e-ASTROGAM

at the heart of the extreme Universe

An observatory for the MeV/GeV domain

http://eastrogam.iaps.inaf.it

https://arxiv.org/abs/1611.02232

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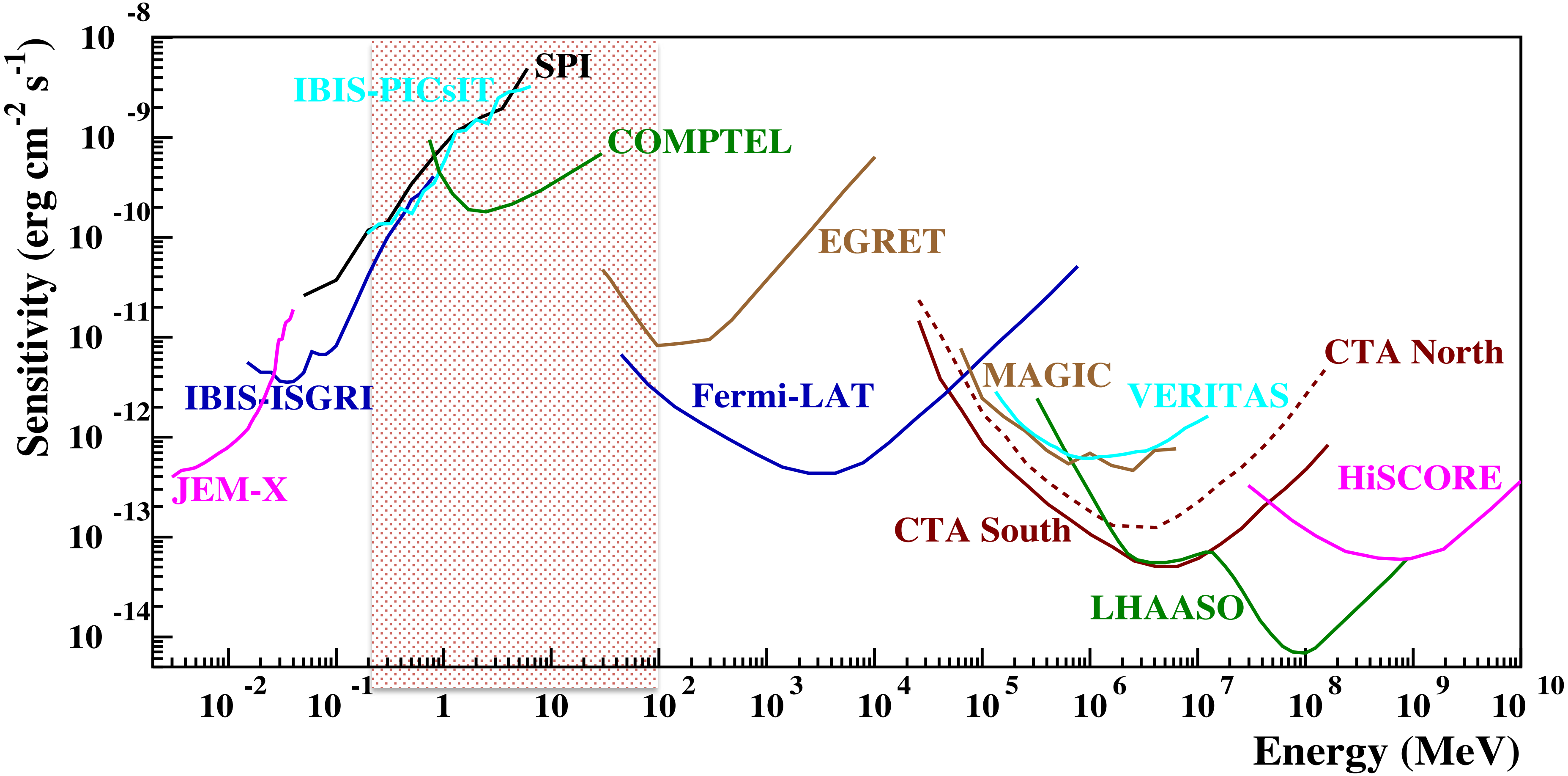
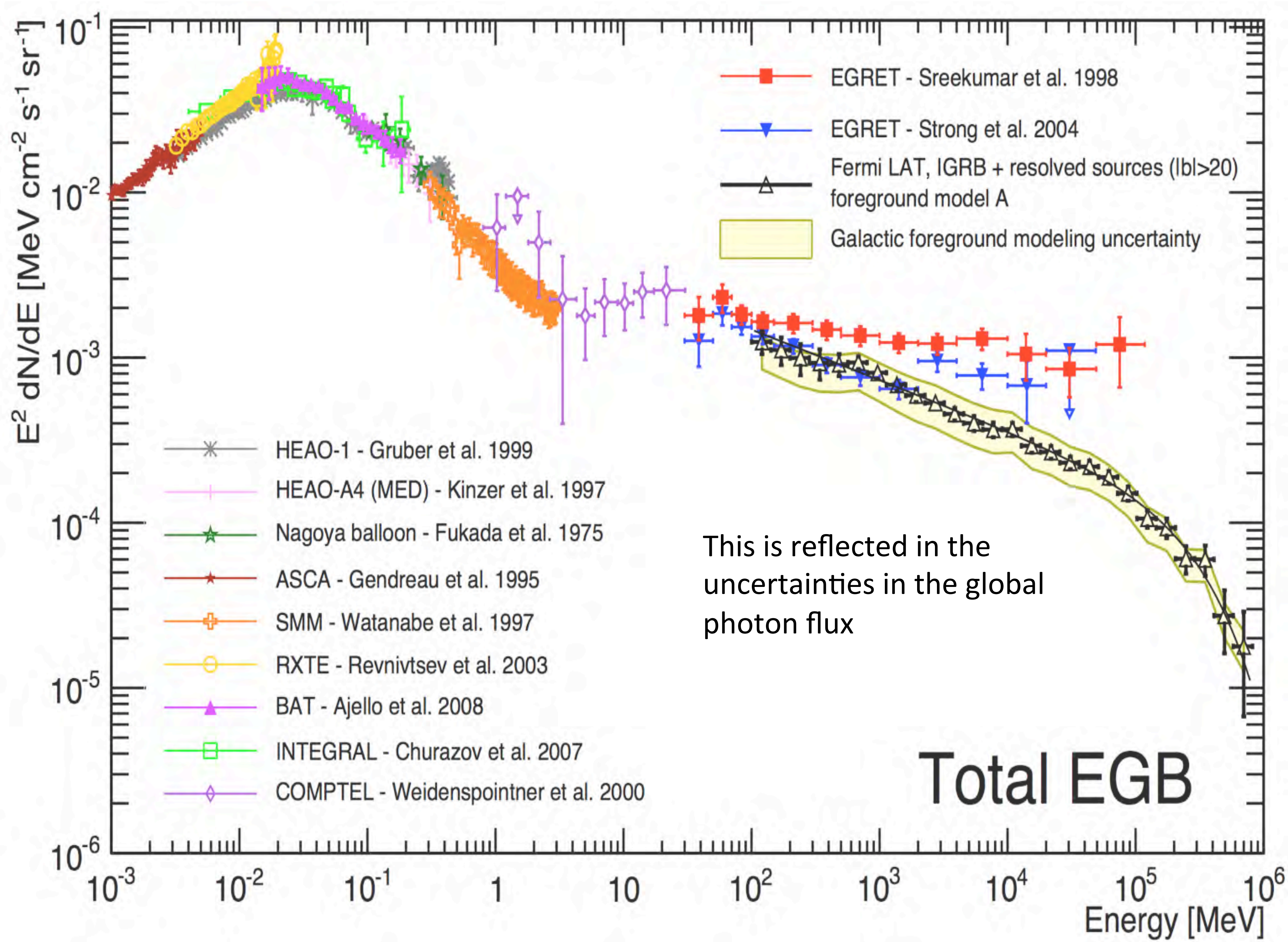
Lisboa, October 2016

The MeV/sub-GeV domain

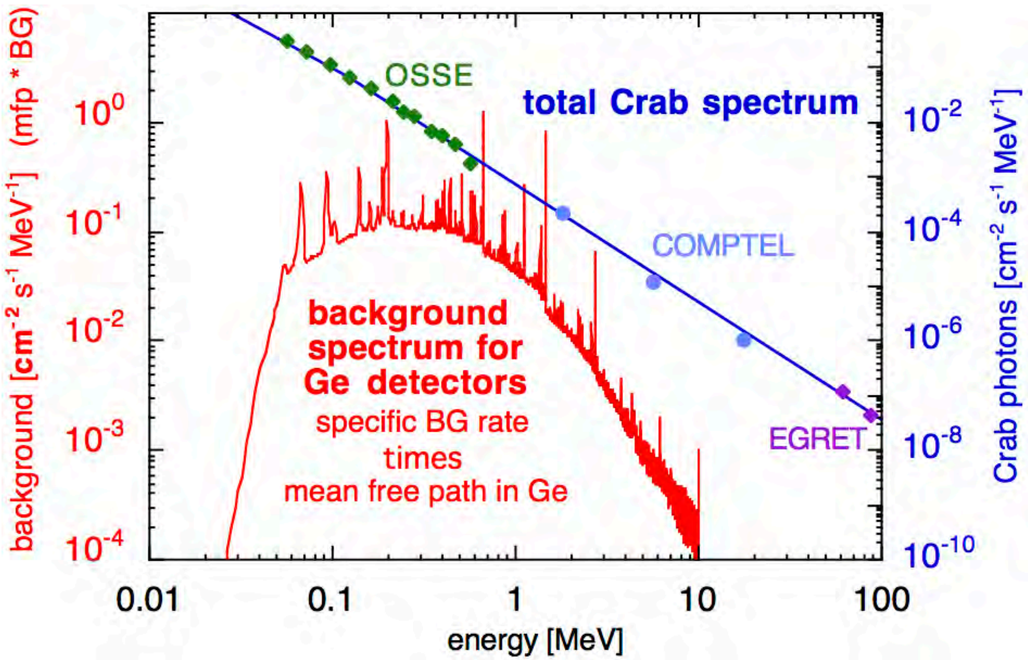


- Worst covered part of the electromagnetic spectrum (only a few tens of steady sources detected so far between 0.2 and 30 MeV)
- Many objects have their peak emissivity in this range (GRBs, blazars, pulsars...)
- Binding energies of atomic nuclei fall in this range, which therefore is as important for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



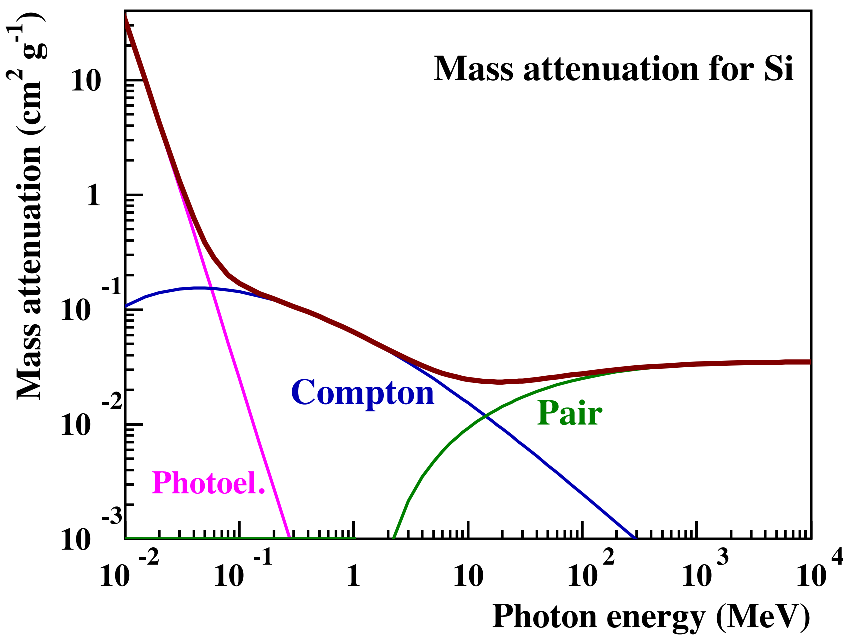
This is reflected in the uncertainties in the global photon flux

Observational challenges



☺ The MeV range is the domain of nuclear γ-ray lines (radioactivity, nuclear collision, positron annihilation, neutron capture)

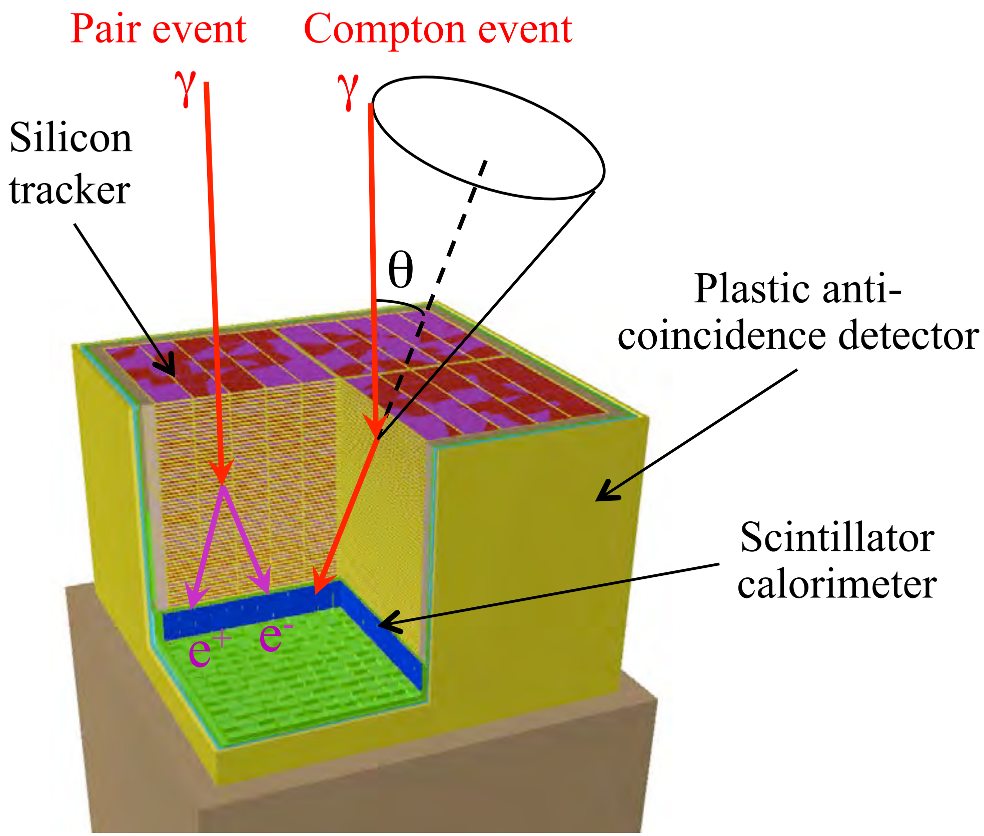
☹ Strong instrumental background from activation of space-irradiated materials

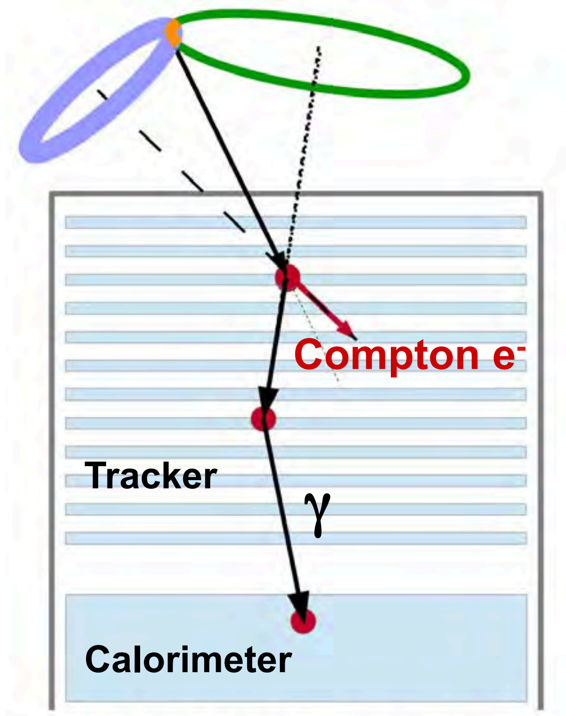


☹ Photon interaction probability reaches a minimum at ~ 10 MeV

☹ Three competing processes of interaction, Compton scattering being dominant around 1 MeV
⇒ complicated event reconstruction

How to measure gamma rays in the MeV-GeV?

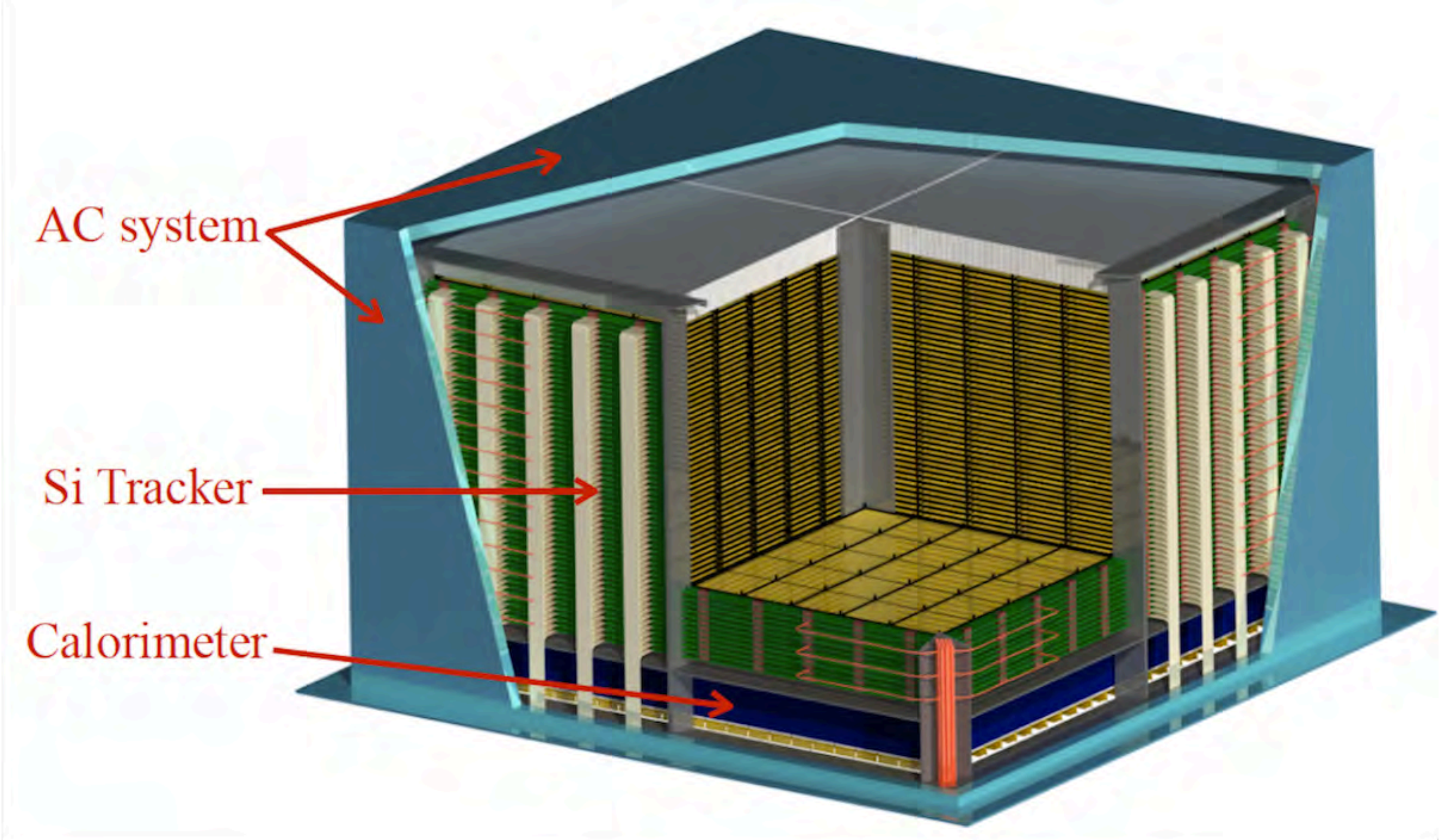




Tracked Compton event

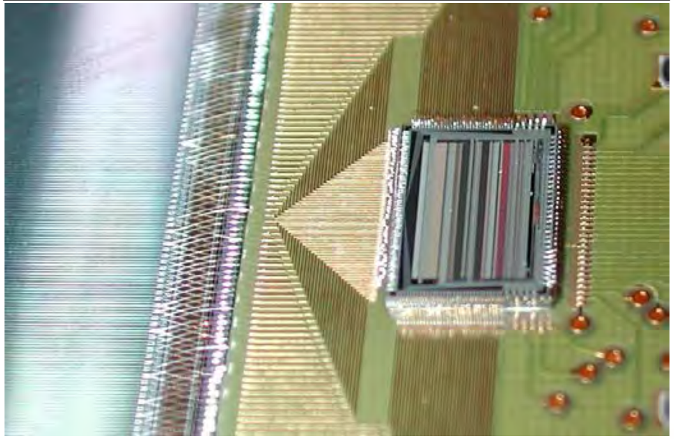
- **Tracker** – Double sided Si strip detectors (DSSDs) for excellent spectral resolution and fine 3-D position resolution ($1 m^2$, 500 μm thick, 0.3 Xo in total)
- **Calorimeter** – High-Z material for an efficient absorption of the scattered photon ⇒ CsI(Tl) scintillation crystals readout by Si drift 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

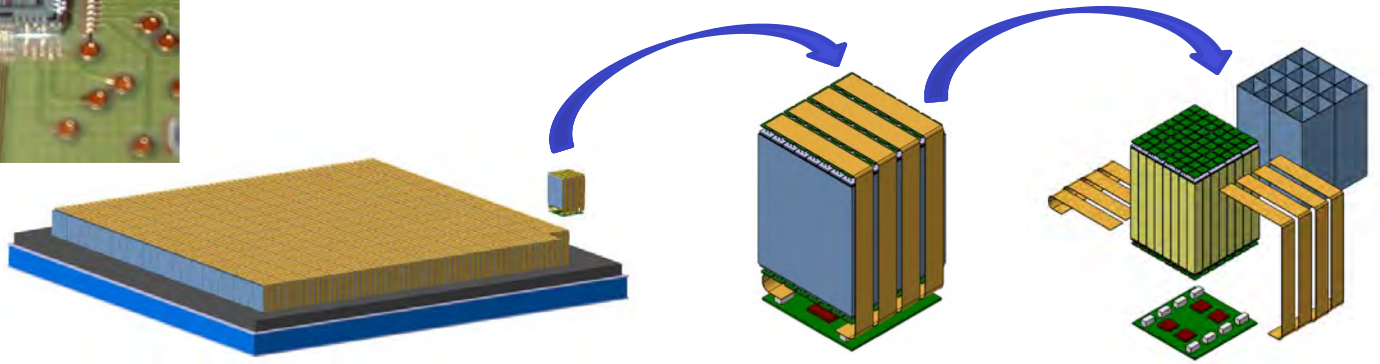


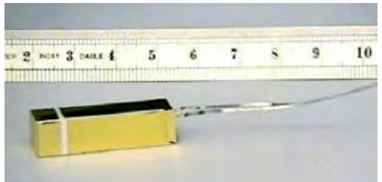
e-ASTROGAM: the payload

Detail of the detector-ASIC bonding in the AGILE Si Tracker



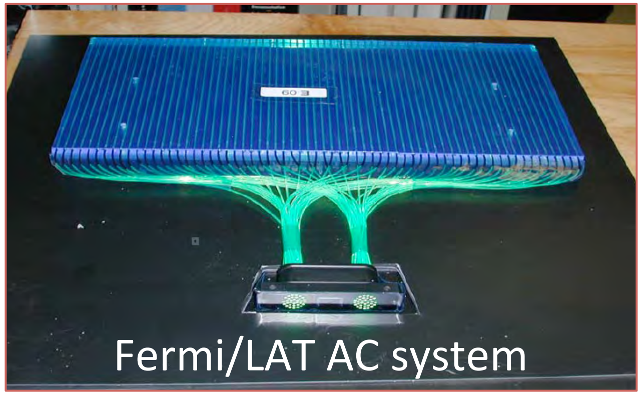
- **Tracker**: 56 layers of 4 times 5×5 DSSDs (5 600 in total) of 500 μm thickness and 240 μm pitch
- DSSDs bonded strip to strip to form 5×5 ladders
- Light and stiff mechanical structure
- Ultra low-noise front end electronics





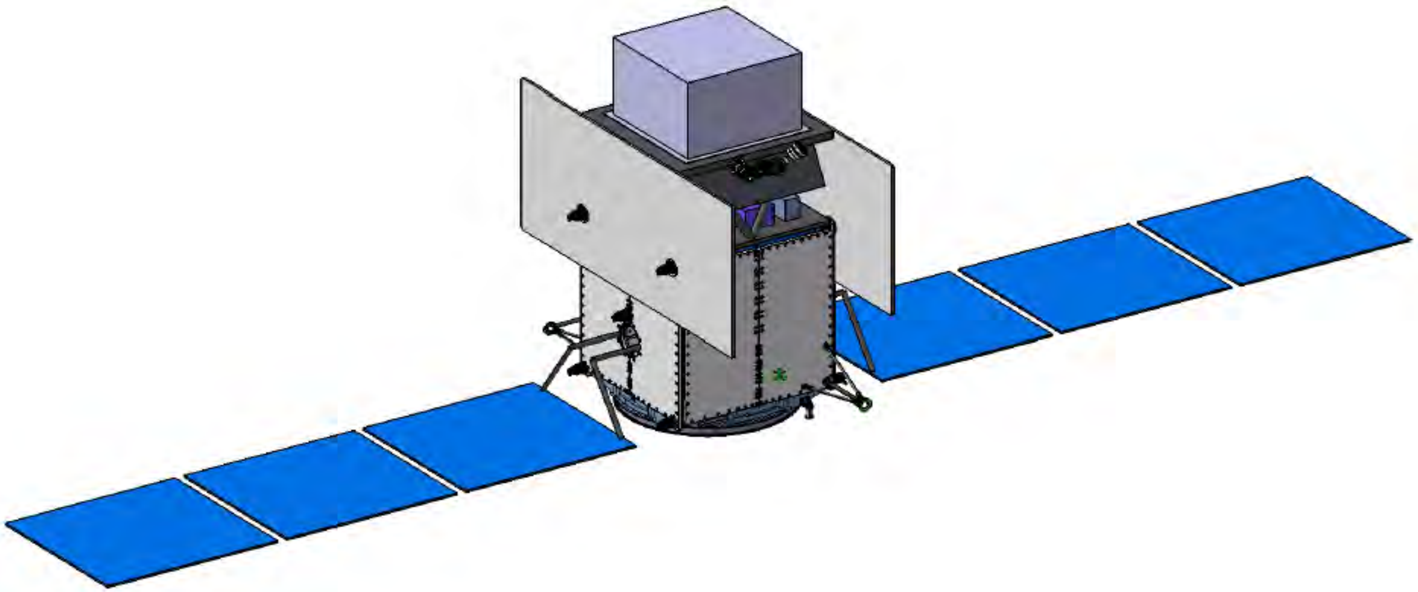
PICSiT CsI(Tl) pixel

- **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…



Fermi/LAT AC system

e-ASTROGAM: spacecraft & satellite



Mass of the satellite: ~2.5 ton
Mass of the payload: ~900 kg
Power consumption: ~1100 W

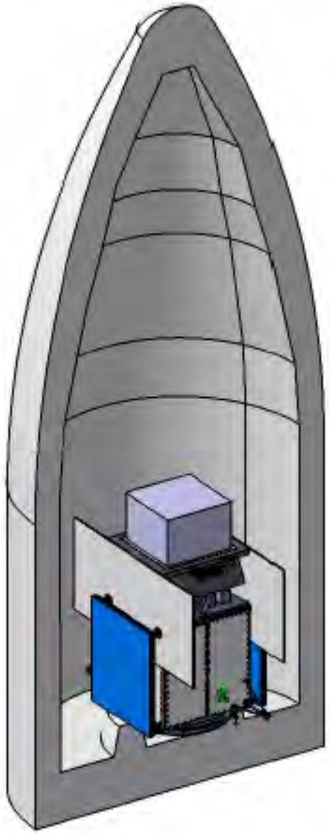
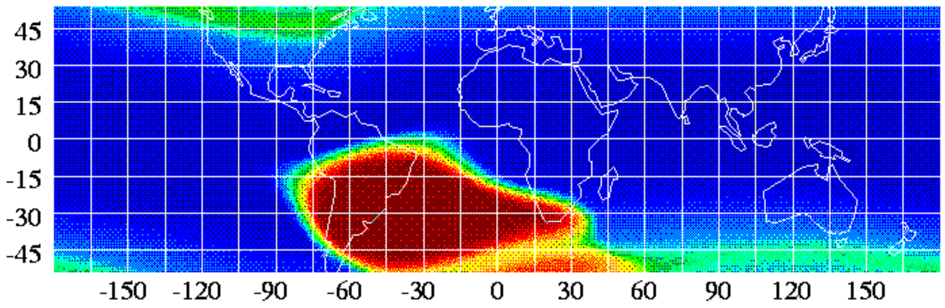
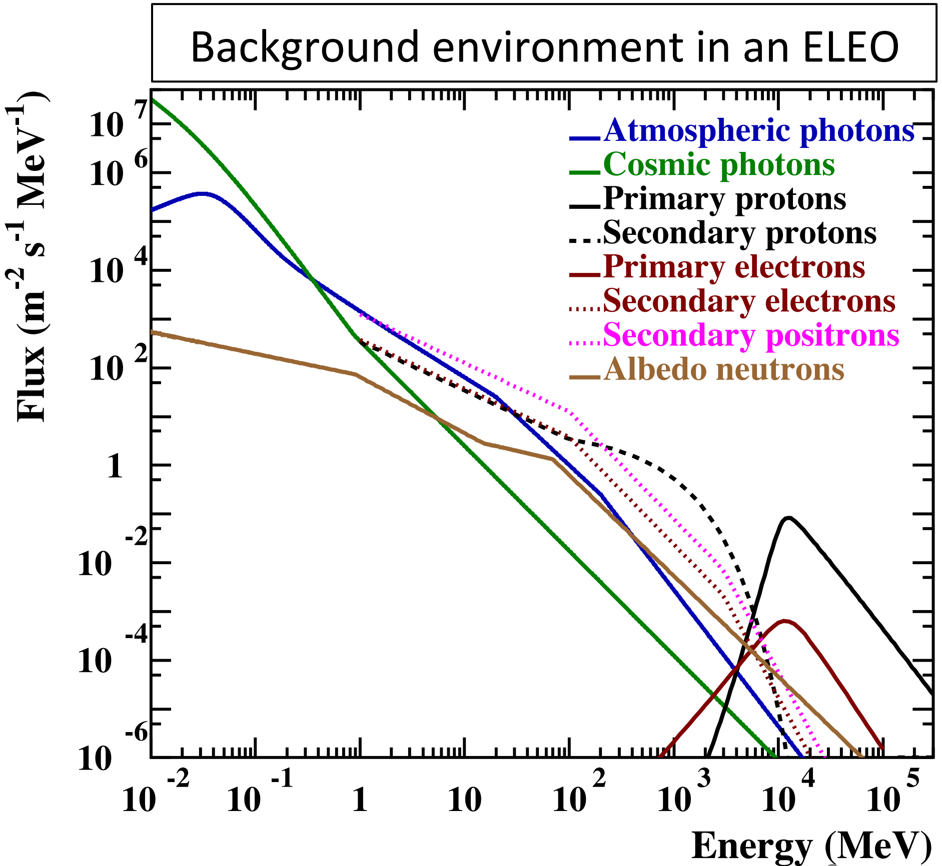


Figure 20: e-ASTROGAM under Ariane 6.2 fairing in upper position.

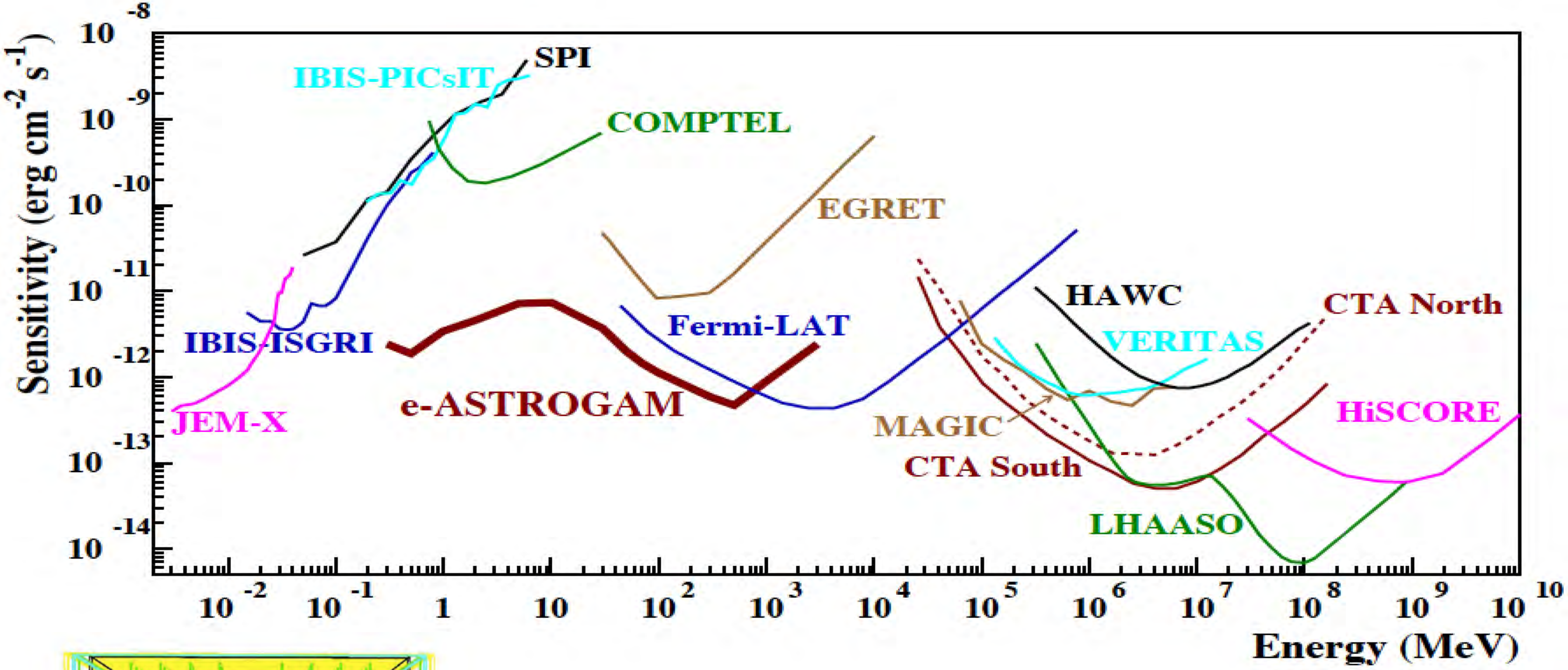
e-ASTROGAM: mission profile

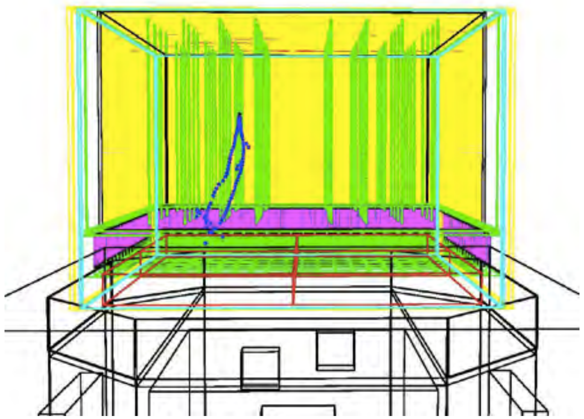
- **Orbit** – Equatorial (inclination $i < 2.5°$, eccentricity $e < 0.01$) low-Earth orbit (altitude in the range 550 - 600 km)
- **Satellite communication** – ESA ground station at Kourou + ASI Malindi station (Kenya)
- **Data transmission** – via X-band (available downlink of 10 Mbps)
- **Observation 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





e-ASTROGAM: performance assessment

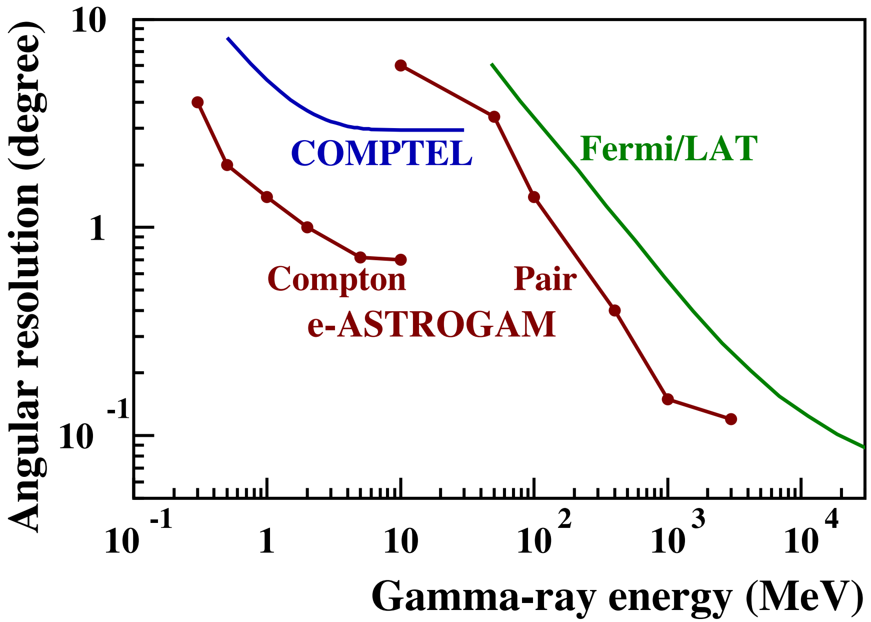




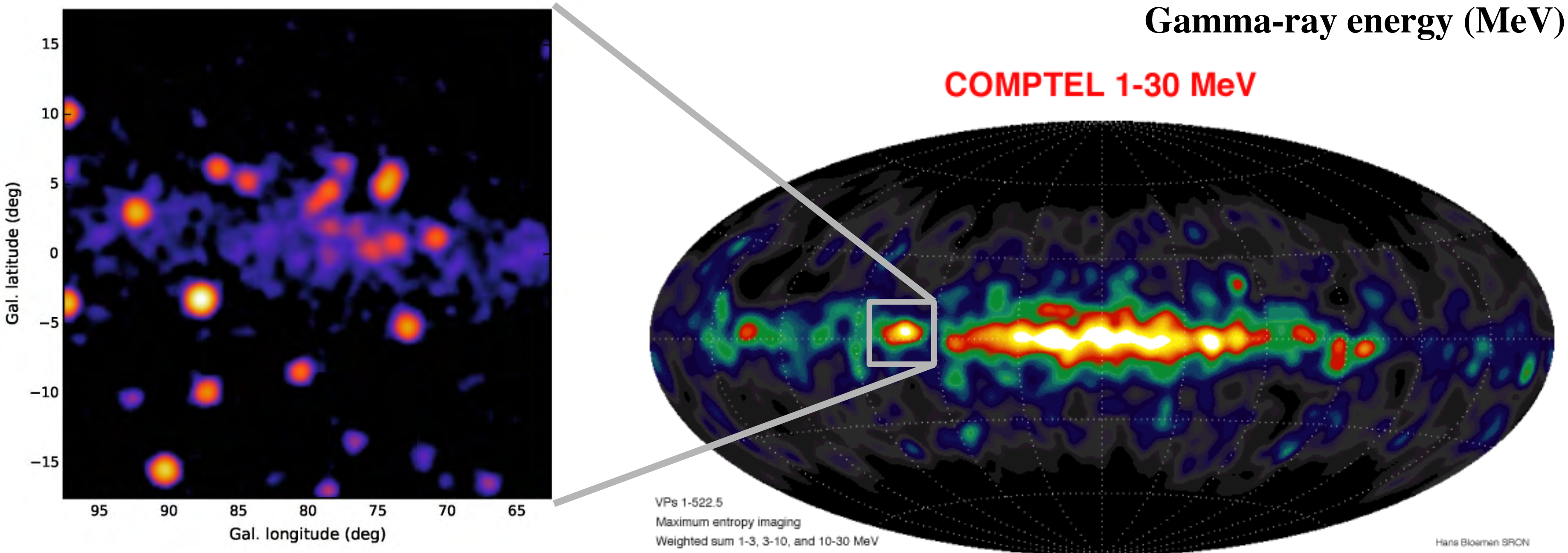
- e-ASTROGAM performance evaluated with **MEGAlib** (Zoglauer et al. 2006) and **Bogemms** (Bulgarelli et al. 2012) – both tools based on Geant4 – and a detailed numerical mass model of the gamma-ray instrument

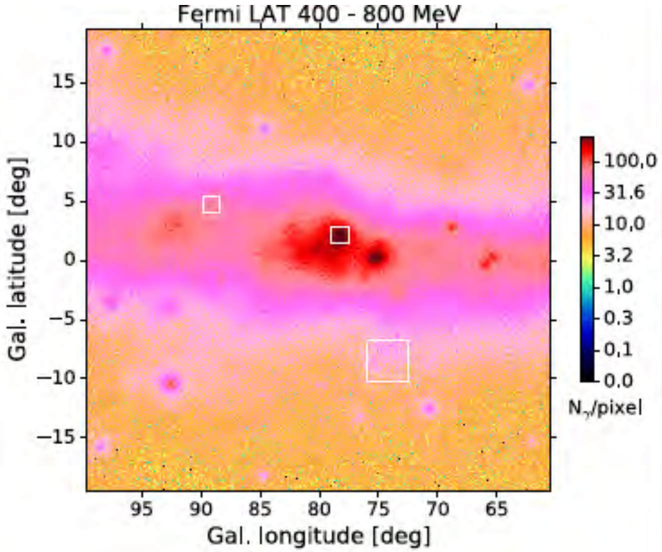
Angular resolution

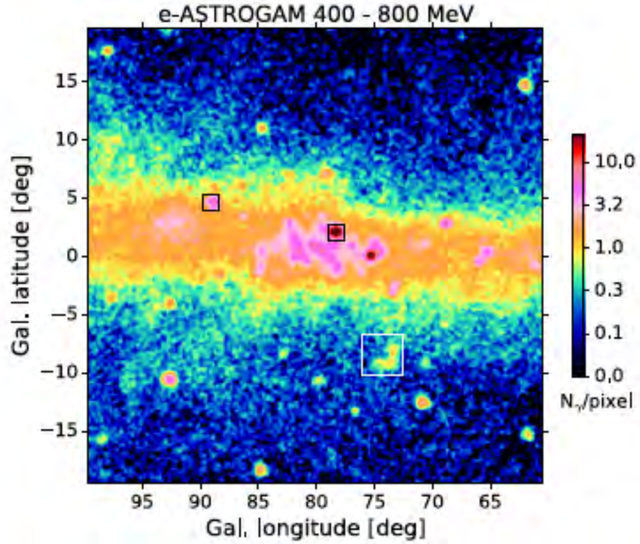
- Angular resolution improved close to the physical limits



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

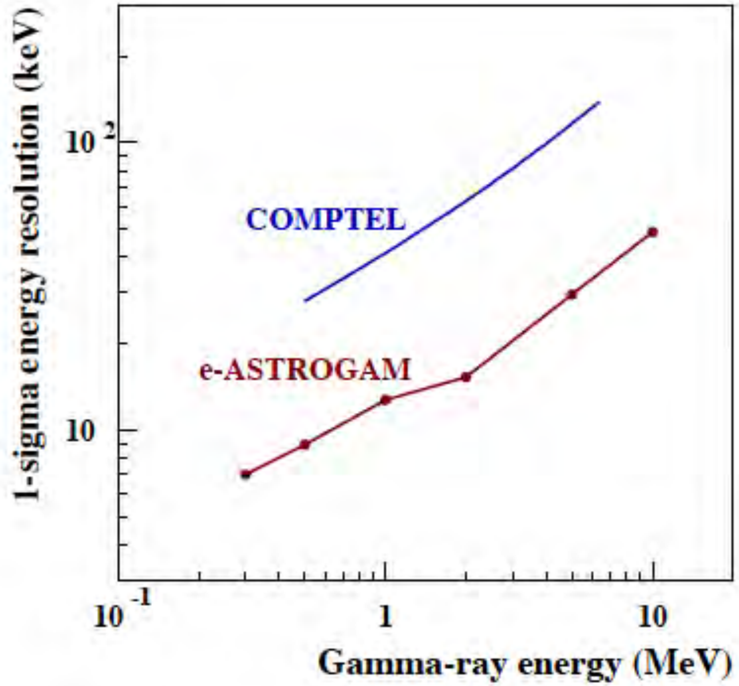






Energy resolution

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



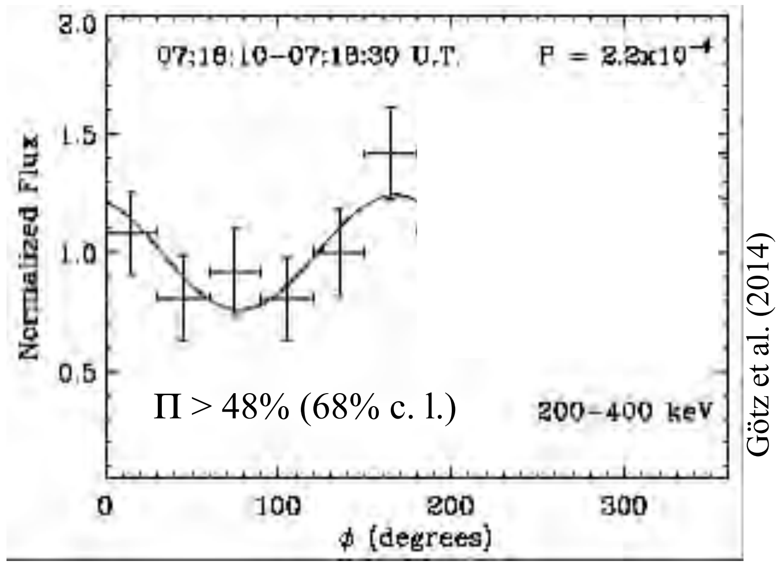
Gamma-ray polarization

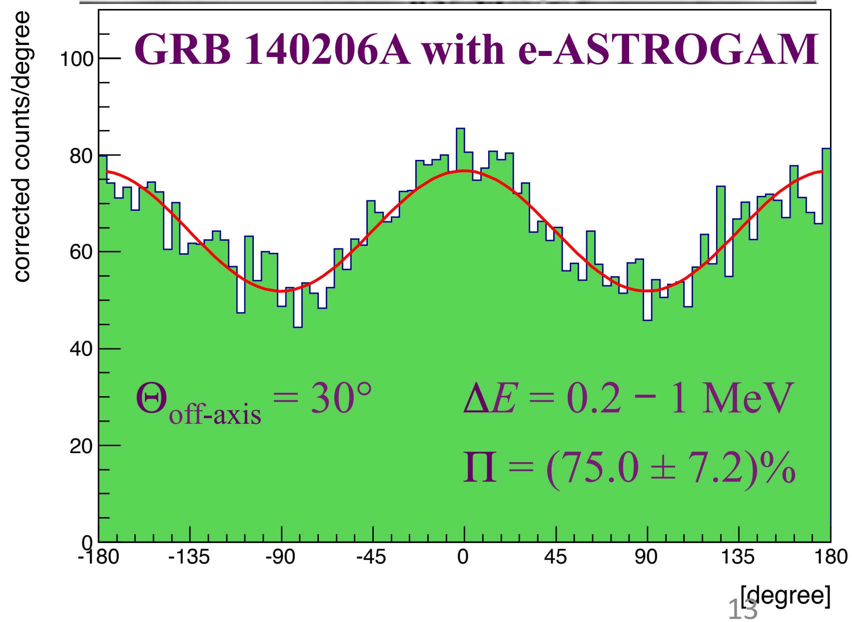
- γ-ray polarization in **objects emitting** **jets** (GRBs, Blazars, X-ray binaries) or with **strong magnetic field** (pulsars, magnetars) ⇒ magnetization and content (hadrons, leptons, Poynting flux) of the outflows + radiation processes

- 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)

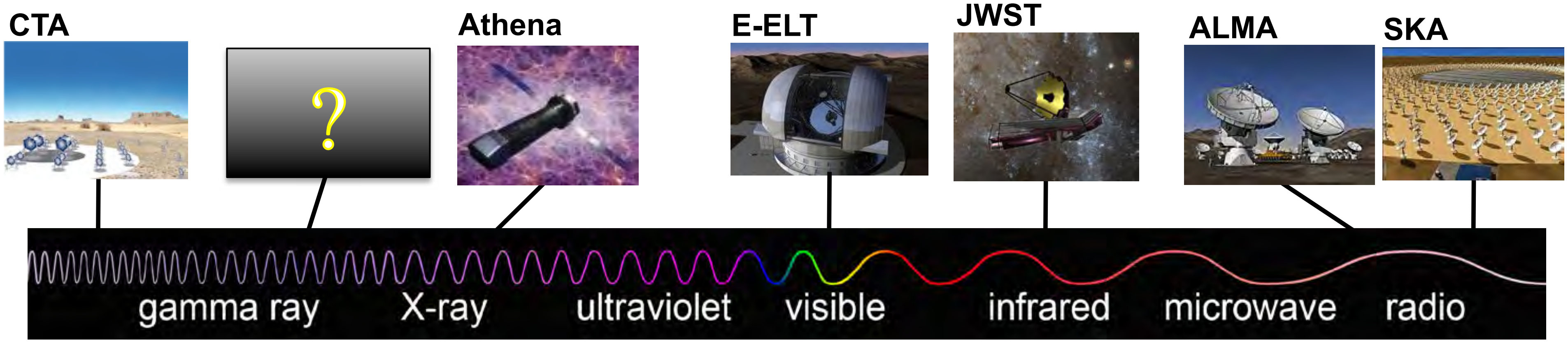
INTEGRAL/IBIS – GRB 140206A ($z = 2.74$)



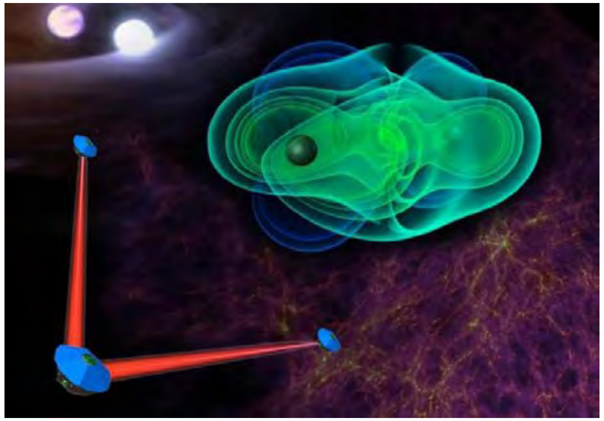


Science with e-ASTROGAM

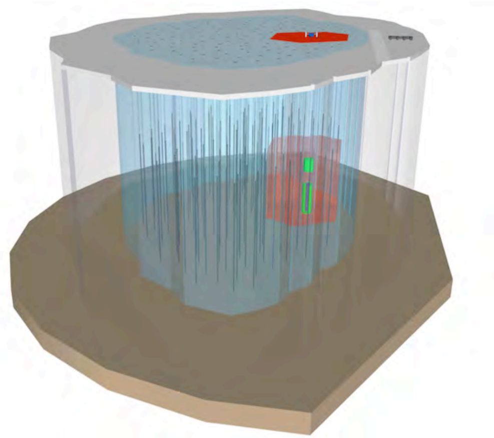
γ-ray astronomy/astrophysics in context



eLISA – Gravitational waves



IceCube-Gen2 – Neutrinos



New Astronomies:
gravitational waves,
neutrinos

- Need for 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

Instrument characteristics

- Best PSF in MeV-GeV
  - Resolve sources
- Calorimetric measurements of MeV lines with high resolution:
  - Positron detection (511 keV line)
  - Measurements of isotopical contents
  - 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

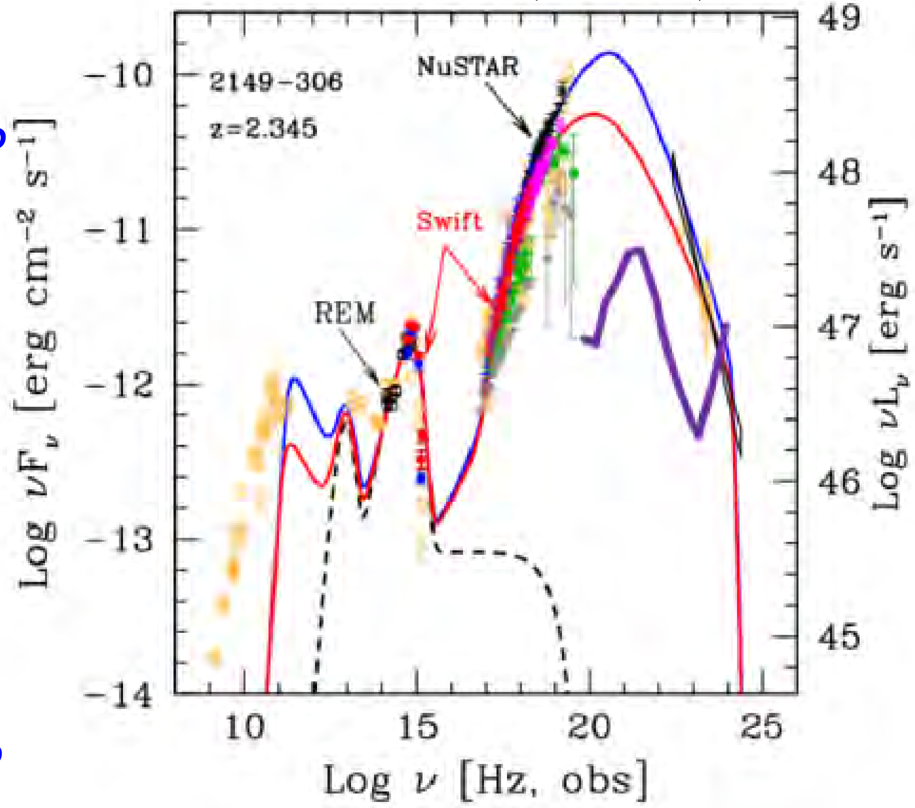
1. Processes at the heart of the extreme Universe: prospects for the Astronomy of the 2030s
   - Determine the composition (hadronic or leptonic) of the outflows and jets (polarimetric capability and spectroscopy)
   - Identify the physical acceleration processes in these outflows and jets (e.g. diffusive shocks, magnetic field reconnection, plasma effects), that may lead to dramatically different particle SED;
   - Clarify the role of the magnetic field in powering ultrarelativistic GRB jets, through time-resolved polarimetry and spectroscopy.
   - Multimessenger astronomy in the 2030s. Joint detection of gravitational waves.
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 core science topic #1

At the heart of the extreme Universe

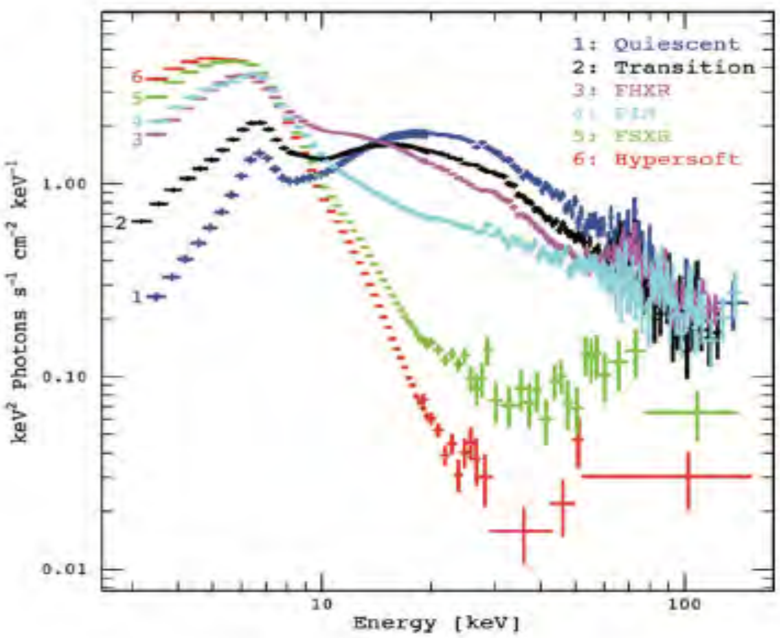
- *Launch of ultra-relativistic jets in **GRBs**? Ejecta composition, energy dissipation site, radiation processes?*
- *Can short-duration GRBs be unequivocally associated to **gravitational wave** signals?*
- *How does the accretion disk/jet transition occur around supermassive black holes in **AGN**?*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

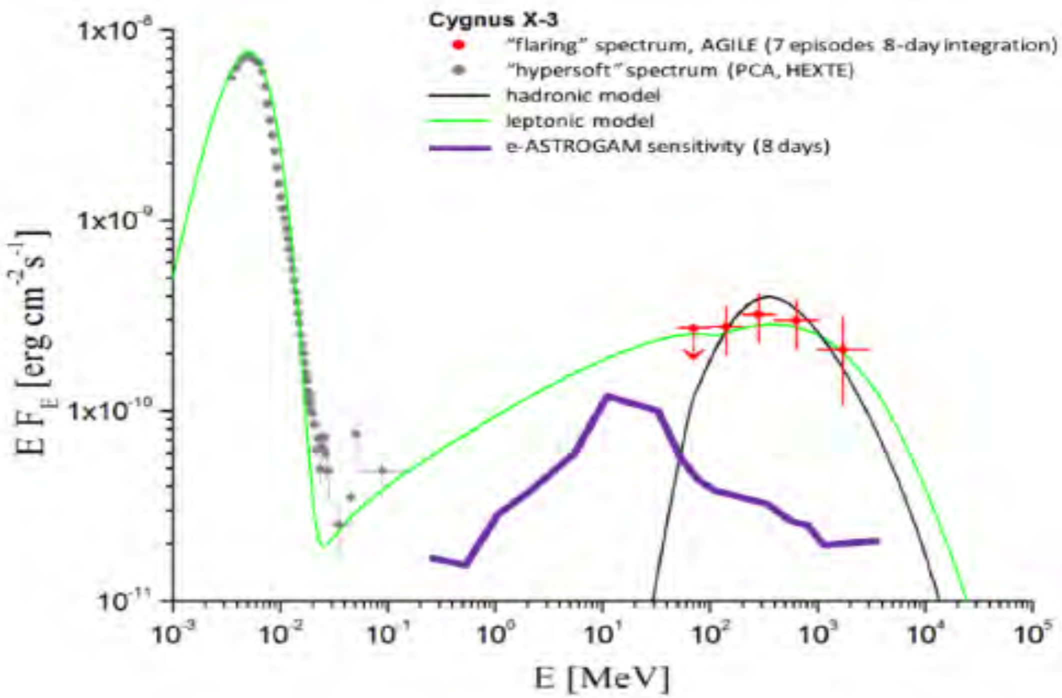
PKS 2149-306 (z = 2.345)



✓ 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





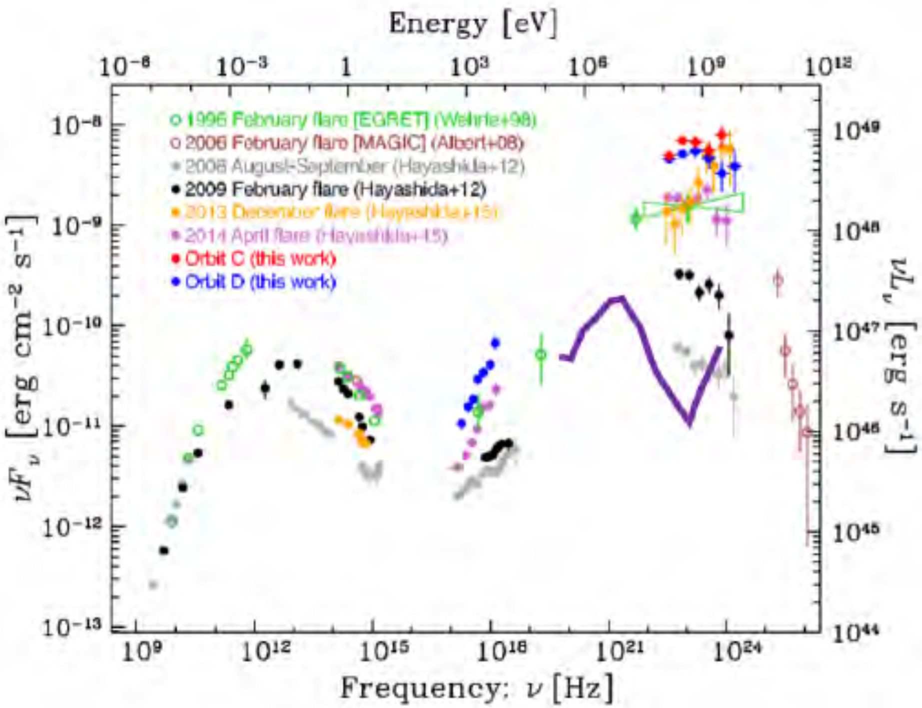
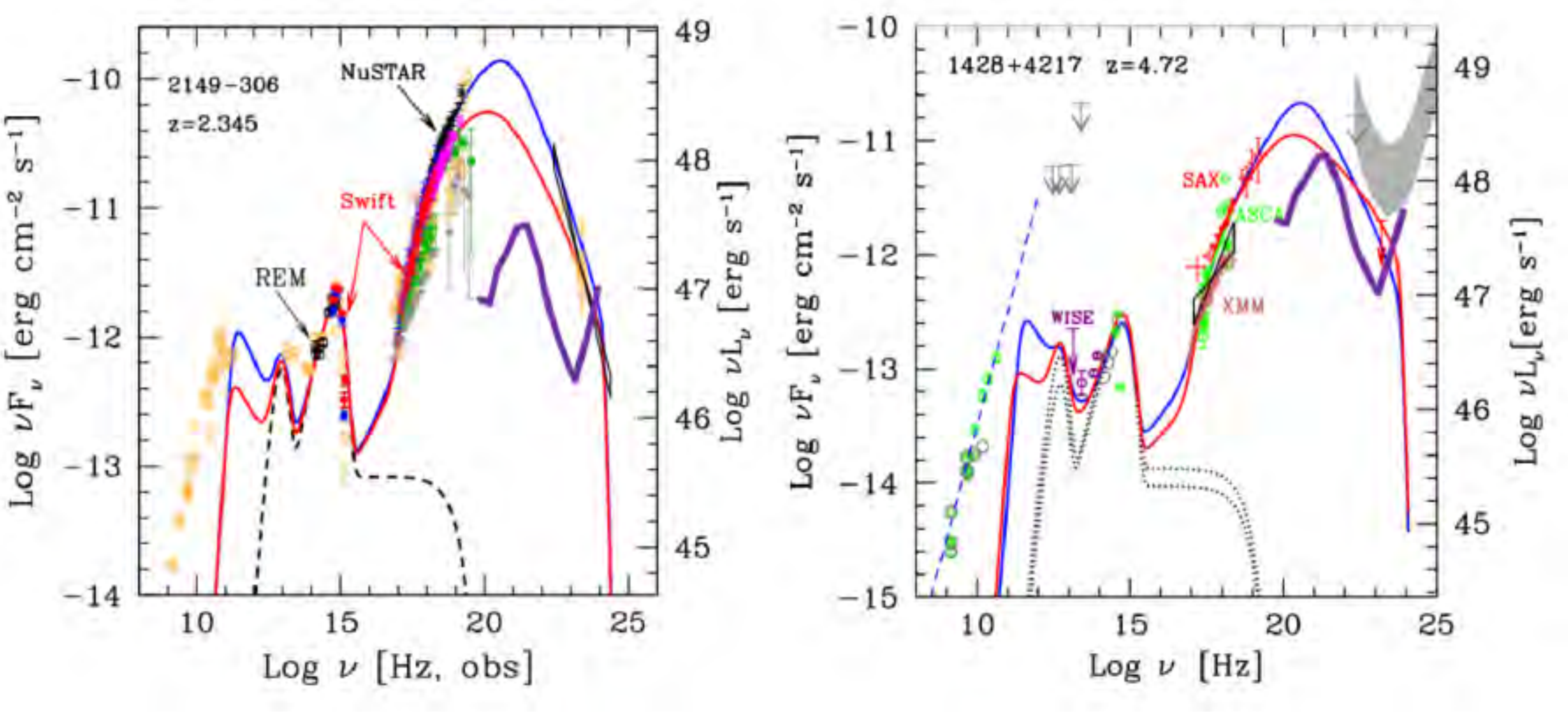
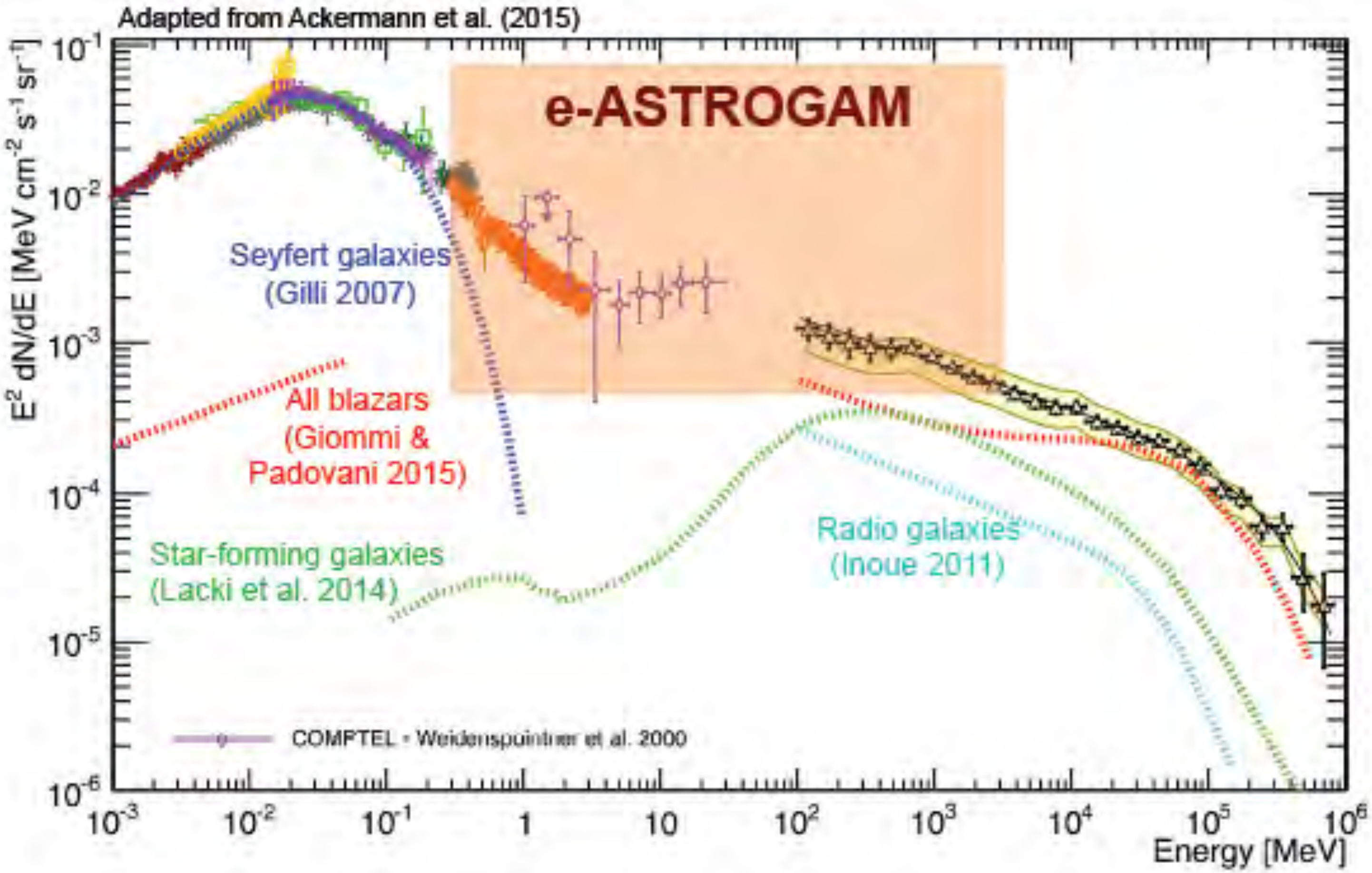


Figure 5: SED from a collection of different spectral states of the FSRQ 3C 279 showing a dramatic gamma-ray flaring activity, including the minute-timescale episode detected by Fermi in June 2015 [13]. The purple solid line is the 3σ e-ASTROGAM sensitivity calculated for a 50 ks exposure.

MeV blazars; cosmology at z up to 4.5



A huge blazar population in an unknown region



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%;
  - 16 GRBs/year with a polarization fraction of 10%
- Possible detection of electromagnetic counterparts of impulsive GW events
  - MeV likely to be the threshold
  - Possible associations GRB/GW
- MeV possible threshold also for the counterparts of neutrino bursts

e-ASTROGAM core science: 2

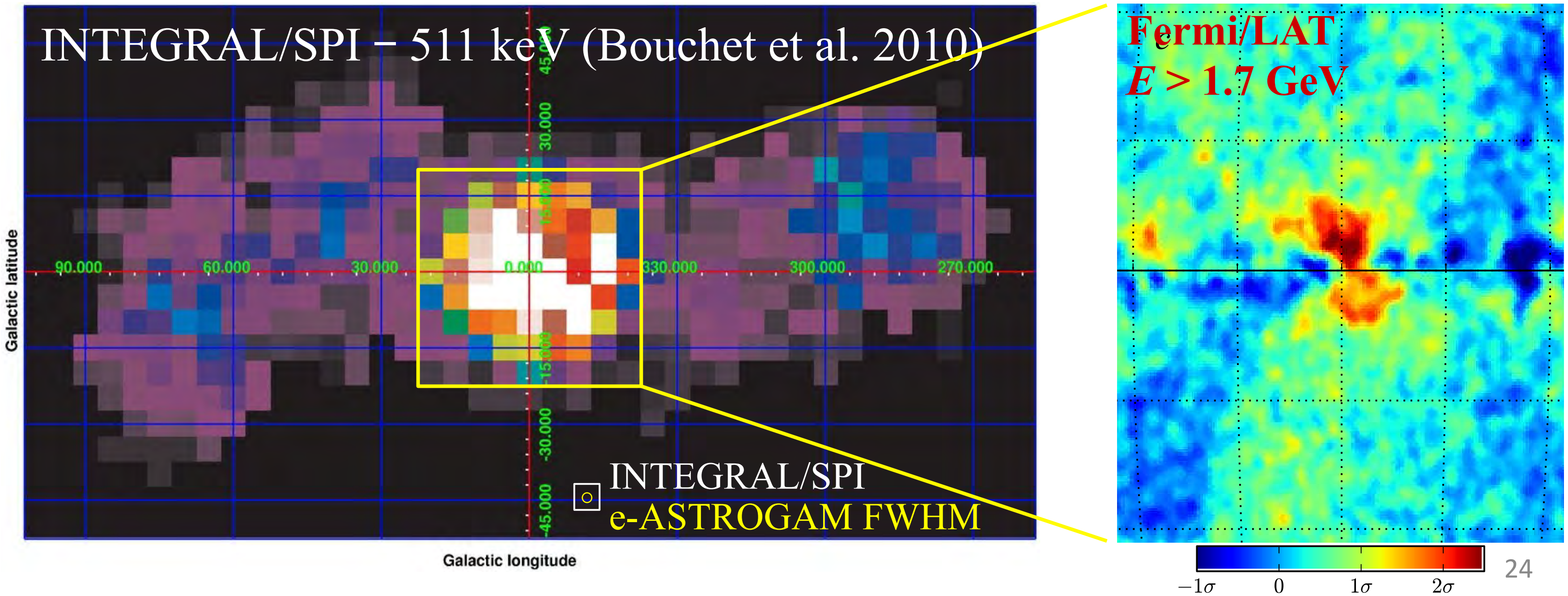
1. Processes at the heart of the extreme Universe: prospects for the Astronomy of the 2030s
2. The origin and impact of high-energy particles on galaxy evolution, from cosmic rays to antimatter
   - origin & propagation of LECR, CR diffusion in interstellar clouds and their impact on gas dynamics and state; wind outflows and their feedback on the Galactic environment (e.g., Fermi bubbles, Cygnus cocoon).
   - detect line emissions from 511 keV up to 10 MeV, thus:
     - origin of the gamma-ray and positron excesses toward the IG;
     - determination of the astrophysical sources of the local positron population. As a consequence e-ASTROGAM will provide a key contribution to the search for DM
3. Nucleosynthesis and the chemical enrichment of our Galaxy

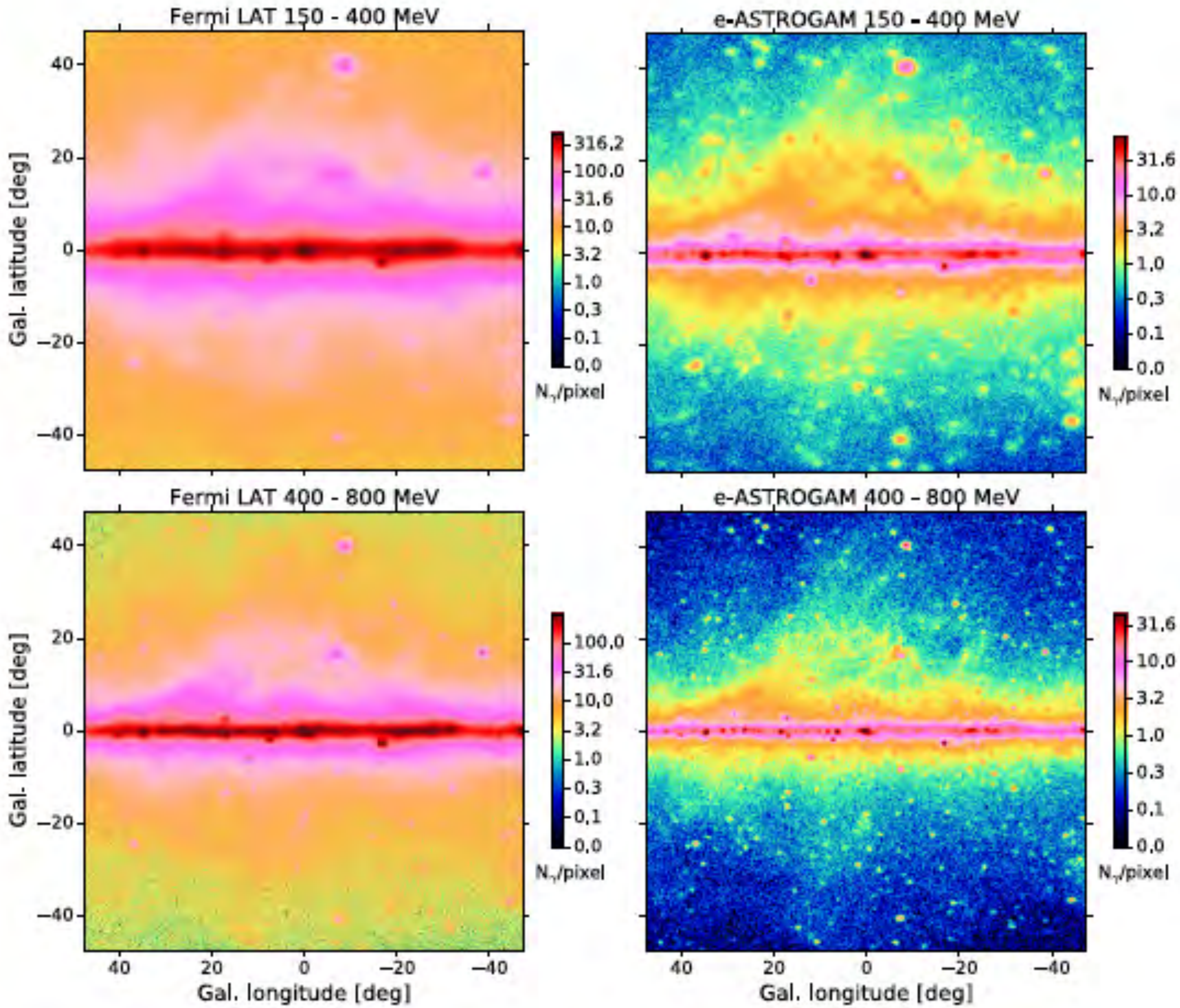
e-ASTROGAM core science topic #2

The high-energy mysteries at the Inner Galaxy

- *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]
N$_\gamma$/pixel
316,2
100,0
31,6
10,0
3,2
1,0
0,3
0,1
0,0
40
20
0
−20
−40

Cosmic rays in the Inner Galaxy; acceleration in SNRs

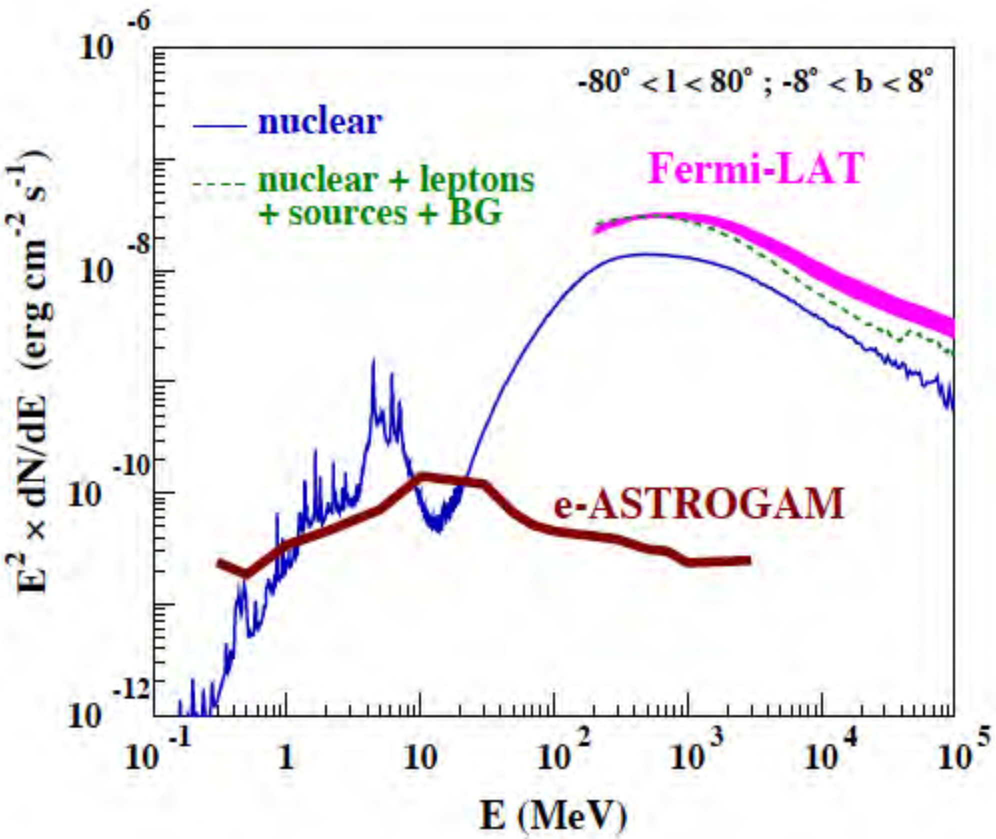
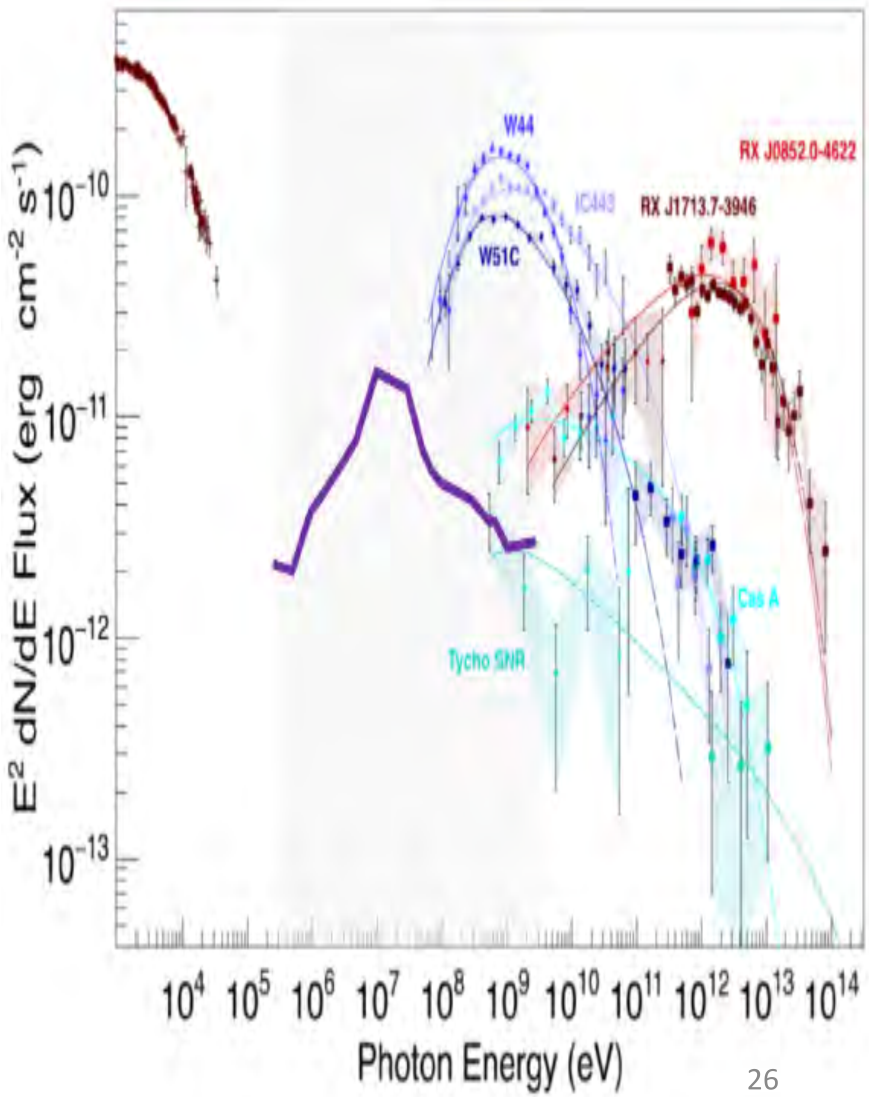


Figure 9: Predicted γ-ray emission due to nuclear interactions of CRs in the Inner Galaxy. The γ-ray line emission below 10 MeV is due to LECRs ([24]). The 1-year sensitivity of e-ASTROGAM (for Galactic background) is superimposed.



Antimatter and Dark Matter

- Unique sensitivity to the 511-keV line
- Sensitivity to many classical positron sources: can determine if the PAMELA/AMS positron excess is due to nearby pulsars

- 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

e-ASTROGAM core science: 3

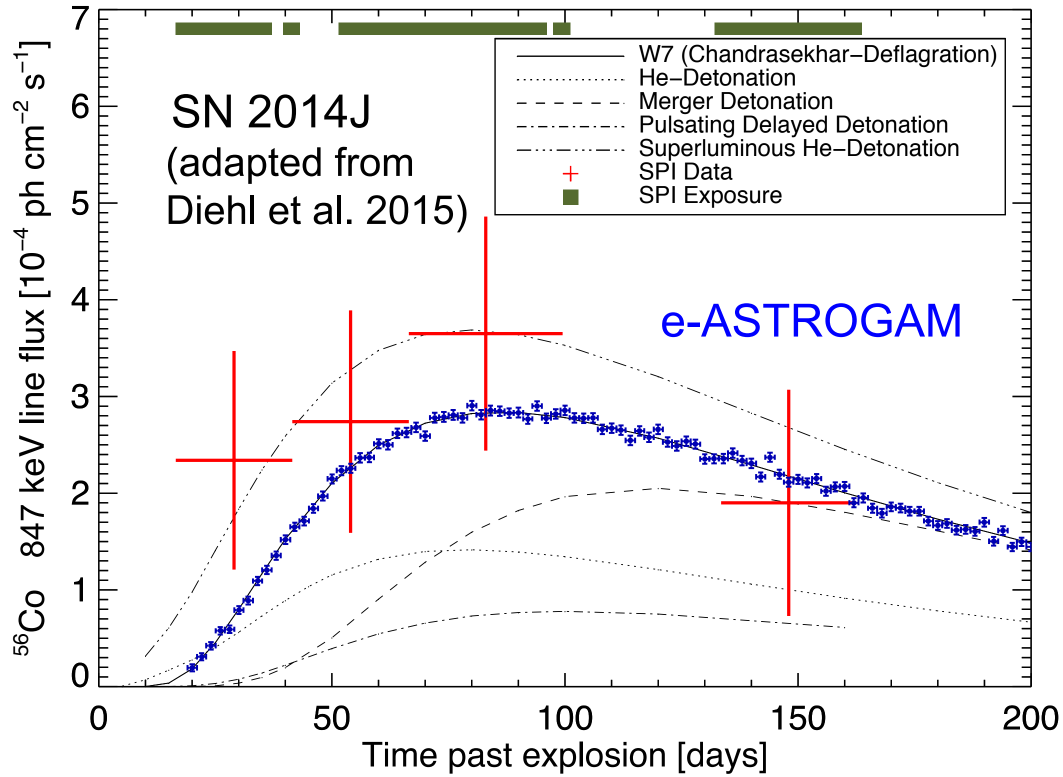
1. Processes at the heart of the extreme Universe: prospects for the Astronomy of the 2030s
2. The origin and impact of high-energy particles on galaxy evolution, from cosmic rays to antimatter
3. Nucleosynthesis and the chemical enrichment of our Galaxy
   – What are the progenitor system(s) and explosion mechanism(s) of thermonuclear SNe?
   – What do we need to understand before using SN Ia for precision cosmology?
   – How do core-collapse supernovae (CCSNe) explode, and what is the recent history of CCSNe in the Milky Way?
   – How are cosmic isotopes created in stars and distributed in the interstellar medium?

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 (1)

- e-ASTROGAM pointings first focused on core science topics. However a very large number of sources will be detected and monitored.
  - e-ASTROGAM will study thousands of sources both Galactic and extragalactic of which many are expected to be new detections. Therefore, a very large community of astronomical users will benet from e-ASTROGAM data available for multifrequency studies through GI programme managed by ESA.
- e-ASTROGAM will detect with unprecedented sensitivity in the MeV-GeV domain phenomena
  - characterized by rapid and very rapid variability timescales (sub-second, second, minutes, hours): GRB, AGN flares, …
  - steady sources

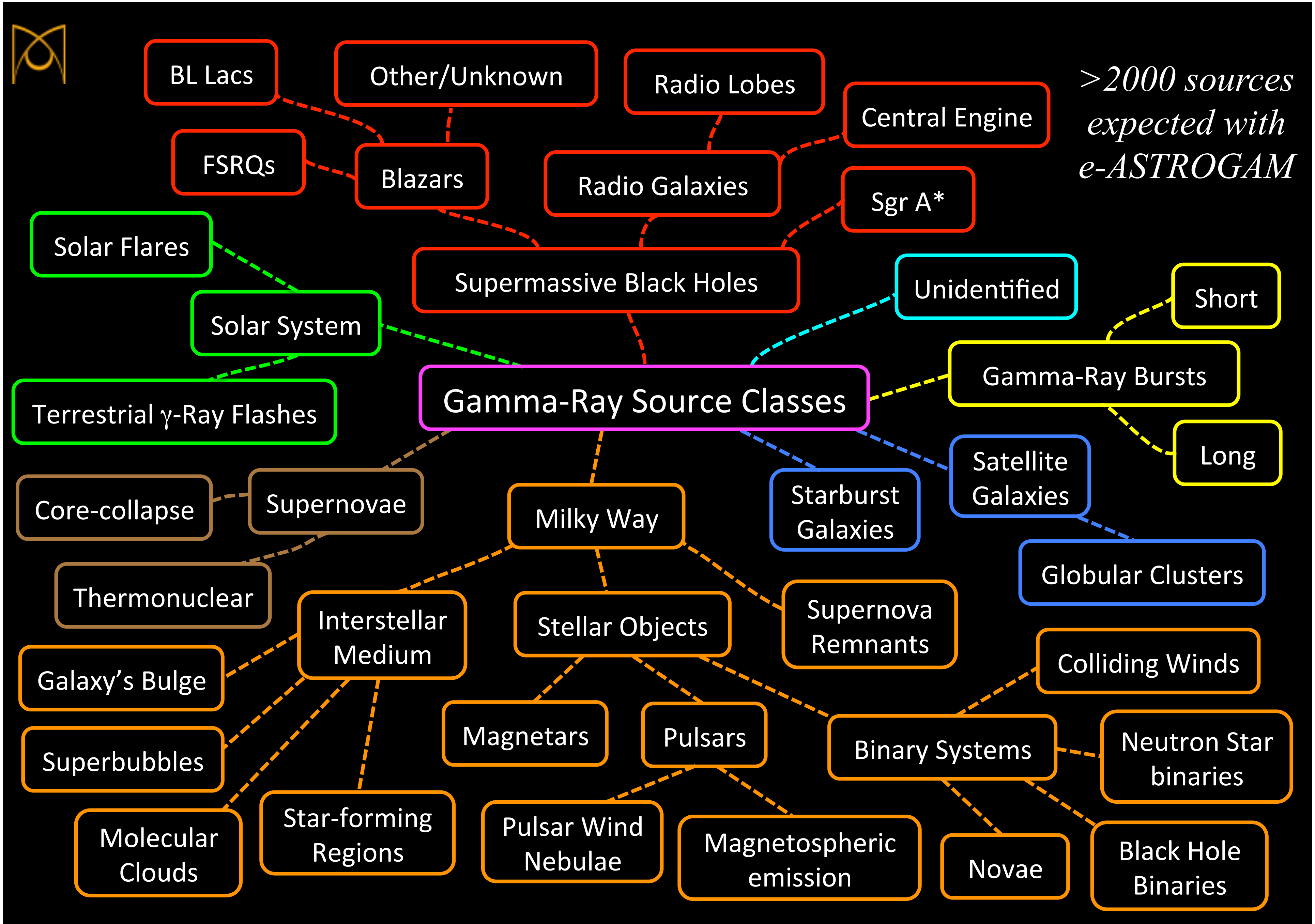
Type	3-yr	New
All sky (above 100 MeV)	> 2000	1200 (including GRBs)
Galactic	~ 600	
Novae	$\sim 4 - 6$	
Supernovae	$\sim 10 - 15$	
GRBs	$\sim 500 - 600$	

e-ASTROGAM Observatory science (2)

- **Diffuse Galactic gamma-ray background**: e-ASTROGAM can determine the underlying CR population and spatial and spectral variations across the Galaxy.
- **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**, a product of the interaction between shocked relativistic pulsar winds and the ISM, for which e-ASTROGAM will obtain crucial data on particle acceleration and propagation.
- **Magnetars**, enigmatic and strongly variable compact stars characterized by very strong magnetic elds that exhibit special phenomena exclusively in the MeV energy range.
- **Galactic compact binaries**, including white dwarfs, neutron stars and solar mass black holes whose spectral transitions and outbursts in the MeV range will be systematically monitored by e-ASTROGAM .
- **Classical novae**, that in addition to line emission in the MeV range can also be studied for their surprising and poorly understood gamma{ray emission up to hundreds of MeV, a product of shock interaction of the nova ejecta with the local ISM.

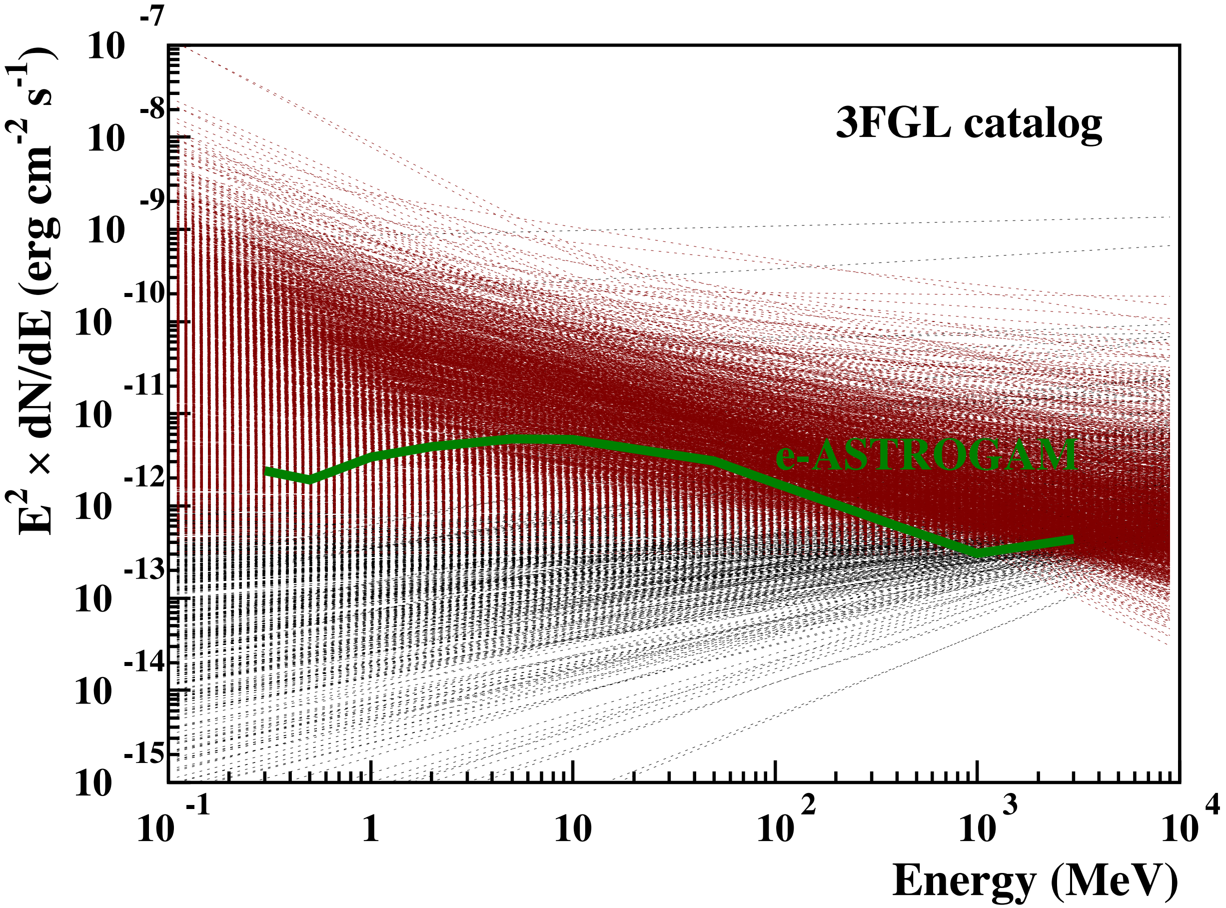
e-ASTROGAM Observatory science (3)

- **Interstellar shocks**, such as the Cygnus cocoon showing the existence of particle acceleration over large distances in the ISM, for which the spectral and angular resolution of e-ASTROGAM will be unique.
- **Blazar population studies** in the MeV range, to be obtained by the detection capability of thousands of sources by e-ASTROGAM.
- **Studies of the propagation of gamma rays over cosmological distances**, for which the attenuation is predicted to be negligible in standard QED - effects of absorption might indicate new physics at work, possibly the existence of axion-like-particles coupling to gamma rays.
- **Solar flares and contribution to "SpaceWeather"**, that will be studied with unprecedented line emission and continuum capability for theoretical modeling as well as fast reaction for alerts.
- **Terrestrial Gamma-Ray Flashes**, an atmospheric phenomenon with possible environmental impact for which e-ASTROGAM can provide continuous monitoring (including the 511-keV line detection).


>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
Interstellar
Medium
Stellar Objects
Supernova
Remnants
Galaxy’s Bulge
Superbubbles
Molecular
Clouds
Star-forming
Regions
Magnetars
Pulsars
Pulsar Wind
Nebulae
Magnetospheric
emission
Binary Systems
Colliding Winds
Neutron Star
binaries
Novae
Black Hole
Binaries

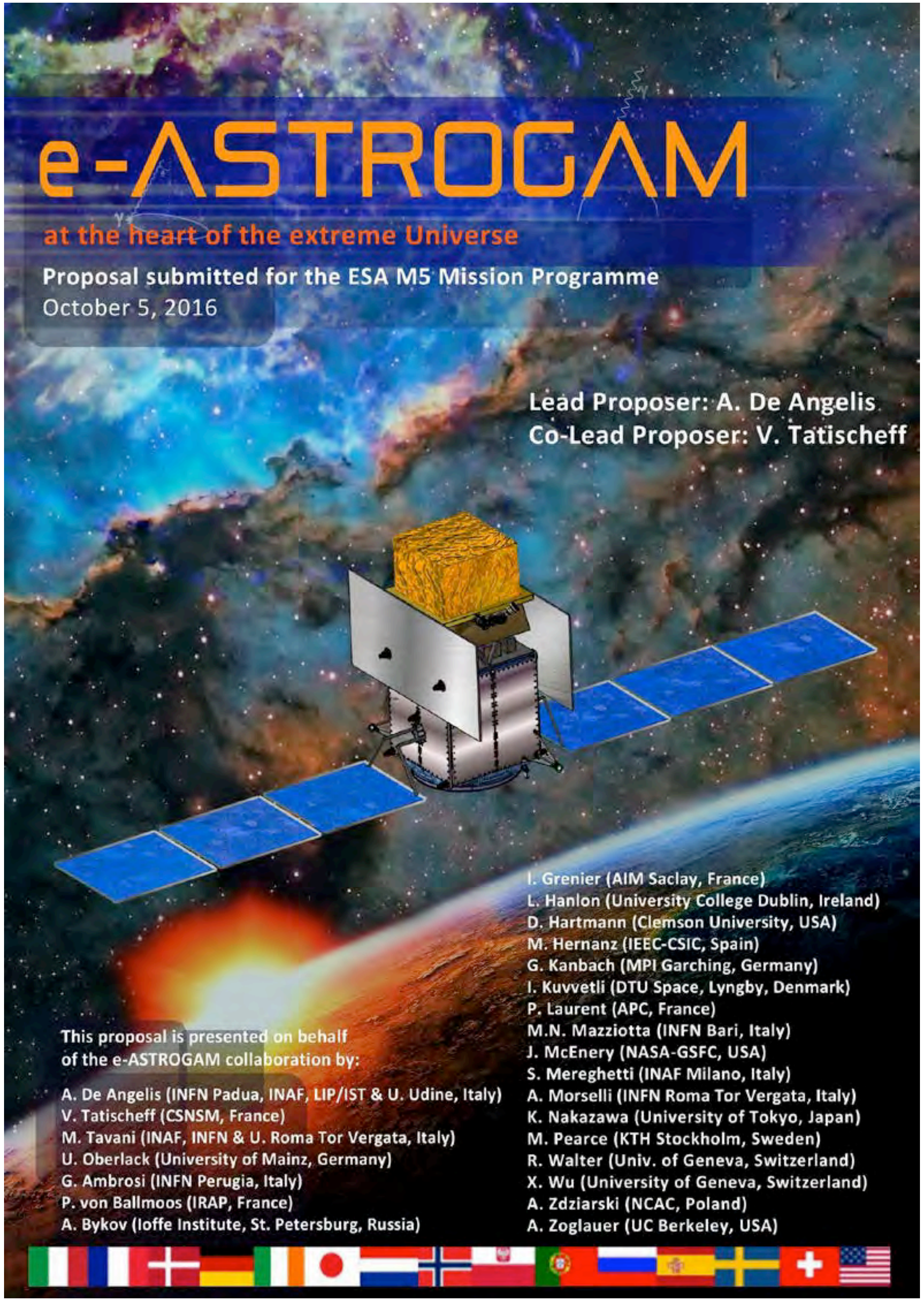
e-ASTROGAM discovery space

- 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

Status of e-ASTROGAM
The e-ASTROGAM Collaboration



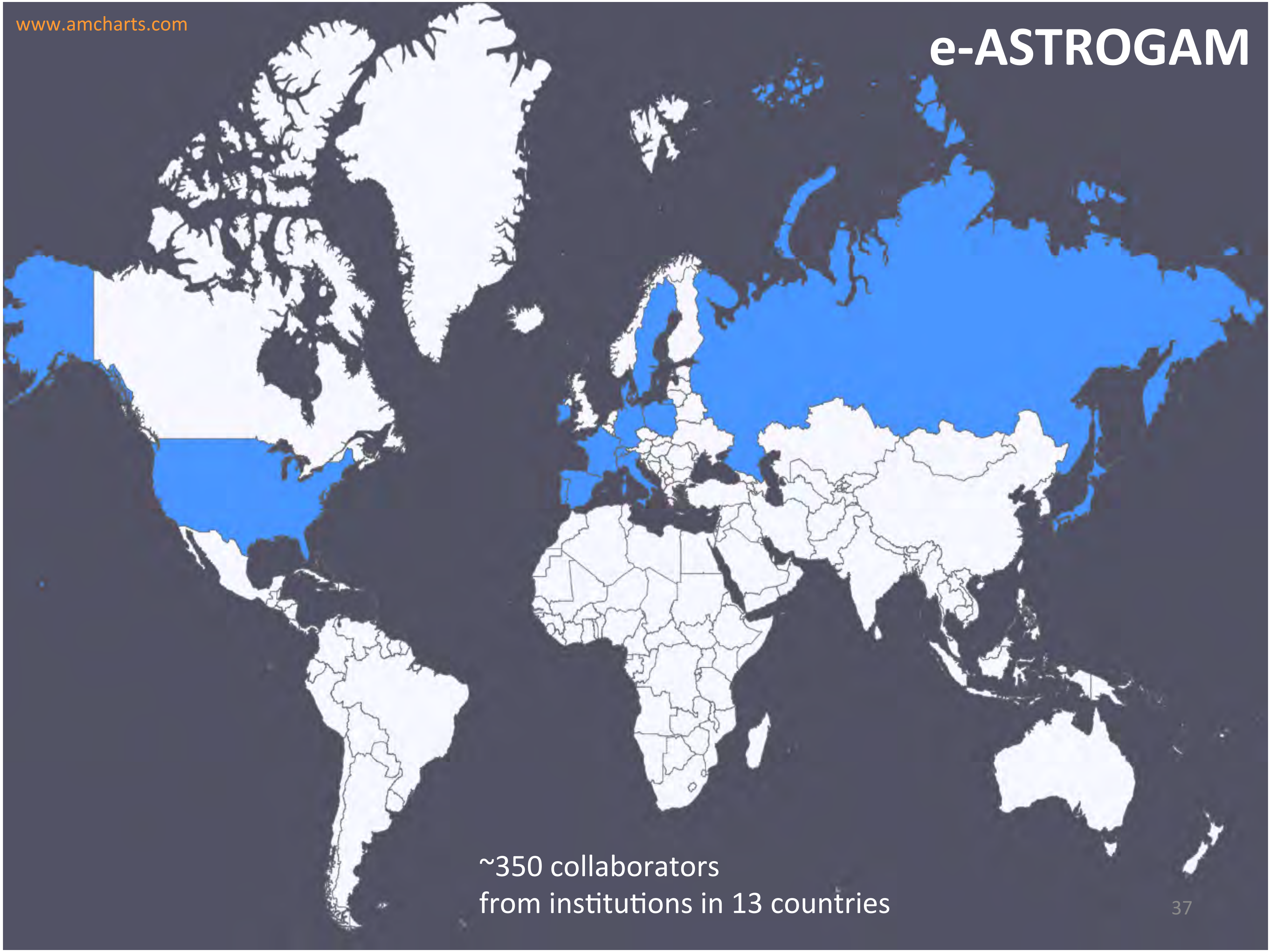
Proposal submitted to
ESA M5 on Oct 5, 2016

First screening after Feb 2017

Expected launch ~2028

Simulation ready; prototypes test
starting in 2017

e-ASTROGAM



~350 collaborators
from institutions in 13 countries

e-ASTROGAM Collaboration

Principal investigator: Alessandro De Angelis (INFN/INAF Padova, U. Udine Italy; LIP/IST, Portugal)
Co-I: Vincent Tatischeff (CSNSM Paris, France)

INFN BA, PD, PG, RM2, TS/UD; INAF; Univ. Bari, Padova, Roma2, Siena, Trieste, Udine

CSNSM, IRAP, APC, CEA, LLR, LUPM, IPNO

Univ. Mainz, Univ. Wurzburg, MPE, RWTH, DESY, Univ. Erlangen

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

University College Dublin, DIAS

DTU

University of Geneva, ISDC, PSI

Jagiellonian University, CBK, NCAC

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

Ioffe Institute

University of Tokyo

Conclusions

- **The MeV / GeV gamma-ray band is one of the richest energy domains of astronomy**

- **e-ASTROGAM will be an essential observatory to study the extreme transient sky at the era of astronomy's new messengers**

- **The e-ASTROGAM payload is innovative in many respects, but the technology is ready**