Recent results on cosmic ray direct observations

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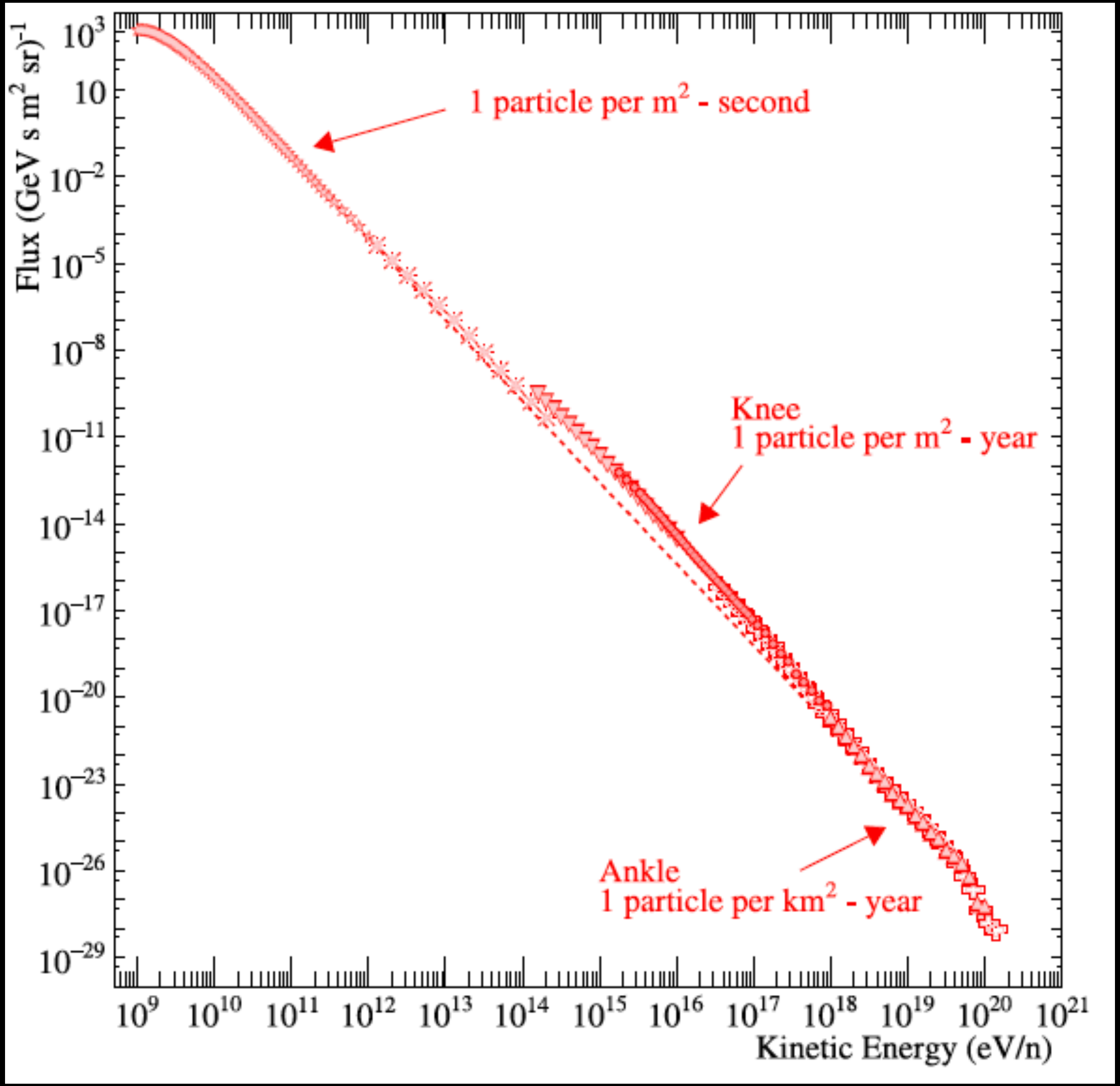
Outline of the presentation

- Main scientific lines
- Measurements
  - Primary Cosmic Rays (p, He, C, O)
  - Heavier nuclei
  - Secondary Cosmic Rays (Li, Be, B, cosmic ray clocks)
  - Antimatter & electrons
- Future experiments
- Conclusions

CR Flux & Composition



Energetic particles and completely ionized nuclei from outer space;

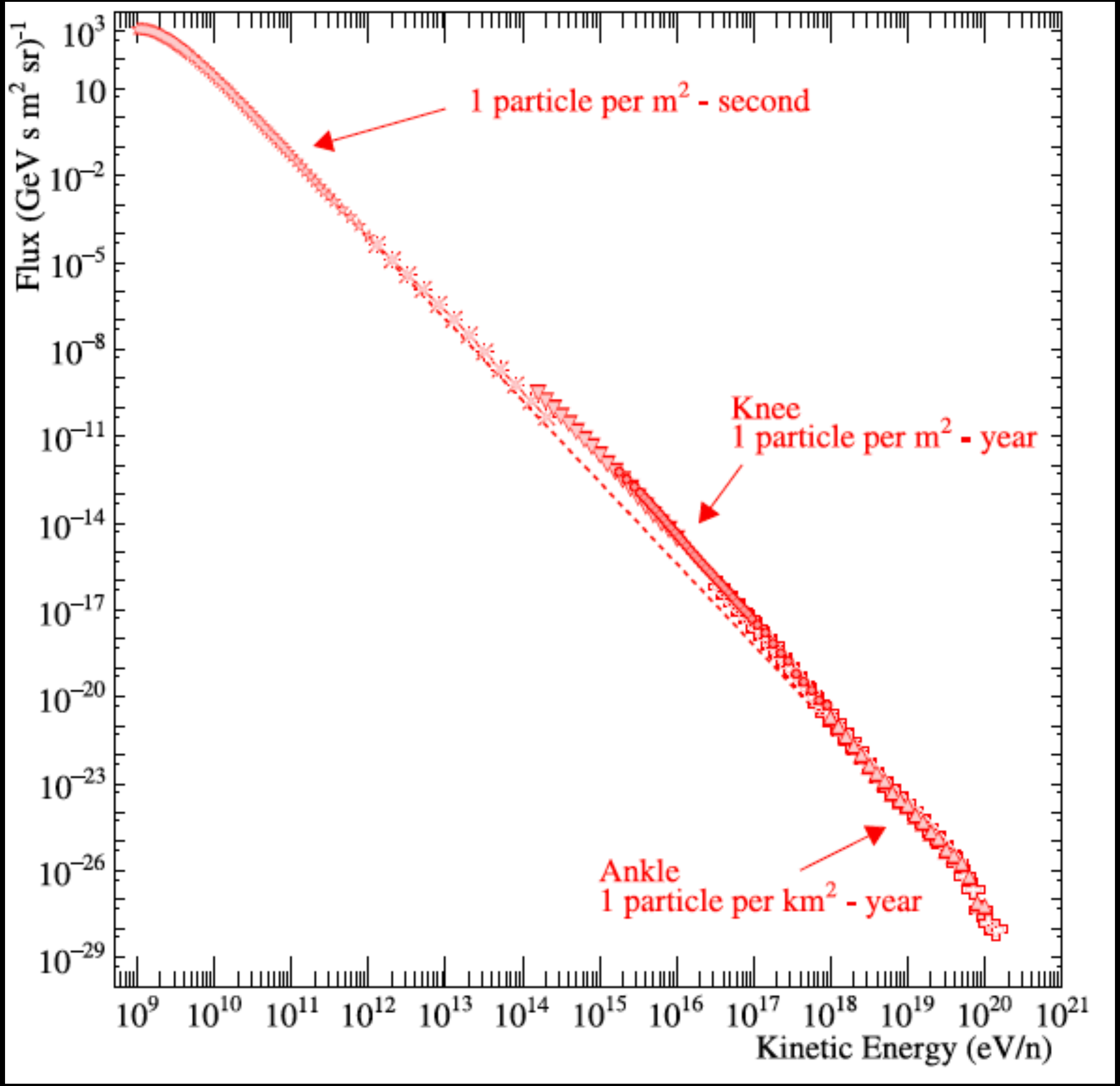
- Many orders of magnitude in energy and flux:

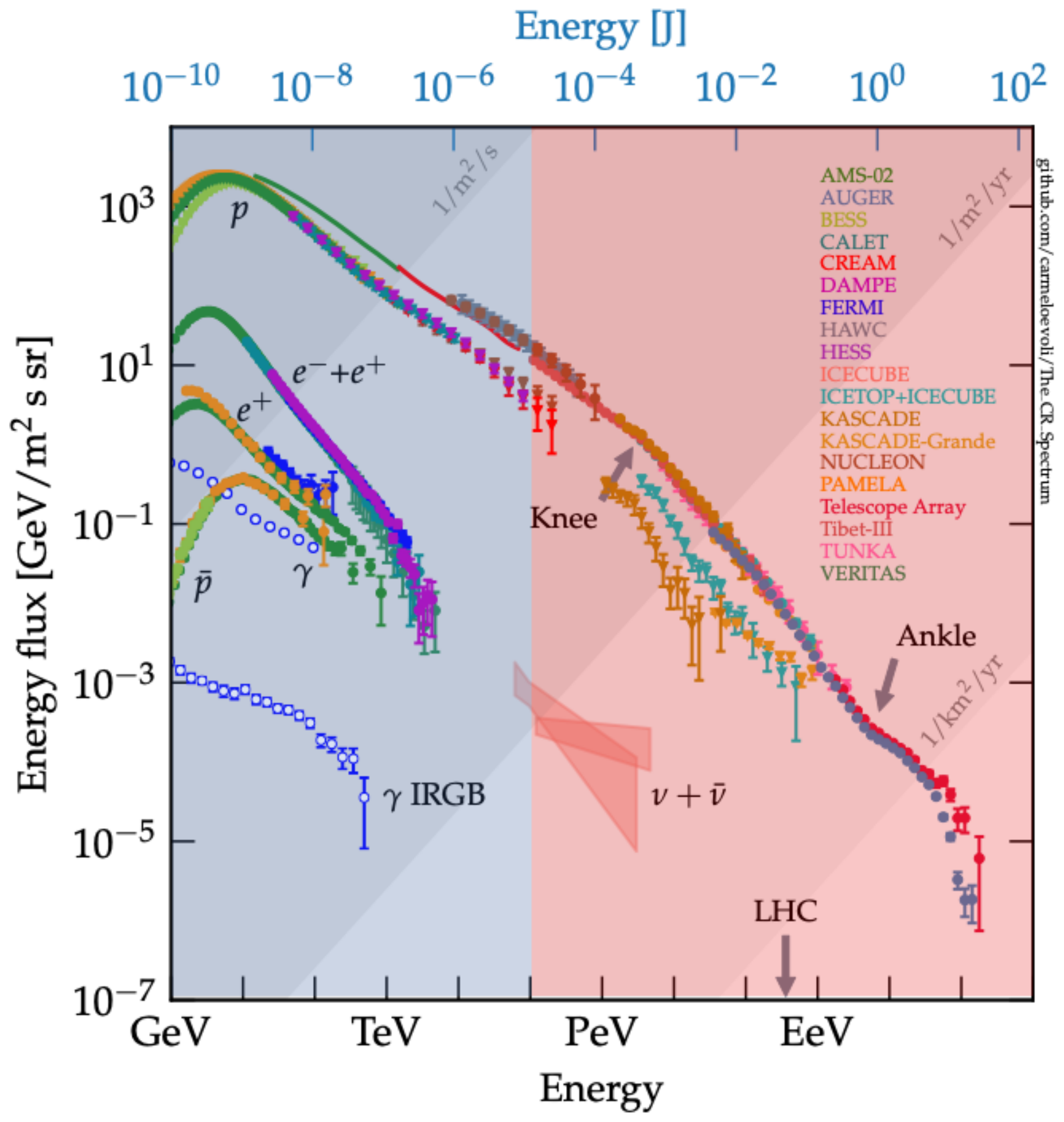
  o E <100 TeV: direct detection;

  o E > 100 TeV: indirect detection by extensive-air-showers;

- Roughly, **the all-particle spectrum is a "power law" in many orders of magnitude of energy and intensity,** with several features (*knee, ankle, …):*
  - *γ = 2,7 until 100 TeV*
  - *γ = 3,3 after 100 TeV*

CR Flux & Composition





Galactic cosmic rays: open questions

- **What is the origin of Galactic cosmic rays (GCR)?**
  - Which are the possible astrophysical sources? Can they be detected individually?
  - What can we learn about the source properties from GCR elemental composition?
  - Does the GCR elemental composition change with energy?

- **How do the Cosmic Accelerators work?**
  - Stochastic acceleration in strong shocks in SN remnants
  - Diffusive shock acceleration occurs in isolated SNR or inside superbubbles ("collective effects") ?
  - Is the "knee" due to a limit in SNR acceleration? Does it depend on the particle rigidity?
  - Are there different astrophysical sites associated with different energy/element regimes?

- **CRs propagation in the Galaxy**
  - What is the energy dependence of the confinment time of CR in the Galaxy?
  - Is there a residual path length at high energy?

- **Are there signatures of new/exotic physics?**
  - Are there anti-matter regions in the universe?
  - What is the nature of Dark Matter? Which possible signatures in CR spectra?

Main physics research lines

-- **The High Energy Frontier** (Sources, Acceleration)

-- **The Composition Frontier** (source material, dust/gas, nucleosynthesis, selection effects)

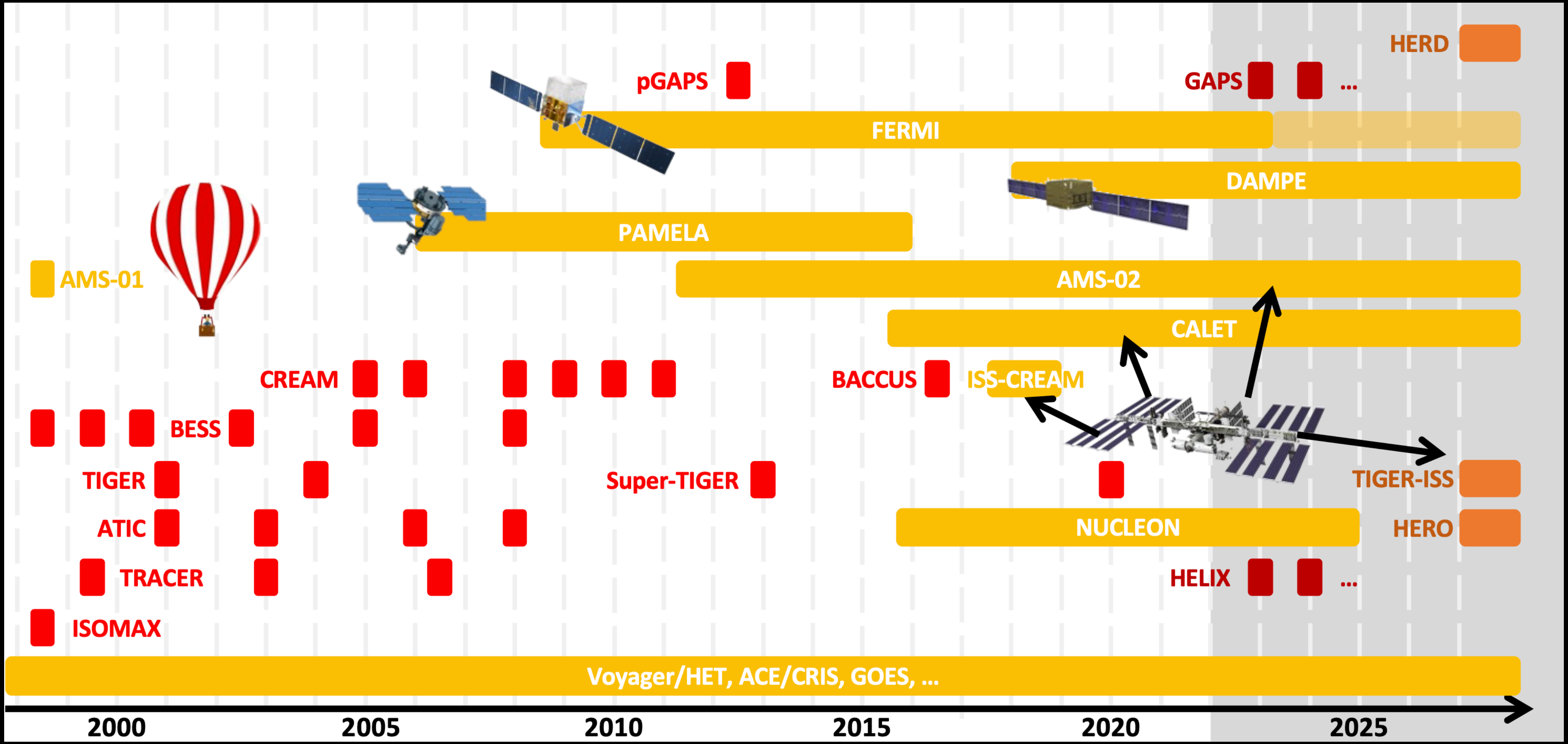
-- **The Anti-matter Frontier** (dark matter limits, anti-matter limits, non-SNR contributions, nearby sources)

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

Existing platforms

- Balloon experiments (CREAM, ATIC, BESS-Polar, TRACER, TIGER&SuperTIGER, ...)
- Satellite experiments (PAMELA, FERMI, DAMPE, NUCLEON, ...)
- Space station experiments (AMS, CALET, ISS-Cream,...)

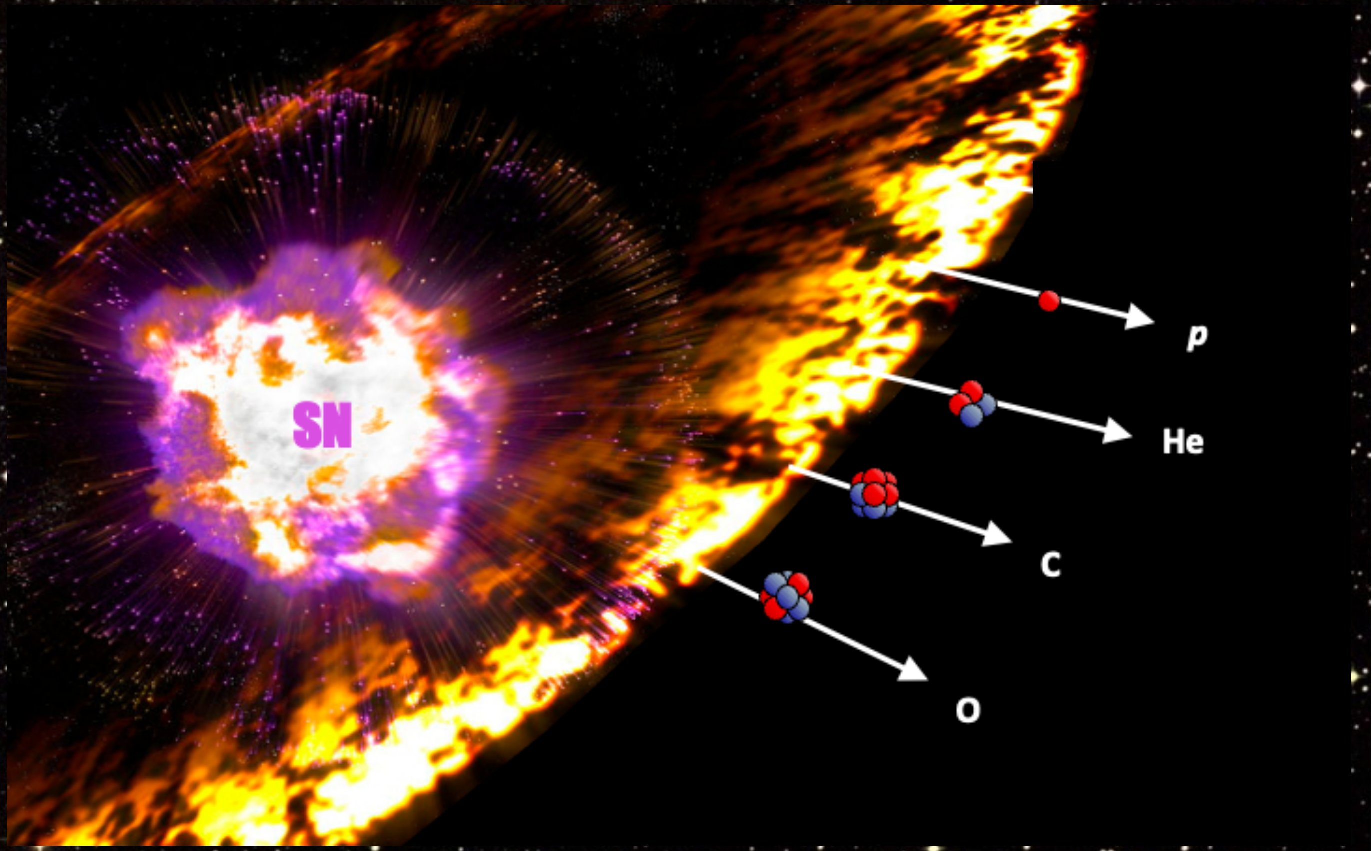
Timeline of Direct Measurement of CRs from 2000



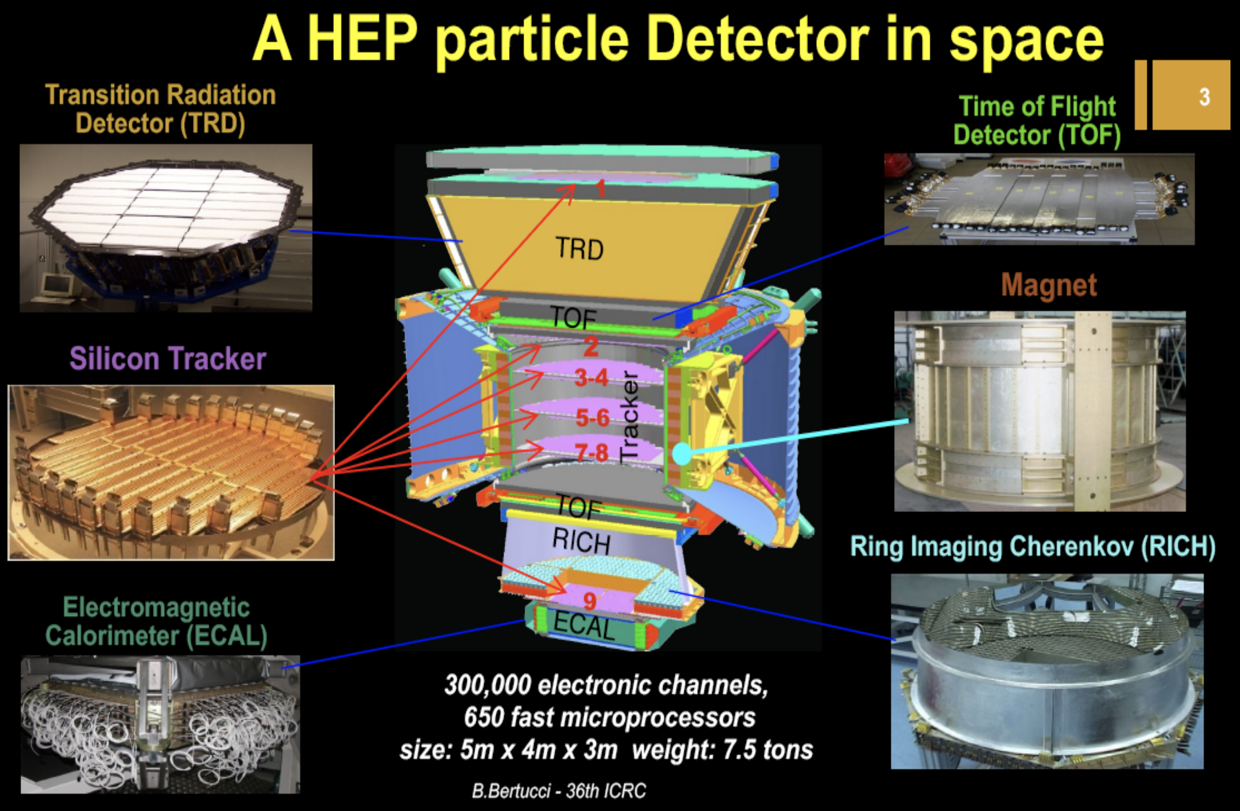
Great legacy from the past (<2000), here we focus on the latest ones.
Not all experiments displayed.

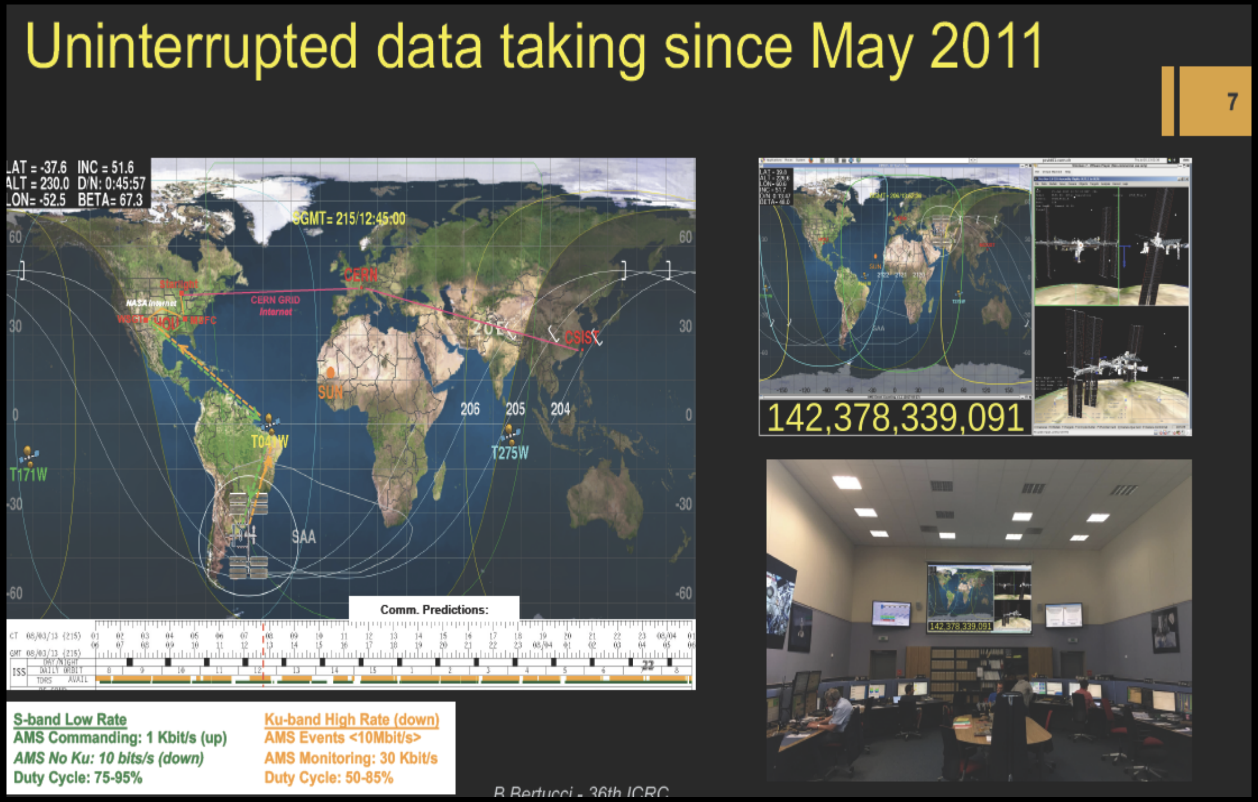
Primary cosmic rays (p, He, C, O)

CR injection and acceleration –
High energy frontier



Alpha Magnetic Spectrometer AMS-02

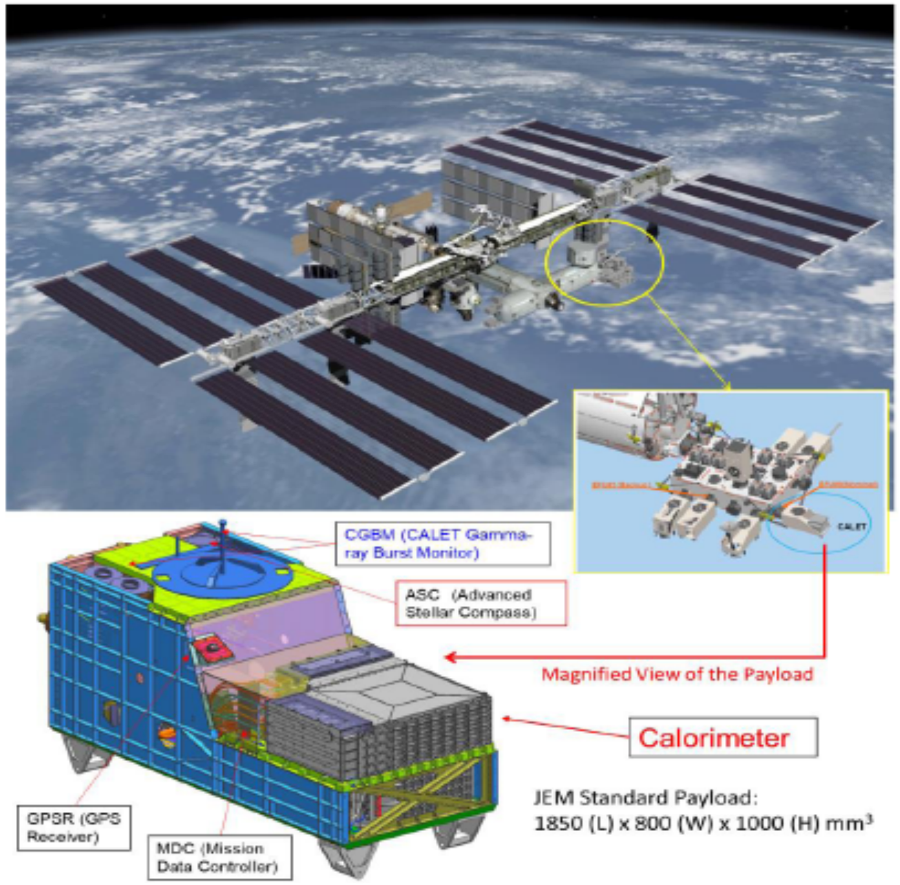




Installed on ISS on 19th May 2011

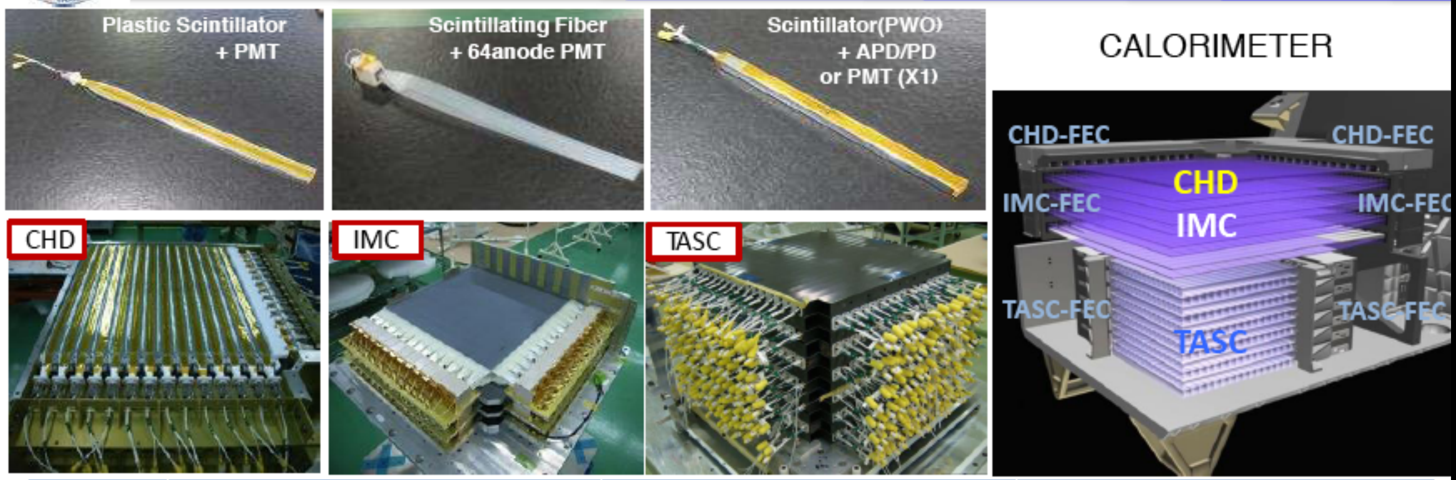
CALorimetric Electron Telescope CALET

Launched August 19th, 2015, on ISS



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

CALET Instrument

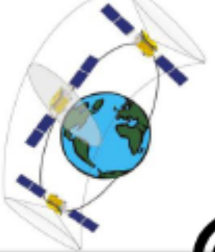


	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Measure	Charge (Z=1-40)	Tracking , Particle ID	Energy, e/p Separation
Geometry (Material)	Plastic Scintillator 14 paddles x 2 layers (X,Y): 28 paddles Paddle Size: 32 x 10 x 450 mm^3	448 Scifi x 16 layers (X,Y) : 7168 Scifi 7 W layers ($3X_0$): $0.2X_0$ x 5 + $1X_0$ x2 Scifi size : 1 x 1 x 448 mm^3	16 PWO logs x 12 layers (x,y): 192 logs log size: 19 x 20 x 326 mm^3 Total Thickness : 27 X_0, ~1.2 λ_I
Readout	PMT+CSA	64-anode PMT+ ASIC	APD/PD+CSA PMT+CSA (for Trigger)@top layer

Dark Matter Particle Explorer DAMPE

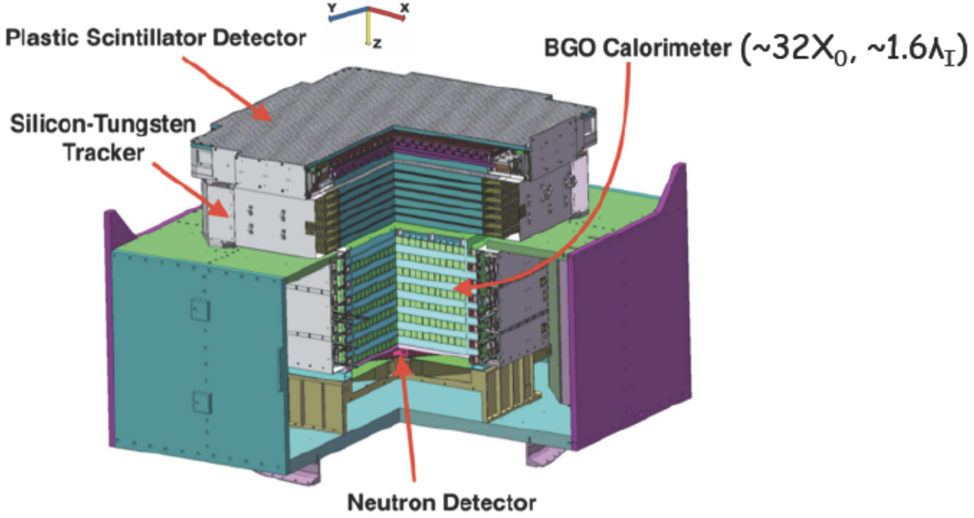
Satellite-borne particle detector, project of the *Strategic Pioneer Program on Space Science*, promoted by the *Chinese Academy of Sciences* (*CAS*).

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

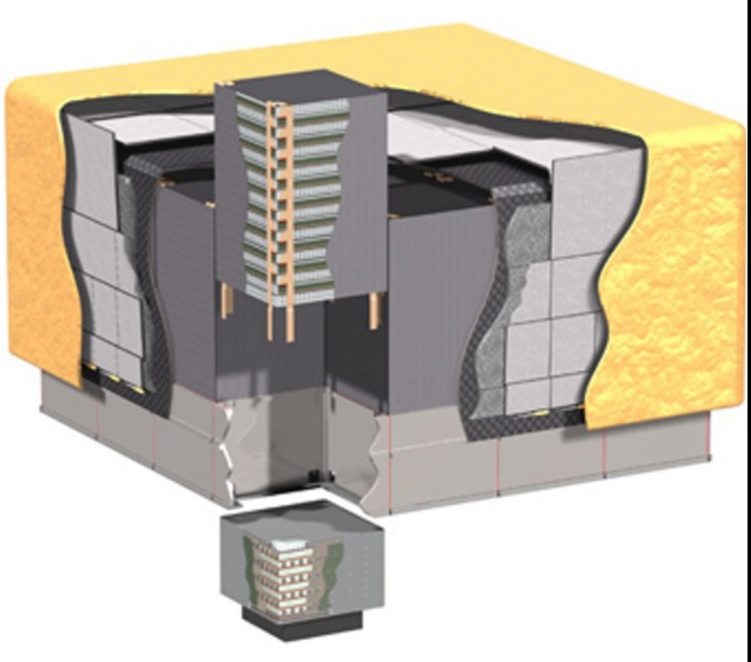
DAMPE Instrument

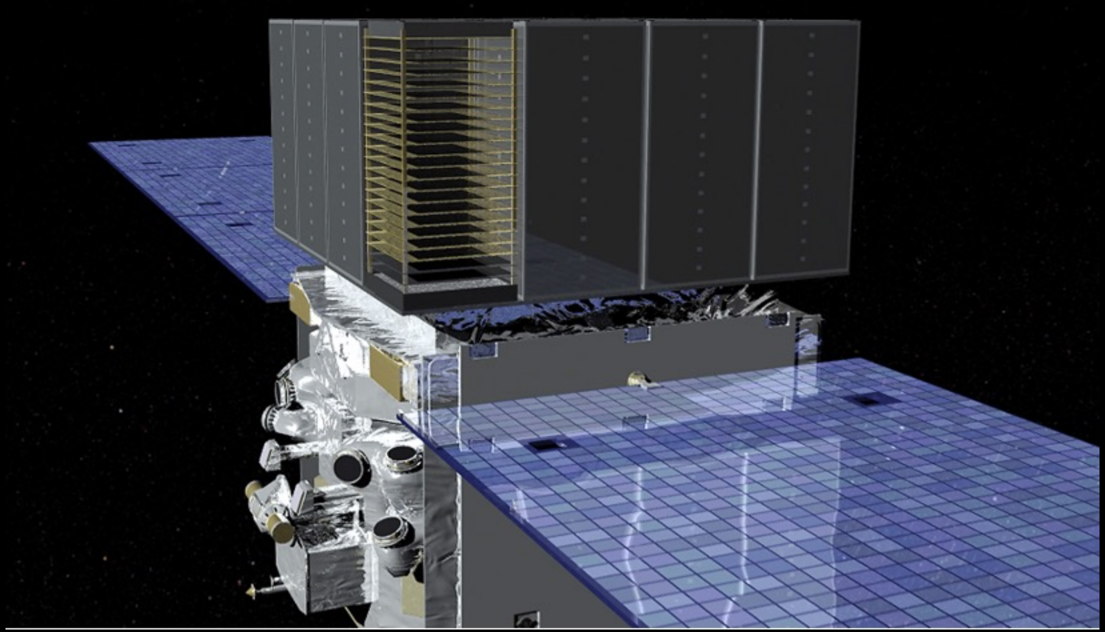


- Charge measurement (dE/dx in PSD, STK and BGO)
- Gamma-ray converting and tracking (STK and BGO)
- Precise energy measurement (BGO Crystals)
- Hadron rejection (BGO and Neutron Detector)

(Chang et al. Astropart.Phys. 95 (2017) 6–24)

Fermi Large Area telescope



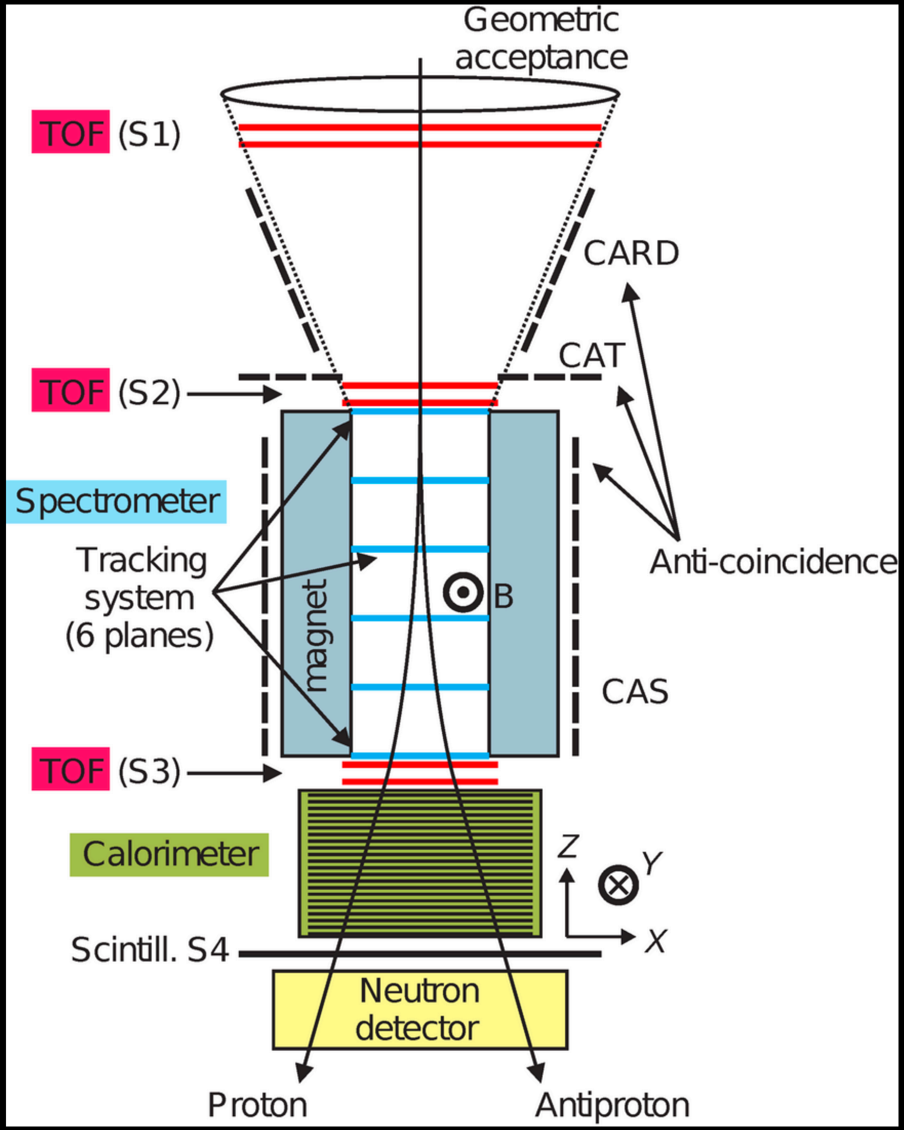


- **Tracker:** tungsten conversion foils + silicon strip detectors, 1.5 radiation lengths on-axis
- **Calorimeter:** 1536 Cesium Iodide crystals, 8.6 radiation lengths on-axis, gives 3D energy deposition distribution
- **Anti-Coincidence Detector:** charged particle veto surrounding Tracker, 89 plastic scintillator tiles + 8 ribbons

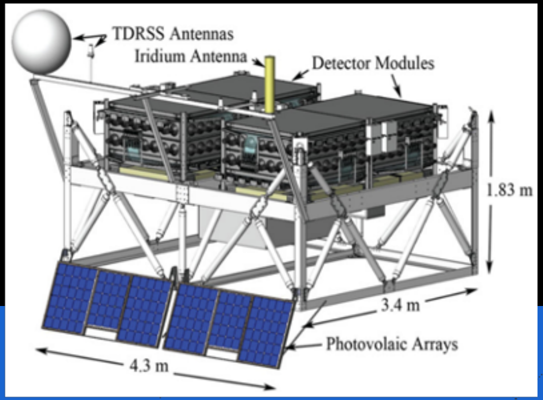
Flying since 11 June 2008

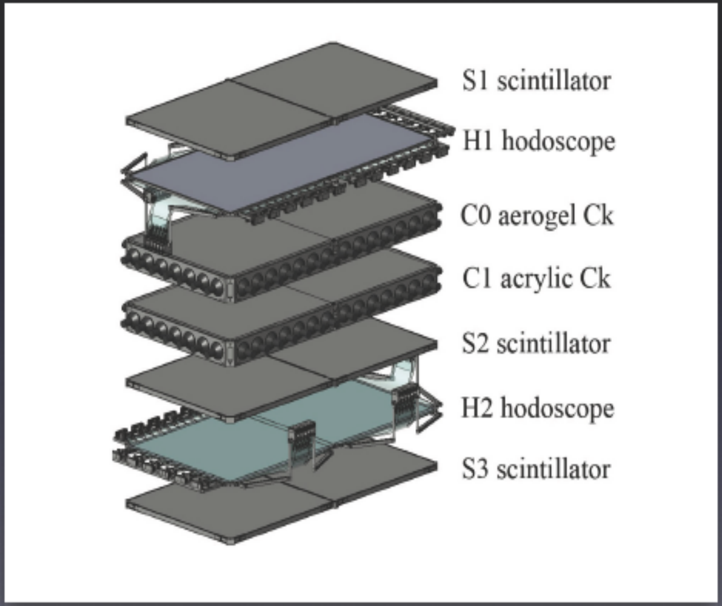
PAMELA (2006-2016)

Flown on Russian Resurs-DK1 satellite from June 2006 until January 2016



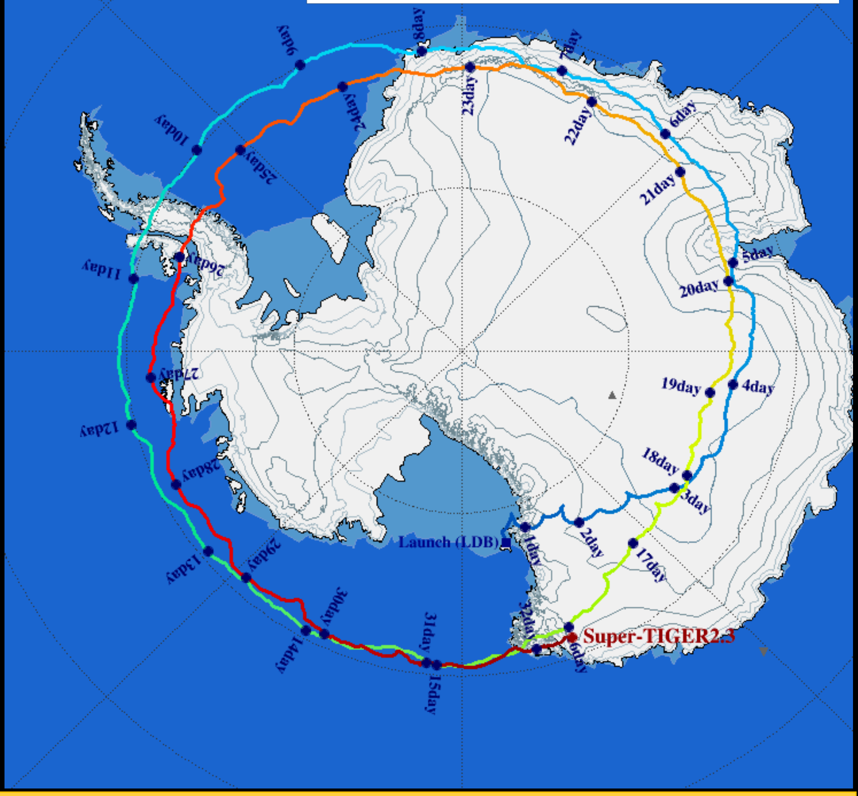
Super Trans Iron Galactic Element Recorder
Super-TIGER Z→41-56





2 modules (1 shown), effective geometry 3.9 m² sr
Plastic scintillators (for Z)
Acrylic (n=1.49) and Aerogel (n=1.043, 1.025)
Cherenkov Detectors (for Z, ß)

- "Super" Trans-Iron Galactic Element Recorder
- A balloon-borne cosmic ray instrument that can measure galactic cosmic ray abundances for Z=~10–60 for energies ~0.8-10 GeV/nuc
- Primary Goals: Measure Z=30–60 abundances to test OB association models for cosmic ray origins
    - R.P. Murphy et al., ApJ 2016
    - N.E. Walsh et al., COSPAR 2018, E1.5-0040-18
    - **N.E. Walsh et al., ICRC 2019, CRD3a**
- Secondary Goals: Spectra, spectral features



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.**

Bess-Polar I and II

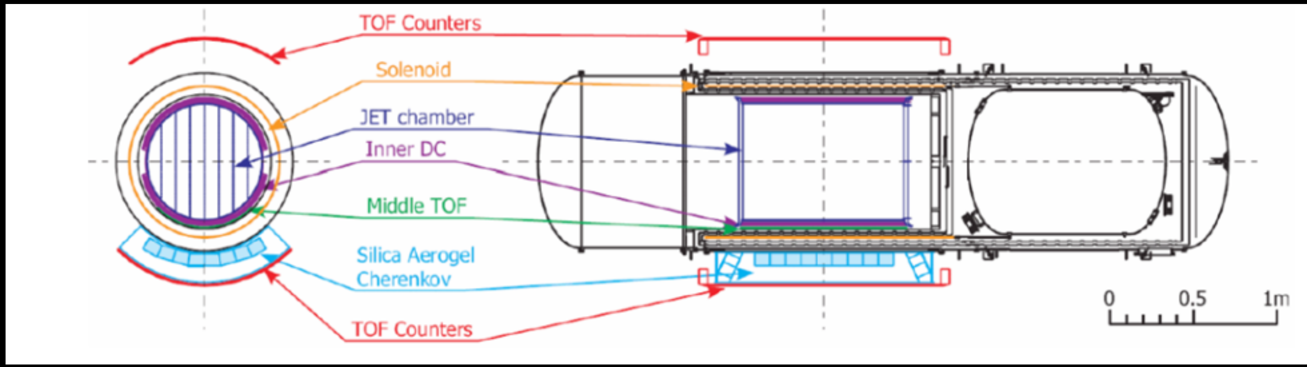
The BESS Project

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)

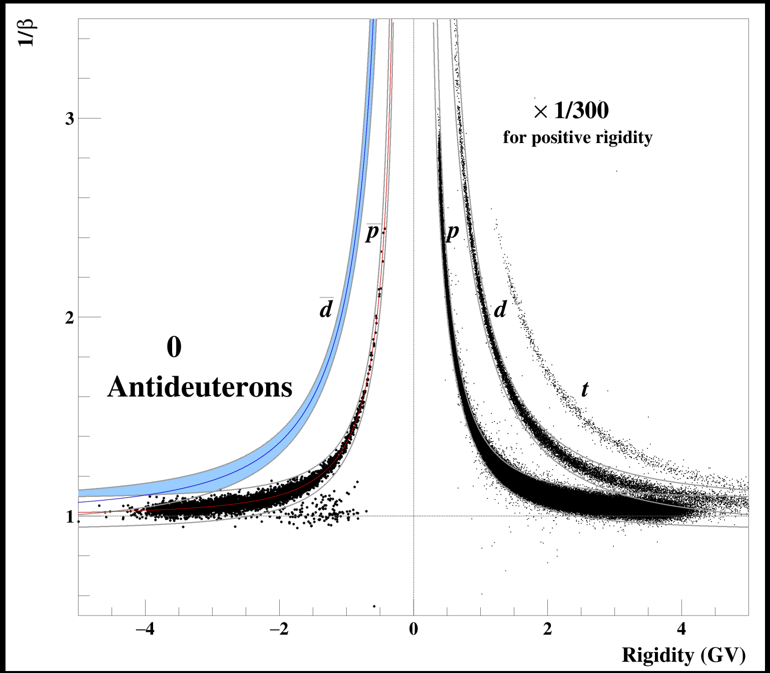
	BESS-Polar I	BESS-Polar II
Launch date	Dec. 13th ,2004	Dec. 23rd , 2007
Observation time	8.5 days	24.5 days
Cosmic-ray observed	9 x 10^8 events	4.7 x 10^9 events
Flight altitude	37~39km (5~4g/cm^2)	~36km (6~5g/cm^2)



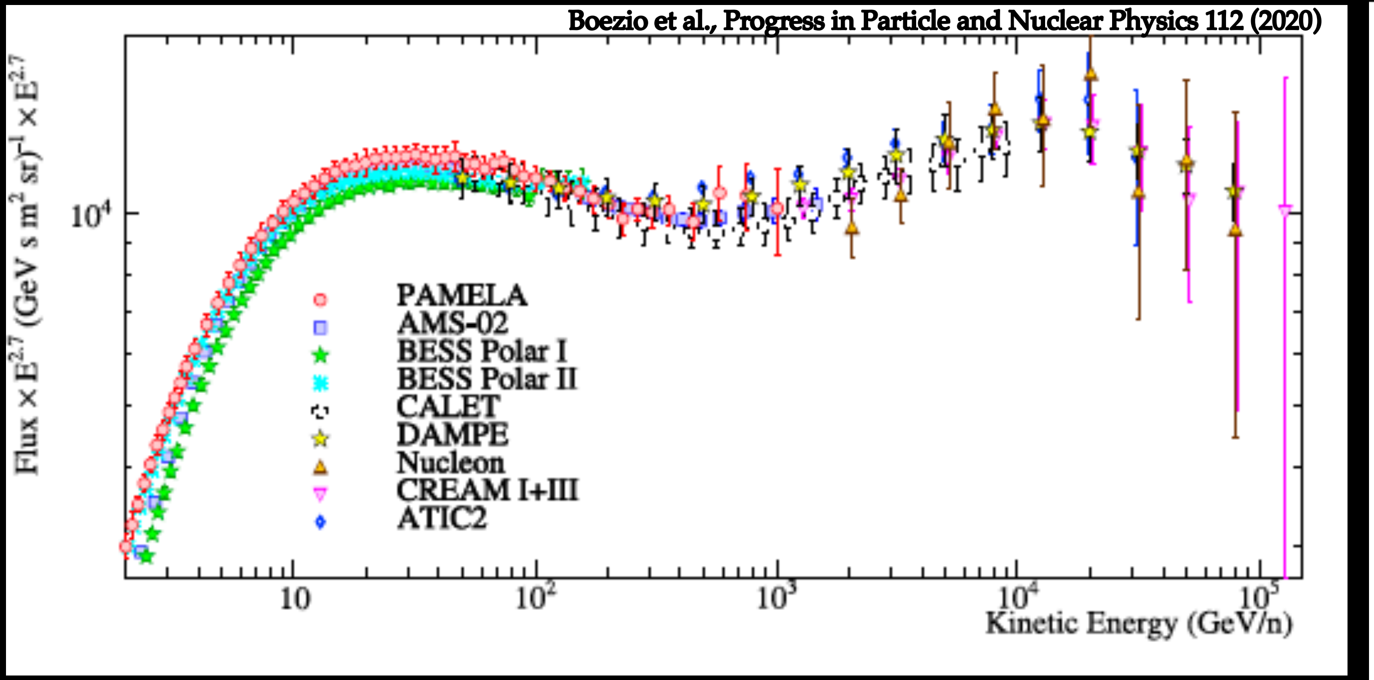
SC Magnet B = 0.8 T
TOF $\Delta\beta/\beta$ = 2%
JET $\Delta R/R(R=1GV)$ = 0.4%
MDR=270 GV

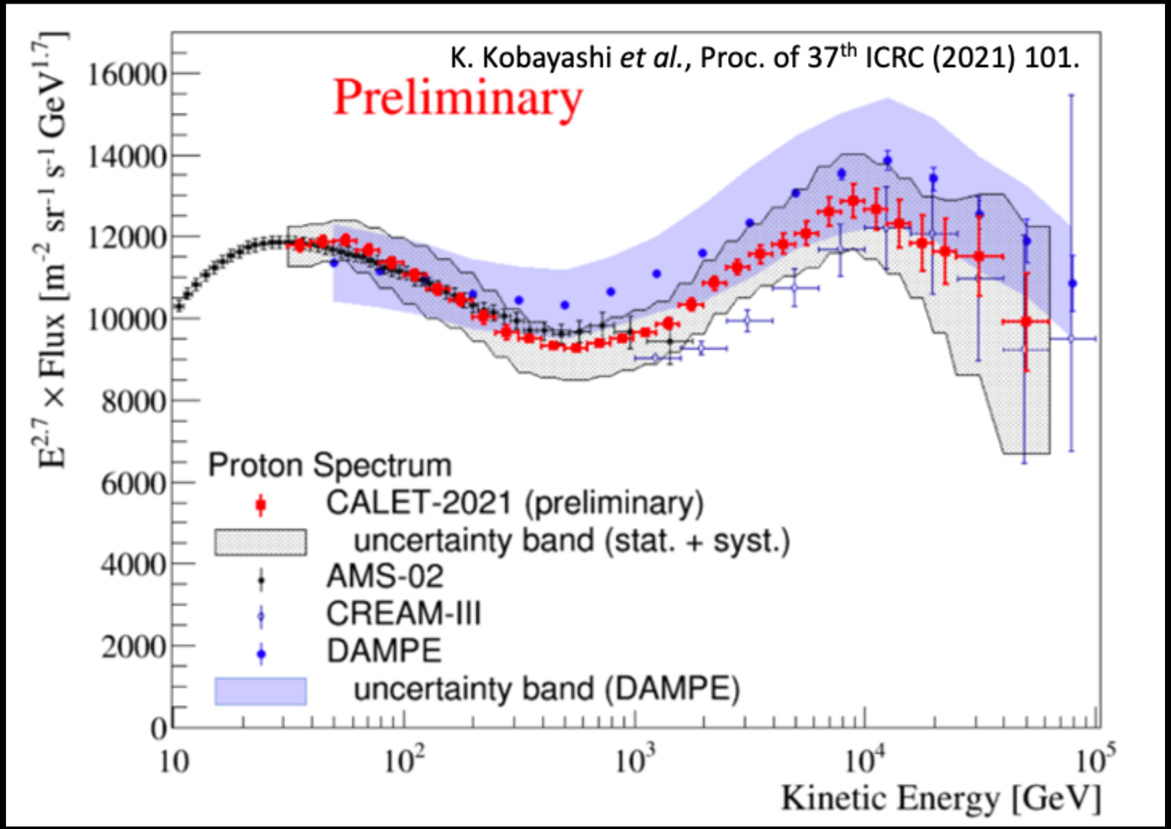
Acceptance = 0.3 m² sr

Geomagnetic cutoff below 0.5 GV



Proton spectrum (1 GeV–> 8 TeV)



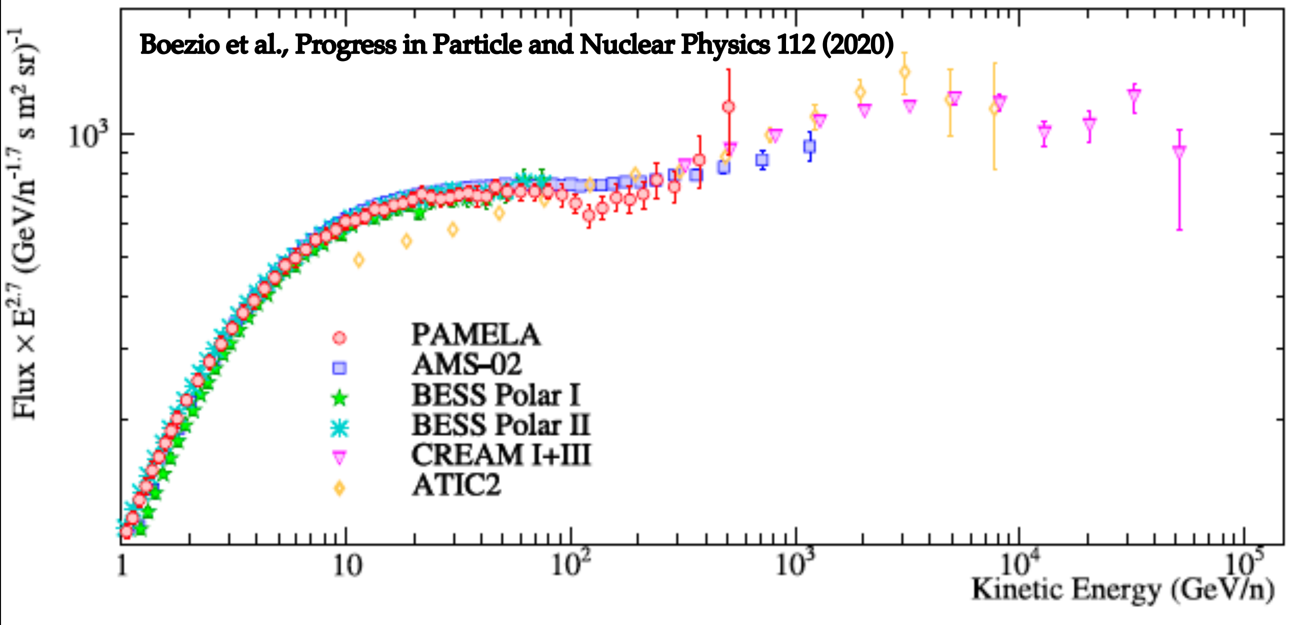


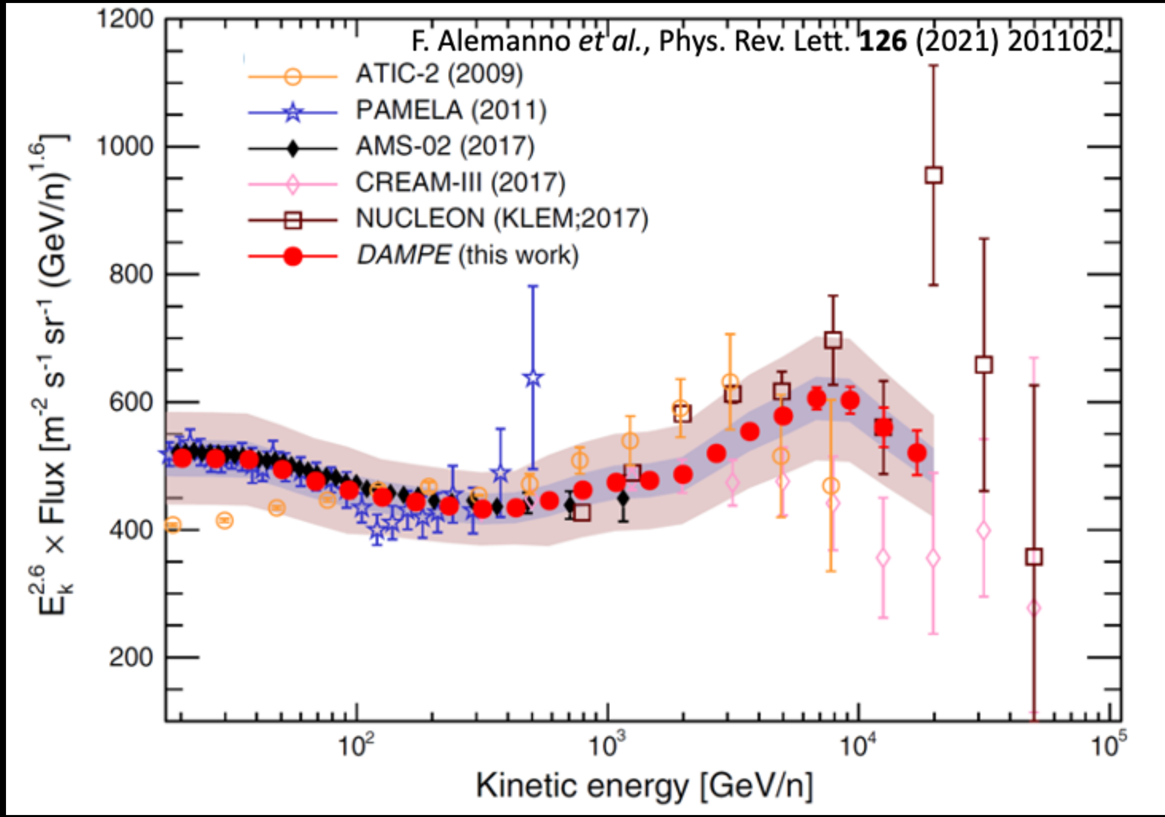
Important features –> deviation from a single power-law!

1) confirmation of the hardening in both species at about 200 GeV (propagation?)

2) softening above 1 TeV (sources?)

Helium spectrum (1 GeV–> 8 TeV)



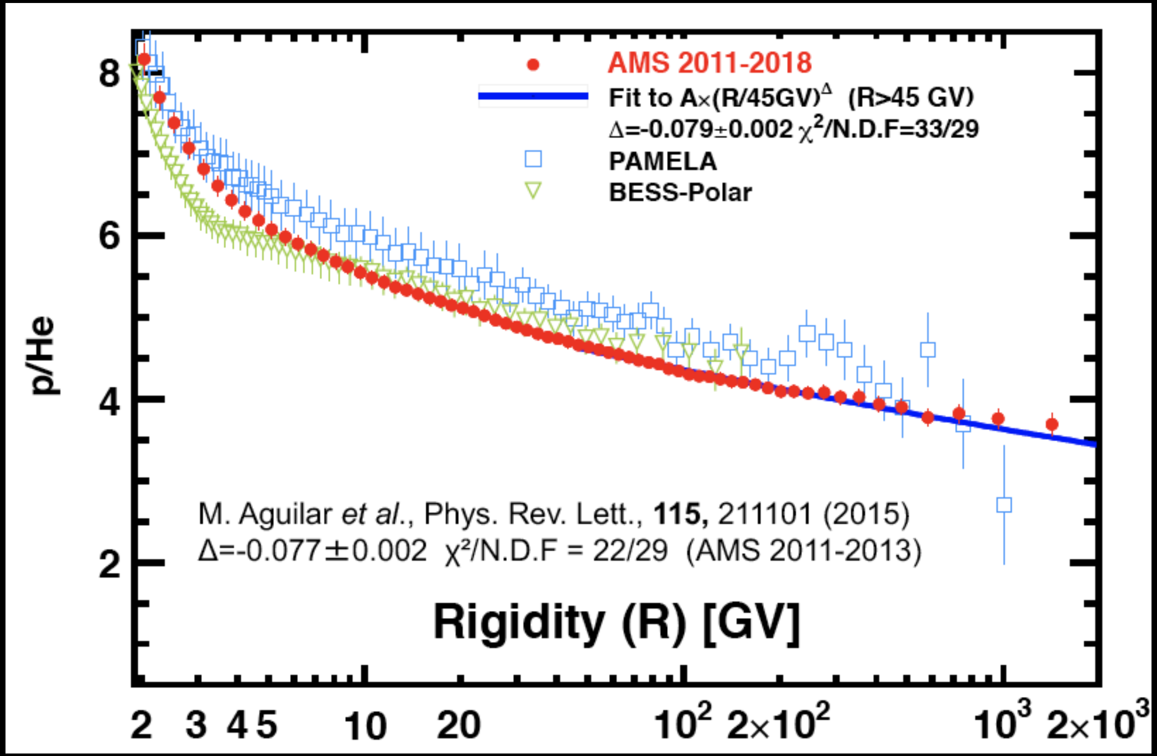


Important features –> deviation from a single power-law!

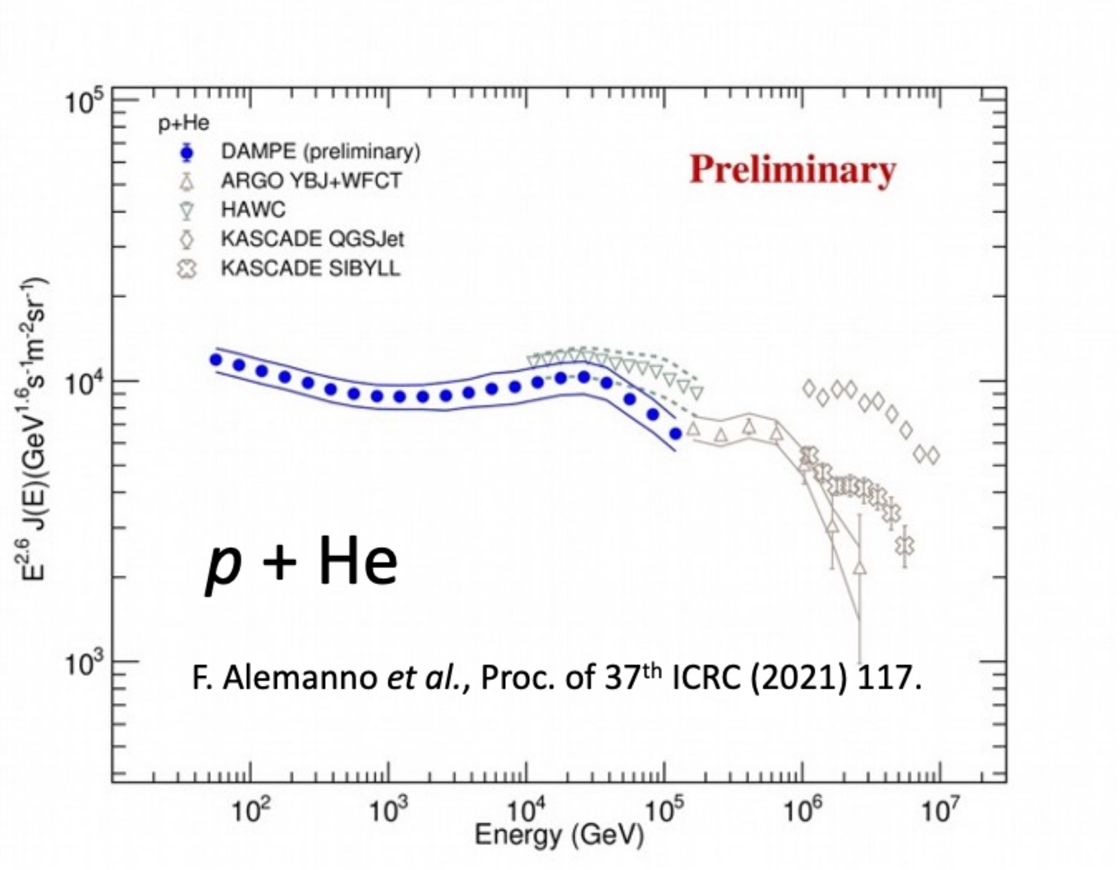
1) confirmation of the hardening in both species at about 200 GeV (propagation?)

2) softening above 1 TeV (sources?)

Proton and helium ratio

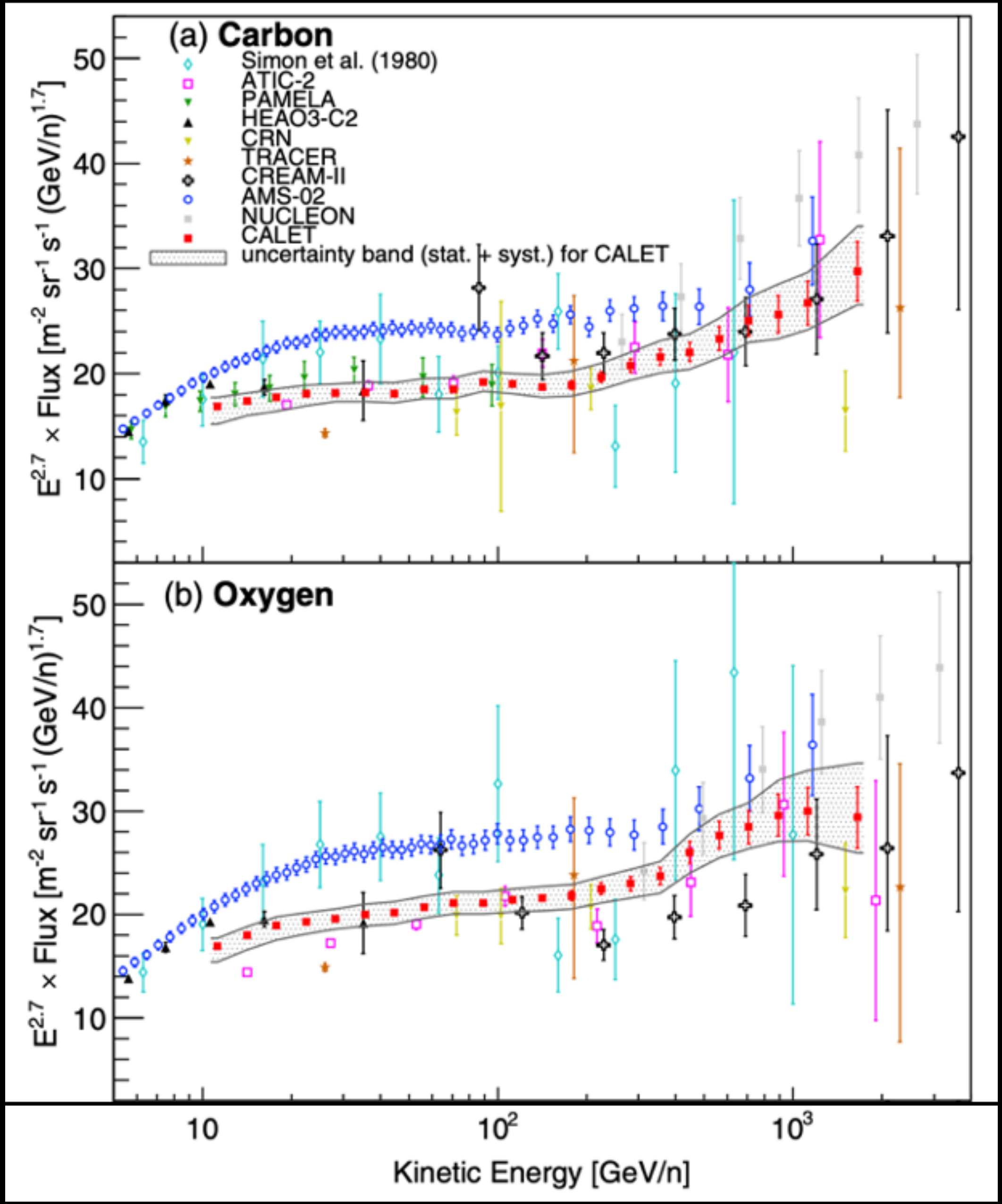


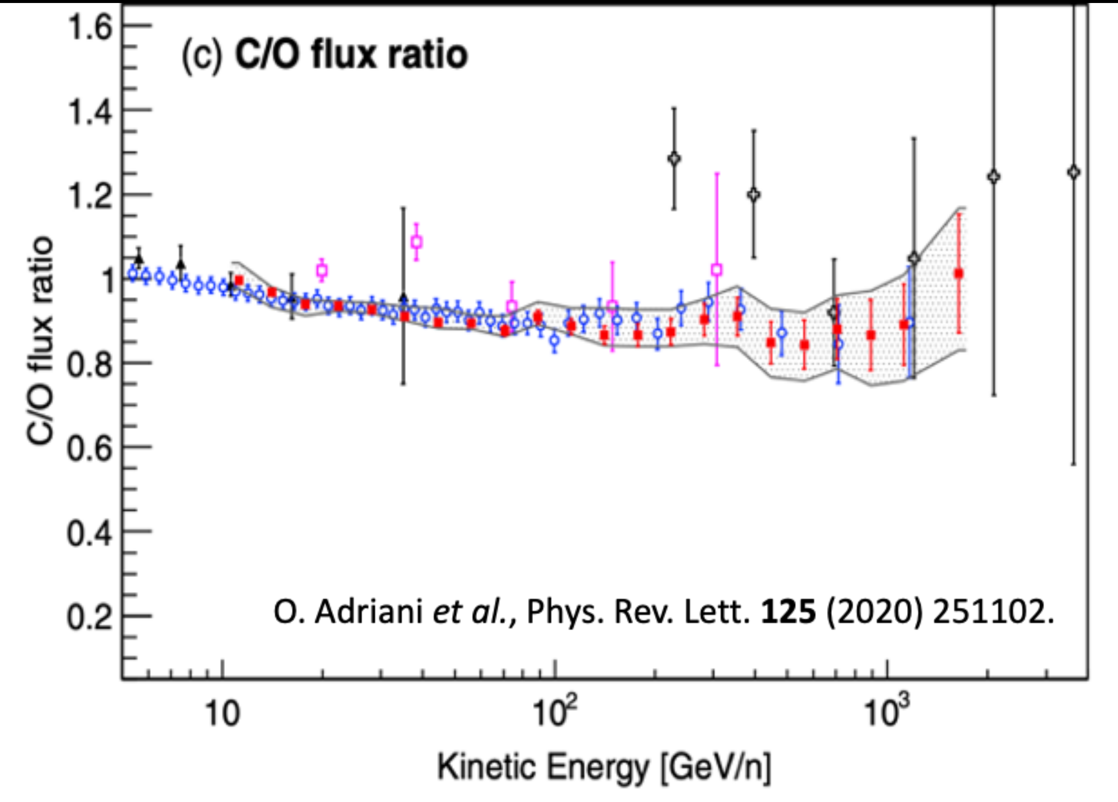
Important feature:
p/He not constant (why?) and smooth up to 1 TV
Flattening after 1 TV?



p+He is also measured by EAS experiments.
Direct comparison possible, bridging the gap between direct/indirect detection.

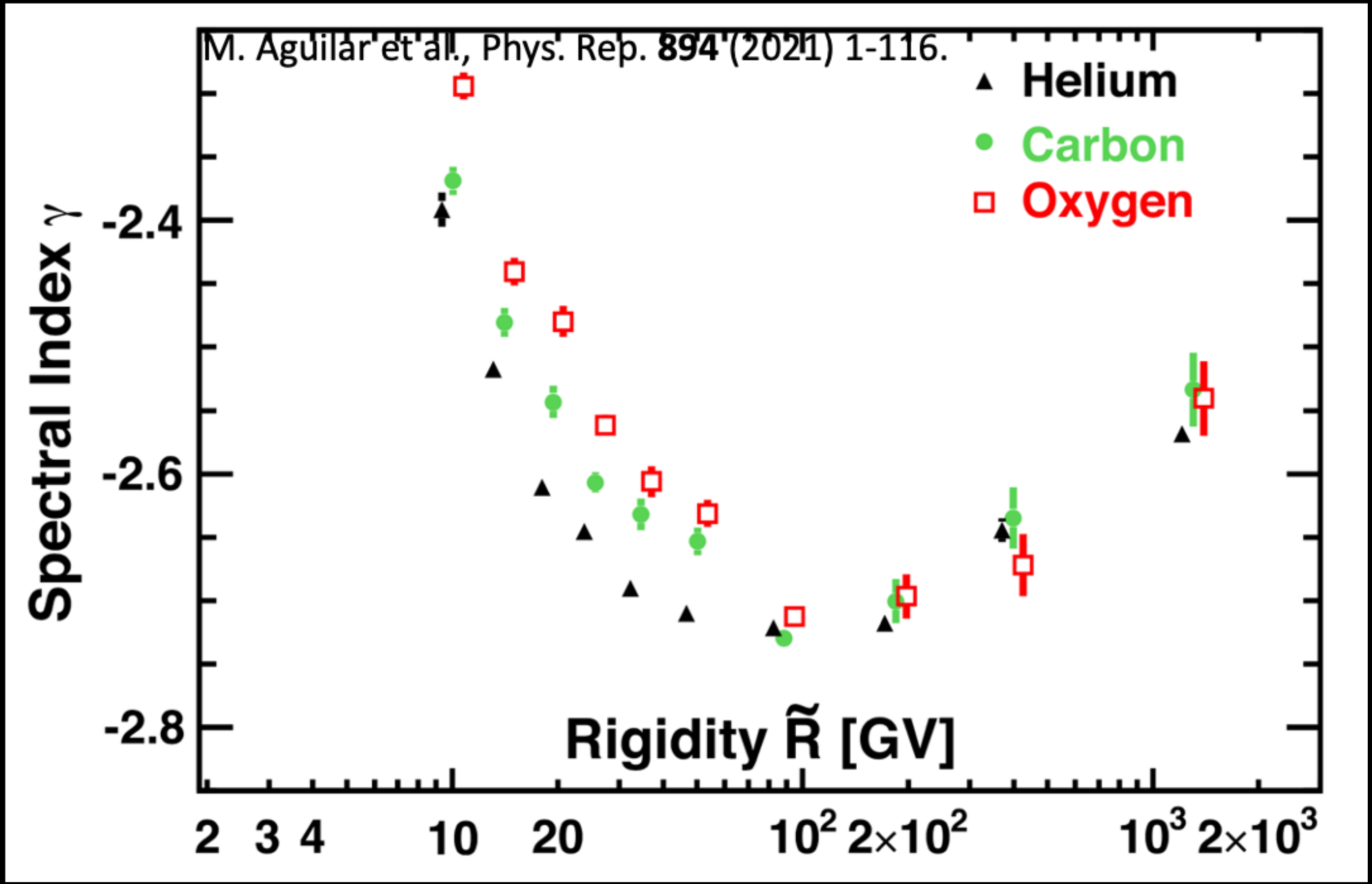
Carbon and Oxygen fluxes





Important features:
C and O show a hardening at hundreds of GeV/n.
Difference in flux normalization between experiments.
C/O is smooth, meaning that C and O have similar hardening. All experiments agree in the C/O.

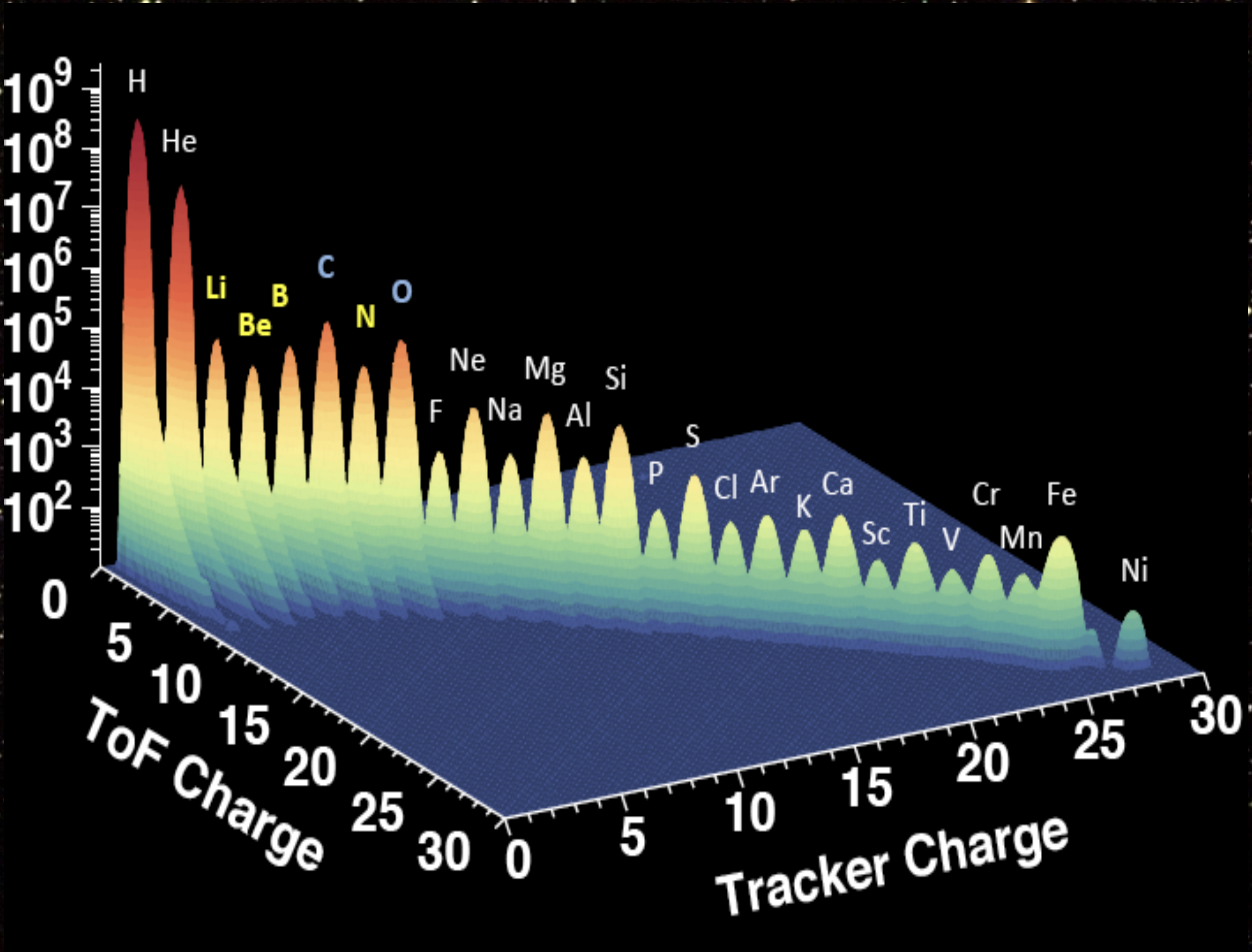
He, C, O spectral indexes

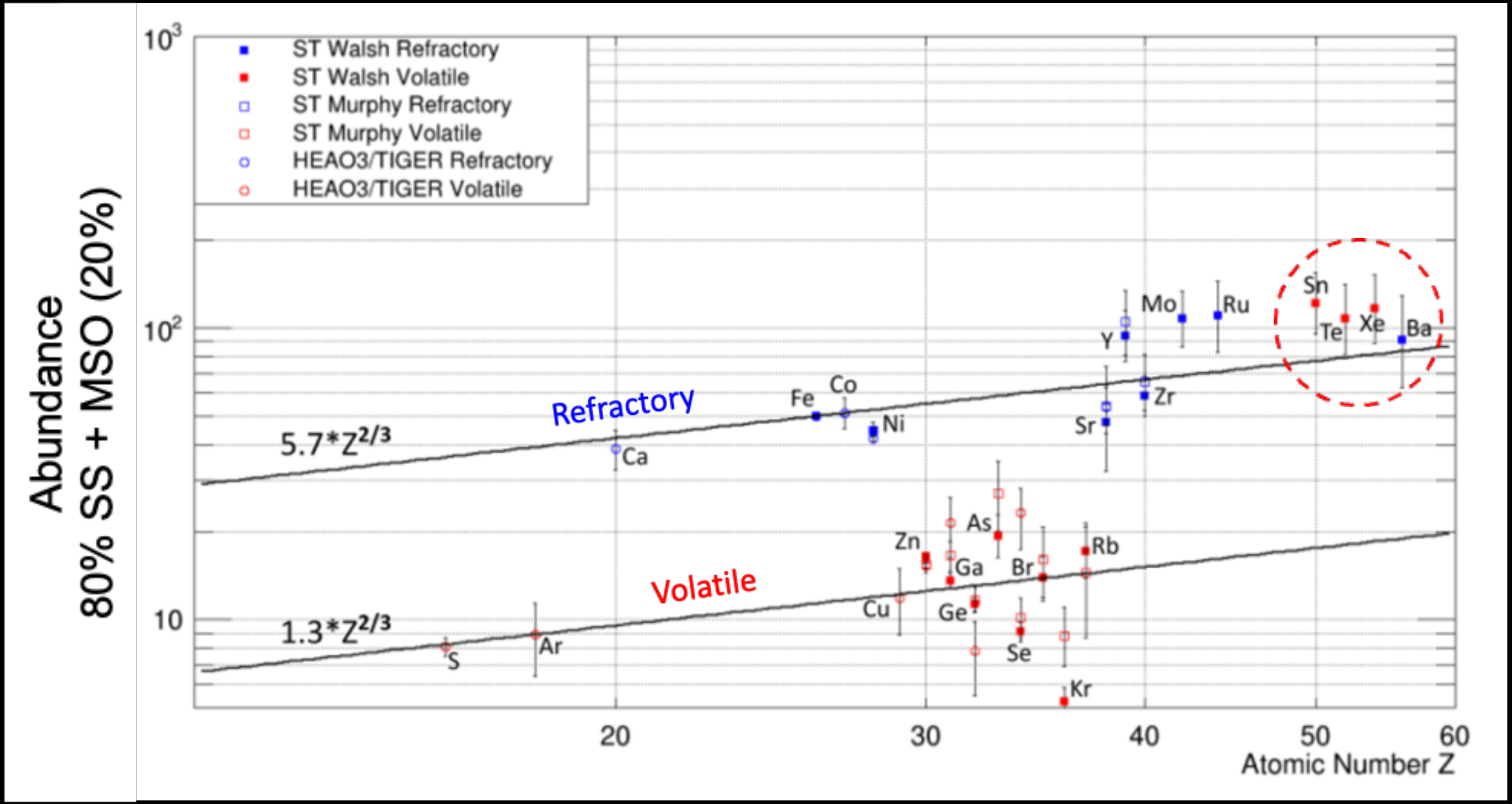


Important feature:
Same rigidity dependence, i.e. hardening, above 100 GeV.

Heavier nuclei

Origin of CRs
CR acceleration –
Composition frontier





Important features:

1) refractory elements that condense in dust grains are preferentially accelerated compared to volatile elements residing in gas;
2) the GCRs are a mix of outflow from "young" massive stars and normal "old" ISM

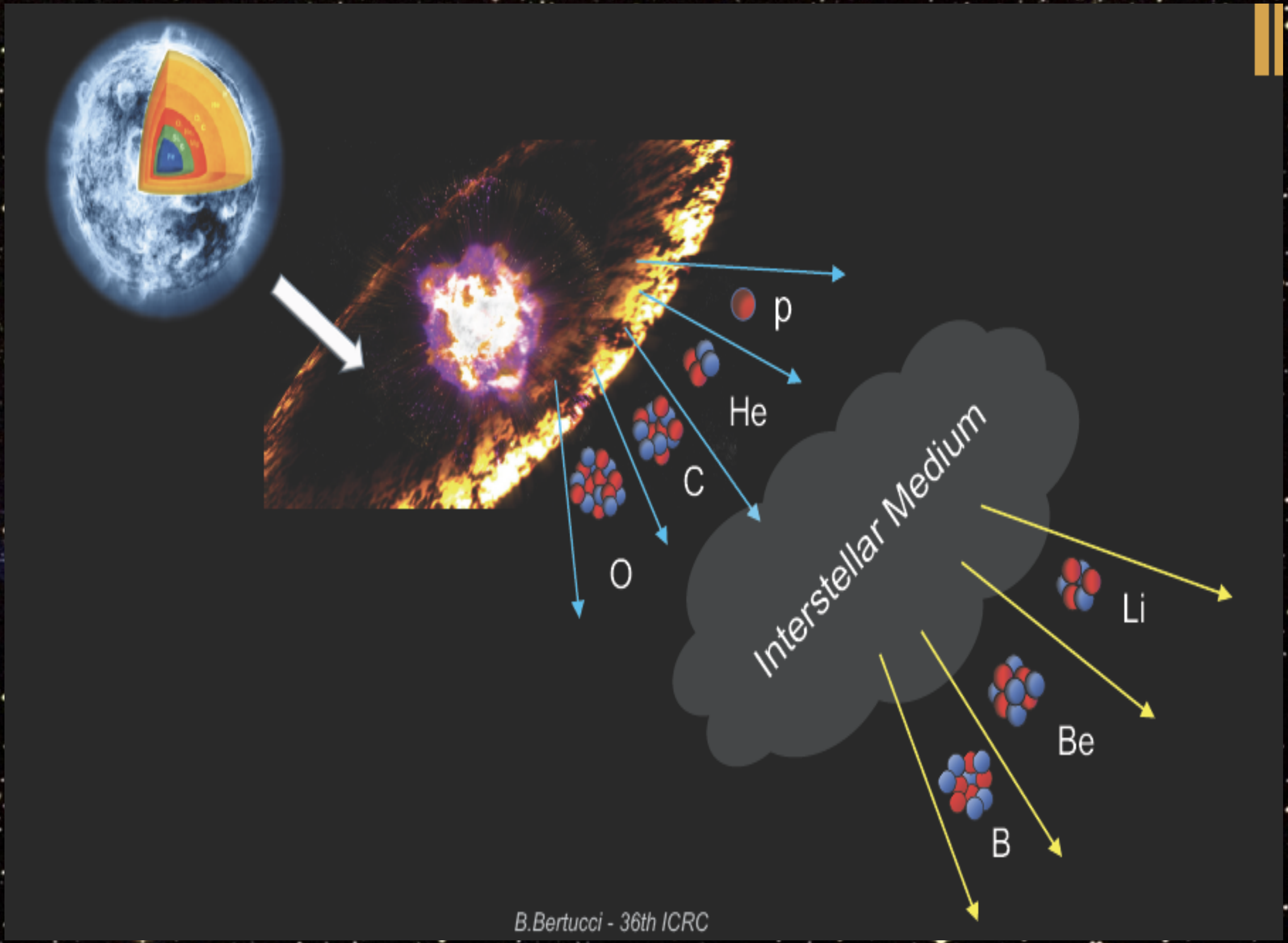
Composition of sources is well described by 80% solar system (SS) + 20% massive star outflows (MSO).

CRs have preferential sources in OB associations (young and massive stars, high-rate of SN).

The model breaks for Z>40. Presence of other sources ?

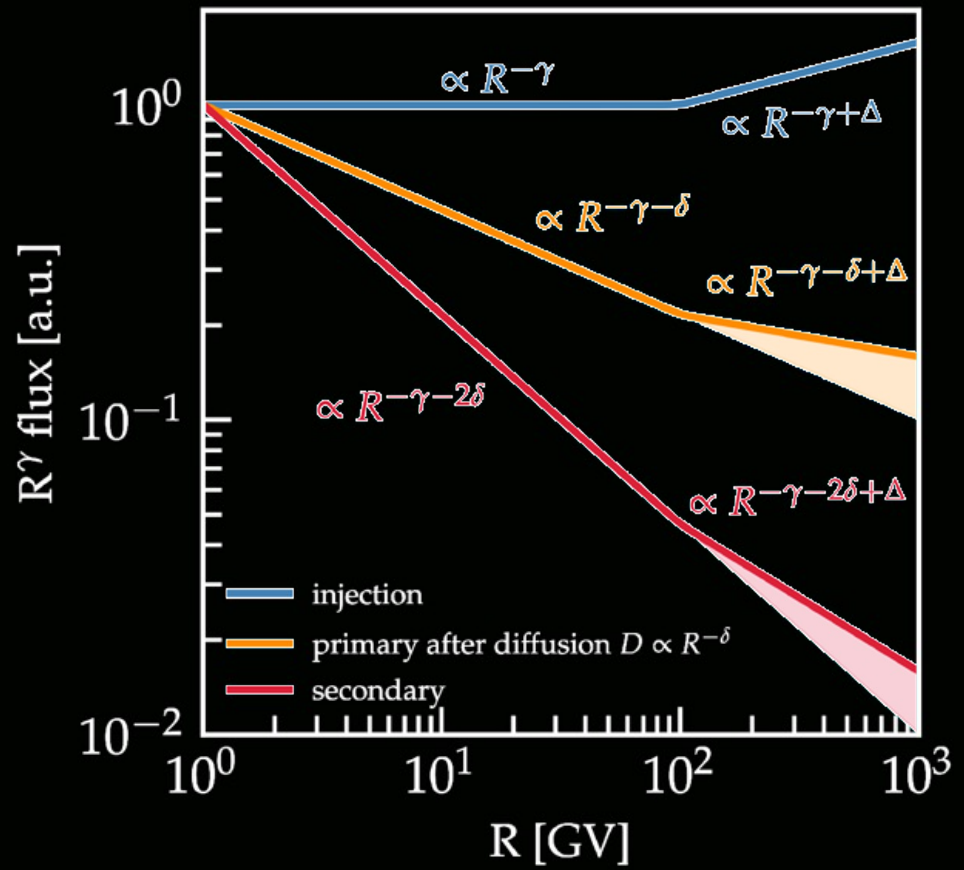
Secondary cosmic rays

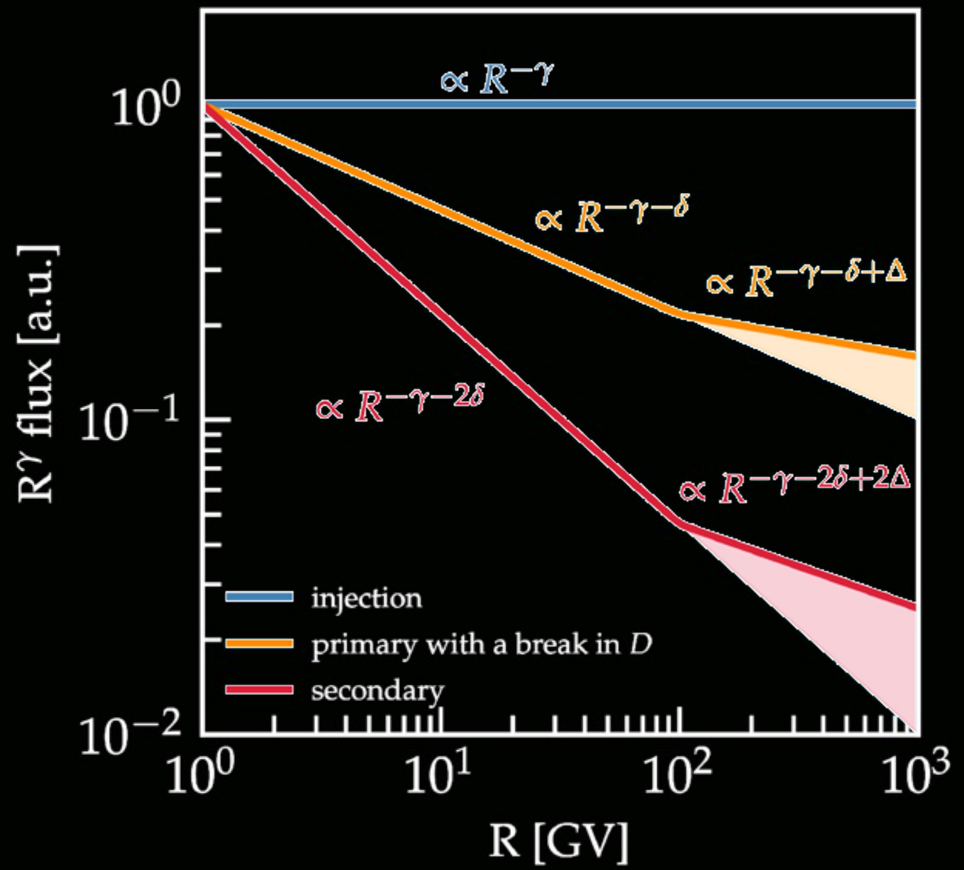
CR propagation –
High energy frontier



Cosmic ray propagation

From C. Evoli (2019).

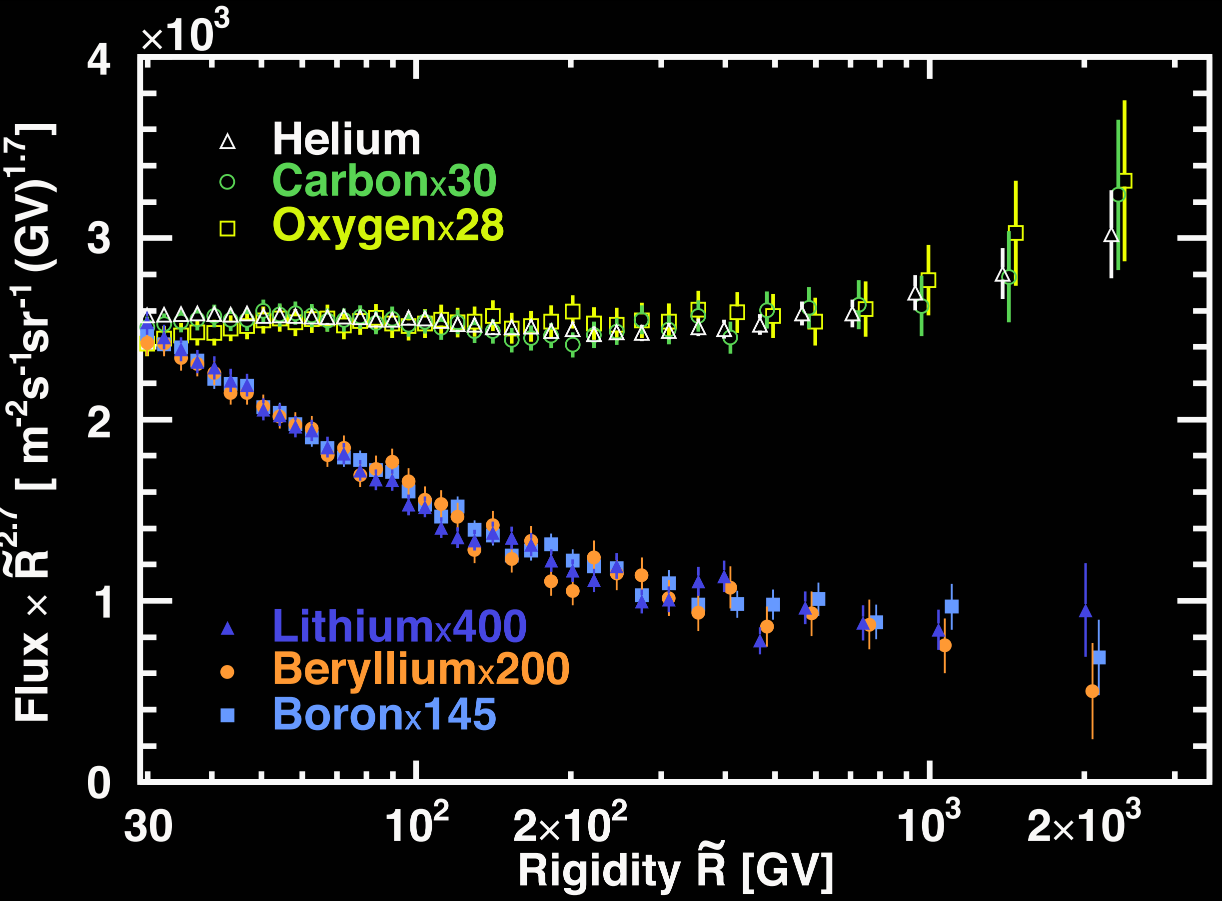


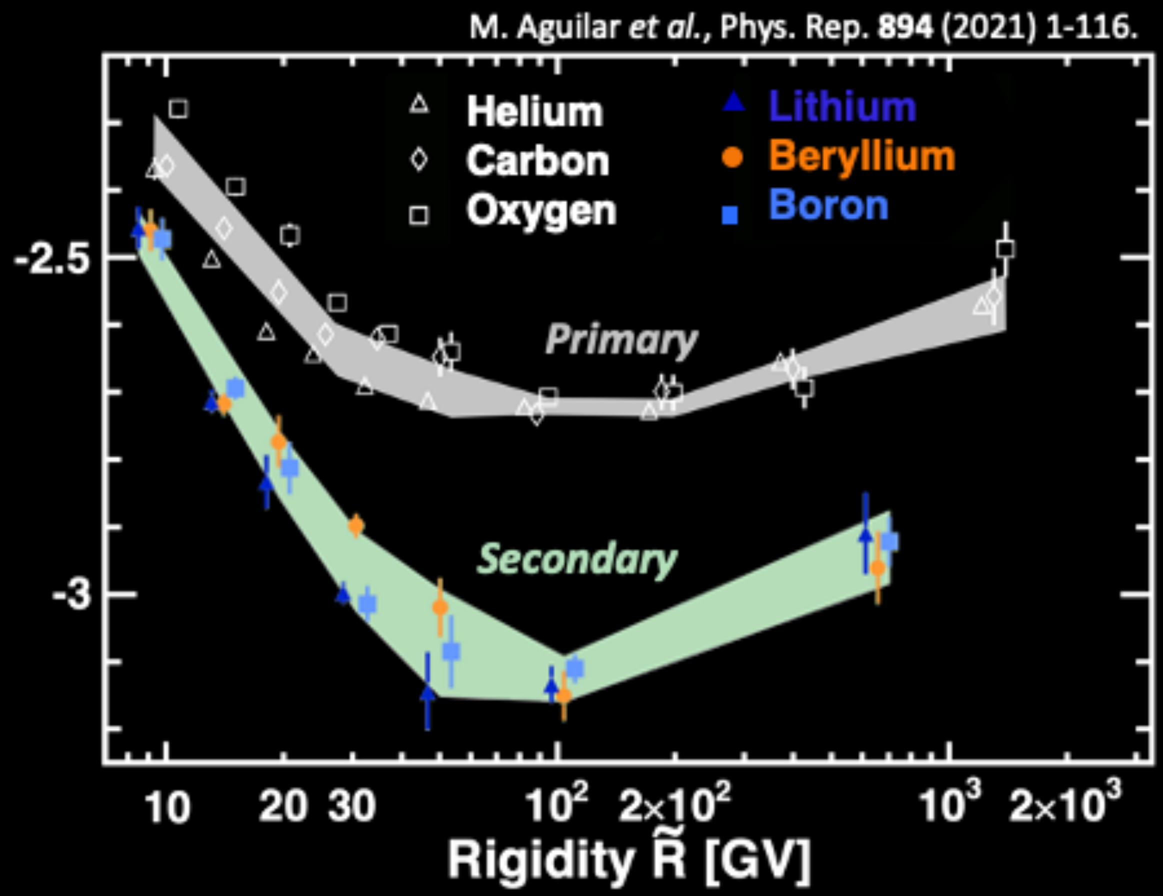


If the hardening in CRs is related to the **injected spectra** at their source, then **similar hardening** is expected both for **secondary** and **primary** cosmic rays.

If the hardening is related to **propagation properties** in the Galaxy, then a **stronger hardening** is expected for the **secondary** with respect to the **primary** cosmic rays.

Light secondary elements Li, Be, B





Important feature:

Secondary/primary ratios harden at 192 GV by $\Delta\gamma = 0.13$.

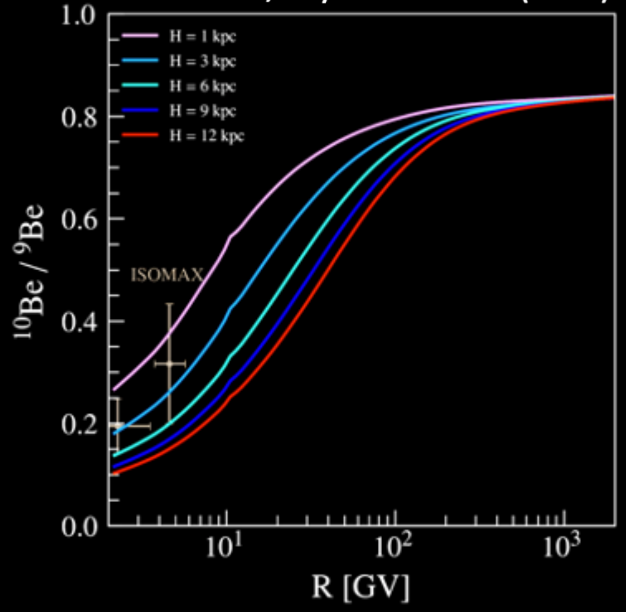
Secondary hardening is stronger –> The flux hardening seems to be a universal propagation effect.

Unstable Be isotopes

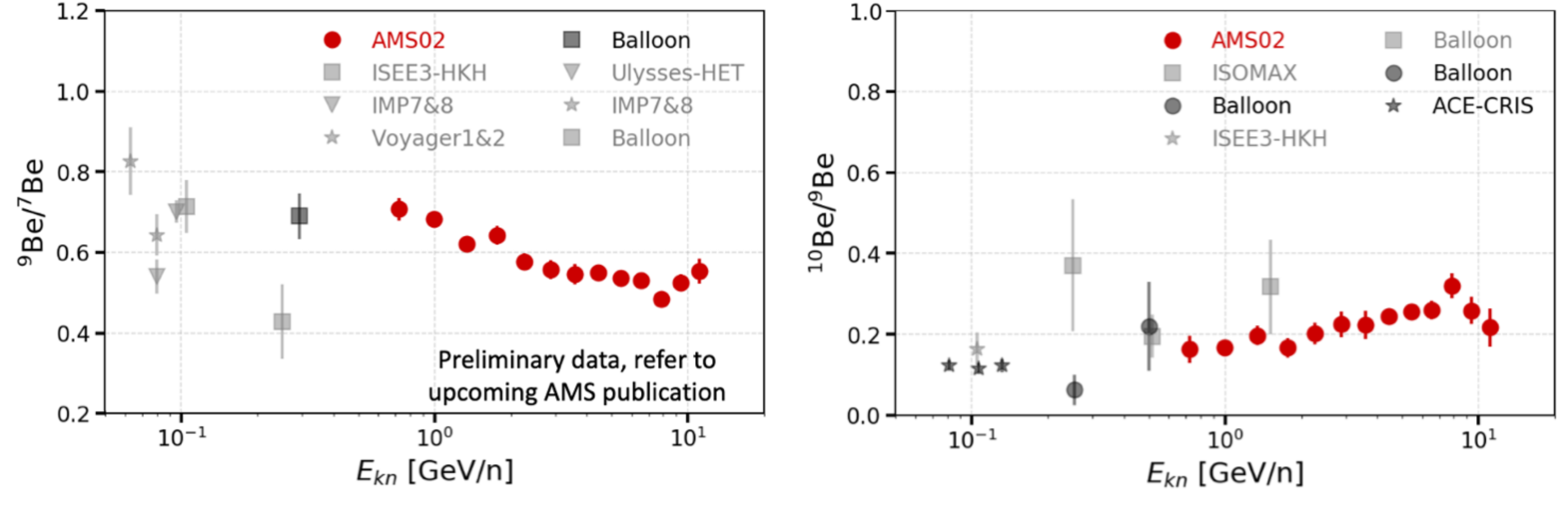
Secondary ^{10}Be → ^{10}B + e^- + ν, with $t_{1/2}$ = 1.4 My.

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

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

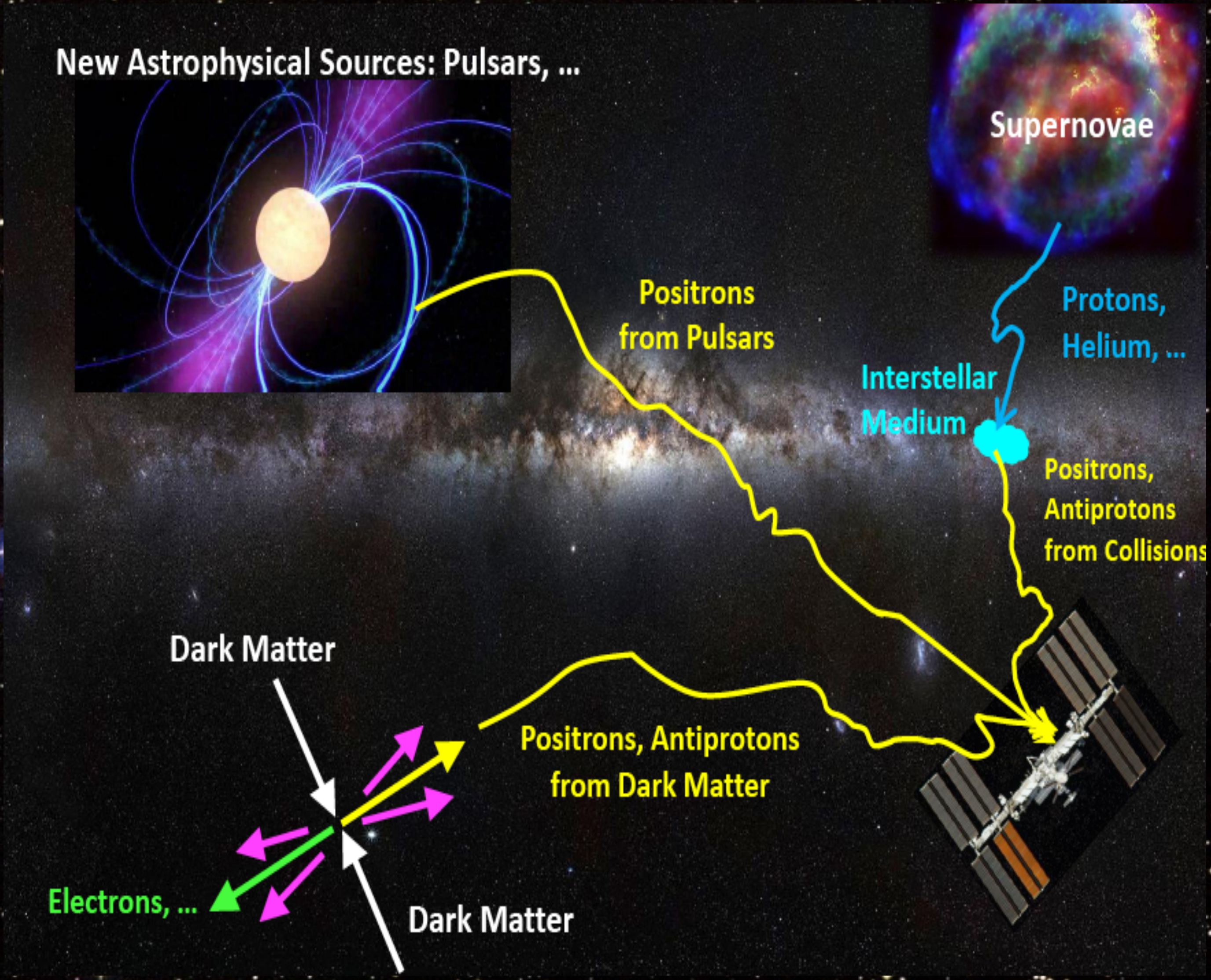


L. Derome *et al.*, Proc. of 37th ICRC (2021) 119.

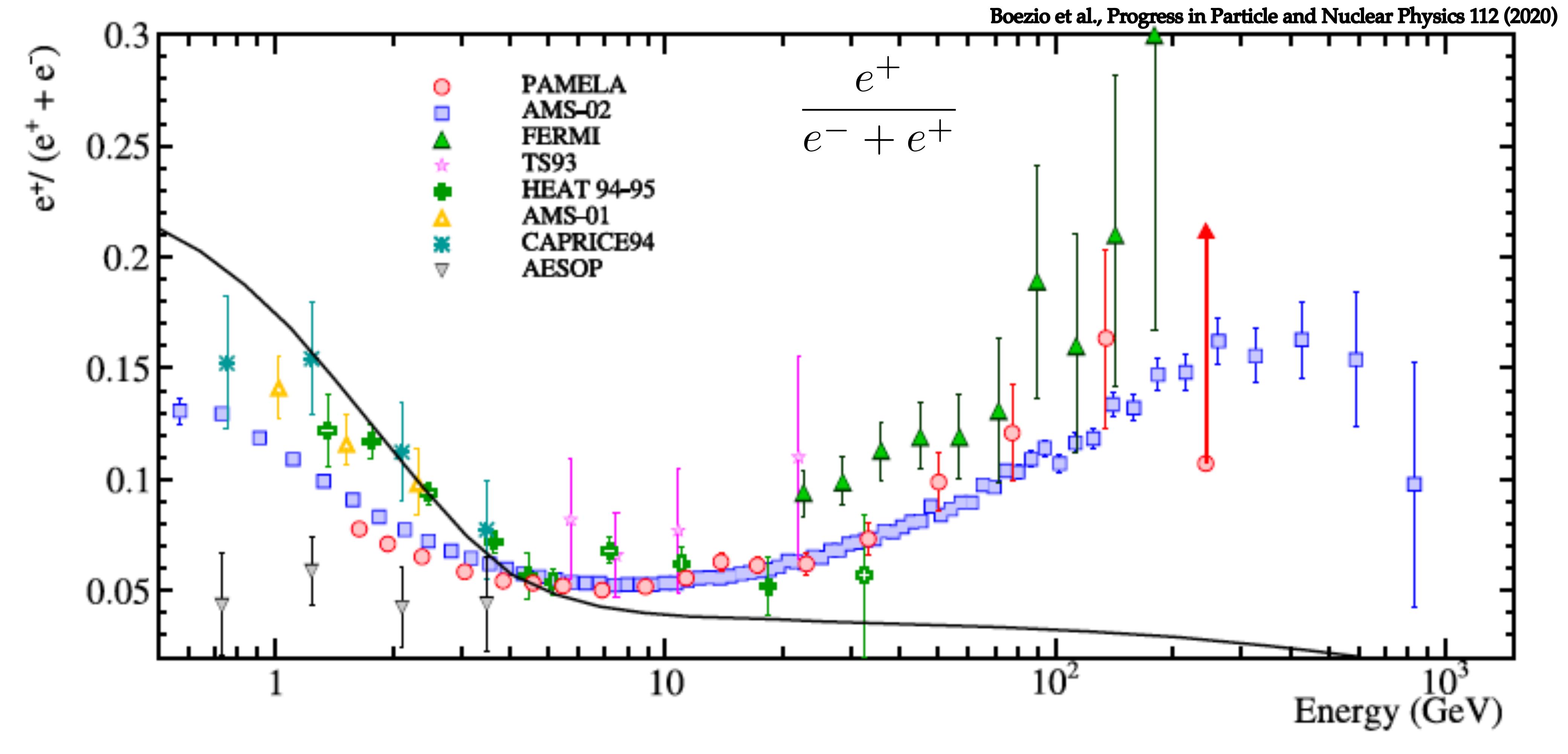


Antimatter & electrons

Propagation/
New sources -
Antimatter frontier



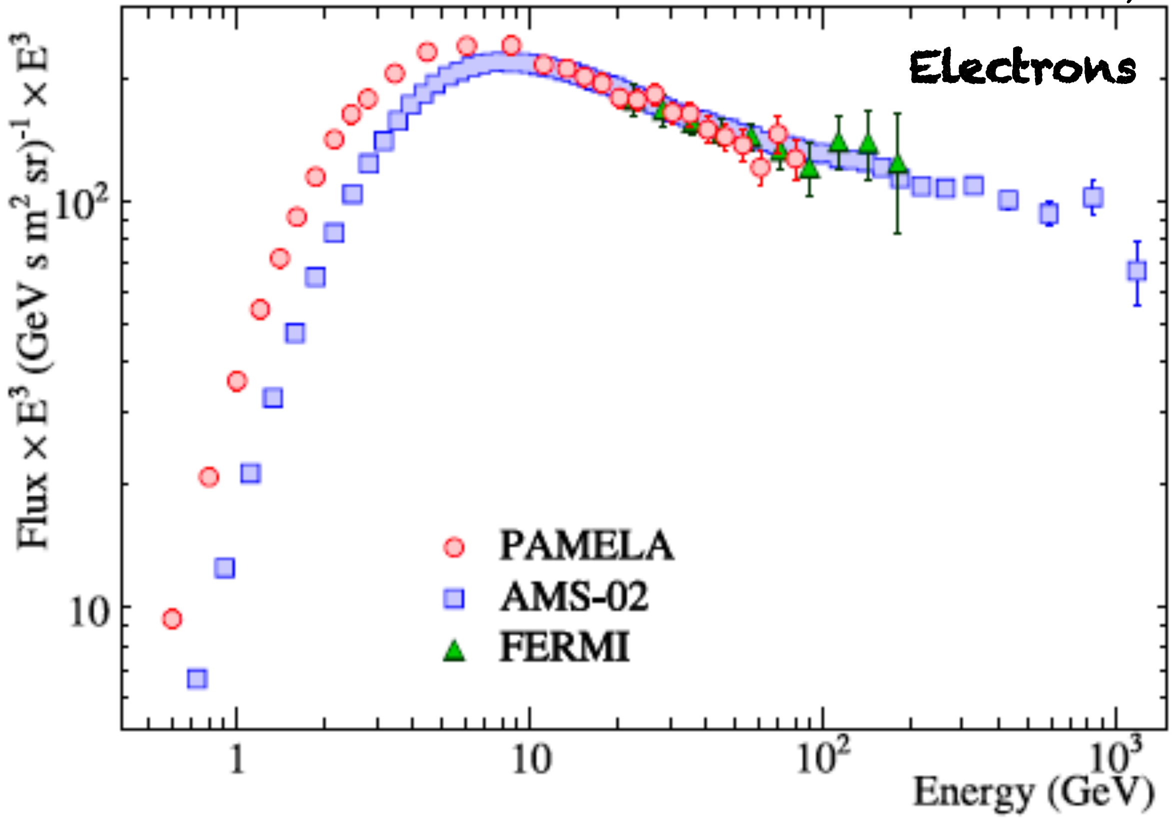
Positron fraction (e+/e- + e+)

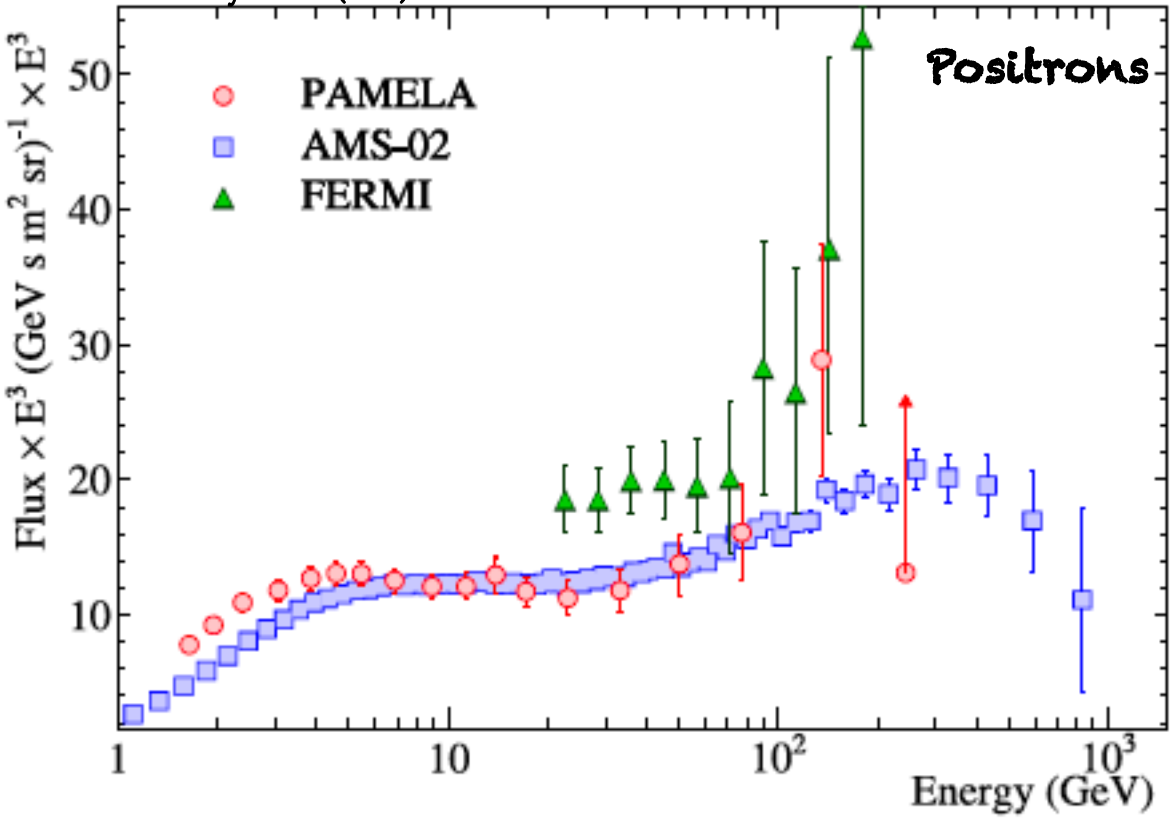


Important feature: clear increase wrt secondary production.
New source of positrons (Pulsars, SNRs, DM)?

Electron & positron fluxes

Boezio et al., Progress in Particle and Nuclear Physics 112 (2020)

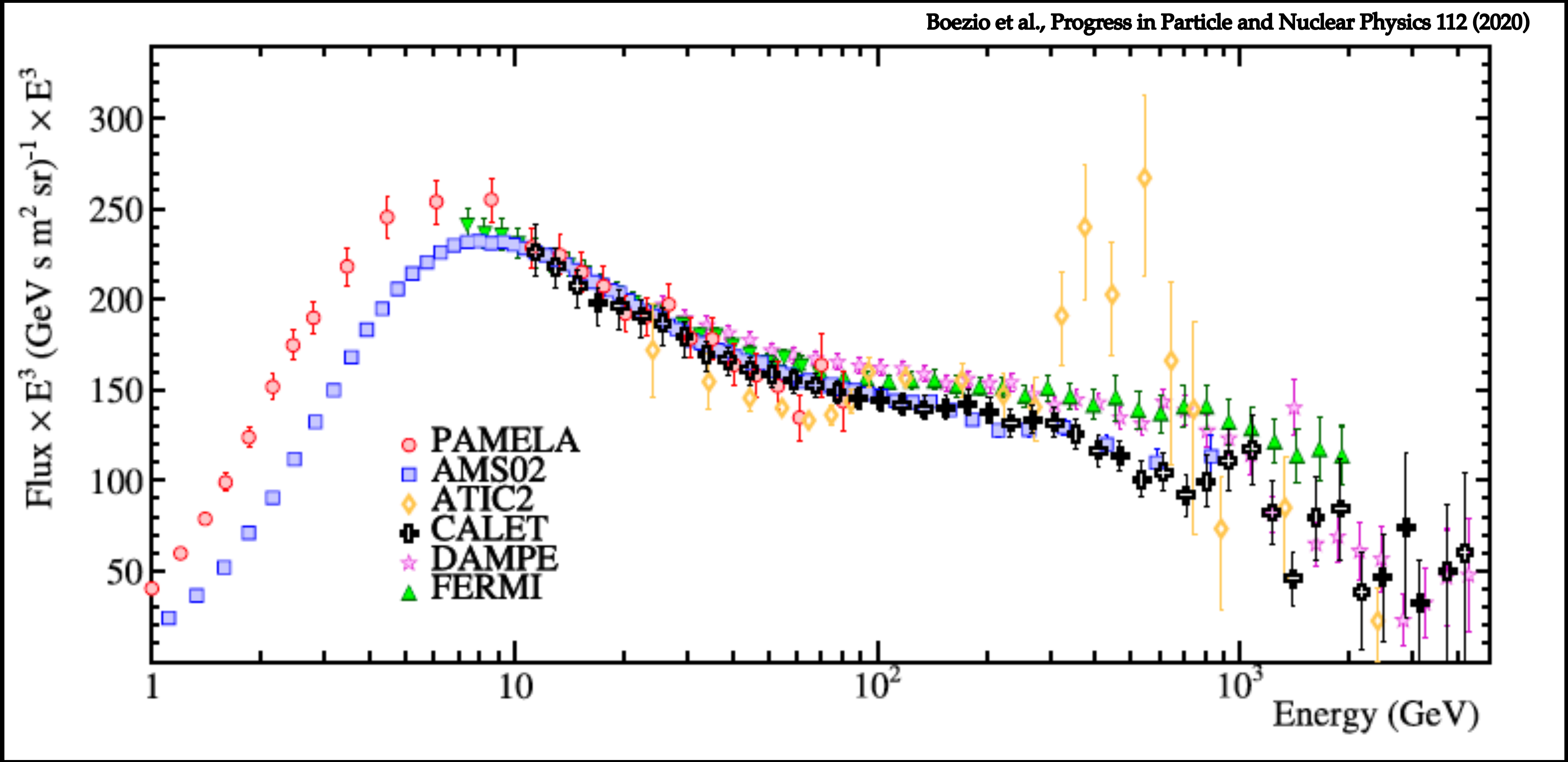




Important feature:

- Only spectrometric experiments can separate electrons from positrons (including Fermi) !
- Electron flux has structures, positron flux has structures

All-electron spectrum from space



Important features:

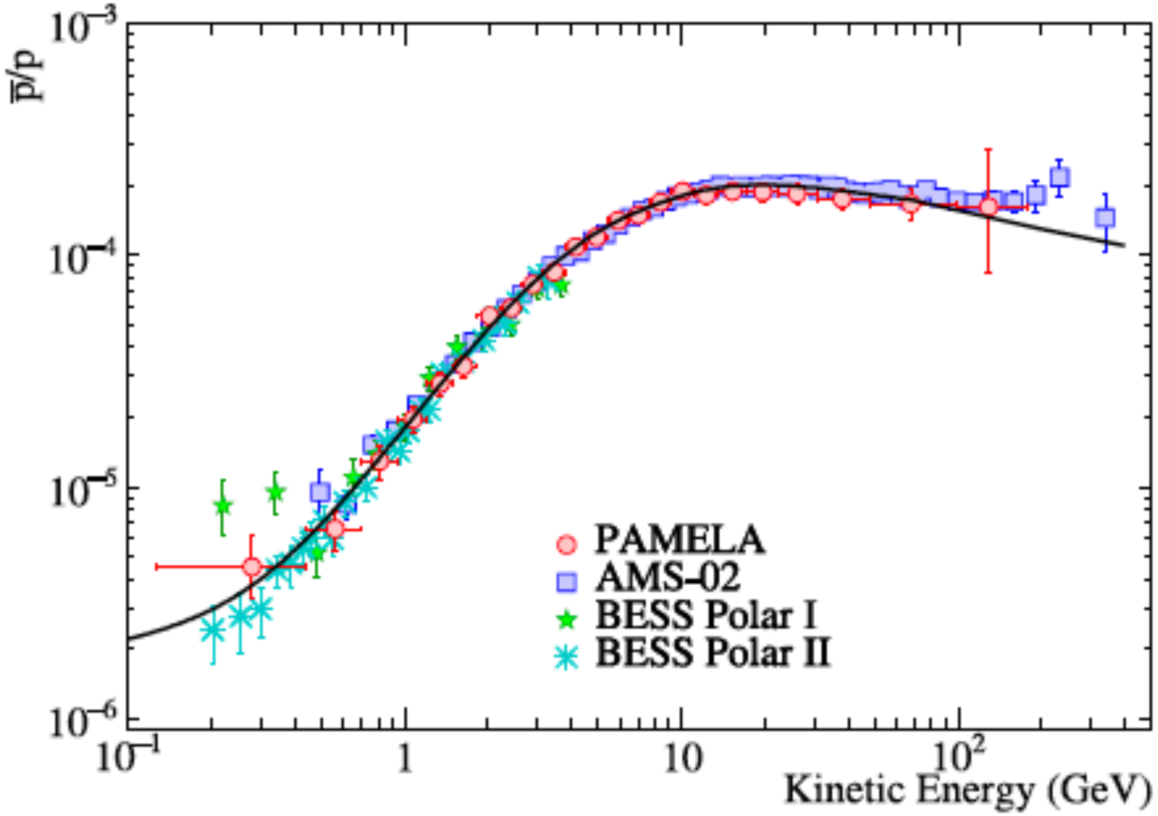
Dropoff at high energy?

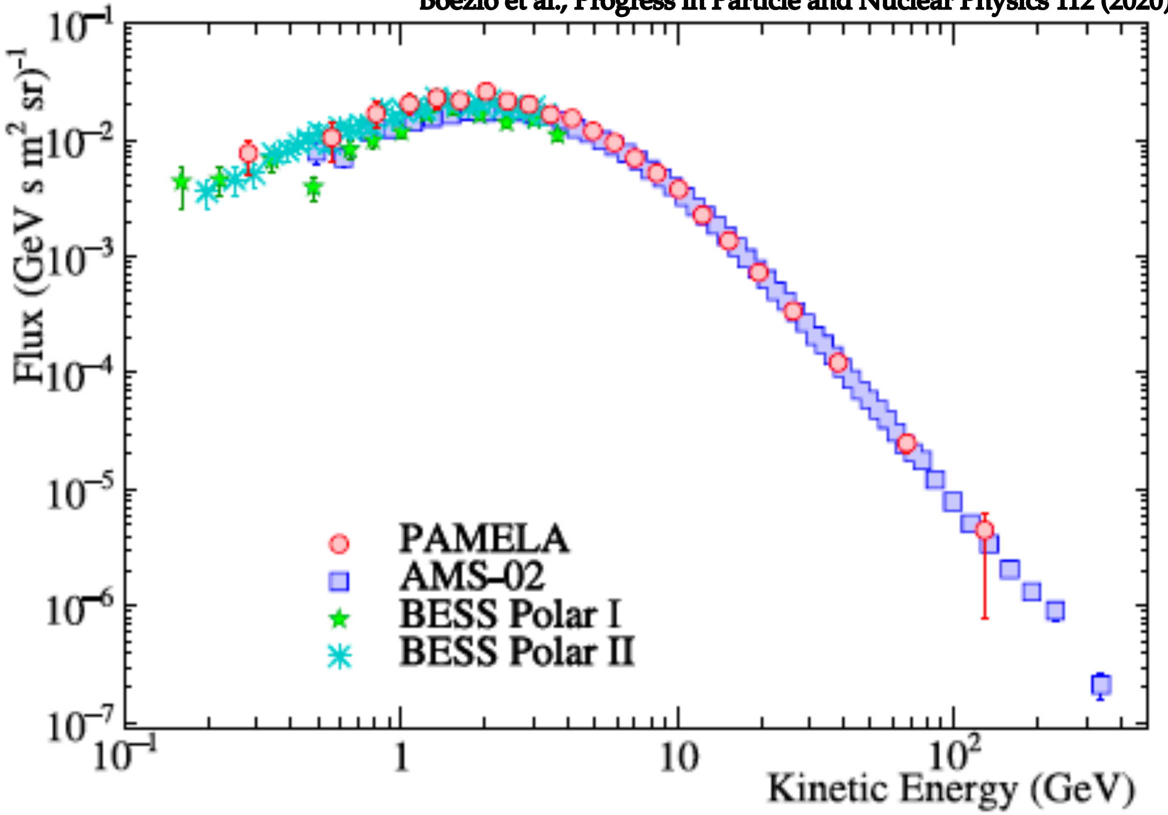
A structure above 2 TeV?

Disagreements between groups of experiment.

Antiproton spectrum

Boezio et al., Progress in Particle and Nuclear Physics 112 (2020)





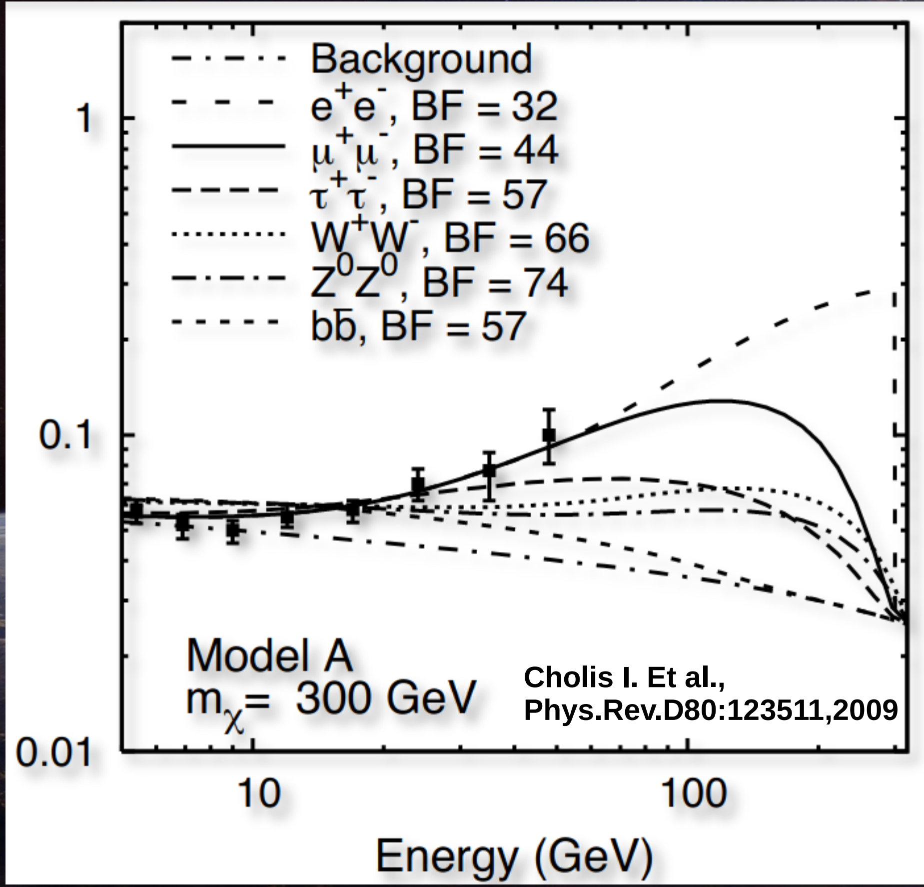
Important feature:

Antip/p maybe flattening for E> tens of GeV ?

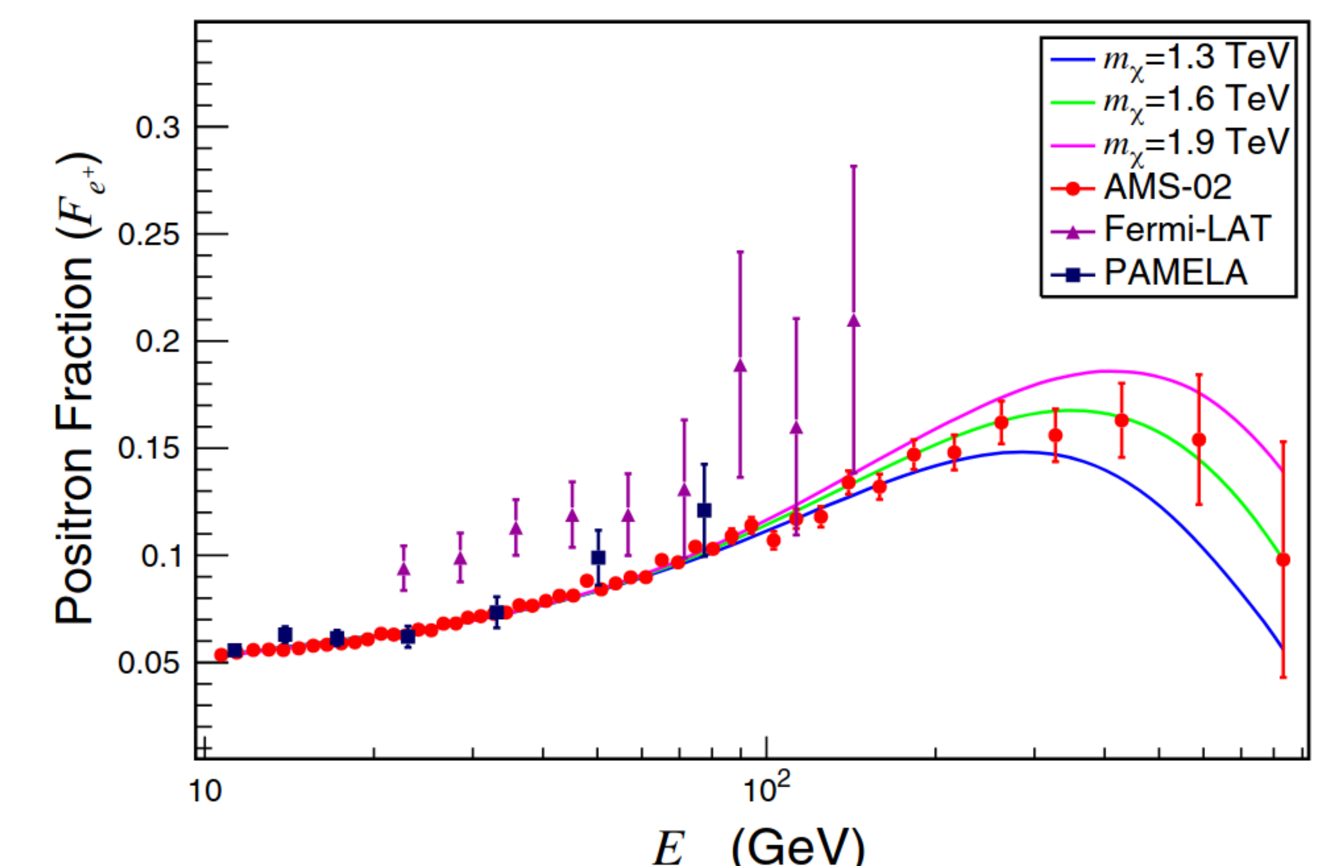
Positron eccess and DM

DM annihilation→ big cross section, high boost factor , leptophilic models

After AMS- 02 measurements, models including DM predict masses > 1-3 TeV



Cholis I. Et al., Phys.Rev.D80:123511,2009



Ghosh S. et al., PHYSICAL REVIEW D 104, 075016 (2021)

Positron eccess and pulsars

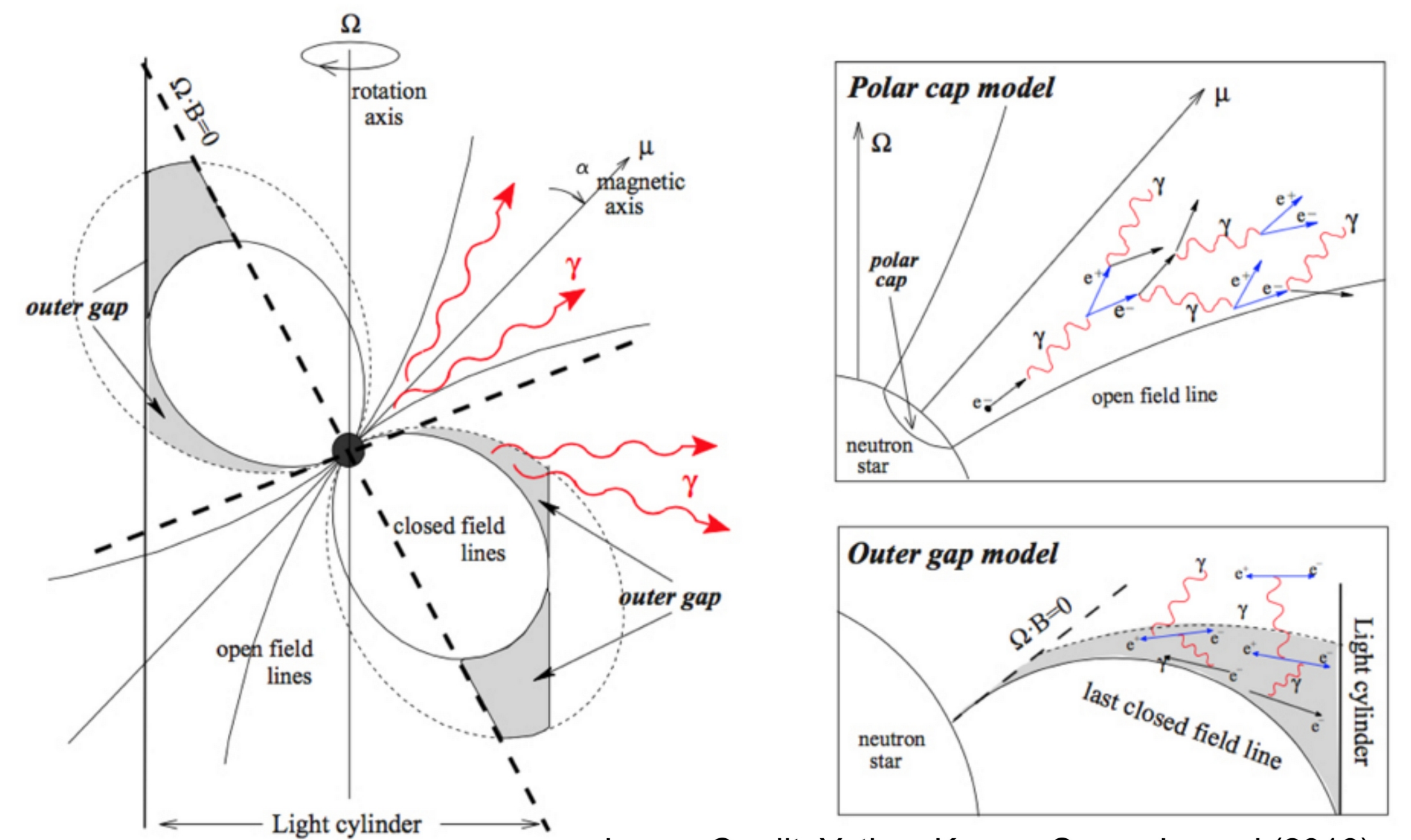


Image Credit: Yating, Kwong-Sang, Jumpei (2016)

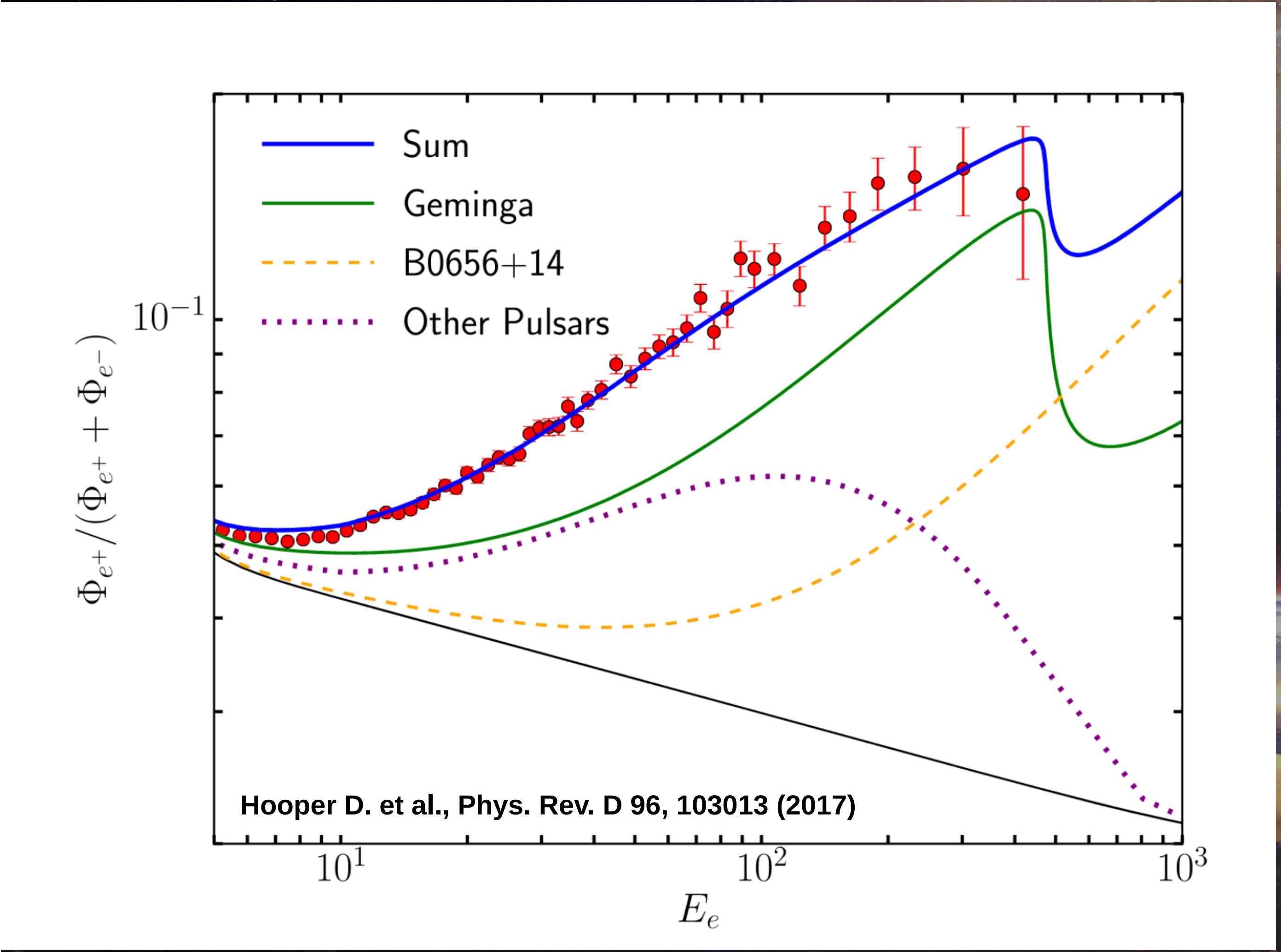
-Electrons are accelerated by the strong magnetic fields, somewhere in the magnetosphere (the location is model dependent)

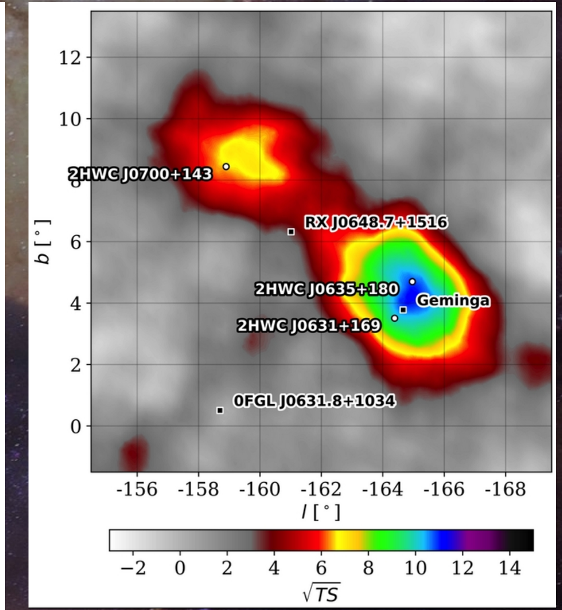
-These electrons then induce electromagnetic cascades through the emission of curvature radiation

-This results in the production of photons with energies above the threshold for pair production in the strong magnetic field

-These electrons and positrons then escape the magnetosphere through open field lines, or after reaching the pulsar wind

Positron eccess, DM and pulsars





Gamma emission (HAWC) from GEMINGA by Inverse Compton. Used to model the mechanism of positrons and electrons emission

"What the HAWC data tell us is that below ~10 TeV or so, electrons leave the region surrounding Geminga before they lose the majority of their energy"

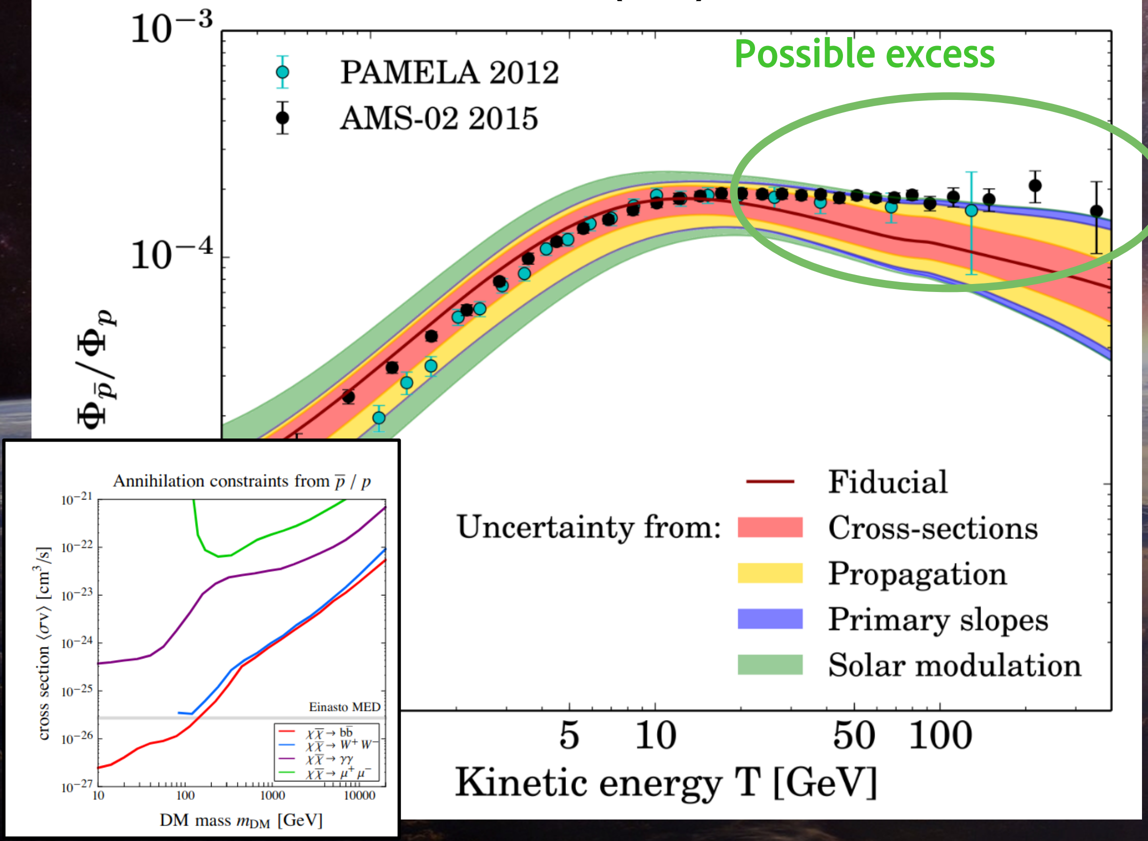
"In light of this result, we conclude that it is very likely that pulsars provide the dominant contribution to the long perplexing cosmic-ray positron excess"

Antiprotons and DM

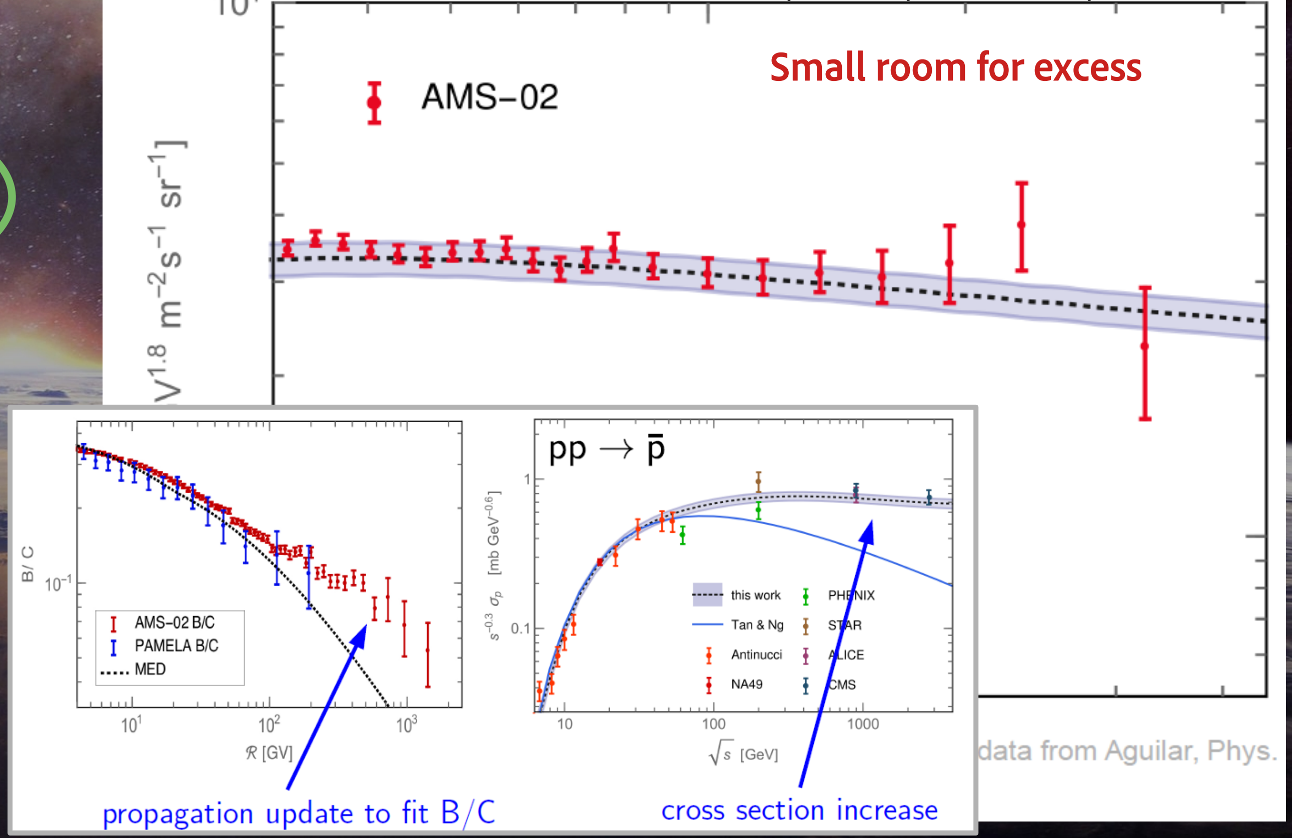
Some modeling for secondary production left room for a possible excess > 50 GeV

More recent measurements of cross sections reduce significantly the room for an excess

Giesen G. et al., JCAP09(2015)023



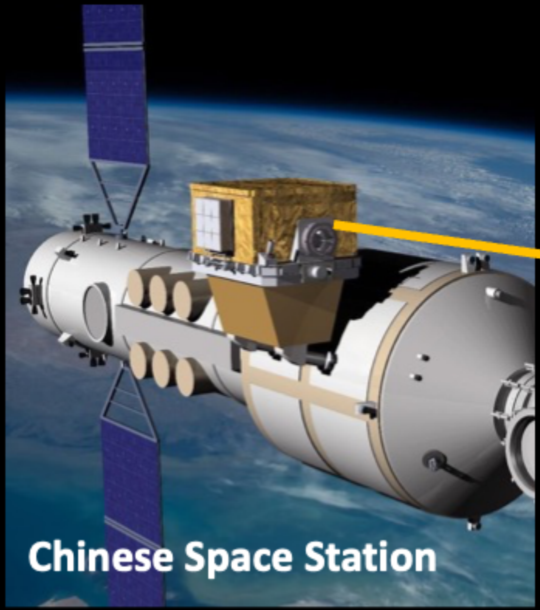
M. Winkler, Dbar19, March 2019, UCLA

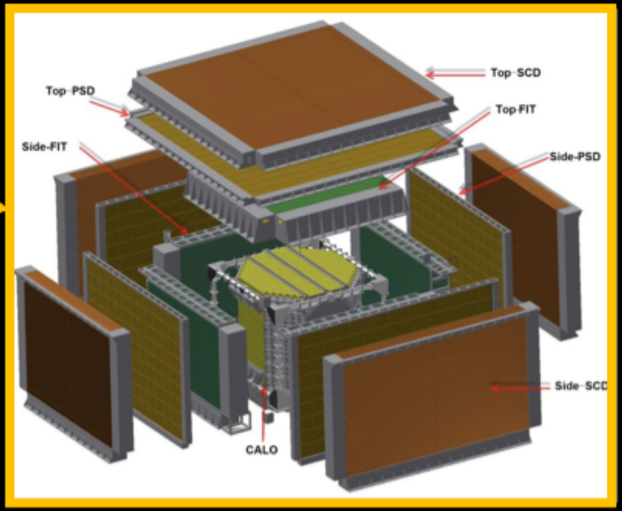


Future experiments

High energy frontier
Composition frontier
Antimatter frontier

Direct Measurement Towards the Knee: HERD





High Energy Cosmic Radiation Detector (HERD)

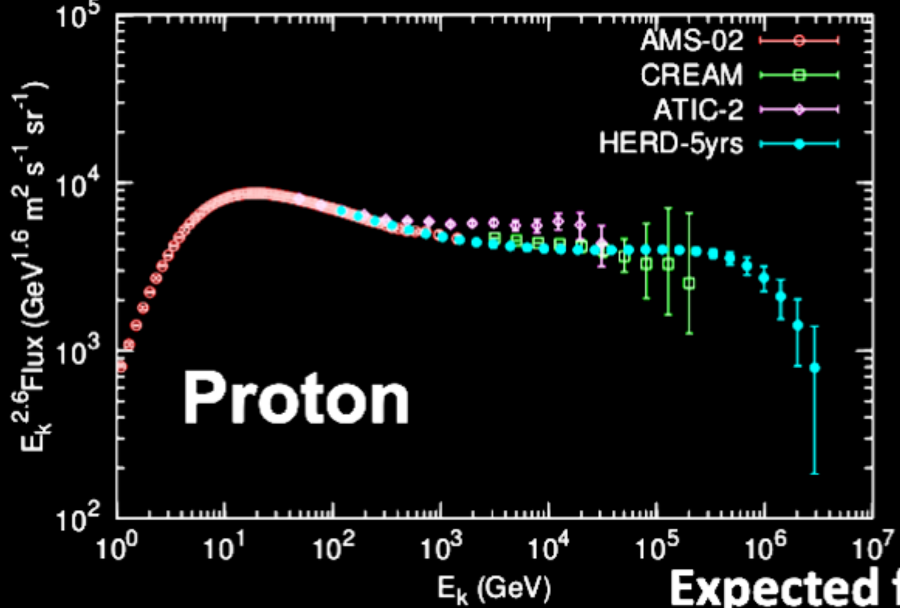
Based on a 3D, homogeneous, finely-segmented calorimeter of 55 X_0 with a wide field of view (2π).

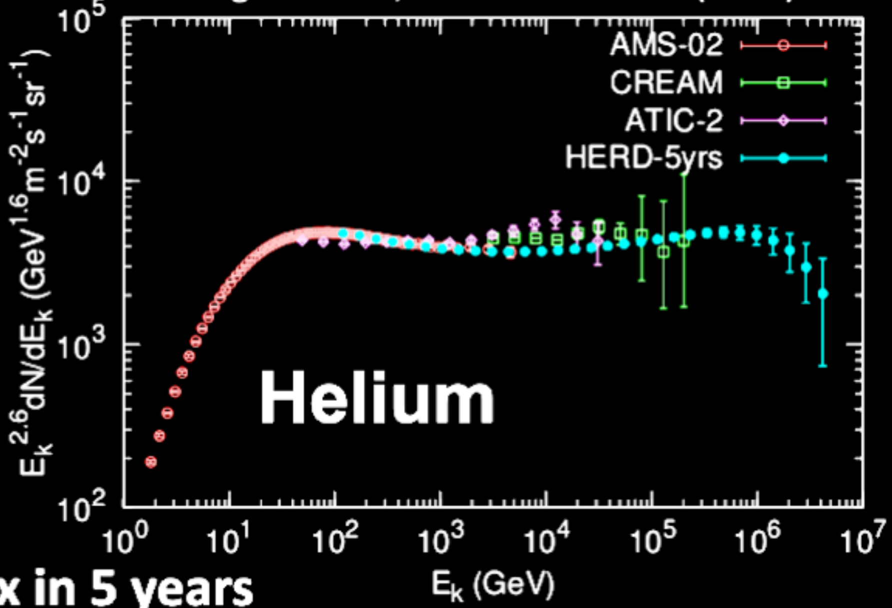
Complemented by other detectors for PID (charge, veto, tracking, ...).

Installation foreseen 2027.

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

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

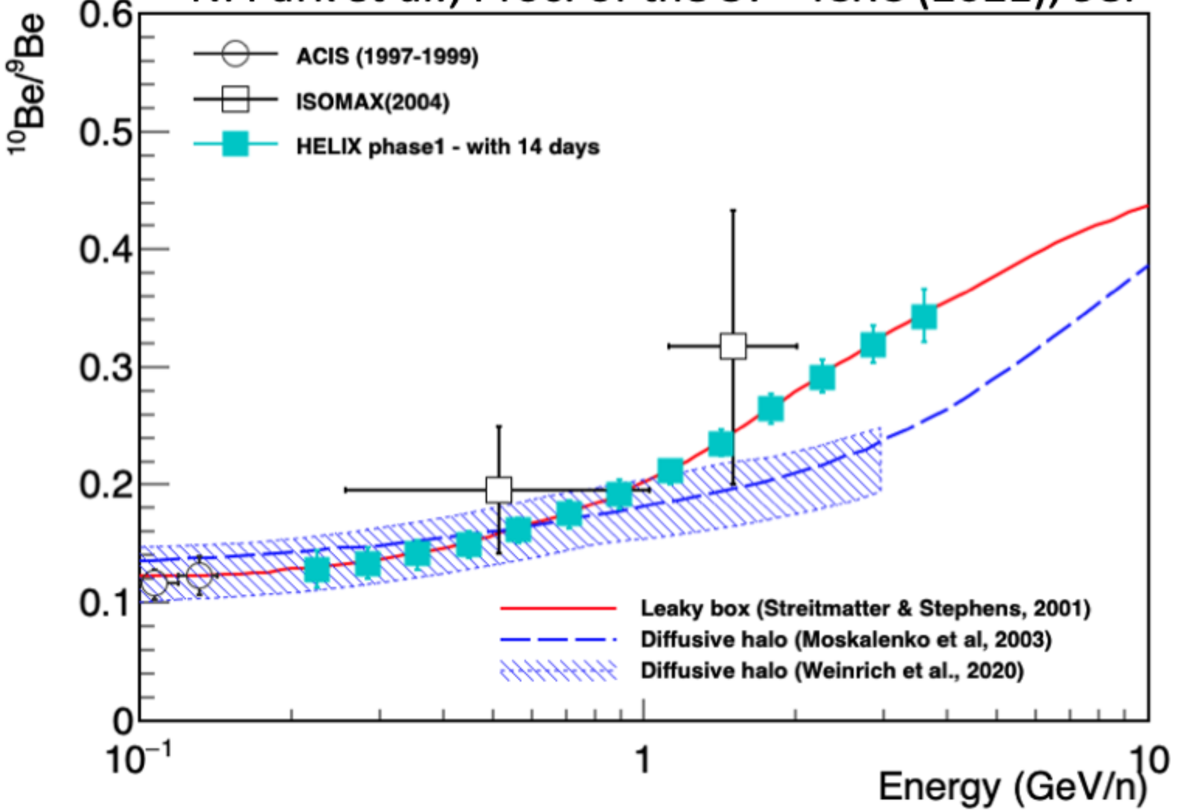


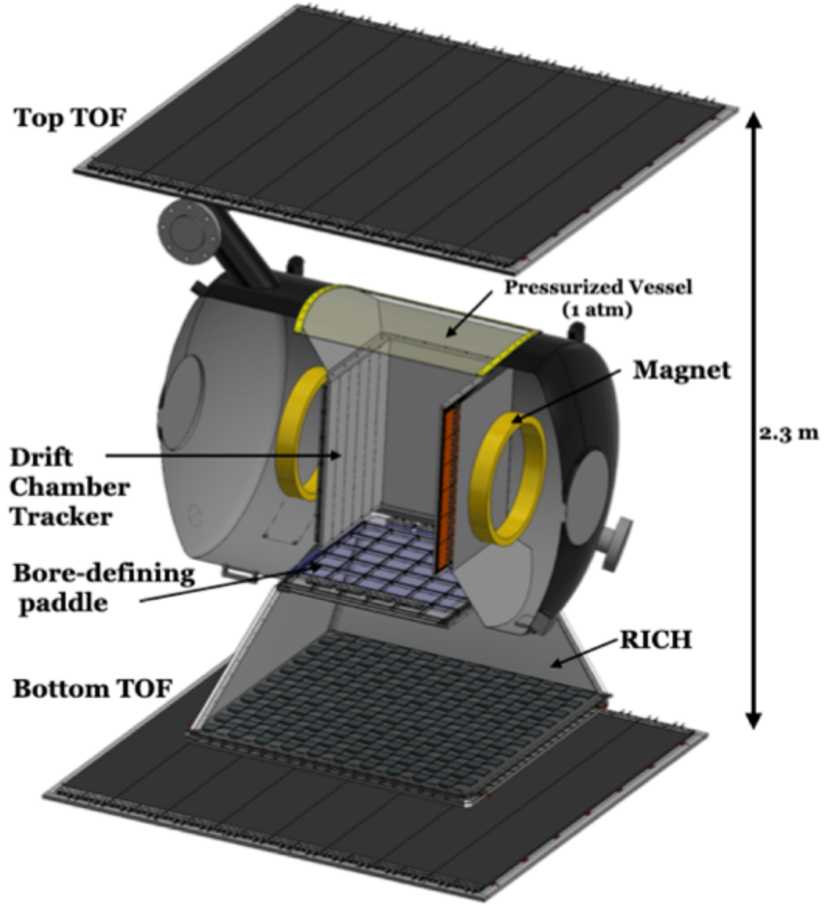


Expected flux in 5 years

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

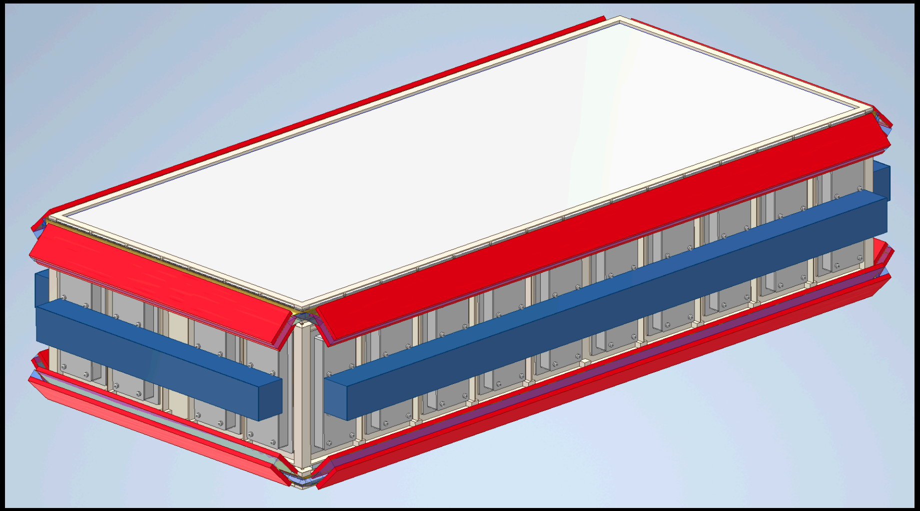
N. Park *et al.*, Proc. of the 37th ICRC (2021), 98.

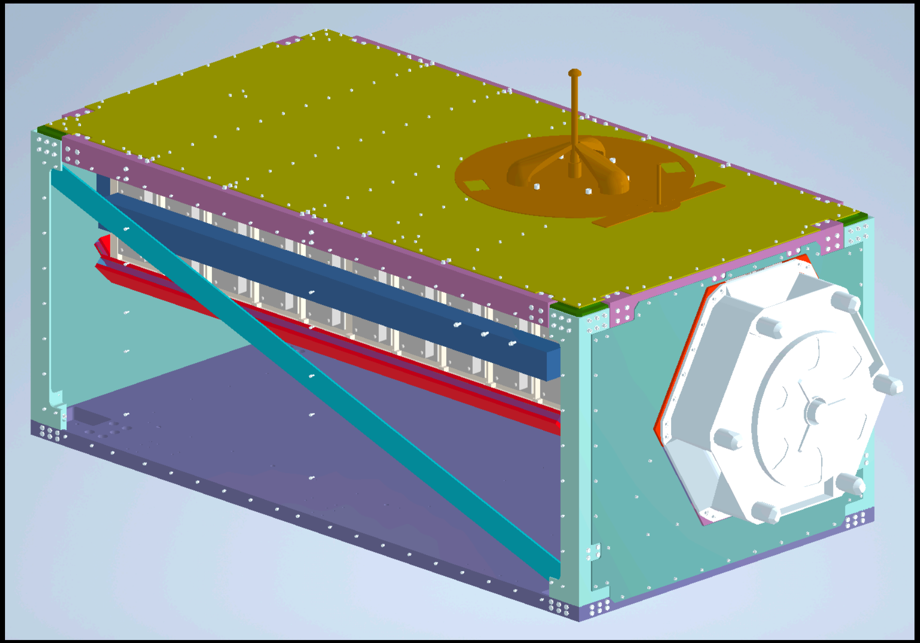




High Energy Light Isotope Experiment (HELIX): a magnetic spectrometer designed to measure the light isotopes from proton up to neon (Z=10). Charged particles are bent by the 1 T superconducting magnet (HEAT), their curvature and momentum are measured by a low low MS high resolution drift chamber. Particle 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%. → First balloon flight will be in 2022 from Sweden.

TIGERISS



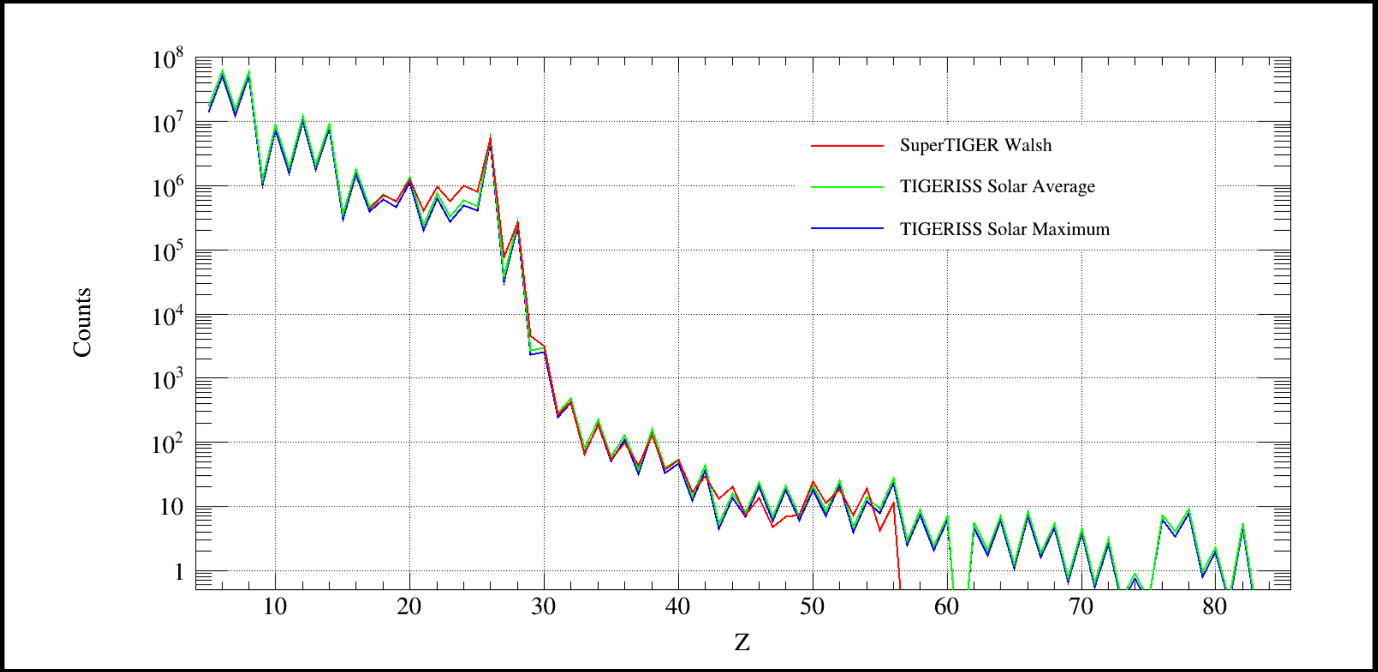


TIGERISS instrument model for the **Japanese Experiment Module "Kibo"** Exposed Facility (JEM-EF) configuration on ISS

In **1 year the statistics of SuperTiger** (see below)

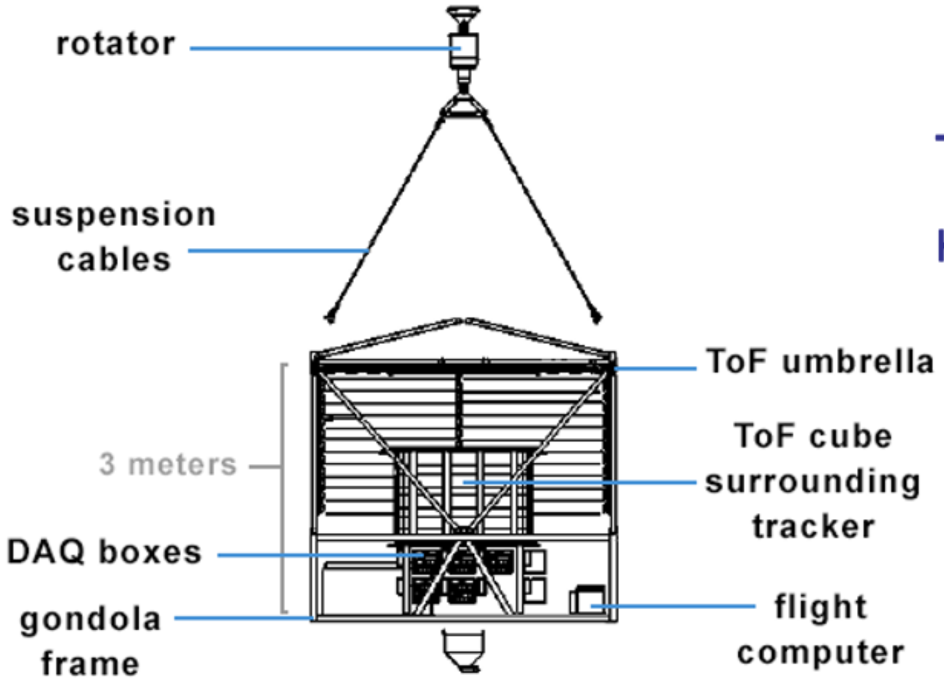
No atmospheric correction —> cleaner signal

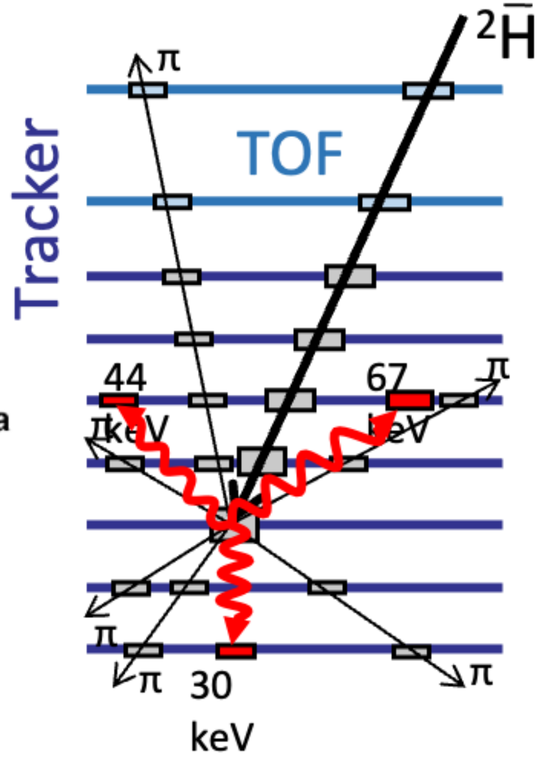
Proposed to the NASA Astrophysics Pioneers Program



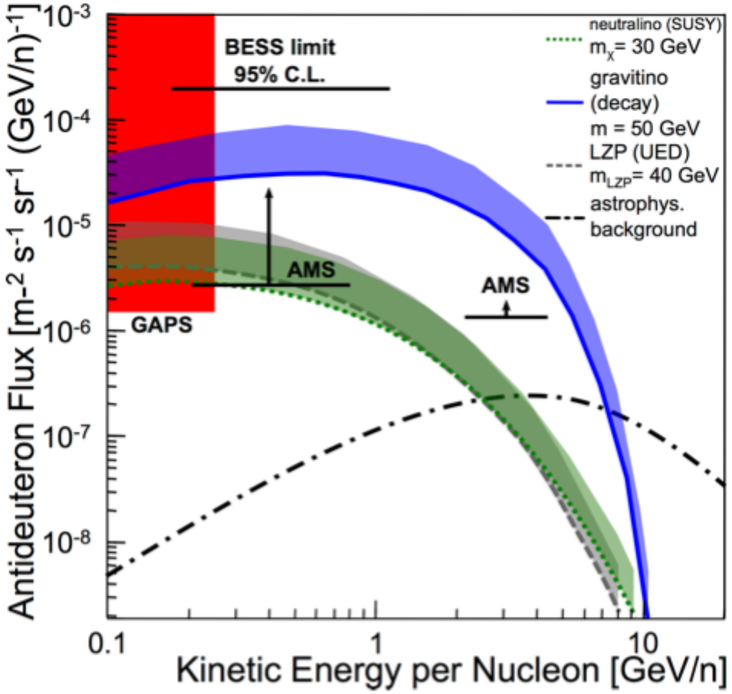
Anti-Matter Search in the Near Future: GAPS

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. In construction, foreseen several balloon campaigns in Antarctica starting from 2023





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



Conclusions: set of «classical» questions

I. Which **classes of sources** contribute to the CR flux in different energy ranges?

II. Are **CR nuclei and electrons accelerated by the same sources**?

III. Which sources are capable of **reaching the highest particle energies**?

IV. Which are the relevant processes responsible for CR **confinement in the Galaxy**?

V. Where is the **transition between Galactic and extra-Galactic CRs**?

VI. What is the origin of the difference between the **chemical composition of CRs and the solar one**?

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In the last decades we developed an «accepted» scenario for CR origin,
that we call «standard paradigm» .
In this framework, many of the classical questions have been (plausibly) answered.

Conclusions: set of «new» questions !

I. What is the origin of the **hardening** **observed in the spectra of CR nuclei** at a rigidity of about 200 GV? And the **flattening** over 1 TeV?

II. Why is the slope of the spectrum of CR **proton and helium different**?

III. What is the origin of the **prominent** break observed at a particle energy of **1 TeV in the electron spectrum**?

IV. What is the origin of the **rise in the positron fraction** at particle energies above 10 GeV?

V. Does the **antiproton/proton ratio** flatten at high energies**?**

VI. Why does the CR composition with OB associations break above Z=40?

VII. .....

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VII. …..

A «new paradigm» is needed.
The following years will tell us much!