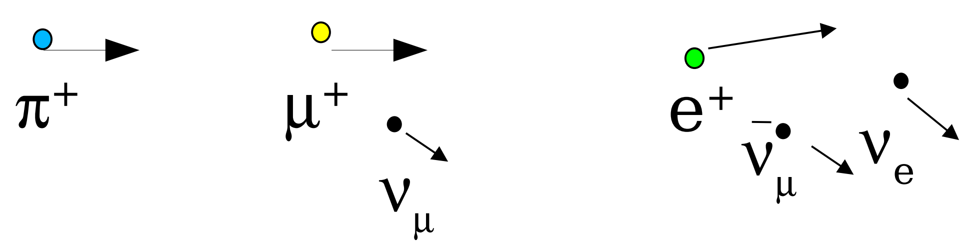
NEUTRINOS: High Energy Neutrino Flux Production During Propagation



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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

4) MULTIMESSENGER APPROACH

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Aims

1) Presence of GZK cut-off?

2) Neutrino production mechanisms

3) Expected cosmic rays spectrum through Fermi acceleration in the source

4) Cosmogenic neutrino flux calculation for proton cosmic rays

5) What if cosmic rays are heavy nuclei?

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1) Presence of GZK cut-off

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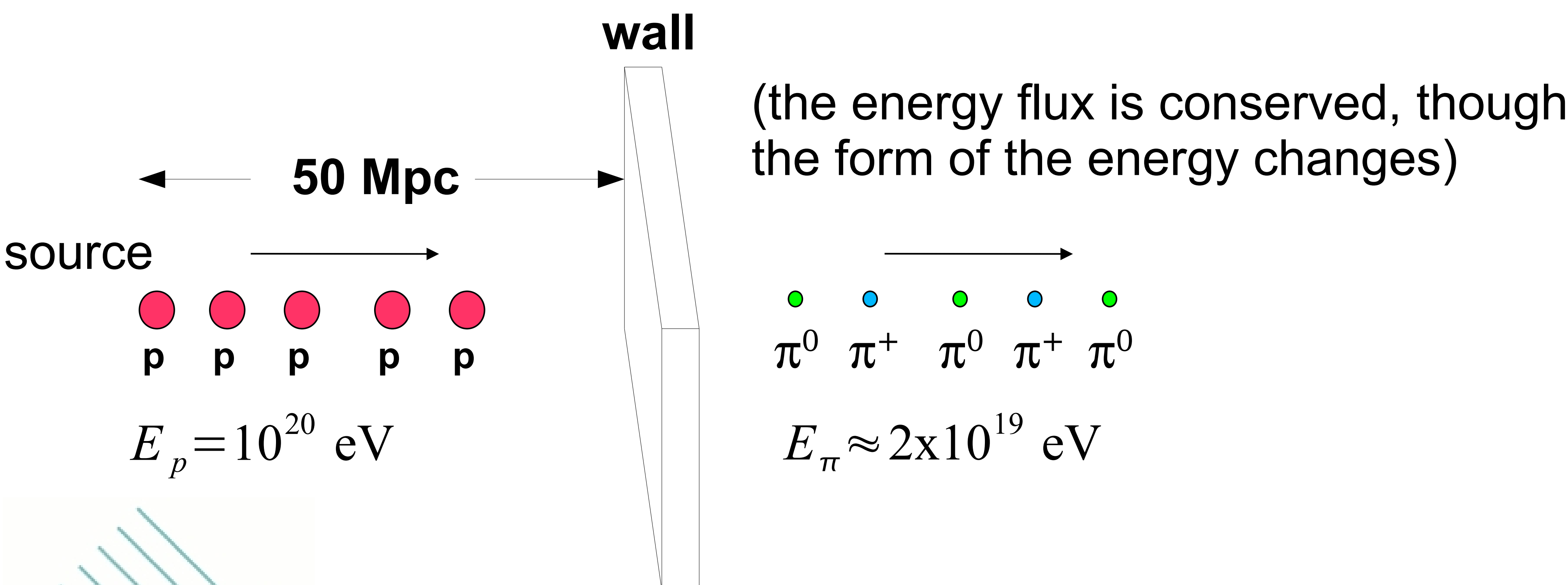
Presence/Absence of GZK cut-off? Crucial for UHE Neutrino Flux

The existence of the CMB photons places a limit on the distance that high energy ($E_{CR} > 10^{20}$ eV) cosmic ray protons can propagate through space to about **50 Mpc**



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Presence/Absence of GZK Cutoff? Crucial for UHE Neutrino Flux

However there are few good candidate sources of high energy cosmic ray protons within a sphere of **50 Mpc** of us (perhaps Cen. A~ **5 Mpc**, M87~ **18 Mpc**, ...?)

An observation of the GZK cutoff would imply cosmologically distant sources whereas failure to see it might be an indication of more local sources (more on this in the last lecture)

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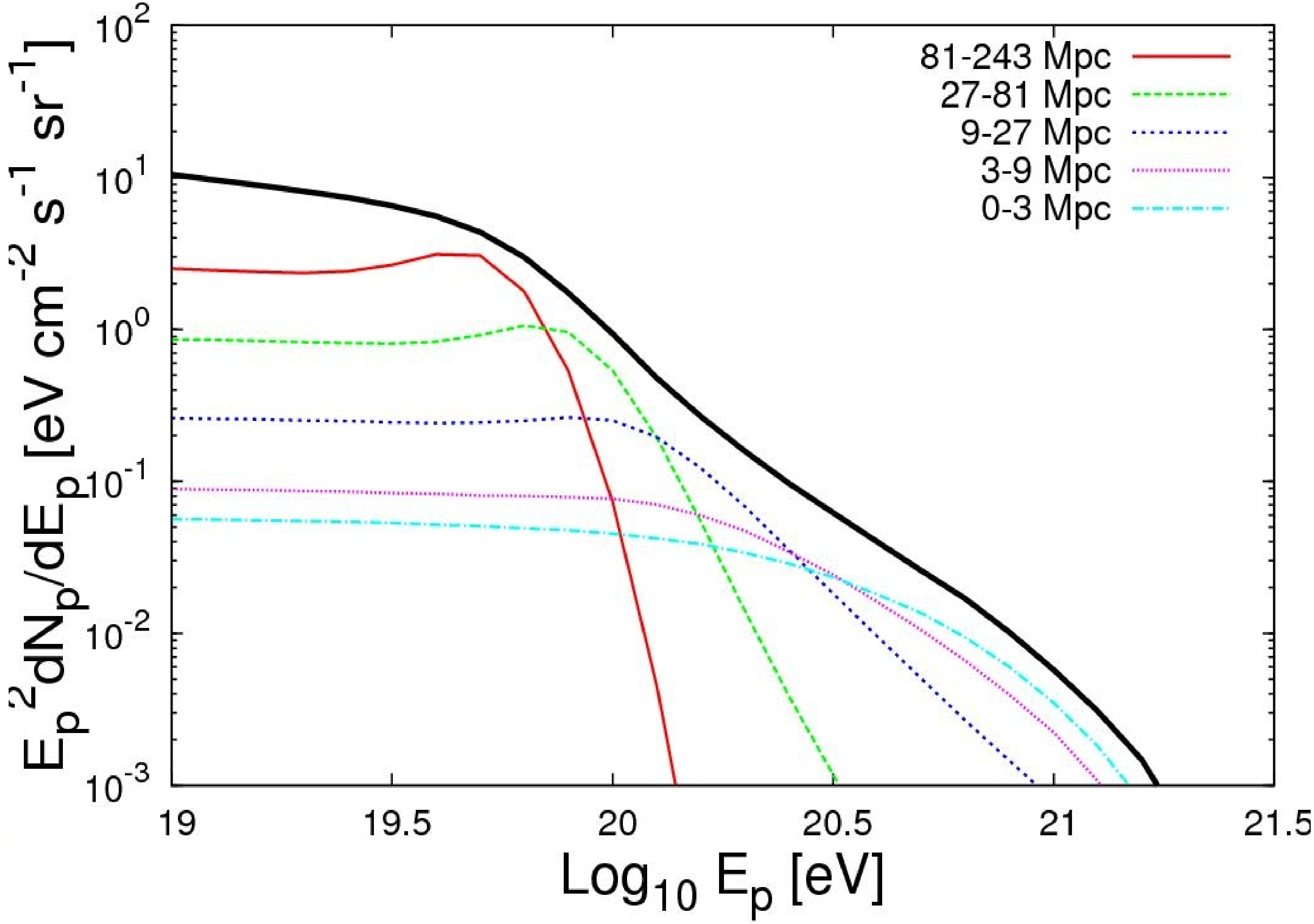
The GZK Feature



Assumptions:

$$E_{\max} = 10^{20.5}\ \text{eV}$$

$$\alpha = 2.0$$

(along with the source distribution mentioned in the previous lecture)

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

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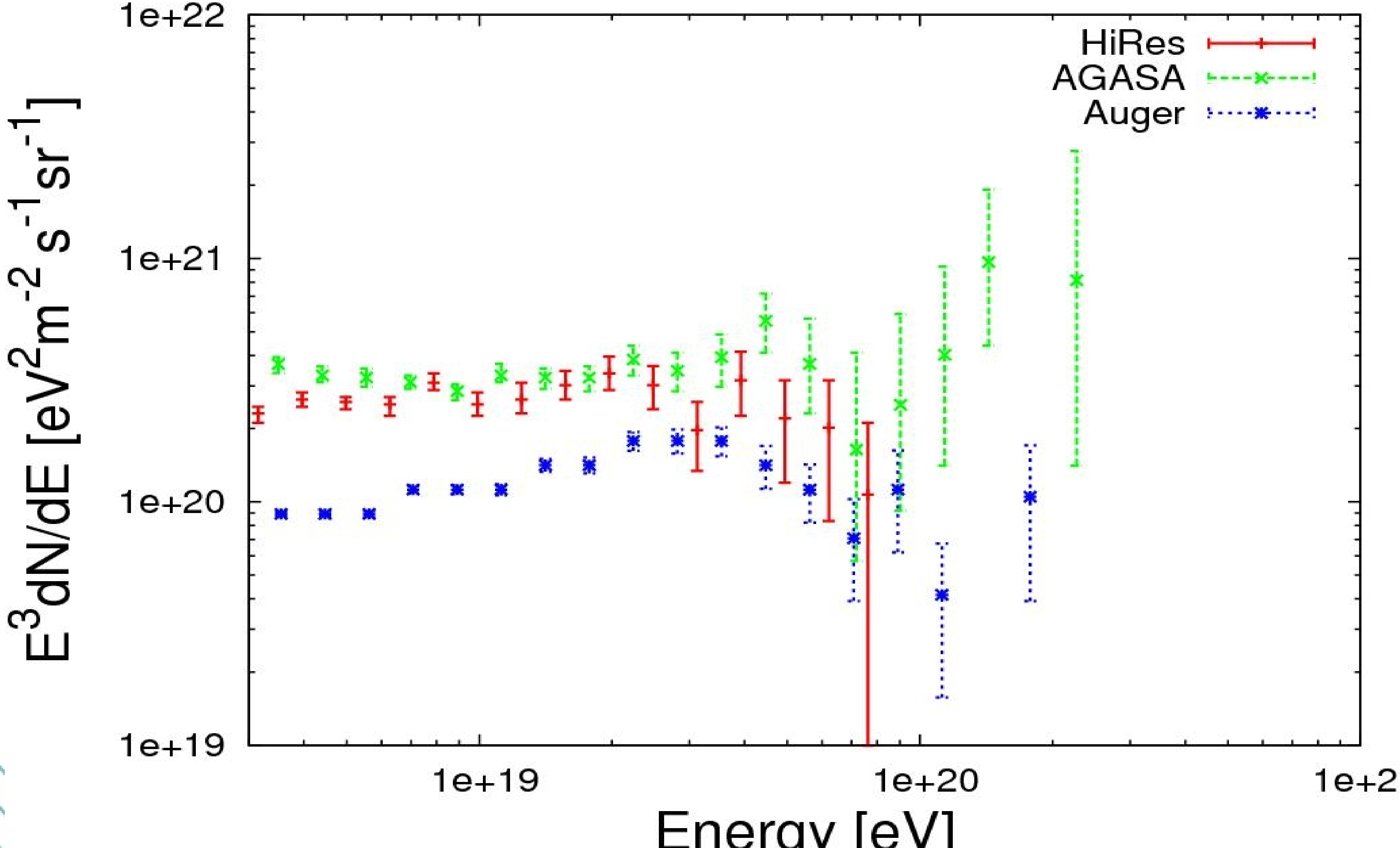
Experiments with Highest Statistics Around the GZK Cutoff Energy-



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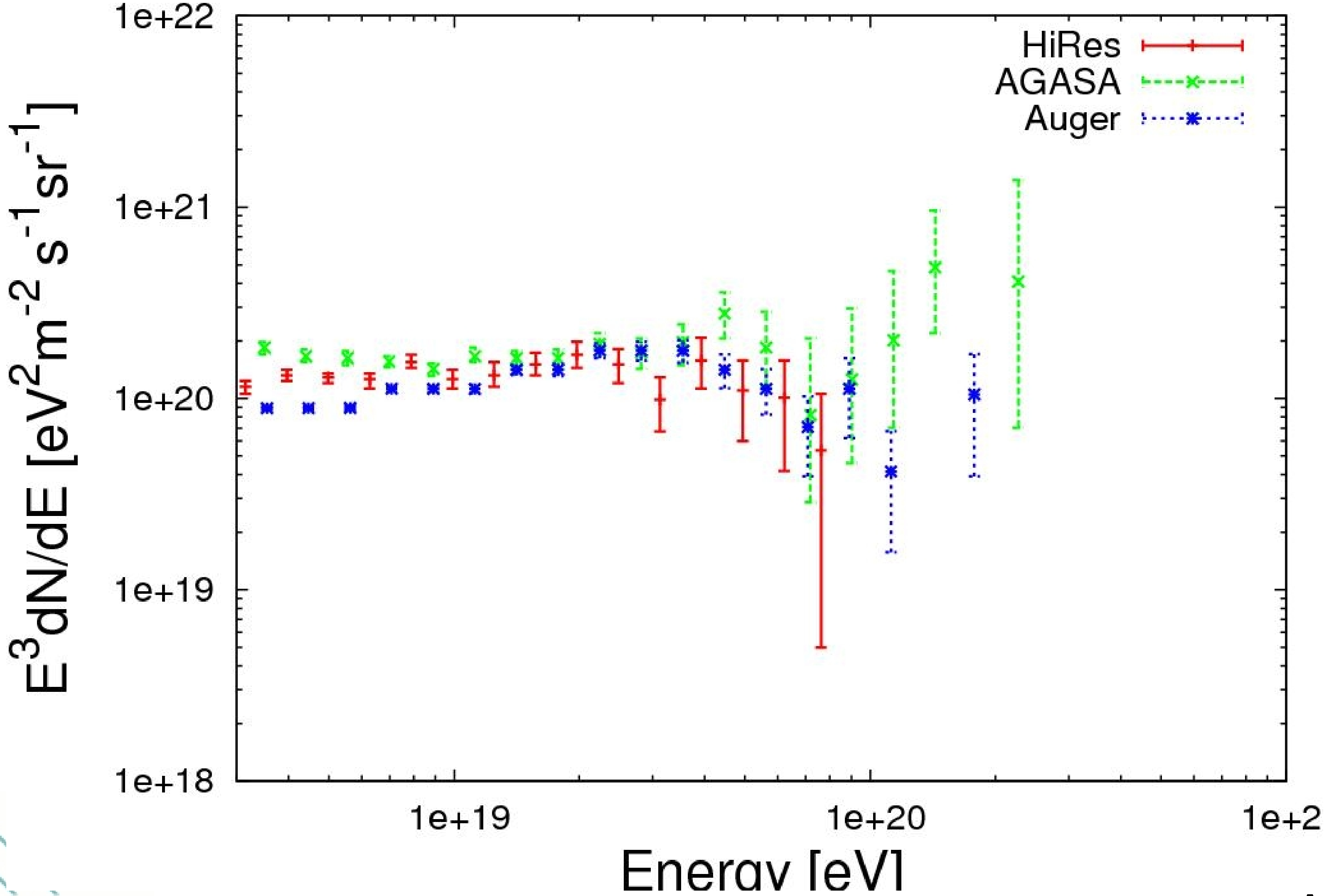
Adjusted Data



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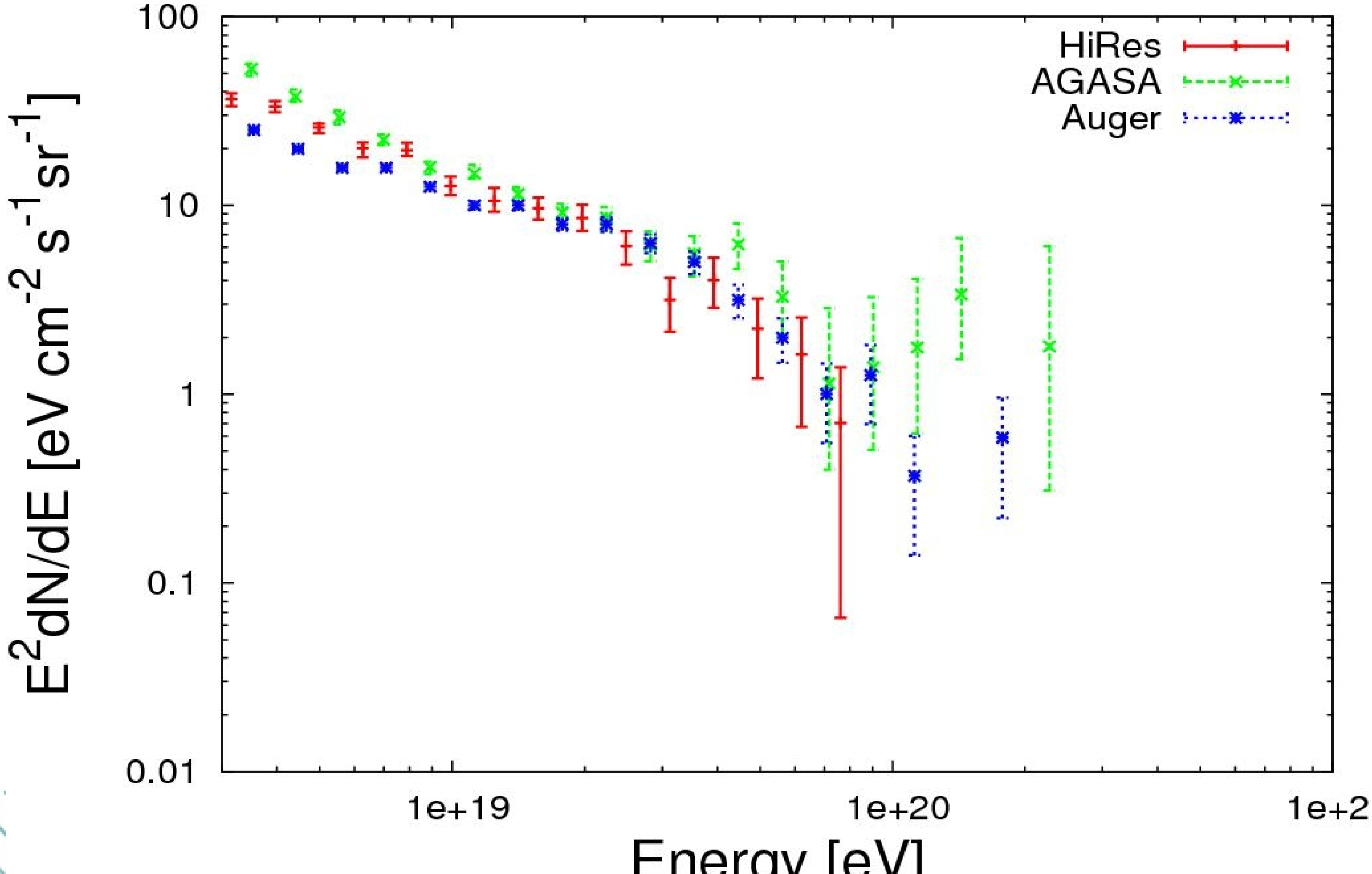
Experiments with Highest Statistics Around the GZK Cutoff Energy-



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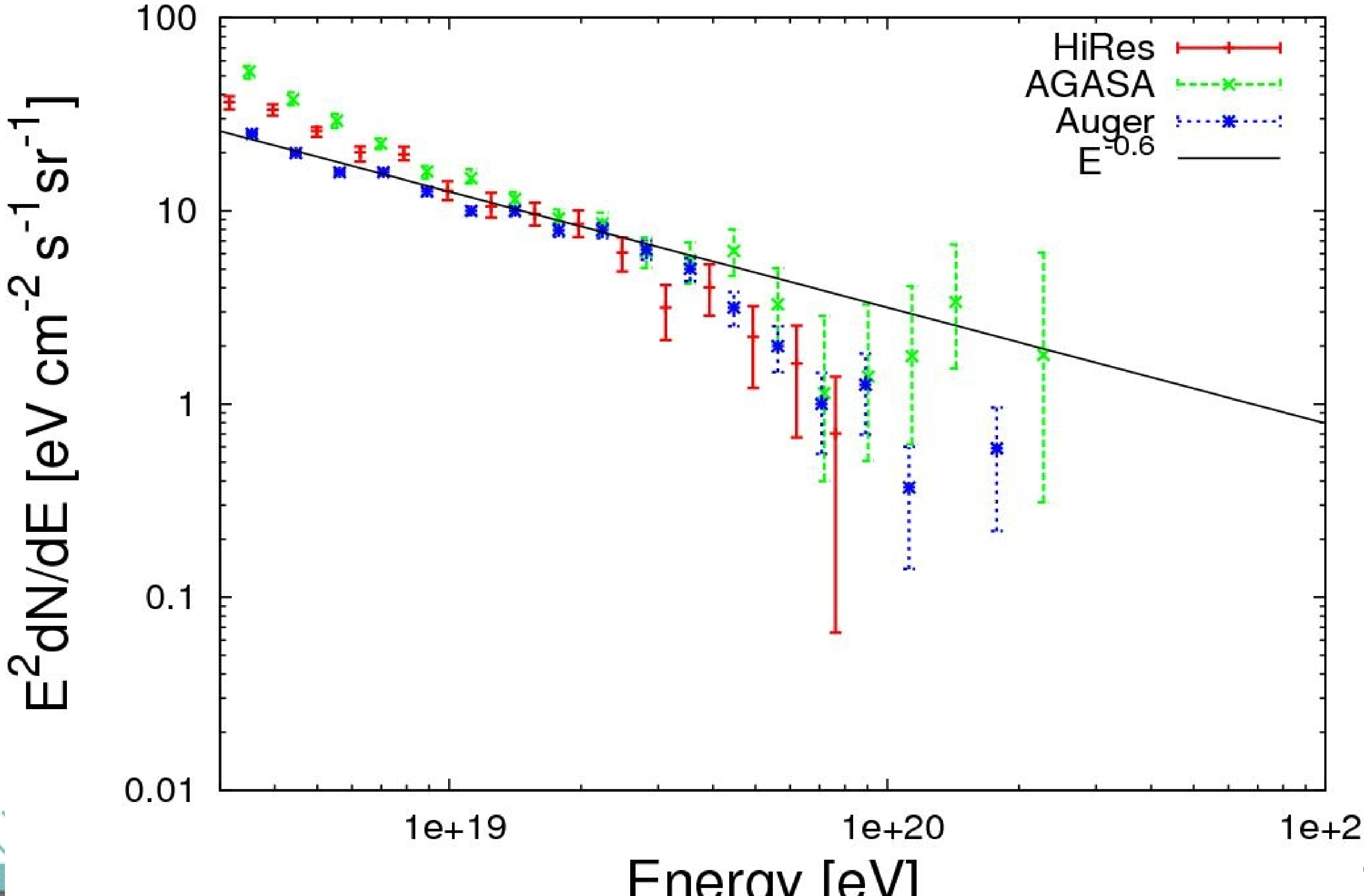
Is the GZK cut-off Present in the Data?



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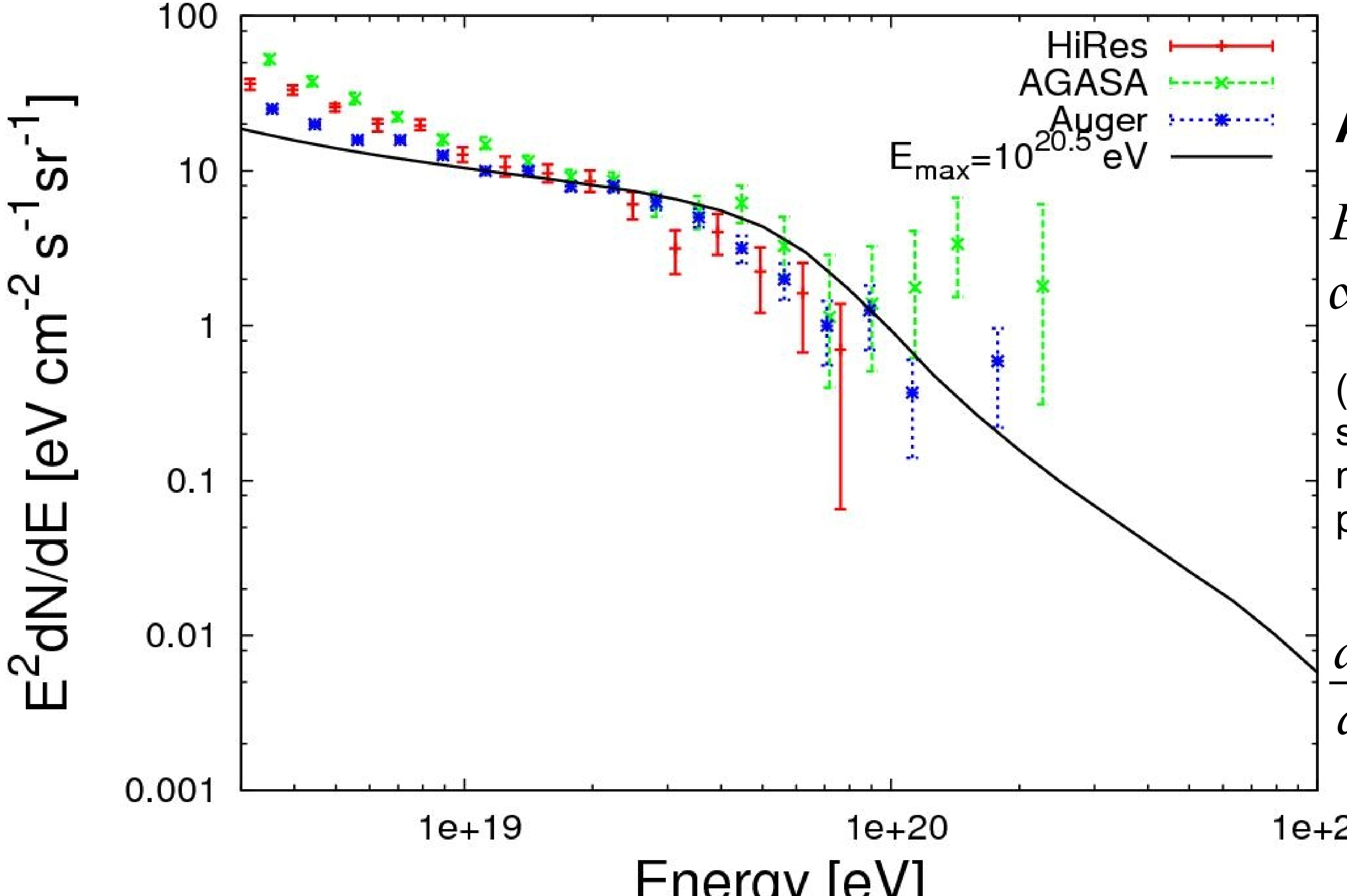
Is the GZK cut-off Present in the Data?



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(along with the source distribution mentioned in the previous lecture)

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Just for Curiosity

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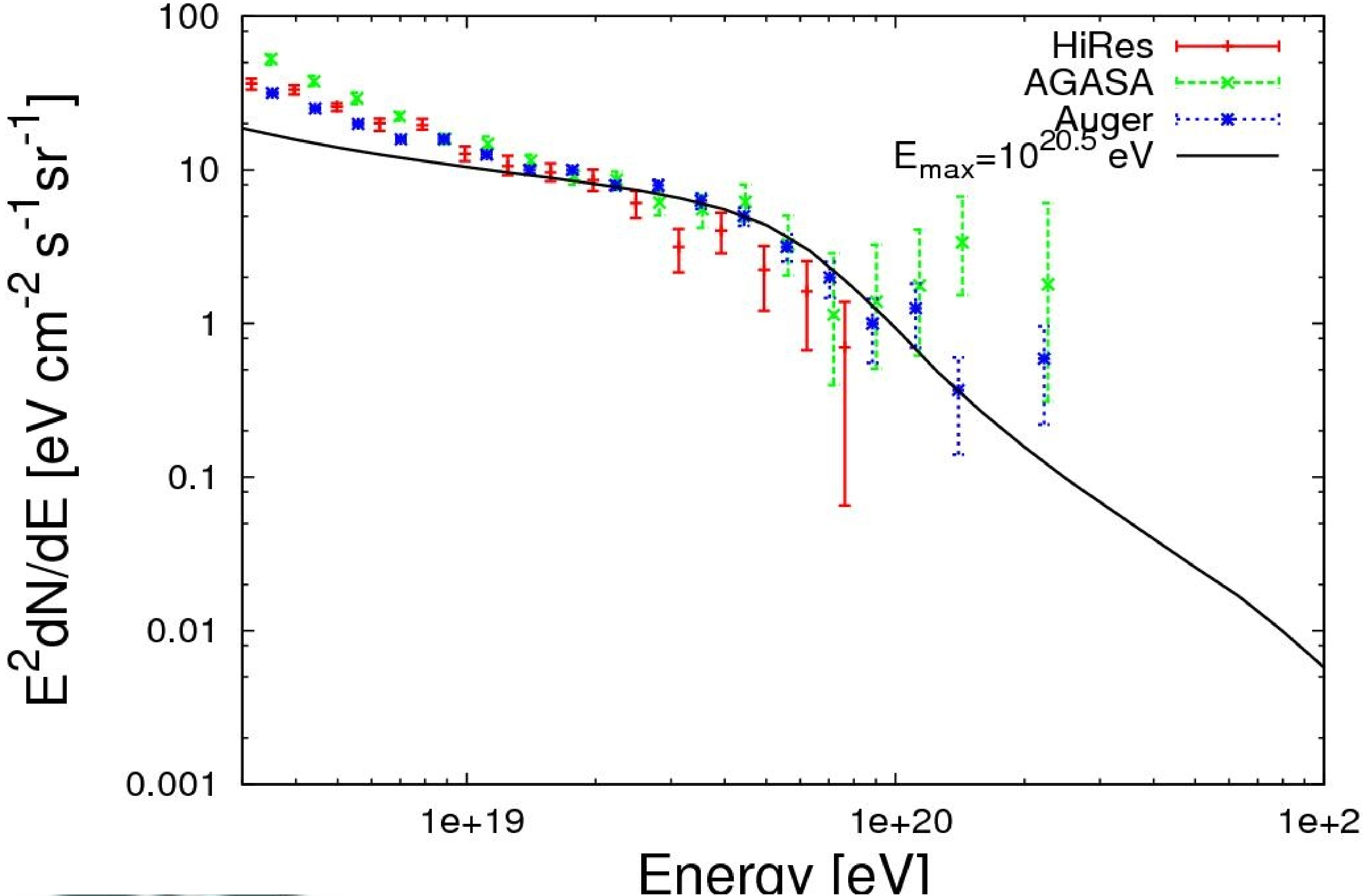
Is the GZK cut-off Present in the Data? (Auger points shifted up 25%)



Assumptions:

$E_{max} = 10^{20.5}$ eV

$\alpha = 2.0$

(along with the source distribution mentioned in the previous lecture)

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

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2) Neutrino Production Mechanisms

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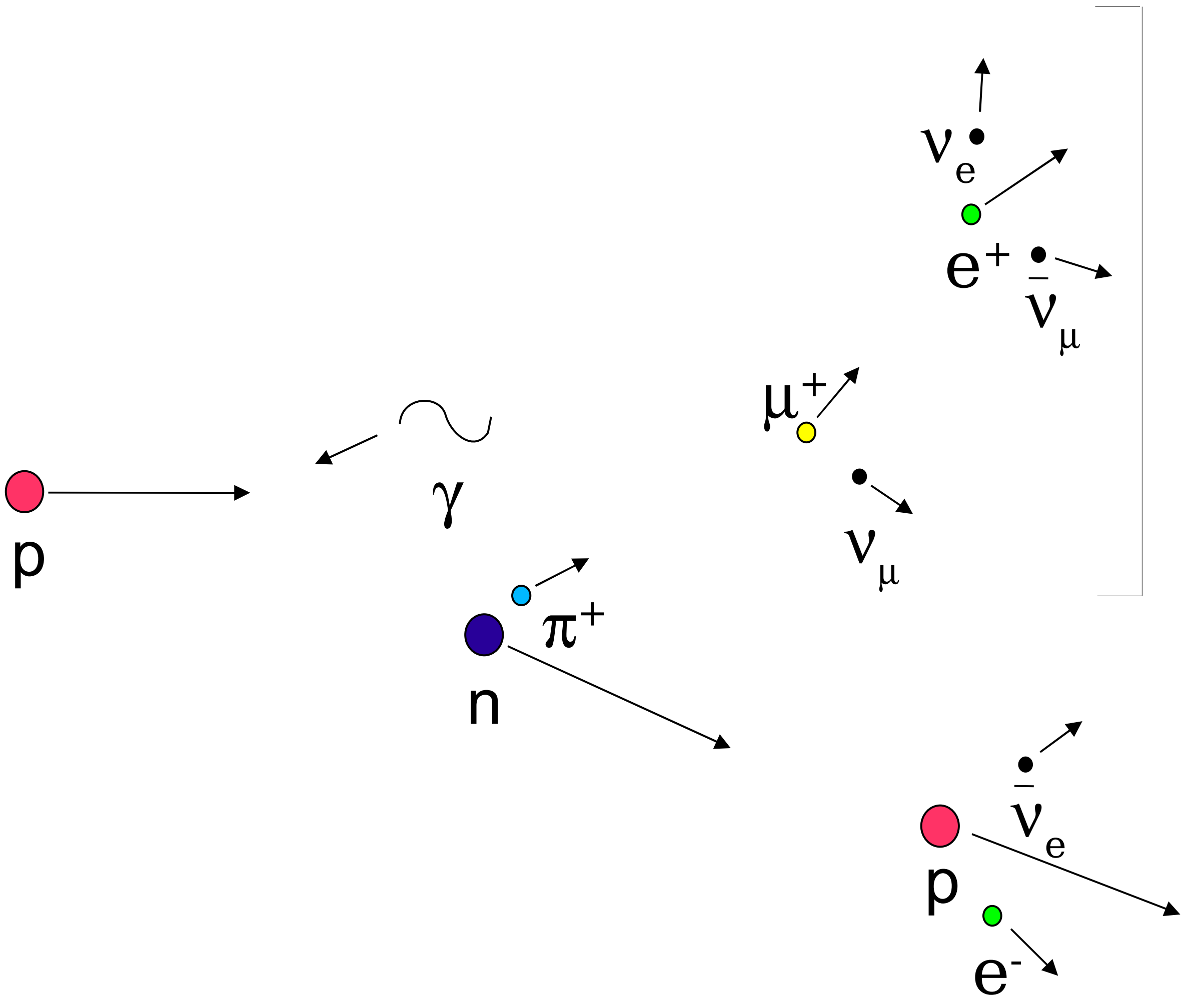
Photo-Pion Neutrino Production



note- each ν takes ~0.05 of initial proton energy

note- ν takes ~0.0005 of initial proton energy

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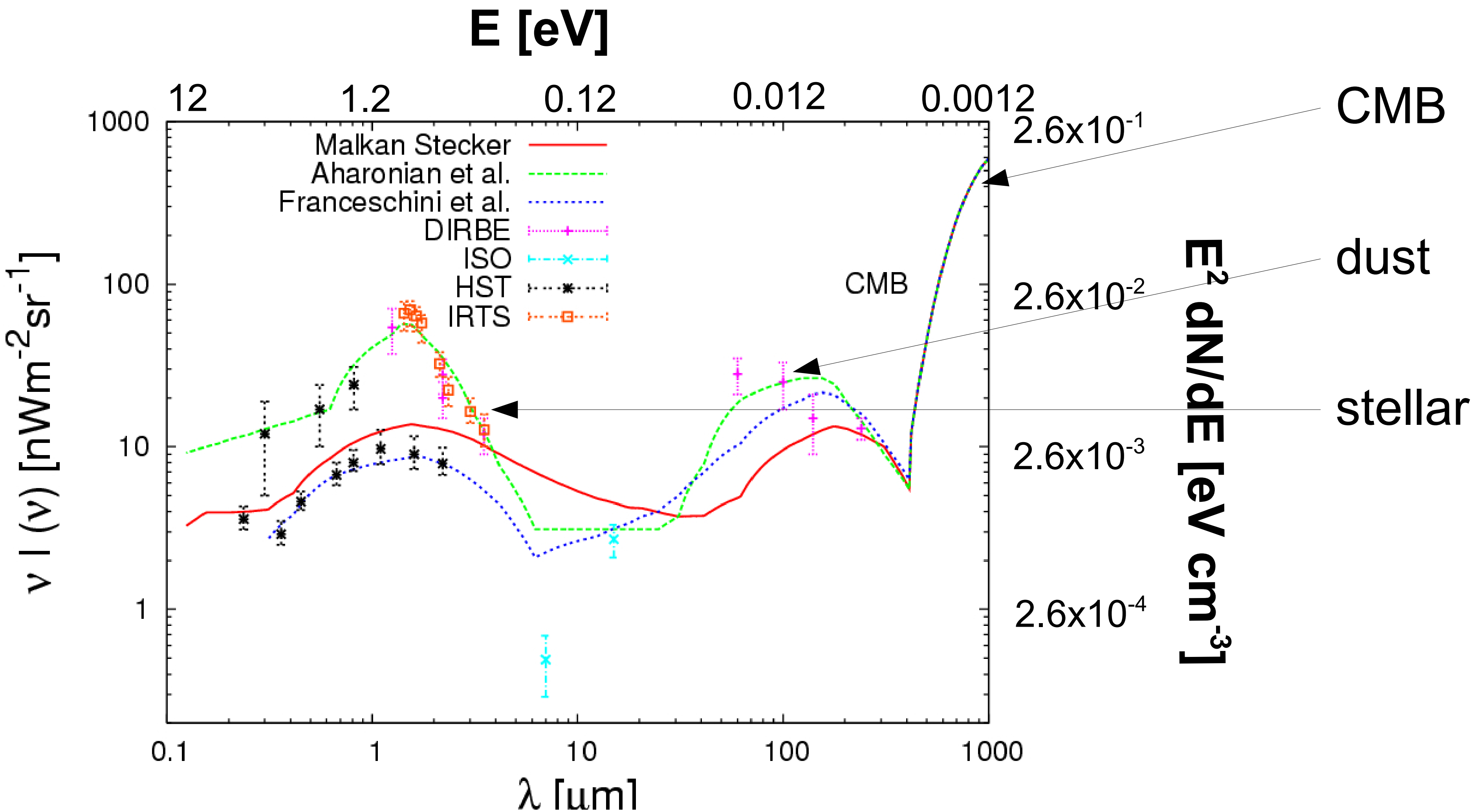
Cosmic Radiation Fields



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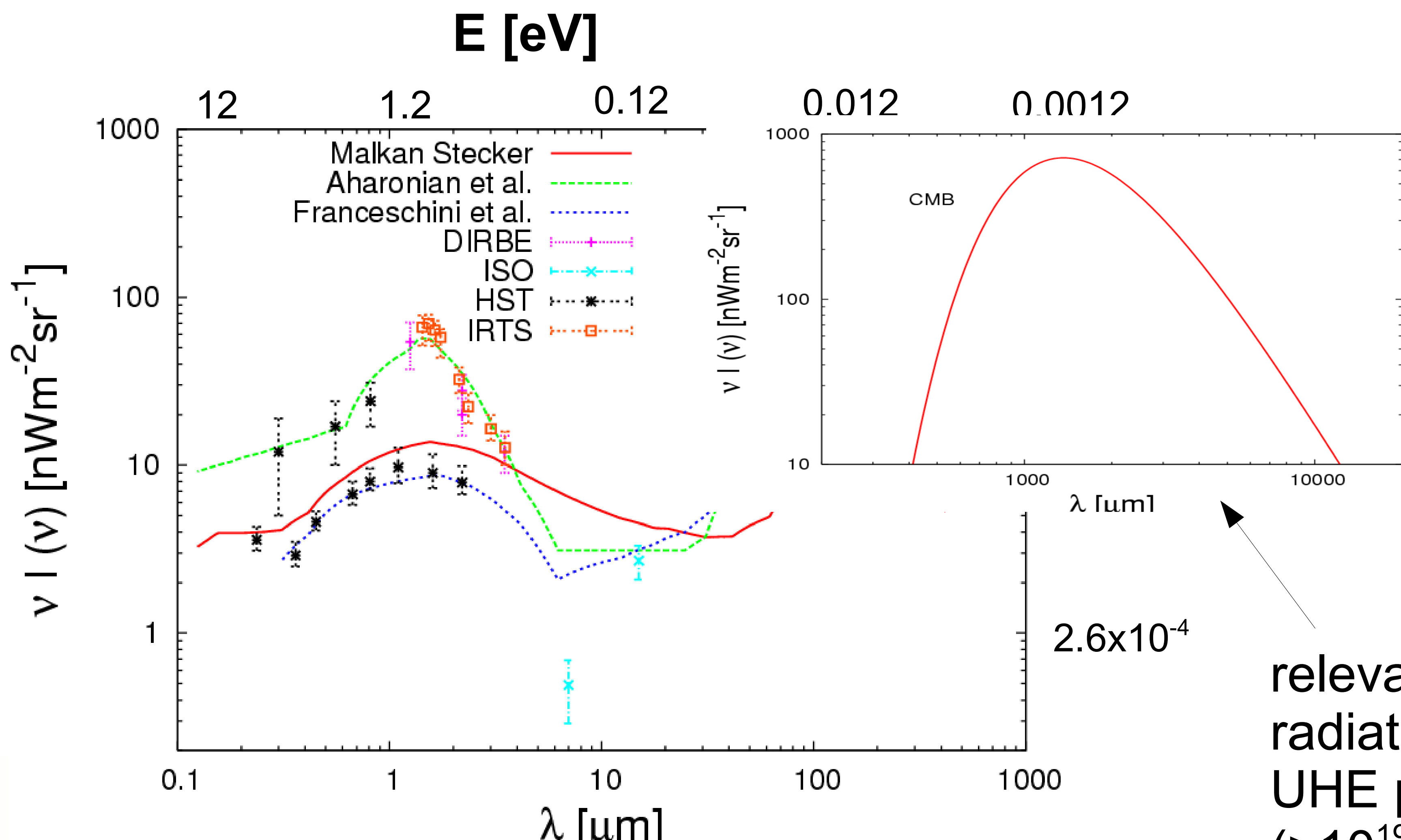
Cosmic Background Radiation Fields



relevant radiation field for UHE protons ($>10^{19}$ eV)

Interactions of Cosmic Ray Protons with CMB:

Pair Creation- $E_\gamma \sim 1\mathrm{MeV}$

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

Photo-Meson Production- $E_\gamma \sim 145\mathrm{MeV}$

$p + \gamma \rightarrow n + \pi^+ / p + \pi^0,$

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

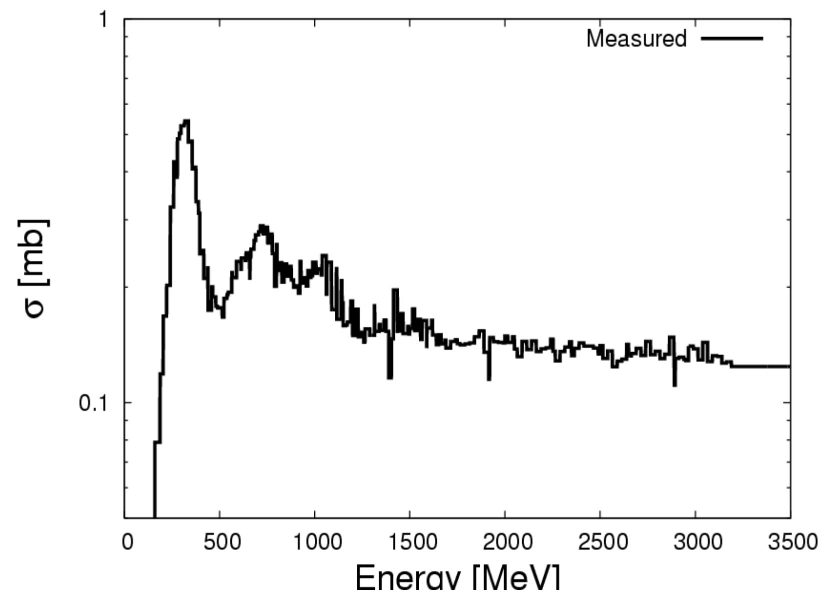


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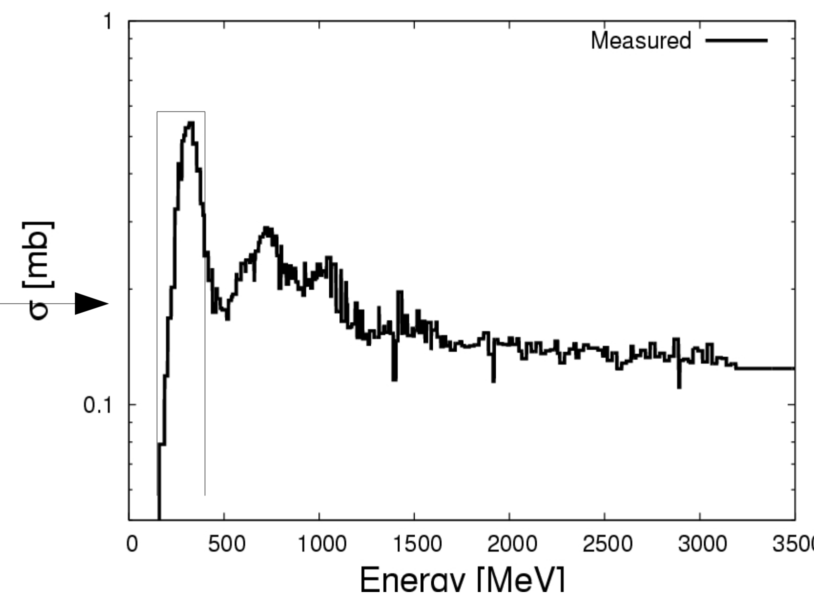
Photo-Pion Production Rate

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

Assuming the cross-section is approximately:

$$\sigma_{p\gamma}(\epsilon_\gamma) = 0; \quad \epsilon_\gamma < E - \Delta$$
$$\sigma_{p\gamma}(\epsilon_\gamma) = \sigma_{p\gamma}; \quad E - \Delta < \epsilon_\gamma < E + \Delta$$
$$\sigma_{p\gamma}(\epsilon_\gamma) = 0; \quad \epsilon_\gamma > E + \Delta$$



where $\sigma_{p\gamma} = 0.5$ mb, $E = 300$ MeV and $\Delta = 100$ MeV

Photo-Pion Production Rate (2)

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

$$\approx 0.2\,\sigma_{p\gamma} \int_{\frac{E-\Delta}{2\Gamma}}^{\frac{E+\Delta}{2\Gamma}} d\epsilon_\gamma\, n(\epsilon_\gamma)$$

where $\Gamma = \frac{E_p}{m_p c^2}$ is the Lorentz factor of the proton

---

Since,

$$n(\epsilon_\gamma)^{BB} = \frac{dn}{d\epsilon_\gamma} = \frac{8\pi}{(hc)^3} \frac{\epsilon_\gamma^2}{e^{\beta\epsilon_\gamma} - 1}$$

Or perhaps more clearly expressed as,

$$n_\gamma = \epsilon_\gamma \frac{dn}{d\epsilon_\gamma} = 400 \frac{\epsilon_\gamma^3}{e^{\beta\epsilon_\gamma} - 1} \text{cm}^{-3}$$

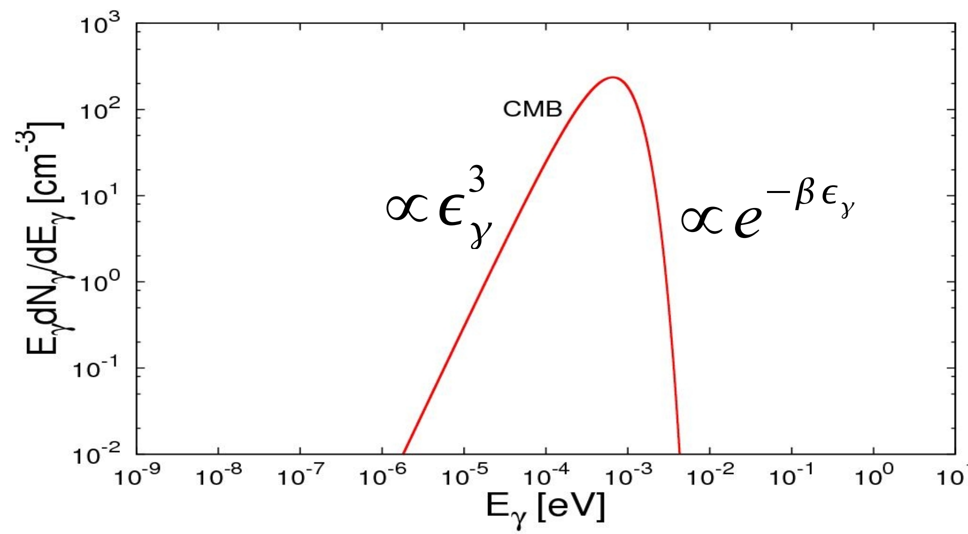


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Photo-Pion Production Rate (3)

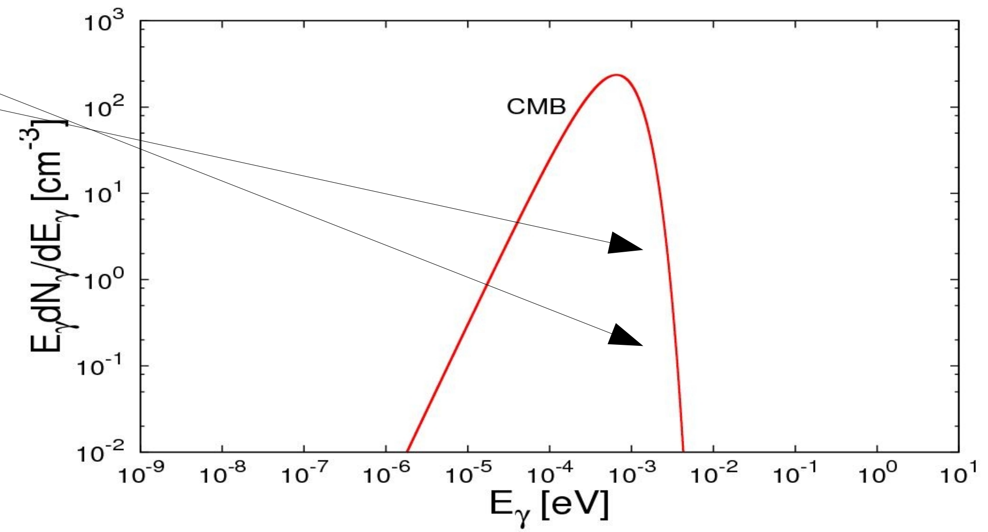
With, $\beta = \frac{1}{kT} = \frac{1}{10^{-3}\ \text{eV}}$

$$R \approx 0.2\,\sigma_{p\gamma} \int_{\frac{E-\Delta}{2\Gamma}}^{\frac{E+\Delta}{2\Gamma}} d\epsilon_\gamma\, n(\epsilon_\gamma)$$

$$\approx \left(\frac{l_0}{e^{-x}(1-e^{-x})} \right)^{-1}$$

where l_0 is 5 Mpc

and $x = \frac{10^{20.53}\,\text{eV}}{E_p}$



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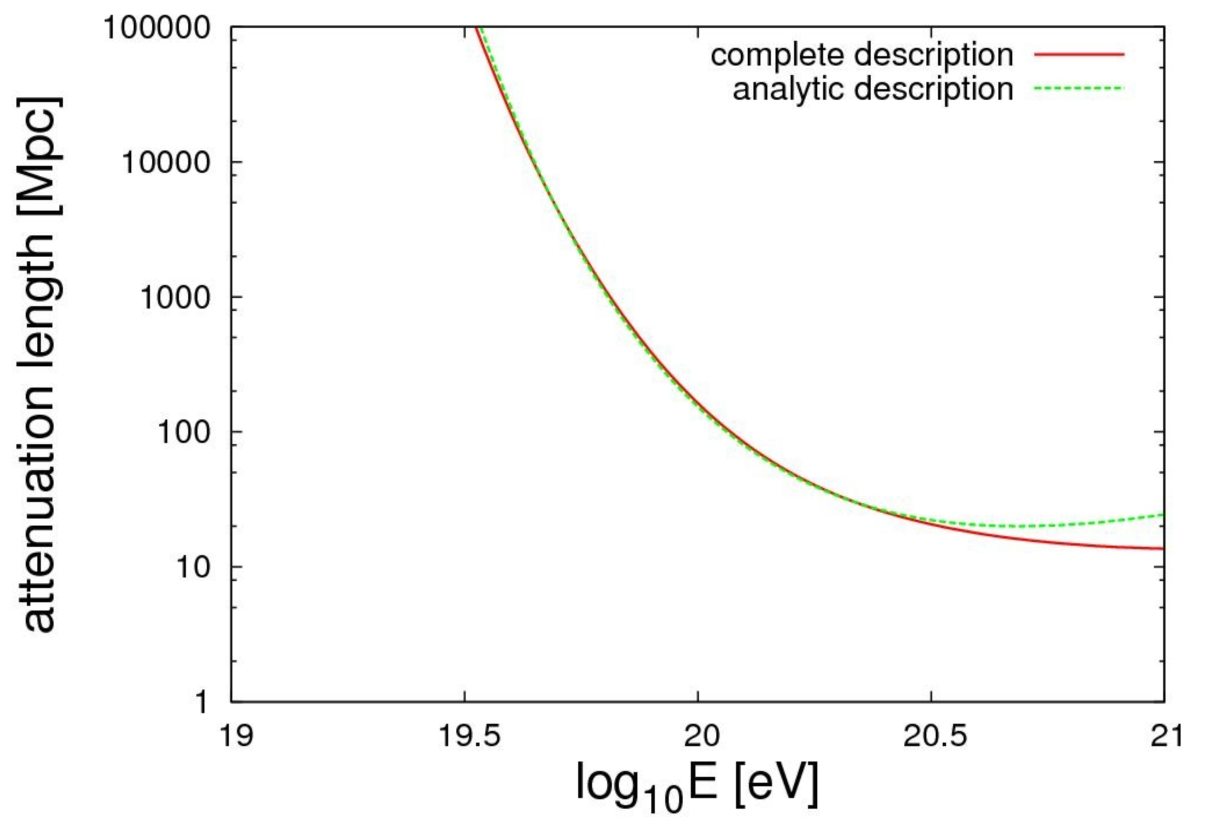

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3) Expected Cosmic-Ray Spectra Due to Fermi acceleration in source

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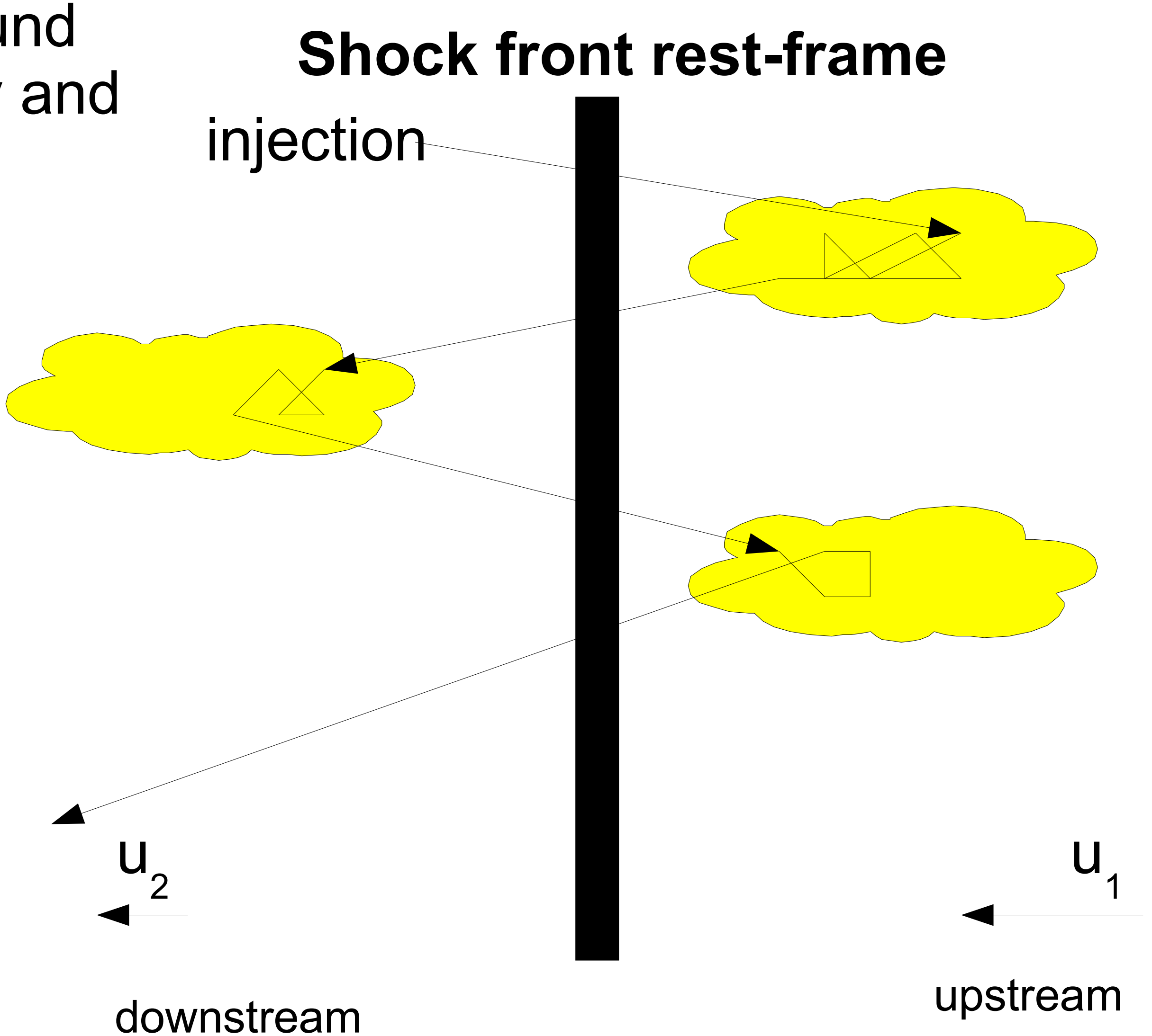
Fermi (First Order) Acceleration

Strong shock wave propagating at supersonic velocity (sound speed depends on density and temperature)

$V = u_1 - u_2$



Fermi Acceleration (more)

<u>Energy</u>

$\Delta E/E = 4V/3c$ (energy gain)

$E_1 = (1+4\beta/3)E_0$, where $\beta = V/c$

$E_2 = (1+4\beta/3)E_1 = (1+4\beta/3)^2 E_0$

$E_n = (1+4\beta/3)E_{n-1} = (1+4\beta/3)^n E_0$

<u>Number</u>

$\Delta N/N = -4V/3c$ (advection downstream)

$N_1 = (1-4\beta/3)N_0$

$N_2 = (1-4\beta/3)N_1 = (1-4\beta/3)^2 N_0$

$N_n = (1-4\beta/3)N_{n-1} = (1-4\beta/3)^n N_0$

So $n \sim 1/\beta$ crossings are needed before the particle population is significantly altered

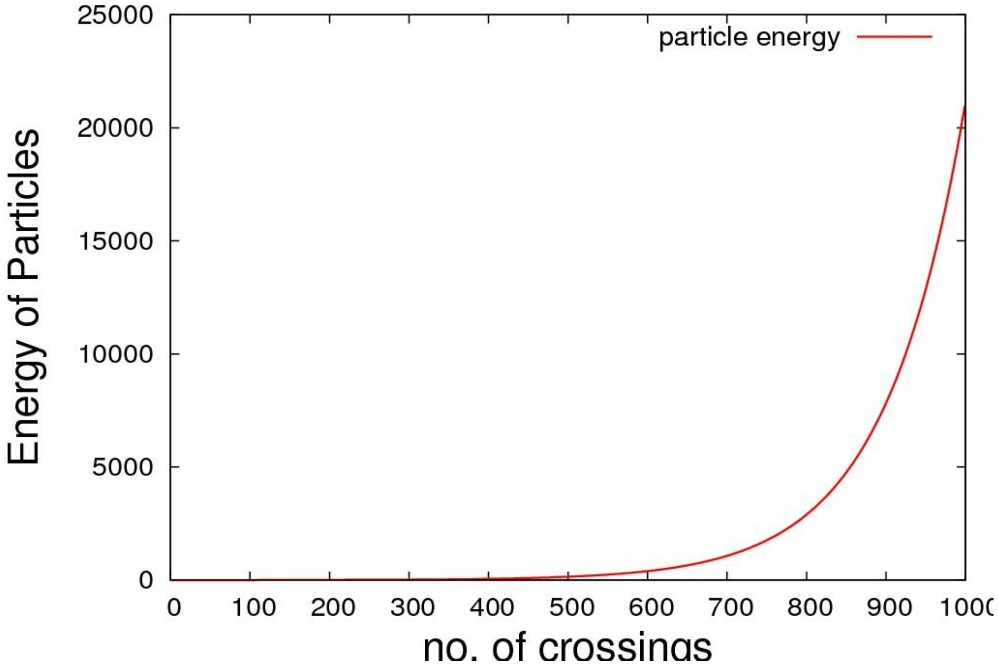
→ SNRs have $v_{sh} \sim 10^3$ km s^{-1} so $\beta \sim 10^{-2}$

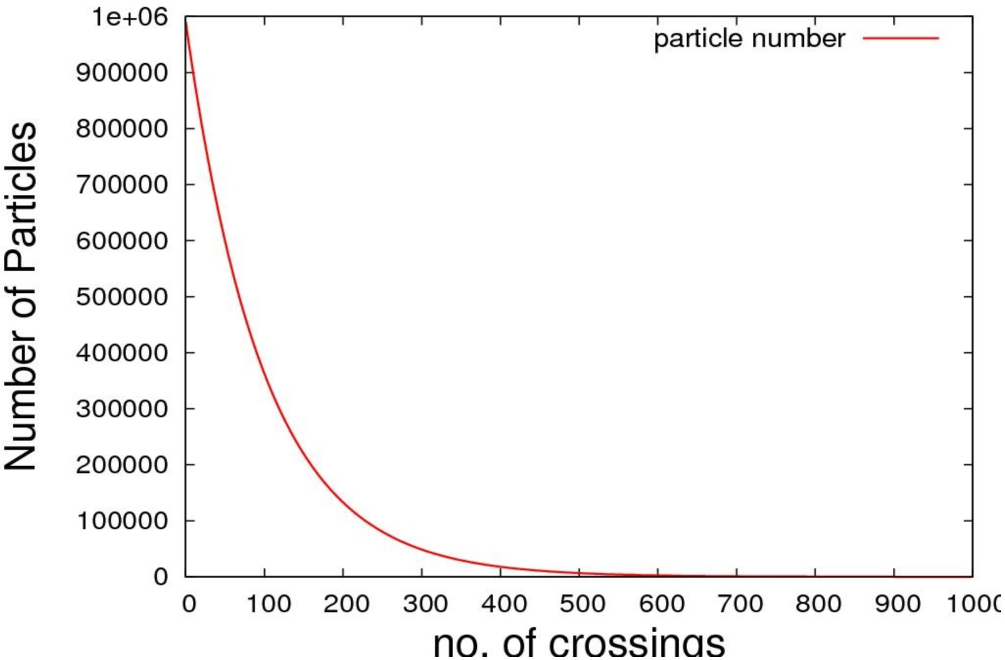
Fermi Acceleration (more)

Energy

Number

$\beta \sim 10^{-2}$





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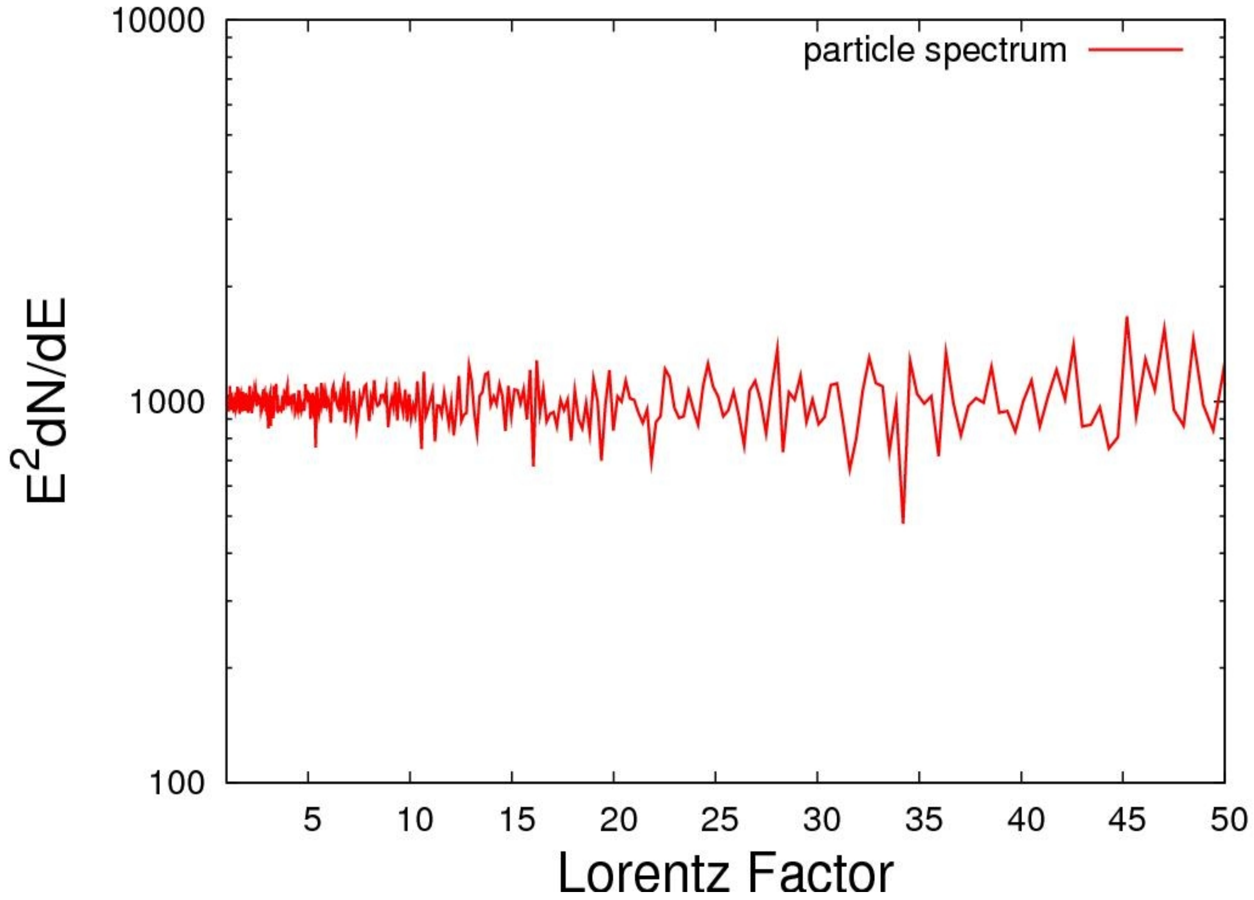
Fermi Acceleration (more)

So,

$$\frac{\Delta N}{\Delta E} = \frac{N_0}{E_0} \frac{(1-4\beta/3)^n}{(1+4\beta/3)^n}$$

$$\approx \frac{N_0}{E_0} (1+4\beta/3)^{-2n}$$

$$\approx N_0 E_0 E^{-2}$$



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4) Cosmogenic Neutrino flux calculation for proton cosmic rays

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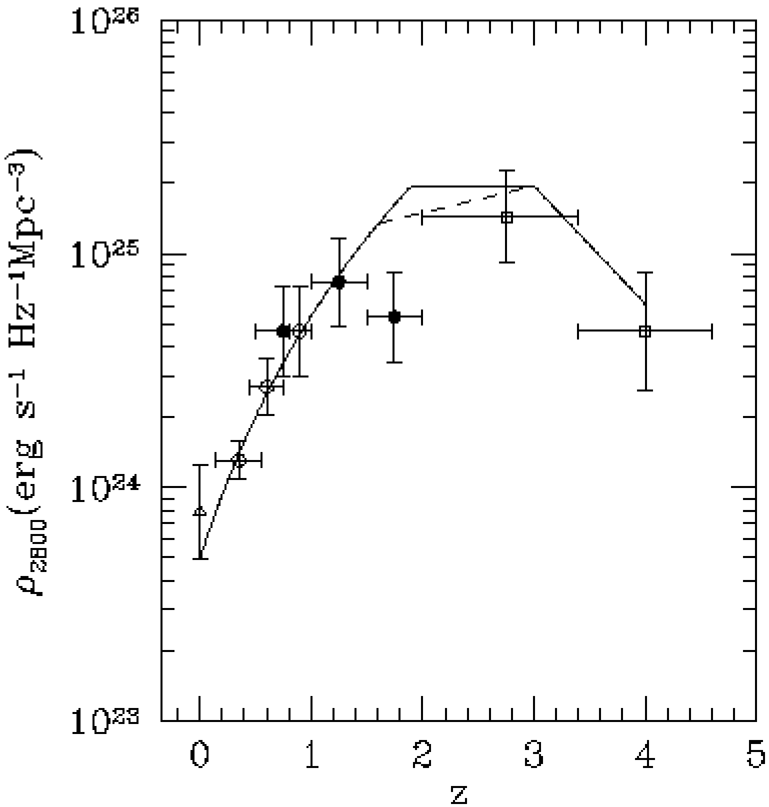
Cosmic Ray Source (Temporal) Evolution- Quasars



$$
\begin{aligned}
dN/dV &= (1+z)^3, && (z<1.9) \\
&= (1+1.9)^3, && (1.9<z<2.7) \\
&= (1+1.9)^3 e^{(2.7-z)/(2.7)}, && (z>2.7)
\end{aligned}
$$

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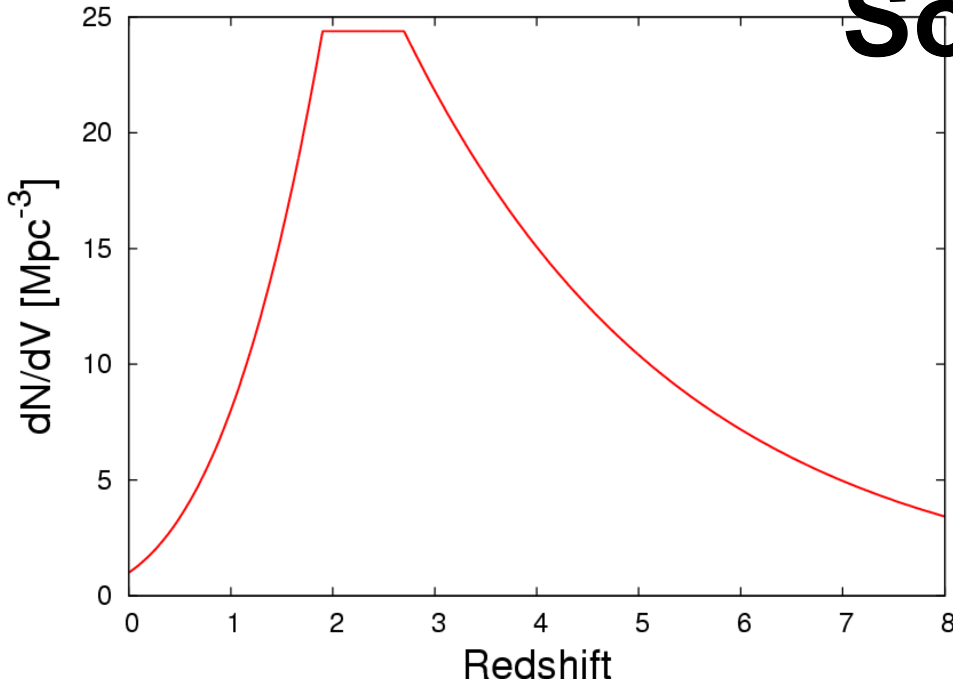
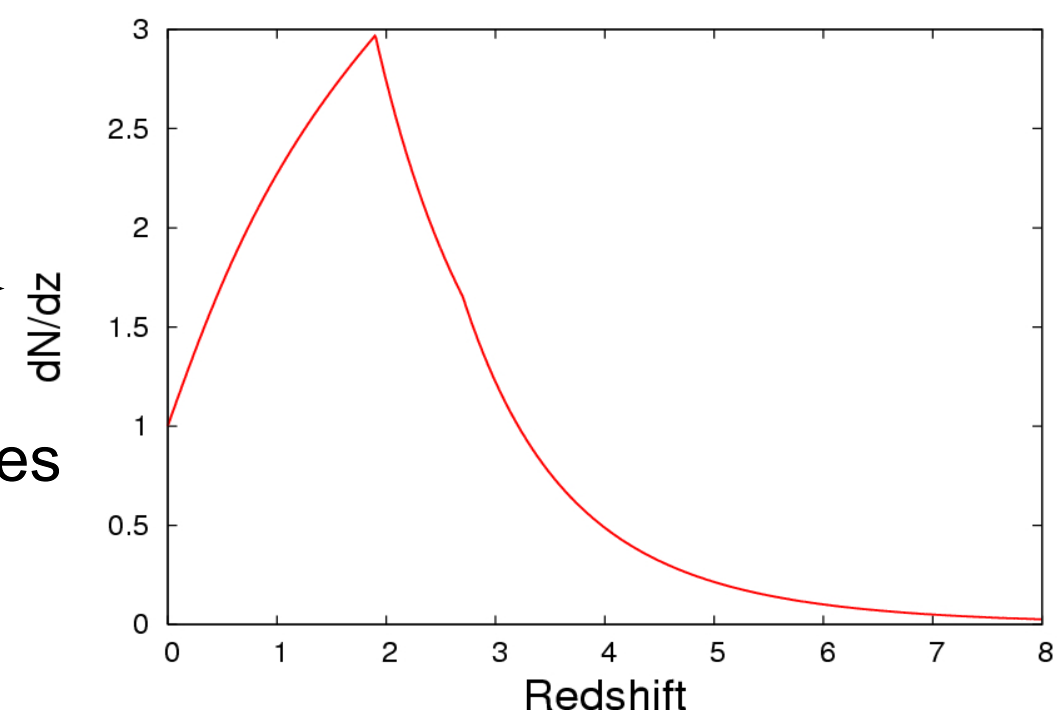
A Cosmological Distribution of Sources



Distribution of sources in a co-moving volume

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

Distribution of sources in redshift



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Cosmogenic Neutrino Energetics

Neutrinos from neutron decay

$n \rightarrow p + e^- + \bar{\nu}_e$, $\quad E_\nu \sim 10^{-3} E_n$

(neutrons generated in photo-pion production with isospin change of proton)

Neutrinos from pion decay

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

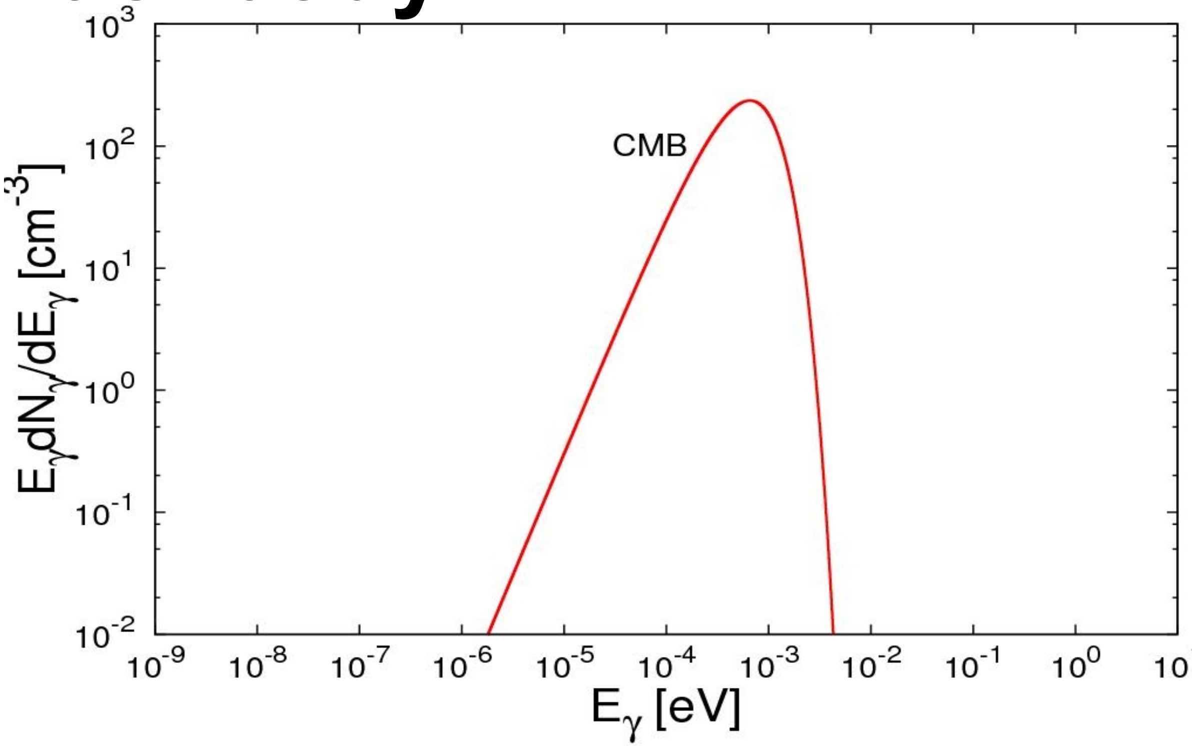
$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

→ $\pi^+ \rightarrow \nu_\mu + e^+ + \nu_e + \bar{\nu}_\mu$, $\quad E_\nu \sim 0.25 E_\pi$, $\quad (E_\pi \sim 0.2 E_p)$

Mean Photon Energy of a Blackbody

$$< E_\gamma^{(BB)} > = \frac{\int_0^\infty d\epsilon_\gamma \epsilon_\gamma \frac{dn}{d\epsilon_\gamma}}{\int_0^\infty d\epsilon_\gamma \frac{dn}{d\epsilon_\gamma}}$$

$$= kT \frac{\int_0^\infty dx \frac{x^3}{(e^x - 1)}}{\int_0^\infty dx \frac{x^2}{(e^x - 1)}}$$



Since, $\int_0^\infty dx \frac{x^n}{(e^x - 1)} = \Gamma(n+1)\zeta(n+1)$ ← (a fun problem to try!)

$$< E_\gamma^{(BB)} > = \frac{\Gamma(4)\zeta(4)}{\Gamma(3)\zeta(3)} kT \approx 2.7\, kT$$

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(more) Cosmogenic Neutrino Energetics

$<E_{\gamma\,(CMB)}> \sim 10^{-3}$ eV,

In Center-of-Mass frame-

$E_{\gamma} \sim 145$ MeV (threshold for pion production)

$\Gamma \sim 10^{11}$, ($E_p \sim 10^{20}$ eV)

So for neutrinos from neutron decay-

$E_{\nu} \sim 10^{16}$ eV

And for neutrinos from pion decay-

$E_{\nu} \sim 10^{18}$ eV

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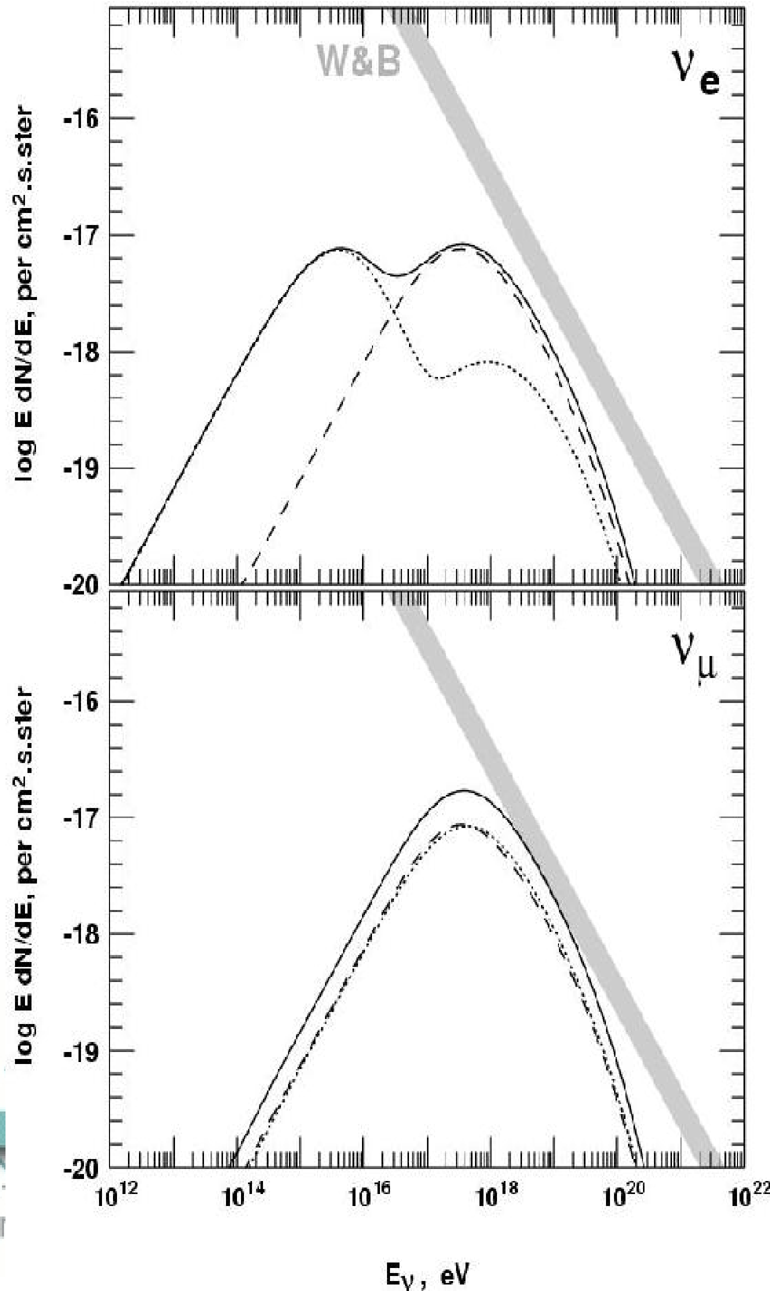
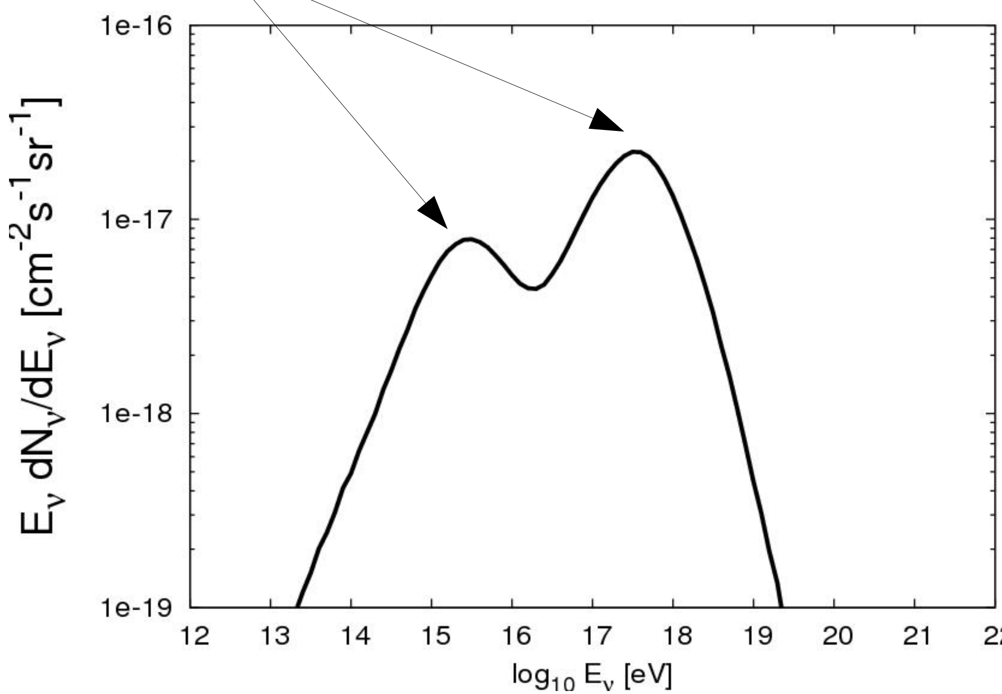
Results from Calculations of the Cosmogenic Neutrino Flux

Engel, **Seckel**, and **Stanev**

(Phys.Rev.D64:093010,2001)

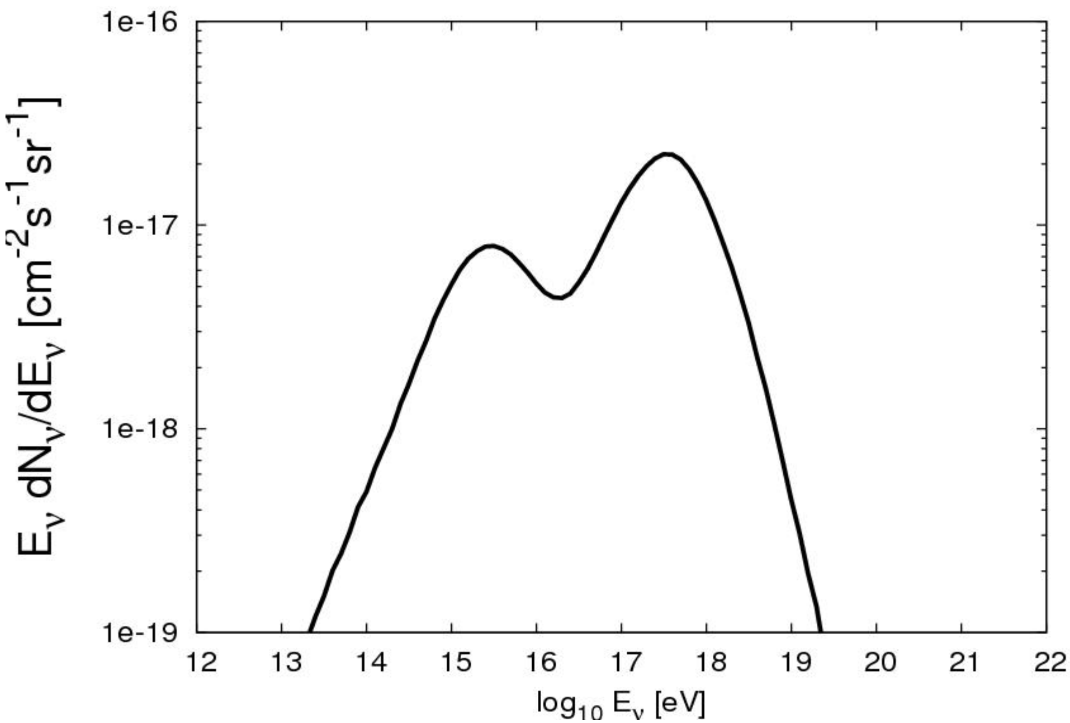


Heights of peaks in ratio 1:3



peak neutrino energy flux is comparable to 10^{19} eV proton energy flux (~10 eV cm^{-2} s^{-1}sr^{-1})

Results from Calculations of the Cosmogenic Neutrino Flux



Assumptions...

n=3 (Quasar-like) source distribution
α=2 injection spectrum

Proton primaries

Unless...

Nearby sources

Lorentz violation

Heavy nuclei primaries

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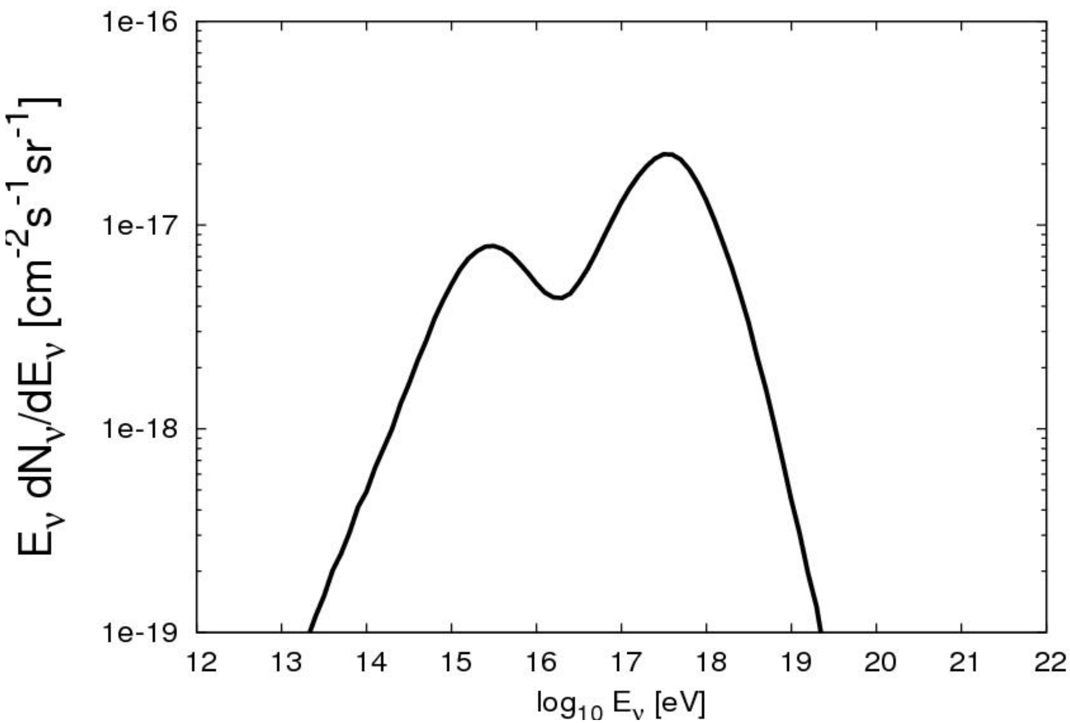
Previous Calculation of the Cosmogenic Neutrino Flux



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Lorentz violation

Heavy nuclei primaries

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5) What if cosmic rays are heavy nuclei?

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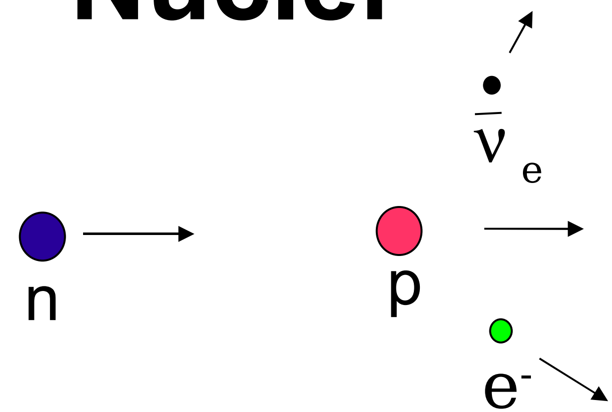
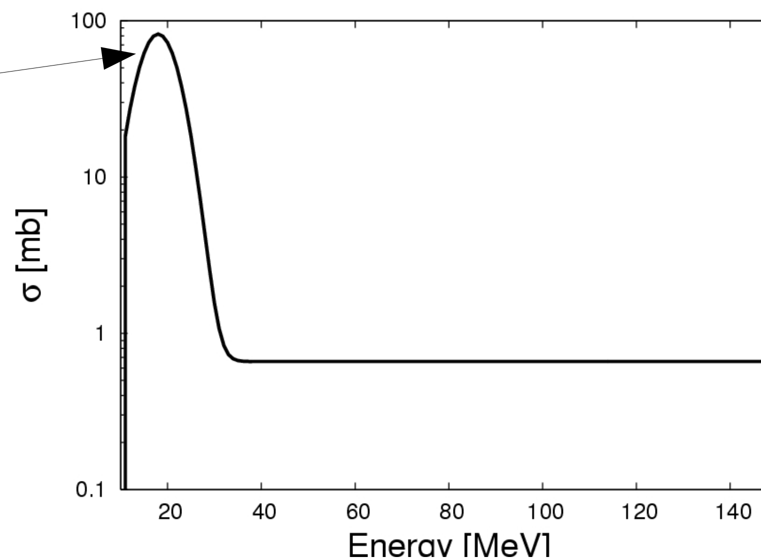
Neutrino Producing Interactions for Nuclei



In **Nuclei Rest** frame-

$E_\gamma \sim 30$ MeV
(giant dipole resonance)



In **Lab** frame-

$\langle E_{\gamma\,(CMB+CIB)} \rangle \sim 10^{-2}$ eV

$\Gamma \sim 10^9$, ($E_N \sim 10^{20}$ eV)

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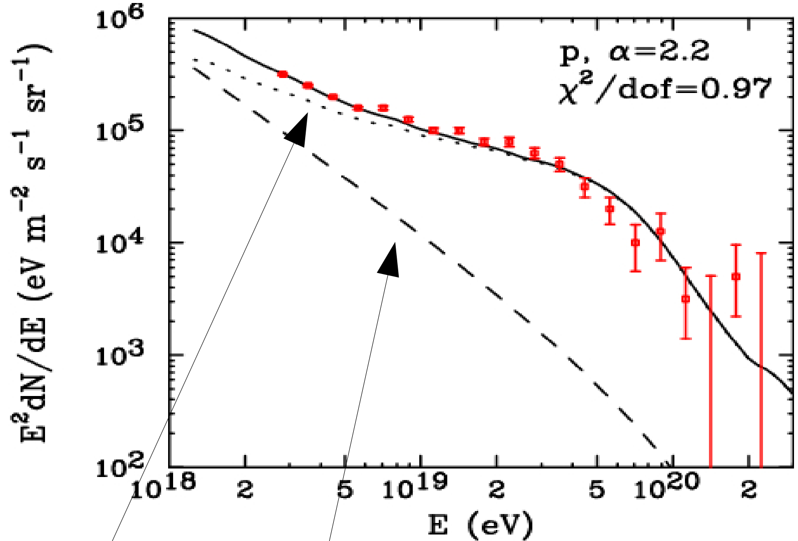
Requiring Good Fits to the Spectrum

Spectrum Plots-

$$E_{max} = \frac{10^{22}}{Z} \text{ eV}$$

protons-



extragalactic protons

nuclei-

galactic protons

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Requiring Good Fits to the Spectrum

Spectrum Plots-

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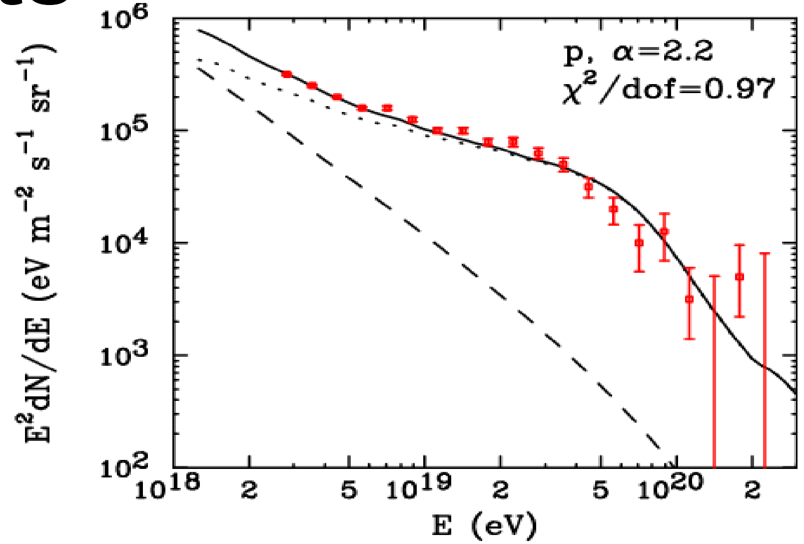
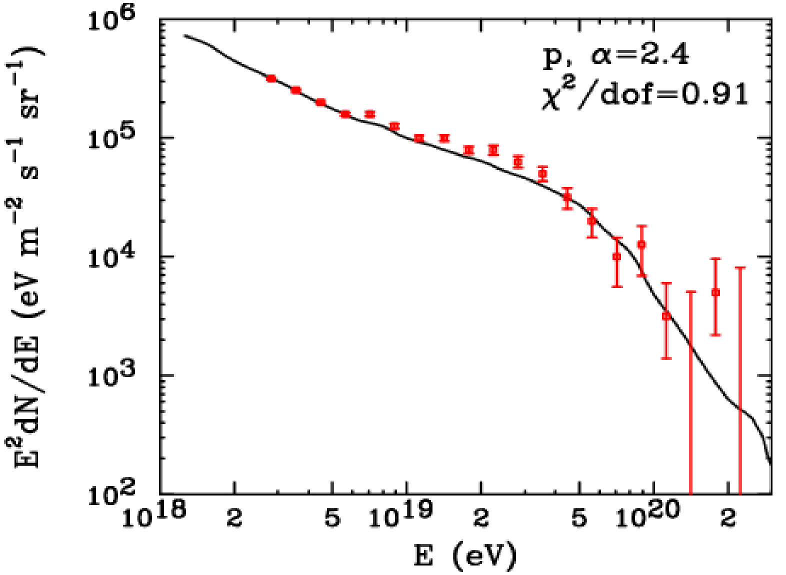
protons-





nuclei-

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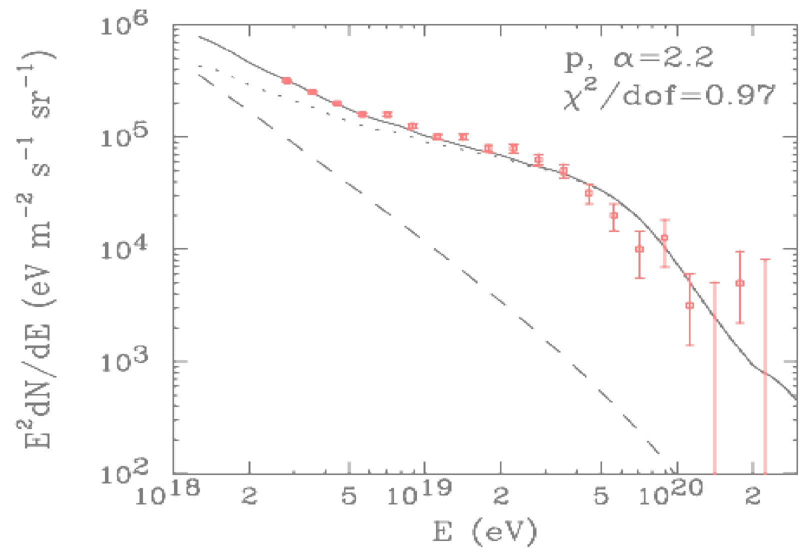
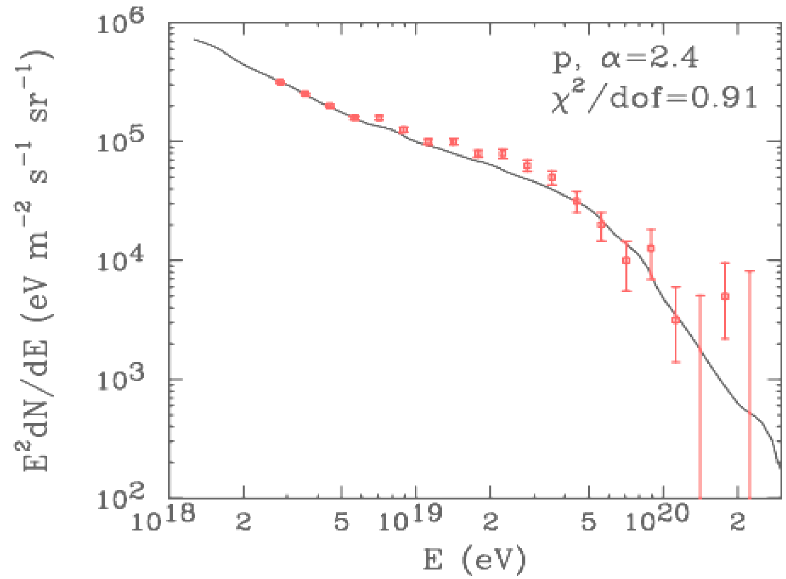
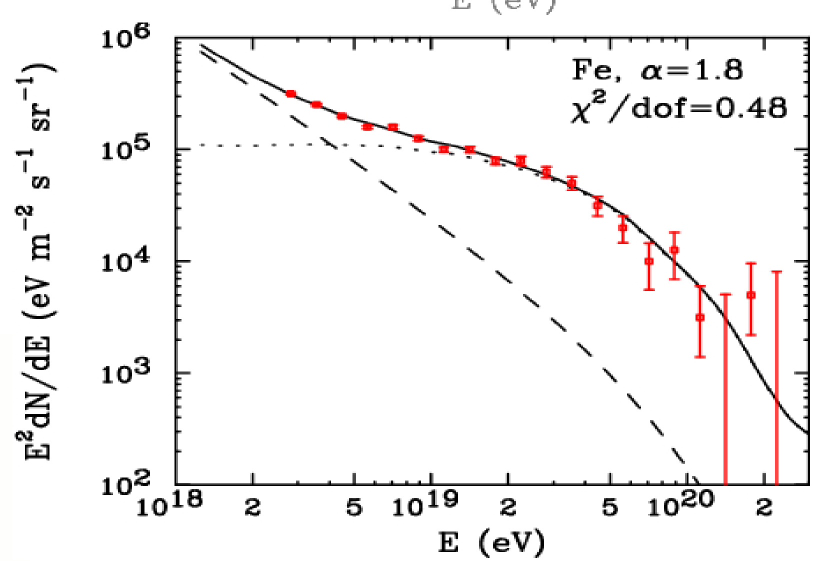
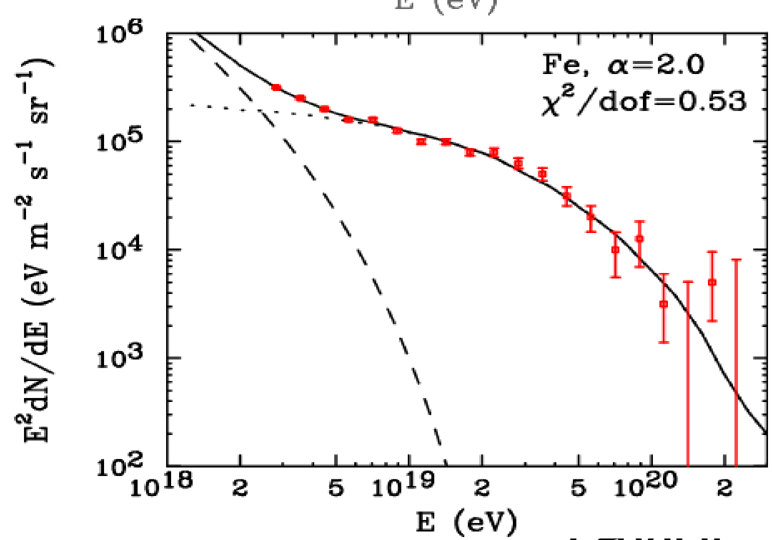




nuclei-





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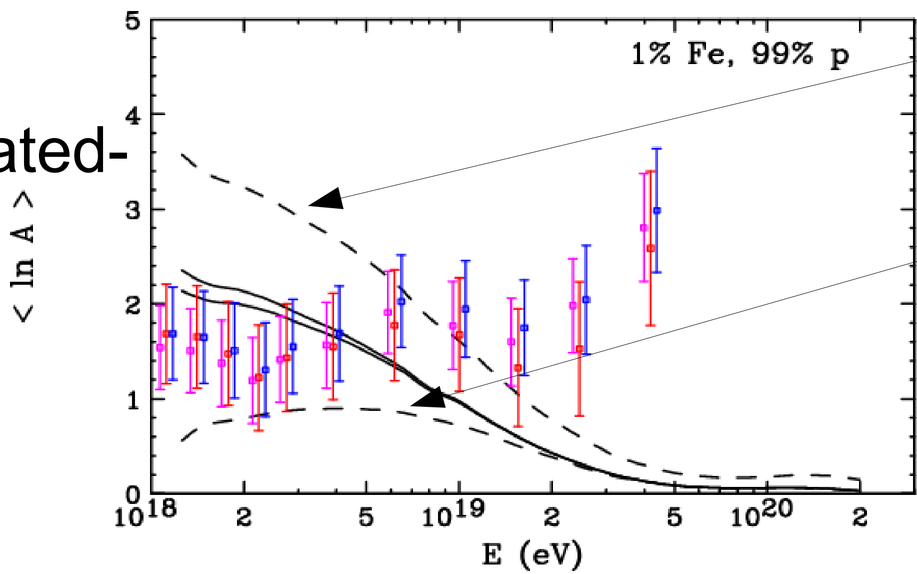
...and Good Agreement with X_{max} Data

<ln A> Plots-

proton dominated-



highest allowed α

lowest allowed α

iron dominated-

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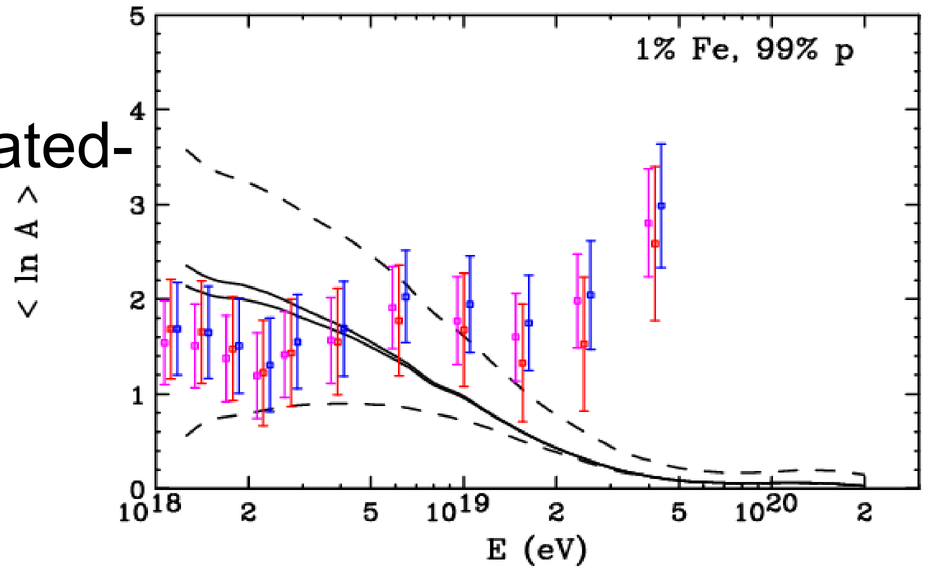
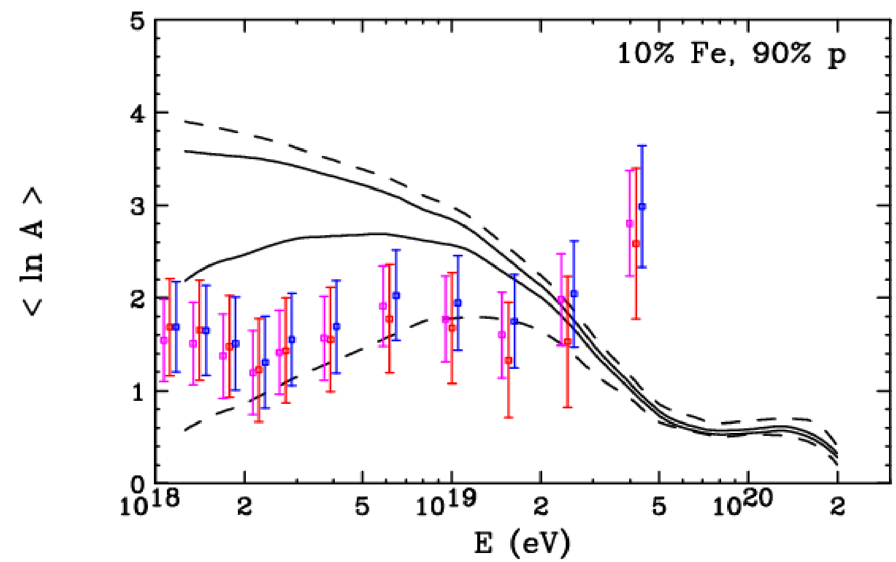
...and Good Agreement with X_{max} Data

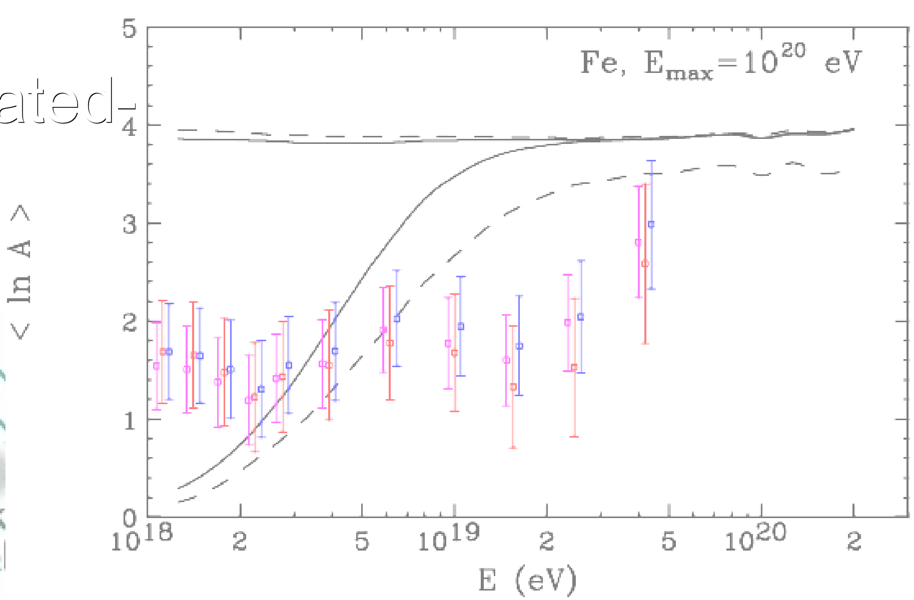
<ln A> Plots-

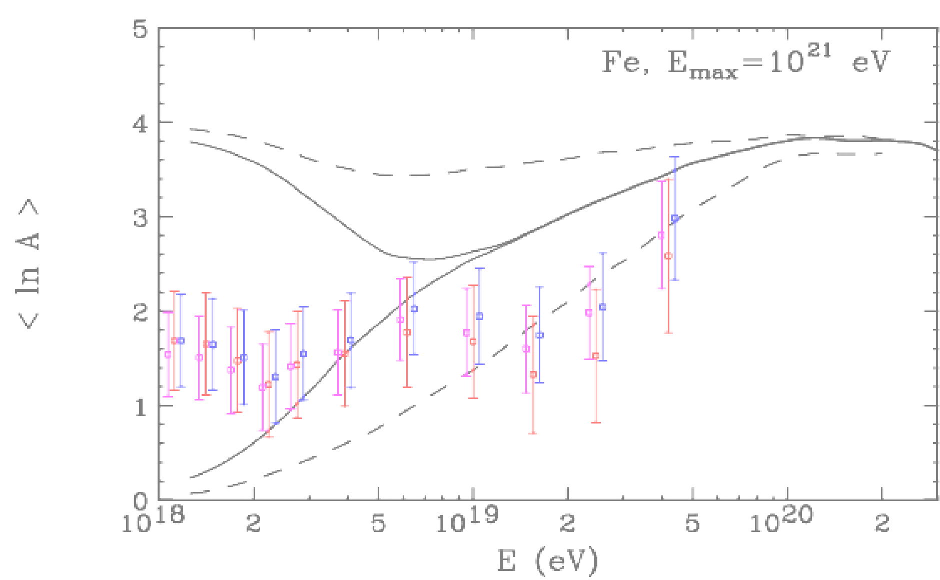
proton dominated-





iron dominated-





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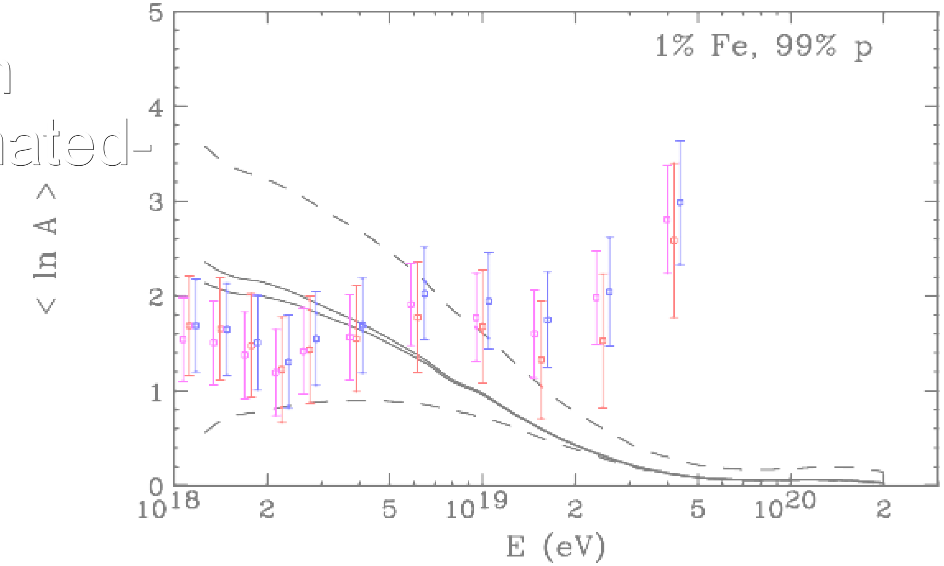
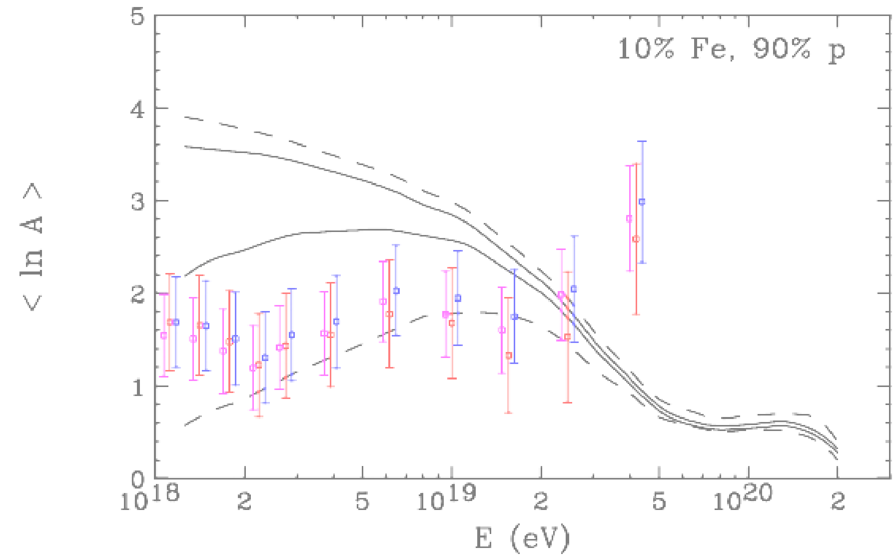
...and Good Agreement with X_{max} Data

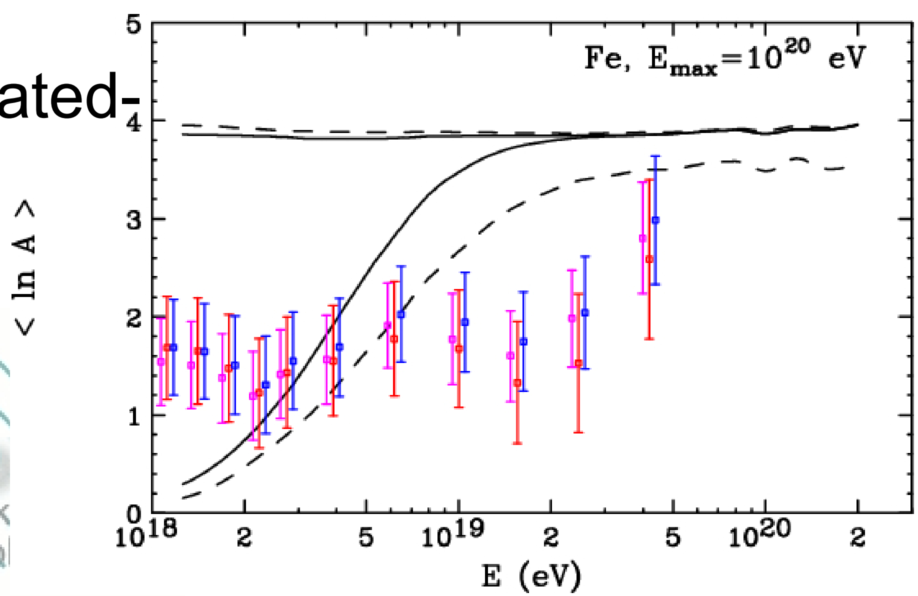
<ln A> Plots-

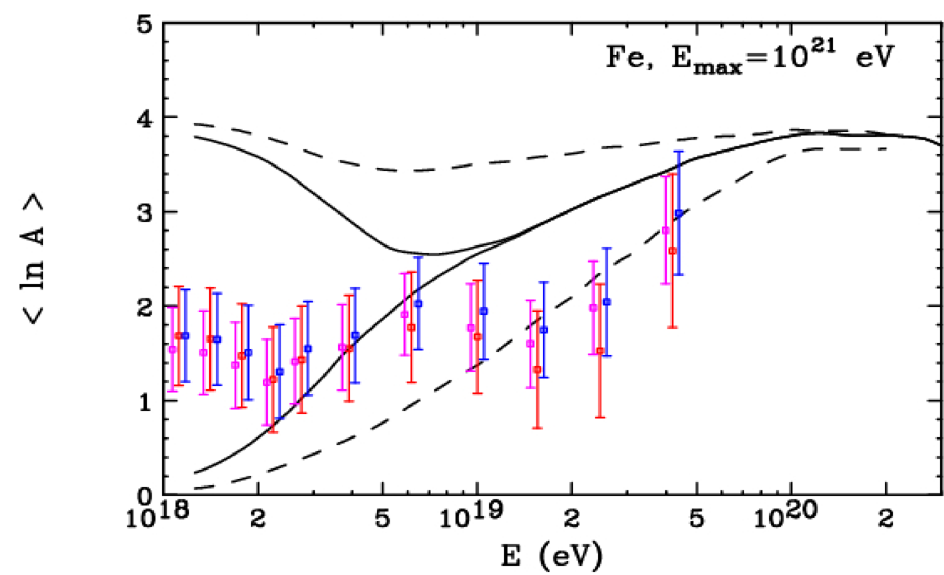
proton dominated-





iron dominated-

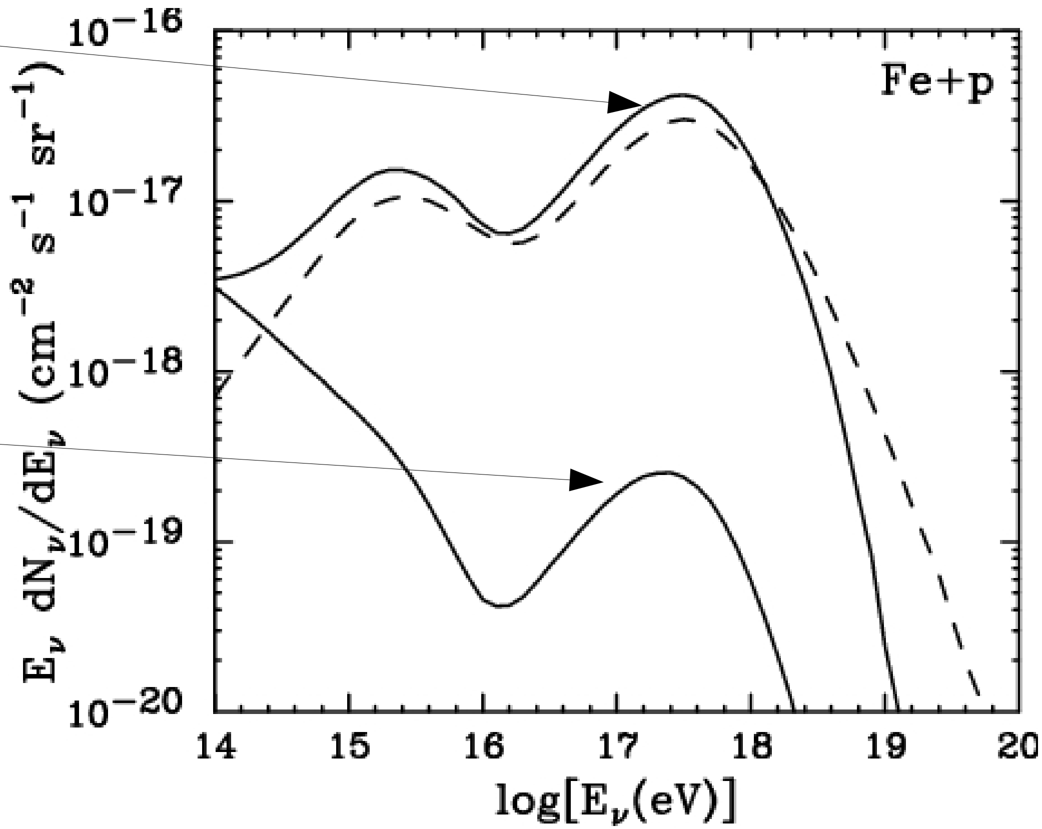




The Cosmogenic Neutrino Flux

The high energy ($>10^{17}$ eV) flux quoted as the "**Guaranteed** flux" value

lowest value compatible with all the data



Smaller value obtained since best agreement found for a dominant Fe fraction with $\mathbf{E_{max}} = 10^{21}$ eV

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Conclusions

- The cosmogenic neutrino flux calculation rests on several important underlying assumptions- the flux typically determined is by no means guaranteed
- An understanding of the true nature of the cut-off feature in the Auger cosmic ray spectrum can help in this respect
- The presence of cosmic ray nuclei in the arriving cosmic ray flux can vastly reduce the cosmogenic neutrino flux

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