LECTURE PLAN:

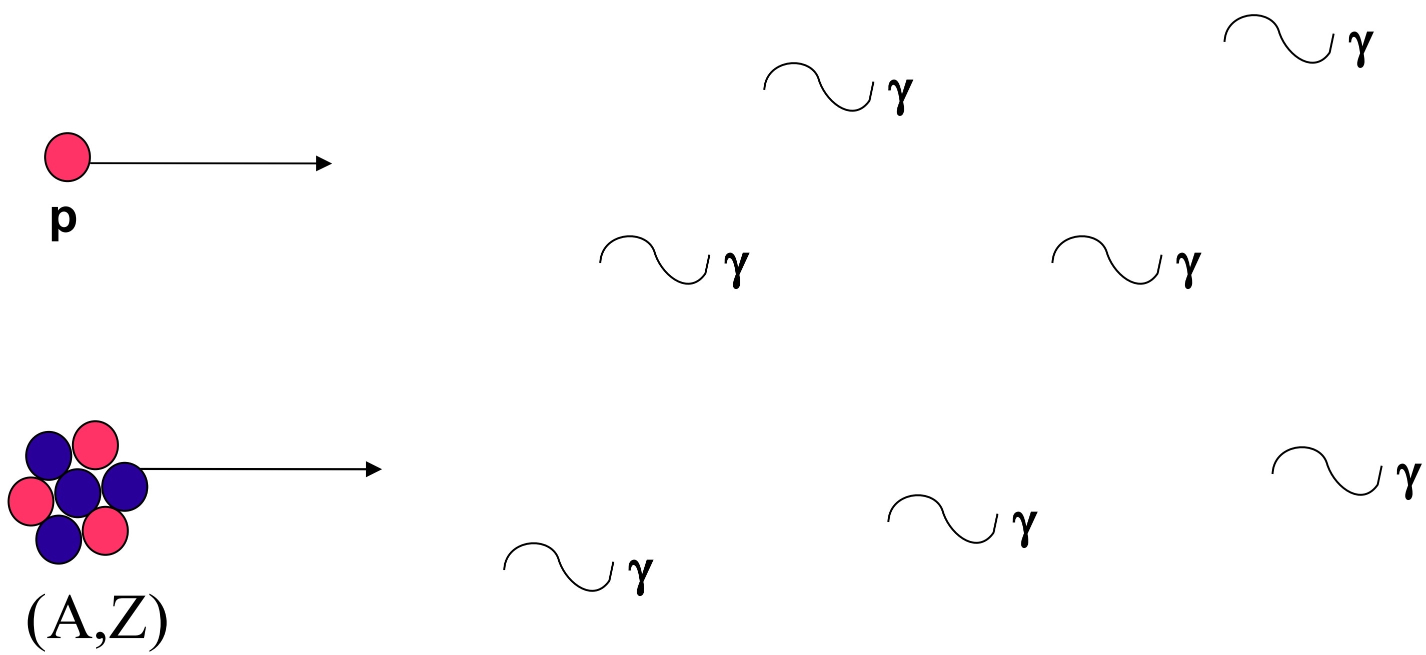
1) COSMIC RAYS- proton interactions with photons, composition, nuclei interactions with photons, different photon targets

2) NEUTRINOS

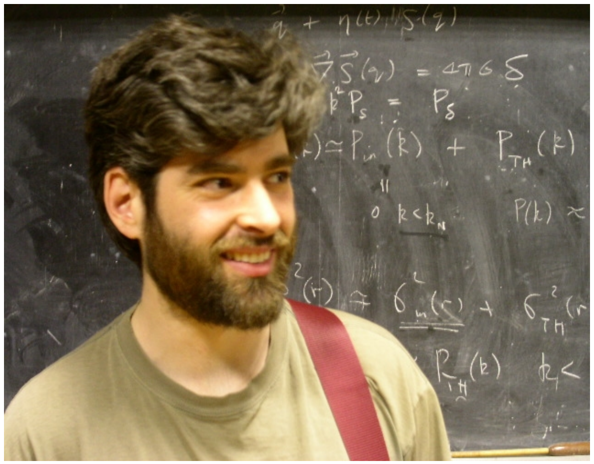
3) PHOTONS

4) MULTIMESSENGER APPROACH

COSMIC RAYS: High Energy Proton and Nuclei Interactions During Propagation



The Propagation of Cosmic Ray Nuclei:



Andrew Taylor
MPIK Heidelberg

Based on papers by:

Dan Hooper, Subir Sarkar, and Andrew Taylor

"*The Intergalactic Propagation of Ultrahigh Energy Cosmic Ray Nuclei*" (**astro-ph/0608085**)

"*The Intergalactic Propagation of Ultrahigh Energy Cosmic Ray Nuclei: An Analytic Approach*" (**astro-ph/0802.1538**)

Aims

1) Protons- dominant cosmic ray interactions

2) Composition- highlight uncertainty

3) Nuclei- dominant cosmic ray interactions

4) Arriving Spectra- cosmic ray spectra for different injected primary particles

5) Analytic- a simple way to understand the nuclei results

1) Cosmic Ray Protons

The Interaction Rate

$$R = \int_0^\infty d\epsilon_\gamma \frac{dn}{d\epsilon_\gamma} \int_{-1}^{1} \frac{1}{2} d(\cos\theta) \frac{d\sigma}{d\cos\theta} (1 - \beta\cos\theta) \quad \text{all values in lab frame}$$

The Interaction Rate

$$R = \int_0^\infty d\epsilon_\gamma \frac{dn}{d\epsilon_\gamma} \int_{-1}^{1} \frac{1}{2} d(\cos\theta) \frac{d\sigma}{d\cos\theta}(1-\beta\cos\theta)$$ all values in lab frame

Since, $\epsilon_\gamma E_p = \epsilon_\gamma{}' E_p (1+\beta\cos\theta)$

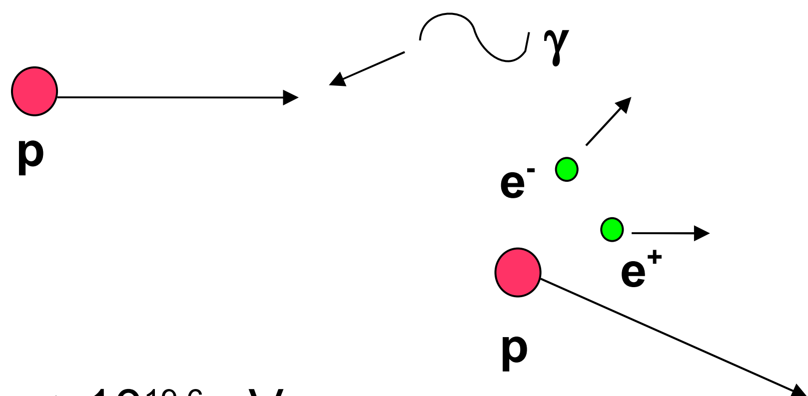
$$(1+\beta\cos\theta)\, d\cos\theta = \frac{\epsilon_\gamma E_p}{\epsilon_\gamma{}' E_p} \frac{d(\epsilon_\gamma E_p)}{\epsilon_\gamma{}' E_p}$$

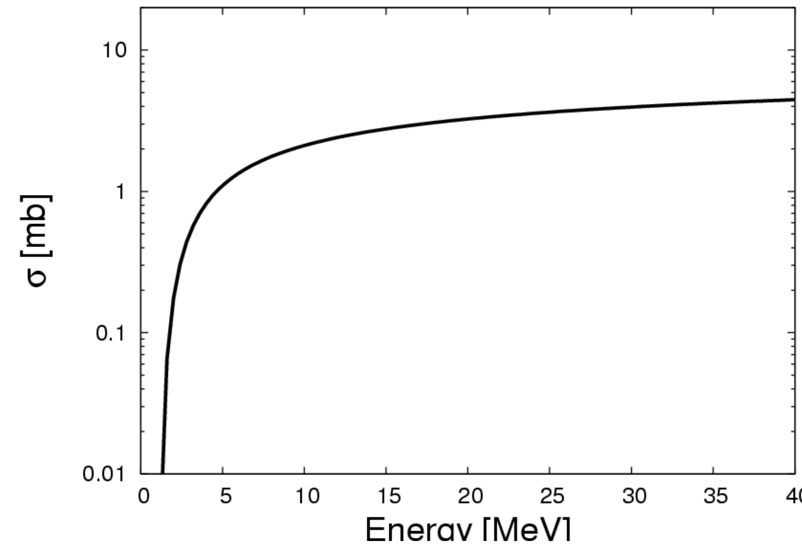
$$R = \int_0^\infty d\epsilon_\gamma \frac{dn}{d\epsilon_\gamma} \int_0^{2\epsilon_\gamma E_p} d(\epsilon_\gamma E_p) \frac{\epsilon E_p}{\epsilon_\gamma{}'^2 E_p^2} \frac{d\sigma}{d(\epsilon_\gamma E_p)}$$

$$= \frac{m_p^2}{2E_p^2} \int_0^\infty d\epsilon_\gamma{}' \frac{n(\epsilon_\gamma{}')}{\epsilon_\gamma{}'^2} \int_0^{2\epsilon_\gamma{}' \frac{E_p}{m_p}} d\epsilon_\gamma \epsilon_\gamma \frac{d\sigma}{d\epsilon_\gamma}$$

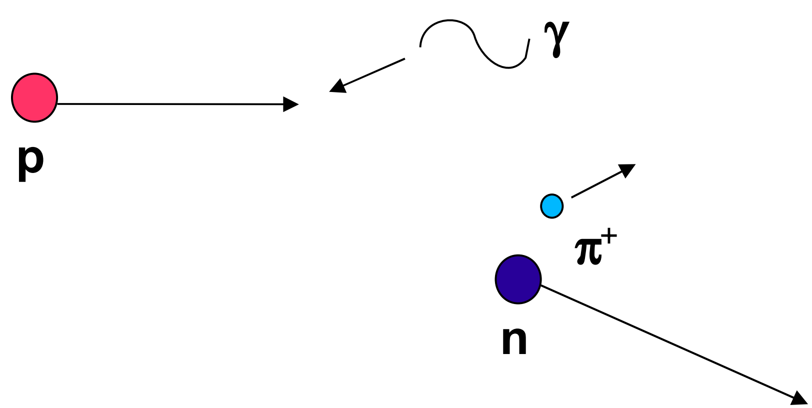
Cosmic Ray Proton Interactions

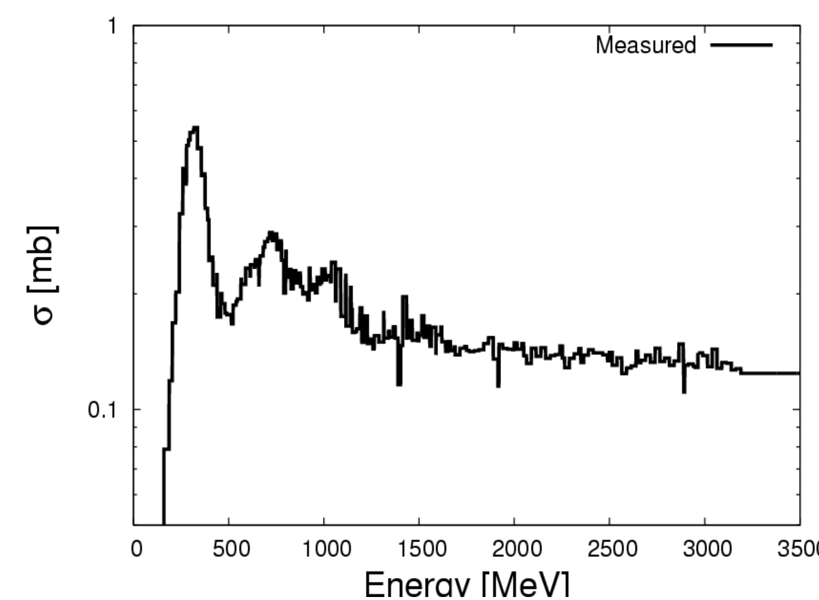
For $E_{proton} < 10^{19.6}$ eV





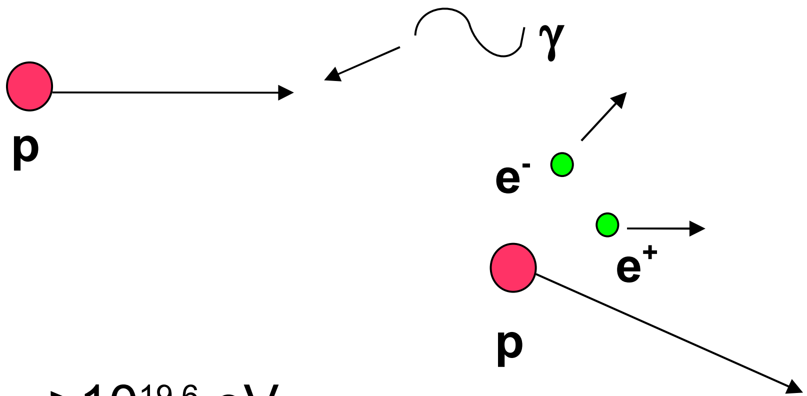
For $E_{proton} > 10^{19.6}$ eV

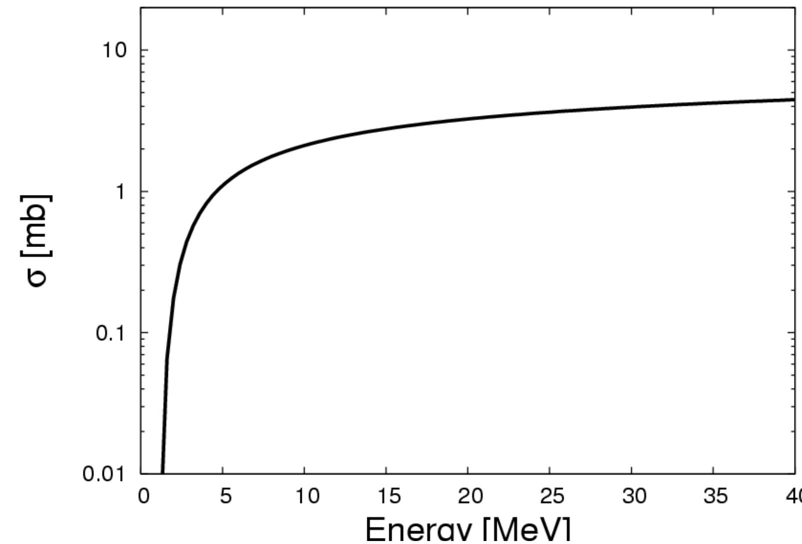




Cosmic Ray Proton Interactions

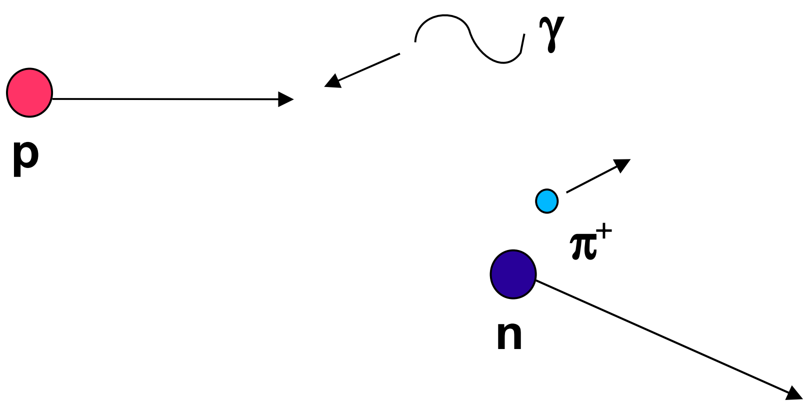
For $E_{proton}<10^{19.6}$ eV

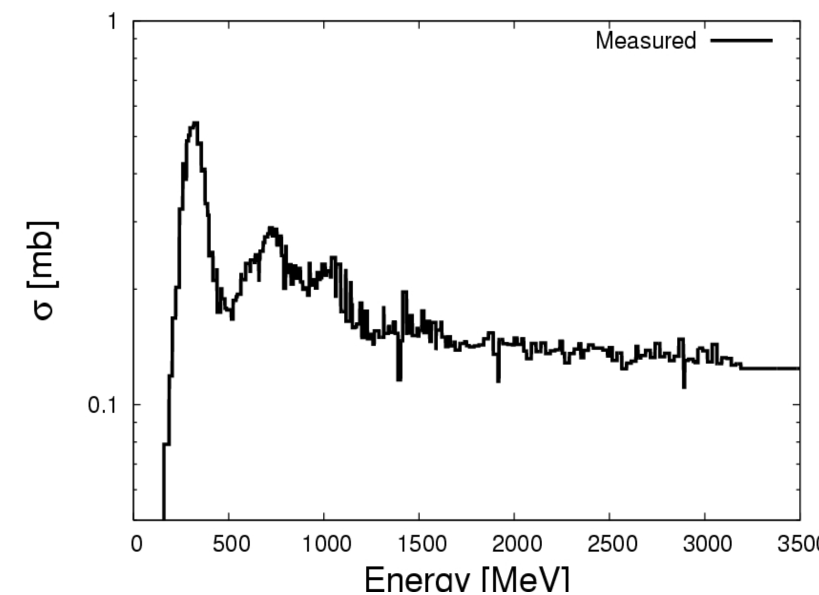




$E_{\gamma}^{th} \sim 1\text{MeV}$

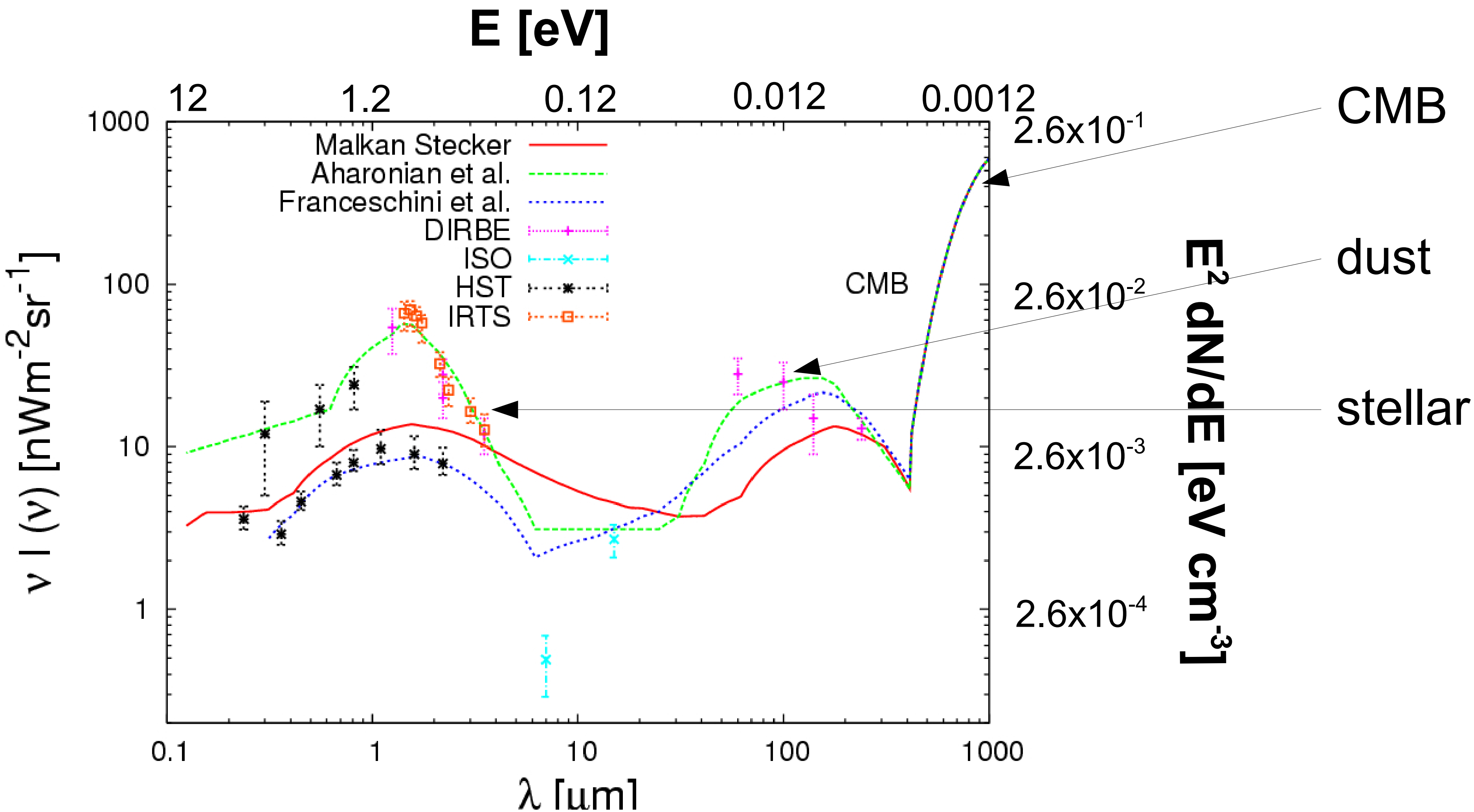
For $E_{proton}>10^{19.6}$ eV



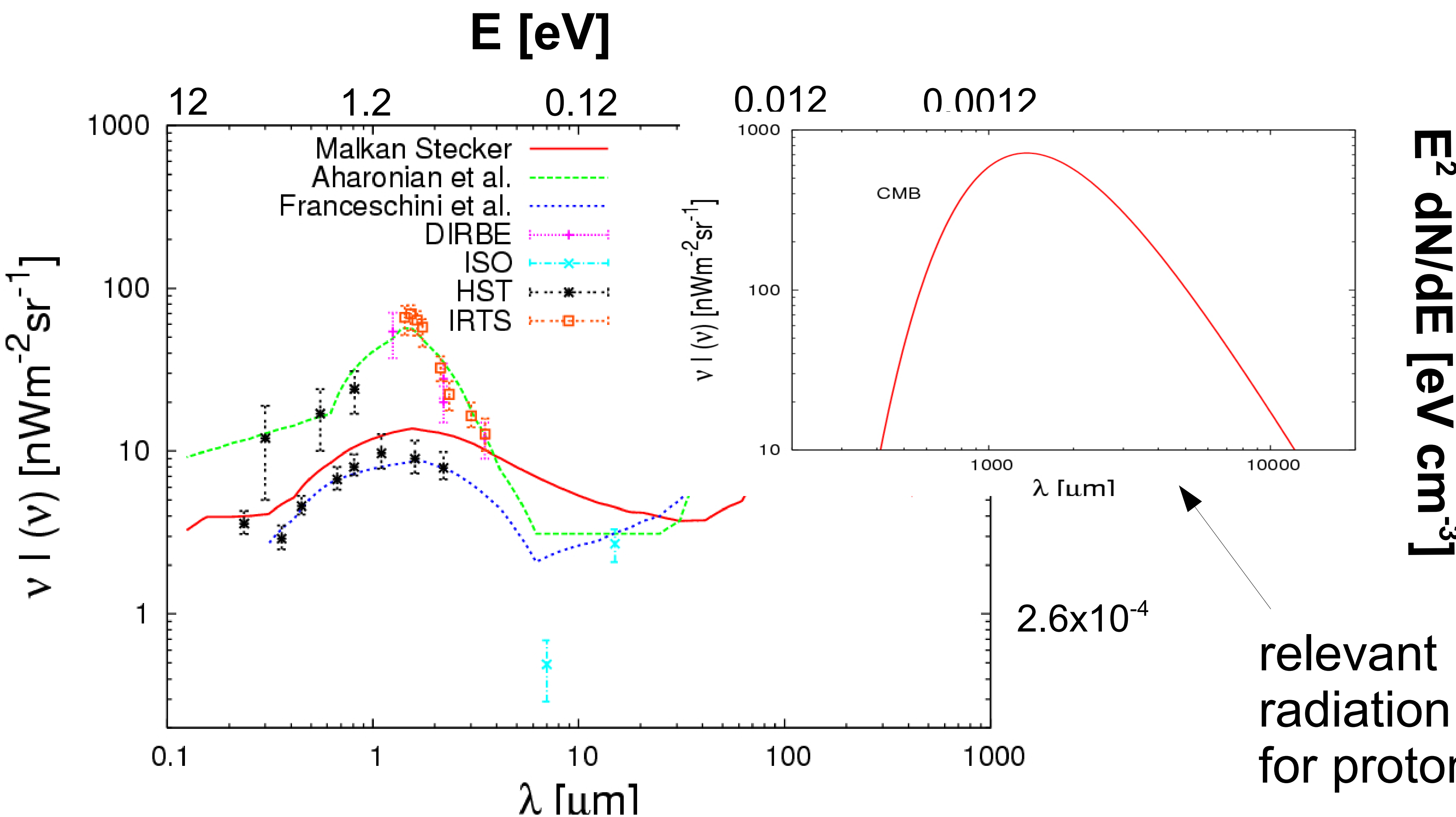


$E_{\gamma}^{th} \sim 140\text{MeV}$

Cosmic Radiation Fields

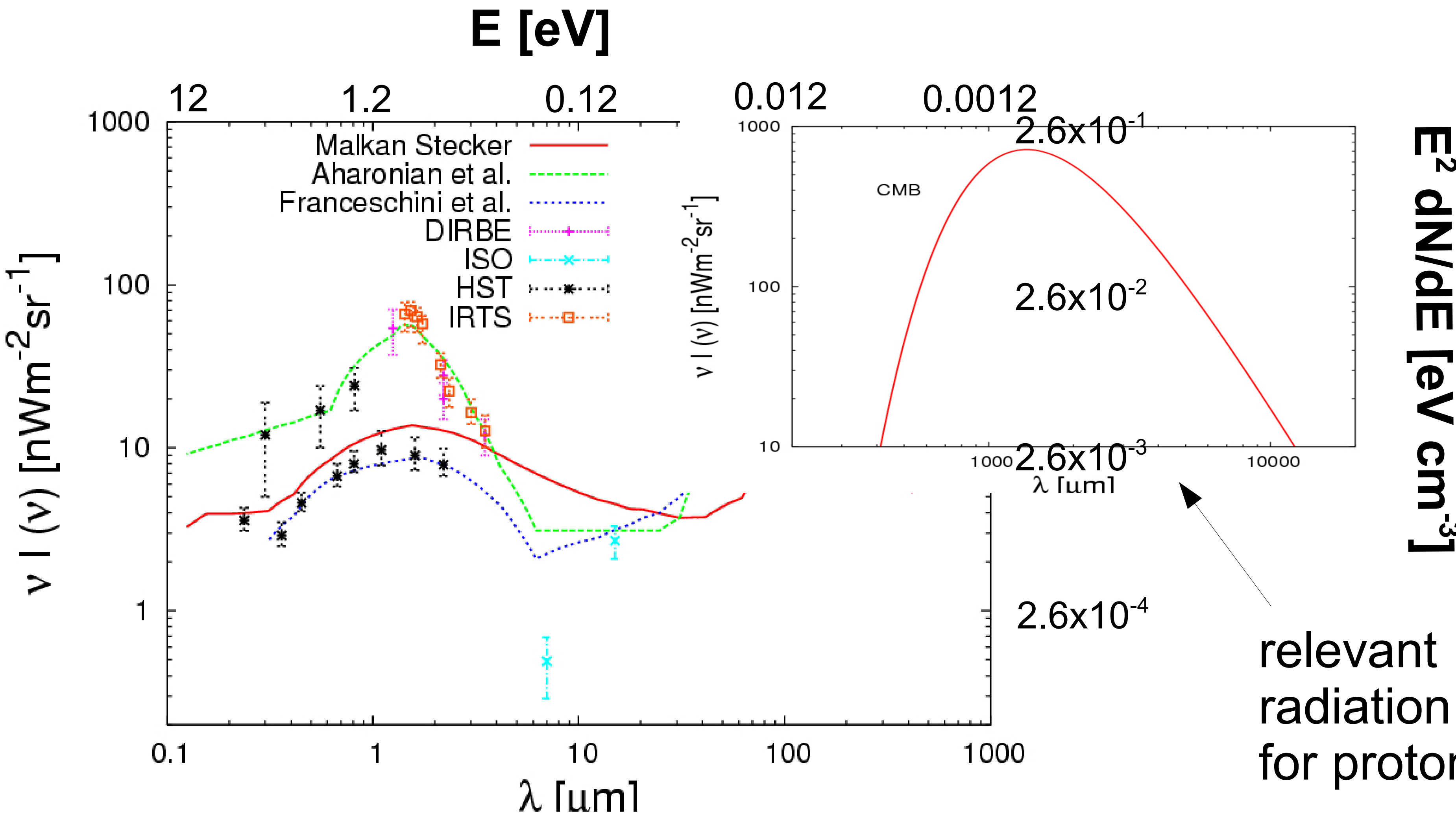


Cosmic Radiation Fields



relevant radiation field for protons

Cosmic Radiation Fields



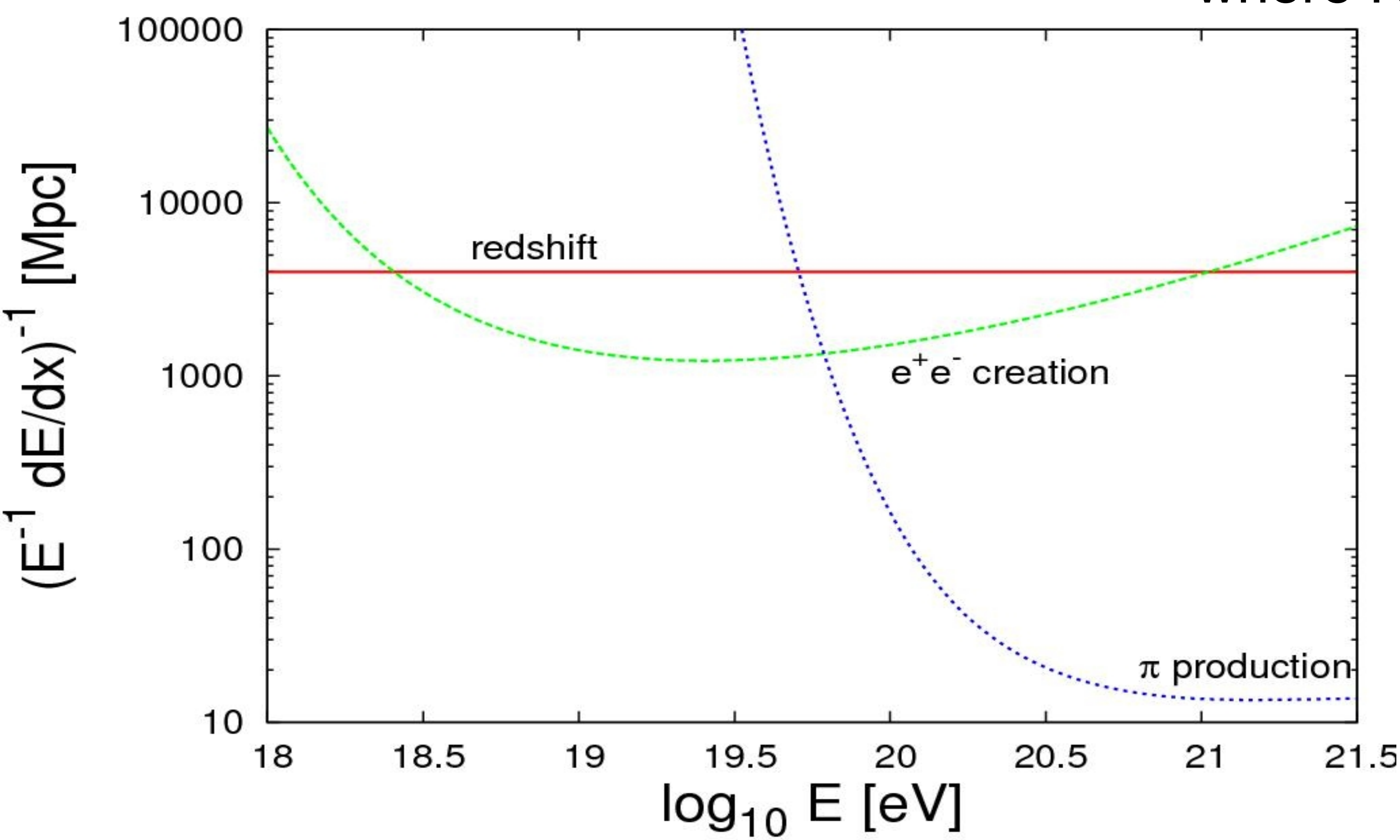
relevant radiation field for protons

Energy Loss Rates due to Proton Interactions

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

where R is the energy loss rate

where K_p is the inelasticity



Energy Loss Rates due to Proton Interactions

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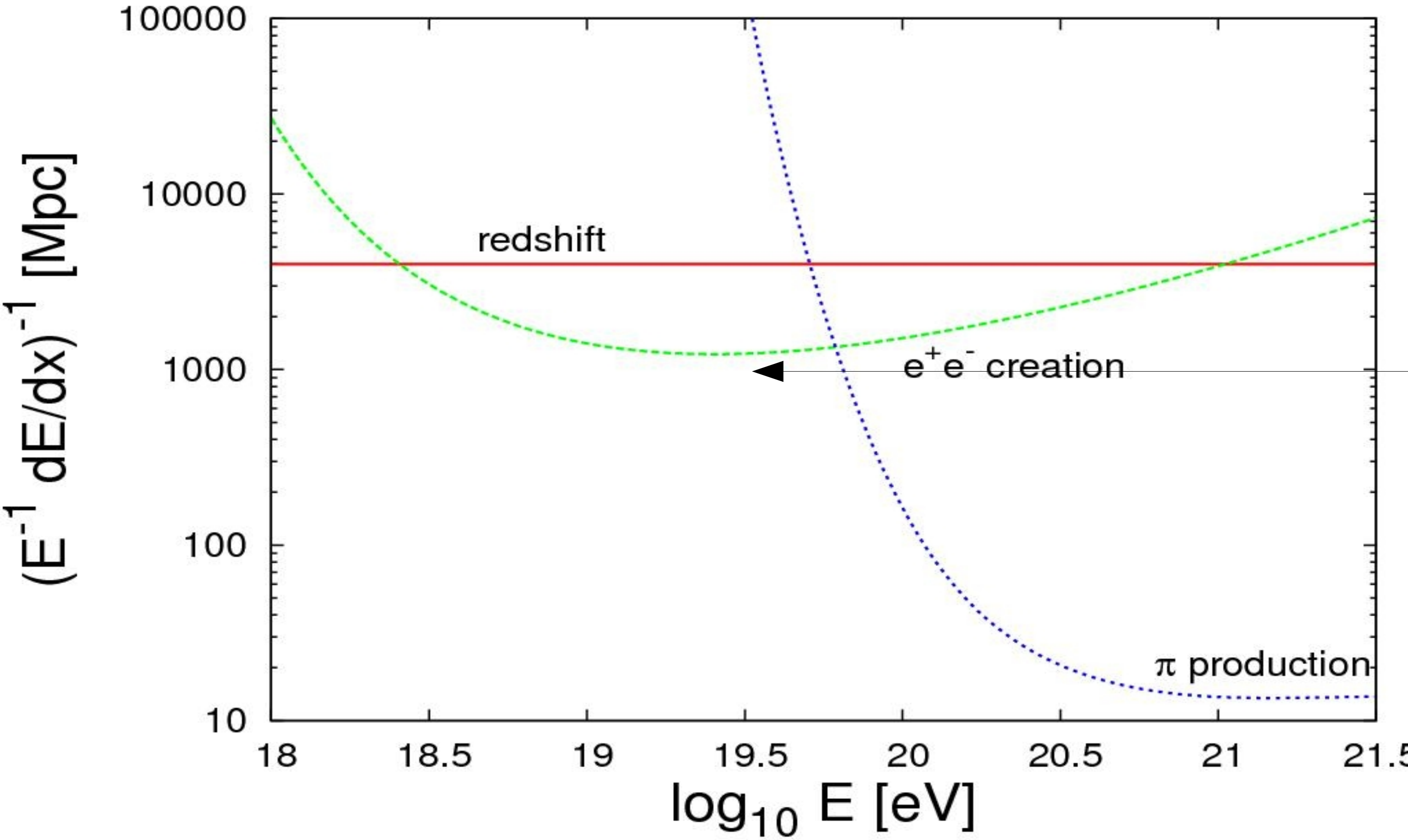
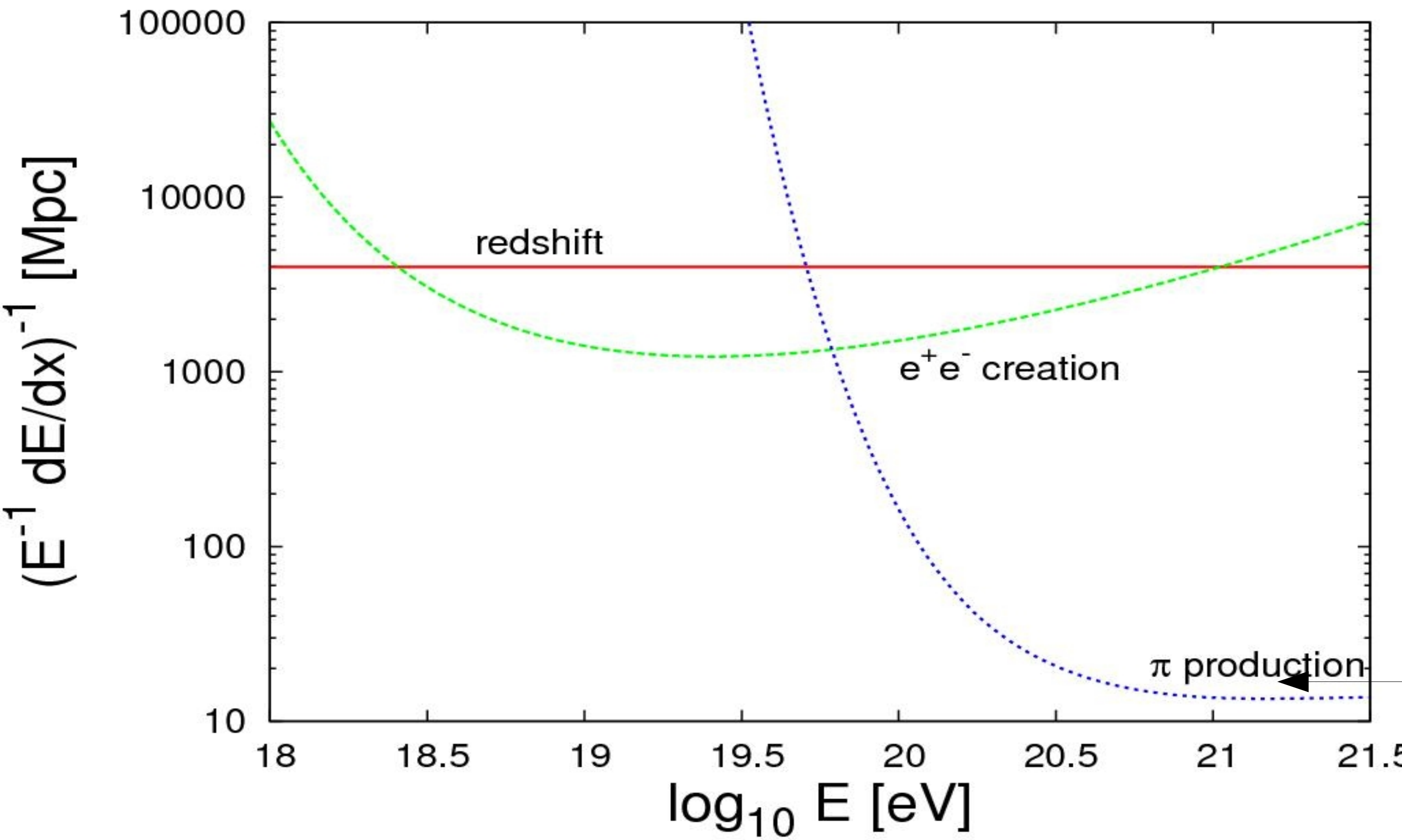


$$\approx \frac{m_p}{m_e} \frac{1}{n_{CMB}\sigma}$$

Energy Loss Rates due to Proton Interactions

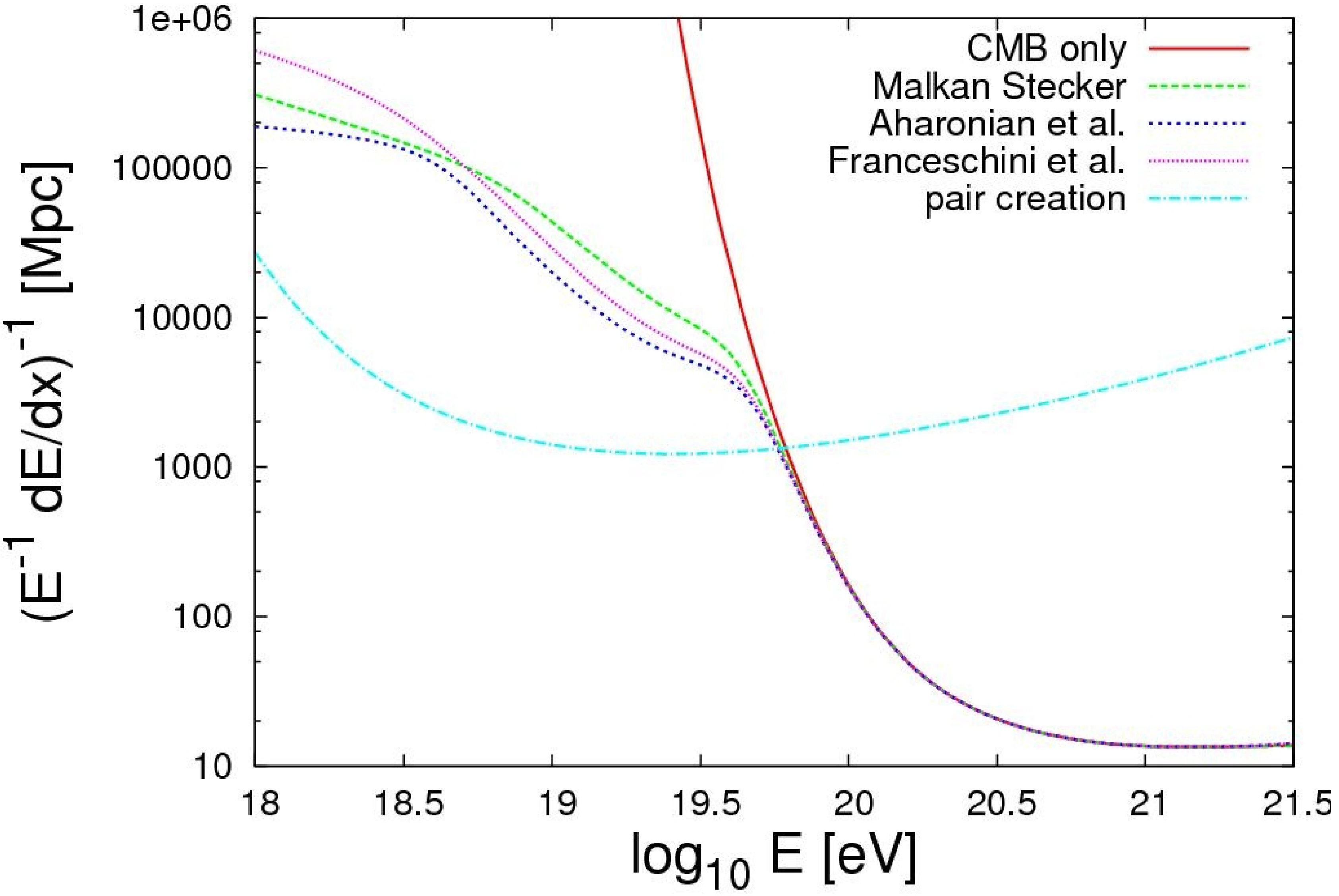
$$R = \frac{m_p^2 c^4}{2E^2} \int_0^\infty d\epsilon \frac{n(\epsilon)}{\epsilon^2} \int_0^{2E\epsilon/m_p c^2} d\epsilon' \epsilon' \sigma_{p\gamma}(\epsilon') K_p$$

where R is the energy loss rate



$$\approx \frac{m_p}{m_\pi} \frac{1}{n_{CMB}\sigma}$$

....with Different IR Backgrounds



2) Could Cosmic Rays be Nuclei?

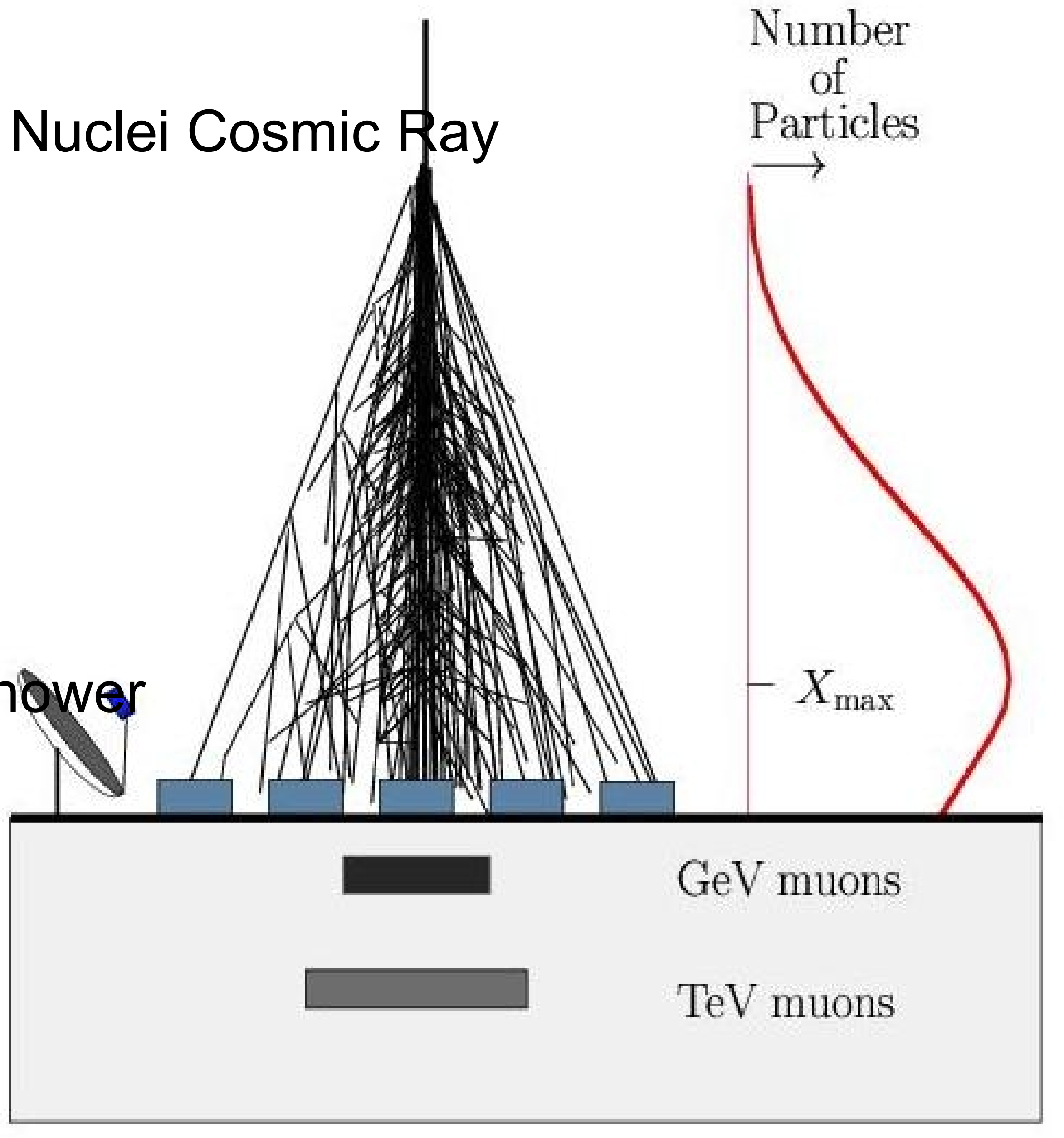
Composition Information in Particle Showers

Differences in Protons and Fe Nuclei Cosmic Ray Showers-

Position of X_{max}
($X_{max}^{p} > X_{max}^{Fe}$)

Variation In Position of X_{max}
(Smaller for Fe)

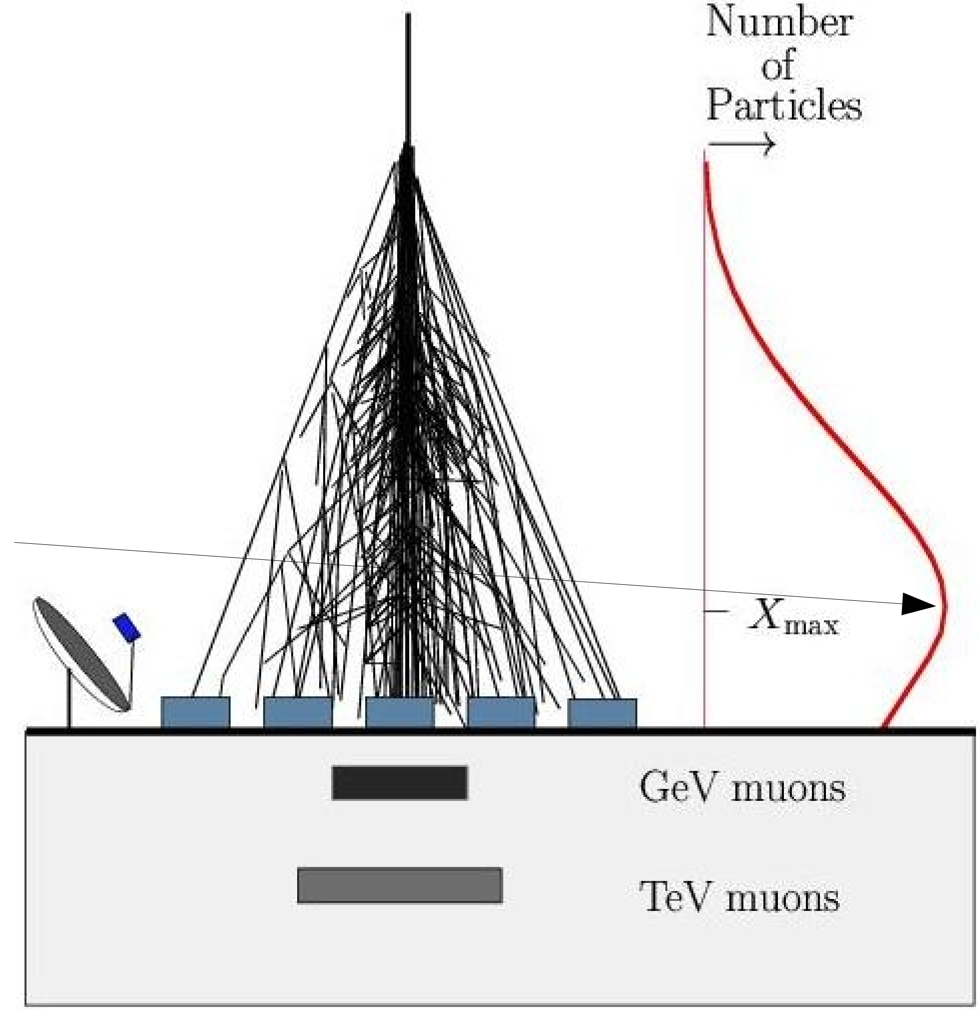
No. of Muons Generated in Shower
(Larger for Fe)



The Shower Maximum- X_{max}

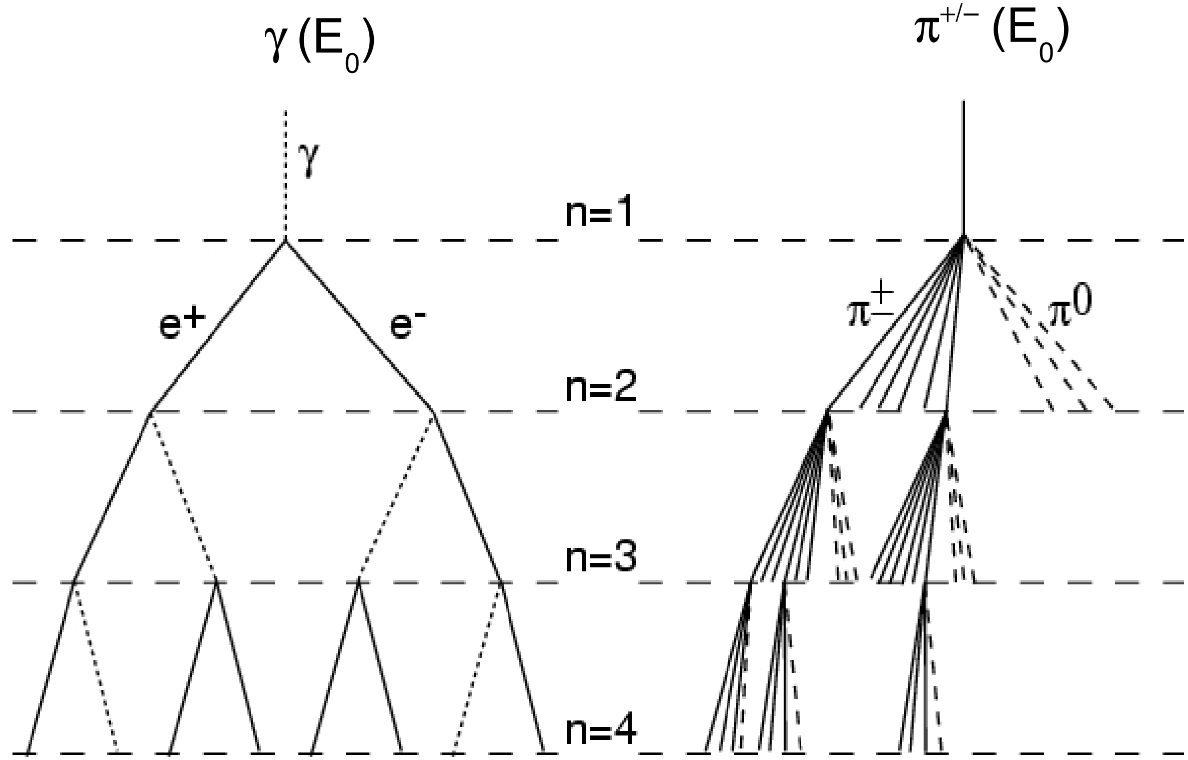
Definition of $\mathbf{X_{max}}$-

The distance from the "top of the atmosphere" where the number of particles in the electromagnetic shower is maximum



X_{max} occurs when interaction lengths of shower particles become longer than the loss lengths (ie. shower particles have fallen below a critical energy)

Heitler Model



$E_{crit.} = 85$ MeV for γ/e showers

$E_{crit.} = 20$ GeV for π showers

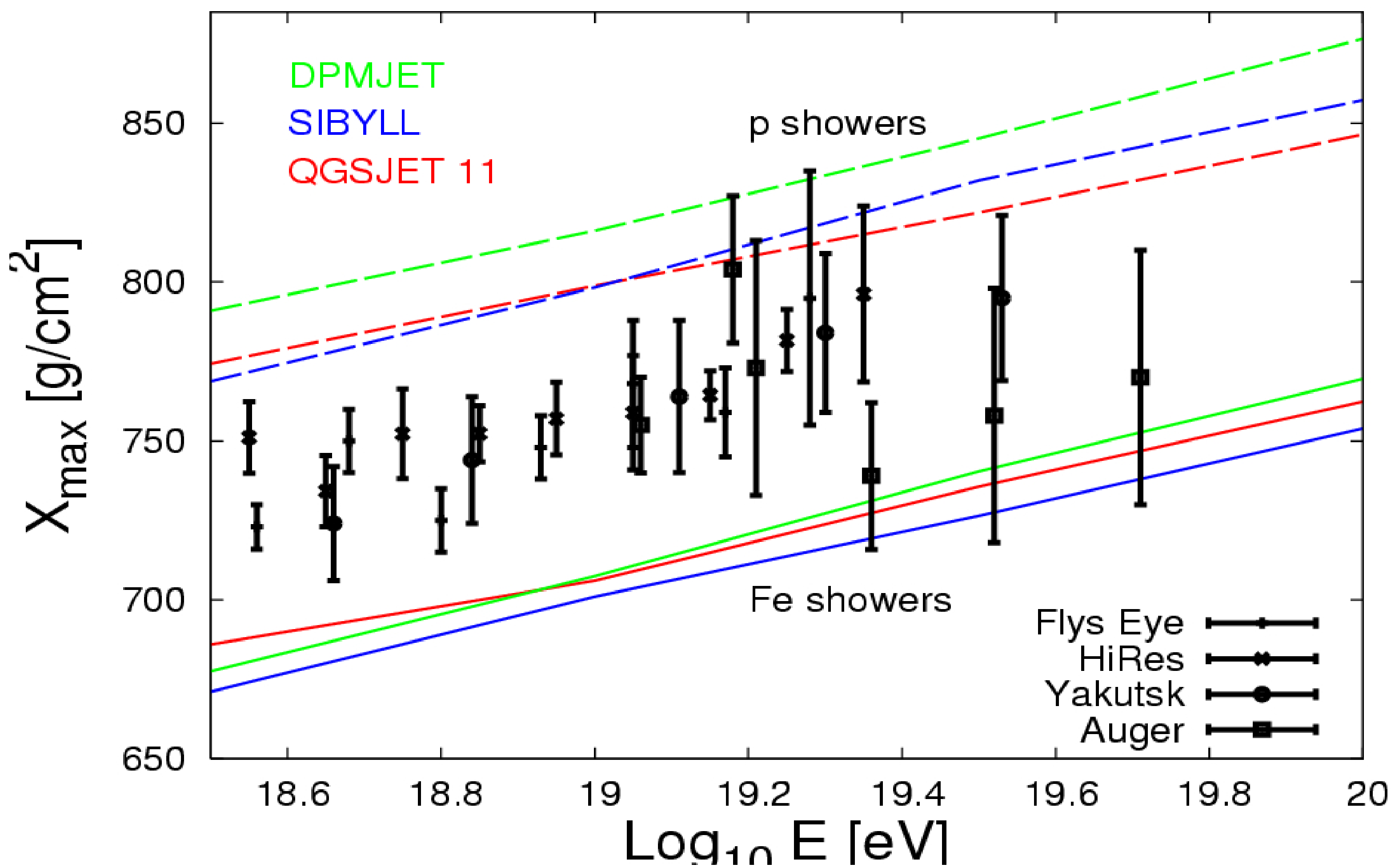
At shower maximum,

$$E_0 = E_{crit.} N_{max}$$

$$N_{max} = 2^{n_{crit.}}$$

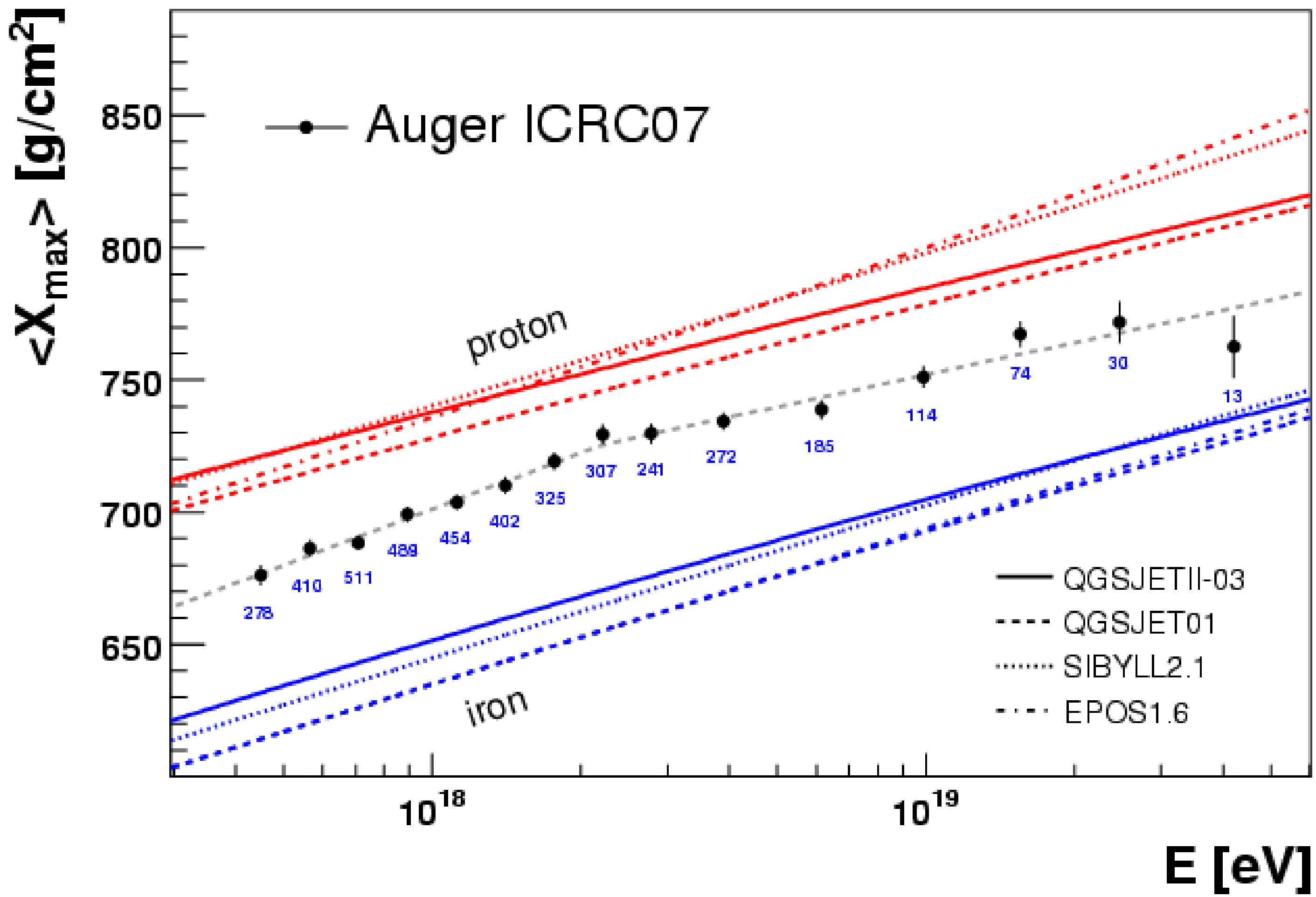
$$X_{max} = n_{crit.} \lambda \ln(2) = \lambda \ln\left(\frac{E_0}{E_{crit.}}\right)$$

X_{max} Data From Different Experiments (pre 2007)



The X_{max} Data From Auger Fluorescence Detector Measurements

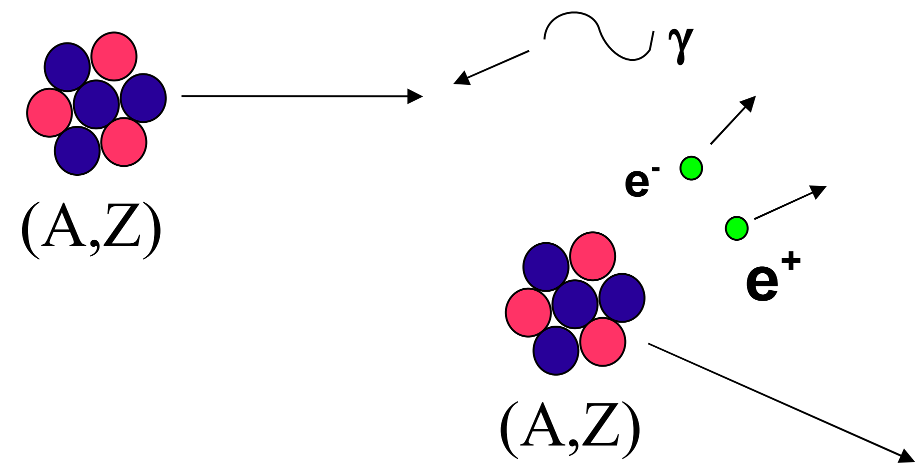
note- logarithmic dependence to energy of primary

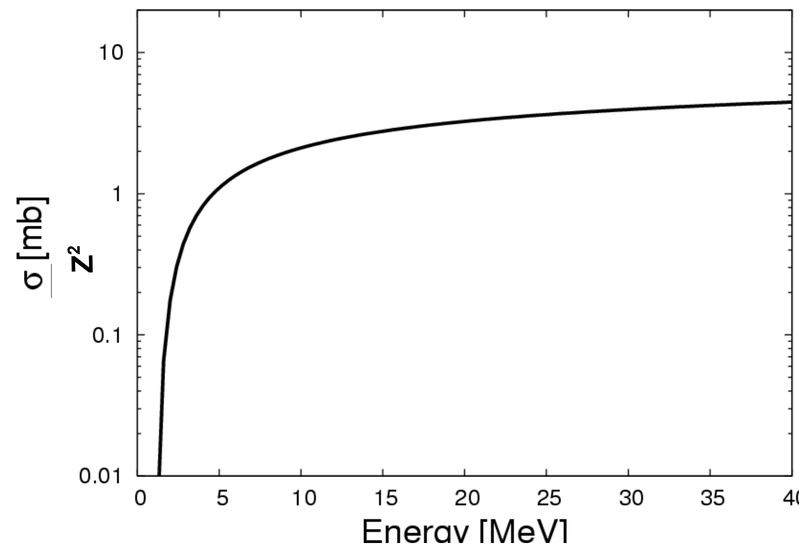


3) Cosmic Ray Nuclei

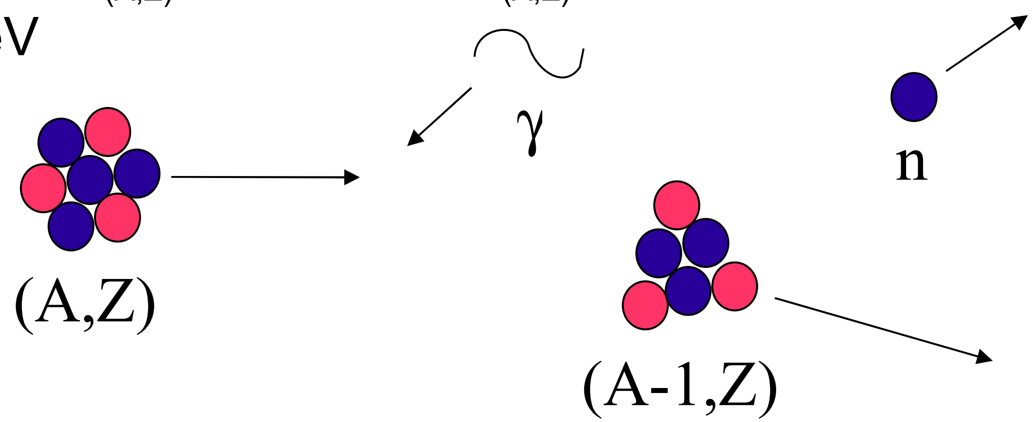
Cosmic Ray Nuclei Interactions

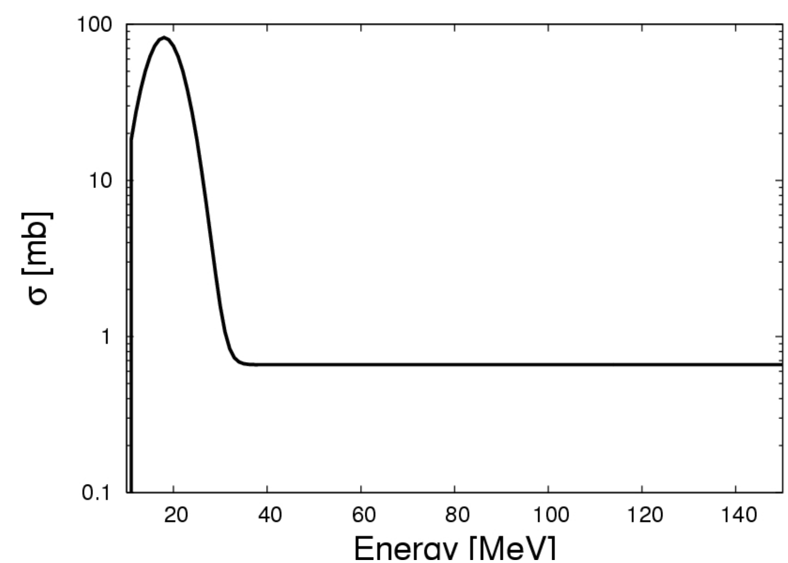
For $10^{19.7} < E_{(A,Z)} < 10^{20.2}$ eV





For $E_{(A,Z)} < 10^{19.7}$ and $E_{(A,Z)} < 10^{20.2}$ eV





Cosmic Ray Nuclei Interactions

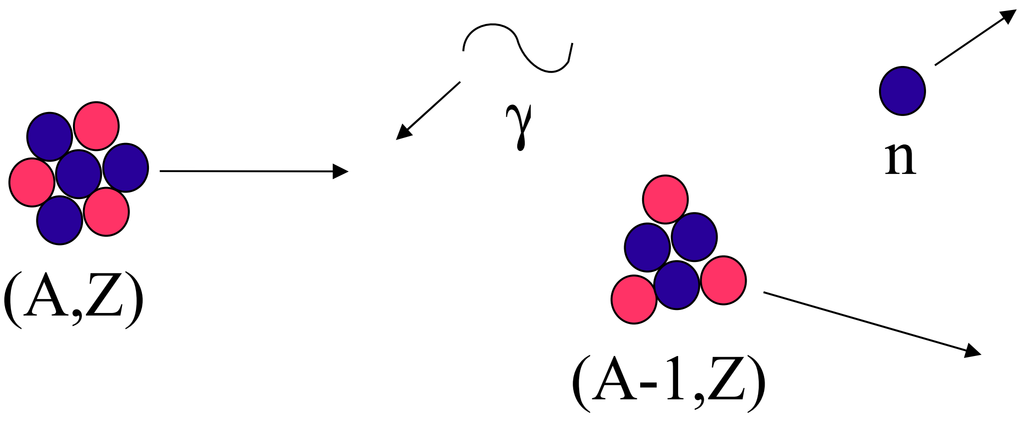
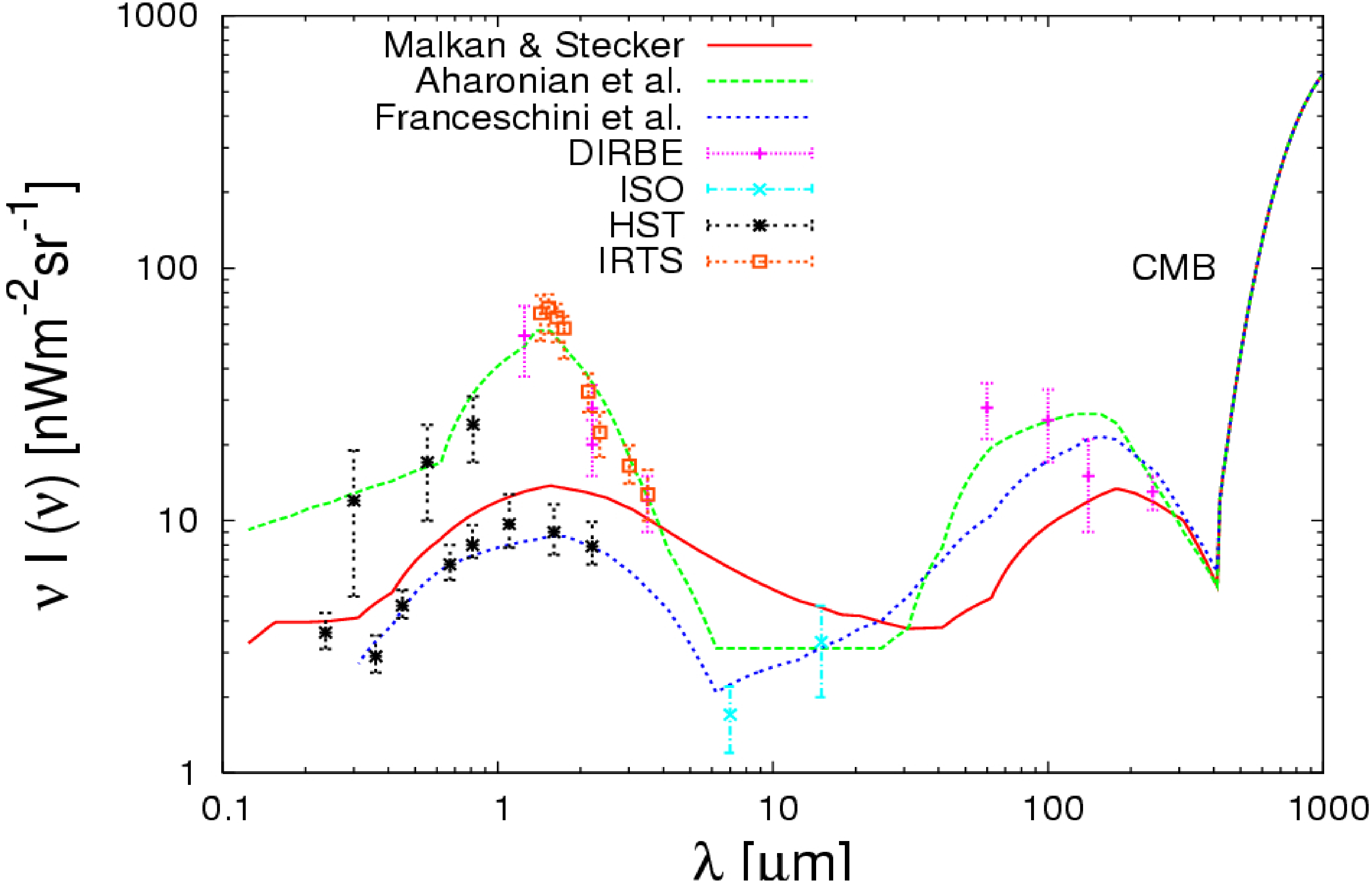


Photo-disintegration-

$$N_{(A,Z)} + \gamma \longrightarrow N'_{(A',Z')} + (Z-Z')p + (A-A'+Z'-Z)n, \quad E_\gamma \sim 30\text{MeV}$$

$$n \longrightarrow p + e^- + \bar{\nu}_e$$

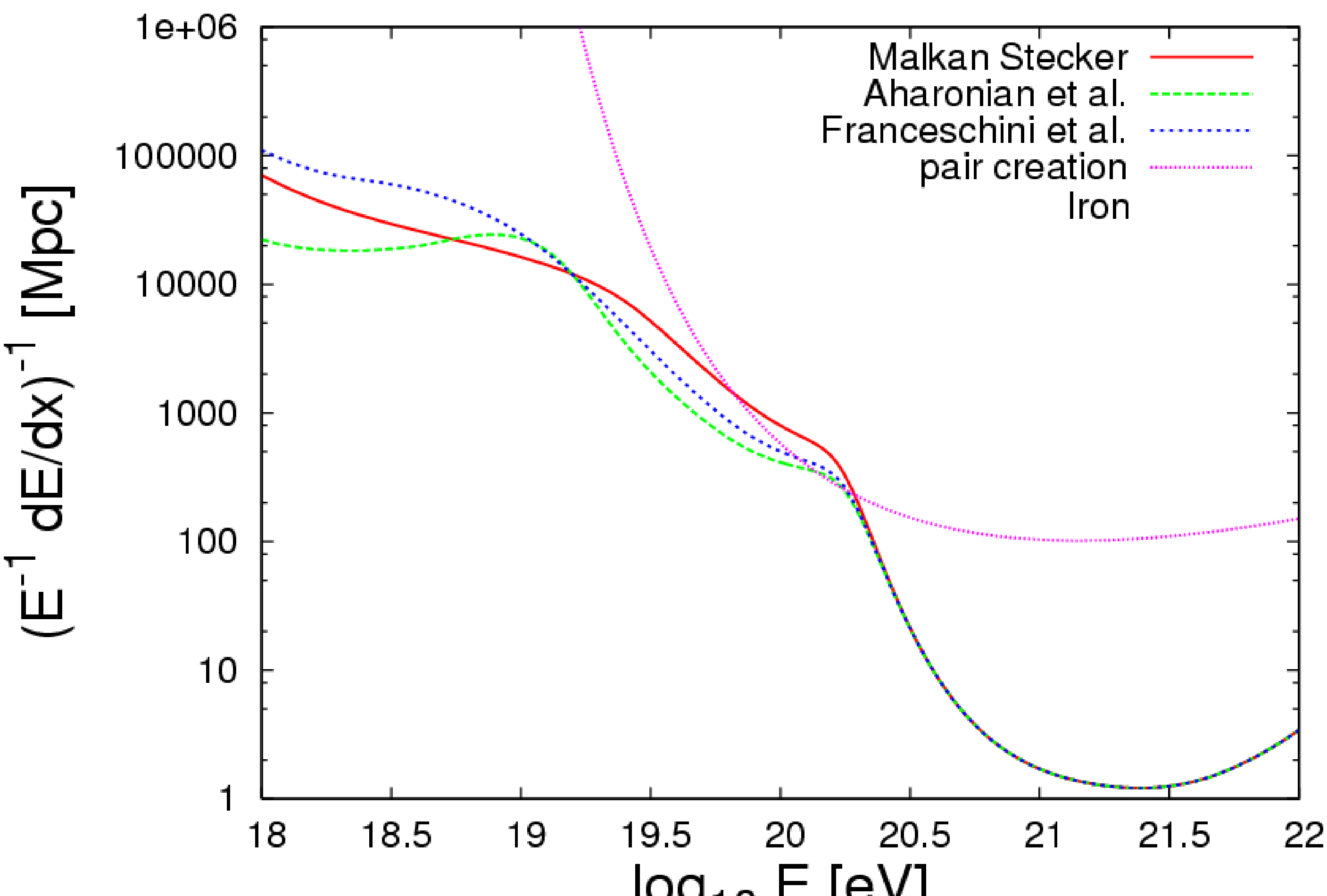
Cosmic Radiation Fields



Energy Loss Rates due to Nuclei Interactions

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

where R is the energy loss rate



Assumptions about High Energy Cosmic Ray Sources

Energy Distribution of Cosmic Rays

– $dN/dE \sim E^{-2}$ motivated by first order Fermi shock acceleration theory

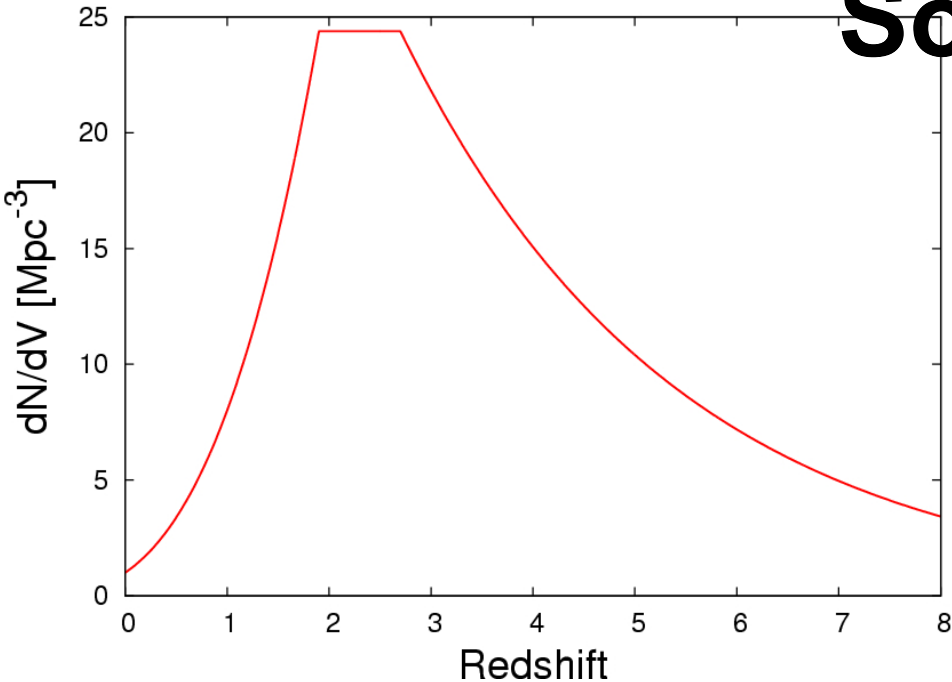
Spatial Distribution of Cosmic Ray Sources

– $dN/dV \sim (1+z)^3$ $\quad 0 < z < 1.9$
$\sim (1+1.9)^3$ $\quad 1.9 < z < 2.7$
$\sim (1+2.7)^3 e^{-z/2.7}$ $\quad 2.7 < z < 8$

motivated by measurements of the luminosity density of Quasars

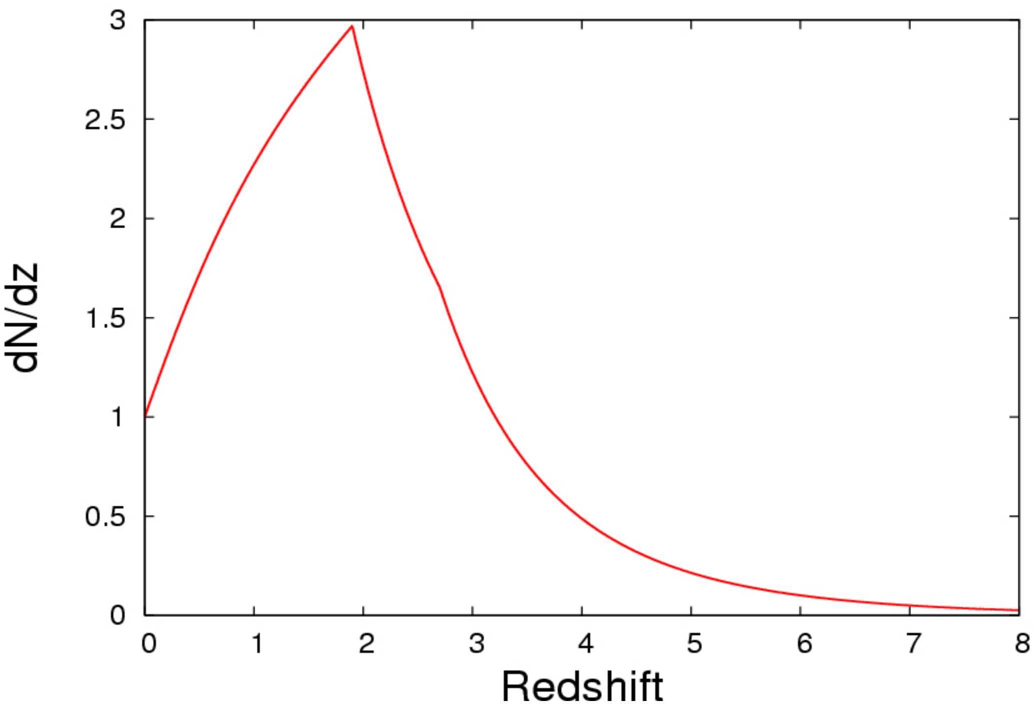
(will say more about this in Lecture 2)

A Cosmological Distribution of Sources



Distribution of sources in a comoving volume

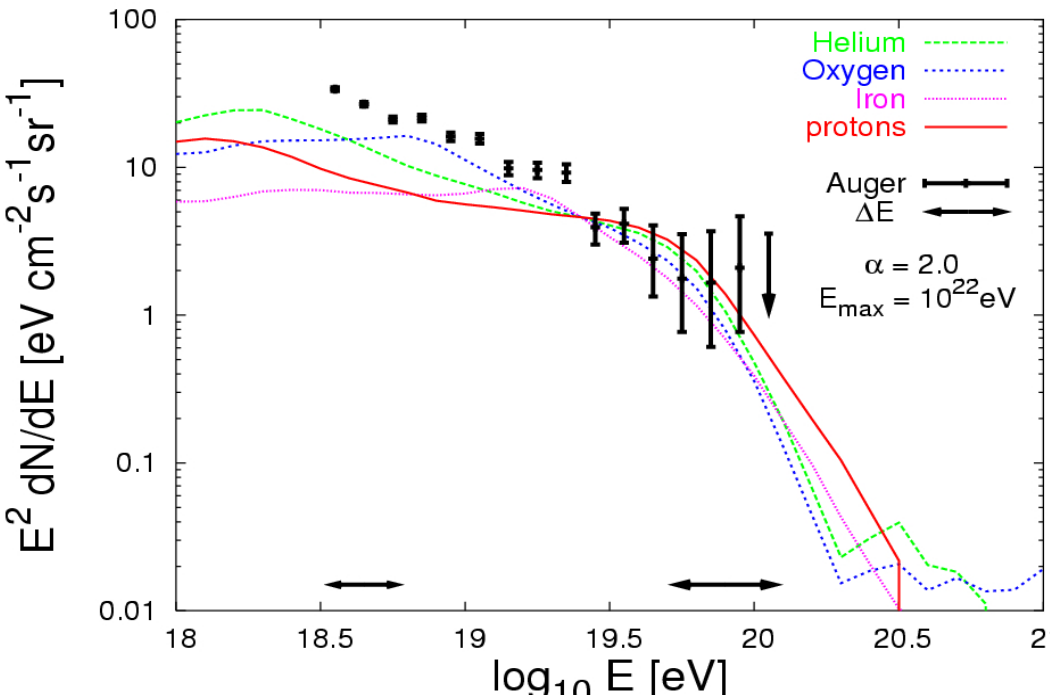
$$dV = 4\pi\chi^2 d\chi$$
$$= 4\pi d_L^{\,2}\, dz/((1+z)^2 H(z))$$

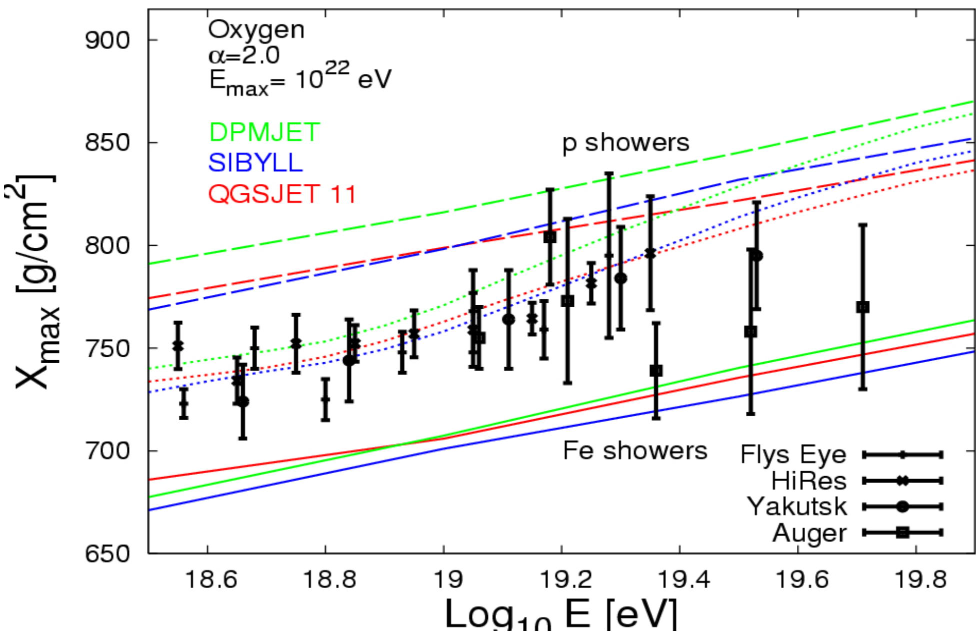


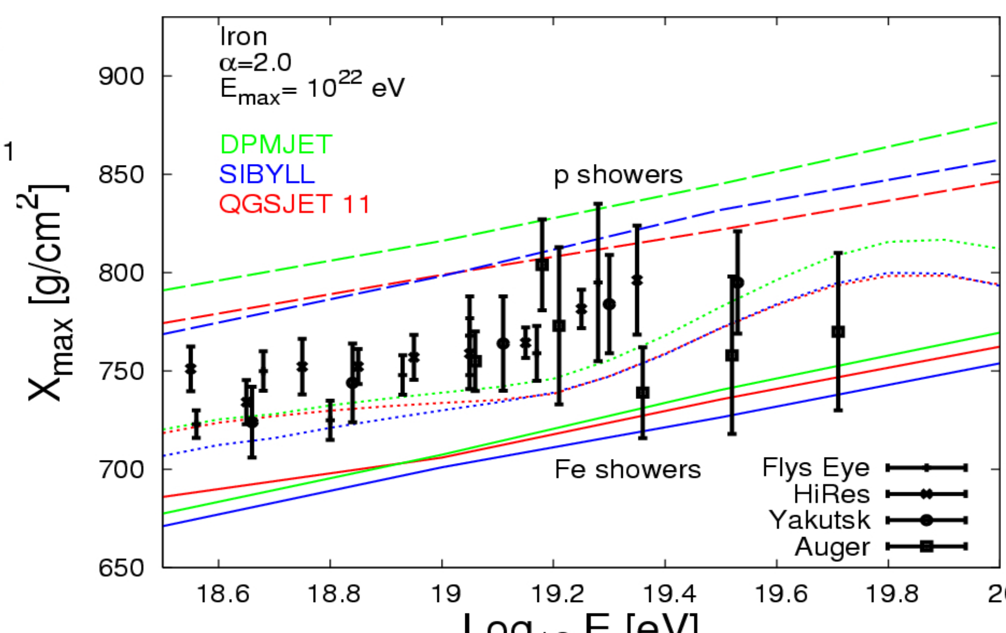
Distribution of sources in redshift

4) Cosmic Ray Spectra for Different Primary Particles

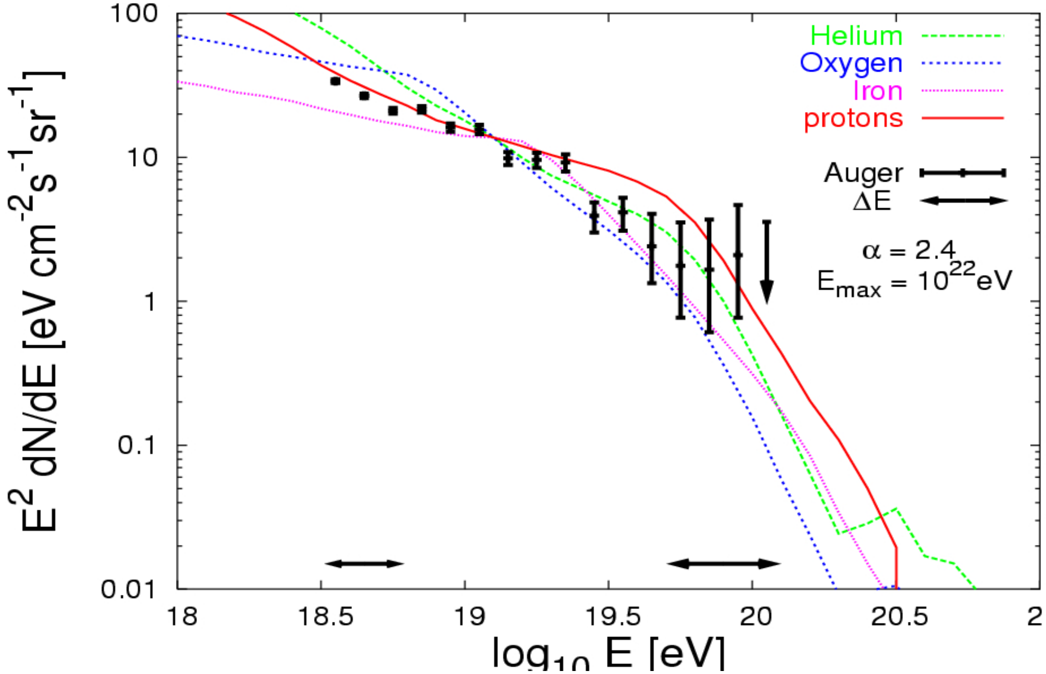
Do Protons or Nuclei Fit the Data?

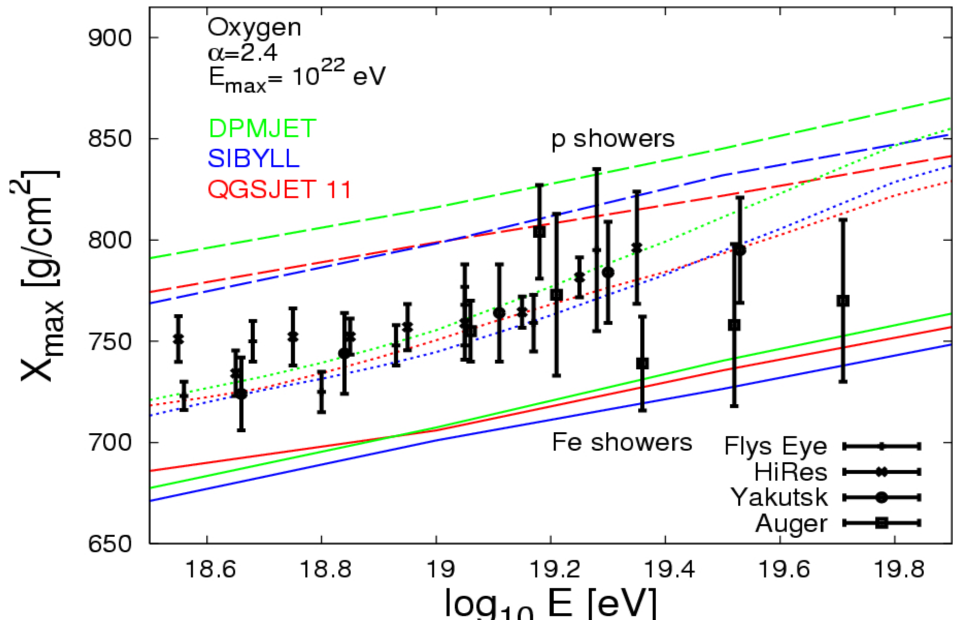


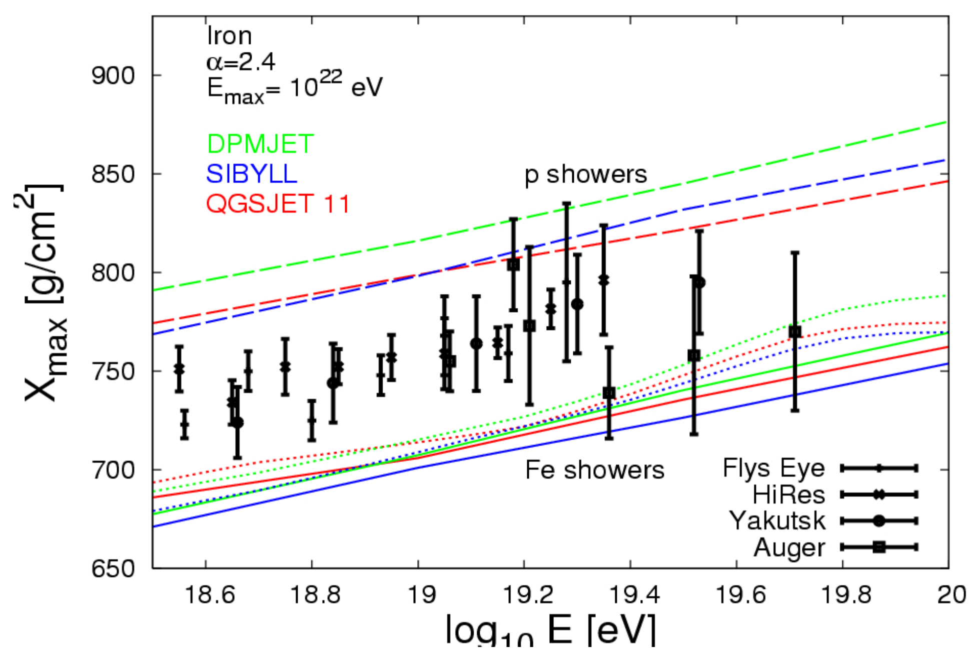




Or


Helium
Oxygen
Iron
protons
Auger
ΔE
α = 2.4
E_max = 10^22 eV
E^2 dN/dE [eV cm^-2 s^-1 sr^-1]
log10 E [eV]


Oxygen
α=2.4
E_max= 10^22 eV
DPMJET
SIBYLL
QGSJET 11
p showers
Fe showers
Flys Eye
HiRes
Yakutsk
Auger
X_max [g/cm^2]
log10 E [eV]


Iron
α=2.4
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DPMJET
SIBYLL
QGSJET 11
p showers
Fe showers
Flys Eye
HiRes
Yakutsk
Auger
X_max [g/cm^2]
log10 E [eV]

5) An Analytic Description of these Results

the differential equation describing the states of the system-

$$\frac{d}{dt}\begin{pmatrix} f_{56} \\ f_{55} \\ f_{54} \end{pmatrix} = \Lambda \begin{pmatrix} f_{56} \\ f_{55} \\ f_{54} \end{pmatrix}$$

$$\Lambda = \begin{pmatrix} -\left(\frac{1}{\tau_{56\to55}} + \frac{1}{\tau_{56\to54}} + \ldots\right) & 0 & 0 \\ \frac{1}{\tau_{56\to55}} & -\left(\frac{1}{\tau_{55\to54}} + \frac{1}{\tau_{55\to53}} + \ldots\right) & 0 \\ \frac{1}{\tau_{56\to54}} & \frac{1}{\tau_{55\to54}} & -\left(\frac{1}{\tau_{54\to53}} + \frac{1}{\tau_{54\to52}} + \ldots\right) \end{pmatrix}$$

by $$f_q(t) = \Sigma_{n=q}^{56} A_n f_n(t)$$

then $$f_q(t) = \Sigma_{n=q}^{56} A_n e^{\lambda_n t} f_n(0)$$

(where A_n values are set by the initial conditions) considering only single nucleon loss, keep only diagonal and first off diagonal elements-

$$\Lambda = \begin{pmatrix} \frac{-1}{\tau_{56\to55}} & 0 & 0 \\ \frac{1}{\tau_{56\to55}} & \frac{-1}{\tau_{55\to54}} & 0 \\ 0 & \frac{1}{\tau_{55\to54}} & \frac{-1}{\tau_{54\to53}} \end{pmatrix}$$

and

$$f_q(t) = \Sigma_{n=q}^{56} \frac{\tau_q \tau_n^{56-q-1}}{\prod_{p=q}^{56} (\tau_n - \tau_p)} e^{\frac{-t}{\tau_n}} f_n(0)$$

INTERACTION OF ULTRA-HIGH ENERGY COSMIC RAYS WITH MICROWAVE BACKGROUND RADIATION

F. A. AHARONIAN[1], B. L. KANEVSKY[2], and V. V. VARDANIAN[1*]

(Received 18 October, 1989)

Abstract. The formation of the 'bump' and the 'black-body cutoff' in the cosmic-ray (CR) spectrum arising from the π-meson photoproduction reaction in collisions of UHE CR protons with the microwave background radiation (MBR) is studied. A kinetic equation which describes CR proton propagation in the MBR with account of the catastrophic nature of the π-meson photoproduction process is derived. The equilibrium CR proton spectrum obtained from the solution of the stationary kinetic equation is in general agreement with the spectrum obtained under assumption of the continuous energy loss approximation. However, the spectra from point sources noticeably differ from those obtained in the continuous loss approximation. Both, the equilibrium and the point source spectra are modified when taking into account the possible deviation of the MBR spectrum from the Planckian one in the Wien region. Thus, for the recently measured MBR spectrum, which reveals an essential 'excess' in the submillimeter region, the 'black-body cutoff' and the preceding 'bump' shift towards lower energies.

1. Introduction

The ultra-high energy cosmic-ray (CR) interaction in the intergalactic space with the microwave background radiation (MBR) gives rise to a 'black-body cutoff' of the CR spectrum predicted more than 20 years ago (Greisen, 1966; Zatsepin and Kuzmin, 1966). Unfortunately, the available experimental data do not allow us to draw an unambiguous conclusion concerning the presence or absence of such a spectral peculiarity (see, e.g., Watson, 1985). At the same time, in the energy range $E > 10^{19}$ eV the Fly's Eye has detected some excess (a 'bump') in the spectrum (Baltrusaitis *et al.*, 1985), which agrees with the evidence obtained by Haverah Park (Cunningham *et al.*, 1980), Volcano Ranch (Linsley, 1985), and Akeno (Teshima *et al.*, 1987) groups to a tendency of spectrum flattening in this energy region. With a lesser confidence this peculiarity is also revealed in the data of Yakutsk (Khristiansen, 1985) and Sydney (Winn *et al.*, 1985) extensive air shower (EAS) arrays.

Hill and Schramm (1985), examining the UHE proton transfer in the MBR field, arrived at a rather important conclusion that due to the pion photoproduction process, besides the 'black-body cutoff', there is also formed a 'bump' (preceding the cutoff). The latter spectral peculiarity is apparently due to a sharp (exponential) energy dependence of the proton-free path (owing to the threshold nature of the $\gamma p \to \pi N$ process, protons with energy $E < 10^{20}$ eV interact only with the Wien 'tail' of the MBR spectrum). Protons with energy $E \geq 5 \times 10^{19}$ eV effectively interact with the MBR, deposit energy

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[2] Institute of Nuclear Physics, Moscow State University, U.S.S.R.
[*] Deceased, August 13, 1989.

Astrophysics and Space Science **167**: 93–110, 1990.

of this equation we present in the form of an iterative series

$$F_n(E, t) = q(E)\,e^{-t/\tau} + q(E)\int_0^t \mathrm{d}t'\, e^{-(t-t')/\tau}\hat{A}F_{n-1}(E, t)\,, \qquad \text{(A2–2)}$$

where $F_0(E, t) = q(E)\,e^{-t/\tau}$ is the initial approximation for the spectrum. For numerical calculations it is convenient to pass to a new function $f(E, t)$ using the replacement

$$F(E, t) = q(E)f(E, t)\,. \qquad \text{(A2–3)}$$

Then for $f(E, t)$ we obtain a solution in the form

$$f_n(E, t) = e^{-t/\tau} + \int_0^t \mathrm{d}t'\, e^{-(t-t')/\tau}\hat{A}_1 f_{n-1}(E, t)\,, \qquad \text{(A2–4)}$$

where the integral term is

$$\hat{A}_1 f = \frac{ckT}{2\pi^2(c\hbar)^3\Gamma^2}\int_{\varepsilon_0}^{\infty} \mathrm{d}\omega_r\, \sigma(\omega_r)\varphi(\omega_r)\omega_r \times$$

$$\times \int_{z_-(\omega_r)}^{z_+(\omega_r)} \mathrm{d}z\, z^{\gamma+1} f(E/z, t)\left[-\ln\left(1 - \exp\left(-\frac{\omega_r z}{2\Gamma kT}\right)\right)\right], \qquad \text{(A2–5)}$$

where $z_\pm$ and φ are determined by the expressions (11).

In the energy region $E \leq 3 \times 10^{20}$ eV the integral term may be approximately presented as

$$\hat{A}_1 f = f(E/z_0, t)z_0^{\gamma-1}/\tau(E/z_0)\,, \qquad \text{(A2–6)}$$

where

$$z_0 = 1 - f(\varepsilon_0)\,. \qquad \text{(A2–7)}$$

The the solution for the function $f(E, t)$ can be presented as

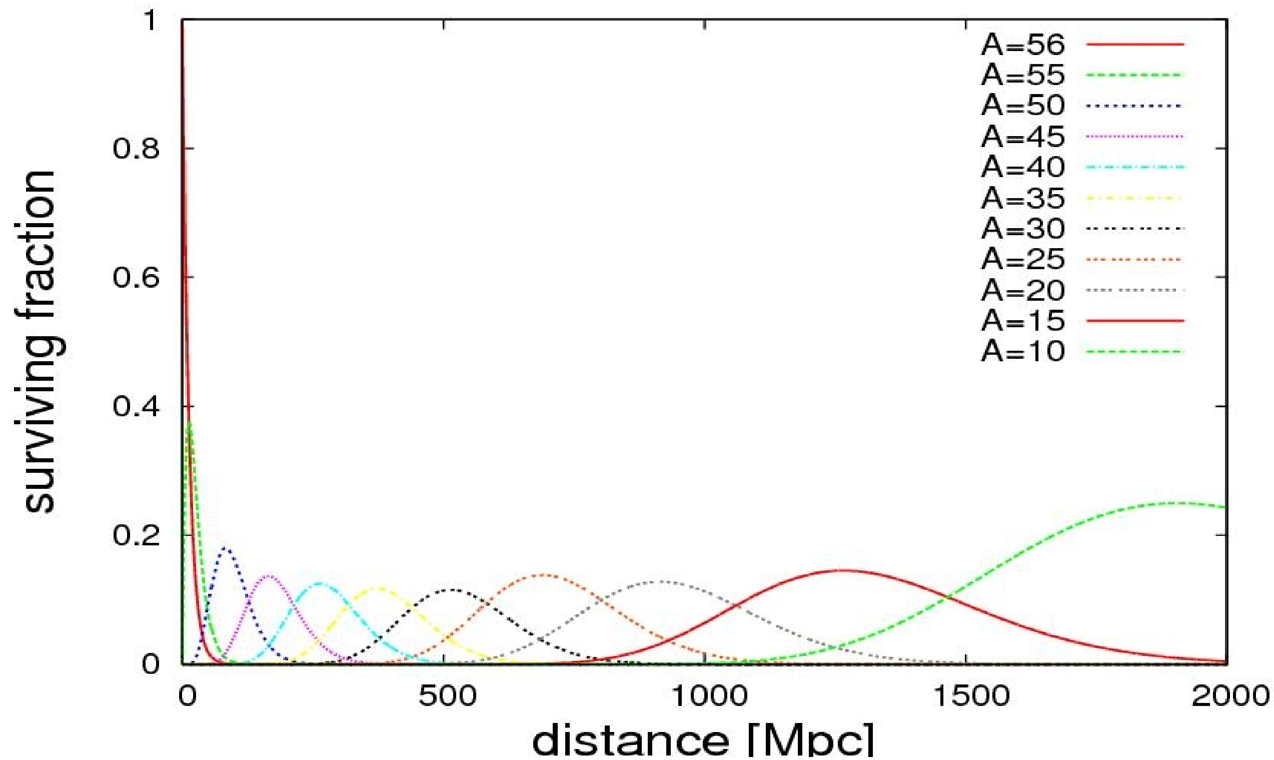
$$f(E, t) = \sum_{n=0}^{\infty} z_0^{n(\gamma-1)} \sum_{j=0}^{n} \frac{\exp(-t/\tau_j)\tau_0/\tau_j}{\prod_{k\neq j}^{n}[1 - \tau_k/\tau_j]}\,, \qquad \text{(A2–8)}$$

where

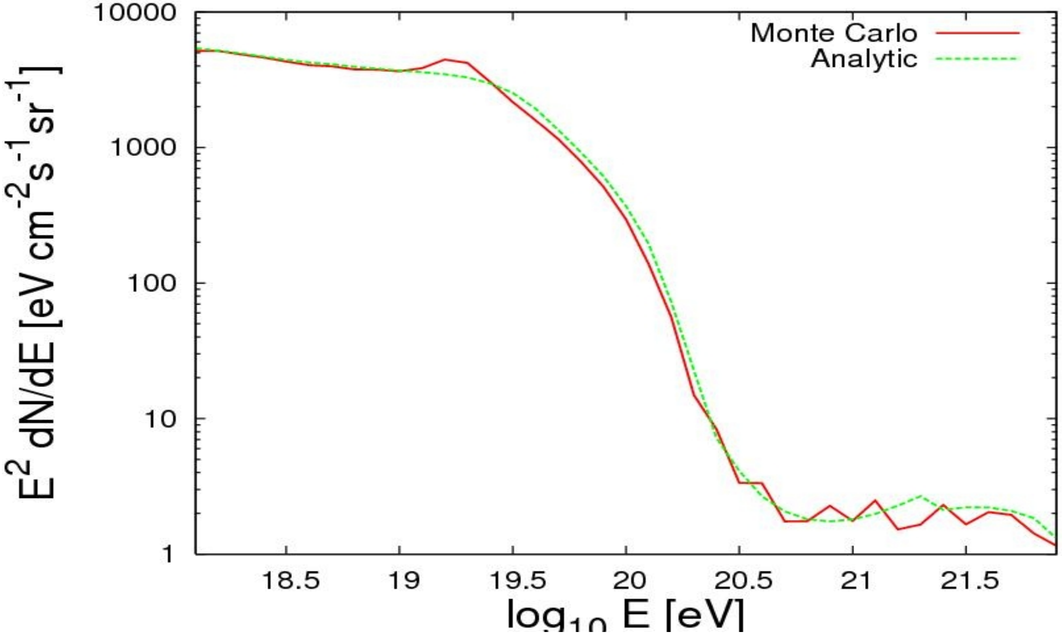
$$\tau_j = \tau(E/z_0^j)\,; \quad \tau_0 = \tau(E)\,. \qquad \text{(A2–9)}$$

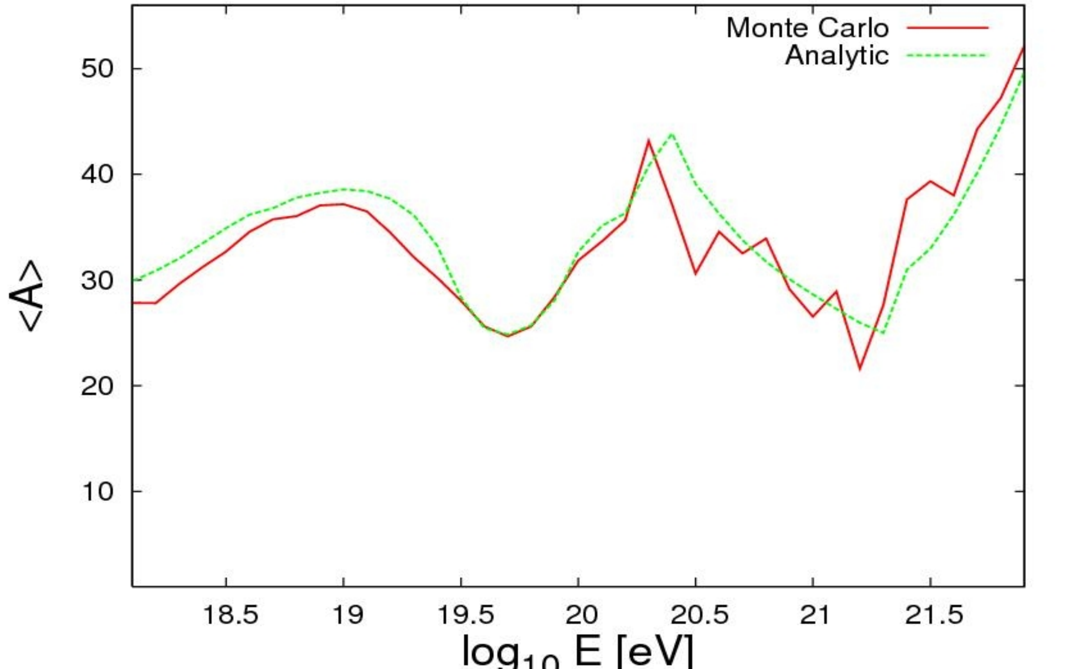
The MBR deviation from the Planckian spectrum (in case of its approximation by the comptonized black-body radiation spectrum (14)) for the proton spectrum from a point source, can be taken into account just like in case of the equilibrium proton spectrum (see Appendix 1).

Injecting a 10^{20}eV Fe Nucleus and Tracking the Subsequent Nuclei-



Comparison of Analytic and Monte Carlo Results





Conclusions

- The Pierre Auger Observatory is able to provide much more than just the cosmic ray flux measurement

- Due to the ln E_0 dependence of X_{max}, excellent energy resolution is required to pull out the composition information

- The X_{max} and energy spectrum data collectively can provide useful information about the source injection spectrum and cutoff energy

- The propagation of nuclei can be easily understood through the application of an analytic description of the photo-disintegration process

Cosmic Ray Showers in the Atmosphere

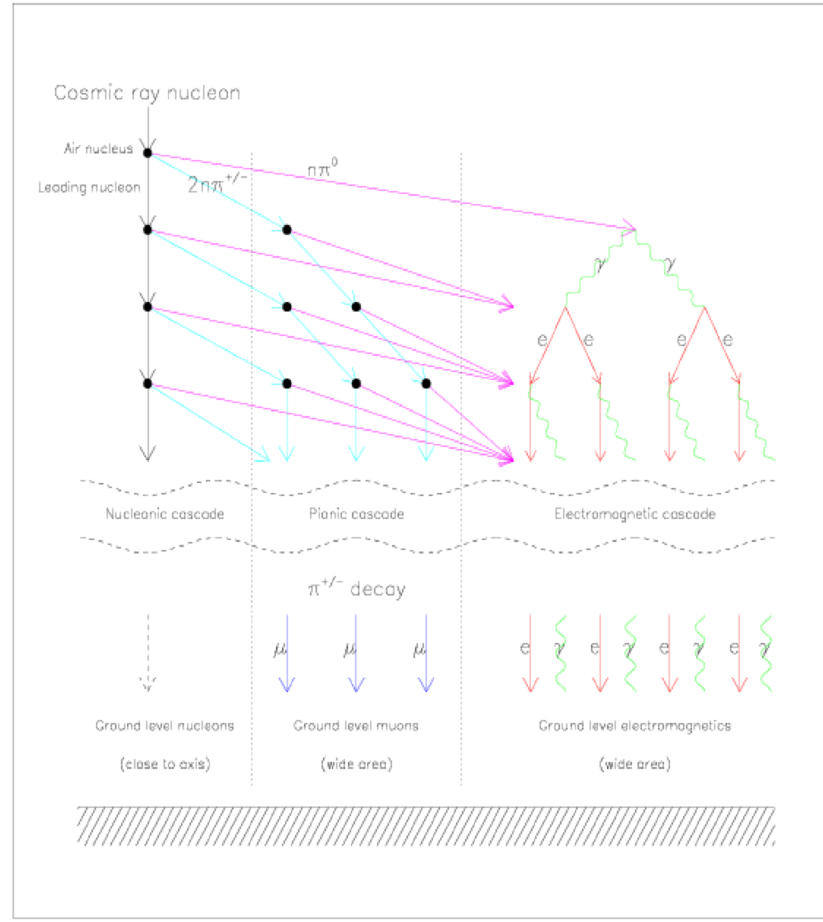
- $$N_\mu^p(E_0) \propto E_0^\beta$$

$$N_\mu^{Fe}(E_0) \propto A\left(\frac{E_0}{A}\right)^\beta \propto A^{1-\beta} E_0^\beta$$

$$\beta \sim 0.85 - 0.92$$

- 40-80 % more muons for Fe showers

90% of the energy of the primary is dissipated into γ and e (in ratio 9:1)



note- more μ than expected are seen in the showers (indication of Fe in showers)