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Ultra-High Energy Cosmic Rays and the GeV-TeV Diffuse Gamma-Ray Flux

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Ultra-High Energy Cosmic Rays and the GeV-TeV Diffuse γ-Ray Flux

Overview

- Propagation of Ultra High Energy Cosmic Rays (UHECR)
- Source model and spectrum fitting
- Possible range of diffuse γ-Ray flux from protons
- Diffuse γ-Ray flux from heavy nuclei. Comparison
- Conclusion

Propagation of Ultra High Energy Cosmic Rays

- Protons and neutrons

Pion production $N\,\gamma_b \rightarrow N'\,\pi\,\ldots$

e^+e^- pair production $p\,\gamma_b \rightarrow p\,e^+\,e^-$

neutron β-decay $n \rightarrow p e^- \bar{\nu}_e$

Propagation of Ultra High Energy Cosmic Rays

- Protons and neutrons

Pion production $N\,\gamma_b \rightarrow N'\,\pi\ \ldots$

$$E_{th} = \frac{m_\pi (m_p + m_\pi/2)}{\epsilon} \simeq 7 \times 10^{16} \left(\frac{\epsilon}{eV}\right)^{-1} eV \qquad (1)$$

For MWB ($\epsilon \simeq 10^{-3} eV$): $E_{th} \simeq 70 EeV$

e^+e^- pair production $p\,\gamma_b \rightarrow p\,e^+\,e^-$

neutron β-decay $n \rightarrow p e^- \bar{\nu}_e$

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$$\text{For MWB } (\epsilon \simeq 10^{-3} eV):\ E_{th} \simeq 70 EeV$$

e^+e^- pair production $p\,\gamma_b \rightarrow p\,e^+\,e^-$

$$E_{th} = \frac{m_e(m_A+m_e)}{\epsilon} \simeq 5\times 10^{14}\left(\frac{\epsilon}{eV}\right)^{-1} eV \qquad (2)$$

$$\text{For MWB } (\epsilon \simeq 10^{-3} eV):\ E_{th} \simeq 5\times 10^{17} eV$$

neutron β-decay $n \rightarrow p e^- \bar{\nu}_e$

Propagation of Ultra High Energy Cosmic Rays

- Protons and neutrons

Pion production $N\,\gamma_b \rightarrow N'\,\pi\,...$

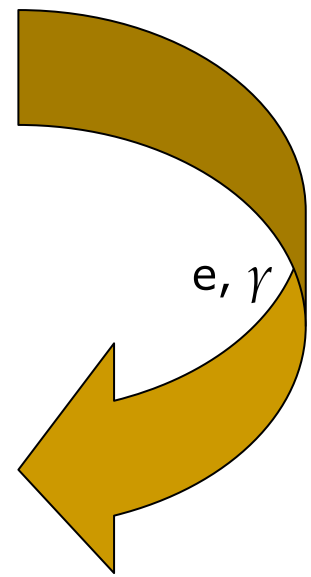
e^+e^- pair production $p\,\gamma_b \rightarrow p\,e^+\,e^-$

neutron β-decay $n \rightarrow pe^-\bar{\nu}_e$

- Electron-photon cascade

e^+ e^- pair production $\gamma\,\gamma_b \rightarrow e^+\,e^-$

Inverse Compton $e\,\gamma_b \rightarrow e\,\gamma$



$$E_{th} = \frac{m_e^2}{\epsilon} \simeq 2.6 \times 10^{11} (\frac{\epsilon}{eV})^{-1} eV$$

$$\text{For MWB } (\epsilon \simeq 10^{-3} eV){:}\ E_{th} \simeq 5 \times 10^{14} eV$$

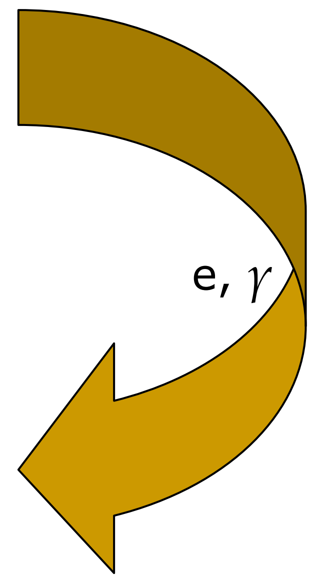
Propagation of Ultra High Energy Cosmic Rays

- Protons and neutrons

Pion production	$N\,\gamma_b \rightarrow N'\,\pi\,\ldots$
e^+e^- pair production	$p\,\gamma_b \rightarrow p\,e^+\,e^-$
neutron β-decay	$n \rightarrow p e^- \bar{\nu}_e$

- Electron-photon cascade

e^+ e^- pair production	$\gamma\,\gamma_b \rightarrow e^+\,e^-$
Inverse Compton	$e\,\gamma_b \rightarrow e\,\gamma$
Synchrotron losses	
Double pair production	$\gamma\,\gamma_b \rightarrow e^+\,e^-\,e^+\,e^-$
e^+ e^- pair production by e	$e\,\gamma_b \rightarrow e\,e^+\,e^-$



Propagation of Ultra High Energy Cosmic Rays

- Nuclei

  Pion production $A\,\gamma_b \rightarrow A\,\pi\,\ldots$

  e^+ e^- pair production $A\,\gamma_b \rightarrow A\,e^+ e^-$

  Photo-disintegration $A\,\gamma_b \rightarrow A'\,N..$

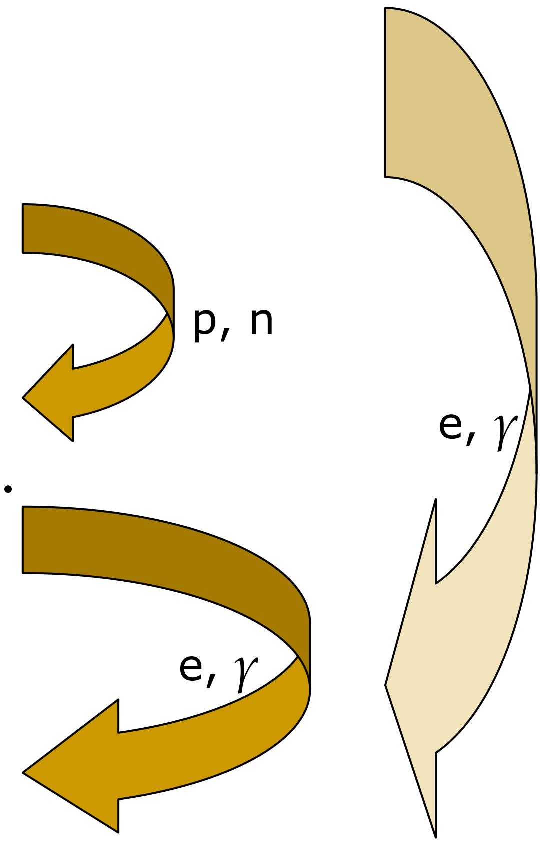
- Protons and neutrons

  Pion production $N\,\gamma_b \rightarrow N'\,\pi\,\ldots$

  e^+ e^- pair production $p\,\gamma_b \rightarrow p\,e^+ e^-$

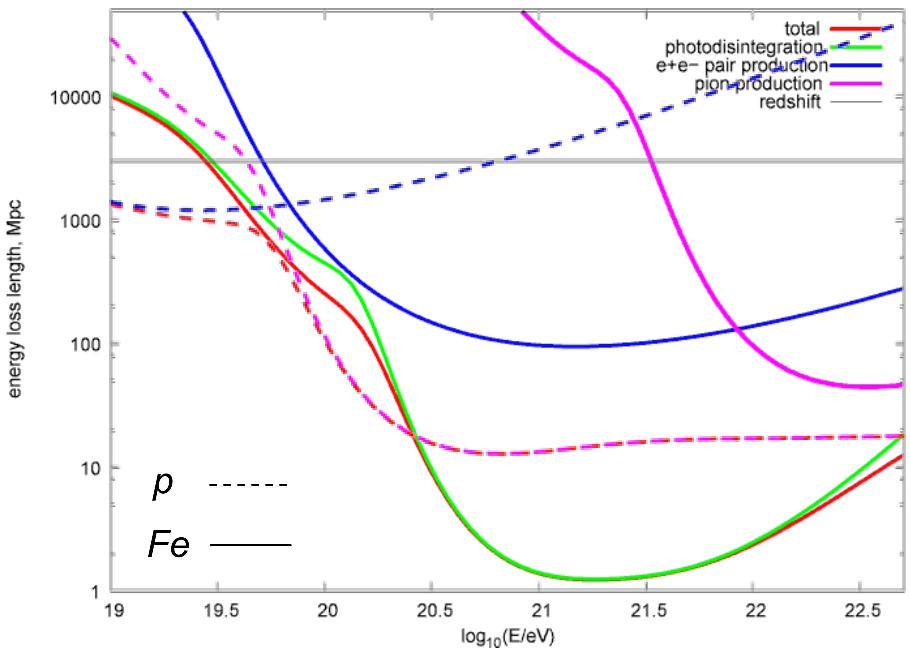
  neutron β-decay $n \rightarrow p e^- \bar{\nu}_e$

- Electron-photon cascade



Propagation of Ultra High Energy Cosmic Rays

- Energy loss length of Fe and protons



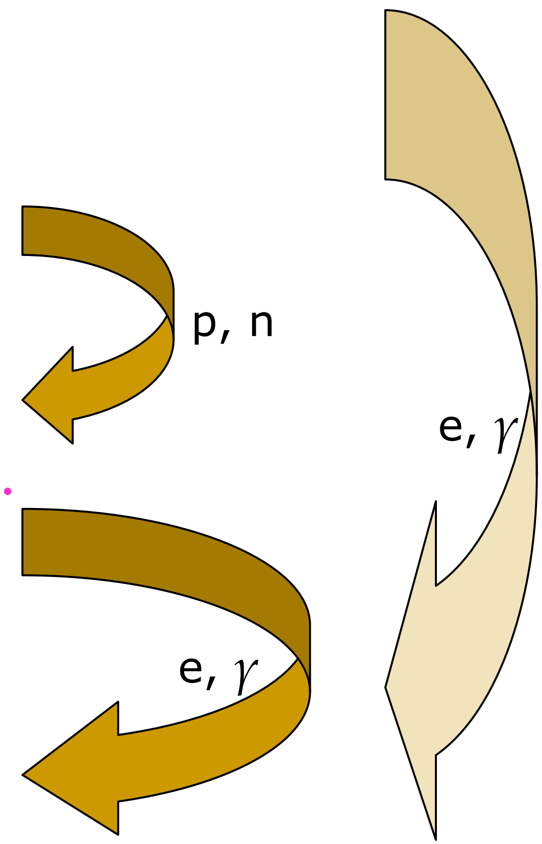
$A\ \gamma_b \rightarrow A\ \pi\ \ldots$

$A\ \gamma_b \rightarrow A\ e^+ e^-$

$A\ \gamma_b \rightarrow A'\ N..$

$N\ \gamma_b \rightarrow N'\ \pi\ \ldots$

$p\ \gamma_b \rightarrow p\ e^+ e^-$



- Electron-photon cascade

Some references on UHECR propagation

π production	A.Mucke et al.,Comp.Phys.Comm.124,290(2000)
Photodisintegration	F.Stecker et al. Astrophys.J. 512 (1999) 521-526. E.Khan et al. Astropart.Phys. 23 (2005) 191-201
e^+e^- pair production	M.J.Chodorowski et al. Astrophys.J.400,181(1992)
Extragalactic magnetic field	K.Dolag et al., astro-ph/0410419
Infrared background	F.Stecker et al. astro-ph/0510449
Radio background	T.A. Clark, L.W. Brown, and J.K. Alexander, Nature 228, 847 R.J. Protheroe, P.L. Biermann, Astropart. Phys. 6, 45

Phenomenological source model:

$$F_{A(p)}(E, z) = f\, E^{-\alpha}(1+z)^{3+m}\Theta(E_{max} - E)\ \Theta(z - z_{min})\ \Theta(z_{max} - z)$$

z – red shift, $\Theta(x)$-step function

Parameter	Name	Values
Power of the Injection Spectrum, $E^{-\alpha}$	α	$2.0 \le \alpha \le 2.7$
End point of the Energy Spectrum	E_{max}	$2\mathrm{x}10^{20} \le E_{max} \le 10^{21}$
Evolution factor: $(1+z)^{3+m}$	m	$-2 \le m \le 4$
Red shift of the nearest source	z_{min}	0; 0.005; 0.01
Maximal source redshift	z_{max}	3

Fitting procedure

$F(E, z) = f\, E^{-\alpha}(1+z)^{3+m}\, \Theta(E_{max} - E)\, \Theta(z - z_{min})\, \Theta(z_{max} - z)$

For each set of parameters we

- Calculate propagated spectrum
- Obtain normalization factor f by fitting HiRes spectrum (maximizing Poisson probability of measured events configuration using number of events in each bin*)
- Calculate goodness of fit defined as fraction of hypothetical experiments which result in worse agreement with the theory than the real data but have the same total number of events

Among all the models we choose a subset which has goodness of fit more than 5% and for this subset we check the range of possible diffuse γ-ray flux

We use two scenarios for fitting:

‘*dip*’ scenario — The fit is done above **2 EeV**

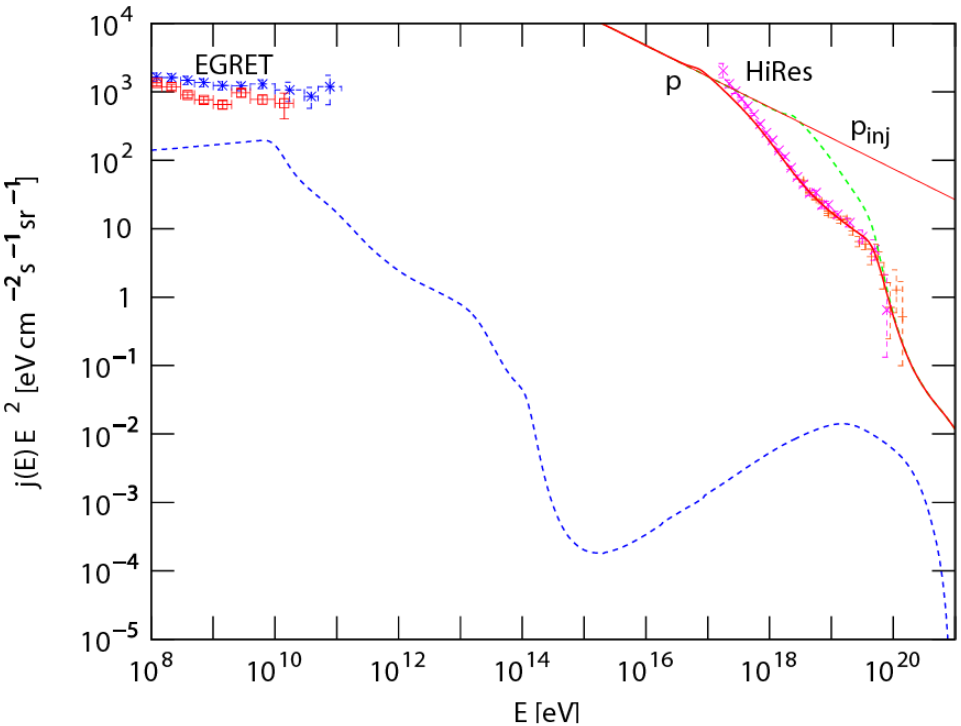
‘*ankle*’ scenario — The fit is done above **40 EeV**

*HiRes Mono spectrum including number of events in each bin http://www.physics.rutgers.edu/~dbergman/HiRes-Monocular-Spectra-200702.html

Fitting procedure

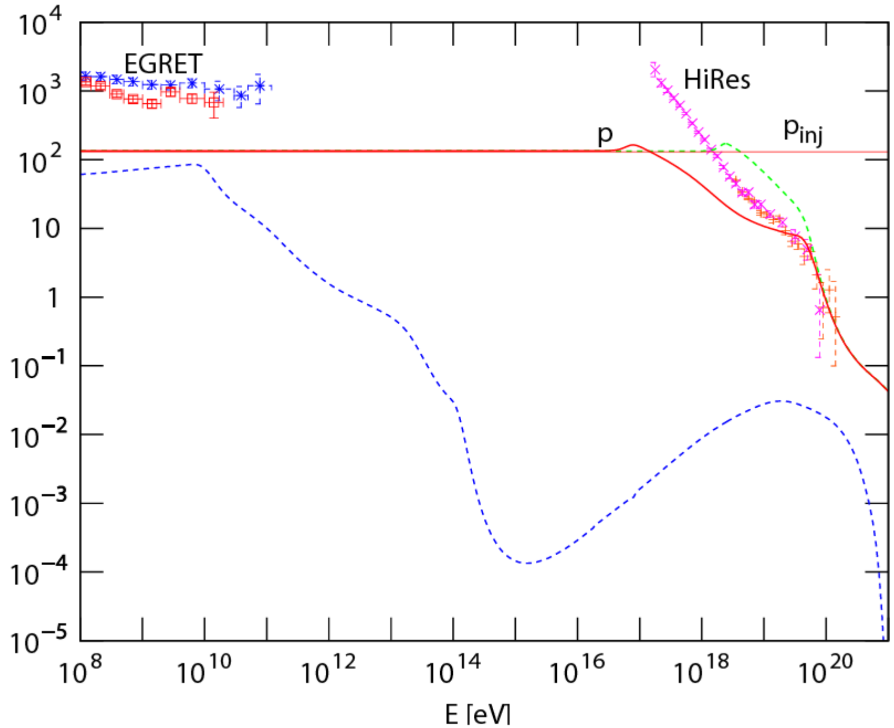
$F(E, z) = f\, E^{-\alpha}(1+z)^{3+m}\,\Theta(E_{max}- E)\ \Theta(z-z_{min})\ \Theta(z_{max}-z)$

'*dip*' scenario



α=2.45; $E_{max}=10^{21}$eV; m=3

'*ankle*' scenario



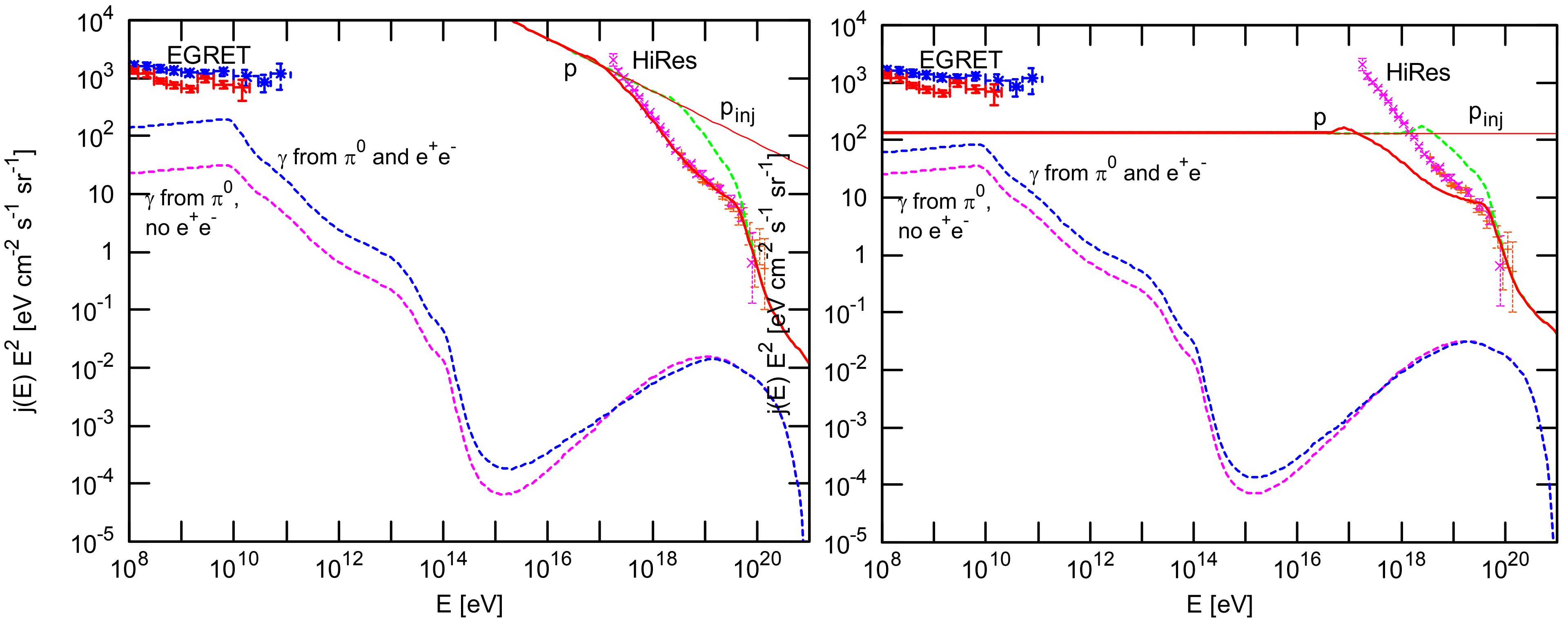
α=2; $E_{max}=10^{21}$eV; m=3

Diffuse Gamma-Ray Flux from protons

- Contribution of e^+e^- production and GZK effect

‘*dip*’ scenario

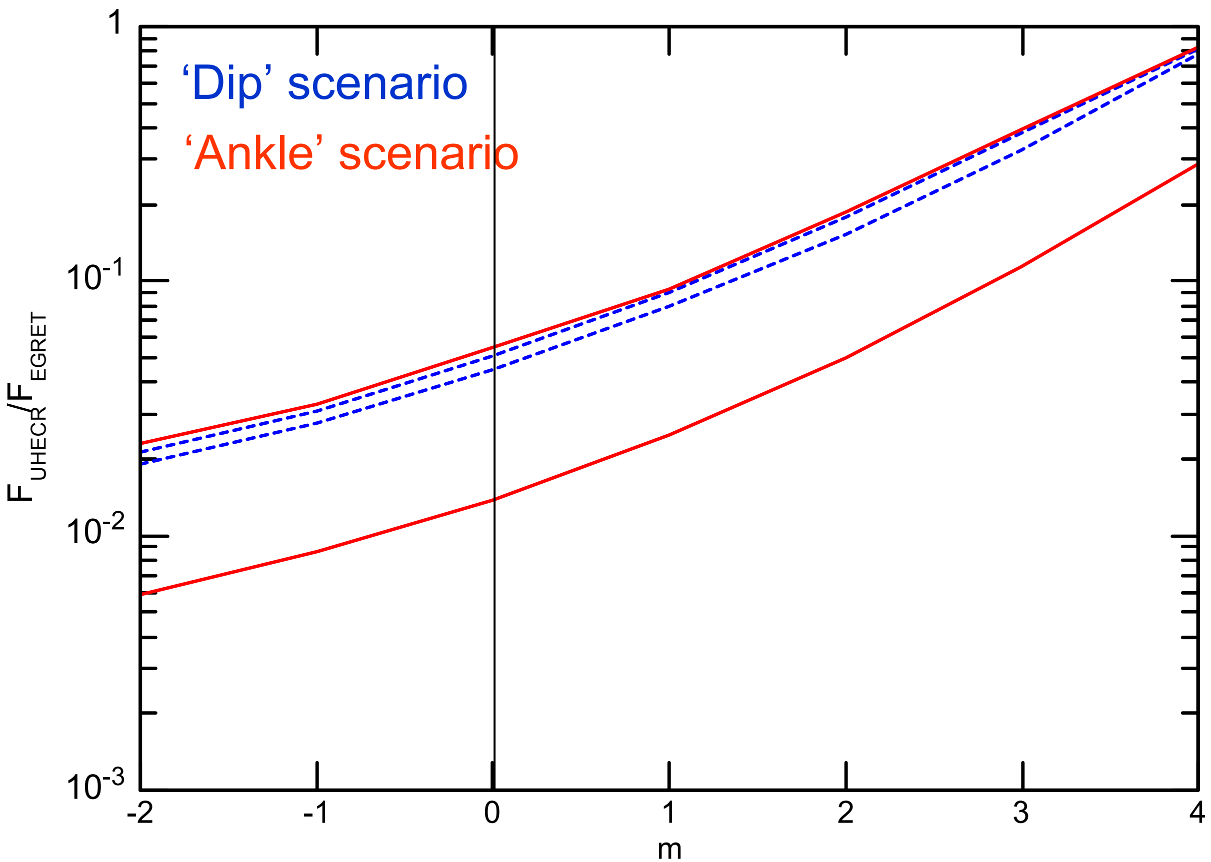
‘*ankle*’ scenario



Diffuse Gamma-Ray Flux

- Dependence on the initial spectrum

$F_{A(p)}(E, z) = f\, E^{-\alpha} (1+z)^{3+m} \Theta(E_{max} - E)\, \Theta(z - z_{min})\, \Theta(z_{max} - z)$



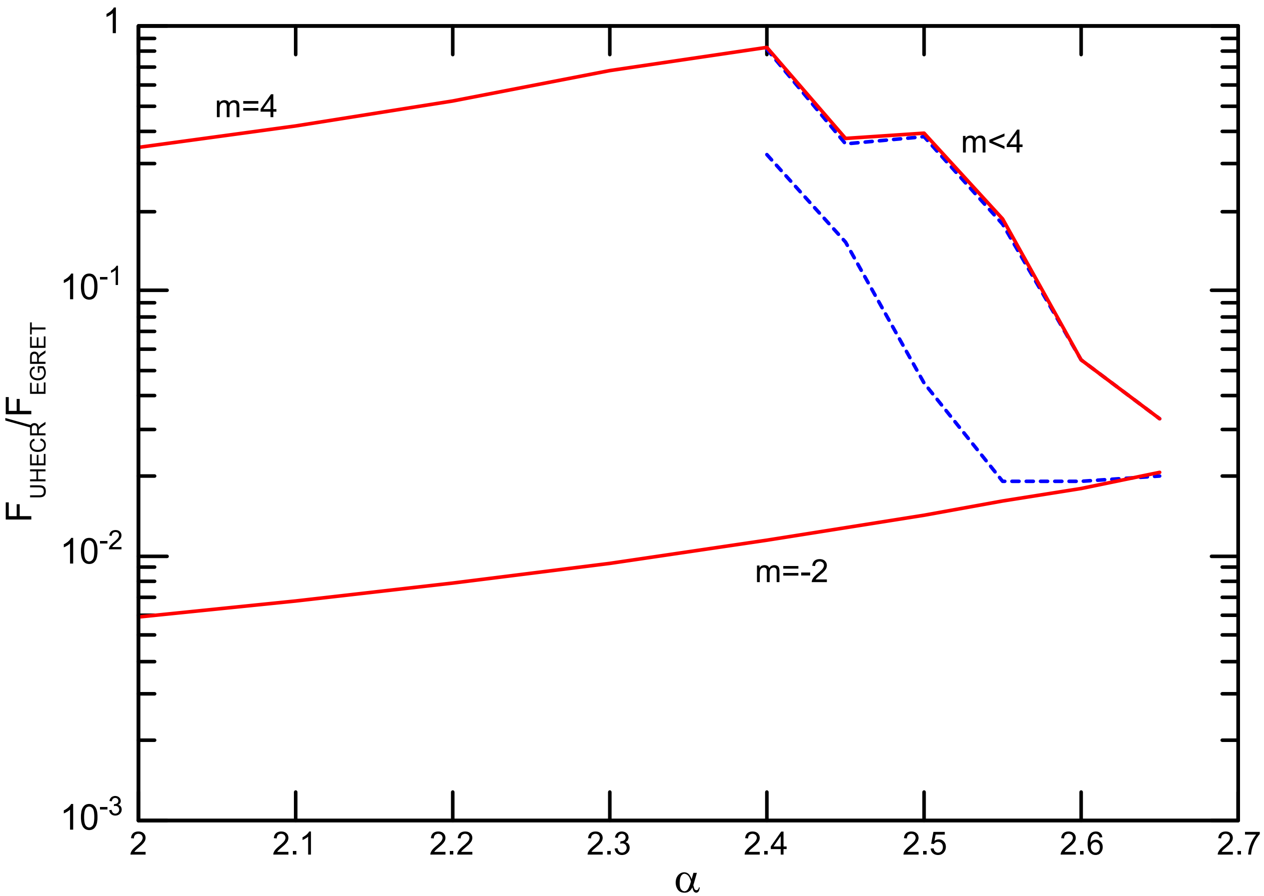
Fraction (predicted to EGRET) of integral fluxes between 1 and 2 GeV
Minimal and maximal value

The contribution of secondary photons from protons is at least ≃1% in realistic models and it may be more than 50% for strong evolution (m > 3)

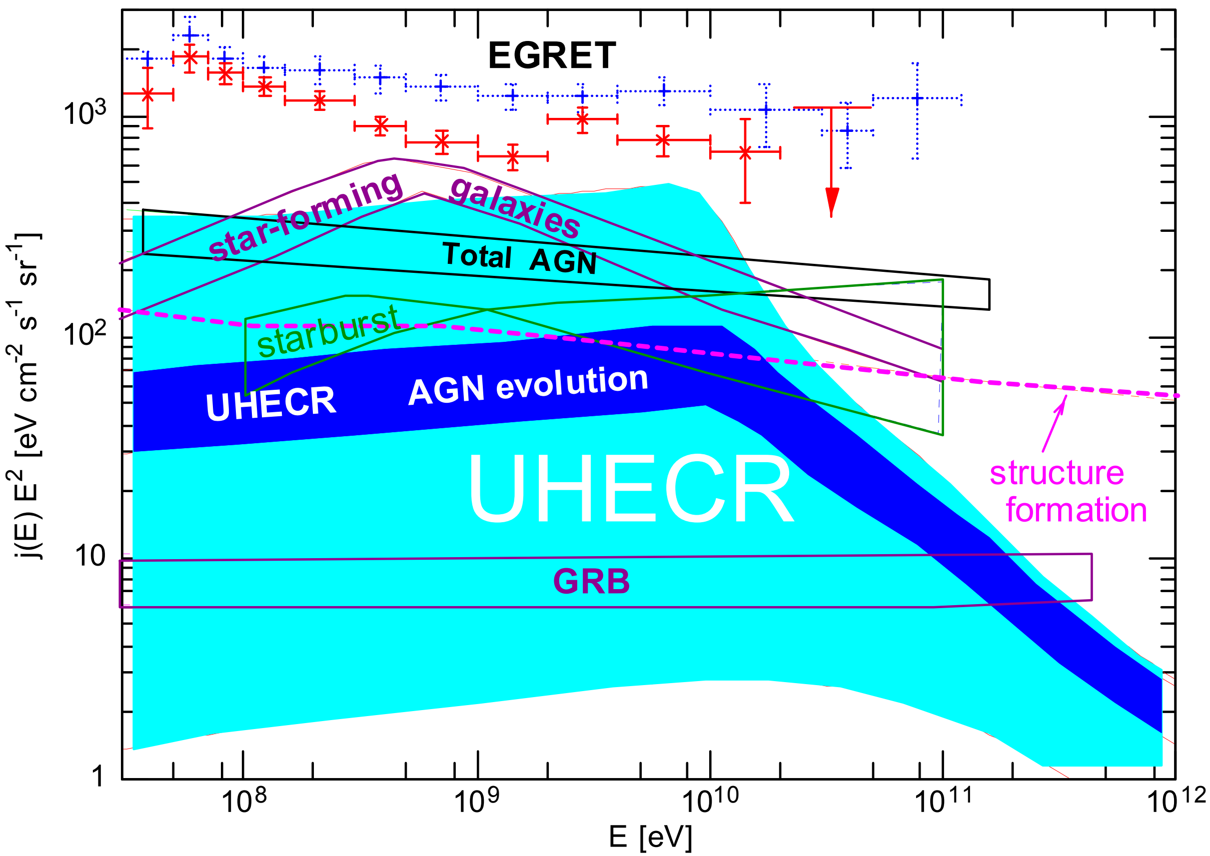
Diffuse Gamma-Ray Flux

- Dependence on initial proton spectrum

$F_{A(p)}(E, z) = f\, E^{-\alpha} (1+z)^{3+m} \Theta(E_{max} - E)\ \Theta(z - z_{min})\ \Theta(z_{max} - z)$



Diffuse Gamma-Ray Flux from protons compared with other possible astrophysical contributions



Star forming galaxies:
V. Pavlidou and B. D. Fields, Astrophys. J. 575, L5 (2002) [arXiv:astro-ph/0207253].

AGN:
C. D. Dermer, arXiv:astro-ph/0605402.

Starburst:
T. A. Thompson, E. Quataert and E. Waxman, Astrophys. J. 654, 219 (2006) [arXiv:astro-ph/0606665].

large scale structure formation shocks:
U. Keshet, E. Waxman, A. Loeb, V. Springel and L. Hernquist, Astrophys. J. 585, 128 2003) [arXiv:astro-ph/0202318].

γ−ray bursts:
C. D. Dermer, arXiv:astro-ph/0610195

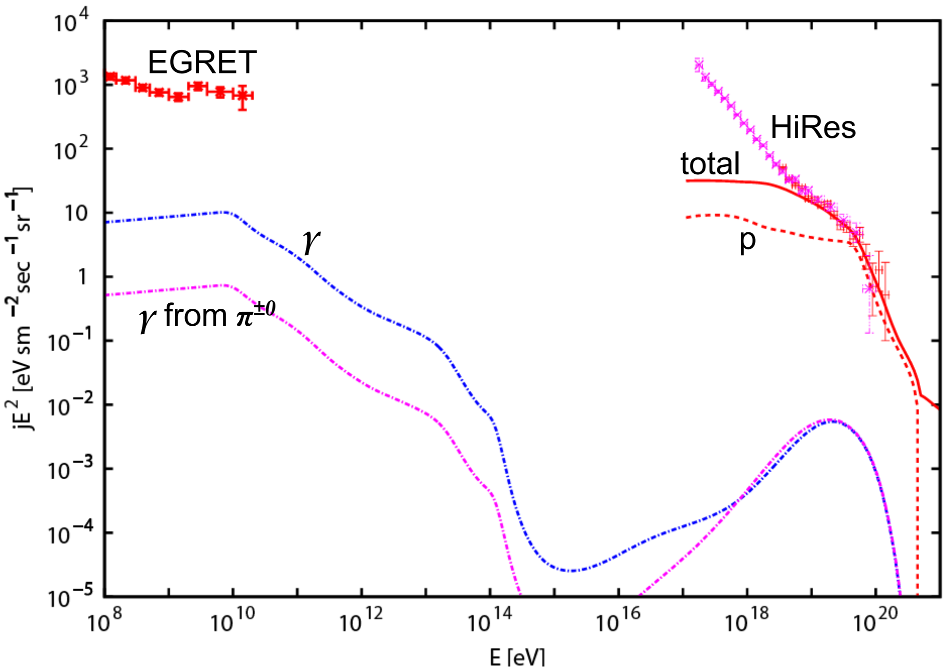
Diffuse Gamma-Ray Flux from nuclei

- e^+e^- production by nuclei and p gives main contribution
- Secondary γ-ray flux can be as low as 0.1% of EGRET bound level

Fit is done above 40 EeV

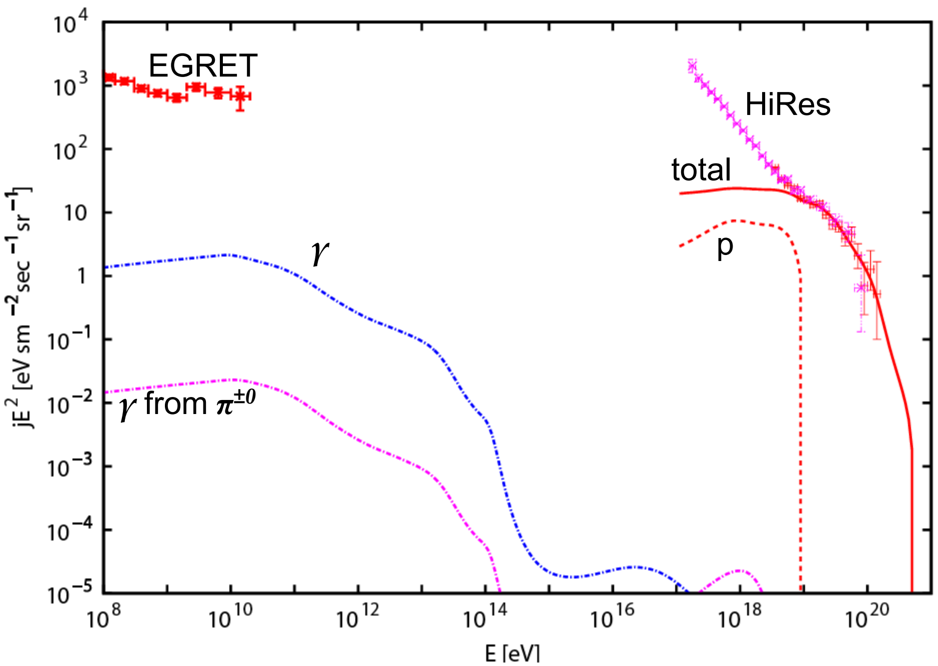
Fe (Z=26)

$E_{max} = Z \times 10^{21}$; α = 2; AGN evolution



$E_{max} = Z \times 2 \times 10^{19}$; α = 2; m=0

ok with Auger, but not supported by composition studies of HiRes!



Conclusions

- Protons contribute no less than 1% to the observed EGRET flux, and up to 50% in the case of strong source evolution
- Future measurements of resolved and unresolved components of the diﬀuse GeV-TeV γ−ray background or upper limits on such components can give important information on UHECR origin and the distribution of their sources
- Nuclei sources are much less constrained in terms of diffuse gamma ray flux they produce

Appendix

Sample transport equation for electrons (includes only pair production PP and inverse Compton scattering ICS)

$$
\begin{aligned}
\frac{d}{dt}N_e(E_e,t) \;=\;& -N_e(E_e,t)\int d\epsilon\, n(\epsilon)\int d\mu \frac{1-\beta_e\mu}{2}\sigma_{\rm ICS}(E_e,\epsilon,\mu) + \\
& \int dE'_e N_e(E'_e,t)\int d\epsilon\, n(\epsilon)\int d\mu \frac{1-\beta'_e\mu}{2}\frac{d\sigma_{\rm ICS}}{dE_e}(E_e;E'_e,\epsilon,\mu) + \\
& \int dE_\gamma N_\gamma(E_\gamma,t)\int d\epsilon\, n(\epsilon)\int d\mu \frac{1-\mu}{2}\frac{d\sigma_{\rm PP}}{dE_e}(E_e;E_\gamma,\epsilon,\mu) + Q(E_e,t)
\end{aligned}
$$

References

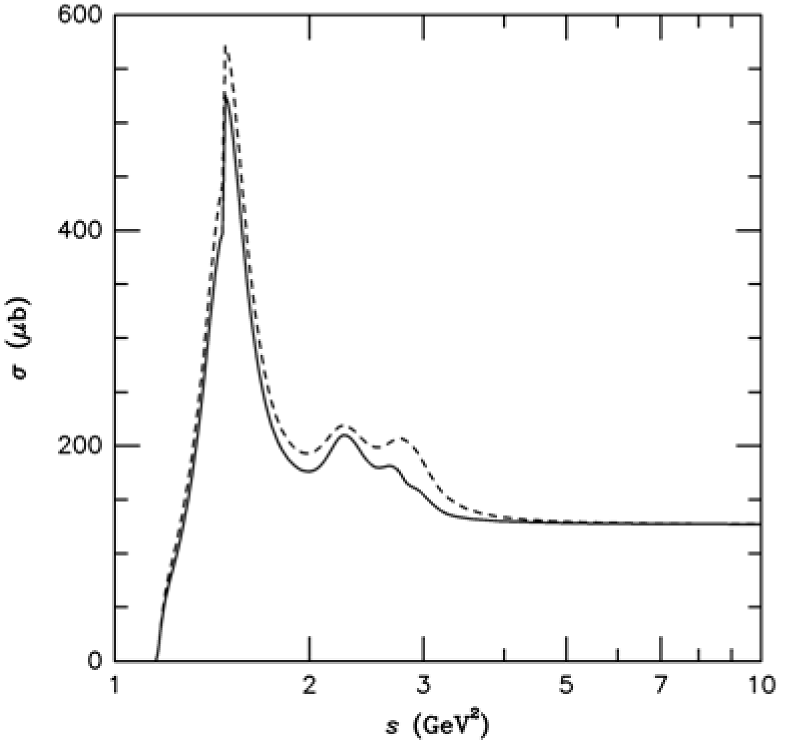
Original work on this subject

O.Kalashev, D.Semikoz, G.Sigl, arXiv:astro-ph/0703099

HiRes spectrum

R. Abbasi et al. [HiRes Collaboration], arXiv:astro-ph/0703099

Greisen-Zatsepin-Kuzmin (GZK) cutoff



$N\,\gamma \rightarrow N'\,\pi\,\ldots$

$N, N' = p$ **or** n

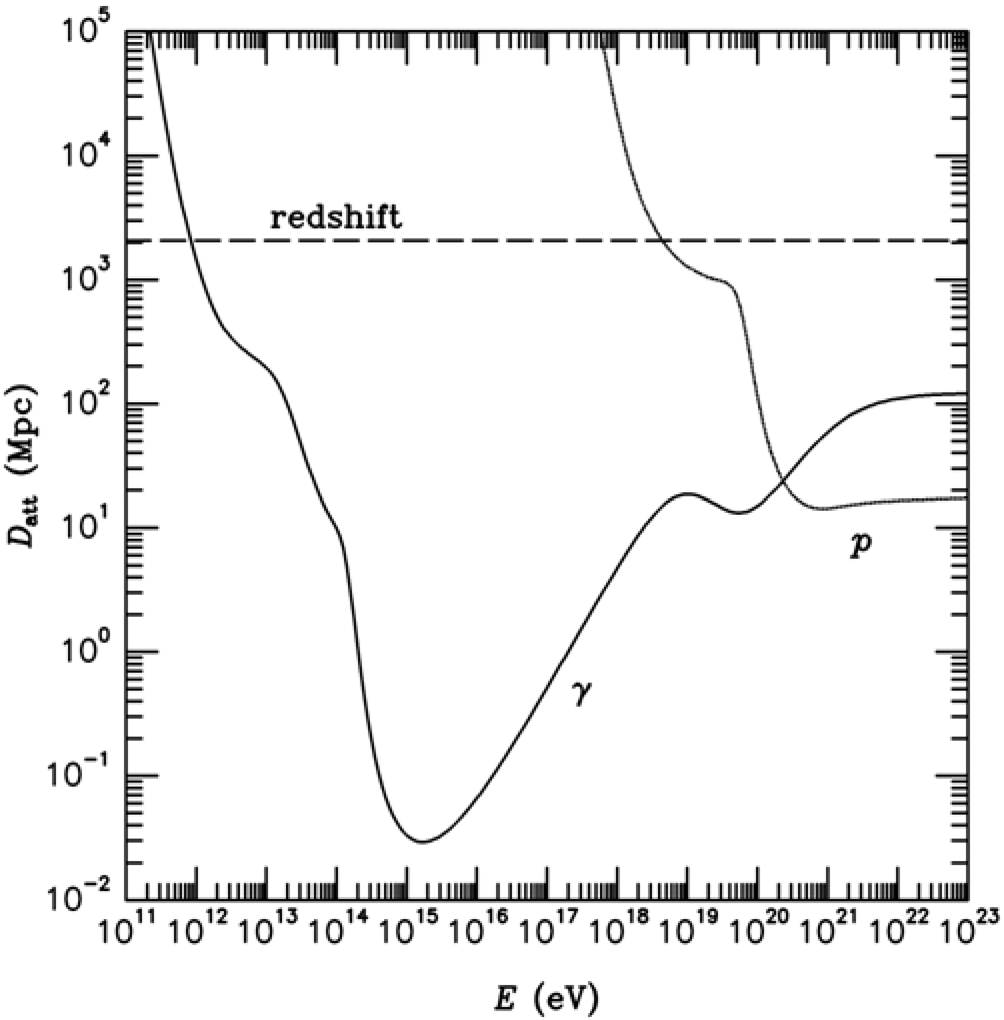
- Interaction length on MWB approaches 6 Mpc
- ~20% of energy is carried away by pions in each interaction
- Threshold energy

$$E_{th} = \frac{m_\pi (m_N + m_\pi/2)}{\varepsilon} \simeq$$

$$\simeq 6.8 \times 10^{16} \left(\frac{\varepsilon}{\mathrm{eV}}\right)^{-1} \mathrm{eV}$$

For MWB $E_{th} \approx 4 \times 10^{19}$ eV

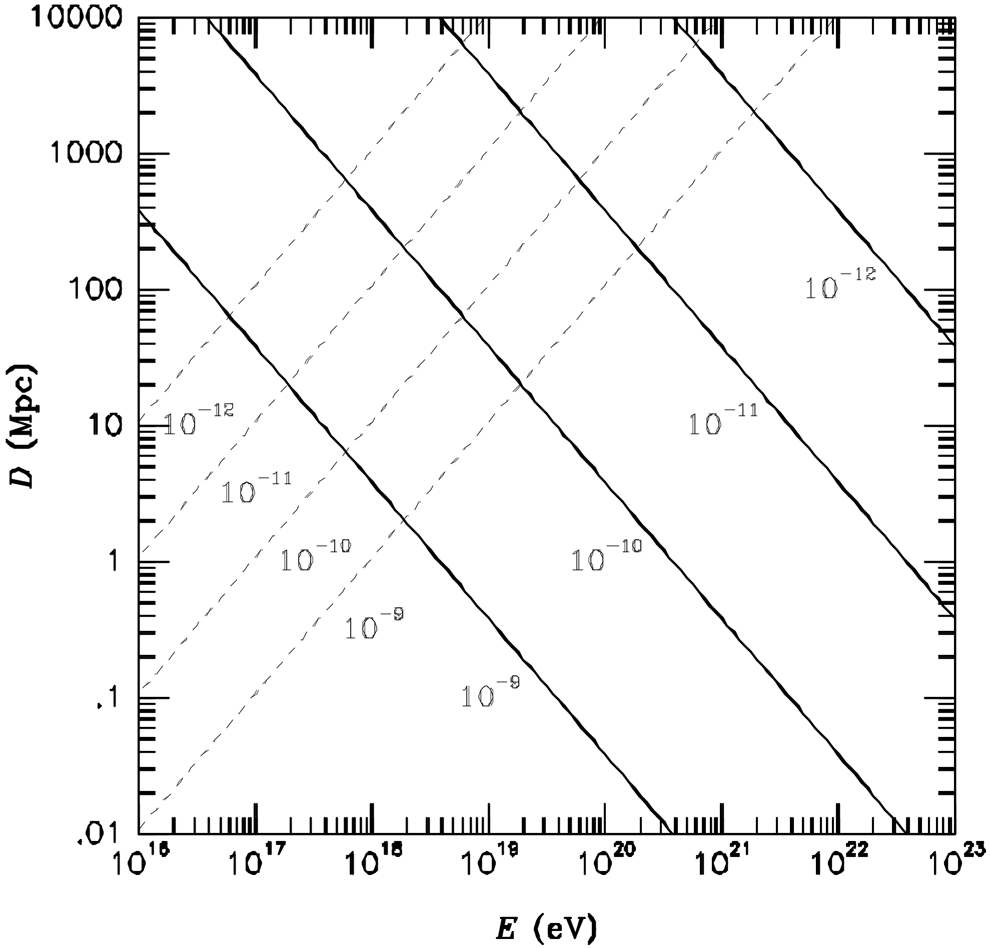
Energy loss lengths



p and γ energy loss lengths
(minimal RB assumed)

Deflection and synchrotron radiation

Gyroradius: $R_g = \frac{E}{qeB_\perp} \simeq 1.1 \times 10^3 \, \frac{1}{q} \left(\frac{E}{10^{21}\,\mathrm{eV}}\right) \left(\frac{B_\perp}{10^{-9}\mathrm{G}}\right)^{-1} \mathrm{Mpc}$



Synchrotron loss length:

$$\frac{dE}{dt} = -\frac{4}{3}\sigma_T \frac{B^2}{8\pi} \left(\frac{qm_e}{m}\right)^4 \left(\frac{E}{m_e}\right)^2$$

$$E_\gamma \simeq \frac{3eB}{2m_e}\left(\frac{E_e}{m_e}\right)^2 \simeq$$
$$2.2 \times 10^{14} \left(\frac{E_e}{10^{21}\,\mathrm{eV}}\right)^2 \left(\frac{B}{10^{-9}\mathrm{G}}\right) \mathrm{eV}$$

The gyroradii and the synchrotron loss rates of electrons for various strengths of the EGMF