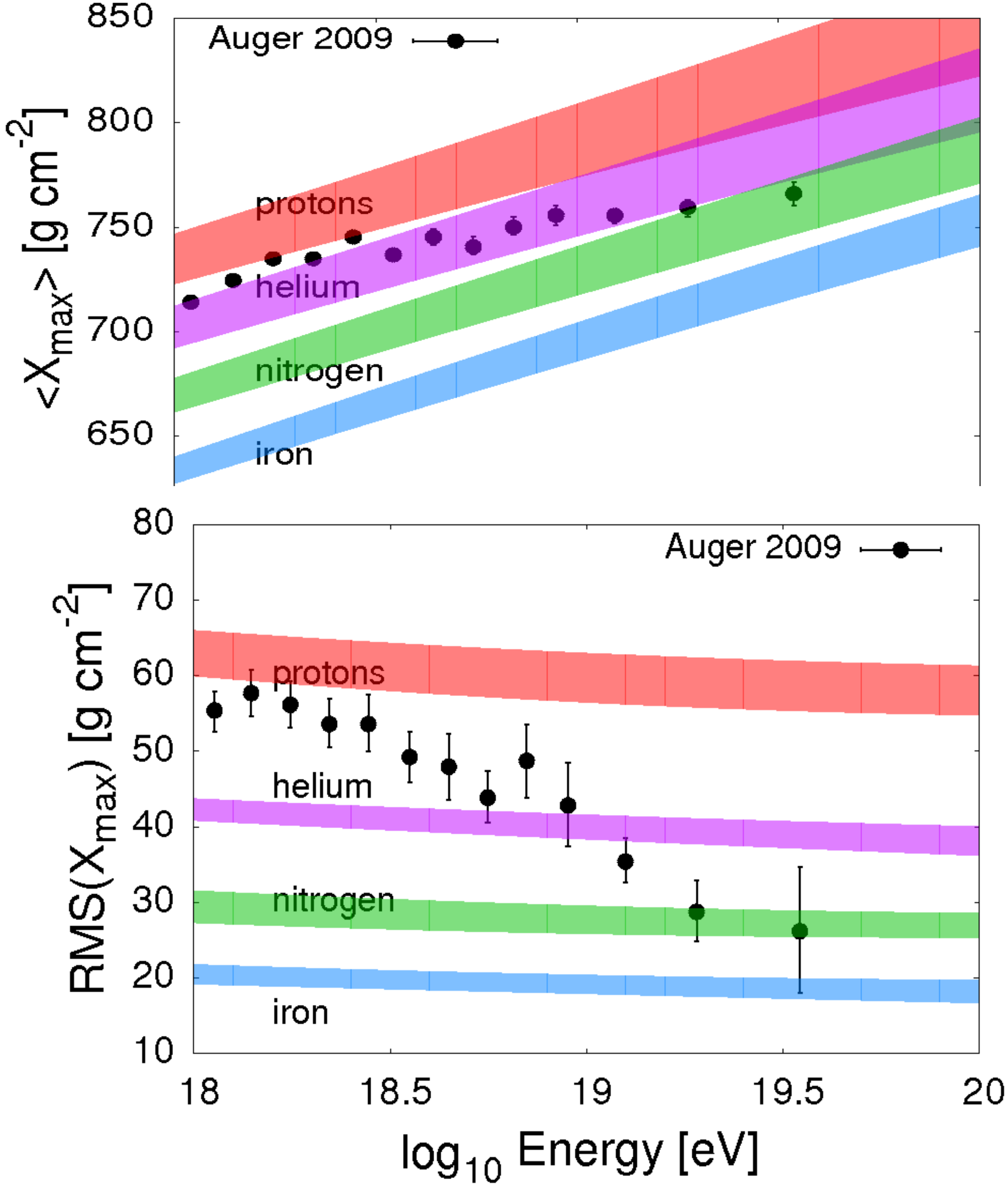
Implications of Auger Composition Results



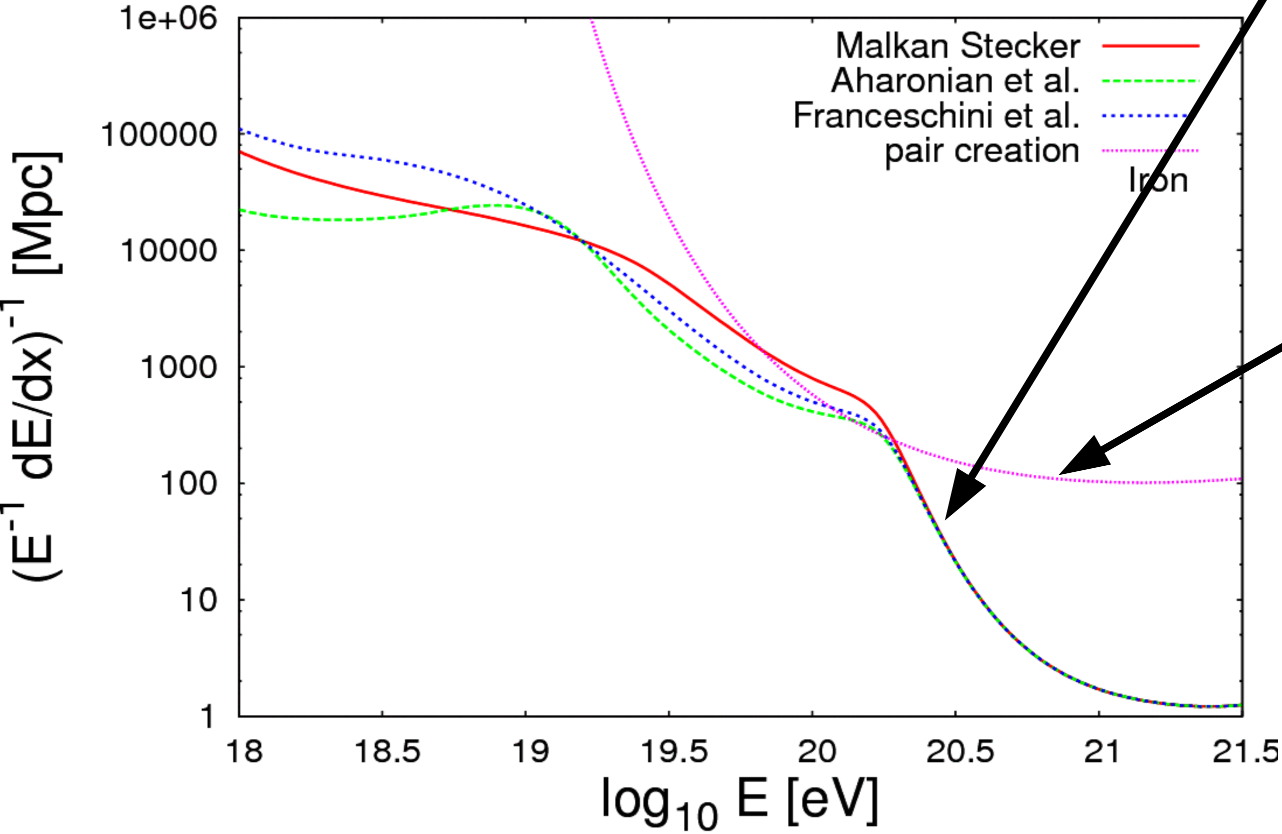
1) What source injection spectra + composition is consistent with Auger Results?

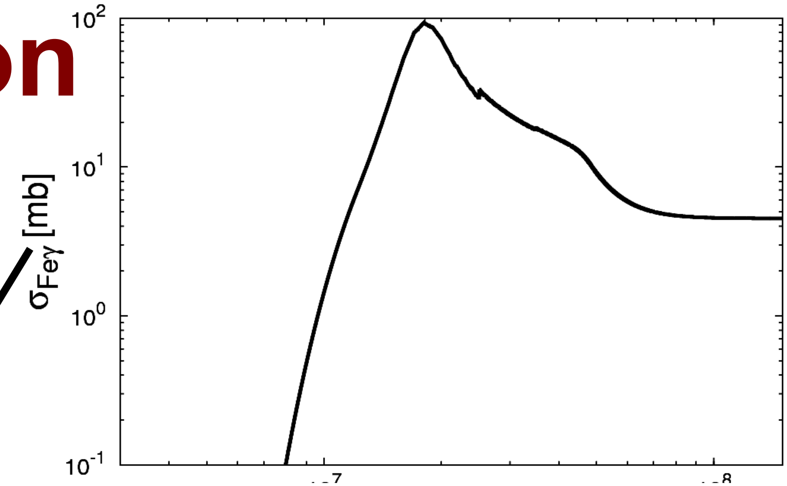
2) What constraints do presence of nuclei place on the local sources?

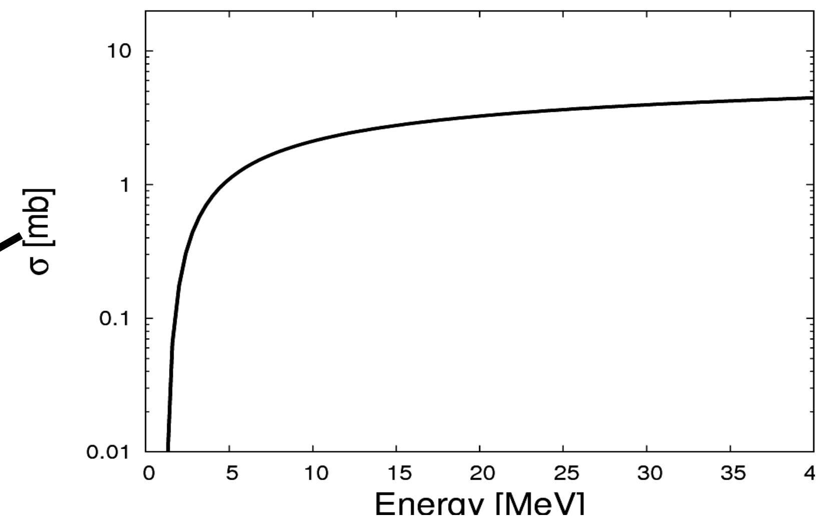
3) Local VHE emitters which might fit the bill

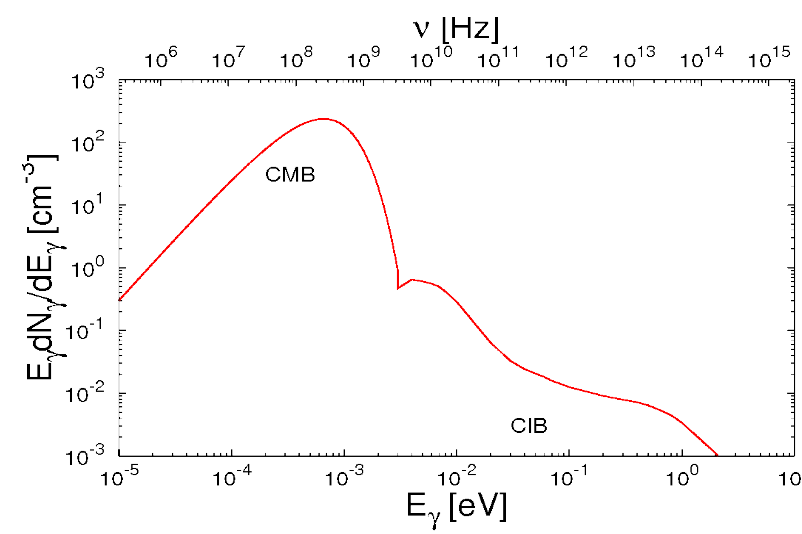
4) What hope do we have to identify these sources?

UHECR Nuclei Propagation From Source to Earth









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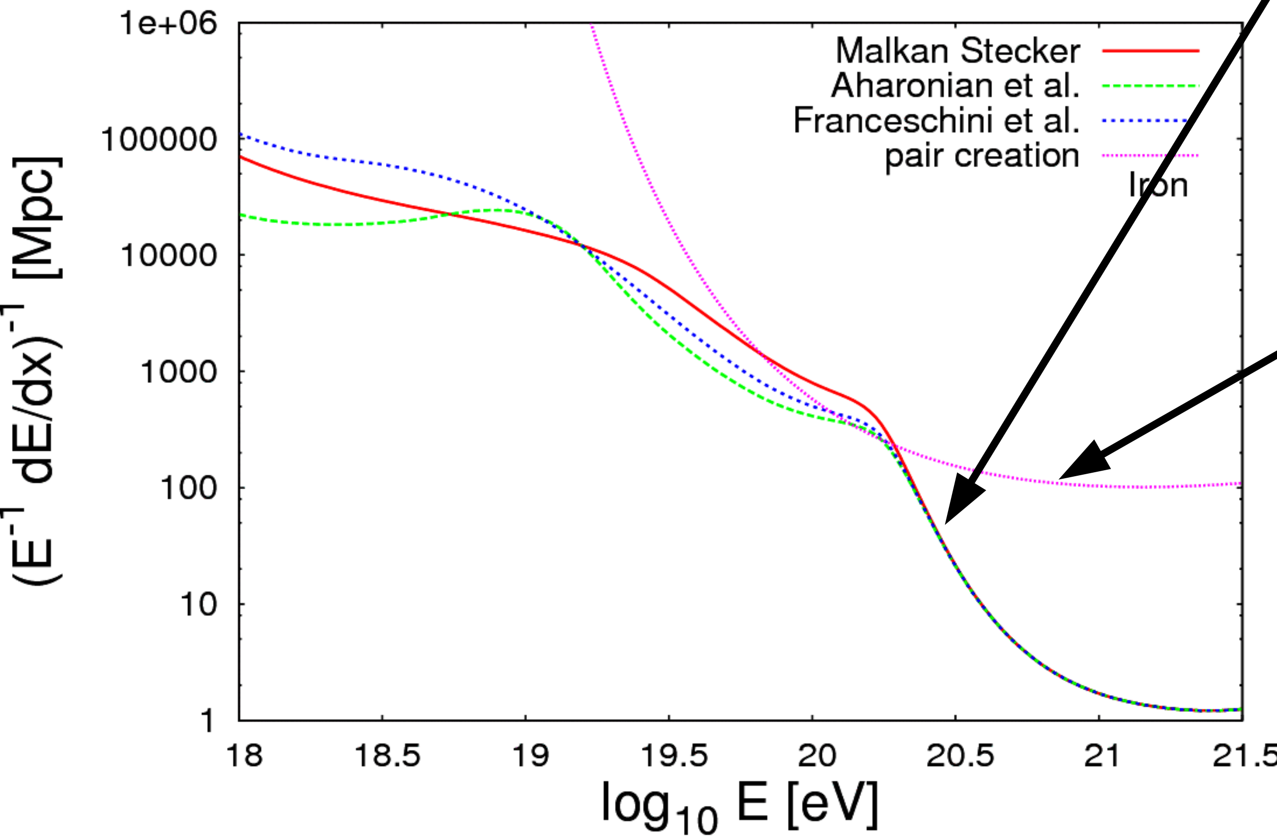
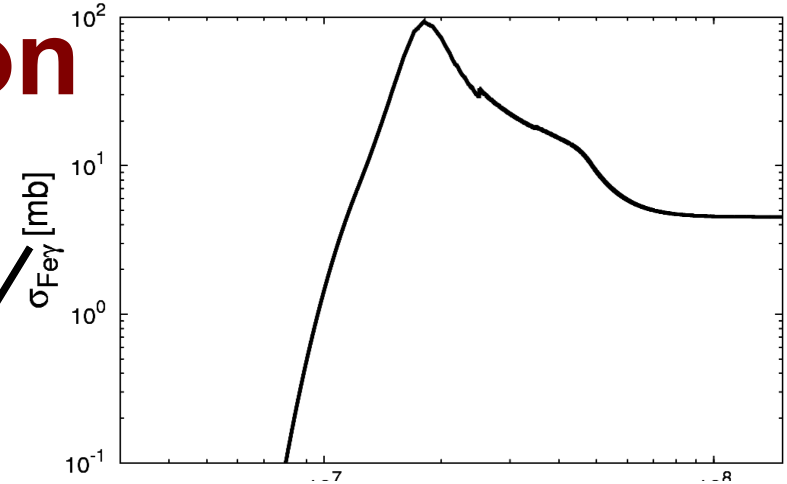
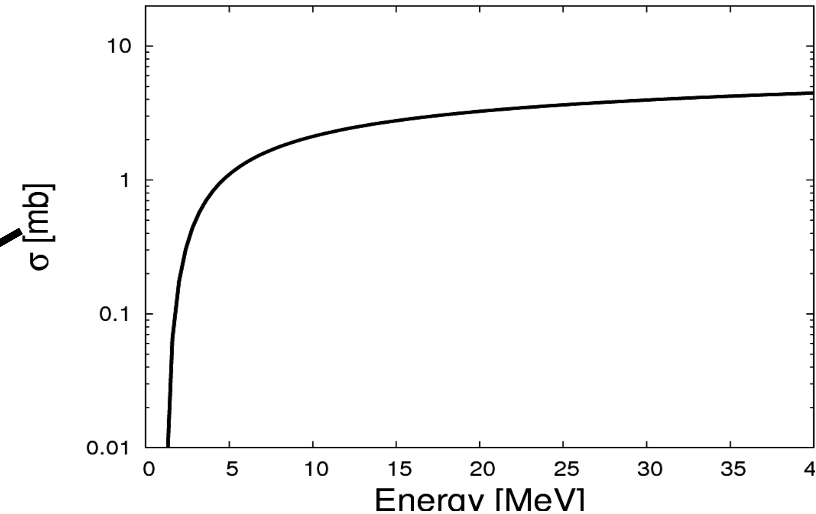
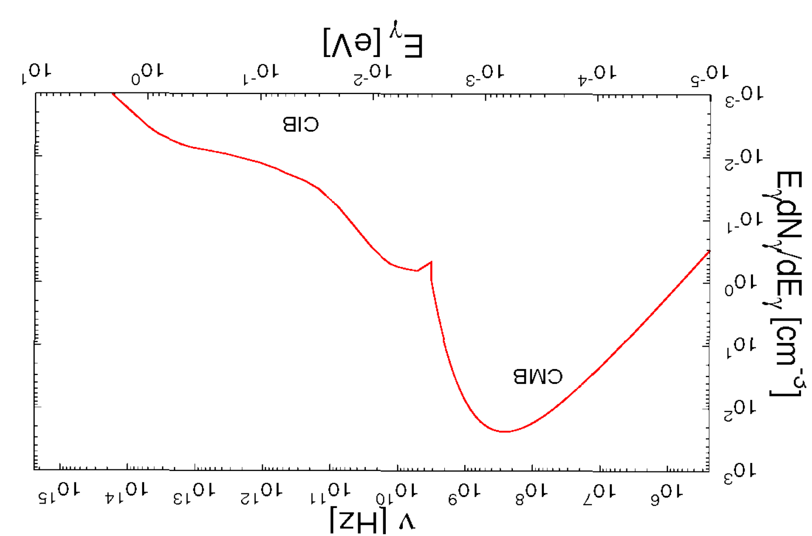
UHECR Nuclei Propagation From Source to Earth









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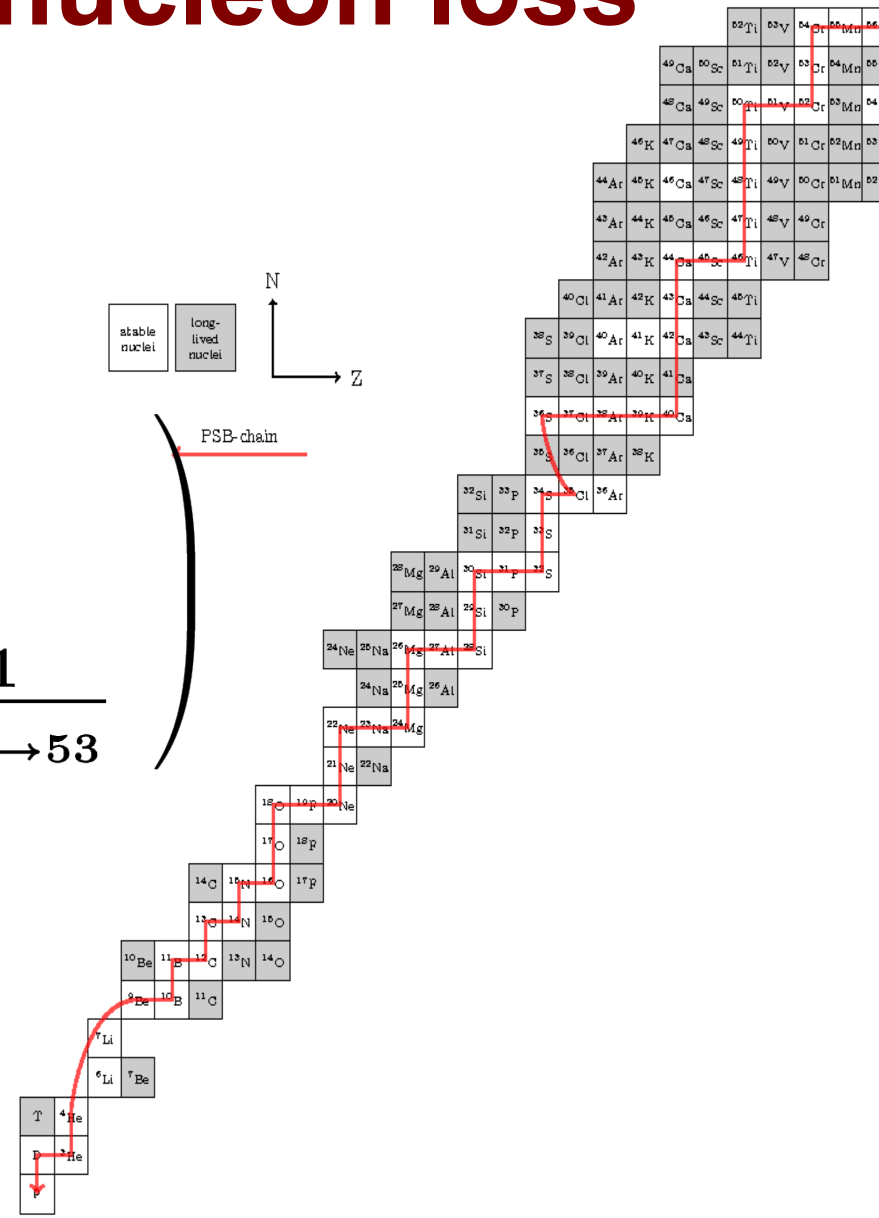
1st Order: Cascade of Nuclei Through Species- single nucleon loss

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

$$\Lambda = \begin{pmatrix} -\frac{1}{\tau_{56\rightarrow 55}} & 0 & 0 \\ \frac{1}{\tau_{56\rightarrow 55}} & -\frac{1}{\tau_{55\rightarrow 54}} & 0 \\ 0 & \frac{1}{\tau_{55\rightarrow 54}} & -\frac{1}{\tau_{54\rightarrow 53}} \end{pmatrix}$$



Whose eigenvalues are

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

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astro-ph/0802.1538

Cascade of Nuclei Through Species- single nucleon loss

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

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

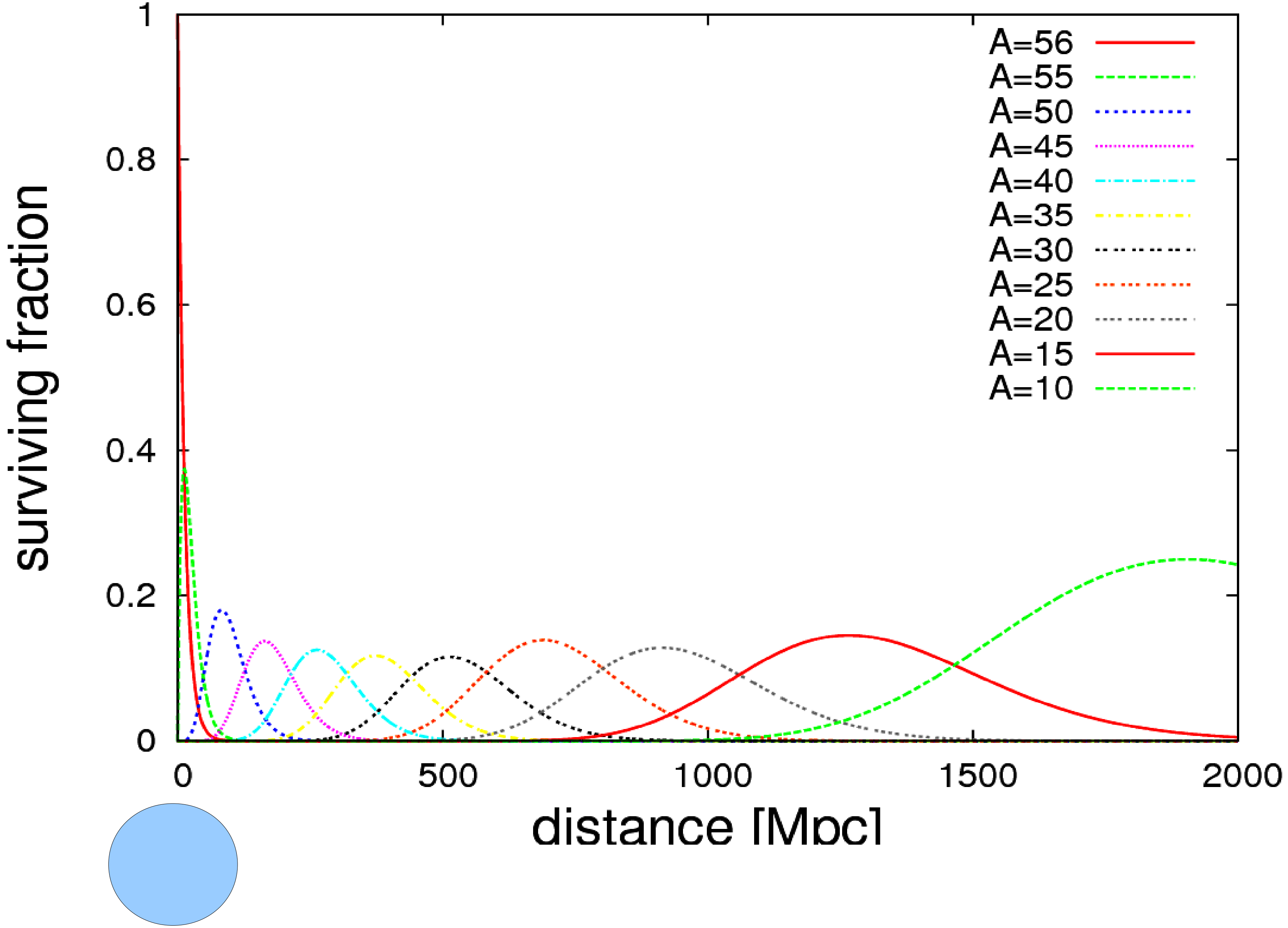
For the case $\tau_{56\rightarrow 55} = \tau_{55\rightarrow 54}\cdots$

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

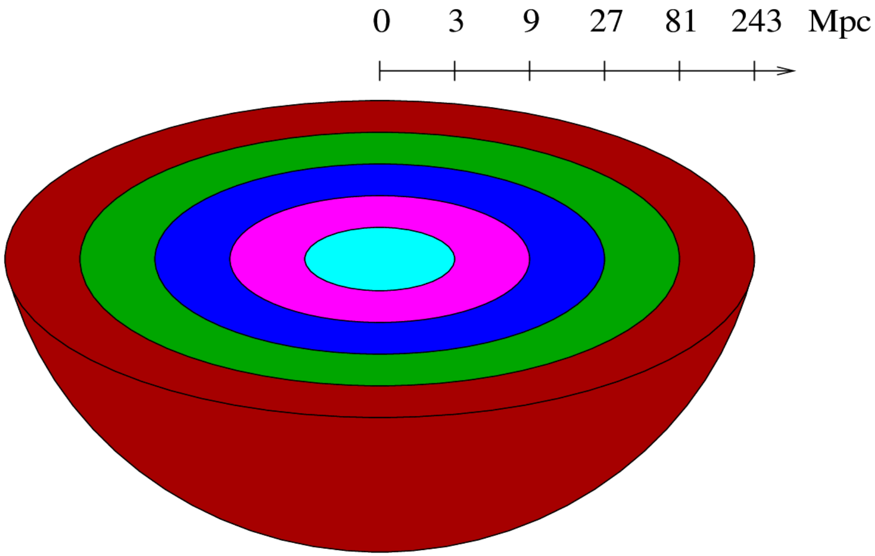
ie. Gaisser-Hillas type function!
(used to describe air showers)

Nuclei Propagation Away from their Source + their Transmutation

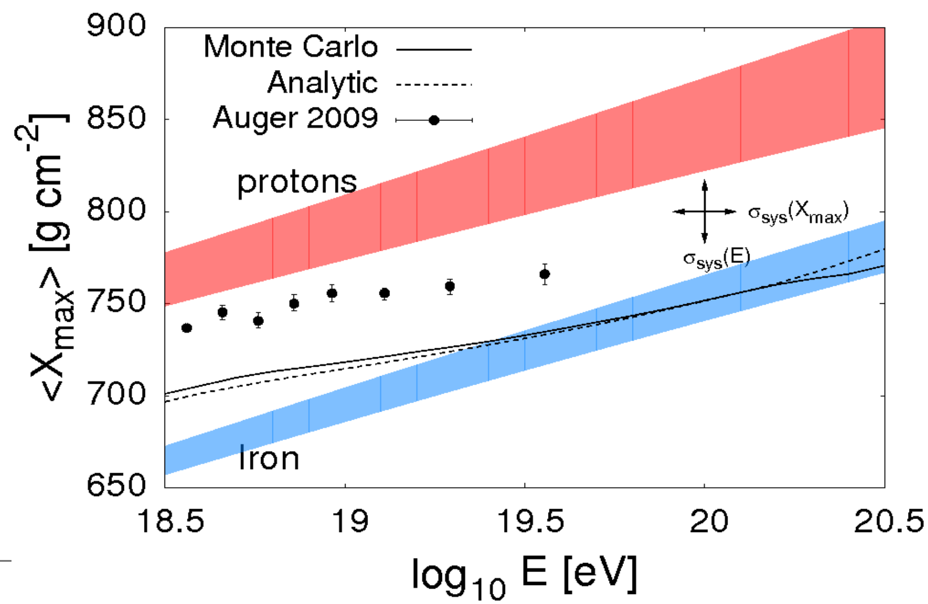
For 10^{20} eV Iron Nuclei at source-

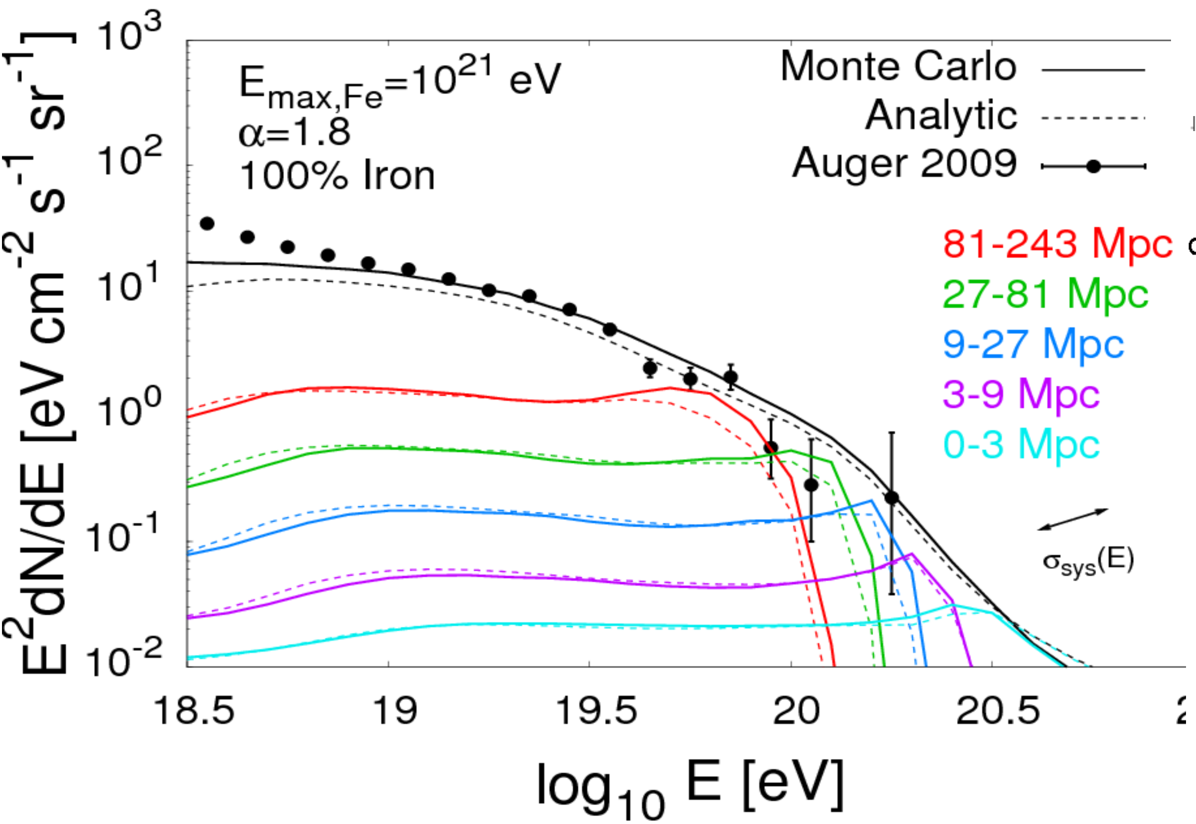


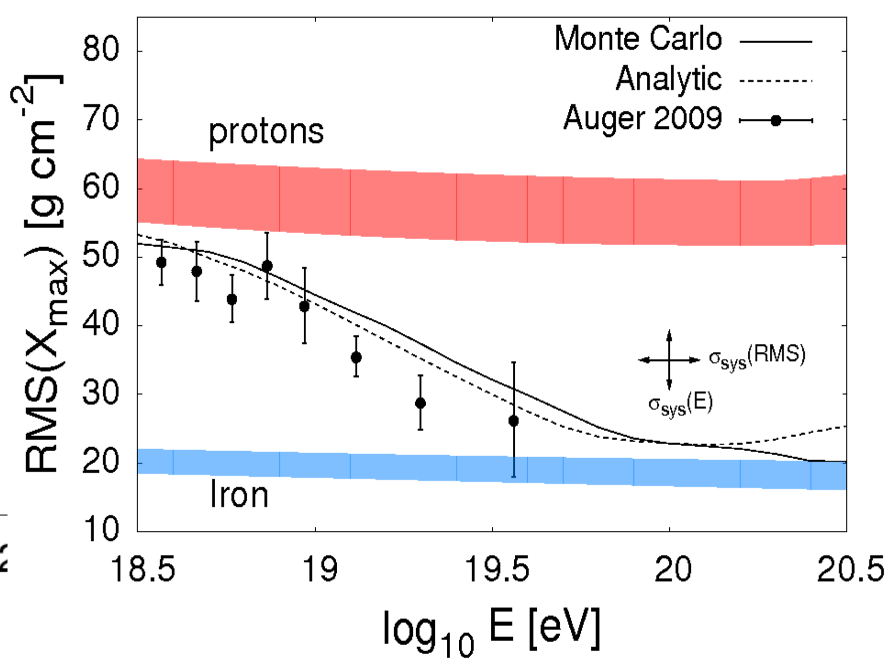
Local Scales Effect Highest Energies



(logarithmic scale)







What is the Source Composition?

Keep It Simple

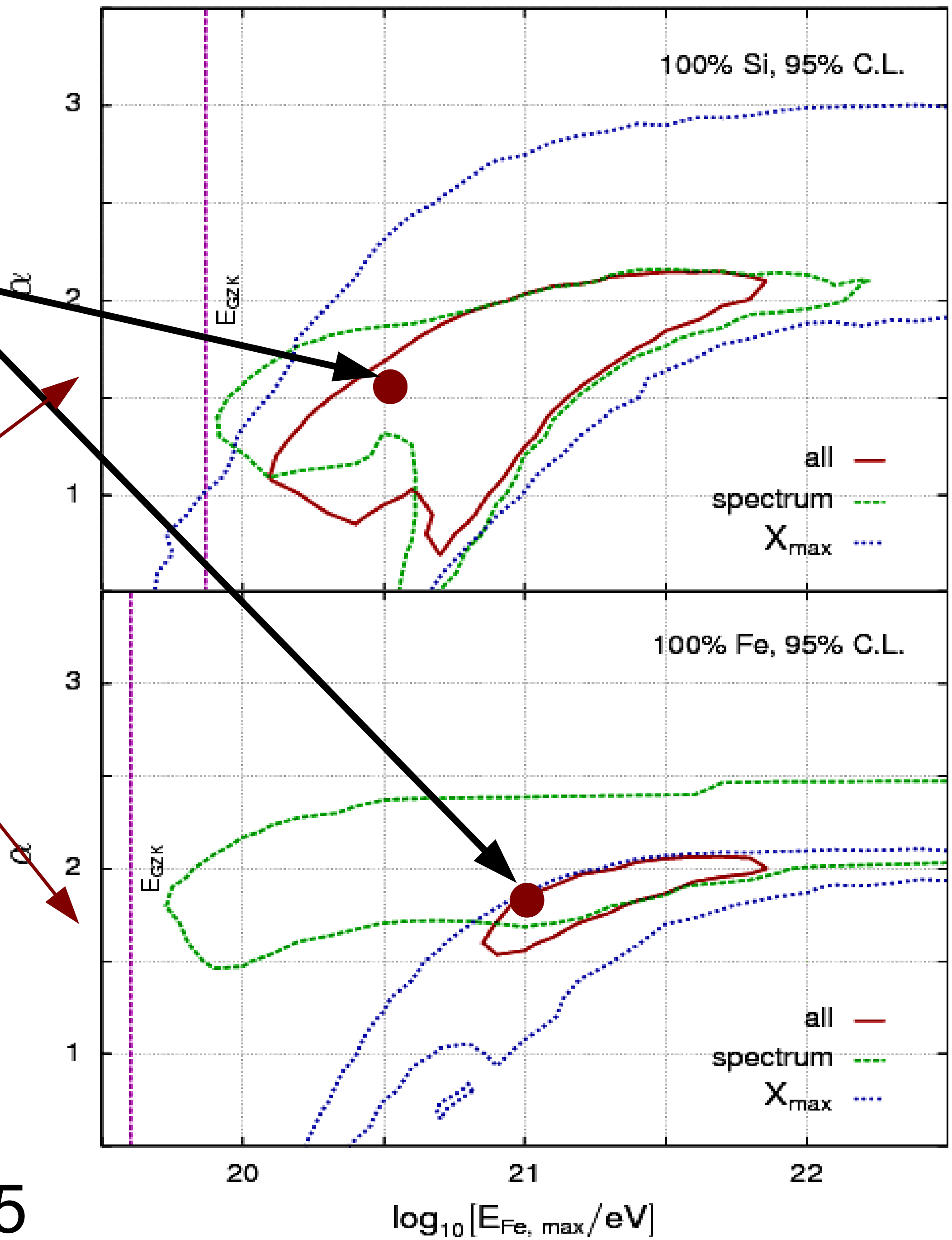
- Single Composition

Example Best-Fit Models

Silicon →

Hard Spectra preferred

Iron →



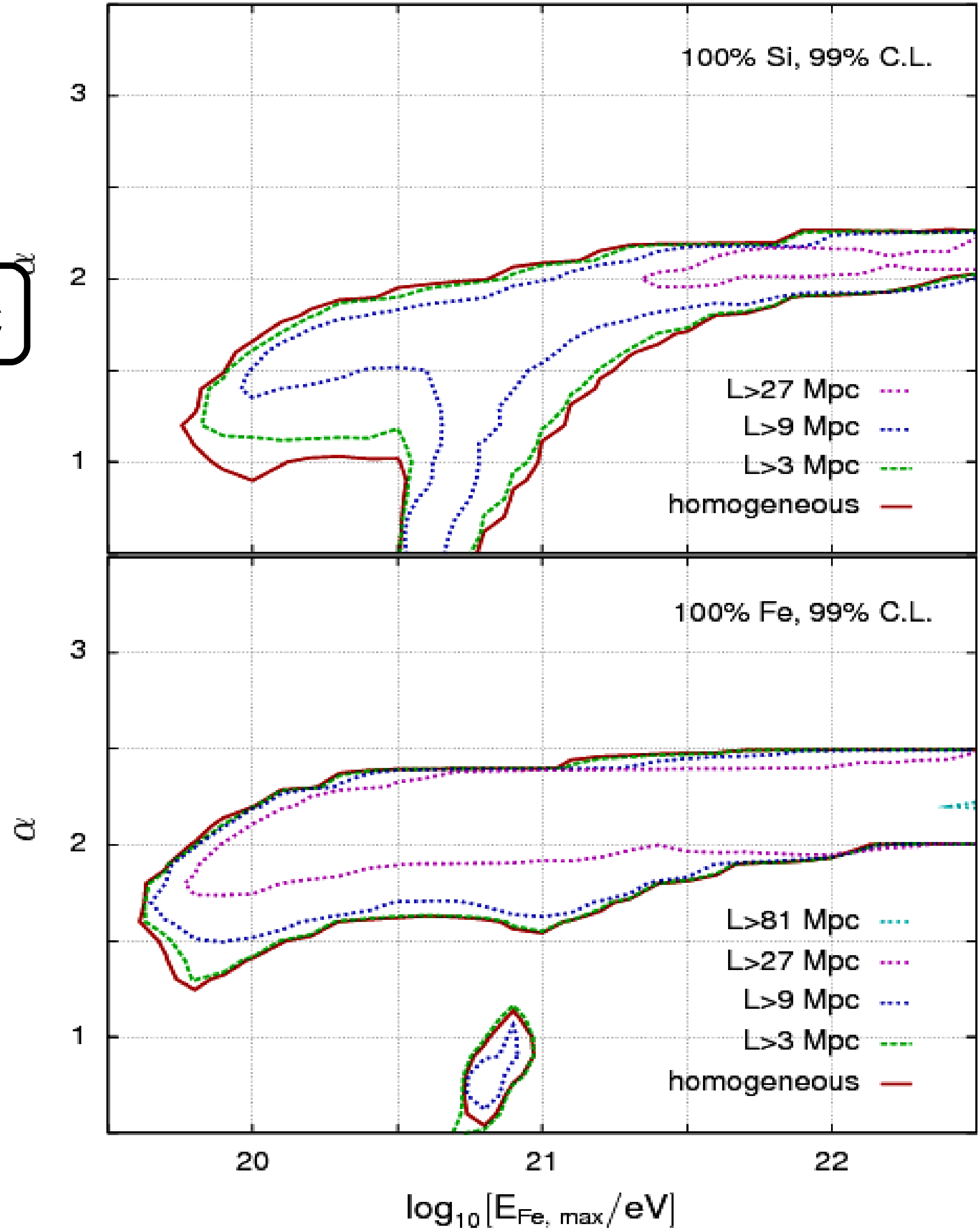
astro-ph/1107.2055

How Far is the Nearest Source?

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

Silicon- D<60 Mpc

Iron- D<80 Mpc



astro-ph/1107.2055

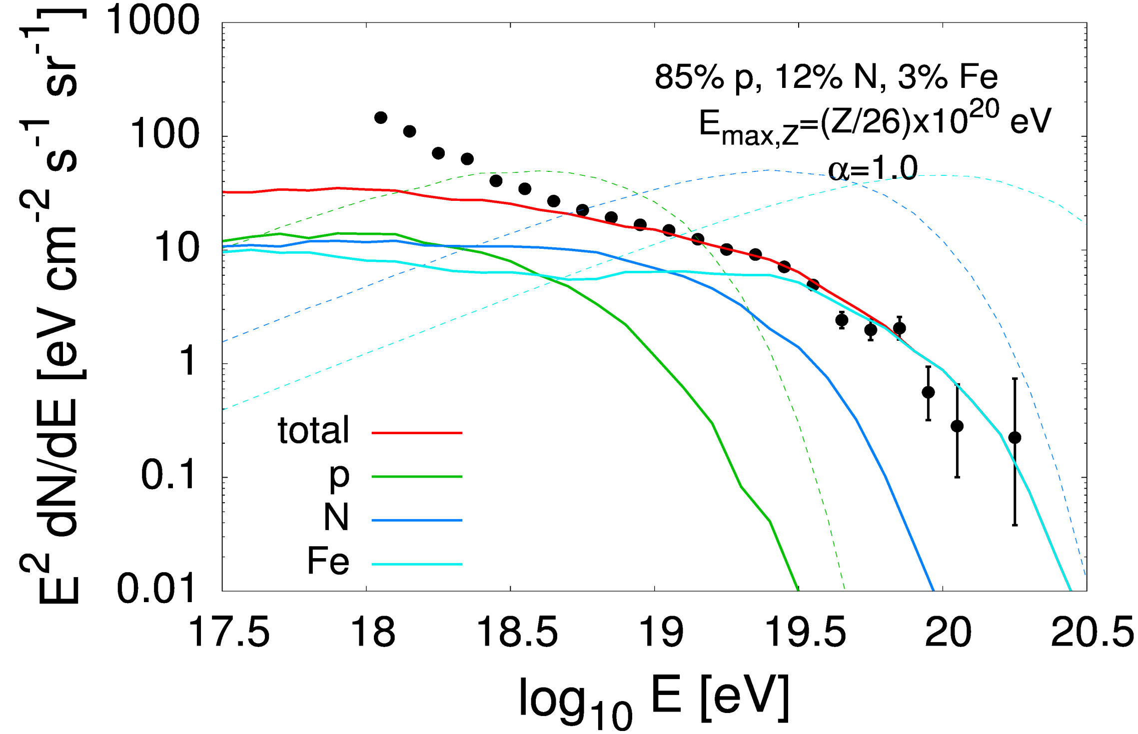
Mixed Composition

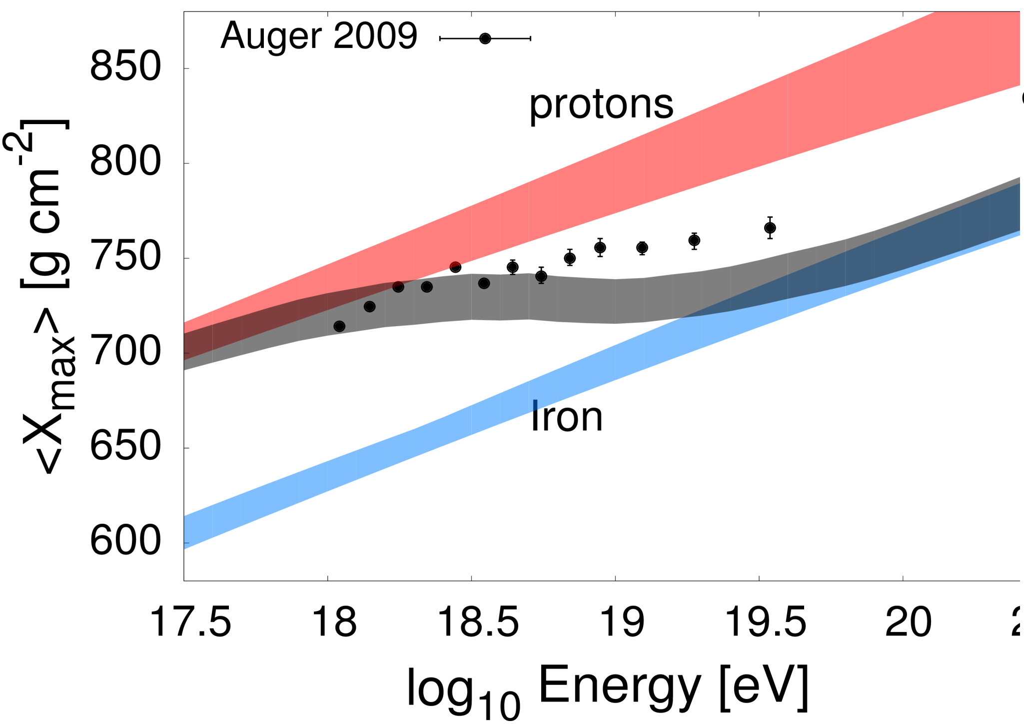
Archetype 1: Harder Low Cutoff

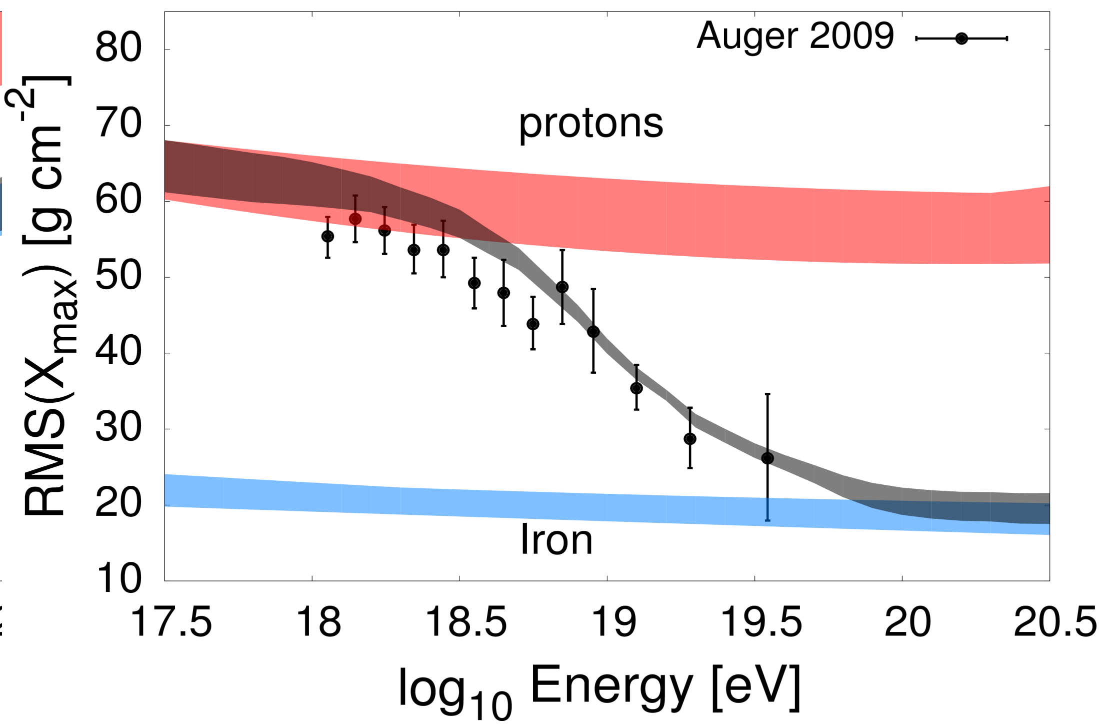
astro-ph/1401.0199

For $E_{max} = 10^{20}$ eV

85%p, 12%N, 3%Fe







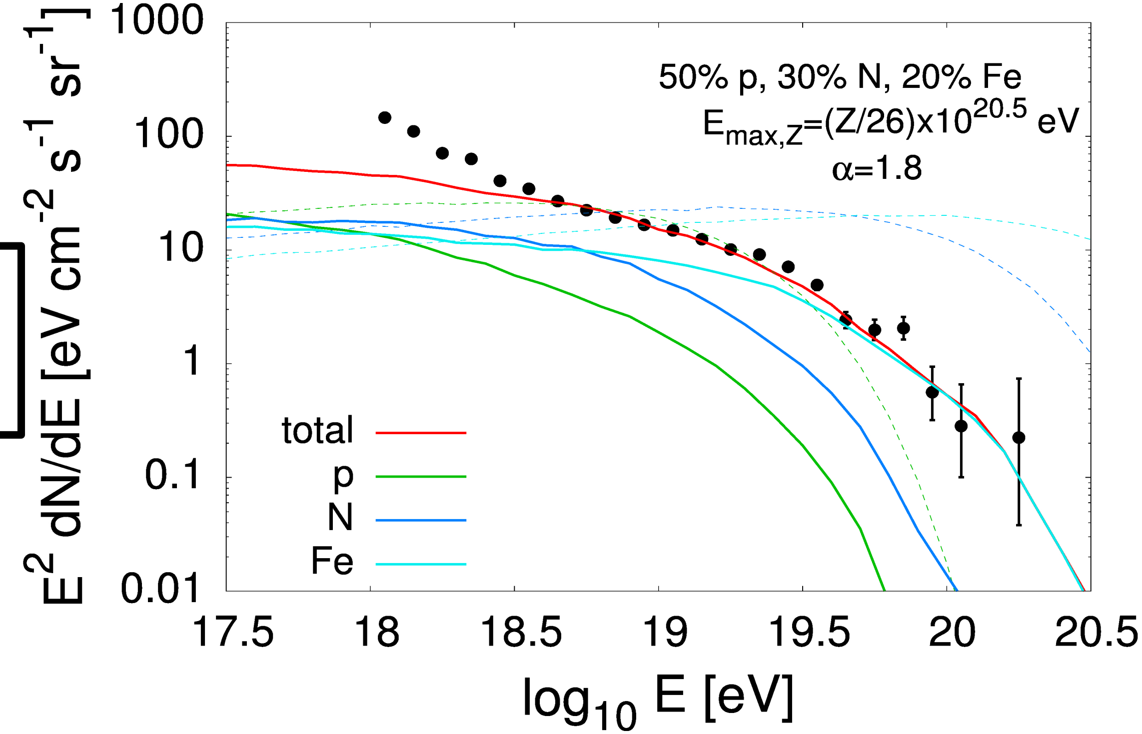
Mixed Composition

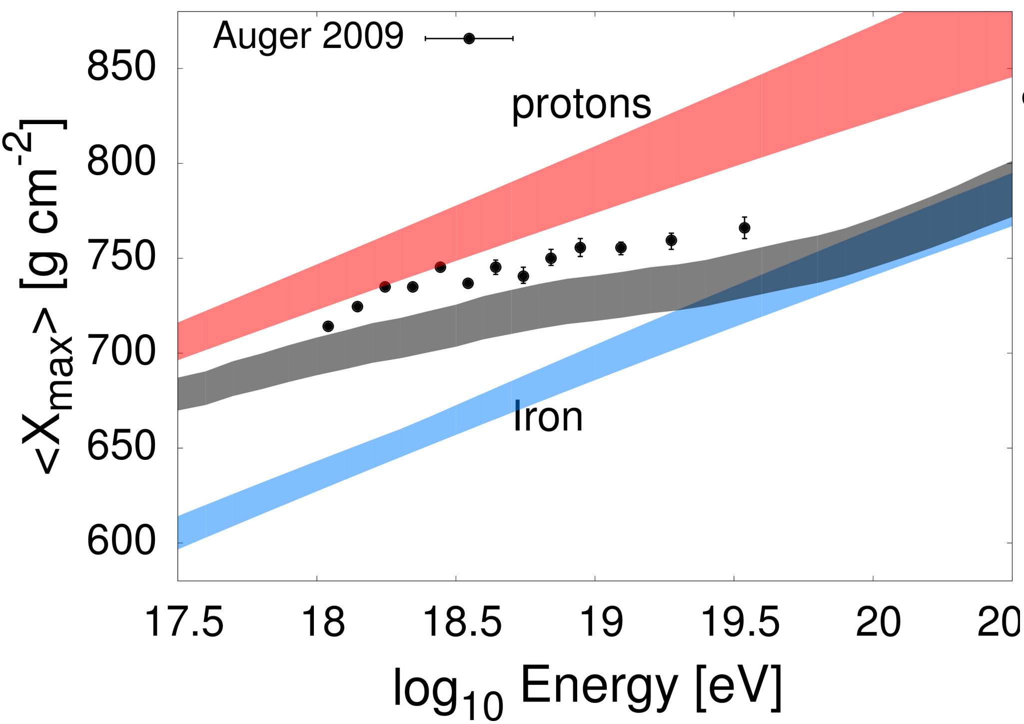
Archetype 2: Softer Higher Cutoff

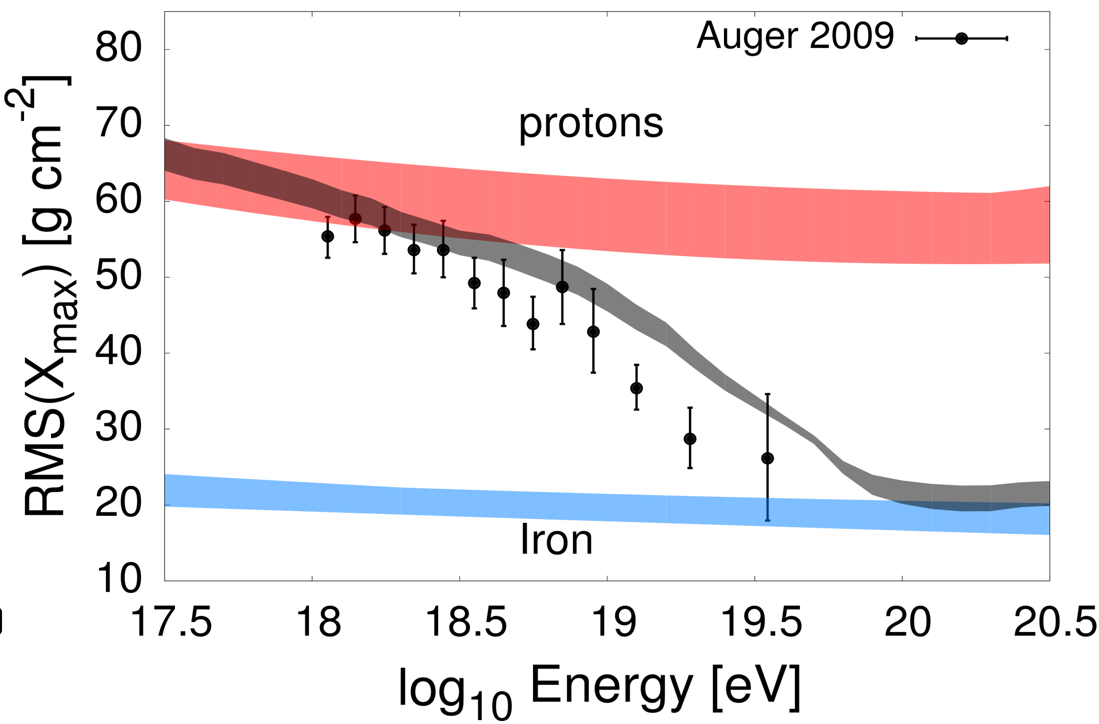
astro-ph/1401.0199

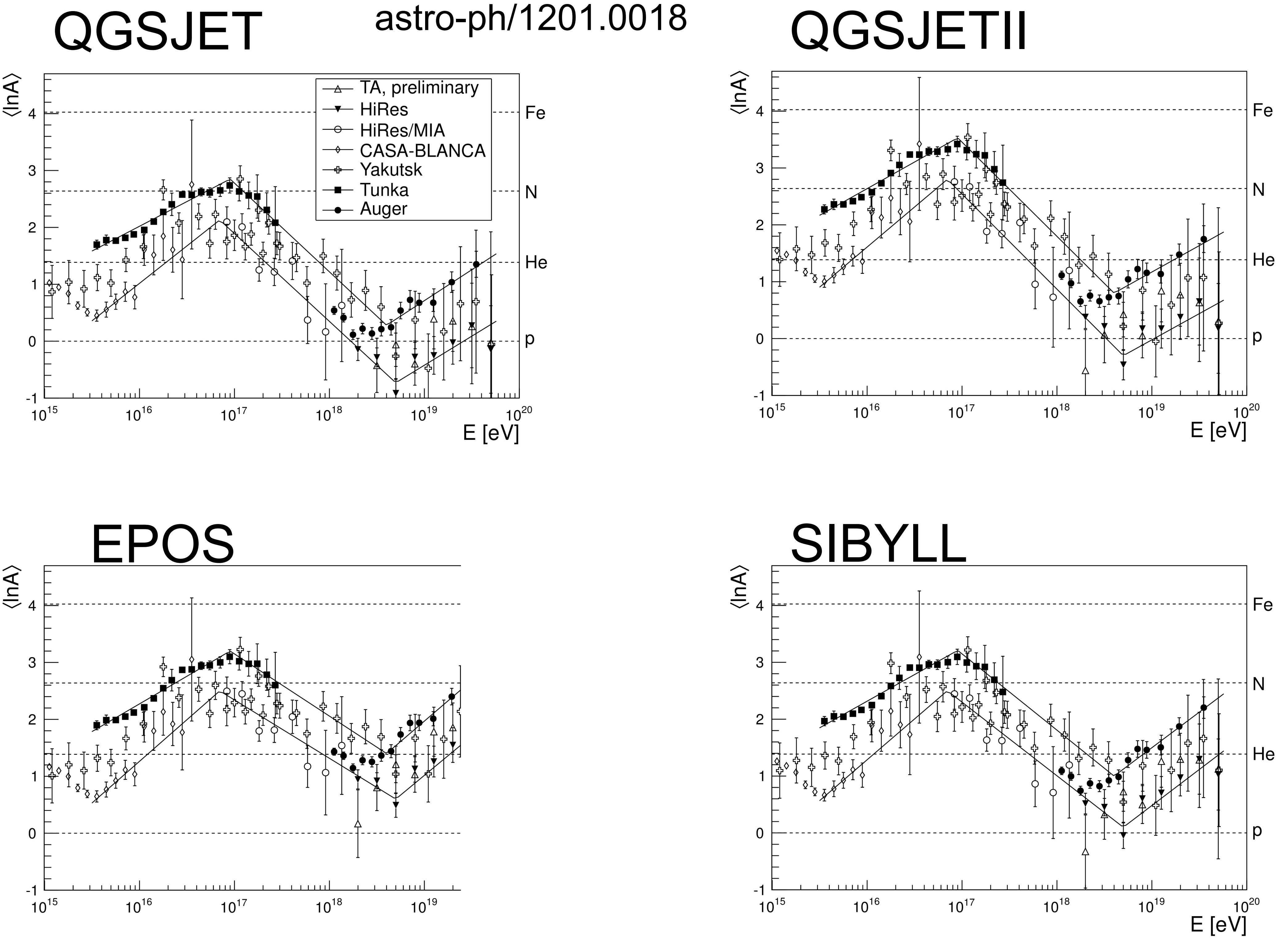
For $E_{max} = 10^{20.5}$ eV

50%p, 30%N, 20%Fe








astro-ph/1201.0018
QGSJET
QGSJETII
EPOS
SIBYLL
⟨lnA⟩
E [eV]
TA, preliminary
HiRes
HiRes/MIA
CASA-BLANCA
Yakutsk
Tunka
Auger
Fe
N
He
p
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}

Summary So Far....

The dominance of nuclei at the high energies provides useful new information about the proximity of UHECR sources

Analytic calculations can be used to describe with reasonable accuracy the spectrum and the composition results

Agreement with both the spectral and composition information require that **local sources** exist which produce **hard spectra**

These requirements remain when the more general case of a mixed composition is considered

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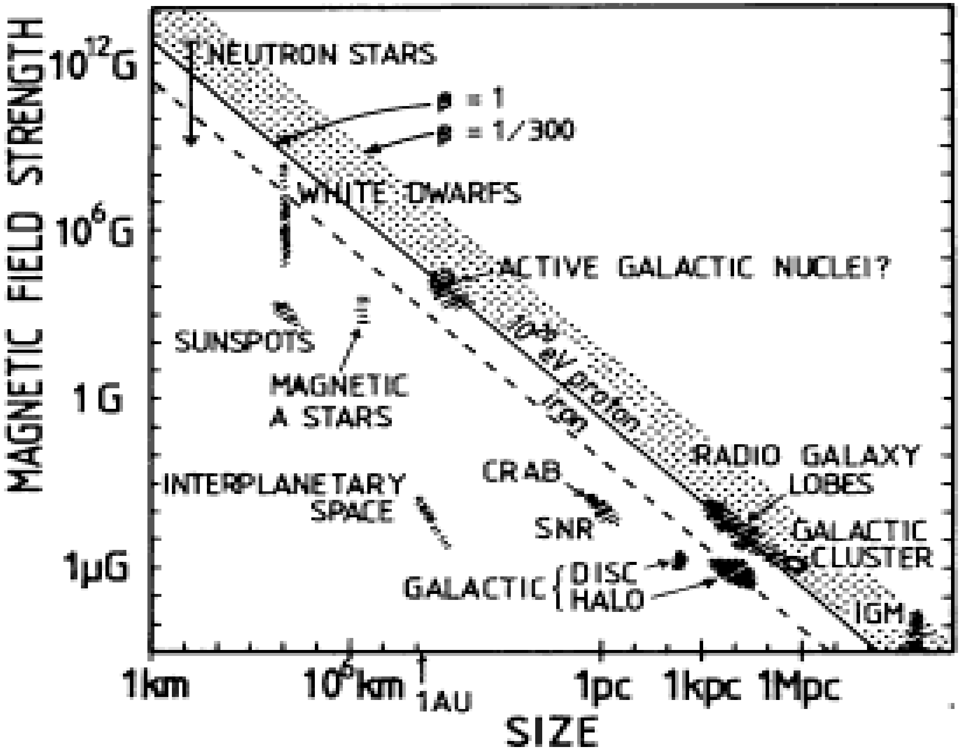
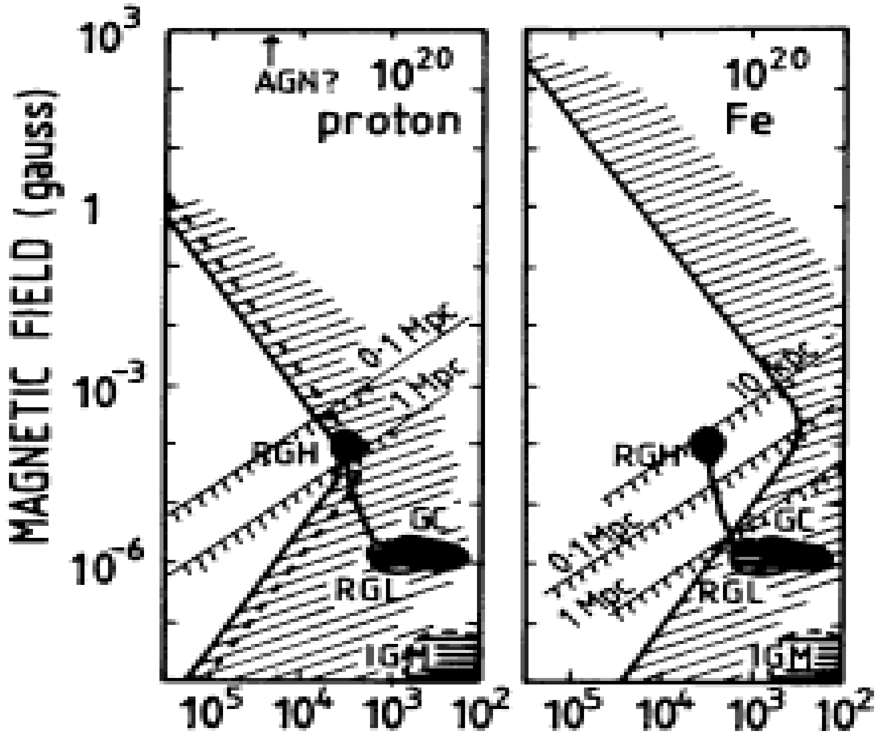
The Need For Hard Spectra Sources of Nearby Heavy Cosmic Rays



Hillas 1984



Velocity of Scatterer (km s^{-1})

Compactness of UHECR Sources: Proton/Nuclei Synchrotron Losses

For a 10^{20} eV cosmic ray:

$$t_{\rm acc} = \eta \frac{r_{\rm larmor}}{c\beta^2}$$

$$t_{\rm esc} = \frac{R^2}{c\eta r_{\rm larmor}}$$

$$\beta Z \left(\frac{R}{\rm kpc}\right) \left(\frac{B}{0.1\ \rm mG}\right) > 1$$

$$t_{\rm loss}^{\rm sync} = \frac{9}{8\pi Z^2 \alpha} \frac{h}{E} \left(\frac{B}{B_{\rm crit}}\right)^2$$

$$t_{\rm loss}^{\rm photo-dis} = 1\ \rm Myr$$

Hillas 1984

Compactness of UHECR Sources: Proton/Nuclei Synchrotron Losses

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$$t_{\rm loss}^{\rm photo-dis} = 1 \text{ Myr}$$

$$\left(\frac{\beta}{Z}\right)^2 \left(\frac{30 \text{ mG}}{B}\right) > 1$$

Hillas 1984

Compactness of UHECR Sources: Proton/Nuclei Synchrotron Losses

For a 10^{20} eV cosmic ray:

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$$t_{\rm loss}^{\rm photo-dis} = 1 \ {\rm Myr}$$

$$Z\beta^2 \left(\frac{B}{0.1 \ {\rm mG}}\right) > 1$$

Hillas 1984

Compactness of UHECR Sources: Proton/Nuclei Synchrotron Losses

-Need for high velocity shocks ($\beta \sim 1$)

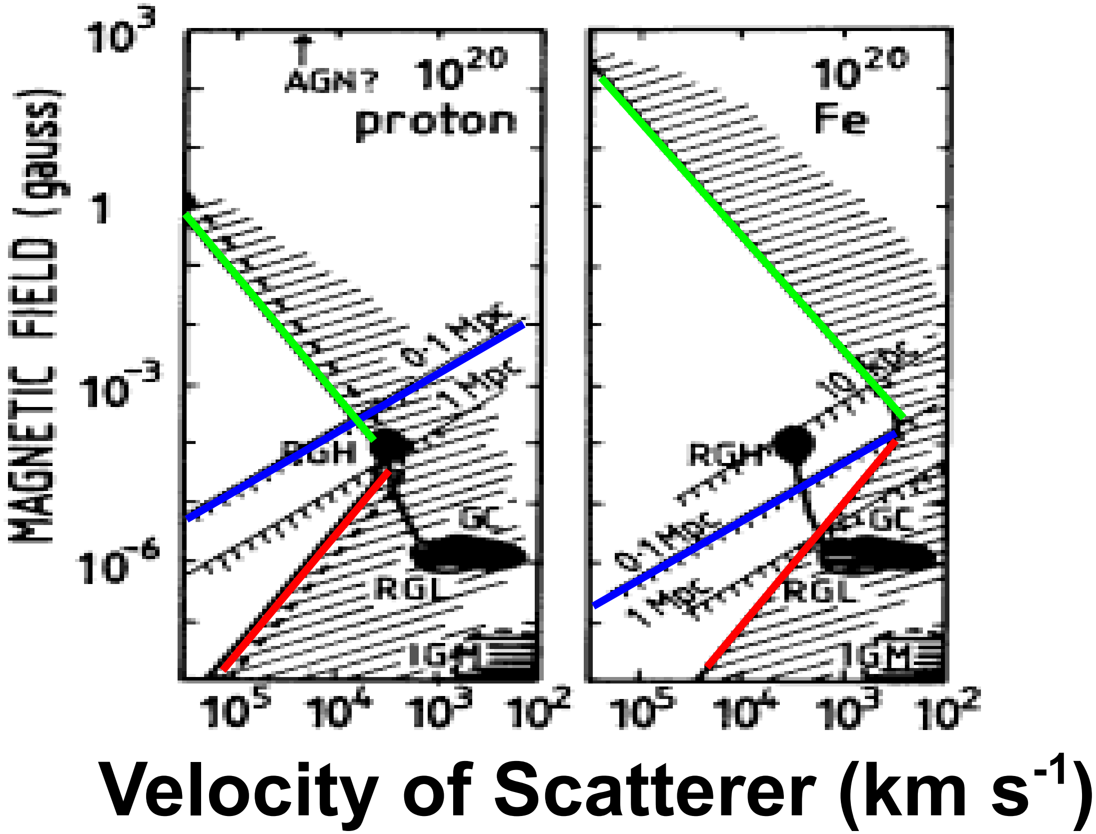
-Need for close to optimal acceleration conditions ($\eta \sim 1$- Bohm Limit)

$$\beta Z \left(\frac{R}{\mathrm{kpc}}\right) \left(\frac{B}{0.1\ \mathrm{mG}}\right) > 1$$

$$\left(\frac{\beta}{Z}\right)^2 \left(\frac{30\ \mathrm{mG}}{B}\right) > 1$$

$$Z\beta^2 \left(\frac{B}{0.1\ \mathrm{mG}}\right) > 1$$

$\eta \sim 10$ (solid lines)



Hillas 1984

Compactness of UHECR Sources: Nuclei Photo-disintegration

$$f = \frac{t_{\rm esc}}{t^{\rm CR\gamma}_{\rm int.}}$$

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

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

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

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

Compactness of UHECR Sources: Nuclei Photo-disintegration

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

Photo-disintegration threshold:

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

Since,

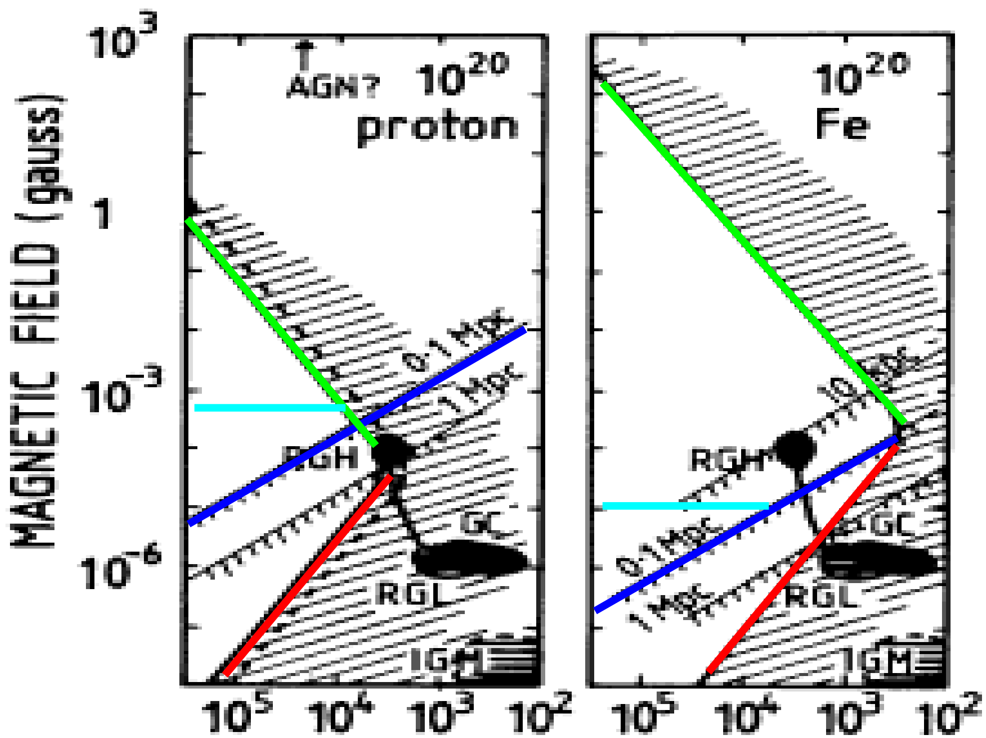
$$L_\gamma[10^{43}\ \mathrm{erg\ s}^{-1}] = 2\times 10^{44}\ \mathrm{eV\ cm}^{-1}$$
$$\sigma_{\mathrm{CR}\gamma}[\mathrm{A\ mb}] = \mathrm{A}\times 10^{-27}\ \mathrm{cm}^2$$
$$eB[1\ \mathrm{mG}] = 0.3\ \mathrm{eV\ cm}^{-1}$$

$$\frac{L_\gamma \sigma_{\mathrm{CR}\gamma} eB}{A} = 6\times 10^{16}\ \mathrm{eV}^2$$

Compactness of UHECR Sources: Nuclei Photo-disintegration

Summary-

$$f^{\mathrm{CR}\gamma} = 50\left(\frac{Z}{26}\right)\left(\frac{L_\gamma}{10^{43}\ \mathrm{erg\ s^{-1}}}\right)\left(\frac{B}{1\ \mathrm{mG}}\right)$$

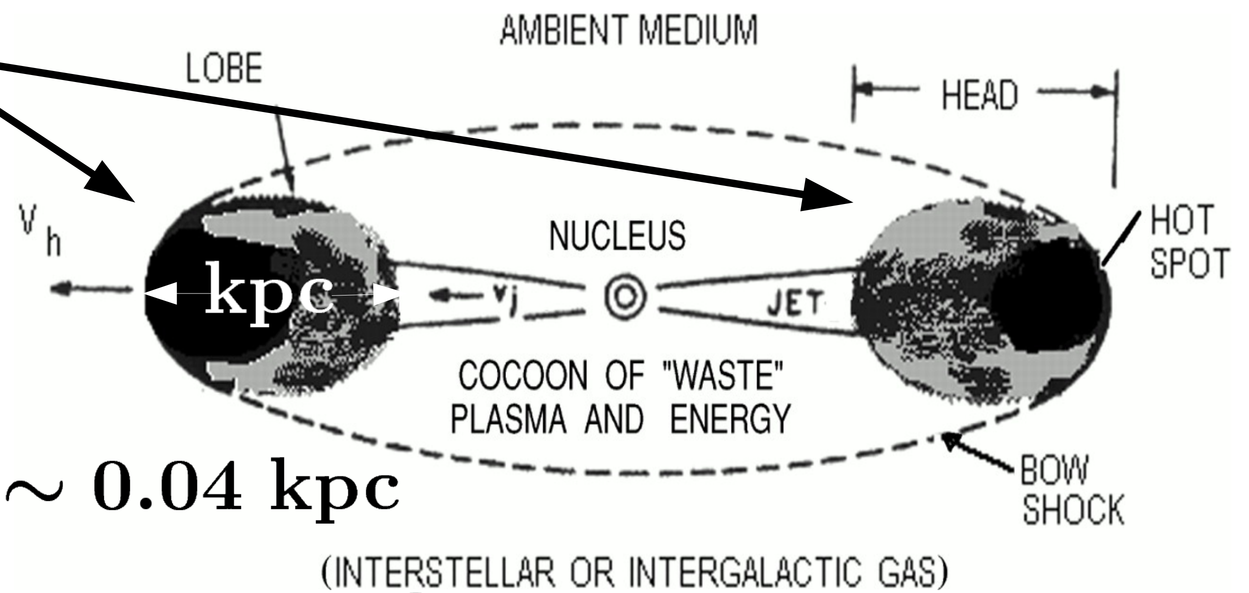


Velocity of Scatterer (km s^{-1})

Example Candidate UHECR Source
(a Nuclei Friendly Environment)

Diagram taken from Ferrari -1998

Stochastic Acceleration in Radio Lobes:



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

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

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

General PROBLEM for Non-Compact Accelerators- ACCELERATION TIME

Example Candidate UHECR Source
(a Nuclei Friendly Environment)

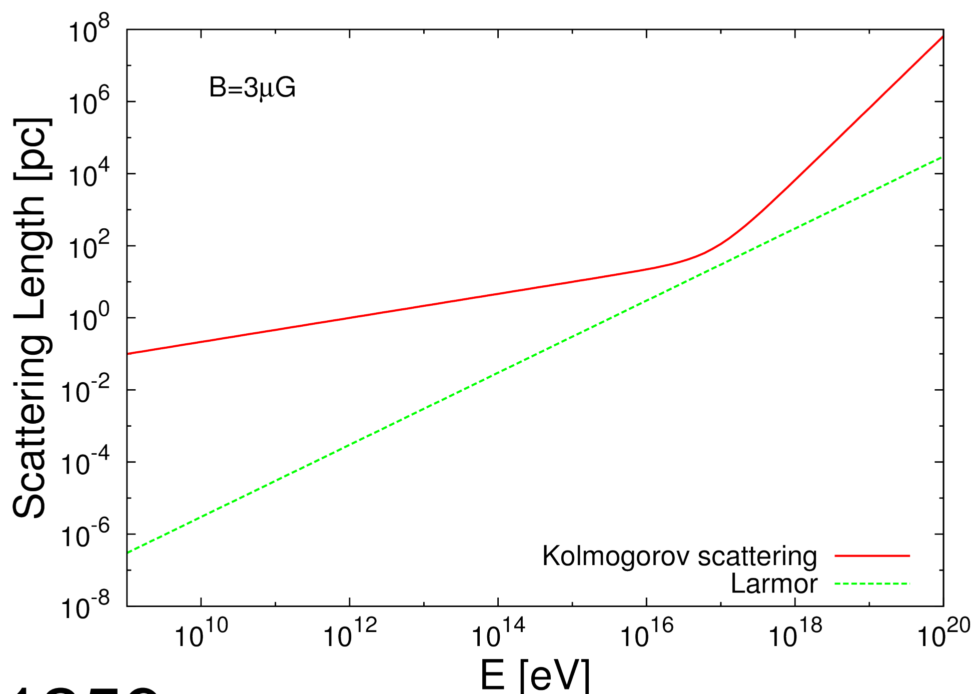
$$t_{\mathrm{acc}} = \eta \frac{r_{\mathrm{larmor}}}{c\beta^2}$$

η dependent on normalisation and slope of magnetic turbulence power-spectrum

$$P(k) \propto k^{-\alpha} \qquad \alpha = \frac{5}{3}$$

Important parameters:

$$\frac{\delta B^2}{B_0^2}, \quad \lambda_{\mathrm{max}}$$



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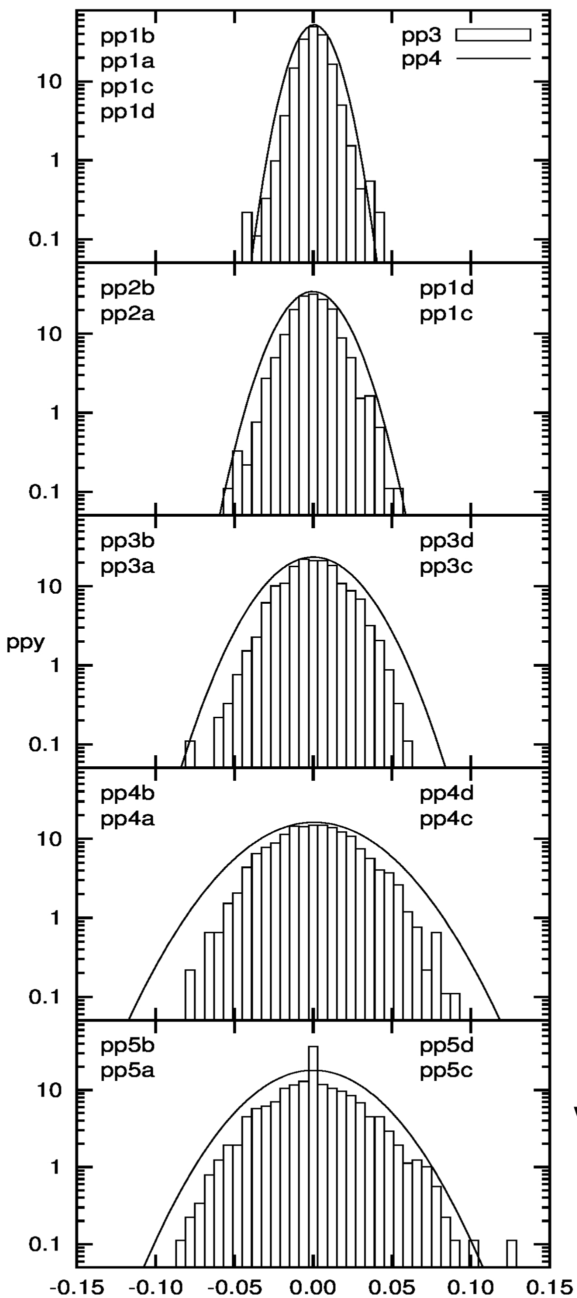
astro-ph/0903.1259

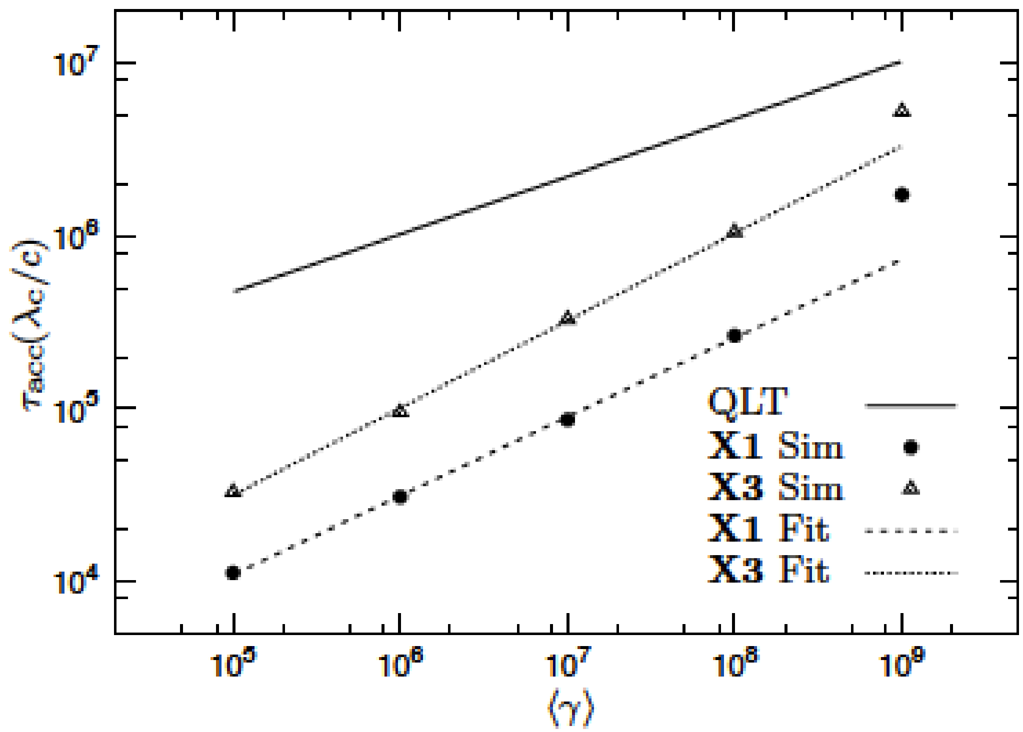
Example Candidate UHECR Source
(a Nuclei Friendly Environment)

astro-ph/0903.1259



time

$$t_{\rm acc} = \eta \frac{r_{\rm larmor}}{c\beta^2}$$



Yes, but requires:

$\beta_A > 0.1$

where $\beta_A = \frac{1}{c}\frac{B}{\sqrt{4\pi m_p n_p}}$

Which Nearby AGN?

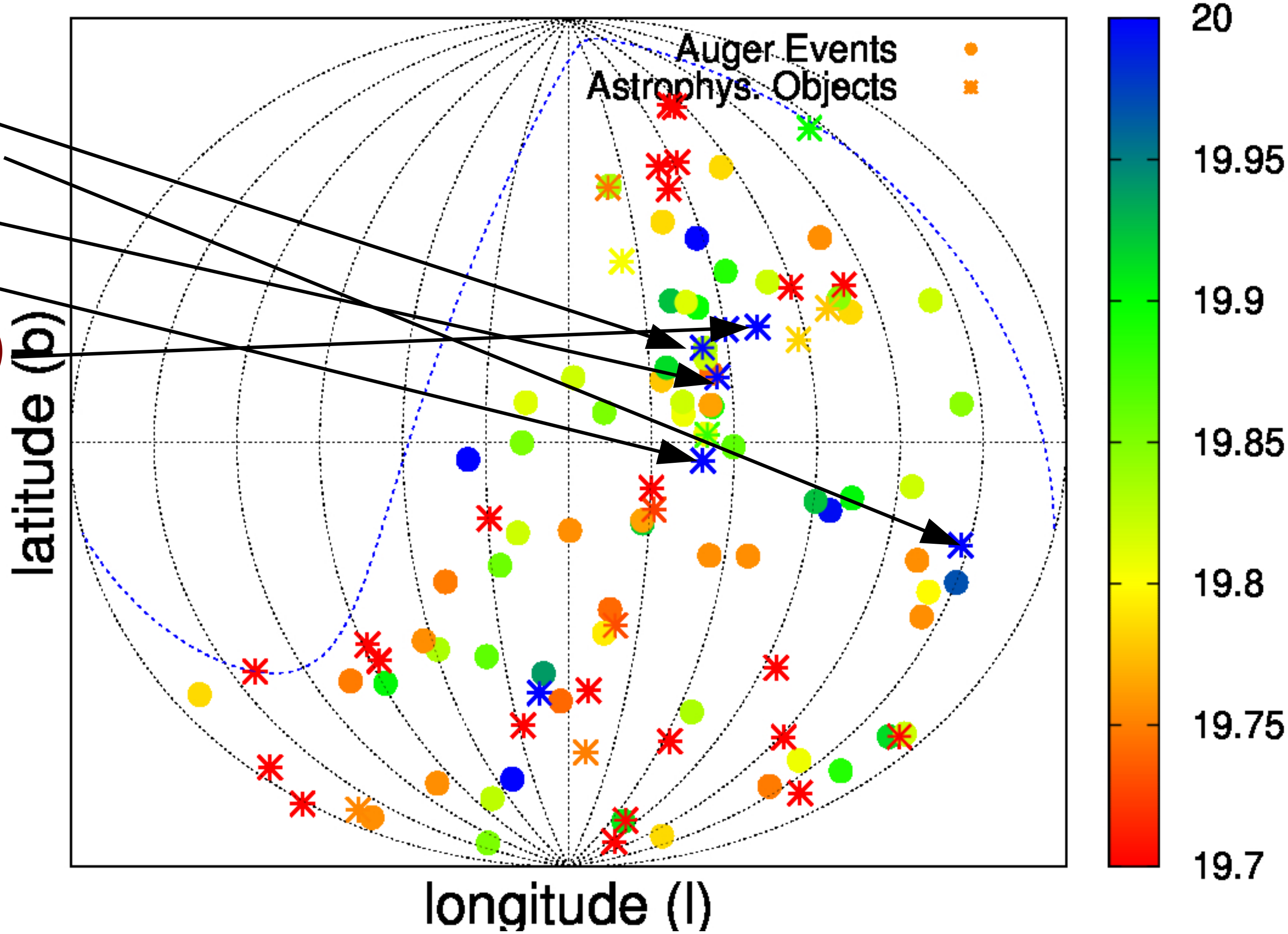
($L_X > 10^{42}$ erg s^{-1}, D<60 Mpc)

TOP 5 in L/D^2:

1) **Cen A (4 Mpc)**
2) **NGC 2110 (30 Mpc)**
3) **NGC 4945 (4 Mpc)**
4) **Circinus (4 Mpc)**
5) **NGC 3783 (40 Mpc)**

(from 1st Integral or Swift 58 month catalogues)

TOTAL: 41



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$$s = log_{10}(L_X/z^2) - 27.5$$

Which Nearby AGN?

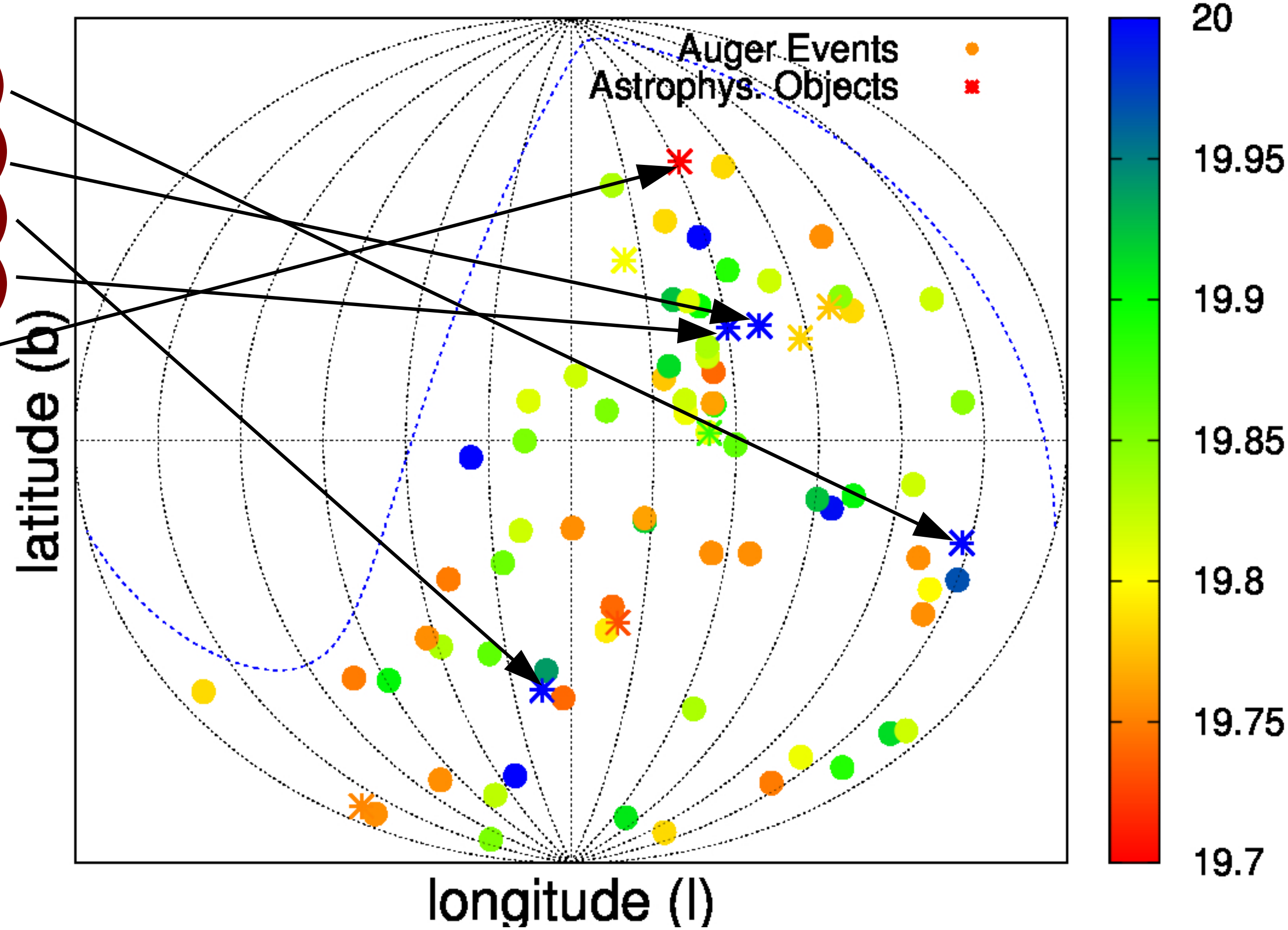
($L_X > 10^{43}$ erg s^{-1}, D<60 Mpc)

TOP 5 in L/D^2:

1) **NGC 2110 (30 Mpc)**
2) **NGC 3783 (40 Mpc)**
3) **NGC 7172 (38 Mpc)**
4) **NGC 4507 (52 Mpc)**
5) **4U 1344 (53 Mpc)**

(from 1st Integral or Swift 58 month catalogues)

TOTAL: 11



$$s = log_{10}(L_X/z^2) - 27.5$$

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VHE gamma-ray Emission Local AGN?

($L_X > 10^{42}$ erg s^{-1}, D<60 Mpc)

TOP 5 in L/D^2:	GeV Emission	TeV Emission
1) Cen A (4 Mpc)	✓	✓
2) NGC 2110 (30 Mpc)		
3) NGC 4945 (4 Mpc)	✓	
4) Circinus (4 Mpc)	✓	
5) NGC 3783 (40 Mpc)		

(from 1st Integral or Swift 58 month catalogues)

AGN Jets

Starburst Activity

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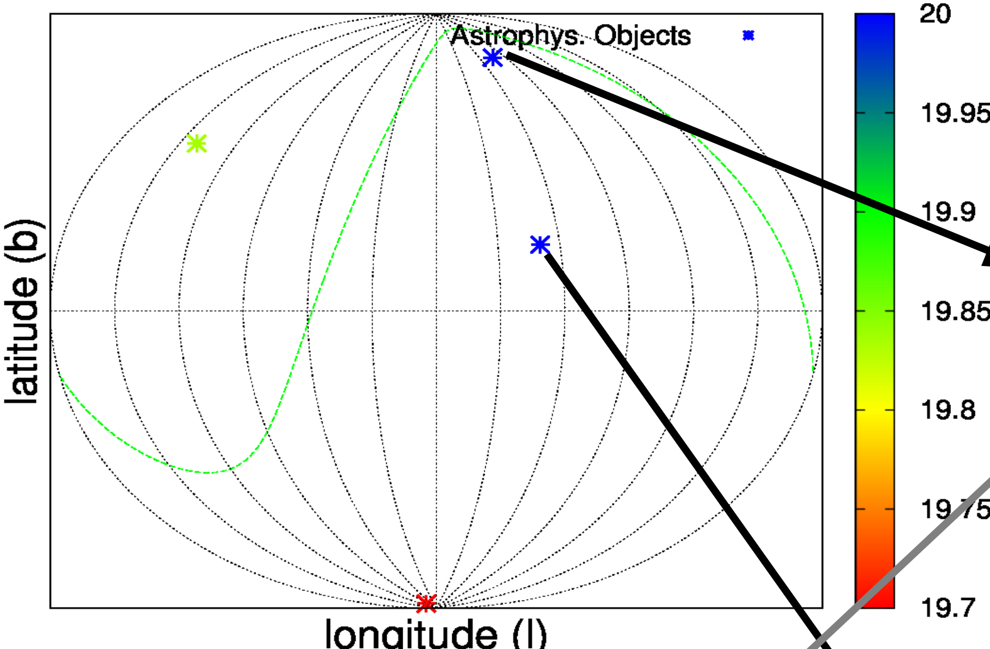
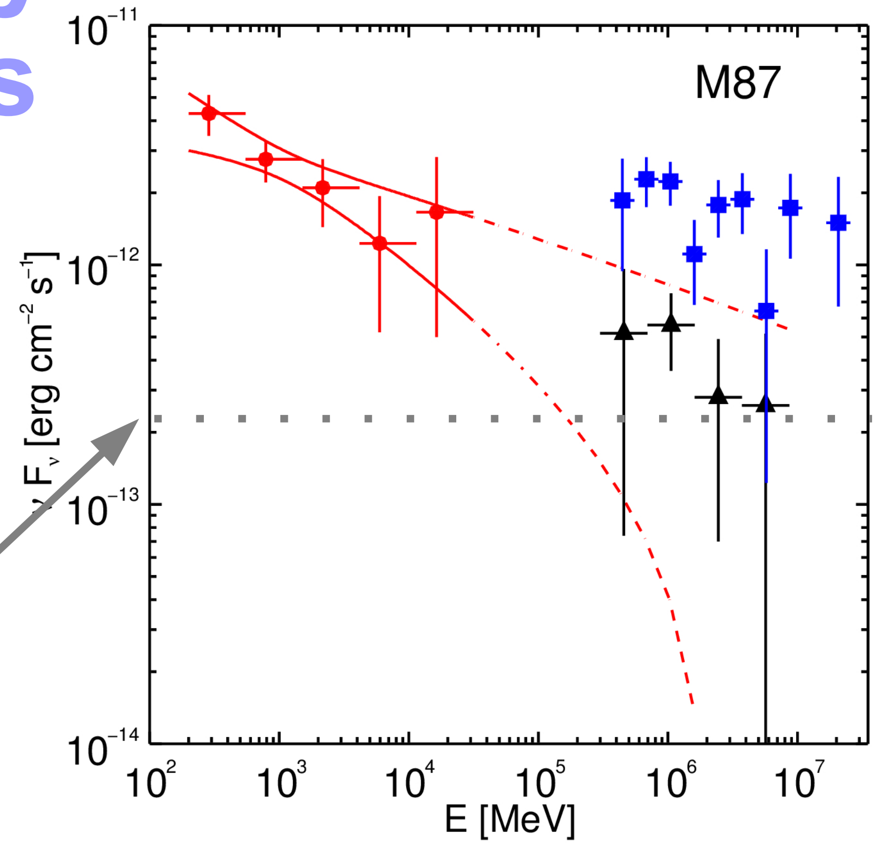
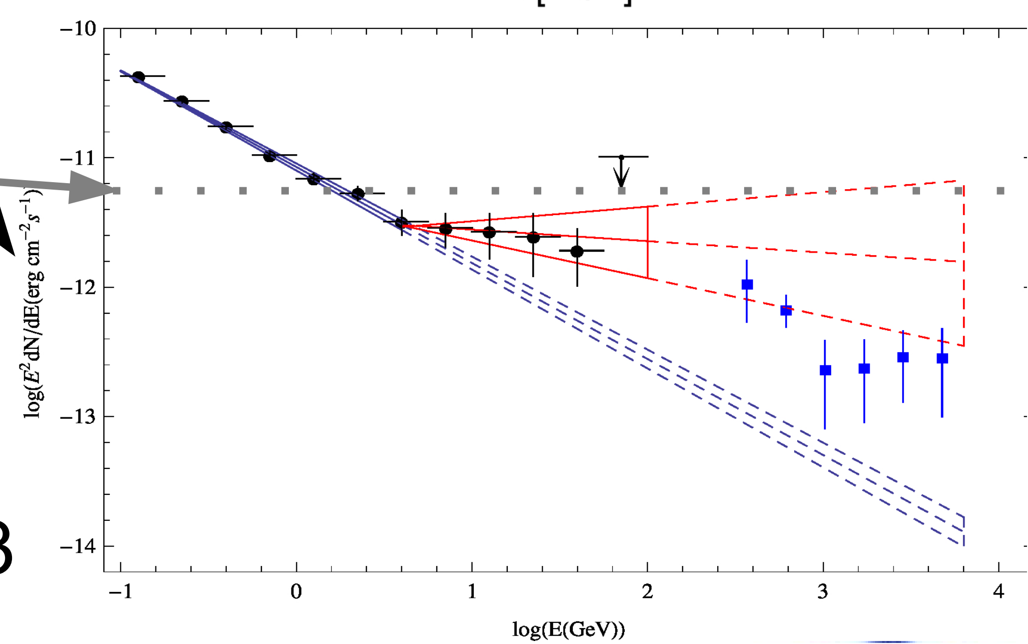
Local AGN Detected by Cherenkov Telescopes

Abdo et al. 2009



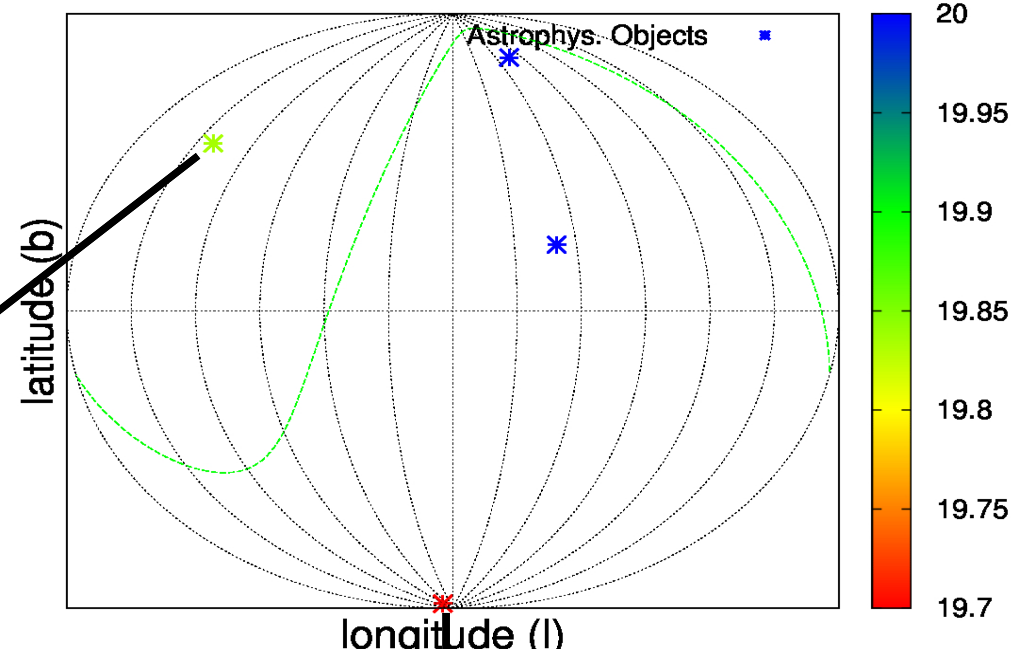


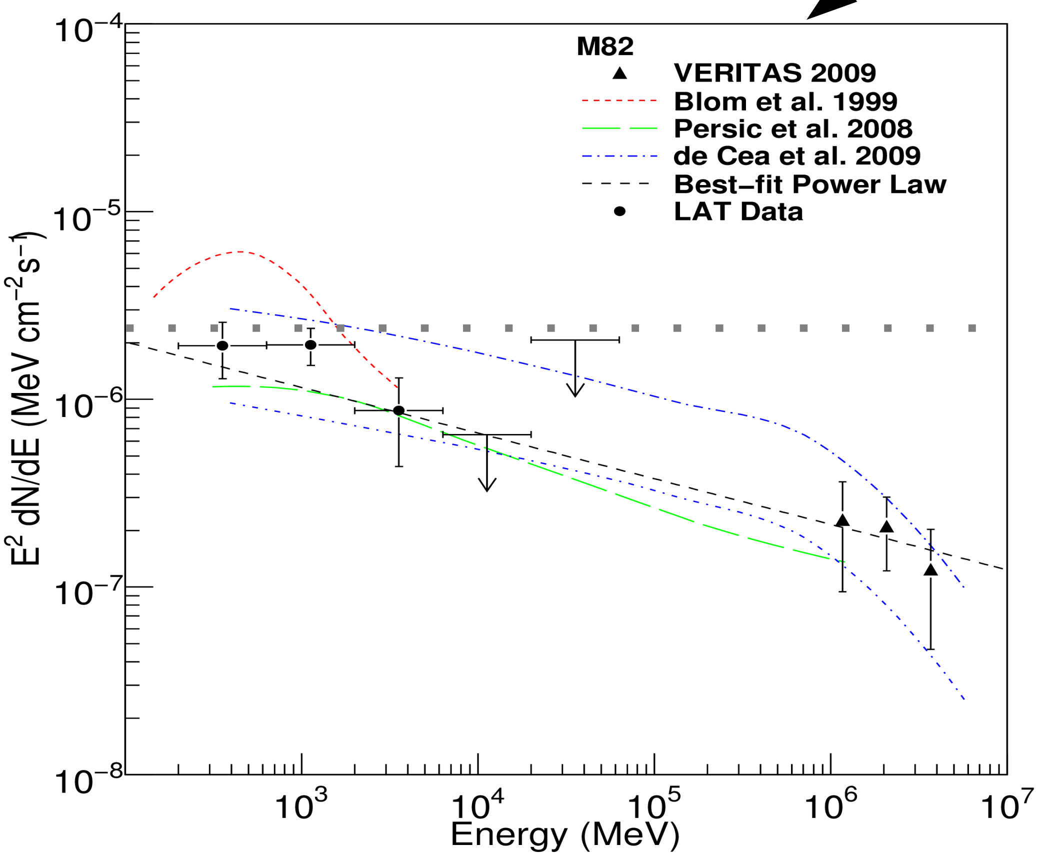
10^{40} erg s^{-1}

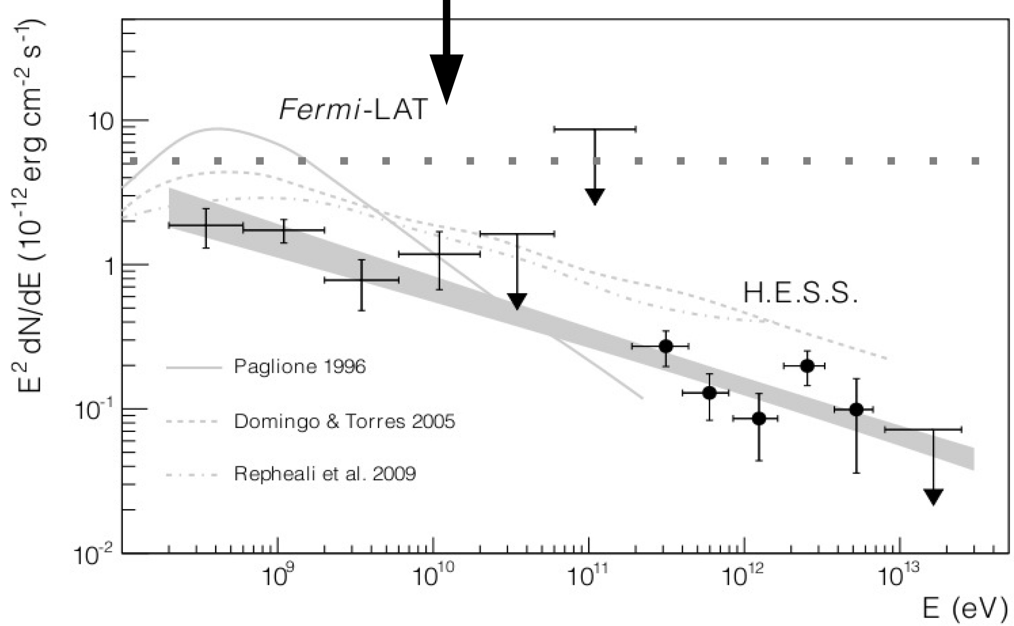


Sahakyan et al. 2013

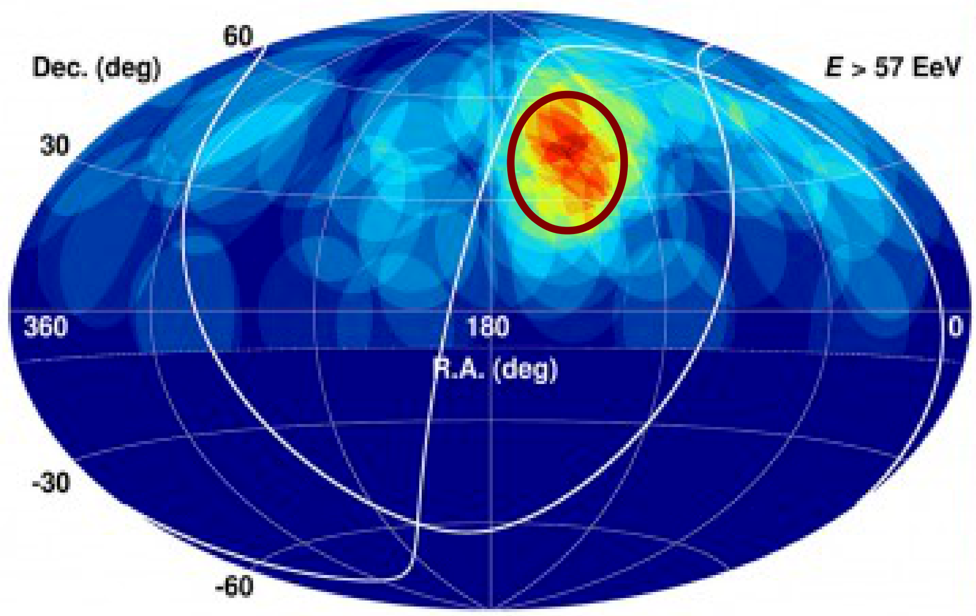
Local AGN/Starburst Galaxies Detected by Cherenkov Telescopes

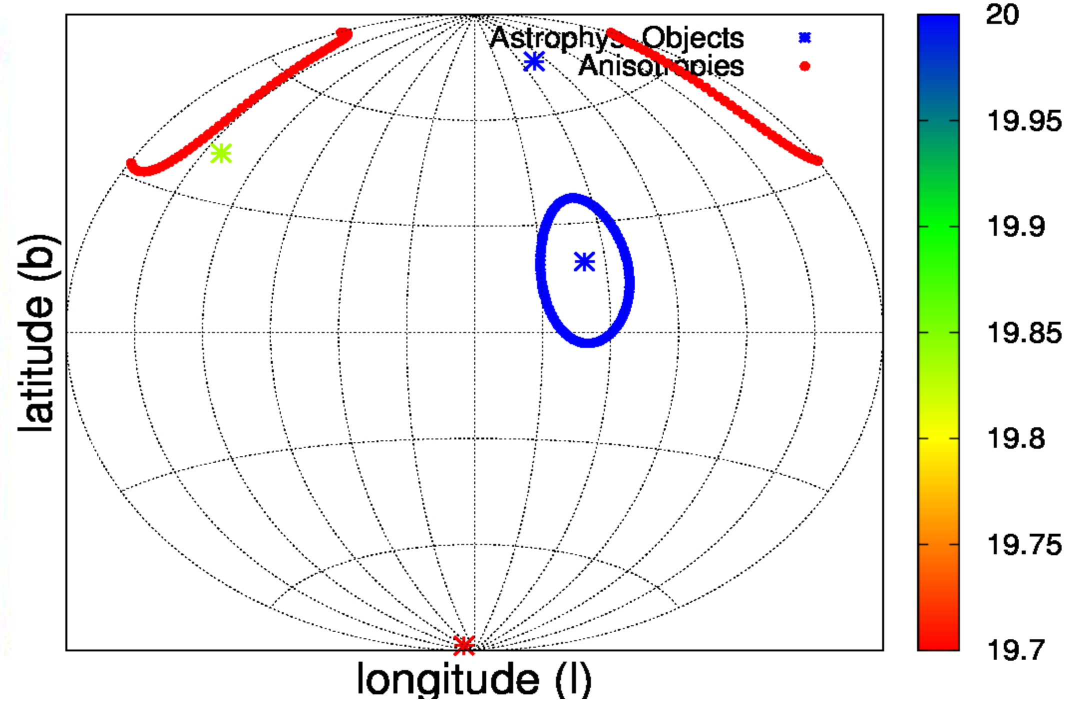


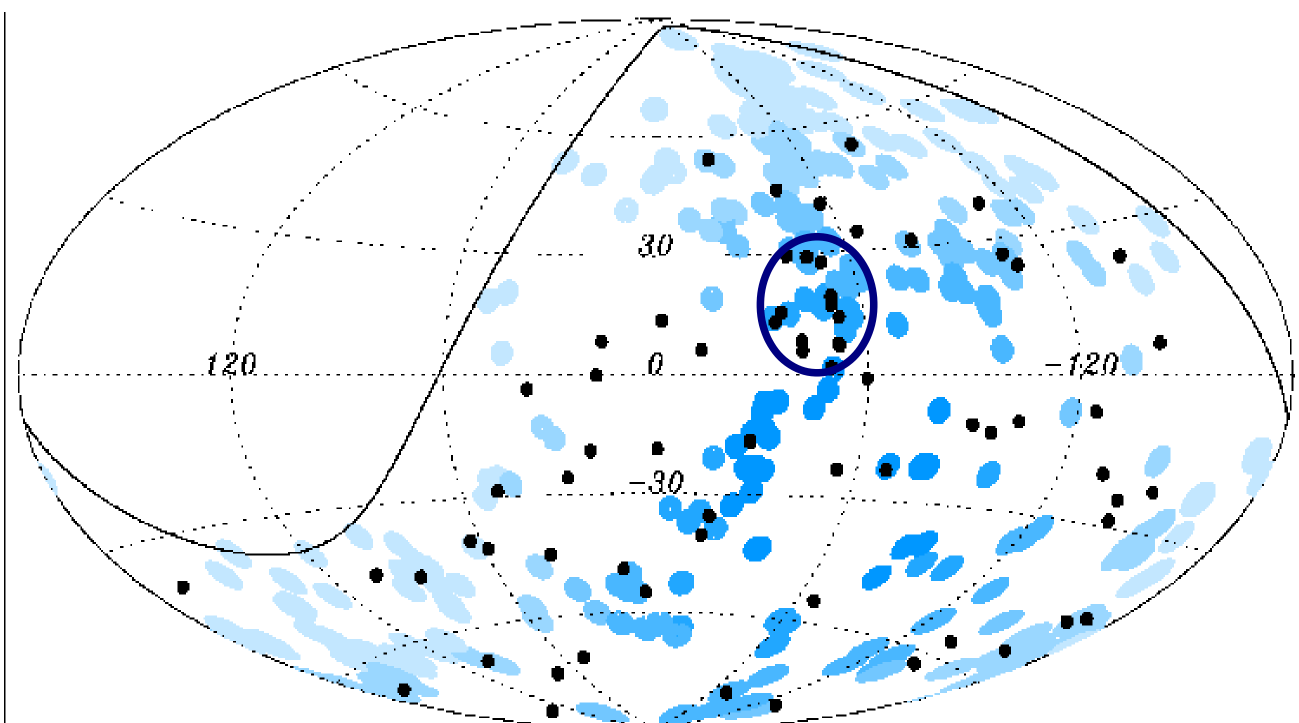




Could There Be A Connection......?







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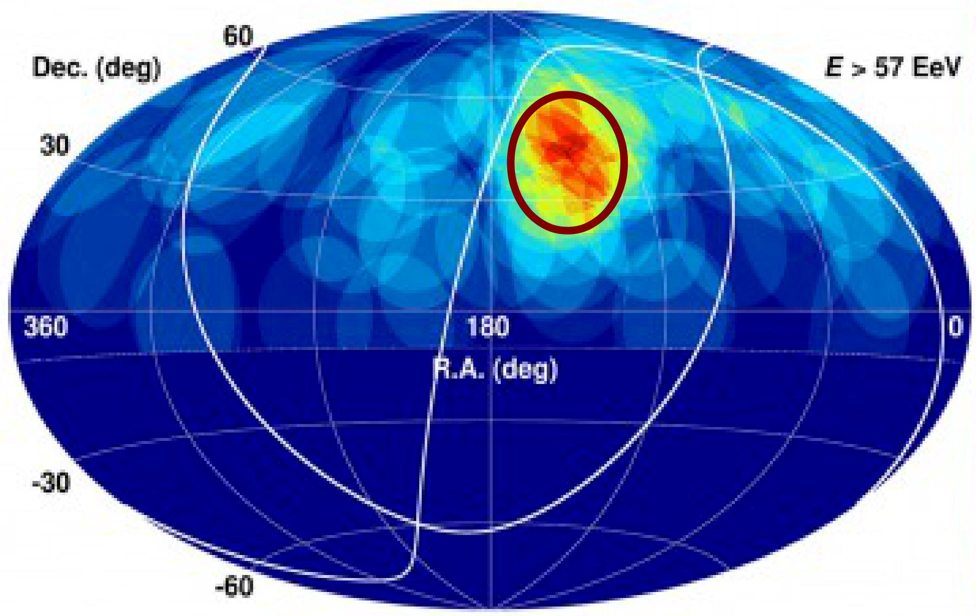
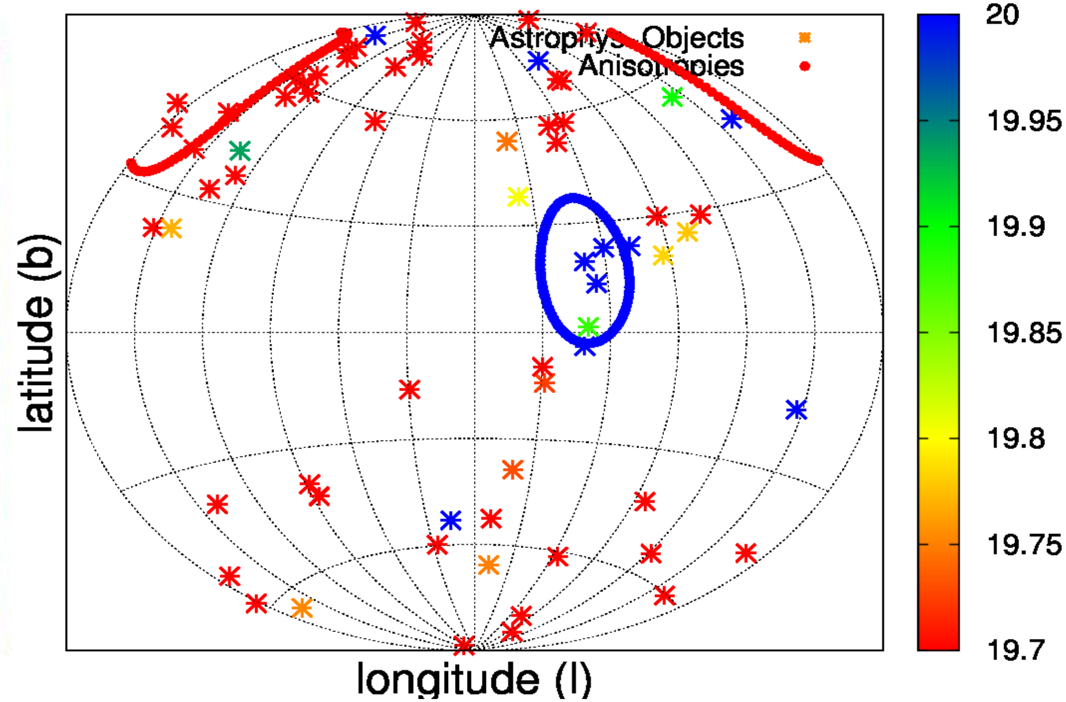
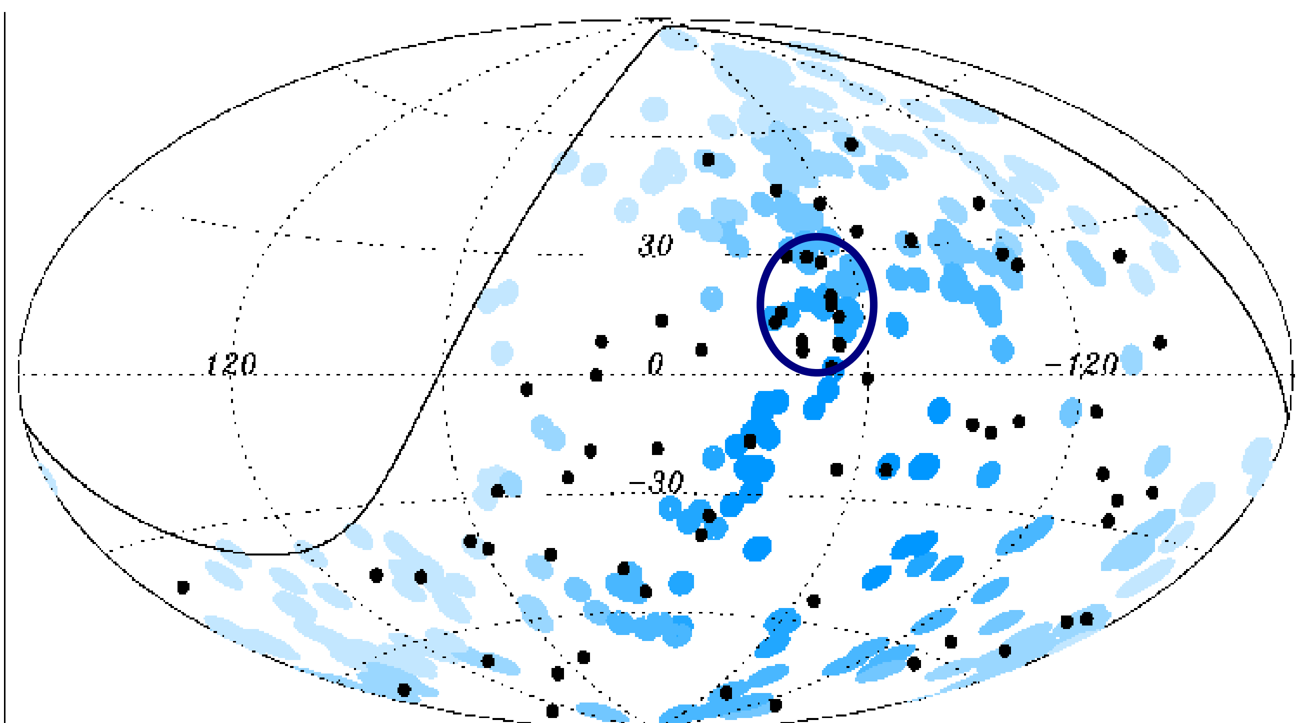
Could There Be A Connection......?







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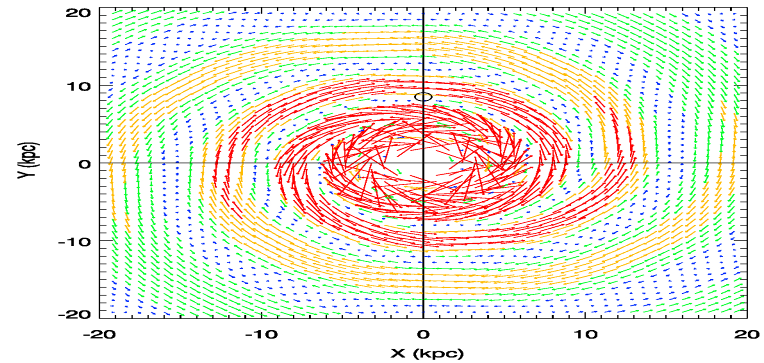
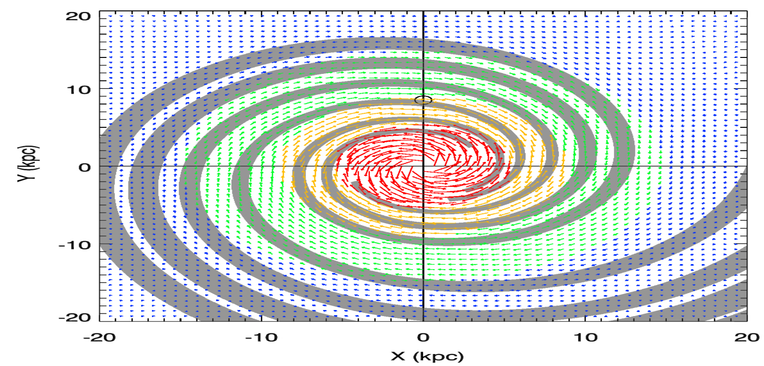
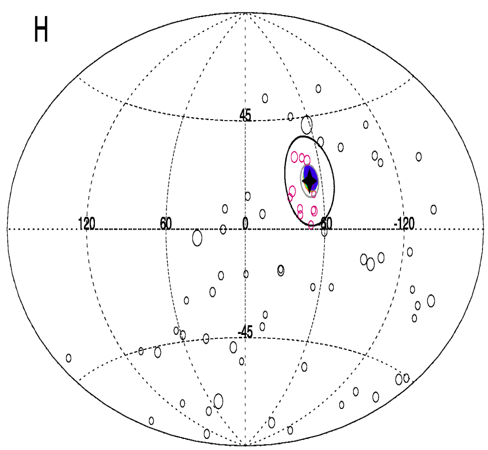
Anisotropy Signatures of UHECR From Cen A?

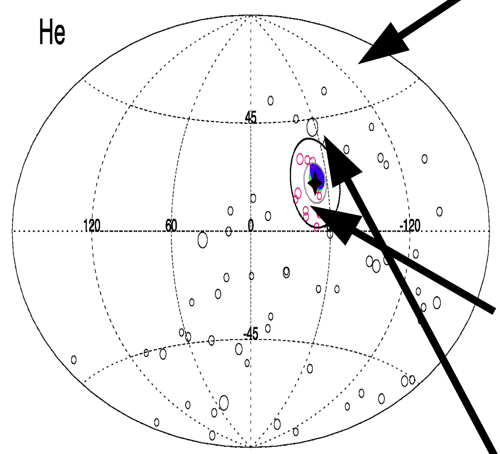




p only



He only

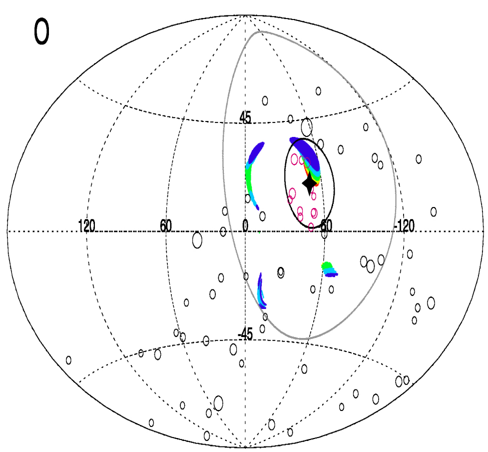


18°

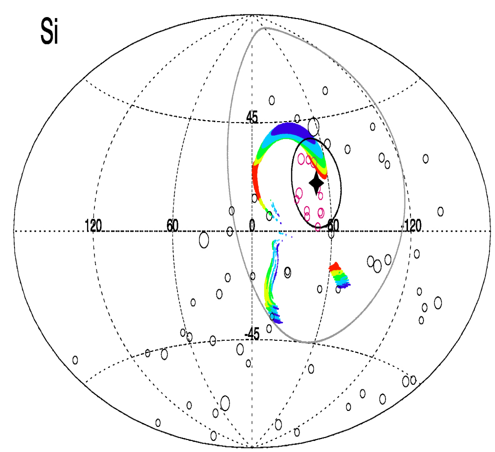
13 events

Cen A

O only



Si only

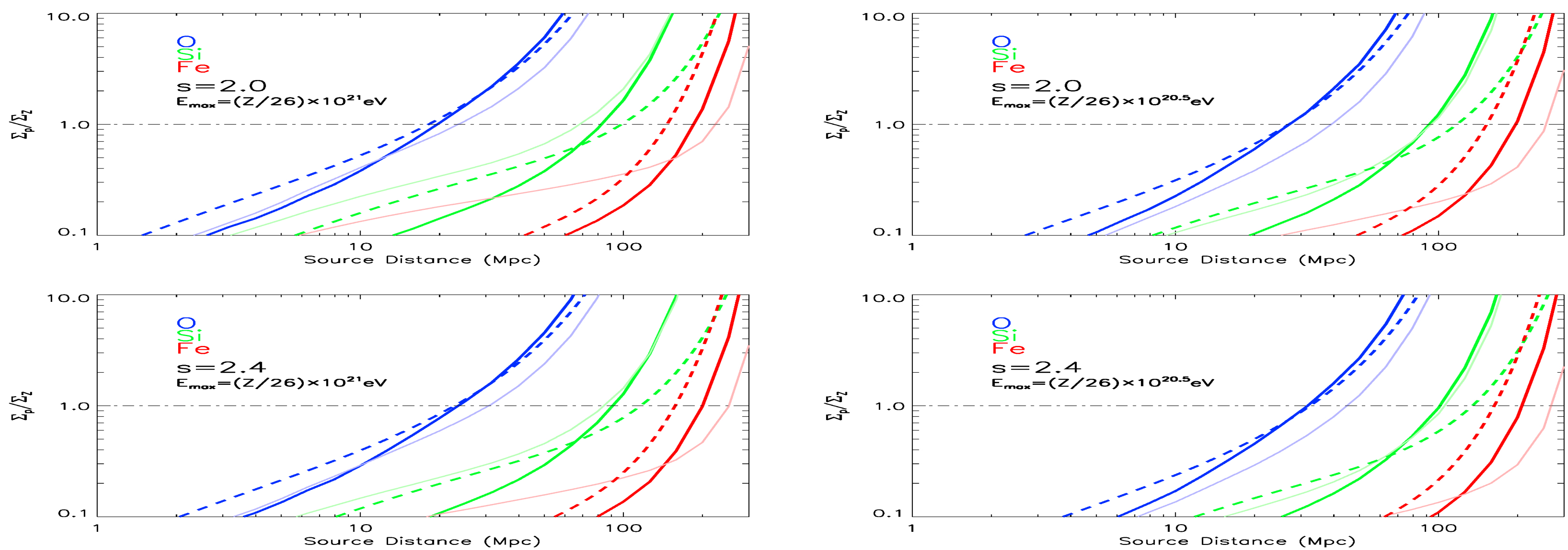


astro-ph/1206.3907

Anisotropy Signatures of UHECR Sources?

$$55 \text{ EeV} < E_Z < 84 \text{ EeV}$$

$$55/Z \text{ EeV} < E_p < 84/Z \text{ EeV}$$



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astro-ph/1308.5699

Conclusion

The dominance of nuclei at high energies provides useful new information about the proximity and spectra of UHECR sources

Intermediate (not compact or too large scale) regions of AGN potentially can satisfy the source requirement criterion

The correlation of UHECR with AGN coupled with their composition information has great potential for providing “depth” information to a potential source

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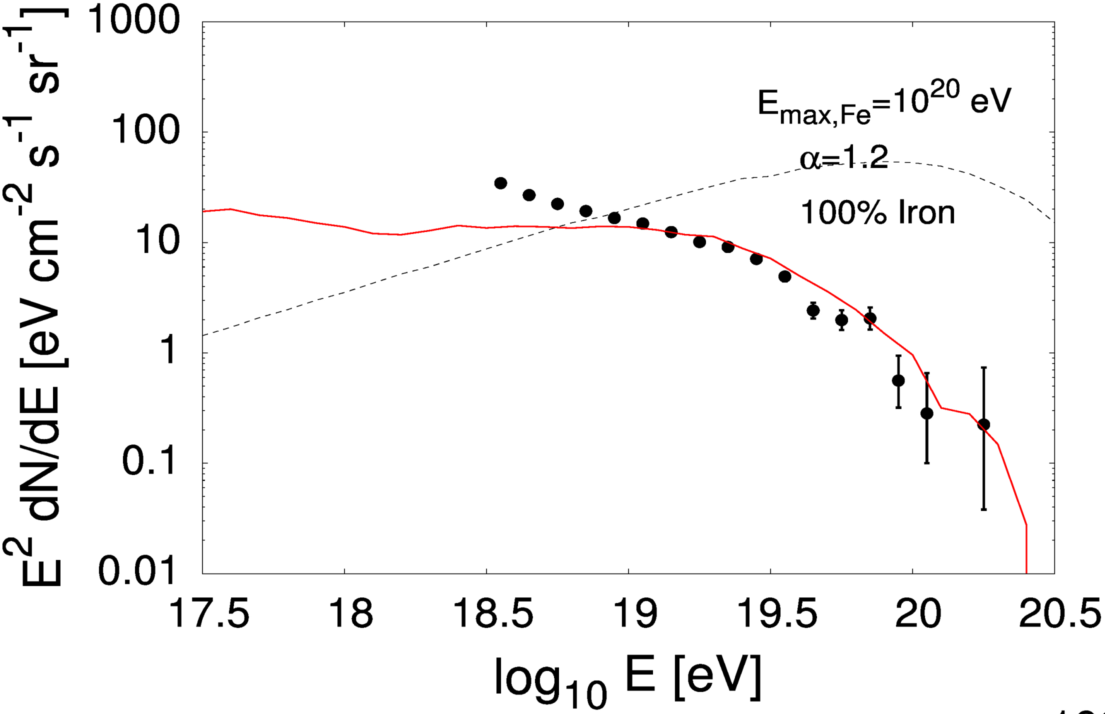
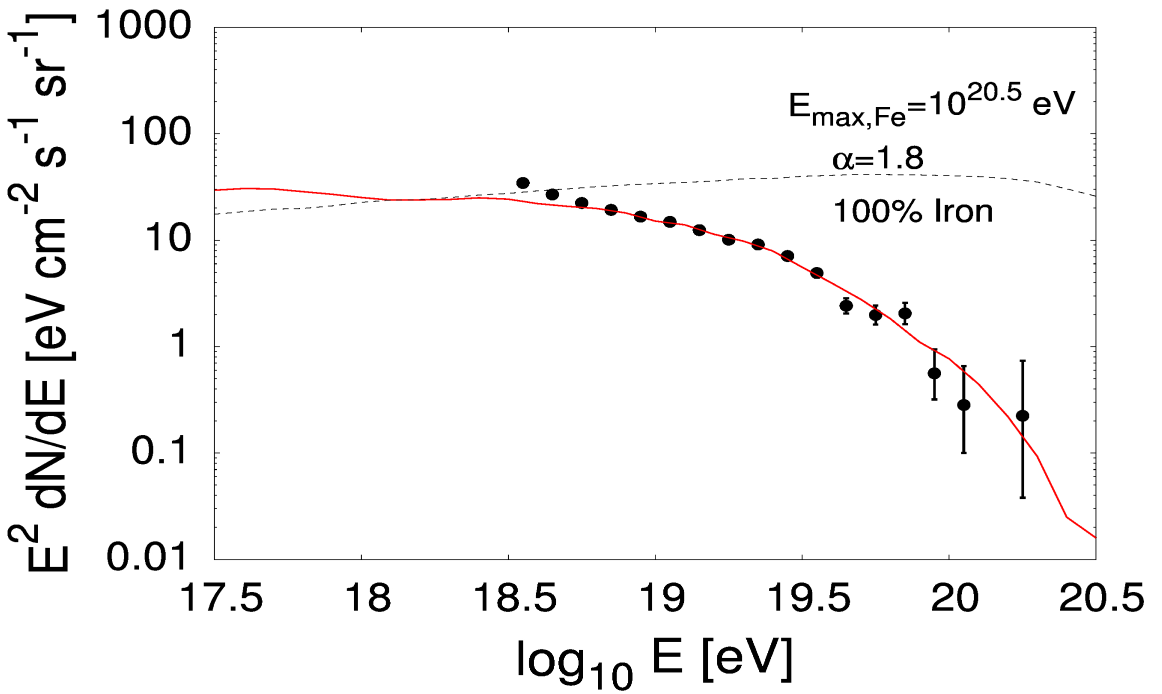
Extra Slides

E_{max} and α Relation





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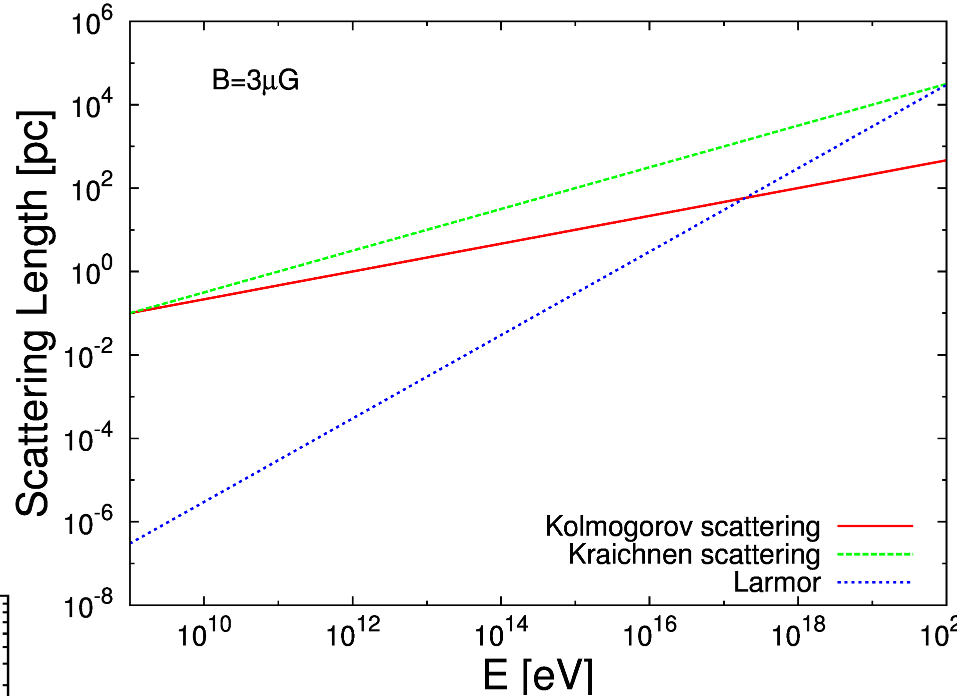
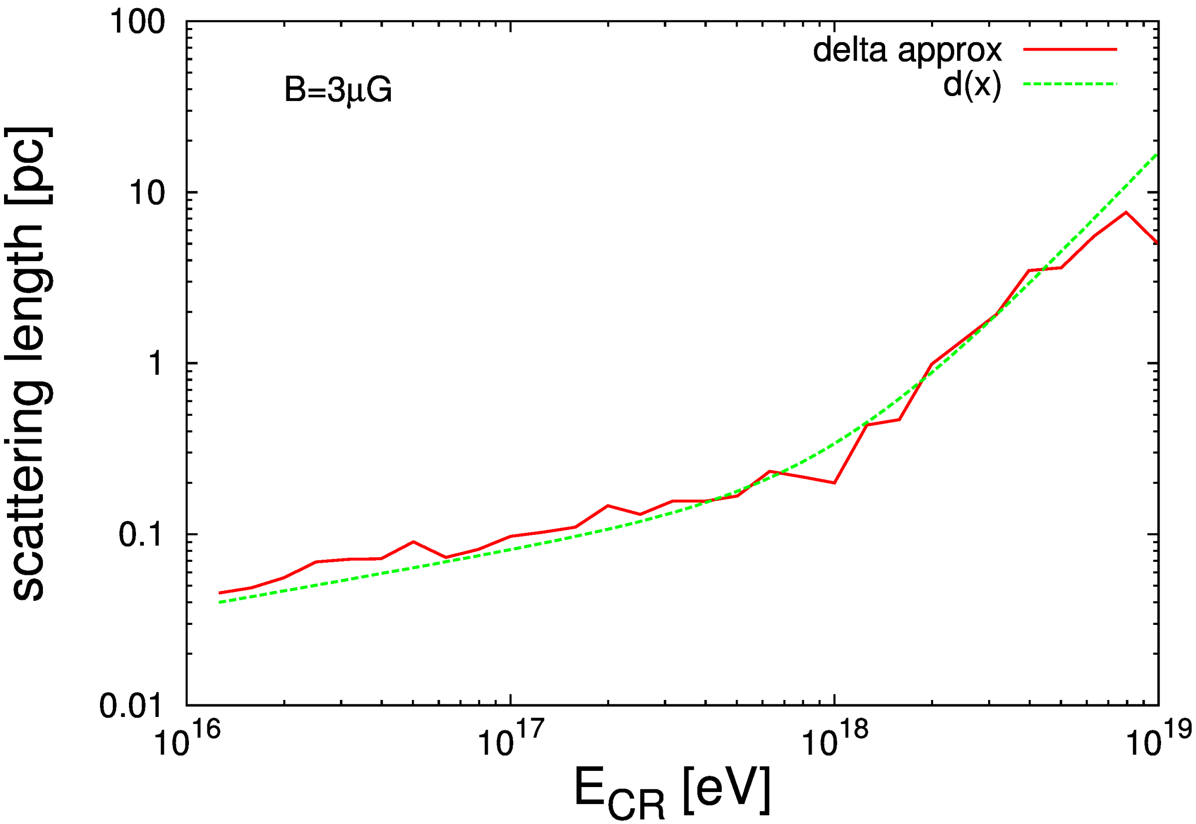
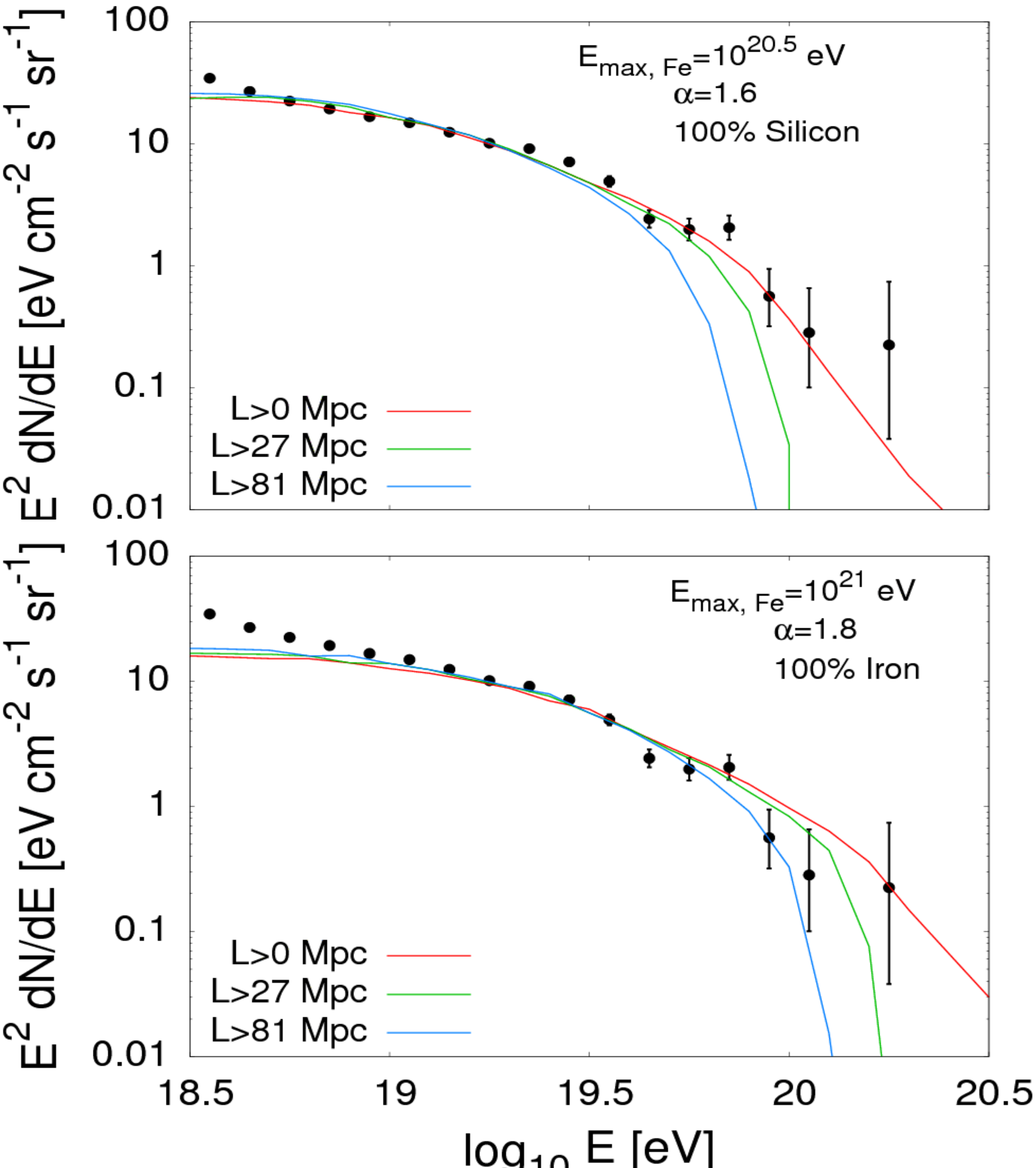
Prospects for CR Astronomy?





How Far is the Nearest Source?



L>0 Mpc

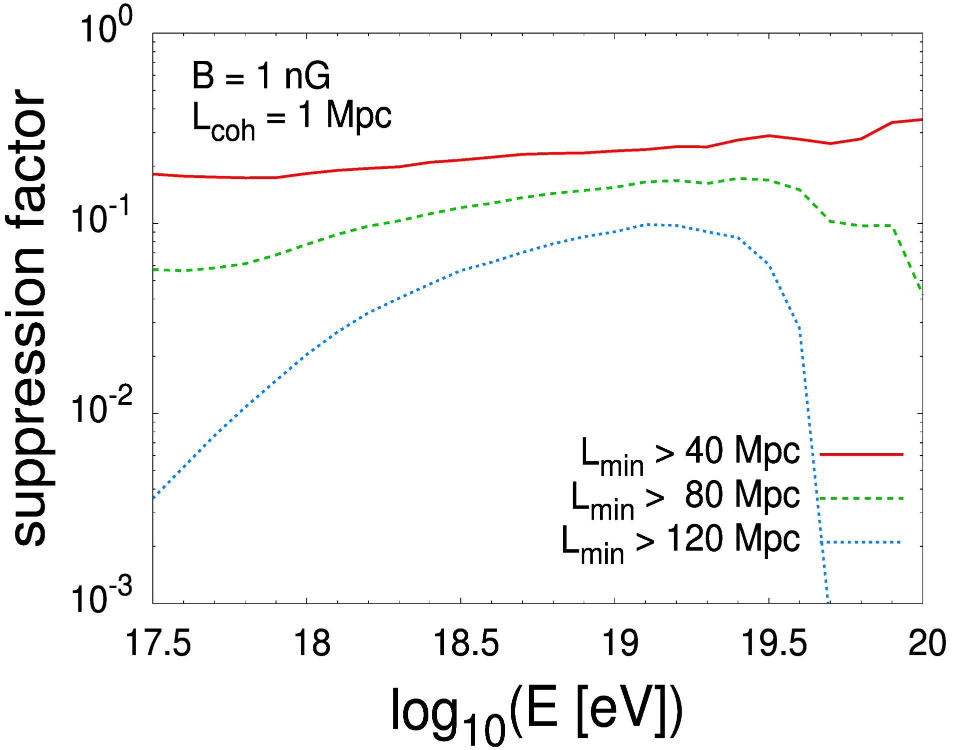
L>27 Mpc

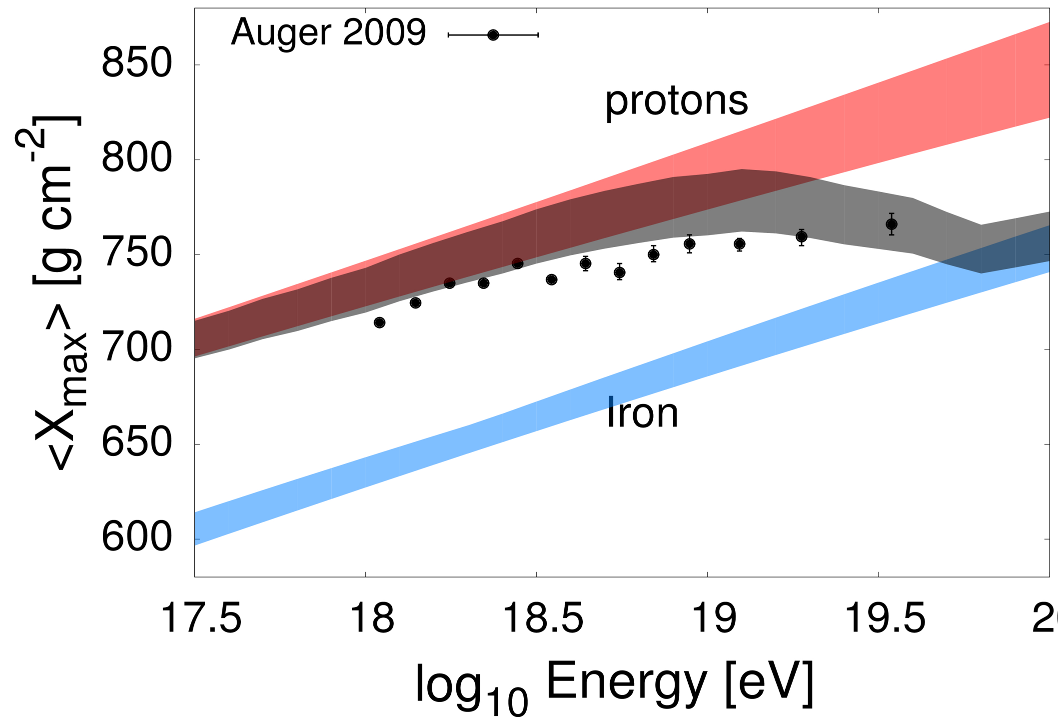
L>81 Mpc

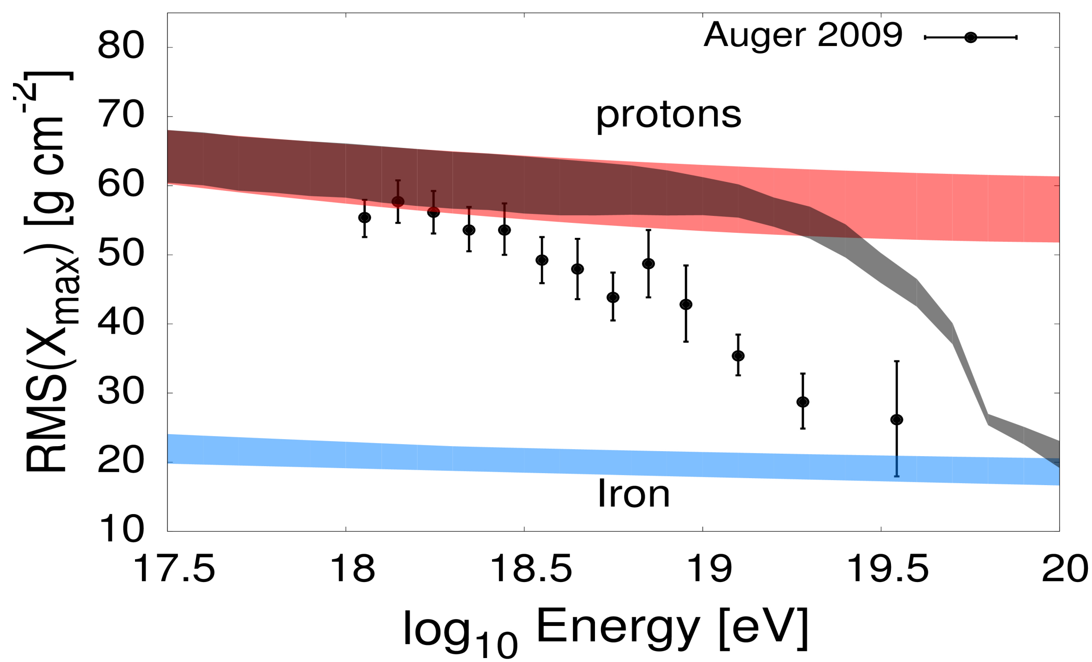
Extragalactic Magnetic Fields

L_{min}>81 Mpc

B=1 nG, L_{coh}=1 Mpc







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The Need for a Heavy Composition

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

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

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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

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

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Extragalactic Magnetic Fields

L>27 Mpc

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$$R_{\mathrm{Larmor}} \approx 4 \left(\frac{E}{10^{20}\ \mathrm{eV}}\right)\left(\frac{\mathrm{n}G}{B}\right)\left(\frac{26}{Z}\right)\ \mathrm{Mpc}$$