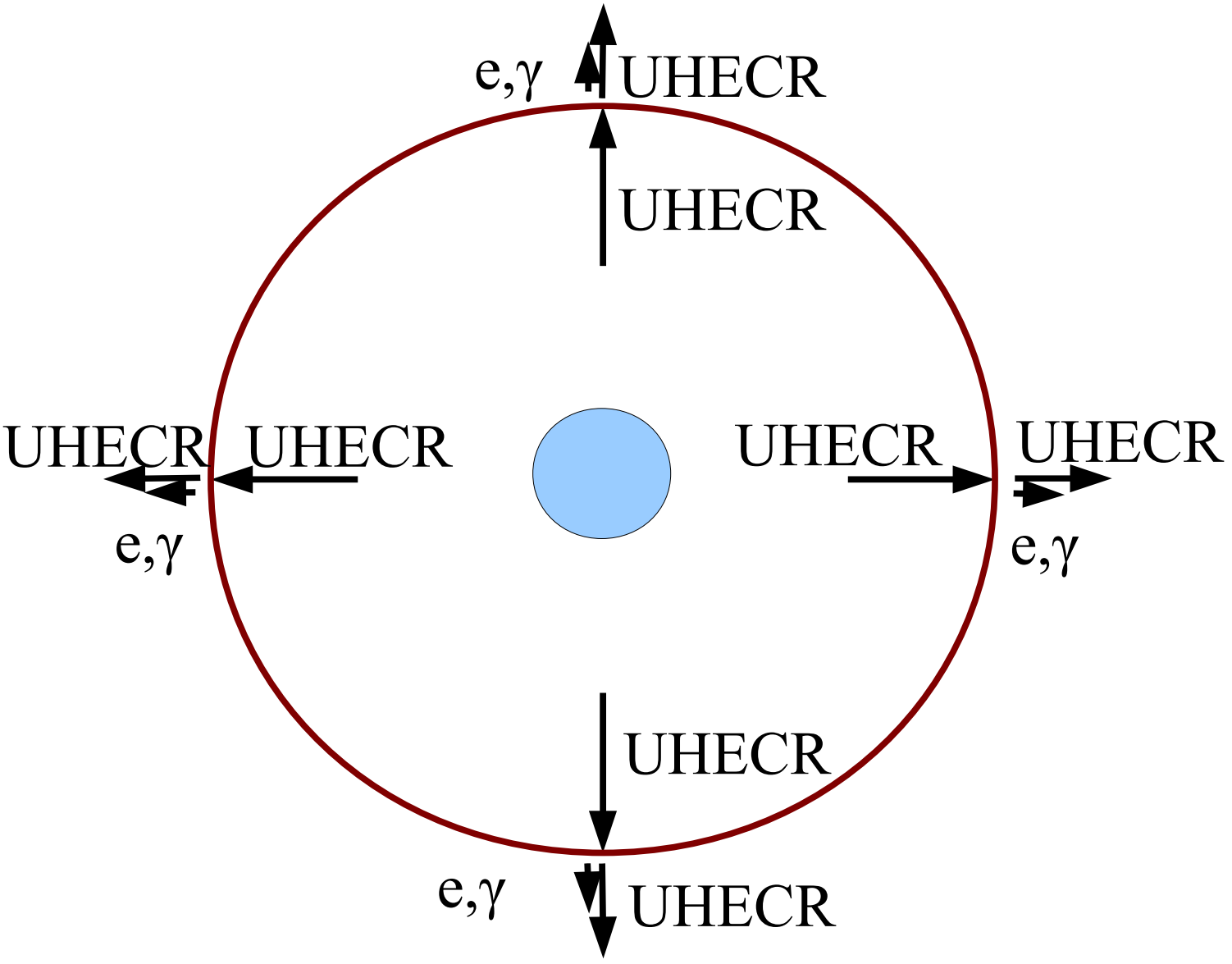
The Origin of Extragalactic Cosmic Rays



Talk(1): Primaries

Spectral + Spatial Arrival Information

1) Auger measurements of the flux- where does extragalactic begin?

2) The angular arrival distribution of UHECR- can we see the sources directly?

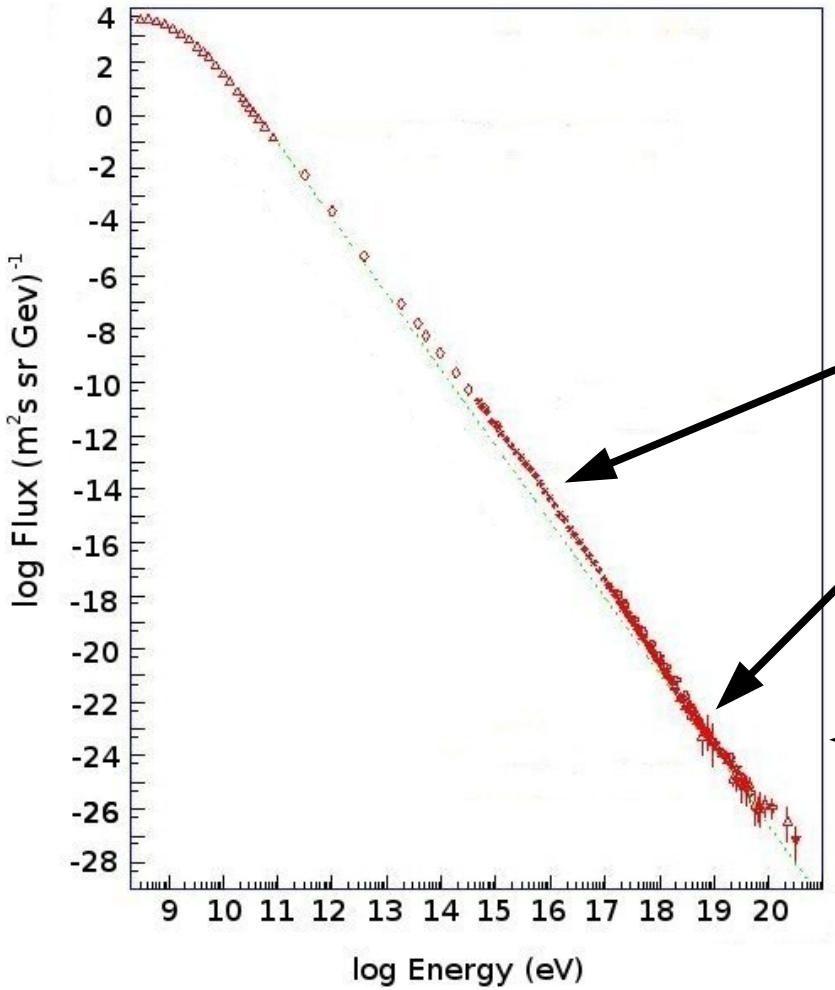
Candidate Sources

3) What composition seems to be arriving?

4) Implications for UHECR source requirements- how to accelerate + not disintegrate?

Part 1:
Spectral + Spacial Distribution

Arriving Flux- Where does extragalactic begin?



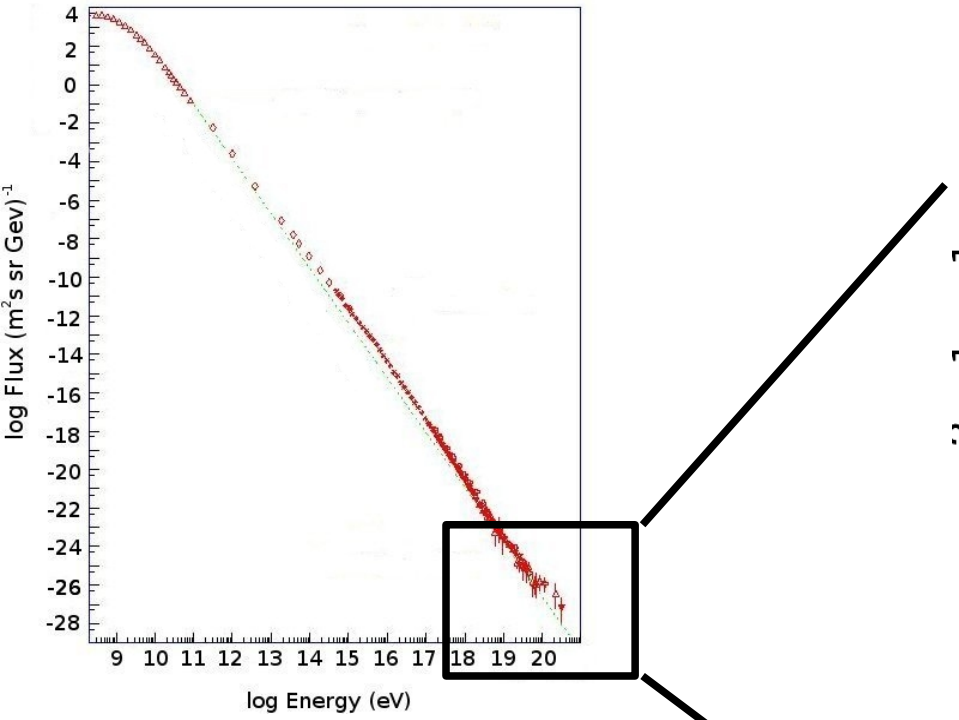
"knee"

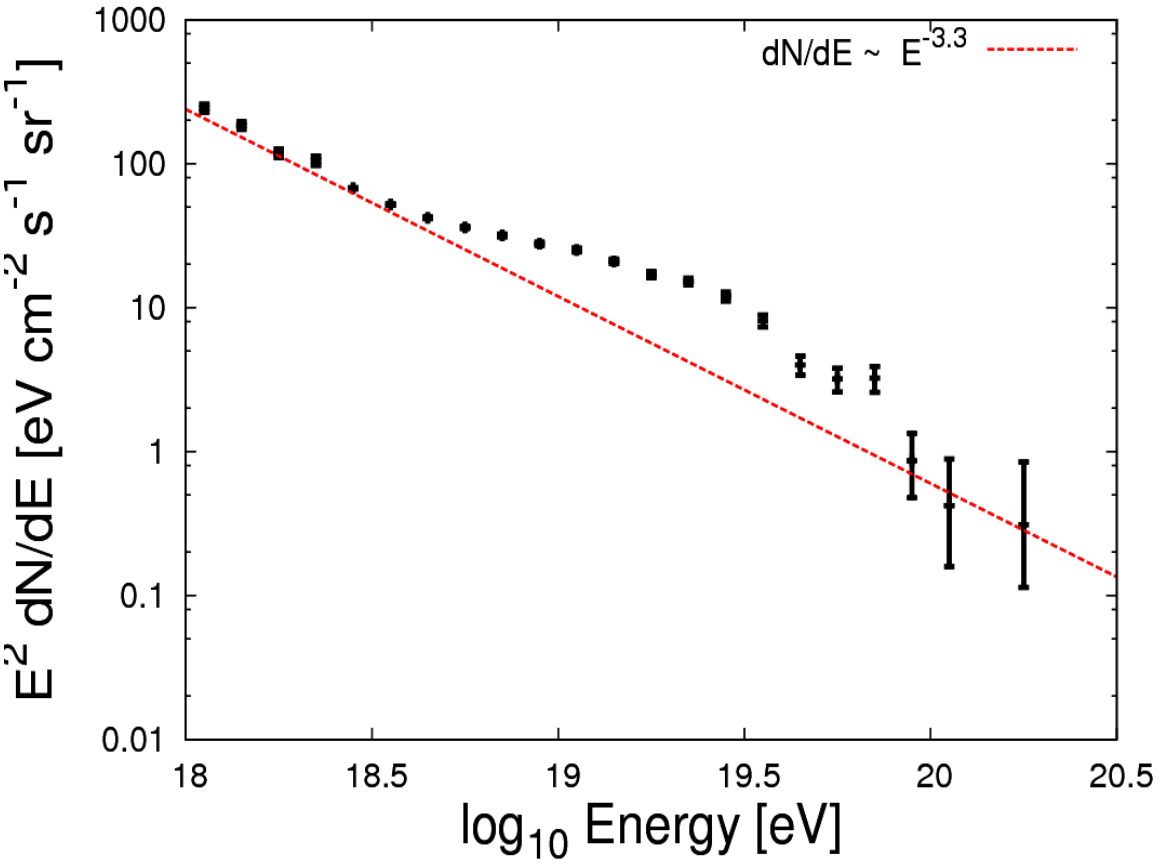
"ankle"

where does extragalactic begin?

.....presumably there should be a signature(s)

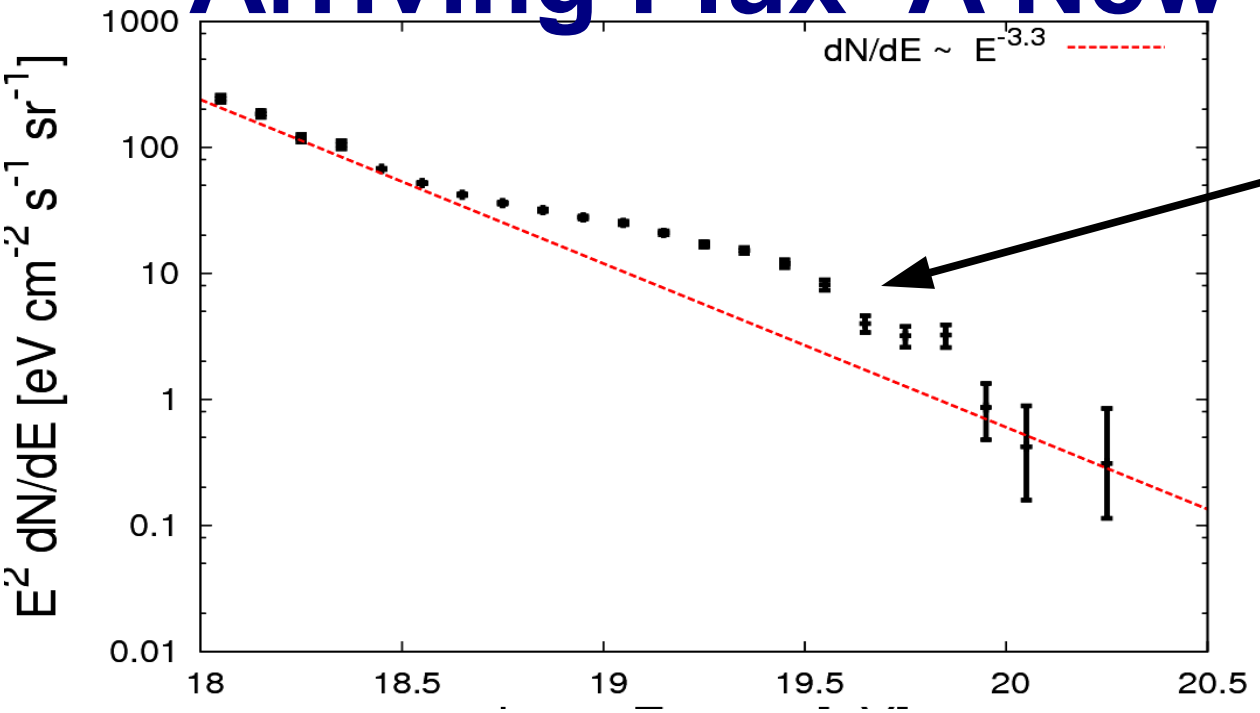
Arriving Flux- A New Component?



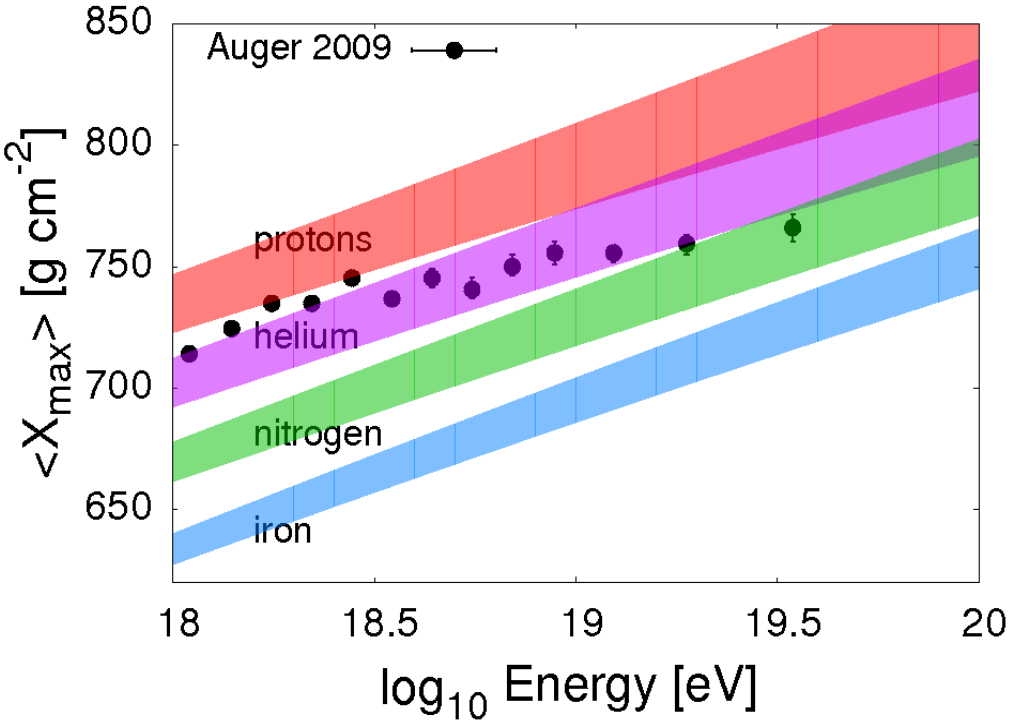


other signatures?

Arriving Flux- A New Component?

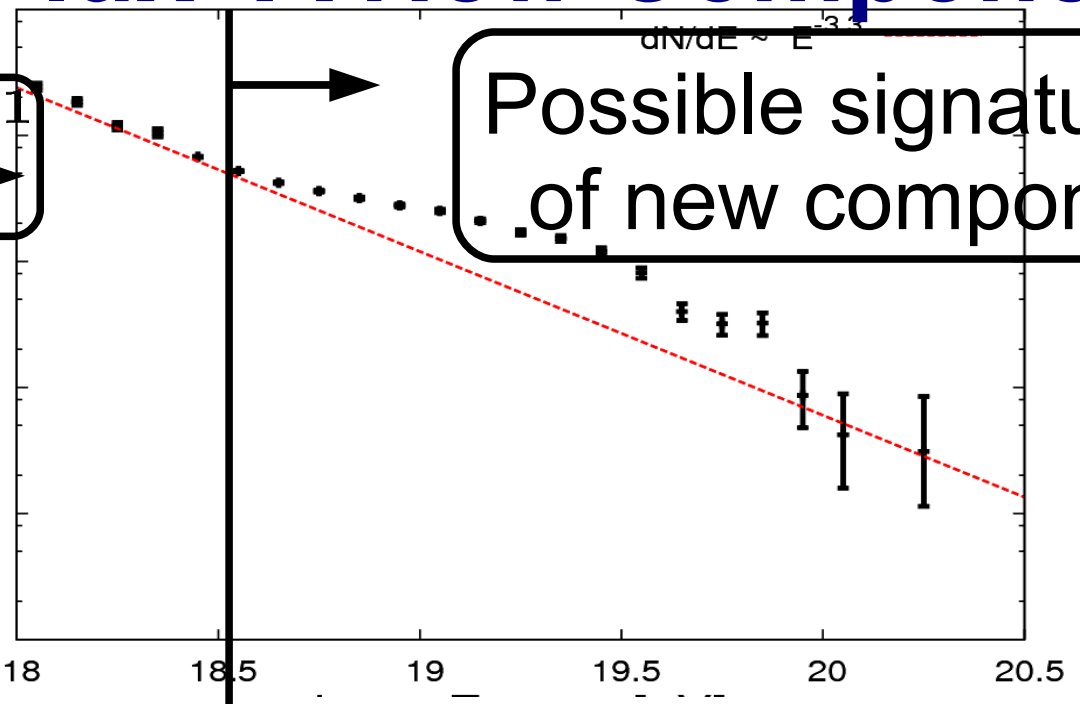


Suppression Feature?

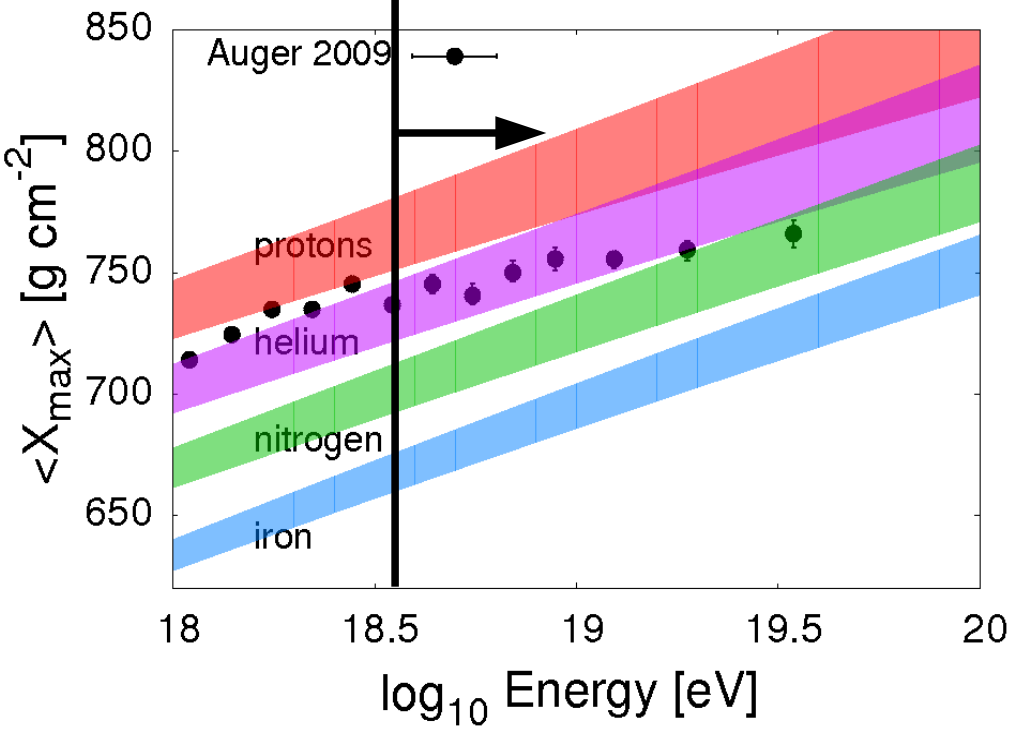


Arriving Flux- A New Component?

$50\ \mathrm{eV\ cm^{-2}\ s^{-1} sr^{-1}}$



Possible signature of new component



Power Density of Sources

Extragalactic Cosmic Rays, E > $10^{18.5}$ eV, have an energy density

$$\left(\frac{4\pi}{c}\right) \times \left(50 \text{ eV cm}^{-2} \text{ s}^{-1}\text{sr}^{-1}\right) \approx 10^{-8} \text{ eV cm}^{-3}$$

$\longrightarrow$ **10^{-20} erg cm^{-3}**

$\longrightarrow$ **10^{54} erg Mpc^{-3}**

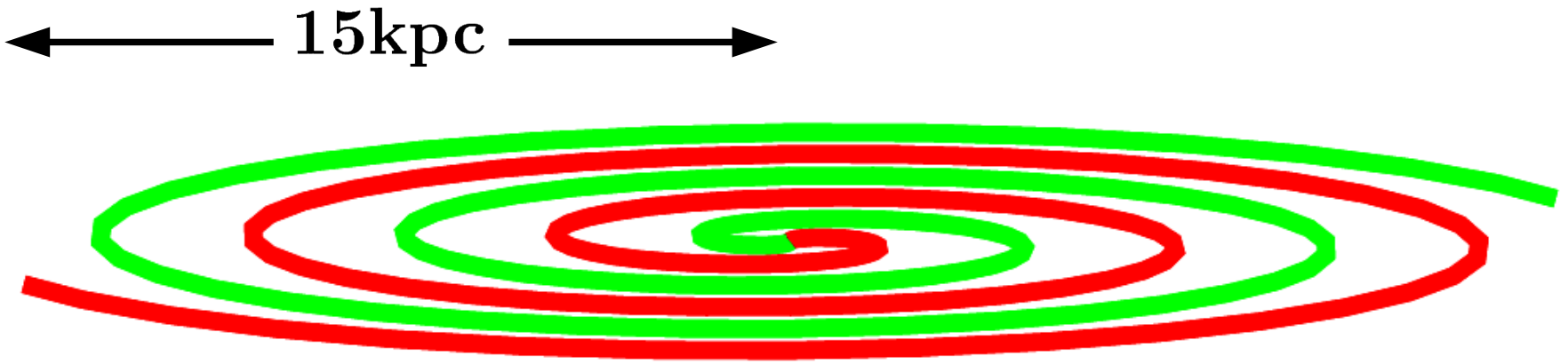
Since these particles have Gyr lifetimes (~10^{16} s)

$$\frac{L_{\rm CR}}{V} \approx 10^{38} \text{ erg Mpc}^{-3} \text{ s}^{-1}$$

From absence of doublets of UHECR events on skymaps,

$$1/V > 10^{-5} \text{ Mpc}^{-3} \longrightarrow L_{\rm CR} < 10^{43} \text{ erg s}^{-1}$$

Arriving Flux- Expected Energy of New Component?



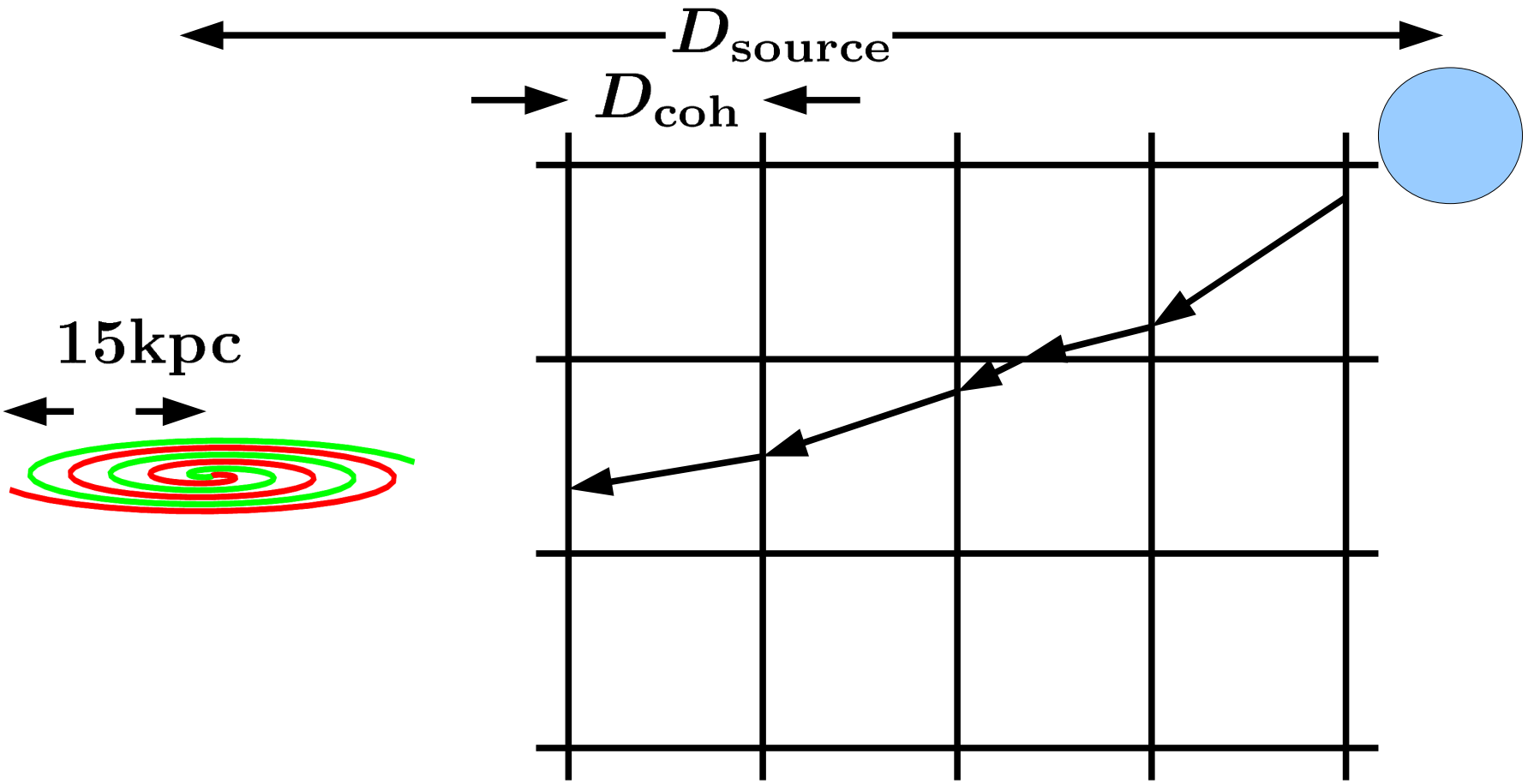
Galactic Bfield Probes:

- Radio Pulsar Rotation/Dispersion Measure
- Radio Zeeman splitting of Hydrogen
- Radio Synchrotron

$$B_{\rm Gal.} \approx 3\mu{\rm G}$$

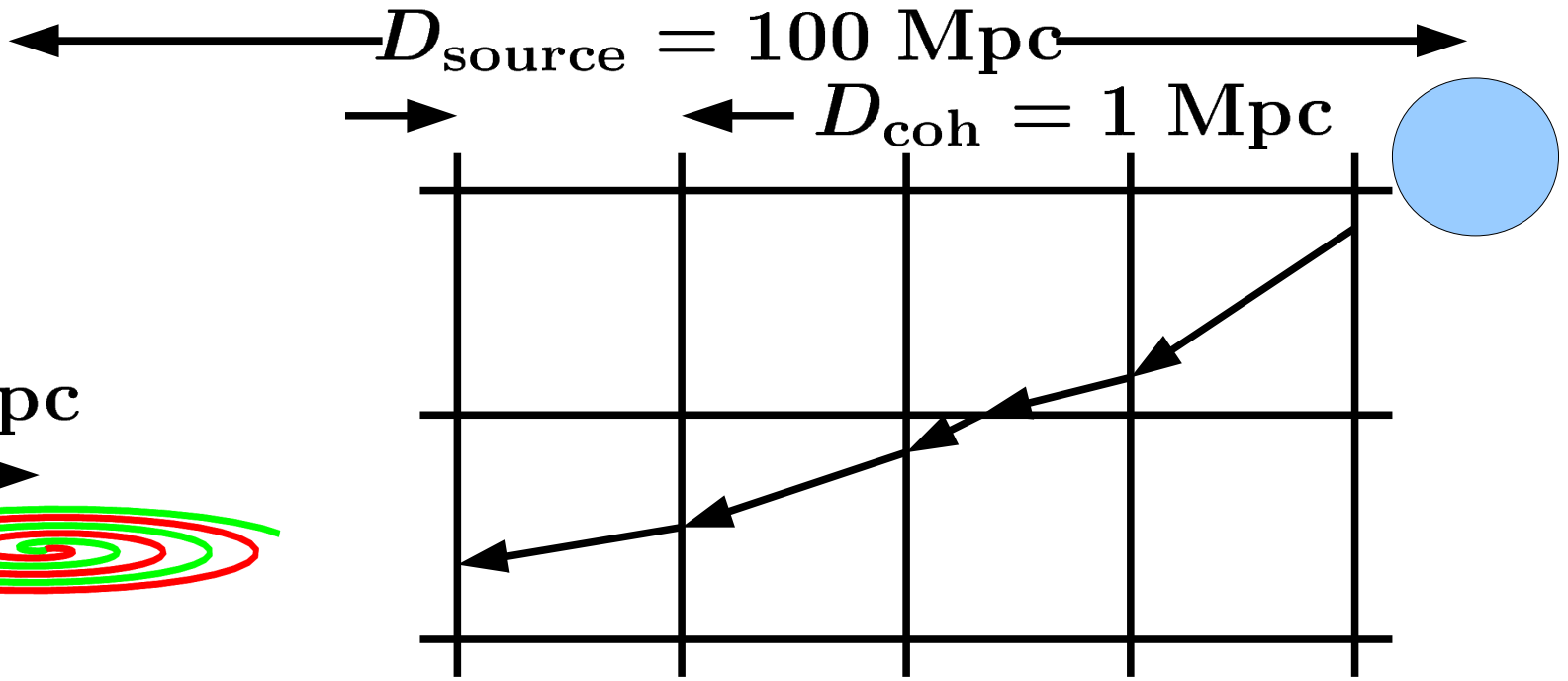
$$R_{\rm Larmor} = 1{\rm kpc}\left(\frac{1}{Z}\right)\left(\frac{E}{10^{18.5}\ {\rm eV}}\right)\left(\frac{3\mu{\rm G}}{B}\right)$$

Those that Leave are Replaced by those that Arrive



$$N_{\rm cells} = \frac{D_{\rm source}}{D_{\rm coh}},\ \Delta\theta_{\rm cell} = \frac{D_{\rm coh}}{R_{\rm Larmor}},\quad \Delta\theta_{\rm tot} \approx N_{\rm cells}^{1/2}\Delta\theta_{\rm cell}$$

Those that Leave are Replaced by those that Arrive



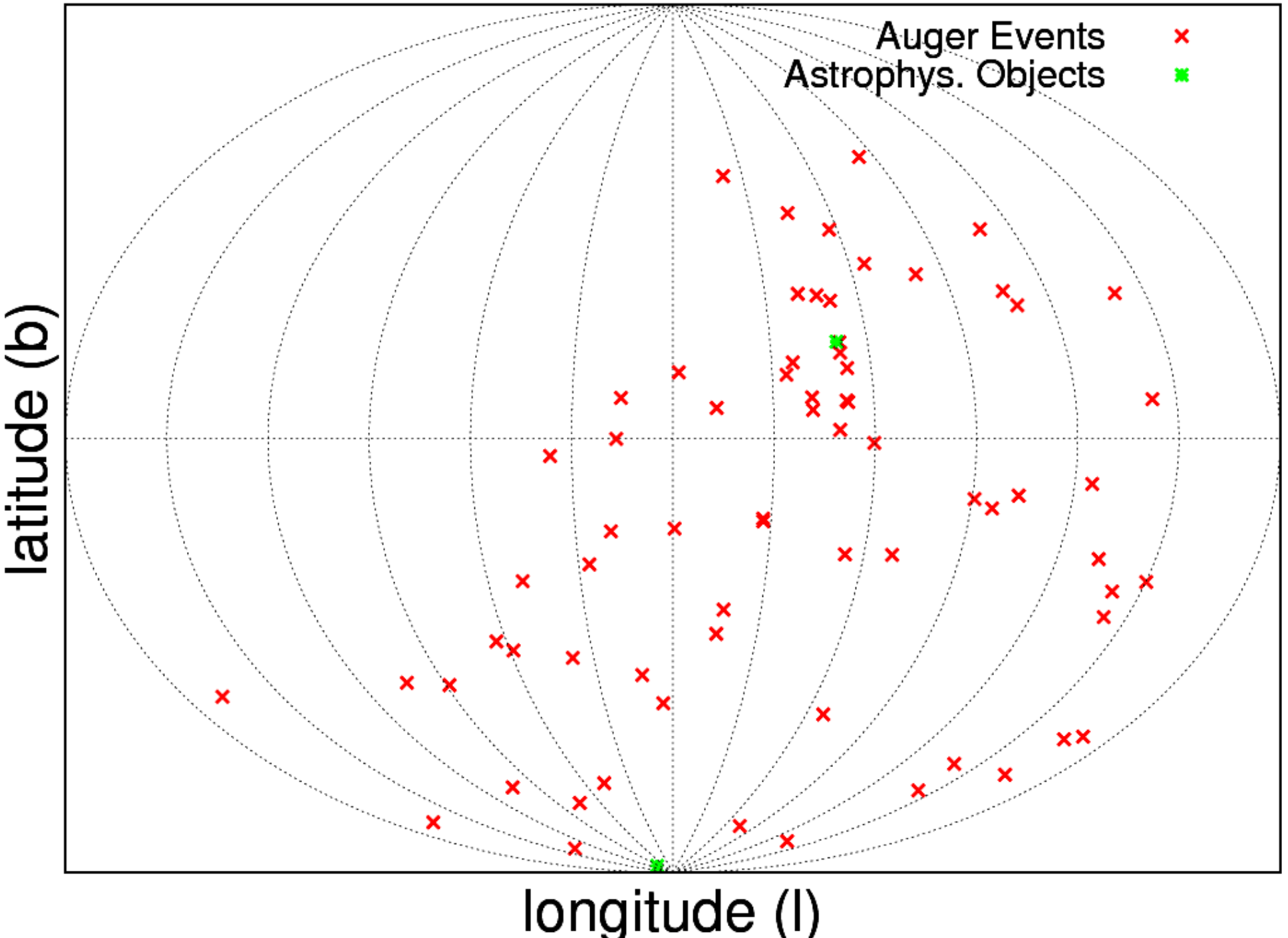
$$R_{\rm Larmor} = 1\ {\rm Gpc}\left(\frac{1}{Z}\right)\left(\frac{E}{10^{20}\ {\rm eV}}\right)\left(\frac{0.1\ {\rm nG}}{B}\right)$$

$$\Delta\theta_{\rm tot} \approx N_{\rm cells}^{1/2}\Delta\theta_{\rm cell} \quad [N_{\rm cells} = 100]$$

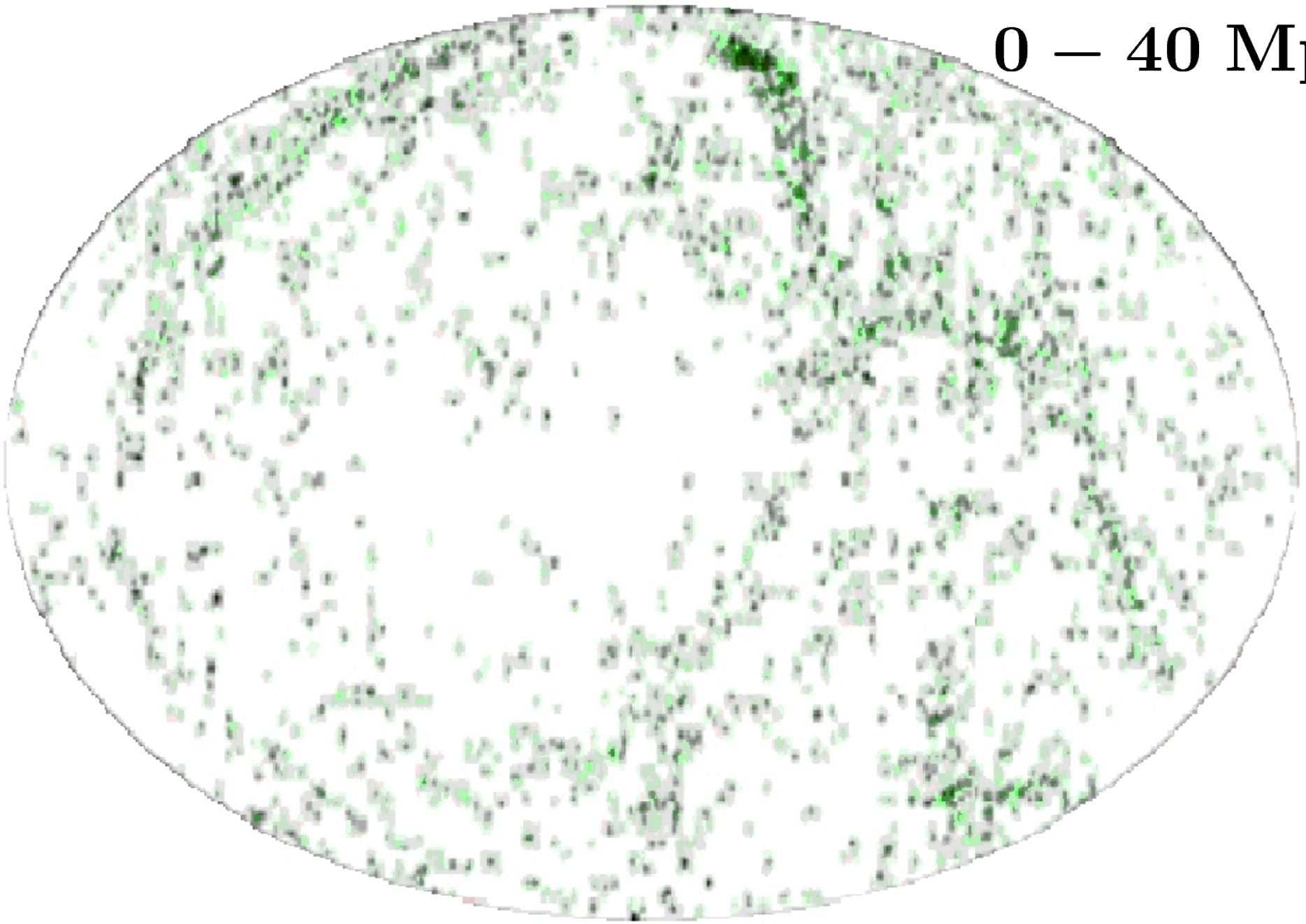
For 10^{20} eV protons: $\Delta\theta_{\rm tot} = 0.01$ rad. (ie. $0.5°$)

For 10^{20} eV iron: $\Delta\theta_{\rm tot} = 0.26$ rad. (ie. $13.0°$)

Can We See UHECR Sources Directly?



Our Local Extragalactic Neighbourhood



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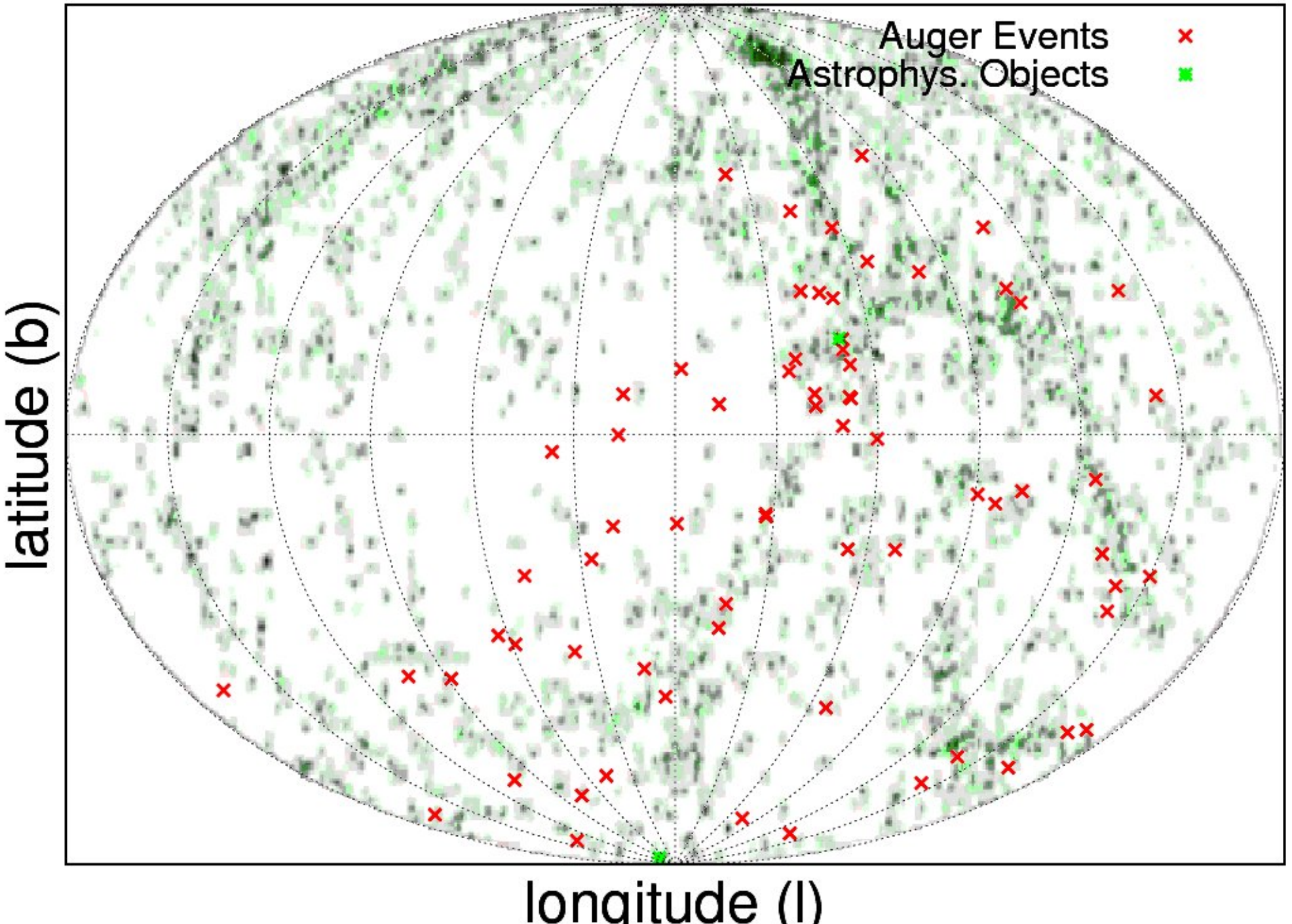
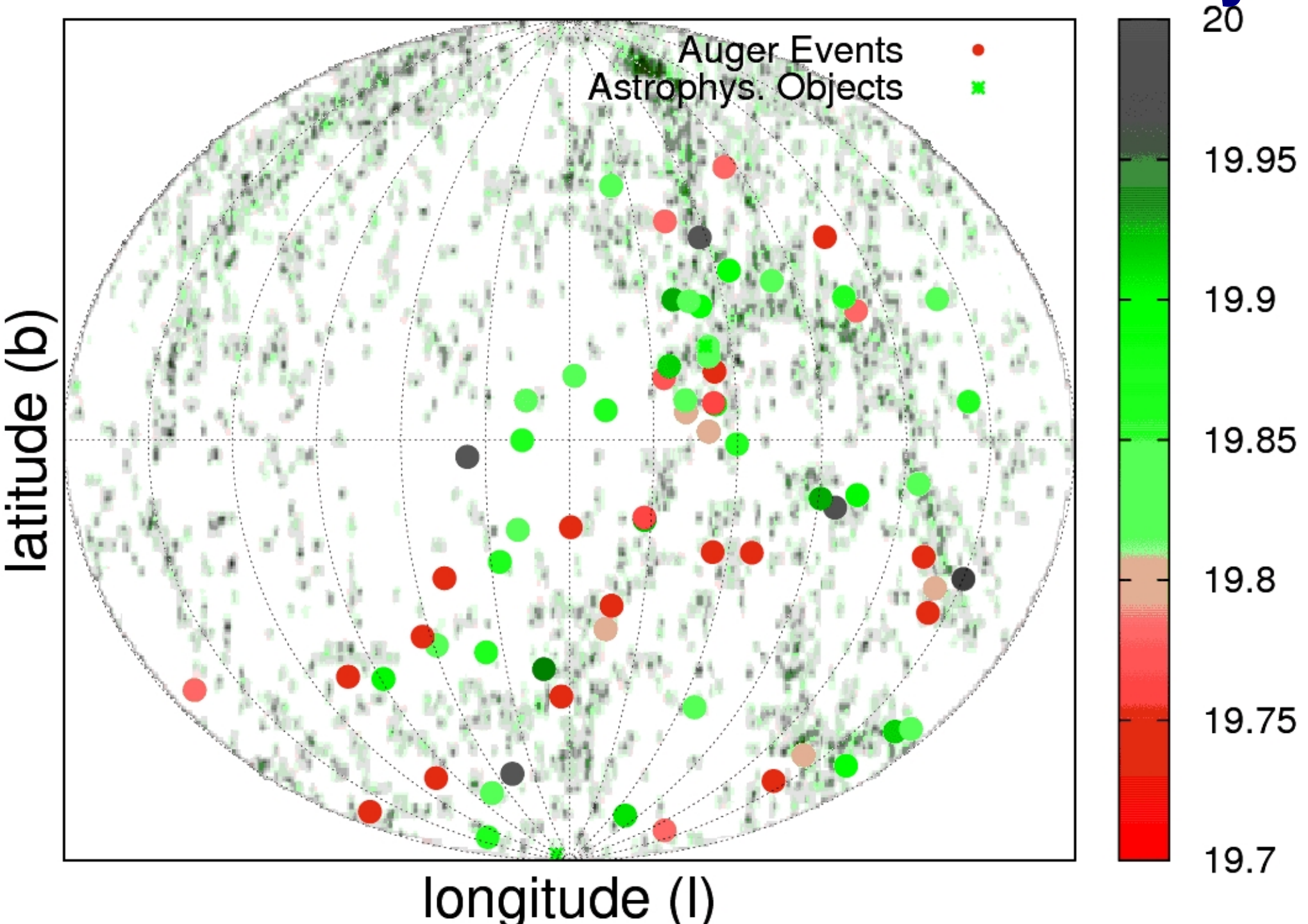
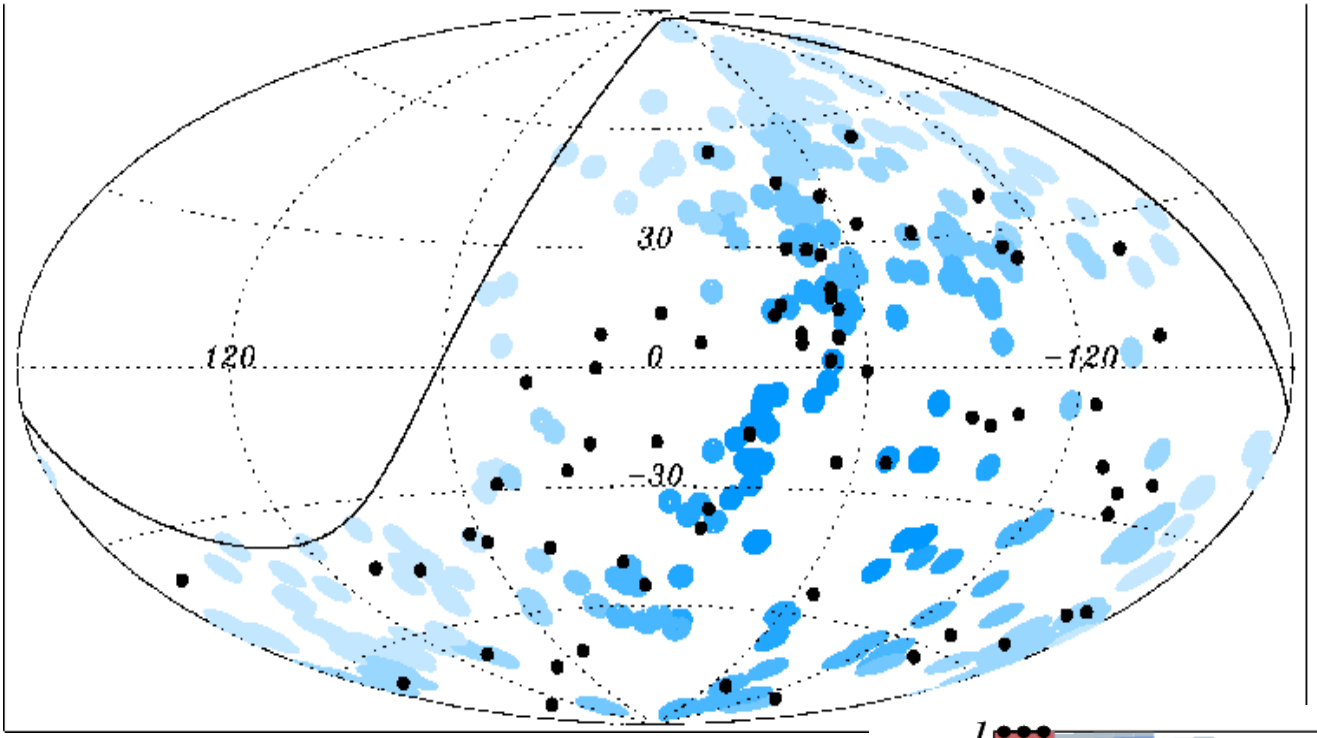


Can We See UHECR Sources Directly?



Can We See UHECR Sources Directly? No....so we resort to statistics!

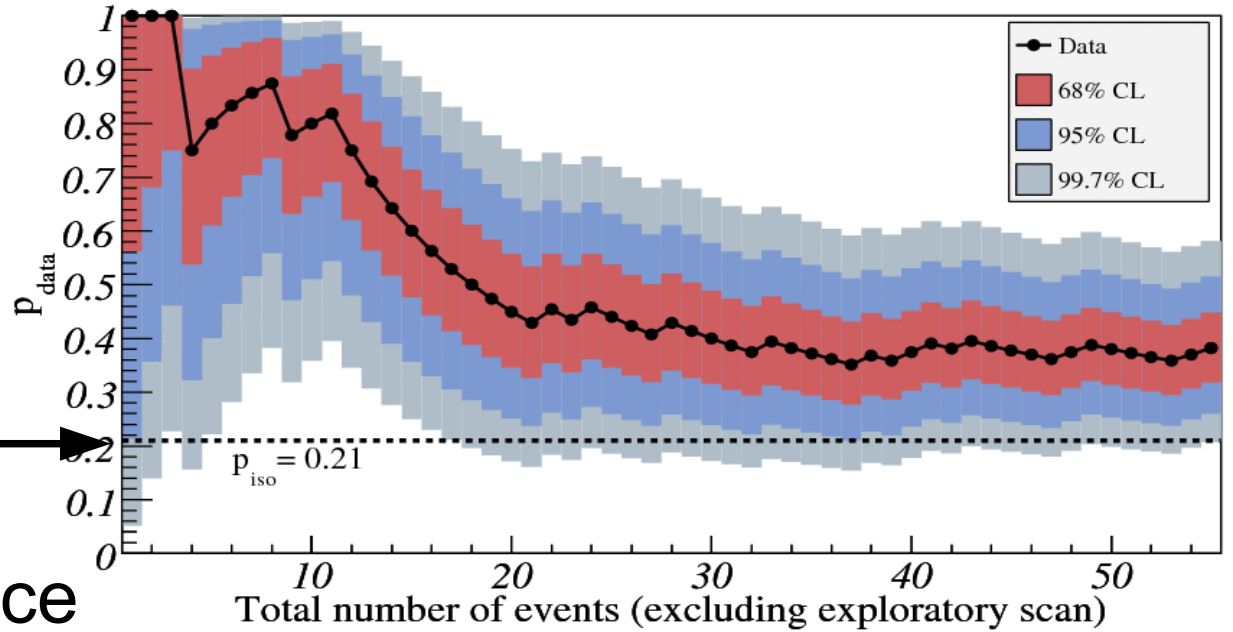


Auger analysis archiv: 1009.1855

292 AGN

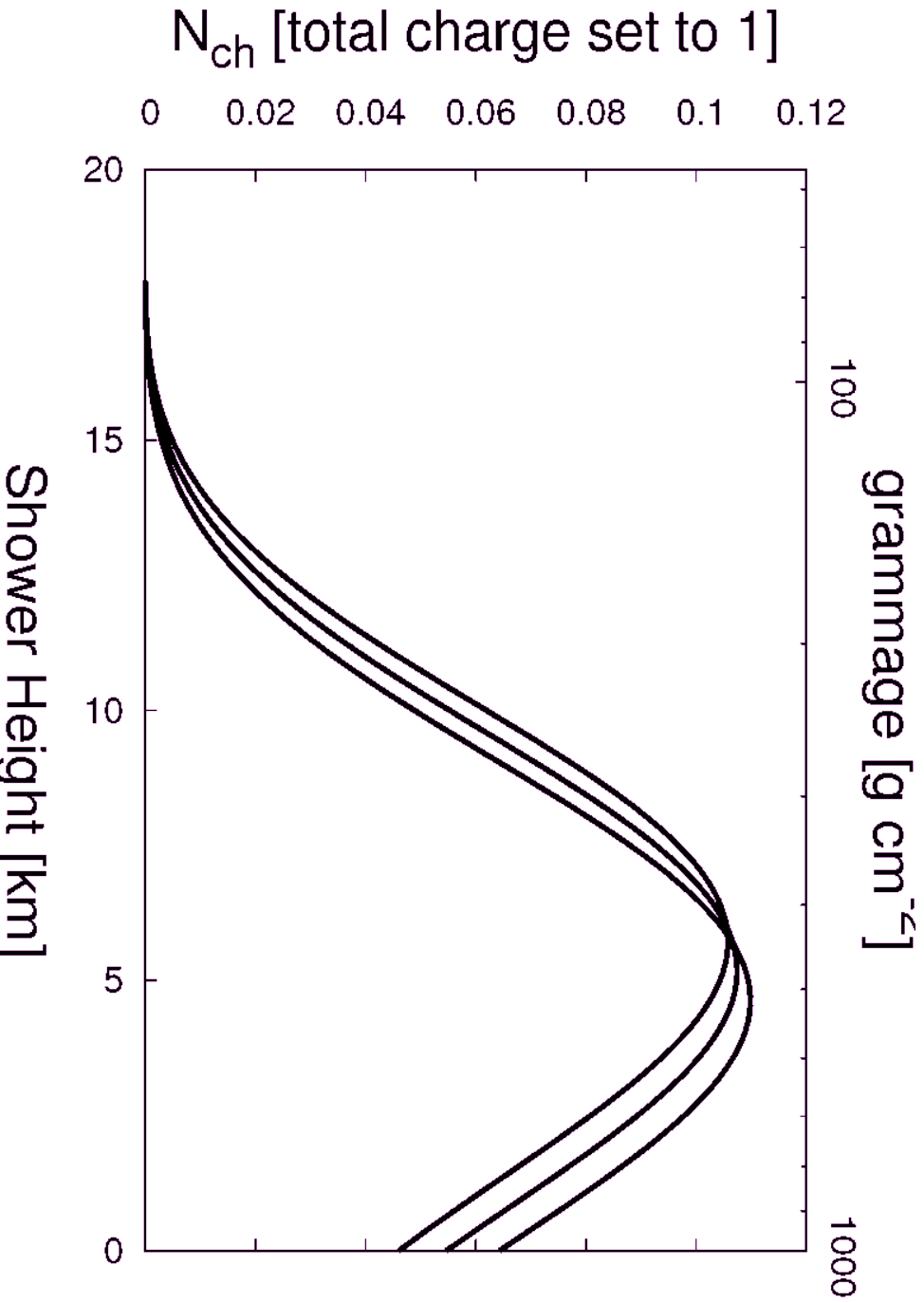
~half the events correlate with an AGN

ie. ~11 events expected to correlate by chance



Part 2:
Candidate Sources

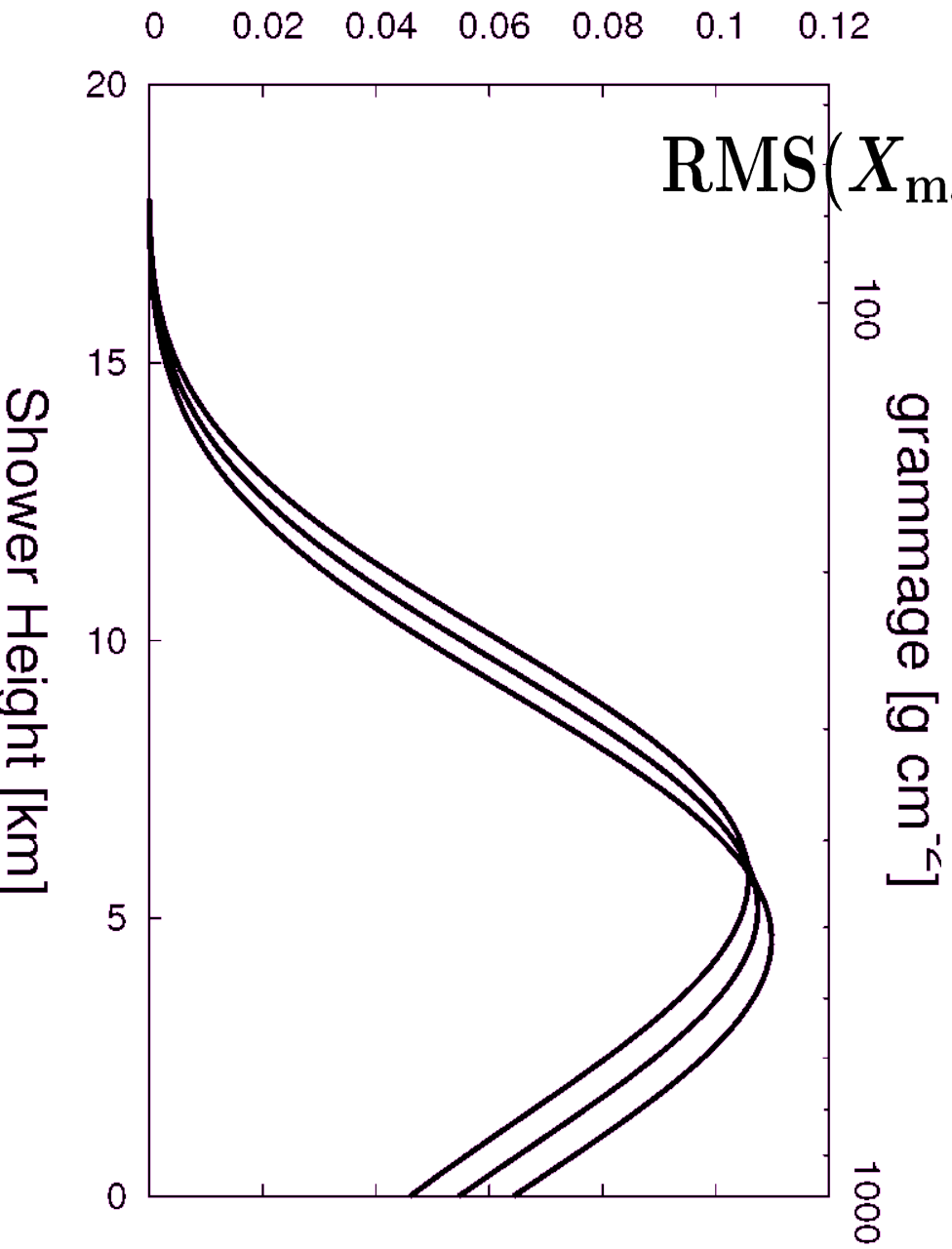
UHECR Air Showers



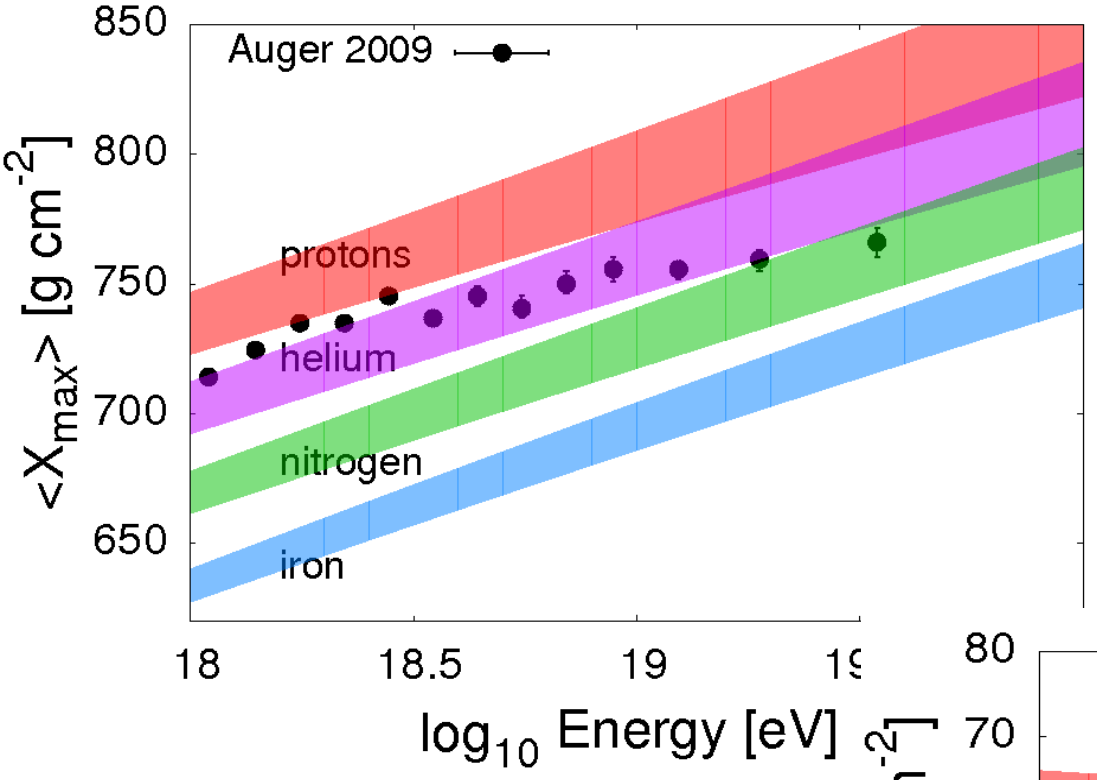
UHECR Air Showers

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

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



Composition Measurements by the PAO

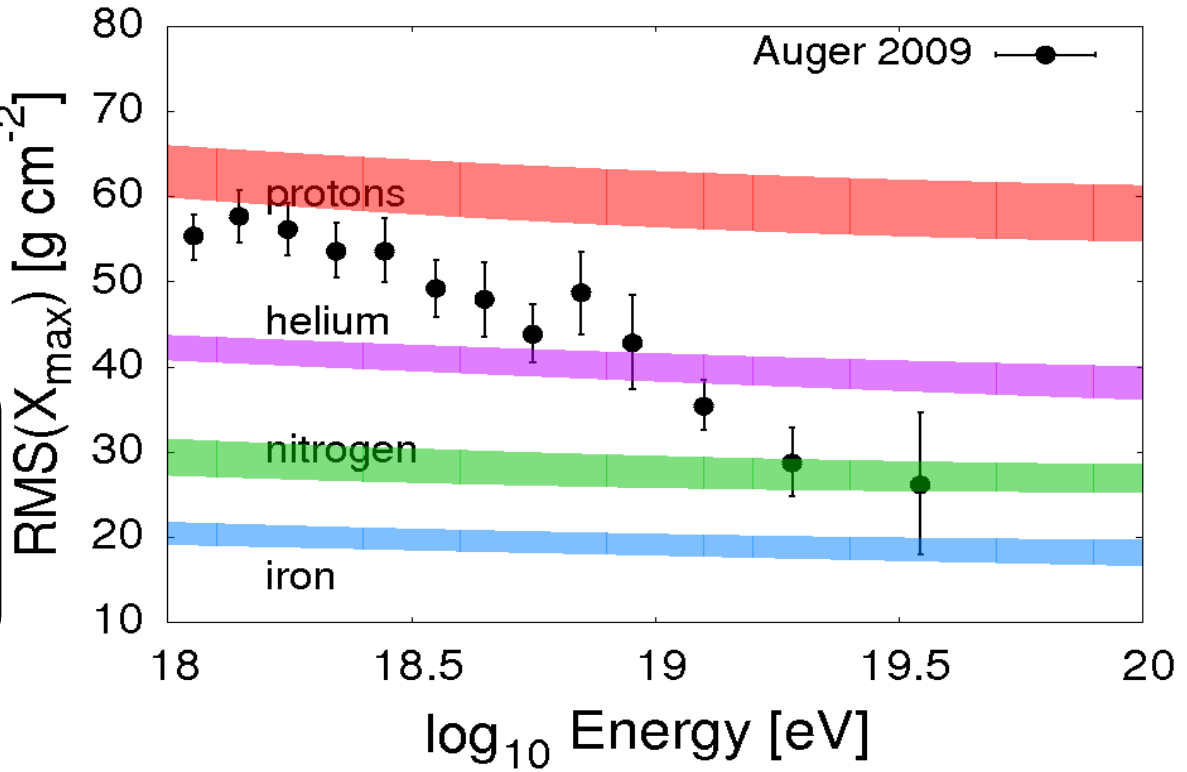


$\leftarrow \langle X_{\mathrm{max}} \rangle$

$$\langle X_{\mathrm{max}} \rangle = \sum_i f_i X_{\mathrm{i,max}}$$

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

$$\mathrm{RMS}^2_{X_{\mathrm{max}}} = \sum_i f_i \mathrm{RMS}^2_{X_{\mathrm{i,max}}} + \sum_i f_i \left(X_{\mathrm{i,max}} - \langle X_{\mathrm{max}} \rangle \right)^2$$



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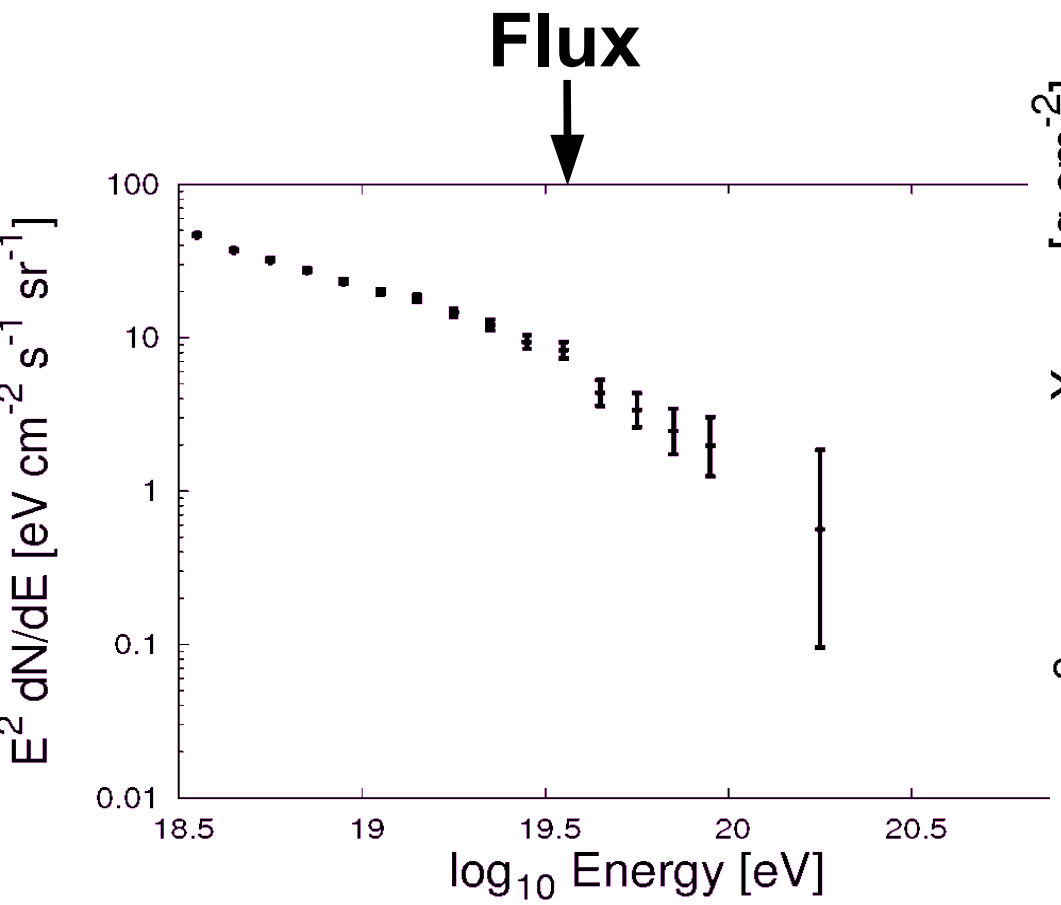
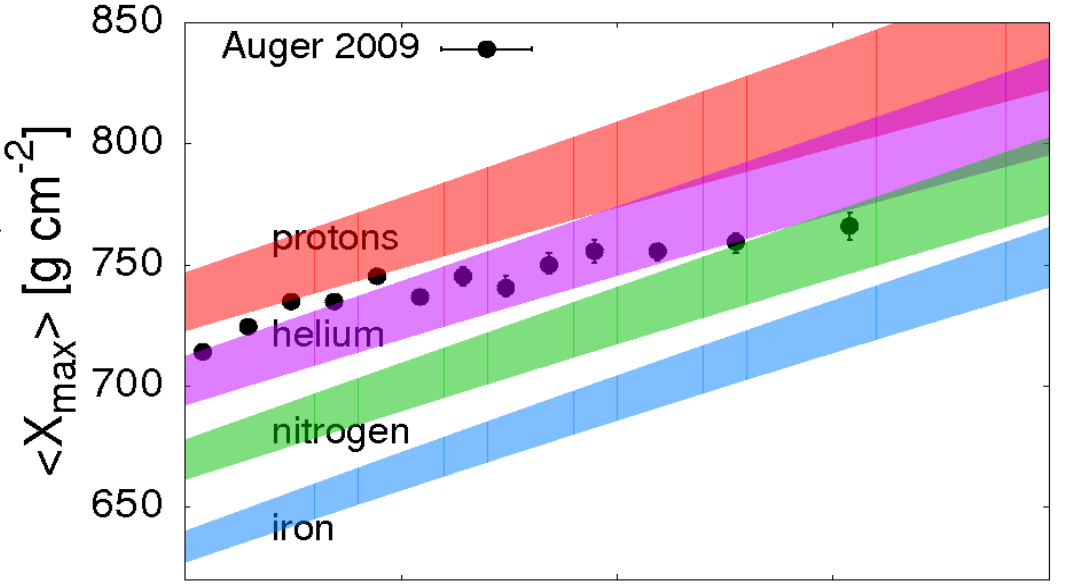
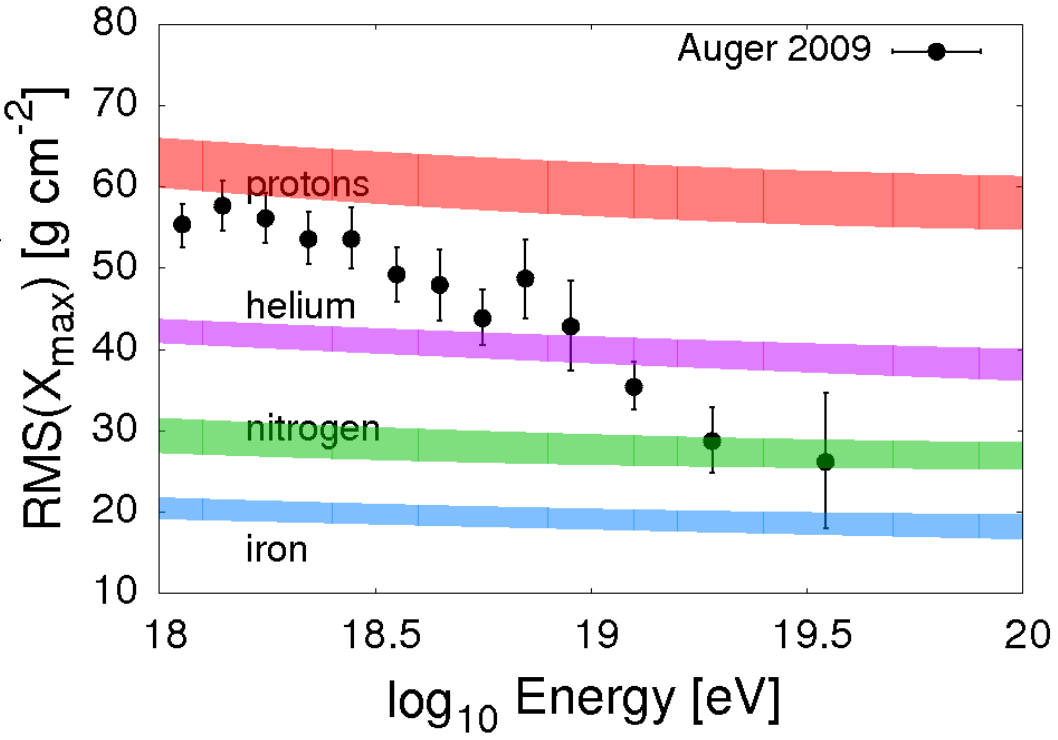
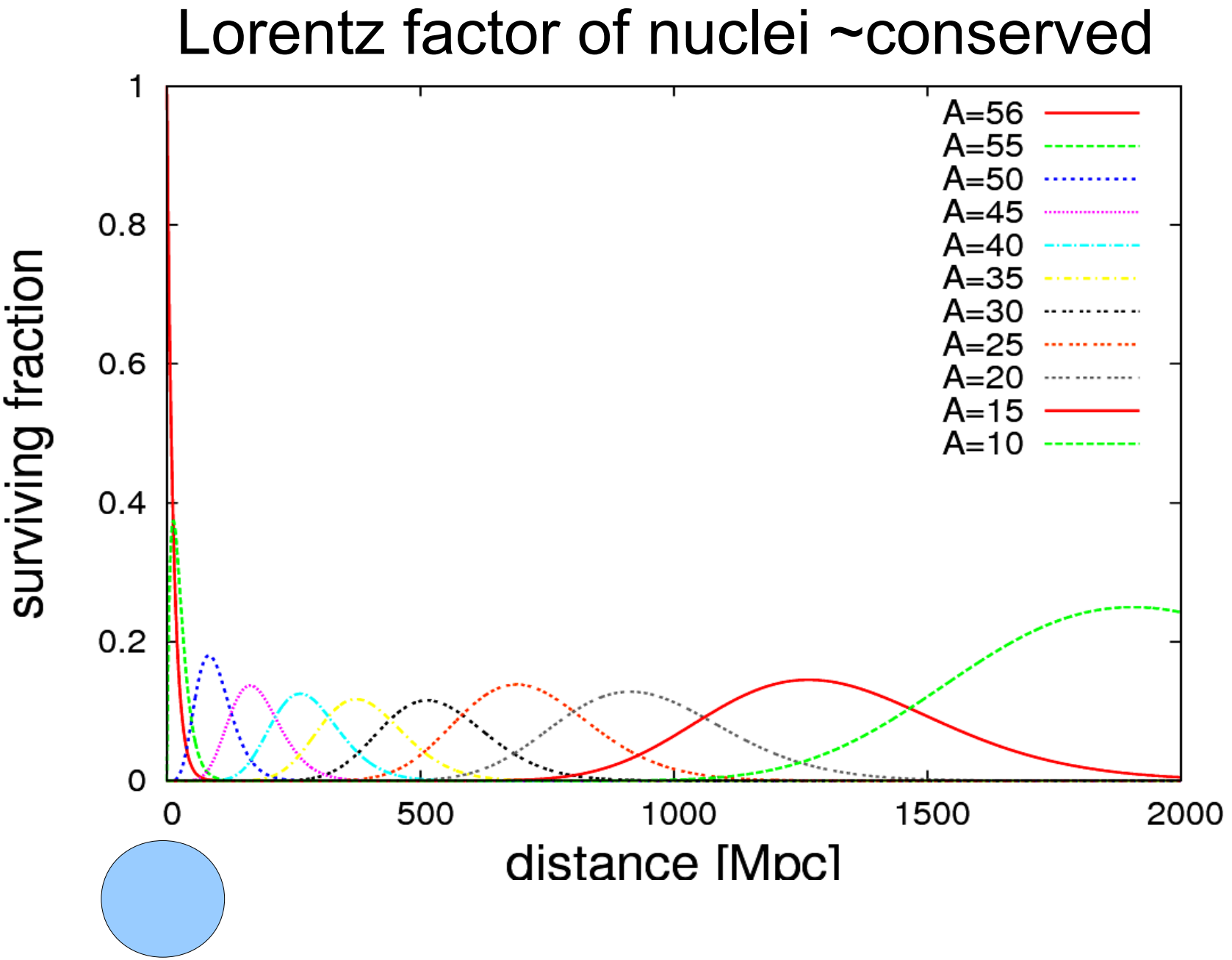




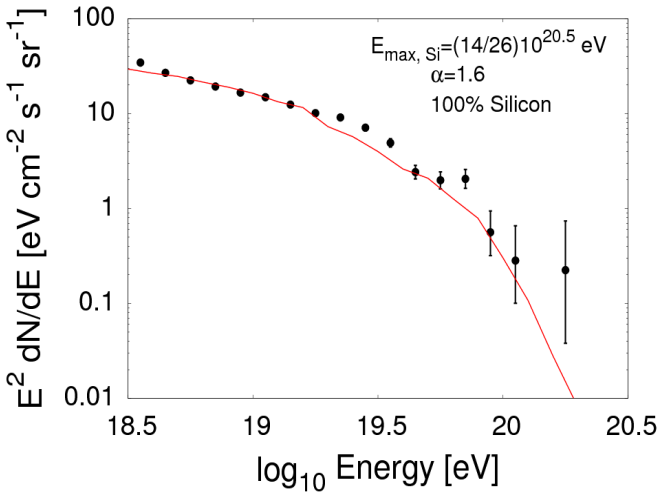


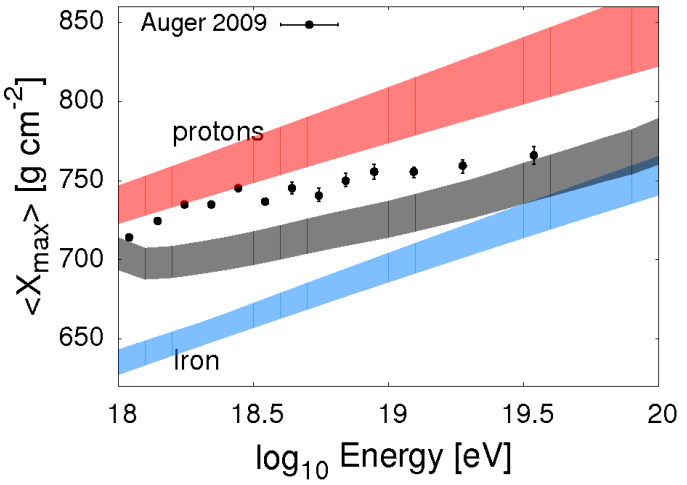
Nuclei Transmutation Away from their Source

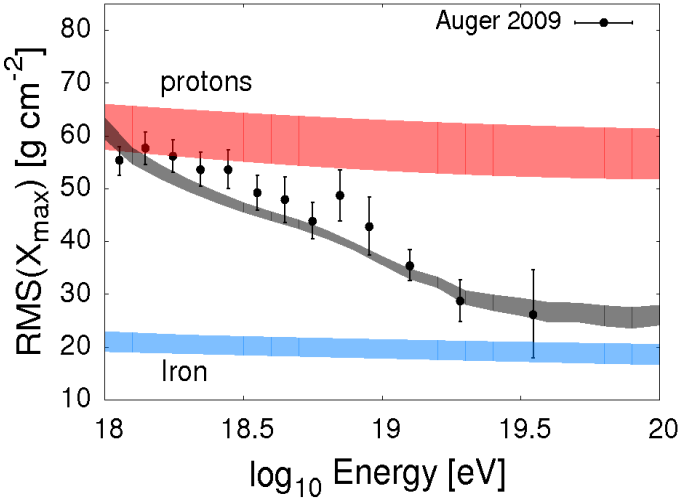


Nuclei Propagation: Undoing Effects of Transmutation

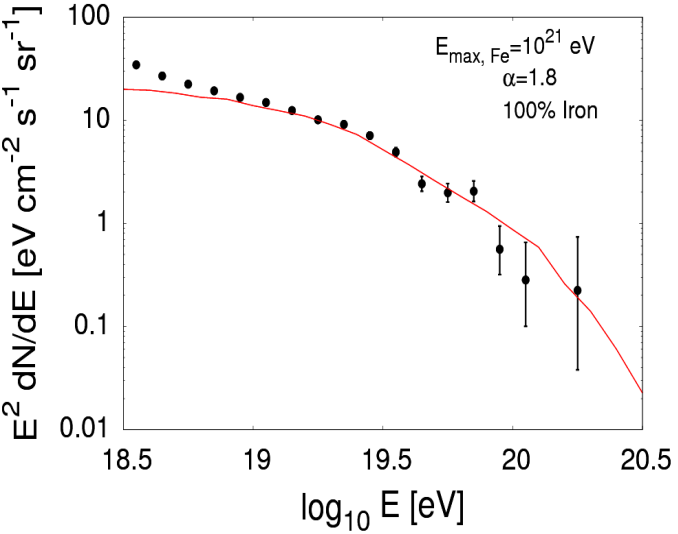
Silicon only?

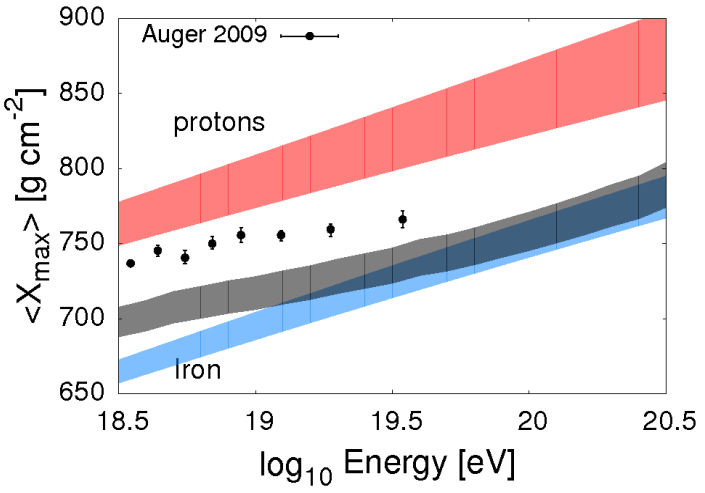


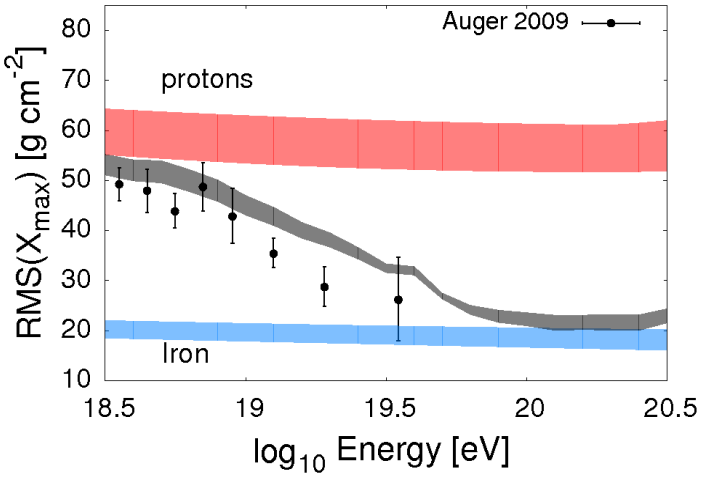




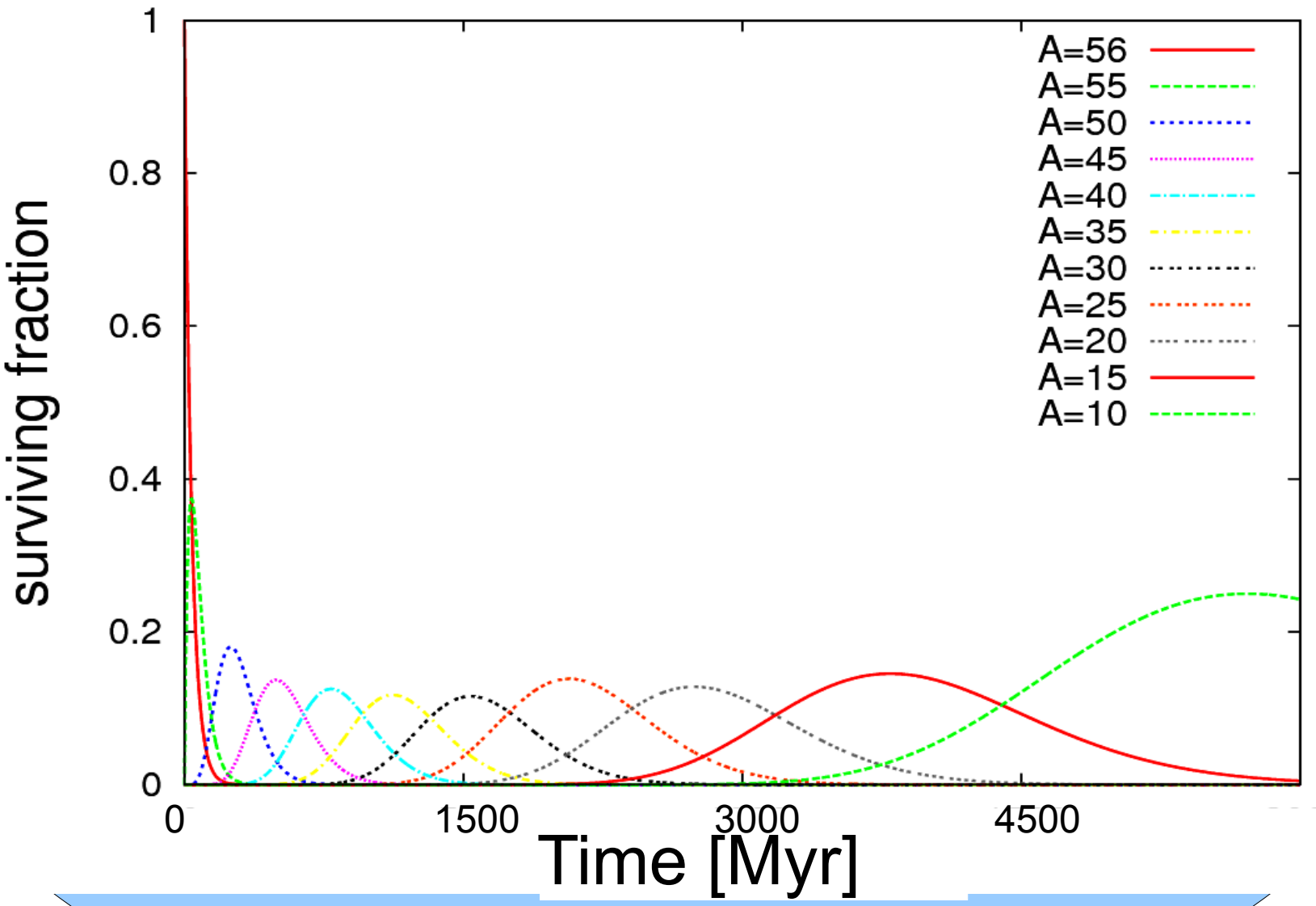
Iron only?







Nuclei Transmutation Within their Source



IMPLICATIONS for UHECR Sources

$$f = \frac{t_{\rm trap}}{t_{\rm int.}^{{\rm CR}\gamma}}$$

$$t_{\rm int.}^{{\rm CR}\gamma} \approx \frac{1}{n_\gamma \sigma_{{\rm CR}\gamma} c}$$

$$n_\gamma = \frac{L_\gamma}{c 4\pi R^2 \epsilon_\gamma}$$

$$t_{\rm trap} \approx \frac{R^2}{2D} = \frac{3R^2}{2R_{\rm Larmor}}$$

$$f^{{\rm CR}\gamma} = \frac{3 L_\gamma \sigma_{{\rm CR}\gamma} Z B}{8\pi \epsilon_\gamma E_{\rm CR}}$$

IMPLICATIONS for UHECR Sources

$$f^{\mathrm{CR}\gamma} = \frac{3 L_\gamma \sigma_{\mathrm{CR}\gamma} Z B}{8\pi \epsilon_\gamma E_{\mathrm{CR}}} = \frac{s_1}{s_2}$$

Photo-disintegration threshold:

$2E_{\mathrm{CR}}\epsilon_\gamma > A m_p c^2 E_{\mathrm{bind.}}$, where $m_p c^2 E_{\mathrm{bind.}} = 10^{16}\ \mathrm{eV}^2$

Since,

$$L_\gamma[10^{44}\mathrm{erg\ s^{-1}}] = 2 \times 10^{45}\mathrm{eV\ cm^{-1}}$$

$$\sigma_{\mathrm{CR}\gamma}[\mathrm{A\ mb}] = \mathrm{A} \times 10^{-27}\ \mathrm{cm^2}$$

$$B[10^{-4}\ \mathrm{G}] = 3 \times 10^{-2}\ \mathrm{eV\ cm^{-1}}$$

$\frac{L_\gamma \sigma_{\mathrm{CR}\gamma} B}{A} = 6 \times 10^{16}\ \mathrm{eV}^2$, ergo.... $f^{\mathrm{CR}\gamma} = 50\frac{Z}{26}$

IMPLICATIONS for UHECR Sources

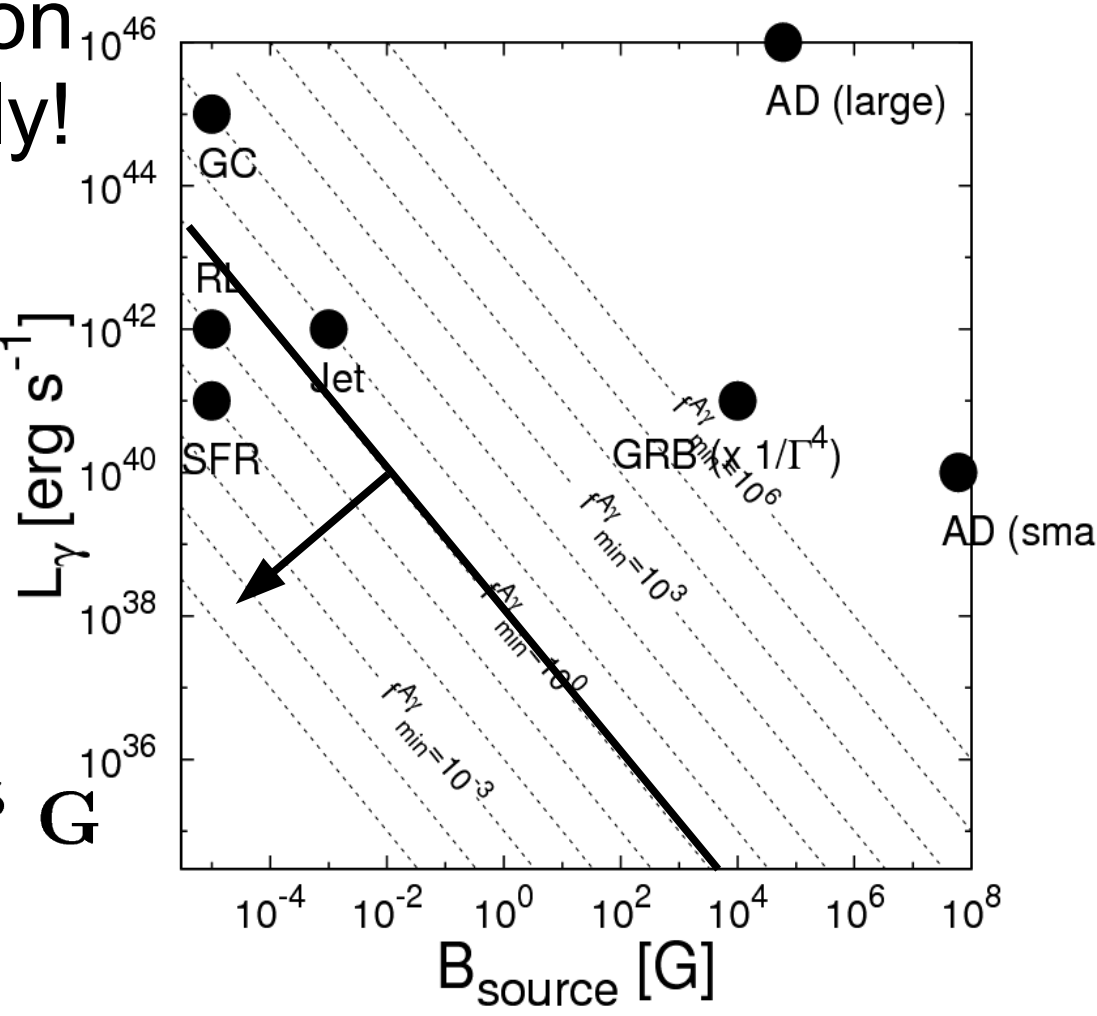
Since, $$\frac{L_\gamma^{\rm Edd.}\sigma_{{\rm CR}\gamma}B^{\rm Edd.}}{A} = 4\times10^{23}\left(\frac{M}{M_\odot}\right)^{1/2}\ {\rm eV}^2$$

Only heavily sub-Eddington power objects need apply!

IF magnetic + photon luminosity are in equipartition:

$$L_\gamma \approx \beta R^2 B^2$$

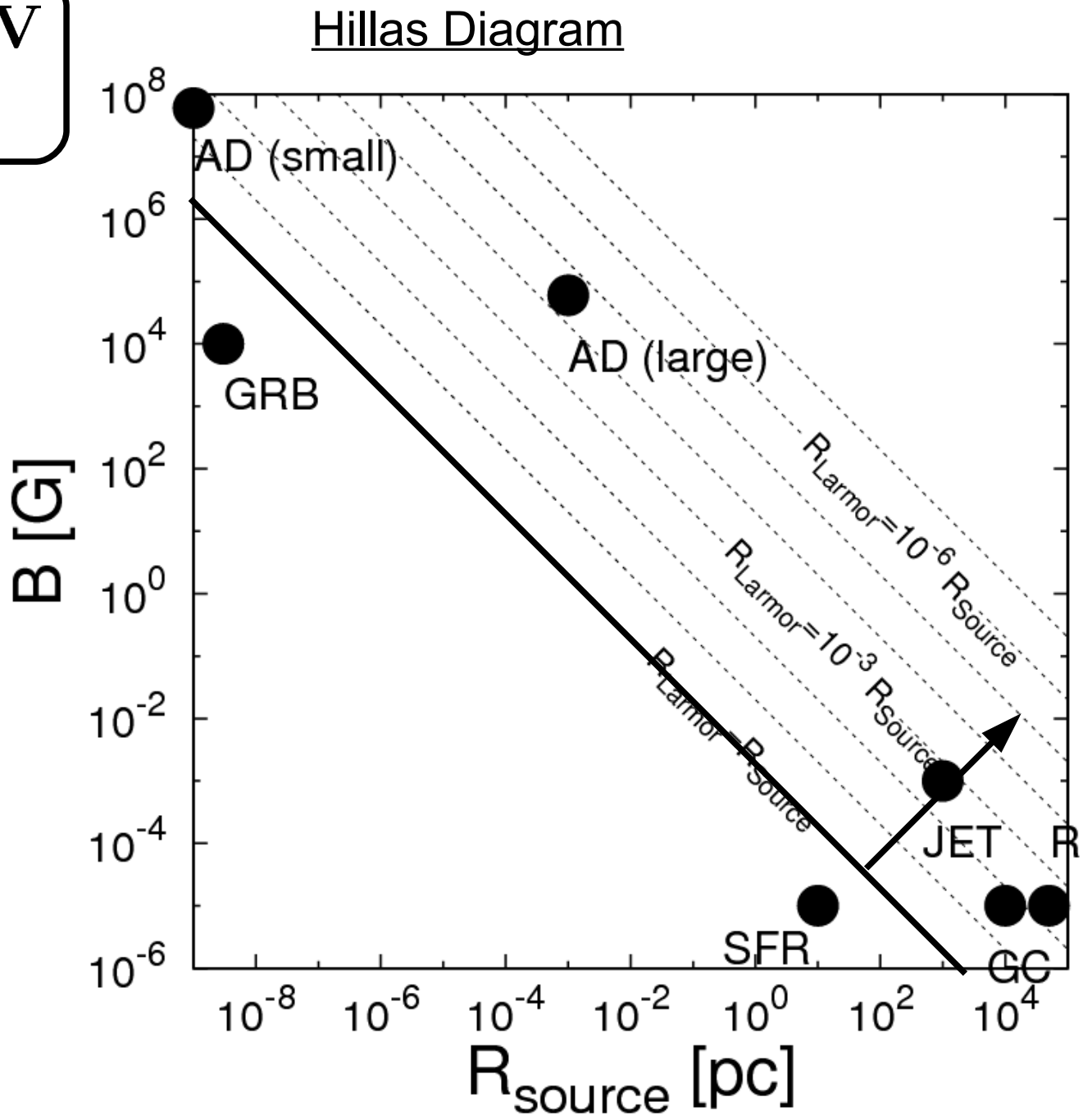
Requiring, $B < 4\times10^{-5}$ G to ensure safe passage.



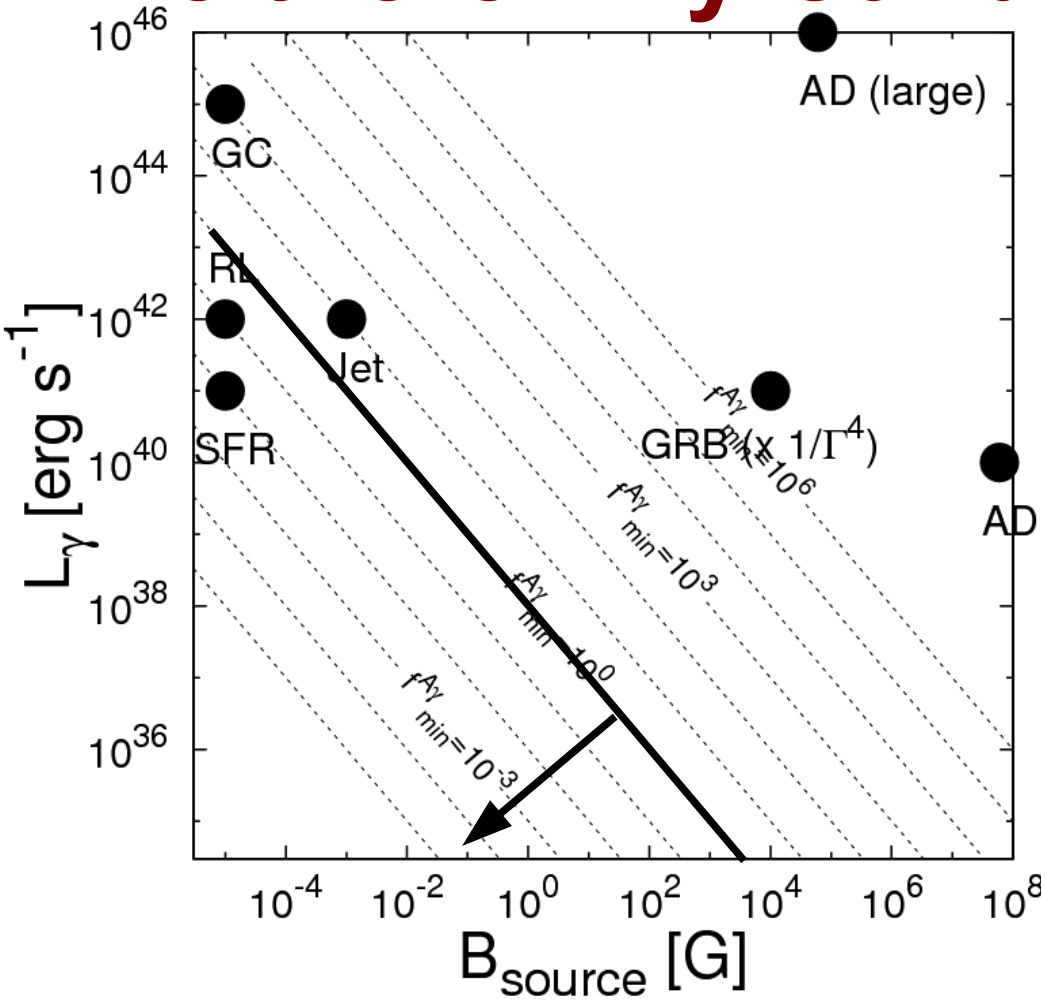
→ OVERALL MESSAGE: Compact Sources Disfavoured

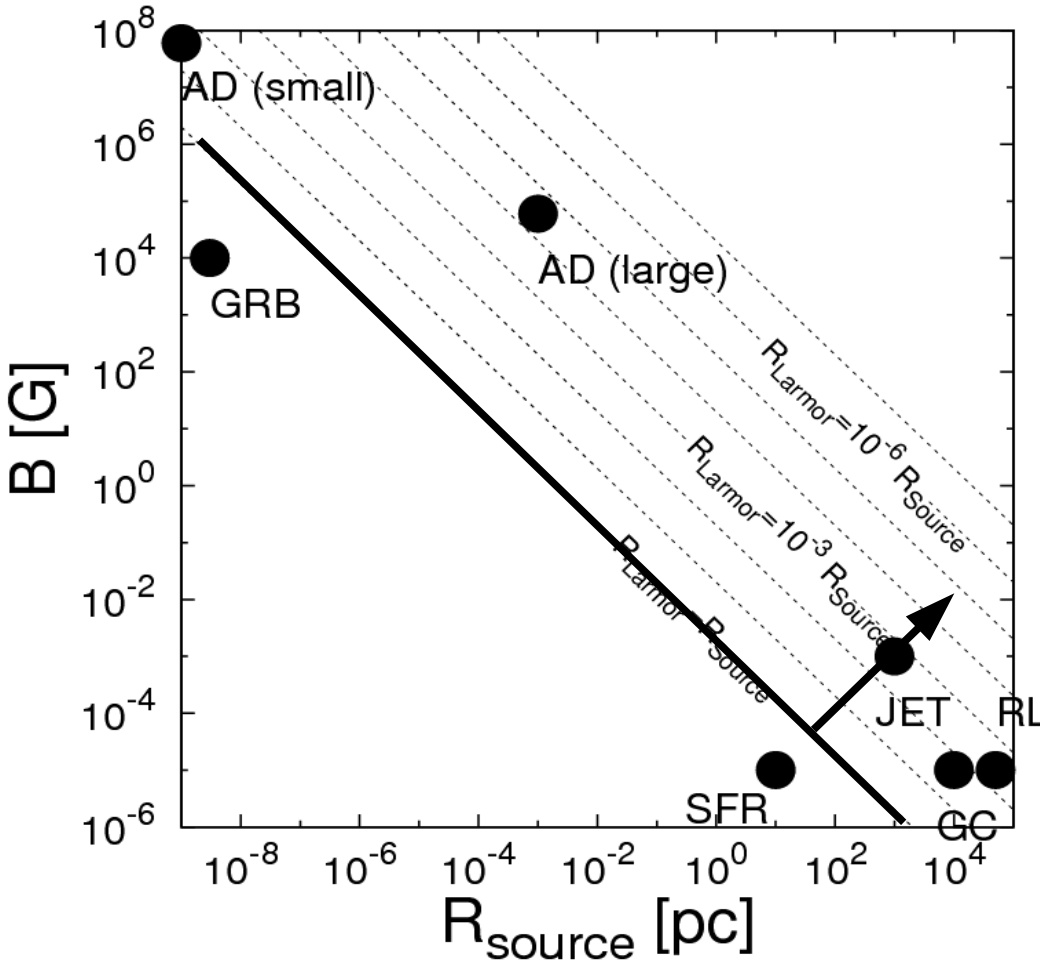
Are there Any Candidate Sources Left?

Accelerators of 10^{20} eV Iron nuclei



Are there Any Candidate Sources Left?

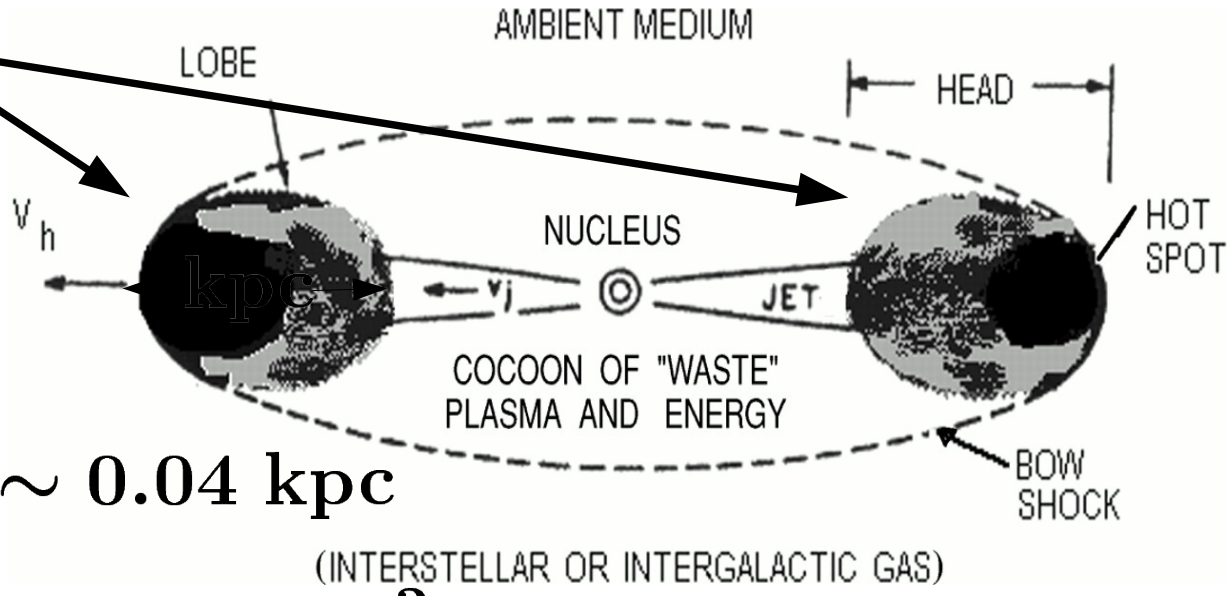




Example Candidate UHECR Source
(a Nuclei Friendly Environment)

Stochastic Acceleration in Radio Lobes:

Diagram taken from Ferrari -1998



$$B_{\rm source} \sim 10^{-4}\ {\rm G}$$

$$\hookrightarrow R_{\rm Larmor}(10^{20}\ {\rm eV\ Fe}) \sim 0.04\ {\rm kpc}$$

$$t_{\rm acc} < 10^{6}\ {\rm yrs} \quad \text{for} \quad \beta_{\rm scat.} > 10^{-2}$$

General PROBLEM for Large Accelerators- ACCELERATION TIME

Conclusion

New Auger measurements suggest that a new component of UHECR begins to dominate at energies above $10^{18.5}$ eV

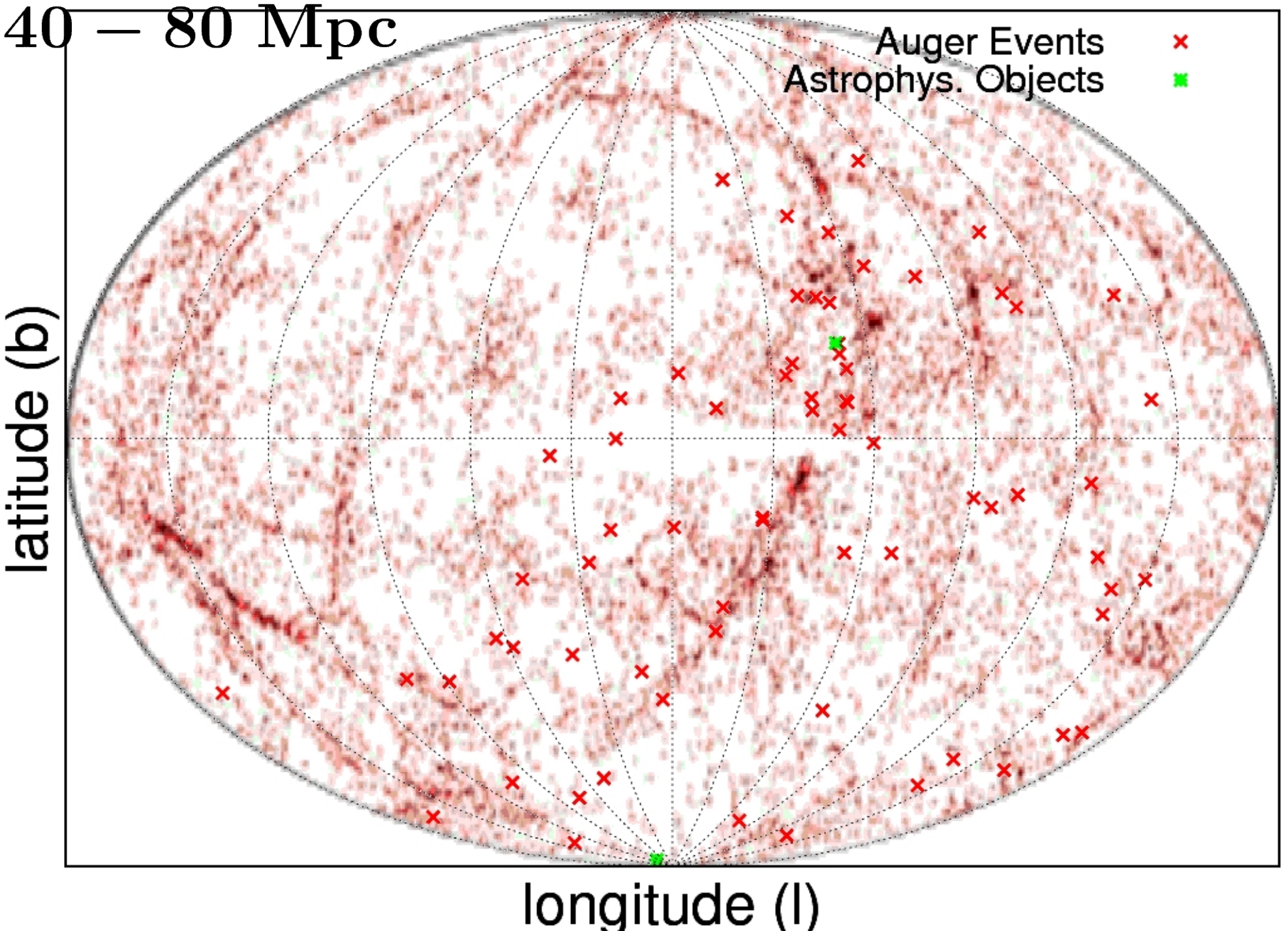
Good evidence now exists that the arrival distribution of UHECR is not isotropic

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

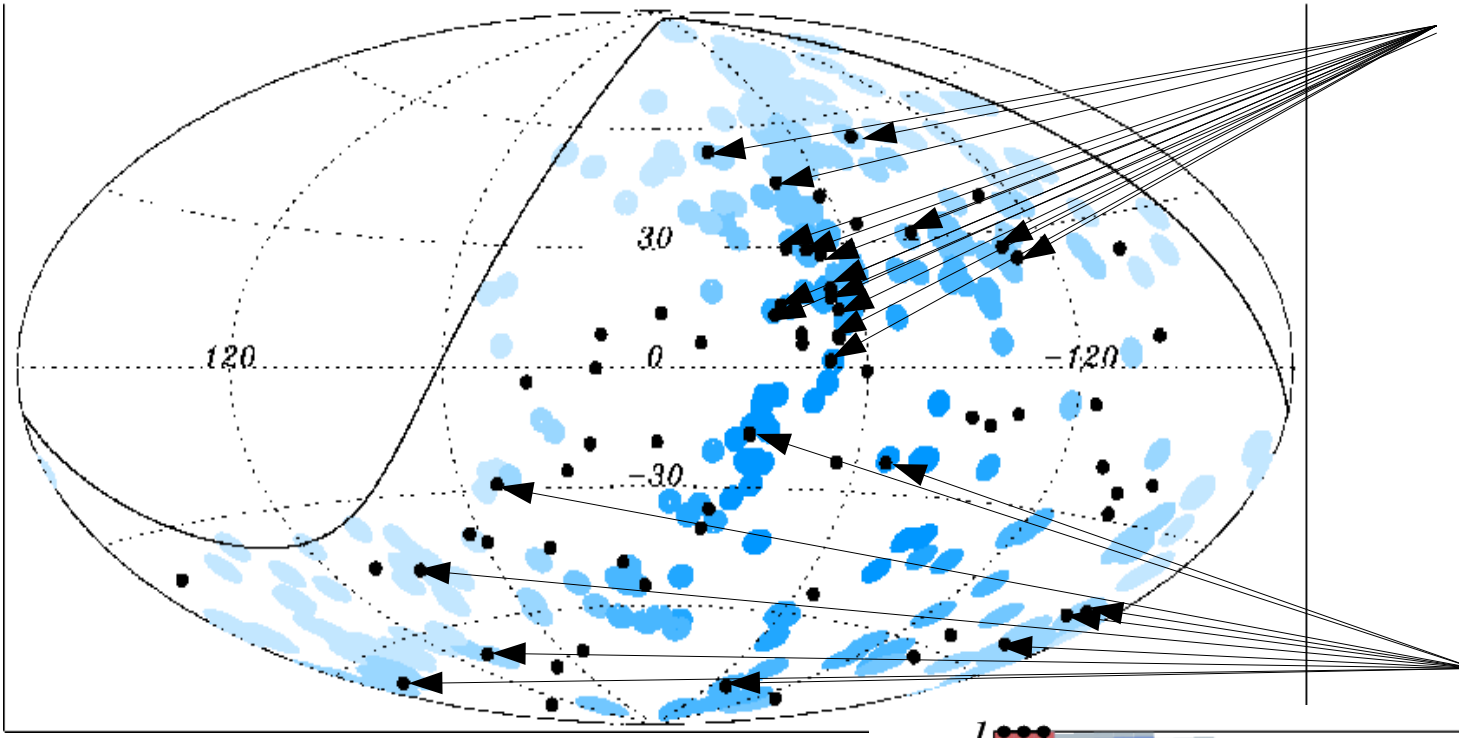
Regions close to luminous objects are excluded as UHECR sources, favouring slow/non-compact accelerators

Extra Slides

Our Local Extragalactic Neighbourhood



Can We See UHECR Sources Directly? No....so we resort to statistics!

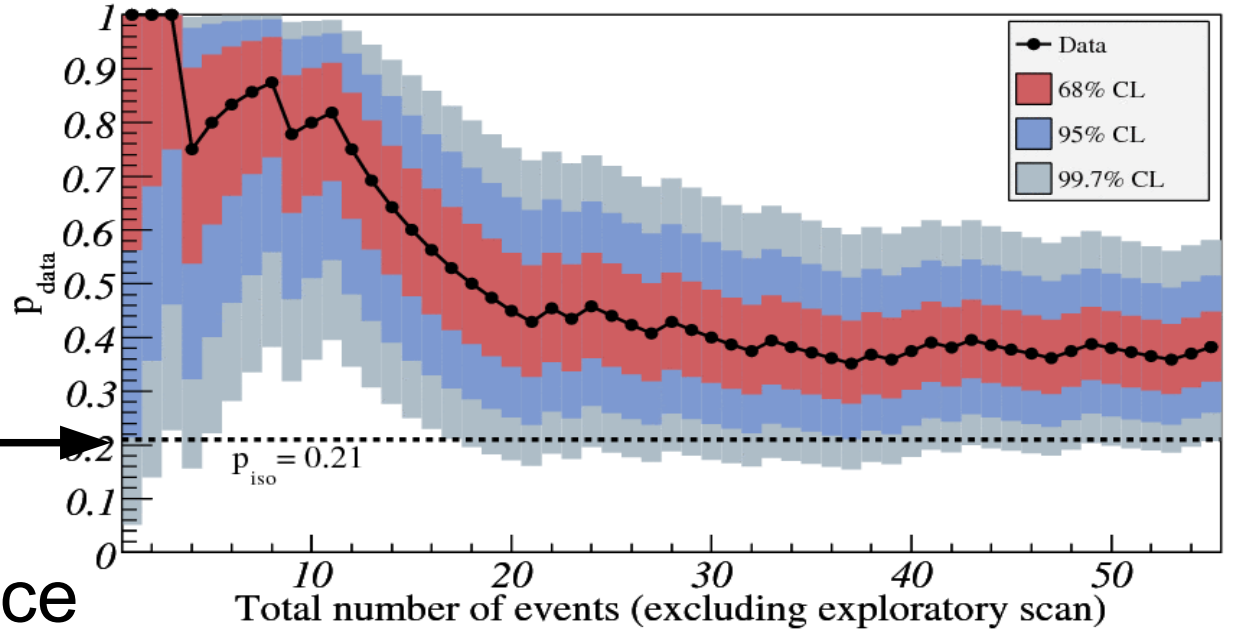


16 correlated events

10 correlated events

~26 of the events correlate with an AGN

ie. ~11 events expected to correlate by chance



Hillas' Hillas Plot