Ultra High Energy Cosmic Rays Astrofisical Sources

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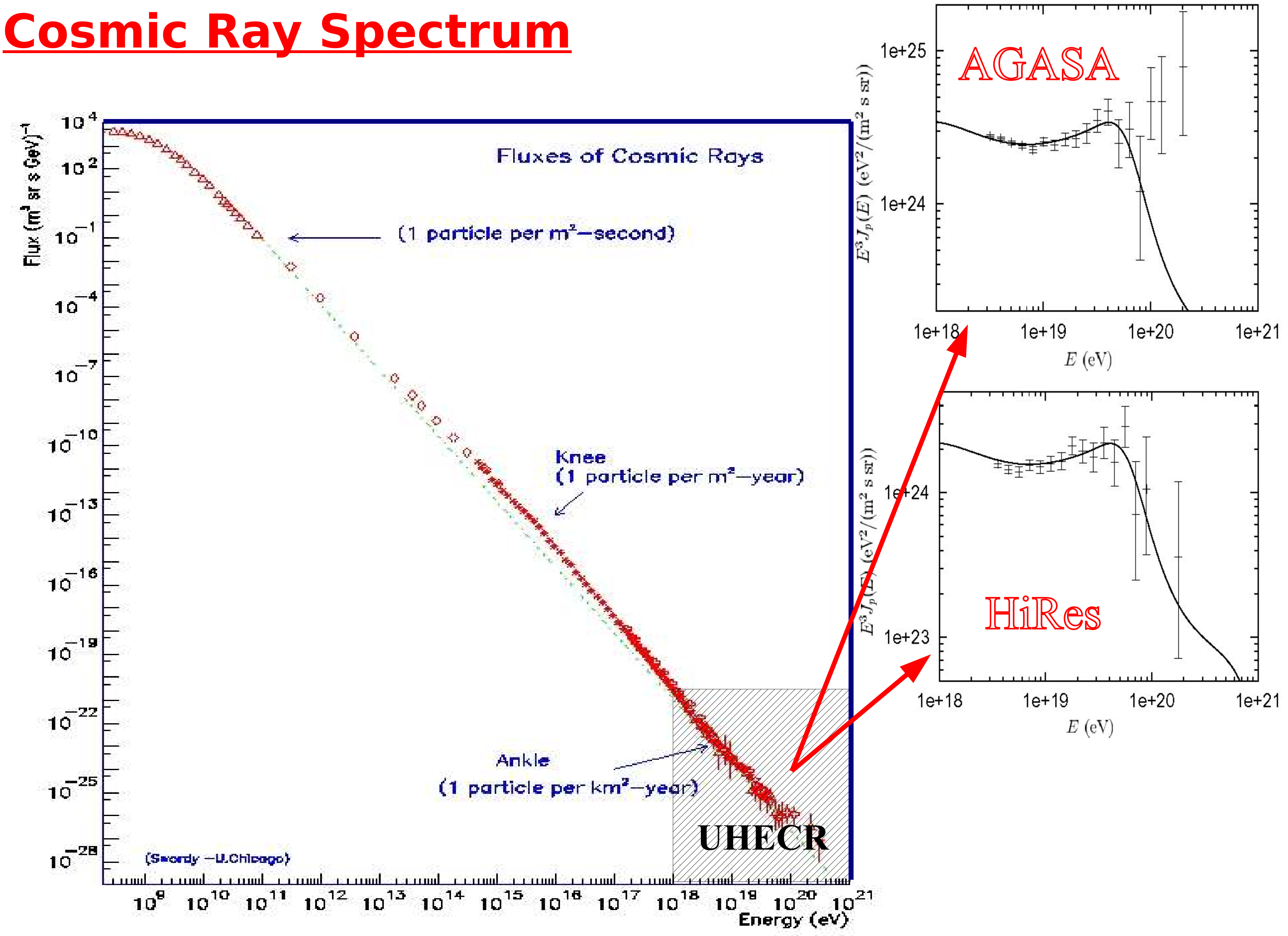
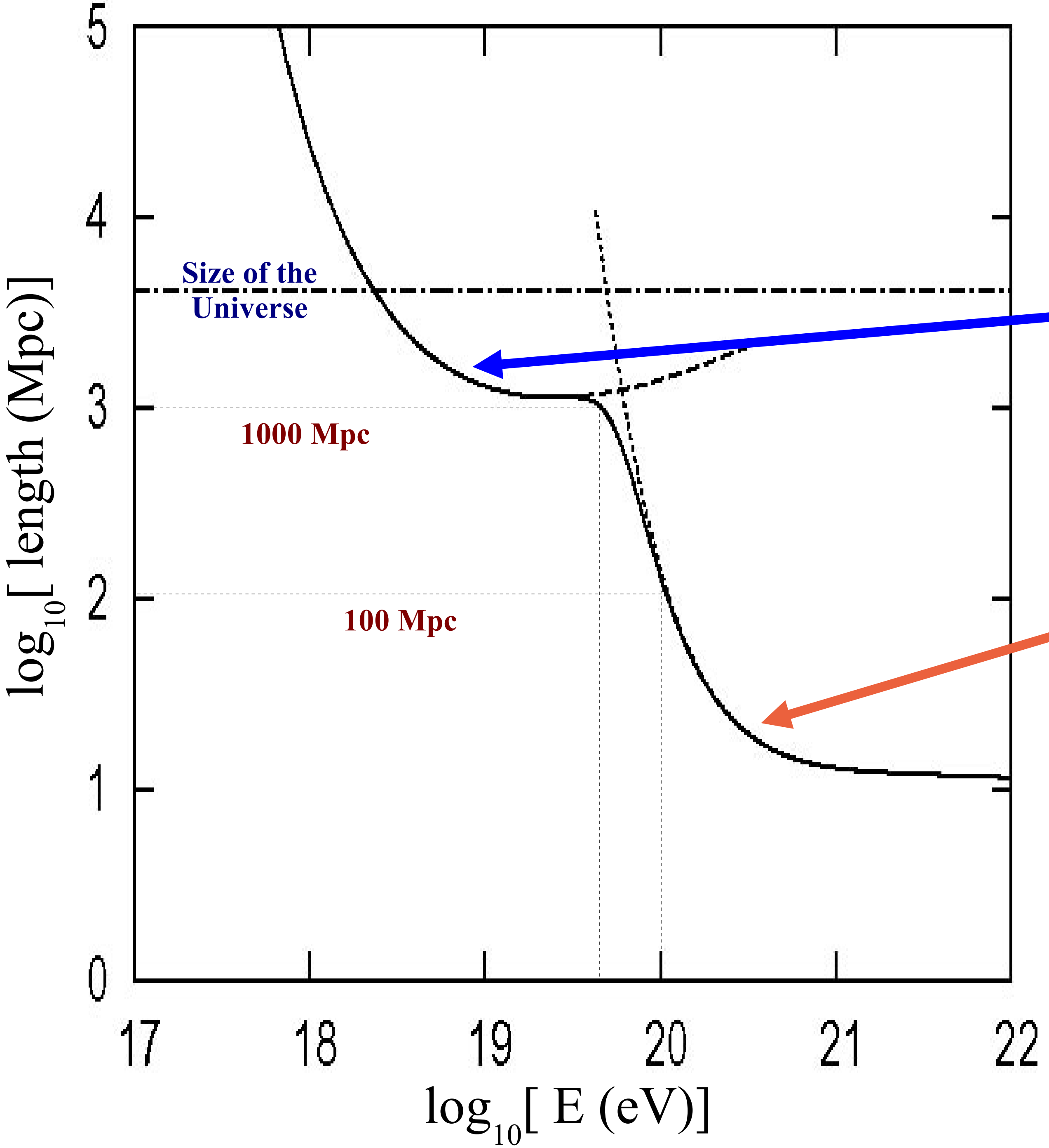
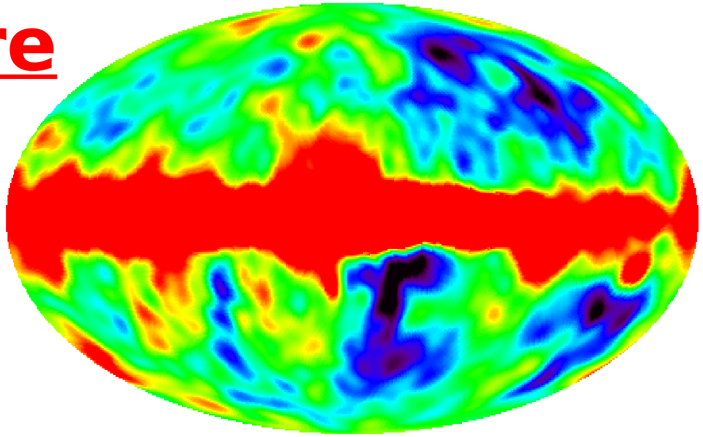
Cosmic Ray Spectrum



UHECR and CMB: the GZK feature





Pair production

$p\,\gamma \rightarrow p\,e^+\,e^-$

Photopion production

$p\,\gamma \rightarrow p\,\pi^0$

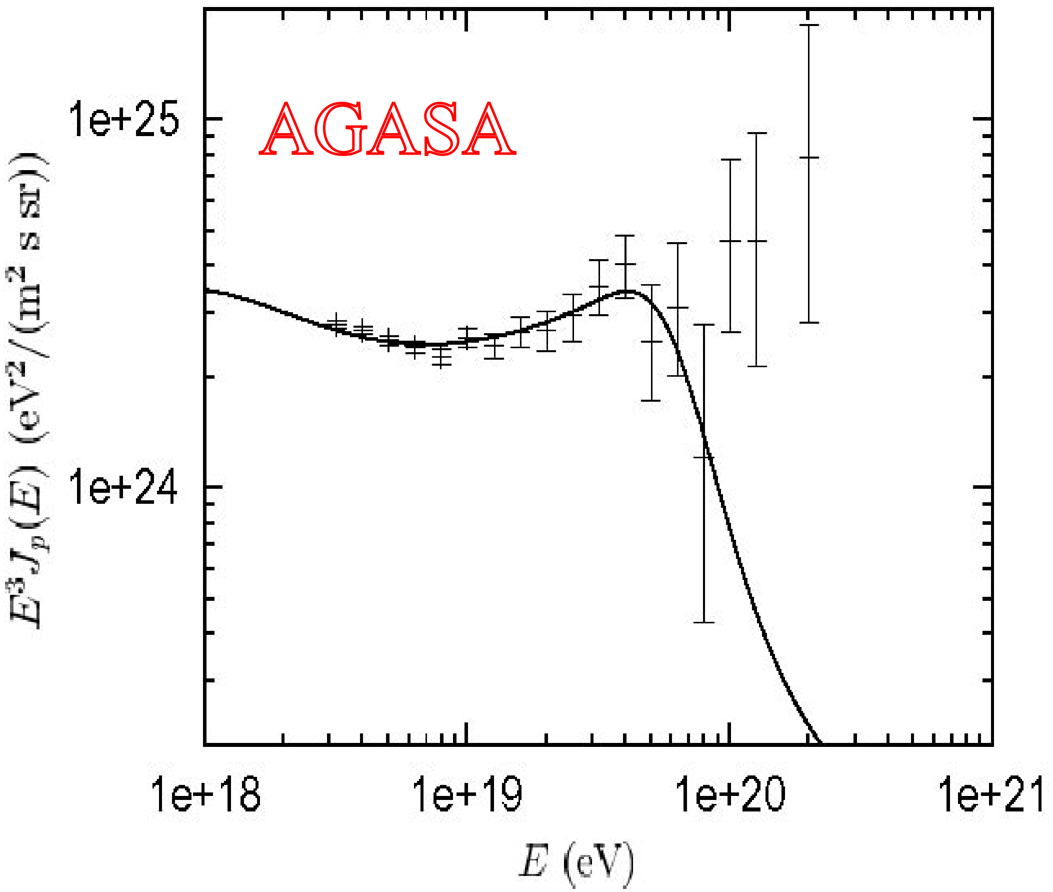
$\rightarrow n\,\pi^+$

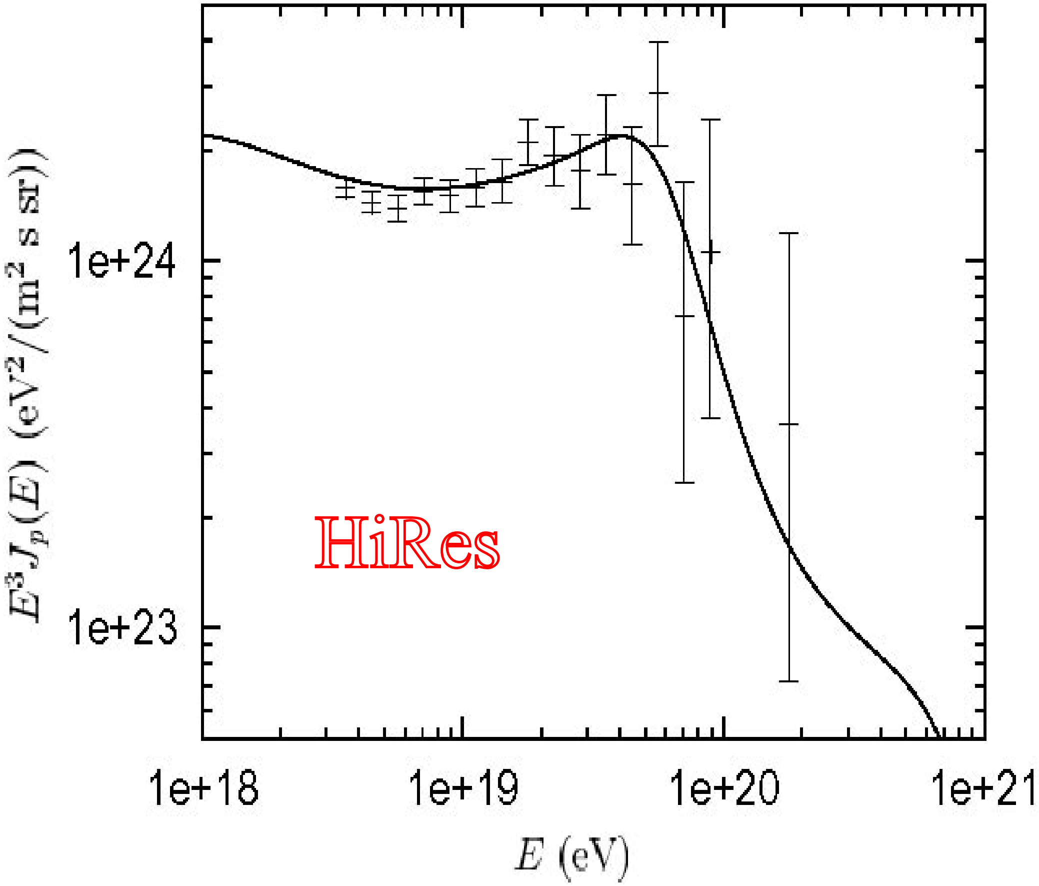
At 10^{20} eV the feature expected is NOT a cutoff !

EVENTS AT ENERGIES $E>10^{20}$eV ARE EXPECTED

if the maximum energy at the source is large enough!

Observational picture... AGASA vs HiRes





AGASA excess difficult to reconcile with the Astrophysical sources

Protons from uniform astrophysical sources good fit of the HiRes data and AGASA data at $E<10^{20}$ eV, required luminosities

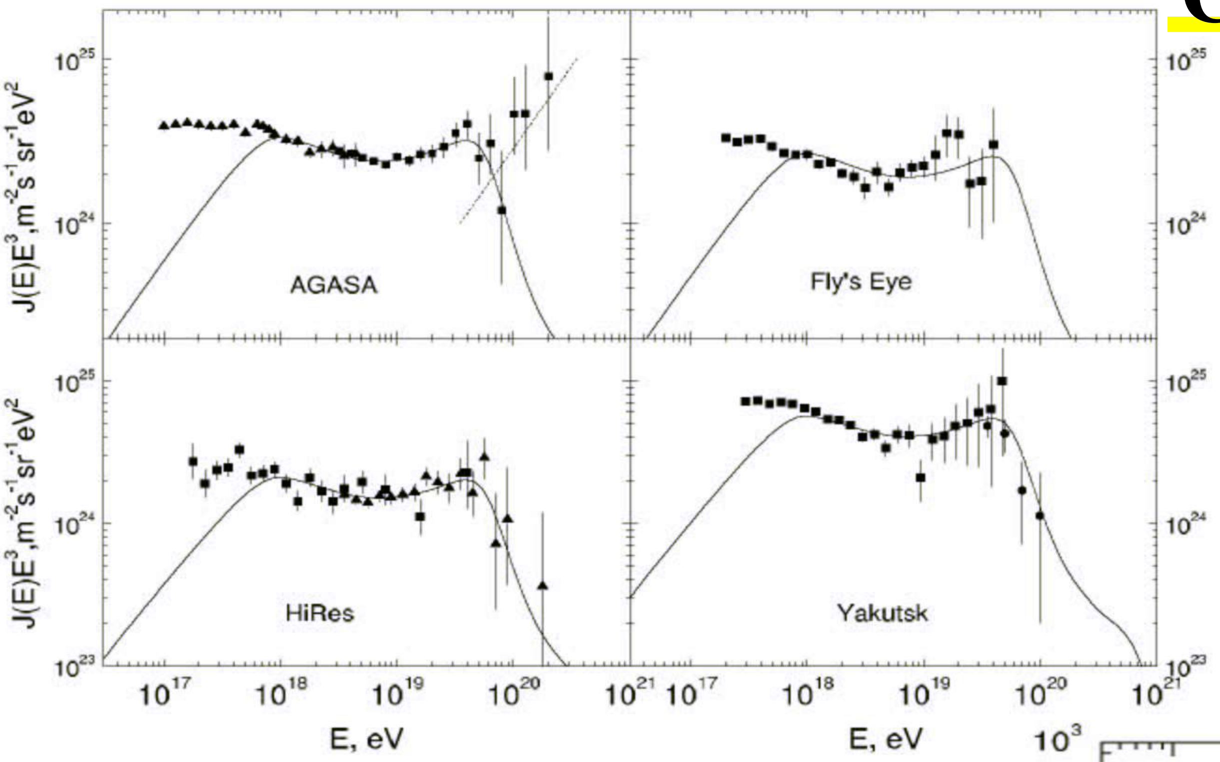
$$L_p \approx 10^{46}\, erg / Mpc^3\, yr$$

(Berezinsky, Gazizov and Grigorieva (2002))

HiRes data Compatible with the GZK suppression. Astrophysical counterparts not seen at $E>5\times10^{19}$ eV

At $E\approx10^{19}$ eV both spectra exhibit a dip, hints of chemical composition?

Chemical Composition

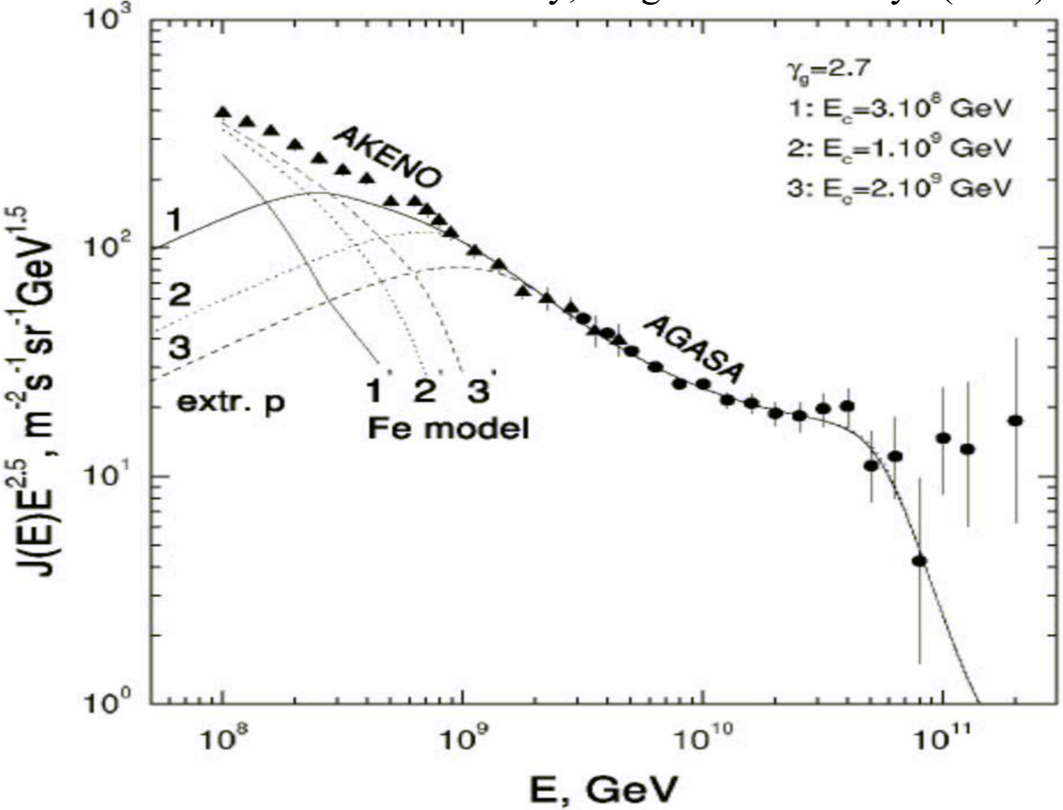


Berezinsky, Grigorieva & Hnatyk (2004)

The dip can be explained trough the pair production in the interaction of [protons] with CMB photons.

If this interpretation is correct [primaries above 10^{18} eV are extragalactic protons]

Berezinsky, Grigorieva & Hnatyk (2004)



Fly's Eye [Dawson et al. 98]

Transition from heavy (at $10^{17.5}$ eV)
to light composition (at ~10^{19} eV)

Haverah Park [Ave et al. 2001]

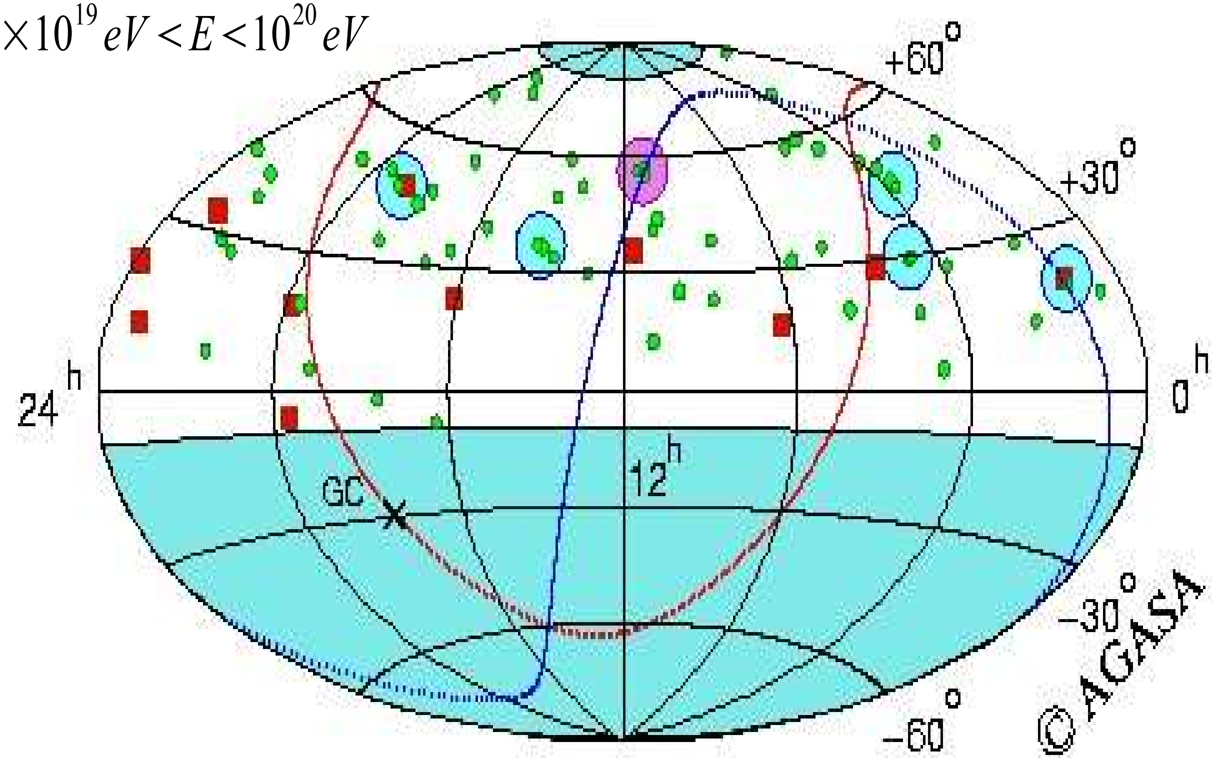
No more than 54% can be Iron above 10^{19} eV
No more than 50% can be photons above 4 10^{19} eV

Similar limits from AGASA

Source Number Density

🟥 $E > 10^{20}\,eV$

● $4\times 10^{19}\,eV < E < 10^{20}\,eV$



Using the small angle clustering it is possible to have indications about the source number density

n_S

As n_s decreases, for fixed flux, sources become brighter

↓

Increased clustering probability

Using many source realizations (MC)

$$n_S \approx 10^{-5}\, Mpc^{-3}$$

Blasi & De Marco (2003)
Kachelriess & Semikoz (2004)

40 sources within 100 Mpc (~20 degrees between sources)

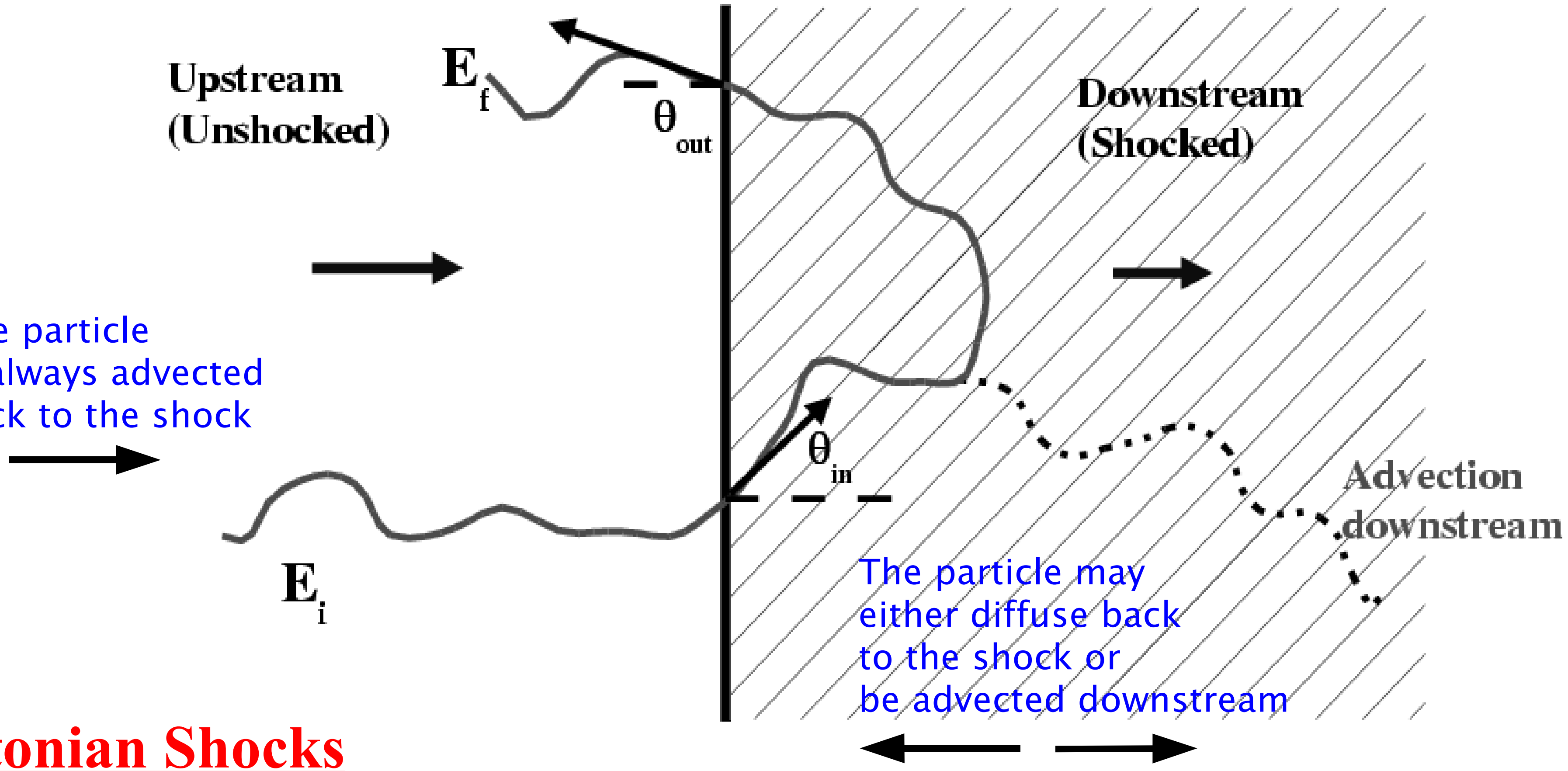
At most one source in the angular bin of 3 degrees! The sources should have been seen in particular at 3 10^{20} eV

BURSTING SOURCES???

or

TOP DOWN???

Shock Acceleration



The particle
is always advected
back to the shock

The particle may
either diffuse back
to the shock or
be advected downstream

Newtonian Shocks

Energy gain: $E_f \approx E\left(1 + \frac{4}{3}V\right)$

The acceleration time depends on how long a particle spends on both sides of the shock.

$$\tau_{acc} = D(E)/V$$

The maximum energy of the accelerated particles can be calculated by requiring that:

$$\tau_{acc} < Min\left[t_{loss}, t_{diff}\right]$$

Time for energy losses

Time of escape from the
acceleration region
R^2 /D(E)

Relativistic Shocks

The main complication is due to the *ANISOTROPY* of the distribution function around the shock!

$$\delta\mu = \left[-1 + \frac{1+3\beta_{rel}}{3+\beta_{rel}}\right] \approx \frac{1}{4}\frac{1}{\gamma_{rel}^{2}}$$

First Interaction

when the particle distribution upstream is still isotropic, a reflection U-D-U can increase the energy of the particle by a factor Γ_{rel}^{2} in one shot

Further interactions

Most particles have μ=-1 therefore the typical energy gain is ~1.
The acceleration time is of order

$$\tau_{acc} \approx \frac{r_L(E)}{\gamma_{sh} c}$$

The maximum energy is calculated by equating the times for acceleration and losses (or escape)

Recently, Vietri (2003) introduced a new and powerful approach to particle acceleration at a shock with arbitrary speed.

In Blasi & Vietri (2004) an analytical method was proposed that gives both the spectrum and the anisotropy of the accelerated particles for an arbitrary shock speed and arbitrary scattering properties of the medium.

Acceleration sites

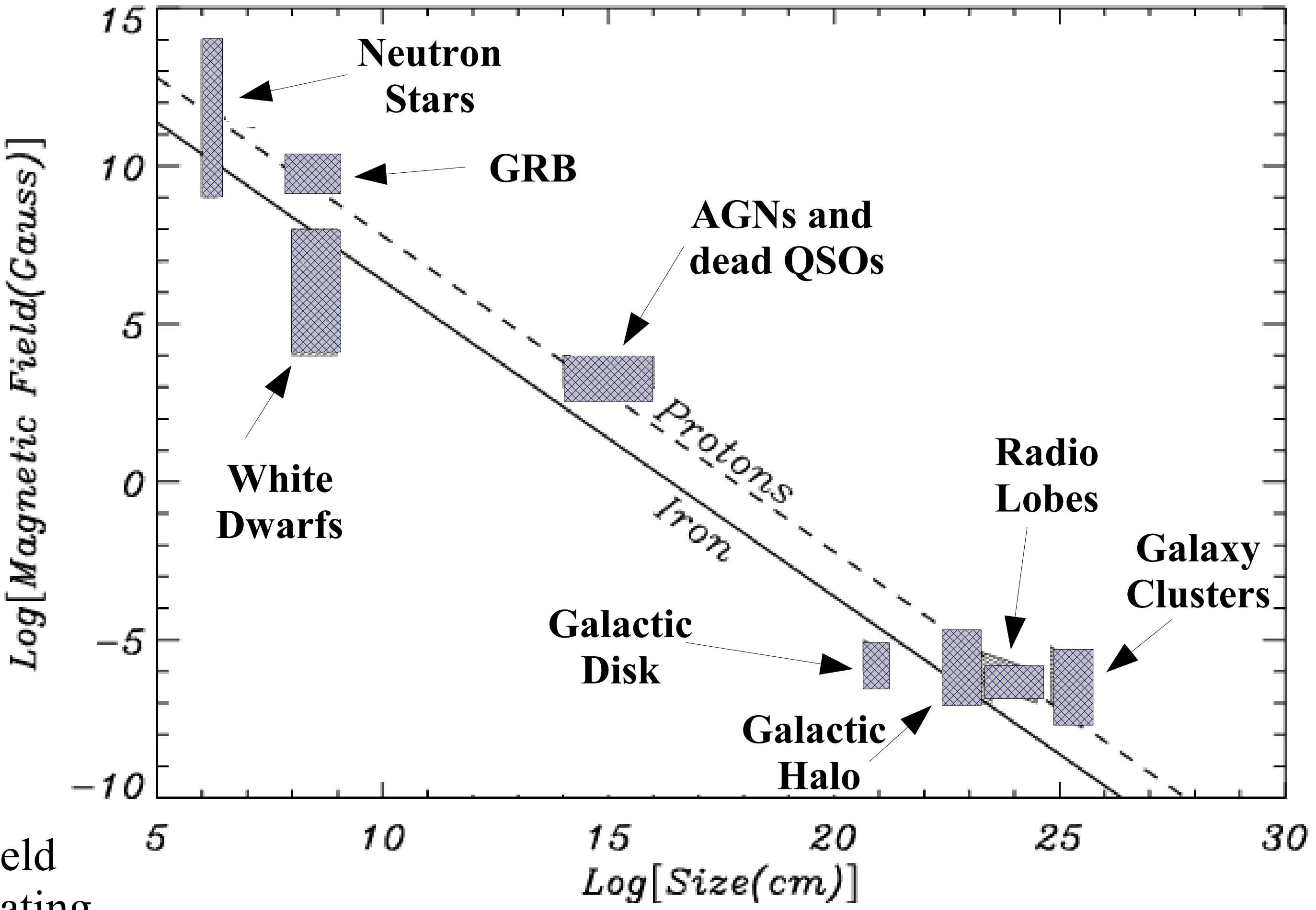
HILLAS PLOT

$$R_L \approx \frac{E}{\beta Z B} \le L$$

$$E_{max} \approx L \beta Z B$$

Size of the accelerating region

Magnetic field of the accelerating region



Shock acceleration at newtonian shock

Radio Lobes [Rachen & Biermann]
AGN's [Berezinsky et al. 02]
...

Shock acceleration at relativistic shocks

Gamma Ray Bursts
[Waxman 95, Vietri 95]

Intergalactic Magnetic Fields

Cosmological origin →

Appreciable field in the voids

Fields in LSS are due to compression and twisting of primordial field

Astrophysical sources →

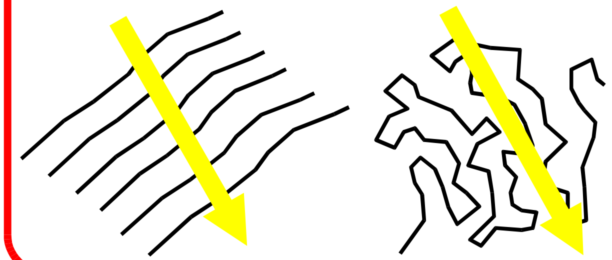
B-field concentrated where sources are, namely in LSS

No appreciable field in most part of the volume of the universe

Very poor experimental evidences

Faraday rotation

$$RM \propto \int_s \vec{B}(s)\cdot d\vec{s}\, n_e(s)$$



The limits from RM are on the component of B parallel to the line of sight. This depends on field topology !

Synchrotron and ICS emission

In clusters of galaxies the field inferred in this way is about ~0.1-1.0 μG (e.g. Coma)

Numerical simulations

Numerical determination of the IMF is based on LSS and MHD simulations

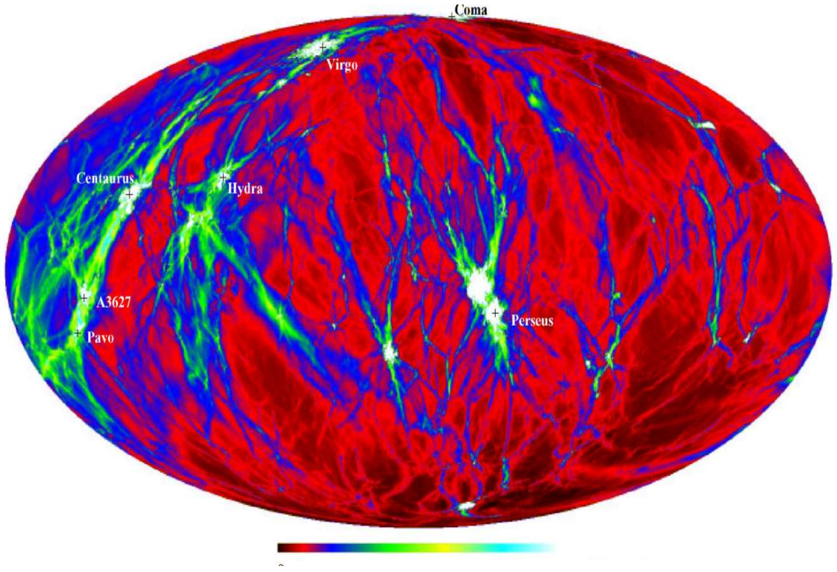
Puzzling results by different groups

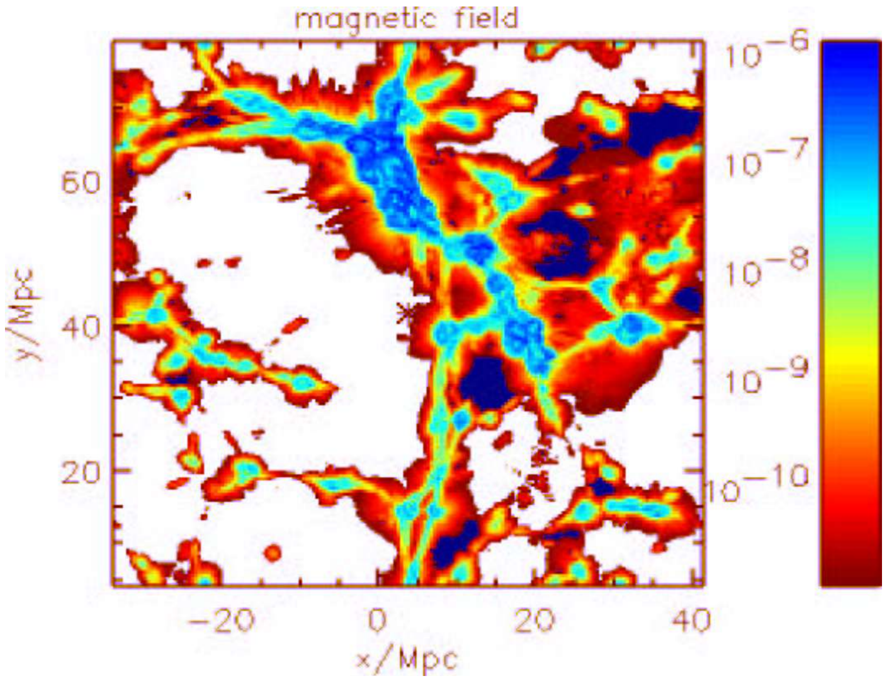
Dolag, Grasso, Springel & Tkachev use constrained simulations, being able to reproduce the local Universe

- **Low B** (0.1 nG in filaments and 0.01 nG in voids)
- **Low deflection angles: < 1° at 4 10^{19} eV**
- **UHECR astronomy is allowed**

Sigl, Miniati & Ensslin use an unconstrained simulation putting the observer * close to a cluster

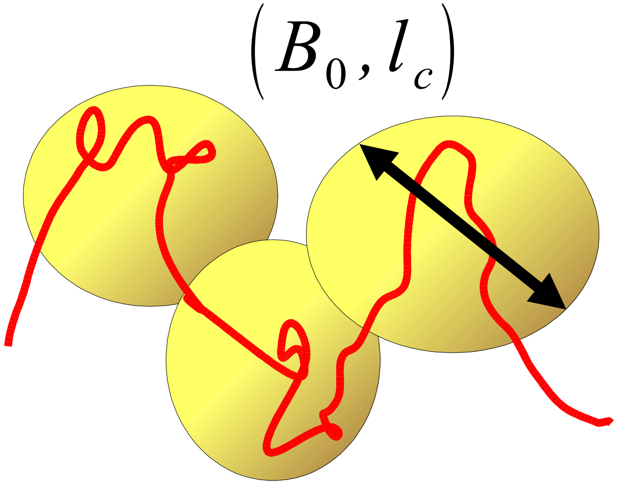
- **High B** (100 nG in filaments and 1 nG in voids)
- **High deflection angles: up to 20° at 10^{20} eV**
- **UHECR astronomy nearly impossible**





UHECR Propagation in IMF

Diffusive Spectrum



The UHECR propagation can be described by a diffusion equation

$$\frac{\partial n}{\partial t} - \vec{\nabla}\cdot[\underbrace{D(E,r,t)}_{\text{diffusion coefficient}}\vec{\nabla} n] - \frac{\partial}{\partial E}[n\underbrace{b(E,t)}_{\text{energy losses}}] = \underbrace{Q(E,t)}_{\text{injection spectrum}}\delta(\vec{r}-\vec{r}_g)$$

In the case in which Q, D, b depend only on energy

$$n(E,r) = \frac{1}{b(E)}\int_E^{E_{max}} dE_g\, Q(E_g)\frac{\exp[-r^2/4\pi\lambda(E,E_g)]}{[4\pi\lambda(E,E_g)]^{3/2}}$$

$$\lambda(E,E_g) = \int_E^{E_g} d\epsilon\, \frac{D(\epsilon)}{b(\epsilon)}$$

Syrovatskii (1959)

From the turbulent spectrum of IMF assuming B = B_0 on the scale l_c

$$D(E) = D_0\left(\frac{E}{E_c}\right)^{\alpha} \qquad E \le E_c$$

$$D(E) = D_0\left(\frac{E}{E_c}\right)^{2} \qquad E > E_c$$

$$D_0 = \frac{1}{3} l_c c$$

$$r_L(E_c) = l_c$$

We used α=1/3 (Kolmogorov) α=1 (Bohm) and α=2.

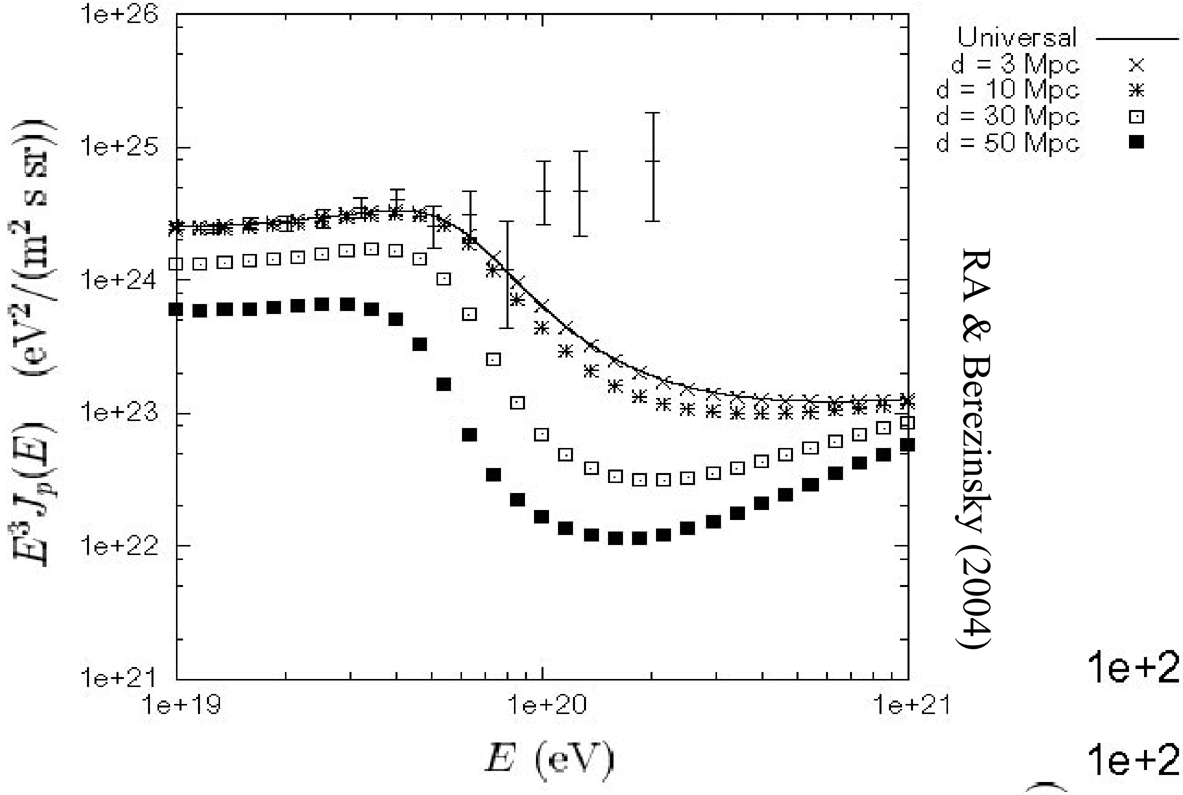
Diffusion approximation

$$t_{pr} = \frac{r^2}{D(E)} \ge t_{rec} = \frac{r}{c}$$

$$r > r_{min} \approx \frac{1}{3} l_d = \frac{D(E)}{c}$$

Otherwise rectilinear propagation

Diffusion at high energies



RA & Berezinsky (2004)

Propagation Theorem

For a uniform distribution of identical sources with separation much less than the characteristic propagation lengths, the UHECRs spectrum does not depend on the magnetic field (universal spectrum)

Magnetic Field and GZK steepening

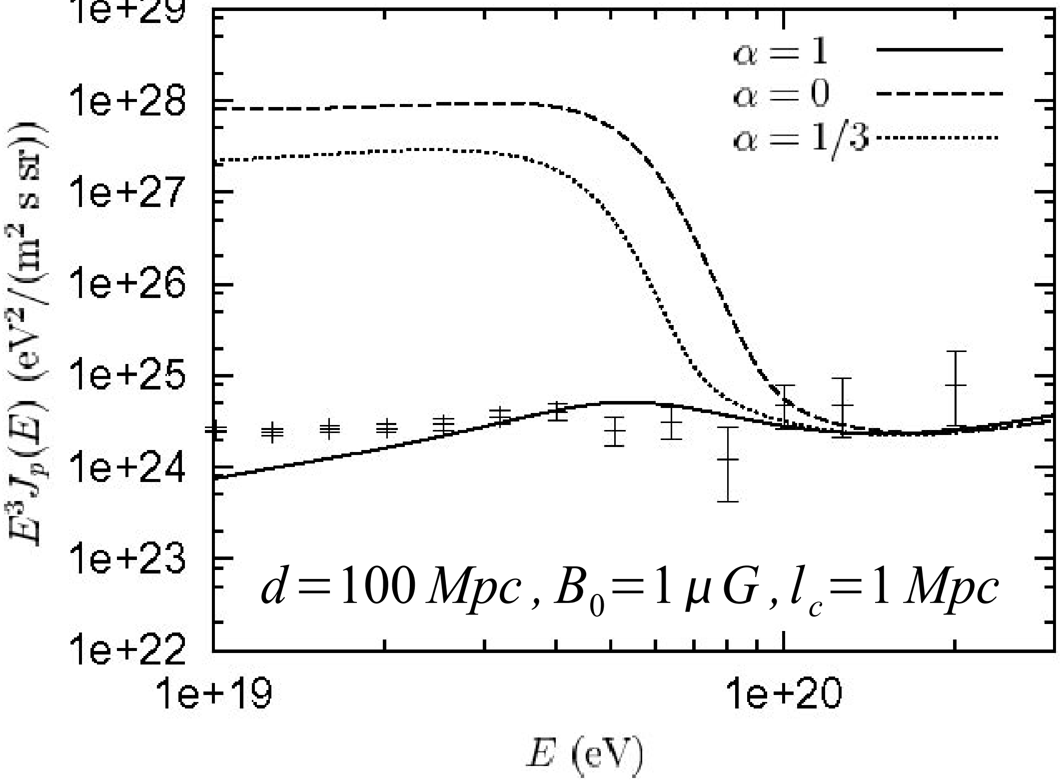
Diffusion implies a longer propagation time at low energies that increases the total energy lost at low energy and hence the suppression of the GZK steepening

$$B_0 \approx 1\,\mu G, \quad n_S \approx 10^{-6}\,Mpc^{-3}$$

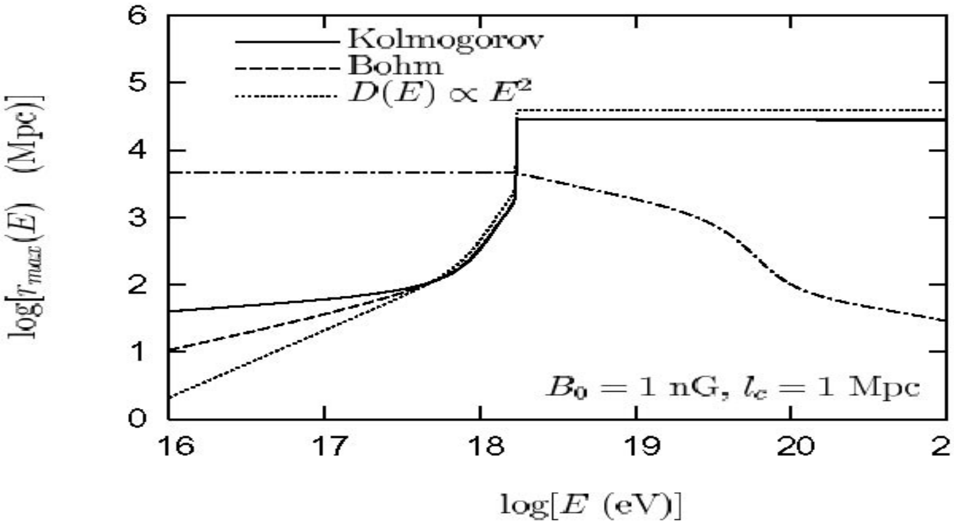
Too high IMF

low source density

RA & Berezinsky (2004)



Diffusion at low energies



RA & Berezinsky (2005)

Maximal distance

$$r_{max}=2\sqrt{\lambda(E,E_{max})}$$

$$E_{max}=min\left[E_g(E,L_{uni}),E_{acc}^{max}\right]$$

At low energy ($E \leqslant 10^{18}$ eV) the maximal distance of the contributing sources is suppressed by diffusion.

The low energy cut off is independent of the IMF. It is related only to pair production energy losses.

Low Energy Flux

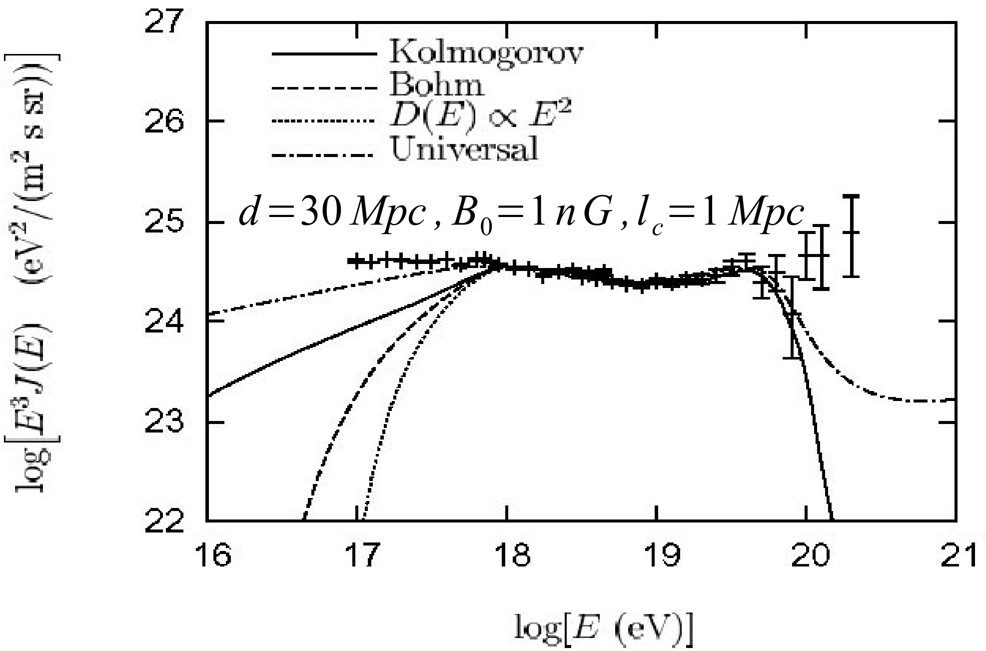
Cut off in the flux at $E \approx 2\times10^{18}$ eV

Single power law at injection $\gamma_g=2.7$

The dip survives also with IMF (reasonable source density and field strength)

$$n_S\approx 3\times10^{-5}\,Mpc^{-3},\quad B_0=1\,nG,\quad l_c=1\,Mpc$$

$L_p\approx 3\times10^{48}\,erg/s$ **above 1 GeV**



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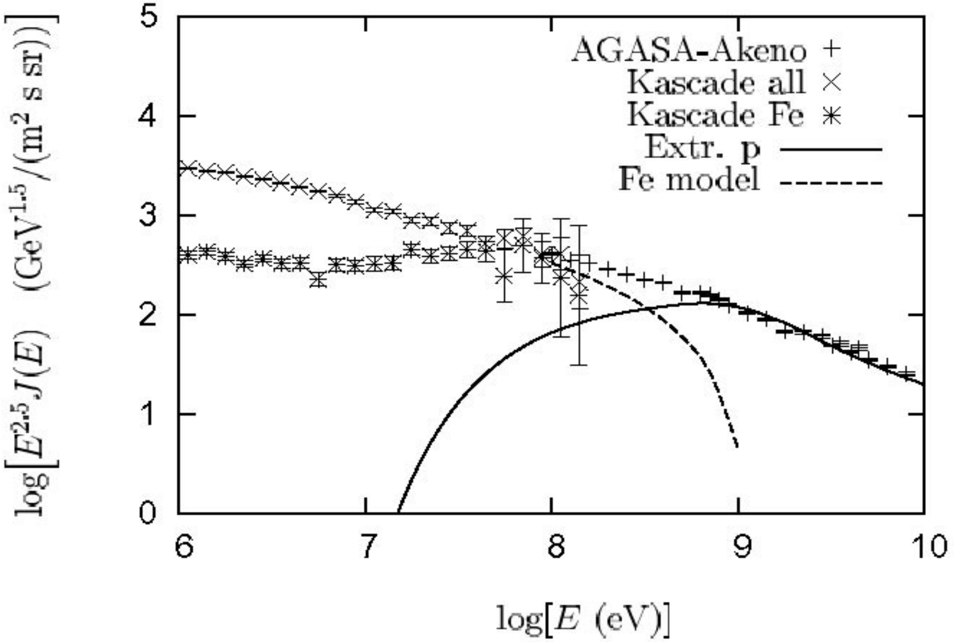
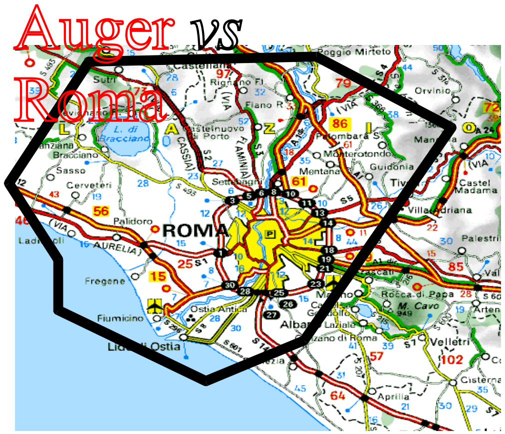


The Future

Pierre Auger Observatory

1600 Cherenkov tanks covering 3000 Km^2 (spacing 1.5 Km)
24 Fluorescence detector (4 peripheral eyes, 6 telescopes each)

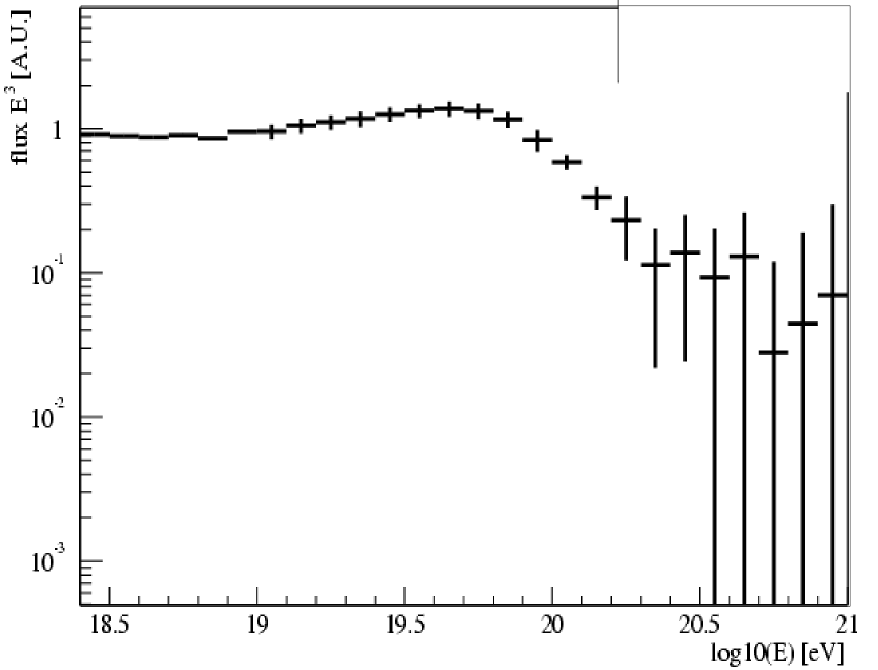


Full sky coverage: one observatory in the north hemisphere and one in the south (now under construction).

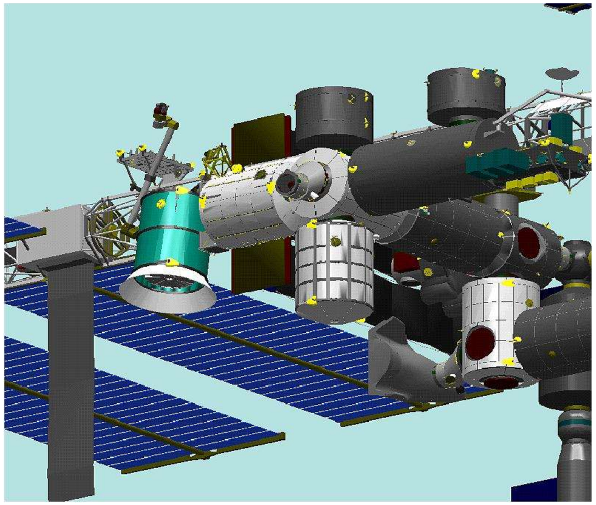
Auger performances

	Surface detector (SD)	Hybrid (SD and Fluorescence)
$E > 10^{19} eV$	$5150/y$	$515/y$
$E > 5\times10^{19} eV$	$490/y$	$49/y$
$E > 10^{20} eV$	$103/y$	$10/y$
$E > 5\times10^{20} eV$	$10/y$	$1/y$

De Marco, Blasi & Olinto (2003)

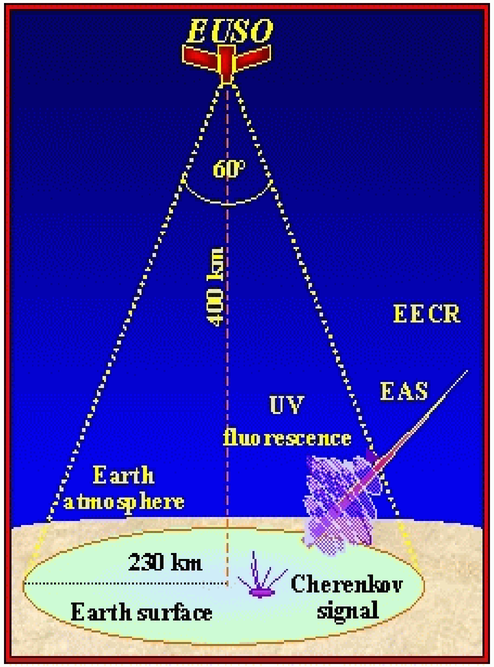


Extreme Universe Space Observatory



Fluorescence signal from above

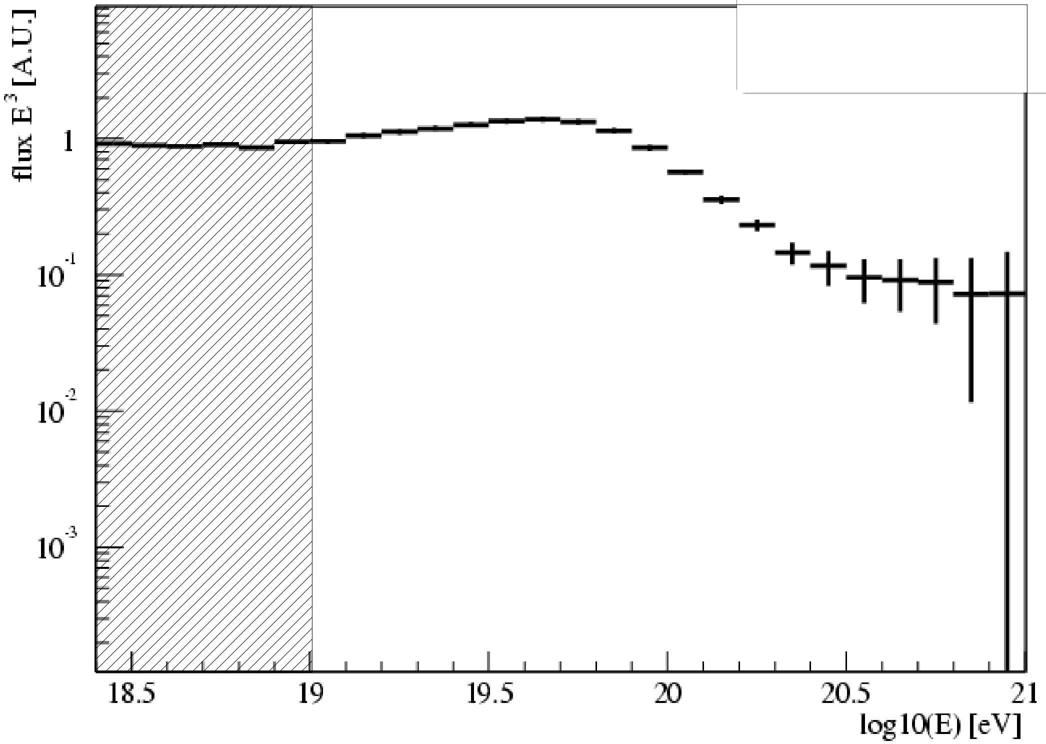
EUSO will sit on the ISS and detect the fluorescence light from the showers developing in the atmosphere



Euso Performances

$$E > 5\times10^{20}\,eV \qquad 200-300/y$$

EUSO should be able to see ALL or MOST sources of UHECRs above 10^{20} eV (within the GZK horizon)



De Marco, Blasi & Olinto (2003)

Conclusions

1. The GZK feature in the spectrum of UHECRs is controversial.
   HiRes does see a suppression which is consistent with the GZK feature,
   AGASA presents an excess at high energy difficult to reconcile with the GZK feature.

2. The DIP present at $E\sim10^{19}$ eV in both the HiRes and AGASA spectra is a strong evidence in favor of extragalactic protons from astrophysical sources at $E>10^{18}$ eV .

3. The existence of Intergalactic Magnetic Fields is still an open question.
   UHECRs spectrum is affected by IMF, using diffusive approximation:

High Energy	suppression of the GZK feature (very high $B\sim1$ μG)
Low Energy	low energy cut-off $E\leq10^{18}$ eV (B independent), single power law at injection $\gamma_g=2.7$ ($B\sim1$ nG), transition form hevy to ligth composition at $E\sim10^{18}$ eV.

4. The small scale anisotropies detected by AGASA give the first hint on the sources density.

5. The Auger and Euso observations are fundamental to accumulate statistics and sky coverage. This data will solve the GZK puzzle providing informations about the IMF intensity, if this is small ($B\leq1$ nG) Astronomy with UHECRs will be possible.