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2043-3

Summer School on Particle Physics in the LHC Era

15 - 26 June 2009

Astroparticle Physics II

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Ultra High Energy Cosmic Rays: Introduction and Origin

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 =
= 2.4×10^{34} Hz
= 1.6×10^{8} erg
= 170 km/h tennis ball

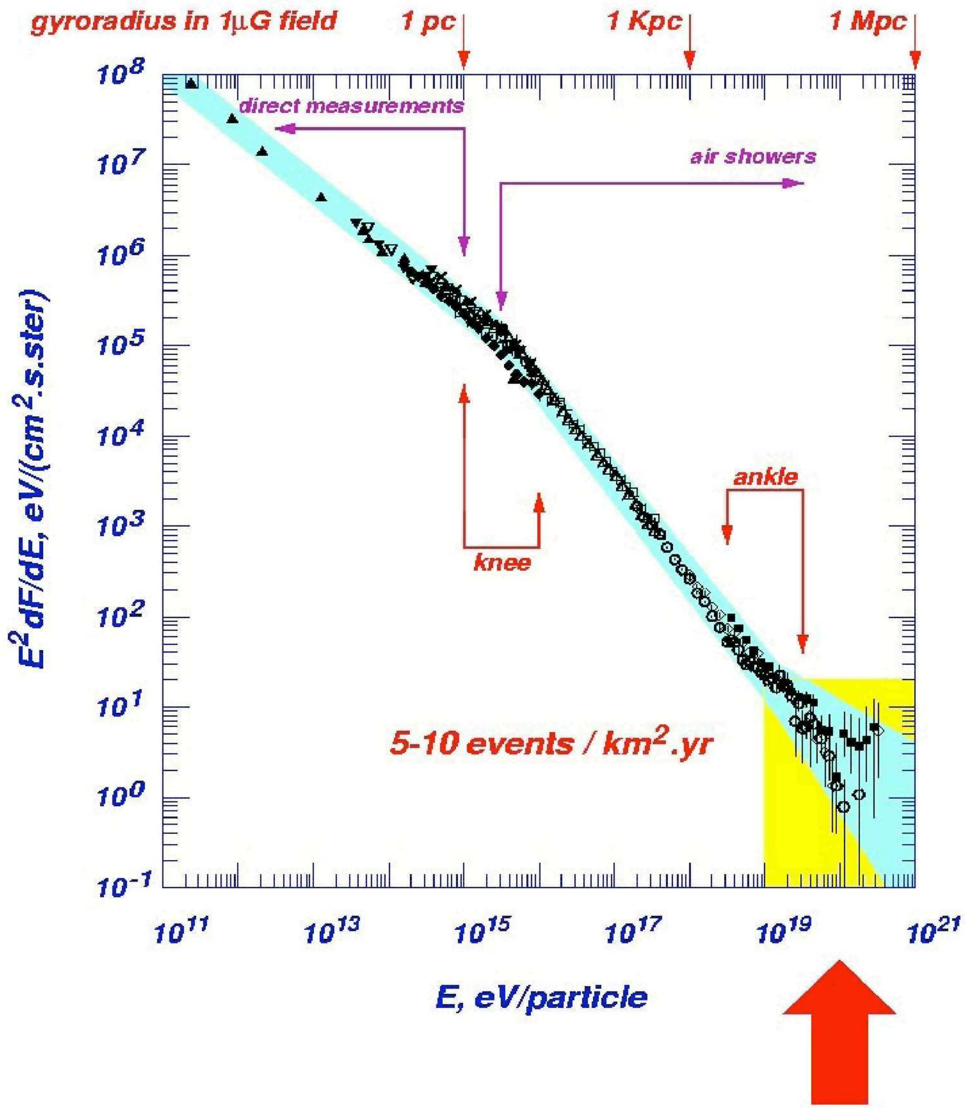
$\sqrt{s}$ equivalent is 300 TeV

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

1) set one: production

2) set two: propagation

Even before Linsley's observation (in 1956) an article by G. Cocconi discussed the possible origin of cosmic rays of such high energy. He concluded that they must be of extragalactic origin because the magnetic fields and the dimension of our Galaxy are not big enough to contain and accelerate them. The giroradius of 10^{20} eV proton in 1 μG field is 100 kpc and event for field strengths bigger by a factor of 5 it equals the dimension of the whole Galaxy.



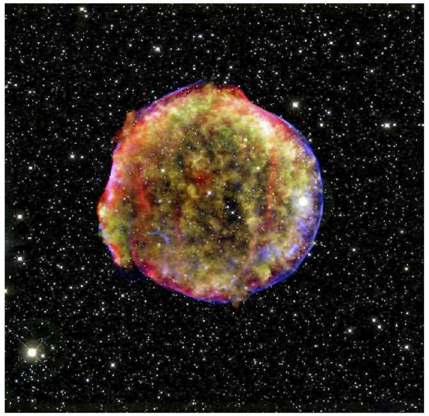
Cosmic ray energy spectrum is smooth, power law like.
It has two main features:

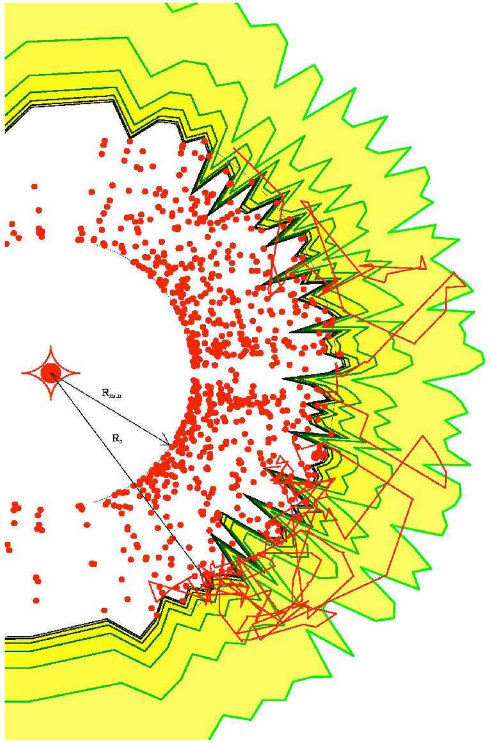
- the knee
- the ankle

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 - their gyroradii are larger than the Galaxy.

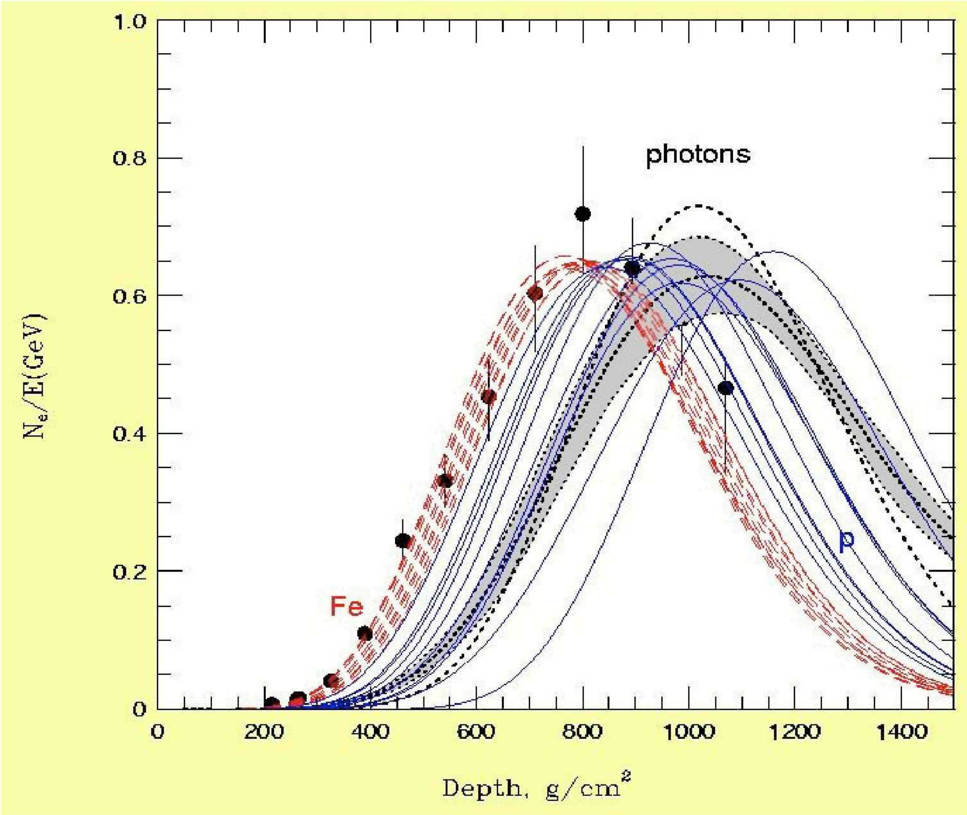




Ginzburg&Syrovatskii have identified supernova remnants (SNR) as possible sites of cosmic ray acceleration. If only 5% of the kinetic energy of the SNR is converted to cosmic rays this would supply all cosmic rays in the Galaxy.

The acceleration proceeds at the shock formed by the expanding SNR envelope. Most productive time is 1000 to 10000 years after the explosion. Shock compression ratios above 4 lead to flat power law spectra. Modern calculations obtain more complicated spectra that are power laws in small energy ranges.

The maximum acceleration energy is between 100 and 5,000 TeV in different estimates. It could be higher when the remnant expands in highly magnetized pre-supernova wind. Heavier nuclei reach Z times the maximum energy.

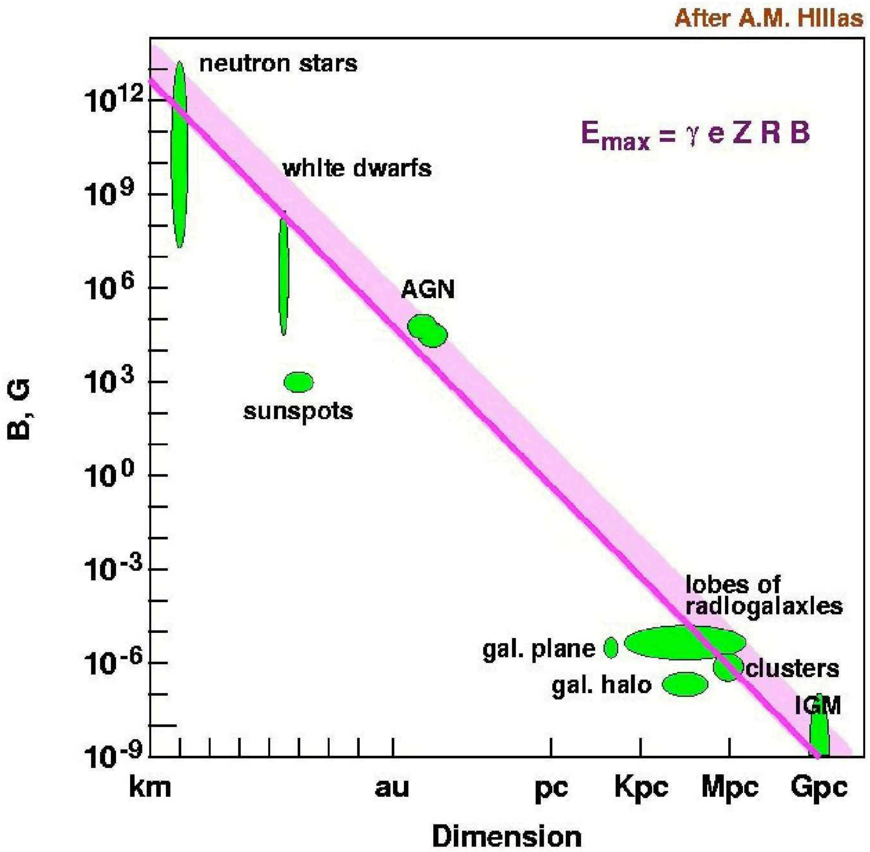


The highest energy shower was detected with the fluorescent technique by the Fly's Eye. The energy estimate is 3×10^{20} eV. The number of charged particles at shower max is 2×10^{11}. The error is not likely to exceed 40%. All contemporary hadronic interaction models give 1.4-1.6 GeV per charged particle at shower maximum.

All giant shower arrays have detected super-GZK showers: Volcano Ranch, Sydney, Haverah Park, Yakutsk, Fly's Eye, AGASA, HiRes and Auger. The Auger Observatory has the highest exposure of 12,000 km2.sr.yr. Former leaders were the AGASA and HiRes experiments that derived different features of UHECR.

What could be the origin of these particles ?

In analogy with the lower energies one is tempted to think that they come from acceleration sites associated with powerfull astrophysical objects. How many such objects exist in the Universe ?

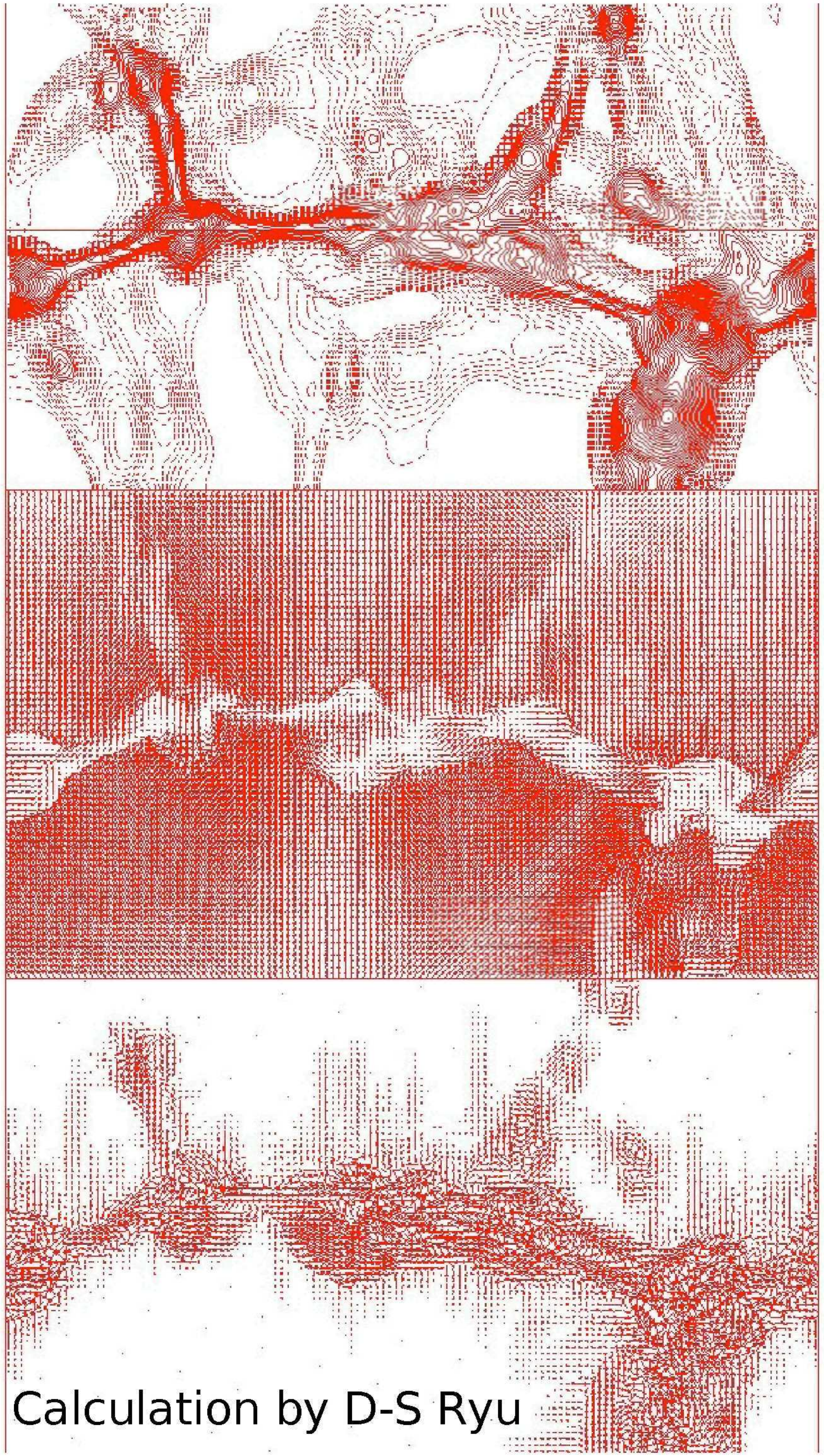


Michael Hillas generated this famous graph more than 20 years ago. It shows the dimensional upper limit for acceleration to 10^{20} eV. The upper edge is for protons and lower one - for iron nuclei. The observed magnetic field values and dimensions of astrophysical objects are indicated. There is a handful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

Possible astrophysical sources of UHE cosmic ray nuclei.
Acceleration scenarios following AM Hillas plot.

How are these models developed?

1) Look at the source luminosity at different wavelengths, mostly radio and X-rays that show nonthermal particles. If all known emission is thermal it can not be a source of UHECR.
2) Look at the source dimensions and structure.
3) Collect information about magnetic field strength. Use Faraday rotation and soft X-ray data. Estimate the possible highest acceleration energy. If high enough start building models.
4) Use the available information to estimate the accelerated particles energy loss. Make certain the energy loss is not faster than the acceleration.

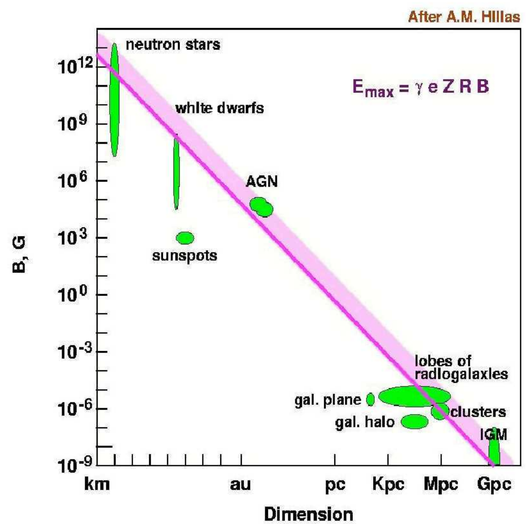


Calculation by D-S Ryu

Shocks from structure formation:
1 nG fields on 50 Mpc distance
needed for 10^{20} eV protons.
Energy loss may be much too large.

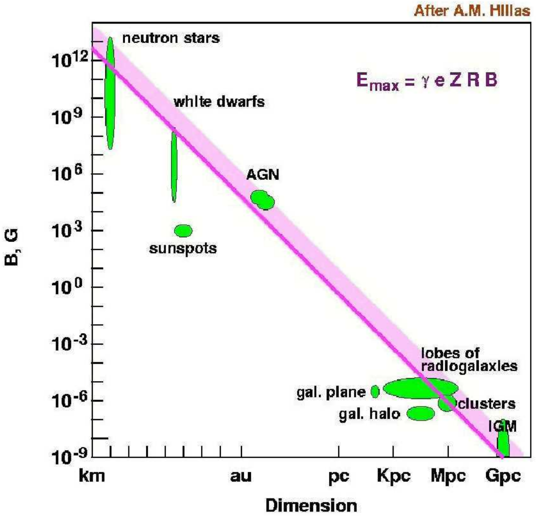
All the information comes from
structure formation MonteCarlo
calculation that aim to reproduce
the current large scale structure.

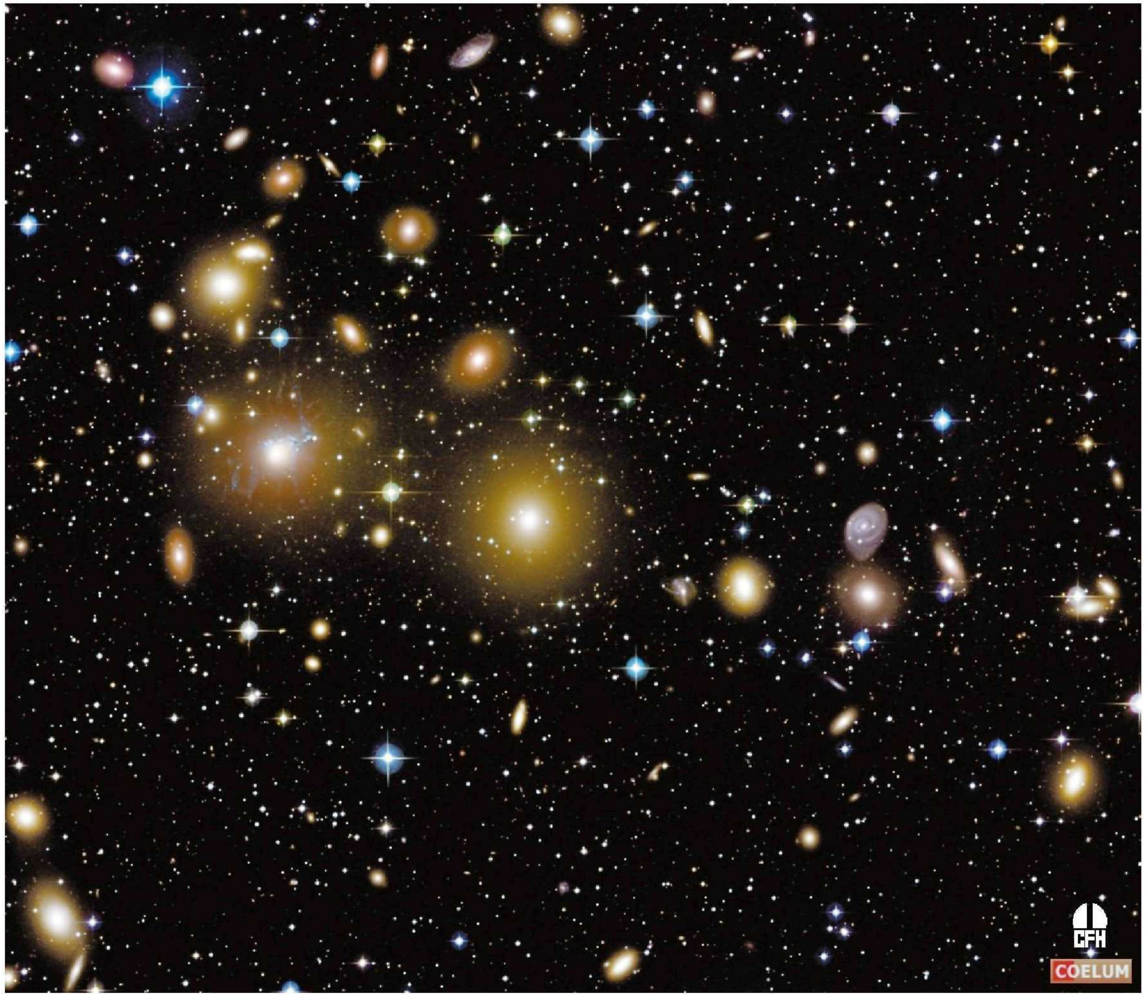
Picture on the left
 top: matter density
 middle: velocity vectors
 bottom: magnetic field vectors

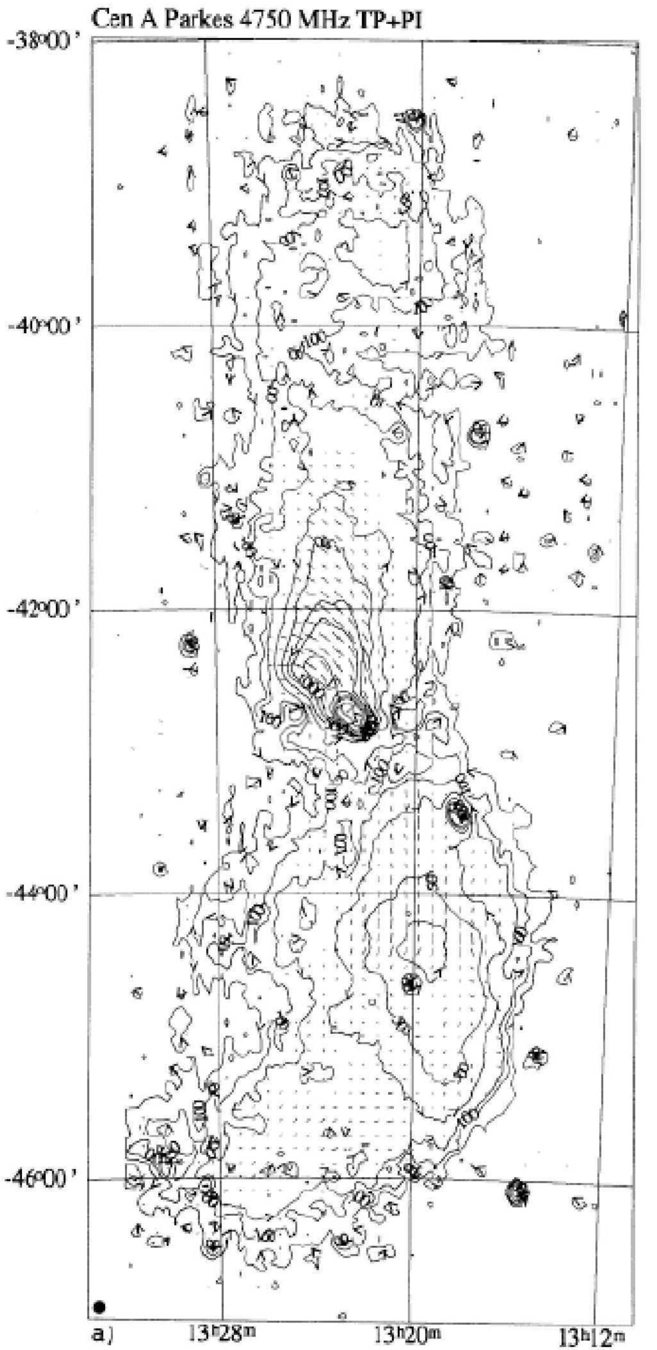


Clusters of galaxies: μG fields observed on 500 kpc scales.
Still the acceleration is too slow and energy losses may prevail.

Perseus cluster of galaxies

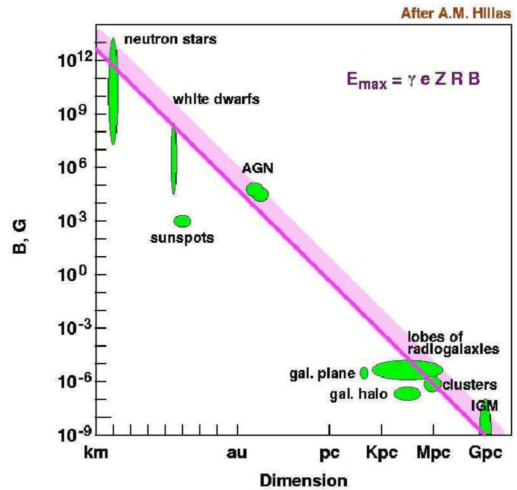






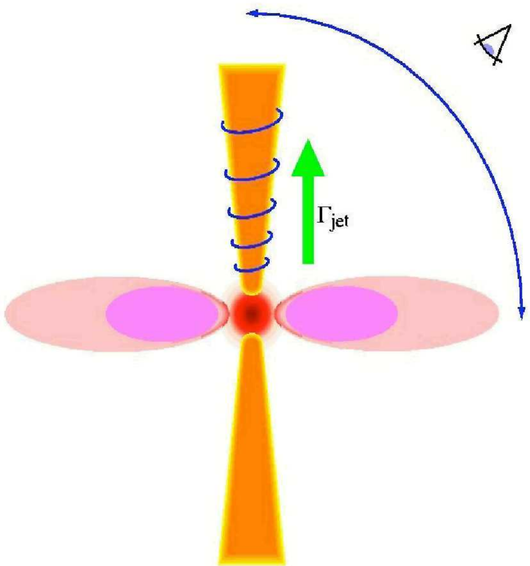
Radiogalaxies: 10 μG fields on 100 kpc scale possible in *red spots* of FRII type galaxies. Since these are jet termination shocks there will be no adiabatic losses.

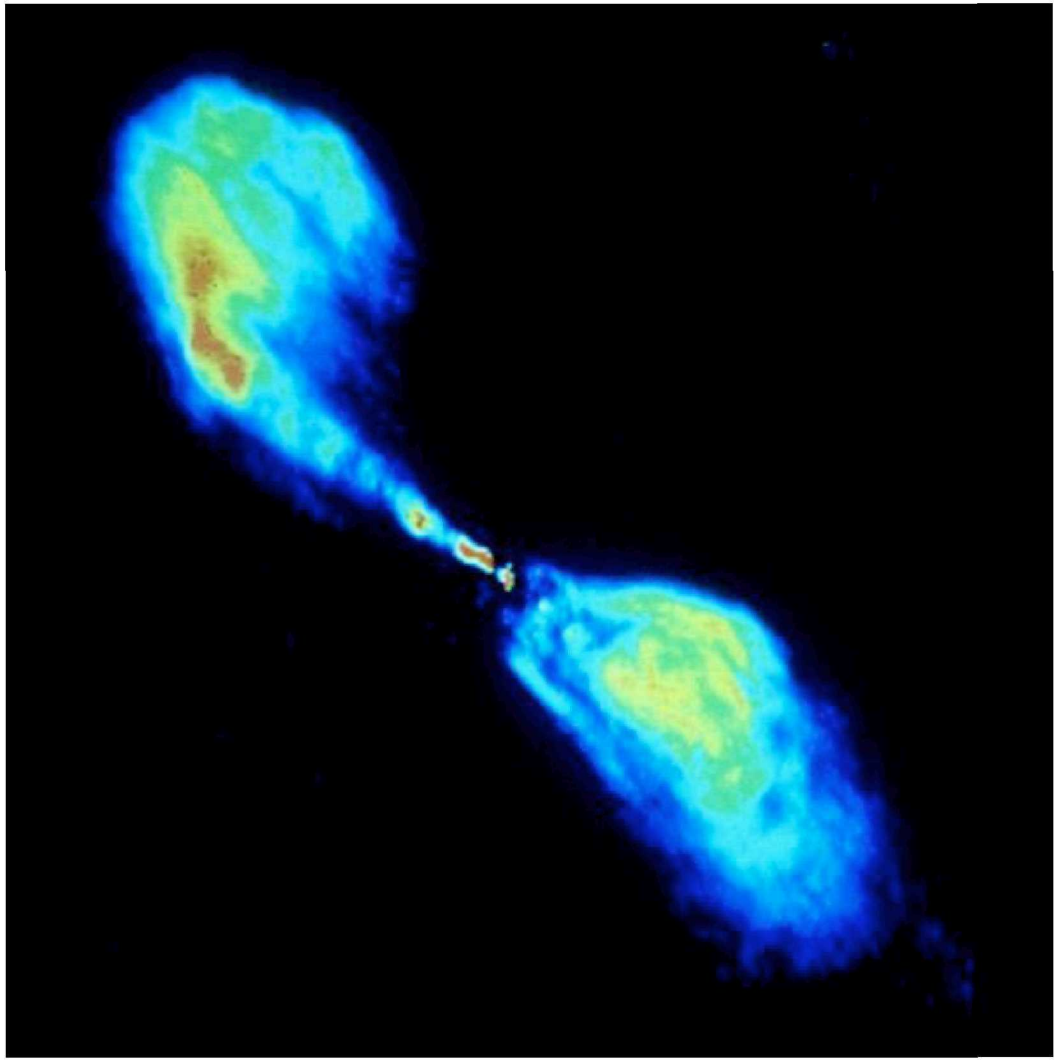
Centaurus A is a nearby radio galaxy. The size of the giant radio lobes is bigger than 500 kpc. Magnetic field is of order 1 μG. The current Cen A does not have enough power to accelerate protons to 10^{20} eV.



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

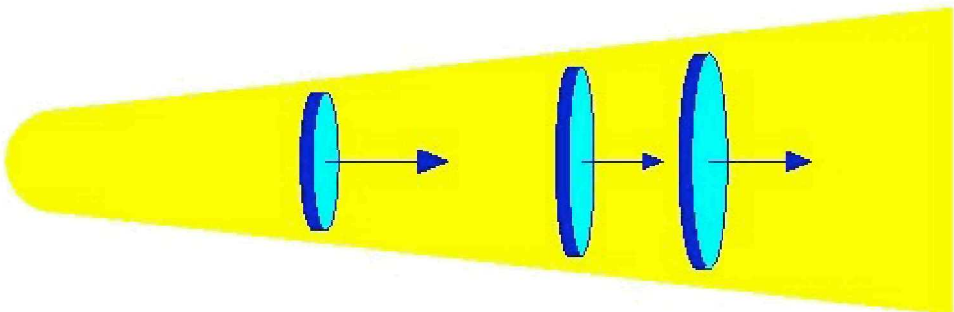
The inner lobe and jets of Cen A. Jets are not very active now and there are no hot spots.





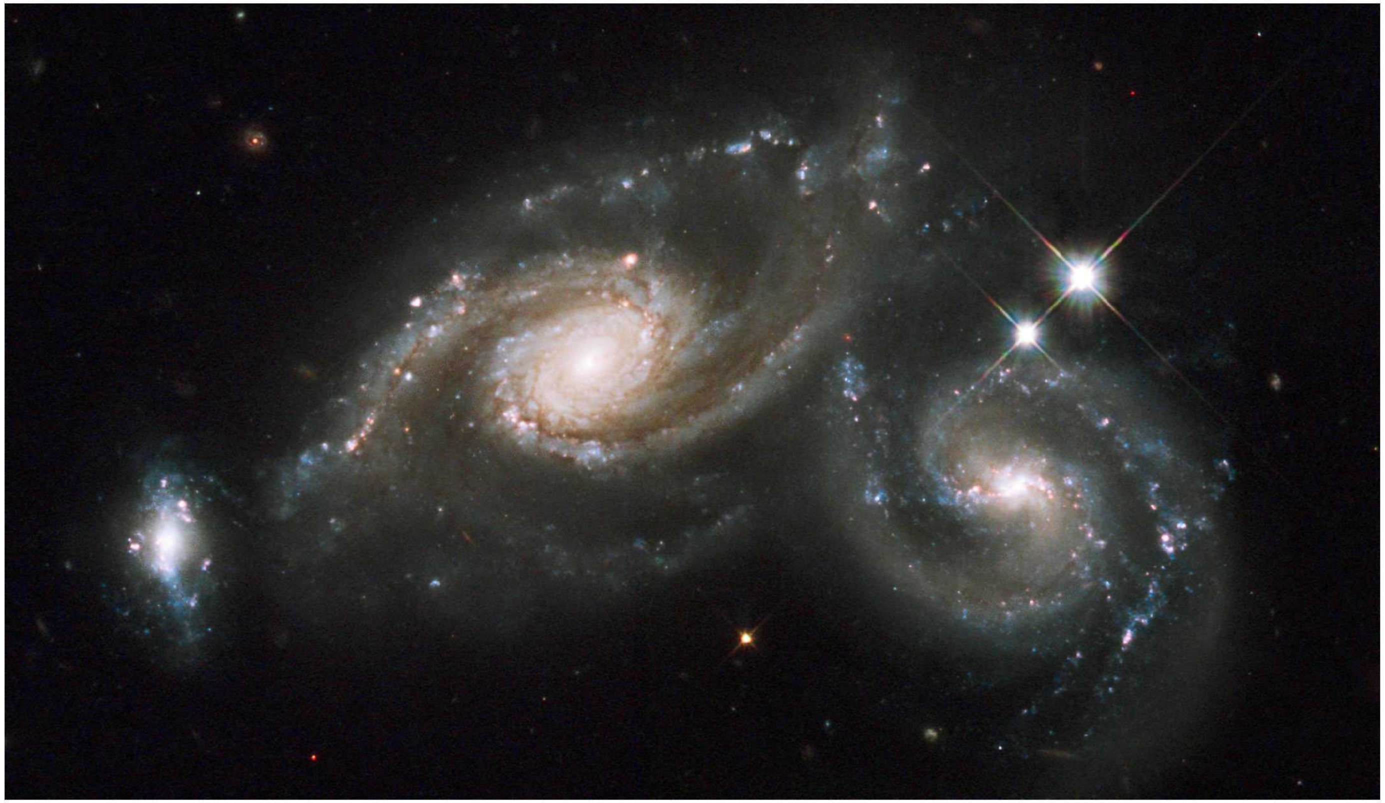
GRB: the extreme case of jet acceleration. The Lorentz factors of GRB are assumed to be between 100 & 1,000. Isotropic luminosity is 10^{53-54} ergs. Suggestion first made when directions of two powerful GRB coincide with most energetic UHECR.

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 Γ^2 (Gamma is the Lorentz factor).



When jets start slowing down the particles are are decelerated

Colliding galaxies: 20 μG 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.

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.

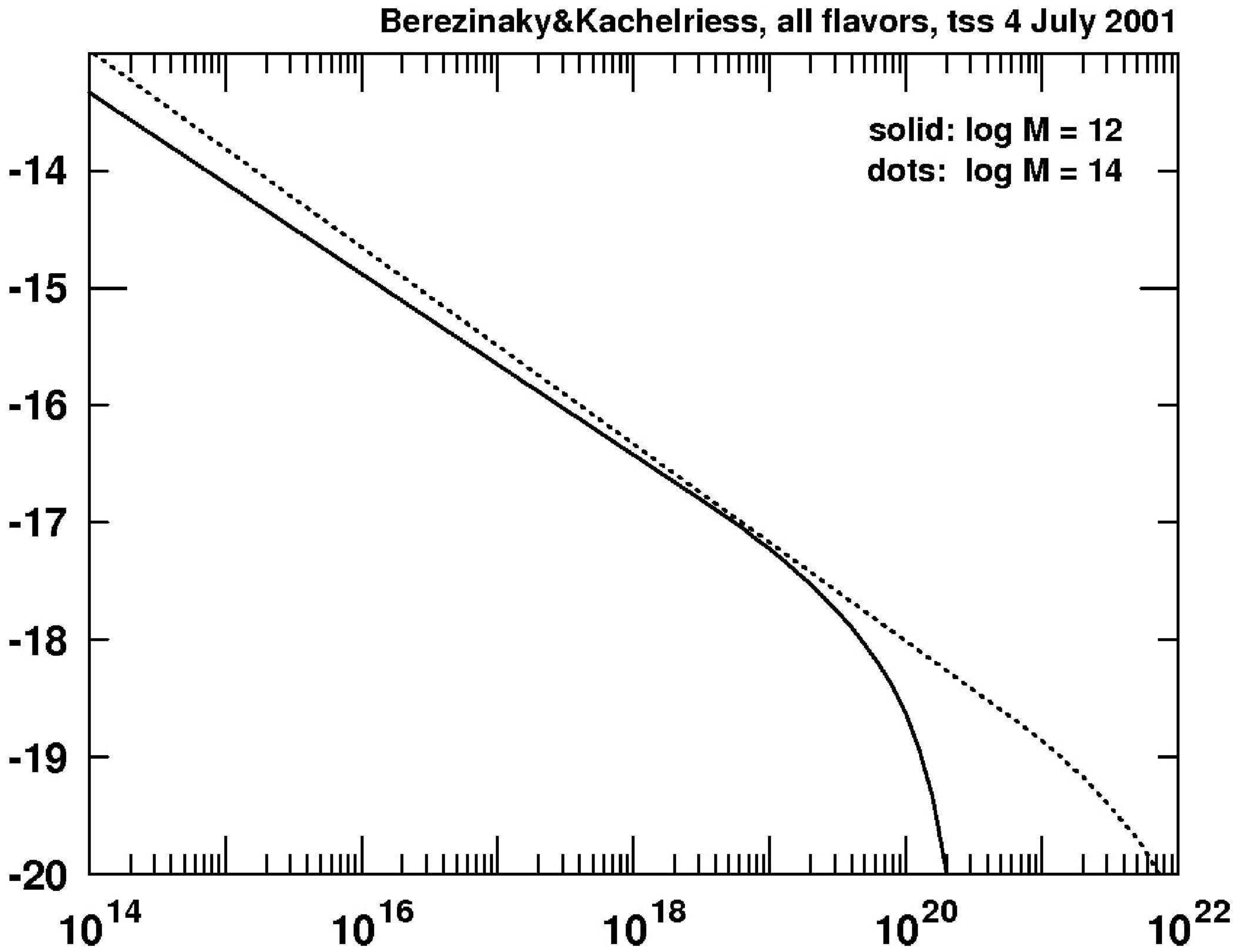
Top-down models: the observed cosmic rays are not accelerated, they are products of the decay of massive X-particles.

Topological defects: Monopoles were first suggested. UHECR emitted during monopole annihilation. Ordinary cosmic strings emit X-particles from their cusps and when they intersect. Superconducting strings emit when their electric current reaches a critical value. Various more complicated scenarios.

Decay of quasi stable X-particles produced in the early Universe: Must have lifetime comparable to Hubble time. Small fraction of cold dark matter.

UHECR have to be either gamma rays or neutrinos – from the fraction of nucleons and mesons in decay. The energy spectrum is flatter than acceleration spectra – $E^{-3/2}$. M_X can be restricted by observed isotropic GeV gamma ray flux to below 10^{23} eV.

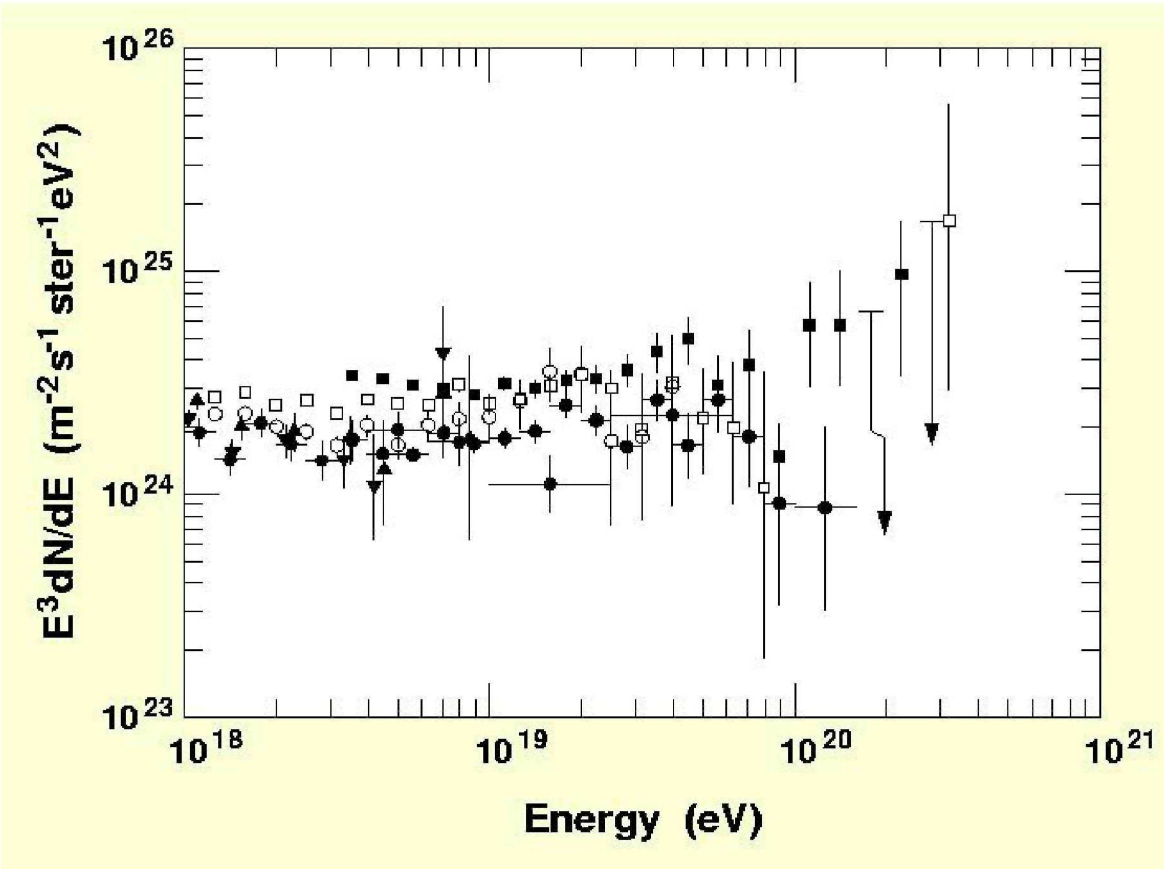
Neutrino fluxes generated in a top/down model of Berezinsky & Kachelriess. Gamma rays have a similar spectrum which is affected by propagation.



Hybrid scenarios:

Z-burst: Ultrahigh energy neutrinos (of unknown origin) interact on massive relic neutrinos that are gravitationally attracted in our cosmological neighborhood. The secondary Z_0 decay to generate UHECR. To have the resonant cross section neutrinos have to have energy $4x10^{21}$ eV/m_ν. It is not known where such neutrinos can be produced.

Experimental data: The spectra measured by several experiments have absolute normalization different by 40%. Note that the differential flux is multiplied by E^3 to emphasize the shape of the spectrum. The results are obtained with the same hadronic interaction model.



The AGASA and HiRes experiments had the highest statistics before Auger Observatory. AGASA shows no end of the cosmic ray spectrum while HiRes does.

Astrophysical parameters derived from data

UHECR source luminosity: 4.5×10^{44} erg/Mpc^3/yr between 10^{19}-10^{21} eV for $\alpha=2$ spectrum (W&B) to 4×10^{46} (same units) for $\alpha=2.7$ (BGG). Strong dependence on spectral index and the minimum acceleration energy.

UHECR source density: 10^{-5} Mpc^{-3} $\pm$ order of magnitude: from the clustering of AGASA data set.

UHECR source distribution:

- isotropic homogeneous + local source + galactic CR
- isotropic homogeneous + top-down + galactic CR
  (no local or top-down sources needed for HiRes)

UHECR source cosmological evolution: depends on injection spectrum. Steep spectra require weak cosmological evolution.

Cosmic rays of energy above 10^{20} eV exist, but their flux is unknown.

Very few astrophysical objects can accelerate charged nuclei to such energy in shock acceleration processes.

Protons and heavier nuclei lose energy in propagation in photoproduction (photodisintegration) on MBR and other photon fields. The sources have thus to be within tens of Mpc from our Galaxy.

The other possibity are `top-down' scenarios where these particles are generated in the decay of ultraheavy X-particles, which could be emitted by cosmic strings or are long lived remnants of the early Universe.

The current experimental data are not able to give us good indication on the type of these UHECR and their arrival direction distributions.

New third (and fourth) giant air shower experiments are being built and designed. They will increase the data sample by orders of magnitude and help understanding the nature and sources of these exceptional events.

Ultrahigh Energy Cosmic Rays propagation

Microwave background

Energy loss processes for protons:
- photoproduction interactions
- pair production interactions
- adiabatic loss due to the expansion of the Universe

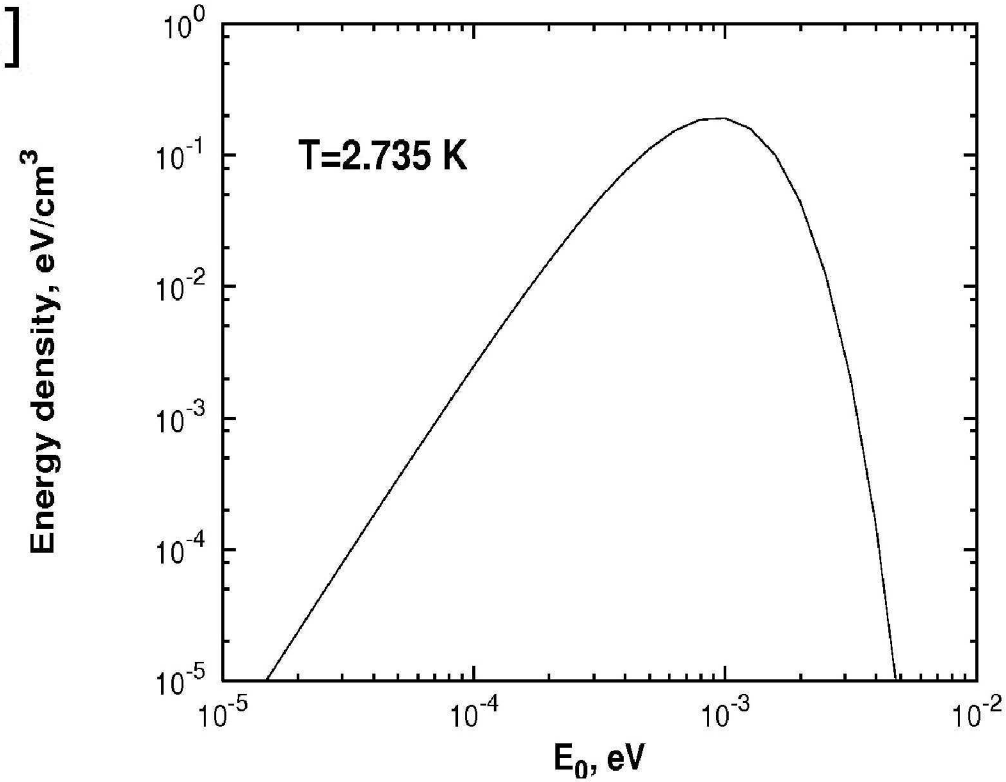
Energy loss processes for heavier nuclei
- photodisintegration
- pair production: cross section grows as Z^2

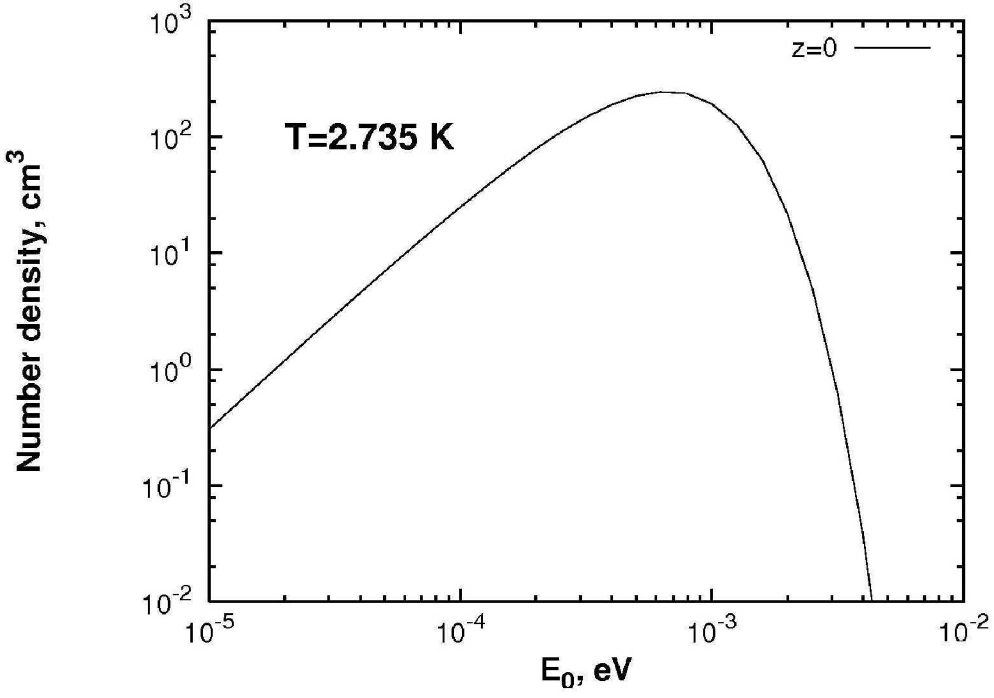
Energy loss of gamma rays

The microwave background is the thermal radiation that remains from the beginning of the Universe. It was discovered by Penzias and Wilson from Bell Labs in 1965. Its current temperature is 2.725°. The energy density of the microwave background radiation (MBR) can be expressed in eV/cm^3. 1 eV = 11,610 K.

$$\rho_E(\epsilon) = \frac{1.32 \times 10^{13} \epsilon^4}{[\exp(kT/\epsilon) - 1]}$$

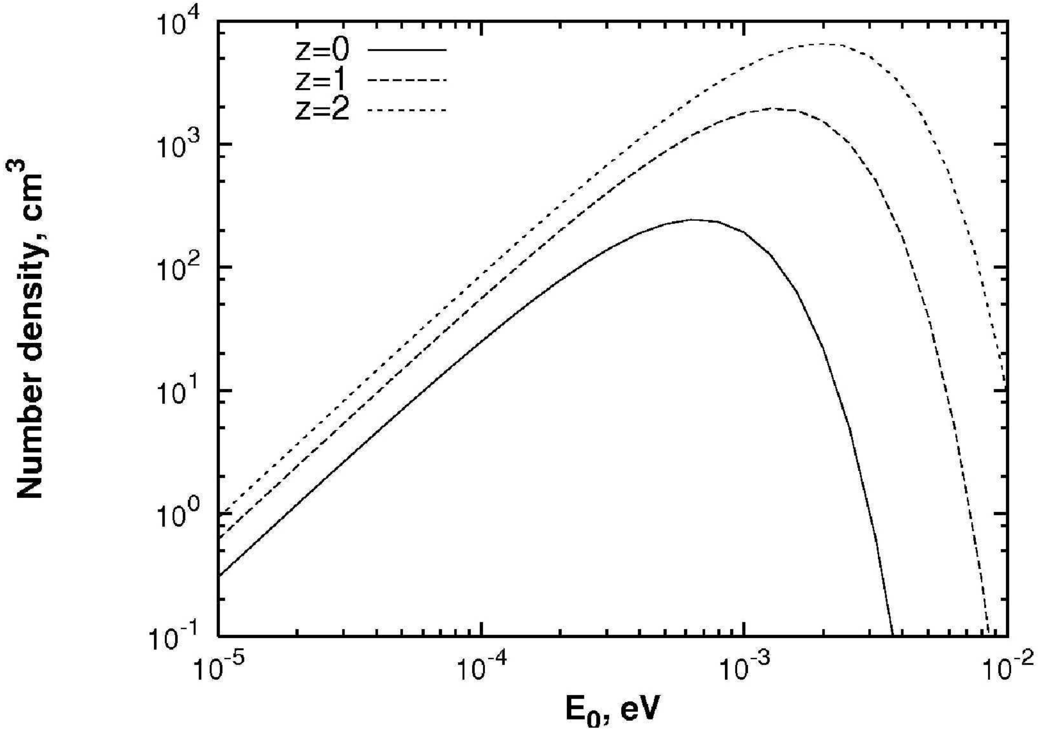
The total energy density is 0.26 eV/cm^3 and the total number of photons is 411 per cubic cm. The number density is important when we view MBR as interaction target.





Current number density of MBR

Evolution of the mbr number density with redshift. The mbr number density increases as $(1 + z)^3$. Energy increases as $(1 + z)$, i.e. Total luminosity increases as $(1 + z)^4$.



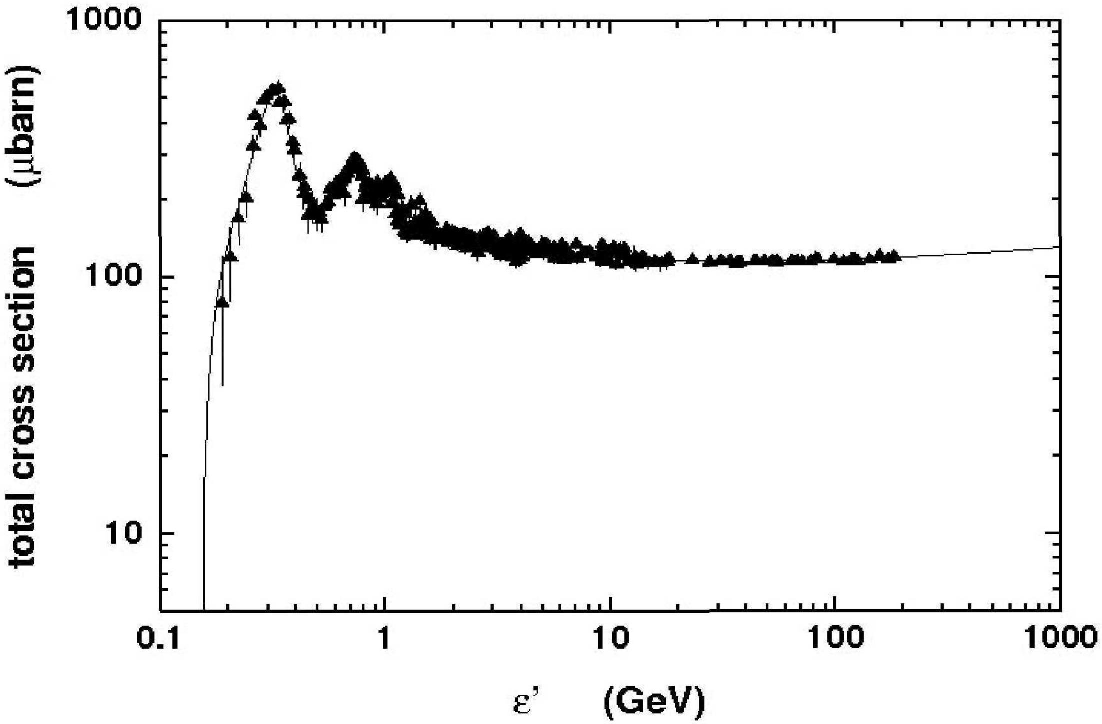
Photoproduction interactions

p + γ = p + π + …

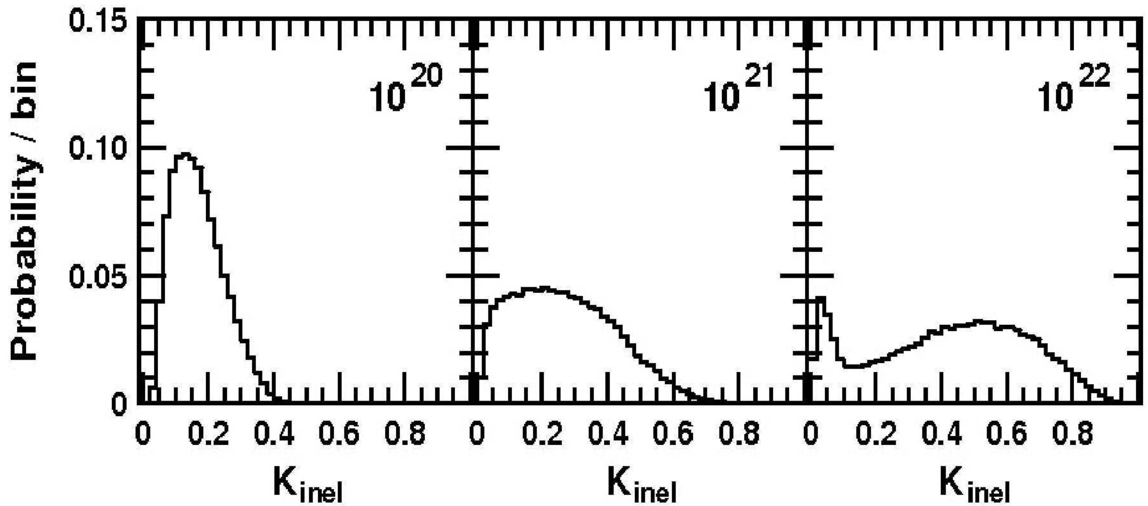
$$s = m_p^2 + 2E_p\epsilon(1 - \beta_p \cos\theta)$$

$$E_p = \frac{m_{\pi^0}}{4\epsilon}(2m_p + m_{\pi^0}) \simeq 10^{20}\,\mathrm{eV}\,.$$

ε' is the photon energy in the proton frame, where the energy threshold is 0.13 GeV

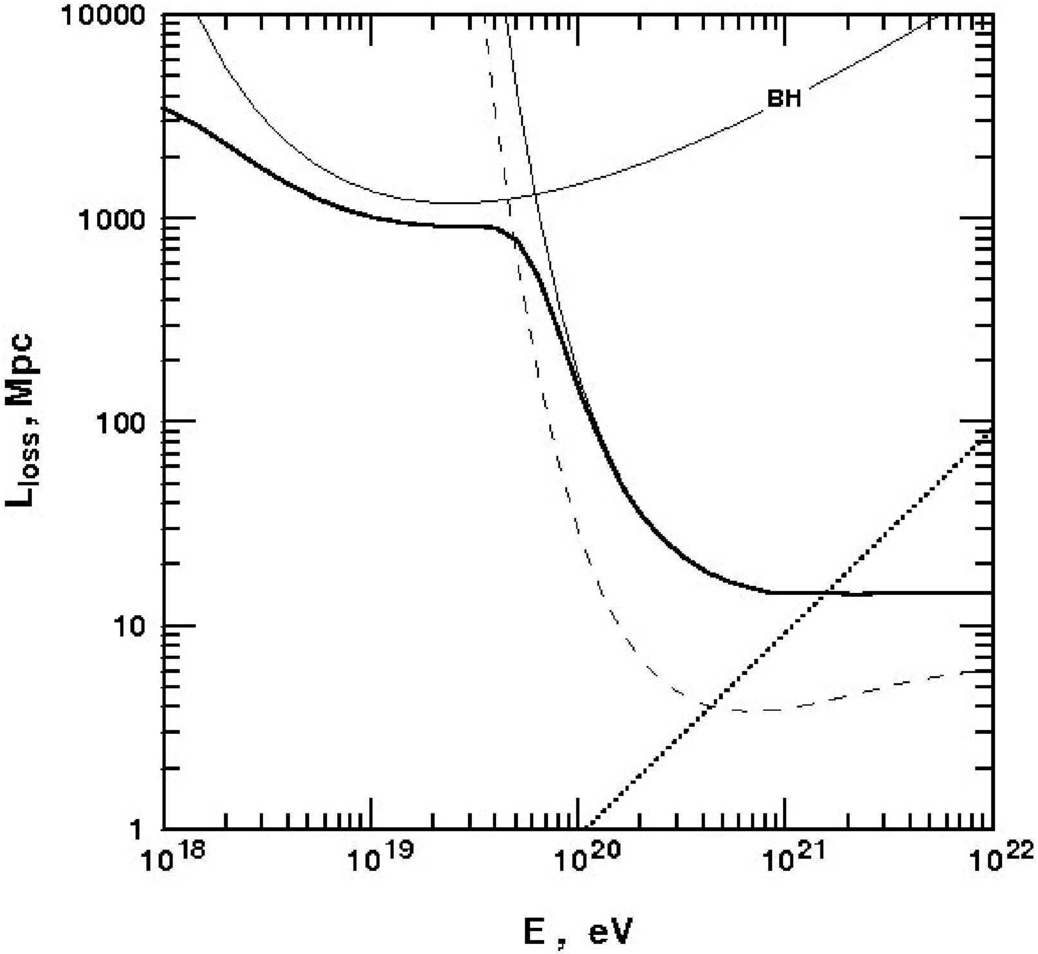


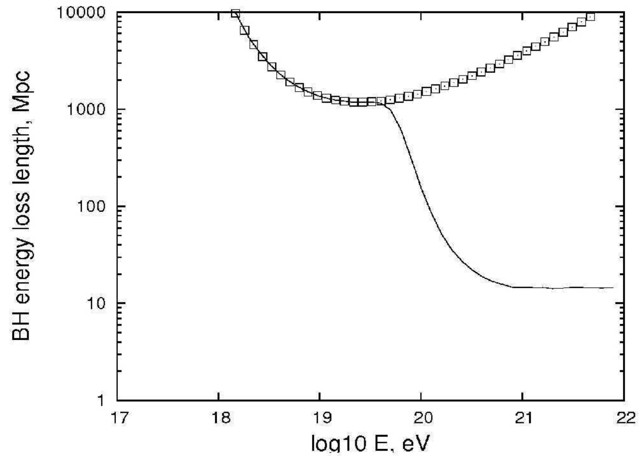
Inelasticity coefficient: the fraction of the proton energy lost in the photoproduction interaction.



$$L_{loss} = \frac{E_p}{dE_p/dx} = \frac{\lambda_{p\gamma}(E_p)}{K_{inel}(E_p)}$$

Energy loss length of UHE protons in MBR





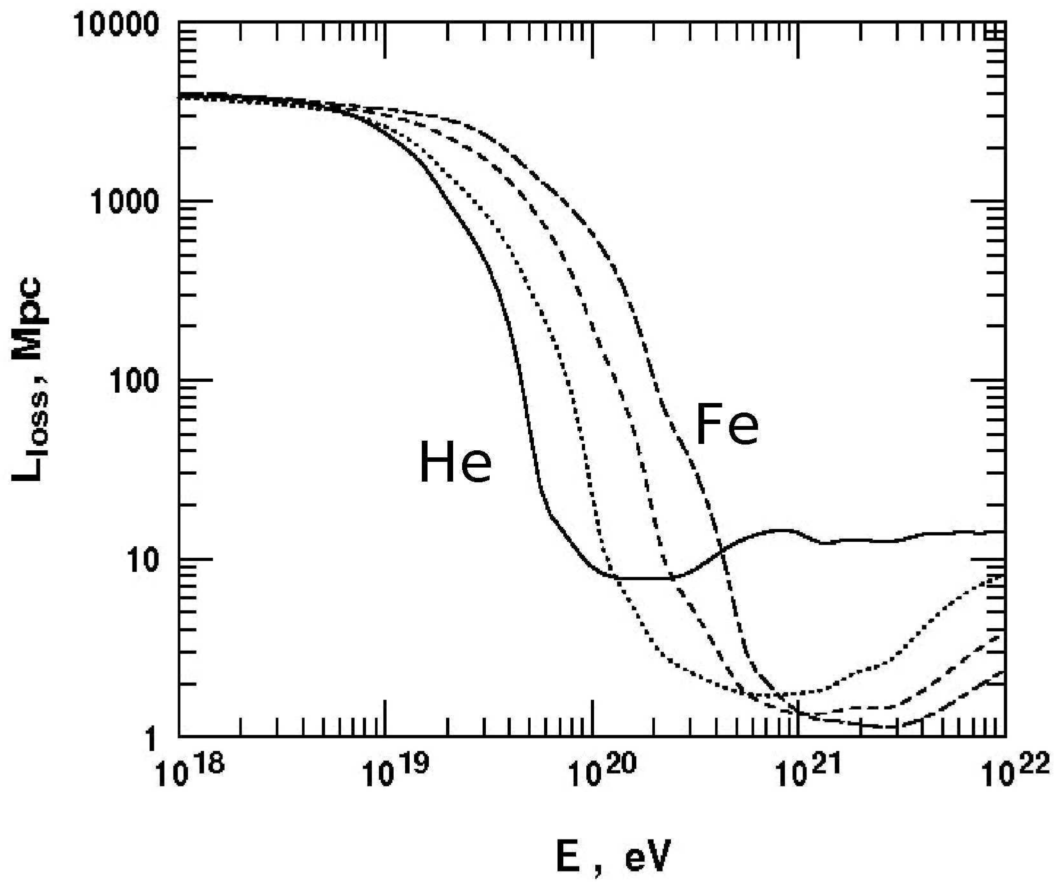
Pair production process

$$\sigma_{pair} = \frac{\pi}{12}\alpha r_e^2\left(\frac{\epsilon'}{m_e} - 2\right)$$

$K_{inel} = 2m_e/E_p$

Adiabatic loss length is $L = c/H_0$, 4 Gpc in this graph.

Energy loss of heavy nuclei: mostly from a different process – photodisintegration, which is the loss of one or two nucleons, i.e. the energy loss per interaction is 1/A. The energy threshold is the binding energy of the nucleus, about 20 MeV for Fe. There is also the decay of unstable nuclei.



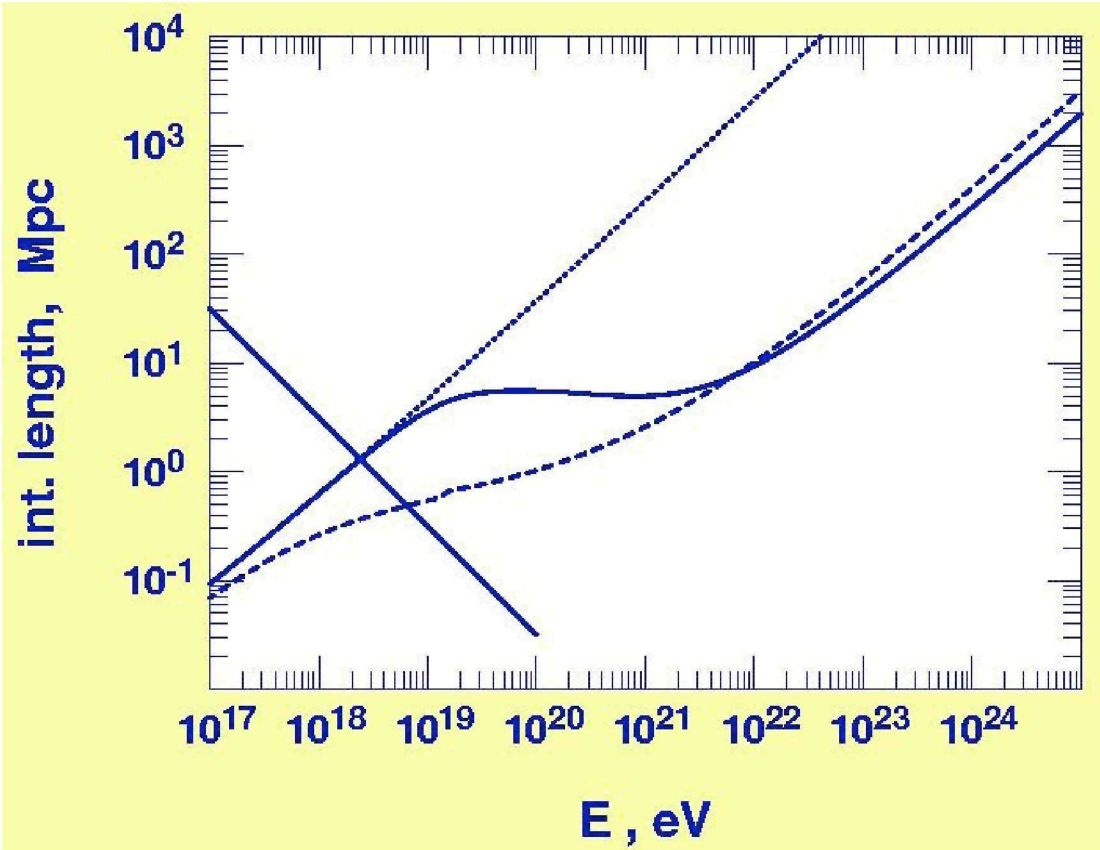
$$\sigma_{\text{phabs}} \equiv \int_0^\infty \sigma(\epsilon')\, d\epsilon' \simeq 60\frac{NZ}{A}$$

The heavy nucleus absorbs a photon and becomes an excited state that releases one or two nucleons. The cross section roughly follows the Thomas-Reiche-Kuhn sum rule. The main process is the giant dipole resonance.

Threshold energy (MeV) for releasing different combinations of nucleons

	Z	A	n	p	2n	np	2p	α
Fe	26	56	11.2	10.2	20.5	20.4	18.3	7.6
Si	14	28	17.2	11.6	30.5	24.6	19.9	10.0
O	8	16	15.7	12.1	28.9	23.0	22.3	7.2
He	2	4	20.6	19.8	28.3	26.1	–	–
Be	4	9	1.7	16.9	20.6	18.9	29.3	2.5

Gamma-ray energy loss: pair production process $\gamma\gamma = e^+e^-$. Radio background plays a very important role as well as the extragalactic magnetic field.



In absence of high magnetic field inverse Compton scattering and pair production create a cascade process.

Comparison of the energy loss length of protons and gamma rays.