Acceleration of the Ultra High Energy Cosmic Rays to the highest energies

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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Paris, May 17

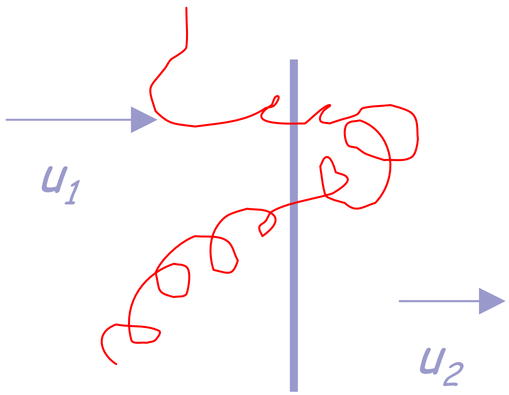
Overview:

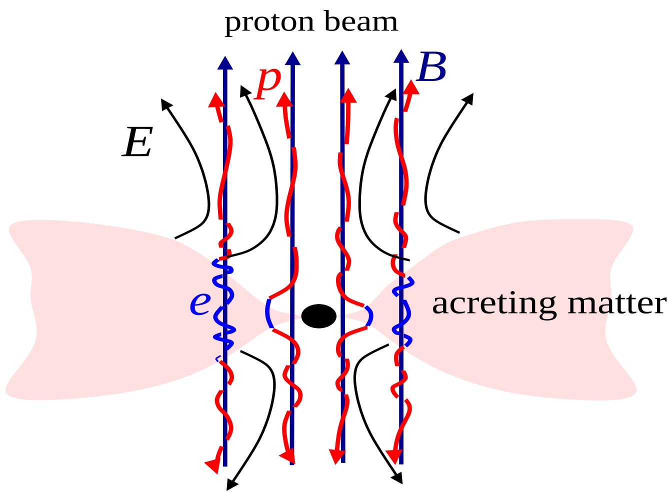
- *Important model restrictions:*
  - *Acceleration and astrophysical objects*
  - *Spectrum and composition. Propagation effects.*
  - *Anisotropy and source density*
  - *Secondary gamma-ray and neutrino fluxes*
- *Theoretical models:*
  - *Extragalactic protons*
  - *Extragalactic nuclei/mixed composition*
- *Conclusions*

Acceleration

First Order Fermi Shock Acceleration

Acceleration in electric field nearby from Black Hole or pulsar



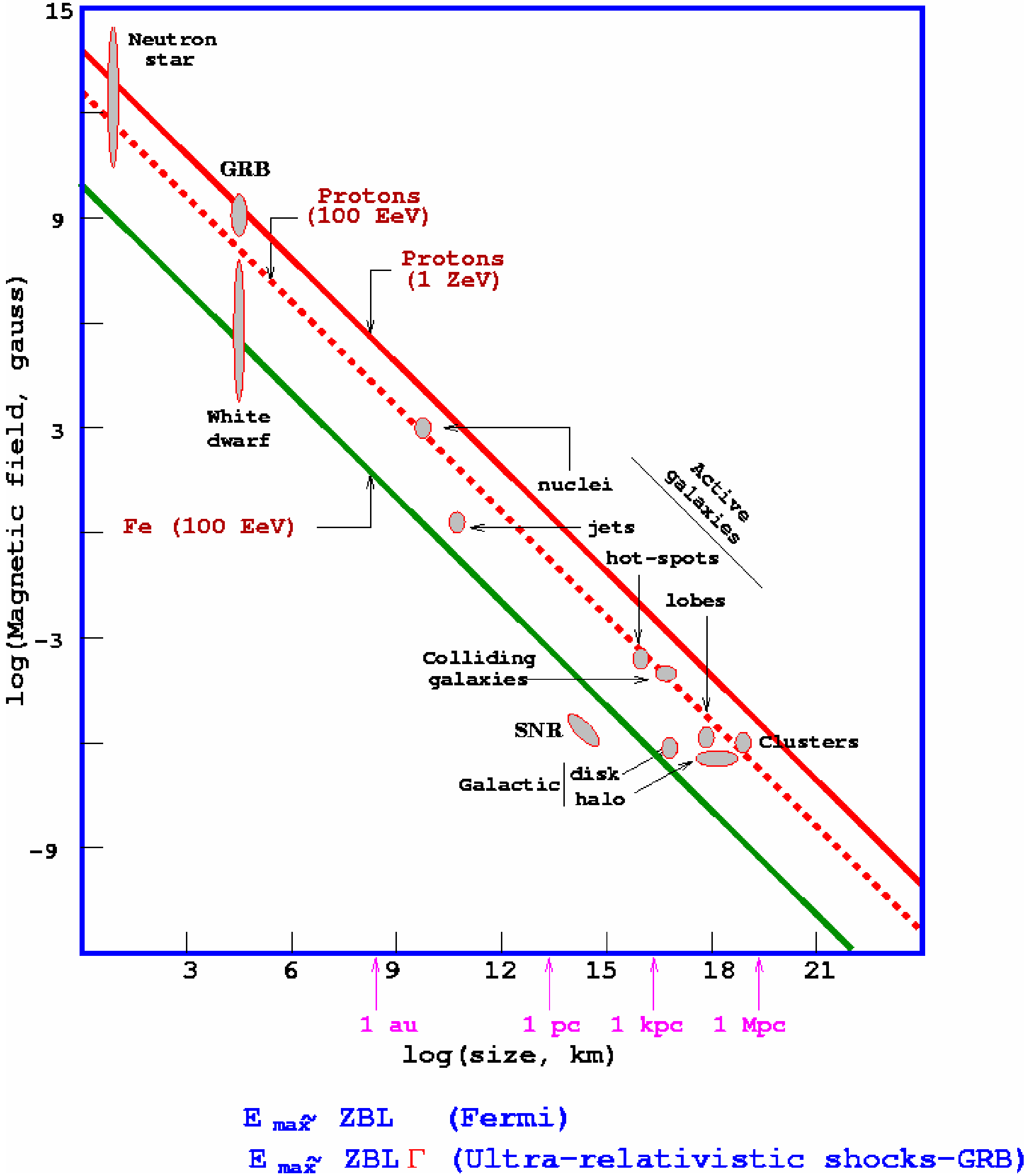


The fractional energy gain per shock crossing depends on the velocity jump at the shock. Together with loss processes this leads to a spectrum E^{-q} with $q > 2$ typically.

Similar to linear accelerator. Energy spectrum has peak around energy corresponding to potential difference. It can be accompanied by large gamma-ray flux due to energy losses.

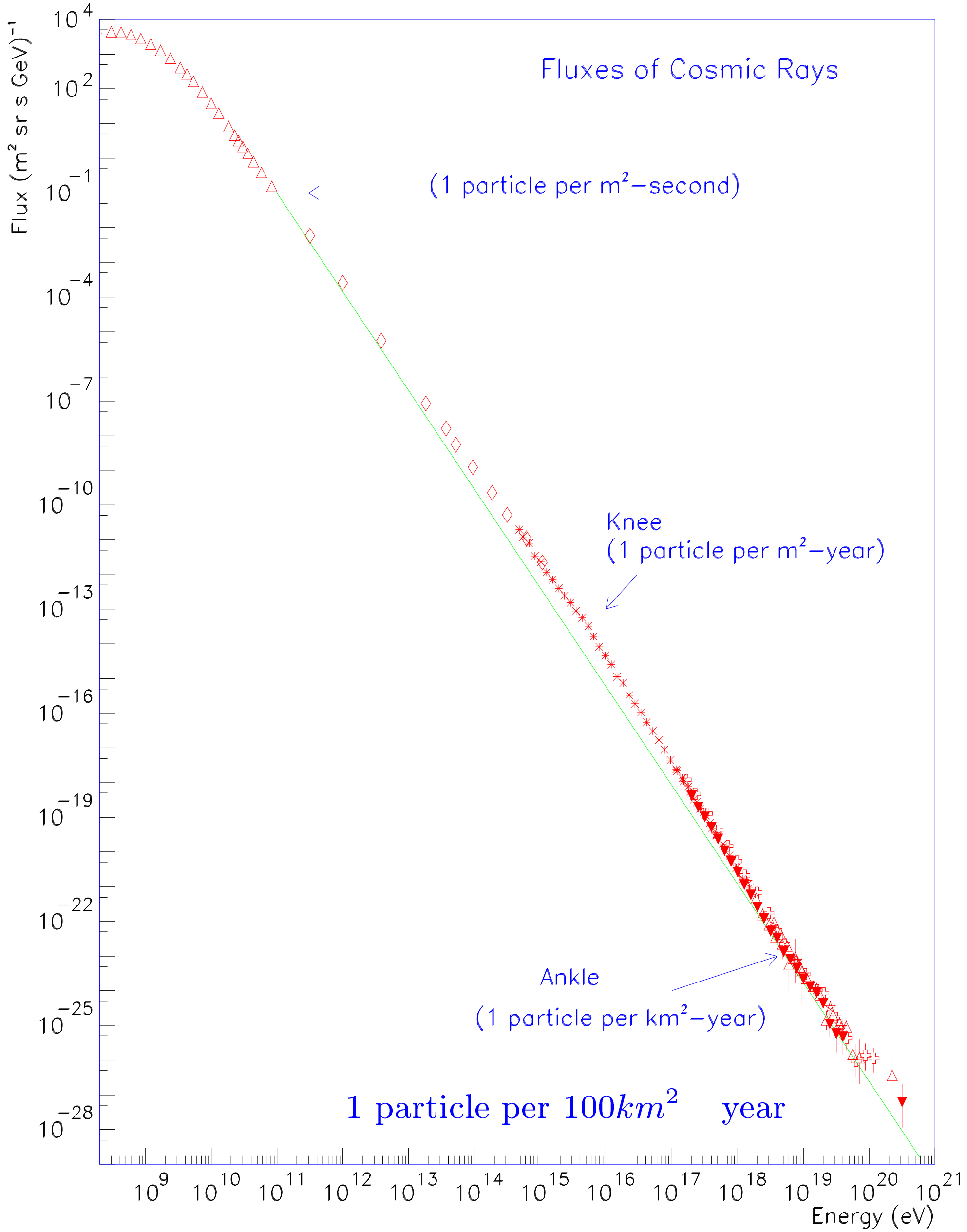
- Only few classes of astrophysical objects are able to accelerate particles to highest energies

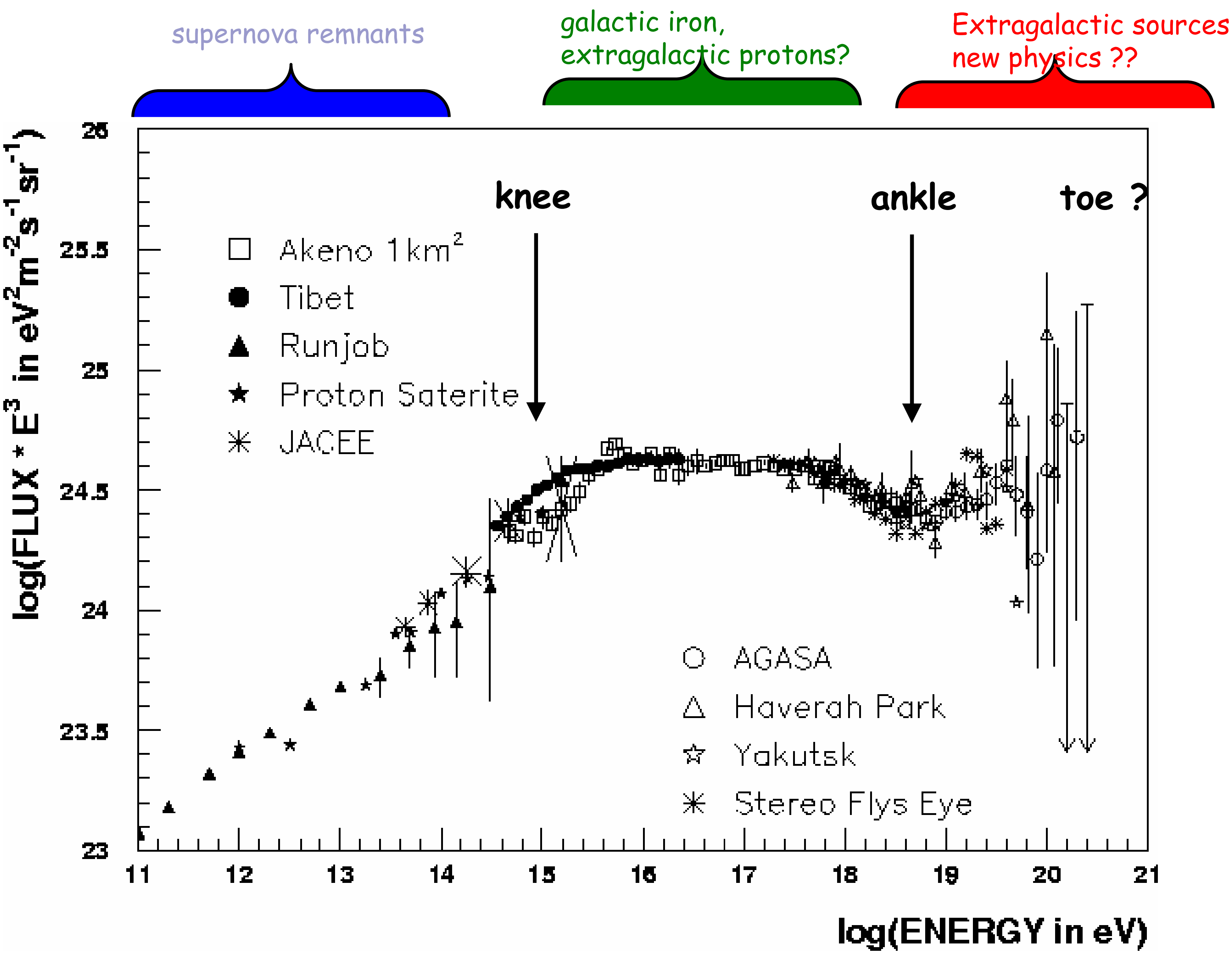
Hillas-plot
(candidate sites for E=100 EeV and E=1 ZeV)



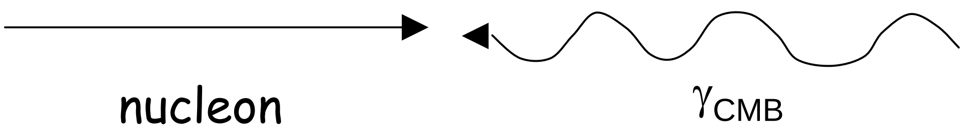
Spectrum and composition.

Sun Galactic (SN remnants) ??? extra Galactic




supernova remnants
galactic iron,
extragalactic protons?
Extragalactic sources,
new physics ??
knee
ankle
toe ?
Akeno 1 km^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)

The Greisen-Zatsepin-Kuzmin (GZK) effect



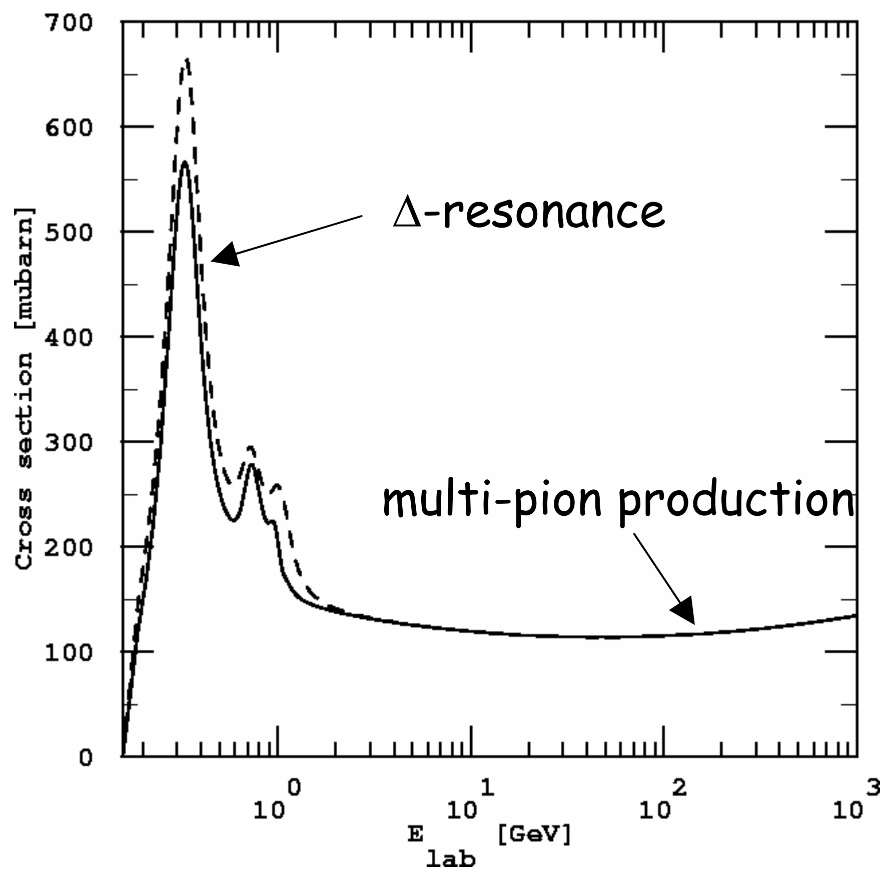
$$E_{th} = \frac{2m_N m_\pi + m_\pi^2}{4\varepsilon} \approx 10^{20}\,\mathrm{eV}$$

Nucleons can produce pions on the cosmic microwave background

$$n_{CMB} = \frac{411}{cm^3}$$

$$l = \frac{1}{\sigma_{p\gamma} n_{CMB}} \approx 8\,\mathrm{Mpc}$$

$$1\,\mathrm{Mpc} = 3 \cdot 10^{24}\,cm$$



Pair production by proton

- Pair production: $$p+\gamma \rightarrow p+e^{+}+e^{-}$$
- Cross section: $$\sigma_{PPP} \prec \alpha \cdot \sigma_T$$

$$\sigma_T = \frac{8\pi}{3}\frac{\alpha^2}{m_e^2} = 6.65 \cdot 10^{-25} cm^2$$

- Interaction length: $$l = \frac{1}{\sigma_{PPP} n_{CMB}} \approx 1\,\mathrm{Mpc}$$

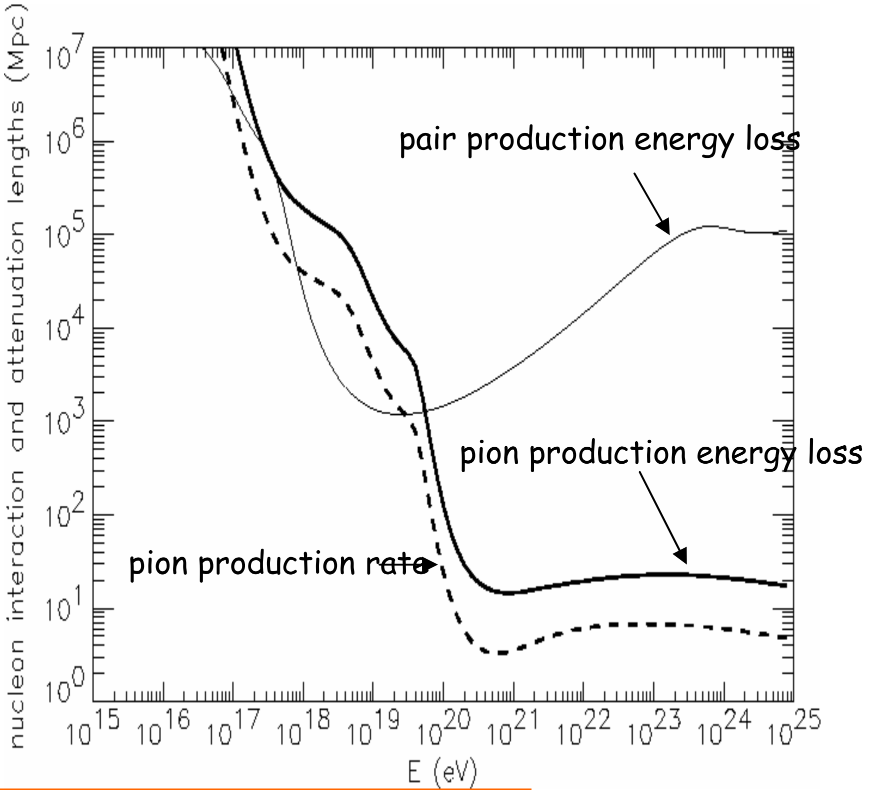
Pair production / pion production

- Pair production losses:

$$R_{PPP} = \frac{1Mpc}{2m_e / M_P} \approx 1000Mpc$$

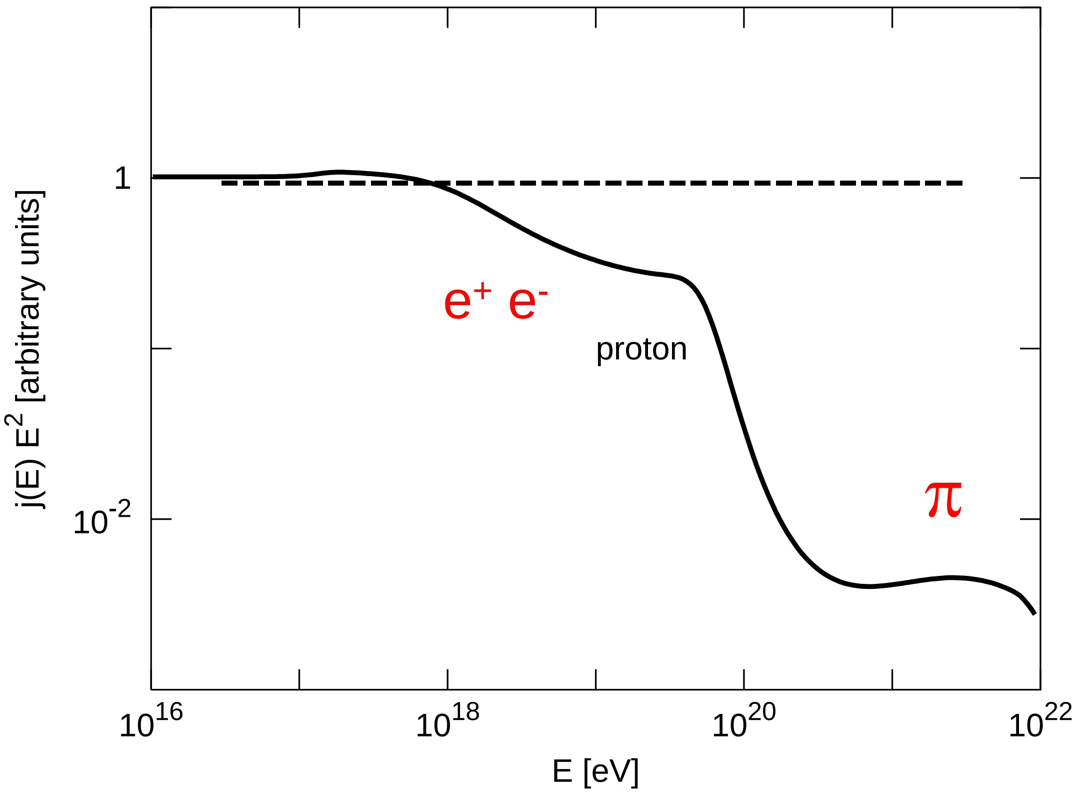
- Pion production losses:

$$R_{GZK} = \frac{8Mpc}{m_\pi / M_P} \approx 50Mpc$$

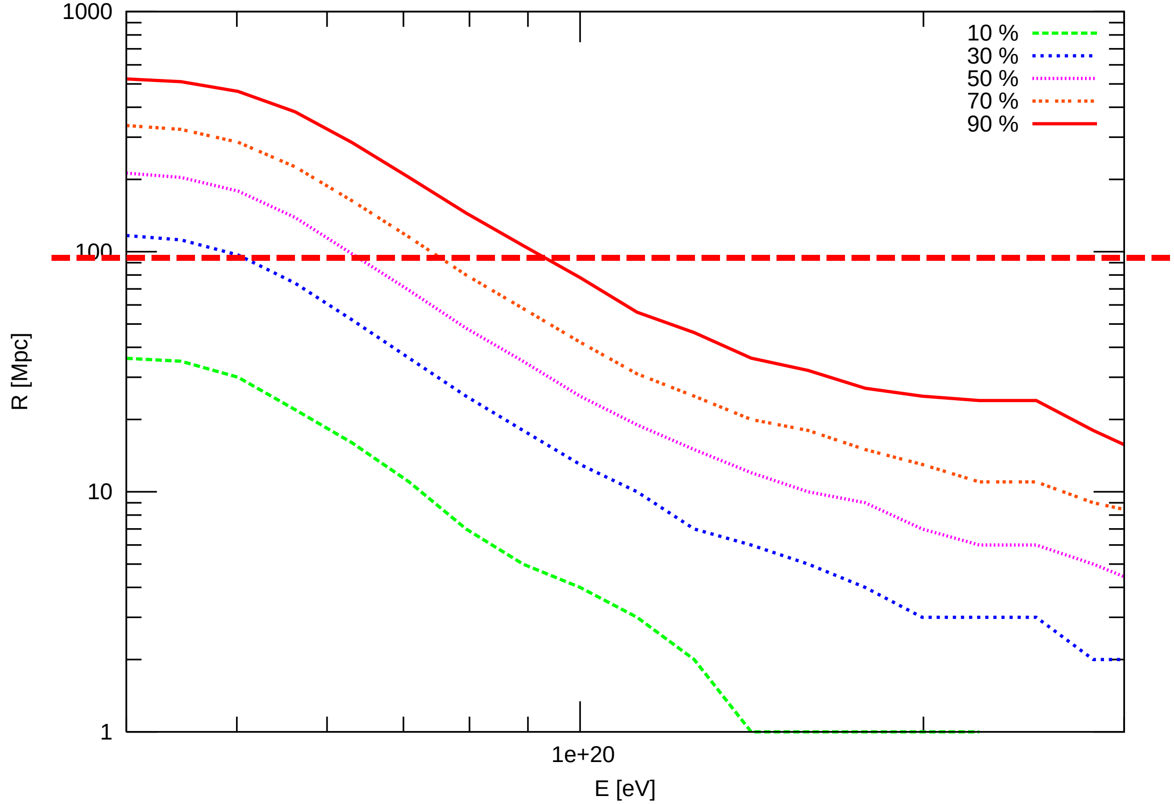


⇒Sources for E>10^{20} eV must be in cosmological backyard within 50-100 Mpc from Earth
(compare to the Universe size ~ 5000 Mpc)

Spectrum of protons

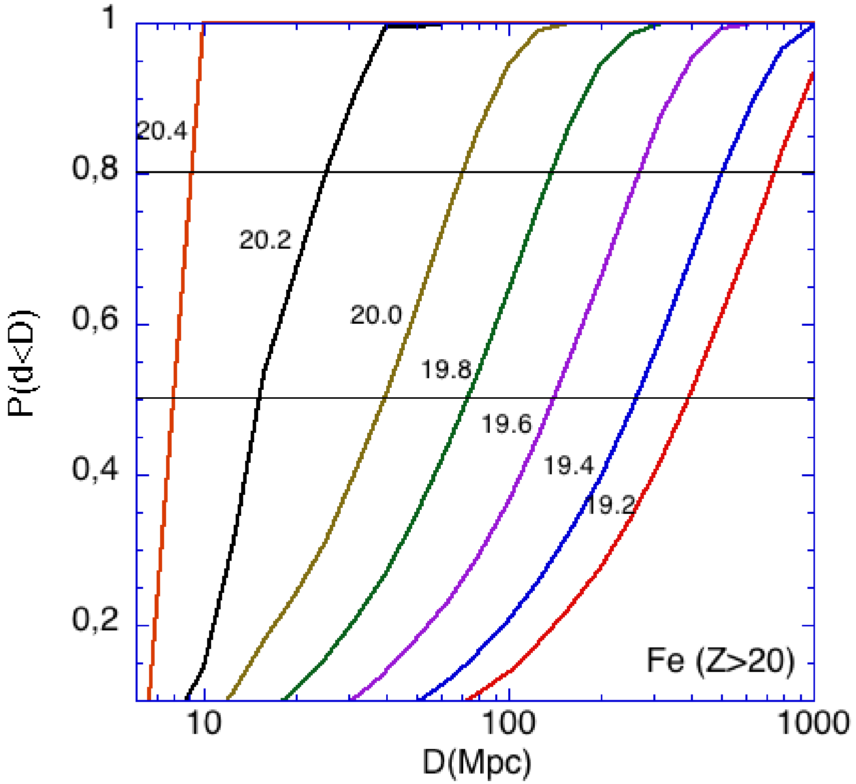


Horizon for protons



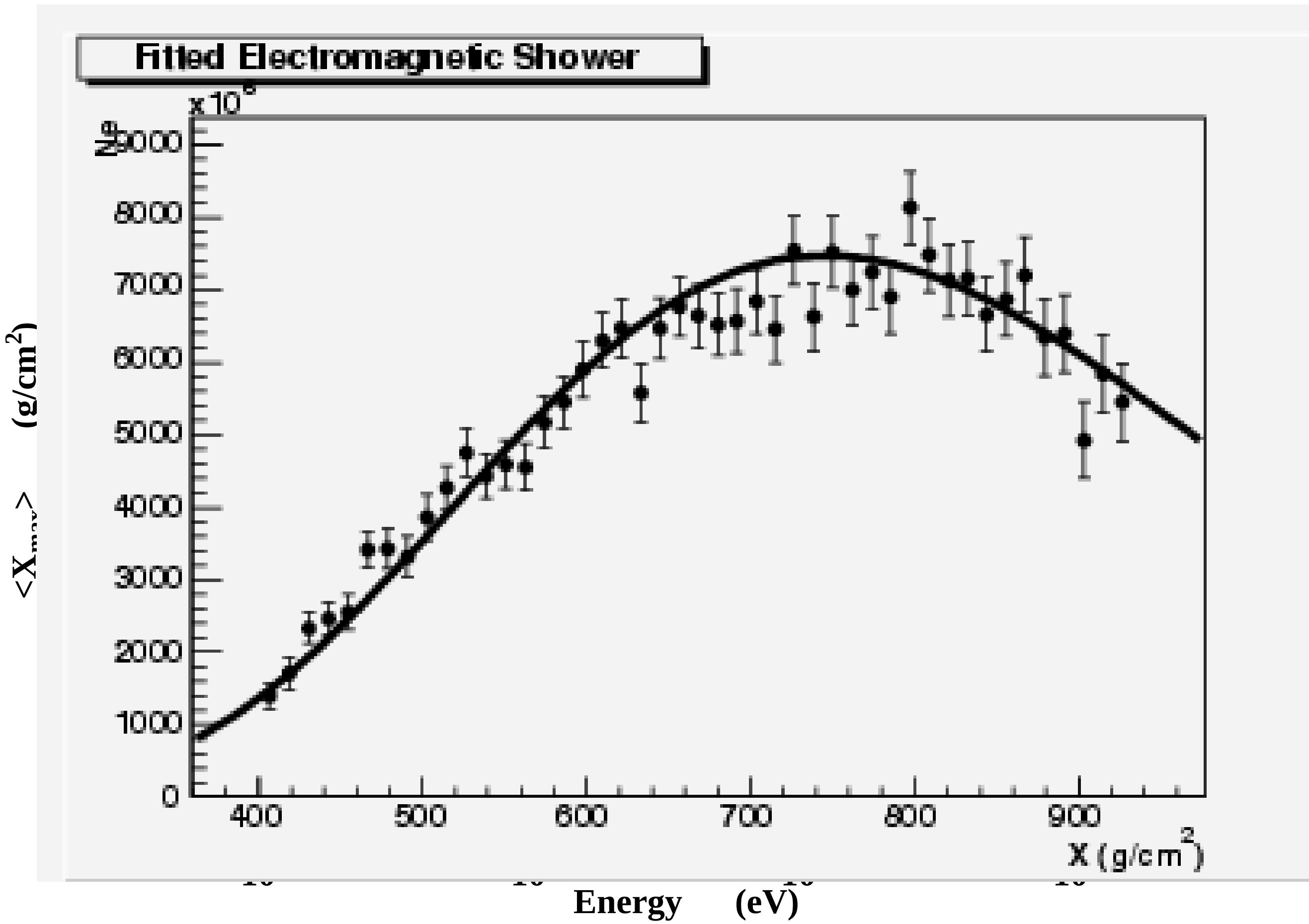
Simulation with SOPHIA, stochastic energy losses, assuming dE/E = 20% event by event

Fraction of Fe



Simulation by D.Allard

Composition study



T.Pierog, R.Engel and D.Heck, astro-ph/0602190

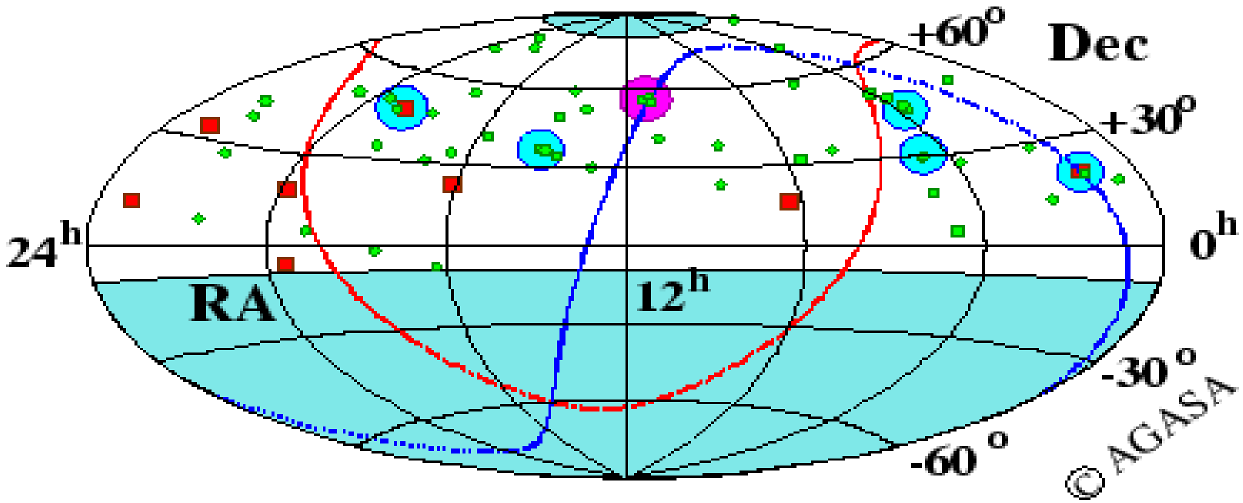
Composition at energies above 10^{19} eV.

- Photons < 2 % (Auger preliminary, ICRC 2007)
- Hadrons > 98% (Auger)
- Neutrinos 0% (AGASA, HiRes & Auger)
- Fe < 50 % (AGASA and HiRes)

- Fe/protons impossible to distinguish event by event, contrary to photons and neutrinos.

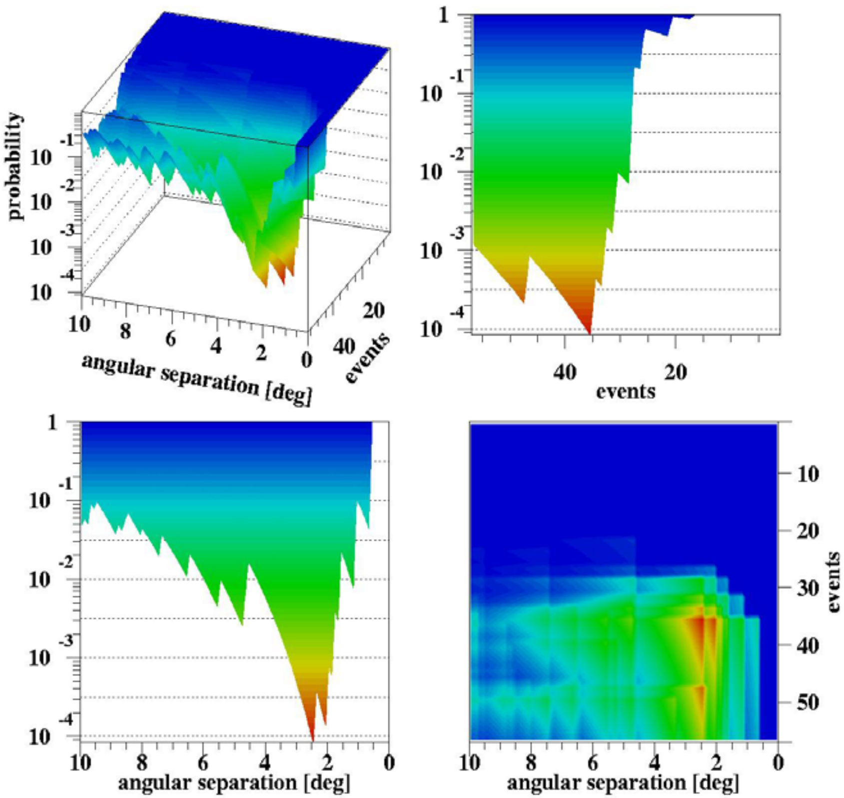
Arrival directions of UHECR.

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.

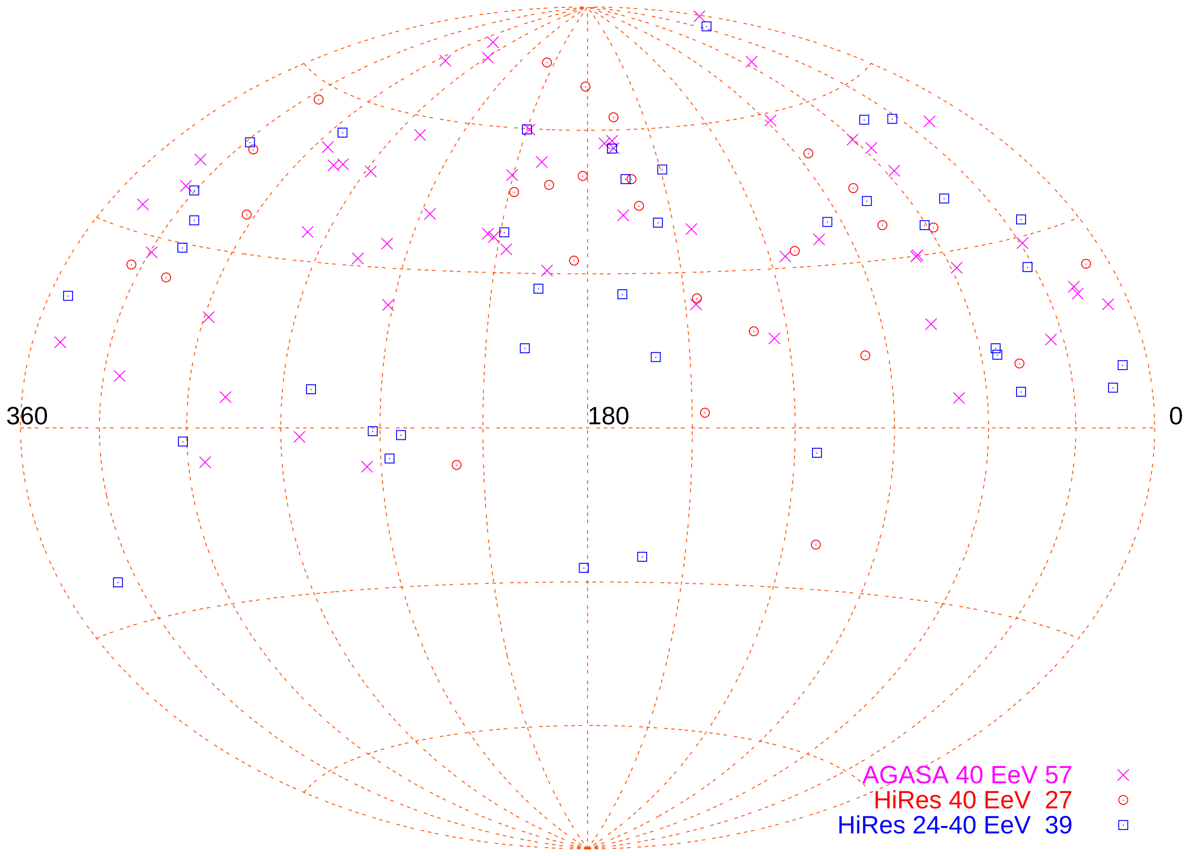
Test of AGASA angular cut.



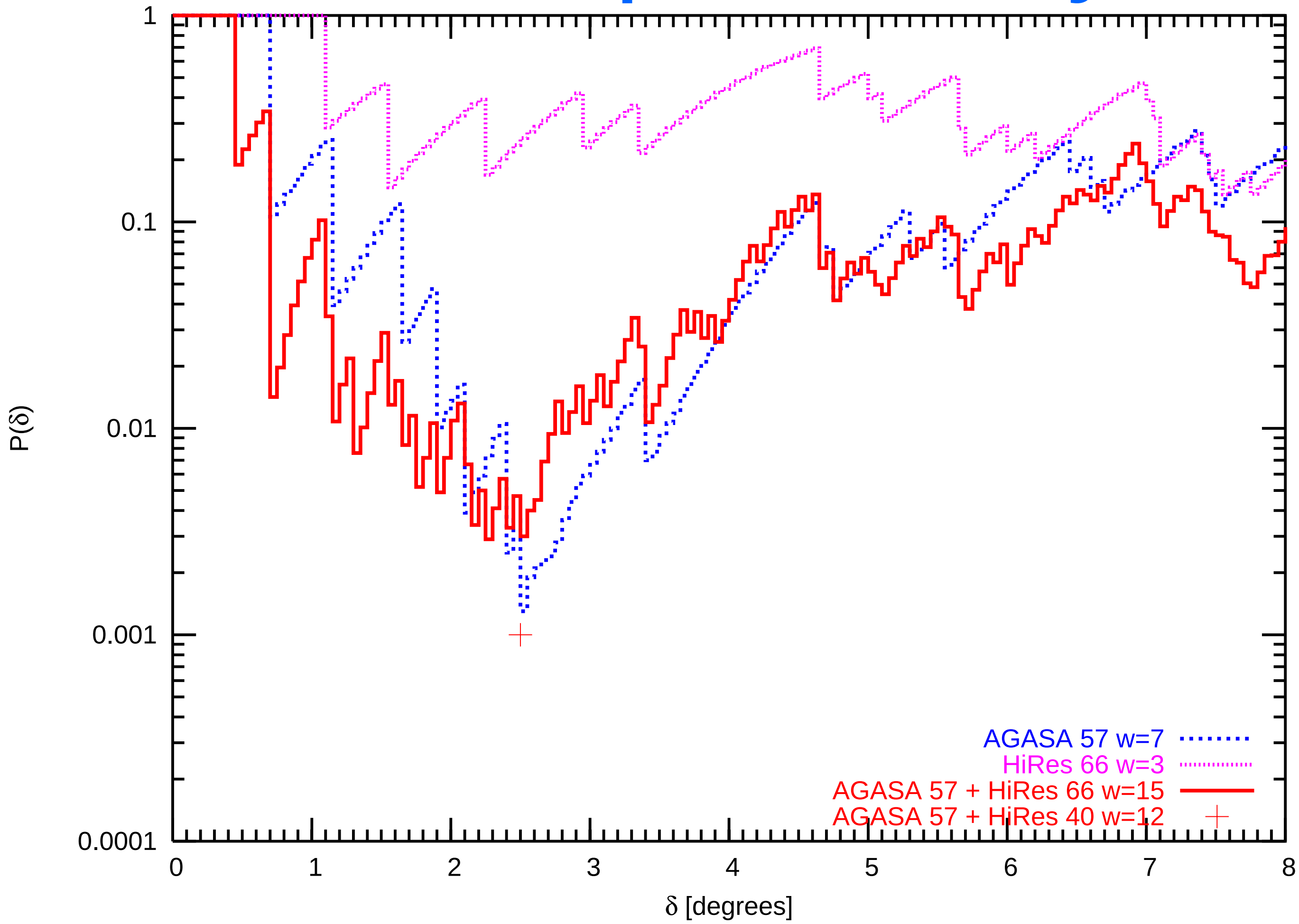
Finley and Westerhoff,
astro-ph/0309159

AGASA clustering is by chance with probability $P = 3 \cdot 10^{-3}$

Arrival directions AGASA and HiRes



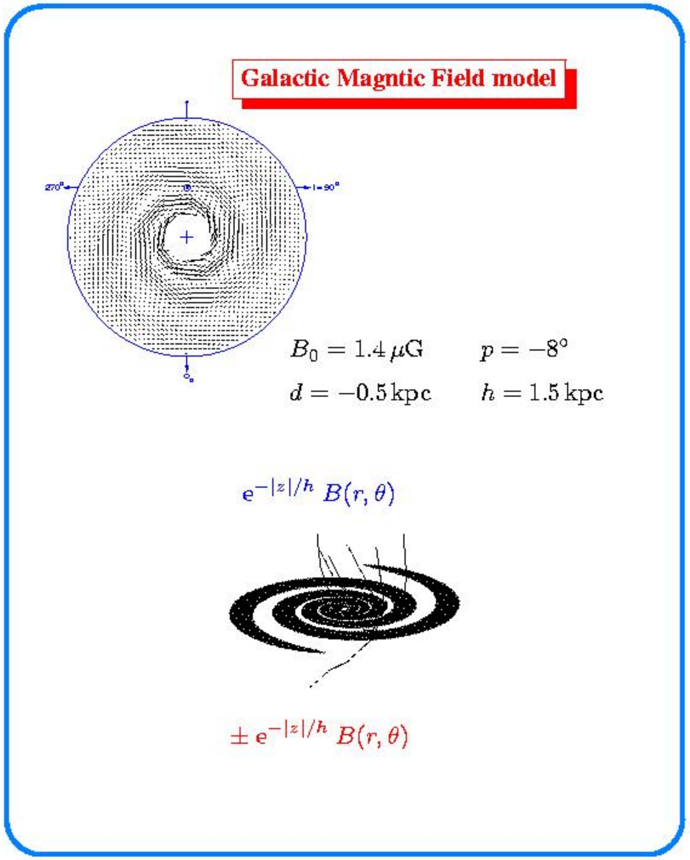
Chance probability



D.S., habilitation thesis

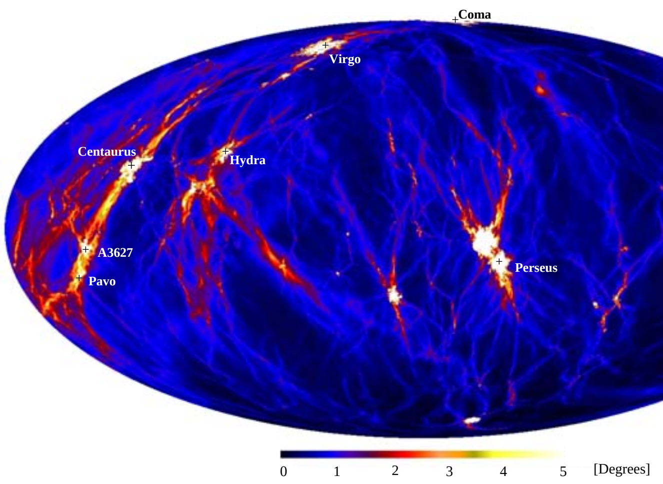
Galactic Magnetic field

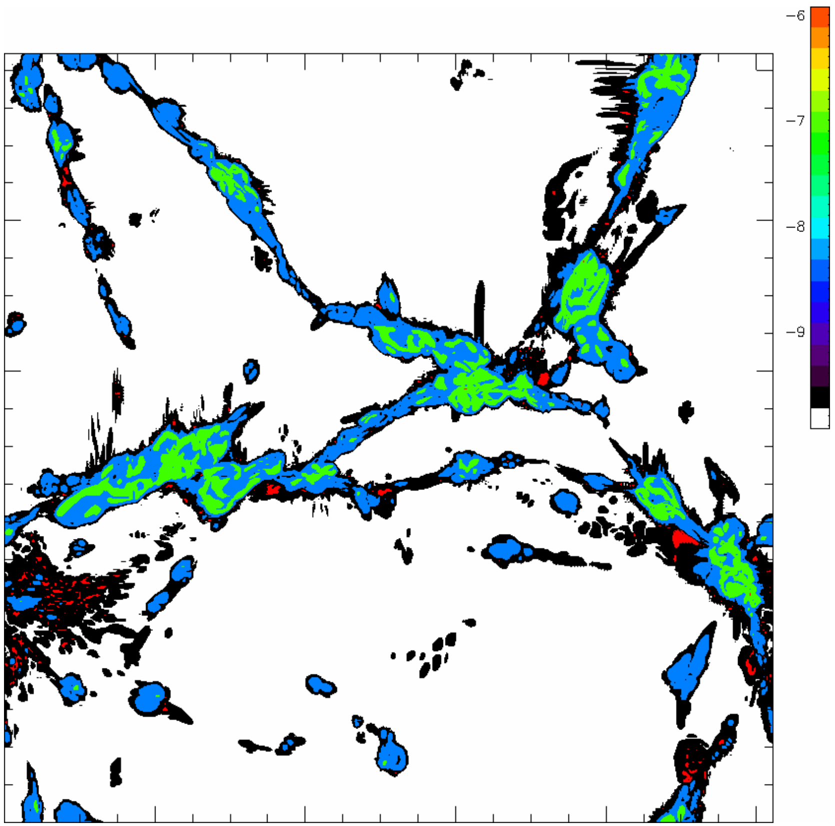
- At energies E > 4×10^{19} eV proton deflection is only 3-5 degrees.



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

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

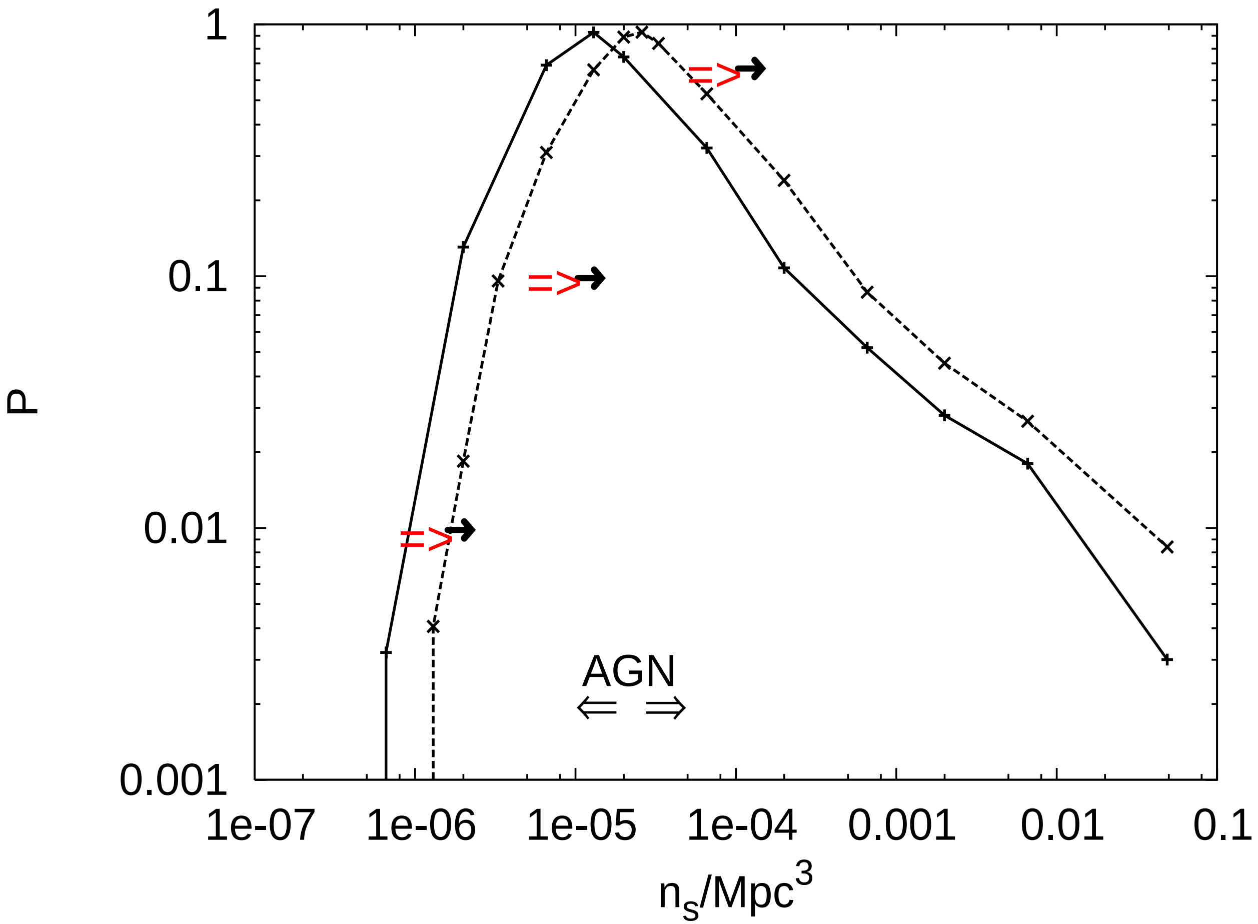




Dolag et al, 2003

Sigl et al, 2002-2003

Density of UHECR sources from AGASA and HiRes data



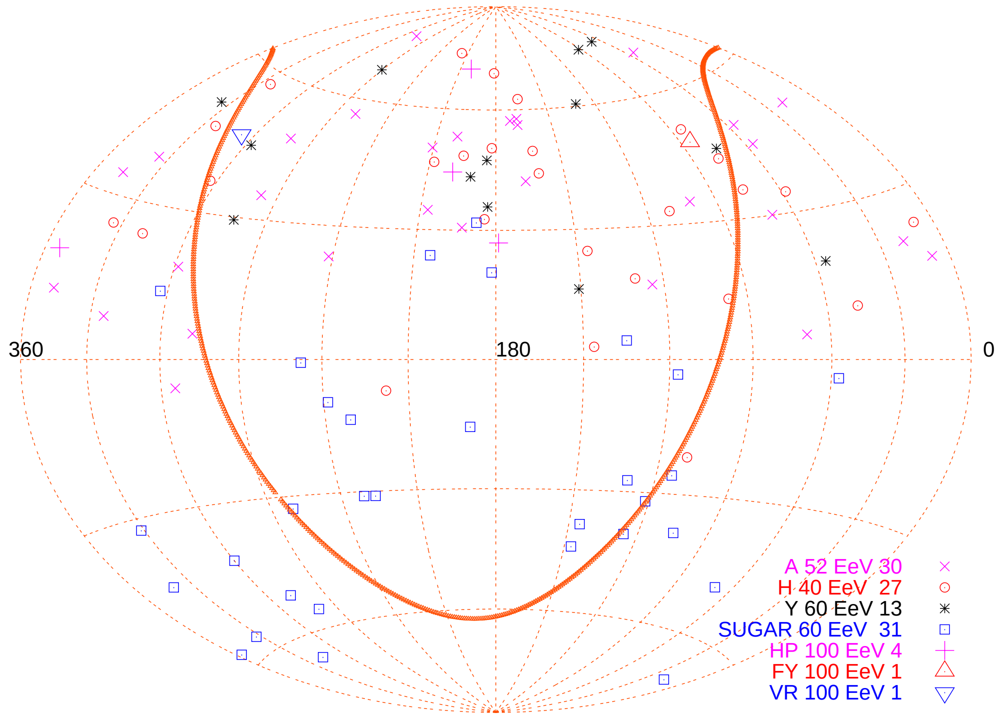
M.Kachelriess and D.S., astro-ph/0405258

Small scale clusters: summary

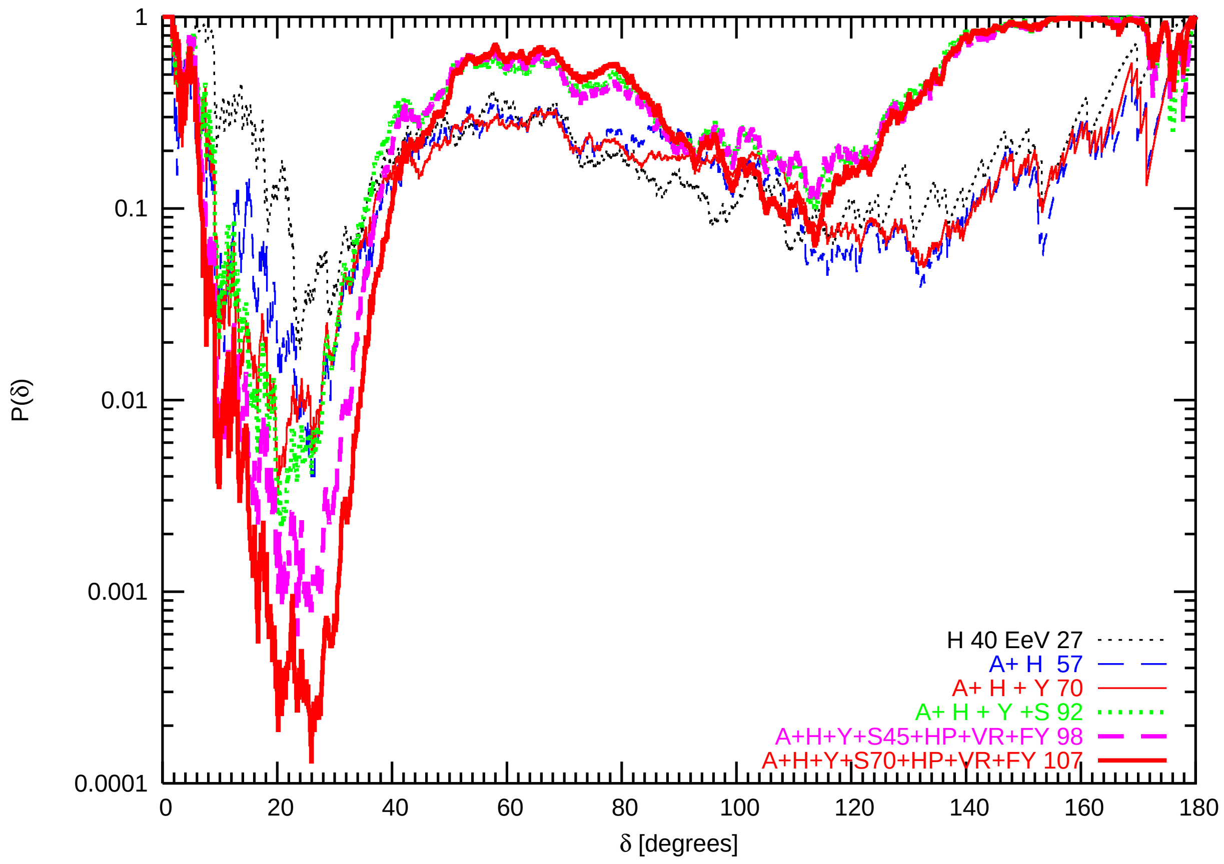
- AGASA sees small scale clusters in arrival directions of cosmic rays at energies $E>4\times10^{19}$eV with significance 3 σ. HiRes data do not contradict to it.
- Galactic magnetic fields are not strong enough to deflect protons at those energies more then for few degrees.
- If extragalactic fields are small, estimate of number of sources agrees with density of AGN.
- Most probable explanation: protons from astrophysical sources. Auger will be able to define source density and probably will find sources.

Clustering on medium scales.

Arrival directions for E>40 EeV in HiRes (E>52 EeV in AGASA)

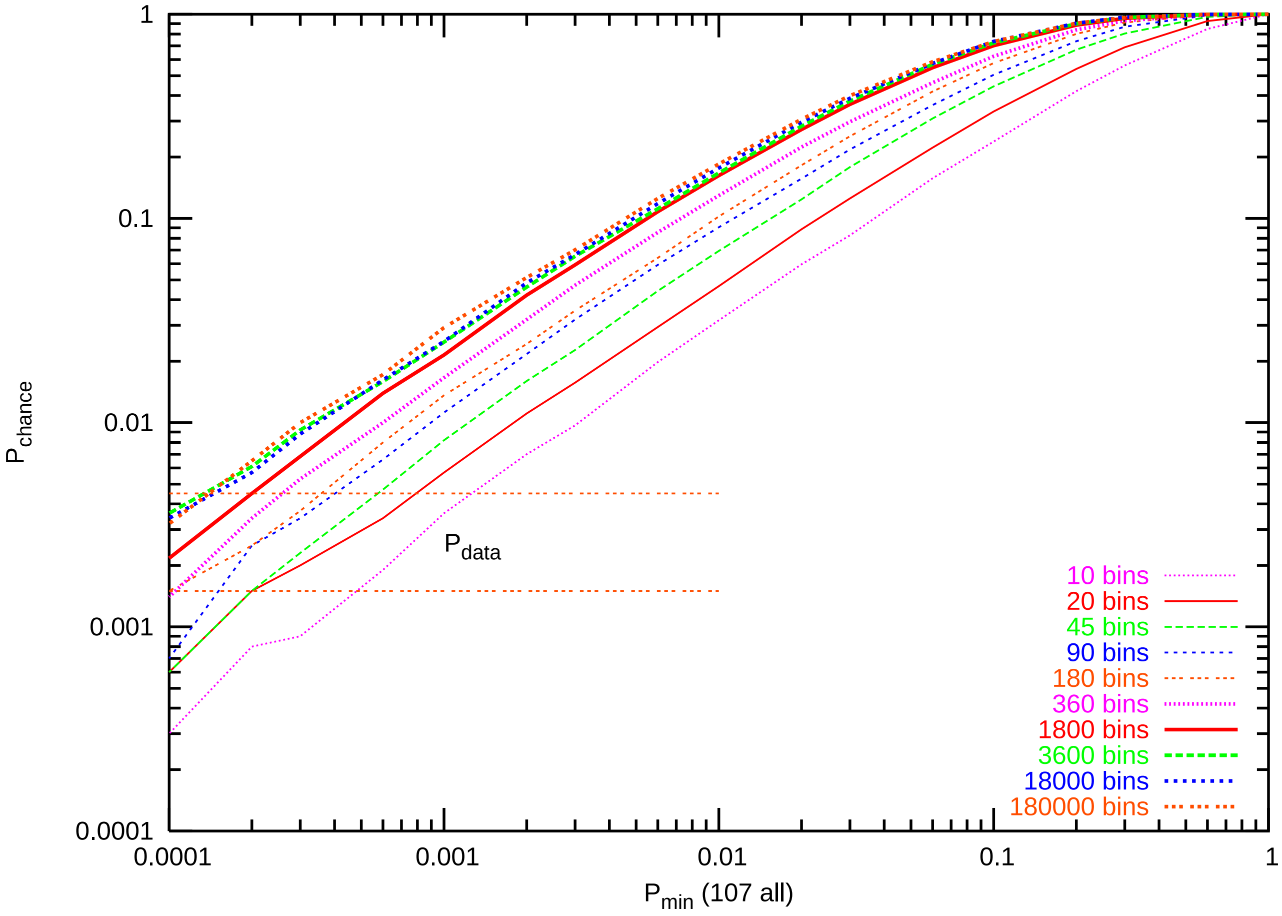


Probability of correlation



M.Kachelriess and D.S., astro-ph/0512498

Chance probability



M.Kachelriess and D.S., astro-ph/0512498

Medium scale clusters: summary

- At energy E>4x10^{19}eV (HiRes scale) medium scale clusters show up at 20-25 degrees with significance ~3 σ.
- Galactic magnetic fields are not strong enough to deflect protons at those energies more then for few degrees.
- Those clusters if real should be connected to local Large Scale Structure and extragalactic magnetic fields.
- Most probable explanation: protons and nuclei from sources connected with LSS. Auger will be able to check this but large statistics needed.

Secondary gamma-rays and neutrinos.

Pion production

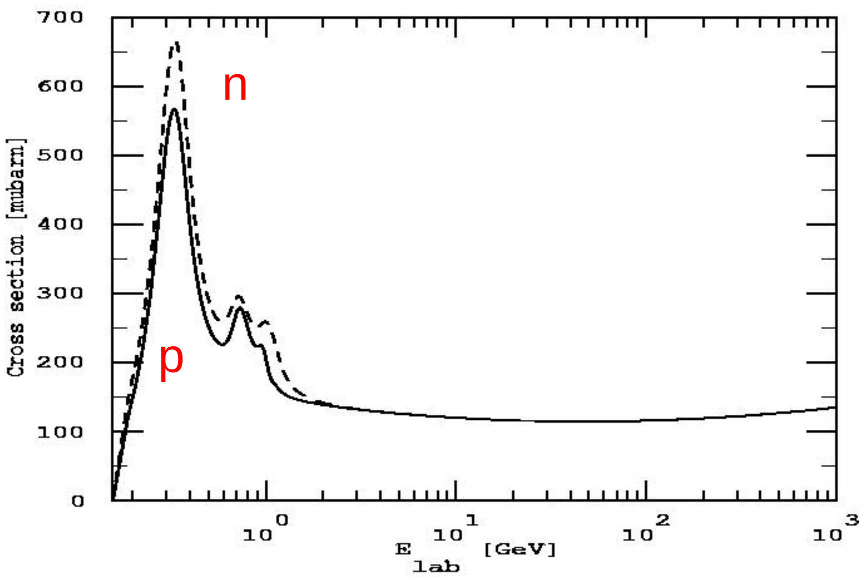
$$N + \gamma_b \Rightarrow N' + \sum \pi^i$$

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

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

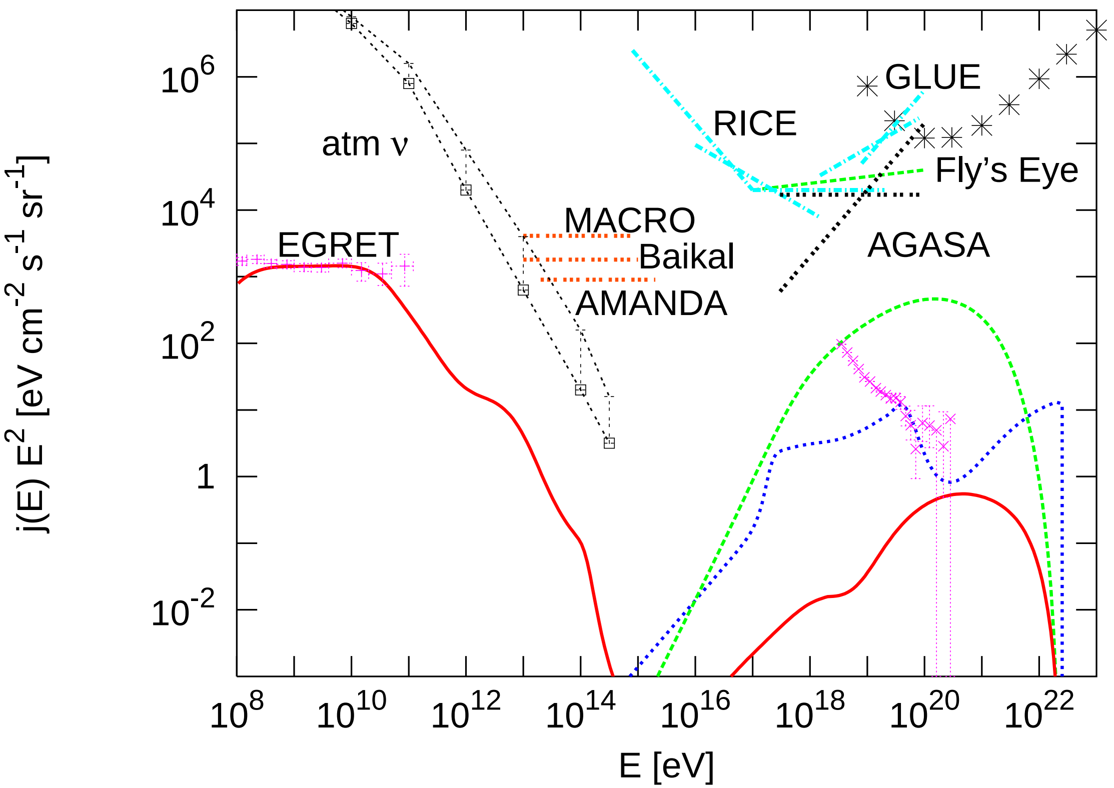
$$\mu^\pm \Rightarrow e^\pm + \overline{\nu}_e + \nu_\mu$$

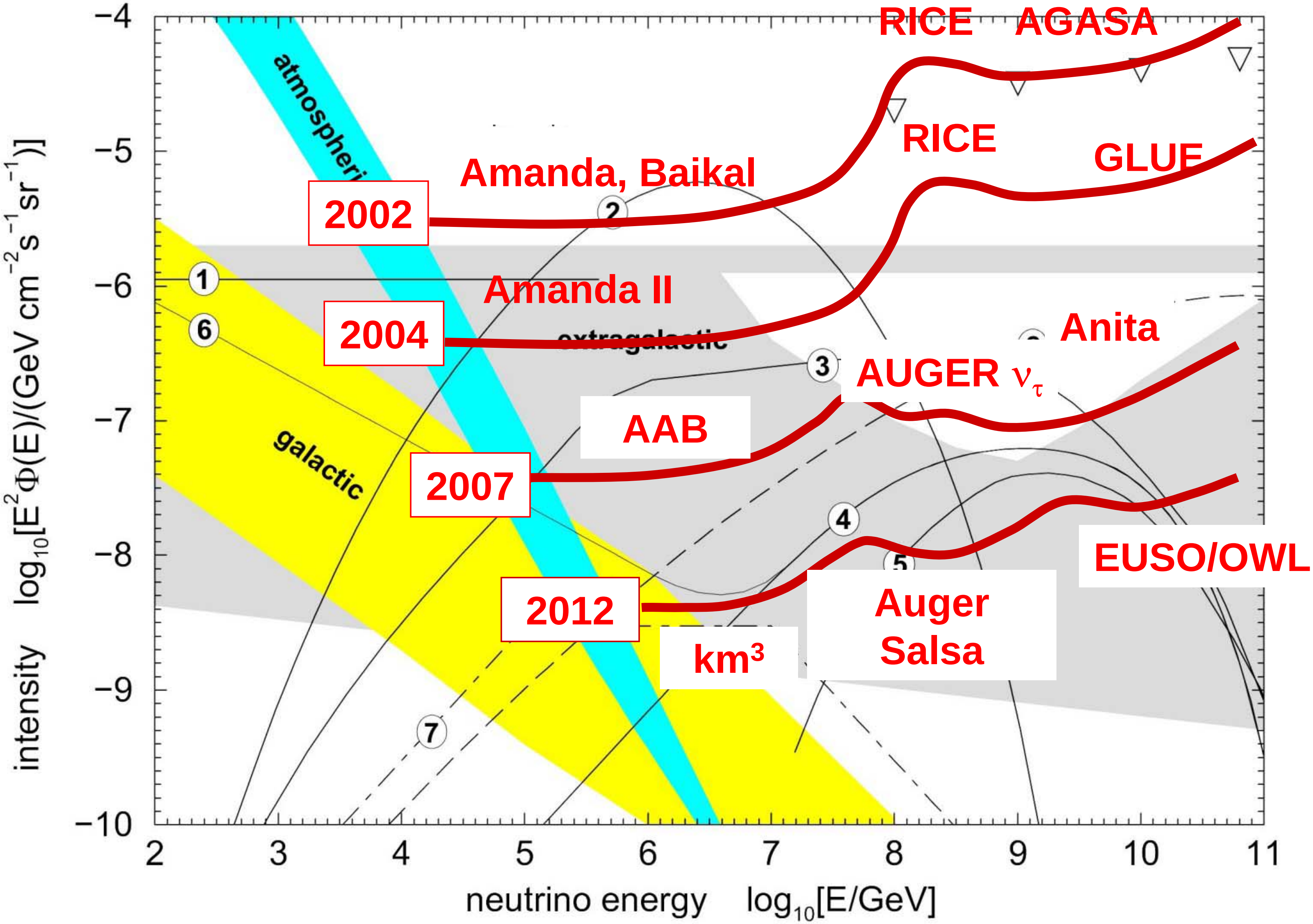
$$n \Rightarrow p + e^- + \overline{\nu}_e$$



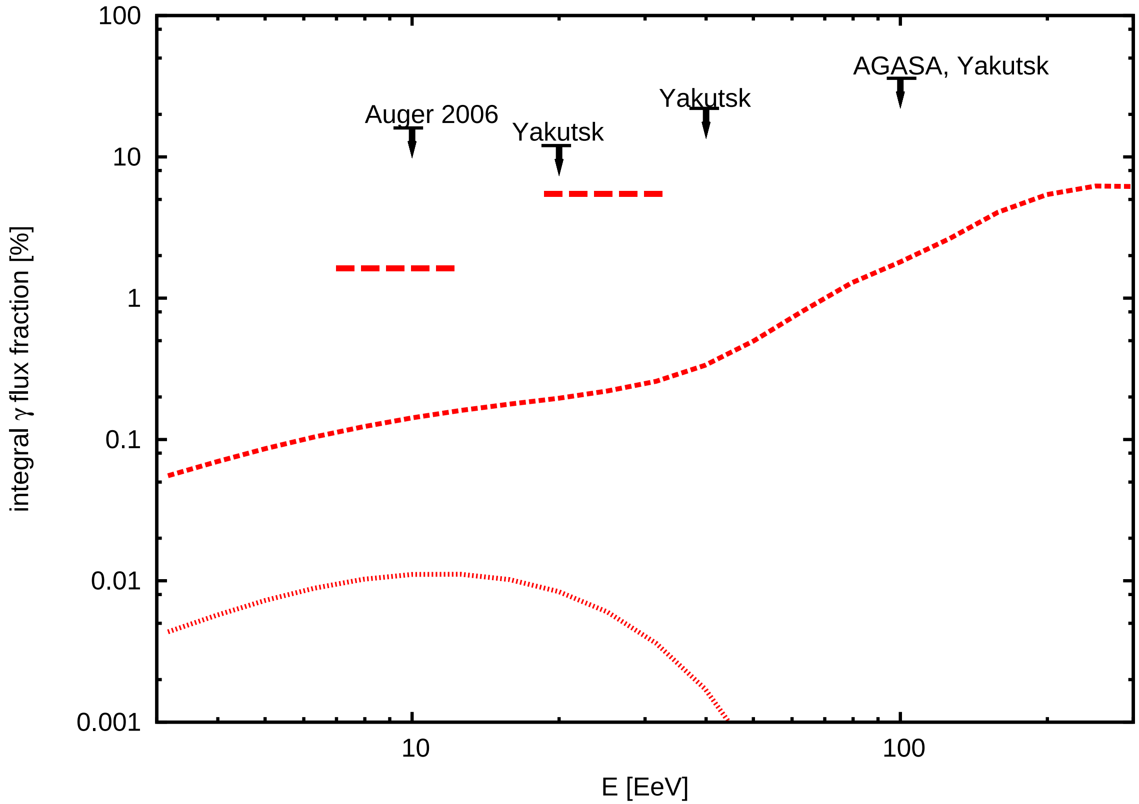
Conclusion: proton, photon and neutrino fluxes are connected in well-defined way. If we know one of them we can predict other ones: $E_\gamma^{tot} \sim E_\nu^{tot}$

UHECR, gamma-ray and neutrino fluxes




RICE
AGASA
RICE
GLUE
Amanda, Baikal
2002
atmospheric
Amanda II
2004
extragalactic
Anita
AUGER ν_τ
AAB
2007
galactic
EUSO/OWL
2012
Auger
Salsa
km³
1
2
3
4
5
6
7
intensity log10[E²Φ(E)/(GeV cm⁻² s⁻¹ sr⁻¹)]
neutrino energy log10[E/GeV]
−4
−5
−6
−7
−8
−9
−10
2
3
4
5
6
7
8
9
10
11

Sensitivity to fraction of photons



G.Gelmini, O.Kalashev and D.S. , astro-ph/0702464

Summary: UHECR photons and neutrinos

- Large fraction of UHECR with energies around GZK cutoff $10^{19}eV<E<10^{20}eV$ most probably are protons from astrophysical sources. Those protons would produce GZK neutrinos + GZK photons.
- GZK photons are 0.01% – 0.1% fraction of UHECR.
- GZK photons and neutrinos can be tested by future experiments

UHECR models and standard physics.

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
- Obey composition measurements
- Interaction in atmosphere similar to hadrons
- Large scale isotropy of arrival directions
- Explain small and medium scale clusters
- Obey gamma-ray and neutrino flux limits
- Highest energy cosmic rays should point back to sources

Minimal model of UHECR

Protons from astrophysical sources

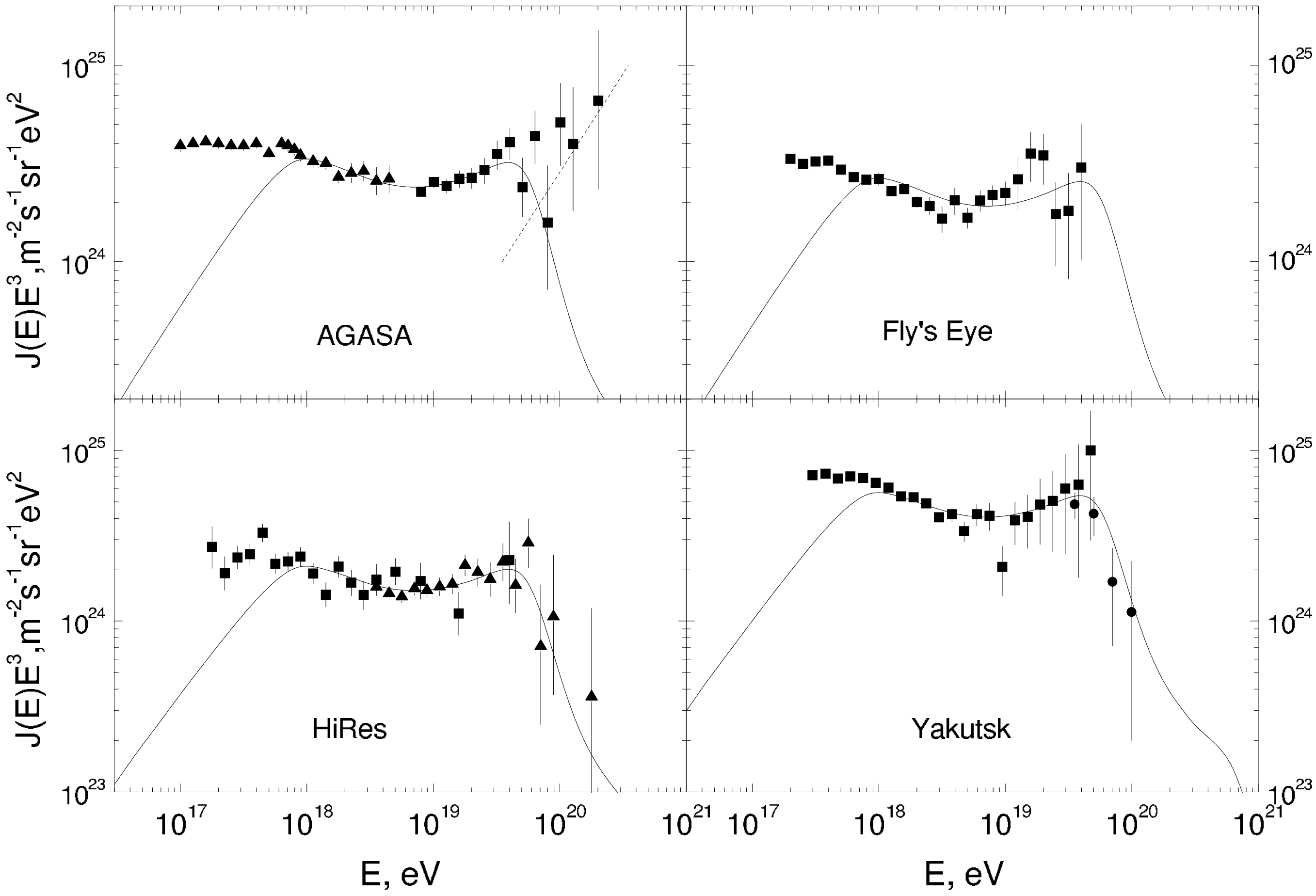
- Most of UHECR with E> 10^{18} eV are protons
- Spectrum of single source
- Luminosity of sources and their distribution

Composition HiRes + QGSJet-I

$$F(E) = \theta(E_{\max} - E) / E^{\alpha}$$

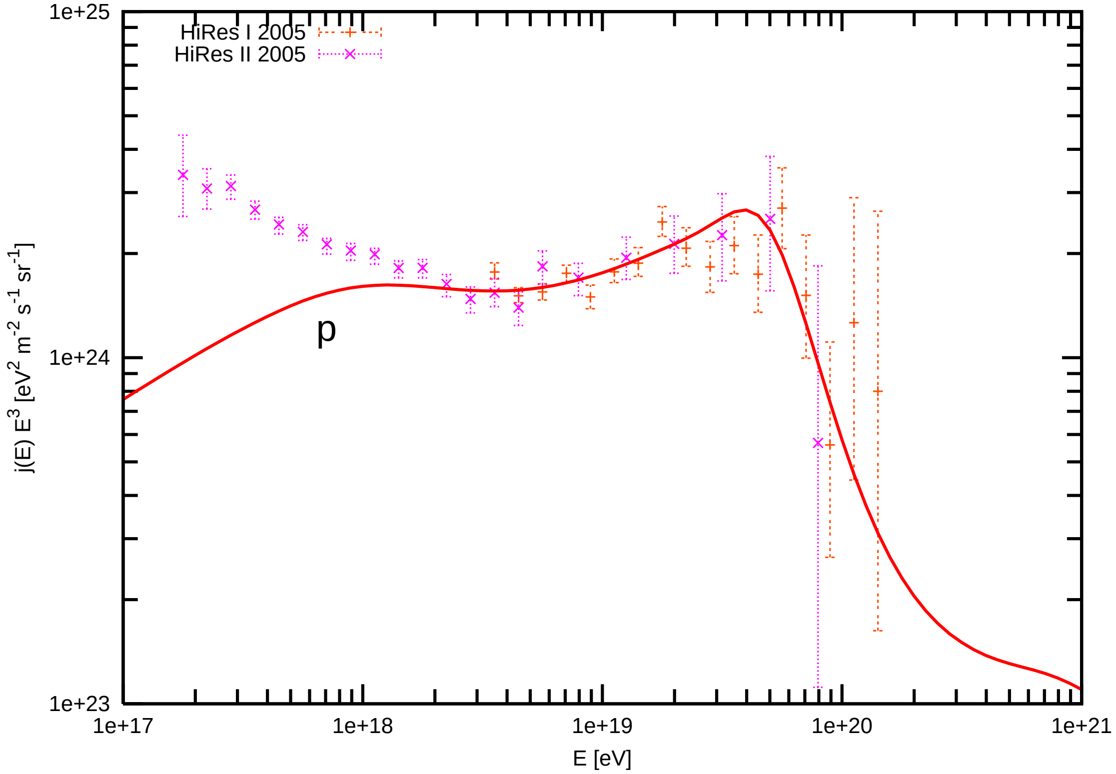
$$n(z) = n_0 \cdot \theta(z_{\max} - z) \cdot \theta(z - z_{\min}) \cdot (1+z)^{3+m}$$

Protons can fit UHECR data



V.Berezinsky , astro-ph/0509069

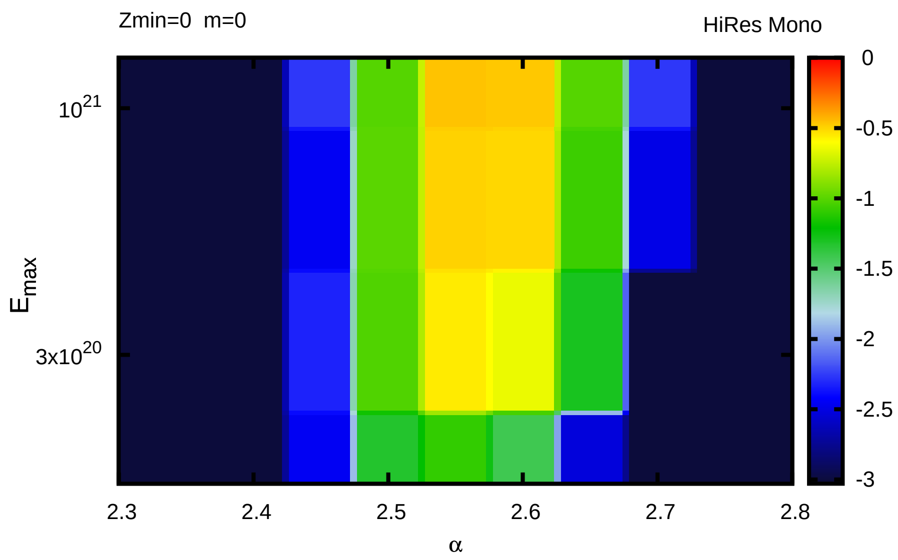
Fit of proton spectrum to HiRes-2005 data

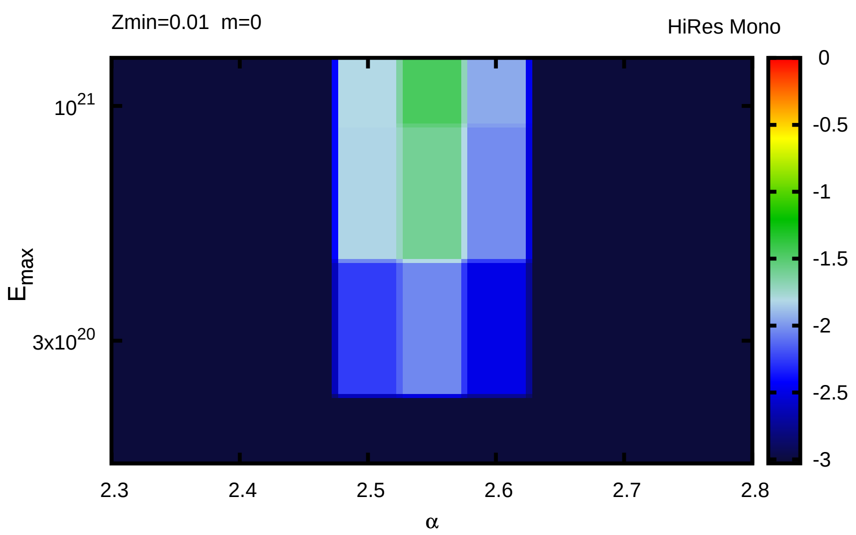


additional parameter E_fit =2 EeV

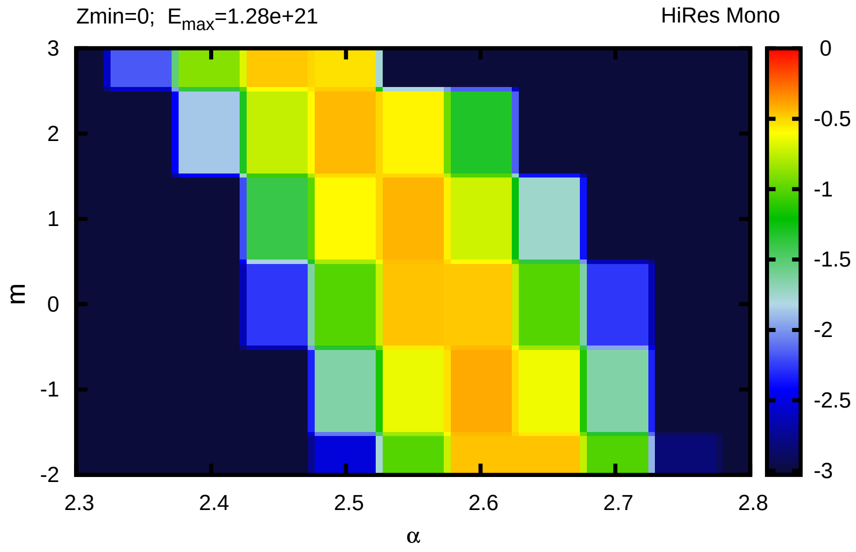
G.Gelmini, O.Kalashev and D.S., astro-ph/0702464

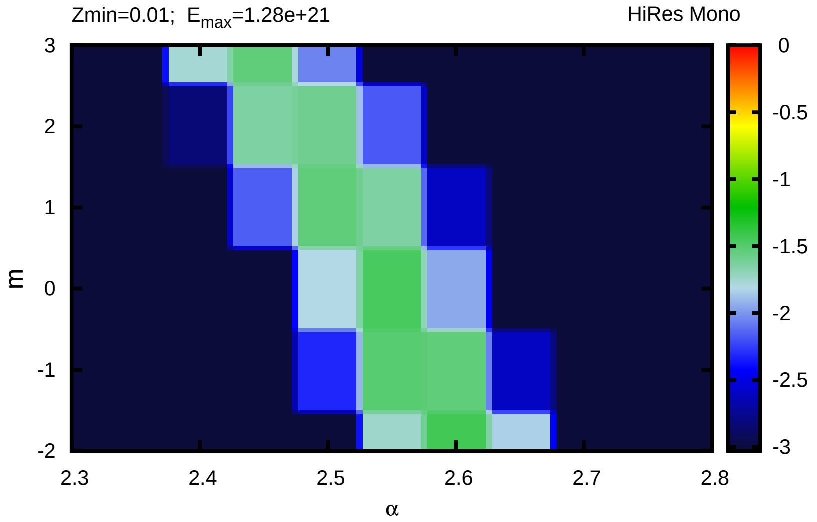
Uniformly distributed sources



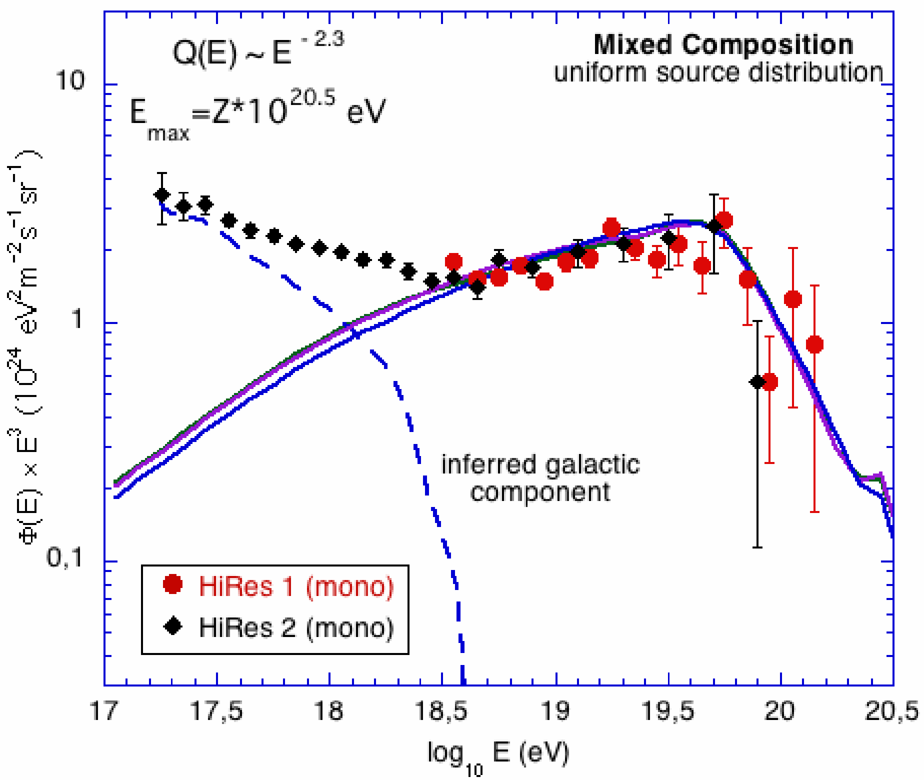


Evolution of sources



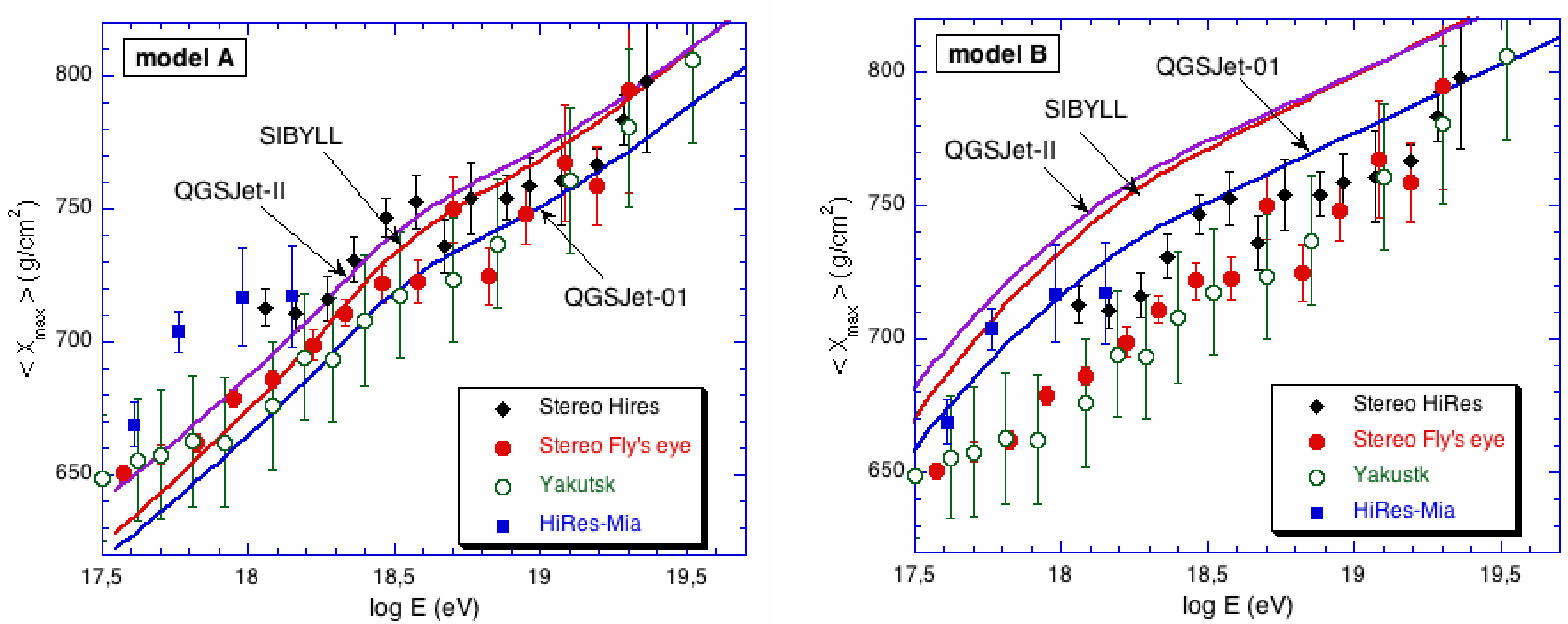


Mixed composition model



D.Allard, E.Parizot and A.Olinto, astro-ph/0512345

Mix model and pure protons versus composition



D.Allard, E.Parizot and A.Olinto, astro-ph/0512345

Conclusions

- UHECR below GZK cutoff can be explained by standard physics.
- UHECR with energies $E>10^{20}$eV if “too many” require new physics or very extreme astrophysics. No big hints so far.
- We are getting close to the predictions of GZK photons and GZK neutrinos, but bigger detectors needed. For neutrinos at least km^3, for photons 10*Auger South.
- A lot of astrophysics can be done at $E>4*10^{19}$ eV: Galactic and extragalactic magnetic fields, sources of UHECR, acceleration mechanism, etc.
  Probably Pierre Auger Observatory will show interesting results in near future. Bigger detectors needed for detailed study!