# Ultra High Energy Cosmic Rays: Propagation

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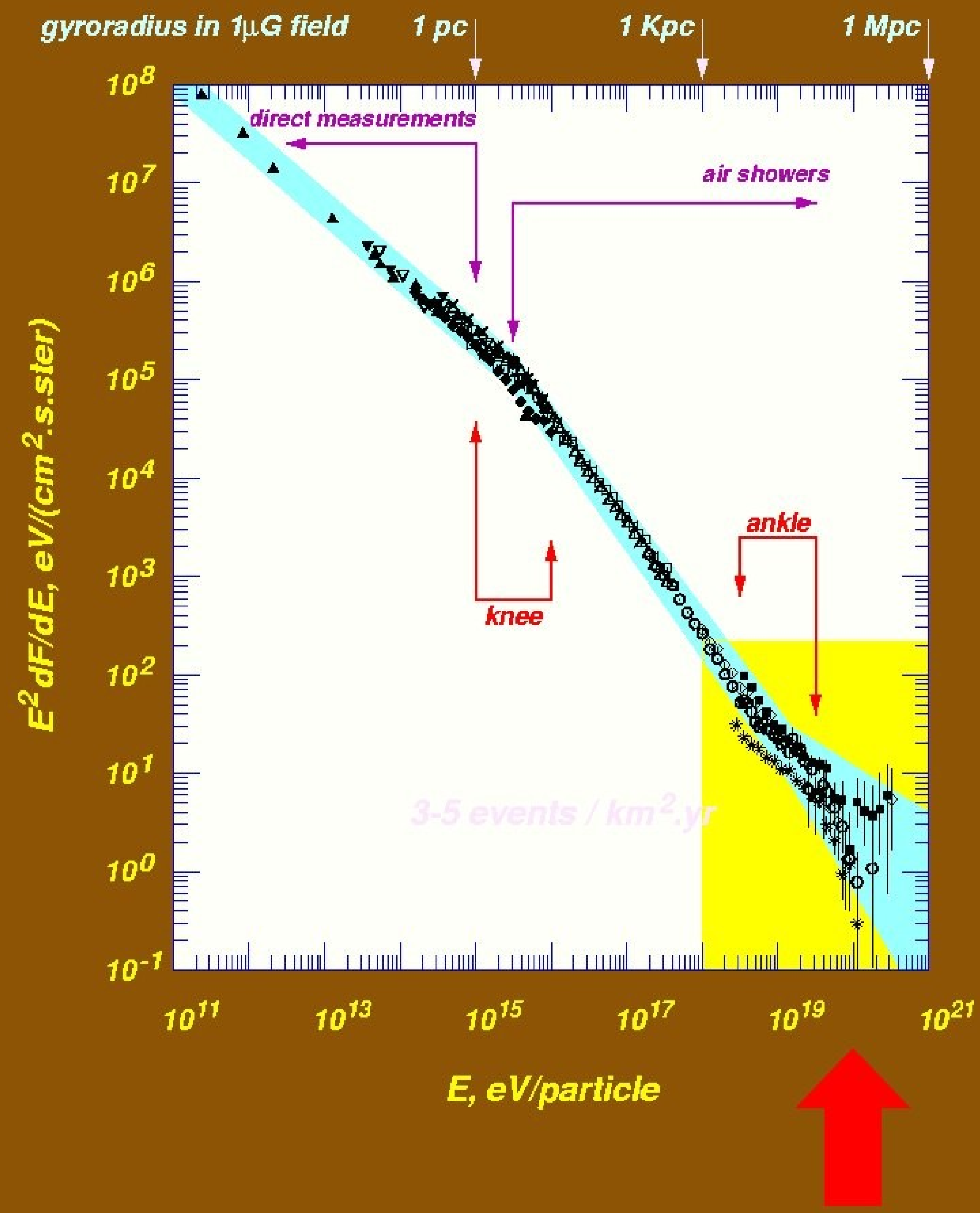
John Linsley (PRL 10 (1963) 146) reports on the detection in Vulcano Ranch of an air shower of energy above $10^{20}$ eV.

Problem: the microwave background radiation is *discovered* in 1965. Greisen and Zatseping&Kuzmin independently derived the absorption of UHE protons in photoproduction interactions on the 3K background.

More problems: such detections continue, the current world statistics is around 10 events.

$10^{20}$ eV =
= $2.4 \times 10^{34}$ Hz
= $1.6 \times 10^{8}$ erg
= 170 km/h tennis ball

$\sqrt{s}$ equivalent is 300 TeV




Cosmic ray energy spectrum is smooth, power law like.
It has two main features:
- the knee
- the ankle

The standard theory is that cosmic rays below the knee are accelerated at common (?) galactic sources, most likely supernova remnants.

Cosmic rays above the knee are accelerated at unknown galactic sources, maybe also supernova remnants. (?)

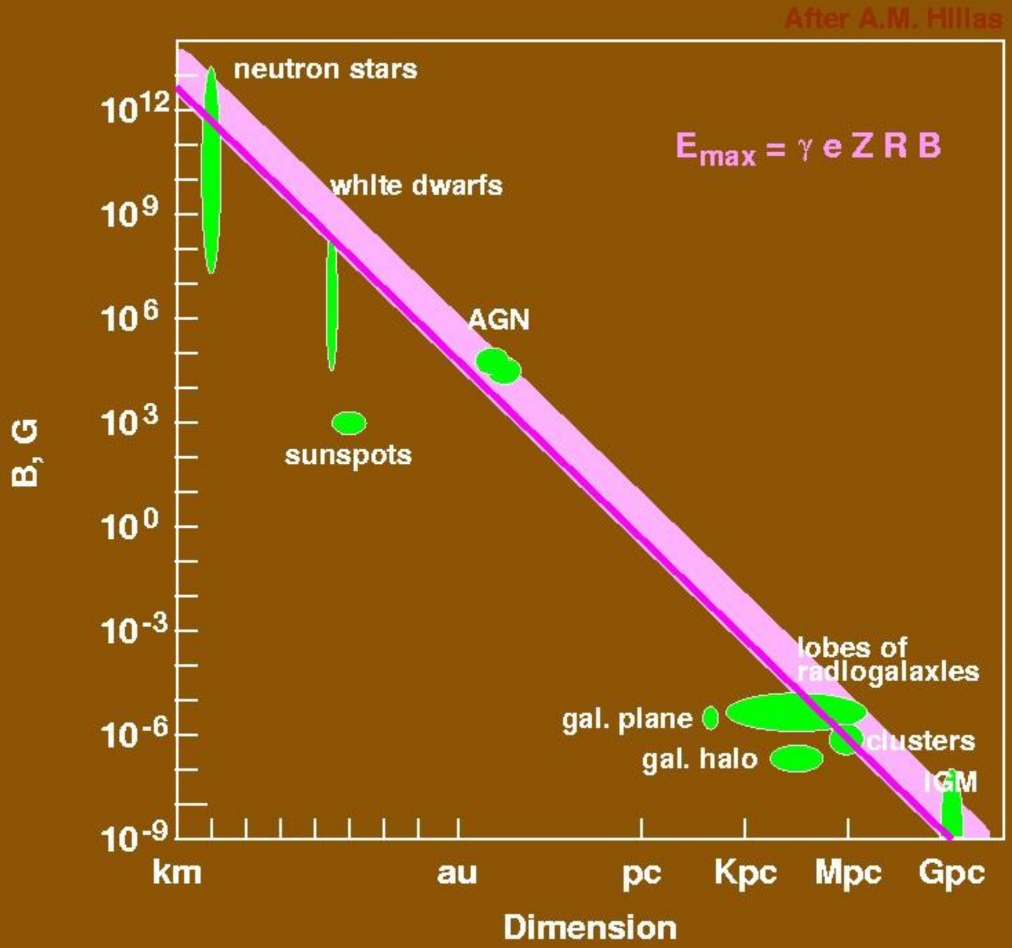
Cosmic rays above the ankle have to be extragalactic, if they are also charged nuclei. Galactic magnetic fields are not strong enough to contain such particles (Cocconi 1956) - their gyroradii are larger than the Galaxy.

These particles **should not** exist because of two sets of problems:

1) set one: **production** (acceleration)
2) set two: **propagation**

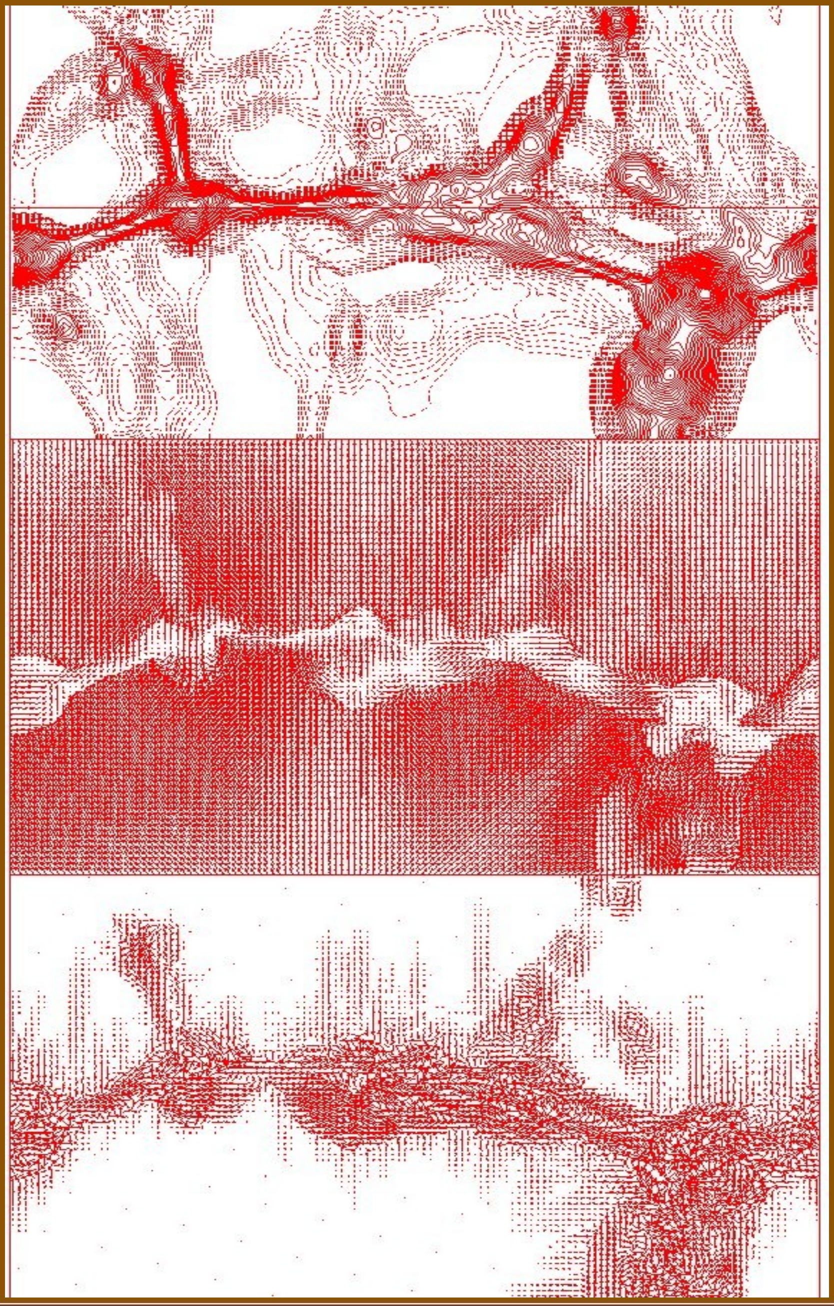
We will discuss the propagation of UHECR in this talk. Since the formation of their spectrum depends on the distance to their sources let's have a look at the possible sources.

In analogy with the lower energy galactic cosmic rays one is tempted to think that they come from acceleration sites associated with powerful astrophysical objects. How many such objects exist in the Universe ?



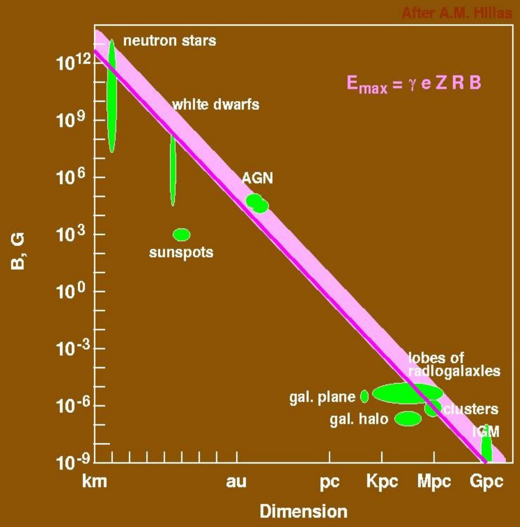

Michael Hillas generated this famous graph more than 20 years ago. It shows the dimensional upper limit for acceleration to $10^{20}$ eV. The upper edge is for protons and lower one - for iron nuclei. The observed magnetic field values and dimensions of astrophysical objects are indicated. There is a handful of objects that could do it with an efficiency of 1.

# Possible astrophysical sources:



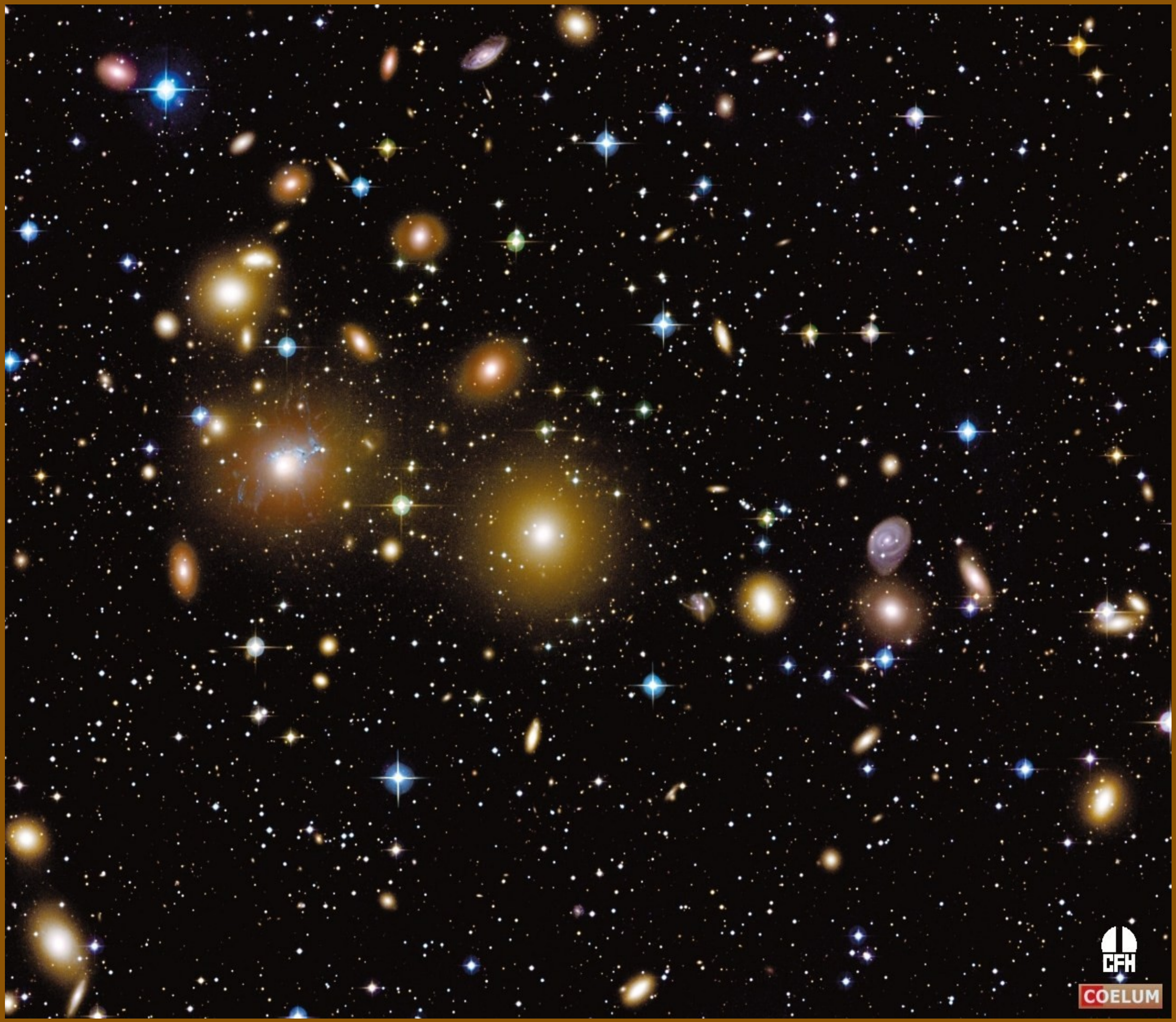
Shocks from structure formation: 1 nG fields on Mpc distance needed for $10^{20}$ eV protons. Energy loss may be much too large.

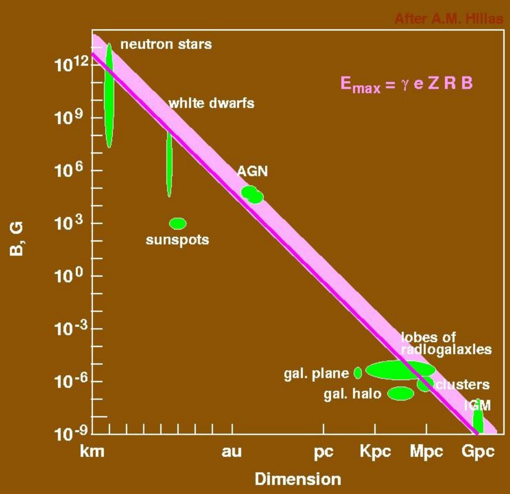
Picture on the left
top: matter density
middle: velocity vectors
bottom: magnetic field vectors

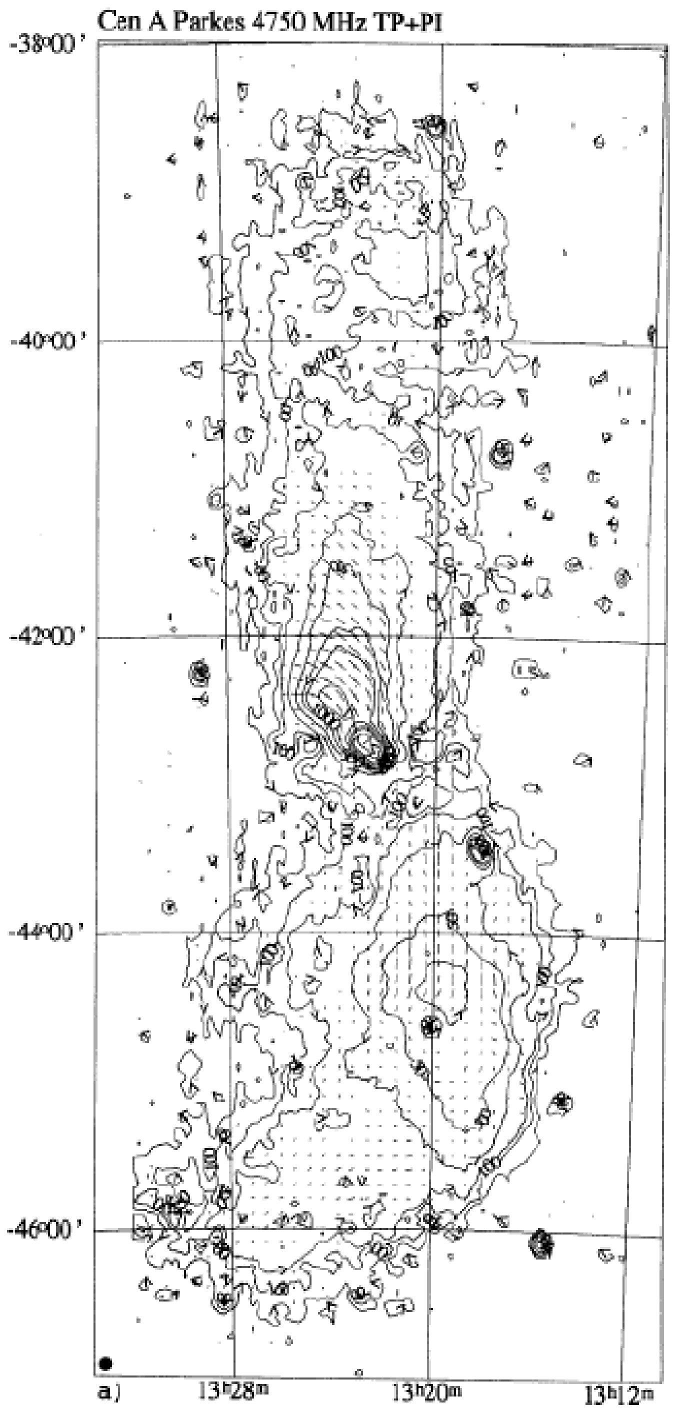


Clusters of galaxies: μ G fields observed on 500 kpc scales.
Still the acceleration is too slow and energy losses may prevail.

Perseus cluster
of galaxies

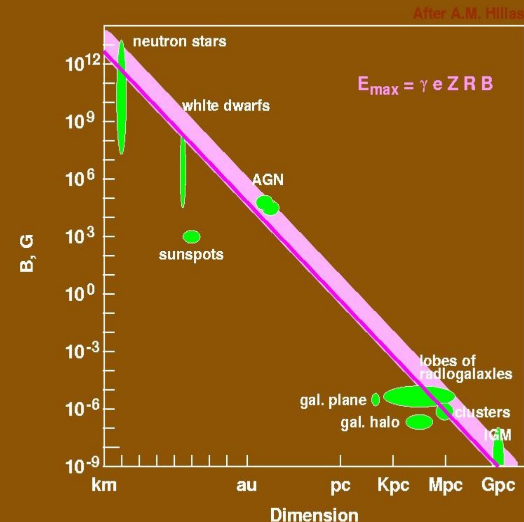




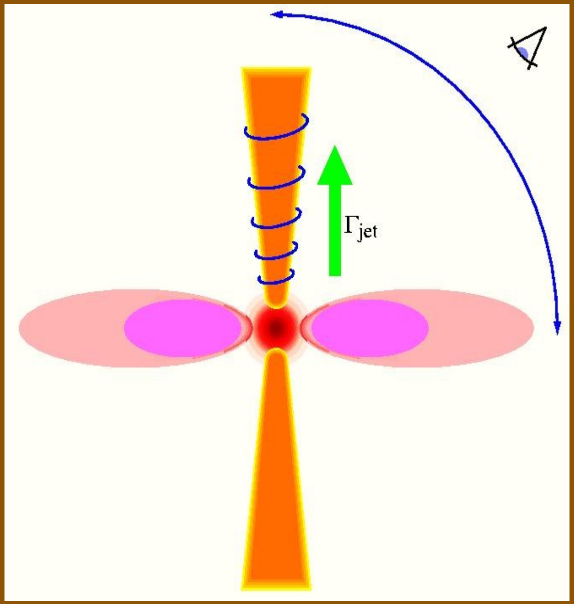

Radiogalaxies: 10 μ G fields on 100 kpc scale possible in *red spots* of FRII type galaxies. Since these are jet termination shocks there will be no adiabatic losses.

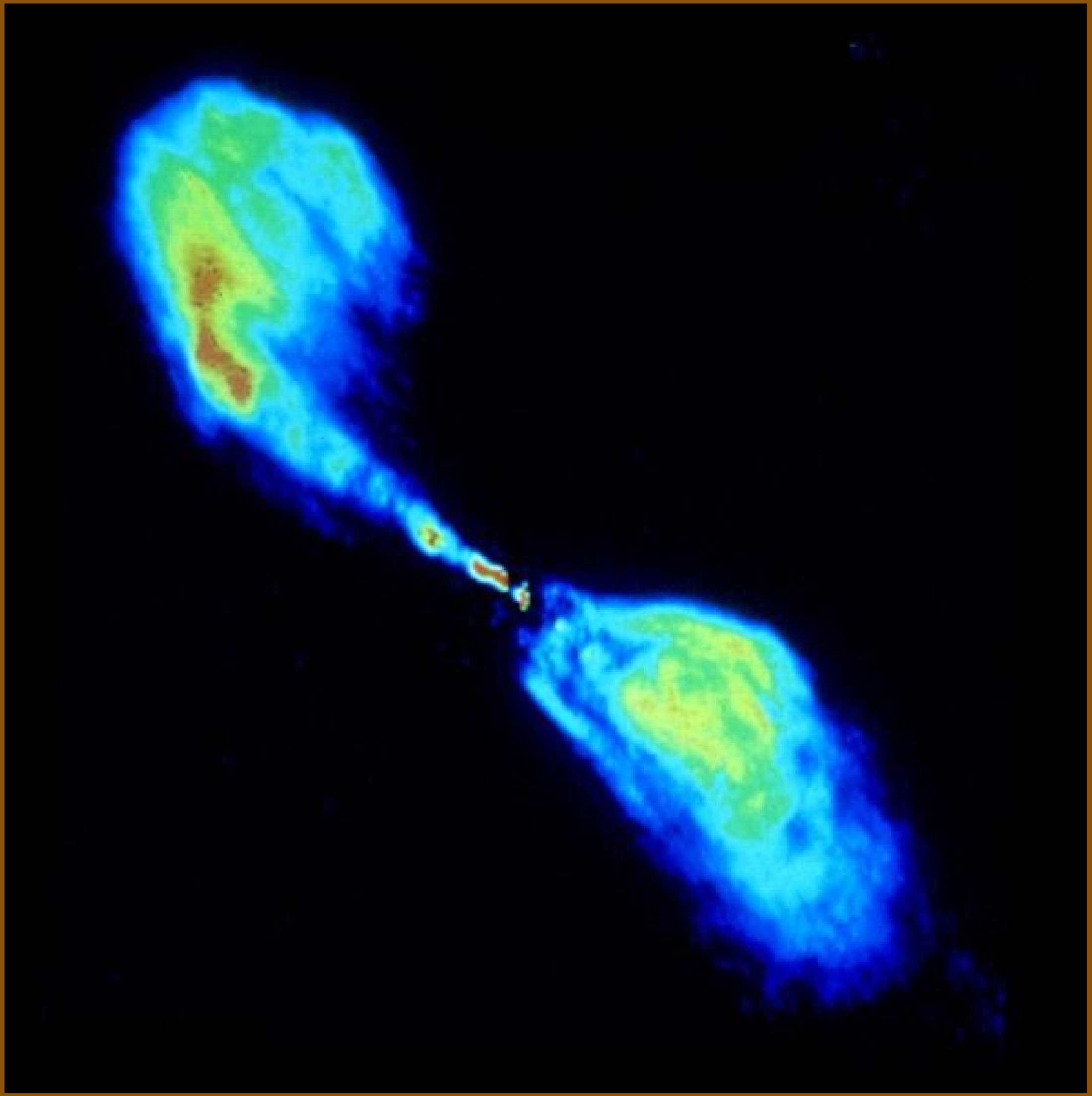
Centaurus A is a nearby radio galaxy. The size of the giant radio lobes is bigger than 500 kpc. Magnetic field is of order 1 μG. The current Cen A does not have enough power to accelerate protons to $10^{20}$ eV.



# AGN jets: the jet Lorentz factor (10) decreases the energy requirements. There should be adiabatic loss.

The inner lobe and jets of Cen A. Jets are not very active now and there are no hot spots.

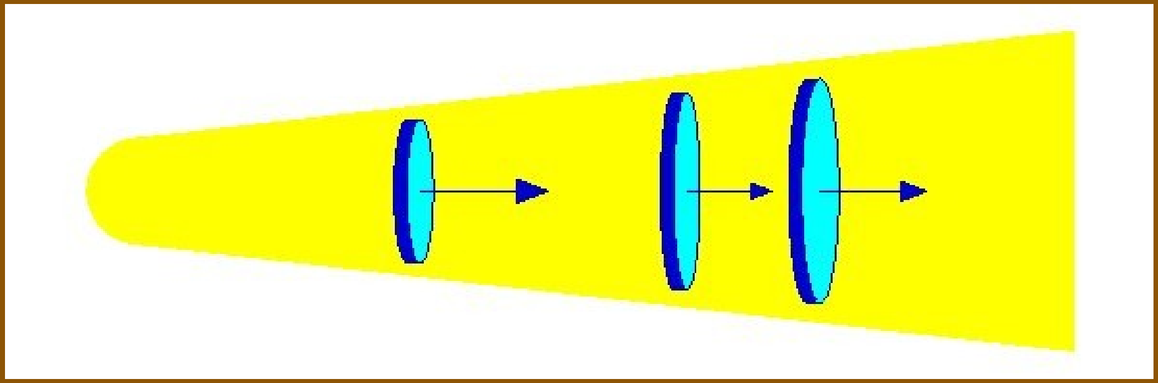


GRB: the extreme case of jet acceleration. The Lorentz factors of GRB are assumed to be between 100 & 1,000. Isotropic luminosity is $10^{53-54}$ ergs. Suggestion first made when directions
of two powerful GRB coincide with most energetic UHECR.

Particle acceleration in AGN jets:

The AGN inner engine pushes blobs of plasma in the jet. They move with different velocity. When a faster moving blob of plasma approaches
a lower one shocks are created in which particle acceleration is quite effective. If the shocks are relativistic each shock crossing increases the particle energy by $\Gamma^2$ (Gamma is the Lorentz factor).



When jets start slowing down the particles are are decelerated

Colliding galaxies: $20\mu G$ fields possible on 30 kpc scales.
Very strong shocks are observed.

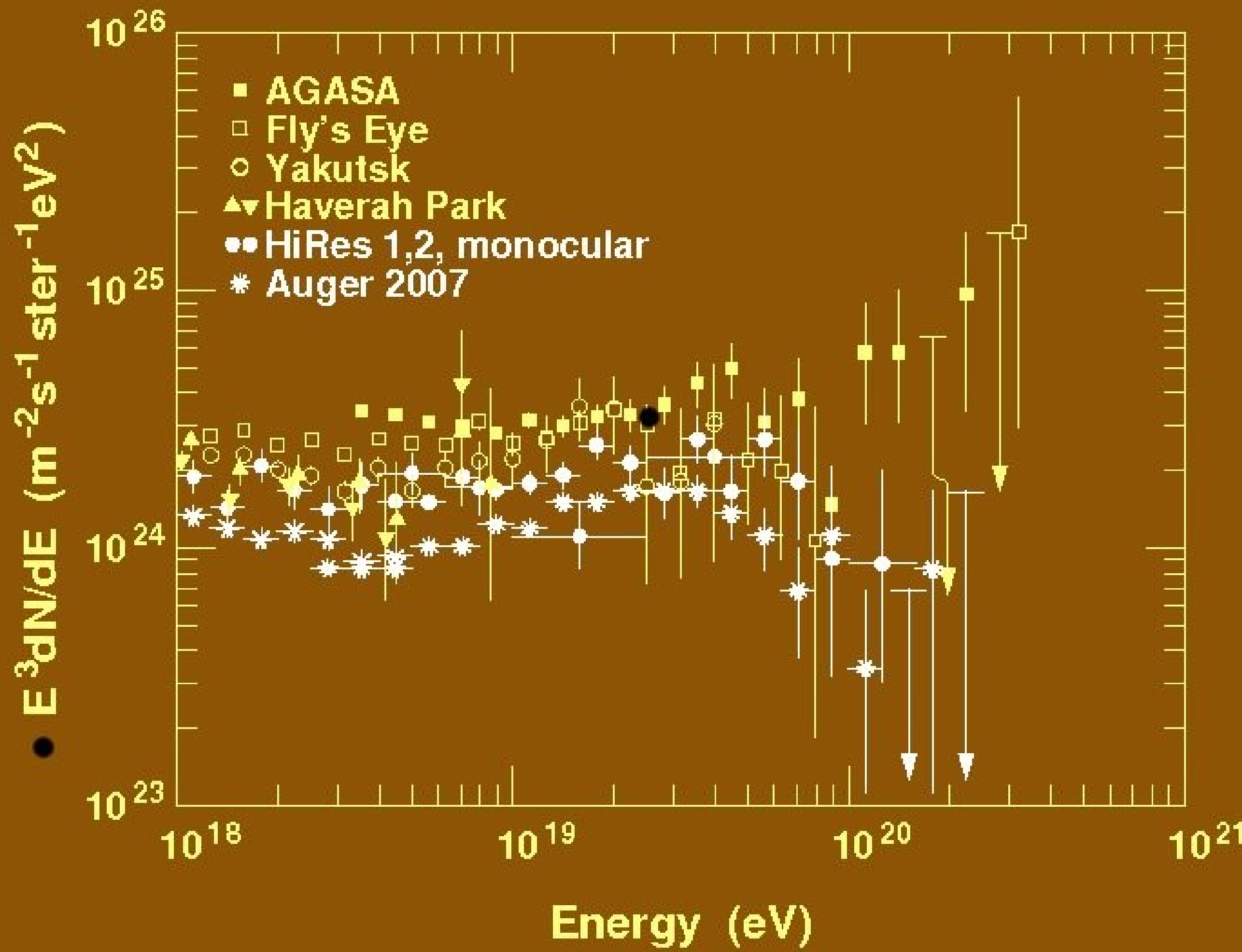
The central black holes very often collide and become a single one with realigned rotation and jet direction.

Quiet black holes: Such objects could exists within 50 Mpc of the Galaxy. $10^9$ $M_\odot$ black hole could accelerate up to $10^{20}$ eV.

Pulsars: Not shock acceleration. Charged particles are accelerated in the strong electrostatic potential drop. Characteristic 1/E energy spectrum. UHECR should be iron nuclei.

All models need to reach its extreme in order to accelerate above $10^{20}$ eV.

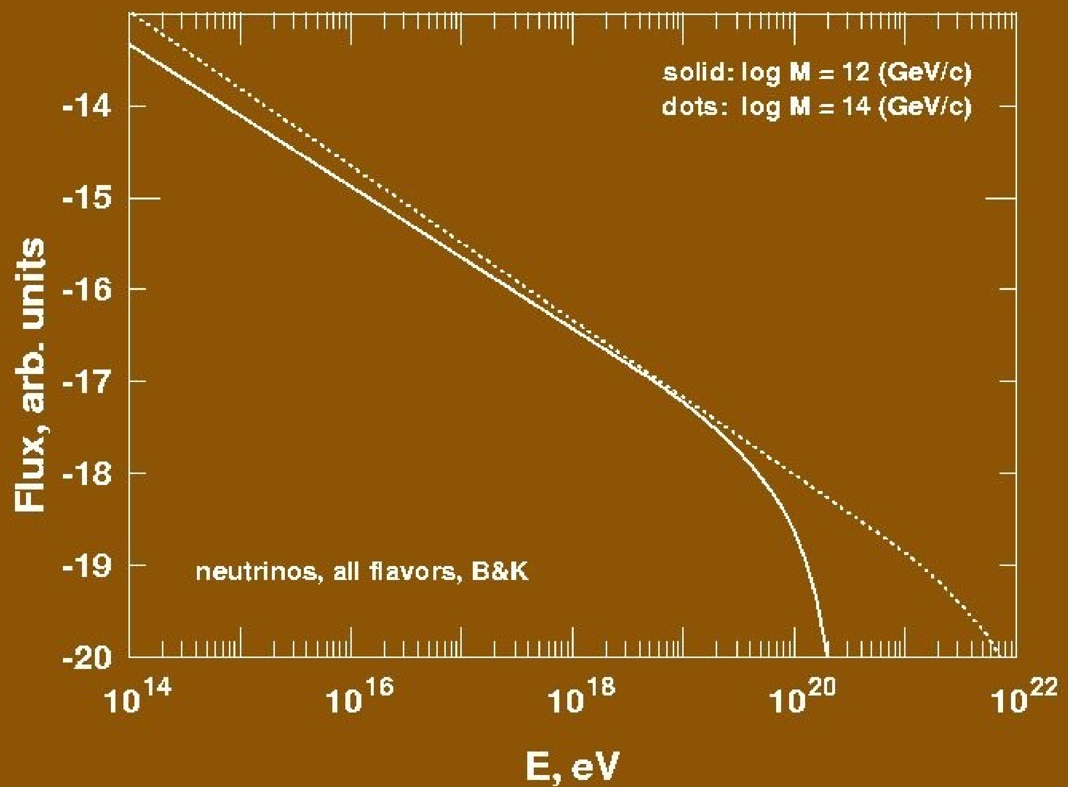
**In all astrophysical acceleration scenarios UHECR are charged nuclei.** It is possible that only neutrons from higher energy nucleon interactions could leave the source. Many of them would decay to protons. This is the biggest difference with `top-down' models that were intended to solve these difficulties.




Since we have no idea how to accelerate particles to such high energy a new set of models appeared that assumed UHECR are product of the decay of a superheavy X particle. They had to be either gamma rays or neutrinos. The neutrino spectrum could continue beyond $10^{20}$ eV.

The data of AGASA encouraged the development of such models.

## Top-down models




Neutrino spectra (sum of all flavors) from the decay of supermassive X particles (Berezinsky& Kachelriess. Gamma ray spectra at source are similar. They undergo cascading in propagation and end up in the GeV range.

The number of decay nucleons would be lower by a factor 30 at the lower energy range and will become equal at the higher energy (or even exceed the neutrinos). The gamma ray fluxes at the source are of the same magnitude. If IHECR are not gamma rays the top-down models are out.

## Hybrid scenarios:

**Z-burst:** A spectacular model: Ultrahigh energy neutrinos (of unknown origin) interact on massive relic neutrinos that are gravitationally attracted in our cosmological neighbor-hood. Interactions proceed through the $Z_0$ resonance and secondary $Z_0$ decay to generate UHECR. To have the resonant cross section neutrinos have to have energy $4 \times 10^{21}$ eV/$m_\nu$ .

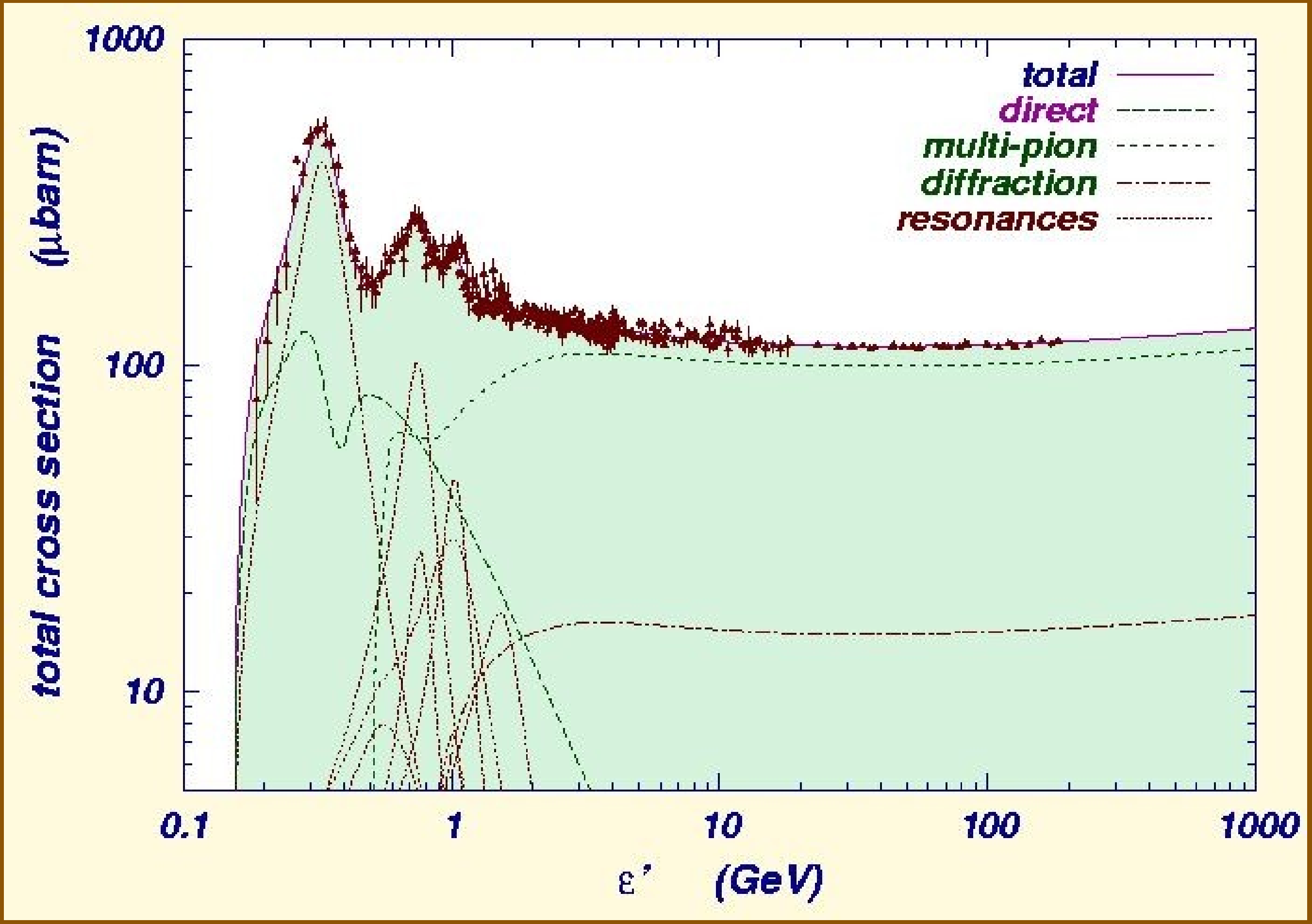
Two problems:

1) How do you generate such high energy neutrinos
2) With the expected low neutrino mass the gravitational attraction becomes more difficult.

**Propagation** of extragalactic cosmic rays

The spectrum of the highest energy cosmic rays is formed in their propagation from the sources to us when they interact in the photon fields of the Universe. Because we do not know what their sources are we have to assume that UHECR sources are isotropically and homogeneously distributed. The possible existence of *nearby* sources could make a significant difference.

The main energy loss process of the ultra high energy protons in the Universe is photoproduction interactions in the microwave background. The photoproduction cross section is very well measured in accelerator experiments.



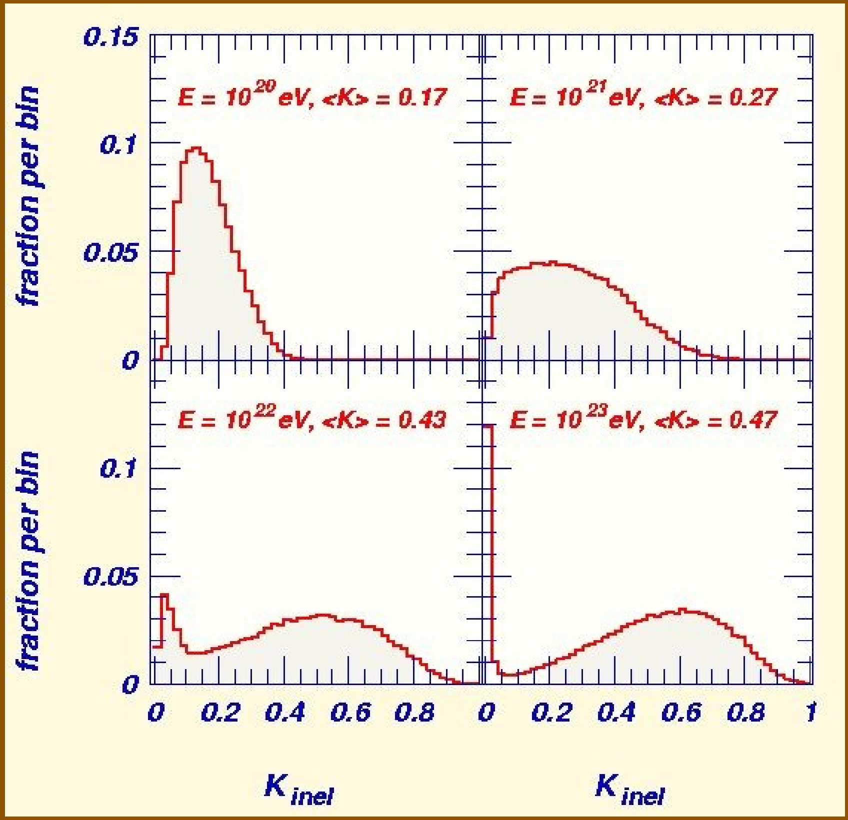

Photoproduc-tion cross section in the mirror system, i.e. photons interacting on target protons.

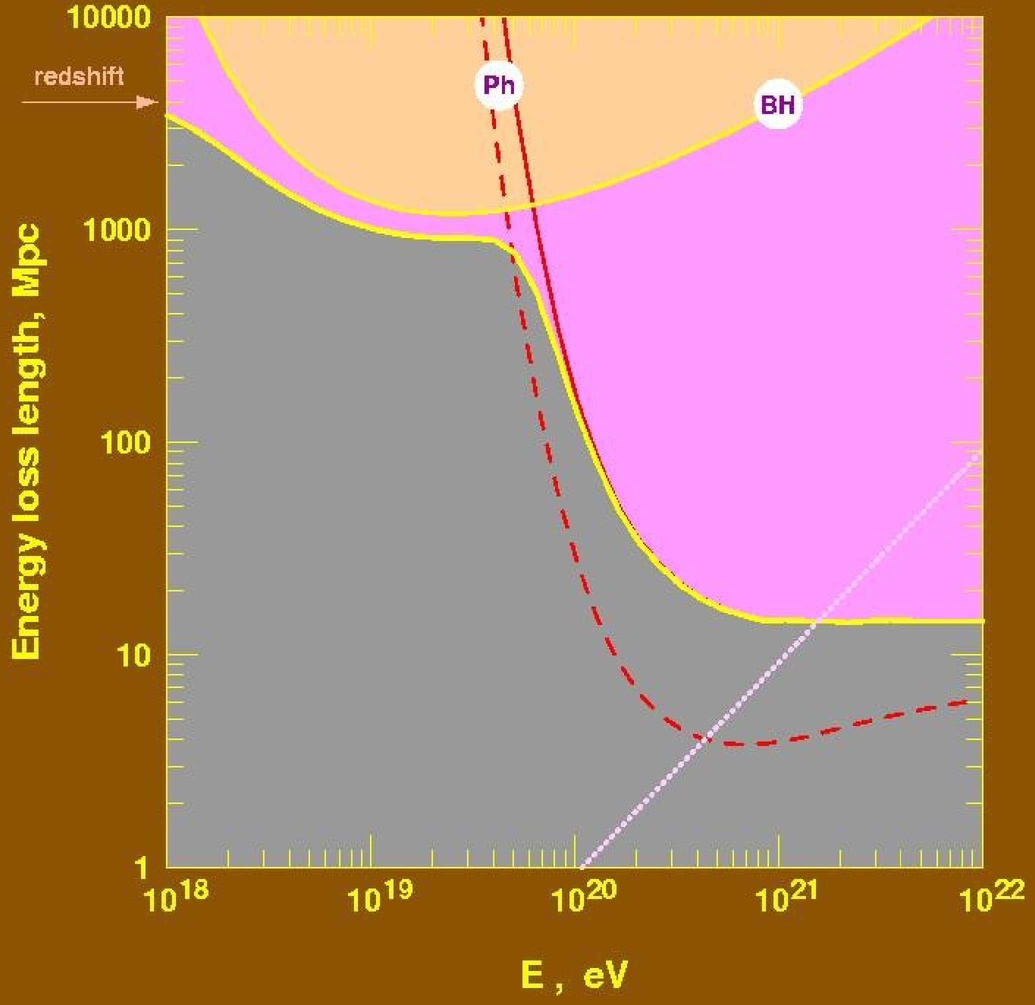
The UHE protons energy is so high that they can interact on photons from the microwave background and produce secondary pions. The threshold is when the center of mass energy exceeds the proton mass + the pion mass:

$$E\varepsilon(1-\cos\theta) > (m_p+m_\pi)^2$$

For the average microwave background photon the threshold is at $10^{20}$ eV. Averaged over the photon spectrum and direction the threshold is half of order of magnitude lowe

The inelasticity of the proton in these interactions is impor-tant energy dependent parameter.
At threshold protons lose less than 20% of their energy. At very high energy the loss can reach 50%.

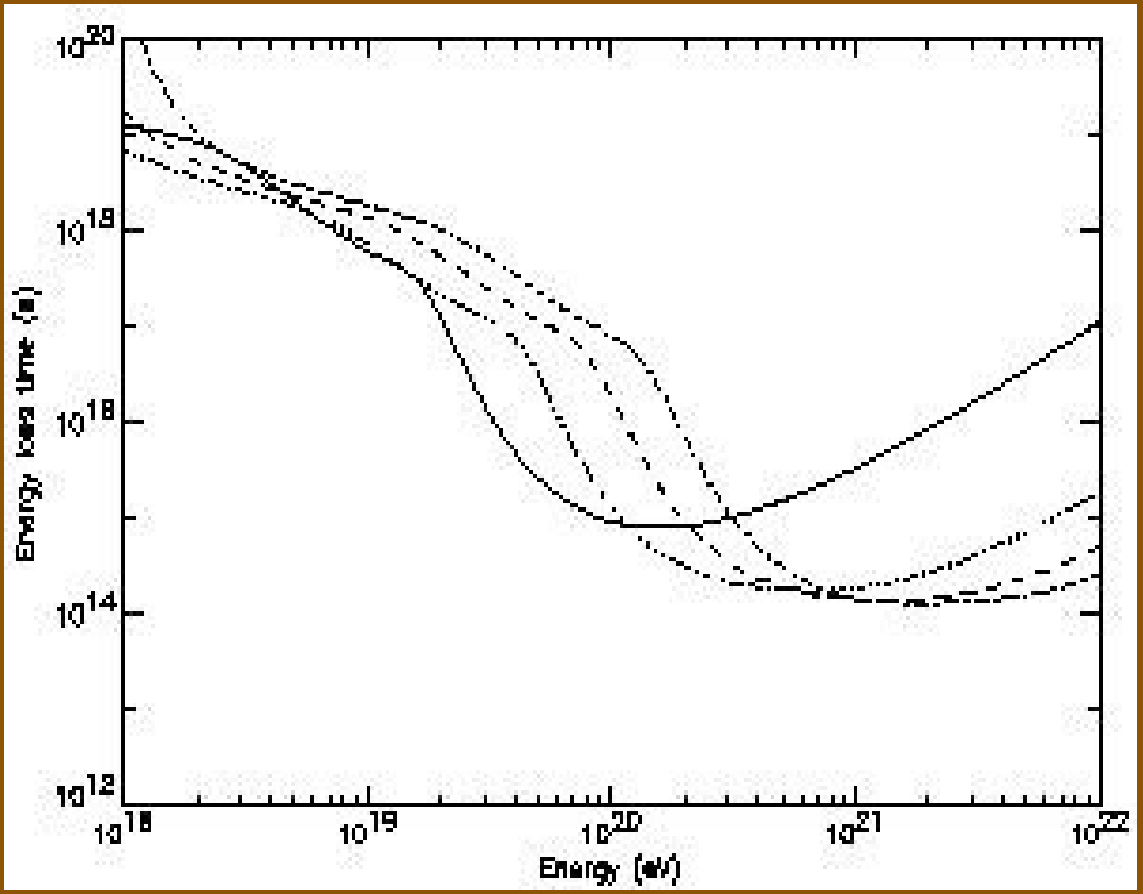





The energy loss length of protons in the microwave background is about 14 Mpc above $4x10^{20}$ eV, about a factor of 4 above the proton interaction length. The arow in the left upper side of the graph shows the energy loss length in the BH electron-positron pair production. The proton energy loss is the ratio of electron to proton mass. The cross section is high.

The mark at 4,000 Mpc shows the energy loss to the expansion of the Universe for $H_0$=75 km/Mpc/s.

Neutron decay length is also shown with dashed line.



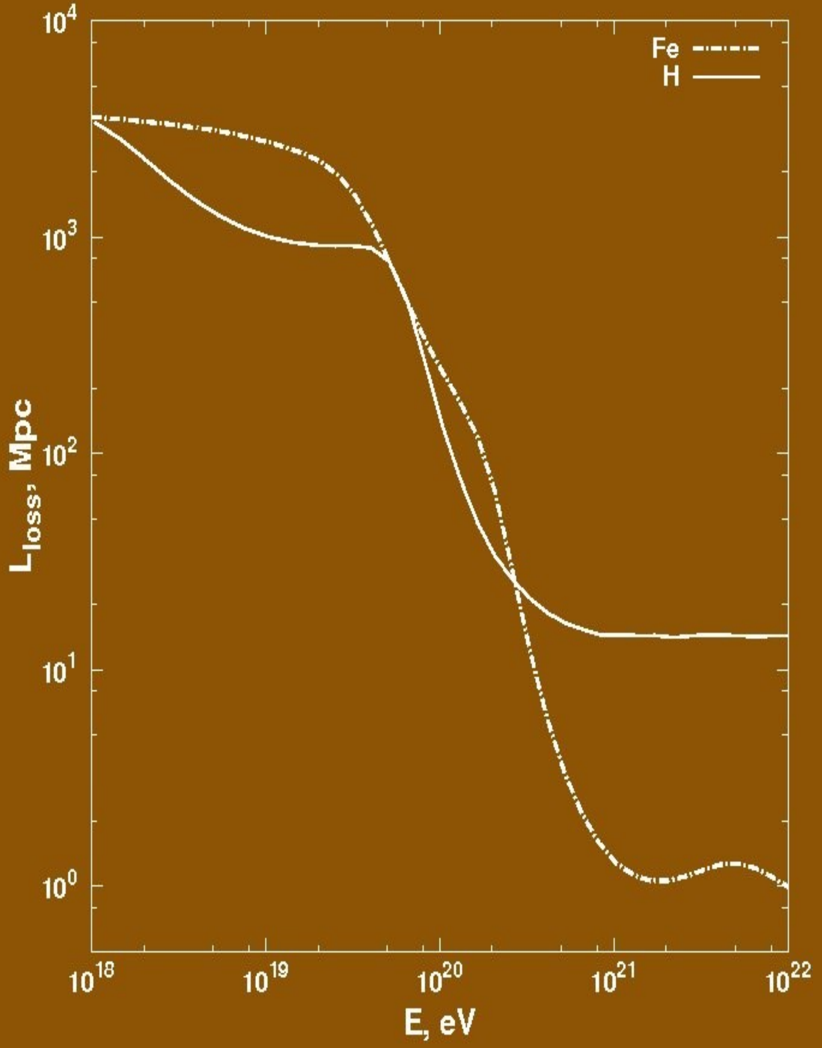

From: Bertone et al

Heavy nuclei lose energy in photodisintegration on all photon fields.
A beam of heavy nuclei injected at large distance from us changes its composition in propagation. At distances larger than the energy loss distance it is a purely proton beam after the secondary neutrons decay.

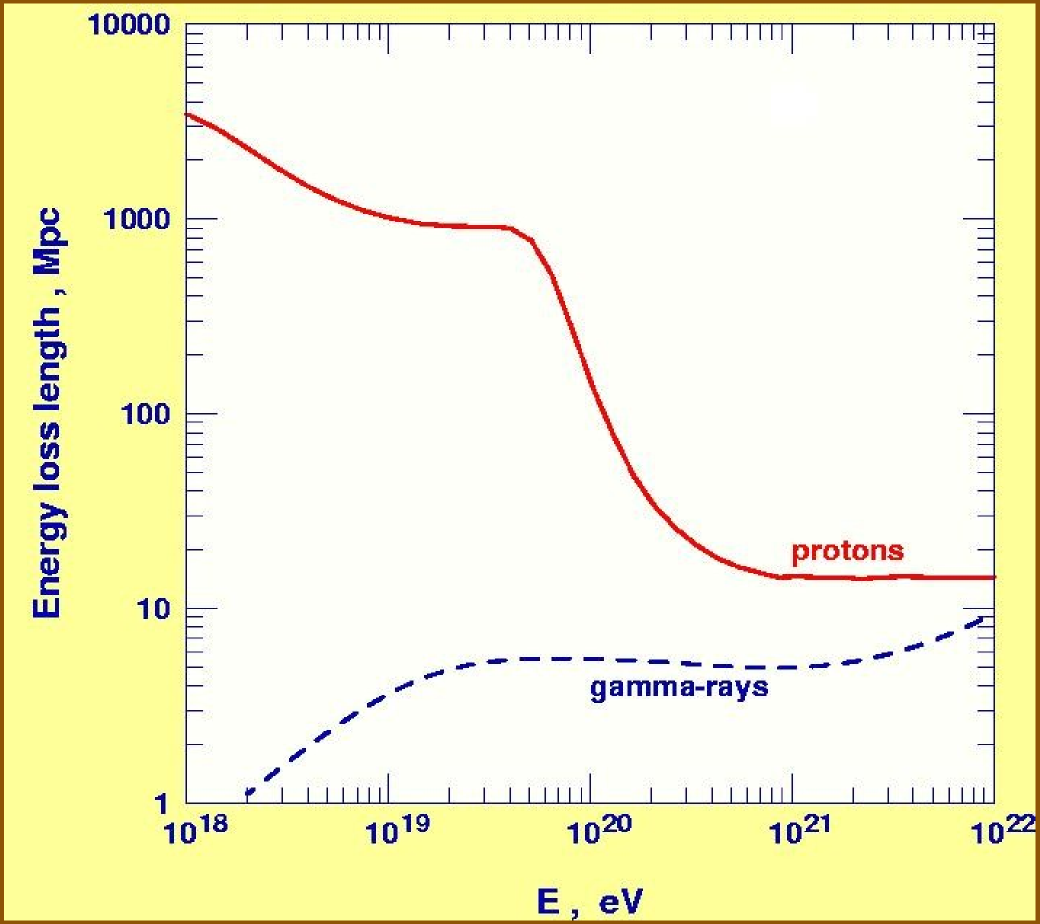
Energy loss time for He, C, Si, and Fe nuclei.
(1 Mpc = $10^{14}$ s)

$$
\begin{aligned}
\frac{dN_{Z,A}}{dt} = {} & N_{Z+1,A}\lambda_{\beta}^{Z+1,A} + N_{Z-1,A}\lambda_{\beta}^{Z-1,A} \\
& + N_{Z,A+1}\lambda_{\gamma,n}^{Z,A+1} + N_{Z+1,A+1}\lambda_{\gamma,p}^{Z+1,A+1} + N_{Z+2,A+4}\lambda_{\gamma,\alpha}^{Z+2,A+4} \\
& + N_{Z,A+2}\lambda_{\gamma,2n}^{Z,A+2} + N_{Z+2,A+2}\lambda_{\gamma,2p}^{Z+2,A+2} + N_{Z+4,A+8}\lambda_{\gamma,2\alpha}^{Z+4,A+8} \\
& + N_{Z+1,A+2}\lambda_{\gamma,np}^{Z+1,A+2} + N_{Z+2,A+5}\lambda_{\gamma,n\alpha}^{Z+2,A+5} + N_{Z+3,A+5}\lambda_{\gamma,p\alpha}^{Z+3,A+5} \\
& - N_{Z,A}\left[\lambda_{\beta}^{Z,A} + \sum_{x}\lambda_{\gamma,x}^{Z,A}\right] ,
\end{aligned}
$$

Comparison of the energy loss length of protons and Fe nuclei. All other nuclei have lower energy loss length.

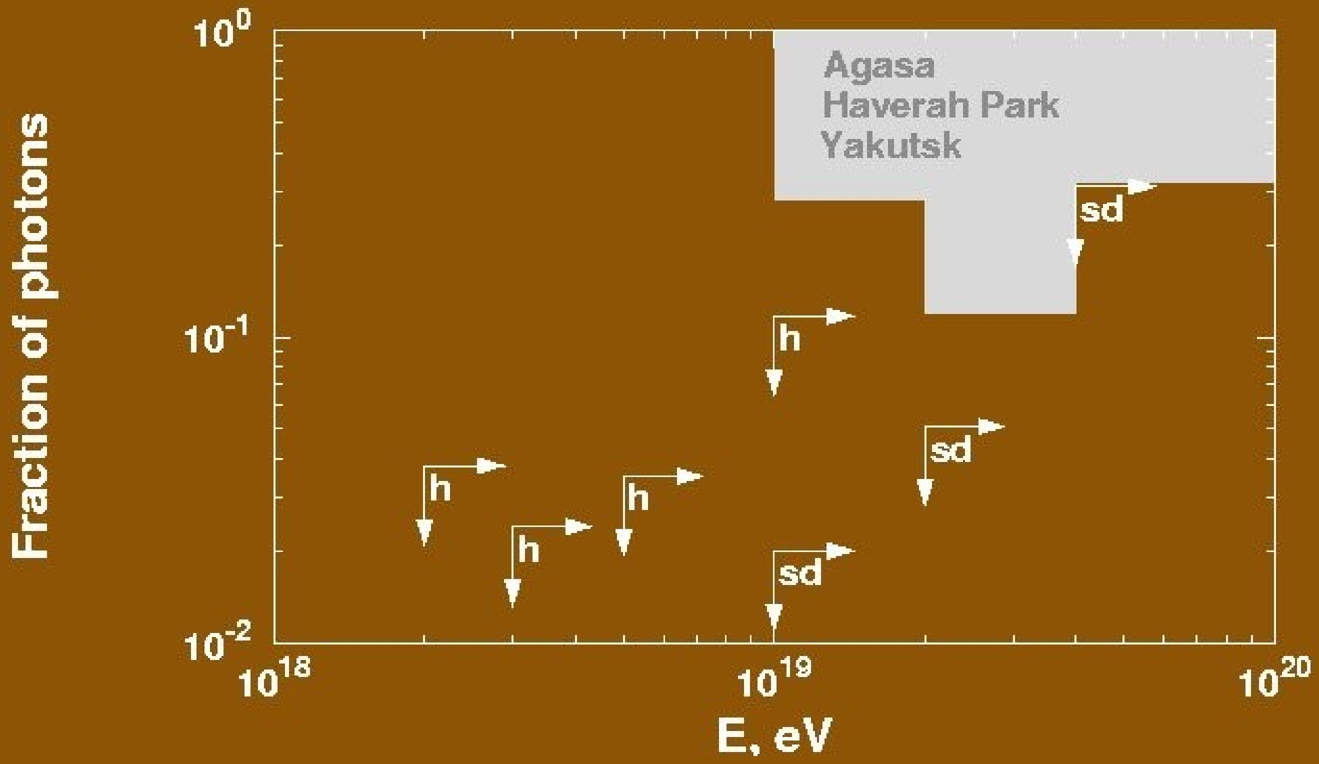



Thanks to D. Allard



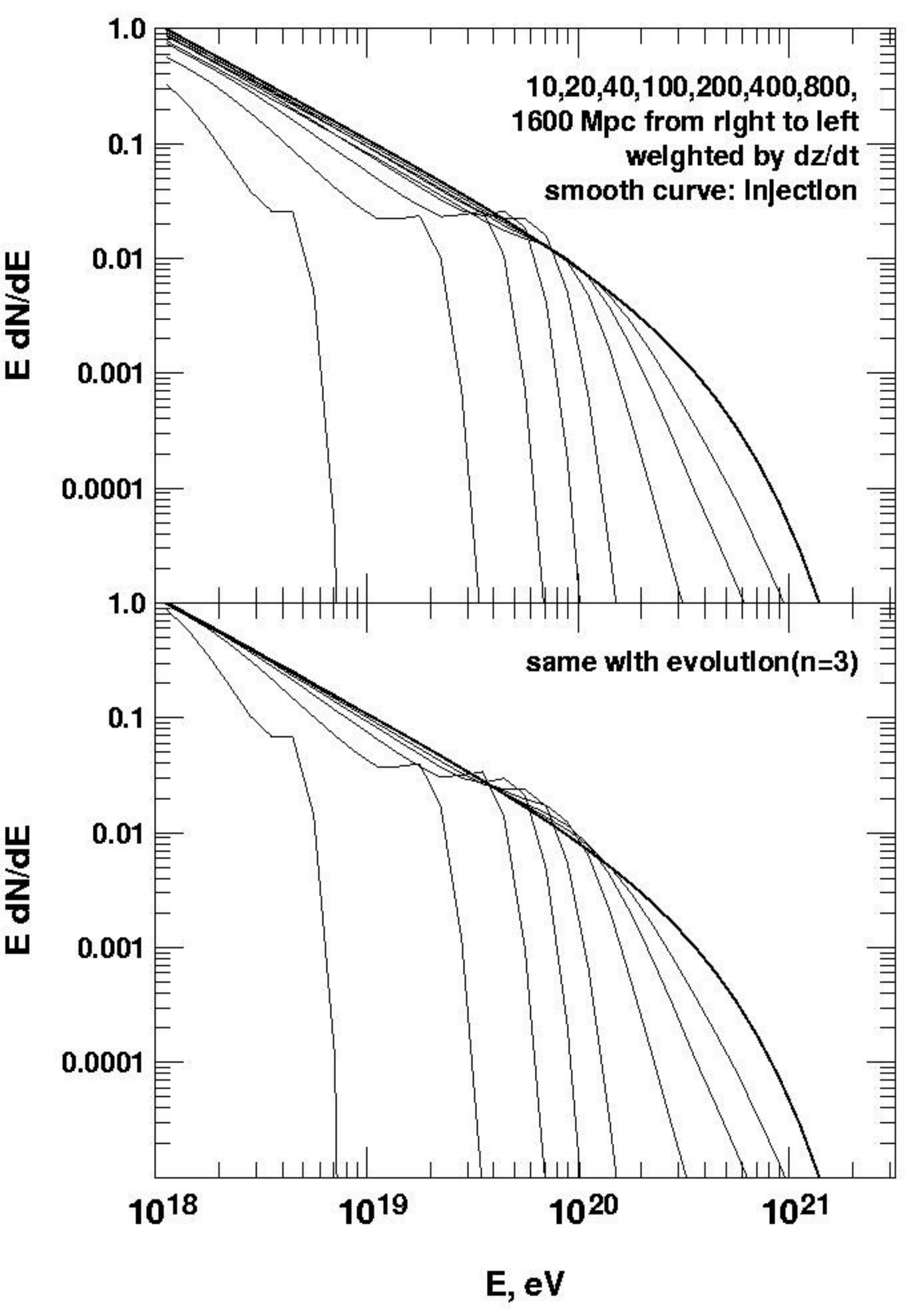

Mostly because of the uncertainties in the MHz radio background and the magnetic field strength, there are arguments about the gamma ray energy loss length.
The estimate here uses B&P radio background and 1 nG magnetic field.

It is obvious, though, that GZK gamma rays, as well as GZK protons, can not travel far. They have to be generated at 2 to 3 energy loss lengths to minimize the (already severe) energy requirements to the sources. There very few potential sources at distance less than 50 Mpc from the Galaxy.




Now TopDown models are not in favour after the Auger Observatory set strict limits on the fraction of gamma rays In the cosmic ray flux. Note the limits are on integral fluxes.

Both Auger and the HiRes experiments set much more milder limits on the flux of UHE neutrinos. The limit on gamma-rays however also limits the neutrino fluxes.



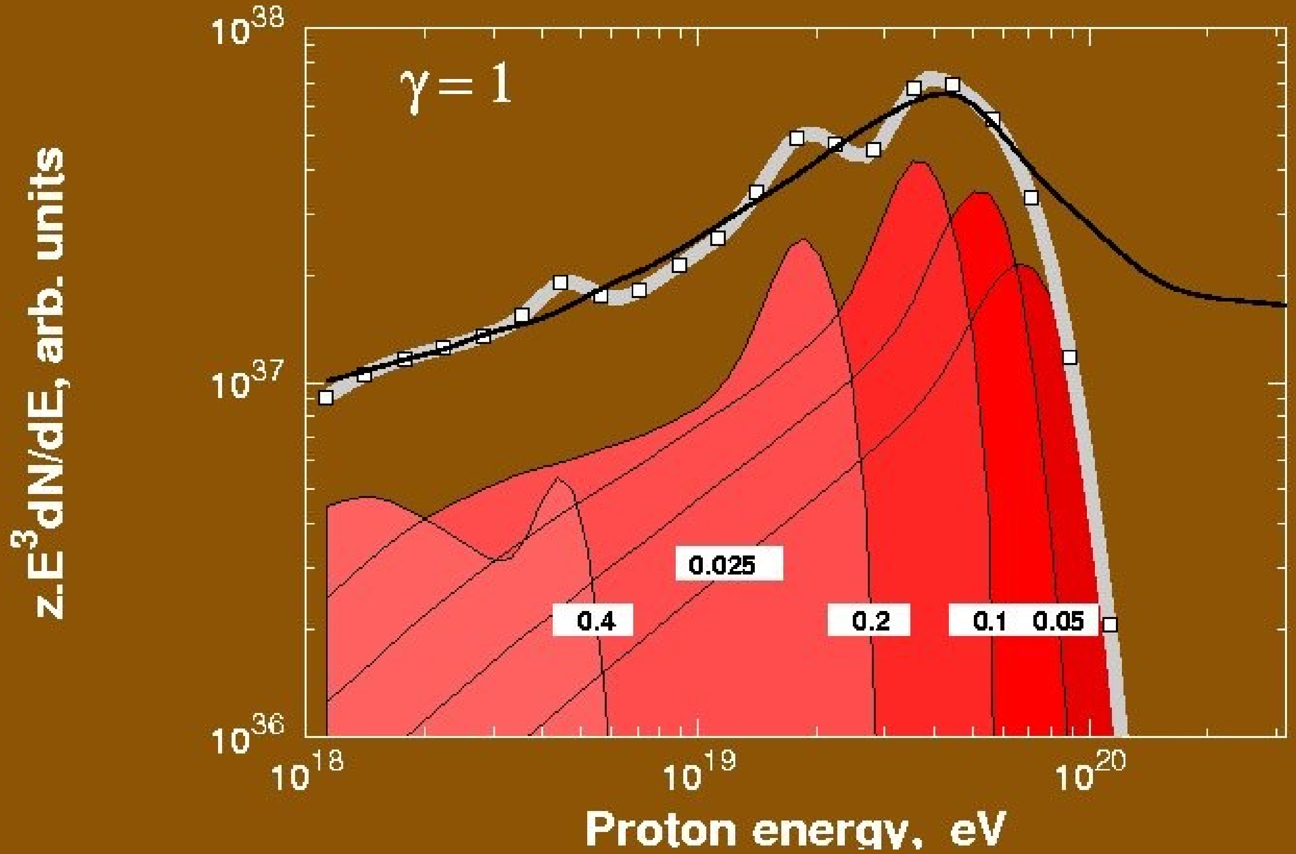

**Evolution** of the cosmic ray spectrum in propagation on different distances.

The solid line shows the injection spectrum.

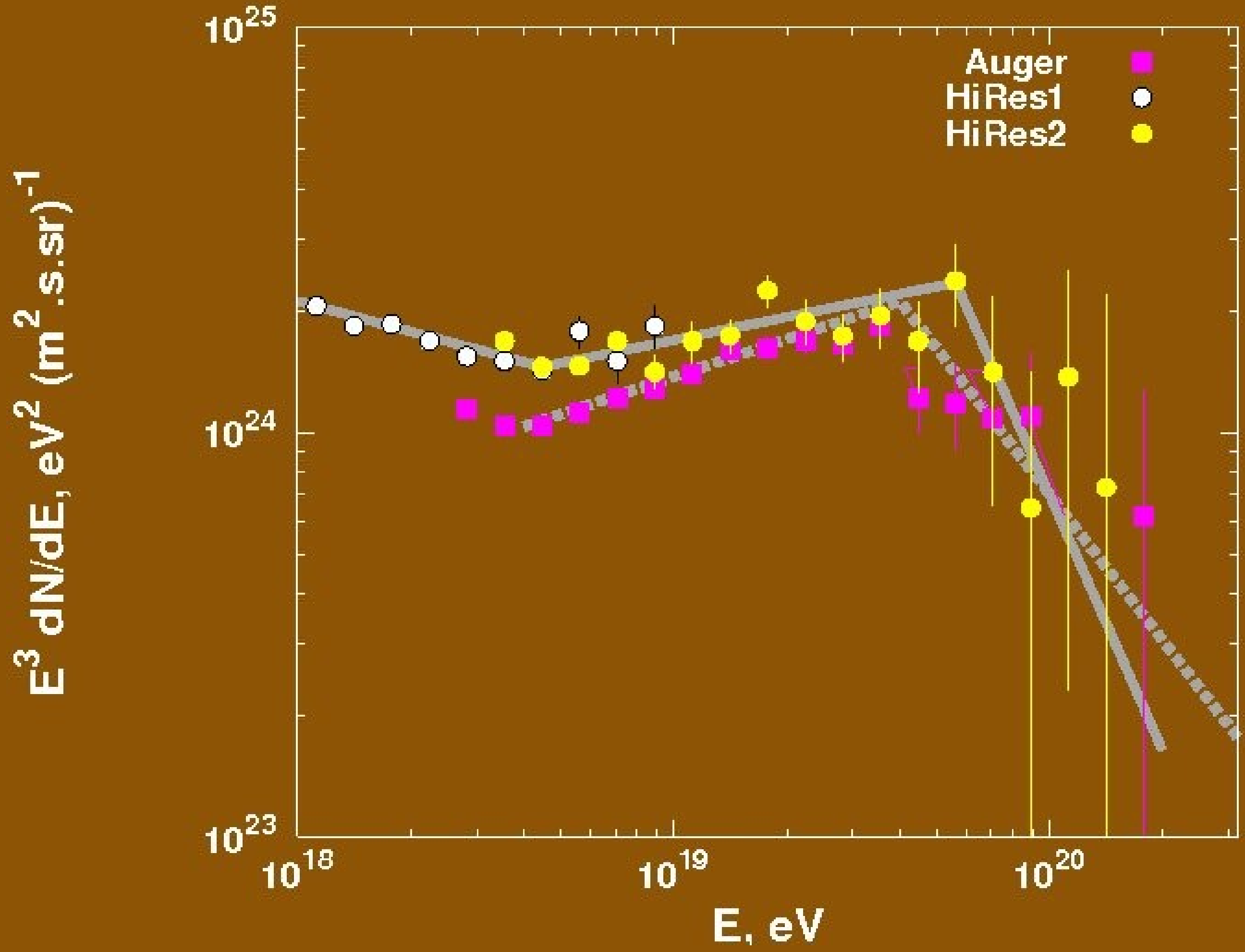
The top panel is without cosmological evolution of the cosmic ray sources and the lower one is with $(1+z)^3$ evolution up to $z = 1.7$.

There is a pile-up of protons just below $10^{20}$ eV. Integration over source distance will produce the expected energy distribution for homogeneous isotropic source distribution.

Because of the strong proton energy loss high redshifts *z* do not contribute much to the highest energy cosmic rays. Here is an example.




Contribution of cosmic ray sources at different redshift to the observed flux. The solid black line is the flux in case of isotropic distribution of the cosmic ray sources and a flat injection spectrum for cosmological evolution $(1+z)^3$.




The spectra of HiRes and Auger as published in Phys. Rev. Lett. Both measurements claim a confirmation of the GZK feature. The differences are small but lead to different interpretations.

The HiRes spectrum has a slope of 2.8 between log10(E) of 18.65 and 19.75 with a steepening to 5.1 at higher energy. Auger has a flatter slope of 2.6 between log10(E) of 18.6 to 19.6 with a steepening to 4.2.

The spectrum measured by HiRes is described very well by the model of Berezinsky et al (2005) which exhibits a very steep ($E^{-2.7}$) acceleration spectrum, pure proton composition and does not need cosmological evolution of the cosmic ray sources.

The spectrum of Auger is more difficult to interpret. It fits equally well three different models:

a) Proton composition with acceleration spectrum $E^{-2.55}$ and no cosmological evolution of the sources.

b) Proton composition with acceleration spectrum $E^{-2.30}$ and very strong cosmological evolution $(1 + z)^5$.

c) Mixed composition: UHECR contain a large amount of heavy nuclei. Acceleration spectrum should be flatter than model b).

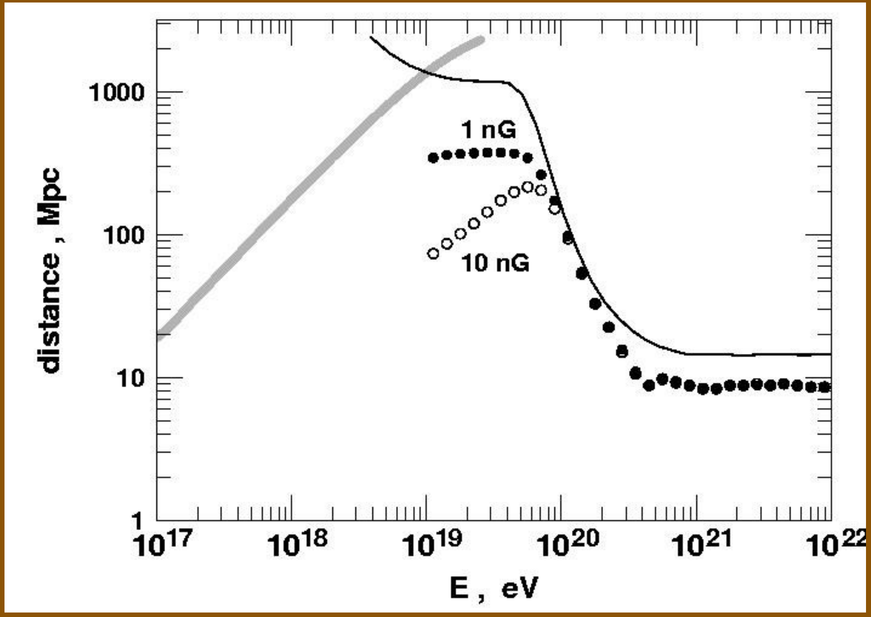
It is not possible to chose between these models without determining the chemical composition of the events.

There is always the possibility of the *disapointing model* (A.A.Watson, Berezinsky et al, 2009).

The propagation of UHECR is influenced very strongly by magnetic fields, both galactic and extragalactic.

- galactic magnetic fields deflect UHECR protons up to 10 degrees away from the direction of their sources. In case of heavy nuclei the deflection is much stronger, as $10^{18}$ V particles gyrate along the magnetic field lines.

- random extragalactic fields, if they have strengths of nG on Mpc scale, can impose a relatively small `horizon'. Protons of energy below $10^{20}$ eV scatter and loose energy so much that they can not reach us in Hubble time. **This may restrict the region from which this particles can reach us.**




Points are results of Monte Carlo propagation. The heavy grey line shows propagation time (analytic estimate, Achterberg) exceeding Hubble time.

## Secondary particles generated in propagation

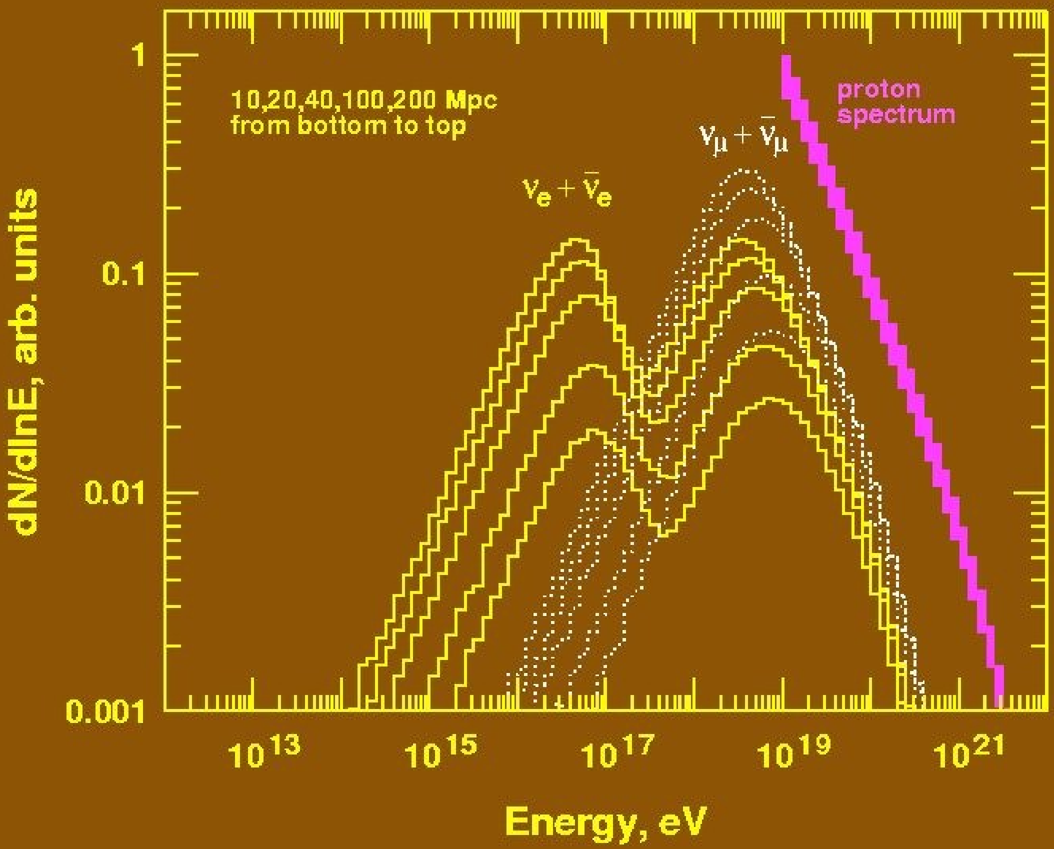
**Cosmogentic neutrinos** are neutrinos from the propagation of extragalactic cosmic rays in the Universe. These neutrinos were first proposed and their flux was calculated in 1969 by Berezinsky & Zatsepin. An independent calculation was done by Stecker in 1973. In 1983 Hill & Schramm did another calculation and used the non-detection by Fly's Eye of neutrino induced air showers to set limits on the cosmological evolution of the cosmic rays sources.

The main difference with the processes in AGN and GRB is that the main photon target is the microwave background (2.75ºK) of much lower temperature than the photon emission of these sources. This raises the proton photoproduction threshold to very high energy:

$$E_p^{min} \simeq \frac{m_\Delta^2 - m_p^2}{2(1-cos\theta)\varepsilon} \simeq \frac{5\times 10^{20}}{(1-cos\theta)}\ \mathrm{eV}$$

Actually the proton photoproduction threshold in the MBR is about $3.10^{19}$ eV. There is also production in the isotropic infrared/optical background.

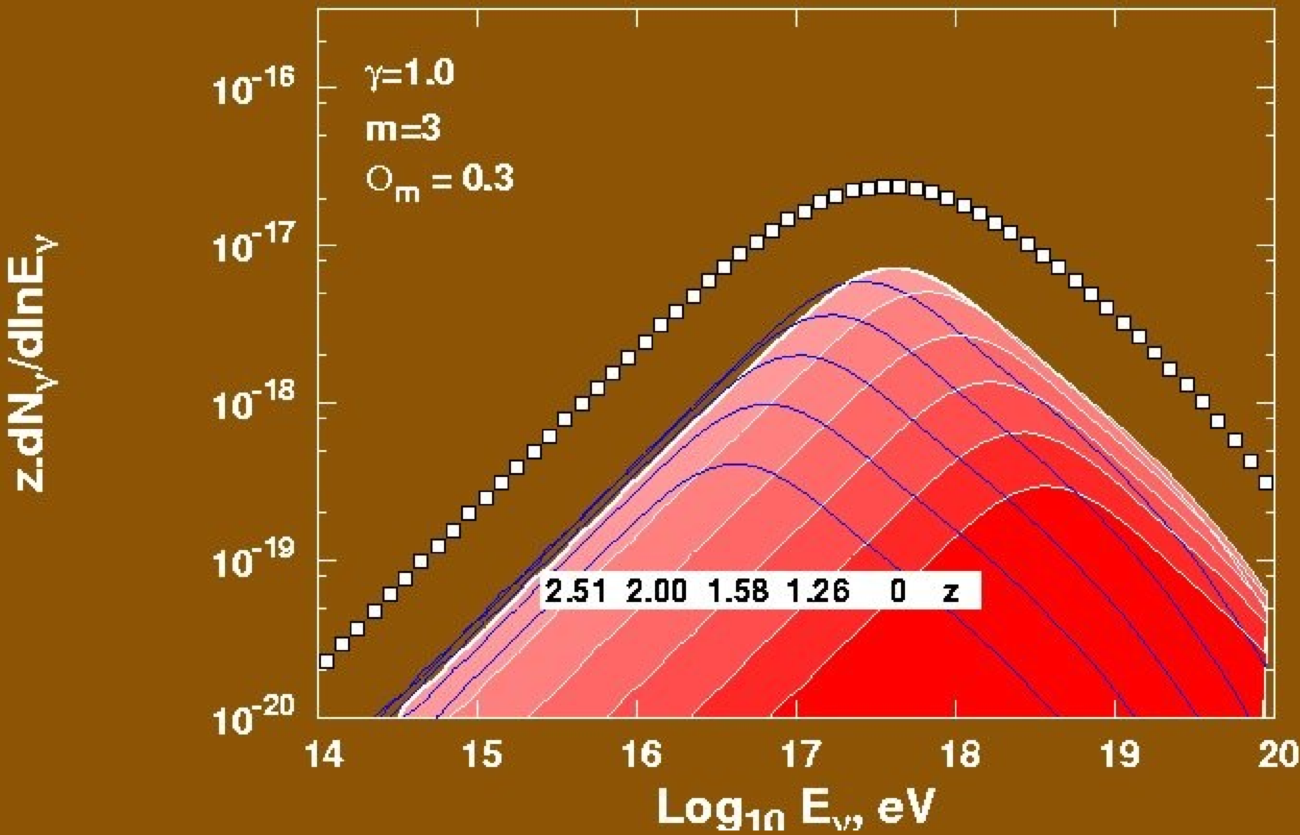
The photoproduction energy loss of the extragalactic cosmic rays cause the GZK effect.




The figure shows the fluxes of electron and muon neutrinos and antineutrinos generated by proton propagation on (bottom to top) 10, 20, 50, 100 & 200 Mpc in MBR. The top of the blue band shows the proton injection spectrum ($E^{-2}$ in this example).

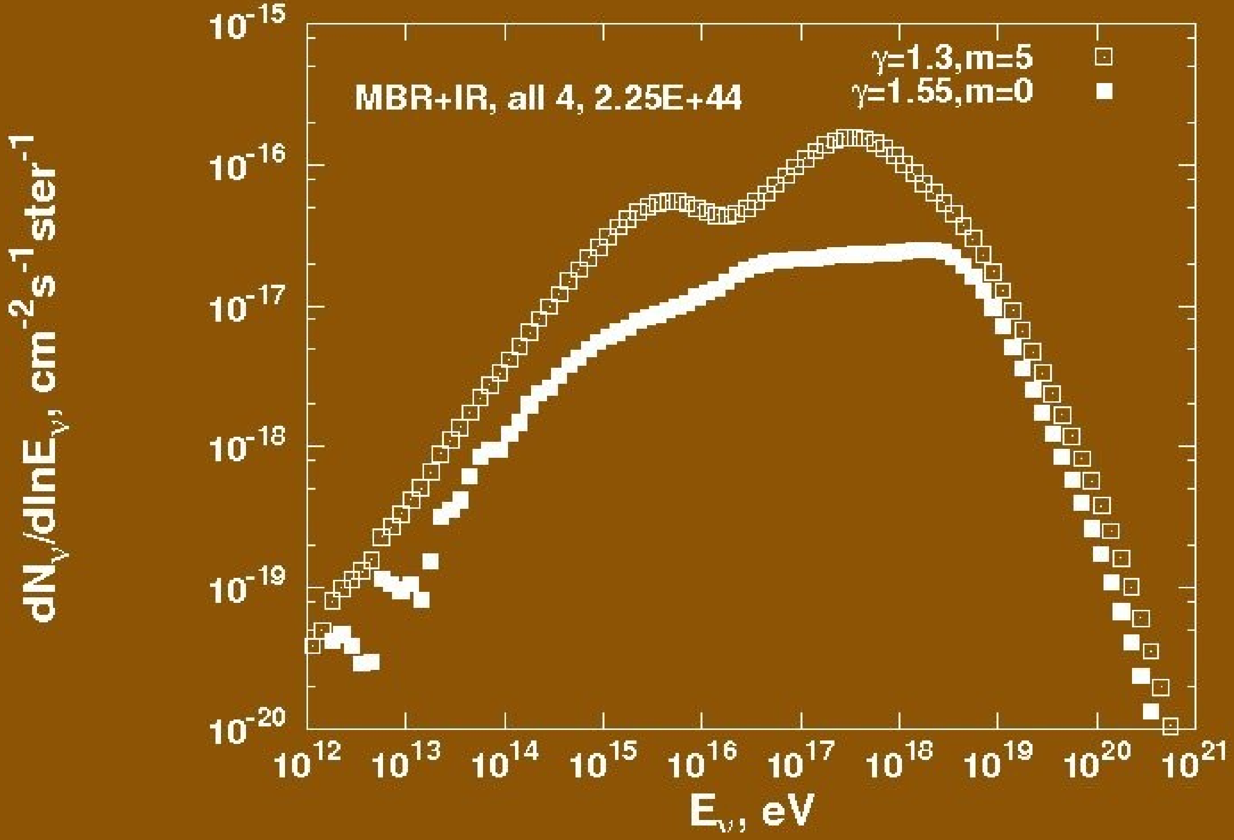
From: Engel, Seckel & Stanev, 2001

Muon neutrinos and antineutrinos are generated with a spectrum similar to the one of electron neutrinos at twice that rate. As far as neutrinos are concerned the cascade development is full after propagation on 200 Mpc. Even the highest energy protons have lost enough energy to be below threshold.
Slightly more of the proton energy loss goes to cosmogenic gamma rays generated in photoproduction and in the BH pair creation.




Cosmogenic neutrinos are very sensitive to the cosmological evolution of the cosmic ray sources because of the lack of energy loss. This could be useful for establishing model for the extragalactic cosmic rays.

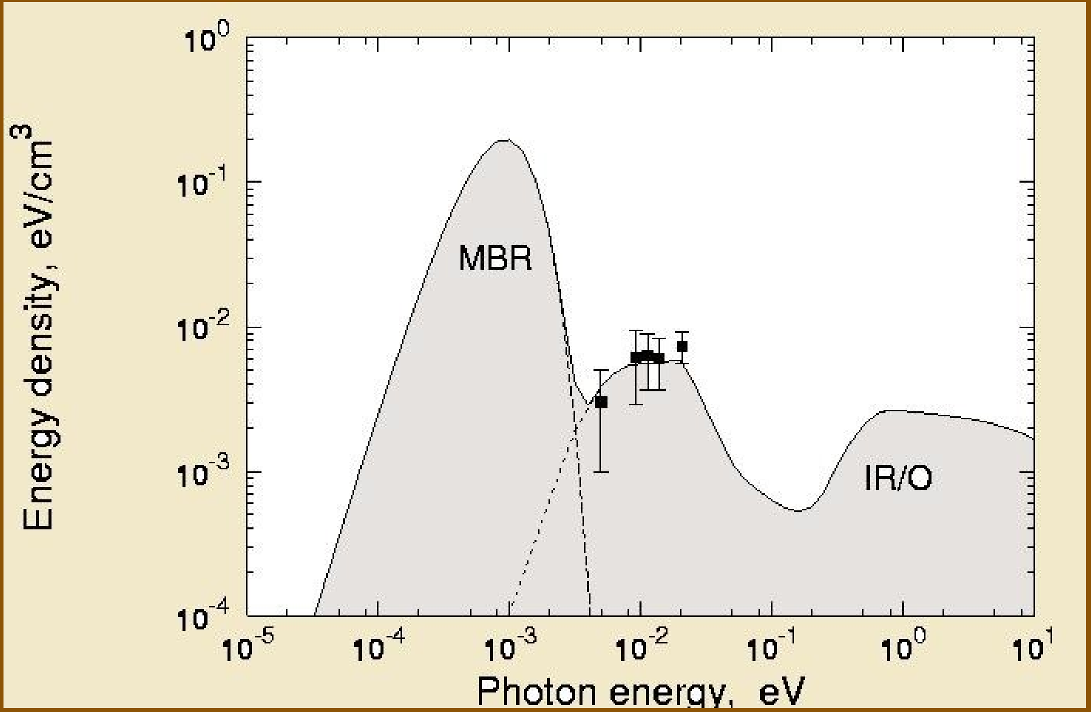
Note the logarithmic scale in redshift. Cosmological parameters are as in the cosmic ray example. The contribution increases until the source luminosity is significant (*z = 2.7 in the W&B model).* At higher redshift the production is still high because of the $(1+z)^3$ increase of the MBR density and the lower energy threshold for photoproduction.




This is what the two proton models that fit well the Auger energy spectrum predict for cosmogenic neutrinos in the case UHECR sources are isotropically distributed in the Universe. If only interactions on MBR were accounted for the difference would be bigger.

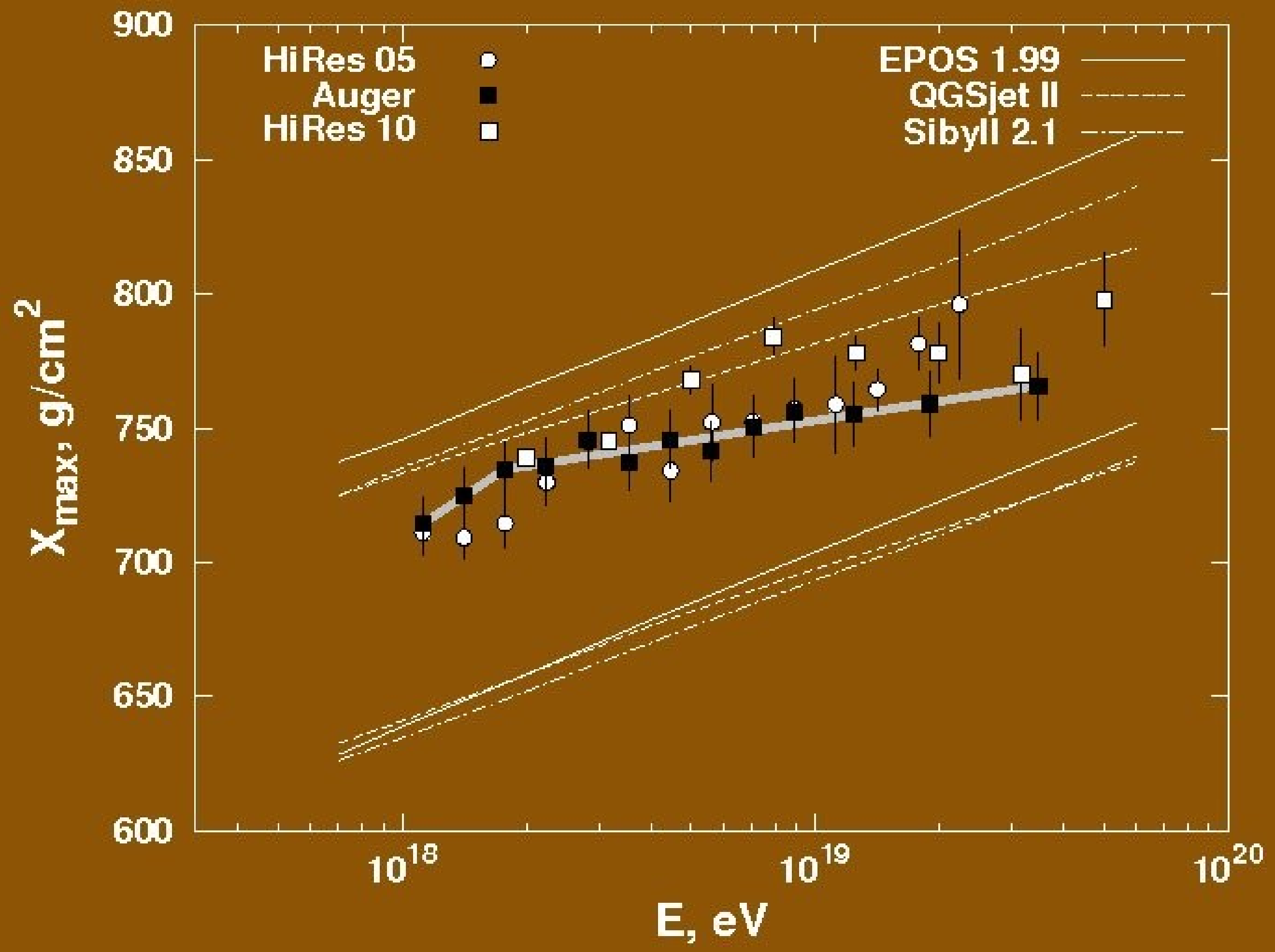
MBR is not the only universal photon field. The infrared/optical background extends over three orders of magnitude in frequency

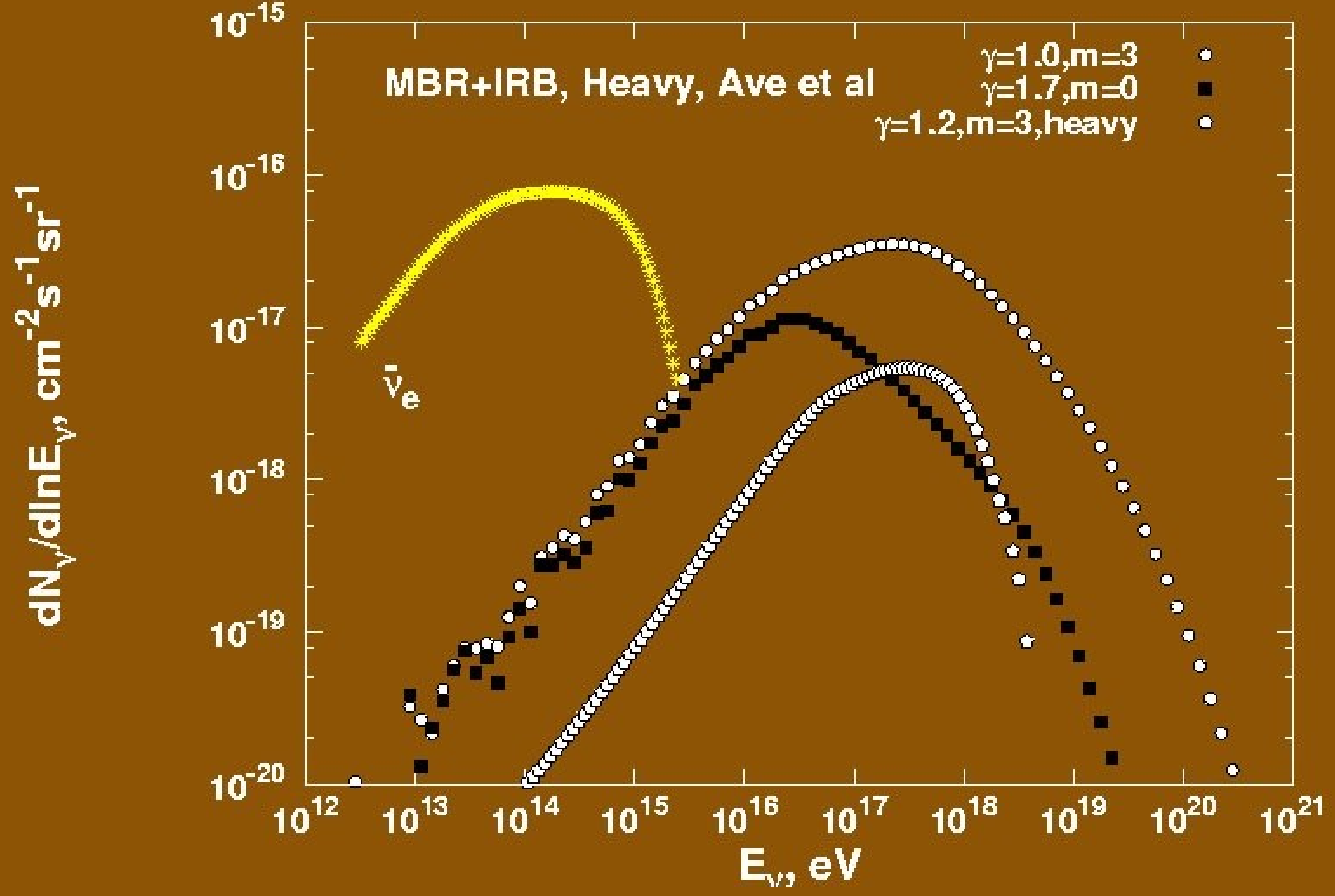
The number density of the IR/0 background is smaller than MBR by about 400. In addition its large energy range decreases #/eV even more. IR/O background has been measured after subtraction of the point sources and has been estimated from the absorption of extragalactic TeV gamma rays . The wavelengths that affect TeV gamma-rays are mostly in the `near' infrared, and the `far' IR is generally less restricted. We now attempt to see if the addition of a small IR&O photon field affects the cosmogenic neutrino fluxes.



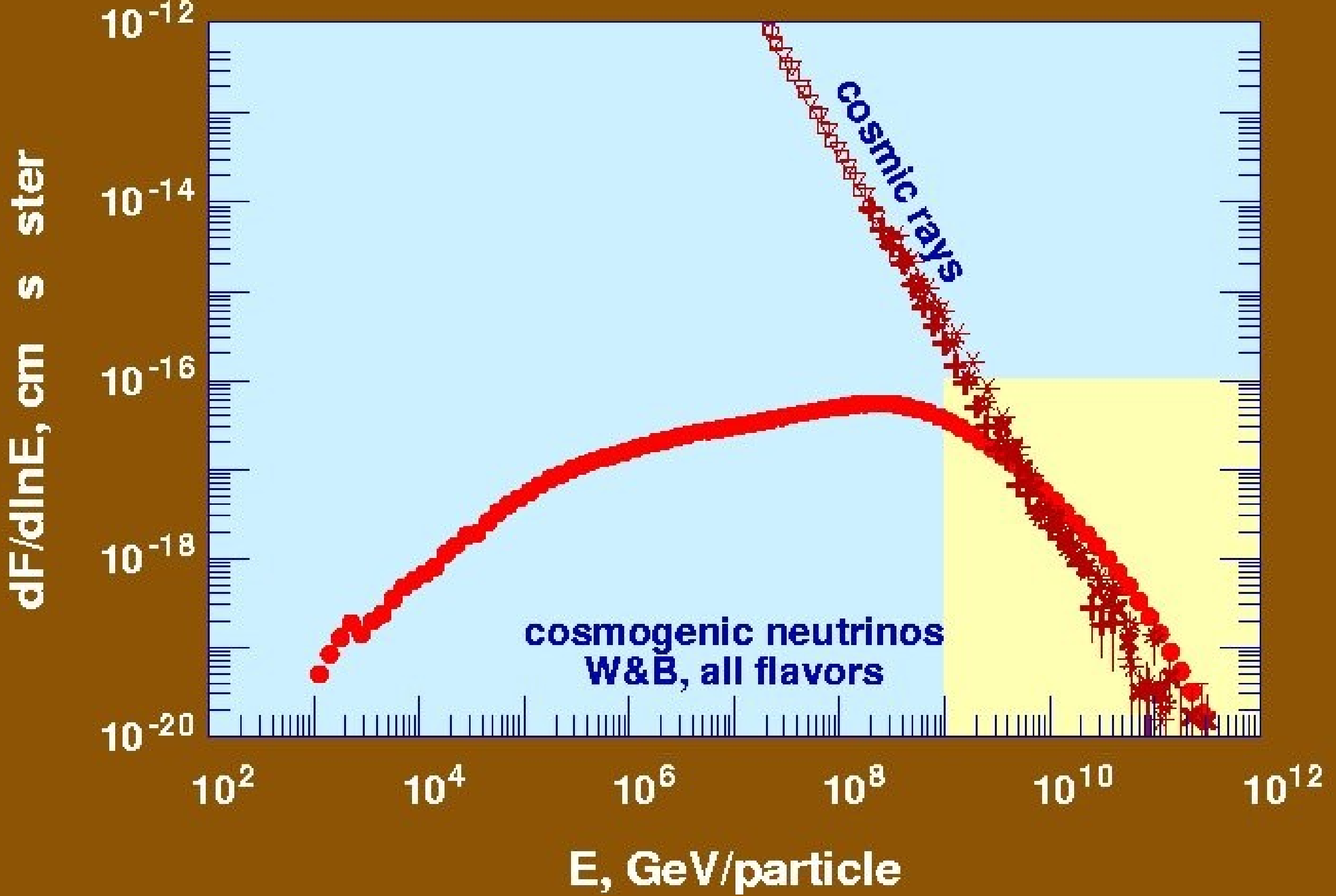

The model of Franceschini et al (2001) is compared to two sets of DIRBE data.

Here are the depth of shower maximum measurements of HiRes (second one is in stereo) and Auger compared to the predictions of three different hadronic interaction models used in the analysis.






In the mixed composition model only the electron antineutrino flux (from neutron decay, yellow symbols) is higher than that in the proton models. The muon neutrino and antineutrino fluxes are lower.




The cosmogenic neutrino flux above $10^{18}$ is the same as the UHECR flux. The difference in the hadron and neutrino cross sections makes it so much difficult to detect. The *theoretical* neutrino rate (no efficiency) is about 0.3 events per $km^3$.yr.

**Summary**

The observed shape of the UHECR energy spectrum is generated during their propagation from their sources to us. It is relatively easy to estimate the shape of the spectrum if UHECR are protons.
in such a case there will be cosmogenic neutrinos generated by the proton energy loss.

If UHECR are heavy nuclei the situation is much more complicated. Not only the energy spectrum. but also the cosmic ray composition will change in propagation. The generated cosmogenic neutrinos will be dominated by lower energy electron antineutrinos that are difficult to detect.