The Cosmic-ray Spectrum across the Knees

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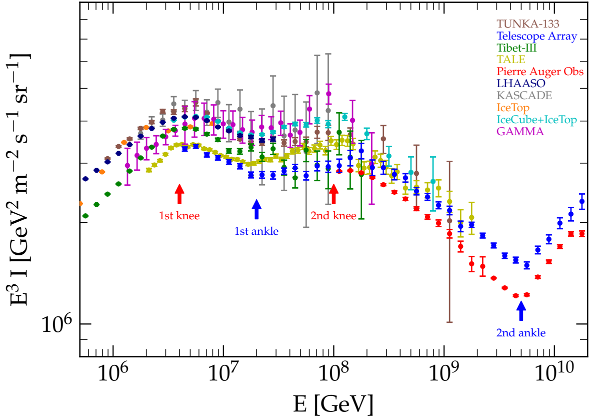
Motivations

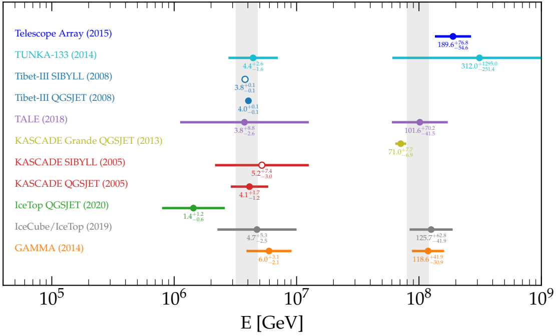
- The specific location and underlying mechanisms of the **transition from galactic to extragalactic cosmic rays** persists as a crucial open question in our field [Hörandel, APh 2003; Kachelrieß & Semikoz, PPNP, 2019; Mollerach, arXiv:2012.10359].
- Understanding this transition has the potential to reveal the **limits of known acceleration processes** both within the Milky Way and in the external (more powerful) sources.
- The energy region lying between the **two knees** is especially critical, as it may hold key information about the **termination of the galactic cosmic ray spectrum.**
- Unprecedented measurements of CR flux and composition in the multi-TeV region (CALET, DAMPE, ISS-CREAM) set the stage for the **direct** measurement of the knee in the next-generation experiments.

The Cosmic Ray Spectrum across the Knees



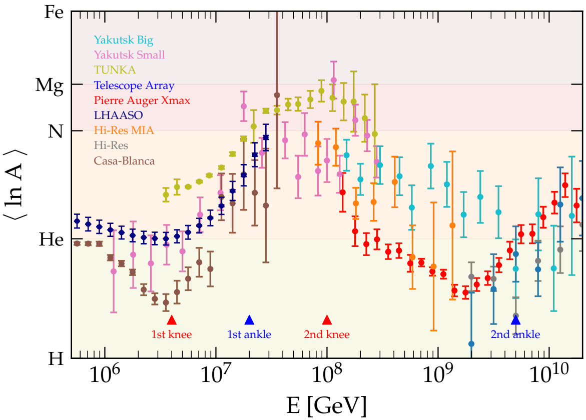
- The all-particle energy spectrum of primary cosmic rays (multiplied by E^3) is shown, including only statistical uncertainties.
- In this energy range, data primarily originates from indirect detection experiments.
- The all-particle spectrum exhibits consistent features when considering statistical, systematic, and energy scale uncertainties.
- The spectrum follows a power-law distribution, approximately $\sim E^{-2.7}$, up to the first knee at a few PeV. Beyond this point, the slope steepens to $\sim E^{-3.1}$, with a subsequent downward bend near 10^{17} eV to $\sim E^{-3.5}$, known as the second knee.

The Energy of the Cosmic Ray Knees



- The first knee is distinctly observed in the all-particle spectrum at approximately 4 PeV.
- The two knees are separated by a factor of about 26, suggesting that the first knee could be primarily associated with protons, while the second knee might correspond to Iron nuclei.
- Historically, the origin of the first knee has been attributed to either:
  1. A shift from diffusive to ballistic propagation as cosmic rays escape the Galaxy.
  2. A cutoff-like feature in the injection spectrum of Galactic sources.

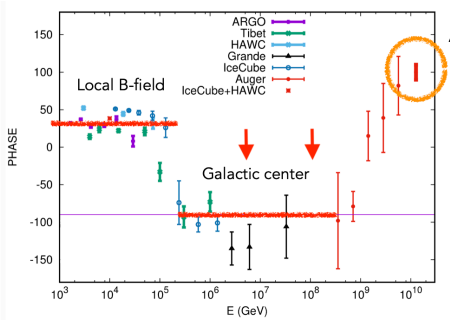
The Composition of Cosmic Ray Knees

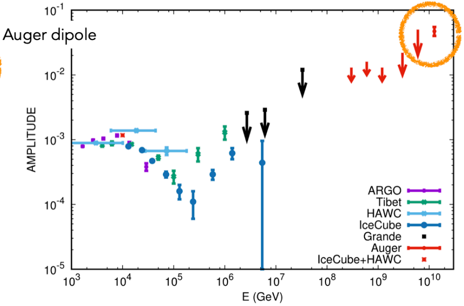


- Measuring composition in this energy region is crucial for testing various hypotheses regarding the transition.
- Significant discrepancies remain among results from different experiments, likely due to unknown systematic uncertainties, particularly in hadronic interaction models (HIM) [Kampert & Unger, APP 35, 2012].
- The first knee is associated with lighter elements, almost coincident with Helium.
- The second knee corresponds to intermediate elements, lighter than Iron.

Cosmic Ray Anisotropy

M. Kachelrieß, D.V. Semikoz, PPNP 109, 2019



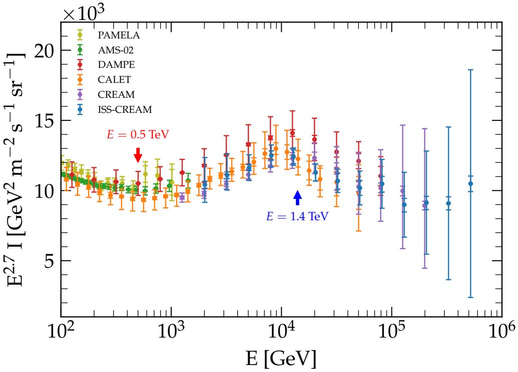


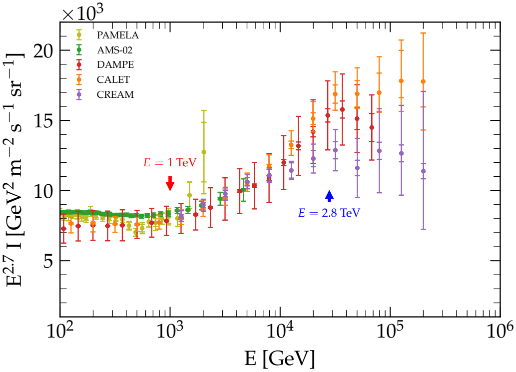
- Up to about the second knee compatible with Galactic origin [M. Ahlers & P. Mertsch, PPNP, 94, 2017]
- The detection of a dipolar anisotropy at energies above 8 EeV marks the evidence that the majority of sources of UHECRs are not in the Milky Way [A. Aab et al., Science 357, 1266 (2017)]
- The direction of the dipole points $\sim 120^o$ away from the Galactic center (significantly larger than what expected in the JF model if sources at the GC)

The End of the Galactic Cosmic Ray Spectrum

GCRs below the knee: the proton and Helium high-energy spectrum

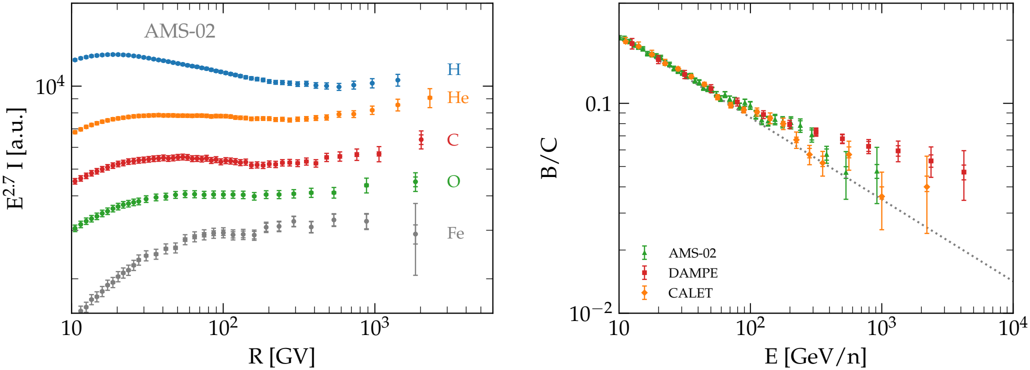
Adriani+, Science, 332, 2011; Yoon+, ApJ, 839, 2017; An+, Science Adv., 5, 2019; Aguilar+, Phys.Rep., 894, 2021; Adriani+, PRL, 129, 2022; Choi+, ApJ, 940, 2022





- Cosmic-ray proton flux measurements from direct experiments show at least 2 breaks below 1 PeV.
- Similar patterns also observed in the Helium spectrum [Alemanno+, PRL, 126, 2021]
- Helium spectrum persisting harder than H up to 100 TeV
- The standard halo model predicts a power-law behaviour for the equilibrium spectrum $E \gg 10$ GeV [CE & Dupletsa, arXiv:2309.00298]

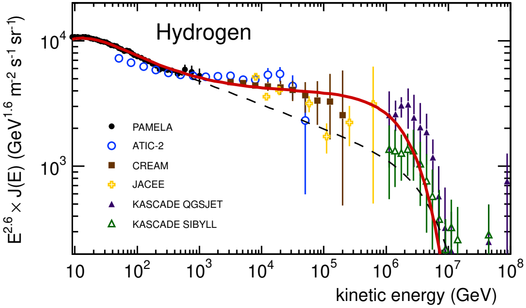
A GCR spectrum hardening at $R \gtrsim 300$ GV: phenomenology

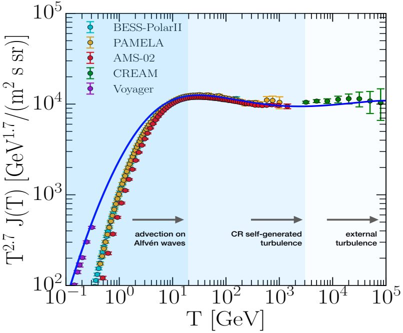


- The break was first hinted by the experiments ATIC-2 [Panov et al. 2009], CREAM [Ahn et al. 2010], while PAMELA [Adriani et al. 2011] provided first measurements below and above the break.
- Spectral break indicates that at least one process among acceleration, escape, or transport cannot be described by a single power law
- The same break observed in the B/C ratio suggests an explanation involving the diffusion coefficient $\longrightarrow$ changes in transport

A GCR spectrum hardening at $R \gtrsim 300$ GV: theory

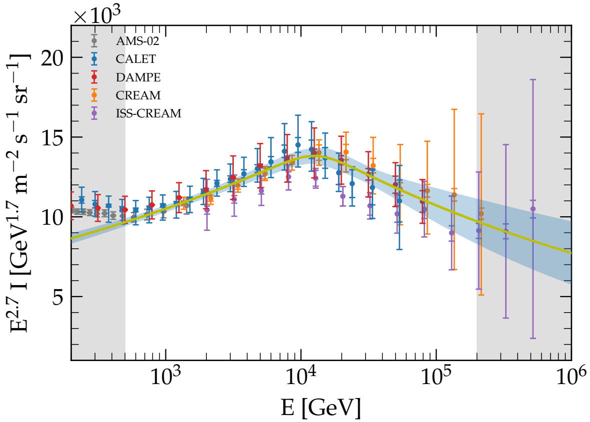
Blasi+, PRL 2012; Tomassetti, A&A 2012; Evoli+, PRL 2018





- Currently, two physical interpretations are proposed:
  - It marks the transition between the self-generation of turbulence by CRs themselves and the large-scale turbulence (similar idea applied to UHECRs $\longrightarrow$ Cermenati's talk).
  - The transition results from differing turbulence conditions in the disk and halo
- It remains unclear if these interpretations fully reproduce the sharpness of the observed feature

A GCR spectrum softening at $R \gtrsim 10$ TV: phenomenology



Measurements from AMS-02, CALET, CREAM, DAMPE, ISS-CREAM

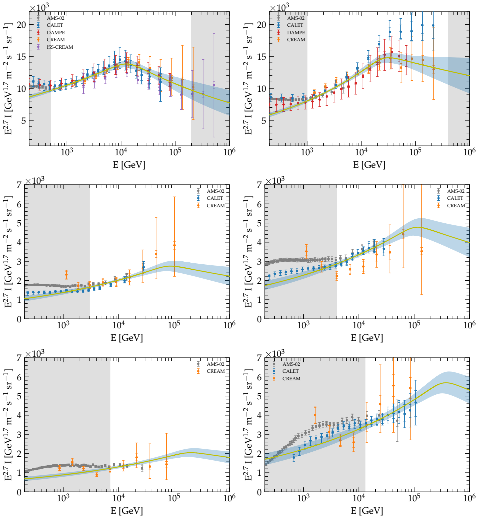
- Above $R \gtrsim 1$ TeV, GCR spectrum can be fitted by a pure rigidity-dependent model

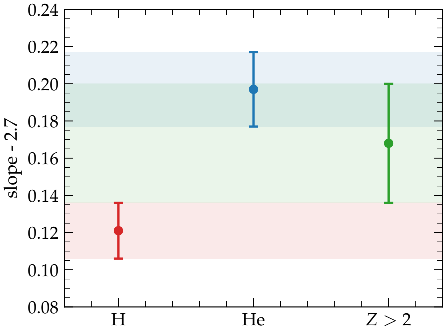
$$\tau_{\rm escape} \lesssim \tau_{\rm loss}$$

- Composition and energy dependence can be fitted by

$$\Phi \propto \Phi_{0,i} \frac{E^{-\alpha_i}}{[1 + (R/R_b)^s]^{\Delta\alpha/s}}$$

A GCR spectrum softening at $R \gtrsim 10$ TV: phenomenology

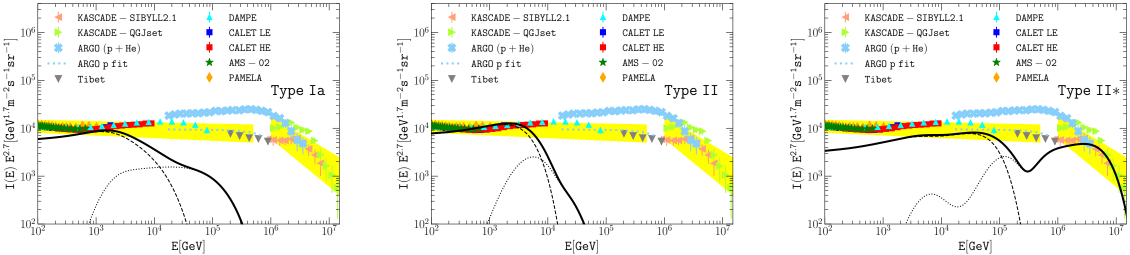




- Measurements are compatible within $\sim$5% energy-scale shift
- Break position at $R_b \simeq 10$ TeV and $\Delta\alpha \simeq 0.2$
- Intermediate-mass nuclei well fitted with the same slope, persistent tension with H and He

The SNR Escape Spectrum and the 10 TeV Softening

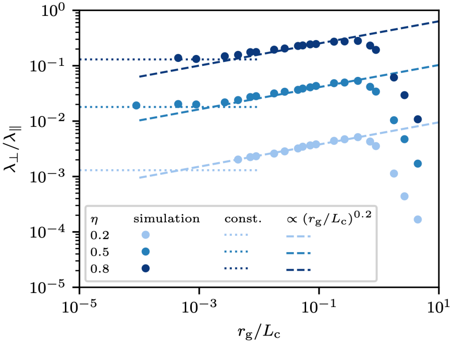
Cristofari+, Astroparticle Physics, 123, 2020; Diesing, arXiv:2305.07697



- Different populations of SNRs exhibit different $E_{\max}$, leading to distinctive features associated with Type Ia supernovae or dips in the spectra of core-collapse supernovae
- Nonetheless, these features should display significant variance $\longrightarrow$ How does this result in only few observable features? [Lipari & Vernetto, APh 2020]
- Could the 10 TeV softening be attributed to the transition between two distinct populations?
- This hypothesis requires a finely-tuned explanation where efficiency $\times$ rate $\times$ energy are very closely aligned.

Cosmic ray transport and the 10 TeV Softening

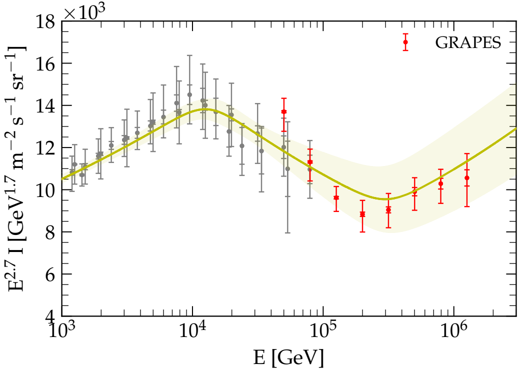
Kuhlen+, 2023, arXiv:2211.05881

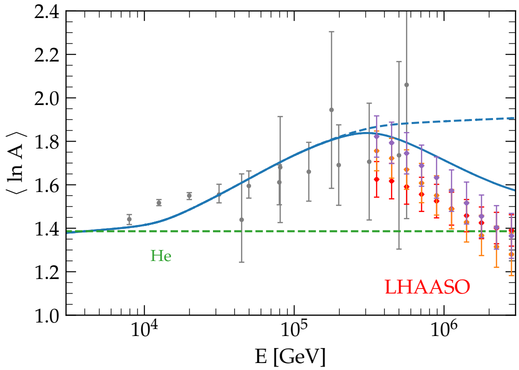


[Kuhlen+, 2023, arXiv:2211.05881]

- New test particle simulations in synthetic turbulence show a change of slope in the $D_\perp$ at about $\lambda \sim L_c$
- For ISM typical fields the mean free path λ becomes close to $L_c \sim 10$ pc at 10 TeV
- Still a lot of theoretical investigation on-going

GCRs: the last mile

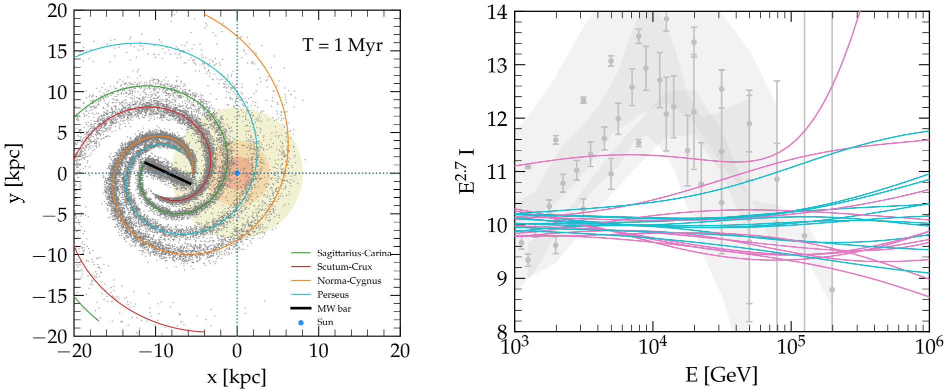




- And yet another break!
- Marginal evidence in ISS-CREAM protons and DAMPE p+He at $\gtrsim 10^5$ GeV
- Detection by indirect measurements with GRAPES $\longrightarrow$ well consistent with the decrease of lnA observed by LHAASO

Lessons from GCRs: Consequences of the Stochastic Nature of Galactic Sources

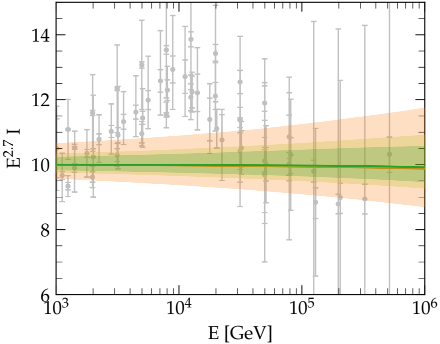
CE+, PRD, 104, 2021

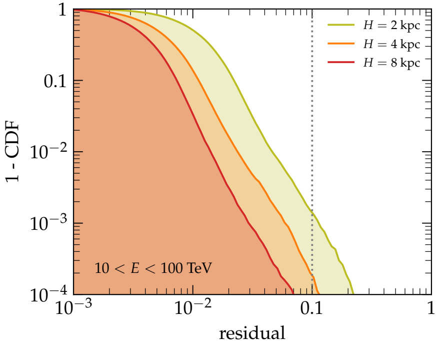


- The CR flux at Earth is inherently stochastic, characterized by a heavy-tail PDF [Lee, ApJ, 1979; Bernard+, A&A, 2012]
- Individual realizations show deviations from a pure power-law at varying levels
- Averaging these realizations leads to the textbook result $\propto E^{-2.7}$ in the mean field limit

Lessons from GCRs: On the CR Spectrum Variance

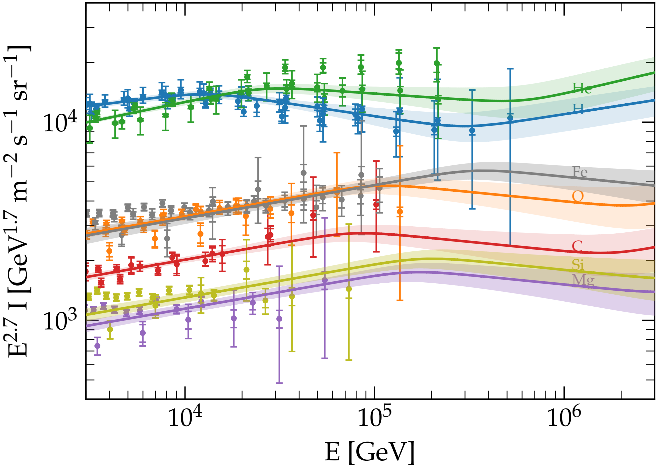
Evoli+, in preparation



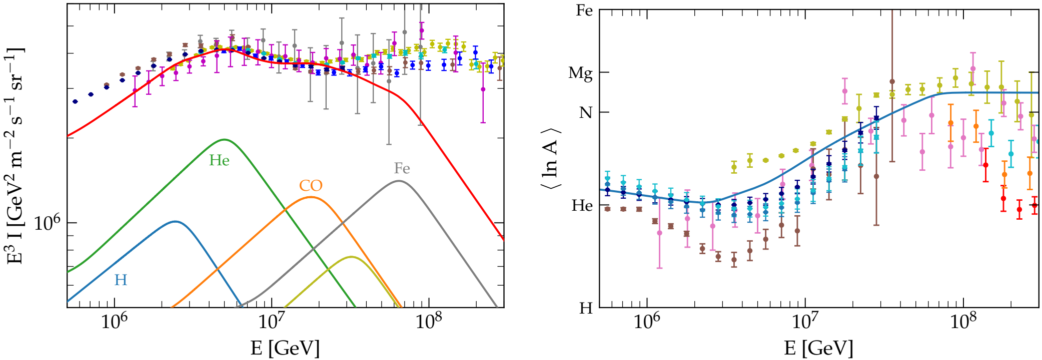


- Smaller halo size increases the variance $\rightarrow$ for $H = 2$ kpc, I found $\lesssim 15\%$ at 1 PeV
- Comparable effect by allowing source parameters to vary individually
- 1-CDF: the fraction of Galaxy to have a residual larger than a given value over the energy range 10 GeV - 100 TeV
- The probability is smaller than $\lesssim 0.1\%$

The GCR composition at the Knee

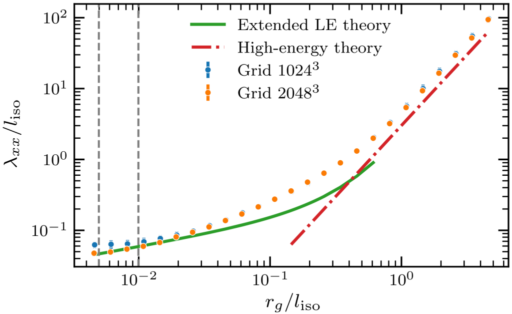


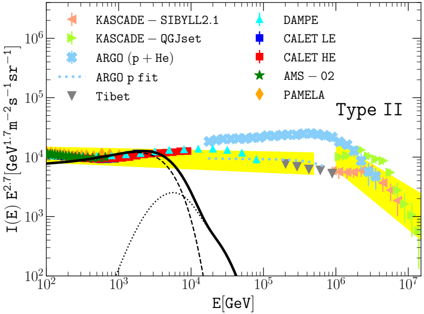
Modelling the first knee



- The first knee corresponds to the **Helium** maximum energy (confirming earlier measurements by EAS-TOP and KASCADE)
- Maximum energy for Galactic CRs $E_p \sim 2$ PeV $\rightarrow$ $E_{\text{Fe}} \sim 50$ PeV
- The little ankle comes from the reduction in composition from Helium to metals
- The observed hardening of the spectrum up to the second knee turns out to result from a **second galactic component**

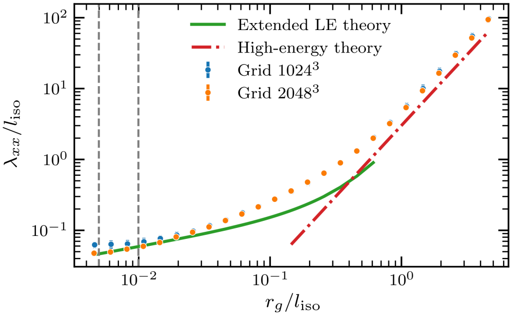
The end of the Galactic spectrum

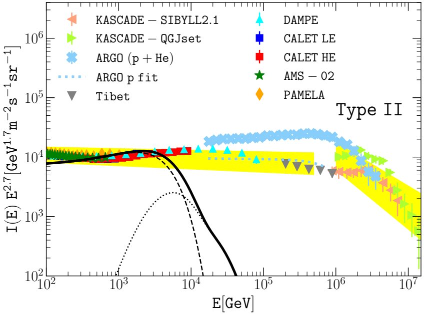




- The first knee is well fitted by a change of slope in individual species of about $\Delta\alpha \lesssim 1$
- Explanations in terms of escape predict a transition between diffusion dominated escape timescale $\tau \propto E^{-1/3}$ to small pitch-angle scattering $\tau \propto E^{-2}$ always predicts a more pronounced break $\Delta\gamma \sim 1.7$ [Dundovic+, PRD, 102, 2020]
- Even larger for the expected GCR source cutoff $\Delta\gamma \gtrsim 2$

The end of the Galactic spectrum

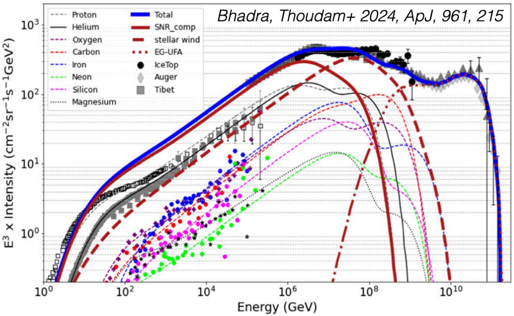




- An additional Galactic population from the first to the second knee? Ad-hoc.
- Hall diffusion? Does it extend over 1 decade? [Candia & Roulet, JCAP, 2006]
- Source maximum energy variance? [Kachelriess+, Phys. Lett. B 634, 2006; Ehlert+, PRD 107, 2023]

$$\frac{dN}{dE}(E) \propto E_{\rm SN} \left(\frac{E}{\rm GeV}\right)^{-\gamma} \exp\left(-\frac{E}{E_{\rm max}}\right)$$

Galactic solution at the second knee



- Reacceleration by Galactic Wind termination shocks [Thoudam+ 2016, A&A, 595, A33; Bustard+ 2017, ApJ, 835, 72; Merten+ 2018, ApJ, 859, 63; Mukhopadhyay+ 2023, ApJ, 953, 49]
- Additional Galactic component: Wolf-Rayet star supernova explosions [Chevrotiere+ 2013, 2014; Biermann & Cassinelli 1993, Stanev+ 1993]
- Additional Galactic component: Star Clusters [Cesarsky & Montmerle 1983; Webb+ 1985; Gupta+ 2018; Bykov+ 2020, Morlino+ 2021, Vieu+ 2022]

Conclusions

- The cosmic ray energy spectrum highlights distinctive features, including the first and second knees, and an intermediate little ankle.
- Recent direct measurements are pivotal for identifying the nature of these features, as they nail cosmic-ray composition at PeV energies.
- The first knee is linked to the maximum energy of Helium at $E \sim 4$ PeV, while the low-energy ankle at $E \sim 2 \times 10^{16}$ eV corresponds to a significant suppression of the Helium component and an increasing relative contribution from intermediate-mass elements.
- The second knee, located at $E \simeq 10^{17}$ eV, is not associated with the steepening of the Galactic Iron component. Instead, it appears to be better explained by the presence of a secondary Galactic component.
- As for interpretations, the first knee aligns more closely with a Galactic escape mechanism rather than a maximum energy limit in sources, although further investigation is required.

Thank you!

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