Future Gamma-Ray Detectors

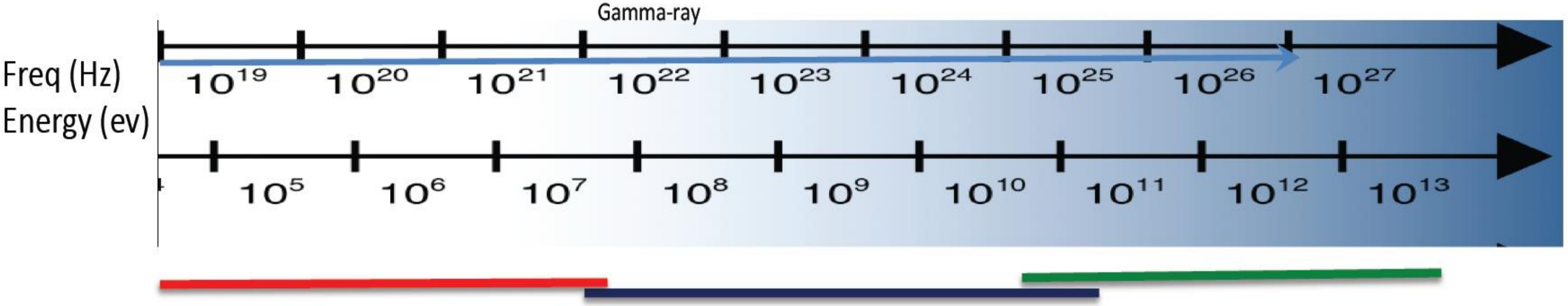
Elisabetta Bissaldi

Member of the Fermi-GBM and
Fermi-LAT Collaborations,
and of the CTA Consortium

Politecnico & INFN Bari
elisabetta.bissaldi@ba.infn.it

Multimessenger Data analysis in the era of CTA

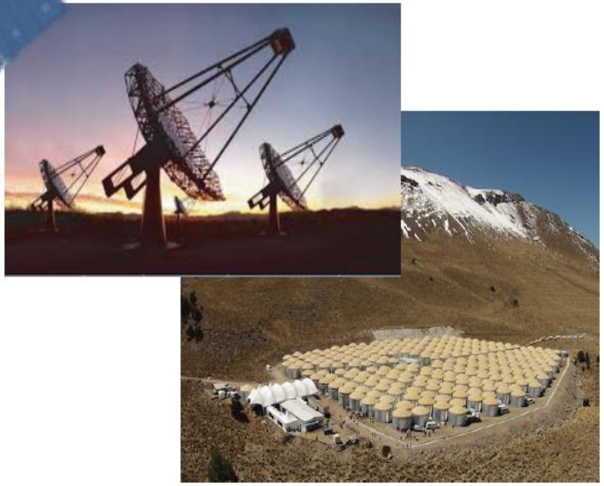
Gamma-ray energy bands



Medium Energy gamma-rays (aka MeV)

High Energy gamma-rays (aka GeV)

Very High Energy (VHE) gamma-rays (aka TeV)



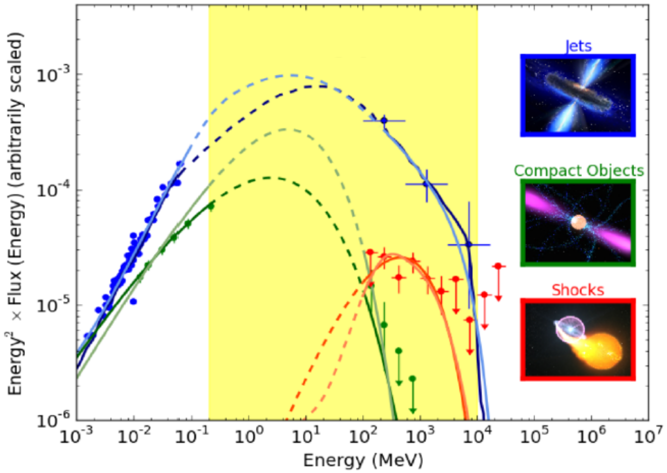
Credit: J. McEnery 2018

Medium-energy Gamma-ray Astrophysics

- Understanding how the Universe works requires observing astrophysical sources at the wavelength of **peak** power output **crucial for source energetics**
- Fermi, NuSTAR, and Swift BAT have uncovered source classes with peak energy output in the poorly explored MeV band

A critical energy band –

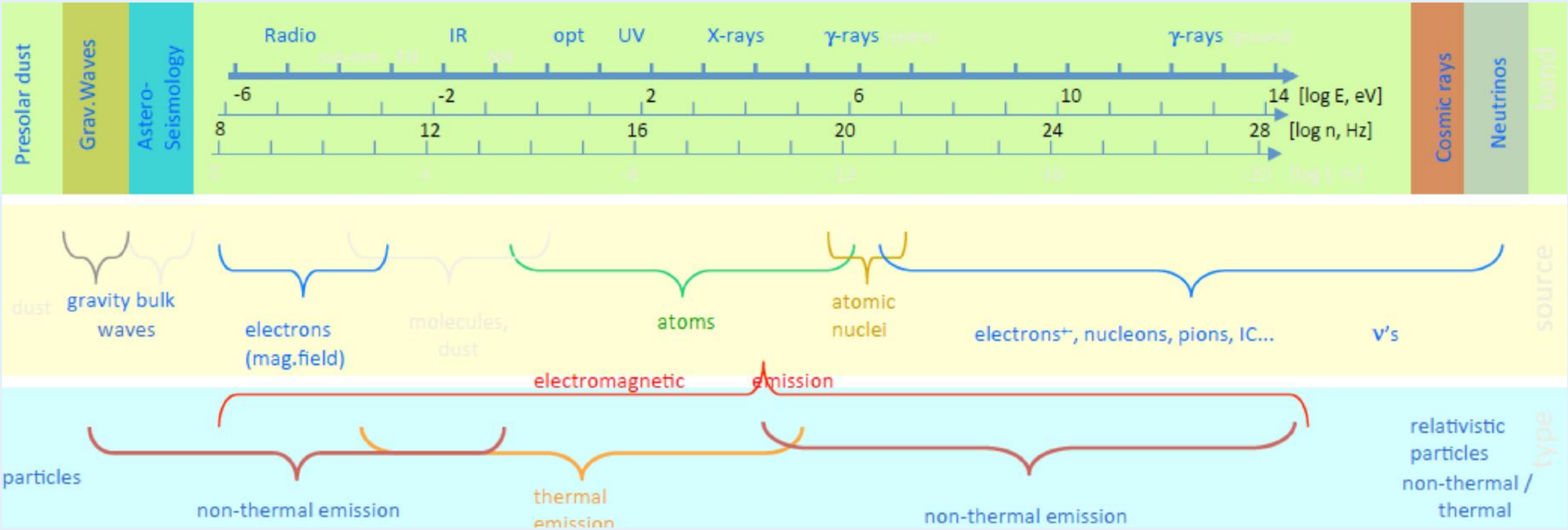
- Transition between the thermal and non-thermal Universe
- Only part of the EM spectrum where it is possible to directly observe nuclear processes (atomic nuclei de/excitations)
- Covers positron annihilation line (511 keV)
- Large population of known sources with peak power output in the MeV range
  - Crucial for source energetics



Credit: J. McEnery 2018

Nuclear processes and the MeV band

- The MeV band is special!

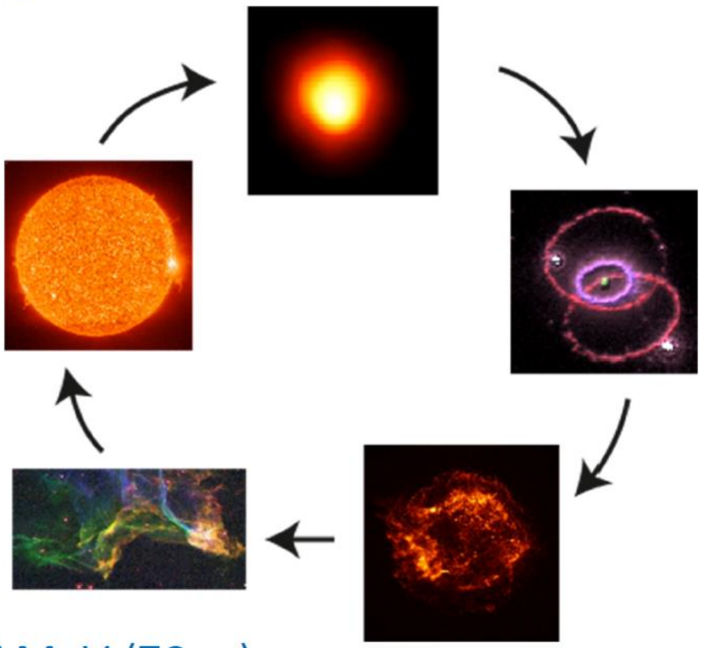


- Nuclear processes (i.e. atomic nuclei de/excitation) only accessible at observational energies of 0.05 to 16 MeV

Gamma-ray Spectroscopy

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

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



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)

Credit: J. McEnery 2018

Nucleosynthesis

Creation and release of new elements:
Stars, supernovae, novae, and mergers

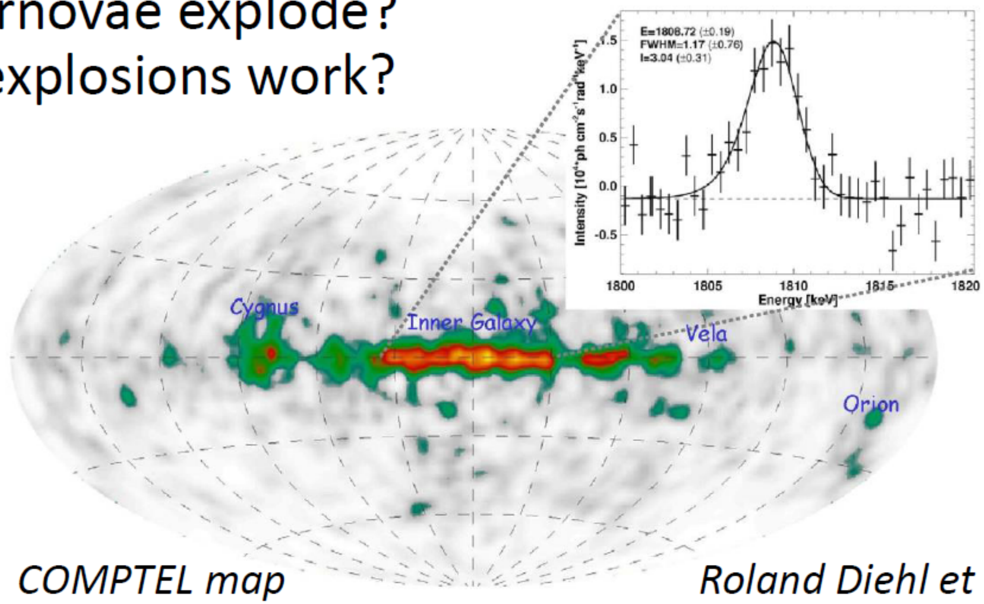
Each nuclear line tells a different story:

^{26}Al: History of star formation over last million years
^{60}Fe: History of core-collapse supernova
^{44}Ti: Young supernova remnants
^{56}Ni: How do type Ia supernovae explode?
^{22}Na & ^{7}Be: How do nova explosions work?

Observe:

- Location
- Fluxes
- Line width & shift
- Temporal evolution

SPI spectrum



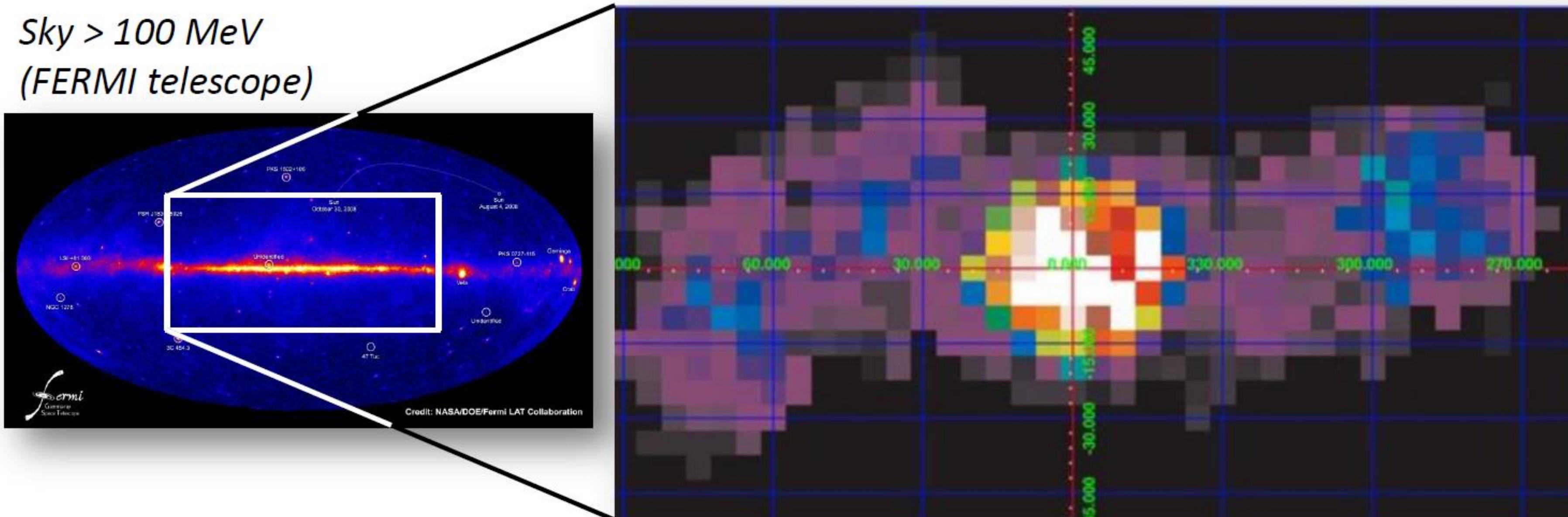
COMPTEL map

Roland Diehl et al.

Understanding the Origin of the 511-keV emission

Sky > 100 MeV (FERMI telescope)

511-keV map (SPI telescope) *Bouchet et al. 2010*



SPI observations (2002 - present):

Very extended 511-keV emission from positron annihilation centered around galactic center/bulge and around the galactic disk

Contributors (how much TBD):

Nuclear decays, novae, supernovae, X-ray binaries, dark matter?

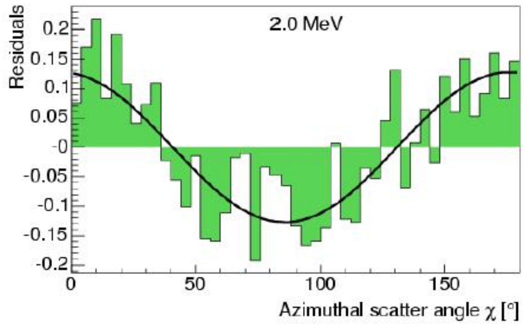
Credit: A. Zoglauer 2019

Open a new dimension: Polarization

Klein-Nishina cross-section:

$$\left(\frac{d\sigma}{d\Omega}\right)_{C,\,unbound,\,pol} = \frac{r_e^2}{2}\left(\frac{E_g}{E_i}\right)^2\left(\frac{E_g}{E_i} + \frac{E_i}{E_g} - 2\sin^2\varphi\cos^2\chi\right)$$

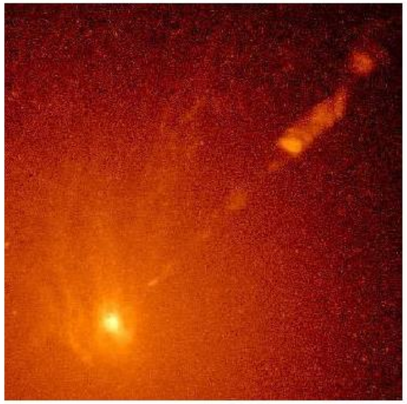
Compton scattering preserves information about the linear polarization of the gamma rays.



Polarization helps to better understand / constrain models about the geometry and emission processes with which the gamma rays are created, for example in

- Pulsars
- AGN (black-hole) jets
- Gamma-ray bursts

Crab pulsar (X-rays, Chandra)

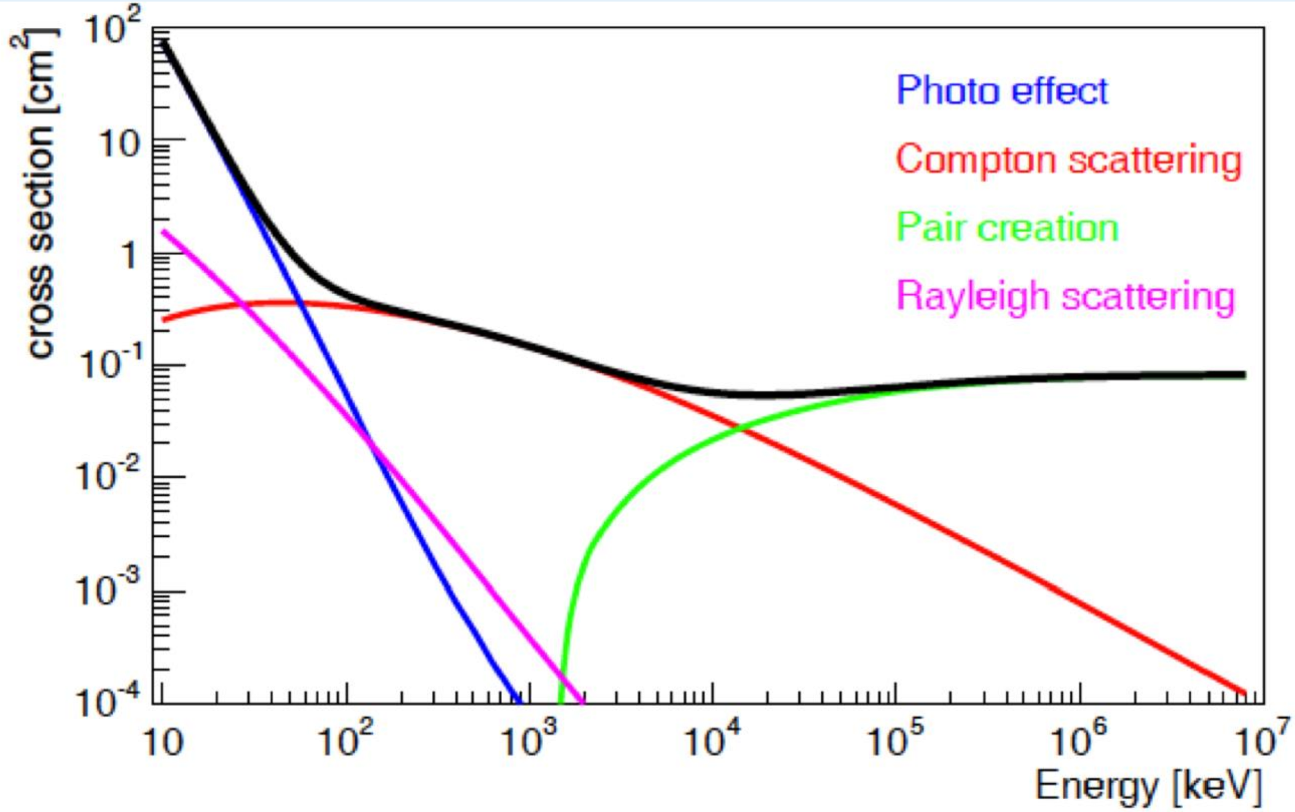


M87 (Hubble)

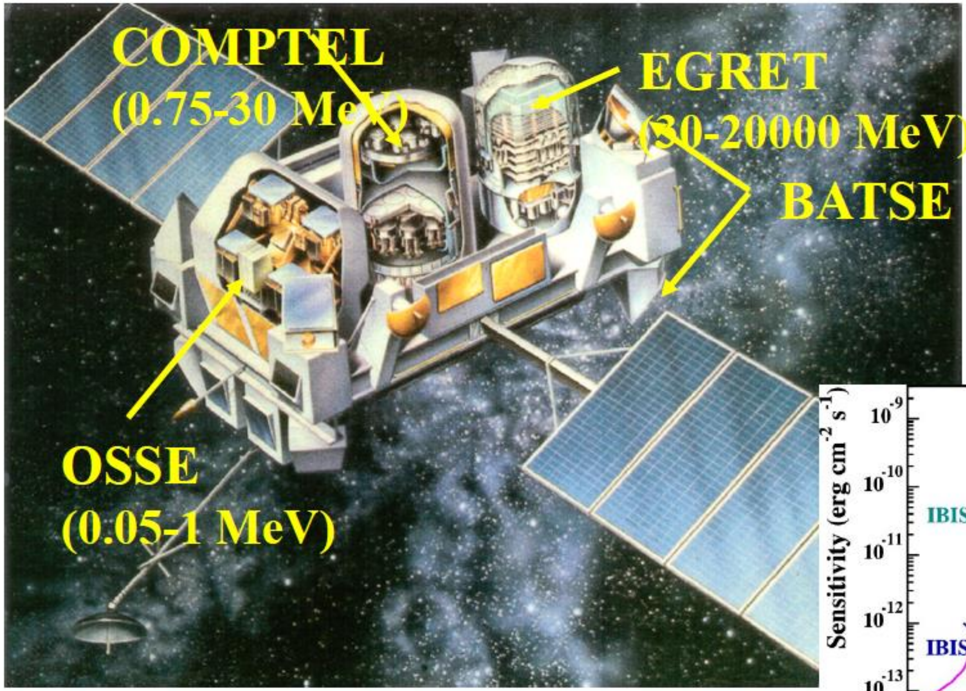
Credit: A. Zoglauer 2019

Detecting MeV Gamma-rays

- To fill the «MeV Gap» we need to consider:
  - Compton scattering
  - Pair production

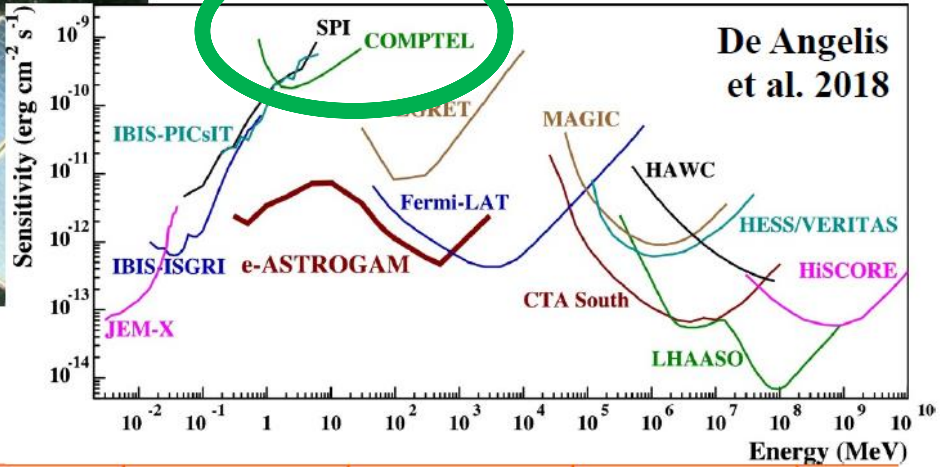


COMPTEL on CGRO



Credit: W. Collmar 2019

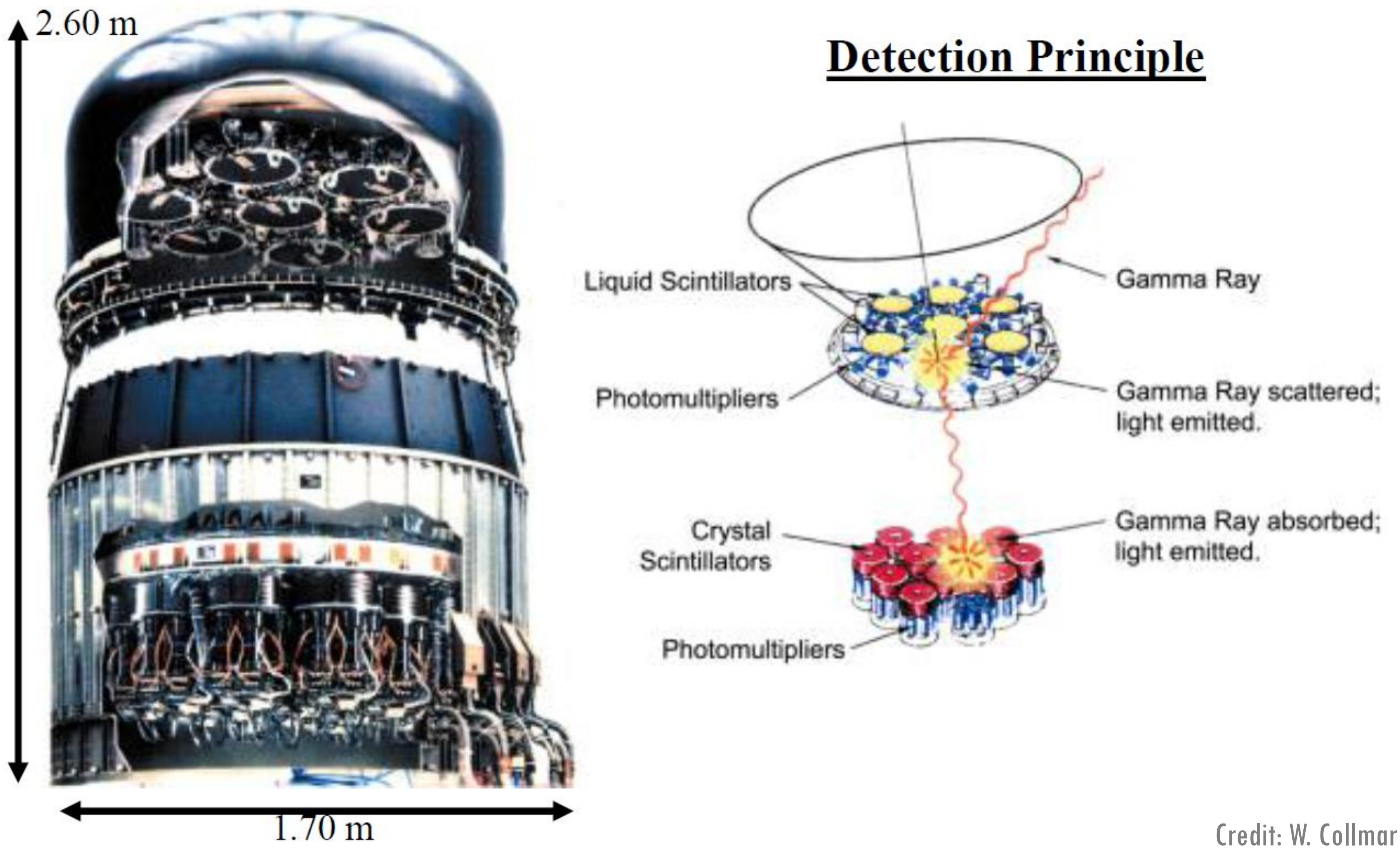
COMPTEL (Compton Telescope)
- mission: Apr. 91 – June 2000
- energy range: 0.75 – 30 MeV
- mounted parallel to EGRET
- "first-generation" experiment
- **pioneered MeV band**



0.01 | 0.1 | 1 | 10 | 100 | 1000 | 10000 MeV

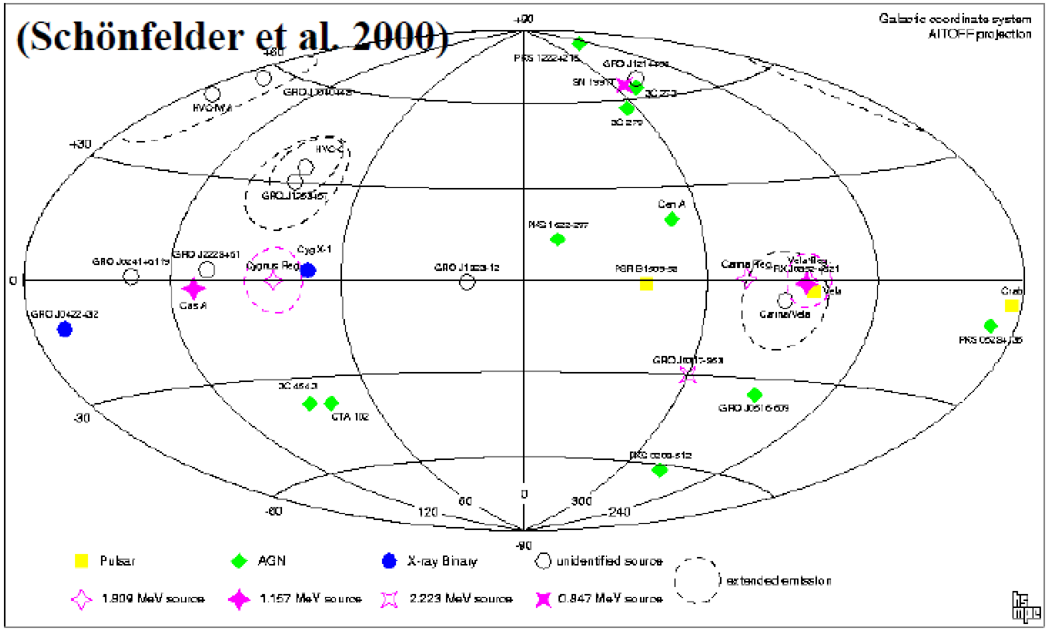
BATSE,OSSE | COMPTEL | EGRET

COMPton TELescope «COMPTEL»



Credit: W. Collmar 2019

First COMPTEL Source Catalog

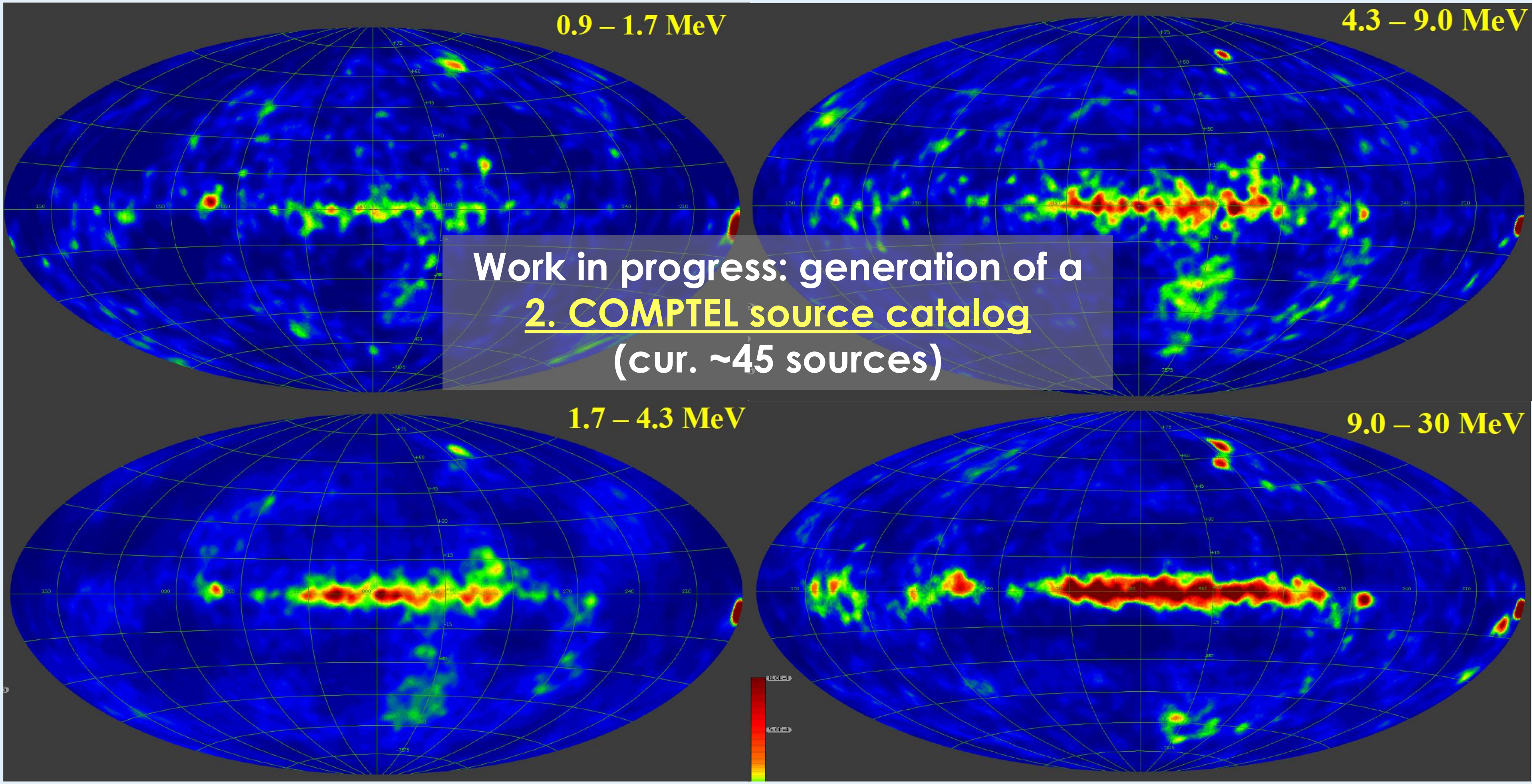


- contains published results of first 5.5 years (April ´91 – October ´96)
- 32 Sources (different nature)
- 31 GRBs / 21 solar flares
- upper limits for various types of objects (e.g. AGN, gal. BHs)

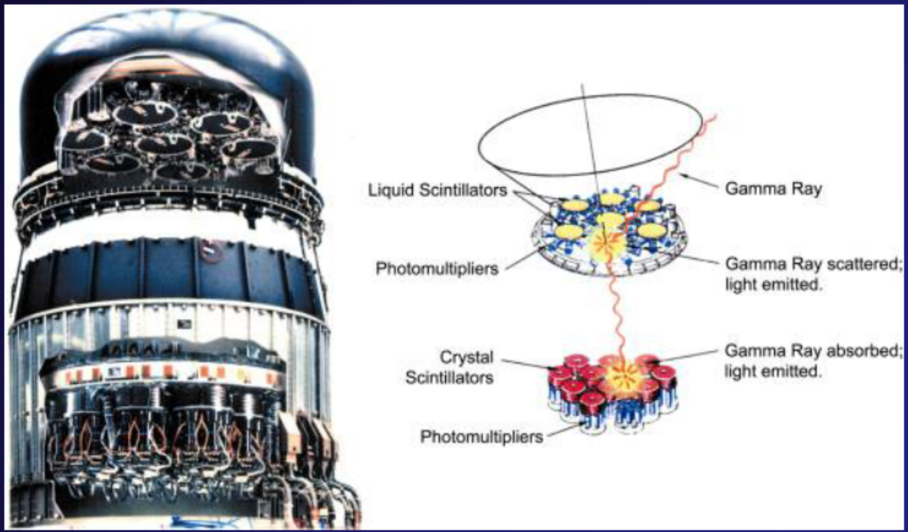
Source Type	#
Pulsars	3
Stellar Binaries	2
SNR (continuum)	1
AGN	10
Unidentified Sources - |b| < 10° - |b| > 10°	 3 5
γ-line sources - 1.809 MeV (^{26}Al) - 1.157 MeV (^{44}Ti) -0.847/1.238 MeV (^{56}Co) - 2.223 MeV (n-capt.)	 3 2 1 1

Recent COMPTEL Re-analysis

- **PRELIMINARY** results by Collmar+2019



COMPTEL & its background



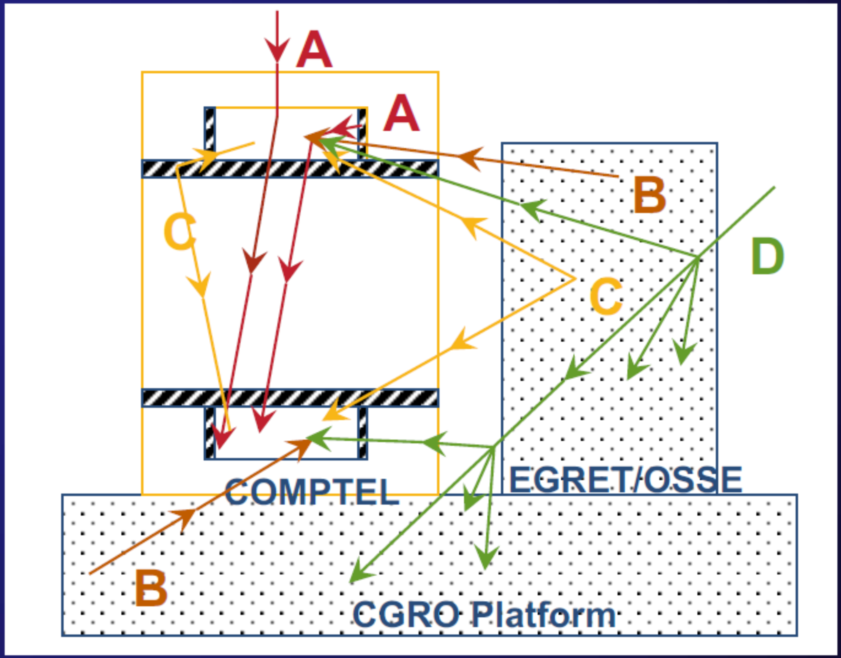
D1: organic liquid scintillator

D2: inorganic NaI scintillator

Photomultiplier Tube (PMT) readout

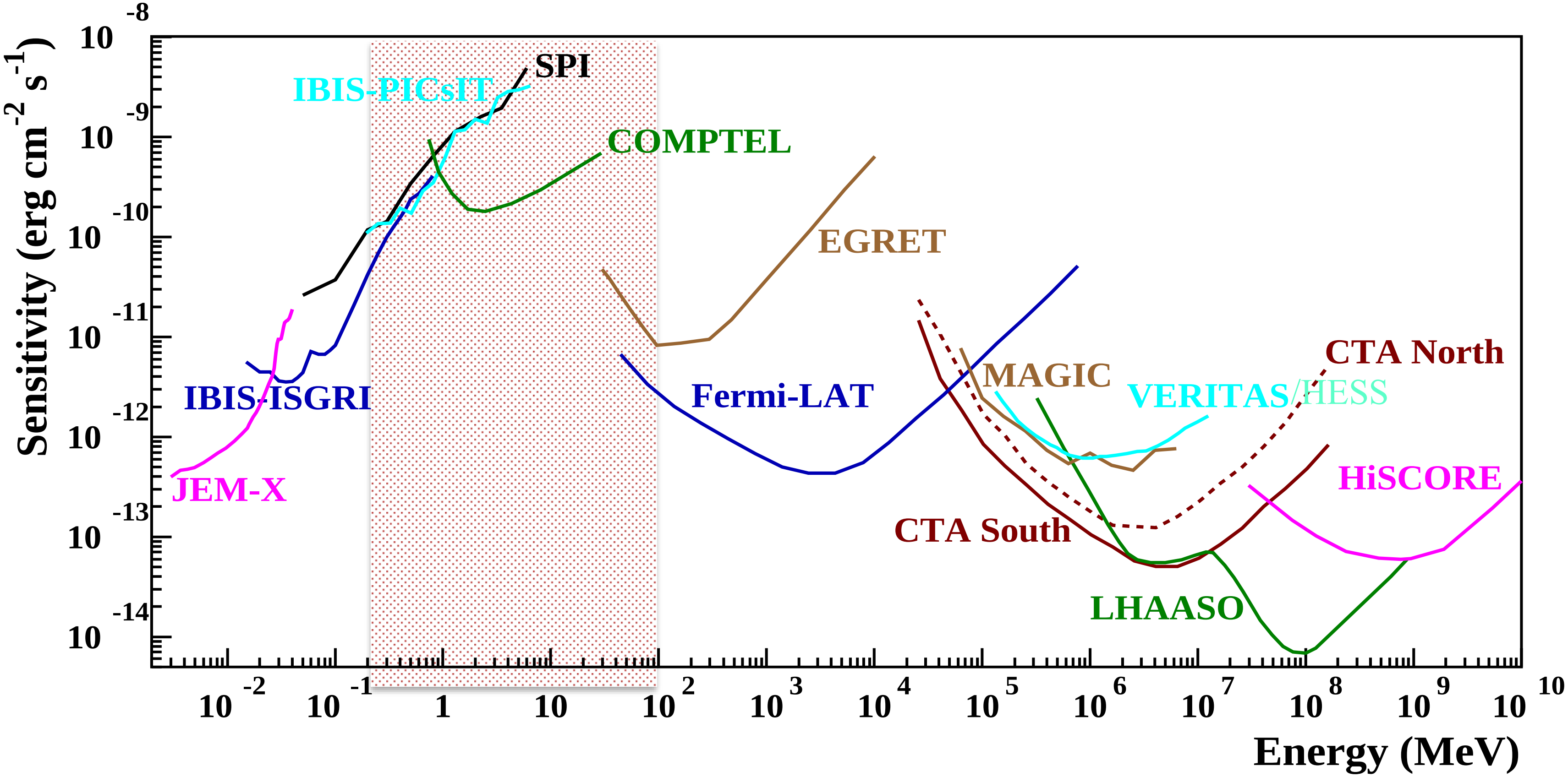
Measured E_1, E_2, Positions, PSD, ***Time-of-Flight***

COMPTEL suffered intense background from particle interactions:



Kappadath, S. C., 1998, Ph.D. Thesis, University of New Hampshire

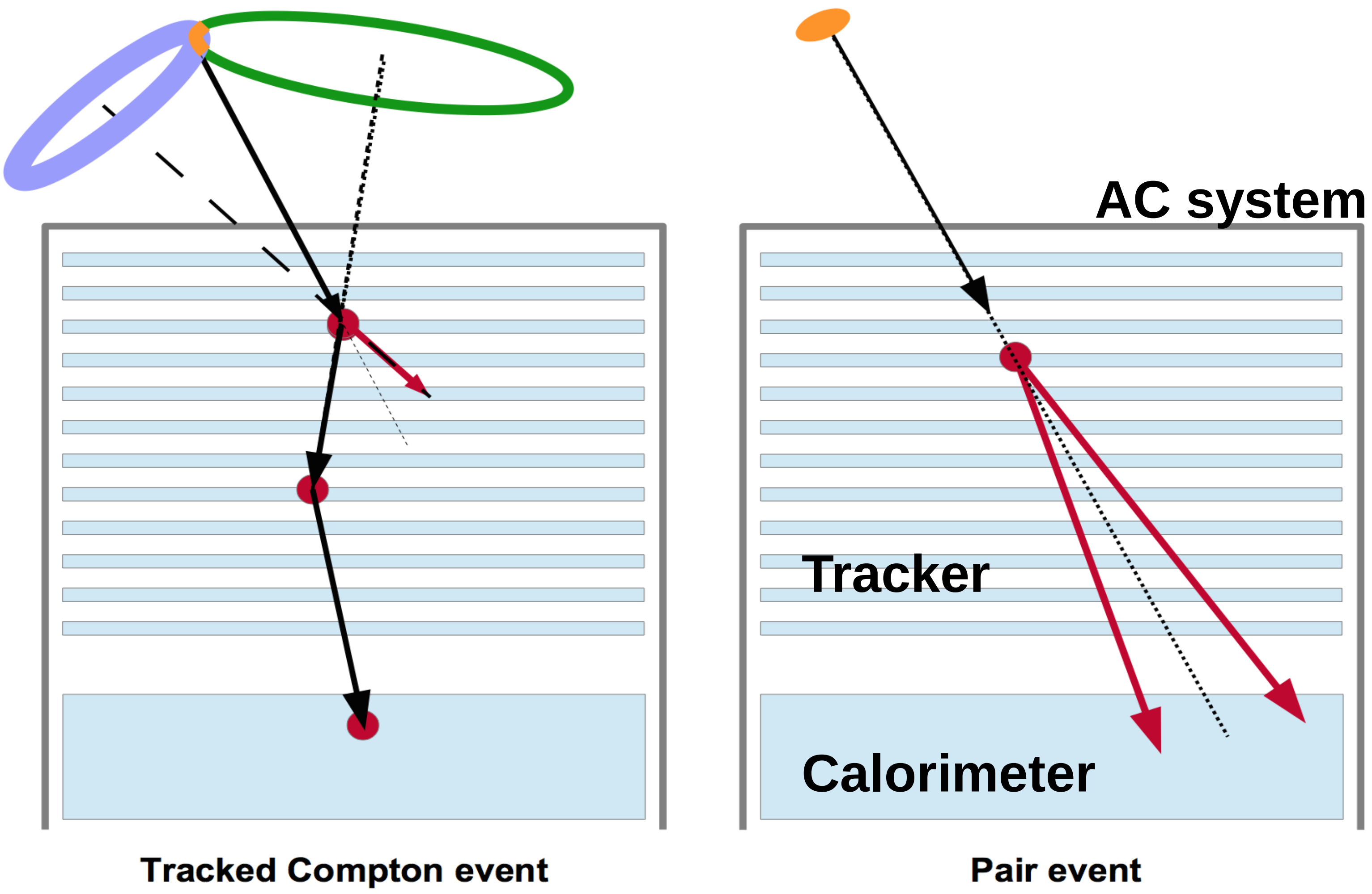
The MeV/GeV domain



- Currently:

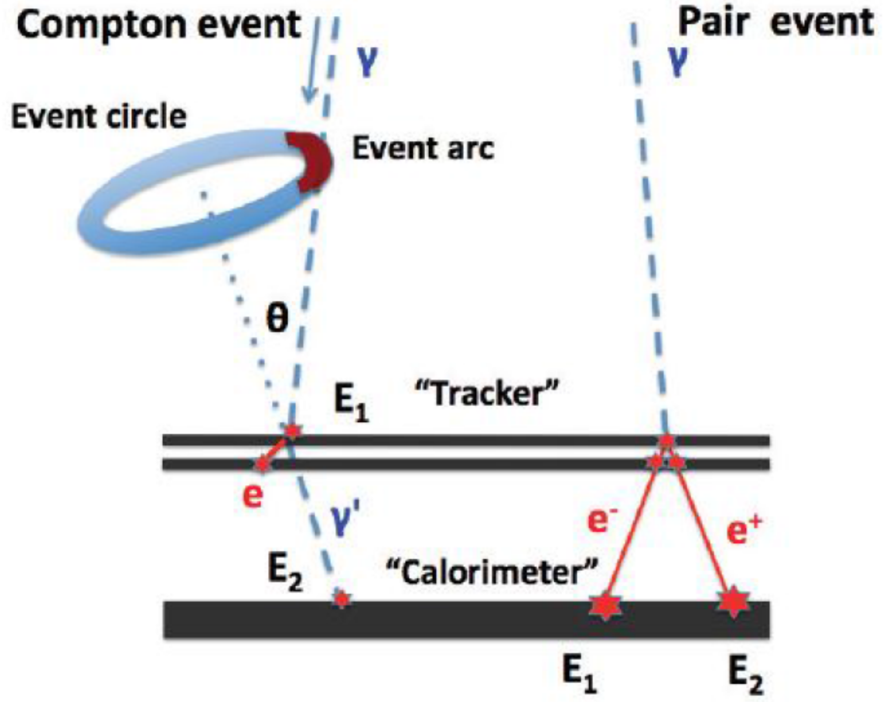
  ➔ Worst covered part of the electromagnetic spectrum
  (only a few tens of steady sources detected so far between 0.2 and 30 MeV)

An instrument that combines two detection techniques

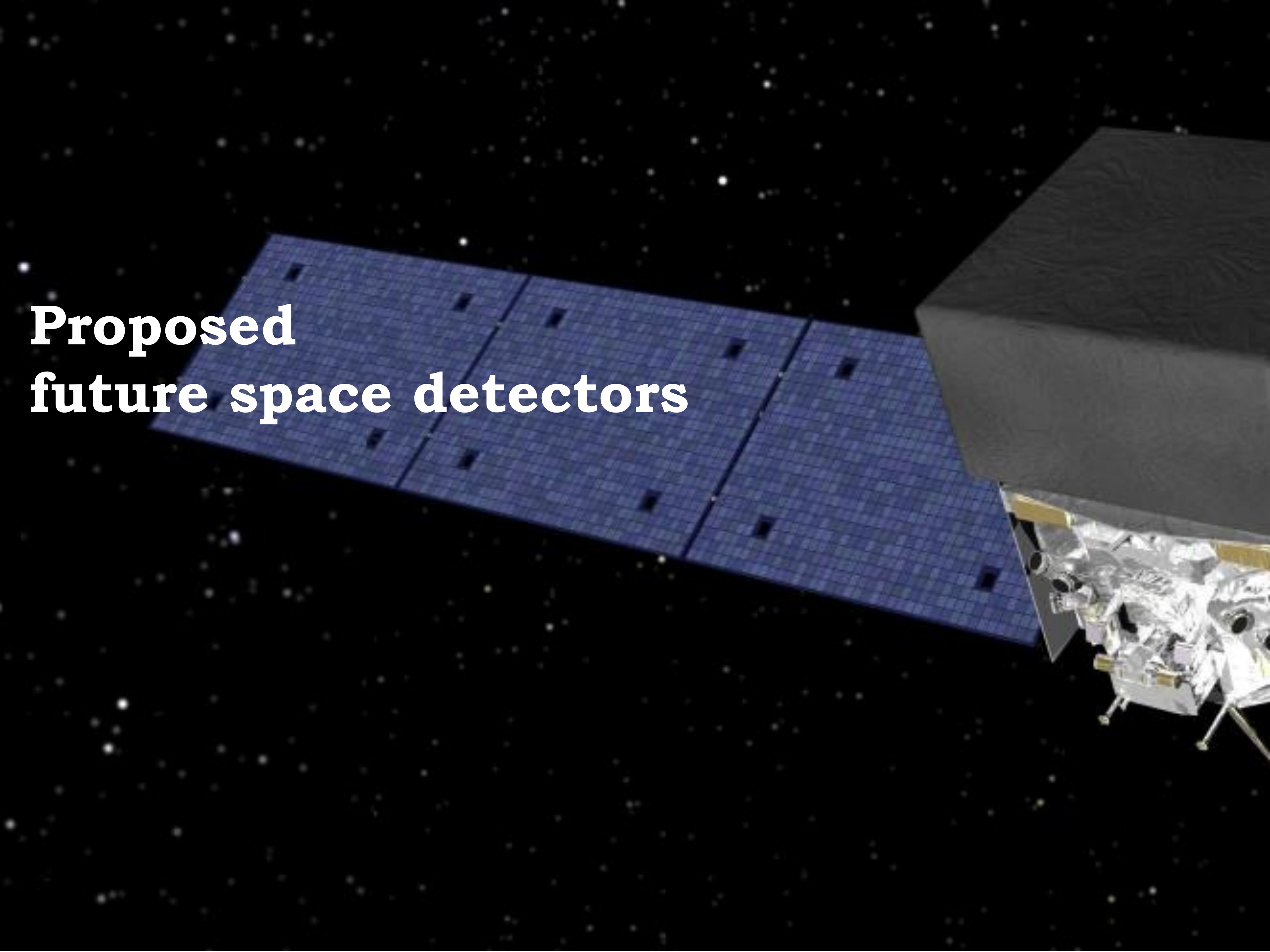


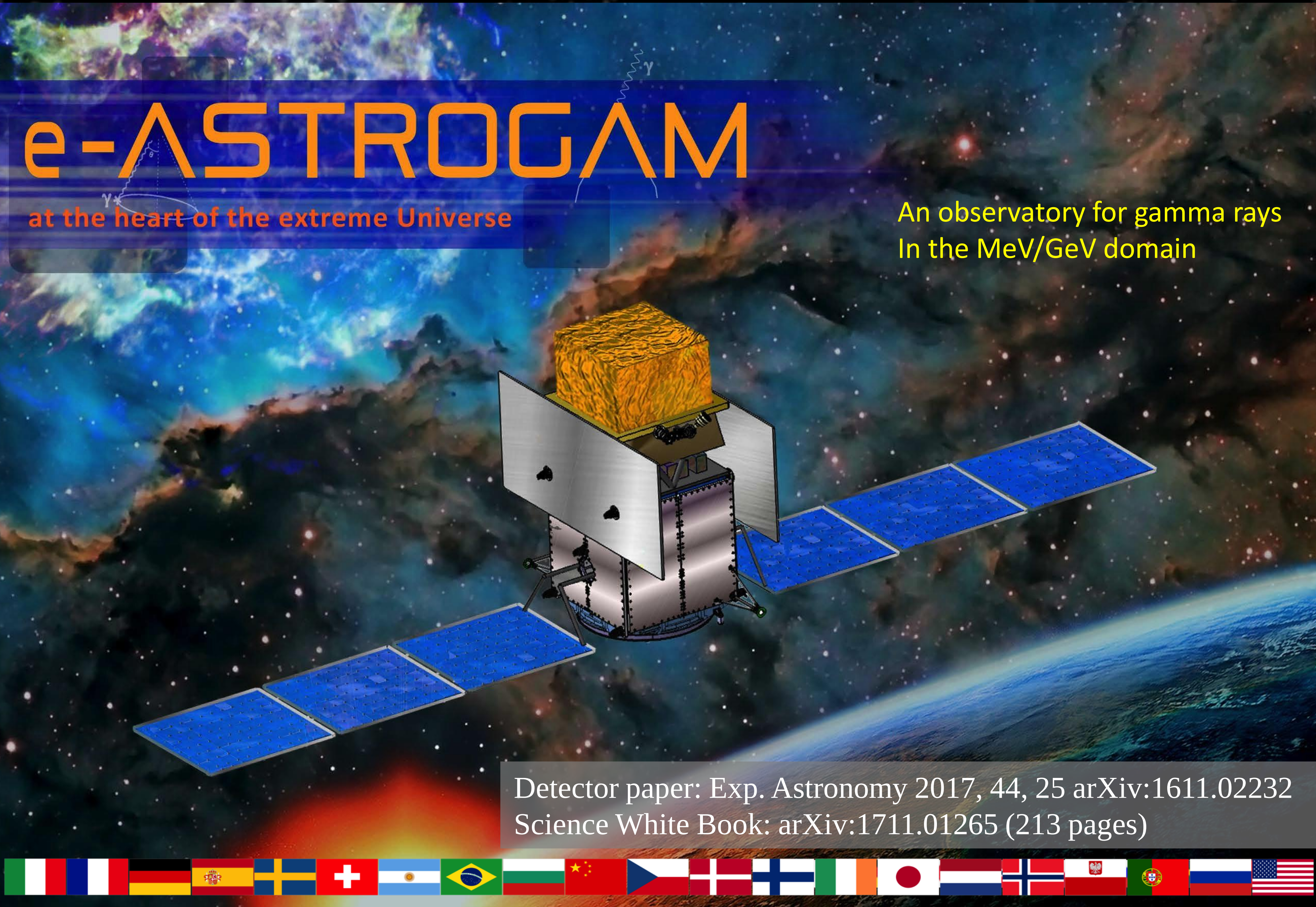
Detection of (sub)MeV-GeV gamma-rays

- Compton regime
  - Require excellent 3D-point resolution and energy resolution
  - Event reconstruction with 2 points and 2 energy measurements!
- Pair regime
  - Tracking resolution is most important
  - Dominated by Multiple Scattering effect
  - Main concern is detector layer thickness
- Difficult to be truly optimal in both regimes across the gap with one detector

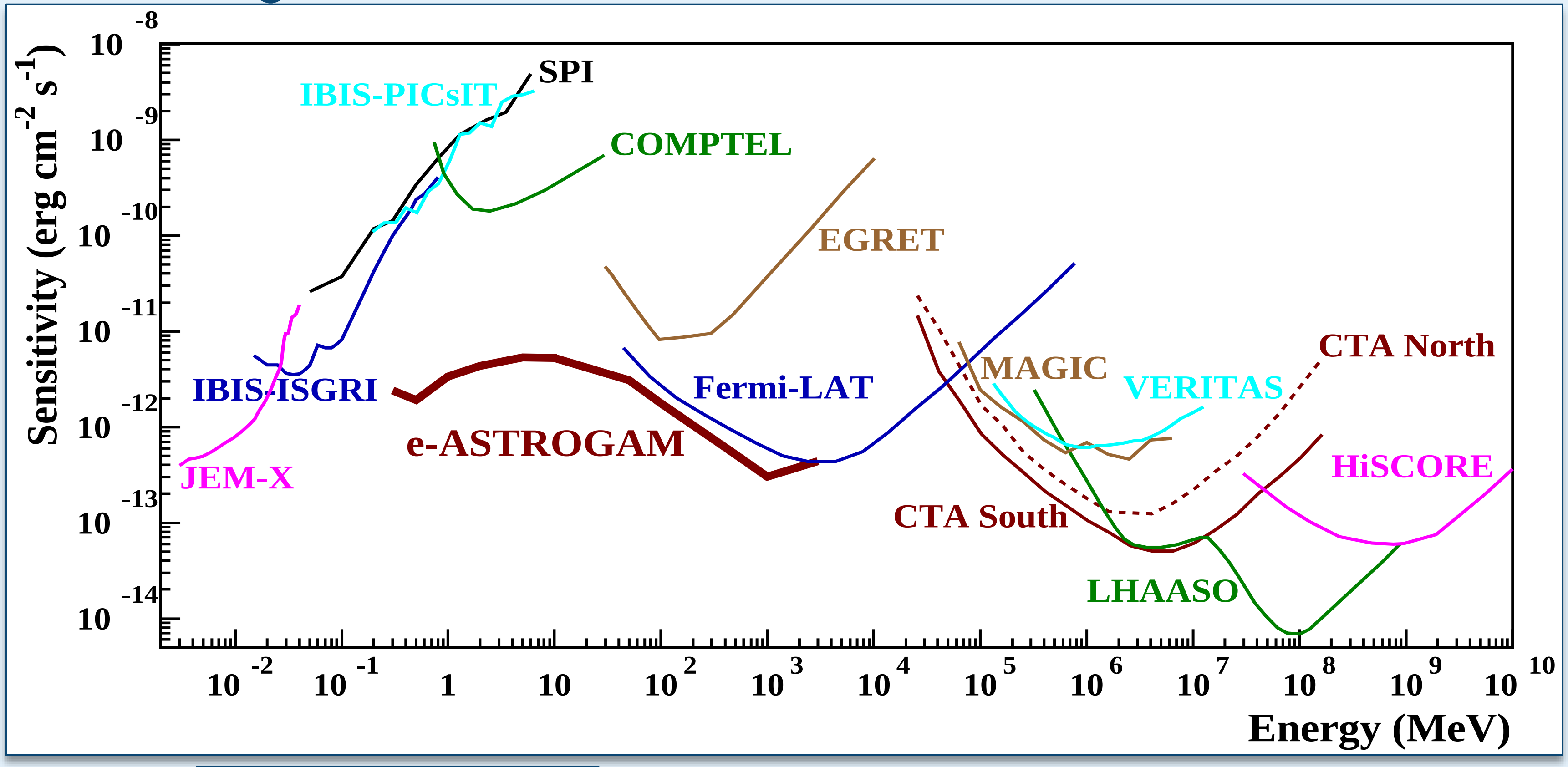


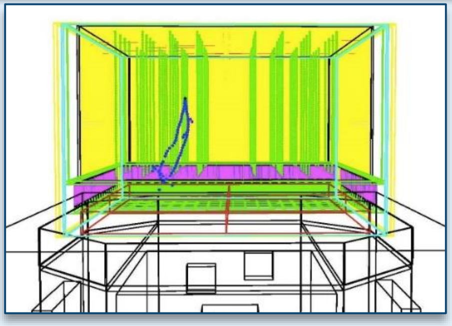
Proposed future space detectors




e-ASTROGAM
at the heart of the extreme Universe
An observatory for gamma rays
In the MeV/GeV domain
Detector paper: Exp. Astronomy 2017, 44, 25 arXiv:1611.02232
Science White Book: arXiv:1711.01265 (213 pages)

e-ASTROGAM performance assessement

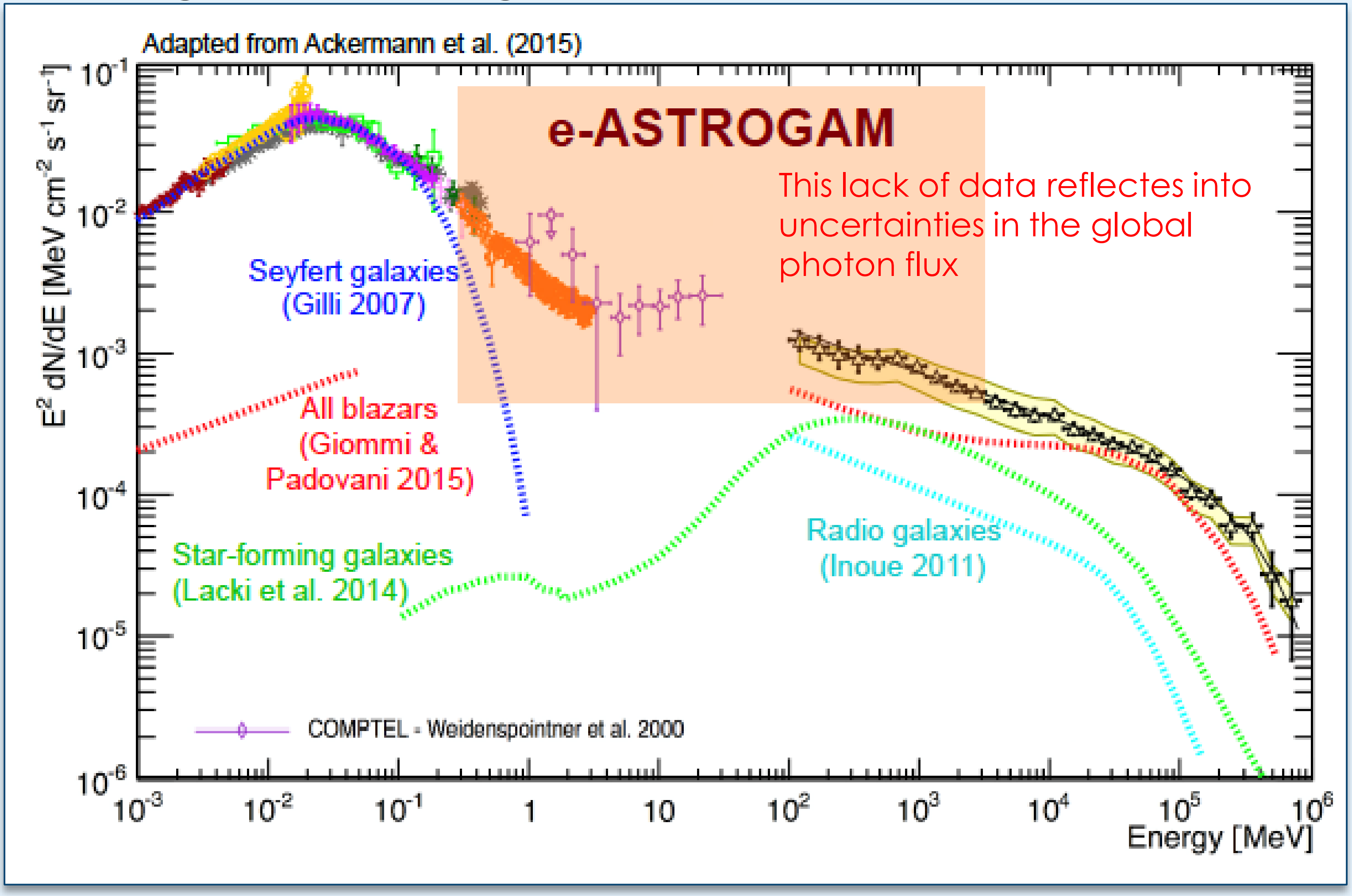




- Evaluated with **MEGAlib** and a detailed numerical mass model of the gamma-ray instrument

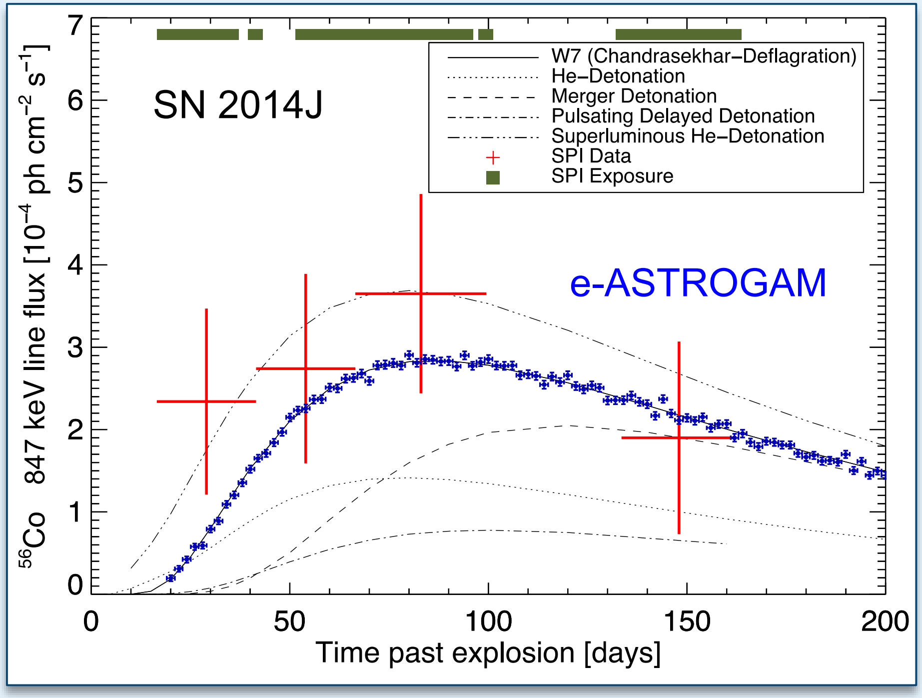
e-ASTROGAM performance assessement

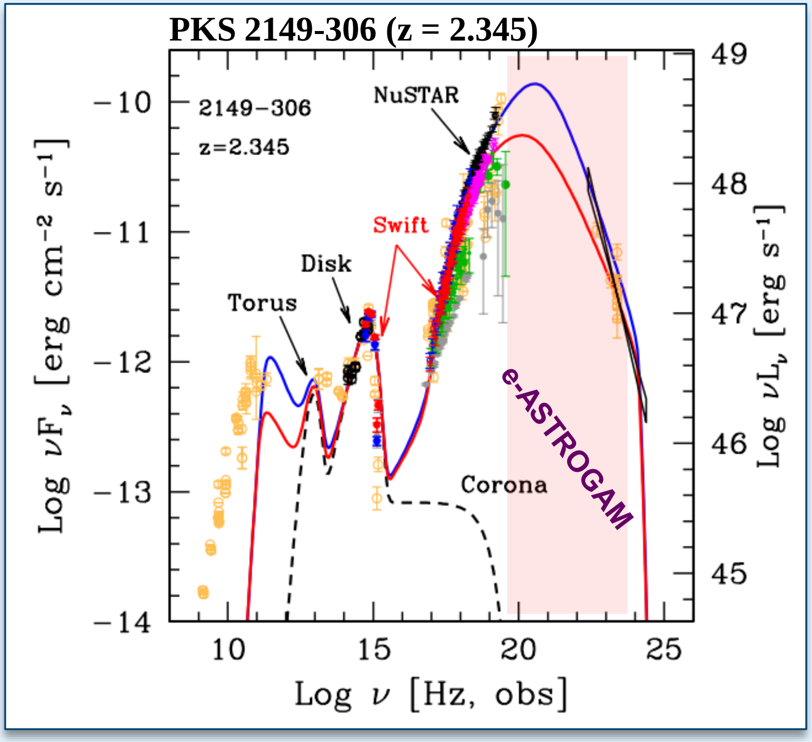
- **Total Extragalactic Background**



e-ASTROGAM Core science motivations

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

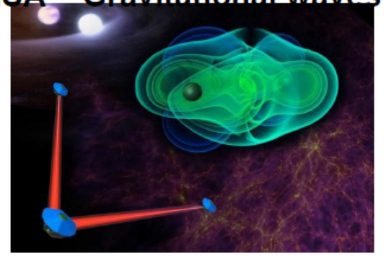




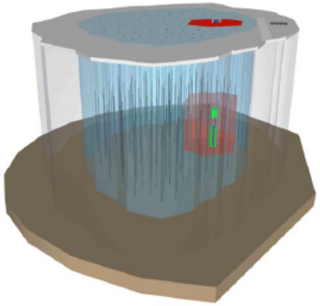
e-ASTROGAM Core Science Motivation

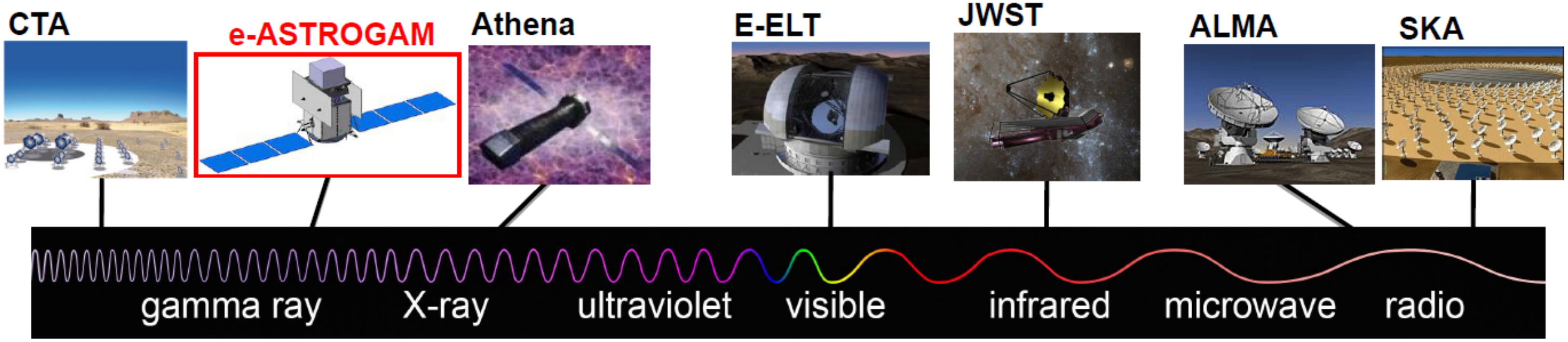
1. Processes at the heart of the extreme Universe (AGNs, GRBs, microquasars): prospects for the Astronomy of the 2030s
2. The origin of high-energy particles and impact on galaxy evolution, from cosmic rays to antimatter
3. Nucleosynthesis and the chemical enrichment of our Galaxy
4. Multi-messenger, multi-wavelength coverage of the sky (with CTA, SKA, eLISA, ν detectors...), with special focus on transient phenomena

eLISA – Gravitational waves



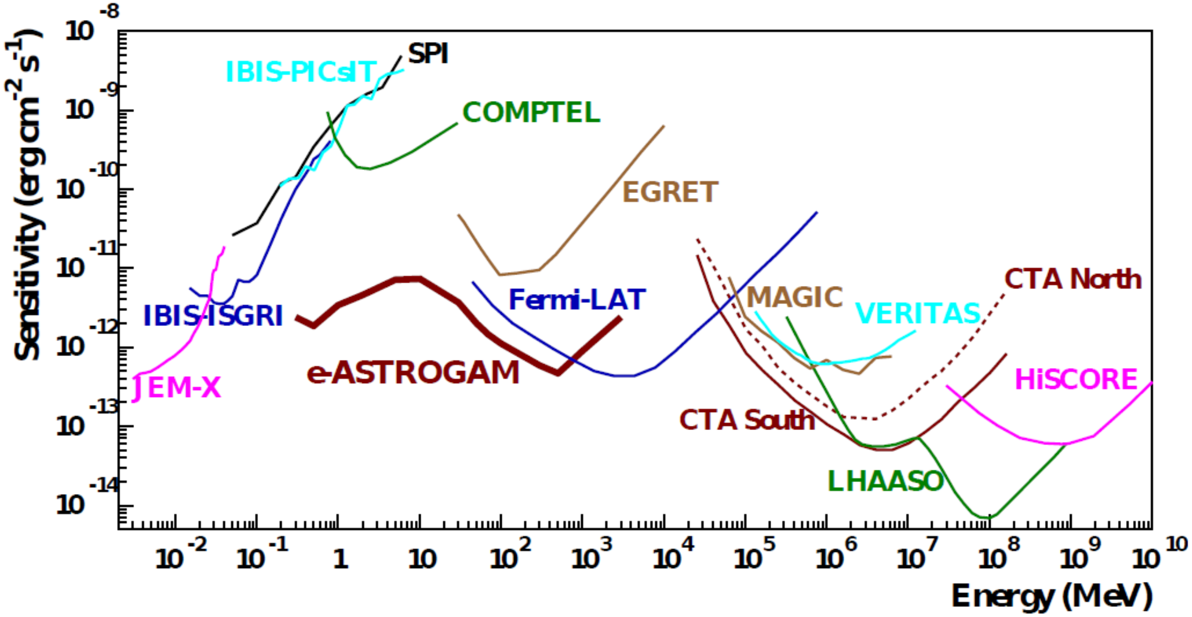
Km3Net/IceCube-Gen2 - ν



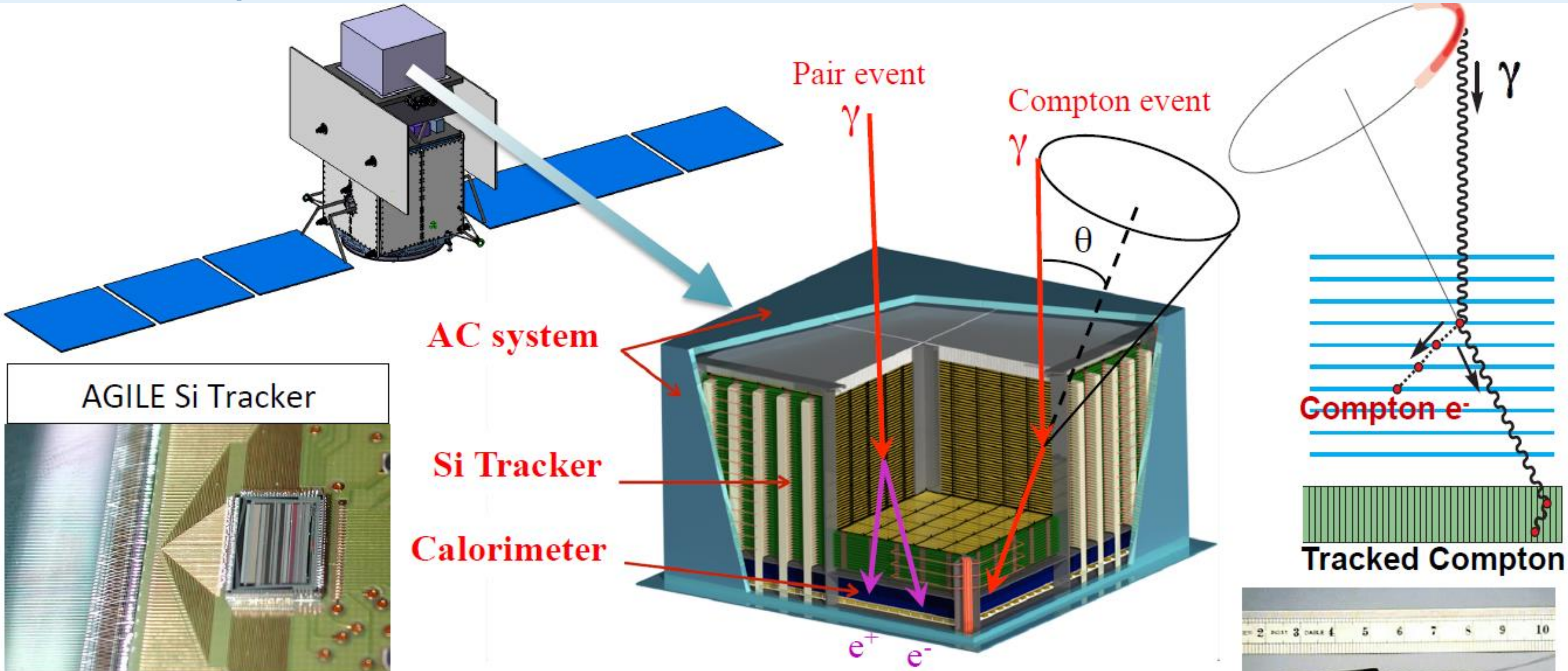


e-ASTROGAM Scientific requirements

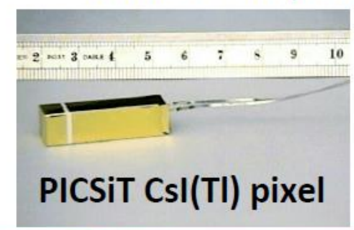
1. Achieve a sensitivity better than that of INTEGRAL/CGRO/COMPTEL by a factor of 20 - 50 - 100 in the range 0.2 - 30 MeV
2. Fully exploit gamma-ray polarization for both transient and steady sources
3. Improve significantly the angular resolution (to reach, e.g., ~ 10' at 1 GeV)
4. Achieve a very large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

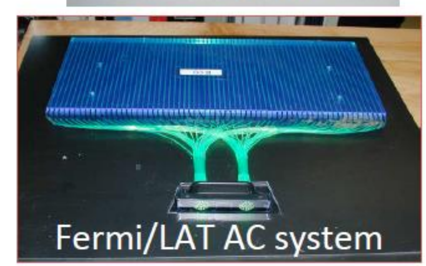


e-ASTROGAM design concept



- **Si Tracker** – Double sided Si strip detectors (DSSDs) for excellent spectral resolution and fine 3-D position resolution
- **3D-imaging Calorimeter** – CsI(Tl) scintillation crystals readout by Si Drift Diodes for better energy resolution
- **Anticoincidence detector** to veto charged-particle induced background ⇒ plastic scintillators readout by SiPMs

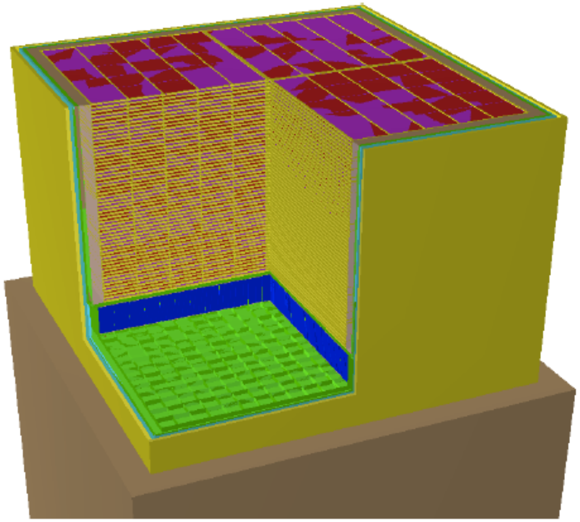




Credit: V. Tatischeff 2019

e-ASTROGAM Tracker

Tracker - Double sided Si strip detectors (DSSDs) for excellent spectral resolution and fine 3-D position resolution (1m^2, 500 mm thick, 0.3 Xo in total)

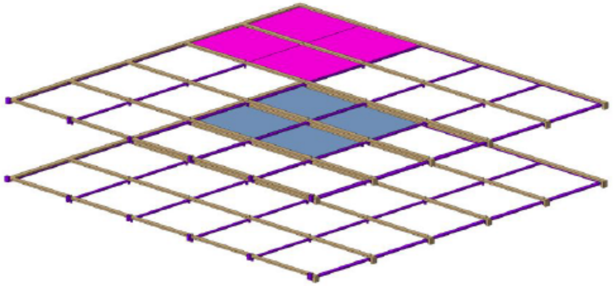


- 56 layers of 4 times 5×5 double sided Si strip detectors = 5600 DSSDs
- Each DSSD has a total area of 9.5×9.5 cm^2, a thickness of 500 μm, a strip width of 100 mm and pitch of 240 μm (384 strips per side), and a guard ring of 1.5 mm
- Spacing of the Si layers: 10 mm
- The DSSDs are wire bonded strip to strip to form 5×5 2-D ladders

⇒ 860 160 electronic channels

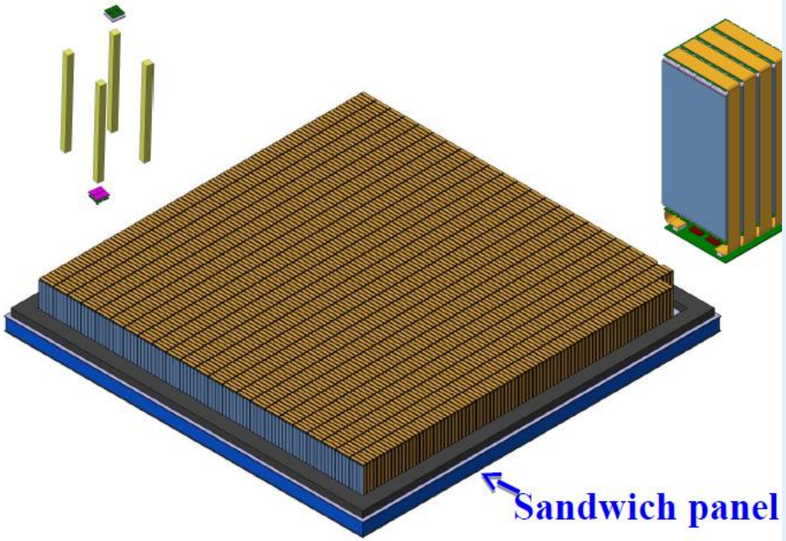
⇒ 26 880 IDeF-X ASICs (32 channels each)

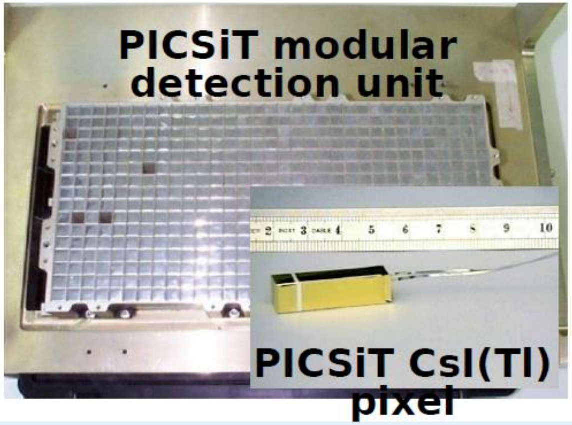
⇒ Power budget = 688 W (800 μW/channel)

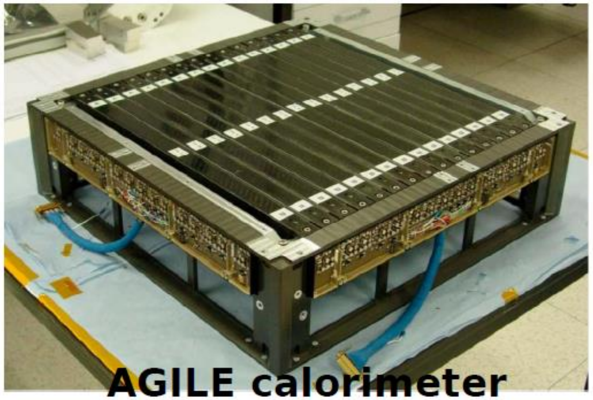


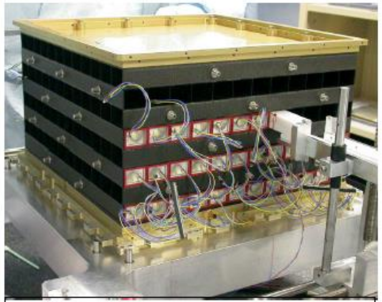
e-ASTROGAM Calorimeter

- 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)







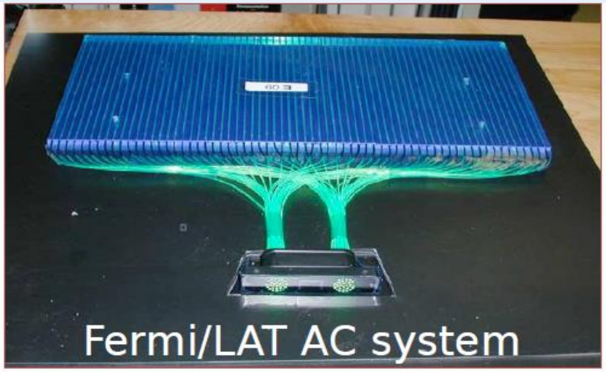


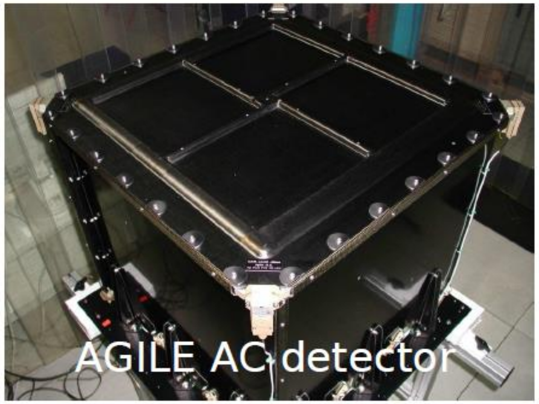
Fermi cal. module

e-ASTROGAM ACD

- 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)

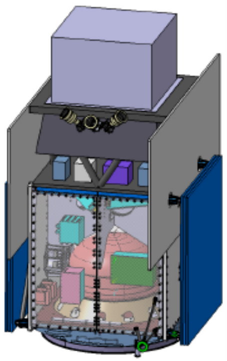
- Wavelength shifting optical fibers buried in trenches convey the scintillation light to Si photomultipliers
- The SiPM signals are readout by the space-qualified VATA64 ASICs from Ideas©
- **Heritage**: Fermi/LAT, AGILE
- Time-of-Flight system formed by two scintillator layers separated by 50 cm below the instrument to reject the particle background from the platform
- Heritage: AMS, PAMELA

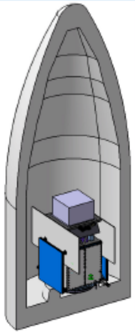




e-ASTROGAM mission proposal

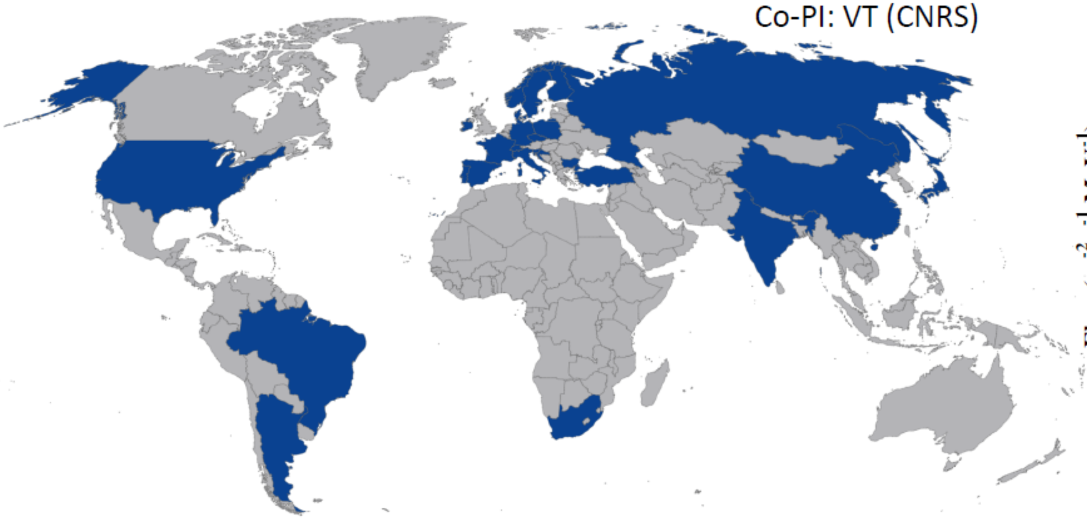
- **Satellite platform** – Thales Alenia Space PROTEUS 800 (SWOT) ⇒ spacecraft wet mass 2.7 tons
- **Low-Earth equatorial orbit** (inclination $i < 2.5°$, eccentricity $e < 0.01$, altitude 550 - 600 km) for optimal background environment
- **Science Collaboration** – more than 400 collaborators in 29 countries

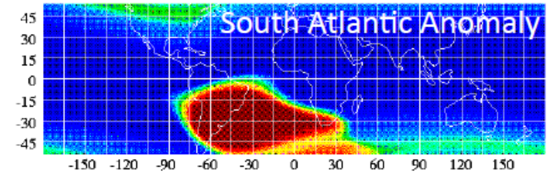


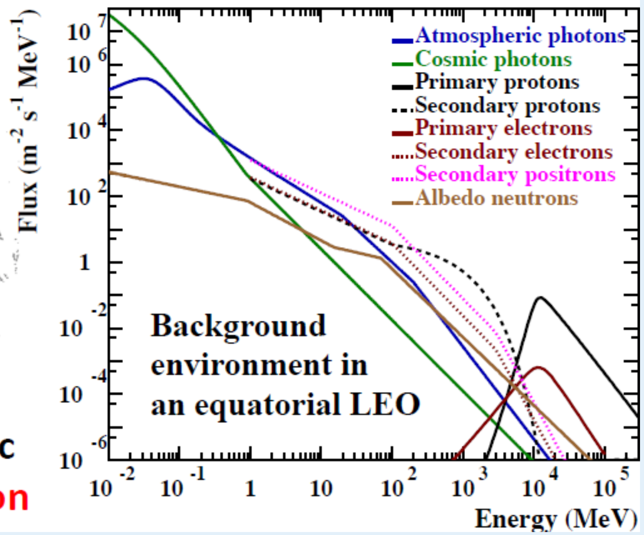


Ariane 6.2

PI: A. De Angelis (INFN)
Co-PI: VT (CNRS)



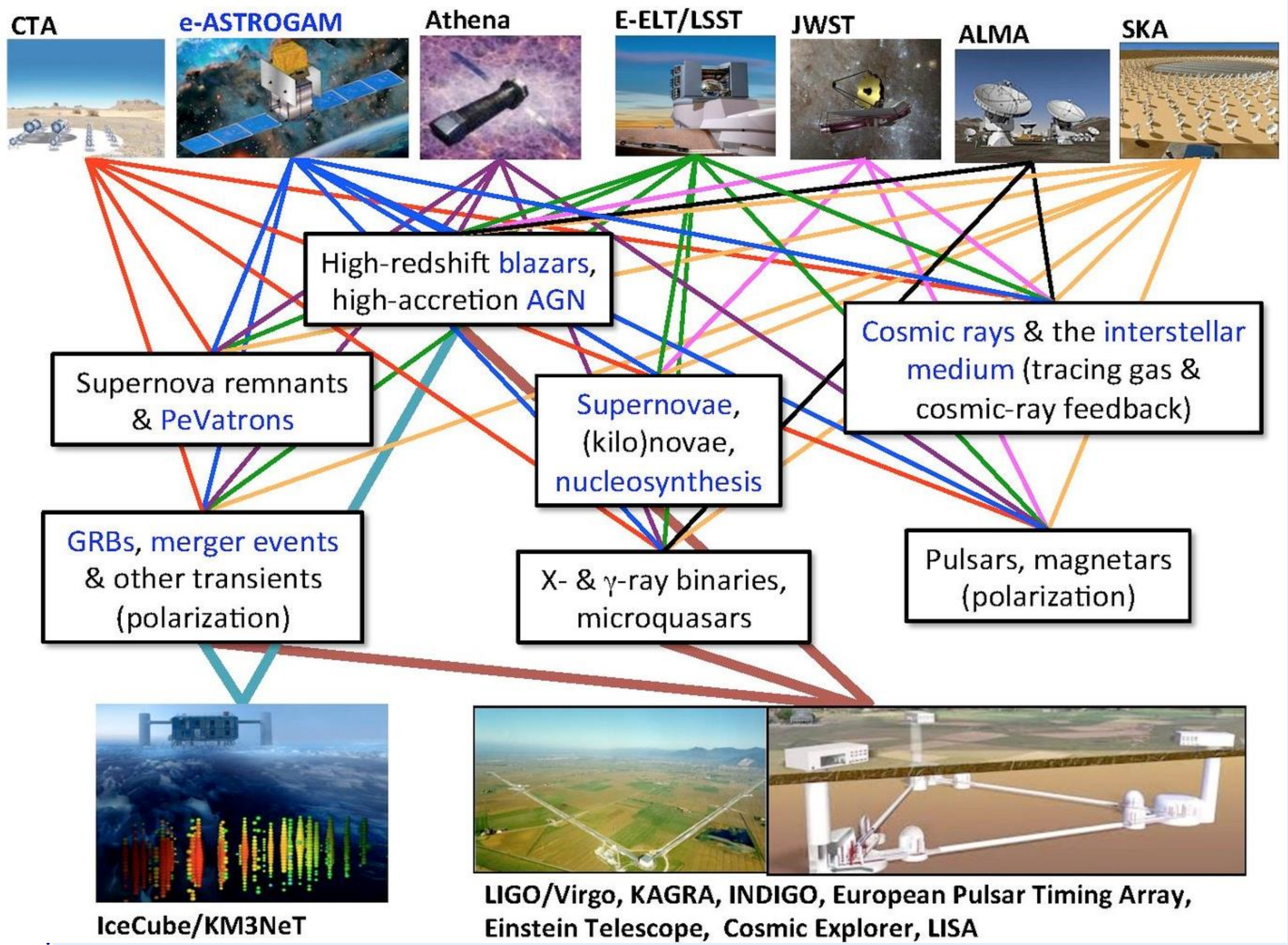




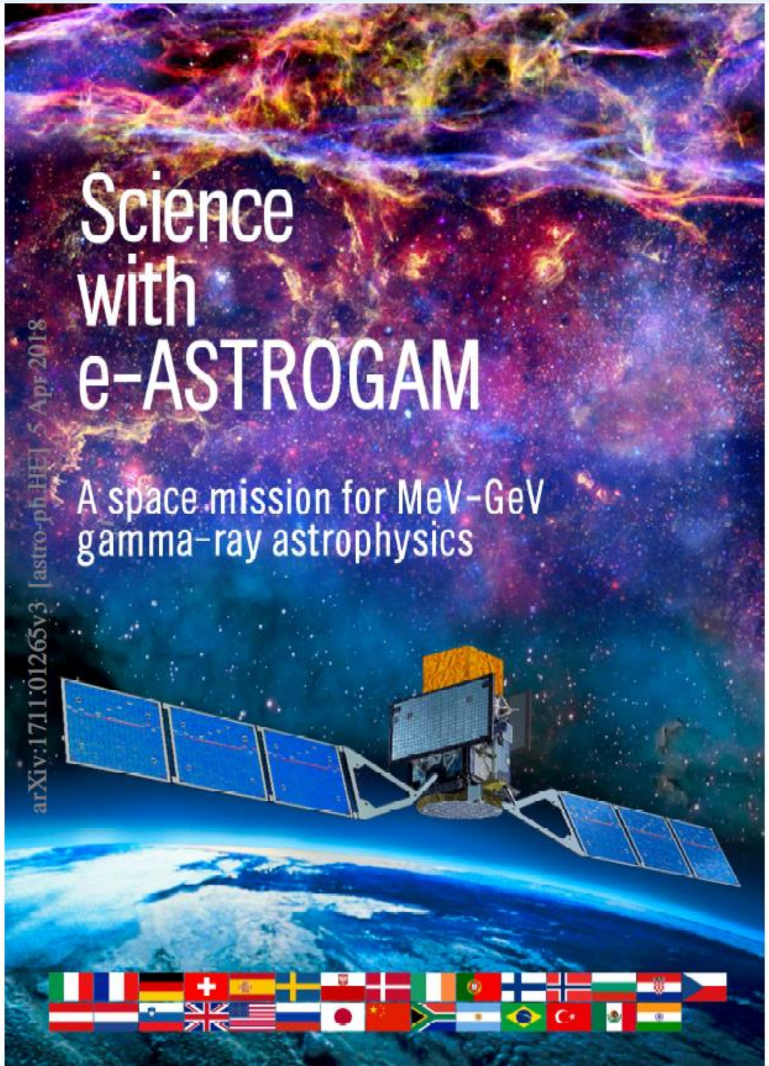
Favourably evaluated by ESA's Technical and Programmatic Evaluation Panel, but finally not selected for the M5 mission

Credit: V. Tatischeff 2019

e-ASTROGAM synergies



e-ASTROGAM Science White Book



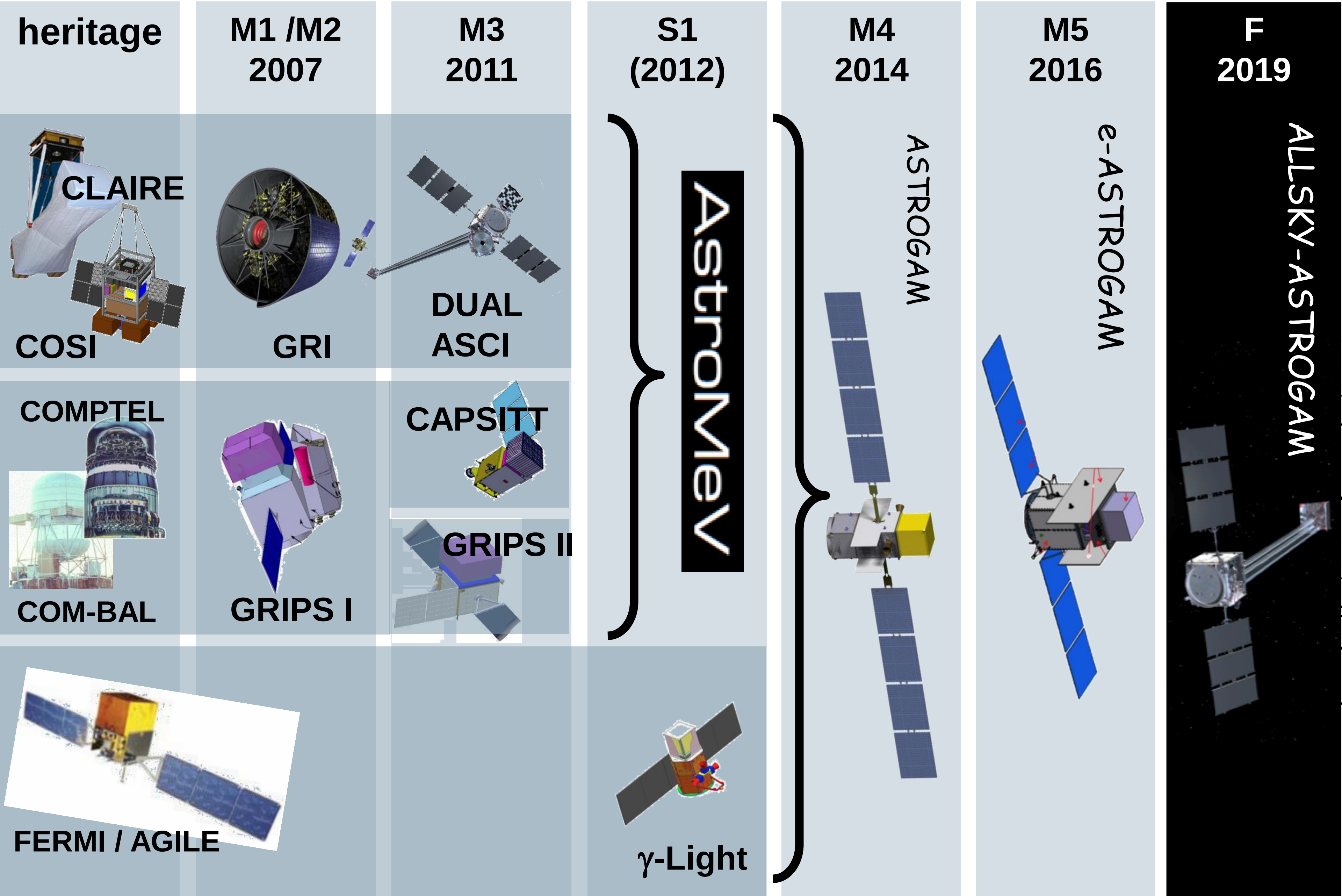
*251 authors, published in Journal of High Energy Astrophysics **19** (2018) 1*

1. **The extreme extragalactic universe:** AGN, GRBs, link to new messengers; **15 papers**
2. **Cosmic-ray interactions:** cosmic-ray origin, Fermi bubbles, CR impact on ISM; **7 papers**
3. **Fundamental physics:** dark matter searches, Axion, primordial black holes, baryon asymmetry; **15 papers**
4. **Explosive nucleosynthesis and chemical evolution of the Galaxy:** supernovae, novae, diffuse radioactivities, 511 keV; **5 papers**
5. **Physics of compact objects:** pulsars, magnetars, pulsar wind nebulae, X- and gamma-ray binaries; **9 papers**
6. **Solar and Earth Science:** Terrestrial gamma-ray flashes, solar flares, Moon; **5 papers**
7. **Miscellanea:** unidentified gamma-ray sources, gamma-SETI etc..; **5 papers**

Wide interest from the scientific community

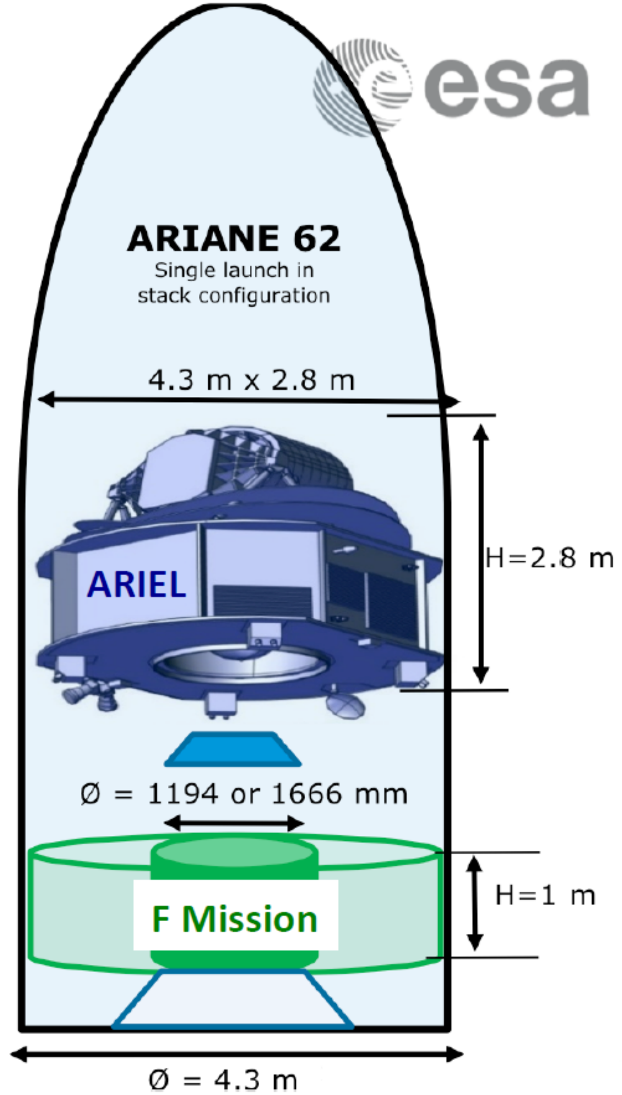
Credit: V. Tatischeff 2019

The path towards Allsky – Astrogam

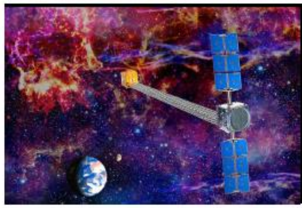


ESA Call for a Fast (F) Mission

- Call in July 2018 for a **"Fast" Mission of modest size** to be launched in 2028 with the ARIEL M4 Mission to an **L2 orbit**
- F-spacecraft wet mass < 850 – 900 kg (depends on Ariane 62 performance)
- **Payload mass < 80 kg** (?); fast and reliable payload development in 3 – 3.5 years; **TRL 6** required by mission selection (Q1 2020)
- Launch in a stacked configuration with the F-spacecraft structure used for holding ARIEL ⇒ **highly non-standard platform**
- L2 orbit (1.5 million km from Earth):
  ☹ **High cosmic-ray background**
  ☺ **No occultation by Earth**

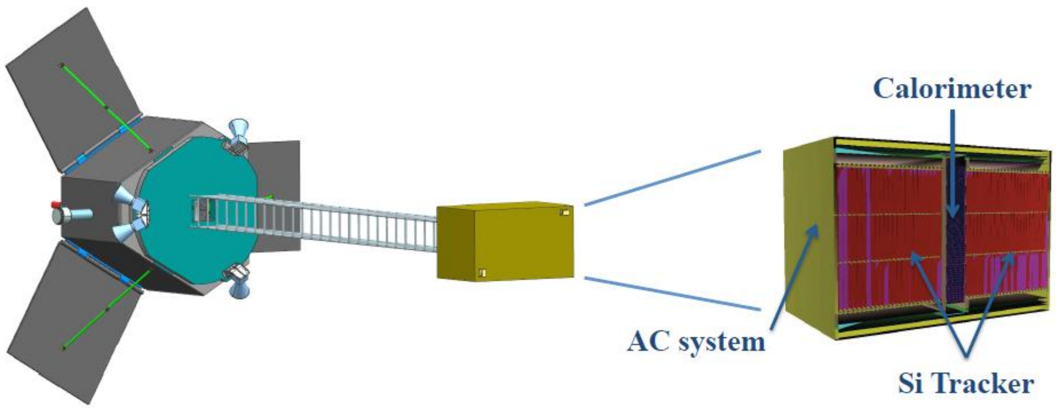


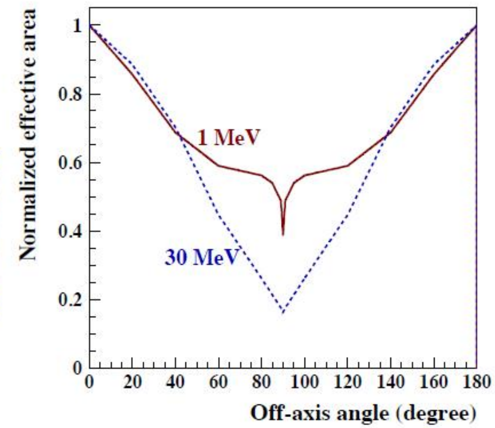
All-Sky-ASTROGAM



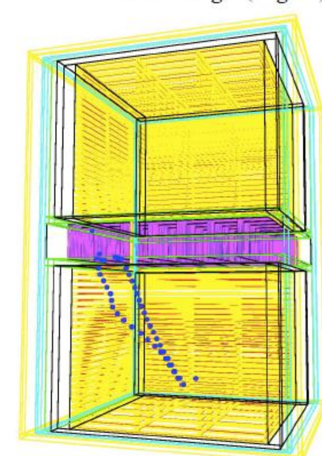
All-Sky-ASTROGAM

The MeV Gamma-Ray Companion to Multimessenger Astronomy





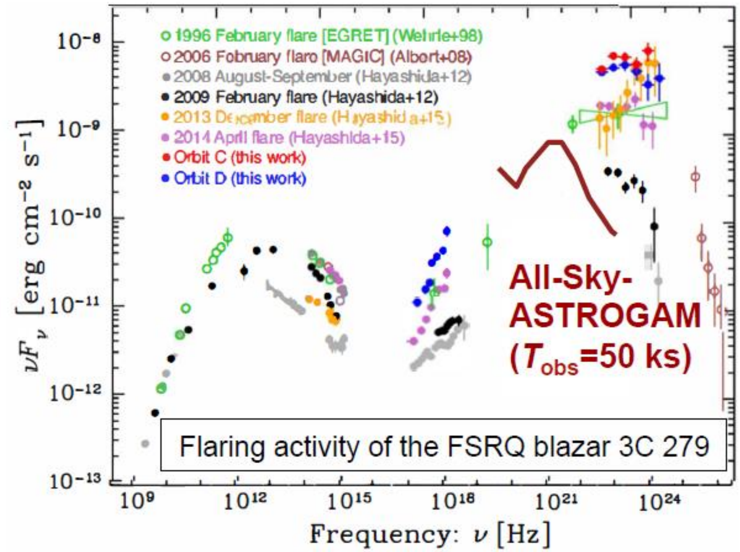
- **All-Sky Gamma-ray Monitor** (0.1 MeV - 500 MeV) with **good localisation** capabilities (e.g. 30 arcmin at 300 MeV) and **excellent sensitivity to polarisation** in the MeV domain
- Gamma-ray Imager (80 kg) attached to a **deployable boom**
  ⇒ **continuous coverage of almost the whole sky**
  ⇒ **reduction of the instrument background** (L2 orbit)
- **High-TRL payload** (Tracker, Calorimeter and Anticoincidence system based on e-ASTROGAM technology)

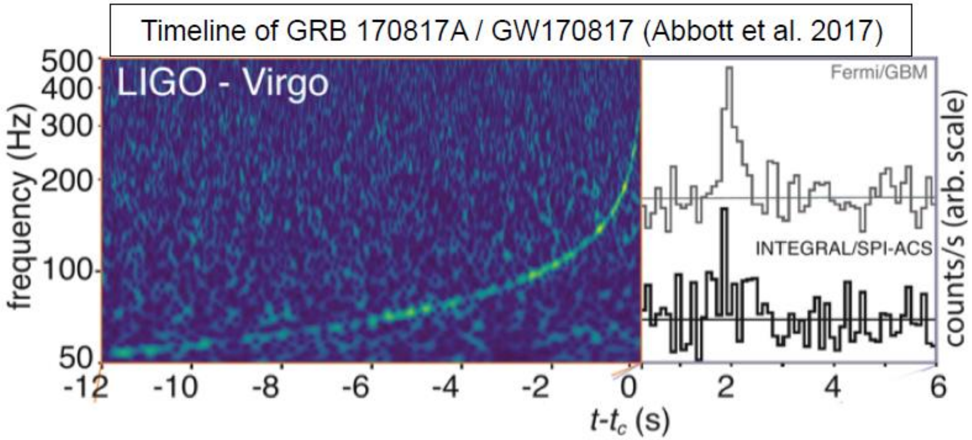


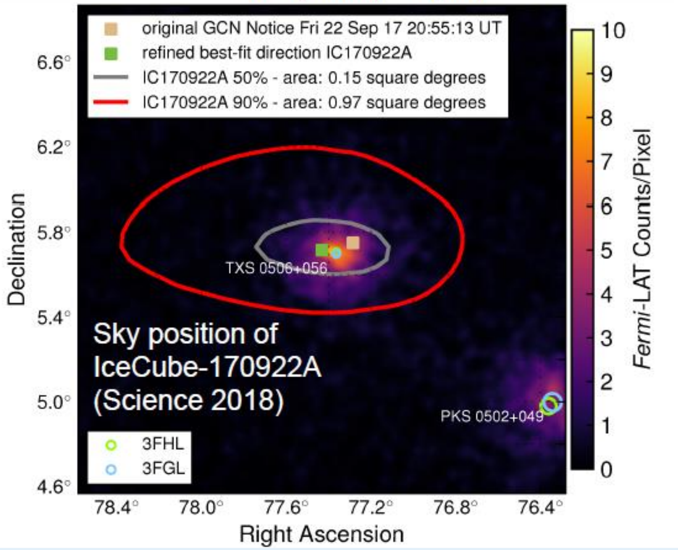
30 MeV pair event

AS-ASTROGAM Monitoring the gamma-ray Universe

- **Bright & intermediate flux transients** (GRBs, AGN, X-ray binaries, novae, Crab flares…) **at different timescales (seconds to weeks)** – crucial to identify the acceleration & radiation processes
- **Electromagnetic counterparts to gravitational wave events** – expected 0.2–6 NS-NS mergers per year with GW detection
- **Identification of high-energy neutrinos sources** (e.g. blazar TXS 0506+056)

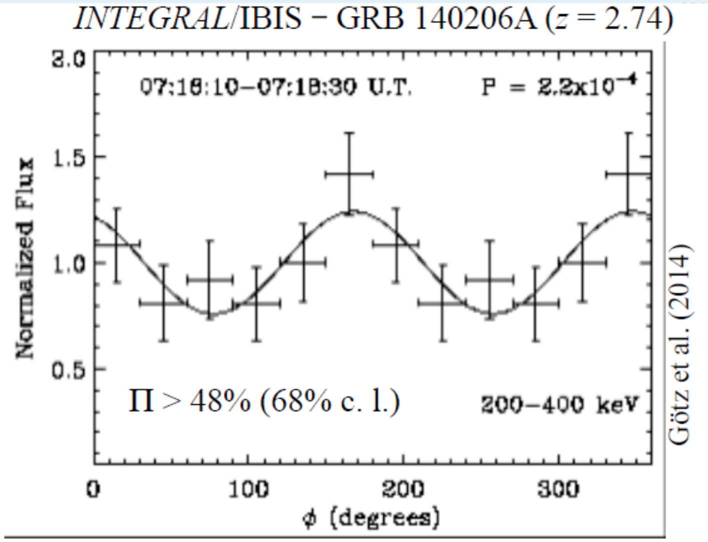


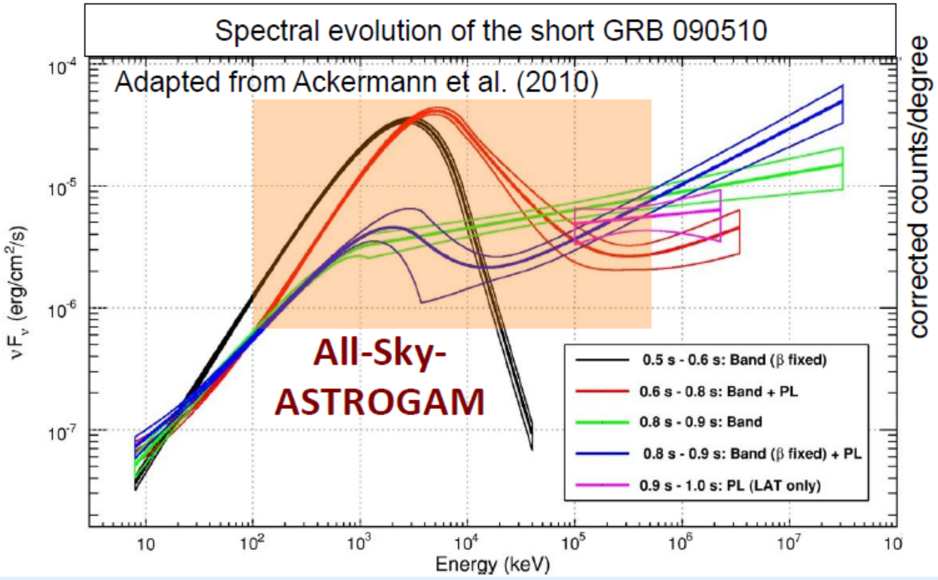


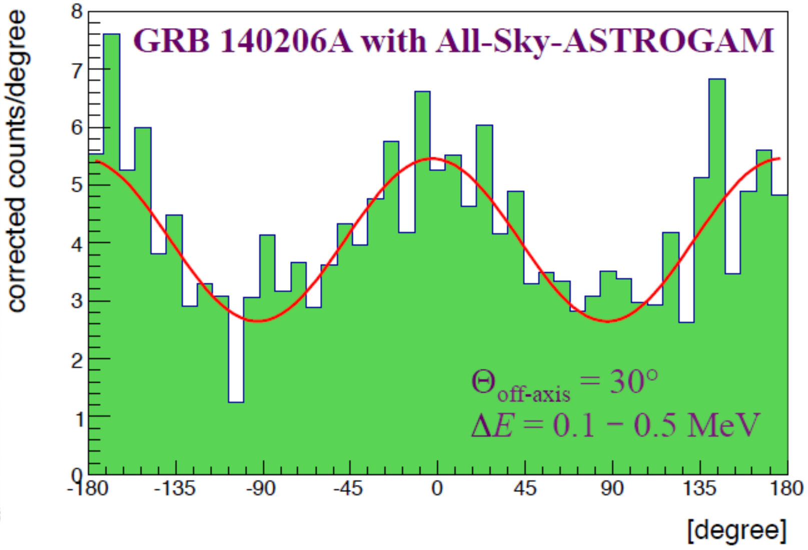


AS-ASTROGAM & GRBs

- **Unprecedented gamma-ray polarimetry**
  ⇒ **GRB jet physical properties** (B-field), energy dissipation sites, radiation mechanisms…
  ⇒ Test of **Lorentz Invariance Violation**
- **Broad-band spectroscopy** with a single instrument
- **Expected detection rate**: ~ 100 GRBs per year

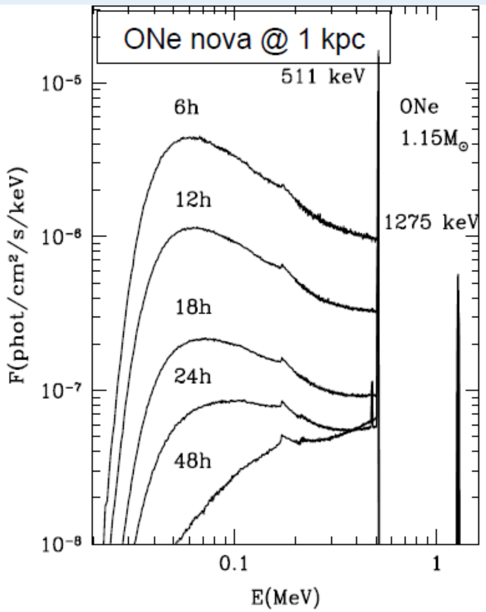


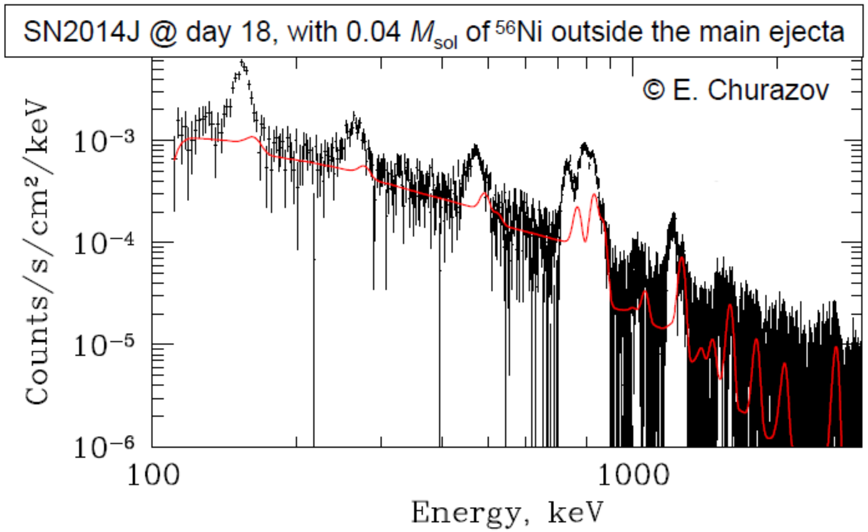


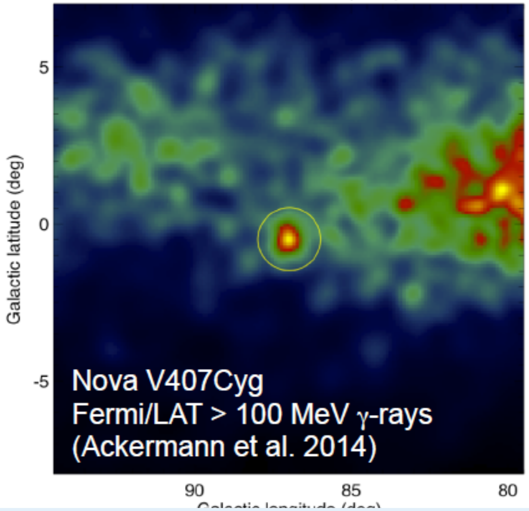


AS-ASTROGAM & Explosive Nucleosynthesis

- **Thermonuclear SNe** – Detection of the **early γ-ray emission before the maximum optical light** is fundamental to understand the **nature of the progenitor** (standard candles for cosmology)
- **Novae** – Sky monitoring is essential to detect (i) **the early e^+-e^- annihilation emission** (before optical max) and (ii) the onset of **particle acceleration in shocks**
- **Core-collapse SNe** – Determination of the **ejected mass of ^{56}Ni** is crucial to understand the explosion mechanism







AMEGO

All-sky Medium Energy Gamma-ray Observatory

AMEGO Science

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

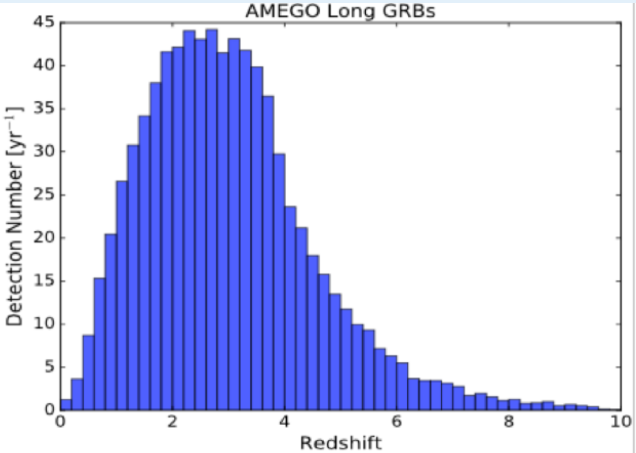
Compact Objects
Identify the physical processes in the extreme conditions around compact objects

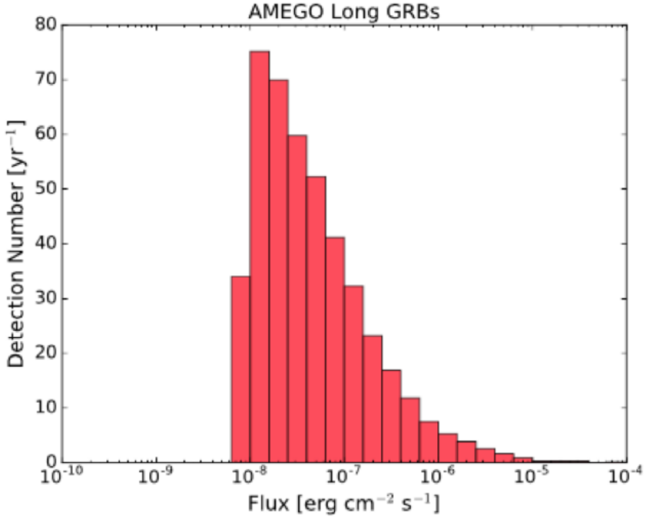
Dark Matter
Test models that predict dark matter signals in the MeV band

MeV Spectroscopy
Measure the properties of element formation in dynamic systems

AMEGO & GRBs

- 440 long GRB/year (determined using method of Lien et al 2014)
  - 19.2/year with z>6
  - All with localization
- Polarization! - 20% MDP for brightest 1% of AMEGO GRB
  - AMEGO observations will probe the GRB emission mechanism and jet composition
- ~80 short GRB/year (by scaling short/long ratio from GBM)
  - Important implications for gravitational wave counterpart searches

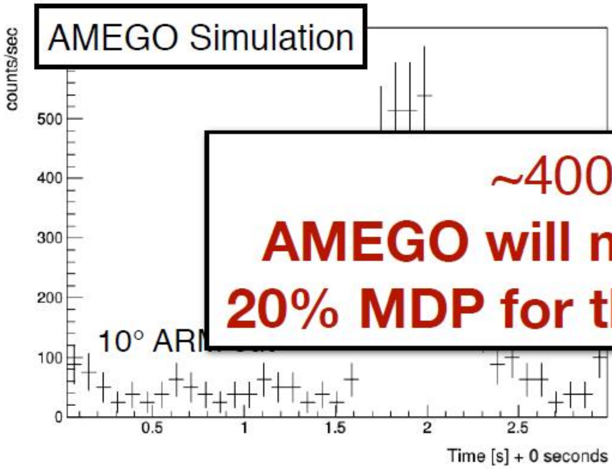




AMEGO & sGRBs as GW Counterparts

Detection of GW/GRB 170817A confirmed binary neutron stars as a progenitor to short GRBs

- Fermi/GBM onboard trigger out to 50 Mpc

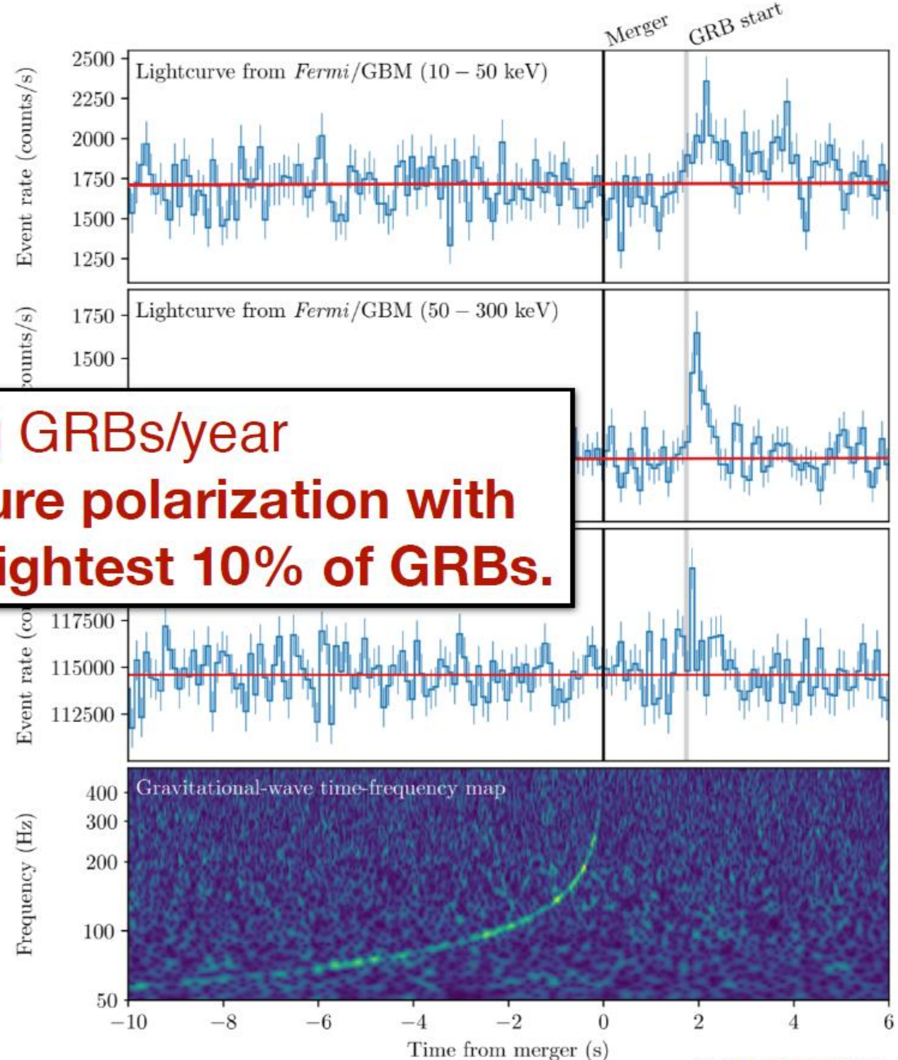


~400 Long GRBs/year

AMEGO will measure polarization with 20% MDP for the brightest 10% of GRBs.

- AMEGO detection out to 130 Mpc with ~1° localization

Larger detection volume;
~60 sGRB/year with localization



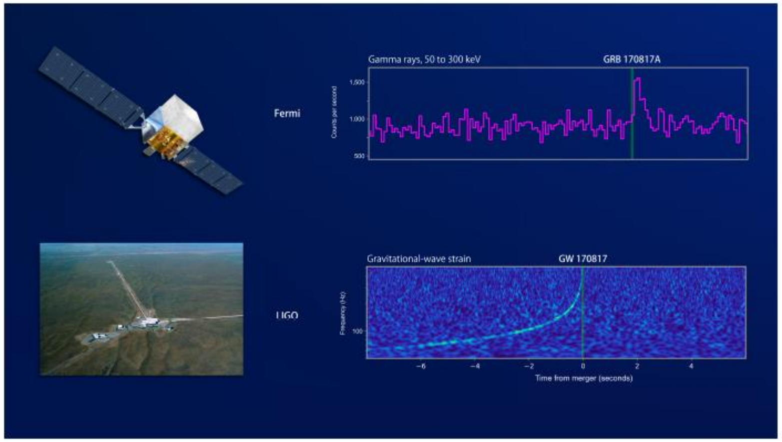
Abbot et al. 2017

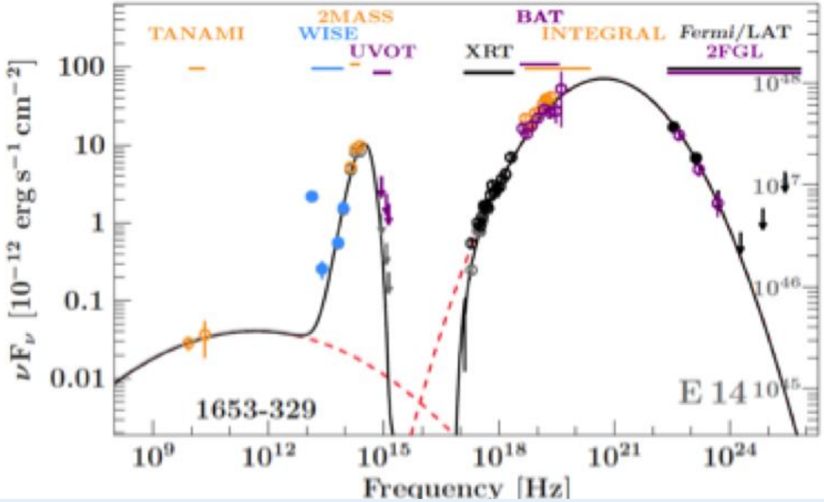
AMEGO & Multimessenger Astrophysics

GRB and GW sources: AMEGO will detect ~80 sGRB/year with ~degree localization - significantly more than any currently operating GRB detector

Do AGN jets accelerate protons to extremely high energies?

- Producing PeV neutrinos, UHECR and high energy gamma-rays
- MeV range is crucial





AMEGO & MeV Blazars

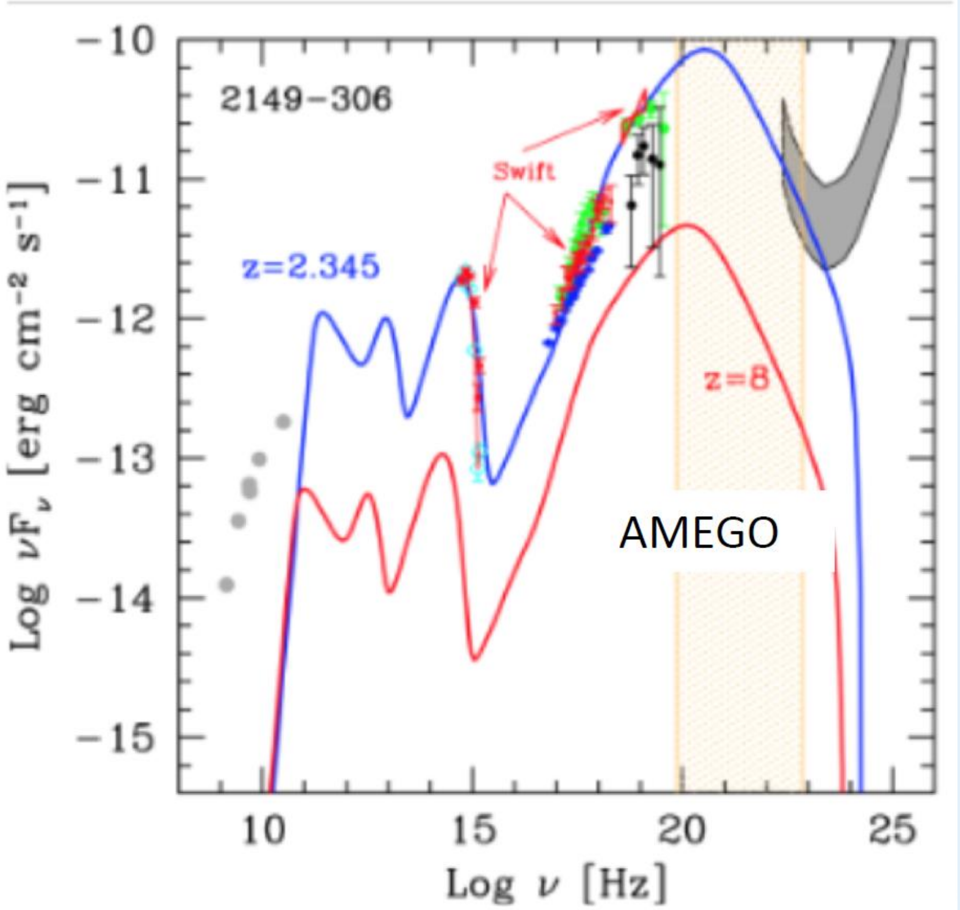
Among the most powerful persistent sources in the Universe

Large jet power, easily larger than accretion luminosity

Host massive black holes, near 10^9 solar masses or more

Detected up to high redshift

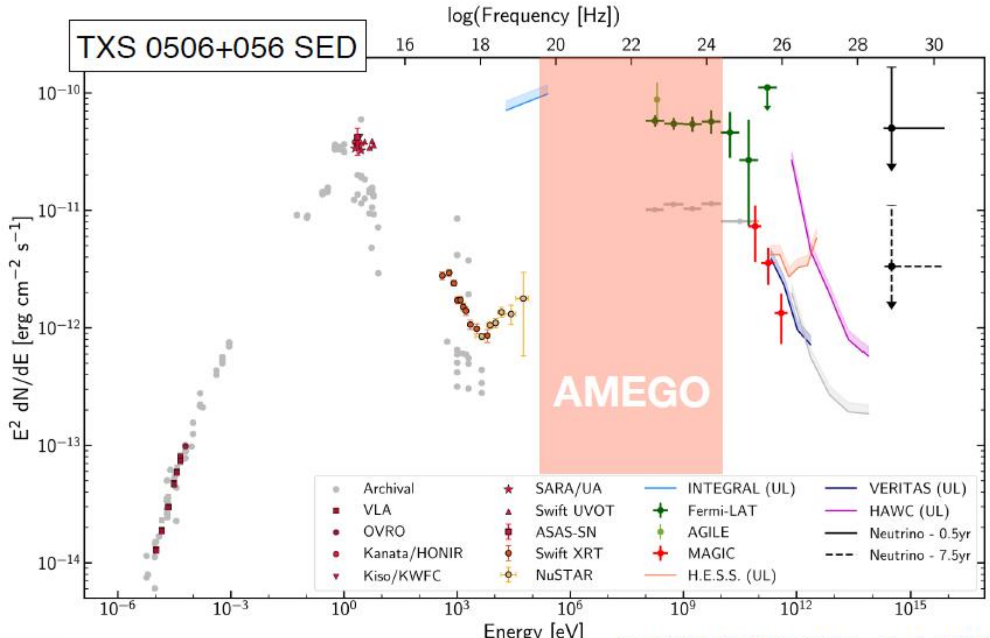
- AMEGO will detect >500 MeV blazars
- ~100 at z>3



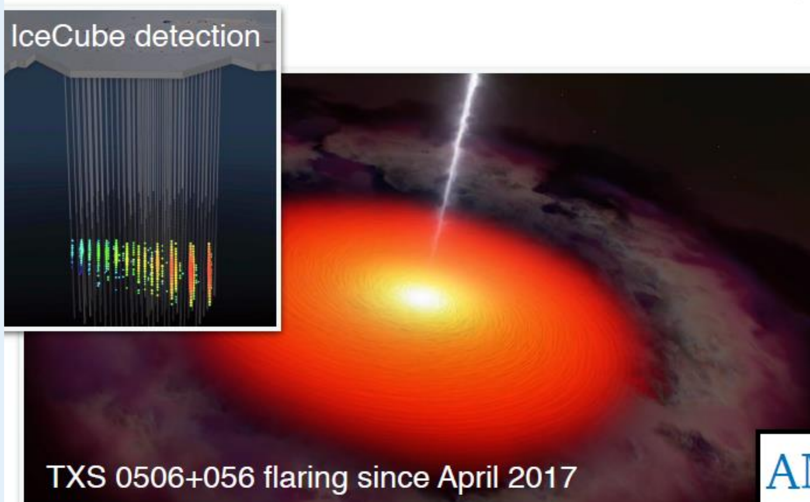
AMEGO & Neutrino Counterparts

IceCube neutrino spatially and temporally coincident with Fermi/LAT flaring blazar detection

- the first known source of high energy astrophysical neutrinos
- indicates hadronic production in the jet
- SED peaks in the MeV



IceCube Collaboration, et al, 2018



High redshift blazars population

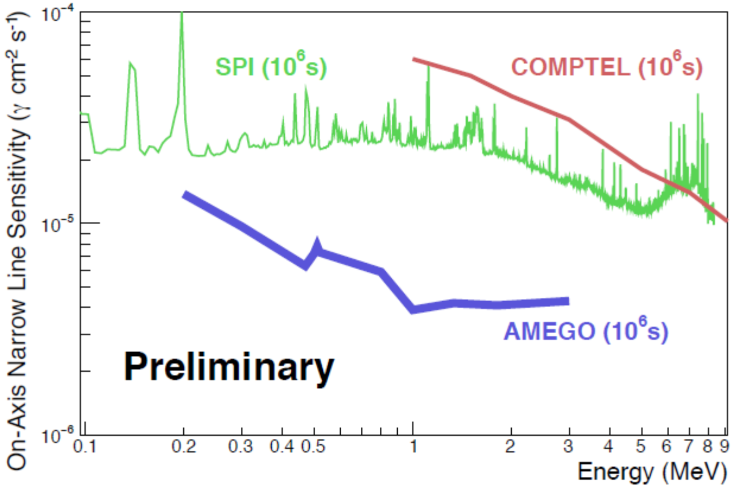
- harbor most massive black holes
- persistent gamma-ray sources unobserved by Fermi/LAT
- peak power output ~1MeV

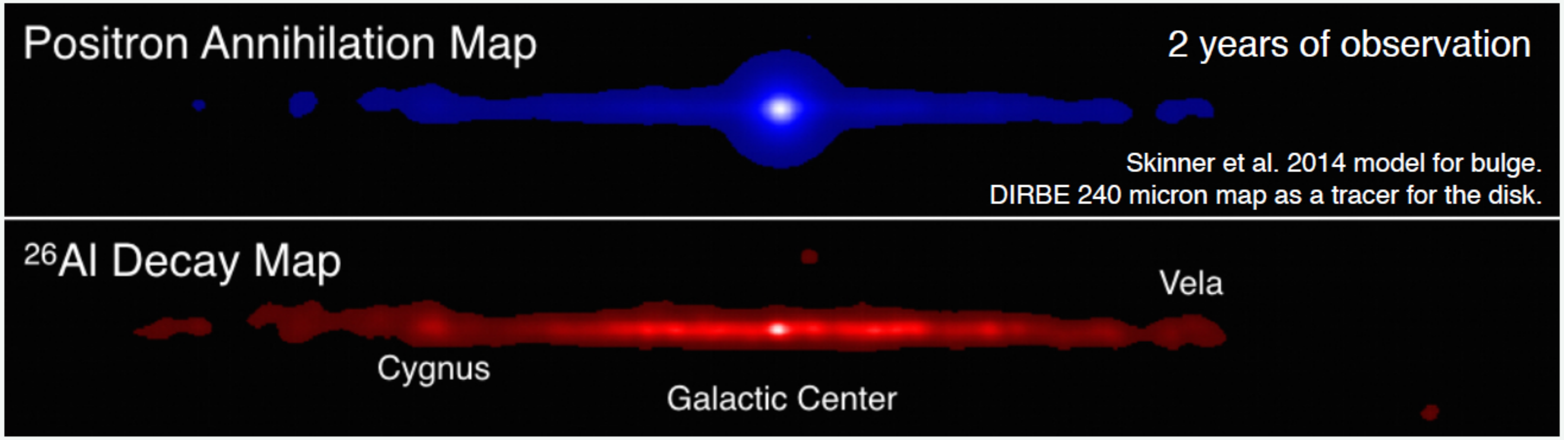
AMEGO will detect >500 blazars to z~6-8

AMEGO & the 511 keV line spectroscopy

Measurements from INTEGRAL/SPI show a strong 511 keV line from annihilation of Galactic positrons

- the source of positrons is highly contested
- propagation distances are unknown
- spatial distribution not well constrained

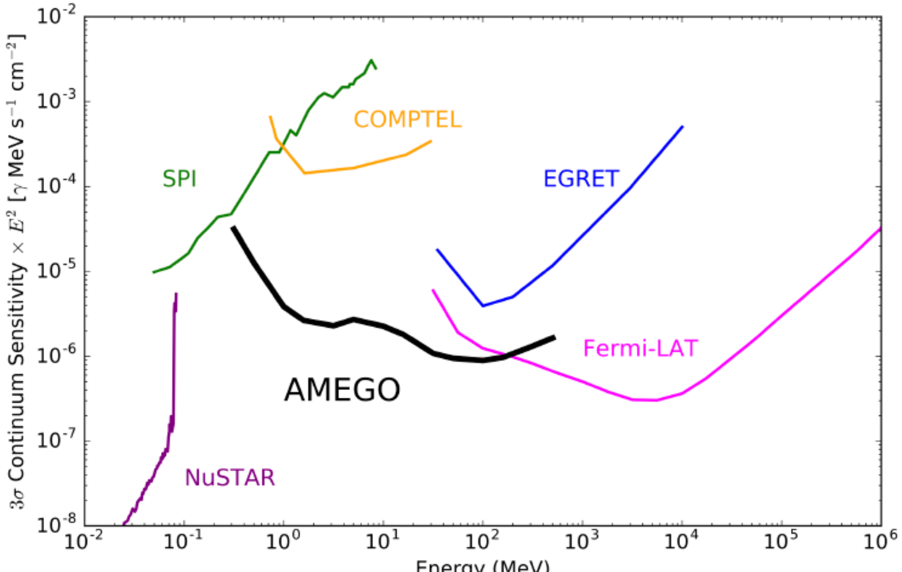


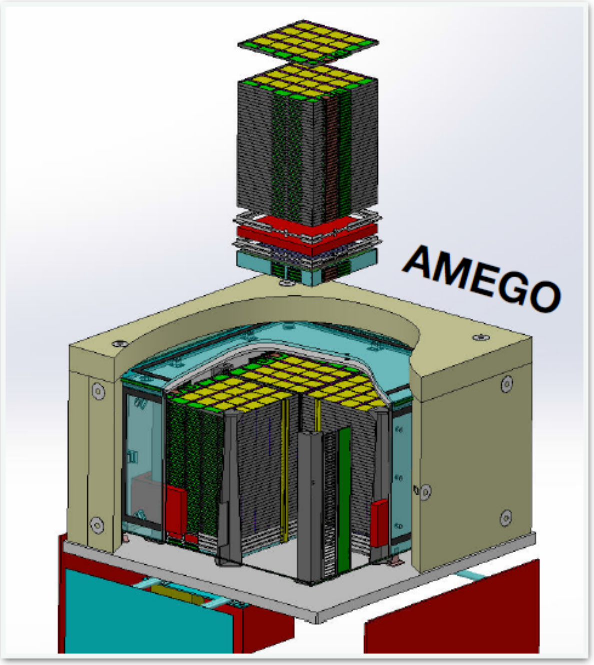


First all-sky, model-independent image of 511 keV emission

AMEGO

A Compton/pair instrument for future discoveries in multimessenger astrophysics



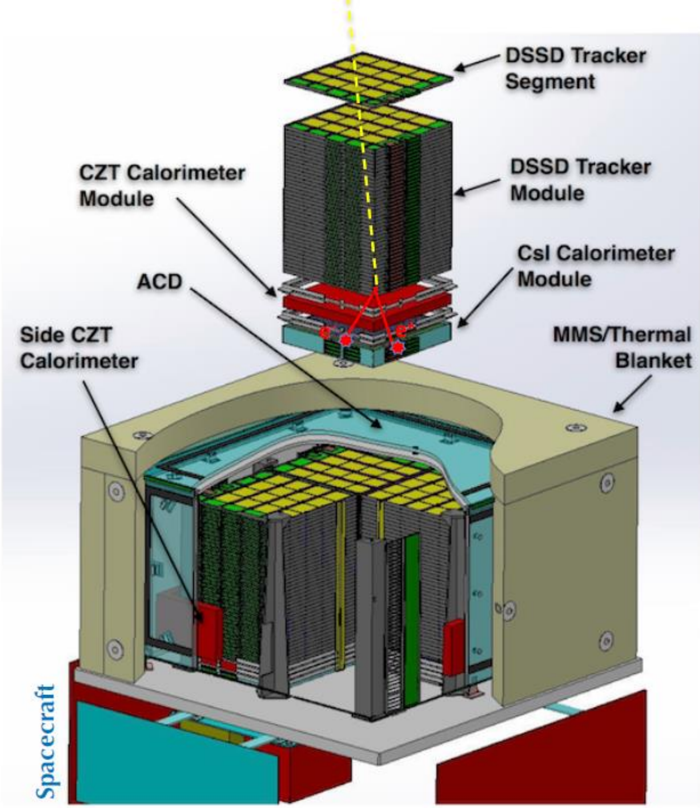


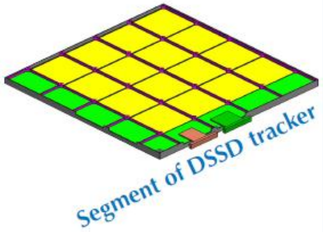
https//asd.gsfc.nasa.gov/amego

Energy Range	200 keV — >10 GeV
Angular Resolution	3° at 1 MeV; 10° at 10 MeV
Energy Resolution	1–5% at 0.2-100 MeV; ~10% at 1 GeV
Field of view	2.5 sr
Survey Mode	80% of sky per orbit

Credit: C. Kierans 2019

AMEGO





Silicon Tracker

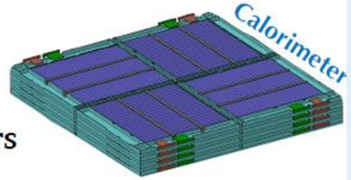
Measures position and energy of Compton scattered electron or track of pair products

- 60 layers of 10 x 10 cm x 0.5 mm DSSD, 0.5 mm strip pitch

CZT Calorimeter

Measures location and energy of Compton scattered photons

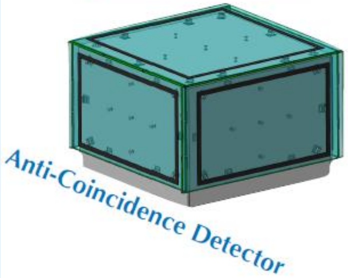
- Array of 0.6 x 0.6 x 2 cm position sensitive CdZnTe bars



CsI Calorimeter

Contains the highest energy pair events

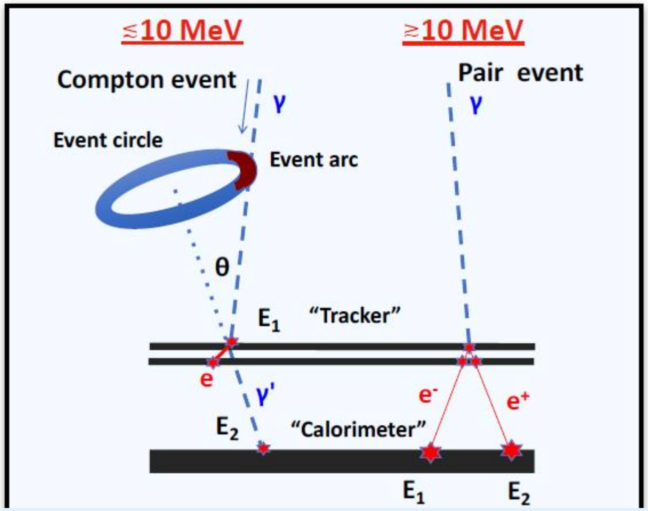
- 6 planes of 1.5 cm x 1.5 cm CsI(Tl) bars



Anti-Coincidence Detector

Vetos cosmic ray events

- plastic scintillator with SiPM readout

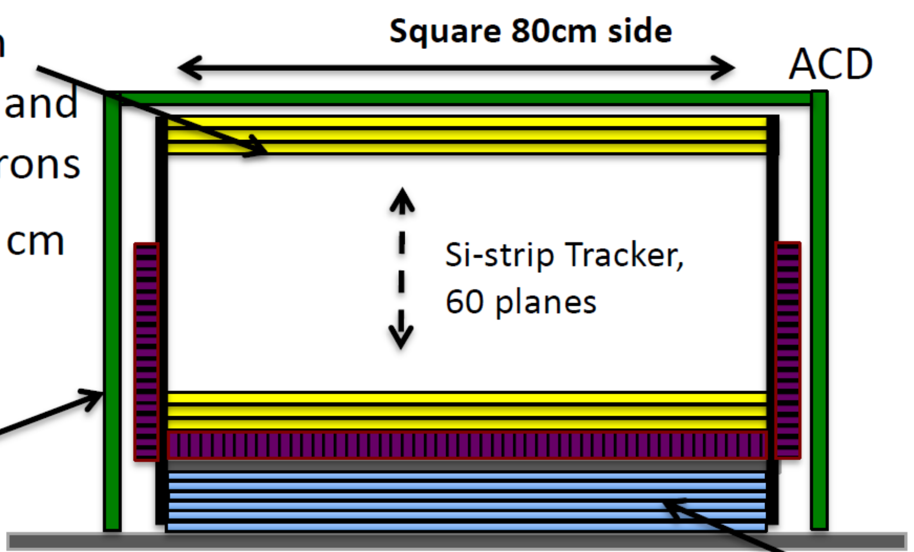


AMEGO Payload

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

Measure location and energy of Compton scattered photons

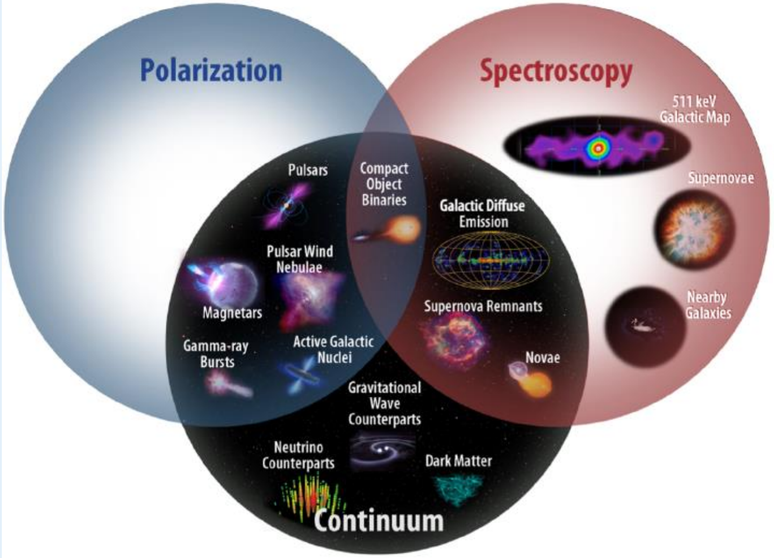
- Layer of 0.6x0.6 x 2cm bar CZT

CsI Calorimeter

Extend upper energy range

- 6 planes of 1.5cm x 1.5 cm bars

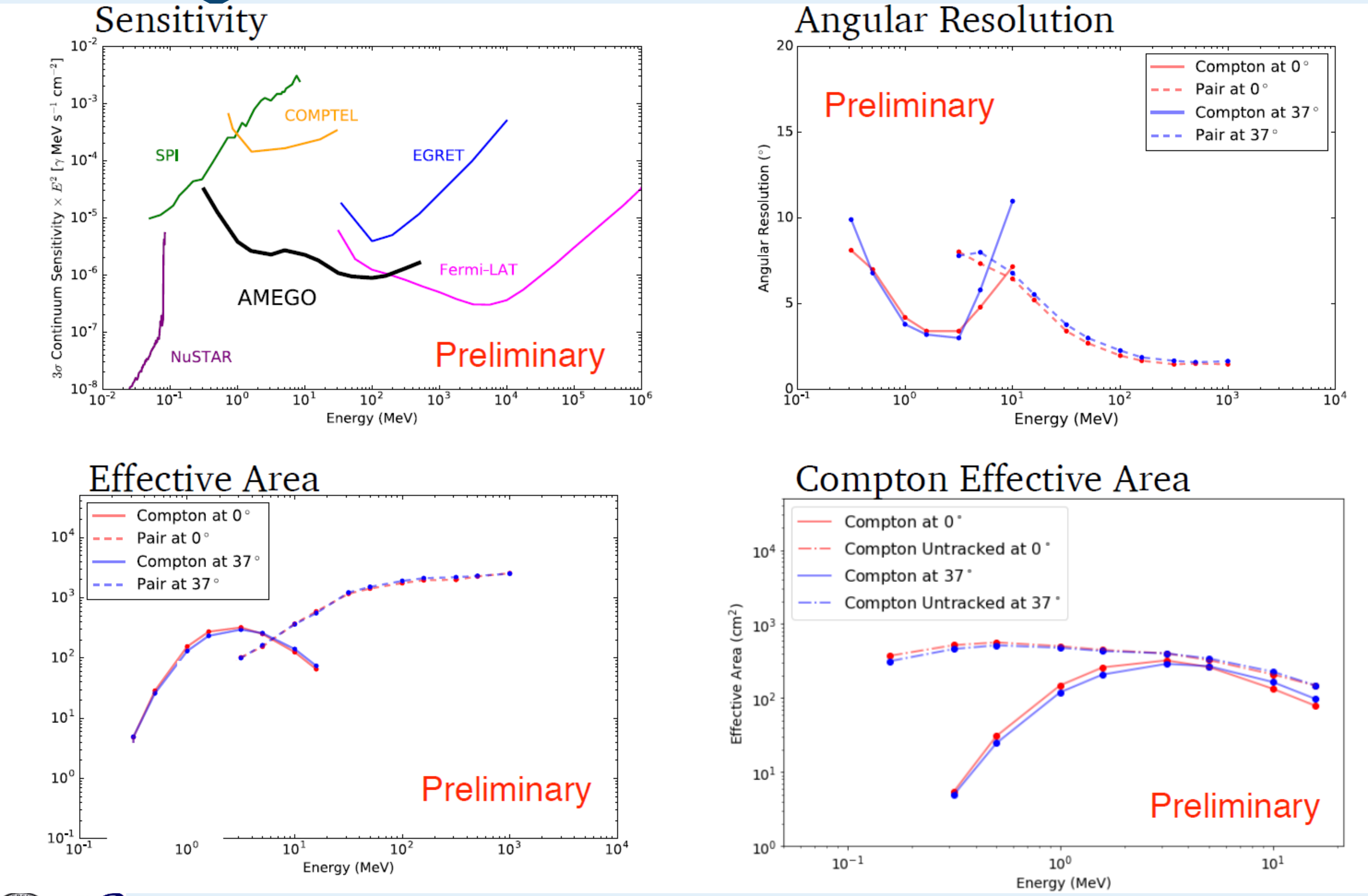
AMEGO Science Objectives



AMEGO will provide three new gamma-ray science capabilities in the MeV band

- AMEGO, optimized for high flux sensitivity, broad energy range and a wide field of view will focus on astrophysical extremes
  - Astrophysical jets and multimessenger astrophysics
  - Compact objects (neutron stars and black holes)
  - Element formation in dynamic environments
  - Dark matter and new physics

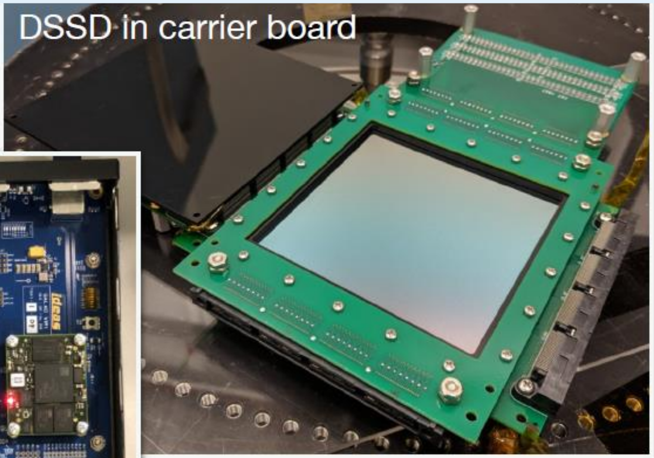
AMEGO simulated performance via MEGAlib

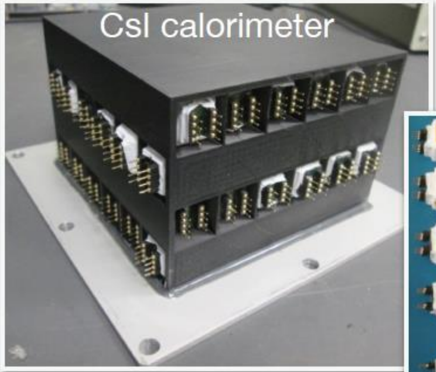


AMEGO current development

Design and development of prototype instrument

- silicon tracker and ACD at Goddard Space Flight Center
- CZT calorimeter at GSFC and Brookhaven
- CsI calorimeter at Naval Research Laboratory



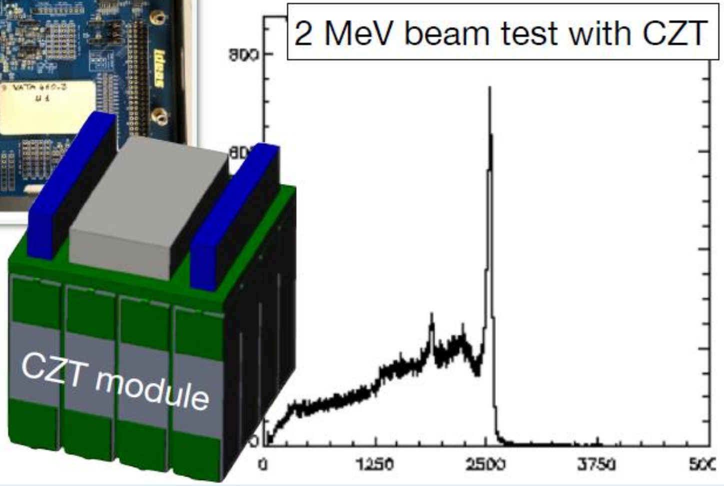


Beam tests in Fall 2019

- verify hardware and ability to reconstruct Compton and pair events
- validate performance and simulations

Balloon flight in Summer 2020

- verify operations in a space-like environment
- study backgrounds



AMEGO current efforts

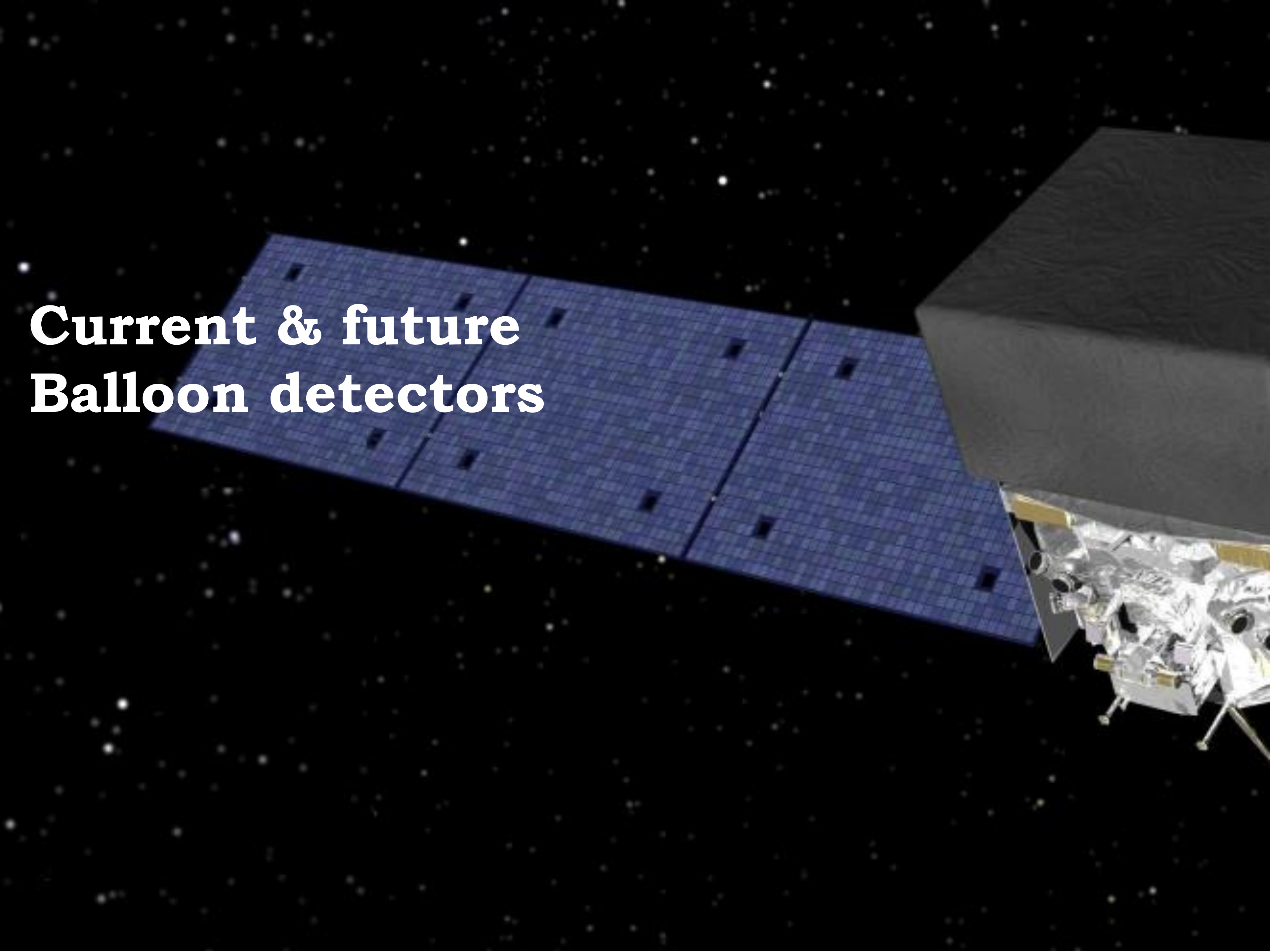
Astro2020 Science White Papers

- Positron Annihilation in the Galaxy
- Prospects for AMEGO Studies of Pulsars
- Neutrinos, Cosmic Rays, and AMEGO
- Gamma rays and Gravitational Waves Events
- Supermassive black holes at high redshifts
- Prospects for AGN Studies at Hard X-ray through MeV Energies
- A Summary of Multimessenger Science with Neutron Star Mergers
- Prospects for Galactic Cosmic Rays, Interstellar Medium, and Associated Gamma-Ray Emission Studies at MeV-GeV Energies
- Magnetars as Astrophysical Laboratories of Extreme Quantum Electrodynamics: The Case for a Compton Telescope
- Prospects for detection of synchrotron halos around middle-age pulsars
- High-Energy Polarimetry as A New Window to Unveil Cosmic Rays and Neutrinos in AGN Jets
- Catching Element Formation In The Act: The Case for a New MeV Gamma-Ray Mission: Radionuclide Astronomy in the 2020s
- etc…

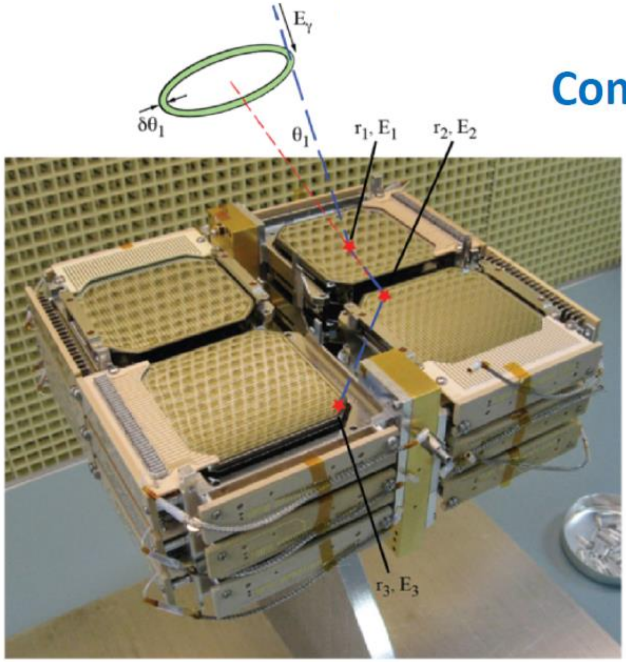
AMEGO Mission White Paper to be submitted Summer 2019

Report to be released ~2022

Current & future Balloon detectors



Compton Spectrometer and Imager (COSI)



Compton regime – focus on polarization and spectroscopy

- Ge strip detectors
- 0.2-5 MeV
- Instantaneous FOV (25% sky)
- Energy resolution of 0.2-1% (FWHM)

- Balloon launch from New Zealand for mid-latitude flight and Galactic Center coverage
- Angular resolution = 5.1 deg (FWHM) at 0.511 MeV
- COSI-X strips are half as wide

COSI Overview

Instrument

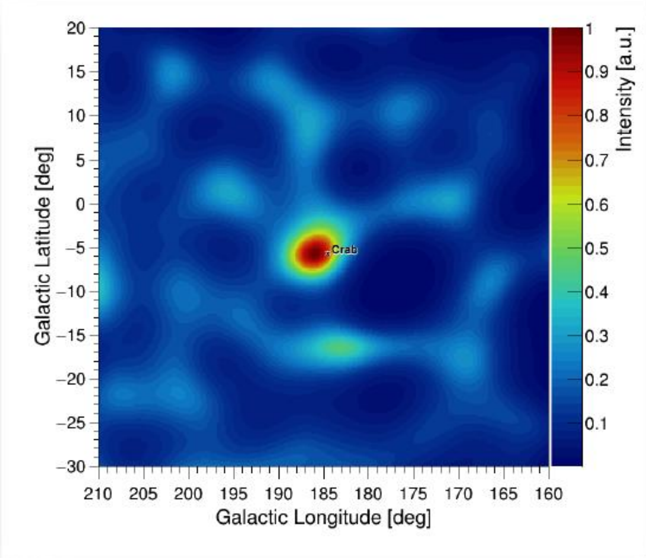
- Balloon-borne Compton telescope
- Energy range: 0.2 – 5.0 MeV
- 12 high-purity Ge double-sided strip detectors with 2 mm strip pitch
- Energy resolution: 1.5-3.0 keV FWHM
- Depth resolution: ~0.5 mm FWHM
- Angular resolution: up to ~4° FWHM
- Large field-of-view: almost 1/4 of full sky

Science Objectives

- Life cycle of (anti-) matter in our Galaxy
- The most violent events and the most extreme environments in our Universe

Balloon Campaigns: 5 in total

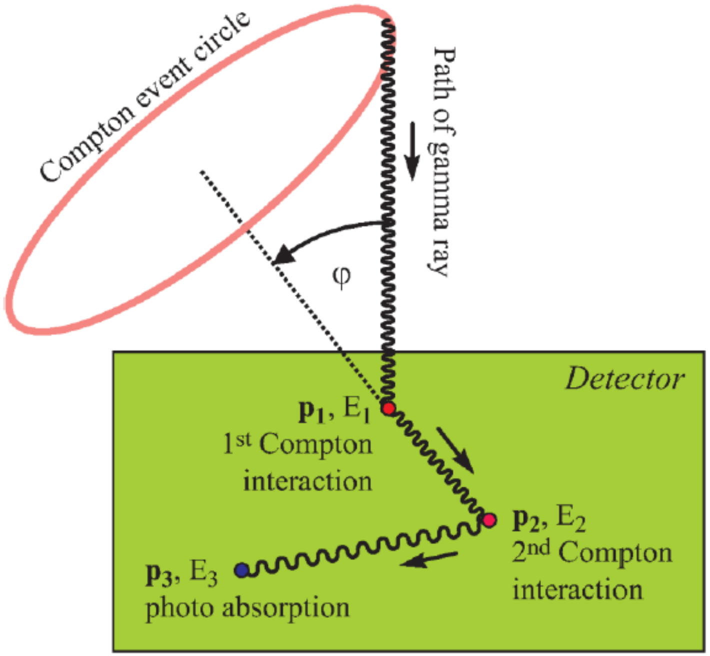
- Last: COSI: 46-day flight from Wanaka, New Zealand, 2016 – 1st science flight of NASA new super-pressure balloon platform
- Next: COSI-2 in 2020 or COSI-X1 in 2022

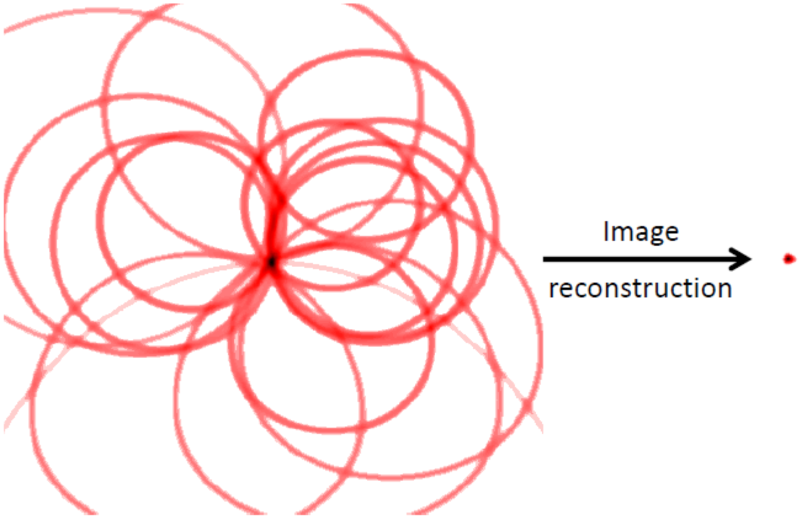


Credi: A. Zoglauer 2019

COSI Overview: Operating principle

Credi: A. Zoglauer 2019



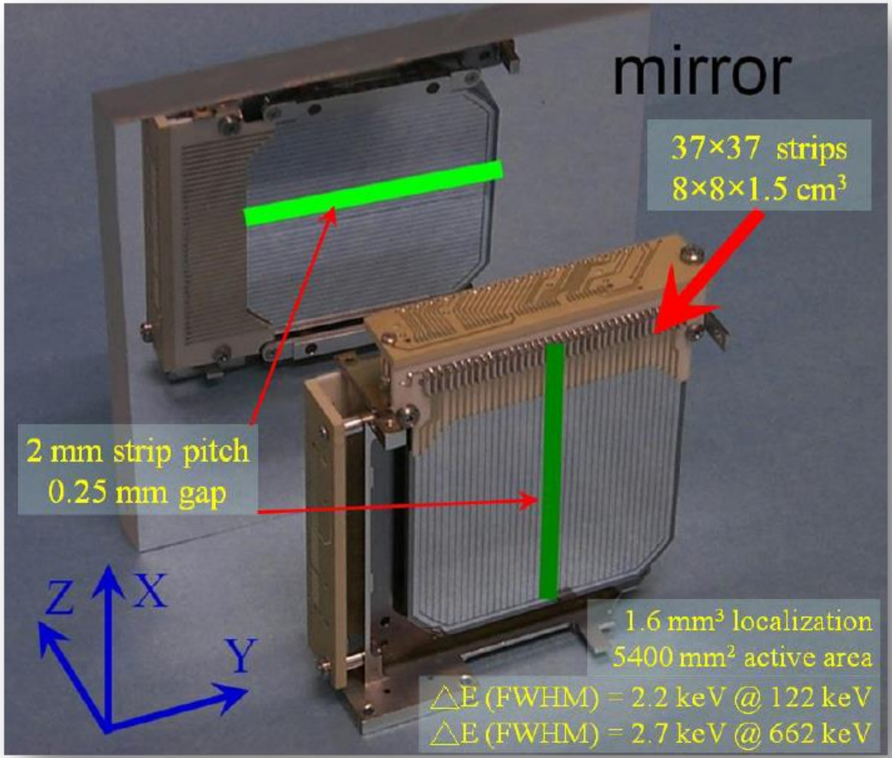


- Photons interact multiple times in active Germanium detectors via Compton scatters
- The interaction sequence has to be determined from information such as scatter angles, absorption probabilities, scatter probabilities
- The origin of a single not-tracked Compton event can be restricted to the so called Compton "event circle"
- The photons originate at the point of all overlap
- Deconvolution creates sky maps

The COSI Germanium detectors

- Size: 8 x 8 x 1.5 cm^3
- Wafer: Ortec, Processing: LBNL
- 37 orthogonal strips per side
- 2 mm strip pitch
- Operated as fully-depleted p-i-n junctions
- Excellent spectral resolution: 1.5 – 3 keV FWHM
- Excellent depth resolution: 0.5 mm FWHM
- 12 are integrated in the COSI cryostat

Credi: A. Zoglauer 2019



The COSI detector HEAD

2x2x3 detector geometry

- Wide field-of-view,
- Good polarimetry

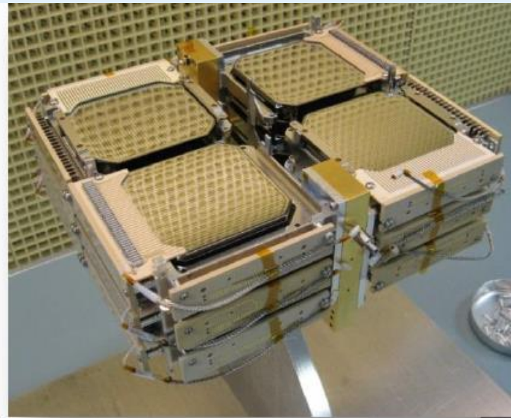
Cryostat & mechanical cooler

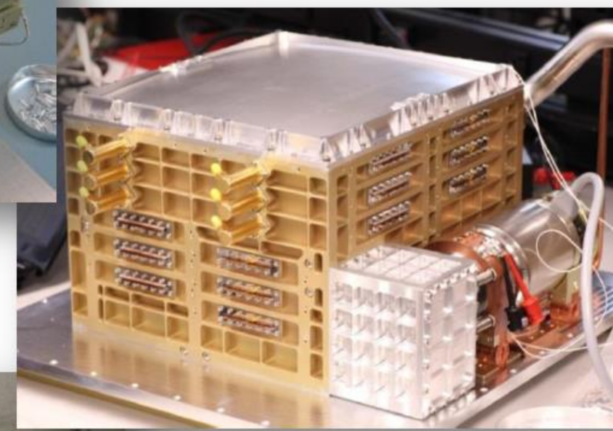
- Constant temperatures
- Enables ULDB flights

CsI shielding

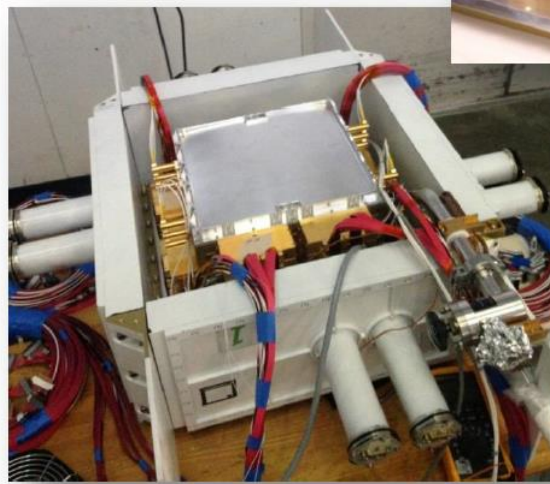
- Veto dominating atmospheric background components
- Read out by PMTs

Credi: A. Zoglauer 2019

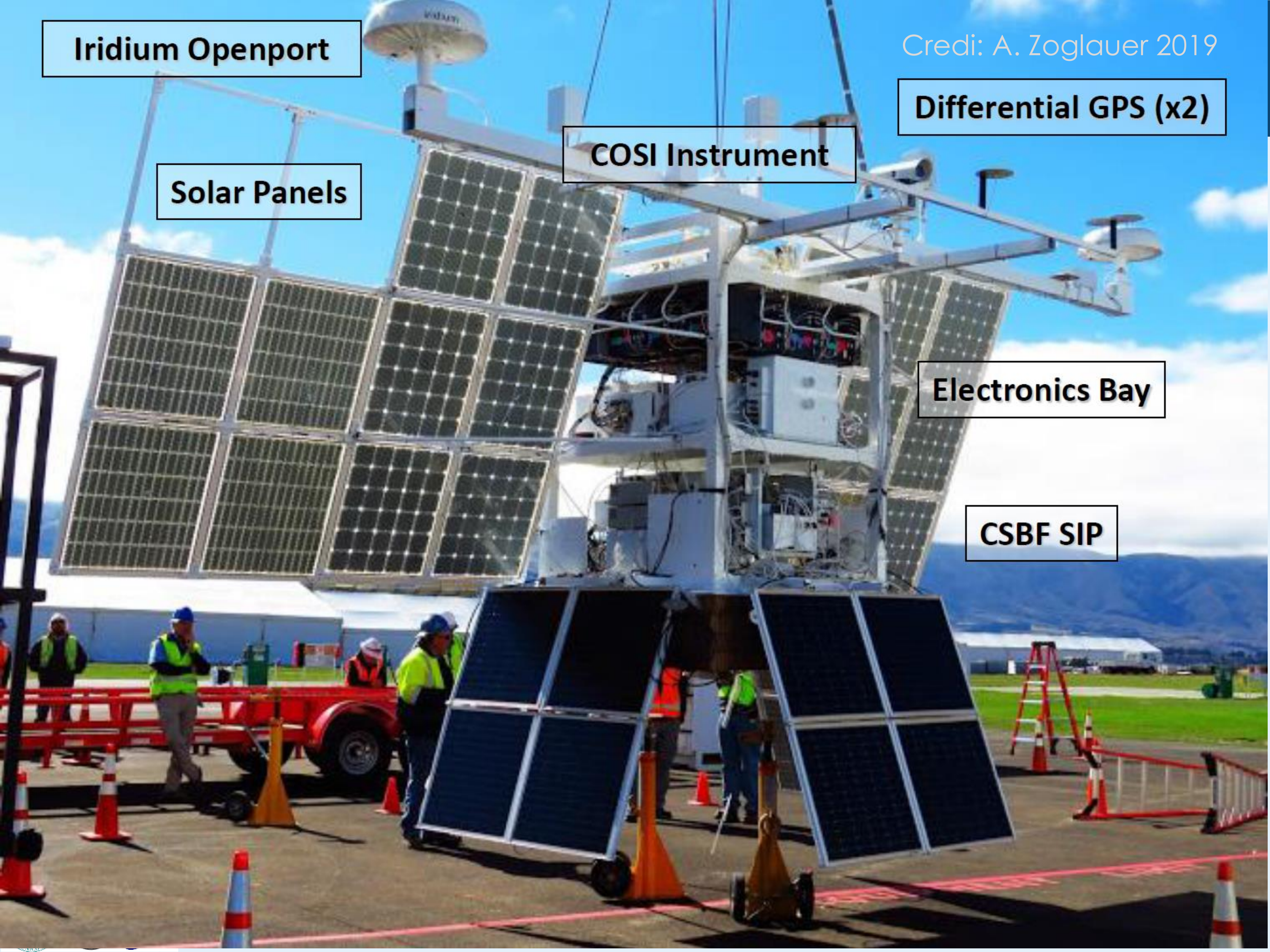




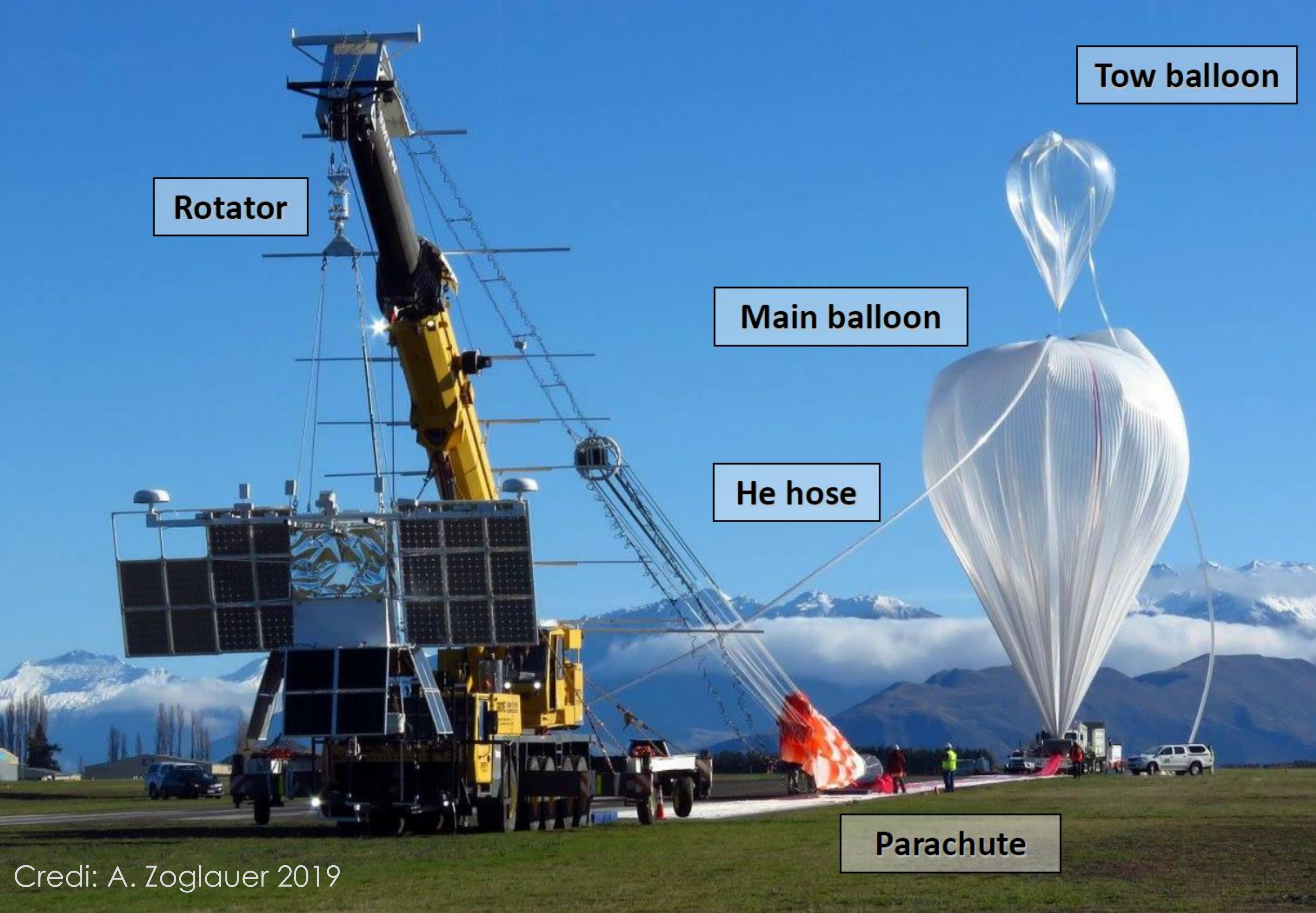
Sunpower CryoTel 10 W lift for 160 W input



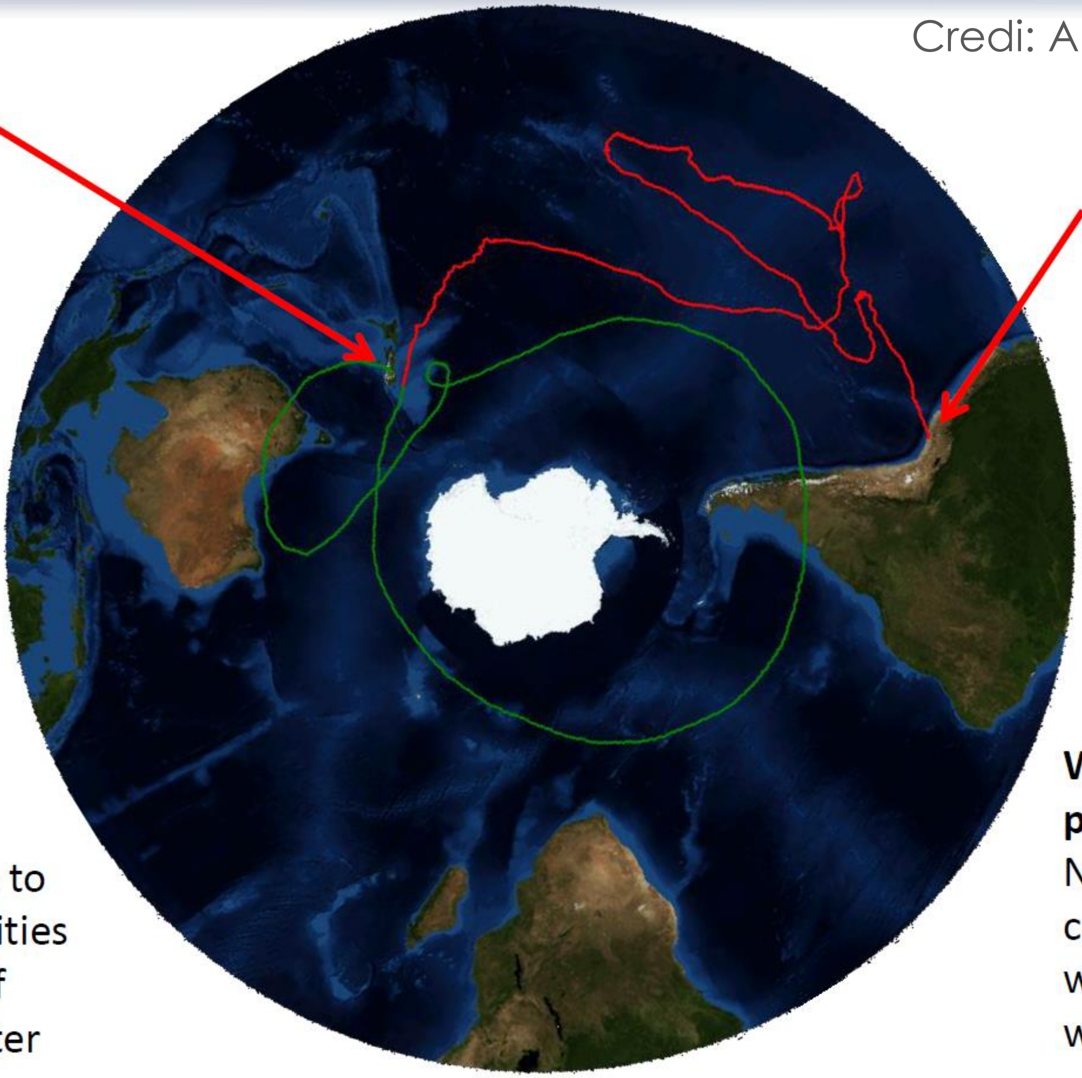
Detector surrounded by (white) CsI shield read out by conventional photo multipliers


Iridium Openport
Credi: A. Zoglauer 2019
Differential GPS (x2)
COSI Instrument
Solar Panels
Electronics Bay
CSBF SIP

Launch: May 16, 2016 from Wanaka, New Zealand



COSI flight path



Launch:
May 16, 2016, Wanaka, NZ

1st circum-navigation (green line) on May 31, 14 days after launch

Why southern Hemisphere?

- Least chance to fly over big cities
- Good view of Galactic Center

Landing:
July 2, Atacama desert, Peru (46 day flight)

Why this flight path?
No possibility to control flight – we go where the winds carry us…

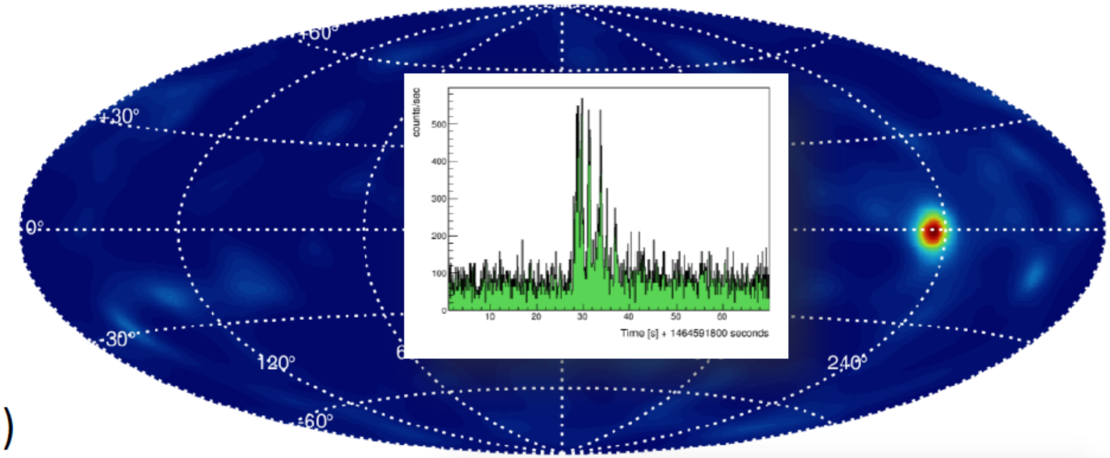
GRB 160503 – Polarization analysis

PhD thesis Alex Lowell (2017)

Credi: A. Zoglauer 2019

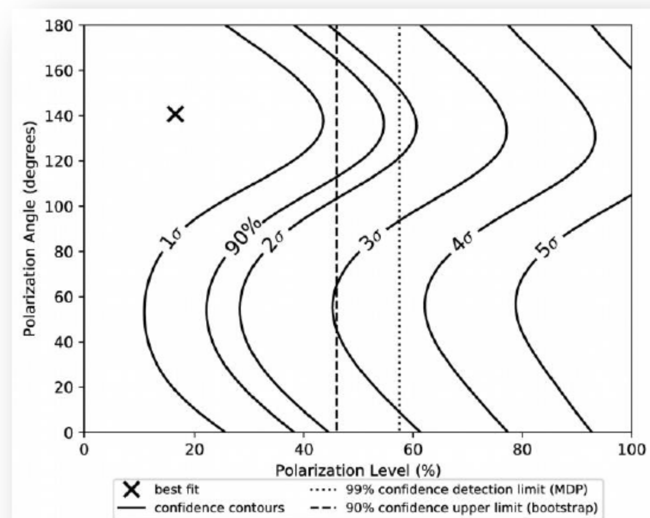
Real-time analysis:

COSI's real-time alert capabilities (a first for a balloon payload) enabled prompt notification to the observer community via GCN (GCN19473, Tomsick+)



Polarization analysis:

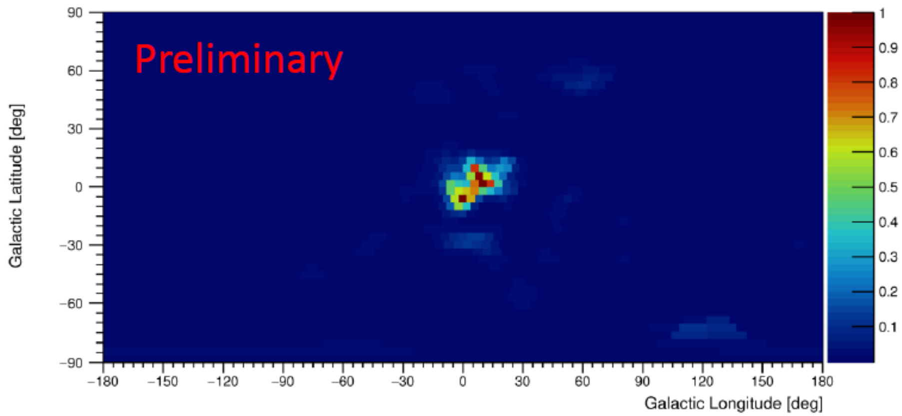
- New ML-approach (Krawczynski+ 2011)
- 90% confidence upper limit: 46%
- Best fit: 16% (+27%, -16%)

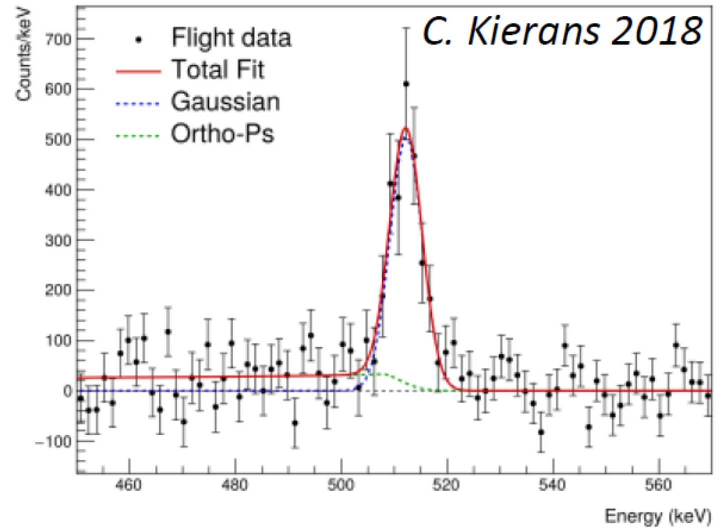


Lowell+ 2017: ApJ: 484, 119 & 484, 120

511-keV Emission from the Galactic Center

PhD thesis Carolyn Kierans (2018) & Andreas Zoglauer





- First image of the Galactic center in 511-keV with a direct imaging telescope using Maximum-Entropy deconvolution fully corrected (background, exposure, atmosphere)
- **Don't over-interpret any structure in the image**, its just 10-days of data

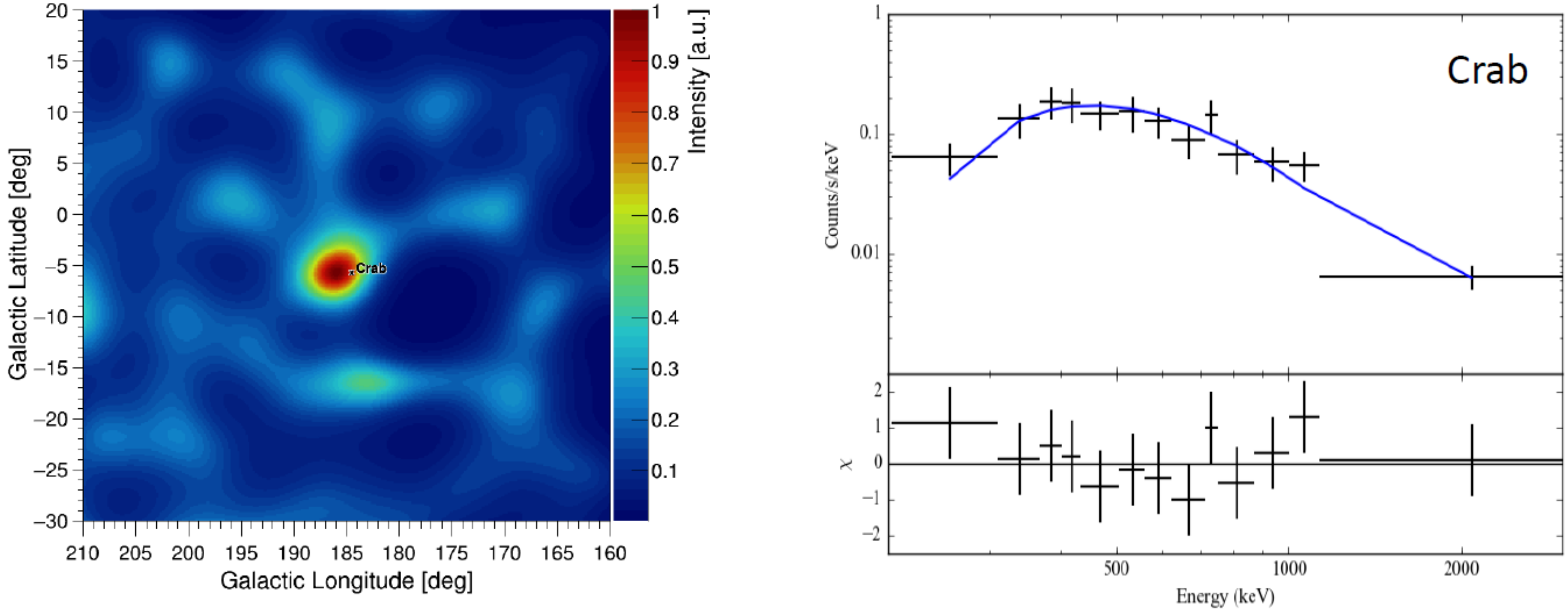
Working on:

- Testing various imaging / model fitting approaches, significance maps
- Event reconstruction and 511-background detection with neural networks

Credi: A. Zoglauer 2019

Spectral analysis pipeline & Crab

PhD thesis Clio Sleator (soon)



- Developed spectral fitting pipeline using xspec
- Test calibration, simulations, detector effects engine & analysis tools by reproducing Crab results
- Analyze detected point sources (polarization)

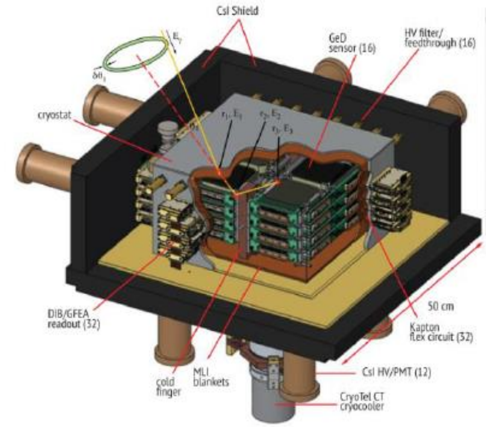
Credi: A. Zoglauer 2019

COSI next steps

COSI-2 (APRA): Re-flight of COSI

COSI is fully assembled and ready for its next flight!

COSI-X (Explorer): Upgraded COSI



Goals:

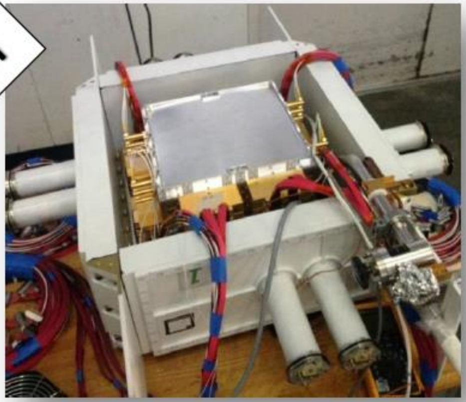
- Build upgraded COSI-like instruments with improved performance
- Perform 3 100-day flights from Wanaka, NZ, starting 2022
- Science: Same as COSI, just with better sensitivity

→ **Waiting for decision from NASA which path forward to take**

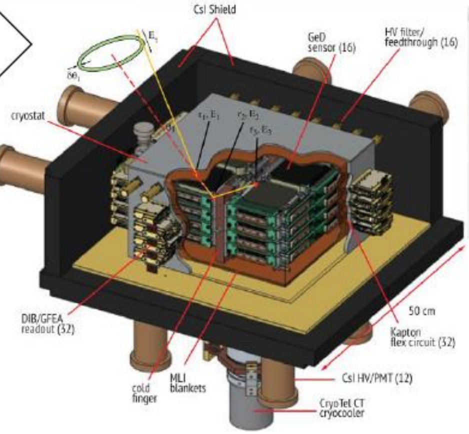
Credi: A. Zoglauer 2019

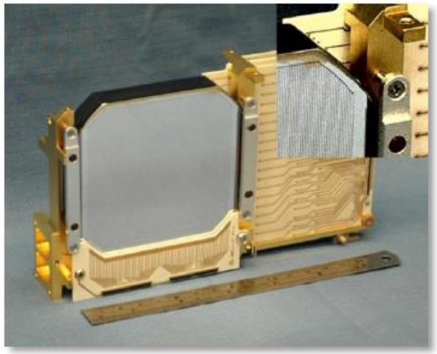
Technology advances for COSI-X

COSI



COSI-X





Upgrade Goals:

- Improved angular resolution
- Increased effective area
- Stronger background rejection

Path forward:

- 3.4x smaller detector strip pitch (with M. Amman)
- ASICs (with E. Wulf, NRL)
- Cryo-cooler upgrades (with T. Brandt, GSFC)
- More detectors (16 vs. 12)
- Better shielding (no gaps)

Credi: A. Zoglauer 2019

ASCOT

The Advanced Scintillator Compton Telescope

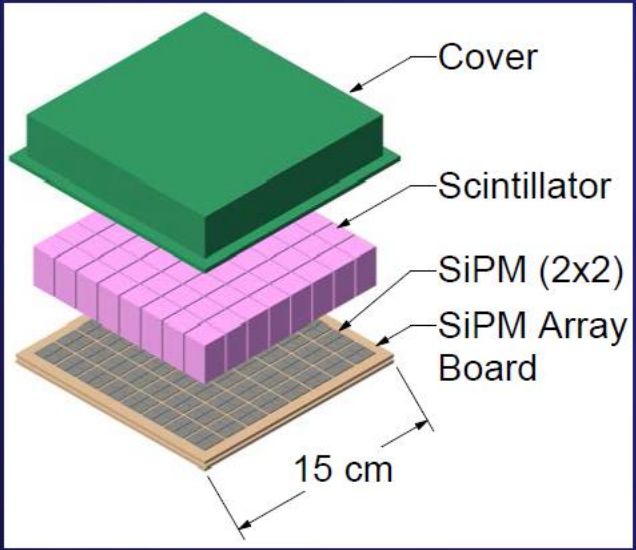
- The ASCOT project is motivated by the theory that the most cost-effective, low-risk way to implement an advanced, ***general-purpose*** Compton telescope is to build directly on the experience of COMPTEL
- A advanced, scintillator-based Compton telescope would use ***modern detector materials*** to improve efficiency, energy resolution, and time-of-flight (ToF) resolution for background rejection
- It would also use ***advanced light readout devices***, such as silicon photomultipliers (SiPMs), to reduce passive mass, volume, and power
- **Project Goal**: Demonstrate technology by imaging Crab Nebula during 1-day balloon flight

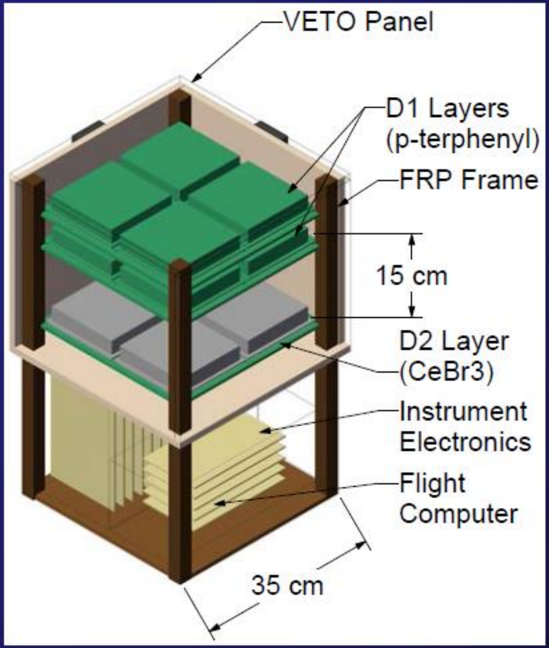
Developed by **University of New Hampshire**

Credit: P. Bloser 2019

ASCOT Insturment overview

- Instrument concept: basic "module" with 8 × 8 scintillator array optically coupled to a 8 × 8 SiPM array
- Each scintillator 15 × 15 × 25 mm^3
- Each scintillator read out by 2 × 2 SiPM array
- Detector layers each 2 × 2 array of modules
- Two D1 layers, one D2 layer (cost)





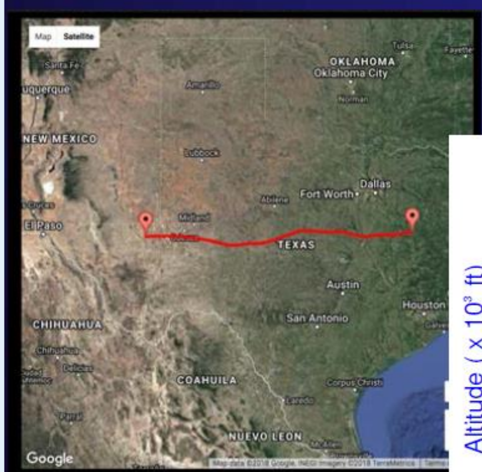
Credit: P. Bloser 2019

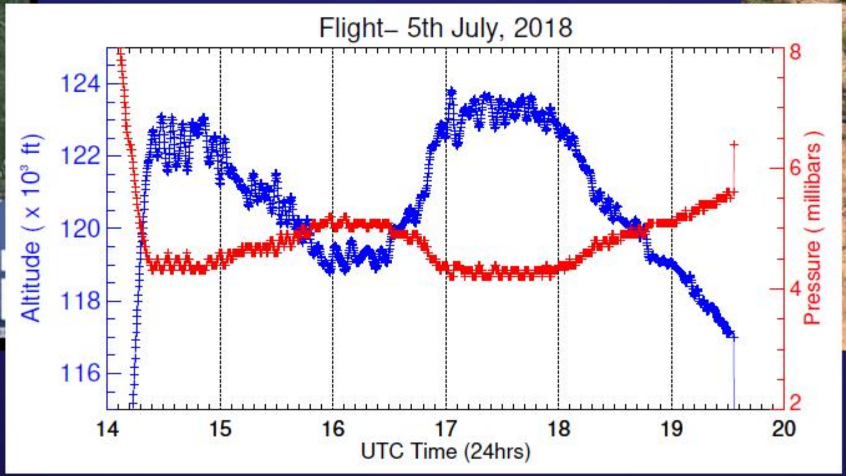
ASCOT Balloon Flight

Credit: P. Bloser 2019

ASCOT Balloon Flight

- Flight achieved float altitude of 119,000 – 123,000 feet
- Stayed at float for five hours while Crab was high in the sky
- Payload flew west at 50 – 75 kts, terminated in West Texas near Pecos
- Flight data and payload recovered with no issues

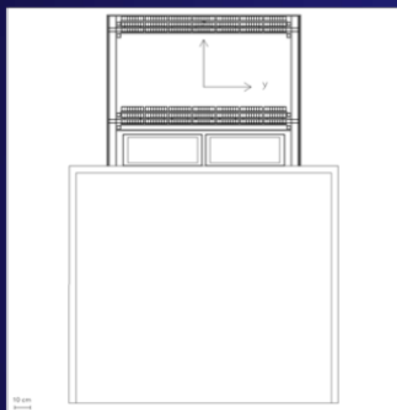


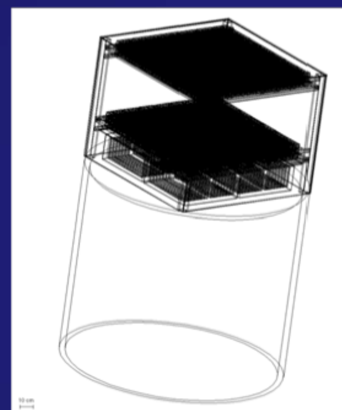


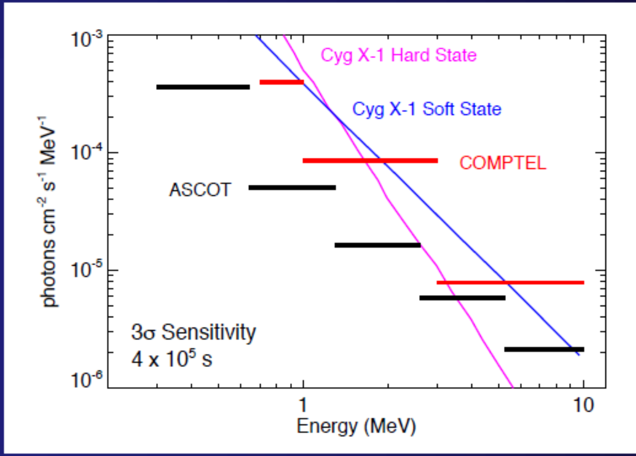
Credit: P. Bloser 2019

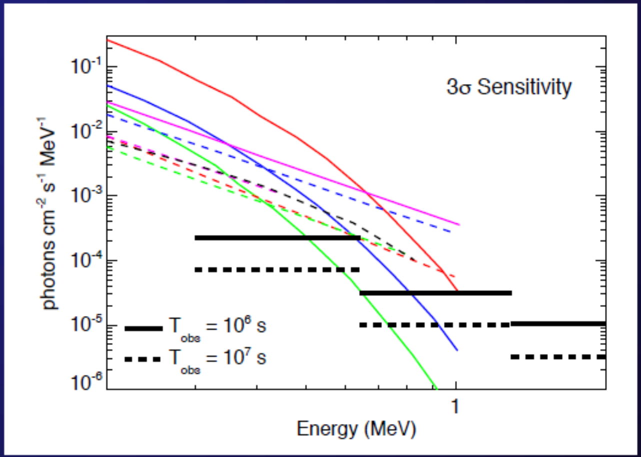
Simulation of Potential Explorer Mission

A few years ago, made a first stab at estimating performance of MIDEX:









- Explorer-sized instrument concept
- Three D1 layers and three D2 layers, 50 cm separation
- Estimate 120 × 120 × 100 cm^3 instrument, ~1000 kg payload
- Simulate response and background
- ~8× better continuum sensitivity than COMPTEL

Credit: P. Bloser 2019

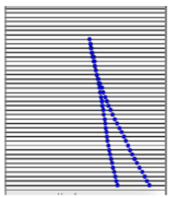
ASCOT – Lesson learned

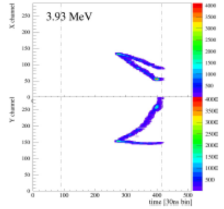
- The recent ASCOT balloon flight has demonstrated the stable operation of scintillator/SiPM detectors in a near-space environment
- Flight data analysis has just begun – expect to image Crab Nebula ~0.2 – 2 MeV
- New detector technologies offer the potential for smaller-scale missions that will still accomplish exciting new science
- We may yet see medium-energy gamma-ray astronomy move forward in our lifetimes!

Credit: P. Bloser 2019

3 technologies

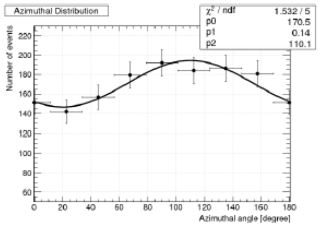
W-less, Si-stack detectors	Emulsions	Gas TPC
AMEGO, e-ASTROGAM	GRAINE	HARPO
1.3°@ 100 MeV	1°@ 100 MeV	0.4°@ 100 MeV
De Angelis *et al.*, Exp. Astr. 44 (2017) 25	Takahashi *et al.*, PTEP 2015 (2015) 043H01	Bernard, Nucl. Instrum. Meth. A 701 (2013) 225

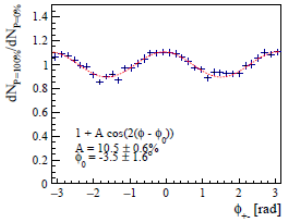




Polarimetry with $\gamma \rightarrow e^+e^-$:

	Ozaki *et al.*, Nucl. Instrum. Meth. A 833 (2016)165	Gros *et al.*, Astroparticle Physics 97 (2018) 10





?	2.4 GeV (50 MeV threshold ?)	11.8 MeV

Combined Compton / pair ?

Yes	?	Yes

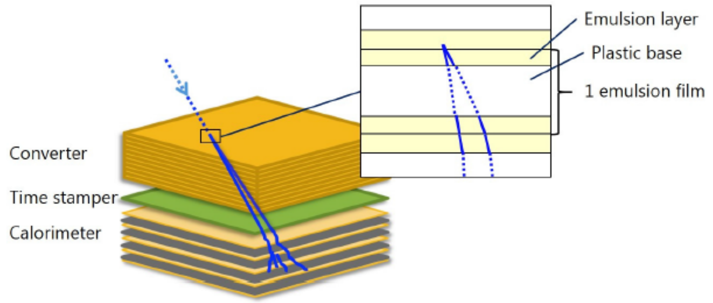
Tanimori *et al.*, Astrophys.J. 810 (2015) 28

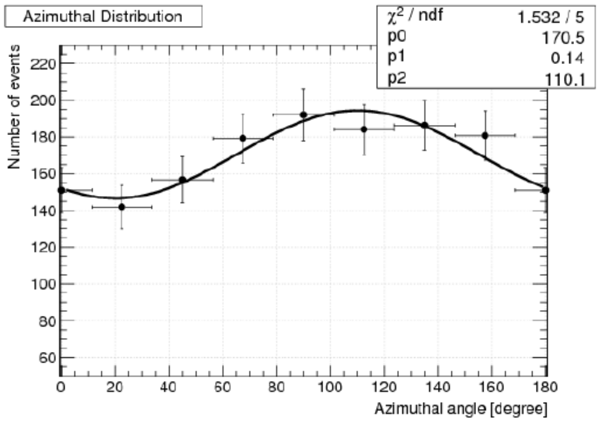
Credit: D. Bernard 2019

GRAINE

Emulsions: GRAINE project (Gamma-Ray Astro-Imager with Nuclear Emulsion)

- Kôbe University - Nagoya University Collaboration





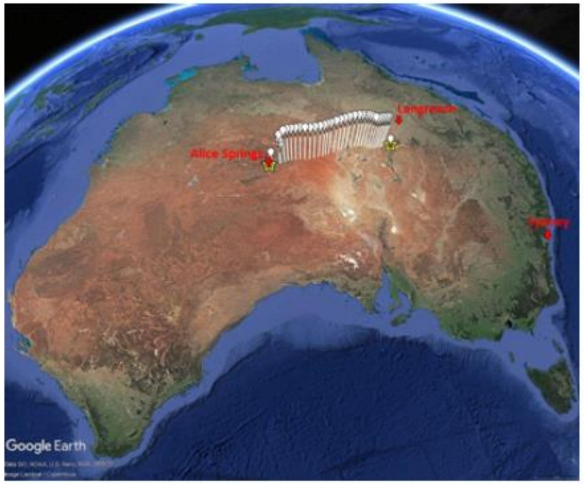
- 2.4 GeV SPring-8/LEPS gamma-ray beam
- Emulsion thickness $200 - 300\mu\mathrm{m}$, bromide crystal size $200\,\mathrm{nm}$; single grain position accuracy $60\,\mathrm{nm}$;
  Takahashi *et al.*, PTEP 2015 (2015) 043H01
  - $\mathcal{A}_{\mathrm{eff}} \times P = 0.14^{+0.07}_{-0.06}$ measured
  - beam $P = 0.66$ estimated
  - $\mathcal{A}_{\mathrm{eff}} = 0.21^{+0.11}_{-0.09}$ calculated, a $3.06\,\sigma$ non-zero polarization observation

Ozaki *et al.*, Nucl. Instrum. Meth. A 833 (2016)165

Credit: D. Bernard 2019

GRAINE balloon test flight

- Goal: see the Vela pulsar gamma-ray emission
- JAXA balloon flight on 26 April 2018, altitude 38 km
- 7 hours of data taken within the Vela pulsar window



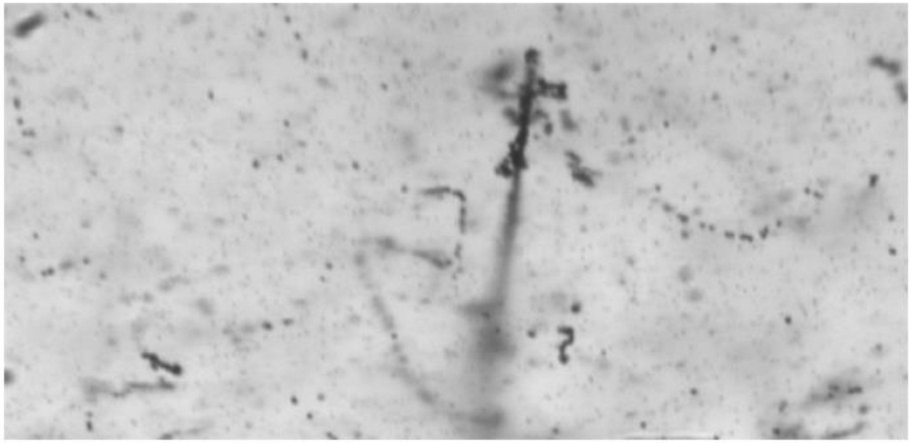


image width ≈ 100 µm

- Stay tuned ..

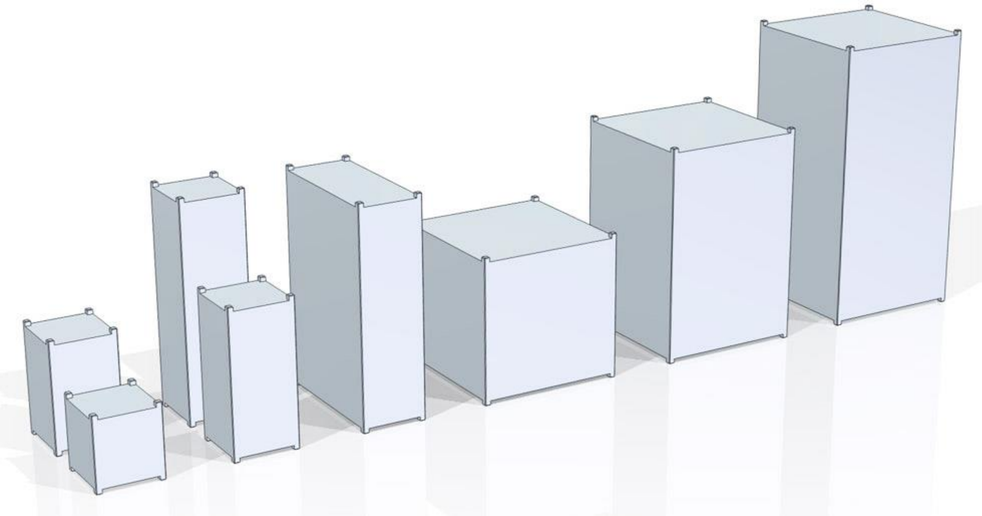
"Balloon-borne telescope looks for cosmic gamma rays", kobe-u.ac.jp, August 8, 2018

Credit: D. Bernard 2019

Nanosatellites for Gamma-ray Astronomy

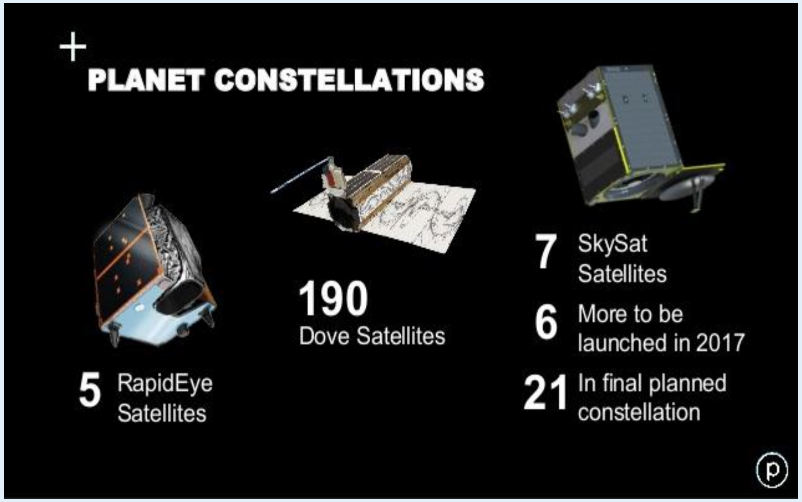
- Satellite classification by mass:
  - Large >1000 kg
  - Medium 500-1000 kg
  - Small < 500 kg
  - ➔ **Nanosatellite: 1-10 kg**
- Satellite classification by volume - **Cubesat**:
  - '1U' – 10 cm x 10 cm x 11.35 cm
  - Provides standard platform capability
  - Up to 27U (30-40 kg)
- Also 'PocketCube':
  - 5 cm x 5 cm x 5 cm

Credit: L. Hanlon

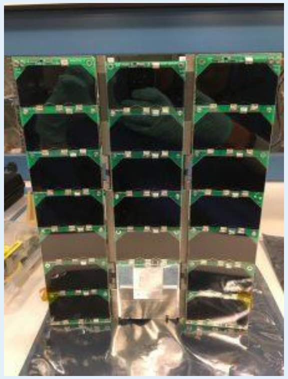


Rationale for Nanosatellites

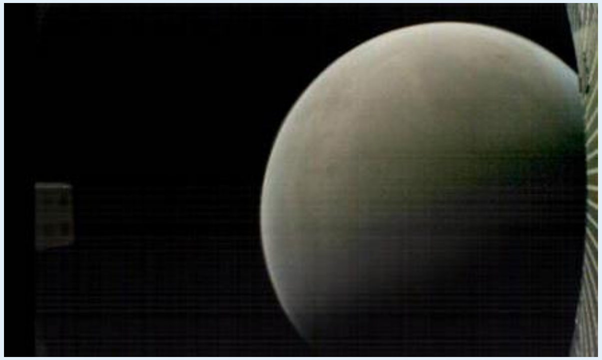
- Standard platform and components **accelerates development** of flight qualified technology via in-orbit demonstration
- Low mass/volume allows piggy-back launches, **reducing costs**
- ‘Flocks’ or ‘constellations’ of hundreds of nanosats provide both **redundancy** and **novel operational concepts**



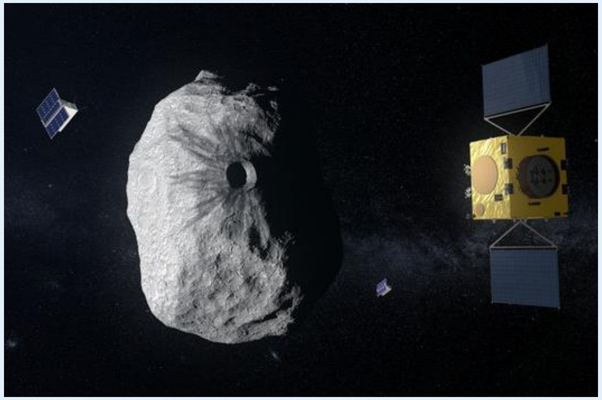
Science with/enabled by Nanosatellites



- **MinXSS Cubesats** (Colorado) measure soft x-ray solar spectrum from 0.4 keV-30 keV with resolution of ~0.15 keV FWHM (e.g. Woods+ApJ, 2017)

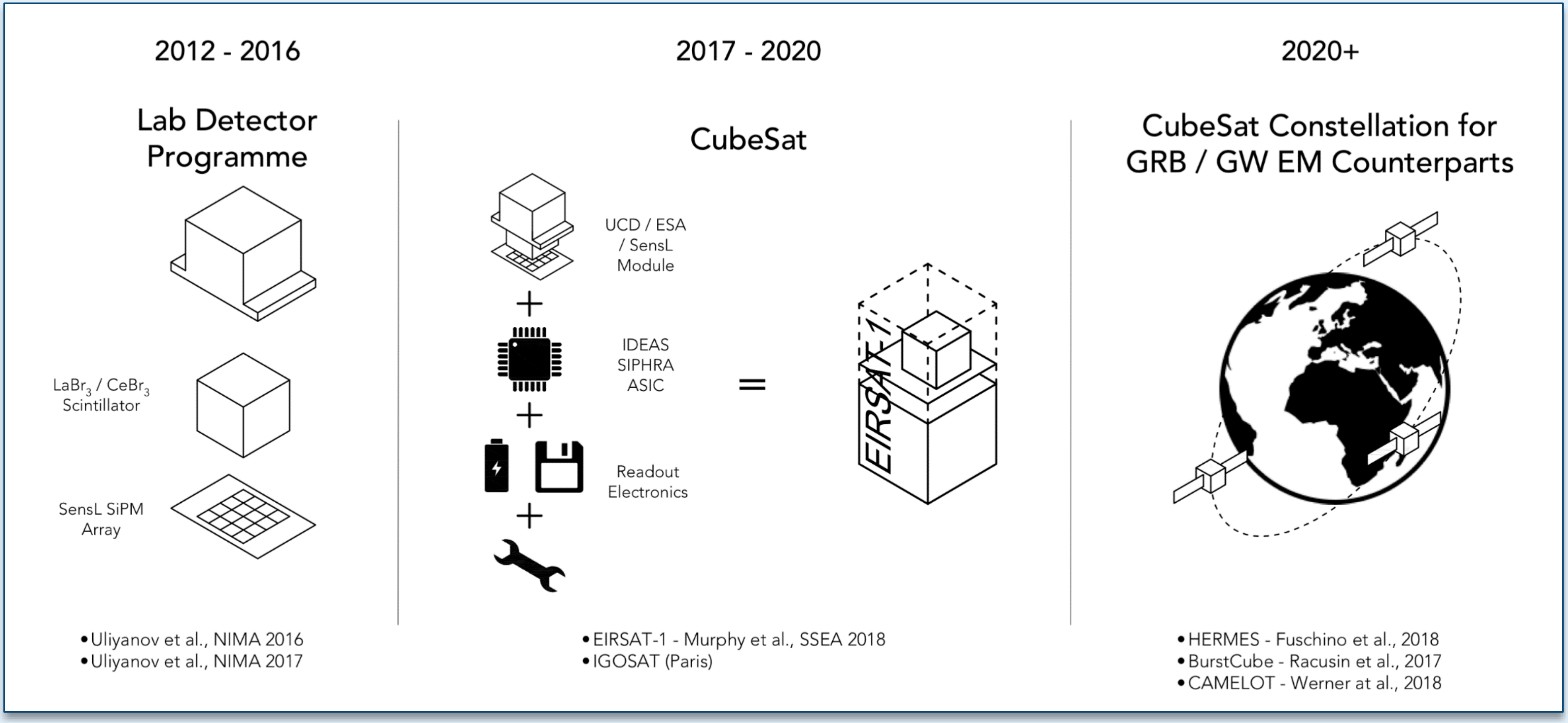


- **NASA's InSight landing** on Mars was supported by **CubeSats** to relay the lander's radio signals back to Earth and return imagery of the planet



- ESA plans to incorporate 2 CubeSats in its **asteroid rendezvous mission**, Hera, as landers and for deep space inter-satellite links

CubeSat Approach to Gamma-Ray Astronomy

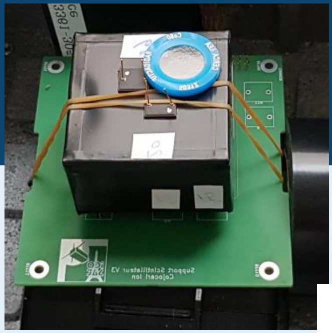


Reference:
https://asd.gsfc.nasa.gov/conferences/grb_nanosats/program.html

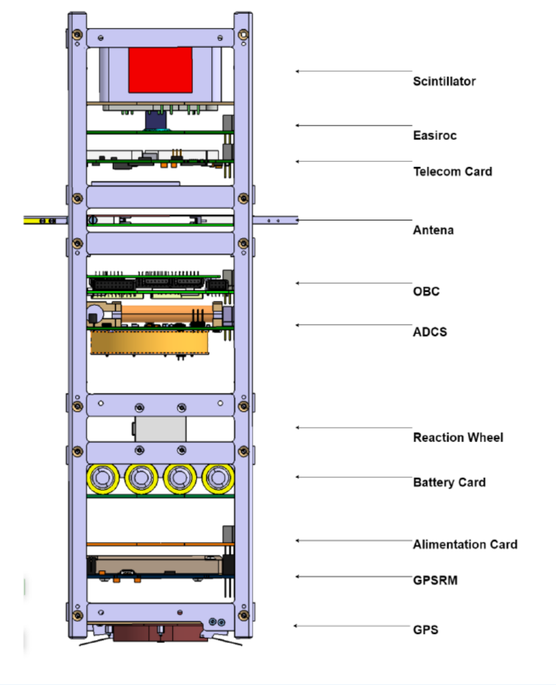
IGOSAT

Ionospheric **G**amma-ray **O**bservations **Sat**ellite

- 3U nanosatellite
- Characterizatio of the **aurora zones and the South Atlantic Anomaly.**
- **Student program** (Paris-Diderot University and CNES)
- 2 payloads:
  - A **scintillator** (CeBr3+plastics readout by SiPM) to measure electrons and gamma-ray spectra and light curves.
  - A **dual frequency GPS system** to get the electron density in the ionosphere.
- Currently preparing the Qualification Model for environment tests late 2019;
- Launch: **end of 2020**.

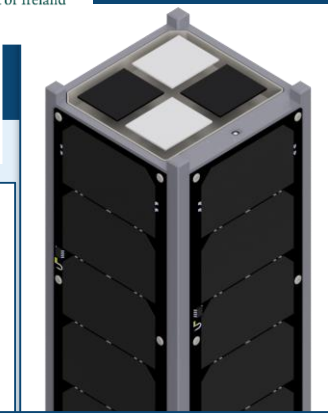


Scintillator payload



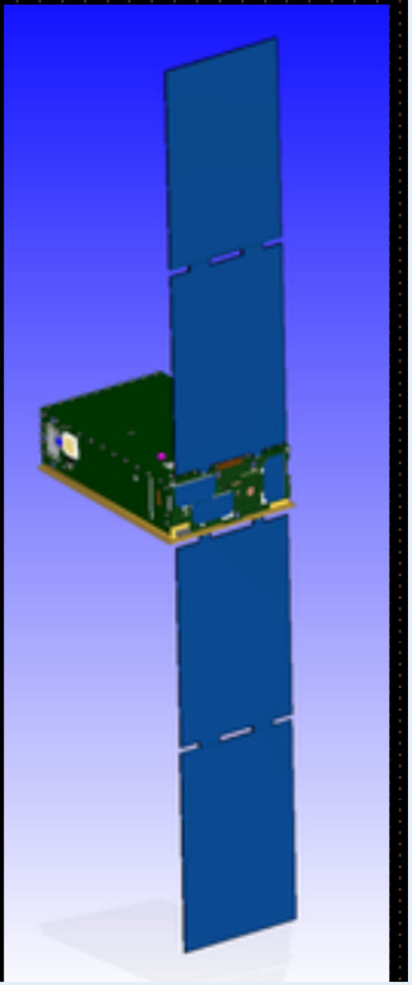
EIRSAT-1

- 2U spacecraft which is compliant with ESA ‘Fly Your Satellite’ Design Specification
- Being implemented by a student team in Dublin
- Currently in Phase D
- Delivery to ESA in mid-2020
- Deployment from ISS is current baseline
- 3 experiment payloads developed at UCD
  - GMOD – a γ-ray detector
  - EMOD – to make LEO measurements of SolarBlack and SolarWhite thermal management coatings developed for Solar Orbiter
  - WBC – a control scheme for flexible mechanical systems



BurstCube Overview

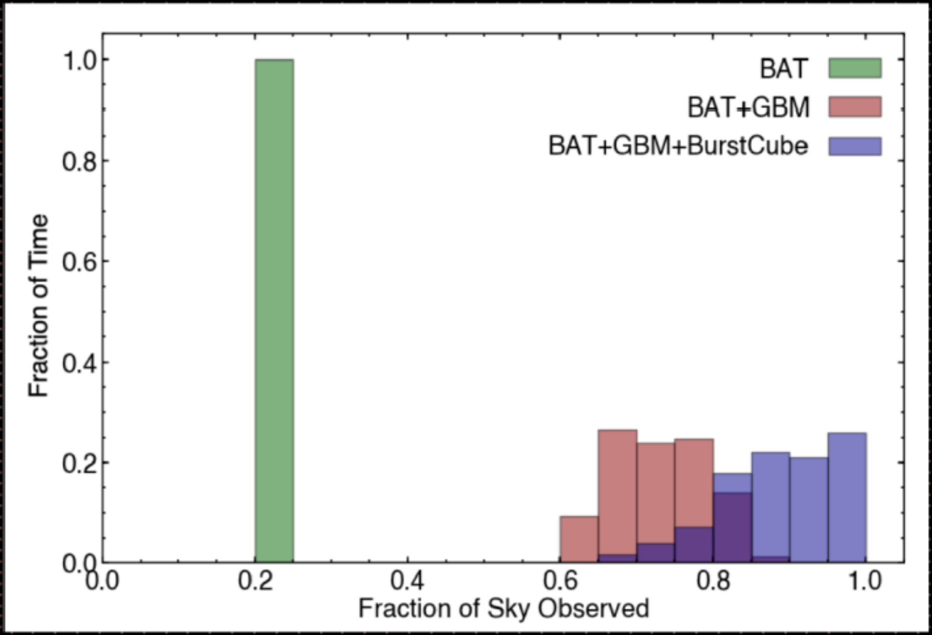
- **6U CubeSat** designed to detect and characterize short gamma-ray bursts (sGRB)
- Detectors: **four CsI scintillators** coupled with arrays of compact low-power Silicon photomultipliers (**SiPMs**)
  - Energy range: 30(50) keV - 1(2) MeV
- Spacecraft: based on NASA/GSFCs 6U platform with many commercially-off-the-shelf components
- Complement existing/future facilities (Swift, Fermi/GBM, Glowbug, MoonBEAM, GRID, Nimble, Bia …)
  - **interim GRB instrument** before next generation missions fly
- BurstCube is funded, in the design phase, ready to **launch late 2021**
  - 6 month mission (1 year goal)



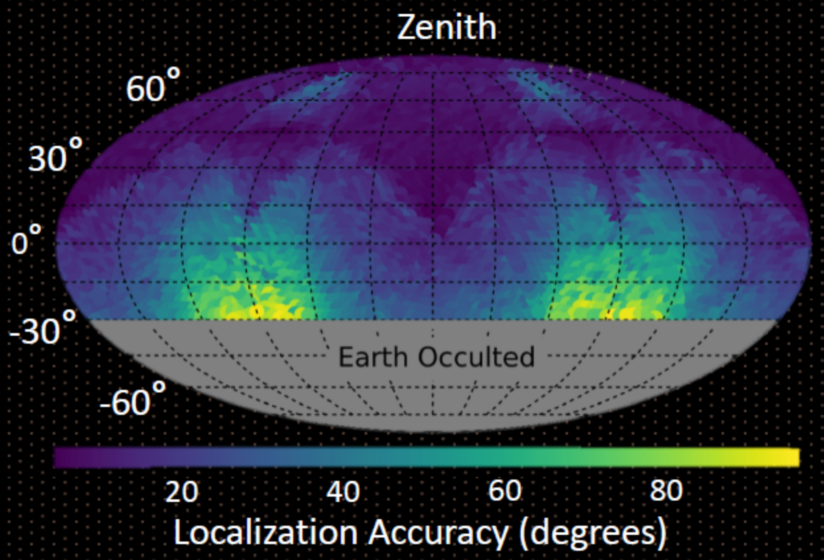
Credit: J. Racusin 2019

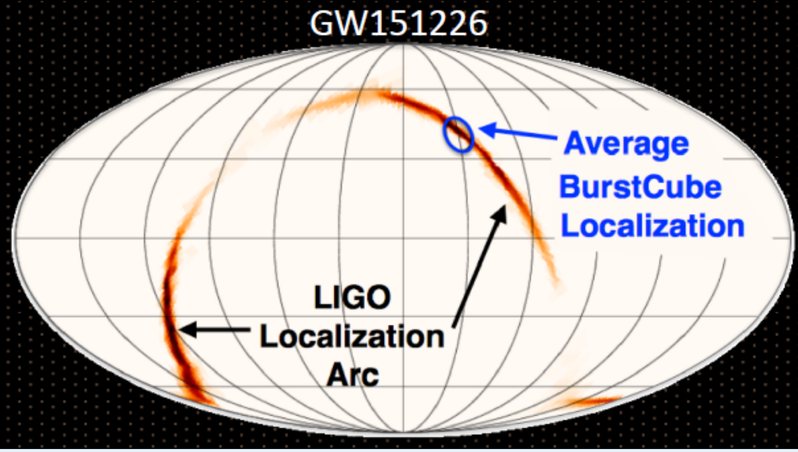
BurstCube Mission Concept

- BurstCube will **detect**, roughly **localize**, and **characterize** GRBs
- This approach is **complementary** to existing or upcoming facilities (e.g. Swift, Fermi/GBM, Glowbug, MoonBEAM, GRID, Nimble, Bia …)
  - Especially if there is a gap between GRB missions operating at the peak of the GW observatory operations.
- Pioneer **low cost**, wide field-of-view **monitoring** of short GRBs.



BurstCube Localizations

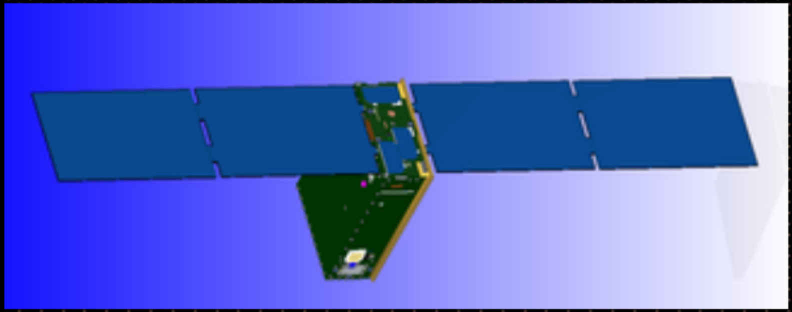


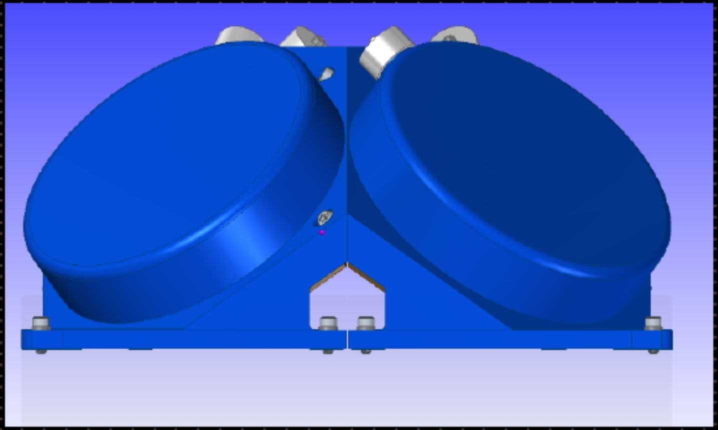


- Enable wide-field follow-up observers in afterglow detection and redshift measurement.
- Will lead to:
  - additional insight into cosmological parameter estimation,
  - constraint on the neutron star equation of state, and
  - an inventory of r-process elements in the Universe constrained by the faint short GRB kilonova signature (seen in the most recent event).

BurstCube Implementatin

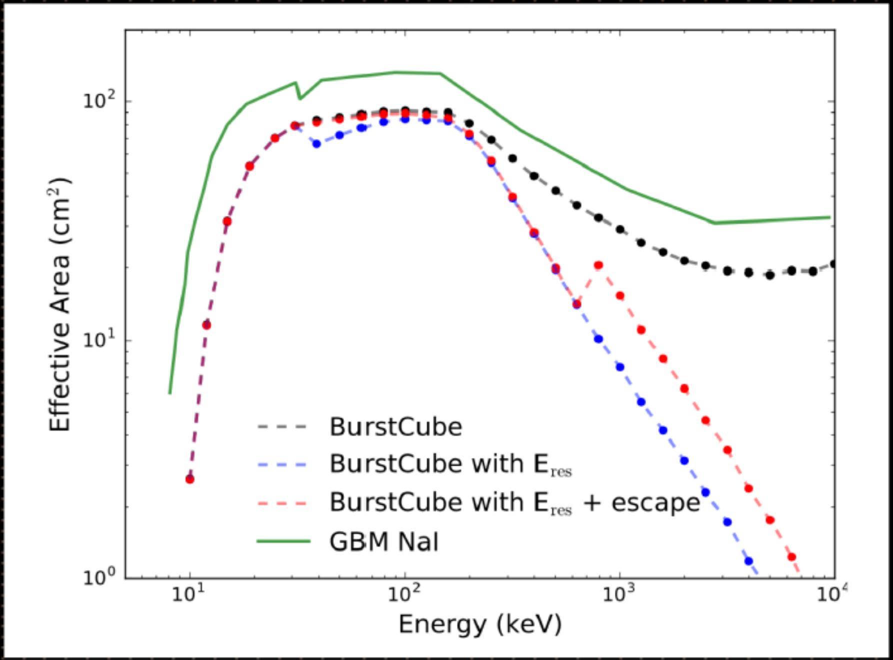
- BurstCube is a 6U CubeSat
  - Deployable Solar Panels & Full ACS
  - 10 cm x 20 cm x 30 cm
- Instrument Package
  - 4 CsI scintillator crystals coupled to arrays of low-power SiPMs with custom electronics
  - 9 cm diameter, 1.9 cm thick
- Zenith/sun pointing
- BurstCube will relay data to the ground via TDRSS
  - 5-15 minute goal
- The instrument hardware and flight software has strong heritage from Fermi-GBM.





BurstCube Performance

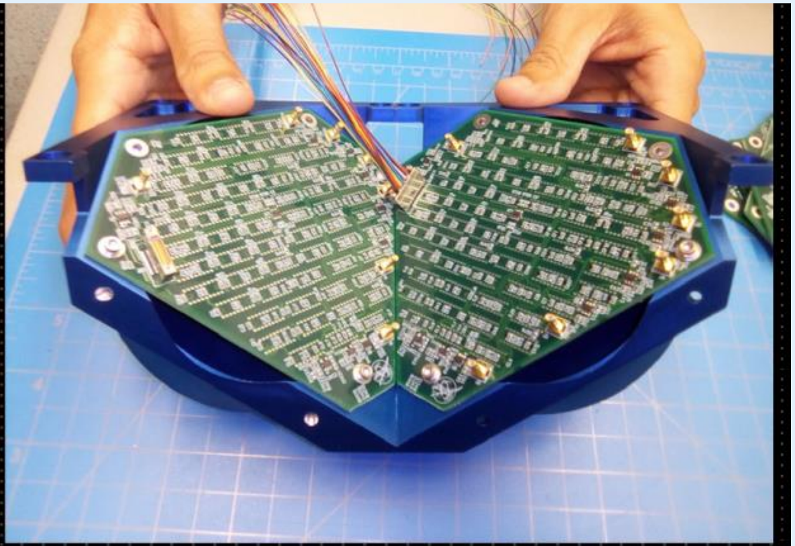
- **Continuous science** operations (except SAA)
- Expected detection of **~25 sGRBs/year**
- Expected detection of **>100 long GRBs/yr** in addition to other gamma-ray transients (solar flares, SGRs, etc.)
- Localizes GRBs based on relative detector intensities
- BurstCube has **competitive performance** with Fermi/GBM

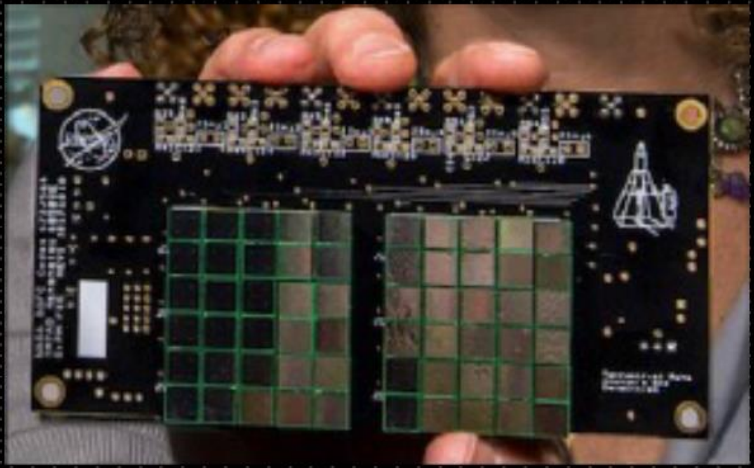


Effective area is 70% that of the larger GBM NaI detectors at 100 keV and 15 degree incidence (MEGAlib based sims)

BurstCube Updates

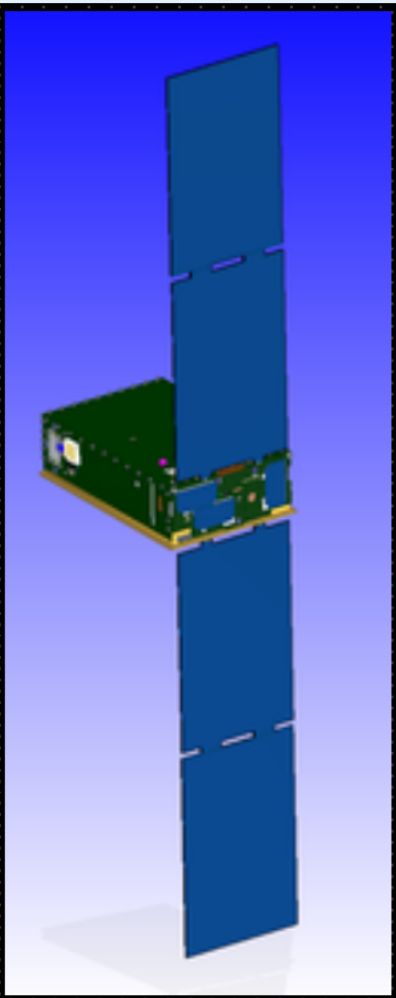
- Design and buildup for BurstCube is underway
  - Mechanical
  - Electrical
  - Communications (TDRSS)
- Prototype/Flight units of CsI crystals, SiPMs, and front-end electronics are ordered and in hand soon (some now)
- Testing current SiPM array designs and Front-end electronics
  - Two sets of 30 6-mm SiPMs in Arrays





BurstCube Status

- BurstCube: a **6U CubeSat** that will **detect and localize** GRBs
  - focus on counterparts of gravitational wave (GW) sources
- Utilizes **four CsI** scintillators coupled with arrays of compact low-power **SiPMs**
- Complements existing facilities and could be an **interim GRB instrument** before next generation missions fly
- BurstCube **will fly in 2021**

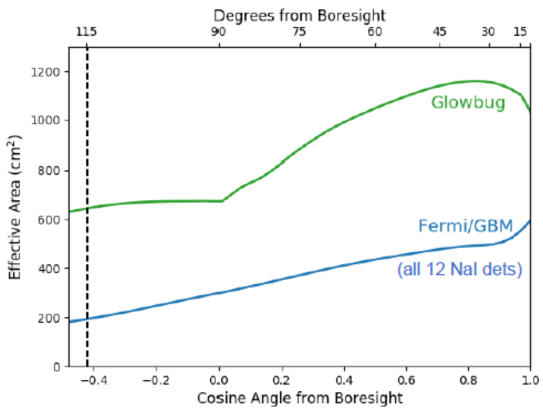


Glowbug

U.S. NAVAL RESEARCH LABORATORY

Glowbug: all-sky 30 keV – 2 MeV band transient monitor optimized for GRBs

Glowbug is funded by APRA for early 2020s launch

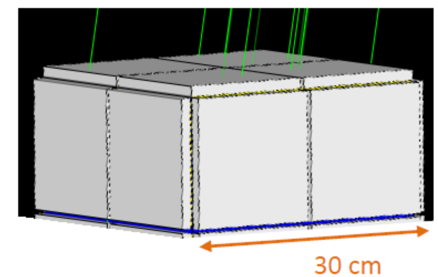


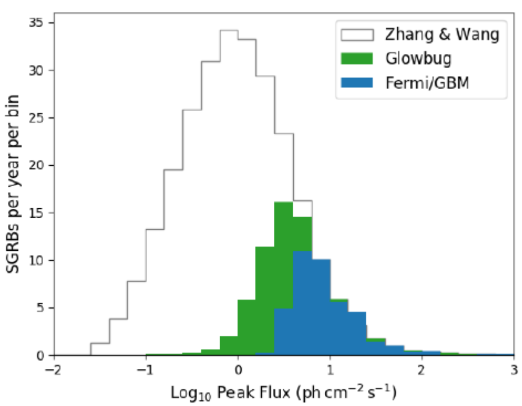
Good sensitivity at low cost

Effective area ~2 x Fermi GBM

Modular array of large area scintillators with SiPM readout

Attached payload Instrument ~40kg



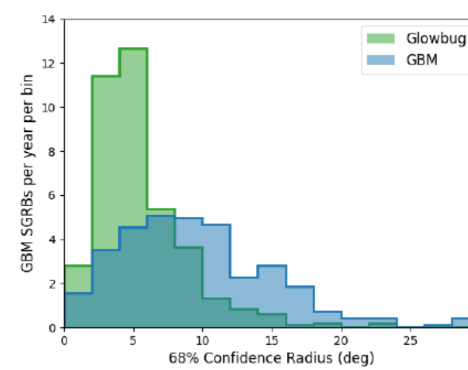


High rate of GRB detections

Rate ~ >70 short GRBs / year

Modest localization ability

Comparable to Fermi GBM



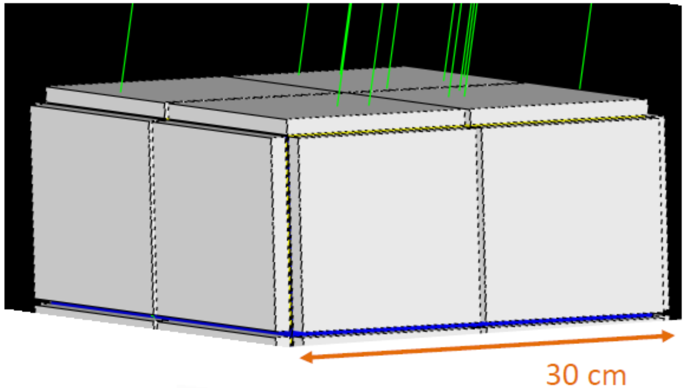
Credit: M. Kerr 2019

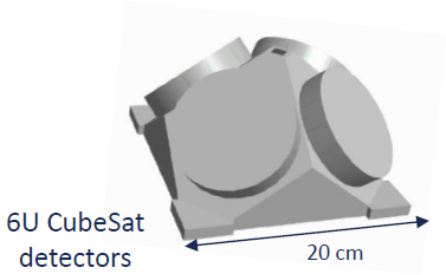
The Glowbug instrument

Tech demonstrator (half-scale) for GAMERA SmallSat mission concept

- Large scintillator array
  - Trade studies indicate complex designs yield only modest improvements to localization capabilities.
  - Modular, rectilinear design simplifies mechanical structure and fabrication
  - CsI(Tl) + SiPM readout
    - Good stopping power; not hygroscopic
    - Low size, weight, and power readout
  - Front end and DAQ from NRL's SIRI-2
    - Low power, space qualified
- Selected by NASA APRA
  - **Funding to begin January 2019**
- Launch via DoD Space Test Program (STP)
  - Proposed for STP-H9 to International Space Station (ISS) in early 2023
  - STP provides integration, launch, and 1 year operations costs

Glowbug detector array





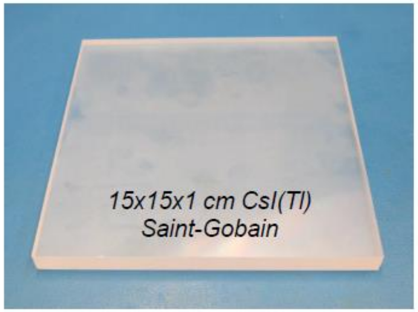
Credit: M. Kerr 2019

The Glowbug detectors

Goal: obtain the best-possible sensitivity (maximal detector area, minimal background) and degree-scale localization as tech demonstrator for SmallSat mission concept

Design concept: large-area array of SiPM-read CsI(Tl) scintillators

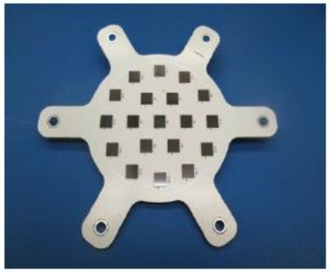
Can be built today with components at TRL 6 or higher

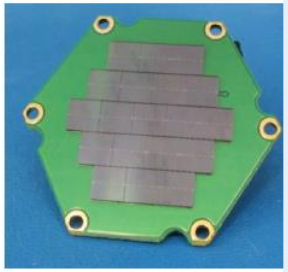


Cesium iodide CsI(Tl): better stopping power and photopeak efficiency than NaI, and is minimally hygroscopic, which eliminates need for hermetic enclosures. Lower activation background.

Silicon photomultipliers (SiPMs): fast readout of large areas of thin scintillators with low size, weight, and power (SWaP). Low cost and low operating voltage

- **Heritage through NRL's Strontium Iodide Radiation Instrumentation (SIRI) program**





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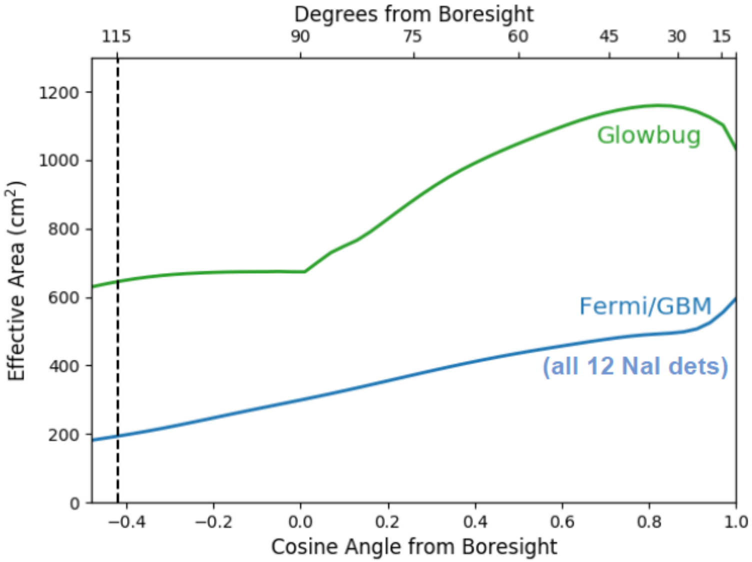
Credit: M. Kerr 2019

Glowbug instrument sensitivity

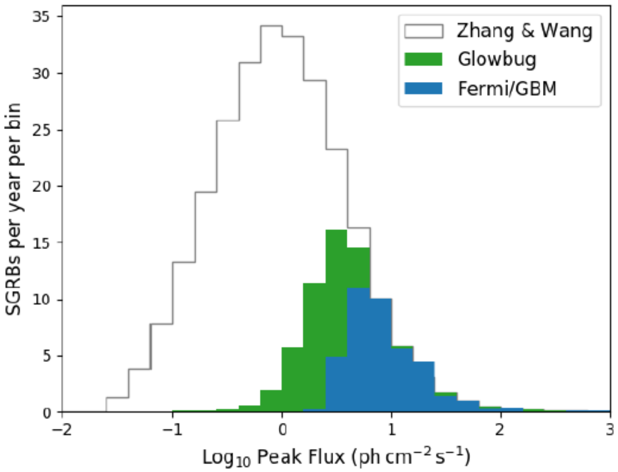
Performance estimated from detailed Monte Carlo simulations of scintillator modules, instrument geometry model, and maximum likelihood analyses performed using realistic GBM background

- **~2x Fermi GBM effective area** (total, 12 NaI dets) for typical GRB spectrum
- **~ ½ x effective area at 2 MeV** of two BGO detectors of Fermi GBM



- Increase in effective area expands horizon for faint sources in local universe by ~1.4

- Estimate **~ 70 sGRB / yr**
- EM counterparts of GW binary mergers



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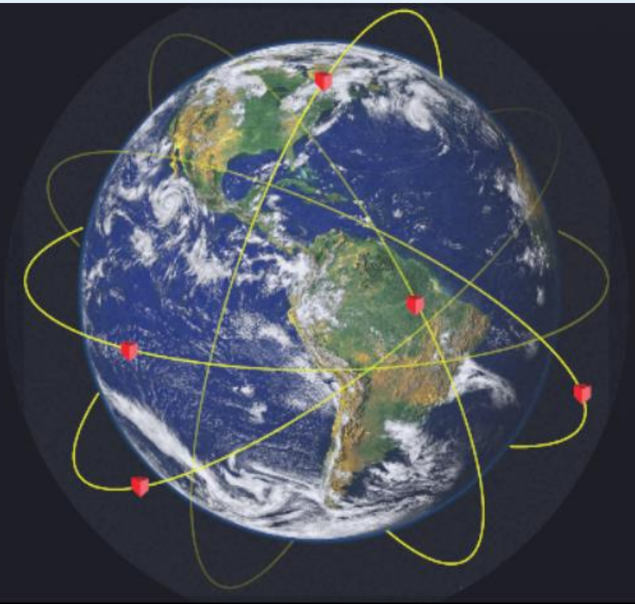
Credit: M. Kerr 2019

HERMES

HermeS

High Energy Rapid Modular Ensemble of Satellites



HERMES: a constellation of nano-satellites for high energy astrophysics and fundamental physics research

http://hermes.dsf.unica.it/

HERMES

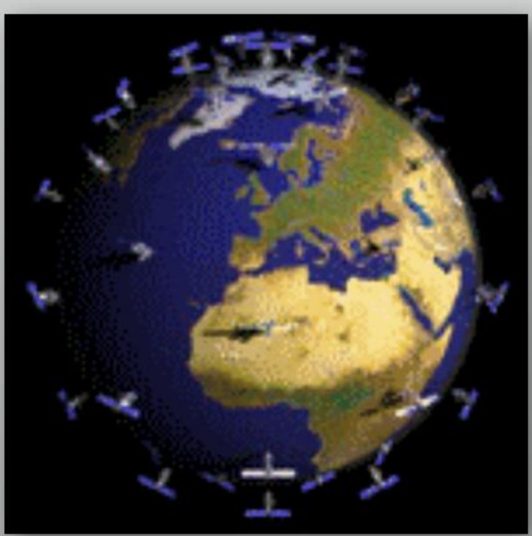
2015: **ASI tecnological project** (R&D on detectors and architecture)
2017: MIUR **Progetto Premiale**, led by ASI: *HERMES Technological Pathfinder*
2018: **H2020** project: *HERMES Scientific Pathfinder*

Disruptive technologies: **cheap**, **underperforming**, **but** producing **high impact**.

Distributed instrument: tens/hundreds of simple units

HERMES is a constellation of CubeSats

*(**H**igh **E**nergy **R**apid **M**odular **E**nsemble of **S**atellites)*



Modularity
- Avoid single point failures, improve hardware
- Pathfinder

Limited cost and quick development
- COTS and in-house components
- Cost reduction of manifacturing: direct launch of QM

HERMES will open the submillisecond time window for GRB science
- Accurate positions
- Quantum gravity tests

Why now? Breakthrough scientific case: electromagnetic counterparts of gravitational wave events

HERMES Mission Concept

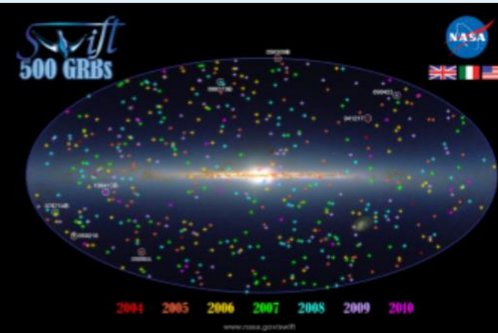
Disruptive technologies: cheap, underperforming, but producing high impact. Distributed instrument, tens/hundreds of simple units

HERMES constellation of cubesat

2016: ASI funds for detector R&D
2018: MIUR funds for pathfinder (Progetti premiali 2015)
2018 H2020 Space-SCI-20 project

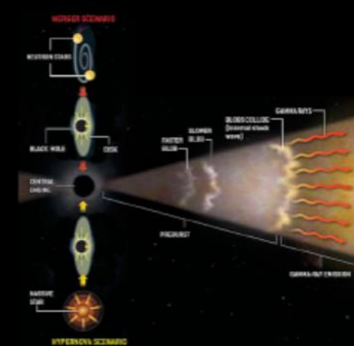
2018 ASI internal proposal

HERMES Main Goals



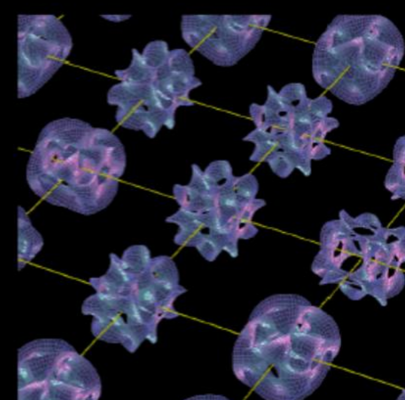
How to *promptly* localise a GRB *prompt* event?

GW/ Multi-messenger astrophysics



How to construct a GRB engine?

Jet / BH / NS physics, GRB progenitors



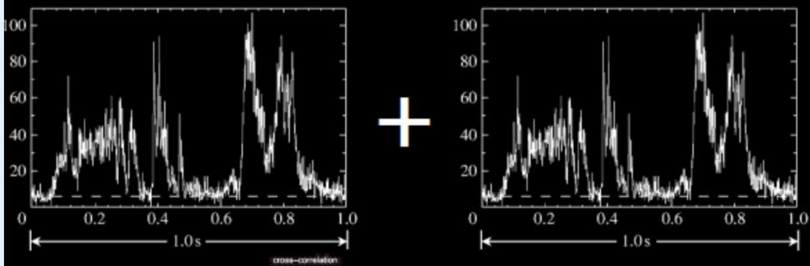
Which is the ultimate granular structure of space-time?

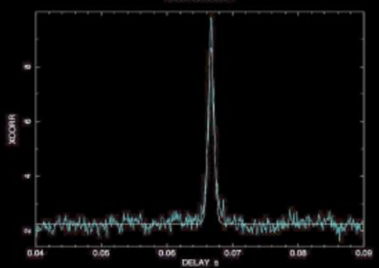
Fundamental physics, quantum gravity

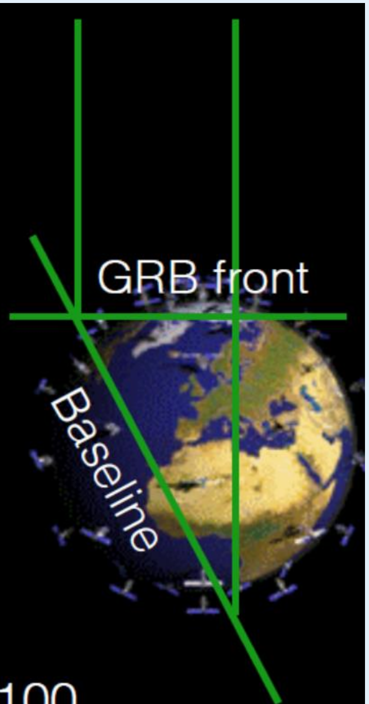
HERMES Main Goals

1. Measure GRB positions through delays between photons arrival times:

$\sigma_{Pos} = \sigma_{CCF} \times c / \langle B \rangle / (N \times (N - 1 - 2))^{1/2}$







$\sigma_{CCF} \sim 10\mu s$

$\sigma_{Pos} \sim 10$ arcsec

if $\langle B \rangle \sim 7000$ km, $N \sim 100$

Arcmin-arcsec positions of ~a few dozen GRB/yr

Prompt(minute) localisation

μs timing

$\Delta t / \Delta E \sim 3\mu s/100$ keV $30\mu s/1$ MeV —> $M_{QG} \sim M_{Planck}$

HERMES Performances

$$\sigma_{Pos} = 2.4°[(\sigma_{CCF}^2 + \sigma_{sys}^2)/(N-3)]^{0.5}$$

<B>~7000km

N(pathfinder)~6-8, active simultaneously 4-6

N(final constellation) ~100, active 50

$\sigma_{Pos(pathfinder)}$ ~ 1 arcmin if $\sigma_{CCF}, \sigma_{sys}$~10usec

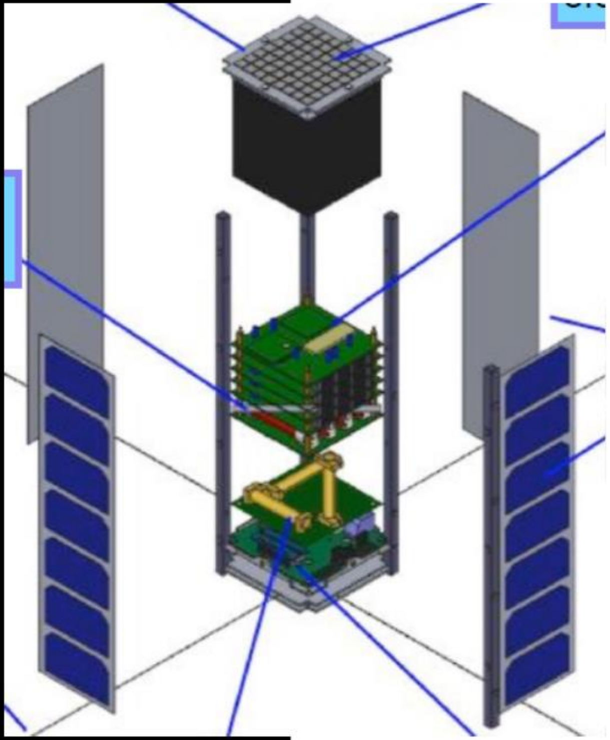
$\sigma_{Pos(FC)}$ <1arcsec if $\sigma_{CCF}, \sigma_{sys}$~10usec

Bright GRBs with msec structure

$\sigma_{Pos(pathfinder)}$ ~ 2.4 deg if $\sigma_{CCF}, \sigma_{sys}$~0.001s

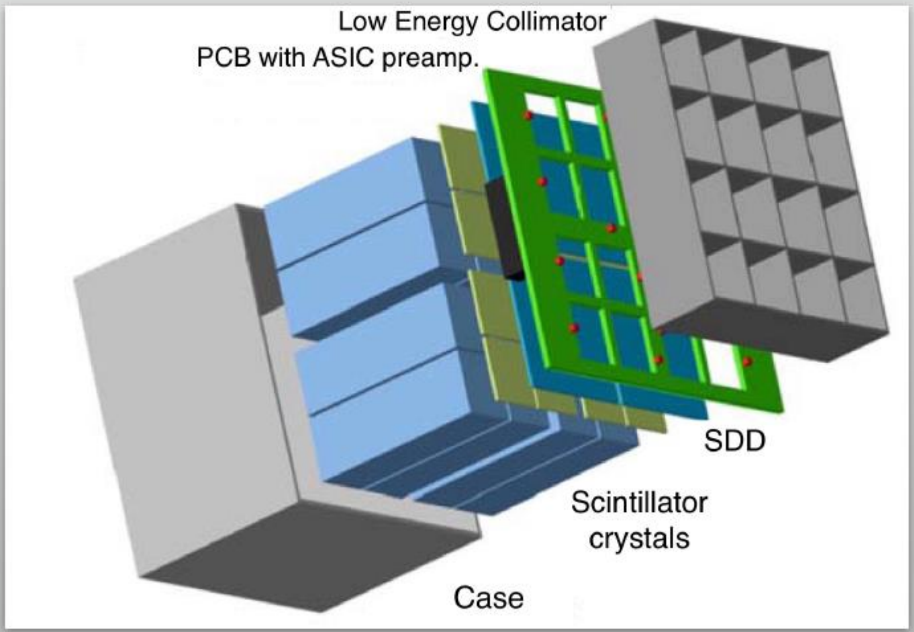
$\sigma_{Pos(FC)}$ ~ 3 arcmin if $\sigma_{CCF}, \sigma_{sys}$~0.001s

Short GRBs without substructure, risetime fraction of second.



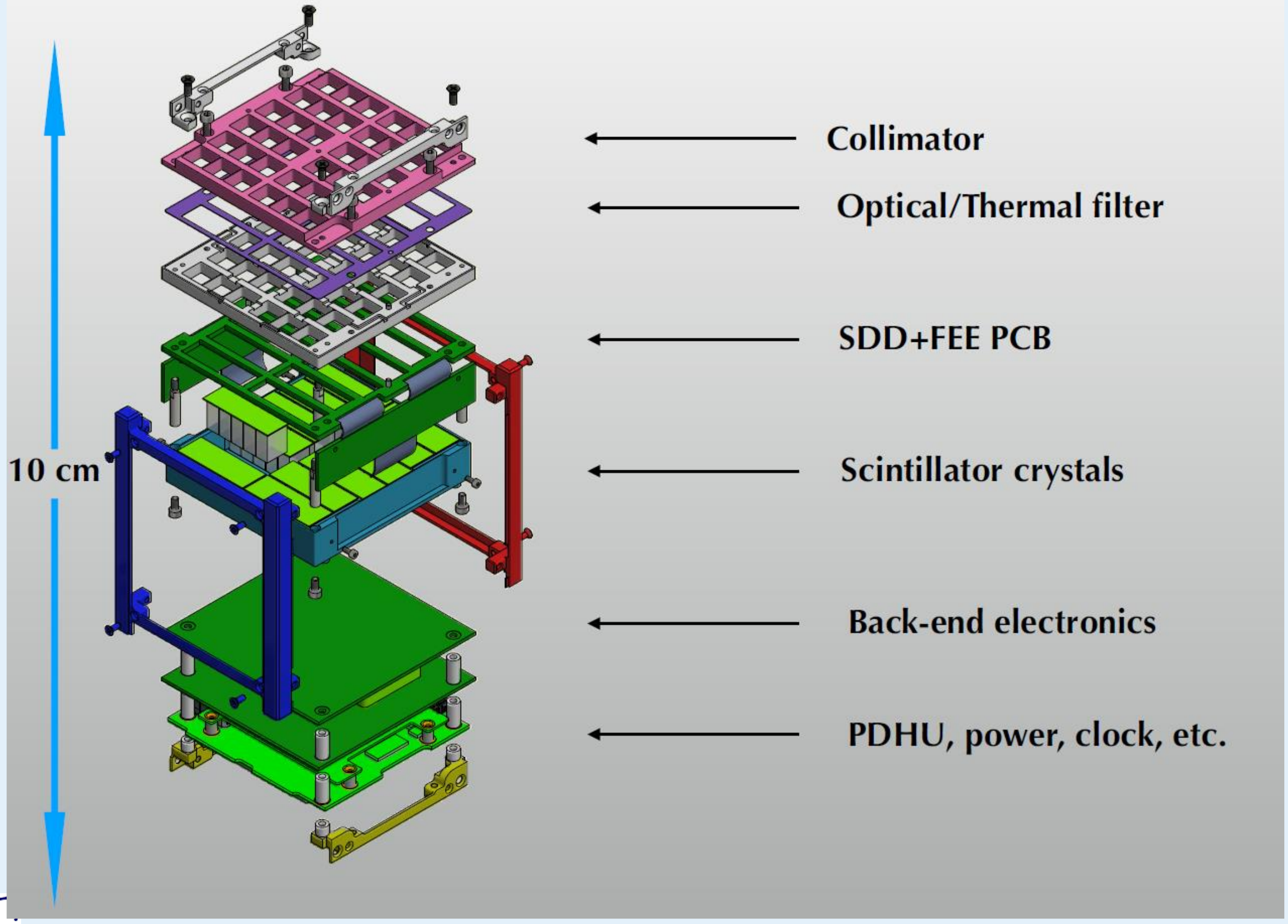
HERMES Detector

- A huge sensitivity band in a modular instrument within 10×10×10 cm^3
- "**Siswich**" architecture: Silicon Drift Detector + scintillator. SDD acts **both** as direct X-ray instrument and as photodiode for scintillator light readout
- Scintillator cristal: GAGG:Ce
- 5–300 keV main scientific band
- Sensitive in **2–2000 keV**
- ~50 cm^2 collecting area
- A few sr FOV at low energies
- Temporal resolution 100 ns
- ~**1.5 kg**
- less than **4 W** power consumption

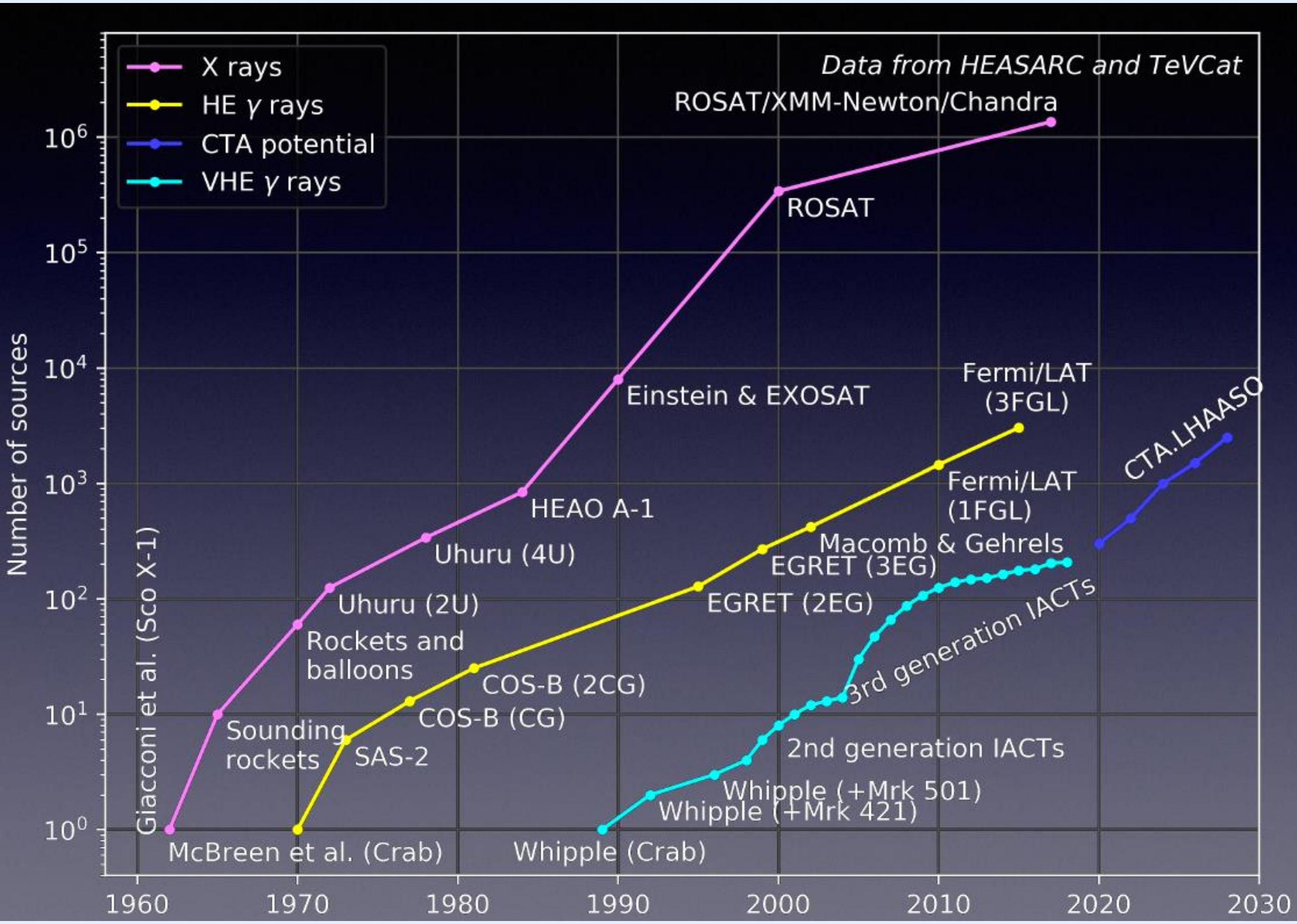


HERMES Detector

A complex detector in 1 liter volume



Space-based high-energy gamma-ray missions

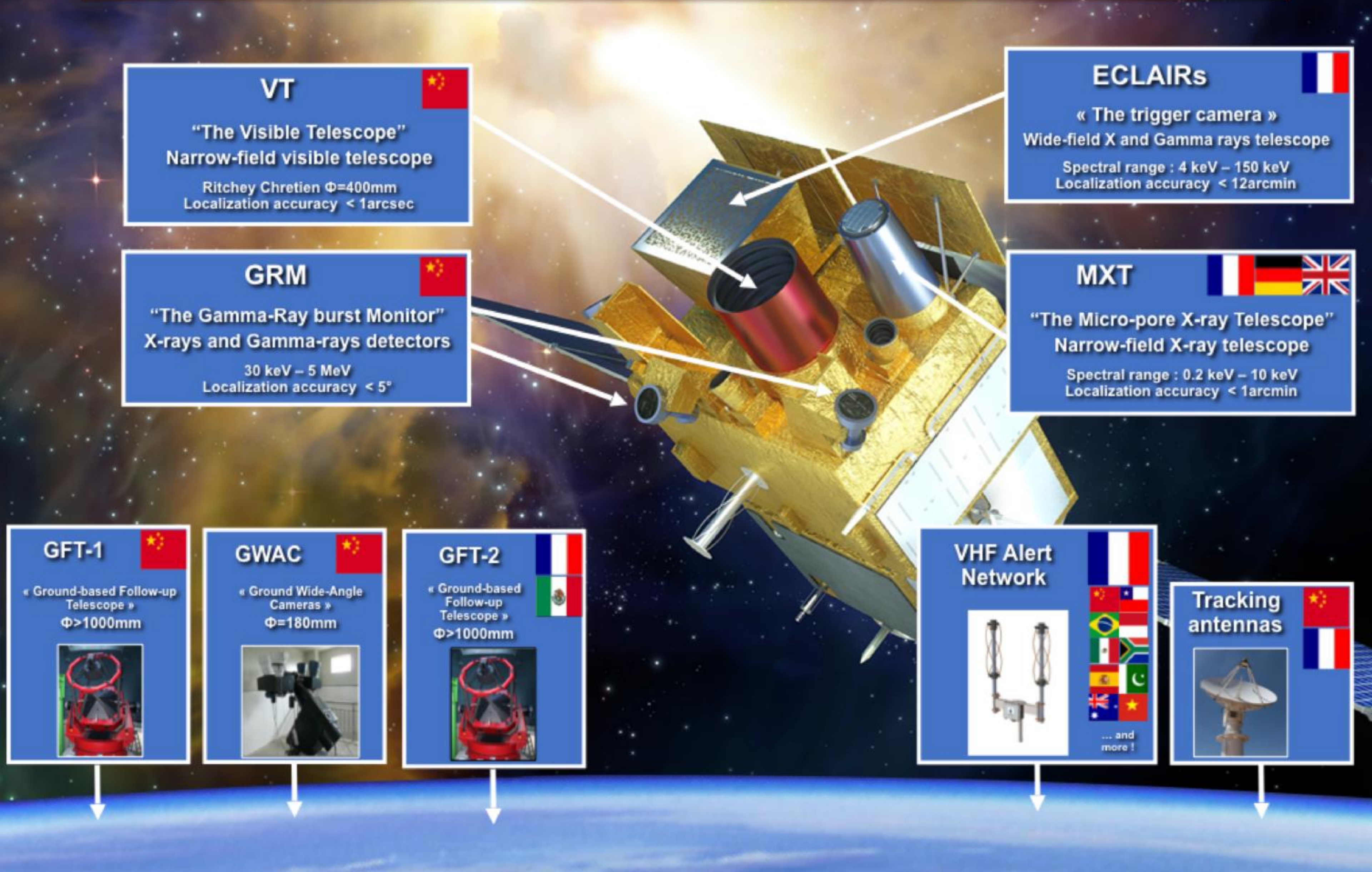


3FGL 3034 sources > 100 MeV
95% extragalactic!
21% BL Lacs
16% FSRQ
19% unclassified blazars +
22% unassociated high lat
Still lots of association work to come! (CTA, HAWC, LHAASO, SPACE??…)

My personal Kifune Plot based on Fegan macro

Credit: Della Volpe 2018

SVOM "Space-based multi-band astronomical Variable Objects Monitor"
a Sino-French mission dedicated to GRBs and HE transients
to be launched end 2021, duration 3+2 years



The SVOM Mission

- SVOM is a set of instruments distributed on the ground and in space, interconnected with each other
- SVOM is designed to study the physics of the GRB phenomenon in all its diversity with good spectral (from infrared to MeV) and temporal coverage for both the prompt and afterglow emission
- *Optimized* observation and follow-up strategy is aiming at redshift determination for a large fraction of SVOM GRBs (>60%)
- SVOM is prepared to play an important role in the time domain astrophysics and in the multi-messenger era
- Launch 2021

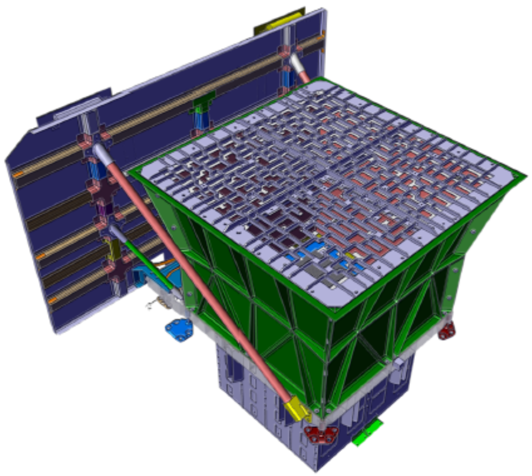
MORE INFORMATIONS

SVOM white paper: arXiv:1610.06892

SVOM Website: http://www.svom.fr/en/

SVOM Payload

- Instruments with Wide FoV

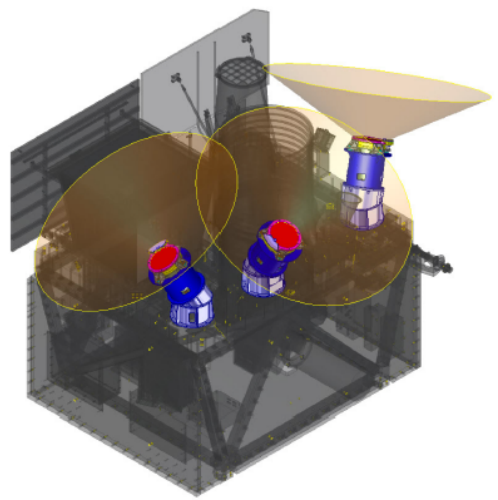


Credit: B. Cordier 2019

ECLAIRs (CNES, IRAP, CEA, APC)

- 40% open fraction
- Detection plane: **1024 cm²**
- **6400 CdTe pixels** (4x4x1 mm^3)
- **FoV: 2 sr** (zero sensitivity)
- Energy range: 4 - 150 keV
- **Localization** accuracy **<12 arcsin** for 90% of sources at detection limit
- Onboard trigger and localization: **~65 GRBs/year**

Well adapted for the detection of lGRB with low EPEAK



GRM Gamma-Ray Monitor (IHEP)

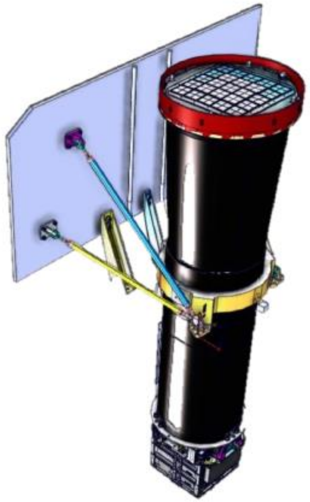
- **3 Gamma-Ray Detectors** (GRDs)
- **NaI(Tl)** (16 cm Ø, 1.5 cm thick)
- Plastic scintillator (6 mm) to monitor particle flux and reject particle events
- **FoV:2 sr per GRD**
- **Energy range: 15-5000 keV**
- Aeff = 190 cm² at peak
- Rough localization accuracy
- Expected rate: **~90 GRBs / year**

Will provide EPEAK measurements for most ECLAIRs GRBs
Will detect GRBs and transients out of the ECLAIRs FOV (with poor localization)

SVOM Payload

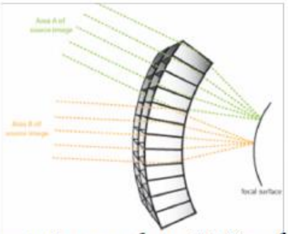
- Instruments with narrow FoV

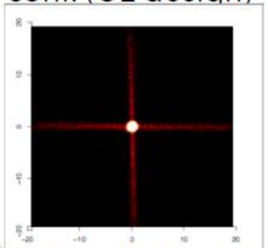
Credit: B. Cordier 2019



MXT Micro-channel X-ray Telescope (CNES, CEA, UL, MPE)

- **Micro-pores optics** (Photonis) with **square 40 µm pores** in a "Lobster Eye" conf. (UL design)
- pnCCD (MPE) based camera (CEA)
- **FoV: 64x64 arcmin²**
- Focal length: 1 m
- **Energy range: 0.2 - 10 keV**
- Aeff = 27 cm² @ 1 keV (central spot)
- Energy resolution: ~80 eV @ 1.5 keV
- **Localization accuracy <13 arcsec** within 5 min from trigger for 50% of GRBs (statistical error only)



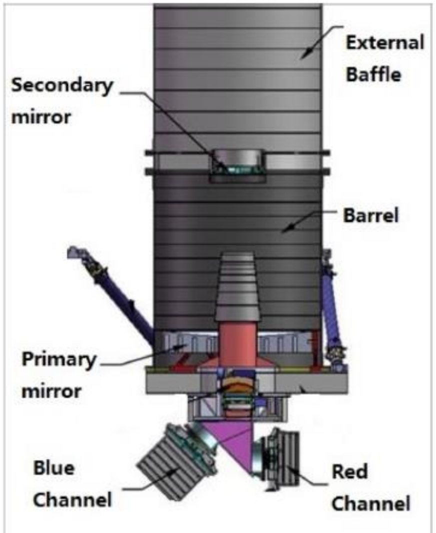


Implements innovative focussing X-ray optics based on « Lobster-Eye » design
Will be able to promptly observe the X-ray afterglow

VT Visible Telescope (XIOMP, NAOC)

- Ritchey-Chretien telescope, 40 cm Ø, f=9
- **FoV: 26x26 arcmin²**, covering ECLAIRs error box in most cases
- **2 channels: blue (400-650 nm) and red (650-1000 nm),** 2k * 2k CCD detector each
- **Sensitivity MV=23 in 300 s**
- Will detect ~80% of ECLAIRs GRBs
- **Localization accuracy <1 arcsec**

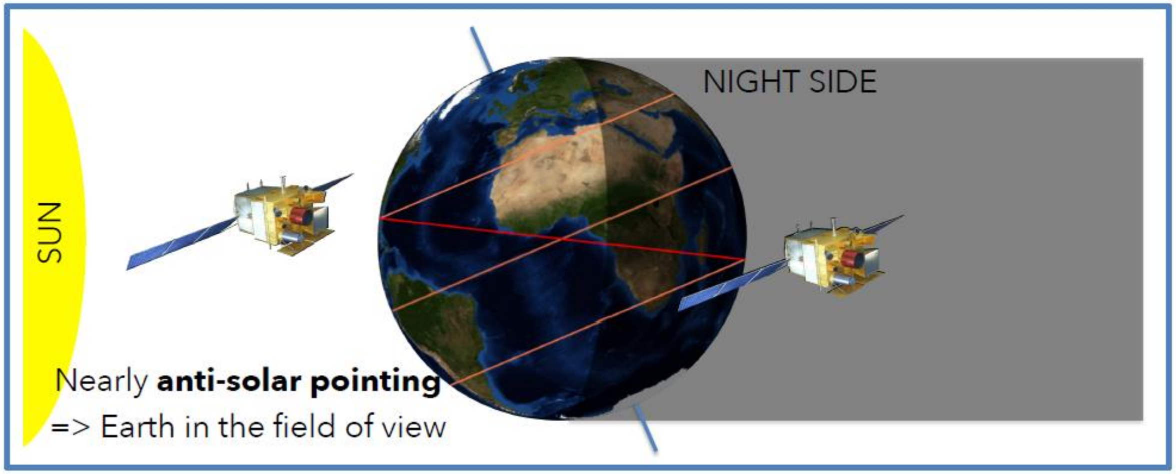
Able to detect high-redshift GRBs up to z~6.5 (sensitivity cutoff around 950 nm)
Can quickly provide redshift indicators due to the presence of two channels

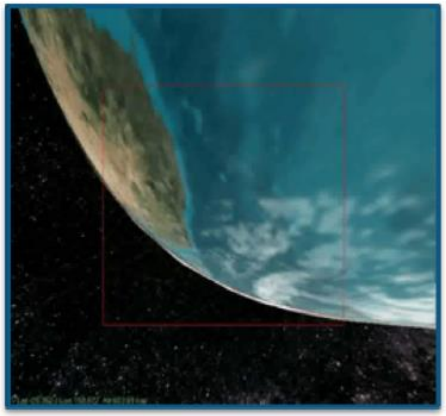


SVOM Orbit and Pointing strategy

Optimizing the ground follow-up of GRB candidates (should increase the success of the ground redshift measurement)

Credit: B. Cordier 2019





65% of duty cycle for ECLAIRs
about 50% for MXT and VT

Waiting between the detection of two GRB candidates…

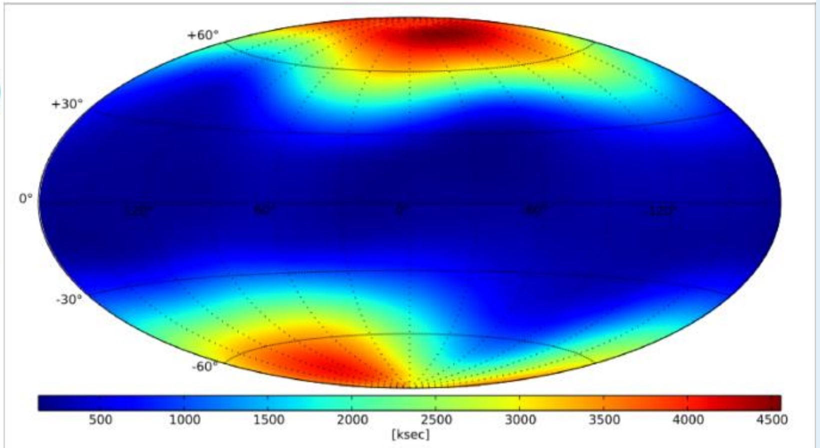
Avoidance of the galactic plane (most of the time)

and also intense sources such as **Sco X-1**

ECLAIRs exposure map →

(65 GRBs/year, 1 ToO per day)

- 4 Ms in the direction of the galactic poles
- 500 ks on the galactic plane



SVOM as an Open Observatory

Credit: B. Cordier 2019

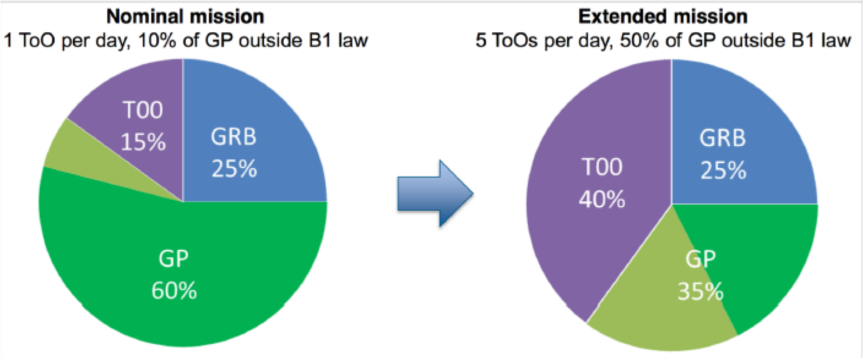
The general program (GP)

- Observation proposals being awarded by a TAC (a SVOM co-I needs to be part of your proposal) for astrophysical targets of interest mostly compliant with the satellite attitude law
- Only 10% of the time can be spent on low Galactic latitude sources during the nominal mission, up to 50% during the extended mission

Target of Opportunity (ToO) programs

- **ToO-NOM** is the nominal ToO which covers the basic needs for efficient transient follow-up alerts sent from the ground to the satellite (GRB revisit, known source flaring, new transient)
- **ToO-EX** is the exceptional ToO which covers the needs for a fast ToO-NOM in case of an exceptional astrophysical event we want to observe rapidly.
- **ToO-MM** is the ToO-EX dedicated to EM counterpart search in response to a multi-messenger alert. What differs from the ToO-NOM and ToO-EX is the unknown position of the source within a large error box…

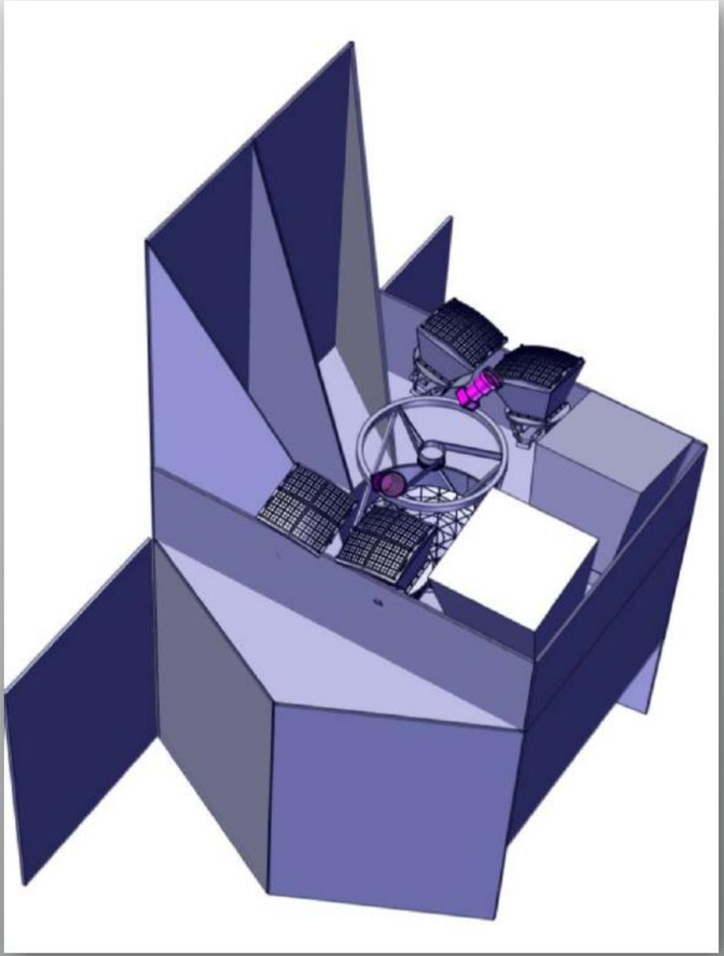
- Initially 1 ToO/day focussed on time domain astrophysics including multi-messengers, will increase during the extended mission



ToO	Approval	From accep-tance/ trigger	GRB inter-ruption	Frequency	Duration
ToO-NOM	PI	<48h	Yes	MAX 1/day => 5/day	1 orbit
ToO-EX	PI	<12h	No	MAX 1/month	1-14 orbits

THESEUS

Transient High Energy Sky and Extreme Universe Surveyor
A **ESA-M5** mission candidate, currently in **Phase A**



Three main instruments:
SXI (Soft X-ray Imager) led by UK
IRT (InfraRed Telescope) led by France
XGIS (X and Gamma Imaging Spectrometer) led by Italy

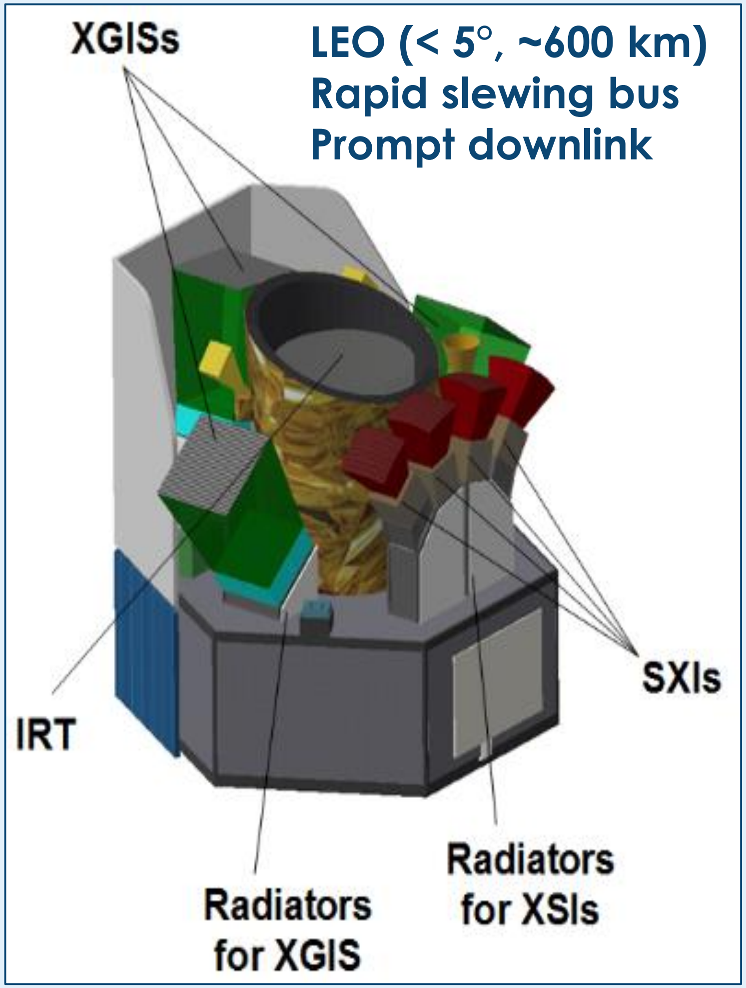
THESEUS
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

- THESEUS Core Science:
  1. Probe the **physical properties of the early Universe**, by discovering and exploiting the population of **high redshift GRBs**
  2. Provide an unprecedented **deep monitoring of the soft X-ray transient Universe**, providing a fundamental contribution to multi-messenger and time domain astrophysics in the early 2030s (synergy with aLIGO/aVirgo, eLISA, ET, Km3NET and EM facilities e.g., LSST, E-ELT, SKA, CTA, ATHENA)
- THESEUS Observatory Science:
  1. Study of thousands of **faint to bright X-ray sources** by exploiting the unique simultaneous availability of broad band X-ray and NIR observations
  2. Provide a flexible follow-up observatory for **fast transient events** with multi-wavelength ToO capabilities and guest-observer programmes.

THESEUS mission concept

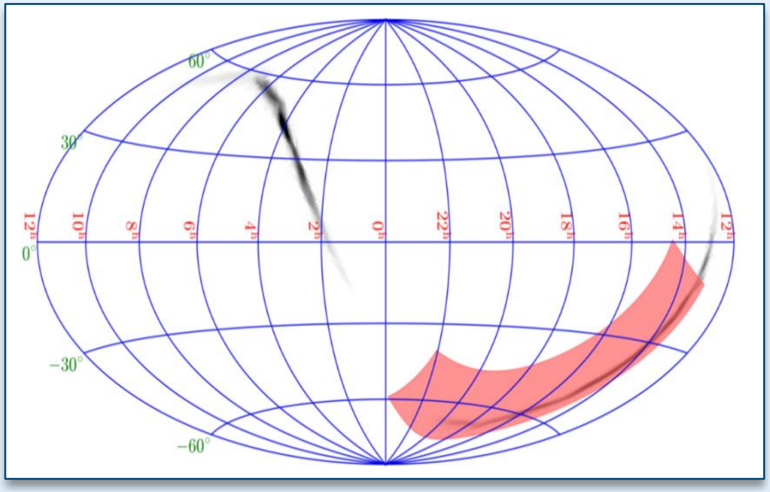
- **Soft X-ray Imager (SXI)**
  - 4 sensitive lobster-eye telescopes
  - **[0.3 - 5 keV]**
  - FOV = ~1sr
  - Source location accuracy 0.5-1'
- **X-Gamma rays Imaging Spectrometer (XGIS)**
  - 3 coded-mask X-gamma ray cameras
    - Bars of Silicon diodes coupled with CsI crystal scintillators
  - **[2 keV – 10 MeV]**
  - FOV of ~2-4 sr, overlapping the SXI
  - ~5' source location accuracy
- **InfraRed Telescope (IRT)**
  - 0.7m class IR telescope
  - **[0.7 – 1.8 μm]**
  - 10'x10' FOV
  - imaging and moderate resolution spectroscopy capabilities (-> redshift)

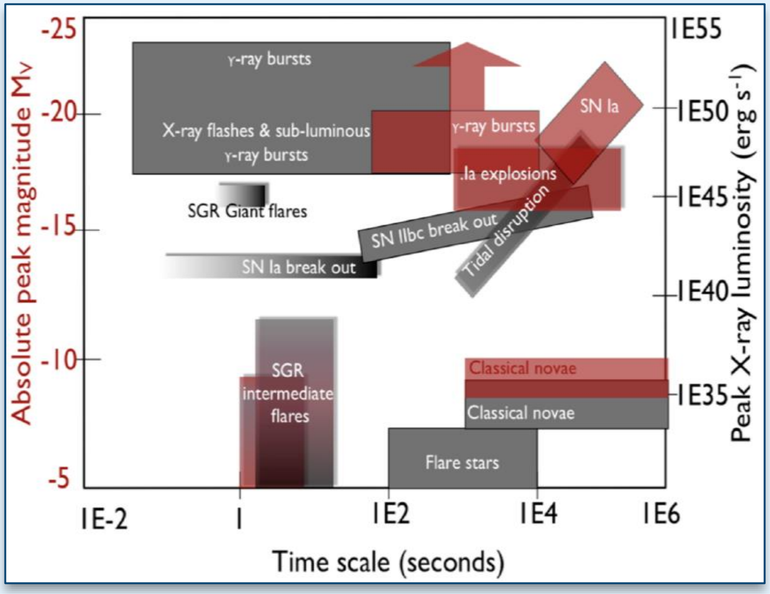
LEO (< 5°, ~600 km)
Rapid slewing bus
Prompt downlink



Exploring the multi-messenger transient sky

- Locate and identify the electromagnetic counterparts to sources of gravitational radiation and neutrinos, which may be routinely detected in the late ‘20s / early ‘30s by next generation facilities like aLIGO/aVirgo, eLISA, ET, or Km3NET;
- Provide real-time triggers and accurate (~1 arcmin within a few seconds; ~1’’ within a few minutes) high-energy transients for follow-up with next-generation optical-NIR (E-ELT, JWST if still operating), radio (SKA), X-rays (ATHENA), TeV (CTA) telescopes; synergy with LSST
- Provide a fundamental step forward in the comprehension of the physics of various classes of transients and fill the present gap in the discovery space of new classes of transients events





The Theseus Mission

- THESEUS, under study by ESA and a large European collaboration with strong interest by international partners (e.g., US) will fully exploit **GRBs as powerful and unique tools to investigate the early Universe** and will provide us with **unprecedented clues to GRB physics and sub-classes**.
- THESEUS will also play a **fundamental role for GW/multi-messenger and time domain astrophysics** at the end of next decade, also by providing a flexible **follow-up observatory for fast transient events with multi-wavelength ToO capabilities and guest-observer programmes**
- THESEUS will enhance importantly the scientific return of next generation facilities in the multi messenger (aLIGO/aVirgo, LISA, ET, or Km3NET) and e.m. (e.g., LSST, E-ELT, SKA, CTA, ATHENA) domain
  - http://www.isdc.unige.ch/theseus/

Theseus Mission Timeline

➔ May 2018: THESEUS selected by ESA for M5 Phase 0/A study

Activity	Date
Phase 0 kick-off	June 2018
Phase 0 completed (EnVision, SPICA and THESEUS)	End 2018
ITT for Phase A industrial studies	February 2019
Phase A industrial kick-off	June 2019
Mission Selection Review (technical and programmatic review for the three mission candidates)	Completed by June 2021
SPC selection of M5 mission	November 2021
Phase B1 kick-off for the selected M5 mission	December 2021
Mission Adoption Review (for the selected M5 mission)	March 2024
SPC adoption of M5 mission	June 2024
Phase B2/C/D kick-off	Q1 2025
Launch	2032

- Smooth CDF study, successful MDR -> Phase A
- Efficient and positive interaction between ESA and consortium