



Proton-Induced electromagnetic cascades and its implications at ultrahigh energies

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Outline

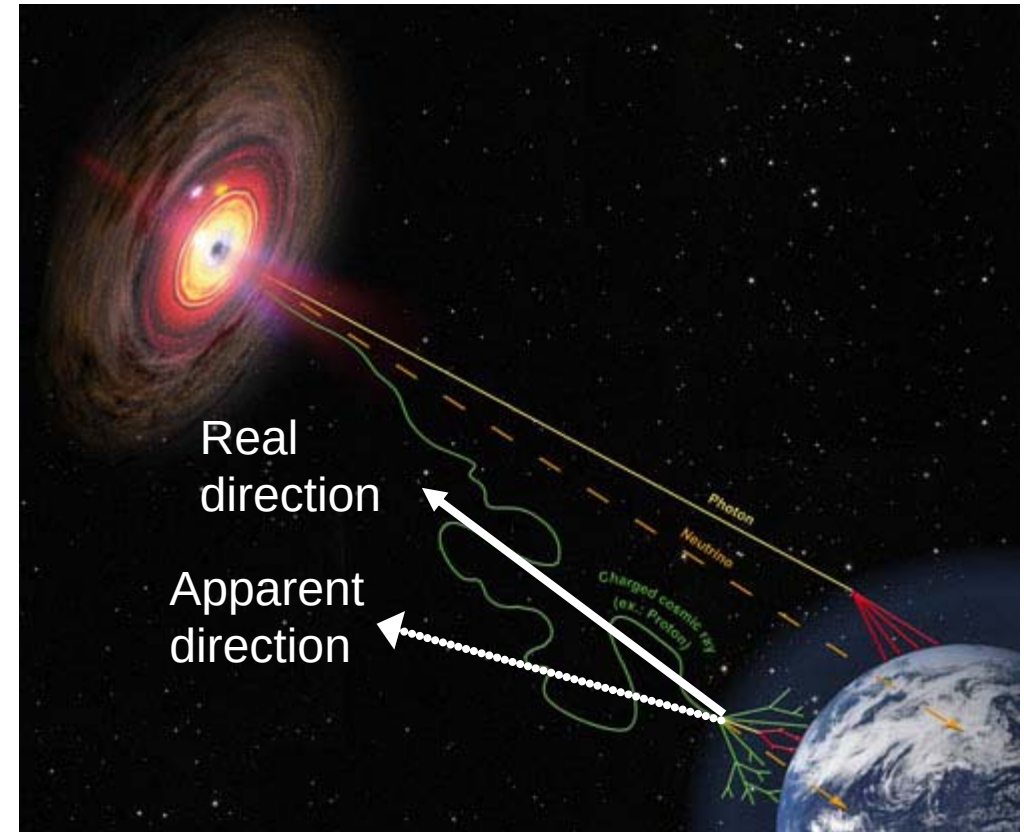
- Introduction
- Effective attenuation length of UHE
photons/electrons
- Neutrinos production in the EM cascades
- Constraint on the distance of UHECRs from
cascade emission



Interactions at UHE energies – what can we learn from them?

- Source of ultrahigh-energy cosmic rays are uncertain (low event rate, magnetic field)
- Interactions: change energies and/or species of UHECRs.

Photomeson process
Bethe-Heitler process
Photodisintegration



Ex: interactions between proton and CMB > GZK cutoff
nuclei and CMB > PSB cutoff



$d < 100 \text{ Mpc}$



Secondary Products

Photomeson

$$p + \gamma \rightarrow \pi^0 \rightarrow 2\gamma$$

$$\rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu, \quad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\rightarrow \pi^- \rightarrow \mu^- + \bar{\nu}_\mu, \quad \mu^- \rightarrow e + \bar{\nu}_e + \nu_\mu$$

Bethe-Heitler

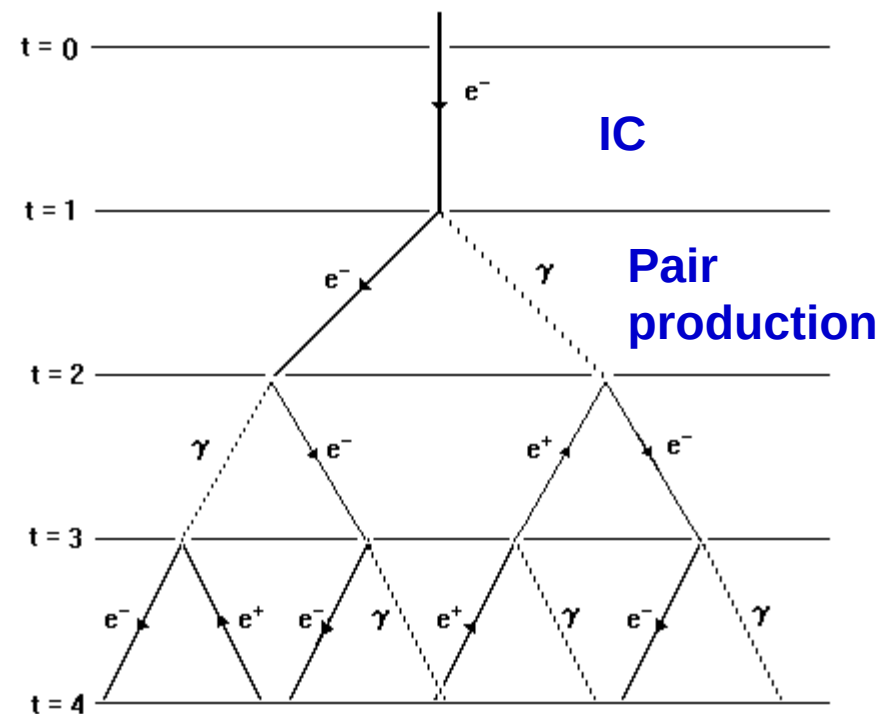
$$p + \gamma \rightarrow p + e^+ + e^-$$

ν



low cross section
Neutral
Travel directly to us

γ
 e





Some other processes at UHE

For UHE photons:

$$\gamma + \gamma \rightarrow 2e^+ + 2e^-$$

Double pair production (DPP)

$$\gamma + \gamma \rightarrow \mu^+ + \mu^-$$

Muons pair production (MPP)

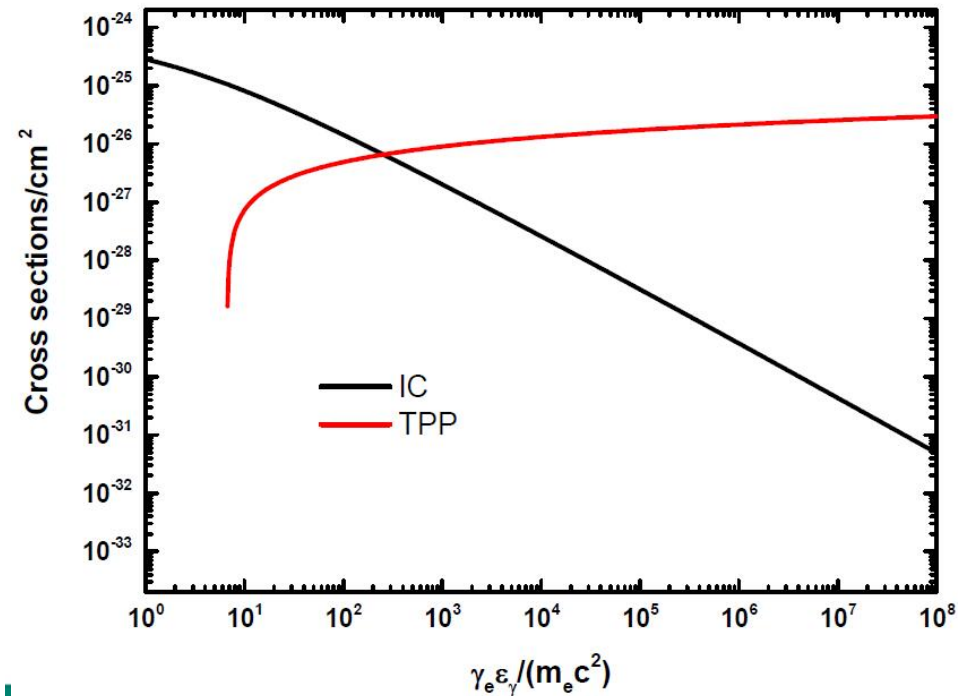
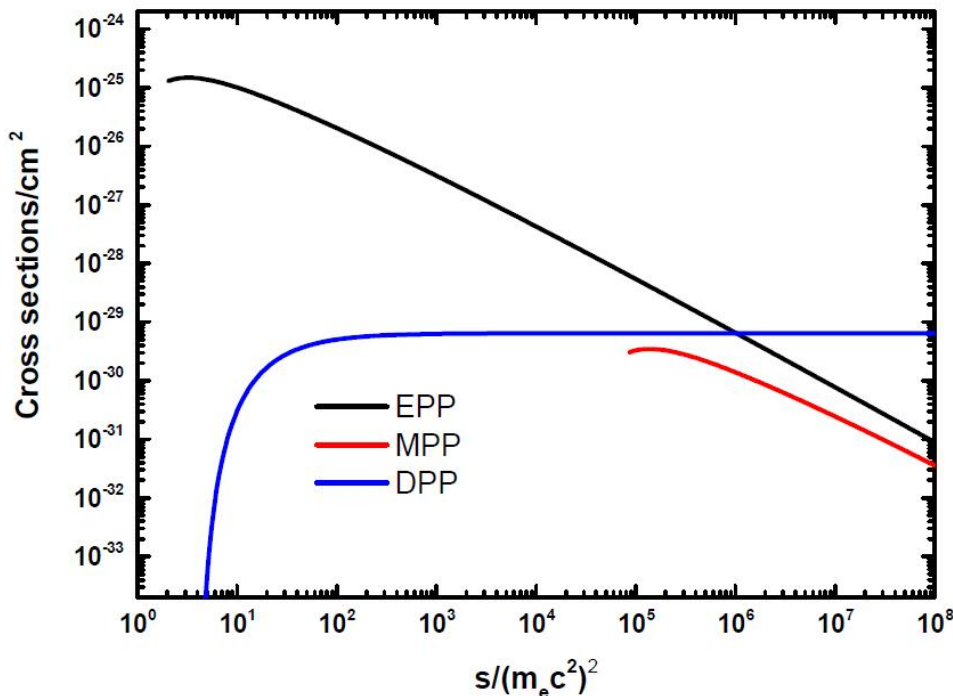
For UHE electrons:

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

Triplet production (TPP)

$$e + B \rightarrow e + \gamma$$

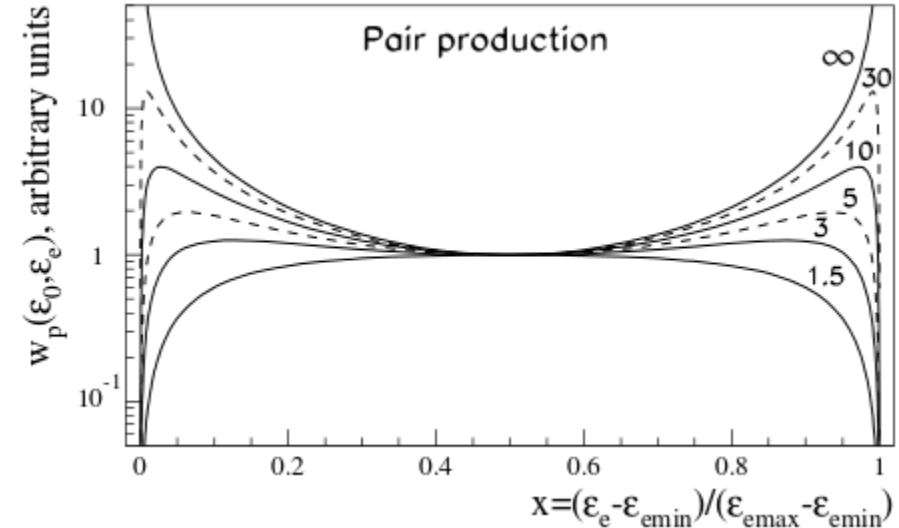
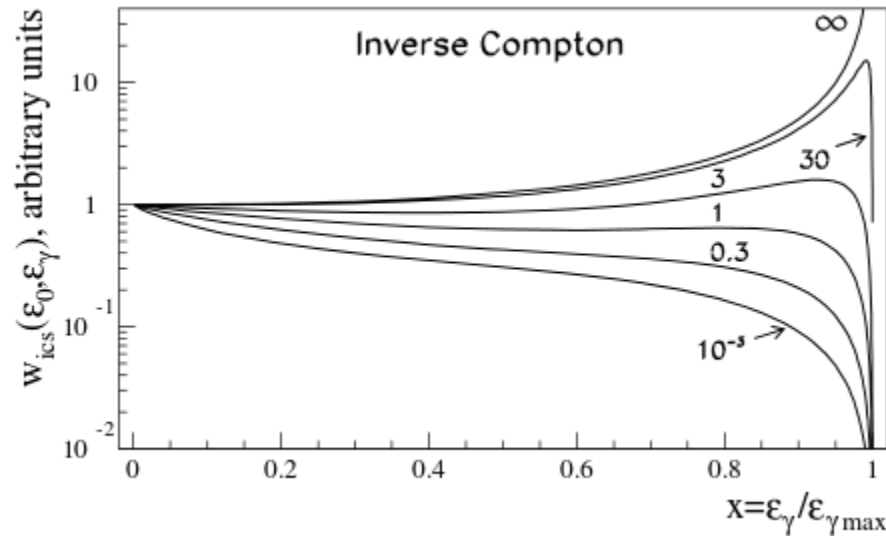
Synchrotron





Leading particle effect

In EPP and IC process, when the center-of-mass energy is very high interaction take places in deep Klein-Nishina regime

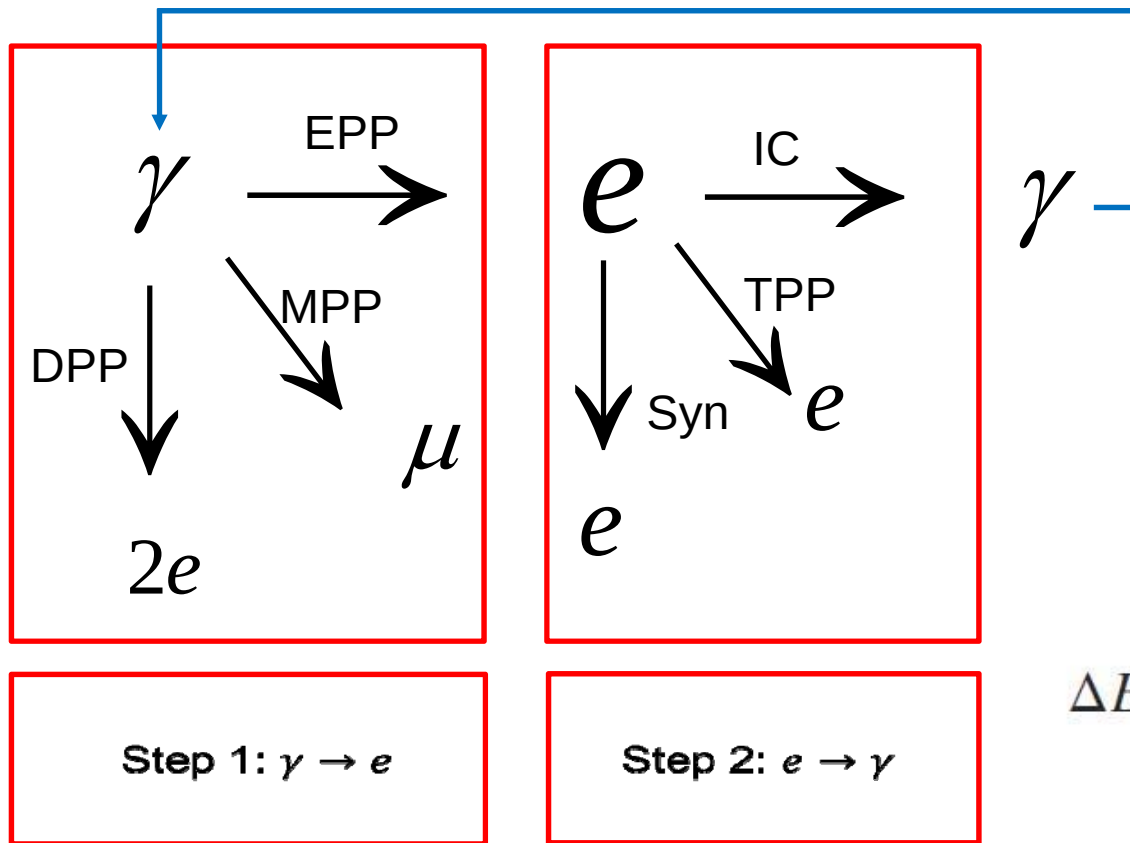


Aharonian & Plyasheshnikov 2003

one of the outgoing particle will take most of the energy of the incident particle



Regeneration of a new high-energy photon/electrons

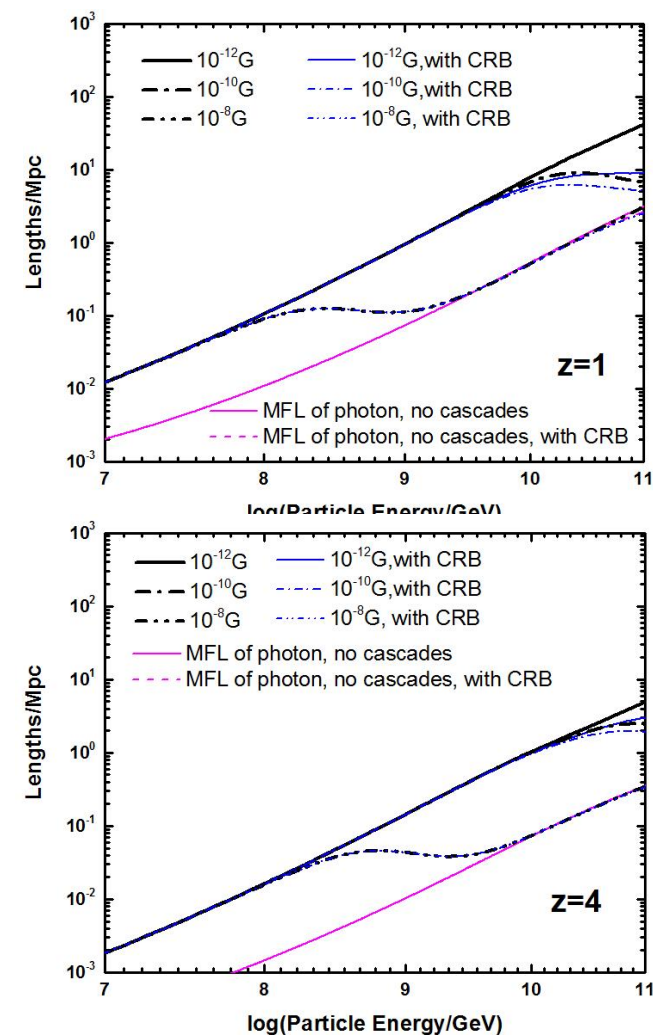
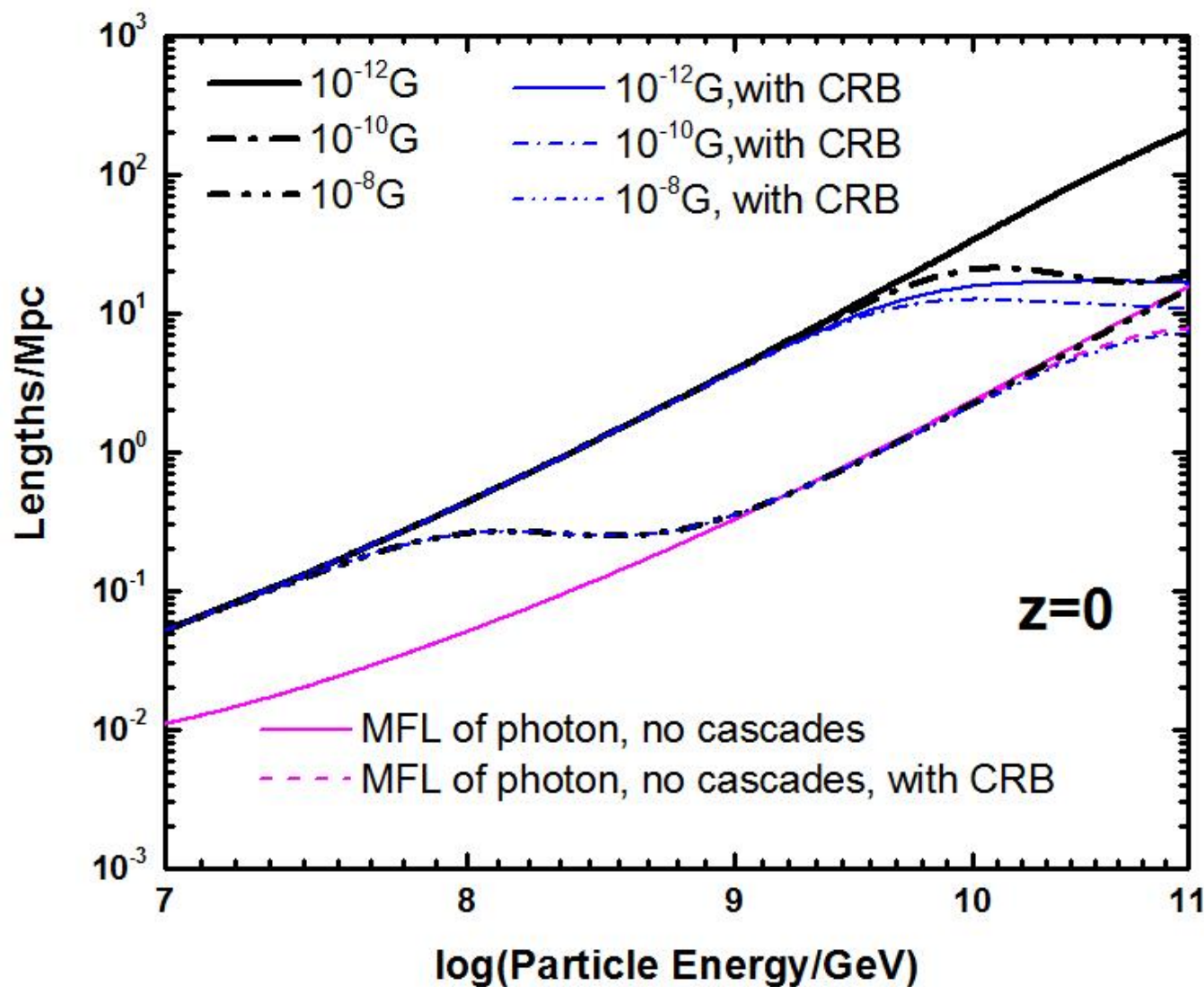


Energy loss in one cycle:

$$\Delta E_{\text{tot}} = t_1 \left(\frac{dE}{dt} \right)_{\gamma \rightarrow e} + y t_2 \left(\frac{dE'}{dt} \right)_{e \rightarrow \gamma},$$

Effective attenuation length:

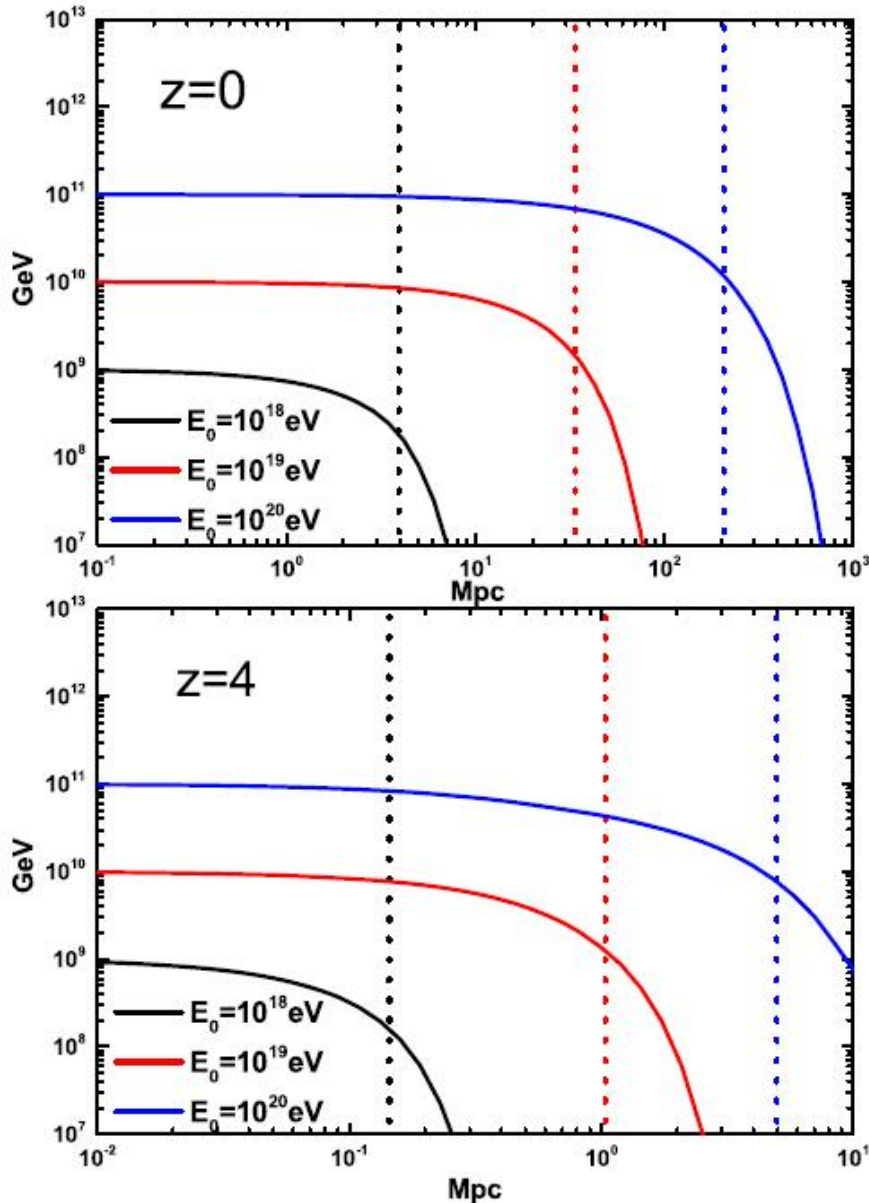
$$\lambda_{\text{eff}} = -cE / \langle dE/dt \rangle_{\text{tot}}.$$



Wang, Liu et al. 2017



Comparison with a simple Monte-Carlo Simulation



Comparison with previous numerical studies

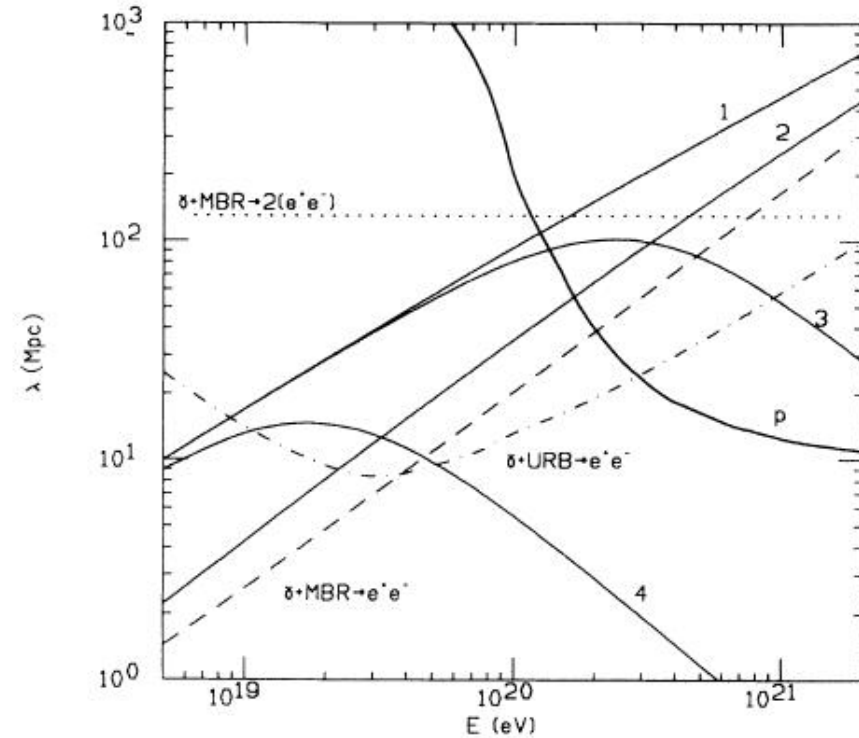
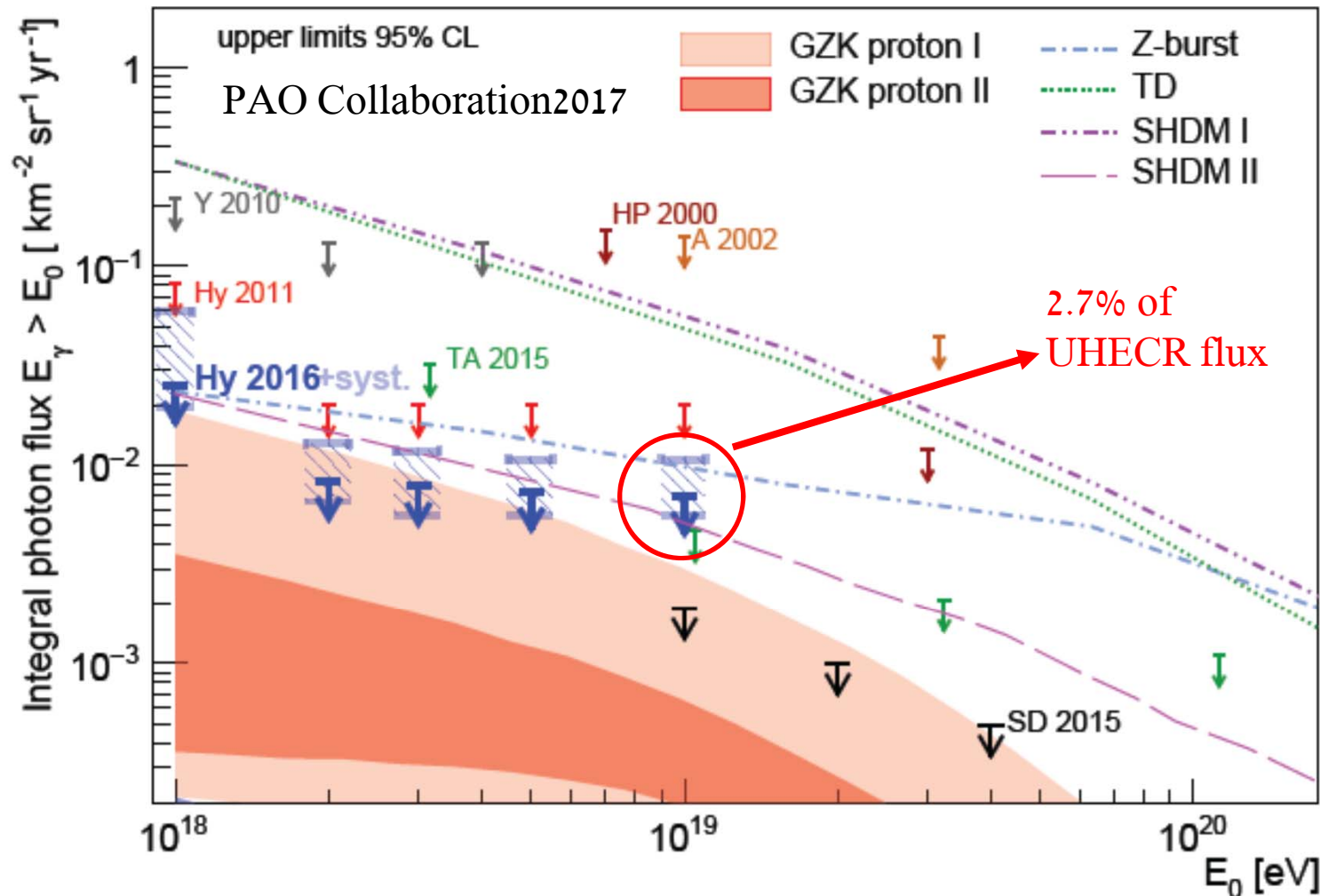


FIG. 2. The attenuation lengths of γ rays and protons in the intergalactic medium. The curve marked p is the attenuation length of protons in the MBR. The dashed and dot-dashed curves are the γ -ray absorption lengths due to single pair production in the MBR and URB fields, respectively. The dotted curve is the absorption length of γ rays in MBR due to double pair production. The curves marked 1, 2, 3 and 4 correspond to the effective penetration lengths of cascade γ rays obtained under different assumptions: (1) cascade in the MBR field only; (2) cascade in the MBR and URB ($w_{\text{URB}} = w_R$) fields; (3) and (4) cascade in the MBR, URB, and IMF fields for $B = 3 \times 10^{-11}$ and 10^{-10} G, respectively.

Aharonian et al. 1992



UHE photon detection probability

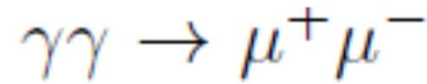


Assuming the same emissivity of the UHE photon and that of UHECRs
 the flux fraction of an UHE photon to UHECRs at Earth to be $\sim (10 \text{ Mpc}/1 \text{ Gpc}) = 1\%$,

MFP of a 10EeV photon MFP of a 10EeV proton



Neutrinos produced from the muon pair production of high-energy photons

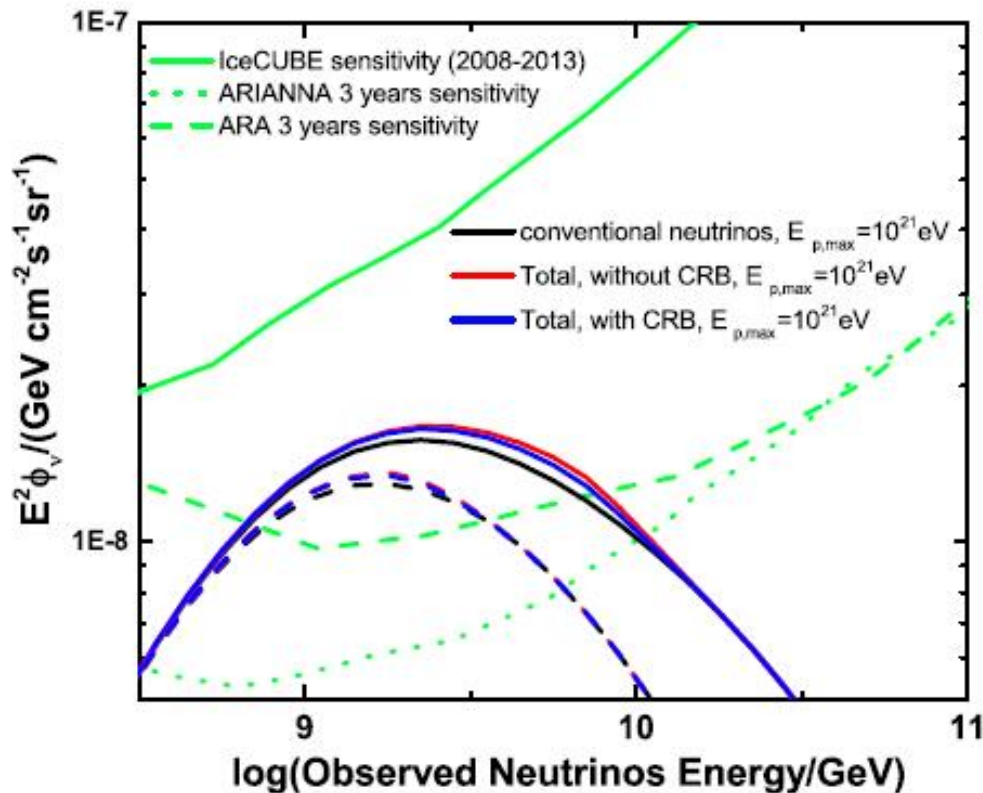


The ratio of the energy lost to the MPP channel to the total energy lost in one cycle

$$R = \frac{\Delta E_{mpp}}{\Delta E_{\text{tot}}} = \frac{(dE/dt)_{mpp}}{\langle dE/dt \rangle_{\text{tot}}} \frac{t_1}{t_1 + t_2}.$$

The average neutrino production rate

$$P_\nu = \frac{2}{3} \left(\frac{dE}{dt} \right)_{mpp} \frac{t_1}{t_1 + t_2},$$



If UHE photons originate from UHECRs

5-10% of the conventional cosmogenic neutrino flux

The fraction goes up to **~15%** in the case of weak IGMF and weak CRB

Without considering the regeneration of high-energy photon, at most **~5%** photon energy can go to muon pairs

Li & Waxman 2007



As the EM cascade developing....

Particle energy decrease, number of particle increases

forming a universal spectrum as long as the cascade fully has developed

$$Q_{\gamma}^{\text{cas}}(E) = \begin{cases} K(E/\varepsilon_X)^{-3/2} & \text{for } E \leq \varepsilon_X, \\ K(E/\varepsilon_X)^{-2} & \text{for } \varepsilon_X \leq E \leq \varepsilon_a \end{cases}$$

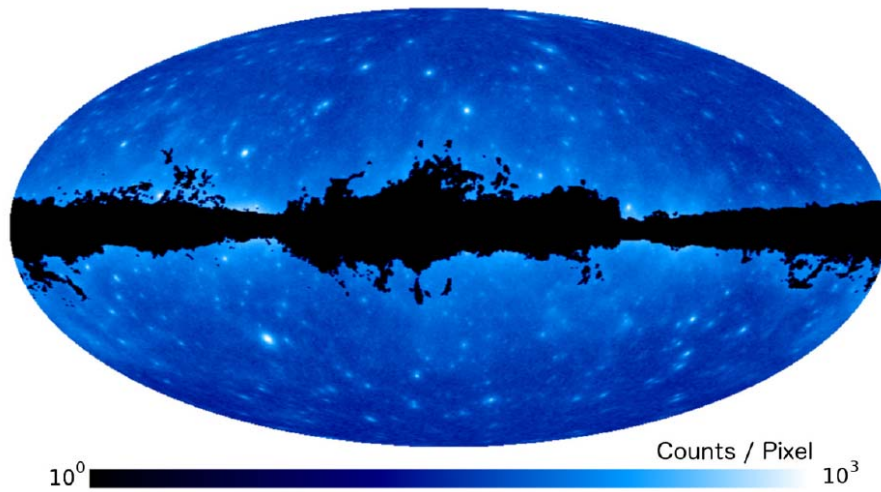
$$\varepsilon_a \approx 100\text{GeV} \quad \varepsilon_X \approx 10\text{MeV}$$

UHECR are injected isotropically

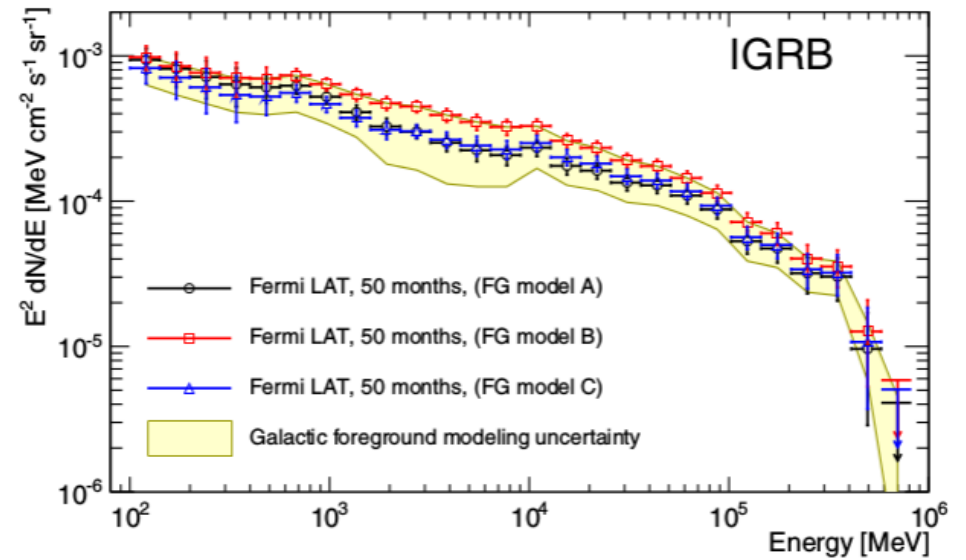


Isotropic gamma-ray background

Extragalactic Gamma-ray background (EGB)



>100MeV, 50 months (Fermi-LAT collaboration 2015a)



EGB = point source + truly diffusive emissions

Resolved
source

unresolved
source

=

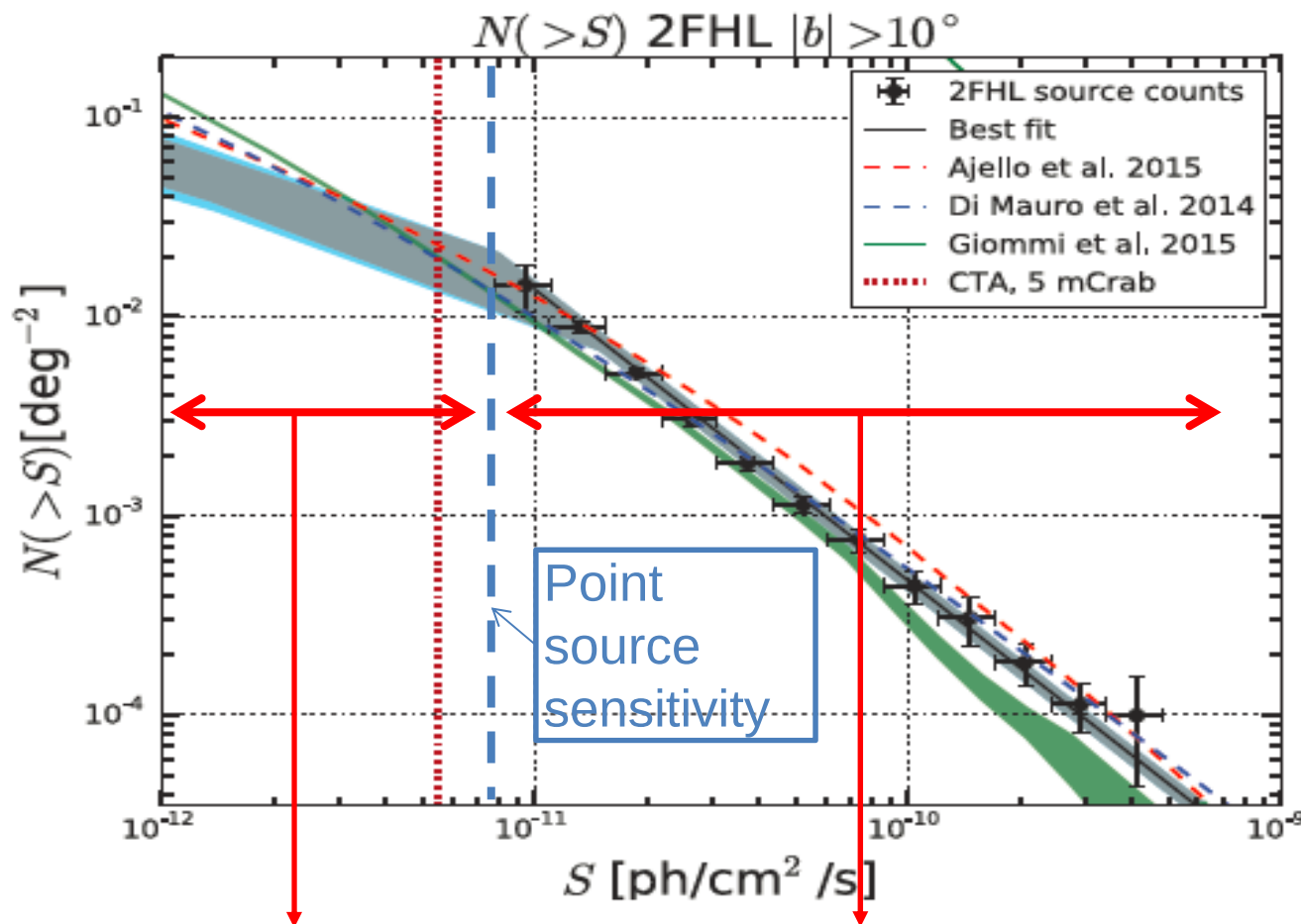
**Isotropic Gamma
Ray Background**



A recent analysis by Fermi-LAT Collaboration shows that

$86^{+16}_{-14}\%$ of the EGB above 50GeV are from extragalactic point sources

source count distribution of 2FHL sources (Fermi-LAT Collaboration 2015b)



Truly diffusive
emission

||

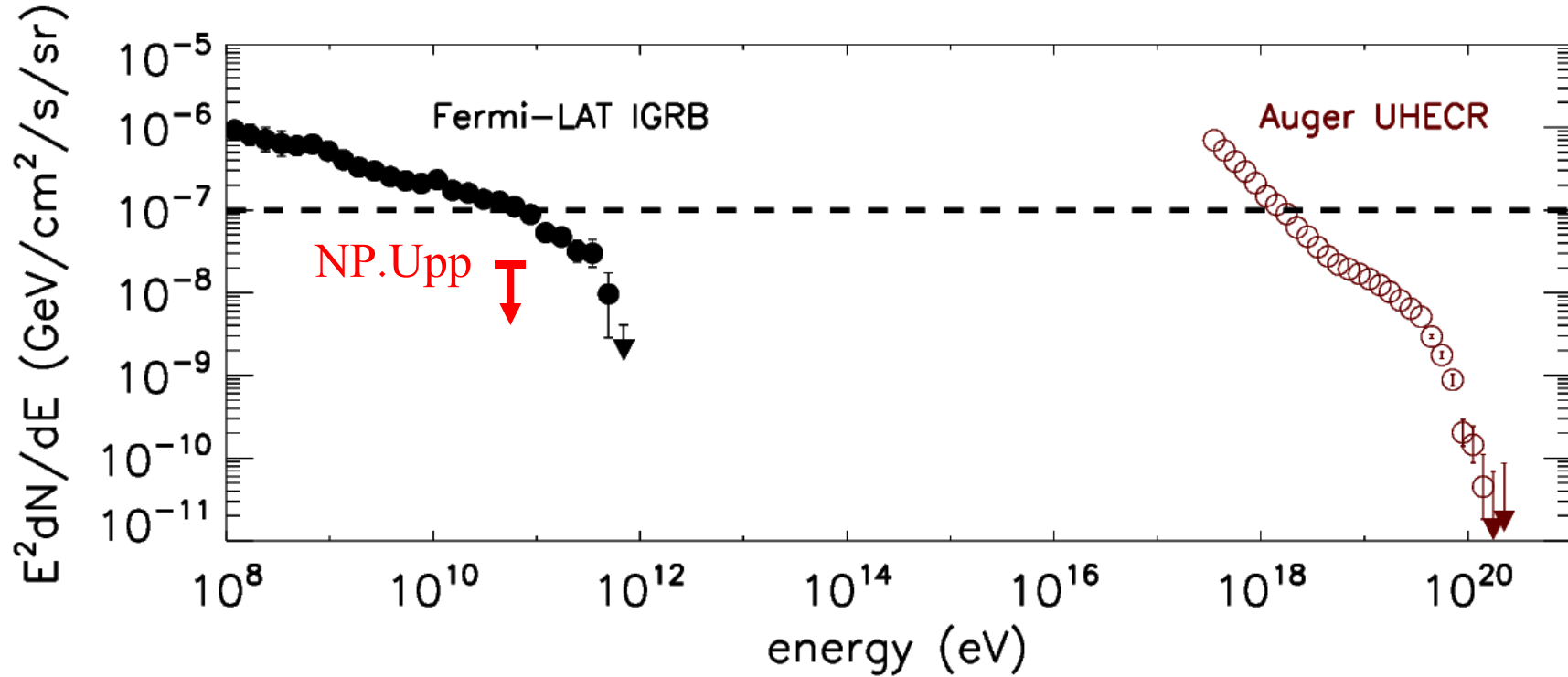
IGRB

|

Contribution from
unresolved sources

Unresolved source
contribute about 46%

Resolved source
contribute about 40%

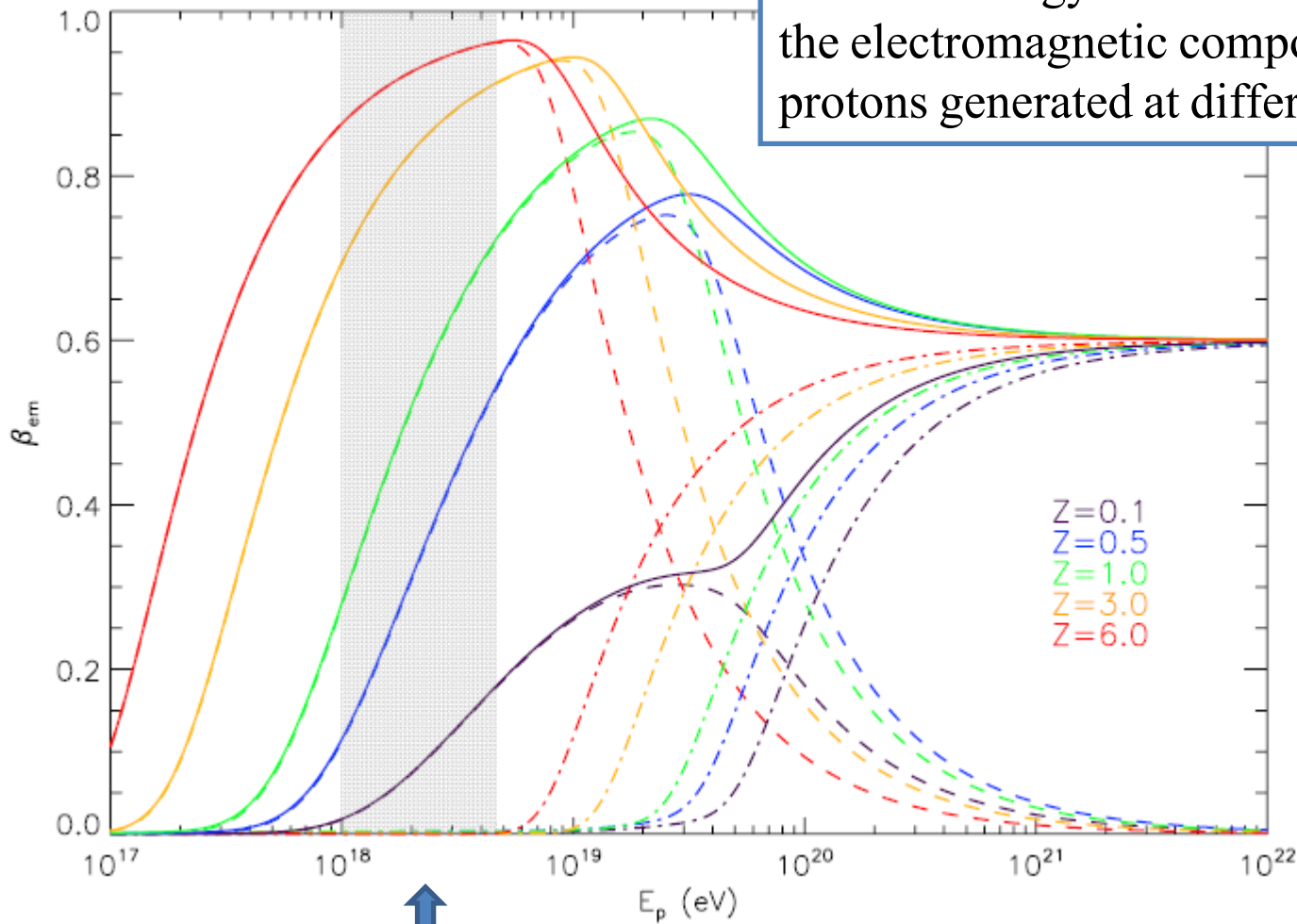


If the observed $\sim 10^{18}$ eV CRs have already been largely attenuated, they must have transferred lots of energies to gamma-ray background



CRs from higher z transfer more energy to cascades

Fraction energy loss of UHE protons into the electromagnetic component for protons generated at different redshifts.



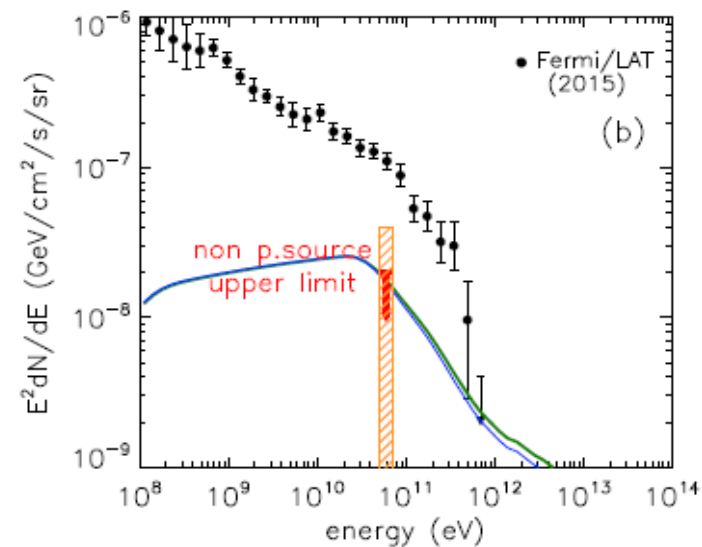
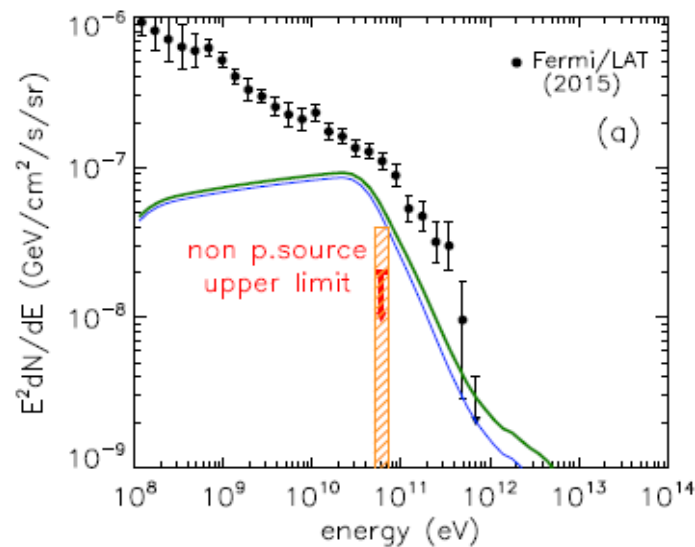
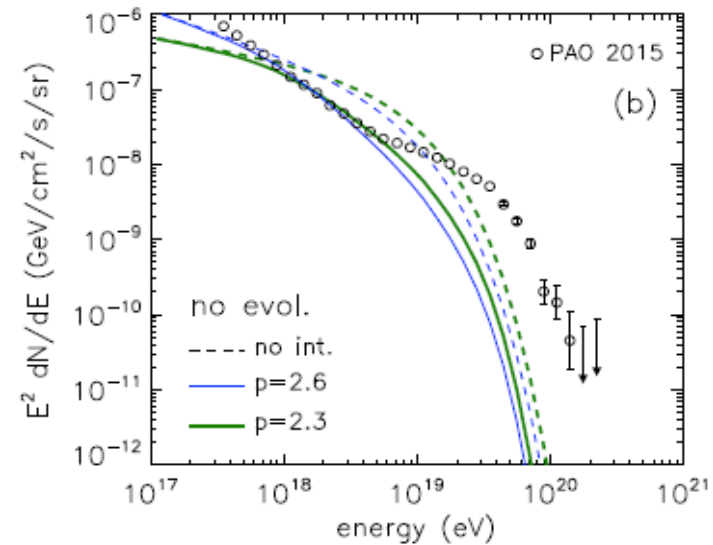
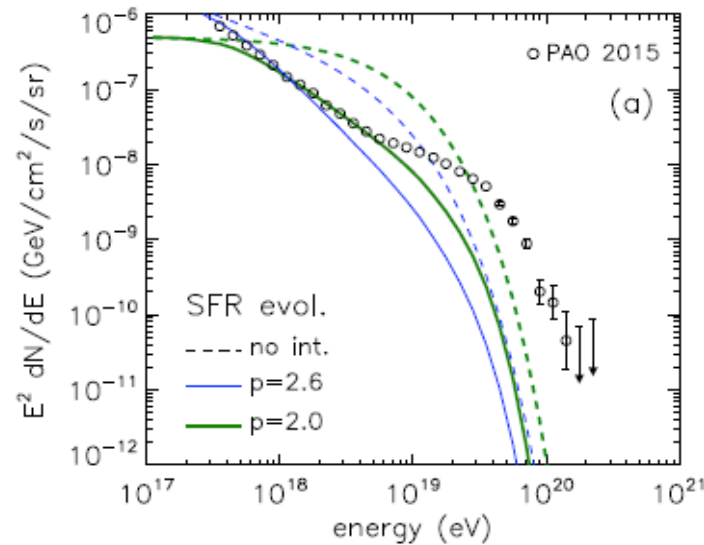
Energy range of interest
(1-4)EeV

Wang, Liu & Aharonian 2011



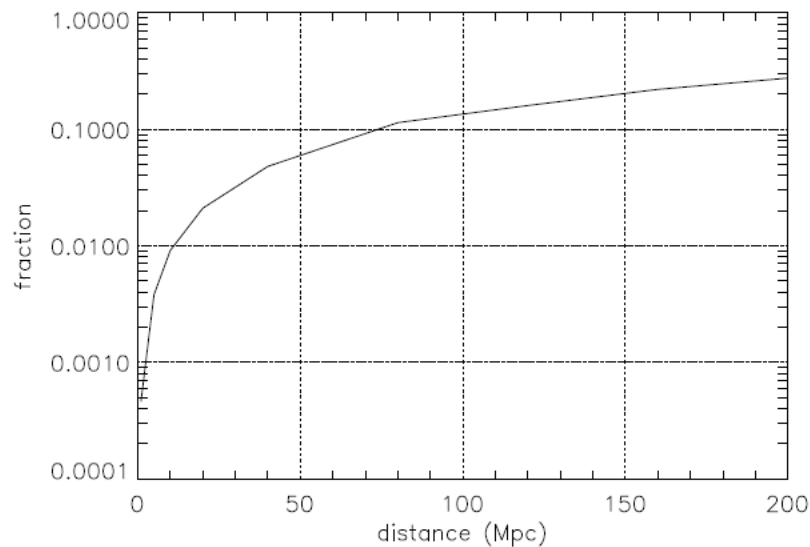
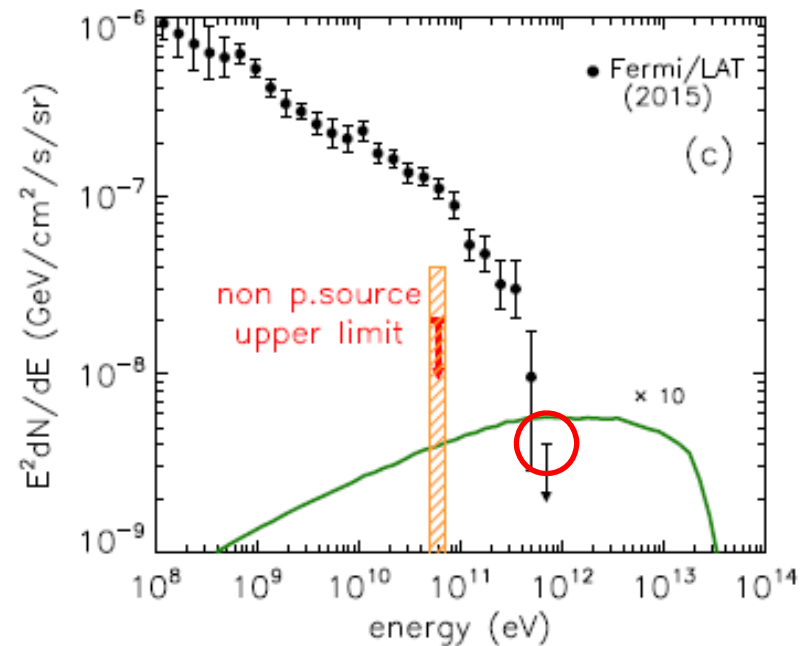
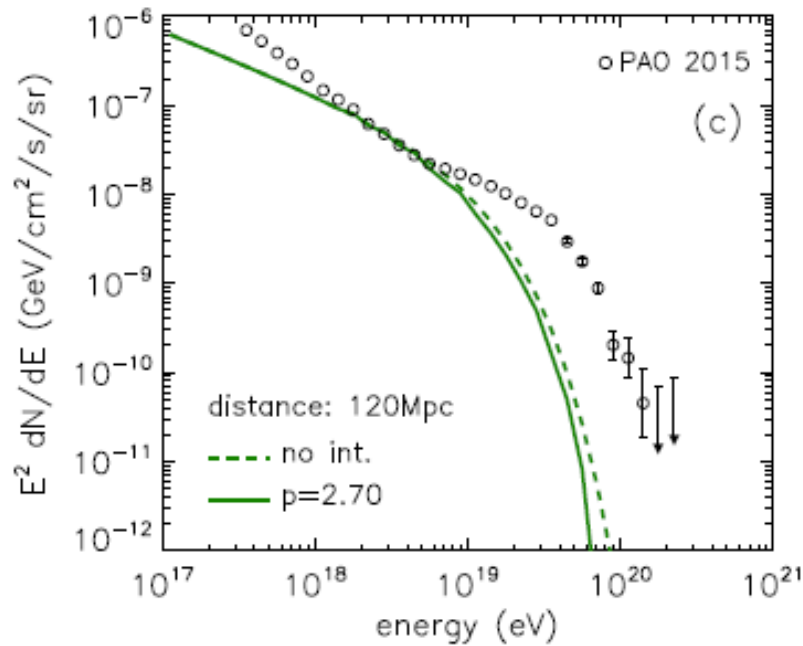
$$S_{\text{SFH}}(z) \propto \begin{cases} (1+z)^{3.4}, & z < 1 \\ (1+z)^{-0.3}, & 1 < z < 4 \\ (1+z)^{-3.5}, & z > 4. \end{cases}$$

$$S(z) = \text{Const.}$$





Local overdensity of the EeV CR sources is required!



Source distance v.s. fraction of IGRB upper limit at 820GeV induced by UHECR propagation



If UHECRs are mainly from local sources...

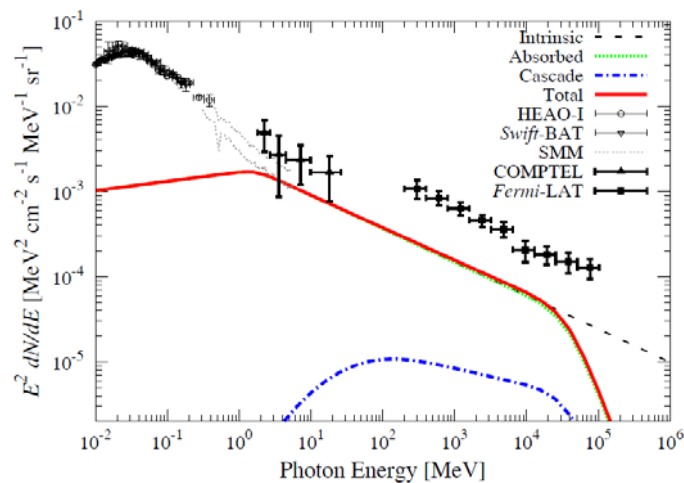
- low cosmogenic neutrino flux is expected
- a large cosmic ray Galactic halo ($\sim 100\text{kpc}$) may be required to avoid anisotropy
- Intergalactic magnetic field might also help isotropization
(but configuration of magnetic field should have feed back on the results)

Some uncertainties that be able to alleviate the tension

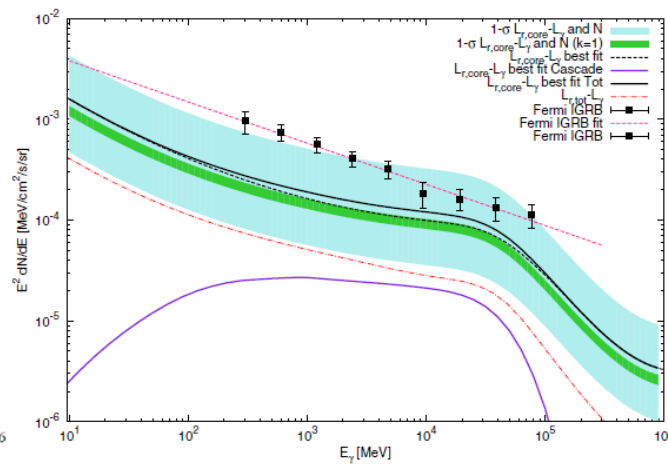
- Galactic gamma-ray foreground model
- EBL model
- Helium nuclei dominates $(1-4) \cdot 10^{18}\text{eV}$ CRs (Berezinsky et al. 2016)

There are other contributions to the measured IGRB... **tension is severer!**

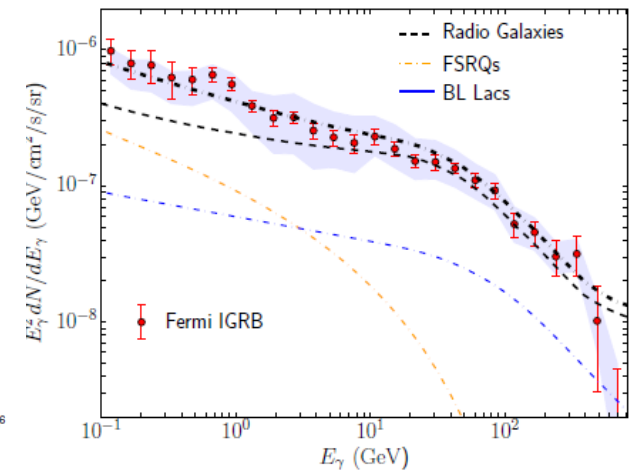
- UHECR above 4EeV and below 1EeV (we only consider 1-4 EeV)
- >100GeV intrinsic photons of ex-galactic sources
- Annihilating Dark Matter (?)
- Radio galaxies (misaligned AGN)



~50% of the unresolved EGB
(Inoue 2011)



at least 10% of IGRB
(Di Mauro et al. 2014)



~80% EGB
(Hooper et al. 2016)



Summary

- Leading particle effect can increase the attenuation length of UHE photon and electrons by about one order of magnitude
 - Increase the detection probability of UHE photon from nearby source
 - Give rise to an extra-component of cosmogenic neutrinos, given a proton composition of UHECRs
- Proton-induced cascade emission finally contribute to the isotropic gamma-ray background
 - resulting in a tension between data of isotropic gamma-ray background and the data of 10^{18}eV cosmic rays.
 - Local sources of 10^{18}eV CRs may be required to reconcile the tension.