Position-sensitive detectors and their readout as an enabling technology for high-energy astrophysics

Experiments in High-energy physics are based on the available detectors and electronics!

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High-energy Astrophysics (or Astroparticle Physics) → explores the Universe by means of studying (or detecting) elementary particles of astronomical origin:

- Charged particles in astroparticle physics: (protons, antiprotons, electrons, positrons, nuclei, muons)
- Gamma-rays (photons with E $\gtrsim$ 0.1 MeV)
- Neutrinos, all-flavors
  - ❖ Gravitational waves: multimessenger phenomena
  - ❖ Dark matter: indirect detection

- ➢ **Comment**: energy units used in particle physics and astrophysics: erg (commonly used), electron-volt (energy gained by an electron while passing 1V potential difference), 1 eV = 1.6 x 10^{-12} erg, and 1 Hz = 6.63×10^{-27} erg)

A few words on the detection specifics in HE Astrophysics

We want to measure charged particles and photons properties (leaving neutrino and gravitational waves off the discussion for now) **of the unknown fluxes** (energy, intensity, spatial distribution, species)

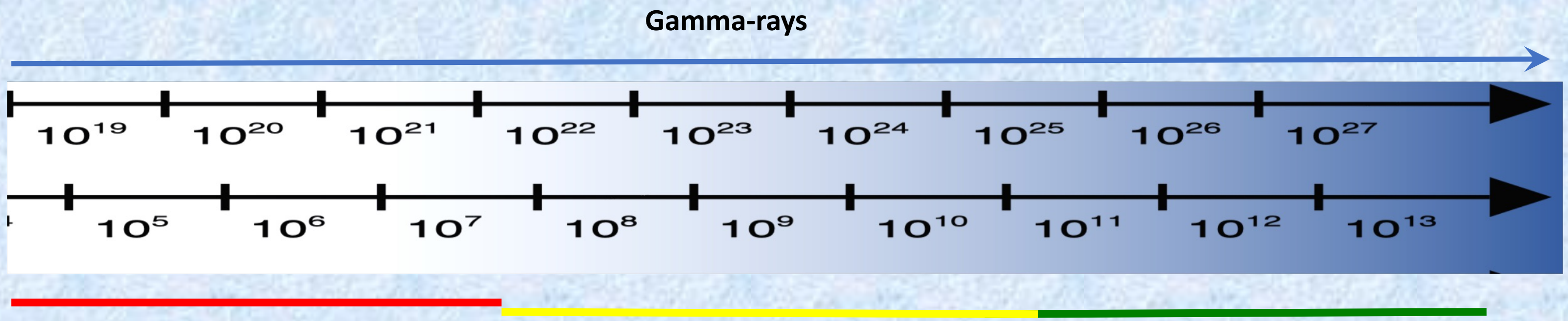
Energy range: usually relativistic energies for charged particles (hereafter charged cosmic rays), and $E \gtrsim 0.1$ MeV for photons

Detector (or detecting system) has to provide:

- ✓ **Particle identification,** in most of measurements with dominating background (e.g., $\boldsymbol{\gamma}$/p $<10^{-4}$, pbar/p $<10^{-4}$, hebar/he $<10^{-8}$, e/p $\sim 10^{-3}$ - 10^{-5} , etc.)
- ✓ Energy measurement,
- ✓ Arrival direction
- ✓ Arrival time,
- ✓ Polarization (where applicable)

In most of the instruments the measurements are provided by not a single detector, but by a combined system of several detectors

Gamma-ray Astrophysics

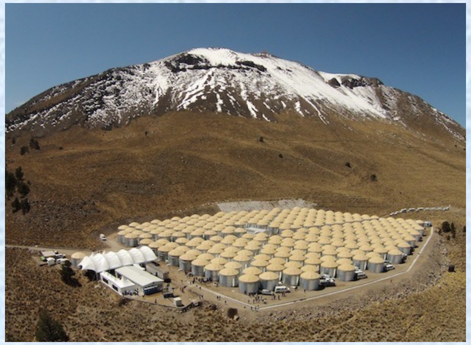


Freq (Hz)
Energy (ev)

Medium Energy gamma-rays (aka MeV)

High Energy gamma-rays (aka GeV)

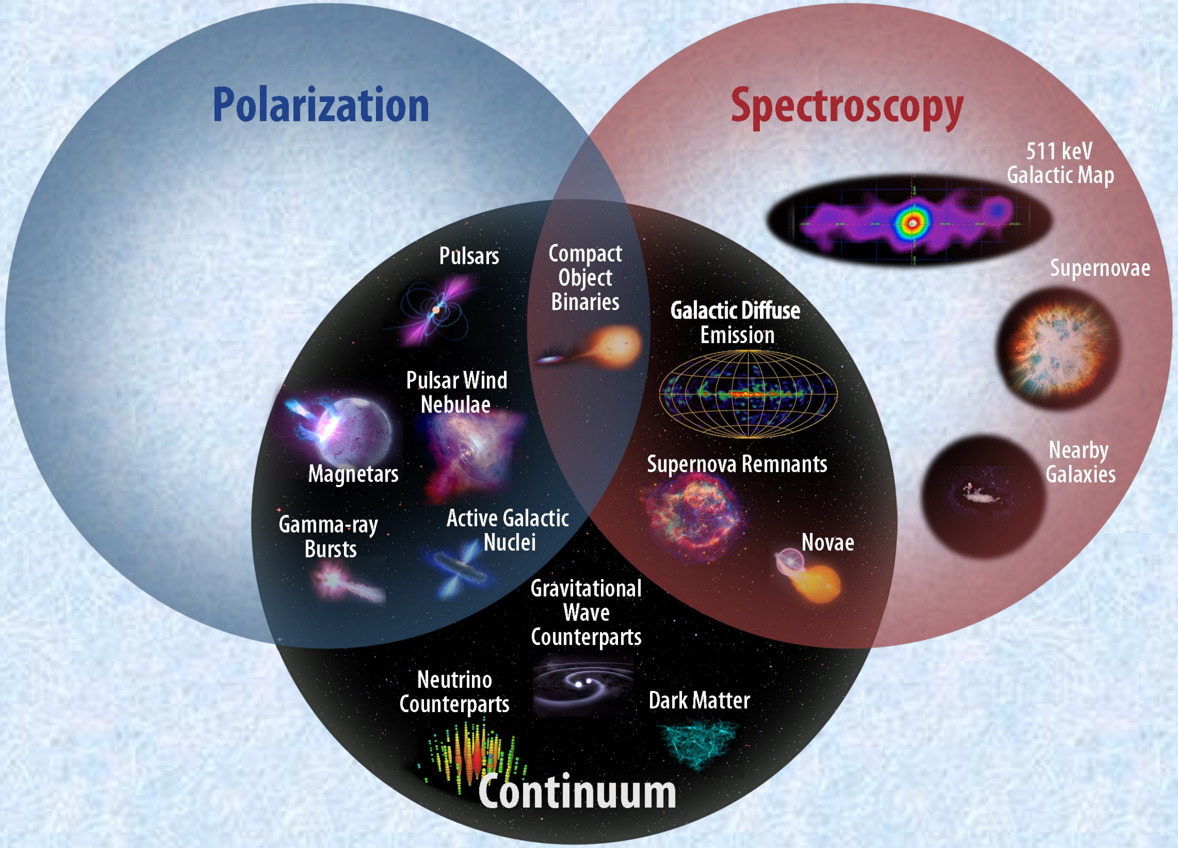
Very High Energy (VHE) gamma-rays (aka TeV)



Comment: Gamma-rays do not reach the Earth surface: to detect them we either have to go to the space or to the upper atmosphere by high-altitude balloons, or explore them on the Earth by the products created in the atmosphere

Why gamma-rays?

- High energy photons are produced in different physical processes and carry key information what process is
- Photons propagate through Universe without deflection in magnetic fields. Their origination point and spectrum at the source can be directly measured.



Needed capabilities in medium-energy and high-energy gamma-ray astrophysics:

- sensitive continuum spectral studies,
- high angular resolution,
- polarization,
- nuclear line spectroscopy.

We are starting a brief tour through the evolution of the high-energy astrophysical experiments with the detectors development:

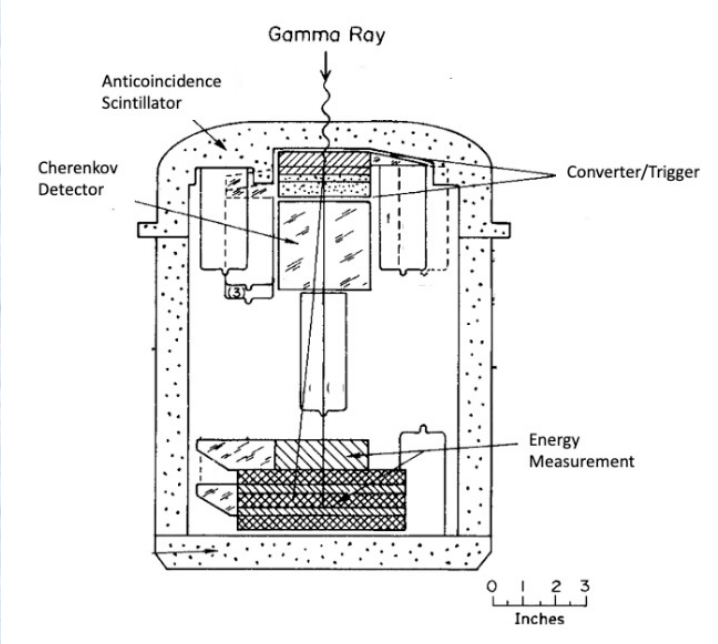
- from gas detectors to the solid-state detectors,
- from discrete single-channel readout electronics to ASICs and FPGA
- current trend: from bulky and HV-hungry PMT to very compact Silicon photomultipliers (SiPM) - however needs more work to finally qualify SiPM for the space flight

Some specifics of the space astrophysical missions -

- **Not always the best existing detectors are used, in opposite to the accelerator experiments 😢 : as higher level of the mission, as more developed the detector must be to minimize the risk of the failure**
- **Long-time reliability: operation >5 years without human direct service**
- **Performance stability**
- **Low power consumption (due to both, limited available power and thermal issues)**

Progress in Astrophysics is driven by the progress in the detectors and their readout

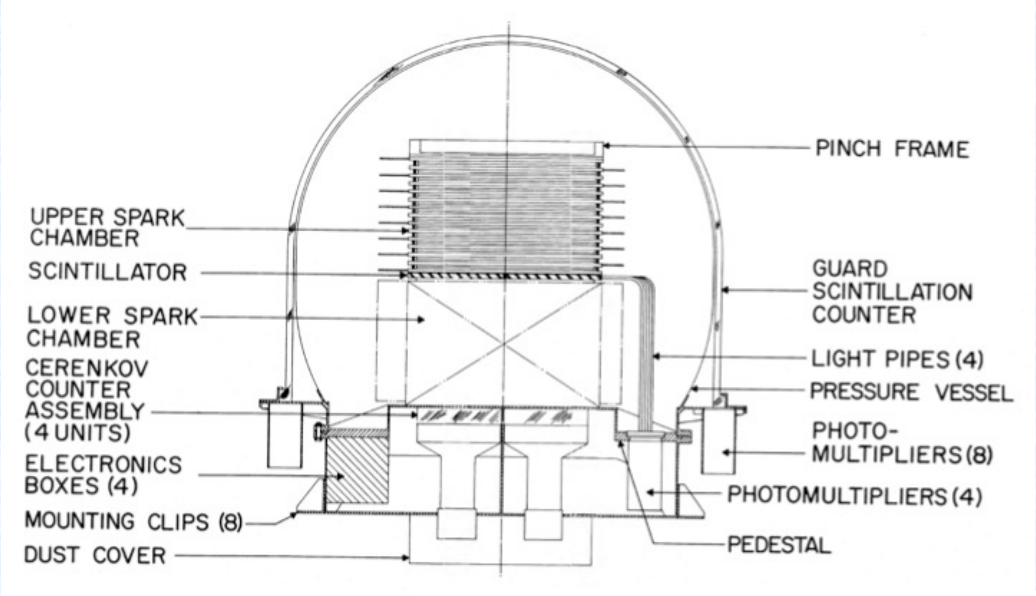
First example: progress in space-based γ-ray astronomy



1967: **γ**-ray counter telescope on **OSO-3**

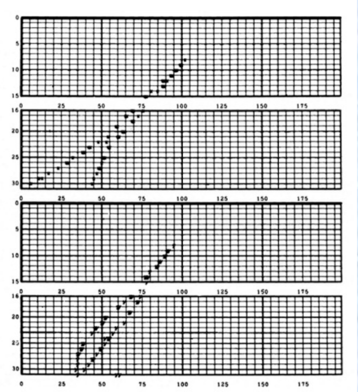
- Plastic and CsI **scintillators** viewed by photomultipliers
- Lucite directional **Cherenkov detector**
- Energy is measured by W-NaI sandwich
- No PSD
- **A_{eff} ≈ 9 cm^2 , PSF ≈ 24°**
- 16 months of operation
- **621 celestial γ-rays detected above 50 MeV**
- **γ-ray emission peak from Galactic Plane and Earth limb**

W. Kraushaar+, ApJ 177, 1972



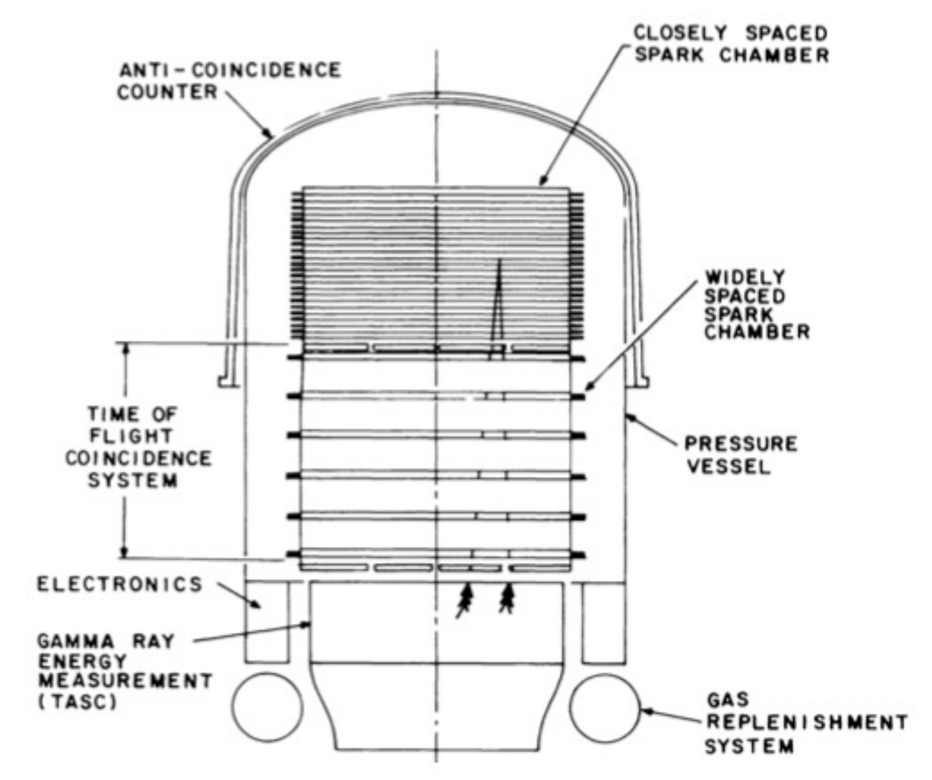
1972: Second Small Astronomy Satellite **(SAS-2)**

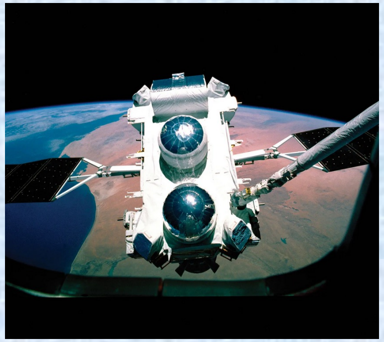
- 32-layer **wire grid spark chamber** with magnetic core readout to determine photon arrival direction: **imaging detector!**
- Energy is reconstructed from the multiple Coulomb scattering
- **A_{eff} ≈ 100 cm^2 , PSF ≈ 2.4° at 100 MeV**
- Operated for about 6 months, about **8,000 good γ-events have been detected**
- **Crab and Vela pulsars were detected (first discovered in 1967 by Jocelyne Bell)**



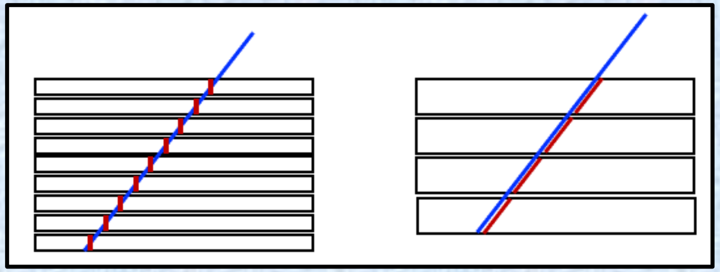
2D photon image

C.E. Fichtel+, ApJ 198, 1975



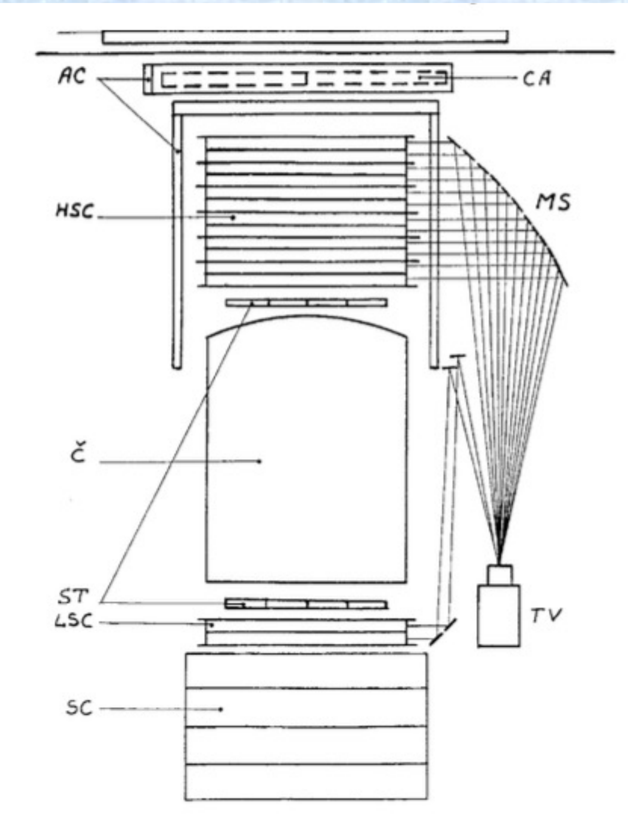


CGRO



Wire-grid spark chamber

Wide-gap spark chamber



1991: Energetic Gamma Ray Experiment Telescope (**EGRET**) onboard **CGRO**

- A wire-grid, **magnetic-core spark chamber**: imaging detector
- A full-absorption NaI calorimeter
- A time-of-flight coincidence system (direction measurement)
- **PMT readout** of all scintillators
- 9+ years of operation
- **$A_{eff} \approx 1{,}500\ cm^2$, PSF ≈ 6° at 100 MeV**
- **271 sources detected, including 5 pulsars, LMC, AGN**

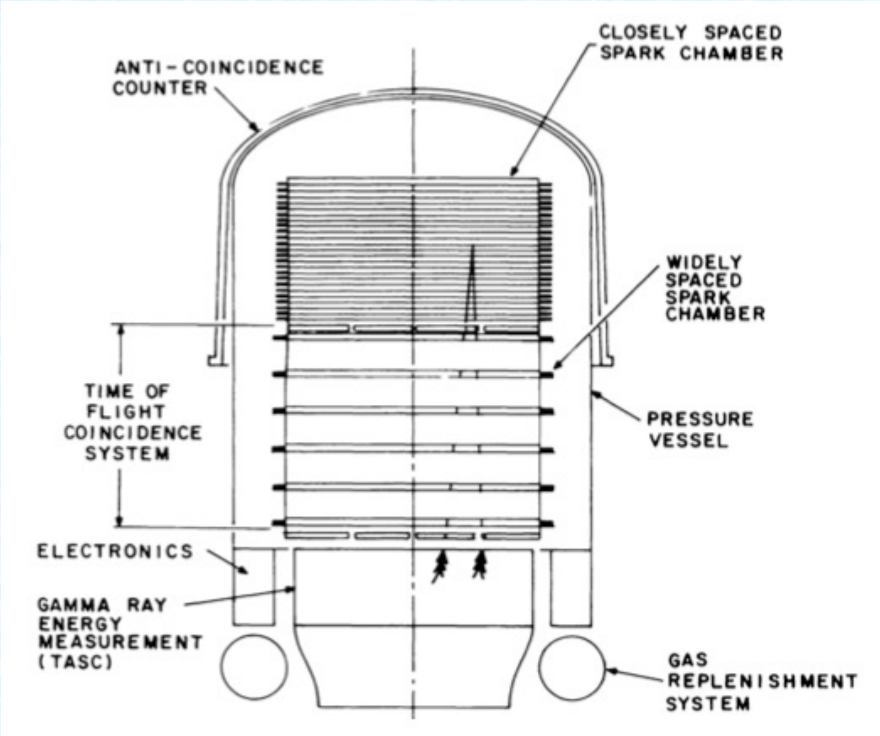
G. Kanbach+, Space Science Reviews, 49, 1989

1991: **Gamma-1** (USSR, France)

- 12-layer stack of wide-gap **optical spark chambers** - imaging detector
- A time-of-flight coincidence system
- Gas **Cherenkov detector** to determine photon direction
- Sandwich Pb-Sci calorimeter
- **PMT readout** of all scintillators and Cherenkov detector
- **$A_{eff} \approx 1{,}500\ cm^2$, PSF ≈ 2° at 100 MeV**
- **Early termination due to power system failure**

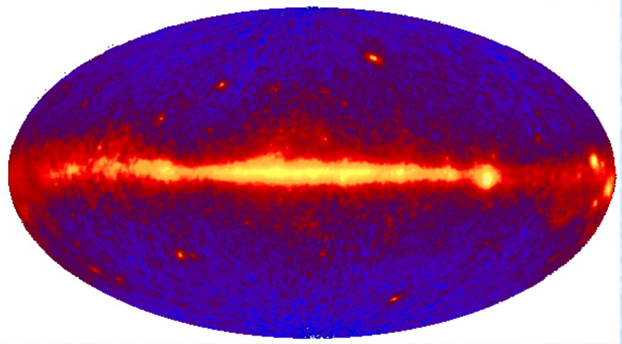
V.V. Akimov+, Space Science Reviews, 49, 1989

Huge progress from EGRET to Fermi-LAT!
From spark chambers to the Silicon-strip multi-layer detectors

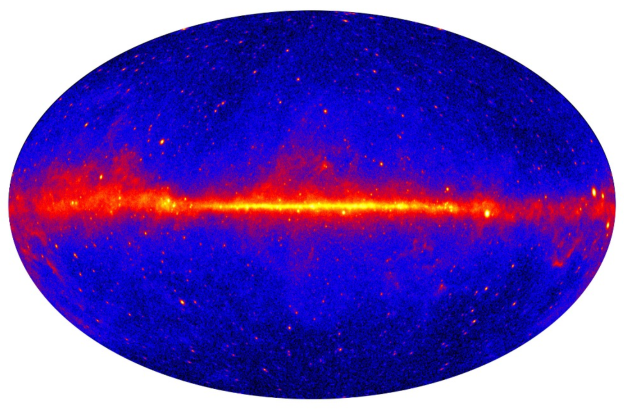


EGRET: based on the **spark chambers**

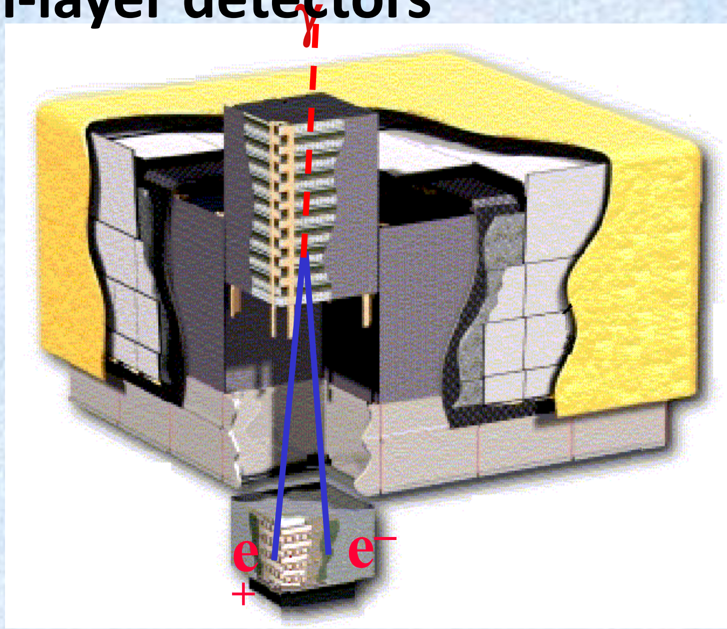
- about 200 **γ**-ray sources detected



EGRET 10-years sky



Fermi-LAT 5-years sky



2008: Fermi-LAT (formerly GLAST)

- Pair-conversion **γ**-ray telescope
- 18-layer **Si-strip tracker**
- 89-segment Anticoincidence detector
- **Hodoscopic** 1,536-log **CsI(Tl) calorimeter**
- Currently operating on orbit for 15+ years
- >6,600 sources detected

W.B. Atwood+, ApJ 697, 2009

Intense search for cosmic primary antimatter, pioneered by Robert Golden: are there any primary antiparticles, or they all are the secondary, produced in cosmic ray interactions?

✓ **Exciting search for enigmatic Dark Matter has started**

Imaging capability is a critical capability in the search for antimatter when the instrument has to be able to recognize a pattern of antimatter interaction with matter (annihilation)

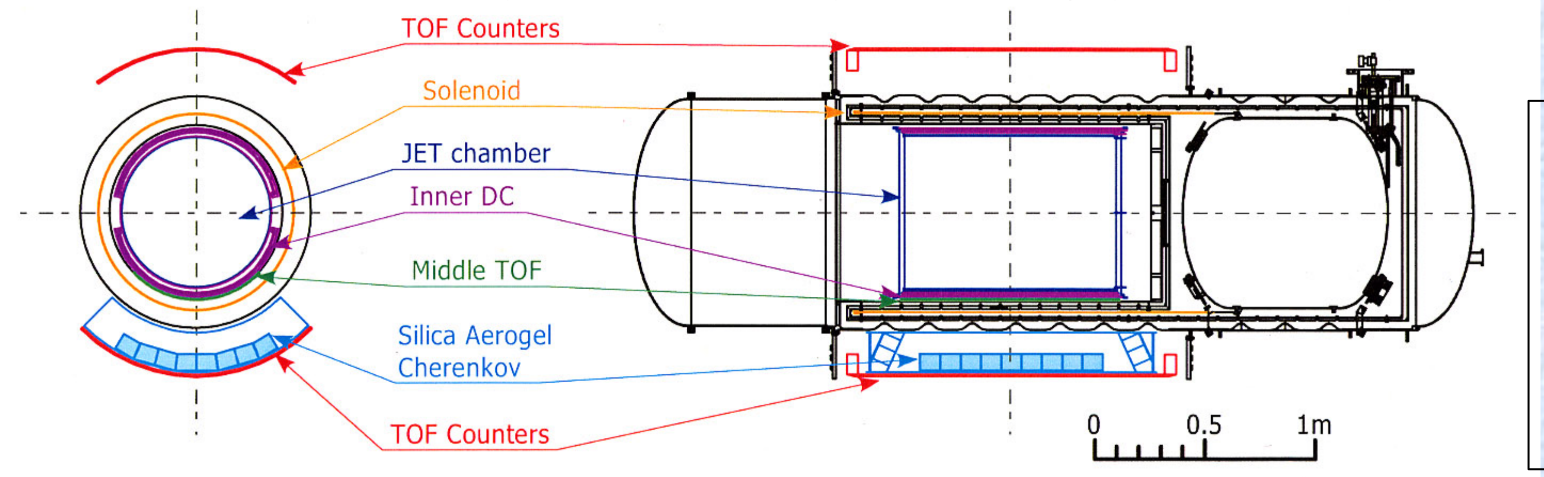
Specific feature:

- Balloon payload
- Coil superconducting magnet
- Unique configuration with incident particles passing through the magnet walls

PSD:

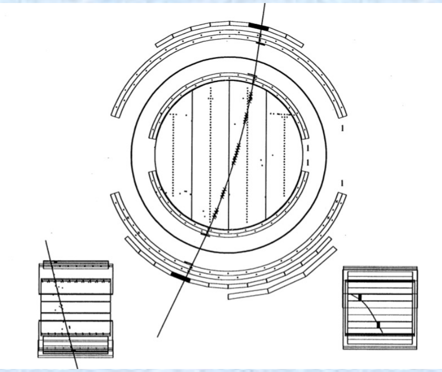
- Jet drift chamber, Drift chamber

BESS: the Balloon-borne Experiment with a Superconducting Spectrometer (Japan - USA - Italy)

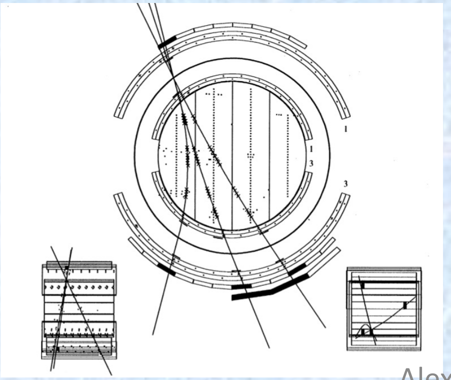


Main results:

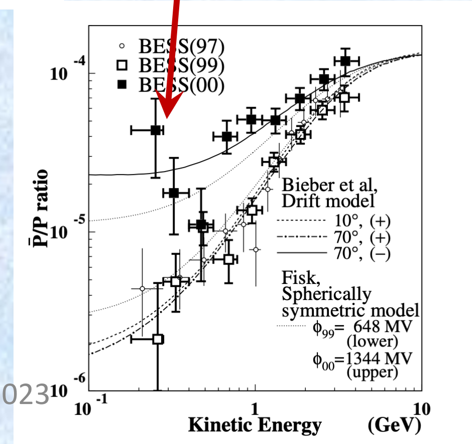
- Many flights from Lynn Lake (Manitoba, Canada), Ft. Sumner, and Antarctica
- First high-statistics reliable detection of cosmic antiprotons, proving their secondary origin
- Upper limits on the cosmic antihelium



Antiproton event



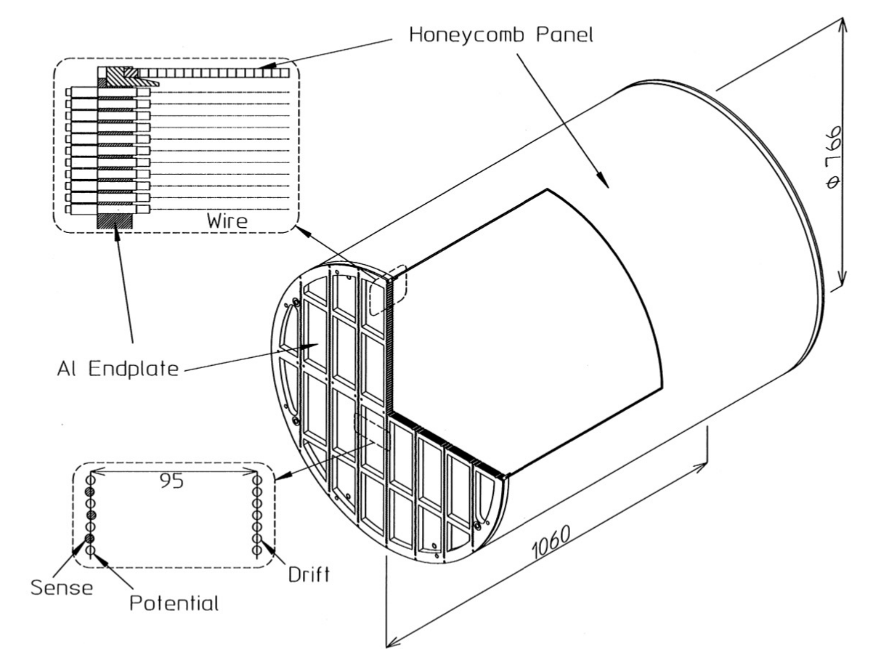
Interacted event



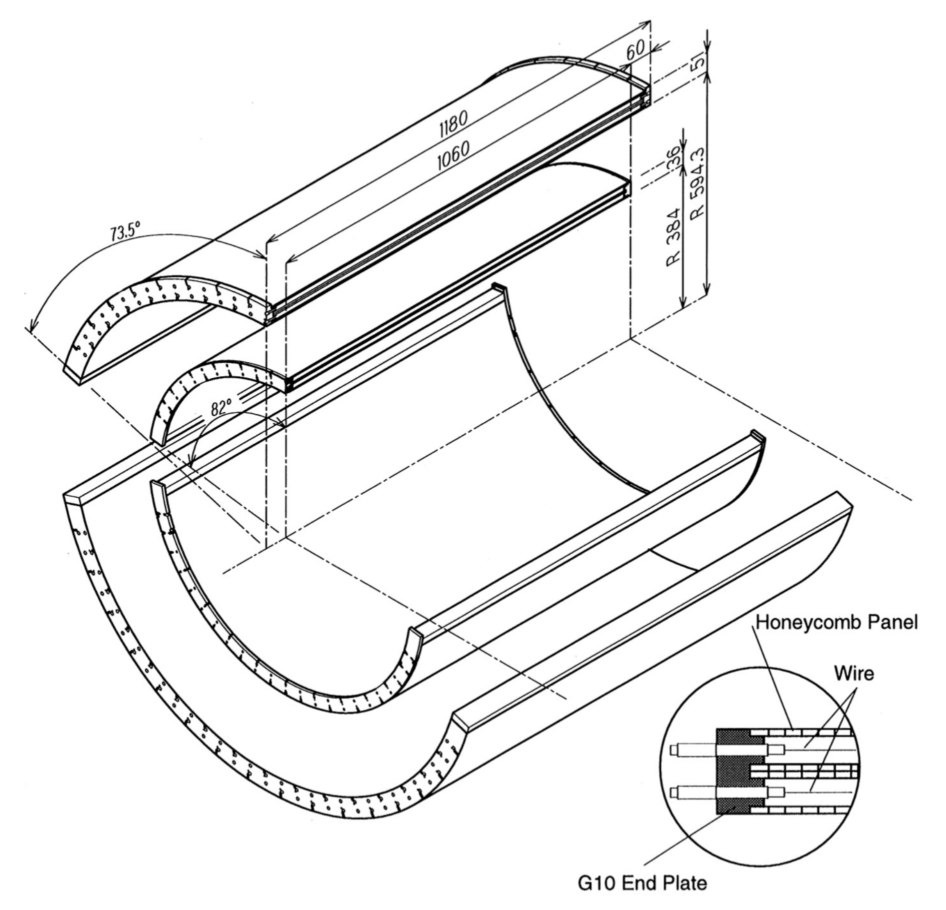
Credit: Y. Ajima+, NIM 1999
Y. Asaoka et al., PRL 2002

BESS

Jet drift chamber



Inner and Outer Drift chamber



Gas mixture: 90% of CO_2 and 10% of Ar 10%, called “slow gas. The drift velocity at 1 atm and with an electric field of 1 kV/cm is about 8.1 mm/μs. This allows for fine position resolution ~200 μm

Important: The average material passed by a penetrating particle is 0.48 g/cm^2 including two chamber walls and wires.

Credit: Y. Ajima+, NIM 1999

Starting in the beginning of 2000th:

- **Massive advance of Application-Specific Integrated Circuits (ASIC). Practically no high-energy physics and astrophysics experiments without ASIC**
- **Wide use of Si, Ge, and CdTe (CdZnTe) detectors**

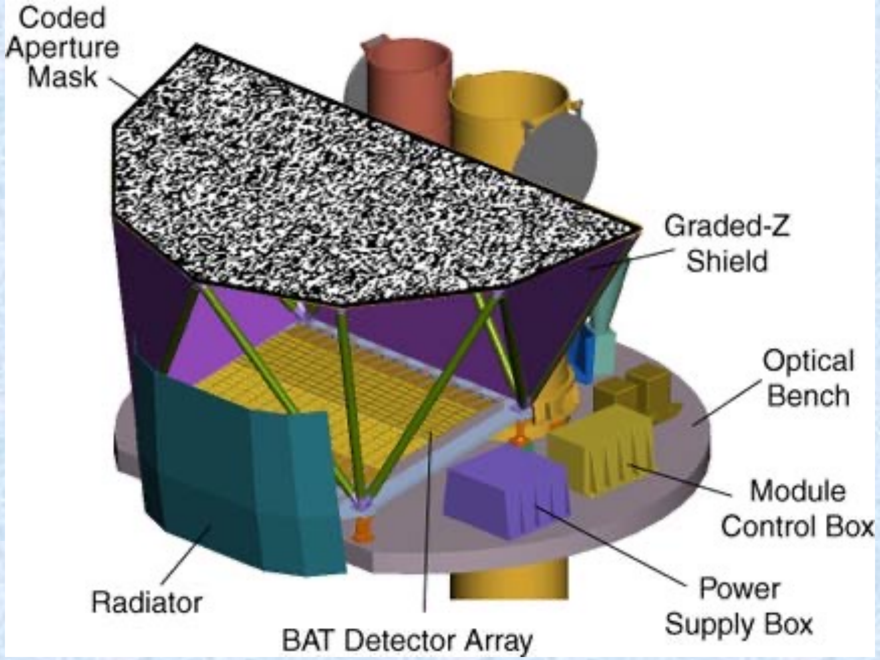
Quick overview of SWIFT and INTEGRAL. Both use solid-state pixelated detectors

Gehrels-SWIFT Burst Alert Telescope (BAT)

Launched in 2004, still in operation

Most powerful mission to detect GRB: As of April 2018, Swift has observed more than 1300 bursts.

Energy range 15 keV - 150 keV



Coded Mask Focal Plane detector: pixelated CdZnTe

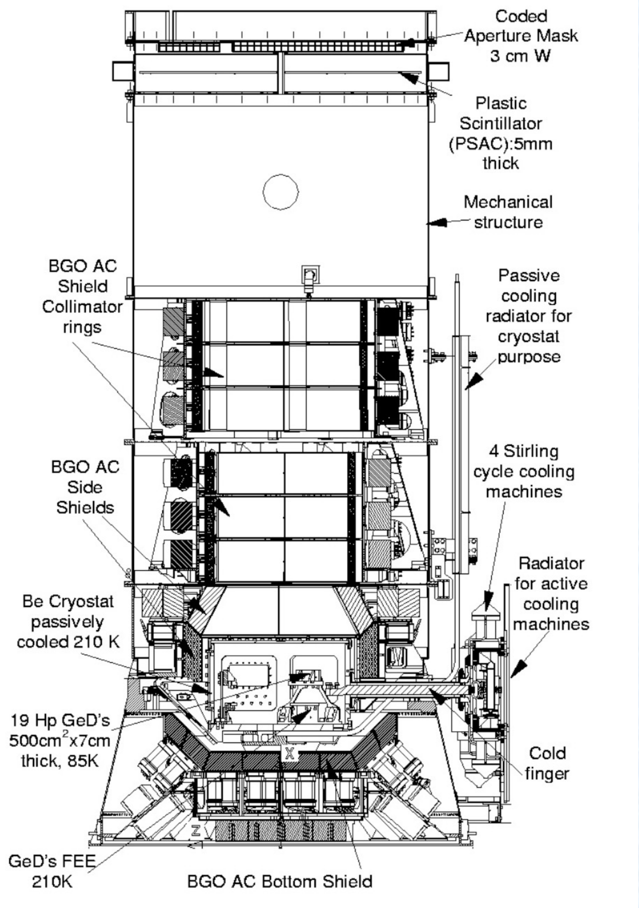
- Area 5,200cm^2, pixel size 4x4x2 mm^3, 256 x 128 pixels
- Angular resolution 17 arcmin
- Field-of-View 1.4 sr

S.W. Barthelmy+, SSR 120, 2005

INTEGRAL

launched in 2004, still in operation

SPI (spectrometer)



High-purity Ge detectors: 19 octagonal detectors with 3.2cm side, 7cm thick

IBIS (Imager)

Energy range 15 keV - 10 MeV

Detector area 2,600 cm^2

Coded Mask Focal Plane detector: 16,384 CdTe detectors, each (4 × 4 × 2) mm^3

G. Vedrenne+, A&A 411, 2003

P. Ubertini+, A&A 411, 2003

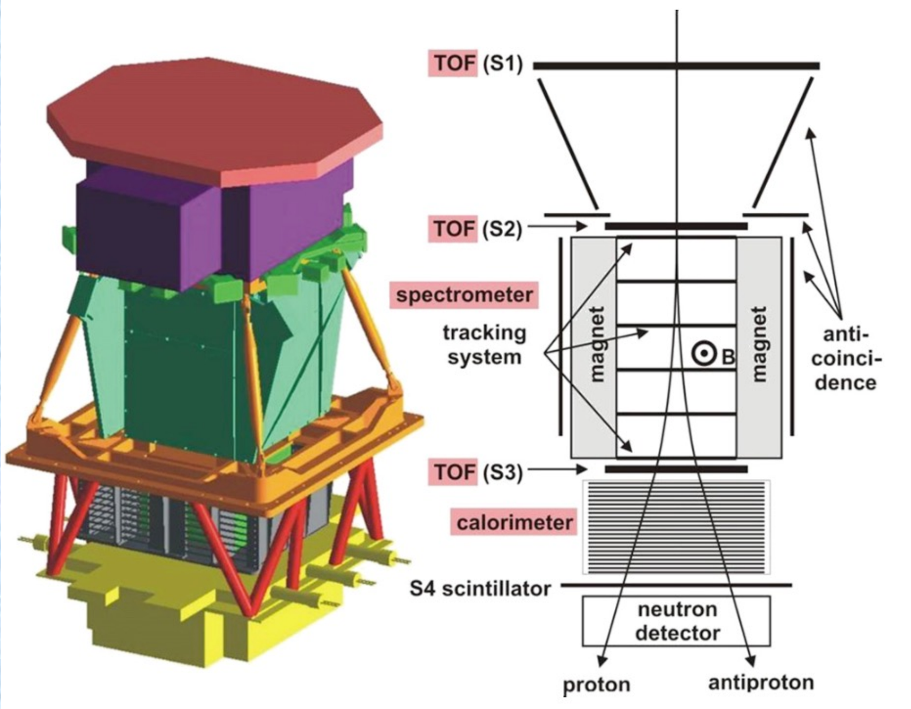
PAMELA: a Payload for Antimatter Matter Exploration and Light nuclei Astrophysics (Italy, Russia, Sweden, Germany)

Space mission, launched in 2006, terminated in 2016

Objectives: search for antimatter and dark matter

Specific features:
- Magnetic spectrometer with uniform 0.43T magnetic field
- High-inclination Low Earth orbit

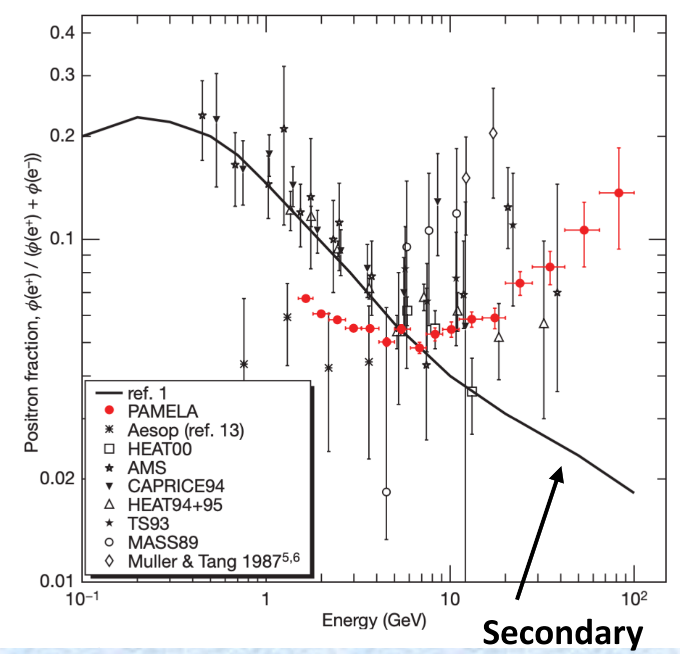
PSD:
- **High-precision double-side Si-strip detector**
- Imaging sampling calorimeter with Si-strip detectors



P.-G. Picozza+, Astroparticle Physics 27 (2007) 296–315

Main results:

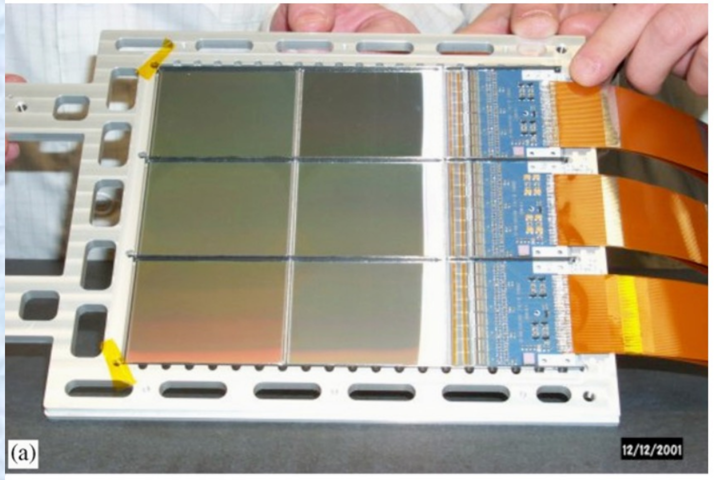
- **An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV has been discovered, O. Adriani et al., Nature 2009. Origin is still unknown**
- **Secondary origin of cosmic antiprotons observed at the Earth, has been confirmed**



Secondary production

PAMELA

A unique double-sided Si-strip detector with fine strip pitch



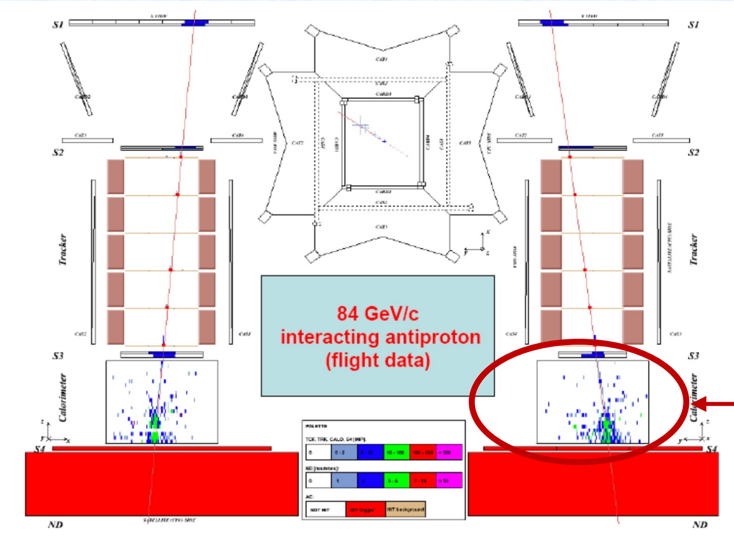
One of the six detector planes (four are placed inside the magnetic cavity, and two - on its upper and lower edge.

- The implantation pitch is 25.5 µm on the junction side (P-side) and 66.5 µm on the ohmic side (N-side).
- Silicon sensor size is 53 mm x 70 mm x 0.3 mm
- Readout by IDEAS VA1 chips
- **Spatial resolution is 3 µm in the magnetic deflection plane (P-side), measured by straight track fit**
- **800 GV MDR is achieved due to such resolution**

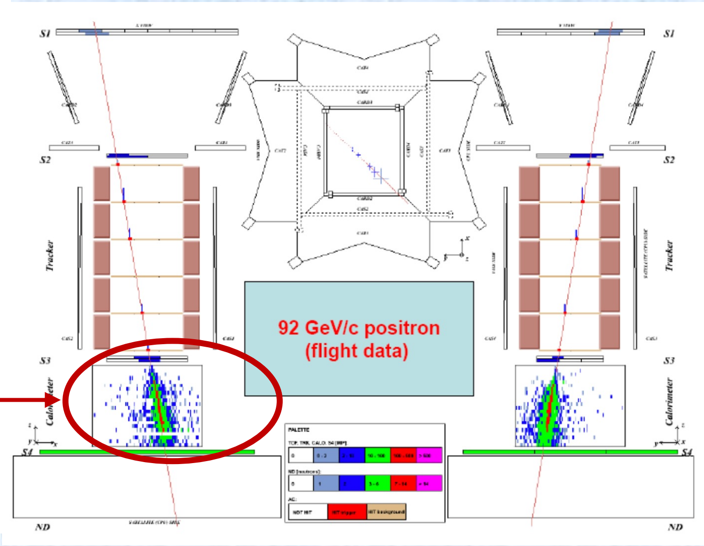
L. Bonechi+, NIM 2007

The sampling imaging calorimeter

- **Provides most of the lepton/hadron rejection power in PAMELA (needs to be ~10^5) by analyzing the shower profile**
- 44 single-sided Si- strip detector planes interleaved with 0.74 X_0 thick W plates.
- Each Si-strip plane consists of 3x3, 380 µm thick, 8x8 cm^2 detectors
- Each detector has 32 strips with 2.4mm pitch

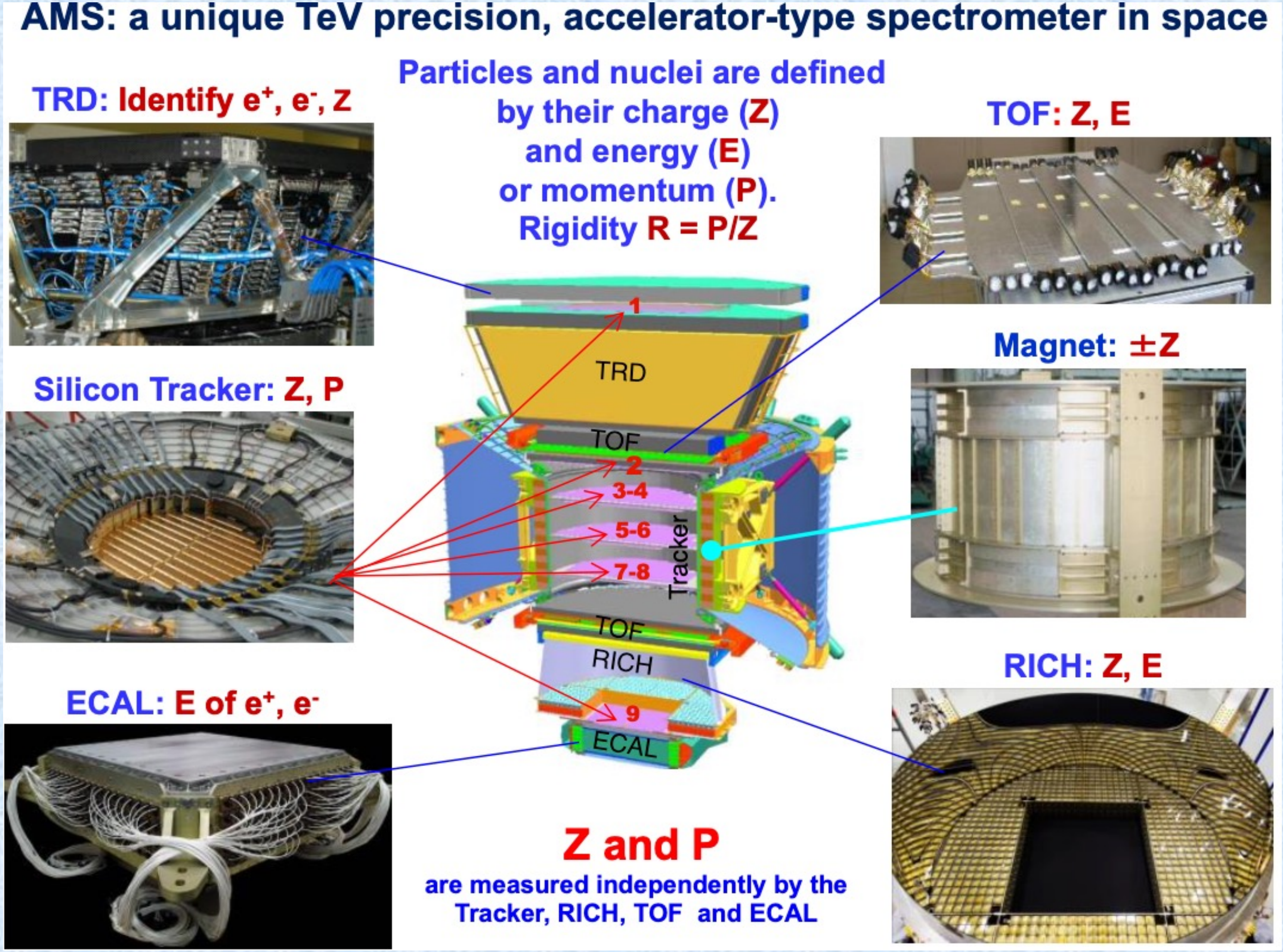


Antiproton (hadron)



Electron (lepton)

V. Bonvicini+, Journal of Physics 160 (2009) 012039



AMS: a unique TeV precision, accelerator-type spectrometer in space

Particles and nuclei are defined by their charge (Z) and energy (E) or momentum (P). Rigidity R = P/Z

TRD: Identify e^+, e^-, Z

TOF: Z, E

Silicon Tracker: Z, P

Magnet: ±Z

ECAL: E of e^+, e^-

RICH: Z, E

Z and P are measured independently by the Tracker, RICH, TOF and ECAL

Launched in May 2011

Specific features:

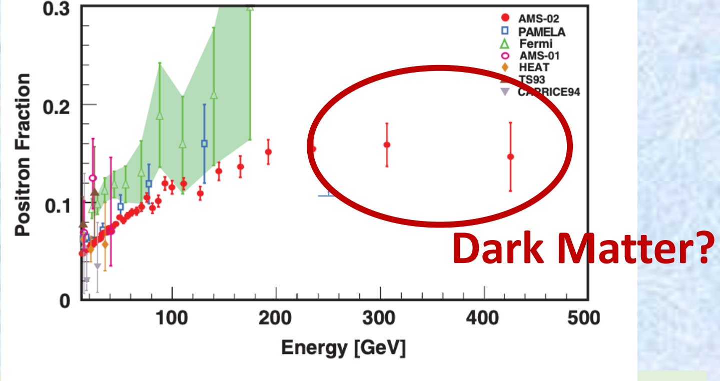
- Magnetic spectrometer on ISS
- High-inclination Low Earth orbit

PSD:

- High-precision double-side Si-strip detector
- Imaging sampling calorimeter with Si-strip detectors

Main results: very many, but no anti-Helium, main mission objective!

Positron fraction



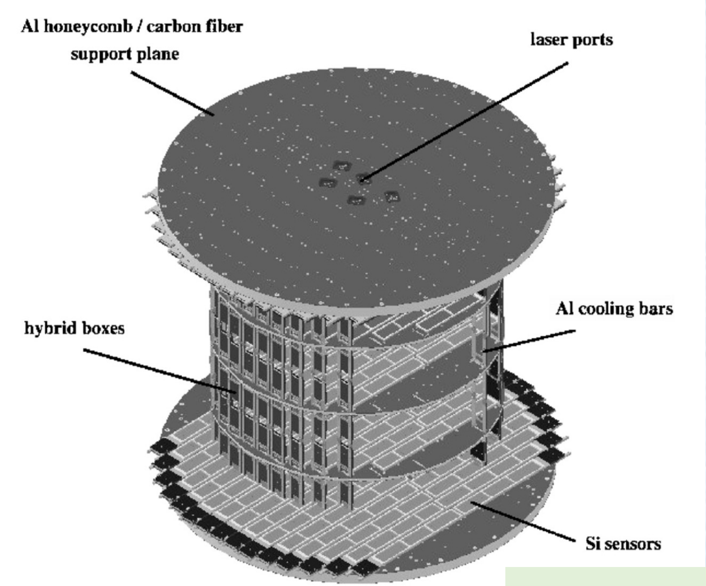
Dark Matter?

Credits: S. S. Ting (CERN lecture, 2016)
V. Chutko, ECRC-2018
J. Casaus, Journal of Physics: (2009) 012045
L. Accardo+, PRL 2014

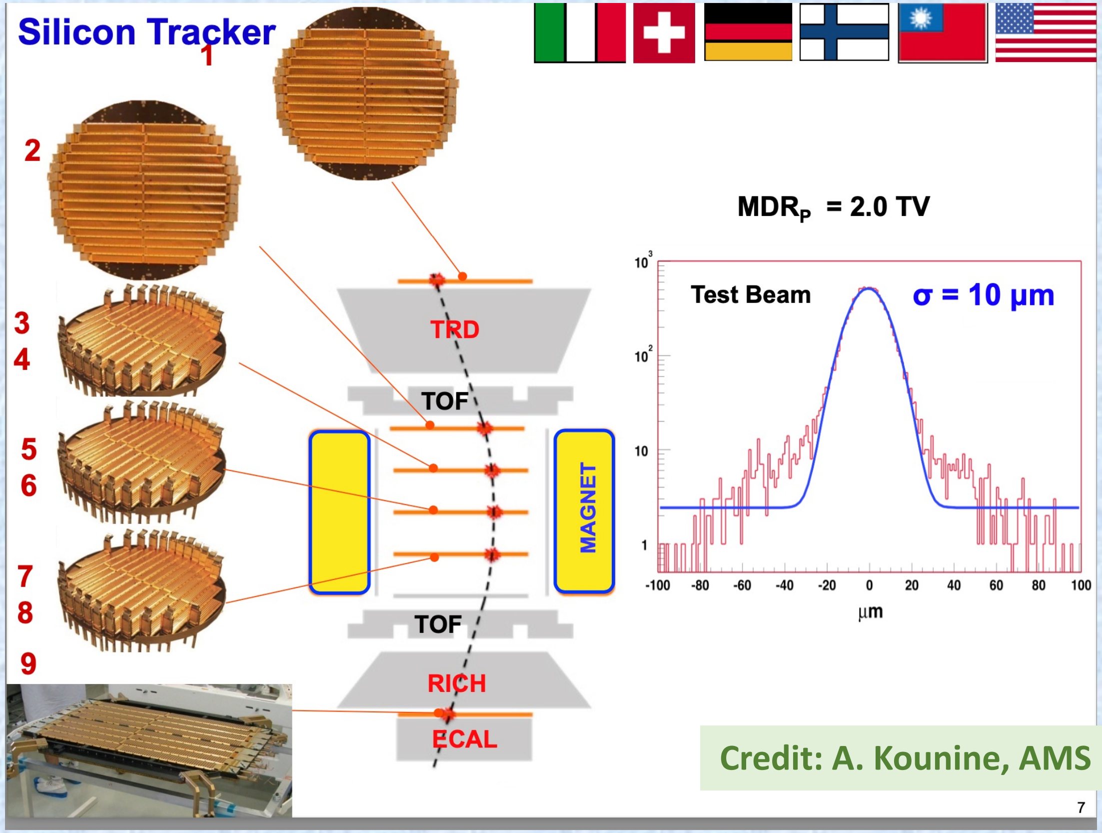
AMS

The Tracker (STD)

- 2264 double-sided sensors, 41.36 x 72.045 x 0.3 mm^3 , made of n- type, high resistivity (>6 kΩ cm) wafers
- P-side (junction): 14µm wide strips with implantation pitch 27.5 µm and readout pitch 110µm; position resolution 8.5 µm
- N-side (ohmic): 15 µm wide strips with implantation pitch 52 µm and readout pitch 208µm; position resolution 30 µm
- Sensor design is similar to that of vertex detectors at the Large Electron-Positron (LEP) collider at CERN
- Readout by Viking chips Hdr9A
- Sensors are grouped in ladders (7-15 sensors per ladder) with max 60cm strip length, to make a round-shape layer (8 in total)
- The 8 layers are arranged in 5 thin support planes - 1st and 5th are at the top and bottom of the magnet cavity, and the planes 2-4 are inside the cavity



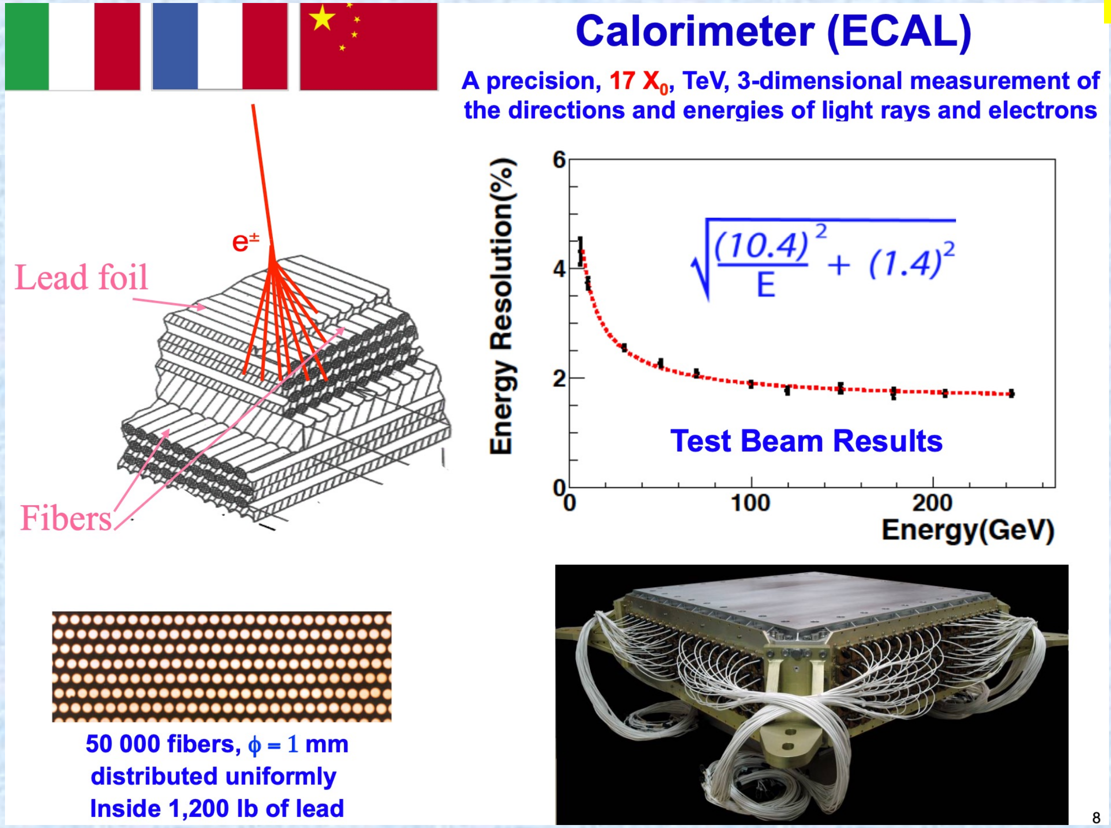
J. Alcaraz+, NIM 2008



Credit: A. Kounine, AMS Days at CERN, 2015

E/m Calorimeter: provides particle ID by shower imaging, and measures the event energy

AMS



Calorimeter (ECAL)

A precision, 17 X_0, TeV, 3-dimensional measurement of the directions and energies of light rays and electrons

50 000 fibers, $\phi = 1$ mm distributed uniformly Inside 1,200 lb of lead

Credit: A. Kounine, AMS Days at CERN, 2015

- Single layer: $0.17X_0$ of lead foil with glued SciFi
- 11 layers with parallel fiber direction are combined in superlayer
- 9 superlayers in total
- The fibers are read out by Hamamatsu R7600-00-M4 multi-anode PMT
- A total of 1296 readout channels (324 PMTs)
- Hadron rejection factor is ~10^4 for E<1 TeV

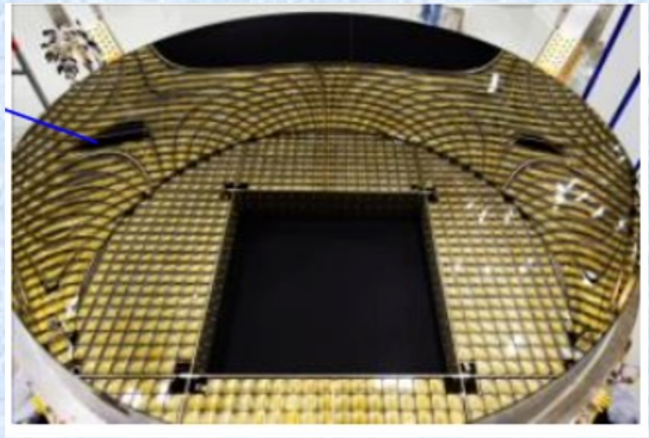
J. Casaus, Journal of Physics: (2009) 012045

Ring-Imaging Cherenkov Detector (RICH)

Multi-anode PMT as a position-sensitive detector

Provides a precise particle velocity measurement ($\sigma(\beta)/\beta <$ 0.1%) for relativistic particles, and determines the particle charge for Z<26, by means of measuring the opening angle of the Cherenkov cone for relativistic particles

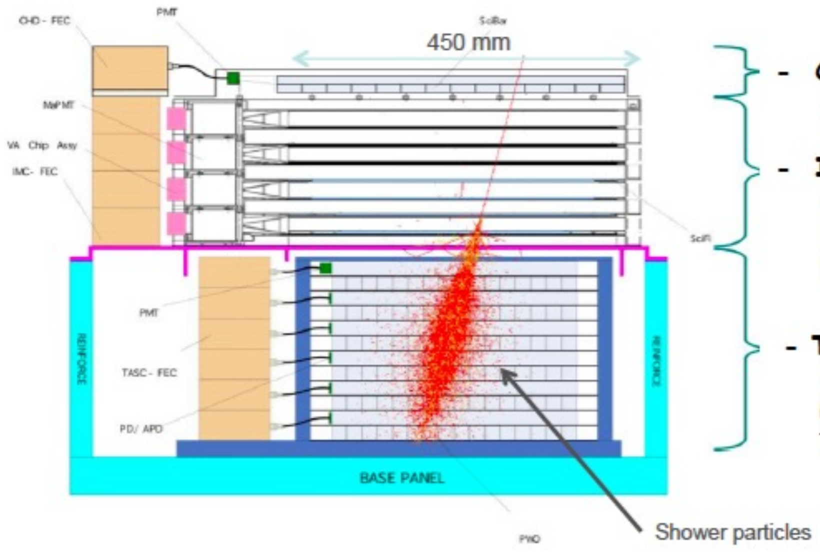
Radiator: 92 25mm-thick silica aerogel tiles (n=1.05) to create the Cherenkov light
Detector plane: 680 R7600-00-M16 multi-anode Hamamatsu photomultipliers for a total of 10,880 readout channels



P. Aguayo+, NIM 2006

CALET: Calorimetric Electron Telescope on the International Space Station (Japan, USA, Italy)

Launched in 2015, currently in operation



- **CHarge Detector (CHD)**
  (Charge Measurement in Z=1-40)
- **Imaging Calorimeter (IMC)**
  (Particle ID, Direction)
  Total Thickness of Tungsten (W): $3X_0$, $0.11\ \lambda_I$
  Layer Number of Scifi Belts: 8 Layers × 2(X,Y)
- **Total Absorption Calorimeter (TASC)**
  (Energy Measurement, Particle ID)
  PWO 20mm x 20mm x 320mm
  Total Depth of PWO: $27\ X_0$ (24 cm) , $1.35\ \lambda_I$

	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Function	Charge Measurement (Z=1-40)	Arrival Direction, Particle ID	Energy Measurement, Particle ID
Sensor (+ Absorber)	Plastic Scintillator : 2 layers Unit Size: 32mm x 10mm x 450mm	SciFi : 16 layers Unit size: 1mm^2 x 448 mm Total thickness of Tungsten: $3\ X_0$	PWO log: 12 layers Unit size: 19mm x 20mm x 326mm Total Thickness of PWO: $27\ X_0$
Readout	PMT+CSA	64 -anode PMT+ ASIC	APD/PD+CSA PMT+CSA (for Trigger) - 2 -

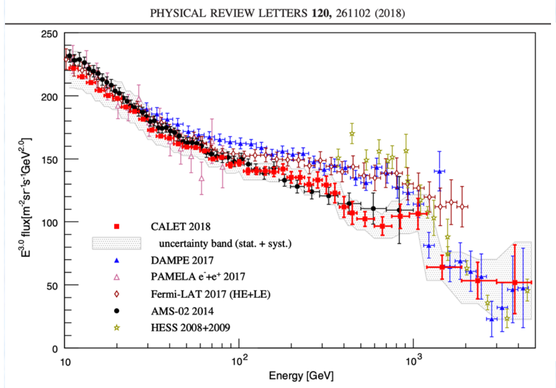
Imaging capability of IMC and TASC provides Particle ID, critical for this experiment

- **IMC:** orthogonal scintillating fibers provide X & Y; layer number provides Z
- **TASC:** calibrated signal attenuation along the PWO log provides X & Y in two consequent layers with orthogonal logs; layer number provides Z
- **Total thickness 30 X_0 !**

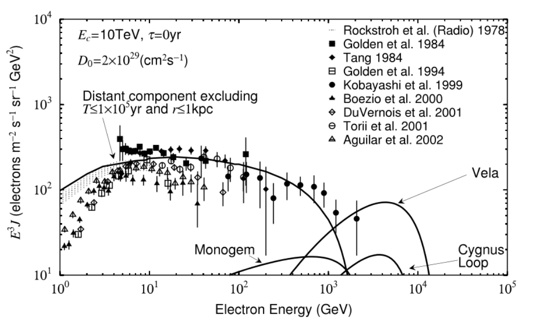
PSD:

- Scintillating fiber Imaging calorimeter
- Total absorption scintillator calorimeter (PWO)

Main results:



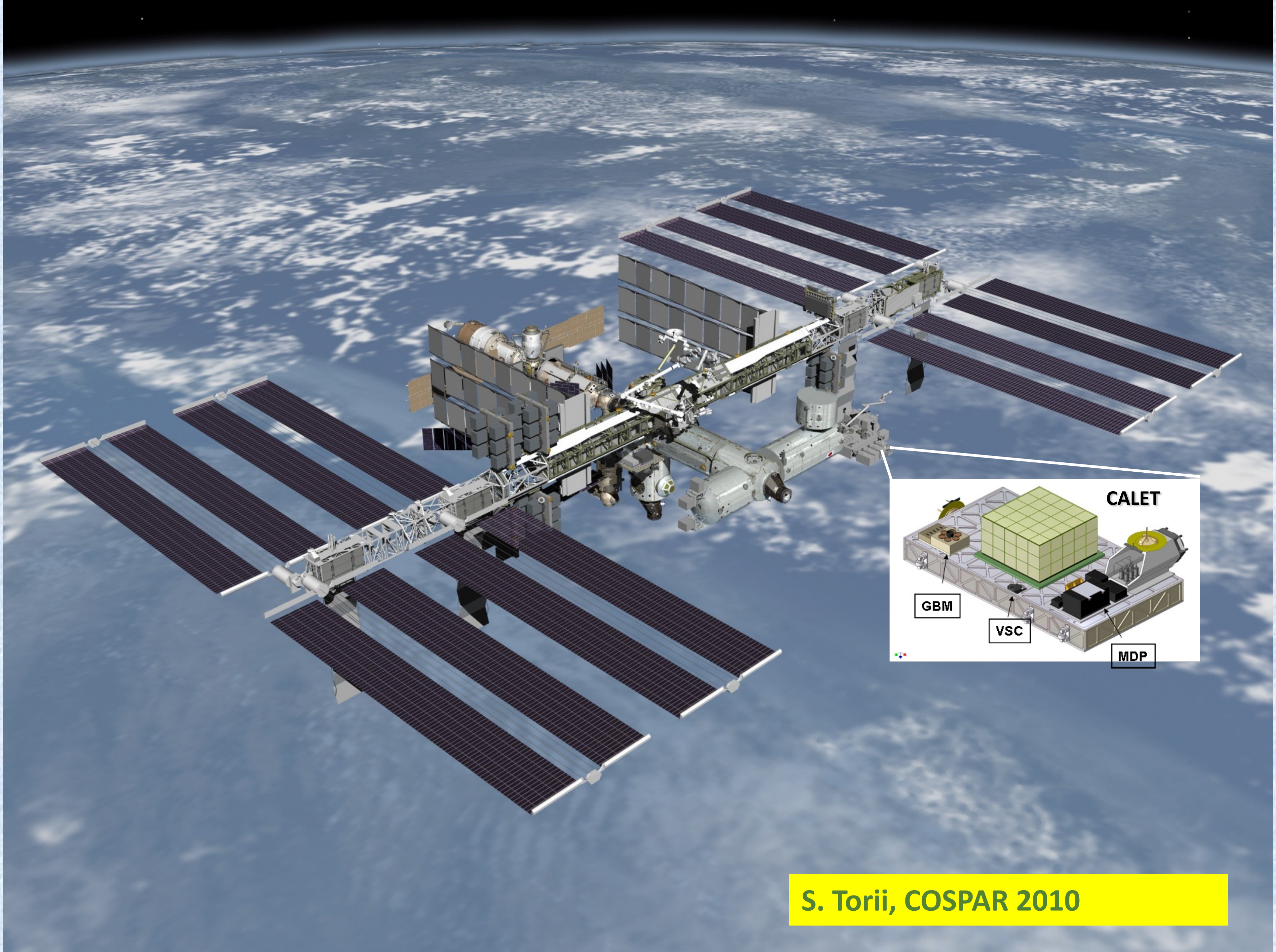
High-energy electron spectrum



Predicted spectrum (Kobayashi et al., 2004)

✓ **Measurements of the Cosmic ray nuclei spectra in few-GeV/n to few-TeV/n energy range, for protons, B, O, Fe, Ni**

S. Torii, TeVPA-2013
P.S. Marrocchesi+, NIM A, 2012

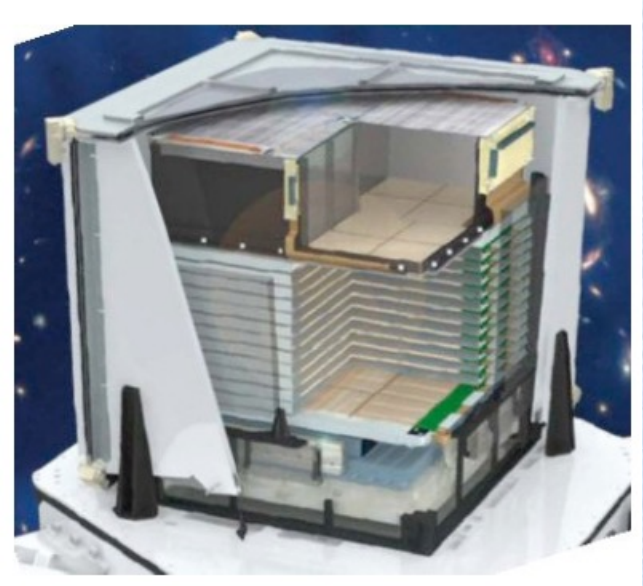


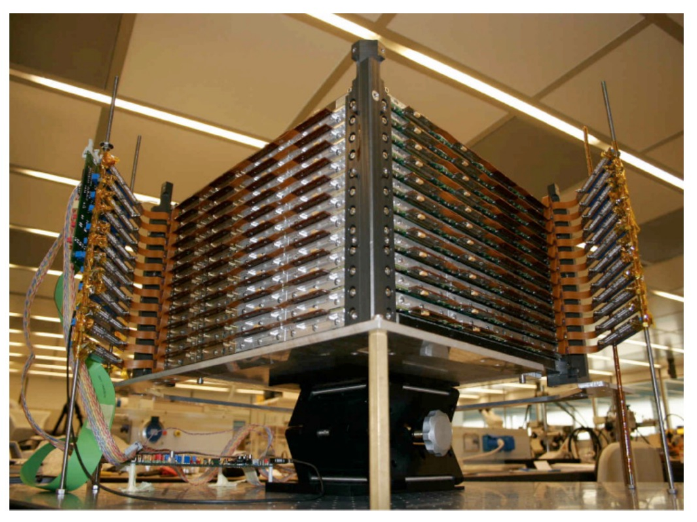
S. Torii, COSPAR 2010

AGILE: *Astro-rivelatore Gamma a Immagini Leggero* (Italy)

Launched in 2007 on equatorial LEO, currently in operation

First new-generation high-energy **γ**-ray telescope on orbit





AGILE Si Tracker

Si-strip detector

- The individual Si-strip detector: 9.5 × 9.5 cm^2, 410 μm thick
- Strip pitch 121 μm, readout pitch 242 μm
- 4 detectors are bonded together to make a ladder
- Four ladders make a plane
- 12 trays, with 2 planes with orthogonal strips in each
- First 10 trays are interleaved with a 245 μm W layer
- **Readout by IDEAS's TAA1**
- **Si wafers provided by Hamamatsu, detectors fabricated by INFN Trieste**
- Position resolution 40-60 μm

Specific features:

- **γ**-ray telescope with **γ** -ray and hard X-ray imagers
- 30 MeV - 50 GeV energy range

PSD:

- Stack of single-side Si-strip detectors

Main activity:

- The monitoring of the **γ**-ray sky with a rapid alert system:
  > 230 ATel and >110 GCN
- Search for GW counterparts and Fast Radio Bursts
- >160 refereed papers

M. Tavani+, AGILE mission, A&A, 2009
G. Barbellini+, The AGILE Silicon tracker, NIM 2002
C. Pittori, RICAP-22

Fermi LAT (formerly GLAST): Gamma-ray Large Area Space Telescope

Launched June 11, 2008, still in full-power operation (15+ years)

Pair-conversion gamma-ray telescope: 16 identical "towers" providing conversion of γ into e^+e^- pair and determination of its arrival direction (Tracker) and energy (Calorimeter). Covered by segmented AntiCoincidence Detector which rejects the charged particles background

Silicon-strip tracker: 18 double-plane single-side (x and y) interleaved with 3.5% X_0 thick (first 12) and 18% X_0 thick (next 4) tungsten converters. Strip pitch is 228 μm; total 8.8×10^5 readout channels

Segmented Anticoincidence Detector: 89 plastic scintillator tiles and 8 flexible scintillator ribbons. Segmentation reduces self-veto effect at high energy.

Hodoscopic CsI Calorimeter **Array of 1536 CsI(Tl) crystals in 8 layers.**

Electronics System Includes flexible, robust hardware trigger and software filters.

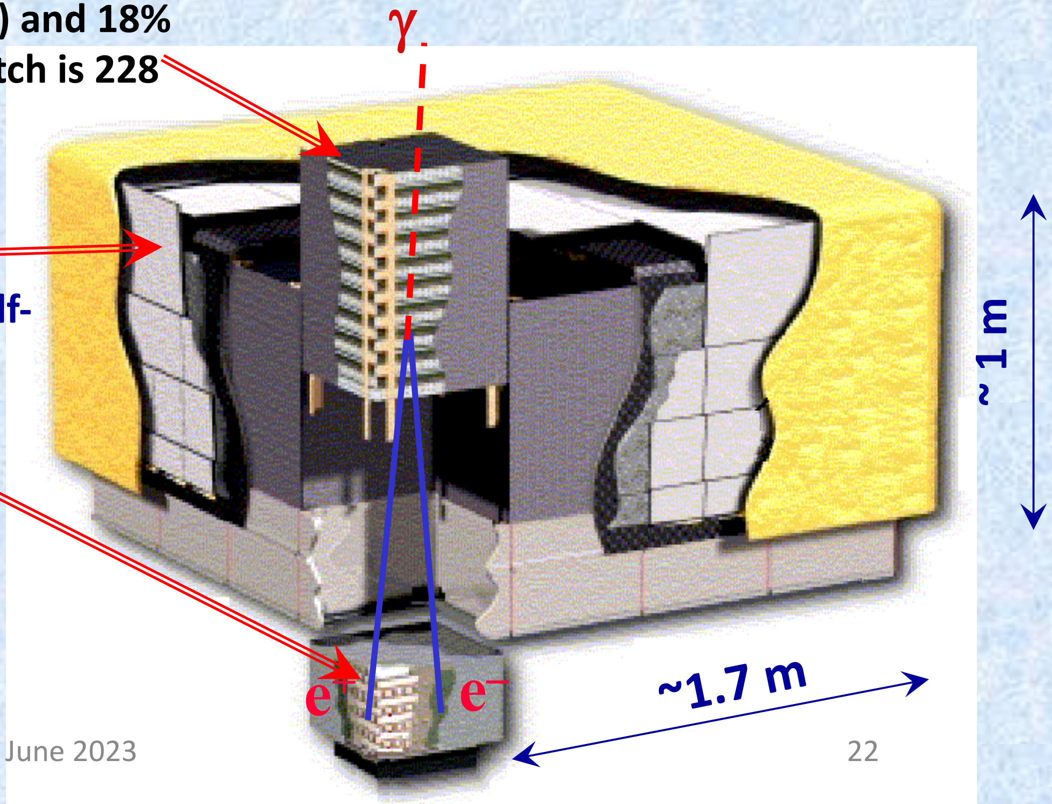
W.B. Atwood+, ApJ 697, 2009

Specific features:

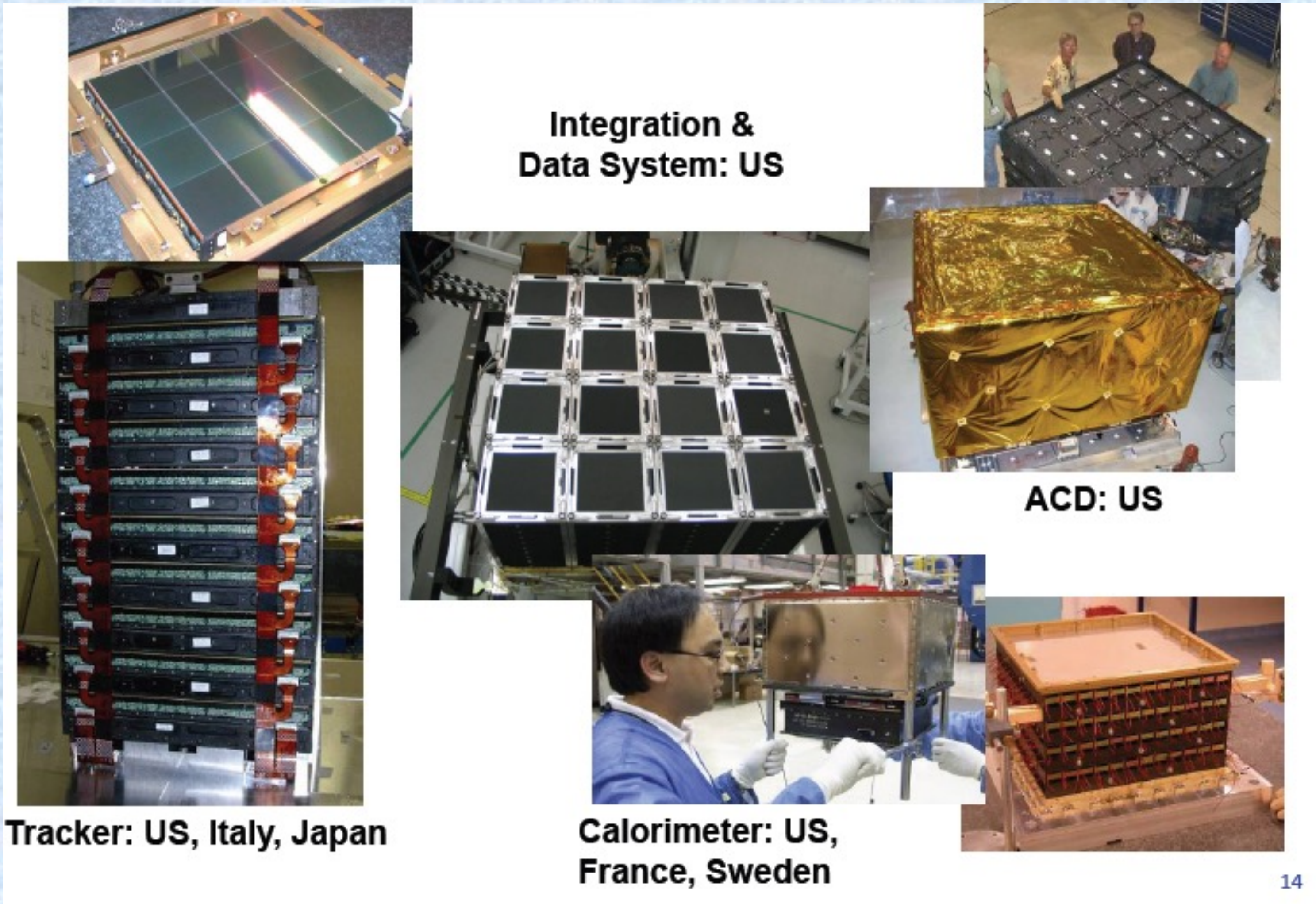
- Inspired by and follows the steps of CGRO/EGRET
- 20 MeV - >300 GeV energy range

PSD:

- Stack of single-side Si-strip detectors
- Position-sensitive CsI log calorimeter



LAT Construction: An international effort (2002-2008)



Integration & Data System: US

ACD: US

Tracker: US, Italy, Japan

Calorimeter: US, France, Sweden

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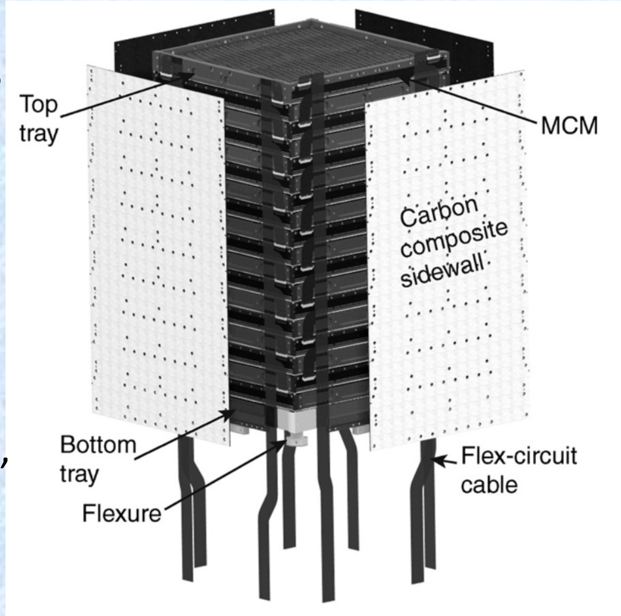
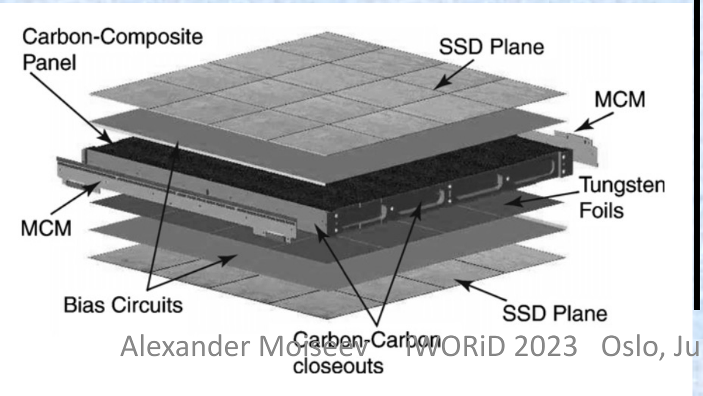
Spacecraft with LAT and GBM before shipping to KSC

LAT Tracker (Hamamatsu -> INFN Bari -> UCSC Santa Cruz

- 16 towers
- In each: 18 x, y tracking planes
- 2 layers (x and y) of SSD in each plane
- 16 upper planes have W converter foil
- Each layer has 4x4 (4 ladders) 9.5 x 9.5 cm, 0.4mm thick SSD



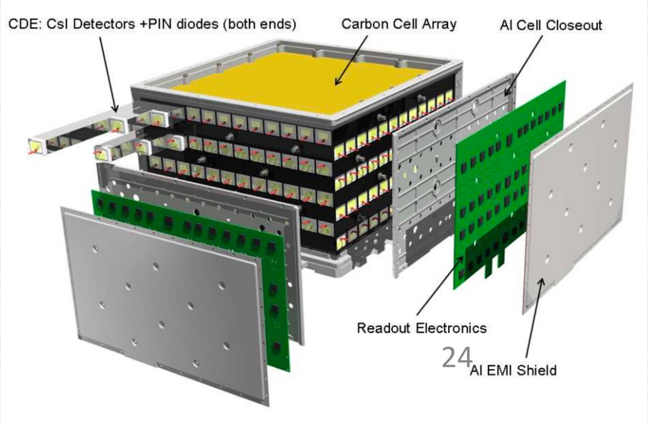
- Each SSD: 384 56-µm wide aluminum readout strips spaced at 228 µm pitch
- Each plane (4 ladders) is readout by a Multi-Chip Module (MCM), consisting of 24 “analog” and 2 “digital” ASICs
- 2 LAT-designed ASIC: an “analog” 64-channel mixed-mode amplifier-discriminator chip (ToT) and a “digital” readout controller (13,824 “analog” chips and 1152 “digital” ones in total)
- **Total for LAT: 74 m^2 of Si**

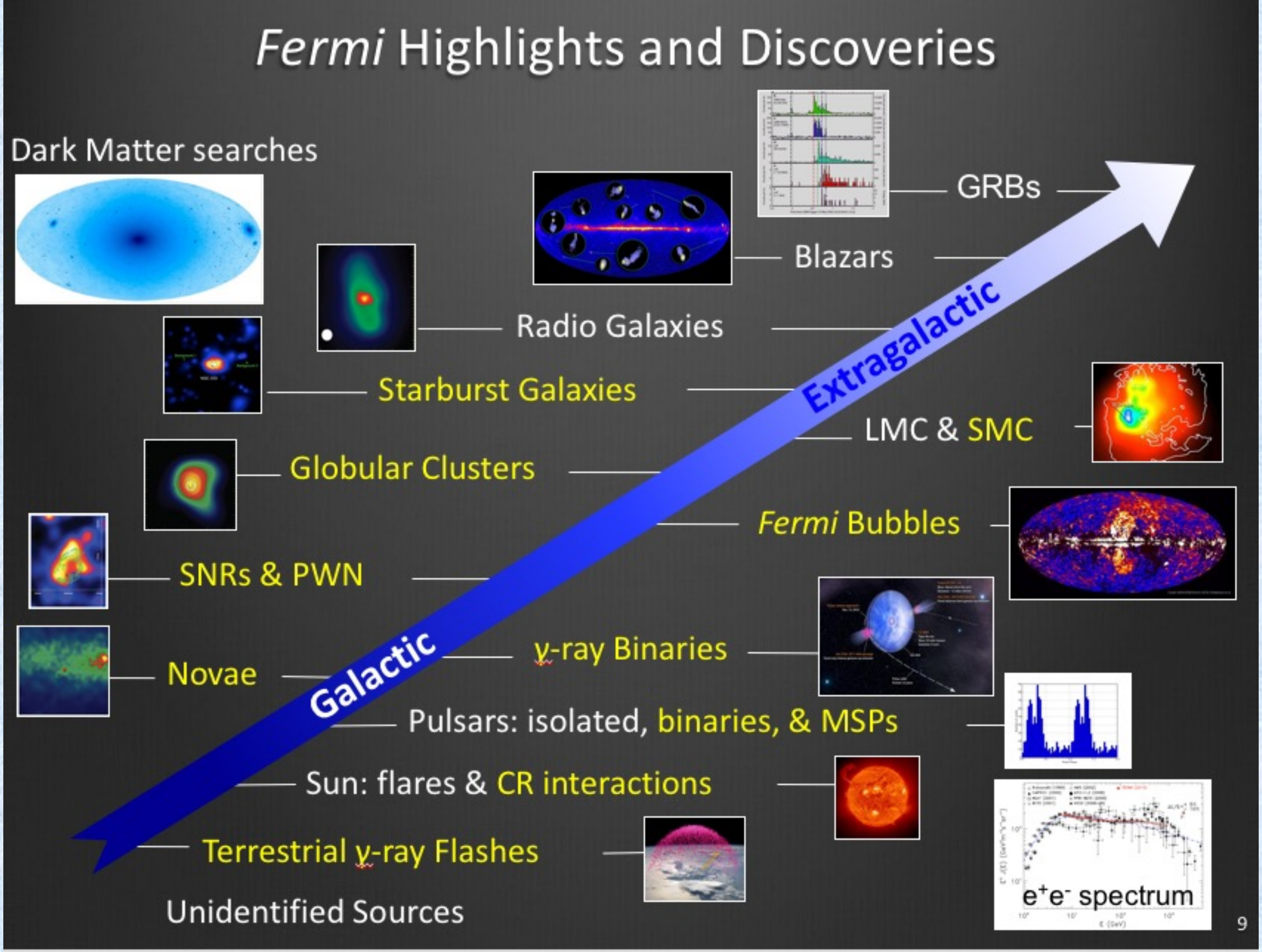


W.B. Atwood+, LAT Tracker, NIM 2007
W.B. Atwood+, LAT, ApJ 2009

LAT Calorimeter (NRL, Saclay, KTH)

- 16 towers (modules)
- Each module: 96 CsI(Tl) crystals, with each crystal of size 2.7 cm × 2.0 cm × 32.6 cm.
- The crystals (the logs) are optically isolated from each other and are arranged horizontally in 8 layers of 12 crystals each, alternatively aligned along x and y axis of LAT
- The total vertical depth of the calorimeter is 8.6 radiation lengths (for a total instrument depth of 10.1 radiation lengths)
- Each log is readout by 2 photodiodes (of different area) on both ends
- **Coordinate along the log axis is provided by the signal ratio on both ends, providing accuracy of up to 1mm**





Fermi Highlights and Discoveries

Dark Matter searches

GRBs

Blazars

Radio Galaxies

Starburst Galaxies

Extragalactic

LMC & SMC

Globular Clusters

Fermi Bubbles

SNRs & PWN

γ-ray Binaries

Novae

Galactic

Pulsars: isolated, binaries, & MSPs

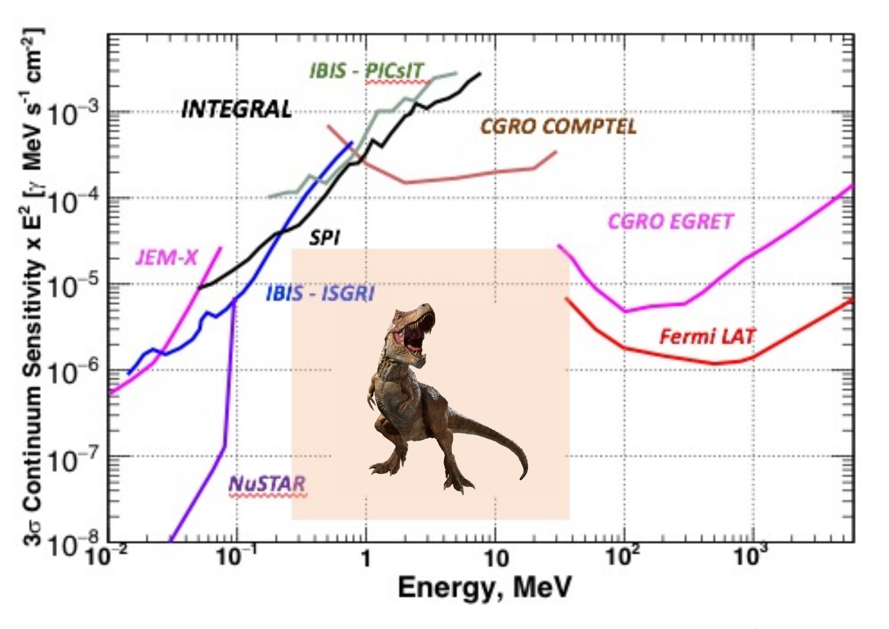
Sun: flares & CR interactions

Terrestrial γ-ray Flashes

Unidentified Sources

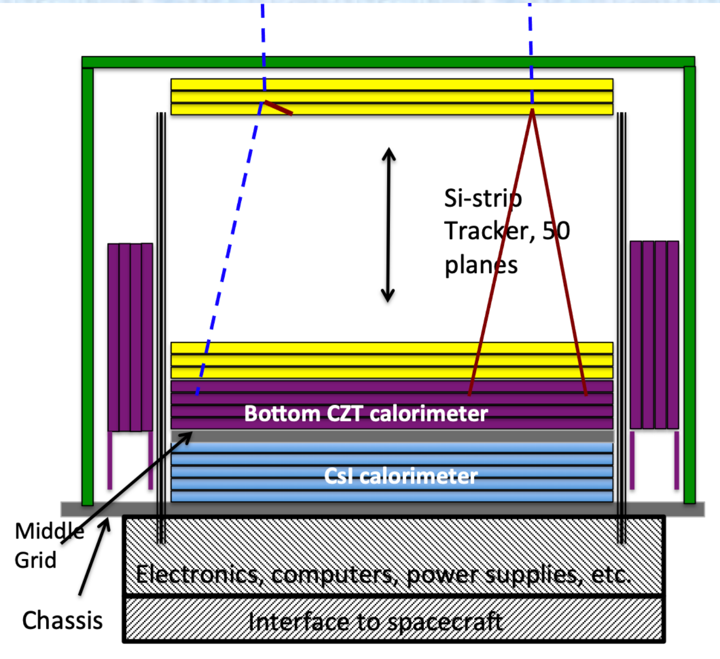
- >750 papers in major journals
- >6,600 sources discovered
- New classes of sources

Next steps, and what detectors do we need?

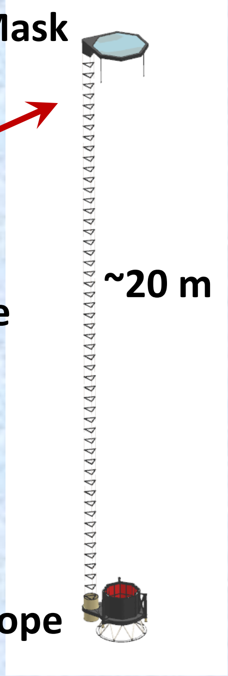


Currently available results: Full of discovery potentials window

Concept of the potential MeV Compton-Gamma Telescope



Possibly with deployable coded aperture mask to achieve arcmin angular resolution



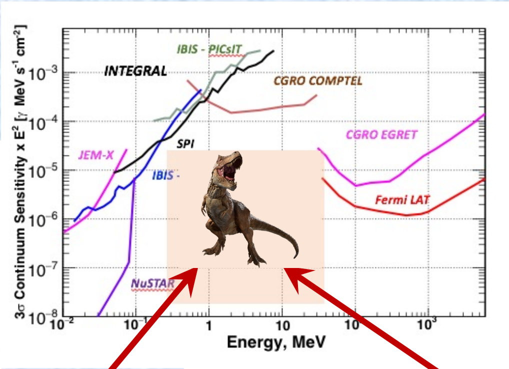
Aiming performance

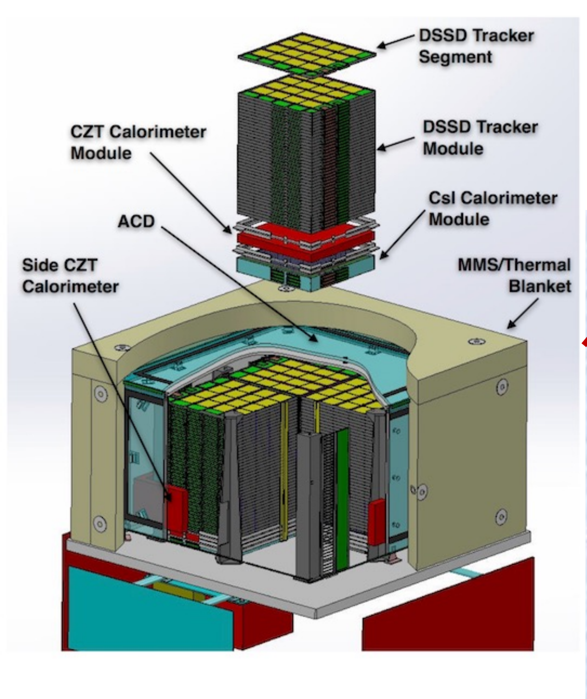
Energy Range	50 keV -> 10 GeV
Angular resolution	~1 arcmin at 0.5-5 MeV, 2-4° above 1 MeV
Energy resolution	<1% (< 2 MeV), 1-5% above
Field of View	1.5 - 2 sr
Polarization sensitivity	<20% MDP for a 1% the Crab flux, 10^6 s
Continuum sensitivity (MeV cm^{-2} s^{-1})	< 1x10^{-6}, 5 years

Needed detecting capabilities

- Self-supporting, large-area (~40x40cm^2), 0.3-0.5mm thick, **double-sided** Si-strip detectors
- **Better: Monolithic Si-Pixel detector**
- 3D sensitive, fine energy resolution, highly efficient (thickness > 15-20 g/cm^2) detector **to enable the Compton mode**

Our dreams (challenging), and what we have already done to open that window

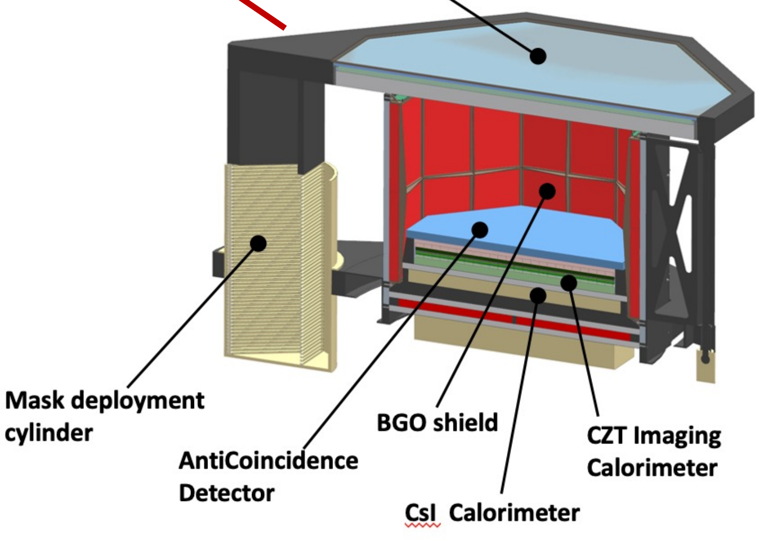




All-Sky Medium-Energy Gamma-ray Observatory (AMEGO)

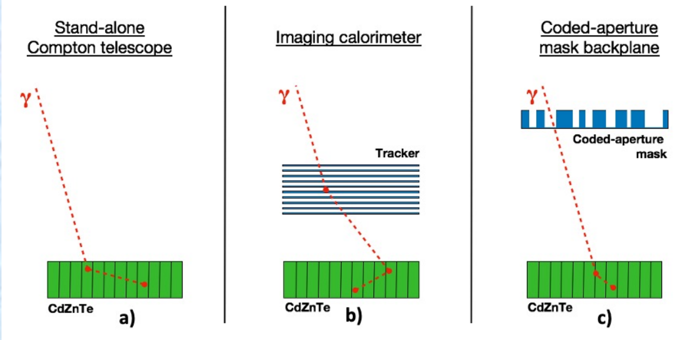
Energy range 100 keV - 10 GeV

AMEGO-X: Reduced version of AMEGO, without the CZT calorimeter

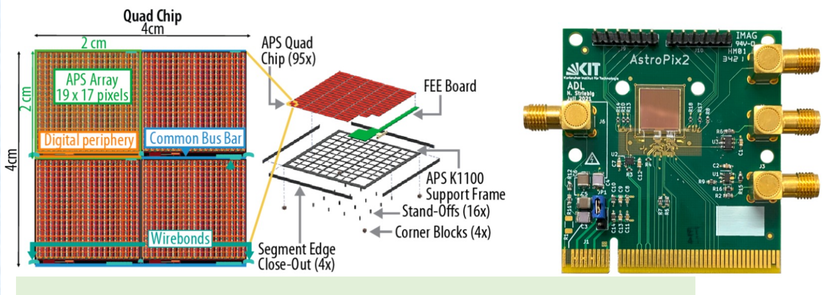


Galactic Explorer with a Coded Aperture Mask Compton Telescope (GECCO)

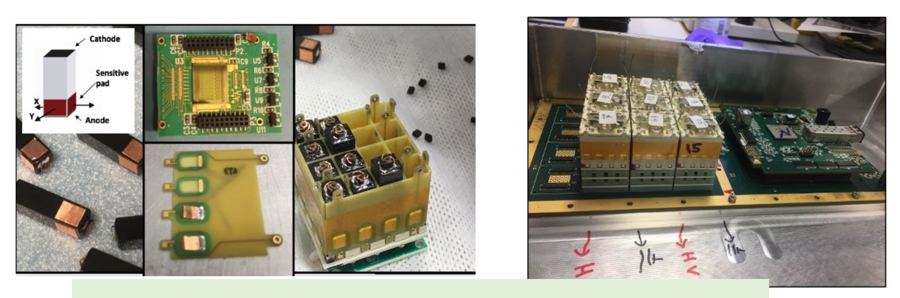
Energy range 50 keV - 10 MeV



Idea: triple modality of the CZT Imaging Calorimeter



AstroPix detector prototype
R. Caputo+, AMEGO-X,arXiv:2208.04990



CZT Calorimeter prototype
A. Moiseev+, GECCO, PoS (ICRC2021) 648

Enabling Technology for AMEGO and GECCO: Modular CdZnTe Imaging Calorimeter

- Basic unit – the module, containing 16 CZT Virtual Frisch-grid bar detectors served by an individual ASIC (Fig.1)
- Approach: The Imager Can be made of practically any needed area by simply plugging needed number of basic units (the modules) into the Motherboard
- We designed and built the prototype containing 9 modules, served by the analog ASIC AVG2 (designed at BNL), and integrated it in the ComPair balloon instrument (to be launched in the beginning of August 2023, from Ft. Sumner, NM), and passed the TVAC tests
- We also fabricated a 4-crate prototype, served by the readout system GDS-100, provided by iDEAS, and based on the wave-front sampling ASIC.
- We tested both prototypes in the laboratory with various radioactive sources (0.5-2.3 MeV), and in the polarized photon beam at TUNL/HIGS (2 - 8 MeV). With the GDS-100 readout we obtained the 1-2% FWHM energy resolution in energy range from 0.5 MeV to 8 MeV (Fig.2 a, b, c). Position resolution was measured with the use of the slit W collimator, and demonstrated <1mm resolution (Fig.2d)

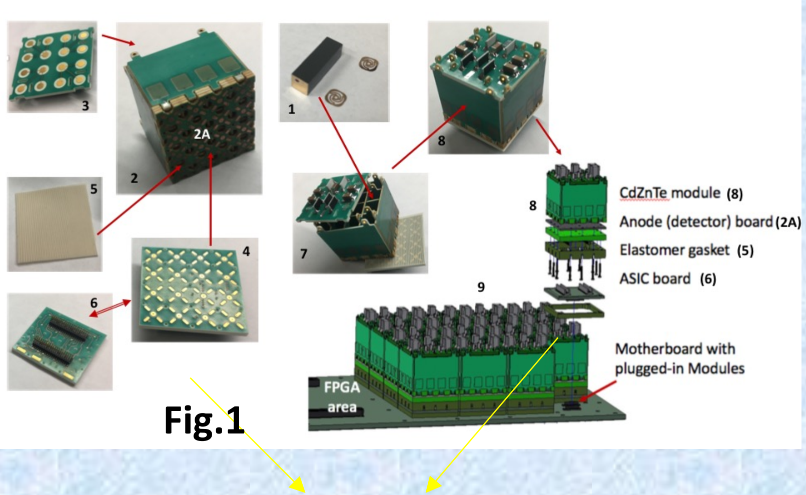


Fig.1

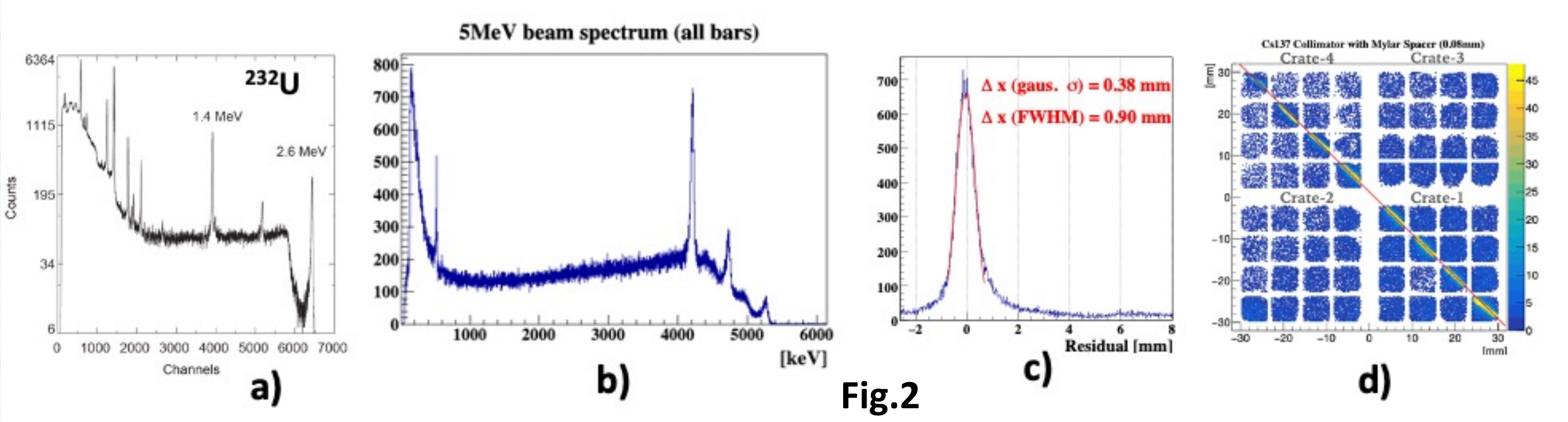


Fig.2

CONCLUSIONS

- The depth of the astrophysical missions scope and a complexity of their instrumentation is rapidly growing.
- Novel detectors, new experimental approaches, progress in electronics open enormous perspectives for answering the questions, yesterday seemed to be impossible to approach.
- Close world-wide collaboration between the industry, detectors developers, accelerator high-energy particle physics and space science scientists, will guarantee the success.
- I tried to tell you the story what we've done, what we are thinking to do, but I'd be very happy to tell you WHY we are doing all this - so, next time!
  - Let me close the talk by my two favorite (however, likely not only my favorite) expressions:

> ***One who wants to do something will find a way; one who does not will find an excuse***
> (Socratus, Confucios, *etc.*)
>
> ***You miss 100% of the shots you do not take*** (Wayne Gretzky)

Thank you, the Organizers, for the wonderful Conference in such a wonderful place! We all will be looking forward to come to Oslo again!

Thank you, the Participants, for your excellent and very informative talks!