Plasmas in Astrophysics and in Laboratory,
20 – 21 June, 2011

High Energy Particle Production by Space Plasmas

A.A.Petrukhin
National Research Nuclear University MEPhI

Contents

Introduction

Cosmic rays are the important source of information about our Universe.

Composition of CR:
protons, nuclei, electrons, photons, neutrinos and possibly other unknown (today) particles.

≥

Cosmic rays energies:
Terms HE, VHE, UHE … are rather relative:
HE – accelerator energies;
VHE – above accelerator energies
(today > 10^{15} eV, “tomorrow” > 10^{17} eV);
UHE – > 10^{18} eV or > 10^{19} eV.

Directions and methods of CR investigations

Directions:

- characteristics of CR flux (energy spectrum, composition, arrival directions);
- CR origin (generation, acceleration, propagation);
- interactions of VHE cosmic rays (above the energies of existing accelerators).

Methods:

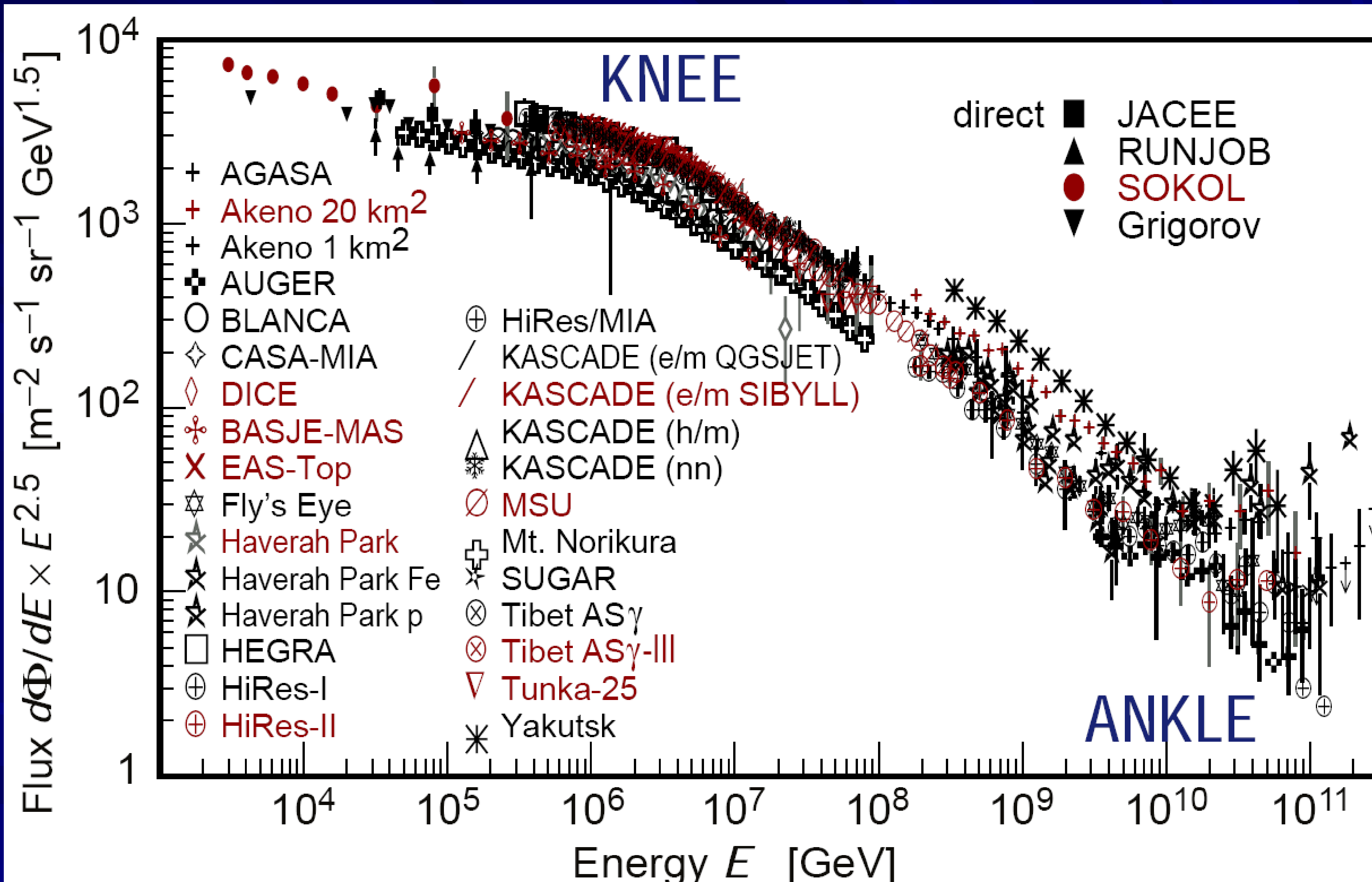
Below 10^{15} eV direct measurements at balloons and satellites are possible.

Above 10^{15} eV – only indirect methods (EAS studies).

What we know about VHE cosmic rays?

1. Flux:
   - permanent in time;
   - isotropic in directions.
2. Energy spectrum
   - ranged at least up to 10^{20} eV;
   - is described by power function with average $\gamma \approx 1.7$;
   - has three peculiarities: knee, ankle & GZK cutoff.
3. Interaction
   - corresponds to accelerator data at energies below 10^{15} eV (about 1 TeV in center-of-mass system);
   - various unusual events are observed starting from several PeV (10^{15} eV) energies.

Results of energy spectrum "measurements"



How can one explain available data about VHE cosmic rays

Taking into account that all data about VHECR have been obtained from results of experiments in the atmosphere, in principle there are two possibilities of their explanation:

- These data are characteristics of CR primary spectrum (Cosmophysical approach);'
- These data are results of CR interactions in atmosphere (Nuclear-physical approach);

Now the first point of view prevails.

Basic ideas of the cosmophysical approach

EAS energy is equal to the energy of primary particle.

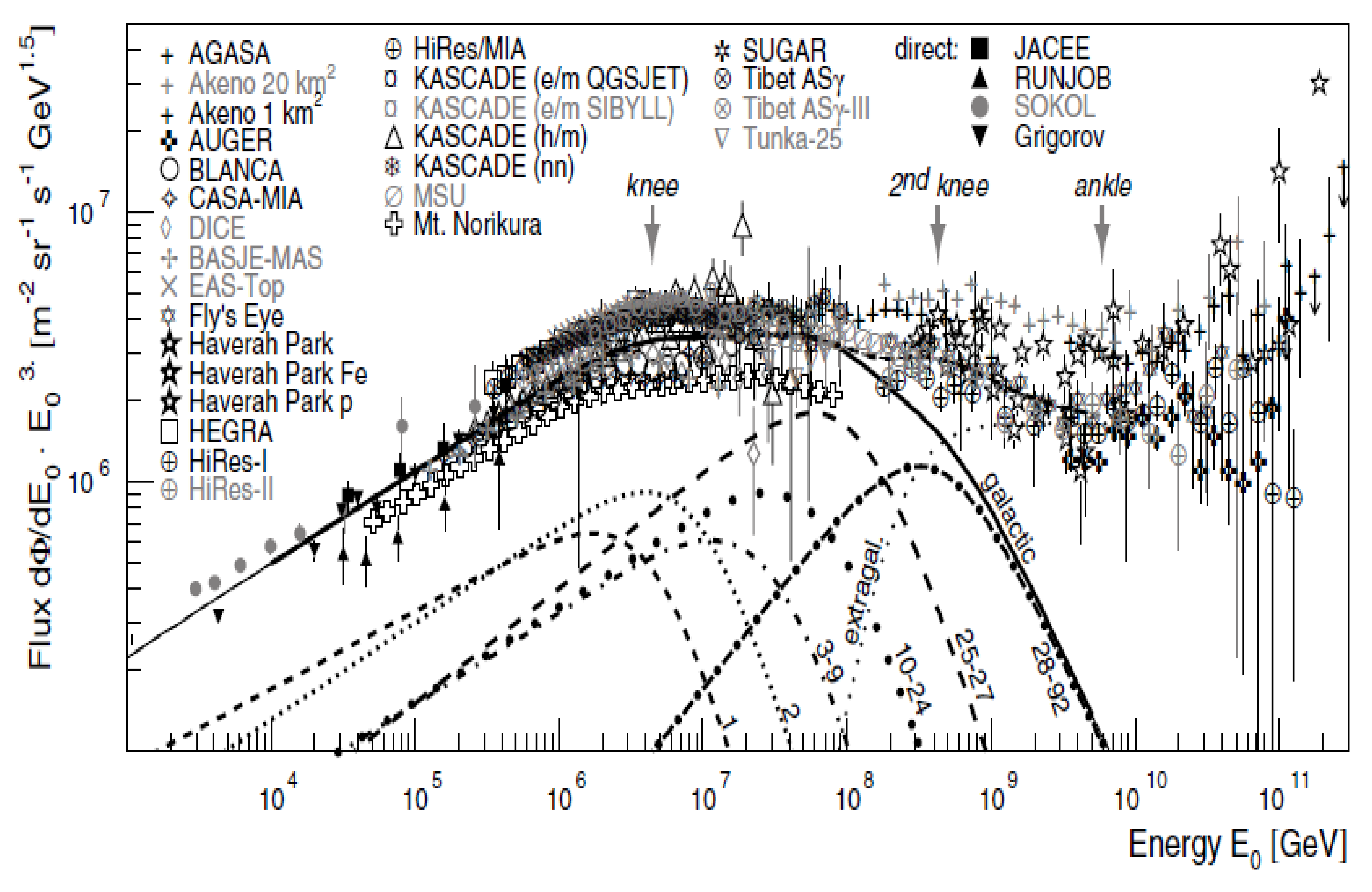
All changes of EAS characteristics in dependence of energy are results of energy spectrum or/and composition changes only.

Primary cosmic rays have galactic origin.

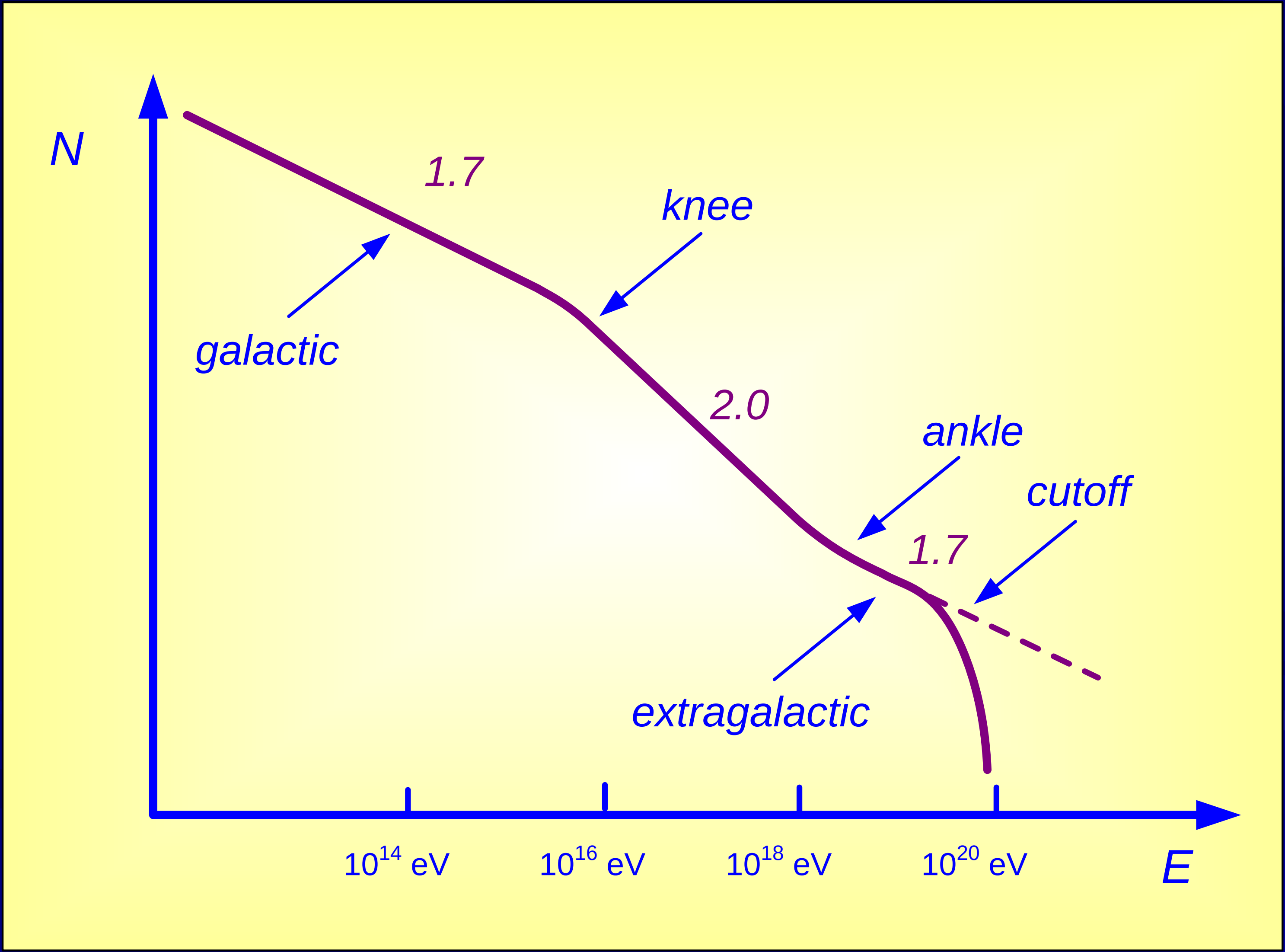
Their acceleration and keeping in Galaxy are determined by their charge *Z* or/and mass *A*.

And the following results were obtained:

Results of energy spectrum interpretation



CR integral energy spectrum



The main problems of cosmic ray origin

1. What are sources of cosmic rays and mechanisms of their acceleration up to so large energies?

2. How to obtain the value of the energy spectrum slope $\gamma \approx$ 1.7, which is necessary for explanations of results CR energy spectrum measurements?

Many ideas were proposed to solve these tasks, but satisfactory generally accepted solution was not found. Therefore I would like to pay your attention to one very interesting model which was proposed by specialists in plasma physics.

Model of CR acceleration in plasma pinches – 1

This model was presented at International conference on plasma physics in New Delhi, India, 1989, by

B.A.Trubnikov, V.P.Vlasov, S.K.Zhdanov
Kurchatov Institute, Moscow

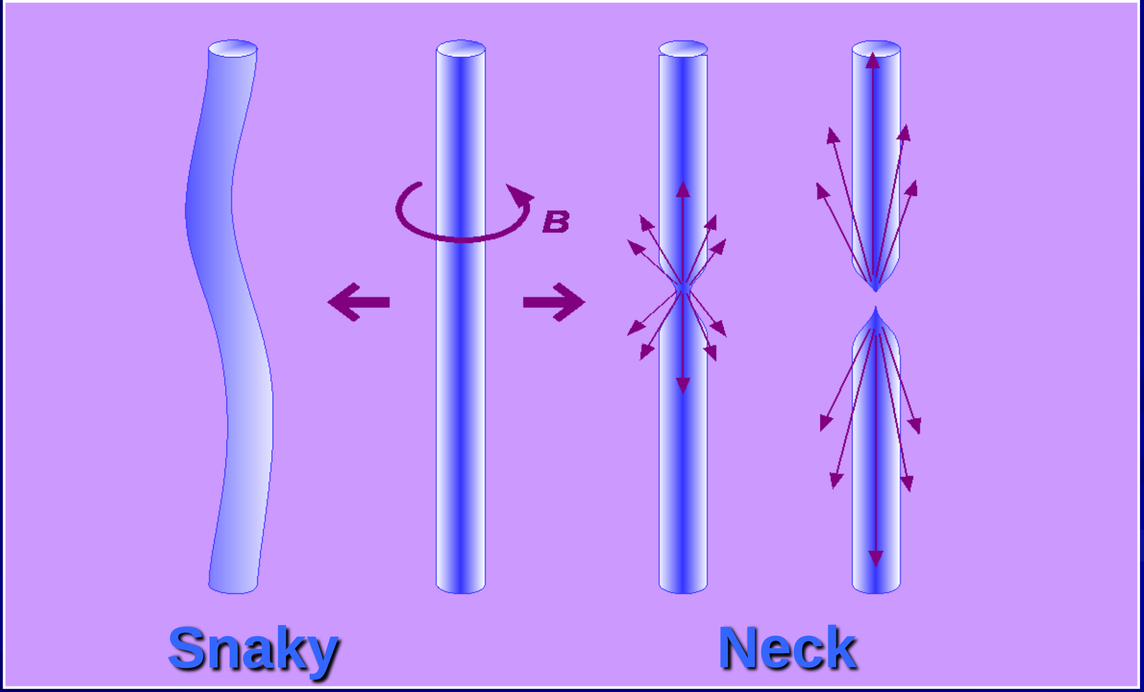
and published in Proceedings of this Conference 1989, v.1, p.257.

The main idea of this model is the following.

In cosmic plasma (of any origin) electrical discharges – "cosmic lightnings" can occur, at which cylindrical pinches are formed, similar to laboratory ones.

Model of CR acceleration in plasma pinches – 2

Two basic instabilities of plasma pinches are known: snaky and neck.



Plasma jets are squeezed out of pinch neck.
These jets are accelerated particle beams.

Model of CR acceleration in plasma pinches – 3

It was shown that energy distribution of particles in jets has the following form:

$$\frac{dN}{dE} \sim E^{-\left(1+\sqrt{3}\right)},$$

which does not depend on pinch sizes, currents in pinches and other parameters.

These parameters determine a proportionality coefficient only.

Model of CR acceleration in plasma pinches – 4

- ☞ In the model the well-known equations of plasma physics are used only.
- ☞ Model has no free parameters except for absolute intensity.
- ☞ Model predicts for the energy spectrum slope the unambiguous value $\gamma = 2.73$.
- ☞ Model has no limitation for accelerated particle energy since in plasma pinch neck:

  density $\rho \to \infty$, when its radius $r \to 0$

Other interesting consequences

- ☞ The composition of accelerated particles will be the same as composition of cosmic plasma, which consists mainly of hydrogen.

- ☞ Model explains the absence of point sources of cosmic rays since pinches, f.e. near Supernova, can be oriented in any direction.

- ☞ At the same time, generation of particles in narrow jets in cylindrical pinches can explain the appearance of correlated particles.

- ☞ But the main advantage of pinch model is possibility to explain the observed CR energy spectrum as a result of interaction model change (nuclear physical approach).

Possible variants of interaction model change

- Inclusion of new (f.e. super-strong) interaction.
- Appearance of new massive particles (supersymmetric, Higgs bosons, relatively long-lived resonances, etc.)
- Production of blobs of quark-gluon plasma (QGP) (better to speak about quark-gluon matter (QGM), since usual plasma is a gas but quark-gluon matter is a liquid).

We considered the last model since it is the most realistic and allows demonstrably explain the inclusion of new interaction.

Quark-gluon matter

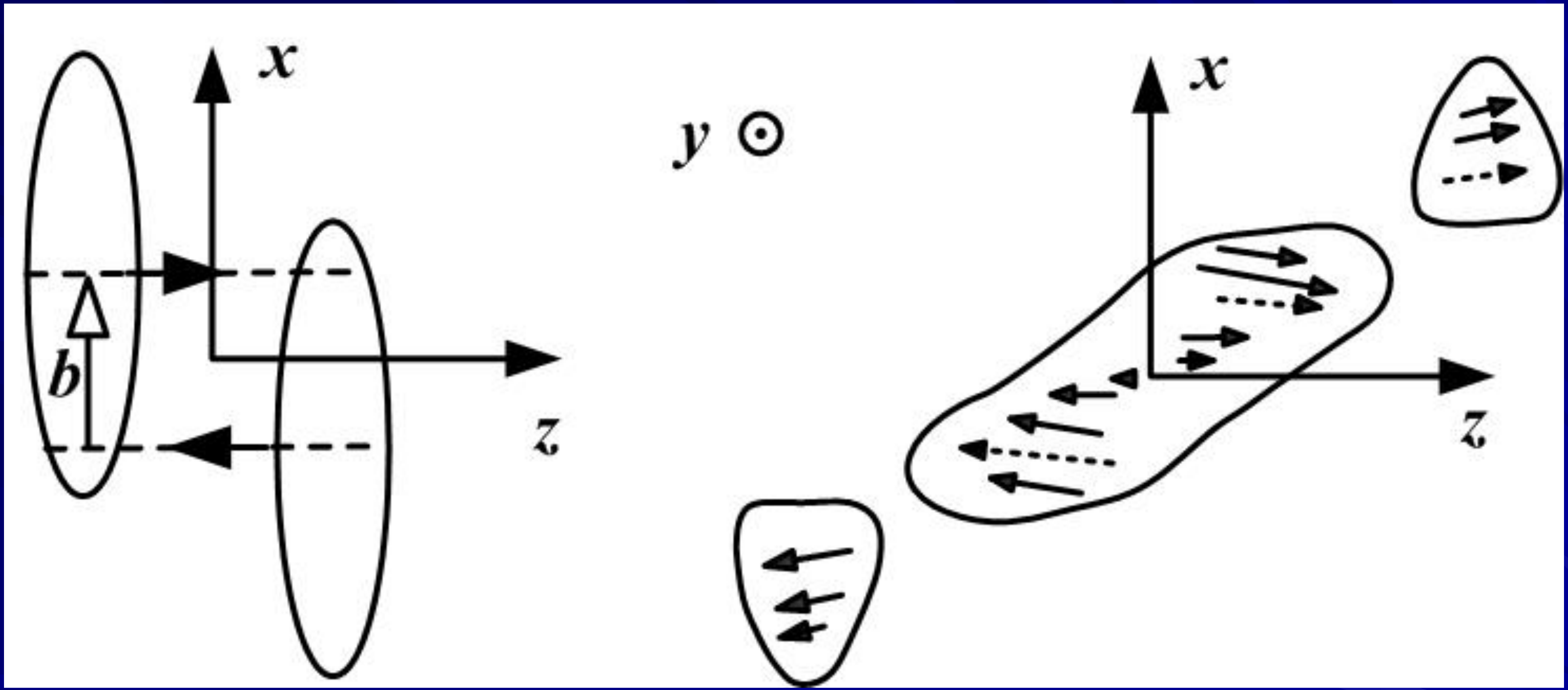
1. Production of QGM provides two main conditions:
   - threshold behavior, since for that large temperature (energy) is required;
   - large cross section, since the transition from quark-quark interaction to some collective interaction of many quarks occurs:

$$\sigma = \pi \bar{\lambda}^2 \rightarrow \sigma \sim \pi\left(\bar{\lambda} + R\right)^2 \; or \; \pi\left(R_1 + R_2\right)^2$$

   where R, R_1 and R_2 are sizes of quark-gluon blobs.

2. But for explanation of other observed phenomena a large value of orbital angular momentum is required.

Orbital angular momentum in non-central ion-ion collisions

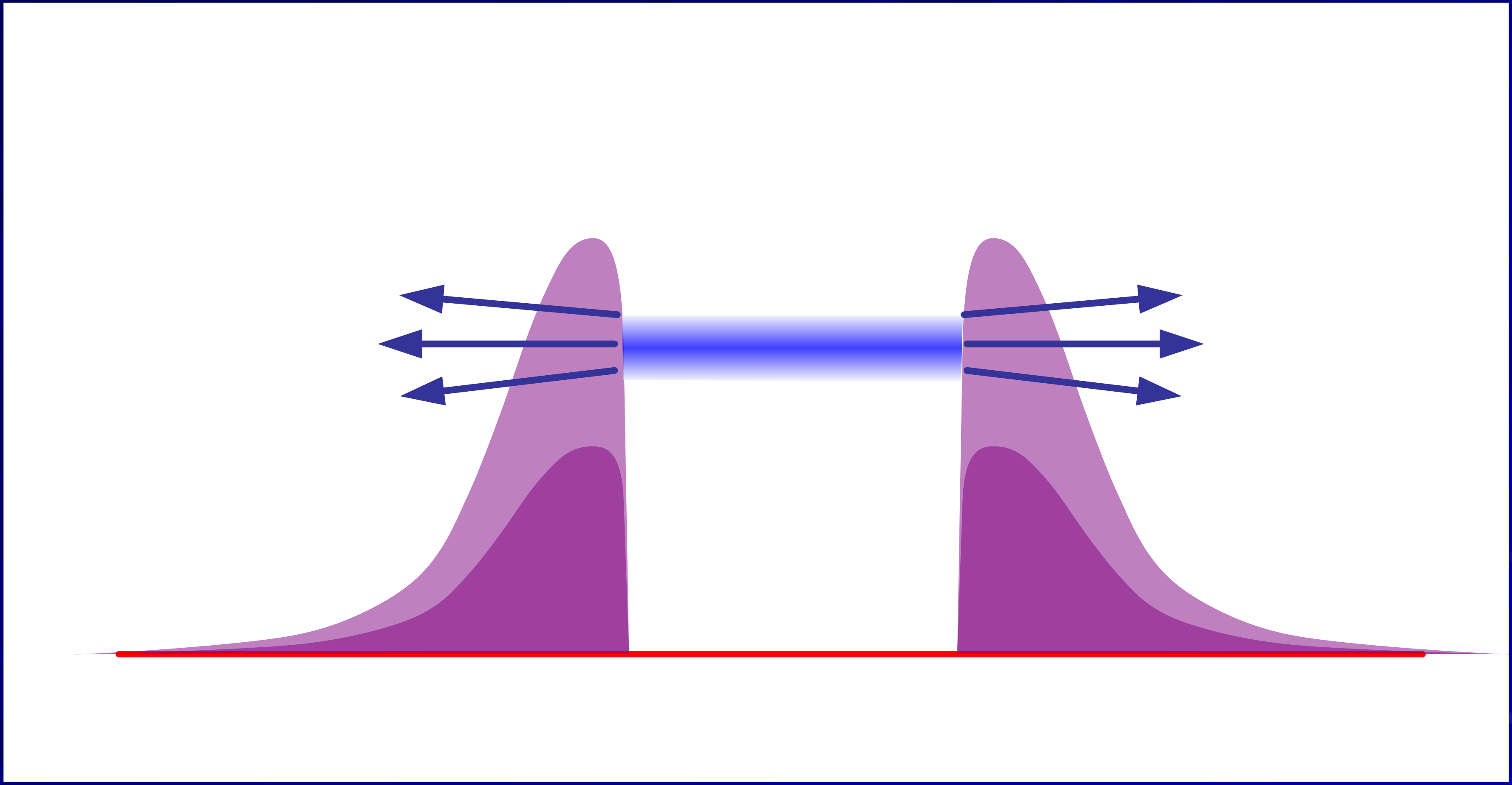


Zuo-Tang Liang and Xin-Nian Wang,
PRL 94, 102301 (2005); 96, 039901 (2006)

Centrifugal barrier

1. As was shown by Zuo-Tang Liang and Xin-Nian Vang, in non-central collisions a globally polarized QGP with large orbital angular momentum which increases with energy $L \sim \sqrt{s}$ appears.
2. In this case, such state of quark-gluon matter can be considered as a usual resonance with a large centrifugal barrier.
3. Centrifugal barrier $V(L) = L^2 / 2mr^2$ will be large for light quarks but less for top-quarks or other heavy particles.

Centrifugal barrier for different masses



How interaction is changed in frame of a new model?

1. Simultaneous interactions of many quarks change the energy in the center of mass system drastically:

$$\sqrt{S} = \sqrt{2m_p E_1} \rightarrow \sqrt{2m_c E_1}$$

where $m_c \approx nm_N$. At threshold energy, n ~ 4 (α - particle)

2. Produced $t\bar{t}$-quarks take away energy $\varepsilon_t > 2m_t \approx 350$ GeV, and taking into account fly-out energy, $\varepsilon_t > 4m_t \approx 700$ GeV in the center of mass system.

3. Decays of top-quarks $t(\bar{t}) \rightarrow W^+(W^-) + b(\bar{b})$

W –bosons decay into leptons (~30%) and hadrons (~70%);

$b \rightarrow c \rightarrow s \rightarrow u$ with production of muons and neutrinos.

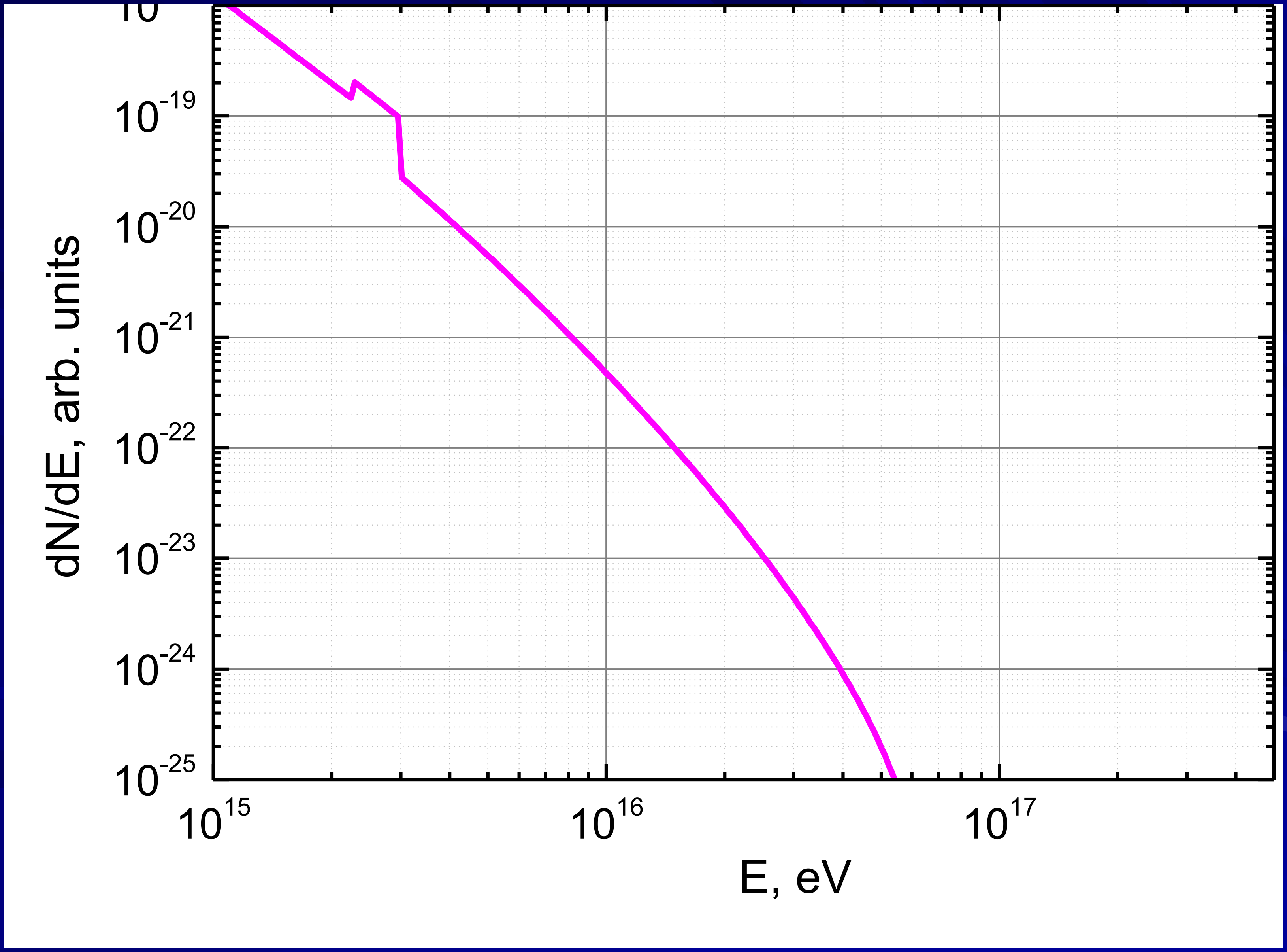
How the energy spectrum is changed?

1. One part of t-quark energy gives the missing energy (ν_e, ν_μ, ν_τ, μ), and another part changes EAS development, especially its beginning, parameters of which are not measured.

2. As a result, measured EAS energy E_2 will not be equal to primary particle energy E_1 and the measured spectrum will be differed from the primary spectrum.

3. Transition of particles from energy E_1 to energy E_2 gives a bump in the energy spectrum near the threshold.

Change of primary energy spectrum



How measured composition is changed in frame of the new approach

Since for QGM production not only high temperature (energy) but also high density is required, threshold energy for production of new state of matter for heavy nuclei will be less than for light nuclei and protons.

Therefore heavy nuclei (f.e., iron) spectrum is changed earlier than light nuclei and proton spectra!!!

To compare the changes of spectra of different nuclei, very simple model was used.

Relation between primary energy E_1 and measured energy E_2

$$E_2 = \frac{\left[\sqrt{2m_c E_1} - \varepsilon_t\left(E_1, A_i\right)\right]^2}{2m_c}$$

where ε_t is total energy of top-quarks in the center-of-mass system.

Threshold energy E_{th}, above which QGM blobs are produced, is determined by nucleus mass number A_i.

In principle, compound mass m_c may depend on A_i and $E_1 > E_{th}$, too.

Simplest model

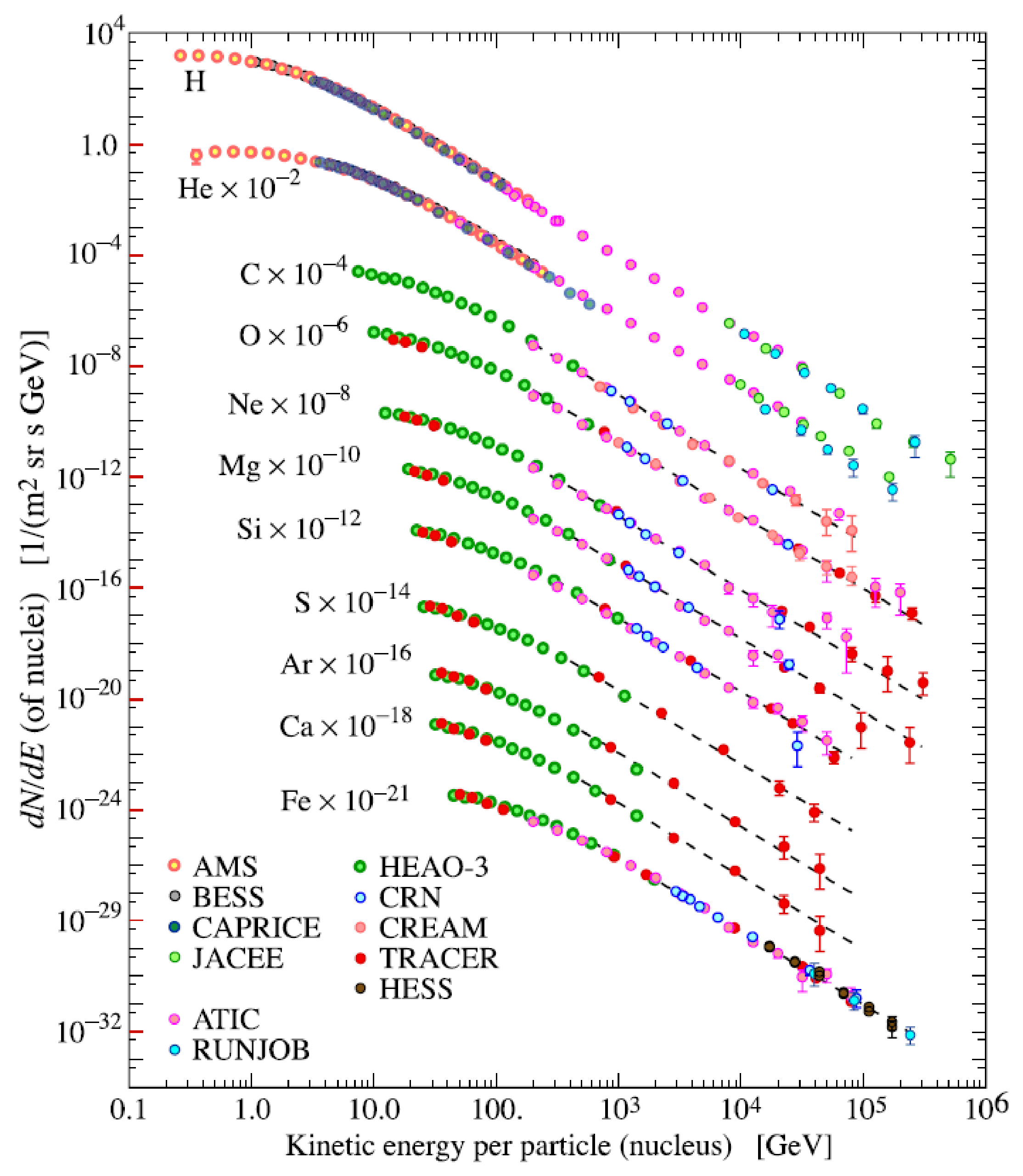
m_c = constant = nm_N.

$$\varepsilon_t = 4m_t \sqrt{\frac{E_1}{E_{th}}} \ln\left(1.7 + \frac{E_1}{E_{th}}\right)$$

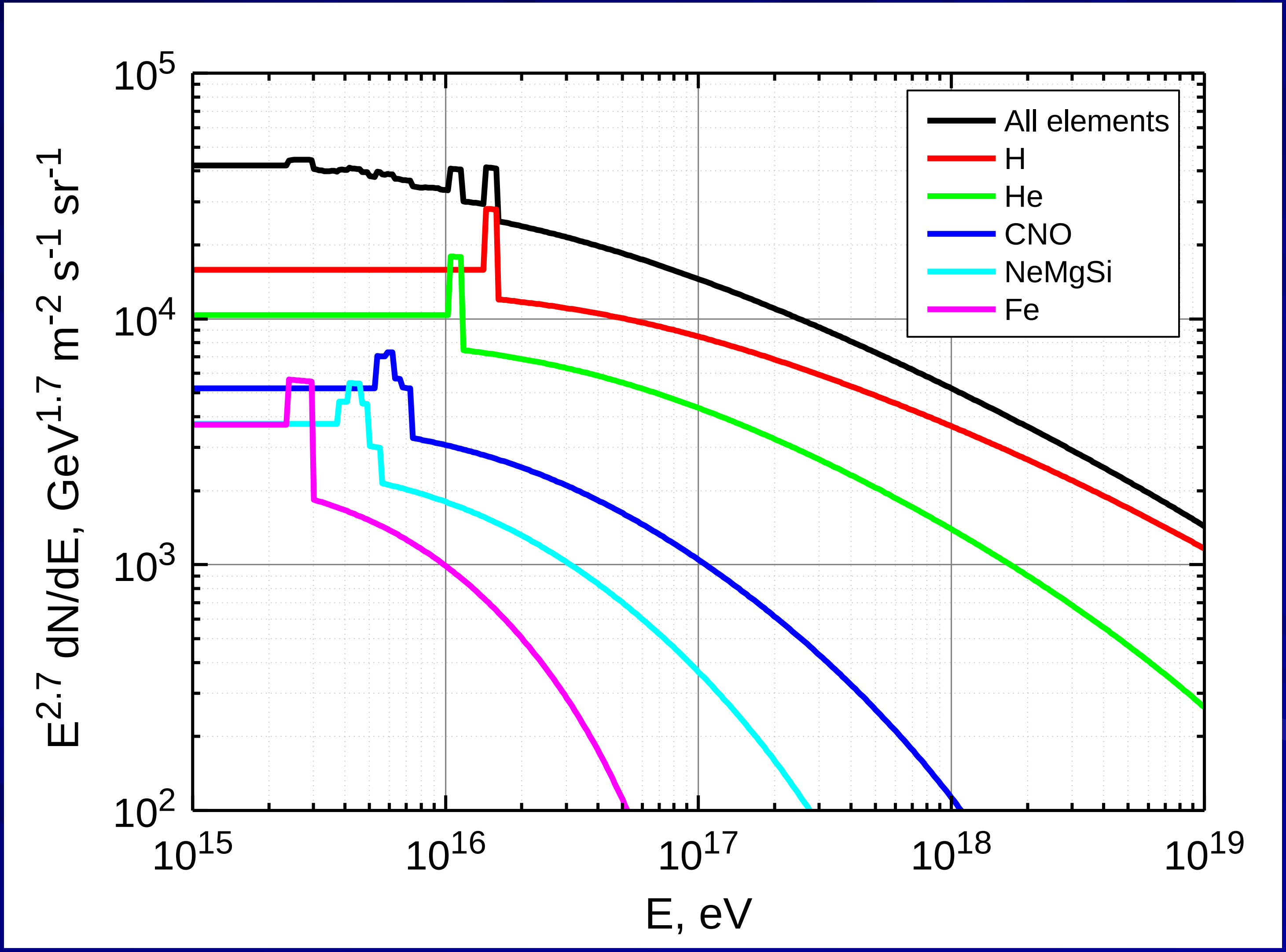
where ln takes into account the increasing of top-quark multiplicity and square root provides transition into the center-of-mass system.

$$E_{th} = m_c 10^6 \left(\frac{56+n}{A_i+n}\right)^{2/3}, \text{ GeV}$$

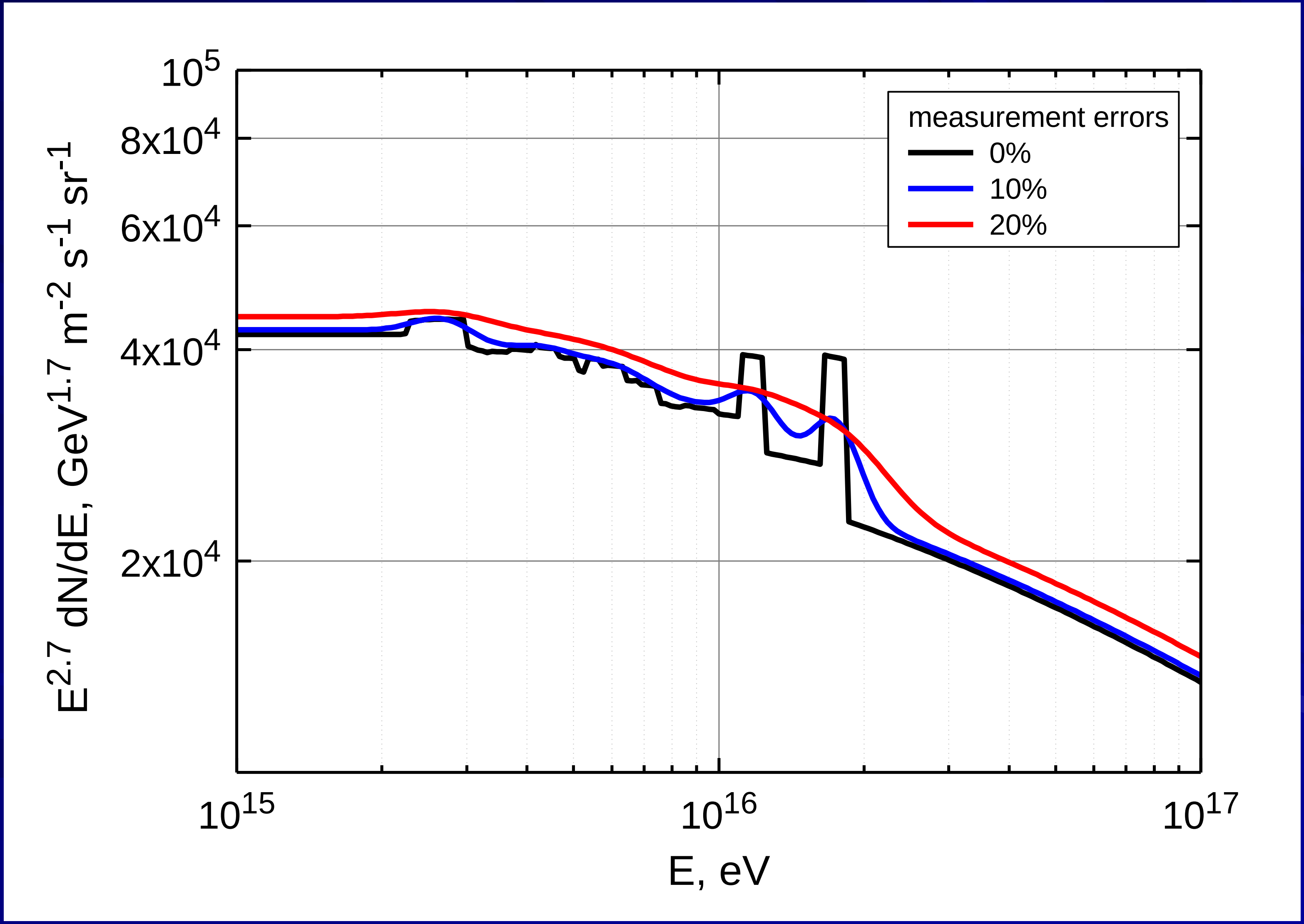
Primary spectra of various nuclei



Measured spectra for some nuclei and spectrum of all particles

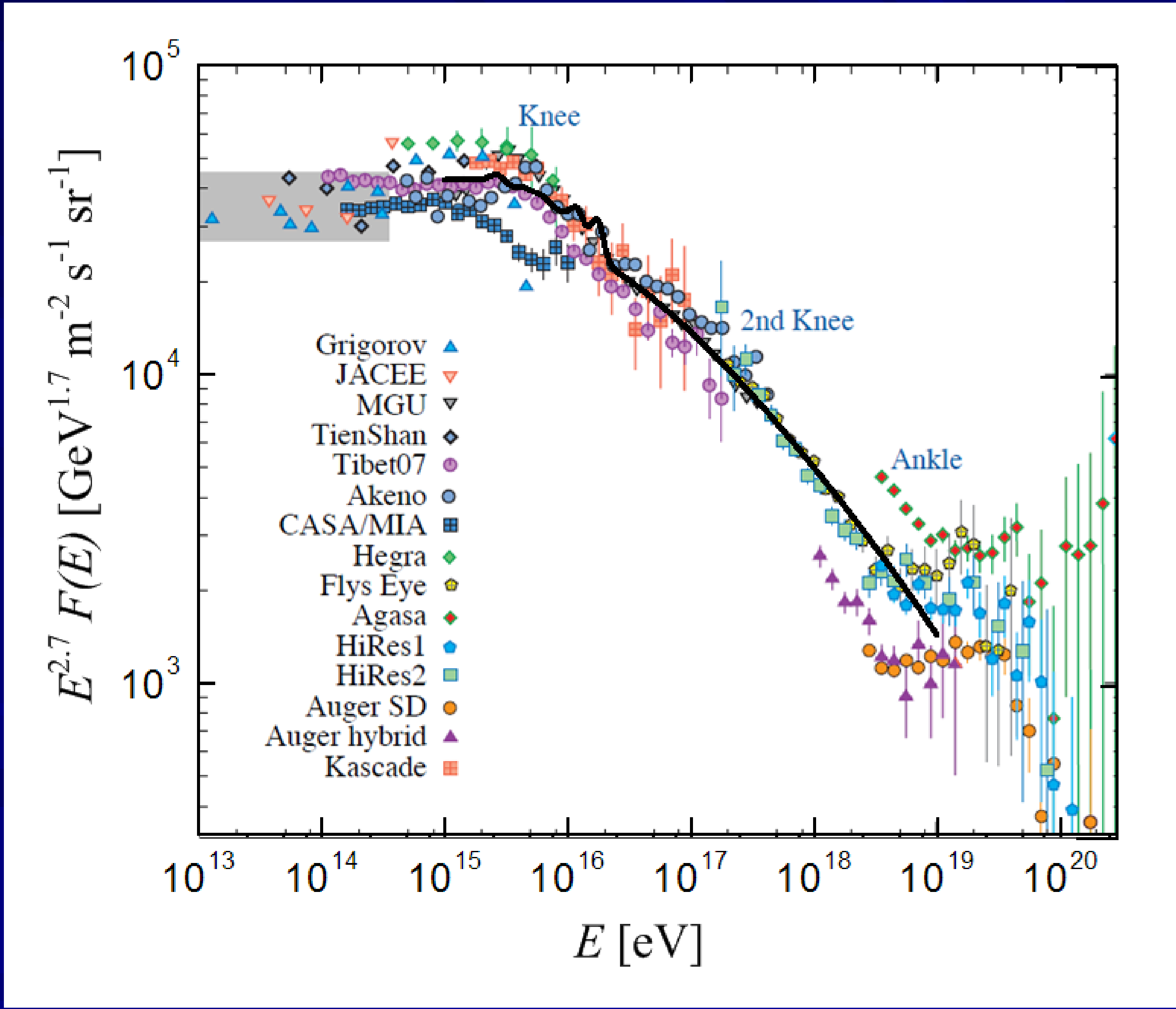


Influence of energy straggling



Comparison with experimental data

(with 10% straggling)

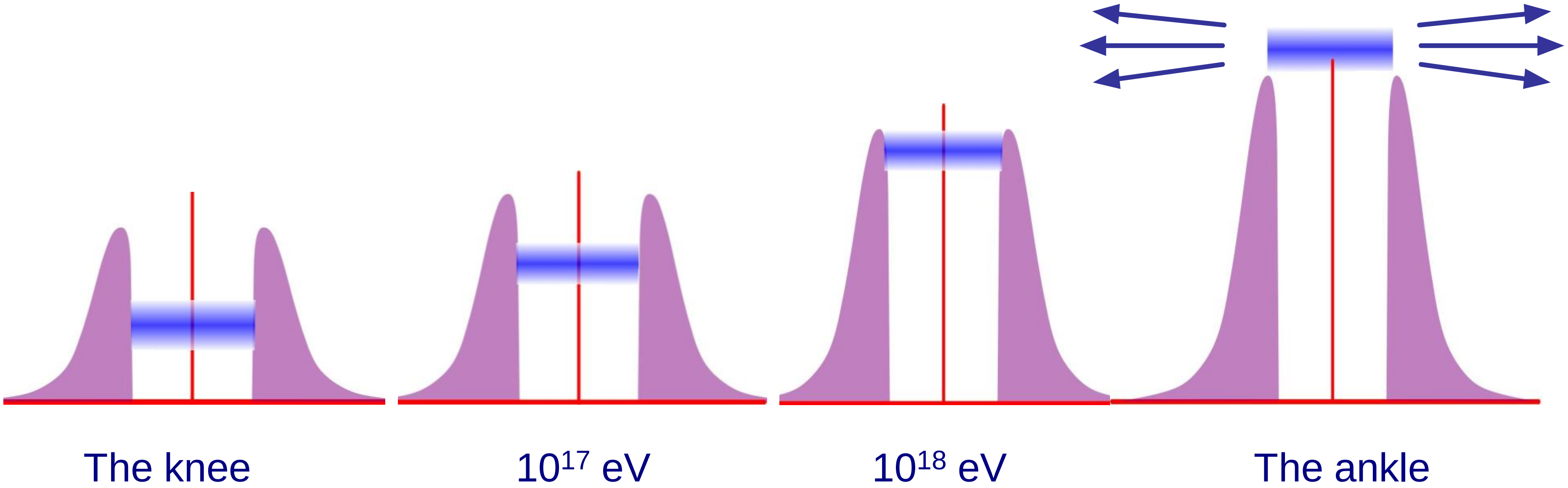


Explanation of the ankle appearance

On the face of it, the considered approach does not explain the behavior of the energy spectrum above the ankle, but this is not so.

With increasing of primary particle energy, the excitation level in blob of QGM can exceed the centrifugal barrier, and it will decay into light quarks.

Illustration of the ankle appearance



In this case, there will be no missing energy and the measured spectrum begins to return to the initial form ($\gamma = 2.7$).

Conclusion

Model of CR generation in plasma pinches is the single which unambiguously predicts the energy spectrum slope equal 2.7 (2.73).

Nuclear-physical approach, in which are combined two types of plasmas, allows solve practically all problems of cosmic ray investigations above the knee.

If this approach is correct, it will be an excellent present to 100 year anniversary of cosmic ray discovery!

Thank you
for your attention!