DIRECT MEASUREMENTS OF COSMIC RAYS

Roberta Sparvoli

Università di Roma Tor Vergata and INFN

Lecture 2

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

24rd Course: "Particles and the Cosmos - Bridging the Infinitesimal and the Infinite" — 29 July - 6 August 2026

Outline of Lecture 2

In this second lecture, we will talk about:

- Energy Spectrum of CR Protons and Helium
- Heavier nuclei spectra
- Elements with Z<40 and 40<Z<56
- Antimatter measurements in GCRs
- Cosmic Rays in the heliosphere
- Future experiments
- Conclusions

Energy Spectrum of CR Protons and Nuclei

We said in lecture 1 that at energies larger than few GeV **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

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 direct measurements experiments.

From the experimental data, some features are clearly visible:

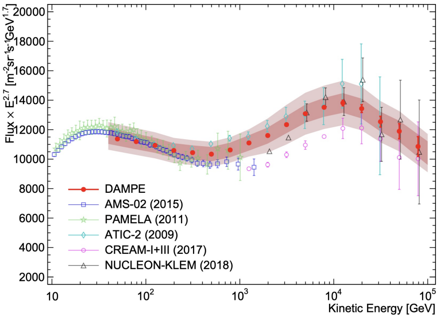
Deviation from a single power-law!

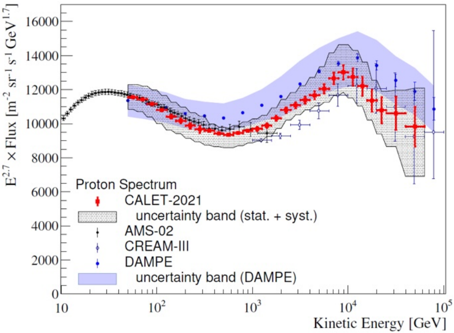
1) a "hardening" in both species at about 300-400 GV (hardening means that the spectrum become less steep)
2) a "softening" above 10 TV (softening means that the spectrum becomes steeper)

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)



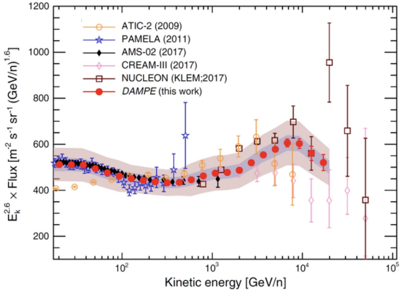


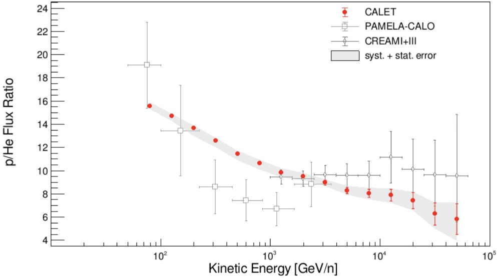
Spectra of protons is not a single power law below the knee:

◇ The **hardening at $R = p/Z \sim 300$ - 400 GV** is well established since first observation by CREAM and PAMELA

◇ The **softening at $R = p/Z \sim 10$ 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:

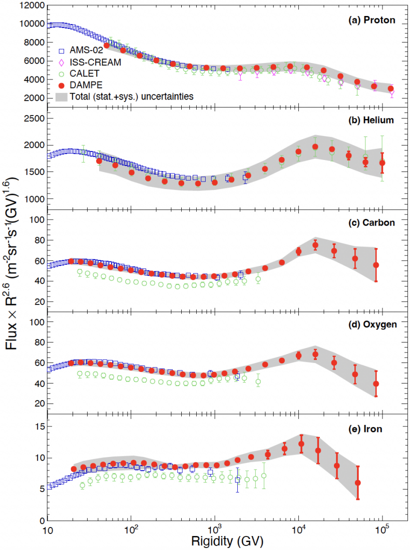
- ◇ **A hardening at R = p/Z ~ 300 - 400 GV**
- ◇ **A softening at R = p/Z ~ 10 TV**

But the He spectrum is slightly harder than that of protons ($\Delta\gamma = 0.1$) !

Heavier nuclei spectra

At first glance, current experiments have shown that the hardening and softening **are present in all elements!**

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



Secondary/Primary ratios

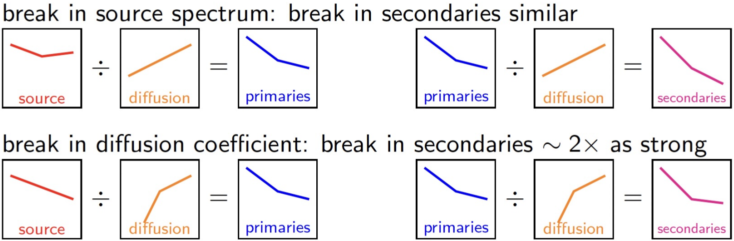


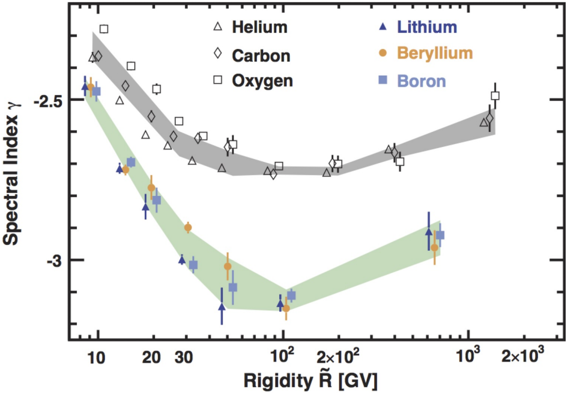
Figure: See P. Mertsch, this school

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**.

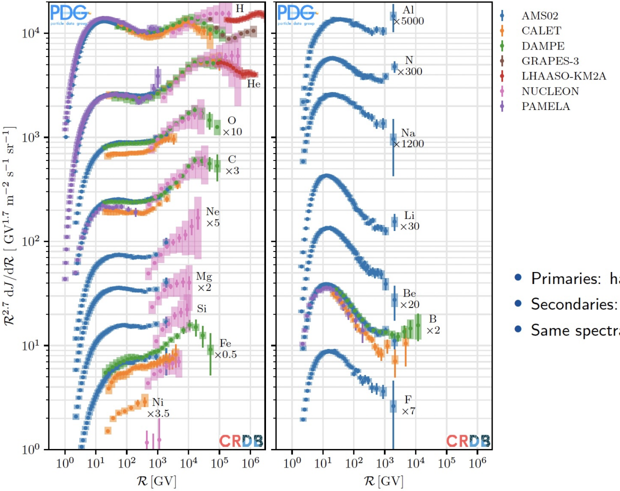
Hardening as universal propagation effect

Aguilar *et al.* (2019)



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

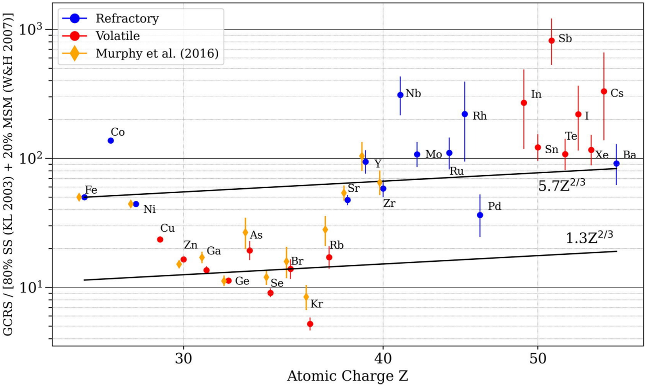
The global picture



- Primaries: harder spectra
- Secondaries: softer spectra
- Same spectral breaks

Figure: See P. Mertsch, this school

Latest Results for Ultra-Heavy Nuclei



UHGCRs are a mix of outflow from "young" massive stars and normal "old" ISM; the composition is well described by 80% solar system (SS) + 20% Massive Star Material (MSM). This mixture is representative of OB associations (young and massive stars, high-rate of SN).

Latest Results for Ultra-Heavy Nuclei

Ultra-Heavy Galactic Cosmic Rays

SuperTIGER has measured cosmic-ray elemental abundances from

$$10 \leq Z \leq 56$$

Main Findings

- Refractory elements that condense in dust grains are preferentially accelerated by SN shocks compared to volatile elements residing in gas;
- Measurements up to $Z = 40$ are consistent with acceleration in OB associations.

Open Questions

- Nuclei with $Z > 40$ do not fully follow the standard OB-association model.
- Data suggest an additional source and/or a different acceleration mechanism.

Matter–Antimatter Symmetry in the Universe

A Cosmological Mystery

One of the most surprising features of the Universe is the apparent absence of antimatter on large scales, despite the near symmetry between matter and antimatter in the laws of physics.

- Every known particle has a corresponding antiparticle.
- CP symmetry implies a close relationship between matter and antimatter.
- CP violation has been observed in weak interactions, but its magnitude appears too small to explain the observed matter dominance.
- As a result, the origin of the matter–antimatter asymmetry remains an open problem in fundamental physics.

Observation

Although antimatter can be routinely produced in laboratories, the observable Universe appears to be overwhelmingly composed of matter.

Can Large Antimatter Regions Exist?

A Possible Scenario

Matter and antimatter could be separated into large domains, forming galaxies and clusters composed of antimatter.

- Antimatter stars and galaxies would emit the same light as ordinary matter.
- In principle, they could therefore be difficult to identify through optical observations alone.
- However, matter and antimatter boundaries would generate intense annihilation radiation.

Observational Constraint

Intergalactic space is not empty: even a very low density of matter would lead to annihilations at matter–antimatter boundaries, producing detectable γ rays.

No convincing evidence of such large-scale annihilation radiation has been observed.

Antimatter in Cosmic Rays

Cosmic-Ray Antimatter

Antimatter particles are observed in cosmic rays and can be produced through several mechanisms.

1. **Secondary production**: interactions of cosmic rays with the interstellar medium;
2. **Astrophysical sources**: particle acceleration and pair production in objects such as pulsars;
3. **Dark matter processes**: annihilation or decay producing $e^{\pm}$, $\overline{p}$, $\overline{D}$, etc.;
4. **Primordial antimatter**: anti-nuclei such as $\overline{D}$, $^{3}\overline{\mathrm{He}}$, $^{4}\overline{\mathrm{He}}$ originating from cosmological antimatter regions.

Key Point

The discovery of antihelium or heavier anti-nuclei would represent a strong indication of primordial antimatter in the Universe.

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:

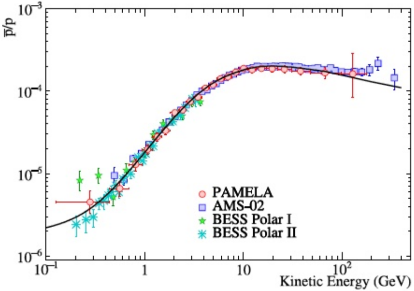
$$p + p \rightarrow p + p + (\overline{p} + p)\,.$$

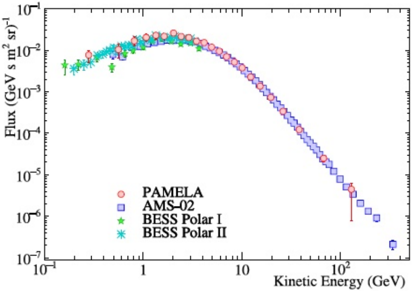
This reaction occurs **above the threshold of $E_{thr} \geq 7 GeV$ of the relativistic proton against the proton at rest**.

Antiparticles are distinguished as **they bend in opposite directions in the magnetic field** with respect to particles.
Magnetic spectrometers provide particle/antiparticle separation. The best constraints on antiproton data come from the **BESS, PAMELA and AMS-02** experiments.

Antiprotons in Cosmic Rays

- Left: $\overline{p}/p$ **ratio** together with calculations of pure secondary production of antiprotons in the Galaxy (black line).
  The measured $\overline{p}/p$ ratio agrees with calculations, consistently with the hypothesis that **the observed antiprotons are secondary particles produced by CR interactions with the interstellar medium**.
- Right: $\overline{p}$ **flux** from different spectrometers.





Cosmic-Ray Antideuteron Search

Why Antideuterons?

Low-energy antideuterons ($\overline{\mathrm{D}}$) are considered one of the most promising indirect probes of exotic matter or dark matter.

The expected astrophysical background is extremely small at low kinetic energies, while dark-matter annihilation or decay could produce a detectable signal.

Experimental Status

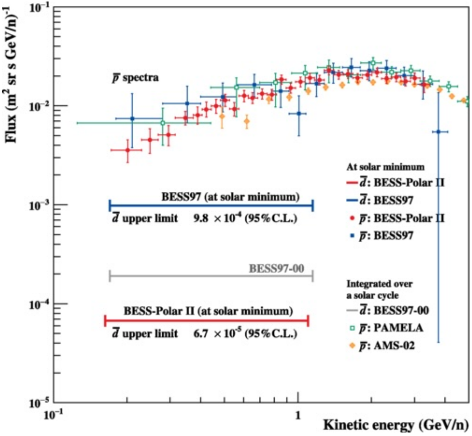
- No confirmed cosmic-ray antideuteron detection so far.
- Current measurements provide upper limits only.
- Antideuteron searches remain statistics limited.

Ongoing Searches

- Space-based magnetic spectrometers continue to search for $\overline{\mathrm{D}}$ candidates.
- Best limits come from the BESS balloon campains
- AMS has not provided final data yet

Cosmic-Ray Antideuteron Search

The BESS experiment provides the lowest upper limit to date for the antideuteron flux of 6.7×10^{-5} $(\mathrm{m}^2\mathrm{s\ sr\ GeV/n})^{-1}$ at the 95% confidence level, between 0.17 and 1.15 GeV/n.



Search for Antihelium in Cosmic Rays

Why Antihelium?

The discovery of an antihelium nucleus

$$^{3}\overline{\mathrm{He}} \quad \text{or} \quad ^{4}\overline{\mathrm{He}}$$

would be revolutionary.
Unlike antiprotons and positrons, their expected secondary production in cosmic-rays is extremely suppressed, making antihelium a probe of new physics.

Possible Origins

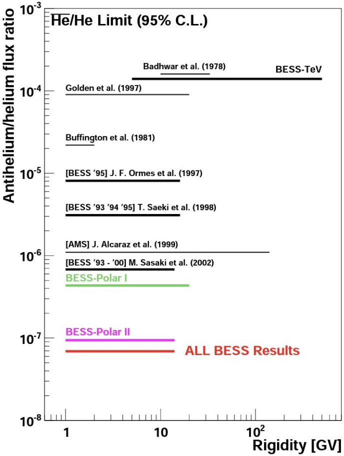
- Primordial antimatter domains
- Antistars or antimatter clouds
- Dark-matter annihilation or decay
- Exotic production mechanisms

Current Status

- No confirmed antihelium detection
- Candidate events by AMS reported and under study
- Upper limits by BESS

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.



The Positron Component of Cosmic Rays

Why Positrons are Interesting

Magnetic spectrometers can determine the sign of the particle charge, allowing separate measurements of electrons and positrons.

The main background originates from misidentified protons, which are much more abundant than positrons.

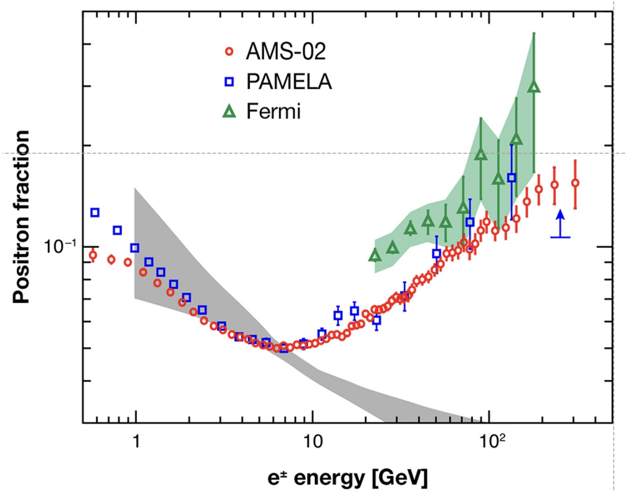
Origin of Positrons

- Most positrons are expected to be **secondary particles**, produced in interactions of cosmic rays with the interstellar medium.
- The positron fraction is therefore a sensitive probe of cosmic-ray propagation and possible additional sources.

The Fermi-LAT experiment, mainly devoted to γ-ray astronomy and not instrumented with a magnetic spectrometer, measures the electron and positron components separately by **exploiting Earth's magnetic field**.

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**.

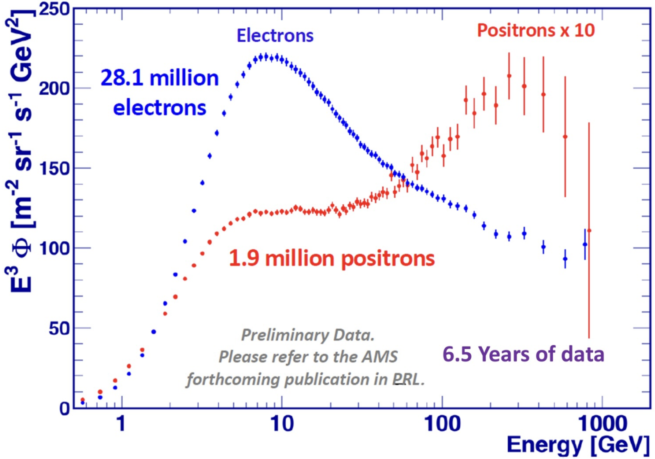
At high energies (above 10 GeV) the positron fraction increases significantly with energy.

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

The Positron Fraction Excess

Experimental Discovery

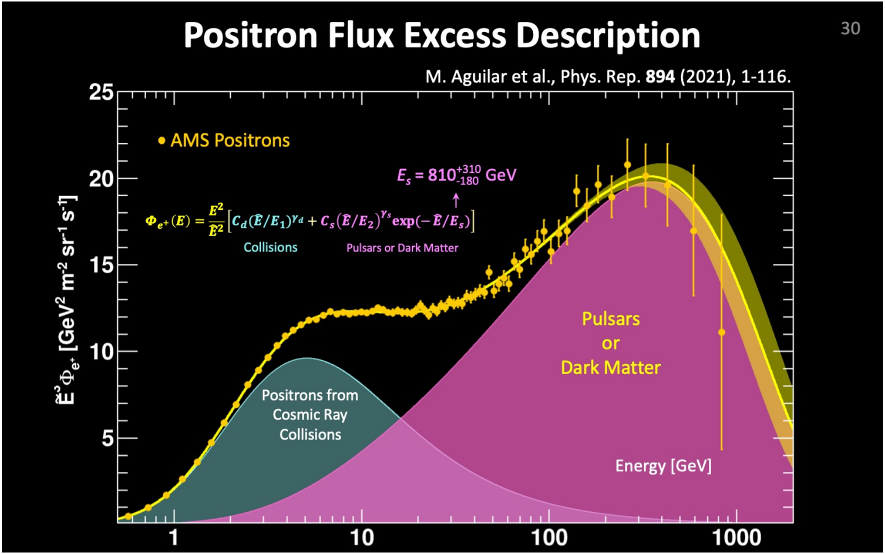
The agreement between PAMELA, Fermi-LAT and AMS-02 data **reduces the possibility of a systematic bias and gives confidence that the increase of the positron flux is to be ascribed to a physical, still unknown, effect**.

Key Observation

- Positron fraction increases from ~ 10 GeV to several hundred GeV.
- Inconsistent with standard secondary-production models.
- Indicates the presence of an additional high-energy positron source.

Possible Explanations

- Dark-matter annihilation or decay
- Astrophysical accelerators (pulsars?)
- Modified cosmic-ray propagation scenarios


Positron Flux Excess Description
30
M. Aguilar et al., Phys. Rep. 894 (2021), 1-116.
• AMS Positrons
$E_s = 810^{+310}_{-180}$ GeV
$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_d(\hat{E}/E_1)^{\gamma_d} + C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)\right]$
Collisions
Pulsars or Dark Matter
Pulsars
or
Dark Matter
Positrons from
Cosmic Ray
Collisions
Energy [GeV]
$\tilde{E}^3\Phi_{e^+}$ [GeV^2 m^{-2} sr^{-1} s^{-1}]
25
20
15
10
5
1
10
100
1000

Pulsars as Sources of Cosmic-Ray Positrons

Basic Idea

Rapidly rotating neutron stars generate intense magnetic and electric fields, capable of accelerating electrons to very high energies.

Production Mechanism

1. Particle acceleration in the pulsar magnetosphere;
2. γ-ray emission by synchrotron and curvature radiation;
3. Pair production:

$$\gamma \to e^+ e^-$$

4. Escape and diffusion through the Galaxy.

Observable Consequences

- Additional high-energy positrons.
- Rise of the positron fraction above ~ 10 GeV.
- Cutoff at energies of several hundred GeV–TeV.
- Possible spectral features from nearby sources.

Pulsars as Sources of Cosmic-Ray Positrons

Candidate Sources

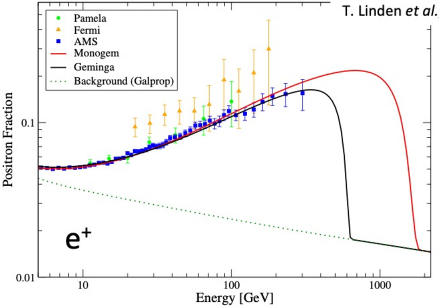
Nearby middle-aged pulsars such as **Geminga** and **Monogem** are among the leading candidates for the observed positron excess. Their surrounding γ-ray halos demonstrate that high-energy $e^{\pm}$ pairs escape into the interstellar medium.

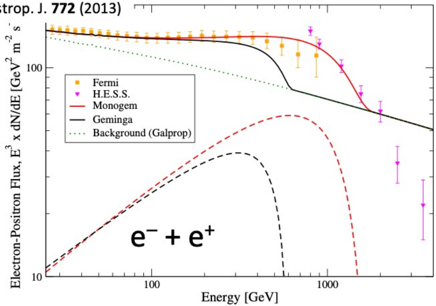
Significance

The pulsar scenario provides a natural astrophysical explanation of the positron excess observed above 10 GeV, without requiring dark-matter annihilation. Current measurements, however, do not yet uniquely distinguish between pulsars and more exotic scenarios.

Positron Flux from Pulsar

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

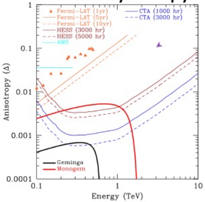


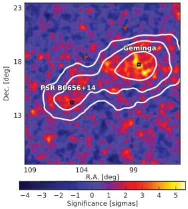


Pulsars spinning produce EM radiation and cosmic rays (pair production).
To distinguish from DM models:
→ **spectral features** of e^+ and of $(e^+ + e^-)$
→ **anisotropy** of e^+ and of $(e^+ + e^-)$

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

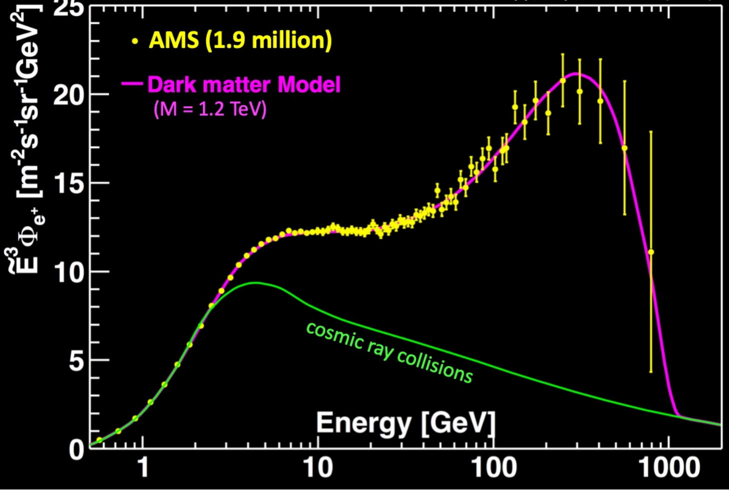
$e^- + e^+$ anysotropy





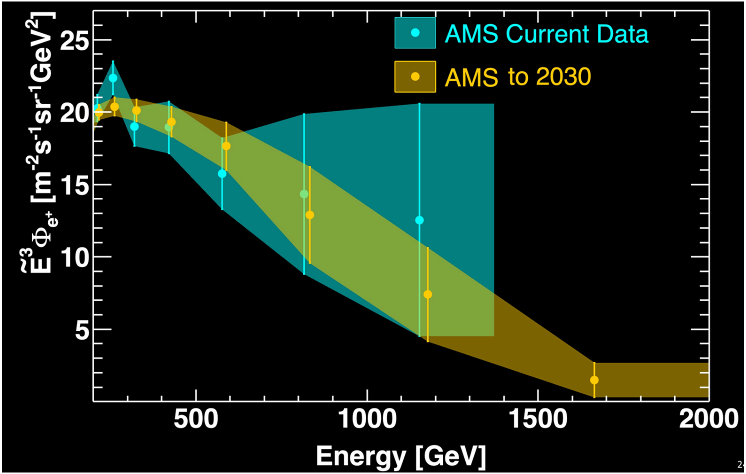
Positron Flux from Dark Matter

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



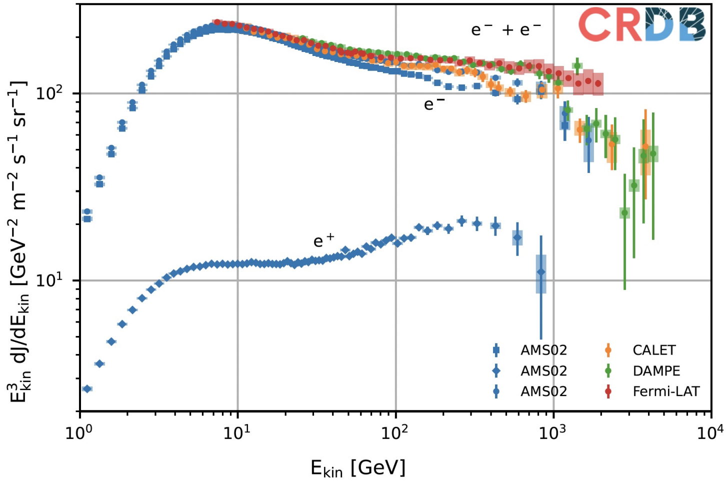
Prospects for AMS

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 experiments.



"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?

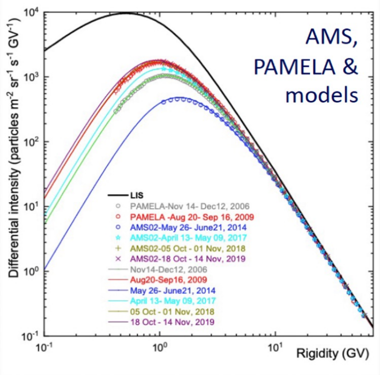
The connection to ground-based experiments (HESS) is definitively established.

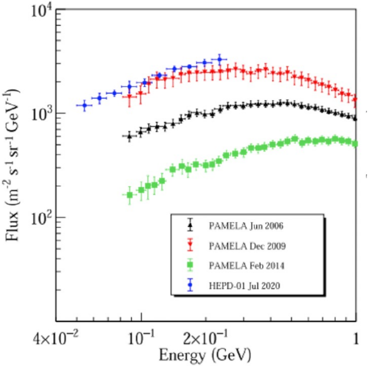
Particles in the heliosphere

Mainly AMS, PAMELA and lately HEPD provided a lot of data for the Heliophysics and Space Weather communities.

Daily data available!

The statistics is so large that we can follow closely the GCRs solar modulation behavior with time.





The Voyager Missions and Cosmic-Ray Physics

Voyager 1 and Voyager 2

Launched in 1977, the Voyager spacecraft completed the exploration of the outer planets and later became the first probes to study the environment beyond the heliosphere.

- Voyager 1 entered interstellar space in 2012.
- Voyager 2 entered interstellar space in 2018.
- Both spacecraft continue to measure energetic particles, plasma, and magnetic fields.

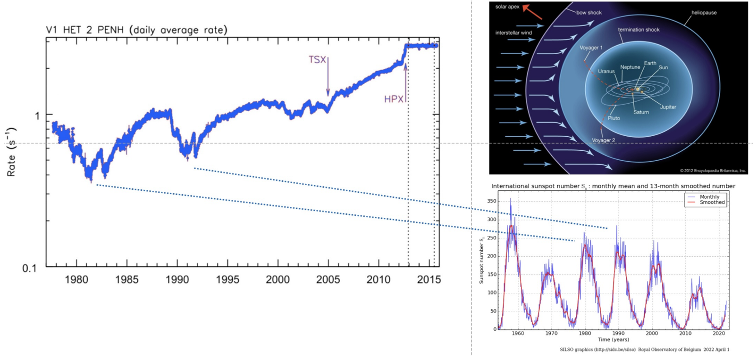
Why Are Voyager Data Unique?

- Measurements are performed **outside the heliosphere**.
- No solar modulation effects.
- Direct determination of the Local Interstellar Spectrum (LIS).
- Access to low-energy cosmic rays unreachable near Earth.

Particles in the heliosphere: Voyager I and II

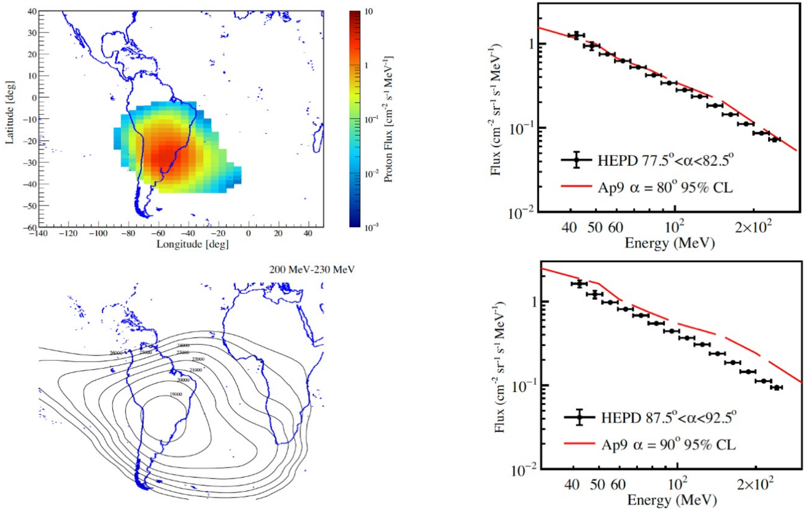
Importance for Modern Cosmic-Ray Physics

Voyager provides the unmodulated interstellar flux used as the reference for interpreting measurements near Earth (AMS-02, PAMELA, CALET, DAMPE). The combination of Voyager and near-Earth observations allows the study of both **Galactic propagation** and **solar modulation**.



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!



Recent Balloon missions: targeted physics at lower cost

Balloon experiments remain essential for focused measurements and technology validation: they can test new detector concepts before space deployment. **Two new missions** just flew and we are expecting the first data release:

HELIX - Flight in 2024 from Sweden

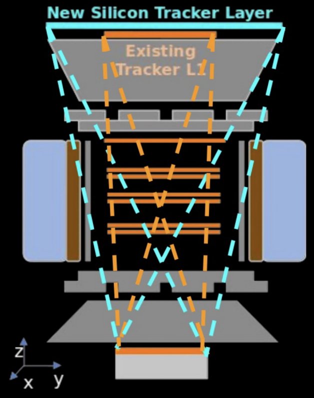
- High Energy Light Isotope eXperiment.
- Balloon-borne magnetic spectrometer.
- Measures light isotope abundances, especially $^{10}\mathrm{Be}/^{9}\mathrm{Be}$.
- Provides information on cosmic-ray residence time and propagation halo size.

GAPS - Flight in 2025 from Antartica

- General AntiParticle Spectrometer.
- Searches for low-energy antiprotons, antideuterons and antihelium.
- Uses exotic-atom formation rather than a magnetic spectrometer.
- Particularly relevant for dark-matter-motivated antimatter searches.

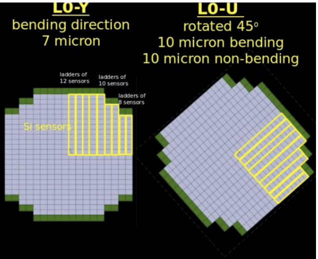
"AMS" upgrade on ISS: Layer-0

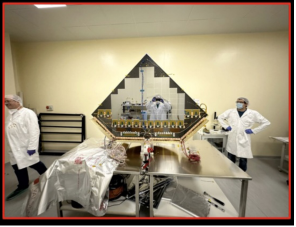
Will increase acceptance, also for positrons/antiprotons



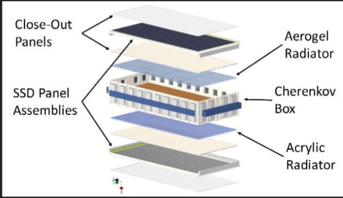
See Yaozu's talk!

- 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

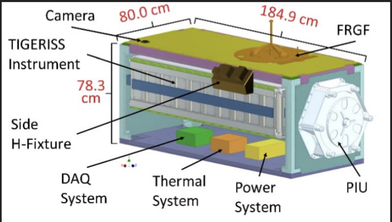


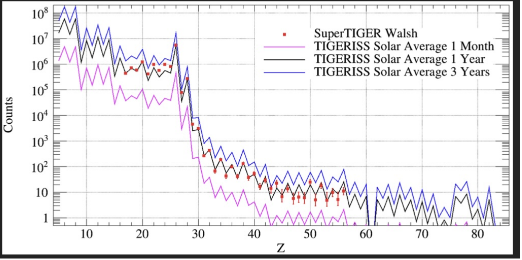


Future experiments: "TIGER-ISS" launch in 2027 on ISS



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





HERD: calorimetric frontier on the Chinese Space Station in 2027

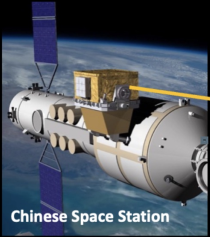
- **HERD**: High Energy cosmic-Radiation Detection facility.
- Planned as a space-station payload.
- Main concept: a deep, 3D, highly segmented calorimeter.
- Designed for:
  - cosmic-ray nuclei at very high energy;
  - high-energy electrons and gamma rays;
  - dark-matter searches through spectral signatures;
  - study of the spectral steepening near the PeV region.

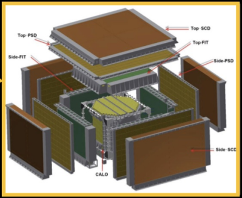
HERD is a key step toward high-statistics direct measurements close to the "knee of cosmic rays

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

Direct Measurement Towards the Knee: HERD

13

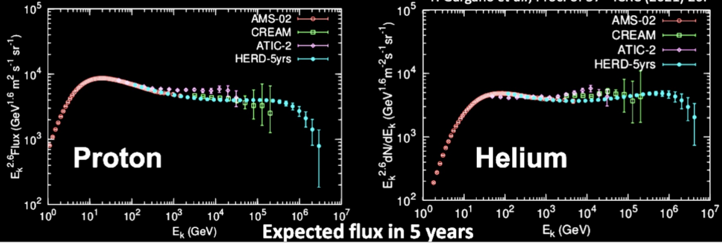




High Energy Cosmic Radiation Detector (HERD)
Based on a 3D, homogeneous, finely-segmented calorimeter of 55 X_0 with a wide field of view (2π).
Complemented by other detectors for PID (charge, veto, tracking, …).
Installation foreseen 2027.

- 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 37[th] ICRC (2021) 26.



Expected flux in 5 years

Next-generation magnetic spectrometers: ALADInO and AMS-100

A major future direction is the return to **large-acceptance magnetic spectrometry**.

- Scientific motivation:
  - precision antiprotons and positrons up to the multi-TeV range;
  - direct search for antideuterons and antihelium;
  - independent test of possible AMS-02 antimatter candidates;
  - simultaneous measurement of nuclei up to the PeV scale.
- **ALADInO**
  - large-acceptance magnetic spectrometer concept (about 10 times AMS-02);
  - superconducting magnet, precision tracker, time-of-flight and 3D calorimeter;
  - orbit to be decided by ESA.
- **AMS-100**
  - very large magnetic spectrometer concept at L2 (about 1000 times AMS-02);
  - designed for much larger acceptance than present instruments.

Conclusions about direct measurements of CRs

1. The flux of GCRs 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. Are anti-deuteron or anti-helium present in GCRs?
4. What is the origin of the positron rise?

   ⋄ Astrophysics—> pulsars?
   ⋄ Dark matter?

5. The electron break at 1 TeV needs to be understood. Which sources?

6. A new source for $Z > 40$ elements?

Perspectives

1. New experiments and data coming soon!
   - HELIX, GAPS, AMS-upgrade, TIGER-ISS, HERD, ...
2. More futuristic magnetic spectrometers are under study;
3. New experiments measuring cross sections are needed! CERN is involved.

ERA OF HIGH PRECISION MEASUREMENTS !

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