Astroparticle Physics: Puzzles and Discoveries

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September 11, 2007

Formula of astrophysical discoveries:

ALL GREATEST DISCOVERIES IN ASTROPHYSICS APPEARED UNPREDICTABLY AS PUZZLES.

WHAT WAS PREDICTED WAS NOT DISCOVERED.

Astrophysical Puzzles and Discoveries

Phenomenon	Puzzle	Physical discovery
QUASARS 1960	LARGE ENERGY PRODUCTION	BLACK HOLES
PULSARS 1967	PERIODIC SIGNAL	NEUTRON STARS
ATMOSPHERIC AND SOLAR NEUTRINOS	NEUTRINO DEFICIT	NEUTRINO OSCILLATIONS
NEUTRINOS FROM SN 1987A	GOOD AGREEMENT WITH NOT PERFECT THEORY	GRAVITATIONAL COLLAPSE

Greatness of False Discoveries

Cygnus X-3

VHE (≥ 1 TeV) and UHE (≥ 0.1—1 PeV) "gamma" radiation from Cyg X-3 was observed in 80s by many detectors: *Kiel, Haverah Park, Fly's Eye, Akeno, Baksan, Tien-Shan, Ooty, Gulmarg, Plateu Rosa, Crimea, Dugway, Whipple …*

Underground muon signal was also detected:

NUSEX, Soudan, MUTRON

In 1990-1991 *CASA* and *CYGNUS* put upper limits, which excluded early observations.

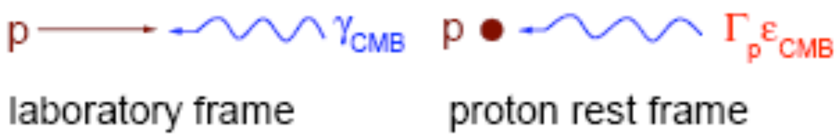
Impact on theoretical astroparticle physics:

- High energy astrophysics with new particles: production, detection and general limits.
- Acceleration in binary systems.

UHE COSMIC RAY PUZZLE

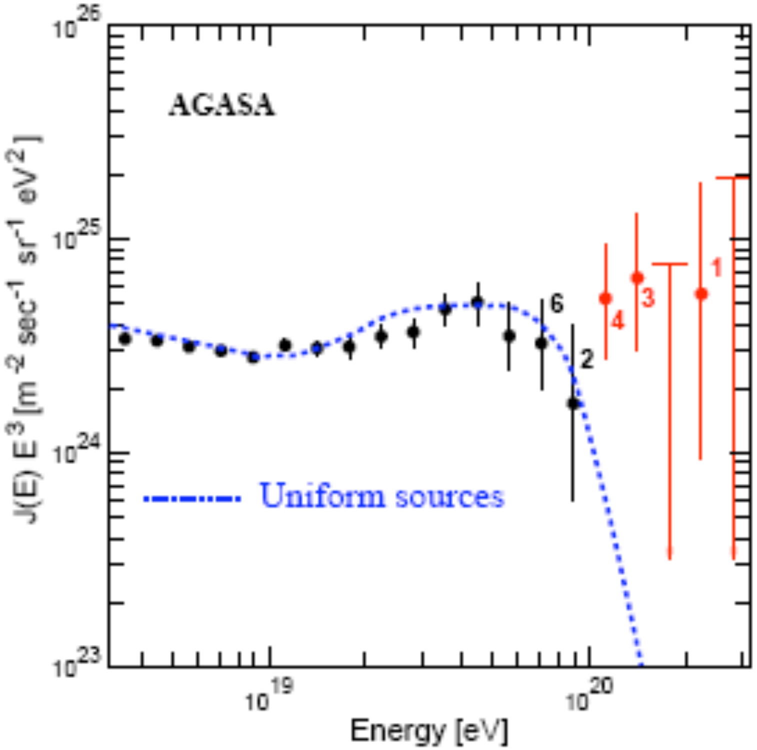
Undiscovered *Greisen-Zatsepin-Kuzmin* (GZK) cutoff (1966)

$$p + \gamma_{\rm CMB} \rightarrow N + \pi$$



$$\Gamma_p \, \varepsilon_{\rm CMB} \sim 140 \text{ MeV},$$

$$E_{\rm GZK} \sim (3 - 5) \times 10^{19} \text{ eV}$$



AGASA (1990 - 2003)

No viable astrophysical solution to 'AGASA excess' was found

SOLUTIONS WITH NEW PHYSICS

motivated by AGASA excess at $E \geq 1 \times 10^{20}$ eV

- **SUPERHEAVY DARK MATTER** ($X \to$ hadrons)

$$M_X > 10^{12}\ \text{GeV}, \quad \tau_X > 10^{10}\ \text{yr}$$

  No radically new physics involved, fits the data

- **RESONANT NEUTRINOS (Z-BURSTS)**

$$\nu + \bar{\nu}_{\text{DM}} \to Z^0 \to \text{hadrons}$$

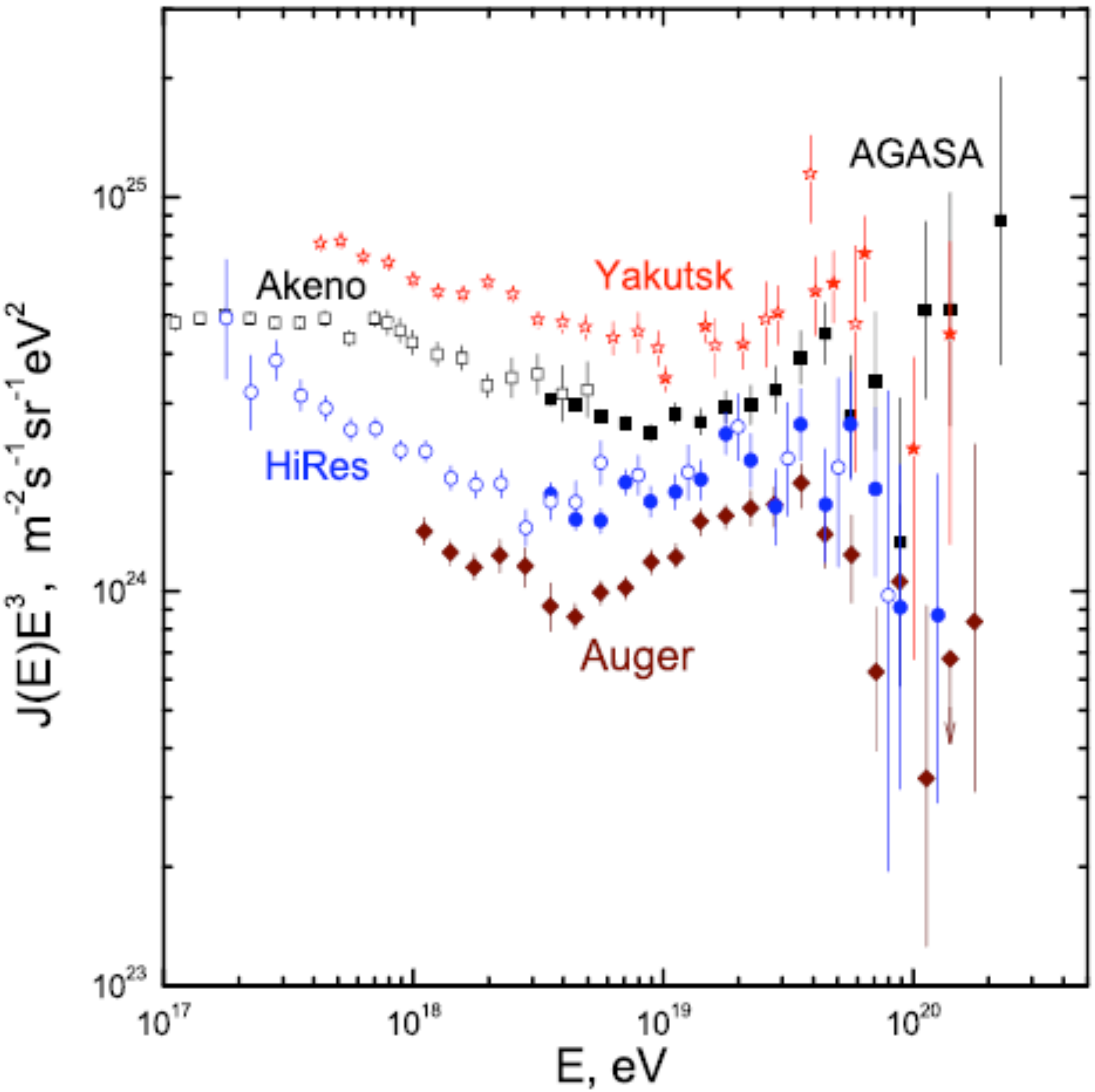
  Excluded: too high flux of neutrinos required

- **TOPOLOGICAL DEFECTS**
  Reliable physics, weak GZK cutoff, disfavoured.

- **NEW PARTICLES**
  Strongly interacting neutrino, light (quasi)stable hadron (e.g. glueballino $\tilde{g}g$), mirror neutrons: not excluded.

- **LORENTZ INVARIANCE VIOLATION**
  Most radical proposal: fits the data.

MEASURED FLUXES OF UHECR



Propagation Signatures

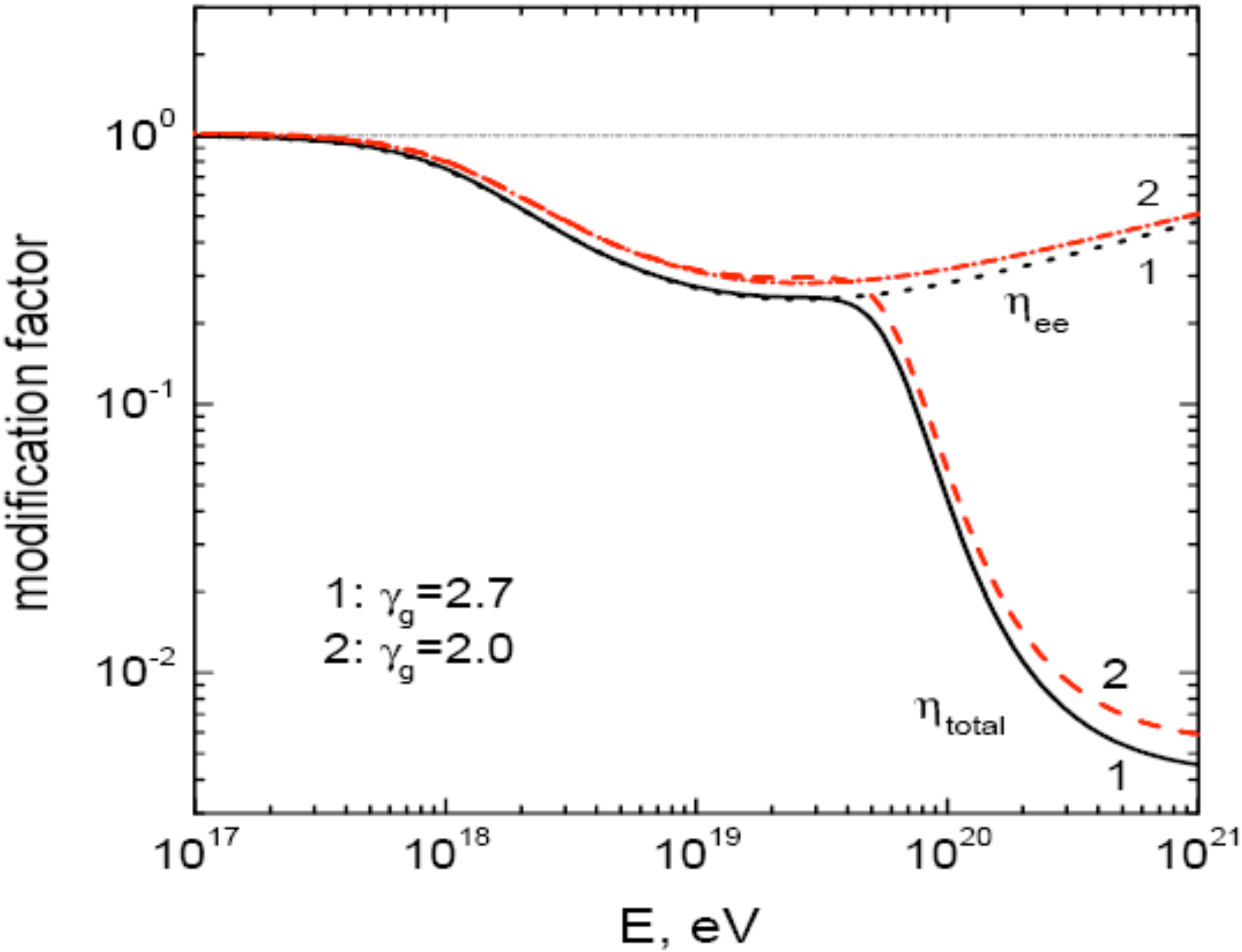
Propagation of protons through CMB in intergalactic space leaves the imprints in the spectrum in the form of the dip (due to $p + \gamma_{CMB} \to p + e^{+} + e^{-}$) and GZK cutoff (due to $p + \gamma_{CMB} \to N + \pi$).

These features are convenient to analyze with help of modification factor

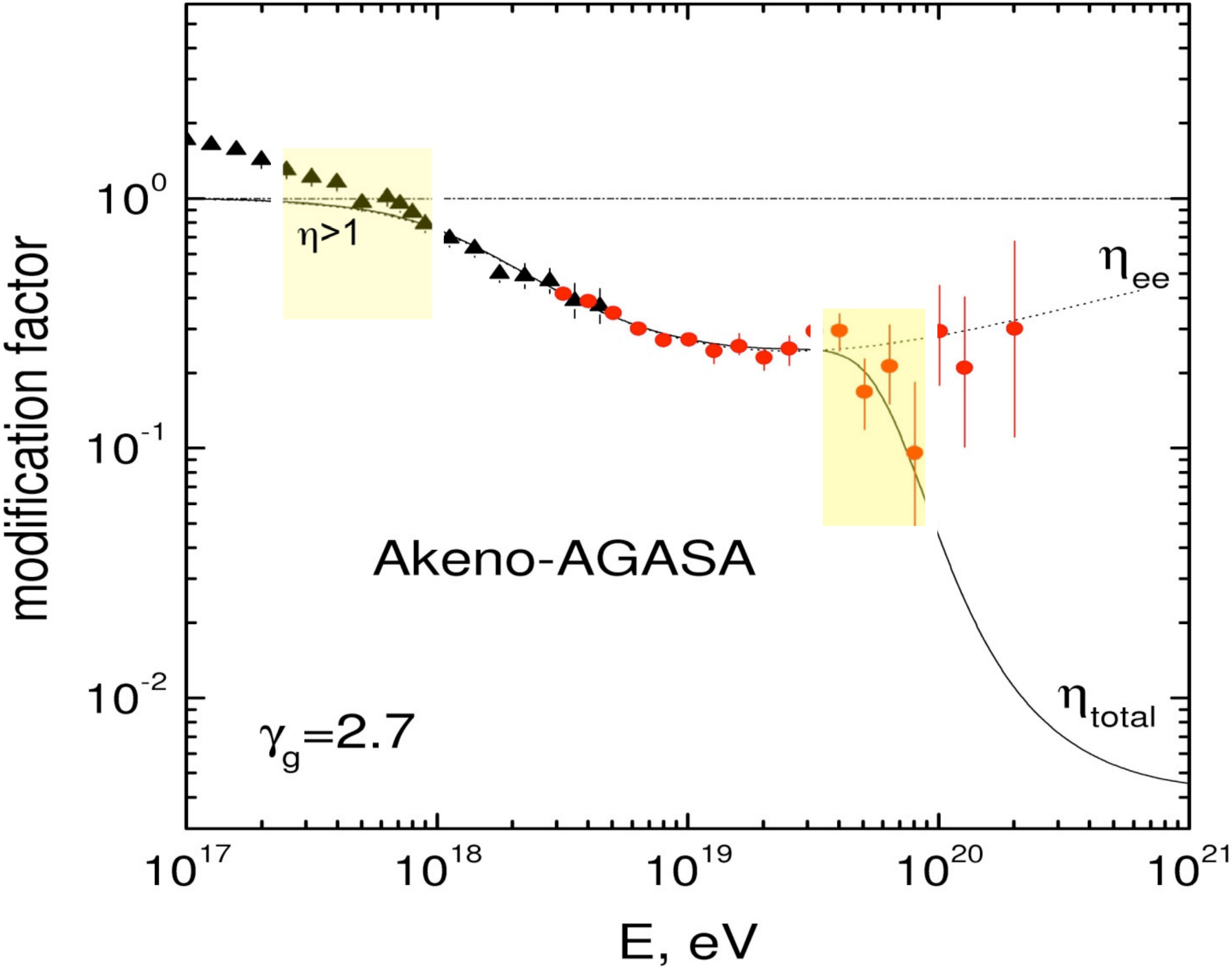
$$\eta(E) = \frac{J_p(E)}{J_p^{\rm unm}(E)}$$

Here $J_p(E)$ includes total energy losses and $J_p^{unm}(E)$ only adiabatic energy losses (redshift).

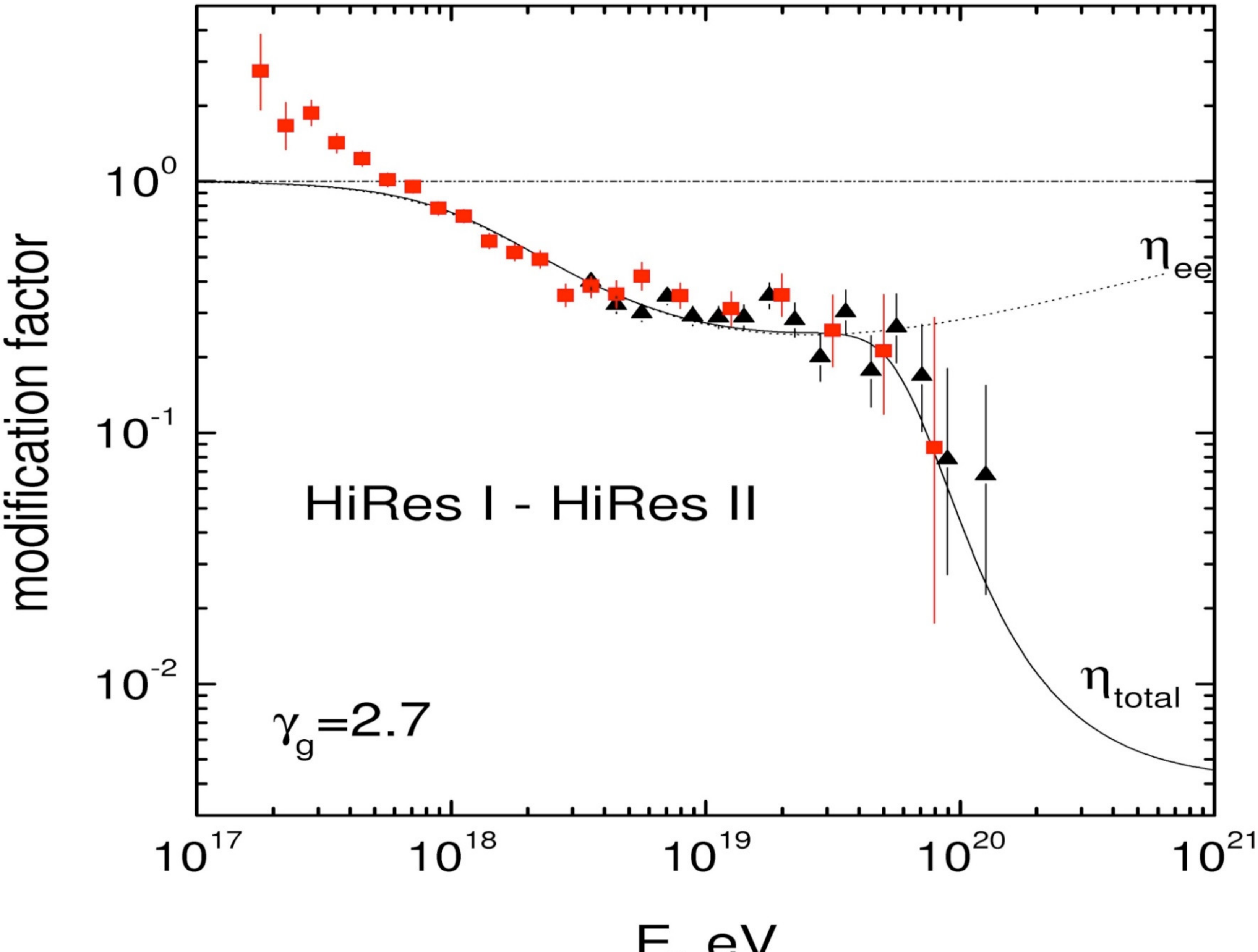
Dip and GZK Steepening in Diffuse Spectrum



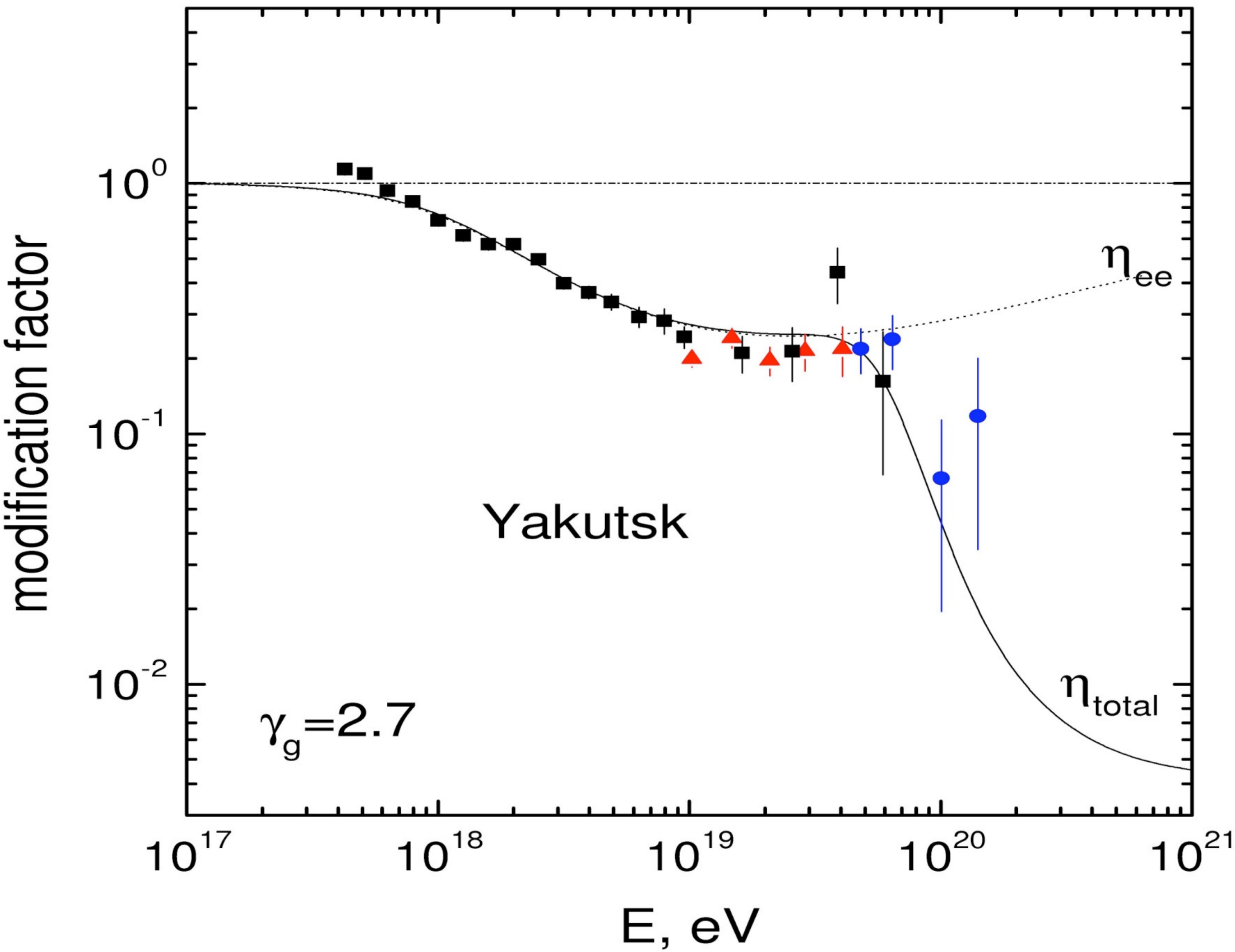
Dip in Comparison with Akeno-AGASA Data



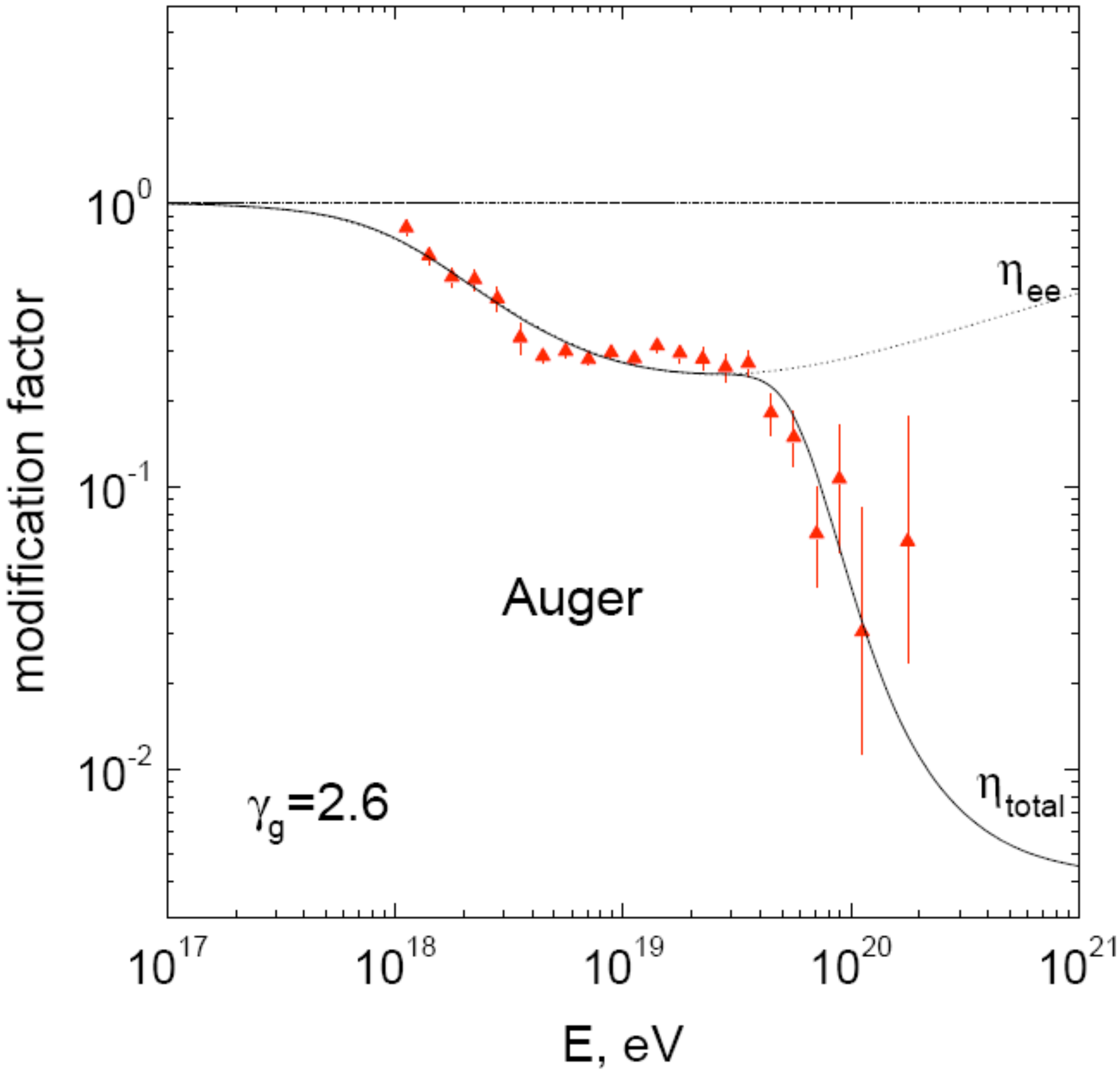
Dip in Comparison with HiRes Data



Dip in Comparison with YAKUTSK Data



Dip in Comparison with Auger 2007 Data



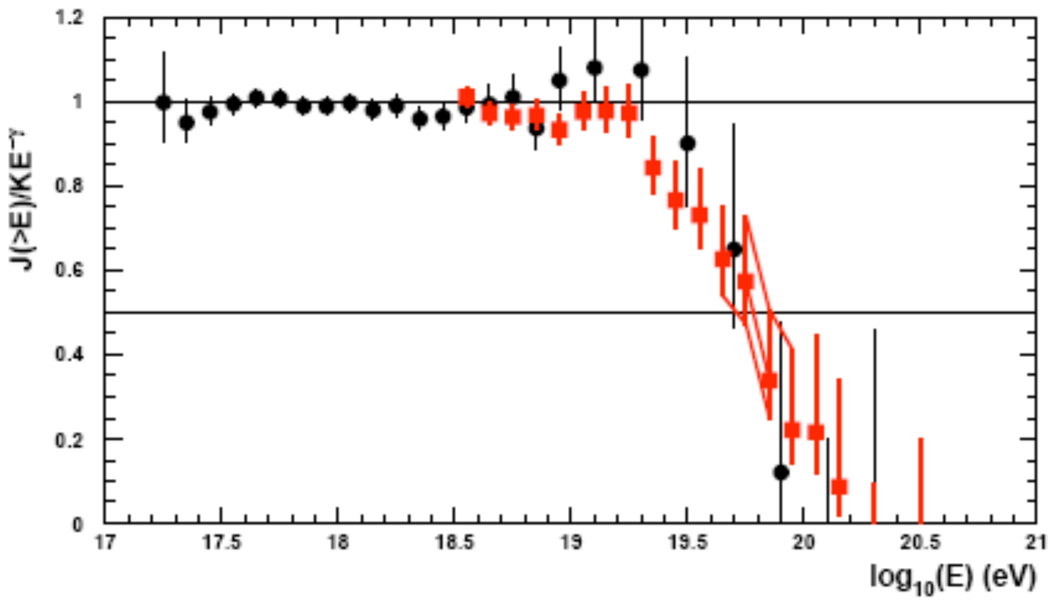
GZK Cutoff in HiRes Data

In the integral spectrum GZK cutoff is numerically characterized by energy $E_{1/2}$ where the calculated spectrum $J(>E)$ becomes half of power-law extrapolation spectrum $KE^{-\gamma}$ at low energies. As calculations (V.B.&Grigorieva 1988) show

$$E_{1/2} = 10^{19.72} \text{ eV}$$

valid for a wide range of generation indices from 2.1 to 2.8. HiRes obtained:

$$E_{1/2} = 10^{19.73 \pm 0.07} \text{ eV}$$

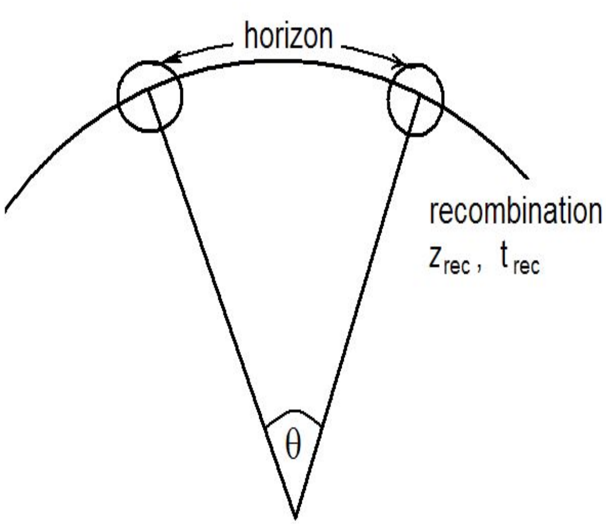


COSMOLOGICAL PUZZLES

IN THE PAST AND PRESENT

The expanding Friedmann solution of the Einstein equation has horizon and flatness problems.

Horizon problem



CMB decouples from matter after recombination ($z_{rec} \approx 1100$, $t_{rec} \approx 1.2\times10^{13}$ s). The regions separated by the horizon size ct_{rec} are seen at angle $\Theta \approx (1+ z_{rec})ct_{rec} /ct_0$.

They cannot have equal temperatures, and CMB cannot be isotropic on the scale $\Theta>2°$.

Flatness problem

Why universe is flat now?
Within Friedmann regime because of initial condition at $t_{Pl} \sim 1/m_{Pl}$.
To have $\Omega -1 \sim O(1)$ now it is necessary to have $\Omega -1 \sim \xi$ at $\xi \sim 10^{-30}$.

Inflation as a Solution

A. Guth, K. Sato, A. Linde, P. Steinhardt

Einstein equation and energy conservation result in equations

$$\begin{aligned} \dot{a}^2(t) &= \frac{8\pi}{3} G a^2(t) \rho \\ \ddot{a}(t) &= \frac{4\pi}{3} G (3\rho + p) a(t) \\ \dot{\rho} &= -3H(p + \rho) \end{aligned}$$

For matter with equation of state $p=-\rho$ and $\rho=\rho_0$ realized e.g. for scalar field φ rolling down in flat potential

$$a(t) = a_0 e^{H_0 t} \quad \text{with} \quad H_0^2 = \frac{8\pi}{3} G \rho_0$$

an initial bubble expands exponentially and it solves the problem of horizon and flatness.

- The whole universe is produced from one causally connected bubble
- $1-\Omega \sim \exp(-Ht)$ provides $\Omega = 1$ at all t. At the end of inflation $1 - \Omega = \varepsilon$ with ε exponentially small.

Where Is Dark Matter
and
Why Is There Dark Energy?

WMAP-07 ΛCDM best fit:

H_0 = 73.2 km/s Mpc , $\Omega_{tot} = 1 + \Omega_k$, $\Omega_k = -0.011 \pm 0.012$
$\Omega_b = 0.0416$, $\Omega_m = 0.238$, $\Omega_\Lambda = 0.716$

Indirect evidence for DM

- $\Omega_m \gg \Omega_b$ (***WMAP***: height of 3d peak is too low without DM)
- Virial mass in galaxies $M_{vir} \gg M_b$
- Theory of LSS formation (hierarchical clustering model)

Direct search for DM

- Observation of modulation signal by ***DAMA***

Alternative explanation

- Modified theory of gravitation at low acceleration
  $a < a_0 \sim 10^8\ cm^2/s$ (***MOND***)

TeVeS Gravity (*Bekenstein 2004*)

- Three gravity fields: $g_{\mu\nu}$, U_{μ} , φ
- One non-dynamical field: σ
- Two dimensional constants: G and l
- Two dimensionless constants: k and K

l and K define the critical acceleration a_0

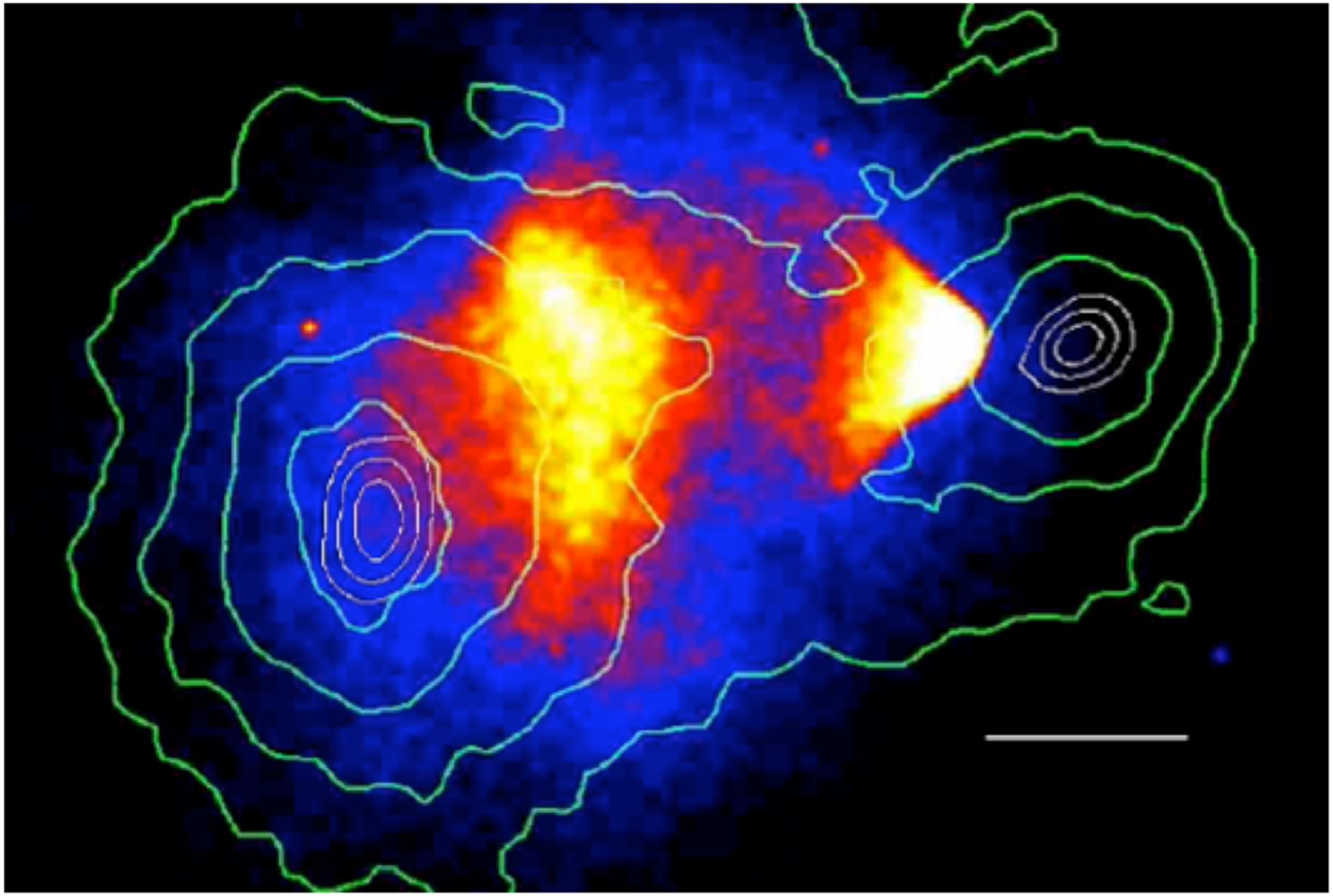
As asymptotic *TeVeS* gives general relativity and Newtonian gravitation and at $a<a_0$ *MOND*

This theory successfully describes (with baryonic matter only): flat rotation curves, high velocities in clusters and lensing . Recently *Dodelson et al* 2006 have demonstrated that galaxy formation can be also explained.

However:
If $\Omega_{CDM} = 0$ the third acoustic peak in *WMAP* would be much lower than observed.

Bullet Cluster 1E0657-558

Weak lensing and X-ray observation



Gravitational potential is not centered by X-ray emitting plasma, which is dominant baryon component ($M_{gas}/M_{gal} \sim 5 - 7$).

Accelerated Expansion of the Universe

Einstein equation
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -8\pi G T_{\mu\nu} + \Lambda g_{\mu\nu}$$
$$= -8\pi G (T_{\mu\nu} - \rho_{\rm vac} g_{\mu\nu})$$

l.h.s. is represented by geometry, r.h.s. by energy density of matter or gravitating fields.

Accelerated expansion can be obtained due to r.h.s. terms as Λ and by dark energy fluid in $T_{\mu\nu}$,

or

by modification of l.h.s. (i.e. gravity equation) .

Priority should be given to lambda term. WMAP data are analyzed in terms of ΛCDM model.

The best fit :

$h = 0.73$, $\Omega_{tot} = 1.0$, $\Omega_b = 0.042$, $\Omega_m = 0.24$, $\Omega_\Lambda = 0.72$.

Λ-term

"Λambda term was introduced first by Einstein, who later took back his proposal. This is a pity. Otherwise he could become famous."

Rocky Kolb.

Λ-term describes the time-invariable vacuum energy ρ_{vac}. It corresponds to the equation of state $p = -\rho$ and $\rho = \rho_{vac} = const$.

When density of matter $\rho_m(t)$ in the expanding universe falls down below ρ_{vac}, universe expands exponentially like in case of inflation

$$a(t) = a_0 \exp(H_0 t)$$

Vacuum-Energy Problem

Λ-term implies vacuum energy

$\rho_\Lambda = \Lambda/8\pi G = \Omega_\Lambda \rho_c = 4\times10^{-47}$ GeV^4 (for Ω_Λ=0.73)

ρ_Λ could be given by energy density of some exotic field(s) σ plus zero-modes of all known particles i. Taking them as quantum oscillators with ground–state energy $\omega/2$,

$$\rho^{(i)}_{\rm vac} = \int_0^{k^i_{\rm max}} \frac{d^3k}{(2\pi)^3}\,\frac{\omega_k}{2}$$

one obtains

$$\rho_\Lambda = \rho_\sigma + \sum_i \rho^{(i)}_{\rm vac} \qquad (1)$$

For example, reliably known quark-gluon condensate energy

$\rho^{\rm QCD}_{\rm vac} \approx 0.03\ {\rm GeV}^4$ is 45 orders of magnitude larger than ρ_Λ (*Dolgov*).

(1) needs unnatural compensation to very small (or zero) value of ρ_Λ.
This is very general problem for all kinds of vacuum energy.

ACCELERATED EXPANSION: MODELS

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -8\pi G \left(T_{\mu\nu} - \rho_{\text{vac}}\, g_{\mu\nu}\right)$$

Acceleration is described by:

1. Vacuum energy $\rho_\Lambda g_{\mu\nu}$ (Λ-term) ; equation of state $p = \omega\rho$ with $\omega = -1$ and $\rho = const$.
2. DE fluid in $T_{\mu\nu}$ term; equation of state $p = \omega\rho$ with $\omega < -1/3$.

It can be realized as:

- ultra-light scalar field rolling down the potential field (quintessence) *Wetterich* 1988, *Peebles & Vilenkin* 1999
- phantom (ghost field) with $\omega < -1$; K-essence, *Chaplygin* gas etc.

Observational data WMAP + SNLS + ($\Omega_{tot} = 1$) :

$\omega = -0.967 \pm 0.07$ favor Λ-term.

3. Modified gravity: modification of l.h.s. (no DE !) e.g. *Dvali et al* 2000 brane model.

Acceleration and Anthropic Approach

Why does acceleration start now?

Why Λ-term is zero or very small?

Why physical parameters are tuned to produce life, e.g. $3\ He^4 \Rightarrow {}_6C^{12}$ resonance?

These questions might have answers not in terms of physical principles, but because in a universe with "wrong" parameters there is nobody to measure them.

From Inflation to Anthropic Principle

Chaotic inflation naturally results in infinite number of universes.

Inflaton field φ with chaotic initial conditions results in self-regeneration process of inflation in different parts of unlimited (superhorizon) space. This process does not have beginning and continues without end.

There are at least two versions of this process: eternal inflation and quantum tunneling (creation of universes from nothing), or quantum fluctuations (space-time foam).

The values of φ and ρ_{vac} have different values in different universes with distribution $W(\rho_{vac})$. It may be peaked at $\rho_{vac} = 0$ or not, but observer exists only when ρ_{vac} is small enough or zero.

“In my book “Many worlds in one” I have written that in one of the infinite number of universes *Elvis Presley* is alive and continues singing his songs. Since that time my mailbox is overfilled: the Elvis’ fans are asking me to forward a letter to him”.

A. Vilenkin

CONCLUSIONS

From three puzzles existing until recently in astroparticle physics:

Where is GZK cutoff?
Where is dark matter?
Why ρ_{vac} is very small or zero?

we have answered to the first two:

- Interaction of protons with CMB is seen as a dip and beginning of GZK cutoff in the UHECR spectrum. HiRes confirms numerically the existence of GZK cutoff.

- The second problem most probably does not exist at all. DM is not seen in directly-search experiments either because sensitivity is still low or because DM particles are superweakly interacting (e.g. gravitino or SHDM particles).

MOND and TeVeS should be considered as interesting alternatives.

- Problem of $\rho_{vac} = 0$ or very small ($\sim 10^{-47}$ GeV^4) is the most serious puzzle of modern physics, but it could be a problem of elementary-particle physics, which predicts the zero-mode energy too high for cosmology. The most reliable case is

$$\rho_{vac}^{QCD} \approx 0.03\, GeV^4$$

Compensation in

$$\rho_\Lambda = \rho_\sigma + \sum_i \rho_{\rm vac}^{(i)}$$

is unnatural and can be found now only in the framework of anthropic theories of many universes.

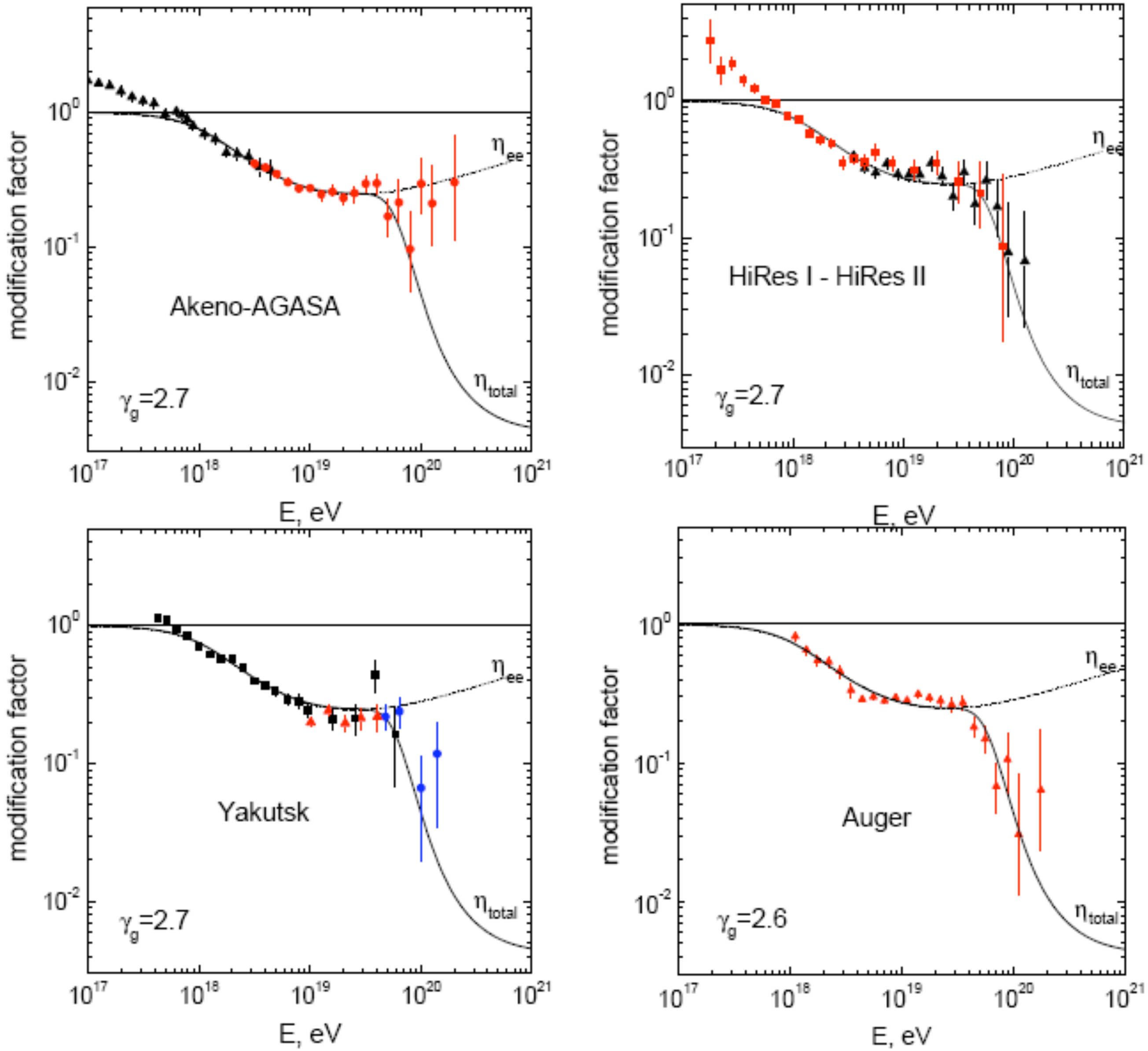
Is Nature Natural or Friendly?

V. Rubakov

Anthropic theory is one of the friendly solutions in physics.

Thank you!

Dip in Comparison with Data

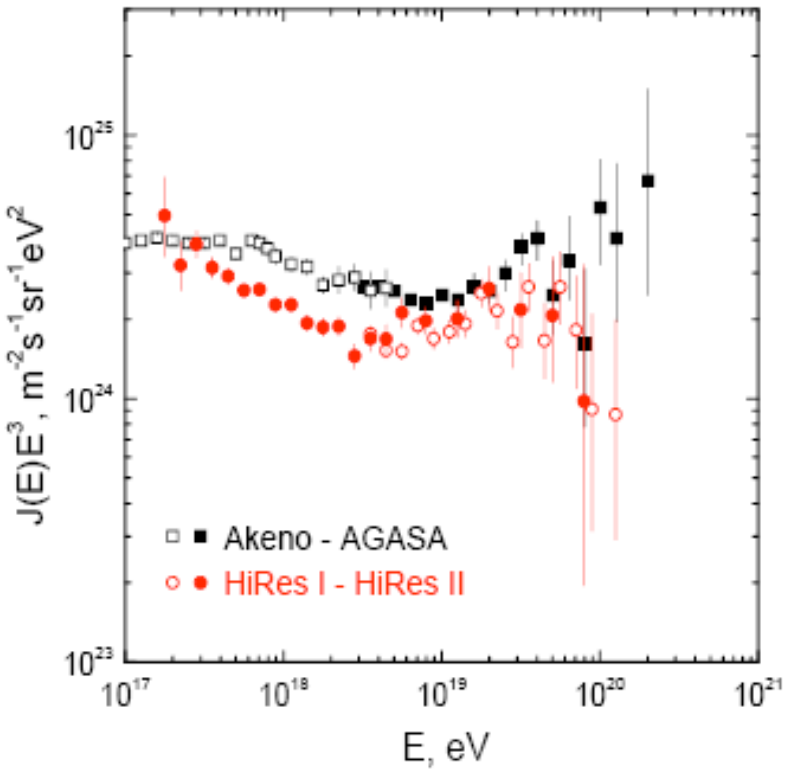


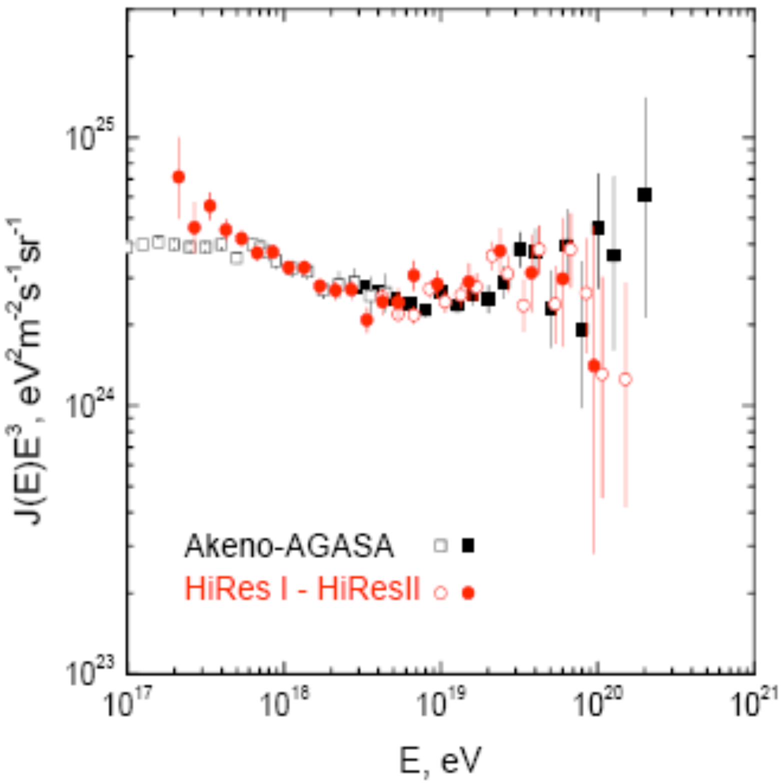
Energy Calibration by Dip

Energy shift $E \rightarrow \lambda E$ for each experiment independently to reach minimum of χ^2 in comparison with theoretical curve $\eta(E)$.

AGASA	$\lambda_{AG} = 0.9$
HiRes	$\lambda_{Hi} = 1.20$
Yakutsk	$\lambda_{Ya} = 0.75$

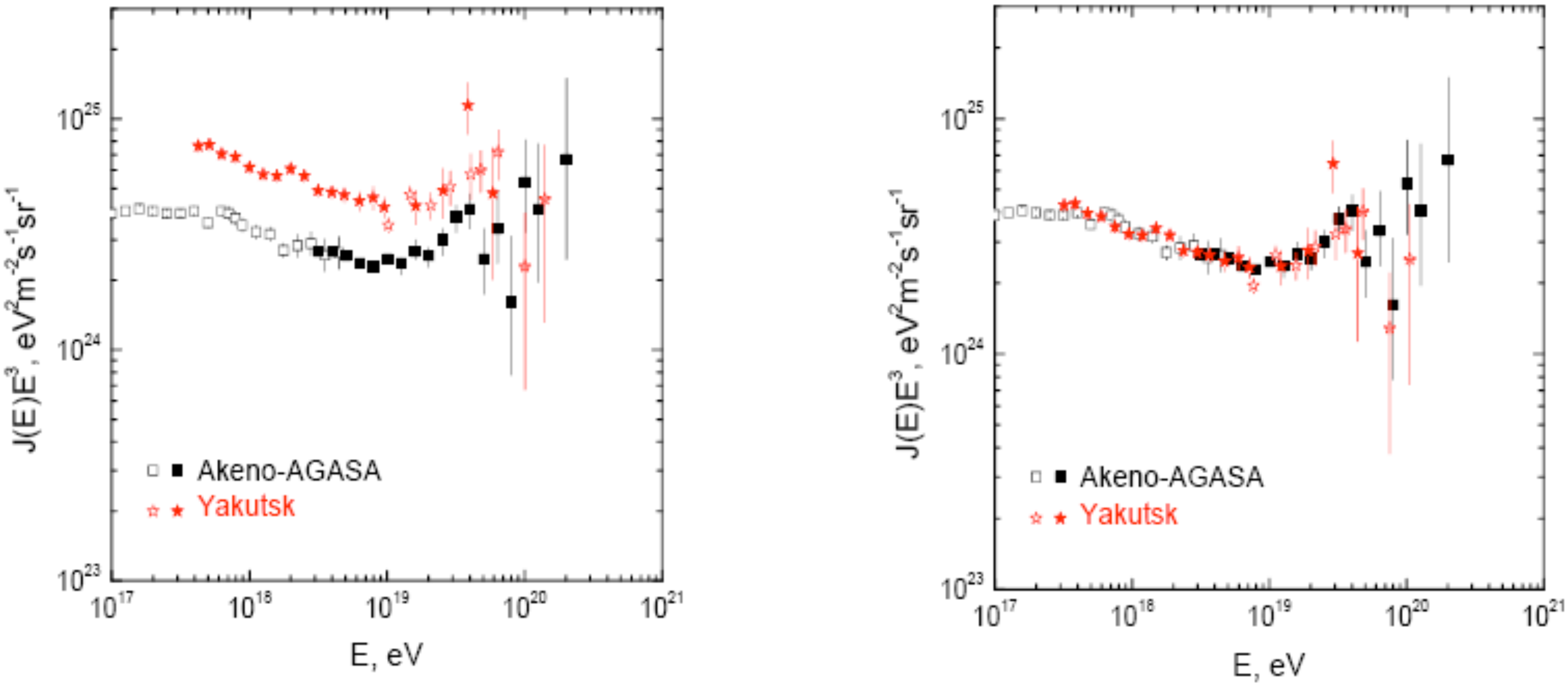
ENERGY CALIBRATION BY DIP : AGASA-HIRES DISCREPANCY





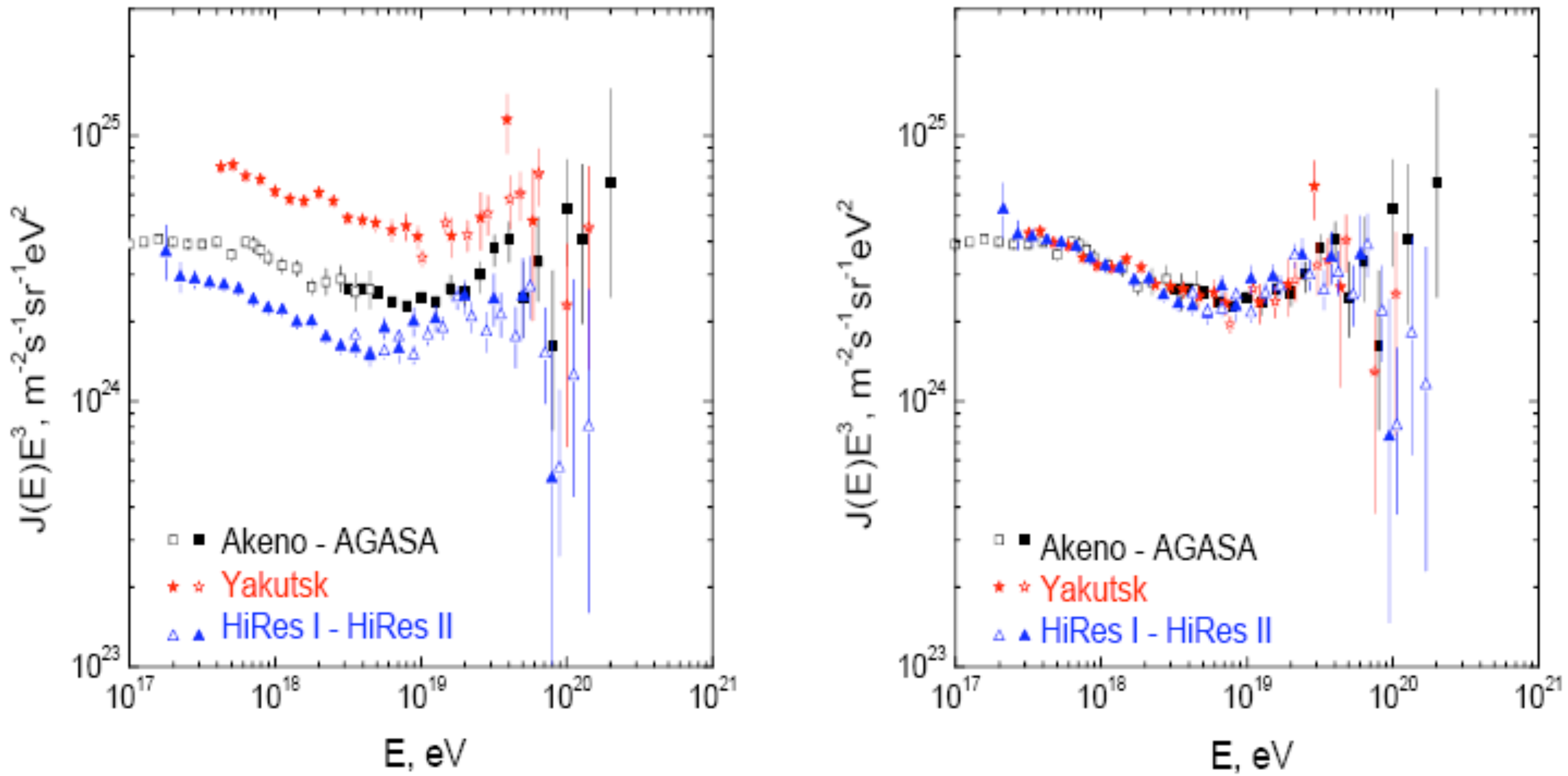
AGASA and HiRes spectra calibrated by the dip. The energy shift needed for $\chi^2_{\min}$ is $\lambda_{\rm AGASA} = 0.9$ and $\lambda_{\rm HiRes} = 1.2$. Both are allowed by systematic errors.

DIP AND AGASA-YAKUTSK DISCREPANCY



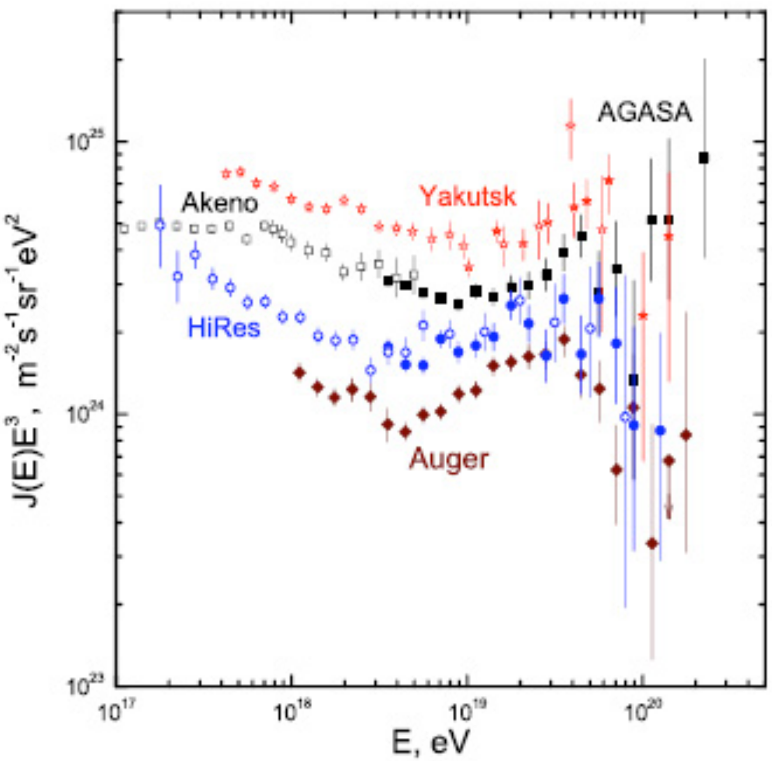
AGASA and Yakutsk spectra calibrated by the dip. The energy shift needed for $\chi^2_{\rm min}$ is $\lambda_{\rm AGASA} = 0.9$ and $\lambda_{\rm Yakutsk} = 0.75$. Both are allowed by systematic errors.

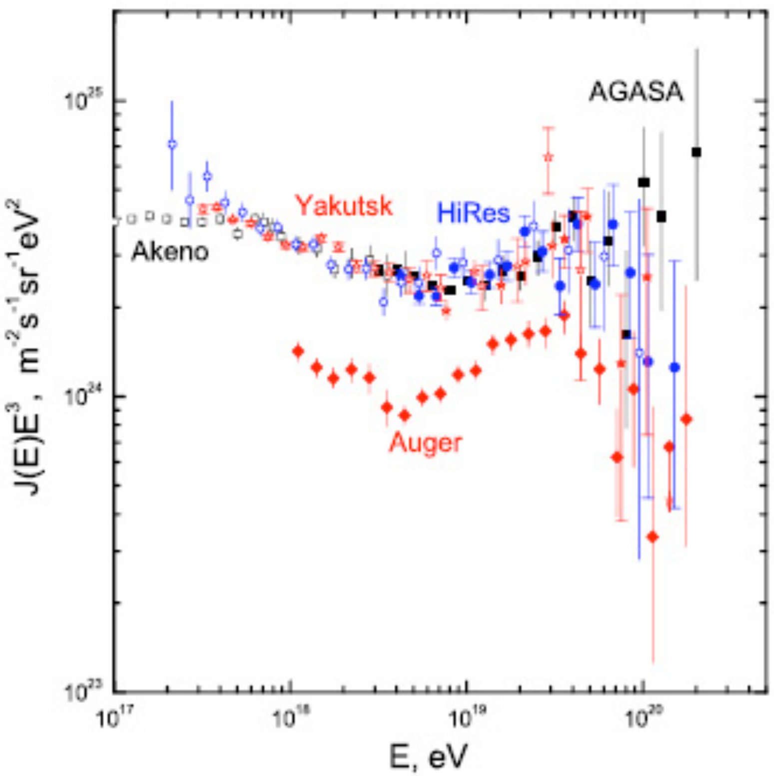
AGASA-HIRES-YAKUTSK DISCREPANCY



AGASA, Hires and Yakutsk spectra calibrated by the dip.

COMPARISON OF AUGER WITH CALIBRATED DATA





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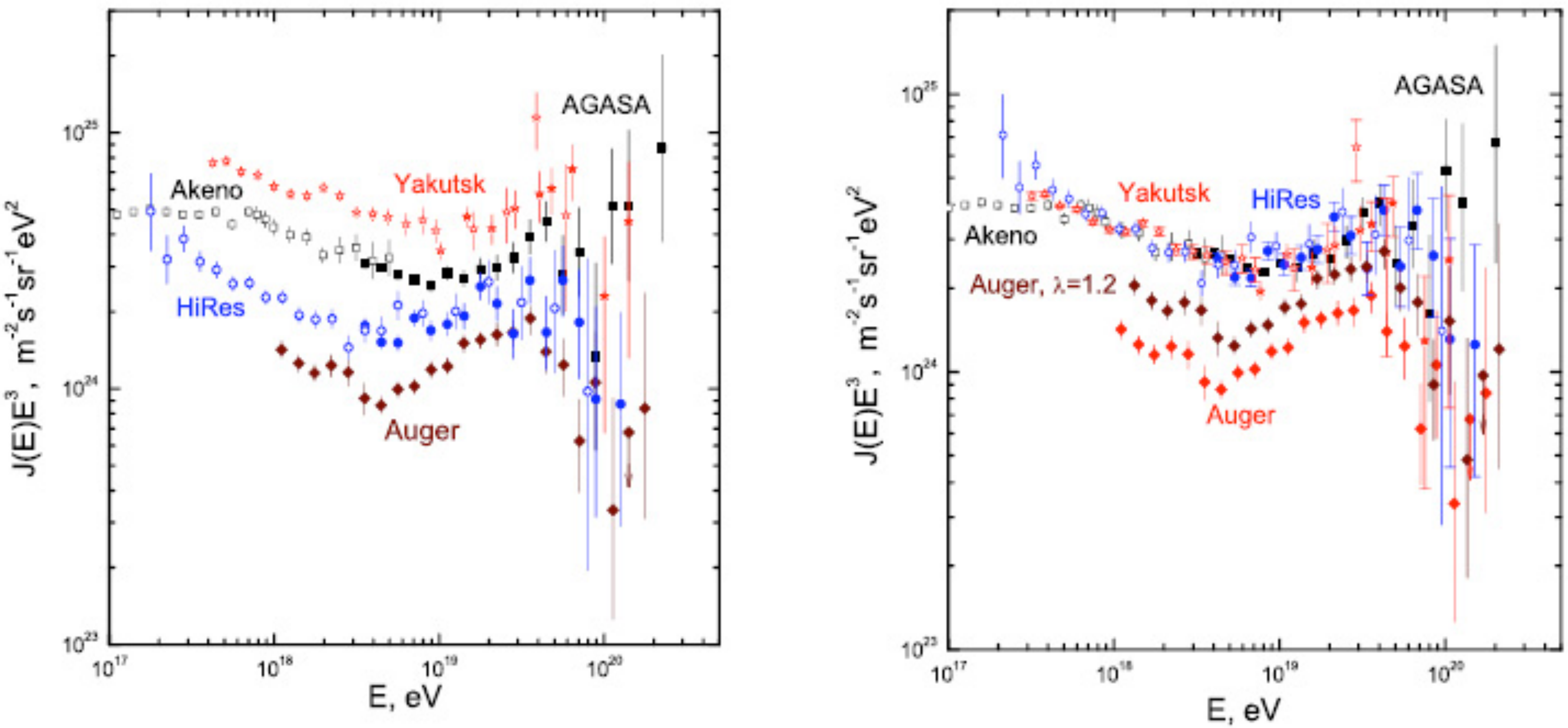


RE-EVALUATED AGASA SPECTRUM (2006)

Phenomenologically re-evaluation comes from two effects:

(i) Aperture (from MC simulation)

$A_{\rm old} = const$ **down to** 4×10^{18} **eV,** $A_{\rm new}(E)$ **at** $E \leq 1 \times 10^{19}$ **eV.**

(ii) Energy evaluation by the Hillas formulae.

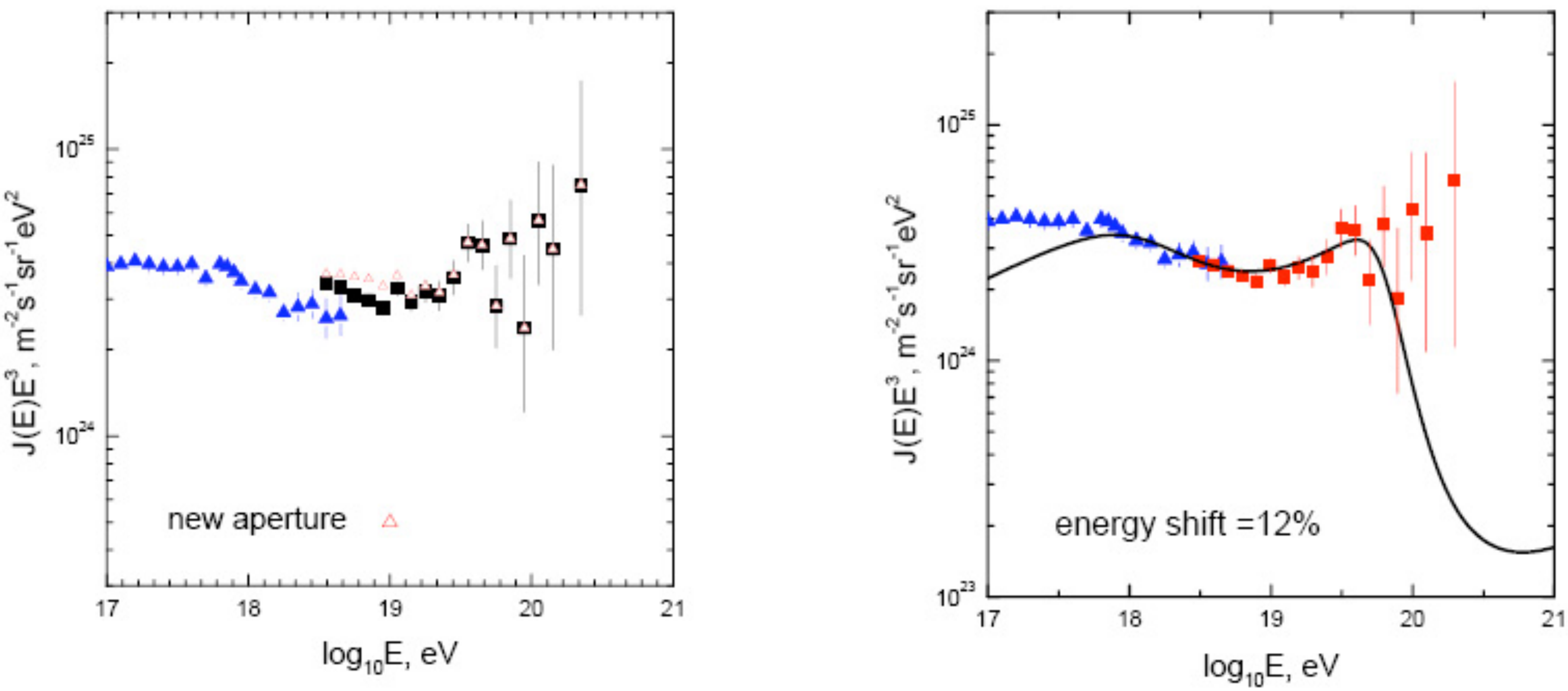
$$\mathbf{E} = \mathbf{a} \times \mathbf{10^{17} S_{600}^{b}}\ \mathrm{eV}$$

$a_{\rm old}$**=2.21,** $b_{\rm old}$**=1.03.**

$a_{\rm new}$**=1.89,** $b_{\rm new}$**=1.01.**

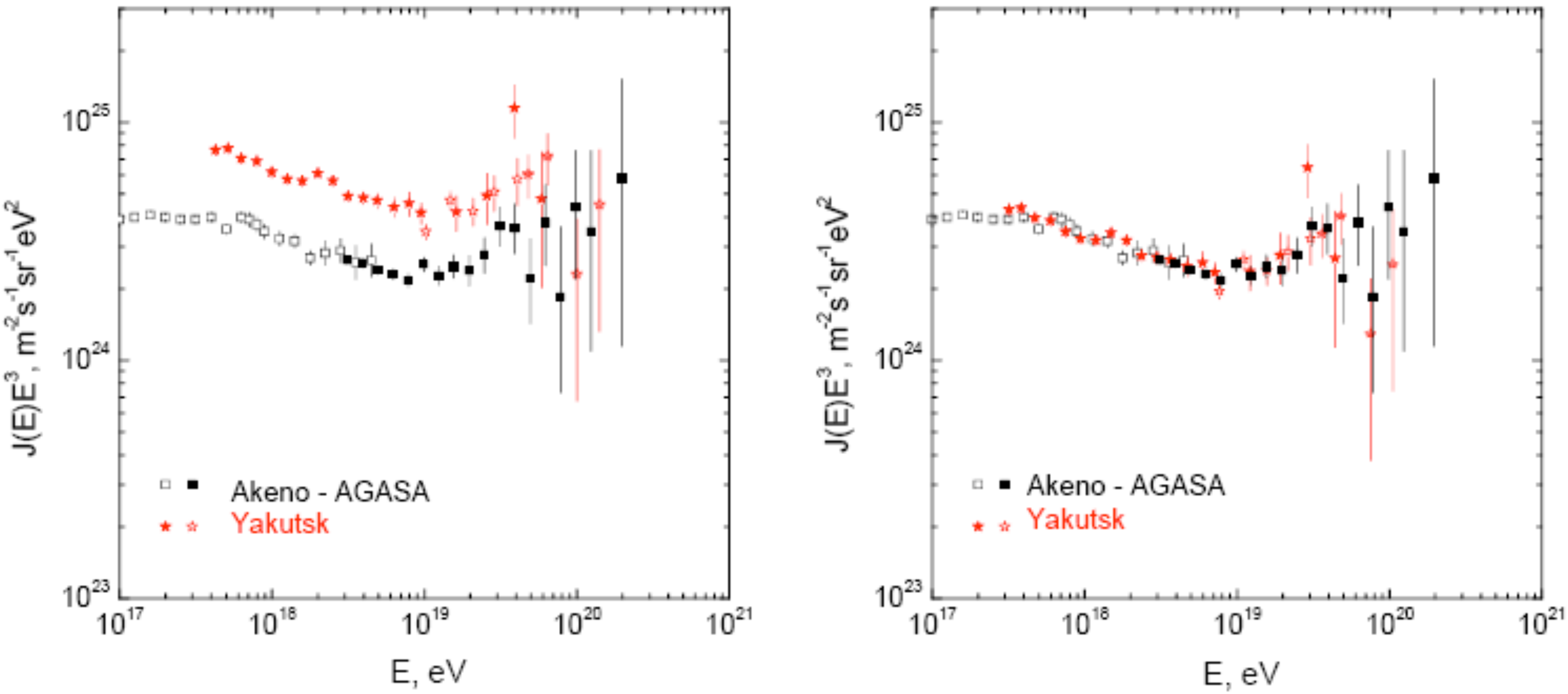
$E_{\rm new}$ (eV)	3×10^{18}	1×10^{19}	3×10^{19}	1×10^{20}	2×10^{20}
$E_{\rm new}/E_{\rm old}$	0.809	0.790	0.773	0.754	0.744

RE-ANALYSED AGASA DATA (2006)



AGASA data corrected by the new aperture (left panel) and AGASA data with new aperture shifted by $\lambda_A = 0.88$ (right panel).

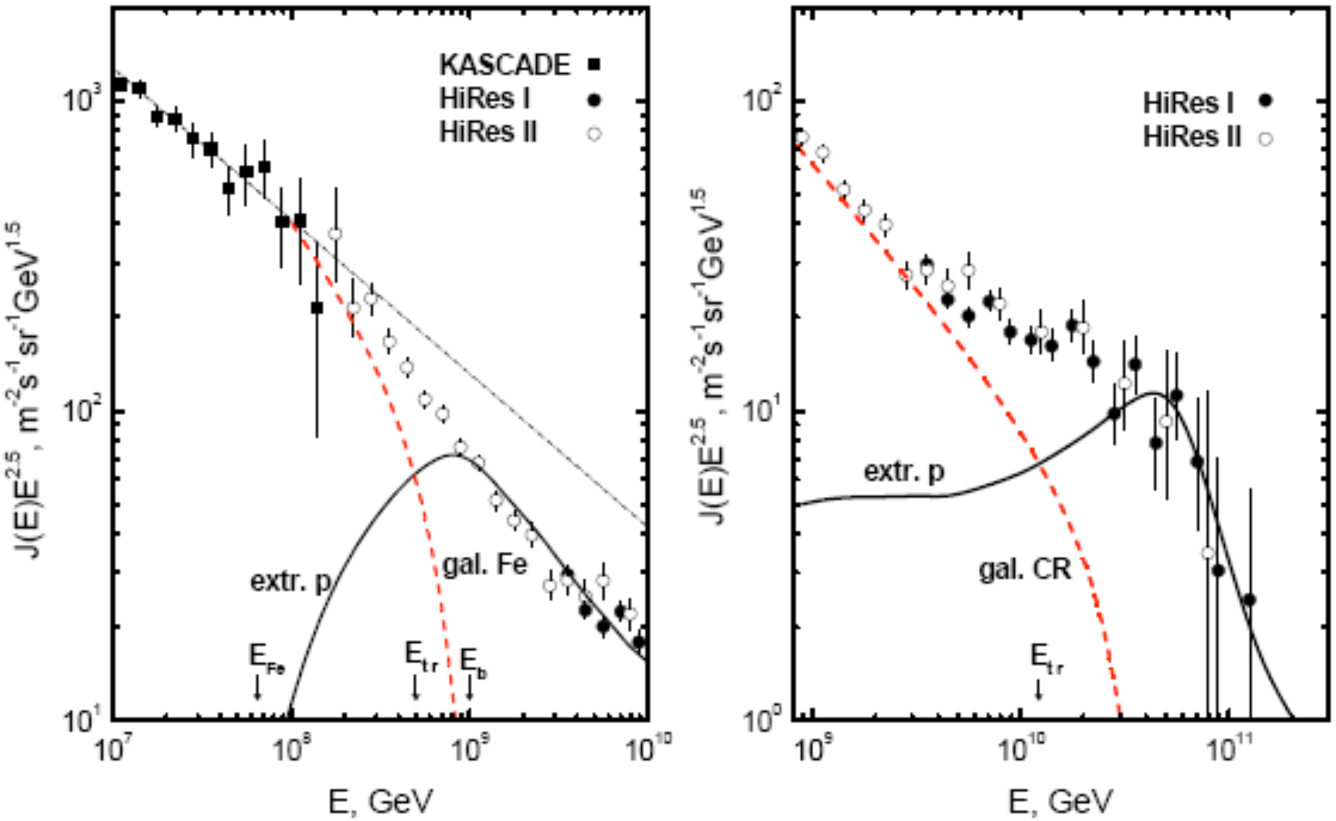
AGASA and YAKUTSK DATA before and after ENERGY SHIFT



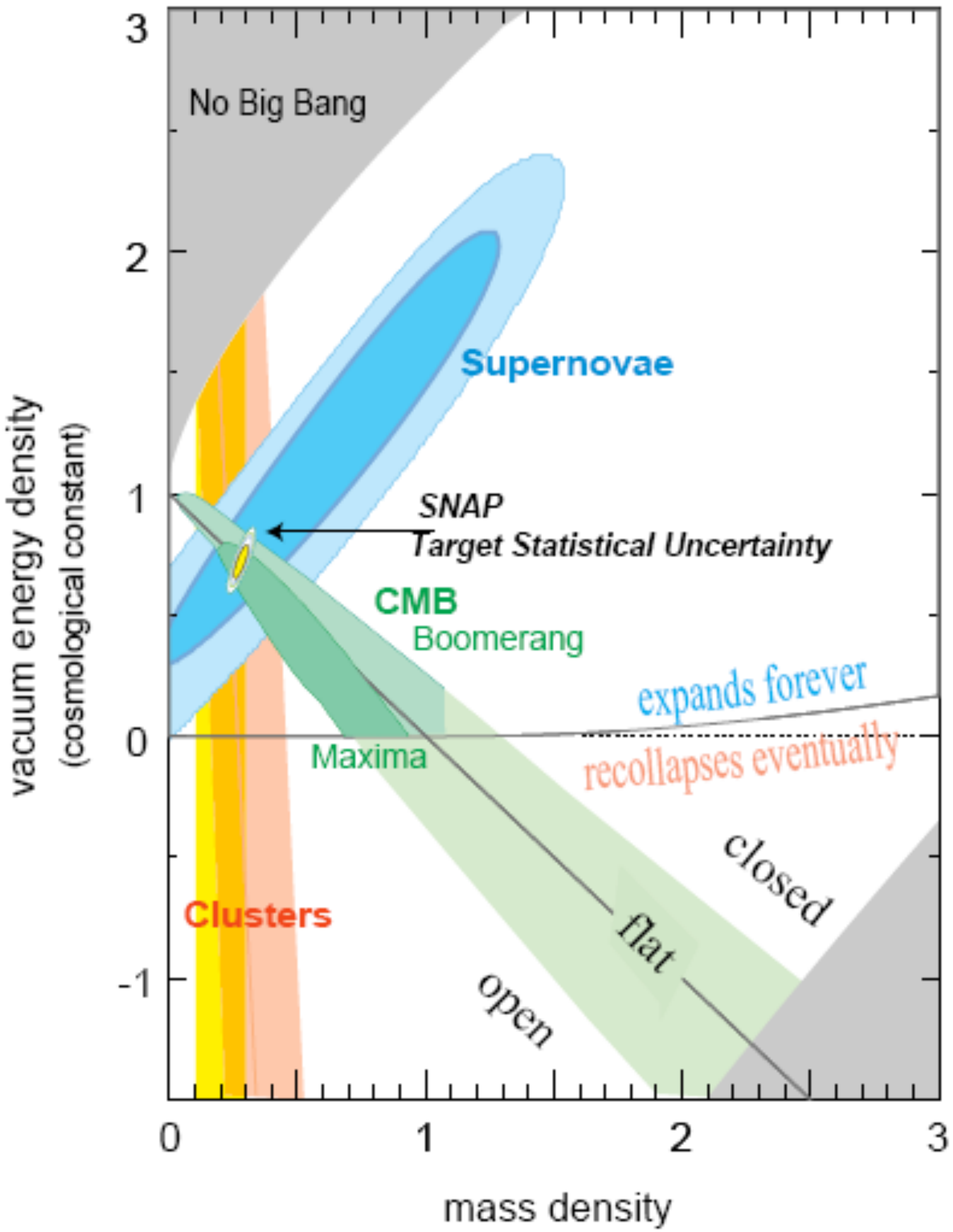
THE DIP and ANKLE TRANSITIONS

In the dip model transition occurs at $E_{\rm tr} < E_b = 1 \times 10^{18}$ eV, i.e. at second knee. This transition agrees perfectly with the standard galactic model.

In the ankle model transition occurs at $E_a = 1 \times 10^{19}$ eV and the galactic flux at this energy is half of the total in contradiction with standard galactic model.

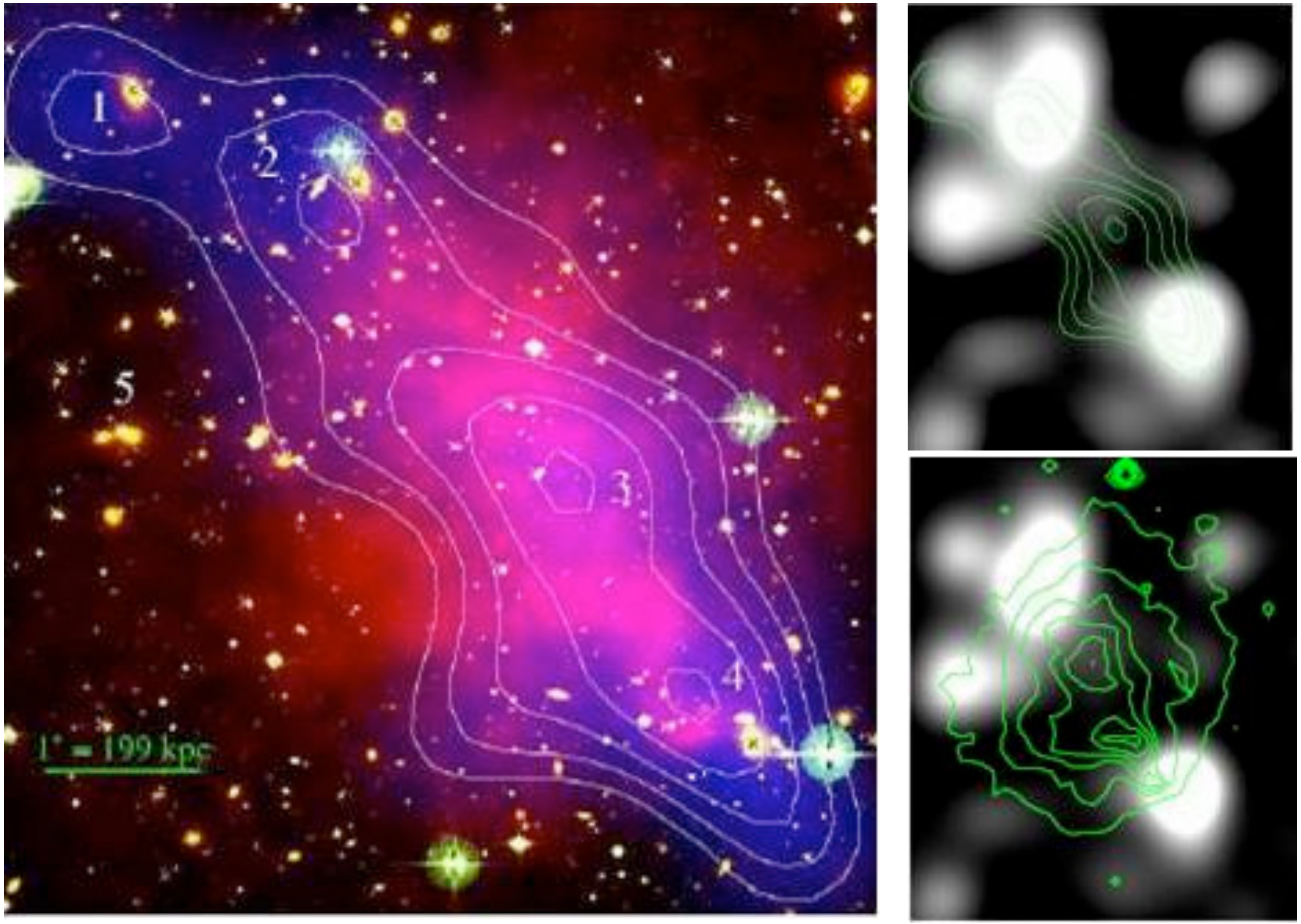


Λ-Term Data



No Big Bang
Supernovae
SNAP
Target Statistical Uncertainty
CMB
Boomerang
Maxima
expands forever
recollapses eventually
closed
flat
open
Clusters
vacuum energy density
(cosmological constant)
mass density
3
2
1
0
-1
0
1
2
3

Abell 520



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