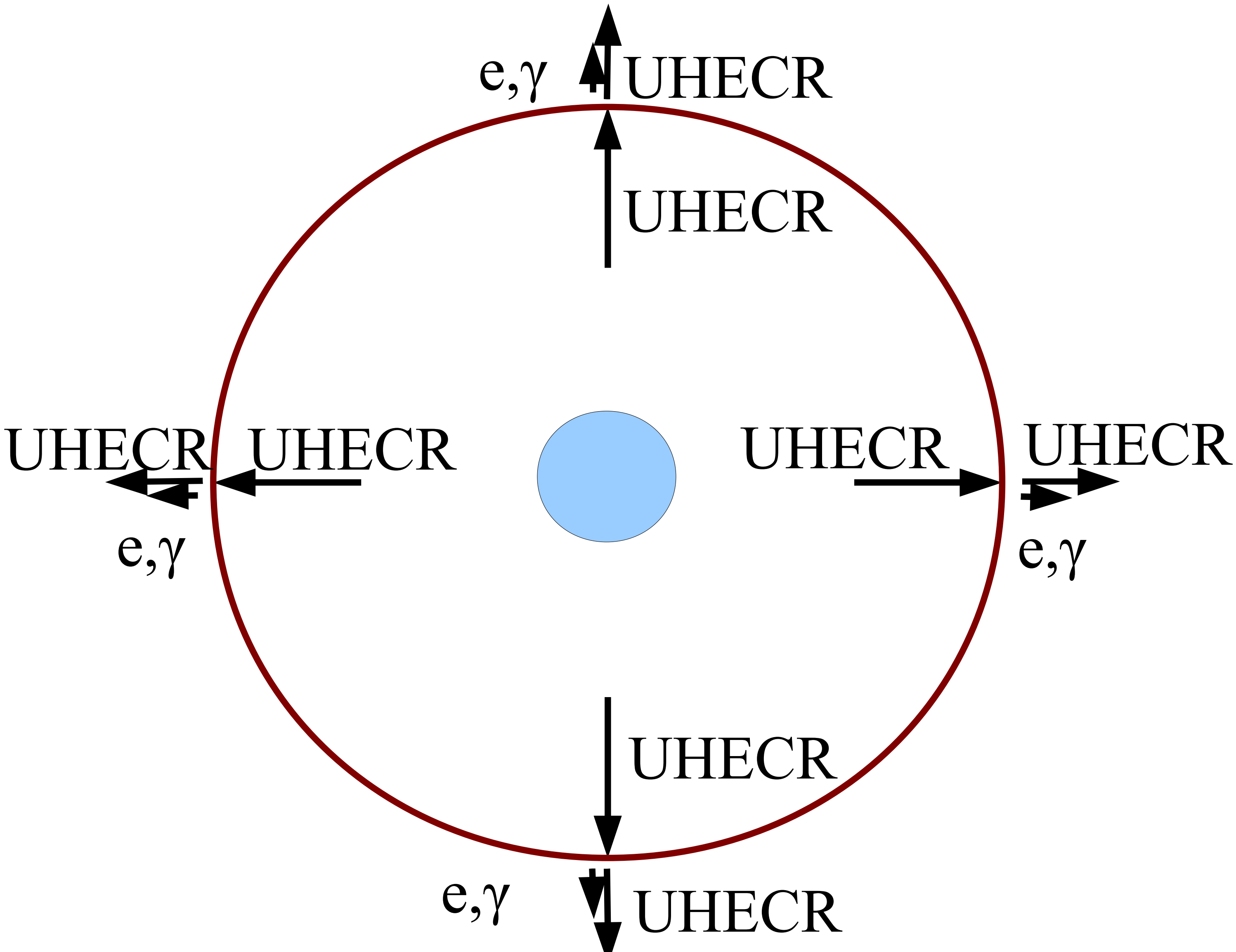
The Origin of Extragalactic Cosmic Rays



Talk(2): “Secondaries”

Composition (lightening of it away from the source)

1) What source injection spectra + composition would be consistent with Auger observational result?

2) What constraints do these fits place on the local source distribution?

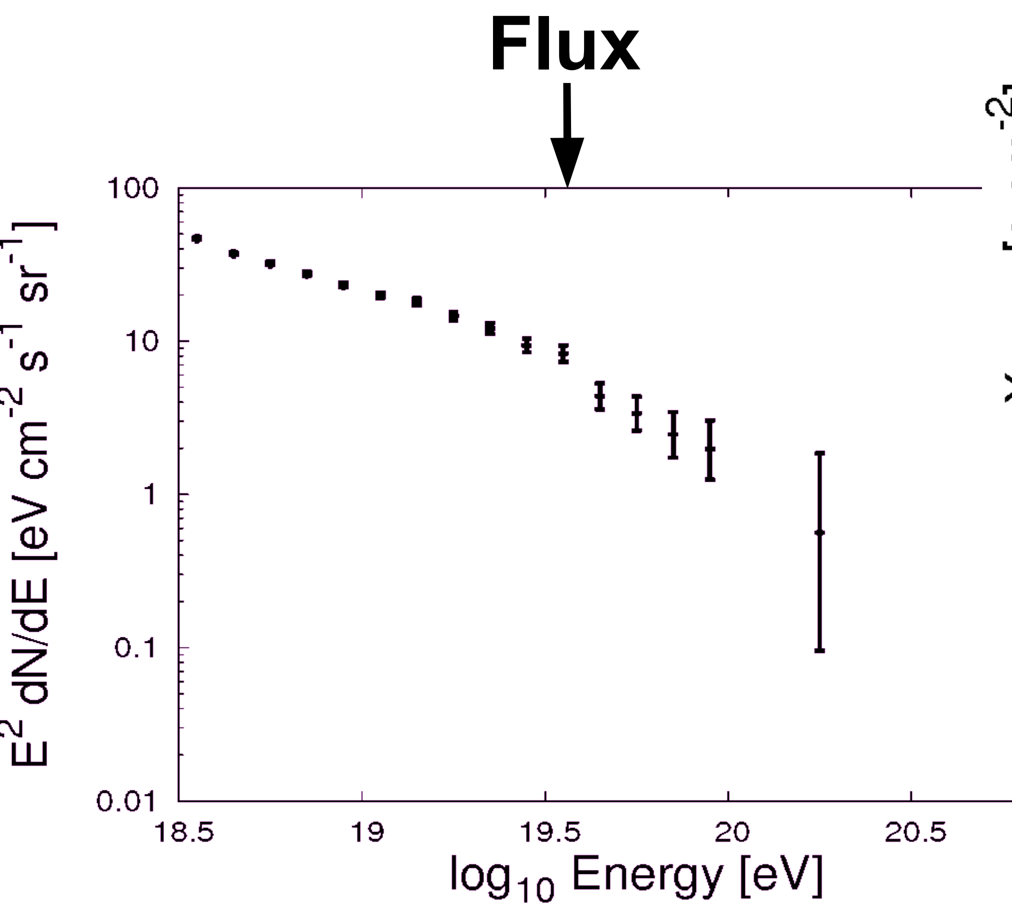
Gamma-Rays Surrounding the Source

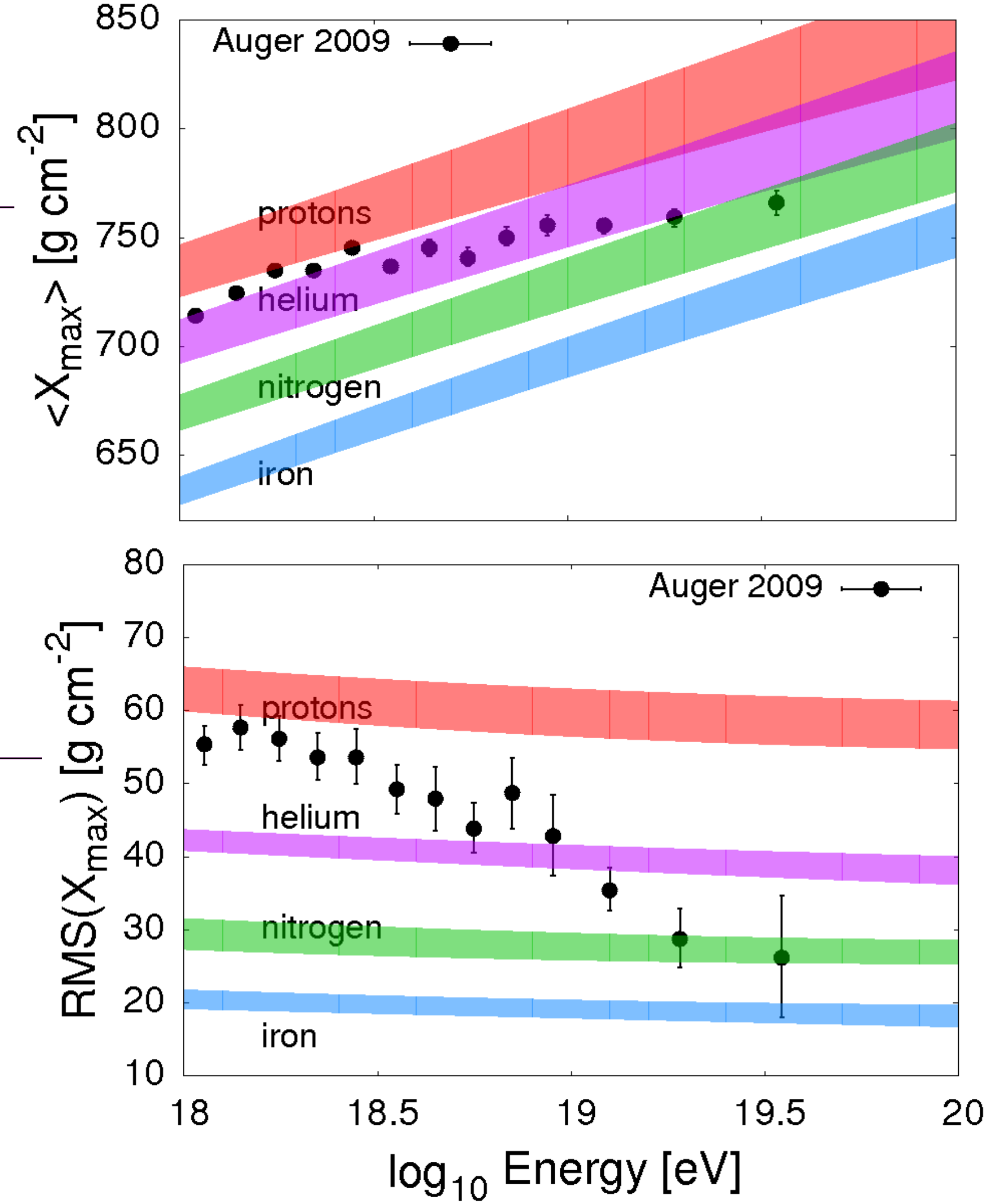
3) Gamma-ray birth + death rates in regions surrounding the source- demographics

4) What current Auger Gamma-Ray limits can say about the sources

Part 1:
Composition

Reminder- The Composition that Arrives



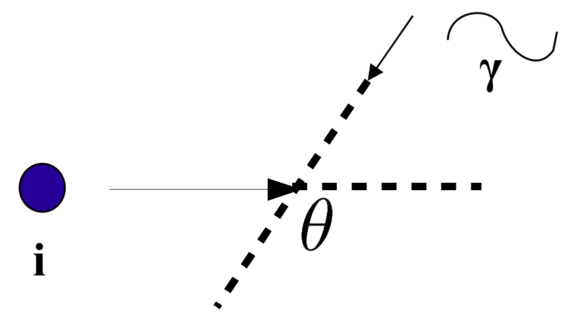


General- Interaction Rate Convolution

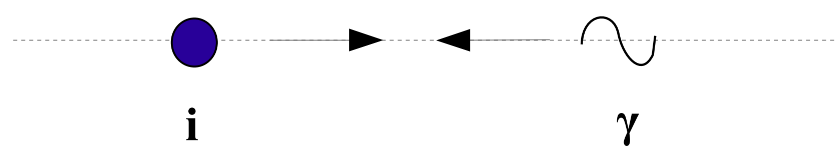
(all values in lab frame)

$$t_{\mathrm{int.}}^{-1} = \int_0^{\infty} \frac{dn}{d\epsilon_\gamma} d\epsilon_\gamma \int_{-1}^{1} \frac{1}{2} \frac{d\sigma}{d(\cos\theta)} (1 - \beta\cos\theta) d(\cos\theta)$$

Lab Frame



Center-of-Mass Frame



target photons ↓ cross-section ↓

$$t_{\mathrm{int.}}^{-1} = \frac{m_p^2}{2E_p^2} \int_0^{\infty} \frac{n(\epsilon'_\gamma)}{\epsilon'^2_\gamma} d\epsilon'_\gamma \int_0^{2\epsilon'_\gamma \frac{E_p}{m_p}} \epsilon_\gamma \frac{d\sigma}{d\epsilon_\gamma} d\epsilon_\gamma$$

Interaction Rate + Attenuation Rate

Interaction Rate

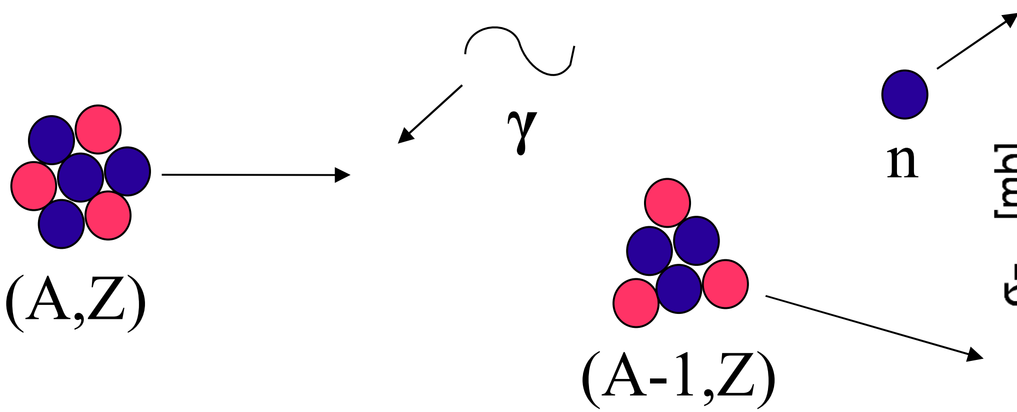
$$t_{\mathrm{int.}}^{-1} = \frac{m_p^2}{2E_p^2} \int_0^\infty \frac{n(\epsilon'_\gamma)}{\epsilon'^2_\gamma} d\epsilon'_\gamma \int_0^{2\epsilon'_\gamma \frac{E_p}{m_p}} \epsilon_\gamma \frac{d\sigma}{d\epsilon_\gamma} d\epsilon_\gamma$$

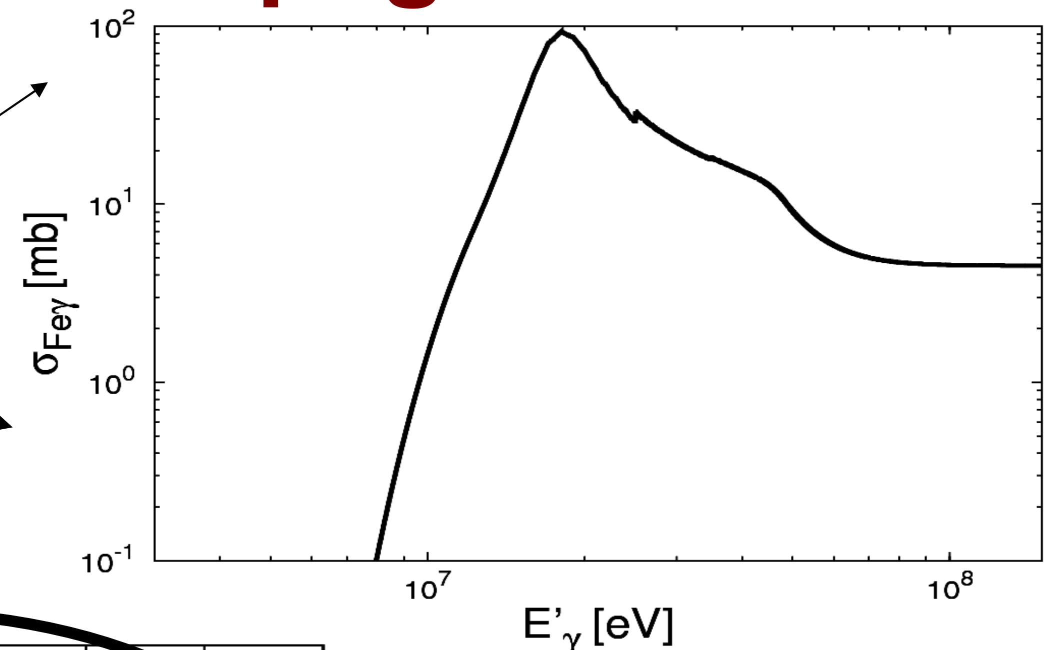
Attenuation Rate

$$t_{\mathrm{att.}}^{-1} = \frac{m_p^2}{2E_p^2} \int_0^\infty \frac{n(\epsilon'_\gamma)}{\epsilon'^2_\gamma} d\epsilon'_\gamma \int_0^{2\epsilon'_\gamma \frac{E_p}{m_p}} K_{p\gamma} \epsilon_\gamma \frac{d\sigma}{d\epsilon_\gamma} d\epsilon_\gamma$$

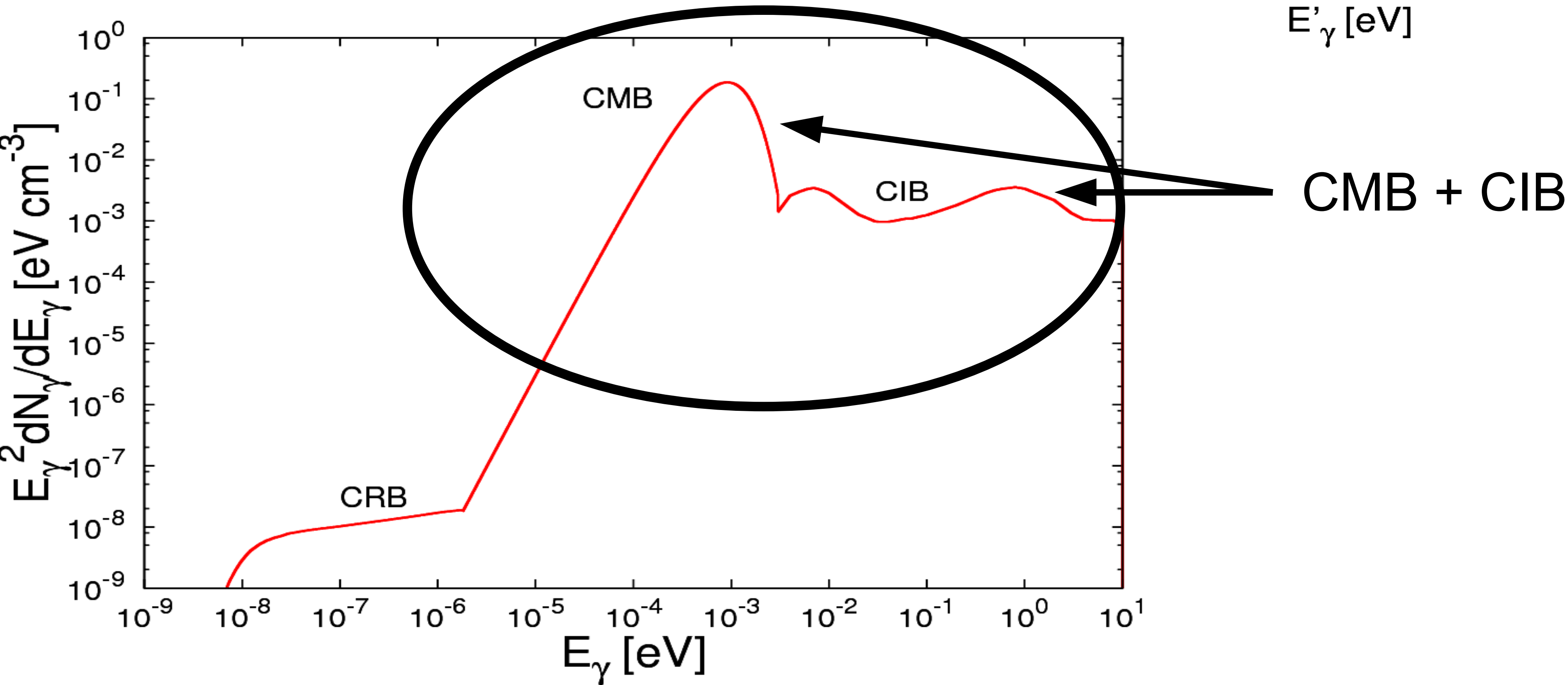
UHECR Nuclei Propagation

nuclei

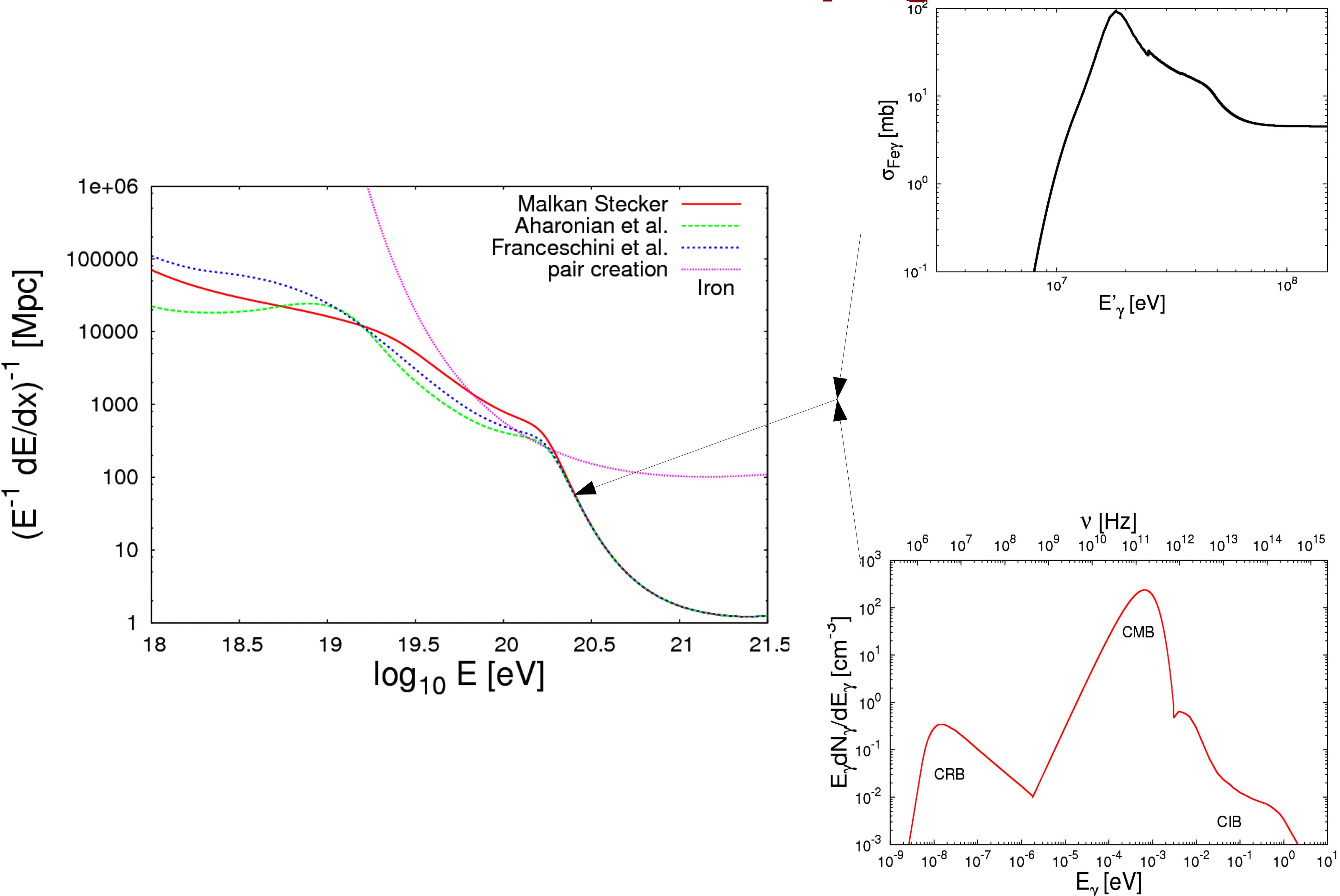




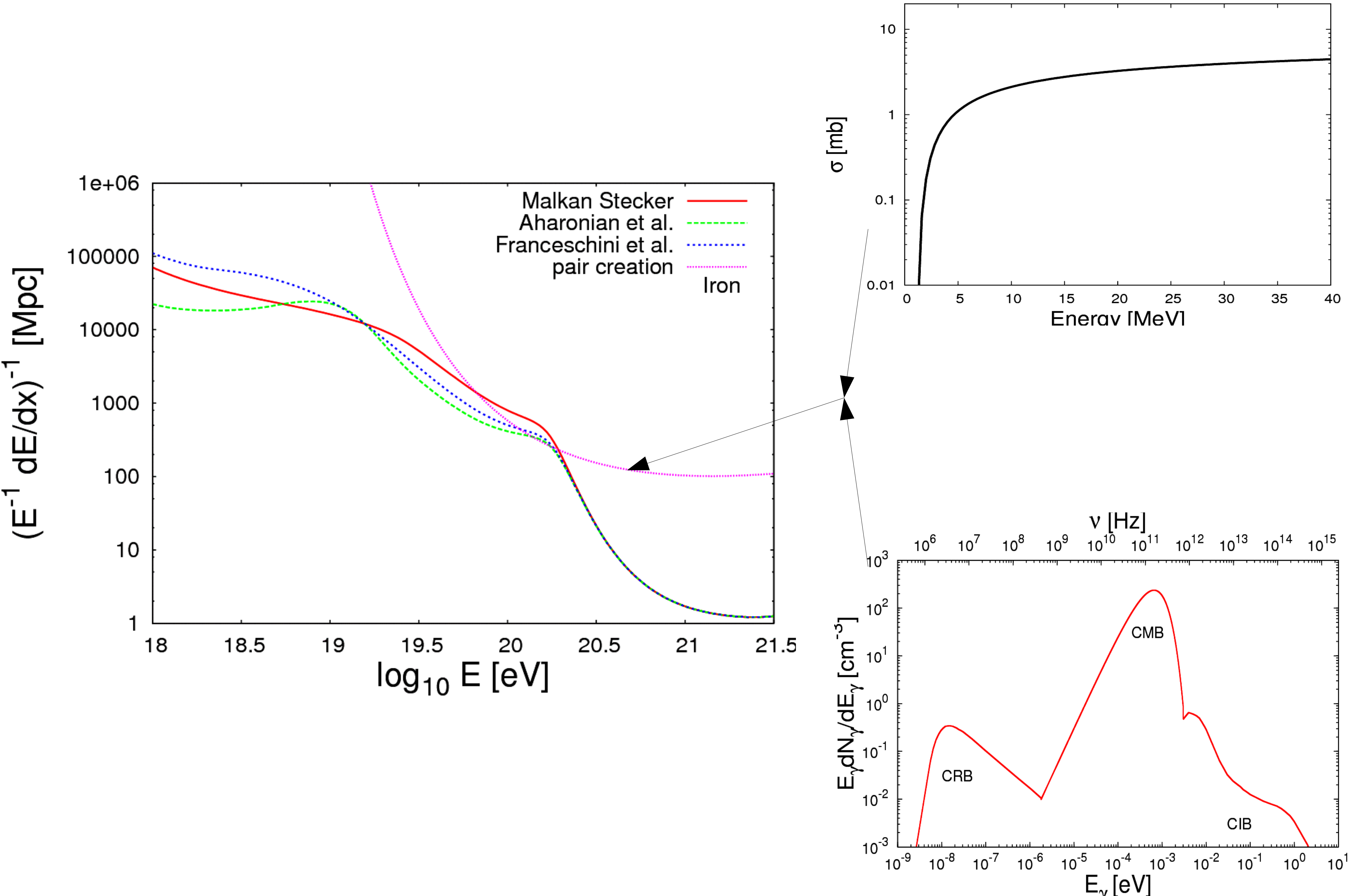
$$s \approx 10^{16}\ \mathrm{eV}^2$$



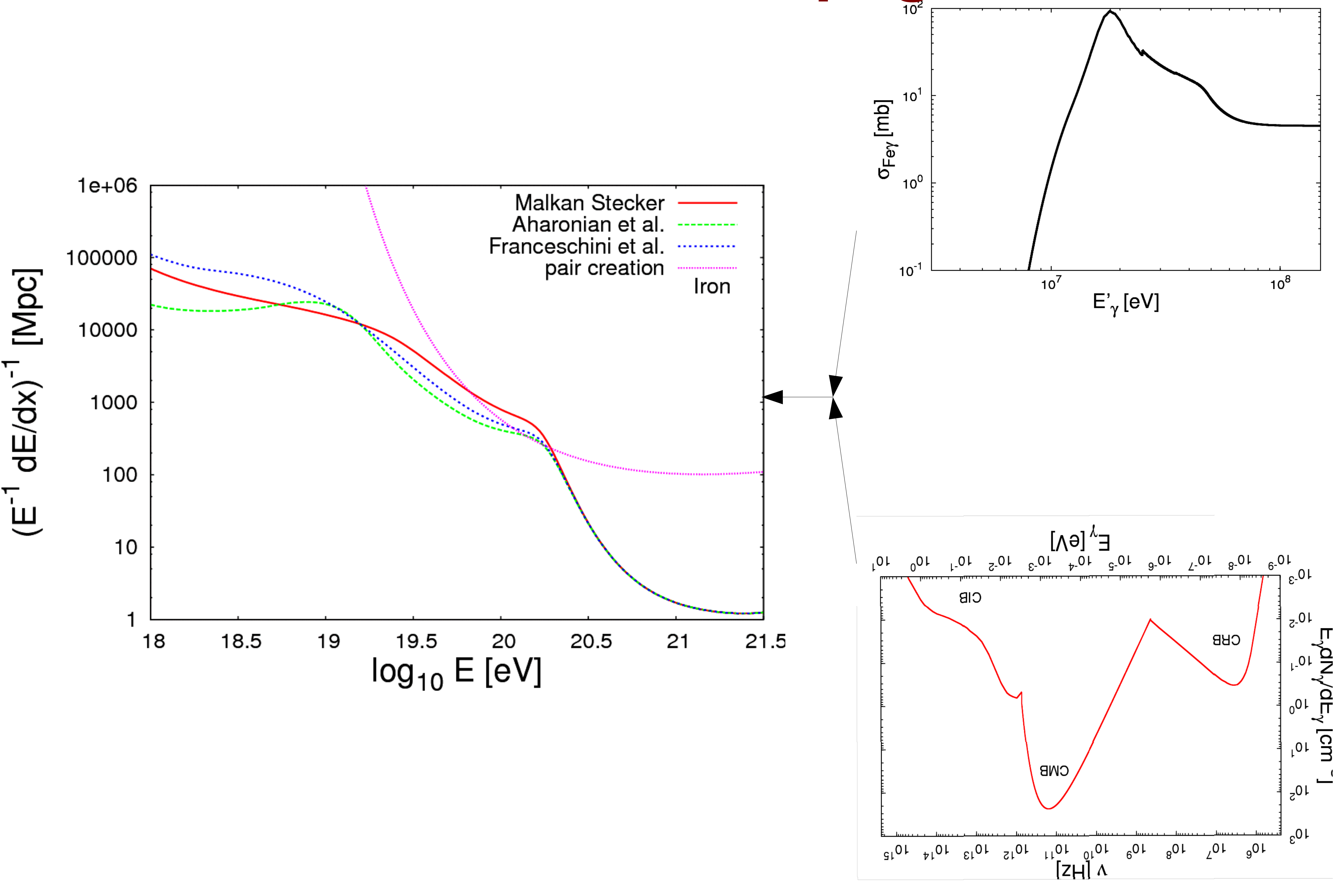
UHECR Nuclei Propagation



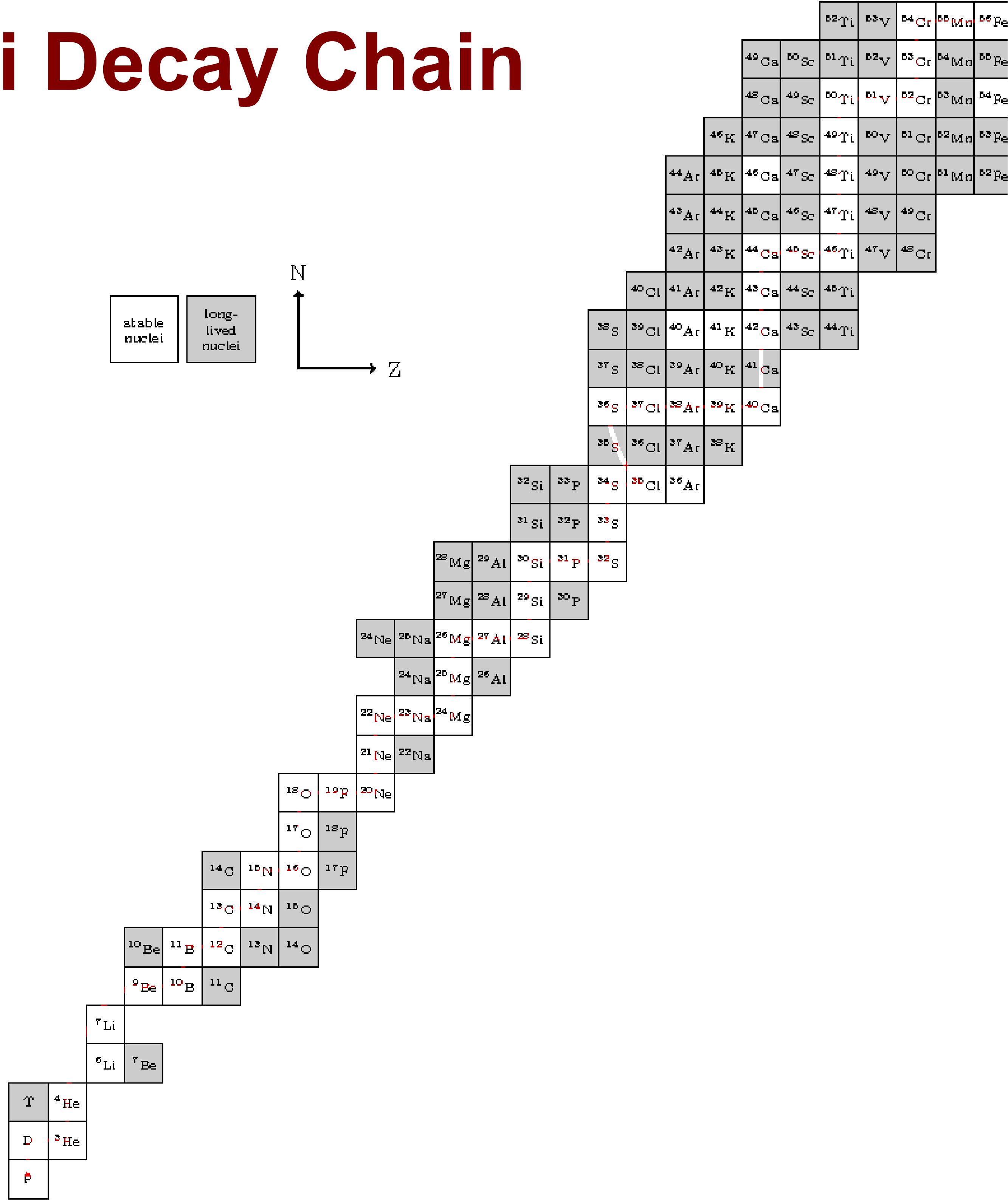
UHECR Nuclei Propagation



UHECR Nuclei Propagation



UHECR Nuclei Decay Chain

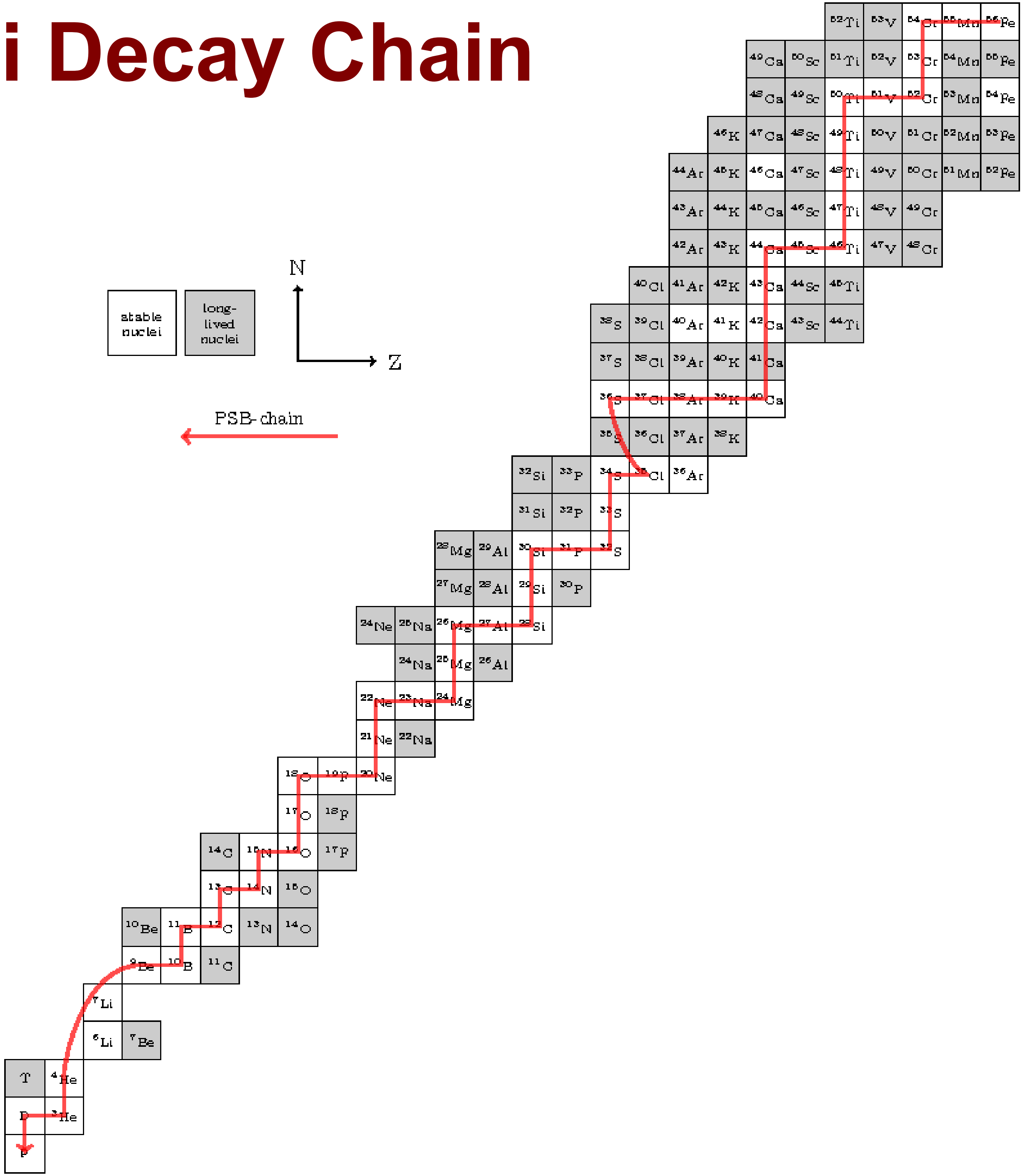


Cascade Through Nuclear Species

$$\frac{\boldsymbol{d}}{\boldsymbol{dt}} \left(\begin{array}{c} \boldsymbol{f_{56}} \\ \boldsymbol{f_{55}} \\ \boldsymbol{f_{54}} \end{array} \right) = \boldsymbol{\Lambda} \left(\begin{array}{c} \boldsymbol{f_{56}} \\ \boldsymbol{f_{55}} \\ \boldsymbol{f_{54}} \end{array} \right)$$

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

UHECR Nuclei Decay Chain



Cascade of Nuclei Through Species- single nucleon loss

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

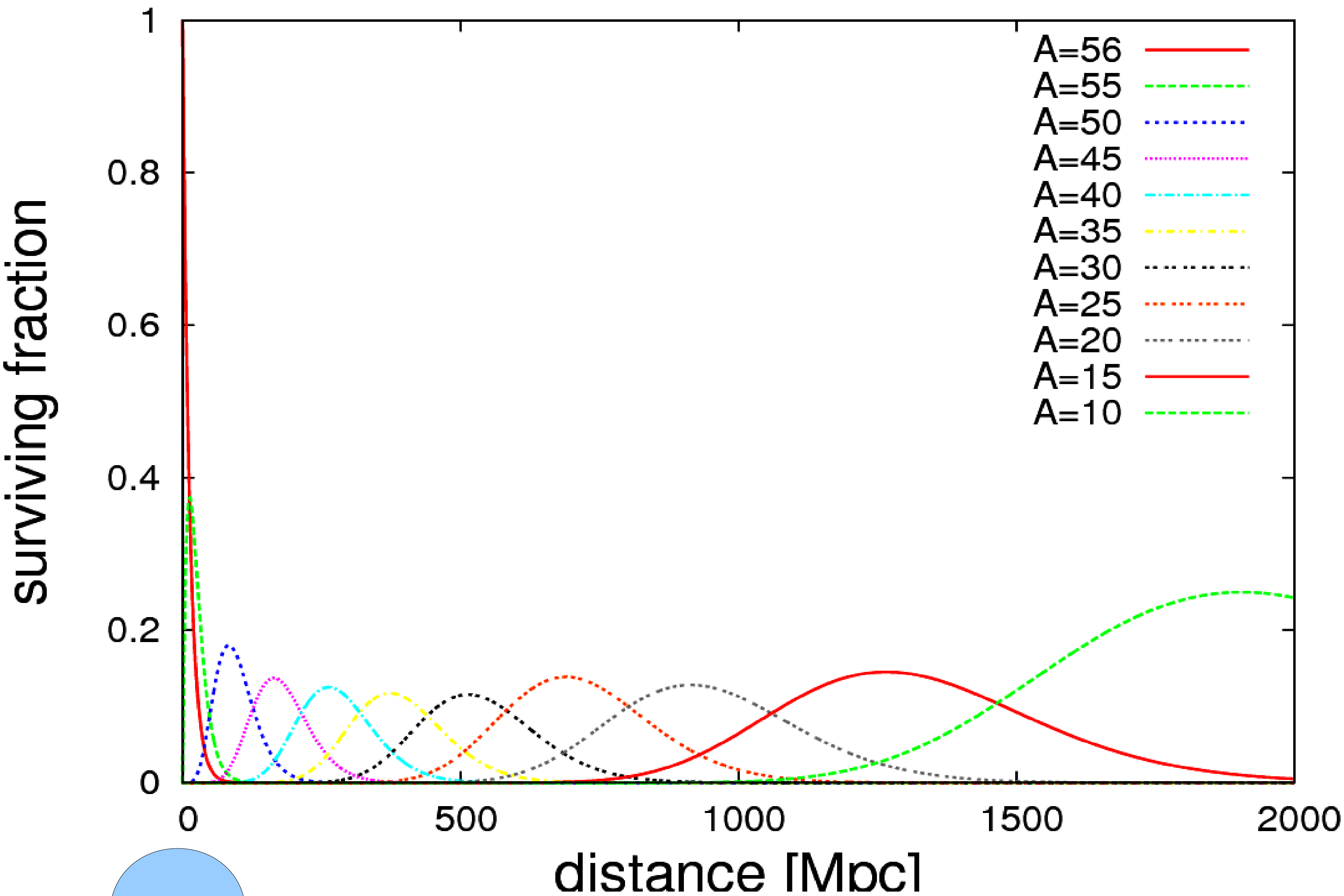
$$\Lambda = \begin{pmatrix} -\frac{1}{\tau_{56\to55}} & 0 & 0 \\ \frac{1}{\tau_{56\to55}} & -\frac{1}{\tau_{55\to54}} & 0 \\ 0 & \frac{1}{\tau_{55\to54}} & -\frac{1}{\tau_{54\to53}} \end{pmatrix}$$

Whose eigenvalues are

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

Nuclei Propagation Away from their Source + their Transmutation

Lorentz factor of nuclei ~conserved



Cascade of Nuclei Through Species- single nucleon loss

Since nuclei Lorentz factor remains ~conserved, and cross-section varies mildly with A (nuclear mass)

$$\tau_{56\rightarrow 55} \approx \tau_{55\rightarrow 54}\cdots$$

For the case $\tau_{56\rightarrow 55} = \tau_{55\rightarrow 54}\cdots$

$$f_q = \frac{t^{(q_{max}-q)}}{\tau_q (q_{max}-q)!} e^{-t/\tau_q}$$

ie. Gaisser-Hillas type function!
(used to describe air showers)

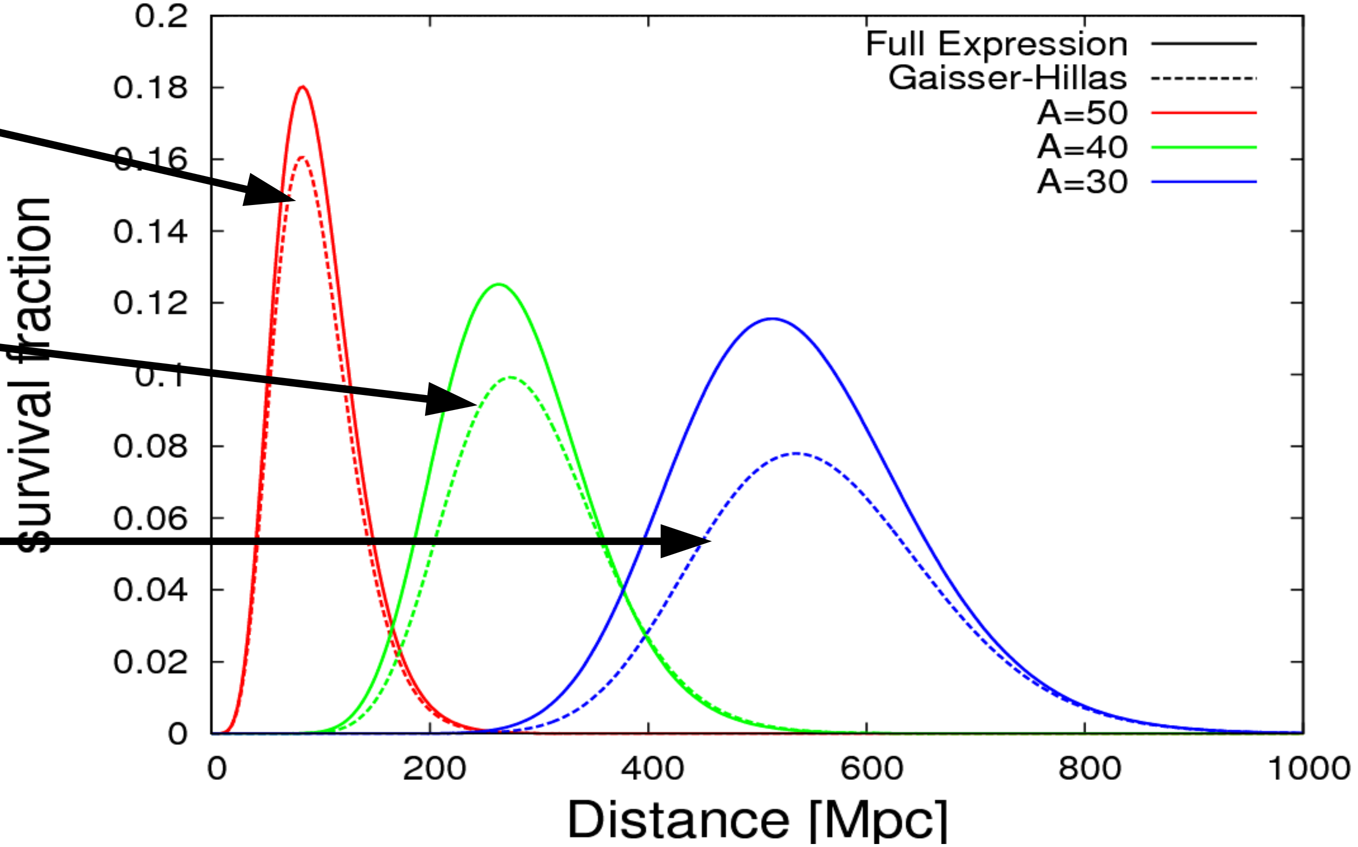
Cascade of Nuclei Through Species- Comparison of Approximation

Starting with Fe, $q_{\max} = 56$

$$f_{50} = \frac{t^6}{6!} e^{-\frac{t}{\tau_{50}}}$$

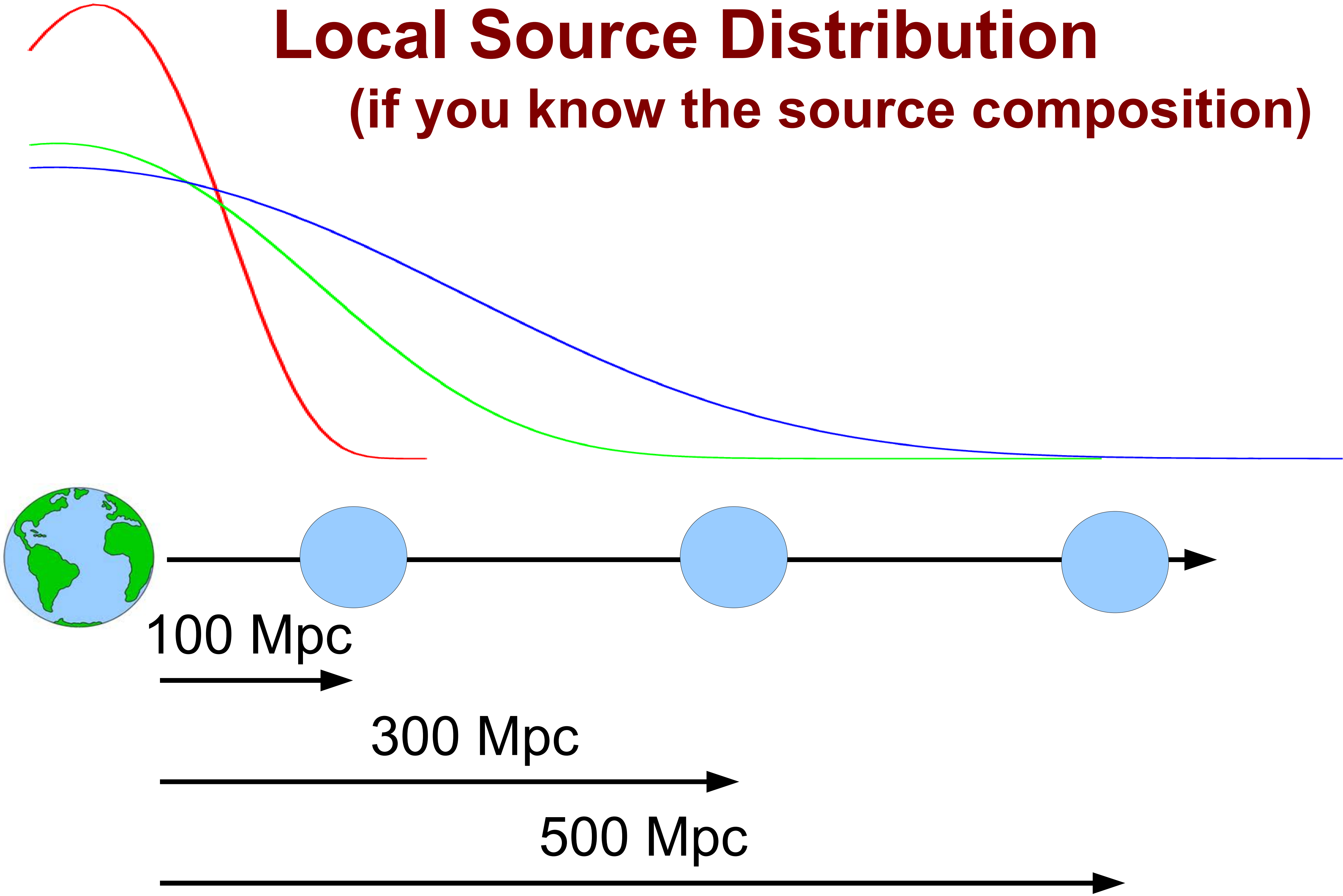
$$f_{40} = \frac{t^{16}}{16!} e^{-\frac{t}{\tau_{40}}}$$

$$f_{30} = \frac{t^{26}}{26!} e^{-\frac{t}{\tau_{30}}}$$



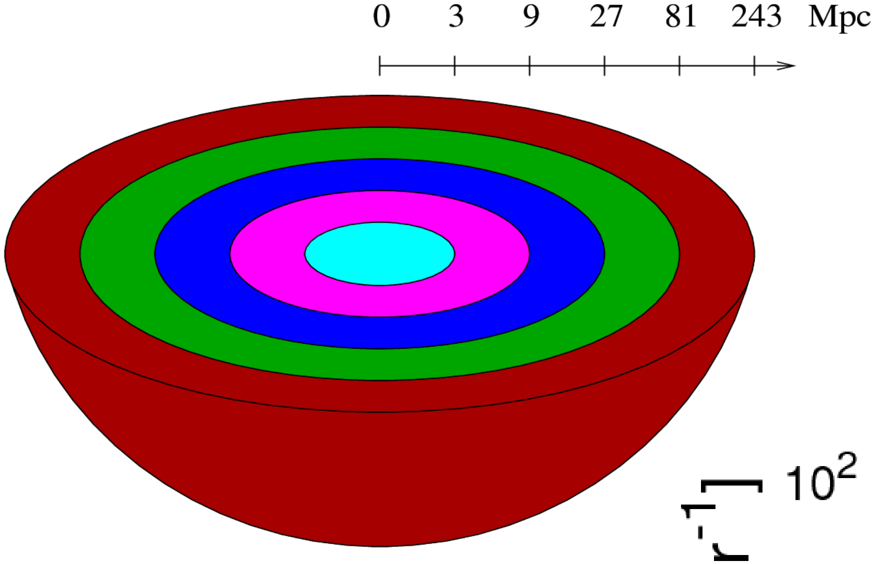
Composition – an Excellent Probe of the Local Source Distribution

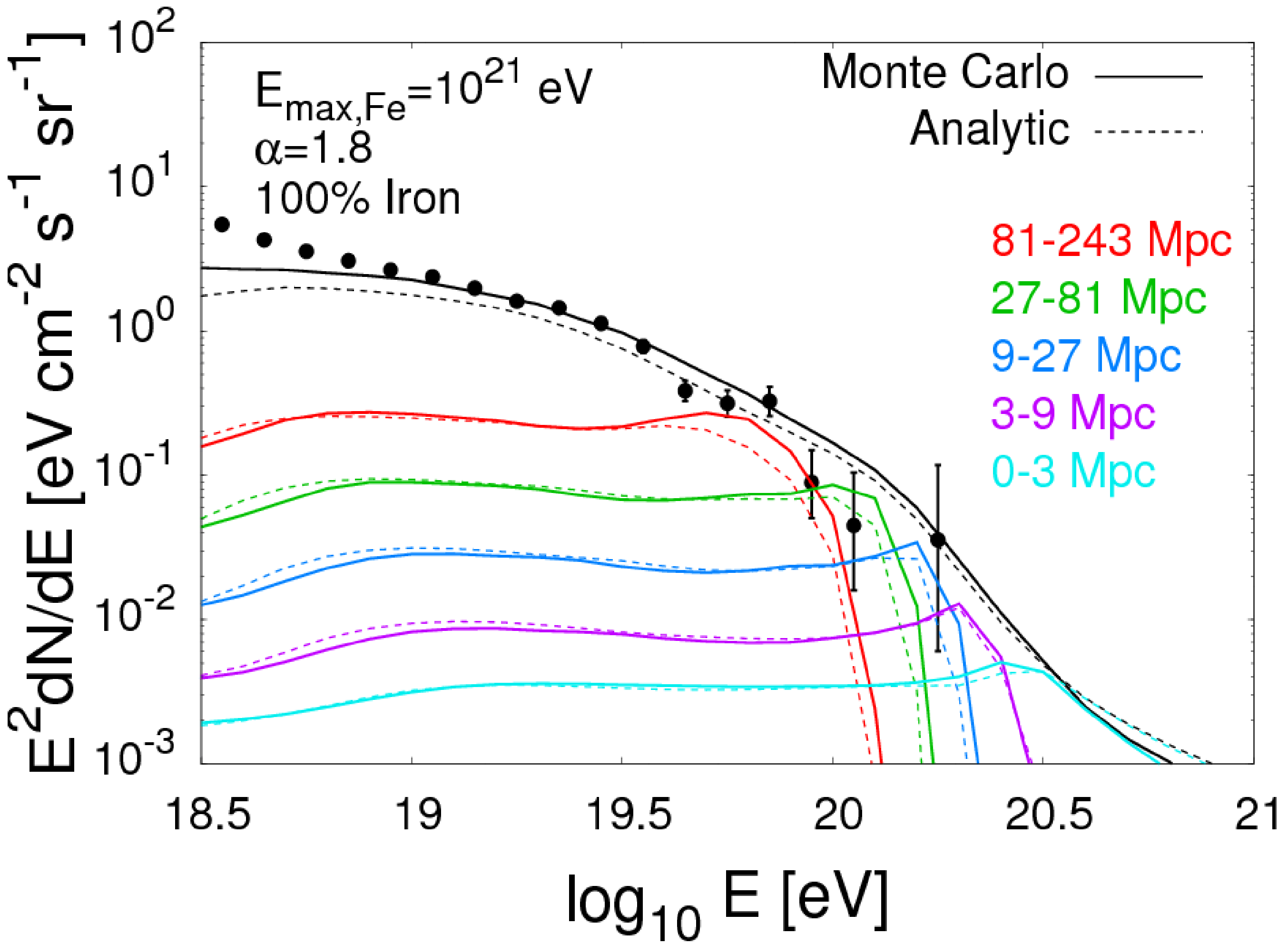
(if you know the source composition)



Local Scales Effect Highest Energies

(logarithmic scale)





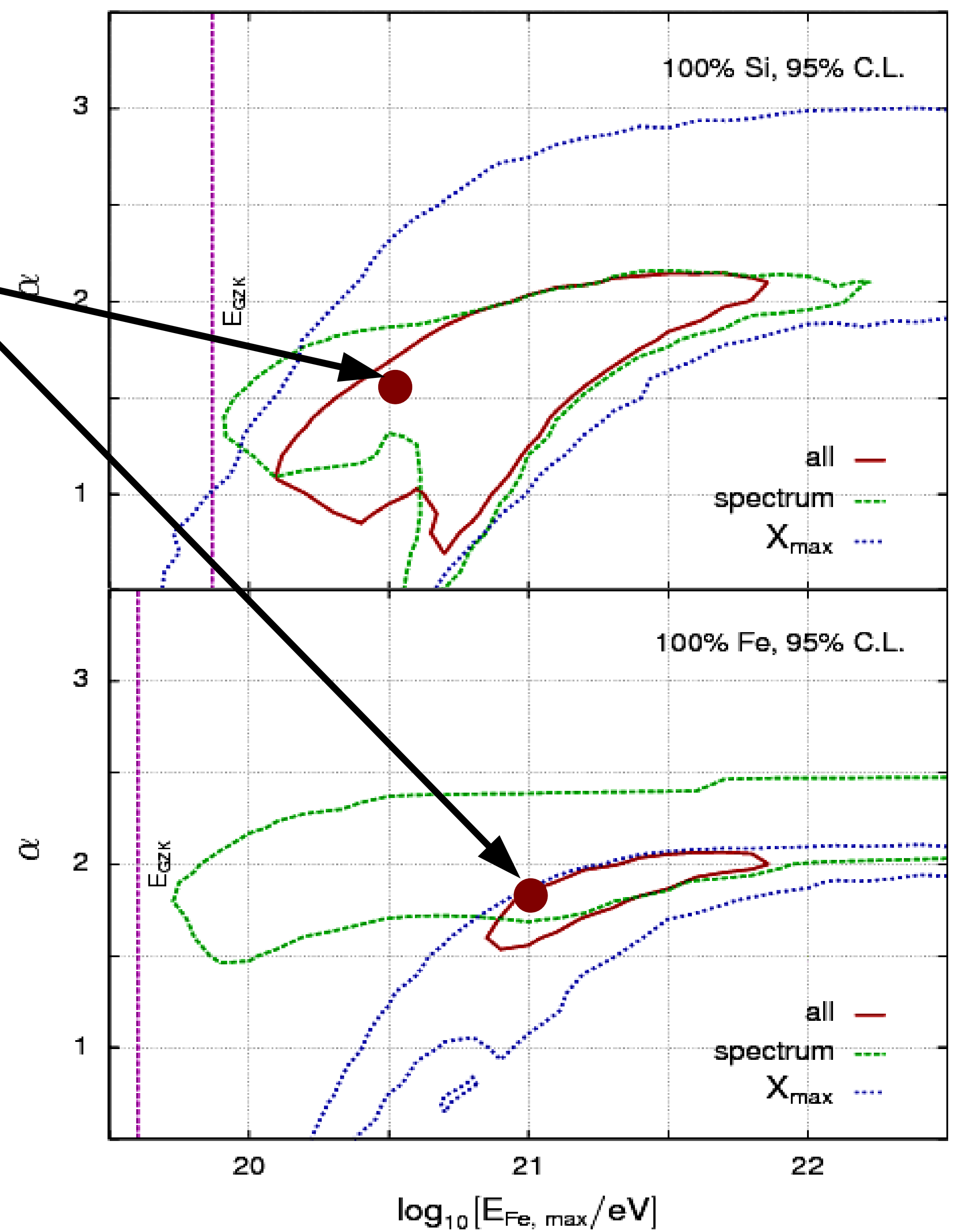
What is the Source Composition?

Keep It Simple
- Single Composition

Example Best-Fit Models

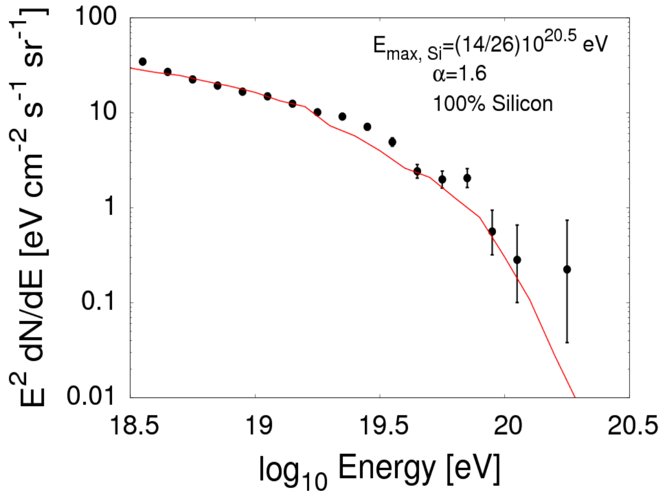
Silicon →

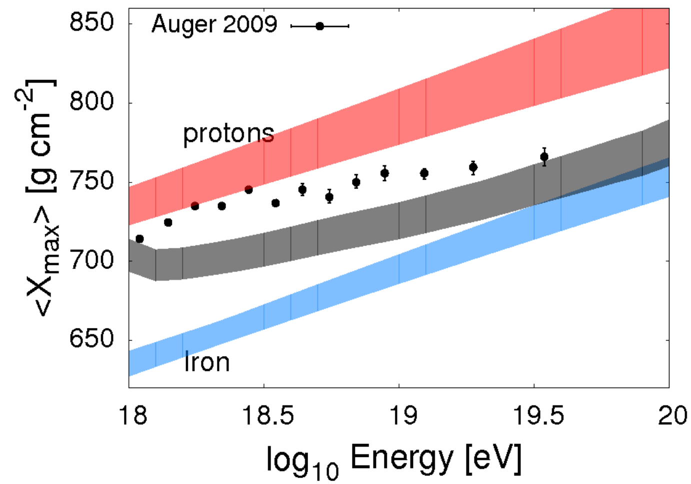
Iron →

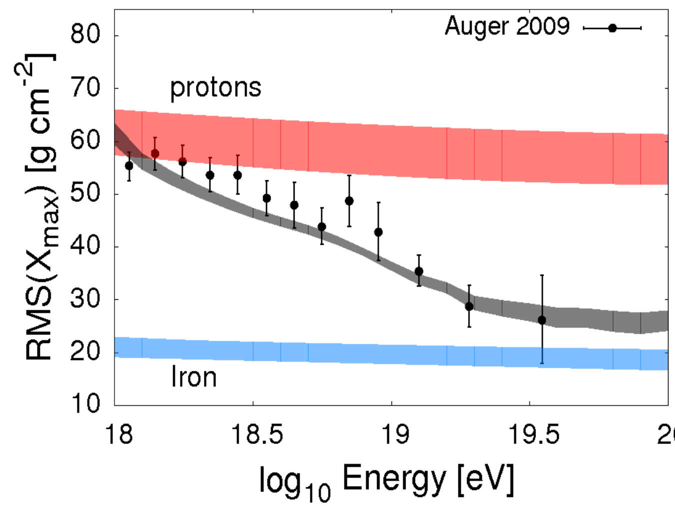


Example Best-Fit Results

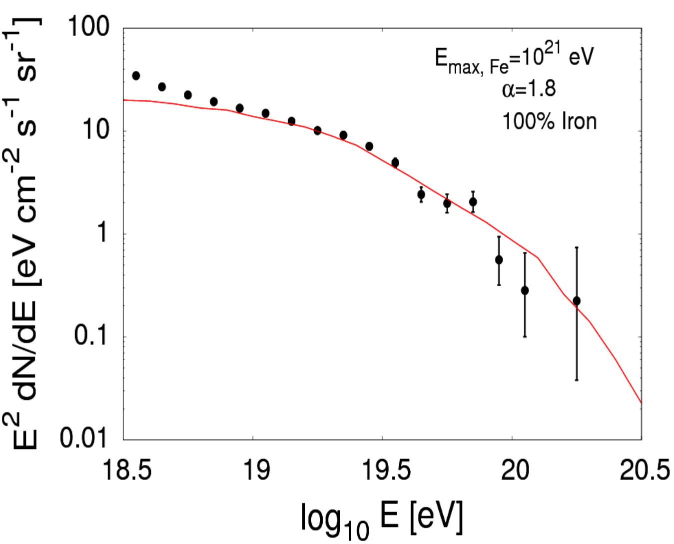
Silicon only?

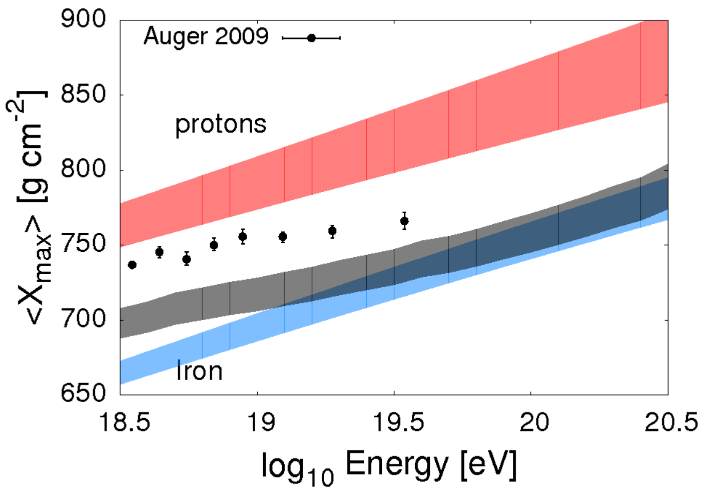


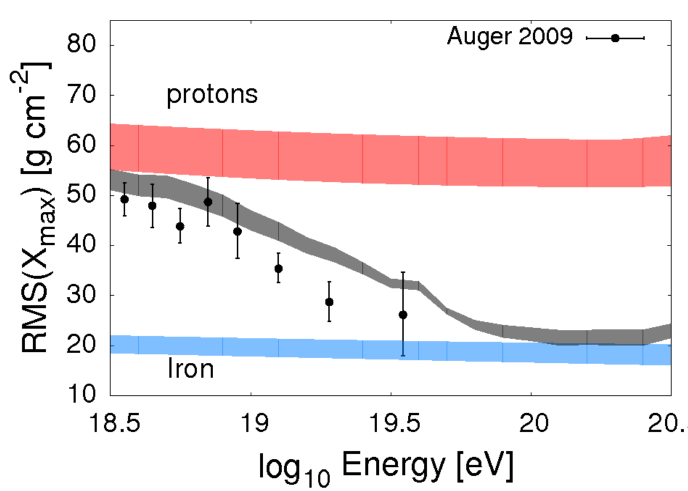




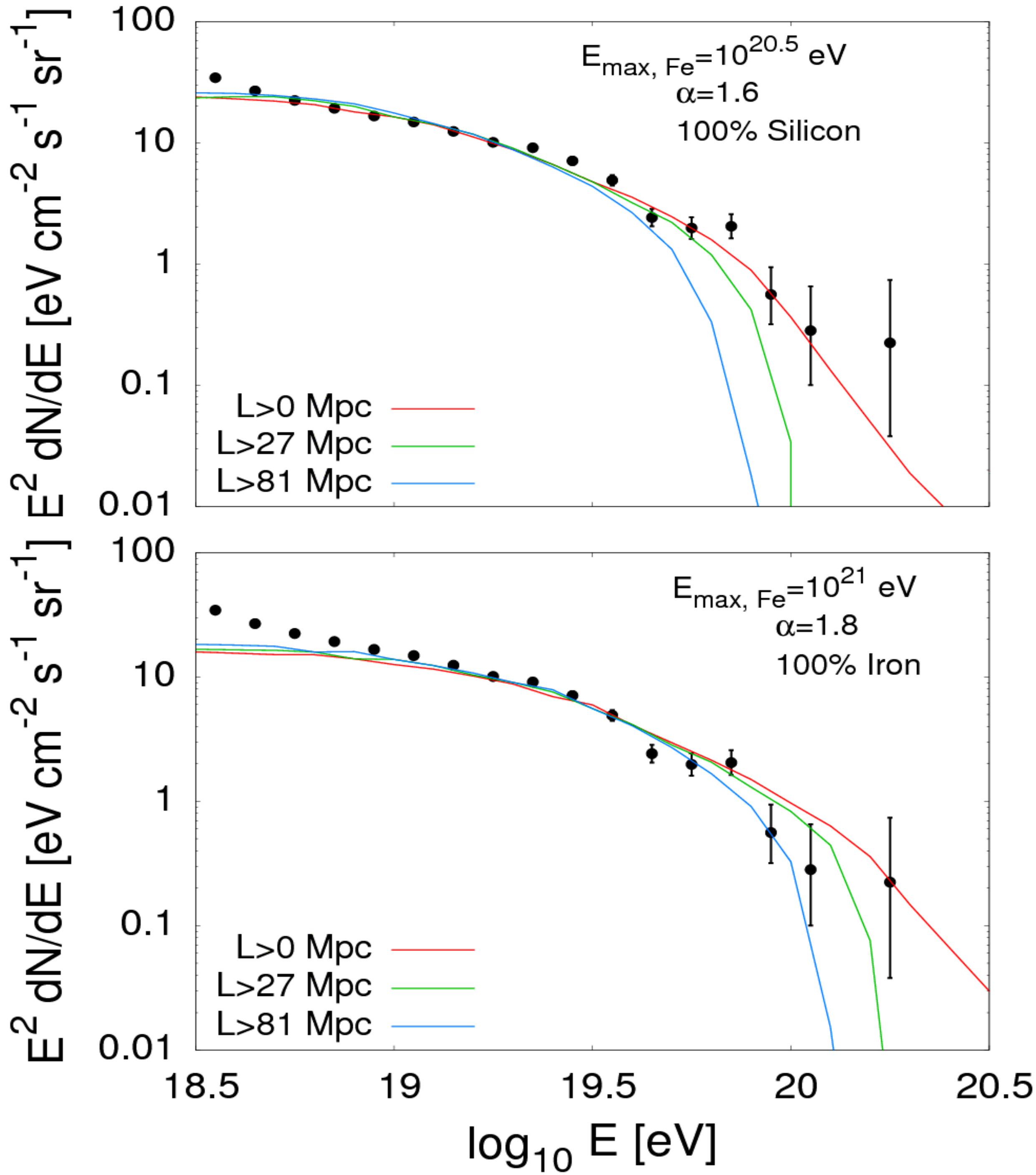
Iron only?







How Far is the Nearest Source?

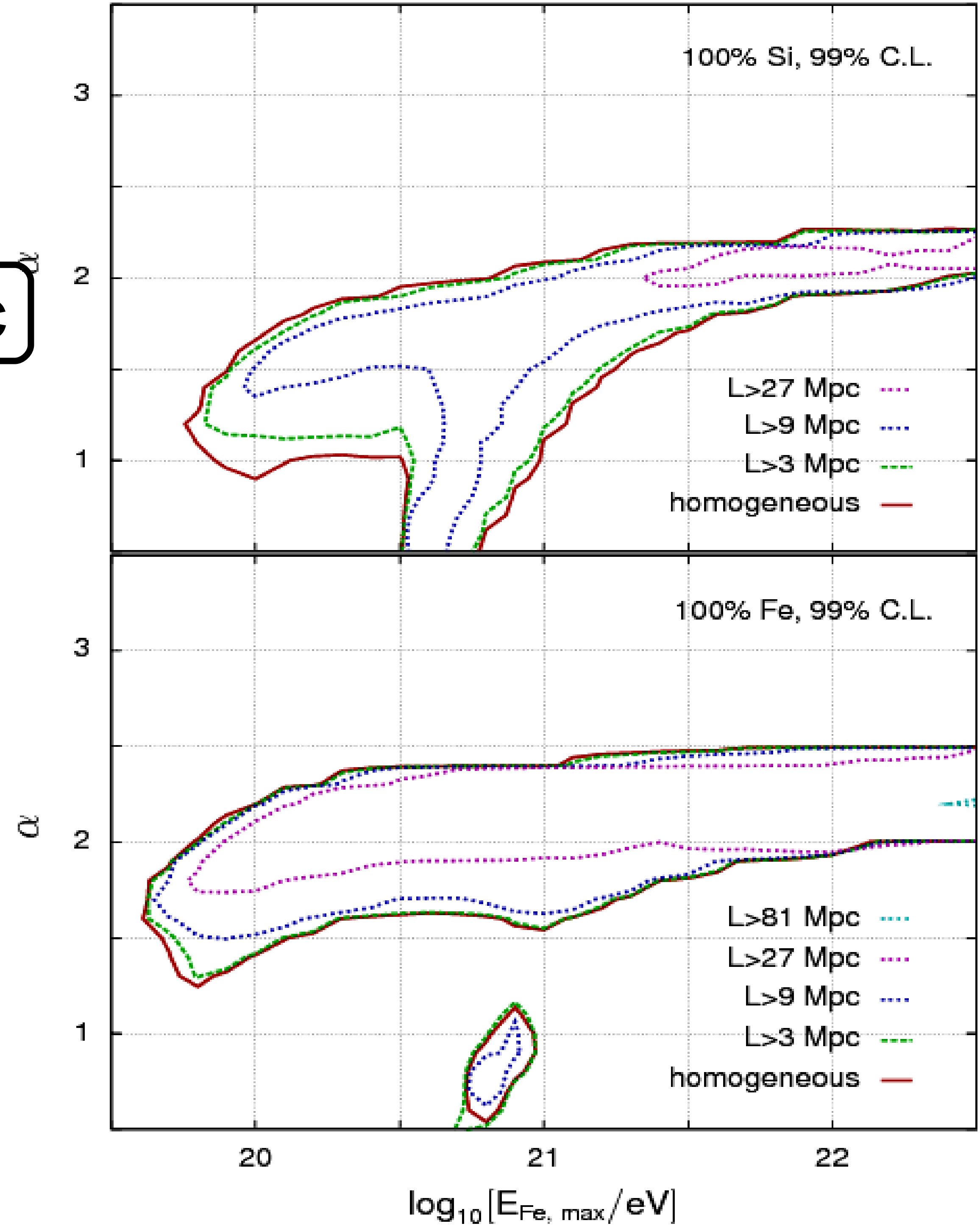


How Far is the Nearest Source?

If E_{max}<10^{22}eV

Silicon- D<60 Mpc

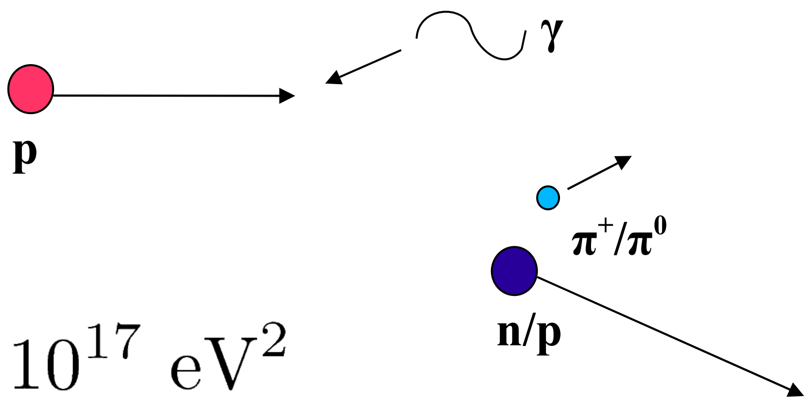
Iron- D<80 Mpc



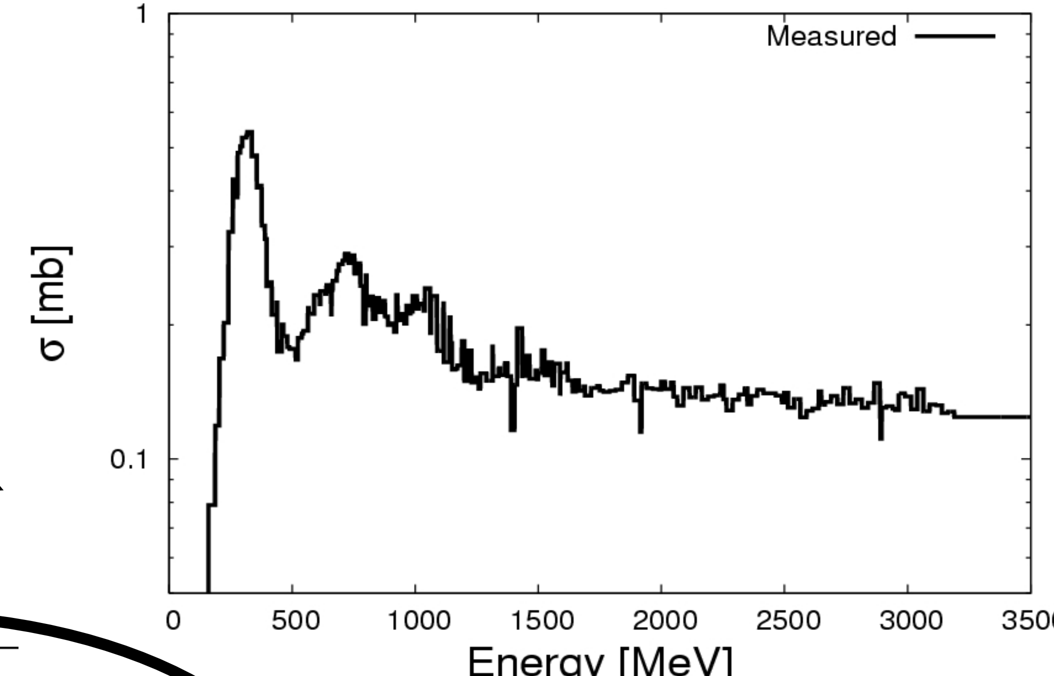
Part 2: Gamma-Rays

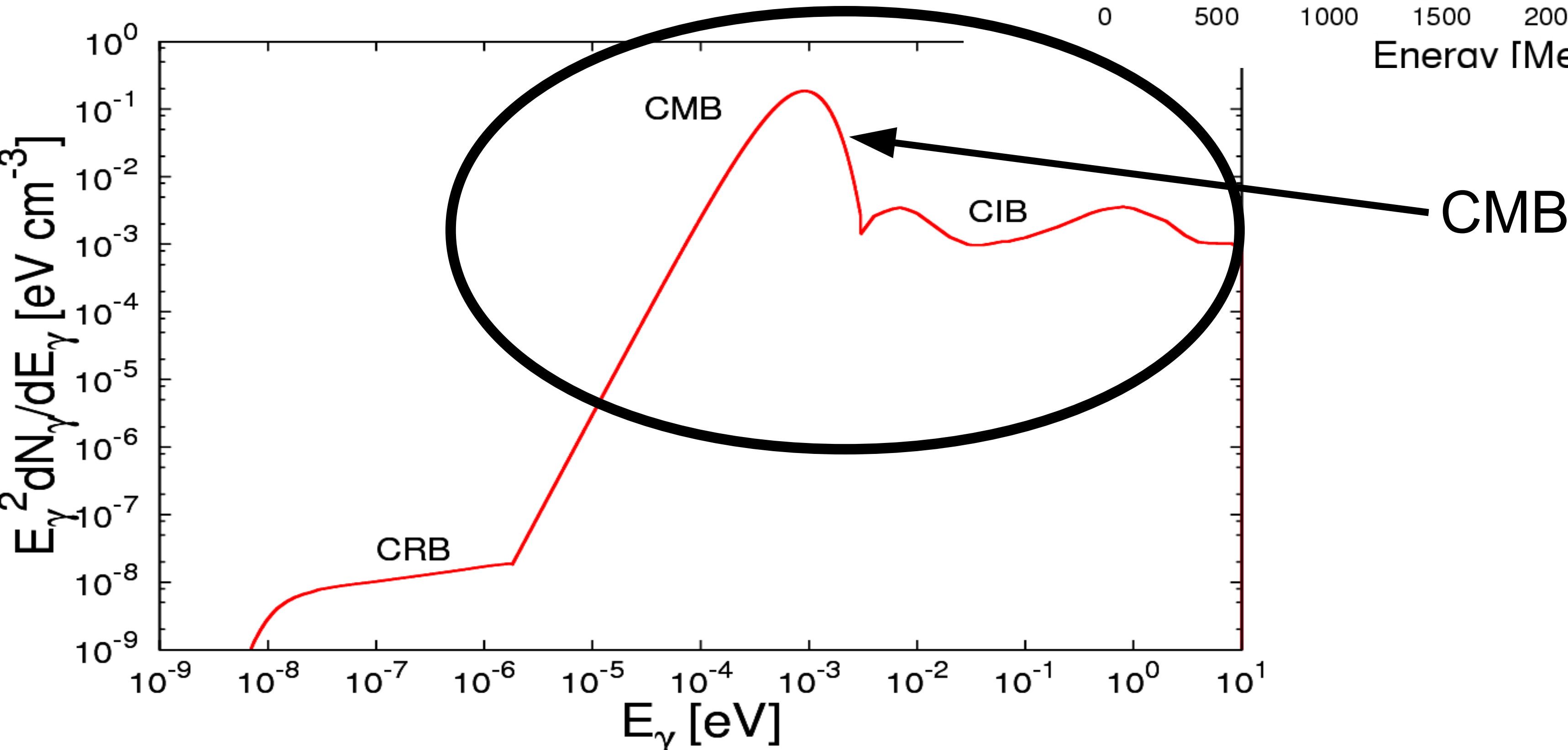
Gamma-Ray Production

<u>protons</u>

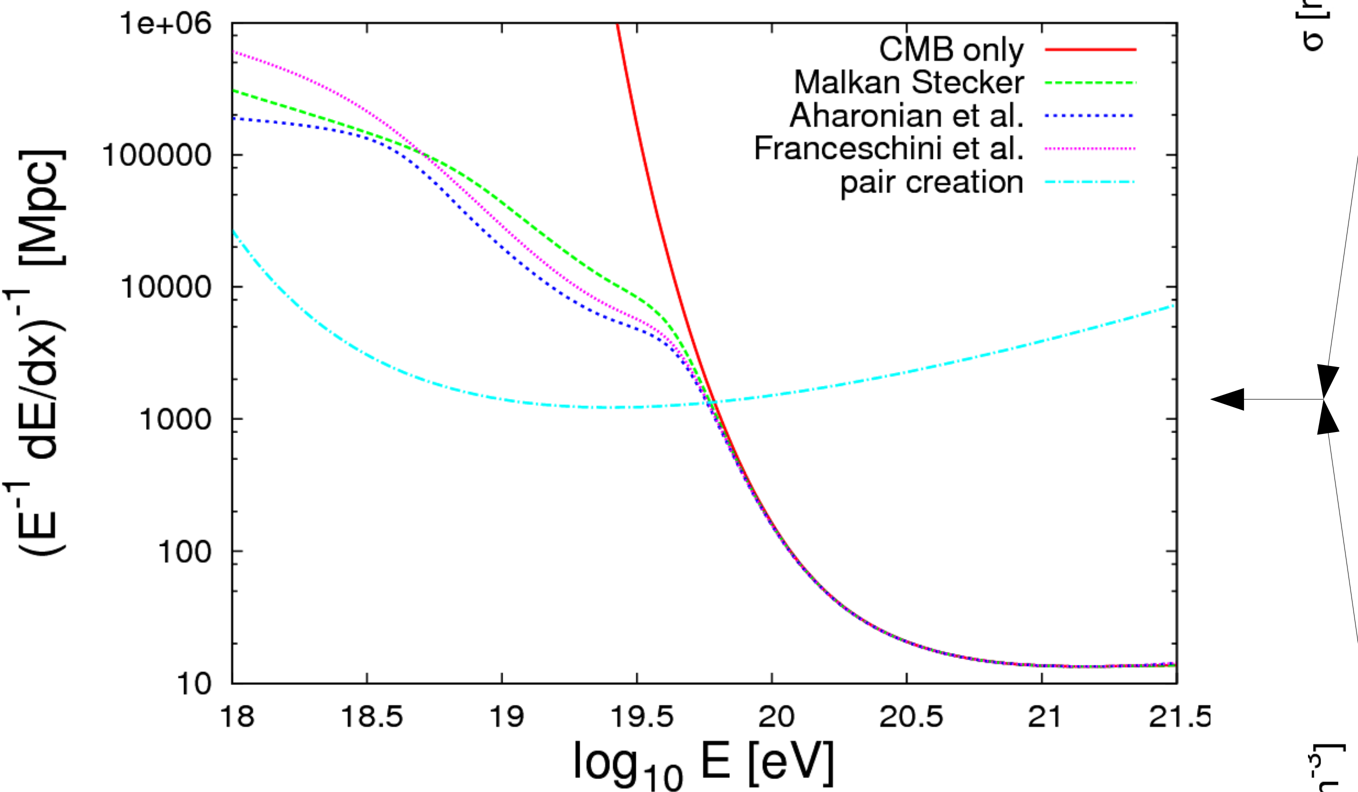


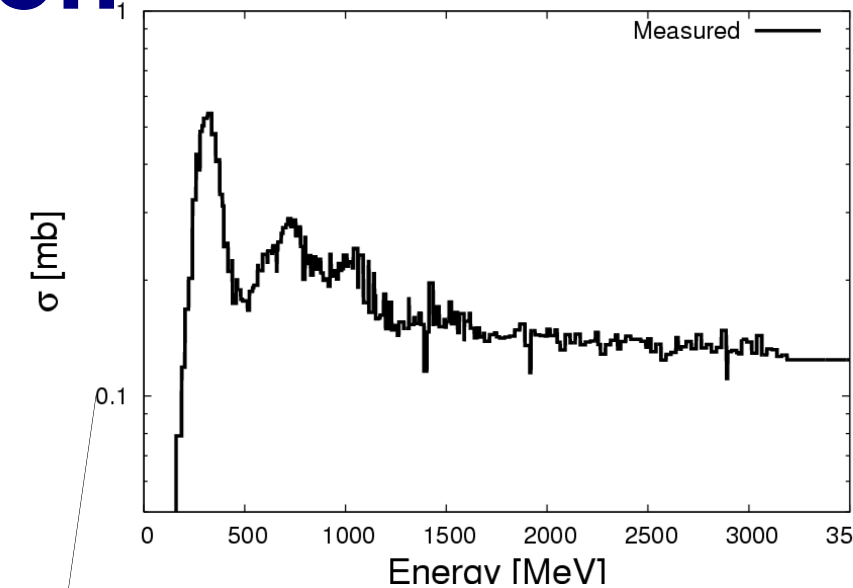
$$s \approx 10^{17}\ \mathrm{eV}^2$$

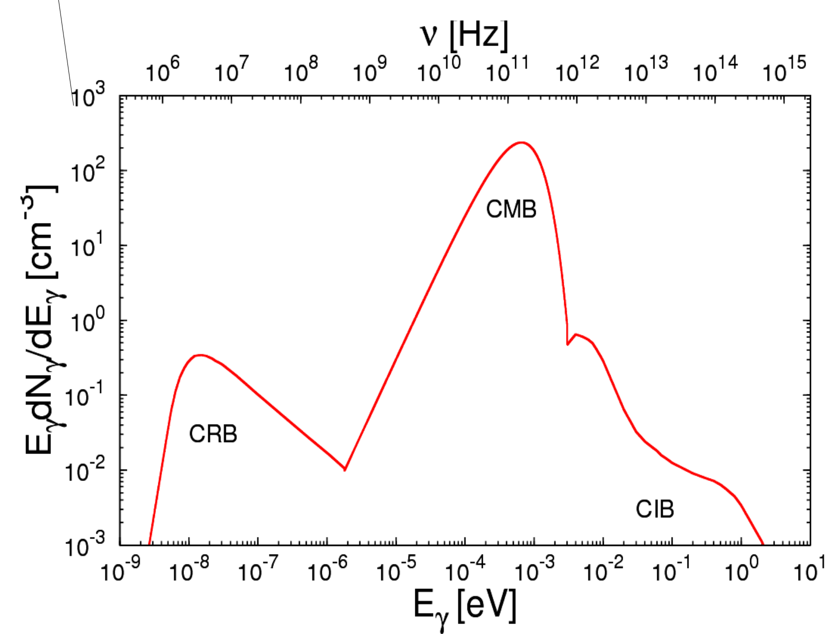




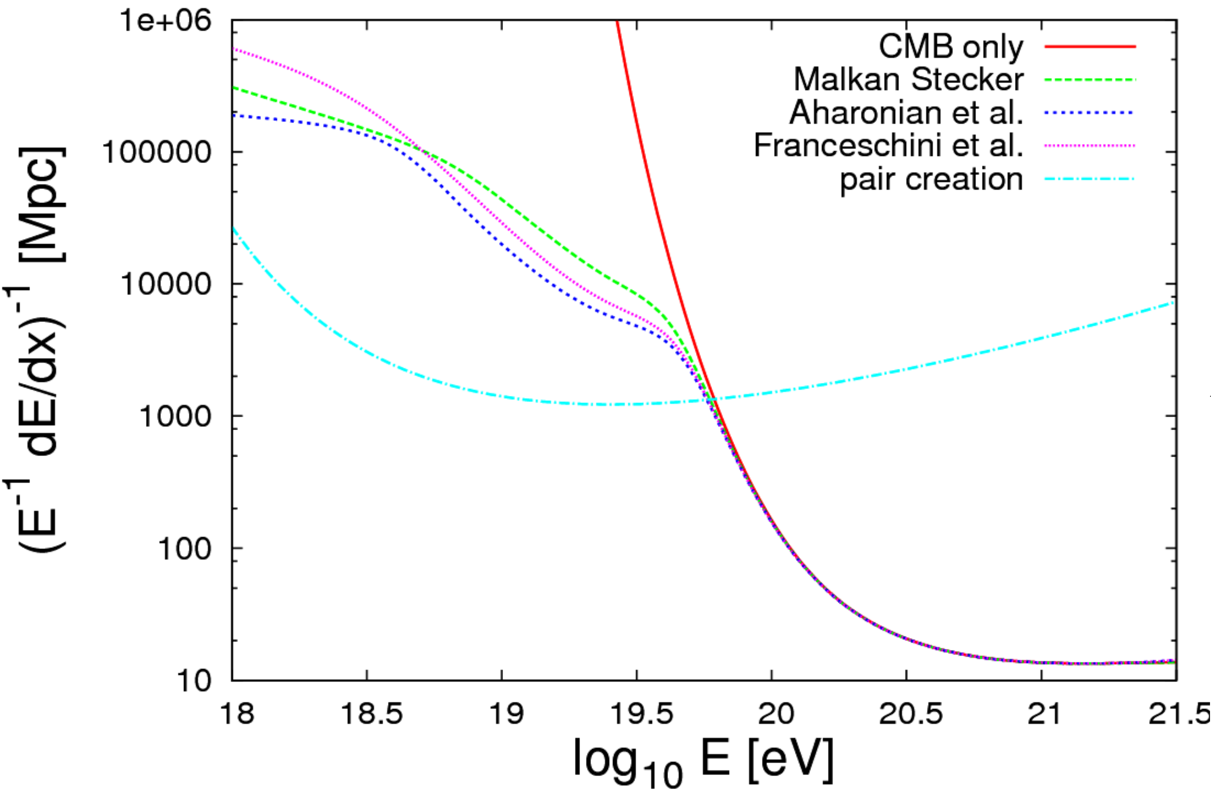
Gamma-Ray Production

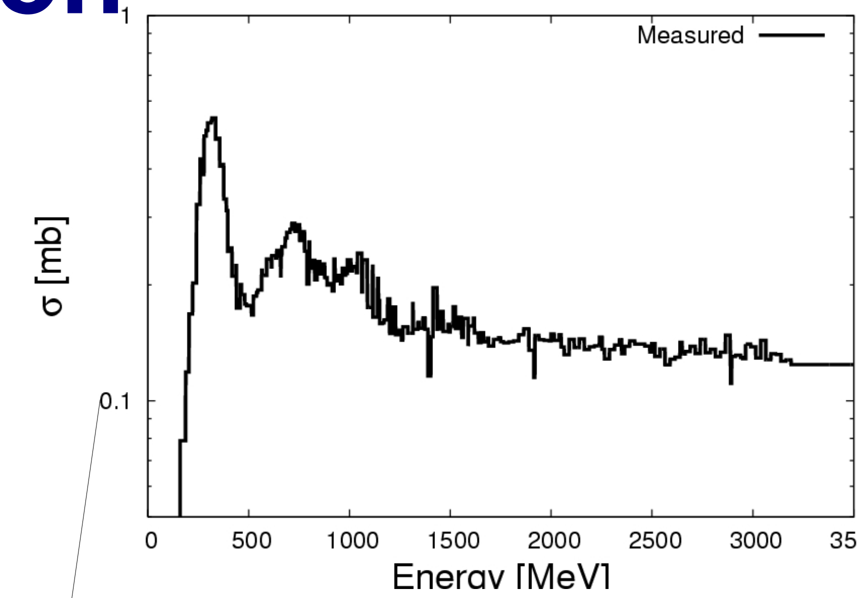


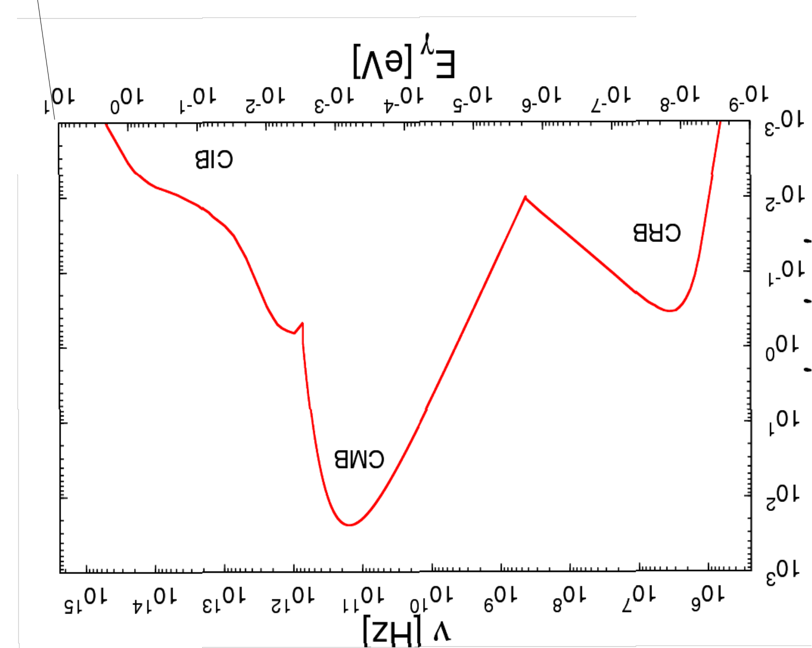




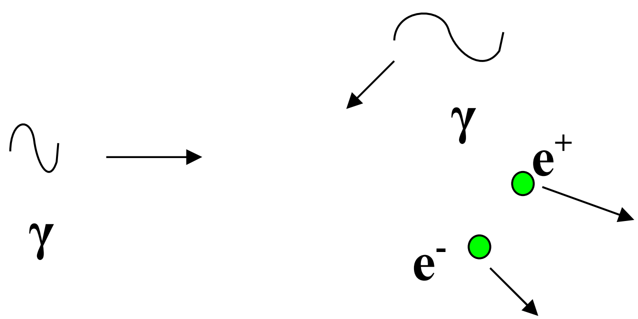
Gamma-Ray Production

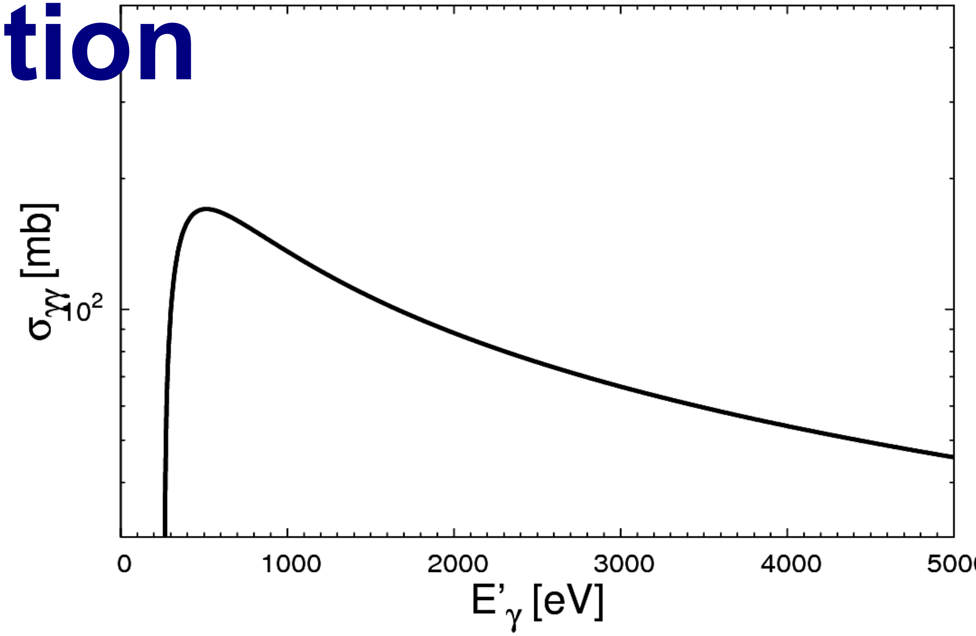






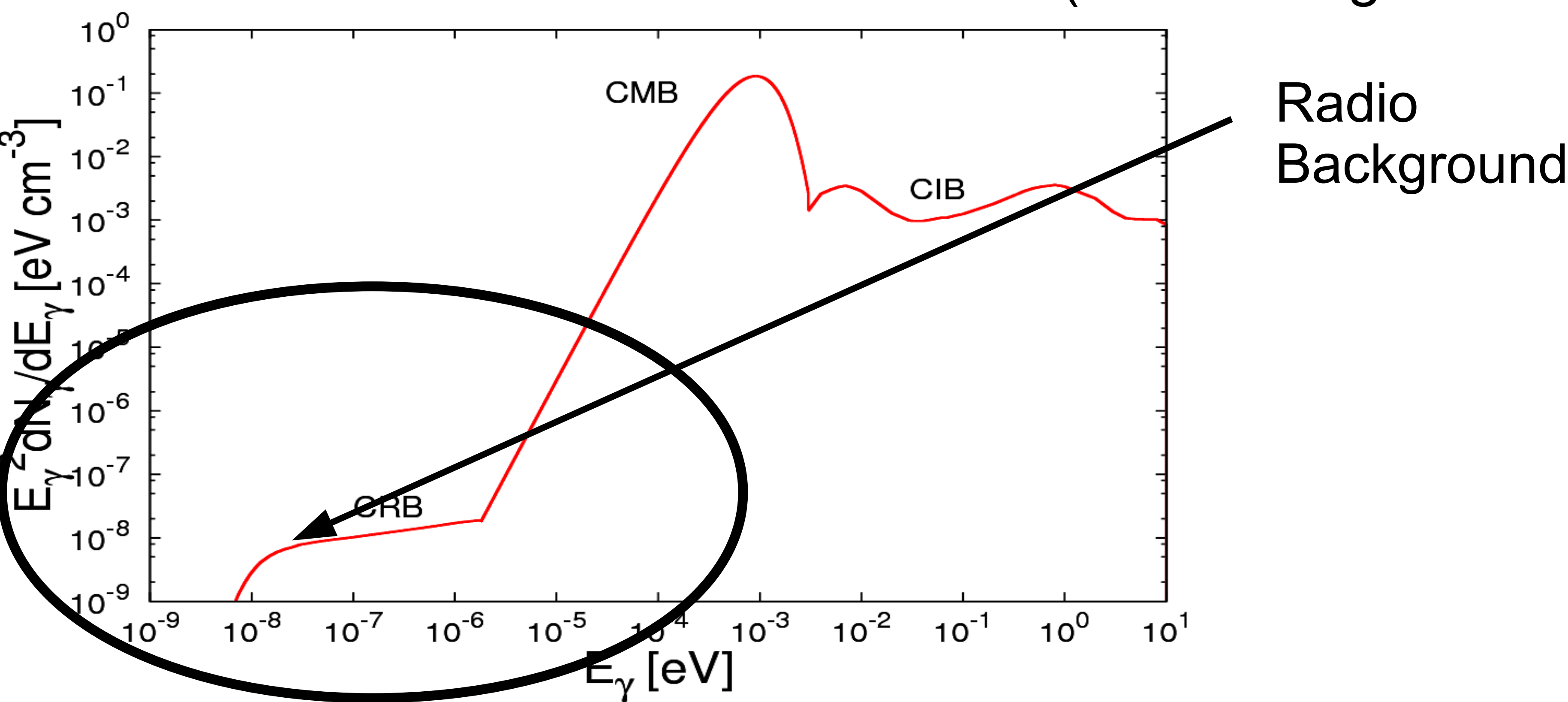
Gamma-Ray Interaction



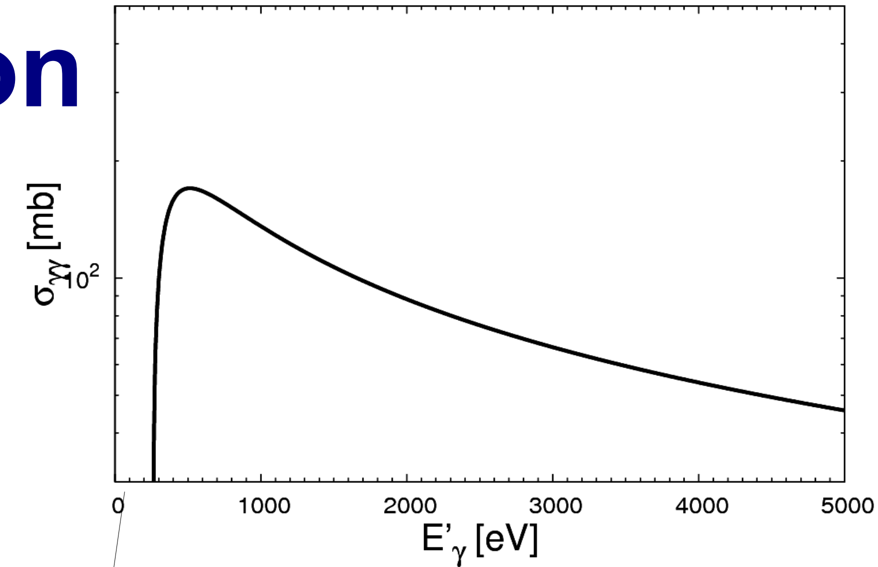


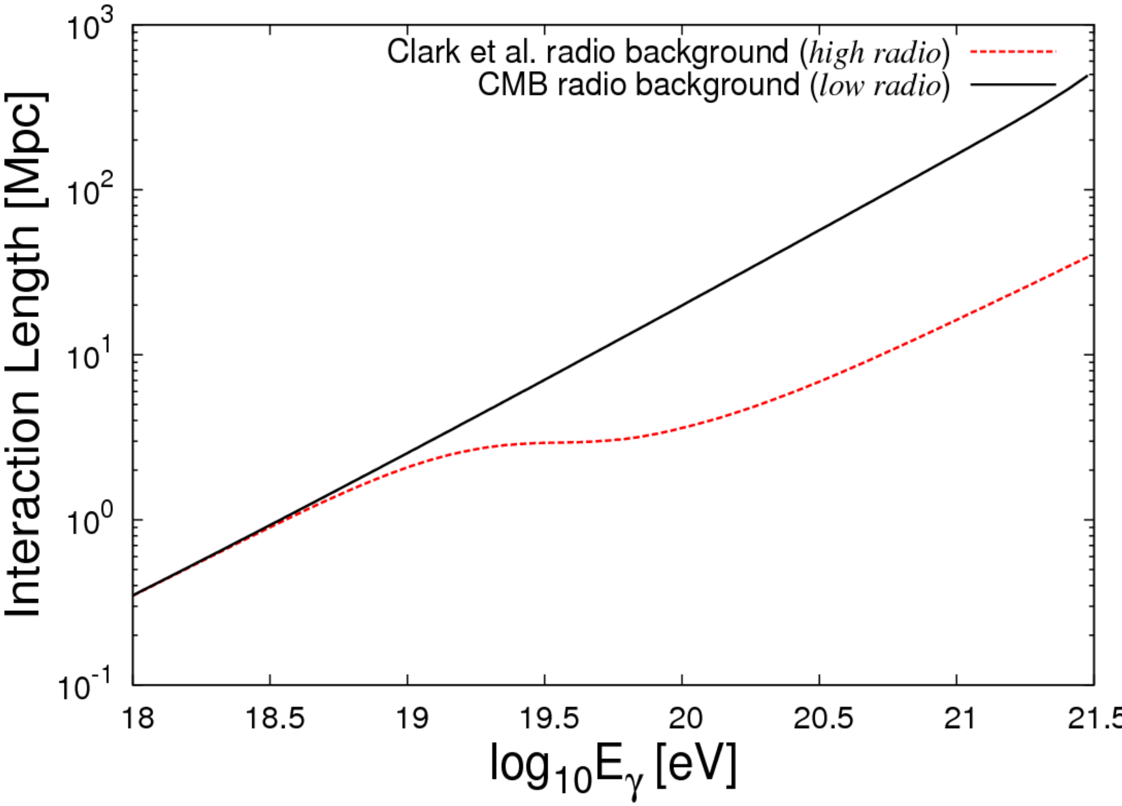
$$s \approx 10^{12}\ \mathrm{eV}^2$$

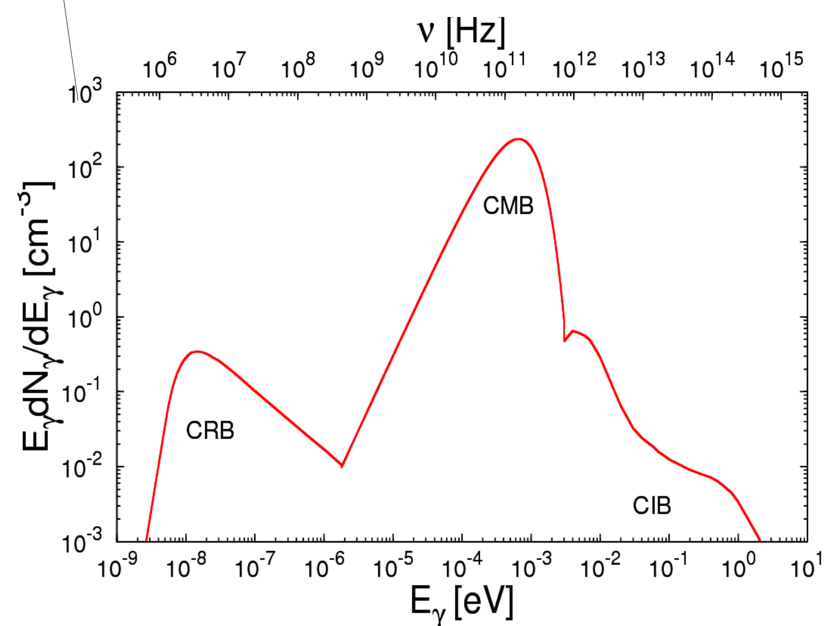
(for colliding 1 GeV photon)



Gamma-Ray Interaction

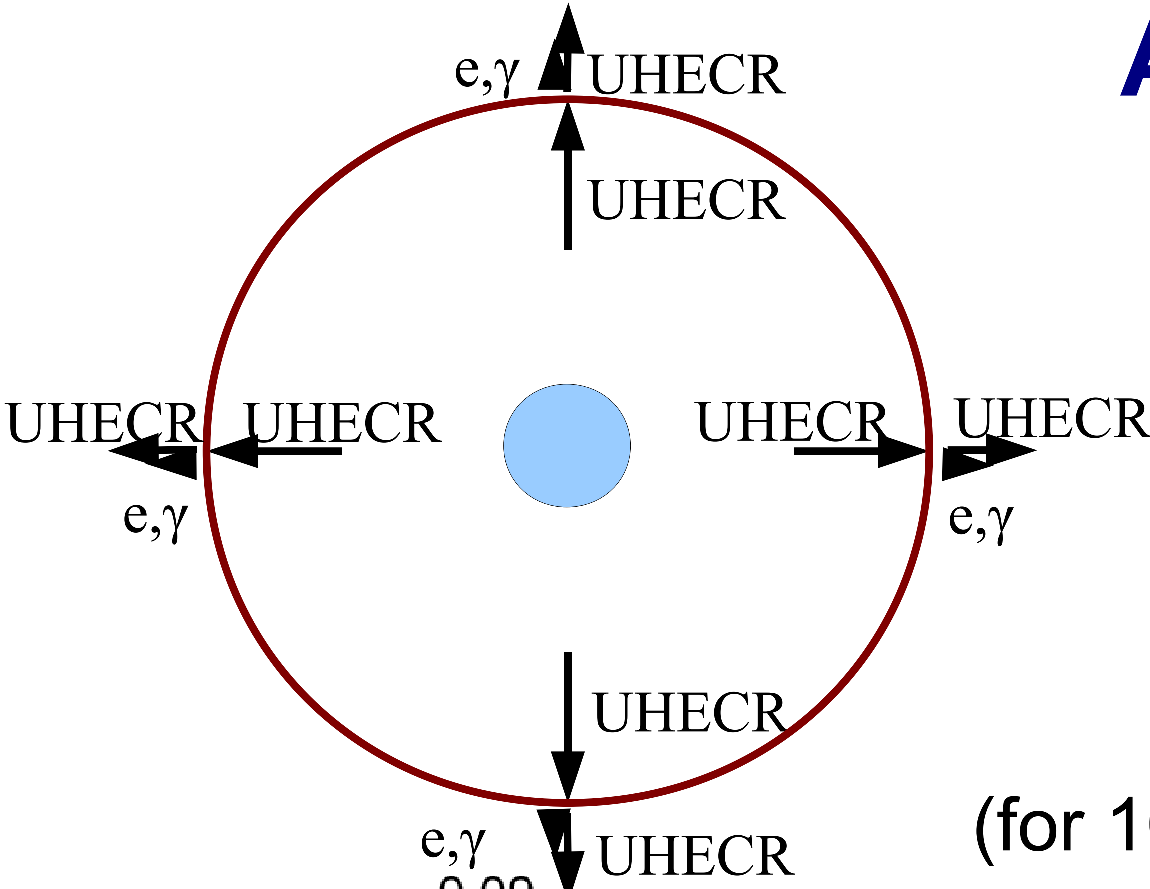




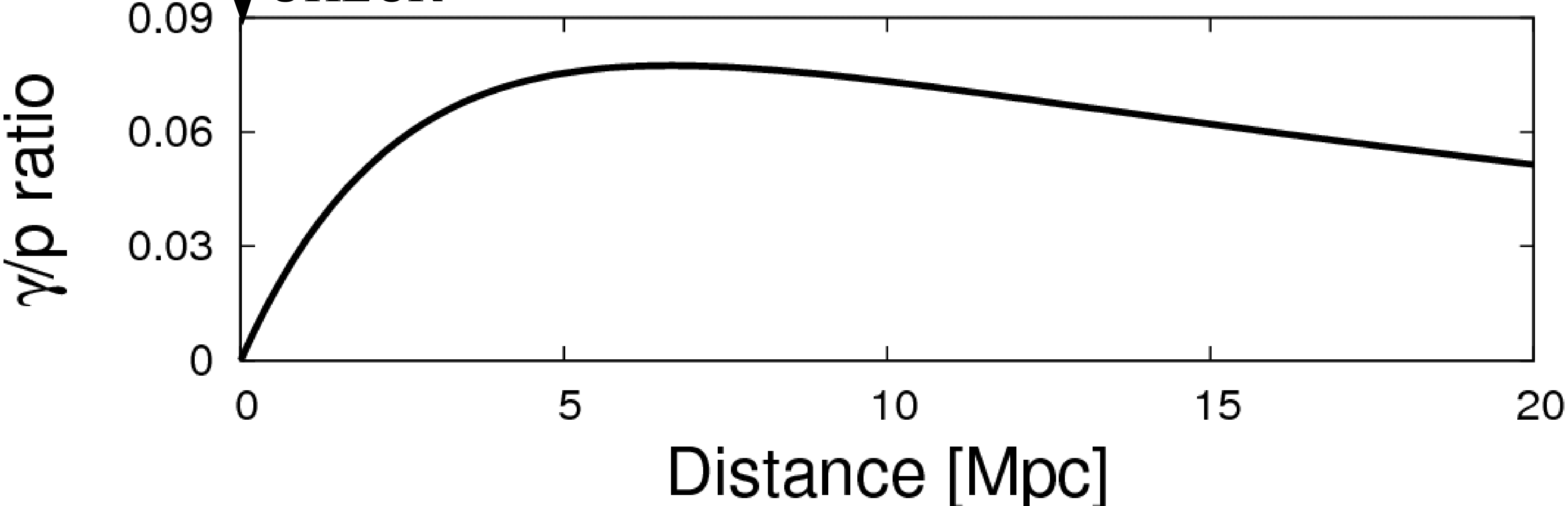


Heavenly Bodies Do Have A Halo Around Them!

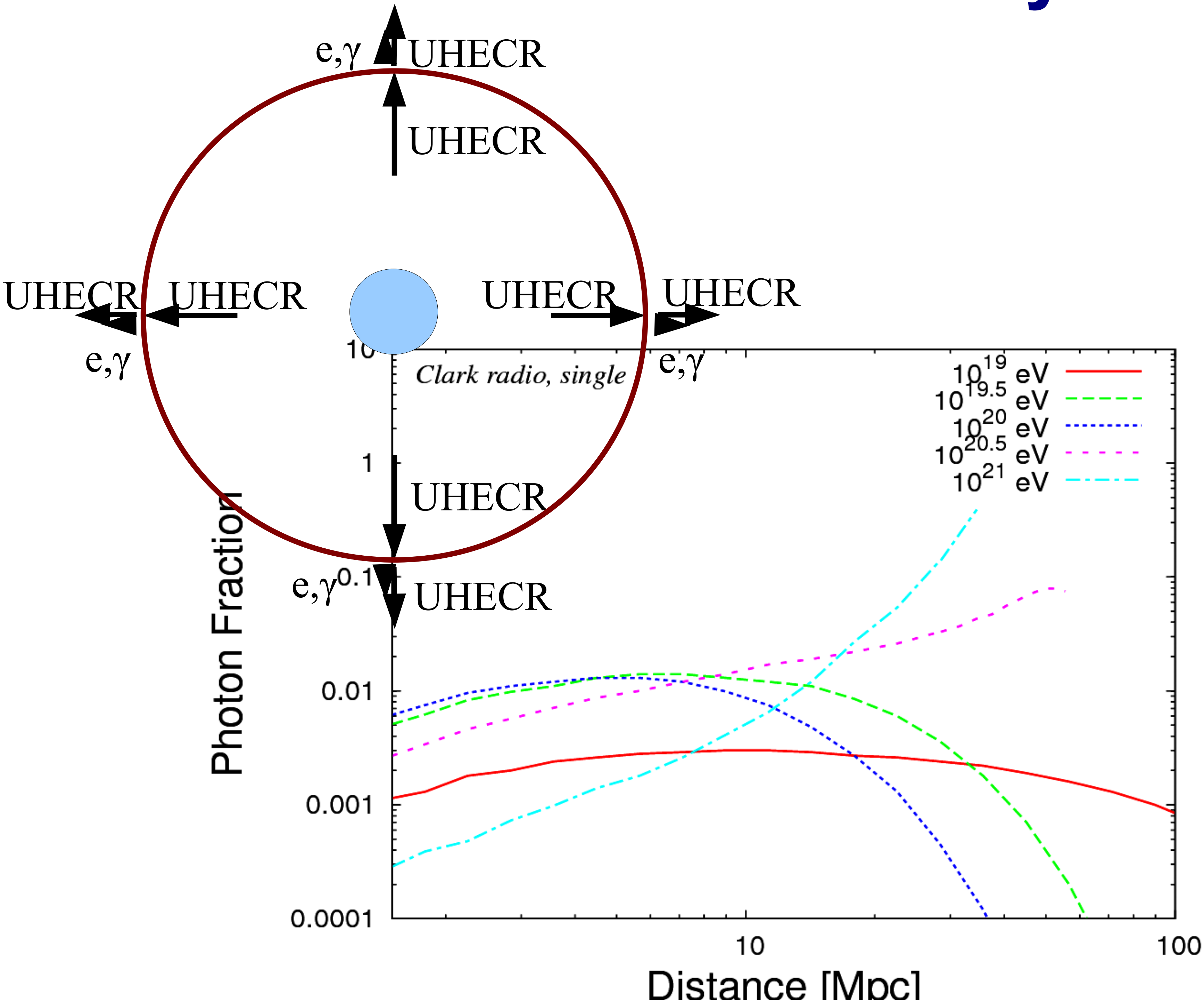
(which acc. UHECR)



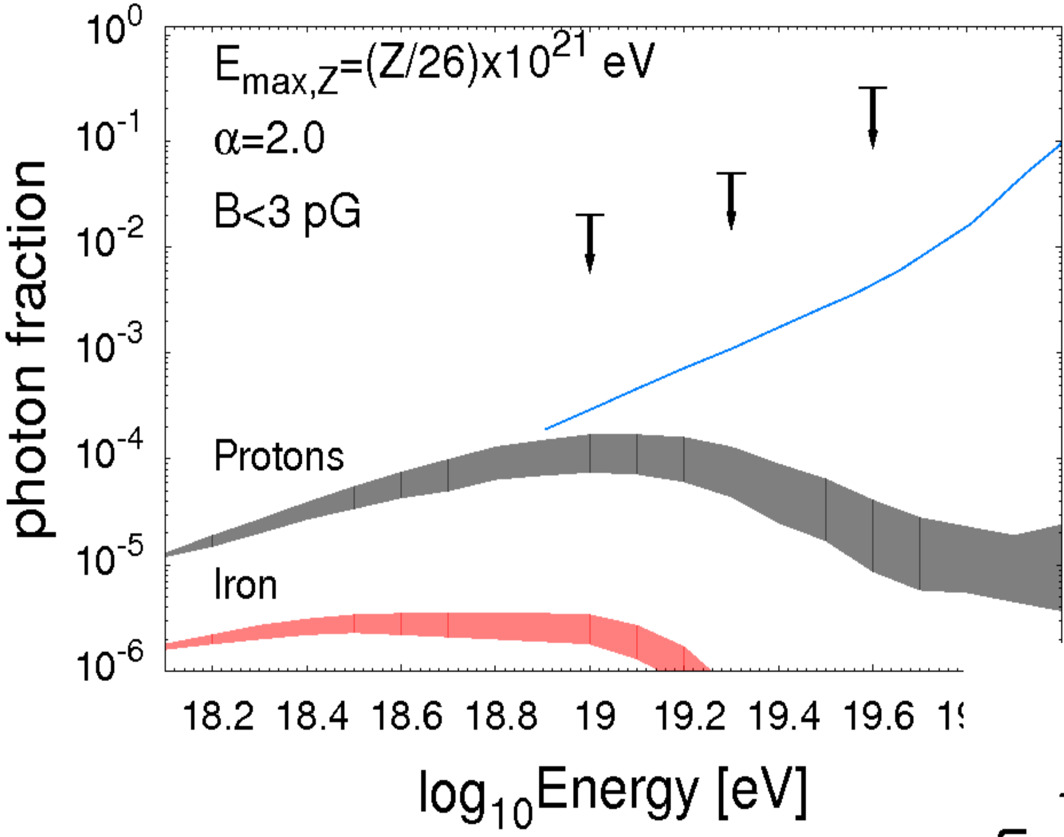
(for 10^{19}eV gamma-rays)



The Halo Around Heavenly Bodies

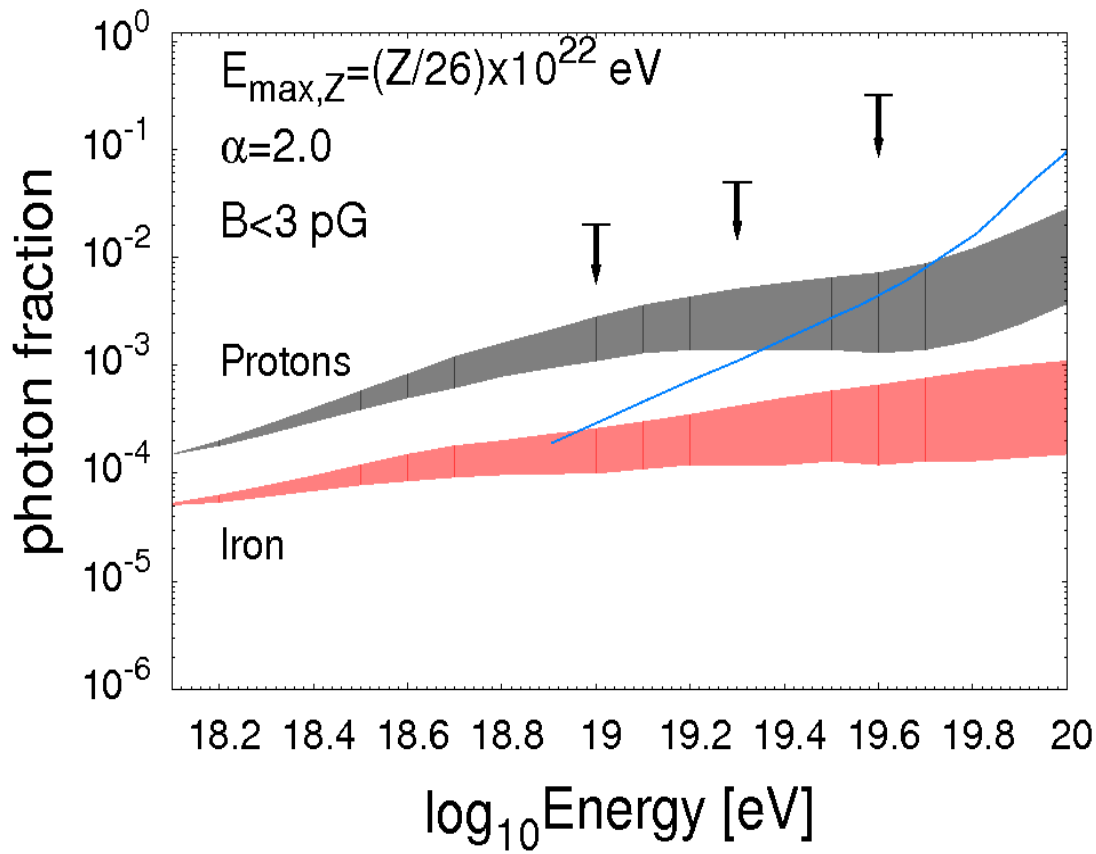


Photon Fractions
(Homogeneous Sources)



← Low cutoff

High cutoff →



Conclusion

The dominance of nuclei at the highest energies provides useful new information about the nature of UHECR sources

Regions close to luminous objects are excluded as UHECR sources, favouring slow acceleration scenarios

UHE photons can provide a useful probe of local sources

Applied to Cen A we expect an UHE photon in 5 years, if 2 UHECR in the PAO 57 UHECR set originated from Cen A.

Extra Slides

General- Interaction Rate Convolution

(all values in lab frame)

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

Since $\epsilon_\gamma E_p = \epsilon'_\gamma E_p (1+\beta\cos\theta)$

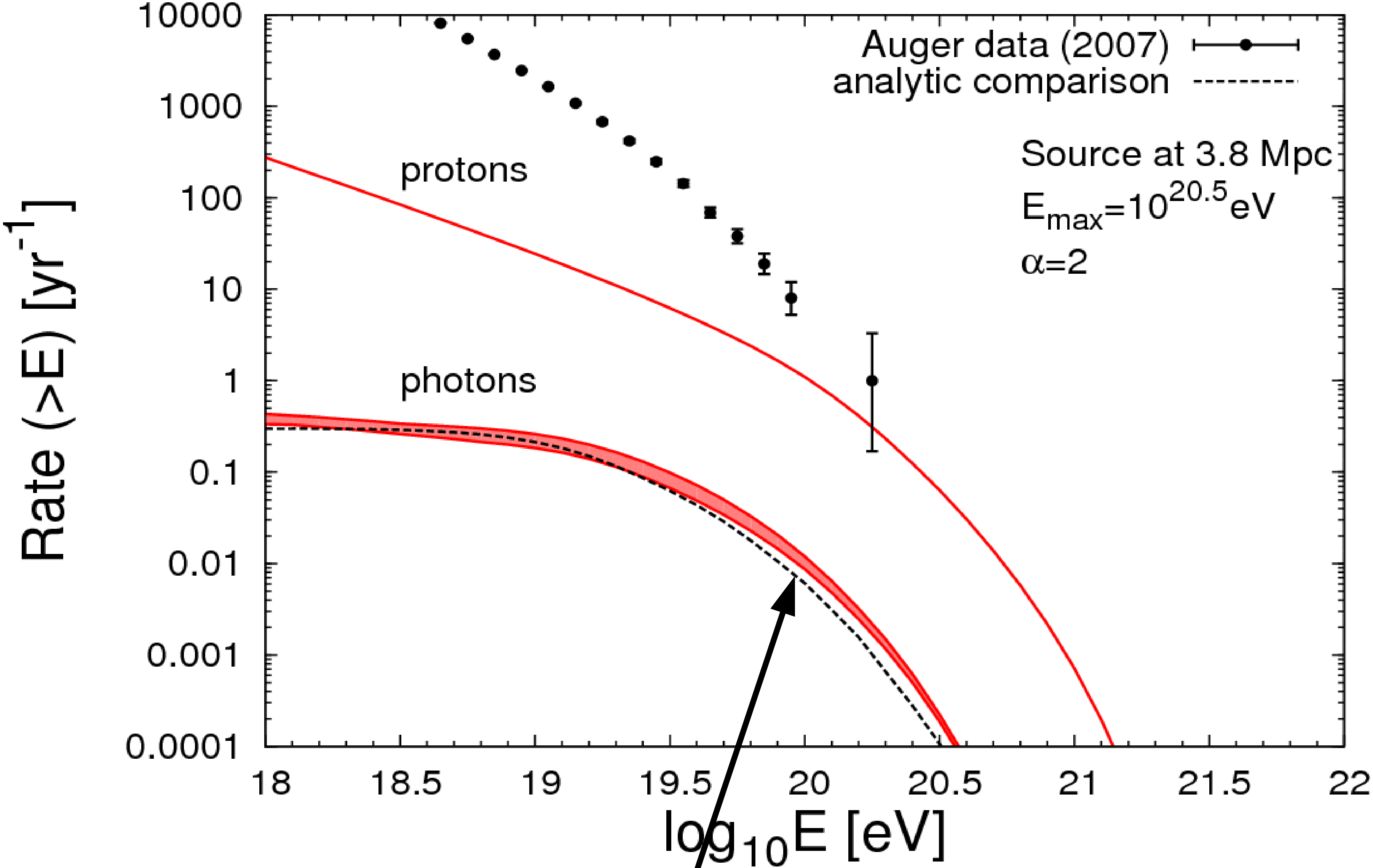
$$(1+\beta\cos\theta) d(\cos\theta) = \frac{\epsilon_\gamma E_p}{\epsilon'_\gamma E_p} \frac{d(\epsilon_\gamma E_p)}{\epsilon'_\gamma E_p}$$

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

lab frame — incident particle's rest frame

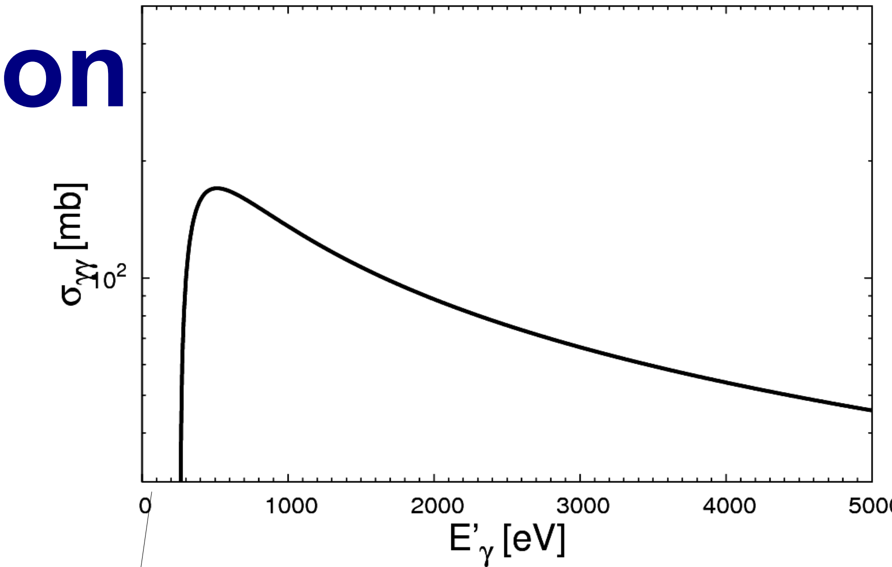
$$R = \frac{m_p^2}{2E_p^2} \int_0^\infty d\epsilon'_\gamma \frac{n(\epsilon'_\gamma)}{\epsilon'^2_\gamma} \int_0^{2\epsilon'_\gamma \frac{E_p}{m_p}} d\epsilon_\gamma \epsilon_\gamma \frac{d\sigma}{d\epsilon_\gamma}$$

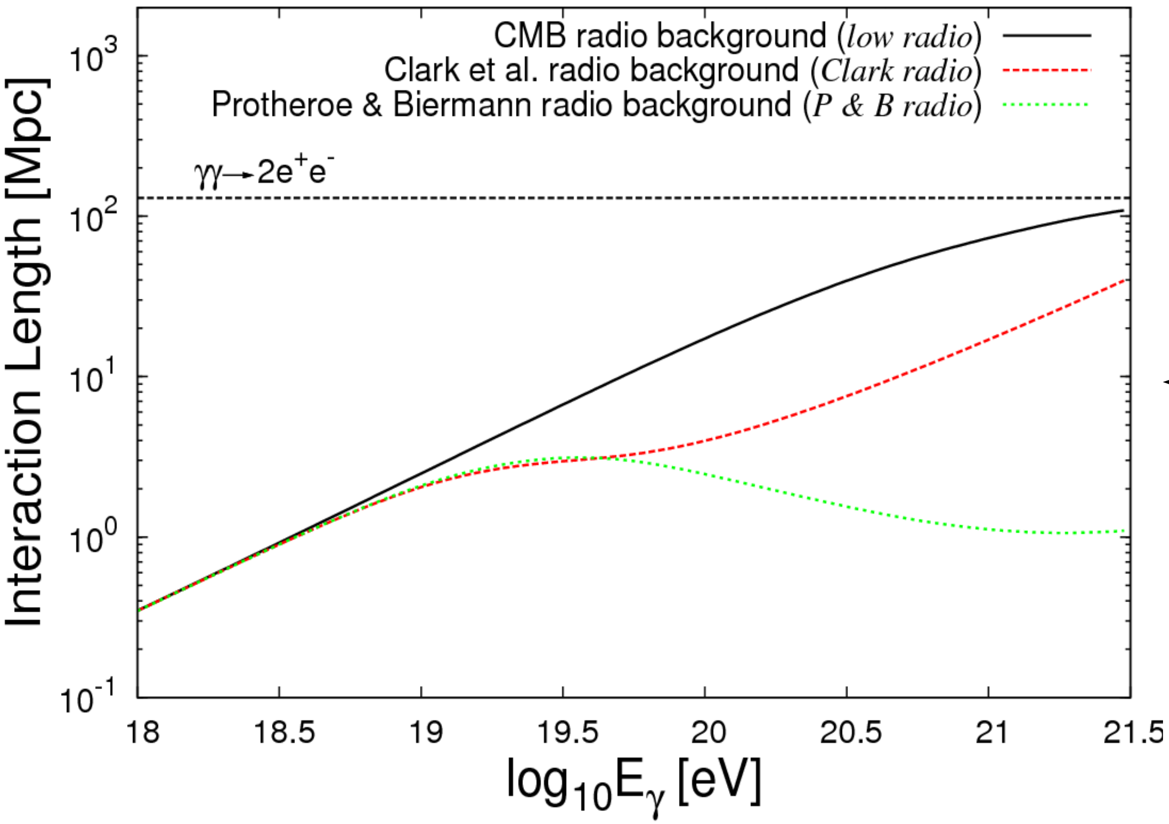
The Halo Around Cen A

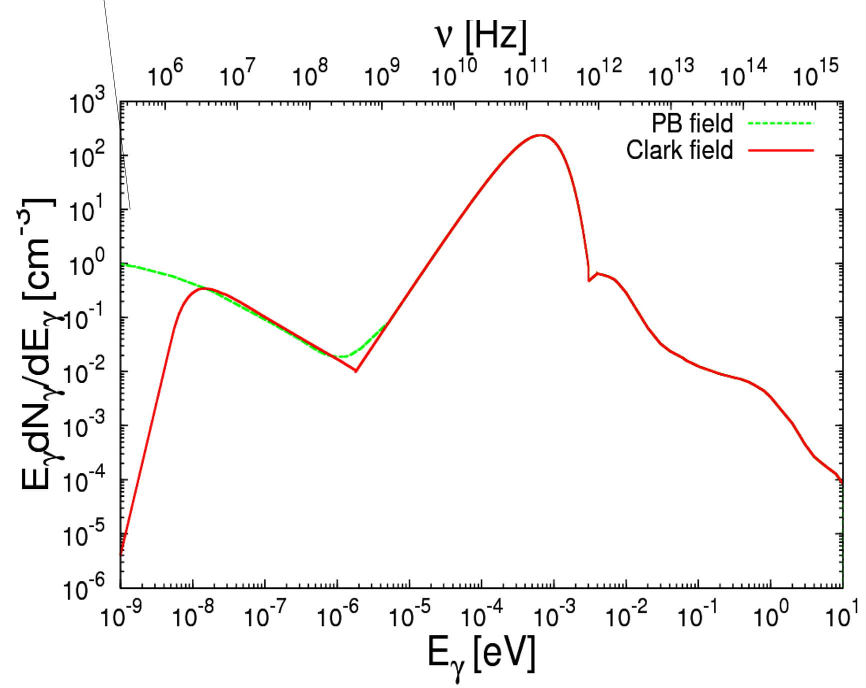


$$\frac{N_\gamma(l)}{N_p(0)} = \frac{l_{\gamma\gamma}(e^{-l/l_{p\gamma}} - e^{-l/l_{\gamma\gamma}})}{(l_{p\gamma} - l_{\gamma\gamma})}$$

Gamma-Ray Interaction







The Halo Around Cen A