DIRECT MEASUREMENTS OF COSMIC RAYS

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Lecture 2

INTERNATIONAL SCHOOL OF COSMIC-RAY ASTROPHYSICS «MAURICE M. SHAPIRO»

23rd Course: “Multi-Messenger Astroparticle Physics” — 20 - 28 July 2024

Outline of Lecture 2

In this second lecture, we will talk about:

- Energy Spectrum of CR Protons and Helium
- Carbon, Oxygen and Iron Fluxes and ratios
- Elements with Z<40 and 40<Z<56 and Be isotopes
- Antimatter measurements in CRs
- Future experiments
- Conclusions

Energy Spectrum of CR Protons and Nuclei

We said inlecture 1 that at energies larger than few GeV (where the contribution of particles coming from the Sun is negligible, see later) **the energy spectrum can be described by a power-law**:

$$\Phi(E) = K\left(\frac{E}{1\ \mathrm{GeV}}\right)^{-\alpha} \quad \frac{\mathrm{particles}}{\mathrm{cm}^2\ \mathrm{s\ sr\ GeV}}$$

The parameter α is the differential spectral index of the cosmic ray flux (or the slope of the CR spectrum) and K a normalization factor.

Different compilations of data exist which determine the parameters K, α using direct measurements of the CR flux. These compilations give results in agreement within $\sim 30\%$.

In the energy range from several GeV to $\sim 10^{16}$ eV (the "knee"), cosmic rays follow a power-law with spectral index:

$$\alpha = 2.7 \qquad\qquad E < E_{knee} = 10^{16} eV$$

Energy Spectrum of CR Protons and Helium

Let us now see the experimental results coming from direct measurements of CR from the major experiments described in the past lecture.

Next slides show the **proton and helium energy spectra (the flux is multiplied by $E^{2.6-2.7}$) and ratio p/He above 1 GeV/n** measured by recent balloon and space experiments (AMS-02, CALET, DAMPE, PAMELA, ...).

From the experimental data, some features are clearly visible:

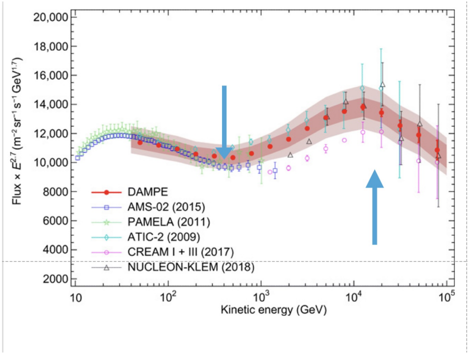
deviation from a single power-law!

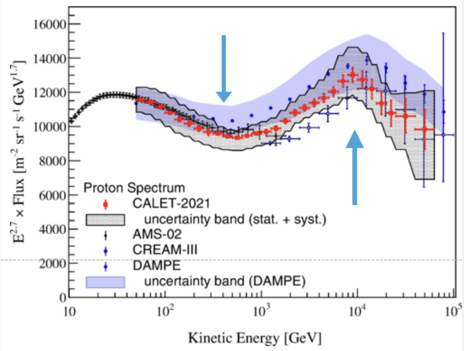
1) a "hardening" in both species at about 300-400 GV (hardening means that the spectrum become less steep)
2) a "softening" above 10 TV (softening means that the spectrum becomes steeper)

p/He not constant!

1) The ratio p/He not is not constant and smooths up to 1 TV
2) p and He, though both primary cosmic rays, behave different.

Proton spectrum (10 GeV–> 100 TeV)

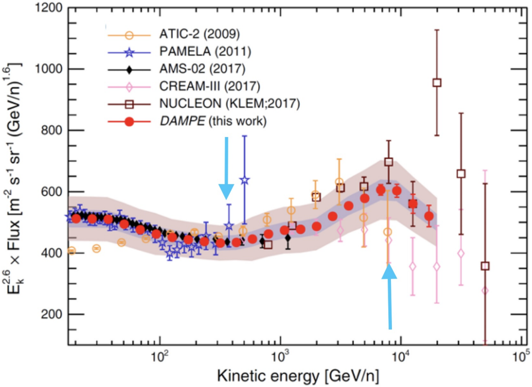




Spectra of protons is not a single power law below the knee:

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

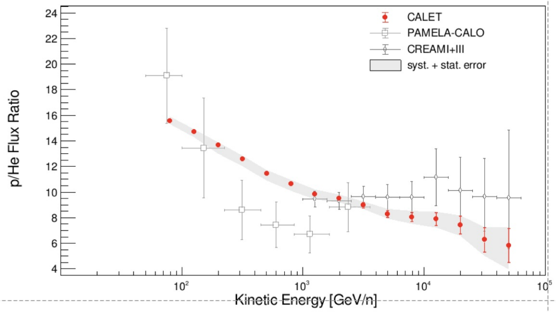
Helium spectrum (10 GeV–> 100 TeV)



As for protons, helium spectrum shows as well:

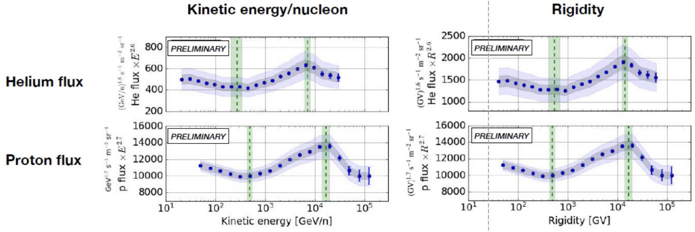
◇ A hardening at R = p/Z ~ 300 - 400 GV
◇ A softening at R = p/Z ~ 10 TV

Proton and Helium ratio



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

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



Possible systematics in CR fluxes

Below 10 GeV/n, the difference among experiments is mainly due to **solar modulation**.

At high energies, **some differences well beyond the quoted statistical only errors are present.** Likely, the main sources of discrepancy arise from the **evaluation of the detector and selection efficiencies** and from the technique used in the **determination of the energy**.

In experiments using magnetic spectrometers (as AMS and PAMELA) the rigidity (and then the energy) is determined by measuring the **curvature of charged particles**. Consequently, the energy resolution depends on the **spatial resolution of the tracking devices** inserted in the magnetic field and on the topology of the event.
The **tracking alignment** is a major ingredient for the correct energy assignment. In fact, a wrong assumption on the absolute position of the tracking sensor with respect to the magnetic field would result in a measurement affected by a systematic bias.

Carbon, Oxygen and Iron Fluxes and ratios

We can now proceed with the latest results of heavier elements.

Carbon and Oxygen are the most abundant - after He - in CRs. Data from the most recent experiments show that:

deviation from a single power-law!

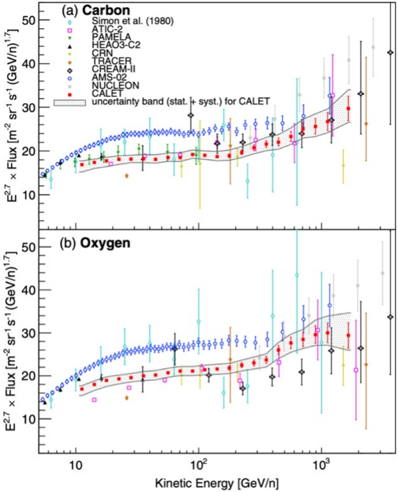
1) C and O show a "hardening" at hundreds of GV. Similar energy dependence observed by AMS-02 and CALET.
Indeed, **current experiments have shown that the hardening is the same for all elements!**

2) C/O is smooth/flat, meaning that C and O have similar hardening.

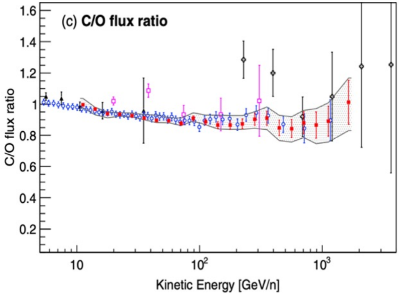
There is an **evident difference in flux normalization between experiments**. All experiments, instead, agree in the C/O.

In addition, if we plot the spectral indexes of He, C and O we find the **same rigidity dependence, namely a hardening above 300 GV**.

Carbon and Oxygen Fluxes



O. Adriani *et al.*, Phys. Rev. Lett. **125** (2020) 251102.

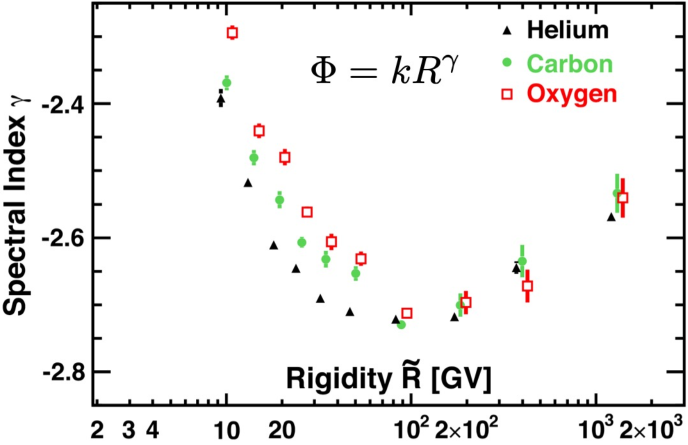


C and O show a hardening at hundreds of GeV/n.
Similar energy dependence observed by AMS-02 and CALET.
Difference in flux normalization between experiments.

C/O is smooth, meaning that C and O have similar hardening.
All experiments agree in the C/O.

Helium, Carbon, and Oxygen Spectral Indices

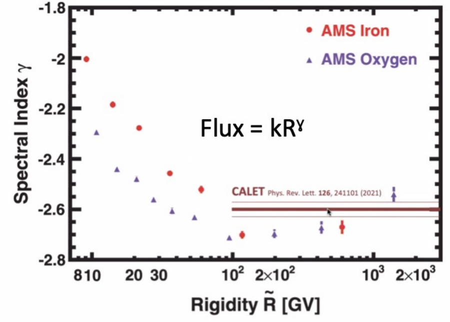
M. Aguilar et al., Phys. Rep. **894** (2021) 1-116.



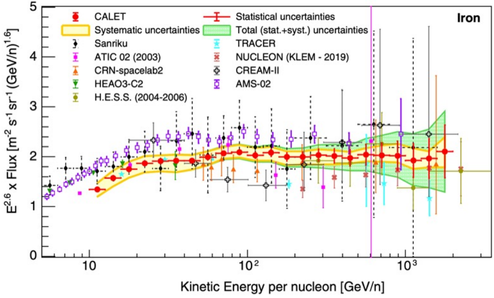
Same rigidity dependence, i.e. hardening, above 60 GeV.

Iron Flux

M. Aguilar *et al.*, Phys. Rev. Lett. **126** (2021) 041104.



O. Adriani *et al.*, Phys. Rev. Lett. **126** (2021) 241101.



Fe has a behaviour similar to He, C, and O.

Similar energy dependence observed by recent AMS-02 and CALET data.

Again some normalization difference.

Possible explanations about the hardening

The spectral hardening that we observe in spectra is coming from **an effect at the source or during propagation?**

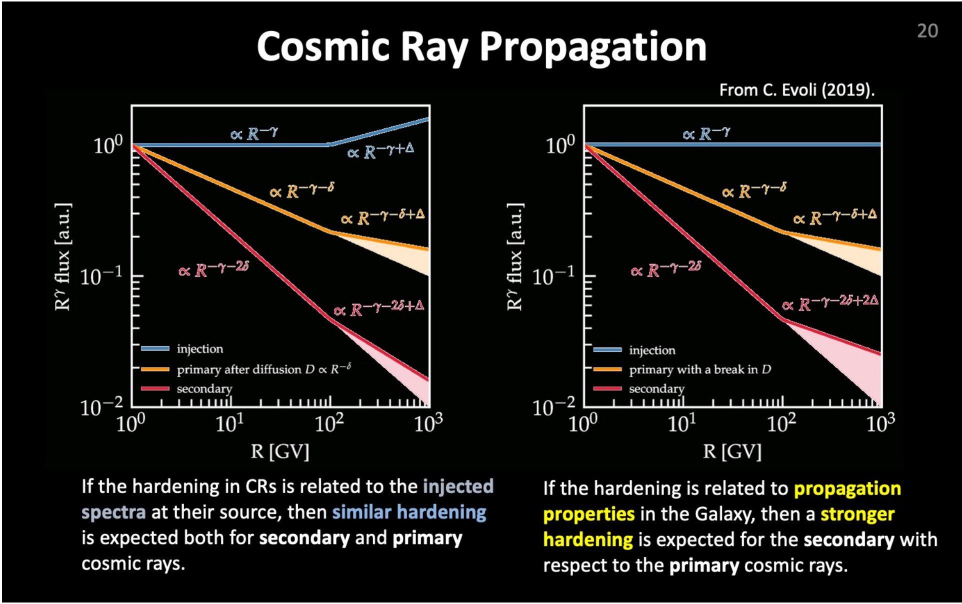
Cosmic ray primaries are mostly produced at astrophysical sources (ex. e-, p, He, C, O, ...), secondaries (ex. Li, Be, B, ...) are mostly produced by the collision of cosmic rays with the ISM.

The best way to understand whether the hardening is due to a "source" effect or a "propagation effect" is to look at the **Secondary/Primary ratios**. In fact:

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**.

Cosmic Ray Propagation

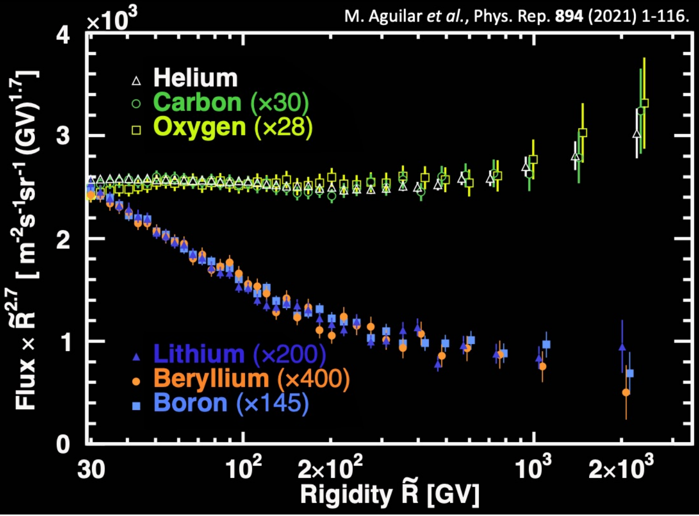


From C. Evoli (2019).

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.

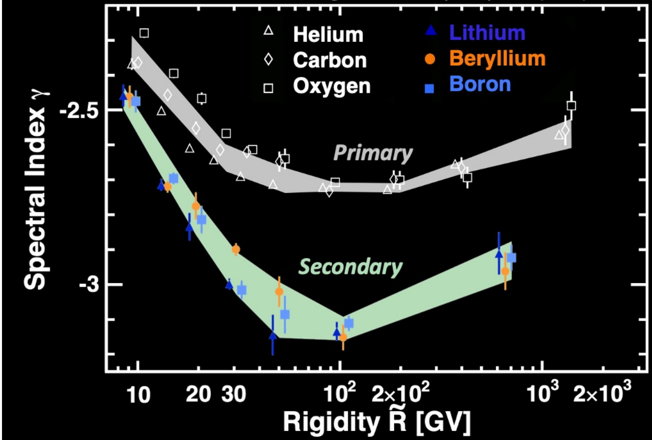
If the hardening is related to **propagation properties** in the Galaxy, then a **stronger hardening** is expected for the **secondary** with respect to the **primary** cosmic rays.

Light Ions Primary and Secondary Fluxes



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

Light Ions Primary and Secondary Spectral Indices



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

All light nuclei fluxes **deviate from single power law** above 200 GV.

Secondary hardening is **stronger**.

This favors the hypothesis that the flux hardening is a **universal propagation effect**.

Possible explanations about the hardening

After examining the latest data about primary and secondary nuclei, we can conclude that:

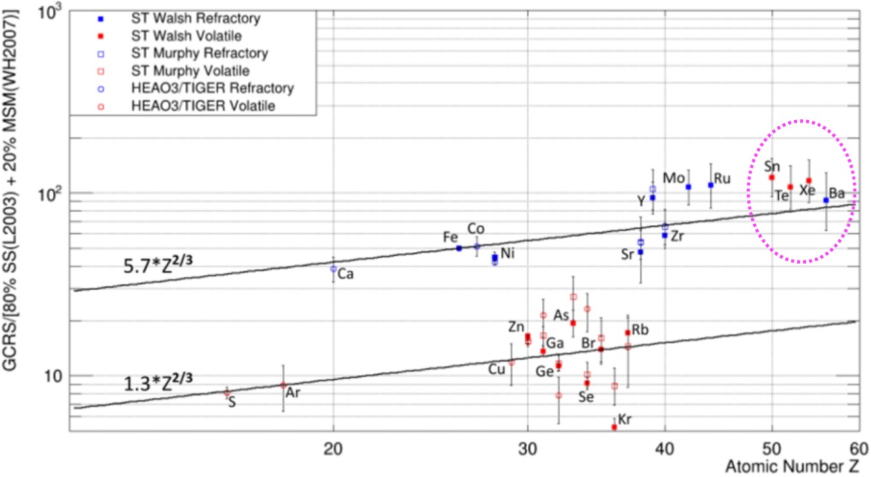
1) All nuclei fluxes deviate from single power law at 300-400 GV.

2) The hardening of secondary CRs is **stronger**. This favors the hypothesis that the flux hardening is a **universal propagation effect**.

3) No "hints" so far about the explanations of the **"softering" of CRs (seen for protons and helium)** at 10 GV.

Elements with Z<40 and 40<Z<56

Latest results from TIGER and Super-TIGER have shown a clear picture:



Elements with Z<40 and 40<Z<56

- Refractory elements that condense in dust grains are preferentially accelerated by SN shocks compared to volatile elements residing in gas;
- the GCRs are a mix of outflow from “young” massive stars and normal “old” ISM;
- Composition of sources is well described by 80% solar system (SS) + 20% massive star outflows (MSO).
- This mixture is representative of OB associations (young and massive stars, high-rate of SN).

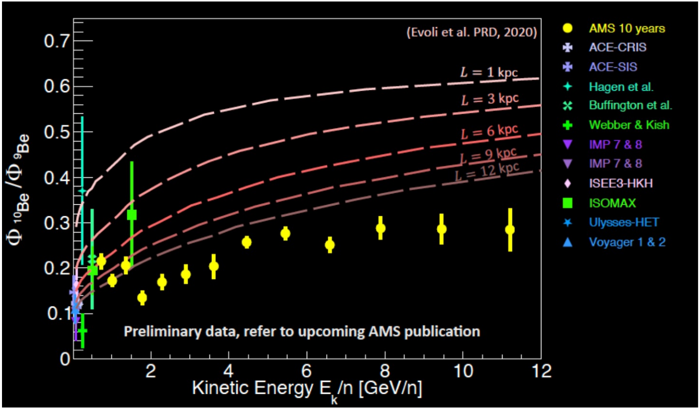
The model breaks for Z>40

Presence of other sources of Cosmic Rays?

Unstable Be isotopes

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

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



By latest AMS data, **tension with transport models??**

Matter-antimatter symmetry in the universe

One of the most surprising aspects of our universe is the **absence of antimatter**, although all the conservation laws seem to indicate an **exact symmetry between matter and antimatter**. Indeed, the CP violation (a violation of the charge conjugation parity symmetry) seen in weak interactions is very small. CP-symmetry states that the laws of physics should be the same if a particle is interchanged with its antiparticle (C-symmetry) while its spatial coordinates are inverted ("mirror" or P-symmetry).

Antimatter is produced at accelerators and, in any case, artificially on Earth. **In cosmic rays there is a fraction of antimatter** of secondary origin, as a product of interaction of primary protons with the interstellar medium.

On a large scale, there is **no evidence of the strong γ and X emission that should result from matter-antimatter annihilation in distant galaxies**, where matter clouds should meet antimatter clouds.

Matter-antimatter symmetry in the universe

One could assume that matter and antimatter remain **separated by large intergalactic spaces, giving rise to star clusters of matter and as many of antimatter**. At astronomical observation, antimatter could not be recognized, producing the same photons as ordinary matter.

However, the intergalactic space that should function as an **interdiction region between matter and antimatter** is not an empty space: observations have shown that in these regions there is a density of matter equal to about 1 atom of hydrogen per cubic meter. Such a presence of matter would be sufficient to trigger an interaction near these boundaries **highlighting the annihilation processes with an easily detectable production of gamma radiation, but this has never been observed**.

Another possibility is that regions dominated by antimatter may exist in the universe, but that matter-antimatter interaction is not observable just because **occurs in regions outside our observable universe**.

Matter-antimatter symmetry in the universe

The possible presence of cosmological antimatter in the Universe is a fundamental physics issue, which can be faced from the experimental point of view.

Anti-matter in cosmic rays can be produced by:

1. Cosmic ray collisions with the galactic medium;
2. Astrophysical objects ($e^{\pm}$ production in pulsars, ...);
3. Dark matter annihilations ($e^{\pm}$, p, $\overline{p}$, ^{2}H, $^{2}\overline{H}$, ...);
4. Primordial origin ($^{2}\overline{H}$, $^{3}\overline{He}$, $^{4}\overline{He}$, ...).

Antiprotons in Cosmic Rays

Antiprotons are a component of the cosmic radiation being produced in the **interaction between CRs and the interstellar matter**. Secondary antiprotons are mainly produced by CR protons interacting with ISM protons:

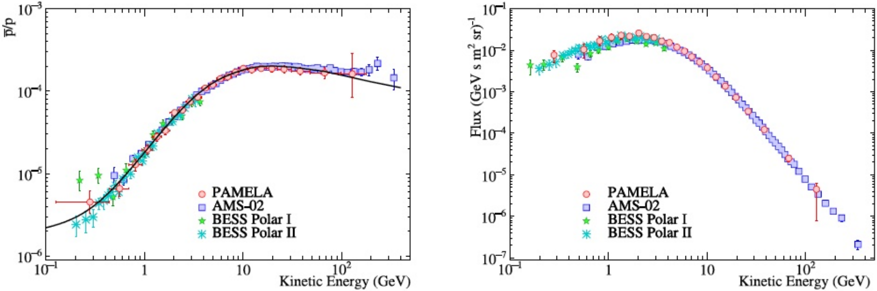
$$p + p \rightarrow p + p + (\overline{p} + p) \, .$$

This reaction occurs **above the threshold of $E_{thr} \geq 7 GeV$ of the relativistic proton against the proton at rest**.

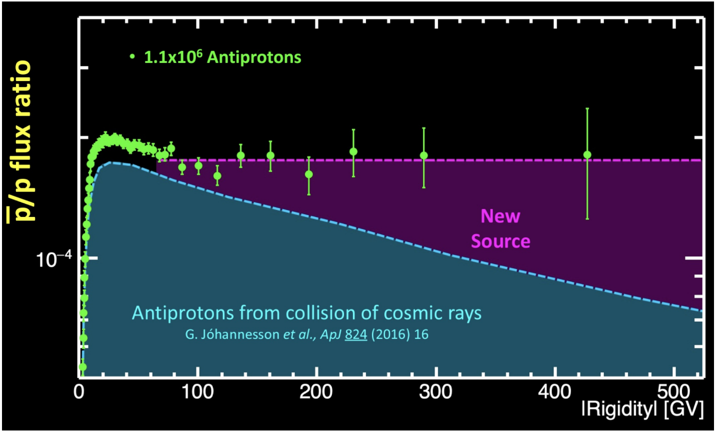
Being exactly the same as particles except for their opposite charge sign, antiparticles are readily distinguished as **they bend in opposite directions in the magnetic field**.
Magnetic spectrometers provide a clear and simple particle/antiparticle separation and probe the existence of antimatter in our Galaxy. The best constraints on antiproton data come from the BESS, PAMELA and AMS-02 experiments.

Antiprotons in Cosmic Rays

On the left plot the antip/p ratio is shown together with the results of detailed theoretical calculations, which assume pure secondary production of antiprotons during the propagation of CRs in the Galaxy (black line). The measured antip/p ratio agrees with calculations, consistently with the hypothesis that **the observed antiprotons are secondary particles produced by CR interactions with the interstellar medium**.



Antiprotons in Cosmic Rays: high energy

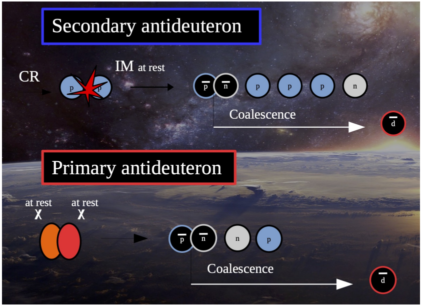


◇ AMS-02 finds a possible **excess of antiprotons over the predictions** (CR collisions) at high energies —> primary antiprotons?

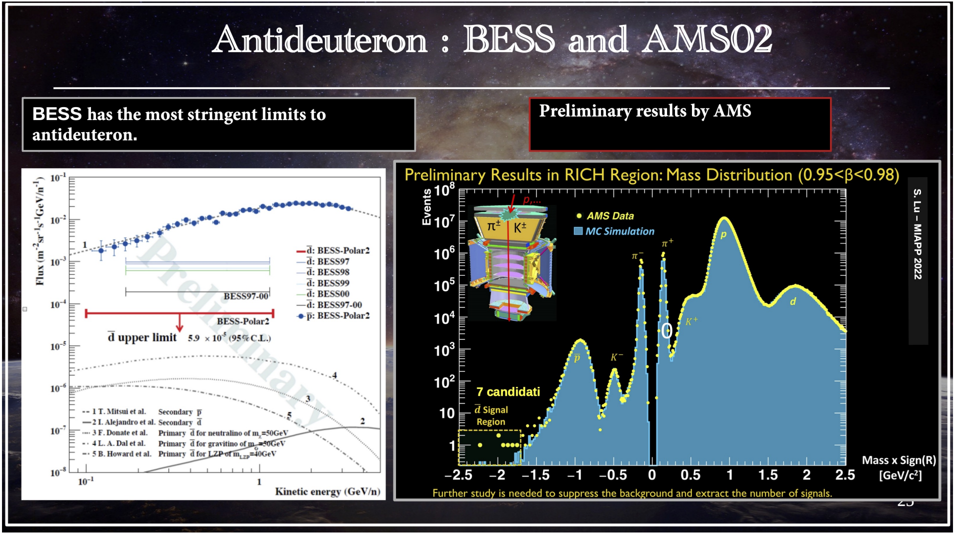
◇ Better knowledge of **cross-sections/CR confinement?**

Antinuclei

No heavier antinuclei have been detected so far. **The detection of a single antideuteron or antihelium nucleus would impact our understanding of the matter/antimatter asymmetry of the Universe**.
The BESS experiment provides the lowest upper limit to date for the antideuteron flux of 5.9×10^{-5} $(\mathrm{m}^2\mathrm{s\ sr\ GeV/n})^{-1}$ at the 95% confidence level, between 0.17 and 1.15 GeV/n. AMS-02 has not provided antideuteron data yet.



Antideuteron



Antideuteron : BESS and AMS02

BESS has the most stringent limits to antideuteron.

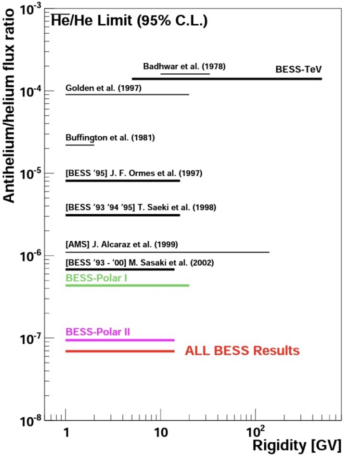
Preliminary results by AMS

Preliminary Results in RICH Region: Mass Distribution (0.95<β<0.98)

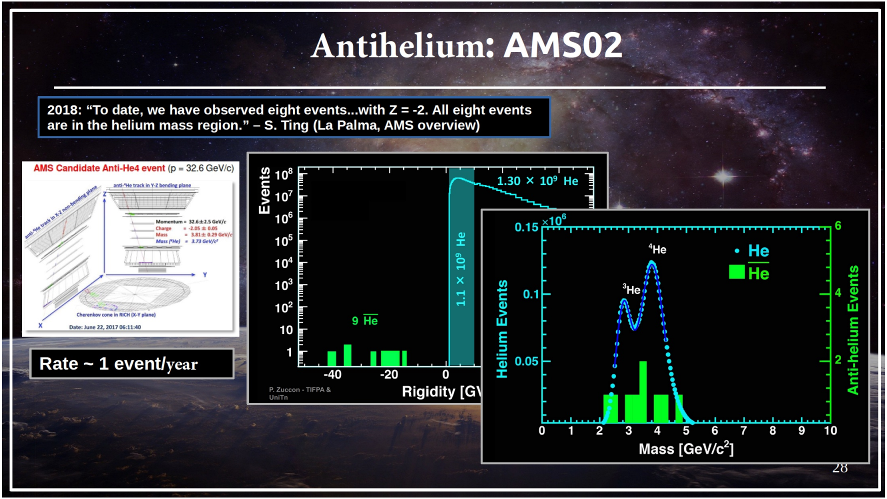
Further study is needed to suppress the background and extract the number of signals.

Antihelium

The BESS experiment provides the lowest upper limit to date on the relative antihelium-to-helium ratio, 1.0×10^{-7} in the rigidity range from 1.6 to 14 GV.



AMS-02 has not published antihelium data yet, but claims the detection of a few candidate events.



Antihelium: AMS02

2018: “To date, we have observed eight events...with Z = -2. All eight events are in the helium mass region.” – S. Ting (La Palma, AMS overview)

AMS Candidate Anti-He4 event (p = 32.6 GeV/c)

Momentum = 32.6±2.5 GeV/c
Charge = -2.05 ± 0.05
Mass = 3.81± 0.29 GeV/c
Mass (^{4}He) = 3.73 GeV/c^2

Date: June 22, 2017 06:11:40

Rate ~ 1 event/year

P. Zuccon - TIFPA & UniTn

Electrons plus Positrons

Electrons and positrons constitute about 1% of the CRs.

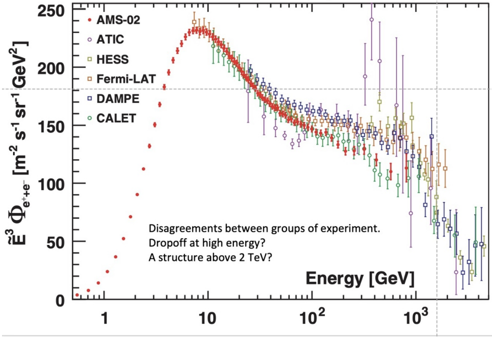
High-energy electrons are subject to synchrotron radiation where the matter density and the magnetic fields are large.
Due to the magnetic fields, **the typical distance over which 1 TeV electron lose half of its total energy is estimated to be 300-400 pc when it propagates within ~1 kpc of the Sun.**

For these reasons, at energies above a few hundred GeV, **the majority of electrons is supposed to be originated by sources closer than a few hundred pc**. High-energy CR electrons really probe CR production and propagation in the nearby region of our Galaxy.

The presence of a **structure in a smooth spectrum** of the lepton component would represent an **important signature for unexpected physics**, in particular from annihilation of dark matter candidates or from the presence of nearby sources and active galactic accelerator of CR electrons.

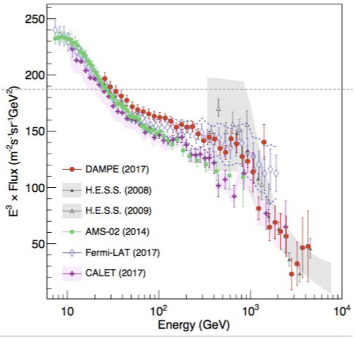
"All-electron" spectrum

In recent years, the knowledge of the leptonic component in the CRs has gained greatly from **Fermi-LAT, PAMELA, AMS-02, CALET and DAMPE.**



M. Aguilar et al., Phys. Rev. Lett. **122** (2019) 101101.

Disagreements between groups of experiment.
Dropoff at high energy?
A structure above 2 TeV?



"All-electron" spectrum

Looking to the measured spectra we can observe a few features in the "all-electron" spectrum:

"All-electron" spectrum

1) Disagreements between groups of experiment (calibration and systematics issues)

2) Dropoff at 1 TeV

3) A structure above 2 TeV?

The connection to ground-based experiments (HESS) is definitively established.

The Positron Component

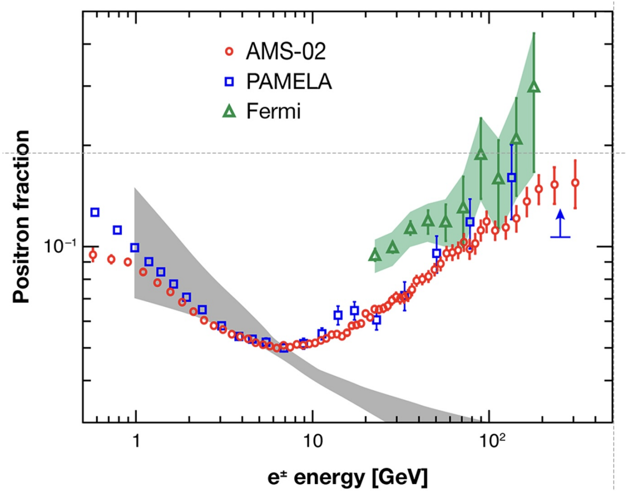
Experiments using magnetic spectrometers can **distinguish the sign of the electric charge**. This allows the measurement of the positron fraction in the $e^{\pm}$ component of CRs as a function of the energy.
The dominant background is represented by **misidentified CR protons (having the same charge sign and being much more abundant)**.
Unlike electrons, which are present as primary component in CR sources, the **vast majority of positrons arise as secondary products of CR interactions in our Galaxy**.

PAMELA and AMS are the best instruments to measure the positron component in CRs.

The Fermi-LAT experiment is mainly devoted to γ-ray astronomy and is also performing CR measurements. It is not instrumented with a magnetic spectrometer: electron and positron components are measured separately by **exploiting Earth's shadow**, which is offset in opposite directions for opposite charges due to the magnetic field of the Earth.

The Positron Fraction

This figure **shows the positron fraction**, i.e. the ratio between $\Phi_{e+}/(\Phi_{e+}+\Phi_{e-})$ measured by FERMI, PAMELA and AMS-02 as a function of the energy E. The dashed area is the GALPROP prediction.



The Positron Component

The results presented several surprises!

The positron-fraction spectrum does not exhibit fine structures and **steadily increases in the region between 10 and 250 GeV**.

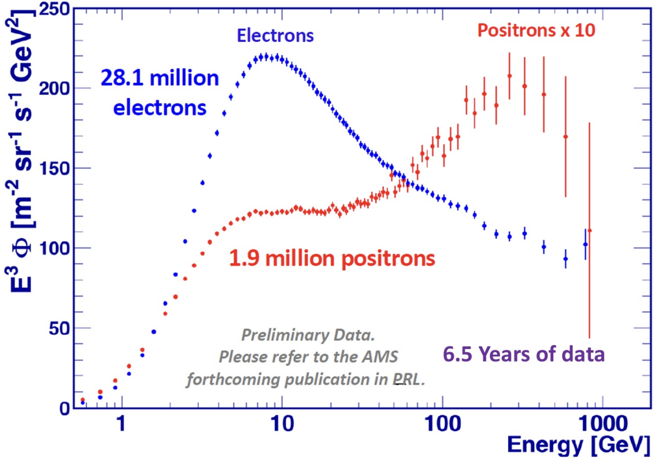
At high energies (above 10 GeV) the positron fraction increases significantly with energy.

This increase is well above that expected from a model in which all positrons are of secondary origin: the heavy black line in the figure shows the result of a calculation based on such an assumption. This increase must be understood.

In order to understand why the ratio increases (**increase of positrons or decrease of electrons?**), the absolute positron flux as been measured.

The Positron Flux

Study of the electron and positron spectra can be done separately



The rise of the positron fraction from 20 GeV is due to an excess of positrons

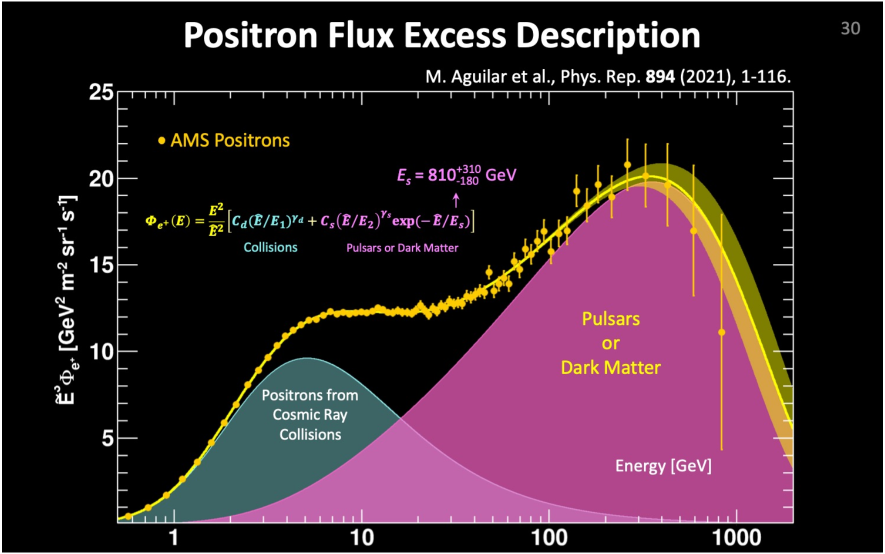
Considerations on the positron component

The agreement between PAMELA, Fermi-LAT and AMS-02 data **reduces the possibility of a systematic bias and gives confidence that the increase of the positron flux is to be ascribed to a physical, still unknown, effect**.

Several theoretical explanations have been proposed to explain the observed excess:

⋄ **astrophysical origin, such as nearby pulsars or microquasars**.

⋄ **exotic sources, as for instance the annihilation of dark matter particles in the proximity of our Galaxy**



Positron Flux Excess Description

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

$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_d(\hat{E}/E_1)^{\gamma_d} + C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)\right]$$

Collisions

Pulsars or Dark Matter

$E_s = 810^{+310}_{-180}$ GeV

Pulsars

A pulsar (from pulsating radio source) is a highly magnetized rotating neutron star that emits beams of electromagnetic radiation out of its magnetic poles. This radiation can be observed only when **a beam of emission is pointing toward Earth** (similar to the way a lighthouse can be seen only when the light is pointed in the direction of an observer), and is responsible for the **pulsed appearance of emission.**

Neutron stars are very dense and have short, regular rotational periods. This produces a very precise interval between pulses that ranges from milliseconds to seconds for an individual pulsar.

The periods of pulsars make them very useful tools for astronomers. Observations of a pulsar in a binary neutron star system were used to indirectly confirm the existence of gravitational radiation. The first extrasolar planets were discovered around a pulsar, PSR B1257+12 in 1992.

Positron production from pulsars

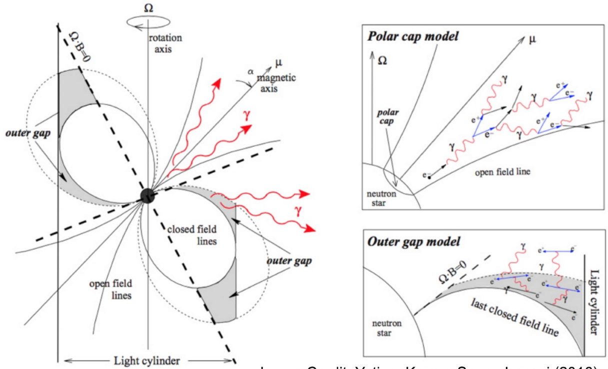


Image Credit: Yating, Kwong-Sang, Jumpei (2016)

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

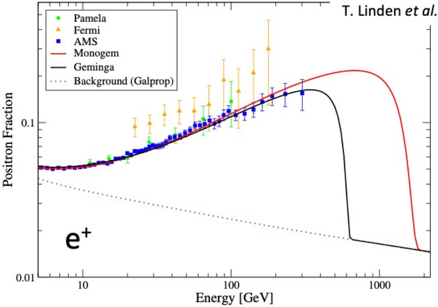
-These electrons then induce electromagnetic cascades through the emission of curvature radiation

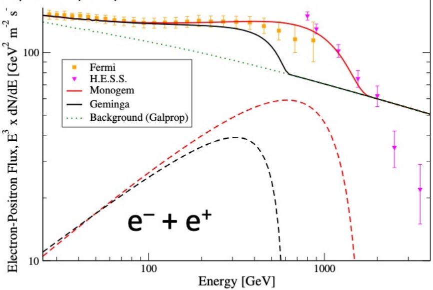
-This results in the production of photons with energies above the threshold for pair production in the strong magnetic field

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

Positron Flux from Pulsar

T. Linden *et al.*, Astrop. J. **772** (2013)





Pulsars spinning produce EM radiation and cosmic rays (pair production).

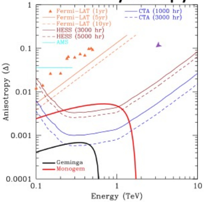
To distinguish from DM models:

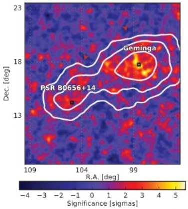
→ **spectral features** of e^+ and of $(e^+ + e^-)$

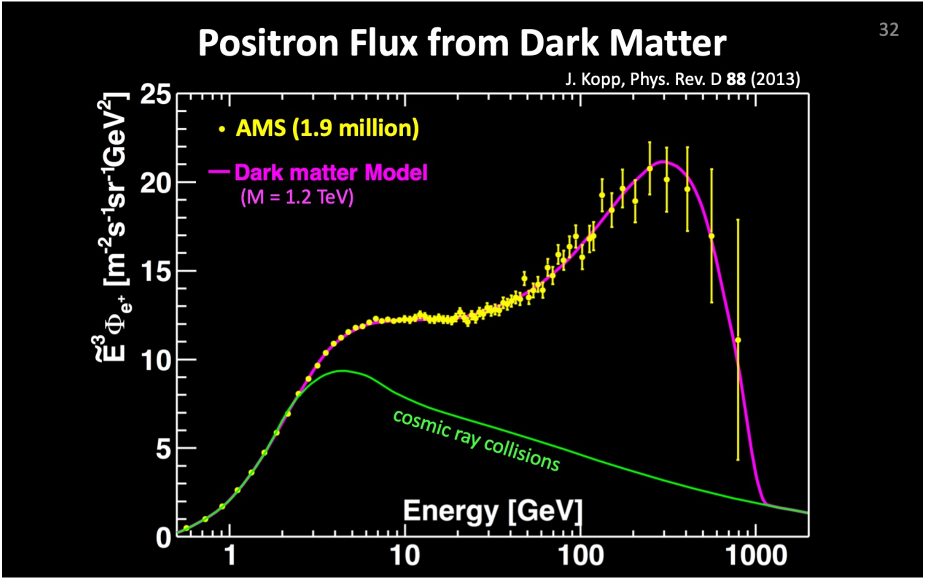
→ **anisotropy** of e^+ and of $(e^+ + e^-)$

Experimentally, studying $e^+ + e^-$ is easier than positron → calorimetric approaches.

$e^- + e^+$ anysotropy





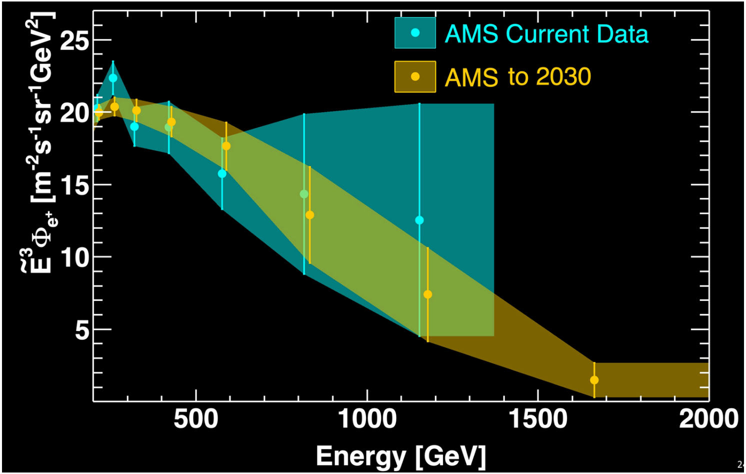


Positron Flux from Dark Matter

J. Kopp, Phys. Rev. D **88** (2013)

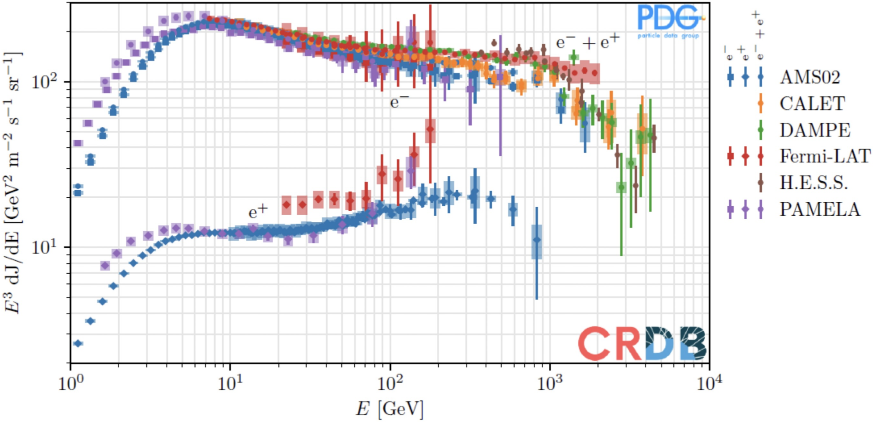
Prospects for AMS

By 2030 AMS plans to add more and better precise points to the positron flux to constrain the models.



Summary of lepton spectra in CRs

We can then summarize all lepton spectra (electrons, positrons, electrons+positrons) as measured so far by space and ground experiments.

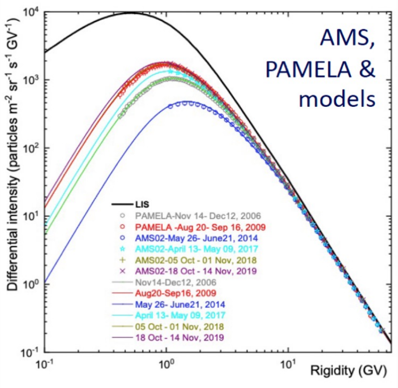


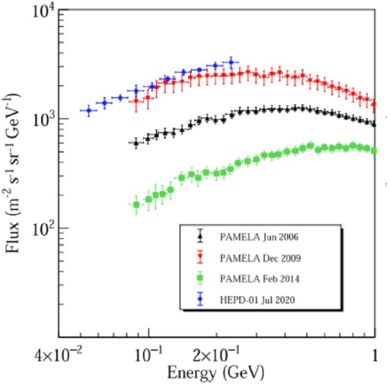
Particles in the heliosphere

Experiments operated in the last 15 years (mainly AMS and PAMELA) provided a lot of data of extreme interest for the HelioPhysics and SpaceWeather communities.

Daily data available !

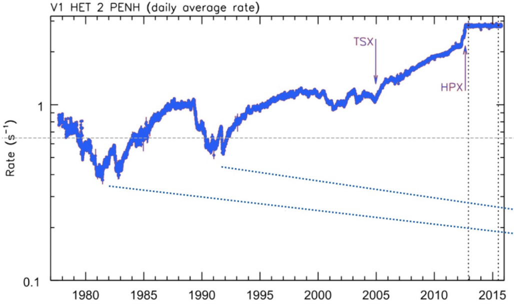
Different experiments/detectors (HEPD-01, CALET, . . .) are sensitive to different energies.

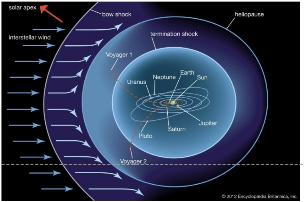


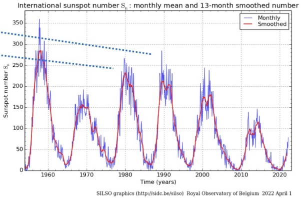


Particles in the heliosphere: Voyager I and II

Voyager II: 20 August 1977; Voyager I: 5 September 1977.
Important feature: **CR anticorrelated to sunspots until inside heliosphere!**
In 2005 flying in Termination Shock (TSX);
Since 2013 left the Heliopause (HPX) and reached the ISM.



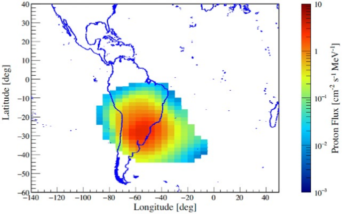


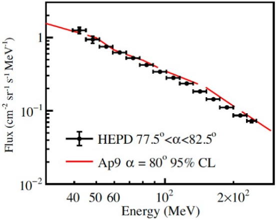


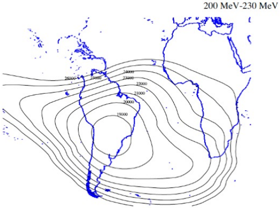
SILSO graphics (http://sidc.be/silso) Royal Observatory of Belgium 2022 April 1

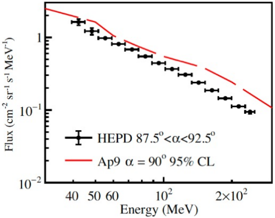
Particles in the magnetosphere: SAA

Most recents results on particles trapped in the SAA: HEPD-01 on CSES-01 → input for AP-9 and AE-9 trapped models!



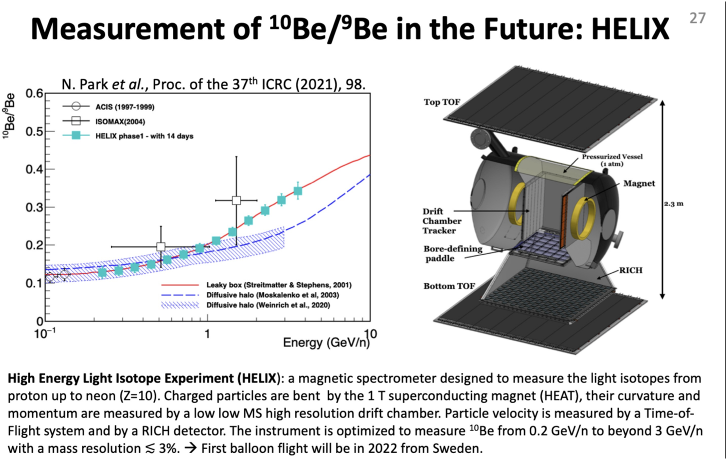






Future experiments: "HELIX" balloon just launched from Kiruna!

A new magnet spectrometer payload to measure ^{10}Be/^{9}Be isotope ratio up to 10 GeV/n and isotopes Z<10



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

27

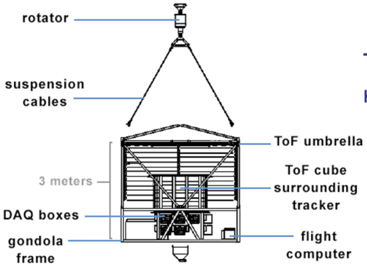
N. Park *et al.*, Proc. of the 37th ICRC (2021), 98.

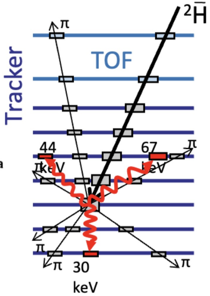
High Energy Light Isotope Experiment (HELIX): a magnetic spectrometer designed to measure the light isotopes from proton up to neon (Z=10). Charged particles are bent by the 1 T superconducting magnet (HEAT), their curvature and momentum are measured by a low low MS high resolution drift chamber. Particle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

Future experiments: "GAPS" launch Dec. 2024 from Antartica

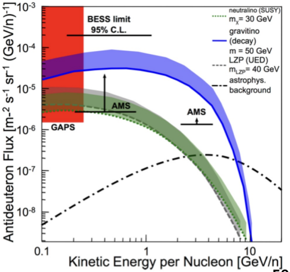
High statistics antiproton spectrum; 2-3 times improved antiD sensitivity compared to BESS. GAPS sensitivity in the 100 - 250 MeV/n range.

General Anti-Particle Spectrometer (GAPS): a balloon-borne instrument designed to detect cosmic ray antimatter stopping it in material forming and exotic atom with the material and detecting the X-ray from orbital transition of the exotic atom and the pion “star” produced by final annihilation. In construction, foreseen several balloon campaigns in Antarctica starting from 2022.



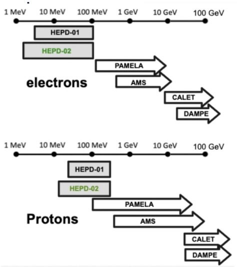


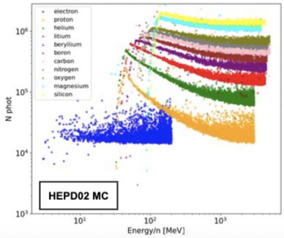
T. Aramaki *et al.*, Phys. Rep. **618** (2016) 1-37.

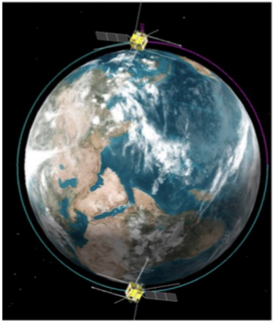


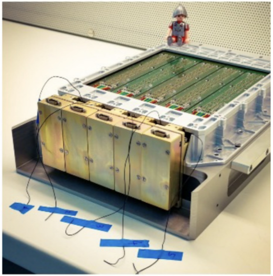
Future experiments: "CSES-02/HEPD-02" launch Dec. 2024

Acceptance: 30-200 MeV protons, 3-100 MeV electrons and light nuclei.
Higher energy window and full coverage wrt HEPD-01.



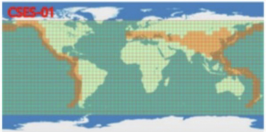






First tracker (and not single layer), based on pixel, operated in space

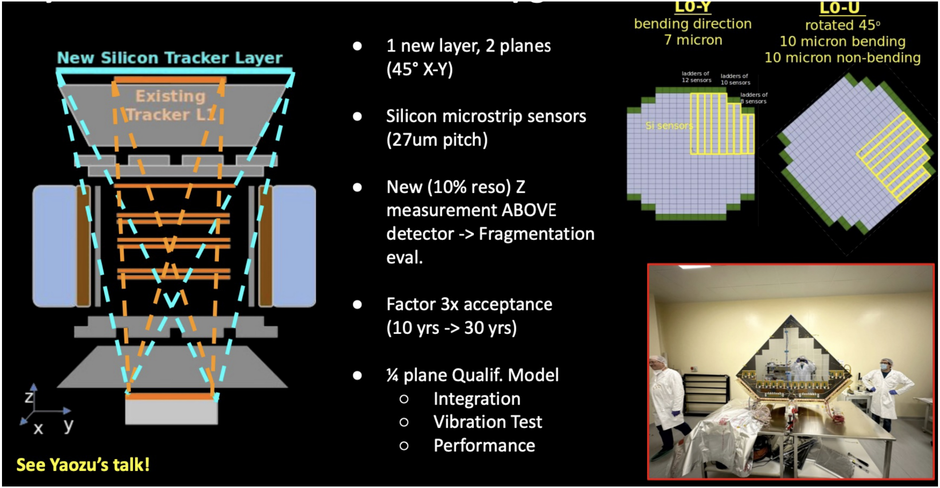
Operation area between lat [-65,65]



Full coverage at extreme latitudes

“AMS” upgrade on ISS: deployed in 2026

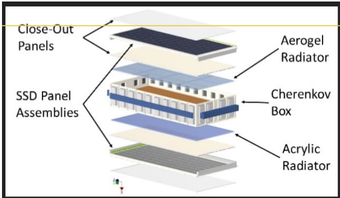
Will increase acceptance, also for positrons/antiprotons



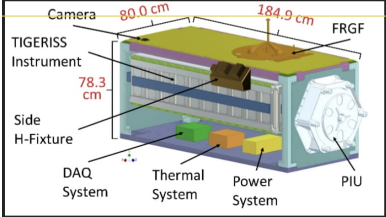
- 1 new layer, 2 planes (45° X-Y)
- Silicon microstrip sensors (27um pitch)
- New (10% reso) Z measurement ABOVE detector -> Fragmentation eval.
- Factor 3x acceptance (10 yrs -> 30 yrs)
- ¼ plane Qualif. Model
  - Integration
  - Vibration Test
  - Performance

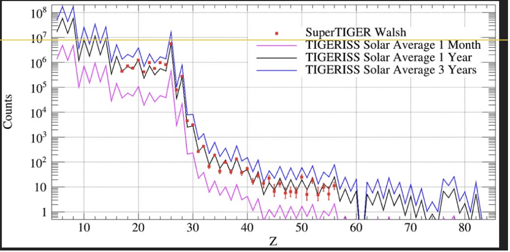
See Yaozu’s talk!

Future experiments: “TIGER-ISS” launch in 2026 on ISS

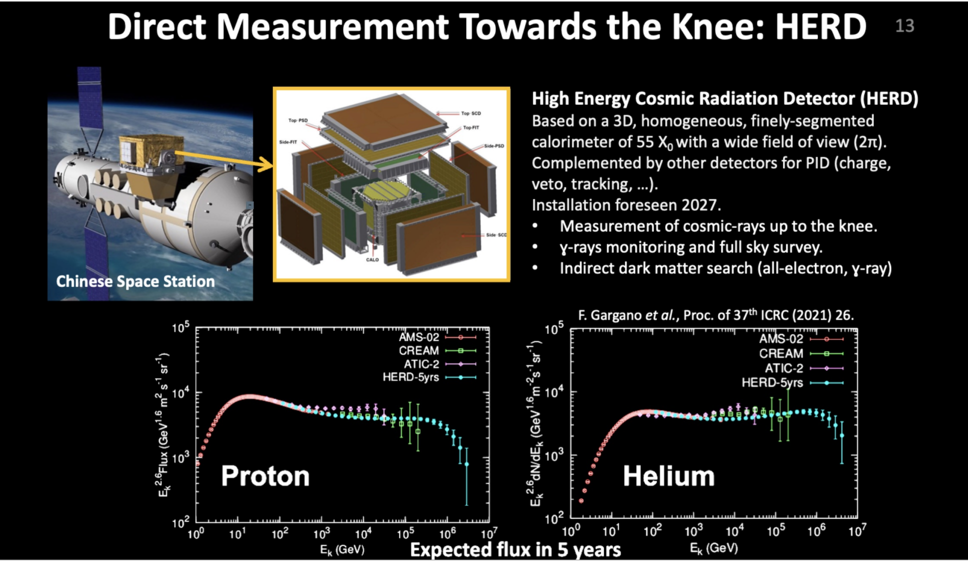


- TIGER-ISS instrument model for the Japanese Experiment Module “Kibo” on ISS
- Silicon strip detector (SSD) for precision charge measurement σQ < 0.24e for **5 ≤ Z ≤ 82** and SiPM Cherenkov detector readout
- In 1 year the statistics of SuperTiger (see below)
- No atmospheric correction –> cleaner signal





Future experiments: "HERD" launch in 2027 on the CSS



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

Conclusions about direct measurements of CRs

1. The flux of CRs is NOT a simple power-law
   - ◇ First break (hardening) —> propagation
   - ◇ Second break (softening) —> ?
2. Why is the slope of the spectrum of CR proton and helium different?
   - ◇ Helium spallation?
   - ◇ Different acceleration sites or mechanisms?
3. What is the origin of the positron rise?
   - ◇ Astrophysics—> pulsars?
   - ◇ Dark matter?
4. What is the origin of the positron rise?
5. Is there room for an exotic production of antiprotons at high energy?
6. Is the electron break at 1 TeV understood?
7. A new source for Z> 40 elements?

Perspectives

1. New experiments and data coming soon!

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

2. New experiments measuring cross sections are needed!

   ⋄ e.g. NA61/Shine @ CERN (B isotopes from C beam, and other light elements), LHCf @ CERN, . . .

ERA OF HIGH PRECISION MEASUREMENTS !

Cosmic ray direct measurements are becoming more precise than the current astrophysical models and cross-sections data.