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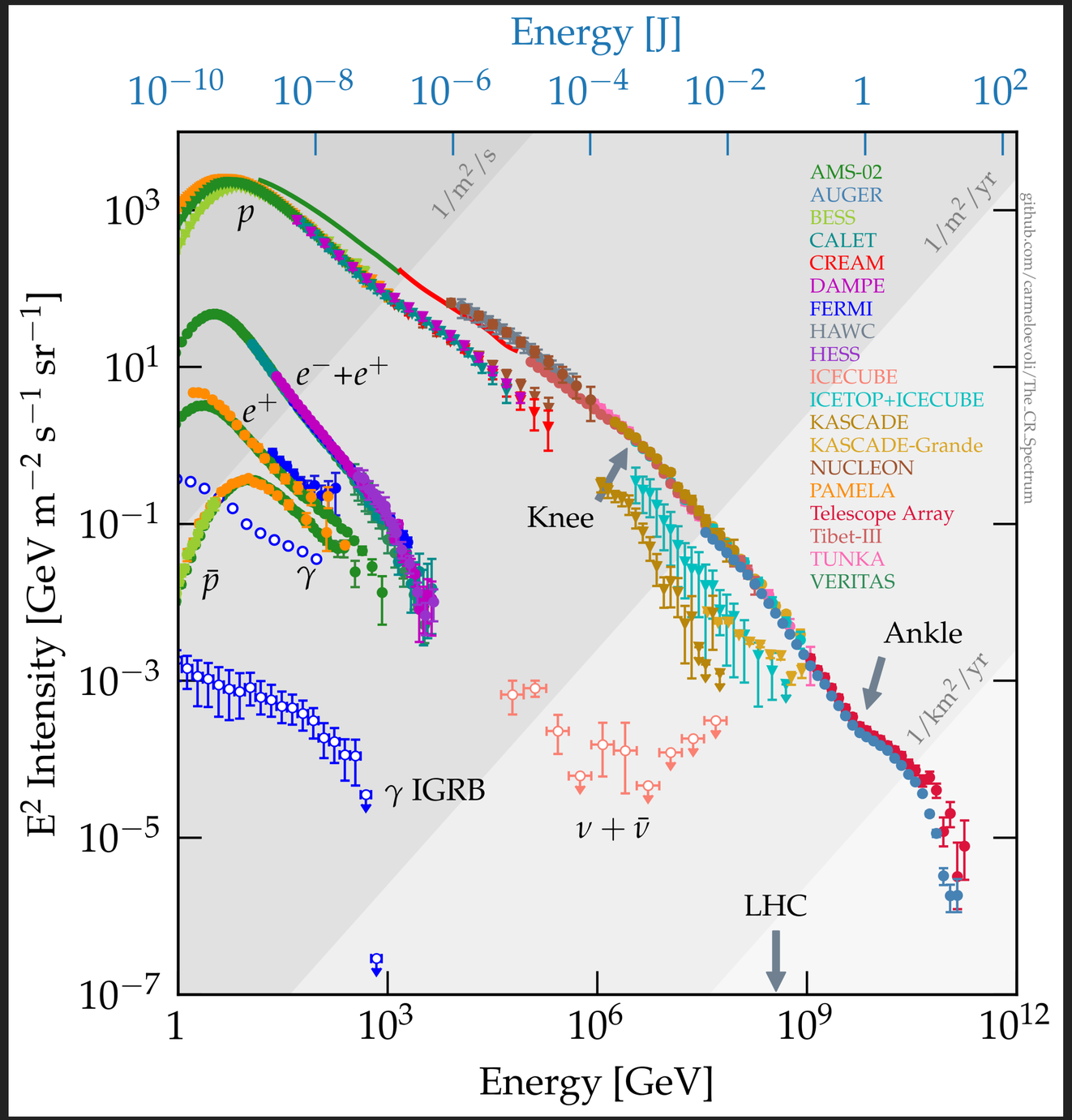
INFN - SECTION OF ROME "TOR VERGATA", ITALY

RECENT RESULTS ON COSMIC RAYS DIRECT OBSERVATIONS



CR FLUX & COMPOSITION

Energetic particles and ionized nuclei from outer space

- Many orders of magnitude in energy and flux:
  - E < 100 TeV: direct detection
  - E > 100 TeV: indirect detection
- Roughly, the all-particle spectrum is a “power law” in many orders of magnitude of energy and intensity, with several features (knee, second knee, ankle, …):
  - $\gamma = 2{,}7$ until 10^{16} eV
  - $\gamma = 3{,}0$ after 10^{16} eV

MAIN RESEARCH LINES FOR "DIRECT DETECTION"

Mainly concerning Galactic Cosmic Rays!

- CR flux reconstruction up to the **highest energy band** (looking for sources and acceleration mechanisms, …)
- CR **compositions studies** (looking for source material, dust/gas distribution, nucleosynthesis, selection effects, …)
- CR **flux modulation** in the low energy band (looking for effects from heliosphere/ magnetosphere, …)
- **Antimatter component** in CRs (looking for dark-matter and anti-matter limits, nearby sources, …)

According to the physics line, different detections techniques have been adopted

EXISTING PLATFORMS

- **Balloon experiments** (CREAM, ATIC, BESS-Polar, TRACER, TIGER&SuperTIGER, ...): very popular in the 80's, but later on they were subsituted by satellite. They returned popular especially with the **NASA Long and Ultra-long Duration Balloon Program (LDB and ULBD)**.

- **Satellite experiments** (PAMELA, FERMI, DAMPE, NUCLEON, ...): started from 2000. No residual atmosphere but challenging&expensive. Several constraints imposed on experiments.

- **Space station experiments** (AMS, CALET, ISS-Cream,...)

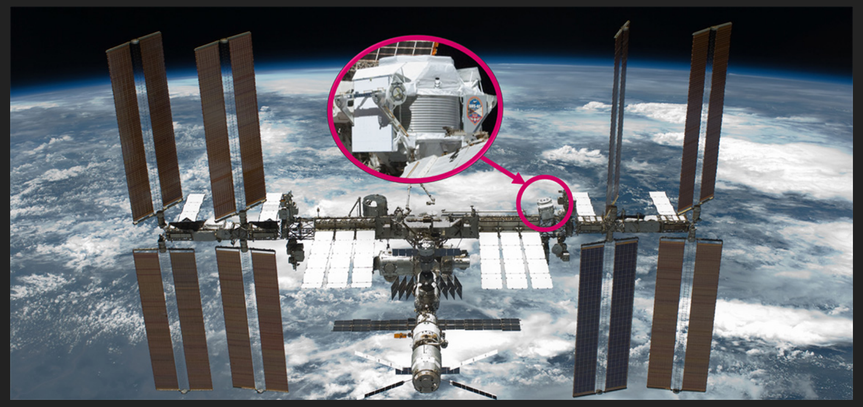
CURRENT AND PAST EXPERIMENTS

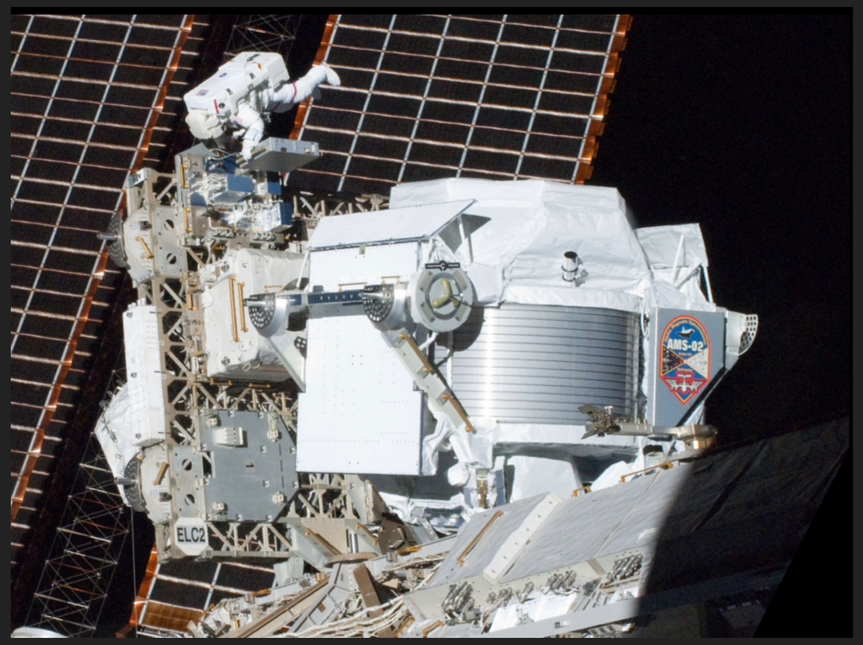
Main differentiation:

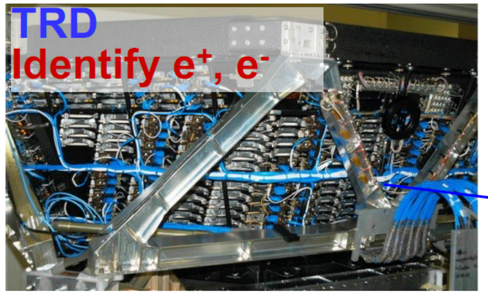
1. **Spectrometers:**
   - Sign of the charge (antimatter, isotopes)
   - Limit in energy by magnetic field
2. **Calorimeters**:
   - Higher energy window

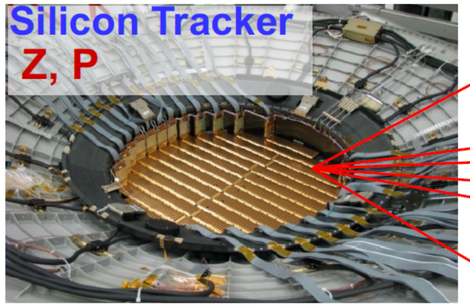
ALPHA MAGNETIC SPECTROMETER "AMS-02"

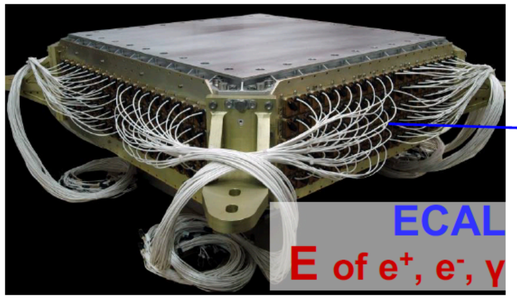
Launched May 16th, 2011, on ISS



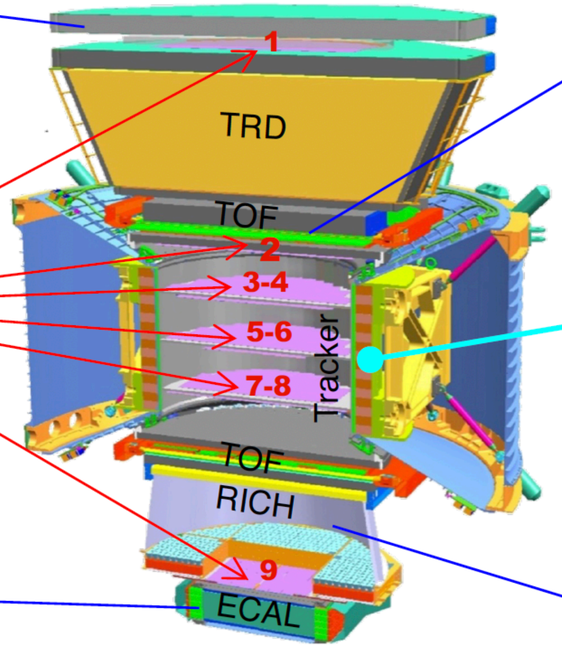




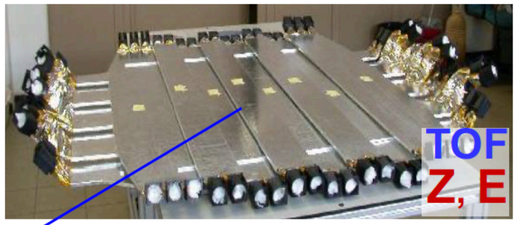


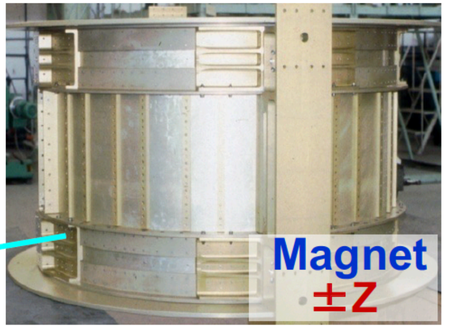


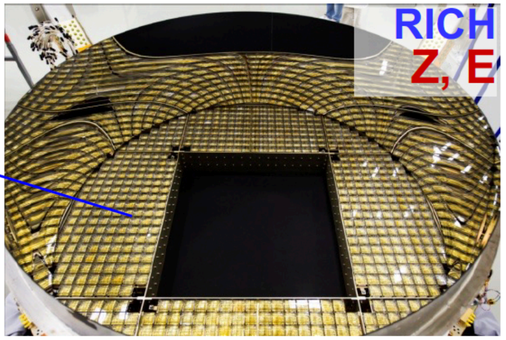
Z, P independently measured by Tracker, RICH, TOF and ECAL



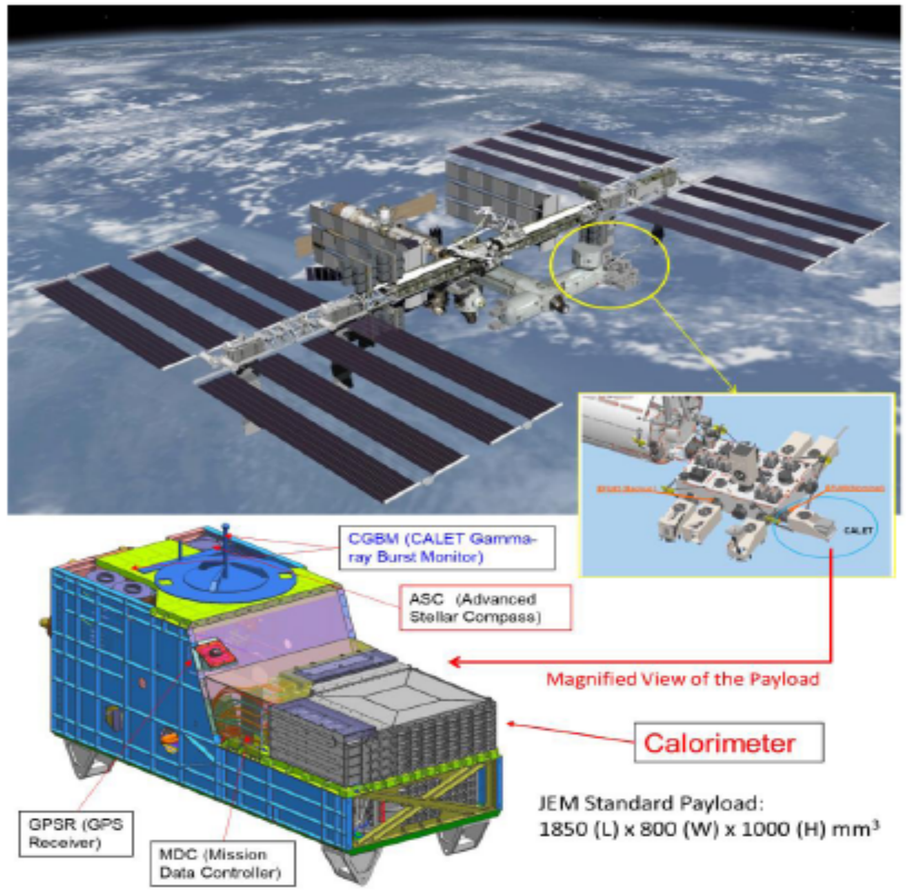
On ISS since 16 May 2011



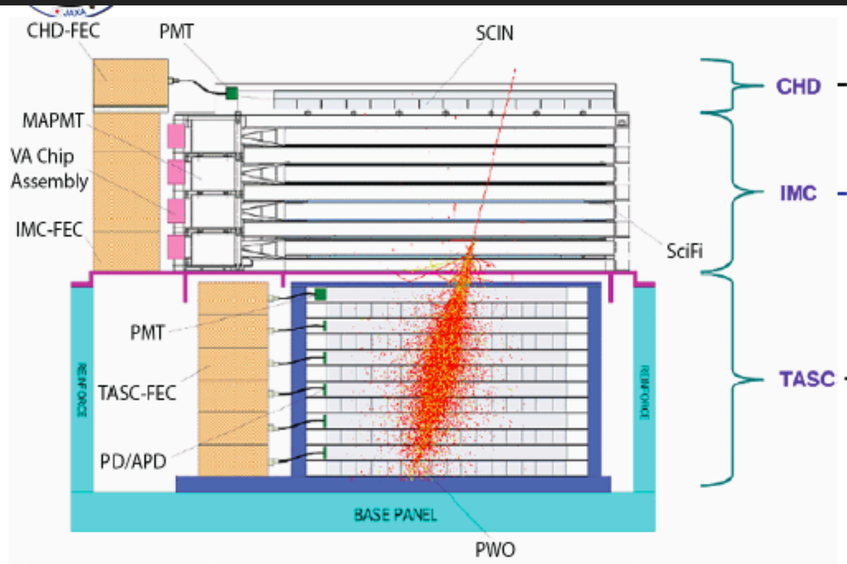




CALORIMETRIC ELECTRON TELESCOPE "CALET" Launched August 19th, 2015, on ISS



Continues stable observation since Oct. 13, 2015 and collected ~1.8 billion events so far.



CHD – **CHarge Detector (CHD)**
(Charge Measurement Z=1-40)

IMC – **Imaging Calorimeter (IMC)**
(Particle ID, Direction)
Total Thickness of Tungsten (W): 3 X_0 , 0.1 λ_I
Layer Number of Scifi Belts: 8 Layers × 2(X,Y)

TASC – **Total Absorption Calorimeter (TASC)**
(Energy Measurement, Particle ID)
PWO 20mm x 20mm x 320mm
Total Depth of PWO: 27 X_0 (24 cm), 1.2 λ_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: 1mm² 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)

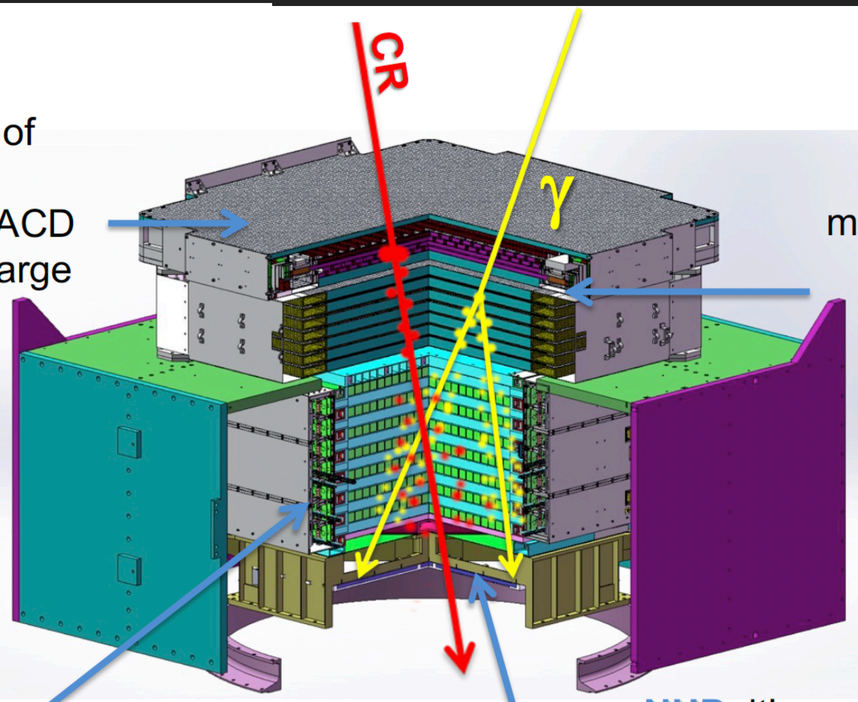
DARK MATTER PARTICLE EXPLORER "DAMPE"

Launched December 17th, 2015

Satellite-borne particle detector, project of the *Strategic Pioneer Program on Space Science, promoted by the Chinese Academy of Sciences (CAS).*

ALTITUDE: 500 km
PERIOD: 95 minutes
ORBIT: Sun-synchronous

- Study of Cosmic Rays composition, origin and propagation
- Search for Dark Matter signatures in lepton and photon spectra
- High Energy Gamma-Ray Astronomy



PSD: double layer of scintillating strip detector acting as ACD (anti-counter) + charge measurement

STK: 6 tracking double layer + 3 mm tungsten plates. Used for particle track, charge measurement and photon conversion (~ 2 X_0)

BGO: the calorimeter is made of 308 BGO bars in hodoscopic arrangement (~31 X_0). Performs energy measurements, hadron/lepton identification (*e/p rejection*), and trigger

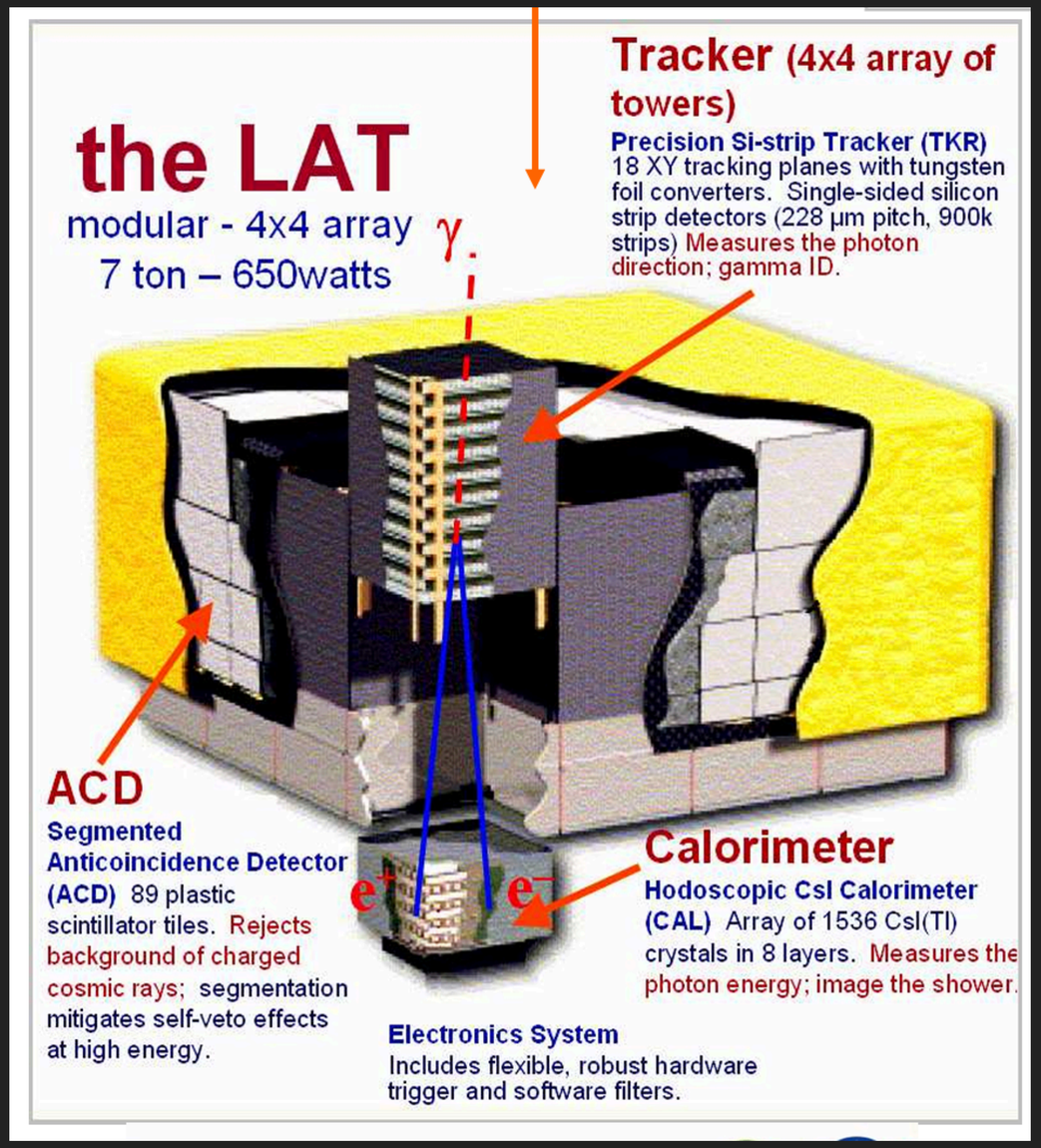
NUD: it's complementary to the BGO e/p rejection, by measuring the thermal neutron shower activity. Made up of boron-doped plastic scintillator

LARGE AREA TELESCOPE ON BOARD "FERMI"

Launched June 11th, 2008

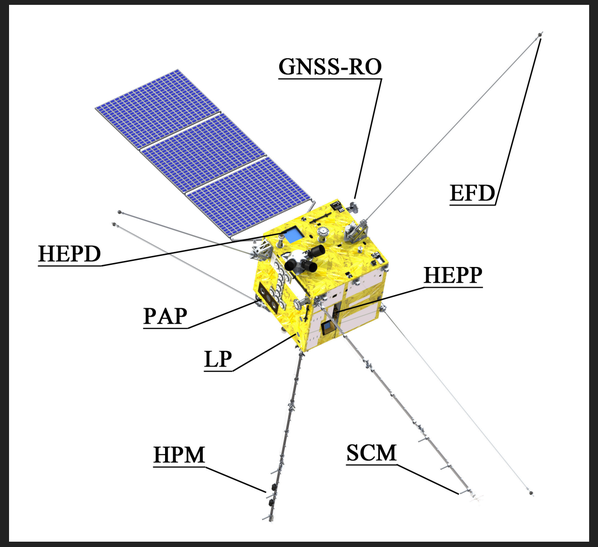
The Fermi Gamma-ray Space Telescope circles Earth every 96 minutes in a 26° inclination orbit at an altitude of 535 km.

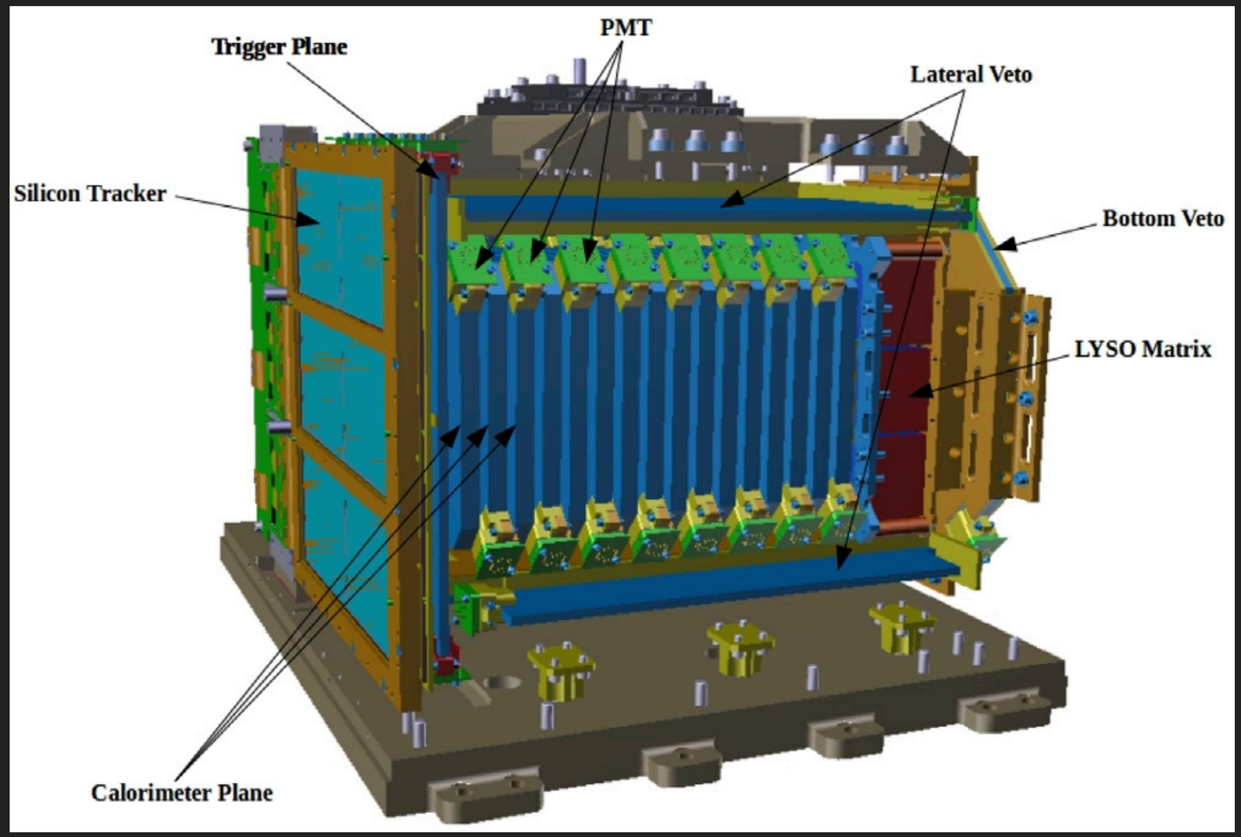
Fermi carries two scientific instruments, the Large Area Telescope (LAT) and the Gamma-ray Burst Monitor (GBM).



HIGH ENERGY PARTICLE DETECTOR ON BOARD "CSES-01" Launched Feb. 18th, 2018

The CSES-01 satellite is based on the Cinese CAST2000 platform and moves in a sun-synchronous orbit at 500 km altitude and with an orbital inclination of approximately 98°. It hosts several payloads, among them HEPD-01



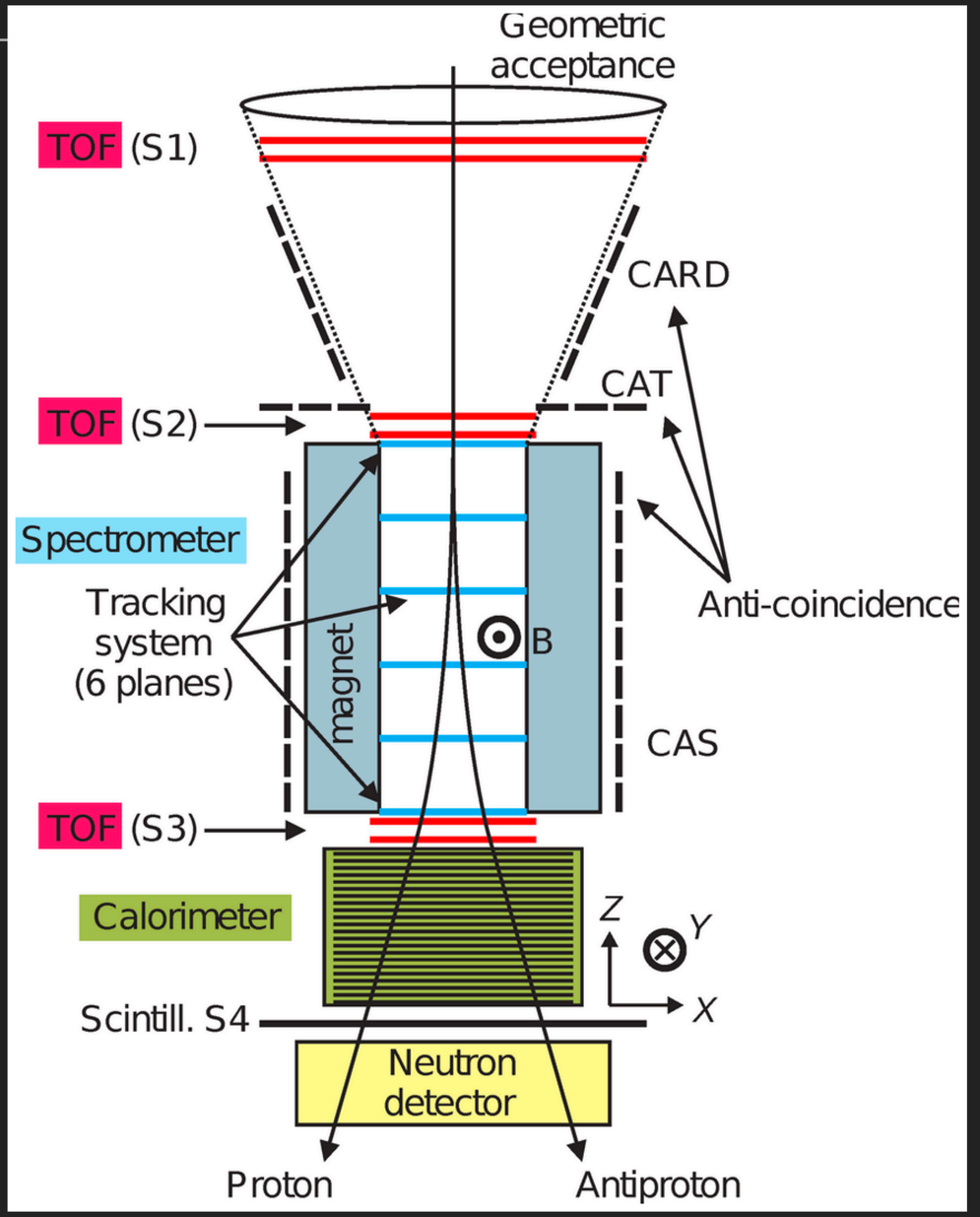


HEPD-01 functional scheme

PAST EXPERIMENTS : "PAMELA" (2006-2016)

FLOWN ON RUSSIAN RESURS-DK1 SATELLITE

FROM JUNE 2006 UNTIL JANUARY 2016



PAMELA detector

"BESS-POLAR I AND II" (2004 & 2007)

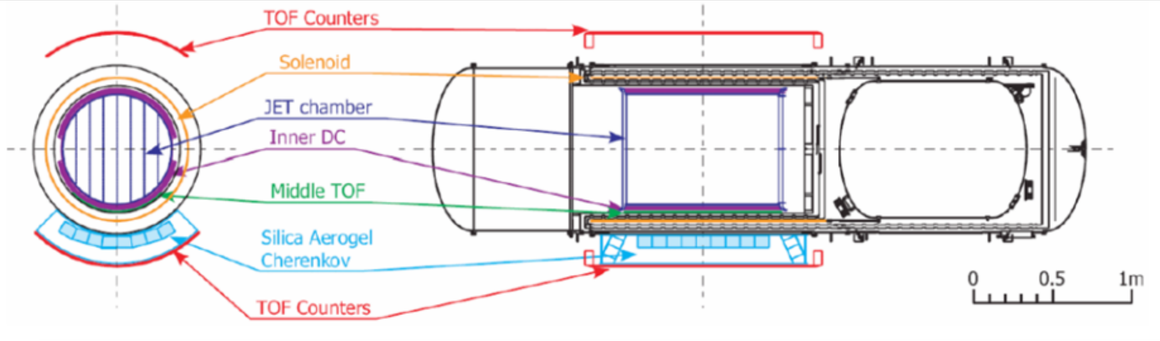
The BESS Project

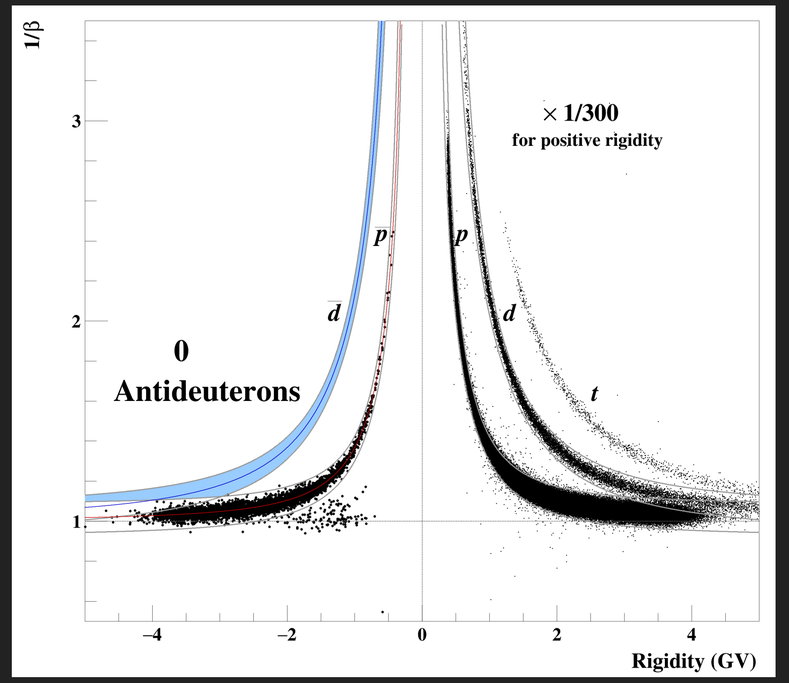
2 BESS-Polar I and II experiment

BESS-Polar I & II flights were carried out over Antarctica.

BESS-Polar I (green),
BESS-Polar II (1st :blue, 2nd :red)

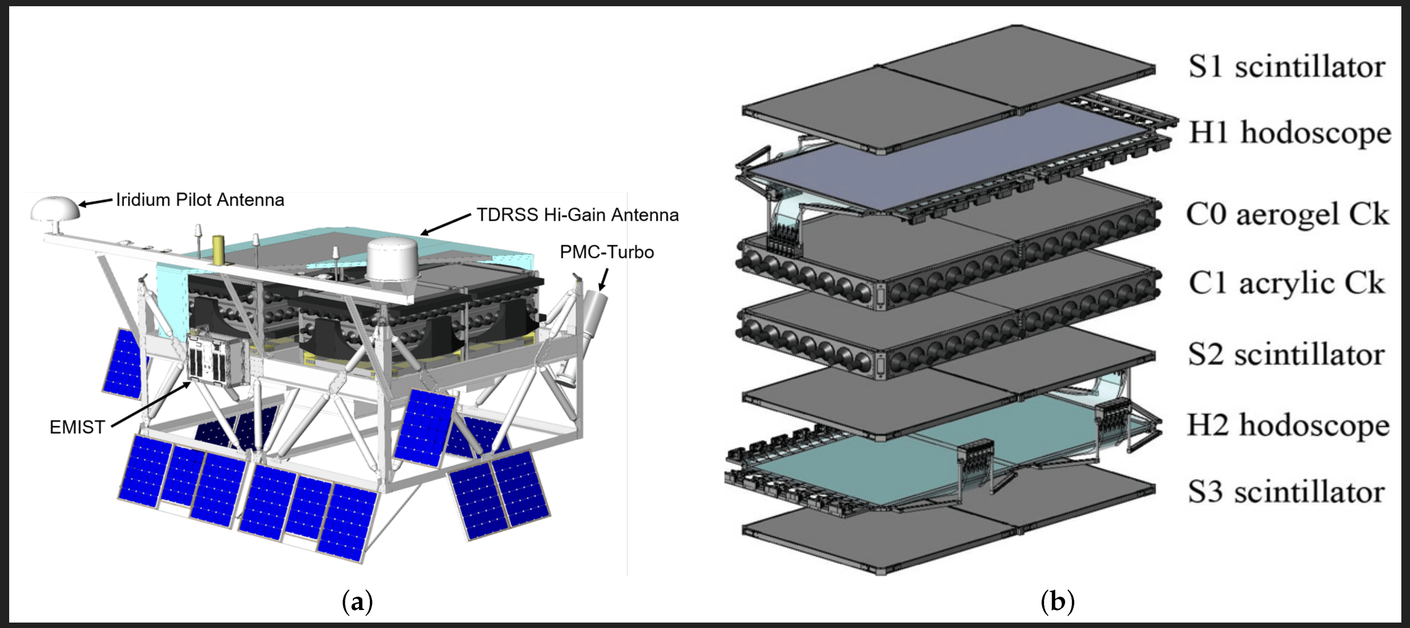
	BESS-Polar I	BESS-Polar II
Launch date	Dec. 13th ,2004	Dec. 23rd , 2007
Observation time	8.5 days	24.5 days
Cosmic-ray observed	9 x 10^8 events	4.7 x 10^9 events
Flight altitude	37~39km (5~4g/cm^2)	~36km (6~5g/cm^2)

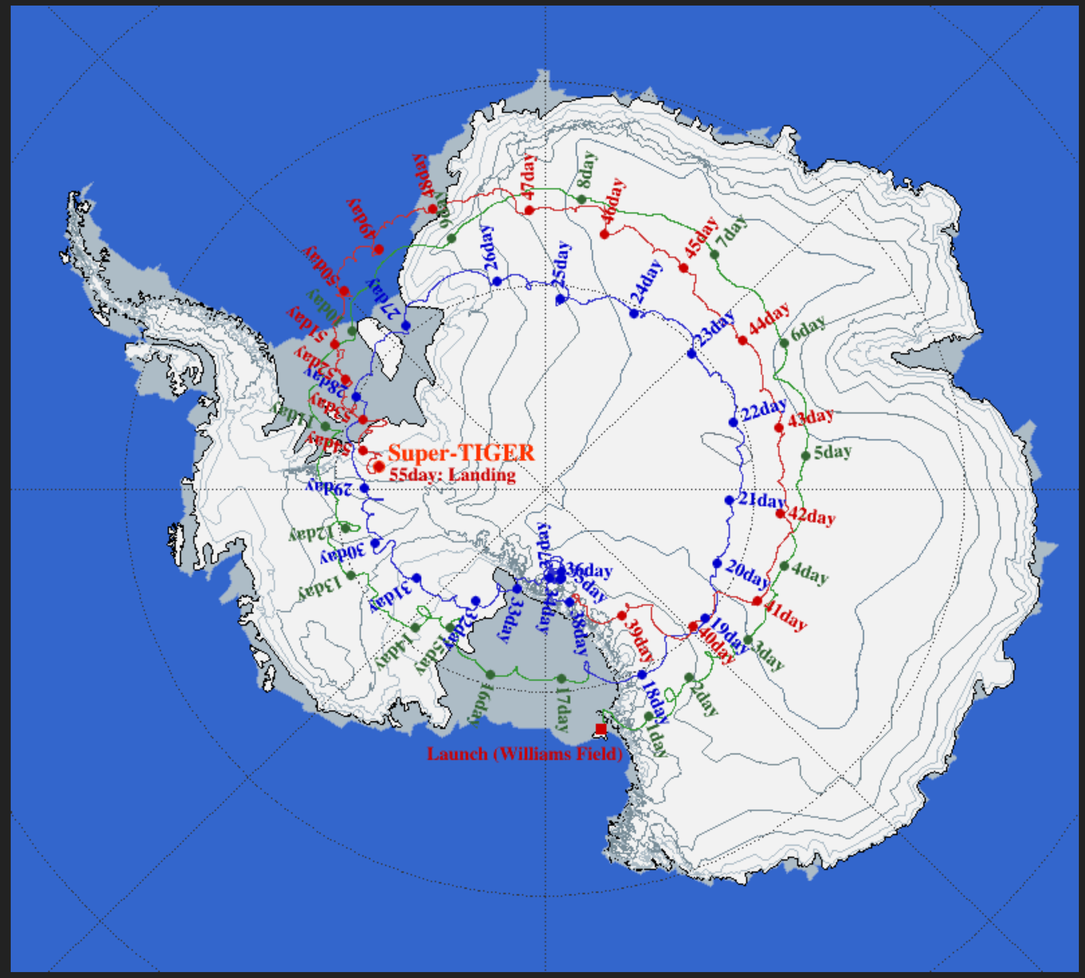




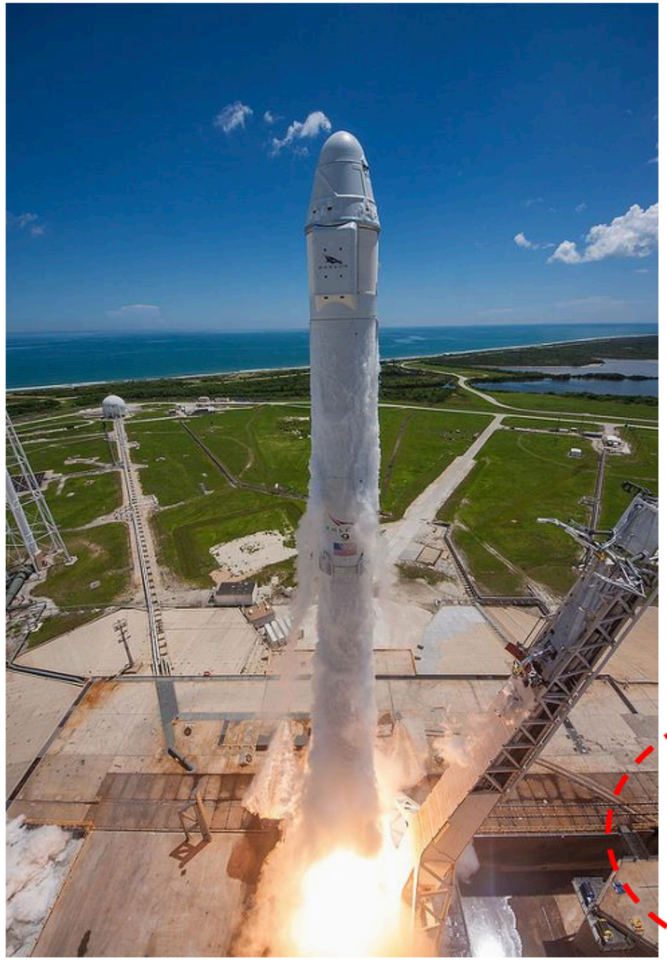
SUPER TRANS IRON GALACTIC ELEMENT RECORDER "SUPER-TIGER" (2012-2019)

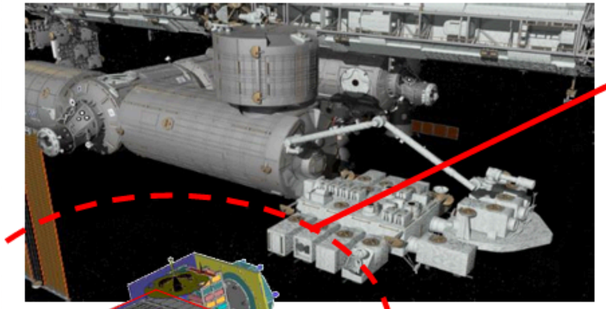
Building on the success of TIGER (launched in 2001 and 2003), SuperTIGER (Super Trans-Iron Galactic Element Recorder) had a record-breaking 55-day flight over Antarctica in December 2012 – January 2013 and a 32-day flight in December 2019 – January 2020.

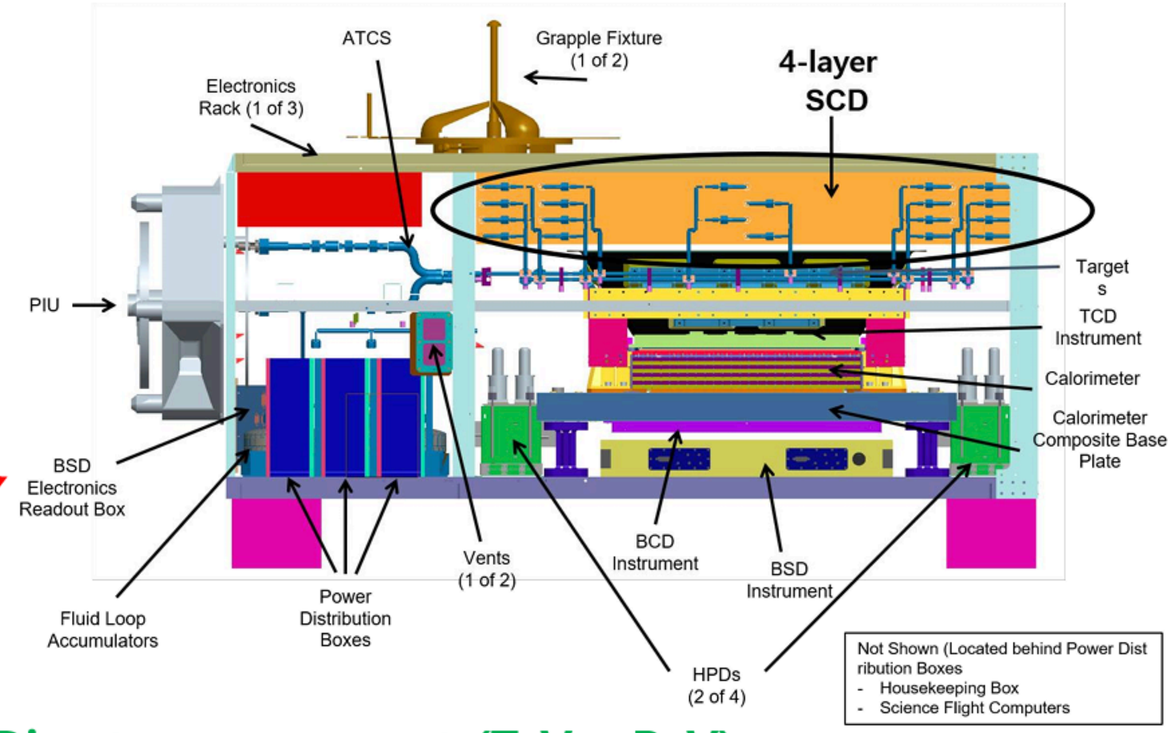




“ISS-CREAM” : 2017 – 2019





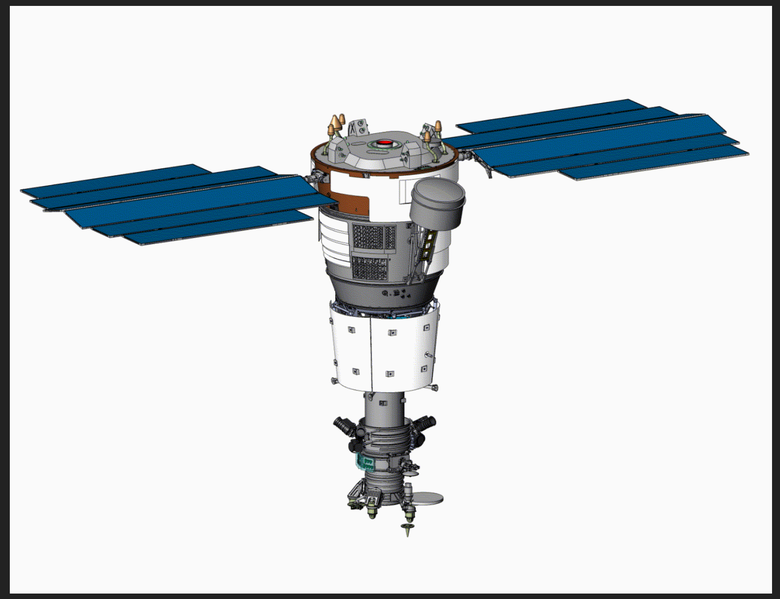


- Launch : Aug. 14, 2017
- Data taken period : Aug. 22, 2017 ~ Feb. 12, 2019 (~ 539 days)
- Design to direct measurement of high-energy cosmic rays

Direct measurement (TeV – PeV)

Silicon Charge Detector (SCD) : Charge measurement, tracking
C-Target & Calorimeter (CAL) : Energy measurement, tracking, trigger
Top/Bottom Counting Detector (TCD & BCD) : e/p separation, trigger
Boronated Scintillator Detector (BSD) : e/p separation by neutron detection

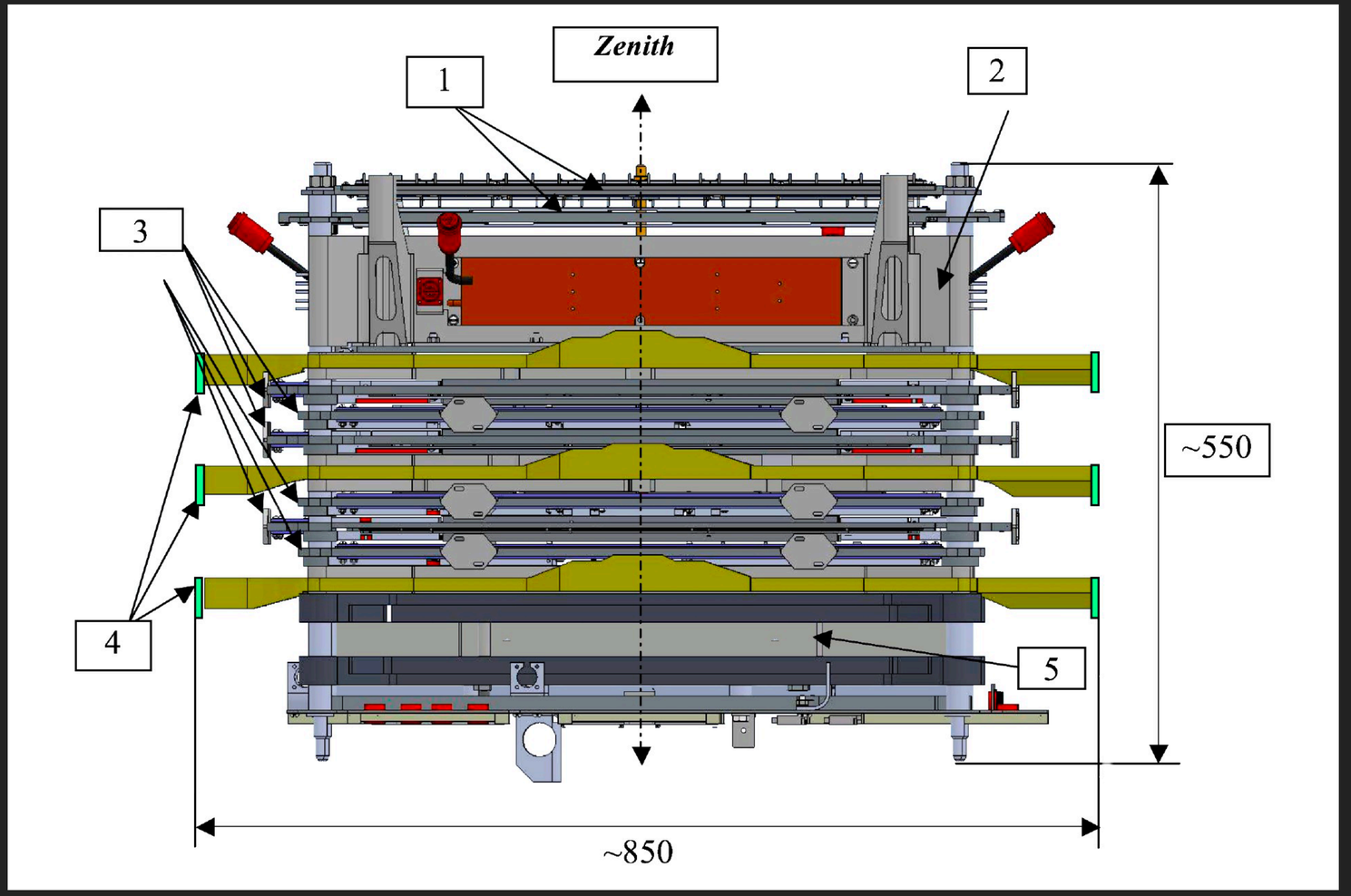
“NUCLEON” (2014–2017)



Apparatus mounted aboard the RESURS-P2 satellite.

Sun-synchronous orbit with an inclination of 97° and an altitude of 475 km.

KLEM technique.

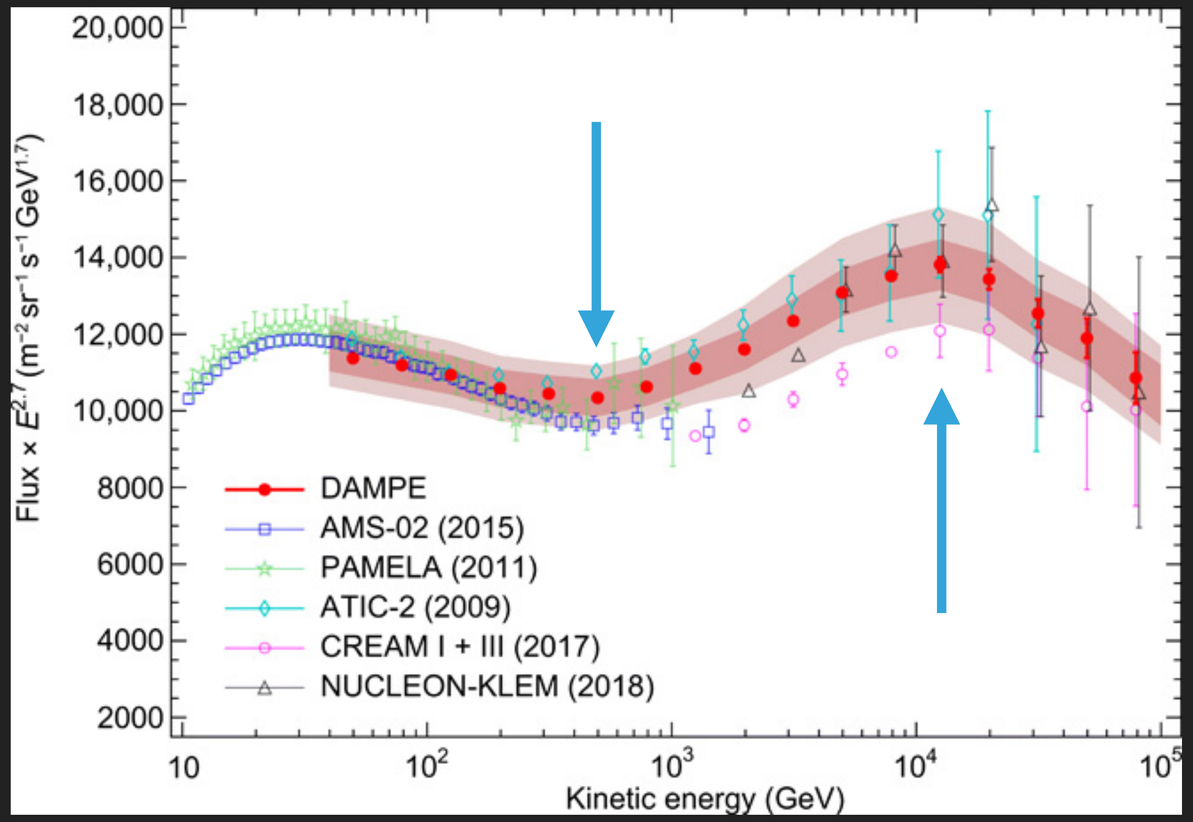


A simplified layout diagram of the NUCLEON spectrometer. 1 – two pairs of planes of the charge measurement system (ChMS); 2 – a carbon target; 3 – six planes of the energy measurement system using the KLEM method (KLEM system tracker); 4 – three double-layer planes of the scintillator trigger system (the trigger system); 5 – a small aperture calorimeter (IC).

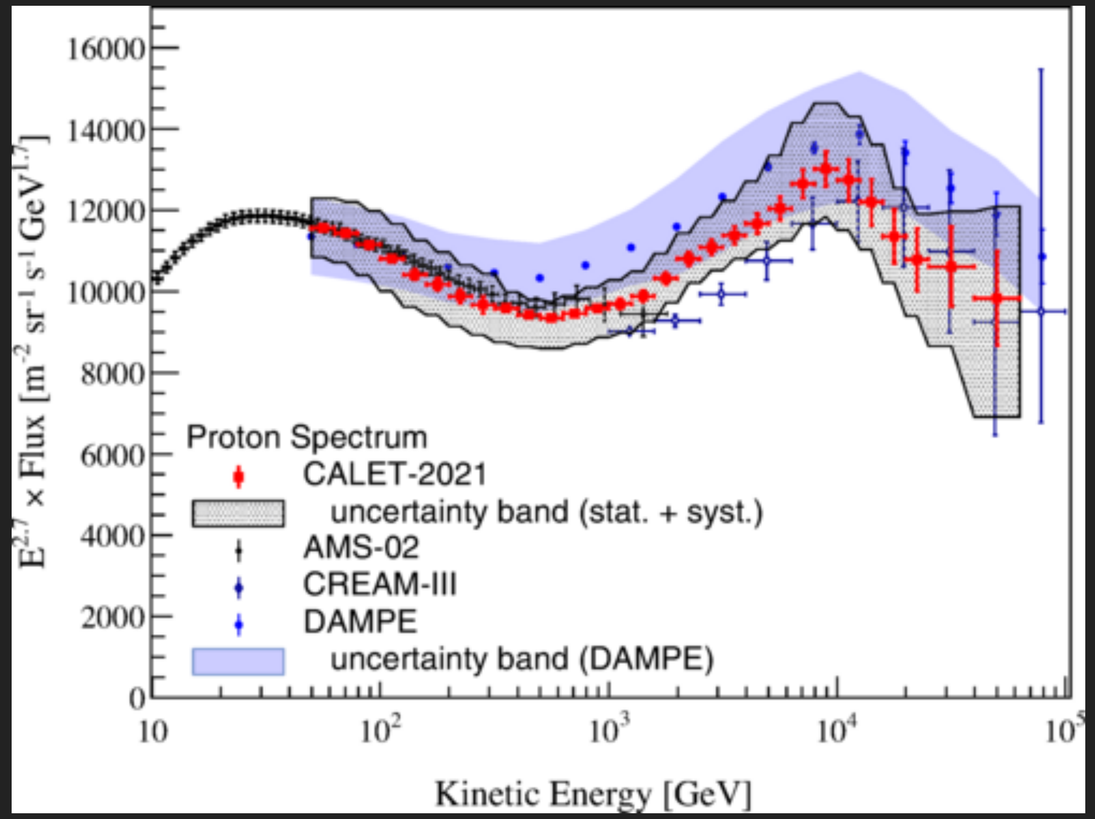
PRIMARY & SECONDARY COSMIC RAYS

- *produced by different sources (inside and outside the Galaxy)*
- *accelerated at different energies by different mechanisms*
- *propagated inside the galaxy through the Interstellar Medium*

PROTON SPECTRUM (10 GEV–> 100 TEV)



Dampe Collaboration - Science Advances, vol. 5, issue 9, September 2019

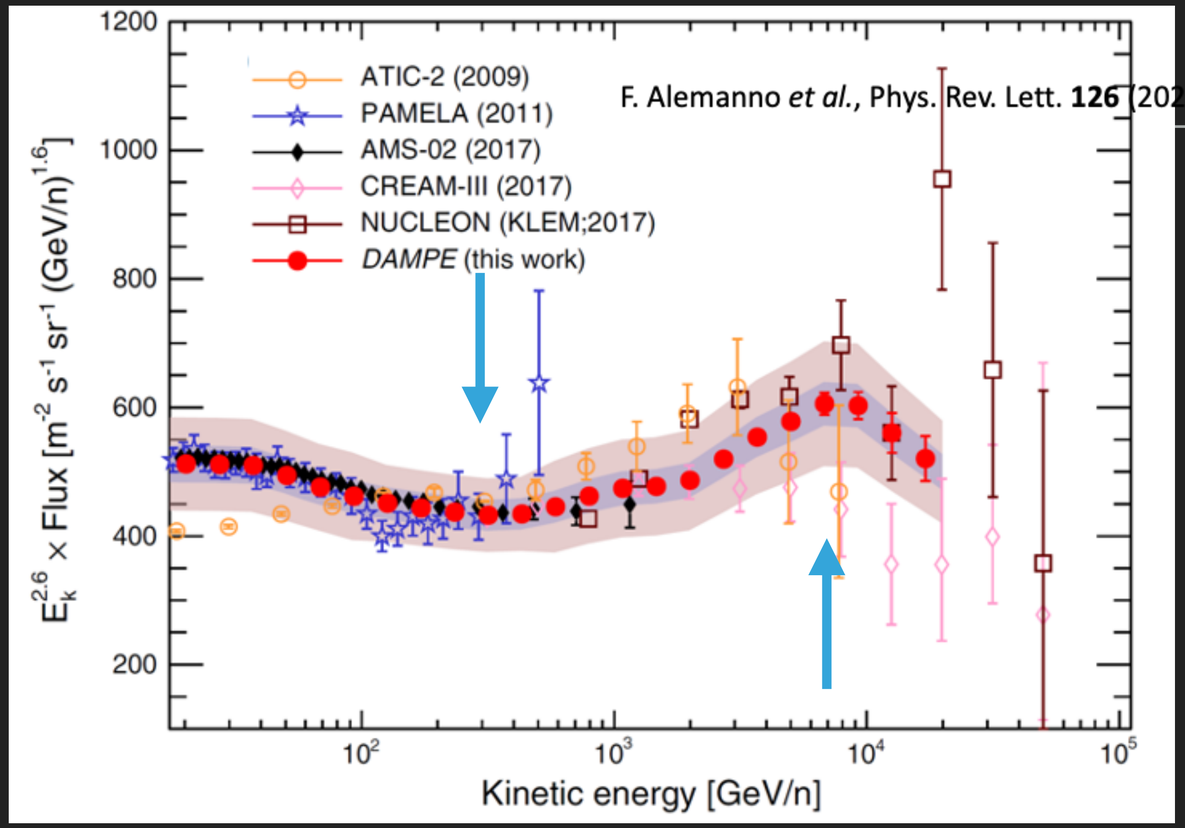


CALET Collaboration - Phys. Rev. Lett. **129**, 101102 - September 2022

Spectra of protons and helium is not a single power law below the knee

- **The hardening at R = p/Z ~ 300 – 400 GV is well established since first observation by CREAM and PAMELA**
- **The softening at R = p/Z ~ 10 TV is observed by different experiments, first strong evidence in DAMPE**

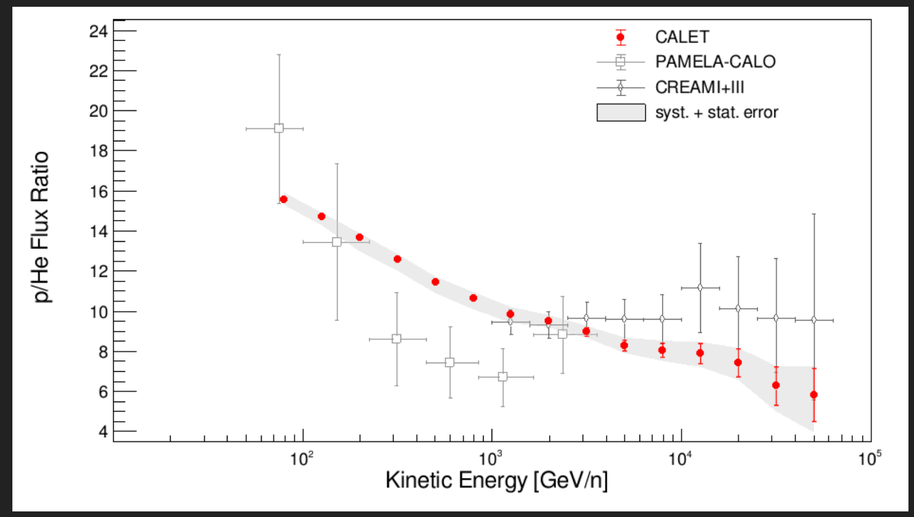
HELIUM SPECTRUM (10 GEV–> 100 TEV)

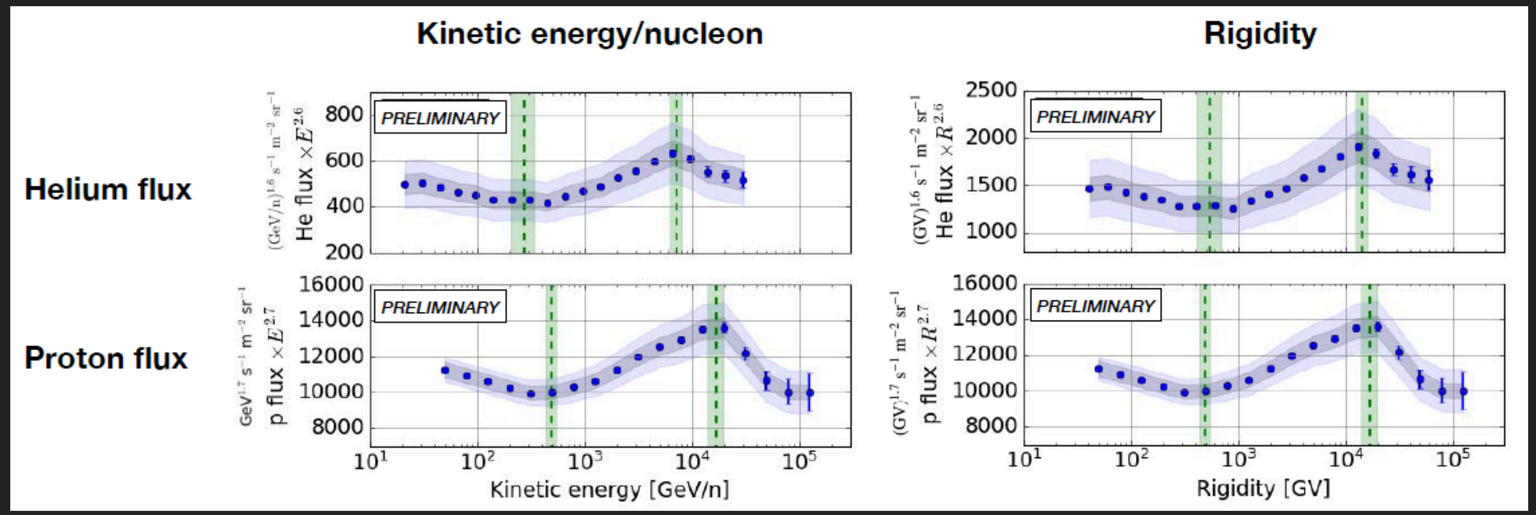


As for protons, helium spectrum shows as well:

- **A hardening at R = p/Z ~ 300 – 400 GV**
- **A softening at R = p/Z ~ 10 TV**

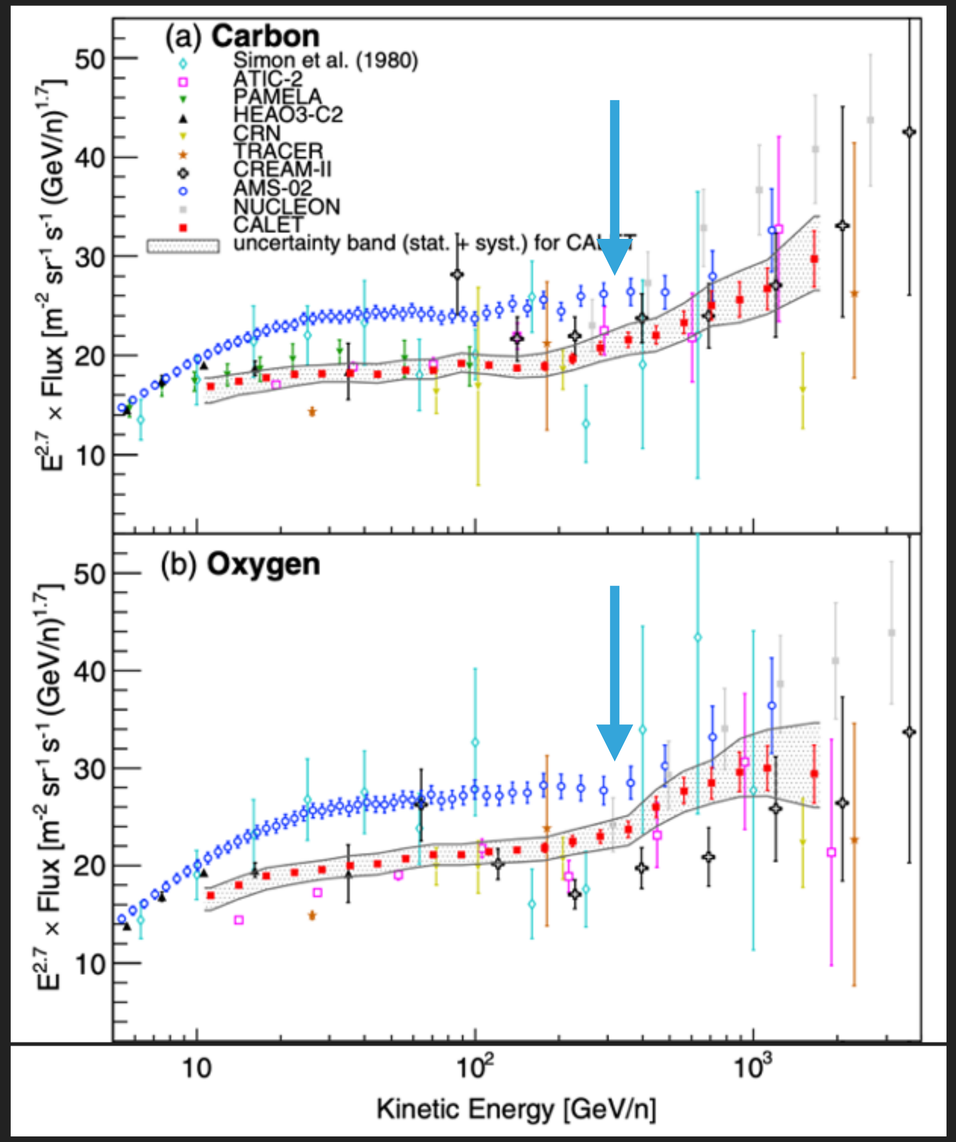
- **The He spectrum is slightly harder than that of protons (Δγ = 0.1) !!**

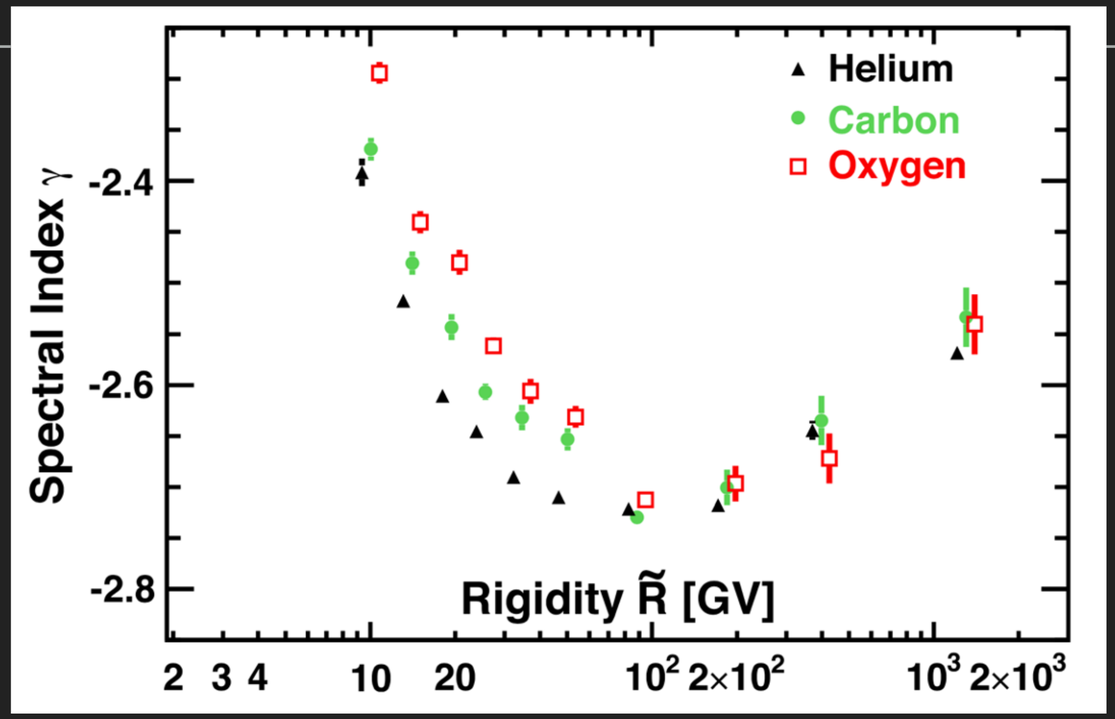




Indeed, a rigidity dependence of both hardening and softening is favoured by data

CARBON AND OXYGEN FLUXES

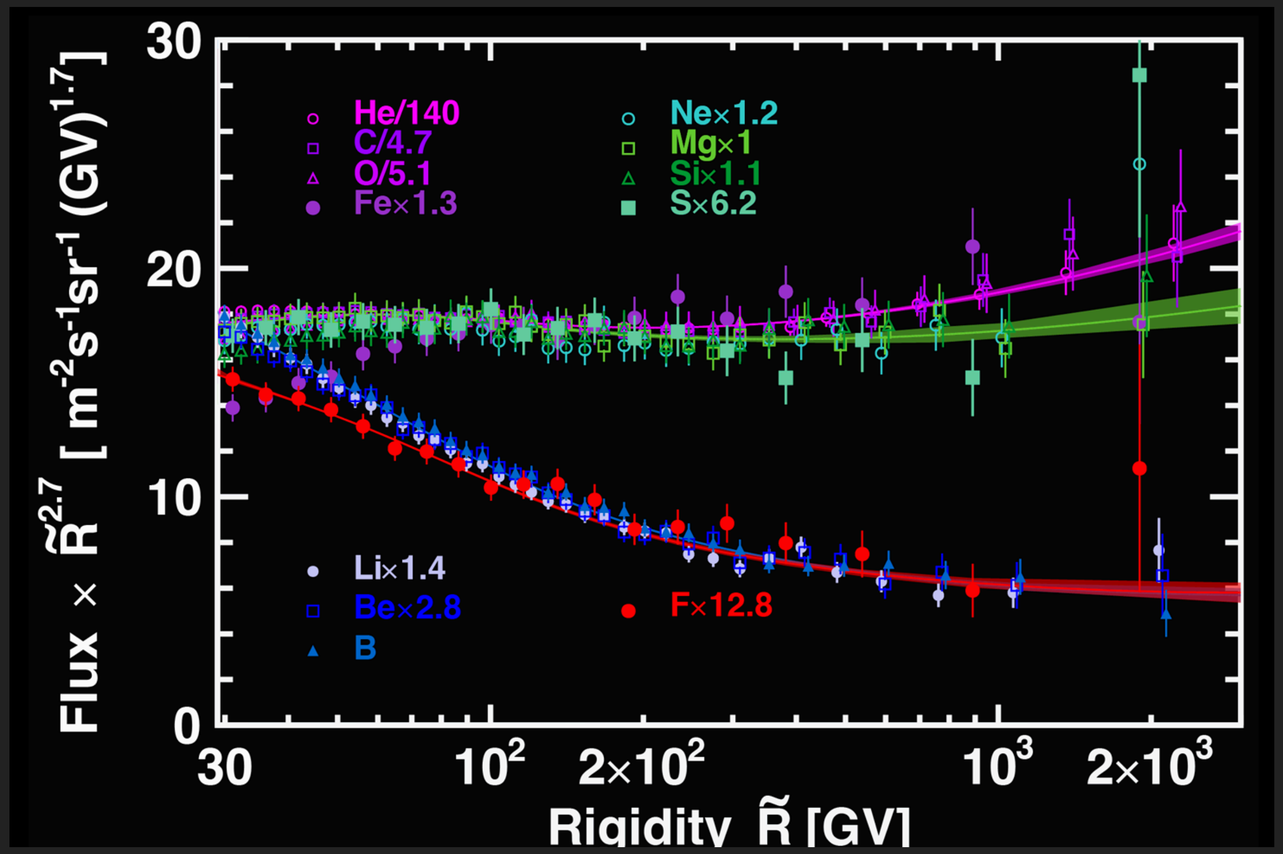


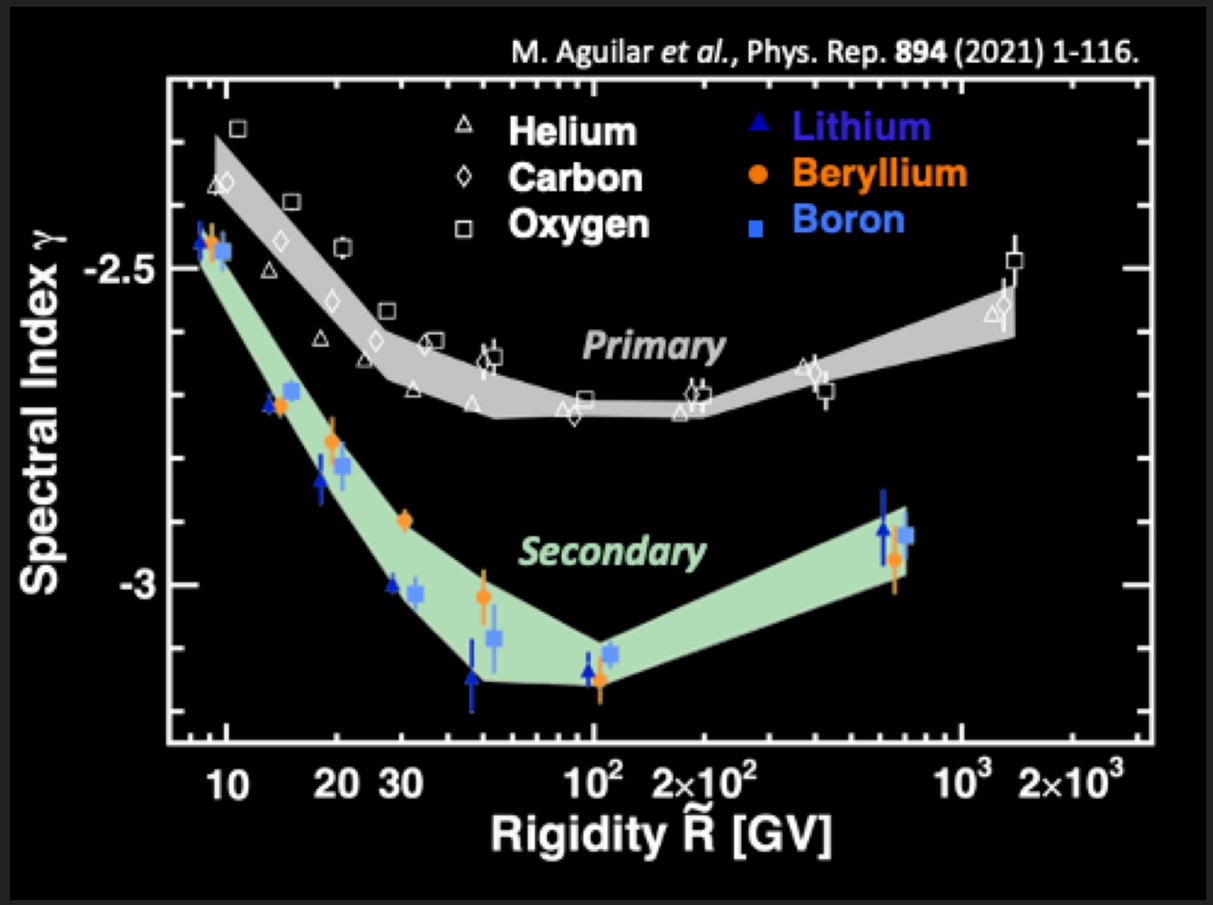


Difference in flux normalization between experiments !

- C and O show a hardening at hundreds of GeV/n. **Same for all elements!**
- He, C and O have the same rigidity dependence, i.e. hardening, at about 300 GV (<u>but different from protons</u>..).

LIGHT SECONDARY ELEMENTS LI, BE, B AND B/C RATIO



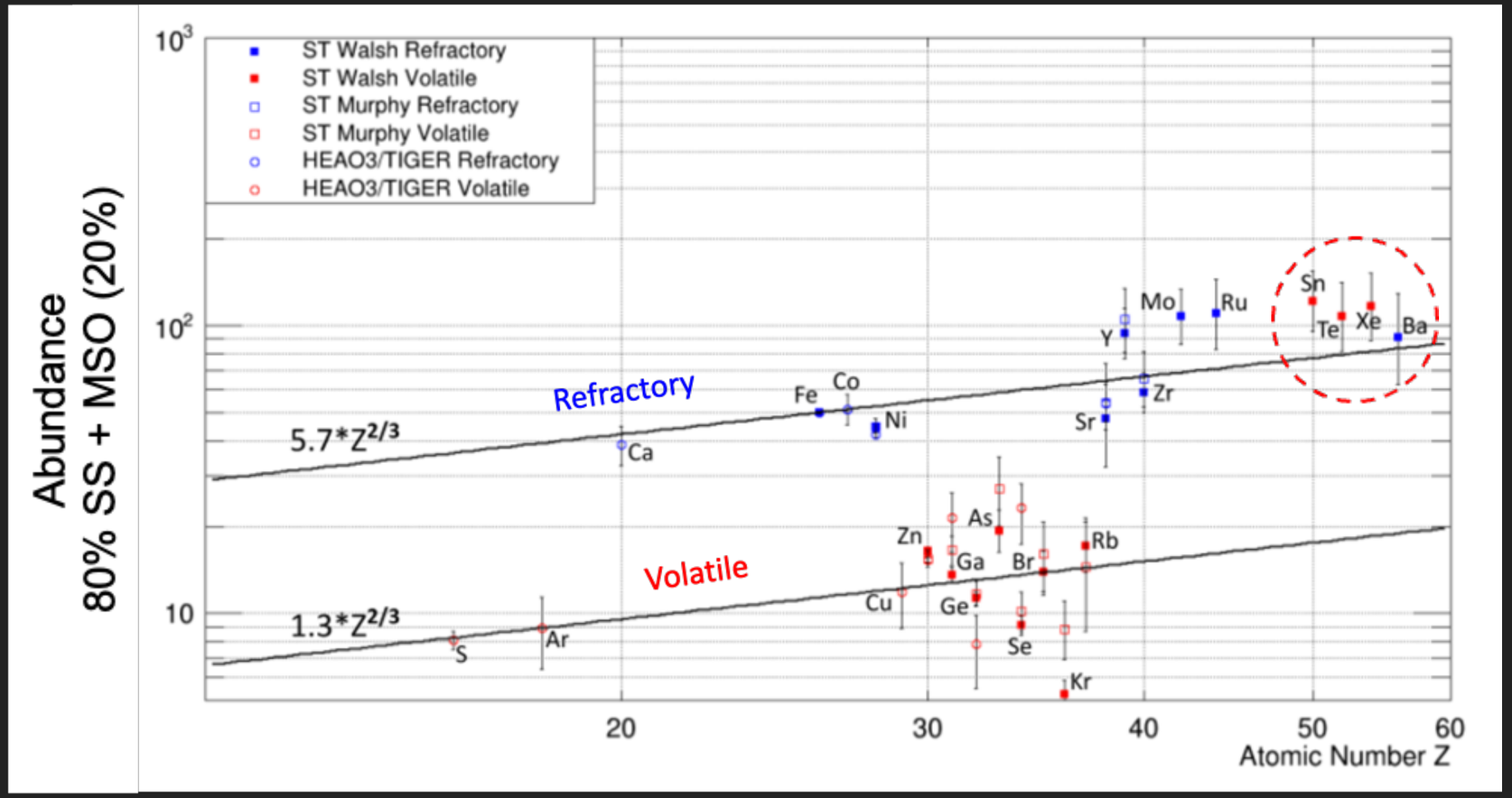


- **Secondary hardening is stronger** –> The flux hardening seems to be a **<u>propagation/diffusion effect.</u>**
- **<u>No clear hints on the softening at 10 TeV</u>**

HEAVIER NUCLEI & UNSTABLE ISOTOPES

- *Mostly related to the origin of CRs and acceleration sites*
- *Composition studies*
- *Cosmic ray clocks and confinement*

ELEMENTS WITH Z<40 AND 40<Z<56



Refractory elements that condense in dust grains are preferentially accelerated by SN shocks compared to volatile elements residing in gas;

the GCRs are a mix of outflow from "young" massive stars and normal "old" ISM;

Composition of sources is well described by 80% solar system (SS) + 20% massive star outflows (MSO).

This mixture is representative of **OB associations** (young and massive stars, high-rate of SN).

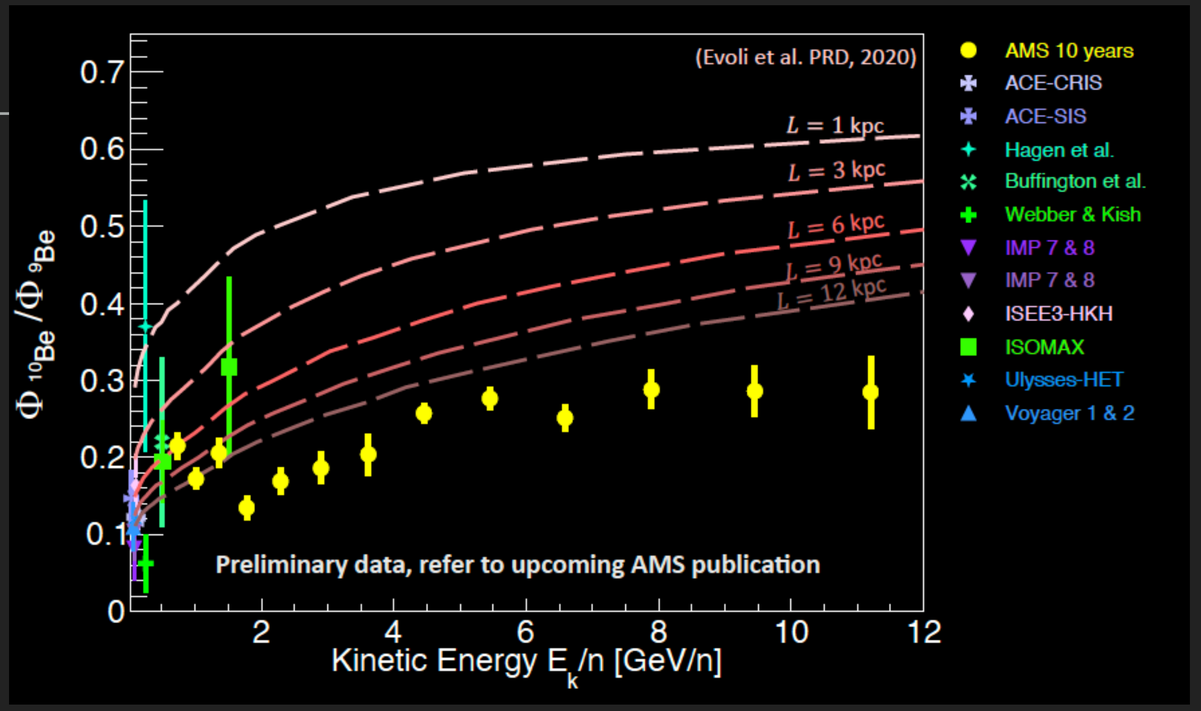
THE MODEL BREAKS FOR Z>40. PRESENCE OF OTHER SOURCES ?

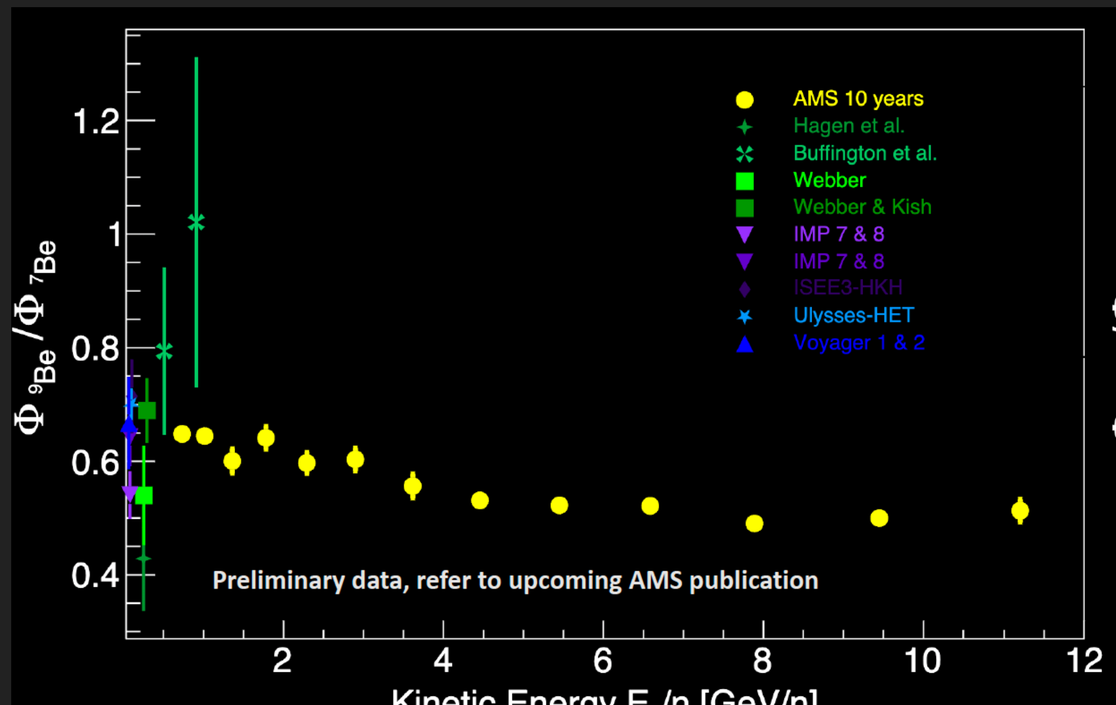
UNSTABLE BE ISOTOPES

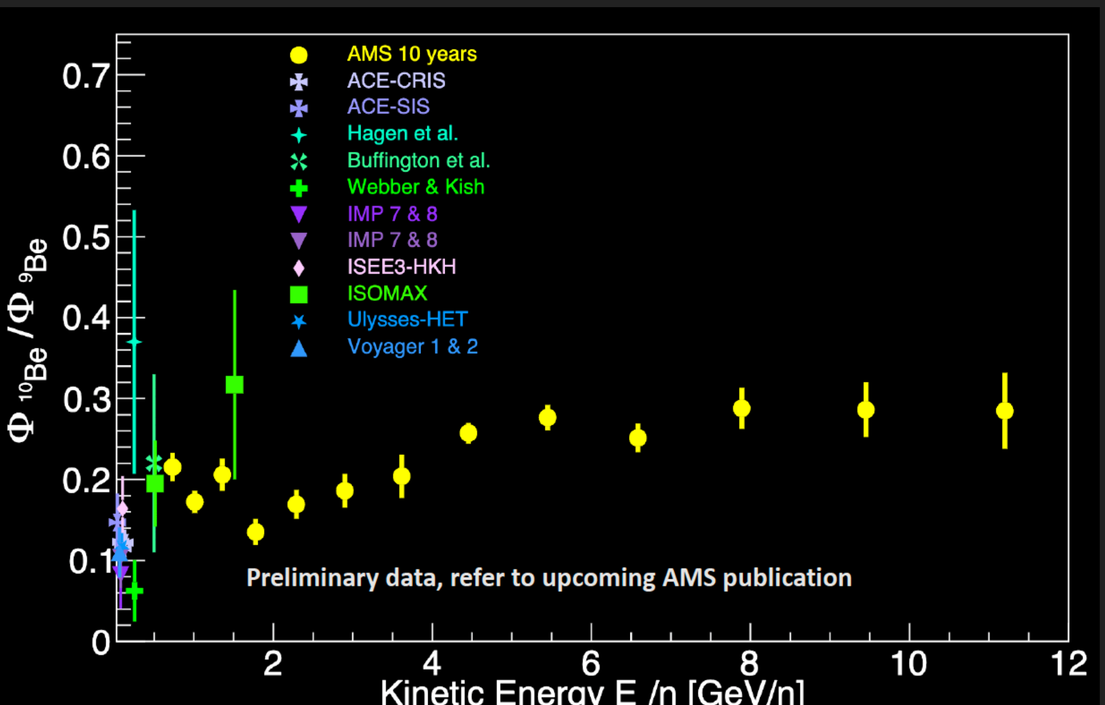
Secondary ^{10}Be –> $^{10}B + e^- + \nu$, with $t_{1/2}$ = 1.6 My.

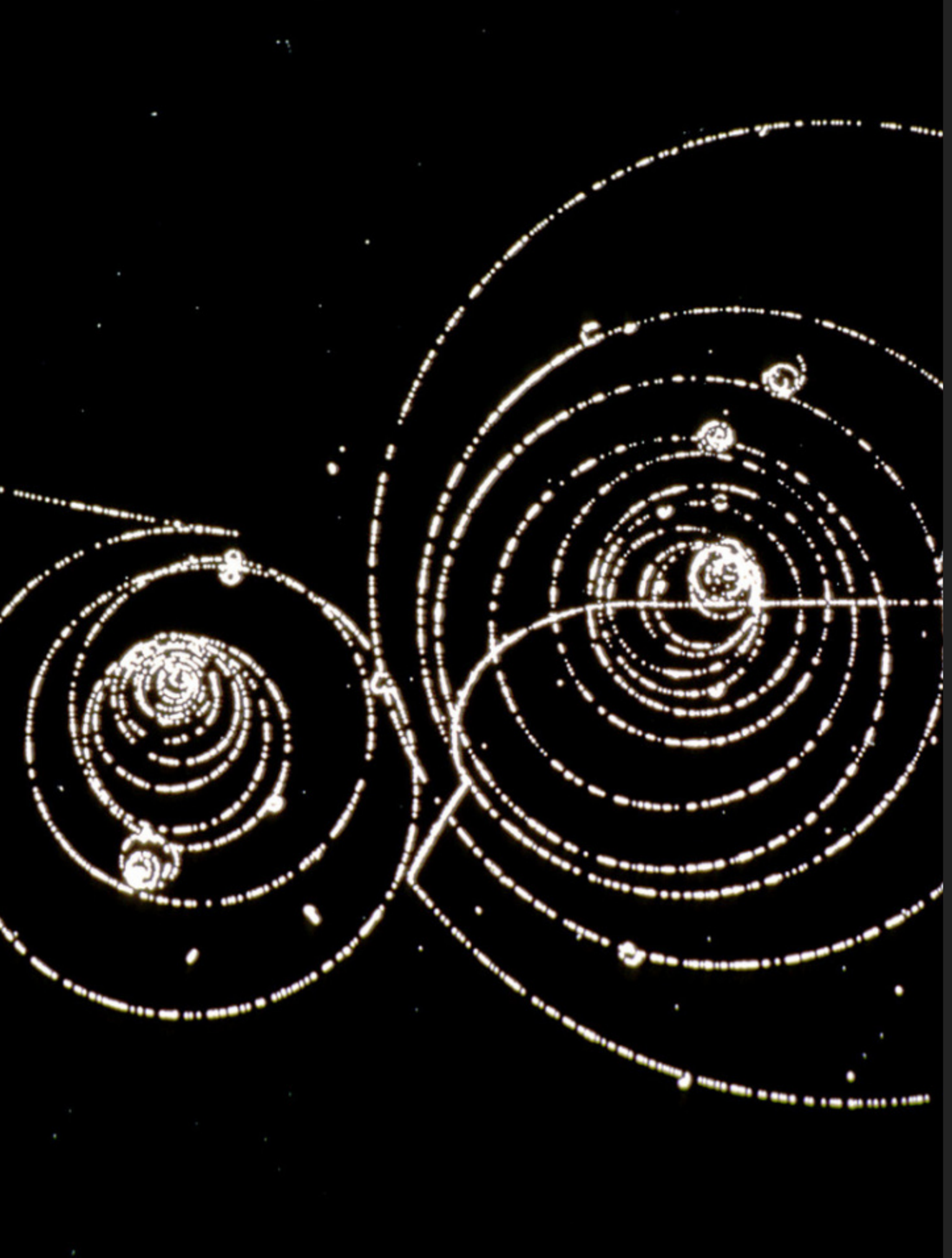
The amount of ^{10}Be (and ^{10}B) depends on the **cosmic ray confinement time** or, in diffusion models, to the **galactic halo size.**

By latest AMS data, tension with transport models??







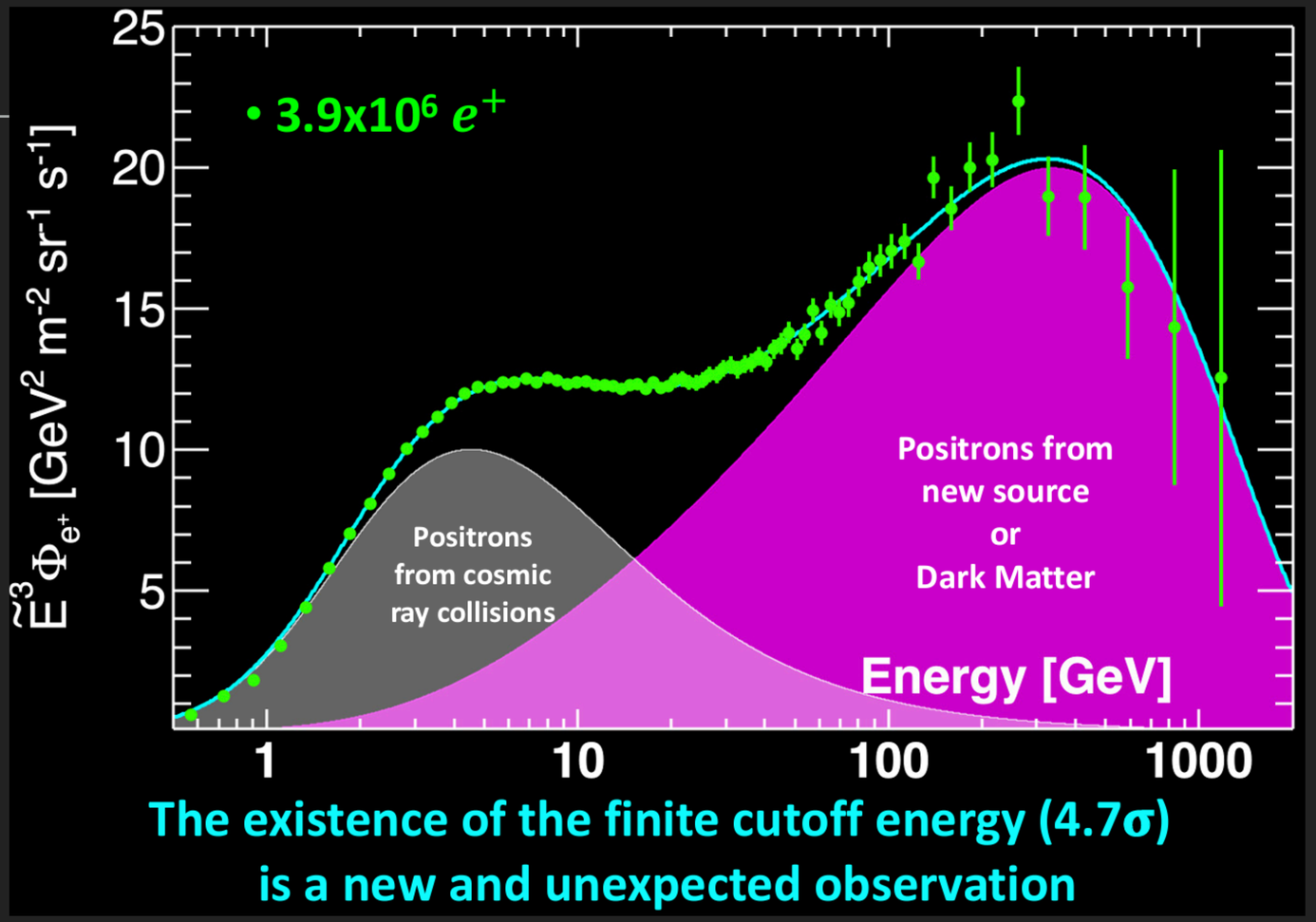


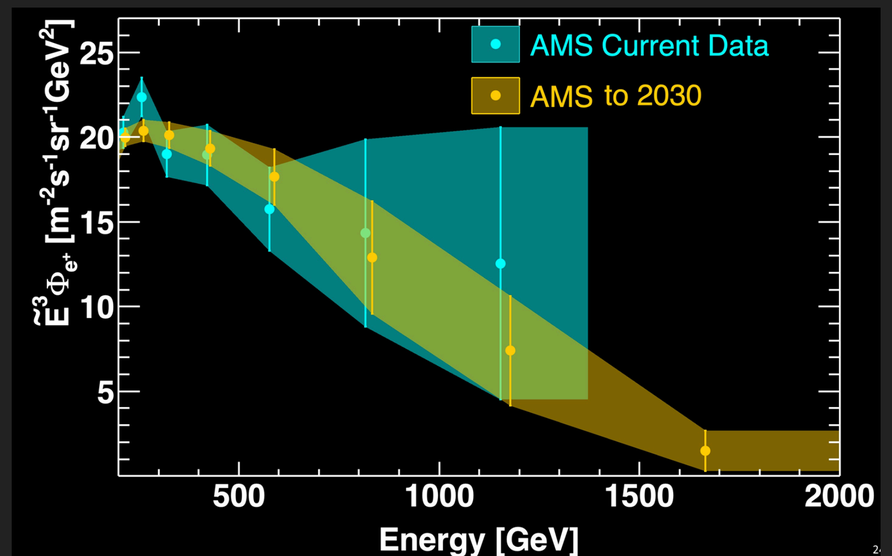
ANTIMATTER & ELECTRONS

- *Test of propagation mechanisms;*
- *Anti-Matter of primordial origin expected to peak at few GeVs;*
- *Dark Matter could be present anywhere to very low energies up to TeVs;*
- *Anti-Matter of Dark Matter origin could be present at GeV or below;*

POSITRON FLUX

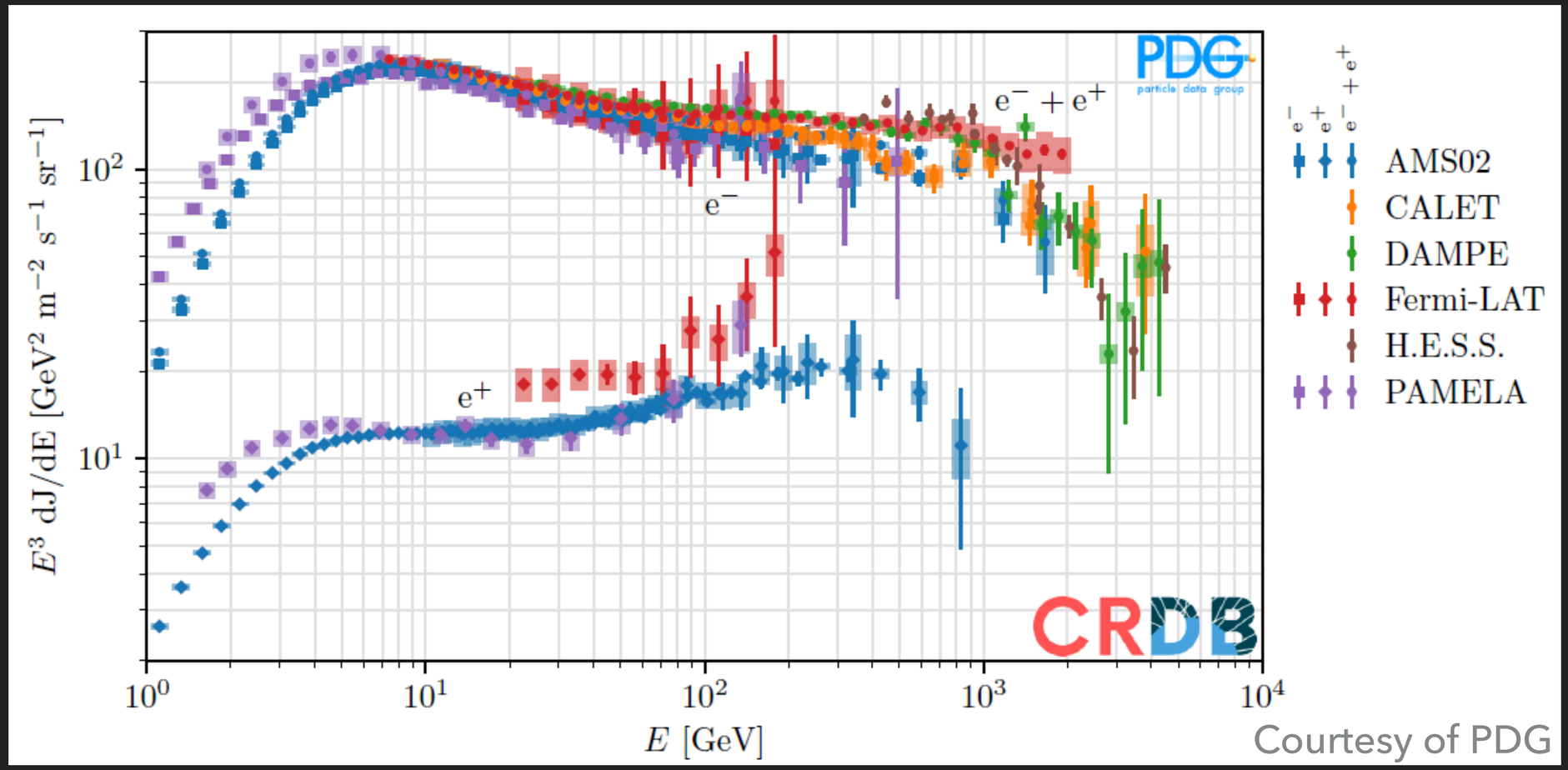
- Evidence for a **new source of positrons; signal has a clear cut-off!**
- Astrophysical explanation calls for **pulsars contribution** –> *highly probable*





- Still room for **DM models?** Important to know how the bumps falls….

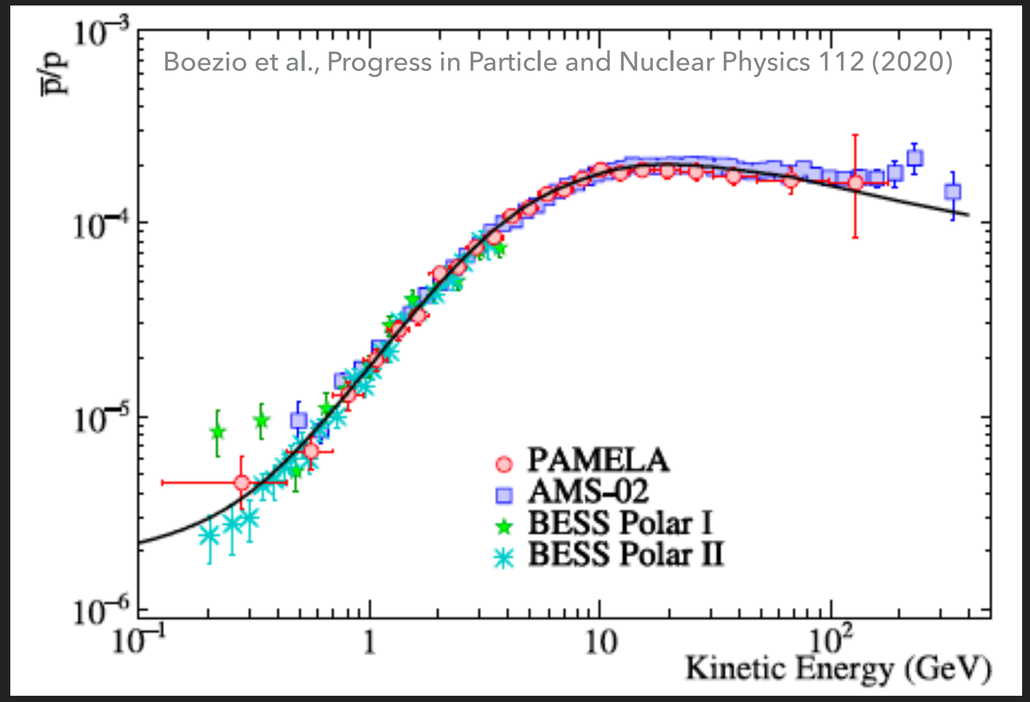
ALL-ELECTRON SPECTRUM FROM SPACE AND GROUND

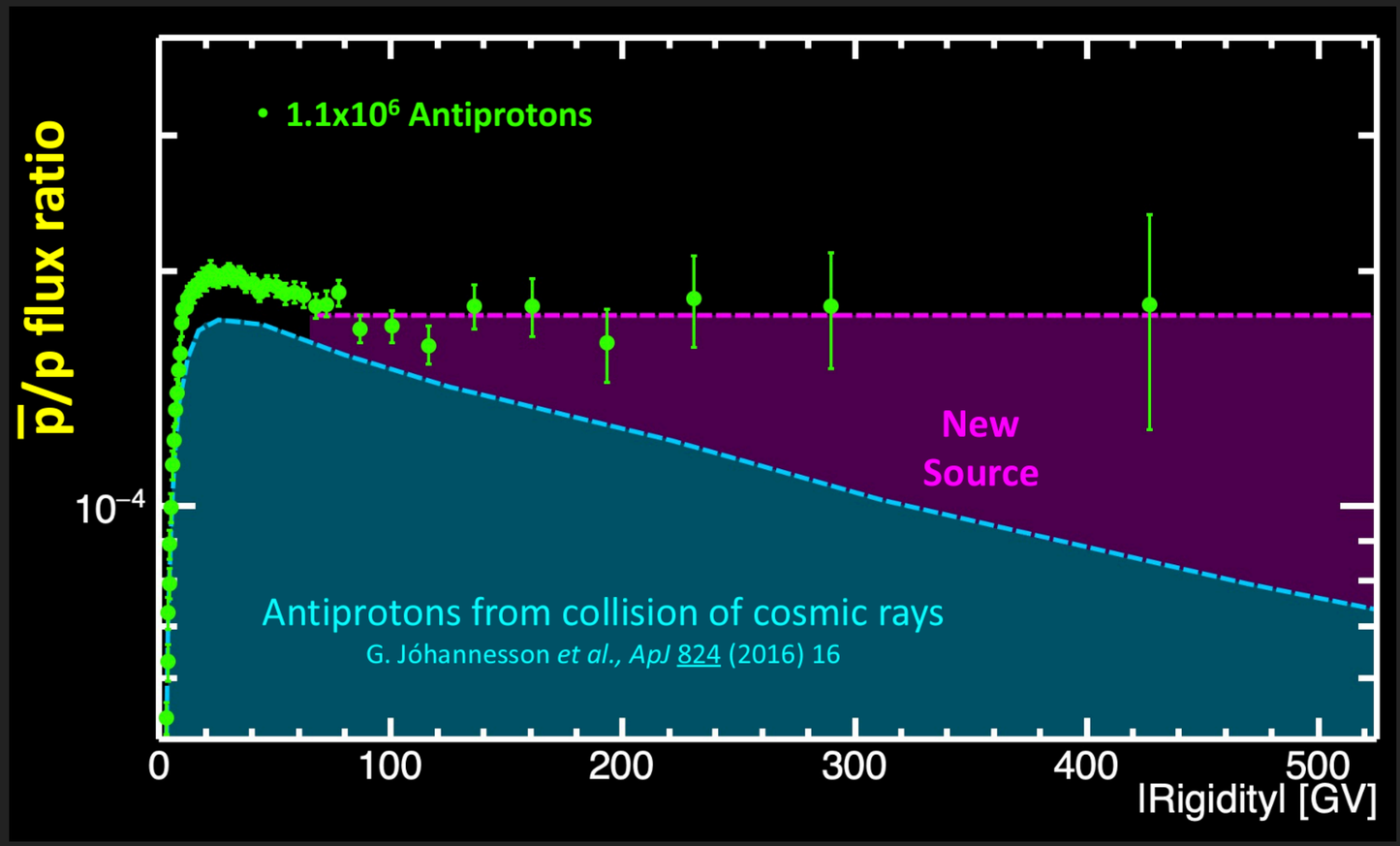


Courtesy of PDG

- Some **disagreements between groups of experiments** (systematics issues)
- Connection to **ground-based experiments**
- **Drop-off at 1 TeV**
- The spectra at high energies dominated by **close and young cosmic ray sources**

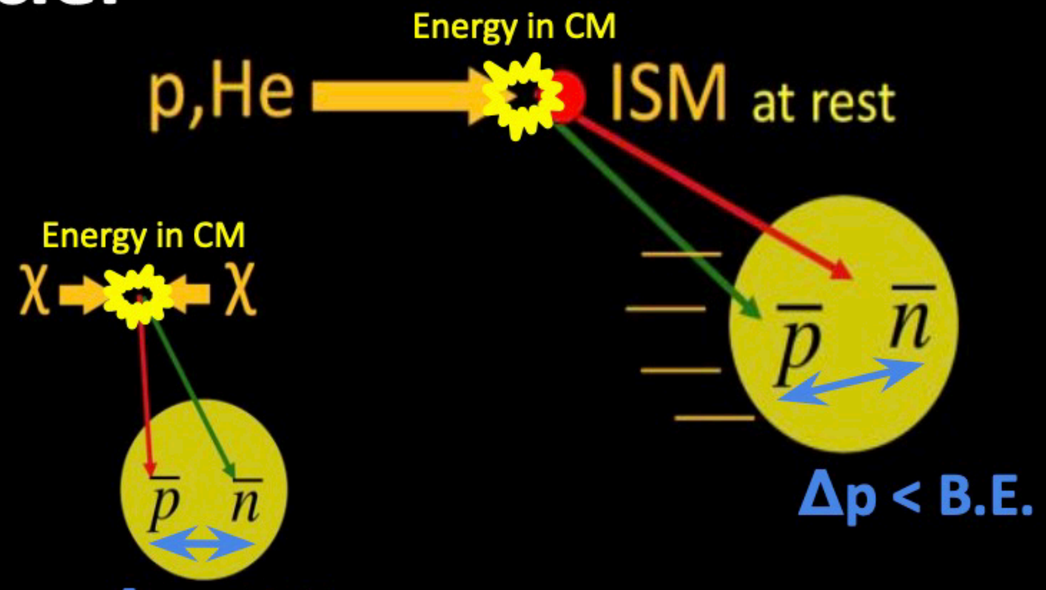
ANTIPROTON/PROTON RATIO

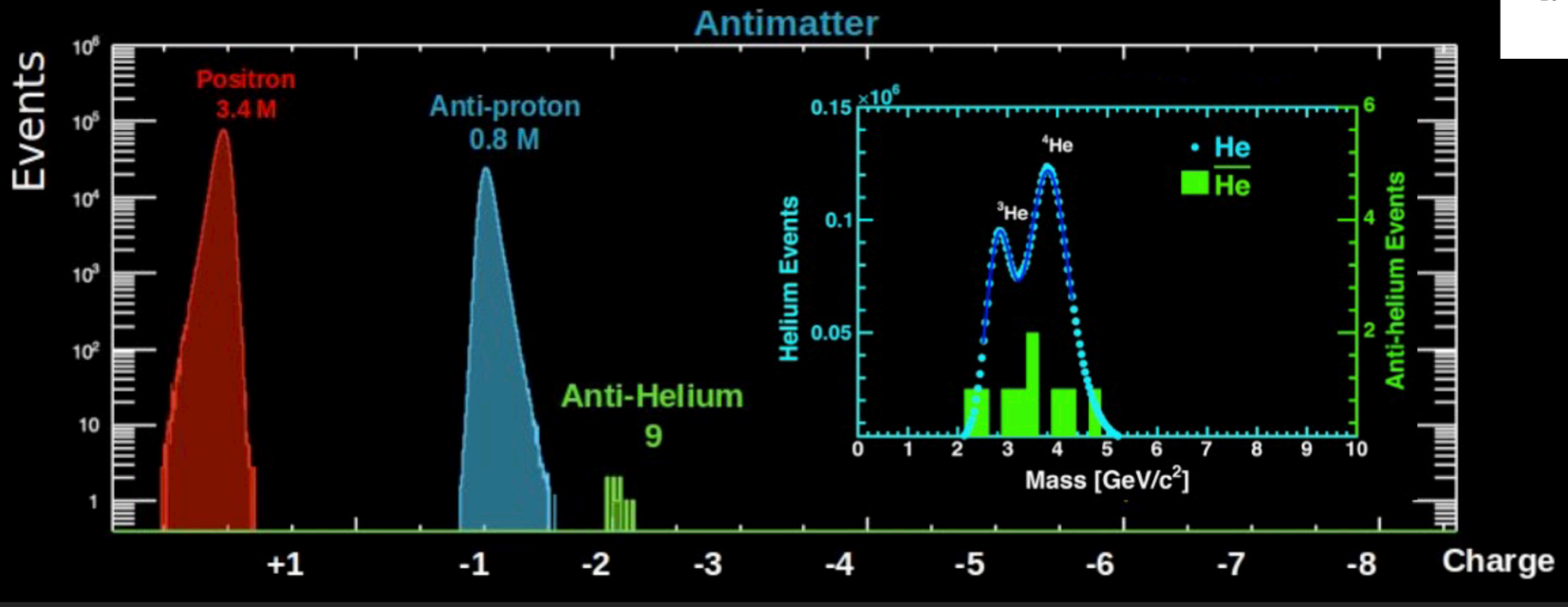


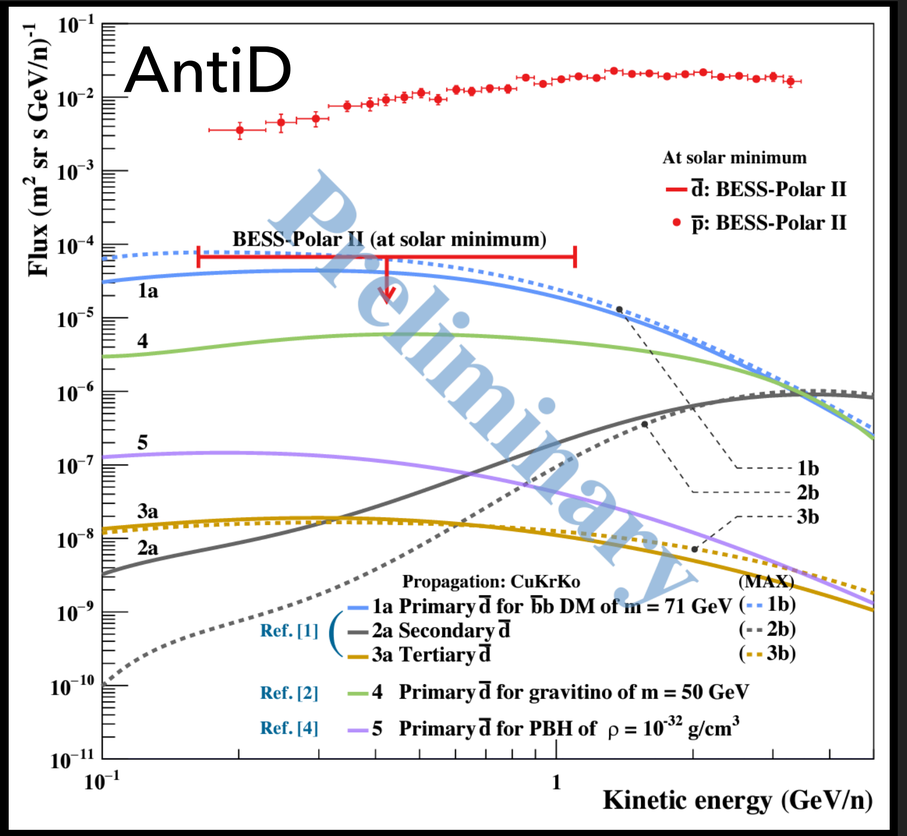


- **No antiproton excess at low energies** (related to primordial AntiMatter/evaporation of primordial BHs)
- Excess of antiprotons over the predictions (CR collisions) at **high energies** –> primary antiprotons?
- Better knowledge of cross-sections/CR confinement?

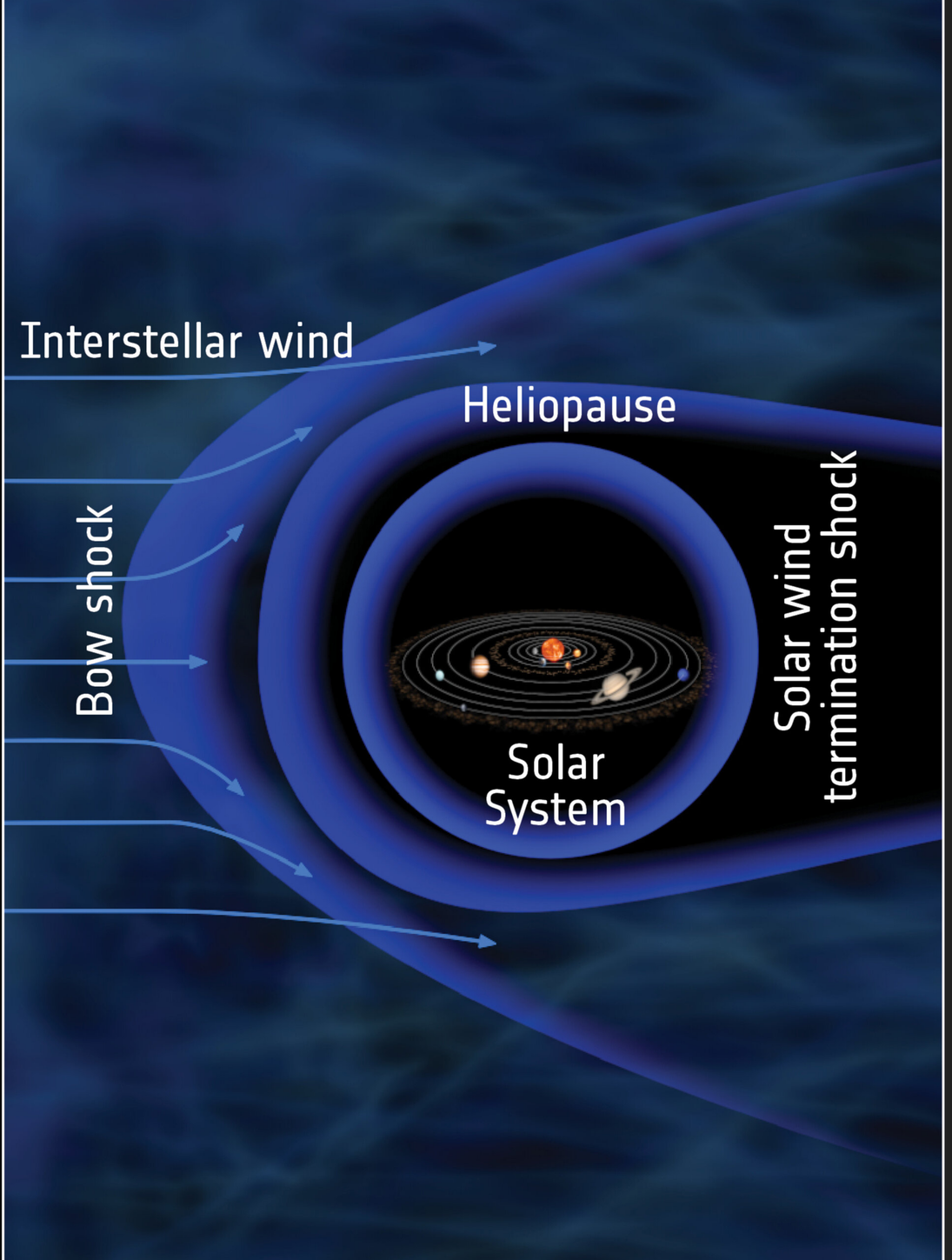
AntiNuclei in CR







- AntiD: Never detected so far in CR
- Hints of DM: (AntiD and 3He)
- 4He are completely unexpected



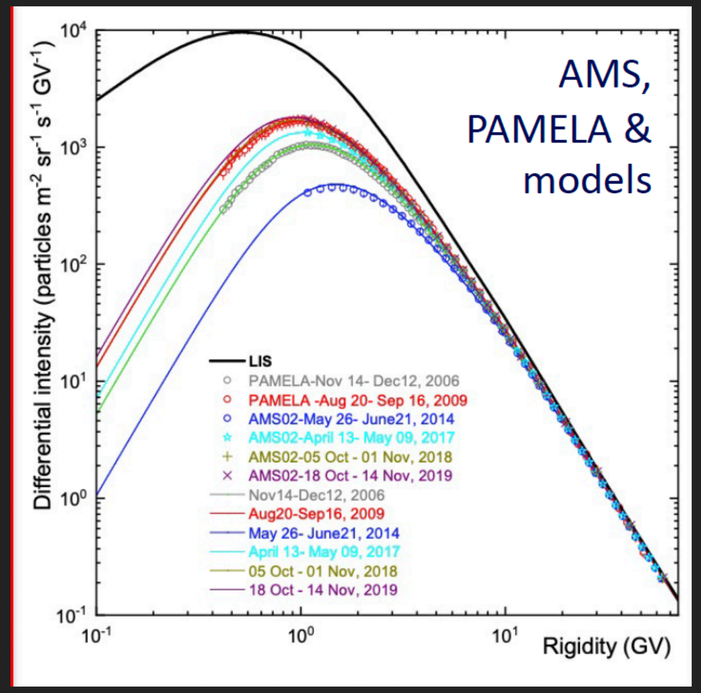
COSMIC RAYS IN THE HELIOSPHERE

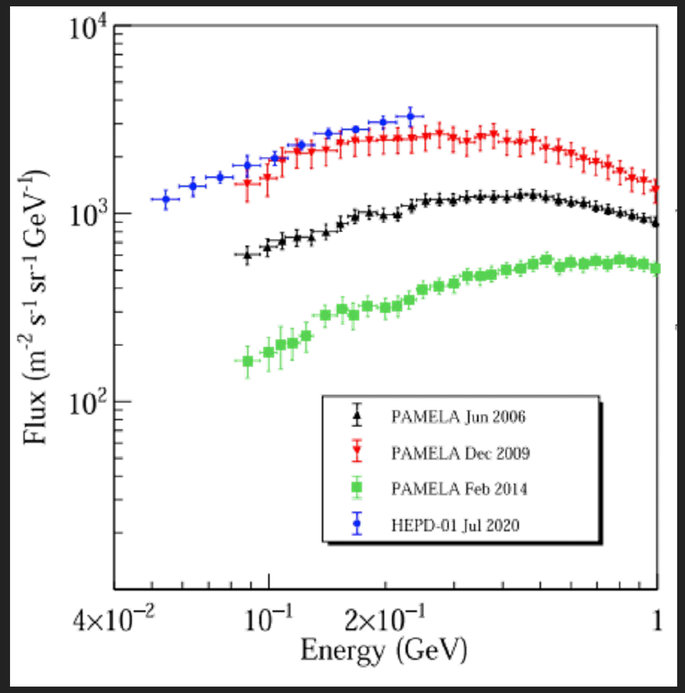
Low energy particles affected by Solar Modulation and by the Earth geomagnetic field

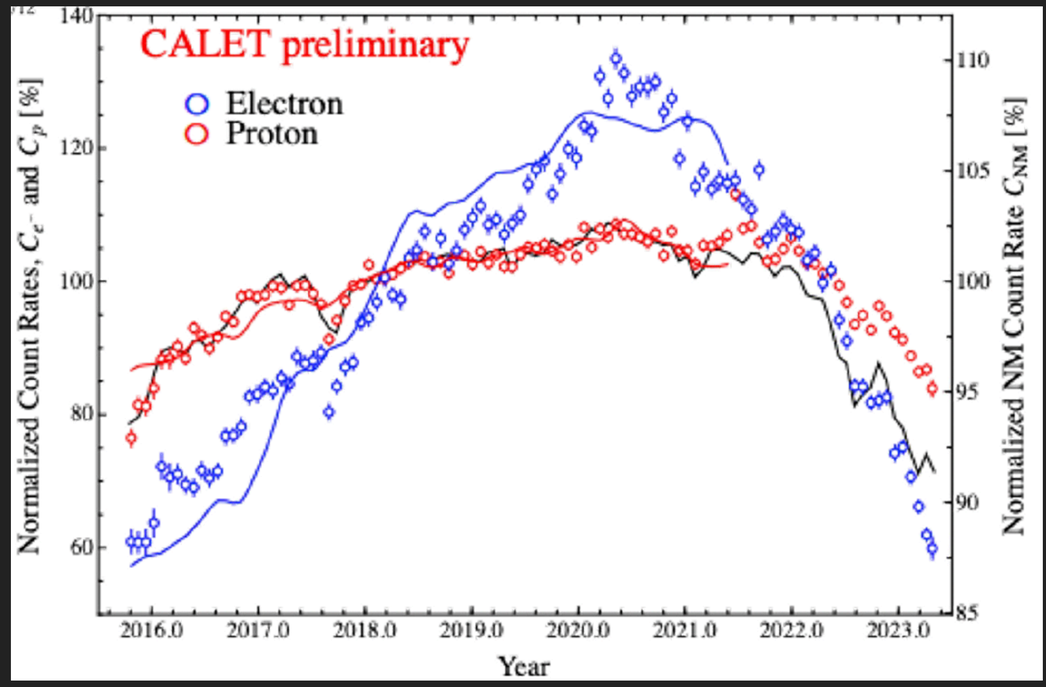
- *solar/geomagnetic effects are "background" / source of systematics for **astrophysics***

- *solar/geomagnetic effects are "background" / source of systematics for **fundamental physics***

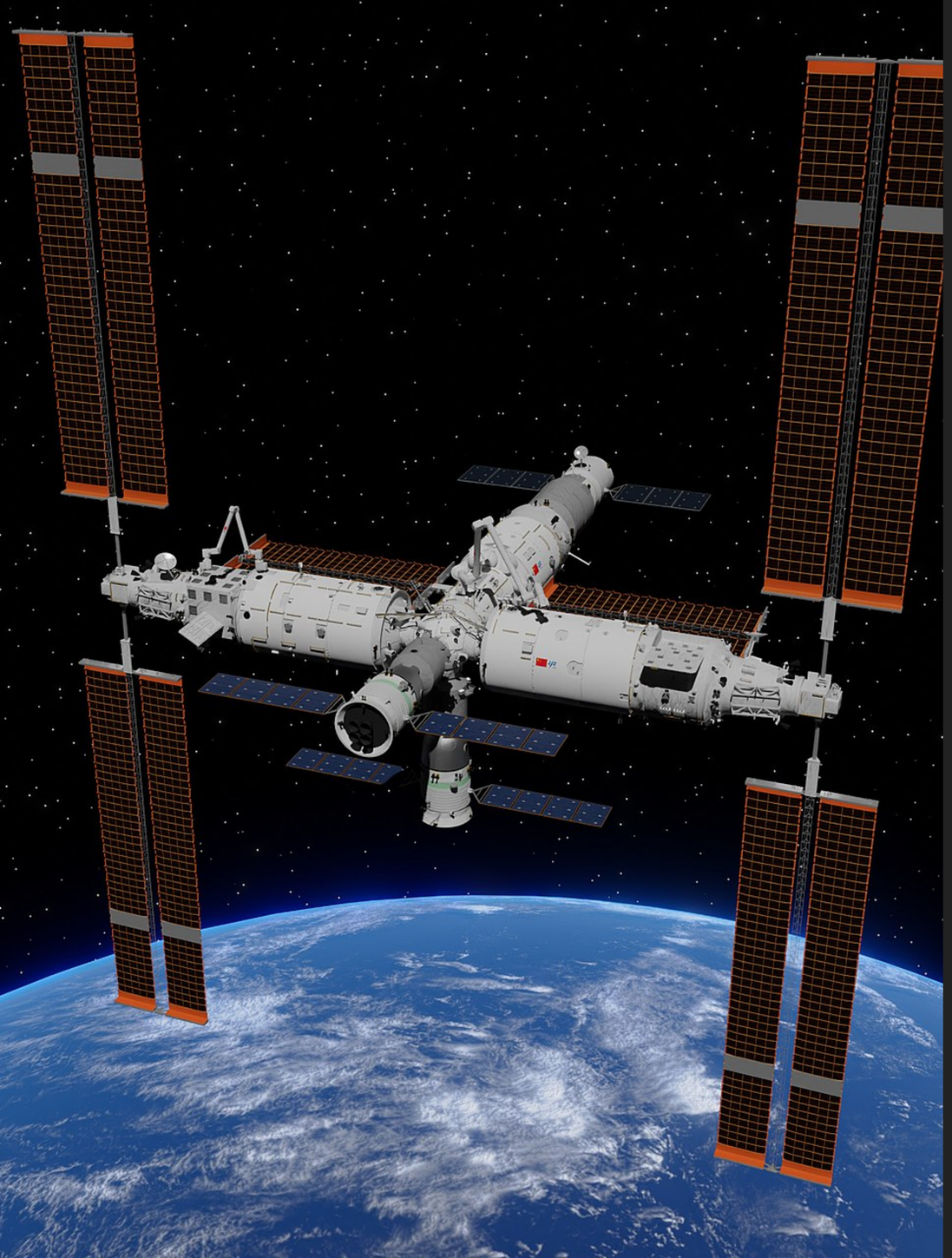
PARTICLES IN THE HELIOSPHERE/SOLAR MODULATION







- Experiments operated in the last ~ 15 years (mainly AMS and PAMELA) provided **a lot of data of extreme interest for the HelioPhysics and SpaceWeather communities**
- **Daily data available !**
- Different experiments / detectors (HEPD-01, CALET, …) are sensitive to **different energies.**



NEAR-FUTURE EXPERIMENTS

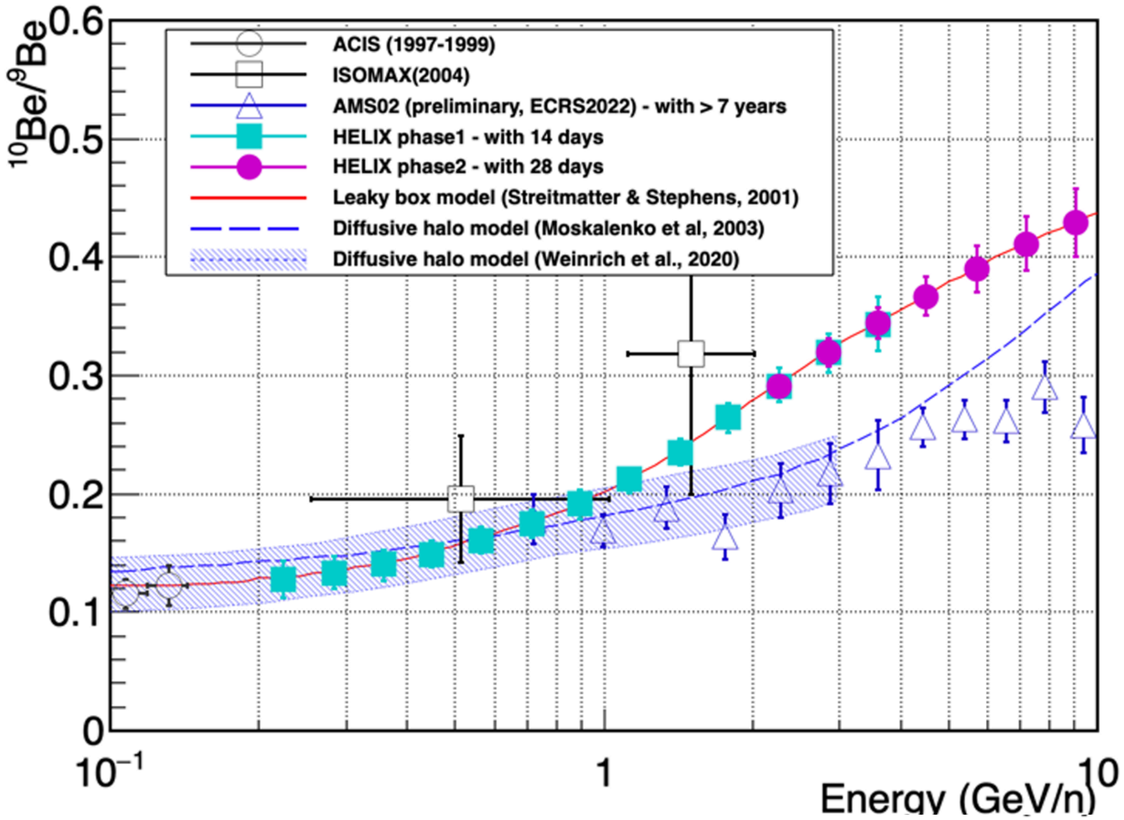
We need data !

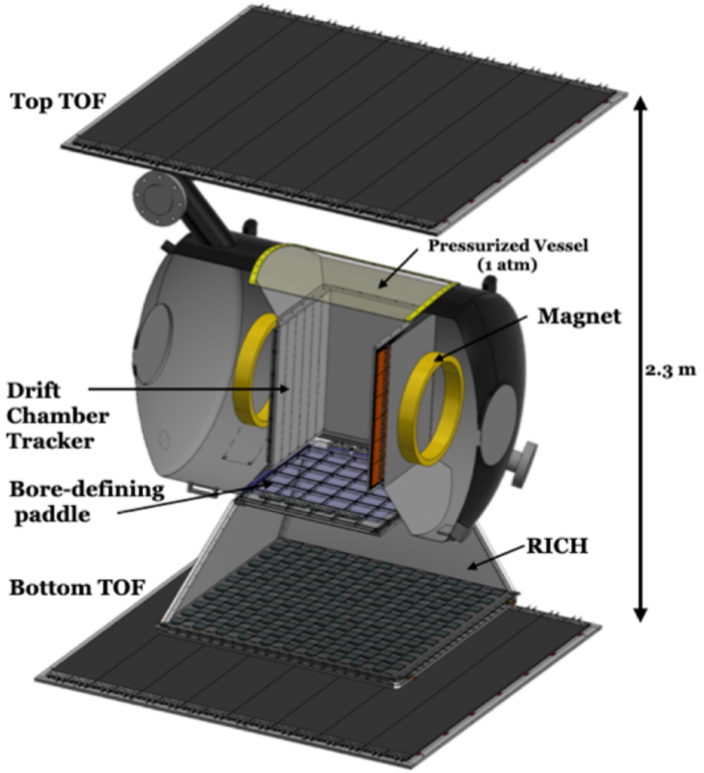
Quite exciting near-future on all science items

"HELIX" BALLOON STAGE 1 : JUST LAUNCHED FROM KIRUNA!

- A new **magnet spectrometer payload** to measure 10Be/9Be isotope ratio up to 10 GeV/n
- Isotopes Z<10
- Stage 1 (7-14 day exposure): covers up to ~ 3 GeV/n

Measurement of $^{10}Be/^{9}Be$ in the Future: HELIX



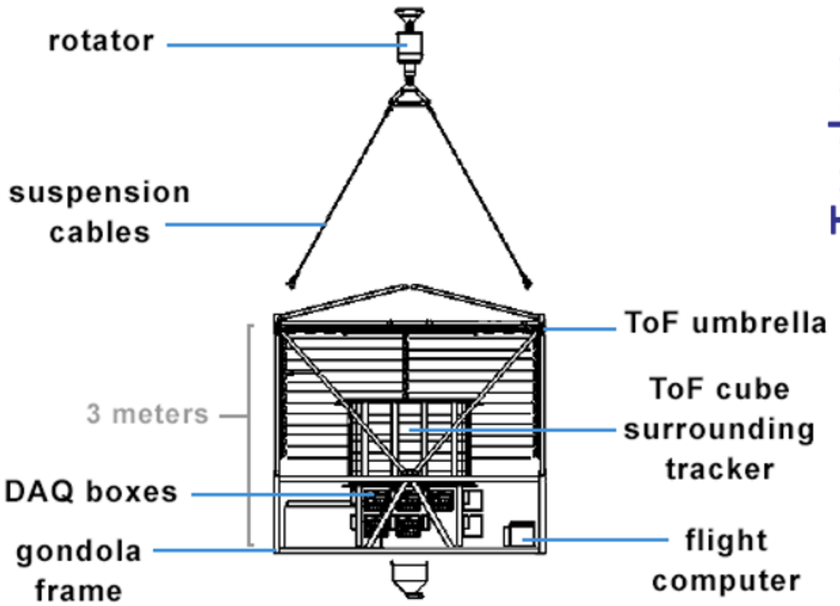


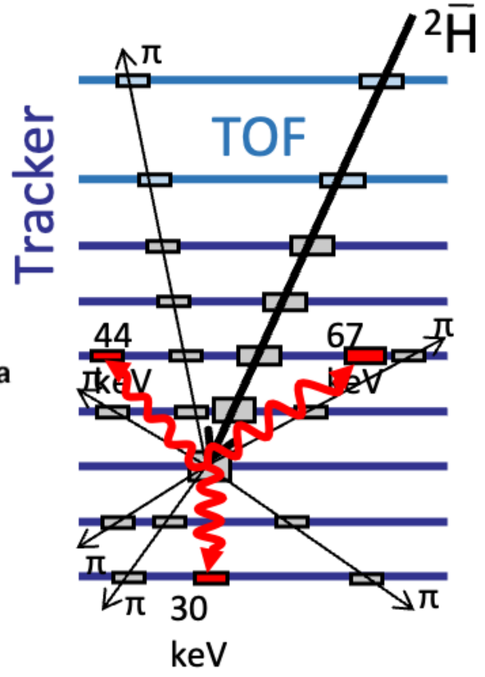
High Energy Light Isotope Experiment (HELIX): a magnetic spectrometer designed to measure the light isotopes from proton up to neon (Z=10). Charged particles are bent by the 1 T superconducting magnet (HEAT), their curvature and momentum are measured by a low low MS high resolution drift chamber. Particle velocity is measured by a Time-of-Flight system and by a RICH detector. The instrument is optimized to measure ^{10}Be from 0.2 GeV/n to beyond 3 GeV/n with a mass resolution $\lesssim$ 3%. →

“GAPS” BALLOON: FIRST LAUNCH DECEMBER 2024 FROM ANTARTICA

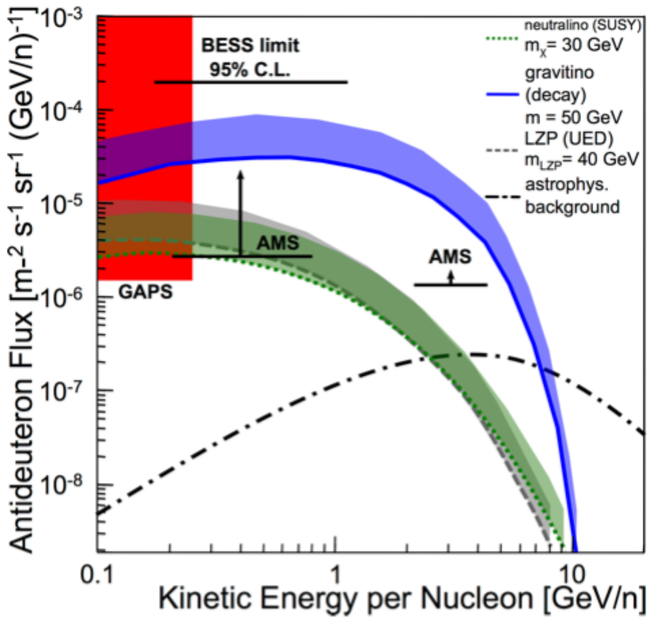
- High statistics **antiproton spectrum**
- 2-3 times improved **antideuteron sensitivity** compared to BESS
- leading sensitivity to low-energy antihelium nuclei
- GAPS sensitivity in the 100 - 250 MeV/n range

General Anti-Particle Spectrometer (GAPS): a balloon-borne instrument designed to detect cosmic ray antimatter stopping it in material forming and exotic atom with the material and detecting the X-ray from orbital transition of the exotic atom and the pion “star” produced by final annihilation.

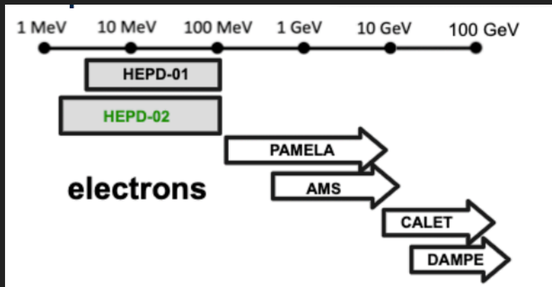


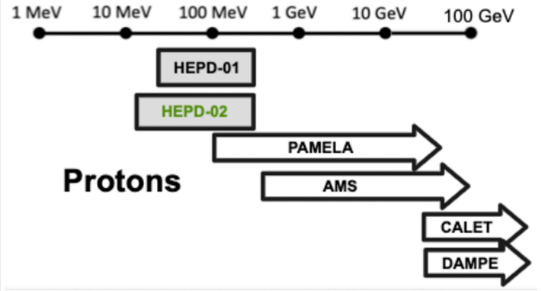


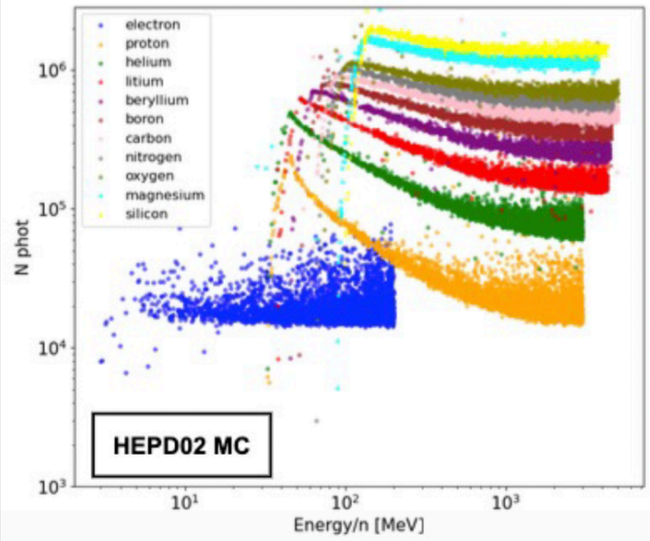
T. Aramaki *et al.*, Phys. Rep. **618** (2016) 1-37.

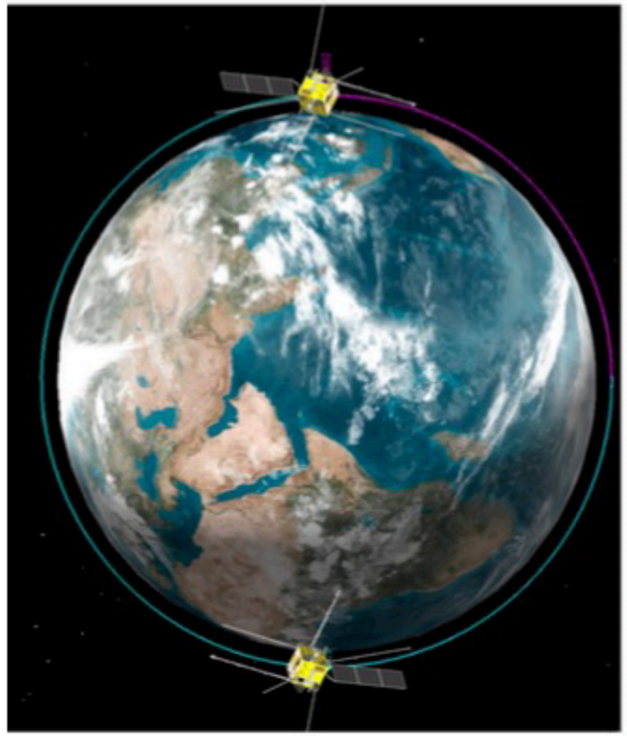


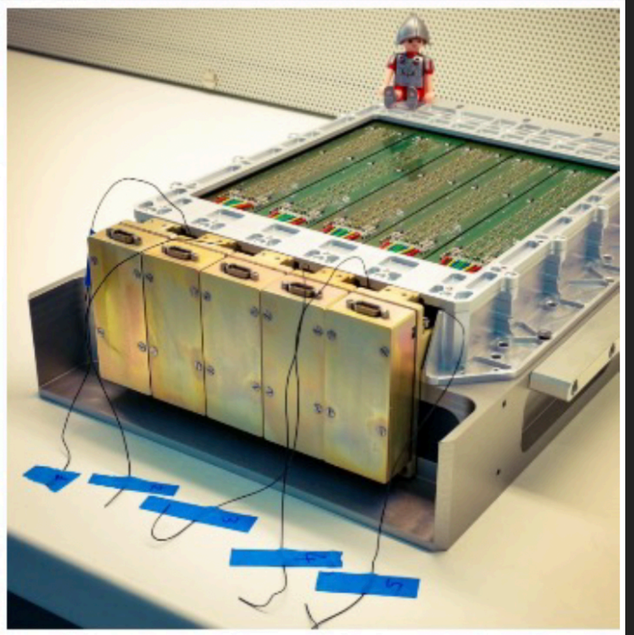
SATELLITE "CSES-02/HEPD-02" : LAUNCH DECEMBER 2024





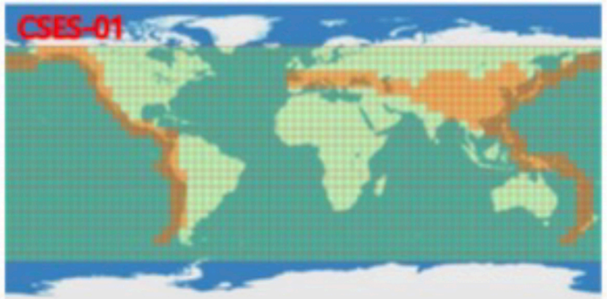




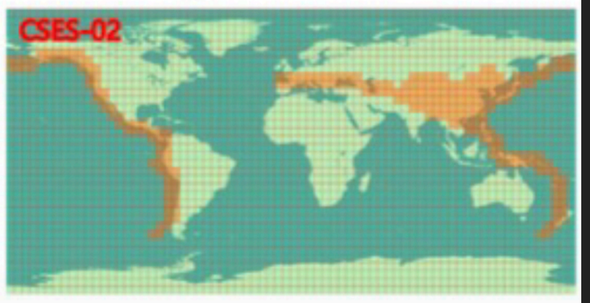


First tracker (and not single layer), based on pixel, operated in space

Operation area between lat [-65,65]

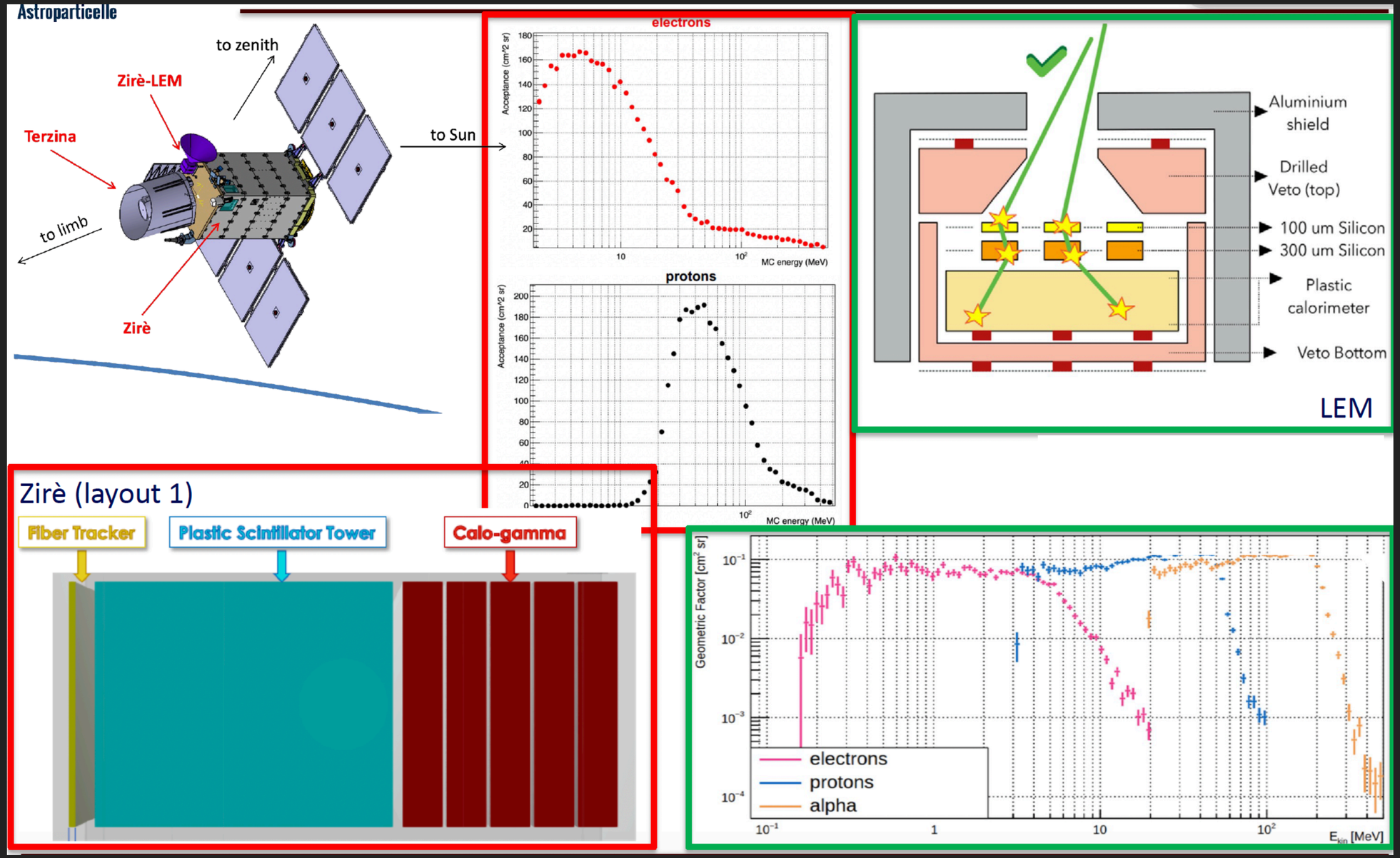


Full coverage at extreme latitudes



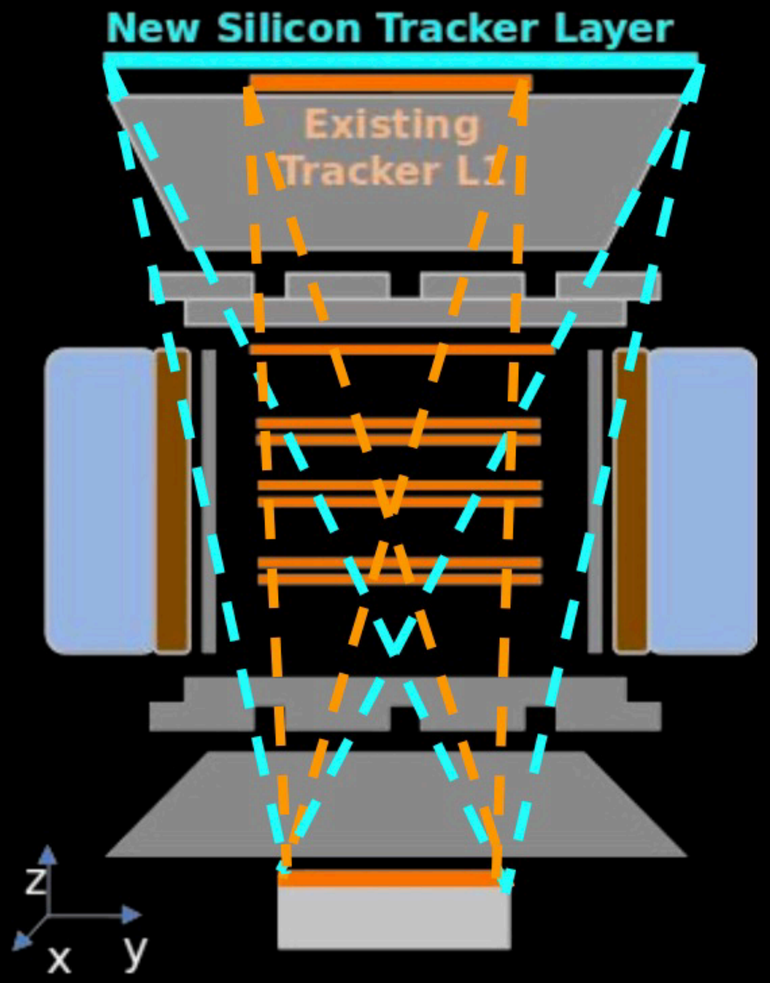
- 30-200 MeV protons
- 3-100 MeV electrons
- Light nuclei
- Higher energy window and full coverage wrt HEPD-01

SATELLITE "NUSES/ZIRE'– LEM" : LAUNCH IN 2025



- **NUSES** (NeUtrino and Seismic Electromagnetic Signals) space mission
- Will fly on a Low Earth Orbit (LEO) at an altitude of 550 km at high inclination of 97.8°
- **ZIRE':** for the detection of low energy photons and Cosmic Rays (CRs) until hundreds of MeV
- **Low Energy Module (LEM)**: lowering the energy threshold down to hundreds of keV for electrons.

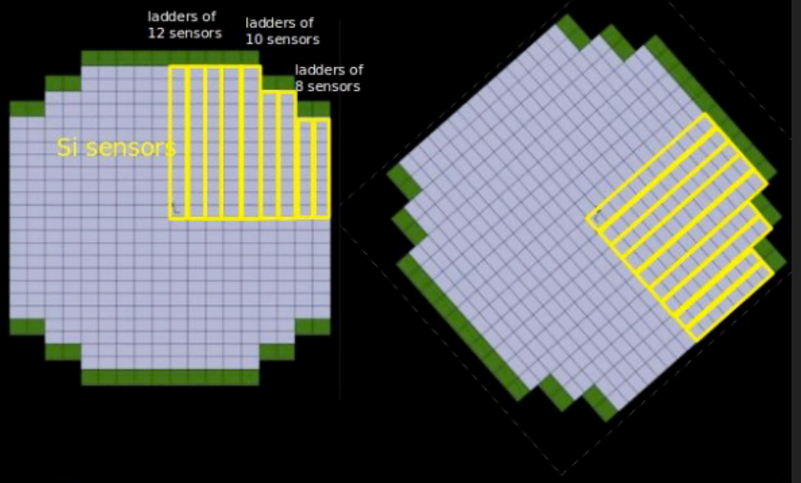
"AMS" UPGRADE ON ISS : DEPLOYED IN 2026



- 1 new layer, 2 planes (45° X-Y)
- Silicon microstrip sensors (27um pitch)
- New (10% reso) Z measurement ABOVE detector -> Fragmentation eval.
- Factor 3x acceptance (10 yrs -> 30 yrs)
- ¼ plane Qualif. Model
  - Integration
  - Vibration Test
  - Performance

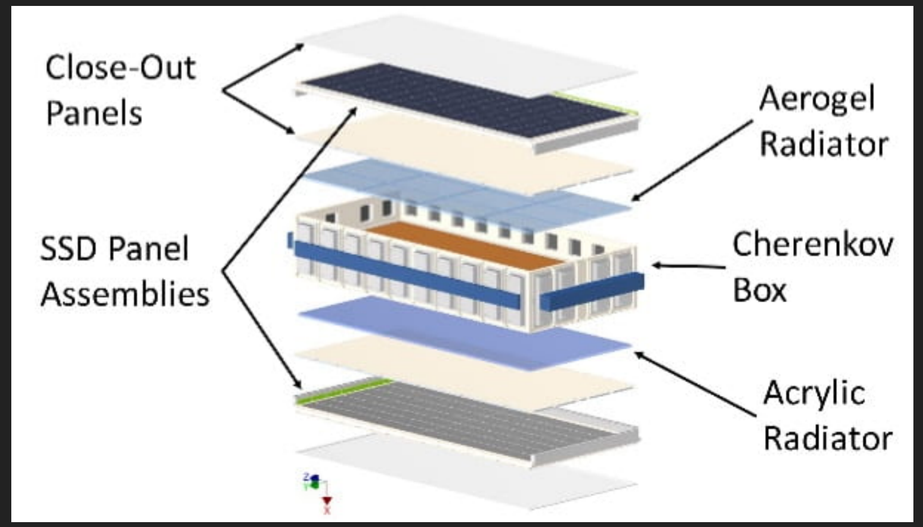
L0-Y
bending direction
7 micron

L0-U
rotated 45°
10 micron bending
10 micron non-bending

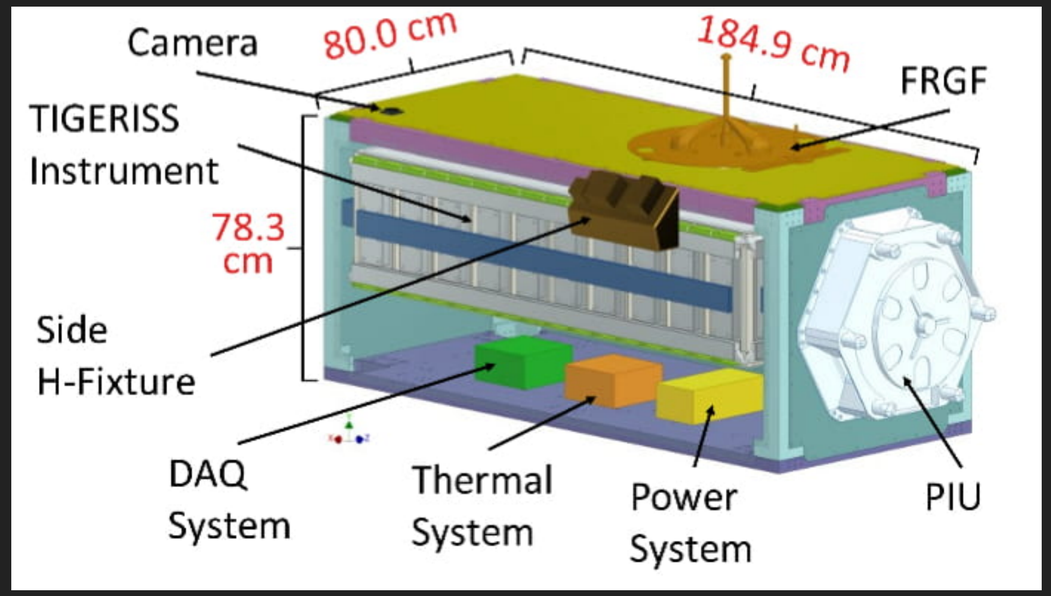


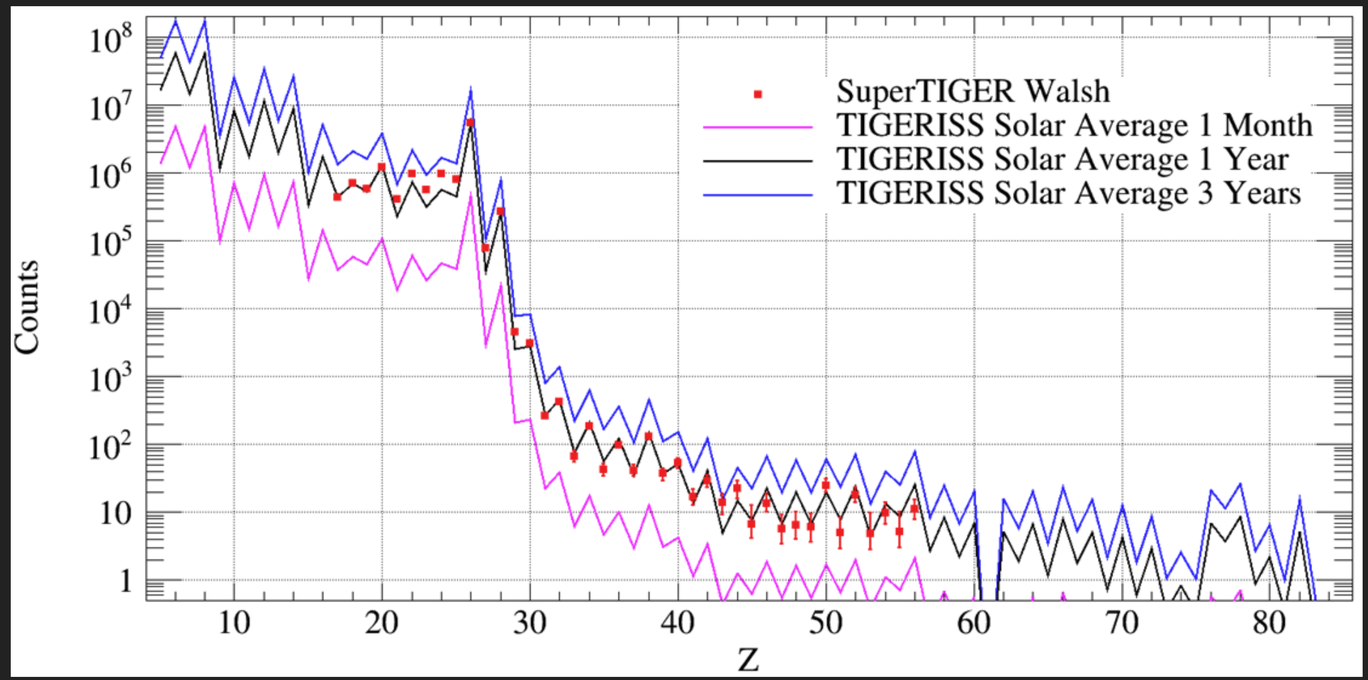
Will increase acceptance, also for positrons/antiprotons

"TIGER-ISS" ON ISS : LAUNCH IN 2026

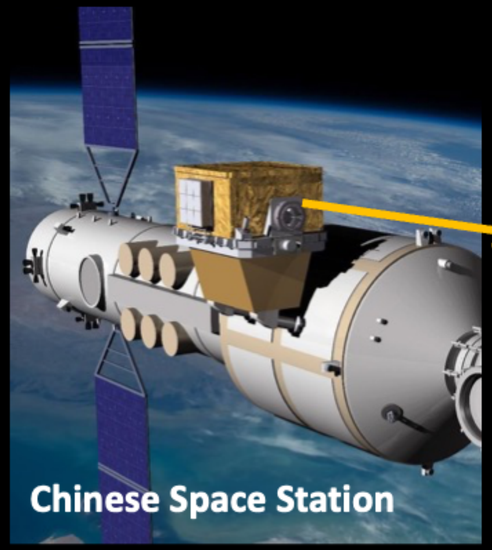


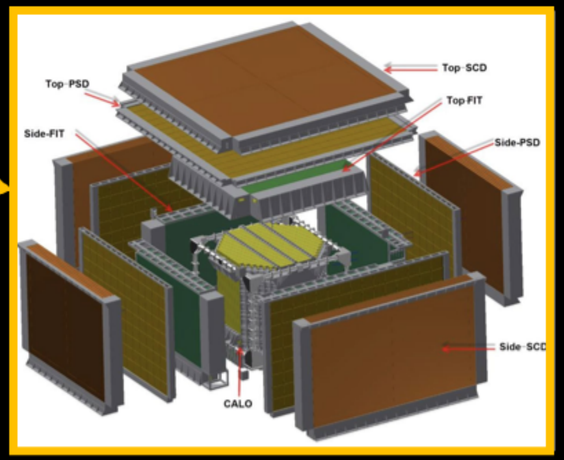
- TIGER-ISS instrument model for the Japanese Experiment Module "Kibo" on ISS
- Silicon strip detector (SSD) for precision charge measurement σQ < 0.24e for **5 ≲ Z ≤ 82** and SiPM Cherenkov detector readout
- In 1 year the statistics of SuperTiger (see below)
- No atmospheric correction –> cleaner signal





"HERD" ON THE CSS : LAUNCH IN 2027





High Energy Cosmic Radiation Detector (HERD)

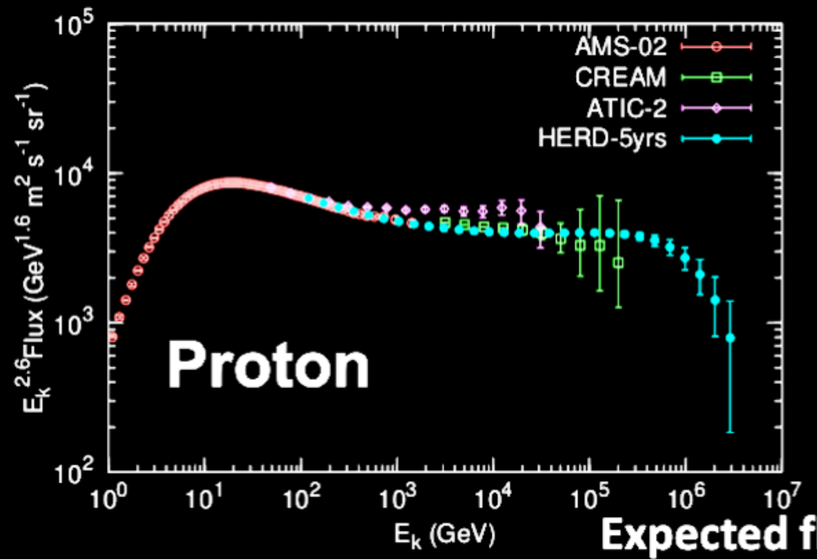
Based on a 3D, homogeneous, finely-segmented calorimeter of 55 X_0 with a wide field of view (2π). Complemented by other detectors for PID (charge, veto, tracking, …).

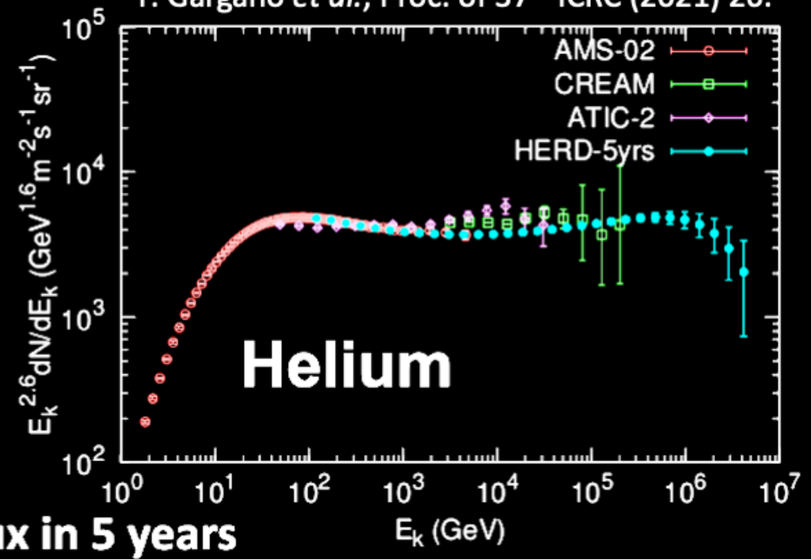
Installation foreseen 2027.

- Measurement of cosmic-rays up to the knee.
- ɣ-rays monitoring and full sky survey.
- Indirect dark matter search (all-electron, ɣ-ray)

G.F. (e)	>3 m^2sr@200 GeV
G.F. (p)	>2 m^2sr@100 TeV
Energy range (e/γ)	10 GeV - 100 TeV (e); 0.5 GeV - 100 TeV (γ)
Energy range (p)	30 GeV - 5 PeV
Charge meas.	Z=1-28; <0.15 c.u.@Z=1
Energy resolution (e)	1%@200 GeV
Energy resolution (p)	<25%@100 GeV – PeV
e/p separation	>3*10^5(90% eff.@100GeV)
Angular resolution	0.1 deg.@10 GeV

F. Gargano *et al.*, Proc. of 37th ICRC (2021) 26.





Expected flux in 5 years

CONCLUSIONS: A REVOLUTION IN THE LAST 15 YEARS!

I. The flux of CRs is NOT a simple power-law …
   - First break (hardening) –> propagation
   - Second break (softening) –> ?

II. Why is the slope of the spectrum of CR proton and helium different?
   - Helium spallation?
   - Different acceleration sites or mechanisms?

III. What is the origin of the positron rise?
   - Astrophysics–> pulsars?
   - Dark matter?

IV. Is there room for an exotic production of antiprotons at high energy?

V. Is the electron break at 1 TeV understood?

VI. A new source for Z>40 elements?

PERSPECTIVES

I. New experiments and data coming soon!

- HELIX, GAPS, CSES-02, NUSES, AMS-upgrade, TIGER-ISS, HERD, ..

II. New experiments measuring cross sections are needed!

- e.g. NA61/Shine @ CERN (B isotopes from C beam, and other light elements), LHCf @ CERN, …
- “XSCRC2024: Cross sections for Cosmic Rays @ CERN” conference!

More in the talks by (C. Evoli), P. Mertsch, I. Moskalenko, … et al. !