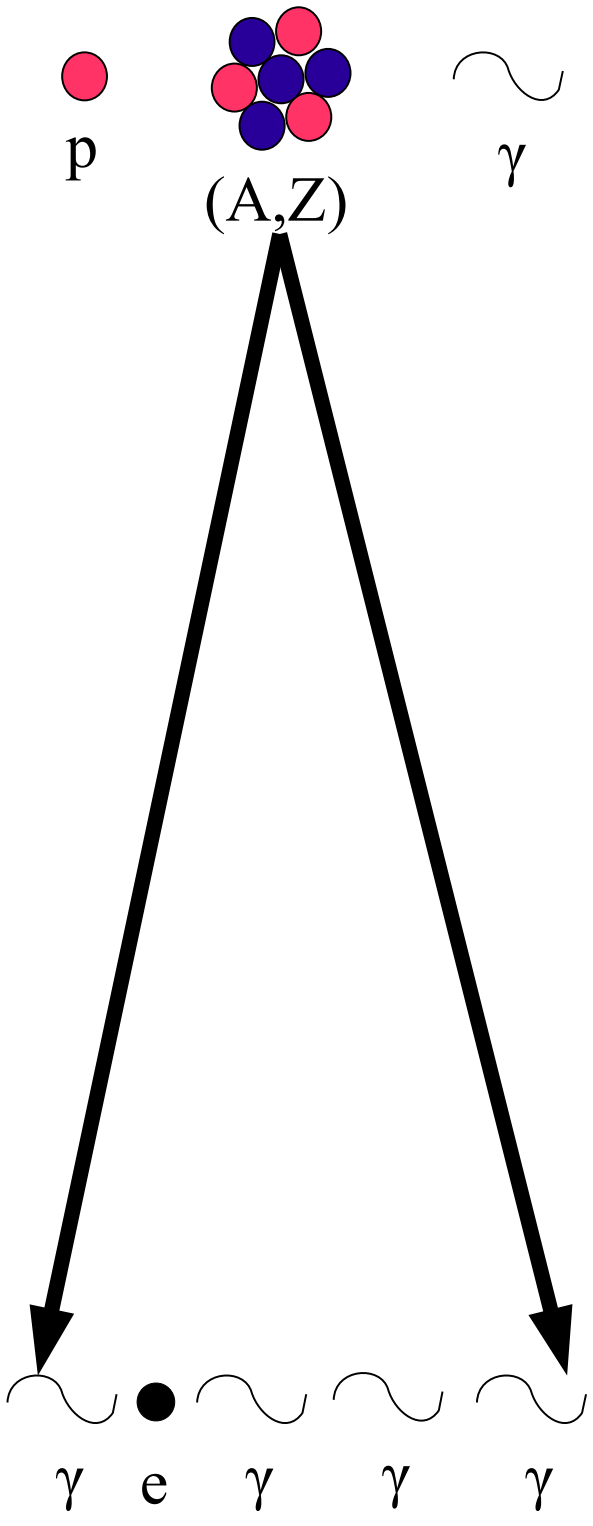


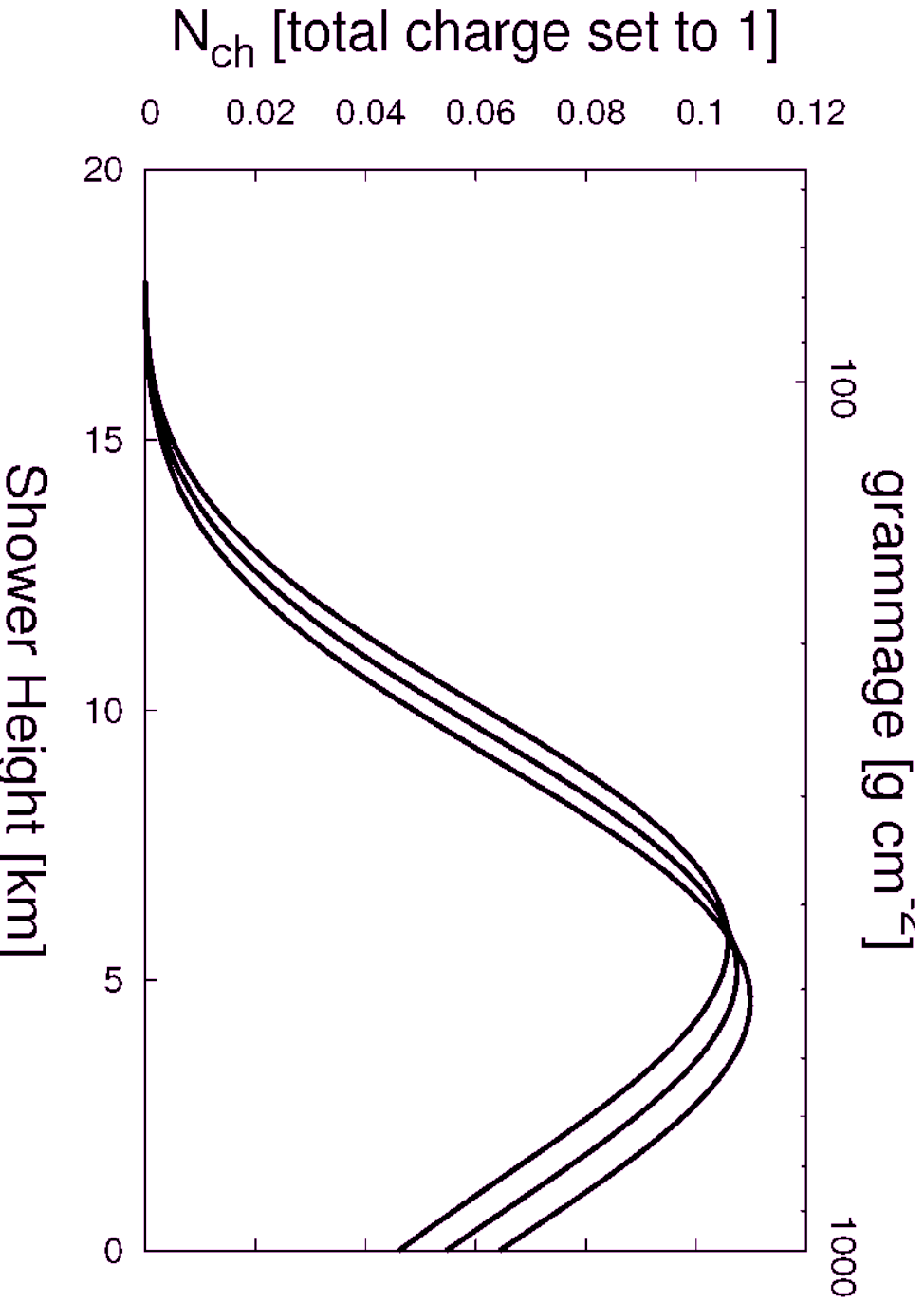
The Heavy Composition of UHECR

Based on work with:

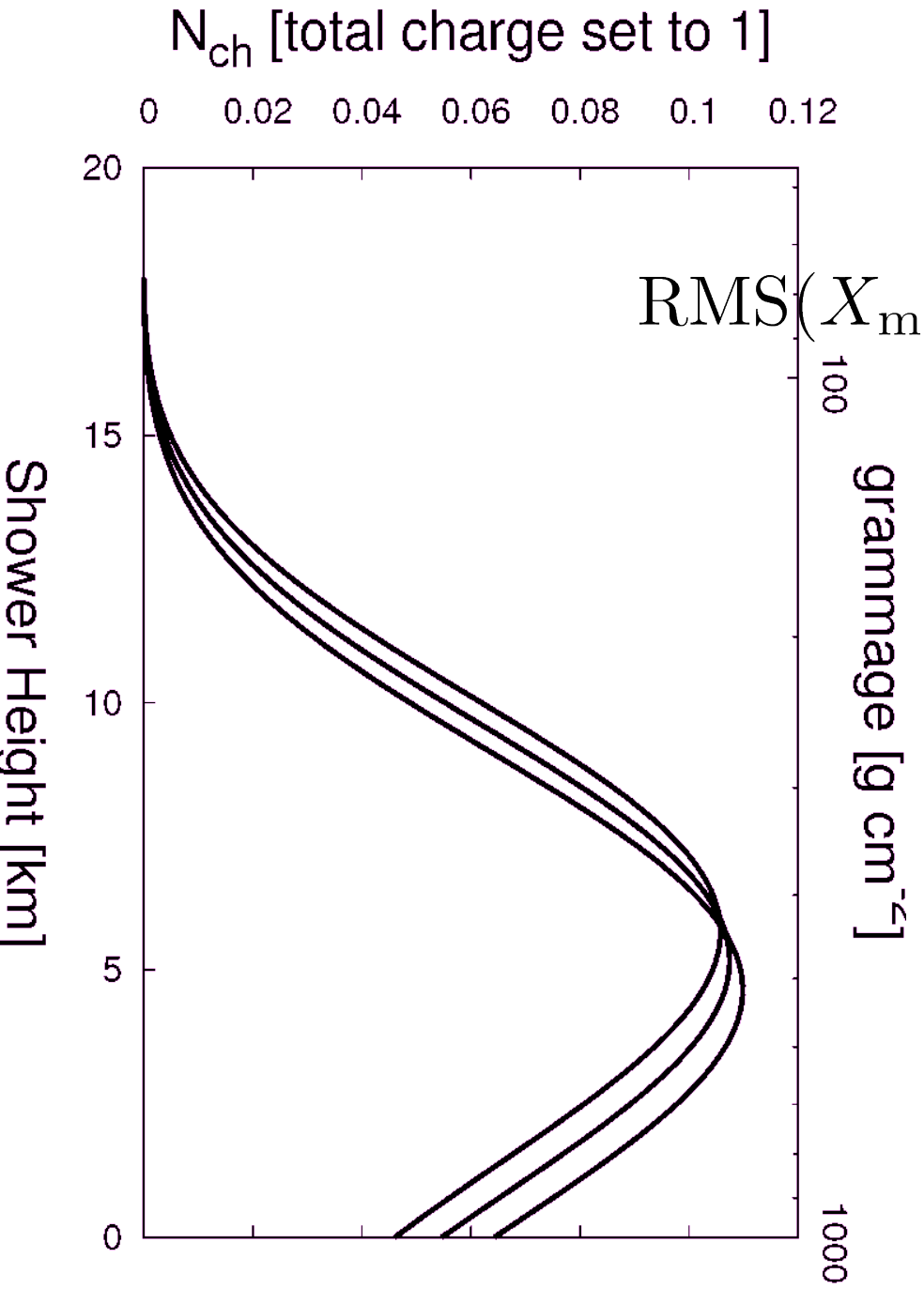
Dan Hooper + Subir Sarkar

astro-ph/0910.1842
astro-ph/1007.1306

UHECR Air Showers



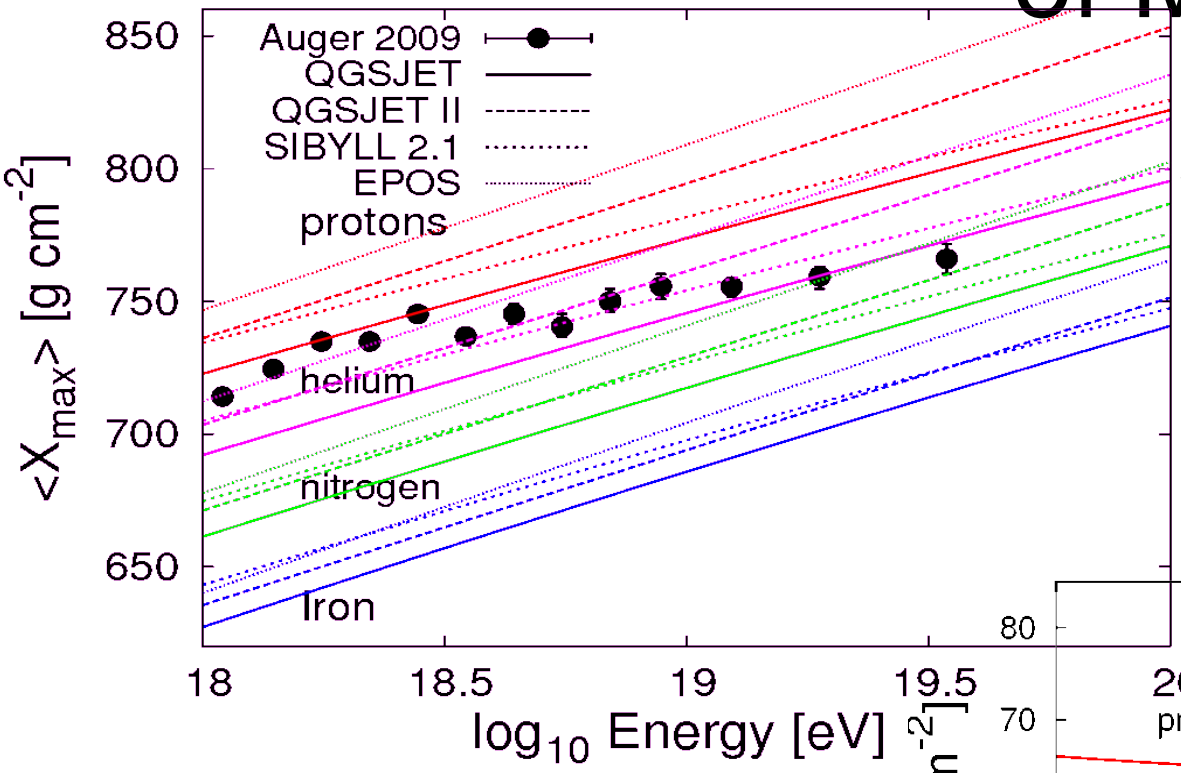
UHECR Air Showers



$$\langle X_{\max} \rangle = \frac{1}{N} \sum_{n=1}^{N} X_{\max,\mathrm{n}}$$

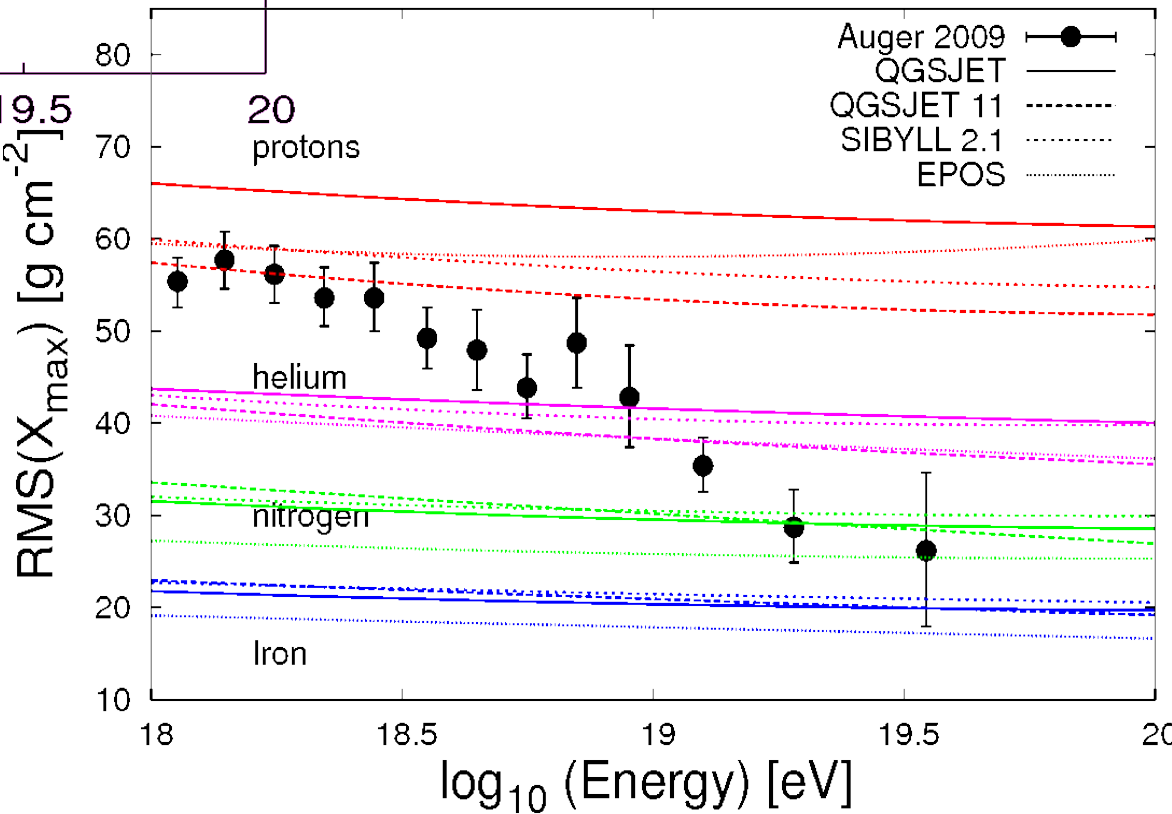
$$\mathrm{RMS}(X_{\max}) = \frac{1}{N} \sqrt{\sum_{n=1}^{N} (X_{\max,\mathrm{n}} - \langle X_{\max} \rangle)^2}$$

Recent Measurements of Moments by Auger



$\langle X_{\max} \rangle$

$\mathrm{RMS}(X_{\max})$



Interpretation- What Does this Mean for Source Composition?

Assume Source Energy Distribution:

$$\frac{dN_{\rm CR}}{dE_{\rm CR}} \propto E_{\rm CR}^{-\alpha} e^{-E_{\rm CR}/E_{\rm cut}}$$

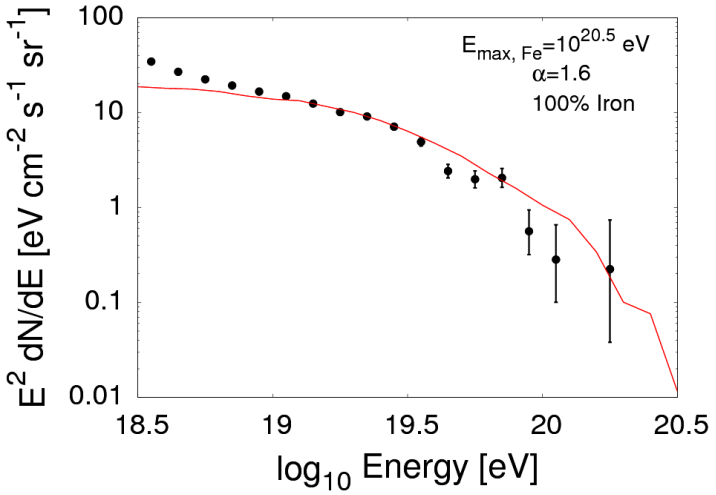
Spectral index α and max energy $E_{\rm max}$ are considered in the range:

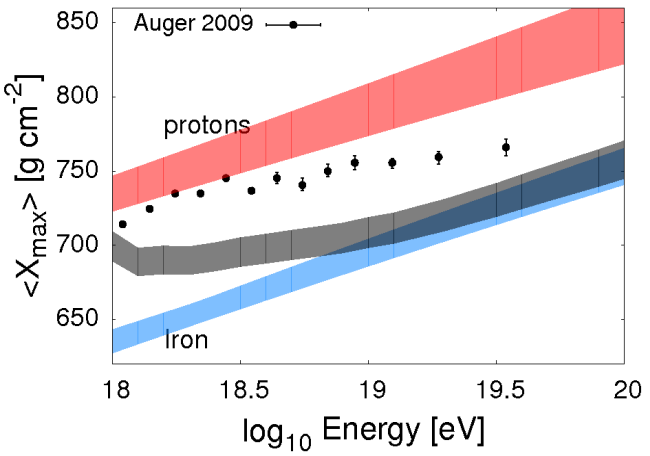
$$1.6 < \alpha < 2.4$$

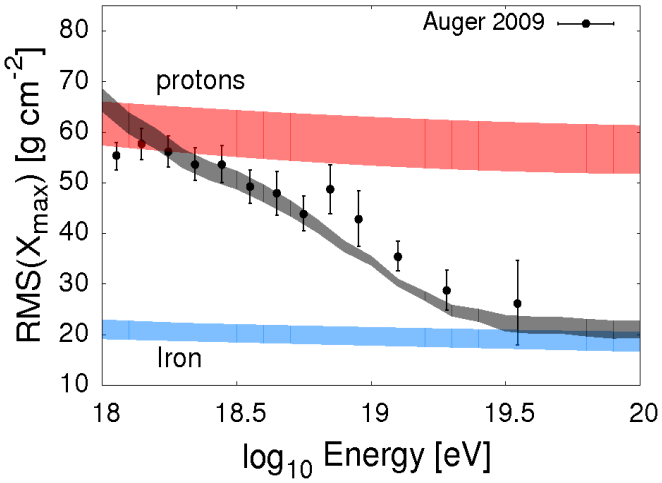
$$10^{20}\ {\rm eV} < E_{\rm max} < 10^{22}\ {\rm eV}$$

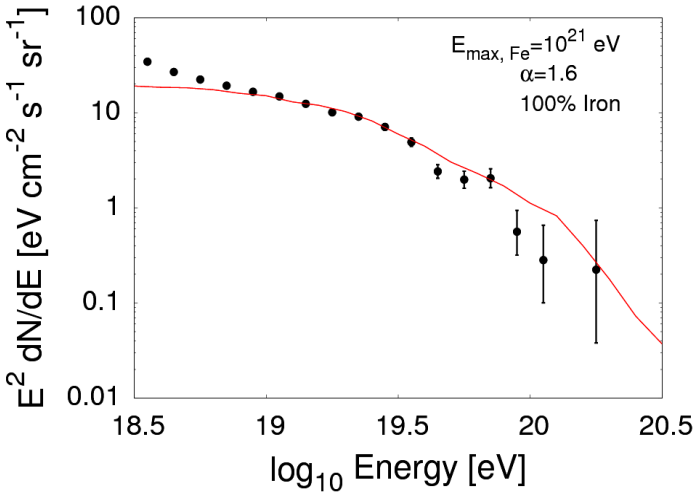
+ Assume Sources have a uniform Spatial Dist.

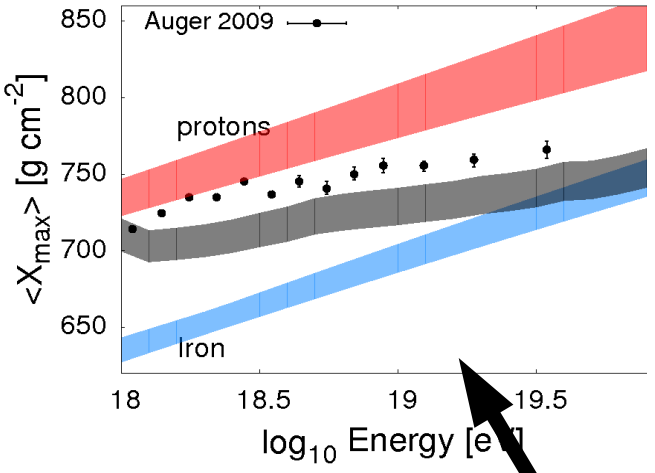
Iron Only Composition?

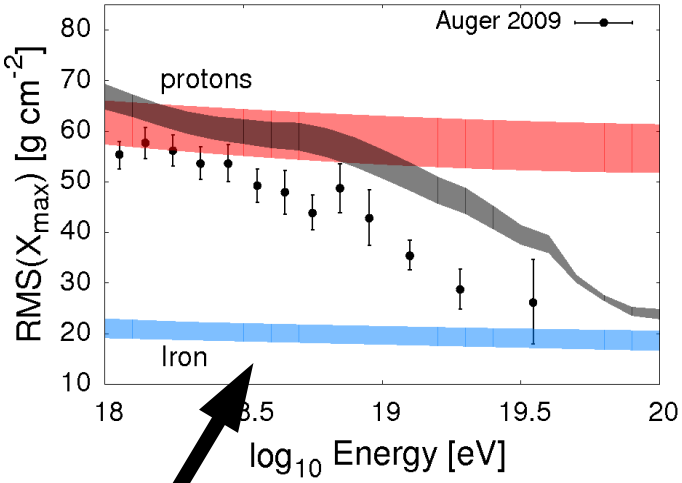












hard to fit both of these simultaneously for Iron

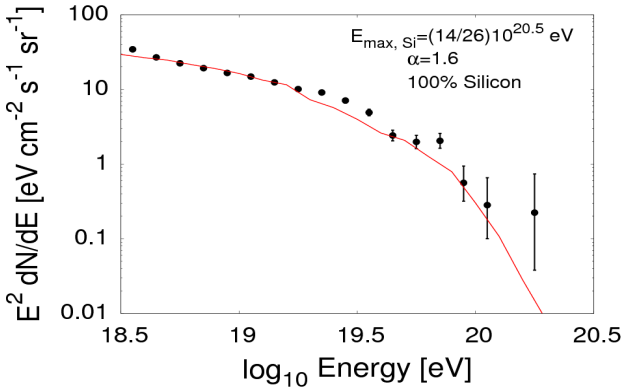
Iron Only Composition?

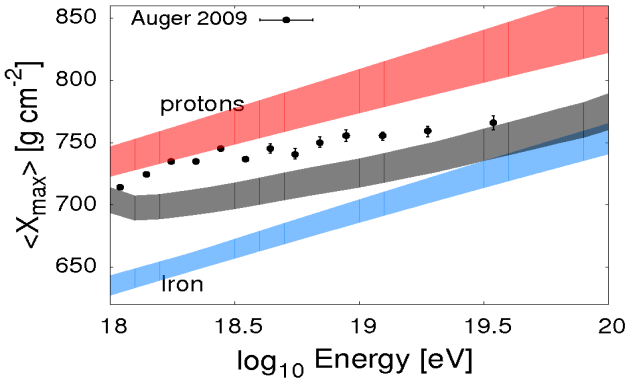
$$\langle X_{\max} \rangle = \sum_{A=1}^{56} f_A X_{\max,A}$$

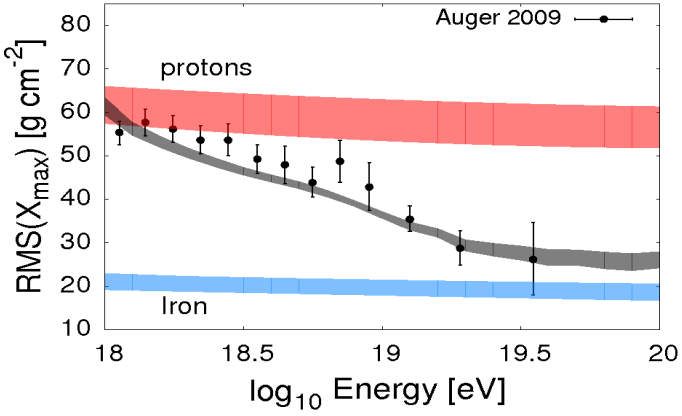
$$\sigma^2_{\rm tot} = \sum_{A=1}^{56} (f_A \sigma^2_A + f_A (X_{\max,A} - \langle X_{\max} \rangle)^2)$$

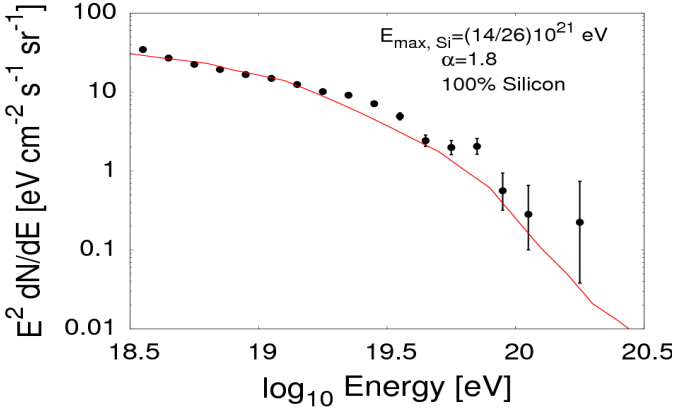
Cause of difficulty in fitting both $\langle X_{\max} \rangle$ and $\mathrm{RMS}(X_{\max})$ simultaneously for Iron

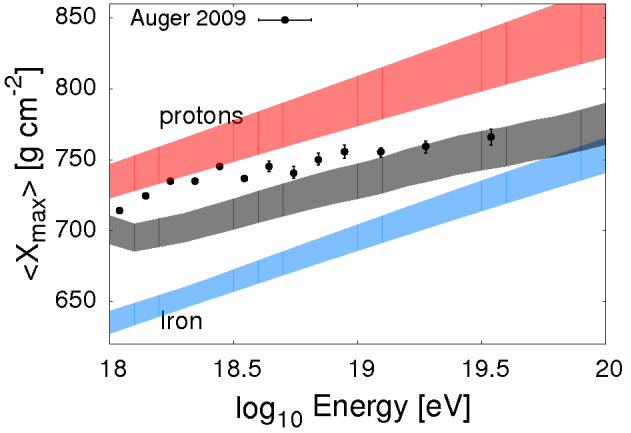
Silicon Only Composition?

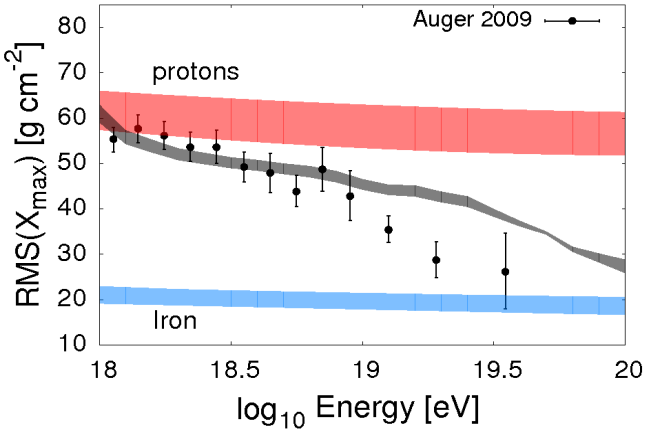






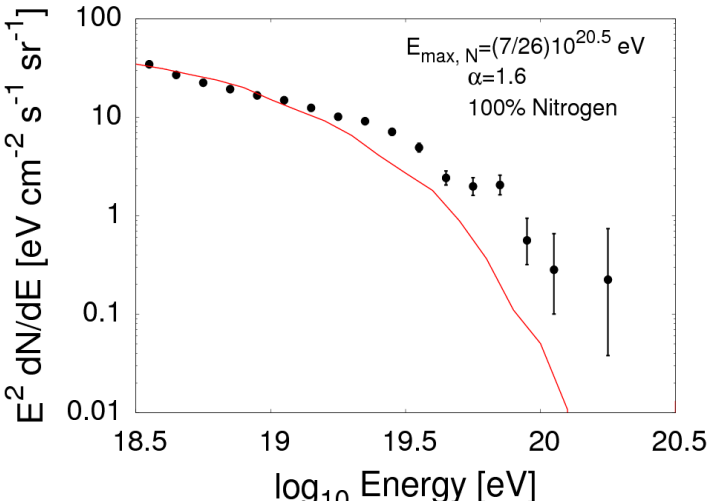


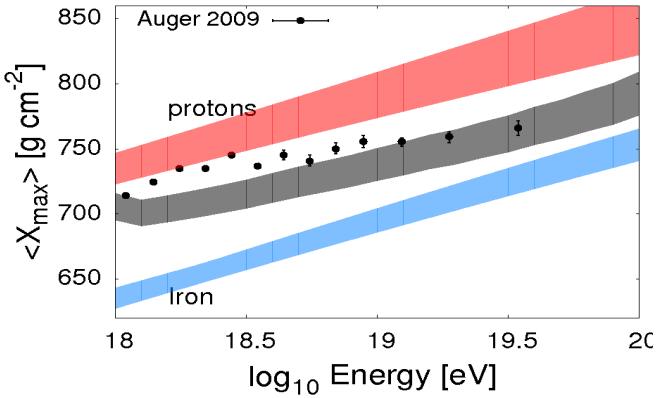


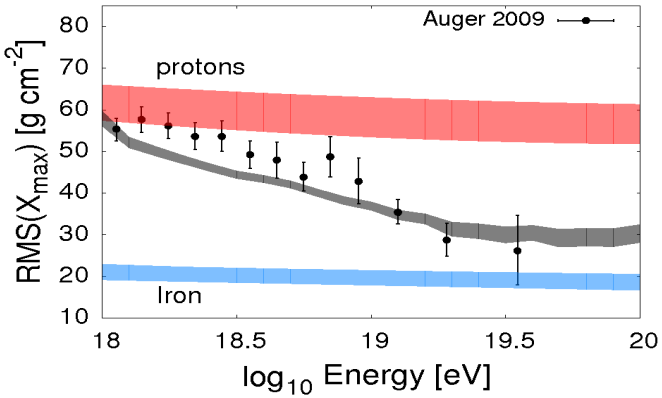


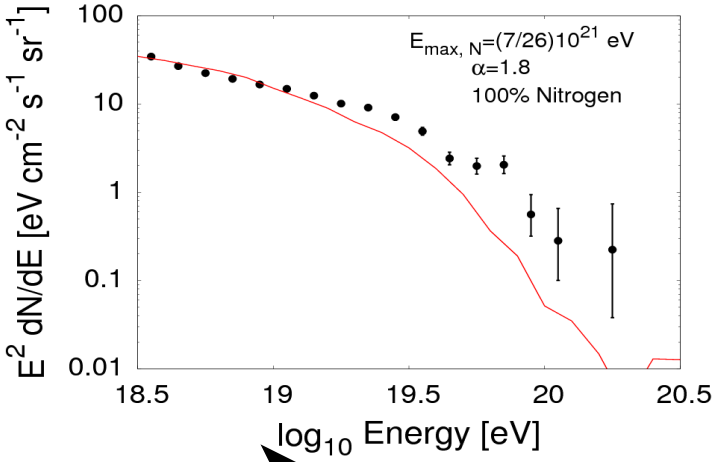
reasonable fits obtained, though hard spectral index required is worrying

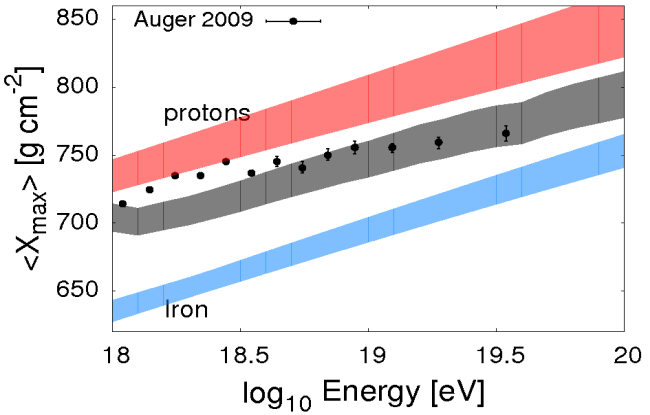
Nitrogen Only Composition?

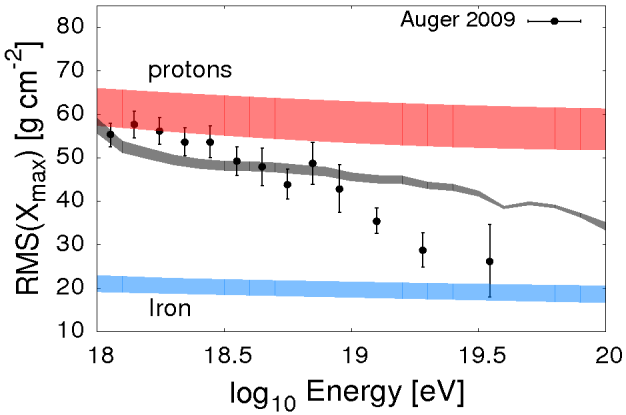






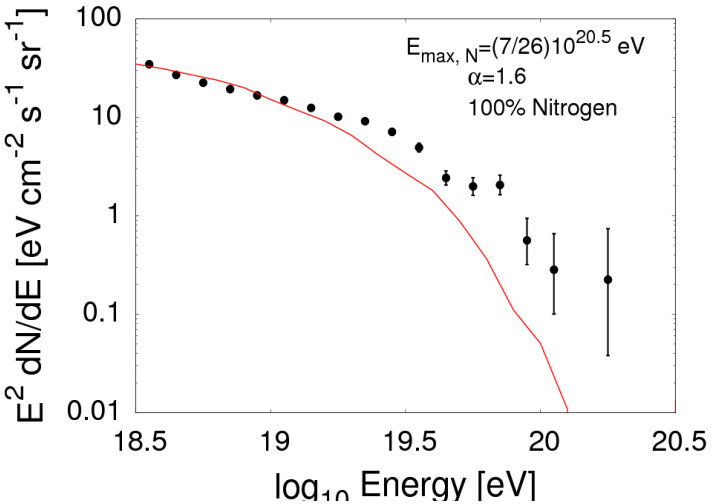


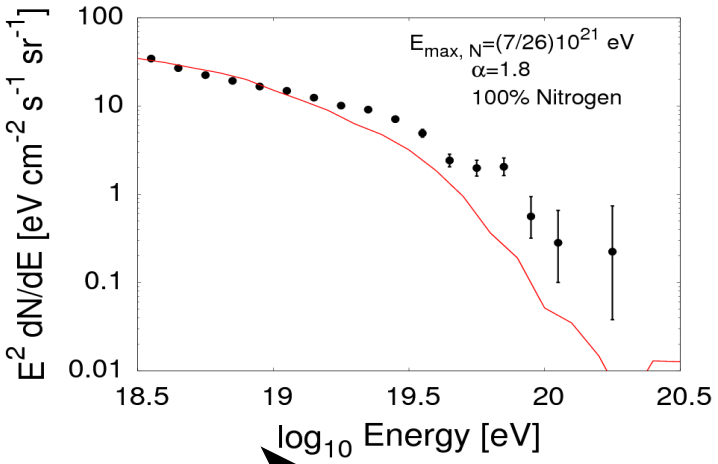




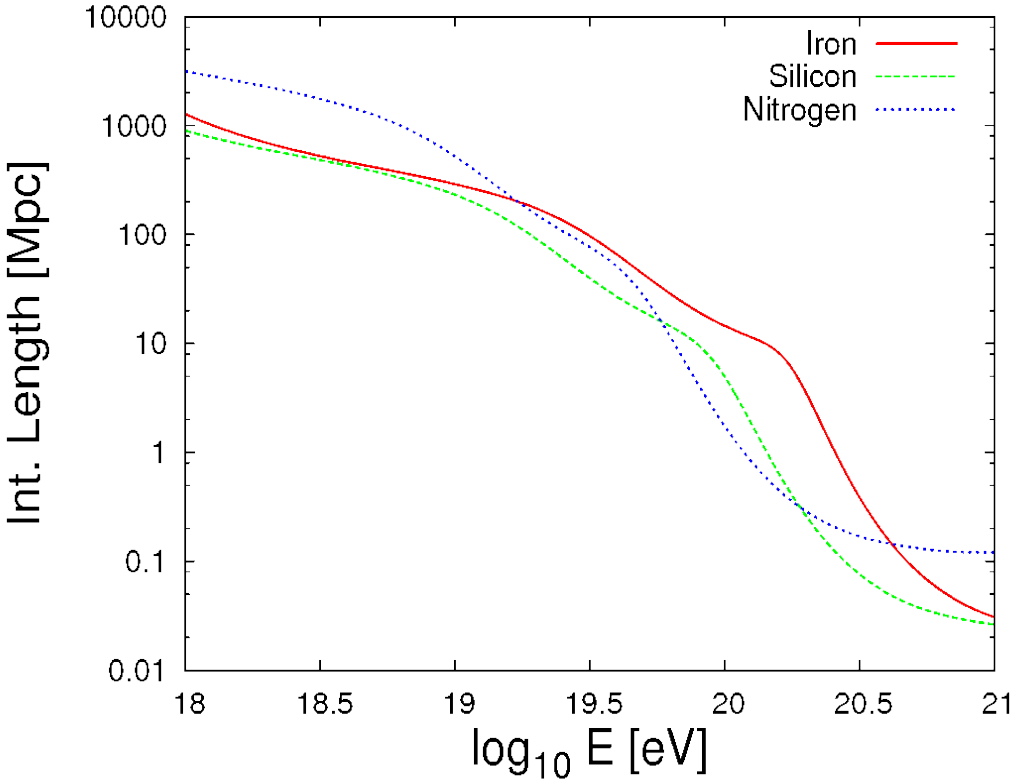
poor spectral fit is a problem for Nitrogen only composition

Nitrogen Only Composition?

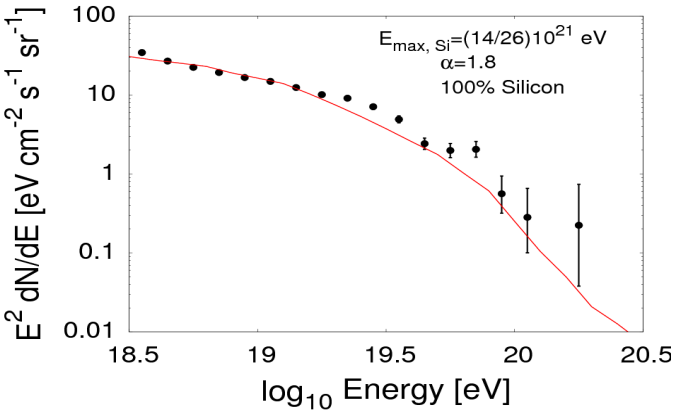


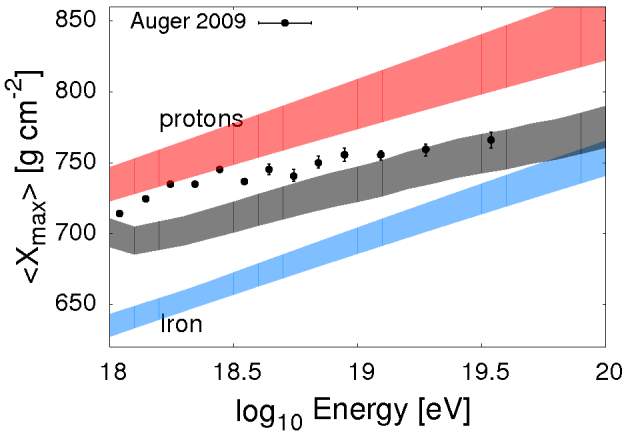


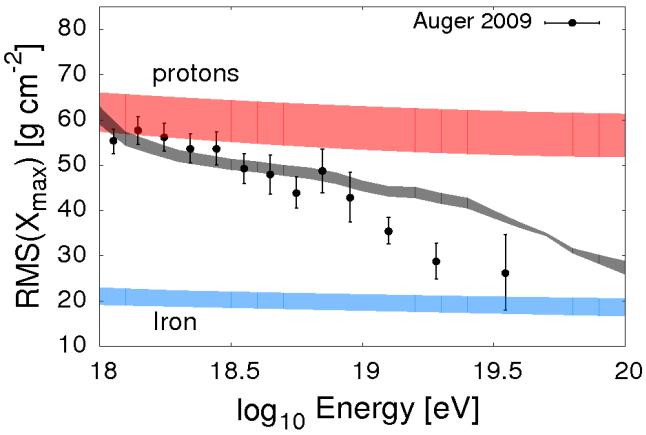
reason



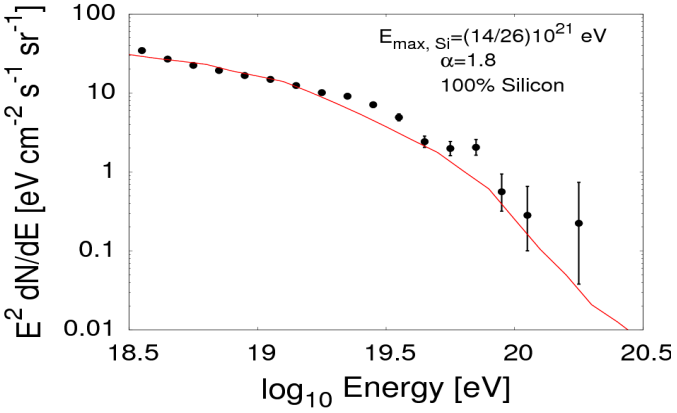
poor spectral fit is a problem for Nitrogen only composition

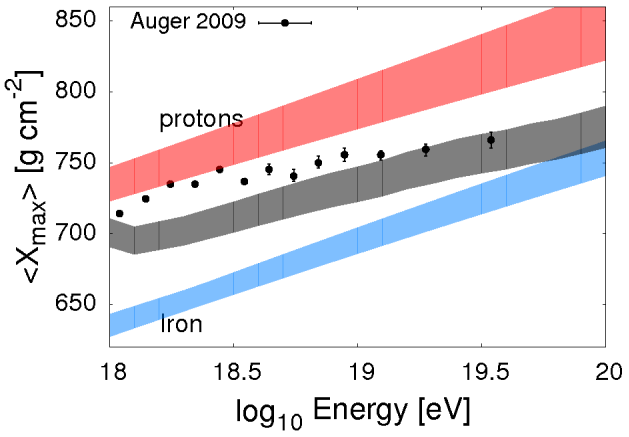


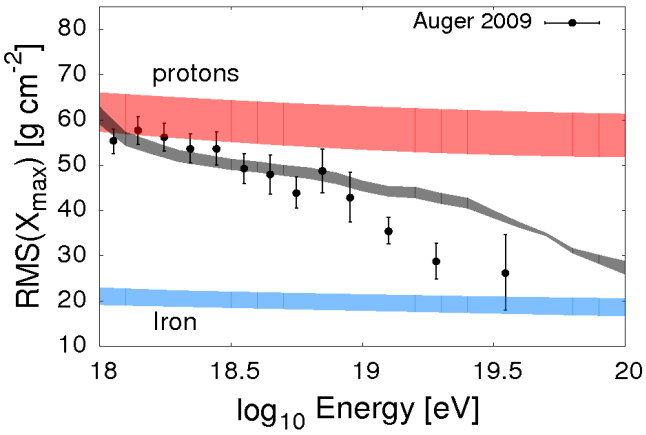


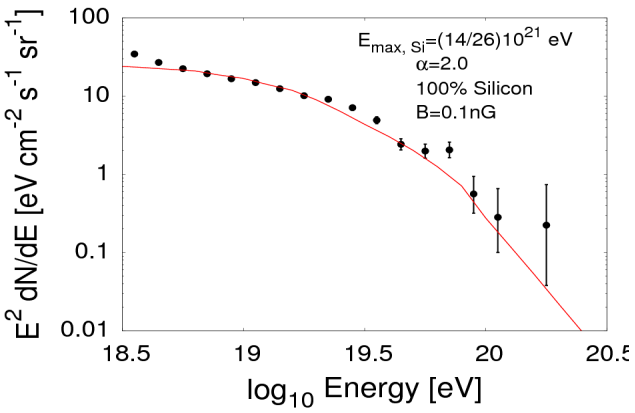


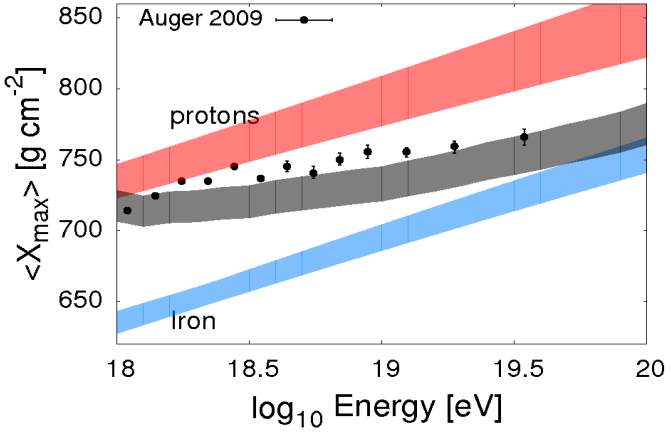
(Silicon) Magnetic Field- B=0 G

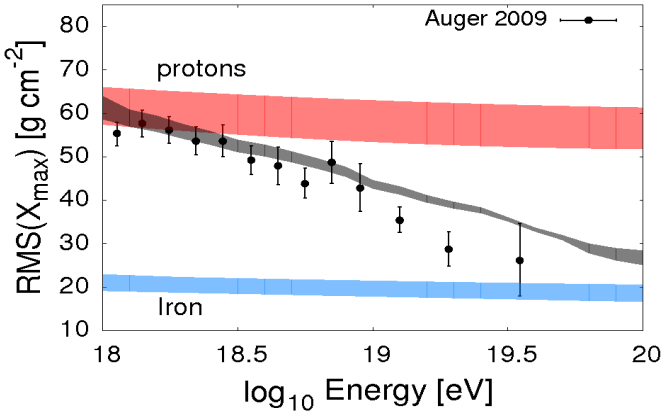




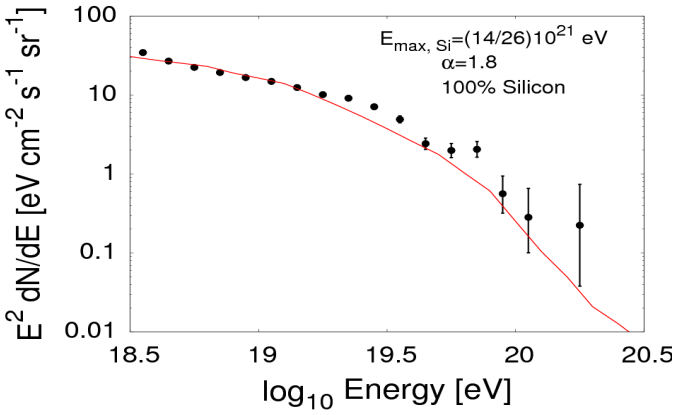


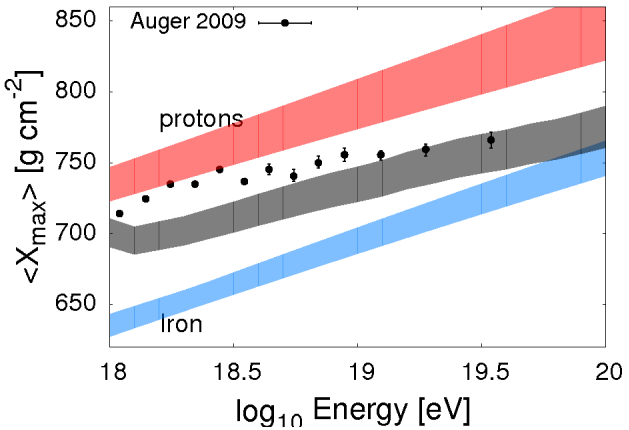


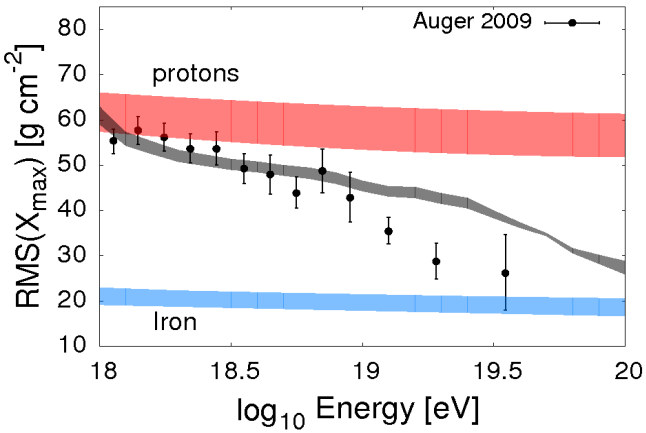


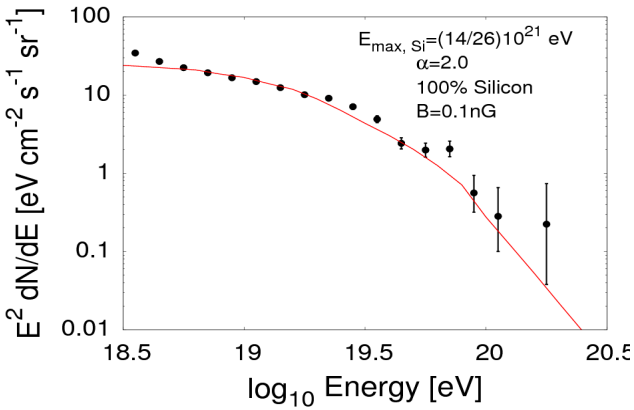


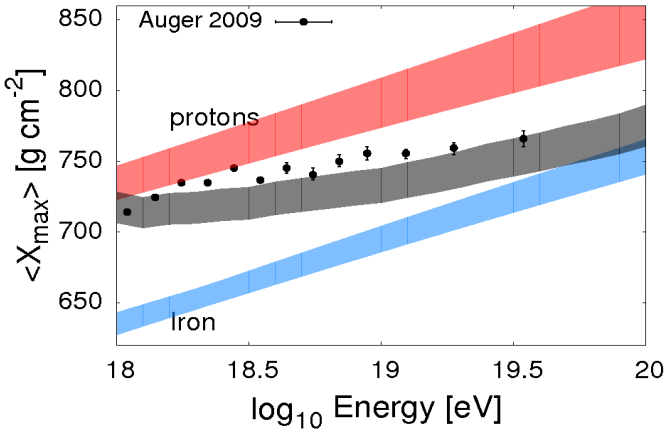
(Silicon) Magnetic Field- B=0.1 nG

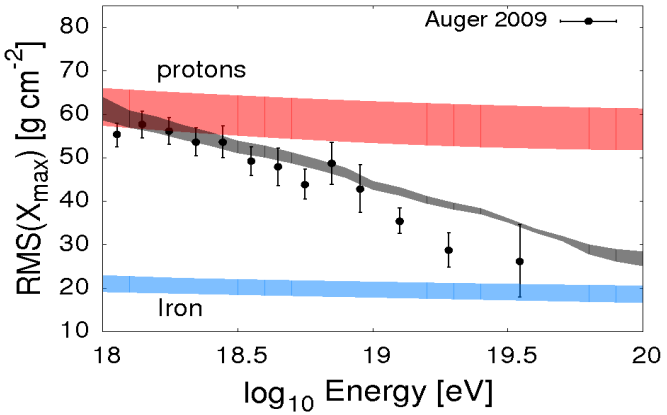


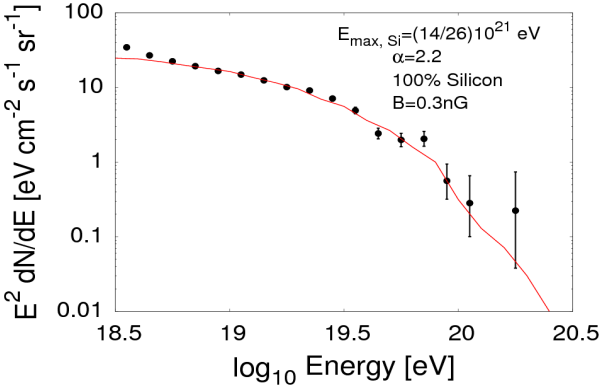


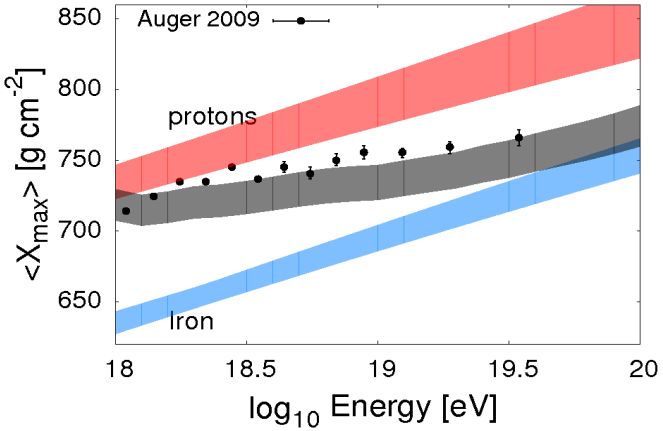


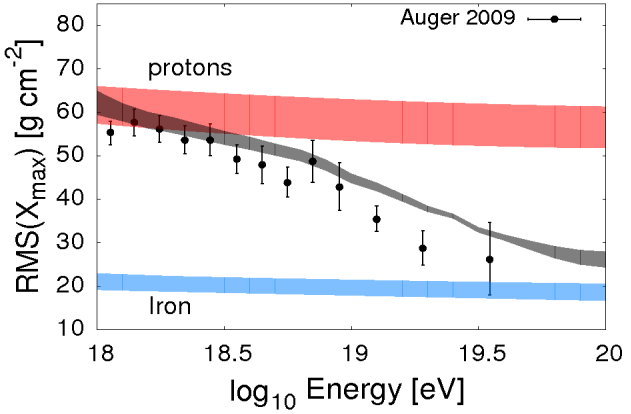










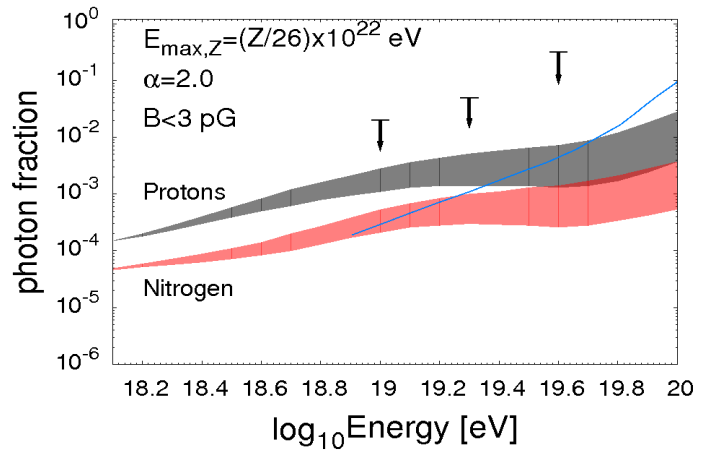


(Silicon) Magnetic Field- B=0.3 nG

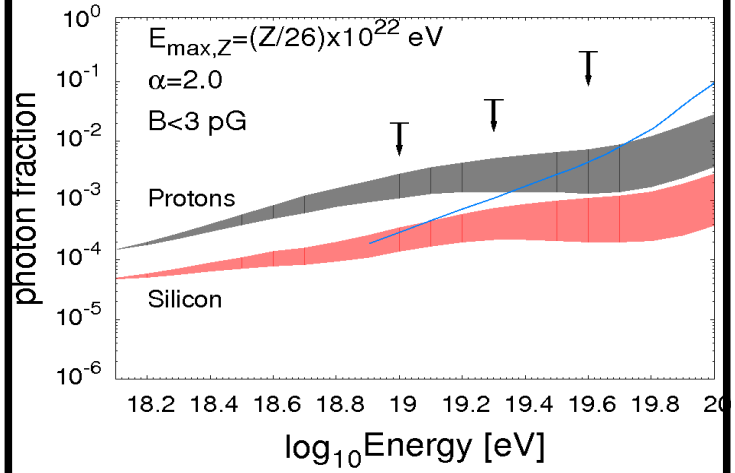
Other Handles on the UHECR Composition

Nitrogen (Z=7)

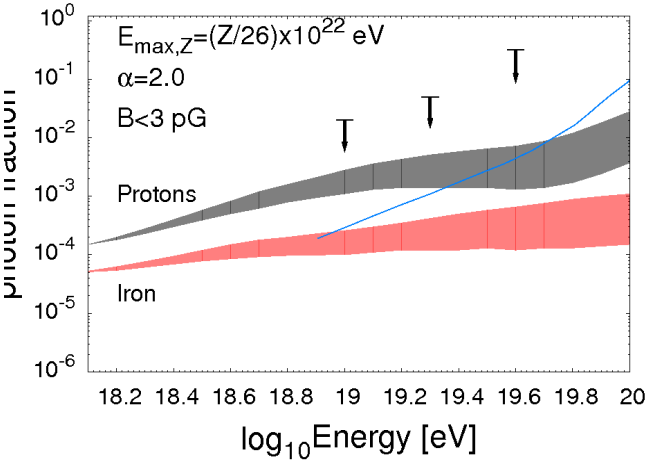
$$E_{\max} = (Z/26)10^{22}\mathrm{eV}$$



Silicon (Z=14)



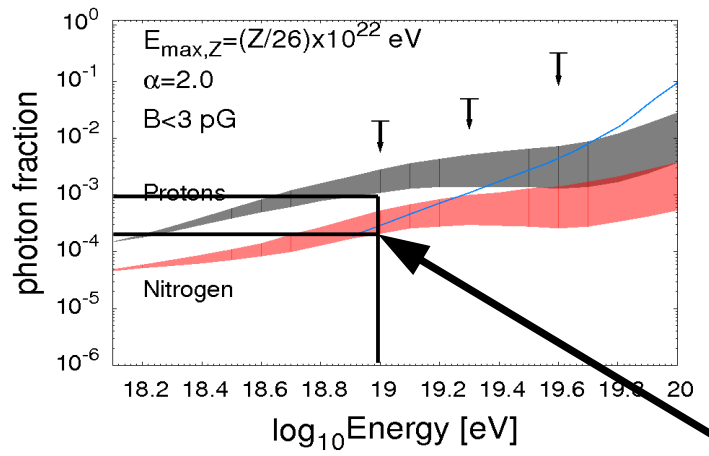
Iron (Z=26)



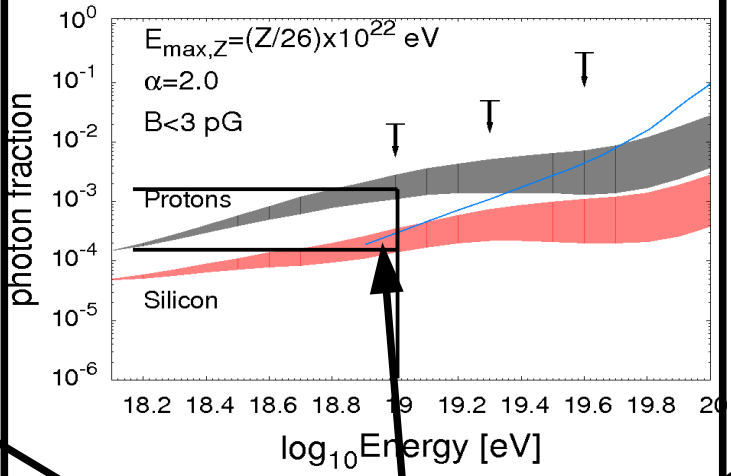
Other Handles on the UHECR Composition

Nitrogen (Z=7)

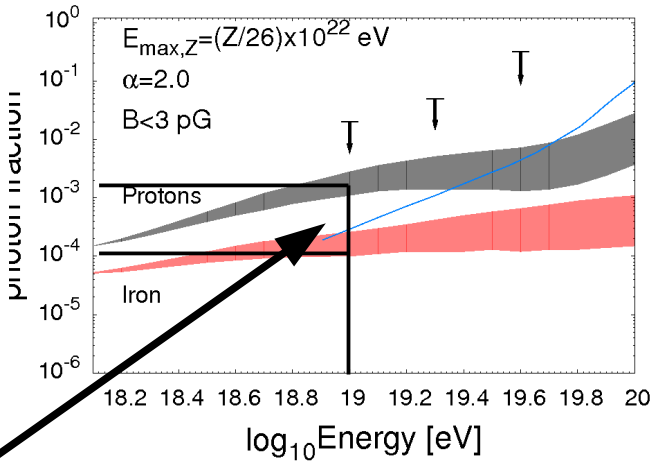
$$E_{\max} = (Z/26)10^{22}\mathrm{eV}$$



Silicon (Z=14)

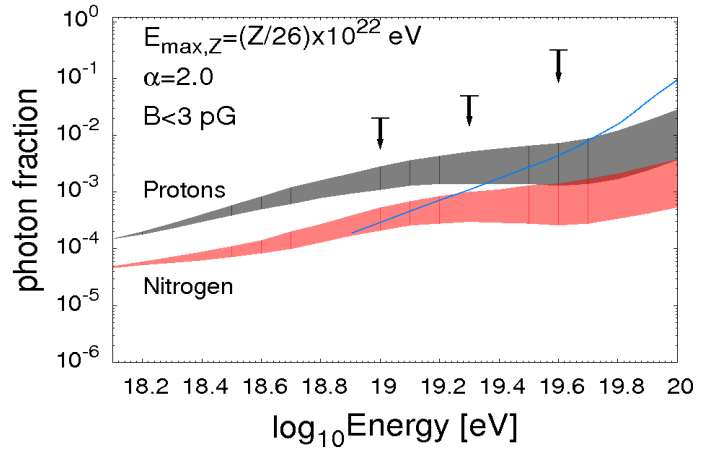
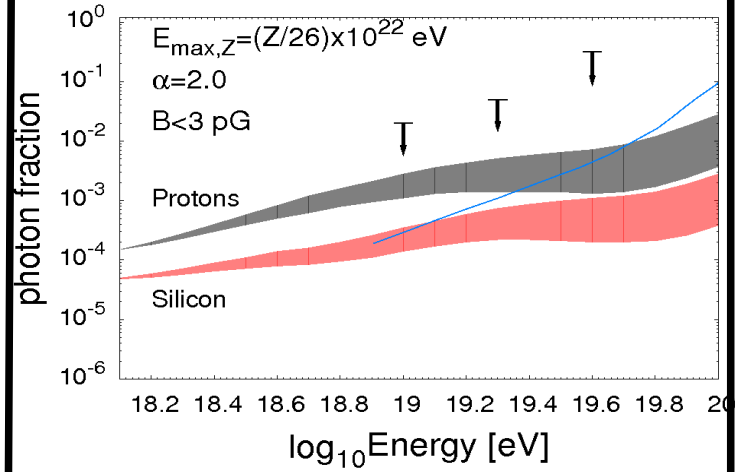
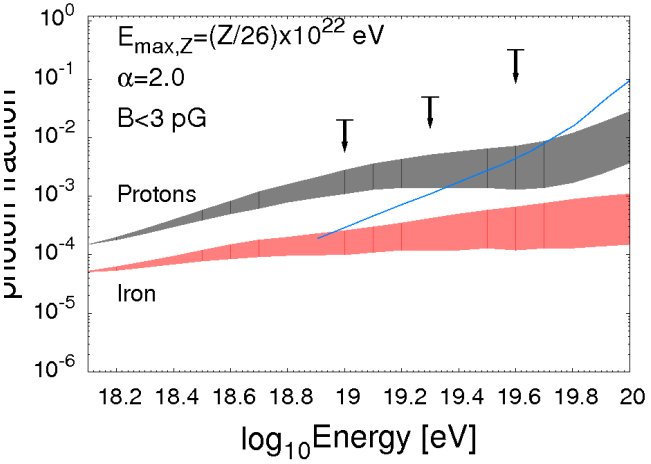
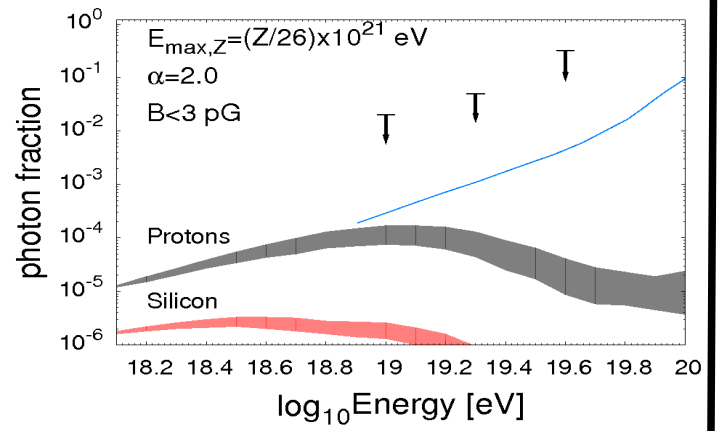
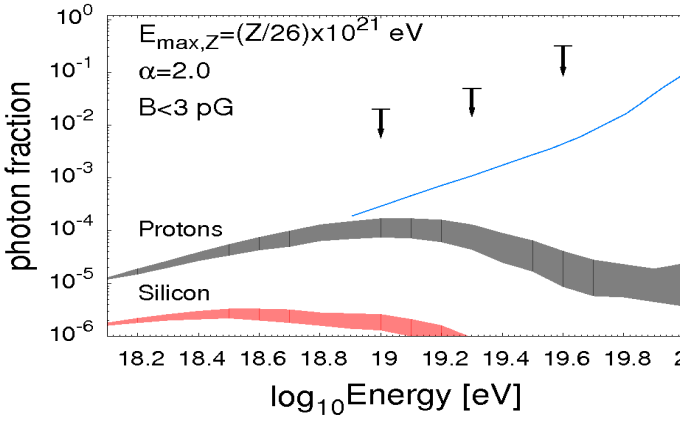
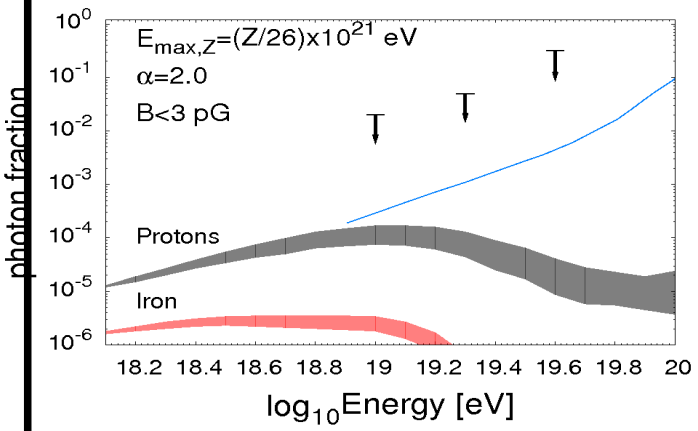


Iron (Z=26)



Basically proportional to Z/A for a $E_{max} >> E_{GZK}$

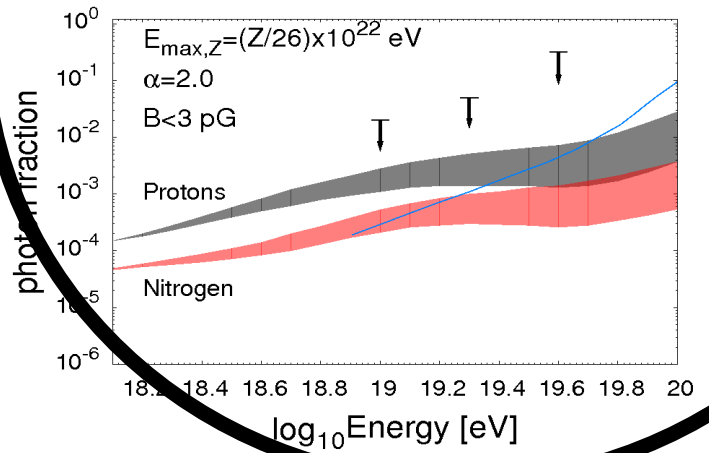
Other Handles on the UHECR Composition

Nitrogen (Z=7)	Silicon (Z=14)	Iron (Z=26)
$E_{\max} = (Z/26)10^{22}\mathrm{eV}$		
		
$E_{\max} = (Z/26)10^{21}\mathrm{eV}$		
		

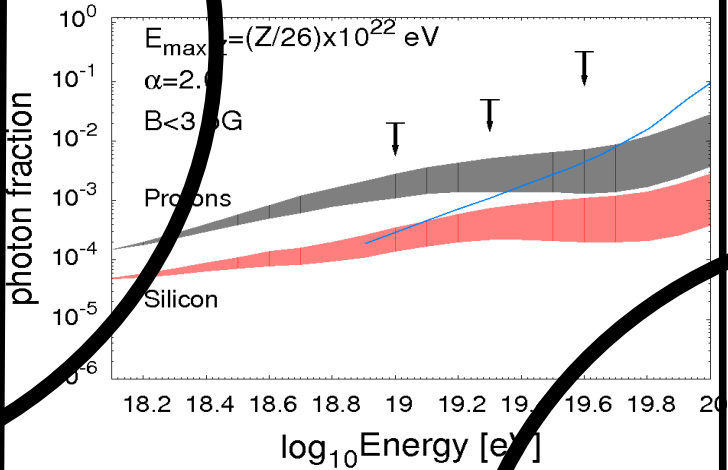
Other Handles on the UHECR Composition

Nitrogen (Z=7)

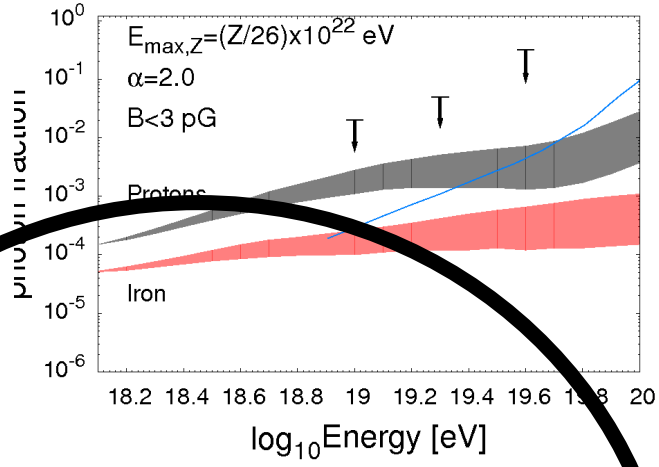
$E_{\max} = (Z/26)10^{22}\mathrm{eV}$



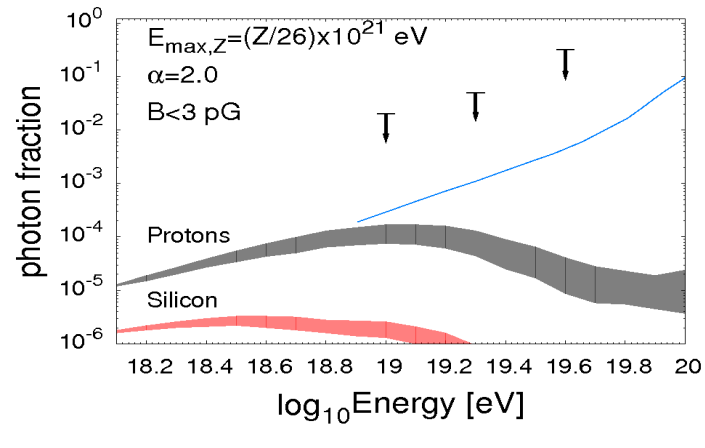
Silicon (Z=14)

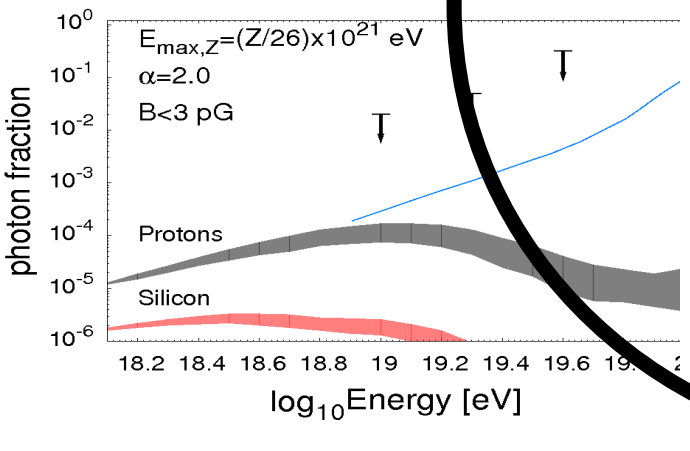


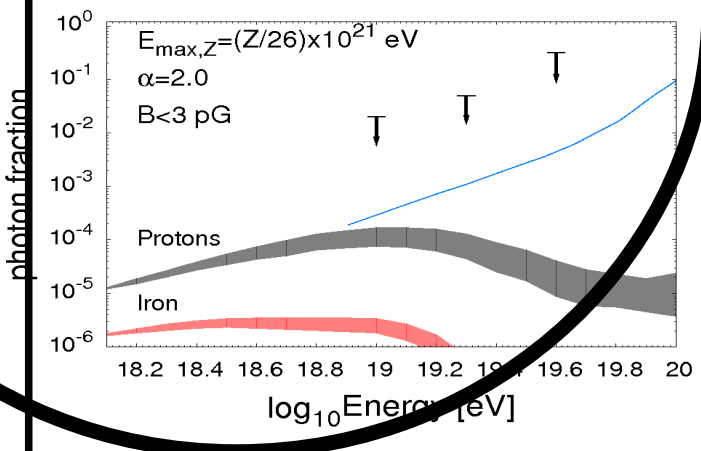
Iron (Z=26)



$E_{\max} = (Z/26)10^{21}\mathrm{eV}$







Summary

If pure composition at source is assumed:

Heavy(ish) composition required;

Difficult to get good agreement with Iron only composition to both $\langle X_{\rm max} \rangle$ and $\rm RMS(X_{max})$ data;

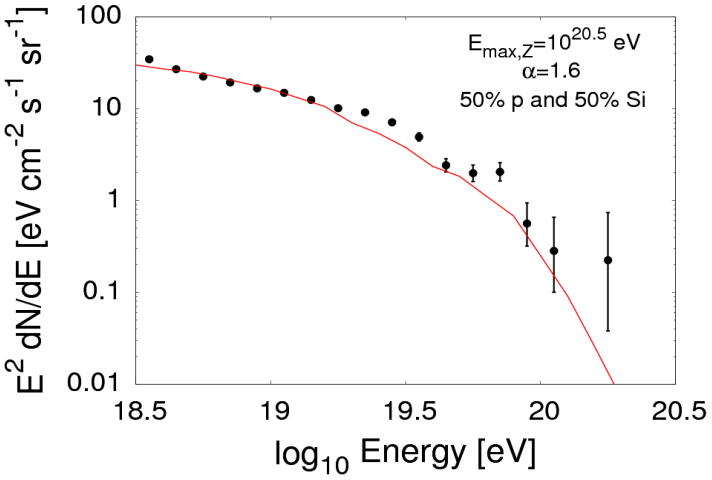
The presence of a ~0.1 nG extragalactic magnetic fields can help improve fits;

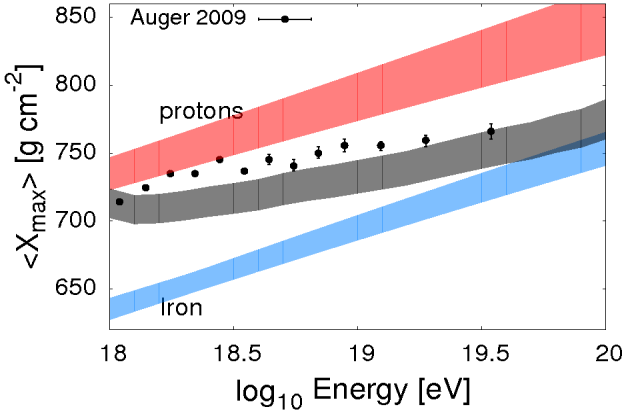
The UHECR photon fraction has some potential to differentiate the composition.

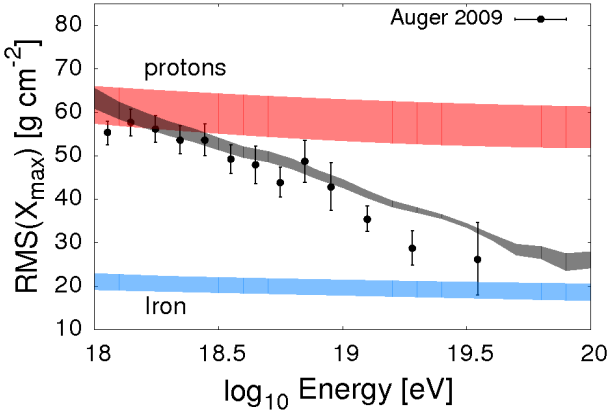
Extra Slides

Mixed Composition Scenario?

50 % protons + 50% Silicon







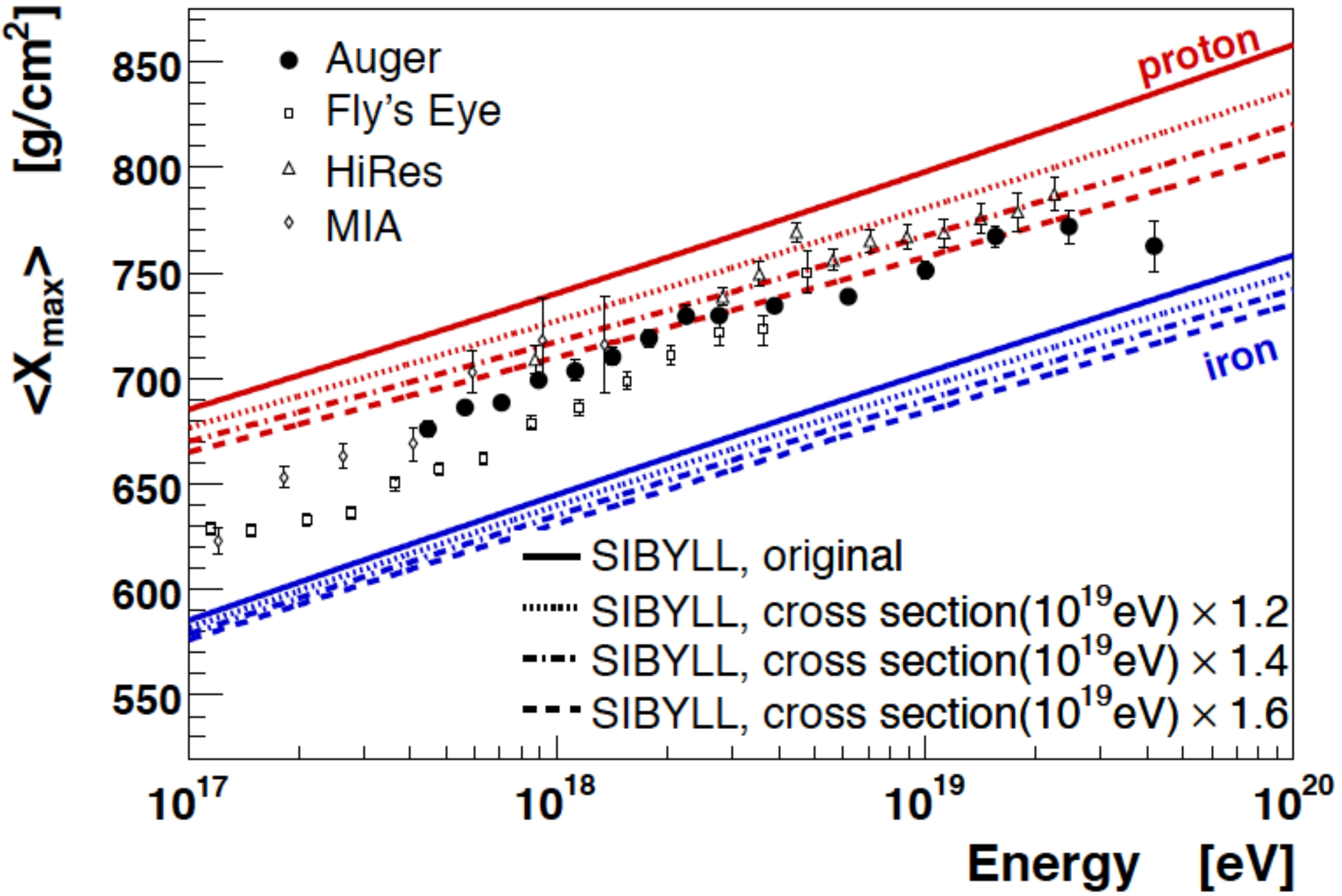
Proton Only Scenario Still Possible?

Change Interaction Properties: — work by Ulrich et al. (Karlsruhe) astro-ph/0906.0418

1) cross-section
2) multiplicity
3) elasticity

Modify these properties with logarithmic scaling from values at 10^{18} eV

Change Interaction Properties: 1) cross-section



A Challenge for this Interpretation- muons