Ultra High Energy Cosmic Rays: status of the problem

U l t r a H i g h E n e r g y \ \ C o s m i c R a y s

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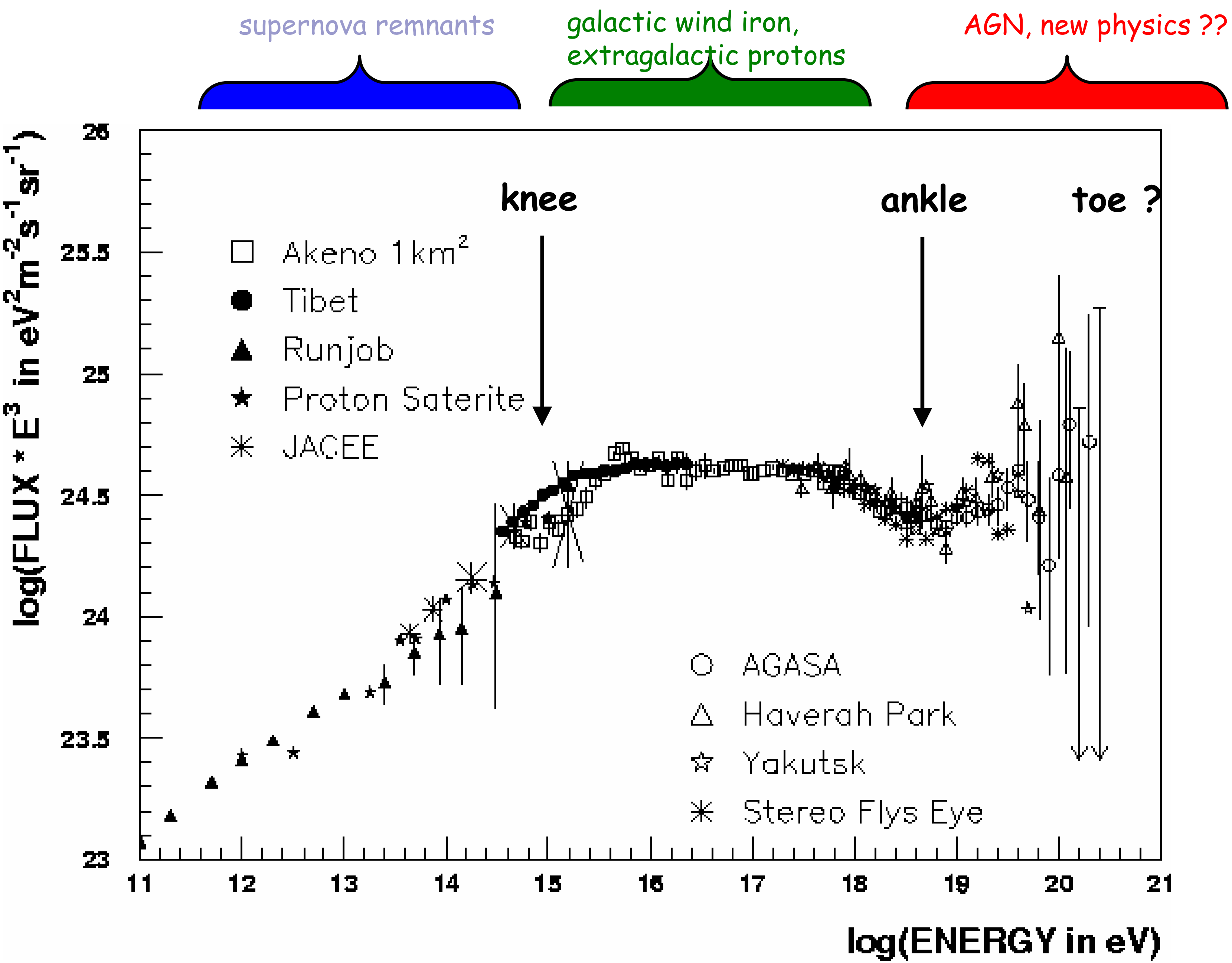
Overview:

- *Introduction: UHECR*
- *Experimental situation:*
  - *Spectrum*
  - *Large scale isotropy*
  - *Small scale clustering*
  - *Composition*
  - *Gamma-ray and neutrino fluxes*

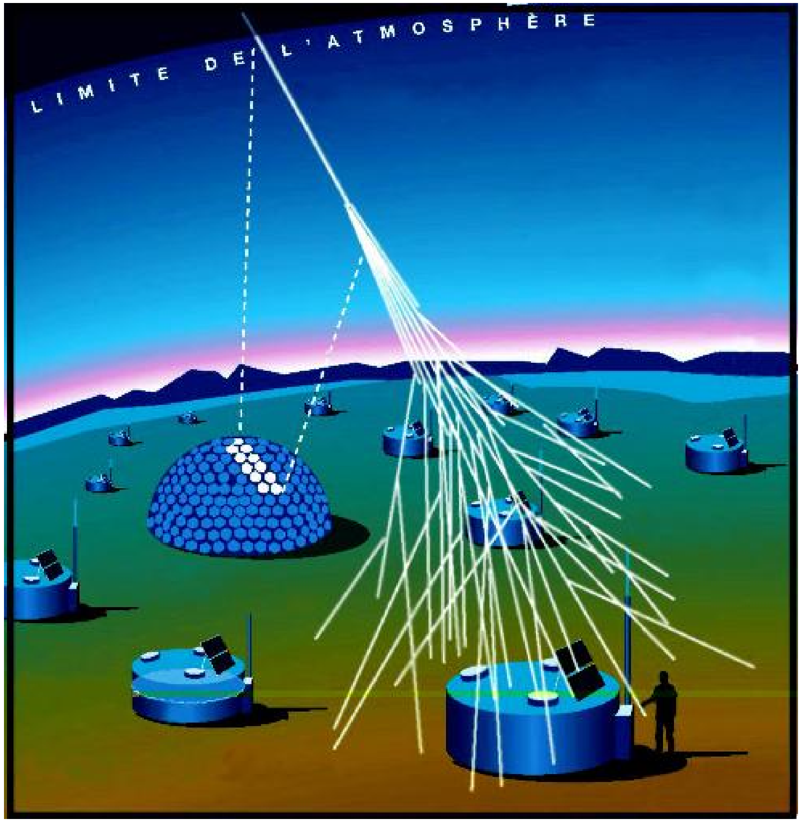
- *UHECR puzzles*
- *Most favorite theoretical models*
- *Conclusion*

INTRODUCTION


supernova remnants
galactic wind iron,
extragalactic protons
AGN, new physics ??
knee
ankle
toe ?
Akeno 1km^2
Tibet
Runjob
Proton Saterite
JACEE
AGASA
Haverah Park
Yakutsk
Stereo Flys Eye
log(FLUX * E^3 in eV^{2}m^{-2}s^{-1}sr^{-1})
26
25.5
25
24.5
24
23.5
23
11
12
13
14
15
16
17
18
19
20
21
log(ENERGY in eV)

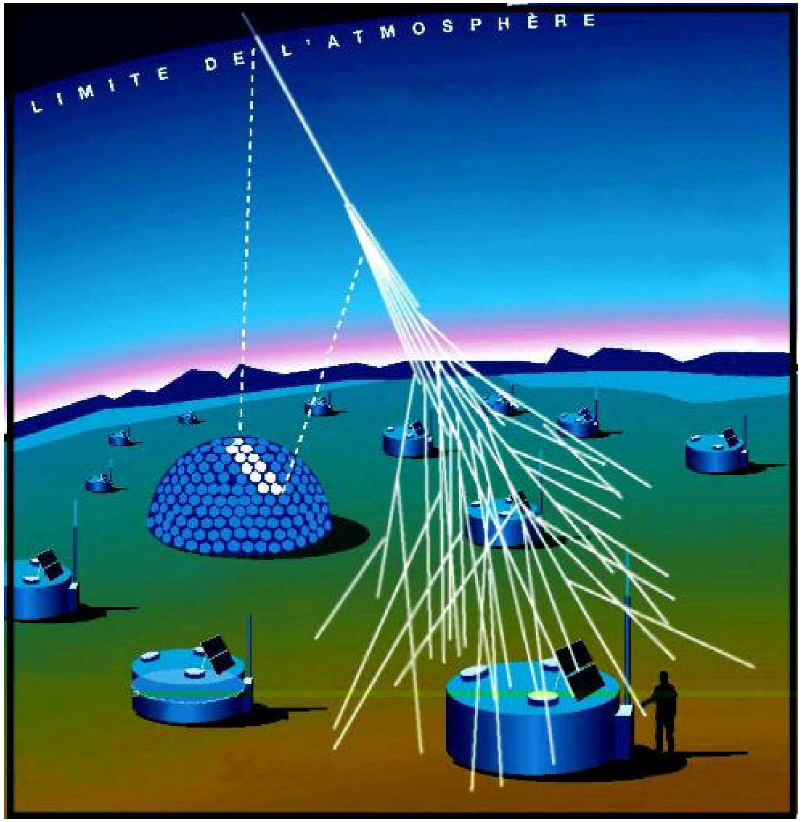
UHECR measurement

- Depth of atmosphere is 900-1200 g/cm^2
- Proton of 10^{19-20} eV energy interact within 80 g/cm^2. Center mass energy is 300 TeV: much larger then LHC!
- Shower develops with final number 10^{10-11} of low energy particles.



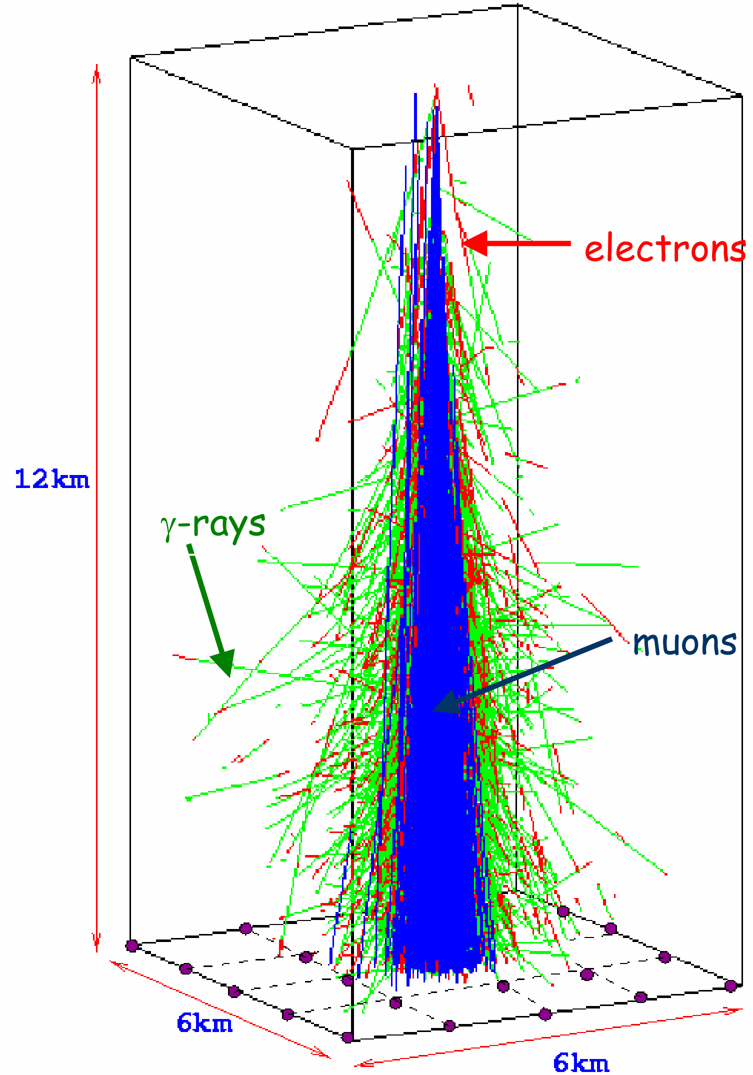
Parameters to measure:

- Energy of primary particle
- Arrival direction.
- Type of primary particle (proton, nuclei, photon, new particle)
- Properties of primary particle: total cross section, type of interaction for new particles.



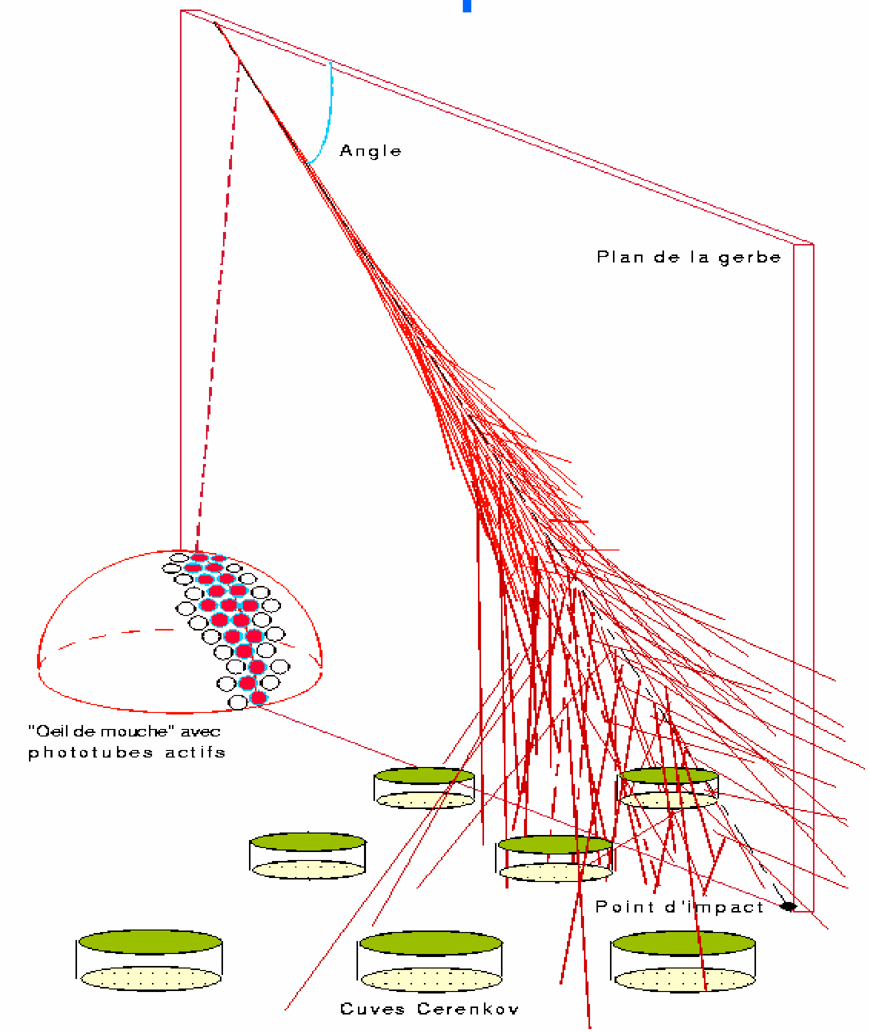
Detection of showers on Earth surface

- Ground array measure footstep of the shower. Final particles at ground level are gamma-rays, electrons, positrons and muons.
- Typically 10^{10-11} photons and electrons in area 20-50 km^2. It is enough to have detectors with area of few m^2 per km^2. Number of low energy particles is connected to primary energy.
- Space/time structure of signal give information on arrival direction.
- Number of muons compared to number of electrons give information on primary particle kind.

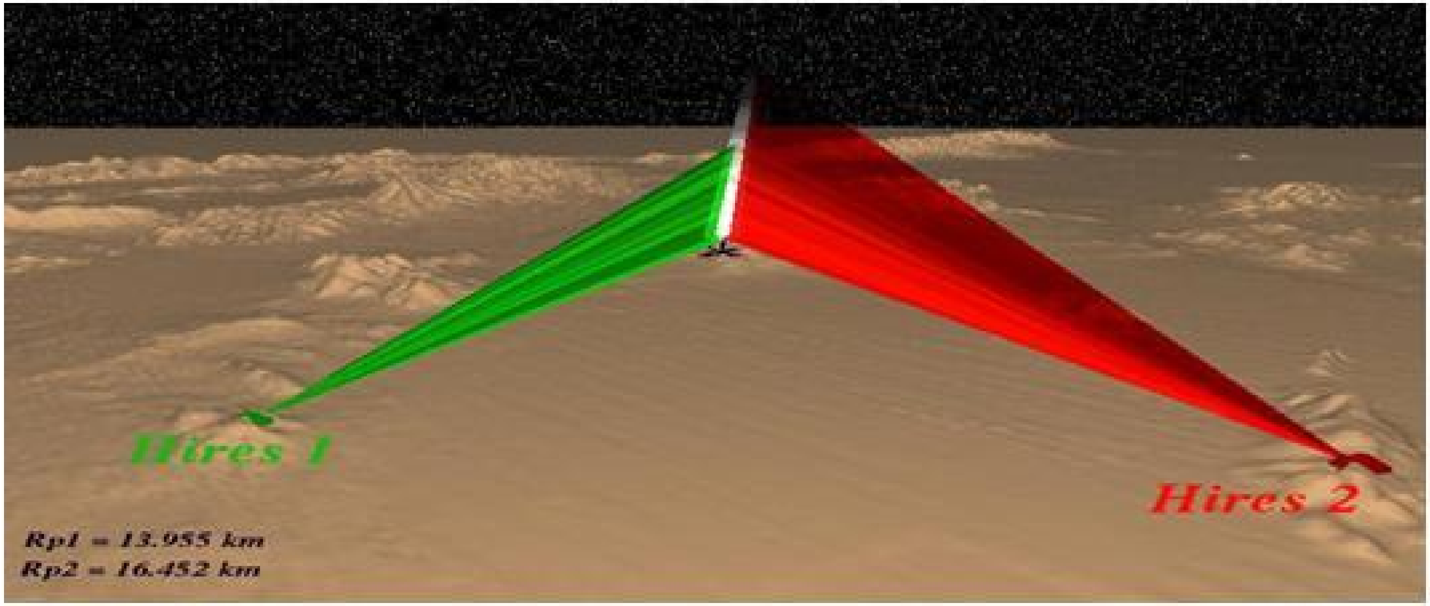


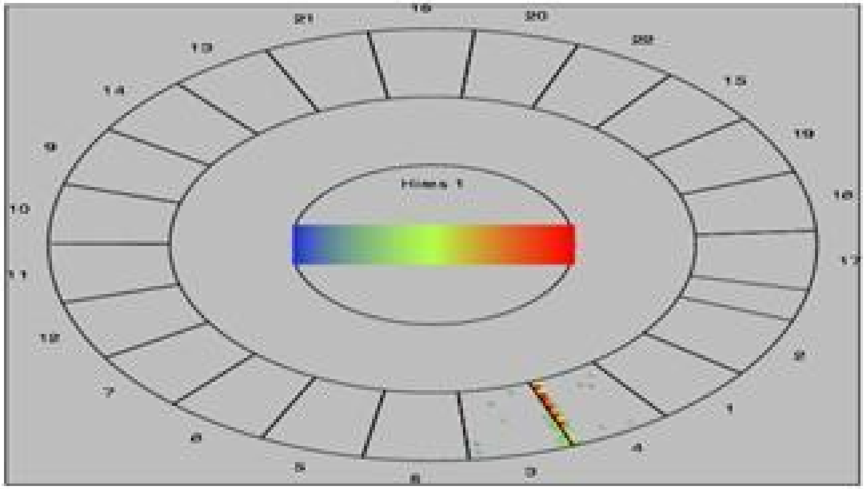
Detection of showers in atmosphere

- Fly's Eye technique mesure fluorescence emission of N_2 by collection of mirrors: shape of the shower.
- Total amount of light connected to energy of primary particle.
- Shape of shower reflects primary particle type
- Time structure of signal gives information on arrival direction.

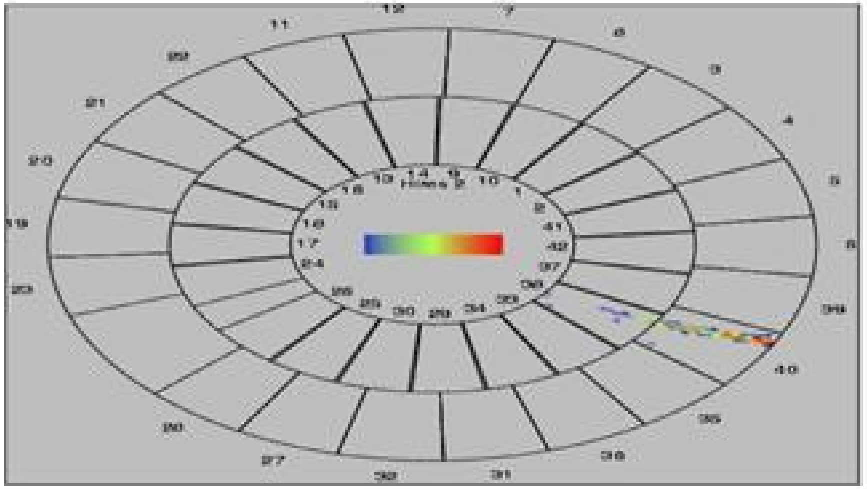


Stereo Event E ~50 EeV





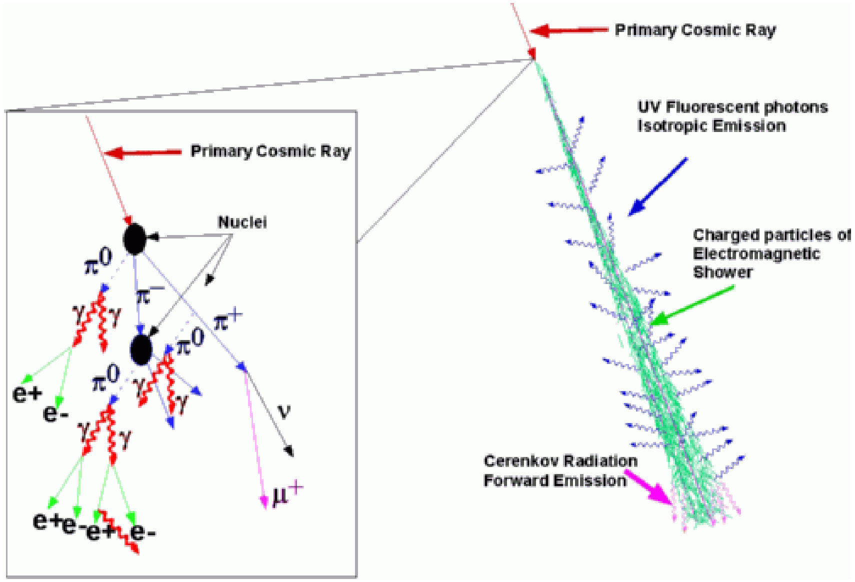
HiRes1



HiRes2

Shower structure: theoretical uncertanty

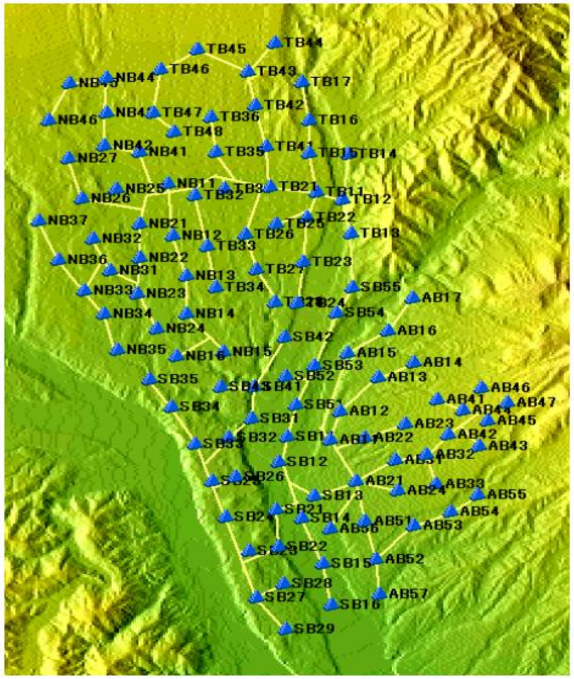
- Extrapolation of accelerator data to high energies with different approaches can give uncertainty up to 30 % in energy estimate for same shower.



AGASA

- AGASA covers an area of about 100 km^2 and consists of 111 detectors on the ground (surface detectors) and 27 detectors under absorbers (muon detectors). Each surface detector is placed with a nearest-neighbor separation of about 1 km.
- Operated till January 2004.

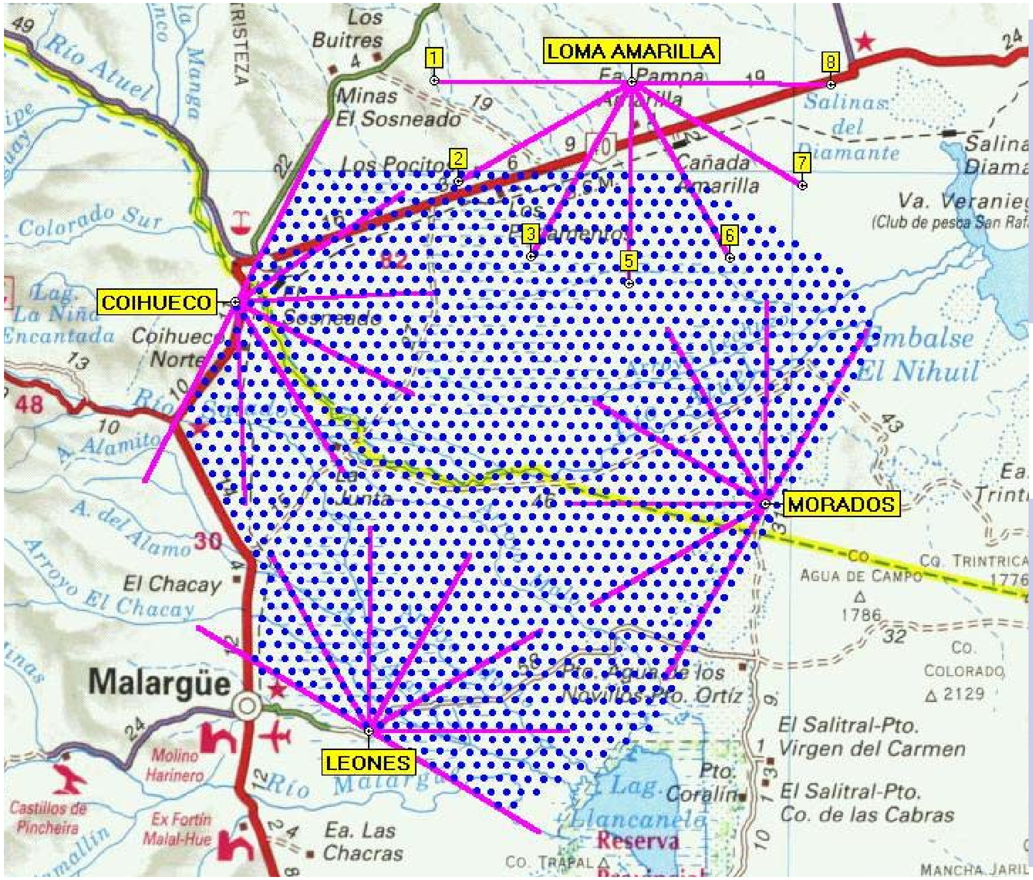
Akeno Giant Air Shower Array



High Resolution Fly's Eye: HiRes

- HiRes 1 and HiRes 2 sit on two small mountains in western Utah, with a separation of 13 km.
- HiRes 1 has 21 three meter diameter mirrors which are arranged to view the sky between elevations of 3 and 16 degrees over the full azimuth range;
- HiRes 2 has 42 mirrors which image the sky between elevations of 3 and 30 degrees over 360 degrees of azimuth.
- Operated in stereo mode since 1999.

Pierre Auger Observatory



Surface Array

1600 detector stations

1.5 Km spacing

3000 Km^2 (30xAGASA)

Fluorescence Detectors

4 Telescope enclosures

6 Telescopes per enclosure

24 Telescopes total

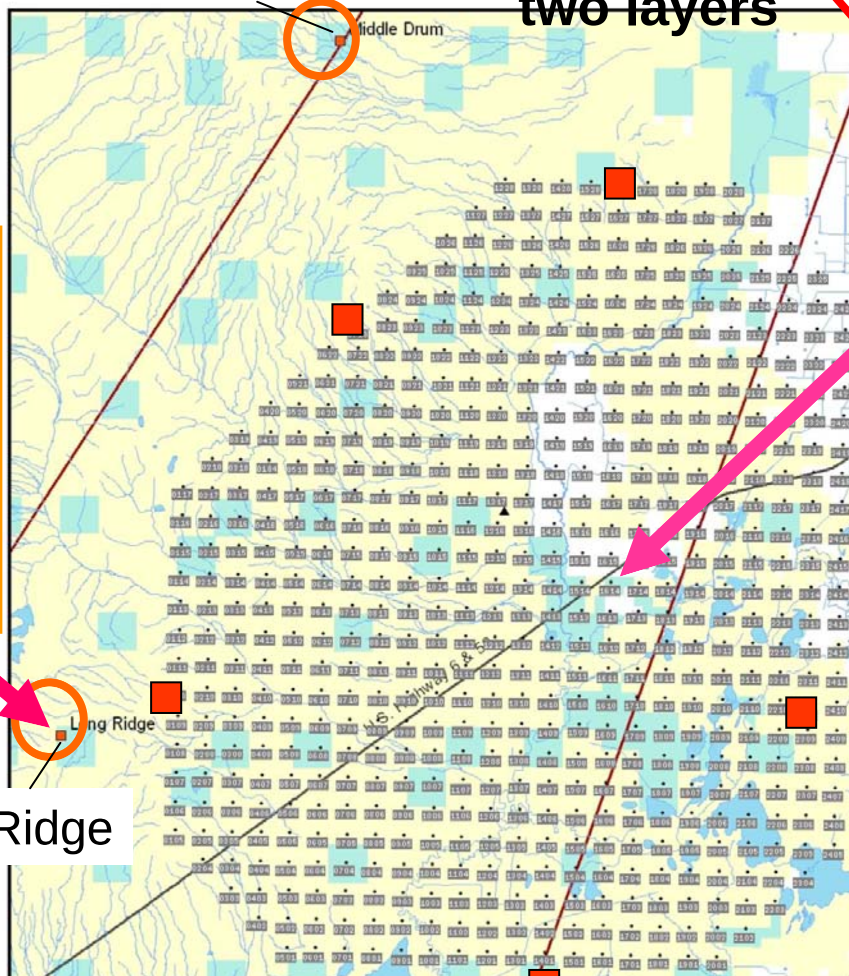
Telescope Array

576 plastic scintillation Surface Detectors (SD)

5 communication towers

3m² 1.2cm t two layers

Atmospheric fluorescence telescope
3 stations FD

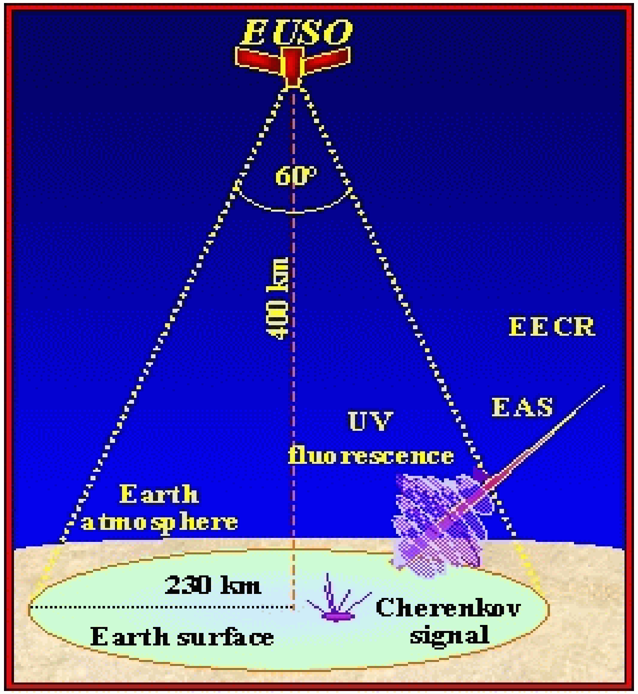


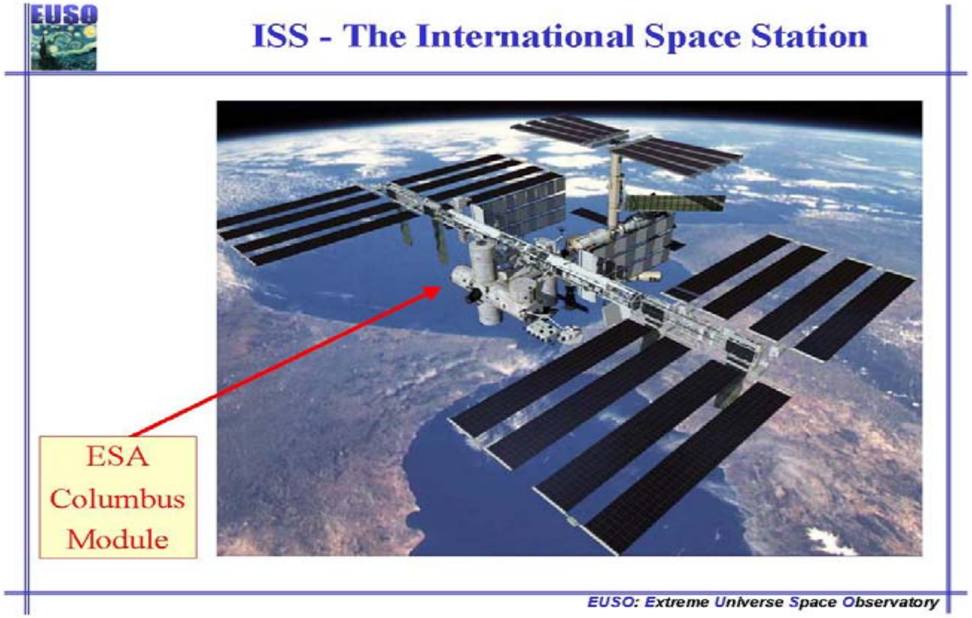
1.2km spacing

20km

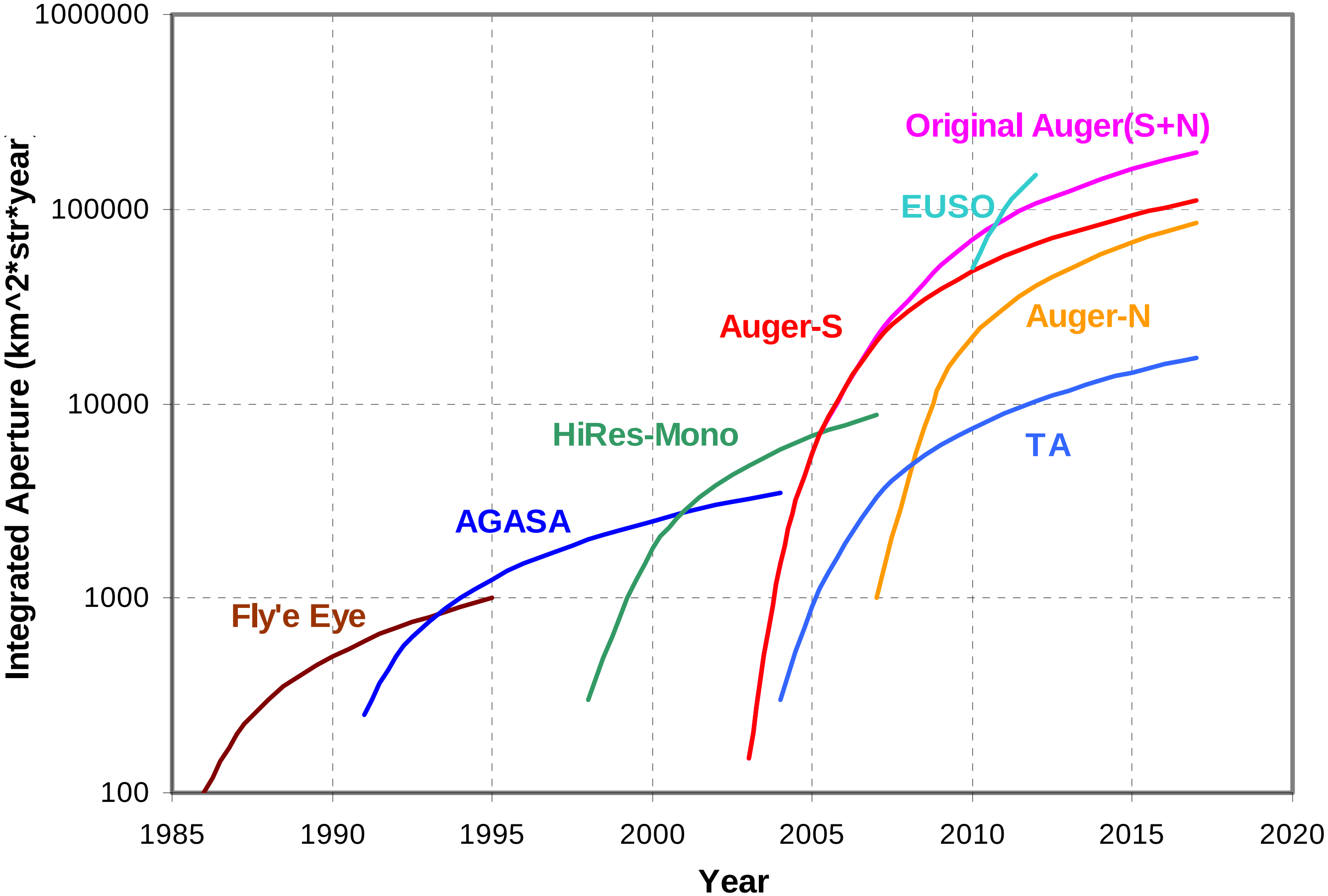
Sensitivity of SD : ~9 x AGASA

Extreme Universe Space Observatory: EUSO





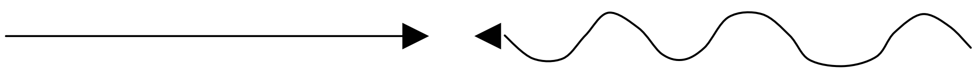
Integrated Exposure
(at 10^{20} eV)



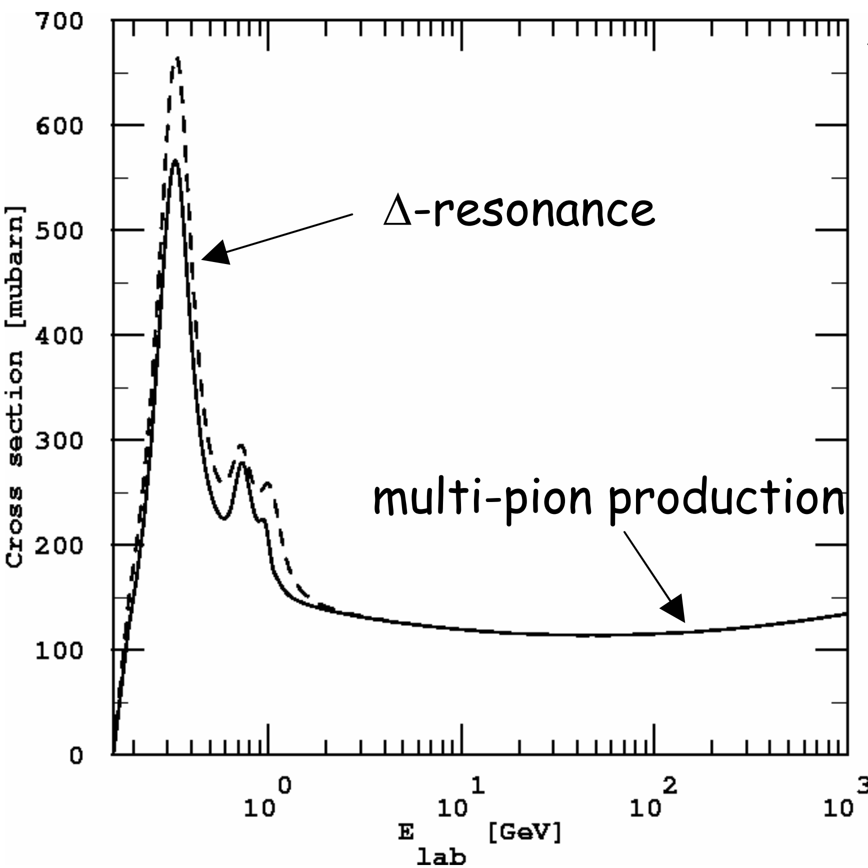
UHECR spectrum

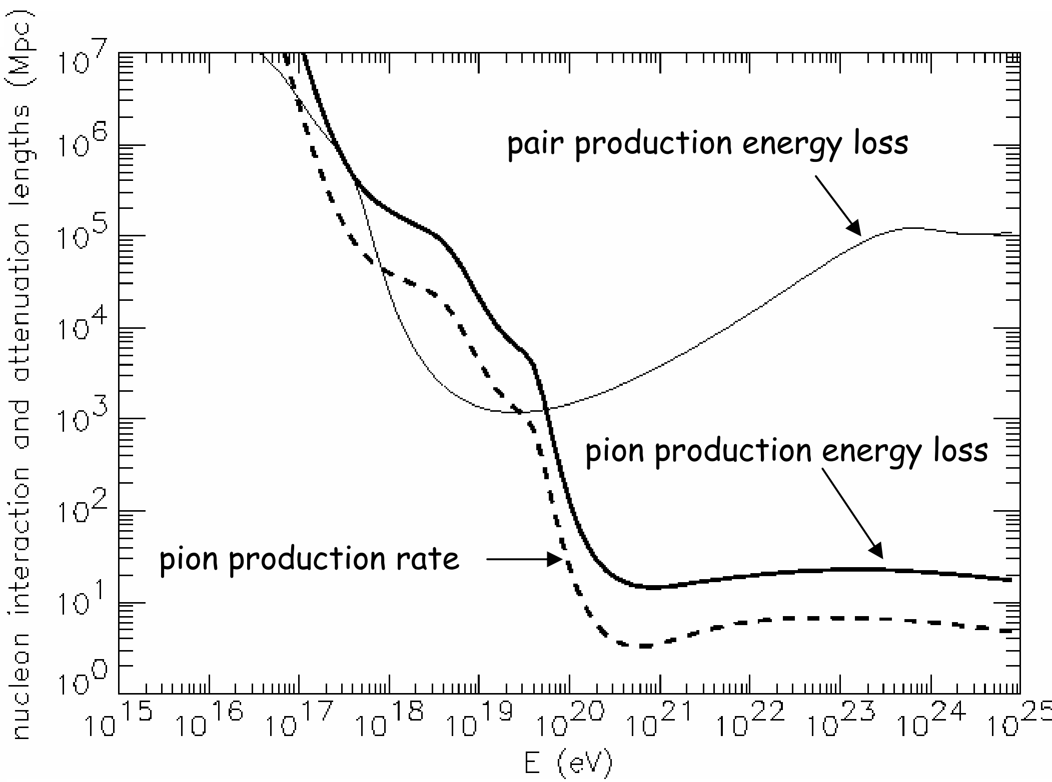
The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background



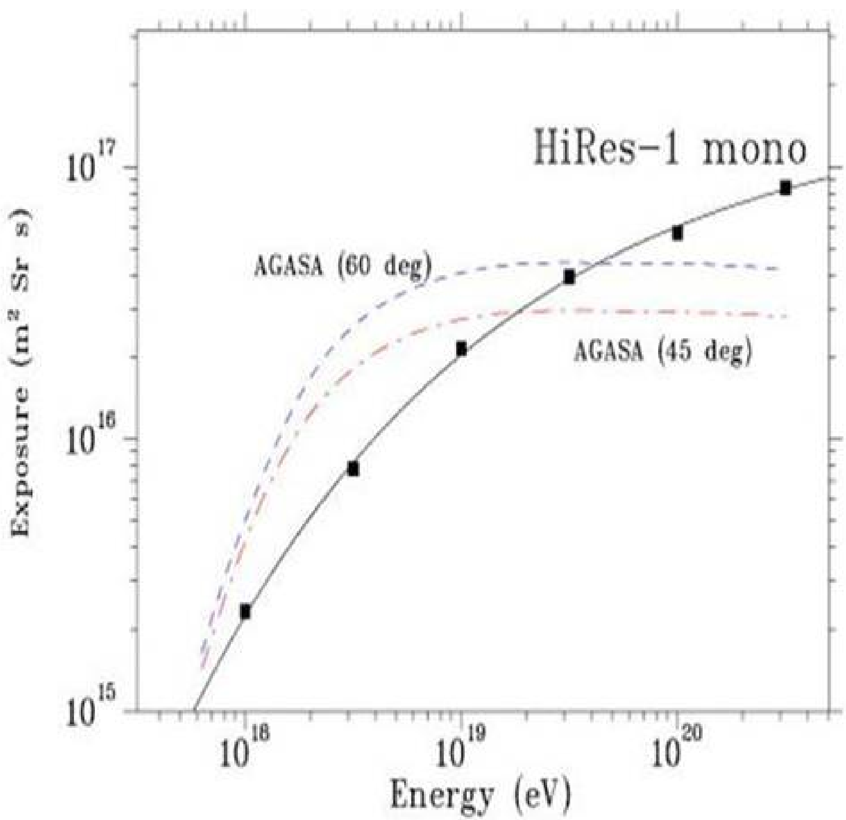
$$E_{\mathrm{th}} = \frac{2m_N m_\pi + m_\pi^2}{4\varepsilon} \approx 4\cdot 10^{19}\,\mathrm{eV}$$

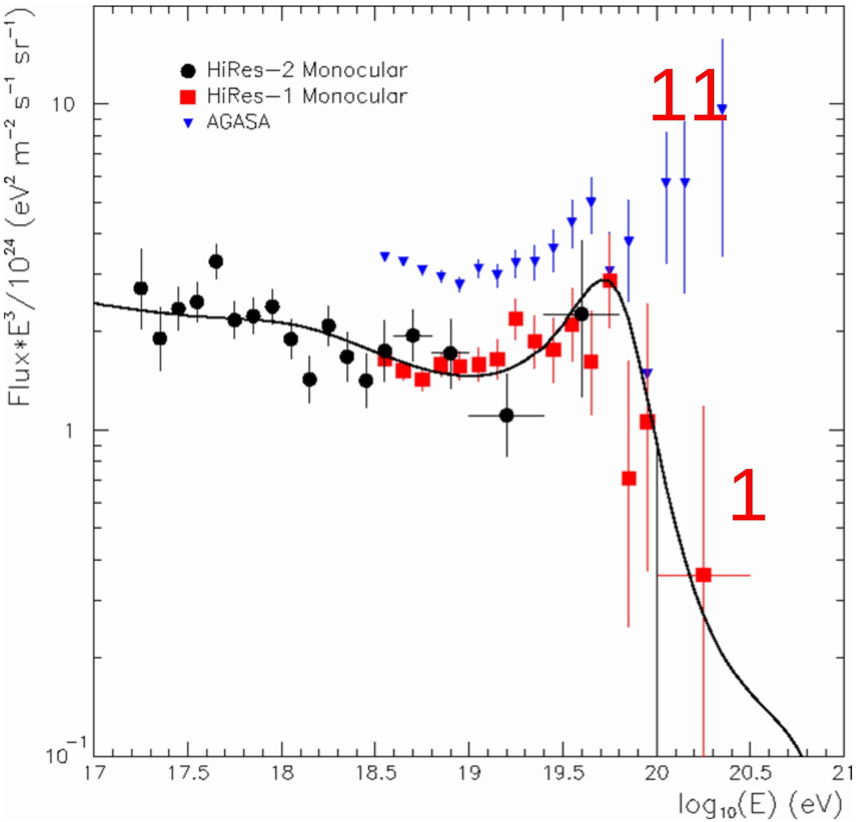




⇒sources must be in cosmological backyard within 50-100 Mpc from Earth
(compare to the Universe size ~ 5000 Mpc)

Disagreement above GZK cutoff

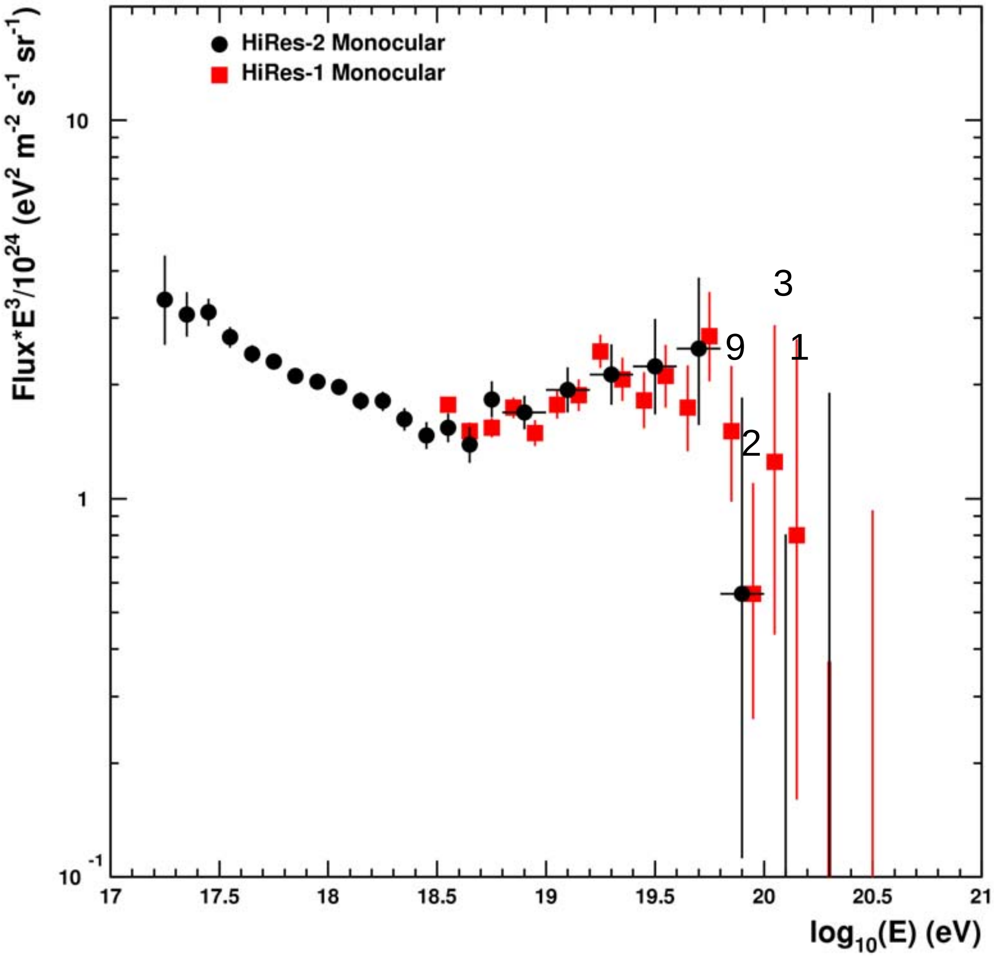




Lowering the AGASA energy scale by about 30% brings it in accordance with HiRes up to the GZK cut-off, but not beyond, where there are 6 AGASA events against 1 HiRes event.

AUGER experiment combining ground array with fluorescence such will resolve this issue.

HiRes 1 (mono)

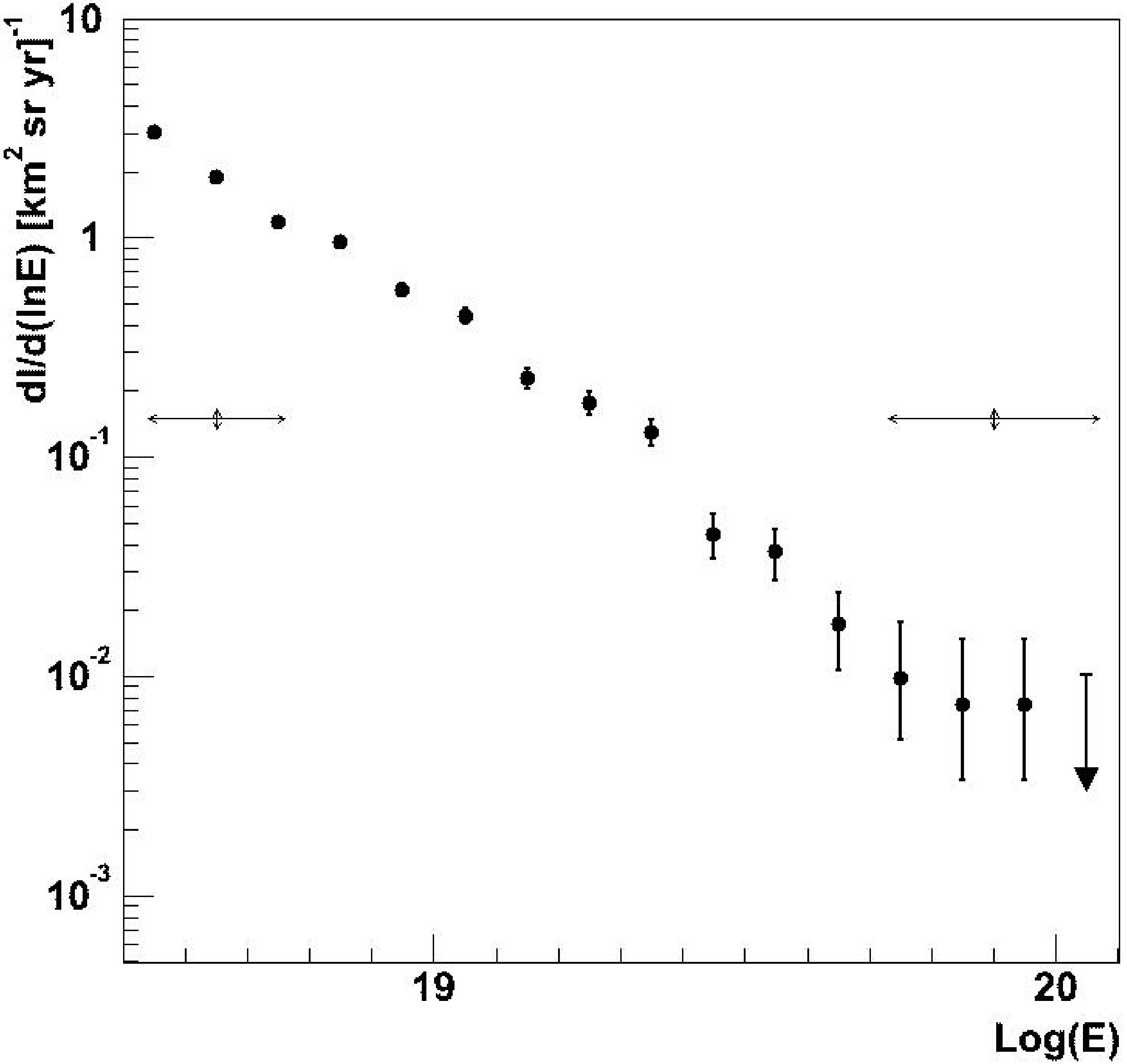


"GZK" Statistics

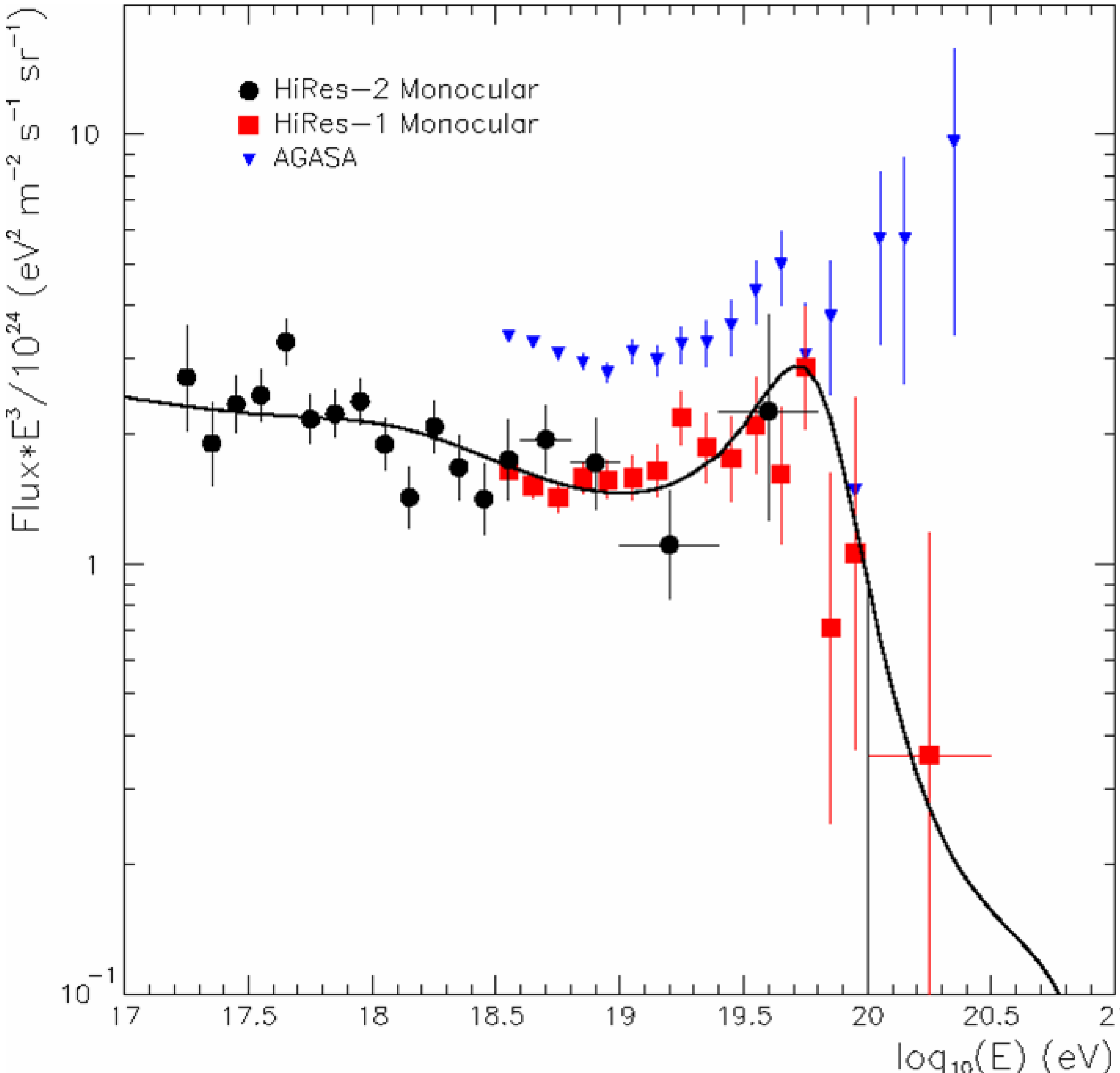
- Expect 42.8 events
- Observe 15 events
- ~ 5 σ

Bergman (ICRC-2005)

Auger Energy Spectrum



HiRes Stereo? /Auger?

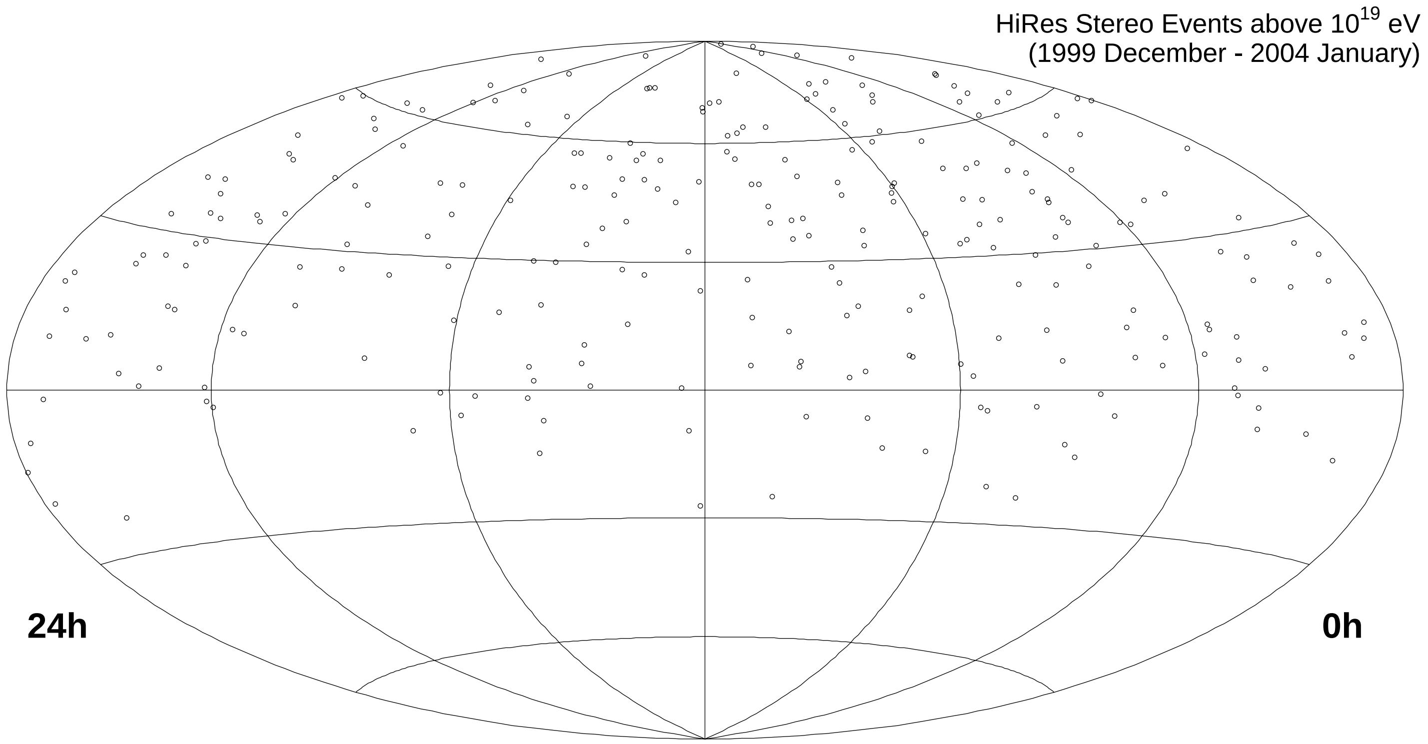


UHECR spectrum: summary

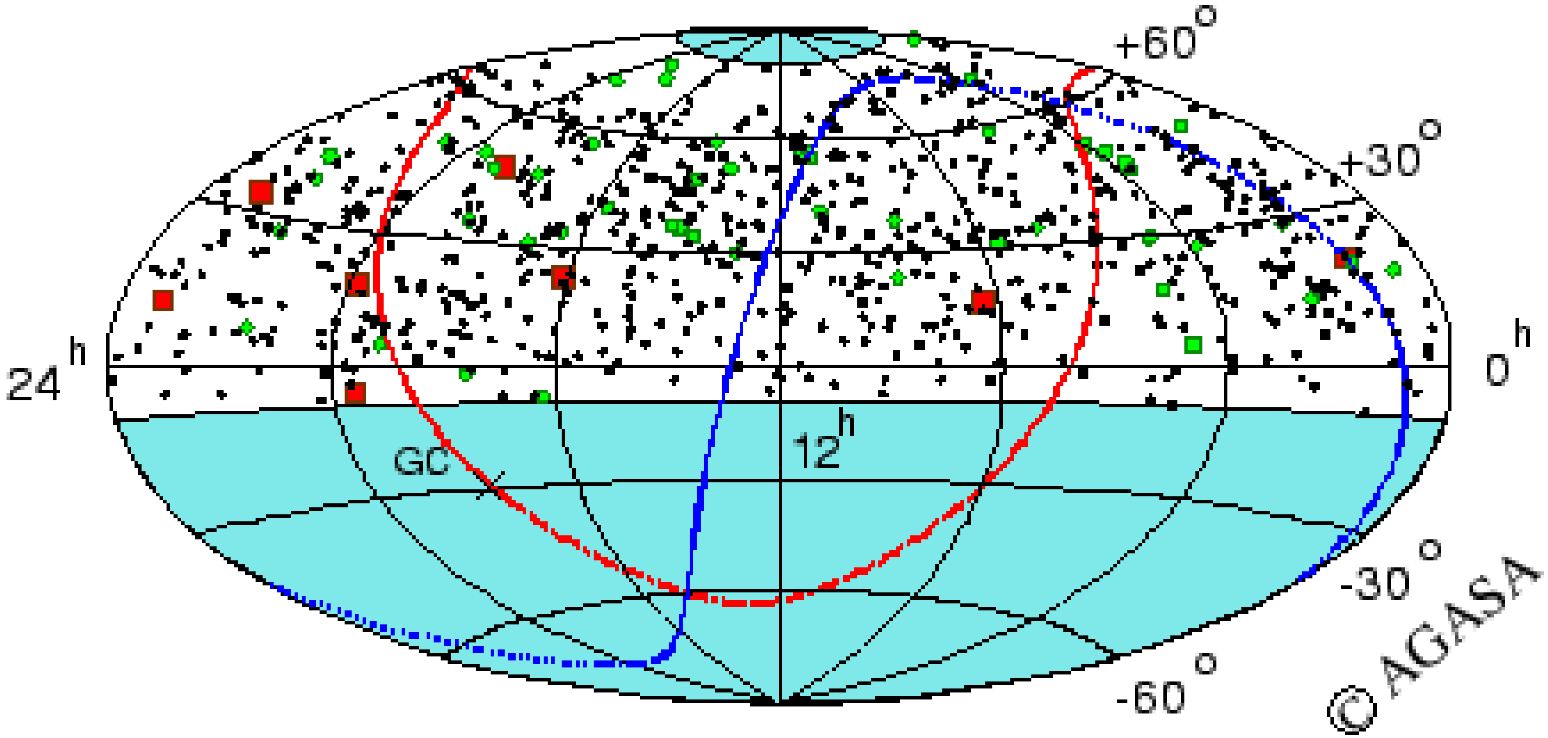
- Two existing experiments have 20-30% systematic errors. They agree within factor 1.5-2 in normalization of flux below cutoff, which corresponds 20-30% energy shift.
- Above cutoff there is a disagreement in flux value on the level ~ 2-3 σ . HiRes mono see cutoff with larger statistics.
- Both experiments see events above cutoff
- Auger will resolve those questions in 1-2 years

2) Arrival directions of UHECR.

HiRes stereo data $E > 10^{19}$ eV

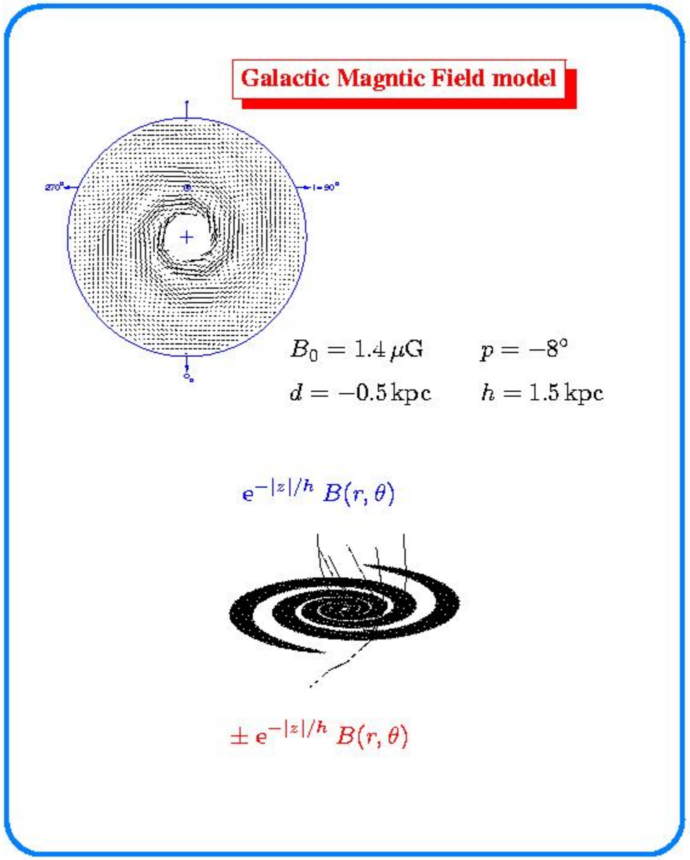


AGASA data E> 10^{19} eV



Galactic Magnetic field

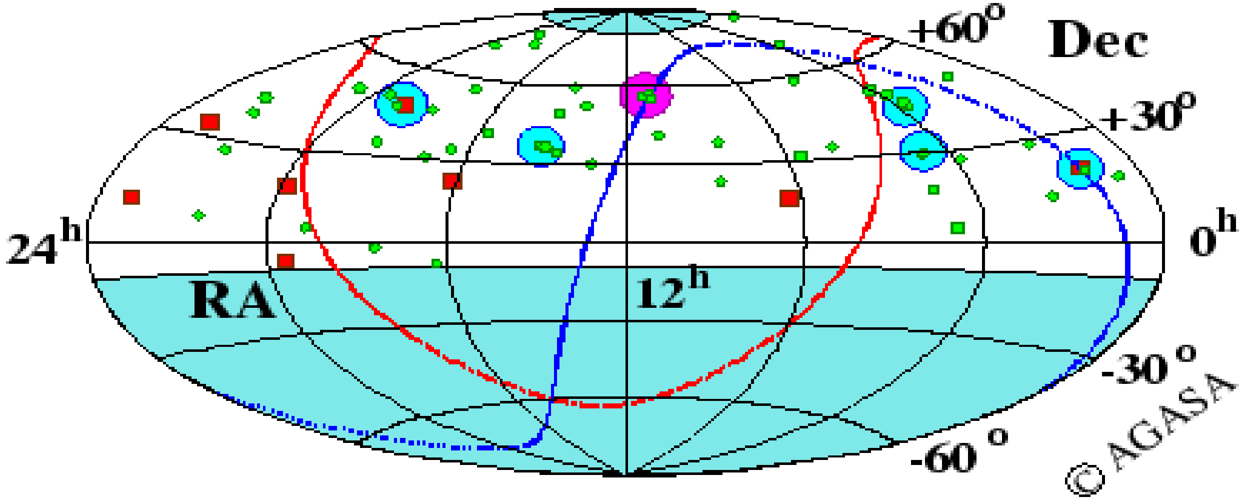
- In average cosmic ray with energy 10^{19} eV will be deflected on 15 degrees and deflection decreases as 1/E at higher energies.
- Models are not very good to follow individual CR at 10^{19} eV but at higher energies E > 4×10^{19} eV deflection is only 3-4 degrees.



Conclusions: angular distribution

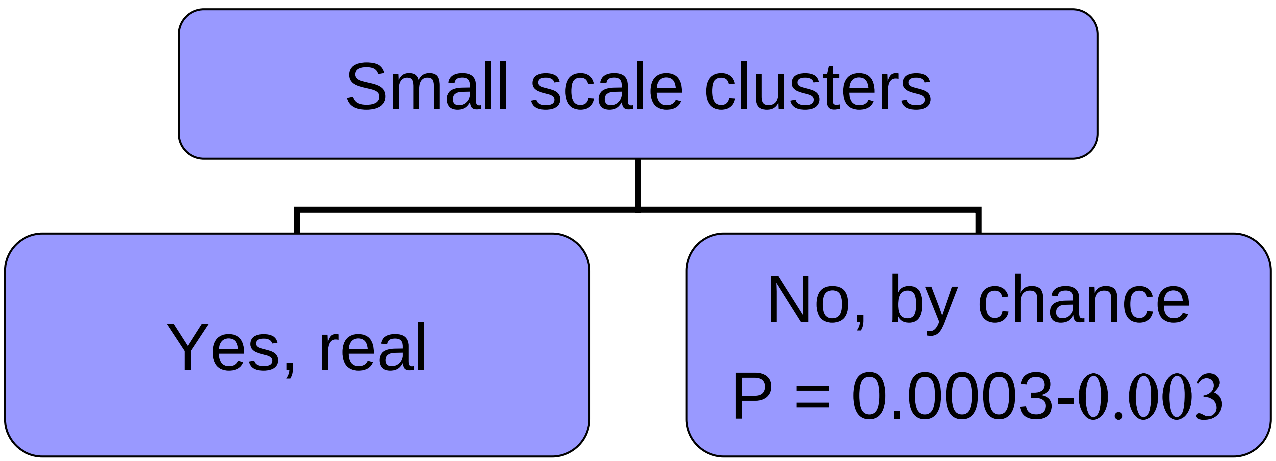
- All experiments see isotropic distribution of cosmic rays with energies 10^{19}eV<E<4x10^{19}eV.
- Galactic magnetic field is not strong enough to randomize CR at those energies.
- Most of showers are hadronic-like.
- Most probable explanation: protons or/and nuclei from extragalactic sources.

AGASA data E> 4x10^{19} eV ~60 events

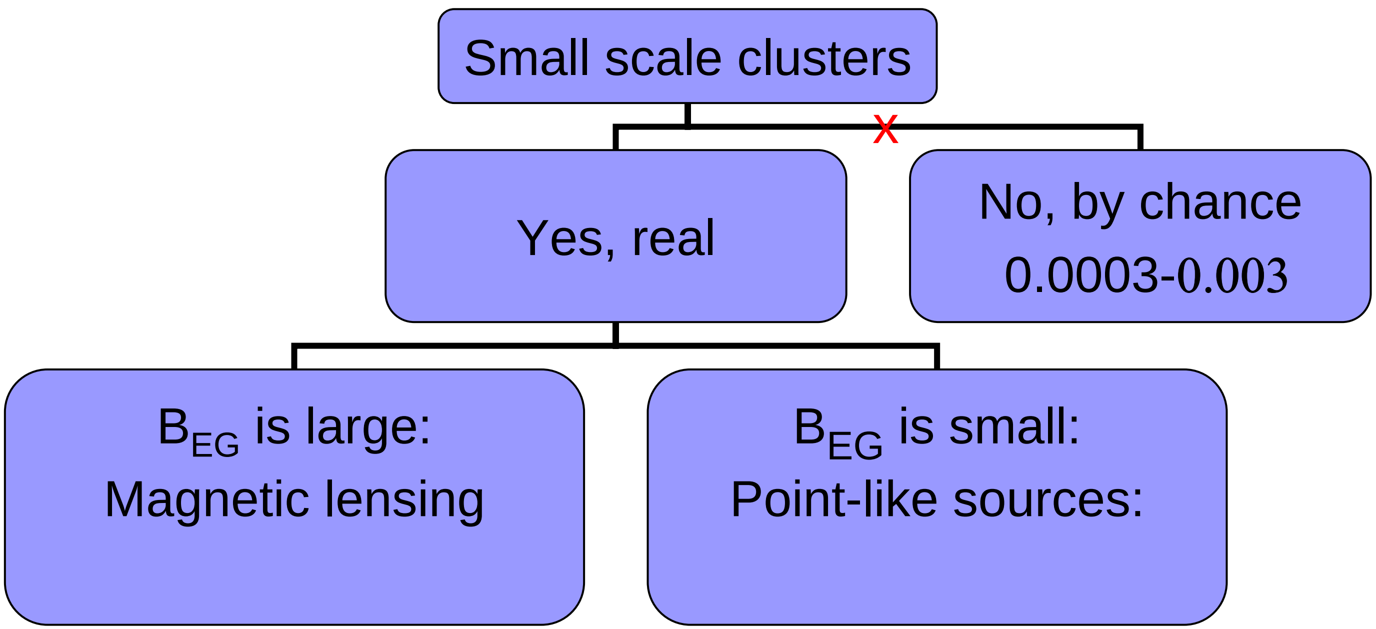


Clusters -- are events which came from the same part of sky within given (usually small) angle from each other. Angle is 2.5 degrees for AGASA.

Is this a real signal?

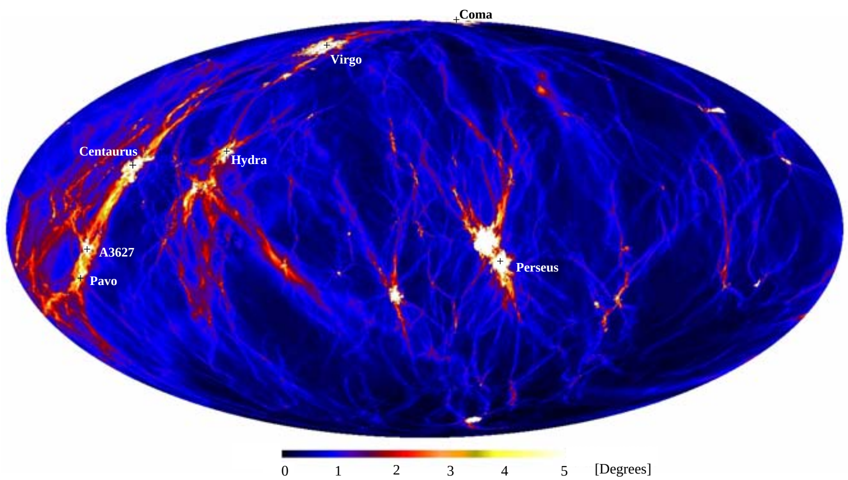


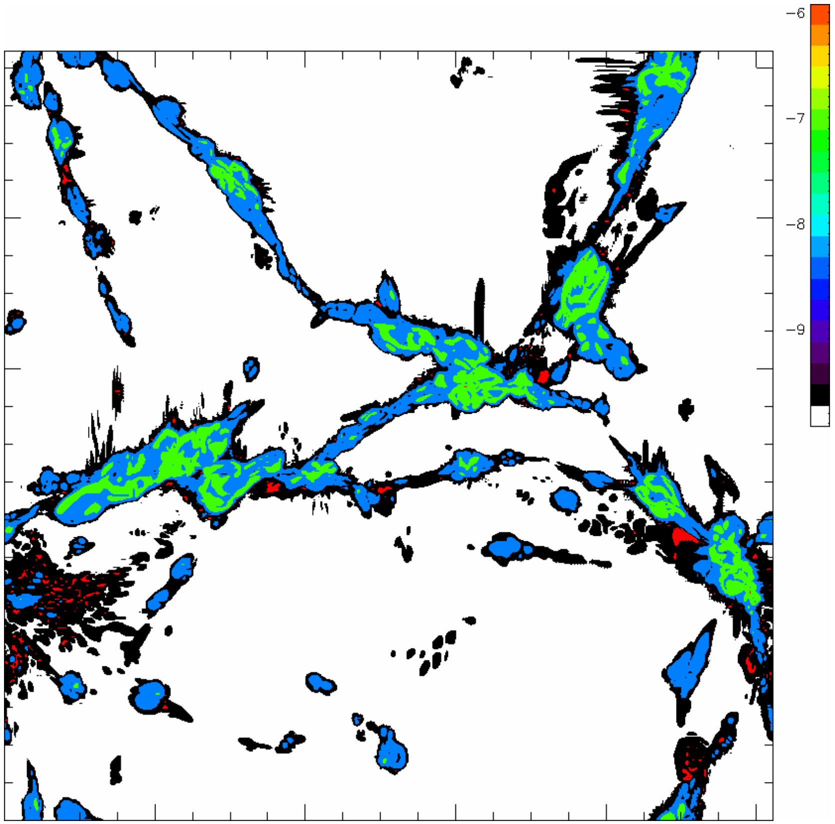
Magnetic lensing or point sources?



Proton deflections in extragalactic magnetic field within 105 Mpc from our Galaxy

Extragalactic magnetic field in R=50 Mpc large scale structure box





Dolag et al, 2003

Sigl et al, 2002-2003

What can we know about sources from small scale clusters?

Small scale clusters

Yes, real

No, by chance

0.0003-0.003

B_{EG} is large:

Magnetic lensing

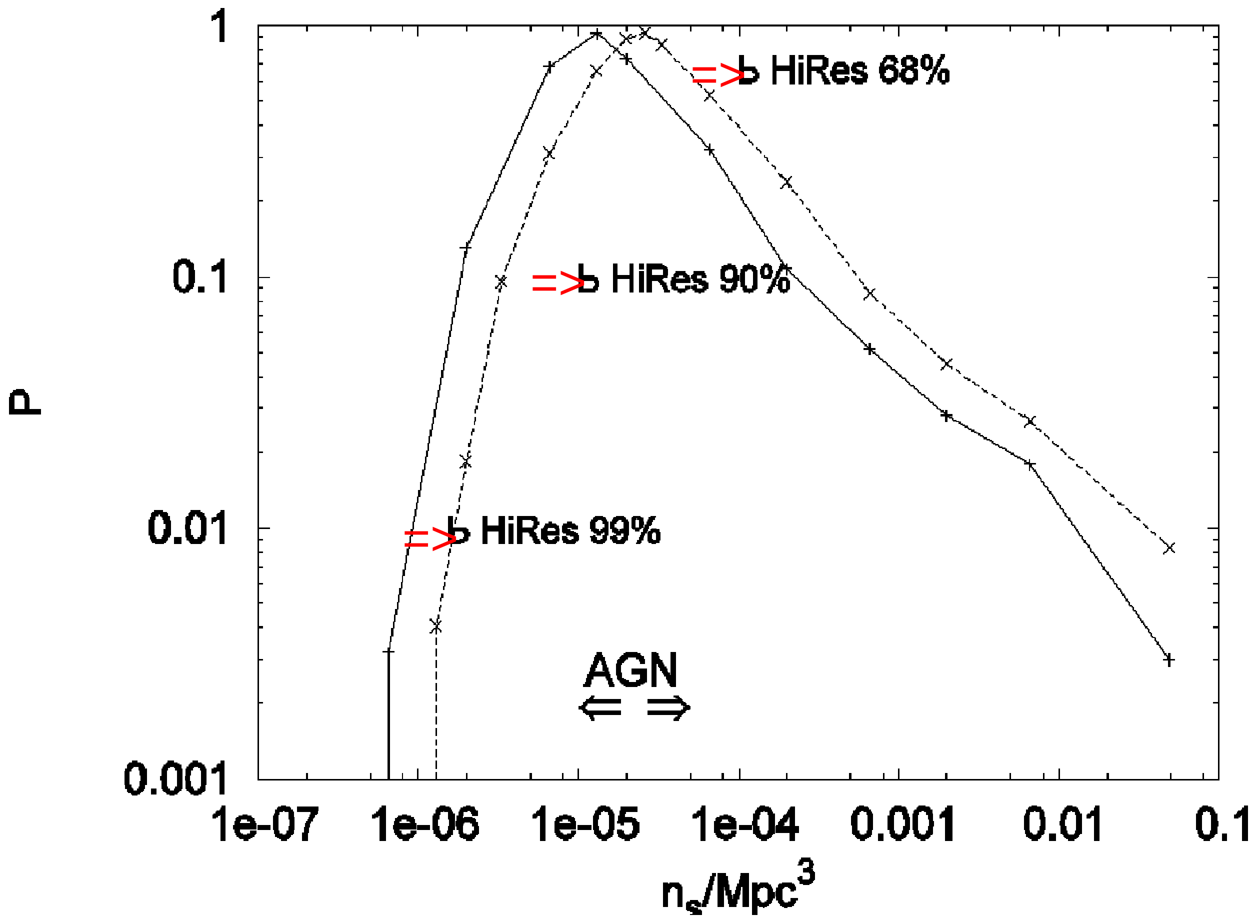
B_{EG} is small:

Point-like sources:

possible to predict

number of sources.

Density of UHECR sources from AGASA and HiRes data



Kachelriess and D.S., 2004

Maximum Likelihood Point Source Search

No significant point source is found in the combined set of HiRes and AGASA events above **40 EeV**.

If the HiRes threshold is lowered to 30 EeV, one more event lands near the triplet. There are now 57 AGASA events and 40 HiRes events.

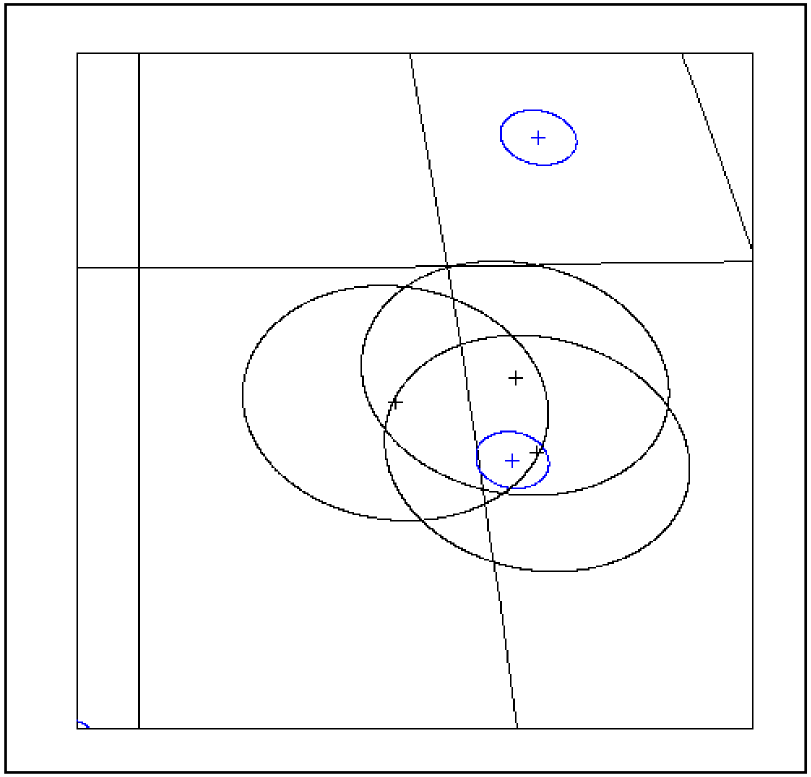
The new highest value of ln(R) = 12.98, and the fraction of MC sets with higher ln(R) is 0.5%

This result contains some biases:

- the clustered AGASA events which were originally used to *establish* the 40 EeV threshold are still included in the sample
- the HiRes energy threshold has to be *changed* to include an event that contributes to the cluster

These biases imply that 0.5% is a *lower bound* on the chance probability.

Abbasi et al., ApJ, in press.



See G. Farrar, astro-ph/0501388 for a different interpretation

Small scale clusters: summary

- AGASA sees small scale clusters in arrival directions of cosmic rays at energies $E>4x10^{19}eV$ with significance 2.5-3.5 σ. HiRes data do not contradict to it.
- Both galactic and extragalactic magnetic fields are not strong enough to deflect protons at those energies more then for few degrees.
- Estimate of number of sources agrees with density of AGN!
- Most probable explanation: protons from AGN. Auger will be able to define source density and probably will find sources.

Composition at energies above 10^{19} eV.

- Photons < 25-30 % (AGASA and Auger)
- Hadrons > 70% (AGASA and HiRes)
- Fe < 50 % (AGASA and HiRes)
- Neutrinos 0% (AGASA and HiRes)

- Impossible to distinguish event by event except of neutrinos.

Gamma-rays and UHE neutrinos.

Pion production

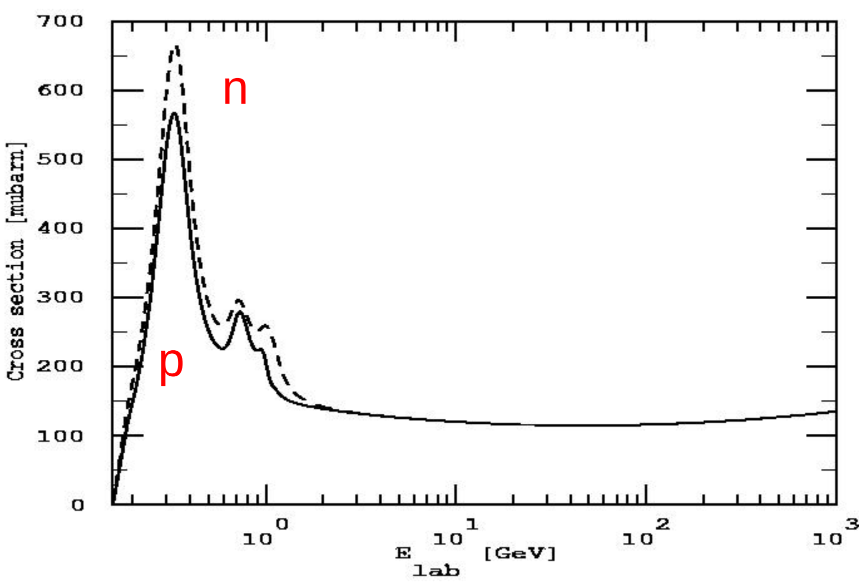
$$N + \gamma_b \Rightarrow N^{'} + \sum \pi^{i}$$

$$\pi^{0} \Rightarrow 2\gamma$$

$$\pi^{\pm} \Rightarrow \mu^{\pm} + \nu_{\mu}$$

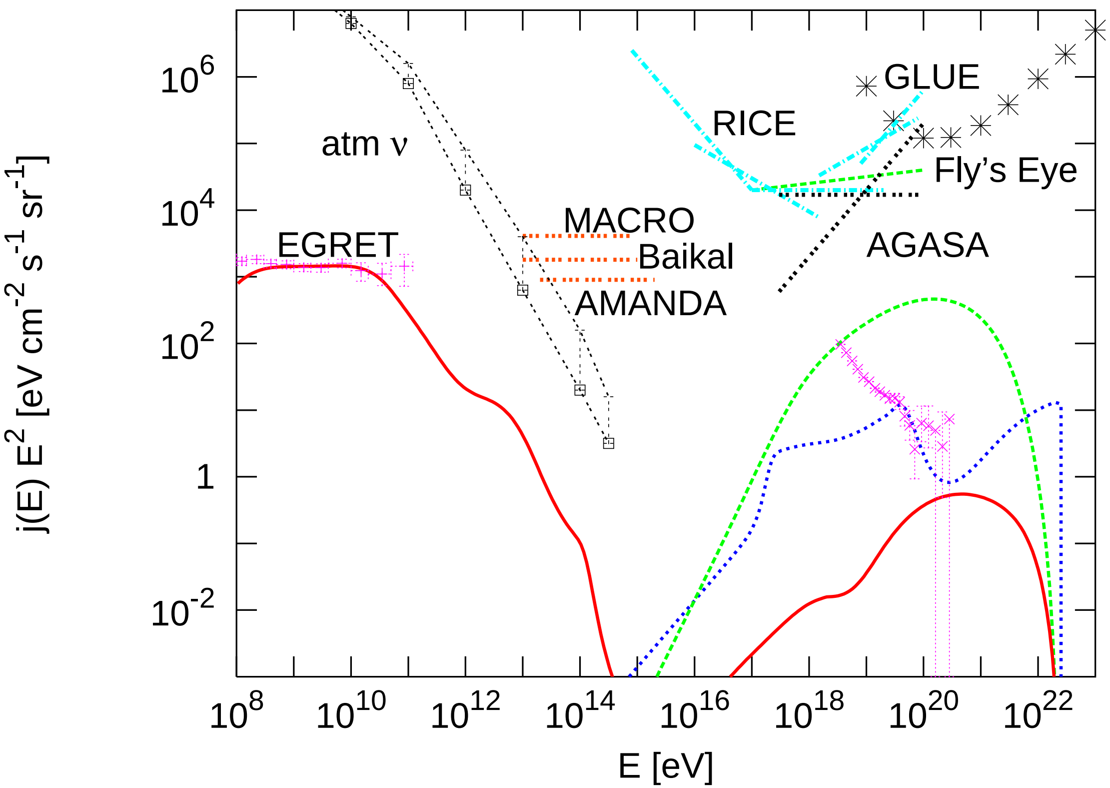
$$\mu^{\pm} \Rightarrow e^{\pm} + \overline{\nu}_{e} + \nu_{\mu}$$

$$n \Rightarrow p + e^{-} + \overline{\nu}_{e}$$



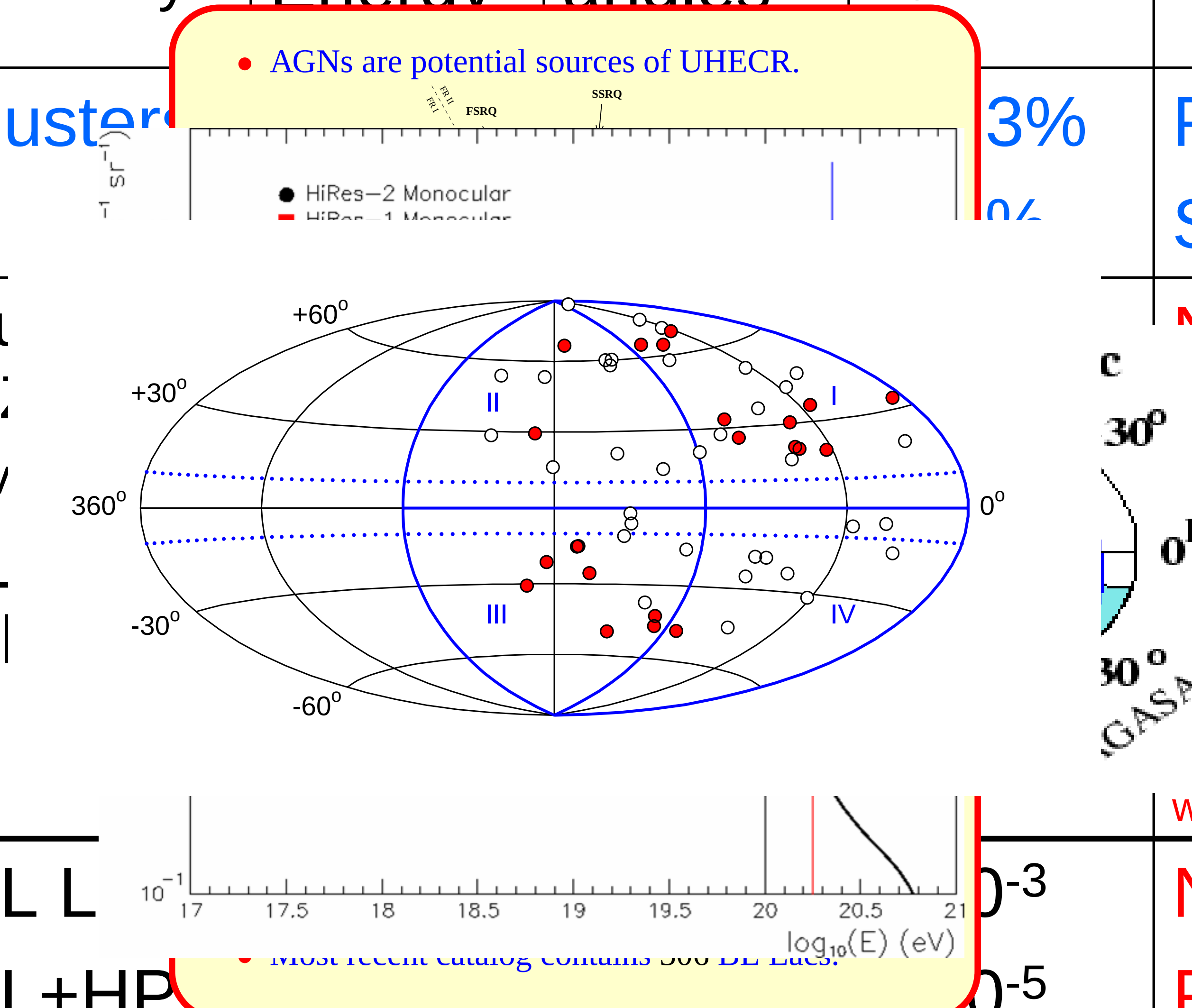
Conclusion: proton, photon and neutrino fluxes are connected in well-defined way. If we know one of them we can predict other ones: $E_{\gamma}^{tot} \sim E_{\nu}^{tot}$

UHECR, gamma-ray and neutrino fluxes



Experimental puzzles in UHECR data as on September 2005

Experiment	Anomaly	Energy	angles	significance	explanation
AGASA (1997) Yakutsk	cluster			3%	Point Sources
AGASA(1995) Yakutsk HiRes	Su G: Ev				New Physics
AGASA (2001)	Bl				New Physics with protons(?)
Hires (2004)	BL L BL+HP			0-3 0-5	New Physics neutral



Most favorite UHECR models.

Modern UHECR model should solve the following problems:

- Acceleration of charged particles to highest energies $E>10^{20}$ eV
- Propagation of UHE particles from source to Earth
- Interaction with atmosphere similar to hadrons
- Large scale isotropy of arrival directions
- Small scale clusters
- Obey gamma-ray and neutrino flux limits
- Highest energy cosmic rays should point back to sources

Model 0

- Clustering is by chance
- There is a cutoff in spectrum
- Composition is Fe dominated
- BL Lac correlation is by chance
- Solution: UHECR are heavy nuclei from sources uniformly distributed in the Universe.
- Problem: Nuclei should escape from acceleration site and reach us from it.

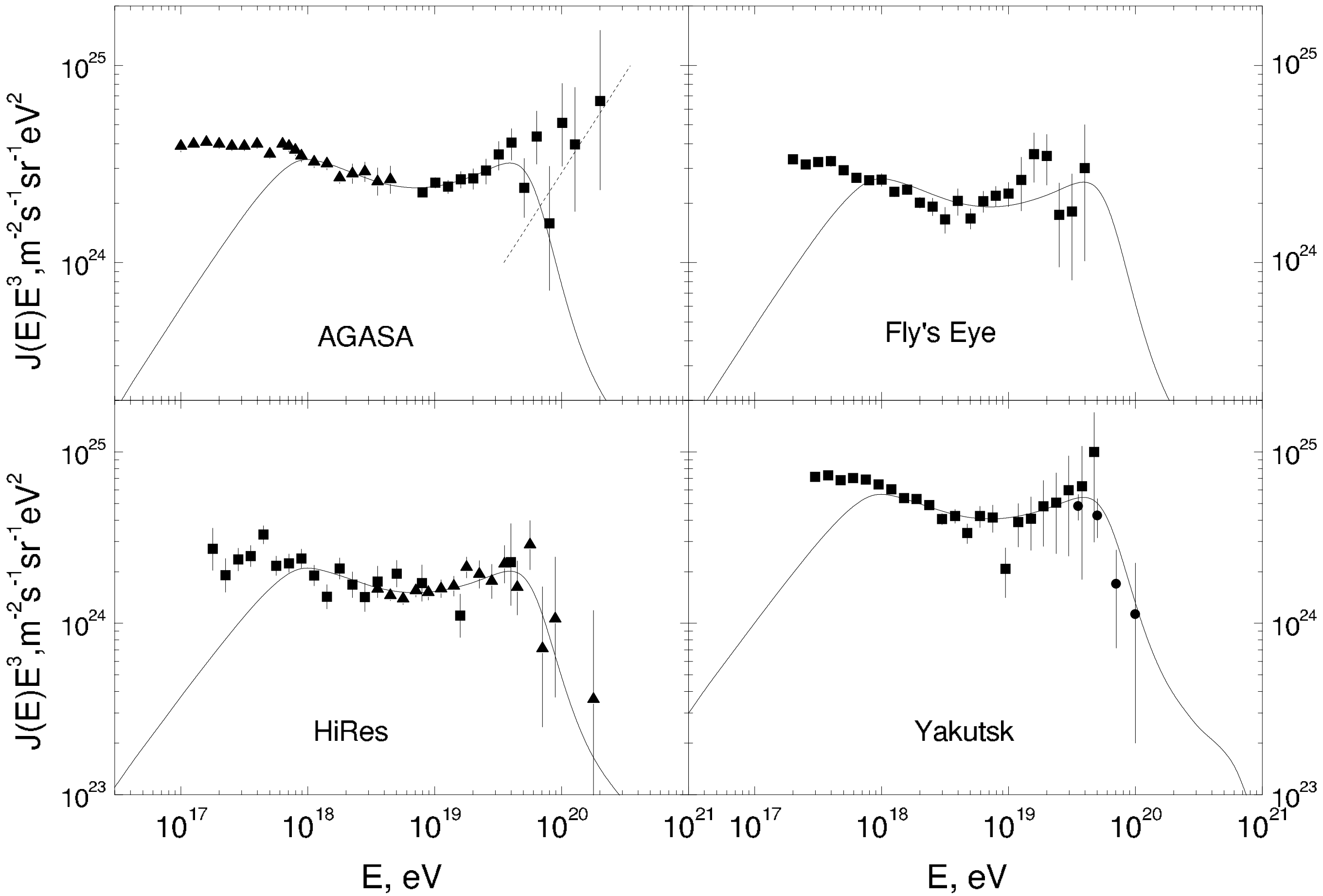
Model 1

- Clustering by chance
- There is a cutoff in spectrum
- Composition is proton dominated
- BL Lac correlation is by chance
- Solution: UHECR are protons from sources uniformly distributed in the Universe.
- Problem: Number of sources should be comparable to the number of galaxies, which is in conflict with acceleration

Model 2

- Clustering is real
- There is a cutoff in spectrum
- Composition is proton dominated
- BL Lac correlation is by chance
- Solution: UHECR are protons from AGN.
- Warning: there is no candidate sources in the direction of highest energy cosmic rays.
- Proposal: compare map of near sources with arrival directions of cosmic rays.

Protons can fit UHECR data

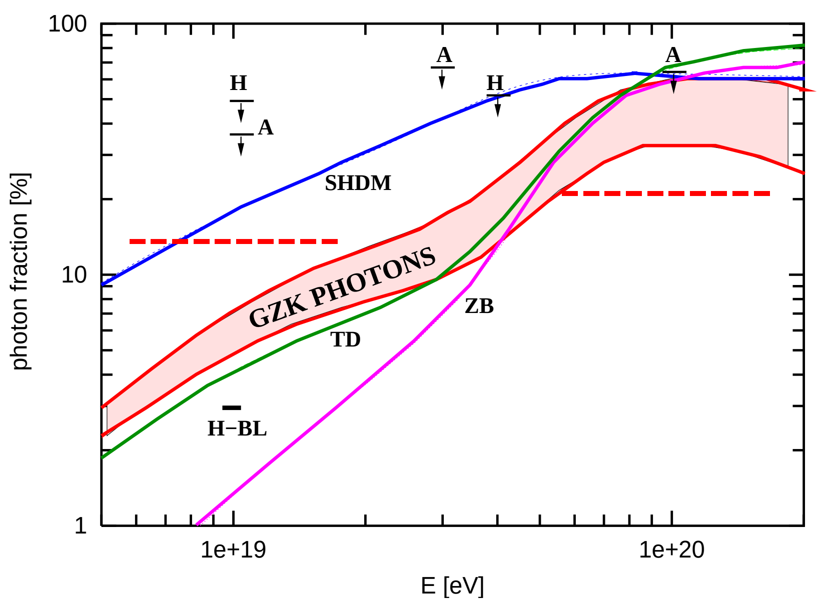


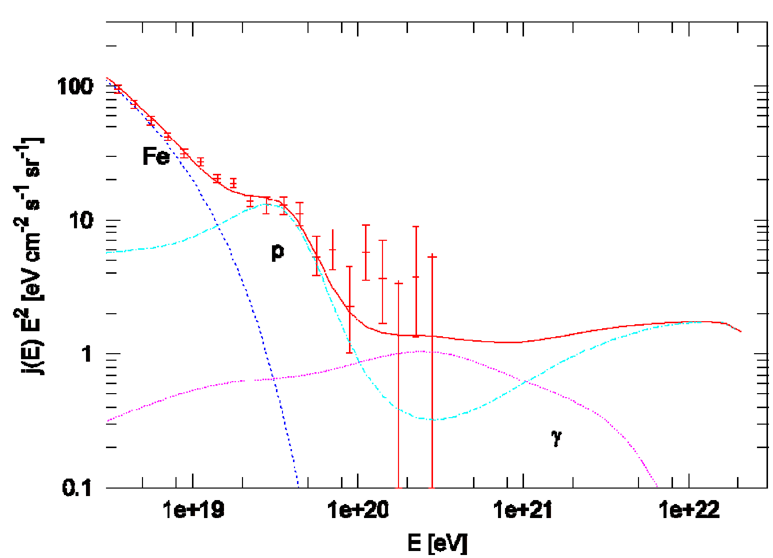
V.Berezinsky , astro-ph/0509069

Model 3

- Clustering is real
- There is no cutoff in spectrum
- BL Lac correlation is by chance
- Solution: UHECR below cutoff are protons from sources uniformly distributed in the Universe. UHECR above cutoff are photons:
  - GZK photons
  - Photons from AGN
  - Topological defects
  - Super-heavy dark matter

GZK photons





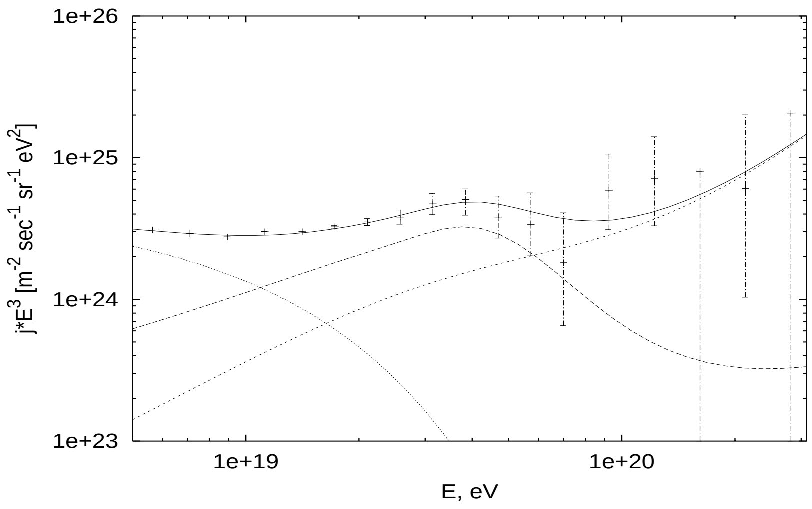
Signature: UHECR should correlate with local and one expects large gamma-ray and neutrino flux.

G.Gelmini, O.Kalashev and D.S. , astro-ph/0506…

γ and p from AGN as UHECR

If $B_{EG}<10^{-12}$G and radio background is minimal photons can come even from z=0.1 sources. Protons should be accelerated to 10^{23-24} eV.

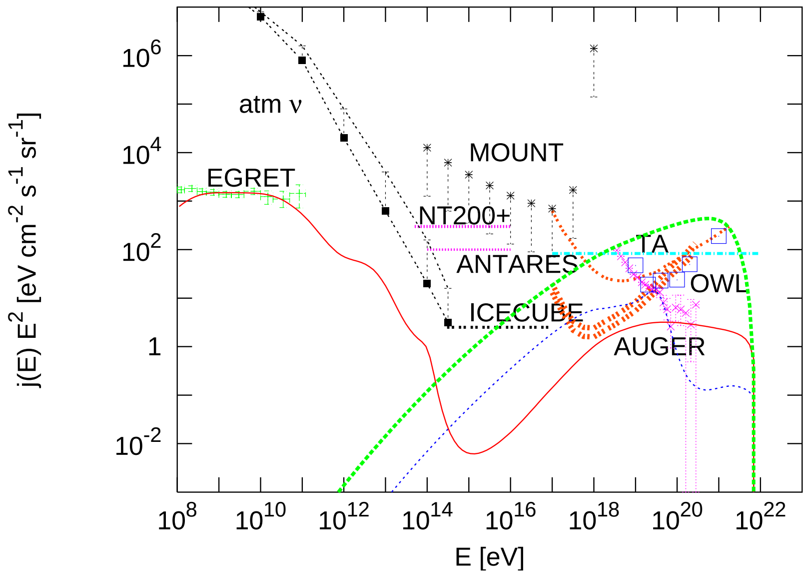
Signature: UHECR should anti-correlate with local LSS and one expects large gamma-ray and neutrino flux. EGRET OK.



O.Kalashev et al, astro-ph/0107130

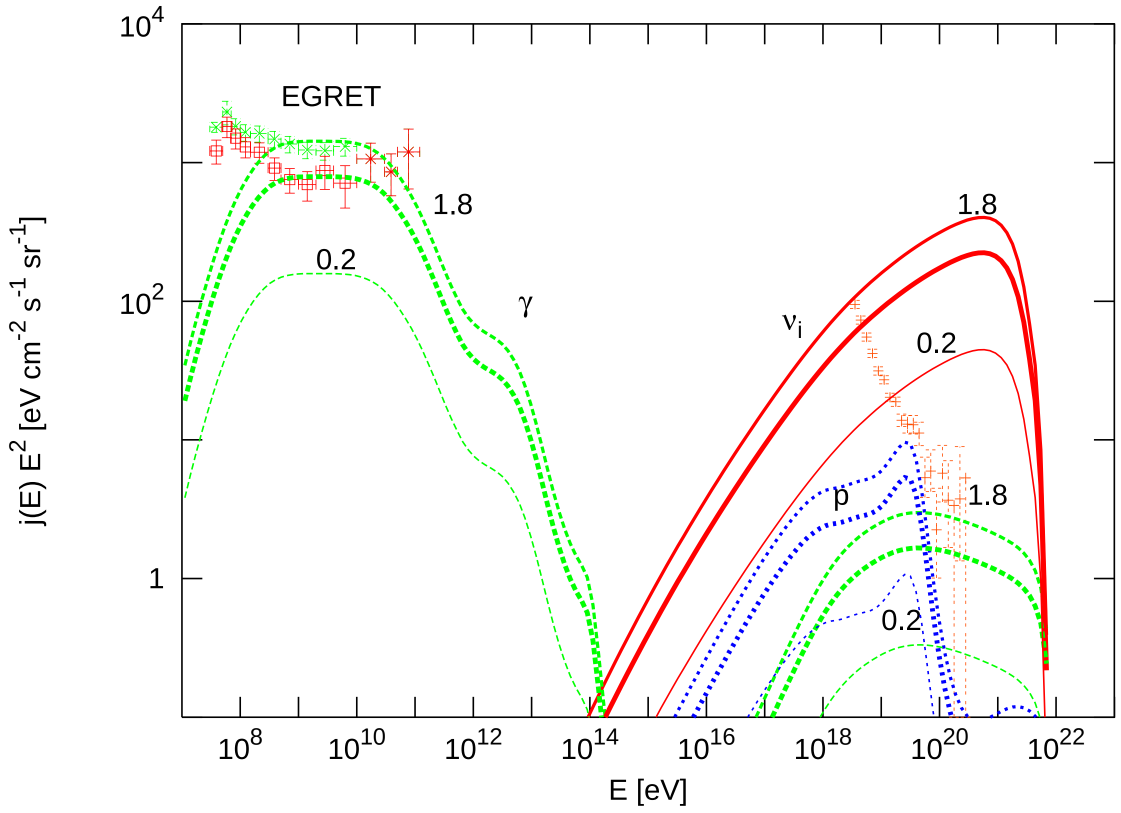
Top-down models

- Topological defects were produced in early Universe.
- Today they decay through GUT-scale particles with masses $10^{13\text{-}15}$ GeV
- UHECR are protons and photons from their decay.



V.Berezinsky and collaborators 1980-90th

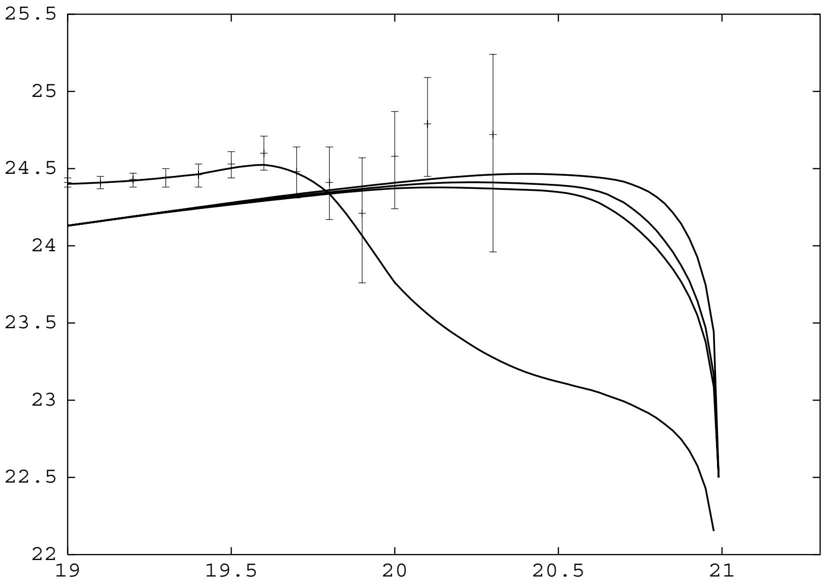
Top-down models: practically excluded by EGRET data



D.S. and G.Sigl, hep-ph/0309328

Super-heavy dark matter model

- Particles with mass $10^{12\text{-}14}$ GeV created in early Universe. Today they decay and produce UHECR.
- Main signature: UHECR are photons. Arrival directions follow DM profile.



V.Berezinsky, M.Kachelriess and A.Vilenkin;

V.Kuzmin and V.Rubakov , 1997

Problem: Disfavored by SUGAR data

M.Kachelriess and D.S., 2003; Kim and P.Tinyakov, 2003

Model 4

- Clustering is real
- There is no cutoff in spectrum
- BL Lac correlation is real
- Solution: UHECR below cutoff are protons from sources uniformly distributed in the Universe. UHECR above cutoff are due to new properties of existing particles:
  - Lorentz invariance violation and protons (Coleman and Glashow)
  - Strongly interacting neutrinos (Nussinov and Shrock, 1998)

Lorentz Invariance violation

- Modification of dispersion relation at high energies
- String theory, D-brains
- Right hand side terms comparable with m² term

$$E^2 - p^2 - m^2 = -2d \cdot E^2 - \xi \frac{E^3}{M_{Pl}} - \zeta \frac{E^4}{M_{Pl}^2}$$

$$d, \xi, \zeta \to 0 \text{ for } E/m \to 1$$

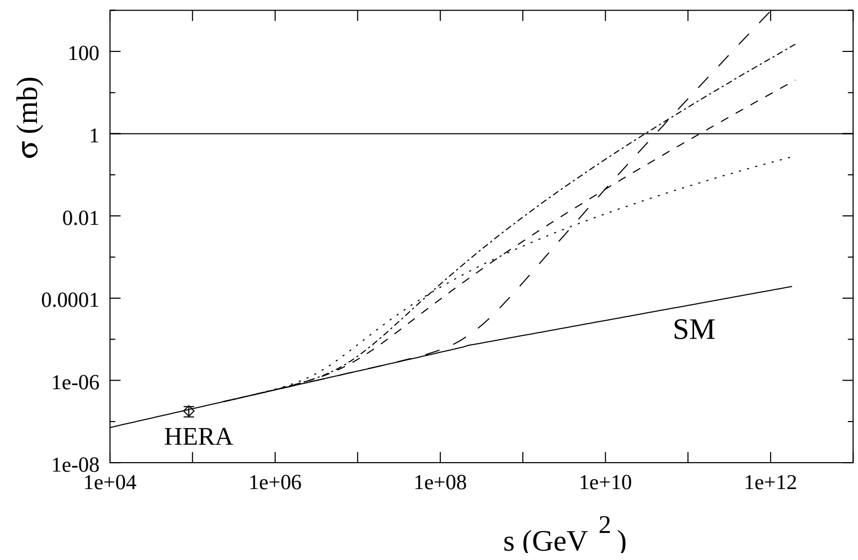
$$x - 1 - \alpha \cdot x^3 - \beta \cdot x^4 = 0$$

$$x = \frac{p}{p_{th}} \qquad p_{th} = \frac{m_\pi^2 + 2m_\pi m_N}{4\varepsilon}$$

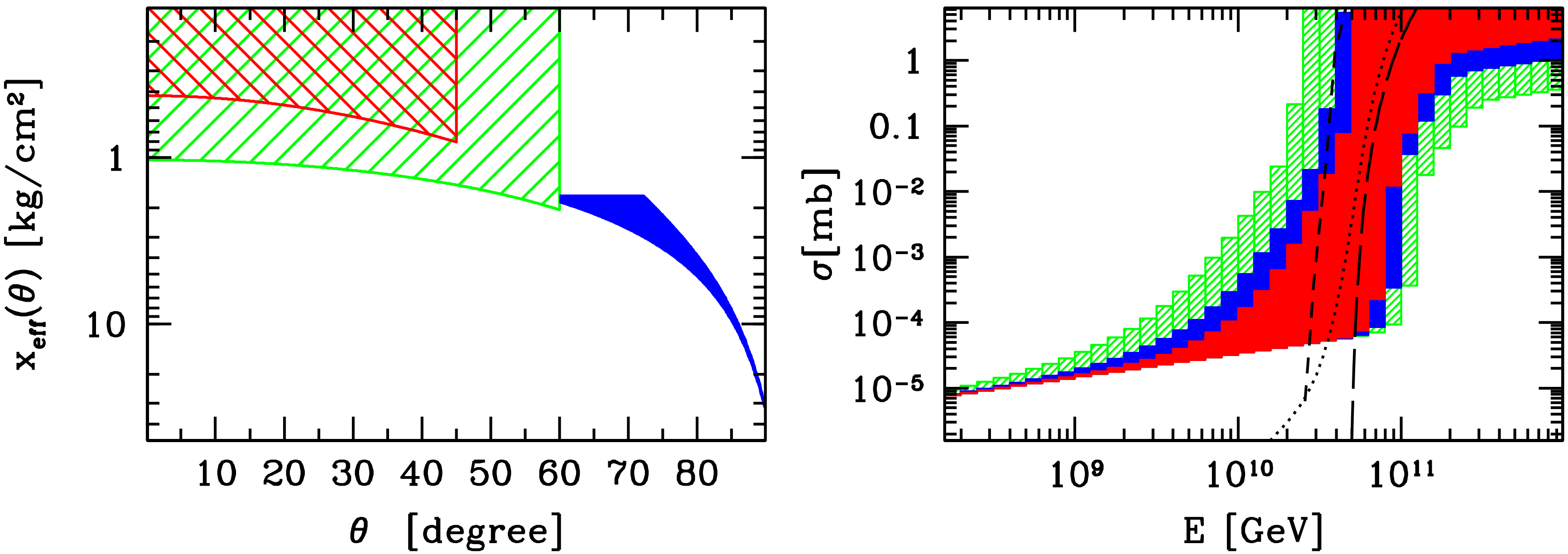
$$d > 5 \cdot 10^{-23} \qquad \xi > 10^{-14} \qquad \zeta > 10^{-6}$$

Strongly interacting neutrinos

- In theories with extra dimensions neutrino-nucleon cross section can be much larger then SM one.
- However, energy dependence is very different from observed one.



Strongly interacting neutrinos



From A.Ringwald, 2005

Model 5

- Clustering is real
- There is no cutoff in spectrum
- BL Lac correlation is real
- Solution: UHECR below cutoff are protons from sources uniformly distributed in the Universe. UHECR above cutoff are new particles:
  - New hadrons
  - Axion-like particles
  - Mirror-world hadrons

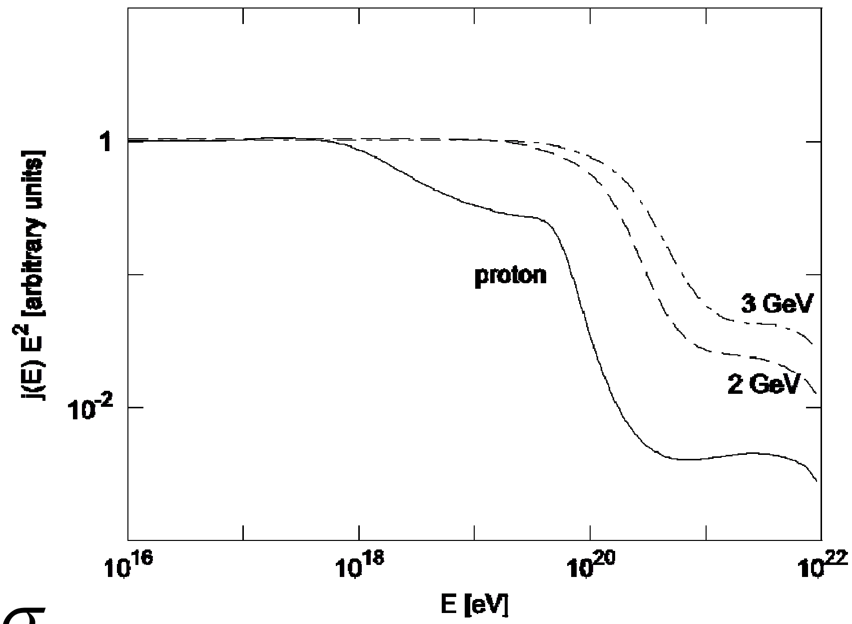
How to avoid GZK cutoff?

- If $M_S > M_P$, threshold energy higher:

$$E_{th} = \frac{m_\pi^2 + 2m_\pi M_S}{2\varepsilon_{CMB}} \approx 2\times10^{20}\,eV\,\frac{M_S}{2GeV}$$

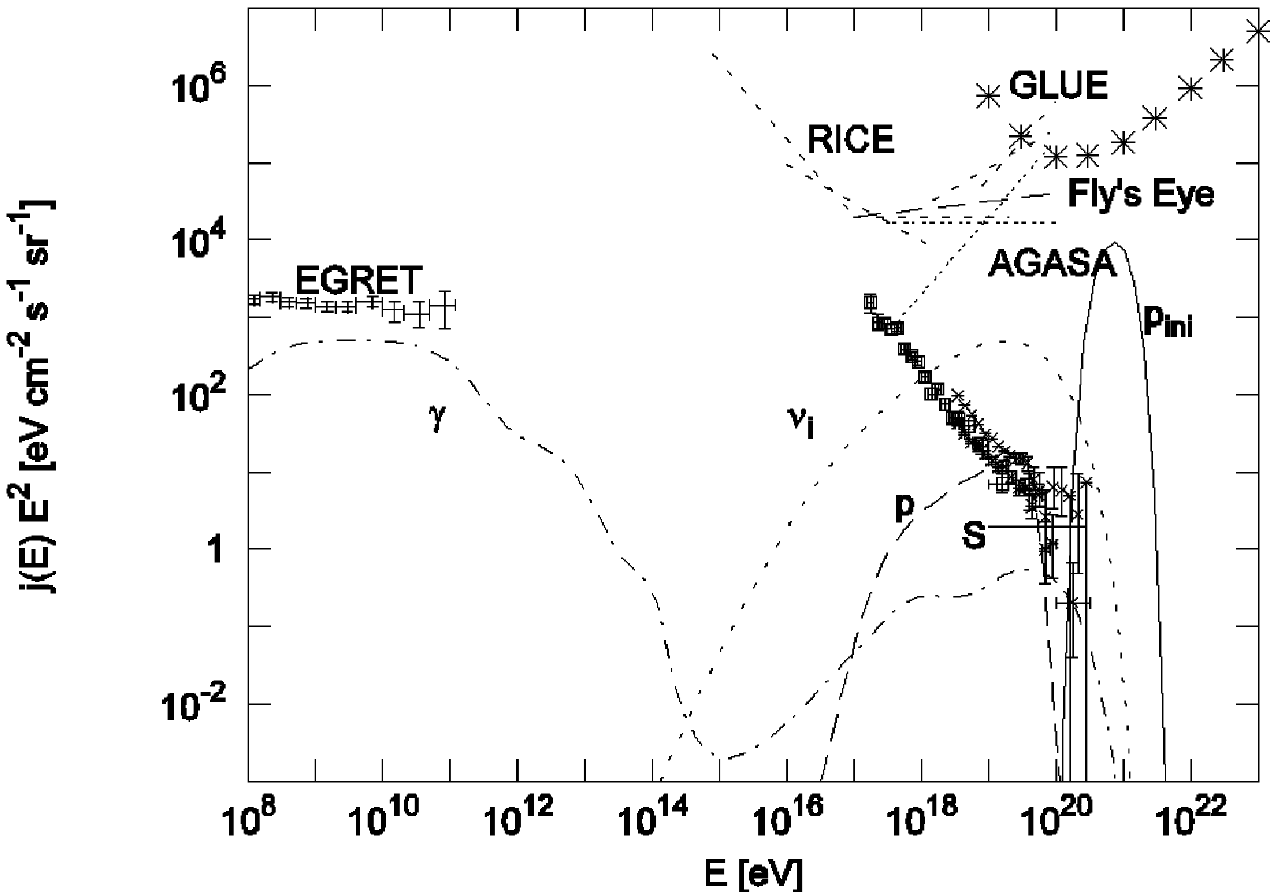
- Massive hadrons lost 95% energy above threshold after :

$$R_{GZK} = \frac{\ln 20}{y_S \sigma_{S\gamma} n_\gamma} \approx 500Mpc\,\frac{y_P}{2y_S}\,\frac{\sigma_{P\gamma}}{5\sigma_{S\gamma}}$$



G.Farrar, 1996

New hadrons



M.Kachelriess, D.S. and M.Tortola, hep-ph/0302161

Conclusions

- Large fraction of UHECR with energies below GZK cutoff $E<10^{20}$eV are protons from astrophysical sources.
- AGASA clusters in arrival directions of UHECR is consistent with AGN as UHECR proton sources. HiRes data does not contradict with this picture.
- UHECR with energies $E>10^{20}$eV require new physics or very extreme astrophysics.
- Correlations with BL Lacs if real require new physics
- Top-down models are difavorate by existing data. Most favorite are models with new particles or with violation of Lorentz invariance. New ideas wanted!