MAIN ISSUES IN COSMIC RAY PHYSICS

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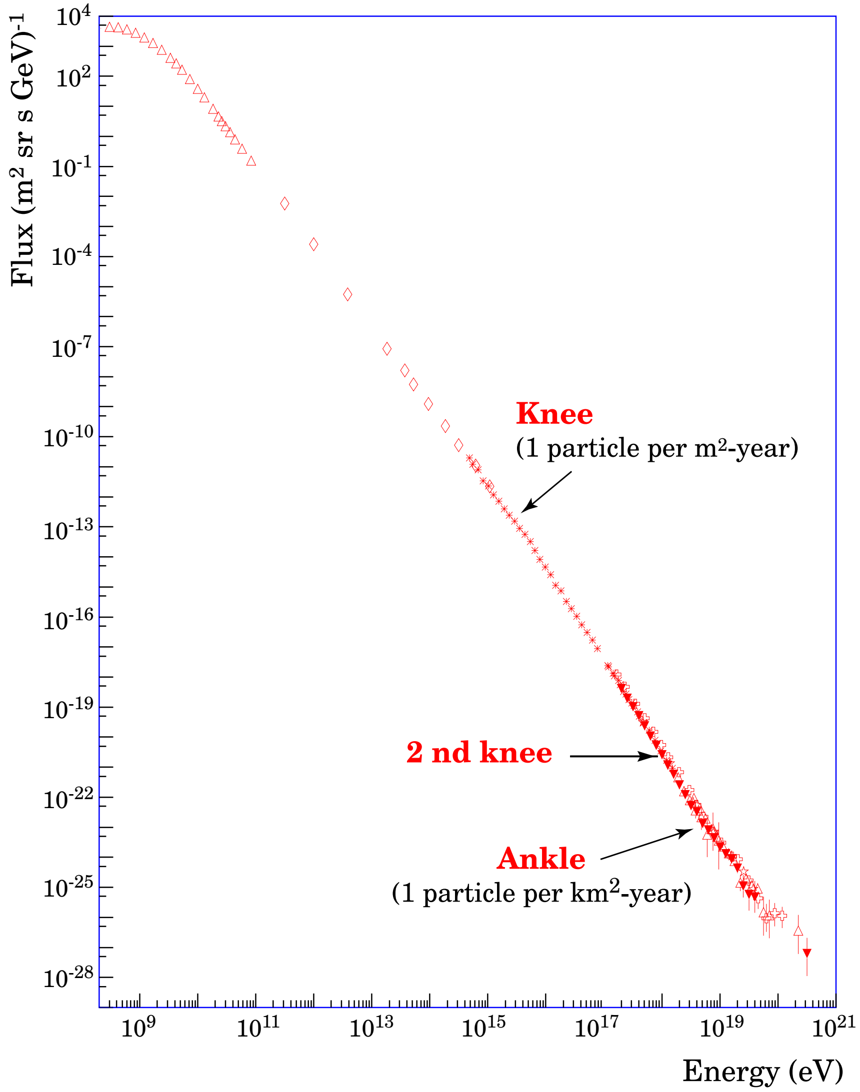
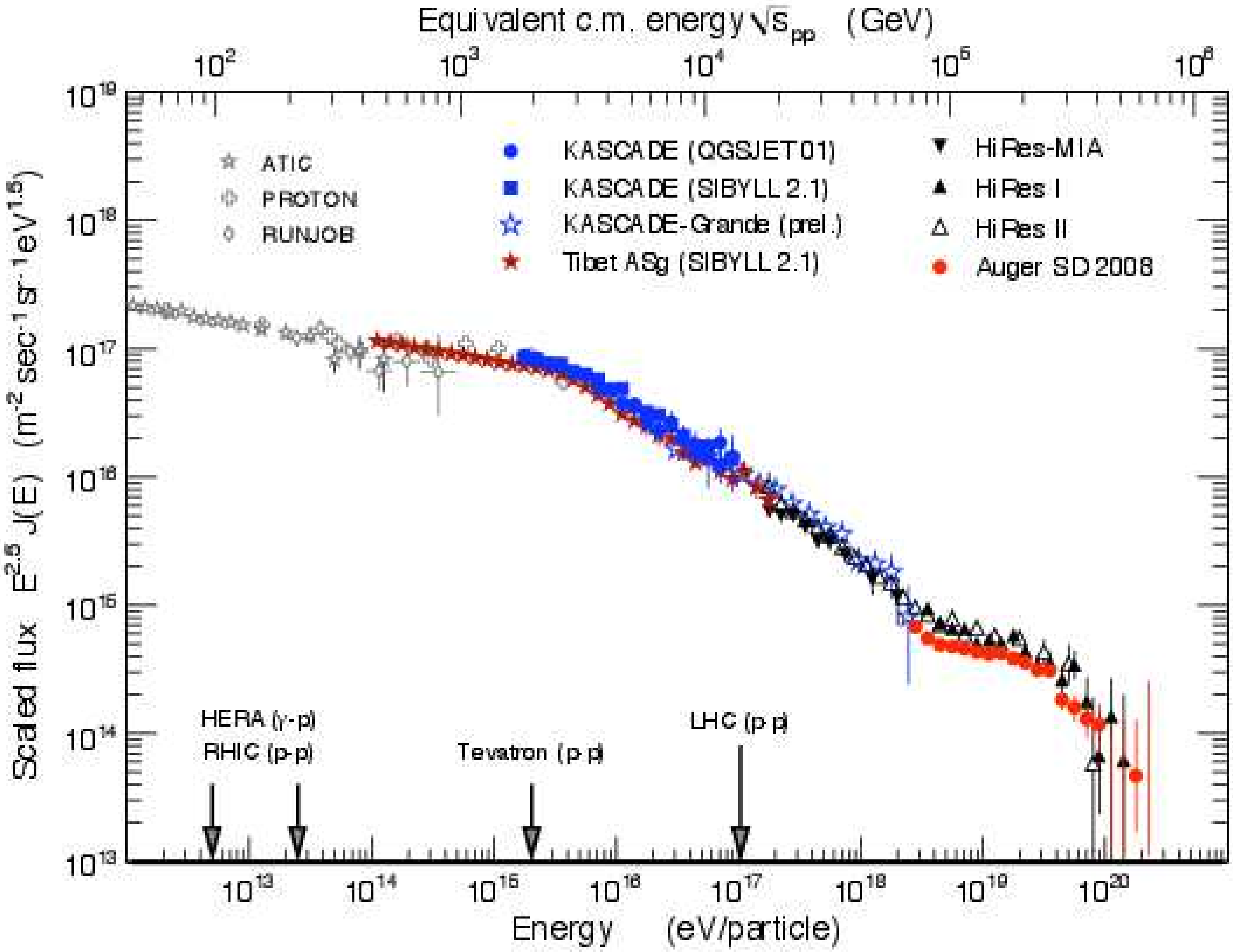
- **Why are we interested in Cosmic Rays?**
- **What are unresolved problems in CRs ?**
- **What are directions of future research?**

Total CR spectrum and features

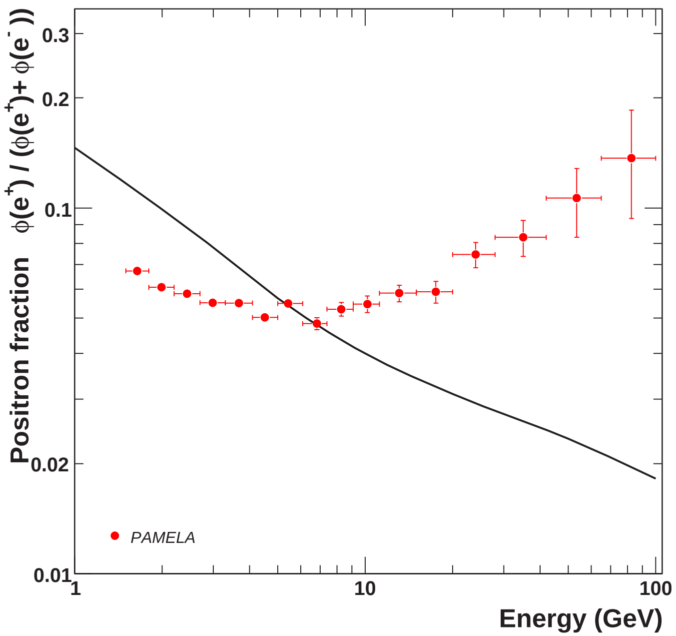


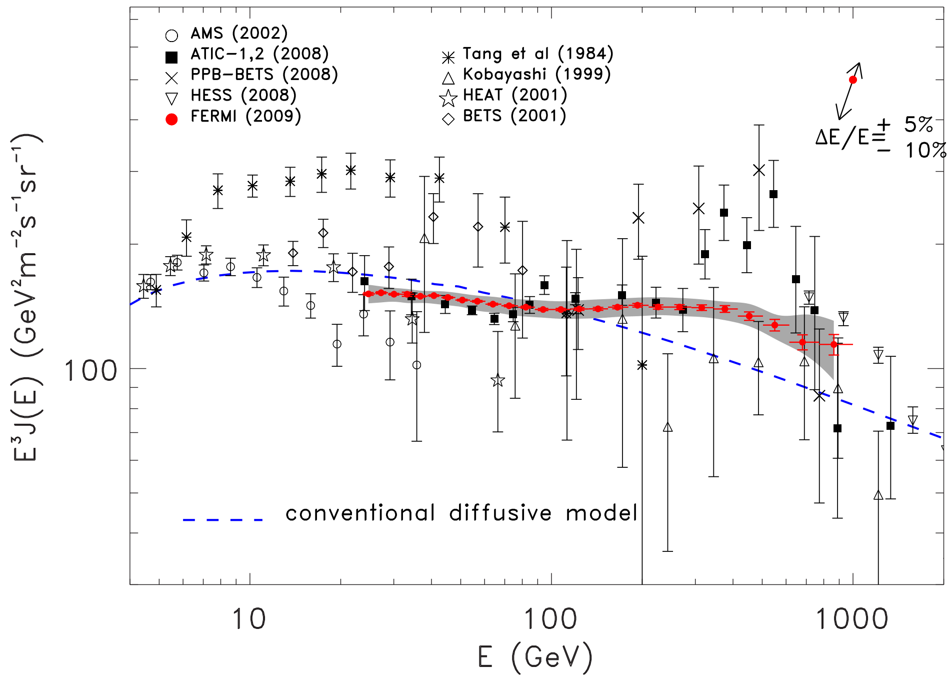
SPECTRA and EXPERIMENTS



PROBLEMS IN COSMIC RAYS

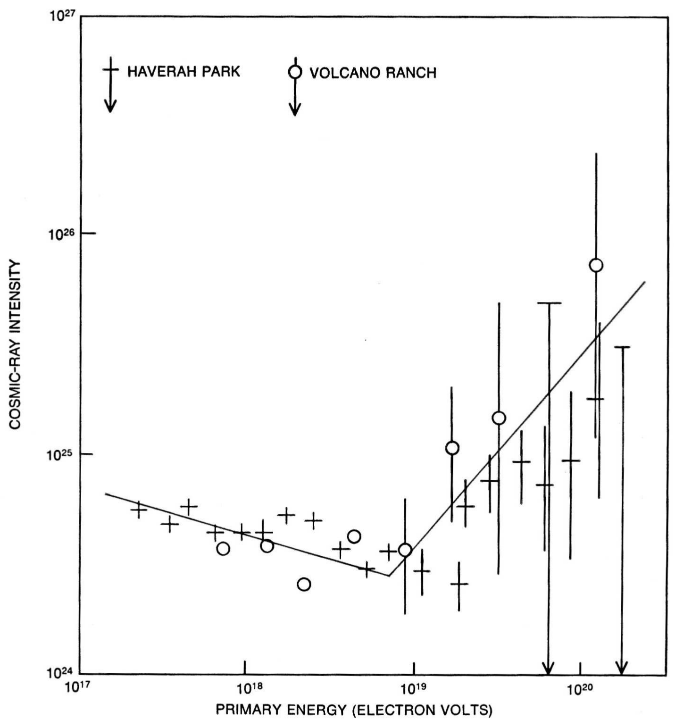
PAMELA and FERMI LAT OBSERVATIONS 2009



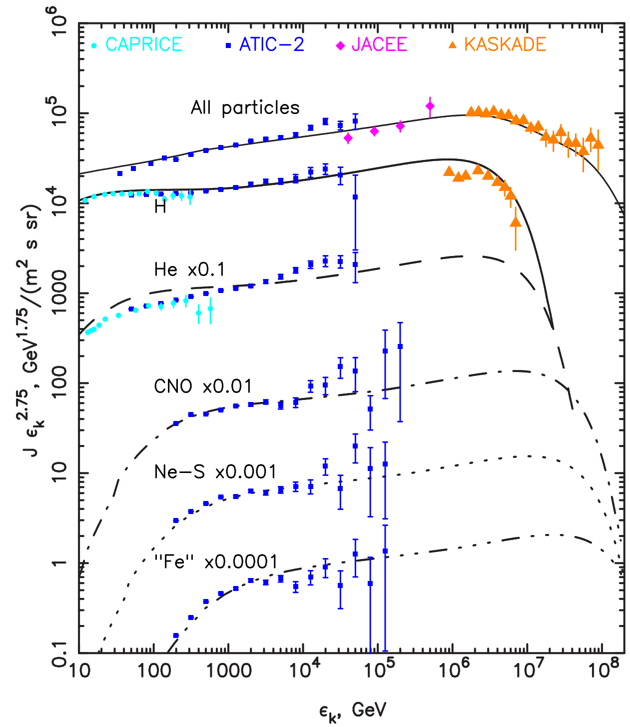


Ankle as transition from galactic to extragalactic CR

Flatness of Helium spectrum



Ankle in Volcano Ranch data



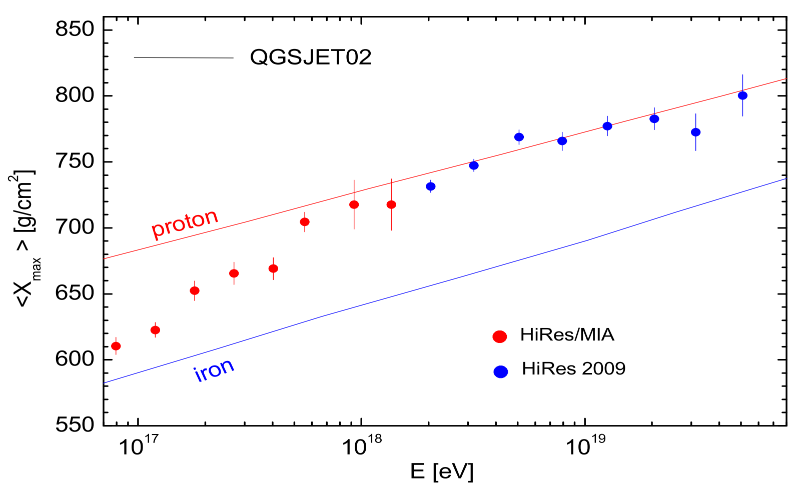
Berezhko and Völk 2007

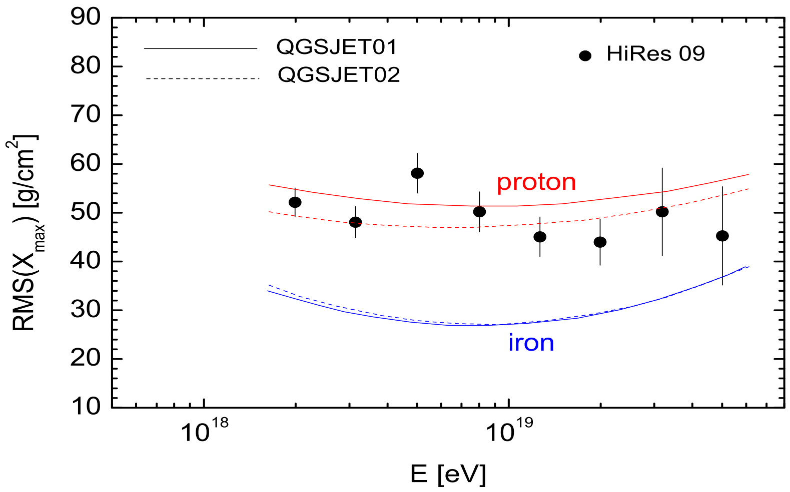
Mass Composition in UHECR at $E > 3 \times 10^{18}$ eV

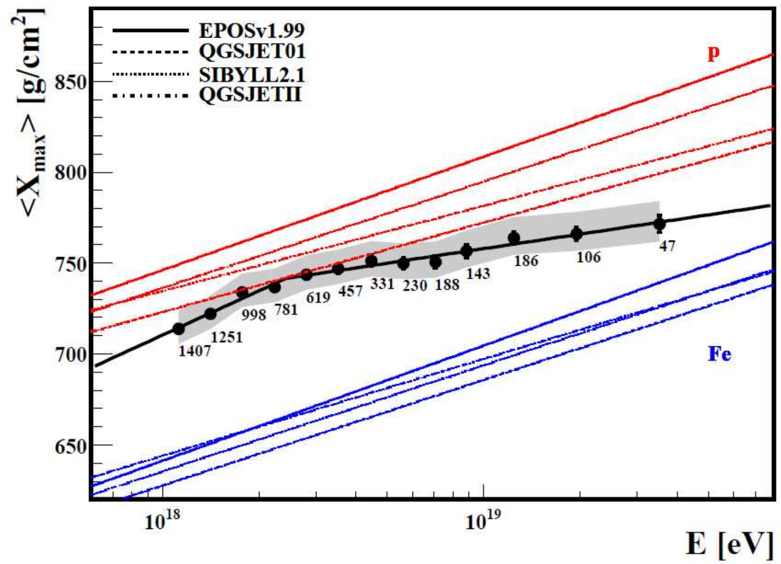
HiRes/TA show the proton-dominated mass composition.

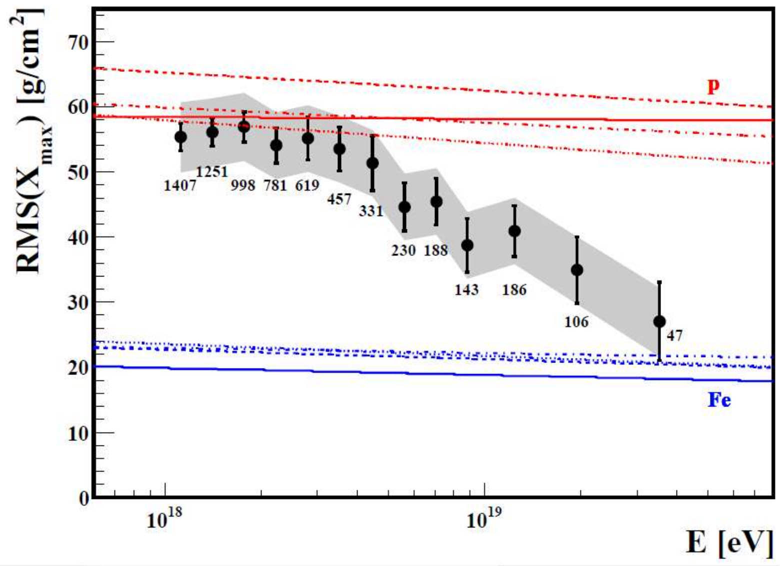
PAO: nuclear composition with steadily increasing mass A with energy.

MASS COMPOSITION: HIRES (top) vs AUGER (bottom)









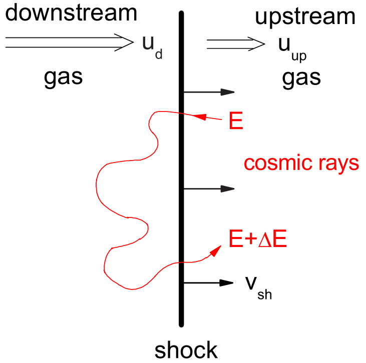
STANDARD MODEL for GALACTIC CRs

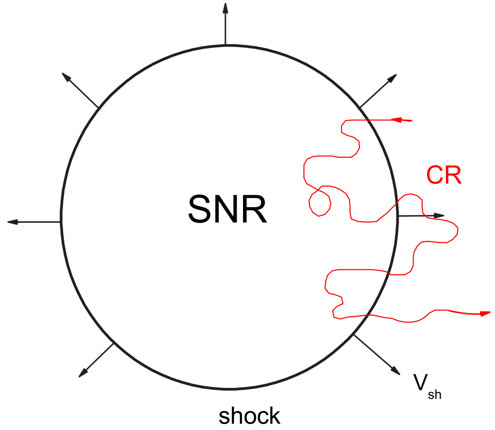
Ginzburg 1951, Ginzburg and Syrovatskii 1960

- **sources:** **SN remnants.**
- **acceleration:** **diffusive shock acceleration.**
  Krymskii 1977, Axford 1977, Bell 1978, Blandford and Ostriker 1978
- **propagation:** **diffusion.**

DIFFUSIVE SHOCK ACCELERATION

$$\frac{\partial f(\vec{x},t)}{\partial t} = \nabla(D\nabla f) - \vec{v}\nabla f + \frac{1}{3}(\vec{\Delta}\vec{v})p\frac{\partial f}{\partial p} + \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial f}{\partial p}\right] + Q_{\rm inj}(\vec{x},\vec{p},t).$$





energy gain at each crossing $\Delta E/E \sim v_{\rm sh}/c$, spectrum $N(E)dE \sim E^{-2}dE$.
$E_{\rm max}$ from: $t_{\rm acc} \leq t_{\rm diff}$, where $t_{\rm acc} \sim D/v_{\rm sh}^2$ and $t_{\rm diff} \sim R_{\rm sh}^2/D$.
For Bohm diffusion $D_B \sim r_L c$: $\mathbf{E_{max} \sim (v_{sh}/c) R_{sh} B}$, $E_{\rm max}$ is too low.
With SNR parameters $v_{\rm sh} \sim 5 \times 10^8$ cm/s, $R_{\rm sh} \sim 10^{19}$ cm and $B \sim 3\ \mu$G :

$$\mathbf{E_{max} \sim 2 \times 10^{14}\ Z\ (B/3\mu G)\ \ eV}$$

(first recognised by Cesarsky and Laggage 1981).

DIFFUSIVE SHOCK ACCELERATION: PROGRESS

- **E_{max} :**
  Acceleration to the highest energies occurs at the beginning of Sedov phase. Non-linear amplification of turbulent magnetic field in the shock precursor due to streaming instability of CR produces magnetic field with strength $\delta B \sim B \sim 10^{-4}$ G (Bell 1978, Bell and Lucek 2000).

$$E_{max} = 4 \times 10^{15} Z \frac{B}{10^{-4} G} \left(\frac{W_{51}}{n_g/cm^3} \right)^{2/5} \text{ eV}$$

$$E_p^{max} = 4 \times 10^{15} B_{-4} \text{ eV}, \qquad E_{Fe}^{max} = 1 \times 10^{17} B_{-4} \text{ eV}$$

- **energy spectrum and particle exit:**
  At fixed SNR age the spectrum of escaped particles is close to δ-function. but time-averaged spectrum is $\propto E^{-2}$ or flatter at highest energies (Ptuskin, Zirakashvili 2006).

PROPAGATION IN THE GALAXY

Diffusive propagation equation for a single source:

$$\frac{\partial f(x,t)}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial f}{\partial x}\right) - \frac{\partial}{\partial x}(uf) + \frac{1}{3}\frac{1}{p^2}\frac{\partial}{\partial p}\left(p^3\frac{\partial u}{\partial x}f\right) - \frac{f}{\tau_A} -$$

$$-\frac{1}{p^2}\ \frac{\partial}{\partial p}\ \left[b(p)\ \frac{\partial f}{\partial p}\right]\ + \frac{1}{p^2}\ \frac{\partial}{\partial p}\left[p^2\ D_{pp}\ \frac{\partial f}{\partial p}\right]\ + Q(\Gamma)\ \delta^3(x - x_g),$$

where $Q(\Gamma) = \frac{(\gamma_g - 2)L_0}{Am_N}\Gamma^{-\gamma_g}, b(p) = dp/dt,$ Γ is Lorentz factor.

SPECTRA: QUALITATIVE ESTIMATES

$$\mathbf{D}(\mathbf{E}) \propto \mathbf{E}^{\mu} \; (\mu = 1/3,\ \mu = 1/2,\ \mu = 0).$$

Protons and primary nuclei (p)

generation: $Q_p(E) \propto E^{-\gamma_g}$, $\tau_{\rm esc} \propto D^{-1}(E) \propto E^{-\mu}$

$$\mathbf{n_p}(\mathbf{E}) \sim \mathbf{Q_p}(\mathbf{E})\tau_{\mathbf{esc}}(\mathbf{E}) \propto \mathbf{E}^{-(\gamma_{\mathbf{g}}+\mu)}$$

High energy primary electrons

$$Q_e(E) \propto E^{-\gamma_g},\ \ n_e(E) \sim Q_e(E)\, \tau_e^{\rm loss}(E) \propto E^{-(\gamma_g+1)}.$$

High energy positrons in ISM ($\mathbf{p+p \rightarrow \pi^+ \rightarrow e^+}$)

generation: $Q_{e^+}(E) \sim n_p(E)\, \sigma\, n_{\rm gas}\, c \ \propto E^{-(\gamma_g+\mu)}$

$$n_{e^+}(E) \sim Q_{e^+}(E)\, \tau_e^{\rm loss} \ \propto E^{-(\gamma_g+\mu+1)}$$

$\mathbf{e^+/e^-}$ ratio

$n_{e^+}/n_{e^-} \propto E^{-\mu}$ in contrast to PAMELA and AMS-02.

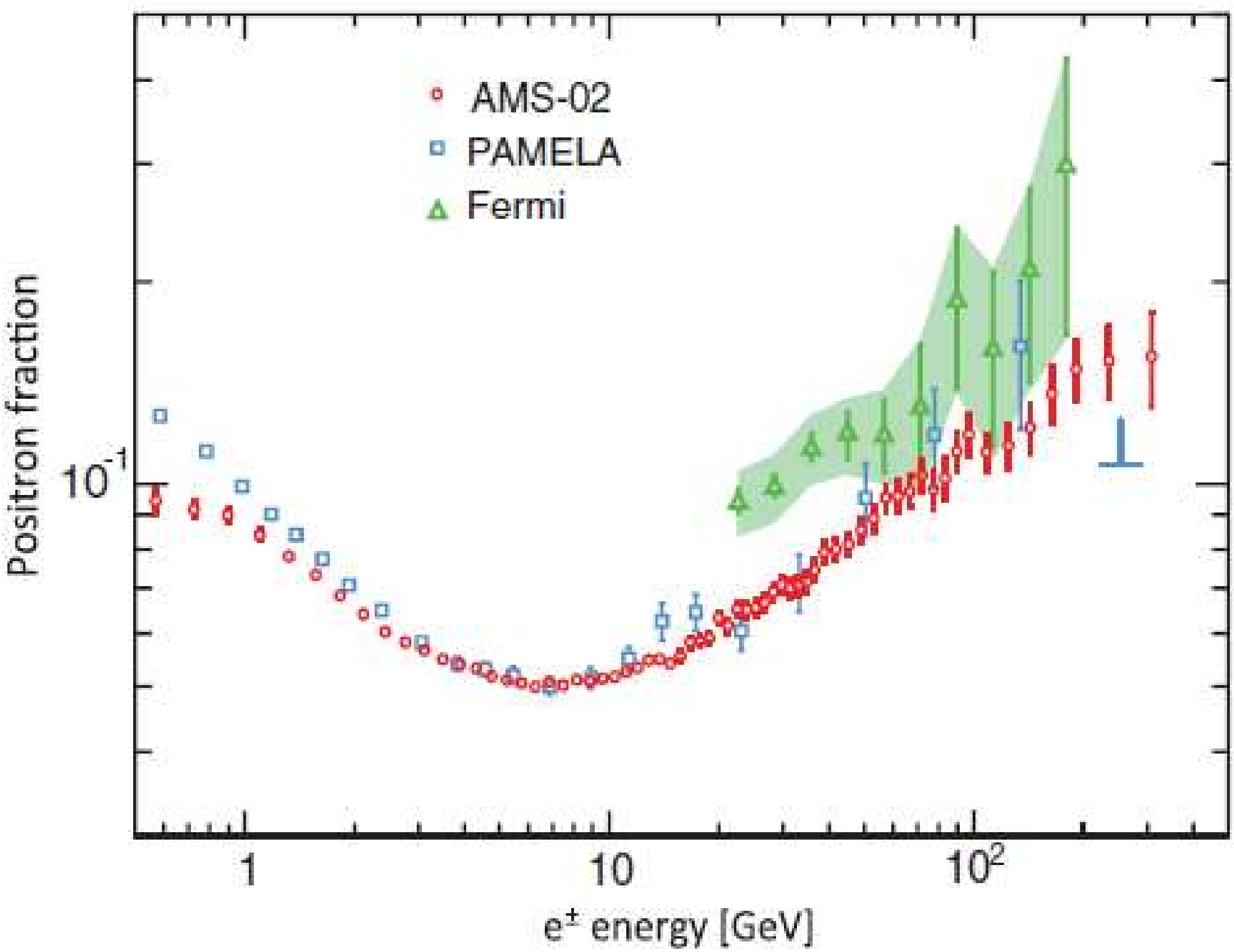
HE positron production in SNR (Blasi mechanism):

$$n_p^{\rm SNR}(E) \propto Q_p(E) t_{\rm acc}(E) \propto Q_p(E) \frac{D(E)}{u^2} \propto E^{-\gamma_g+\mu}$$

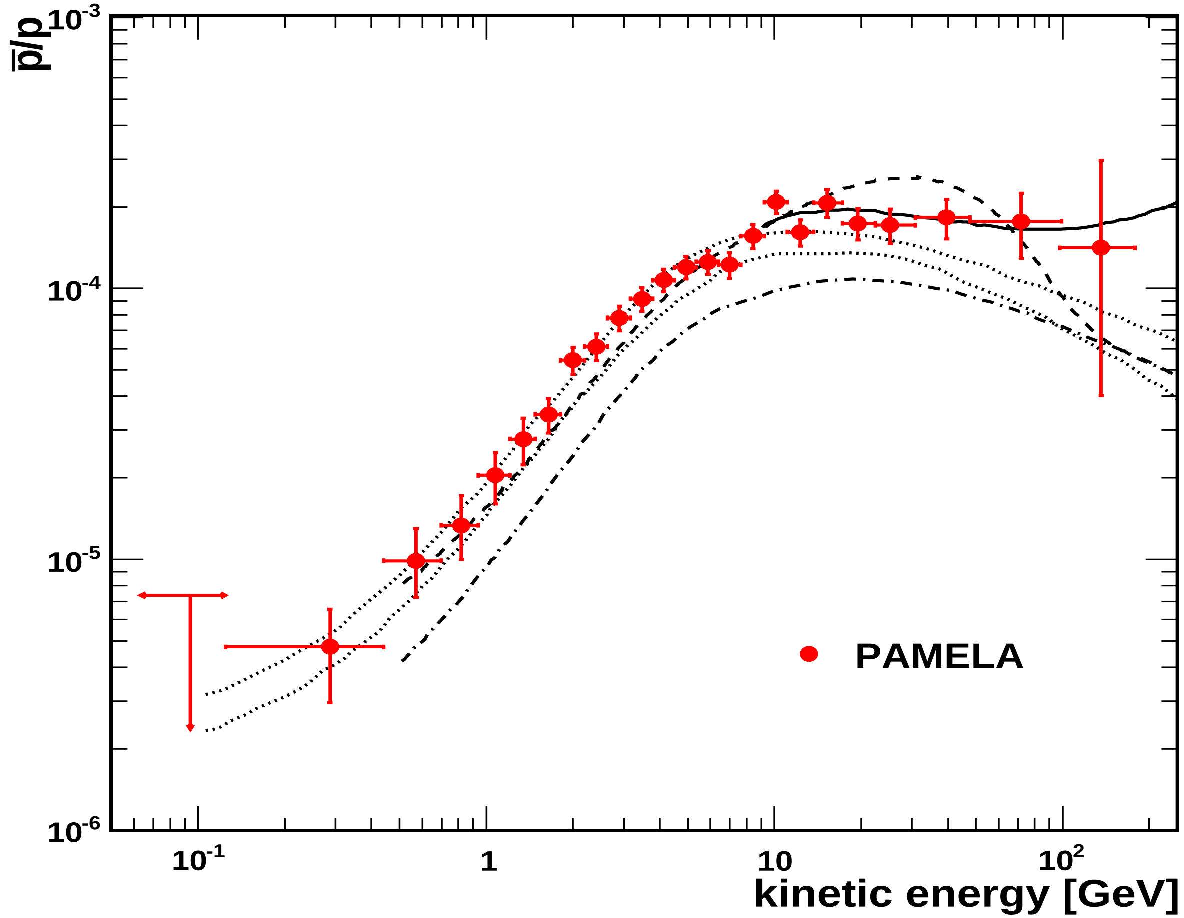
$$Q_{e^+}(E) \propto n_p^{\rm SNR}(E) \sigma n_{\rm gas} c \propto E^{-\gamma_g+\mu}$$

$$\mathbf{e^+/e^- \propto Q_{e^+}/Q_{e^-} \propto E^{\mu}}$$

PAMELA and AMS POSITRON EXCESS



PAMELA ANTI-PROTON to PROTON RATIO



MECHANISMS OF EXCESS PRODUCTION

- **The natural sources beyond GCR SM are pulsars (e^+e^- only) and DM (both e^+e^- and $\bar{p}p$).**
- **Only nearby pulsars may be sources of positrons. Examples of young nearby pulsars Crab and Vela-X show their inconsistency with PAMELA - AMS results (Della Torre et al 2013).**
- **Supersymmetric DM models have problems with PAMELA - AMS data (Bergstrom et al 2013). To describe strong e^+e^- and weak $\bar{p}p$ excess leptofilic DM models are needed. They must be very complicated (Dev et al 2013).**
- **Solution to both e^+e^- and $\bar{p}p$ excesses is given by 'Blasi enhancement' (production in SNRs within GCR SM (Blasi 2009 and Blasi and Serpico 2009), but numerically these calculations are in strong contradiction with MC simulations by Kachelrieß, Ostapchenko and Tomas 2011.**

Positron excess in GCR SM (P. Blasi 2009)

Production of positrons due to $pp \rightarrow \pi^+ \rightarrow e^+$ in the region of acceleration.

$$Q_{e^+}(E) = \int dE' n_p(E', x) \frac{d\sigma(E', E)}{dE'} n_g(x) c$$

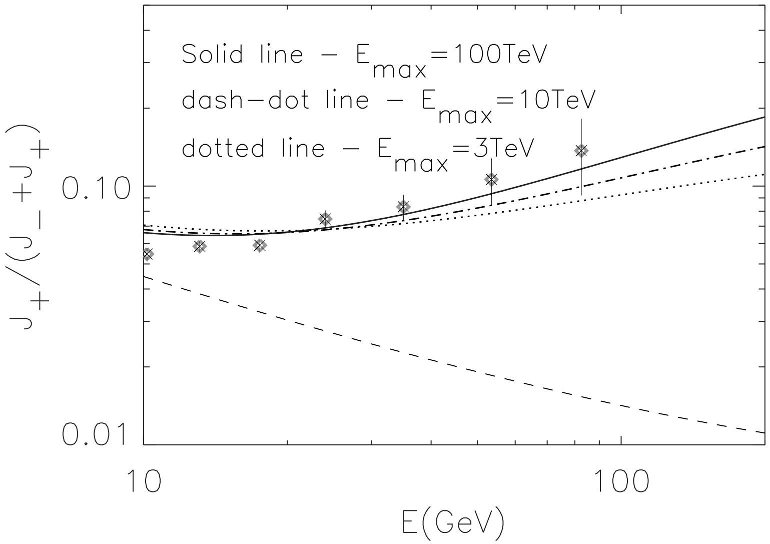
Acceleration of injected positrons :

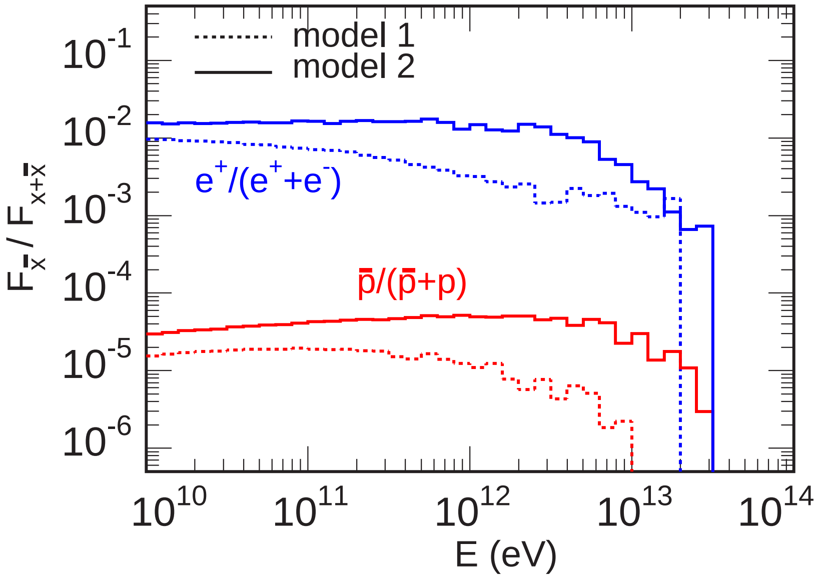
$$D\frac{\partial^2 f_{e^+}}{\partial x^2} - v\frac{\partial f_{e^+}}{\partial x} + \frac{1}{3}\frac{dv}{dx}p\frac{\partial f_{e^+}}{\partial p} + Q_{e^+}(p, x) = 0.$$

The accelerated positrons propagate in Galaxy diffusively with parameters:

$$D(E) = D_0 E^{\mu}, \quad \mu = 0.6, \quad E_{\max} = 100 \text{ TeV}$$

Comparison: Blasi 2009 vs Kachelrießet al 2011.





Blasi: $e^+/(e^+ + e^-)$ ratio

Kachelrieß et al: $e^+/(e^+ + e^-)$ ratio

INCOMPLETENESS and PROBLEMS of GCR SM

Acceleration and sources

- **Injection for shock acceleration.**
- **Confinement, exit and $E_{\rm max}$.**
- **Alternative acceleration/sources (subdominant).**

Propagation

- **Magnetic field is not known in detail.**
- **Breaking of diffusive regime.**
- **Re-acceleration uncertainties.**

Problems of GCR Standard Model

- **Flatness of He spectrum.**
- **Anisotropy $\delta(E) \propto D(E) \propto E^{\mu}$ is too large at high energy.**
- **ratios: $e^+/(e^+ + e^-)$, $\bar{p}/(\bar{p} + p)$, secondary/primary nuclei.**
- **No observed pp-produced gamma and neutrino radiations from SNR. Indications: IC 443 and W 44.**

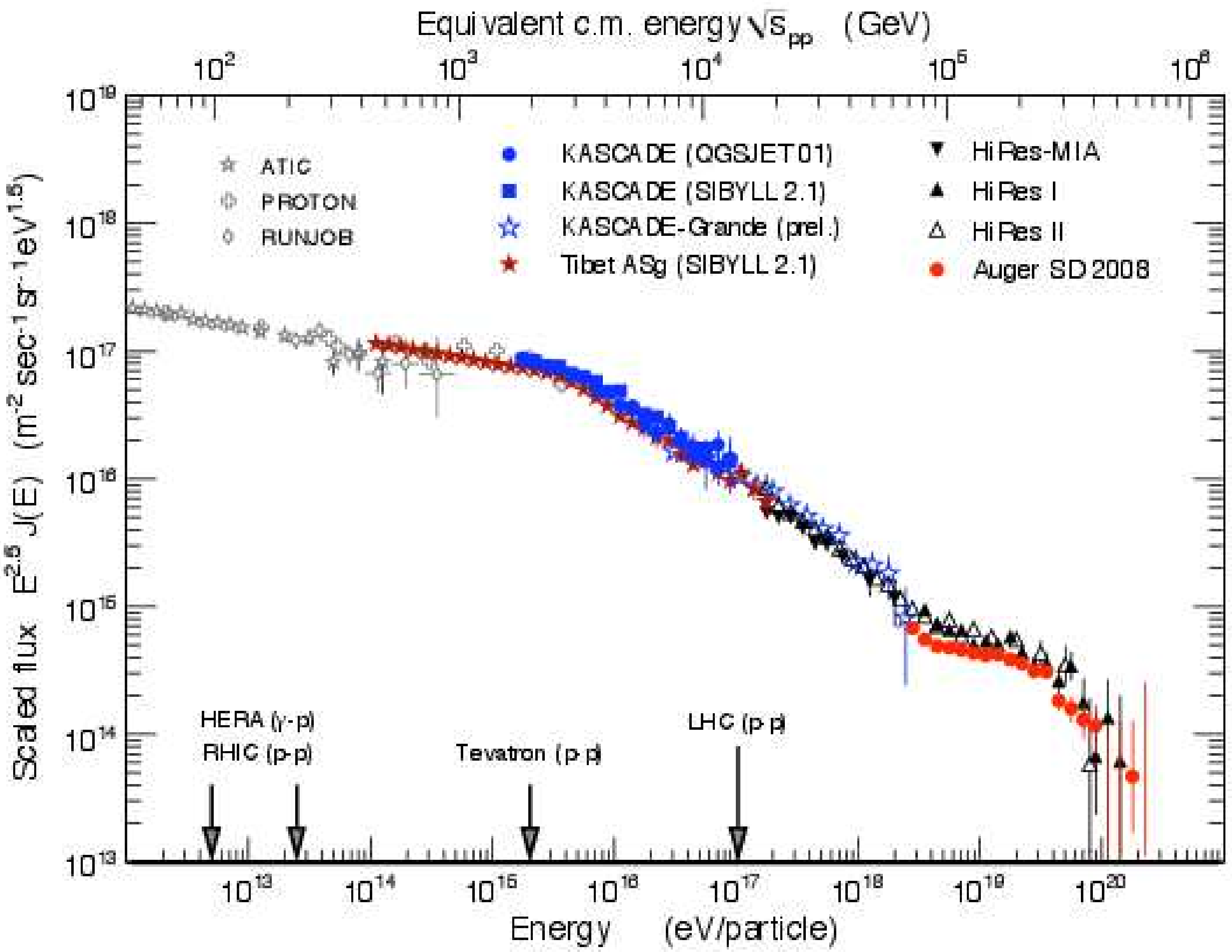
SPECTRAL FEATURES in COSMIC RAYS

and

ANKLE PROBLEM

based on the works of LNGS group: R. Aloisio, V.B., P.Blasi, A. Gazizov, S. Grigorieva, M. Kachelriess and S. Ostapchenko.

TWO OBSERVED FEATURES



Two observed features :

- **Proton knee:** MSU, Khristiansen and Kulikov 1958 $E_p \sim (2-3)$ PeV.
- **Ankle:** Volcano Ranch, Linsley 1963, $E_a \approx 10$ **EeV.**

Predicted spectral features :

Diffusive shock acceleration: $E_p^{\text{knee}} = E_p^{\max}$ as interpretation,

Iron knee $E_{\text{knee}}^{Fe} = ZE_p^{\max} \approx 80$ PeV : predicted by DSA and confirmed by Kascade-Grande 2012.

$E_a \approx (4-5)$ EeV: **transition to extragalactic CRs** as interpretation of **ankle**.

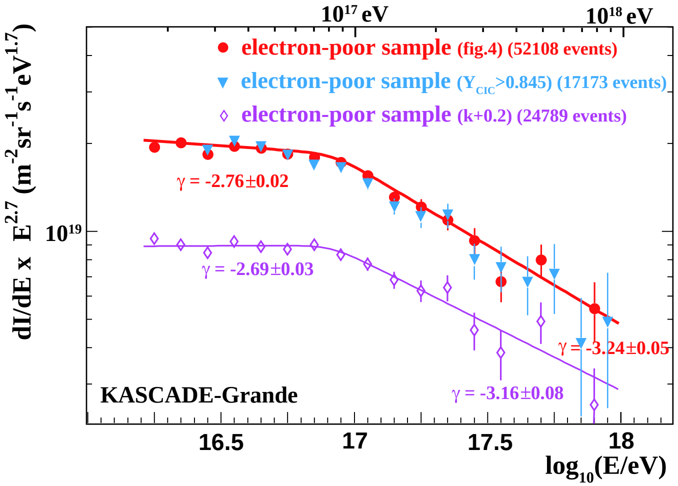
Extragalactic nuclei interacting with extragalactic light: $A + \gamma_{\text{light}} \to (A-1) + N$, Gerasimova, Rozental 1961.

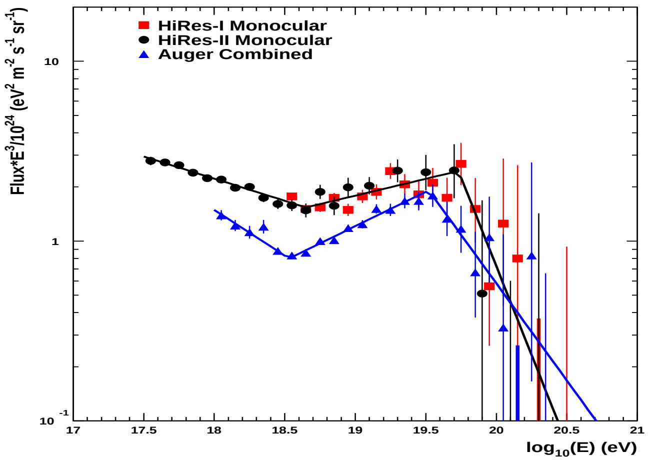
Extragalactic protons interacting with CMB
Greisen, Zatsepin, Kuzmin (GZK) 1967:

$p + \gamma_{\text{cmb}} \to p + e^+ + e^-$ ($E_{\text{pair}} \approx 2$ EeV)

$p + \gamma_{\text{cmb}} \to N + \pi$, ($E_{\text{gzk}} \approx 50$ EeV.

OBSERVED CR FEATURES





Observed Iron knee and ankle in power-law approximation

HiRes : $E_a = 4.5 \pm 0.5$ EeV

TA : $E_a = 4.9 \pm 0.3$ EeV

Auger : $E_a = 4.2 \pm 0.1$ EeV

Kascade-G : $E_{\rm knee}^{Fe} \approx 80$ PeV

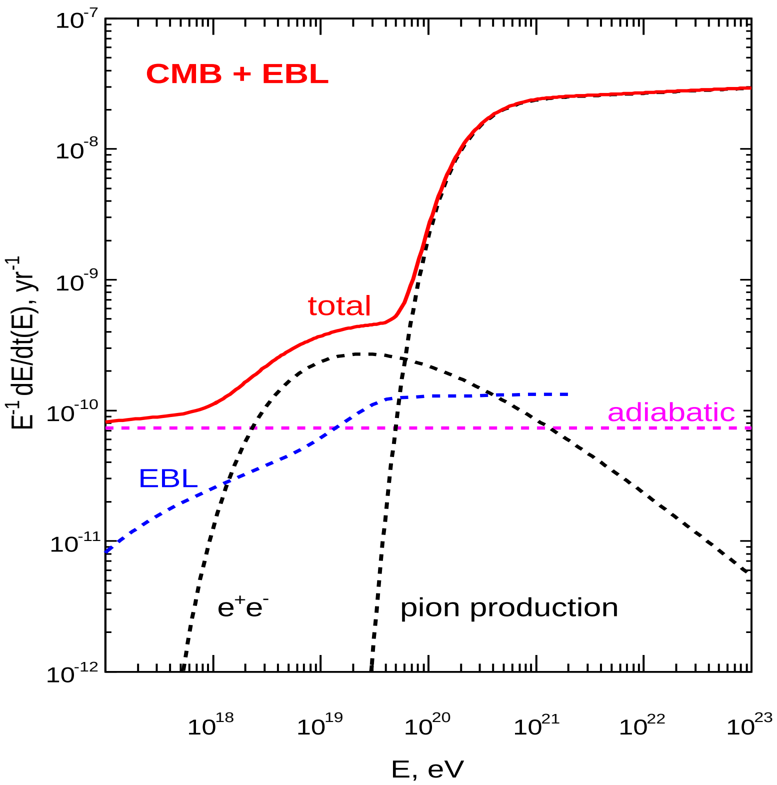
GZK cutoff : $p + \gamma \to N + \pi$, $E_{\rm gzk} \approx 50$ EeV, $E_{1/2} = 52.5$ EeV

HiRes : $E_{\rm gzk} = 56.2^{+5.4}_{-4.9}$ EeV $\qquad \log E_{1/2} = 19.73 \pm 0.07$

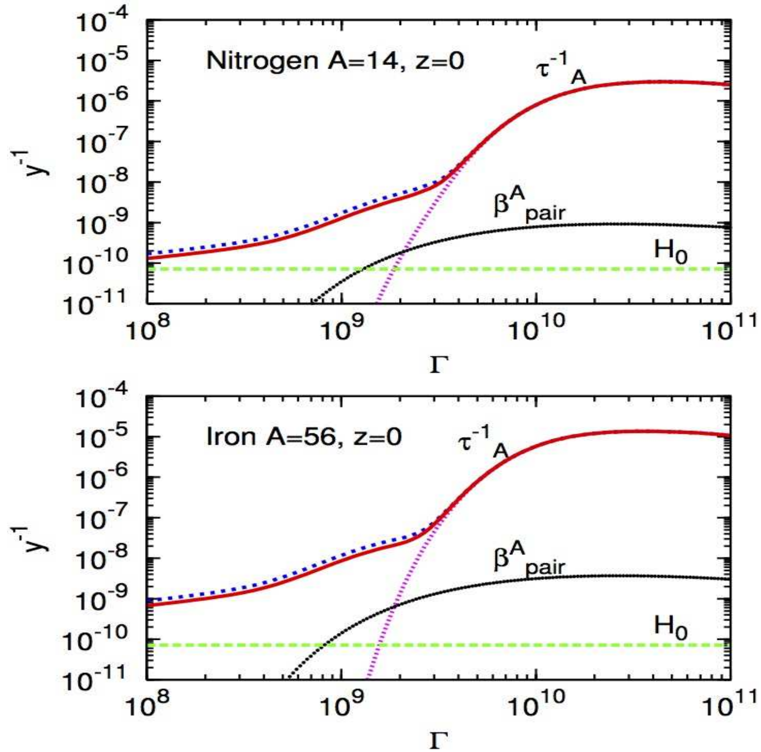
TA : $E_{\rm gzk} = 48 \pm 1.0$ EeV $\qquad \log E_{1/2} = 19.69 \pm 0.1$

Auger : $E_{\rm cut} =$ **25.7**$^{+1.1}_{-1.2}$. EeV $\qquad$ **theory BG 1988 :** $\log E_{1/2} = 19.72$

Signatures of particle propagation through CMB and EBL



$E_{\rm eq1} = 2.4 \times 10^{18}$ eV, $\quad E_{\rm eq2} = 6.1 \times 10^{19}$ eV



INTERACTION SIGNATURES AND MODEL-DEPENDENT SIGNATURES

We want to see **observational signatures of interaction**, but in our calculations **model-dependent quantities** also appear, such as **distances** between sources, their cosmological **evolution**, modes of **propagation** (from rectilinear to diffusion), local source **overdensity** or **deficit** etc.

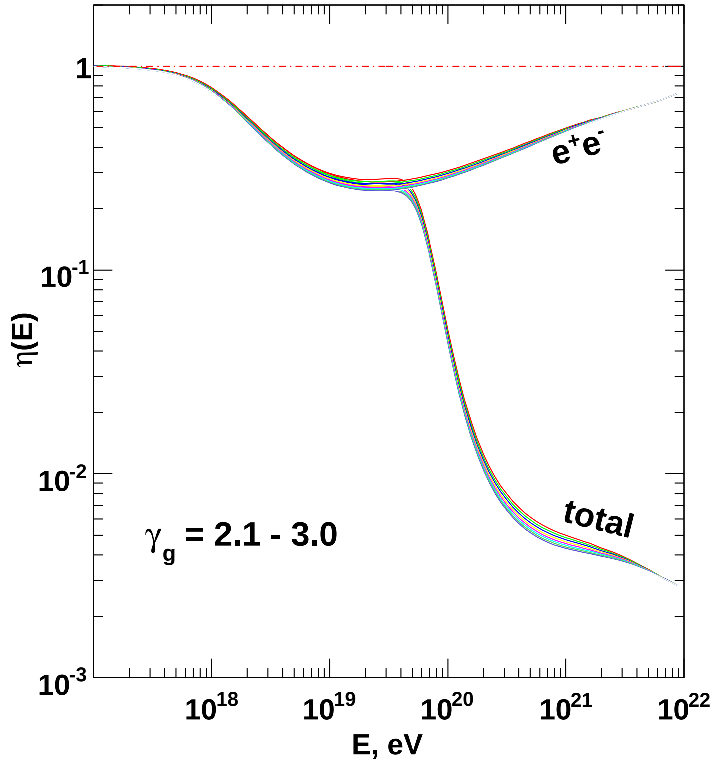
Energy spectrum in terms of **modification factor** characterizes well the **interaction signatures**.

MODIFICATION FACTOR

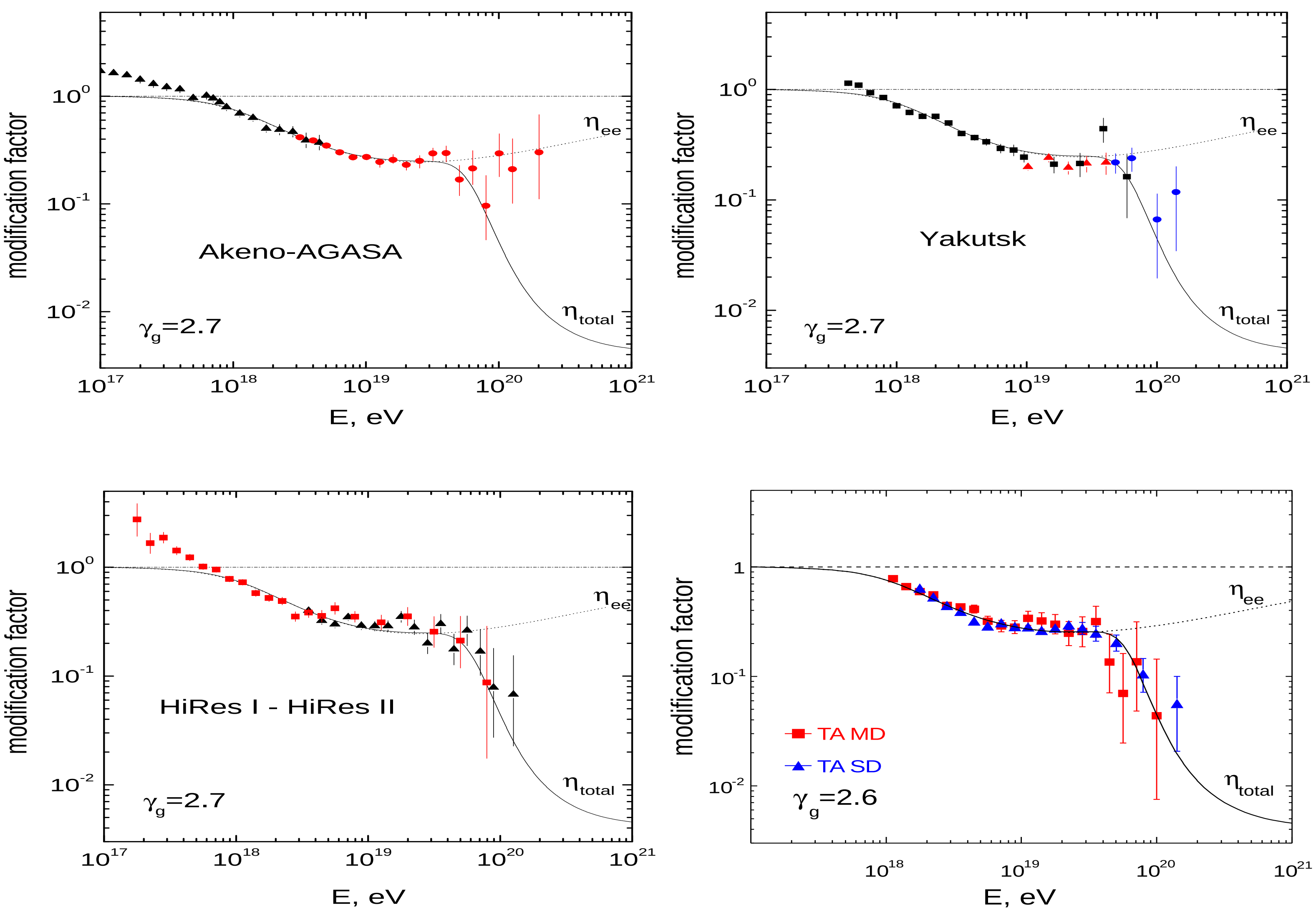
$$\eta(E) = \frac{J_p(E)}{J_p^{\rm unm}(E)}$$

where $J_p^{\rm unm}(E) = KE^{-\gamma_g}$ includes only adiabatic energy losses. Since many physical phenomena in numerator and denominator compensate or cancel each other, dip in terms of modification factor is less model-dependent than $J_p(E)$.

It depends very weakly on:
γ_g and $E_{\rm max}$,
modes of propagation (rect or diff),
large-scale source inhomogeneity,
source separation within 1-50 Mpc,
local source overdensity or deficit,..
It is modified by presence of nuclei ($\gtrsim 15\%$).
Experimental modification factor:
$\eta_{\rm exp}(E) = J_{\rm obs}(E)/KE^{-\gamma_g}$.

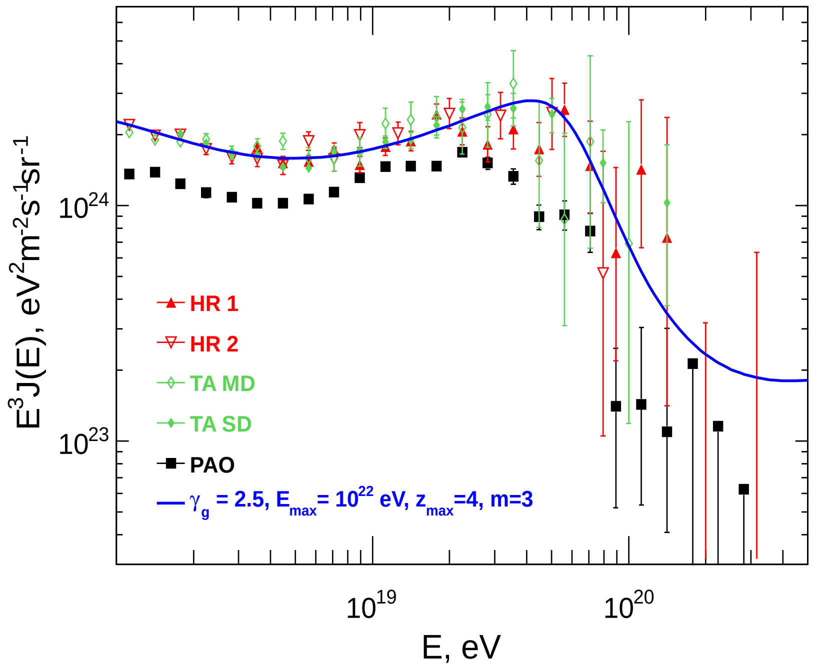


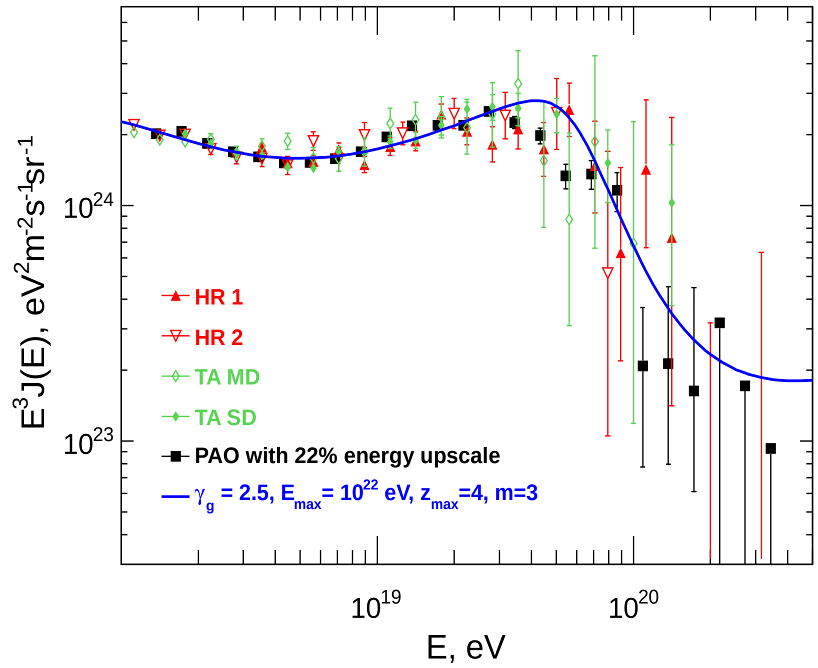
Comparison of pair-production dip with observations



DIP in AUGER 2011 DATA

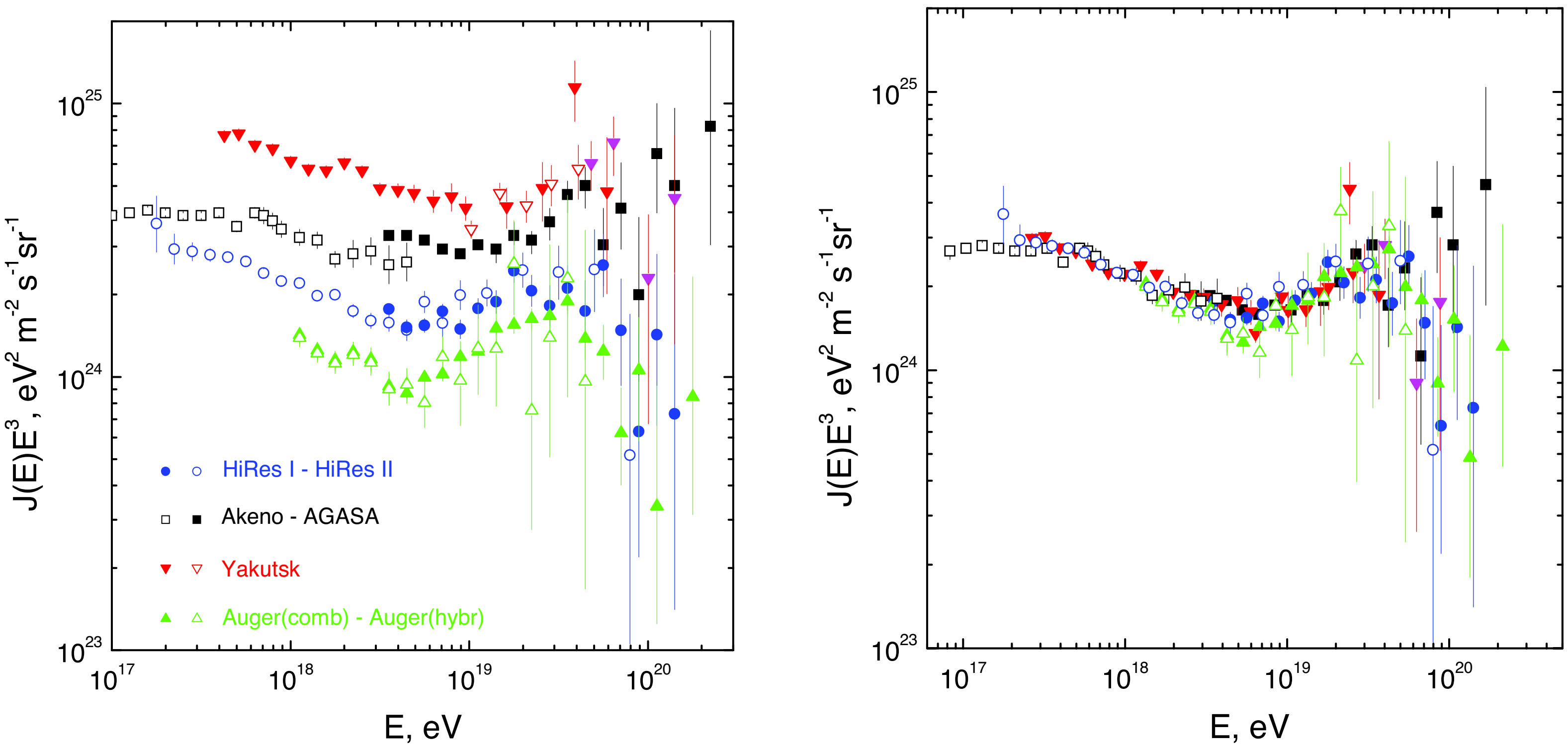
In modification factor presentation 2011 χ^2 is large. $\chi^2_{\min}$ can be reached in model-dependent presentation in terms of natural spectrum $E^3J(E)$, using energy shift $\lambda = 1.22$ and cosmological evolution. As a result of χ^2-minimization absolute Auger flux coincides with HiRes and TA.





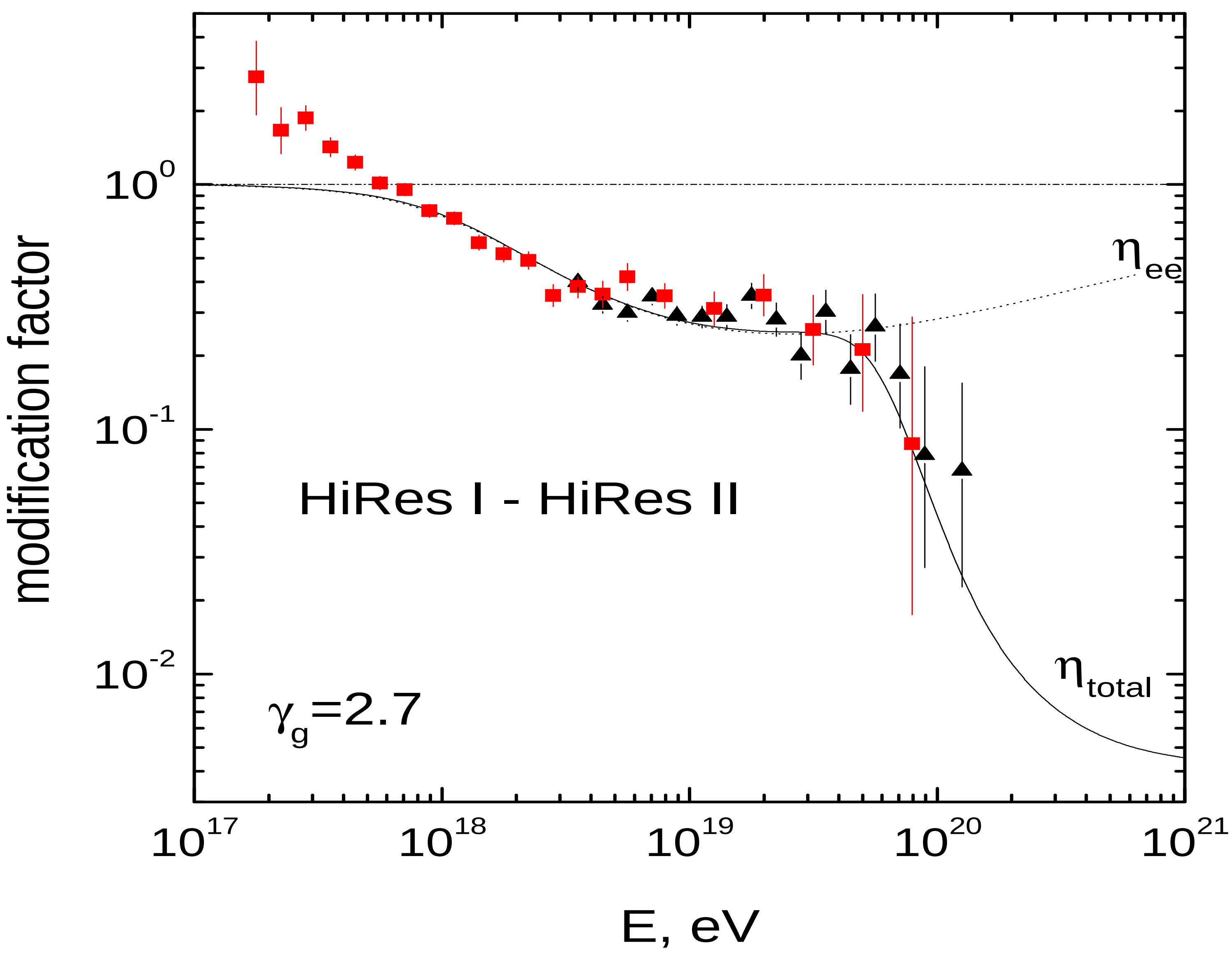
Recalibration of all detectors using χ^2 minimization

V.B., A. Gazizov, S. Grigorieva 2006

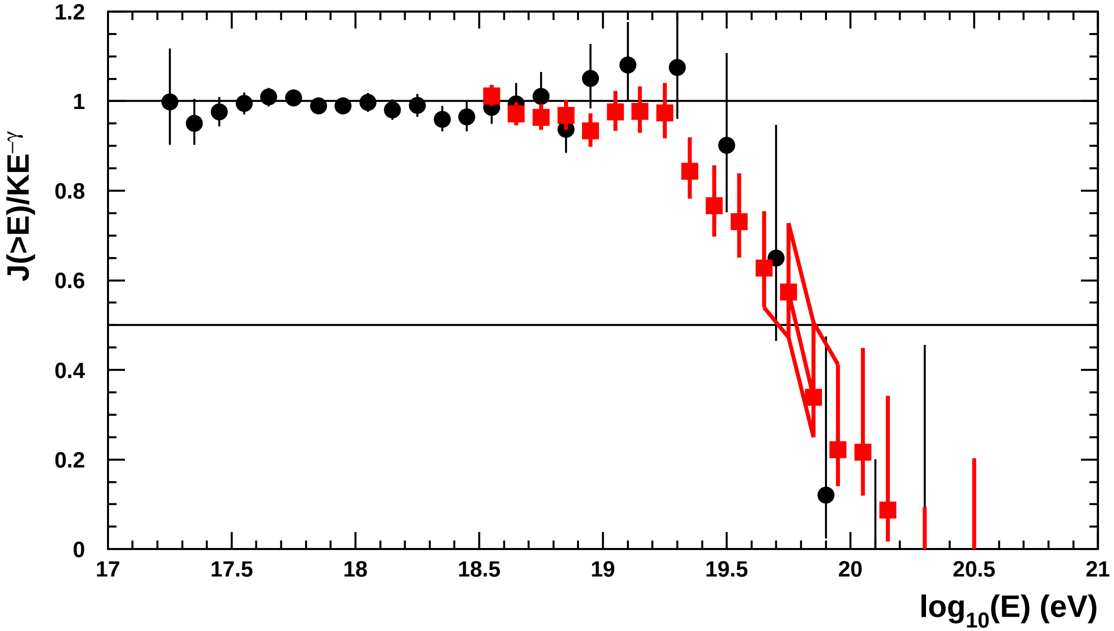


Recalibration factors: $\lambda = 1.2$ (Auger), $\lambda = 1.0$ (HiRes), $\lambda = 0.75$ (AGASA), $\lambda = 0.625$ (Yakutsk).

GZK CUTOFF IN HiRes DIFFERENTIAL SPECTRUM



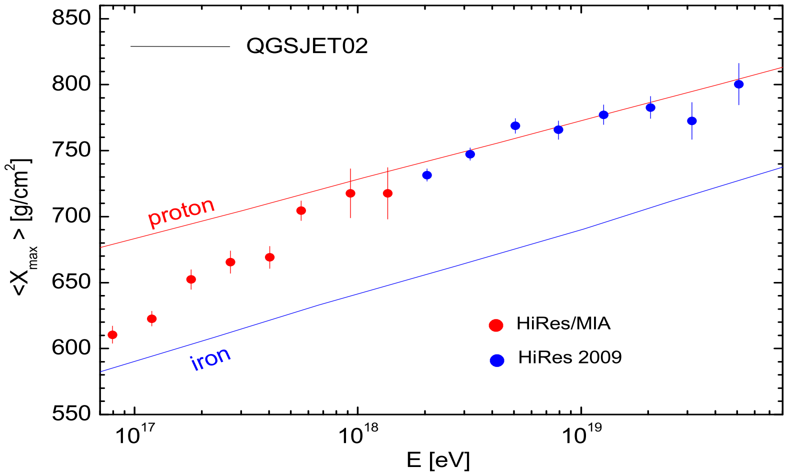
GZK CUTOFF IN HiRes INTEGRAL SPECTRUM

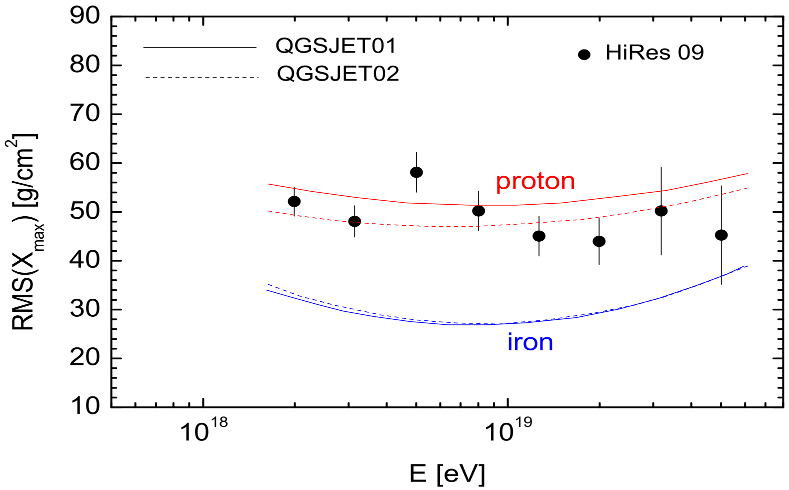


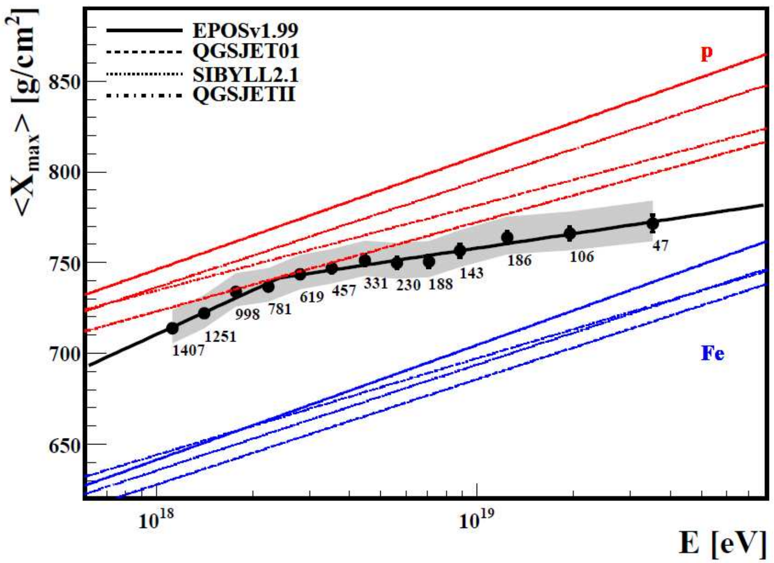
$E_{1/2}$ in HiRes integral spectrum confirms that steepening in the differential spectrum is the GZK cutoff:

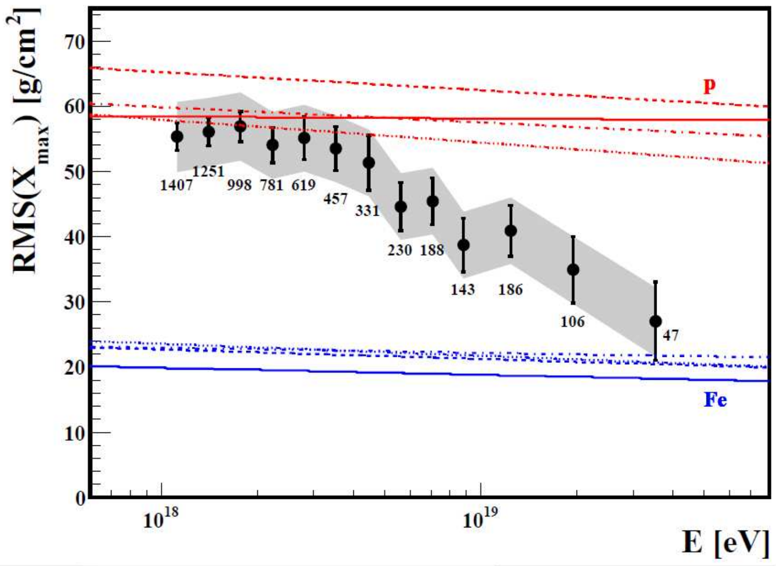
$$E_{1/2}^{meas} = 10^{19.73\pm0.07}\ \mathrm{eV} \quad \mathrm{cf} \quad E_{1/2}^{theor} = 10^{19.72}\ \mathrm{eV}$$

MASS COMPOSITION: HIRES (top) vs AUGER (bottom)









ANISOTROPY and ANKLE

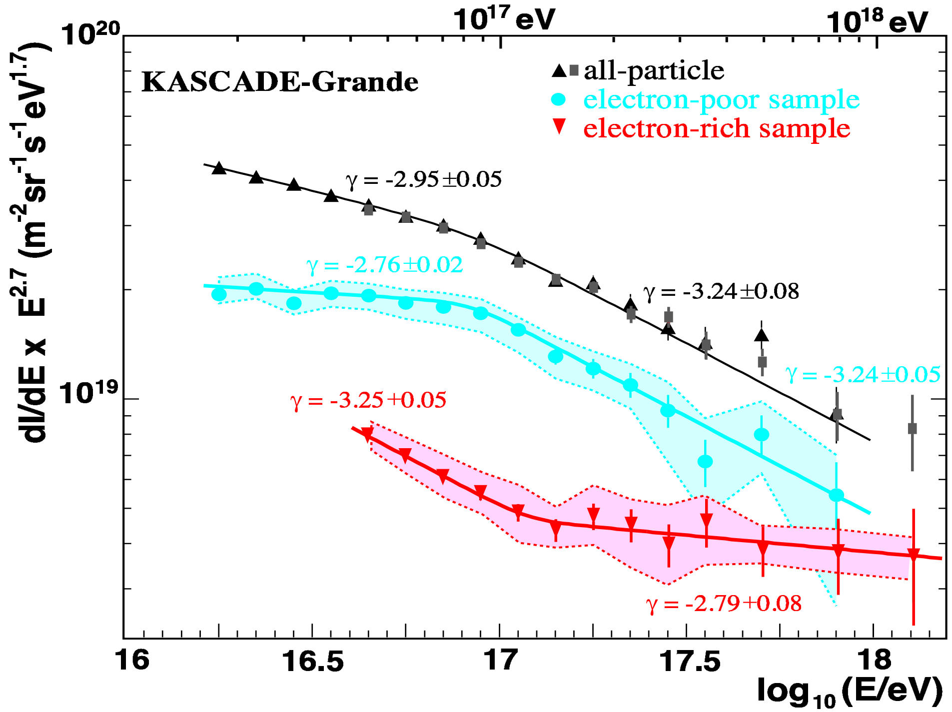
According to measurements of all three largest detectors, Auger, HiRes and Telescope Array, the mass composition at (1 - 3) EeV. i.e. below the ankle, is **proton-dominated**, or **p + He - dominated**. If galactic, such composition is excluded by recent measurements of anisotropy (Auger 2011 and 2012). Then ankle with $E_a \approx (4-5)$ EeV cannot be the feature of **transition from galactic to extragalactic** cosmic rays. Transition should occur at lower energy **in agreement with dip model.** Recent MC simulation for galactic particles (Giacinti et al 2012) confirms this conclusion

Thus ankle can be interpreted either as intrinsic property of pair-production dip or, in case of Auger results, like transition from extragalactic protons to extragalactic nuclei.

KASCADE-Grande: 2013 BREAK-THROUGH

'Small' 700×700 m^2 array with scintillation and muon detectors.
p+He component is separated by muon content with properties:

- p+He component at 0.1 - 1.0 EeV separated as 'electron-rich' using special event criteria, 6300 events.
- extragalactic, otherwise anisotropy at $E \sim 1$ EeV.
- flat spectrum $\gamma = 2.79 \pm 0.08$, cf $\gamma = 3.24 \pm 0.08$ for total.



CONCLUSIONS

- **GCR SM, based on the diffusive shock acceleration in SNRs (triumph of theory !) and diffusive propagation in the Galaxy, describes well the basic observations, knees, spectra, secondary/primary nuclei ratios etc. However, the SM is incomplete and meets some problems.**

- **The basic proof of GCR SM, detection of hadronic gamma-rays and neutrinos from SNRs, is still missing, though there are some indications of hadronic gamma-rays from dense molecular clouds nearby SNRs: W 28,
W 44 and IC 443. Detection of HE hadronic gamma-rays and HE neutrinos from SNRs has status of highest-priority observations.**

- **Until recently the problems of GCR SM include:(i) flatness of He spectrum, (ii) large $\mu = 0.7$, and (iii) too large dipole anisotropy predicted at high energy due to large μ. These problems do not look serious at present due to data of PAMELA and progress in theory.**

- **Positron excess as observed by PAMELA and AMS can be explained in principle by Blasi enhancement. The detailed MC is needed to confirm it, If not, it means the discovery most probably of DM.**

- **In any case measurement of the ratios for $\bar{p}/p$, secondary/primary nuclei and fluxes of anti-nuclei at higher energies by space detectors will give most valuable information for cosmology and propagation of CRs.**

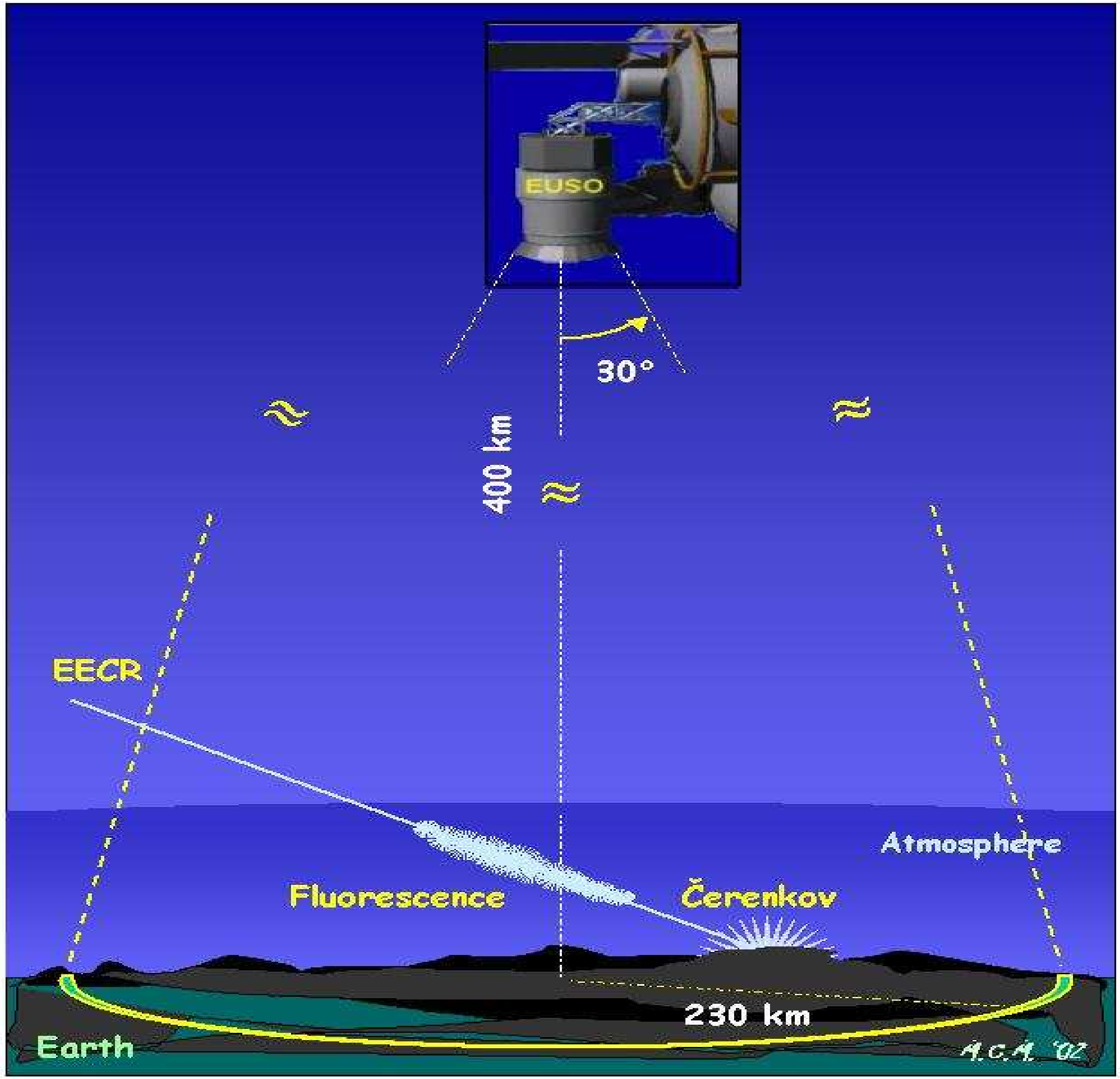
- **The energy region $10^{17} - 10^{18}$ eV is extremely interesting for CRs. It includes Iron knee and transition from galactic to extragalactic CRs In 2012 - 2013 Kascade-G discovered the Iron knee and extragalactic 'light component' there. A detector with area 1 km^2 is needed with potential to resolve proton and nuclei components. As minimum such array should have scintillation and muon detectors. Such detectors already exist or planned: AMIGA, TALE, Tunka-133, LHAASO.**

- **UHECR ($E > 1$ EeV) is characterised by conflict in measured mass composition between Auger (steadily increasing A from protons to Iron), and HiRes and TA (proton-dominated mass composition).**

- **Dip model agrees well with HiRes data (proton-dominated mass composition, pair-production dip, and GZK cutoff), and naturally contradicts to mass composition of Auger.**

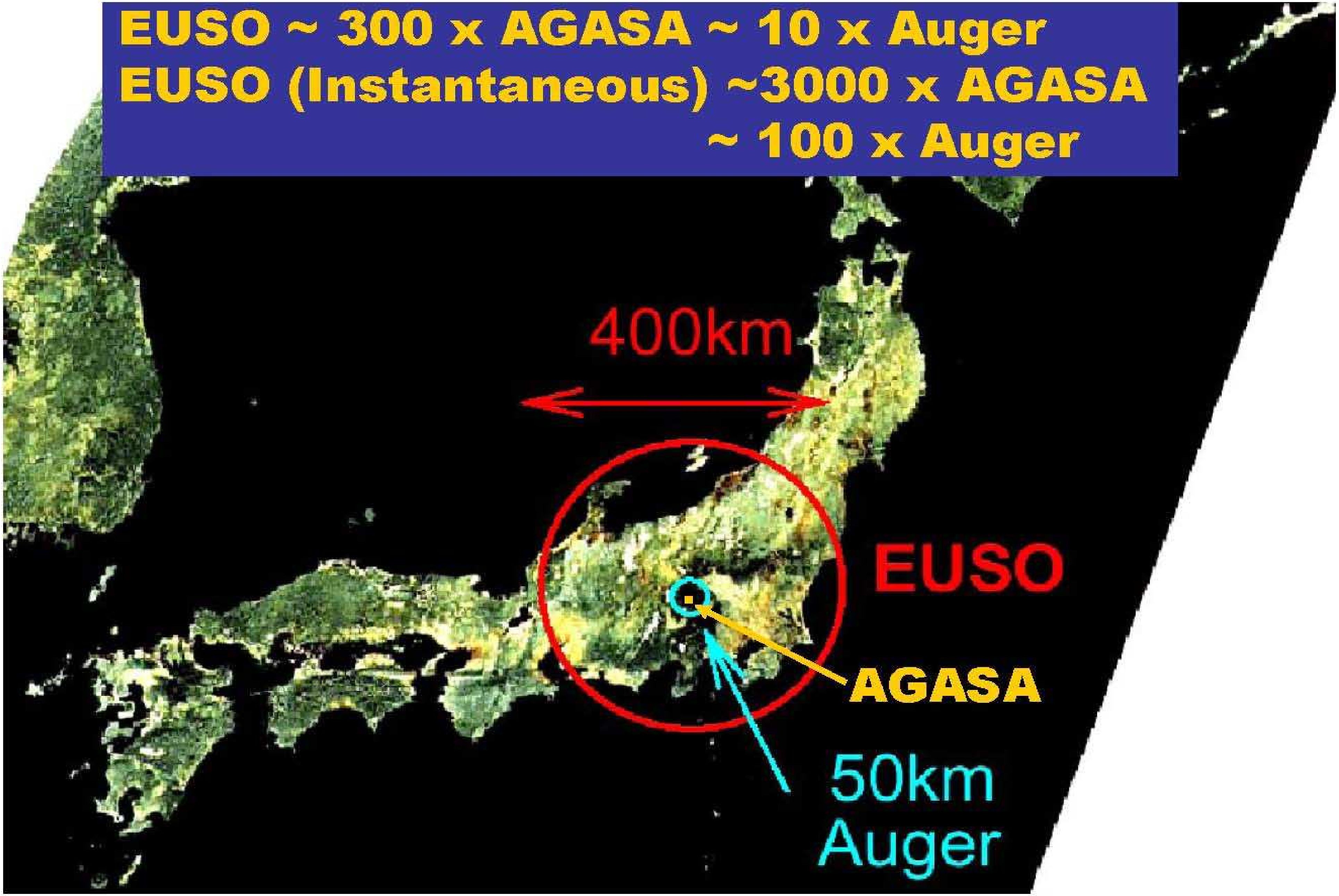
- **There are projects of measuring UHECR and neutrino fluxes by fluorescent detectors from the space: JEM-EUSO, KLPVE and Super-EUSO.**

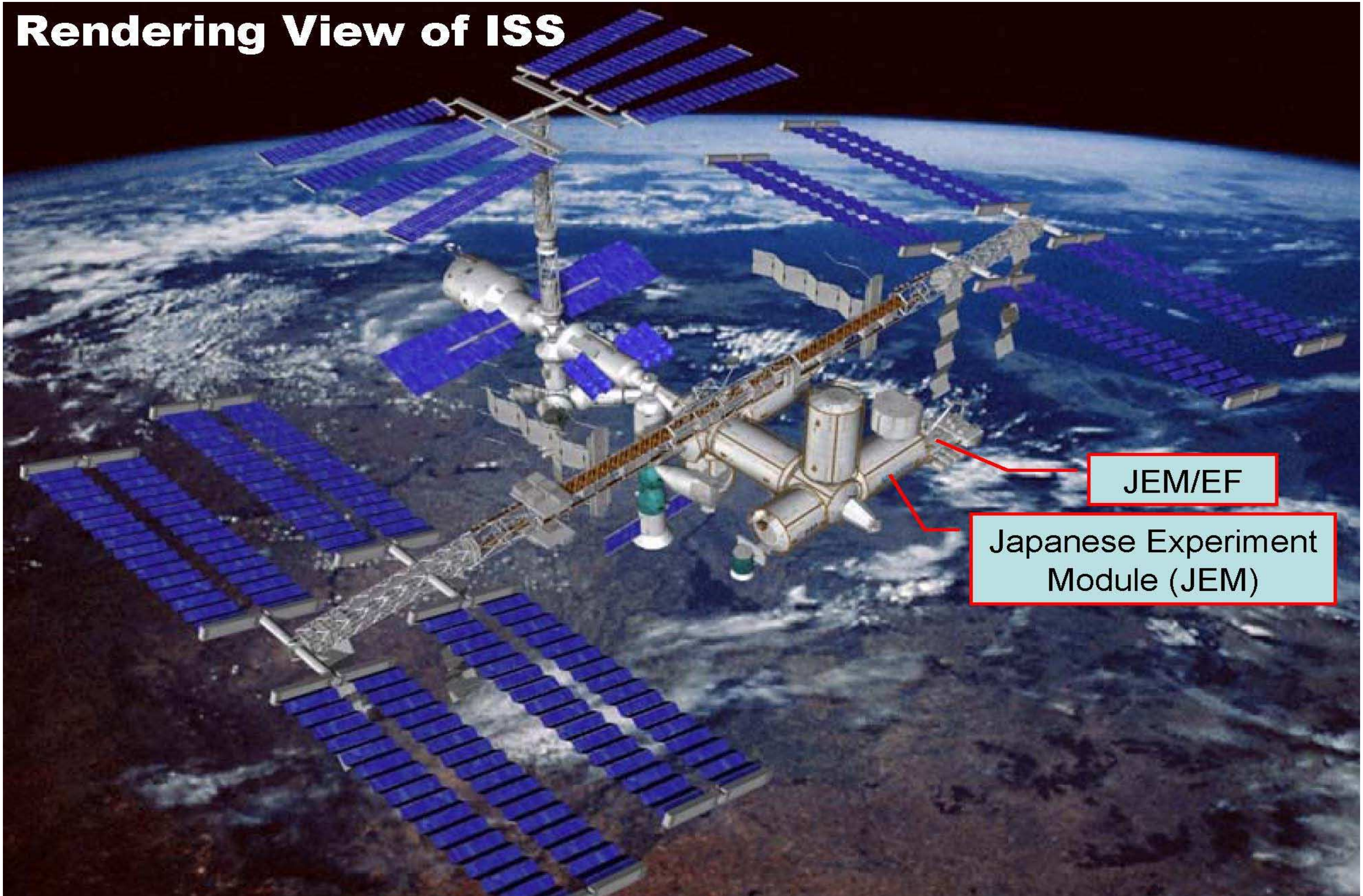
PRINCIPLES OF EUSO OBSERVATIONS



Field of View of EUSO

EUSO ~ 300 x AGASA ~ 10 x Auger
EUSO (Instantaneous) ~3000 x AGASA
~ 100 x Auger





Rendering View of ISS
JEM/EF
Japanese Experiment Module (JEM)

H-IIA Launch Vehicle

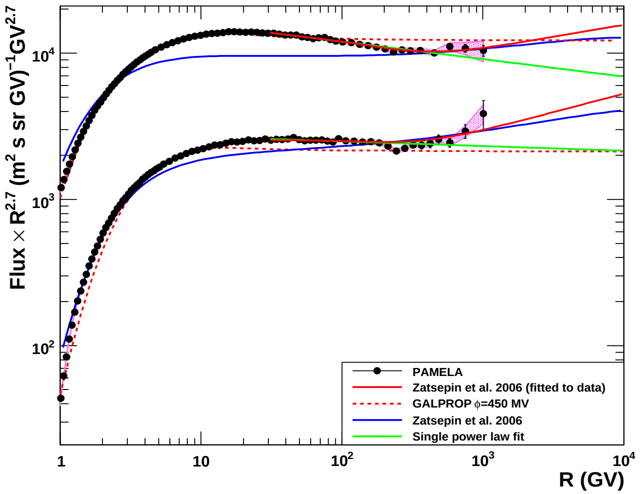
Nov. 29, 2003
Accident happened
for the H-IIA Launch Vehicle No 6

Feb. 26, 2005
The H-IIA Launch Vehicle No. 7 with MTSAT-1R was launched successfully.

Jan. 24, 2006
The H-IIA Launch Vehicle No. 8 with the Advanced Land Observing Satellite "Daichi“ (ALOS) was launched successfully.

Feb. 18, 2006
The H-IIA Launch Vehicle No. 9 with the Multi-functional Transport Satellite 2 (MTSAT-2) was launched successfully.

PROBLEM of FLATNESS



$$Q(E) \propto E^{-2}, \;\; n(E) \propto Q(E) D^{-1} \propto E^{-(2+\mu)}$$

$$\gamma = 2 + \mu$$

$$\gamma_p = 2.820 \pm 0.003(\mathrm{stat}) \pm 0.005(\mathrm{syst})$$

$$\gamma_{He} = 2.732 \pm 0.005(\mathrm{stat}) \pm 0.005(\mathrm{syst})$$

$$\Delta\gamma = \gamma_p - \gamma_{He} = 0.101 \pm 0.001$$

Flattening e.g. due to direct and inverse shocks (V.B. and Ptuskin 1989)