BACHELOR THESIS DEFENCE

Probing the antimatter in the Universe

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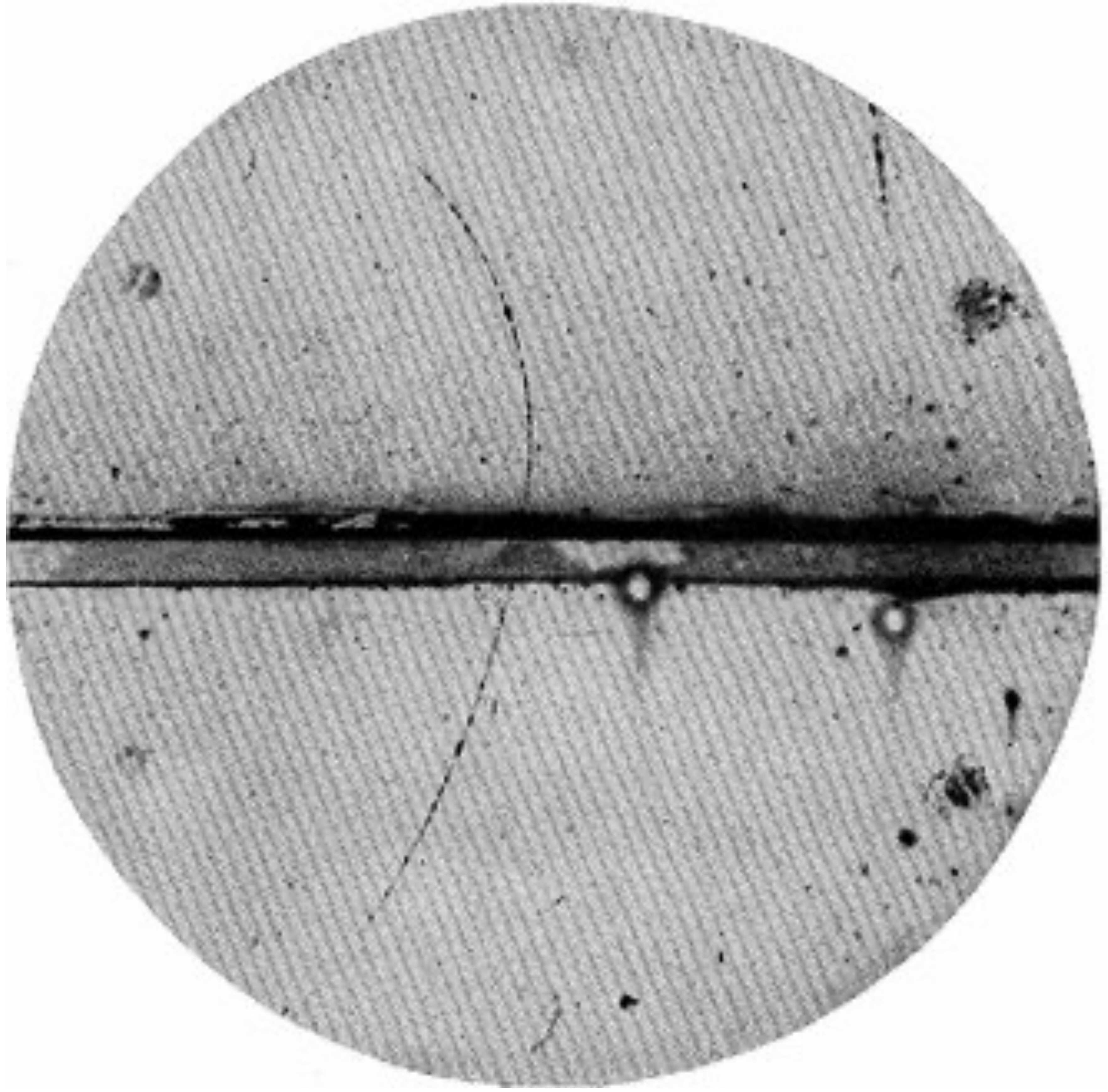
Contents

Introduction and historical overview

1928 – Dirac: Combined relativity + QM → predicted antiparticles.

1932 – Anderson: Discovery of the positron in cosmic rays.

1936 – Nobel Prize: First antimatter particle confirmed → birth of antimatter physics.



Matter-antimatter problem of the universe

Big Bang predictions
• Equal amounts of matter & antimatter should form (matter–antimatter symmetry).

Annihilation process
• Matter + antimatter → gamma rays (energy).
• Would leave Universe filled only with radiation.

Observations today
• No anti-galaxies or anti-stars detected.
• Universe is dominated by matter (baryon asymmetry).

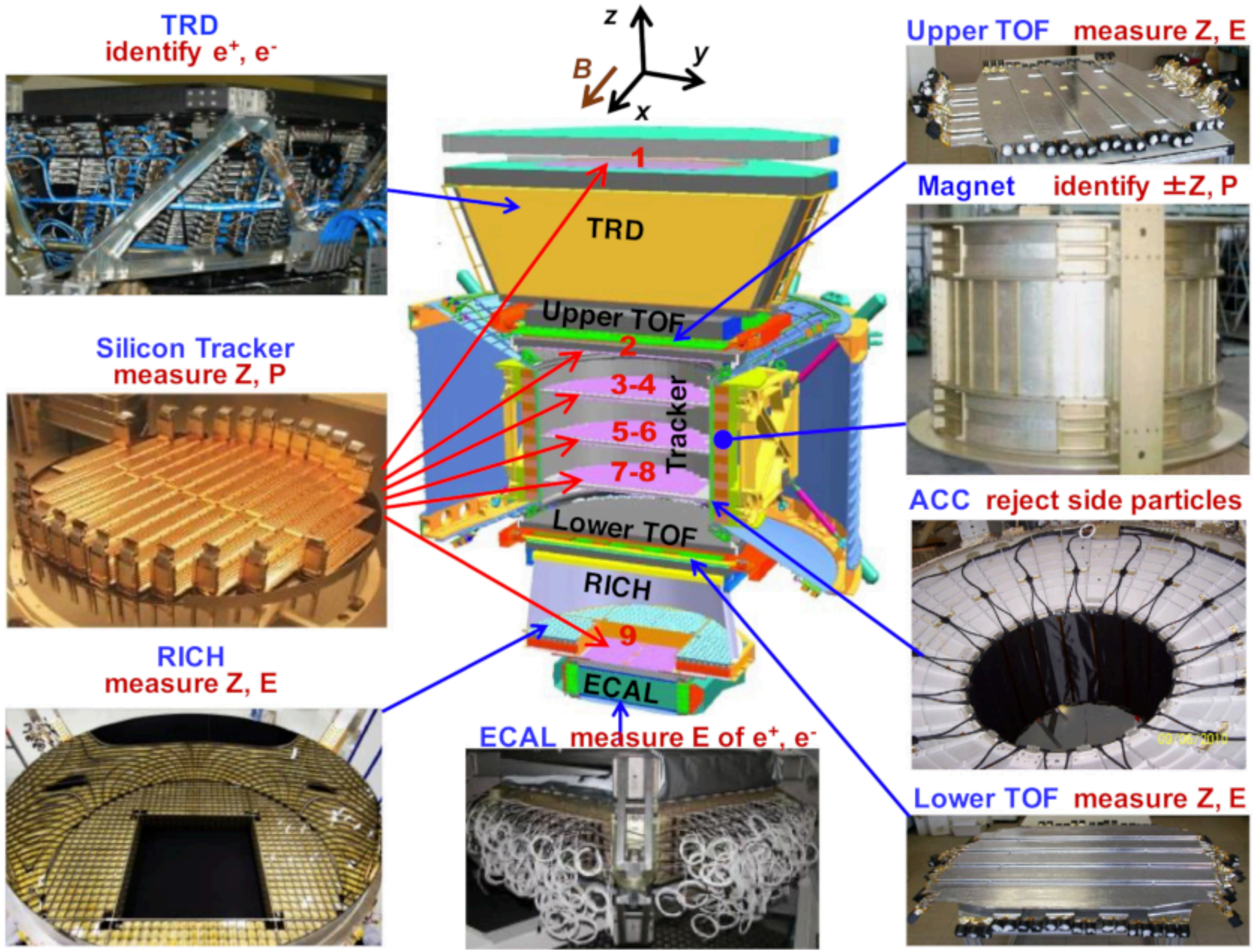
Central question
• Why do we see this imbalance?
• Where did the antimatter go?

Alpha-Magnetic Spectrometer (AMS)

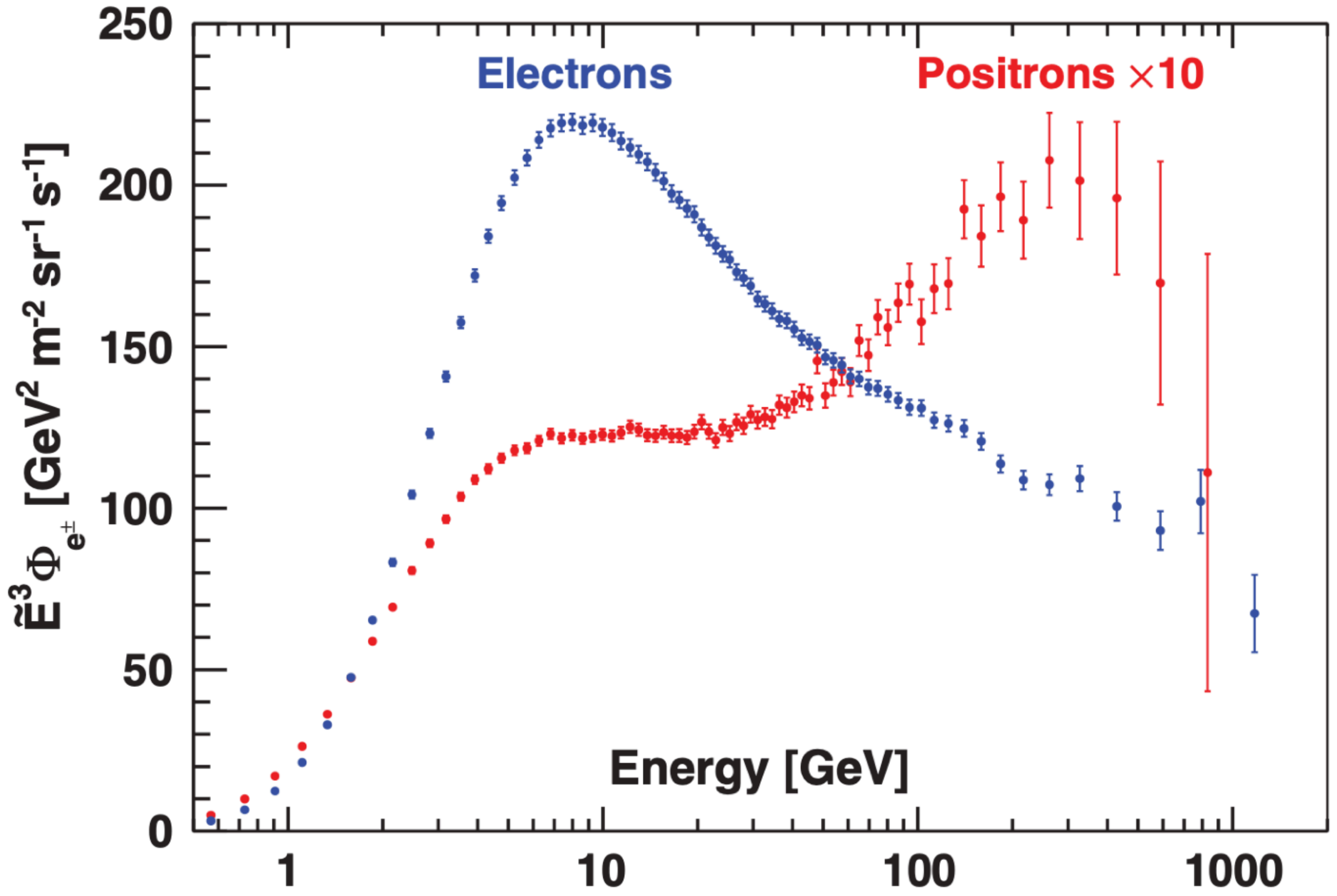
- **Launched in 2011, mounted on the International Space Station.**
- **Works for more than 10 years continuously.**
- **Built by a large international team (60+ institutes, led by CERN).**
- **Why in space?**
  • Earth's atmosphere blocks and distorts cosmic rays.
  • ISS location allows long-term, direct measurements.
- **Main goals:**
  • Search for **primordial antimatter** (antihelium, antinuclei).
  • Look for **dark matter signals** in positron/antiproton data.
  • Measure the **flux of cosmic rays** with high precision up to TeV energies.
- **Status:** still running, collecting huge statistics.

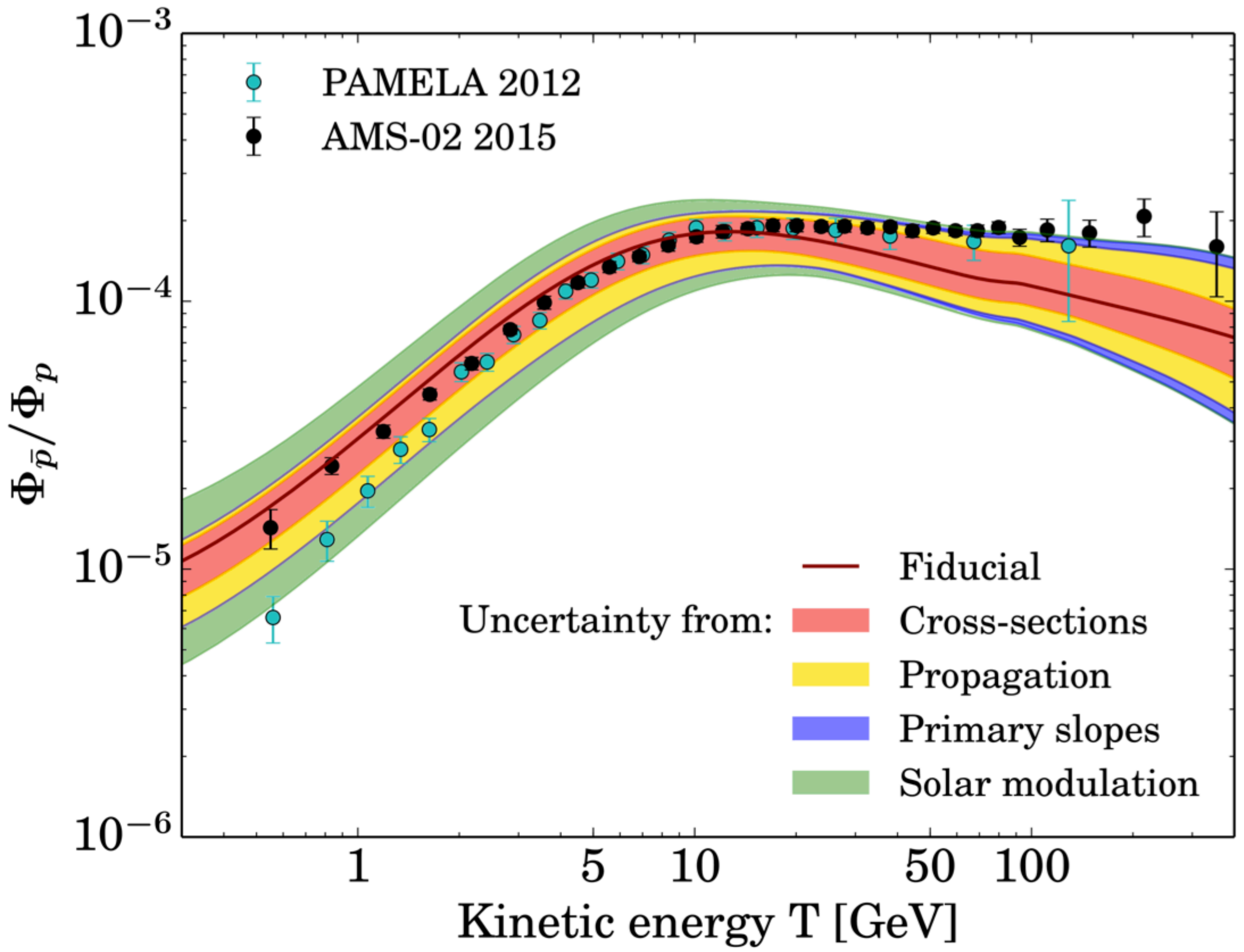
AMS Experimental Setup

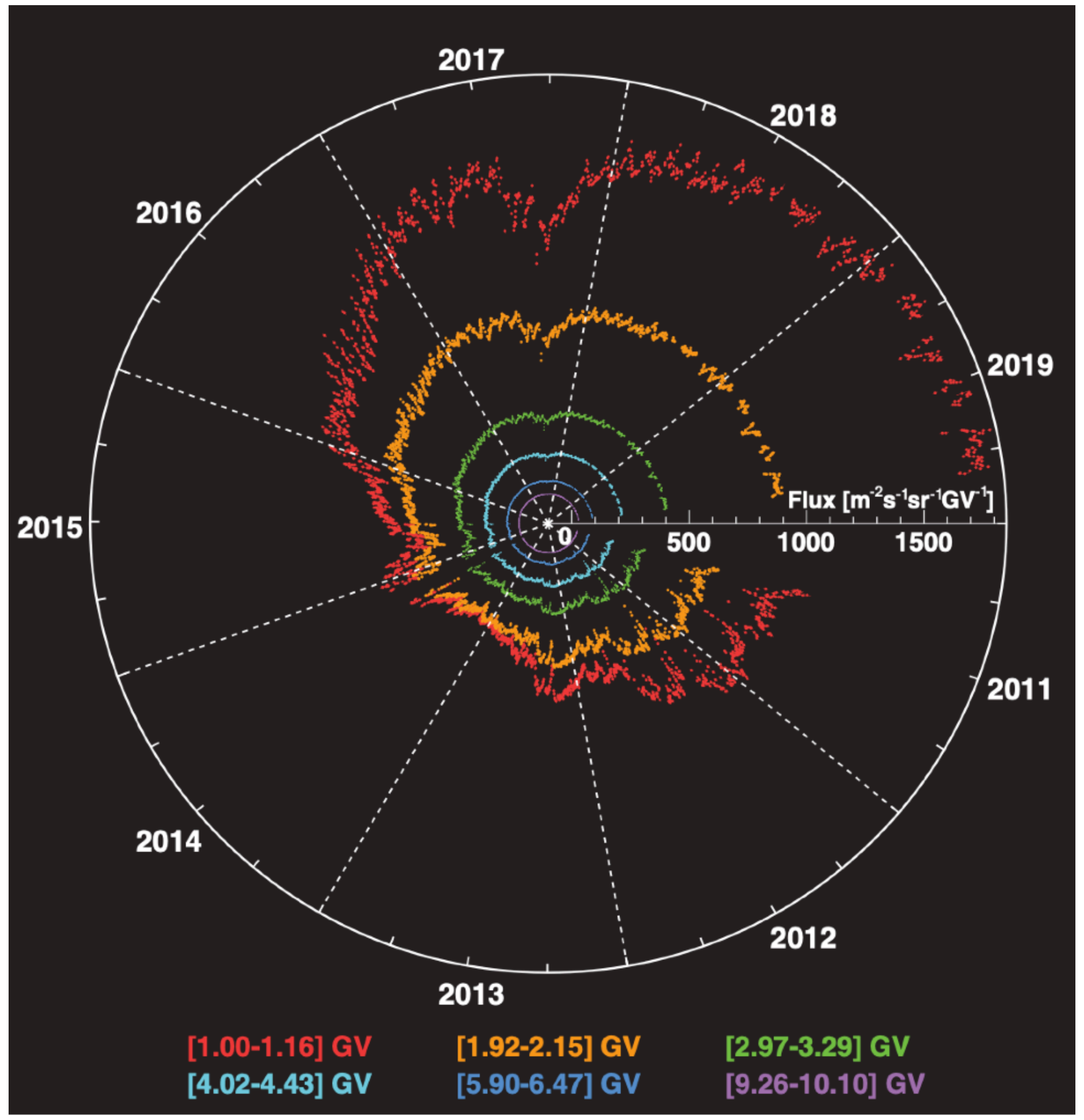
- **Magnet**: bends charged particles → separates matter from antimatter (opposite curvature).
- **Silicon tracker**: measures momentum and charge sign.
- **Time-of-Flight (TOF)**: measures particle velocity and direction (upward or downward).
- **Transition Radiation Detector (TRD)**: tells electrons/positrons apart from protons.
- **Ring Imaging Cherenkov Detector (RICH)**: precise velocity and charge measurement.
- **Electromagnetic Calorimeter (ECAL)**: measures energy and particle type from showers.



AMS Results







Positron Fraction

- Fraction of positrons compared to total electrons and positrons.
- Models predict it should decrease with energy.
- AMS shows it increases above about ten GeV, up to around three hundred GeV, then flattens.
- Suggests there are extra sources such as pulsars or dark matter.

Antiproton to Proton Ratio

- At low energies agrees well with predictions.
- Above one hundred GeV, AMS sees about twenty percent more antiprotons than expected.
- Could mean our models of cosmic-ray transport need improving, or it could be a sign of new models.

- Plot shows proton flux over time (2011–2019).
- Variations caused by the Sun's magnetic field and solar wind.
- Solar effects are different for positive and negative charges.
- Important for antimatter studies: must correct positron and antiproton data.
- AMS gives daily monitoring of solar cycles, making results more reliable.

Balloon-borne Experiment with Superconducting Spectrometer (BESS)

- **First flights in the 1990s. Multiple missions over two decades.**

- **Launches from Japan and long-duration flights over Antarctica.**

- **Designed to:**
  • Search for cosmic antimatter (antiprotons, antihelium nuclei).
  • Provide precise measurements of cosmic-ray spectra at low energies.
  • Test models of cosmic-ray propagation in the Galaxy.

- **Advantage of balloon flights:**
  • Reach about 40 km altitude, above almost all of the atmosphere.
  • Much cheaper and quicker than space missions.

BESS Experimental part

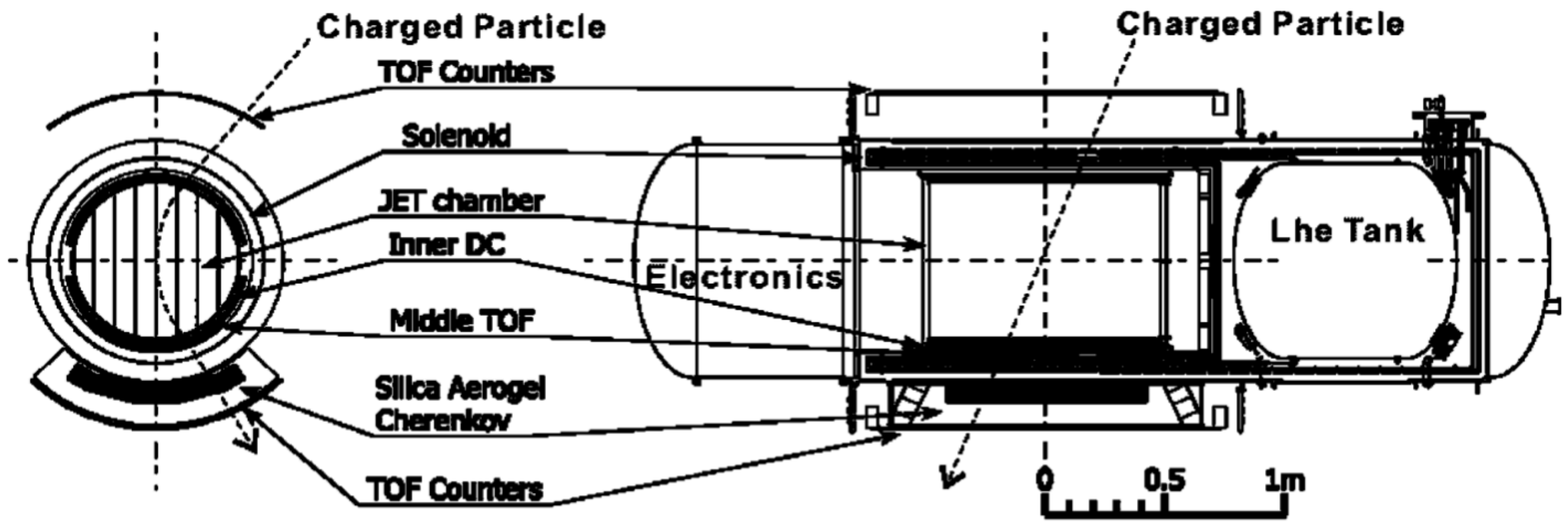
Superconducting solenoid magnet
• Provides a strong magnetic field.
• Bends particle tracks → separates matter from antimatter.

Drift chambers
• Track the curvature of charged particles.
• Measure momentum and charge sign with high precision.

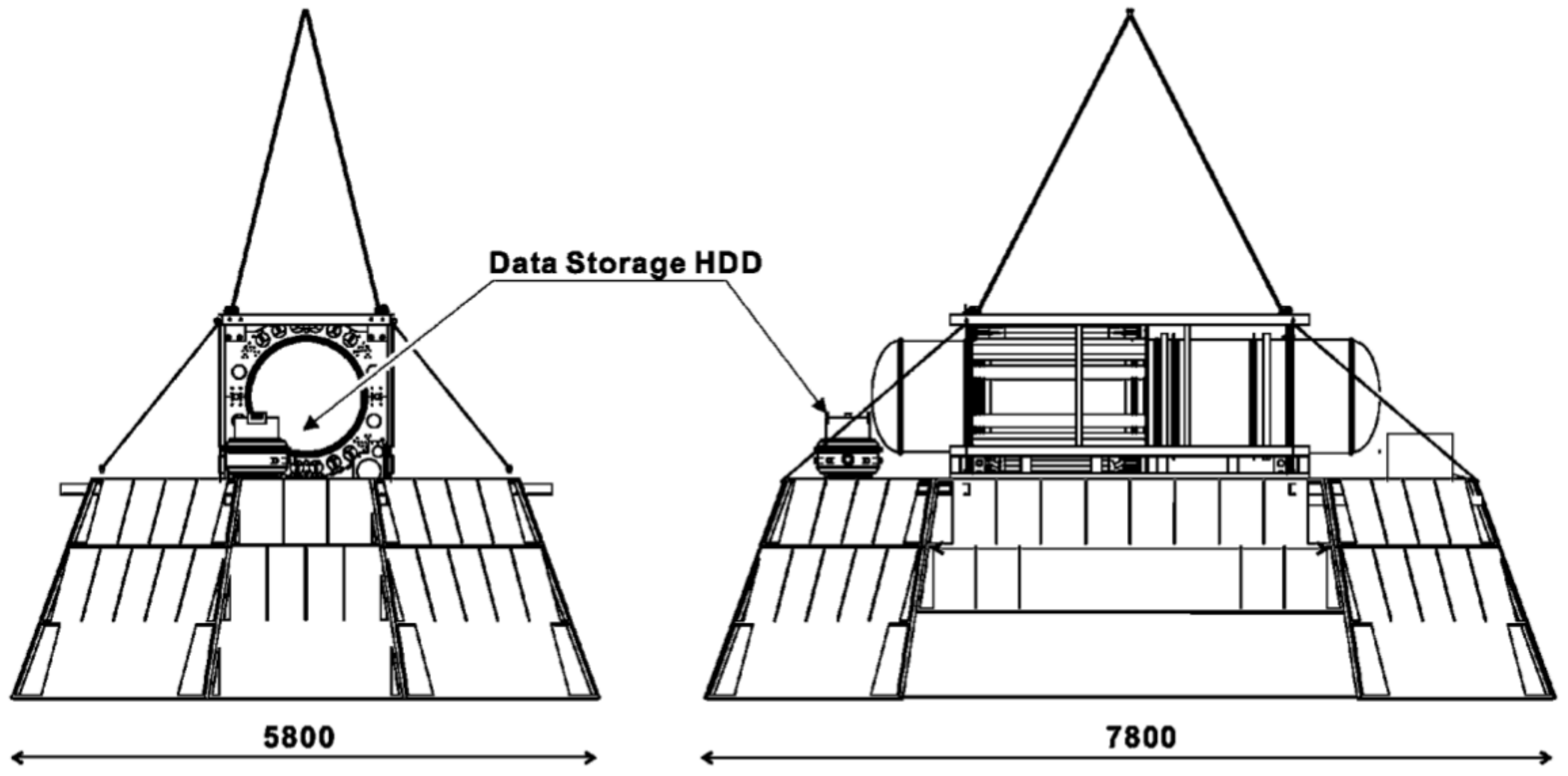
Time-of-Flight (TOF) counters
• Measure velocity of particles.
• Tell whether particles come from above (space) or below (atmosphere).

Aerogel Cherenkov counter
• Identifies particle type by detecting Cherenkov light.
• Helps distinguish light particles (electrons/positrons) from heavier ones (protons, antiprotons).

Instrument layout
• Compact, lightweight → ideal for balloon payloads.
• Optimised specifically for antiproton and antihelium searches.

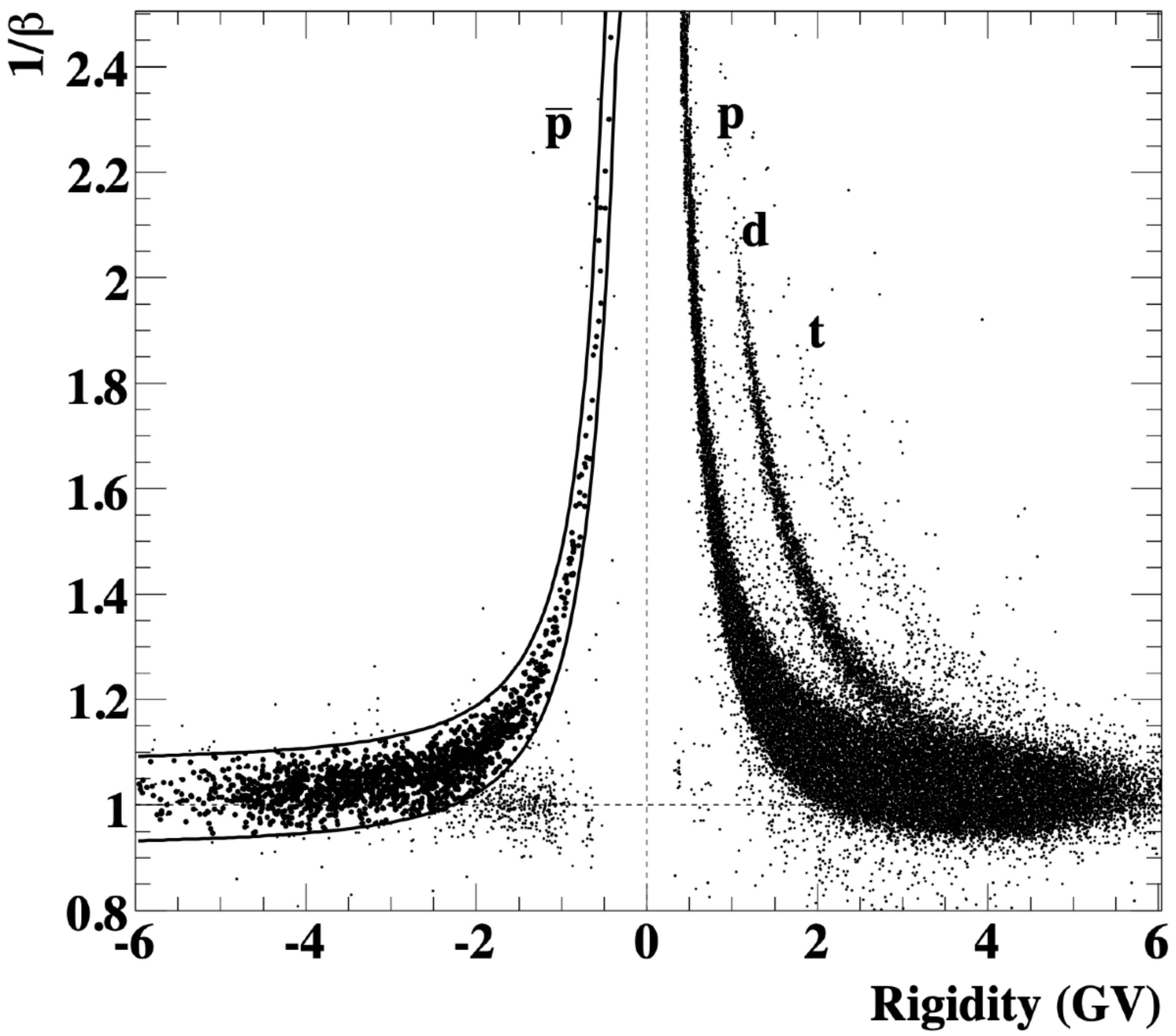


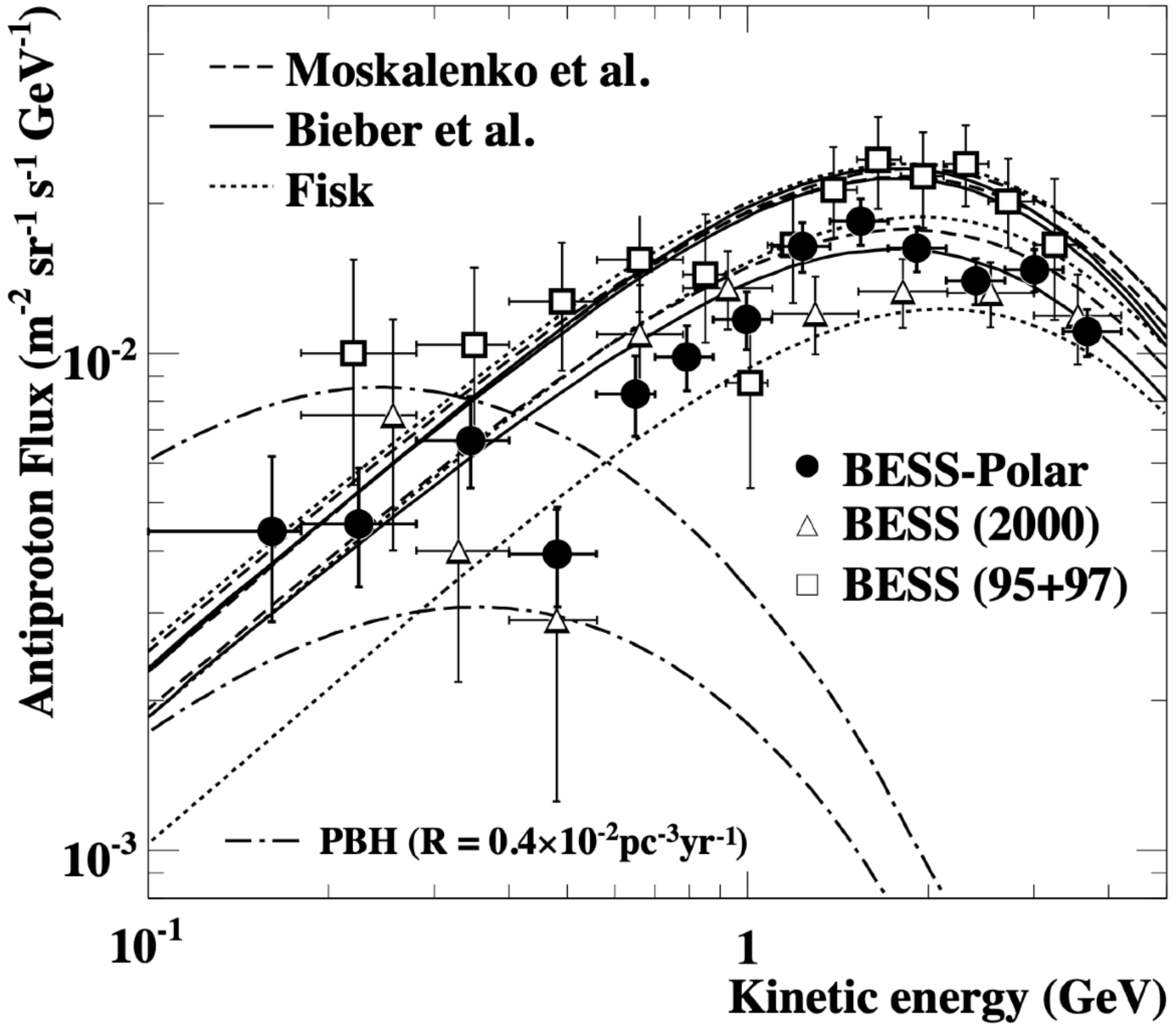
(a)

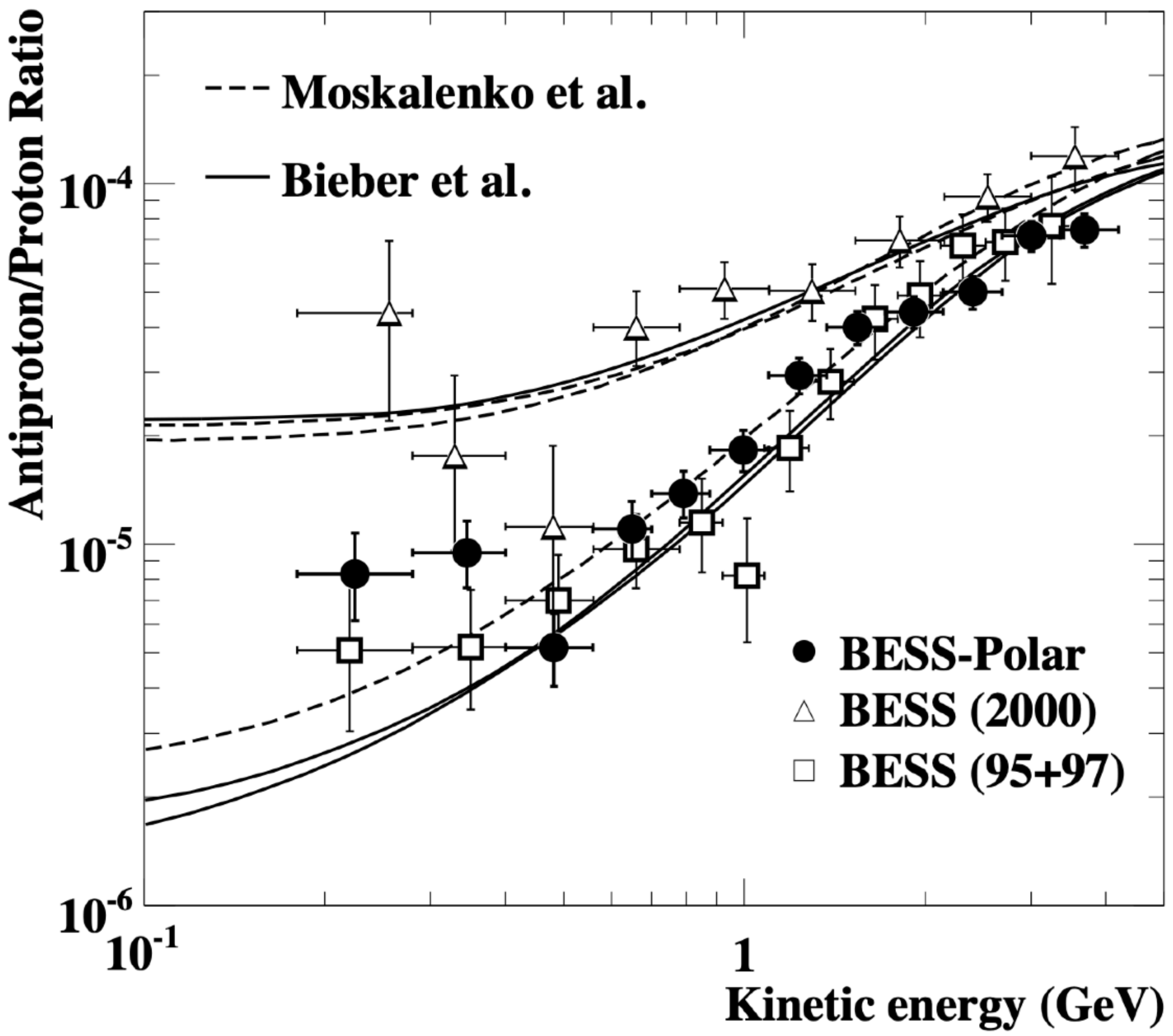


(b)

BESS Results







- Uses rigidity (momentum/charge) vs. inverse velocity (1/β).
- Protons dominate → form a large positive band.
- Antiprotons appear as a separate, clean track on the negative side.
- Shows BESS can distinguish antiprotons from protons and background with high precision.

- Antiproton flux measured over multiple BESS flights.
- Clear peak at ~2 GeV, falls at higher energies.
- Matches predictions of secondary production.
- Exotic sources (e.g. primordial black holes) not required.

- Ratio of antiprotons to protons vs. energy.
- Consistent across multiple BESS flights.
- Fits well within secondary production models.
- No excess → no evidence for a primary antiproton source.
- Antihelium search: none detected.
- Upper limit: <1 antihelium nucleus per billion helium nuclei.

International Gamma-Ray Astrophysics Laboratory (INTEGRAL)

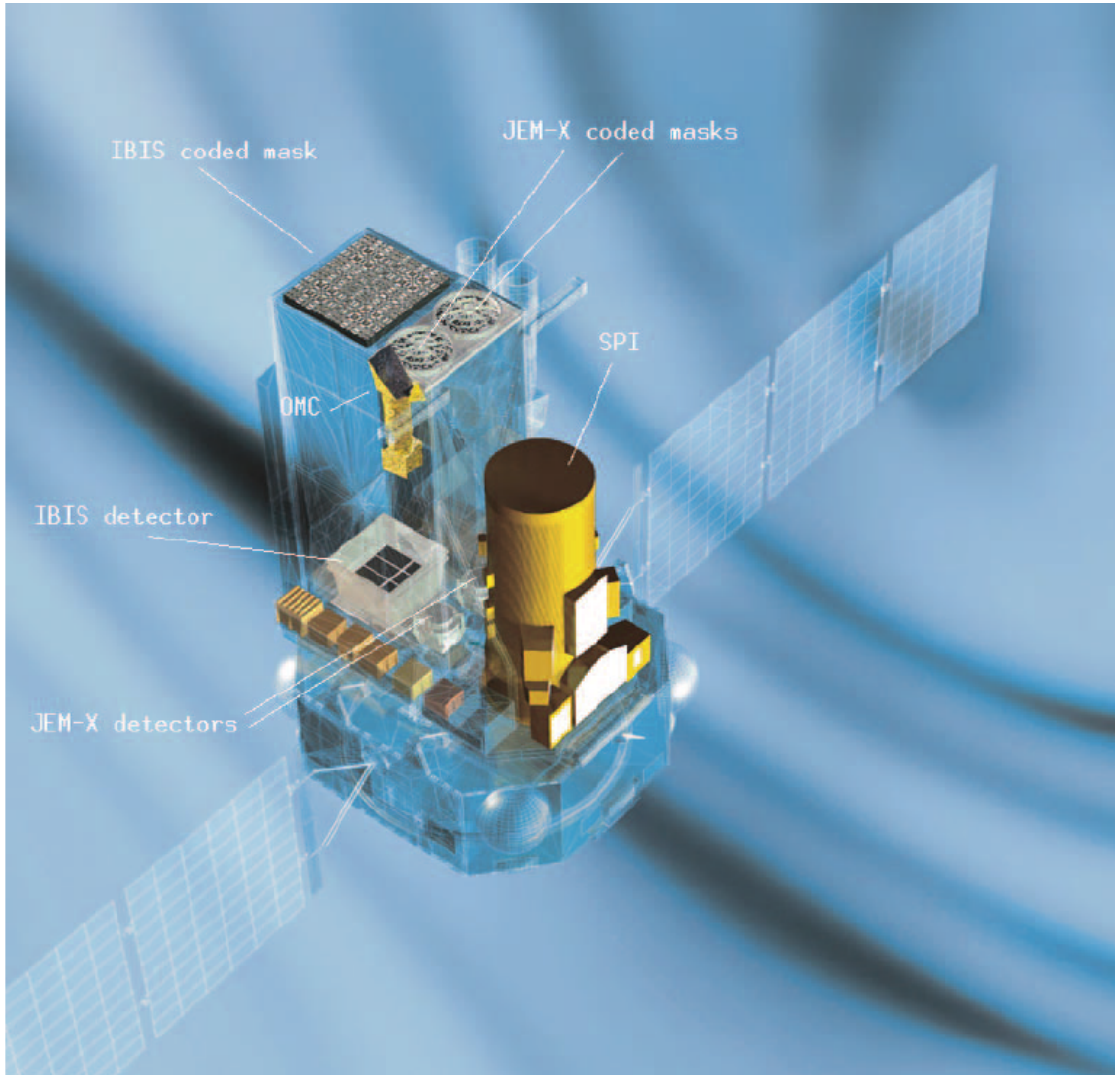
- **Launched in 2002, designed for 5 years, still operating after 20+ years.**

- **Built by a large international collaboration (Europe, Russia, USA, Japan).**

- **Studies the Universe in gamma rays, X-rays, and optical light.**

- **Key scientific goals:**
  • Map the 511 keV gamma-ray line from electron–positron annihilation.
  • Understand the origin of Galactic positrons.
  • Study compact objects: black holes, neutron stars, pulsars, supernovae.
  • Explore cosmic nucleosynthesis and radioactive isotopes.

- **Orbit:** highly elliptical Earth orbit → long, uninterrupted observing times, less background noise.



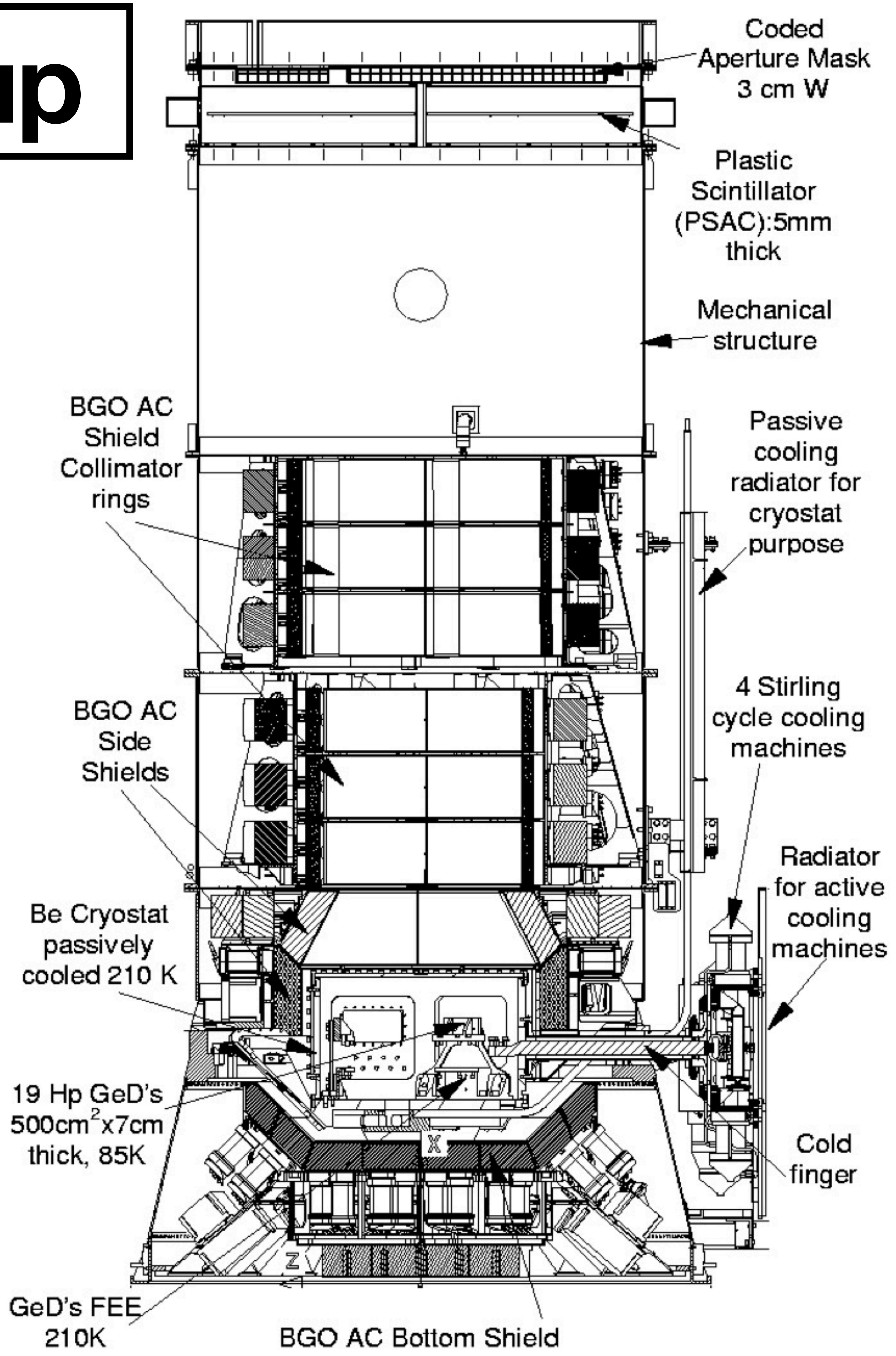
INTEGRAL Experimental setup

SPI (Spectrometer on INTEGRAL)
- High-resolution gamma-ray spectroscopy.
- Uses germanium detectors cooled to very low temperatures.
- Especially sensitive to the 511 keV annihilation line from positrons.

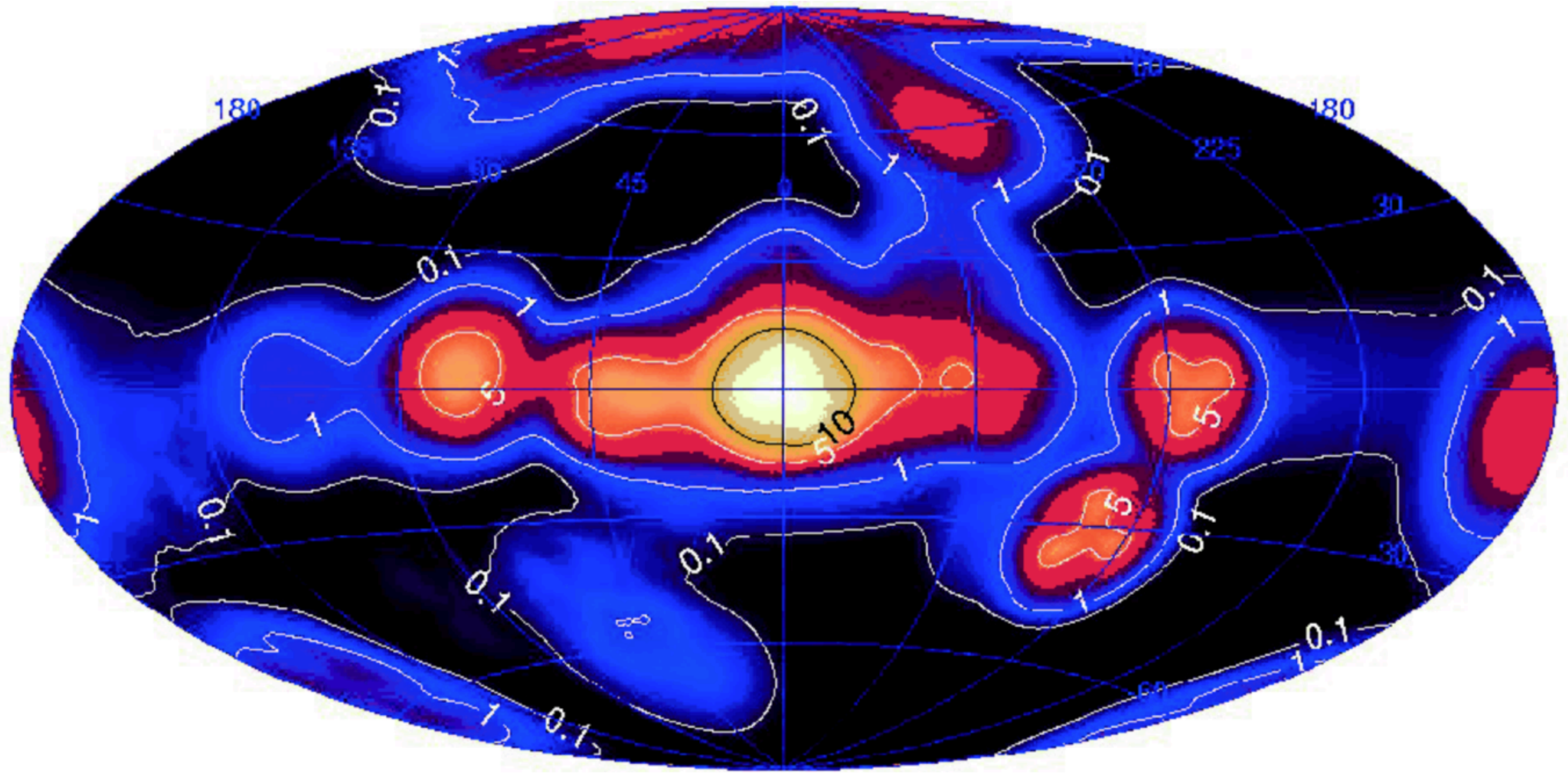
IBIS (Imager on Board the INTEGRAL Satellite)
- Produces gamma-ray images with arcminute resolution.
- Uses coded-mask technology to locate sources.
- Identifies compact objects and separates overlapping signals.

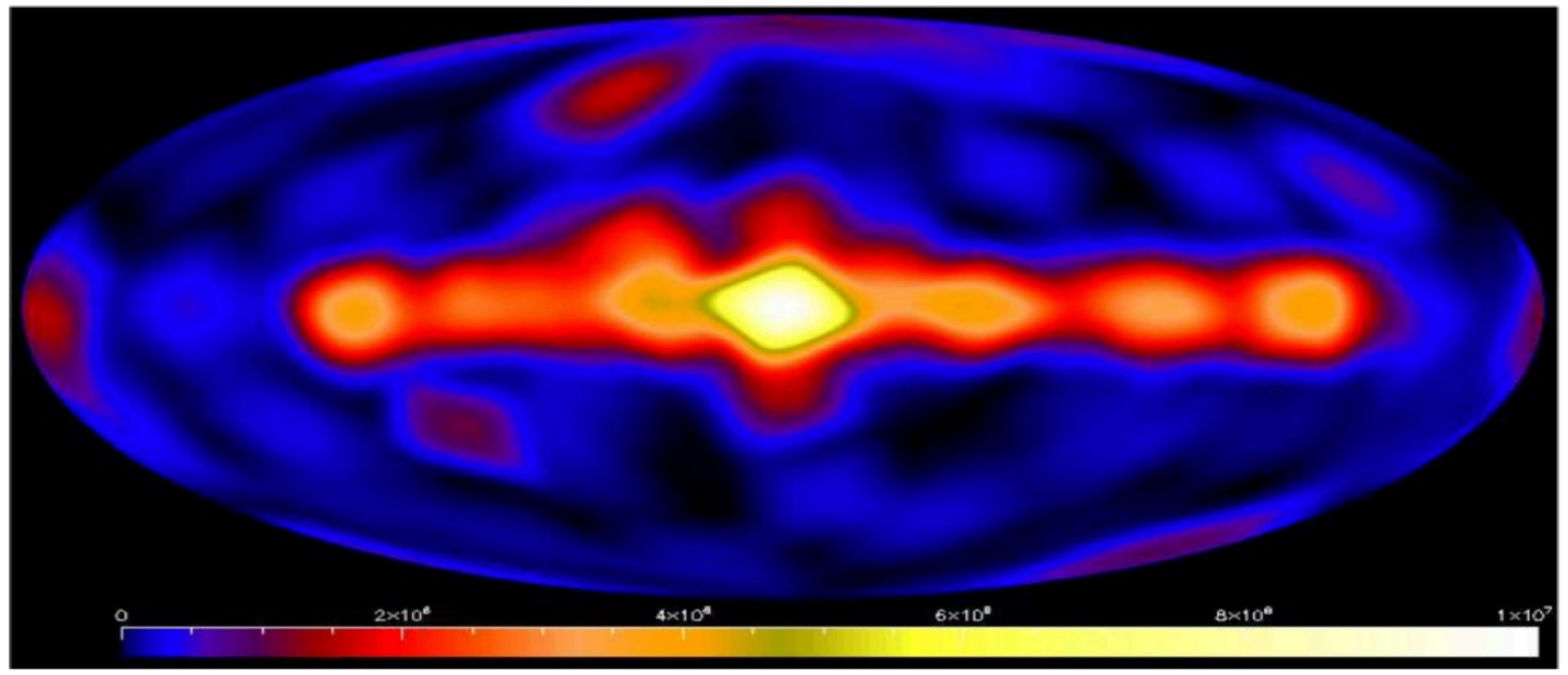
JEM-X (Joint European X-ray Monitor)
- Observes the X-ray sky in parallel with gamma-ray instruments.
- Complements SPI and IBIS by covering lower-energy photons.
- Helps study accreting objects like X-ray binaries.

OMC (Optical Monitoring Camera)
- Provides simultaneous optical light measurements.
- Tracks variability of gamma-ray sources in visible light.
- Links high-energy events to their optical counterparts.



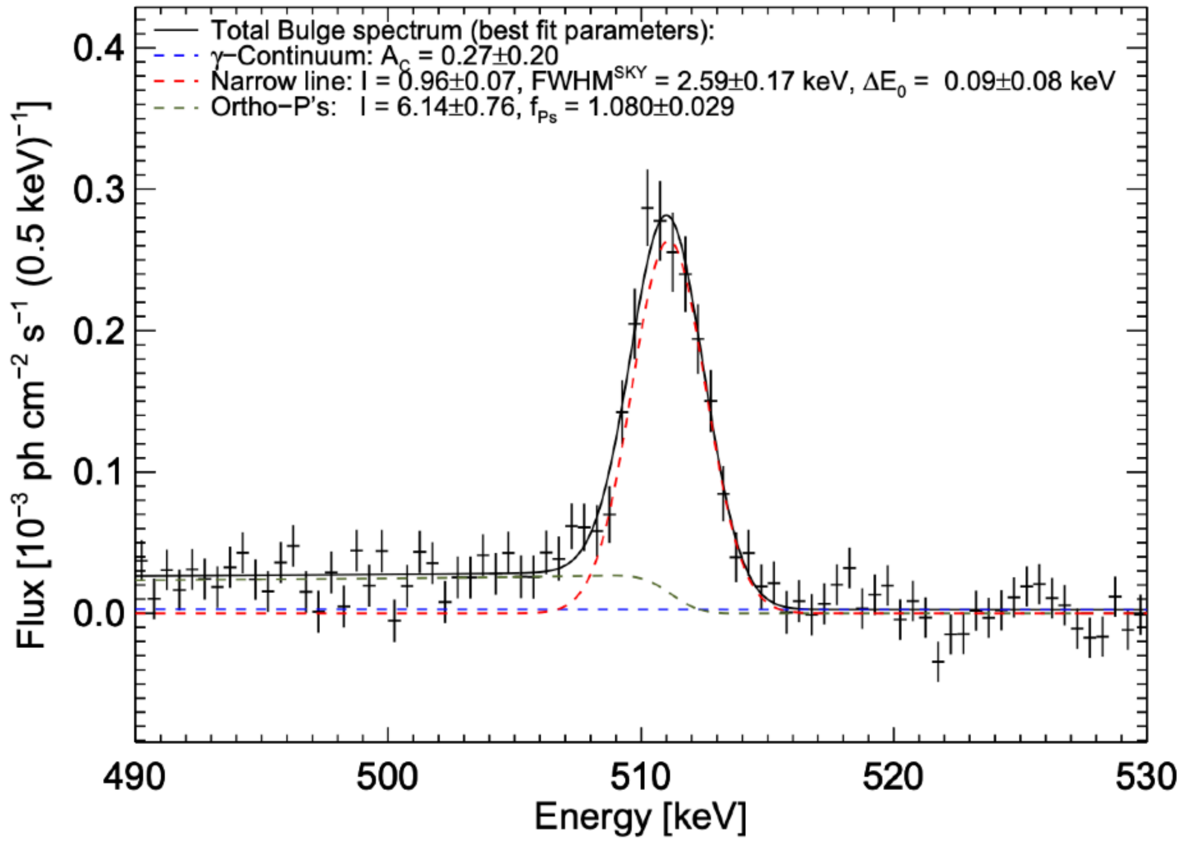
INTEGRAL Results



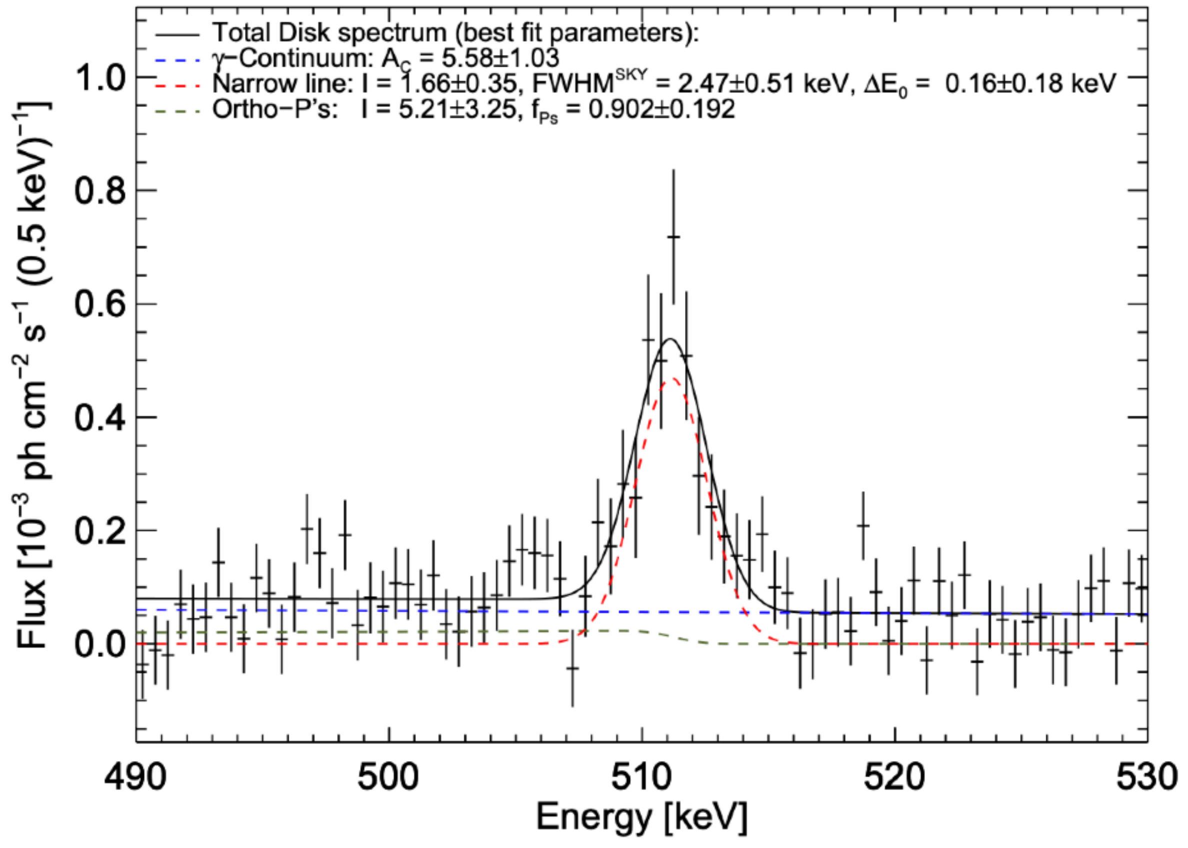


- SPI spectrometer gave the first high-quality maps and spectra.
- Bulge flux: ~9.9 × 10^{-4} photons/cm²/s, line width 2–3 keV.
- Emission extended across 8–10° around Galactic Centre.
- Bulge much brighter than the Galactic disk (unexpected).
- Indicates large amounts of positrons in the Milky Way.

- IBIS imager used to check for point-like 511 keV emitters.
- Deep all-sky survey: ~10 Ms exposure near Galactic centre.
- No compact sources detected (e.g. no single X-ray binary or microquasar dominates).
- Upper limit for point sources: 1.6 × 10^{-4} photons/cm²/s.
- Implies positrons are produced in many sources and travel before annihilation.



(a) Bulge.



(b) Disk.

- SPI measured a narrow 511 keV line plus a broad continuum.
- Continuum from positronium formation.
- High positronium fraction → positrons slow down in the interstellar medium.
- Suggests annihilation happens in warm/cold phases of interstellar gas.

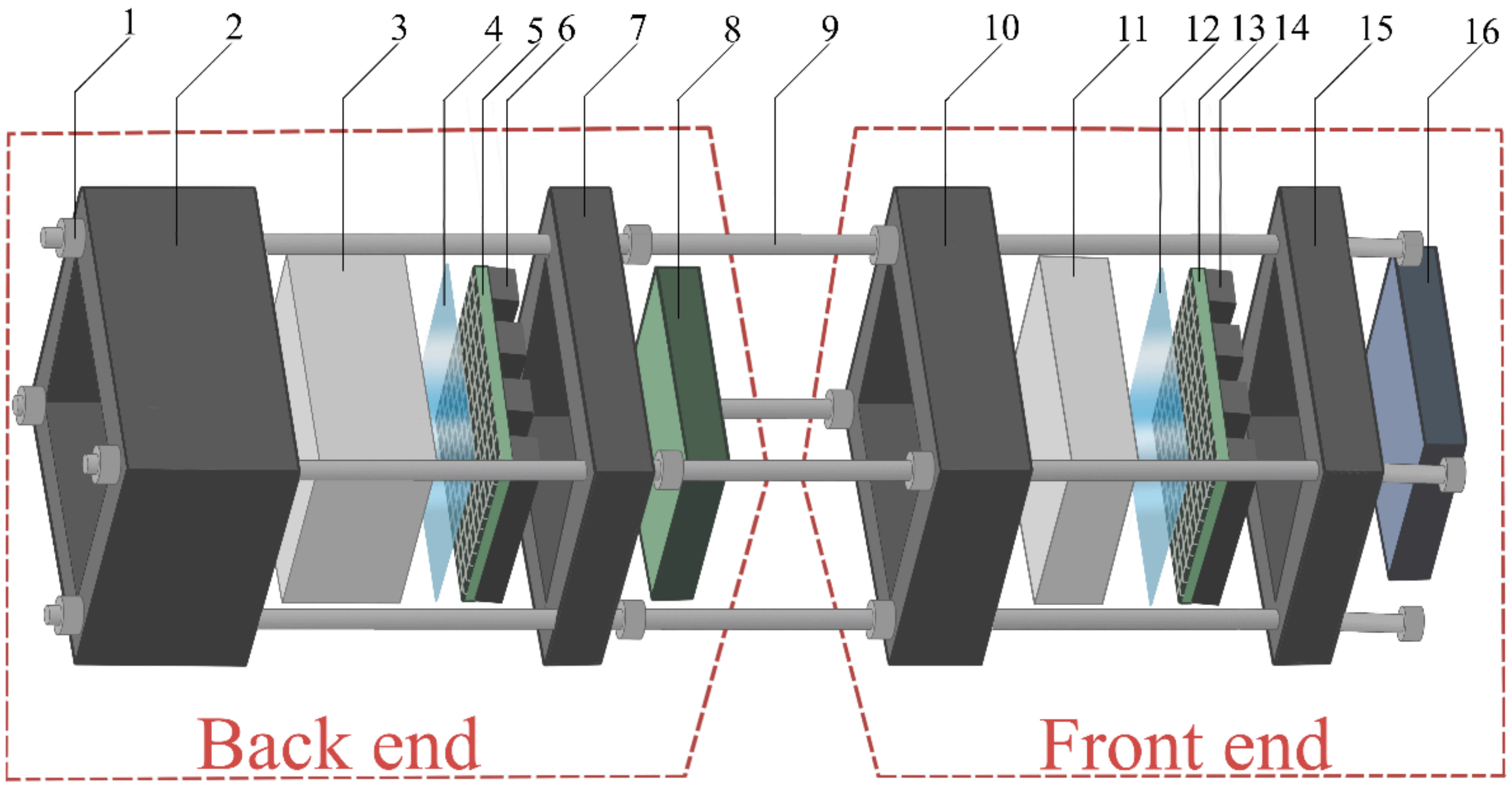
Compton Telescope

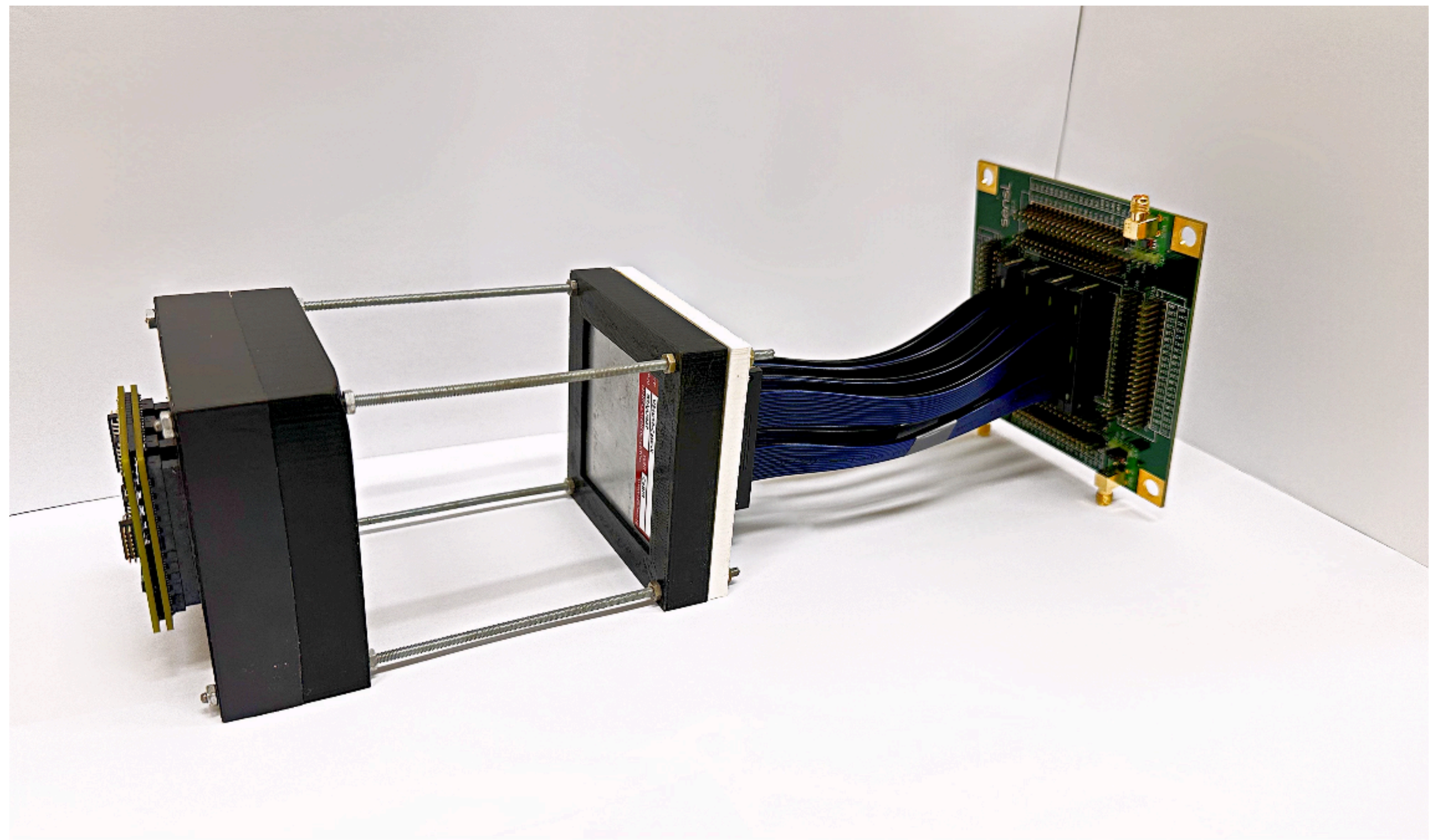
Goal: detect gamma rays in the MeV range, especially the 511 keV line.

Principle: Compton scattering
- Photon first scatters in one detector (scatterer)
- Then absorbed in another detector (absorber).
- Energies and positions measured → incoming direction reconstructed.

Detector design:
- Two layers of **$CeBr_3$ scintillator crystals** (scatterer + absorber).
- Read out by **SiPM arrays** (silicon photomultipliers).
- Electronics: fast timing, sub-nanosecond precision.

Advantages:
- Compact, lightweight → suitable for nanosatellites.
- Sensitive to gamma rays in the MeV range (including antimatter signals).





Results

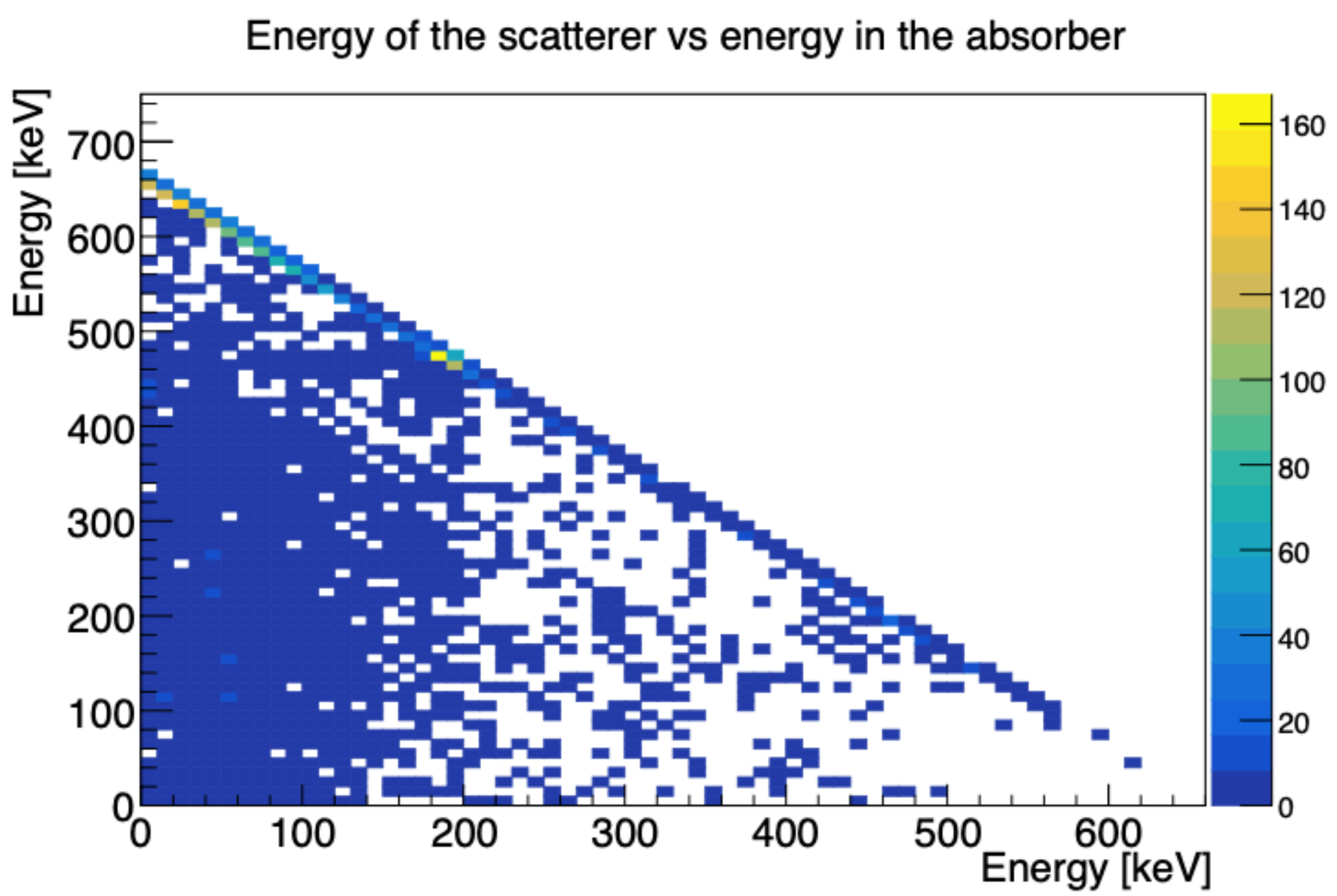
Calibration and linearity
- Tested with γ-ray sources: ^{22}Na, ^{137}Cs, ^{60}Co.
- Energy response was **linear across all gamma lines**.

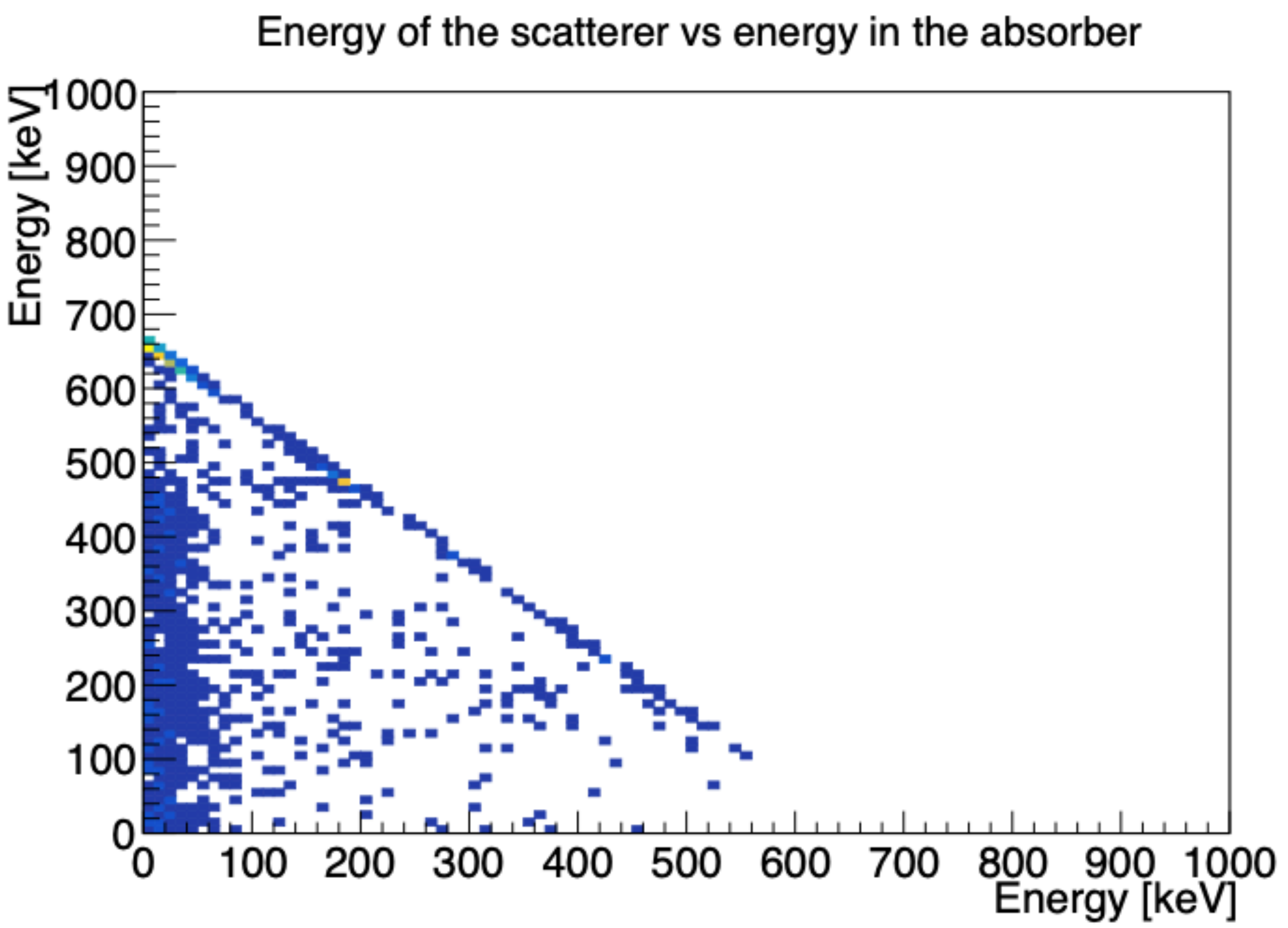
SiPM bias and energy resolution
- Increasing bias improved resolution up to an **optimal point**.
- Beyond that, **dark noise dominated**.

Role of crystal thickness
- **Thick $CeBr_3$ crystal** → higher efficiency (better stopping power).
- **Thin $CeBr_3$ crystal** → better energy resolution.
- Assigned roles: front scatterer (thin) and back absorber (thick).

Monte Carlo validation
- Confirmed reconstruction of Compton events.
- Showed **trade-off between efficiency and angular acceptance** with spacing.
- Best performance at **5 cm separation** (ε ≈ 0.45, FOV ≈ 1 sr).
- 180° scattering events gave best energy & timing resolution.

Conclusion
- Compact $CeBr_3$ + SiPM design is **efficient, modular, and low-power**.
- Suitable for **nanosatellite payloads** with competitive performance.





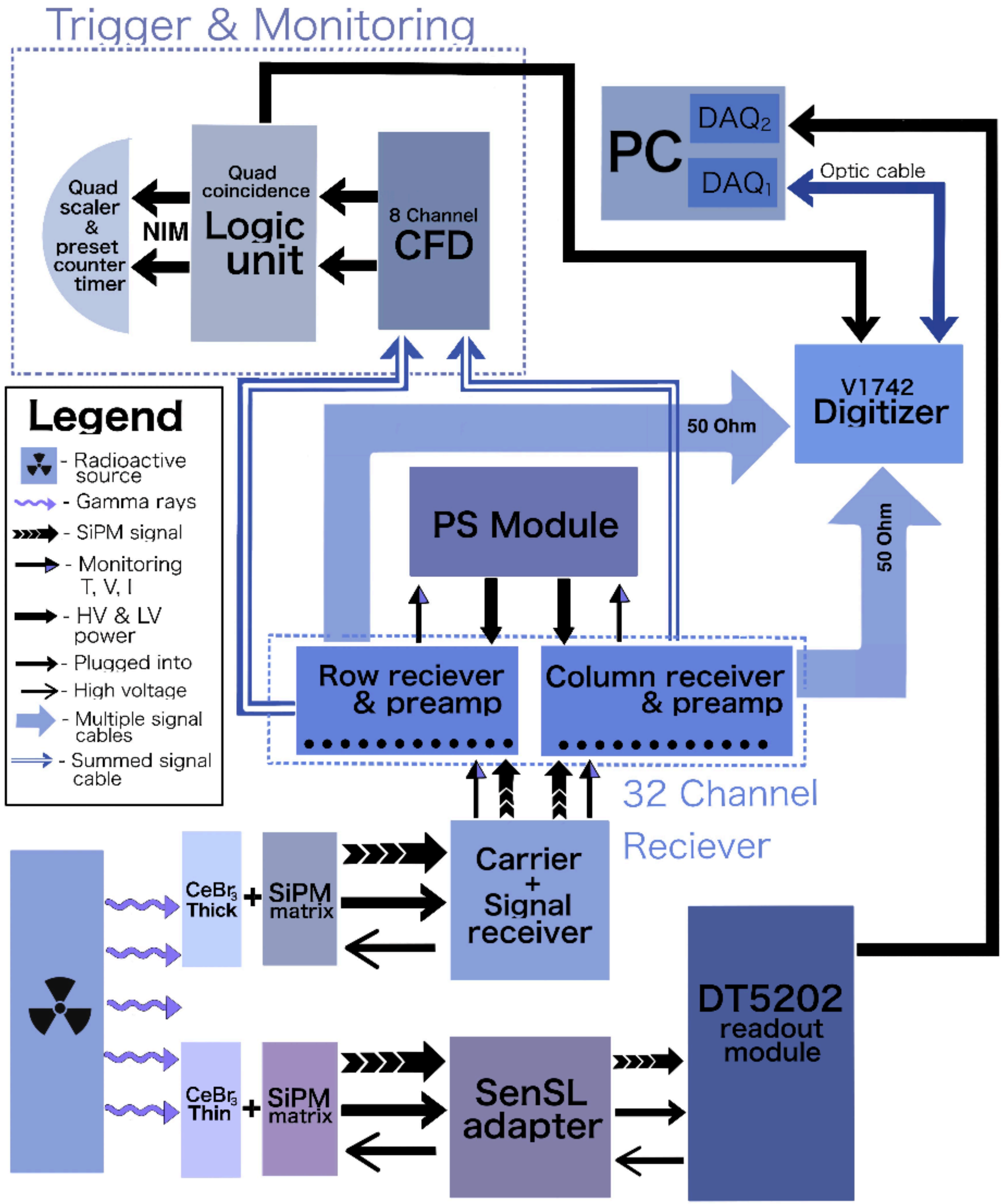
Conclusions

- Antimatter remains one of the central open questions in physics: its absence in the observable Universe is unexplained.
- Space experiments (AMS, BESS) provide precise measurements of antiprotons and positrons, revealing anomalies that may hint at new physics.
- INTEGRAL has mapped the Galactic 511 keV annihilation line, revealing the distribution of positron annihilation in the Milky Way.
- Proposed nanosatellite Compton telescope with $CeBr_3$ + SiPM design shows feasibility for compact Gamma-ray studies.
- Results confirm the potential of modern detectors for advancing antimatter research.

Question 1.

In Figure 5.2, a device is labeled with the abbreviation CFD. What is this device, and what is its function?

- **CFD = Constant Fraction Discriminator.**
- Timing module that triggers at a fixed fraction of the pulse height.
- Removes time walk (timing dependence on amplitude).
- In our setup: gives precise, amplitude-independent timestamps for scatterer/absorber coincidence.



Question 2

Why was a SiPM chosen for the described Compton telescope, rather than a more "traditional" vacuum PMT?

- **Compact & lightweight** → suitable for nanosatellites.
- **Low operating voltage** (~30–60 V for SiPMs vs. ~900–1500 V for MAPMTs/PMTs).
- **Insensitive to magnetic fields**