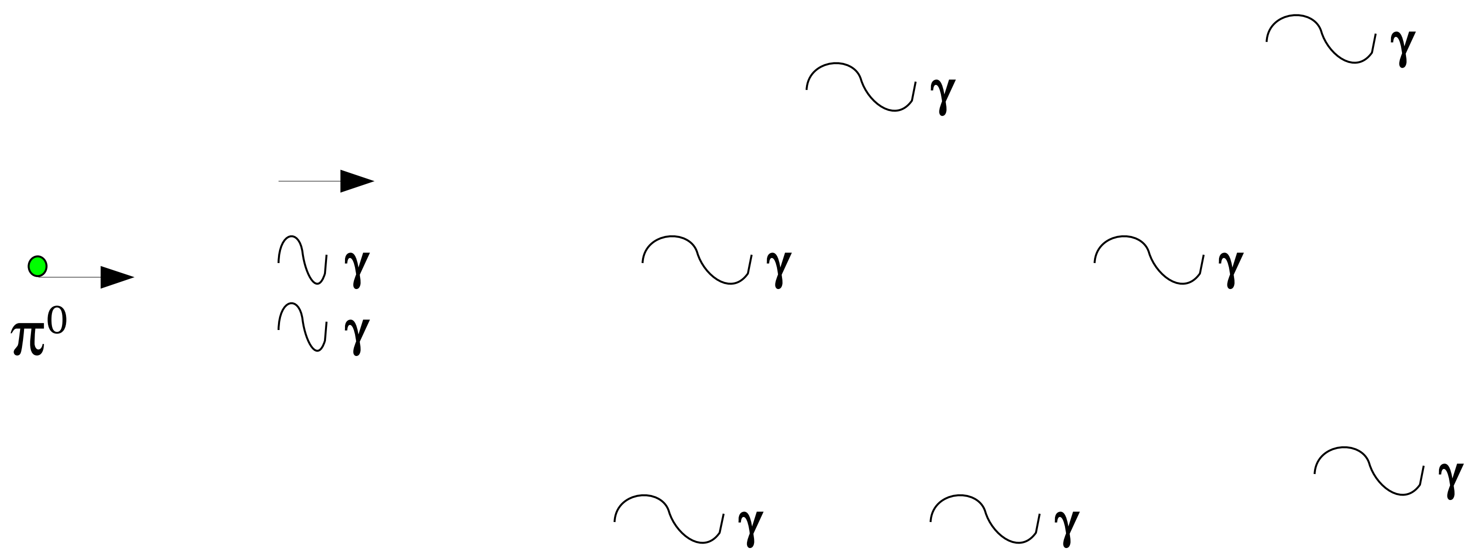
PHOTONS:High Energy Photon Flux Production and Propagation



Max-Planck-Institut für Kernphysik

Andrew Taylor

LECTURE PLAN:

1) COSMIC RAYS- proton interactions with photons, composition, nuclei interactions with photons, different photon targets

2) NEUTRINOS- presence of GZK-cutoff, photo-pion production mechanism, interaction rate, cosmic ray spectra, source distribution

3) PHOTONS- photon flux production, photon flux attenuation, competition of rates, e/γ cascades

4) MULTIMESSENGER APPROACH

Andrew Taylor

What **Percentage** of Cosmic Rays are Expected to be Photons? (>10^{18}eV)

Dan Hooper

Subir Sarkar

Paolo Coppi

Max-Planck-Institut für Kernphysik

Andrew Taylor

Aims

1) High Energy photon production through cosmic ray interactions

2) Difficulties for a high energy photon in the Universe

3) A comparison of proton and photon propagation through extragalactic space

4) The photon/proton ratio expected at Earth

5) What energy does the electron get?

6) What happens to the electron energy?

(5–6: EM Showers)

Max-Planck-Institut für Kernphysik

Andrew Taylor

1) Photon Production

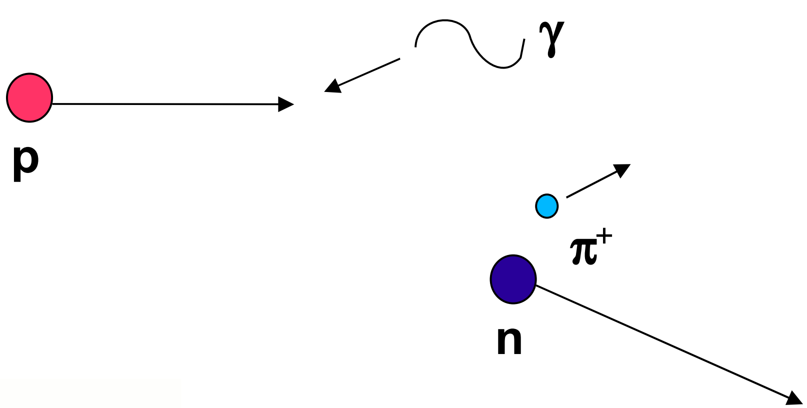
Max-Planck-Institut für Kernphysik

Andrew Taylor

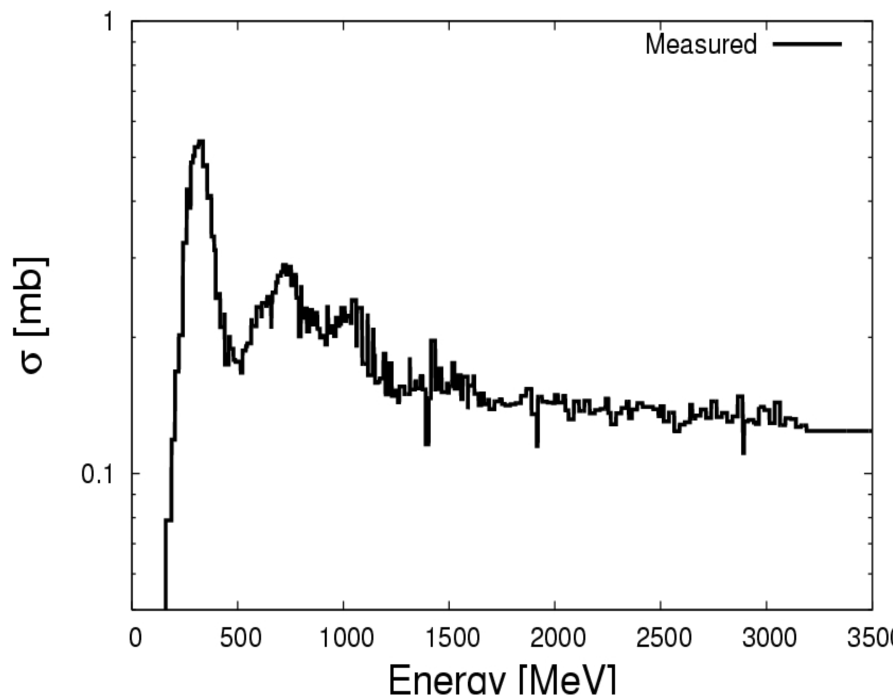
Why any Cosmic Rays should be Photons?

Charged Pion production interaction with CMB γ

For $E_{proton} > 10^{19.6}$ eV



(photon energy in proton frame)

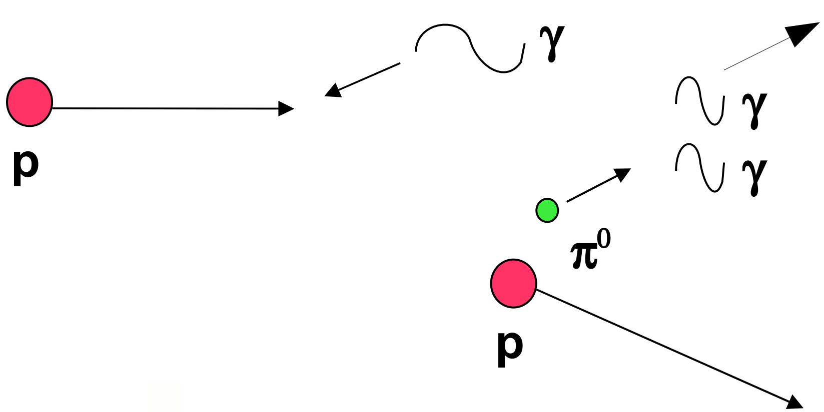


Max-Planck-Institut
für Kernphysik

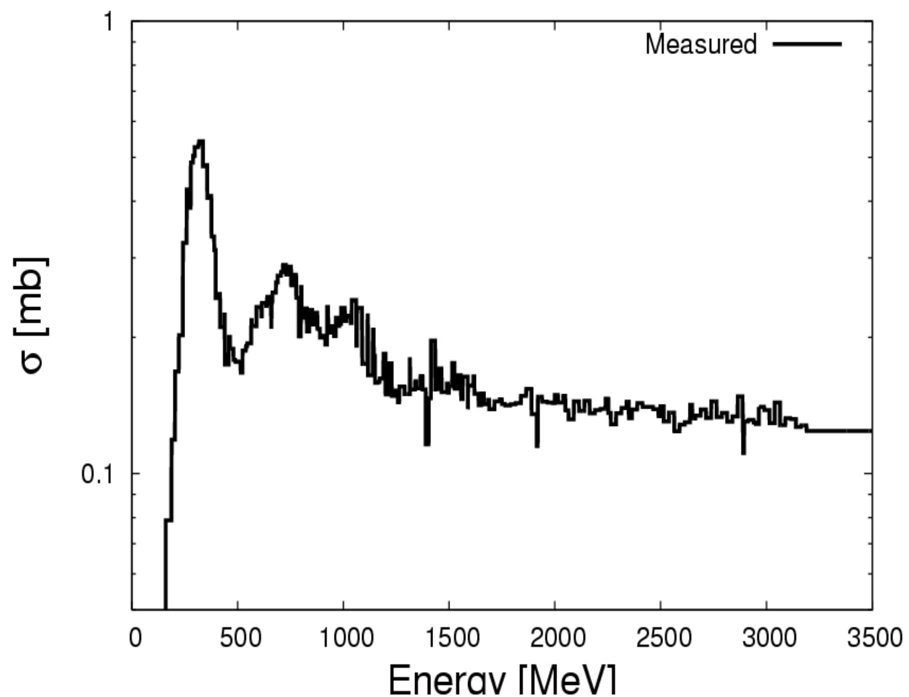
Why any Cosmic Rays should be Photons?

<u>Neutral Pion production interaction with CMB γ</u>

For $E_{proton} > 10^{19.6}$ eV



(photon energy in proton frame)

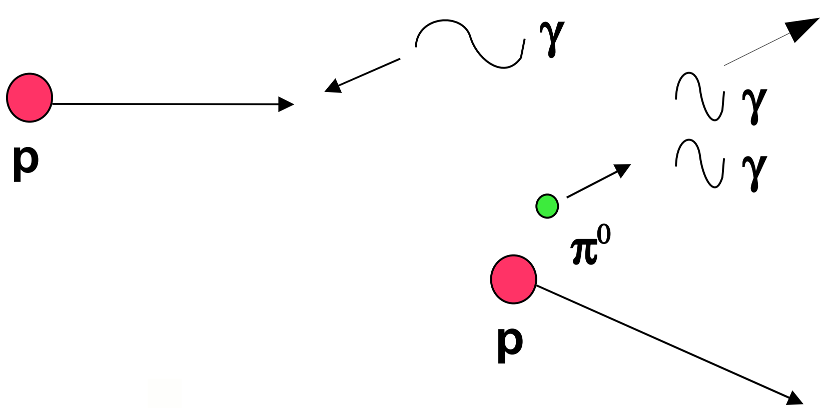


From isospin considerations for the Delta-resonance decay, neutral pions are twice as likely to be produced as charged pions

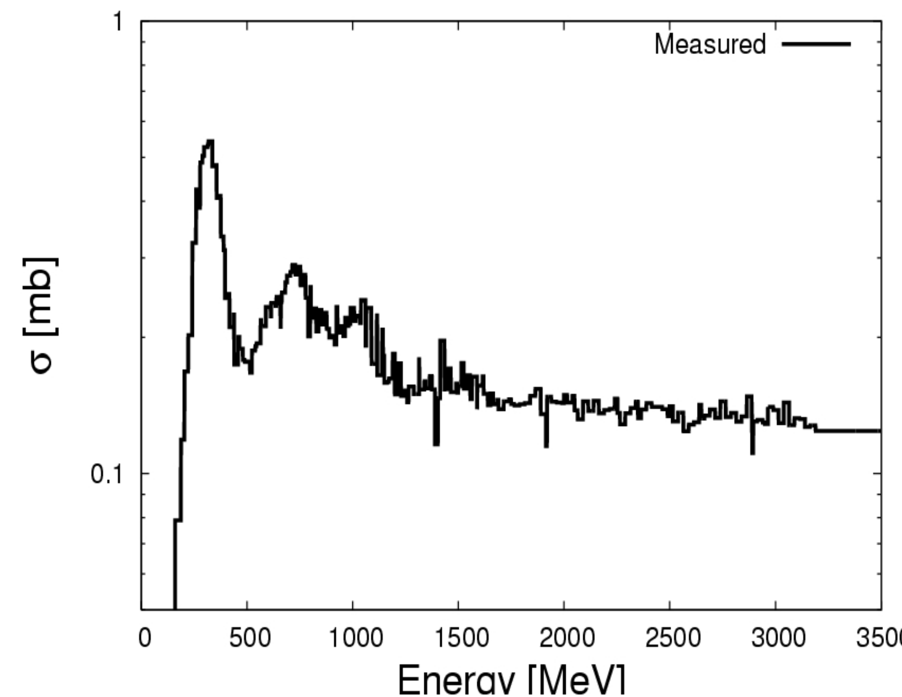
Why any Cosmic Rays should be Photons?

<u>Neutral Pion production interaction with CMB γ</u>

For $E_{proton} > 10^{19.6}$ eV



(photon energy in proton frame)



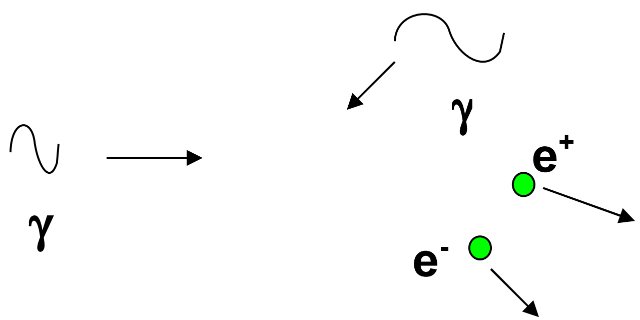
However, close to threshold, where direct pion production dominates, charged pion production is more likely

2) The Struggles of the Photon

Max-Planck-Institut für Kernphysik

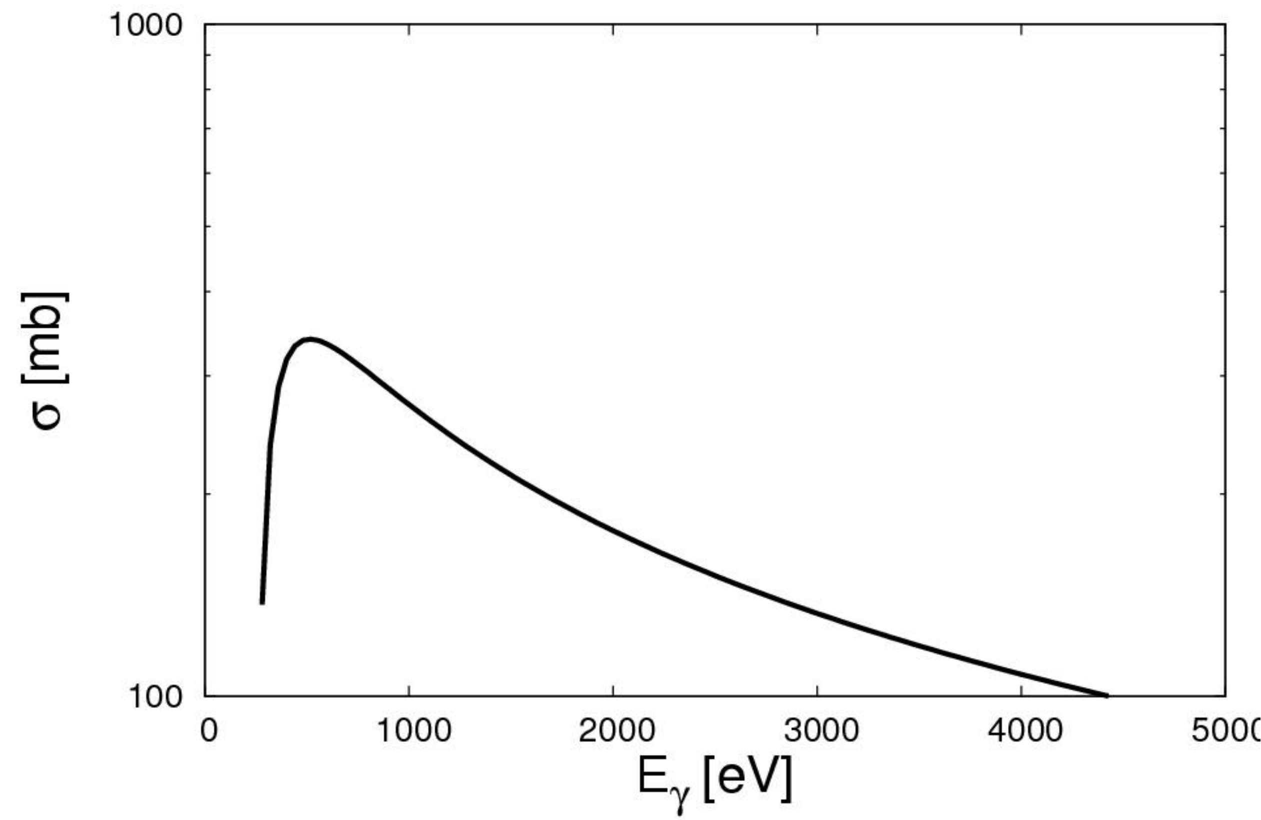
Andrew Taylor

Why aren't most Cosmic Rays Photons above $10^{19.6}$eV?



(and what happens to the electrons energy?)

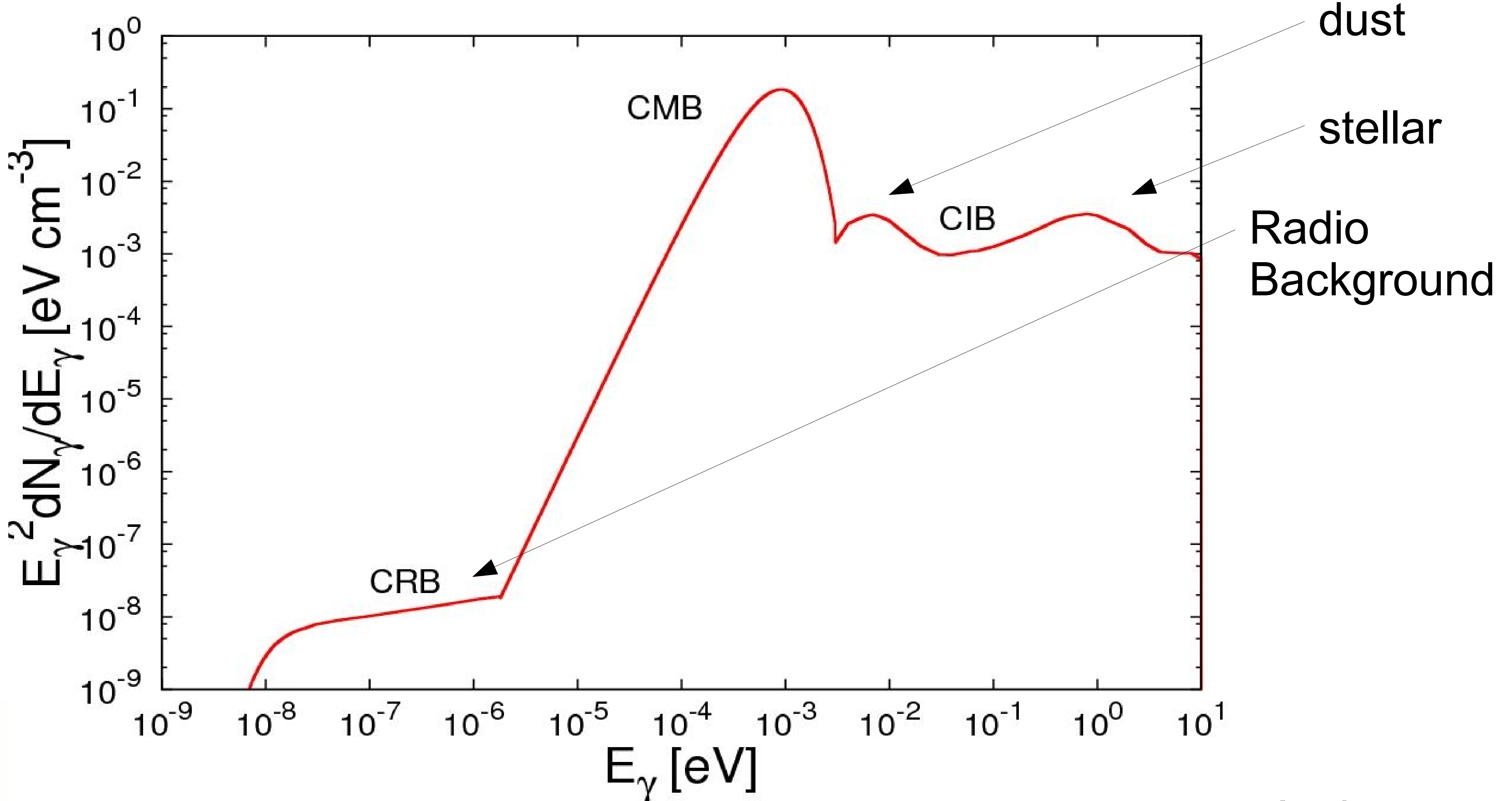
(photon energy in lab frame- for a GeV photon)



Max-Planck-Institut für Kernphysik

Uncertainties in the Radio Background

(the spanner in the works)

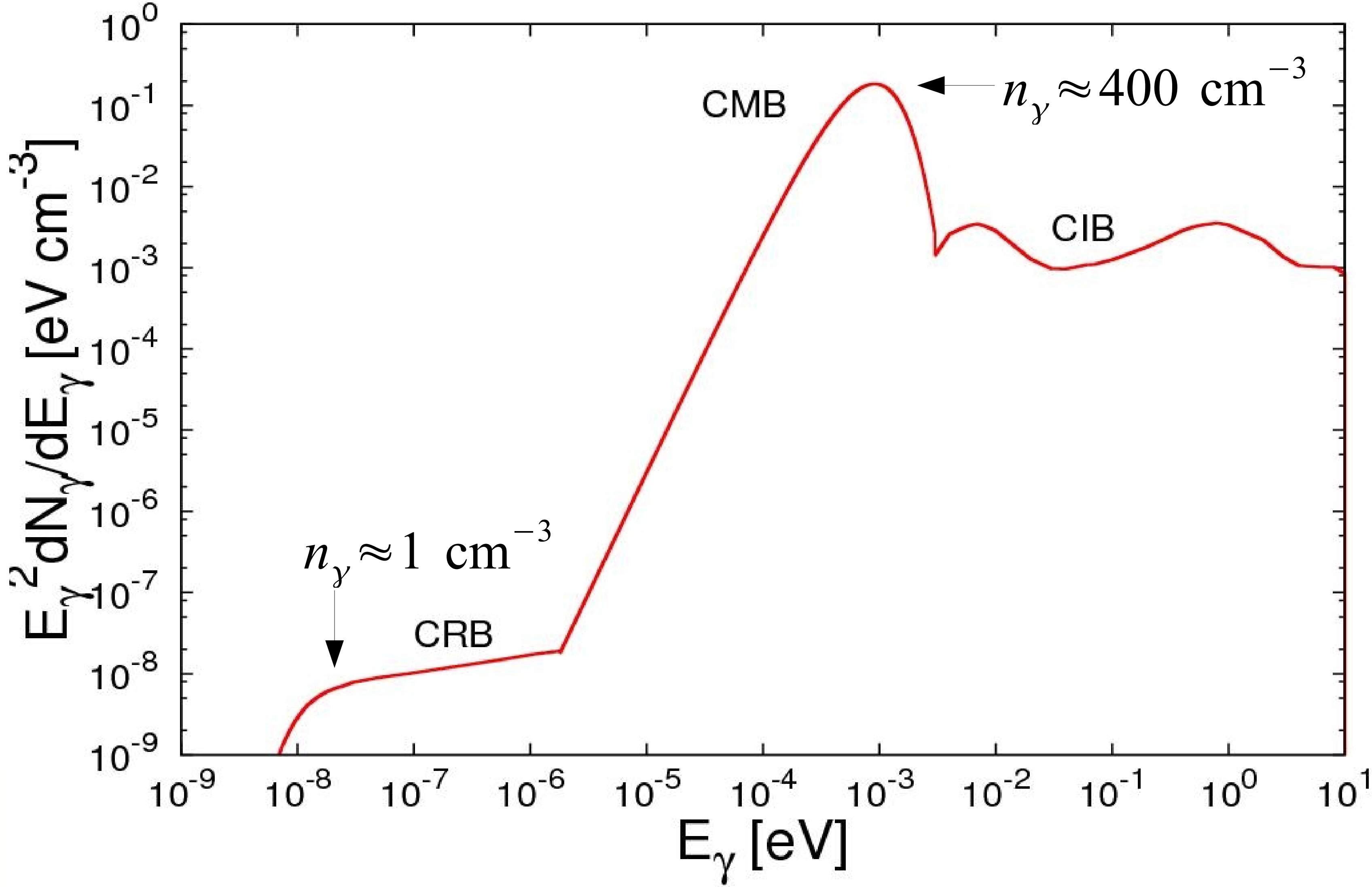


Max-Planck-Institut für Kernphysik

Andrew Taylor

Uncertainties in the Radio Background

(the spanner in the works)



Max-Planck-Institut für Kernphysik

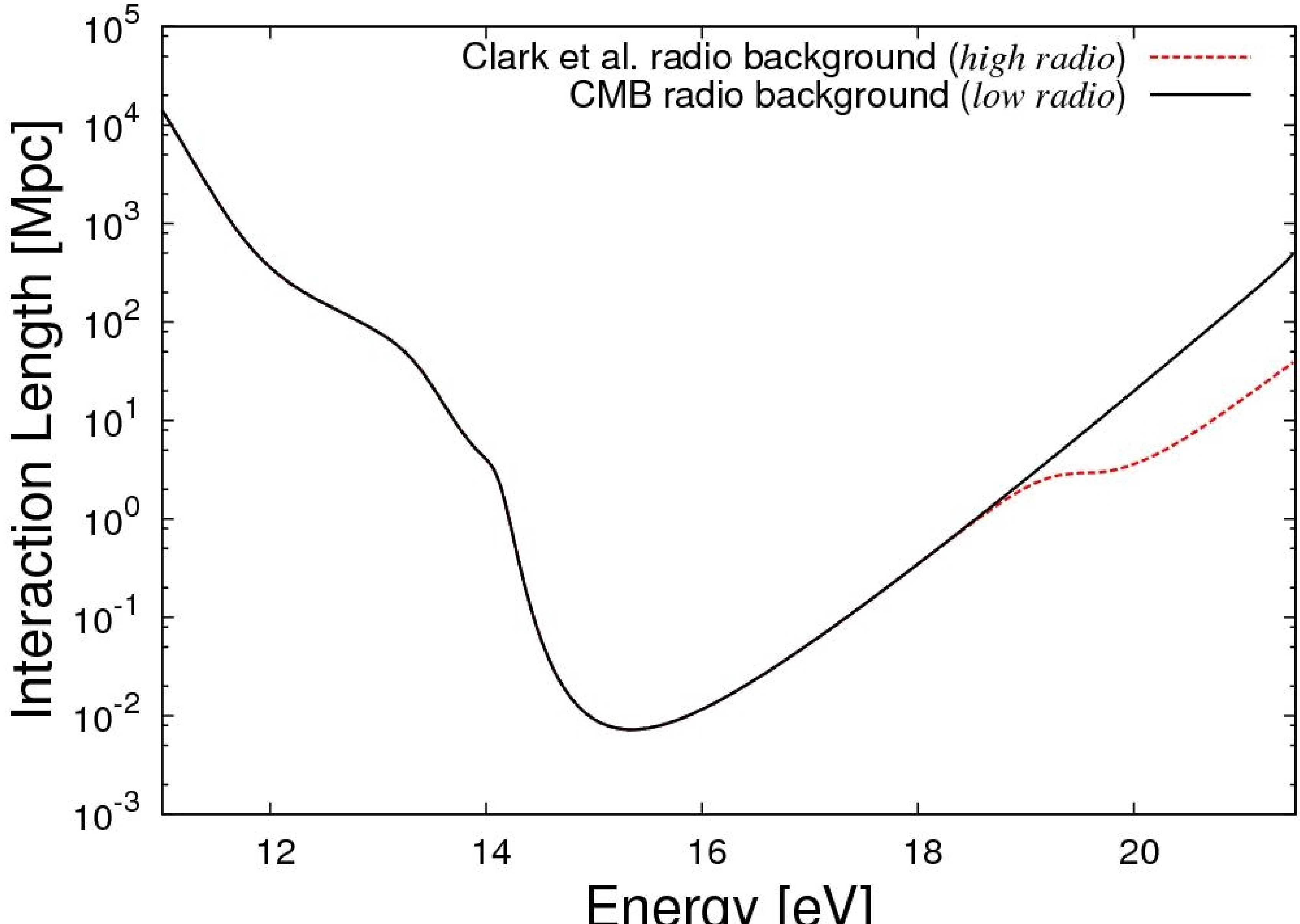
Andrew Taylor

3) Photon and Proton Attenuation Rates

Max-Planck-Institut für Kernphysik

Andrew Taylor

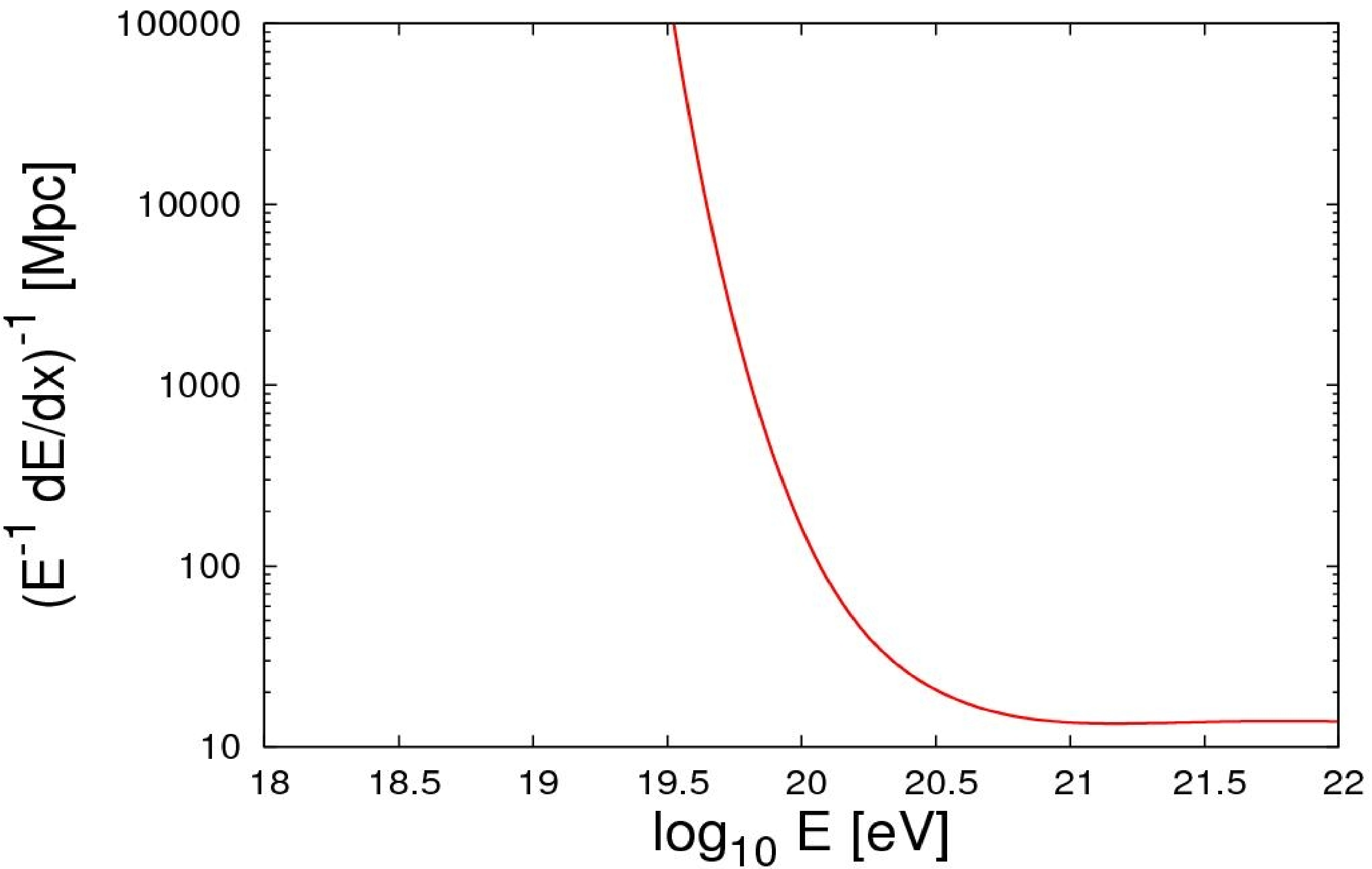
Photon (Cosmic Ray)- Photon (CMB) Interaction Lengths



Proton (Cosmic Ray)- Photon (CMB) Loss Lengths

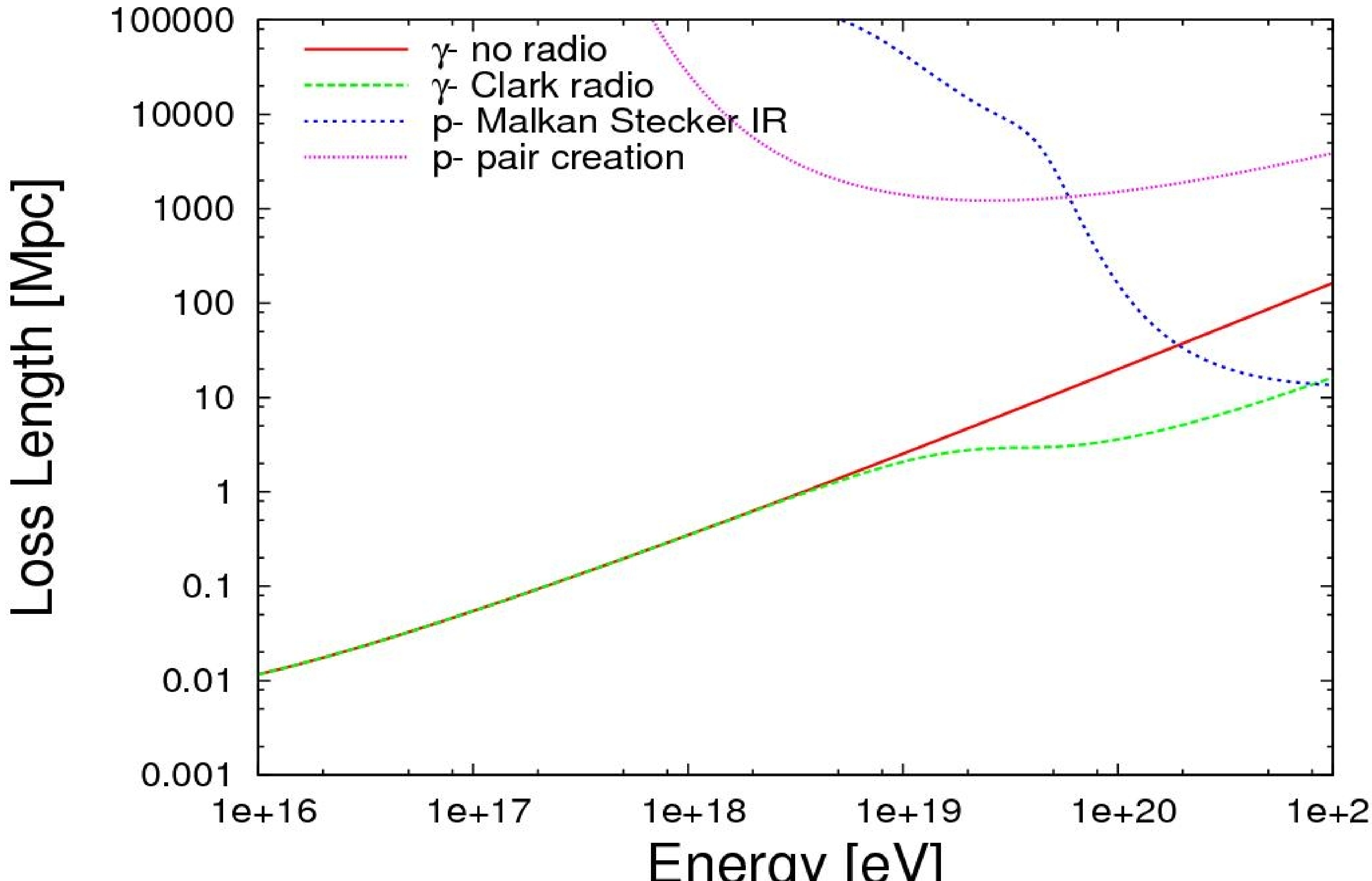
$$R = \frac{m_p^2 c^4}{2E^2} \int_0^\infty d\epsilon \, \frac{n(\epsilon)}{\epsilon^2} \int_0^{2E\epsilon/m_p c^2} d\epsilon' \, \epsilon' \sigma_{p\gamma}(\epsilon') K_p$$

(where R is the energy loss rate)



Max-Planck-Institut für Kernphysik

A Comparison of the Photon and Proton Loss Lengths



Max-Planck-Institut
für Kernphysik

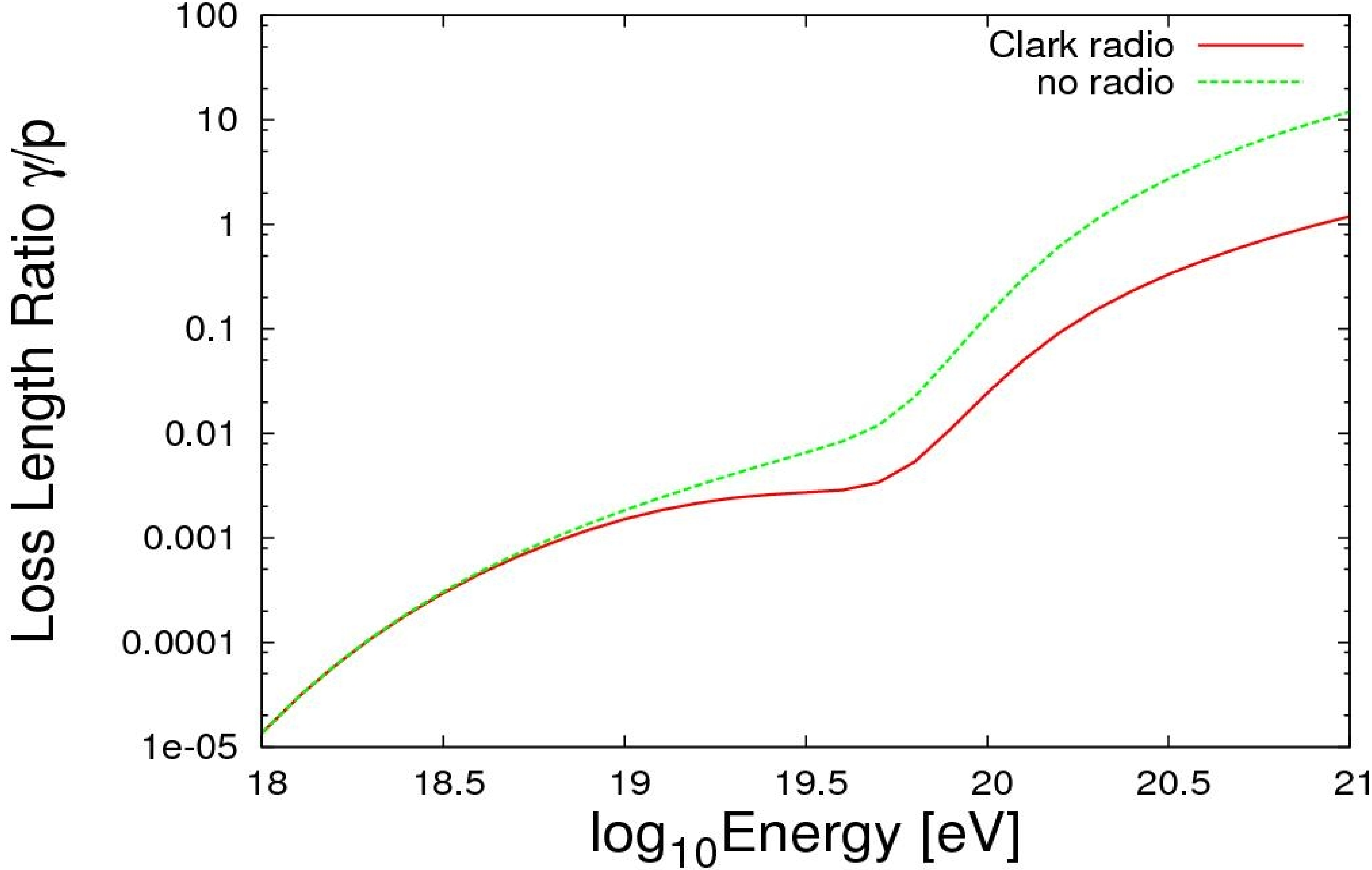
Andrew Taylor

4) The Photon/Proton Ratio at Earth

Max-Planck-Institut für Kernphysik

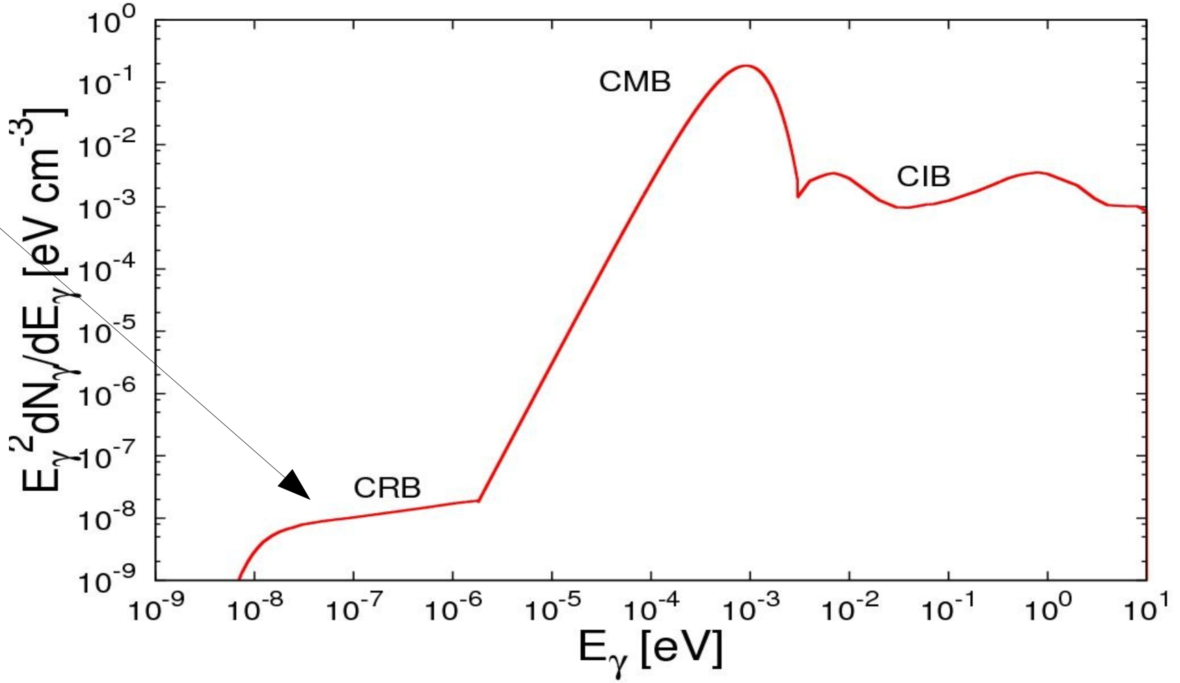
Andrew Taylor

The Photon/Proton Loss Length Ratio



Assuming.....

1) A large radio background
($U_B = 10^{-8}$ eV cm^{-3})

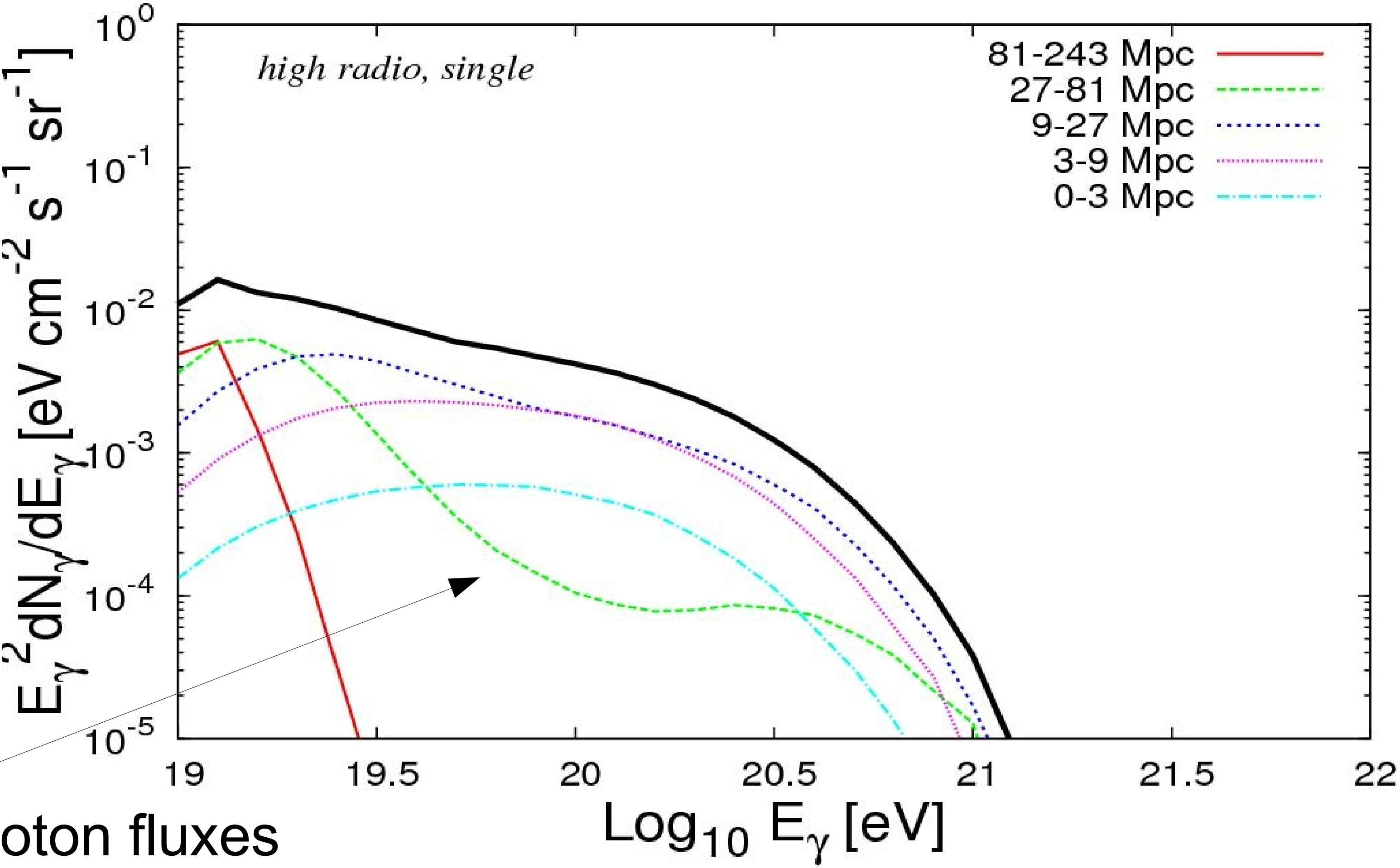


2) A single pair production interaction occurs **only**
(synchrotron losses dominate electron cooling)

3) A uniform distribution of the cosmic ray sources locally
(in the < 300 Mpc region)

Andrew
Taylor

The Photon Flux

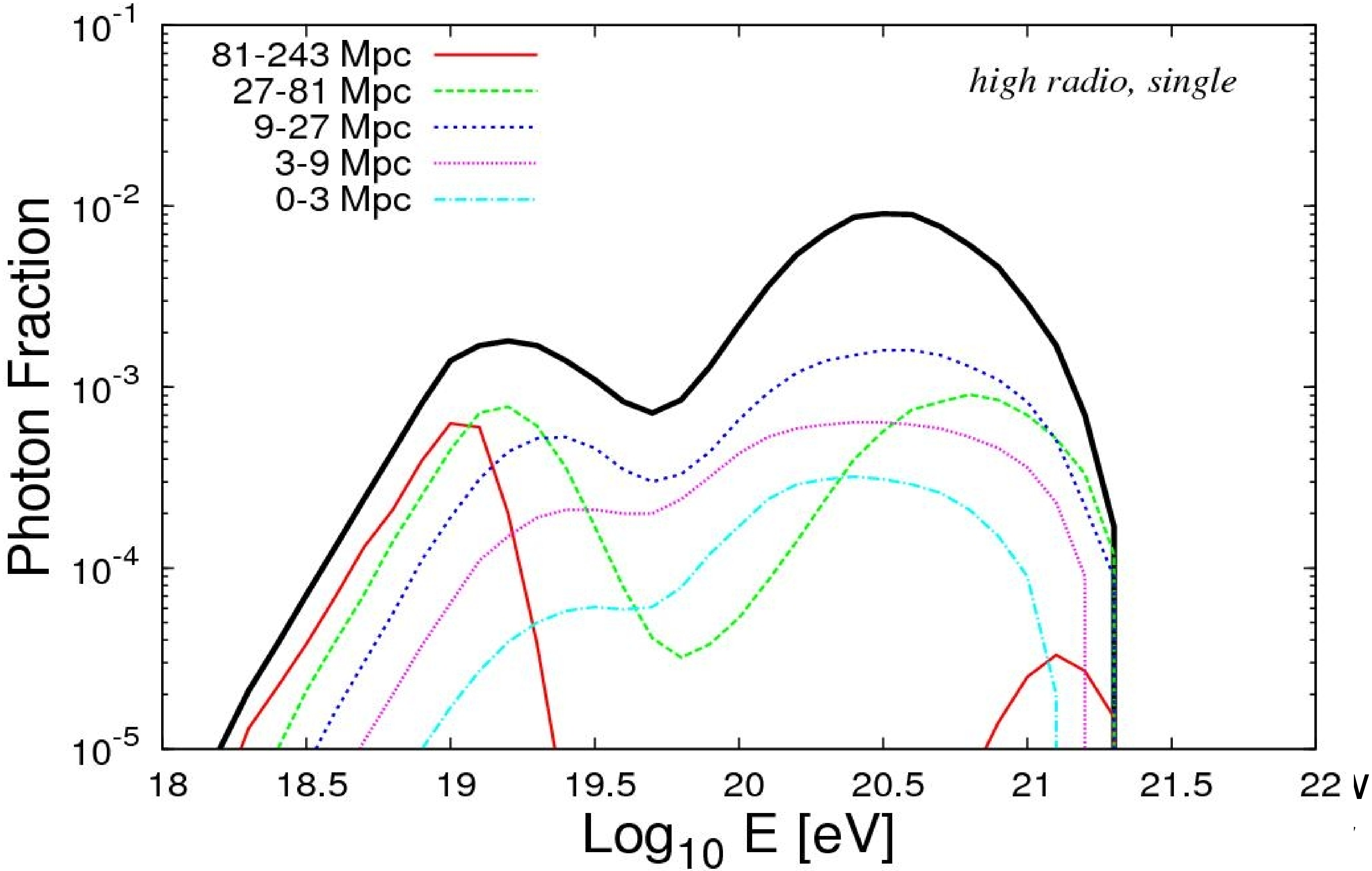


dip feature in photon fluxes from more distant shells

Max-Planck-Institut für Kernphysik

Andrew Taylor

The Photon Fraction

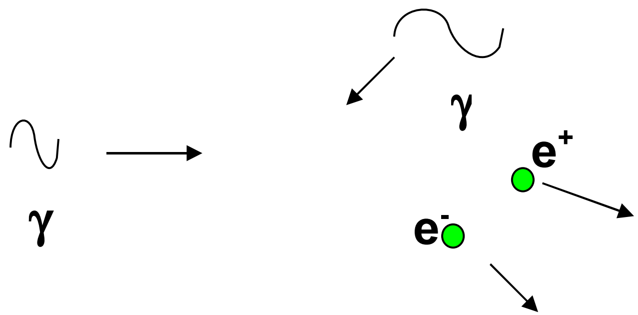


5) What energy does the electron get?

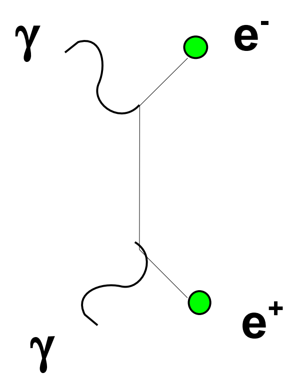
Max-Planck-Institut für Kernphysik

Andrew Taylor

Pair Production Physics



Pair Production:



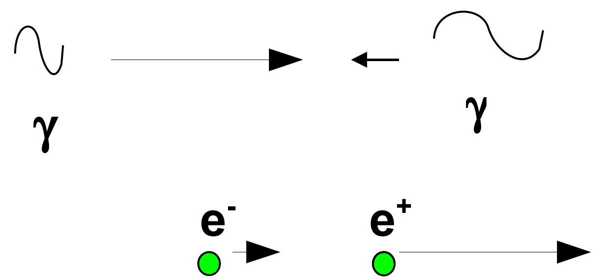
In center-of-mass frame, electron/positron pair are produced with equal energy

Max-Planck-Institut für Kernphysik

Andrew Taylor

Pair Production Physics (2)

But, boosting back from the center-of-mass frame to lab frame, one of the electron's tends to take nearly all the energy.



Let, $s = \frac{E_\gamma E_\gamma^{bg}}{(m_e c^2)^2}$ (the squared center-of-mass energy of the collision)

$$E_e = \Gamma(1+\beta) E_e^{cm} = \Gamma\sqrt{s} \longrightarrow E_e^{cm} = \frac{\sqrt{s}}{2}$$

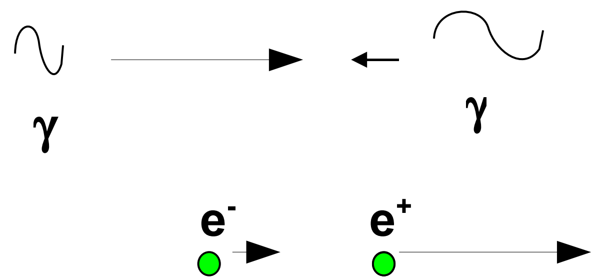
$$E_e = \Gamma(1-\beta) E_e^{cm} = \frac{\sqrt{s}}{2\Gamma}$$

Max-Planck-Institut für Kernphysik

Andrew Taylor

Pair Production Physics (2)

But, boosting back from the center-of-mass frame to lab frame, one of the electron's tends to take nearly all the energy.



Let, $$s = \frac{E_\gamma E_\gamma^{bg}}{(m_e c^2)^2}$$ (the squared center-of-mass energy of the collision)

$$E_e = \Gamma(1+\beta) E_e^{cm} = \Gamma\sqrt{s}$$

$$\Gamma \approx \frac{E_\gamma}{\sqrt{s}}$$

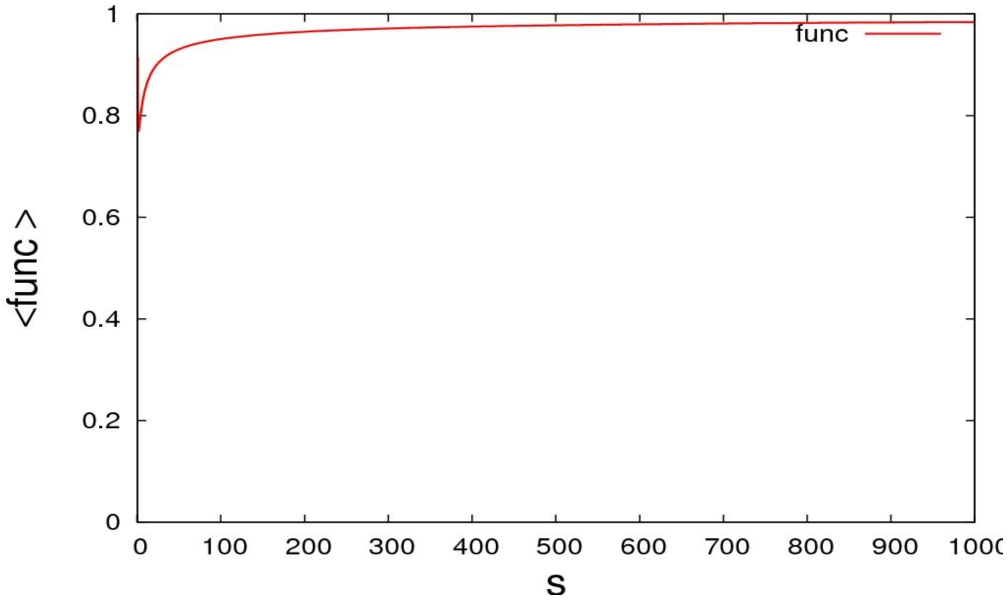
$$E_e = \Gamma(1-\beta) E_e^{cm} = \frac{\sqrt{s}}{2\Gamma}$$

Max-Planck-Institut für Kernphysik

Andrew Taylor

Pair Production Physics (3)

So, $$\frac{E_e}{E_\gamma} = \frac{4s - 1}{4s} f(s)$$



At large center-of-mass energies ("s"), one of the electrons produced via pair production carries most of the energy

Max-Planck-Institut für Kernphysik

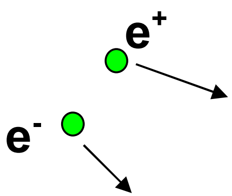
Andrew Taylor

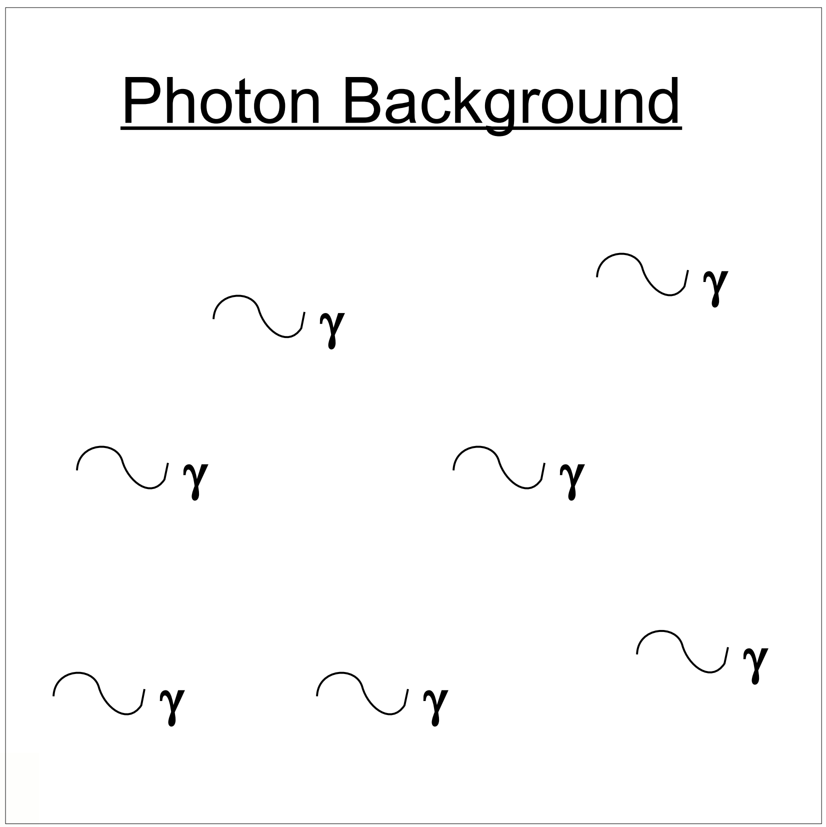
6) What happens to the electron energy?

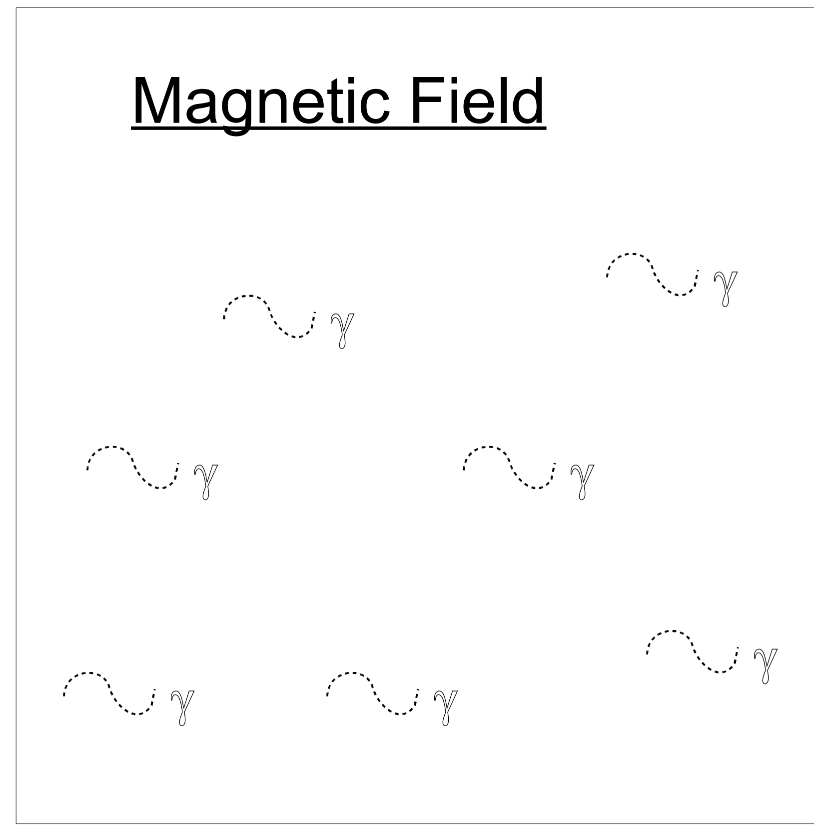
Max-Planck-Institut
für Kernphysik

Andrew
Taylor

What Happens to the Electron Energy?





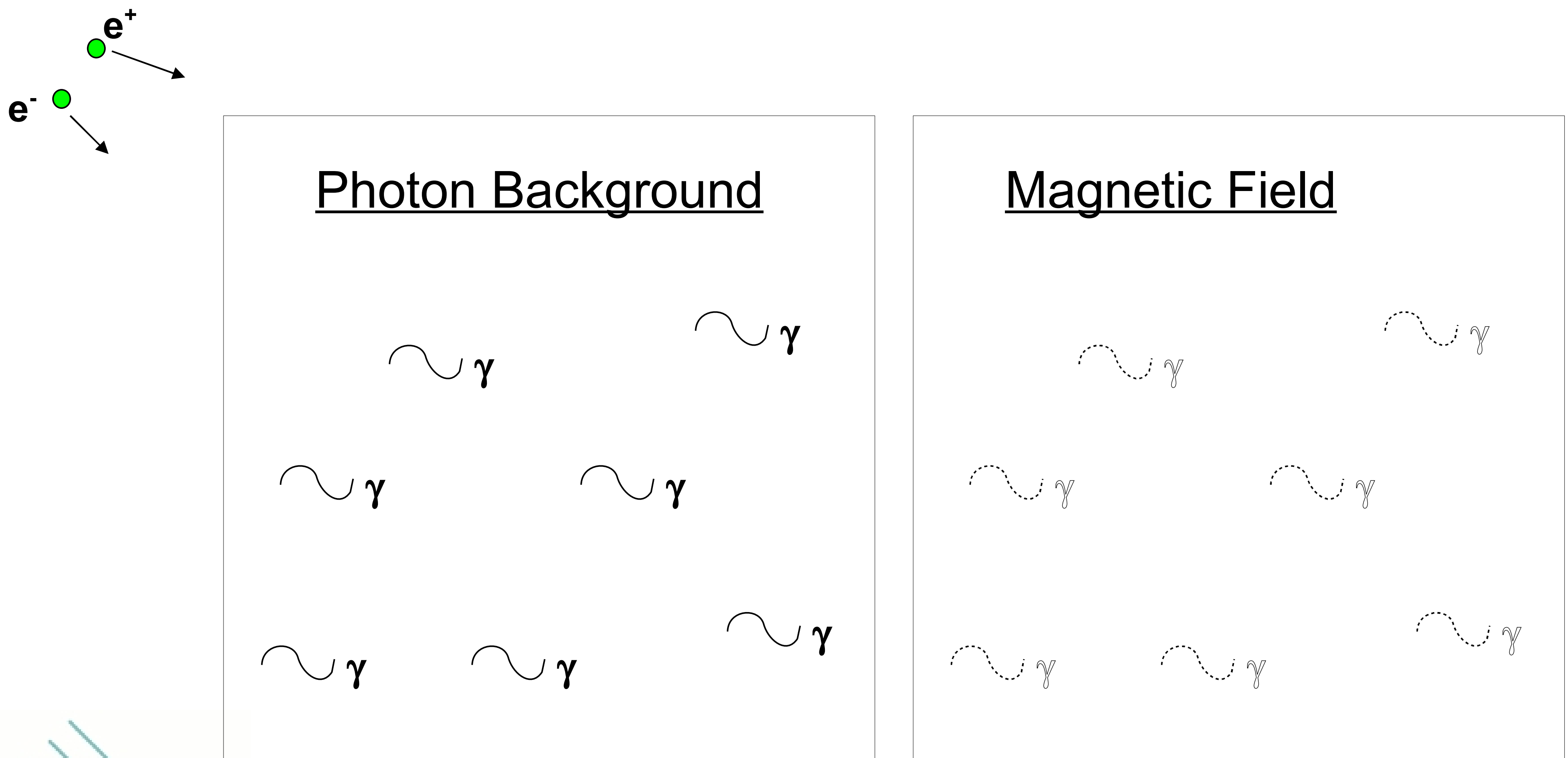


$$U_\gamma^{CMB} = 0.25 \quad \text{eV cm}^{-3}$$

$$U_B = 10^{-8} \quad \text{eV cm}^{-3}$$

Andrew Taylor

What Happens to the Electron Energy?



$$U_\gamma^{CMB} = 0.25 \;\; \text{eV cm}^{-3} \qquad U_B = 10^{-8} \;\; \text{eV cm}^{-3}$$

$$\longrightarrow \; B = 3 \times 10^{-10} \;\; \text{G}$$

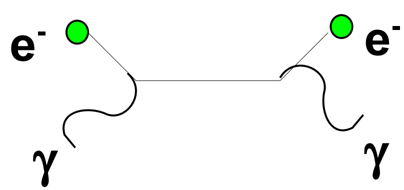
Max-Planck-Institut für Kernphysik

What Happens to the Electron Energy?

2 options for electron interactions:

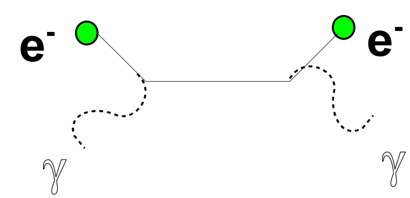
Photon Background

Inverse Compton Scattering:



Magnetic Field

Synchrotron:



Max-Planck-Institut für Kernphysik

Andrew Taylor

Competition of Processes

Both interactions are described by similar physics:

energy density of scattering field

If **Thomson** scattering → $$\frac{dE}{dt}=\frac{4}{3}\sigma_T \Gamma^2 U$$

Since $U_\gamma^{CMB}=0.25\ \text{eV cm}^{-3}$ $\quad$ $U_B=10^{-8}\ \text{eV cm}^{-3}$

Naively IC should win! ....but is the scattering in the **Thomson** regime?

Max-Planck-Institut für Kernphysik

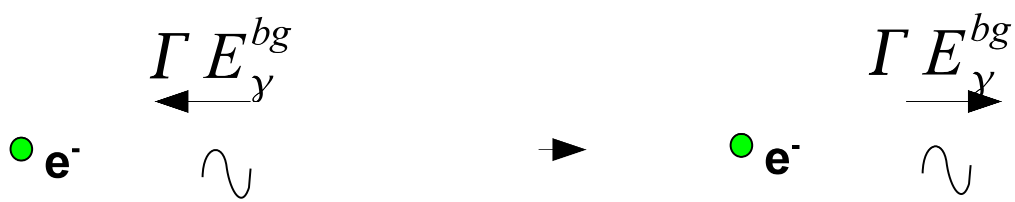
Andrew Taylor

Thomson Regime

For **Thomson scattering,** assumption is that the photon in the electron's frame has it's momentum reversed- ie. it's the center-of-mass frame!

Applies when, $\Gamma E_\gamma^{bg} < m_e c^2$

<u>Thompson scattering</u> (underlying assumption)



(in electron rest-frame)

$$E_\gamma = \frac{4}{3}\Gamma^2 E_\gamma^{bg}$$

Max-Planck-Institut für Kernphysik

Andrew Taylor

Synchrotron Photons

Treating magnetic field as a virtual photon field,

$$E_\gamma^{bg} = \left(\frac{B}{B_{crit}}\right) m_e c^2 \quad \text{, where } B_{crit} \approx 4\text{x}10^{13}\,\text{G}$$

If, $B = 10^{-10}\,\text{G}$

$$E_\gamma^{bg} = 10^{-18}\,\text{eV}$$

If, $E_e = 10^{19}\ \text{eV}\,,\ \ \Gamma = 2\text{x}10^{13}$ → $\Gamma\, E_\gamma^{bg} = 2\text{x}10^{-6}\ \text{eV}$ (Thomson)

Since, $E_\gamma = \frac{4}{3}\Gamma^2 E_\gamma^{bg}$

The synchrotron photons get energy → $E_\gamma = \frac{4}{3}\text{x}\,4\,\text{x}\,10^{26}\,\text{x}\,10^{-18} = 5\text{x}10^6\ \ \text{eV}$

Inverse Compton Photons

$E_\gamma^{bg} = 10^{-3}$ eV (CMB background)

If, $E_e = 10^{19}$ eV, $\Gamma = 2\text{x}10^{13}$

Then, $\Gamma E_\gamma^{bg} = 2\text{x}10^{10}$ eV → Not Thomson

Hence, our naïve conclusion that IC out-competes synchrotron was <u>wrong</u>

When Thomson Scattering Doesn't Apply- the Klein Kishina regime

When $\Gamma E_{\gamma}^{bg} \geq m_e c^2$ (center of mass frame is **very different** to electron rest frame)

Let, $$b = \frac{4 E_e E_{\gamma}^{bg}}{(m_e c^2)^2}$$ (which physically represents the squared center-of-mass energy in the collision)

Can re-write, $$E_{\gamma} = \frac{4}{3} \Gamma^2 E_{\gamma}^{bg}$$

↓

as $$E_{\gamma} = \frac{1}{3} b E_e$$

Max-Planck-Institut für Kernphysik

Andrew Taylor

When Thomson Scattering Doesn't Apply- the Klein Nishina Regime

So the energy exchange is,

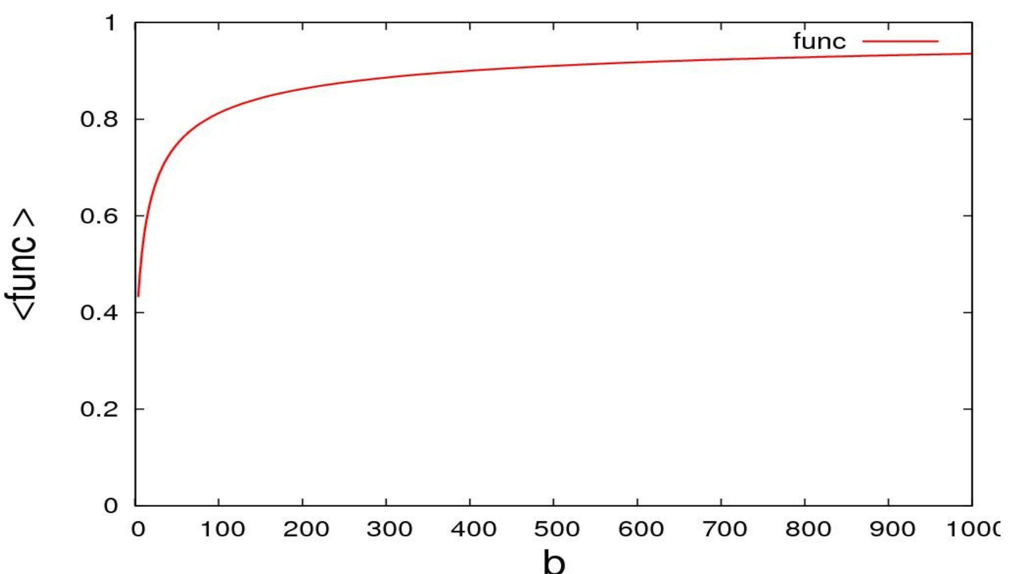
$$\frac{E_\gamma}{E_e} = \frac{b}{3}$$

Thomson: $b < 1$

But $\frac{E_\gamma}{E_e}$ shouldn't become larger than 1....what went wrong?

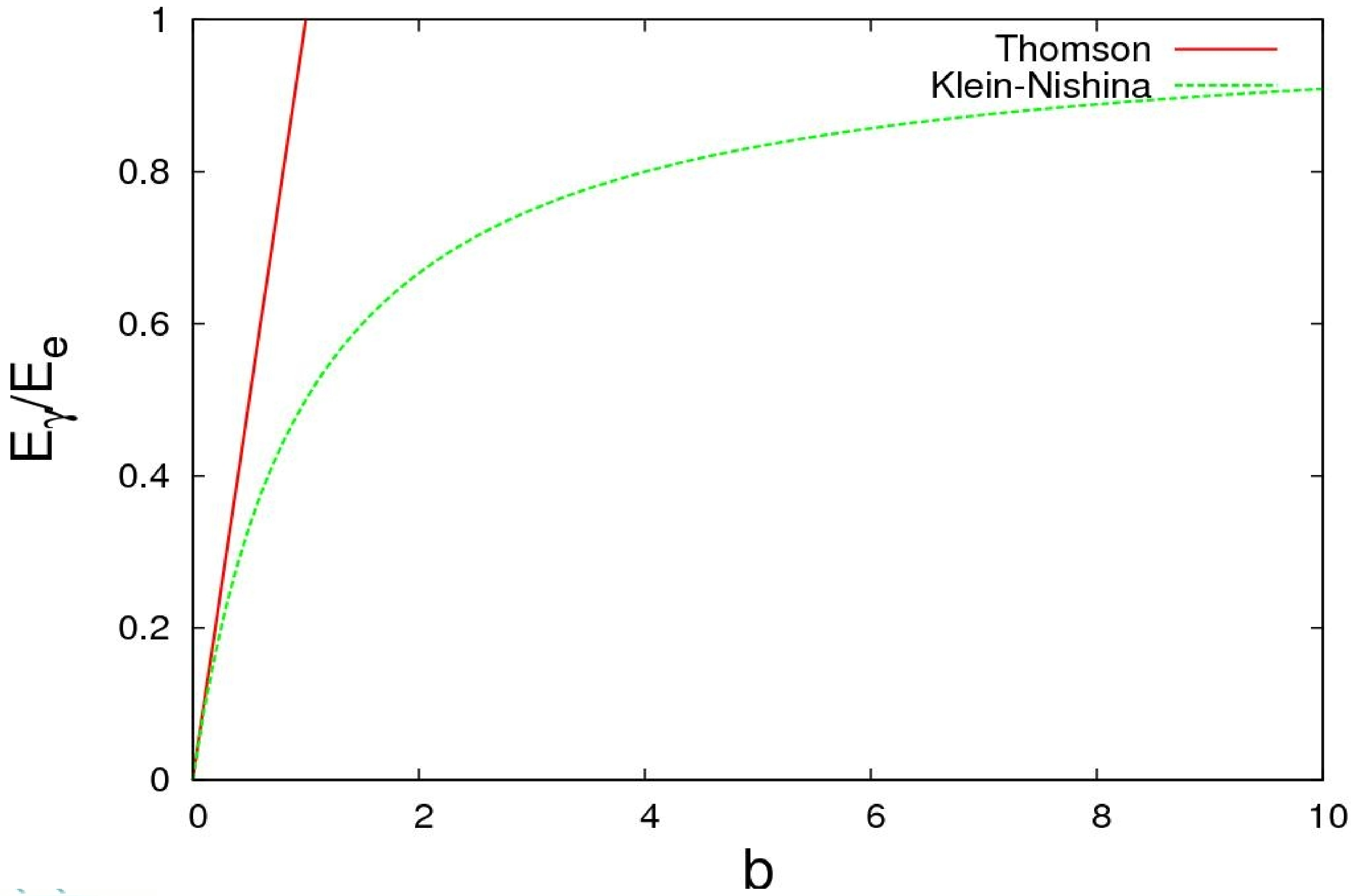
Complete description is actually,

$$\frac{E_\gamma}{E_e} = \frac{b}{(1+b)} f(b)$$



Max-Planck-Institut für Kernphysik

Klein-Nishina Description



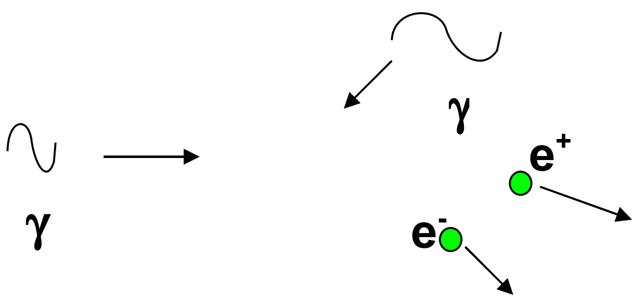
Max-Planck-Institut für Kernphysik

Andrew Taylor

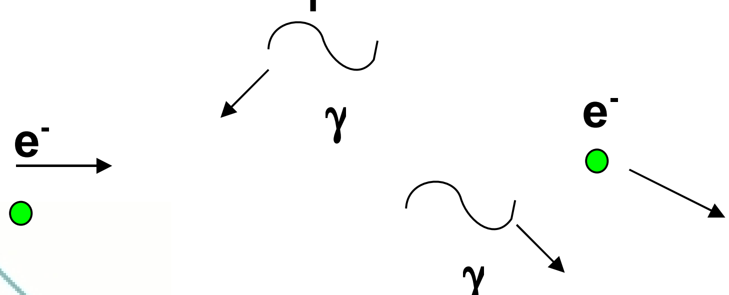
e/γ Cascades

The repetition of **2 processes**:

1) Pair Production



2) Inverse Compton



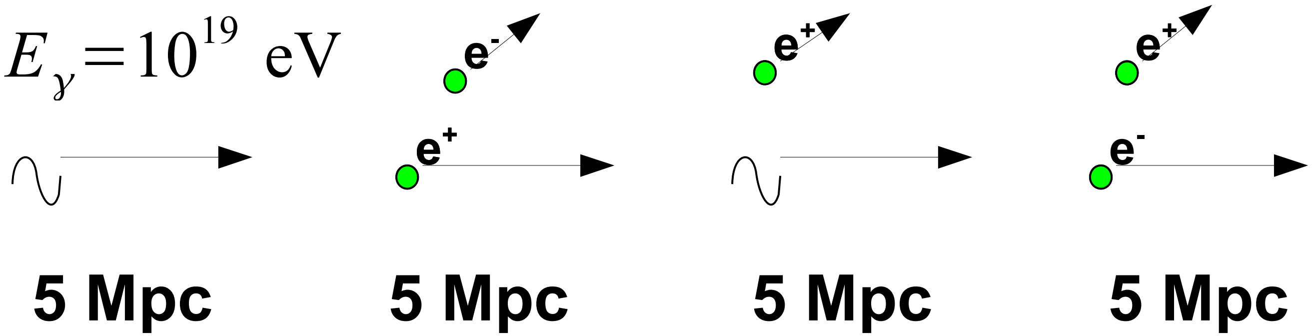
Max-Planck-Institut für Kernphysik

Andrew
Taylor

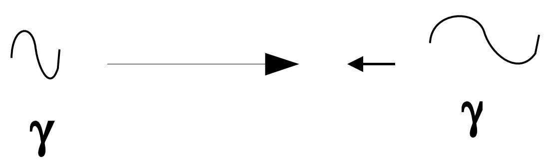
Leading Particle Description

$E_\gamma = 10^{19}$ eV

(ignore secondary particles)

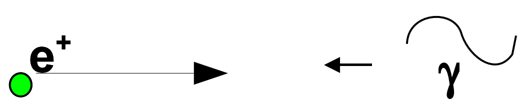


$E_\gamma = 10^{19}$ eV, $E_\gamma^{bg} = 10^{-3}$ eV



$$\left(s = 4\text{x}10^4, \ \ \frac{E_e}{E_\gamma} \approx 0.99 \right)$$

$E_e = 10^{19}$ eV, $E_\gamma^{bg} = 10^{-3}$ eV



$$\left(b = 1\text{x}10^5, \ \ \frac{E_\gamma}{E_e} \approx 0.99 \right)$$

Max-Planck-Institut für Kernphysik

So the high energy particle simply changes from a neutral to charged state and back spending roughly equal times in each state.

Andrew Taylor

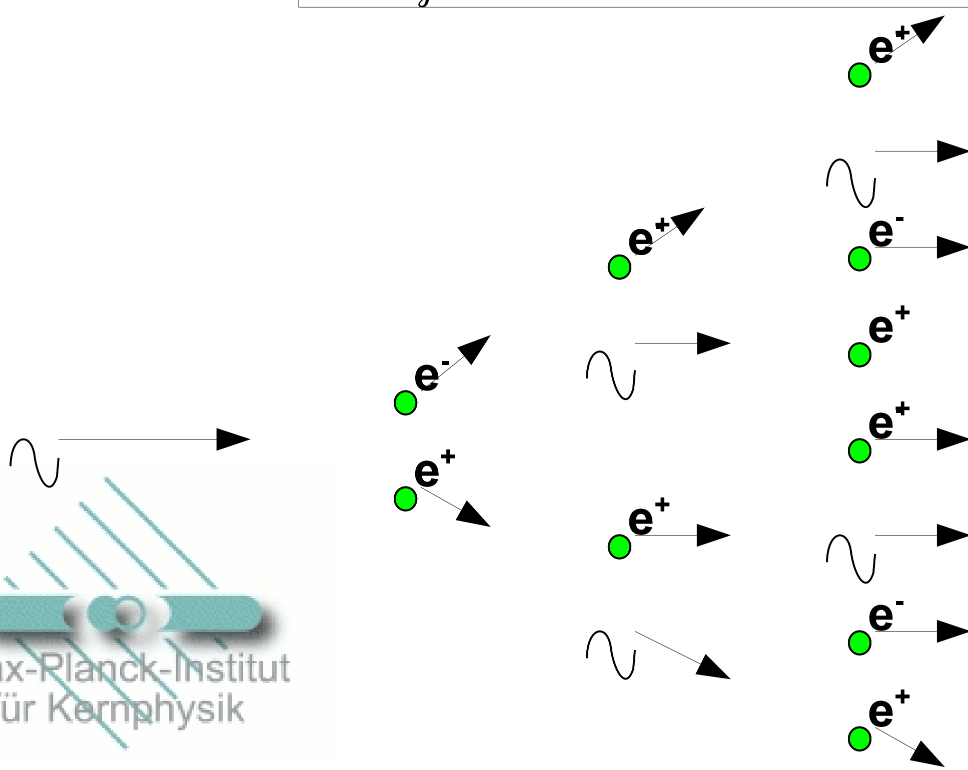
The Spanner in the Works

However, with the radio background with -

$$E_\gamma^{bg} = 10^{-8}\ \text{eV} \longrightarrow U_\gamma^{CRB} = 10^{-8}\ \text{eV cm}^{-3}$$

If, $E_e = 10^{19}\ \text{eV}, \Gamma = 2\text{x}10^{13}$

Then, $\Gamma E_\gamma^{bg} = 2\text{x}10^{5}\ \text{eV} \longrightarrow$ ~Thomson

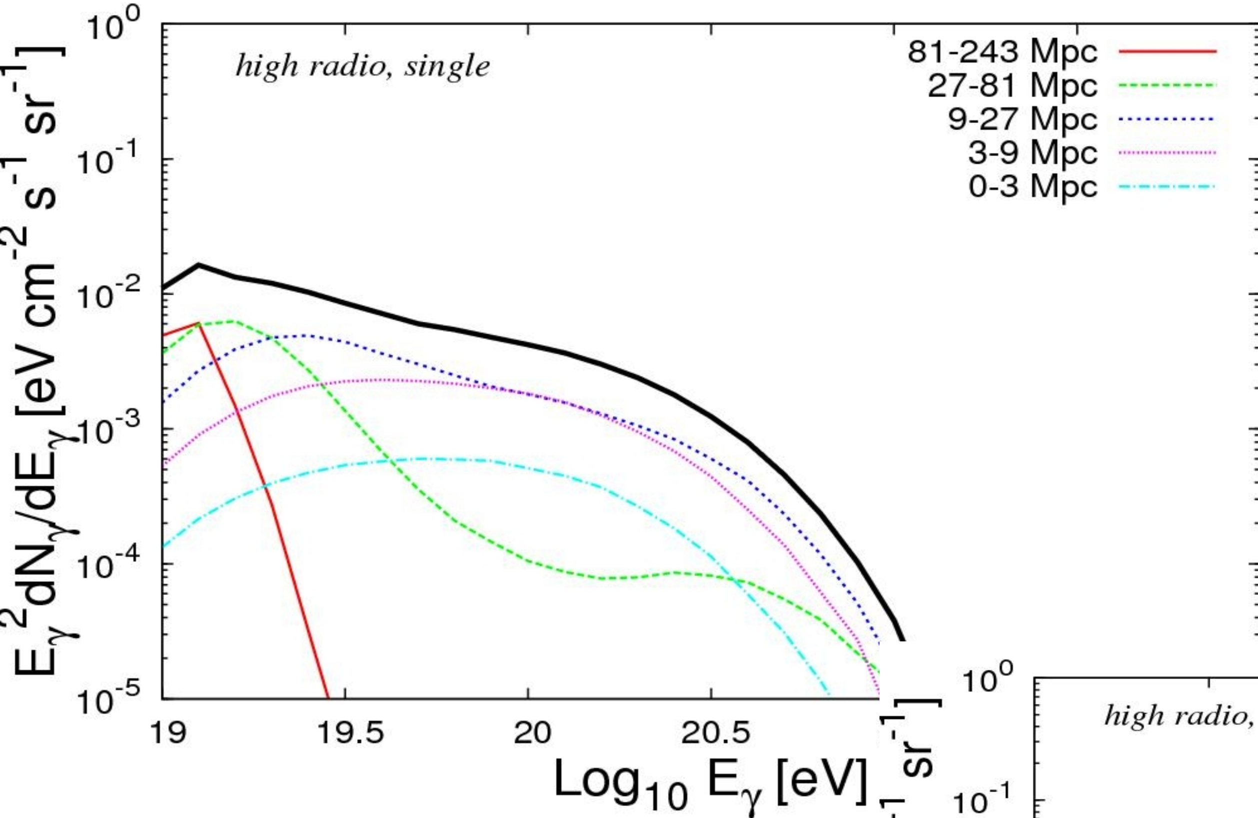


new particles **cannot** be ignored- particle multiplication headache!

Max-Planck-Institut für Kernphysik

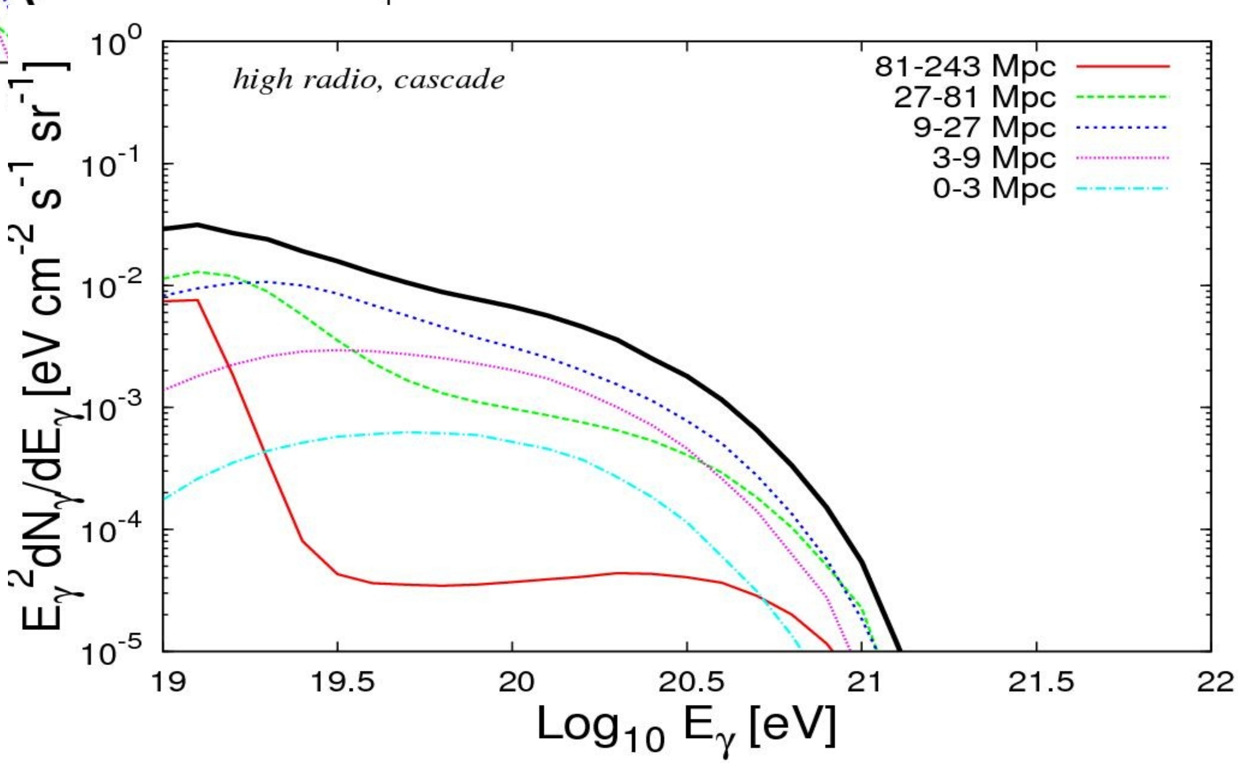
Andrew Taylor

The Photon Flux- with cascading



no cascading

with cascading



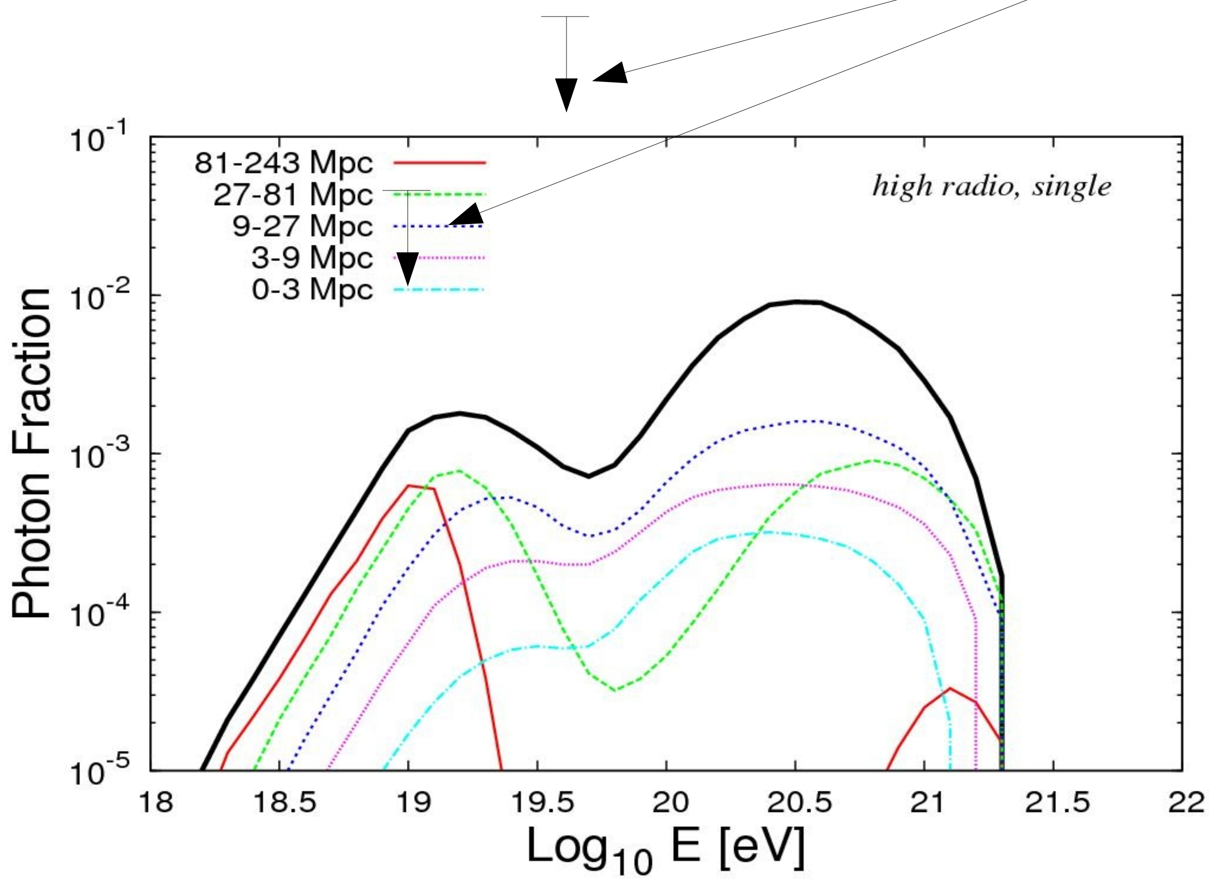
Max-Planck-Institut
für Kernphysik

Conclusion

- High energy photon production is an inevitable consequence of the GZK cut-off's existence
- The present uncertainty in the radio background and extragalactic magnetic field strengths lead to various possibilities for the propagation of the electromagnetic energy through the system
- If the radio background and extragalactic magnetic field are low, a simple leading particle description with the particle alternating between neutral and charged states may be used
- The radio background provides low energy photons, prematurely putting the cascade into the Thomson regime

The Photon Fraction- data

Auger data



Max-Planck-Institut für Kernphysik

Andrew Taylor