

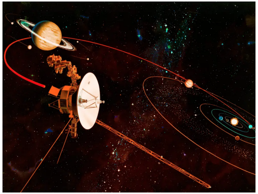
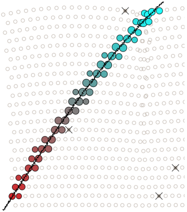
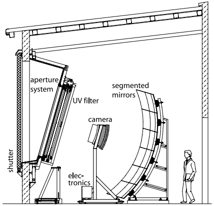

Measurements of Cosmic Rays

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věd České republiky

Faculty
of Science

Palacký University
Olomouc

IDPASC

11th IDPASC school, Olomouc, 29/08 – 07/09/2022

Discovery of cosmic rays

Victor Franz Hess, balloon flights (1912): cosmic origin of radiation explaining discharge of electroscopes

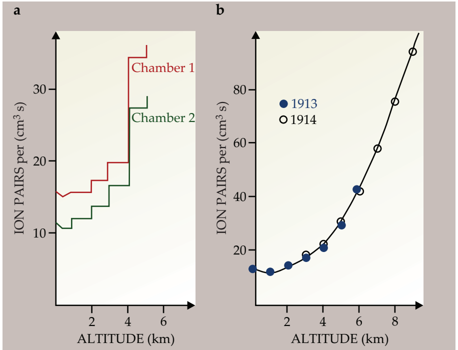


Figure 3. The rate of atmospheric ionization as a function of altitude, as measured **(a)** by Victor Hess on 7 August 1912, and **(b)** by Werner Kolhörster in 1913. (Adapted from ref. 2.)

Nobel Prize (1936)

"…new vistas for the understanding of the structure and origin of matter"

plot: Physics Today 65, 2, 30 (2012)

Early days and new particles

Dmitri Skobeltsyn (1927): cloud-chamber photo of cosmic ray tracks

Robert Millikan (1928): name "cosmic rays"

Werner Kolhörster and Walther Bothe (1929): coincidence in Geiger–Müller counters interlaid with 4 cm of gold

Arthur Compton (1932): corpuscular nature of the radiation

Bruno Rossi (1932, 1933): cosmic rays traverse one meter of lead, cosmic radiation is mostly positive

Carl Anderson (1932): discovery of positron (Nobel Prize (1936) together with Hess)

Carl Anderson, Seth Neddermeyer (1936): discovery of 'meson' (mass between electron and proton) → muon

Marcel Schein (1940): cosmic rays should be mostly protons

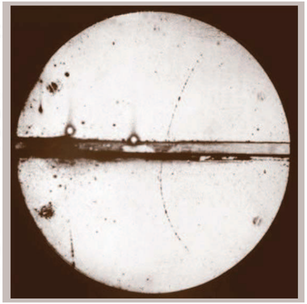
George Rochester and Clifford Butler (1947): discovery of neutral K meson

Cecil Powell (1947): discovery of pion (Nobel Prize 1950)

Discovery of Λ hyperon (1947)

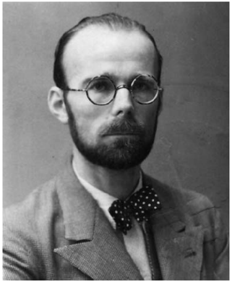
Cecil Powell (1948): discovery of positive K meson

Cosmic rays contain not only protons but also heavier nuclei (1947)



source: Physics Today 65, 2, 30 (2012); auger.org

Discovery of extensive air showers



Pierre Victor Auger (1938)

cascades of particles produced by cosmic rays in the atmosphere

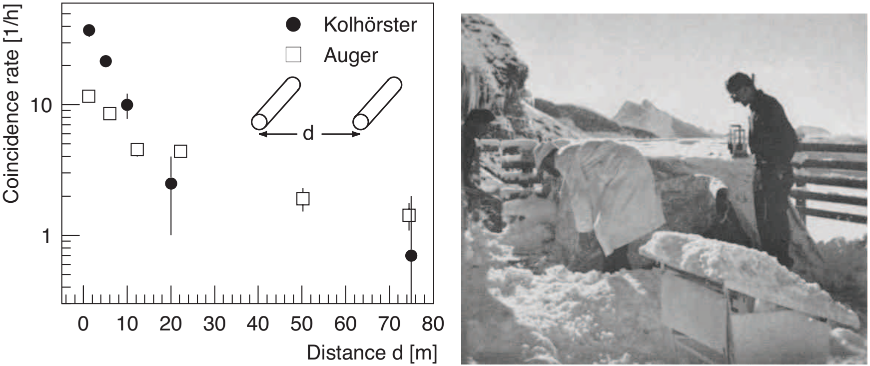
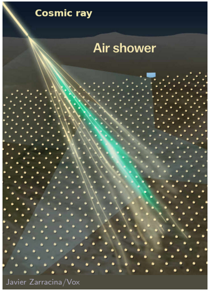


FIGURE 7. *Left*: Coincidence rate as a function of the distance between two Geiger-Müller counters as obtained by W. Kolhörster [23] and P. Auger [24]. *Right*: P. Auger measuring air showers at the Jungfraujoch in Switzerland [25].



Javier Zarracina/Vox

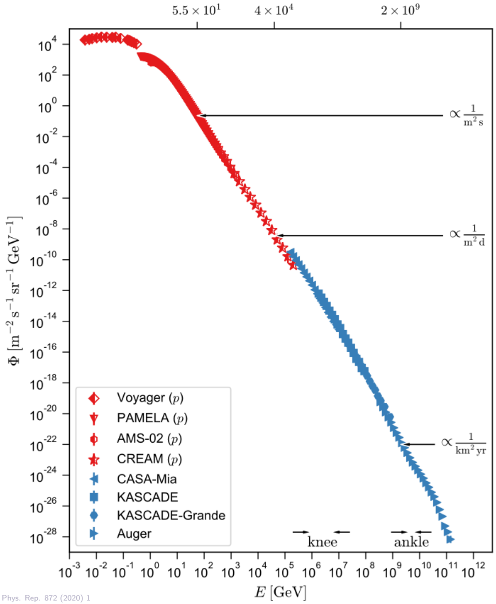
J. Hörandel, AIP Conf. Procs. 1516, 52 (2013)

Cosmic rays below 100 TeV

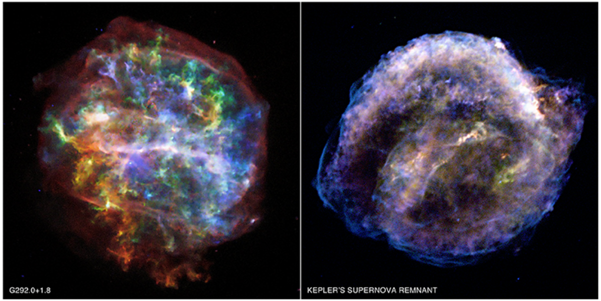
direct measurements

see review by S. Gabici, arXiv:2203.14620, for more details

Energy spectrum of nuclear species: direct measurements



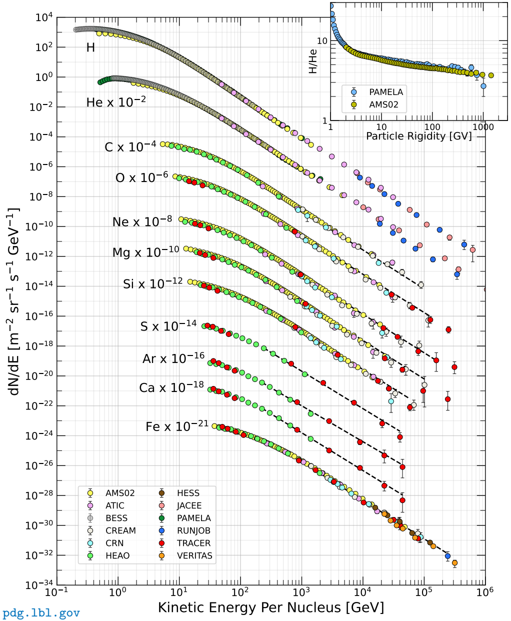
Phys. Rep. 872 (2020) 1



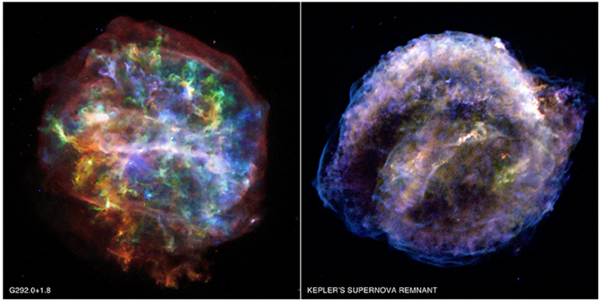
Cosmic rays $\equiv$ charged particles

mostly atomic nuclei $\approx$ 90% H, 9% He, 1% 'metals' ($Z > 2$), with small amount of electrons, positrons, antiprotons

Energy spectrum of nuclear species: direct measurements



pdg.lbl.gov



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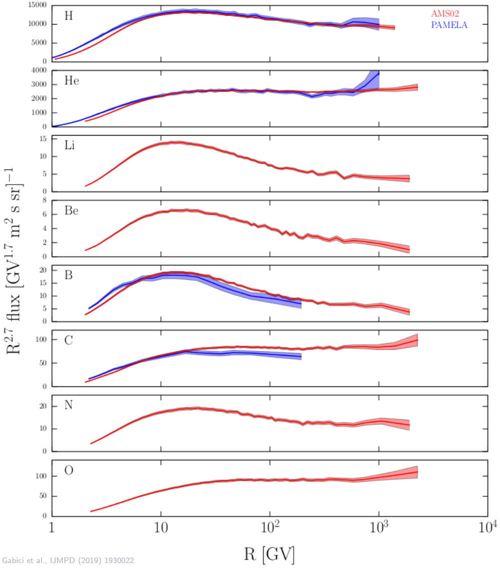
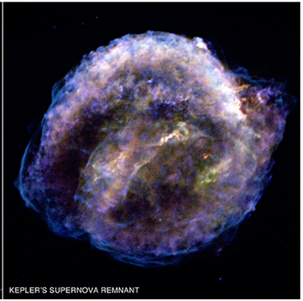
Energy spectra: featureless power laws for $E \gtrsim$ few $\times$ 10 GeV?..

Energy spectrum of nuclear species: direct measurements



S. Gabici et al., IJMPD (2019) 1930022

rigidity $R = pc/(Ze)$



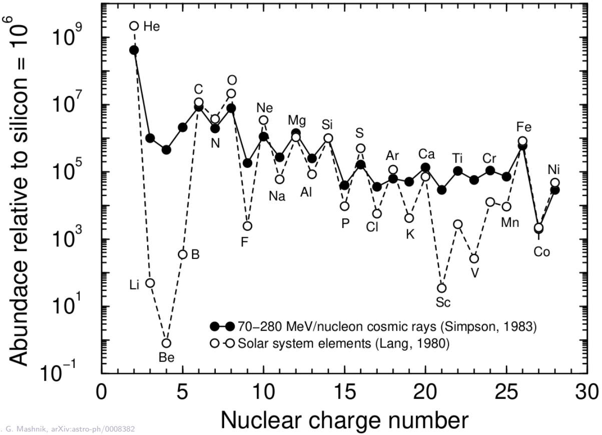
Energy spectra: featureless power laws for $E \gtrsim$ few $\times$ 10 GeV?..

Roughly $\propto R^{2.7}$ for rigidity $R \gtrsim 10$ GV, but

◇ evidently spectra of LiBeB are remarkably softer

◇ much more is happening here!

Elemental abundances in solar system and cosmic rays



S. G. Mashnik, arXiv:astro-ph/0008382

hydrogen abundance is about $10 \times$ helium

Solar system: CNO/LiBeB $\approx 10^6$

Cosmic rays (CR): CNO/LiBeB ~ 10

Spallogenic nucleosynthesis

direct channel

$$\mathrm{CR} + \mathrm{ISM\ nucleus} \to \mathrm{LiBeB} + X$$

reverse channel

$$\mathrm{CR\ CNO} + \mathrm{ISM\ nucleus} \to \mathrm{LiBeB} + X$$

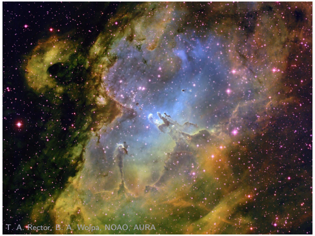
$$\alpha + \alpha \to \mathrm{LiBe} + X$$

Role of low energy CR and open questions

Dynamics of Interstellar Molecular Clouds (IMC)

- IMCs are star formation regions
- dynamics and evolution of IMC/protoplanetary disks depends on gas ionization (magnetic pressure support against gravity, turbulence)
- IMCs are cold & diluted, but with a complex chemistry (water, ammonia, ethyl alcohol, sugar and amino acids)

  catalyst: protonated hydrogen H_3^+ from the H_2 ionization


T. A. Rector, B. A. Wolpa, NOAO, AURA

IMC temperatures are only from 10 K to 30 K
what keeps them slightly (10^{-7}) ionized?

Low energy CR is the only agent able to penetrate to the densest ICM parts and influence their dynamics

A few immediate questions

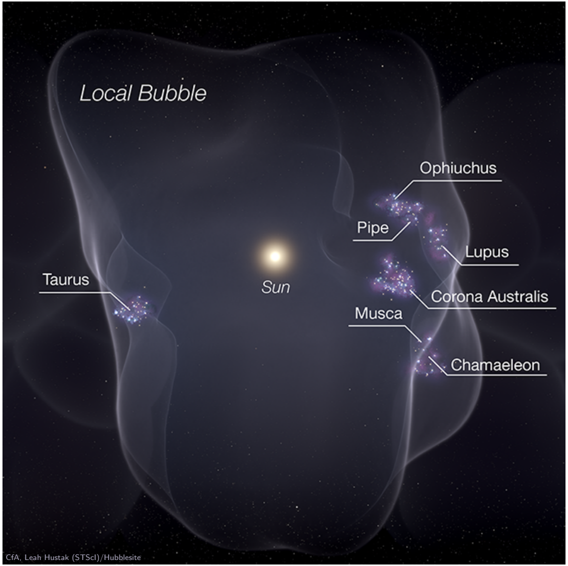
◇ what are the sources of low-energy cosmic rays?

◇ are sub-GeV and higher energy particles produced by the same sources?

◇ is the low-energy CR flux same over the entire Milky Way?

The Local Bubble

The low-energy CR flux measured by us can be a local feature



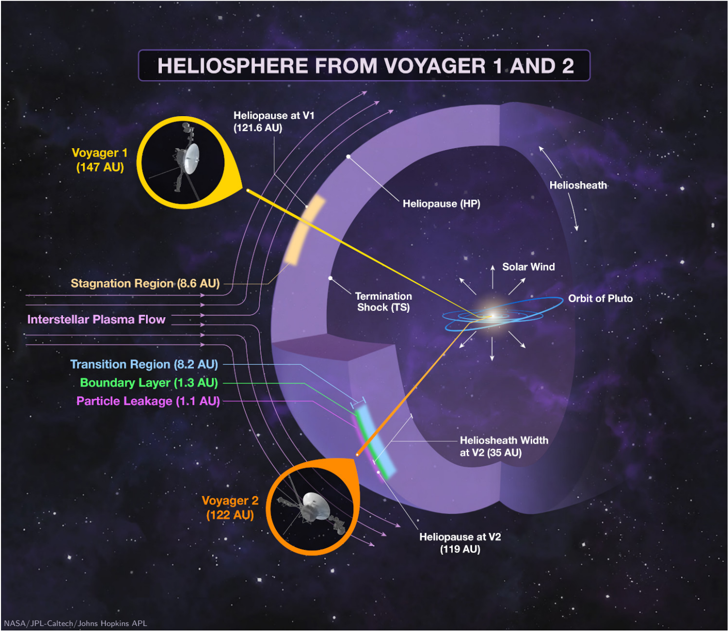
CfA, Leah Hustak (STScI)/Hubblesite

> The Local Bubble
> “a cavity of low-density, high-temperature plasma surrounded by a shell of cold, neutral gas and dust”

- around 1000 light years wide
- started around 14 Myr ago
- the Sun entered into the Bubble around 5 Myr ago
- around 15 supernovae explosions sweeping gas to the shell
- surface is reach in star formation regions
- low-energy CR fluxes can be different in local bubbles

Nature 601 (2022) 334

Interstellar CR spectra



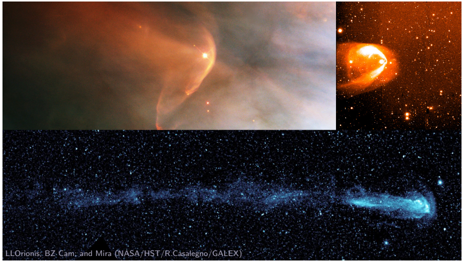
NASA/JPL-Caltech/Johns Hopkins APL

Leaving heliosphere

Voyager 1 in 2012

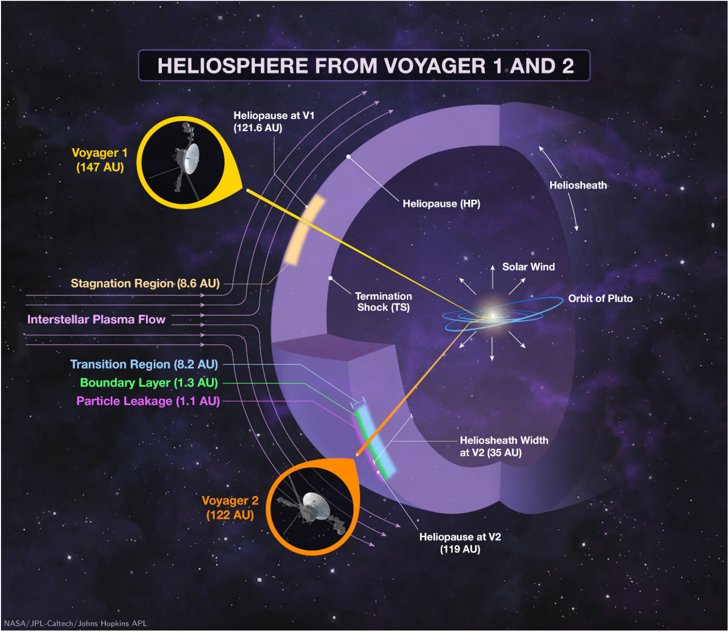
Voyager 2 in 2018

Astrospheres



LLOrionis, BZ Cam, and Mira (NASA/HST/R.Casalegno/GALEX)

Interstellar CR spectra



NASA/JPL-Caltech/Johns Hopkins APL

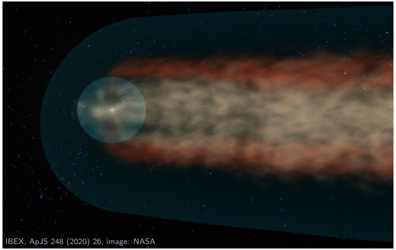
Leaving heliosphere

Voyager 1 in 2012

Voyager 2 in 2018

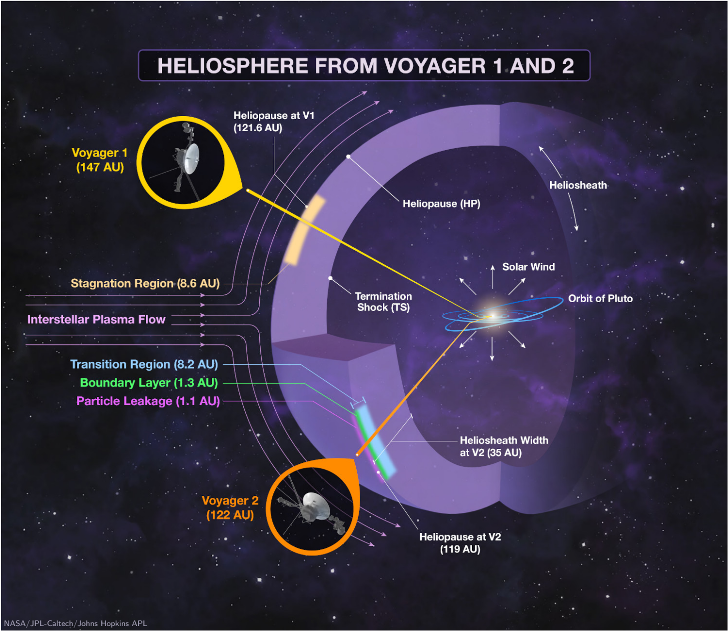
Heliosphere

Interstellar Boundary Explorer (2020)



IBEX, ApJS 248 (2020) 26, image: NASA

Interstellar CR spectra



NASA/JPL-Caltech/Johns Hopkins APL

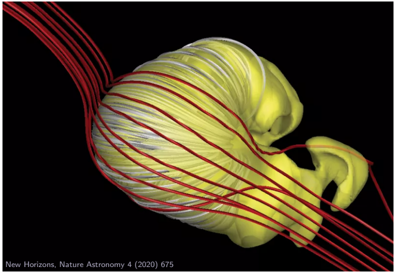
Leaving heliosphere

Voyager 1 in 2012

Voyager 2 in 2018

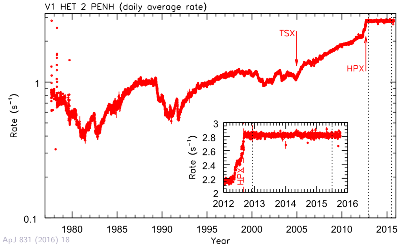
Heliosphere

New Horizons (2020)



New Horizons, Nature Astronomy 4 (2020) 675

Interstellar CR fluxes

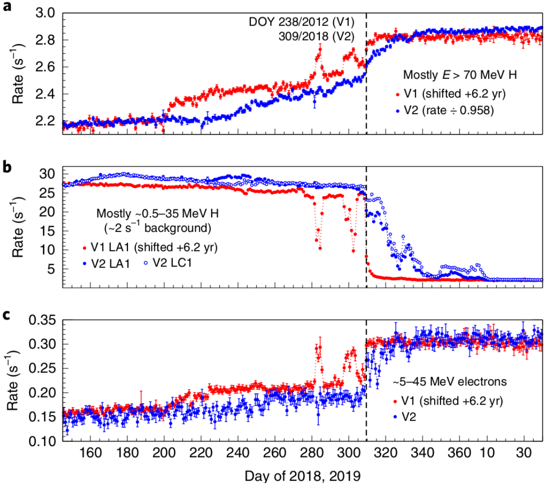


ApJ 831 (2016) 18

Voyager 1 counting rate (mainly protons > 70 MeV)

Heliopause crossing is marked with HPX

11-year solar cycle is clearly seen in data before 1995



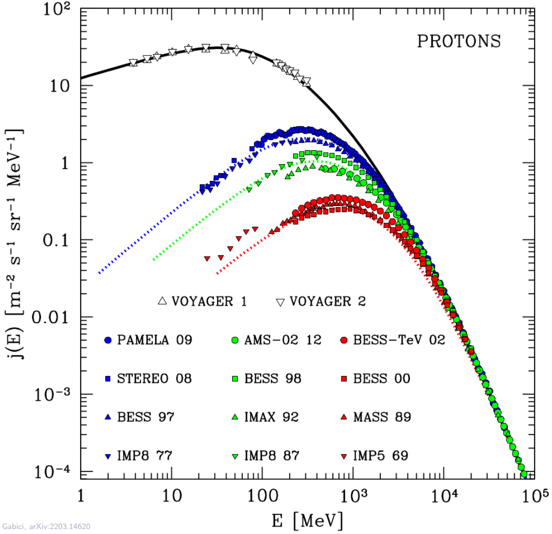
Voyager 1 & 2 counting rates near HPX

b. Anomalous CRs (mostly solar system H)

Voyager 1: two jumps before HPX due to interstellar flux invasions

Fluxes are stable after HPX

Solar modulation of CR spectra



S. Gabici, arXiv:2203.14620

Near-Earth (1 au) data for different solar activity periods

minimum

intermediate

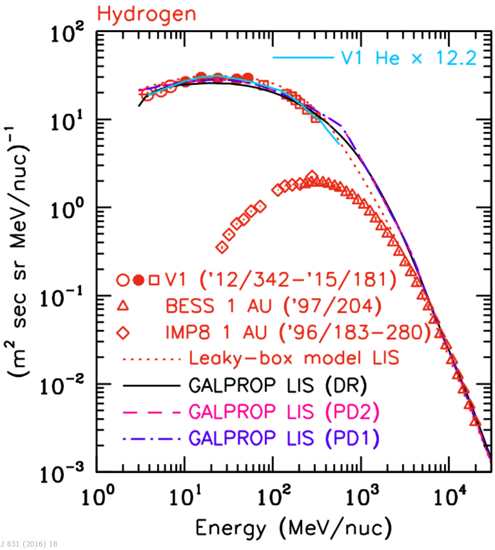
maximum

Solar wind affects fluxes of $R \lesssim 10$ GV particles

demodulation of fluxes is complicated and uncertain

Voyager data provide possibility to determine the modulation potential

Proton to helium ratio from Voyager 1



ApJ 831 (2016) 18

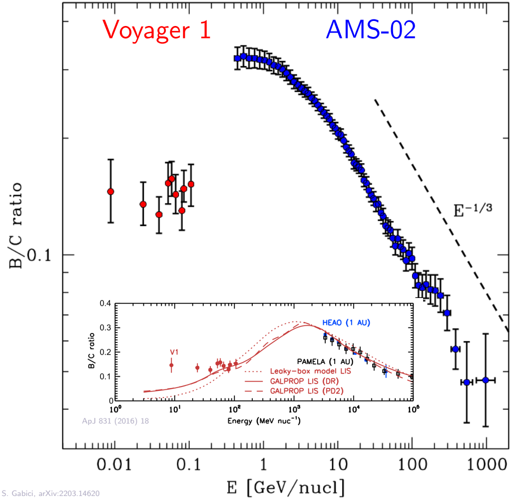
p/He is nearly constant ≈ 12.2

would not be the case for rigidity-dependent solar modulation

for unclear reasons above tens of GeV, H spectrum is slightly softer than He spectrum

CR residence time in the Milky Way

Boron comes from spallation $\mathrm{C,O} \rightarrow \mathrm{B}$



ApJ 831 (2016) 18

S. Gabici, arXiv:2203.14620

B/C depends on

- ◇ confinement time of B in Galaxy (energy-dependent)
- ◇ spallation time of B to lighter elements

Voyager data is difficult to interpret (see inset plot)

from AMS-02 data (at 10 GeV/nucleon energy)

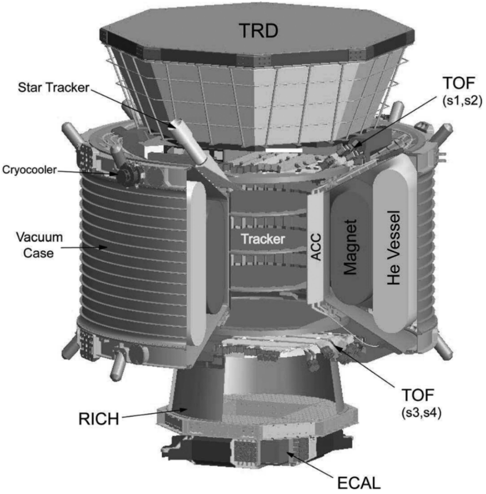
- ◇ residence time in ISM 4 Myr (grammage of 7 $\mathrm{g\,cm^{-2}}$)

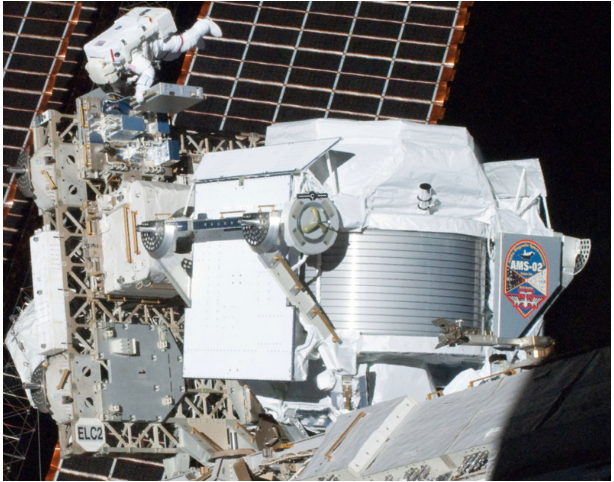
$^{10}\mathrm{Be}/^{9}\mathrm{Be}$ (< 1 Gev/nucleon) measurements

- ◇ CRs escape time ≈ 100 Myr
- ◇ CRs stay most of time in Galactic halo (not in ISM)

Direct CR measurements at 1 au (centered on AMS-02 and DAMPE)

Alpha Magnetic Spectrometer on the International Space Station





ams02.space, Physics Reports 894 (2021) 1–116

Direct CR measurements at 1 au (centered on AMS-02 and DAMPE)

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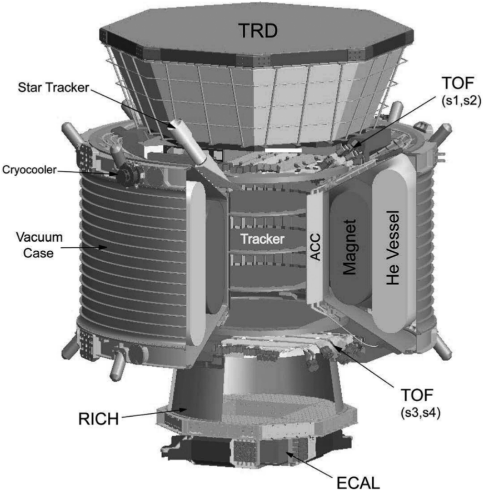
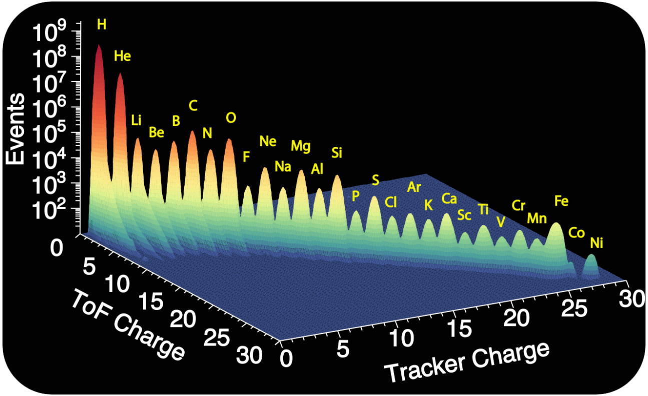


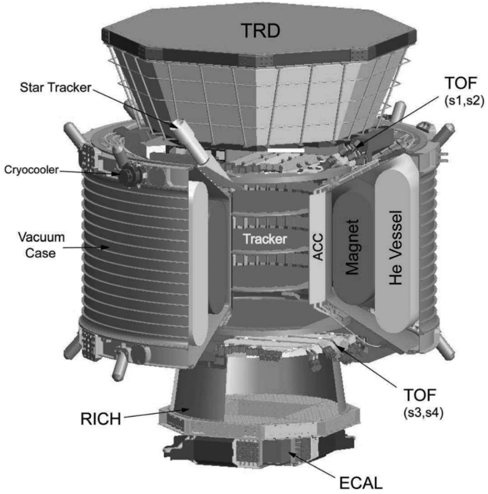


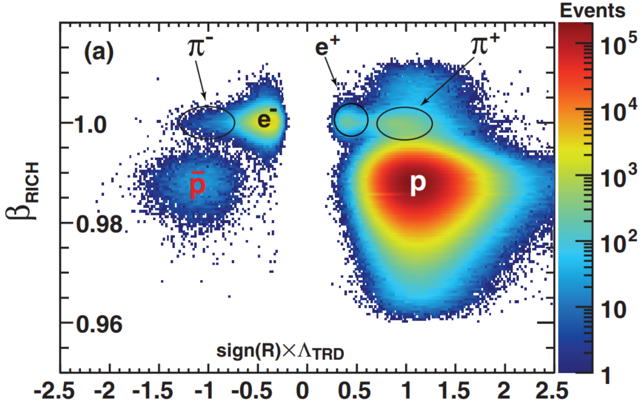
excellent energy and charge resolution. . .

`ams02.space`, Physics Reports 894 (2021) 1–116

Direct CR measurements at 1 au (centered on AMS-02 and DAMPE)

Alpha Magnetic Spectrometer on the International Space Station



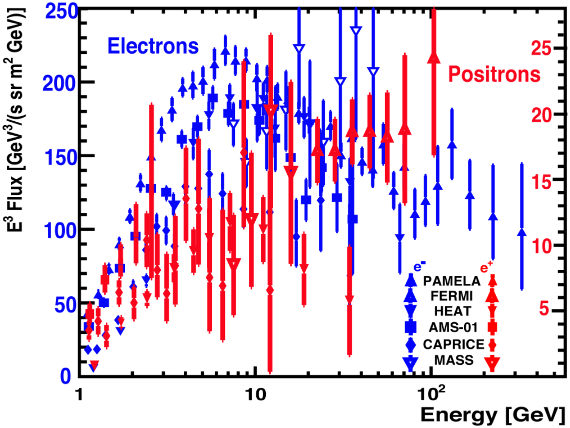


and matter-antimatter discrimination

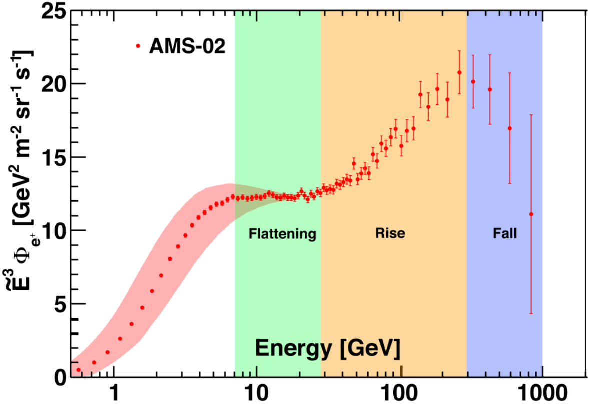
`ams02.space`, Physics Reports 894 (2021) 1–116

AMS-02 positron spectrum

Before AMS–02



AMS–02, note the energy range



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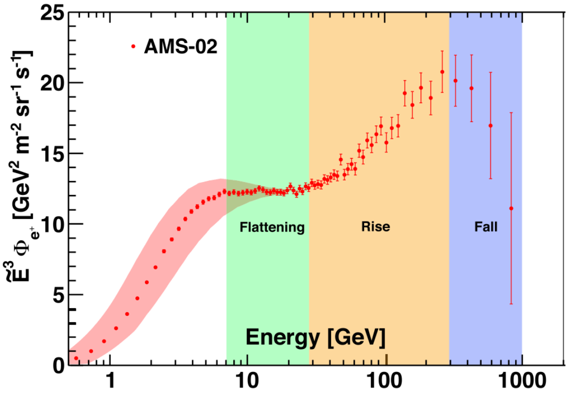
AMS-02 positron spectrum



Positron production mechanisms

diffuse

- ◇ CR interactions with ISM

‘source’

- ◇ acceleration in astrophysical objects
- ◇ dark matter annihilation (?)

Spectral features

hardening at 25.2 ± 1.8 GeV

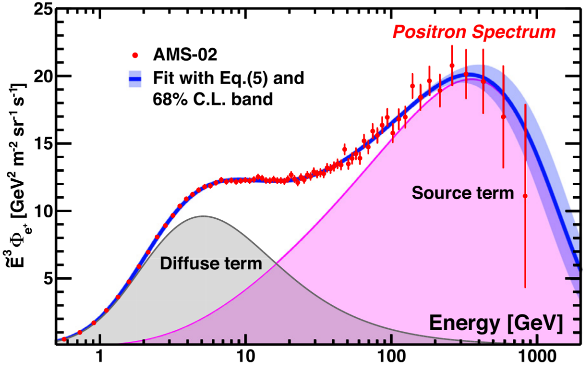
drop-off at 284^{+91}_{-64} GeV

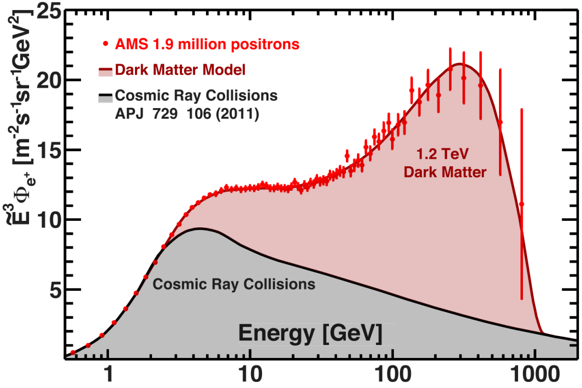
energy cutoff of ‘source’ contribution 810^{+310}_{-180} GeV (with a significance $> 4\sigma$)

`ams02.space`, Physics Reports 894 (2021) 1–116

Contributions to AMS-02 positron spectrum

Diffuse and ‘source’ contributions





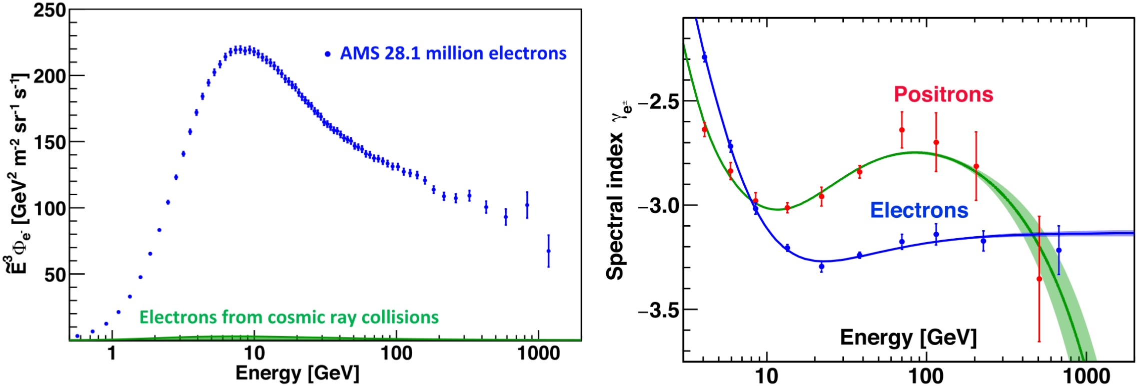
positron flux is found to be consistent with isotropy (expected in case of the dark matter origin)

◇ more statistics at higher energies needed to test the dark matter hypothesis

◇ no consistent description of positron, antiproton, Be/C, B/C, Be/O, B/O et al. data exists yet

AMS-02 electron spectrum

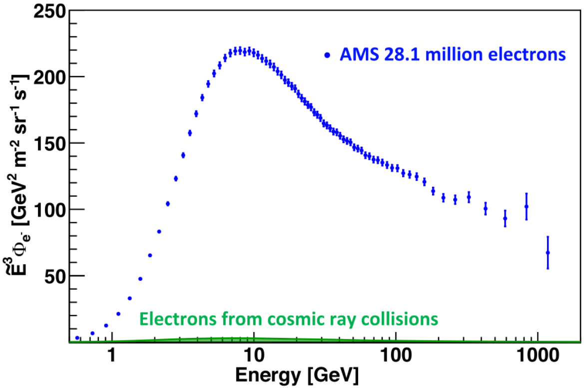
Diffuse contribution is minor

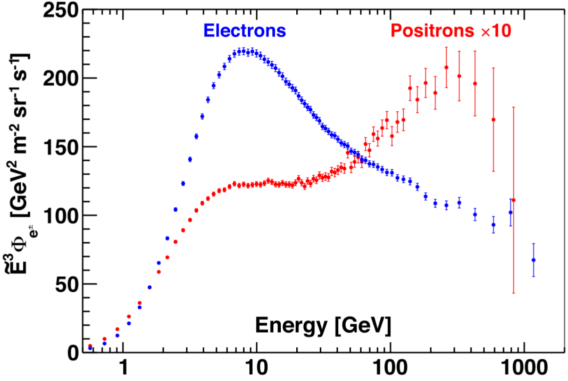


- ◇ electron spectrum is described well with two power laws
- ◇ cutoff for $E < 1.9$ TeV is excluded at the 5σ
- ◇ high-energy electrons and positrons come from different sources

AMS-02 electron spectrum

Diffuse contribution is minor





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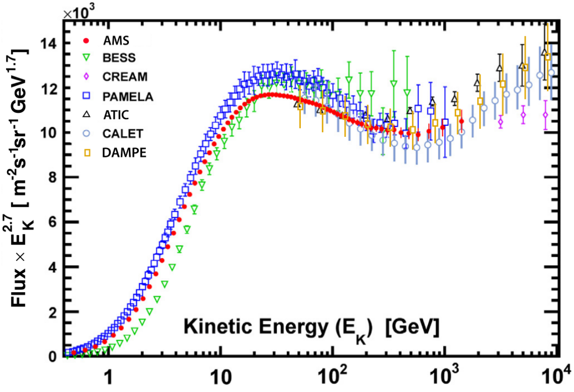
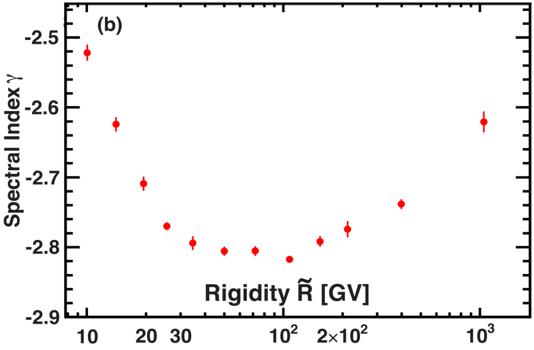
- ◇ high-energy electrons and positrons come from different sources

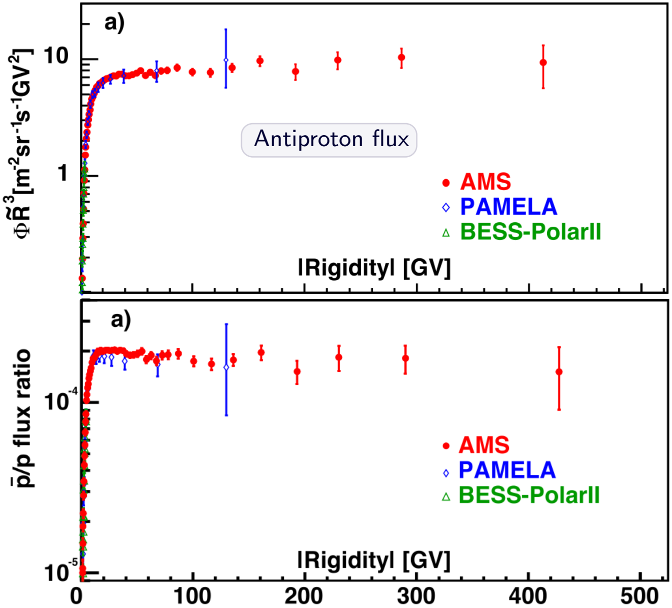
Proton spectrum below 10 TeV





- ◇ not a single power law for $R > 45$ GV (where solar modulation is negligible)
- ◇ spectrum is becoming progressively harder for $R > 200$ GV
- ◇ other changes above 10 TeV?

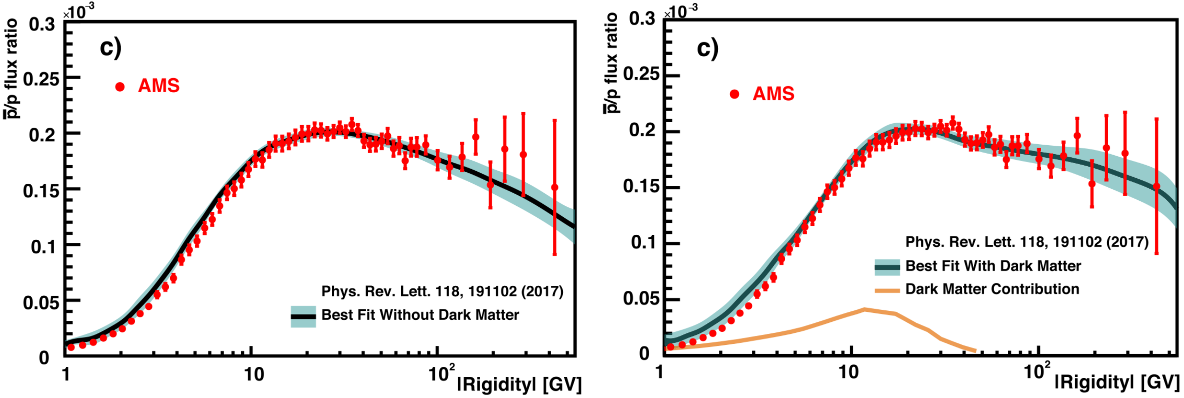
Antiprotons



p and $\bar{p}$ fluxes have similar shapes

not expected if antiprotons come only from CR interactions with ISM

Dark matter contribution to antiproton flux?



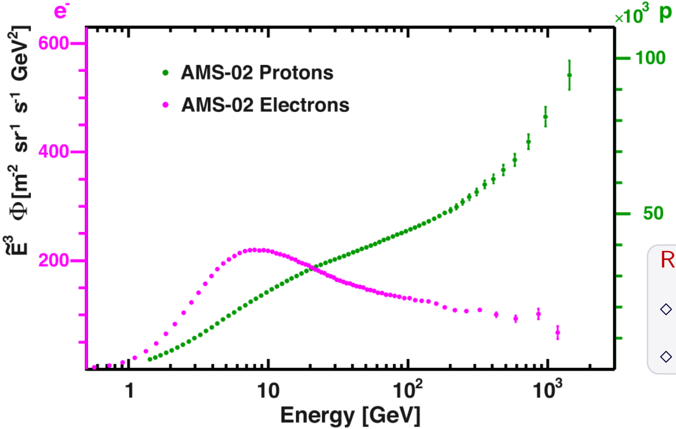
◇ qualitative description can be achieved with/without dark matter contribution

◇ cutoff at high energies is expected in case of the dark matter origin

◇ successful astrophysical model should describe data on p, $\bar{\mathrm{p}}$, $\mathrm{e}^{\pm}$, nuclei

Protons vs electrons

Electrons and protons are mostly primary cosmic rays

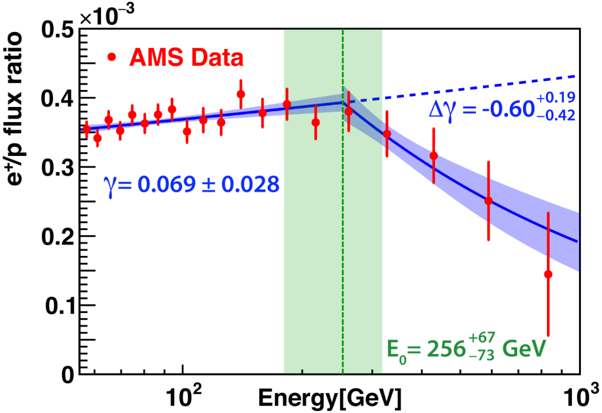


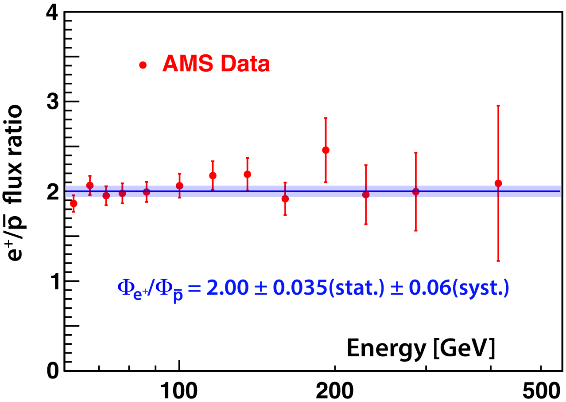
Remarkably different behavior

- ◇ electron flux is described well with two power laws
- ◇ proton flux has varying power index

softer electron spectrum is expected due to larger energy losses in ISM

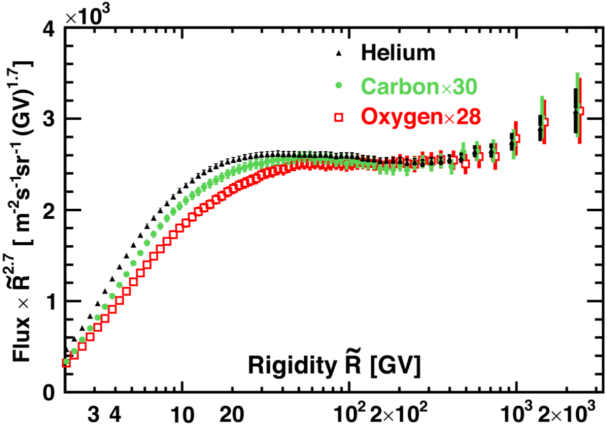
Protons, antiprotons, electrons, positrons

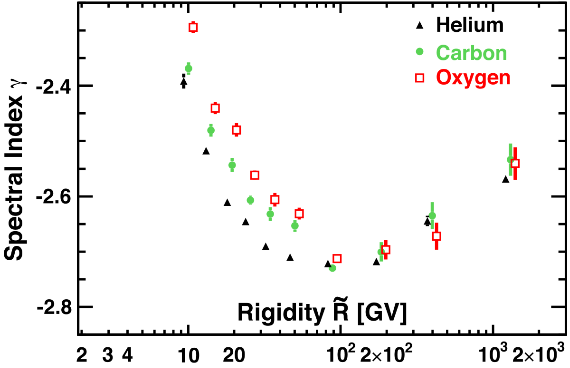




- ◇ p and p̄: similar shapes ($E < 400$ GeV) — not expected if p̄ are only secondary
- ◇ electron spectrum for $E > 10$ GeV is softer than proton spectrum — propagation effect
- ◇ positron spectrum is harder than proton spectrum for $60 - 260$ GeV
- ◇ positron to antiproton ratio is compatible to const for $60 - 400$ GeV — common source?

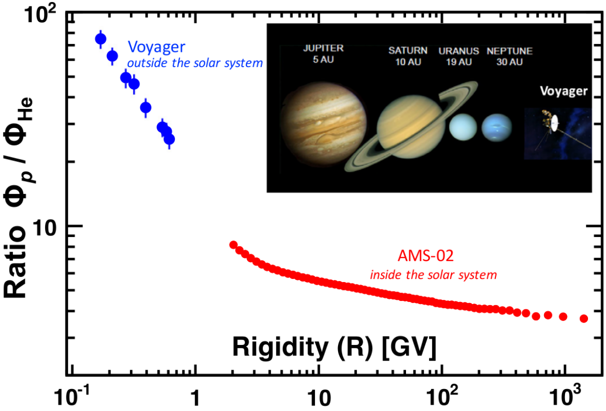
Spectra of helium, carbon, oxygen





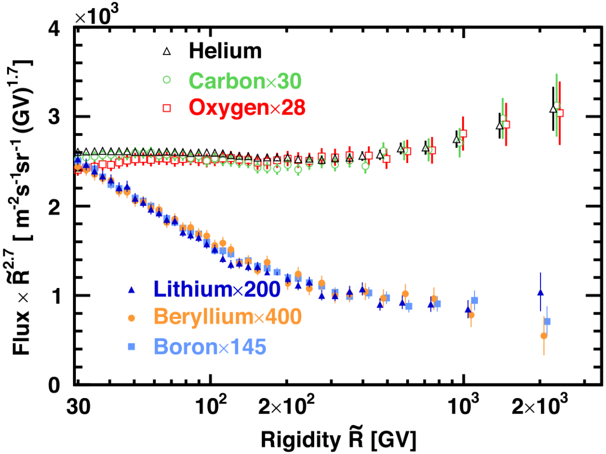
- ◇ nearly same behaviour for $R > 60$ GV
- ◇ unexpected/unexplained hardening for $R > 200$ GV

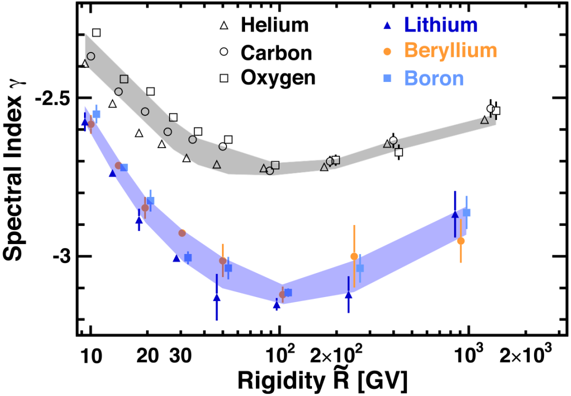
Proton to helium ratio



- ◇ above 3.5 GV, p/He is decreasing as $A + C(R/3.5\ \mathrm{GV})^{\Delta}$; $\Delta = -0.3$
- ◇ becoming constant ≈ 3.15 at highest rigidities
- ◇ are protons composed from soft and hard components?

Secondary nuclei





◇ similar rigidity dependence of LiBeB fluxes for $R > 30$ GV

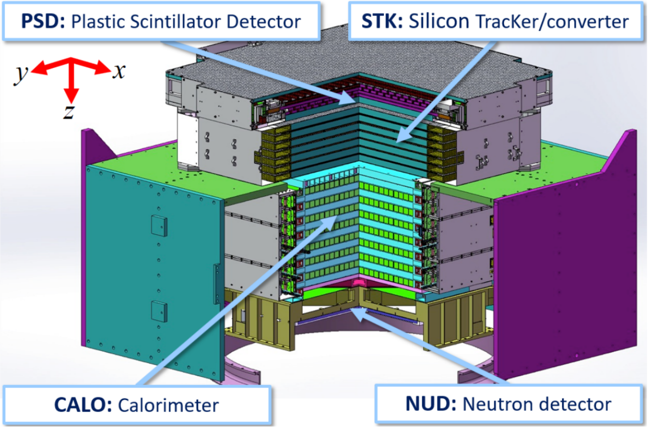
◇ strangely, spectral hardening of LiBeB is by $\Delta\gamma \approx 0.14$ larger than of HeCO

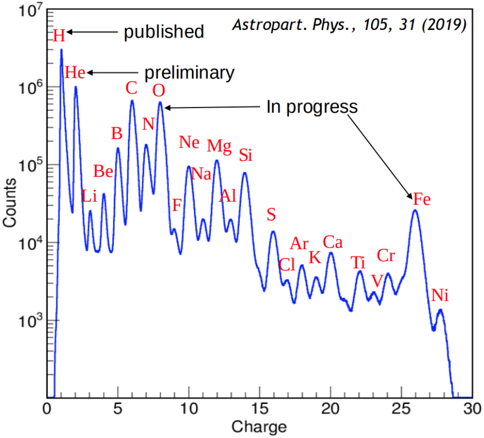
more results (other nuclei, isotopes etc.): Physics Reports 894 (2021) 1–116

Direct CR measurements at 1 au: DAMPE

DArk Matter Particle Explorer *aka* Wukong at 500 km orbit

Energy ranges: γ-rays/electrons (5 GeV – 10 TeV), protons/heavy nuclei (50 GeV – 100 TeV)




Astropart. Phys., 105, 31 (2019)

dpnc.unige.ch/dampe/, ApP 95 (2017) 6

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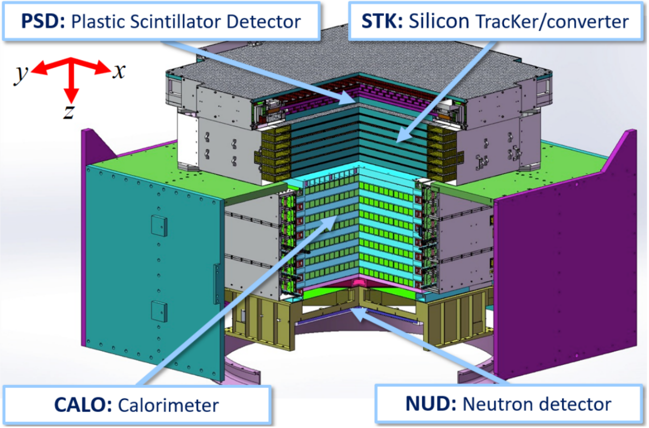
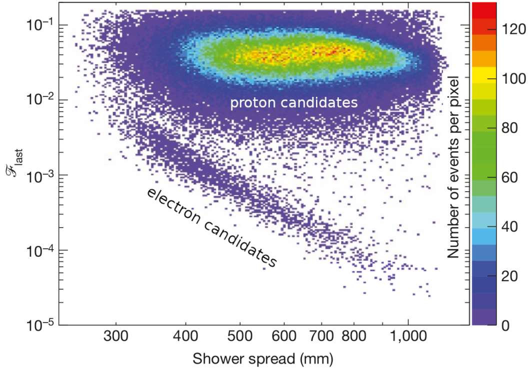


PSD: Plastic Scintillator Detector

STK: Silicon TracKer/converter

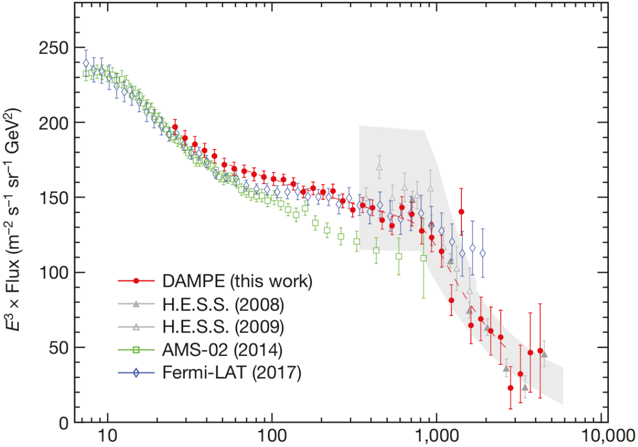
CALO: Calorimeter

NUD: Neutron detector



dpnc.unige.ch/dampe/, ApP 95 (2017) 6

Electron + positron spectrum (530 days of observation)



- ◇ 55 GeV to 2.63 TeV: good fit with a smoothly broken power law
- ◇ break at 0.9 TeV (observed by H.E.S.S., but not by Fermi-LAT): γ changes from 3.1 to 3.9. Energy cutoff in pulsars/SNRs? Linked to dark matter properties?

doi:10.1038/nature24475 (2017)

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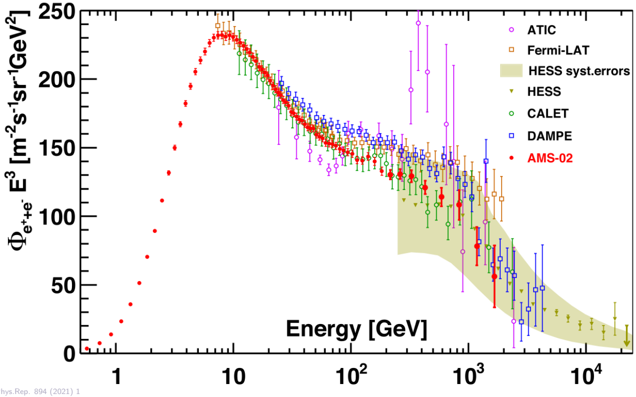

Phys.Rep. 894 (2021) 1

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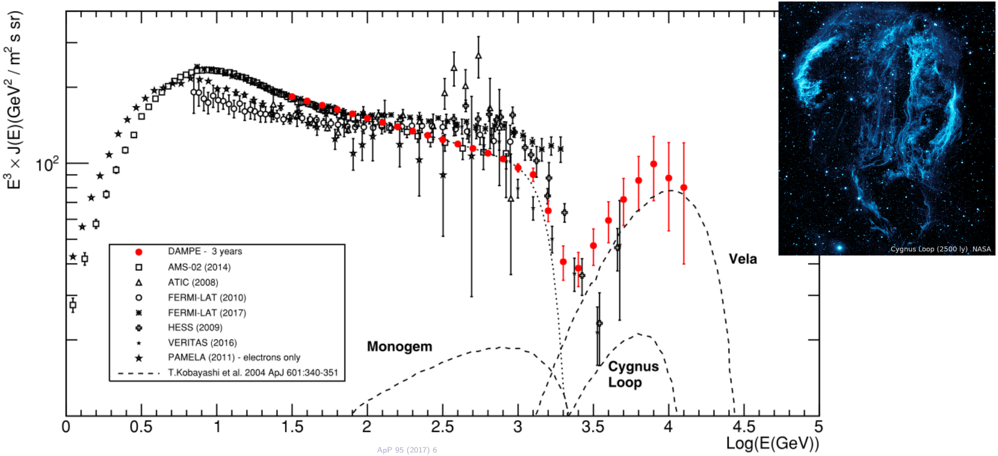
- ◇ break at 0.9 TeV (observed by H.E.S.S., but not by Fermi-LAT): γ changes from 3.1 to 3.9.
  Energy cutoff in pulsars/SNRs?
  Linked to dark matter properties?
- ◇ (AMS-02, CALET, HESS) and DAMPE do not agree well (energy scale systematics?)

doi:10.1038/nature24475 (2017)

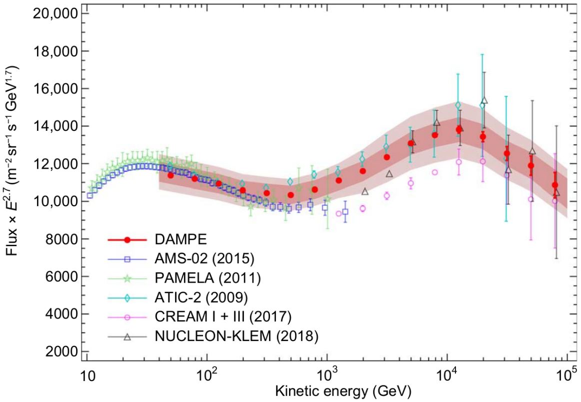
Electron + positron spectrum

Expectations: electrons/positrons from nearby supernova remnants



ApP 95 (2017) 6

Proton spectrum



◇ spectral hardening at a few hundred GeV

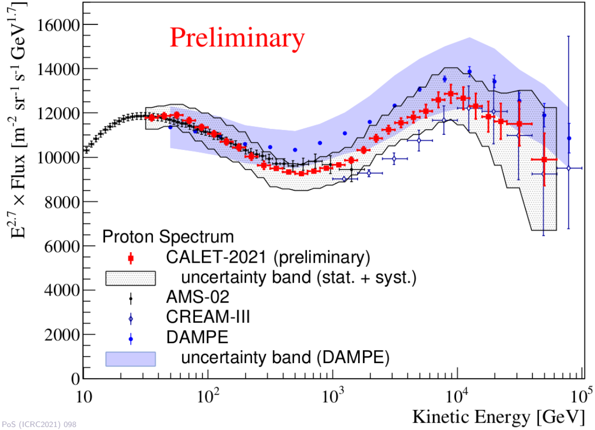
◇ strong evidence of a softening at ≈ 13.6 TeV, γ changes from 2.60 to 2.85

Possible reasons of 10 TeV softening

- energy cutoff for a particular CR population
- local source
- presence of various types of sources

Sci. Adv. 2019; 5:eaax3793

Proton spectrum



- ◇ spectral hardening at a few hundred GeV
- ◇ strong evidence of a softening at ≈ 13.6 TeV, γ changes from 2.60 to 2.85
- ◇ observed as well by CALET and CREAM-III

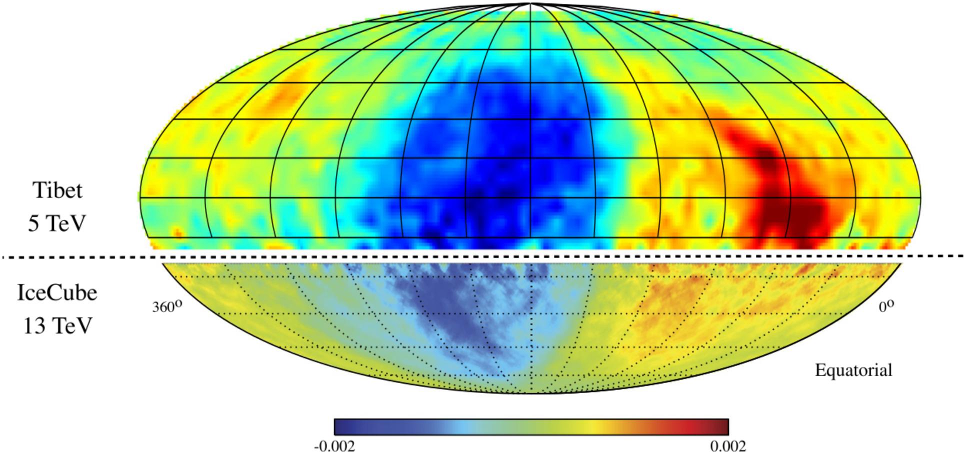
Possible reasons of 10 TeV softening

- energy cutoff for a particular CR population
- local source
- presence of various types of sources

Sci. Adv. 2019; 5:eaax3793

Anisotropies in arrival directions (air-shower observatories)

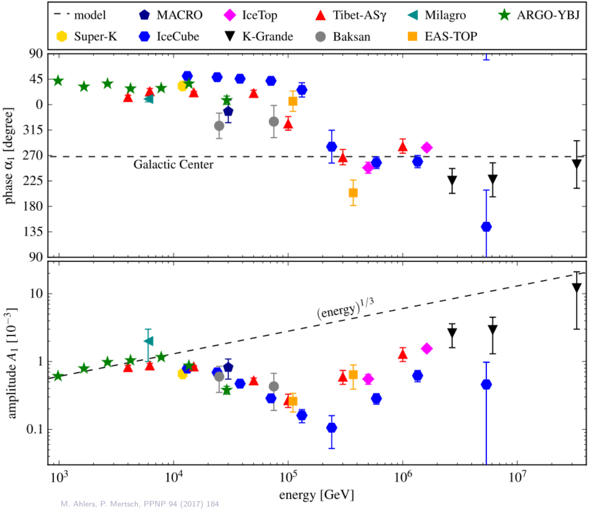
- ◇ Isotropic diffusion & SNR-(pulsar-)like source distribution: dipole aligned with the Galactic center (R.A. 266°)
- ◇ Anisotropic diffusion: dipole aligned with the magnetic field direction



M. Ahlers, P. Mertsch, PPNP 94 (2017) 184

Anisotropies in arrival directions (air-shower observatories)

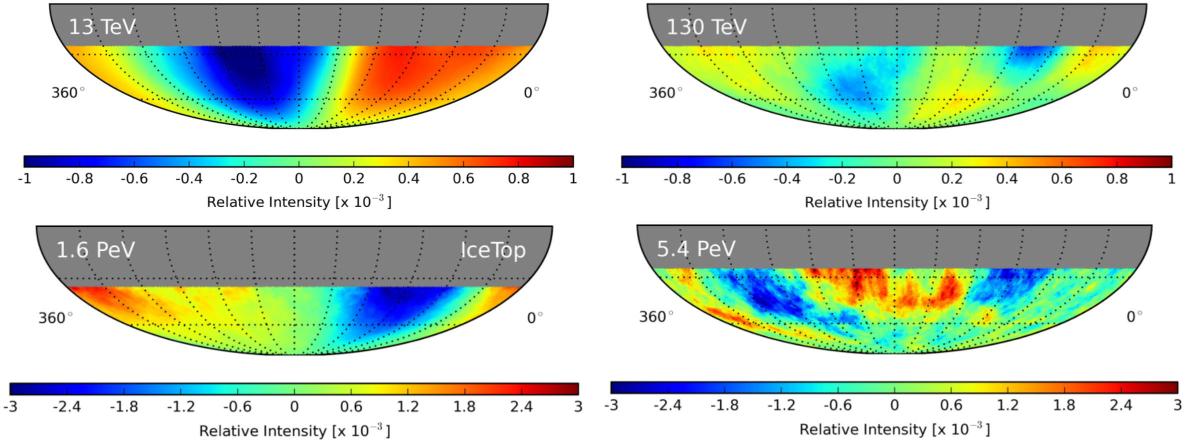
Phase flips towards the Galactic center above 100 TeV, amplitude starts growing



M. Ahlers, P. Mertsch, PPNP 94 (2017) 184

Anisotropies measured by IceCube/IceTop

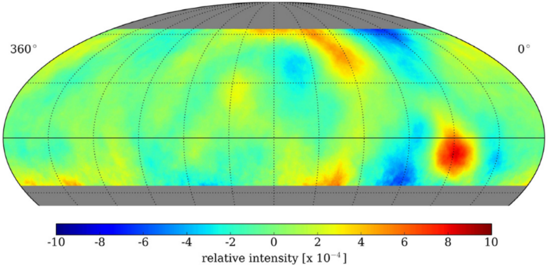
Visualisation of the amplitude and phase change with energy



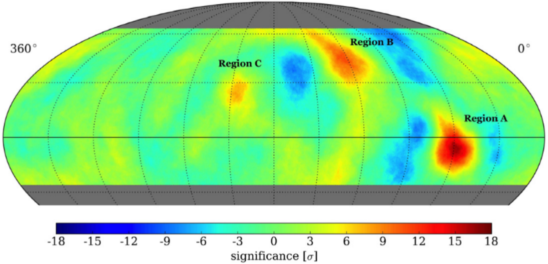
ApJ 826 (2016) 220

Small scale anisotropies from HAWC

Relative intensities after subtracting dipole, quadrupole and octupole terms



2 TeV



Regions A, B

observed as well by Milagro, Tibet ADγ, ARGO-YBG

Region C

observed as well by ARGO-YBG

M. Ahlers, P. Mertsch, PPNP 94 (2017) 184

Local effects in heliosphere

Non-diffusive propagation

Non-uniform pitch-angle diffusion

Turbulent magnetic fields

Exotics (strangelets, dark matter)

ApJ 796 (2014) 108

New observational puzzles

- Hardening of nuclei spectra at $R \sim 300$ GV
- Difference in slopes of proton and helium spectra
- Nearly same slopes of protons, antiprotons and positrons at $E > 10$ GeV
- Break at ~ 1 TeV in the electron spectrum
- Rise of positron fraction at $E > 10$ GeV
- Small scale anisotropies
- Isotropic CR flux up to very high energies
- Anisotropy phase pointing away from Galactic center at $E < 100$ TeV

for more details see S. Gabici et al., IJMPD (2019) 1930022