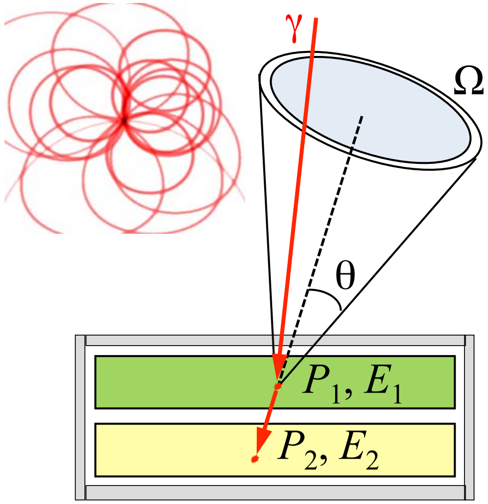
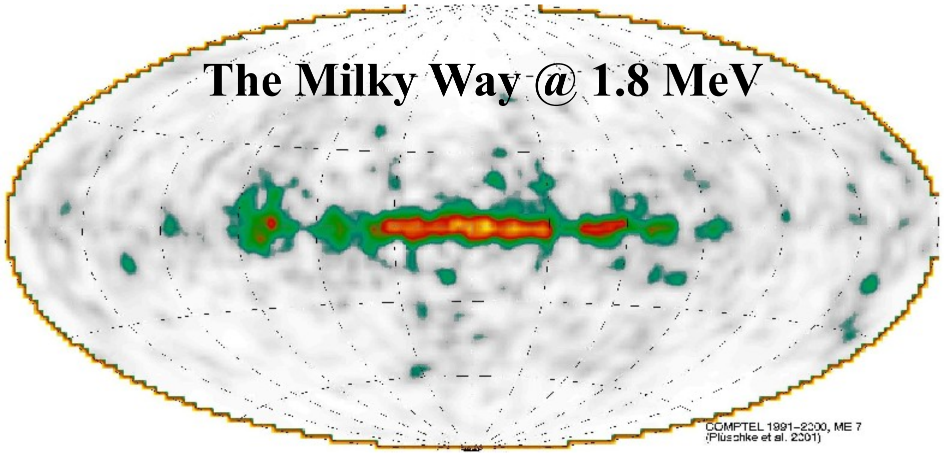
Compton telescopes for gamma-ray space astronomy

Vincent Tatischeff (IJCLab Orsay)



$$E_\gamma = E_1 + E_2$$
$$\cos\theta = 1 + m_e c^2[1/(E_1+E_2)-1/E_2]$$



COMPTEL 1991–2000, ME 7
(Plüschke et al. 2001)

Workshop Compton, CPPM Marseille, November 30 - December 1, 2021

First Compton telescope for γ-ray astronomy

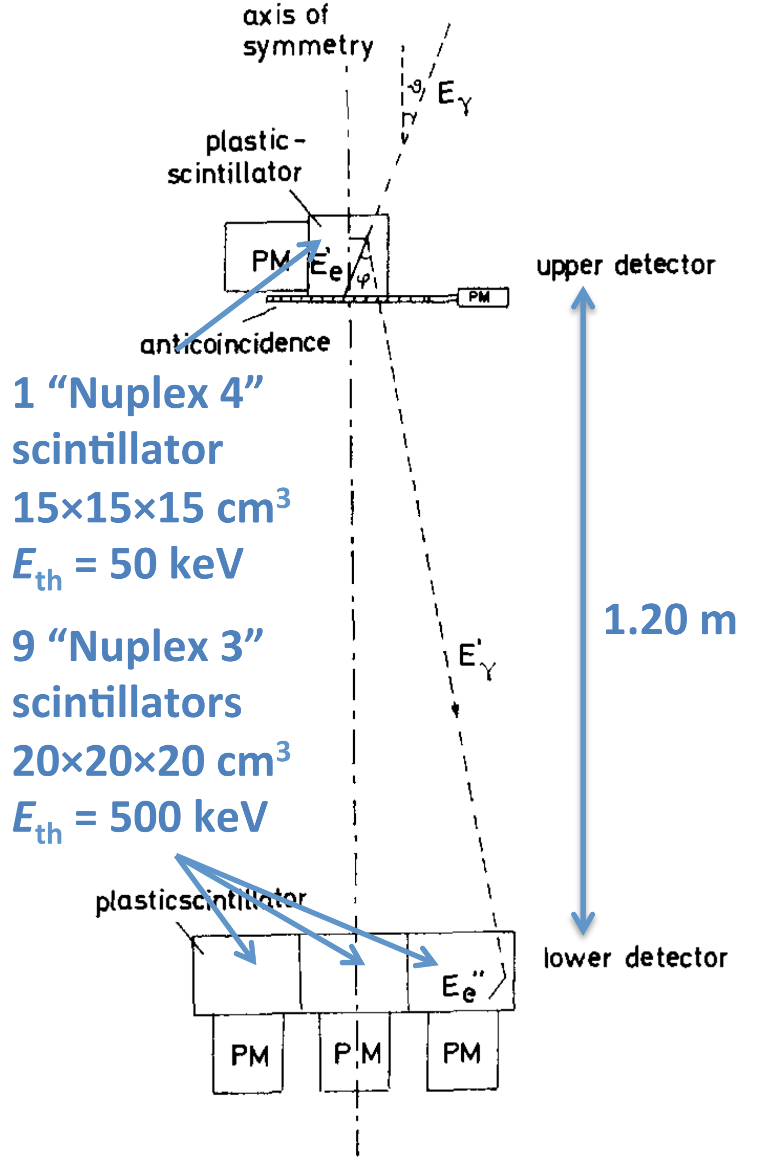
- **Schönfelder et al. (1973)**, NIM (nearly 2 years before Todd et al. 1974, Nature): results of a prototype in the laboratory (MPE Garching)
- **Double Compton telescope** with plastic scintillators (correction factor $E'_\gamma = f(E''_e)$ estimated with calibration sources)

⇒ Energy resolution of $\approx 40\%$ (FWHM)

- **Time of flight** measurement to reduce the background (sub-ns resolution and 1.2 m between the 2 detectors)

⇒ Absolute detection efficiency of $\approx 0.5\%$

- Balloon-borne experiment in 1973 (Schönfelder & Lichti 1974): **extragalactic origin of the MeV gamma-ray radiation**

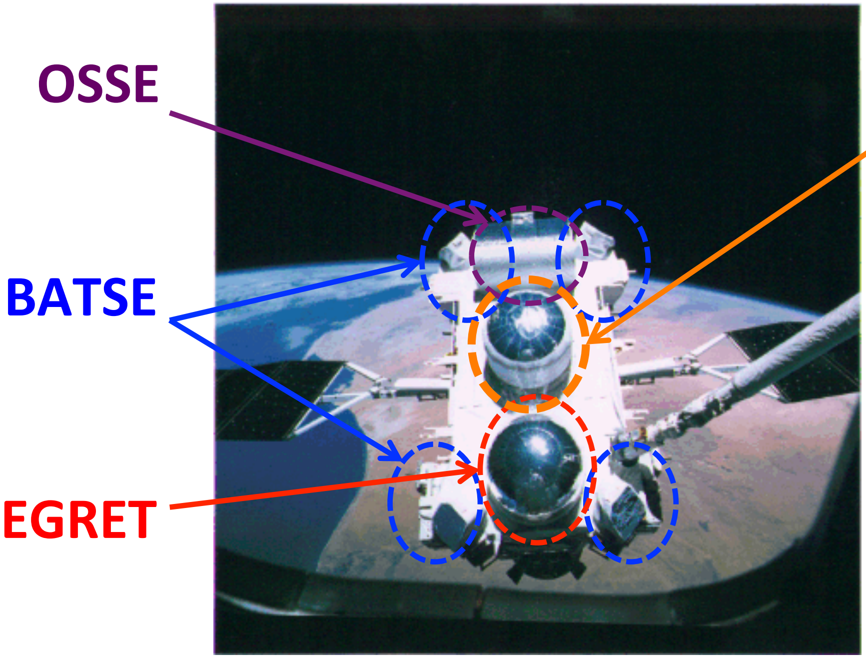


1 “Nuplex 4” scintillator
15×15×15 cm^3
E_{th} = 50 keV

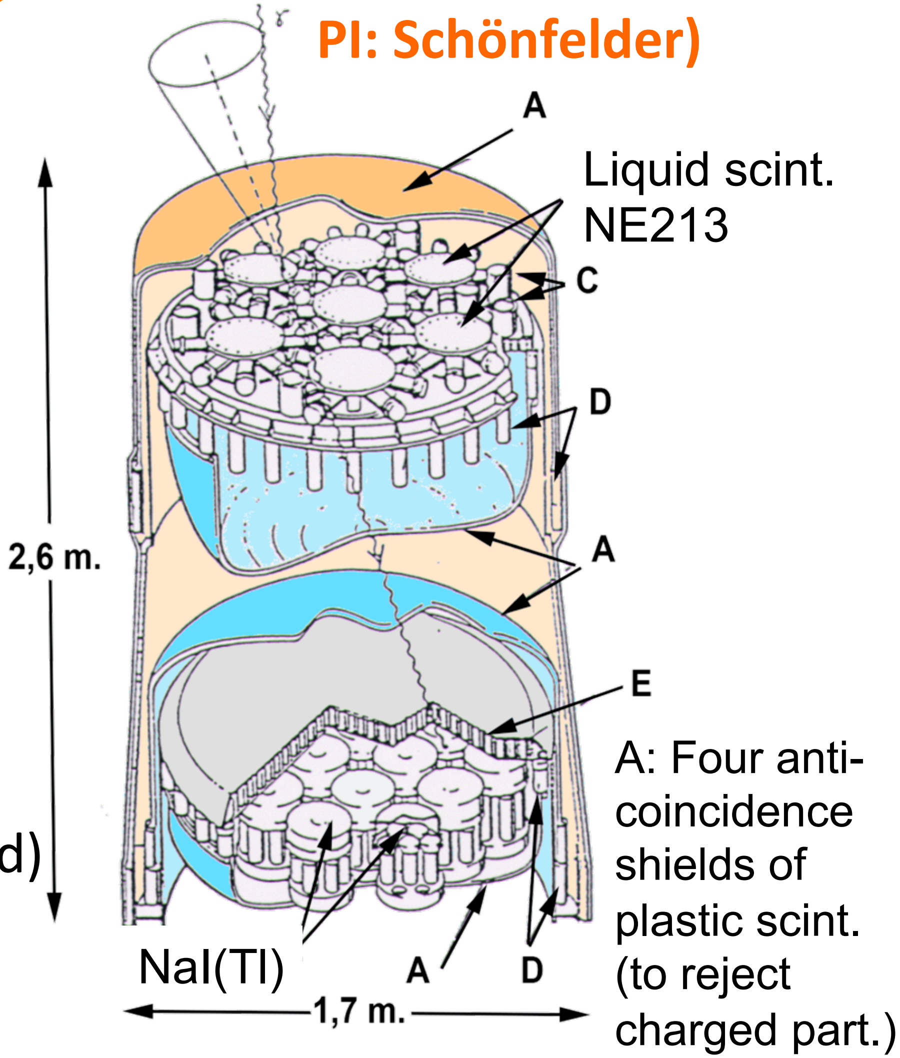
1.20 m

9 “Nuplex 3” scintillators
20×20×20 cm^3
E_{th} = 500 keV

COMPTEL on CGRO (NASA)



COMPTEL (0.75 - 30 MeV; PI: Schönfelder)

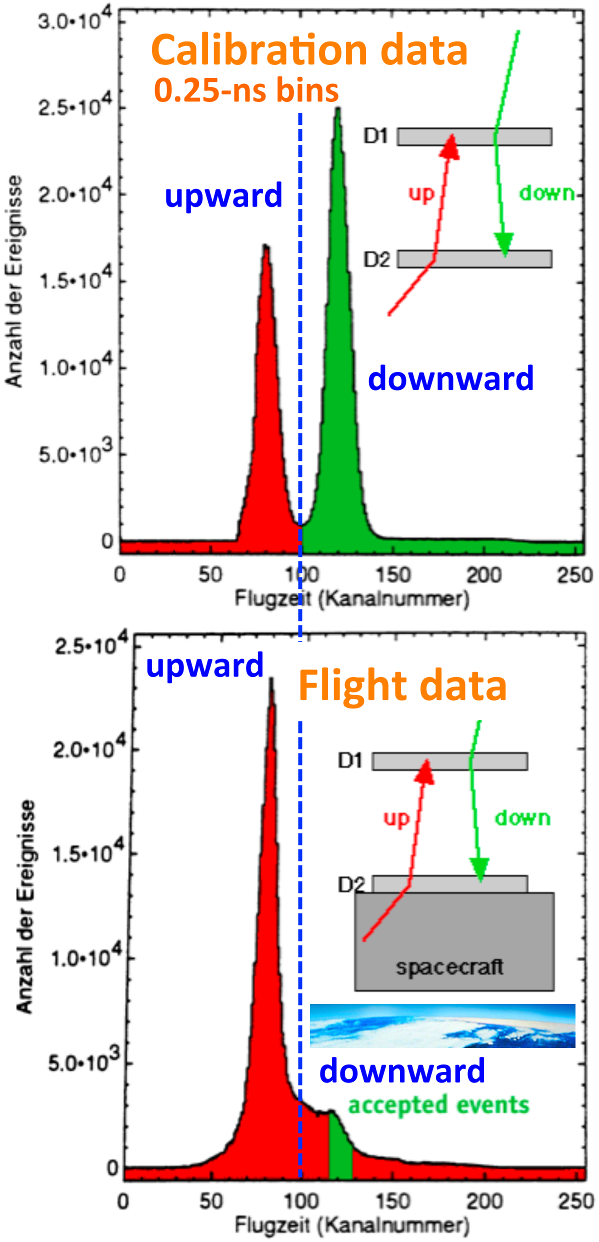


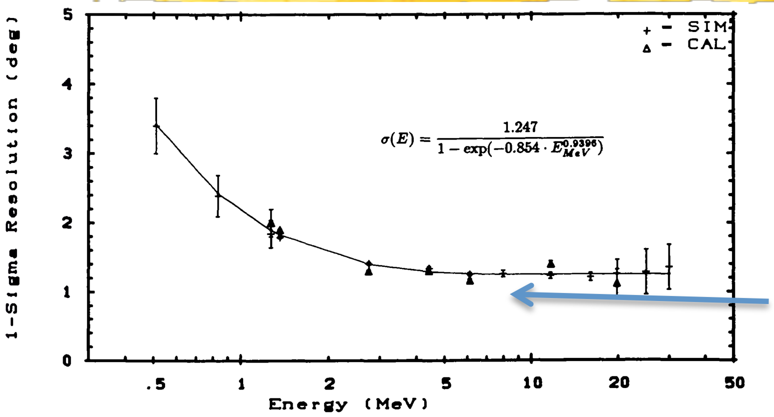
A: Four anti-coincidence shields of plastic scint. (to reject charged part.)

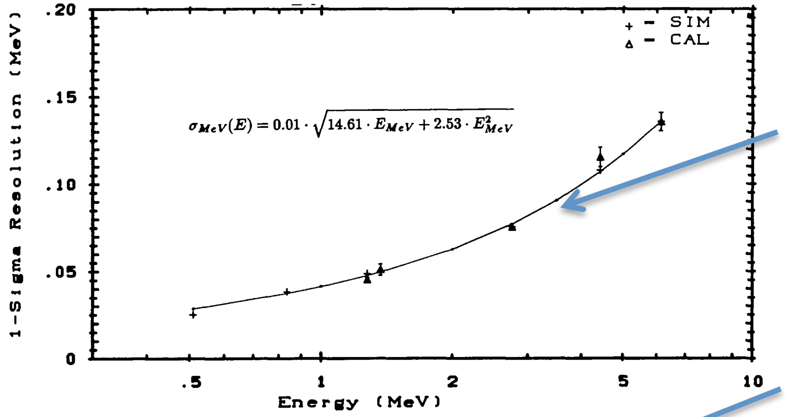
❑ **Compton Gamma Ray Observatory**

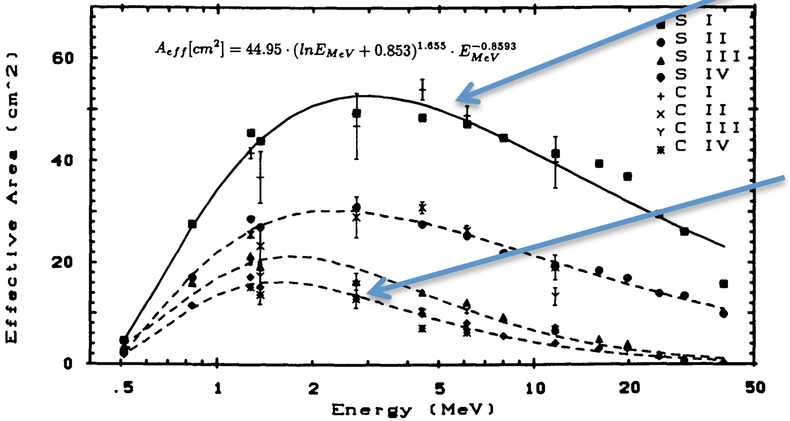
- 2nd of NASA's Great Observatories
- $\Delta E = 30$ **keV - 30 GeV**
- **17 tons** (heaviest astrophysical payload)
- Launched on **April 5, 1991** (Atlantis) on a low-Earth orbit (450 km)
- Forced re-entry on **June 4, 2000**

COMPTEL on CGRO (NASA)









Field of view: 1 sr
(8% of the sky)

Angular resolution:
5° FWHM @ 1 MeV
3° FWHM @ E>5 MeV

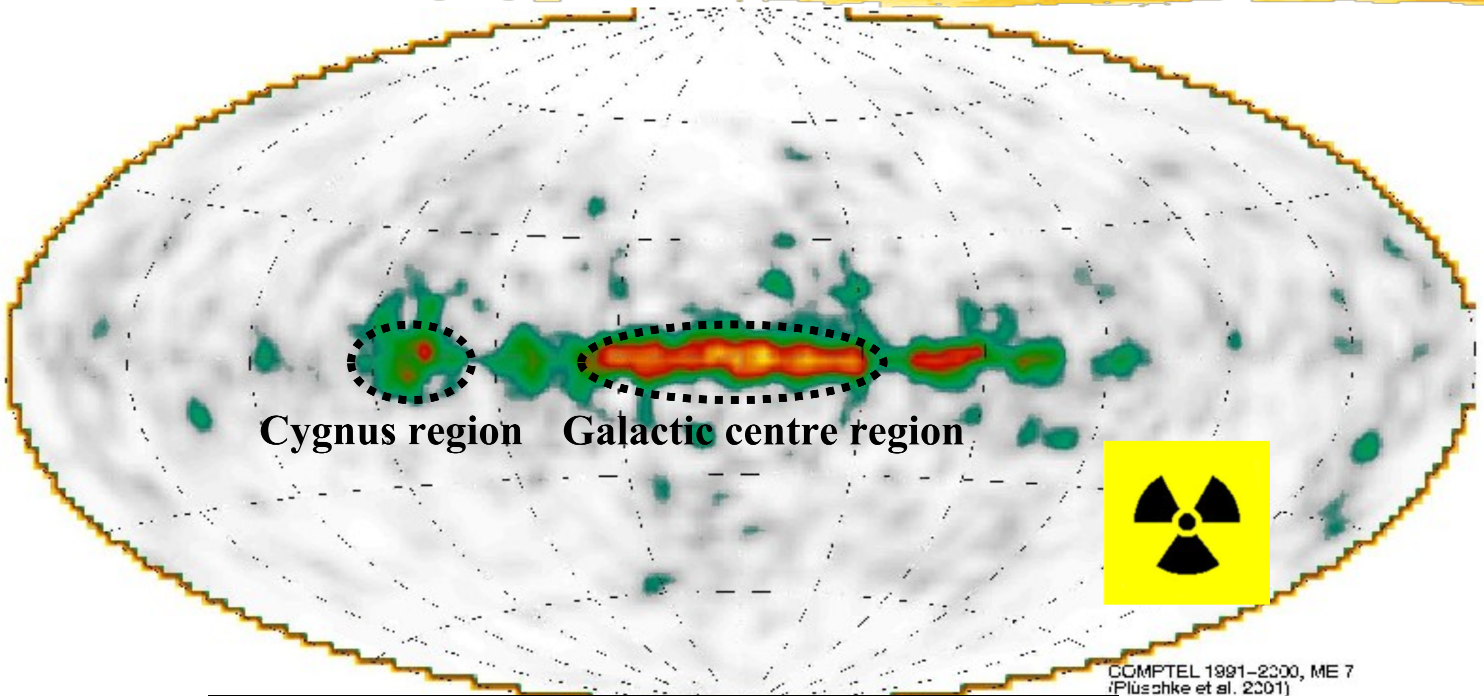
Energy resolution:
10% FWHM @ 1 MeV
(γ-ray line spectrometry)

Effective area before event selection:
< ~**50 cm^2**

Effective area after event selection:
< ~**10 cm^2**

Total mass: 1324 kg

First map of the Galactic radioactivity

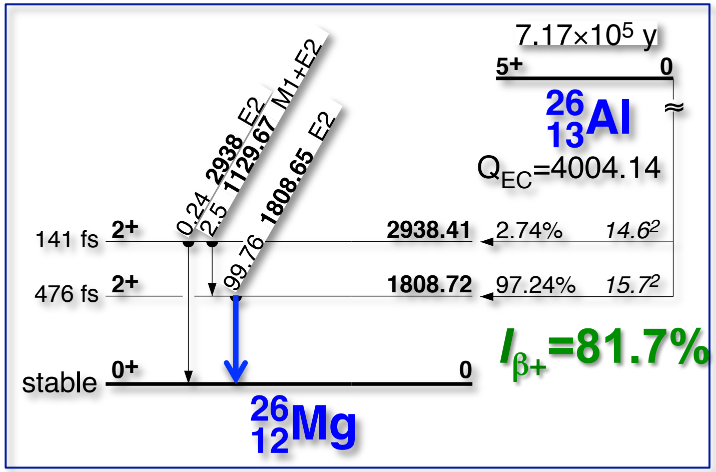


Representation of the Milky Way face-on

CGRO/COMPTEL ^{26}**Al** 1.8 MeV map,
9 years observing time (Plüschke et al. 2001)

- Accumulated mass of ^{26}Al in the Galaxy: **1.7 - 3 M_{sol}**
- ^{26}Al is mainly synthesized in massive stars and supernova explosions

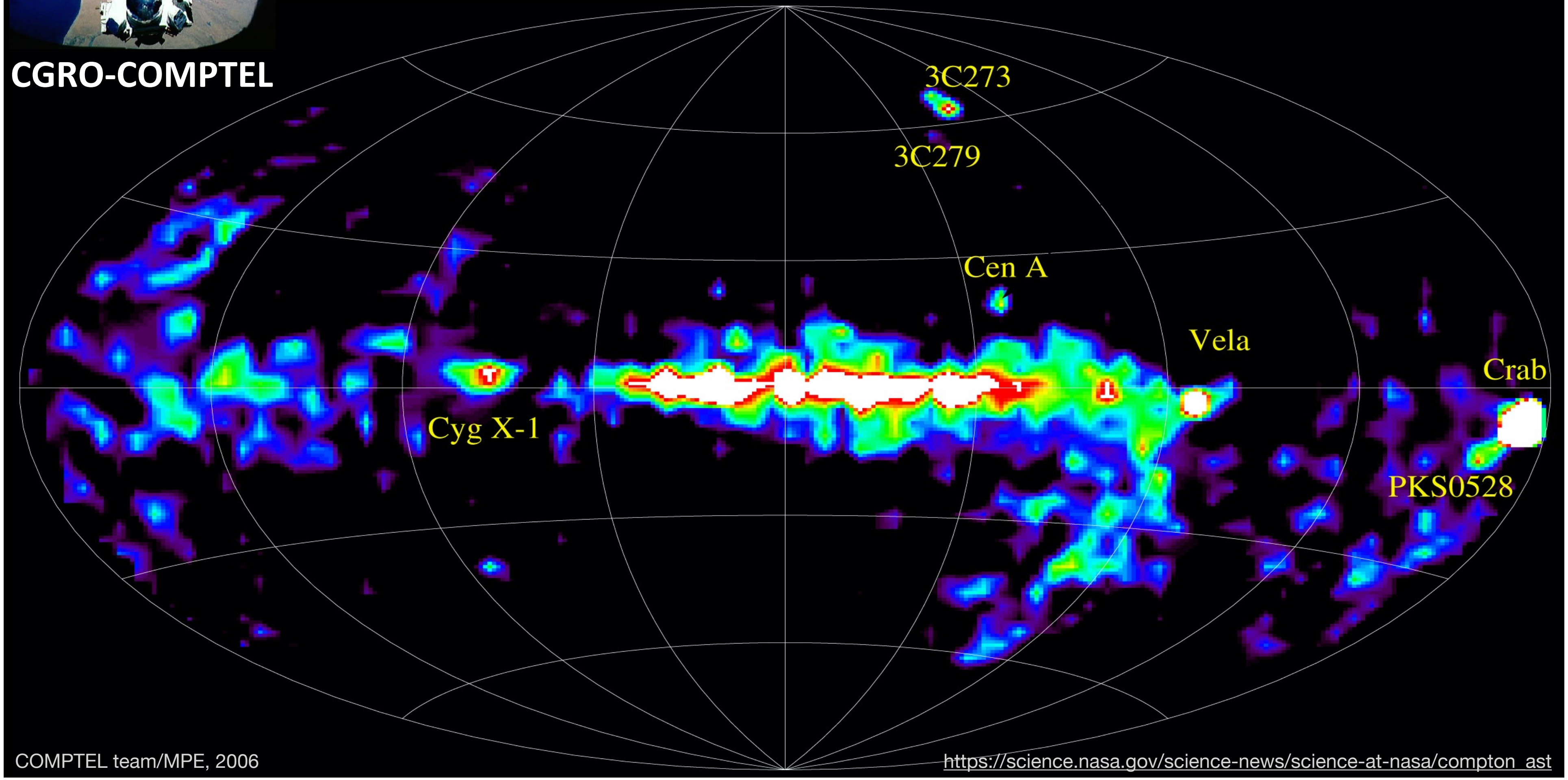
⇒ Core-collapse supernova rate in the Galaxy: **1.9±1.1 per century** (Diehl et al. 2006, 2021)



Gamma-ray sky in 1 - 30 MeV

CGRO-COMPTEL

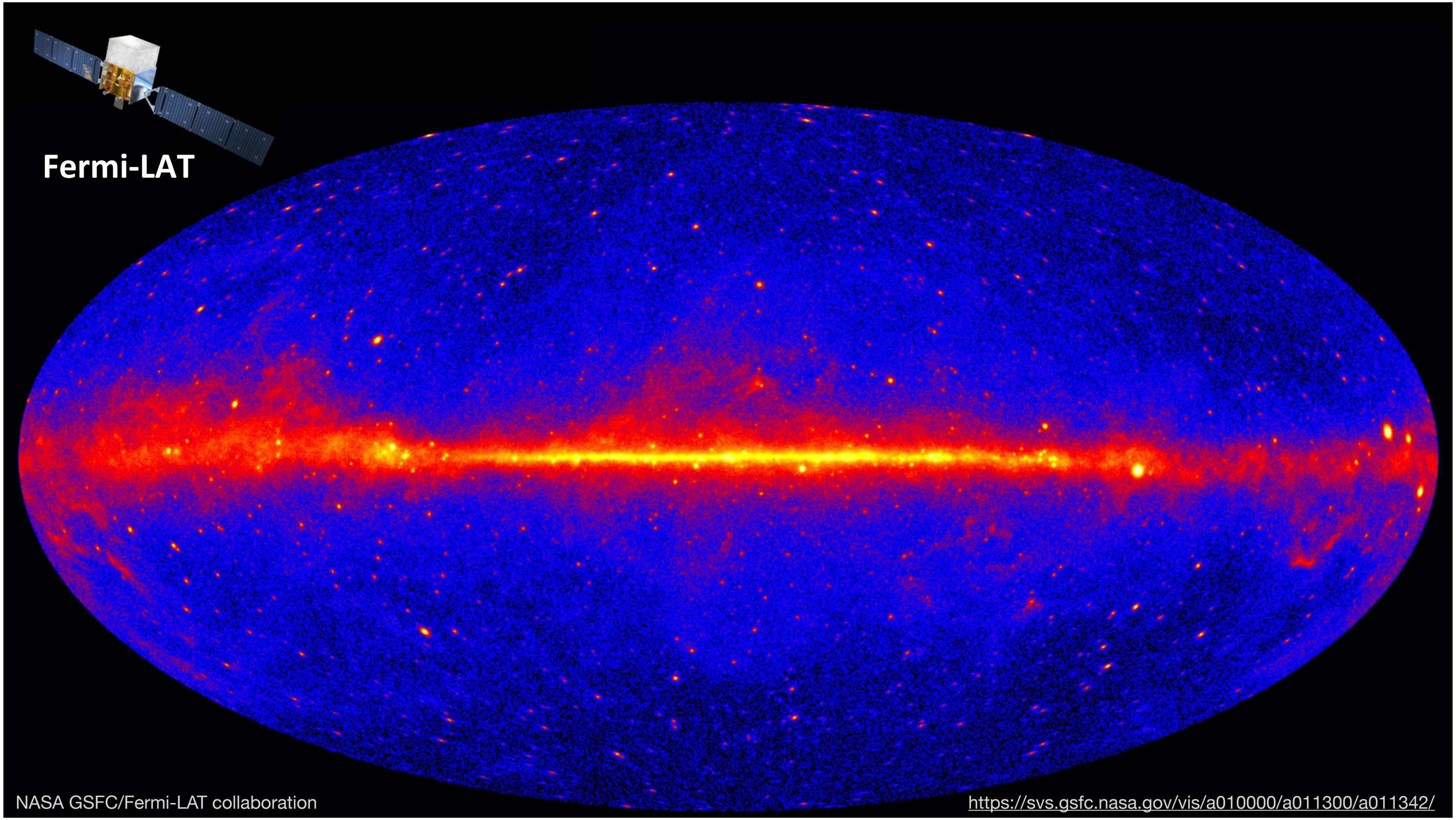
First catalogue of MeV sources (32 steady sources; Schönfelder et al. 2000)



COMPTEL team/MPE, 2006

https://science.nasa.gov/science-news/science-at-nasa/compton_ast

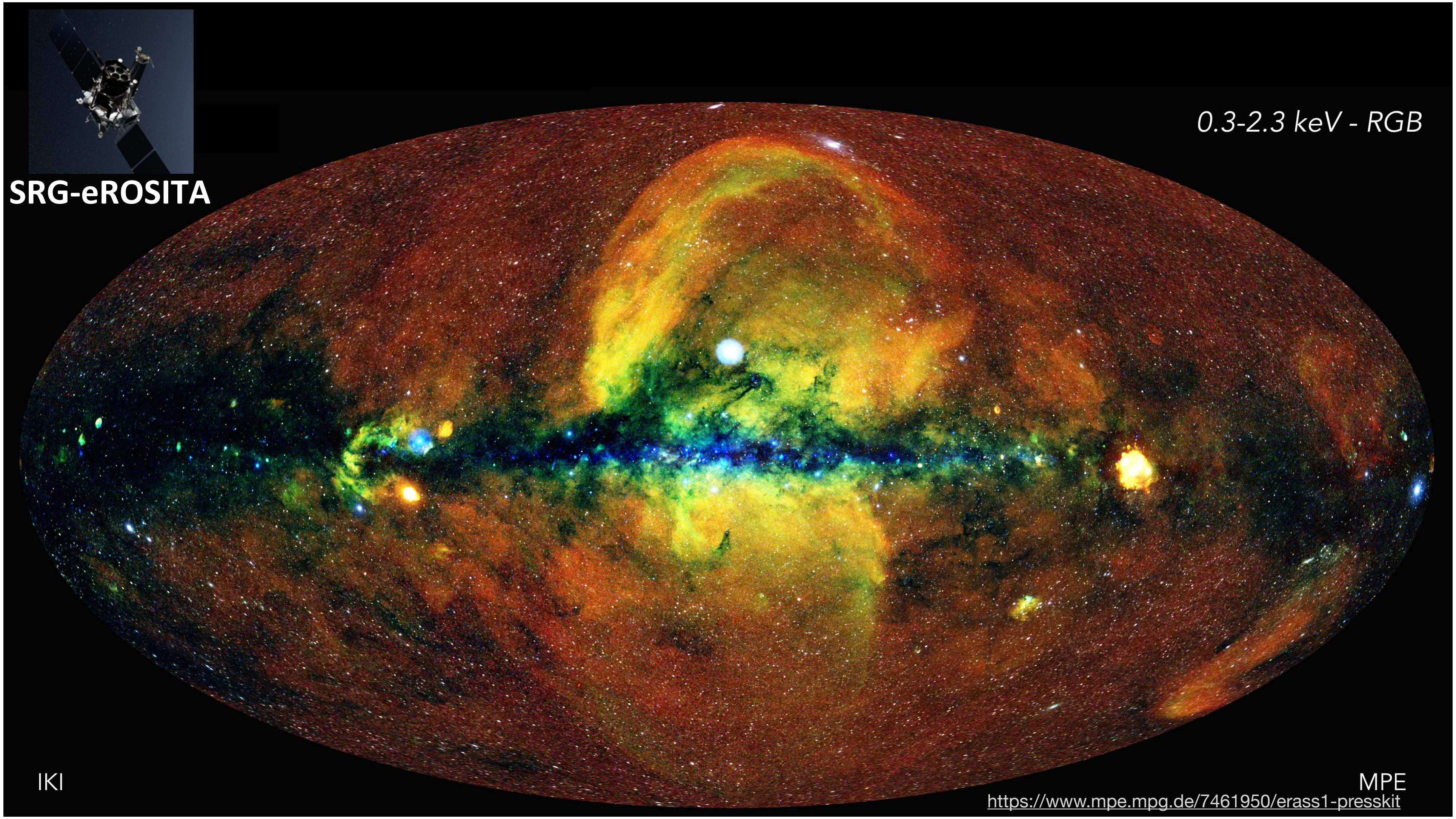
Gamma-ray sky > 1 GeV



NASA GSFC/Fermi-LAT collaboration

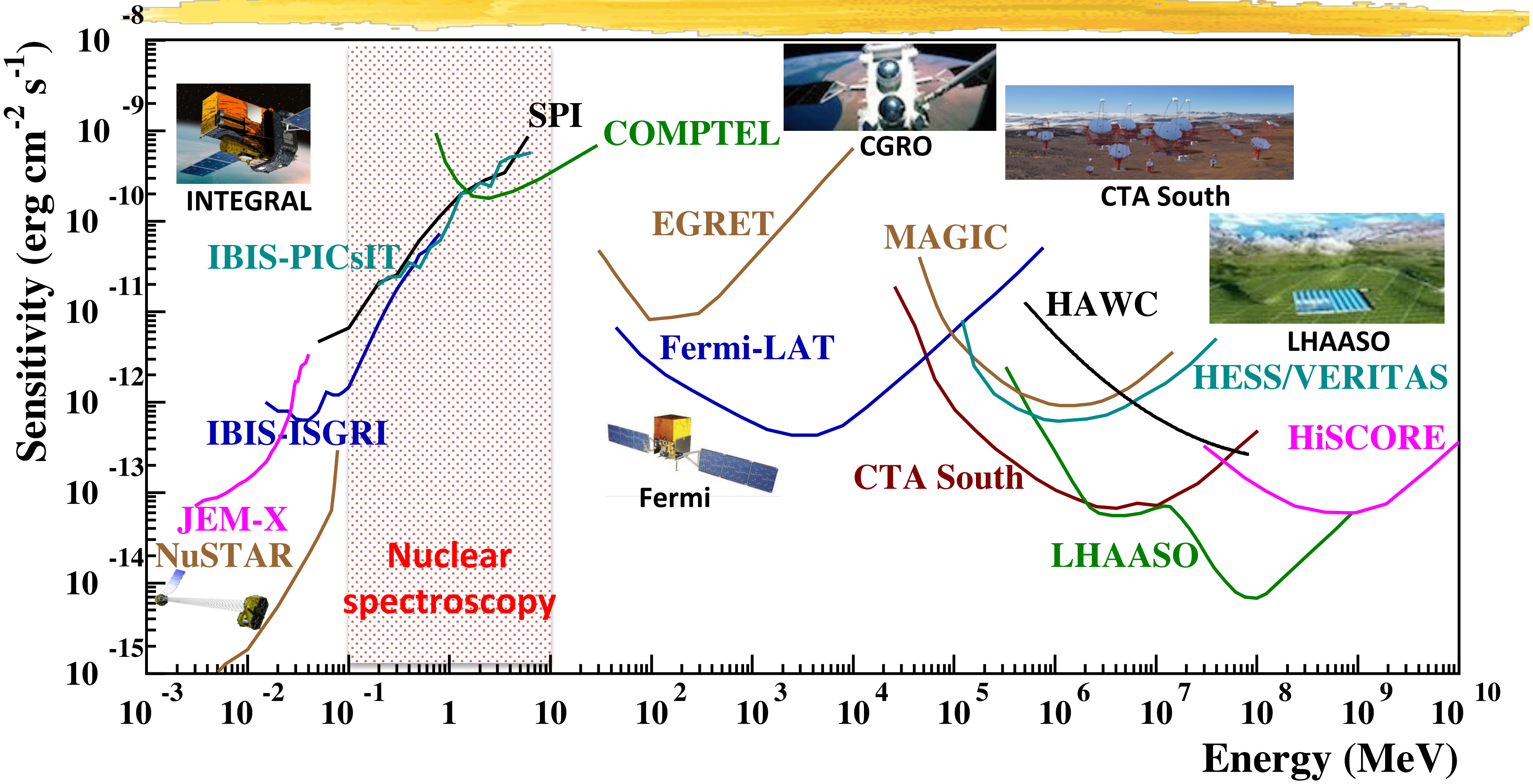
https://svs.gsfc.nasa.gov/vis/a010000/a011300/a011342/

X-ray sky in the keV range



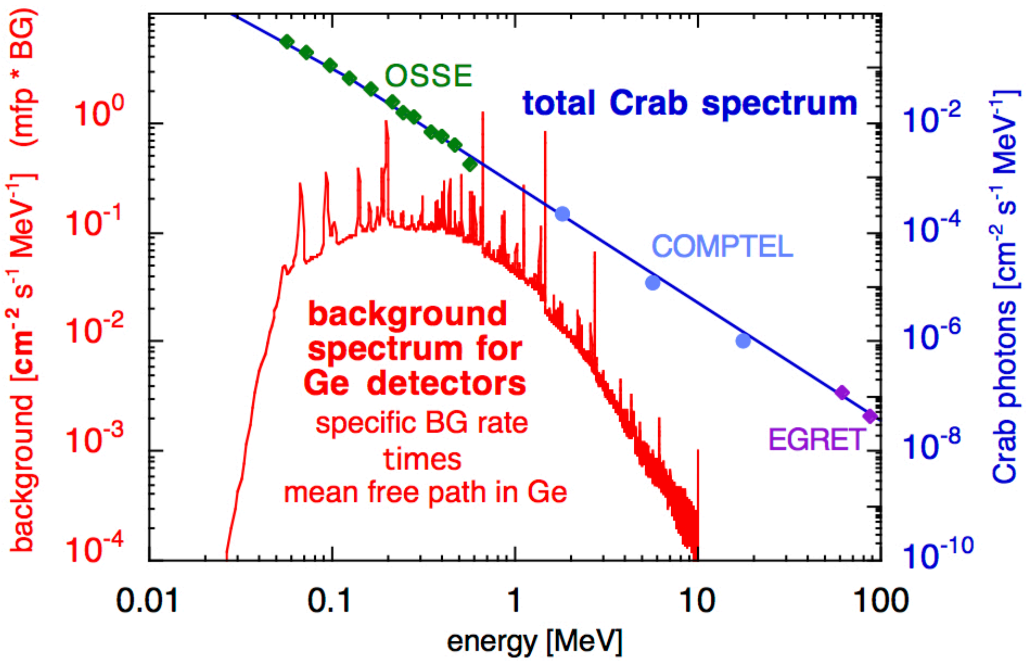
https://www.mpe.mpg.de/7461950/erass1-presskit

Gamma-ray astronomy in the MeV domain

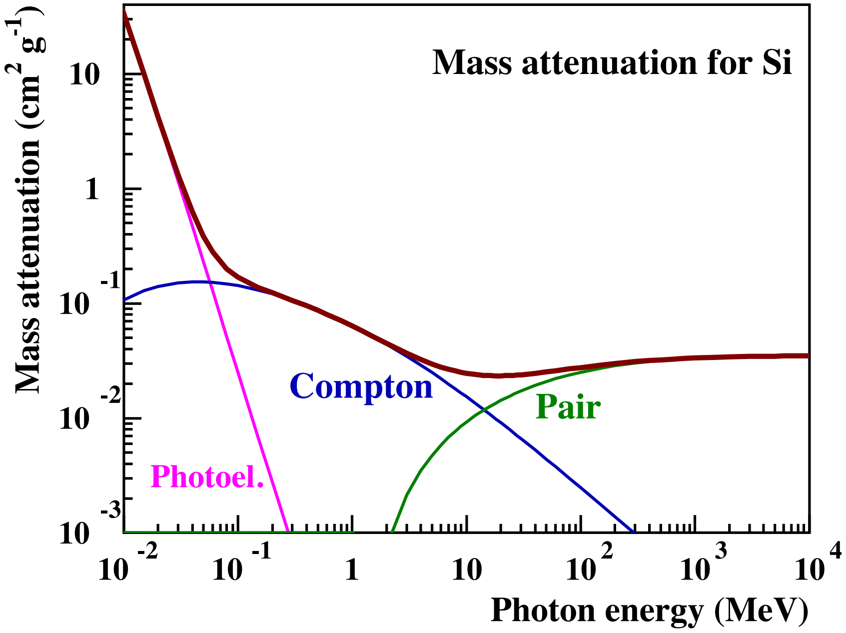


- **Worst covered part of the EM spectrum** (only a few tens of known steady sources so far between 0.5 and 30 MeV vs. 5500+ sources in the current Fermi/LAT catalog)
- Domain of **nuclear spectroscopy**
- Many objects have their **peak emissivity** in this range (GRBs, blazars, pulsars...)

Observational challenges for MeV γ-ray astronomy



- ☺ 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



Telescope concepts in MeV γ-ray astronomy

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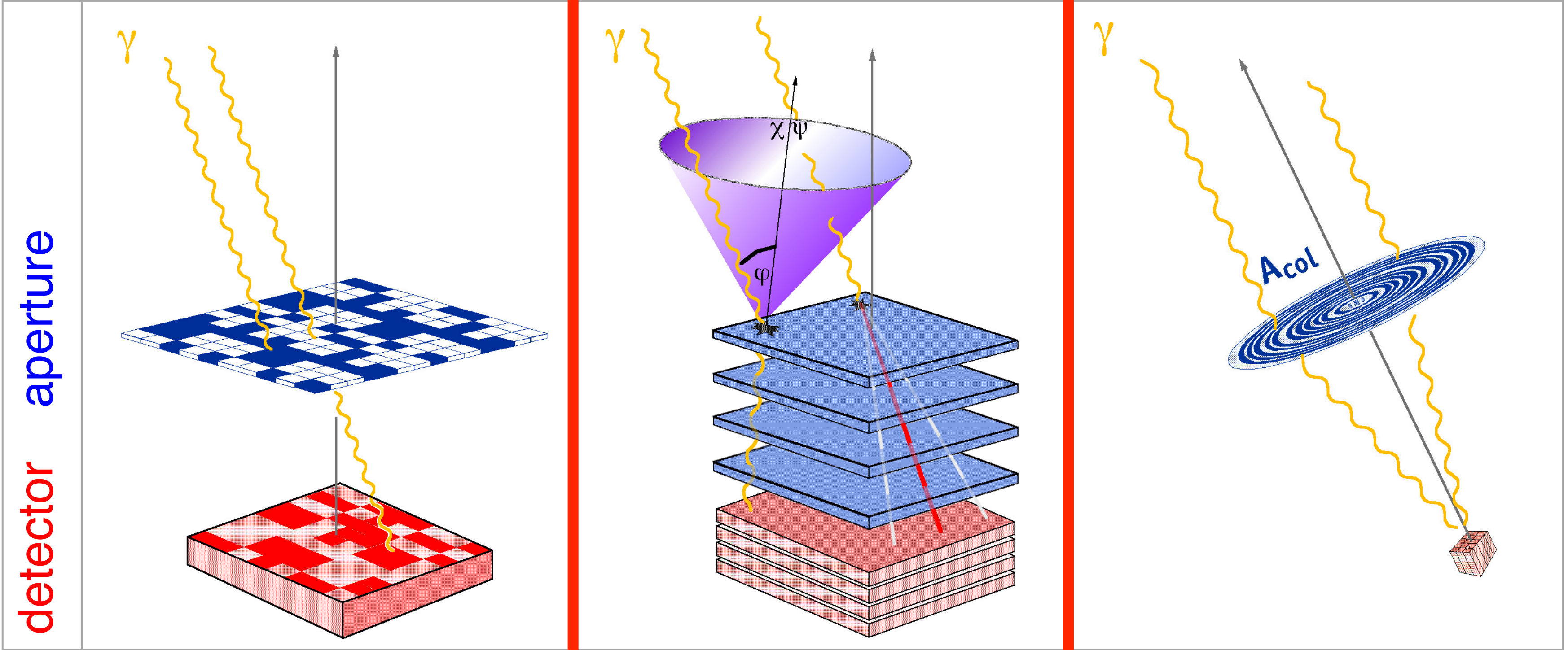
geometric optics absorption	**quantum optics** incoherent scattering	**wave optics** coherent scattering

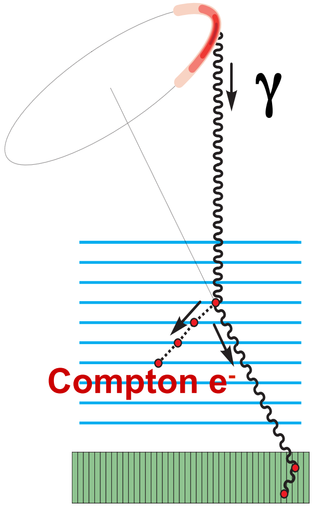


ex. coded masks "on-off" collimators	ex. Compton telescopes tracking chambers	ex. Laue lenses Fresnel lenses
Ex: *INTEGRAL*/SPI and IBIS	**Ex**: *CGRO*/COMPTEL	**Ex**: CLAIRE (IRAP)
☹ Background + ΔE range	☹ Limited angular resolution	☹ Small field-of-view + ΔE range

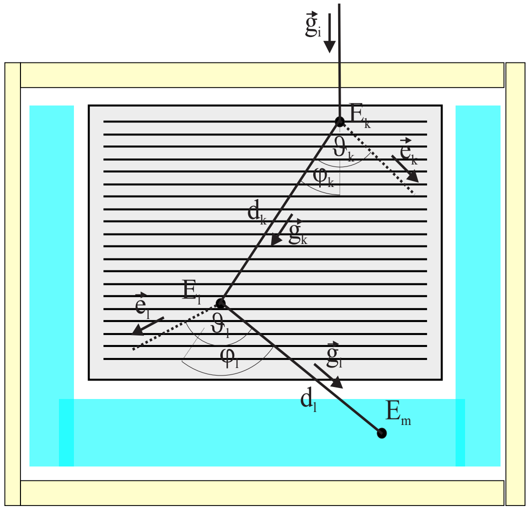
MEGA: First advanced Compton telescope

☐ **How to do better than COMPTEL?**

- **Compact design** to increase efficiency
- Measure the **direction of the recoil e-** (tracked Compton) to reduce the event circle to an arc and improve the S/N ratio
- Use **redundant information** to find the correct order of Compton scatters
- Improve the **3-D position resolution** (~1 mm^3)
- Improve the **spectral resolution** (~1%)

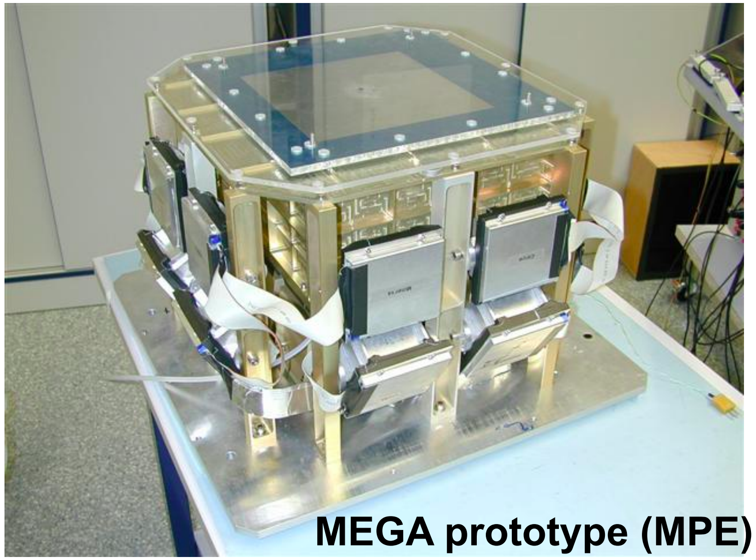


Tracked Compton



☐ **MEGA**: Medium Energy Gamma-ray Astronomy telescope (Kanbach et al. 2005)

- Stack **of double-sided silicon strip detectors** (DSSD) as the scattering & tracking detector
- **Pixelated CsI(Tl)/PIN diode** detectors for the absorption of the scattered radiation.

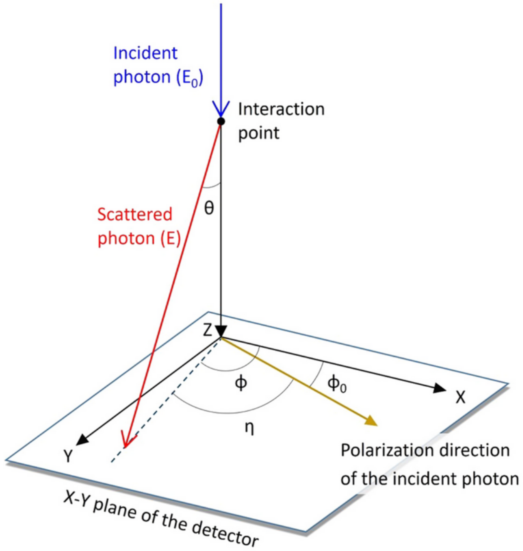


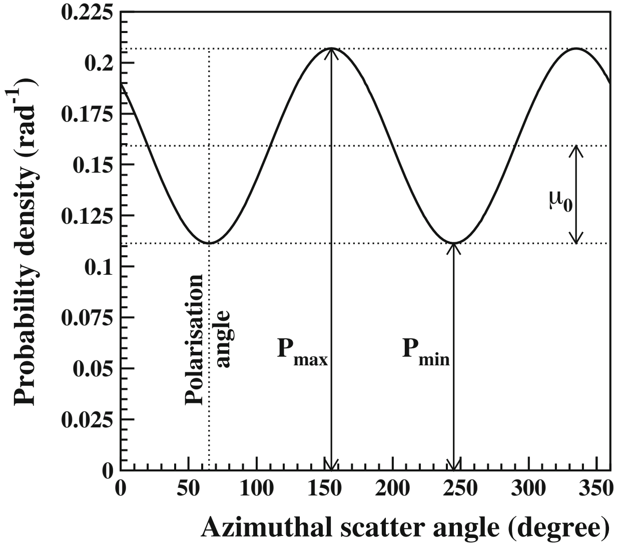
MEGA prototype (MPE)

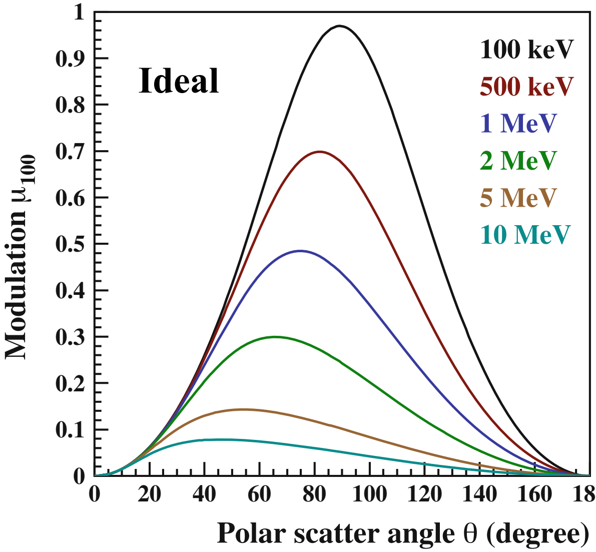
Polarimetry with a Compton telescope

Cross section for Compton scattering of a **linearly polarised** photon:

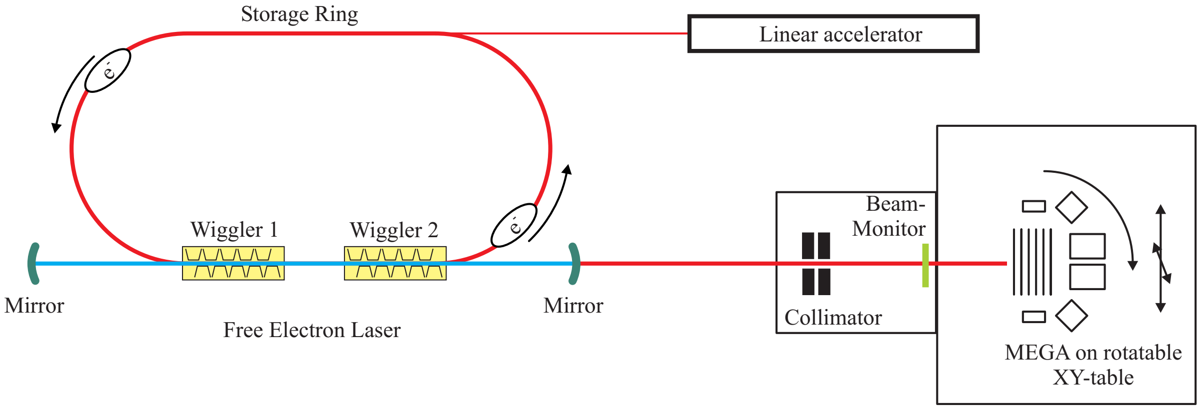
$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{KN}} = \frac{r_e^2\varepsilon^2}{2}(\varepsilon + \varepsilon^{-1} - 2\sin^2\theta \cos^2\eta)$$



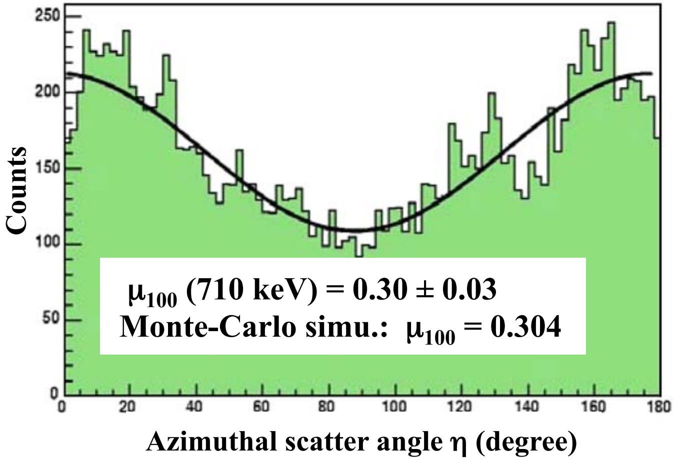




Calibration of the MEGA prototype with 100% polarized γ-rays produced at the High Intensity Gamma-ray Source (Duke Univ.)



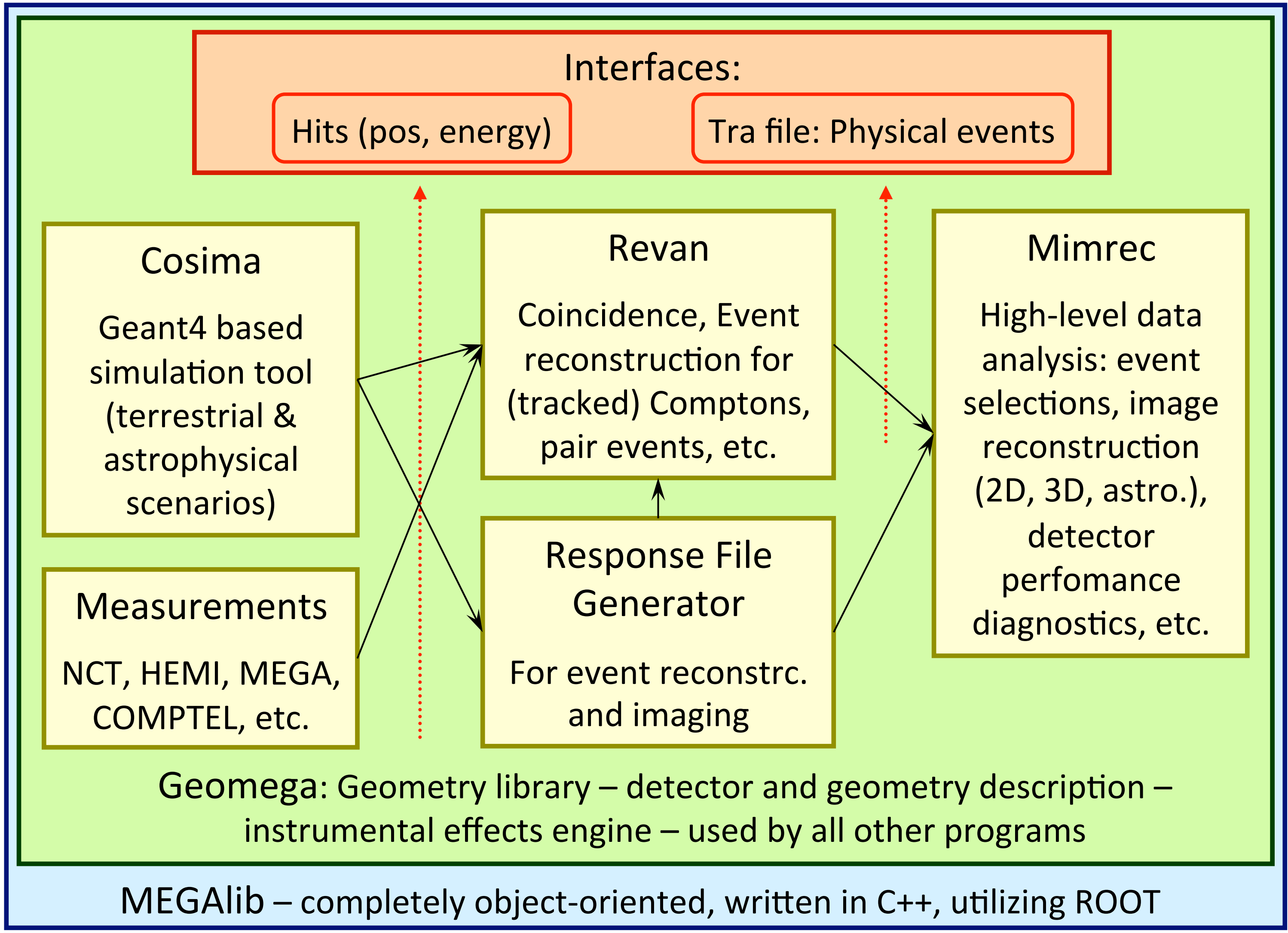
Geometry corrected polarization signature



μ_{100} (710 keV) = 0.30 ± 0.03
Monte-Carlo simu.: μ_{100} = 0.304

MEGAlib: megalibtoolkit.com

Lead developer: **Andreas Zoglauer** (MPE & Berkeley)



Interfaces:

Hits (pos, energy)

Tra file: Physical events

Cosima

Geant4 based simulation tool (terrestrial & astrophysical scenarios)

Measurements

NCT, HEMI, MEGA, COMPTEL, etc.

Revan

Coincidence, Event reconstruction for (tracked) Comptons, pair events, etc.

Response File Generator

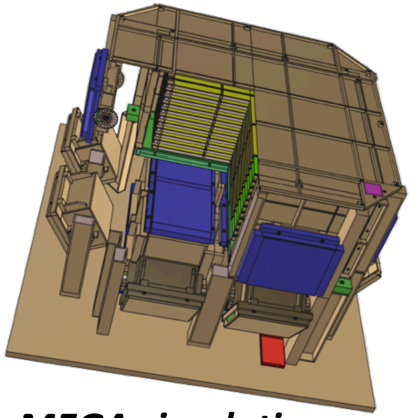
For event reconstrc. and imaging

Mimrec

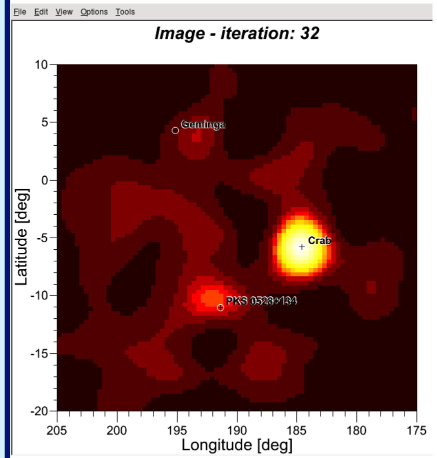
High-level data analysis: event selections, image reconstruction (2D, 3D, astro.), detector perfomance diagnostics, etc.

Geomega: Geometry library – detector and geometry description – instrumental effects engine – used by all other programs

MEGAlib – completely object-oriented, written in C++, utilizing ROOT

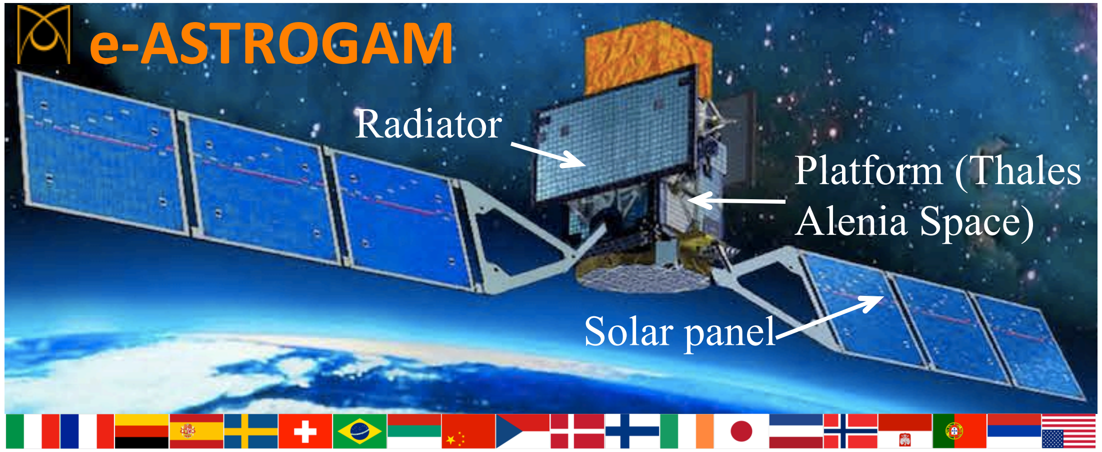


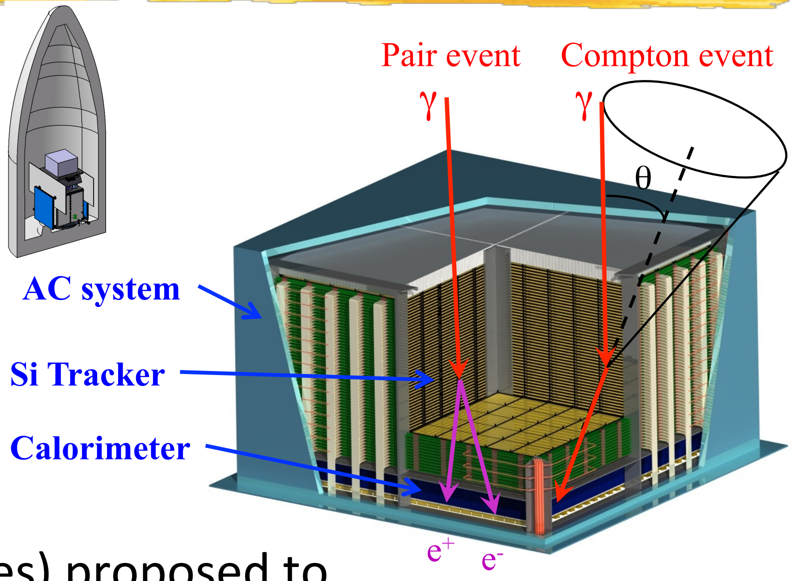
MEGA simulation geometry (Geomega)



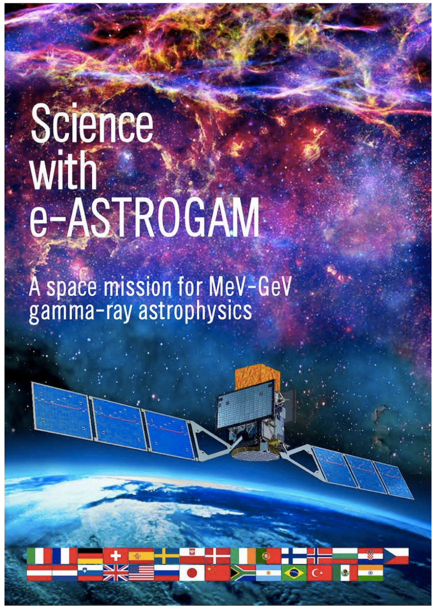
COMPTEL view of the Galactic anti-center (Revan+Mimrec)

From MEGA to e-ASTROGAM





- **Medium-size mission** (550 M€ + national agencies) proposed to the **European Space Agency** in 2017 (co-PIs: A. de Angelis & VT)
- Broad spectral range (100 keV - few GeV) with unprecedented sensitivity in the 1-30 MeV energy domain => **broad science case** (see https://arxiv.org/abs/1711.01265)
- Highly ranked by ESA but finally not selected
- Perspective: **European/Russian collaboration** where Russia would provide the launch and the satellite platform and Europe the gamma-ray telescope (with contributions from Ioffe & IKI)

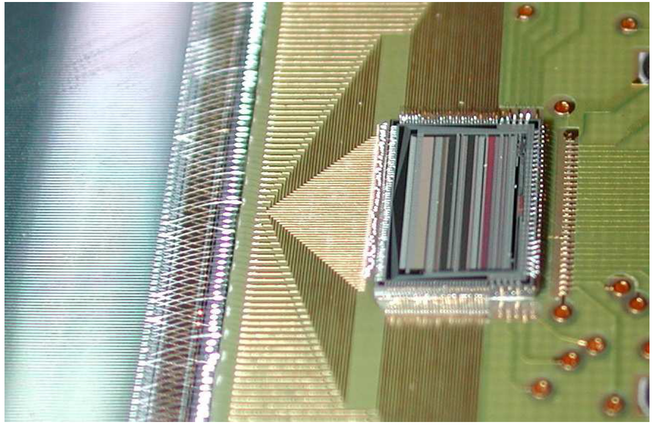


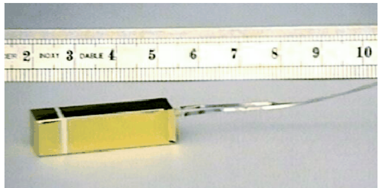
Science with e-ASTROGAM

A space mission for MeV-GeV gamma-ray astrophysics

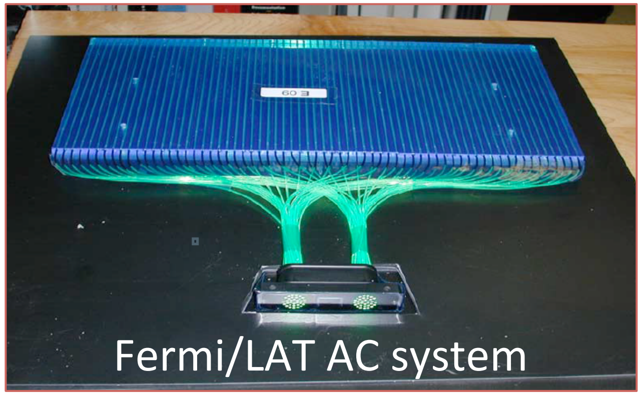
e-ASTROGAM payload

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



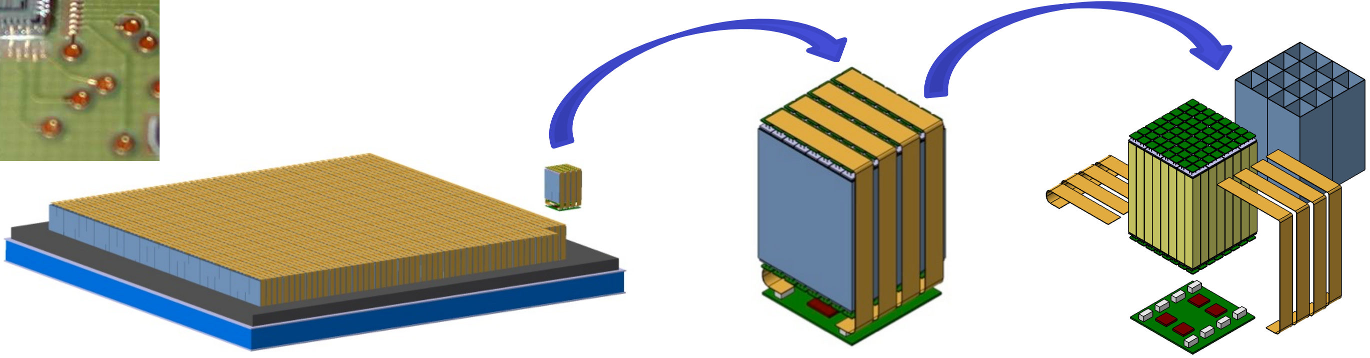


PICSiT CsI(Tl) pixel



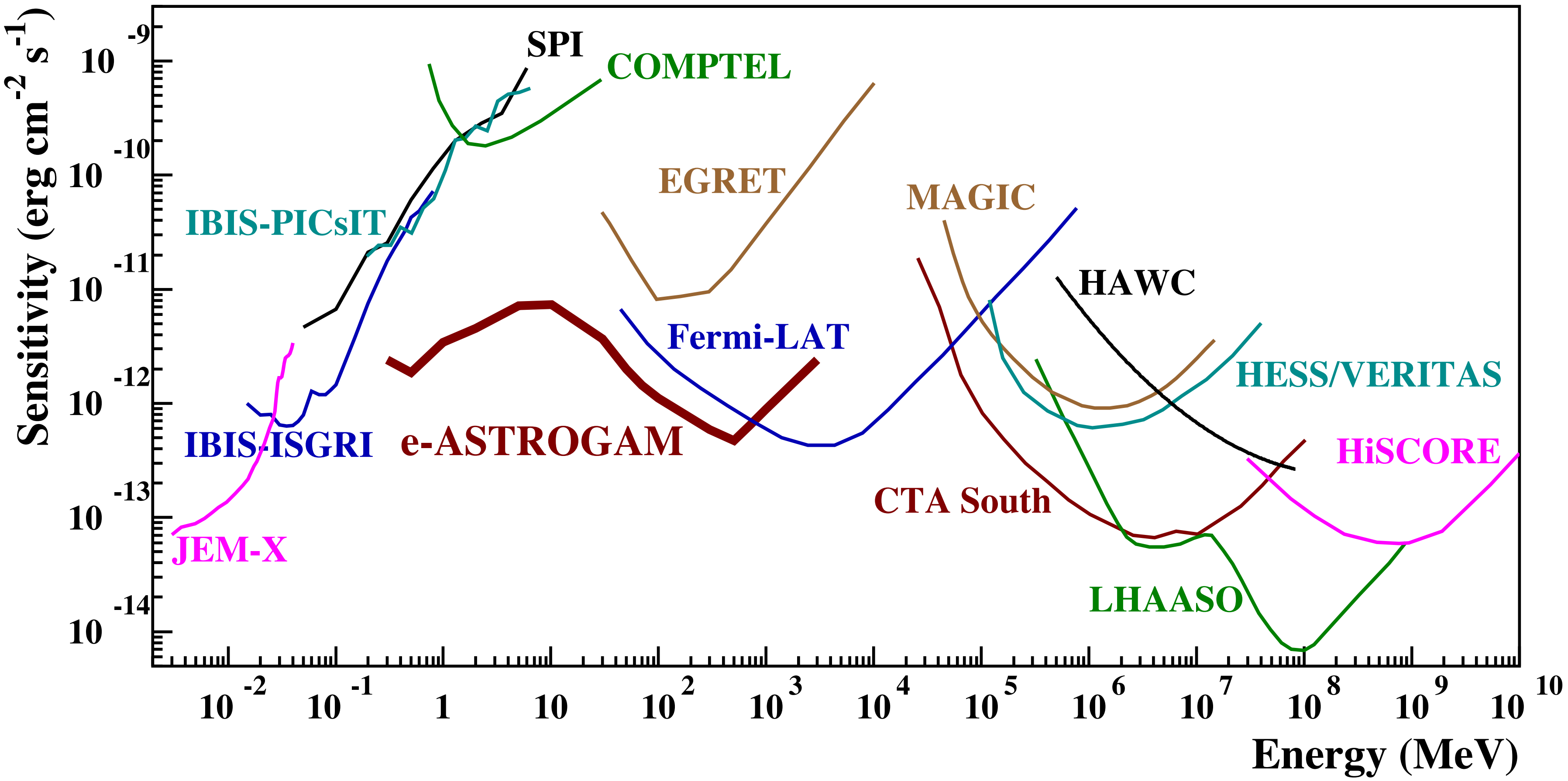
Fermi/LAT AC system

- **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

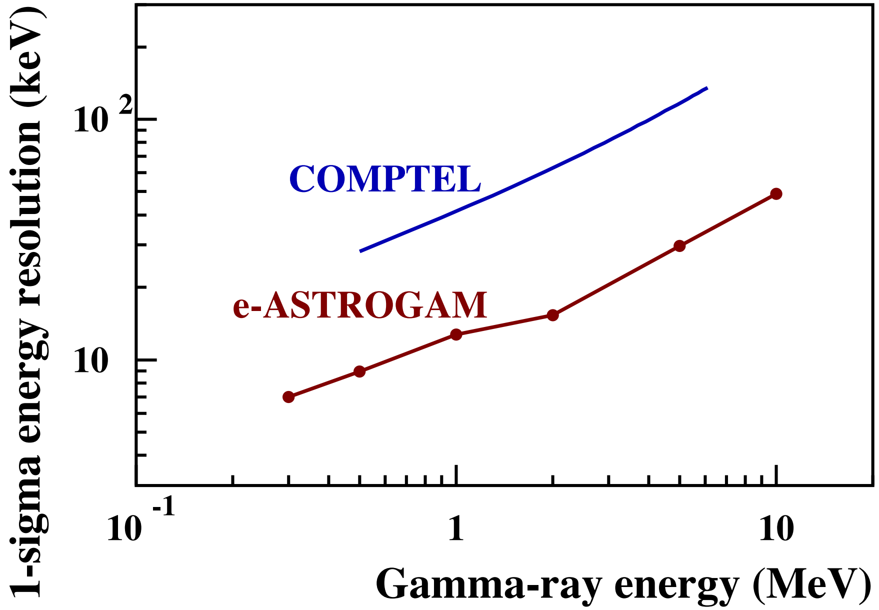


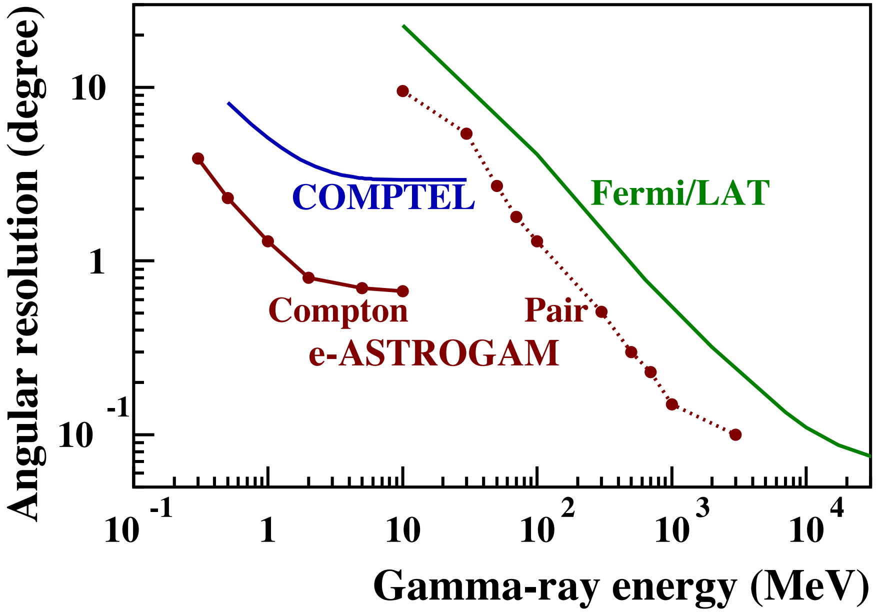
- **Calorimeter**: 33 856 CsI(Tl) bars coupled at both ends to low-noise Silicon Drift Detectors
- **Anti-coincidence detector**: segmented plastic scintillators coupled to SiPM by optical fibers
- **Heritage**: AGILE, Fermi/LAT, AMS-02, INTEGRAL, LHC/ALICE…

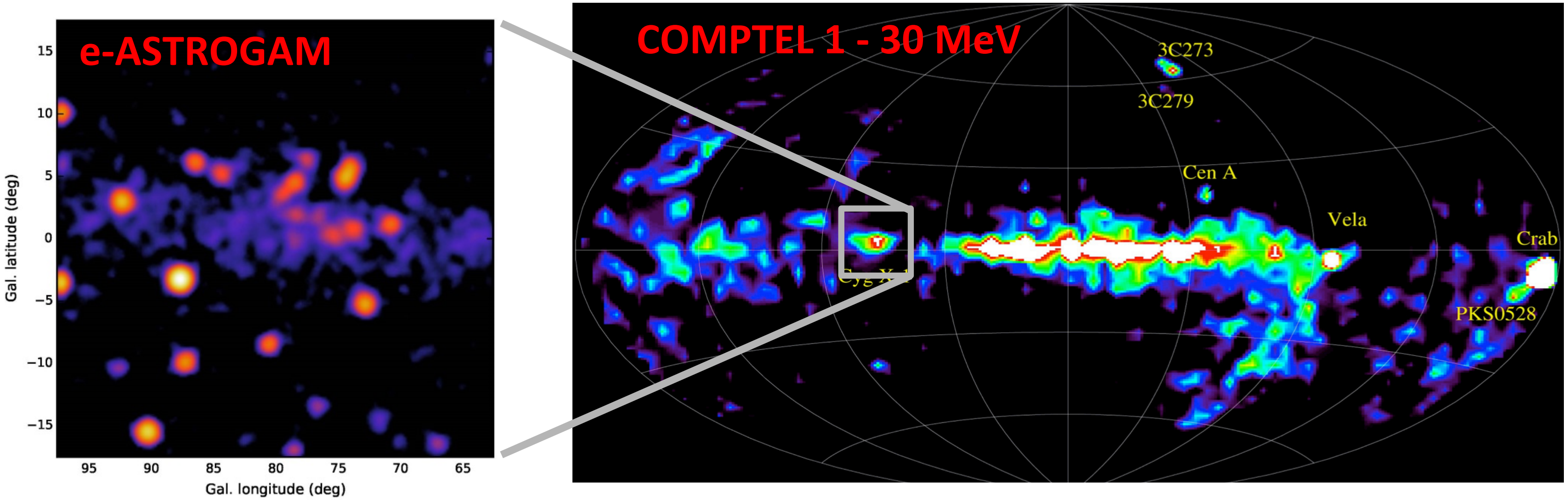
e-ASTROGAM simulated performance



e-ASTROGAM simulated performance







Advanced Compton telescopes in the US

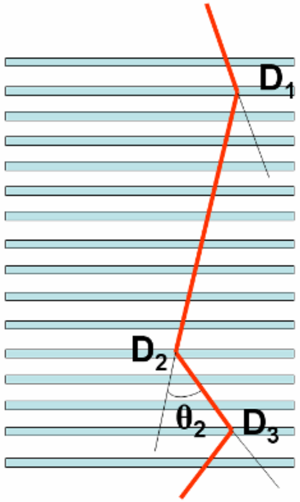
- NASA Vision Mission Concept Study **in 2005** to study promising technologies for an **Advanced Compton Telescope** (Boggs et al. https://arxiv.org/abs/astro-ph/0608532)
- Instrument mass, power and dimension constraints (assuming launch with Delta IV): 1850 kg, 2000 W, 4 - 5 m
- "Science performance" parameter: sensitivity to the 847 keV line (^{56}Co) from SN Ia

Si/ Ge	Ge	Si / CdZnTe	Si	Liquid Xe	Xe / LaBr$_3$	Plastic / LaBr$_3$
NRL / Berkeley	Berkeley	Berkeley	NRL	Colombia / Rice Univ.	GSFC / New Hampshire	New Hampshire
D1: 27 layers of 2-mm thick 10x10 cm^2 DSSDs (3888 detectors) **D2**: 4 layers of 16-mm thick 9.2x9.2 cm^2 Ge cross-strip (576 detect.)	**D1/D2**: 6 layers of 10x18 Ge cross-strip detectors, each 9.2x9.2 cm^2 and 16-mm thick (1080 detect.)	**D1**: 4x4 towers with 80 layers of 150-μm thick 10x10 cm^2 DSSDs (20 480 detectors) **D2**: arrays of 2x2x2 cm^3 CZT (~102 000 pixels)	**D1/D2**: 3x5 towers with 64 layers of 3-mm thick 10x10 cm^2 DSSDs (15 360 detectors)	**D1/D2**: 6x6 towers of Liquid Xe TPC, each 3-cm (7-cm) thick for D1 (D2) and 22x22 cm^2 area, each viewed by 64 1'' PMTs	**D1**: 2x2x4 gas Xe TPC of 80x80x50 cm^3 read out by μ-well det. **D2**: arrays of 5x5 mm^2 LaBr$_3$ 8-cm (4-cm) thick on the bottom (sides) (322 000 det.)	**D1**: 5 layers of 60x60 cubes of plastic scintillat., each 2x2x2 cm^3 (18 000 detect.) **D2**: 4 layers of 60x60 cubes of LaBr$_3$, each of 2x2x2 cm^3 (14 400 detect.)

From NRL ACT to the CAPSiTT proposal

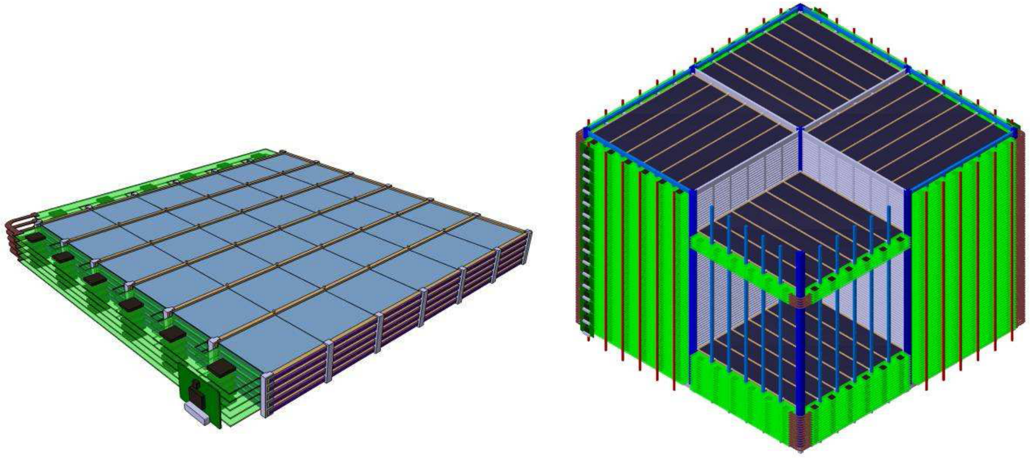
- **3-Compton technique** can provide the incident γ-ray energy **without measuring the full energy deposit**: $E_1 = D_1 + \frac{\overbrace{D_2 + \left[D_2^2 + \frac{4 m_e c^2 D_2}{1 - \cos\theta_2} \right]^{\frac{1}{2}}}^{E_2}}{2}$

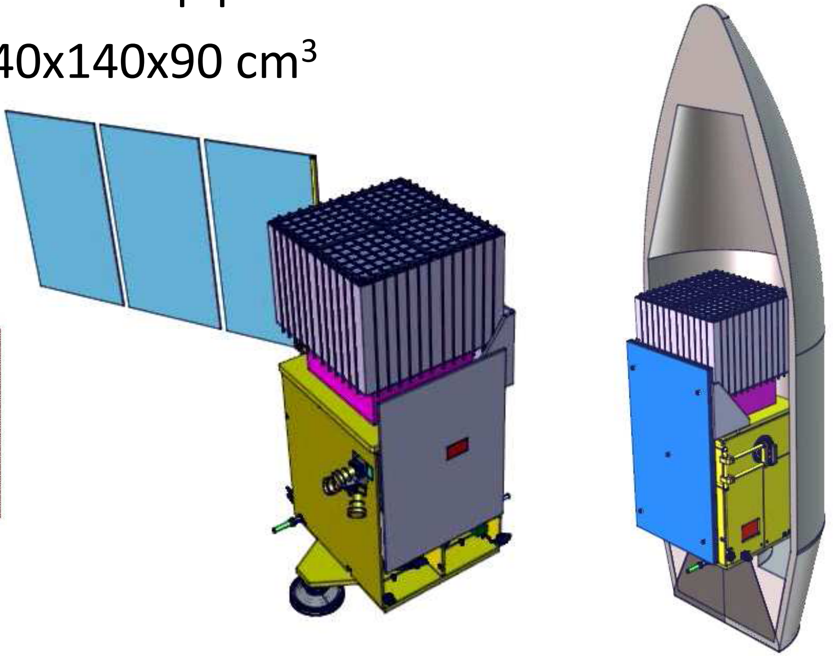
⇒ "Light" Compton telescope with **no calorimeter**



○ **CAPSiTT**: Medium-size mission proposal to ESA in 2010 (PI: F. Lebrun)

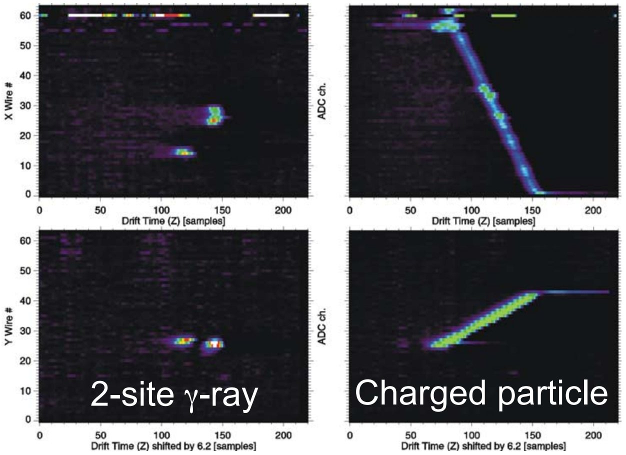
- Tracker: 4 towers with 80 layers of 6x6 Si DSSDs (11520 detectors)
- Each DSSD is 10x10 cm^2 and **2-mm thick**, with a strip pitch of 1.5 mm
- Mass: 920 kg (!), Power: 338 W, Volume: 140x140x90 cm^3
- Not selected by ESA (DSSD procurement?)

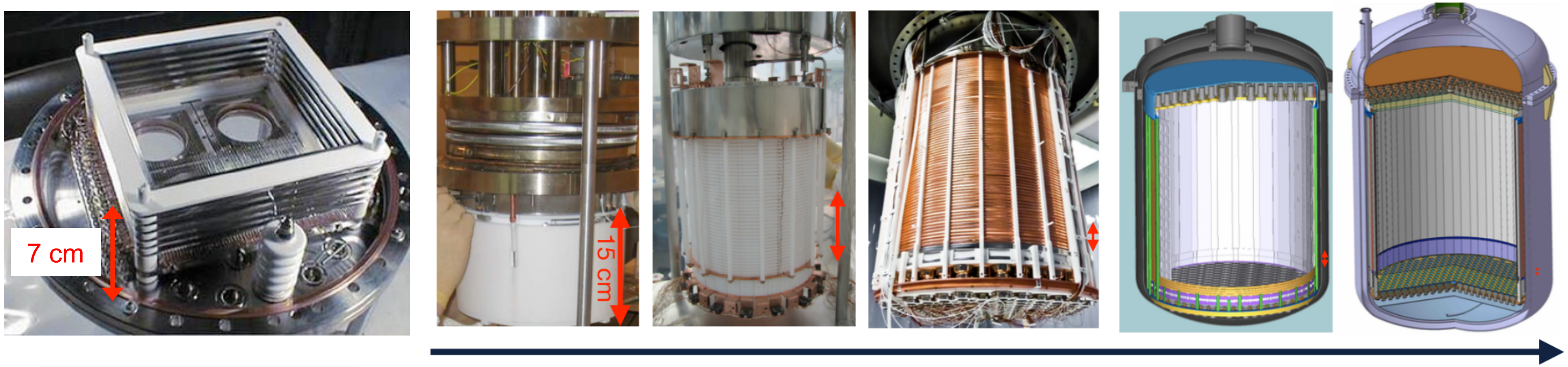




From LXeGRIT ACT to the DARWIN Experiment

- **LXeGRIT**: Liquid Xenon Gamma-Ray Imaging Telescope (Aprile et al. 2004)
- Both ionization and scintillation signals used to measure the 3-D position and energy, and **reject background**
- **Successful balloon flights** in (1997, 1999, and) 2000: measurement of the atmospheric γ-ray background
- **XENON/DARWIN**: best sensitivity to **WIMP dark matter**

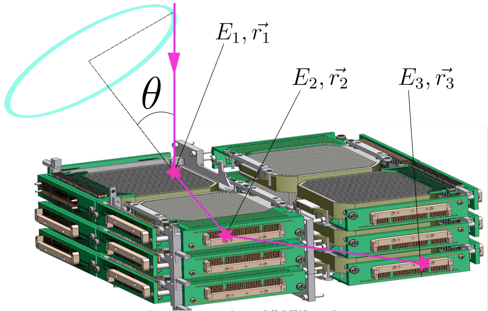


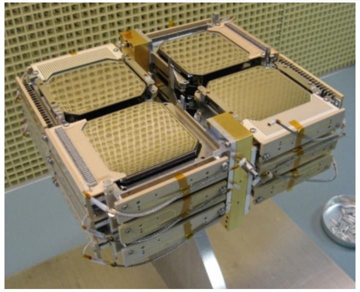


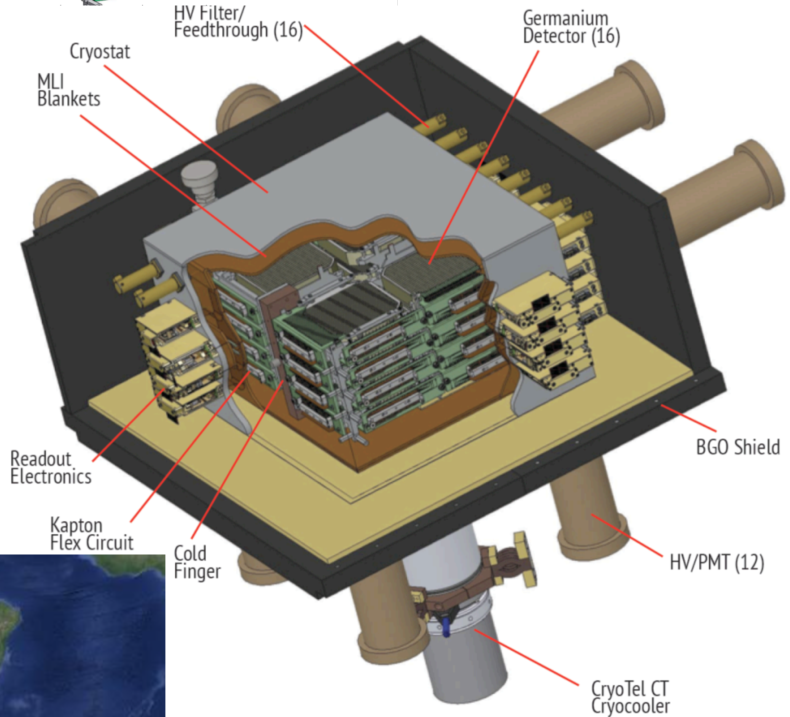
LXeGRIT	XENON10	XENON100	XENON1T	XENONnT	DARWIN
~1988 – 2004	2005 – 2007	2008 – 2016	2012 – 2018	2019 – 2023	2025 –
21 kg	~15 kg	~62 kg	~2 t	~5.9 t	40 t
7 cm	15 cm	30 cm	1 m	1.5 m	2.6 m

COSI: The Compton Spectrometer and Imager

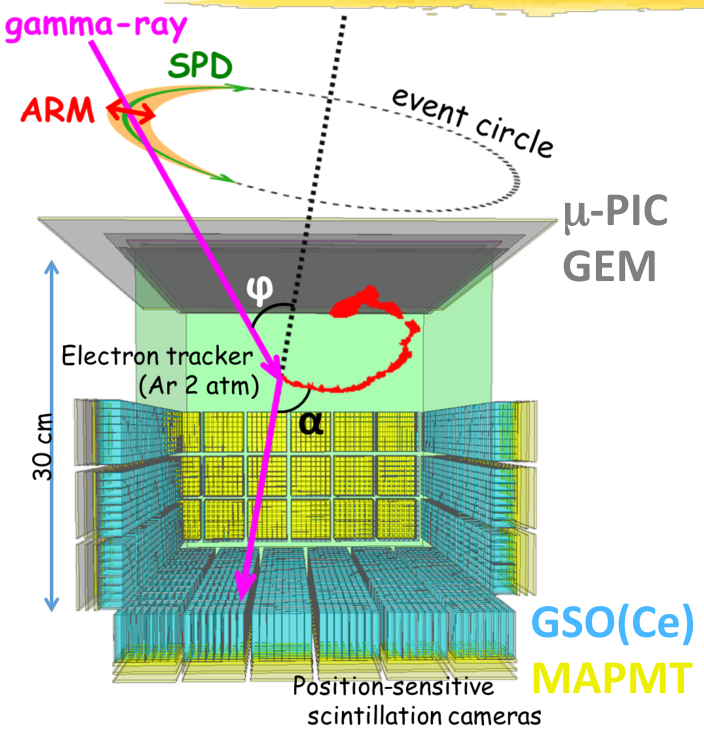
- **COSI**: Compton Spectrometer and Imager (Tomsick et al. 2019)
- **Selected as a NASA's Small Explorer (SMEX) mission in Oct. 2021 for a launch in 2025**
- 16 **crossed-strip Ge** with 3-D position resolution, each 8x8x1.5 cm^3 with 2x64 strips, cooling (-77° K) using a Stirling cryocooler
- ΔE=0.2–5 MeV (radioactivities + polarization), FOV=25% sky, Δθ=3.2° FWHM @ 511 keV
- Balloon experiments in 2005, 2009, 2014 and **2016** (46-day flight; Kierans et al. 2017)





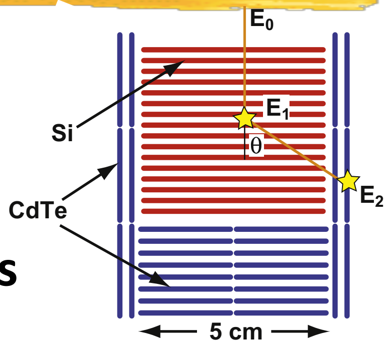


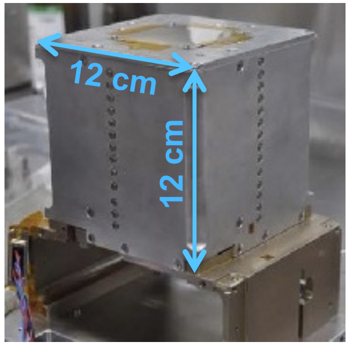
Advanced Compton telescopes in Japan

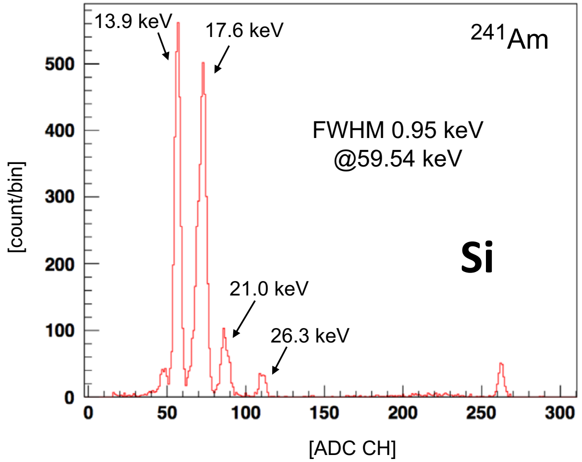


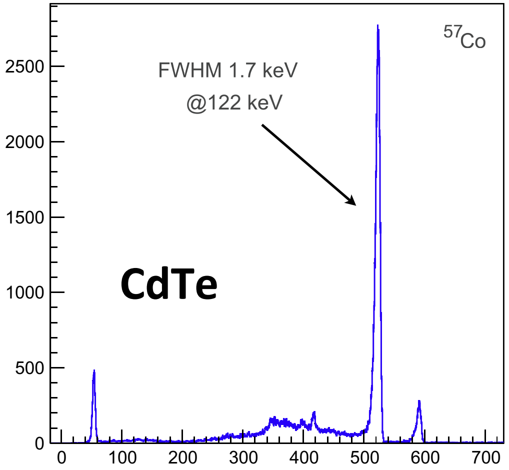
- **SMILE**: Sub-MeV/MeV γ-ray Imaging Loaded-on-balloon Experiments
- Ar TPC of 30x30x30 cm^3 => **Compton e- tracking**
- **Balloon flights** in 2006 & 2018 (Takada et al. 2021)

- **Si / CdTe camera** (Takahashi et al. 2002; Watanabe et al. 2014)
- Si: 16x16 **pixels** of 3.2x3.2 mm^2 => 5.12x5.12 cm^2; CdTe: 8x8 **pixels**
- 32 layers of Si (0.6 mm thick) and 8+2 (side) layers of CdTe (0.75 mm)
- $\Delta E=60-600+$ keV with $A_{eff}\sim4$ cm^2 @ 100 keV, $A_{eff}\sim0.8$ cm^2 @ 511 keV
- Spectral resolution: **1.6% FWHM @ 662 keV** (low noise VATA ASIC)



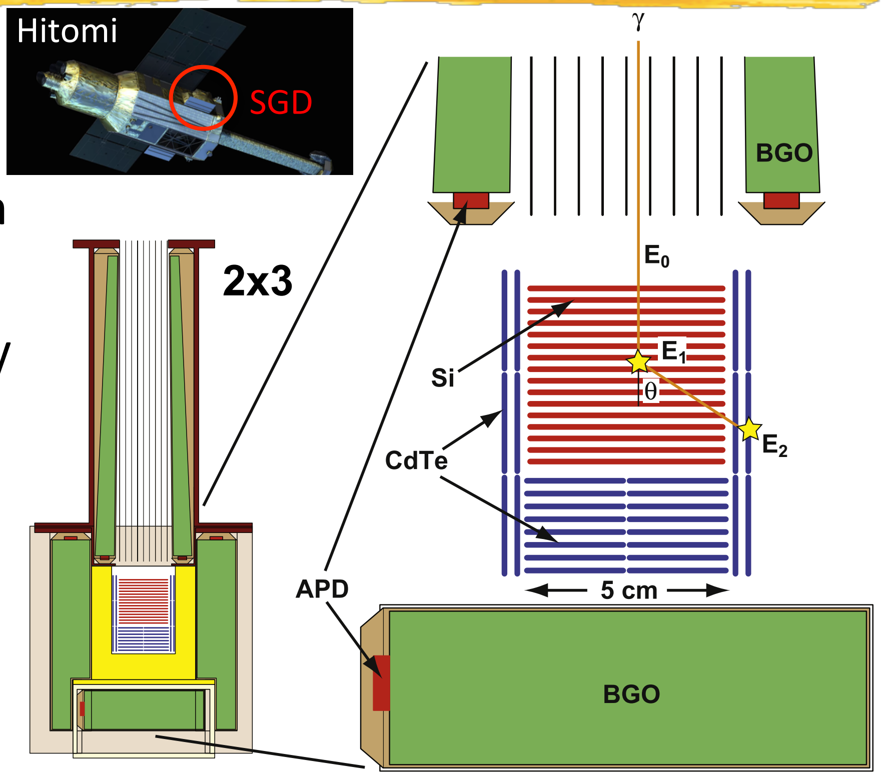






SGD aboard Hitomi & ASTROCAM

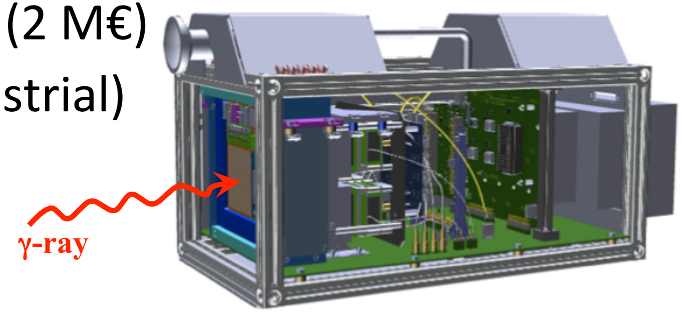
- **SGD**: Soft Gamma-ray Detector (first semiconductor Compton camera in orbit)
- **Narrow-FOV Compton telescope** (~0.6°) with excellent (activation) background rejection
- Mass: 2x158 kg (two sides); power: ~24.5x2 V
- Launch of **Hitomi** satellite on Feb. 17, 2016, start of nominal observations on March 24, spacecraft contact lost on March 26, 2016 ☹
- **Polarimetry of the Crab nebula** with 5 ks exposure time (Hitomi Coll., PASJ **70**, 2018)



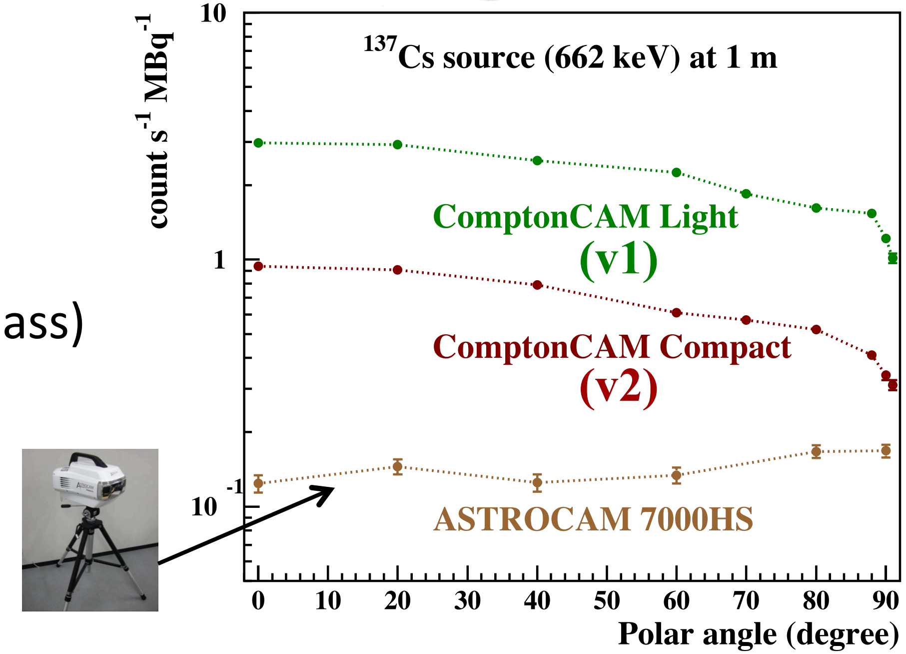
- Release of the **ASTROCAM Compton camera** (8+4 Si+ CdTe layers) by Mitsubishi Heavy Industries *Ltd.* after the Fukushima accident (Matsuura et al. 2014)

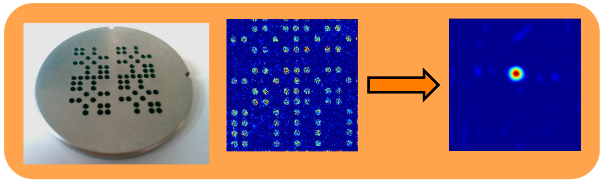
ComptonCAM

- **Development of a portable gamma camera of Compton type for decommissioning of nuclear facilities**
  - **Public-private partnership** led by **IJCLab** with 2 SMEs (Systel Electronique & THEORIS), funded by Andra - PIA (2 M€)
  - From TRL 3 (proof of concept) to TRL 8 (pre-industrial)
  - Two **patents** in the pipeline



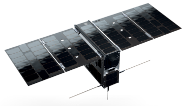
- **Advantage of a Compton camera over pinhole or coded mask devices**
  - Larger field of view (close to 2π sr)
  - Better response above 1 MeV for the detection of ^{60}Co (radioactive waste)
  - Larger detection area (for the same mass) ➔ better sensitivity

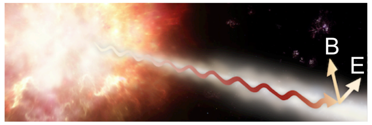




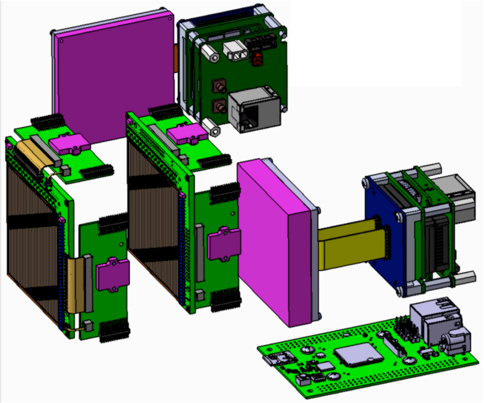
COMCUBE

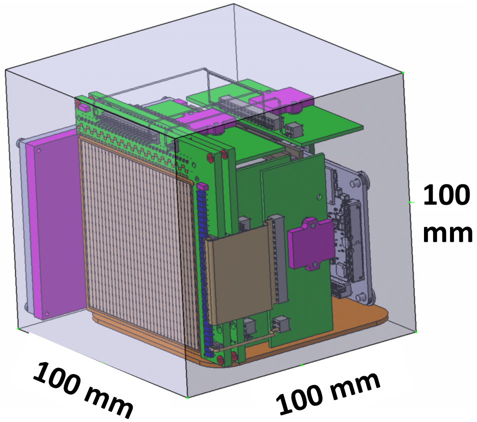
- **Compton Telescope CubeSat mission project for**
  - **Space qualification** of crucial technologies (DSSSD, Calorimeter module)
  - Gamma-ray sky monitoring for **multi-messenger astronomy**
  - **Gamma-ray burst polarimetry**

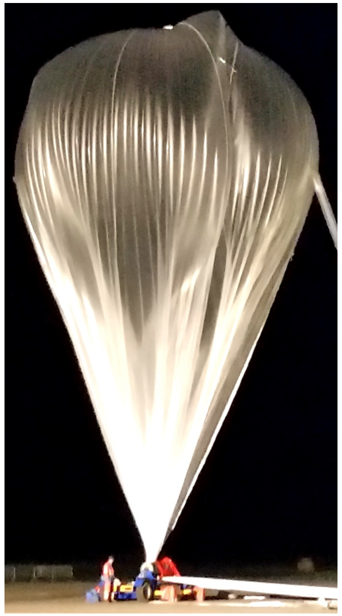




- **COMCUBE 1U: balloon flight qualification of a 1U Payload model**
  - Funded by the EU H2020 program AHEAD2020 until 2023 (WP11, 420 k€)
  - Coll.: **IJCLab**, UCD (Dublin), CEA-IRFU (Saclay), INFN (Rome), Johannes Gutenberg Univ. (Mainz), LIP (Coimbra), IRAP (Toulouse)
  - Proposal to CNES for a balloon experiment in 2023
  - Challenge: **compact design** (also for ComptonCAM v2)





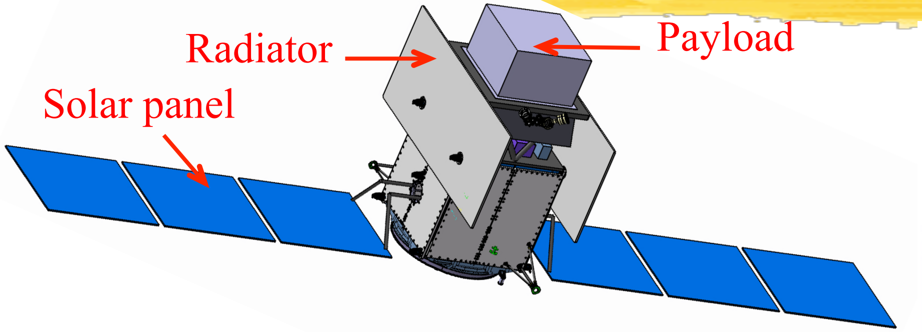


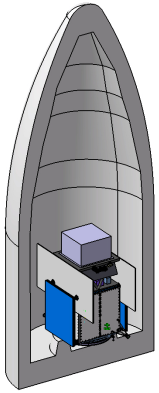
Conclusions

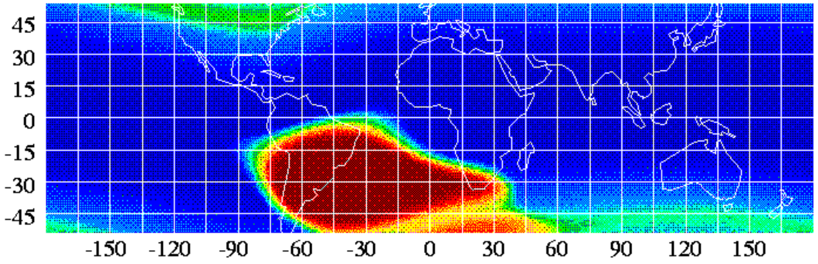
- The value of a Compton telescope for gamma-ray space astronomy has been demonstrated by **CGRO/COMPTEL**
- The creation of advanced Compton telescopes in Europe, the US and Japan has led to the development of several **promising technologies**
- The next **major gamma-ray space observatory** (when?) should include an advanced Compton telescope

Extra slides

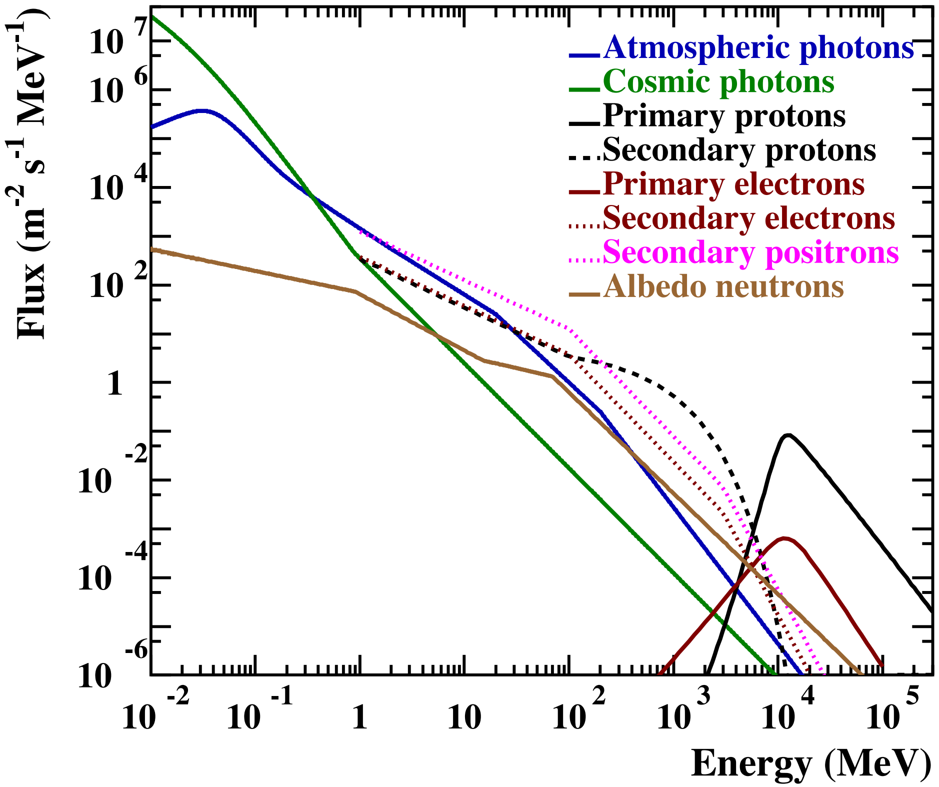
e-ASTROGAM satellite and mission profile





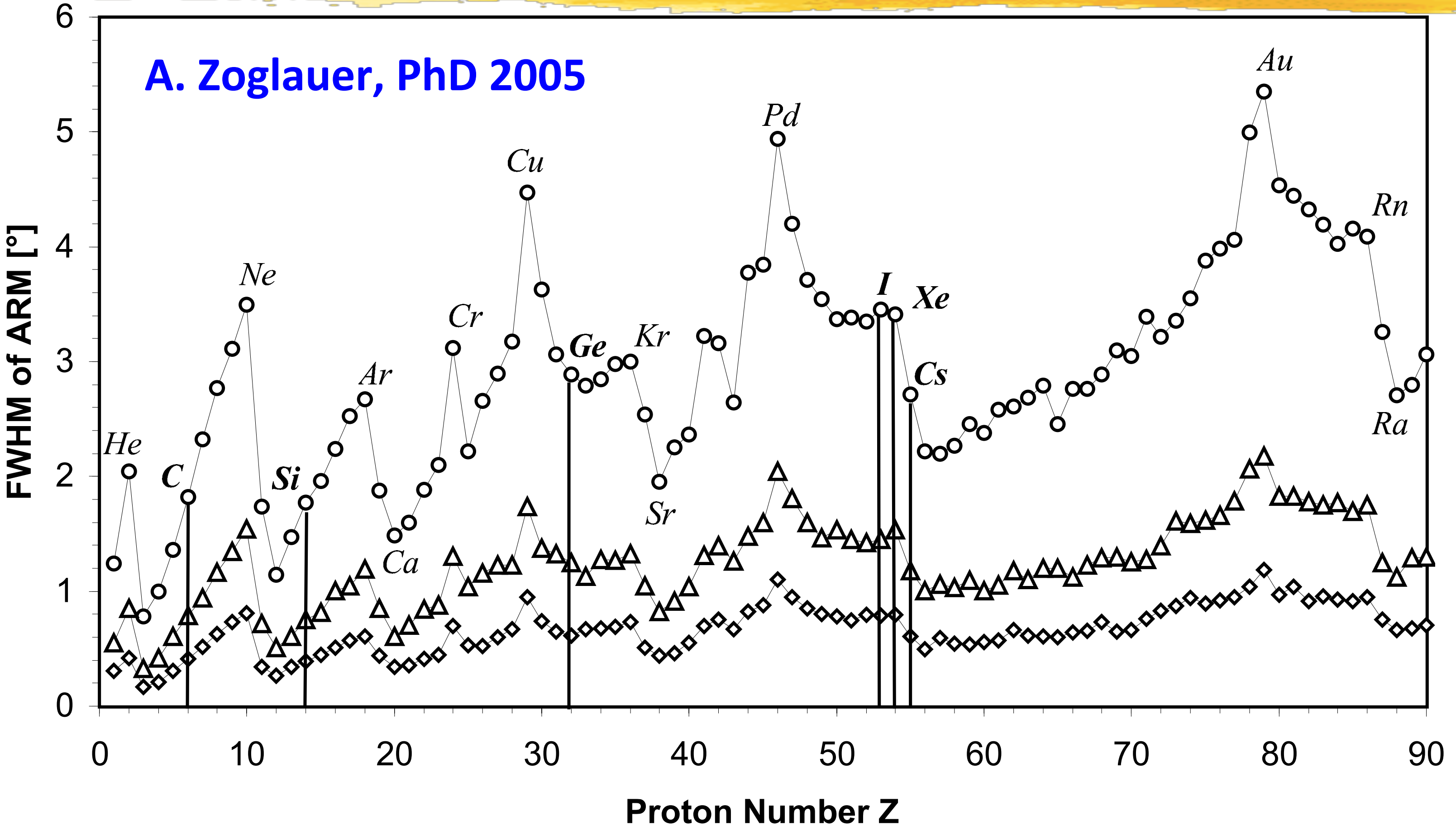


Background environment in an ELEO



- **Platform** – Thales Alenia Space PROTEUS 800 (SWOT CNES/NASA)
- **Orbit** – Equatorial (inclination $i < 2.5°$, eccentricity $e < 0.01$) low-Earth orbit (altitude in the range 550 - 600 km)
- **Launcher** – Ariane 6.2
- **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

Doppler broadening


A. Zoglauer, PhD 2005

Material	Si	Ge	CdZnTe	Xe	NE213	CsI	NaI
FWHM at 200 keV [degree]	1.80	2.85	3.50	3.30	1.75	2.95	3.00
FWHM at 500 keV [degree]	0.80	1.25	1.55	1.45	0.75	1.25	1.40
FWHM at 1000 keV [degree]	0.40	0.65	0.85	0.80	0.40	0.75	0.85