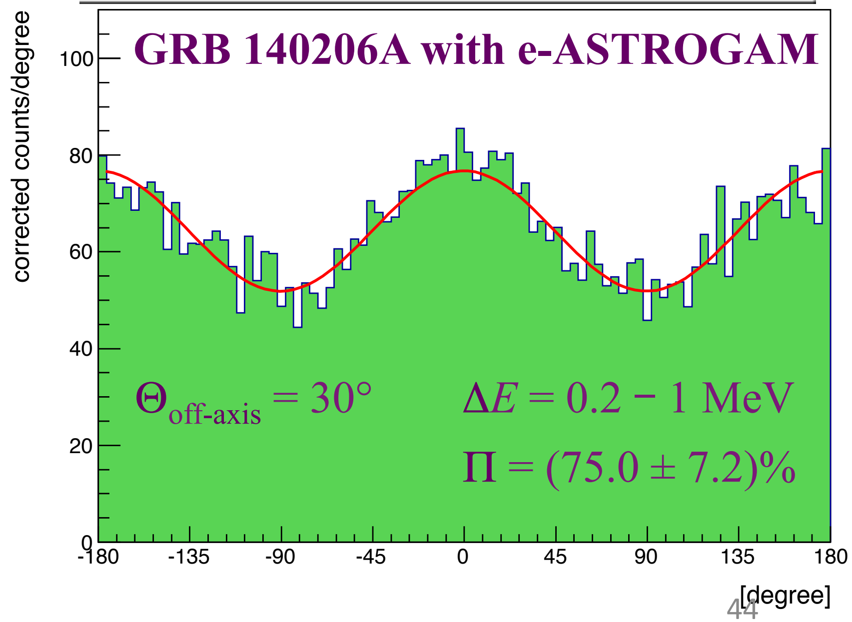
- γ-ray polarization in **objects emitting jets** (GRBs, Blazars, X-ray binaries) or with **strong magnetic field** (pulsars, magnetars) ⇒ magnetization and content (hadrons, leptons, Poynting flux) of the outflows + radiation processes

- γ-ray polarization from **cosmological sources** (GRBs, Blazars) ⇒ fundamental questions of physics related to Lorentz Invariance Violation (vacuum birefringence)

✓ e-ASTROGAM will measure the γ-ray polarization of ~ **200 GRBs per year** (promising candidates for highly γ-ray polarized sources)

INTEGRAL/IBIS – GRB 140206A ($z = 2.74$)



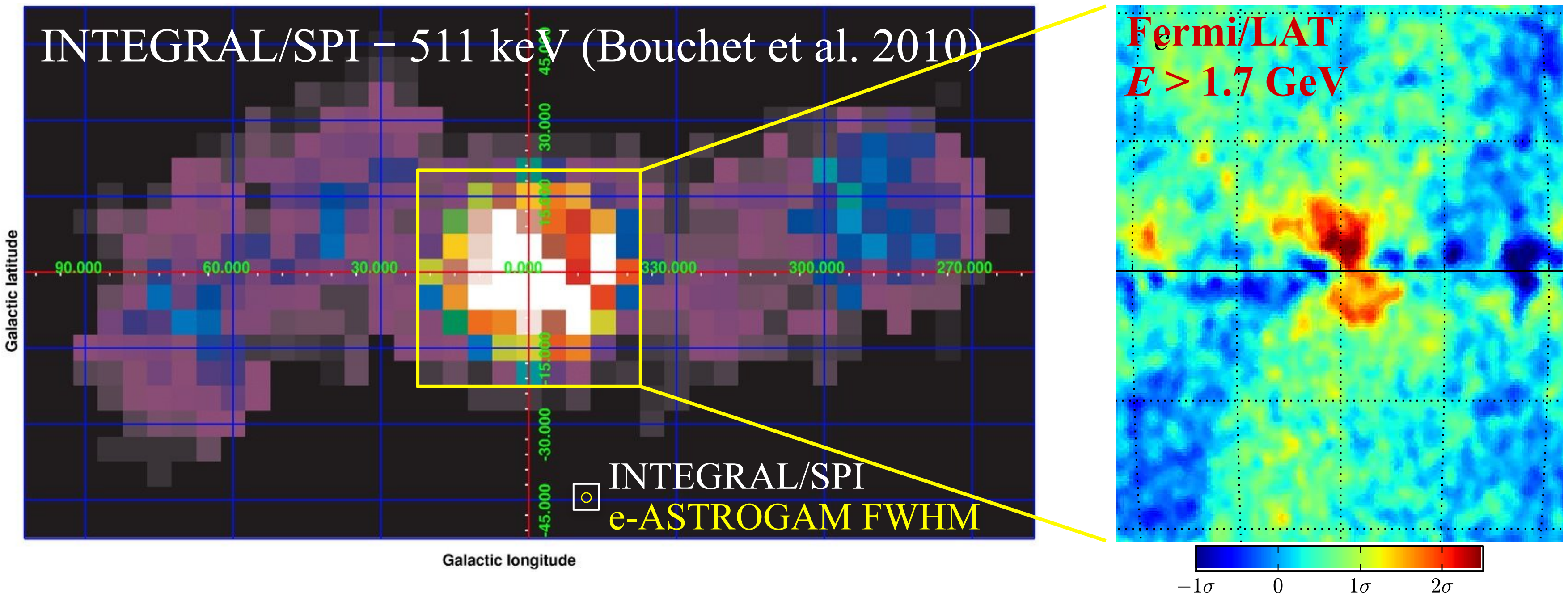


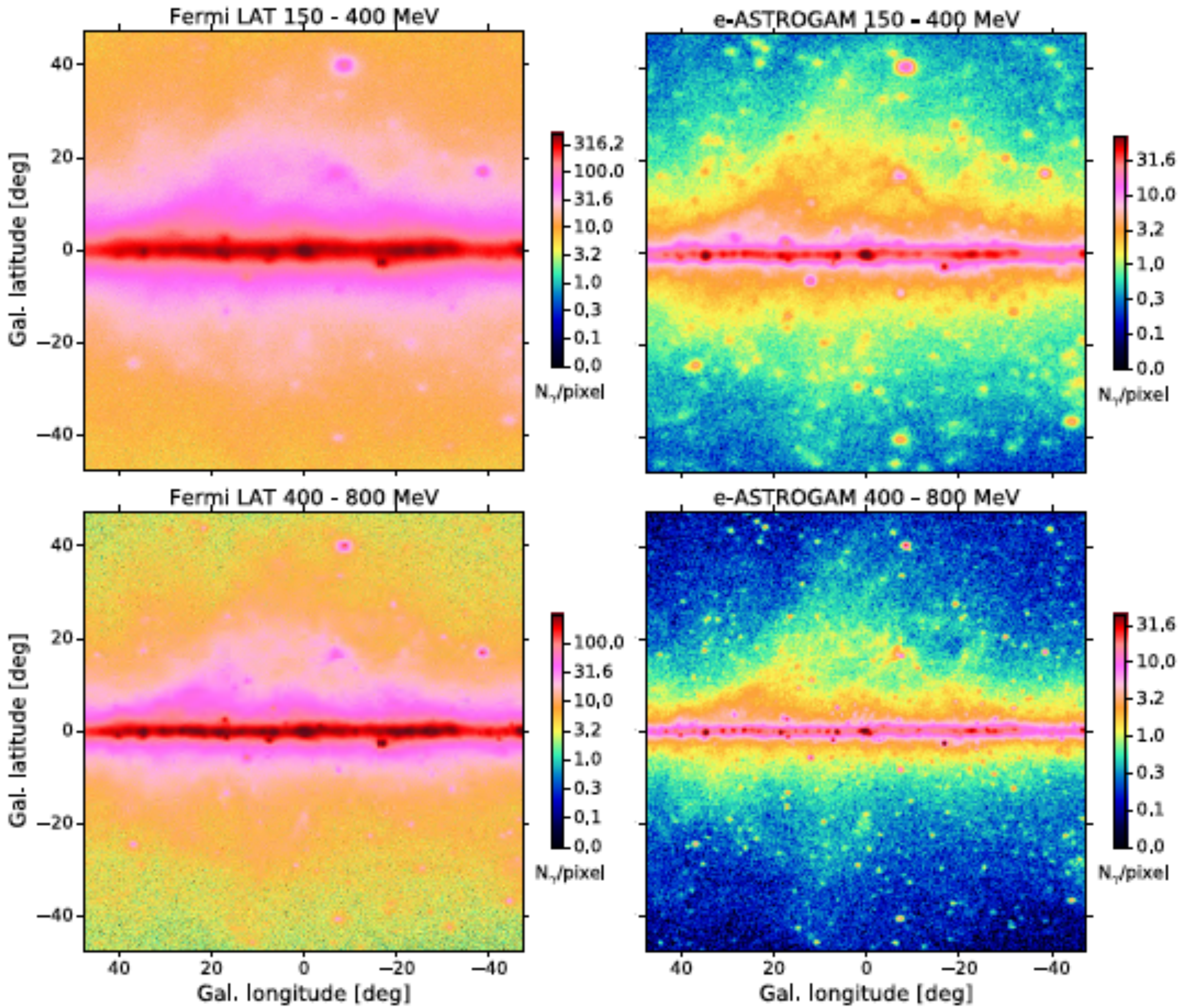
e-ASTROGAM core science topic #2

Origin & impact of HE particles on Galaxy evolution: CR, antimatter, …

- *Origin of the **Fermi Bubbles** and of the **511 keV emission** from the Galaxy's bulge? Are these linked to a past activity of the central **supermassive black hole**? What is causing the **GeV excess** emission from the center region?*

✓ With a **sensitivity** and an **angular resolution** in the MeV – GeV range significantly improved over previous missions, **e-ASTROGAM** will enable a detailed **spectro-imaging** of the various high-energy components





Fermi LAT 150 - 400 MeV
e-ASTROGAM 150 - 400 MeV
Fermi LAT 400 - 800 MeV
e-ASTROGAM 400 - 800 MeV
Gal. latitude [deg]
Gal. longitude [deg]
40
20
0
−20
−40
316.2
100.0
31.6
10.0
3.2
1.0
0.3
0.1
0.0
N_γ/pixel

Cosmic rays in the Inner Galaxy; acceleration in SNRs

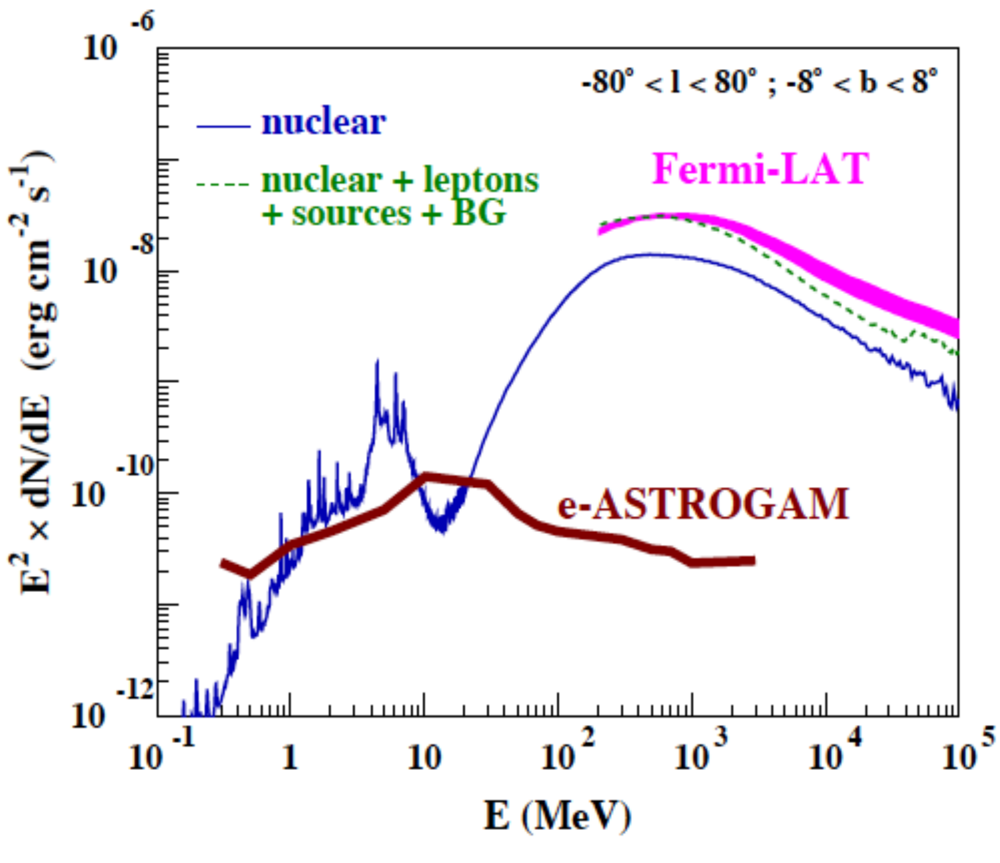
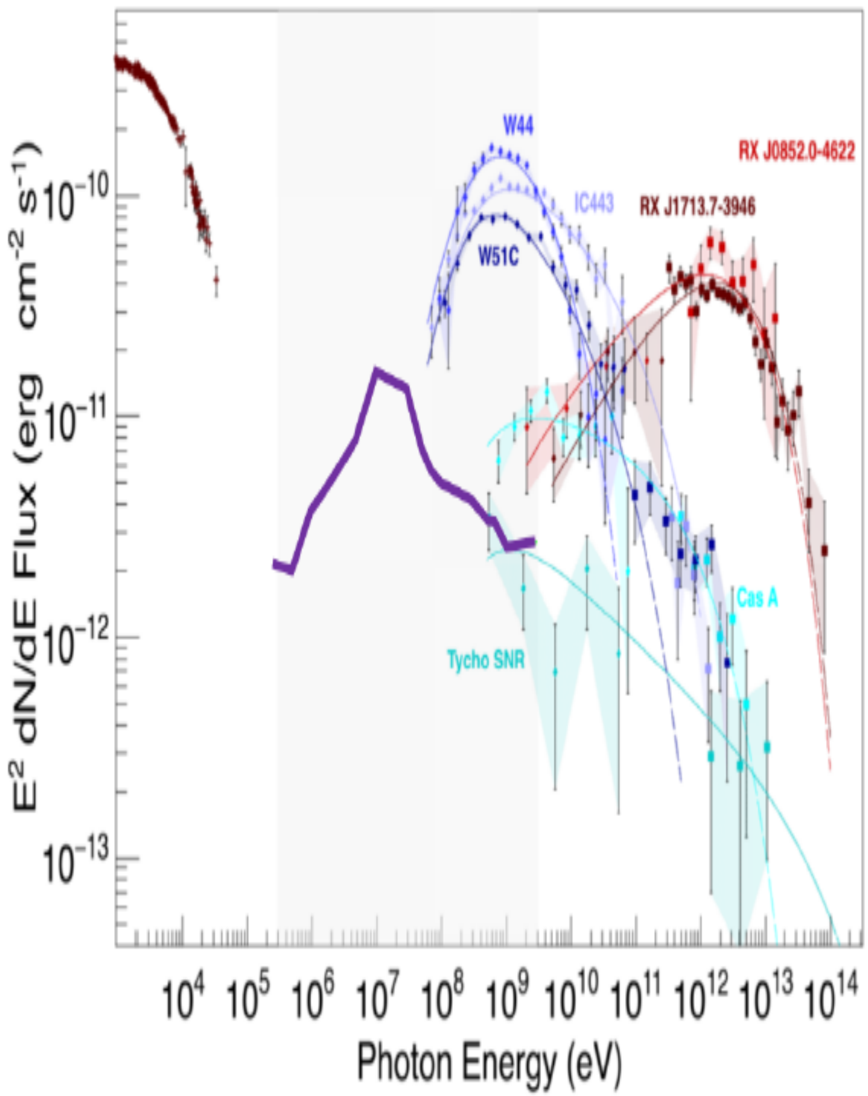


Figure 9: Predicted γ-ray emission due to nuclear interactions of CRs in the Inner Galaxy. The γ-ray line emission below 10 MeV is due to LECRs ([24]). The 1-year sensitivity of e-ASTROGAM (for Galactic background) is superimposed.



Antimatter and Dark Matter

- Unique sensitivity to the 511-keV line
- Sensitivity to many classical positron sources: can constrain the contribution from nearby pulsars in the positron excess seen by PAMELA/AMS-02

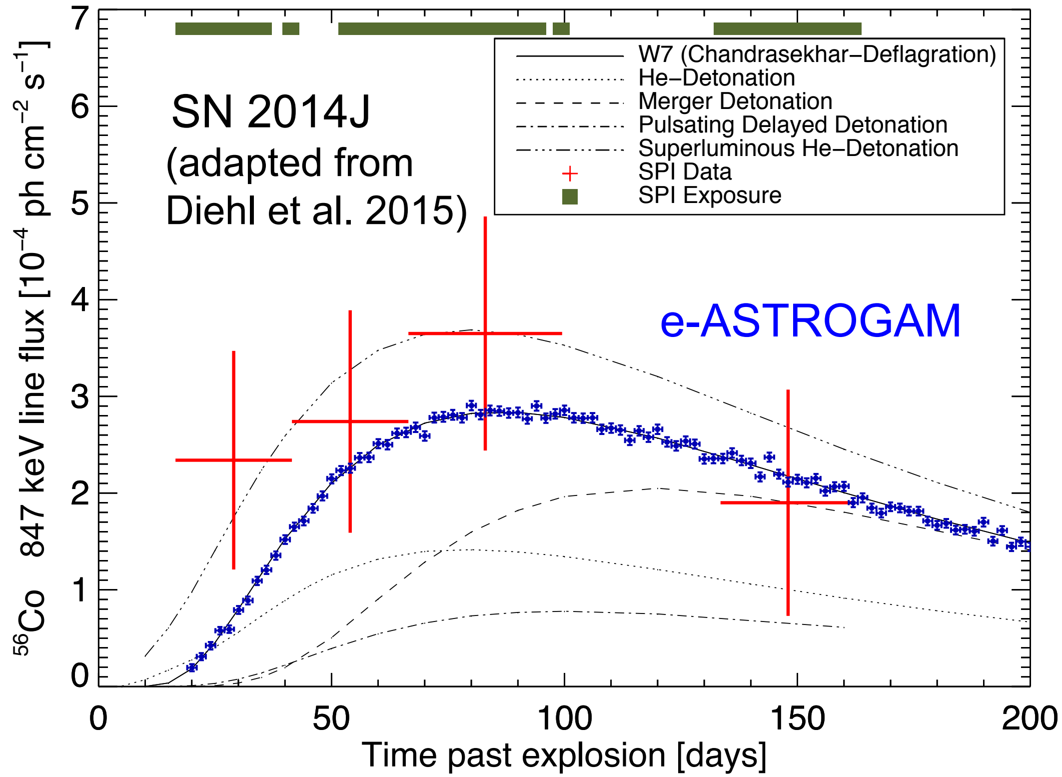
- The MeV region is the missing ingredient to determine the photon background from the Inner Galaxy: clarify if there is a photon excess (which might be due to DM, new particles)
- The MeV region is where the bulk of photons from WIMPs below 100 GeV is expected
- In some models, MeV dark matter
  - Plus Axions, ALPs:
    - Sensitivity to photons emitted by SNRs (Meyer et al. 2016)
    - Sensitivity to photon/ALP oscillations (Roncadelli et al. 2011; Hooper et al. 2009)

e-ASTROGAM core science topic #3

Supernovae, nucleosynthesis, and Galactic chemical evolution

- *How do thermonuclear and core-collapse SNe explode? How are cosmic isotopes created in stars and distributed in the interstellar medium?*

✓ With a remarkable improvement in **γ-ray line sensitivity** over previous missions, **e-ASTROGAM** should allow us to finally understand the progenitor system(s) and explosion mechanism(s) of **Type Ia SNe** (^{56}Ni, ^{56}Co), the dynamics of **core collapse** in massive star explosions (^{56}Co, ^{57}Co), and the history of **recent SNe** in the Milky Way (^{44}Ti, ^{60}Fe...)



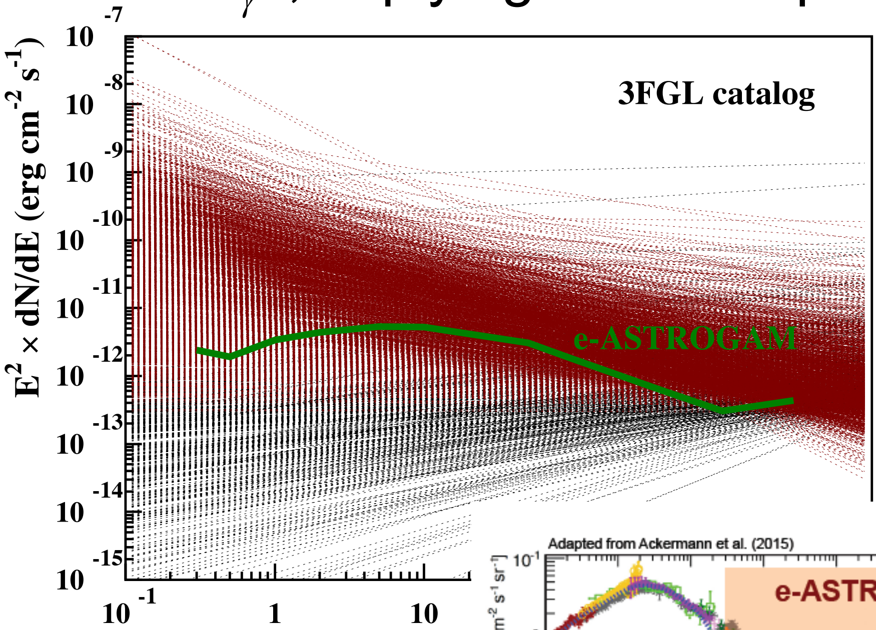
e-ASTROGAM Observatory science

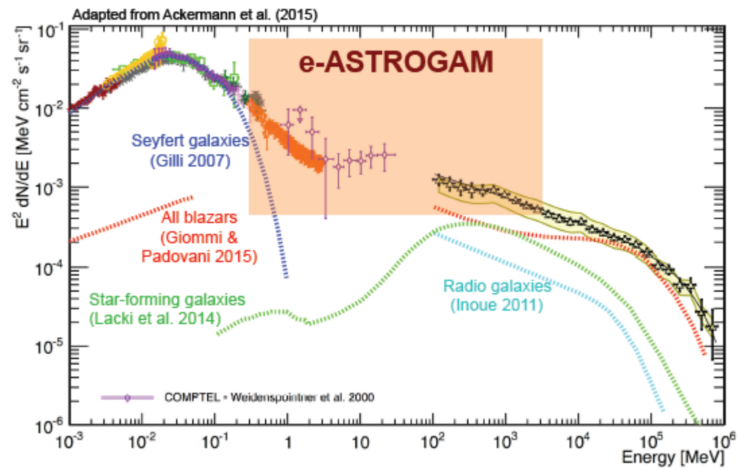
- e-ASTROGAM pointings first focused on core science topics. However a very large number of sources will be detected and monitored.
  - Thousabds of sources both Galactic and extragalactic, many new detections. Therefore, a very large community of astronomical users will benefit from e-ASTROGAM data available for multifrequency studies through GI programme managed by ESA.
- Phenomena and sources
  - characterized by rapid and very rapid variability timescales (sub-second, second, minutes, hours): GRB, AGN flares, …
  - steady
  - unexpected

Type	3 yr	New sources
Total	3000 – 4000	$\sim$1800 (including GRBs)
Galactic	$\sim$ 1000	$\sim$400
MeV blazars	$\sim$ 350	$\sim$ 350
GeV blazars	1000 – 1500	$\sim$ 350
Other AGN ($<$10 MeV)	70 – 100	35 – 50
Supernovae	10 – 15	10 – 15
Novae	4 – 6	4 – 6
GRBs	$\sim$600	$\sim$600

e-ASTROGAM discovery space

- Over 3/4 of the sources from the 3rd *Fermi*-LAT Catalog (3FGL), 2415 sources over 3033, have power-law spectra (E_γ > 100 MeV) steeper than E_γ^{-2}, implying that their peak energy output is below 100 MeV

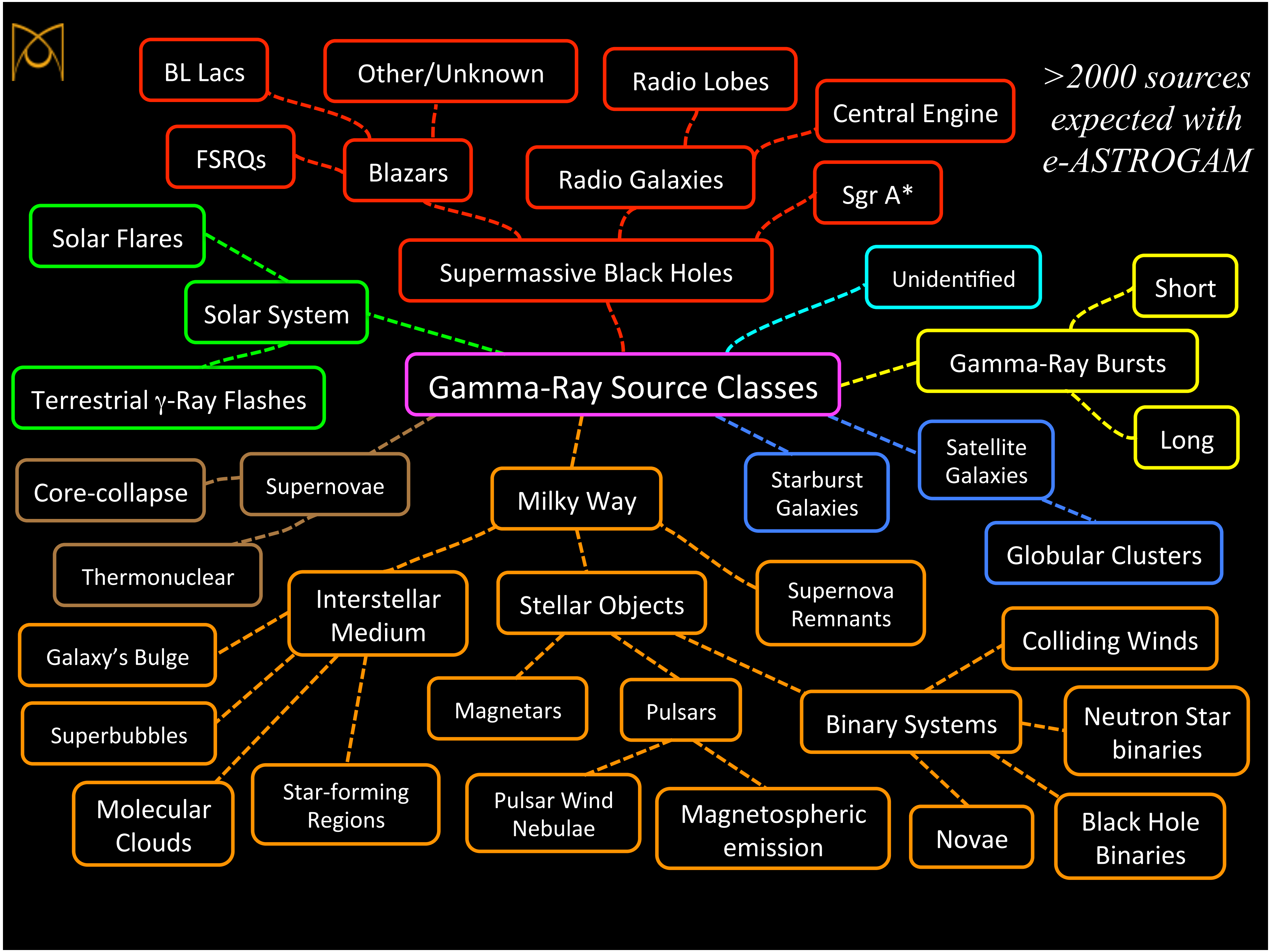




- These includes more than 1200 (candidate) blazars (mostly FSRQ), about 150 pulsars, and nearly **900 unassociated sources**
- Most of these sources will be detected by **e-ASTROGAM** ⇒ large discovery space for new sources and source classes

e-ASTROGAM Observatory science

- Diffuse Galactic gamma-ray background
- Pulsars and millisecond pulsars both isolated and in binaries, whose (pulsed or unpulsed) emission will be observable in a spectral range rich in information to discriminate between different particle acceleration models
- PWNe, for which e-ASTROGAM will obtain crucial data on particle acceleration and propagation
- Magnetars
- Galactic compact binaries, including NS and BHs whose spectral transitions and outbursts will be monitored
- Interstellar shocks
- Propagation over cosmological distances (LIV, ALPs, …)
- Novae
- Solar flares and terrestrial gamma-ray flashes



>2000 sources expected with e-ASTROGAM
Gamma-Ray Source Classes
Supermassive Black Holes
Blazars
BL Lacs
Other/Unknown
FSRQs
Radio Galaxies
Radio Lobes
Central Engine
Sgr A*
Solar Flares
Solar System
Terrestrial γ-Ray Flashes
Unidentified
Short
Gamma-Ray Bursts
Long
Satellite Galaxies
Starburst Galaxies
Globular Clusters
Core-collapse
Supernovae
Thermonuclear
Milky Way
Supernova Remnants
Interstellar Medium
Stellar Objects
Galaxy's Bulge
Superbubbles
Molecular Clouds
Star-forming Regions
Magnetars
Pulsars
Pulsar Wind Nebulae
Magnetospheric emission
Binary Systems
Colliding Winds
Neutron Star binaries
Black Hole Binaries
Novae

First e-ASTROGAM Science Workshop

- Padova, Feb 28 (start at 13h30)/ Mar 1-2 (end on Mar 2 at 14h)
- Setup a team for a white book (possibly w/ AMEGO)
- Contributed talks & posters on multimessenger astrophysics welcome
- Google “agenda infn e-ASTROGAM workshop”

Second e-ASTROGAM Science Workshop

2nd e-ASTROGAM Workshop, joint to AMEGO Workshop: towards a White Book on MeV Gamma-ray Astrophysics

chaired by Alessandro De Angelis (PD), Riccardo Rando (PD), Julie Mc Enery (NASA Goddard)

from Friday, 13 October 2017 at **10:45** to Saturday, 14 October 2017 at **16:45** (Europe/Rome)
at **Munich (Ambiance Rivoli Hotel)**
Albert-Roßhaupter-Straße 22

Description This scientific workshop, open to contributions, continues the discussion on the e-ASTROGAM (and AMEGO) science: exploration of the Universe in the MeV domain. After the 1st workshop held in Padova in February 2017, we aim at finalizing our "White Book" on the opportunities of astronomy, astrophysics and astroparticle physics from observations of cosmic gamma rays in the MeV domain.

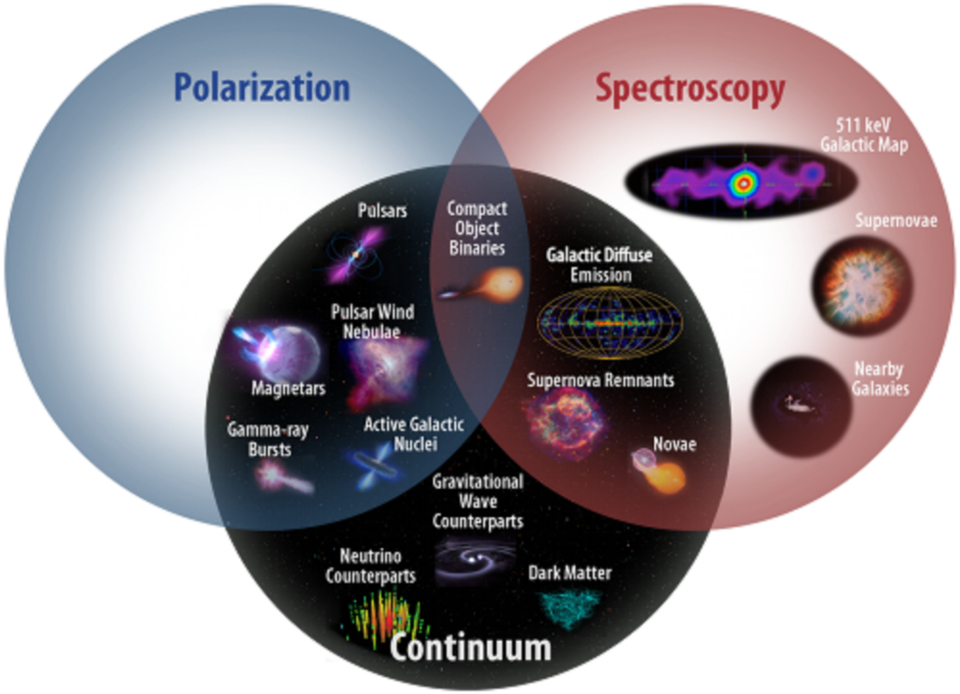
More documentation is available at the homepage http://eastrogam.iaps.inaf.it

The conference fee covers breaks and renting the room and the facilities. 30 rooms are pre-booked at the hotel at a preferential rate (specify eASTROGAM in the reservation).

Participants Solen Balman; Juan Abel Barrio; Denis Bernard; Martina Cardillo; Paolo Cumani; Alessandro De Angelis; Domitilla de Martino; Alberto Dominguez; Yongwei DONG; Michele Doro; Fabio Gargano; J. Eric Grove; Elizabeth Hays; Margarita Hernanz; Jordi Isern; Stefan Lalkovski; Manuela Mallamaci; Dmitry Malyshev; Karl Mannheim; Ajello Marco; Manel Martinez; Mario Nicola Mazziotta; Roberto Mignani; Alexander Moiseev; Aldo Morselli; Uwe Oberlack; Josep M. Paredes; Carlotta Pittori; Martin Pohl; Riccardo Rando; Javier Rico; Pablo Saz Parkinson; Andy Strong; Vincent Tatischeff; Marco Tavani; Roberto Turolla; Roland Walter; Silvia Zane; Andrzej Zdziarski

https://agenda.infn.it/conferenceDisplay.py?confId=13913

AMEGO, the All-sky Medium Energy Gamma-ray Observatory, is an Astrophysics Probe mission concept designed to explore the MeV sky.



AMEGO

AMEGO Science

Understanding Extreme Environments

Astrophysical Jets

Understand the formation, evolution, and acceleration mechanisms in astrophysical jets

Compact Objects

Identify the physical processes in the extreme conditions around compact objects

Dark Matter

Test models that predict dark matter signals in the MeV band

MeV Spectroscopy

Measure the properties of element formation in dynamic systems

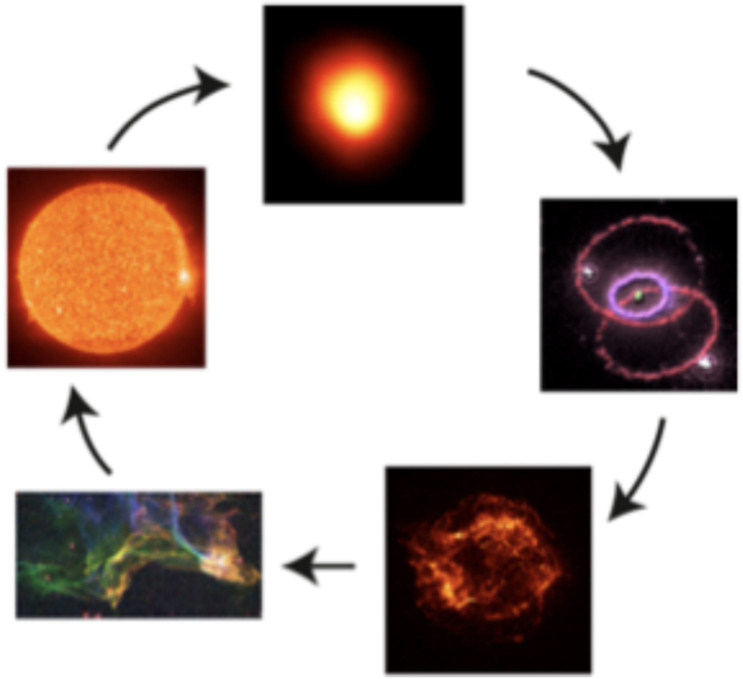
AMEGO

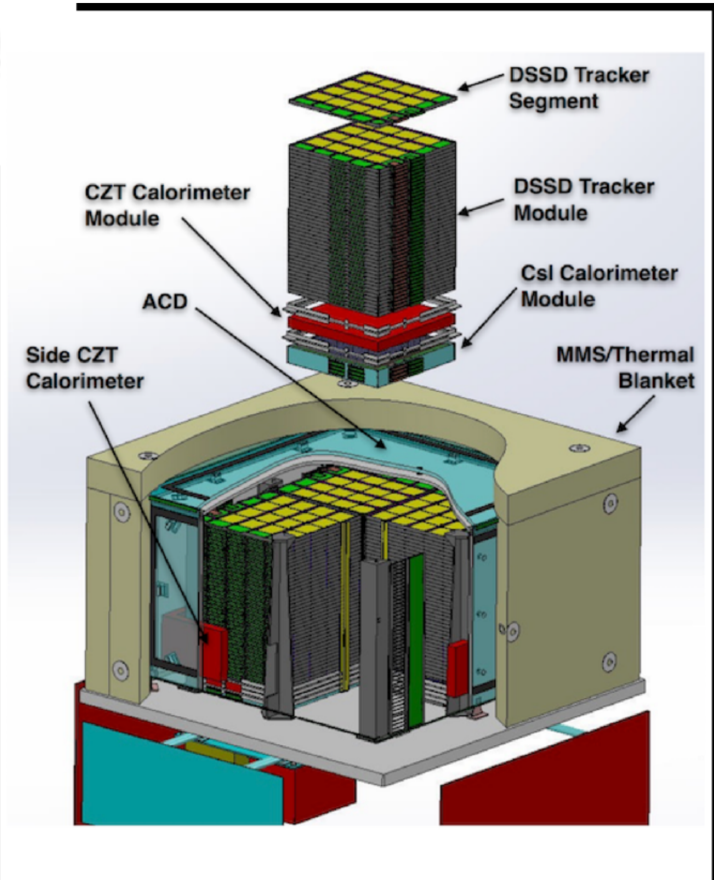
Element Formation in Dynamic Systems

Nuclear lines explore Galactic chemical evolution and sites of explosive element synthesis (SNe)

- Electron-positron annihilation radiation
  - $e^+ + e^-$ -> 2g (0.511 MeV)
- Nucleosynthesis
  - Giants, CCSNe (^{26}Al)
  - Supernovae (^{56}Ni, ^{57}Ni, ^{44}Ti)
  - ISM (^{26}Al, ^{60}Fe)
- Cosmic-ray induced lines
  - Sun
  - ISM

56Ni: 158 keV 812 keV (6 d)
56Co: 847 keV, 1238 keV (77 d)
57Co: 122 keV (270 d)
44Ti: 1.157 MeV (78 yr)
26Al: 1.809 MeV (0.7 Myr)
60Fe: 1.173, 1.332 MeV (2.6 Myr)





AMEGO: All-sky Medium Energy Gamma-ray Observatory

Tracker

Incoming photon undergoes pair production or Compton scattering. Measure energy and track of electrons and positrons

- 60 layer DSSD, spaced 1 cm
- Strip pitch 0.5mm

CZT Calorimeter

Measures location and energy of Compton scattered photons, and head of the shower for pair evens

- Array of 0.6x0.6 x 2cm vertical CdZnTe bars

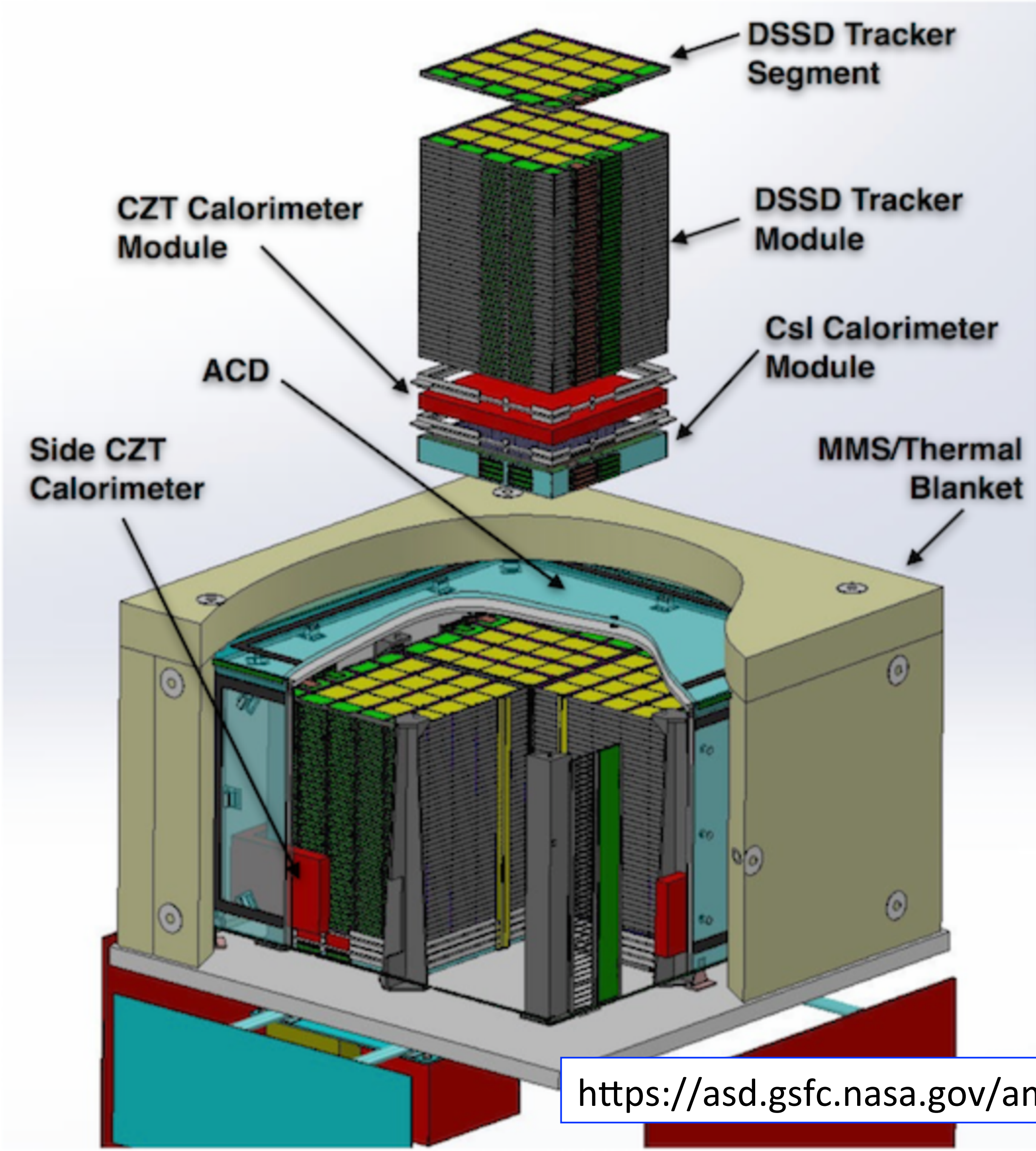
CsI Calorimeter

Extends upper energy range

- 6 planes of 1.5cm x 1.5 cm CsI (Tl) bars

Instrument concept:

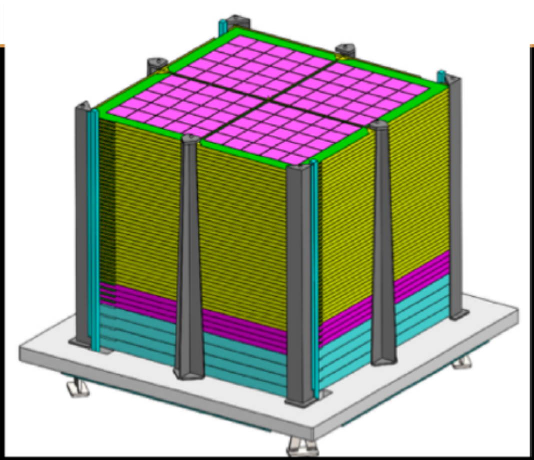
- Maximized performance in 1 MeV – 100 MeV range, with full range 0.2 MeV – 10 GeV
- Simplicity, long-term (~10 years) reliability, max use of already space-qualified technology
- Sensitive to both γ-ray interactions: pair production and Compton scattering
- Minimized amount of passive elements in detecting zone of the instrument (no passive γ-ray converters as in LAT)
- Use fine segmentation of all detecting elements to provide the best particle tracking and event identification



https://asd.gsfc.nasa.gov/amego/

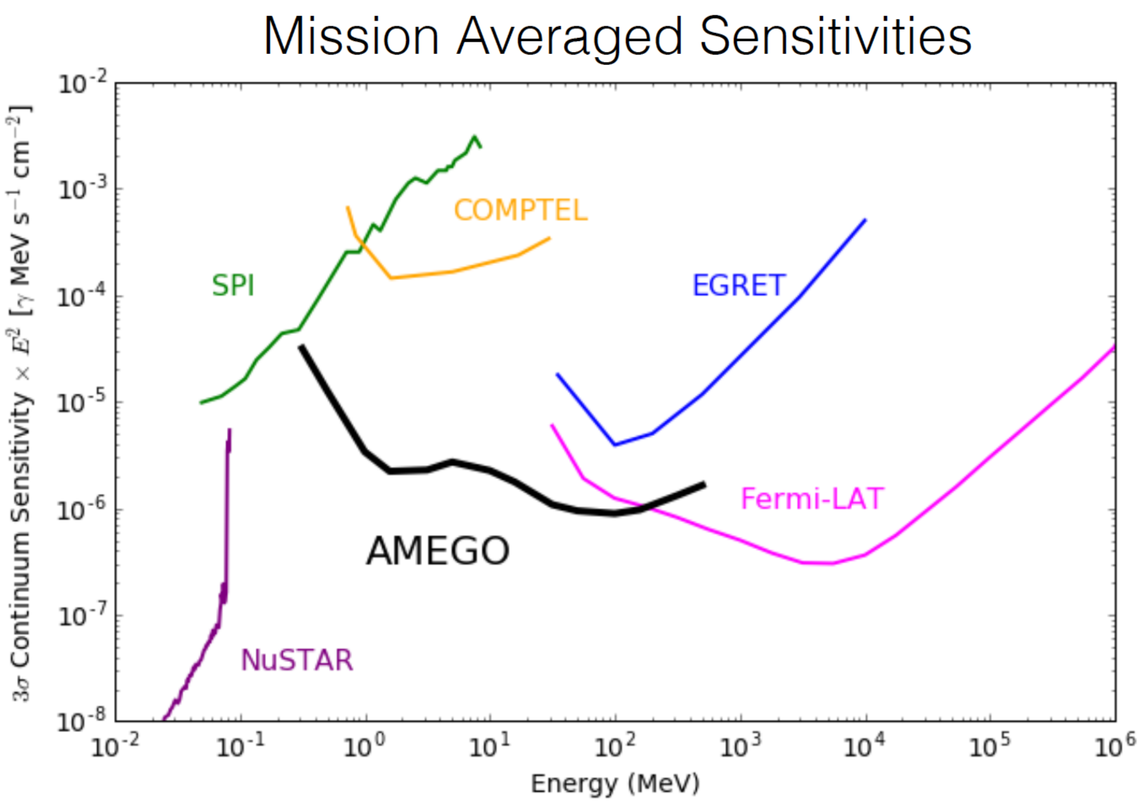
AMEGO Instrument Summary

Energy Range	300 keV -> 10 GeV
Angular resolution	3° (3 MeV), 6° (10 MeV), 2° (100 MeV)
Energy resolution	<1% (< 1 MeV), 1-5% (1-100 MeV), ~10% 91 GeV)
Field of View	2.5 sr (20% of the sky)
Line sensitivity	$<6\times10^{-6}$ ph cm^{-2} s^{-1} for the 1.8 MeV ^{26}Al line in a 1-year scanning observation
Polarization sensitivity	<20% MDP for a source 1% the Crab flux, observed for 10^6 s
Continuum sensitivity (MeV cm^{-2} s^{-1})	3×10^{-6} (1 MeV), 2×10^{-6} (10 MeV), 8×10^{-7} (100 MeV)



AMEGO

AMEGO Capabilities



Summary

- **The almost unexplored MeV / GeV gamma-ray band is one of the richest energy domains of astrophysics**
- **ASTROGAM/AMEGO will fill the gap and they will be essential observatories to study the extreme transient sky in the era of astronomy's new messengers**
- **ASTROGAM/AMEGO payloads are innovative in many respects, but the technology is ready**

AMEGO-X

AMEGO-X — ALL-SKY MEDIUM ENERGY GAMMA-RAY OBSERVATORY EXPLORER

Home Science Instrument References Conferences Contacts

About AMEGO-X

AMEGO-X, the All-sky Medium-Energy Gamma-ray Observatory eXplorer, is a multimessenger astronomy mission concept proposed to the 2021 MIDEX Announcement of Opportunity, to be launched no later than Dec. 2028.

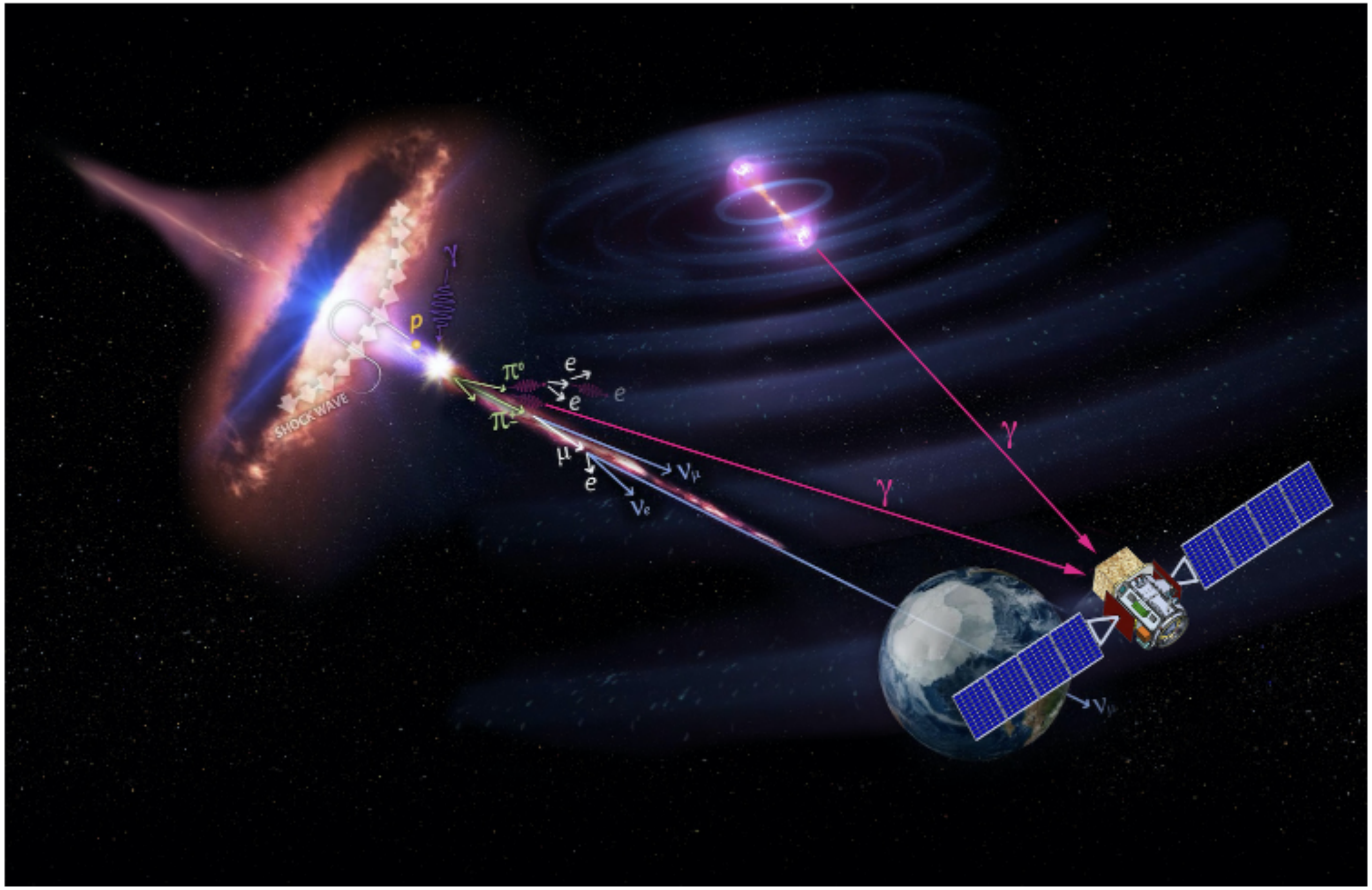
Multimessenger astrophysics (*New Messengers New Physics*) is a priority theme of the Astro2020 Decadal Survey report, and the highest priority for space missions on small and medium scale platforms. This science is poised to revolutionize our understanding of the extreme universe. Data from AMEGO-X will answer the following questions pertaining to all cosmic messengers:

- Do supermassive black holes accelerate cosmic rays and produce neutrinos?
- How do binary neutron star mergers produce relativistic jets and what is the structure of those jets?
- Where are the cosmic rays accelerated in our Galaxy?

To answer these questions, AMEGO-X will be sensitive to gamma-ray photons in the energy range from about 100 keV to 1 GeV and transient events down to about 25 keV. During its three-year baseline mission, AMEGO-X will observe nearly the entire sky every two orbits, building up a sensitive all-sky map of gamma-ray sources and emission. Want to learn more? Check out the list of publications or see when and where to find us at upcoming conferences.

https://asd.gsfc.nasa.gov/amego-x/index.html

AMEGO-X



Multimessenger Astrophysics

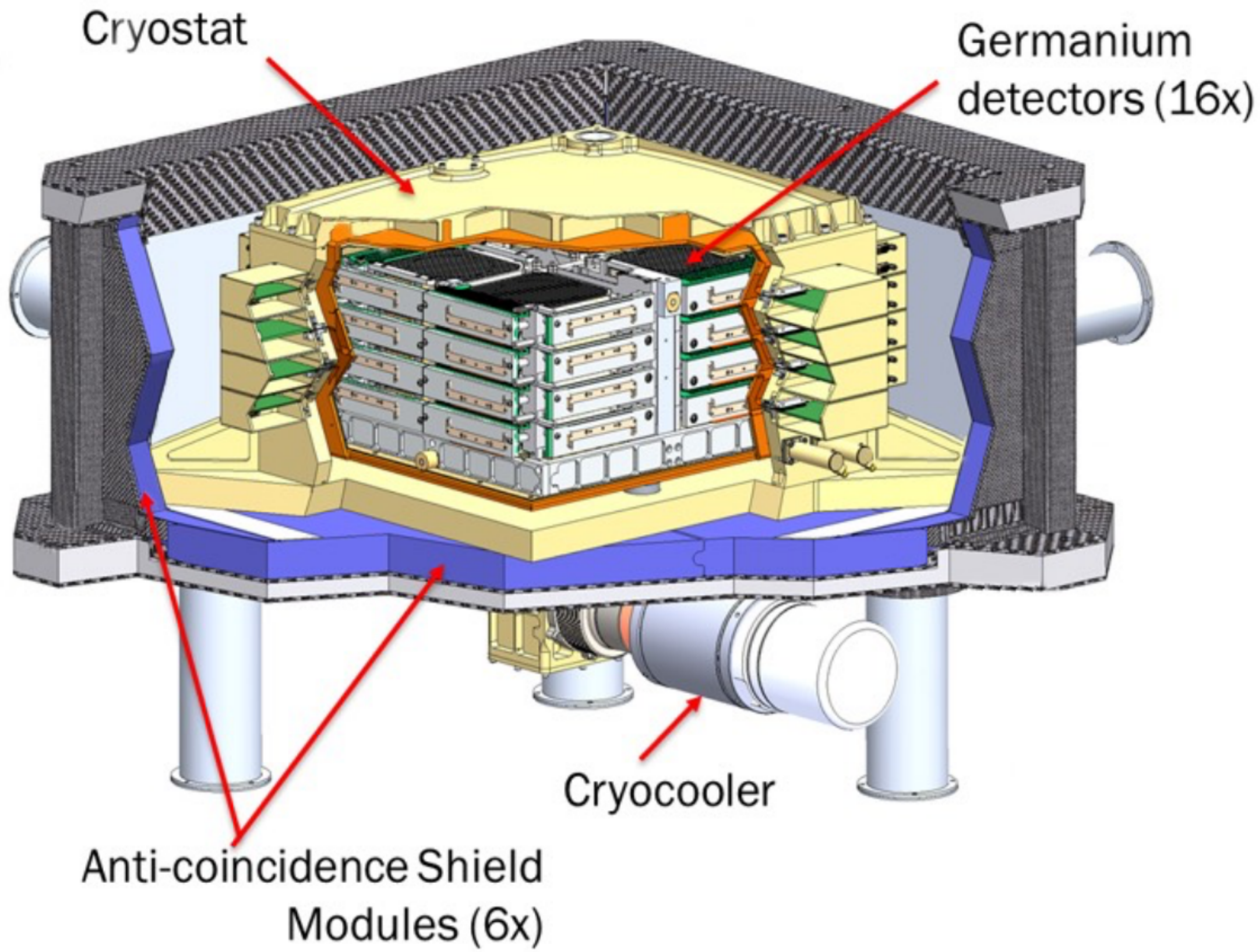
AMEGO-X

Continuum Astrophysics

COSI

https://cosi.ssl.berkeley.edu/

COSI



https://cosi.ssl.berkeley.edu/

COSI

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

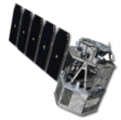
COSI
A Gamma-ray
Space Explorer

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

COSI

COSI Science Goals

COSI
A Gamma-ray Space Explorer



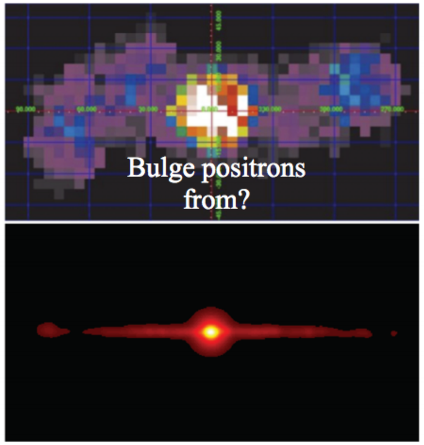
Revolutionizing our understanding of creation and destruction of matter in our Galaxy and beyond

Energy range: 0.2-5 MeV γ-rays

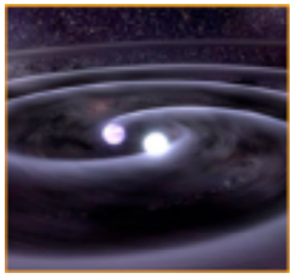
1. Uncover the origin of Galactic positrons
2. Reveal Galactic element formation
3. Gain insight into extreme environments with polarization
4. Probe the physics of multi-messenger events

Goal 1: Positrons

511 keV with INTEGRAL (Bouchet+10)



Goal 4: MMA



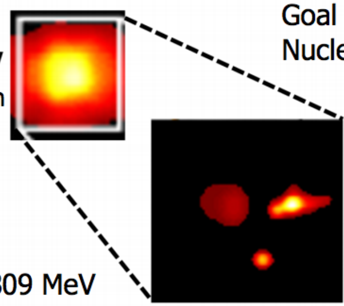
Goal 3: Polarization

Cygnus region

Goal 2: Nucleosynthesis

Now

Simulation with COMPTEL



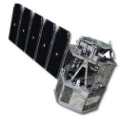
COSI

^{26}Al 1.809 MeV

COSI

COSI Science Goals

COSI
A Gamma-ray Space Explorer



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

1. Uncover the origin of Galactic positrons

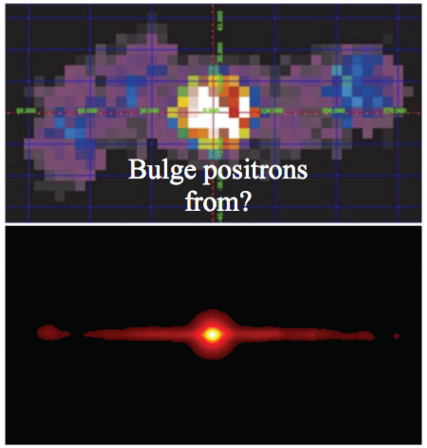
- Strong 511 keV signature at the center of the Milky Way (10^{-3} ph cm^{-2} s^{-1})

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

- Source of the positrons:
  - Disk emission may be explained by positrons from β^+ decay of stellar nucleosynthesis products (e.g. Al-26, Ti-44)
  - Origin of bulge positrons is unknown
  - Other candidates: Co-56, DM, LMXRB, GRBs, SgrA*, …

Goal 1: Positrons

511 keV with INTEGRAL (Bouchet+10)



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

COSI

COSI Science Goals

COSI
A Gamma-ray
Space Explorer

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

2. Reveal Galactic element formation

- Study Galactic chemical evolution through products of SNe nucleosynthesis

- Integrated history over ~Myr
    - Al-26 (1809 keV; half-life: 0.7 Myr)
    - Fe-60 (1173 keV, 1332 keV; half-life: 2.6 Myr)

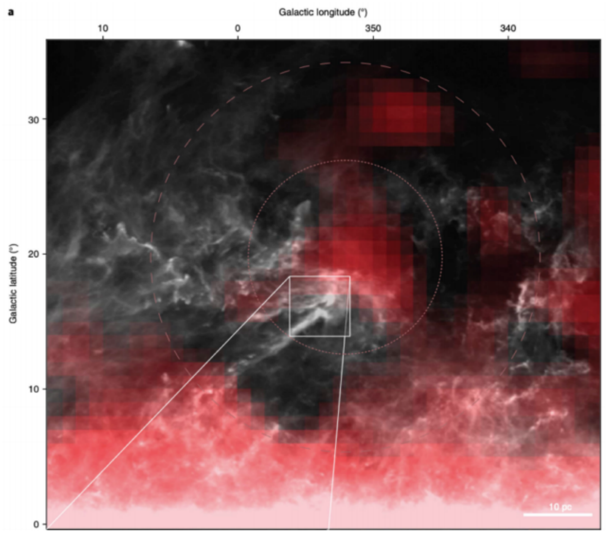
- Young SN remnants in last ~100 years
    - Ti-44 (1157 keV; half-life: 60 years)

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

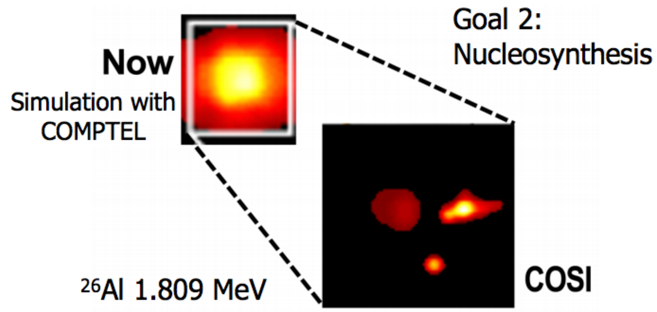
Forbes et al. 2021, Figure 1

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

Gray: Planck dust map



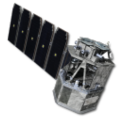
Cygnus region



COSI

COSI Science Goals

COSI
A Gamma-ray Space Explorer

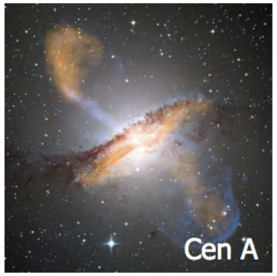


Revolutionizing our understanding of creation and destruction of matter in our Galaxy and beyond

3. Gain insight into extreme environments with polarization

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

Goal 3: Polarization



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

COSI

CCT: COSI-APRA (balloon) overview

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A Gamma-ray
Space Explorer

Balloon-borne compact Compton 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
- FOV: 25% of the sky (~π steradian)

COSI

COSI's GeD Array

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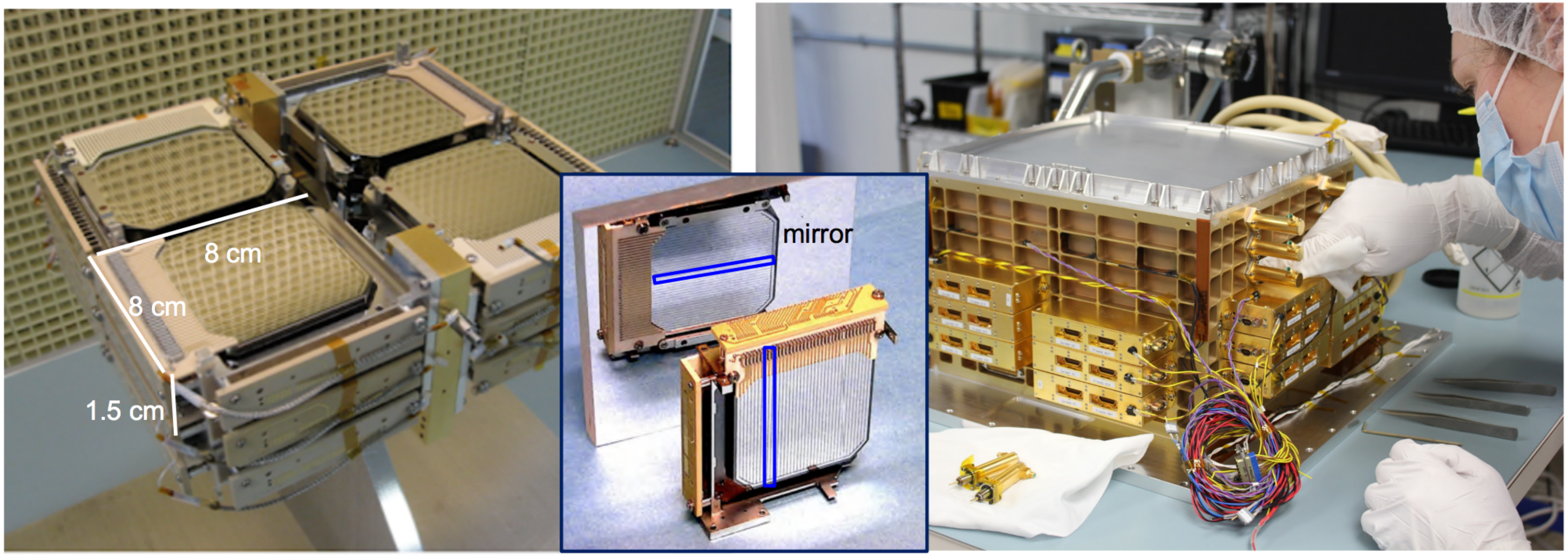
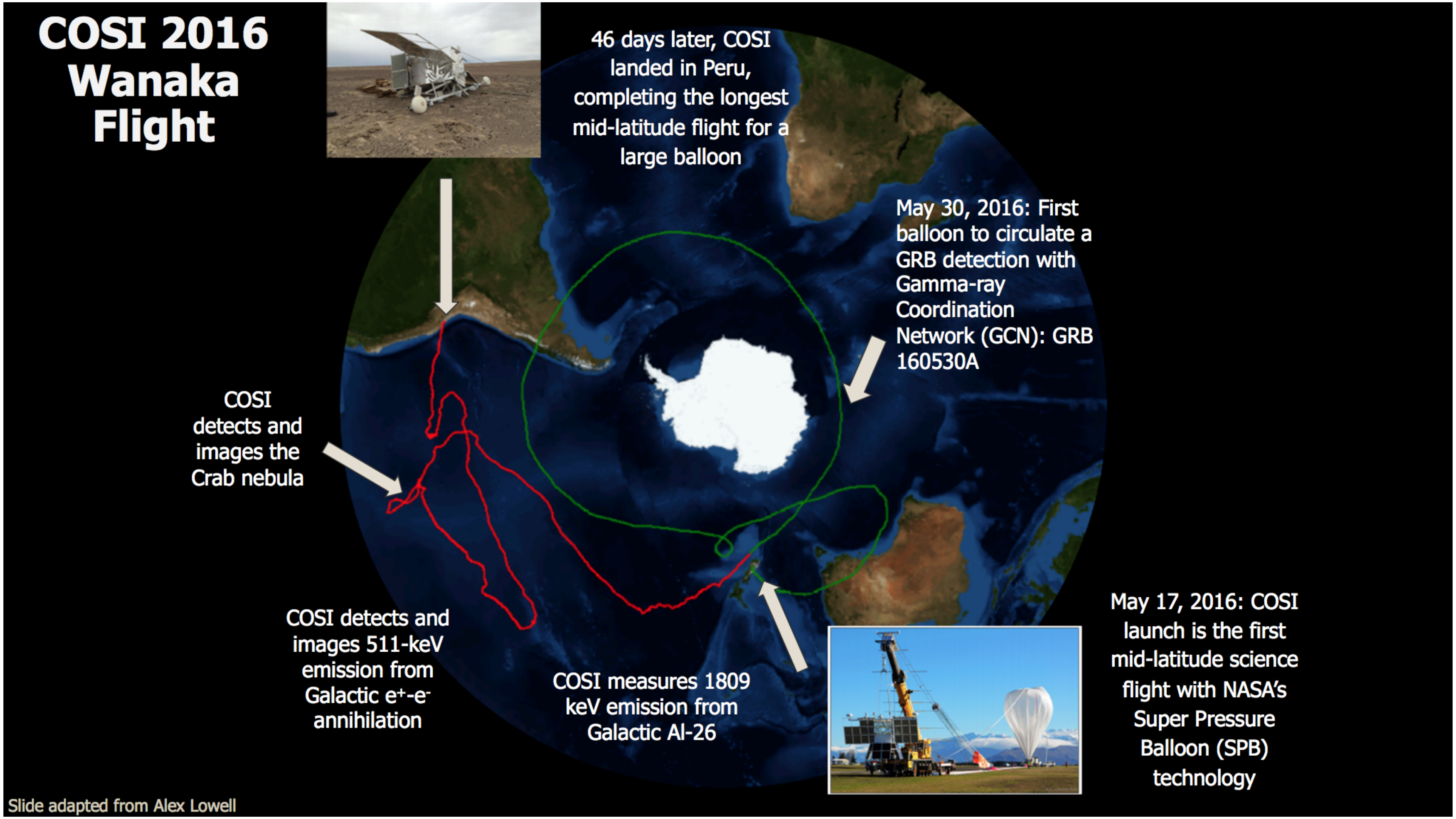
A Gamma-ray
Space Explorer



- 12 HPGe cross-strip detectors
- 12 x 37 strips x 2 sides = 888 strips of 2 mm pitch
- 3D position resolution of 2 x 2 x 0.5 mm^3

- Detectors housed in aluminum cryostat
- Operating conditions: ~84 K, 10^{-6} Torr

COSI



COSI 2016 Wanaka Flight
46 days later, COSI landed in Peru, completing the longest mid-latitude flight for a large balloon
May 30, 2016: First balloon to circulate a GRB detection with Gamma-ray Coordination Network (GCN): GRB 160530A
COSI detects and images the Crab nebula
COSI detects and images 511-keV emission from Galactic e+-e- annihilation
COSI measures 1809 keV emission from Galactic Al-26
May 17, 2016: COSI launch is the first mid-latitude science flight with NASA's Super Pressure Balloon (SPB) technology
Slide adapted from Alex Lowell

COSI

COSI 2016 flight: Science resume

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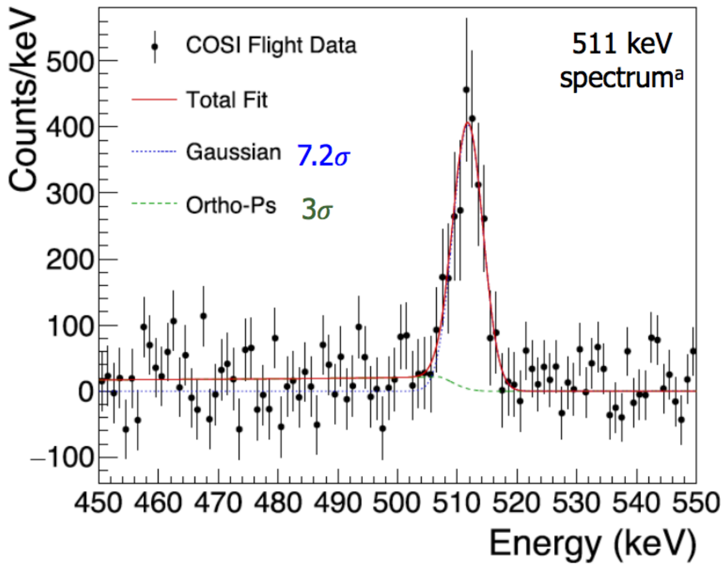
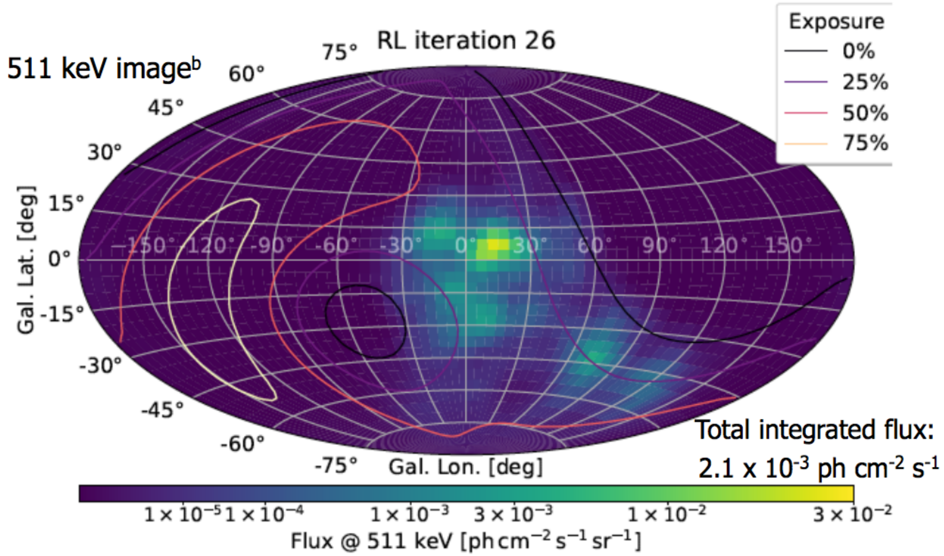
A Gamma-ray
Space Explorer

1. Uncover the origin of Galactic positrons





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, The Astrophysical Journal, 895, 44
[b]Siegert et al. 2020, The Astrophysical Journal, 897, 45

COSI

Measurement of Galactic Al-26 in the COSI 2016 Flight

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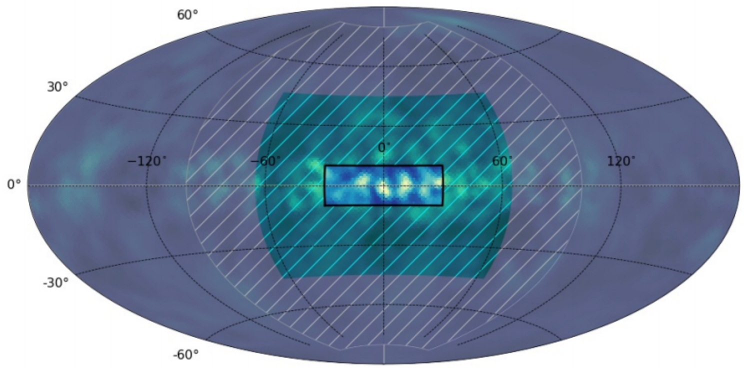
Beechert (2021) ICRC 2021 proceedings: https://arxiv.org/abs/2109.10365; Beechert et al. (2021), submitted to ApJ

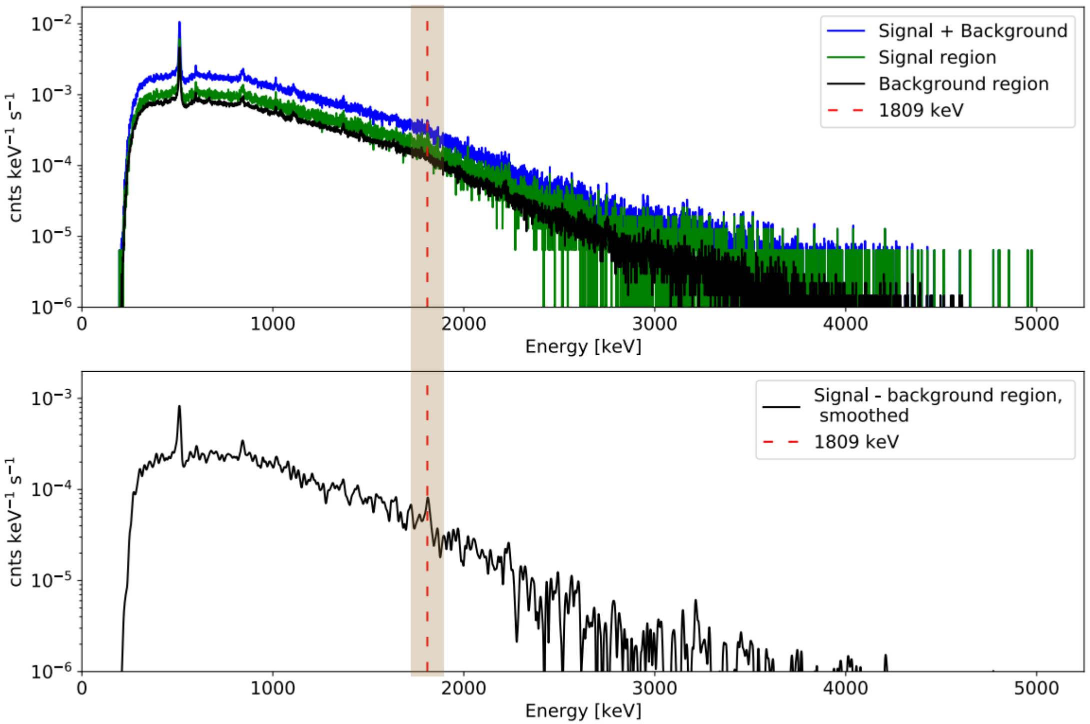
Pointing cuts over the SPI 1.8 MeV image
(Bouchet et al. 2015)



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

Signal region exposure time ~156 ks
BG region exposure time ~1356 ks

Flight spectra

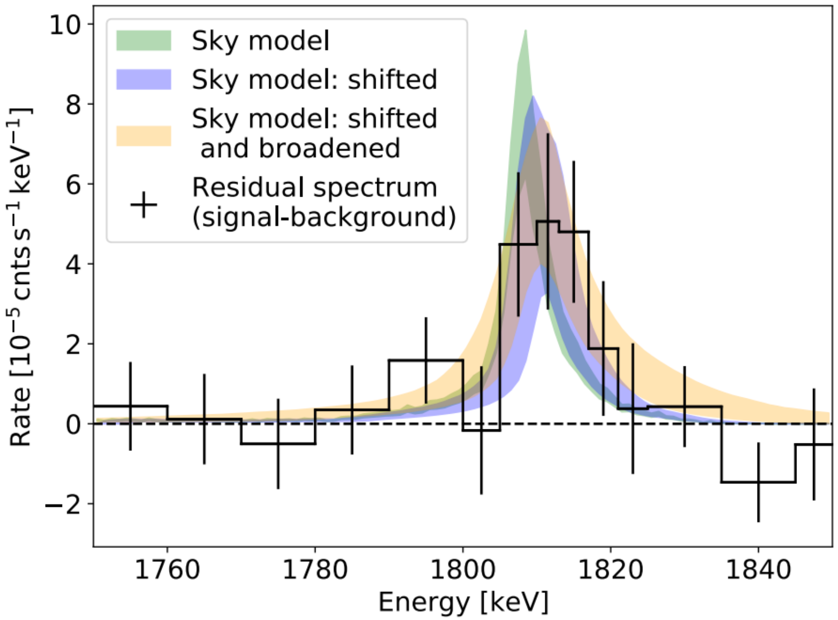


COSI

COSI 2016 flight: Science resume

COSI
A Gamma-ray
Space Explorer

2. Reveal Galactic element formation



Measurement of Galactic Al-26

The Bulge	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 Al-26 in the Inner Galaxy

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

COSI

COSI 2016 flight: Science resume

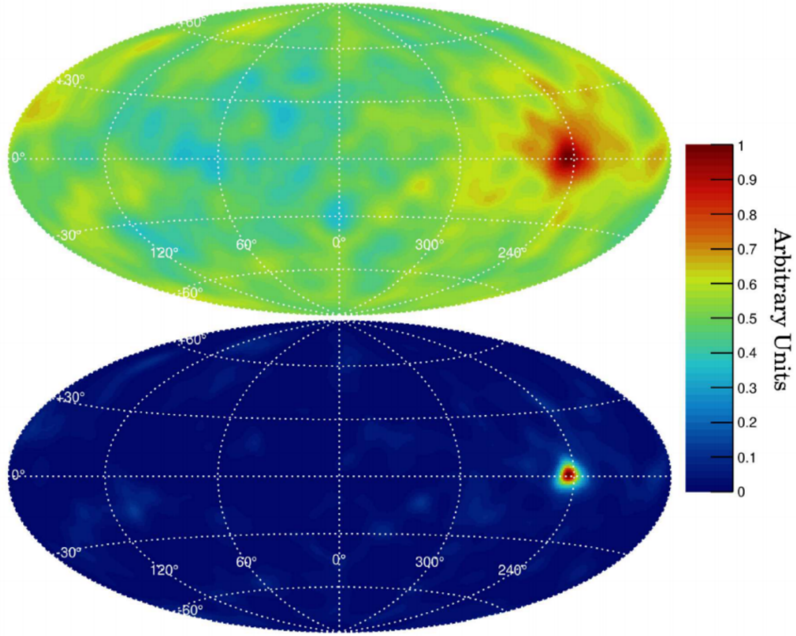
COSI
A Gamma-ray
Space Explorer

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]



COSI images[a] of GRB160530A (ℓ = 243.4°, b = 0.4°)
Top: zero iterations (back-projection of Compton cones),
Bottom: ten iterations of LM-MLEM deconvolution algorithm.

4. Probe the physics of multi-messenger events

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

[a]Lowell (2017), University of California, Berkeley

COSI

COSI: A Gamma-ray Space Explorer

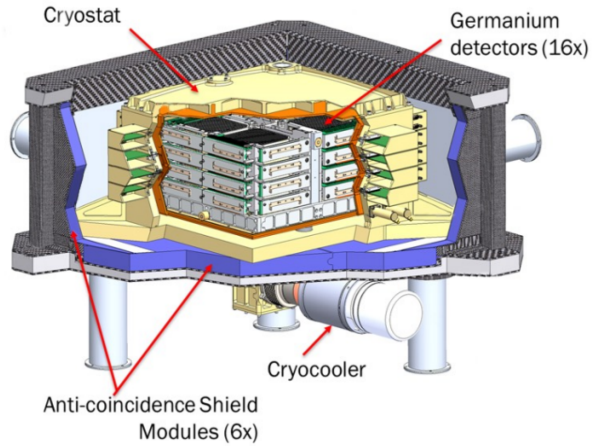
COSI
A Gamma-ray
Space Explorer

Tomsick (2021) ICRC 2021 proceedings: https://arxiv.org/abs/2109.10403
Astro2020 APC White Paper: https://arxiv.org/pdf/1908.04334.pdf

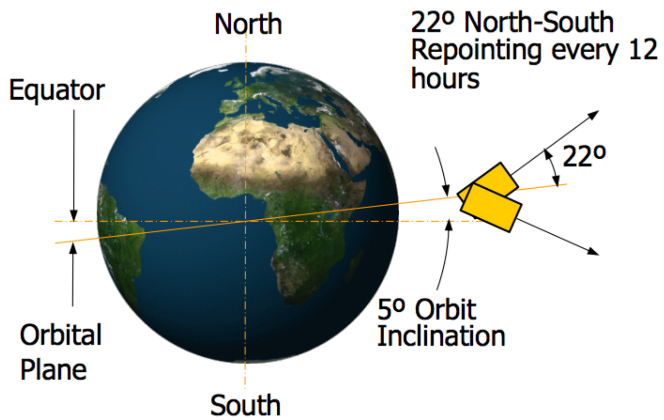
Oct 18, 2021
RELEASE 21-134

NASA Selects Gamma-ray Telescope to Chart Milky Way Evolution

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



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



COSI

COSI requirements

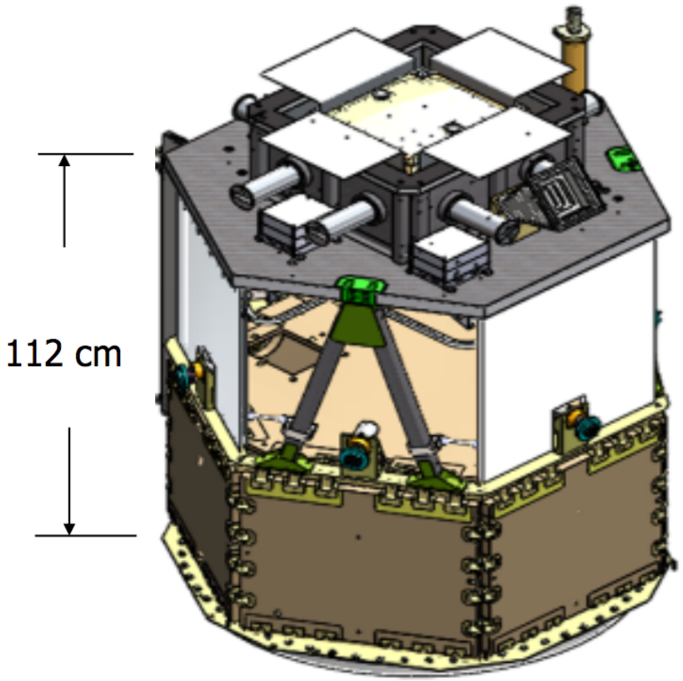
COSI
A Gamma-ray
Space Explorer

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

COSI

Overview of Instrument and Requirements

COSI
A Gamma-ray
Space Explorer



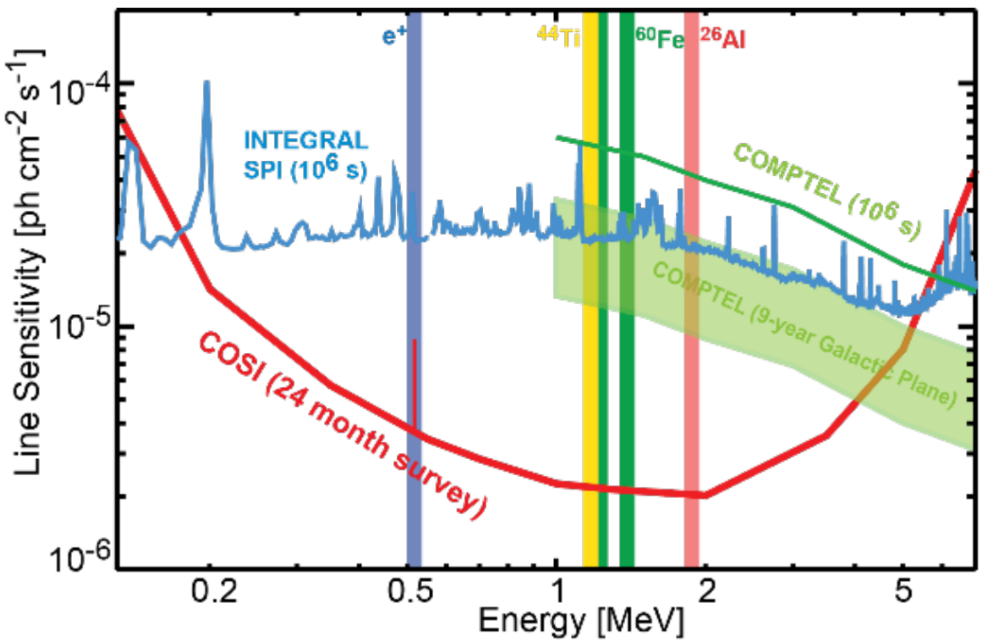
COSI instrument/payload and spacecraft

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

COSI

Improvement over previous and current missions

COSI
A Gamma-ray
Space Explorer



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

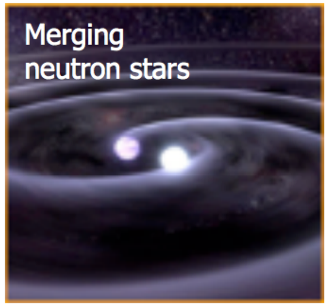
COSI

Multi-messenger sources

COSI
A Gamma-ray
Space Explorer

I. Neutron star merger (NSM)

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



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

→ Over its 2-year prime mission, COSI will

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

COSI

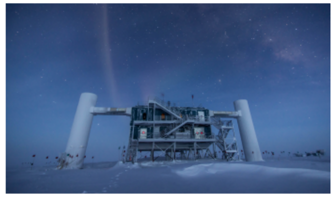
Multi-messenger sources

COSI
A Gamma-ray
Space Explorer

II. High-energy neutrino

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

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY



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

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

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

COSI

Multi-messenger sources

COSI
A Gamma-ray
Space Explorer

III. Nearby SNe

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

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

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

COSI

Summary

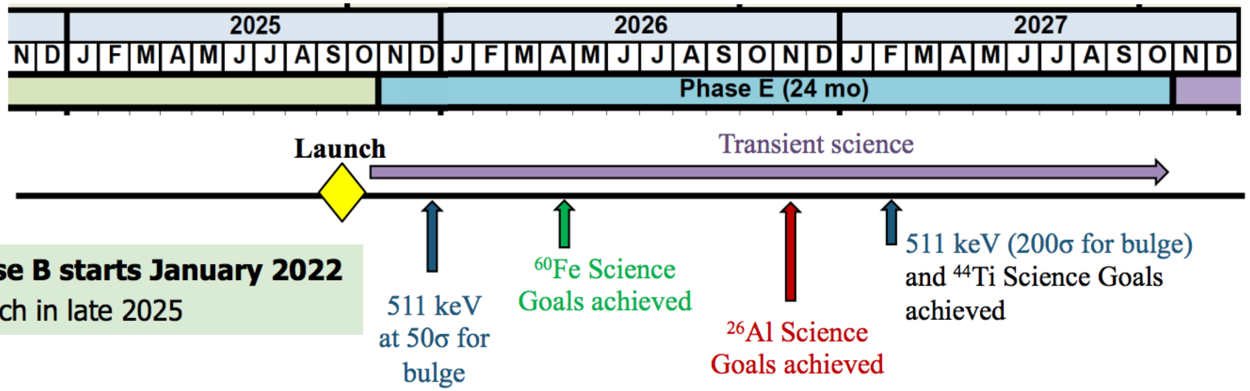
COSI-APRA: CCT in MeV regime

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

COSI: COSI-APRA instrument upgraded to NASA SMEX

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

Phase B starts January 2022
Launch in late 2025



Transient science

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

Emission line science