

Recent results in cosmic-ray astrophysics

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The dawn of cosmic-ray astrophysics

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N. 1, 1956
1° Semestre

The Nature of Cosmic Radio Emission and the Origin of Cosmic Rays.

V. L. GINZBURG
Academy of Sciences of the USSR - Moscow

CONTENTS. — 1. Introduction. — 2. The magnetic bremsstrahlung nature of cosmic radio emission. — 3. The origin of cosmic rays.



THE DISTRIBUTION OF RELATIVISTIC ELECTRONS IN THE GALAXY AND THE SPECTRUM OF SYNCHROTRON RADIO EMISSION

S. I. Syrovatskii

P. N. Lebedev Physical Institute, Academy of Sciences, USSR

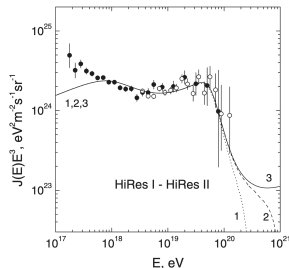
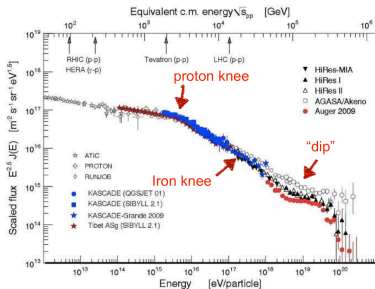
1959

The problem of the diffusion of particles is solved, taking into account the regular changes of the particle energy during this process. The spatial distribution and the energy spectrum of electrons, whose energy changes because of radiation emission in the magnetic field, were found on the assumption that the sources occupy an ellipsoidal volume and inject into interstellar space relativistic electrons with an energy spectrum $Q\epsilon^{-\gamma_0}$. The case when the distribution of the sources coincides with the flat subsystem of the galaxy and $\gamma_0 = 2$ is considered in detail. The energy spectra of electrons along the line of sight in different directions and the corresponding intensities of synchrotron radiation.

- ▶ The birth of **cosmic-ray astrophysics** dates back in the '50, thanks to works by Vitaly Lazarevich Ginzburg (1916-2009) and Sergei Ivanovich Syrovatskii (1925-1980)
- ▶ The founding idea was to connect the diffuse synchrotron emission from the entire Galaxy with the flux of relativistic electrons measured at the Earth
- ▶ Amazing predictions:
 1. the GZK effect at roughly ~ 50 EeV as the maximum energy protons can travel through the CMB without significant absorption [Greisen, PRL 16, 1966; Zatsepin & Kuzmin, JETPL, 1966]
 2. the knee as a signal of transition to meta-galactic origin as the maximum energy protons can be trapped in MW [Cocconi, Nuovo Cimento 3, 1956]
- ▶ Since the very beginning truly **multi-messenger** in nature

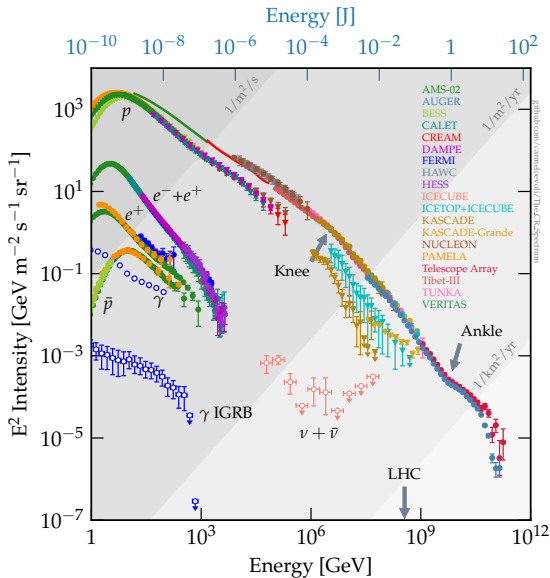
The common wisdom after ~ 50 years

Strong+, Ann. Rev. Nucl. Part. Sci. 57, 2007; Berezhinsky+ PRD 74, 2006



- Galactic CRs are accelerated at SNRs through DSA \rightarrow universal injection spectrum ~ 2.4 (almost ISM composition)
- Propagation in the Galaxy is diffusive on background Kolmogorov-ish turbulence $E^{1/3}$ (+ reacceleration)
- Positrons and antiprotons are both pure products of pp collisions
- The knee at ~ 4 PeV is caused by proton E_{\max}
- Z dependent knees up to second knee (Fe) \rightarrow transition to extra-galactic CR occurs somewhere around 10^{17} eV
- A second extra-galactic population exists injecting mostly protons with a steep spectrum $\sim 2.6 \rightarrow$ features mainly due to particle physics effects (the "dip" model)

The cosmic-ray spectrum in 2023



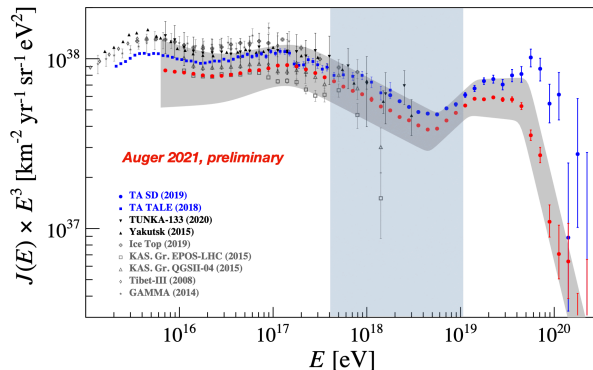
The cosmic-ray spectrum in 2023

- ▶ CRs are a **non-thermal** population of relativistic particles that pervade the solar system, galaxies, clusters and intergalactic space
- ▶ **Almost a perfect power law** over more than 11 energy decades!
- ▶ At low energy $dN/dE \propto E^{-2.7} \rightarrow E^2 dN/dE \propto E^{-0.7}$
→ most of the energy is in \sim GeV CR protons
- ▶ energy density near Earth $\sim 2 \times 10^{-12} \text{ erg cm}^{-3} \sim \text{eV cm}^{-3}$
→ **close to equipartition, important agent for ISM ionization, driving Galactic outflows, ...**
- ▶ Evidence of departures from a perfect power law: most spectacular are the **knee** and the **ankle**
- ▶ Spectrum cut-off at $\gtrsim 10^{20} \text{ eV} \rightarrow$ **GZK or cosmic-ray sources out of steam?**
- ▶ Particles observed at energy higher than any terrestrial laboratory $\sqrt{s_{\text{LHC}}} \sim 2 \times 10^{17} \text{ eV}$
- ▶ Composition at 10 GeV: $\sim 99.2\%$ are nuclei, $\sim 0.7\%$ are electrons, $\sim 0.1\%$ are **anti-matter** particles (positrons and antiprotons)

News from the UHECR land

The UHECR spectrum: a consistent picture at last!

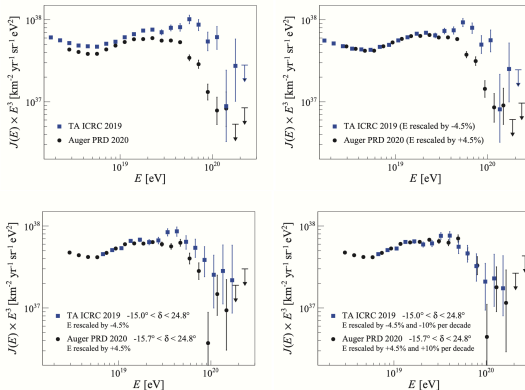
V. Verzi et al., UHECR2022 Proceedings



- ▶ Similar features: ankle, instep, suppression
- ▶ Agreement on the **ankle** position at $E_{\text{ankle}} \sim 5 \text{ EeV}$
- ▶ Some tension in the very-high-energy region $E \gtrsim 10^{19} \text{ eV}$

Comparison Auger-TA Spectrum

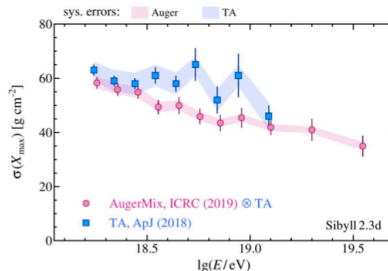
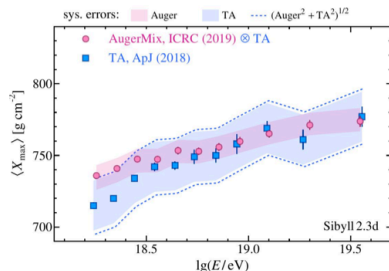
Bergman et al., UHECR2022 Proceedings



- ▶ In perfect agreement up to $\sim 10^{19}$ eV after a rescaling of the energy by an overall 9% factor (full-declination band in the upper row)
- ▶ A small tension (how significant?) persists even in the common declination band (bottom-left)
- ▶ Full agreement if the energy scale is rescaled in an energy dependent way by 20%/decade

Comparison Auger-TA Composition

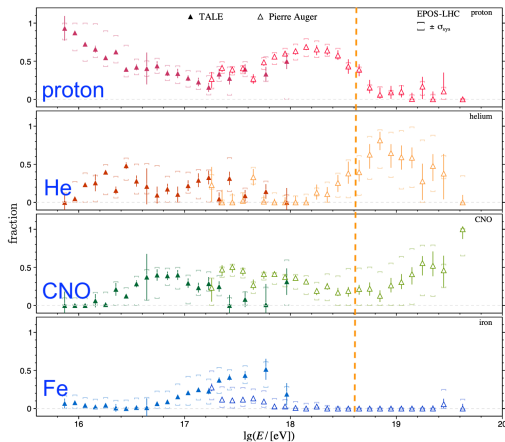
Bergman et al., UHECR2022 Proceedings



- ▶ Both TA and Auger measure the nuclear composition by observing the $\langle X_{\max} \rangle$ distributions
- ▶ However **different strategies** in selecting the data sets for the measurements → consistent results?
- ▶ Joint-work to perform a comparison of composition measured by Auger **as it would have been seen** at TA
- ▶ No robust difference in the $\langle X_{\max} \rangle$ distributions is found between TA and Auger (not true for all HIMs)
- ▶ Small disagreement in the width $\sigma(X_{\max})$ at energies between $10^{18.5}$ and 10^{19} eV

From $\langle X_{\max} \rangle$ to mass composition at Earth

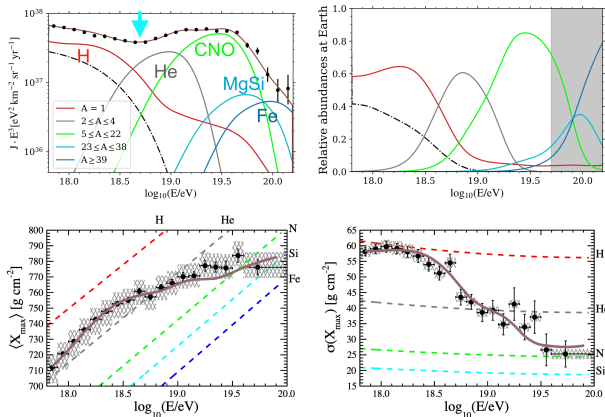
Abbasi+, for TA Coll., Astrophys. J. 909, 2021; Bellido+, for Auger Coll., ICRC2017



- ▷ $\langle X_{\max} \rangle$ distributions fitted with four-mass Gumbel function from LHC-tuned interaction models
- ▷ Large light-elements (H+He) below the ankle
- ▷ Heavy elements (Fe) almost absent

Combined fit of spectrum and composition

E. Guido, UHECR2022 Proceedings, arXiv:2211.02857



- ▶ A recent combined-fit model extended to low energies $\lesssim 10^{18} \text{ eV}$ to include the ankle feature
- ▶ Extensive scrutiny of uncertainties (HIM, source evolution, detector effects and systematics...)
- ▶ Instep region as a super-position of masses \rightarrow intermediate mass dominated
- ▶ Additional information including arrival directions in the fit (see T. Bister's talk)

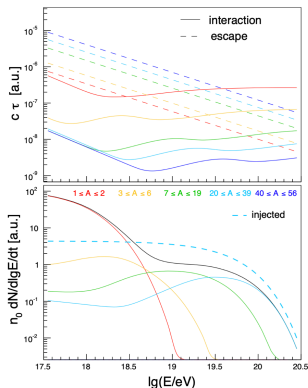
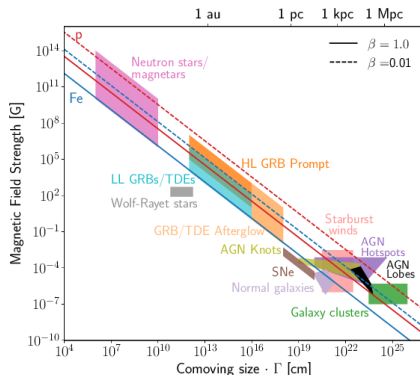
E. Guido, UHECR2022 Proceedings, arXiv:2211.02857

* from $E_{\min} = 10^{17.8}$ eV.

- A set of small navigation icons typically found in Beamer presentations, including symbols for back, forward, search, and other slide controls.

Making sense of hard spectra

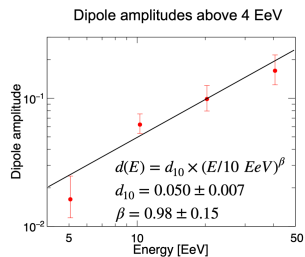
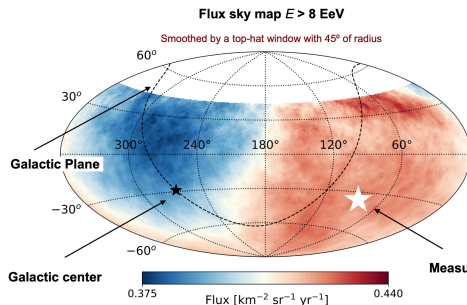
Unger, Farrar & Anchordoqui, PRD 2015



- ▶ Smaller maximum energy → less stringent requirement in terms of source efficiency!
- ▶ However the unusually hard spectra require non standard acceleration → magnetic reconnection?
- ▶ or it might reflect energy losses inside sources + energy dependent escape → what about the new combined fit?

Large-scale anisotropy with full-Auger analysis

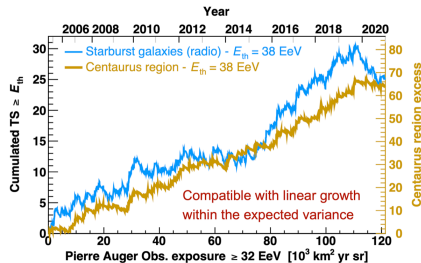
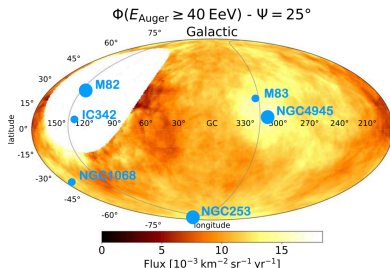
A. Aab et al., Science 357, 1266 (2017)



- ▶ Detection of a dipolar anisotropy at energies above 8 EeV is the **long sought evidence** that the majority of sources are not in the Milky Way
- ▶ The direction of the dipole points $\sim 120^\circ$ away from the Galactic center (significantly larger than what expected in the JF model if sources at the GC)
- ▶ Significance increases with exposure, latest update $\sim 6.6\sigma$ (ICRC2021 Proc.)
- ▶ Dipole amplitude increases linearly with energy

Intermediate/small scale anisotropy: search for localized excesses

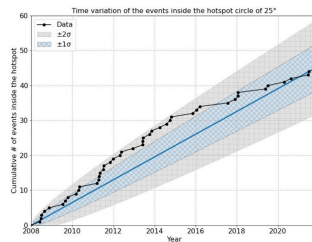
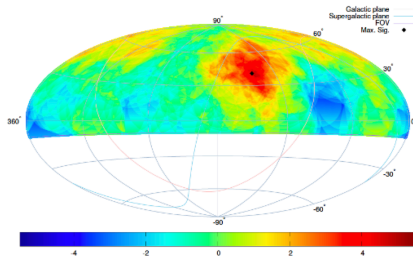
P. Abreu et al., ApJ 935, 170 (2022)



- ▶ Local indication of departure from isotropy for $E \gtrsim 41$ EeV in direction of Centaurus region
- ▶ Most significant local excess: $N_{\text{obs}} = 153$ events versus $N_{\text{exp}} = 97.7$ events from isotropy ($\sim 4\sigma$)
- ▶ Global correlation: the starburst model adds the excess in the Galactic South Pole (NGC253)
- ▶ Full-sky coverage using TA and Auger increases significativity as the two most UHECR-bright sources are NGC4945 and M82 **in opposite hemispheres** [see Di Matteo et al., UHECR2022 Proceedings]
- ▶ 5σ deviation from isotropy expected **in 2025 ± 2 years**

Updates on the TA Hotspot and the Perseus-Pisces supercluster Excess

Kim et al., UHECR2022 Proceedings



- ▶ TA hotspot: In 14 years of data 44 out of 205 events are detected (16.9 events from isotropic distribution) with $E > 57$ EeV
- ▶ The rate of events inside the hotspot circle increases with time as expected
- ▶ A new excess (mostly in lower energy events $E > 25$ EeV) in the direction of the Perseus-Pisces supercluster is claimed
- ▶ Similar significance $\sim 3.6\sigma$

Anisotropy constraints on sources

More on G. Farrar and M. Unger's talks

- ▶ Identifying sources by anisotropy measurements is hampered by the uncertainties on the IGM and Galactic magnetic fields:

$$\bar{\theta} = 2.3^\circ Z \left(\frac{E}{50 \text{ EeV}} \right)^{-1} \left(\frac{\bar{B}}{1 \text{ nG}} \right) \left(\frac{D}{10 \text{ Mpc}} \right)^{1/2} \left(\frac{l_c}{1 \text{ Mpc}} \right)^{1/2}$$

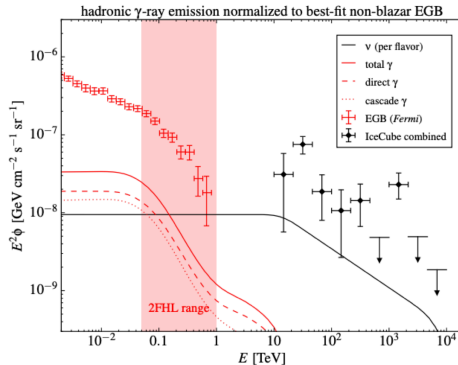
- ▶ However, intermediate elements have **reduced horizon for photo-disintegration** and maybe **still enough rigidity** to point almost back to their sources

$$\text{mean free path} \sim A^{-1}$$

- ▶ On the other hand, the connection **arrival directions-source positions** may be obtained in a statistical sense, eventually marginalizing over the magnetic field uncertainties [Capel and Mortlock, MNRAS 2019]
- ▶ However, the possible correlation with SBGs does not inevitably imply that they are the sources of UHECRs
- ▶ Still unclear if SBGs are able to accelerate particles up to UHECR energy in these objects [Anchordoqui, PRD 2018; Peretti et al., MNRAS 2022]
- ▶ If so, they would be able at the same time to account for the UHECR spectrum and the IceCube diffuse neutrino flux [Condoirelli et al., PRD 2023]

The diffuse neutrino sky

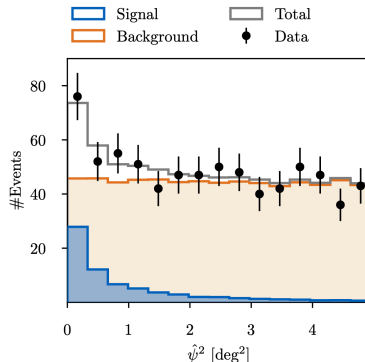
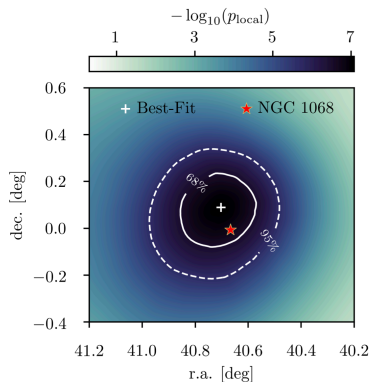
Murase & Waxman, PRD 94, 2016; Murase+, PRL 116, 2016; Bechtol+, ApJ 836, 2017



- ▷ Diffuse cosmic neutrino flux discovered at last! [Aartsen+, PRL 113, 2014]
- ▷ In order not to overshoot the measured γ -ray background a majority of neutrino sources has to be dark in GeV γ -rays
- ▷ A new class of astrophysical objects for which most photons and cosmic rays are trapped inside \rightarrow **cocoons**

NGC1068 as neutrino source

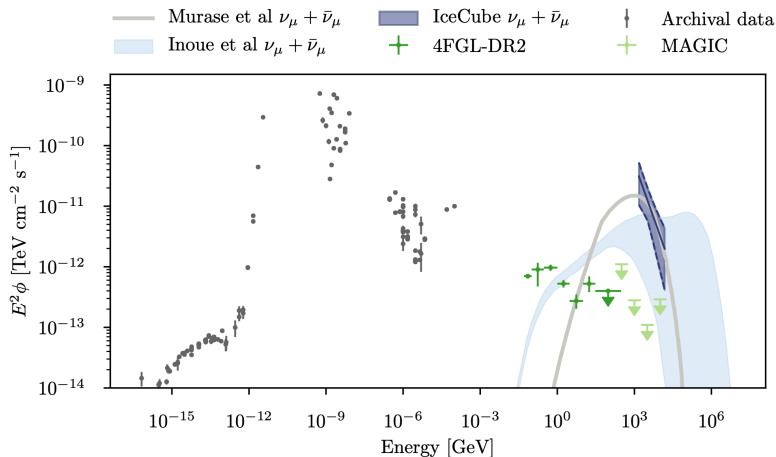
Abbasi+, Science 378, 2022



- ▶ Announced in Nov 22 the **first direct evidence of TeV ν -emission** from a nearby active galaxy (4.2σ significance)
- ▶ NGC1068(M77) is a nearby (14 Mpc) AGN, the brightest type-2 Seyfert galaxy and with **intense star-forming activity**
- ▶ softer spectrum ~ 3.2 than the diffuse flux $\sim 2.5 \rightarrow$ we are looking at a cutoff? No UHECR protons!
- ▶ NGC1068 also contributes to the SBG excess found by Auger (at 10%) [A. Aab+, ApJL 853, 2018]

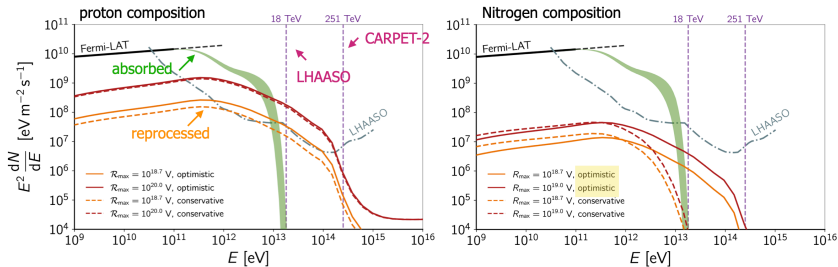
NGC1068 as neutrino source

Abbasi+, Science 378, 2022; Inoue+, ApJL 891, 2020; Murase+, PRL 125, 2020



GRBs as UHECR sources

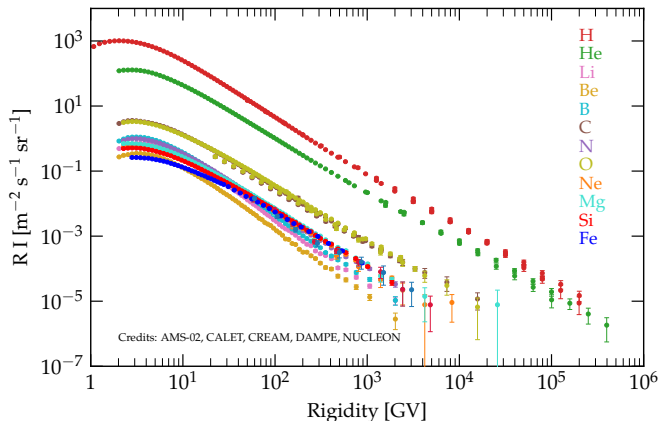
Das & Razzaque, A&A 670, 2023; Alves Batista, arXiv:2210.12855



- ▶ GRB 221009A ($z = 0.151$) drew much attention because the events detected by LHAASO at $E \simeq 18 \text{ TeV}$ and Carpet-2 at $E \simeq 251 \text{ TeV}$ should not have arrived at Earth **due to EBL absorption** (still not confirmed)
- ▶ Possible contribution from line-of-sight emission by UHECRs [Essey+, PRL 104, 2010; Kusenko & Voloshin, PLB 707, 2012]
- ▶ Temporal and angular coincidences can only occur if LOS magnetic fields are not exceedingly strong $B \simeq 10^{-13} \text{ G}$
- ▶ In **optimistic scenario** (weak-B field, $\mathcal{R} \gtrsim 1 \text{ EeV}$) γ -rays with energies of up to $\sim 1 \text{ PeV}$ from GRB 221009A could reach Earth even for Auger-like composition

News from the Galactic CR land

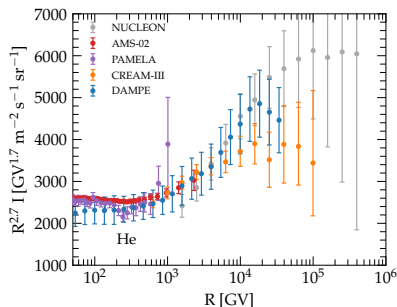
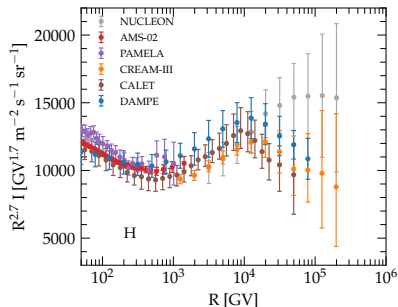
Galactic Cosmic Rays: the realm of direct measurements



- Direct measurements reaches the multiple TeV scale
- The spectrum of each isotope includes contributions from many different parents (both in terms of fragmentation and decays) giving to each observed isotope a **potentially very complex history**

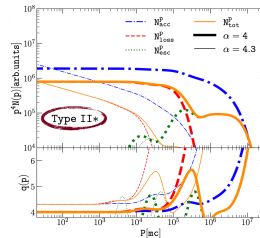
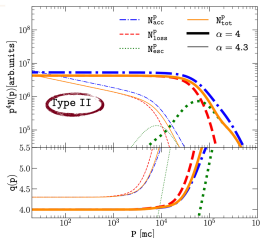
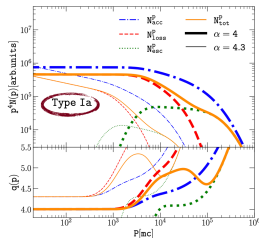
Galactic Cosmic Rays: a decade of suprires

PAMELA Coll., Science 2011; AMS-02 Coll., PRL 2015; CREAM Coll., ApJ 2017; NUCLEON Coll., JETP 2018; DAMPE Coll., Science 2019



- ▷ Spectra of protons and helium are not a single power law below the knee → some physics kicking in?
- ▷ The **hardening** at $R = p/Z \sim 300 - 400$ GV is well established since first observation by CREAM and PAMELA
- ▷ AMS-02 confirmed the same break for **almost all nuclei** and due to transport!
- ▷ The **softening** at $R = p/Z \sim 10$ TV is observed by different experiments, first strong evidence in DAMPE (no explanation so far)
- ▷ The He spectrum (at Earth!) is slightly **harder** than that of protons

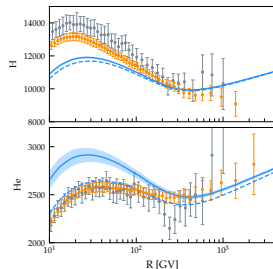
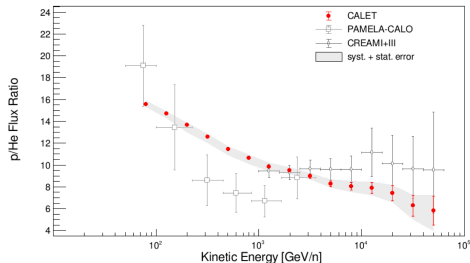
Some consideration on spectral features



- ▶ Fluctuations in the CR proton/nuclei spectra below 100 TeV are negligible hence it is **unlikely to have one due to a local source** [Genolini+, A&A, 2017; Evoli+, PRD 2020]
- ▶ There are different populations of SNR with different E_{max} → expected features associated with Type Ia SNe, or dips in the spectra of core collapse SNe [Cristofari+, Aph 2020; Diesing, arXiv:2305.07697]
- ▶ However, these features are not universal but rather depend on the local conditions → variance? how ends up in having only one feature? [Lipari & Vernetto, Aph 2020]

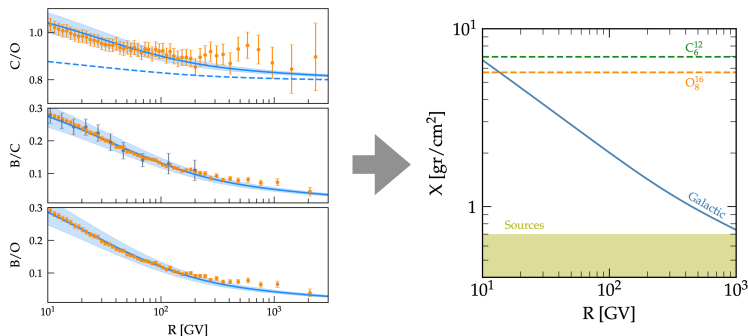
The low-energy problem with injection slopes

Evoli et al., PRD 99, 2019; Weinrich et al., A&A 639, 2020



- Differences between the proton and helium spectra measured up to ~ 60 TeV/n [Adriani et al., PRL 130, 2023]
- At odds with what one would expect in the case of **pure rigidity dependent acceleration** [Caprioli, Varenna Lecture Notes 2022]
- H is **softer** than nuclei, while He is **harder**: $\Delta\gamma \sim \pm 0.05$
- Problematic even for models of the difference between H and He injection based on the different A/Z at shocks [Hanusch+, Apj 2019]

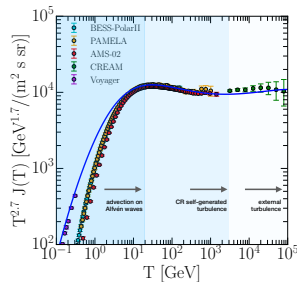
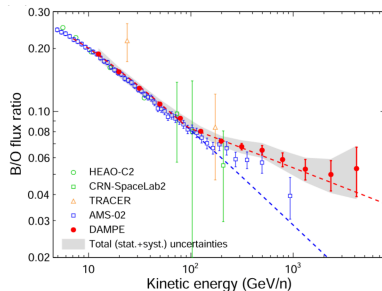
News on grammage indicators



- ▶ These ratios return the energy dependence of grammage (assuming to know cross-sections), hence the properties of galactic transport [Evoli+, PRD 2019; Boschini+, ApJS 2020; Weinrich+, A&A 2020; Korsmeier+, PRD 2021]
- ▶ Shaded areas show **uncertainty from fragmentation cross sections**, still the dominant one [Genolini et al., PRC 2018]
- ▶ Consistent picture for nuclei from Carbon to intermediate mass elements Ne, Si, Mg, and S (see B. Schroer's talk)

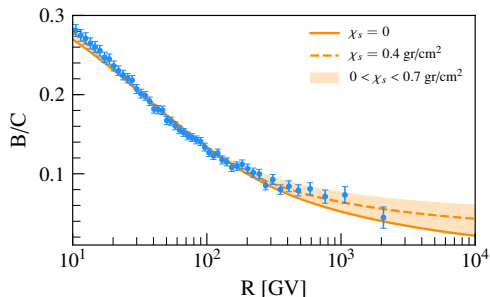
The change of transport regime at 300 GV

DAMPE, Science Bulletin 67, 2022; Evoli+, PRL 2018



- ▶ At 300 GV something new is happening in terms of **CR transport in the Galaxy**: evidence in the secondary/primary ratio → grammage
- ▶ At present two physical interpretations are at hand:
 1. The transition marks the energy at which the self-generation of turbulence by the CR themselves runs out of steam [Blasi+, PRL 2012]
 2. The transition is due to different turbulence conditions in the disk and in the halo [Tomassetti, A&A 2012]
- ▶ Problematic in terms of **sharpness** of the feature

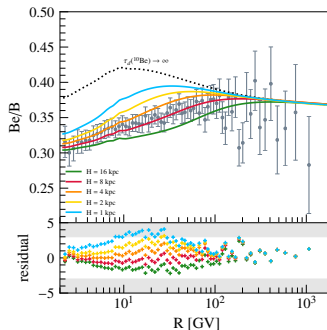
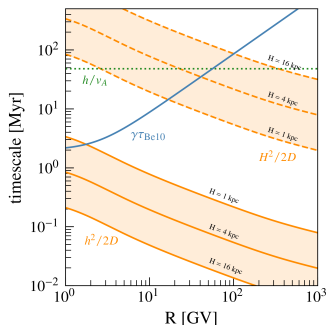
Additional effects not included in this picture



- ▶ Second-order Fermi acceleration in the ISM [Ptuskin et al., 2006, ApJ 642; Drury & Strong, 2017, A&A 597]
- ▶ Shock re-acceleration of secondary nuclei [Blasi, 2017, MNRAS 471; Bresci et al., 2019, MNRAS 488]
- ▶ Grammage at the sources [D'Angelo et al., 2016, PRD 94; Nava et al., 2016, MNRAS 461; Jacobs et al., 2022, JCAP 05]
- ▶ Secondary production at the sources [Blasi, 2009, PRL 103; Mertsch & Sarkar, 2014, PRD 90]
- ▶ Although theoretically motivated, still not needed to reproduce data [Evoli+, PRD 99 (2019)]
- ▶ However, hints on a **flattering of the B/C** at the highest energy from DAMPE, NUCLEON...

News on residence time indicators

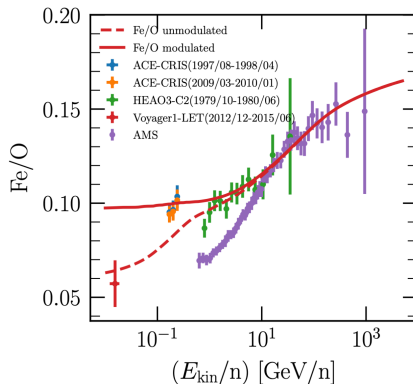
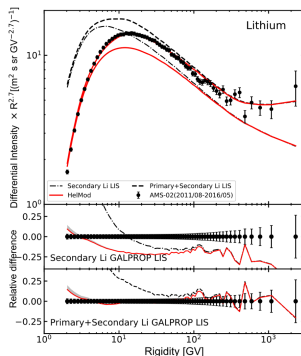
Evoli et al., PRD 101 (2020)



- ▶ Traditionally the ratio $^9\text{Be}/^{10}\text{Be}$ has been used as **CR clock** → however no measurements of this ratio at $E \gtrsim 1$ GeV/n
- ▶ Since ^{10}Be decays to ^{10}B the ratio **Be/B** is affected twice (excellent recent AMS-02 data!)
- ▶ Make sure that ^{10}Be decays outside the disc (hostile to CR transport) → at \gtrsim few GeV this is certainly the case
- ▶ Preference for **large halos** $H \gtrsim 5$ kpc [Weinrich et al., A&A (2020), Maurin et al., arXiv:2203.07265] → consequences also for anisotropy

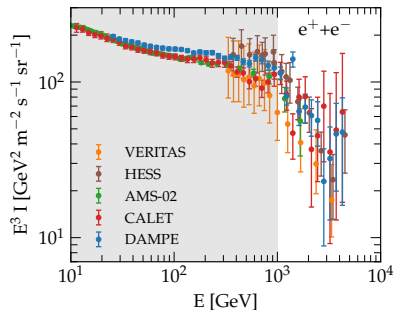
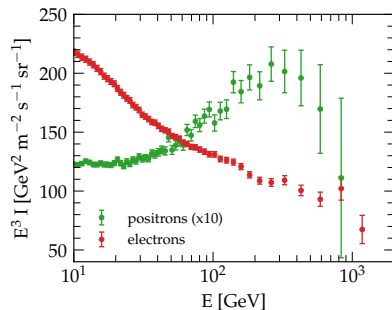
Anomalies in GCR species

Boschini+, ApJ 889, 2020;



- ▶ Li spectrum appears somewhat **flatter at high energies** → may imply a **primary** Li component?
- ▶ Secondary production account for $\sim 80\%$ of the observed flux → production cross-sections? Unlikely!
- ▶ Iron and Oxygen are both **pure** primaries, less theoretical uncertainties [see B. Schroer's talk]
- ▶ Disturbing disagreement between calorimeters (e.g., CALET/DAMPE) and spectrometers (e.g., AMS-02) for almost all nuclei

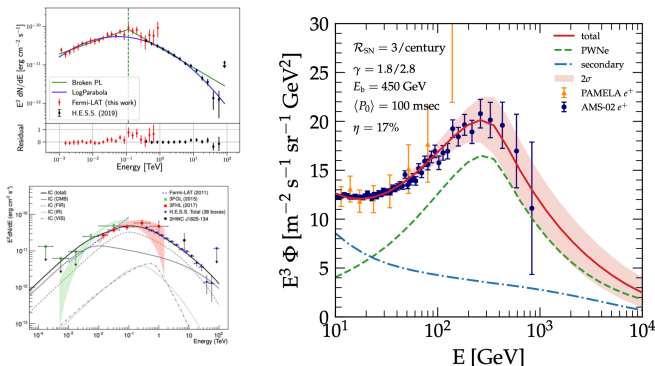
Galactic factories of cosmic electrons and positrons



- ▶ In recent years there has been a dramatic improvement in the measurement of the spectrum of e^\pm
- ▶ Electrons after propagation much steeper than protons \rightarrow even accounting for energy losses injected with steeper spectrum $\Delta\gamma \sim 0.3$ [Evoli+, PRD 2021]
- ▶ Problematic to achieve during acceleration unless B is very strongly amplified [Diesing & Caprioli, PRL 2020; Cristofari+, A&A 2021]

The break in the pulsar spectrum from PWNe

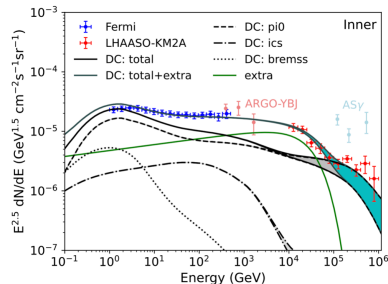
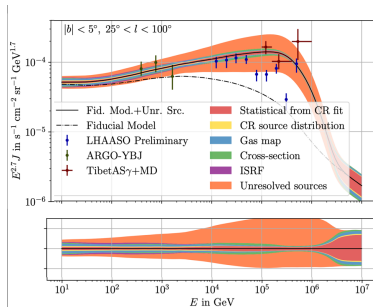
Principe et al., A&A 640, A76 (2020), H.E.S.S. Collaboration, A&A 621, A116 (2019)



- ▶ Good example of getting **close to the identification of sources!**
- ▶ Combined spectra of **HESS J1825-137** and **HESS J1825-137** by Fermi-LAT and H.E.S.S. data
- ▶ γ /X-ray emissions by PWNe are well described by a **hard spectrum** (with $1 < \alpha_L < 2$) at low energies, which then steepens to $\sim E^{-2.5}$ **beyond \sim few hundred GeV** [Bucciantini+, MNRAS 2011]
- ▶ HAWC has detected bright and spatially extended TeV gamma-ray sources surrounding the Geminga and Monogem pulsars [HAWC coll., Science 358 (2017)] associated with the **release of pairs in the ISM** [detected also in FERMI, see Linden+, PRD 2019; Di Mauro+, PRD 2019]

VHE diffuse emission above 10 TeV

Amenomori+, PRL 126, 2021; Cao+, arXiv:2305.05372

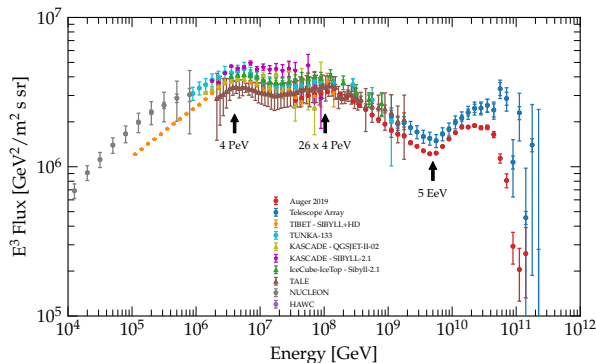


- significantly improved measurements of the **VHE diffuse emission** from both the inner and outer Galactic plane by Tibet-AS γ and LHAASO
- candidate population of unresolved sources contributing to high-energy are pulsars or pulsar wind nebulae [Aharonian & Atoyan 2000; Linden & Buckman 2018; Vecchiotti et al. 2022; Zhang+, arXiv:2305.06948] or CR self-trapped cocoons [D'Angelo+, MNRAS 474, 2018]
- Non-trivial spatial dependence of the diffusion coefficient [Gaggero+, PRD 91, 2015]
- Consequences on the diffuse neutrino signal from MW [De La Torre Luque+, A&A 672, 2023; Schwefer+, arXiv:2211.15607]

News on the transition border

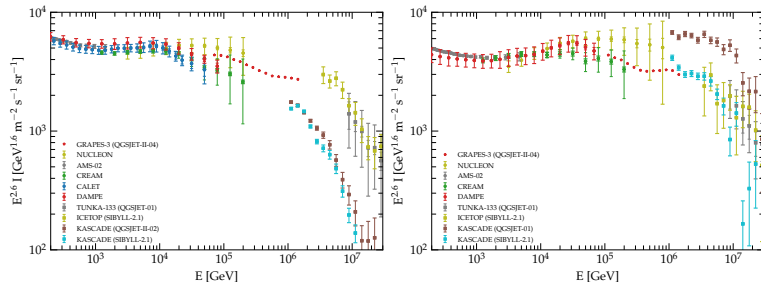
The end of the Galactic spectrum

Aloisio+, JCAP 2014; Globus+, PRD 2015; Thoudam+, A&A 2016



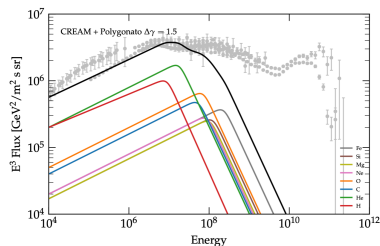
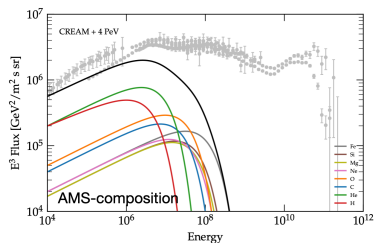
- ▶ If (first) knee is made by $H \rightarrow$ Galactic CRs end with heavy elements at ~ 100 PeV (second) knee
- ▶ Maximum energy of Galactic accelerators OR a change in the transport regime (diffusive \rightarrow ballistic)?
- ▶ The Larmor radius of these particles in the Galactic B-field $r_L = \frac{p}{ZeB} \sim 100 \text{ pc} \left(\frac{E}{\text{PeV}} \right) \left(\frac{\mu_G}{ZB} \right)$

New views on the CR knees



- The first knee should be reached by He rather than protons (indirect measurements still in large disagreement, see Di Sciascio's talk)

New views on the CR knees



- ▶ Assuming AMS-02 based composition → Peters' cycle is not a good description of data
- ▶ We need at least **one more population!** Galactic or Extra-Galactic?
- ▶ Crucial goal for the near future is **to reach the knee by direct detection experiments** → ISS-CREAM, HERD, ...

Conclusions

- ▶ Data in the latest two decades have been forcing us to revisit most (if not all) of our ideas after the founding era → extremely dynamic field
- ▶ The standard model certainly needs modifications
- ▶ Whether such modifications are small adjustments or cracking of the pillars it will be critically assessed during this conference!

Thank you!

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