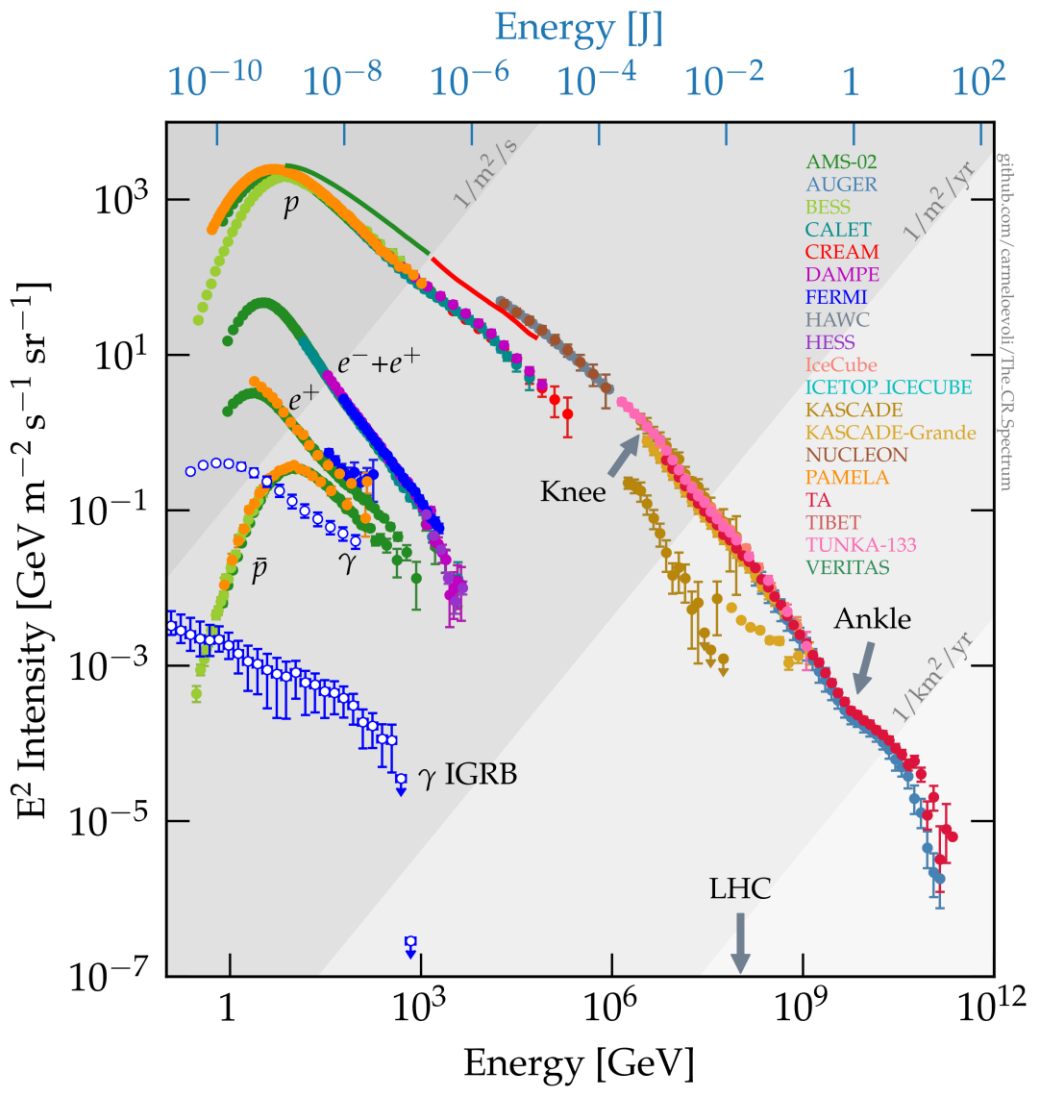
Radiazione Cosmica dallo Spazio

Carmelo Sgrò – INFN-Pisa

Con l’aiuto di molti!

Introduction

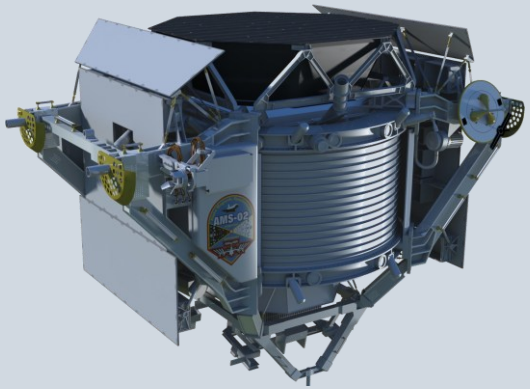


- Large variety of radiation from celestial sources
  - Charged particles, Ions, γ-ray, etc.
- Direct detection from space only
  - Galactic charged particles
- Limit at high energy:
  - Flux and energy measurement
- Limit at low energy:
  - Local magnetic field (Earth and Sun) for charged particles
  - Detection technique for photons

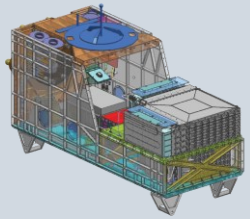
INFN involvement

2005 2010 2015 2020 2025

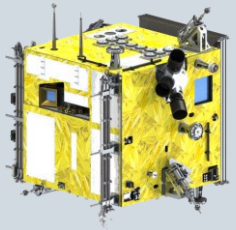
Pamela



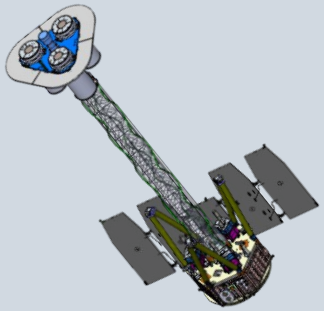
AMS-02



CALET

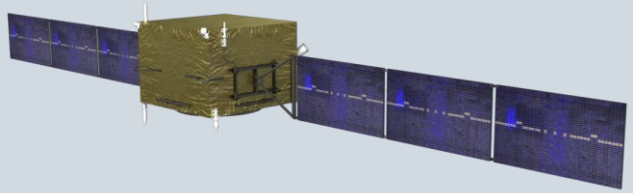


CSES-01



IXPE

Fermi

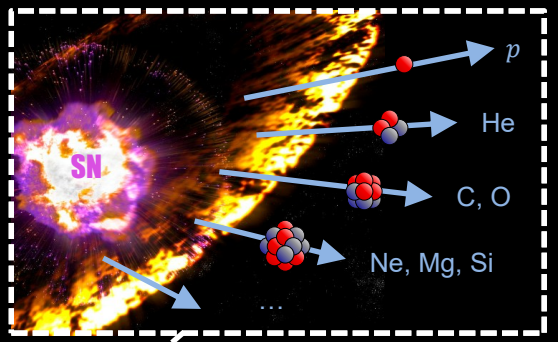


DAMPE

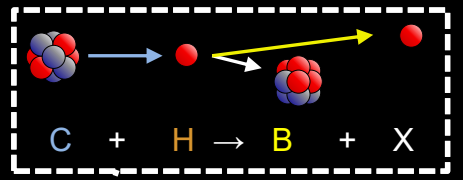
- Some of the present (and past) in-orbit missions
- Magnetic spectrometers and calorimetric detectors
- Charged and neutral radiation
- Low Earth Orbit

Galactic Cosmic Rays

- **Origin**: Shock acceleration in SNRs for primary CRS (p, C-N-O, Fe)
- **Propagation**: Diffusive propagation in interstellar & interplanetary turbulence.
- Collisions with ISM gas and production of secondaries: Li-Be-B, antimatter, γ-rays, etc.
- Exotic contribution: dark matter, primordial antimatter.



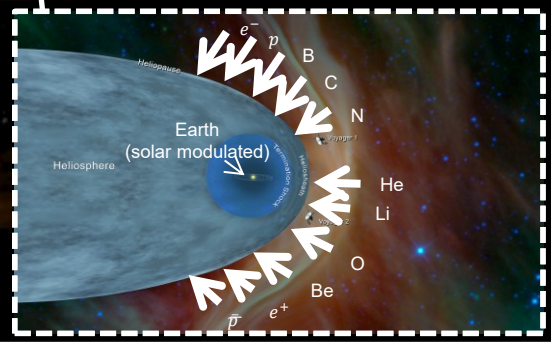
Primary GCRs (e^-, p, He, C, O, Ne, Mg, Si, ..., Fe) are thought to be accelerated by astrophysical processes (as supernovae shocks) in our Galaxy.



Secondary GCRs (e^+, $\bar{p}$, Li, Be, B, F, sub-Fe, …) are produced from collision of primaries with the interstellar medium.

Galactic Disk

Heliosphere

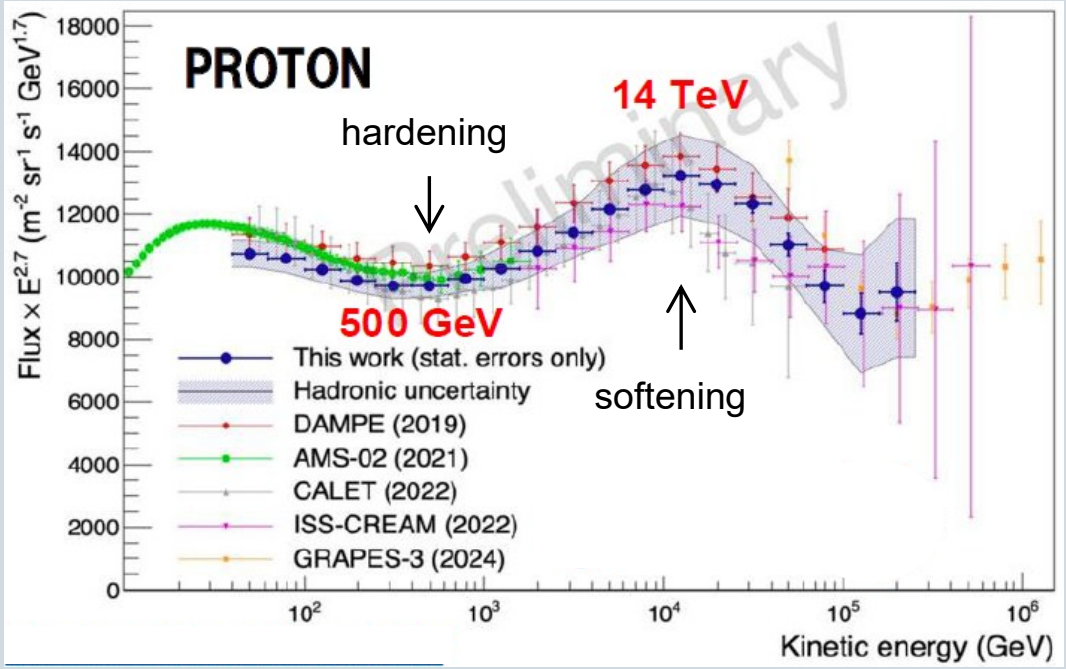


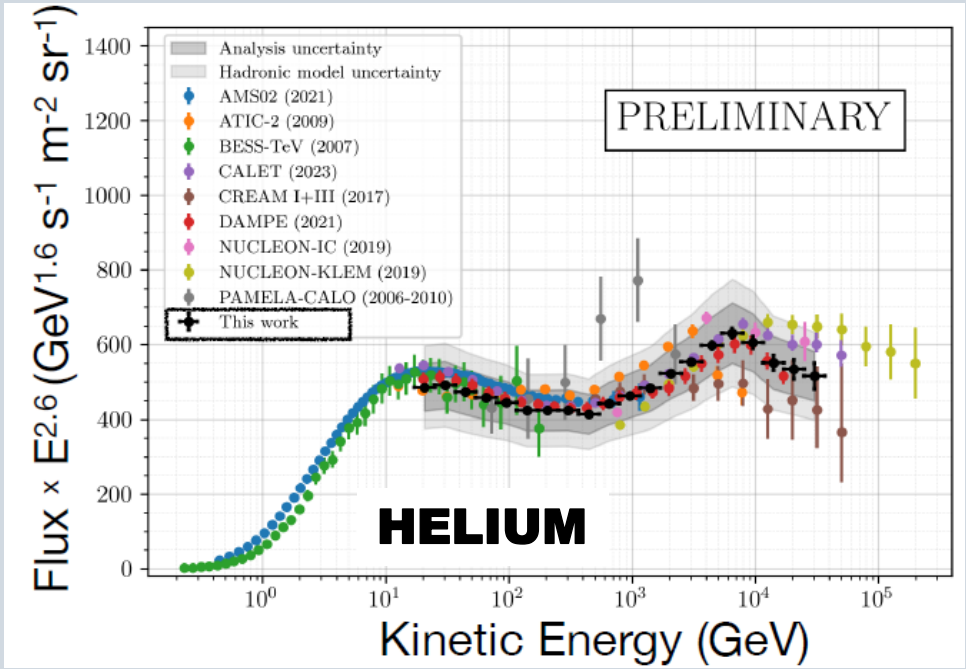
Cosmic rays close to Earth
- Solar activity (e.g. modulation)
- Earth magnetic field

Adapted from A. Oliva

Proton and Helium flux

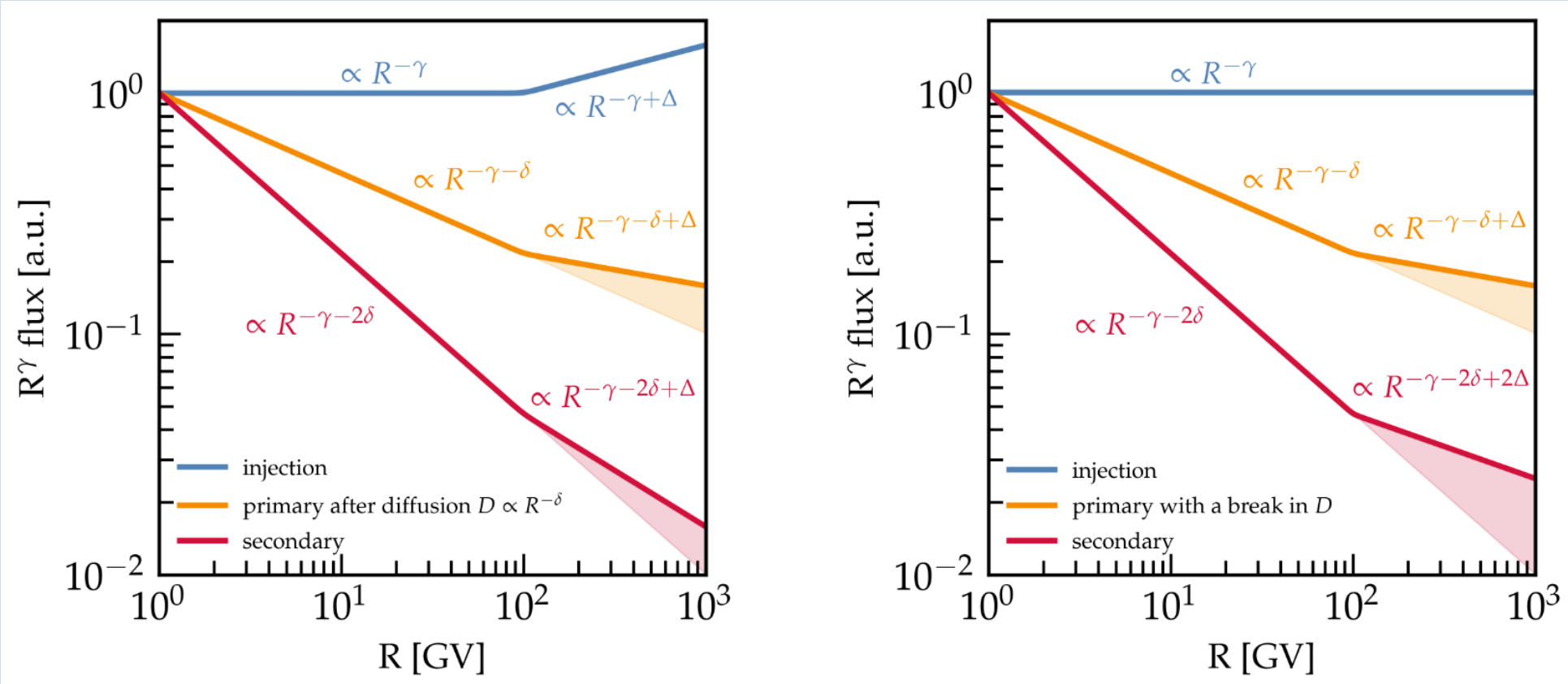
I. De Mitri NOW 2024





- Most abundant elements in cosmic rays, measured by many experiments with good resolution
- Significant structures above 100 GeV have been found: not a single power law
- How can we explain features and spectral indices?

About the origin of the break: injection or diffusion?

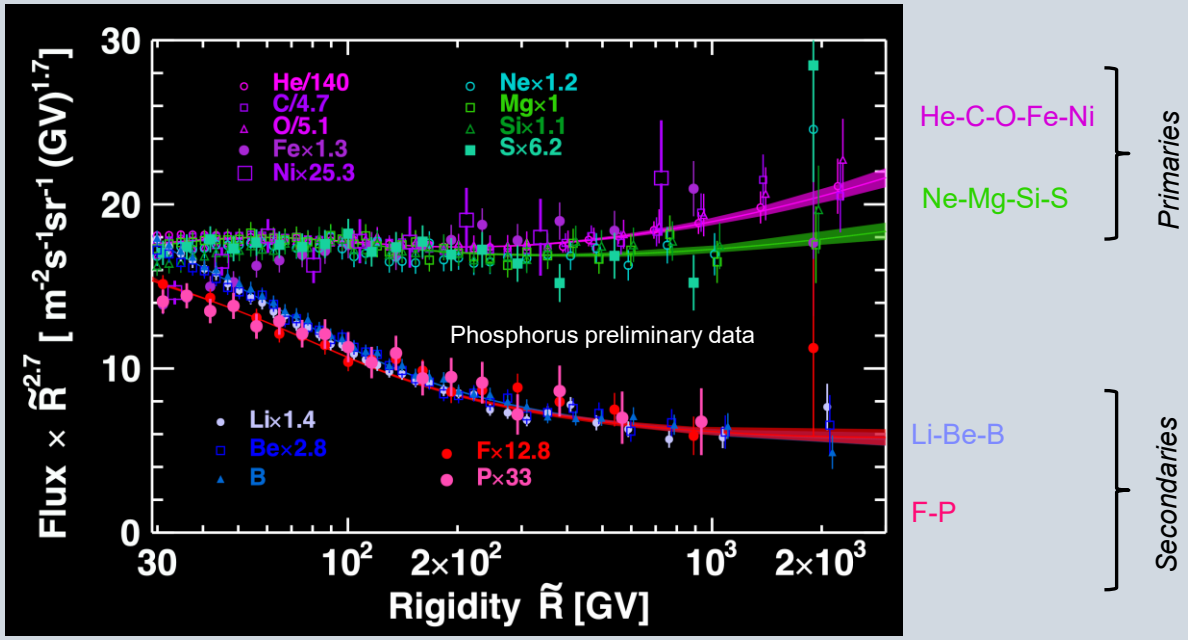


C. Evoli 2019

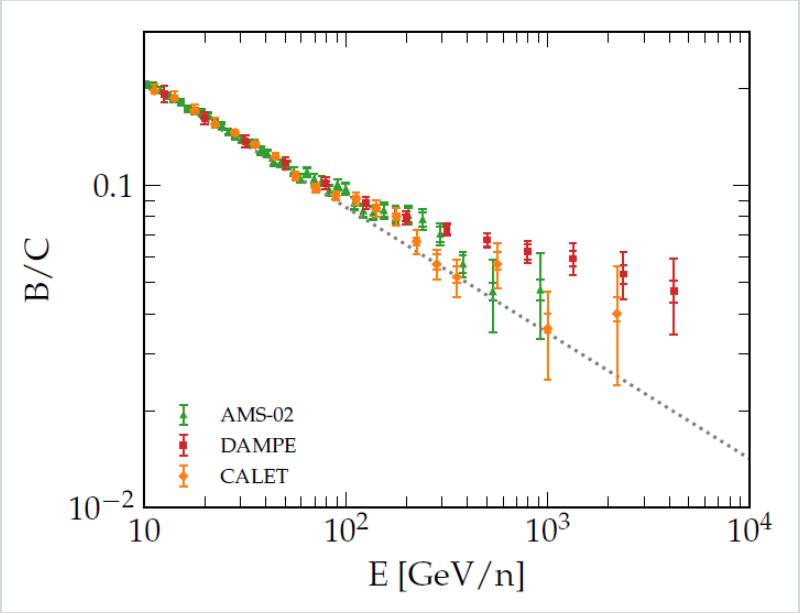
- Different behavior of secondary particles in the two scenarios

Primary and Secondary Species

M. Aguilar *et al.*, Phys. Rep. 894 (2021) 1-116

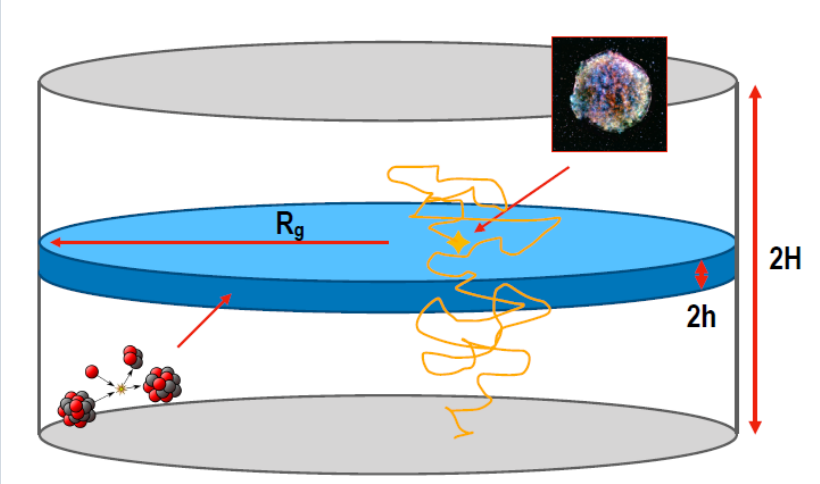


C. Evoli CRISM-MAC 2024

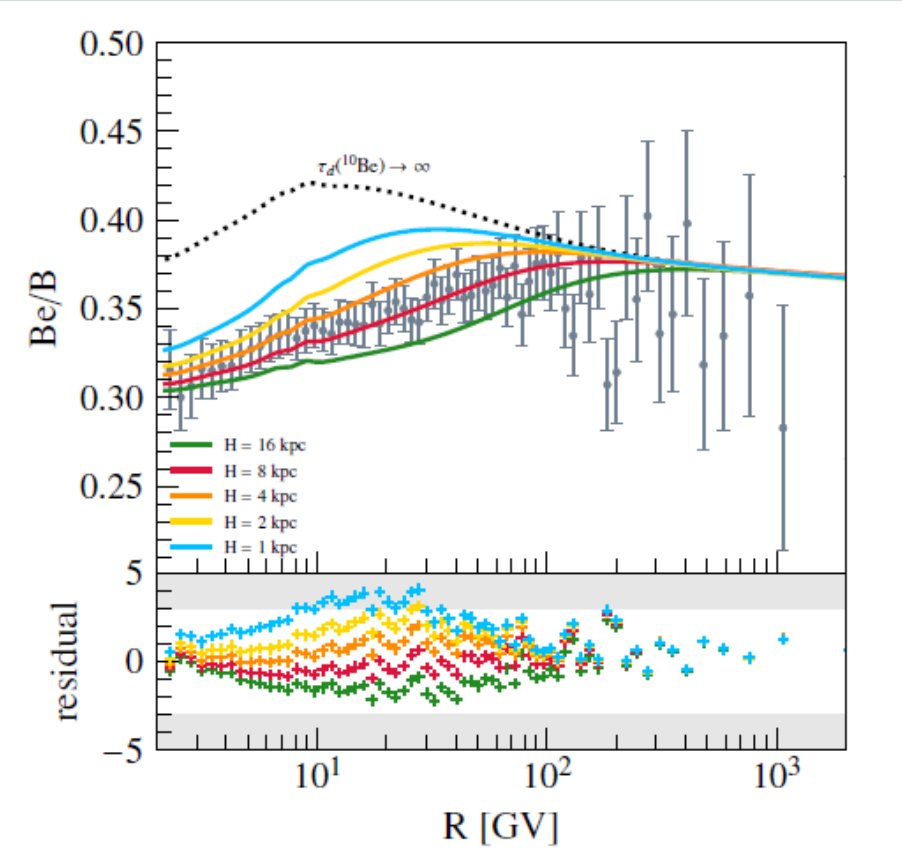


- All cosmic rays (both primary and secondaries) show a spectral hardening at about 200 GV
- Secondary harden more than primaries favoring the existence of a propagation feature
- The same break observed in B/C suggests something is going with the diffusion coefficient
- Not yet a model that fits all species with a single set of parameters (e.g. still need different injection index for p and He)

Unstable isotopes: ^{10}Be



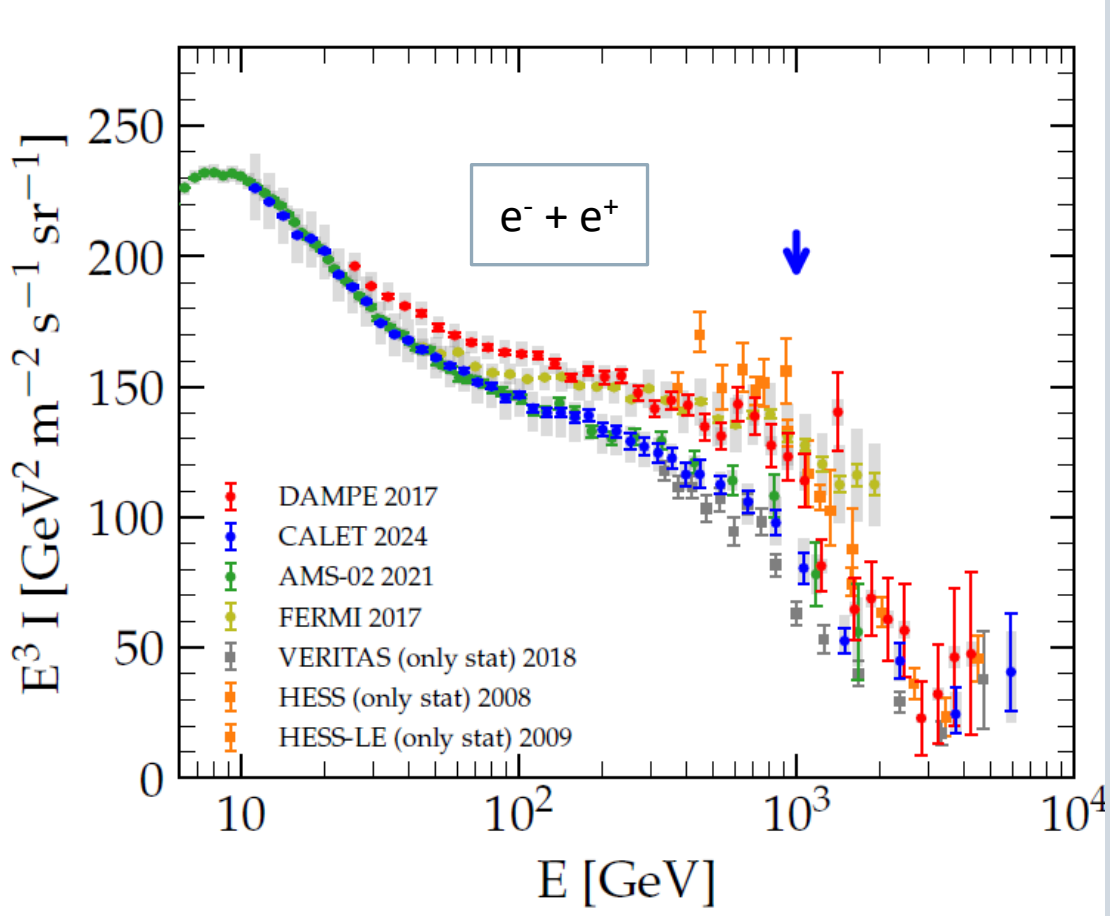
C. Evoli et al., Phys. Rev. D 101 (2020) 023013



- GCRs injection and propagation in 'thin' disc
  - H represents the diffusive halo height
- ^{10}Be is a β− unstable isotope that decays into ^{10}B with a half-life of approximately 1.4 Myrs
- The amount of ^{10}Be with respect to other secondaries, depends to the galactic halo size
- AMS-02 data on Be/B shows a preference for large halos H $\gtrsim$ 5 kpc
- New measurement on ^{10}Be are expected soon

Adding leptons to the picture

C. Evoli TeVPA 2024



- Primary Electrons lose energy primarily through:
  - Synchrotron emission in the halo magnetic field $\langle B \rangle \simeq 1\ \mu G$
  - IC scattering on interstellar radiation fields (CMB, IR, UV, …)
- Energy losses dominate over diffusion
  - "Local" primary particles
- High-precision experimental data from current generation of experiments
  - Space detector and IACT
- Most prominent feature is the break at ~1 TeV
  - Injection or propagation?

Looking at arrival direction

- Search for sources looking at the distribution of arrival direction
- Just in case of a dominant, nearby injection source
- Only upper limit up to now

M. Ackermann et al. Phys. Rev. D 82 (2010) 092003

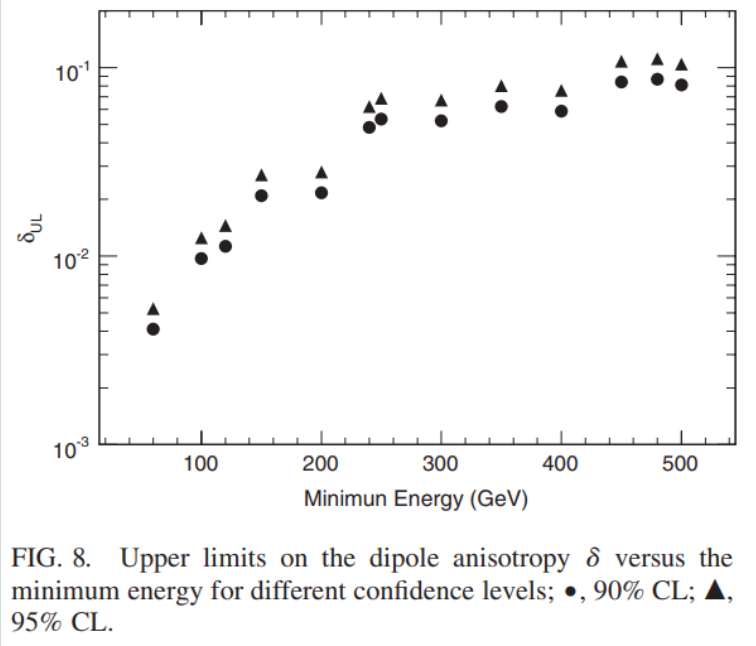


FIG. 8. Upper limits on the dipole anisotropy δ versus the minimum energy for different confidence levels; •, 90% CL; ▲, 95% CL.

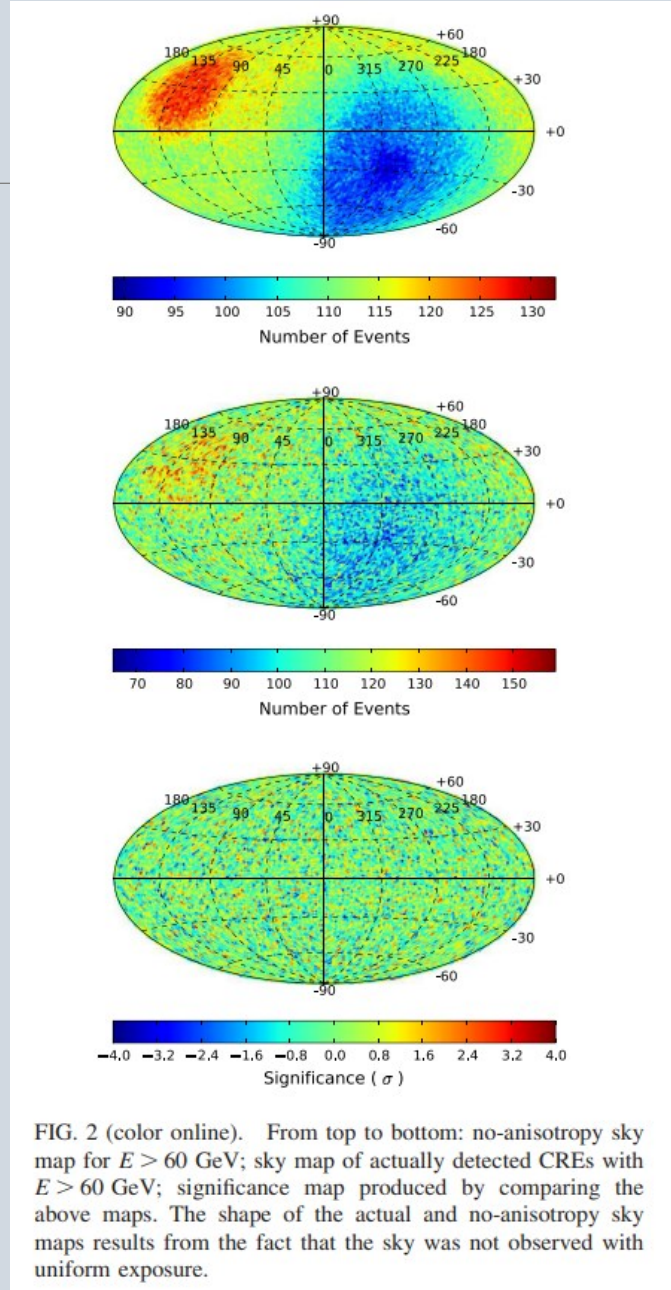
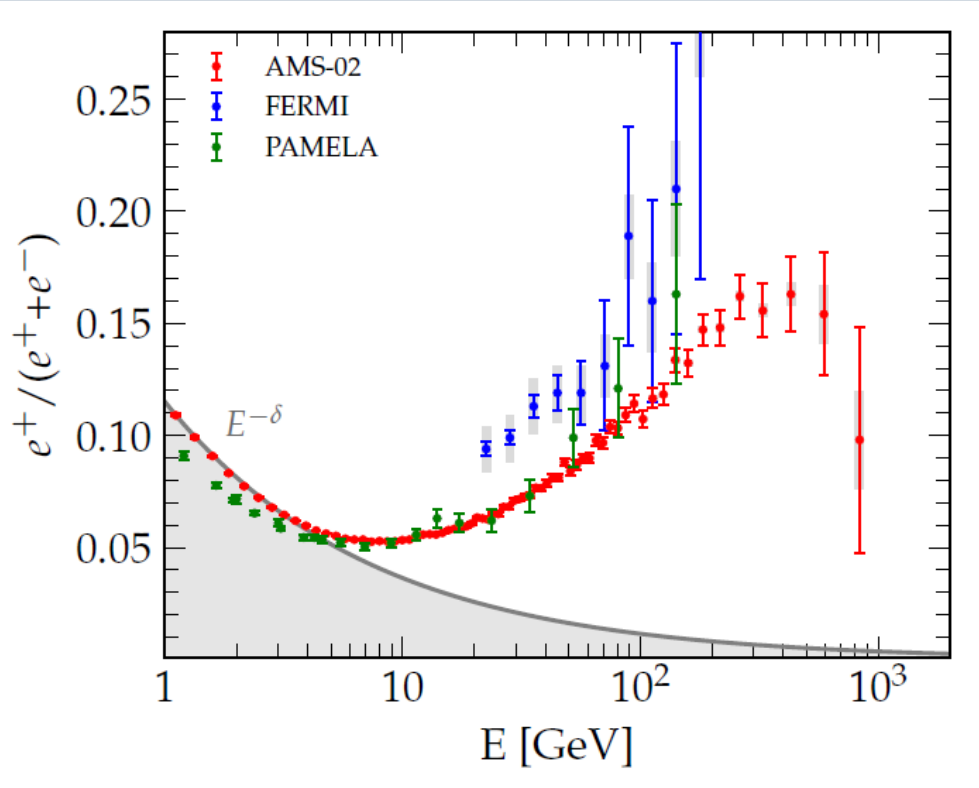


FIG. 2 (color online). From top to bottom: no-anisotropy sky map for $E > 60$ GeV; sky map of actually detected CREs with $E > 60$ GeV; significance map produced by comparing the above maps. The shape of the actual and no-anisotropy sky maps results from the fact that the sky was not observed with uniform exposure.

The famous positron fraction

C. Evoli TeVPA 2024



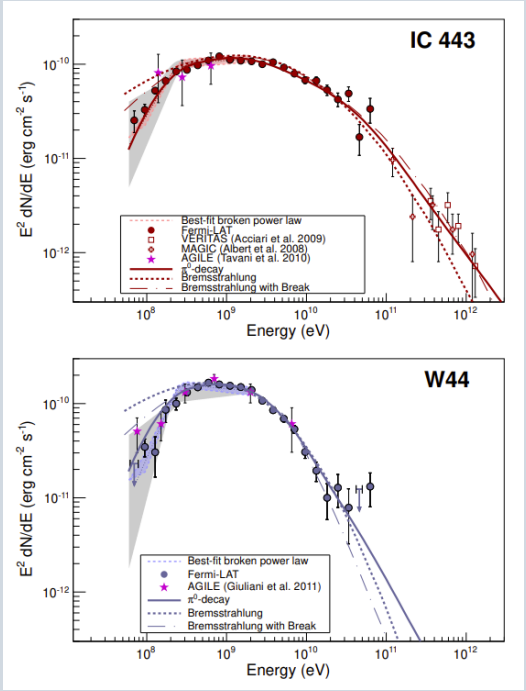
- $E^{-\delta}$ is expected in standard propagation scenario
- A new source of positron is needed!

- Is it a hint of Dark Matter?
  - DM searches in a dedicated presentation
  - There are valid alternatives, like PWN

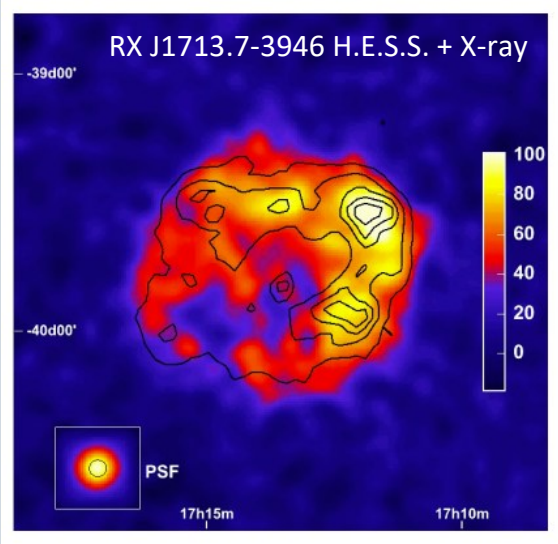
Dedicated talk later

Injection sources

- Supernova remnants (SNRs) are expected to be good candidates for CR acceleration
  - Diffusive shock acceleration (DSA) mechanism
- Deep study in multiple wavelength of potential source is very important
  - Here only a few example
  - Spectra, Morphology, Magnetic field turbulence (polarization), etc…

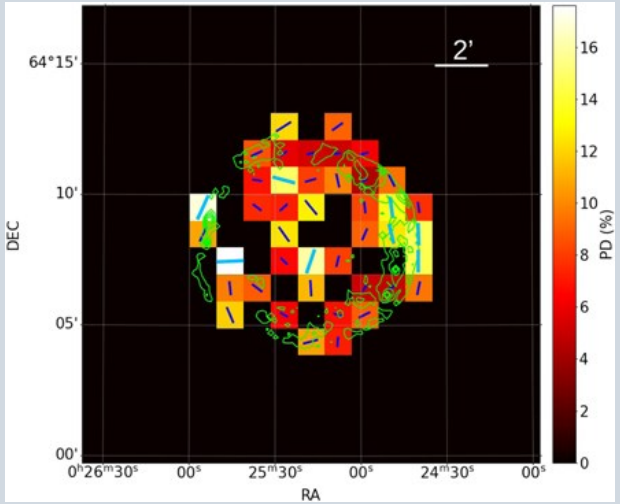


M. Ackermann et al. Science 2013, 339, 807–811



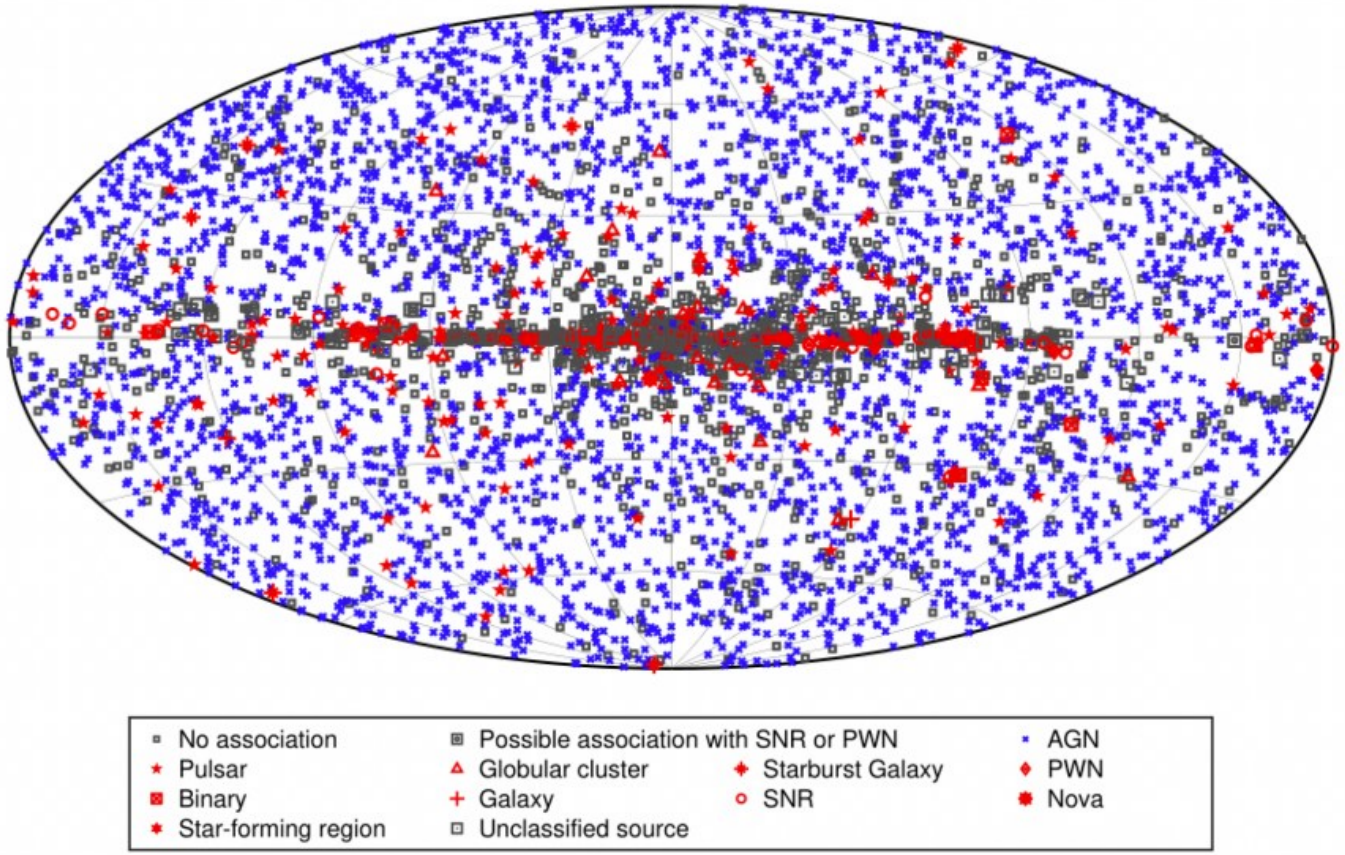
D. Berge ICRC 2005

Tycho X-ray polarization map (IXPE) with intensity contour (Chandra)
Polarization ~12% (rim)



R. Ferrazzoli et al 2023 ApJ 945 52

Sources population



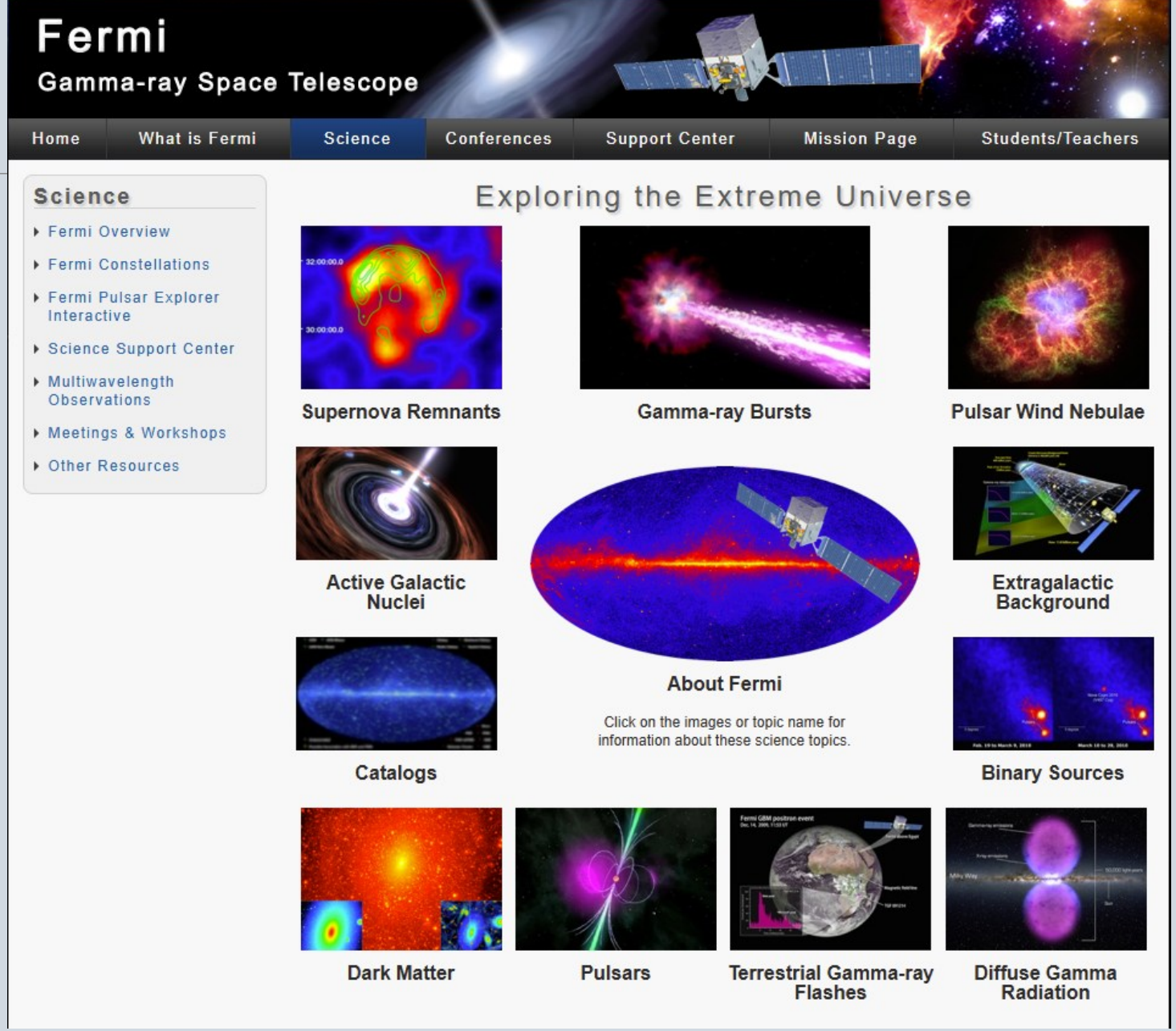
4FGL-DR4 - 4° Fermi Catalogue, Data Release 4

- Population study:
  - Systematic study of all detected sources
  - How sources are distributed
  - What are common characteristics
  - …
- Catalogues
  - Usually mission-specific
  - Class specific (GRBs, Pulsar, etc..)
  - Complex and long work
- Non only for CR physics:
  - Candidate for DarkMatter searches
  - Diffuse emission
  - …

The High Energy Sky

- Vast research area
  - Fermi Science homepage as an example
- Strong interplay among observatories
  - Different energy range
  - Different instrument performance

- Only a few highlight here



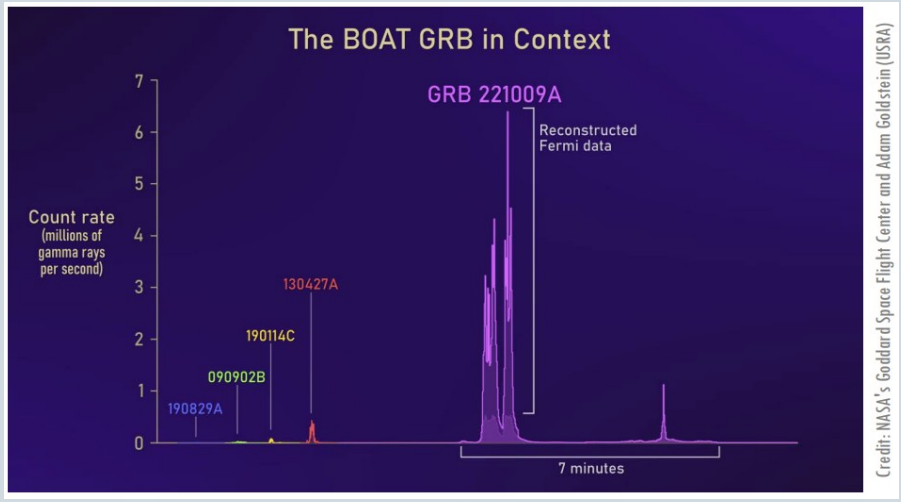
https://fermi.gsfc.nasa.gov/science/

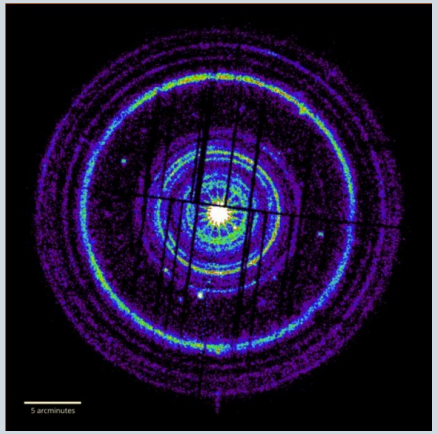
Transient sources: Gamma Ray Bursts

- Multiple observatories are required to cover the full energy spectrum (from optical telescopes to γ-rays)
- Large field of view or quick repointing in crucial for full sky coverage

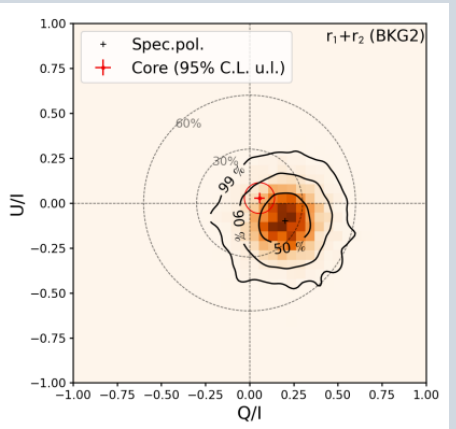
- Famous example GRB 221009A
  - The brightest GRB ever detected
- Detected by many instruments
  - Swift and GBM trigger and localization
  - Peak emission too bright for LAT conventional analysis
  - 18 TeV event claimed by LHAASO
    - Quite puzzling, EBL absorption?
  - X-ray rings due to light scattering in dust
  - X-ray polarization (upper limits)
    - IXPE TOO repointing

- New missions dedicated to this topic are under development





XMM-Newton



IXPE
M. Negro et al.
2023 ApJL 946 L21

Multi-messenger astrophysics

- Grown after routine observation of GW transient events
  - Expectations from next generation of neutrino telescopes
- Follow-up observation of public triggers (ATel or GCN Circular)
- Private informations via MoU between experiments

Dedicated talk later

KM3-230213A Blazar Candidate Counterparts
arXiv:2502.08484

Fermi-LAT Gravitational Waves Table

This page displays the outcomes of the Fermi-LAT automatic follow-up analysis pipeline used to search for electromagnetic counterparts of gravitational waves (GW). For a detailed explanation of the analysis techniques, please refer to 2017ApJ...841L..16V. Furthermore, the Fermi-LAT Collaboration has published additional papers on GW events such as GW150914, LVT151012 and GW151226, GW170104, and GW170817

All analysis results presented here should be considered preliminary, unless otherwise stated. If you have any questions, please write to Niccolò Di Lalla.

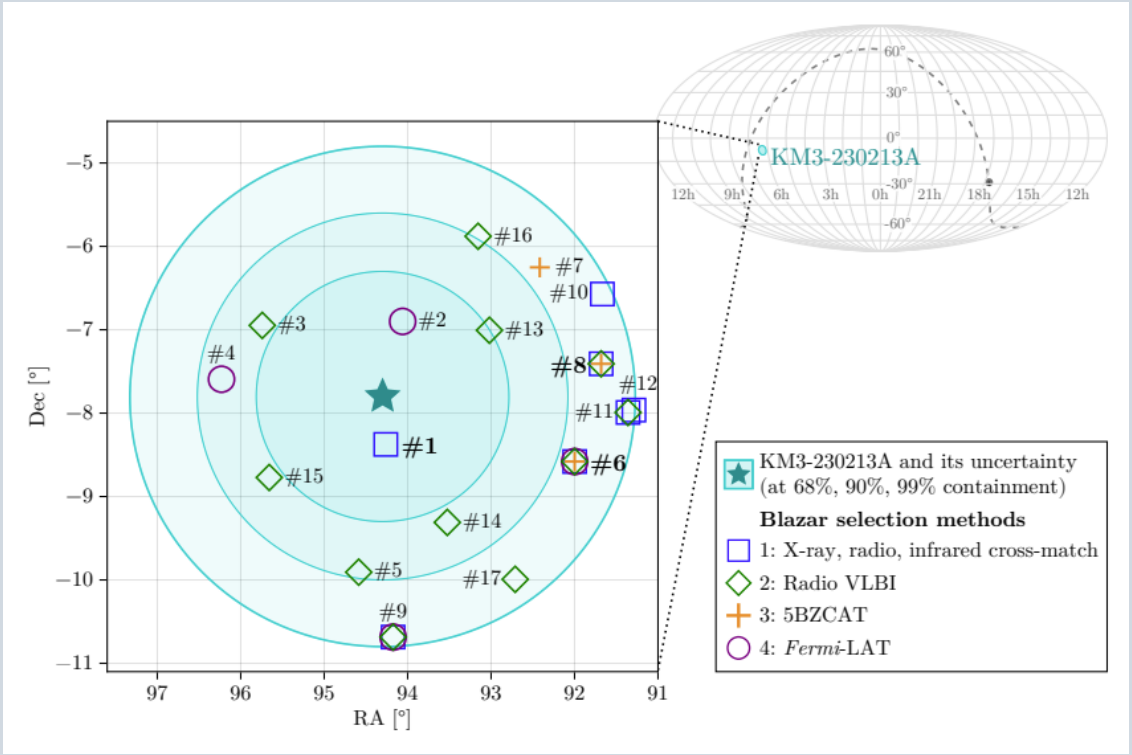
Click on the following buttons to access the table associated with the corresponding observing cycle:

O3 | O4

Stop your mouse cursor over the table headings to view a short explanation of the columns in the table or check the legend here.

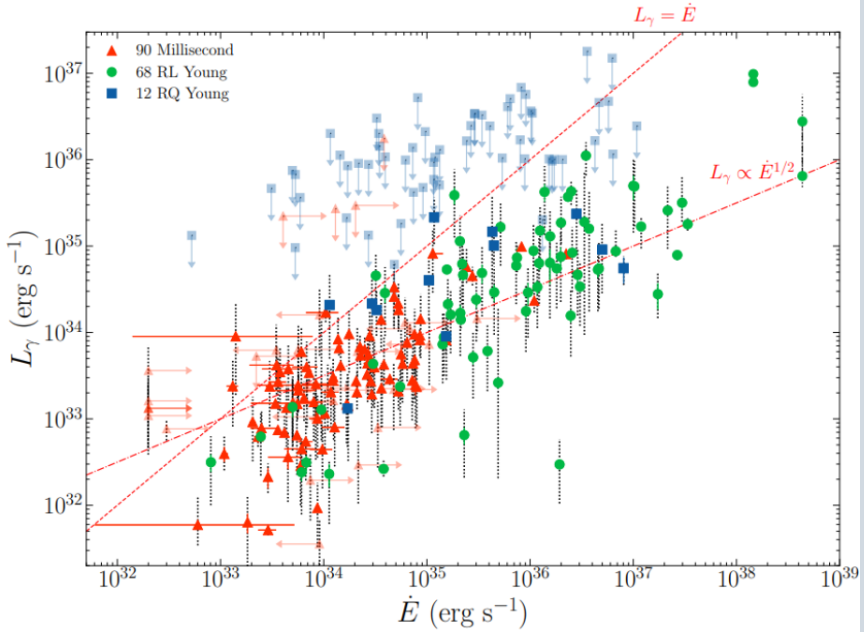
* Information taken from GraceDB (LIGO-Virgo-KAGRA Collaboration).

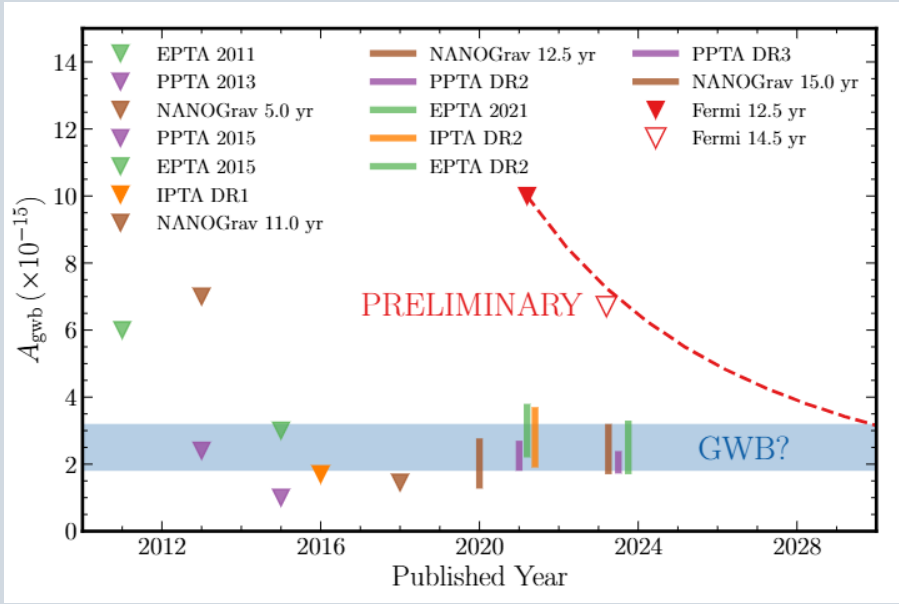
Trigger Name*	Date*	Time (UTC)*	GraceDB*	FAR (Hz)*	Highest Probability*	Has NS? (%)*	Has Remnant? (%)*	Has MassGap? (%)*	Inst. Coverage (%)	FTI TS max	ATI TS max	Flux UB (erg/cm2/s)	Analysis report
S250119cv	2025-01-19	19:02:38	Link	4.0e-20	BBH: 100.0%	0.0	0.0	0.0	3.9	11.3	12.6	6.7e-10	Link (v01)
S250119ag	2025-01-19	02:51:38	Link	3.3e-13	BBH: 100.0%	0.0	0.0	0.0	14.5	14.6	13.1	4.4e-10	Link (v02)
S250118t	2025-01-18	02:32:25	Link	4.0e-10	BBH: 100.0%	0.0	0.0	0.0	34.7	**32.9**	22.2	9.2e-10	Link (v02)
S250118dp	2025-01-18	17:05:23	Link	5.6e-25	BBH: 100.0%	0.0	0.0	0.0	43.8	11.4	12.0	7.4e-10	Link (v02)
S250118az	2025-01-18	05:58:02	Link	9.8e-09	BBH: 99.2%	0.0	0.0	18.7	1.5	16.9	12.2	8.2e-10	Link (v01)
S250114ax	2025-01-14	08:22:03	Link	4.1e-27	BBH: 100.0%	0.0	0.0	0.0	SAA	18.1	3.3	4.5e-10	Link (v02)



Gamma-ray Pulsar Timing Array

- Pulsar Timing Array exploit monitoring time of arrival of an ensamble of pulsars search for GW at nHz frequencies
  - Millisecond pulsars are stable clocks
  - Gravitational Wave Background (GWB) cause the time of arrival of the pulses to vary
- Fermi-LAT contributed by increasing the number of known millisecond pulsars
  - Timing monitoring done by radio telescopes
- Gamma rays are not affected by the interstellar medium, and timing models are simpler
  - Can perform a direct search for GWB





Upper limits (downward triangles) on and candidate signal ranges (bars) of the amplitude A_{gwb} of a stochastic gravitational wave background

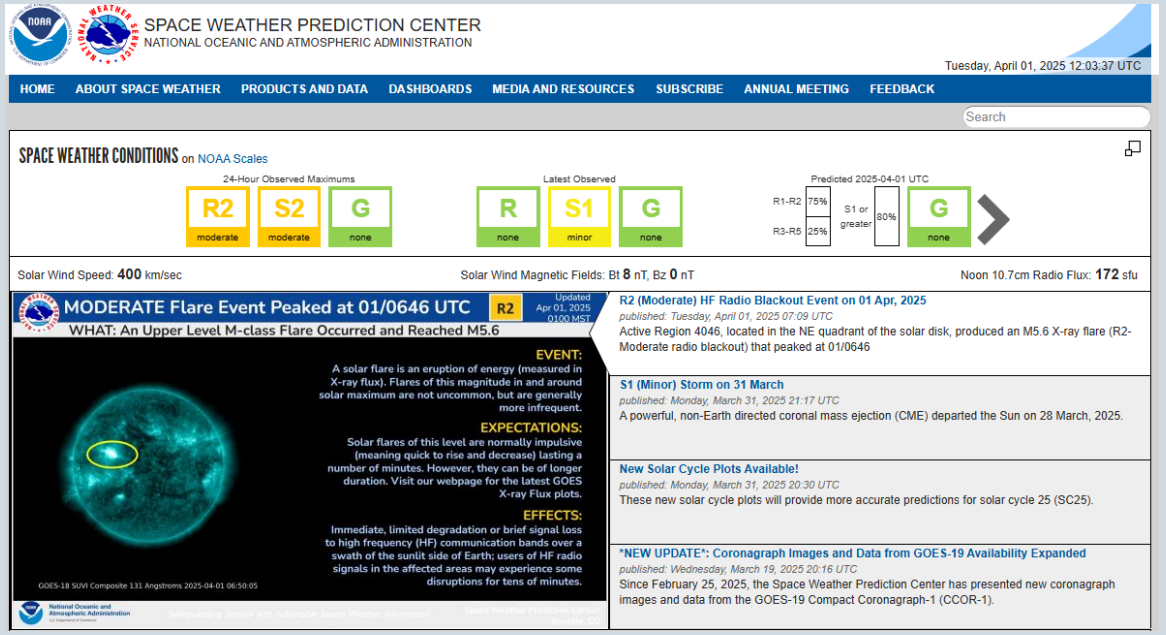
- Data Release 1
  - 35 gamma bright MSPs
  - 12.5 yr
- Data release 2
  - 14.5 yr
  - Improved pulsar profile models

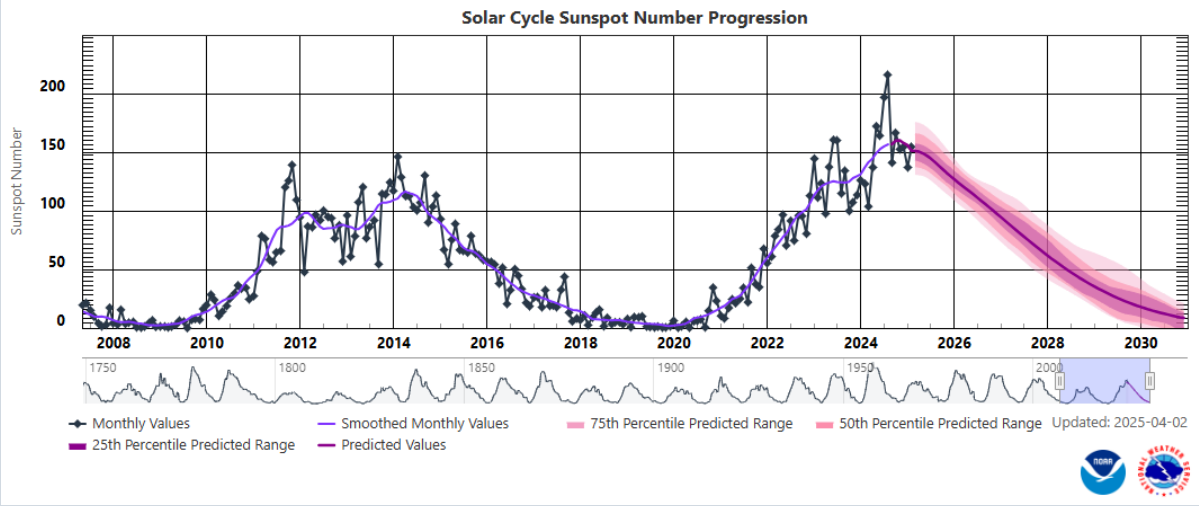
M. Kerr ICRC 2023

Solar physics and Space Weather

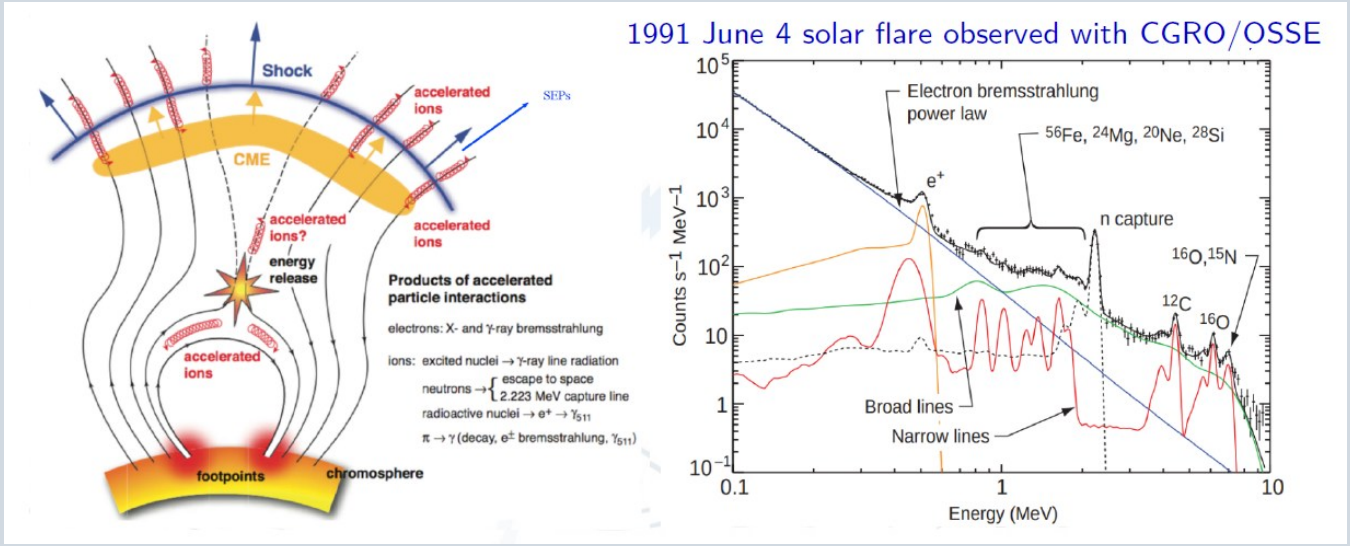
- Solar activity has enormous impact on our lifes and experiment
  - Satellite operation (e.g. 2024 May 11 geomagnetic storm)
  - Continuously monitored by many instruments
- Close to maximum of solar cycle
- Huge physics content
  - Sun emission at all wavelength including γ-ray
  - Solar Flares
  - Modulation of charged Cosmic Rays
  - …

https://www.swpc.noaa.gov/

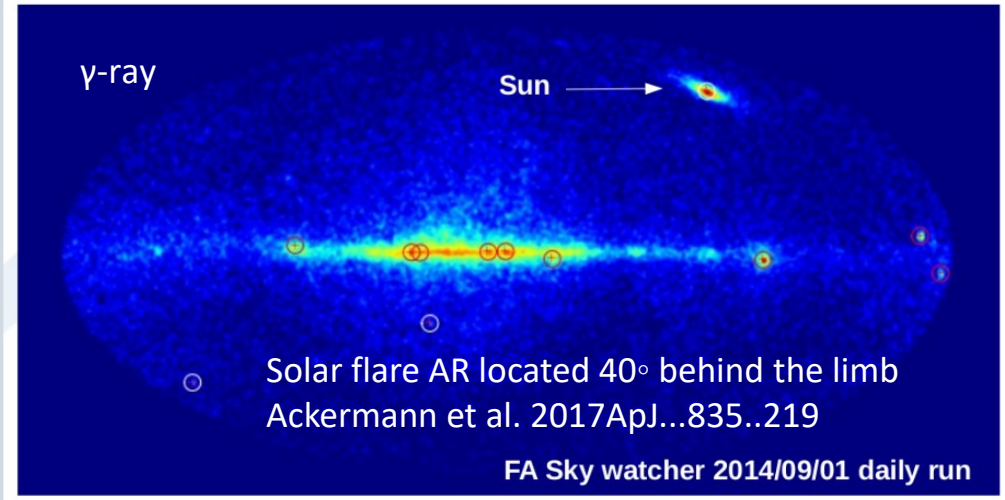


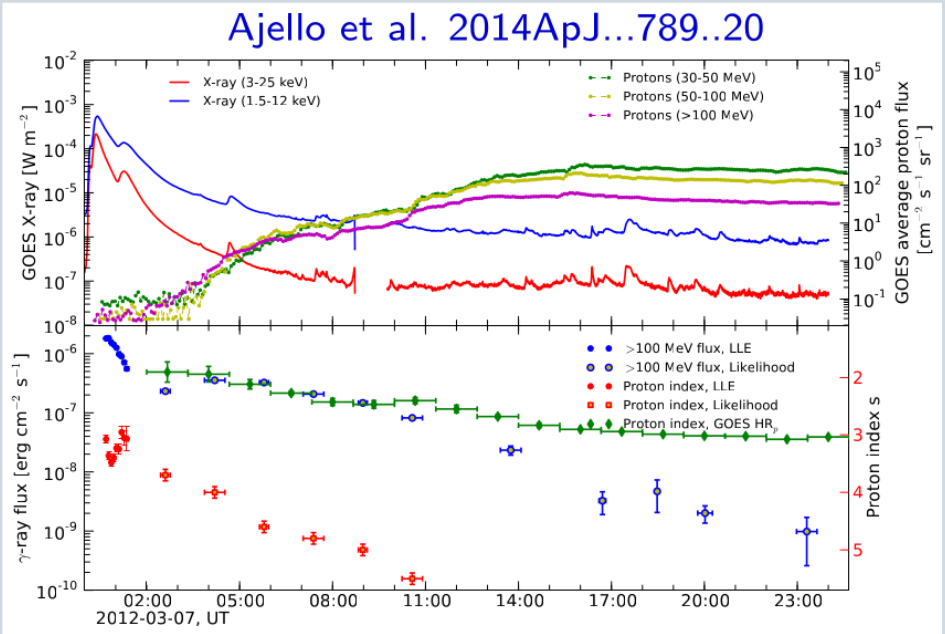


Solar Flares



- Particles accelerations in a nearby object
  - Shocks
  - Magnetic reconnection
  - Deexcitation lines
- Multiple observatories available
  - Photons and charged particles
  - Spectra and time series



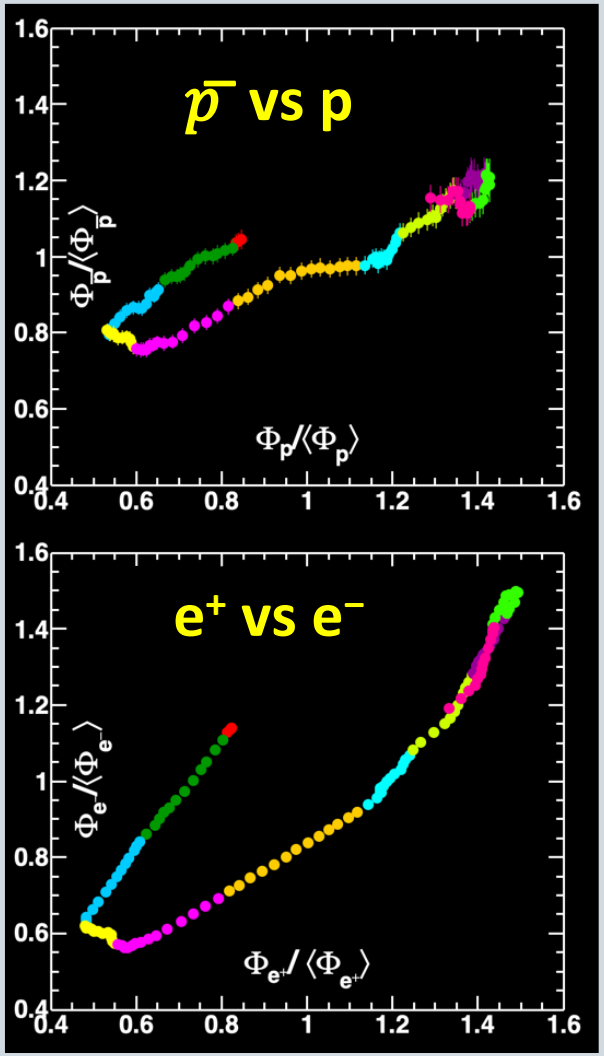


Effect of solar modulation to charged particles

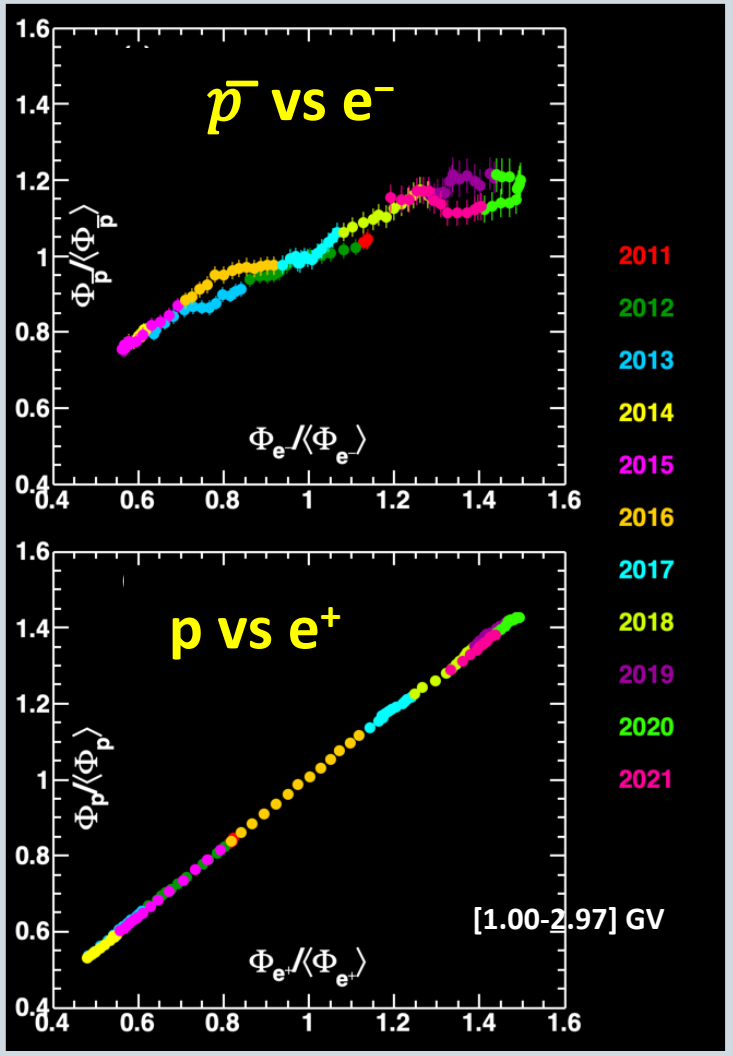
- Affects “low’energy” particles
- Studies done by several missions: Baloon exp.,Pamela, CSES01 (HEPD) etc.
- Recently we have a measurement of particle spectra for an entire solar cycle
  - AMS02 2011->2021
  - p, e^-,e^+, and $\bar{p}$
- A hysteresis between particles of opposite sign is clearly measured
- Solar modulation is a complex phenomena
- Expect more data future measurements

M. Aguilar et. al. Phys. Rev. Lett.134 (2025) 051002L

same mass, opposite charge



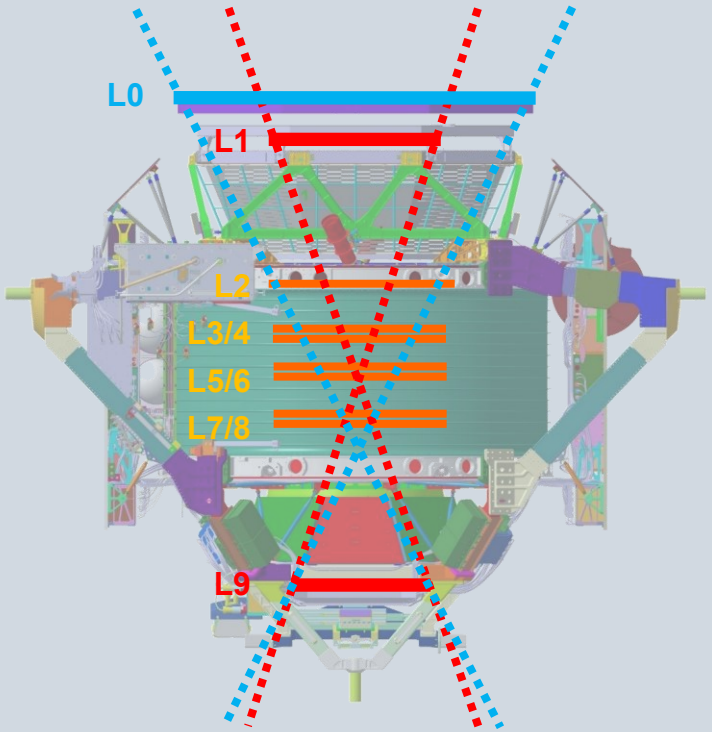
same charge, different mass

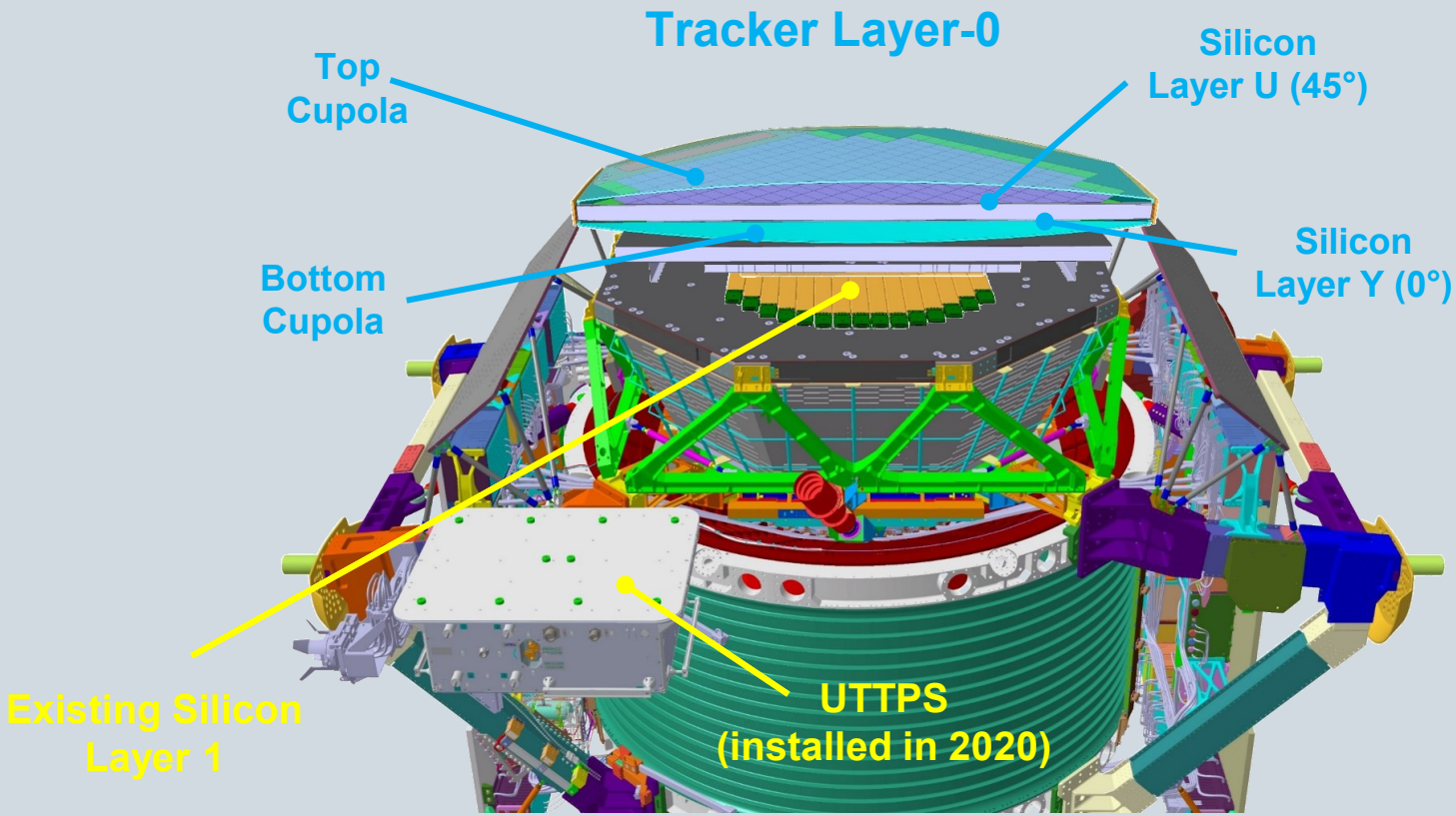


AMS-02 Upgrade with new L0 tracker plane

- The increase of 300% in the acceptance
  - Best use of the time left on the ISS, end-of-life expected at the end of 2030
- Installation foreseen in 2026

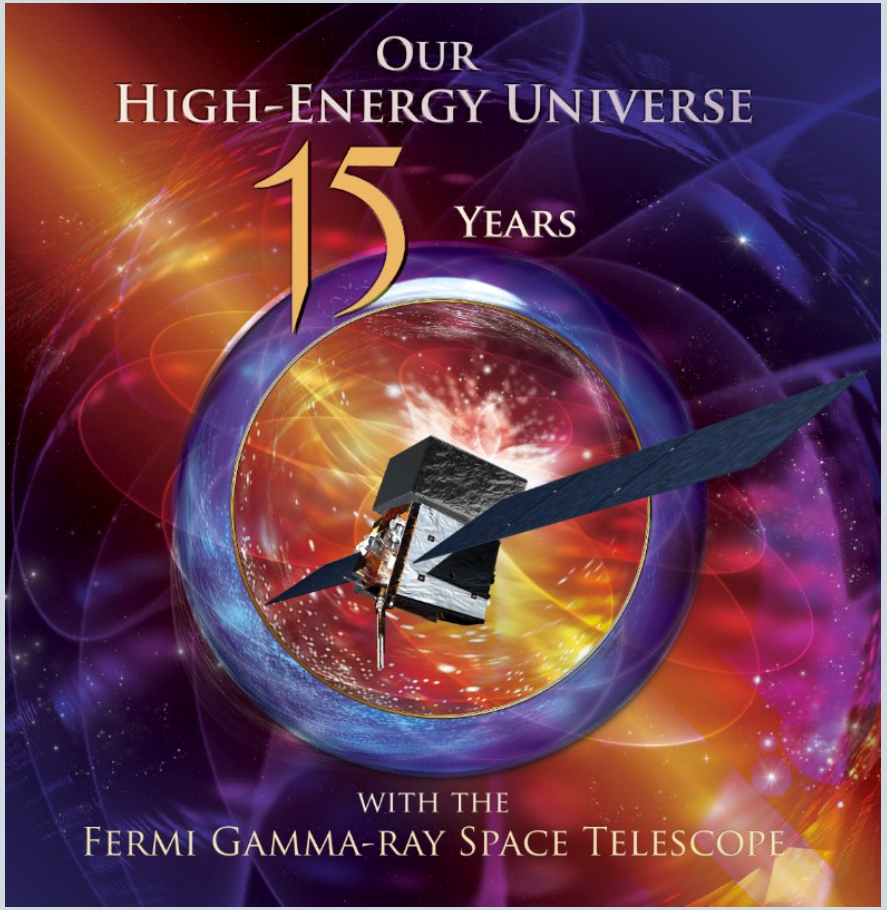
From A. Oliva CSN2 Feb. 2025





NASA observatories: Senior Review

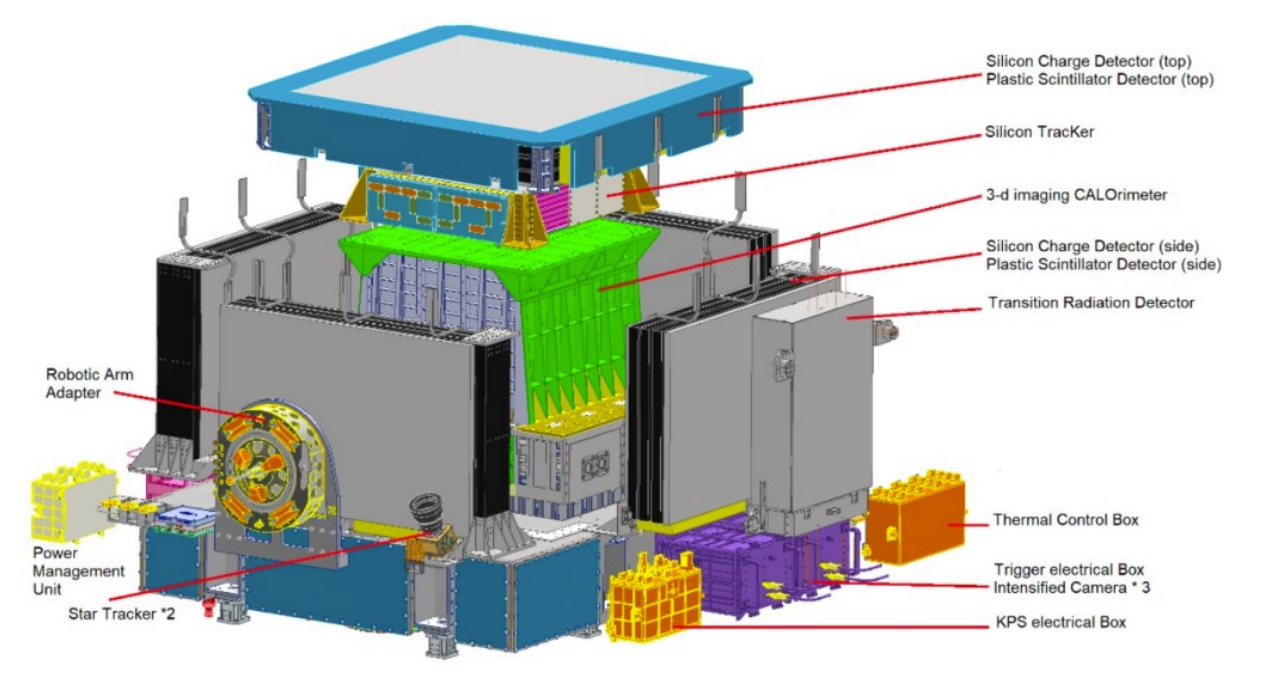
- Review of all aperating mission review every 3 years
  - Fermi and IXPE are involved



- Fermi is operating nominally without any major failure
  - Still our workhorse for γ-rays
  - It's getting old: time to think at new the generation

- IXPE is also performing well
  - General Observer Facility
  - Exploration mission

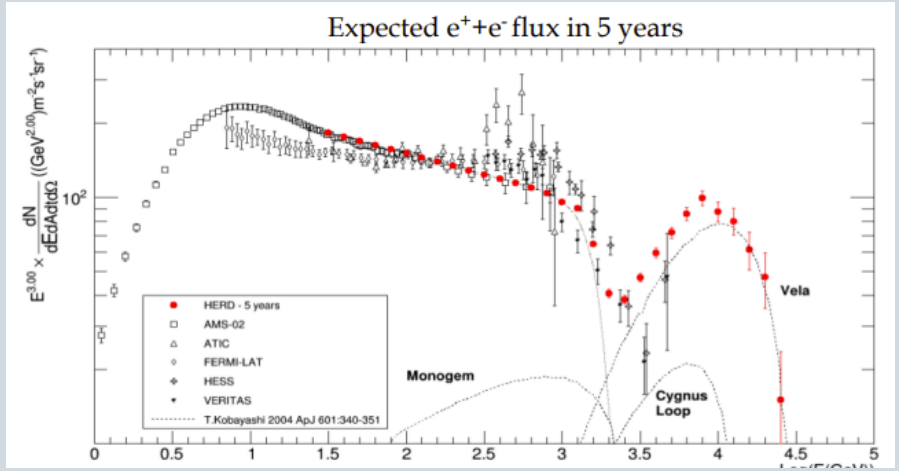
HERD on China's Space Station



- Facility for high-energy cosmic radiaton
  - Next generation experiment
  - Large acceptance and best performance to explore the ~10 TeV range
- Based on a 3D, homogeneous, isotropic and finely-segmented calorimeter
  - Concept developed at INFN

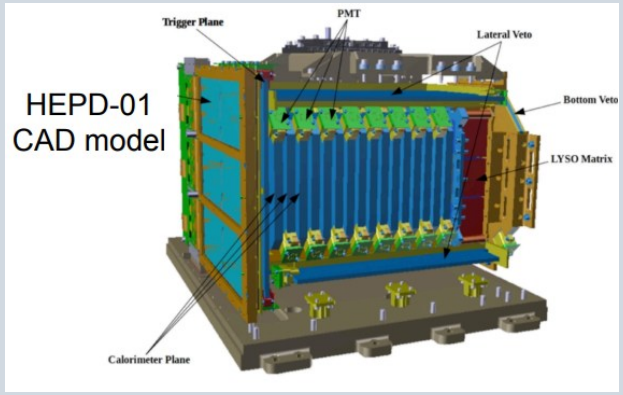
China-only HW
From G. Ambrosi CSN2 Feb. 2025

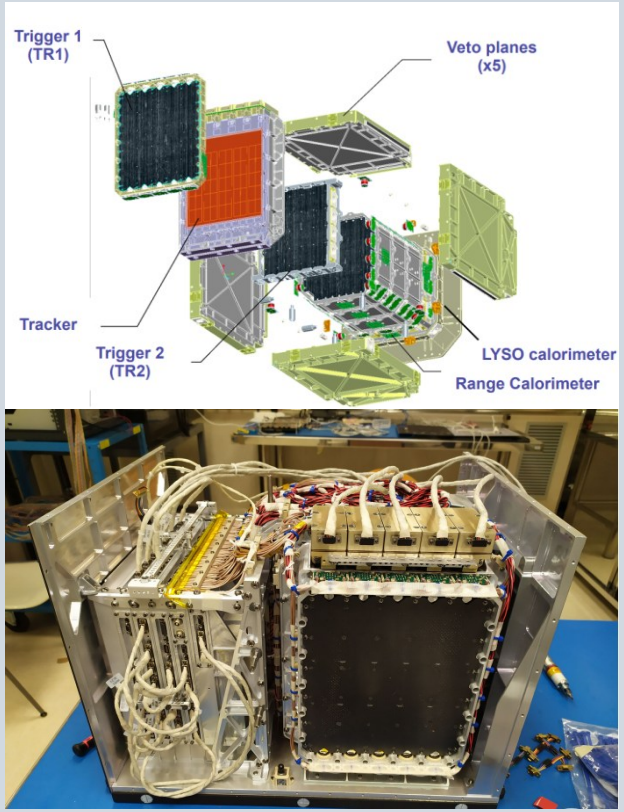
Well known issue with hardware export…

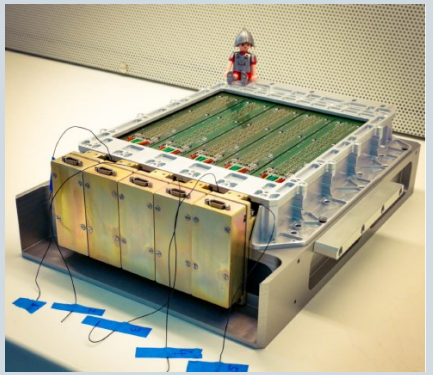


CSES-02 about to launch

- CSES-02 ready for launch in 2025
- Same platform of CSES-01
  - Several instruments on board
  - Including a new High-Energy Particle Detector
  - Evolution of previous model



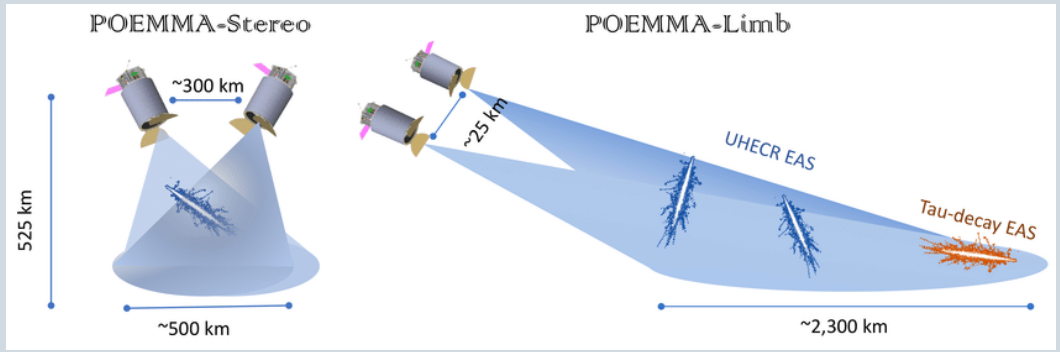




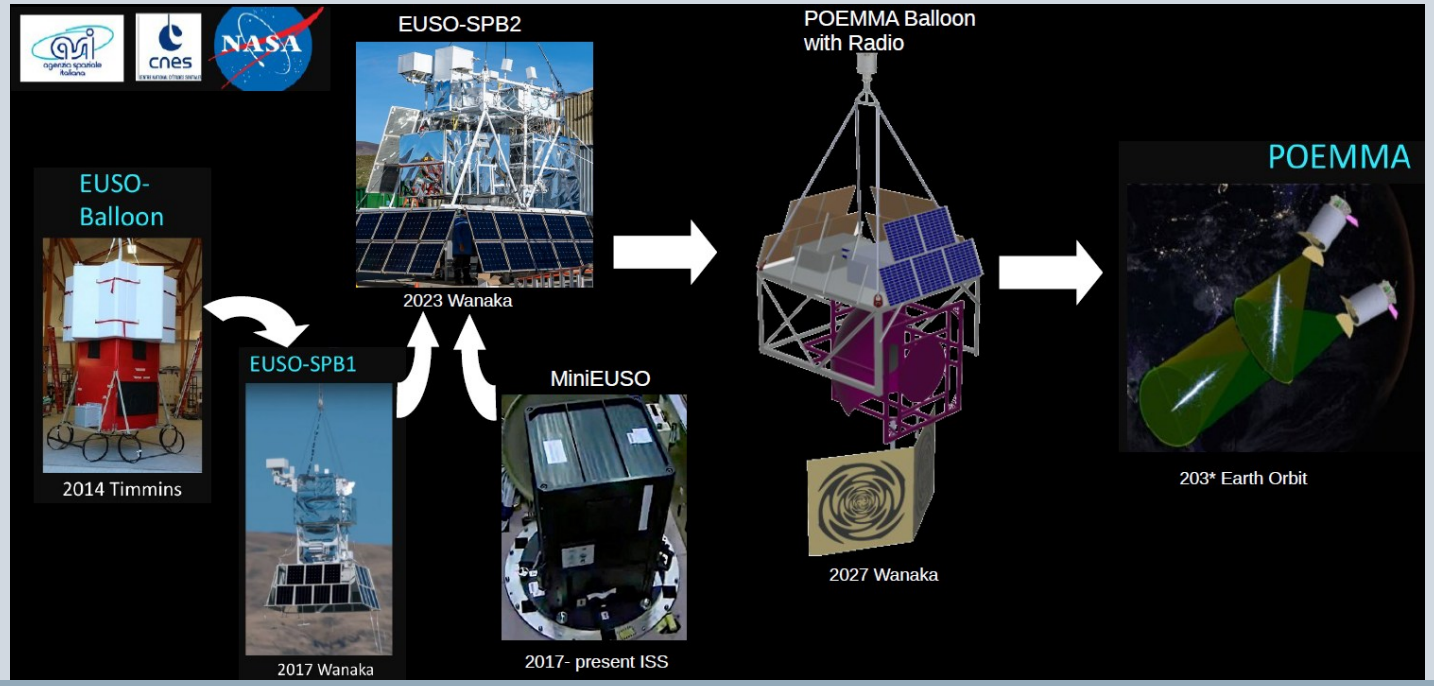
HEPD-02 main improvements:

- Pixel tracker (MAPS modules)
  - ~28 µm pixel pitch
  - First MAPS in space
- 2 Trigger planes
- Range calorimeter planes reduced from 16 to 12 (15x15x1 cm^3 thick)
- Lyso: from 9 cubes to 6 bars (5x15x2.5 cm^3)
  - 2 layers, 3 bars each

Atmospheric shower form space

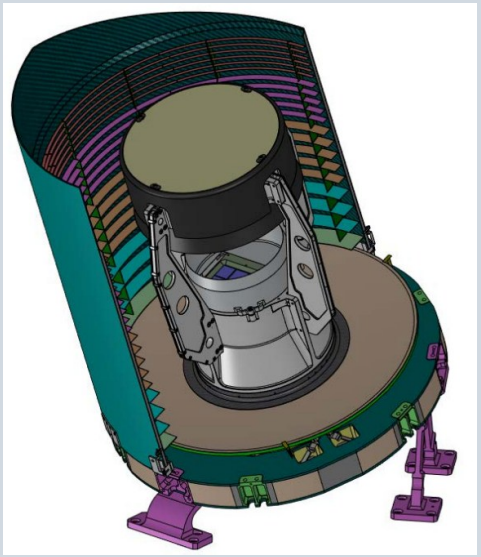


- Measuring CR fluorescence from above
  - Fluorescence, Cherenkov and radio emission
- Long development path
  - Including ballon flight and prototipes on ISS
  - Next step is POEMMA - Balloon with Radio (PBR)
    - Launch 2027

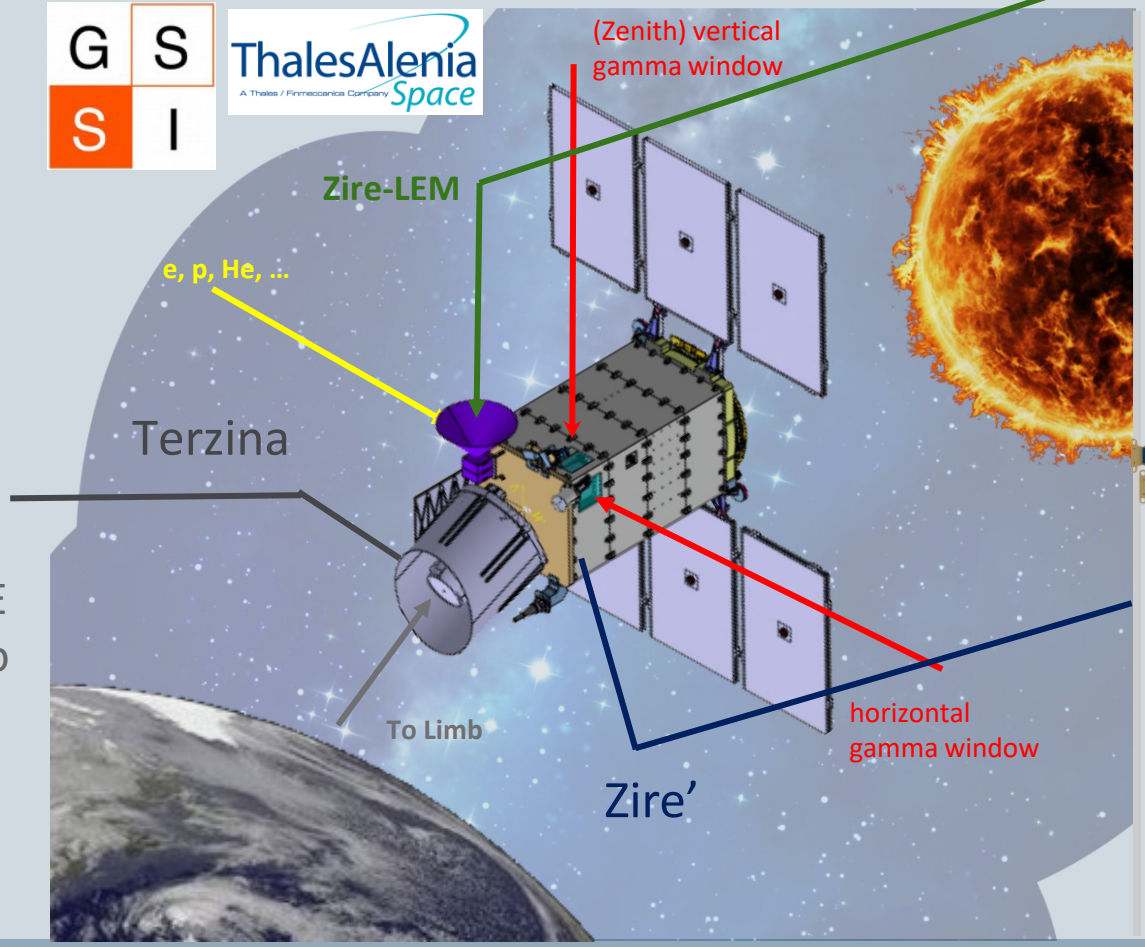


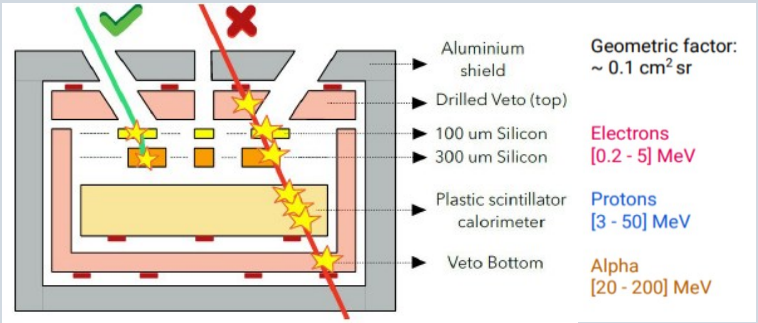
NUSES

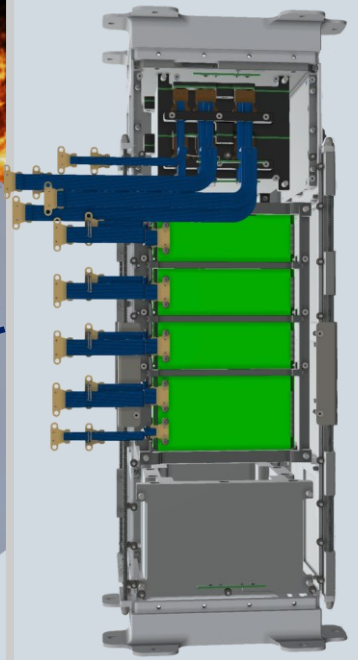
- Current launch window at the end of 2026



Pathfinder for future missions devoted to UHE cosmic rays and neutrino astronomy through **space-based** atmospheric **Cherenkov light** detection.







Measure the flux (E<300 MeV) of cosmic e^-, p and light nuclei

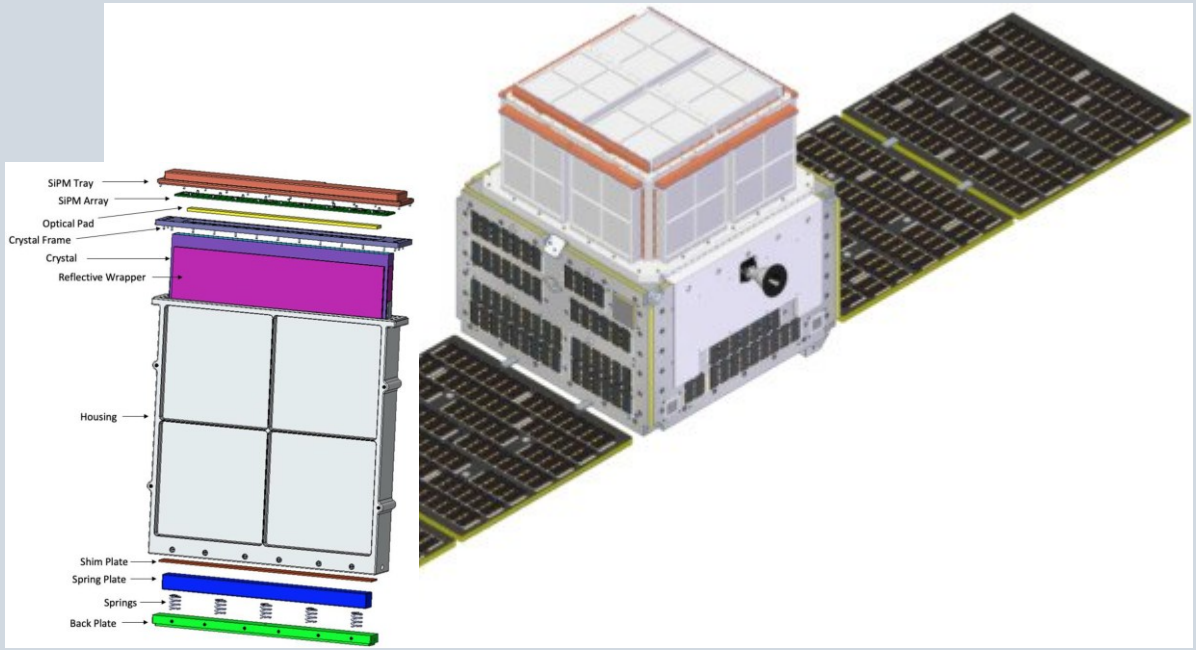
- Fiber TracKer (FTK)
  - 3 double layer XY
- Plastic Scintillator Tower (PST)
  - 32 Plastic Scintillator layers
- Anti-Coincidence System (ACS)
  - 9 PS layers surrounding the detector
- Calorimeter (CALOg)
  - Matrix 4x4x2 of LYSO/GAGG crystals

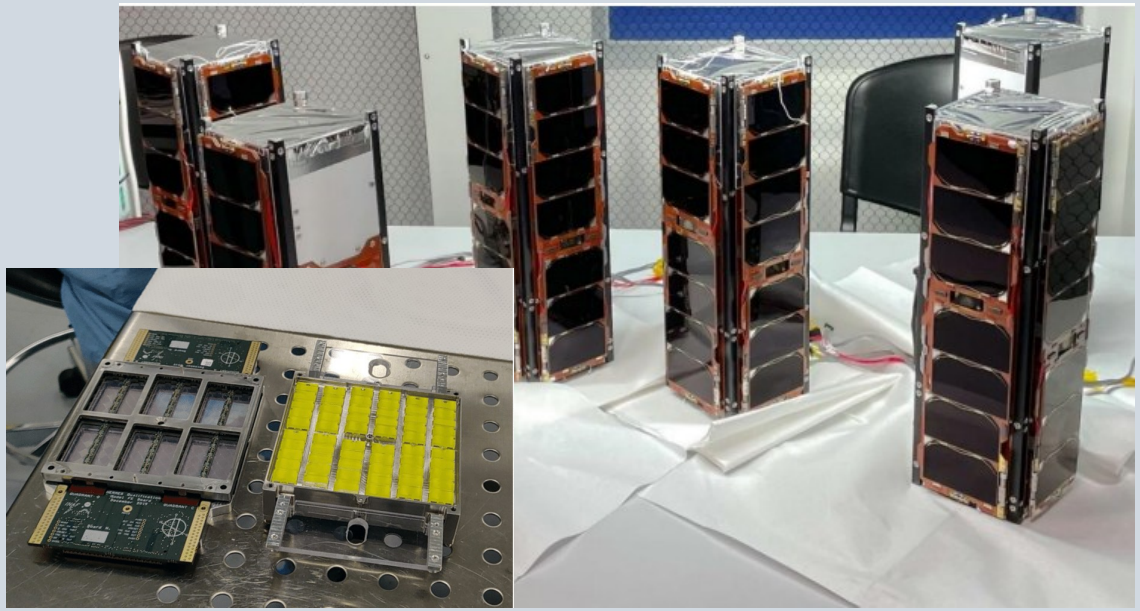
New experiments dedicated to GRB

- NASA StarBurst
  - “Pioneers” program
  - Expected launch in mid-2026
- Similar concept of Fermi GBM
- Larger effective Area (>400% GBM)
- CsI(Tl) Crystal with SiPM readout

No direct INFN participation,
but important scientific interest

- ASI HERMES constellation
  - Pathfinder with 6 cubsat
  - Launch March 15, 2025
- GAGG Crystal + SDD readout (γ-ray + X-ray)
- Currently in commissioning phase

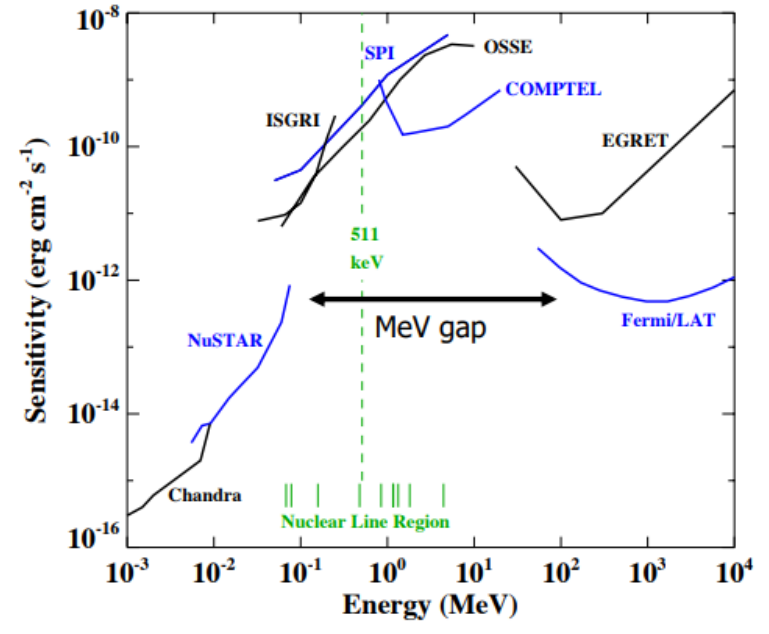




MeV Gap: lack of telescopes in the Compton regime

- Rich scientific potential in the 0.1-100 MeV range
- Compton regime is difficult:
  - Need good position and energy resolution of single hits
  - Combined with large area and good background suppression
- Several proposals failed up to now
  - Performance not good enough
  - Technology not ready

arXiv:2208.07819



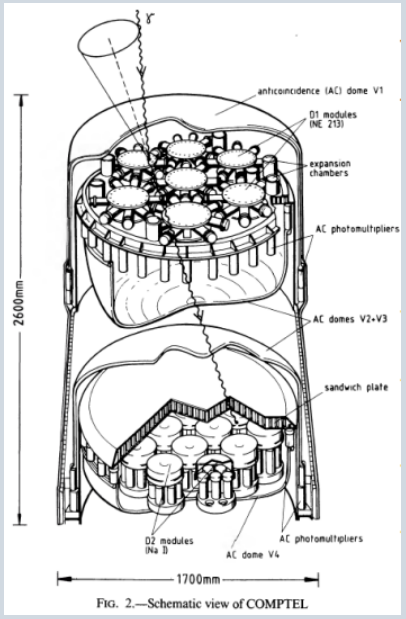
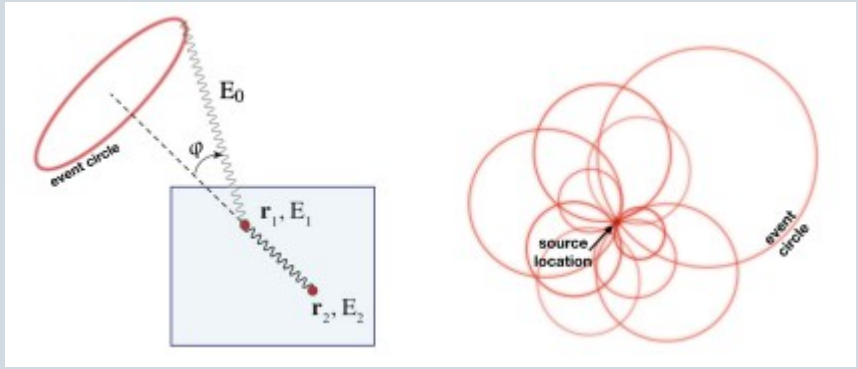


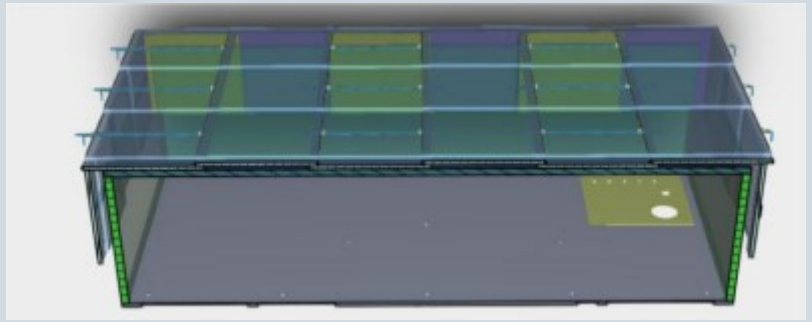
FIG. 2.—Schematic view of COMPTEL

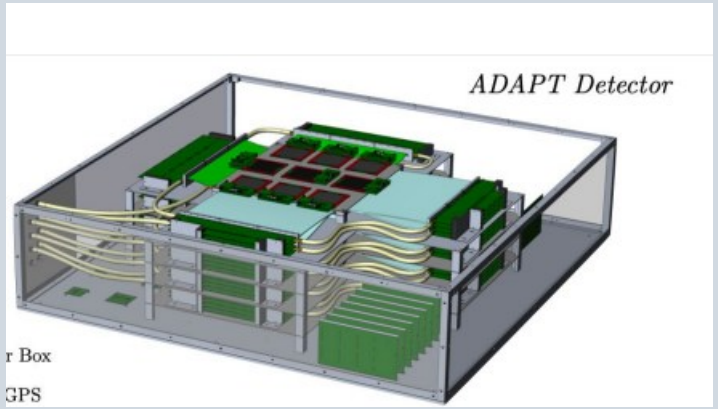


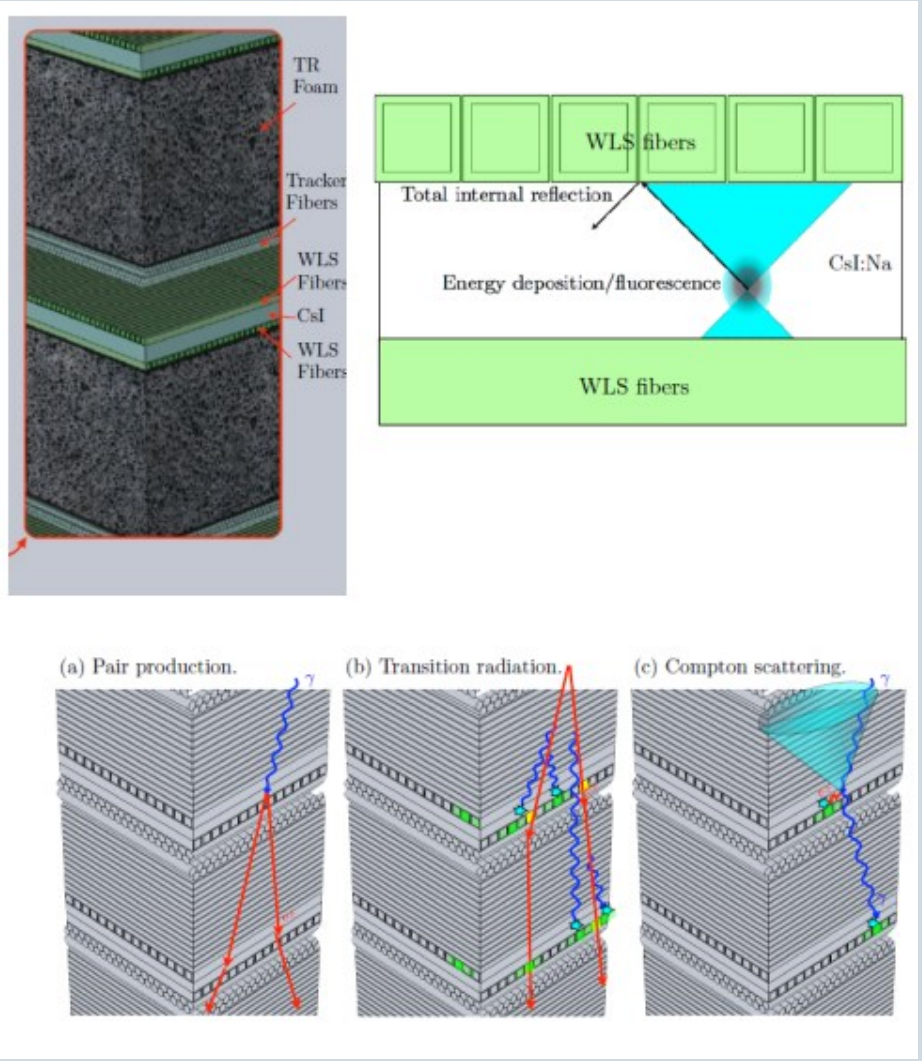
$$\cos\varphi = 1 - \frac{m_e c^2}{E_2} + \frac{m_e c^2}{E_1 + E_2}$$

Antarctic Demonstrator for APT (ADAPT)

- Advanced Particle-astrophysics Telescope detector design
  - Combine a pair and Compton telescope in one design
  - 20 layers of 5mm thick CsI(Na) with crossed wavelength shifting fiber (WLS fiber) readout
  - 20 x - y scintillating optical fiber tracker (SOFT) layers using interleaved 1.5mm round scintillating fibers
- The Antarctic Demonstrator for APT
  - NASA grant for a long-duration flight
  - Winter 2025 launch campaign
- INFN contribution
  - Detector electronics design
  - Full Anticoincidence detector



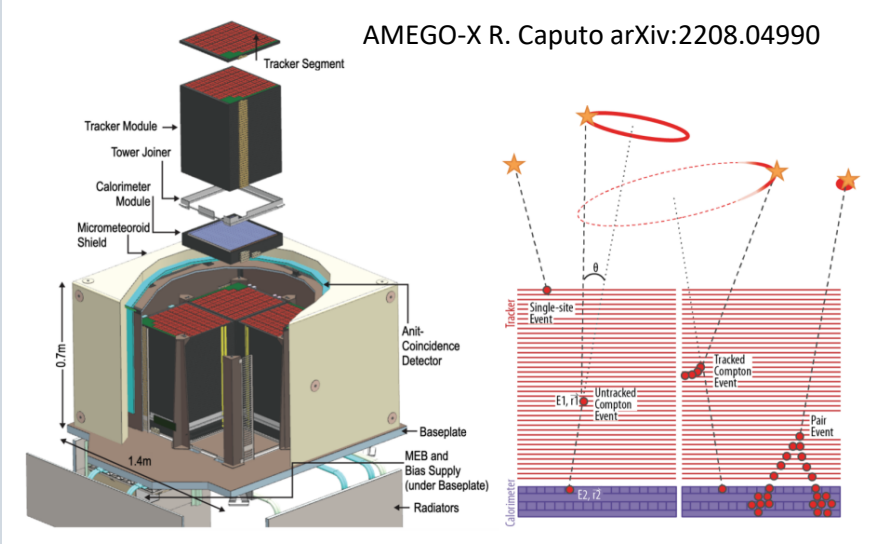


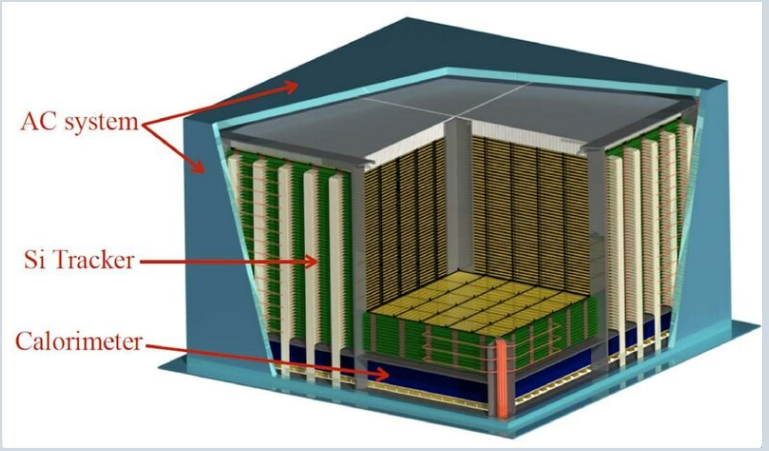


NASA and ESA future opportunities

- Next NASA call (for medium mission) expected in 2027
  - AMEGO-X proposal
    - Silicon tracker + Crystal calorimeter
    - Active Pixel Sensors (AstroPix) specifically developed
    - Failed in 2021 call for lack of TRL
- Next ESA call M8 just opened for a Medium (M) and Fast (F) missions
  - https://www.cosmos.esa.int/web/call-for-missions-2025
    - M-Class Cost at Completion: 670M€
    - Selection of missions for study: end 2026
    - Launch: “around 2041”
  - ASTROGAM proposal
    - Similar concept, details currently under discussion (AstroPix?)
    - Unsuccesfull in previous M5 and M7 calls

AMEGO-X R. Caputo arXiv:2208.04990

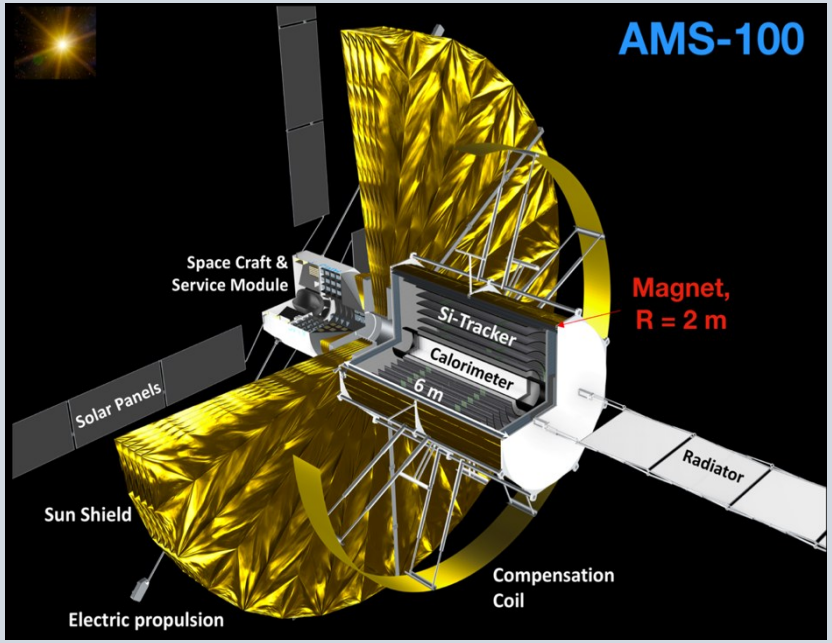




Large Magnetic Spectrometers

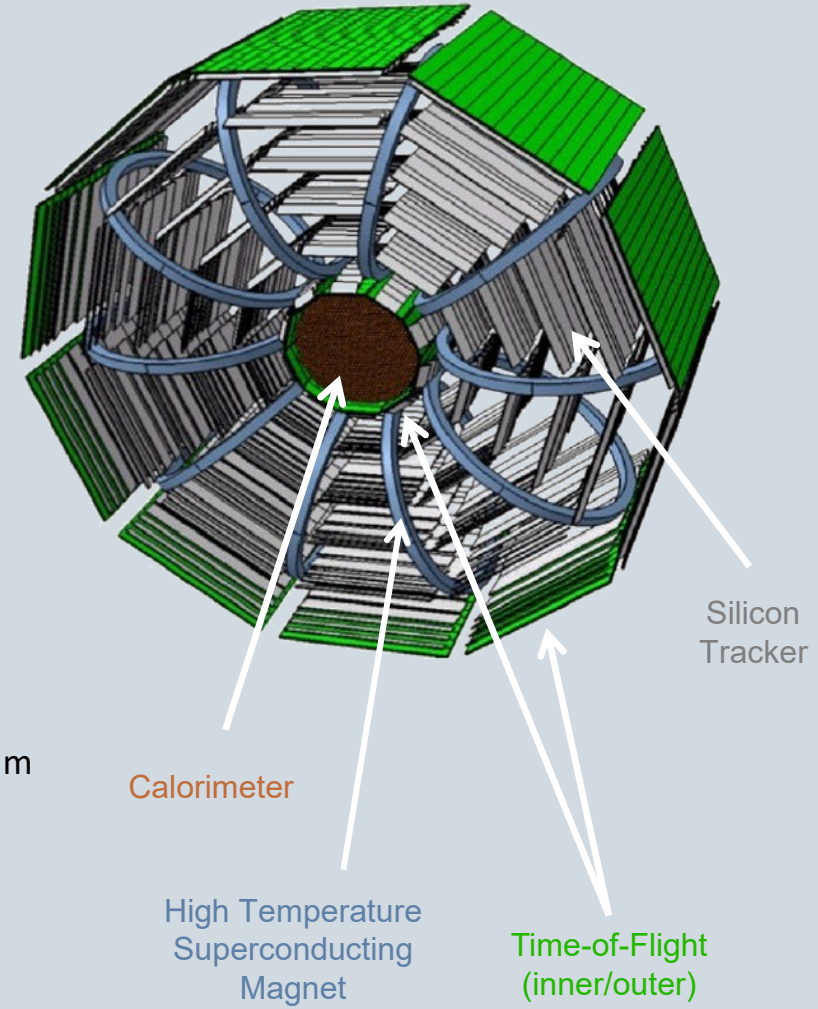
AMS-100

Dimensions	⌀ = 4.4 m, L = 6 m
Weight	40 t
Power	10 kW
Magnetic Field	1 T
Acceptance	100 m^2 sr
MDR	100 TV
Cal. thickness	70 X_0



Voyage 2050
Strategic vision of the ESA Scientific Program

Pathfinder/demonstrator highly recommended



ALADINO

Dimensions	⌀ = 4.4 m, L = 2 m
Det. weight	6.5 t
Power	3 kW
Magnetic Field	0.8 T
Acceptance	>10 m^2sr
MDR	>20 TV
Cal. thickness	61 X_0

Conclusions

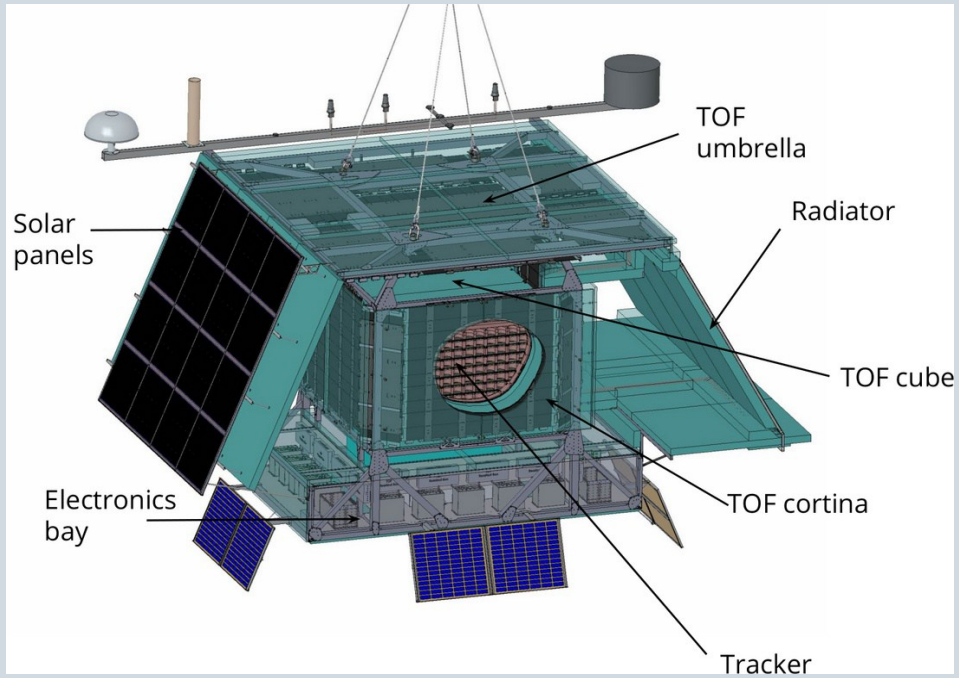
- Great progress in many measurements in recent years
  - Astro-particle physics more complicated than previously expected
    - Not “simple” power-law spectra
- All topics strongly interconnected
  - Need a combination of many measurements for a clear picture
  - Including astrophysics observation at multiple wavelength
- Multi-messenger astrophysics will be more important in the future
  - Transient and source searches
  - Expectation from neutrino observatories
- Workhorse satellites in INFN fleet are getting older
  - Several small mission planned/in construction
  - Several non-INFN mission of interest are in preparation
- Large missions are hostages of international politics
  - Need to be prepared to benefit from any opportunity

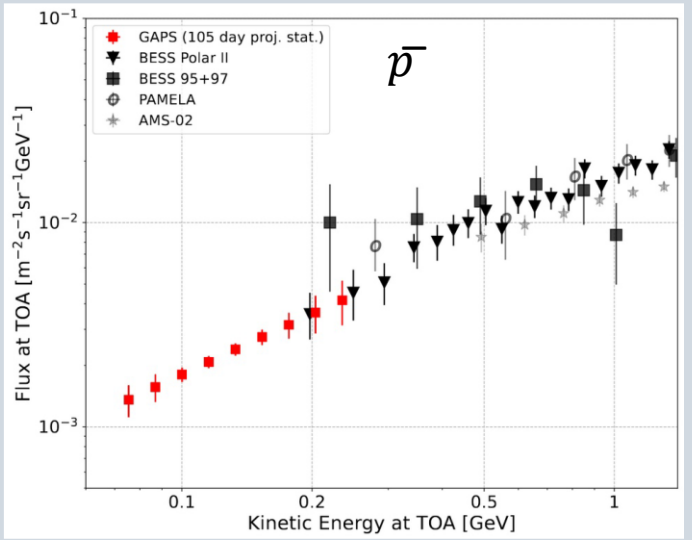
EXTRA

GAPS

- The General AntiParticle Spectrometer dedicated to low-energy cosmic-ray antinuclei search
- Antartic long-duration balloon flight
- Launch attempt in Dec. 2024 was unsuccessful -> next opportunity at the end of 2025

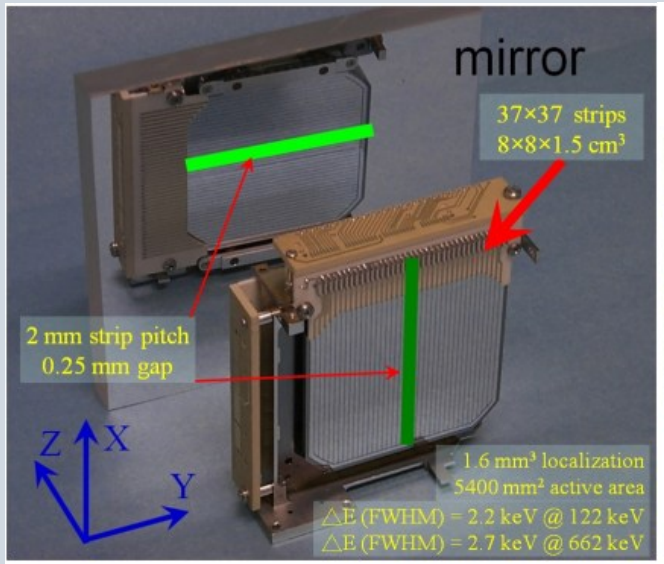
From M. Boezio CSN2 Feb. 2025

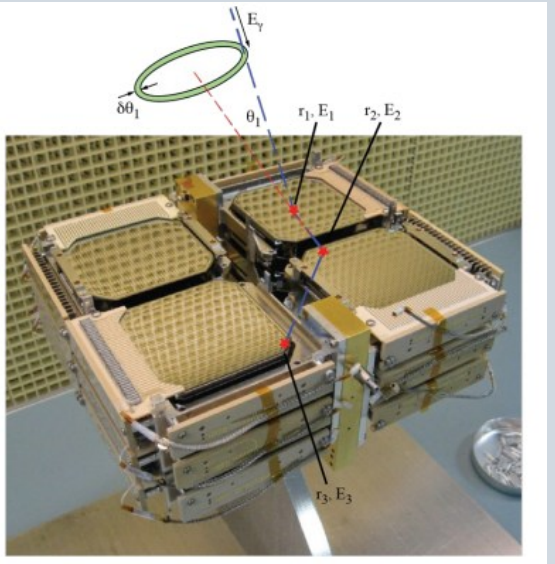


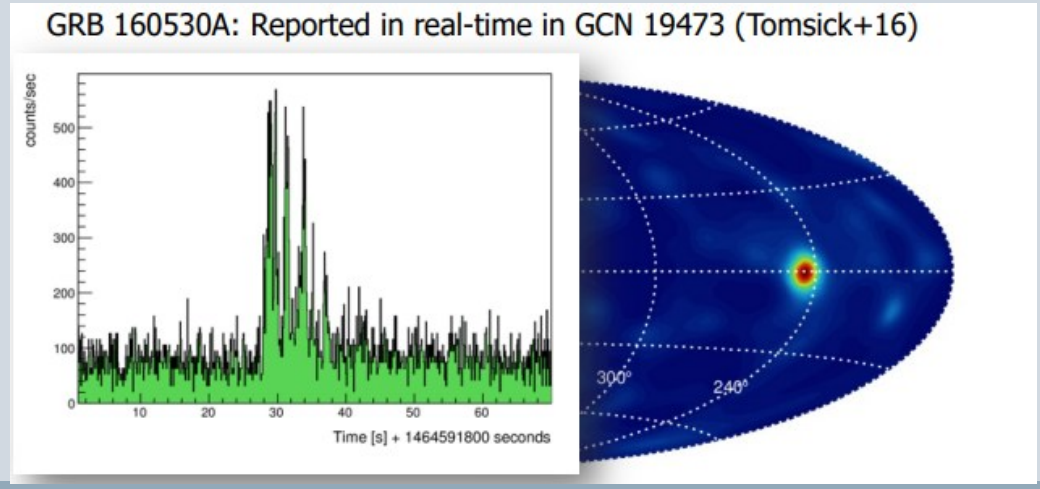


COSI

- Compton telescope for observing 0.2-5 MeV gamma-rays
- NASA Small Explorer satellite
  - Planned launch in 2027
- Discovery space
  - Nuclear lines for studies of nucleosynthesis
  - 511 keV e^-e^+ annihilation line
  - High levels of polarization
  - Multimessenger astrophysics
- Germanium double-sided strip detectors
  - Semiconductor detectors at cryogenic temperatures
  - 3-dimensional position sensitivity
  - Proof of concept demonstrated with COSI-balloon
- Results from 46-day flight in 2016
  - GRB 160530A
  - Lines at 511 keV and ^{26}Al (~1.8MeV)
  - Crab nebula





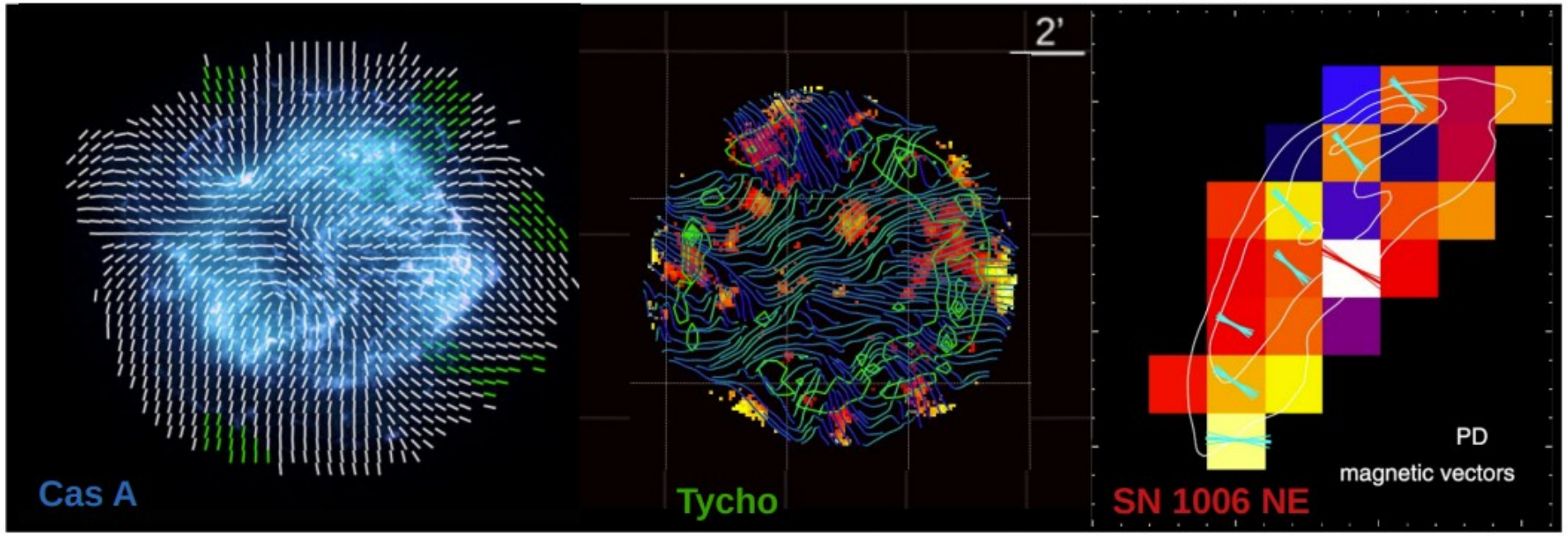


J. Tomsick ASAPP2023

IXPE
Imaging
X-Ray
Polarimetry
Explorer

SNR WITH IXPE

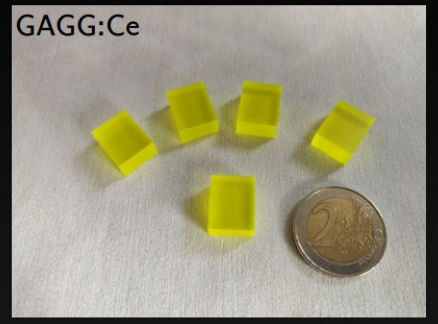
THE THREE REPORTED 1ST YEAR TARGETS

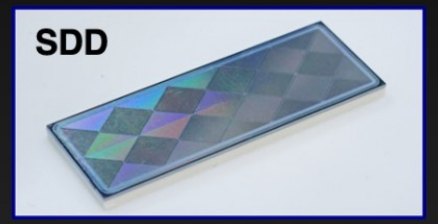


- Same radial magnetic field morphology
- Different polarization degree (different turbulence levels?)
- Possible dependence of turbulence on ambient medium density

	PD (rim) %	PD (SNR) %	PD (peak) %	Magnetic field morphology
Cas A	4.5 ± 1.0	2.5 ± 0.5	~15	Radial
Tycho	12 ± 2	9 ± 2	23 ± 4	Radial
SN 1006 NE	22.4 ± 3.5	...	31 ± 8	Radial

From
R. Ferrazzoli
Vulcano2024





Segmented design
(60 GAGG:Ce crystals, 120 SDD cells)

Redundancy

Particle bkg suppression

Mass: **1.57 kg**

Power: **2.14 W** (max)

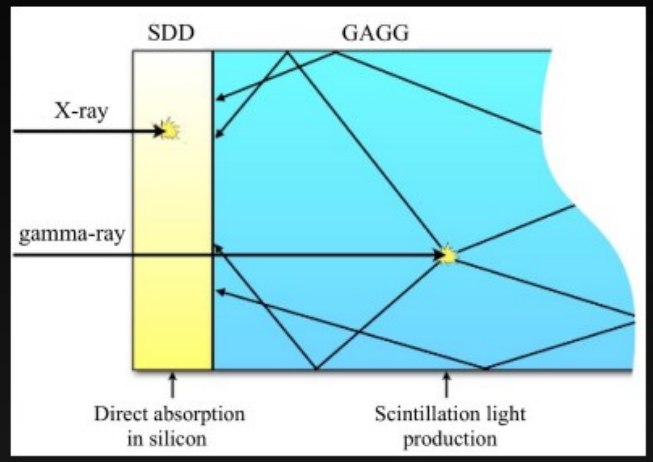
Dim.: **10×10×10 cm³**

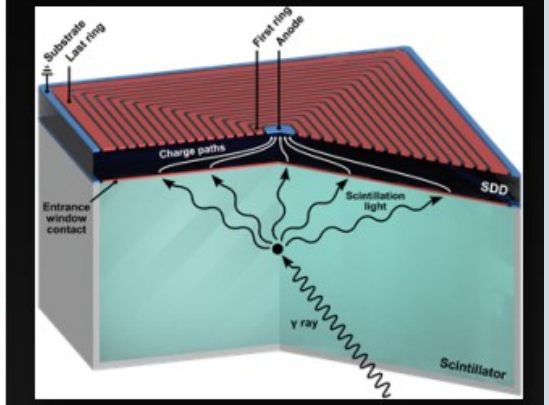
THE HERMES PATHFINDER MISSION DESIGN

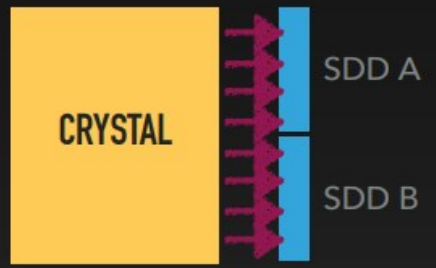
Siswich principle:

Use the Silicon Drift Detector both as a direct X-ray detector and as a photodetector for scintillation photons

Huge sensitivity band in a compact and segmented design







Discrimination between X and S events with **dual readout** of a single crystal

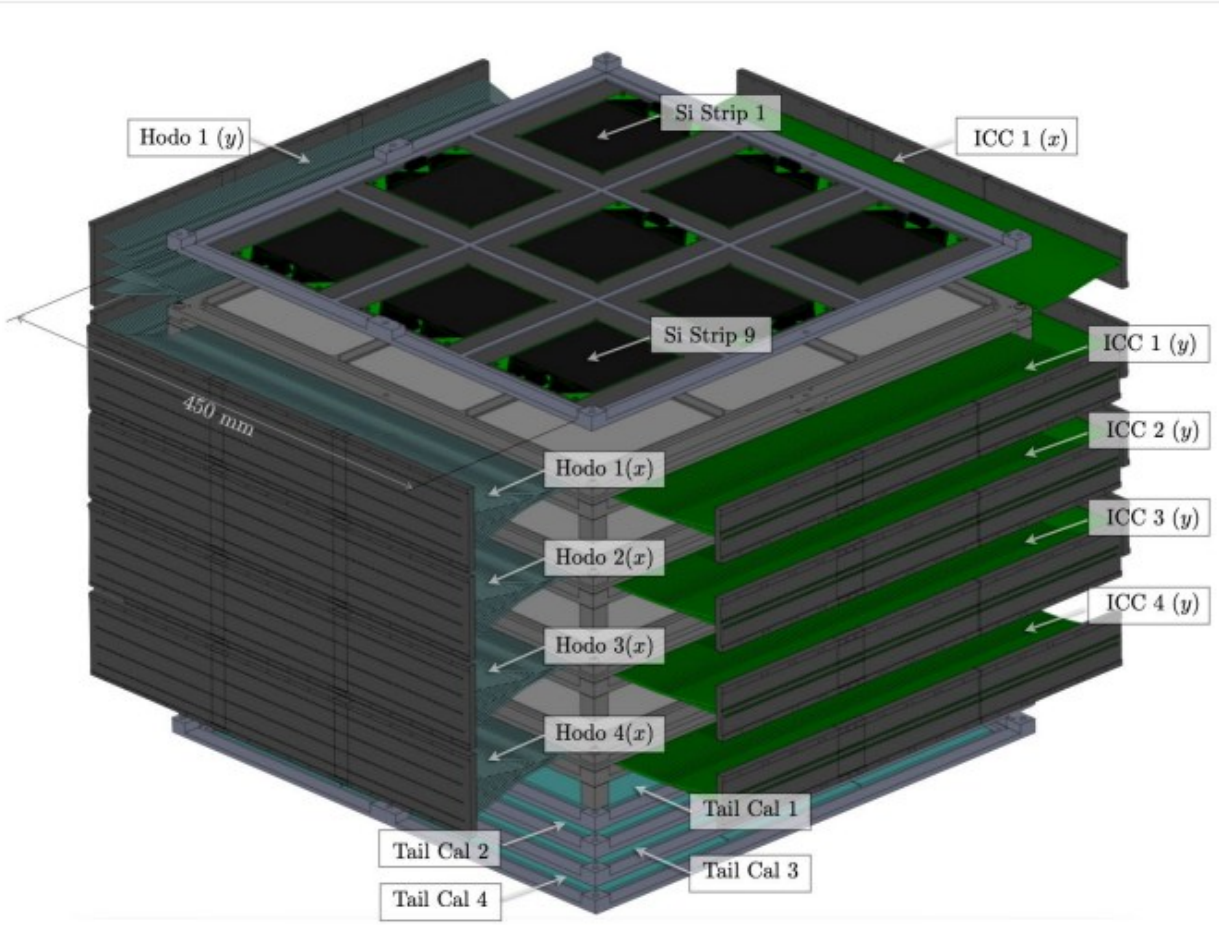
Essentially: 2 instruments in one

ADAPT detector stackup

- **4 layers**
- **3x3 modular design for 45x45cm² active area**

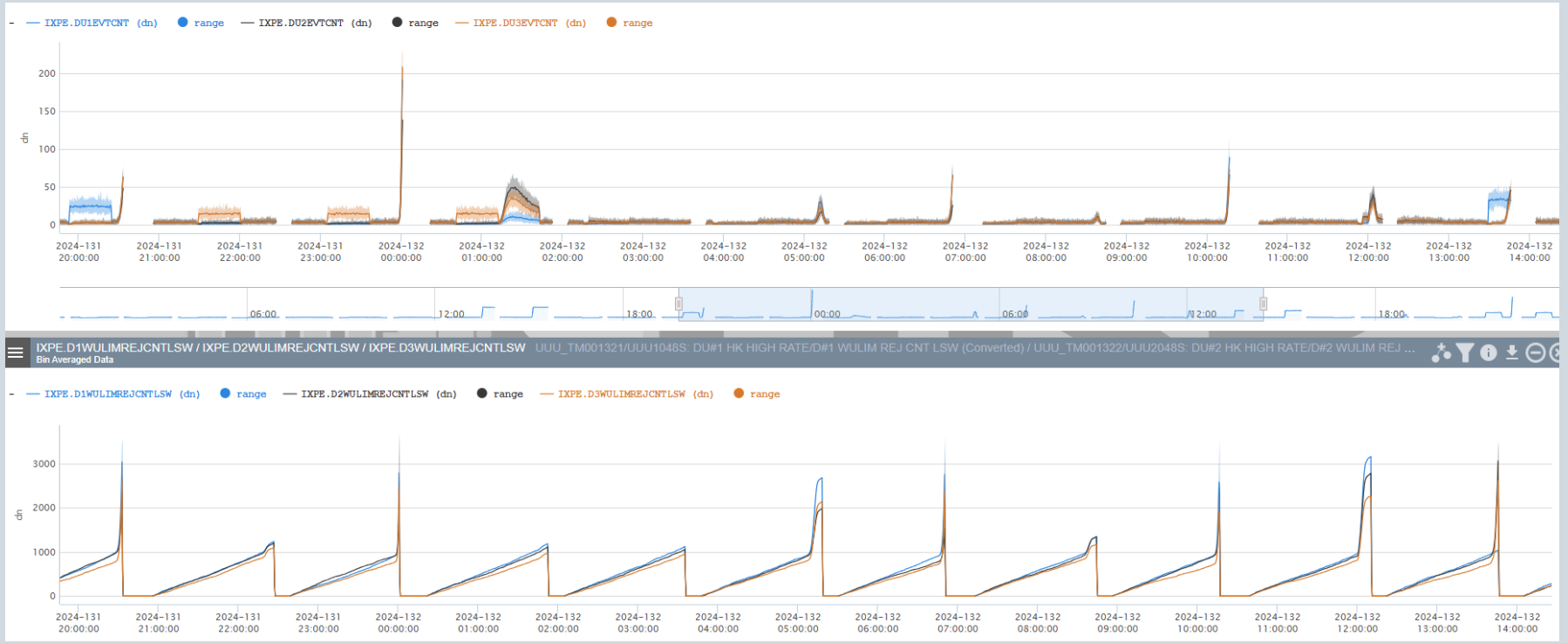
Detector stackup

1. **SSDs:** *Silicon Strip Detectors* for CR charge identification, Compton.
2. **ICCs:** *Imaging CsI Calorimeter* modules. CsI:Na tiles with crossed 2mm WLS fiber+SiPM readout and SiPM CsI *Edge Detectors.*
3. **Hodoscope:** *Scintillating Fiber Tracker* modules, crossed interleaved 1.5 mm scintillating fibers+SiPM readout.
4. **Tail Counters:** Integrating CsI modules with Edge Detectors only



Di Venere L. - ASAPP 2023 6

IXPE event rate during G5 2024 May 11 geomagnetic storm



Da: **SWPC Product Subscription Service** <SWPC.Products@noaa.gov>
Date: sab 11 mag 2024, 04:58
Subject: ALERT: Geomagnetic K-index of 9 (G5)
To: <alessio.trois@inaf.it>

```
Space Weather Message Code: ALTK09
Serial Number: 7
Issue Time: 2024 May 11 0246 UTC

ALERT: Geomagnetic K-index of 9o
 Threshold Reached: 2024 May 11 0240 UTC
Synoptic Period: 0000-0300 UTC

Active Warning: Yes
NOAA Scale: G5 - Extreme
```

https://en.wikipedia.org/wiki/May_2024_solar_storms