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Nonmonotonic change with energy of the mean logarithmic mass of cosmic rays in the knee region: the mechanism of formation of this feature and sources of particles

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АЛТАЙСКИЙ ГОСУДАРСТВЕННЫЙ УНИВЕРСИТЕТ

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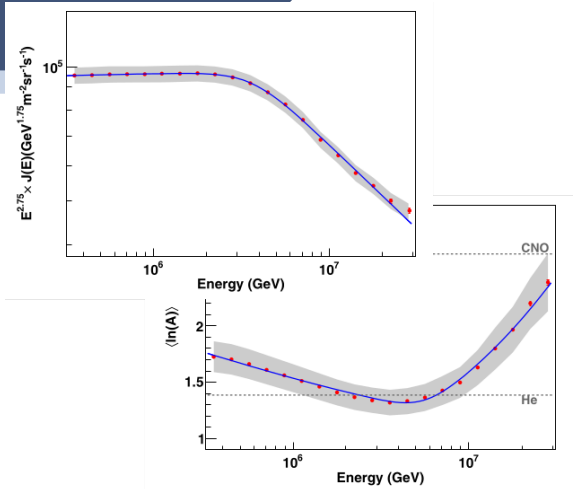
All-particle CR energy spectrum

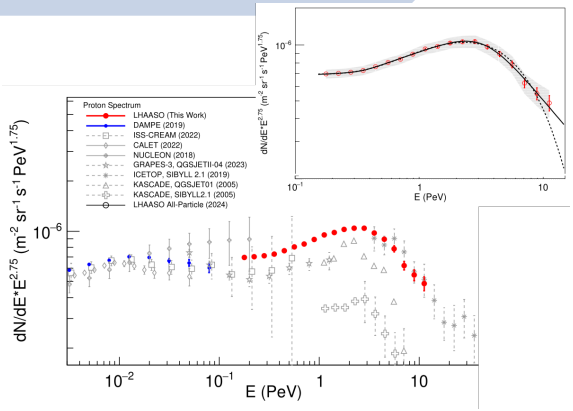
Recently, the Large High Altitude Air Shower Observatory (LHAASO) published measurements of the all-particle CR energy spectrum and the mean logarithmic mass of CRs with unprecedented accuracy in $0.3 - 30$ PeV. The mean logarithmic mass shows a nonmonotonic change with energy, a feature observed for the first time.



Phys. Rev. Lett., 2024, V. 132, 131002

The CR proton energy spectrum

Results of a precise measurement of the CR proton energy spectrum from 0.15 to 12 PeV using LHAASO.



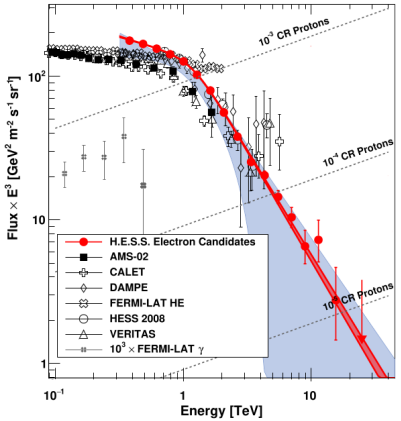
Best fitting spectrum of protons using function for three power-law components and for two power-law components with an exponential cut-off.

arXiv:2505.14447v1 [astro-ph.HE] 20 May 2025

Energy spectrum cut-off

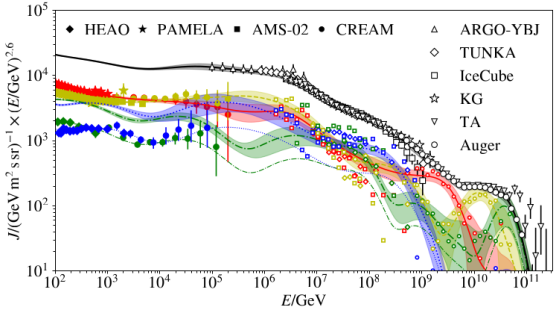
PeV gamma-ray emission and TeV electrons

The results of measurement of the diffuse gamma-ray emission at energies between 10 TeV and 1 PeV clearly indicate that CR sources effectively accelerate electrons, positrons, protons and other nuclei to energies greater than those accepted as the upper limit for CRs accelerated by galactic sources.



H.E.S.S. // Phys. Rev. Lett., 2024, V. 133, 221001

Phenomenological approach



Dembinski, H. P., Engel, R., Fedynitch, A., et al. 2018, ICRC (Busan), 301, 533

Phenomenological studies of the cosmic-ray flux and its mass composition in the knee region have been conducted in many papers utilizing the most up-to-date data available at different times. However, this technology is not a model in the usual sense since it does not try to explain the data.

Main goal of contribution

In this work, we present a new approach to describe the mechanisms of formation of this feature.

The key elements of this approach are the non-classical diffusion model of cosmic rays developed by the authors in which the knee in the observed spectrum occurs naturally without the use of additional assumptions, as well as power-law asymptotics before and after the knee, and a soft spectrum of particle generation in cosmic ray source.

Nonclassical CRs diffusion

The equation for the density of particles with energy E at the location $\mathbf{r}$ and time t, generated in a fractal-like medium by Galactic sources with a distribution density $S(\mathbf{r}, t, E)$ can be written as

$$\frac{\partial N(\mathbf{r}, t, E)}{\partial t} = -D(E, \alpha, \beta) \mathrm{D}_{0+}^{1-\beta} (-\Delta)^{\alpha/2} N(\mathbf{r}, t, E) + S(\mathbf{r}, t, E). \qquad (1)$$

$D(E, \alpha, \beta) = D_0(\alpha, \beta) E^{\delta}$ is the anomalous diffusivity;

$(-\Delta)^{\alpha/2}$ is the fractional Laplacian ("Riesz operator");

D_{0+}^{β} Riemann-Liouville fractional derivative.

CRs energy spectrum

Global component J_G

Determined by numerous old ($t \geq 10^6$ yr) distant ($r \geq 1$ kpc) sources

$$J_G(\mathbf{r}, E) \sim E^{-\gamma-\delta/\beta}.$$

Local component J_L

Contribution of nearby ($r < 1$ kpc) young ($t < 10^6$ yr) sources

$$J_L(\mathbf{r}, t, E) = J_{\mathsf{TeV}}(\mathbf{r}, t, E) + J_{\mathsf{PeV}}(\mathbf{r}, t, E)$$

Observed flux of galactic CRs

$$J(\mathbf{r}, t, R) = J_G(\mathbf{r}, R) + J_{\mathsf{TeV}}(\mathbf{r}, t, E) + J_{\mathsf{PeV}}(\mathbf{r}, t, E).$$

In the case of a point pulse source with a power-law spectrum of generation $S(\mathbf{r}, t, E) = S_0 E^{-\gamma} \delta(\mathbf{r}) \Theta(T - t) \Theta(t)$

$$J_L(\mathbf{r}, t, E) = \frac{c S_0 E^{-\gamma}}{4\pi D(E, \alpha, \beta)^{3/\alpha}} \times \\ \times \int\limits_{\max[0, t-T]}^{t} d\tau \tau^{-3\beta/\alpha} \Psi_3^{(\alpha,\beta)} \left(|\mathbf{r}| (D(r, \alpha, \beta)\tau^{\beta})^{-1/\alpha} \right), \quad (2)$$

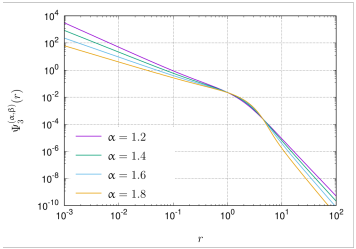
where $\Psi_3^{(\alpha,\beta)}(\rho)$ fractional stable distribution density (Uchaikin and Zolotarev, 1999).

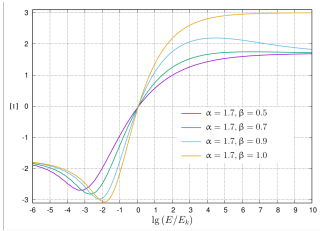
Break in the energy spectrum

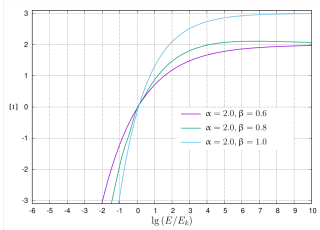
The observed spectral index η at the energy at the breakpoint $E = E_k$ is equal to the index of the particle generation spectrum in the source: $\eta|_{E=E_k} = \gamma$.

For $E \ll E_k$ and $E \gg E_k$

$$\eta|_{E \ll E_k} = \gamma - \delta$$
$$\eta|_{E \gg E_k} = \gamma + \delta/\beta.$$







Tools for restoring source parameters

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ELEMENTARY PARTICLES AND FIELDS
Experiment

New Break Near 10 TeV in the Energy Spectrum of Protons According to Data from Space-Based Instruments: Astrophysical Interpretation

A. A. Lagutin[1)*] and N. V. Volkov[1)**]

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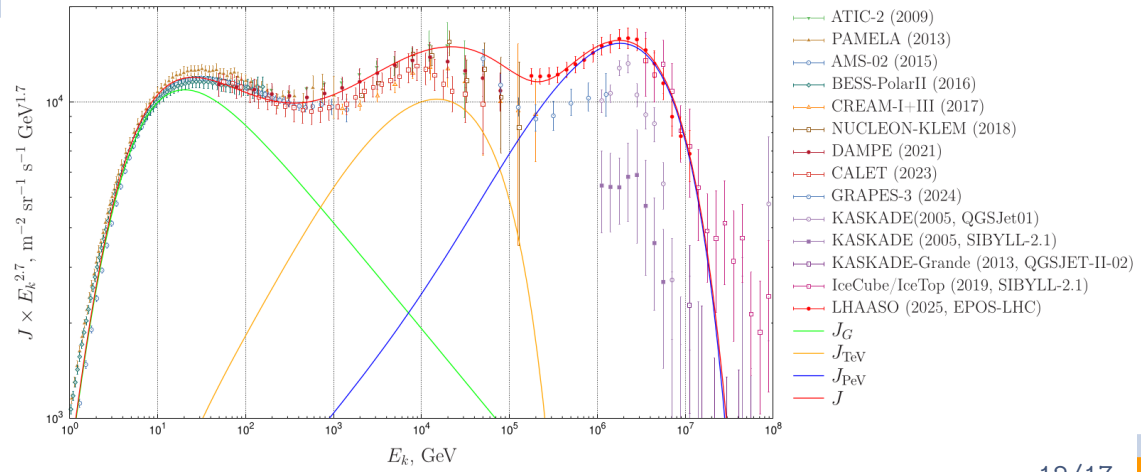
ELEMENTARY PARTICLES AND FIELDS
Experiment

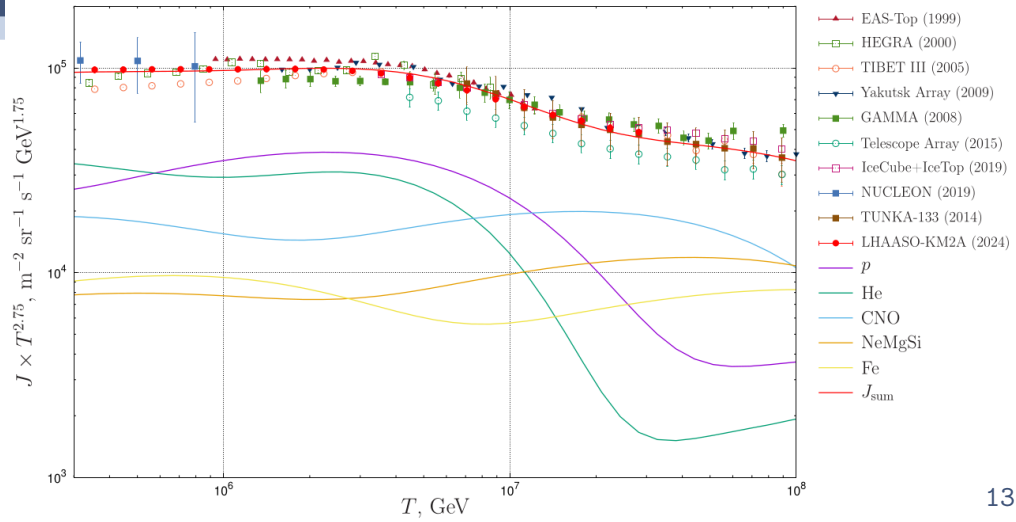
Where are the Pevatrons that Form the Knee in the Spectrum of the Cosmic Ray Nucleon Component around 4 PeV?

A. A. Lagutin[1)*] and N. V. Volkov[1)**]

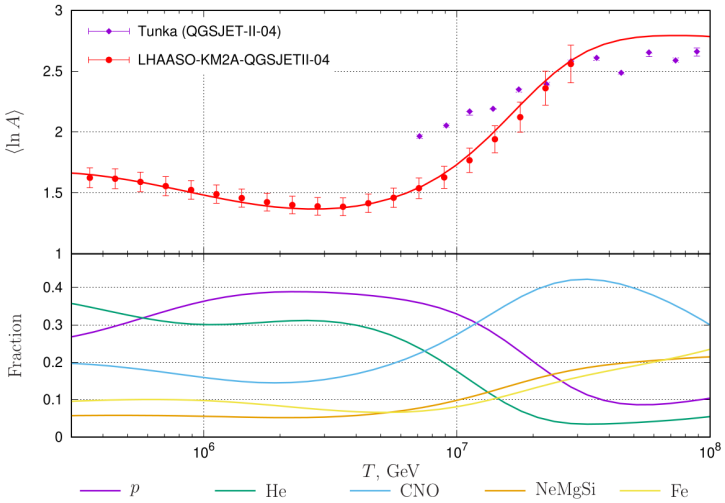
Spectrum of protons



All-particle spectrum



Mean logarithmic mass of CRs



Results and conclusion

To obtain a more complete picture of the spectrum formation in the region of the knee and the sources that form it, we carried out calculations of the spectra of the main groups of nuclei in the energy range of 1 TeV - 100 PeV.

It is shown that the behavior of the all-particle spectrum and mass composition in the knee region is determined by local pevatrons located at a distance of $750 - 900$ pc from the Earth. The position of the knee practically coincides with the break in the spectrum of helium nuclei. The contribution of the light components $p + \mathrm{He}$ is about 70%, the CNO group provides $\sim 13\%$. The energy spectrum index of the light components is -2.61 before the knee. The nonmonotonic change in the mean logarithmic mass is due mainly to a decrease in the contribution of the CNO group in the energy range of $0.3 - 3$ PeV.

Thanks!

Questions and Comments

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The most likely candidates for sources

Tevatrons

Source	r, pc	$t, 10^5$ yr
Loop I	120	2.0
Loop II	175	4.0
Loop III	200	4.0
Loop IV	210	4.0
Vela	250	0.46
Geminga	400	3.4
Lopus Loop	400	0.36

Pevatrons

Source	r, pc	$t, 10^5$ yr
Monoceros	600	0.46
Cyg. Loop	770	0.20
CTB 13	600	0.32
S 149	700	0.43
STB 72	700	0.32
CTB 1	900	0.47
HB 21	800	0.23
HB 9	800	0.27
RCW 36	900	11.0