Direct measurements of cosmic ray protons and nuclei in space

Valerio Vagelli

Italian Space Agency (Rome, IT) & INFN (Perugia, IT)

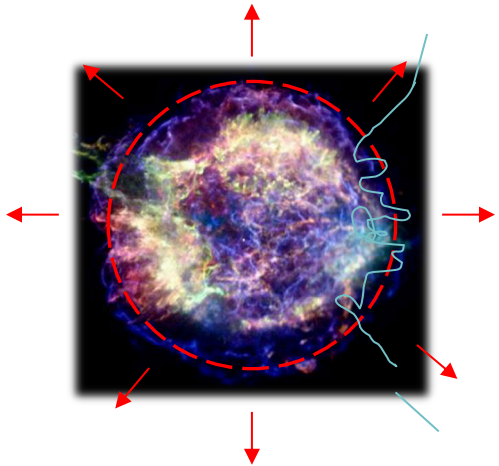
Multimessenger Astronomy

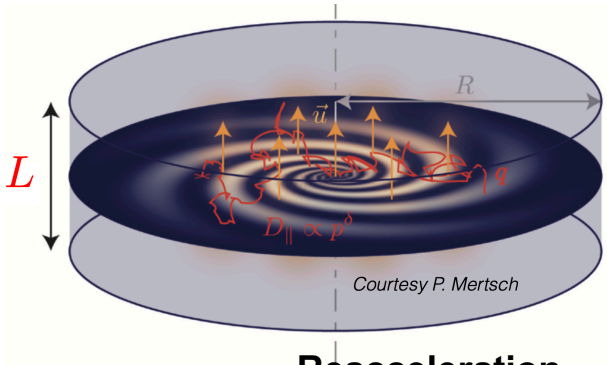
www.particlezoo.net

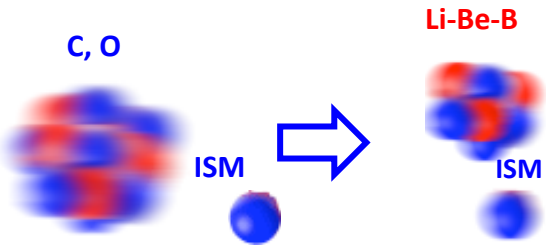
Origin, Acceleration and Propagation

Three pillars behind the physical paradigm

- **Shock acceleration in SNRs**: origin of primary CRs (p, C-N-O, Fe …)
- **Diffusive transport** in interstellar and interplanetary magnetic turbulence
- **Collision with ISM** --> Secondary CRs production (Li-Be-B, antimatter, …)







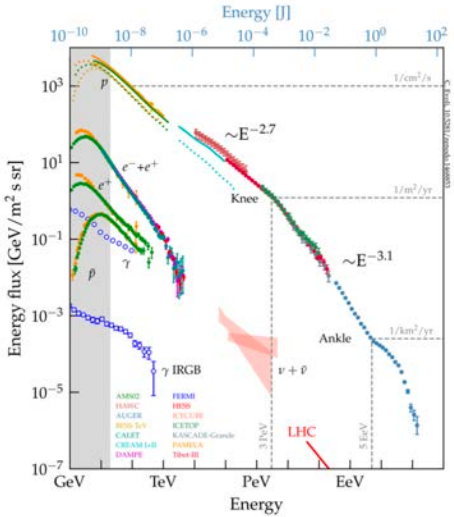
Sources | **Reacceleration (Rigidity diffusion)** | **Decay / Fragmentation**

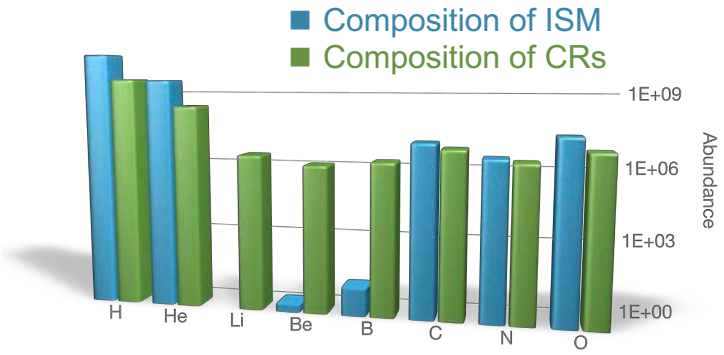
$$\frac{\partial \psi}{\partial t} = Q + \nabla \cdot (K \nabla \psi) + \frac{\partial}{\partial R} R^2 K_R \frac{\partial}{\partial R} \frac{1}{R^2} \psi - \frac{\partial}{\partial R} [\dot{R} \psi] - \Gamma_t \psi$$

Spatial diffusion | **Losses**

Origin, Acceleration and Propagation

Era of precision CR measurements in the GeV-TeV range

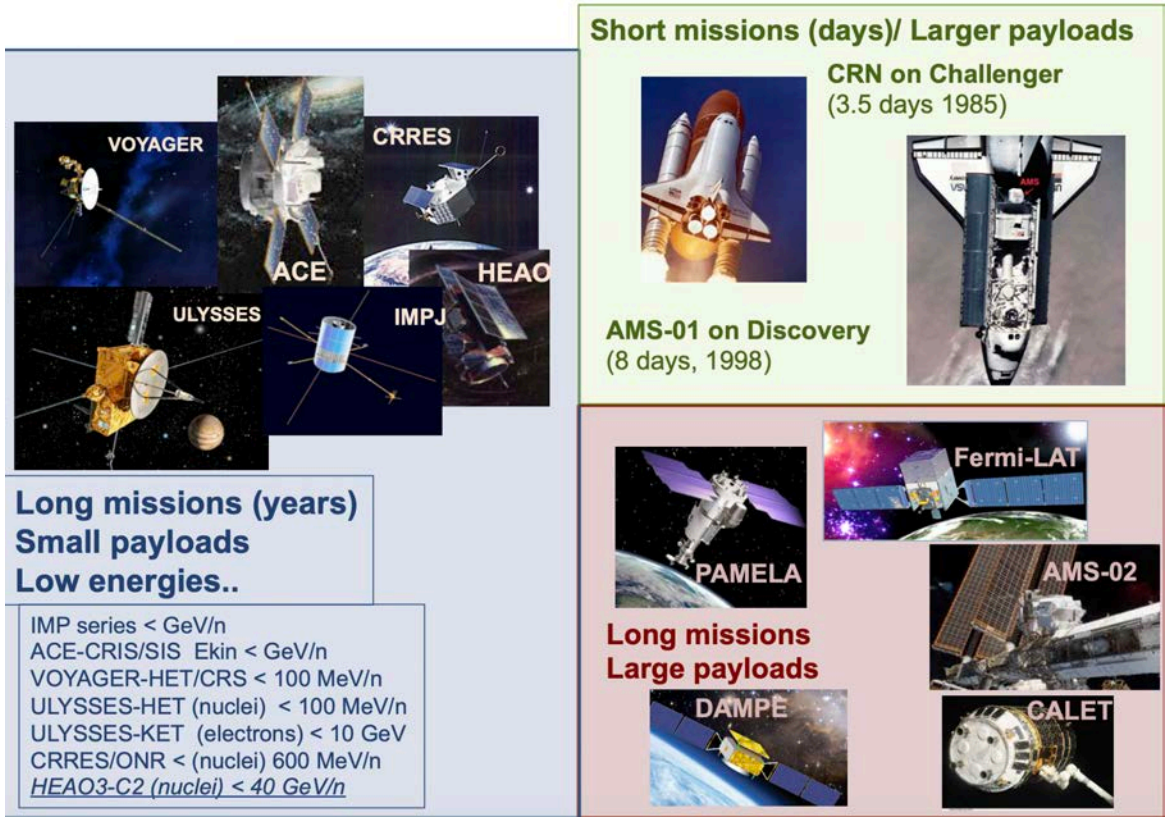




Which classes of sources contribute in different energy ranges?
Are CR electrons and protons accelerated by the same sources?
What is the origin of CR antimatter?
How do CR interact with the solar magnetosphere?

%-level accuracy provide the framework to verify the idea in origin, acceleration and propagation of cosmic rays

Measurement of Cosmic Rays in Space

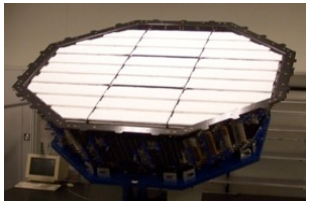


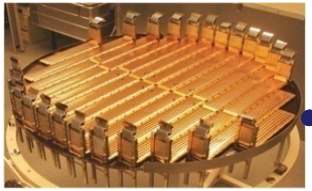
Access to space with **long duration missions** provided **direct measurements of CRs** before their interaction with the atmosphere.

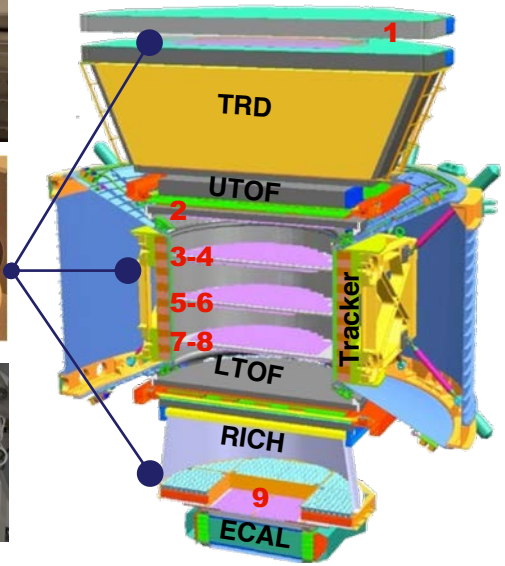
Limited acceptance prevents investigation towards the highest CR energies but allows **precision measurements of CR spectra and composition**

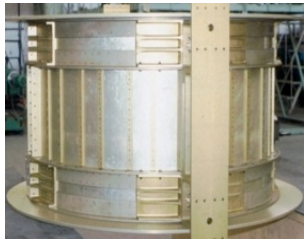
Measurement of Cosmic Rays in Space

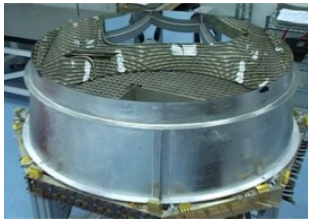
AMS-02 on ISS









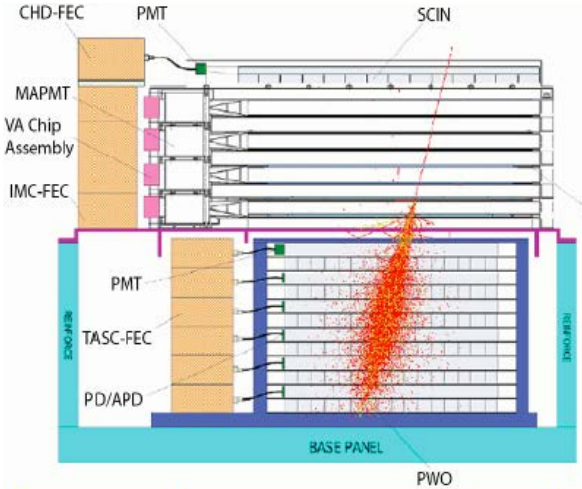


	e⁻	P	Fe	e⁺	$\bar{P}$	$\bar{He}$
TRD						
TOF						
Tracker + Magnet						
RICH						
ECAL						

Multiple and Independent Measurement of
Charge (Z), **Energy** (β, p, E) and **Charge Sign** (±).

Measurement of Cosmic Rays in Space

CALET on ISS



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)

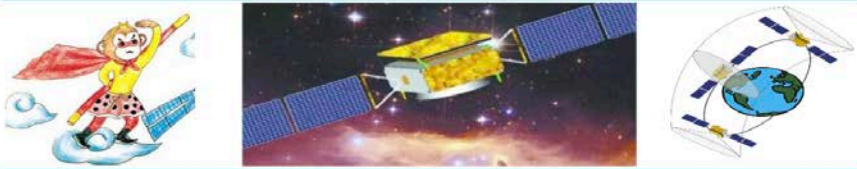
PWO 20mm x 20mm x 320mm
Total Depth of PWO: 27 X_0 (24 cm), 1.2 λ_I

	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)

Measurement of Cosmic Rays in Space

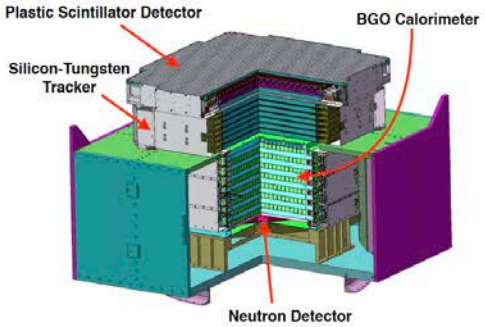
DAMPE on satellite

DArk Matter Particle Explorer Satellite



DArk Matter Particle Explorer Spectrum

- Plastic Scintillator Array
  - Response : Z=1~26
- Silicon Tracker
  - 12 layers Si-strip
- BGO Calorimeter
  - 14 layers , ~32X_0
- Neutron Detector
  - Plastic scintillator with Boron



Altitude: 500 km

Inclination: 97.4065°

Period: 95 minutes

Orbit: sun-synchronous

Life： > 3 years

Energy: 5 GeV – 10 TeV

Res: 1.5% @ 800 GeV ($e^{\pm}$)

Acc: 0.3 m^2 sr (for $e^{\pm}$)

Ang: 0.1 degree @ 100 GeV

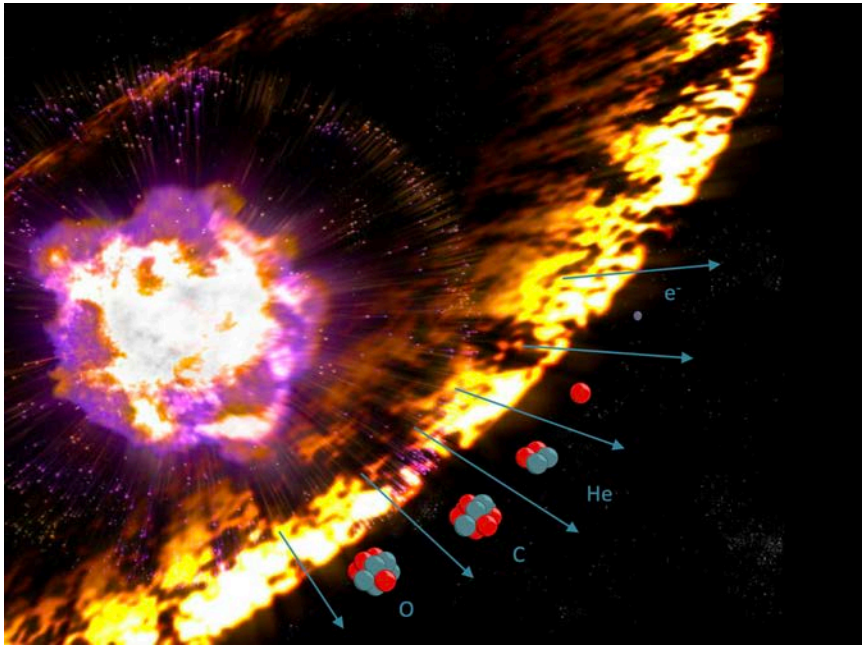
Weight: 1450 kg

Power: 300 W

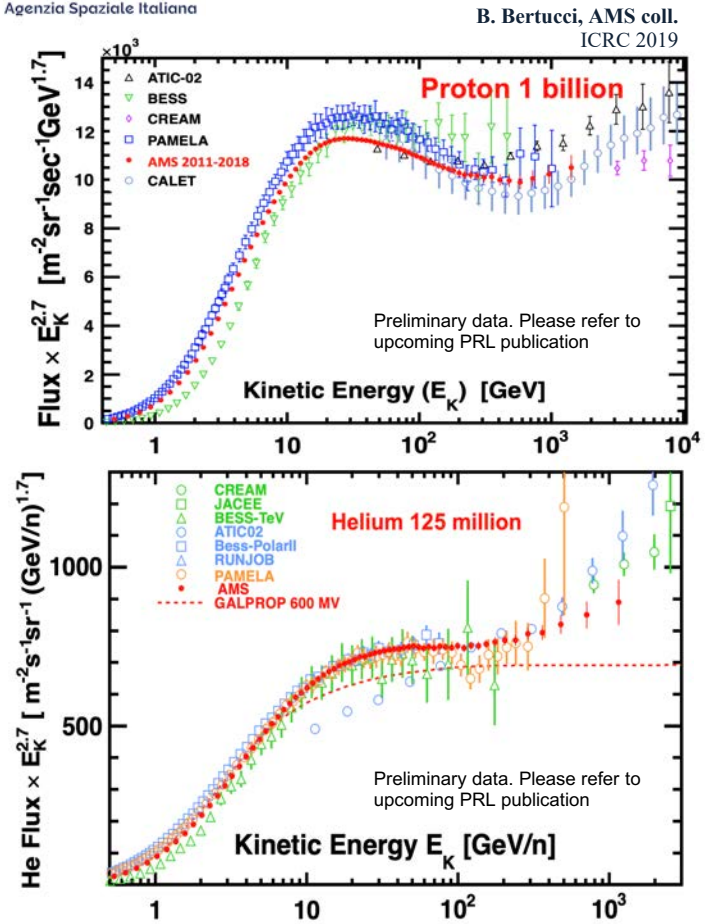
Size: 1.2 m×1.2 m×1.0 m

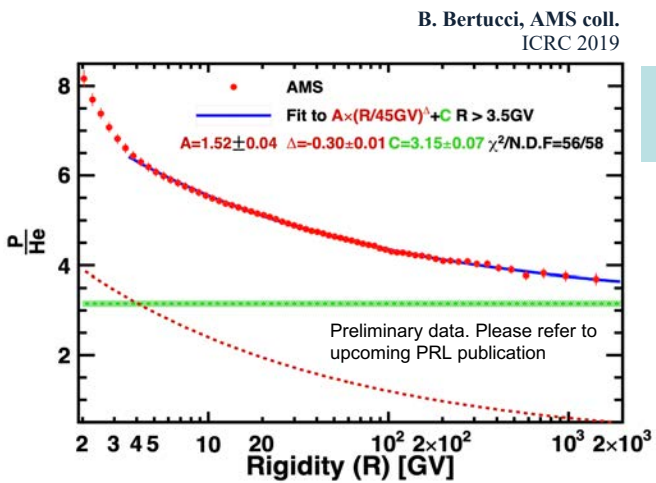
The current scenario

- **Protons and Helium**
- Heavier nuclei
- Antimatter
- Anisotropy
- Solar modulation



Primary cosmic rays





Rigidity Dependent p/He ratio

Protons and Helium up to TeV/n

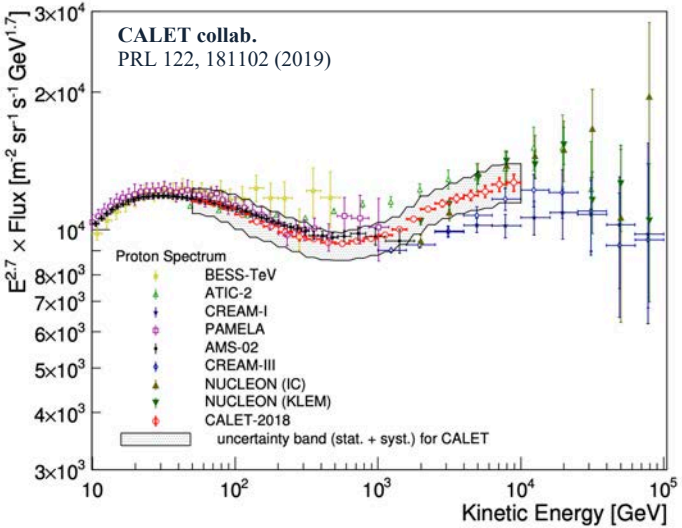
Common deviation from single power law at 200 GV

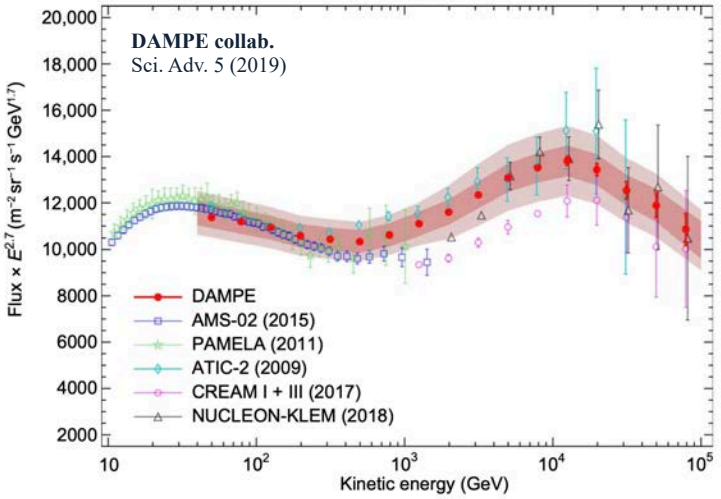
Proton spectrum softer by Δγ=0.1 → **violation of universality of spectral indices**

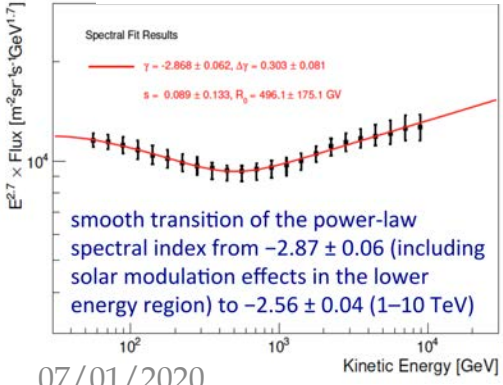
Rigidity dependent ratio: different source or injection mechanisms

Hint of ratio flattening towards high rigidities?

Primary cosmic rays







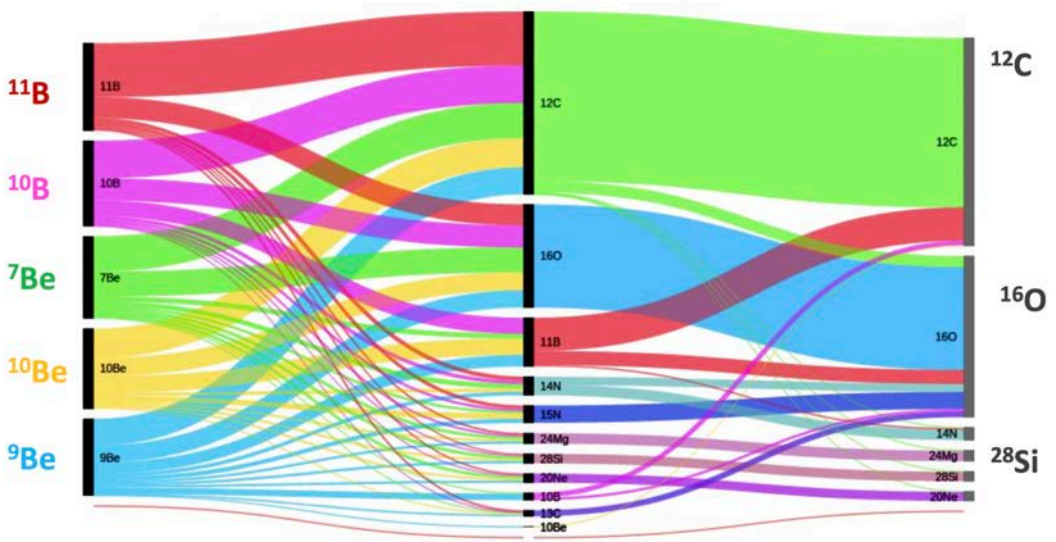
Protons up to 100 TeV

Coherent measurements with the same instrument in space from below 1 TeV (spectrometers) to supra-TeV energies (ballon experiments)

Confirmation of spectral hardening but at higher energy
Spectrum softnening at 10 TeV
The next challenge is the precise measurement region 10 TeV – 100 TeV, where published results have large uncertainties

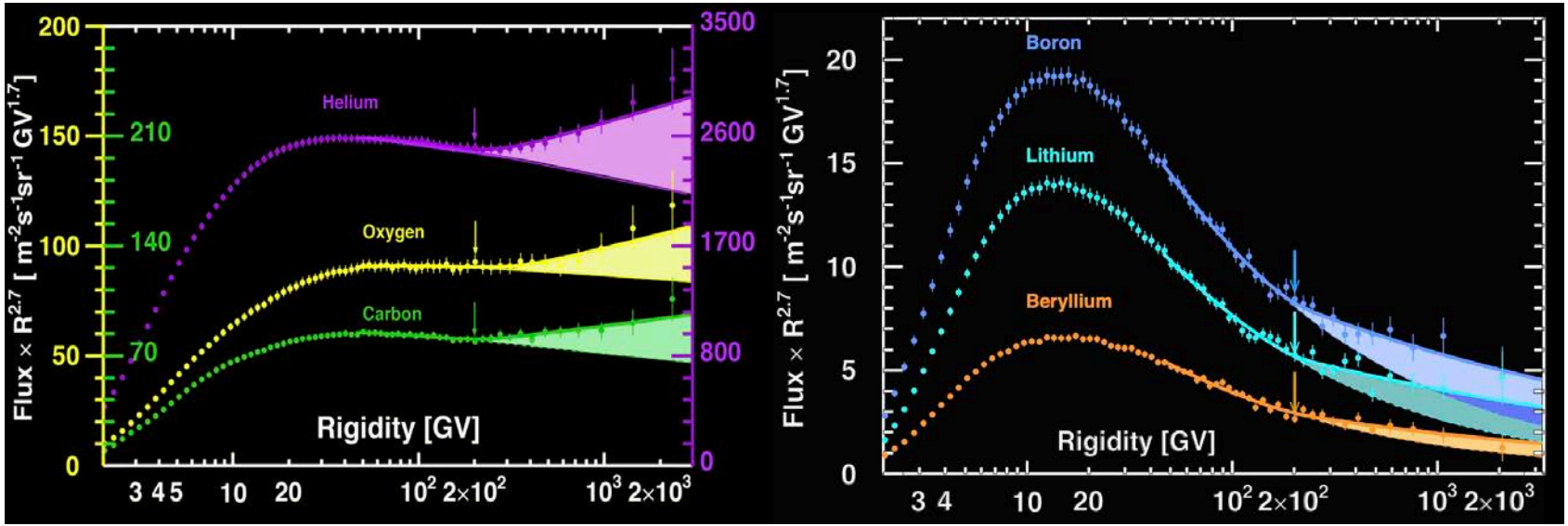
The current scenario

- Protons and Helium
- **Heavier nuclei**
- Antimatter
- Anisotropy
- Solar modulation



Heavy Nuclei

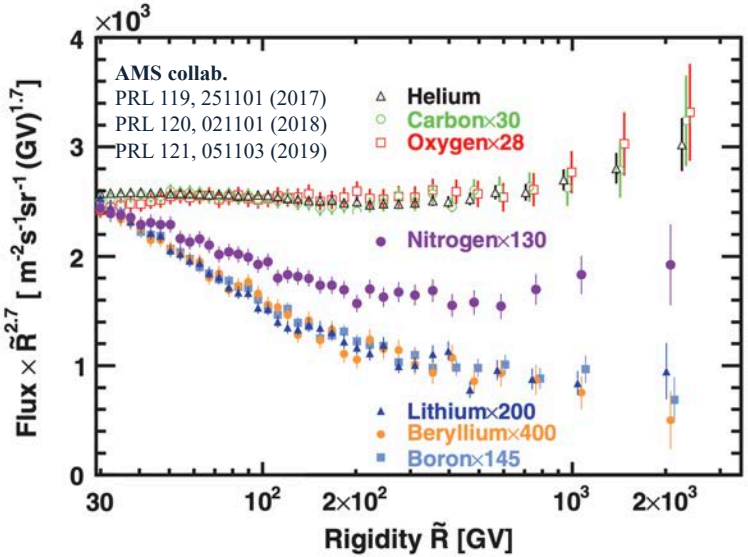
B. Bertucci, AMS coll.
ICRC 2019

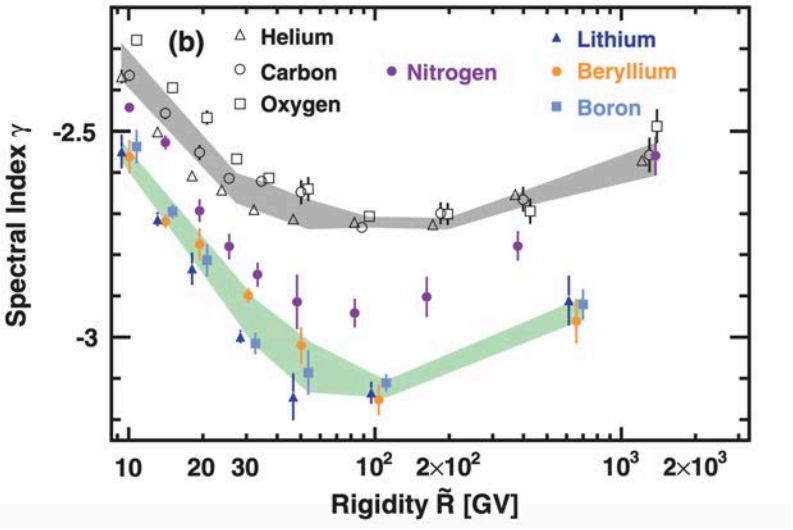


Measurements of nuclei up to O (Z=8)

Spectral hardening observed for all species at similar rigidities but with different intensities

Heavy Nuclei – Primary CRs





Measurements of nuclei up to O (Z=8)

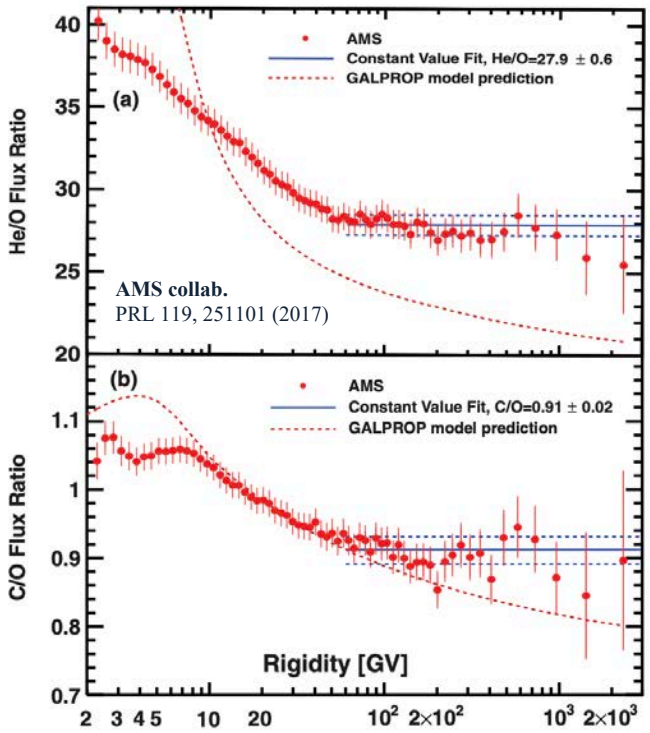
He,C,O: pure primary CRs, similar spectral behavior

Li,Be,B: not accelerated in astrophysical sources (secondary CRs), similar spectral behavior

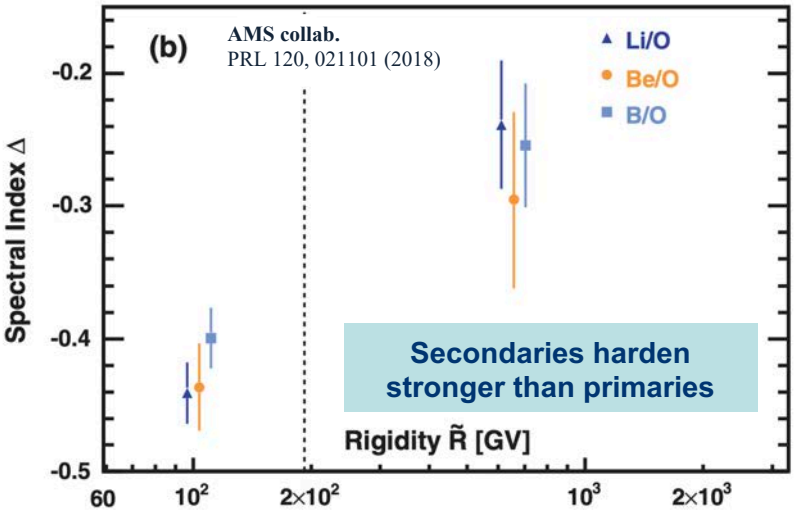
N: peculiar, both primary and secondary (secondary component 70% at GV, 30% at TV)

First time precise determination of spectral features for energies above 100 GeV

Heavy Nuclei – Primary CRs

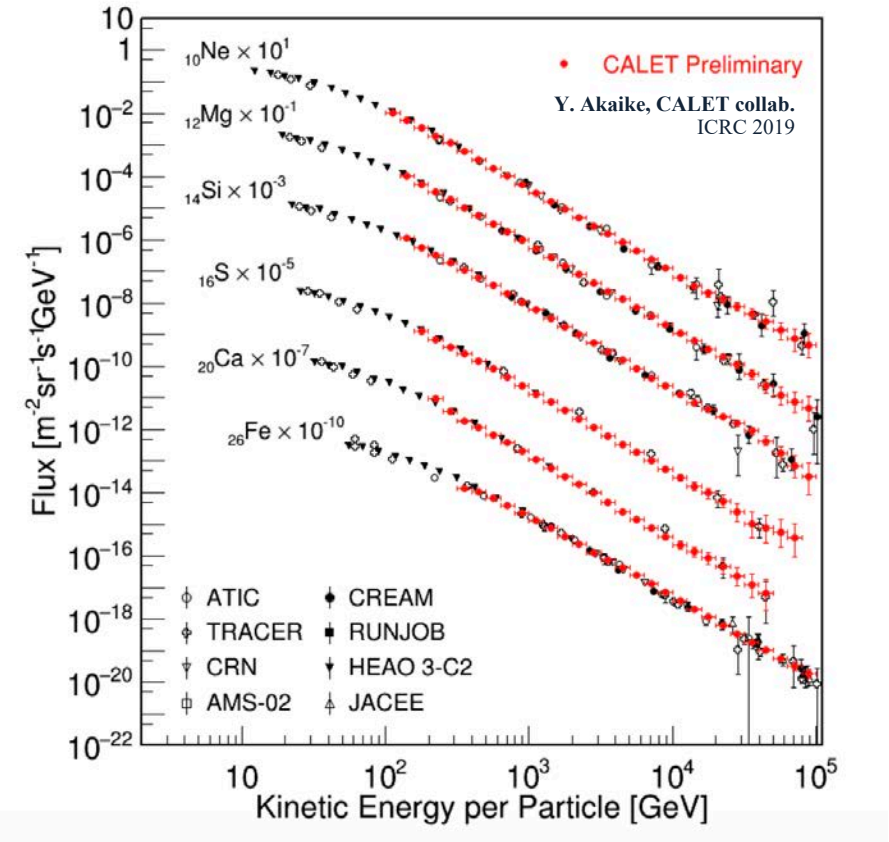


Primary ratios are rigidity independent above 60 GV

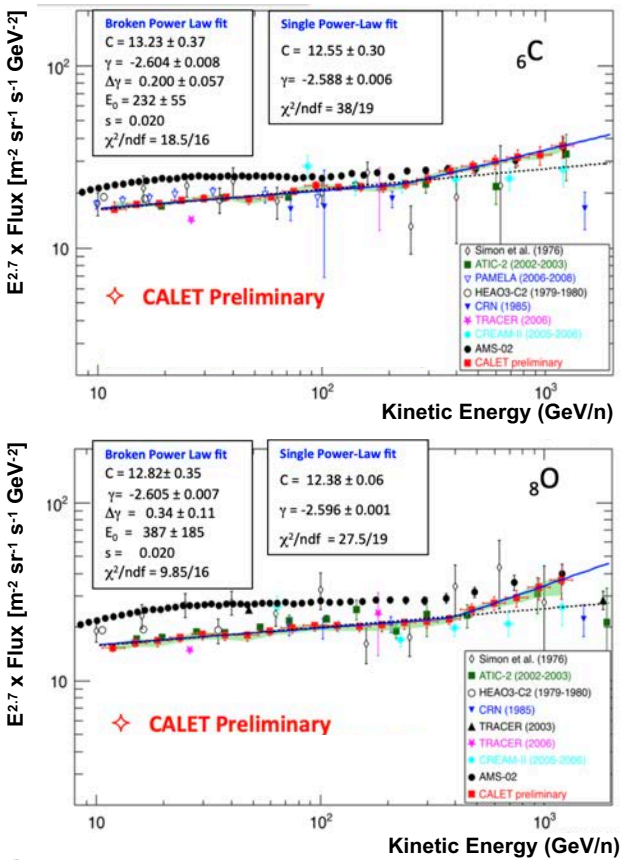


The secondary/primary ratio hardens above 200 GV by $\Delta\gamma=0.13$. This favors a **propagation effect origin** of the common hardening observed in heavy nuclei CRs

Heavy Nuclei – Primary CRs

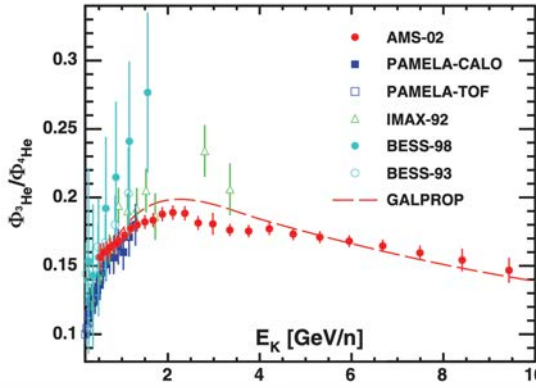


P. Maestro, CALET collab.
COSPAR 2018

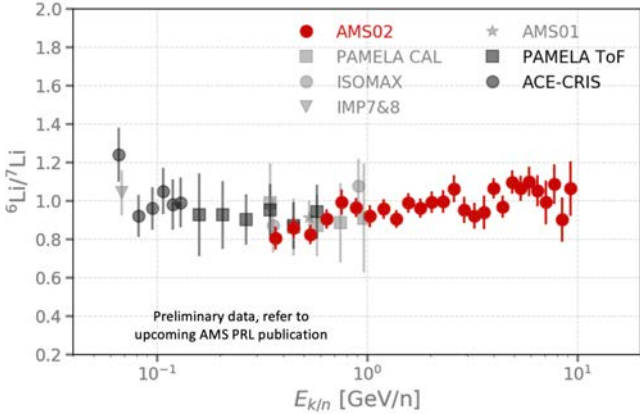


Light nuclei isotopes

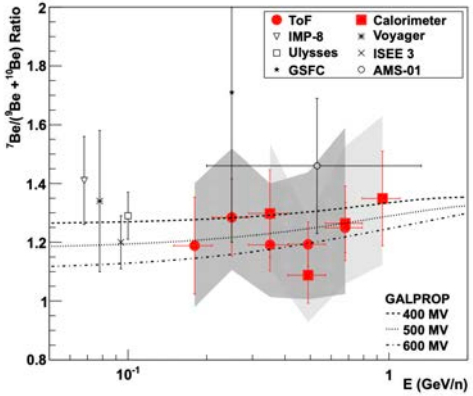
AMS collab.
PRL 123, 181101 (2019)

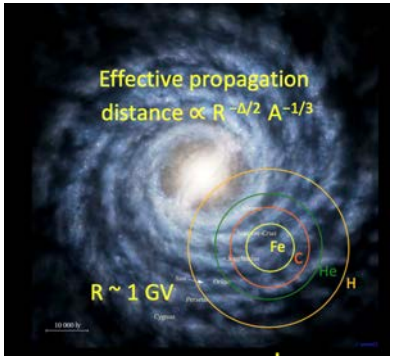


L. Derome, AMS collab.
ICRC 2019



PAMELA collab.
Astrophys.J. 862 (2018) no.2, 141





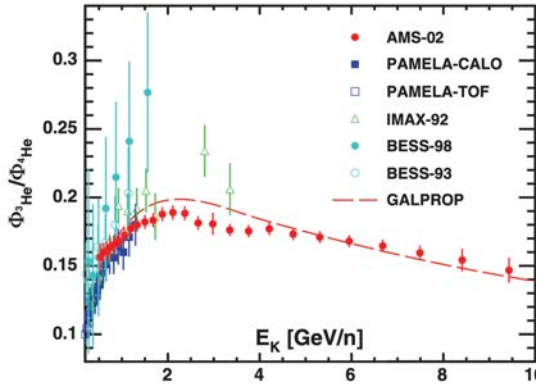
Isotopic composition of CRs provide details on origin and propagation

^3He / ^4He, secondary/primary: probes the largest distance in CR propagation
^6Li / ^7Li, secondary/secondary: probes secondary spallation cross sections from C and O
^7Be / (^9Be+^{10}Be), unstable/stable: probes propagation history of CRs ("radioactive clock")

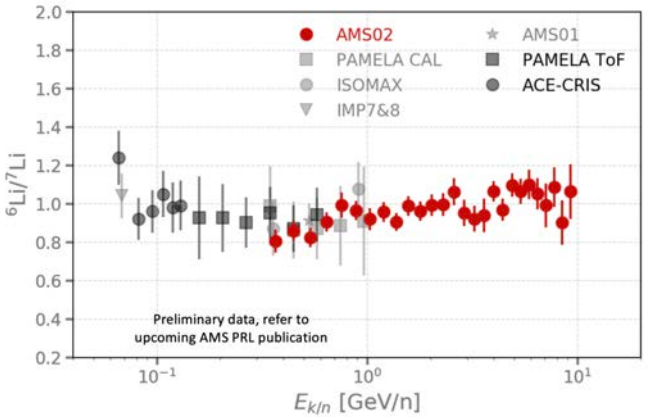
PAMELA and AMS-02 are providing unprecedented accuracy data on isotopic composition at low energies

Light nuclei isotopes

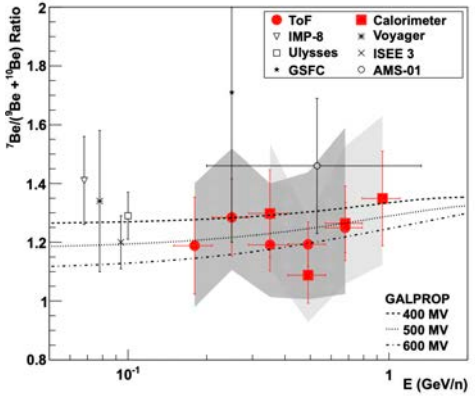
AMS collab.
PRL 123, 181101 (2019)

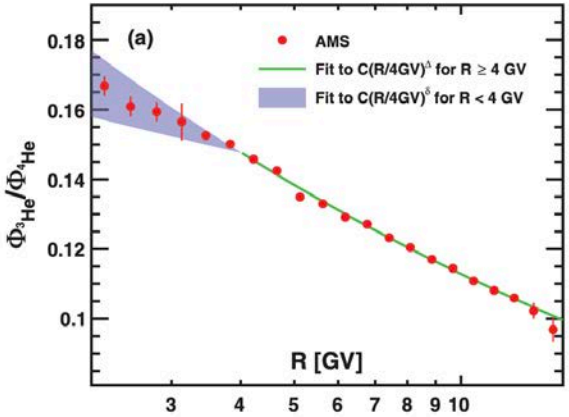


L. Derome, AMS collab.
ICRC 2019



PAMELA collab.
Astrophys.J. 862 (2018) no.2, 141

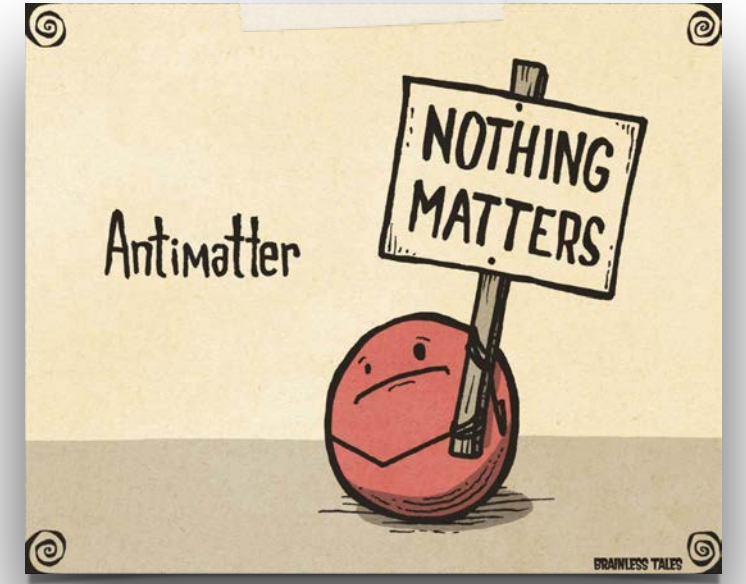




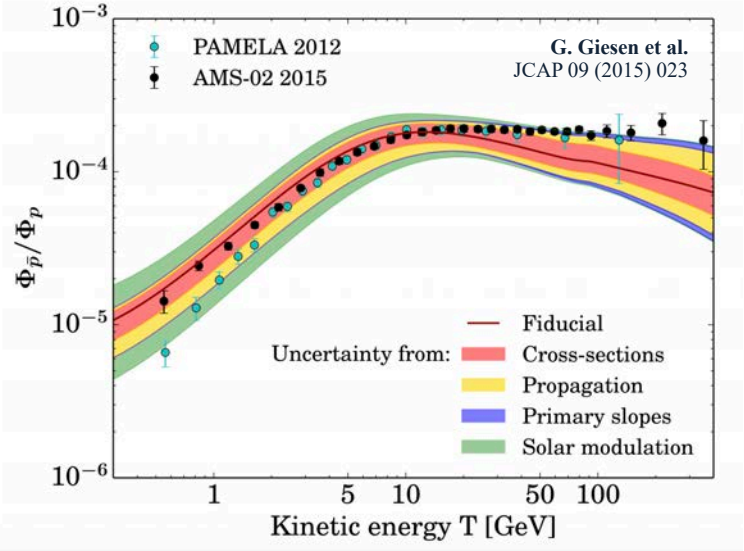
$^3He/^4He$ measured as function of rigidity for the first time.
Power law above 4 GV with Δ~0.3, similarly as B/C species

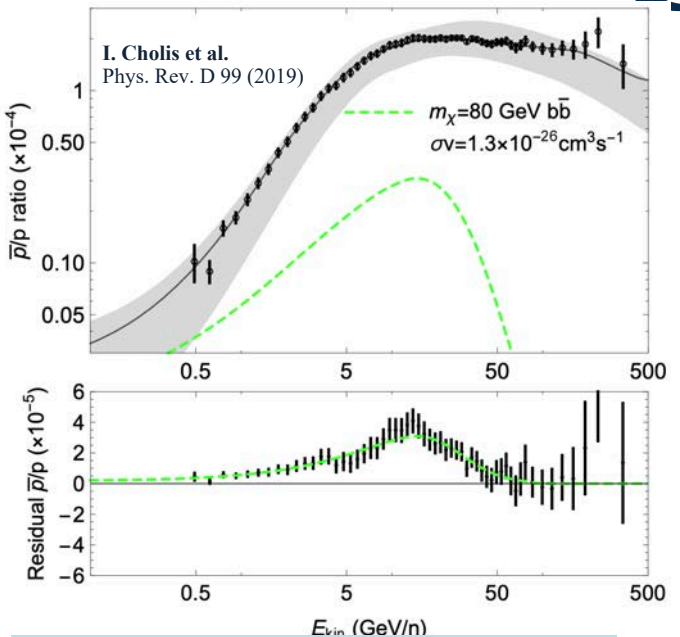
The current scenario

- Protons and Helium
- Heavier nuclei
- **Antimatter**
- Anisotropy
- Solar modulation



Antimatter - AntiProton





High energy antiproton excess?

Traditionally investigated for evidence of DM excess

Flat anti-p/p ratio, in tension with purely secondary production

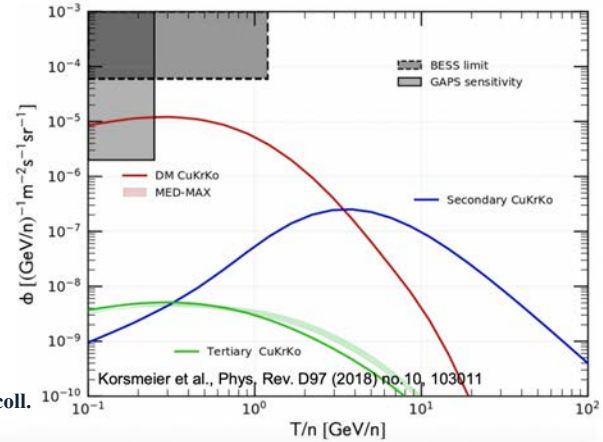
Large uncertainties on propagation and nuclear fragmentation smooth out the tension.

Low energy antiproton excess?

Excess > 3σ with DM->bbar with masses 50-100 GeV (compatible with models explaing GeV GC γ-ray excess)

Interpretation difficult due to **large uncertainties on propagation, nuclear physics and charge, time and energy dependent effects of solar modulation**

Antimatter - AntiDeuteron



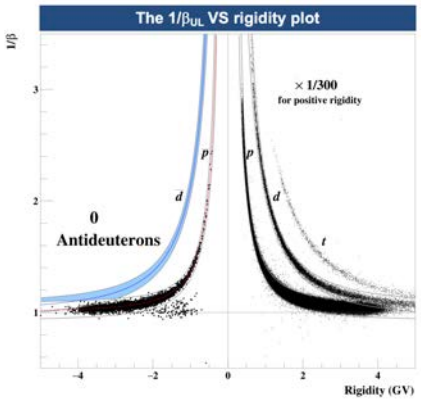
K. Sakai, BESS coll.
ICRC 2019

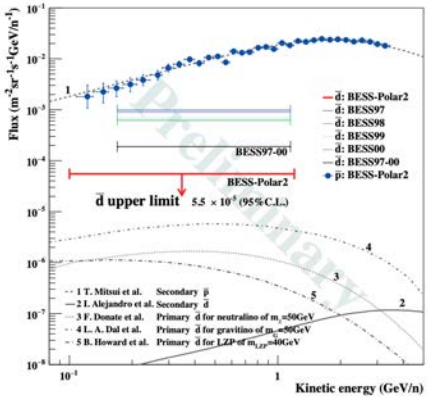
Low-energy Antideuteron are a **golden channel for indirect DM searches in CRs**

Secondary Anti-D production from CR interactions below 1 GeV/n suppressed by kinematical and dynamical constrainst

Low energy Anti-D yield by DM annihilation or decay is orders of magnitude more intense than secondary production: **un-ambiguous identification of DM origin for low-energy anti-D**

Anti-D identification is challenging (high D contamination, isotopic separation from anti-p)





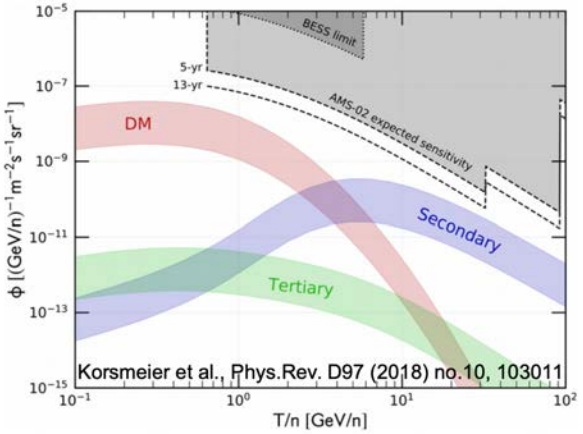
No Anti-D observed yet in Cosmic Rays

However, anti-D from DM may be in reach of current space and balloon detectors.

Most recent constraint set by BESS collaboration using BESS Polar I & II flights

New constraints/observations expected from AMS-02 and GAPS

Antimatter - AntiHelium



Low-energy AntiHelium is the **diamond channel for indirect DM searches in CRs**

As for anti-D, secondary CR production of anti-He is strongly suppressed at low energies
Anti-He is however not in reach of current detectors, unless some exotic mechanism is used

No Anti-He observed yet in Cosmic Rays

AMS-02 has candidate anti-He events (1 candidate/10^8 He)

S. J. Ting, AMS collab.
AMS Days 2018

Status of the AMS complex antimatter analysis

To date we have observed eight Z = -2 events with mass around He.

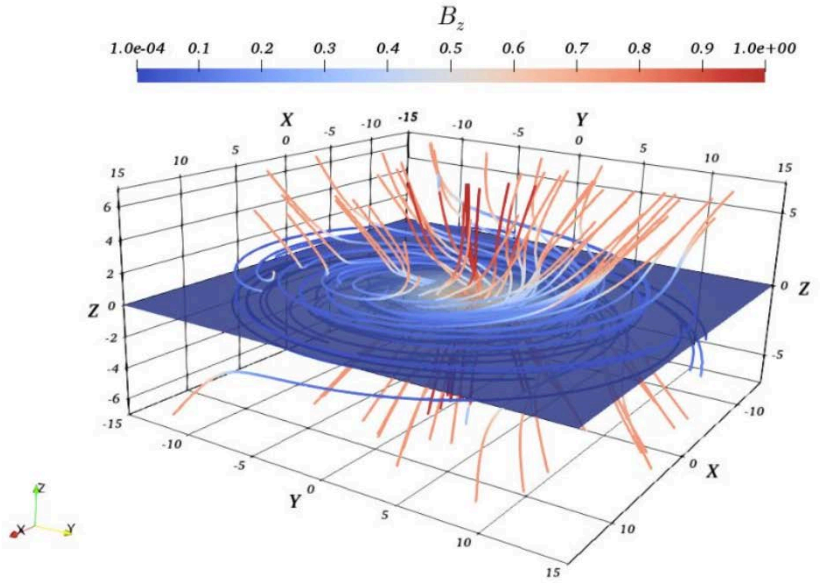
The corresponding sample with Z = +2 amounts to one billion helium events.

With the anti-Helium to Helium ratio of less than 1 in 100 million, detailed understanding of the instrument is required.

We are performing final detector verifications before announcing the results

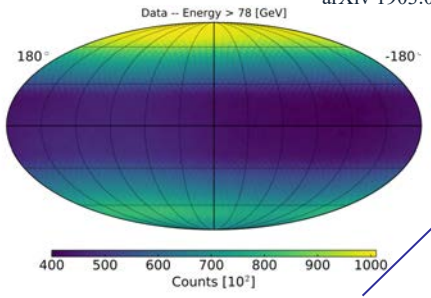
The current scenario

- Protons and Helium
- Heavier nuclei
- Secondary cosmic rays
- Isotopes and antimatter
- **Anisotropy**
- Solar modulation

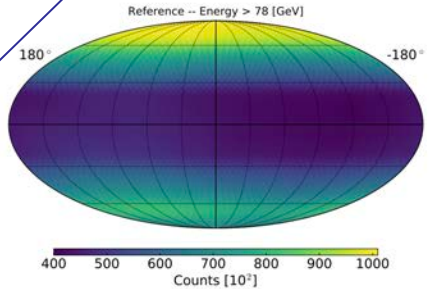


Anisotropies

Fermi-LAT collab.
arXiv 1903.02905 [astro-ph.HE]

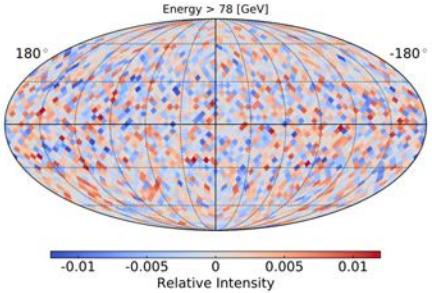


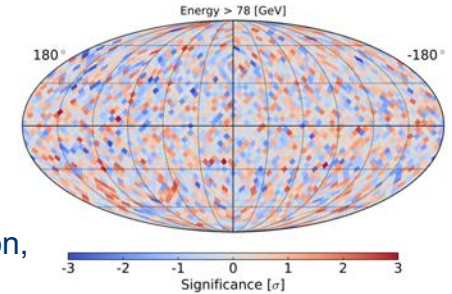
DATA map



REFERENCE map

RELATIVE map





SENSITIVITY map

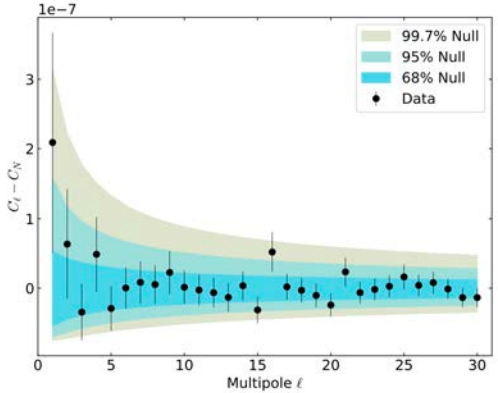
Cosmic ray anisotropy

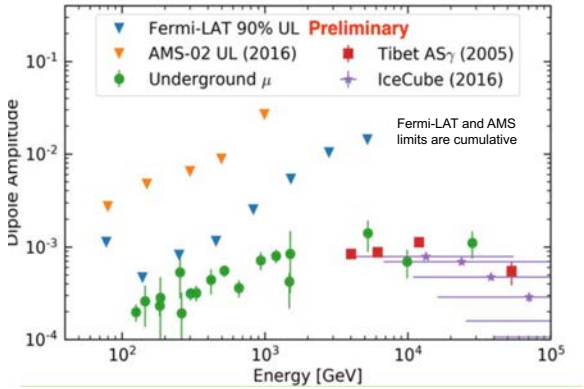
Measured from TeV to EeV by ground experiments (limited composition resolution, 1D measurement in right ascension, insensitive to declination).
May provide information on the **distribution and gradient of sources** around Earth

Largest CR proton dataset for anisotropy measurement above 78 GeV collected in 8 years by the Fermi-LAT satellite, hint of dipole found in full-sky observation

Anisotropies

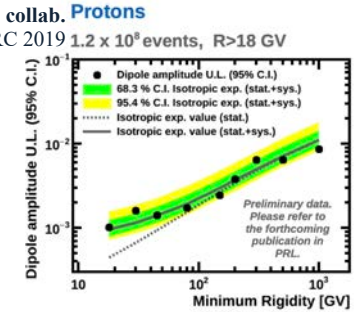
J. Vandenbroucke, Fermi-LAT coll.
ICRC 2019



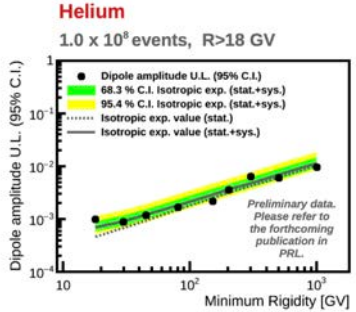


Fermi-LAT: Hint of proton dipole anisotropy $\delta = 3.9 \pm 1.5 \cdot 10^{-4}$ ($p<0.01$) / interpretation also as UL

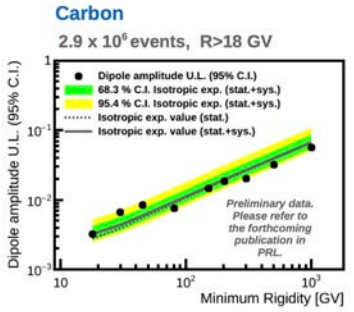
I. Gebauer, AMS collab.
ICRC 2019



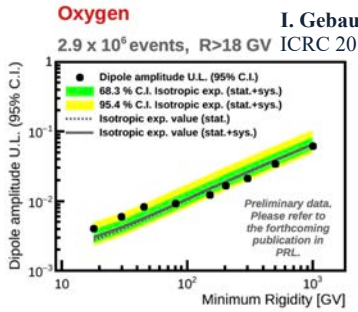
Upper limit on dipole amplitude:
δ_p(>200 GV) < 0.38% at 95% C.I.



Upper limit on dipole amplitude:
δ_{He}(>200 GV) < 0.36% at 95% C.I.



Upper limit on dipole amplitude:
δ_C(>200 GV) < 1.9% at 95% C.I.



Upper limit on dipole amplitude:
δ_O(>200 GV) < 1.7% at 95% C.I.

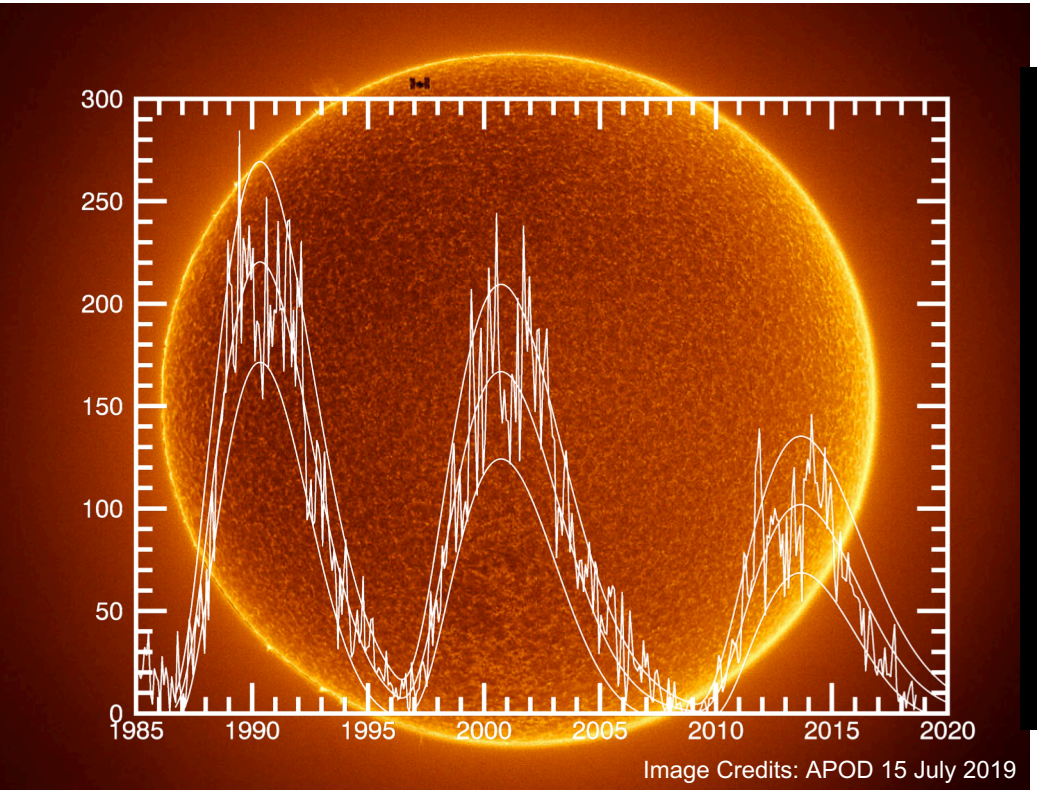
I. Gebauer, AMS collab.
ICRC 2019

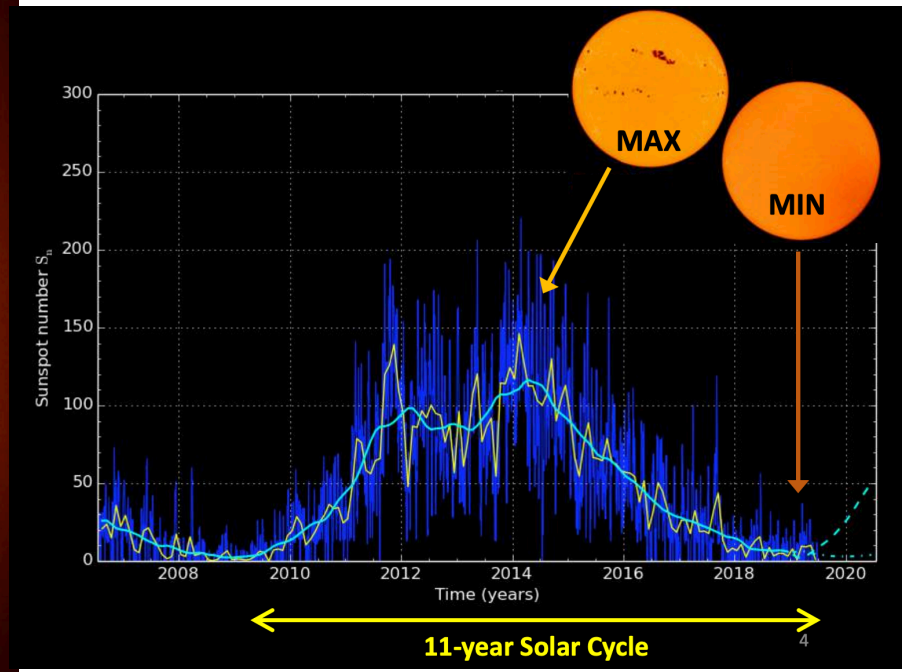
AMS-02: No dipole anisotropy found in p, He, C, O, dipole UL @ R>200 GV: 0.4% (p,He), 2%(C,O)

The current scenario

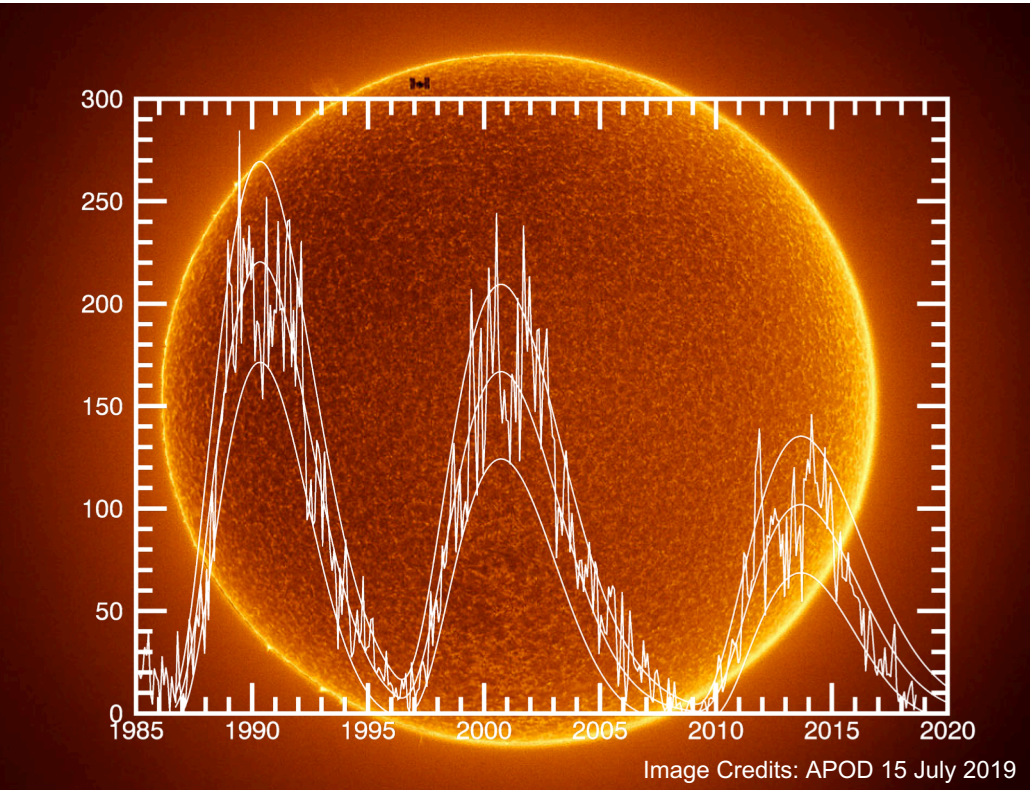
- Protons and Helium
- Heavier nuclei
- Secondary cosmic rays
- Isotopes and antimatter
- Anisotropy
- **Solar modulation**

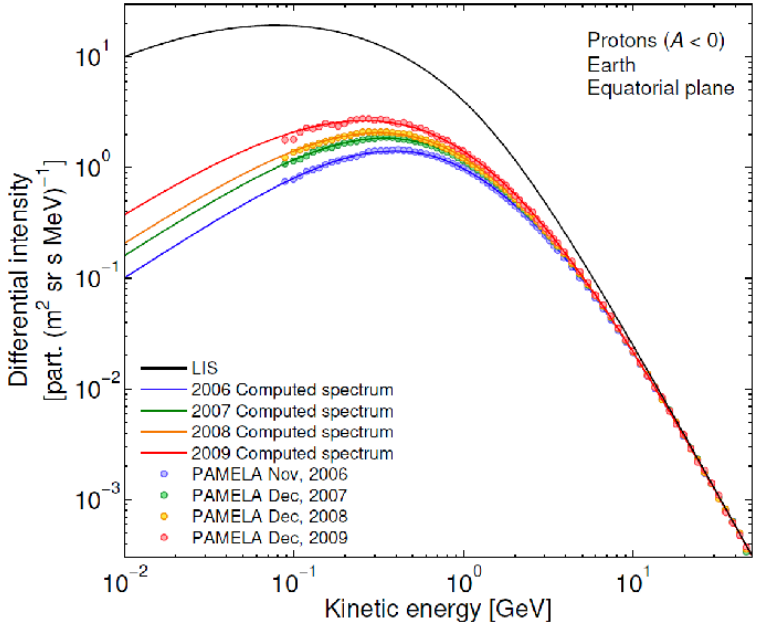
Solar physics





Solar physics

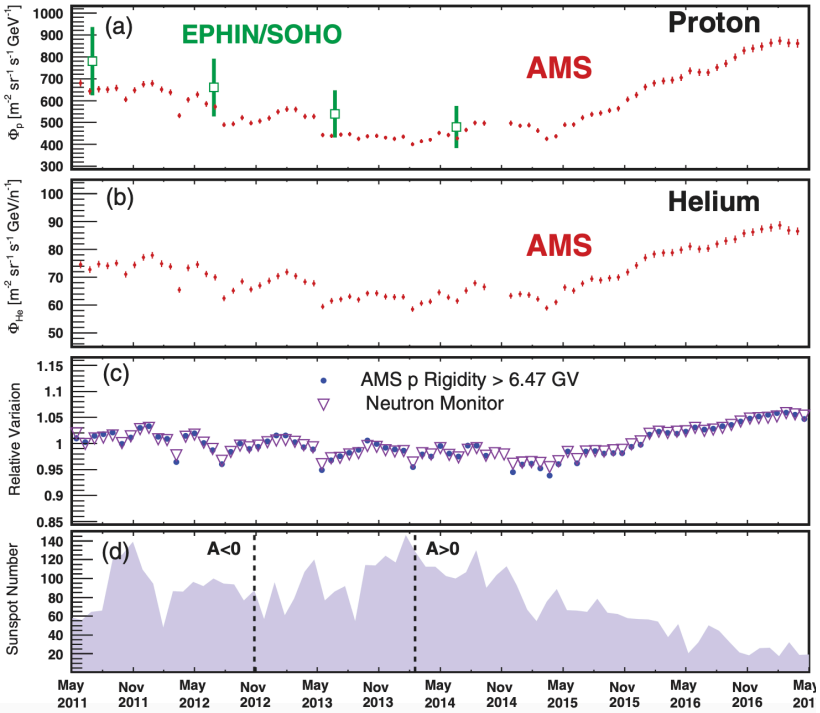


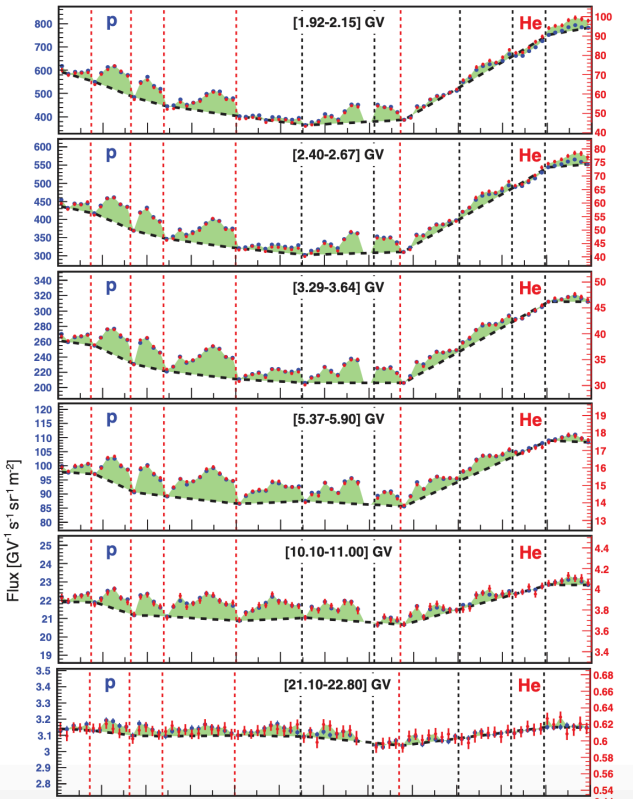


Solar modulation is a time, energy, particle and space dependent effect

Solar physics

Proton and Helium solar modulation



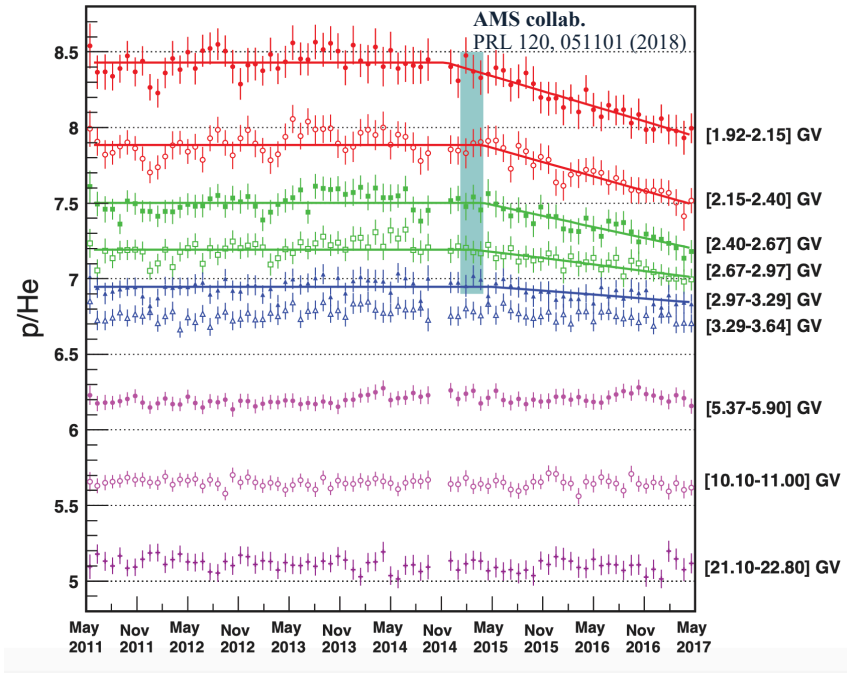


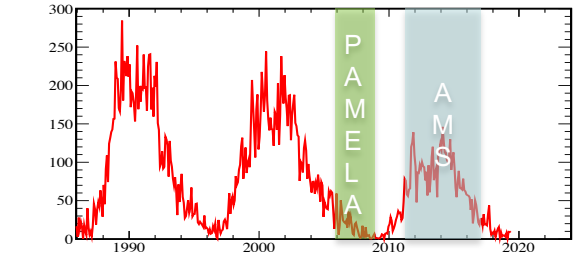
Long term modulation correlated to 11-years solar cycle

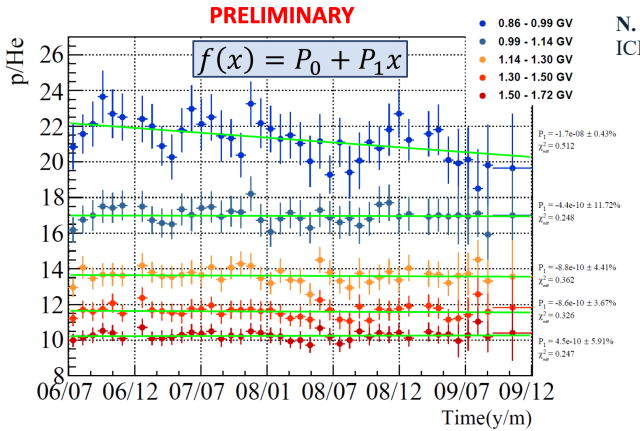
Short term structures

Solar physics

Proton and Helium solar modulation







N. Marcelli, PAMELA coll.
ICRC 2019

The p/He ratio shows a time dependence at low rigidities.

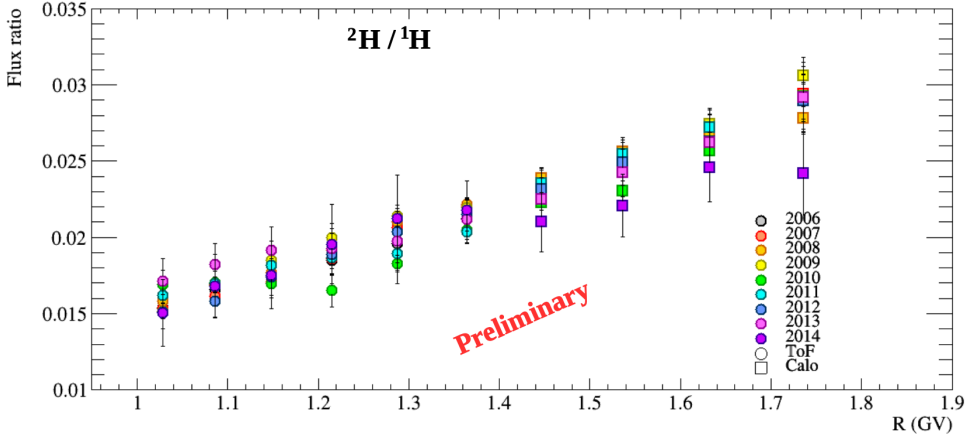
Possible interpretation: Mass/charge dependence of the diffusion coefficient / Different LIS for p and He / Isotopic composition effect in the He flux

Solar physics

Proton and Helium isotope solar modulation

Investigation of the isotope time dependence may disentangle the presence of mass dependent effects in the solar modulation

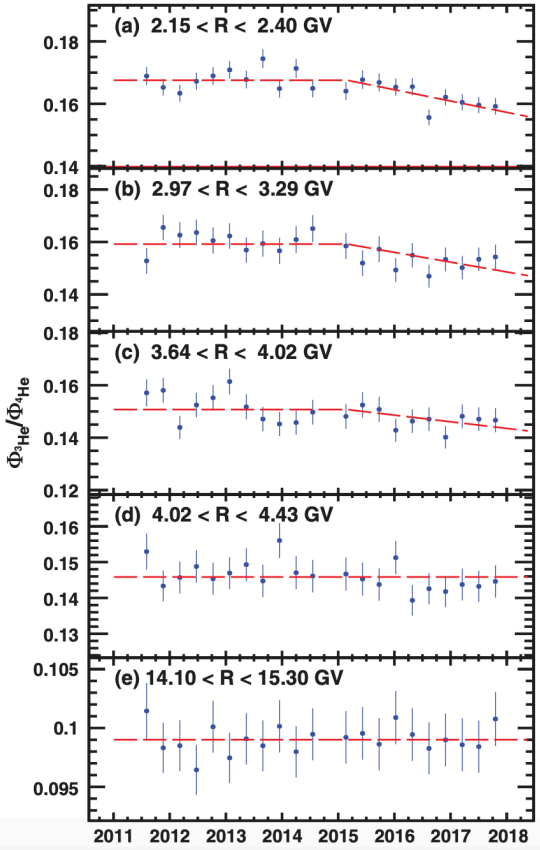
R. Munini, PAMELA coll.
ICRC 2019



Preliminary analysis of PAMELA $^2H/^1H$ show no clear time dependence
AMS $^3He/^4He$ shows that the ratio depends on time up to ~ 4GV.

Evidence of mass dependent solar modulation

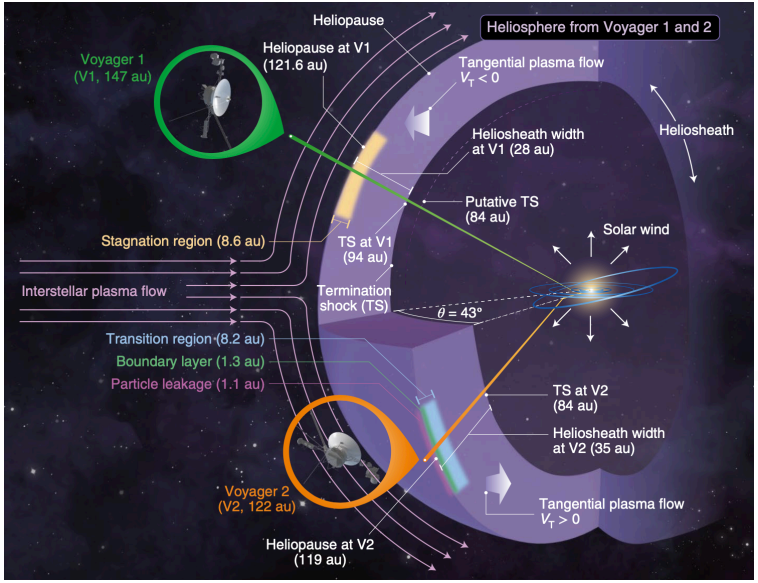
AMS collab.
PRL 123, 181101 (2019)

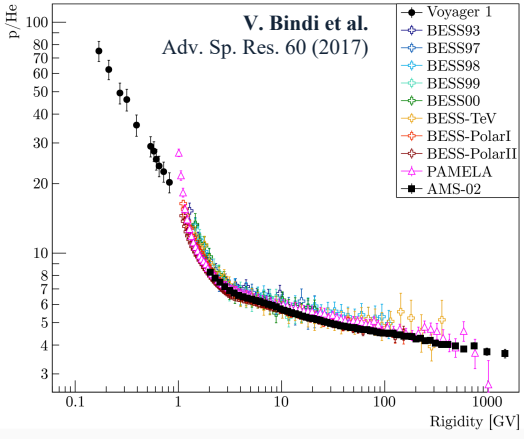


Solar physics

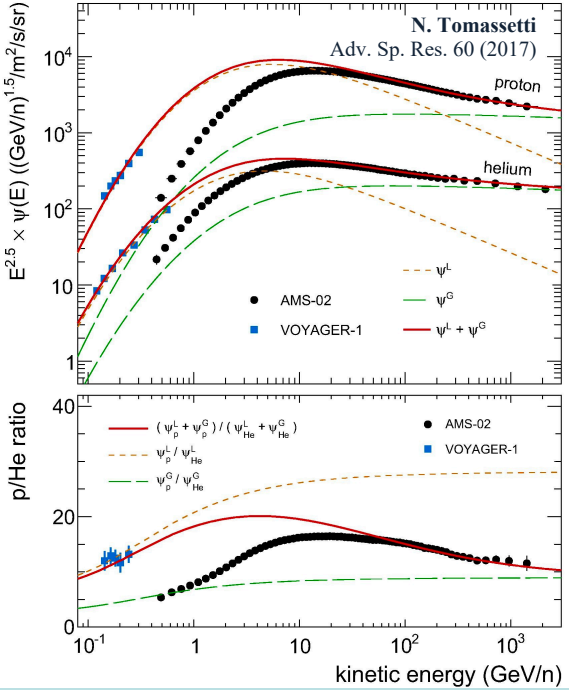
Direct measurement of LIS spectra

S. M. Krimigis et al.
Nature Astronomy 3 (2019)





Interstellar data beyond heliopause from Voyager-1 has provided unique information on un-modulated spectra for understanding local CR features



Voyager-2 has recently (11/2018) crossed the heliopause after 41 years from 1977 (!)

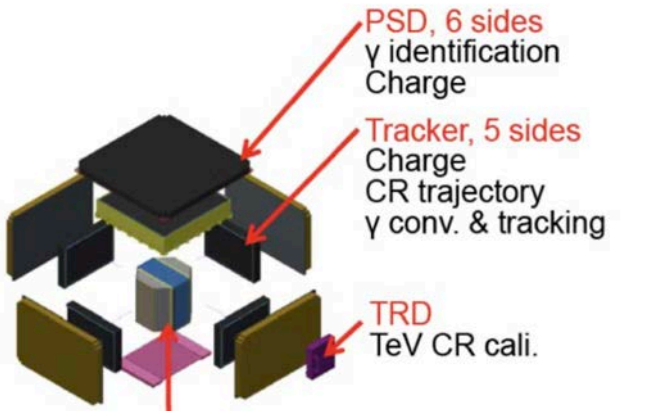
Exciting results are being produced by the analysis of Voyager-2 latest data. **Stay tuned**

WHAT NEXT…

Credits: A. Kolb, "Space Oddity"

Future facilities (space-I)

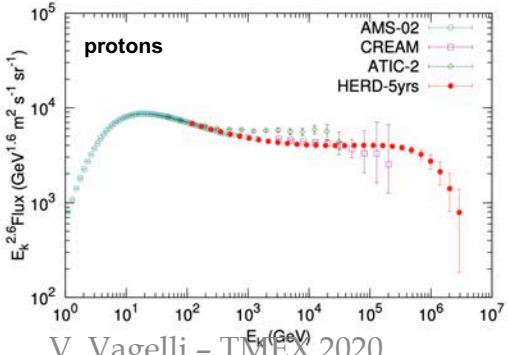
HERD: High Energy cosmic Radiation Detection facility

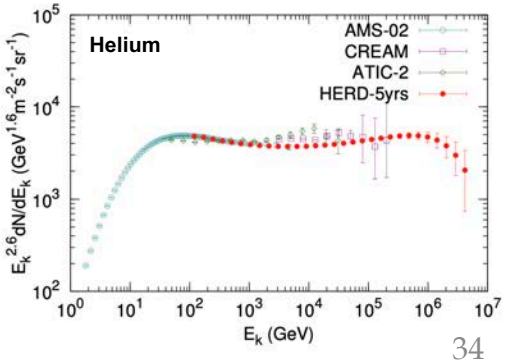


HERD is a china-led mission (with EU partners) onboard the CSS for measurement of 30 GeV – 3 PeV cosmic rays that continues the legacy of Fermi-LAT, CALET and HERD detectors.

The core is a 60 X0 LYSO calorimeter (based on the CaloCube project) with 70° opening angle, **isotropic response** and 1% energy resolution for $e^{+/-}$ / 20% for nuclei.

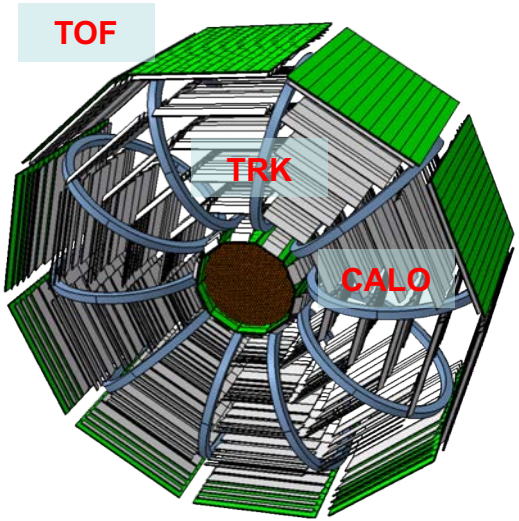
Wide scientific spectrum:
Precise analysis of electron spectrum above 10 TeV
Spectra and CR chemical composition up to the knee
Gamma-ray astrophysics

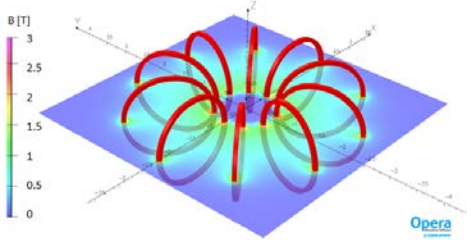




Future facilities (space-II)

ALADINo: A Large Antimatter Detector IN space



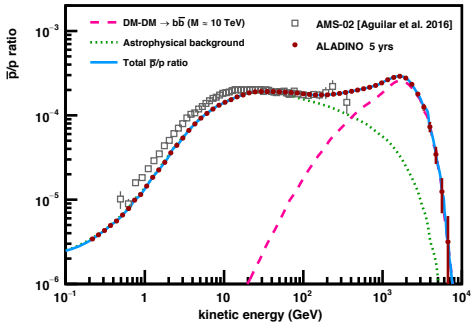


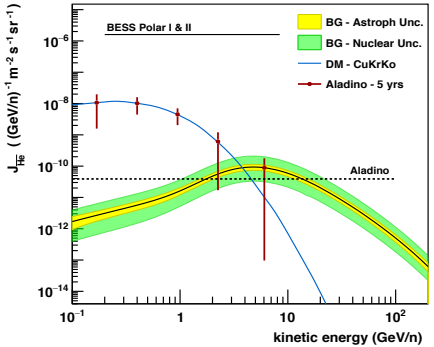
ALADINO is a concept for a spectrometer to be operated il L2 for measurement to extend the legacy of PAMELA and AMS-02 detectors.
Presented at ESA VOYAGE 2050

The core is a isotropic calorimeter "à la HERD" surrounded by a tracking system inside **high temperature superconducting coils** (<B>=0.8T)

Wide scientific spectrum:
Precise analysis of positron and antiproton spectrum up to 10 TeV
Spectra and CR chemical composition up to the knee
Anti-D and anti-He spectra

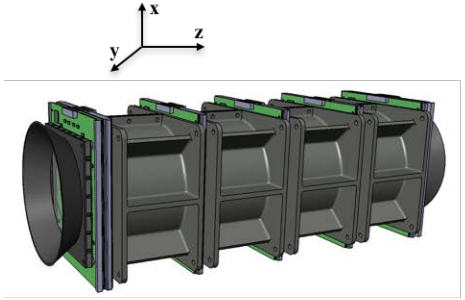
R. Battiston
ESA Voyage 2050 (2019)

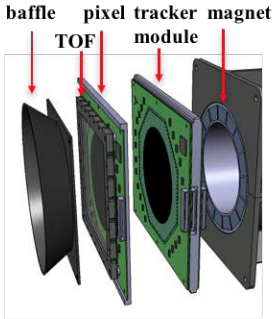


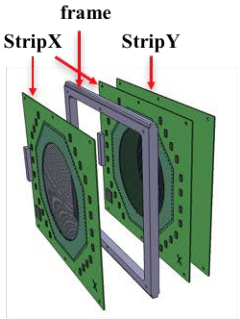


Future facilities (space-III)

PAN: Penetrating particle ANalyzer

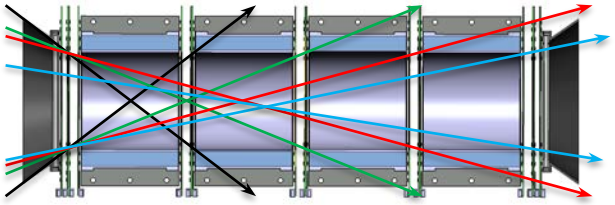






PAN is a concept for a spectrometer to be operated as ancillary module of exploration missions or detector array in the solar system

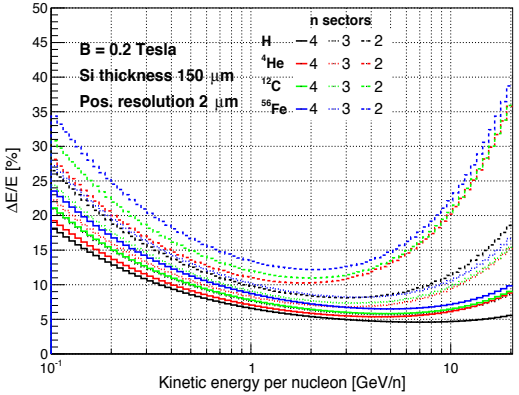
Precise measurement of CR energy, charge, sign of the charge and time dependences in the [100 MeV – 20 GeV] range using a spectrometric approach in **long duration planetary and exploration missions**



SECTORS	4	3	2	1 (*)
GF (cm² sr) 1 side	3	5	10	32
ΔE/E (H, 2 GeV)	5%	6%	8%	20%
Opening angle	25°	33°	47°	80°

(*) Bending angle method

X. Wu et al.
Adv Space Res. 63 (2019)

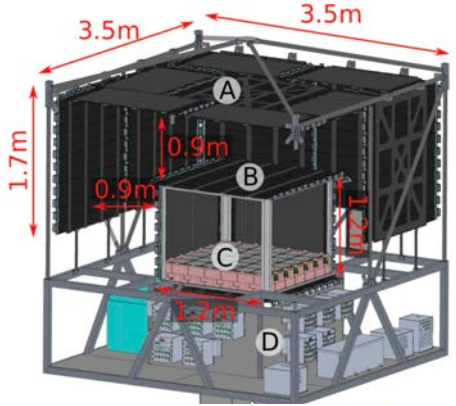


Wide scientific spectrum:
- Cosmic ray physics
- Solar physics (SEPs)
- Solar system exploration

"Mini-PAN" demonstrator funded by EU H2020 FET_OPEN

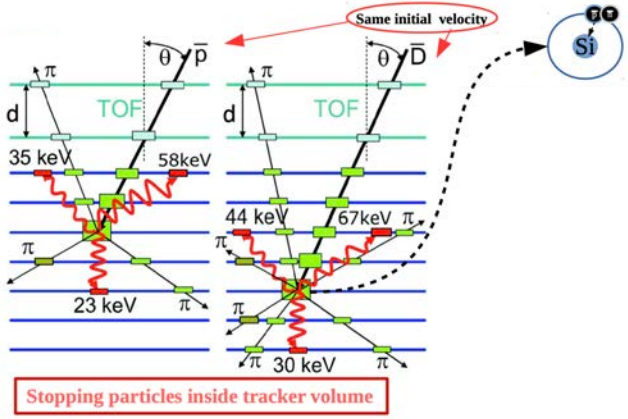
Future facilities (balloon-I)

GAPS: General AntiParticle Spectrometer

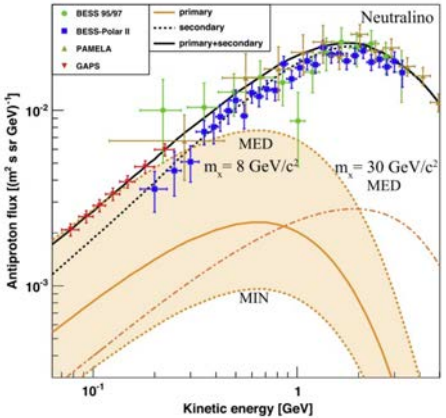


GAPS is a balloon-borne flight for measurement of low energy (<0.25 GeV/n) **antideuteron**, **antiproton** and search of **antihelium**
ToF system (A,B) and a 10-layer SiLi tracker (C)
Novel detection technique based on **exotic atom formation** and subsequent decay and annihilation with **X-rays and pion emission**

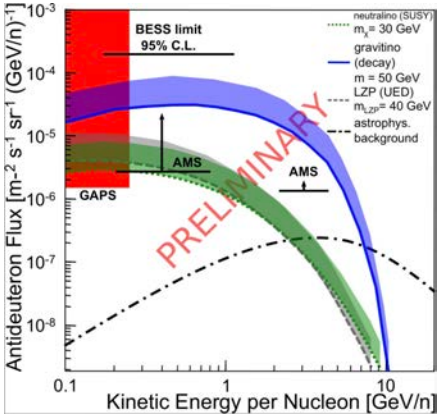
1 LDB flight (35 days): 1500 anti-p
3 LDB flights: sensitivity to anti-D (2 10^{-6} [m^2 s sr GeV/n]$^{-1}$)



T. Aramaki
Astrop. Phys 59 (2014)

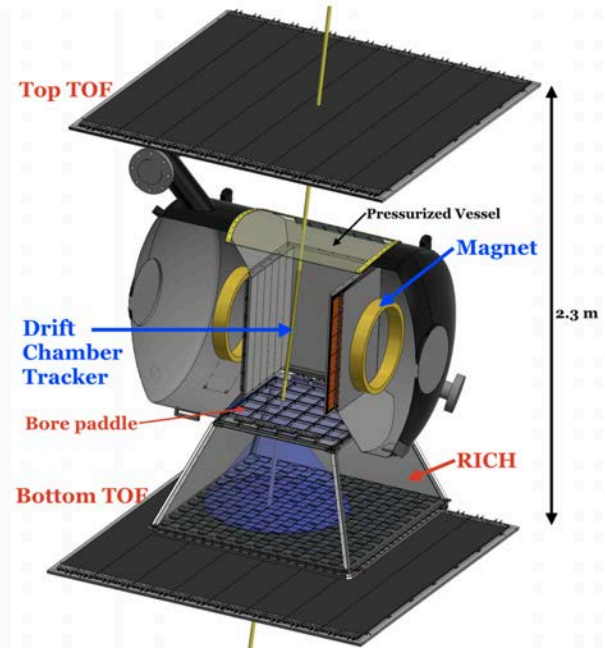


S. Quinn, GAPS collab.
Anti-d 2019



Future facilities (balloon-II)

HELIX: High Energy Light Isotope eXperiment

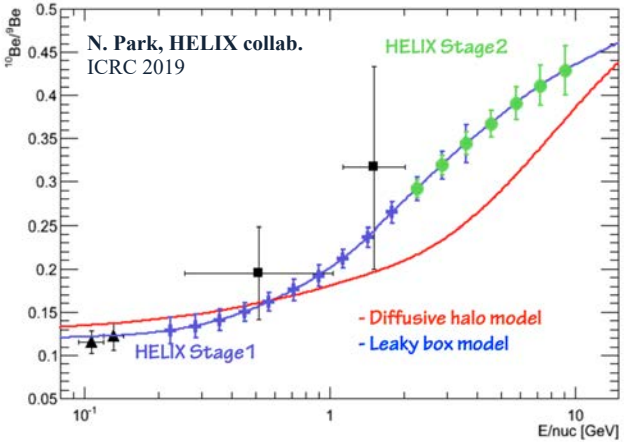


HELIX is a balloon-borne flight for measurement ^{10}**Be/**^{9}**Be** and other **isotopes** with mass resolution of % up to 10 GeV/n

Rigidity measurement with **drift chamber tracker** (Δx~65μm) inside NbTi **superconducting magnet from HEAT**

Velocity measurement with **RICH** (dβ/β~10^{-3}) + **TOF** (dt<50ps) systems

Integration in progress
First flight in Antartica in 2020
7-14 days with 0.1m^{2}sr exposure



a golden age of new cosmic ray measurements