Cosmic Rays measurement in space

V. Formato – INFN Sezione di Roma Tor Vergata

25/01/2023 – Status and prospects of astroparticle physics

What are cosmic rays?

Particles coming from outer space

Mostly of galactic origin (at least in this talk...)

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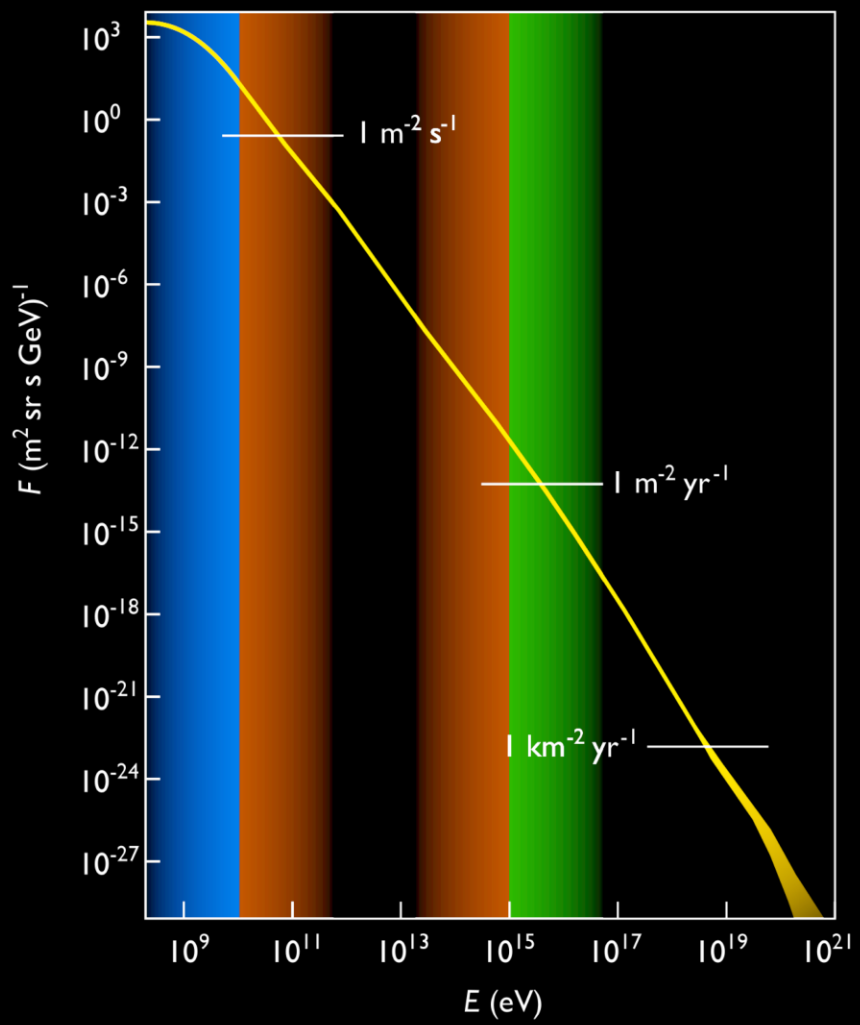

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Accelerated by SNE shocks in the Galaxy**

Spend ~Myr random-walking against the galactic magnetic field, traversing the Interstellar Medium (ISM)***

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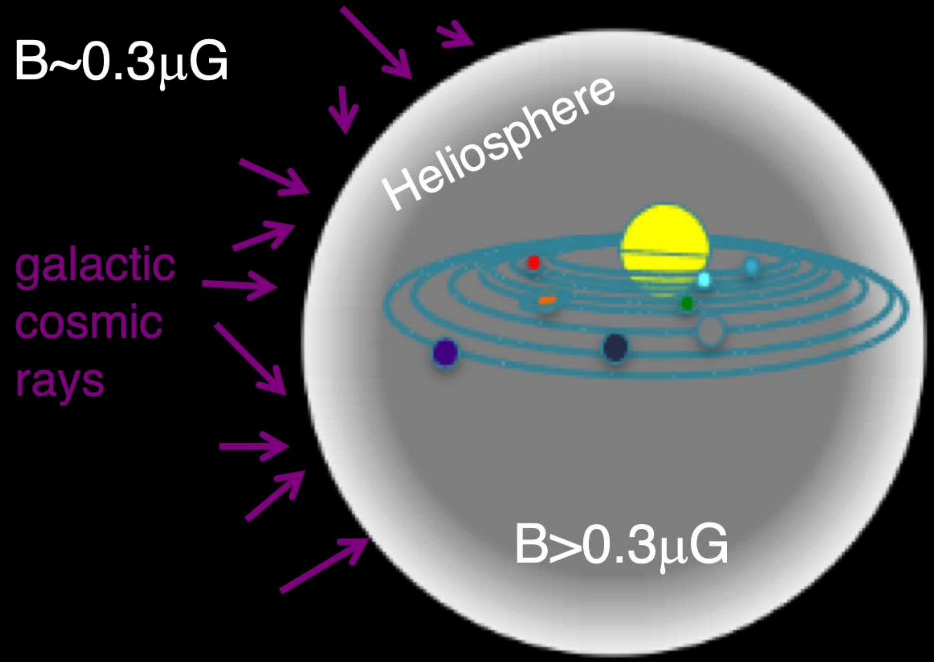

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Mostly of galactic origin (at least in this talk…)

Accelerated by SNE shocks in the Galaxy**

Spend ~Myr random-walking against the galactic magnetic field, traversing the Interstellar Medium (ISM)***

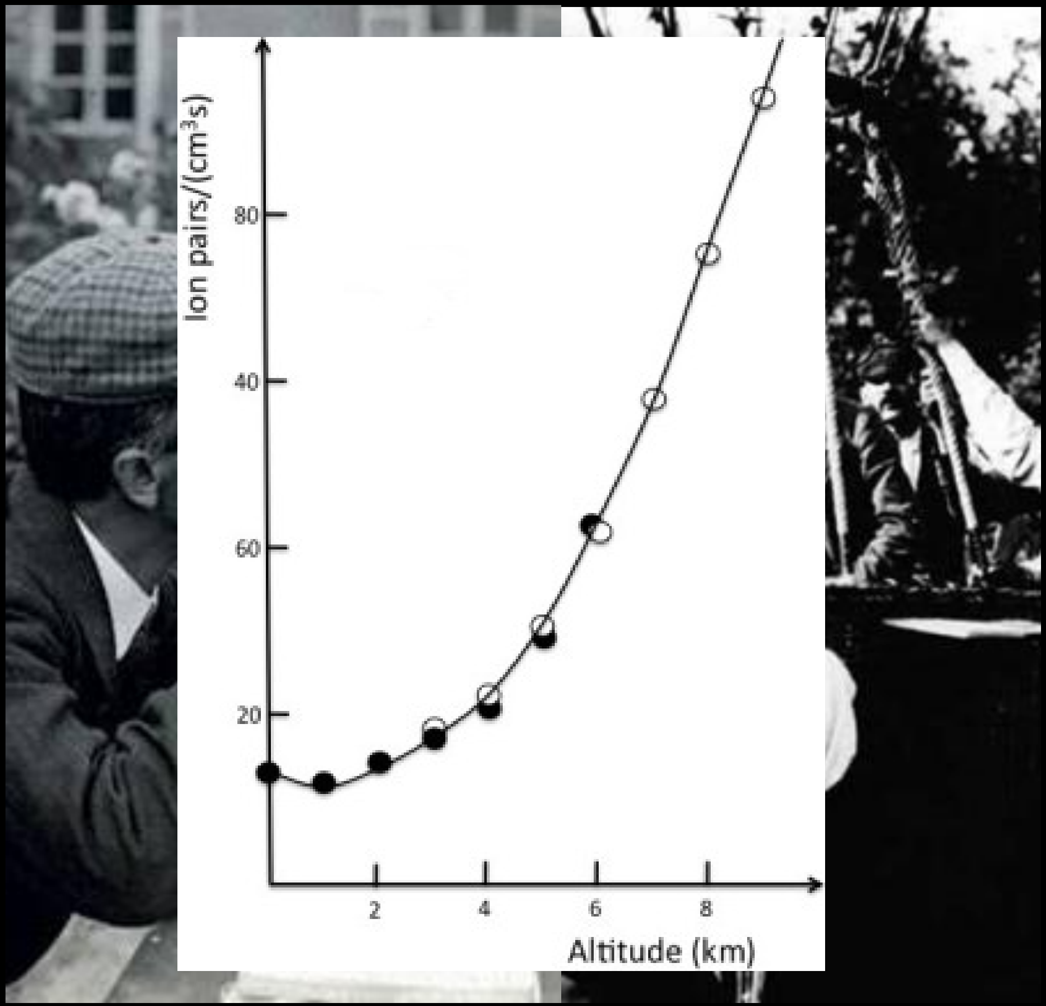
Some will eventually reach the solar system and diffuse through the heliosphere

The early days


Discovered in the early 1900s

Started as “spontaneous discharge of electroscopes”, which increased in rate with altitude (and decreased underwater)

The early days



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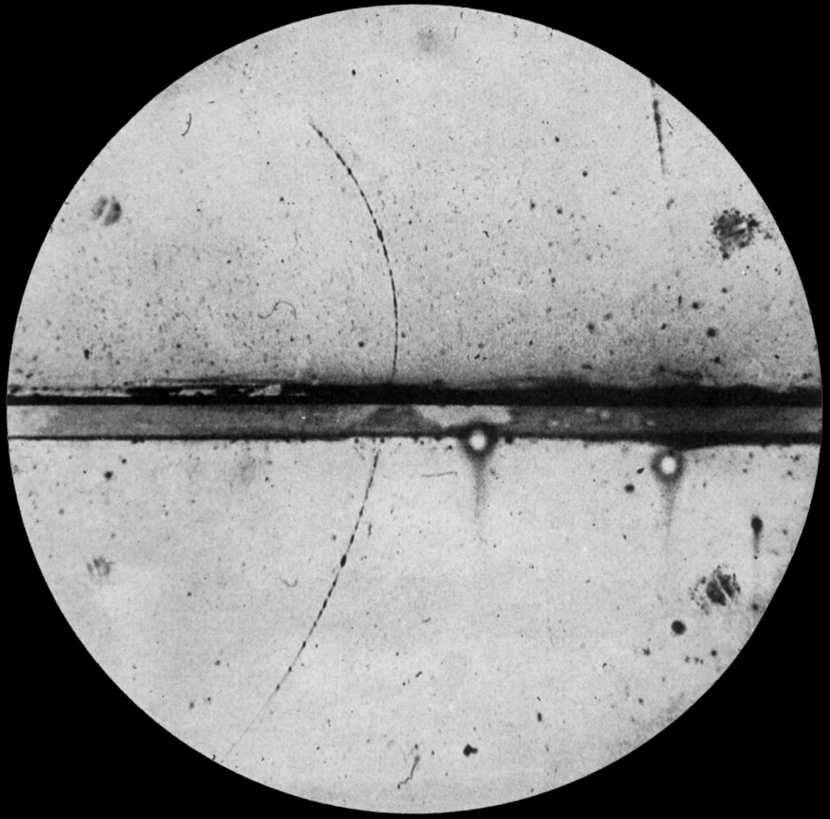

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Eventually gave birth to what we know today as “Particle physics”. All major discoveries came through the study of cosmic rays.

The early days

Particle	Year	Discoverer (Nobel Prize)	Method
e^{+}	1897	J.J. Thomson (1906)	Discharges in gases
p	1919	E. Rutherford	Natural radioactivity
n	1932	J. Chadwick (1935)	Natural radioactivity
e^{+}	1933	C.D. Anderson (1936)	Cosmic Rays
$\mu^{\pm}$	1937	S. Neddermeyer	Cosmic Rays
$\pi^{\pm}$	1947	C.F. Powell (1950)	Cosmic Rays
$K^{\pm}$	1949	C.F. Powell (1950)	Cosmic Rays
π^{0}	1949	R. Bjorklund	Accelerator
K^{0}	1951	R. Armenteros	Cosmic Rays
Λ^{0}	1951	R. Armenteros	Cosmic Rays
Δ	1952	C.D. Anderson (1936)	Cosmic Rays
Θ^{-}	1952	R. Armenteros	Cosmic Rays
$\Sigma^{\pm}$	1953	A. Bonetti	Cosmic Rays
p^{-}	1955	O. Chamberlain (1959) E. Segré (1959)	Accelerators
anything else	> 1955	various groups	Accelerators
ν oscillations	1998	SuperKamiokande	Cosmic Rays

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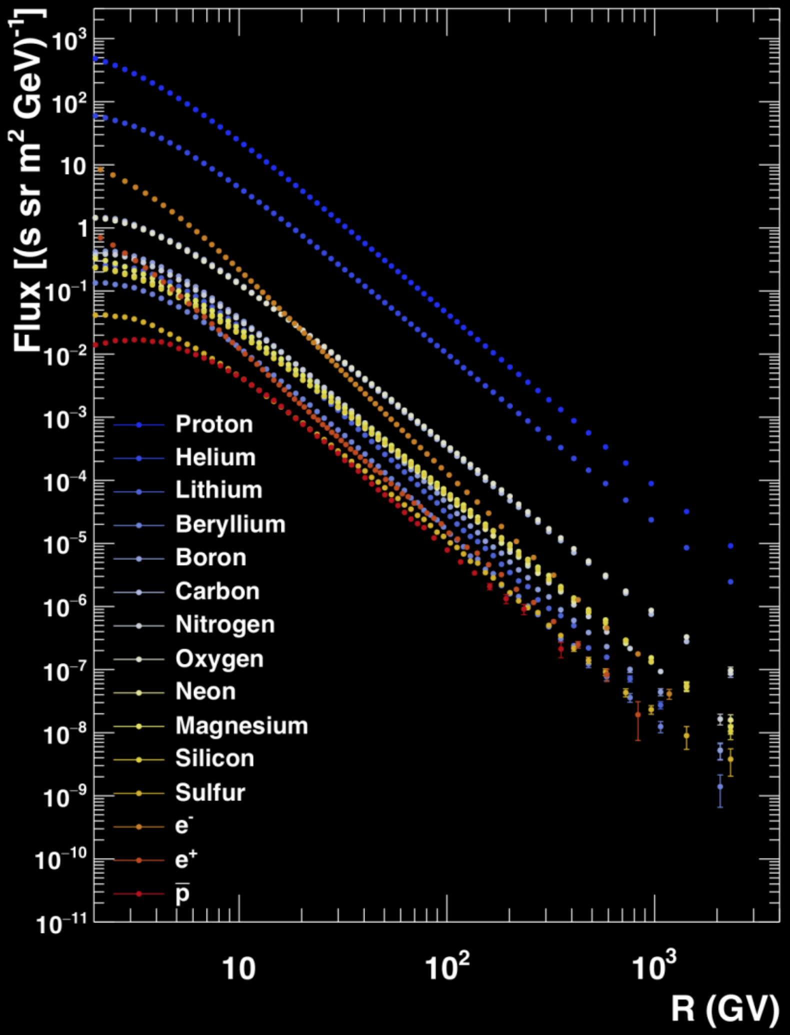
Started as “spontaneous discharge of electroscopes”, which increased in rate with altitude (and decreased underwater)

Eventually gave birth to what we know today as “Particle physics”. All major discoveries came through the study of cosmic rays.

…well, at least until the advent of particle accelerators.

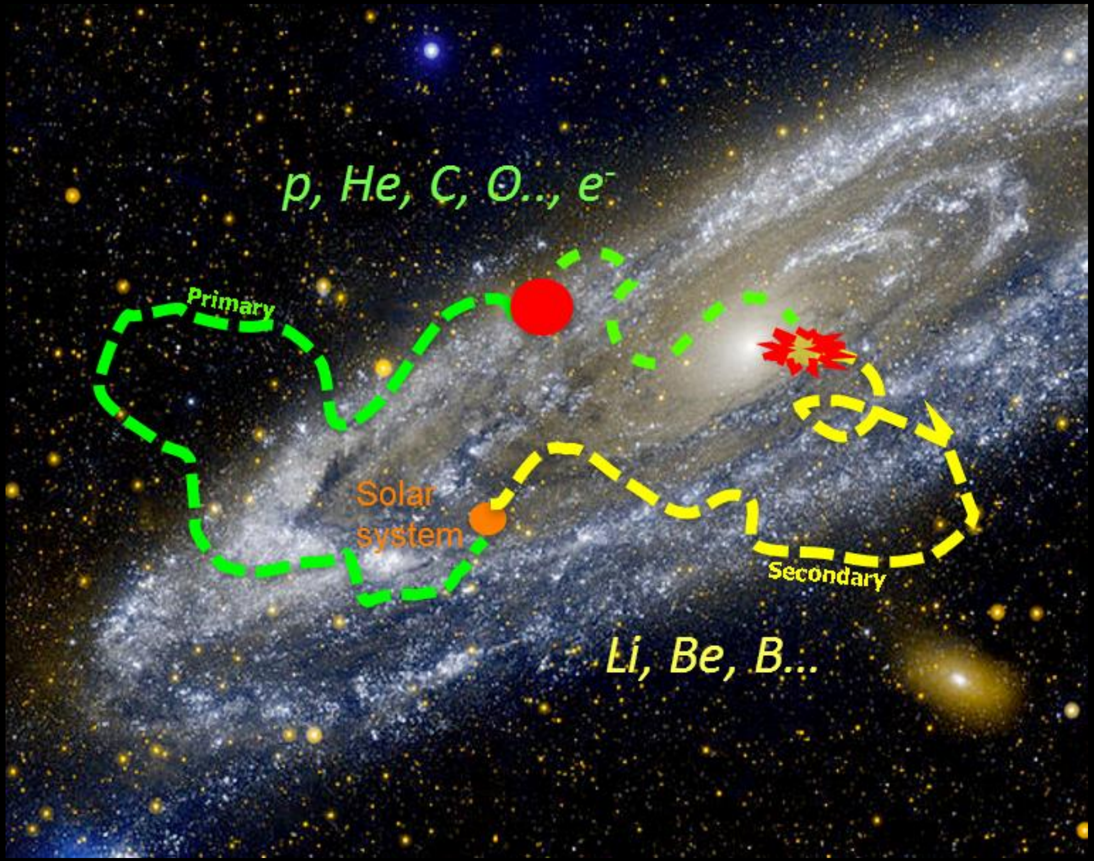
"Standard model" of cosmic rays



Mostly composed by protons (~89%) and helium nuclei (~9%), heavier nuclei (~1%), electrons (~1%) and traces of antimatter

Distributed according to a power-law spectrum which extends over several orders of magnitude in energy

"Standard model" of cosmic rays



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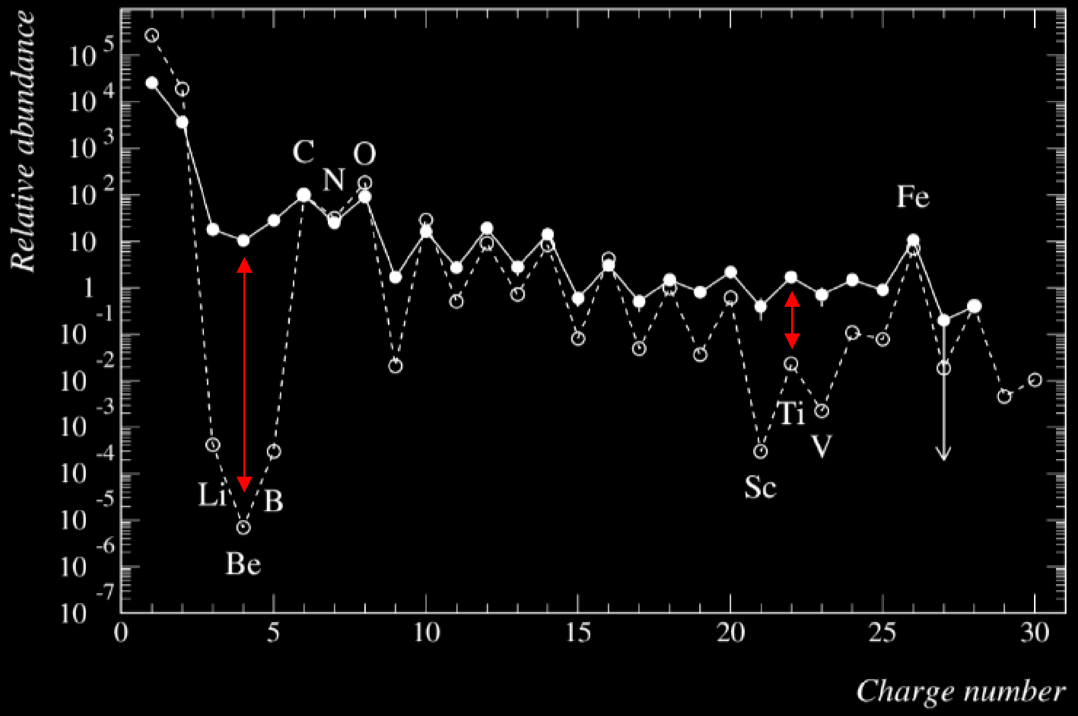
During propagation cosmic rays can interact with the ISM, this creates a distinction between "primary" and "secondary" cosmic rays

The measurement of CR nuclei energy spectra carries information about sources, acceleration and propagation processes of all CRs.

"Standard model" of cosmic rays



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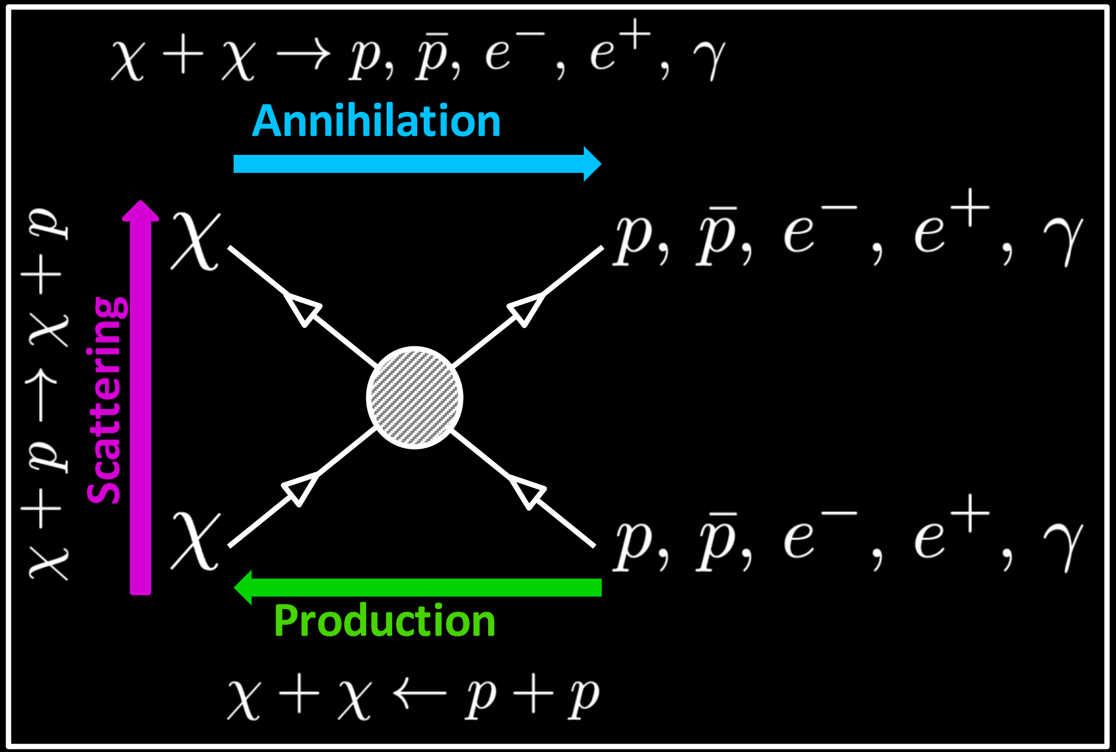
Opportunities for "new physics"?

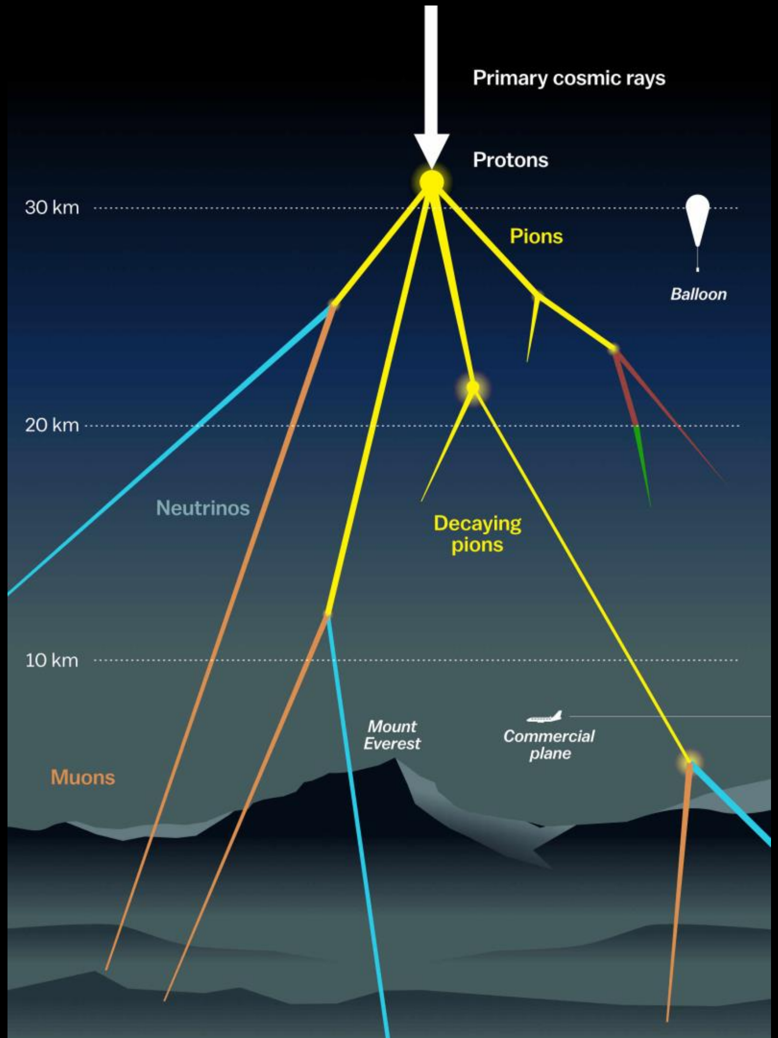


The low amount of secondary antimatter makes it a golden channel for any search for new physics

Any new effect should then produce an excess of positrons and/or antiprotons.

(And heavier antimatter is even rarer)

Space: The final frontier



Fortunately, we are surrounded by several km of atmosphere.

But this makes measuring cosmic rays more difficult.

For several decades cosmic rays research has been based on using balloons to elevate the instrumentation as high as possible, and still does today.

But several efforts have been made to study cosmic rays outside of the Earth atmosphere.

Challenges for space experiments

Pro:
- No atmosphere

Con:
- Extremely expensive
- Instruments are very limited in terms of weight budget (and thus size/sensibility)
- Instruments are very limited in terms of power budget (especially on free-flying satellites)
- Every electronic component must be space-qualified (and radiation-hard)

Is it worth the effort?

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Is it worth the effort?

Yes

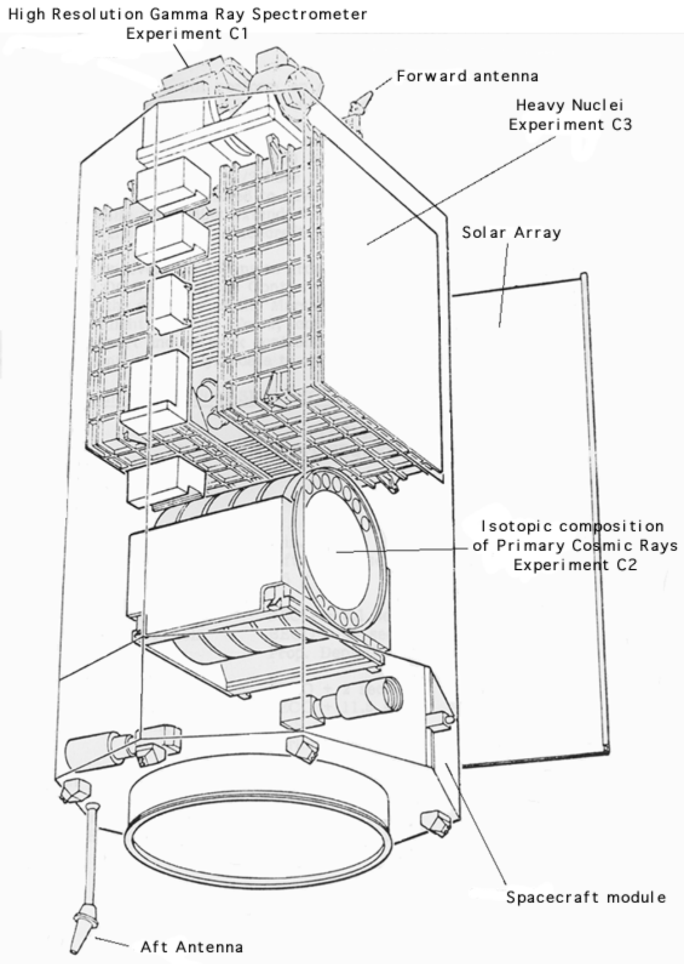
Disclaimer

This talk is focused on space-borne experiments

This talk is focused on galactic cosmic rays

...so apologies if some missions or detectors are missing

The ghost of experiments past (HEAO-3)



The High Energy Astronomy Observatory 3 (1979-1981)

Two instruments on board dedicated to cosmic ray measurement up to ~30 GeV/n

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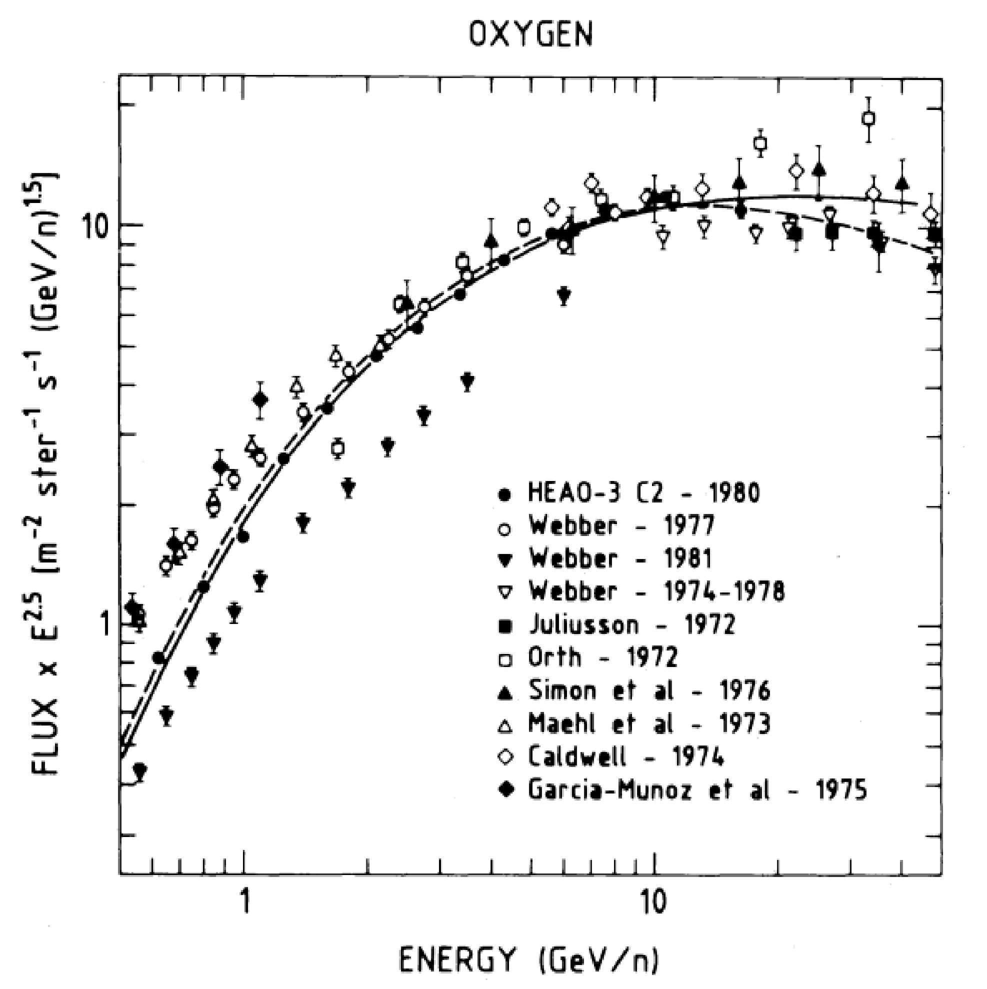

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In particular C2 provided flux measurement for nuclear species from Z=4 to Z=28 using a stack of 5 Cherenkov detectors.

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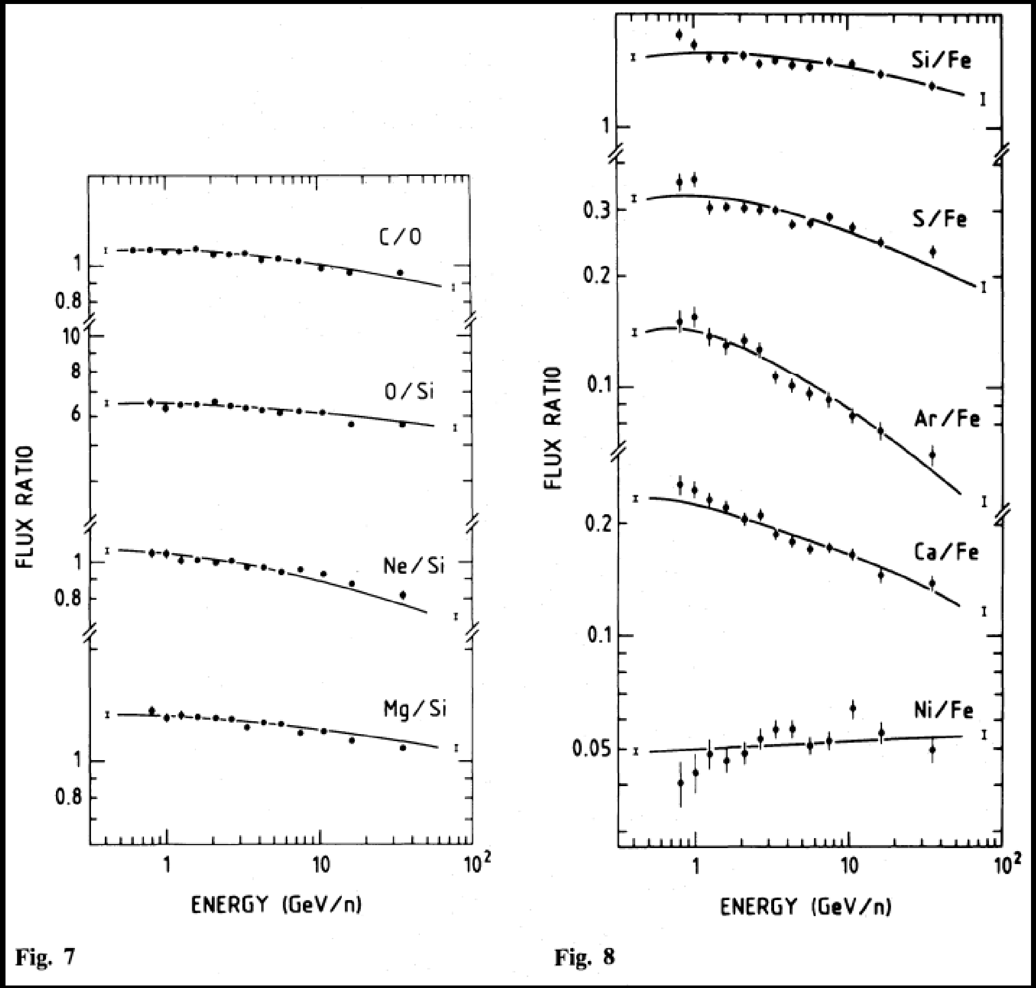

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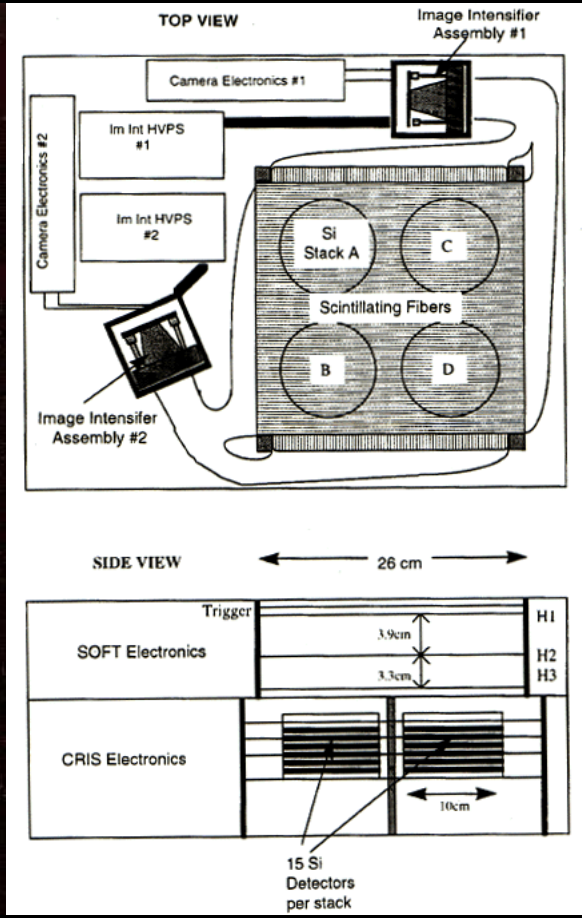

The Cosmic Ray Isotope Spectrometer on the Advanced Composition Explorer (1997-today)

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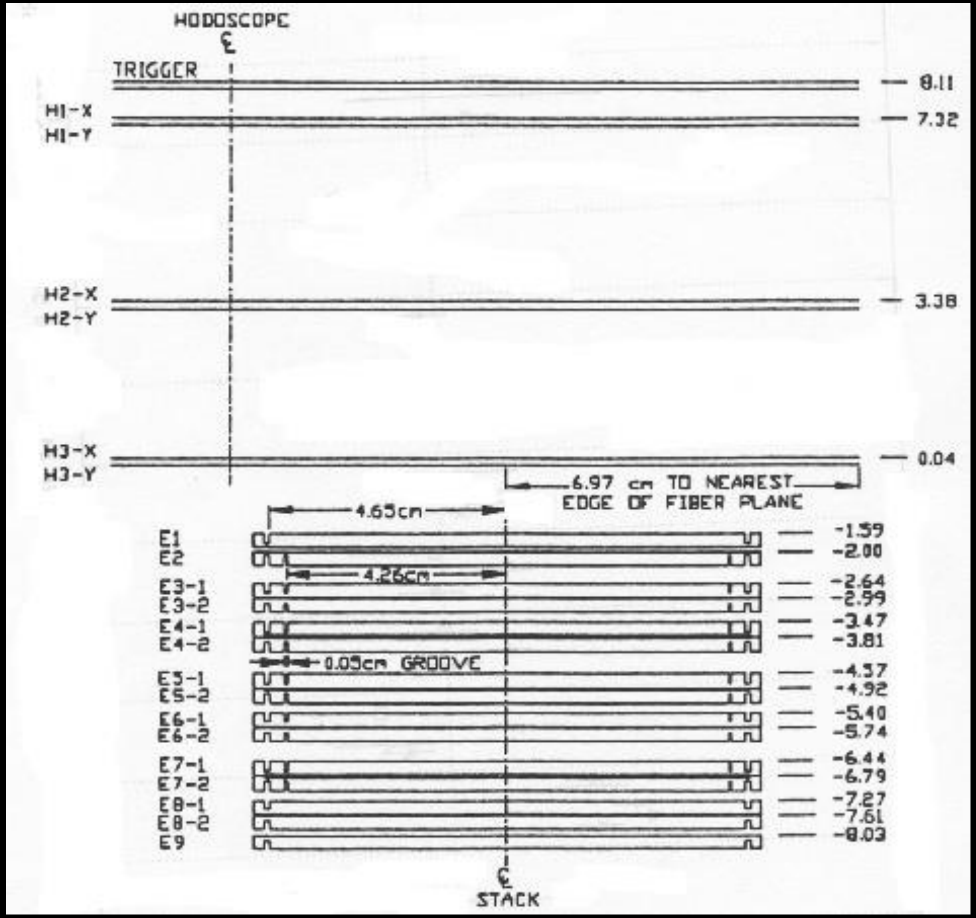

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Composed by 4 stacks of silicon detectors with a scintillating fiber tracker on top.

Particle ID by measuring dE/dx in the silicon detectors and total energy by absorption in the silicon stack.

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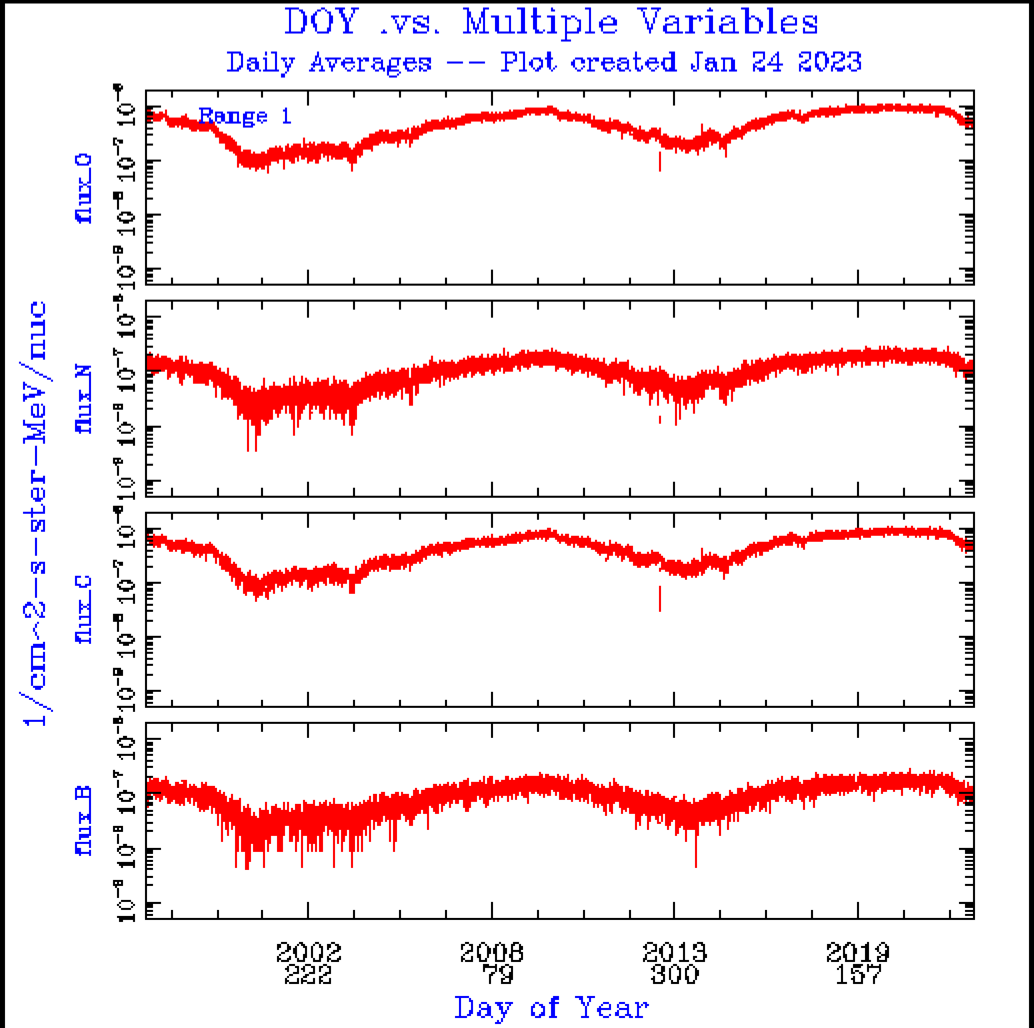

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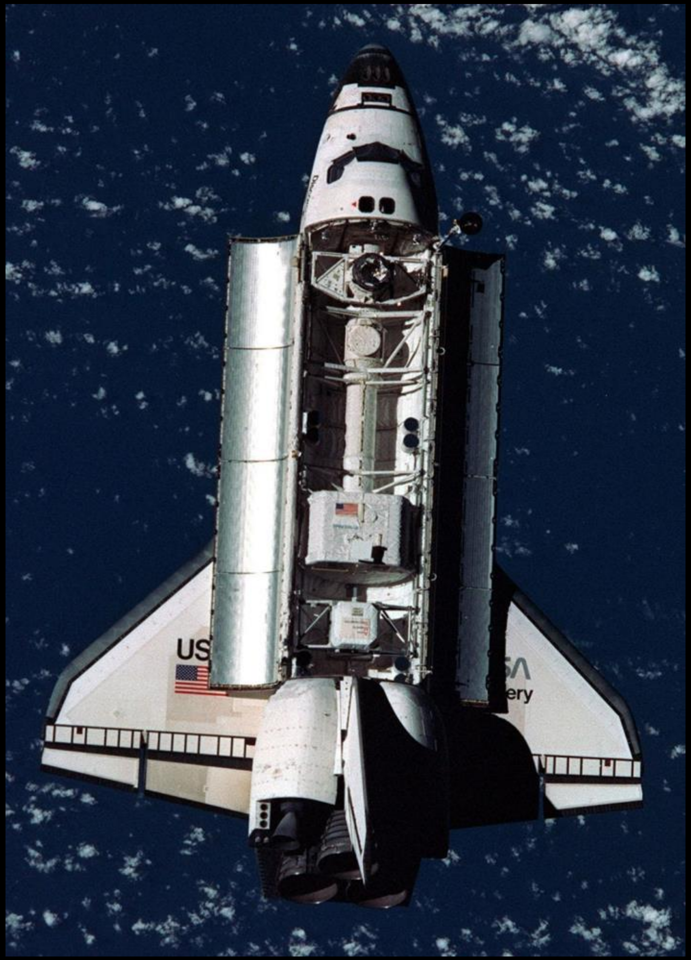
Can measure a wide variety of nuclear species, separating isotopes although at very low energy (~ GeV).

The ghost of experiments past (AMS-01)



Prototype for the AMS-02 detector, flown on the Space Shuttle Discovery in June 1998

Demonstrated the feasibility of silicon microstrip trackers in space

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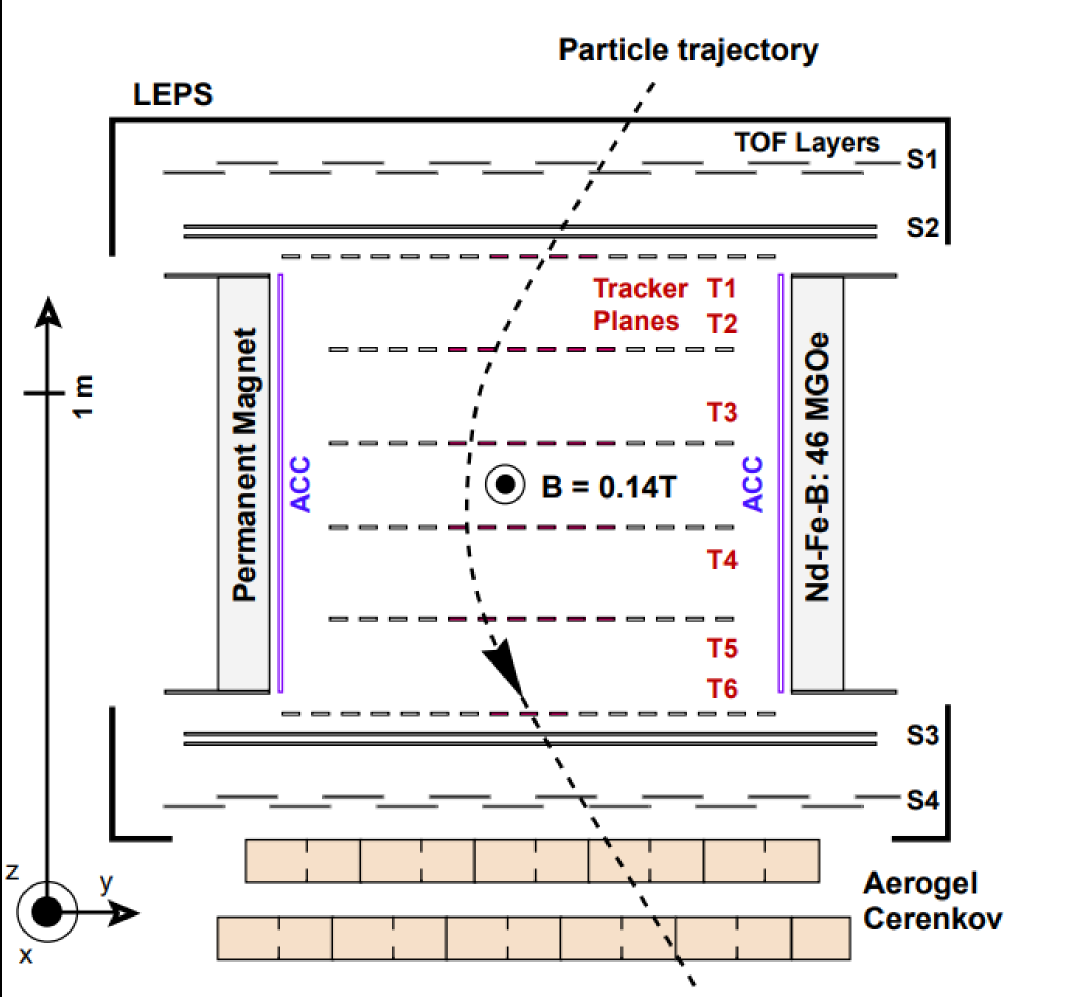

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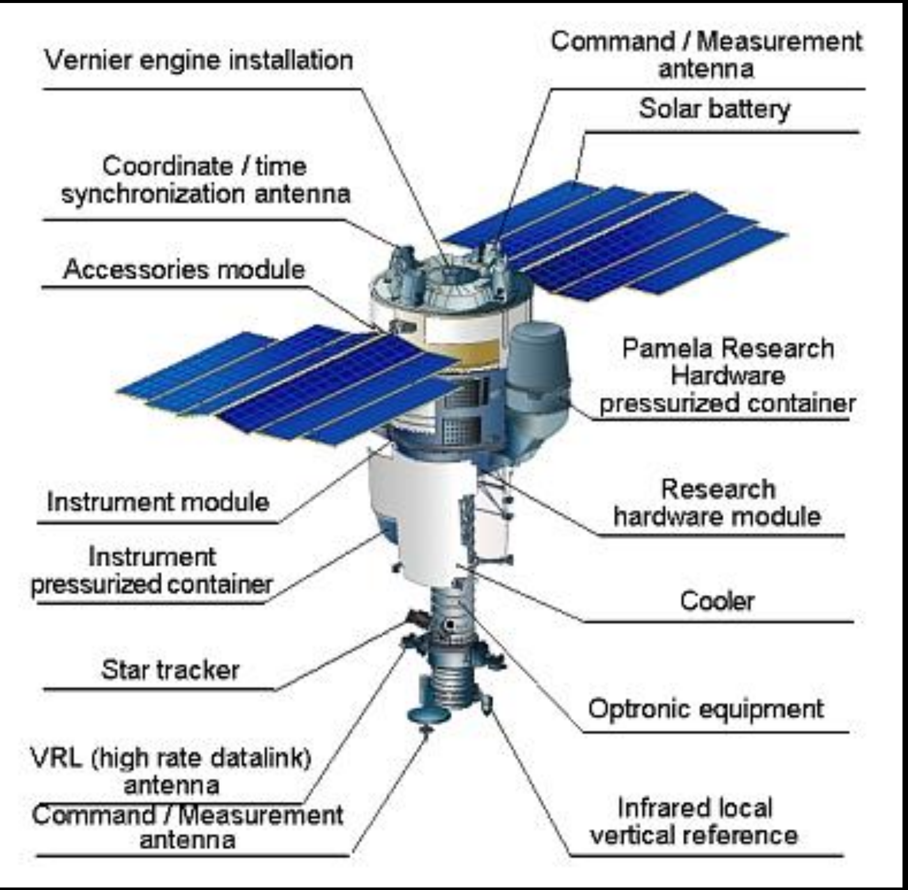
First "real" particle detector flown in space

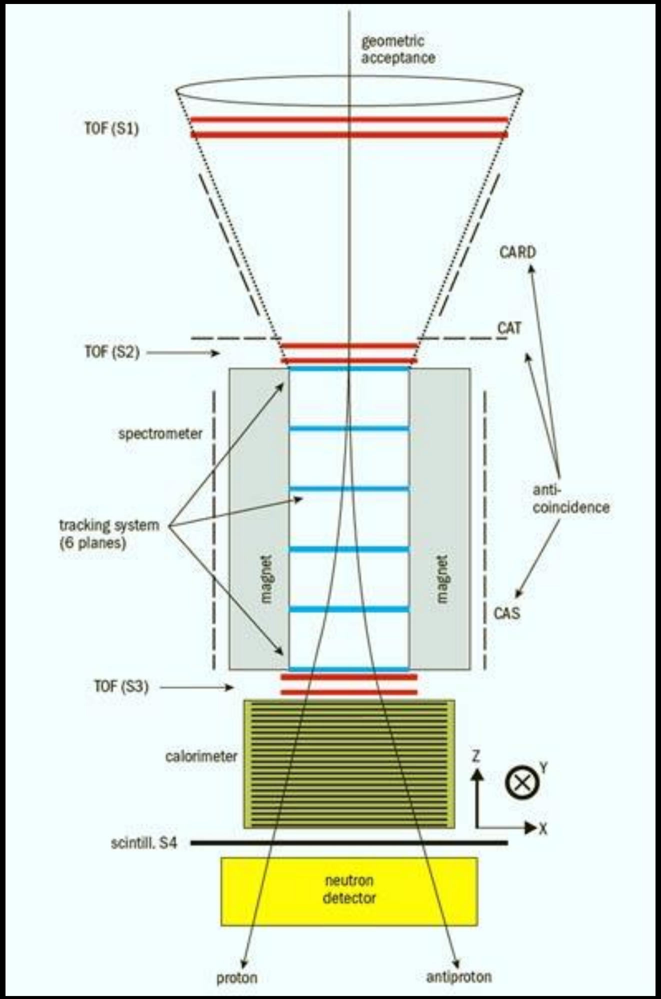
It was a real demonstrator of what a full-fledged particle detector could do outside the atmosphere for cosmic ray physics

The ghost of experiments past (PAMELA)



Payload for Matter, Antimatter and Light-Nuclei Astrophysics (2006-2014)

The ghost of experiments past (PAMELA)



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First detector in space to reach the TeV range, highly optimized for Z=1 particles (especially antimatter)

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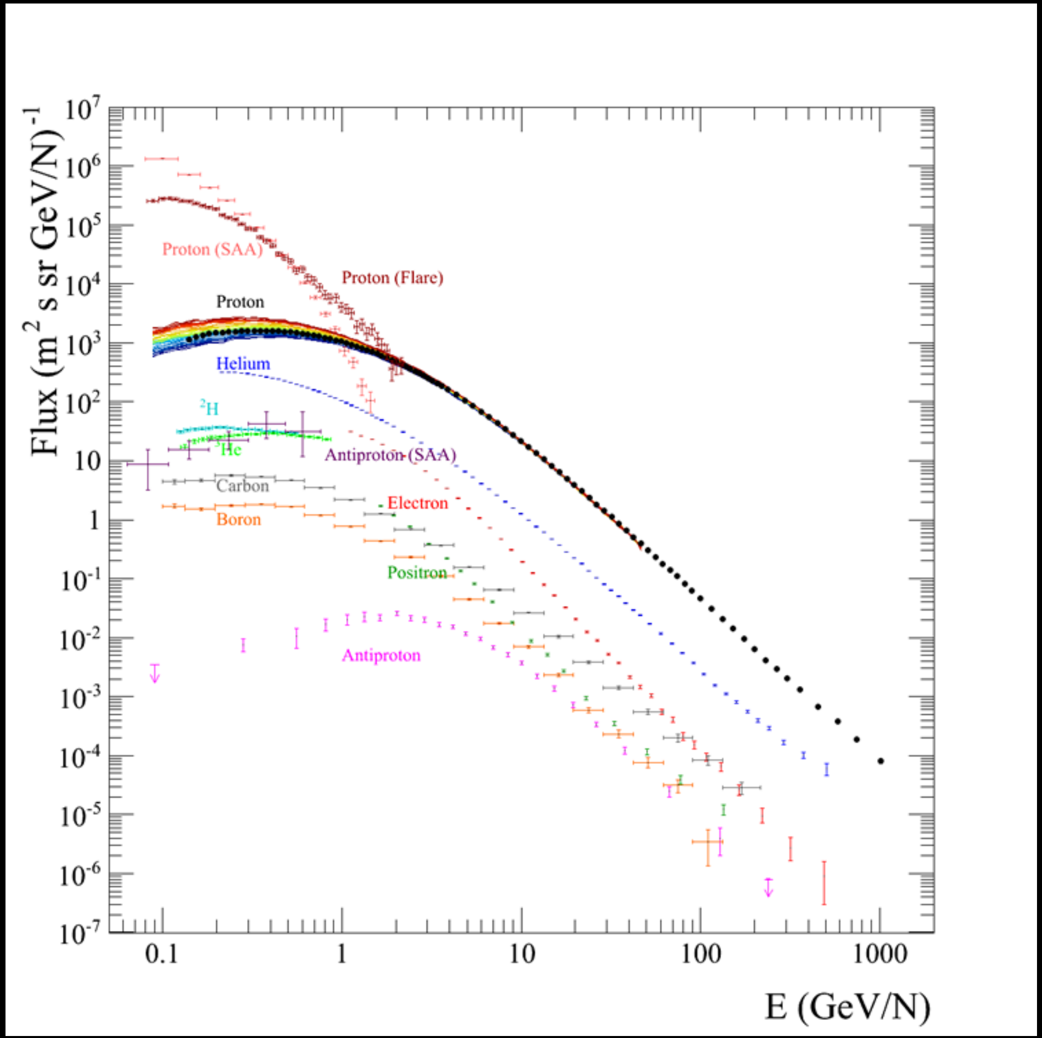

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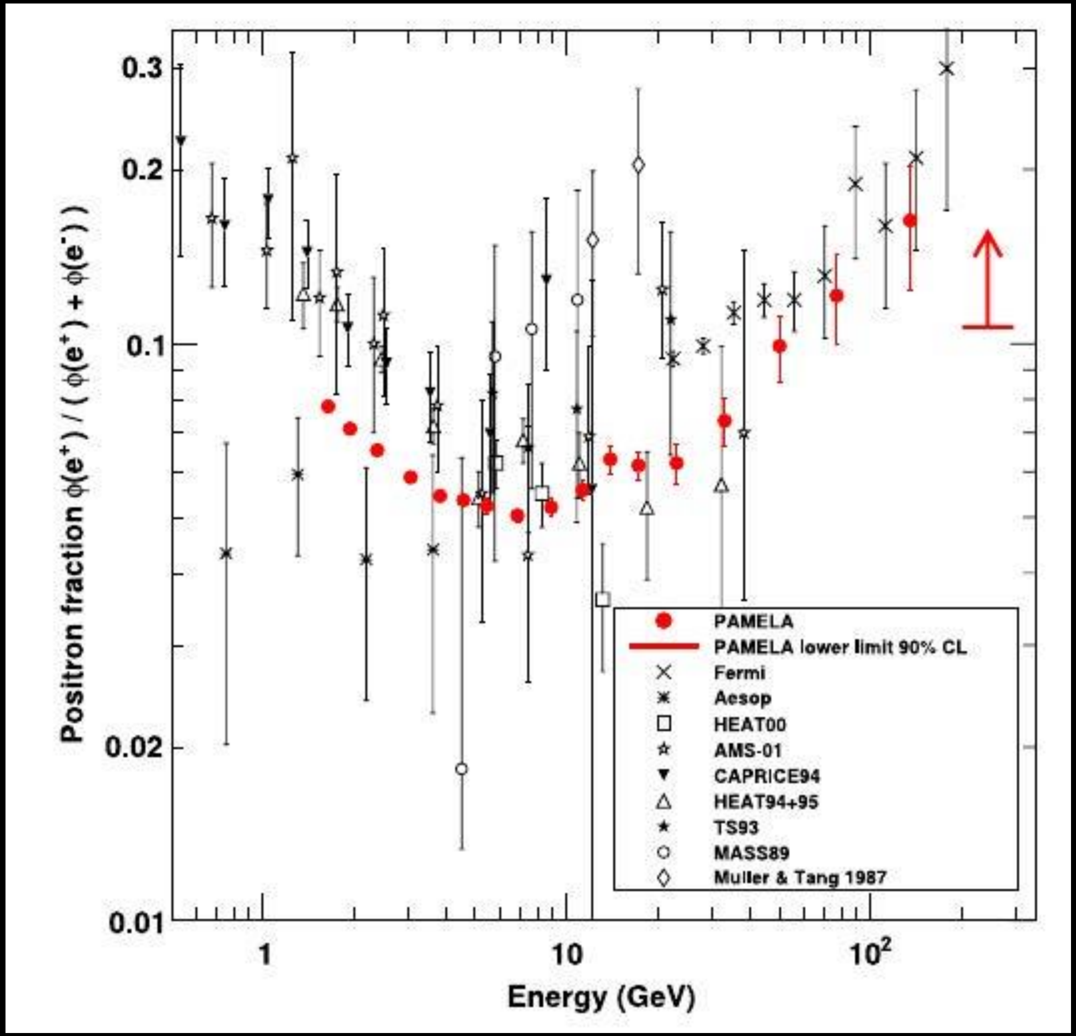

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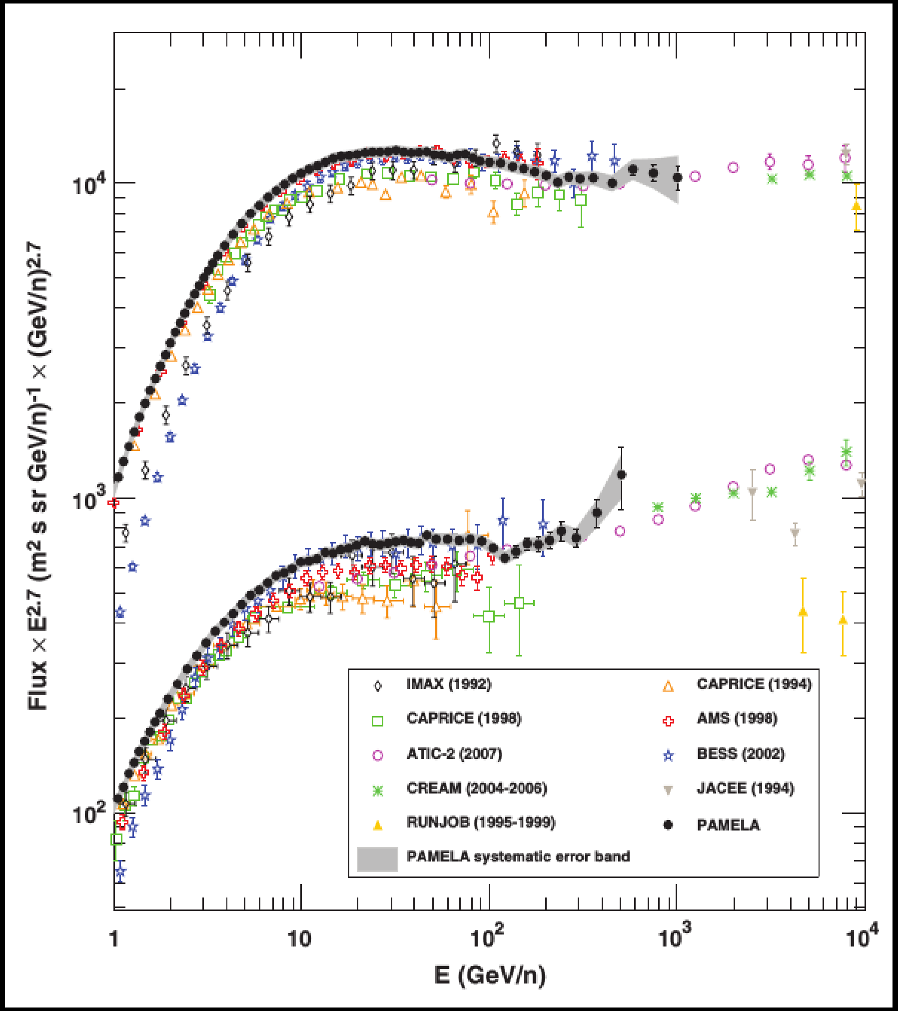

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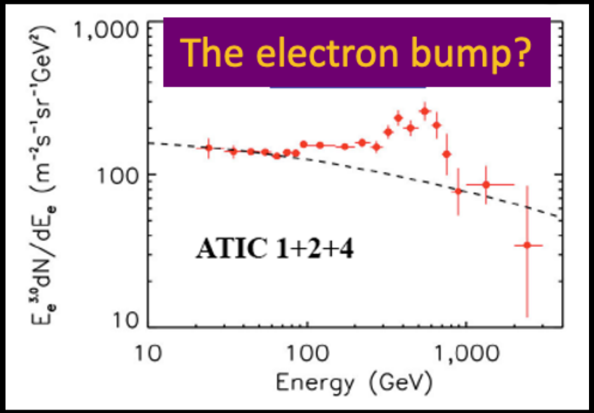
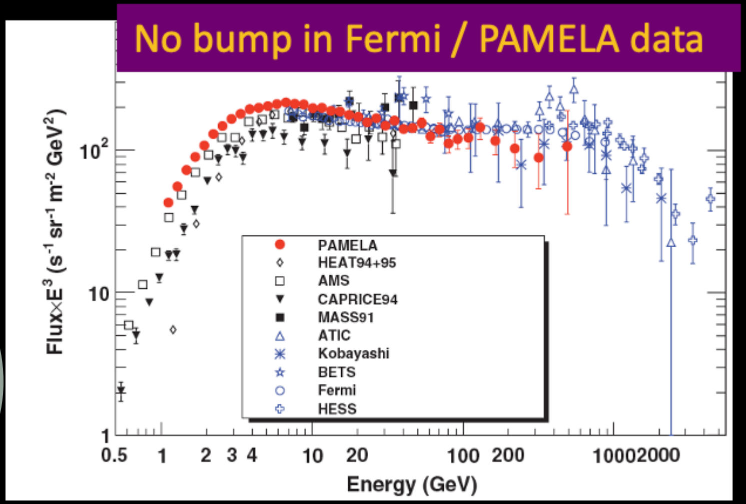
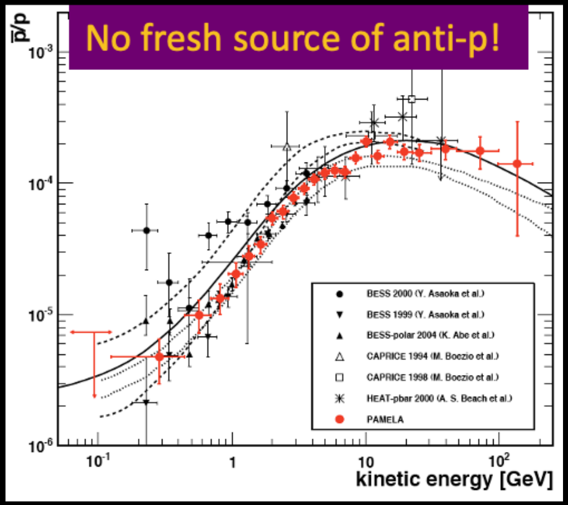
First comprehensive set of measurements of multiple cosmic rays species from the same detector.

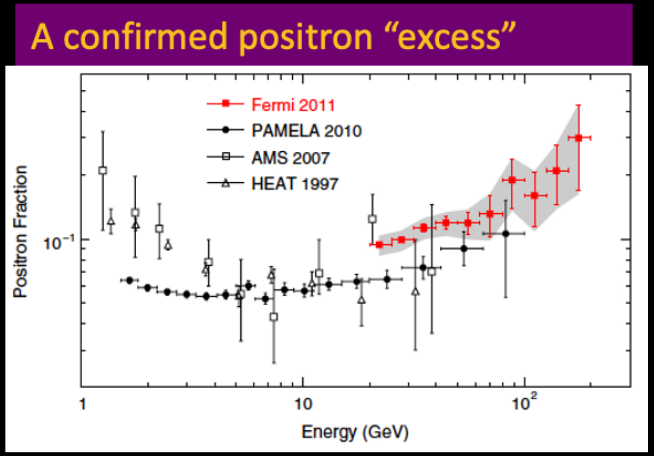
2009 – Found a significative positron excess at high energy
2011 – First proof that cosmic ray spectra deviate from the single power-law assumption

The antimatter puzzle (2011)



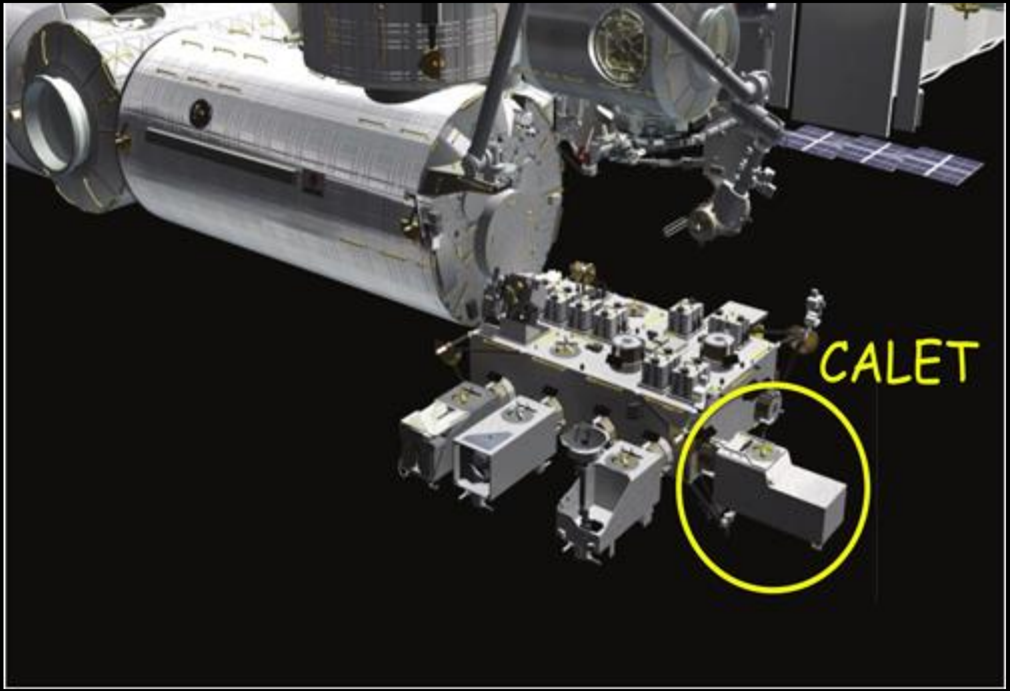




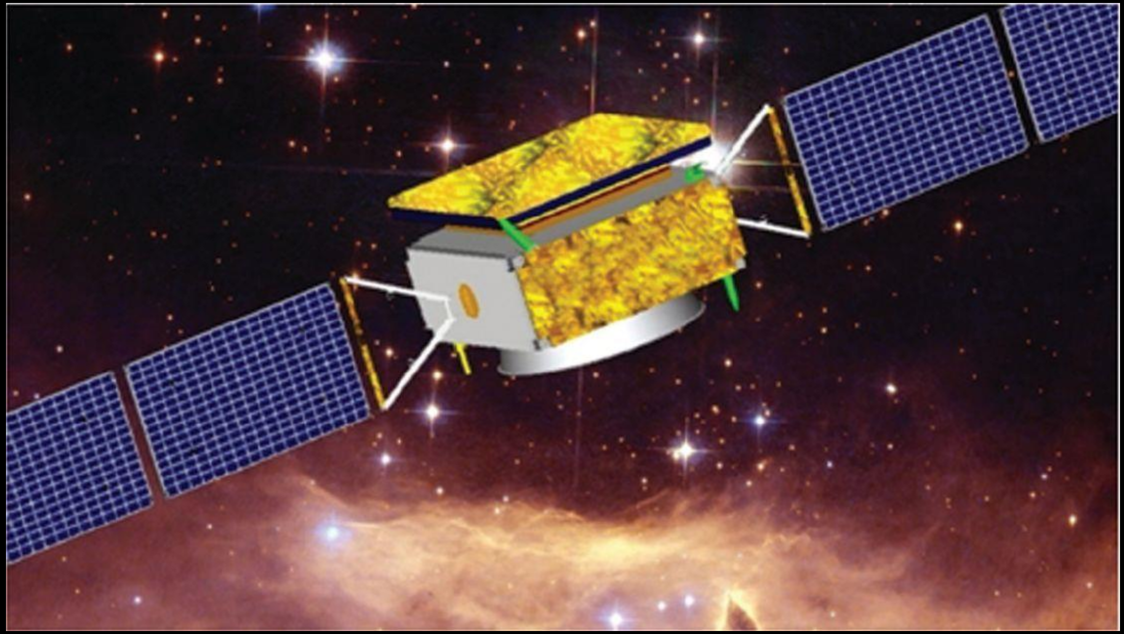


The ghost of experiments present (CALET and DAMPE)

CALorimetric Electron Telescope (2015-today)



DArk Matter Particle Explorer (2015-today)



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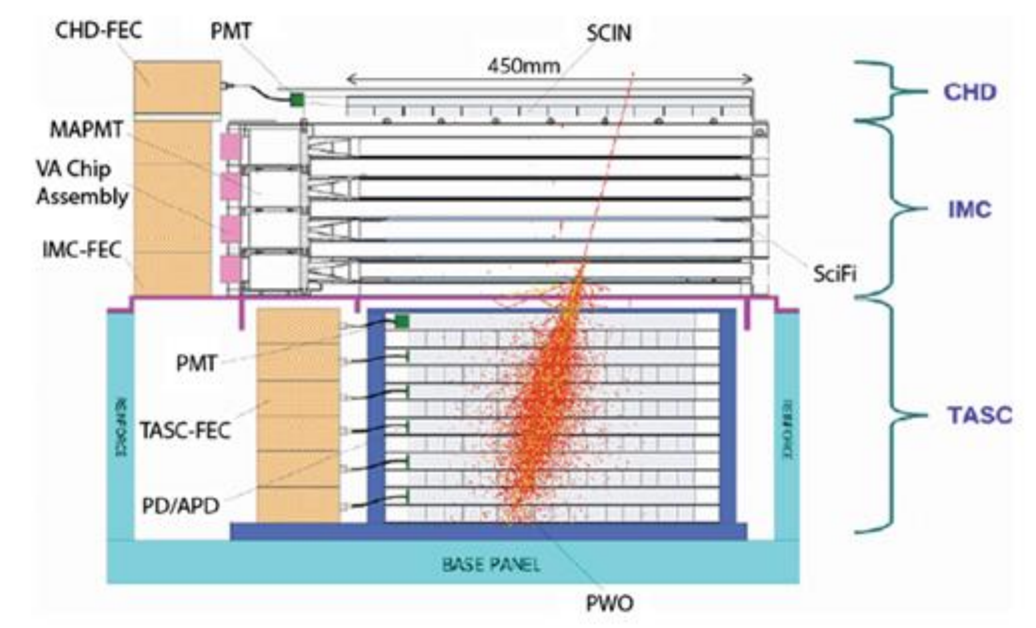

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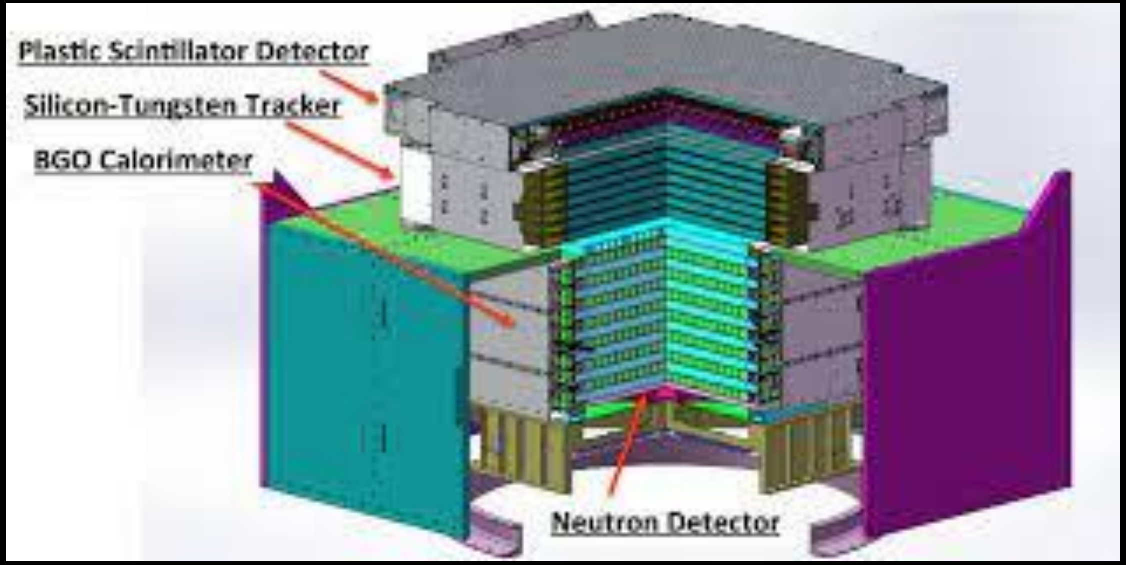


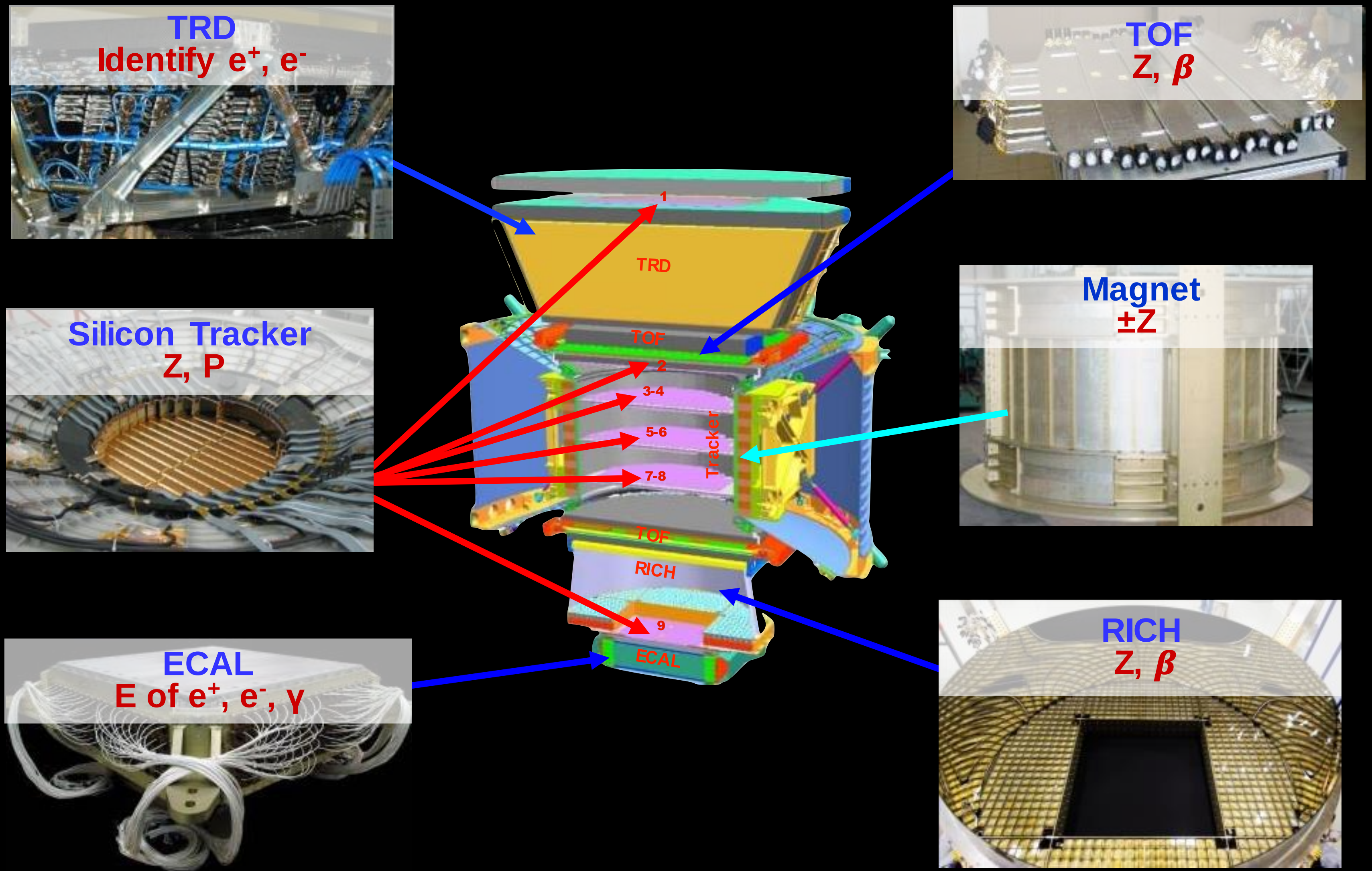
The ghost of experiments present (AMS-02)

Alpha Magnetic Spectrometer (2011-today)

Taking data on the truss of the ISS for the last 12 years. Largest magnetic spectrometer in space so far.

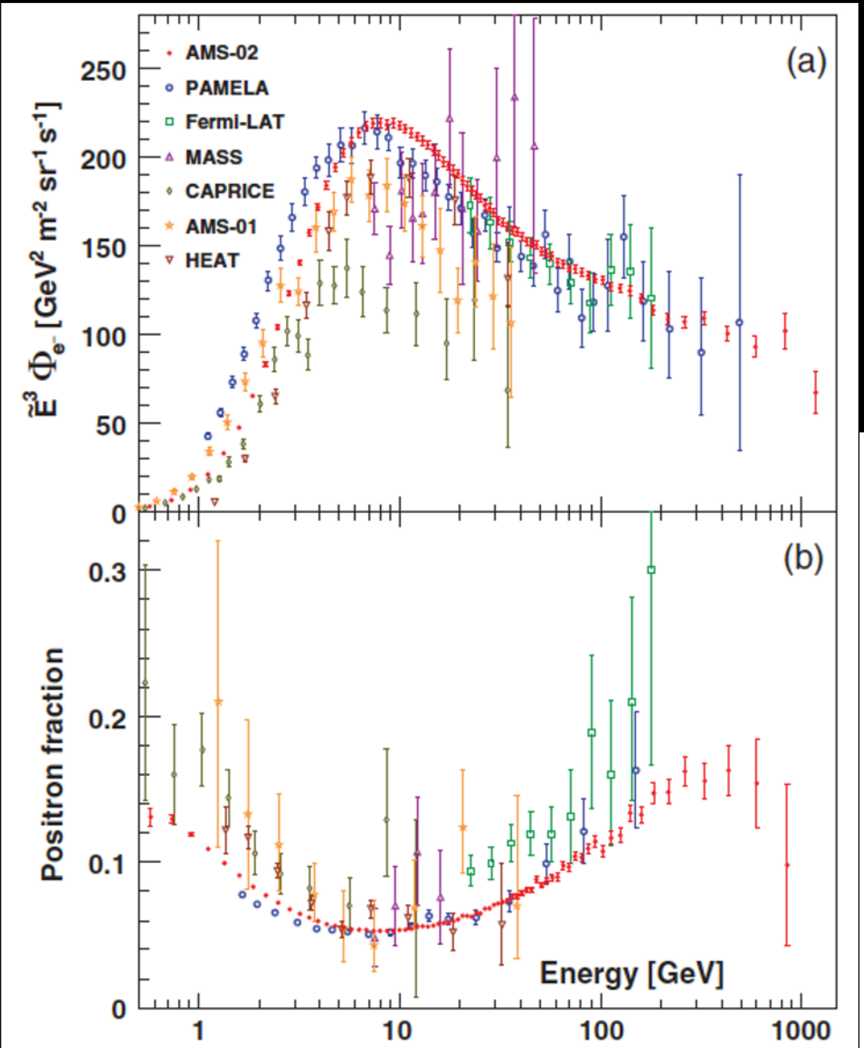
The ghost of experiments present (AMS-02)

Full-fledged particle detector, redundant measurement of particle charge and momentum



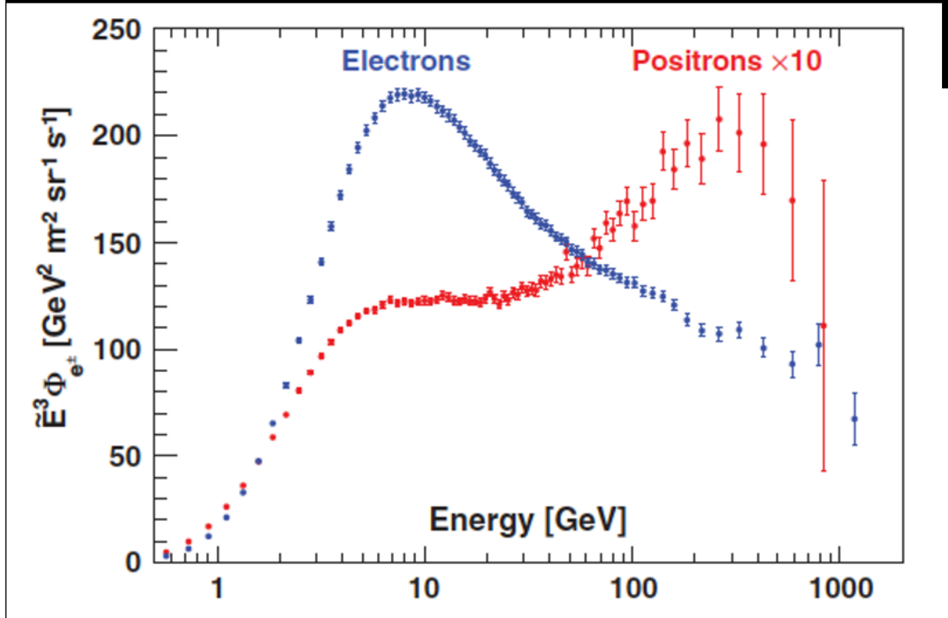
Electron and positrons

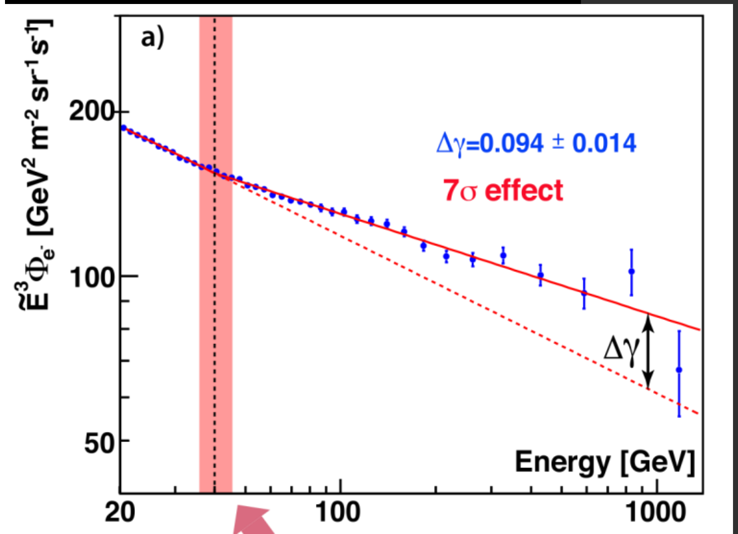
M. Aguilar et al., Phys.Rept. 894 (2021) 1-116



Clear hardening of the positron spectrum, followed by a steep descent (clearly visible also in the positron fraction)

The electron flux also hardens at higher energies





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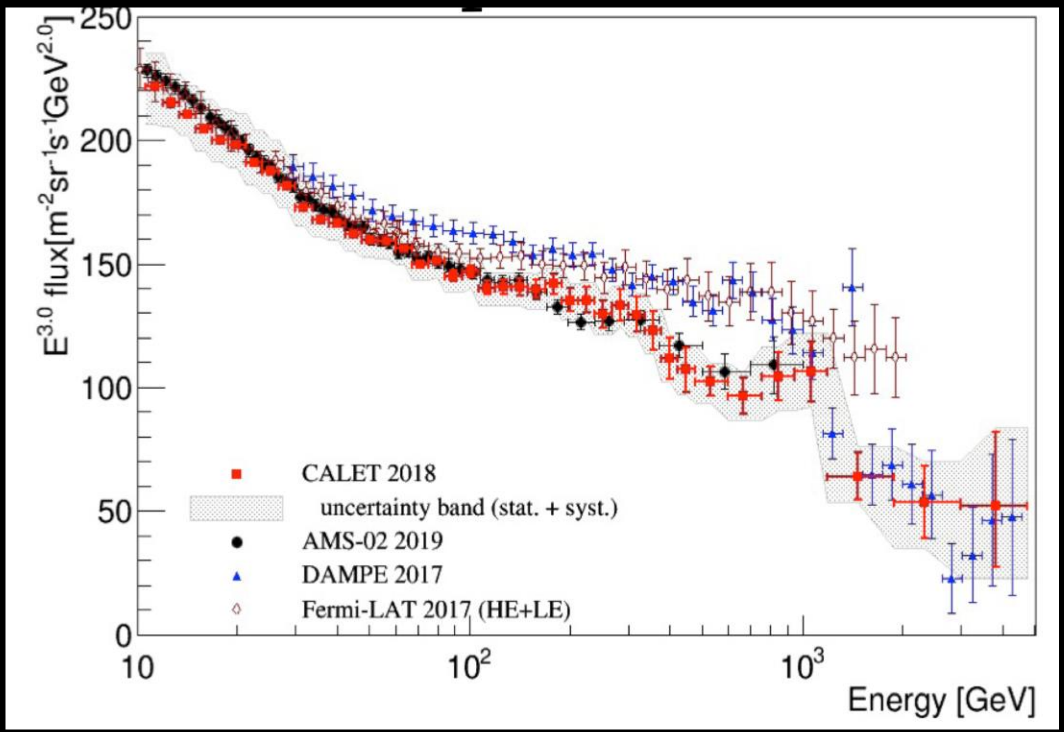


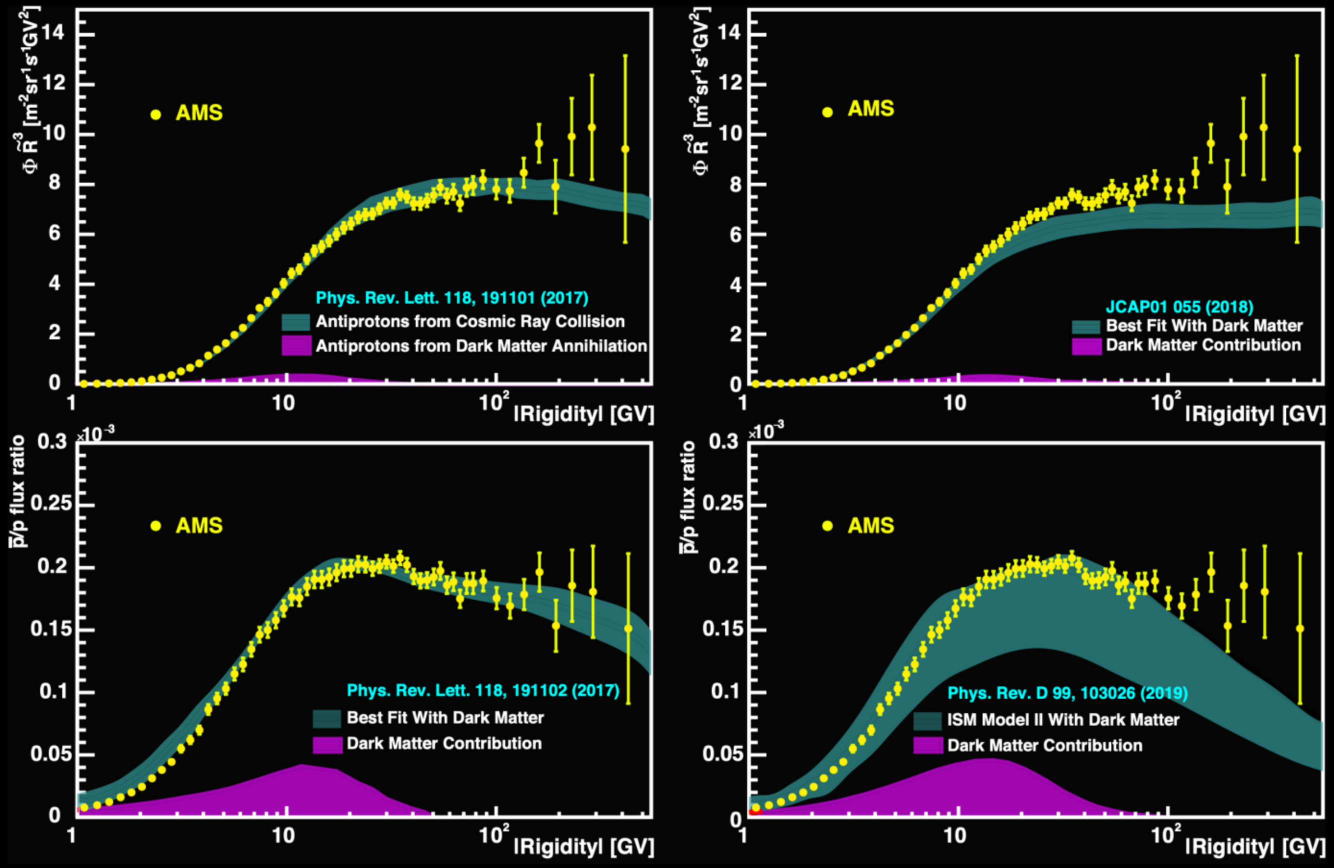
G. Ambrosi et al., Nature 552 (2017) 63-66
O. Adriani et al., PRL 119, 181101 (2017)
M. Aguilar et al., Phys.Rept. 894 (2021) 1-116

Measurements cluster into two groups: AMS-CALET, Fermi-DAMPE

Both CALET and DAMPE report a significant flux reduction above 1 TeV

Conventional diffusive models struggle to reproduce these data, and rely on the addition of CR sources to make up for the “missing flux” (DM, PWNe, close and/or old SNRs, millisecond pulsars, unknown nearby sources, etc…)

Antiprotons

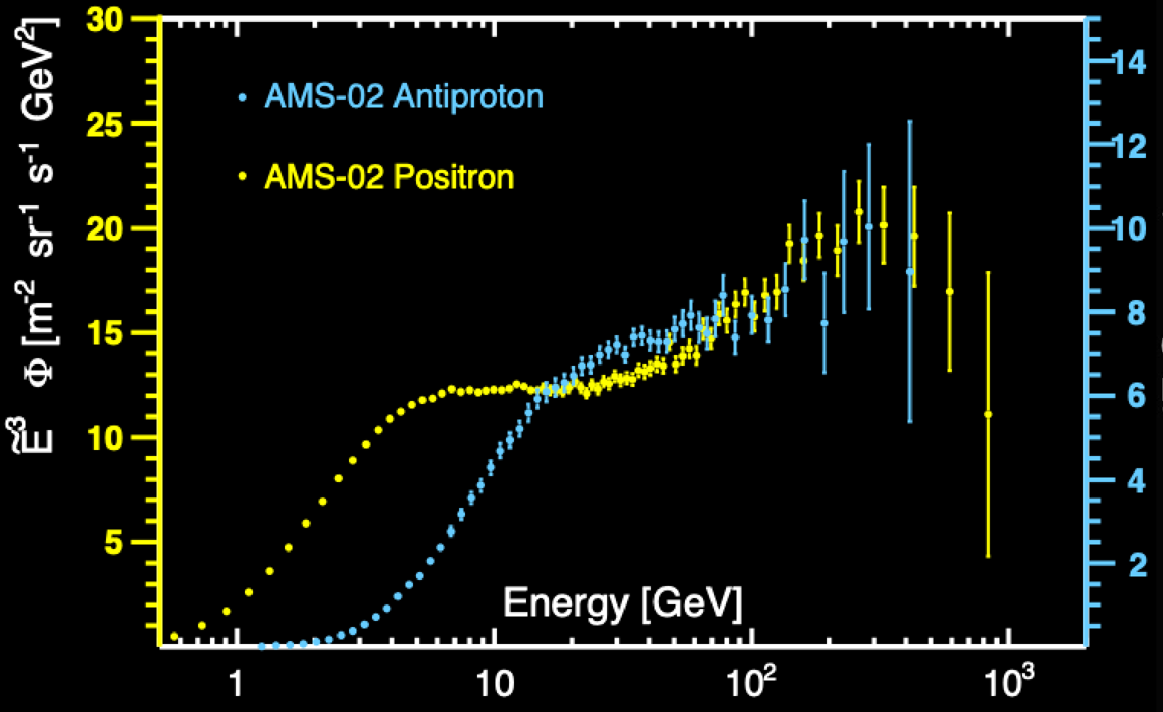


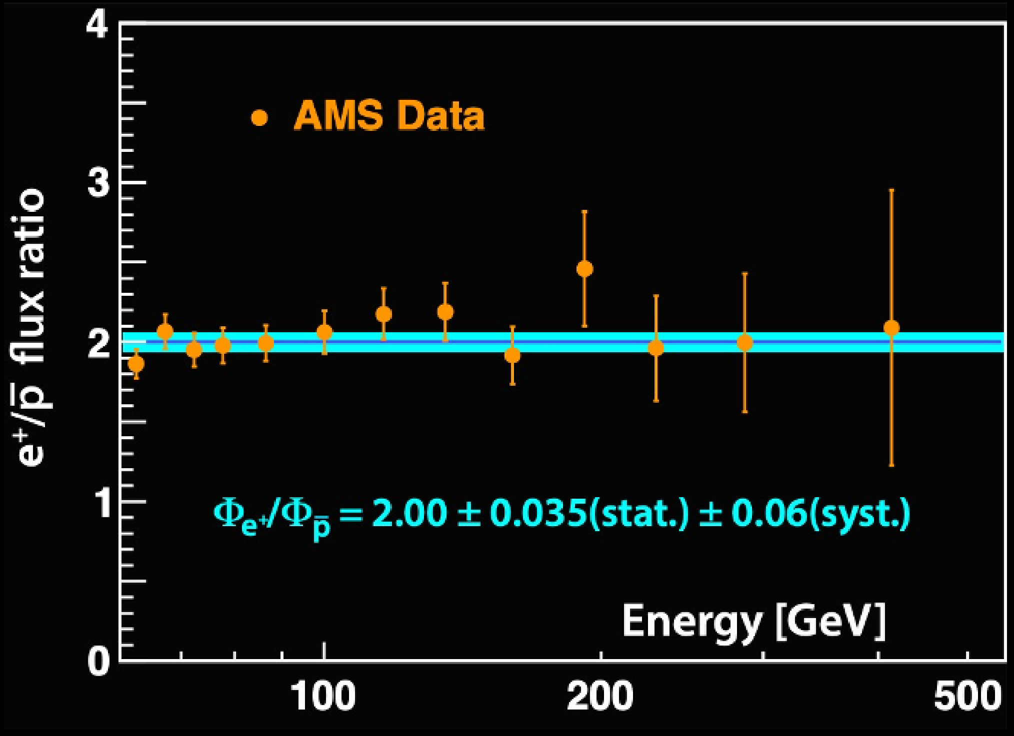
Unfortunately, no extra contributions are visible in the antiproton spectrum or in the pbar/p ratio.

Eventual DM signals are hard to fit (especially since the high-energy behavior of the pbar flux predictions is highly dependent the pbar production cross-sections which are not well known in this energy range)

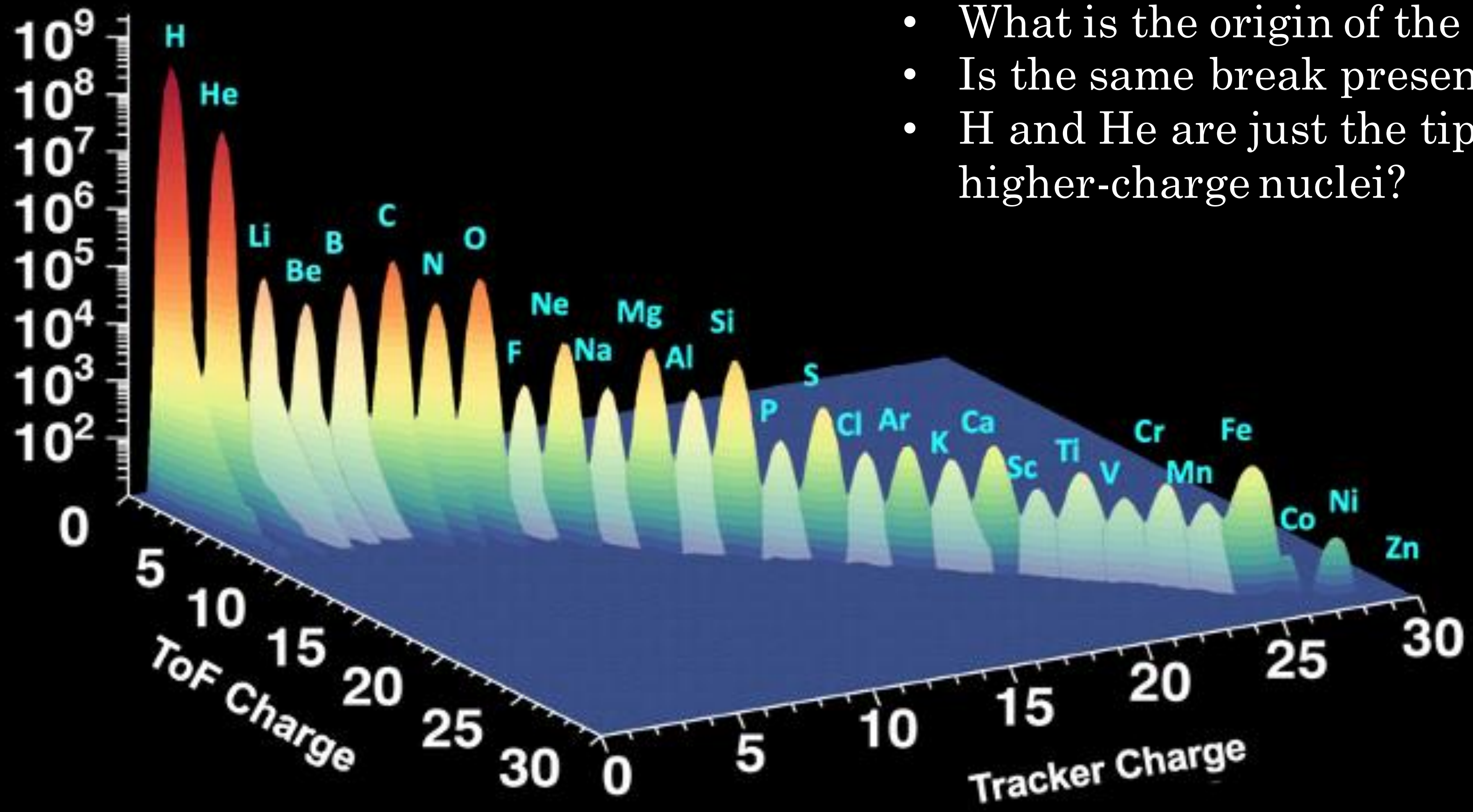
Antiprotons

Nevertheless, the fact that the positron/pbar ratio appears to be constant above 60 GV poses an interesting puzzle



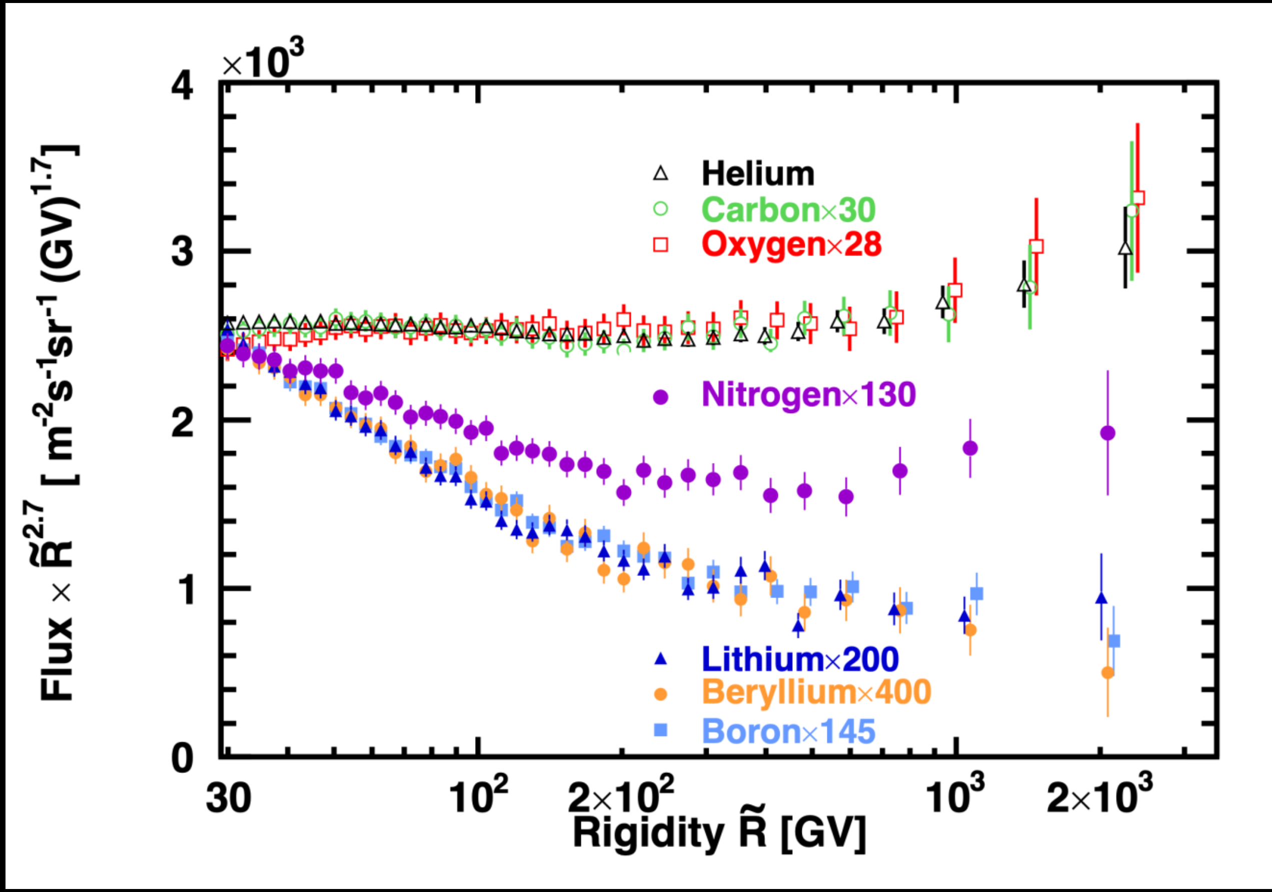


Cosmic ray nuclei



- What is the origin of the spectral break?
- Is the same break present in secondaries?
- H and He are just the tip of the iceberg, what about higher-charge nuclei?

The situation in 2019



M. Aguilar et al., PRL 119, 251101 (2017)
M. Aguilar et al., PRL 120, 021101 (2018)
M. Aguilar et al., PRL 121, 051103 (2018)

He, C, O

- Are mostly primary species
- Show the same spectral shape above ~50 GV
- Show the same spectral break at ~300 GV

Li, Be, B

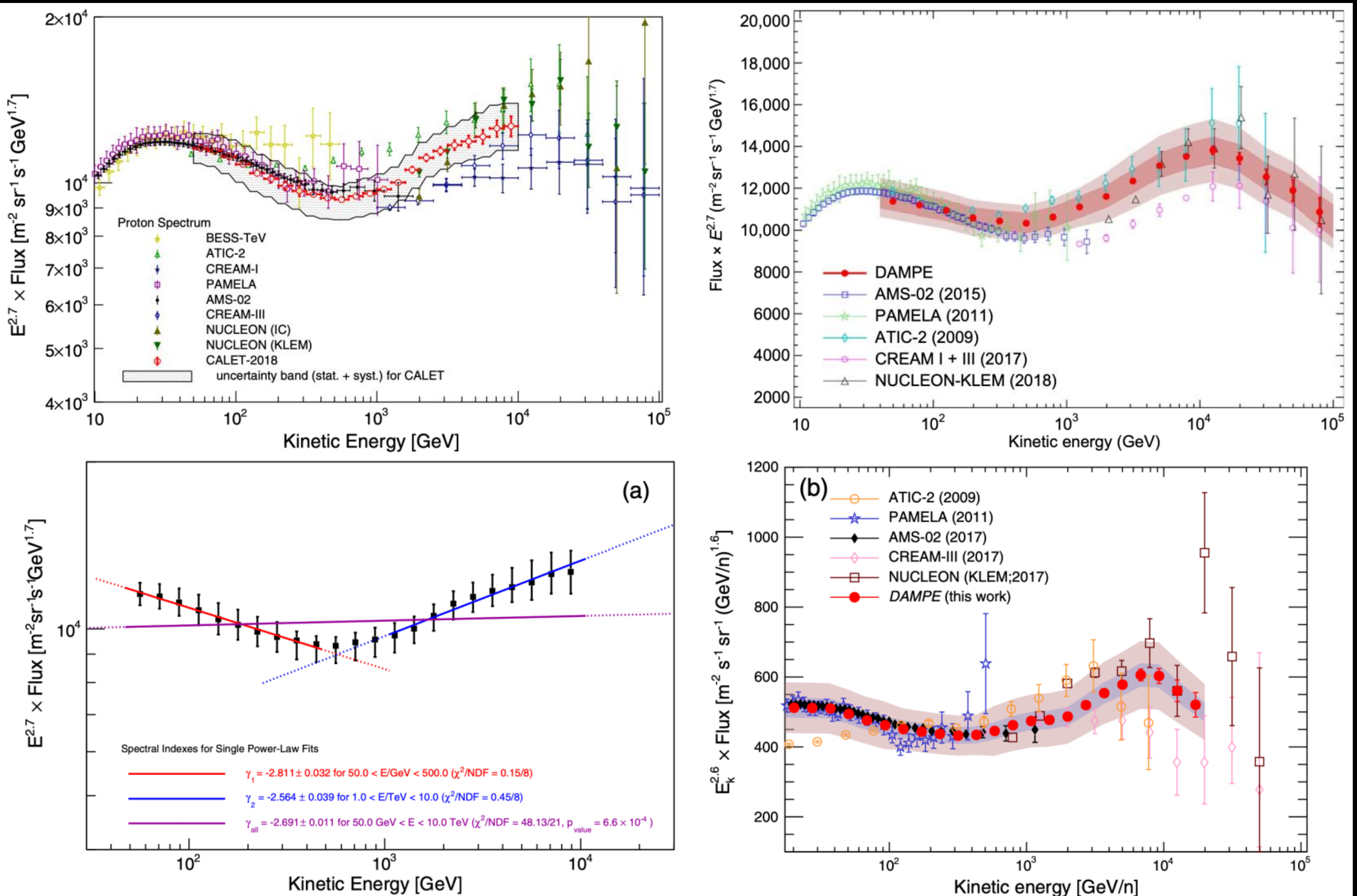
- Are mostly secondary species
- Show the same spectral shape above ~20 GV
- Show the same spectral break at ~300 GV

But the magnitude of the break in secondaries is double the one in primaries, pointing to a propagation effect

N

- Shows a spectral shape with mixed primary and secondary components

Proton and Helium

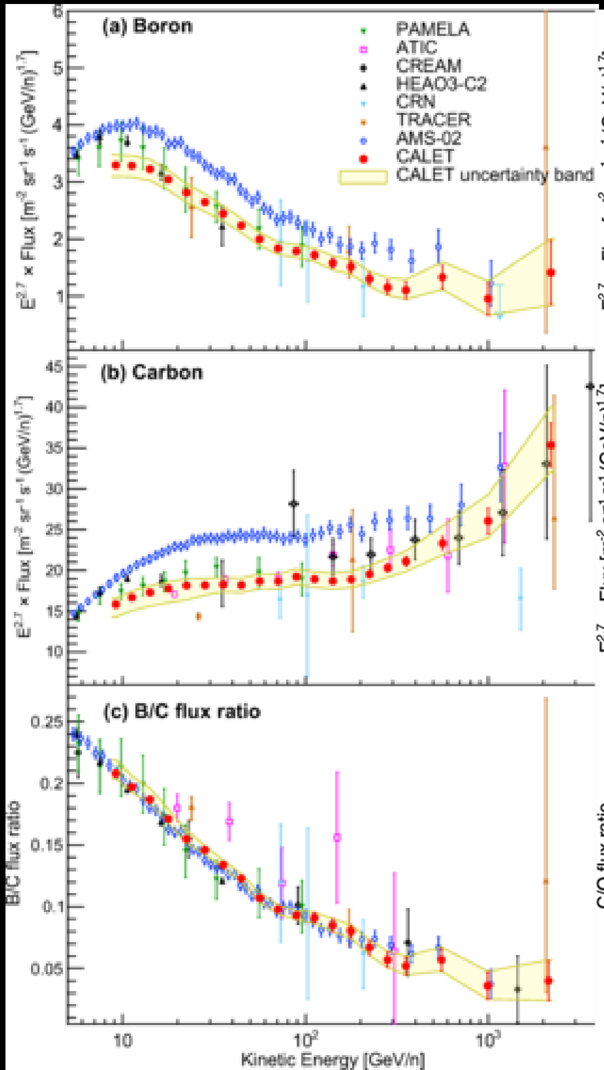


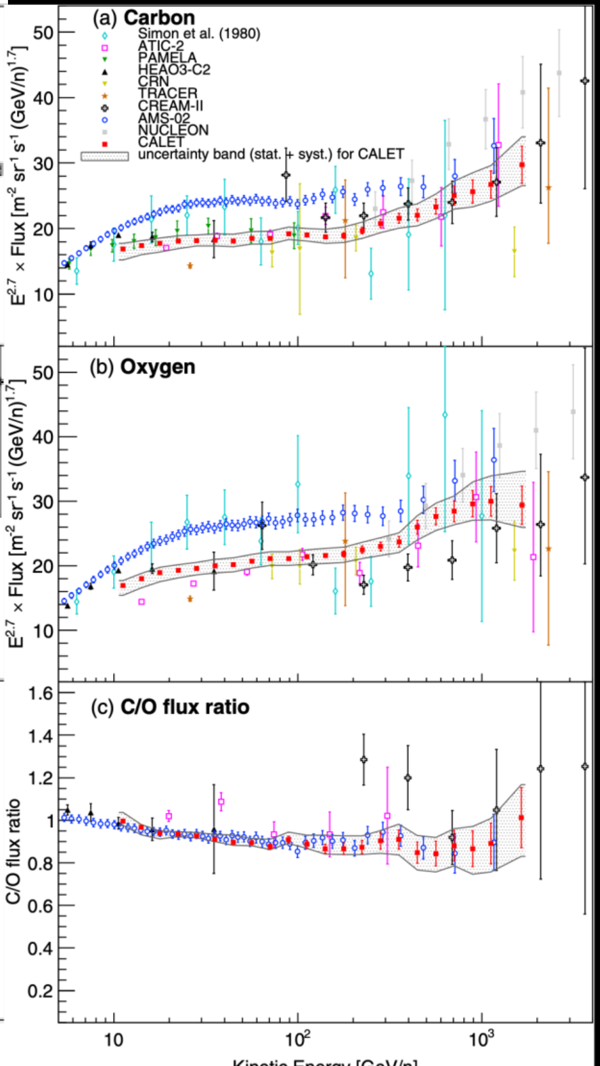
A spectral softening at tens of TeV appears after the break at ~500 GeV

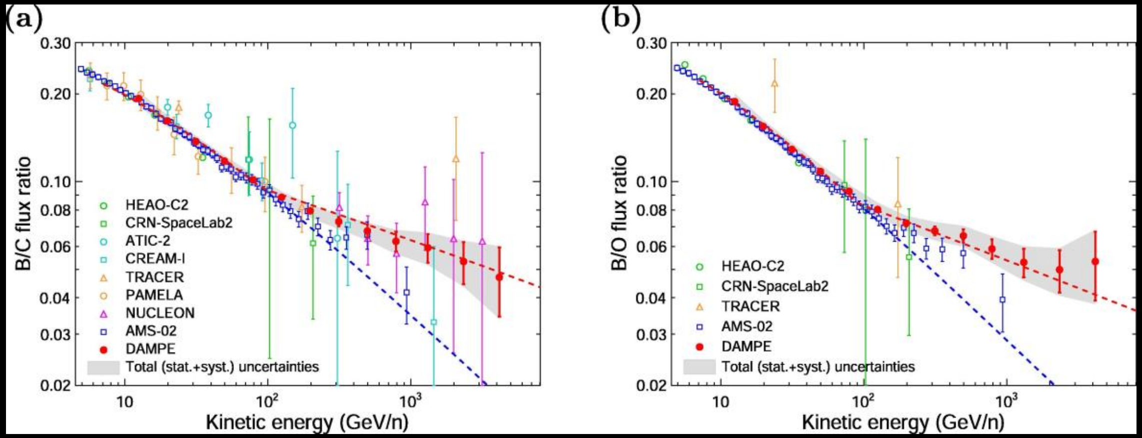
Among the possibilities:
This is the contribution of an individual source (Shape of the bump determined by the source spectrum, age and distance)

This is a new population of CRs
(And the position in energy of the spectral features is related to environmental parameters)

Heavier nuclei





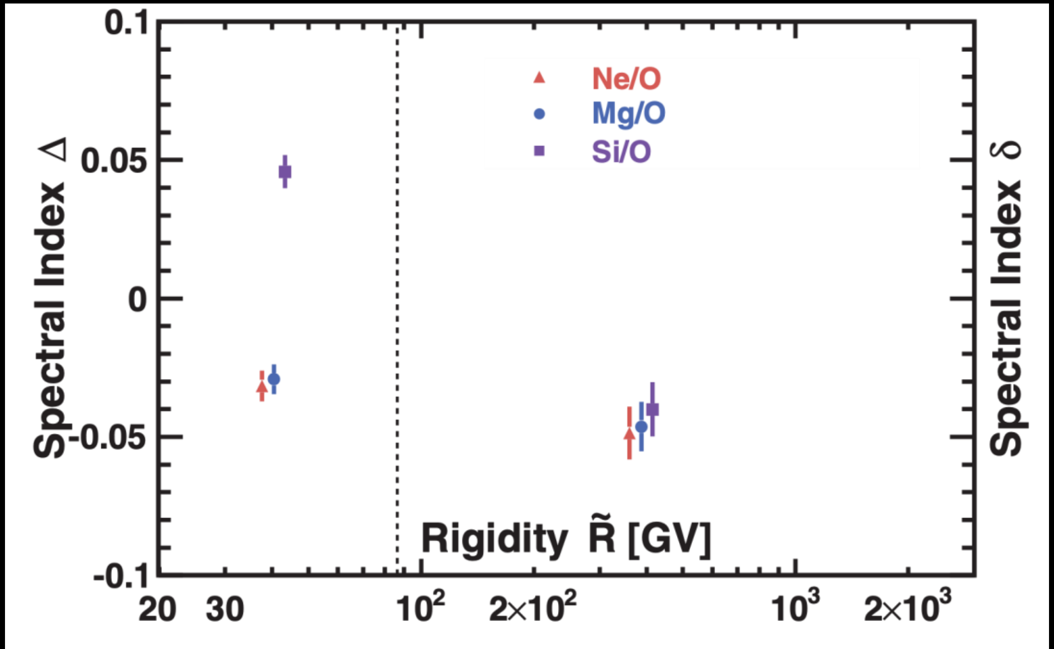


Measurements up to several TeV/n
Similar spectral break observed in both C and O

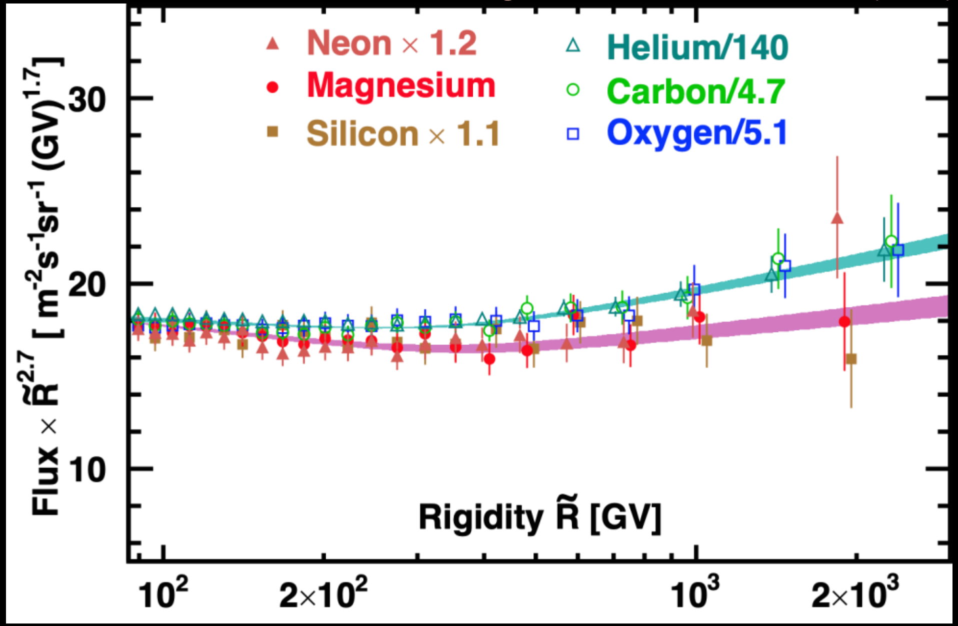
C/O ratio flat above 25 GeV/n similarly to what observed by AMS-02

B/C and B/O exhibit spectral break at ~200 GeV/n similarly to what observed by AMS-02

Heavier nuclei



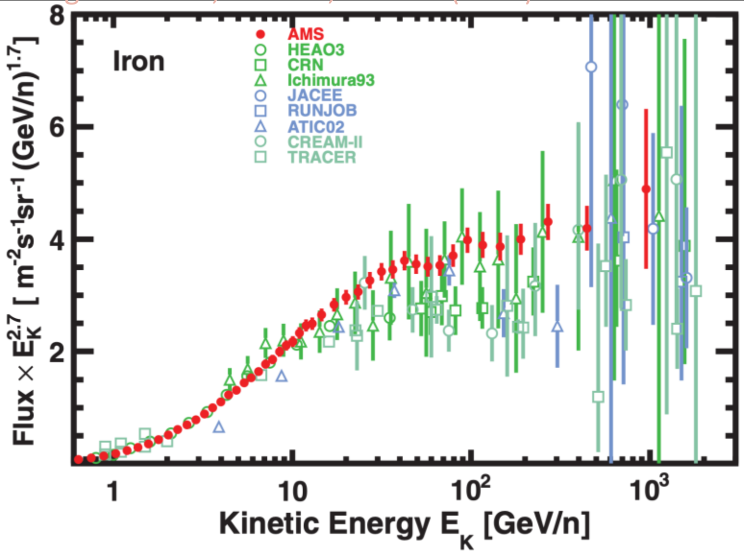
M. Aguilar et al., PRL 124, 21102 (2020)

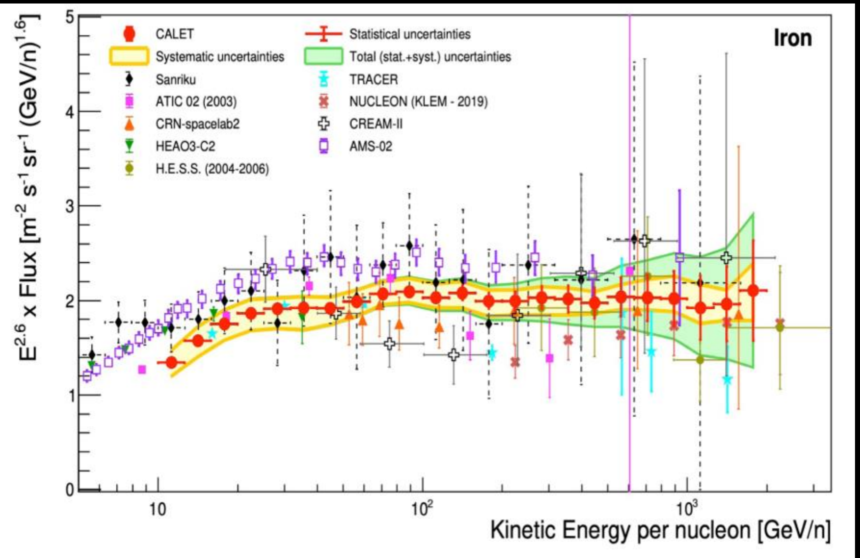


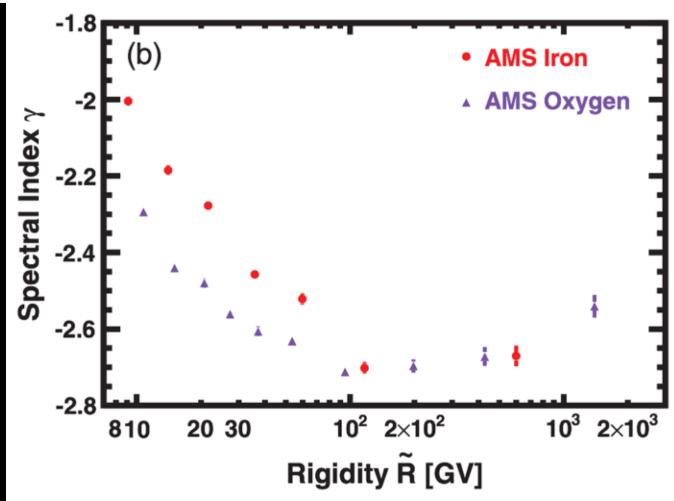
To examine the rigidity dependence difference between low-Z He, C and O and high-Z Ne, Mg and Si primaries the Ne/O, Mg/O, and Si/O flux ratios were studied. Their ratios differs by a power law by more than 5σ above 86.5 GV showing that Ne, Mg and Si is a different class of primary CRs than He, C and O.

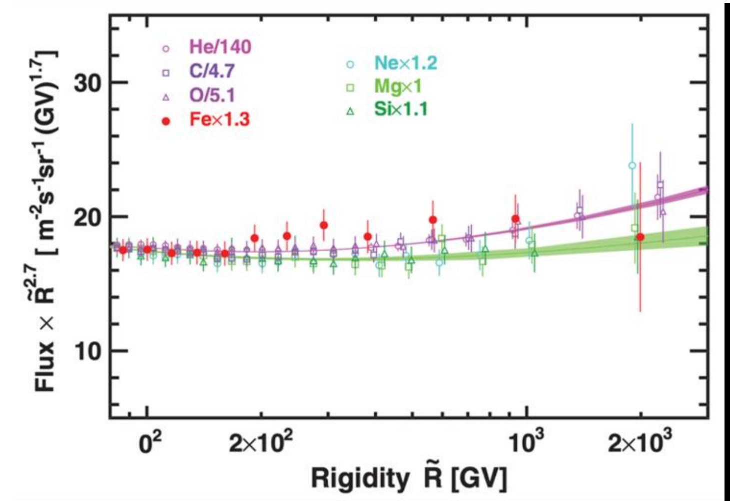
Heavier nuclei - Iron

M. Aguilar et al., PRL 126, 041104 (2021)





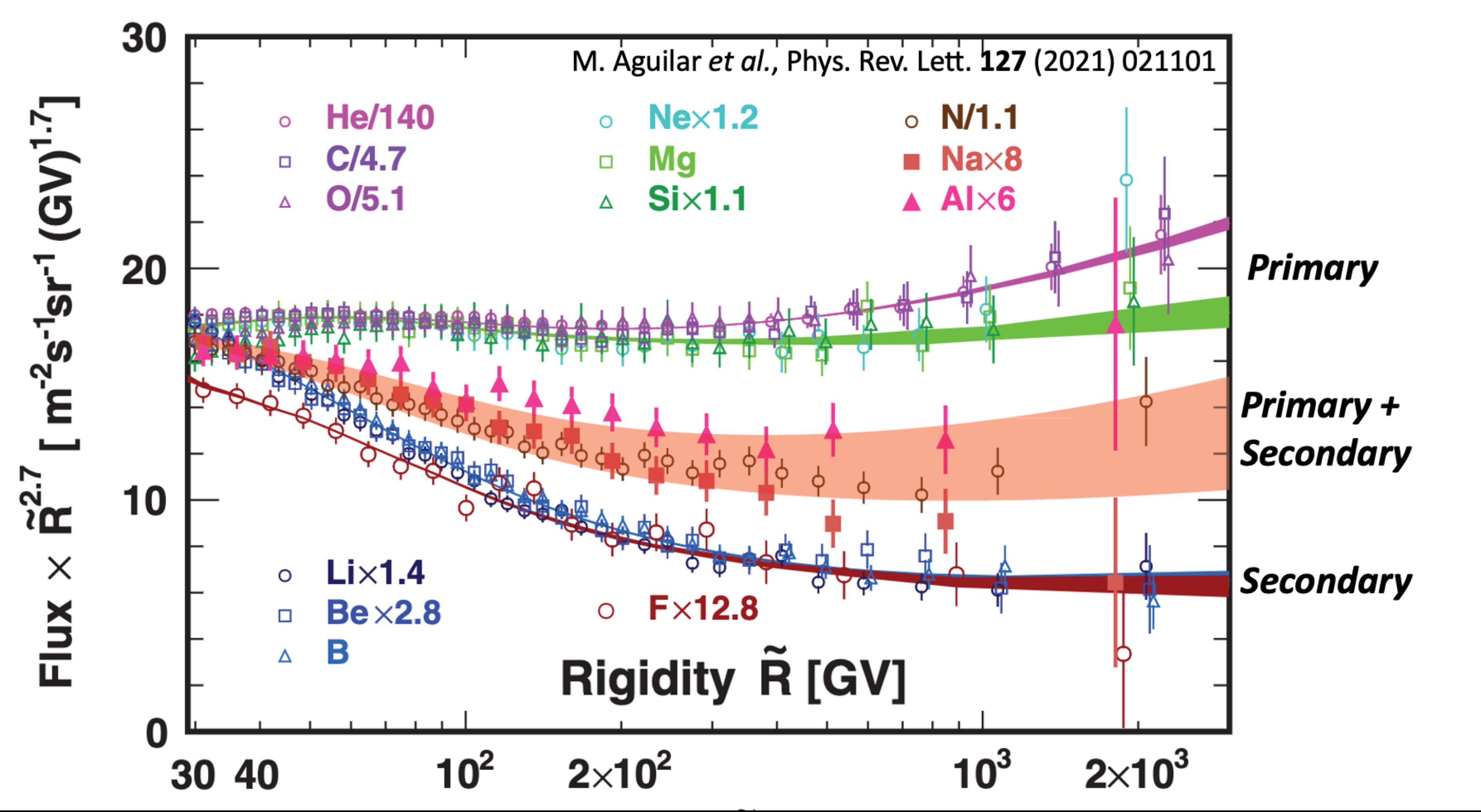




First precise measurements of the Iron flux up to the TeV region

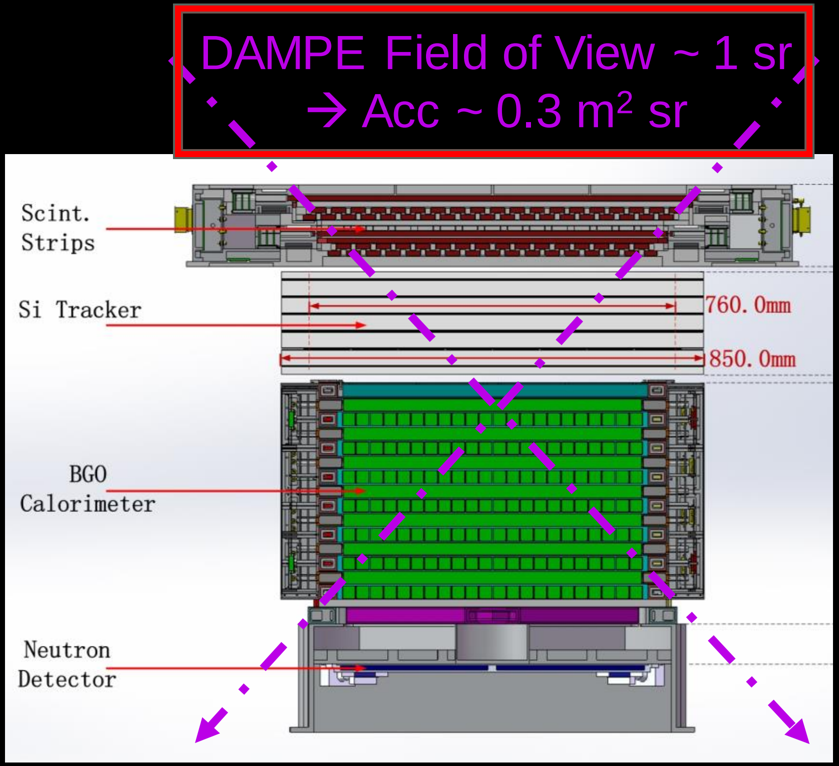
Fe belongs to the He, C, and O class of primary cosmic rays, which have a different rigidity dependence with respect to Ne, Mg, and Si.

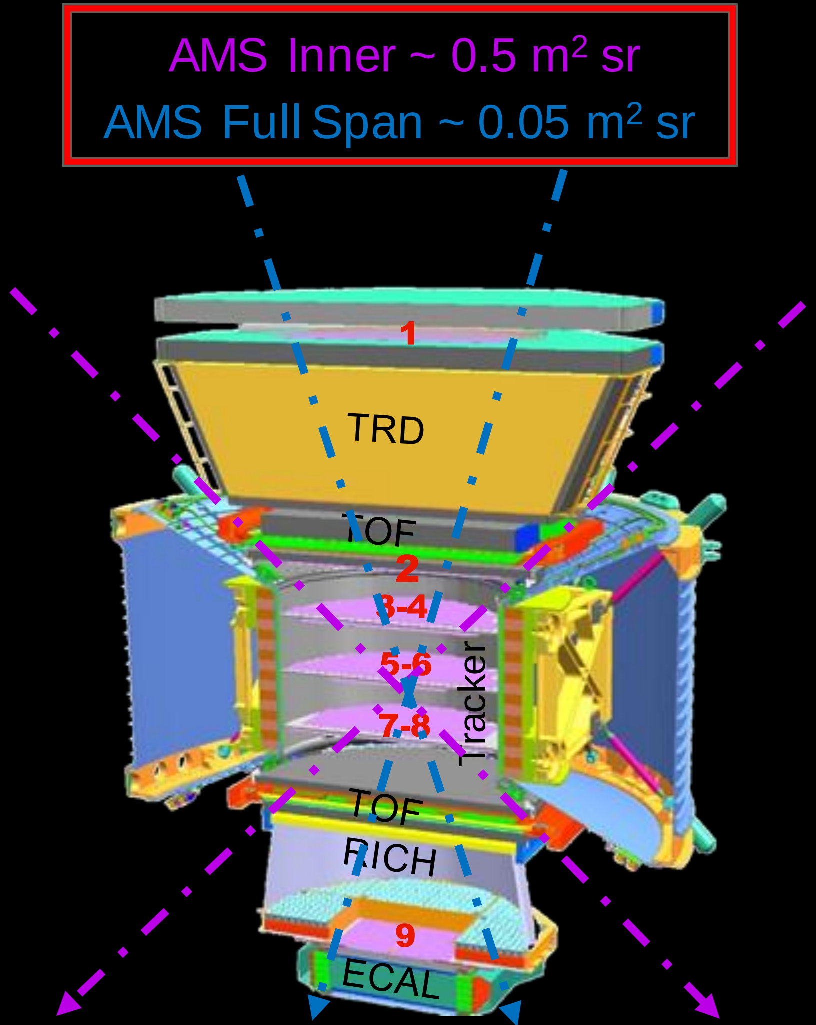
A complex picture…



Open questions

Current operating “telescopes”

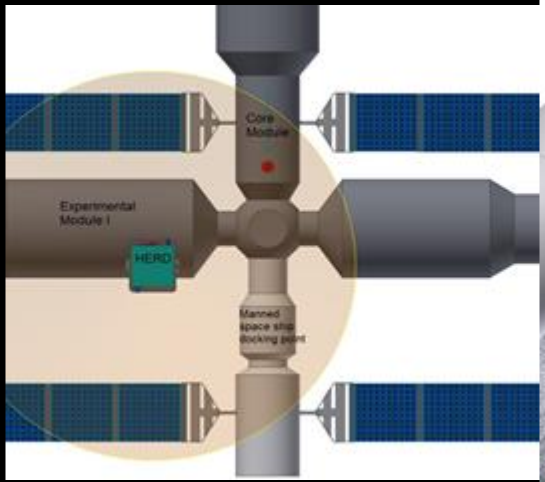


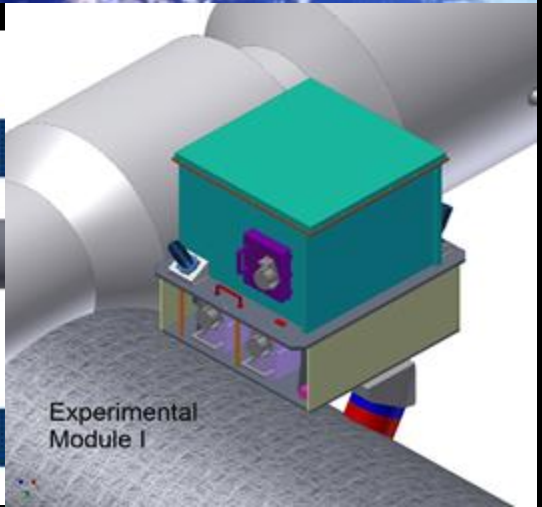


All the current and past detectors are designed as 'telescopes': they're sensitive only to particles impinging from "the top"

limited FoV → small acceptance

The ghost of experiments yet to come (HERD)





CSS expected to be completed in 2025

Life time	> 10y
Orbit	Circular LEO
Altitude	340-450 km
Inclination	42°

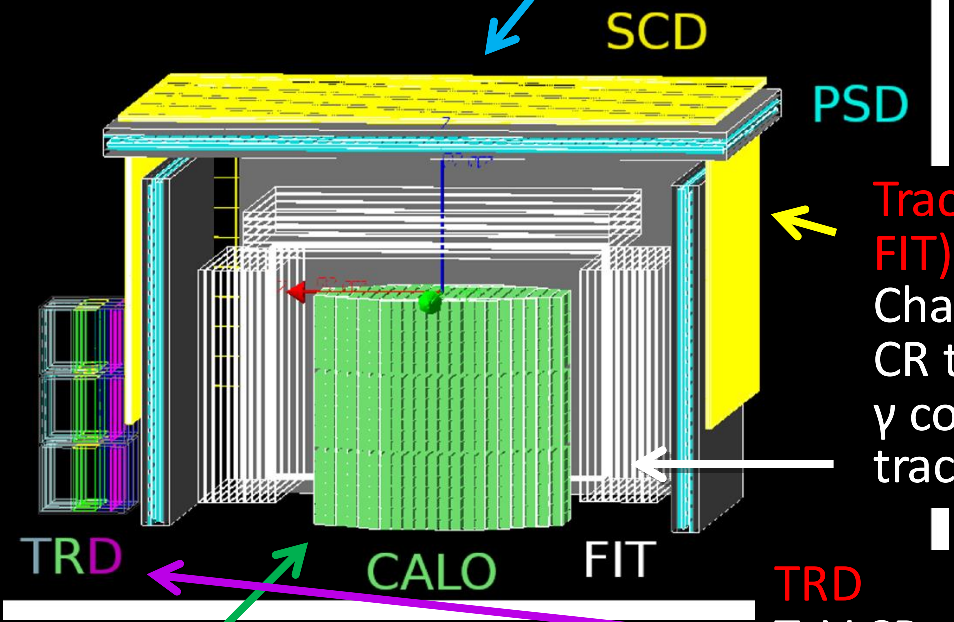
HERD expected to be installed around 2026

Life time	> 10y
FOV	+/- 70°
Power	< 1.5 kW
Mass	< 4 t

The ghost of experiments yet to come (HERD)

~ 300k readout channels

PSD, 5 sides
γ identification
Charge



Tracker (SCD + FIT), 5 sides
Charge
CR trajectory
γ conversion &
tracking

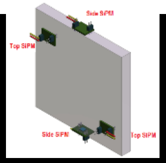
TRD
TeV CR calibration

CALO: 3-D
Energy
e/p separation

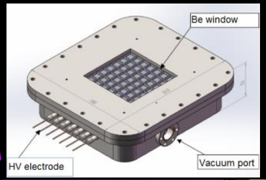
~7500 LYSO crystals (55 X_0, 3 λ_I)
Trigger sub-system
Dual readout with IsCMOS &
PD/SiPM

@INFN Perugia

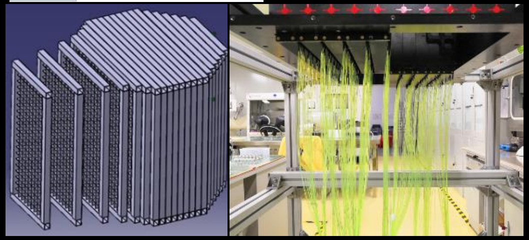
@Univ. of Geneva
@CIEMAT Madrid



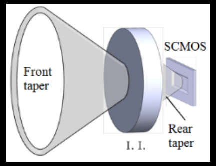
@INFN BA-GSSI-LE-PV-NA & IHEP



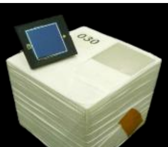
@Guangxi Univ.



@IHEP



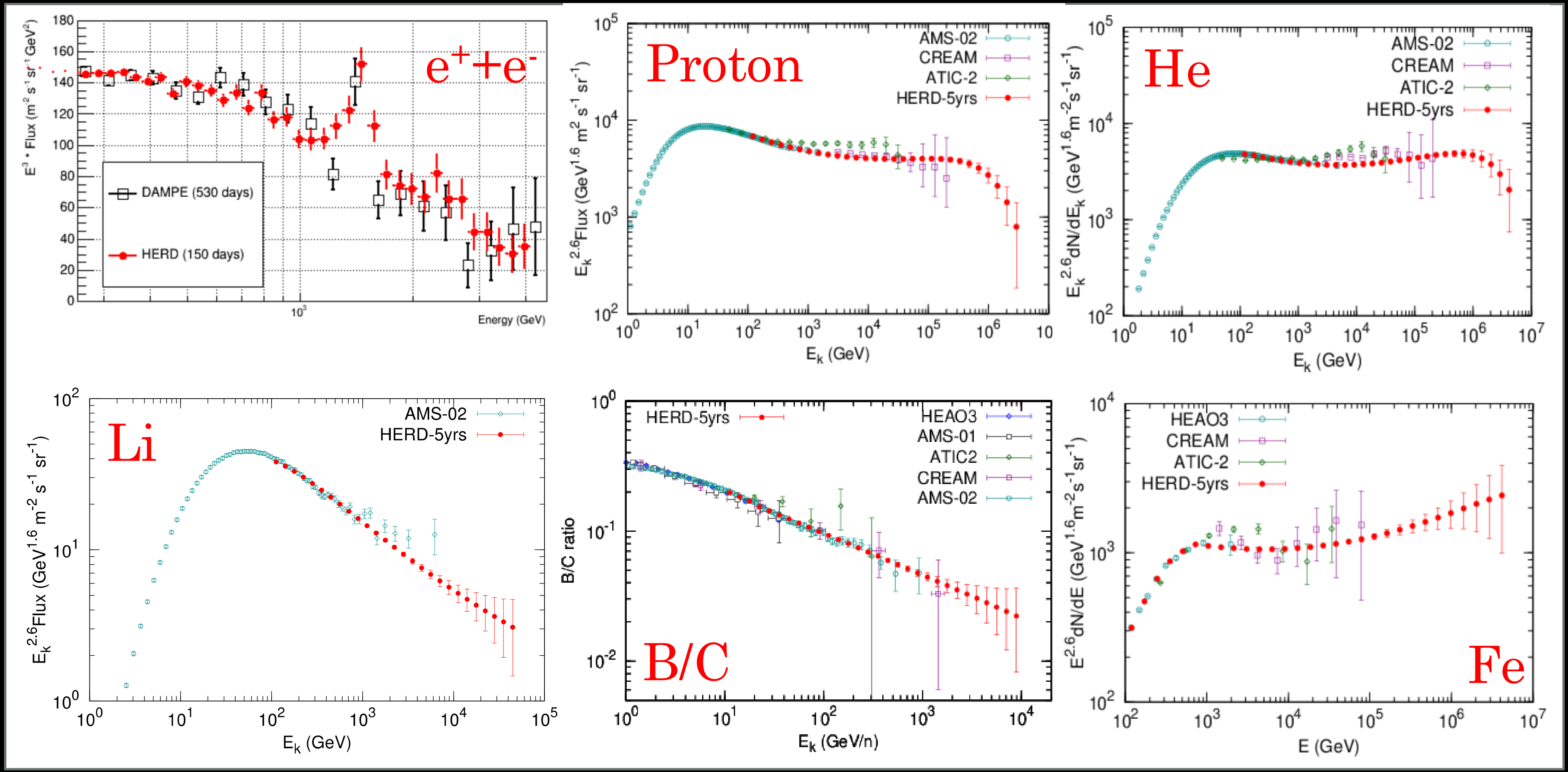
@XIOPM



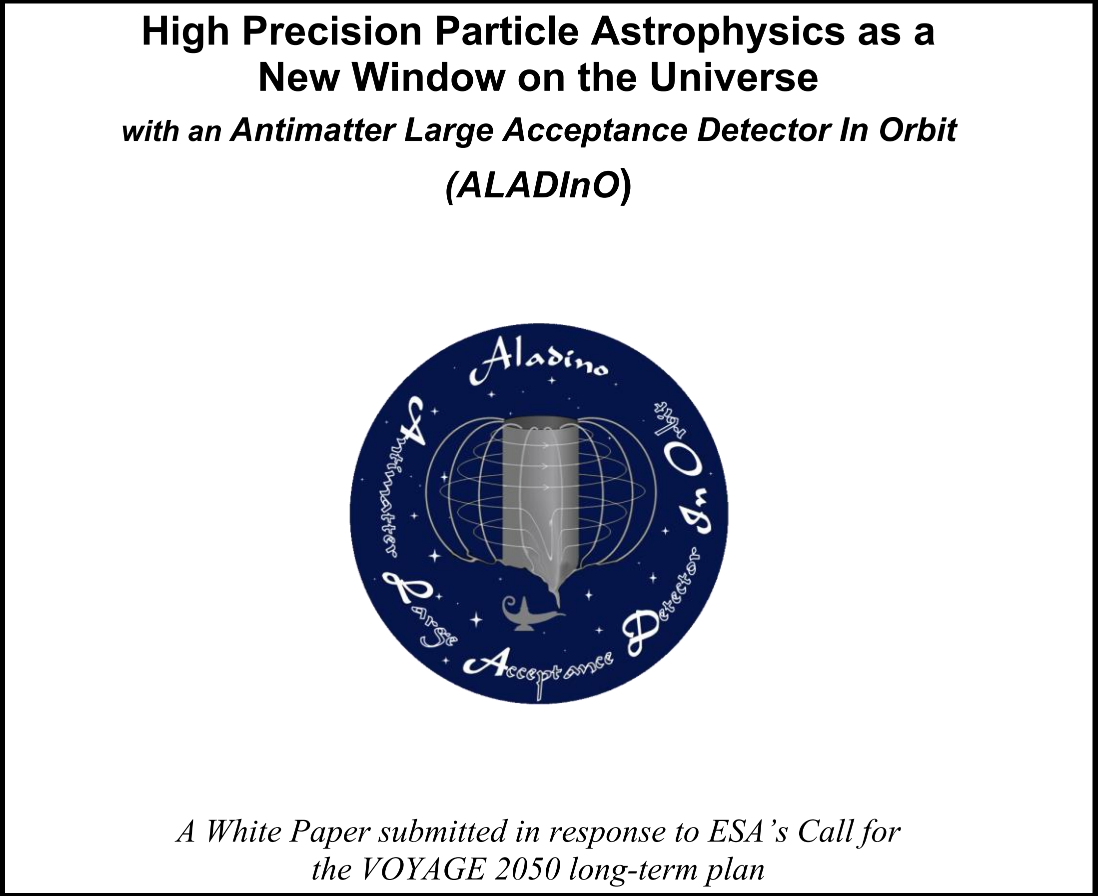
The ghost of experiments yet to come (HERD)

Item	Value
Energy range (e/γ)	10 GeV - 100 TeV (e); 0.5 GeV-100 TeV (γ)
Energy range (nuclei)	30 GeV - 3 PeV
Angle resolution	0.1 deg.@10 GeV
Charge resolution	0.1-0.15 c.u
Energy resolution (e)	1-1.5%@200 GeV
Energy resolution (p)	20-30%@100 GeV - PeV
e/p separation	$\sim 10^{-6}$
G.F. (e)	>3 m^2sr@200 GeV
G.F. (p)	>2 m^2sr@100 TeV
Field of View	~ 6 sr
Envelope (L*W*H)	~ 2300*2300*2000 mm^3
Weight	~ 4000 kg
Power Consumption	~ 1400 W

The ghost of experiments yet to come (HERD)



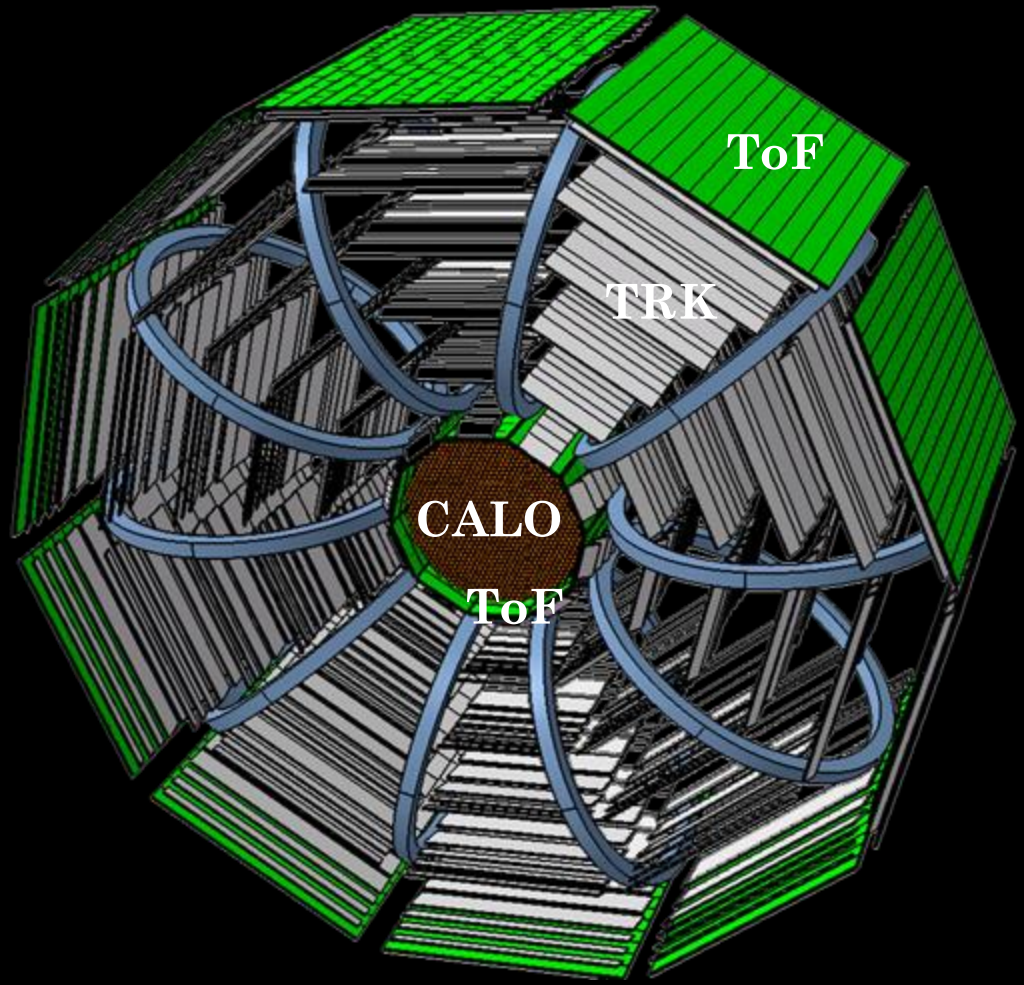
The ghost of experiments yet to come (ALADInO)



High Precision Particle Astrophysics as a New Window on the Universe

***with an Antimatter Large Acceptance Detector In Orbit* (*ALADInO*)**

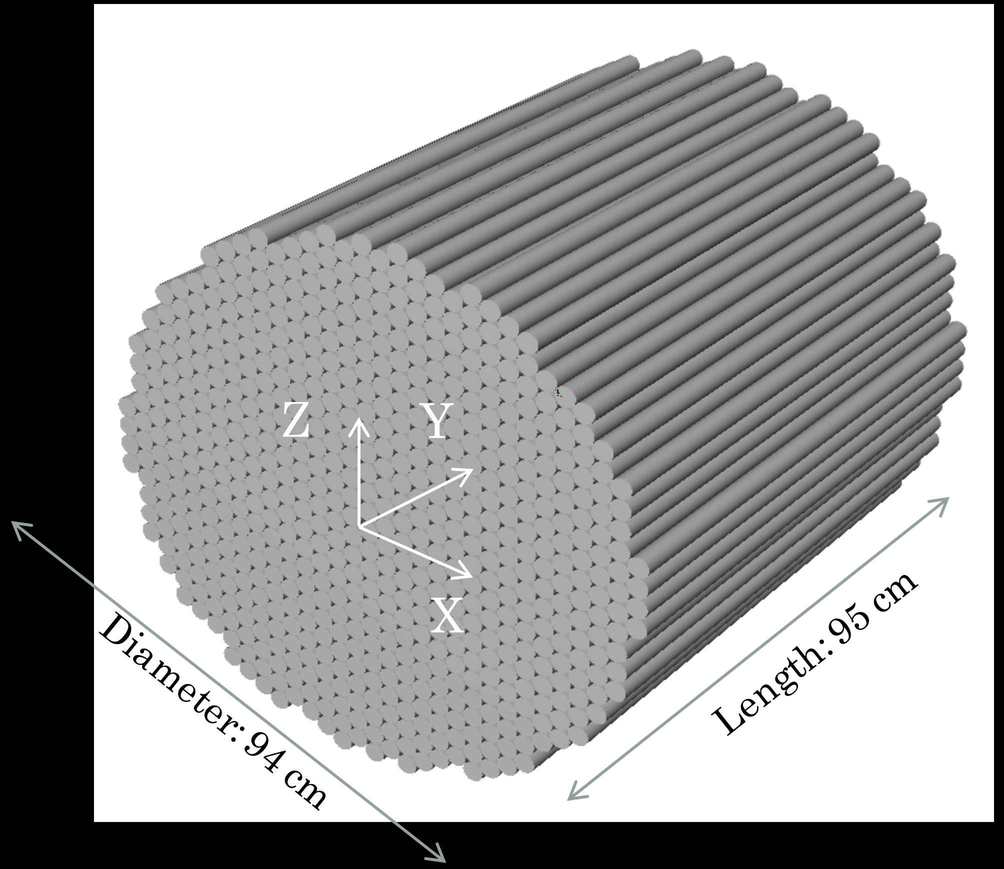
A White Paper submitted in response to ESA's Call for the VOYAGE 2050 long-term plan

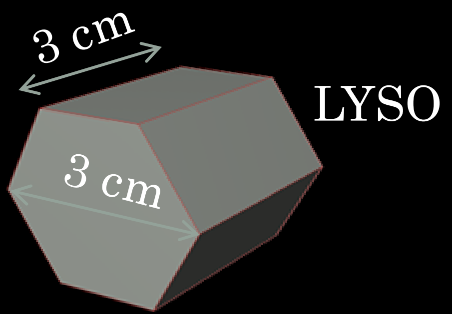


https://www.cosmos.esa.int/web/voyage-2050/white-papers
https://www.cosmos.esa.int/documents/1866264/3219248/BattistonR_ALADINO_PROPOSAL_20190805_v1.pdf

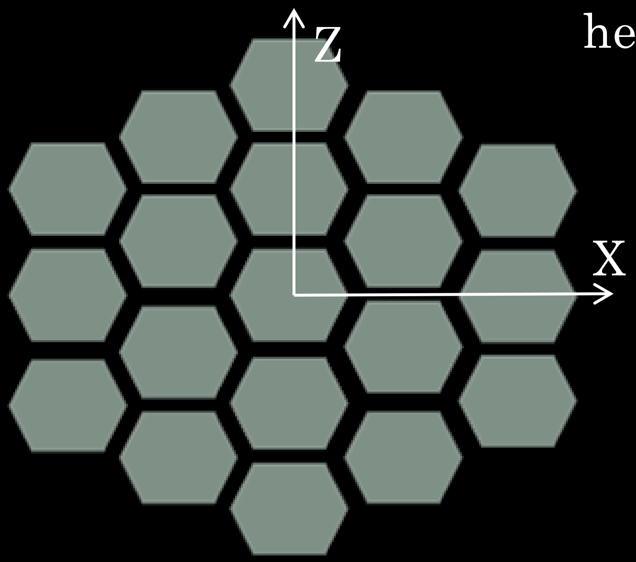
The ghost of experiments yet to come (ALADInO)

Weight~(2300+300) kg
N. crystals: ~20.000





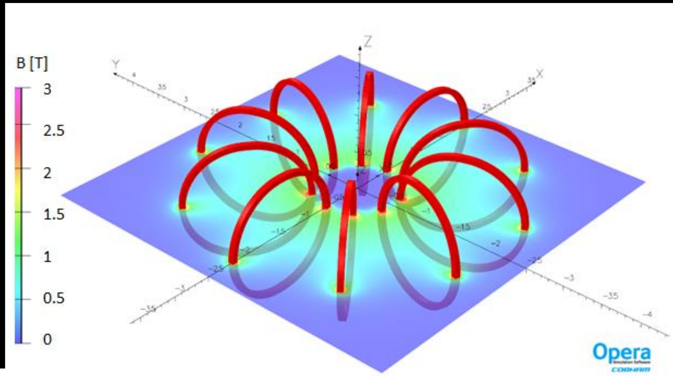
Basic crystal: hexagonal base prisma

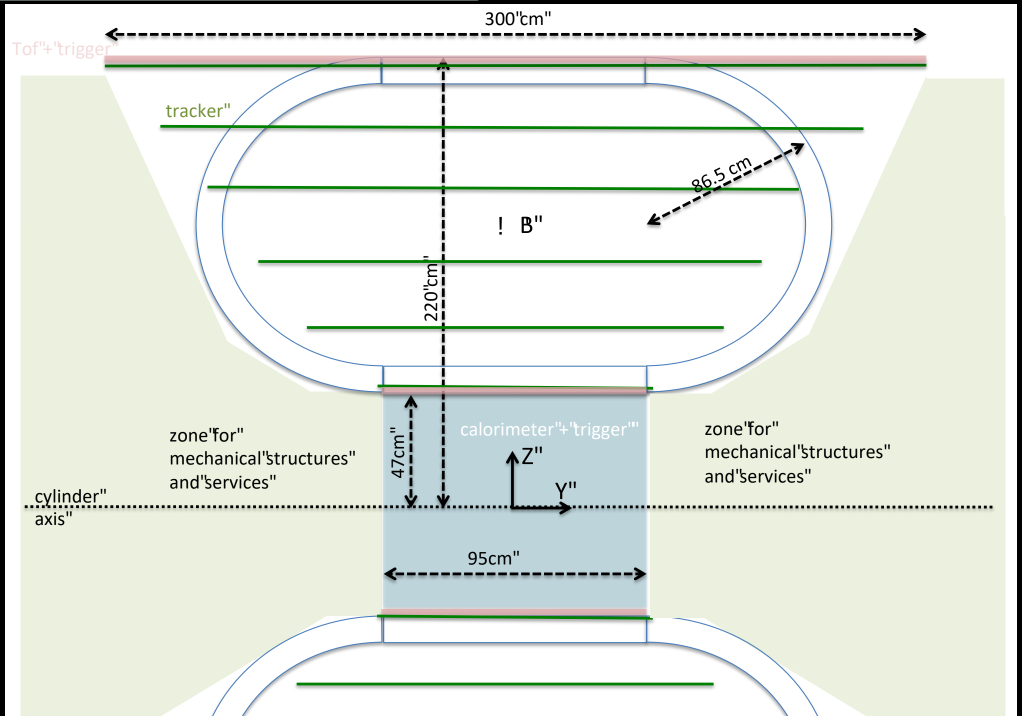


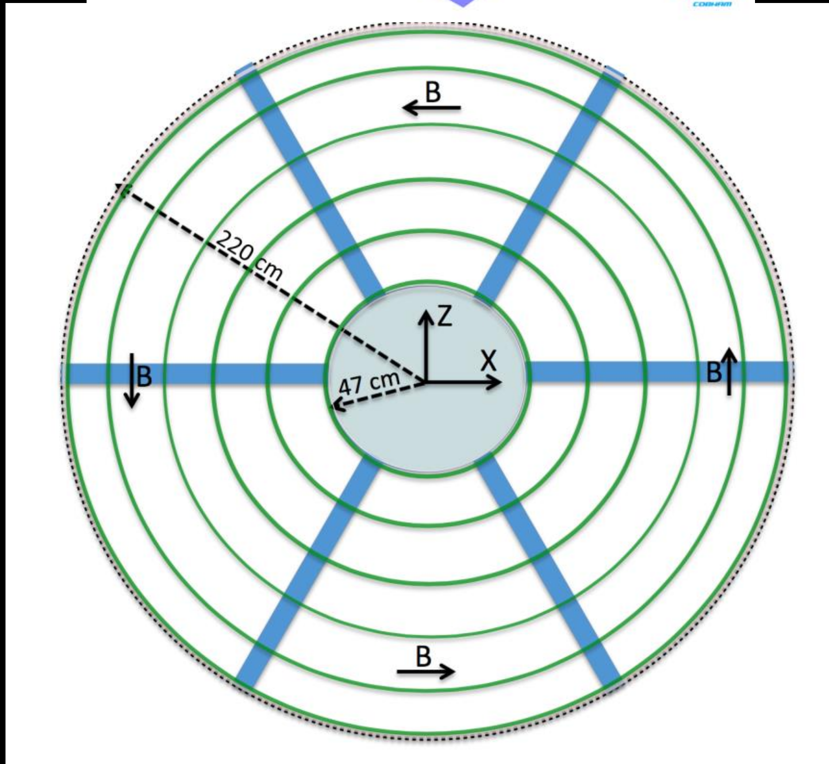
The ghost of experiments yet to come (ALADInO)

Benefit from the R&D of high temperature superconducting magnets (MgB_2, YBCO and in particular REBCO) for space applications (T $\approx$ 15÷40°K)

Field 0.8 T
Bending power > 1.1 T m
Weight ~ 1000 Kg

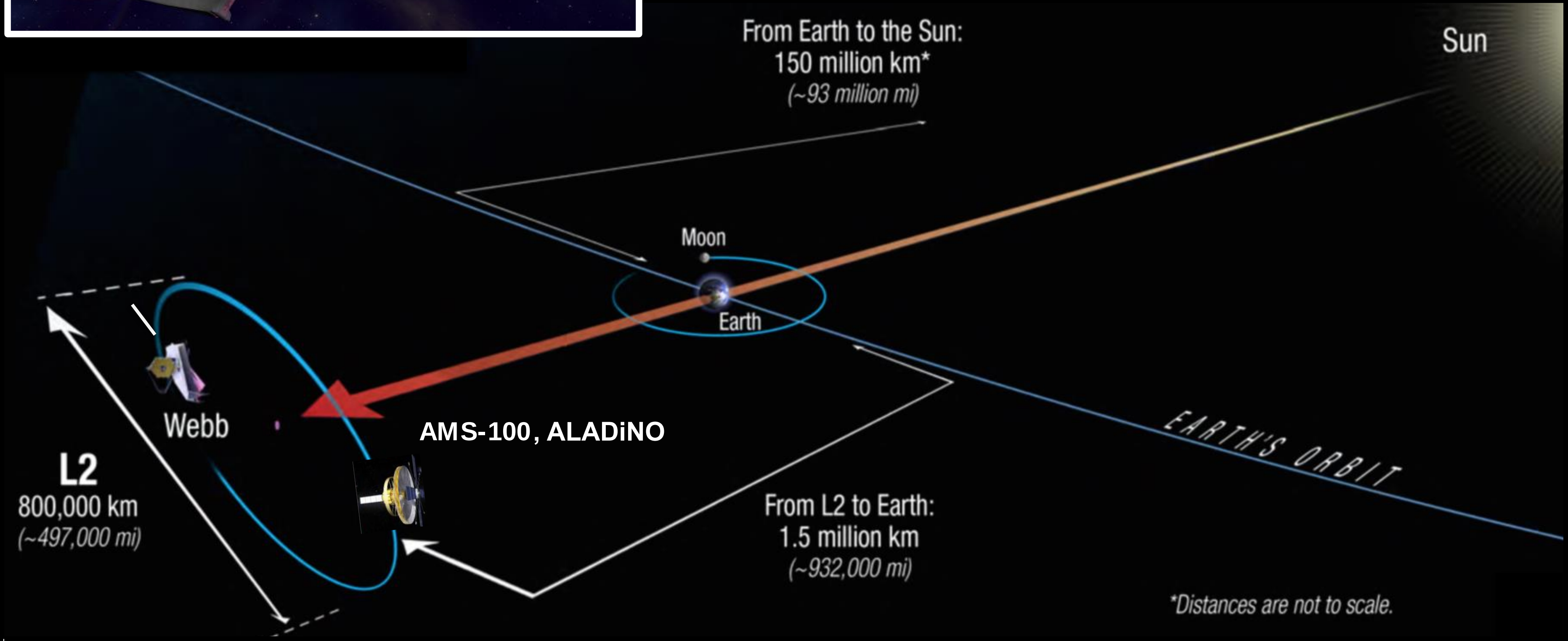






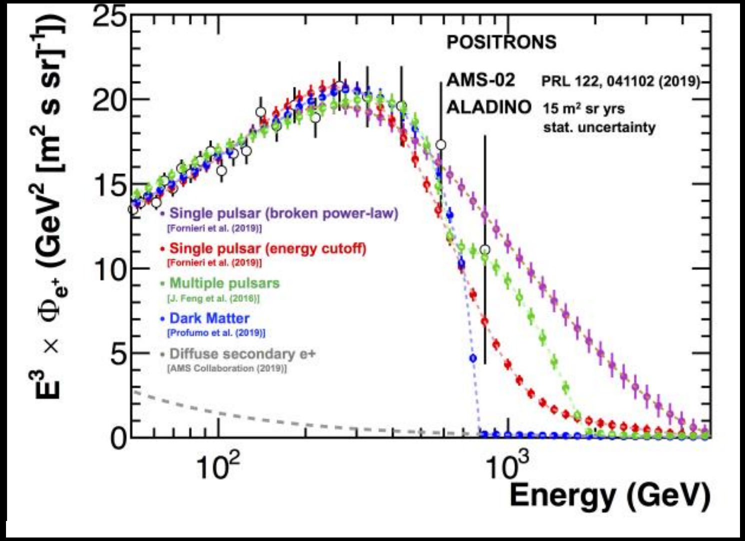
The ghost of experiments yet to come (ALADInO)

The best place where to operate a cryogenic superconducting magnet is the Lagrange Point 2, like the Webb space telescope

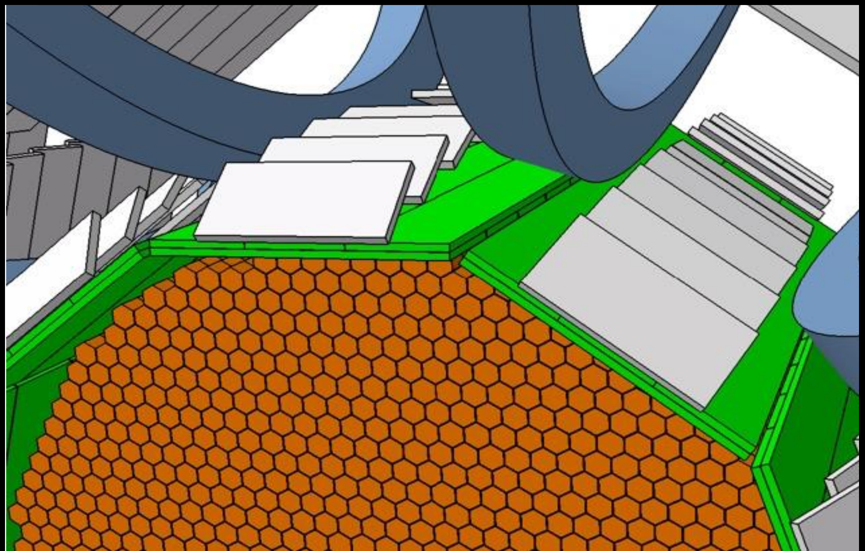


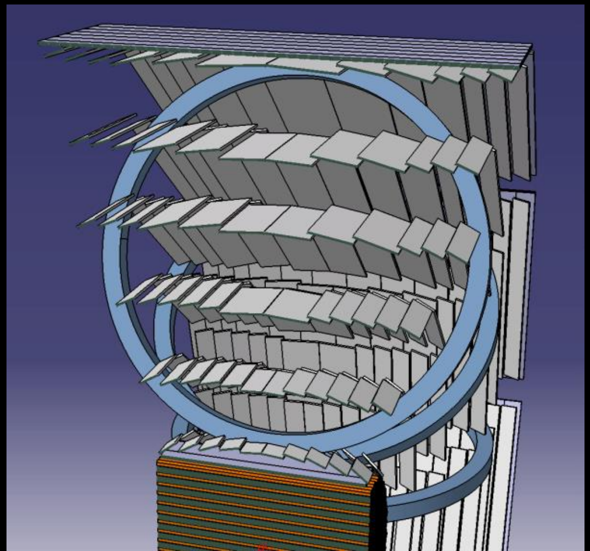
The ghost of experiments yet to come (ALADInO)

Calorimeter acceptance	~ 9 m^2 sr
Spectrometer acceptance	>10 m^2 sr (~ 3 m^2 sr w/i CALO)
Spectrometer Maximum Detectable Rigidity (MDR)	> 20 TV
Calorimeter depth	61 X_0, 3.5 λ_I
Calorimeter energy resolution	25% ÷ 35% (for nuclei) 2% (for electrons and positrons)
Calorimeter e/p rejection power	> 10^5
Time of Flight measurement resolution	~100 ps
High energy γ-ray acceptance (Calorimeter)	~ 9 m^2 sr
Low energy γ-ray acceptance (Tracker)	~ 0.5 m^2 sr
γ-ray Point Spread Function	< 0.5 deg



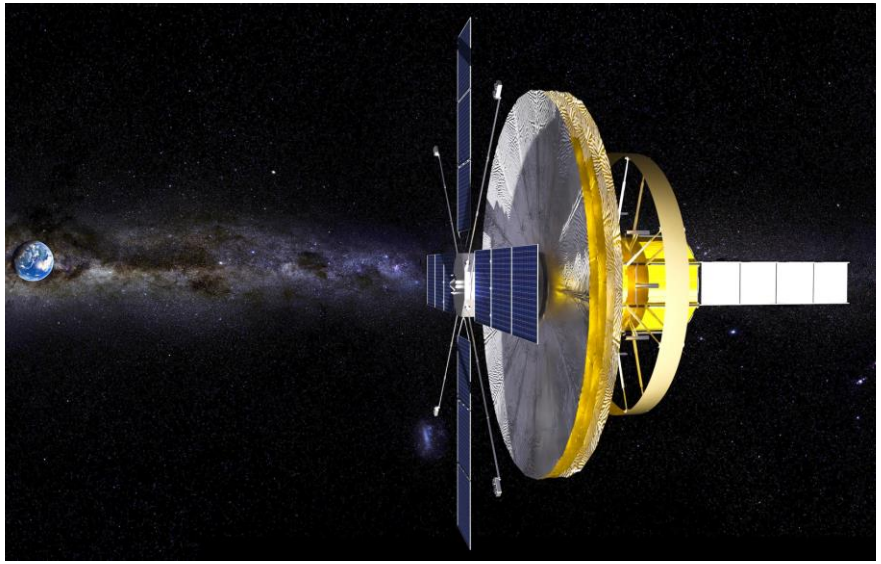
Weight: ~ 6 Tons
Power: ~ 4 kW
channels: 2.5 M

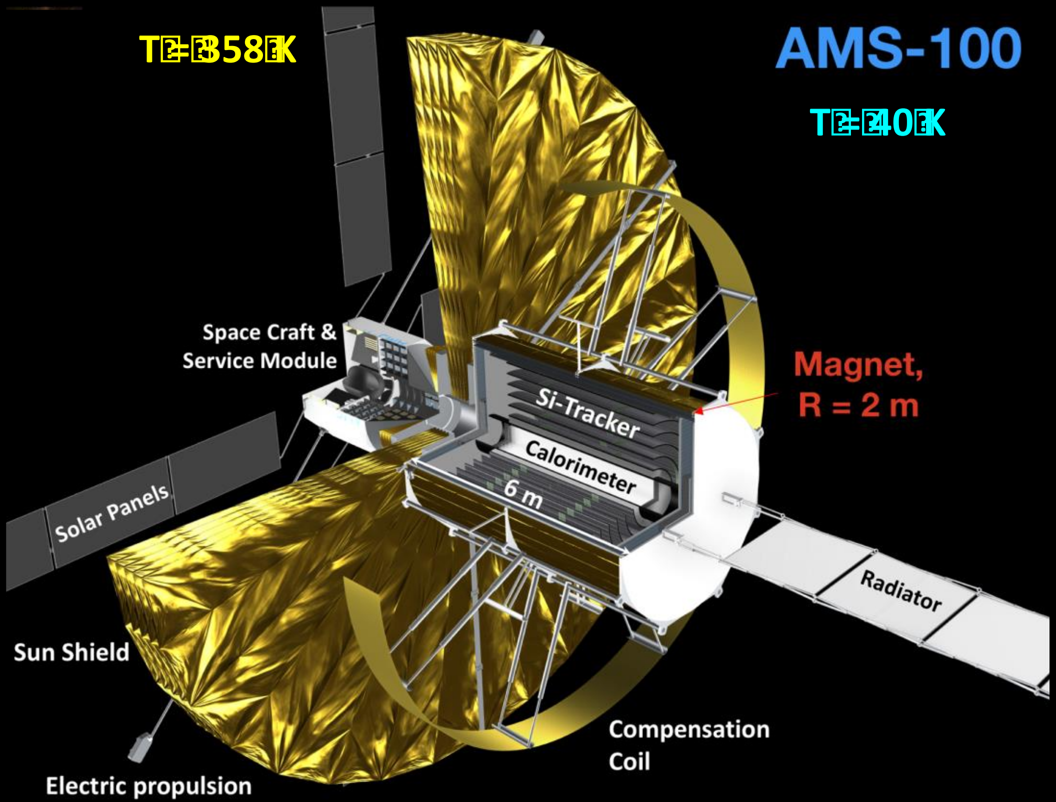




The ghost of experiments yet to come (AMS-100)

AMS-100
The Next Generation Magnetic Spectrometer in Space –
An International Science Platform for Physics and Astrophysics at Lagrange Point 2

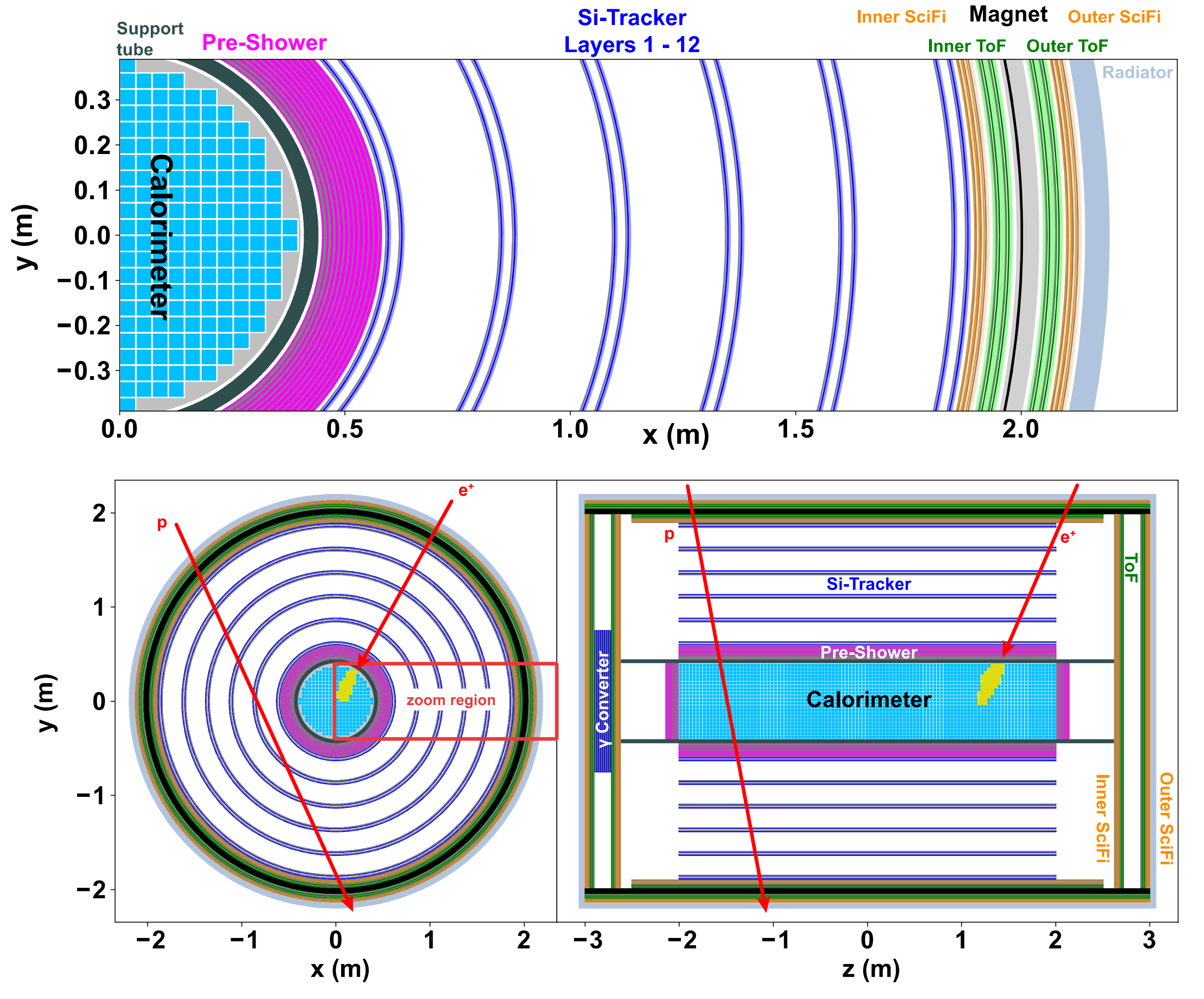




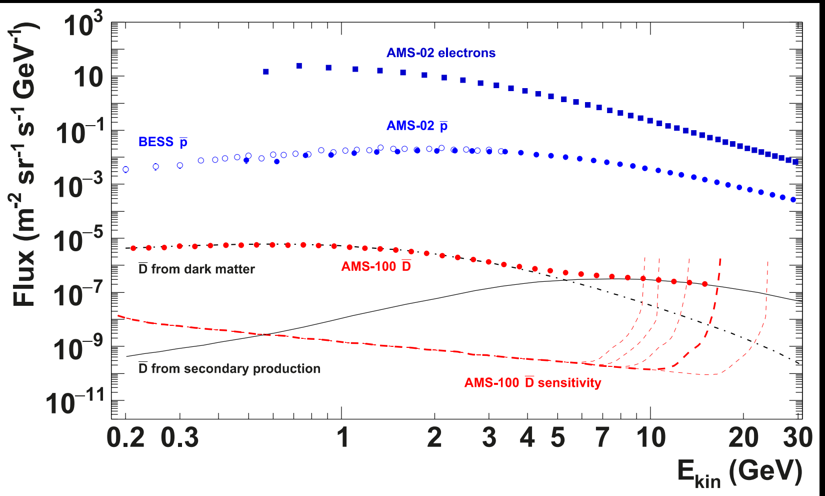
https://www.cosmos.esa.int/web/voyage-2050/white-papers
https://www.cosmos.esa.int/documents/1866264/3219248/SchaelS_AMS100_Voyage2050.pdf
arXiv:1907.04168v1 [astro-ph.IM] 9 Jul 2019

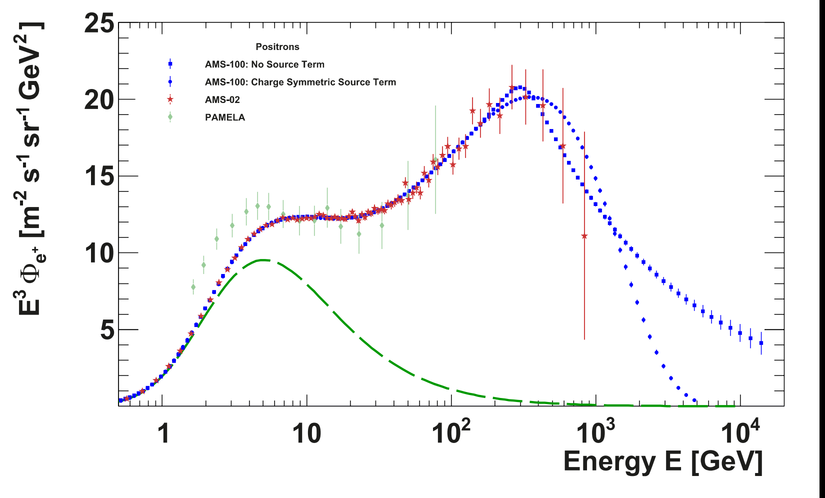
The ghost of experiments yet to come (AMS-100)

- The Calorimeter is essentially based on the HERD design
- A Pre-Shower (silicon detectors + tungsten) is foreseen to provide an angular resolution for γ-rays similar to the Fermi-LAT one
- An additional external γ-ray converter on the end-cap is foreseen to increase the γ-ray acceptance



The ghost of experiments yet to come (AMS-100)





Quantity	Value	
Acceptance	100 m^2 sr	
MDR	100 TV	for $\lvert Z \rvert = 1$
Material budget	$0.12\,X_0$	
of main solenoid	$0.012\,\lambda_I$	
Calorimeter depth	$70\,X_0,\ 4\,\lambda_I$	
Energy reach	10^{16} eV	for nucleons
	10 TeV	for e^+, $\bar{p}$
	8 GeV/n	for $\bar{D}$
Angular resolution	4″	for photons at 1 TeV
	0.″4	for photons at 10 TeV
Spatial resolution (SciFi)	40 µm	
Spatial resoultion (Si-Tracker)	5 µm	
Time resolution of single ToF bar	20 ps	
Incoming particle rate	2 MHz	
High-level trigger rate	few kHz	
Downlink data rate	∼28 Mbps	
Instrument weight	43 t	
Number of readout channels	8 million	
Power consumption	15 kW	
Mission flight time	10 years	

Conclusions

The last decade represented a major advance in the experimental knowledge of CR entering the field in the “precision era”

Interpretation of the new data leads to a lively debate, especially since new features and patterns start to emerge in the hadronic component of CRs, and no definite answer has emerged for the antimatter component puzzle

New space experiments are being planned or dreamed to connect the direct measurements with indirect measurements and push forward the boundaries of existing measurements