Gamma rays from cosmologically distant sources of UHECR

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Outline

- Cosmologically distant sources
- Gamma-ray traces of UHECR and IGMF
- Synchrotron gamma rays as signature of UHECR
- Gamma rays from distant blazars as signature of CR
- Conclusion

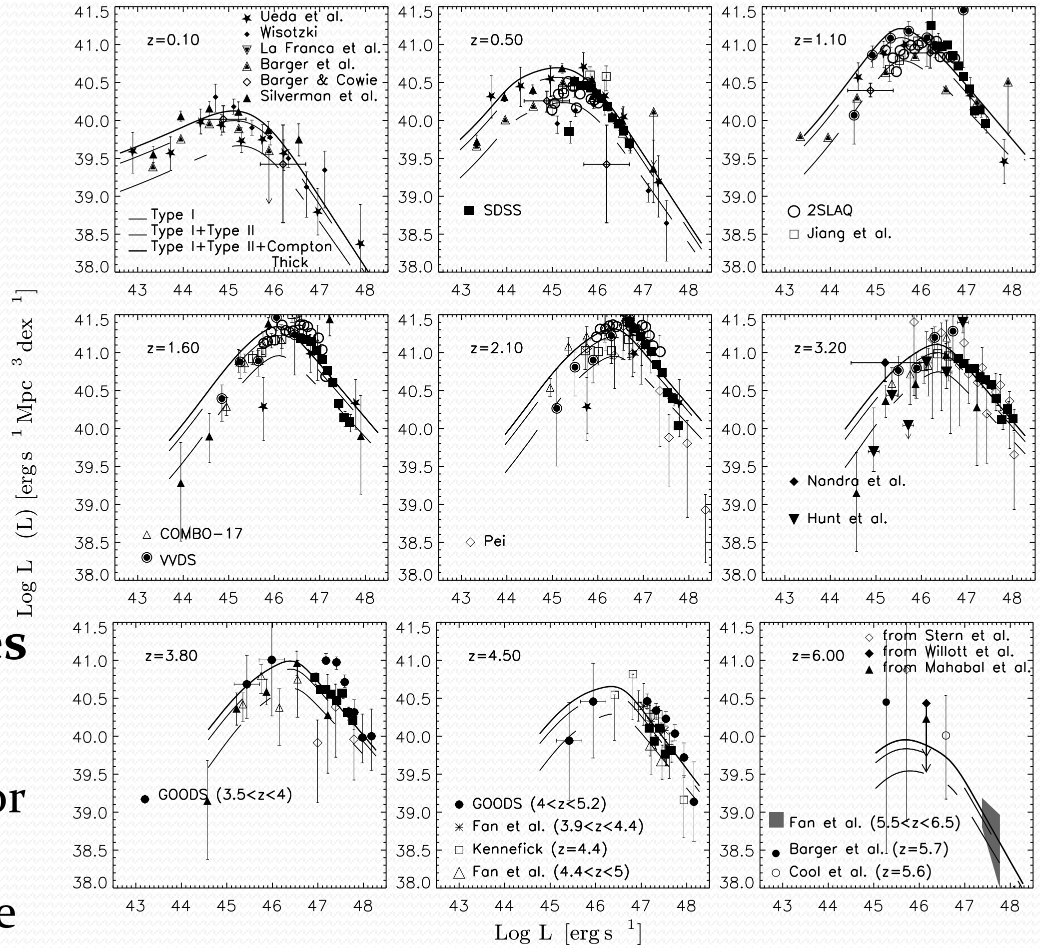
Why cosmologically distant sources?

With increase of redshift:

- Energetic increases
- Probably more effective accelerators
- Number of luminous sources increases

In context of gamma signatures of UHECR :

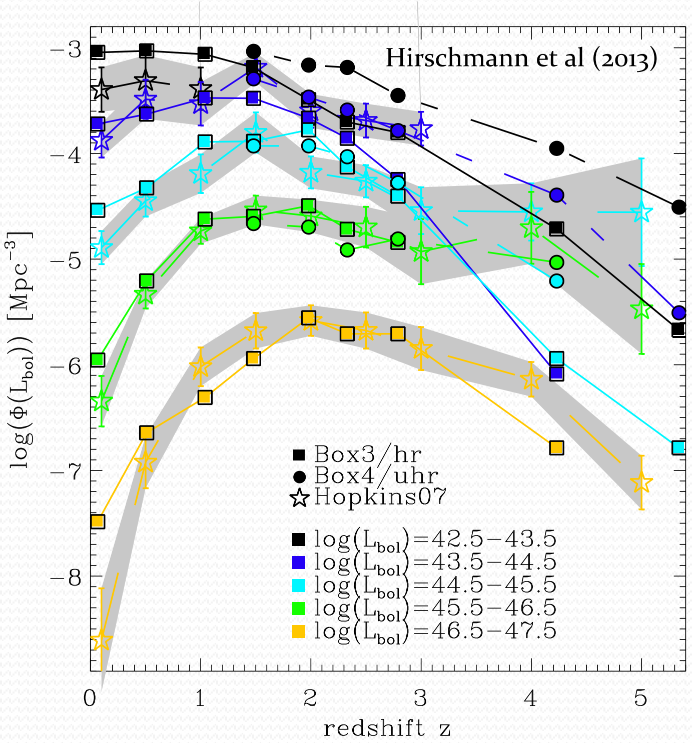
- Relaxed requirements for accelerator
- Large redshifts allow to discriminate CR – induced cascade from blazars



Shankar et al (2009)

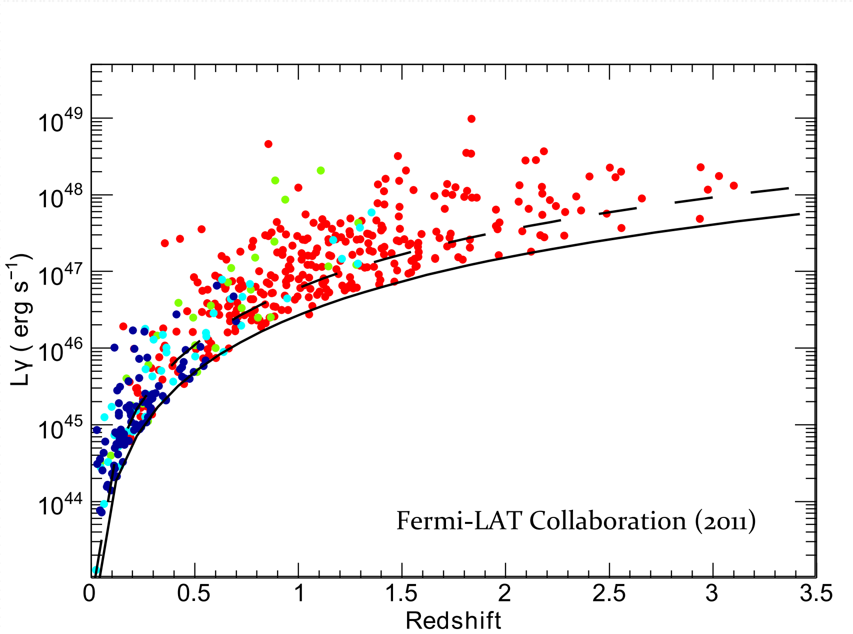
Distribution of AGNs with redshift

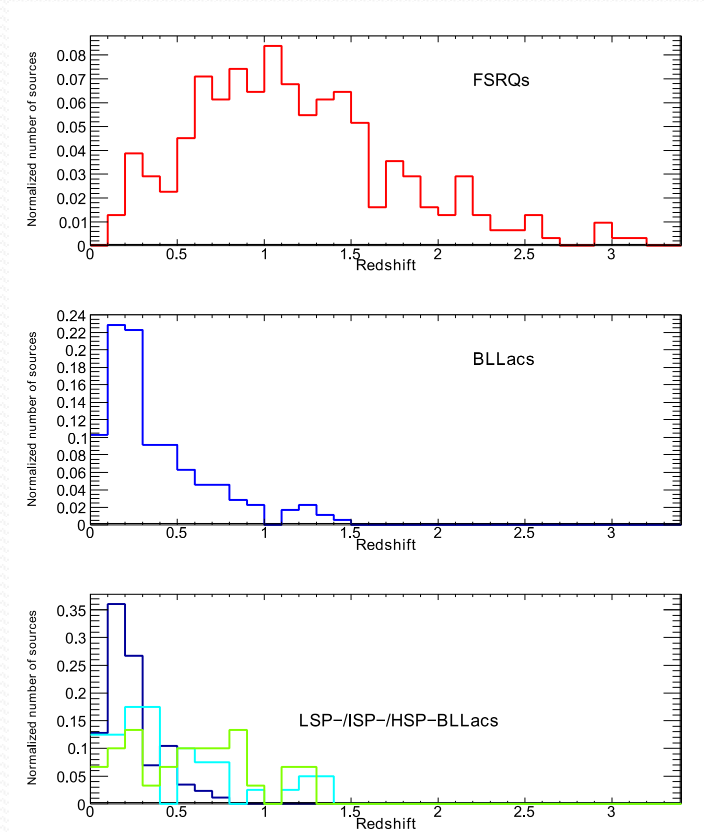
- The maximum of the distribution is for most luminous AGNs with L=10^{45}-10^{48} erg/s is at redshift z=2-3.



Source type distribution

- The Second Catalog of Active Galactic Nuclei

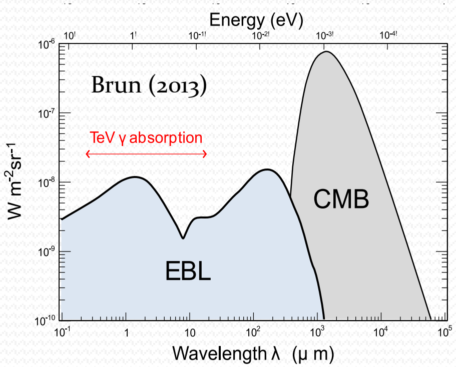




- More distant and luminous are FSRQs
- Small part of BLLacs at z~1

Gamma-ray traces of UHECR

- Intergalactic medium: CMB+EBL
- Photomeson production (mostly CMB)



$$p+\gamma_b \to p+\pi^0 \to p+2\gamma$$

$$p+\gamma_b \to n+\pi^+ \to p+e^- +\bar{\nu}_e + e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$$

$$p+\gamma_b \to p+\pi^+ + \pi^- \to p+e^+ + \nu_e + 2\bar{\nu}_\mu + e^- + \bar{\nu}_e + 2\nu_\mu$$

  - Final products $E_\gamma \sim 10^{19} E_{p,20} eV$ $E_{e^\pm} \sim E_\nu \sim 5\cdot 10^{18} E_{p,20} eV$

- Bethe-Heitler pair poduction (CMB+EBL)

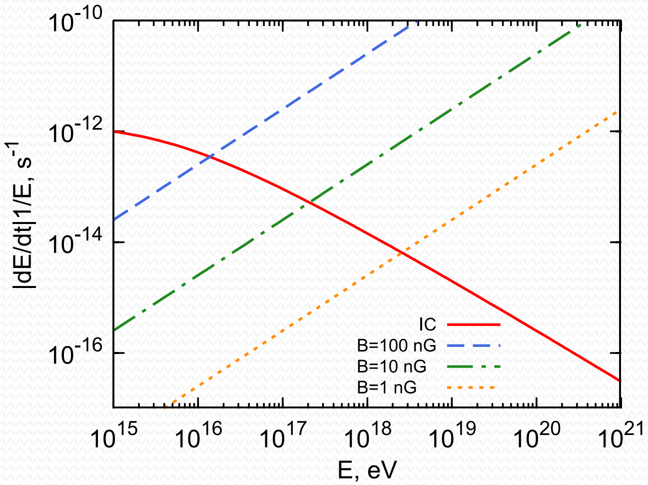
$$p+\gamma_b \to p+e^+ + e^-$$

  - Final products $E_{e^\pm} \sim 10^{15} E_{p,18} eV$

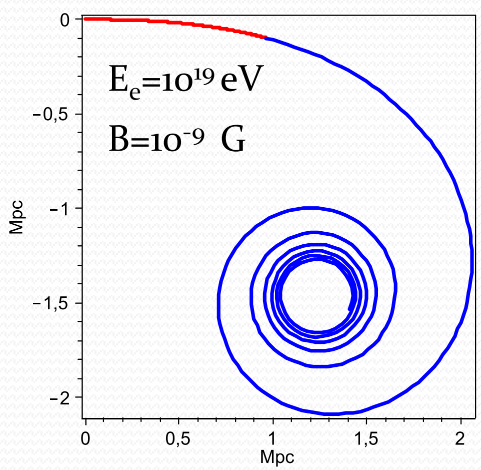
- Pair production $\gamma + \gamma_b \to e^+ + e^-$

Two scenarios 1

- Synchrotron losses > IC losses (10^{-10} G < B< 10^{-7} G)
  - Energy of electrons is effectively converted to synchrotron gamma rays of GeV and TeV energy band
  - Almost all energy is radiated on the initial part of path



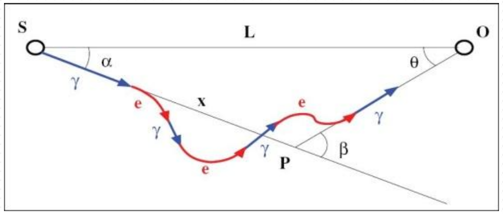
Energy loss rates of electrons



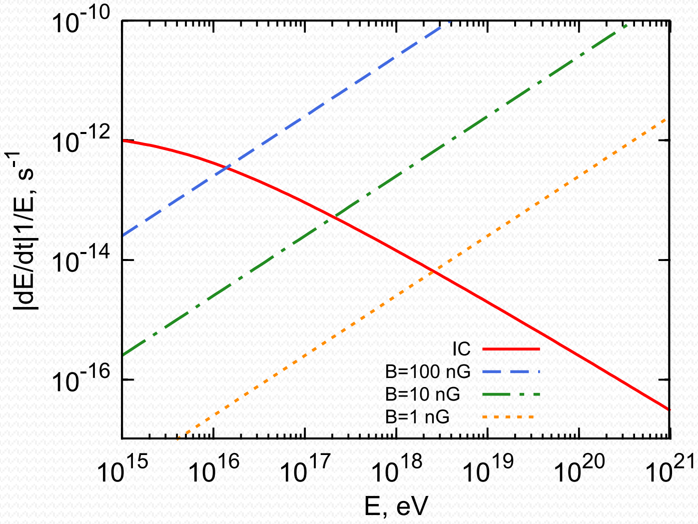
Illustrative: movement of electron in the constant magnetic field

Two scenarios 2

- IC losses > Synchrotron losses
  - Electromagnetic cascade: $\gamma + \gamma_b \rightarrow e^+ + e^-$ ➡ $e^\pm + \gamma_b \rightarrow e^\pm + \gamma$
  - Magnetic field 10^{-14} G < B< 10^{-10} G :
    - Strong deflection
    - Hardly detectable gamma ray halo
  - Magnetic field B< 10^{-14} G:
    - Collimated beam of gamma rays



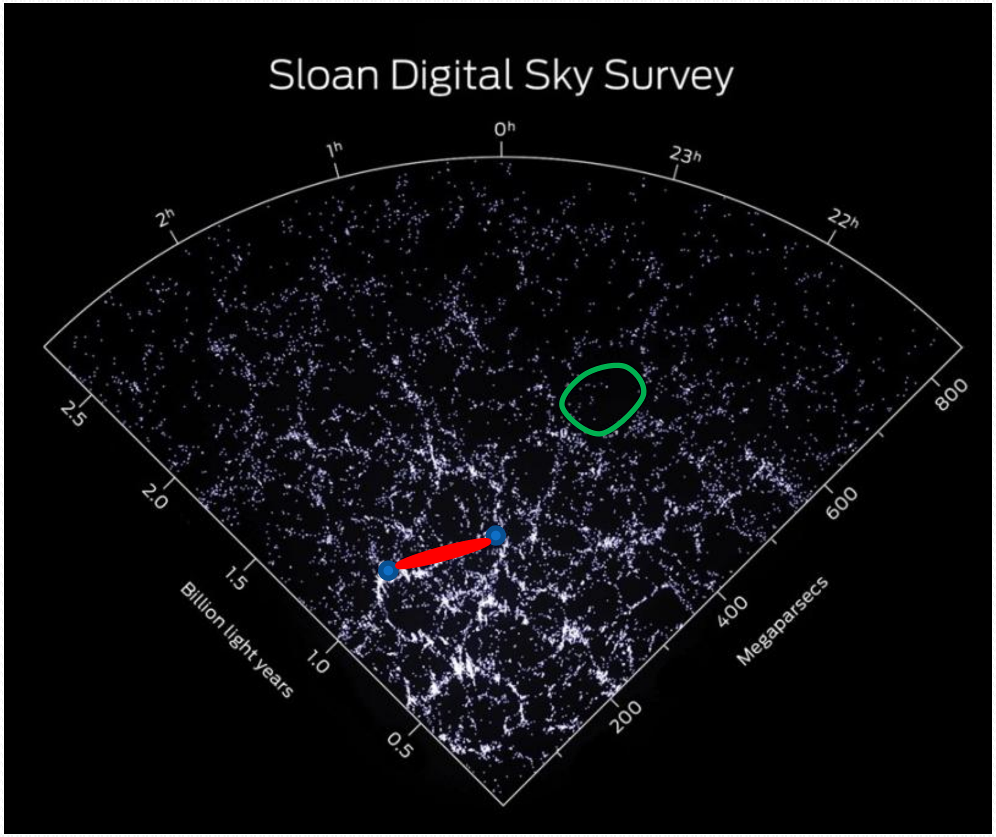
Dolag et al. (2009)



Energy loss rates of electrons

Intergalactic magnetic fields

- **Clusters of galaxies**
  - 2 - 10 Mpc
  - $B=10^{-6}$ G
  - Faraday rotation
- **Filaments**
  - 50-80 Mpc
  - $B=10^{-9} - 10^{-8}$ G
  - Low frequency synchrotron radiation
- **Voids**
  - 10-150 Mpc
  - $B=10^{-17} - 10^{-15}$ G
  - Electromagnetic cascades from blazars

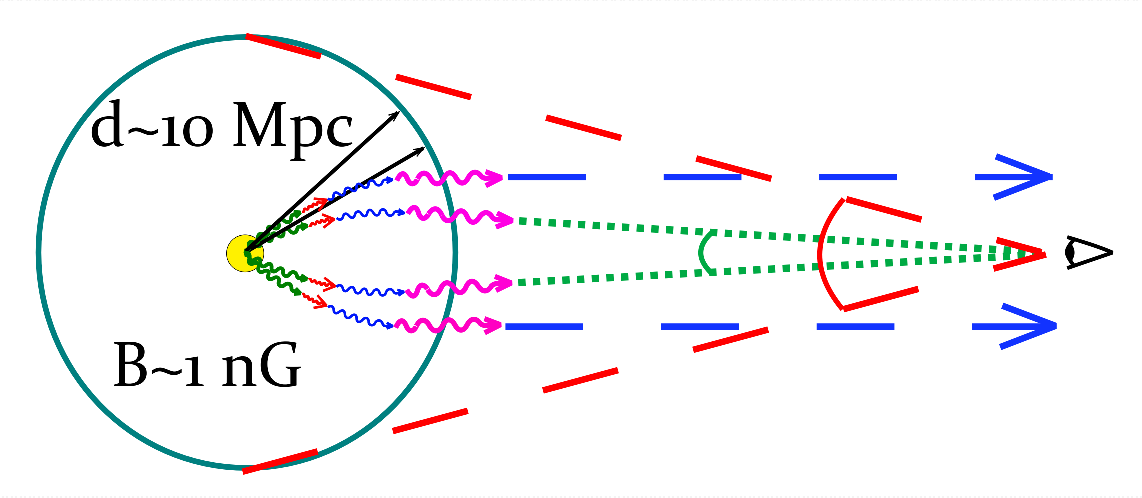


http://spectrum.ieee.org/aerospace/astrophysics/the-cosmological-supercomputer

Scenario 1

Synchrotron radiation from the source of UHECR located at environment with strong magnetic field 10^{-10} G < B< 10^{-7} G (filaments)

Overview



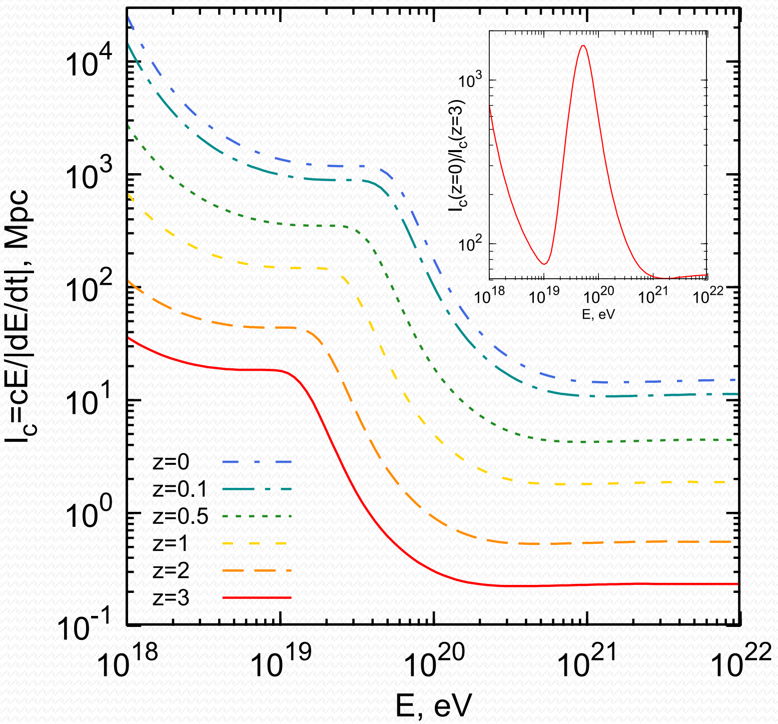
- Small deflection angles of protons and electrons result in collimated beam of synchrotron gamma rays
- Apparent angular size of gamma-ray source is smaller than angular size of the radiation region
- Non-variable source

Interaction of protons at large redshifts

- Energy loss of UHE protons at different redshifts changes according

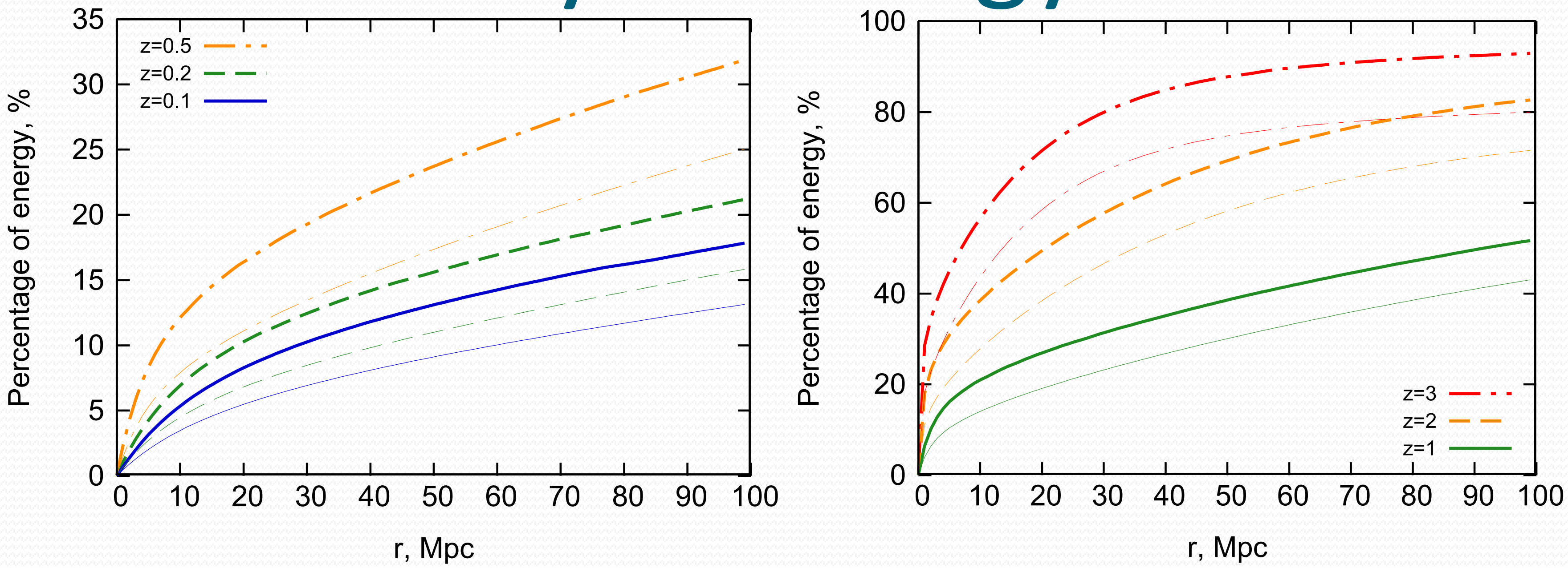
$$\beta(E,z) = (1+z)^3 \beta_0((1+z)E)$$

- Faster energy losses ~$(1+z)^3$
  - Interaction lengths are shorter: from 15 Mpc at z=0 to 0.2 Mpc at z=3
- Interaction with more energetic photons ~ 1+z
  - Less energetic protons produces energetic electrons via photo-hadronic interactions
  - Relaxed requirements for acceleration
    - Increase number of UHECR sources seen in gamma rays



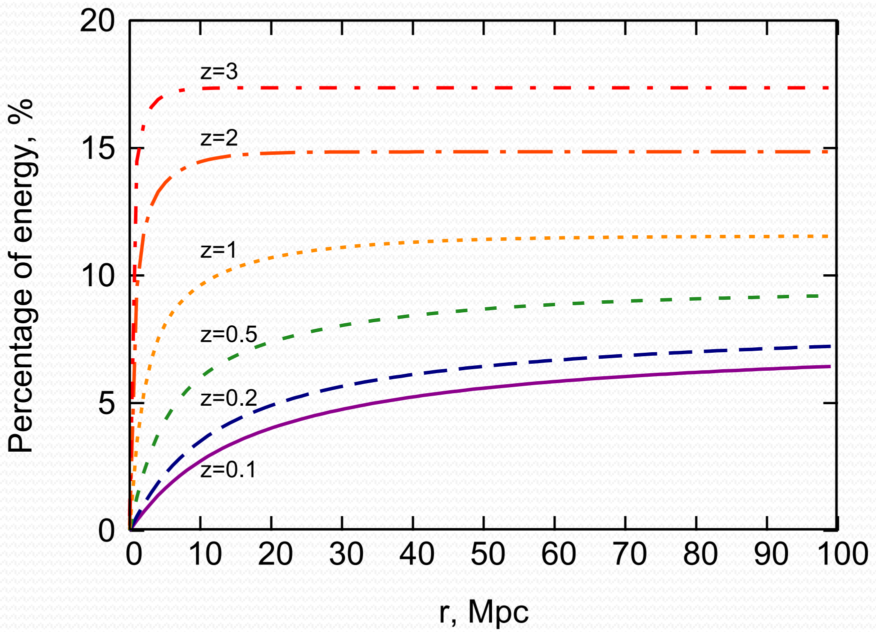
Prosekin et al (2011)

Efficiency of energy transfer

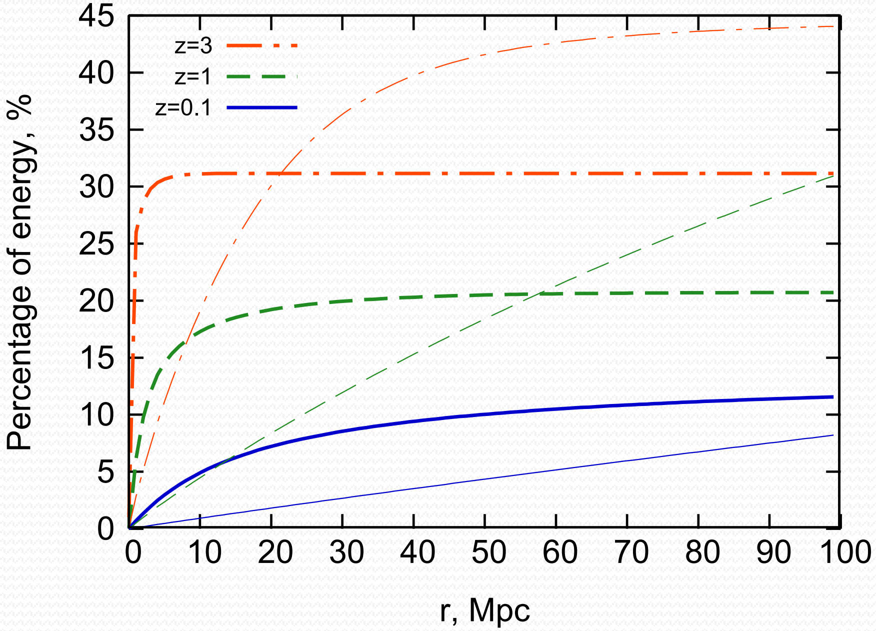


- Energy losses of protons with E>10^{18} eV increases from 19% to 93%
- Energy transferred to the electrons increases from 13% to 80 %

Efficiency of energy transfer



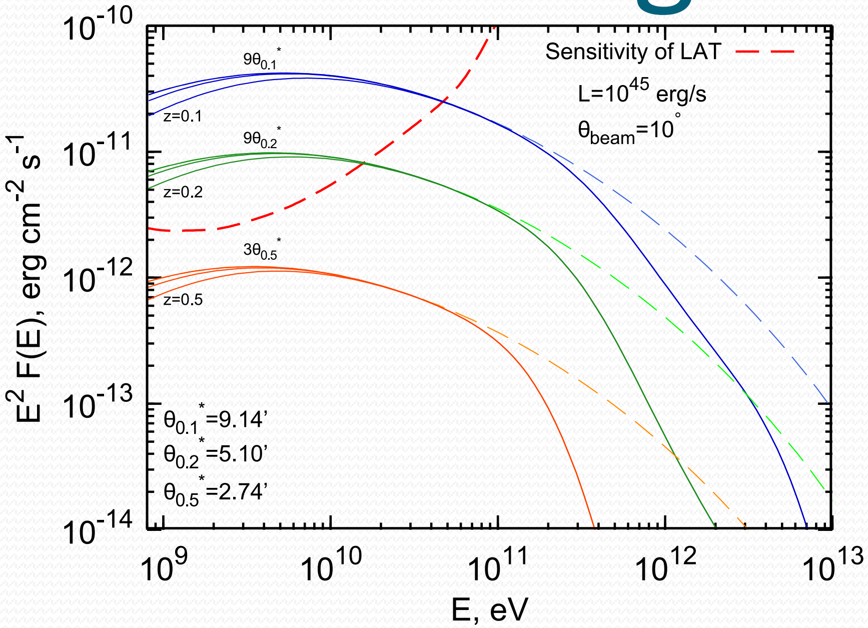
For protons with E>10[18] eV

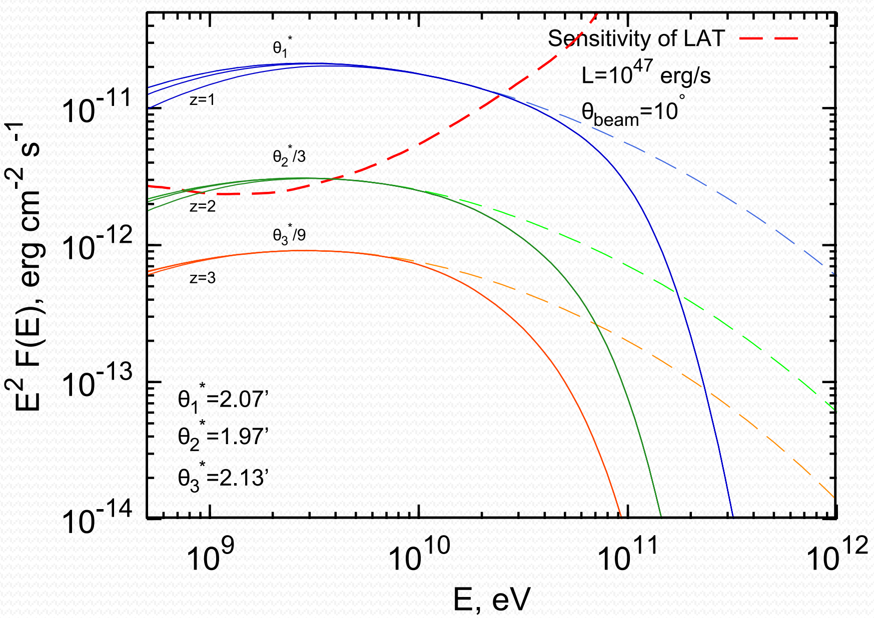


For protons with E>10[19] eV

- All the possible energy is transferred at first 5 Mpc at z=3
- Considerable part of the energy goes to electrons produced via pair production

SED of gamma-ray signal





- Flux of gamma rays is detectable by Fermi LAT for isotropic luminosity $L=10^{45}$ -10^{47} erg/s
- For sources at z>0.2 the gamma ray source is point like for Fermi LAT
- Flux is suppressed at TeV energies
- With increase of strength of magnetic field spectra shifts to higher energy proportionally to increase of magnetic field strength
    - At large magnetic fields energetic part of the spectra will be absorbed due to interaction with EBL

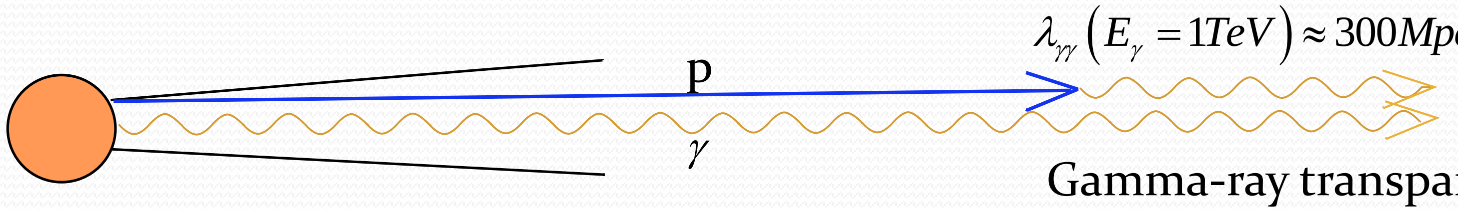
Scenario 2

Gamma rays from electromagnetic cascade induced by cosmic rays
in the environment with weak magnetic field 10^{-17} G < B< 10^{-15} G (voids)

Distant TeV blazars

- The flux of blazars with redshift z>0.1 at TeV energies should be significantly suppressed due to gamma-ray absorption in EBL
- Recovered intrinsic spectrum $F_{obs}(E)\exp(\tau(E,z))$ some of them (1ES 0229+200 (z=0.139), 1ES 0347+121 (z=0.185), 1ES 1101+232 (z=0.186)) seems harder than it is expected in standard models with photon index $\Gamma>1.5$
- Explanations
  - Intrinsic properties of the radiation
  - Gamma-ray induced cascade
  - Cosmic-ray induced cascade
- Cosmological distant blazars observed at TeV energies the only feasible explanation is cosmic-ray induced cascade

Blazars as CR sources



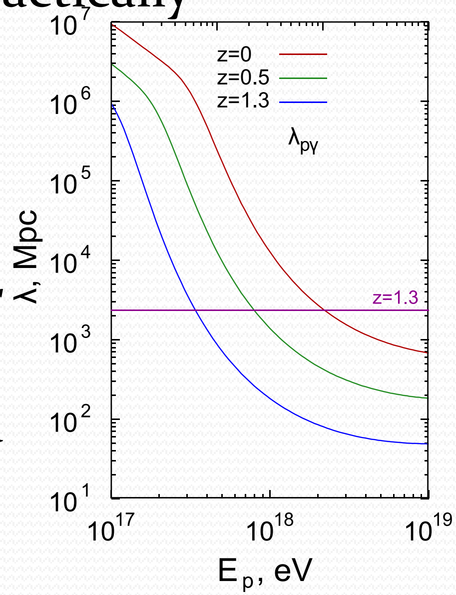
- Protons with energies E=10^{17}-10^{19} eV has large interaction length relative to pair production process
- In the magnetic field B<10^{-15} G protons propagates practically rectilinearly

$$\theta_p \approx 0.05\text{arcmin}\left(\frac{10^{18}\text{eV}}{E_p}\right)\left(\frac{B}{10^{-15}\text{G}}\right)\left(\frac{L}{\text{Mpc}}\frac{d}{\text{Gpc}}\right)^{1/2}$$

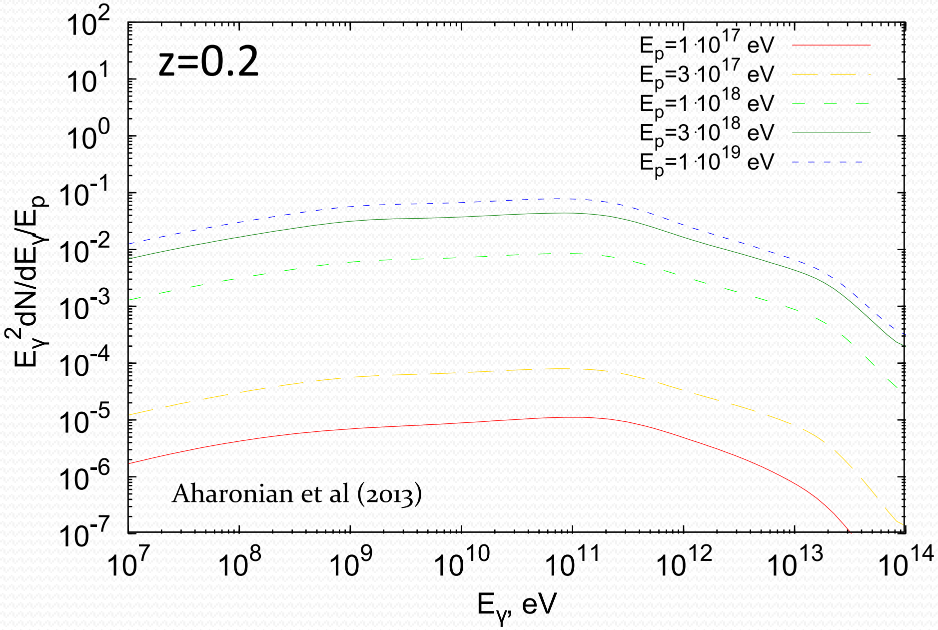
- Mean free path without encounter with galaxy cluster

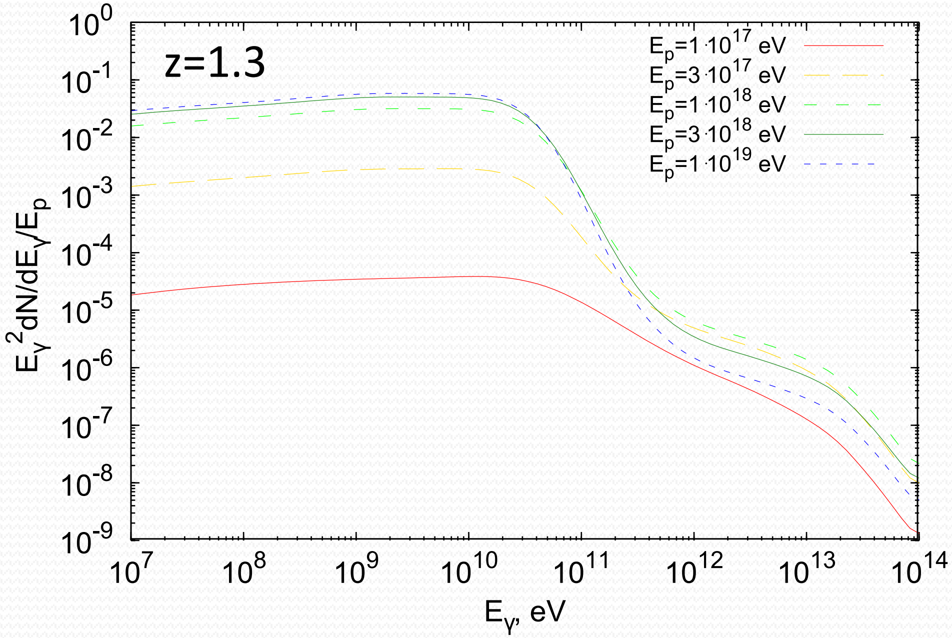
$$L_{\min} \sim 1/(\pi R^2 n) \sim (1-5)\times 10^3\,\text{Mpc}$$

- Encounter of the structure with strong magnetic field significantly suppresses the flux of gamma rays



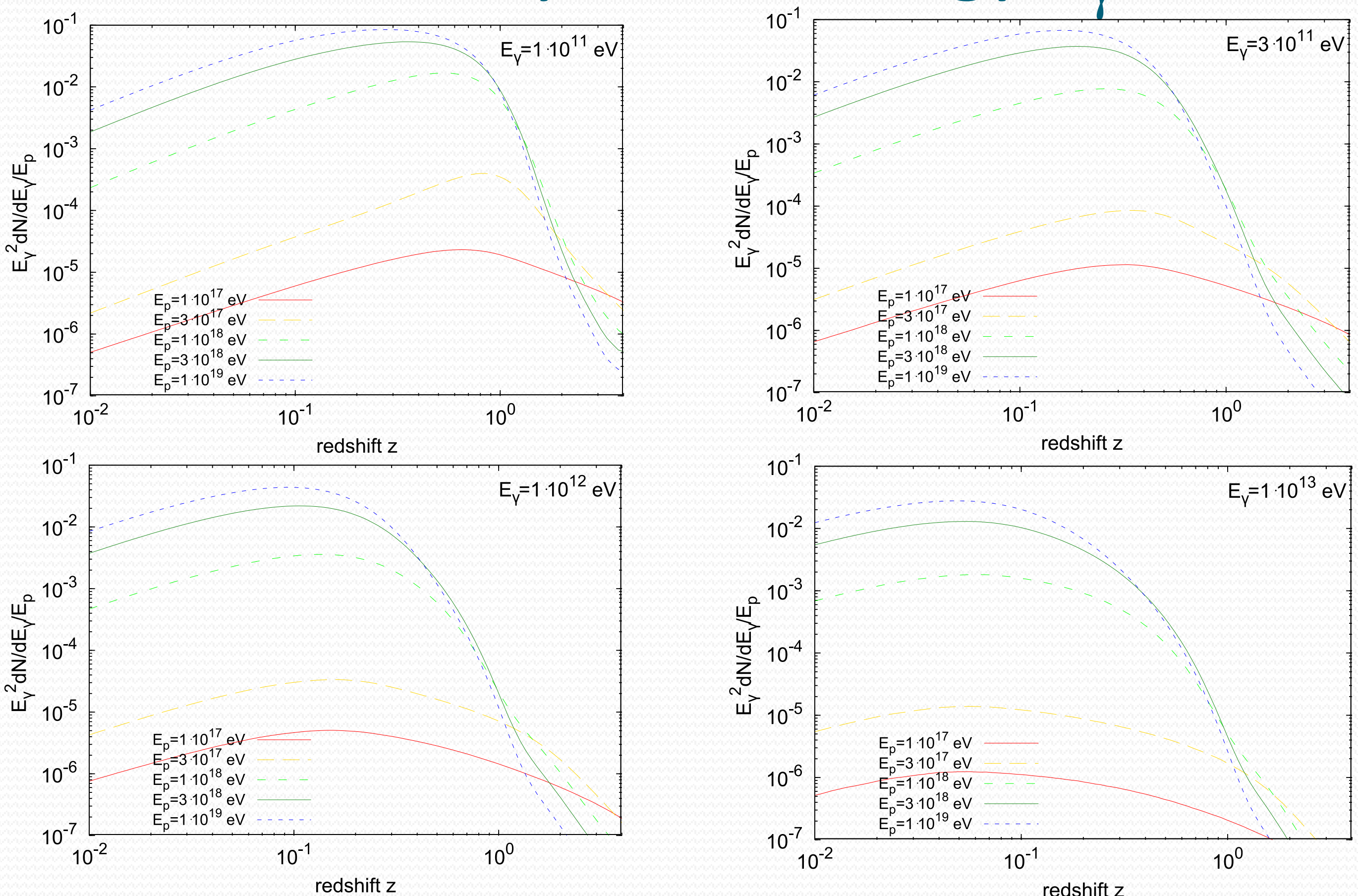
Cascade spectra at small and large redshifts





- For small redshifts spectral shape of secondary photons does not depend on the initial energy of protons with maximum at $E=10^{11}$ eV
  - For a nearby source the spectral shape of secondary photons is independent of the details of the proton energy spectrum
- For large redshifts spectral shape of secondary photons significantly depends on initial energy of protons with hardening at E>1 TeV
- For large redshifts mostly the low-energy protons with $E\sim 10^{17}$ eV enter the gamma-ray transparency zone

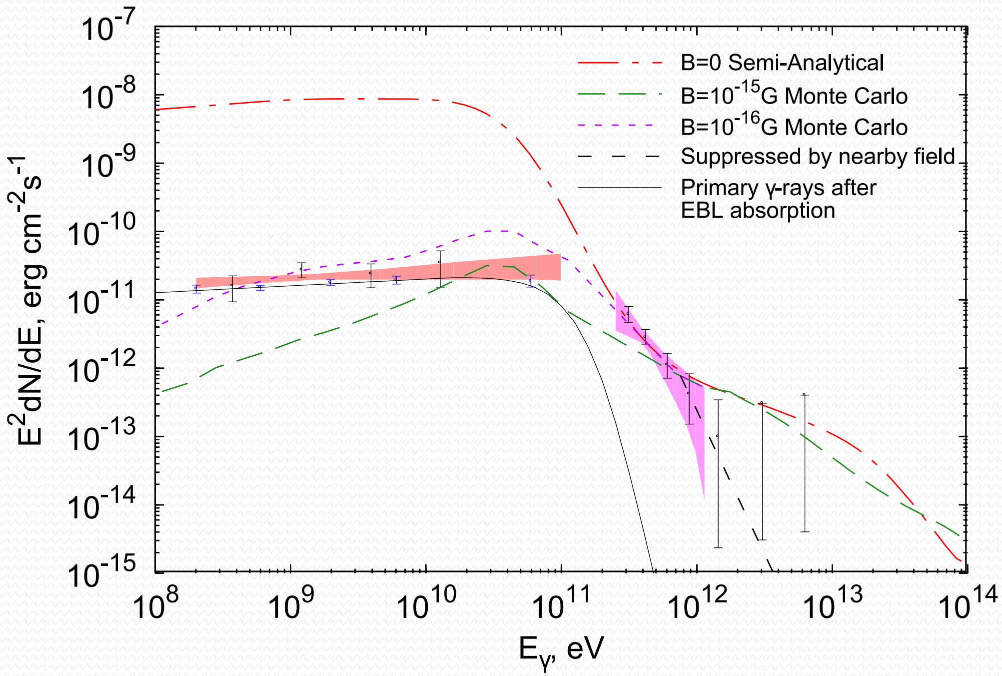
Efficiency of energy transfer to the flux of gamma rays with energy E_γ



- The efficiency reaches maximum of 10% at intermediate redshifts z =0.1–0.3
- The efficiency falls down to 10^{-4}-10^{-5} at redshift z~1
- The most efficient transfer of energy for protons with initial energy $E=10^{18}$ eV

Case of PKS 0447-439 at z=1.3

- In spite on the low efficiency protons still can explain TeV radiation from cosmologically distant blazars if B<10^{-15} G
- The suppression of flux at GeV energies due to deflection of electrons in the electromagnetic cascade
- To fit the Fermi data the magnetic field should be B~10^{-16} G
- If magnetic is strong (B>10^{-14} G) in the vicinity of the observer (~100 Mpc), the flux is suppressed at TeV energies



Implications

- Deflection of protons $\theta_p \approx 0.05\text{arcmin}\left(\frac{10^{18}\text{eV}}{E_p}\right)\left(\frac{B}{10^{-15}\text{G}}\right)\left(\frac{L}{\text{Mpc}}\frac{d}{\text{Gpc}}\right)^{1/2}$
- Deflection in the cascade $\theta_{cas} \approx 3.8\text{arcmin}\left(\frac{10^{12}\text{eV}}{E_\gamma}\right)\left(\frac{B}{10^{-15}\text{G}}\right)$
  - The main contribution to deflection is from cascade
  - Energy-dependent angular broadening can provide a direct measurements of IGMF in a given direction
- Time delay of protons $\Delta\tau_p \approx 1.5\cdot 10^6\text{s}\left(\frac{E_p}{10^{18}\text{eV}}\right)^{-2}\left(\frac{B}{10^{-15}\text{G}}\right)^2\left(\frac{L}{1\text{Mpc}}\right)\left(\frac{d}{1\text{Gpc}}\right)^2$
- Time delay in the cascade $\Delta\tau_\gamma \approx 1.3\cdot 10^6\text{s}\left(\frac{E_\gamma}{10^{12}\text{eV}}\right)^{-5/2}\left(\frac{B}{10^{-15}\text{G}}\right)^2$
  - For B~10^{-15} G any variability of the initial signal on the scales of the order 1 month and shorter is smeared out
  - In framework of this model any observed variability shorter than month means B<10^{-15} G
- Isotropic luminosity L=10^{50}erg/s is needed
- Luminosity with beaming L=10^{47}erg/s which is of the order of Eddington luminosity of black hole with mass M~10^9M$_{sol}$

Conclusion

- As AGNs is more active at the epoch of z=2..3 there are more accelerators of UHECR
- The discovery of UHECR sources is possible through their gamma rays signatures
- Two significantly different cases should be distinguished:
- Synchrotron gamma rays
  - Strong nG level magnetic field, short interaction lengths
  - At large redshifts relaxed condition for accelerators
- Gamma rays produced through cascade
  - Weak fG level magnetic field, large interaction length
  - At large redshifts only cosmic rays production in blazars can explain TeV gamma rays