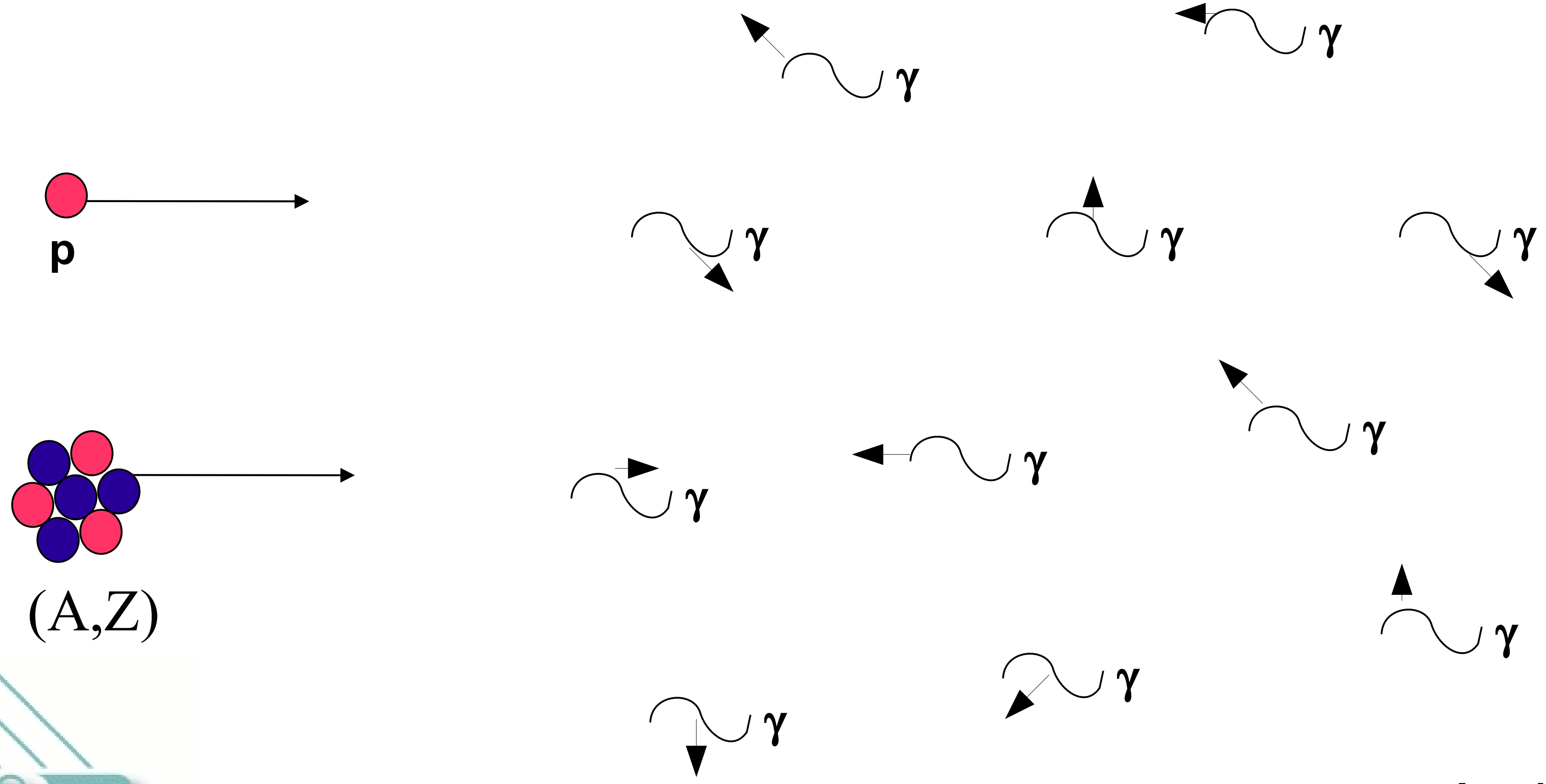
# Propagating UHECRs- Knowns and Unknowns



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# Aims

1) **Relevant Interactions-** dominant interactions which will be considered here (primary particles)

2) **Propagation Losses-** what are the impeding radiation fields and how well known are they?

3) **Analytic Description of Propagation Losses-** describing it all with just a pen and paper

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# 1) Relevant Interactions (knowns)

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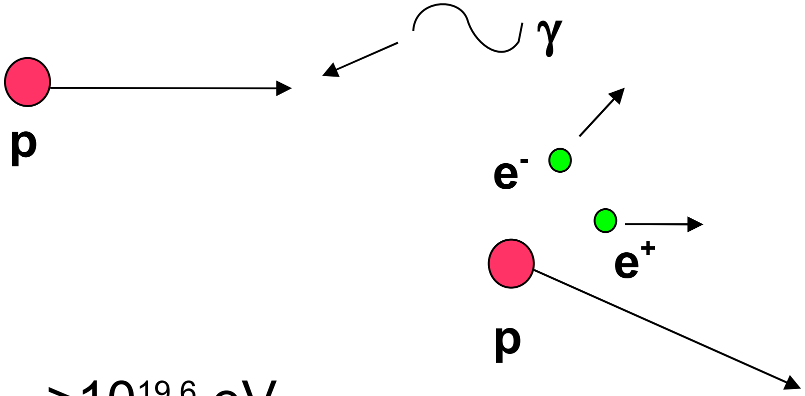
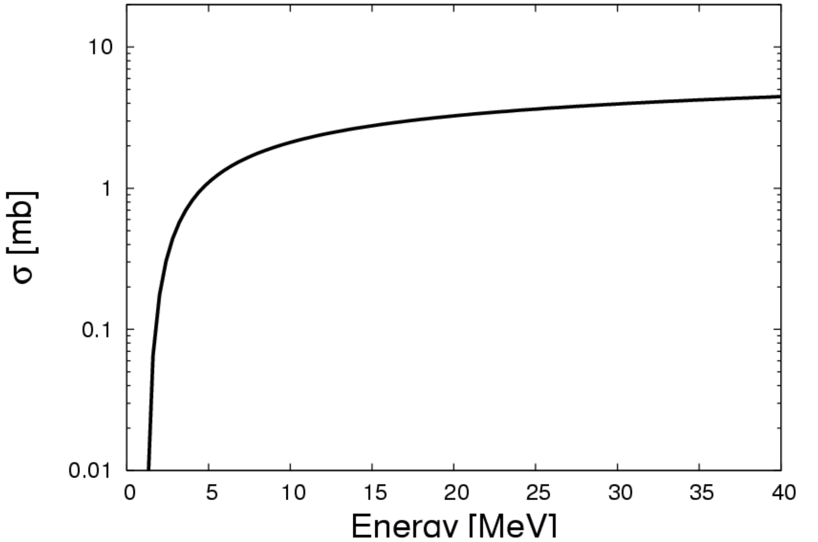
# Cosmic Ray Proton Interactions

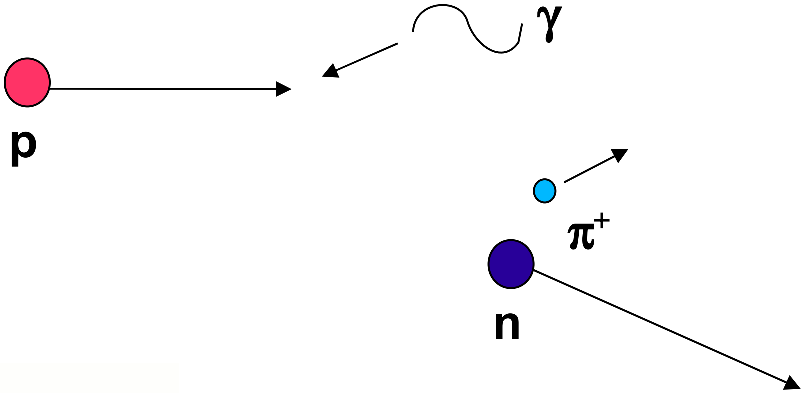
For $E_{proton} < 10^{19.6}$ eV

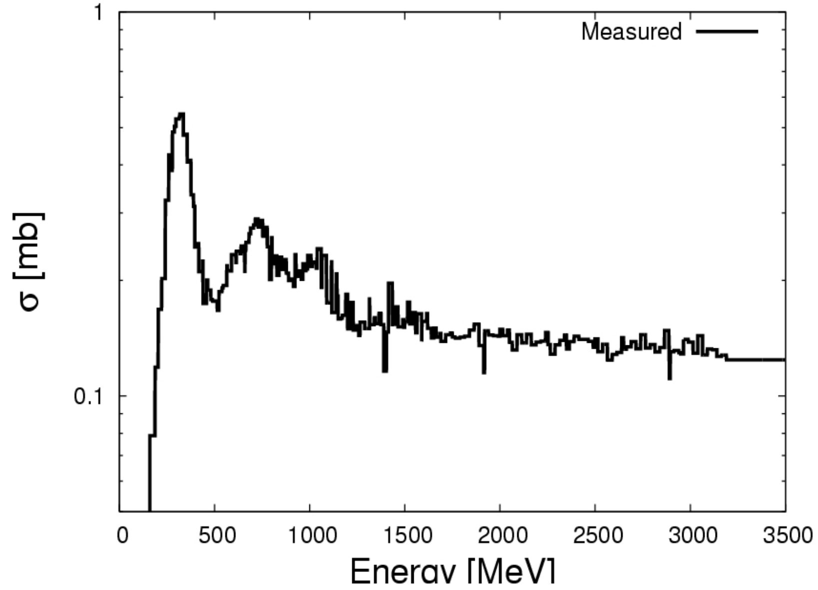




$$E_\gamma^{th} \sim 1\mathrm{MeV}$$

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

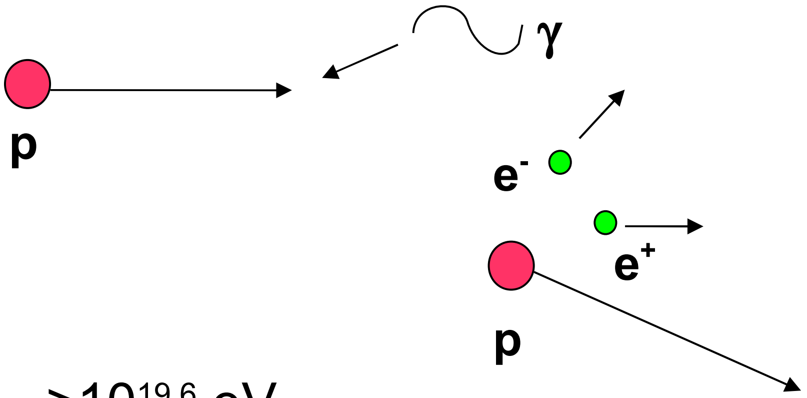


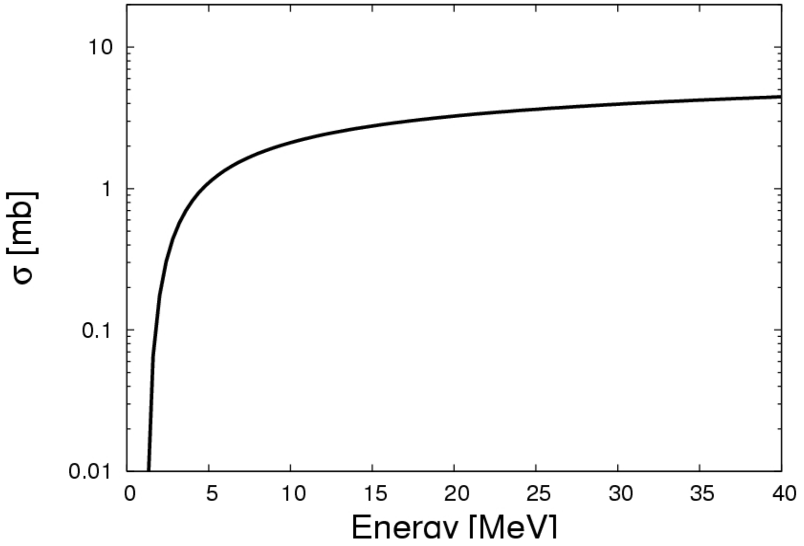


$$E_\gamma^{th} \sim 140\mathrm{MeV}$$

# Cosmic Ray Proton Interactions

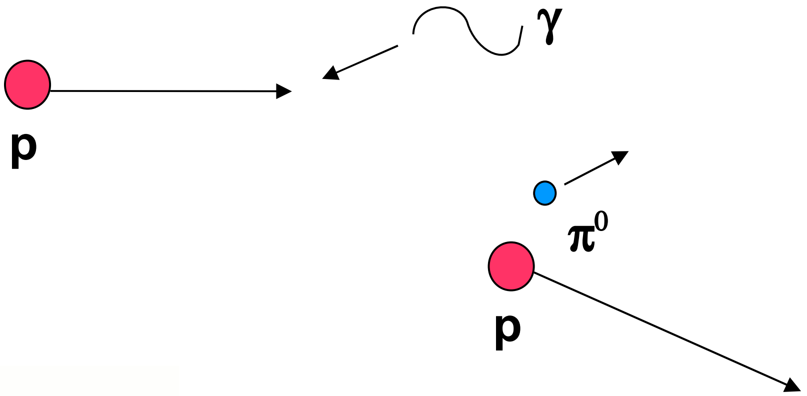
For $E_{proton} < 10^{19.6}$ eV

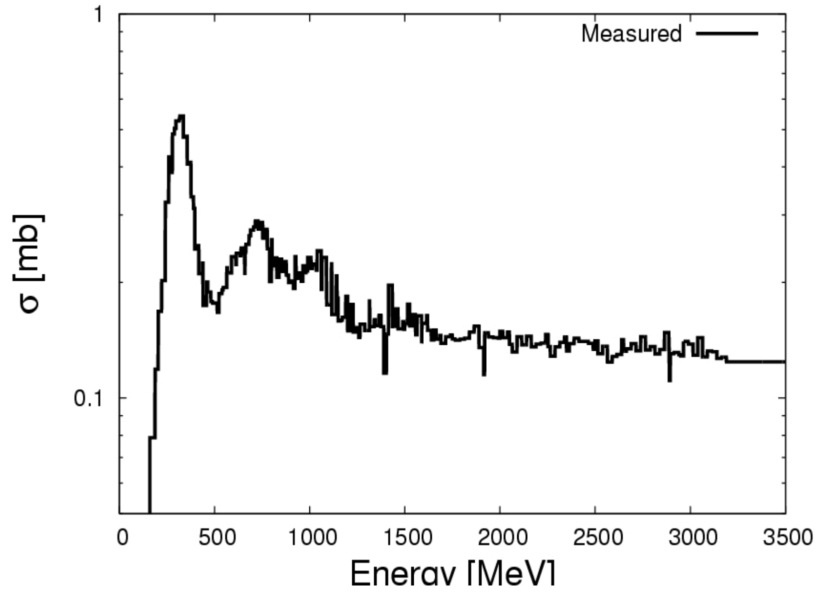




$E_{\gamma}^{th} \sim 1\text{MeV}$

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





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

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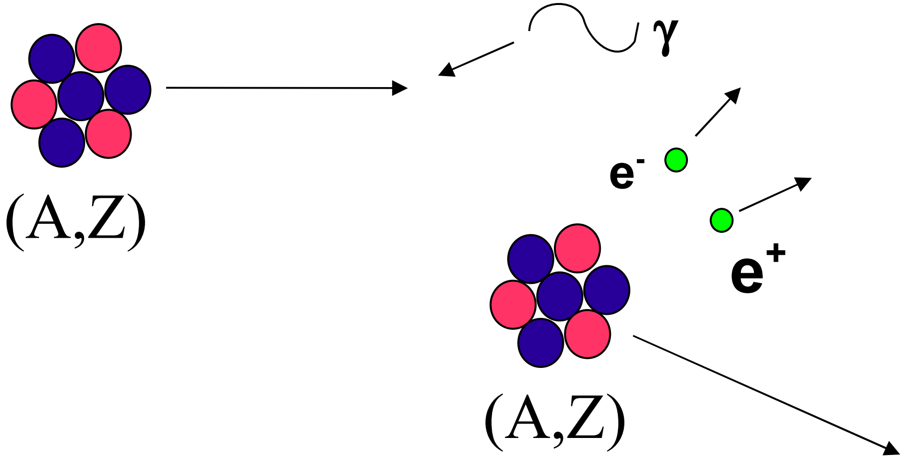
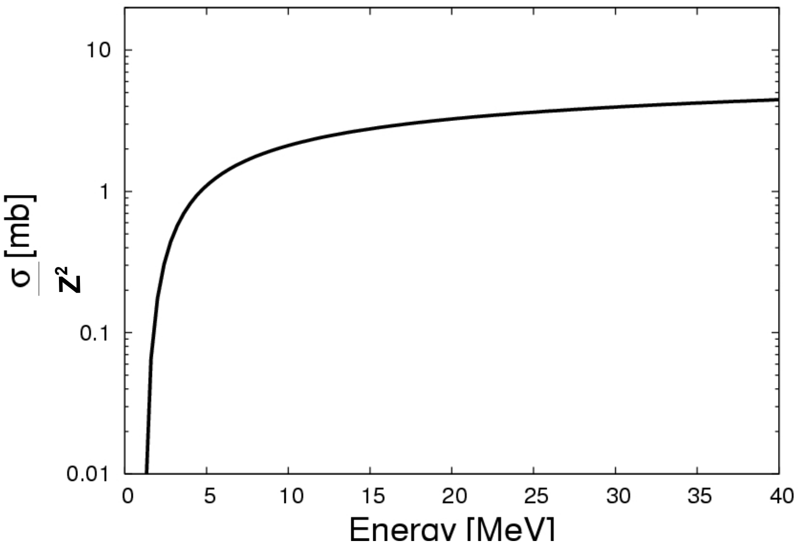
# Cosmic Ray Nuclei Interactions

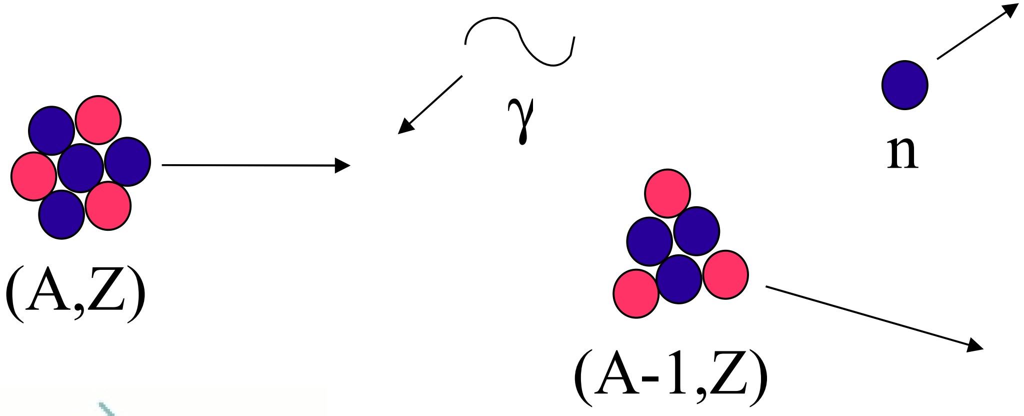
For $10^{19.7} < E_{(A,Z)} < 10^{20.2}$ eV

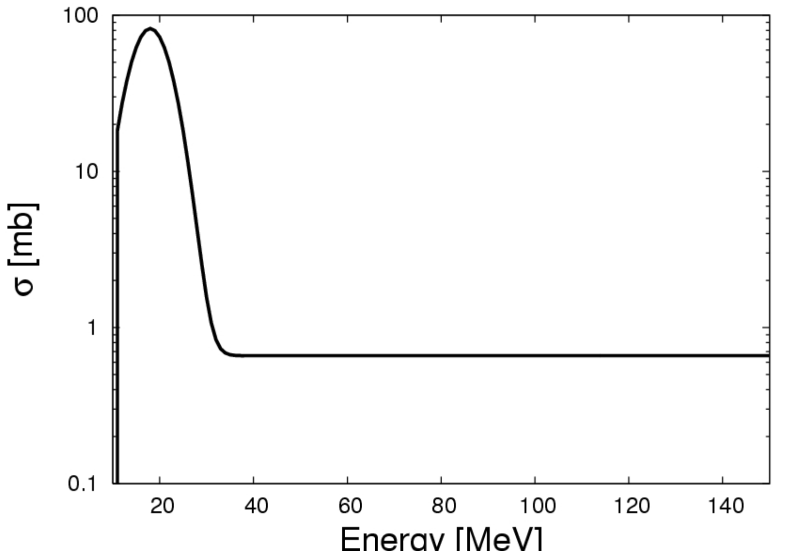




$E_{\gamma}^{th} \sim 1\mathrm{MeV}$

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





$E_{\gamma}^{th} \sim 10\ \mathrm{MeV}$

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# 2) Extragalactic Losses (knowns + unknowns)

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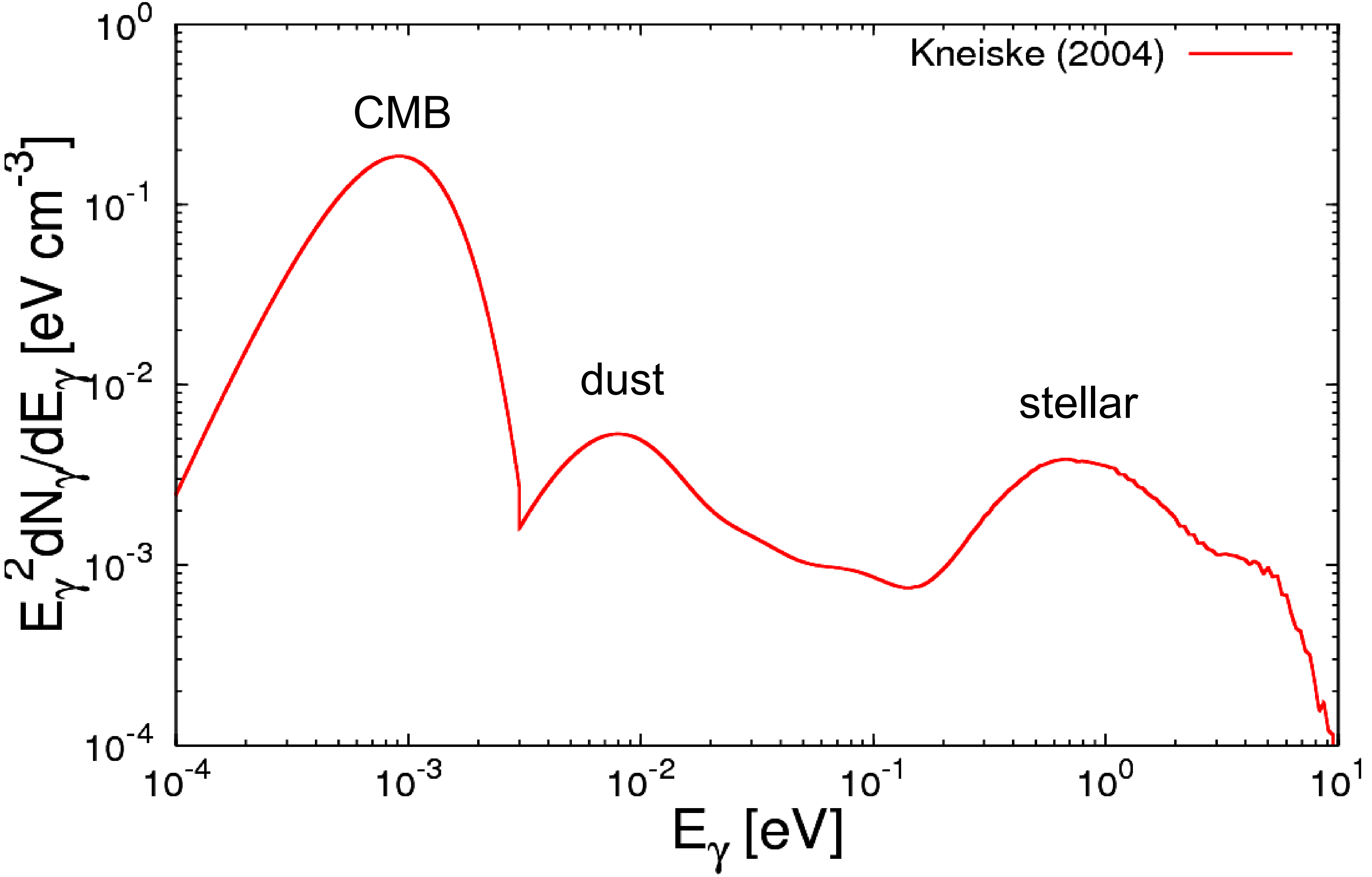
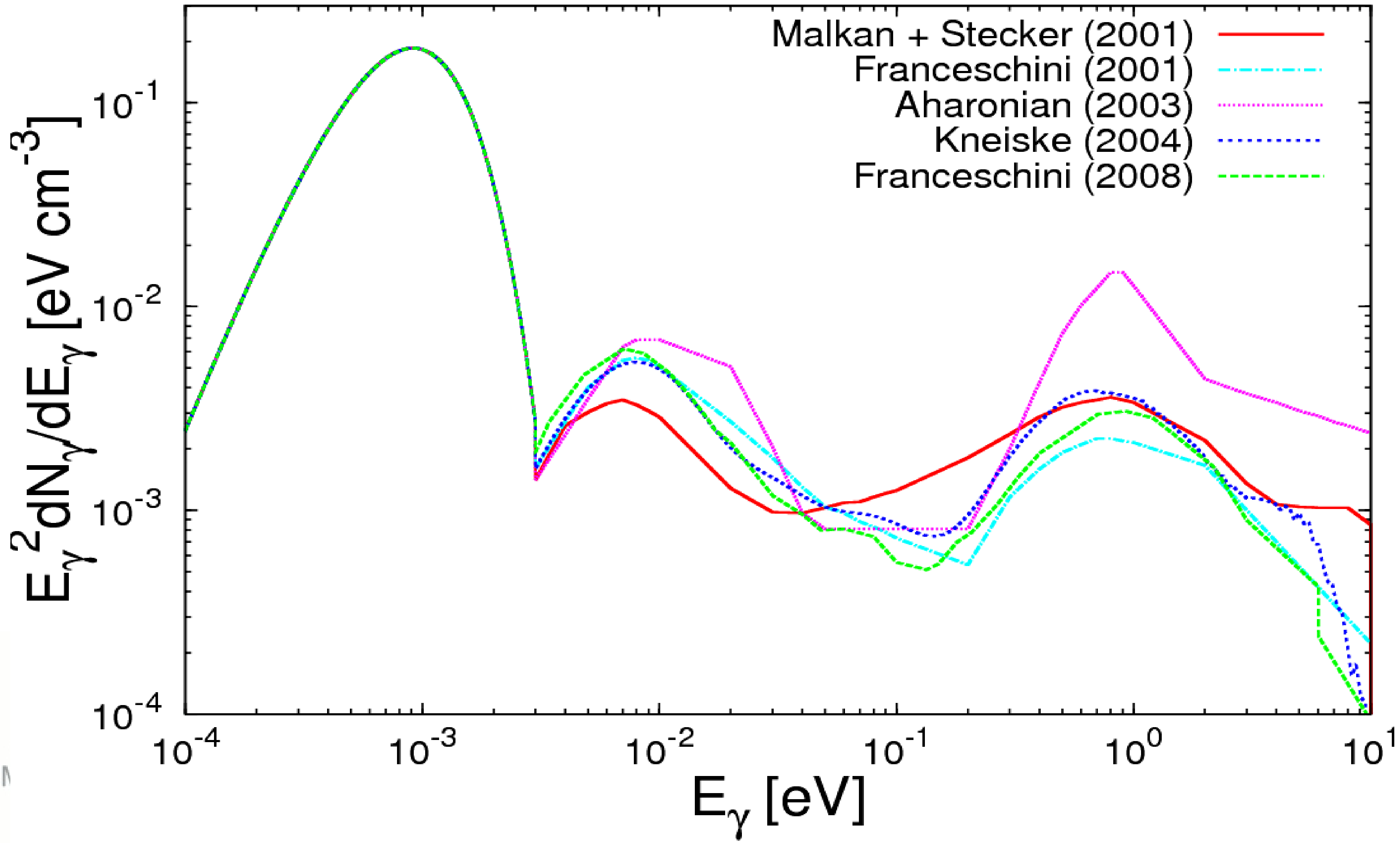
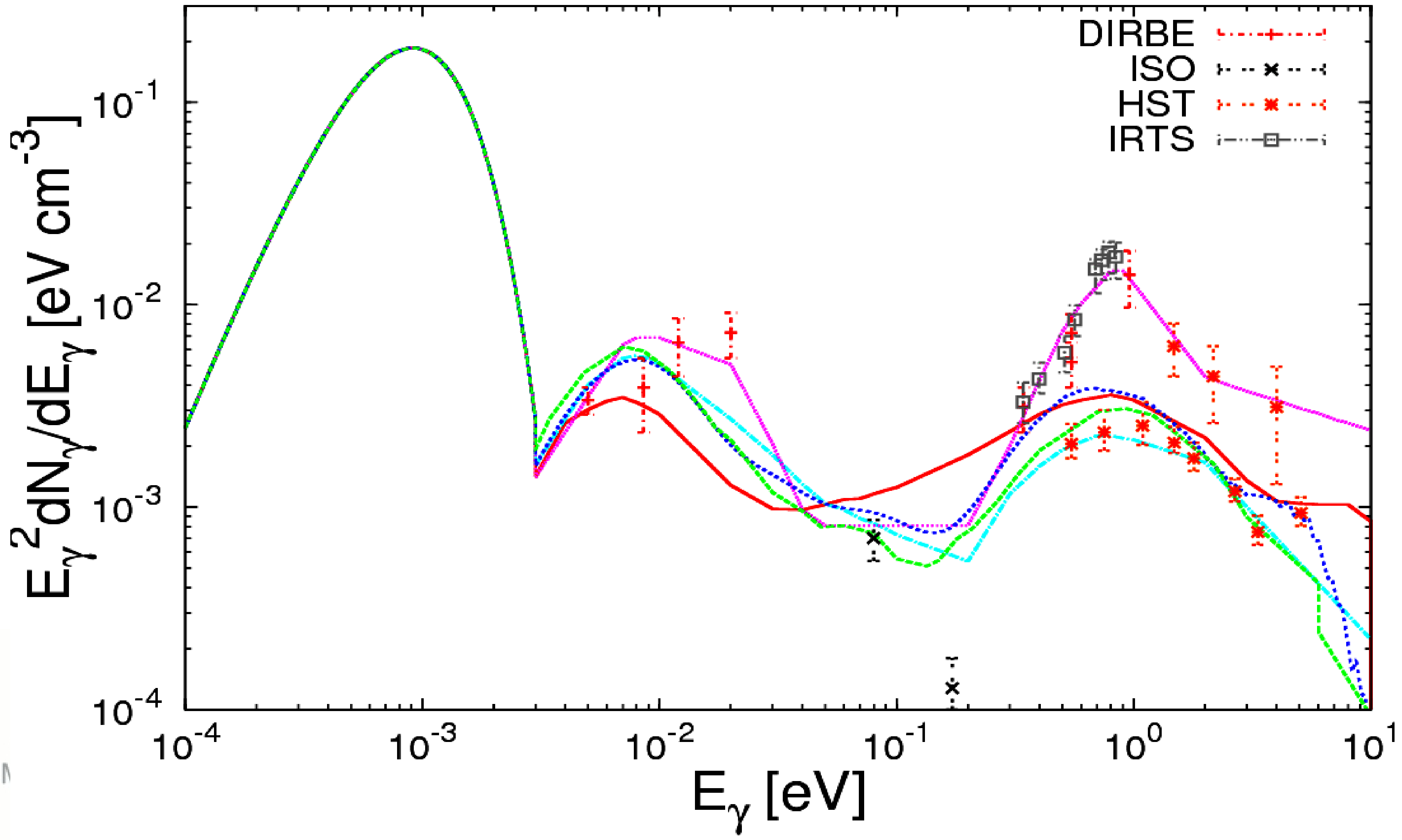
# Dominant Impeder to UHE protons + nuclei- Cosmic Radiation Fields



# Uncertainties in the Cosmic Infrared Background



# Uncertainties in the Cosmic Infrared Background (know your enemy)

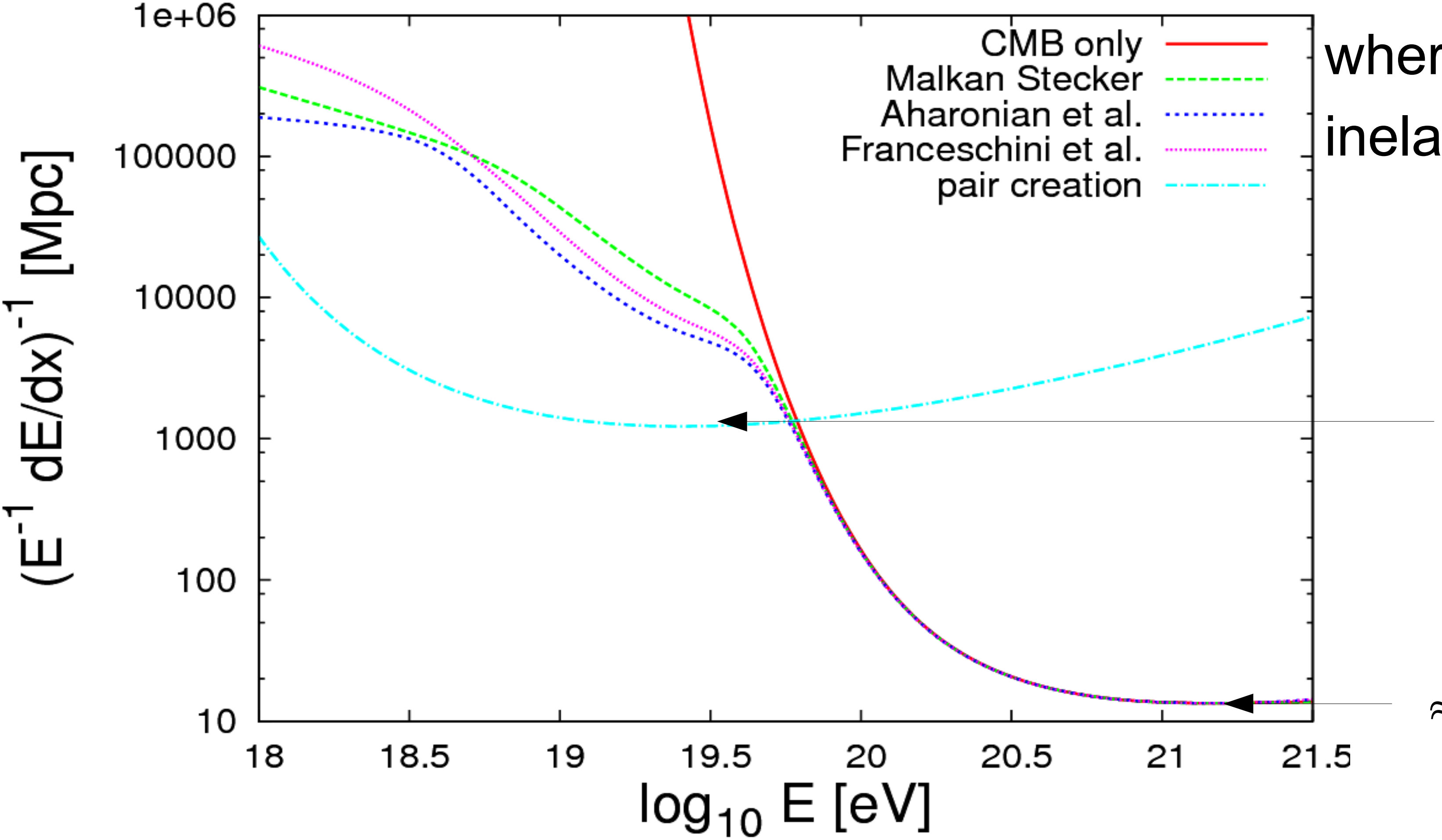


# Energy Loss Rates due to UHE Proton Interactions

$$R=\frac{1}{2\Gamma_p^2}\int_0^\infty \frac{1}{\epsilon_\gamma^2}\frac{dn_\gamma}{d\epsilon_\gamma}d\epsilon_\gamma\int_0^{2\Gamma_p\epsilon_\gamma}d\epsilon_\gamma{}'\epsilon_\gamma{}'\sigma_{p\gamma}(\epsilon_\gamma{}')K_p$$

where R is the energy loss rate

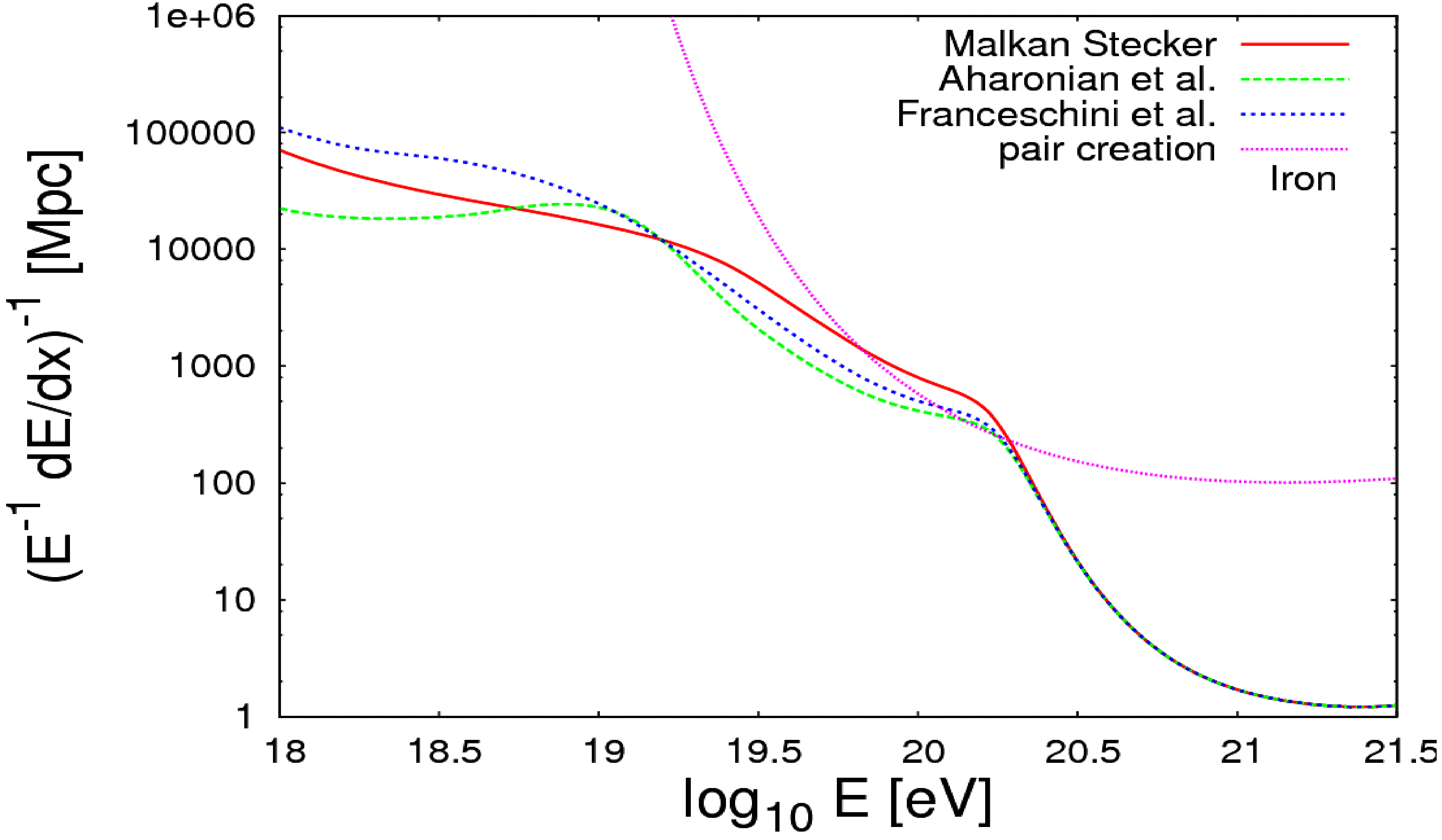
where $K_p$ is the inelasticity



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

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

# Energy Loss Rates due to UHE Nuclei Interactions



# Assumptions about High Energy Cosmic Ray Sources

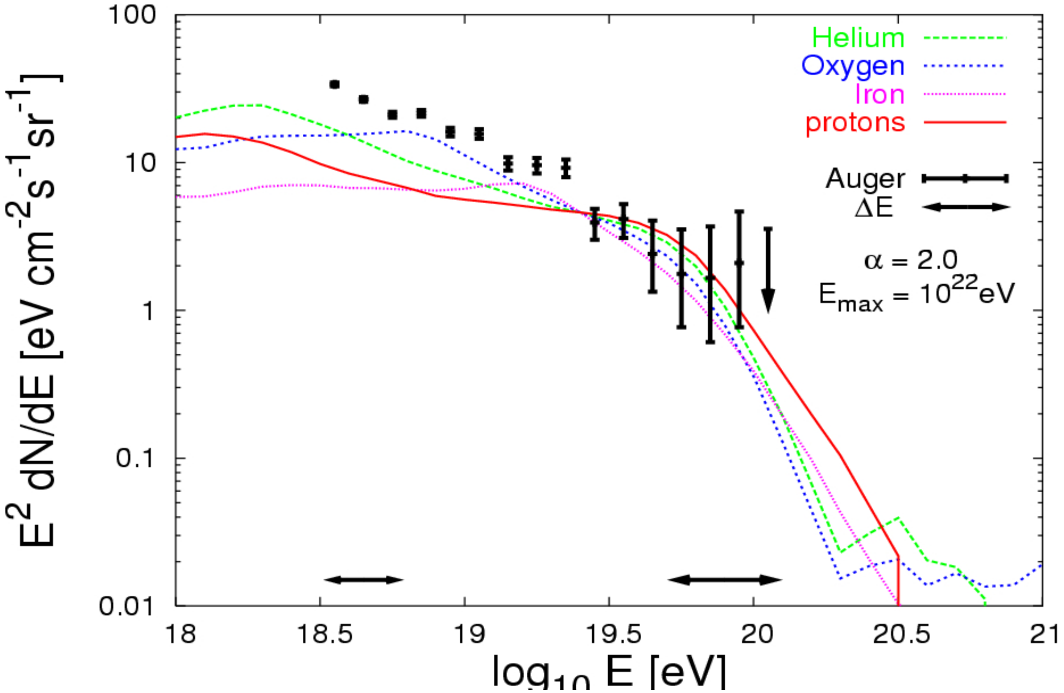
**Energy Distribution** of Cosmic Rays

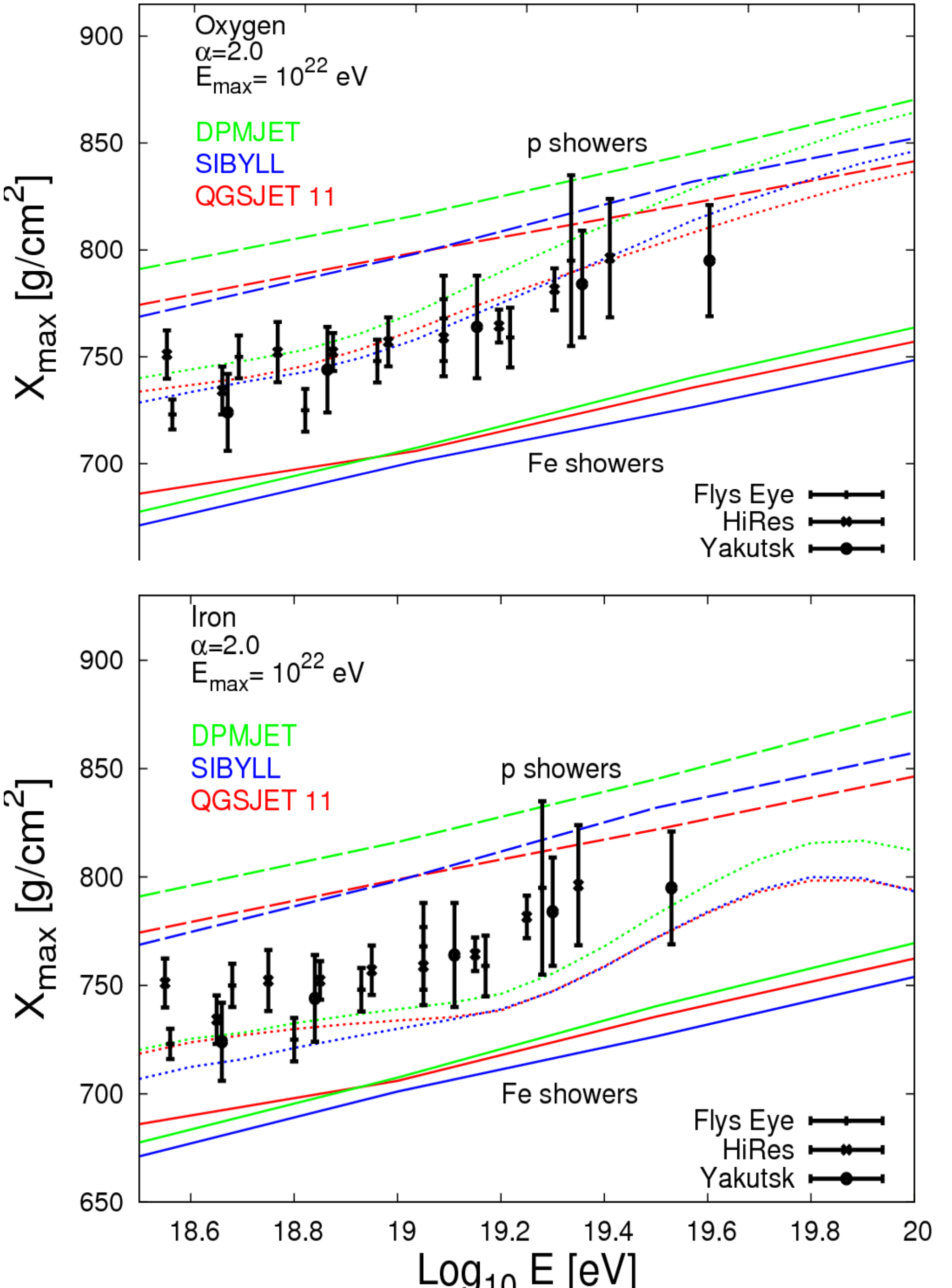
- $dN/dE \sim E^{-2}$ motivated by first order Fermi shock acceleration theory

**Spatial Distribution** of Cosmic Ray Sources

- $dN/dV \sim (1+z)^3$

# Do Protons or Nuclei Fit the Data? $\alpha=2$





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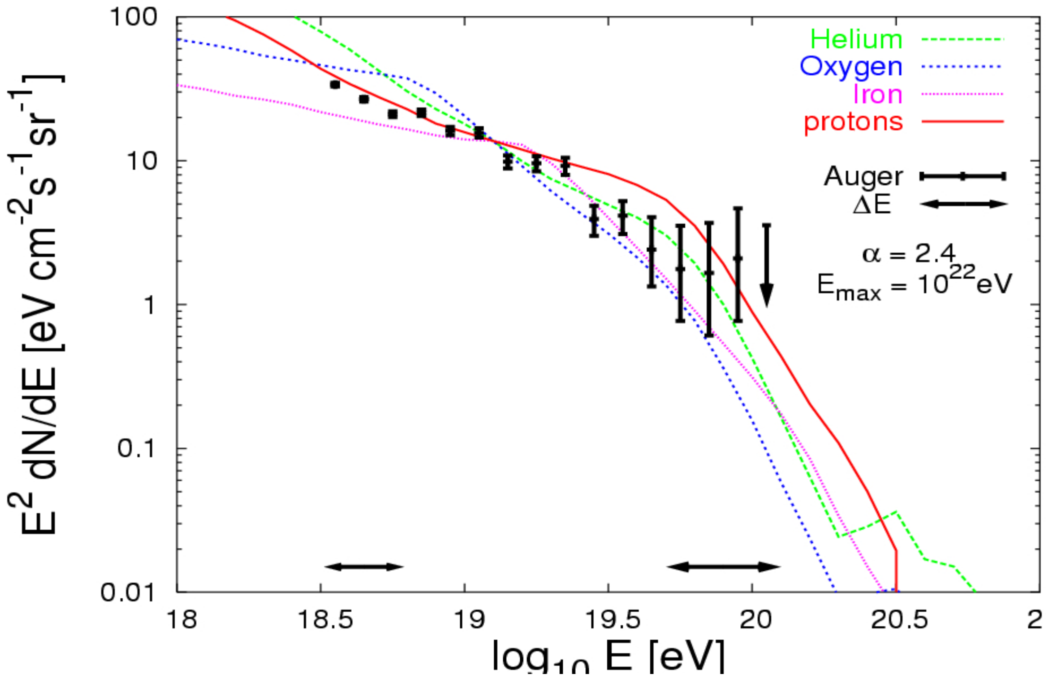
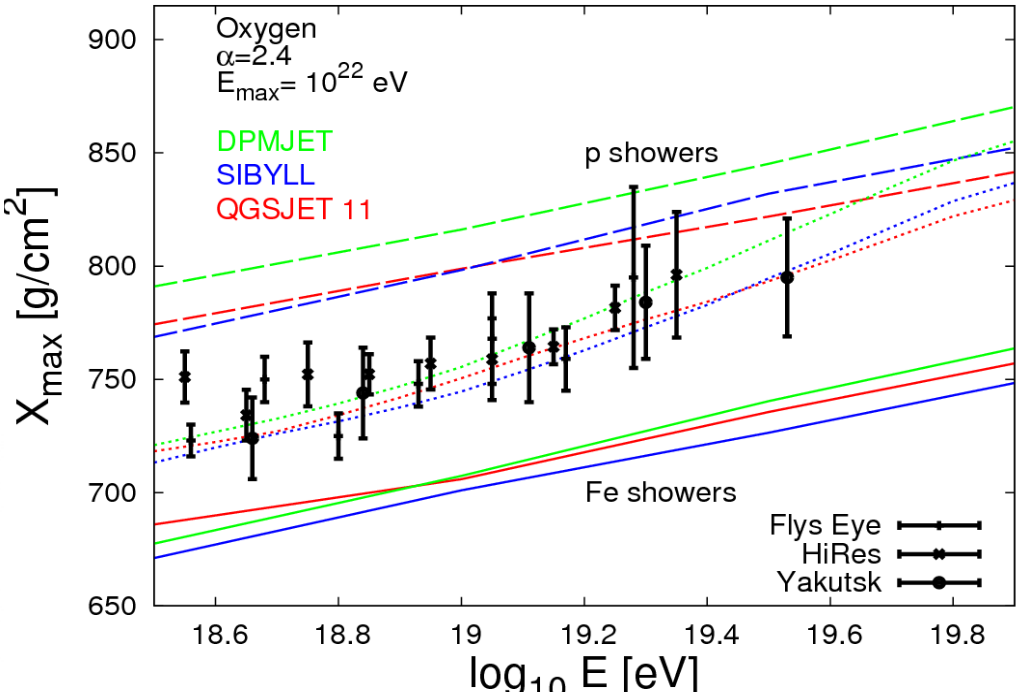
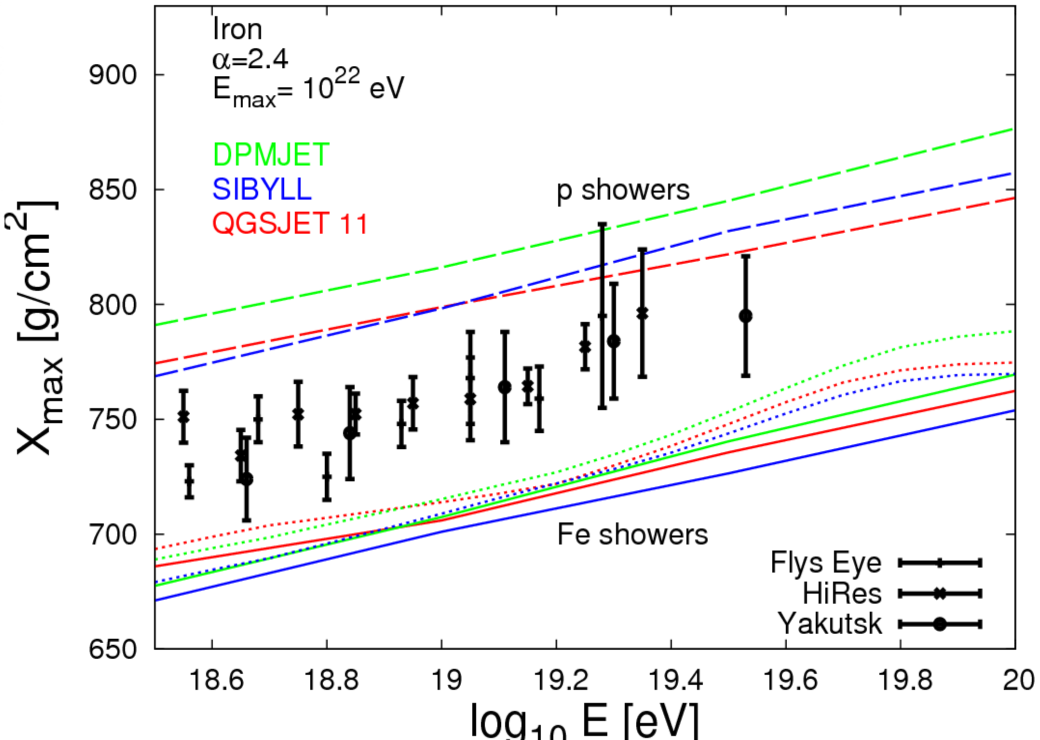
# Or $\alpha=2.4$







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# 3) Analytic Methods to Propagate UHECR

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# the differential equation describing the energy states of the system-

$$\frac{d}{dt}\begin{pmatrix} f_0 \\ f_1 \\ f_2 \end{pmatrix} = \Lambda \begin{pmatrix} f_0 \\ f_1 \\ f_2 \end{pmatrix}$$

$$\Lambda = \begin{pmatrix} -\left(\frac{1}{\tau_{0\rightarrow 1}} + \frac{1}{\tau_{0\rightarrow 2}} + \ldots\right) & 0 & 0 \\ \frac{1}{\tau_{0\rightarrow 1}} & -\left(\frac{1}{\tau_{1\rightarrow 2}} + \frac{1}{\tau_{1\rightarrow 3}} + \ldots\right) & 0 \\ \frac{1}{\tau_{0\rightarrow 2}} & \frac{1}{\tau_{1\rightarrow 2}} & -\left(\frac{1}{\tau_{2\rightarrow 3}} + \frac{1}{\tau_{2\rightarrow 4}} + \ldots\right) \end{pmatrix}$$

by $f_q(t) = \Sigma_{n=q}^{10} A_n f_n(t)$

then $f_q(t) = \Sigma_{n=q}^{10} A_n e^{\lambda_n t} f_n(0)$

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considering only single pion loss, keep only diagonal and first off diagonal elements-

$$\Lambda=\begin{pmatrix} \frac{-1}{\tau_{0\to1}} & 0 & 0 \\ \frac{1}{\tau_{0\to1}} & \frac{-1}{\tau_{1\to2}} & 0 \\ 0 & \frac{1}{\tau_{1\to2}} & \frac{-1}{\tau_{2\to3}} \end{pmatrix}$$

and

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

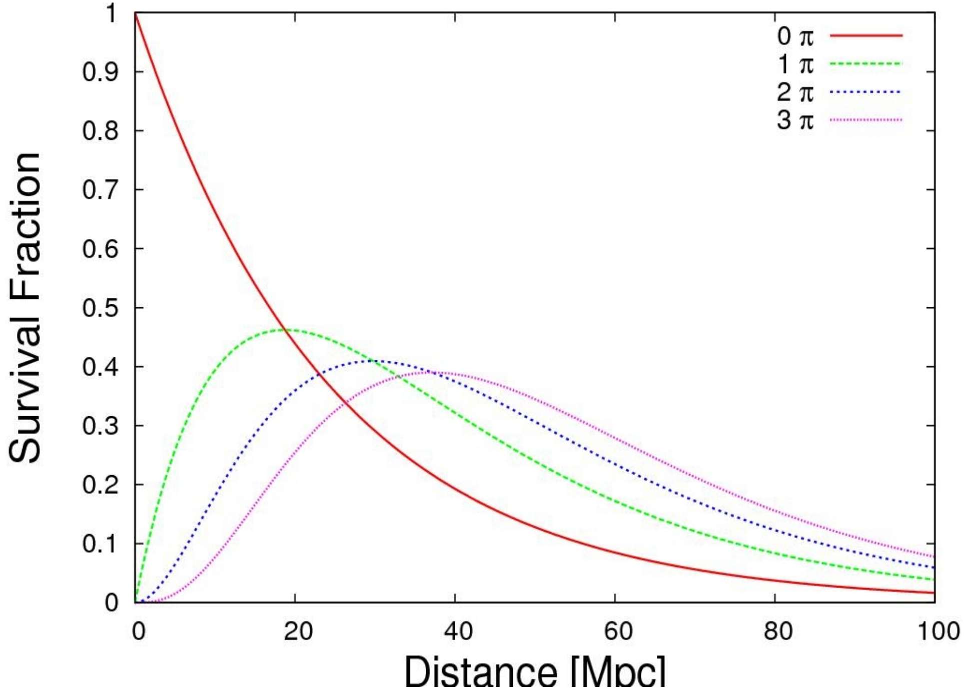
# considering only single pion loss, keep only diagonal and first off diagonal elements-

$$\Lambda = \begin{pmatrix} \frac{-1}{\tau_{0\rightarrow 1}} & 0 & 0 \\ \frac{1}{\tau_{0\rightarrow 1}} & \frac{-1}{\tau_{1\rightarrow 2}} & 0 \\ 0 & \frac{1}{\tau_{1\rightarrow 2}} & \frac{-1}{\tau_{2\rightarrow 3}} \end{pmatrix}$$

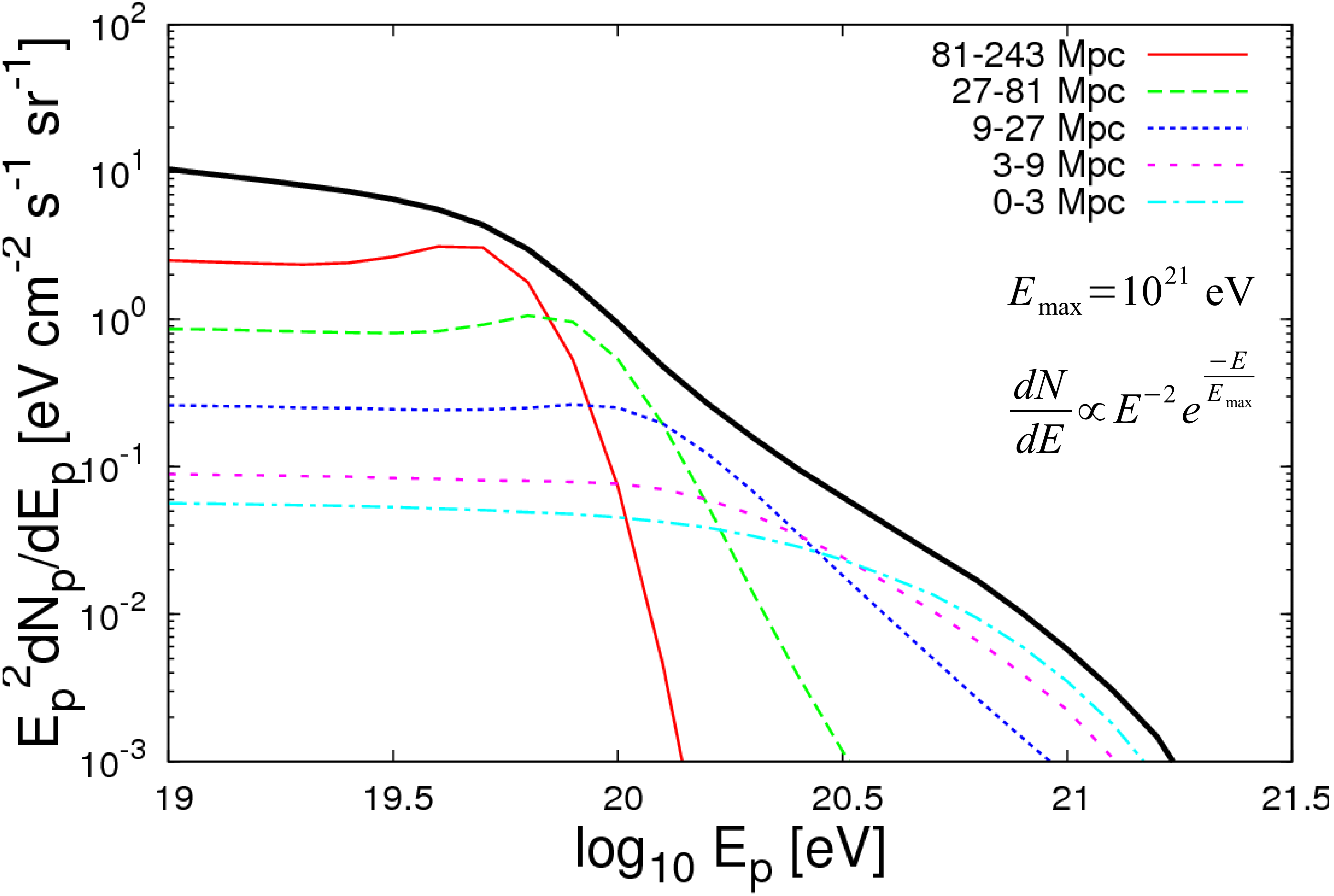
and

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

Injecting a $10^{20}$eV Proton and tracking it-



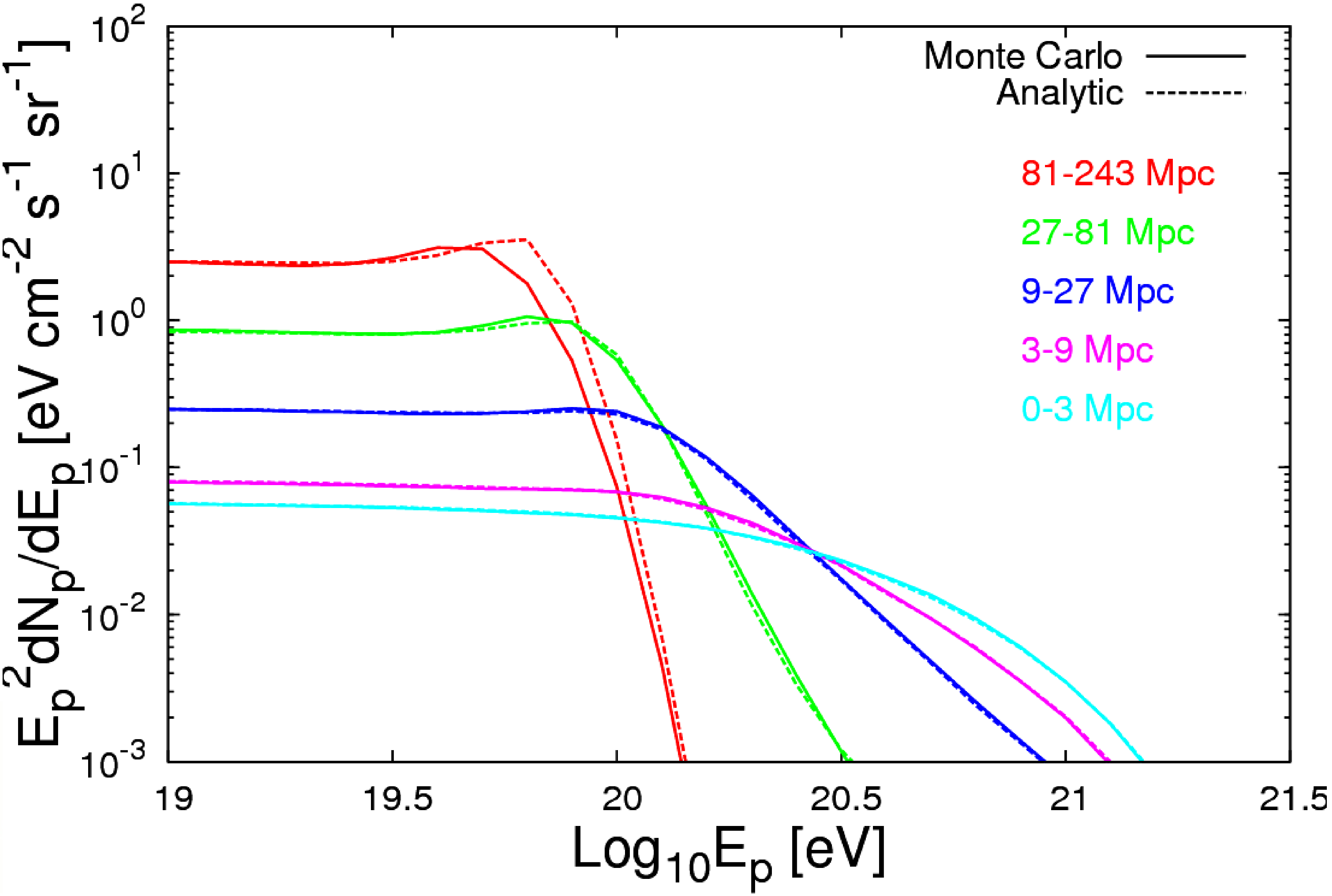
# Monte Carlo- Arriving Proton Flux from Shells



$$E_{\max} = 10^{21} \text{ eV}$$

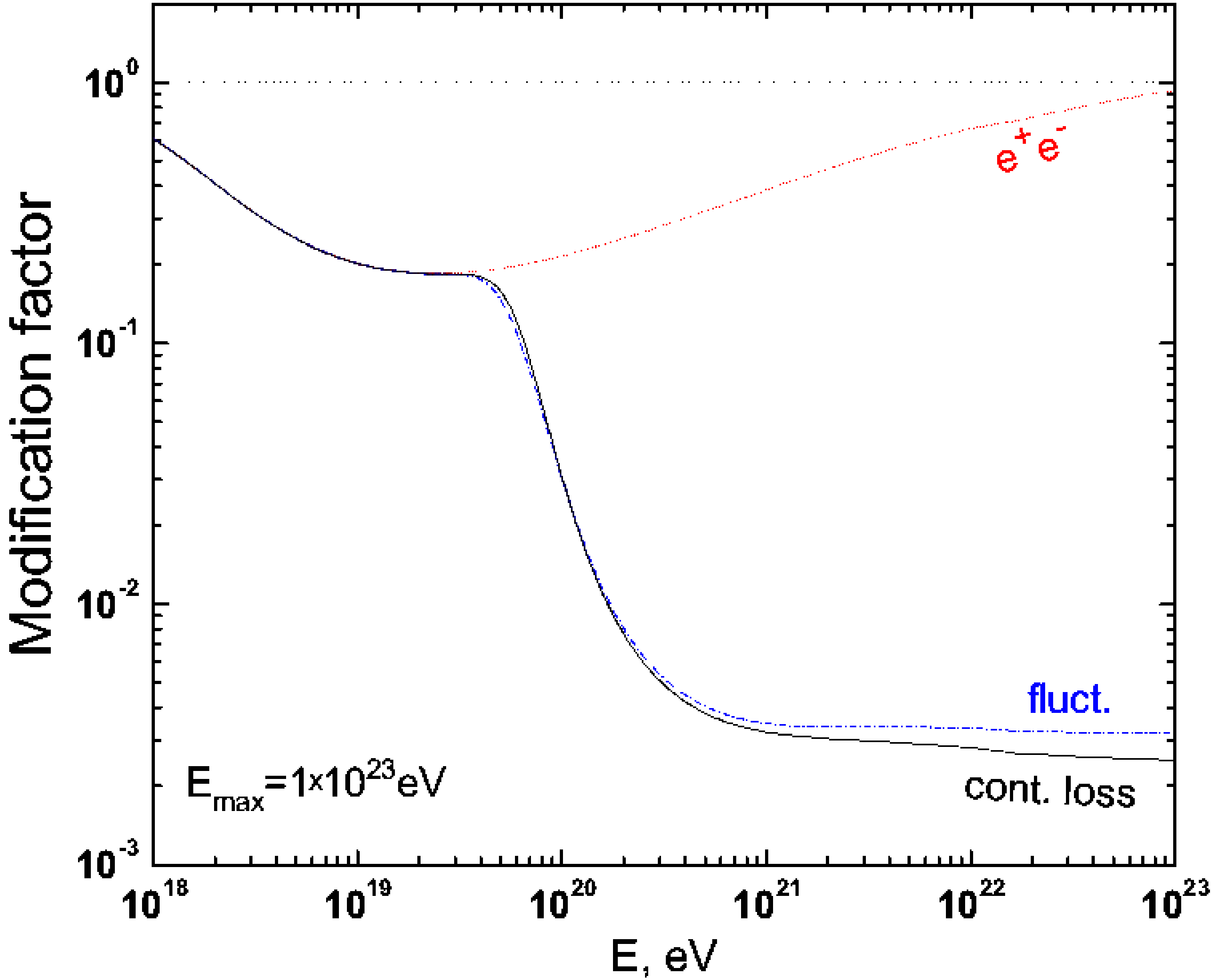
$$\frac{dN}{dE} \propto E^{-2} e^{\frac{-E}{E_{\max}}}$$

# Comparison of Monte Carlo and Analytic Shell Fluxes



# Continuous Energy Losses vs Stochastic Losses
# Photo-pion Emission

Berezinsky et al.
Astro-ph/0204357



# ...and nuclei?

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# Differential equation describing occupation of nuclear states-

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

$$\Lambda = \begin{pmatrix} -\left(\frac{1}{\tau_{56\rightarrow 55}} + \frac{1}{\tau_{56\rightarrow 54}} + \ldots\right) & 0 & 0 \\ \frac{1}{\tau_{56\rightarrow 55}} & -\left(\frac{1}{\tau_{55\rightarrow 54}} + \frac{1}{\tau_{55\rightarrow 53}} + \ldots\right) & 0 \\ \frac{1}{\tau_{56\rightarrow 54}} & \frac{1}{\tau_{55\rightarrow 54}} & -\left(\frac{1}{\tau_{54\rightarrow 53}} + \frac{1}{\tau_{54\rightarrow 52}} + \ldots\right) \end{pmatrix}$$

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)

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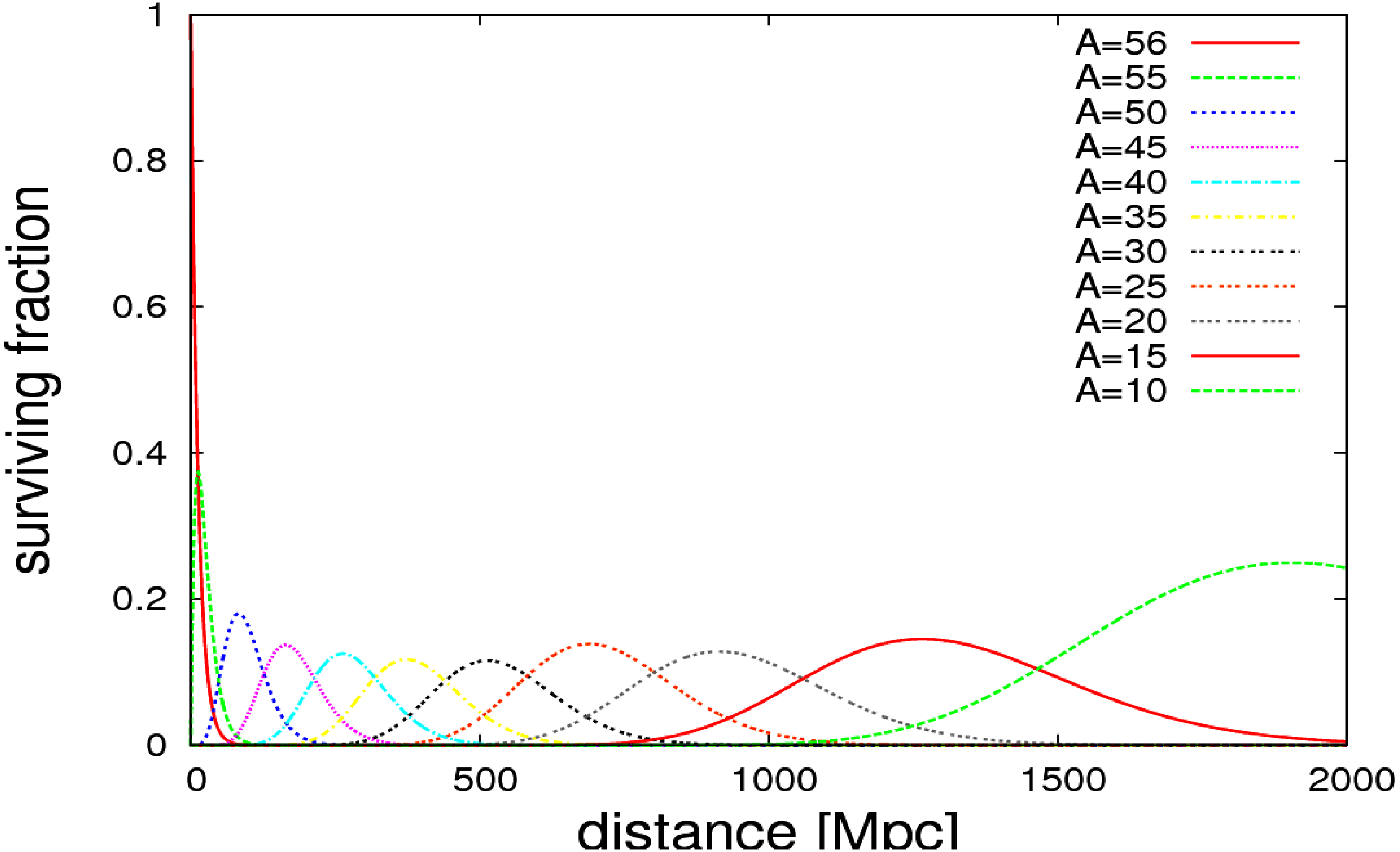
# Injecting a $10^{20}$eV Fe Nucleus and Tracking the Subsequent Nuclei (assume no Lorentz factor slippage)-



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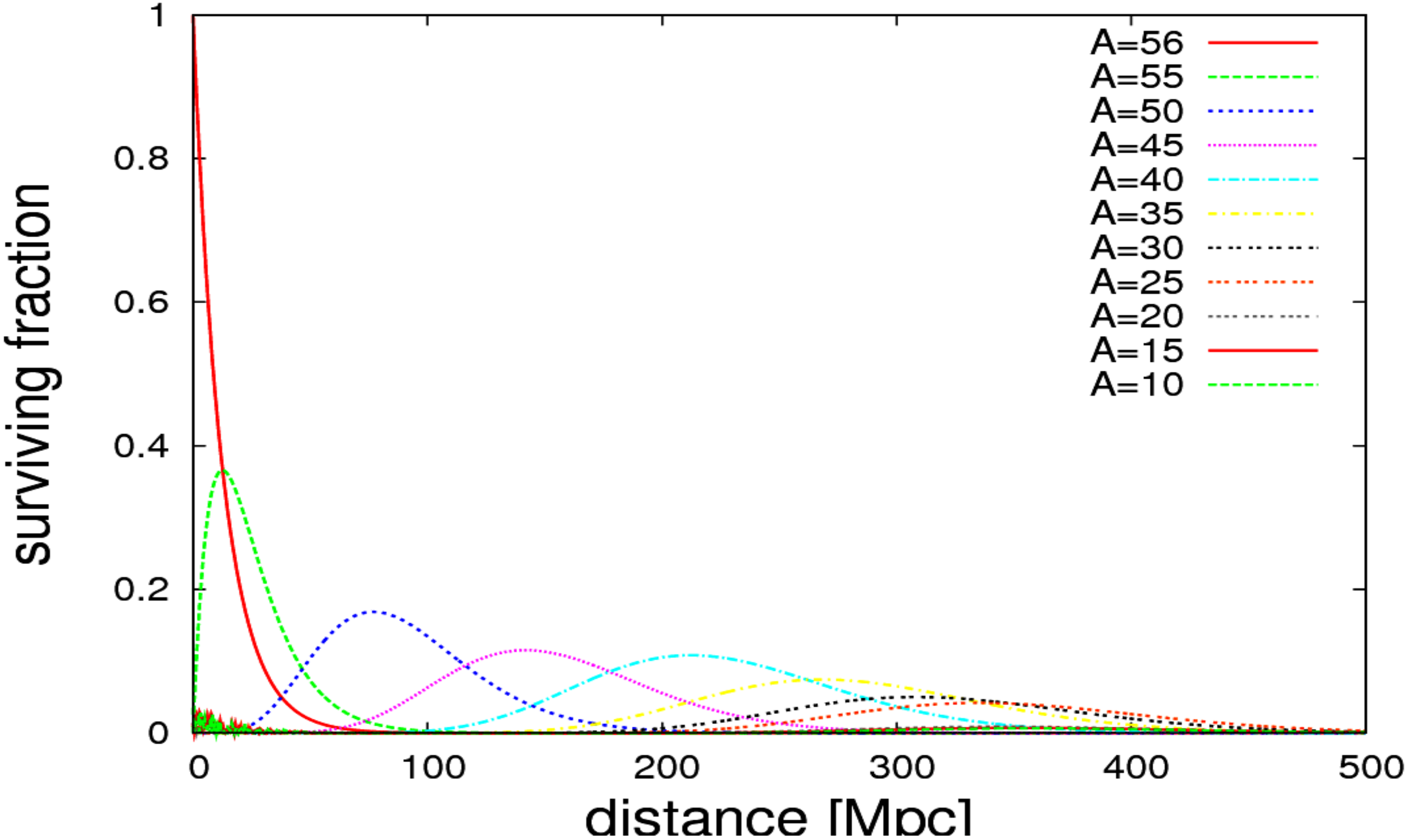
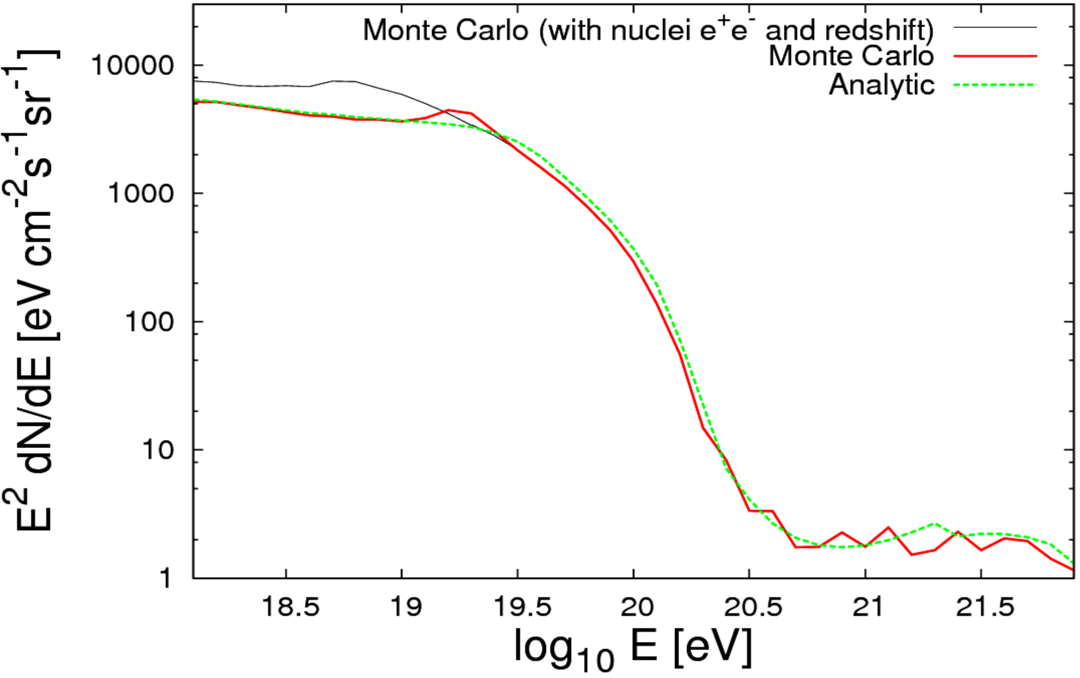
# Distribution of Nuclei Each with $10^{20}$ eV

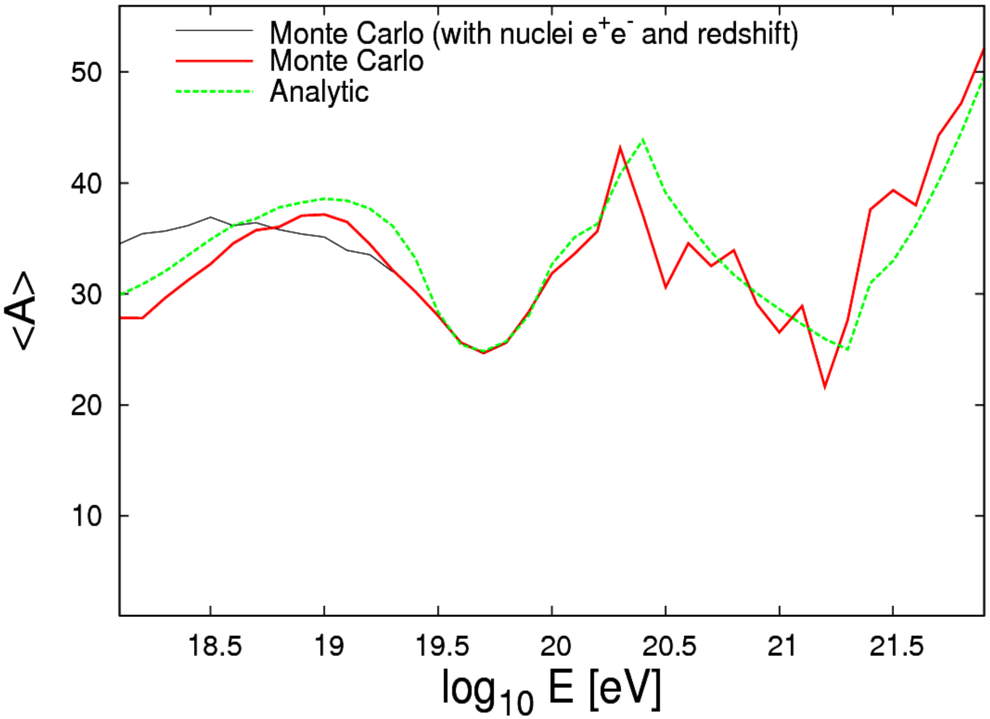


# Comparison of Analytic and Monte Carlo Results



$$E_{\max} = \left(\frac{Z}{26}\right) 10^{22}\ \text{eV}$$

$$\frac{dN}{dE} \propto E^{-2} e^{\frac{-E}{E_{\max}}}$$



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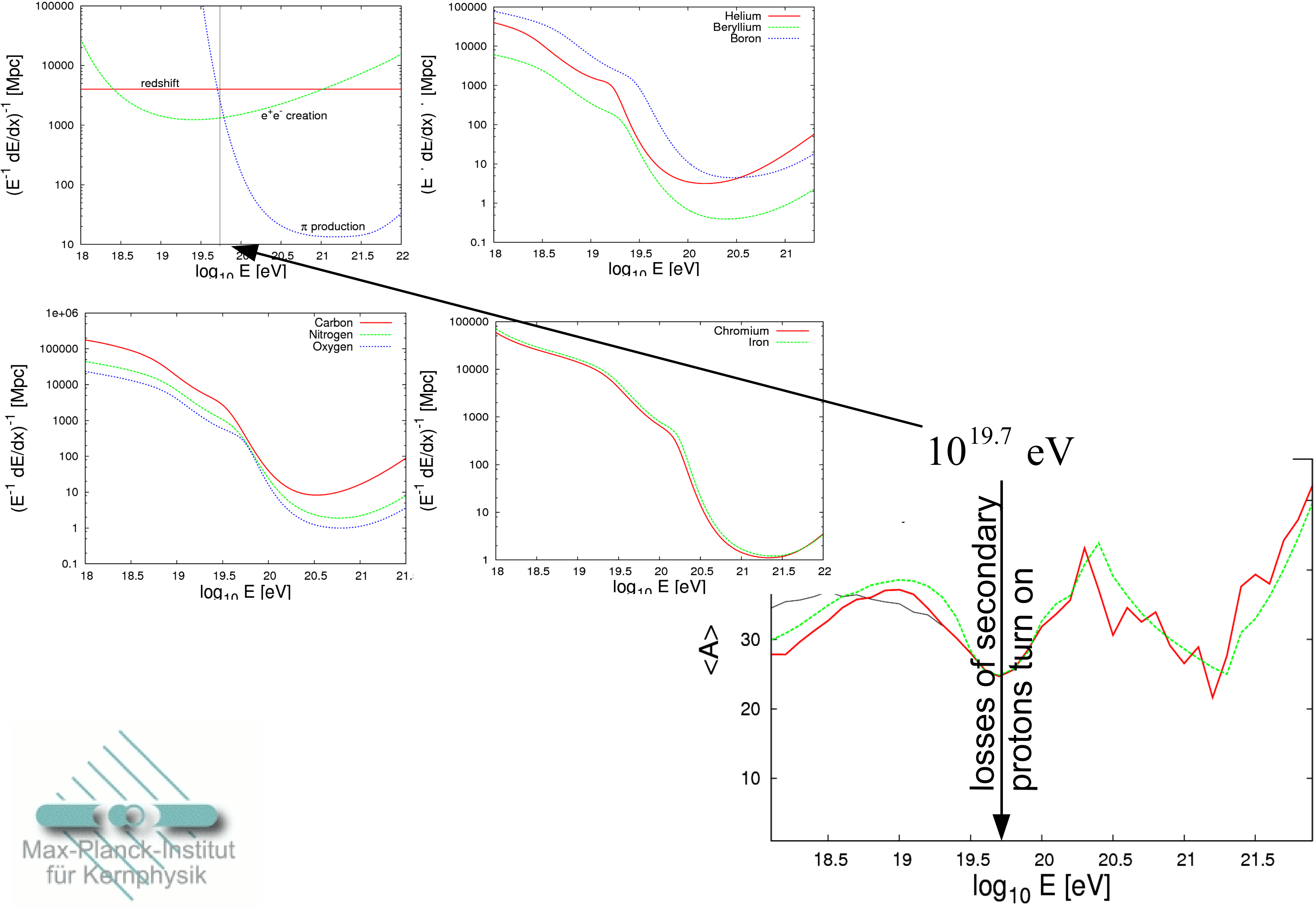
# Explanation of <A> Plot



$10^{19.7}$ eV

losses of secondary protons turn on

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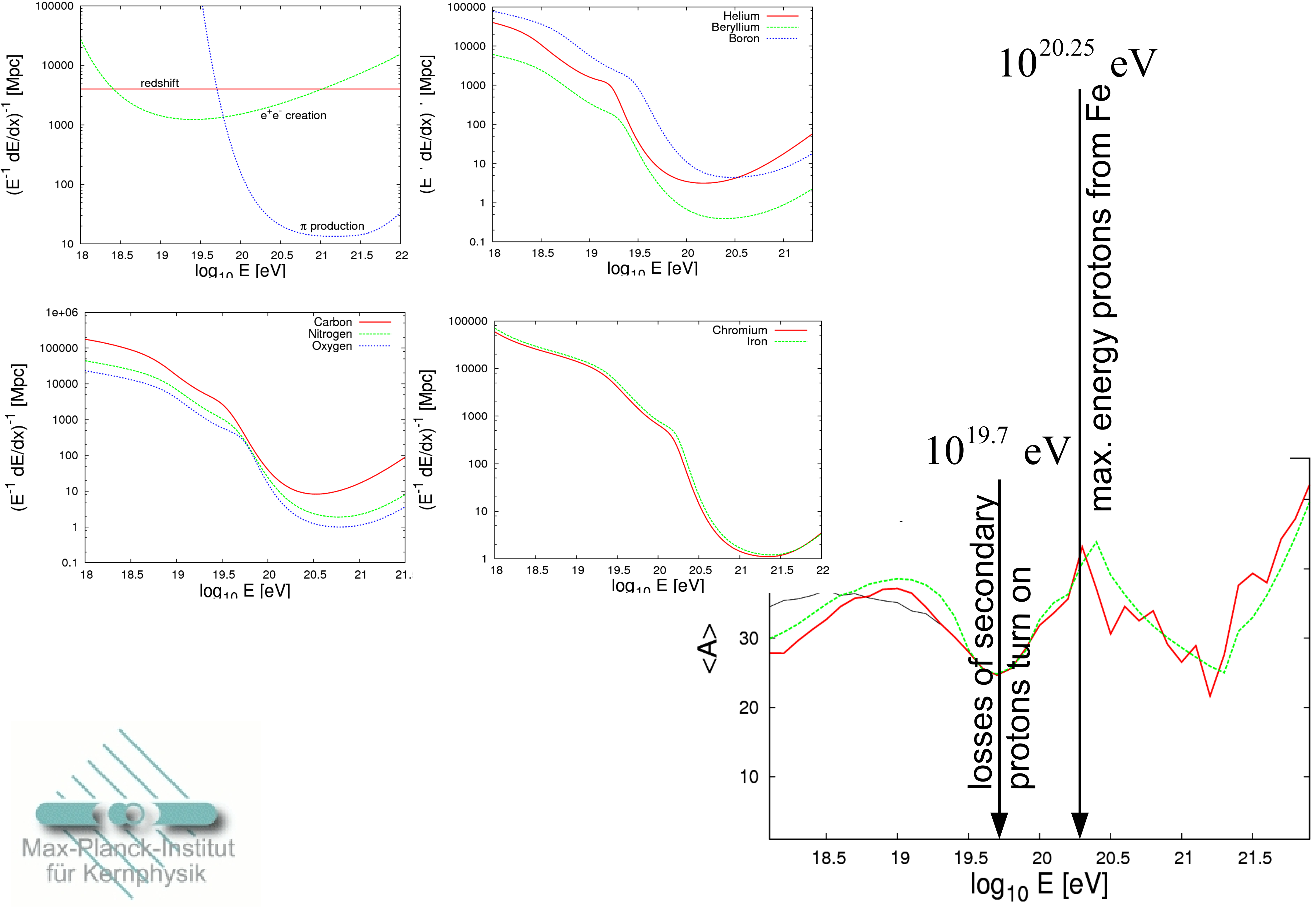
# Explanation of <A> Plot



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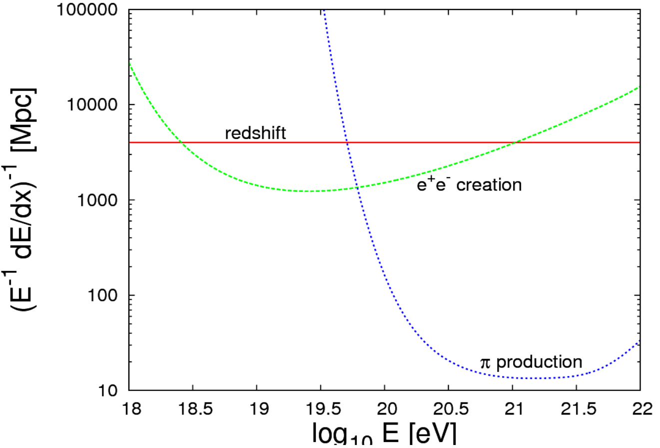
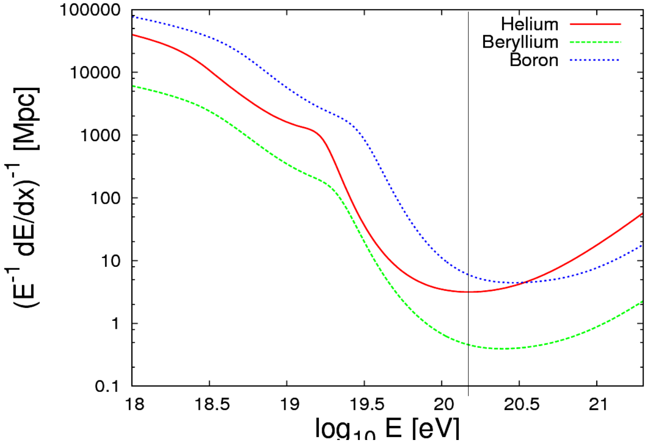
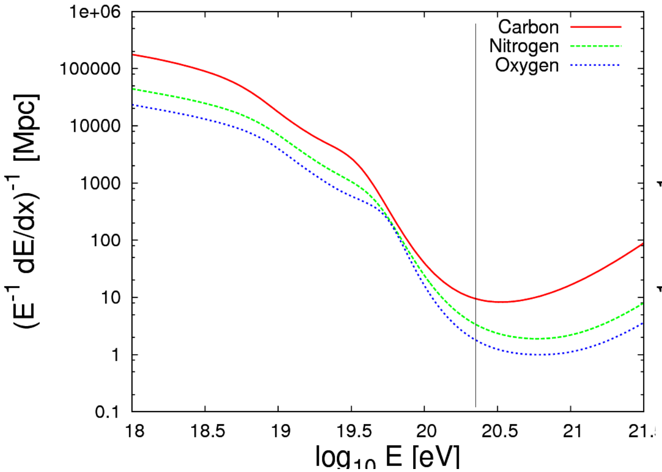
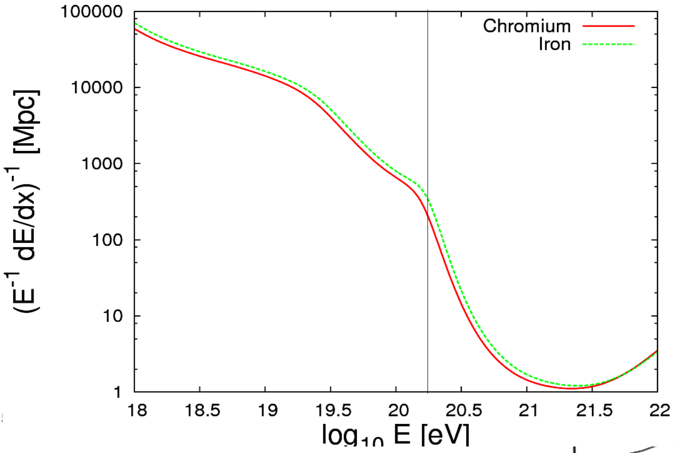
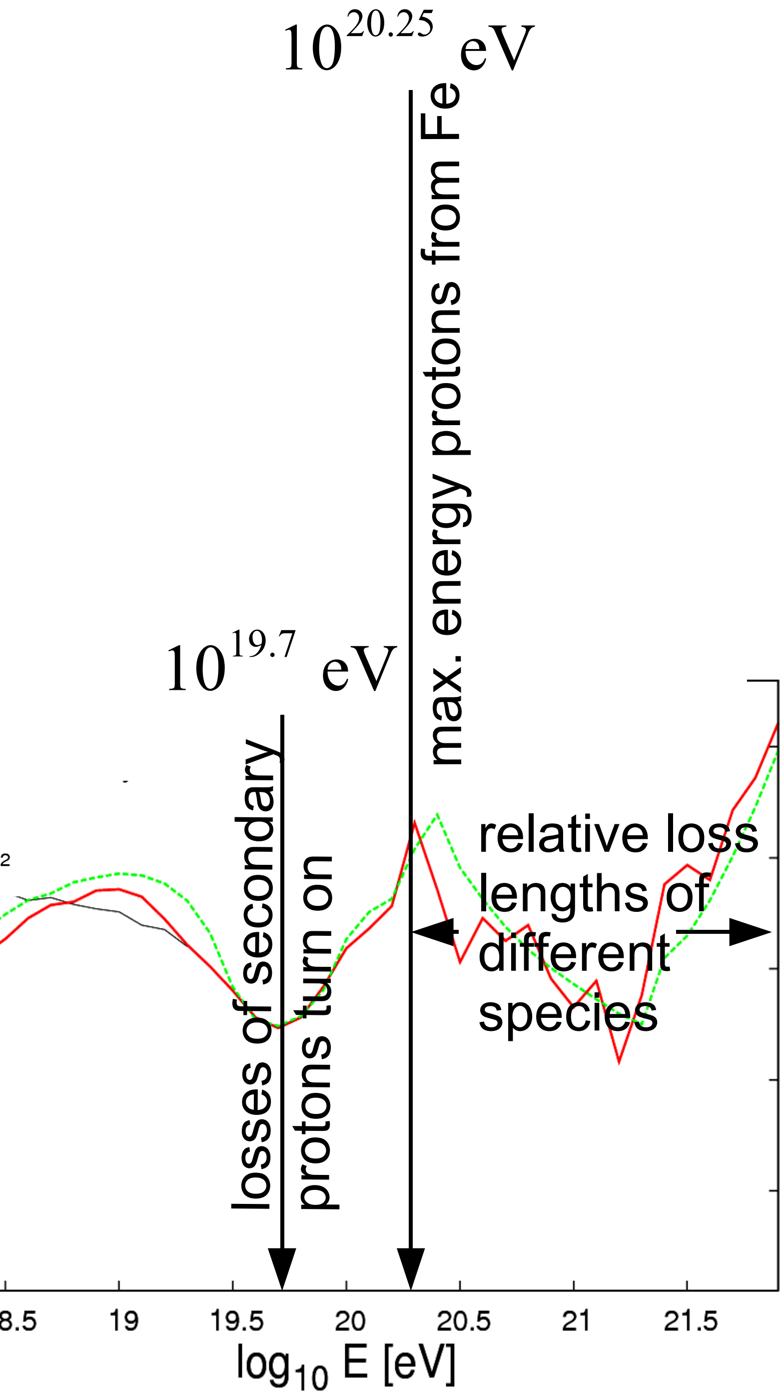
# Explanation of <A> Plot











$10^{20.25}$ eV

max. energy protons from Fe

$10^{19.7}$ eV

losses of secondary protons turn on

relative loss lengths of different species

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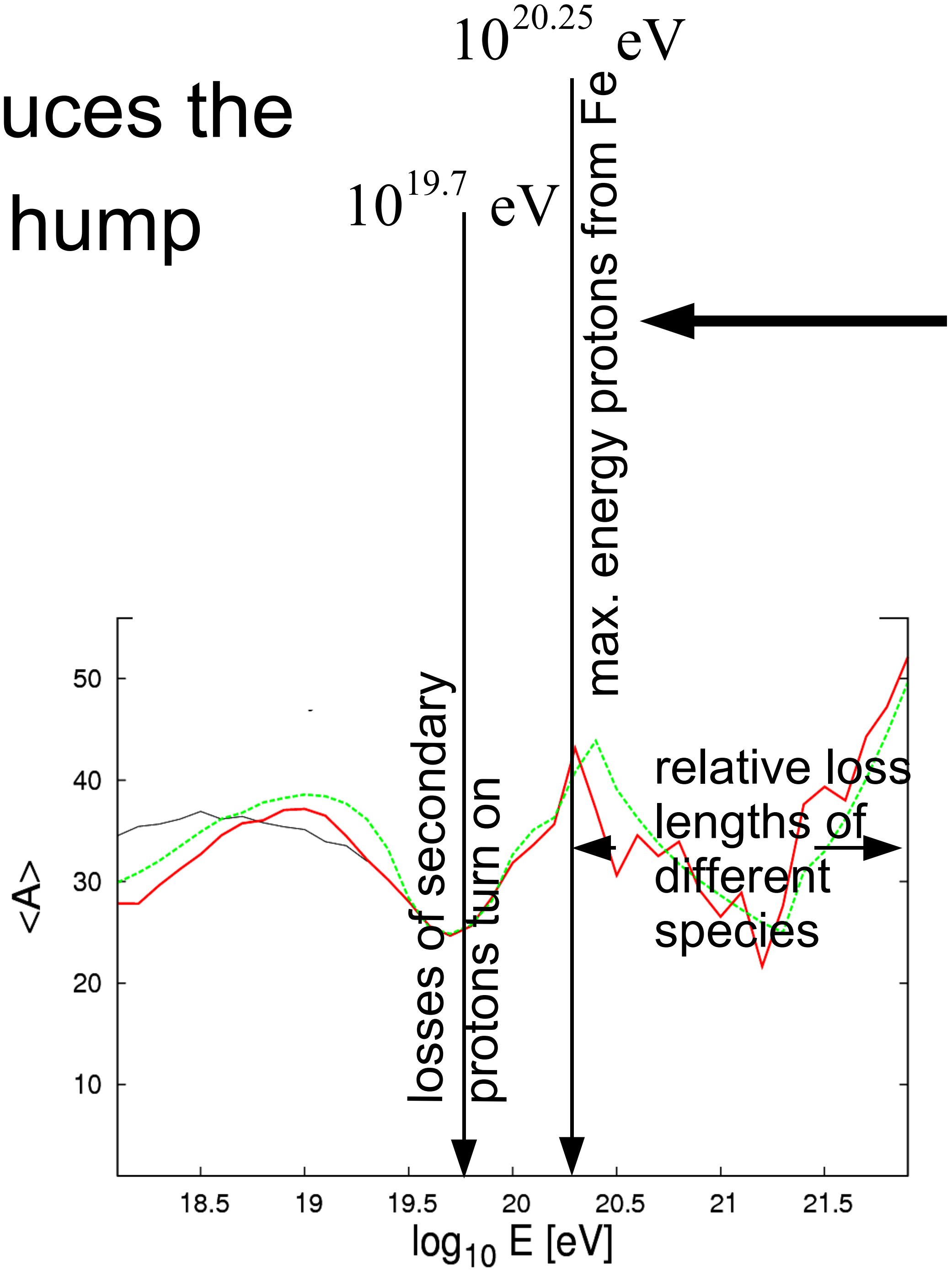
# Dependence on $E_{max}$?

Reducing $E_{max}$ reduces the presence of dip + hump features



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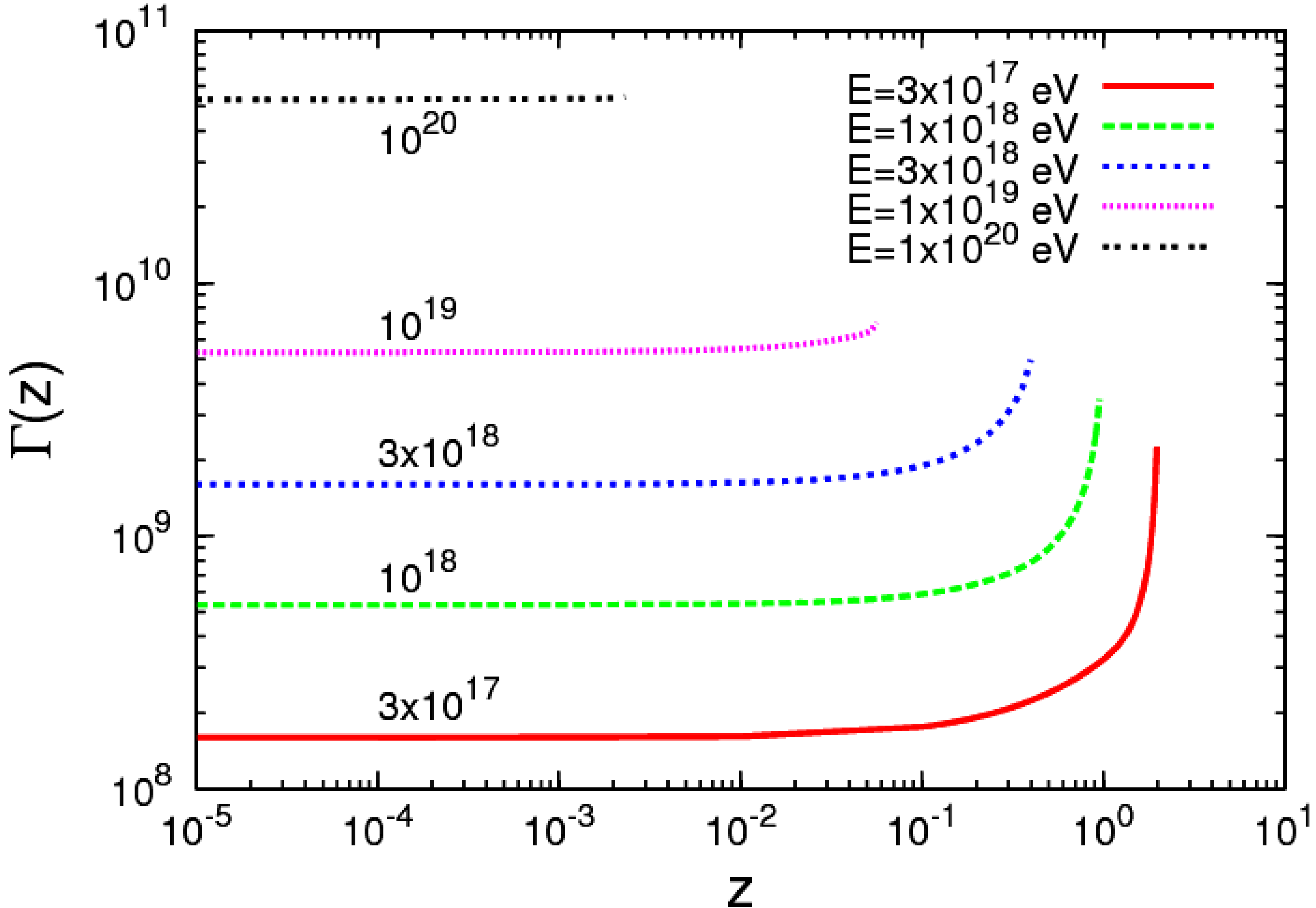
# Alternatively- consider particle interactions a set distance (delta function) + worry about Lorentz factor slippage (through pair loss interactions)

Aloisio et al.
Astro-ph/0802.4452



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# Conclusions

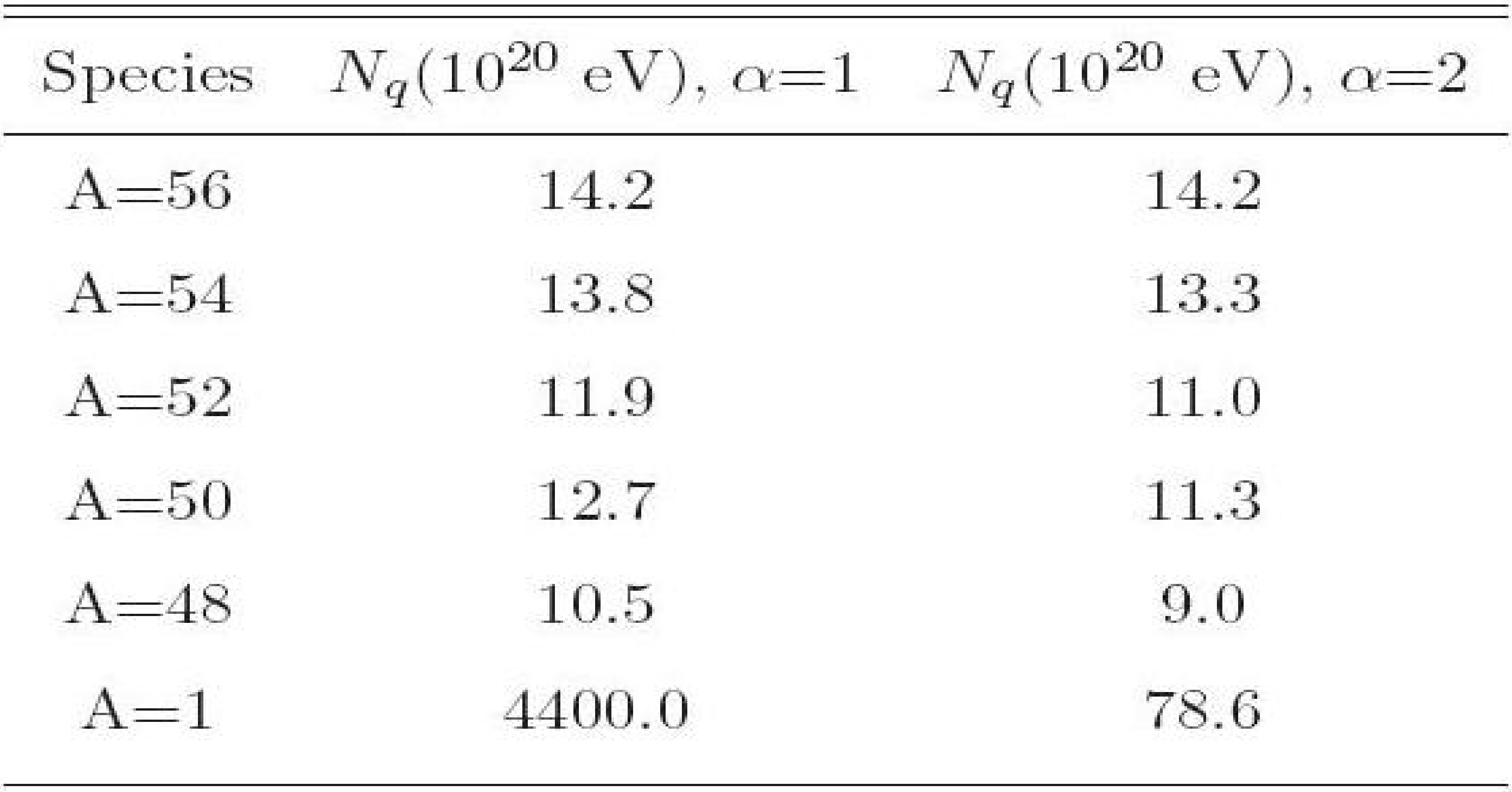
- The losses of UHECR within their source environment are a largely unknown quantity

- The losses of UHECR in extragalactic space are better understood, despite uncertainties in the CIRB

- Simple analytic descriptions of nuclei losses are able to provide a reasonably accurate description of the flux evolution of UHECR nuclei caused by propagation losses

- Simple analytic descriptions are also able to describe the flux evolution of UHECR protons

# Breakdown of Components of Arriving Flux at $10^{20}$ eV



| Species | $N_q(10^{20}$ eV), $\alpha$=1 | $N_q(10^{20}$ eV), $\alpha$=2 |
|---|---|---|
| A=56 | 14.2 | 14.2 |
| A=54 | 13.8 | 13.3 |
| A=52 | 11.9 | 11.0 |
| A=50 | 12.7 | 11.3 |
| A=48 | 10.5 | 9.0 |
| A=1 | 4400.0 | 78.6 |

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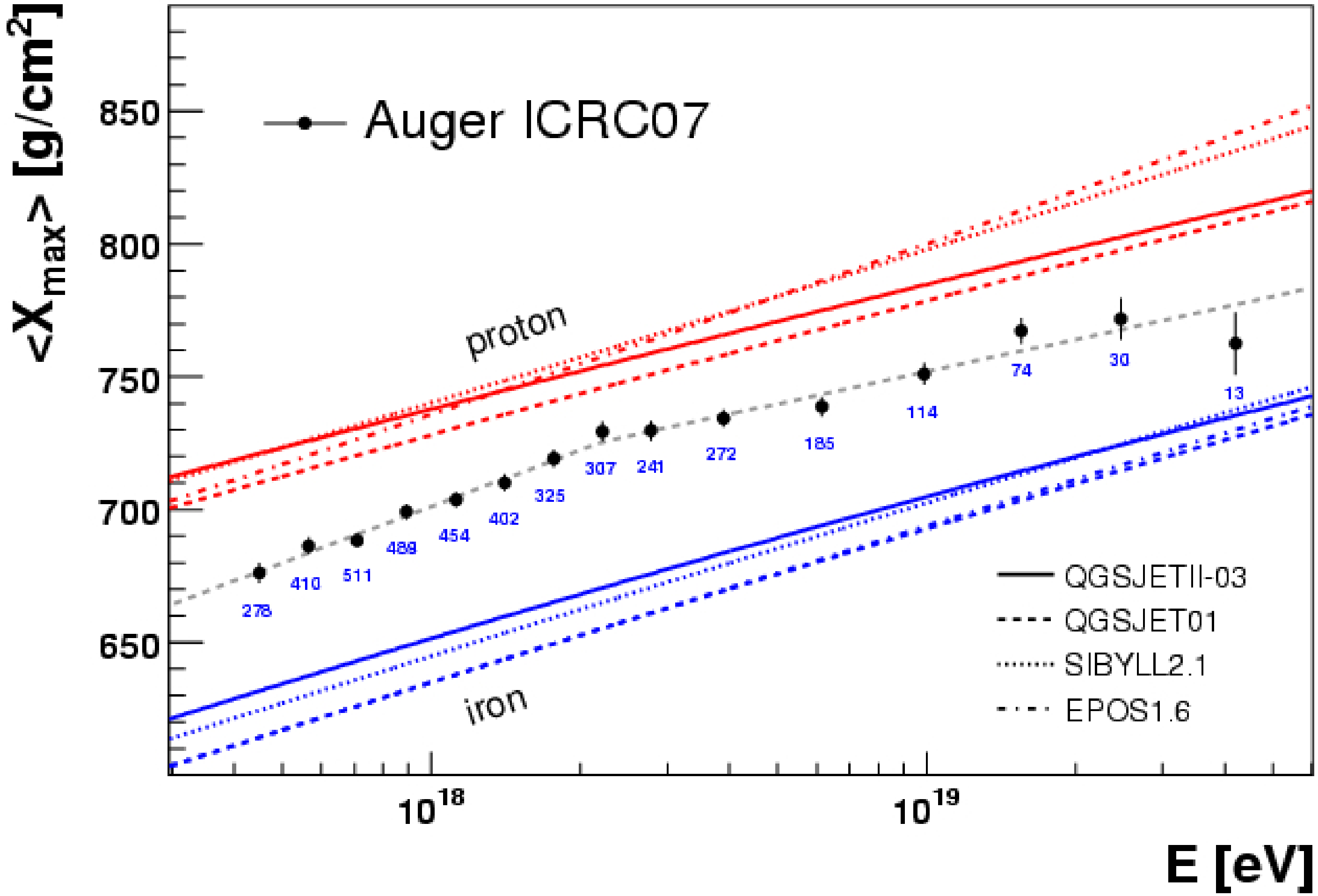
# The $X_{max}$ Data From Auger Fluorescence Detectors (2007)

note- logarithmic dependence on energy of primary



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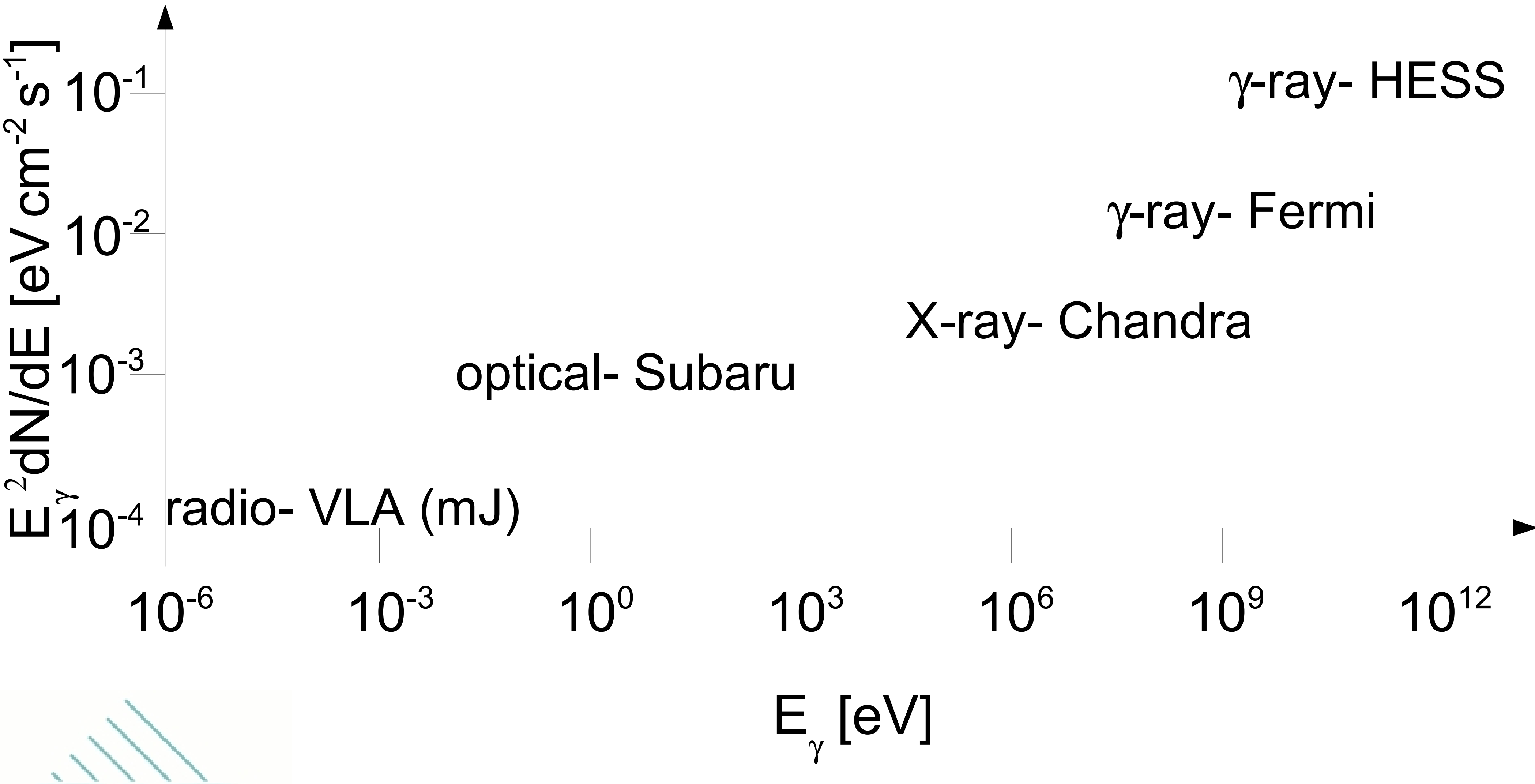
# Sensitivity of γ-Detectors



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# Sensitivity of Detectors