# Lecture Plan:

1) Cosmic Ray acceleration- accelerated spectrum, efficient accelerators, nuclei friendly

PROBLEMS

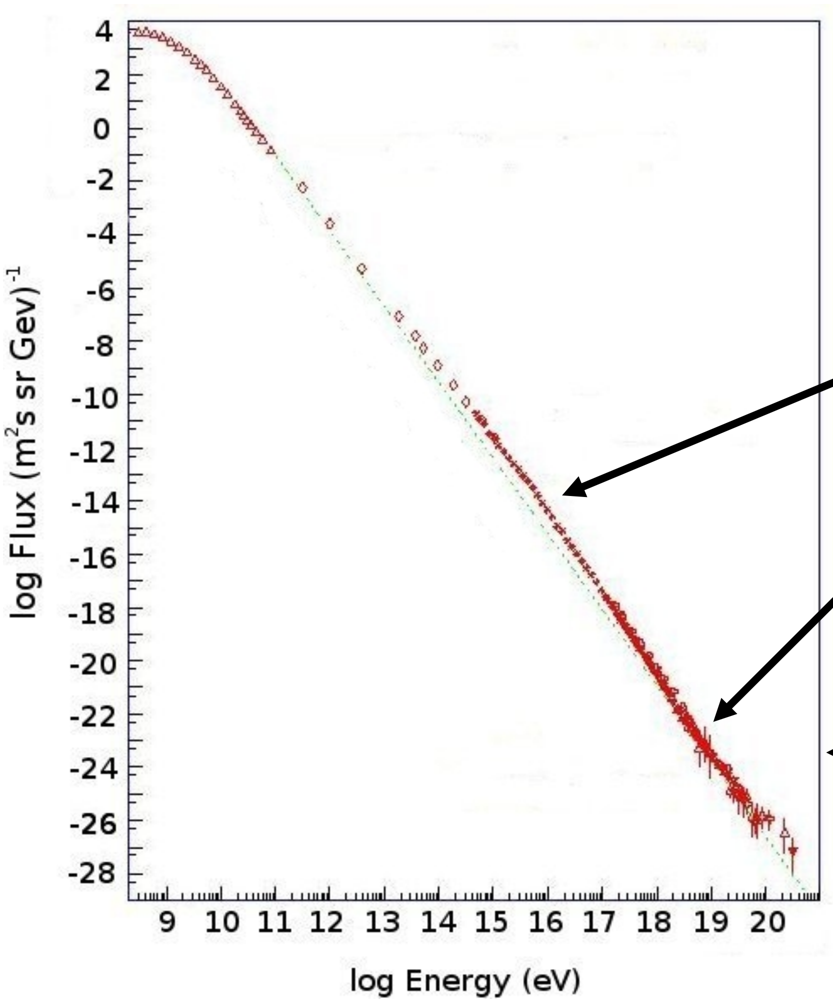
2) Cosmic Ray proton + nuclei interaction rates in extragalactic radiation fields

PROBLEMS

3) Cosmic Ray propagation through Galactic and extragalactic magnetic fields

# Where Does the Extragalactic Spectrum Begin?

# Arriving Flux- a Signature for the Onset of an Extragalactic Component?




“knee”

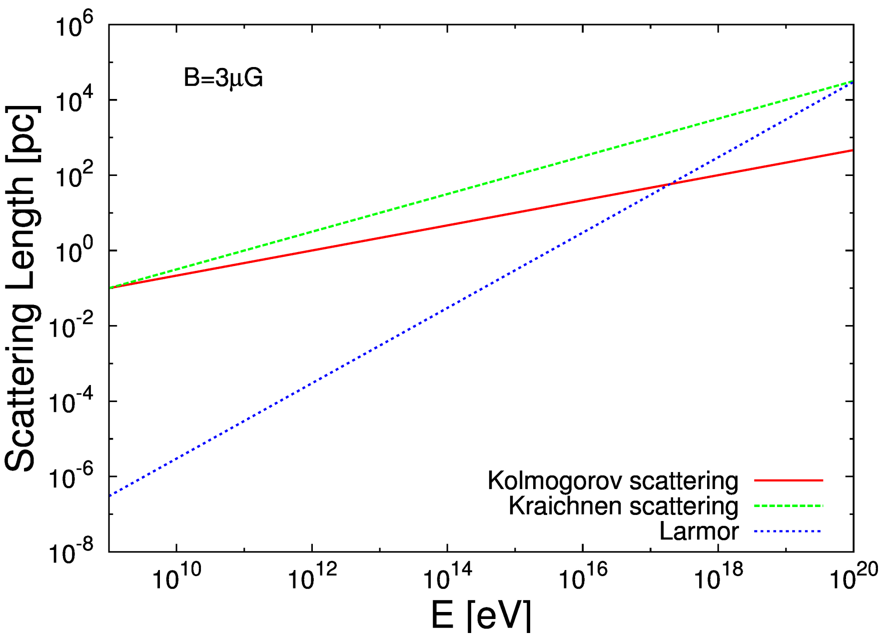
“ankle”

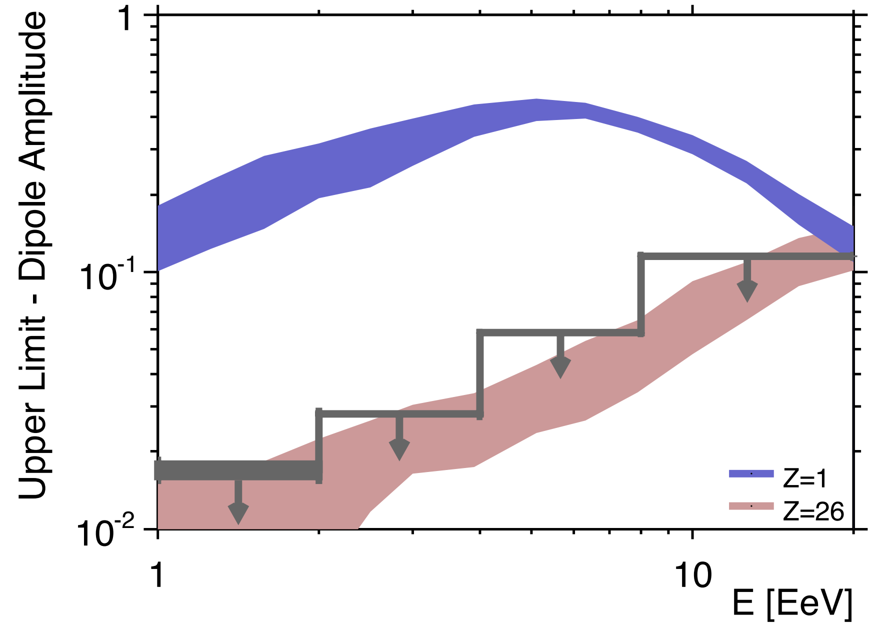
where does extragalactic begin?

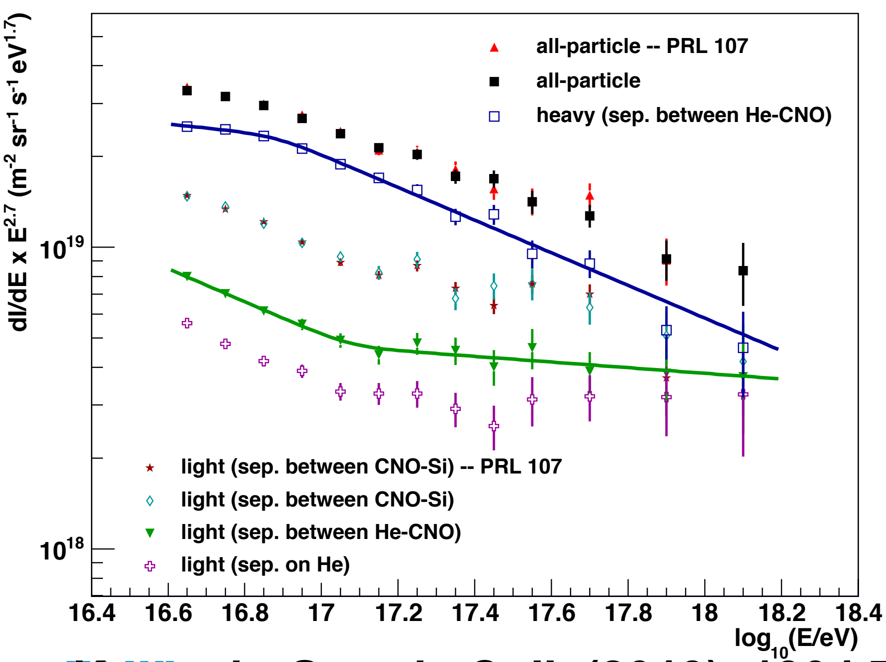
.....presumably there should be a signature(s)

# Transition Energy Probes

Anisotropy constraint: **Giacinti et al. (2011), 1112.5599**
**Pierre Auger Collab. (2012), 1212.3083**

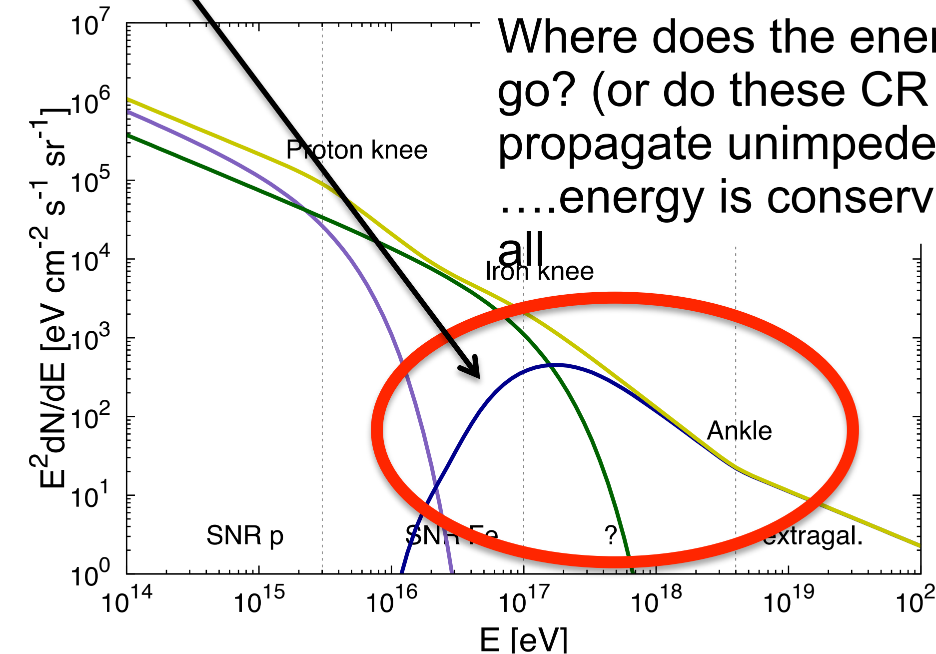



**Kascade-Grande Coll. (2013), 1304.7114**

Magnetic horizon effect

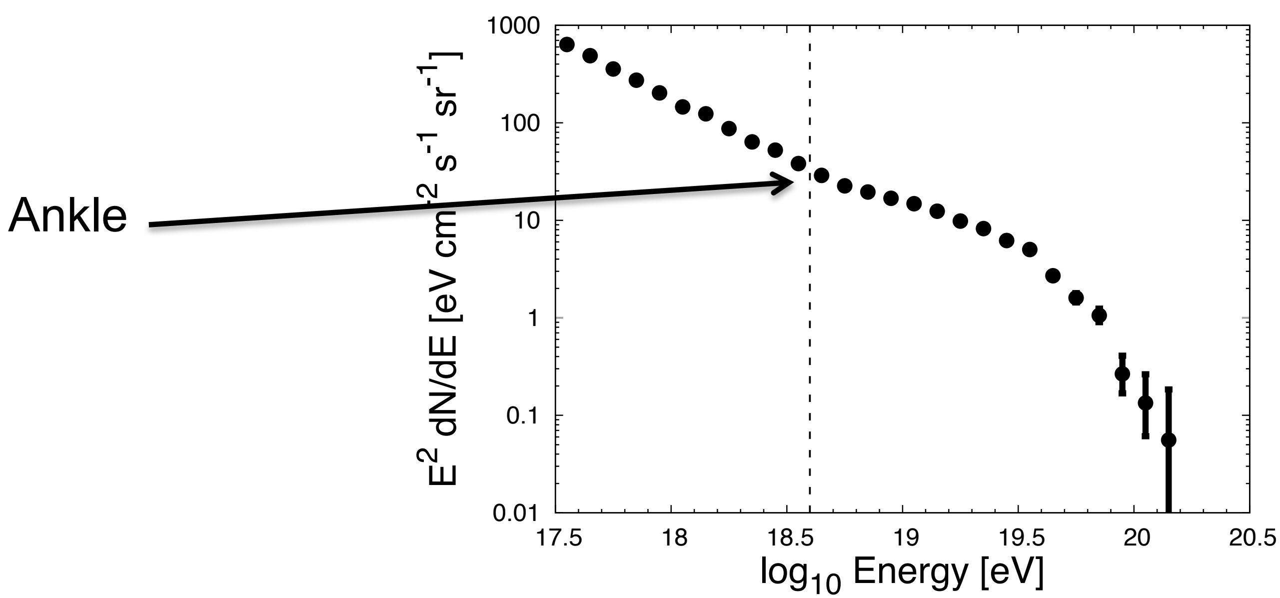



Where does the energy flux go? (or do these CR propagate unimpeded?) ….energy is conserved after all

# Why Consider UHECR to Understand the Galactic/Extragalactic Transition?

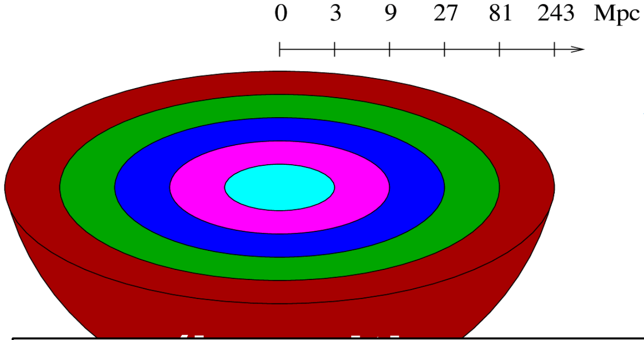
Since the ankle feature appears at an energy of $\sim 10^{18.6}$ eV, a new extragalactic source class is presumed to begin to dominate here (in the first instance)

Information obtained about this source class from investigations into the UHECR sources may provide new insights into Galactic-Extragalactic transition energy

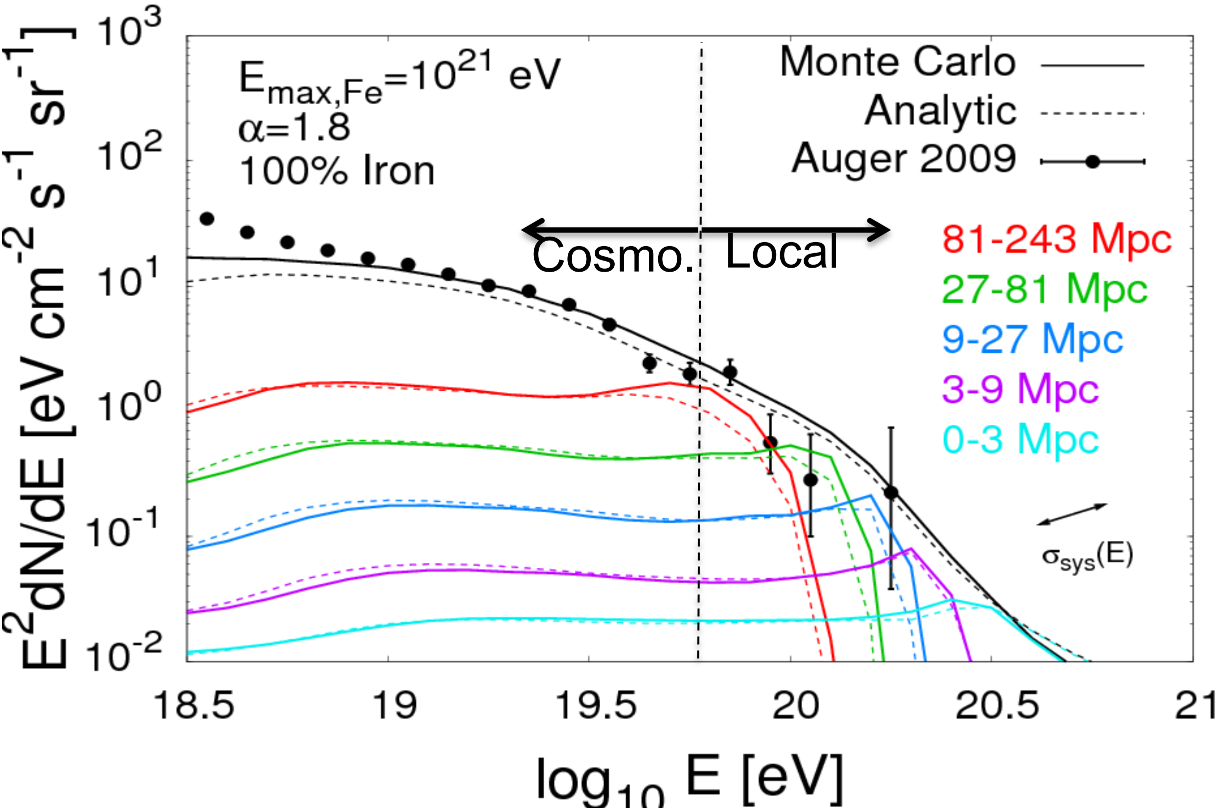


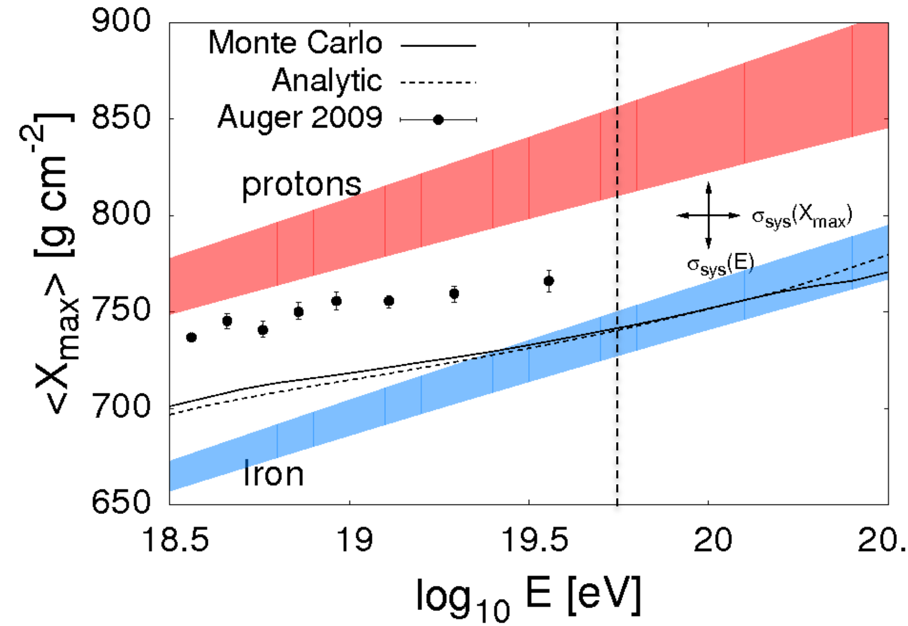
# Mapping Cosmic Ray Energy to Source Distance

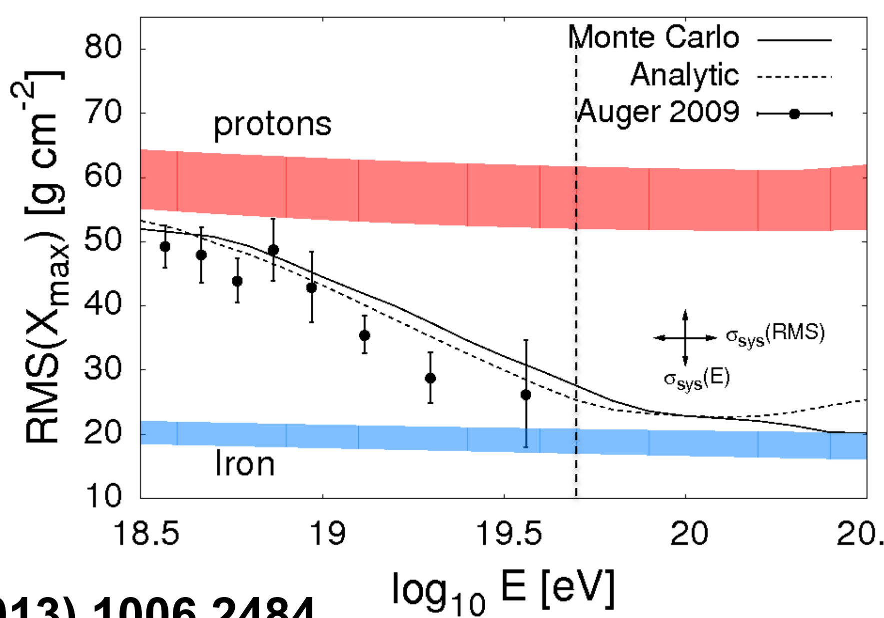
# Local Scales Effect Highest Energies: Analytic Treatments




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



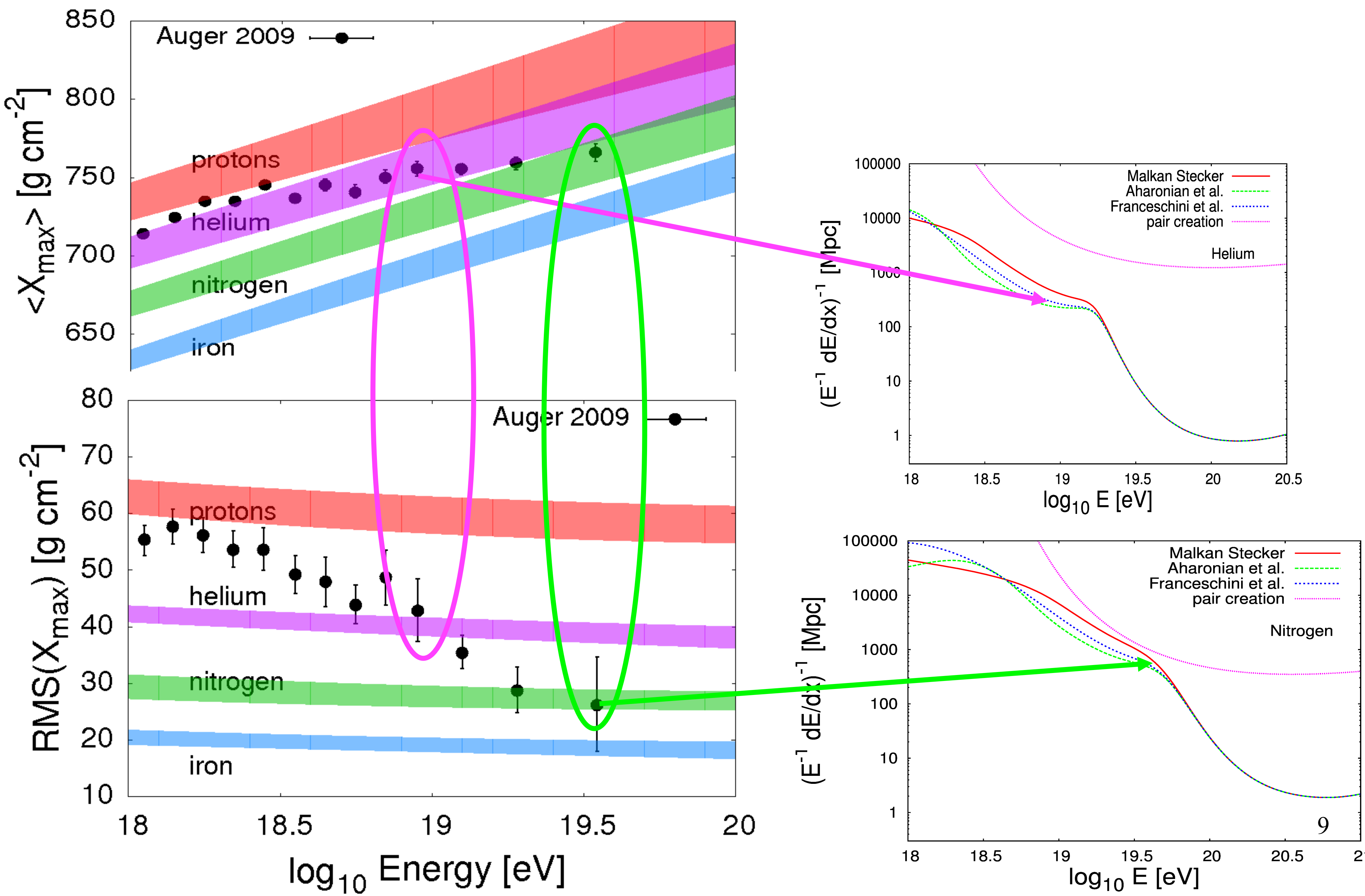




**Hooper et al. (2008), 0802.1538** **Aloisio et al. (2013) 1006.2484**

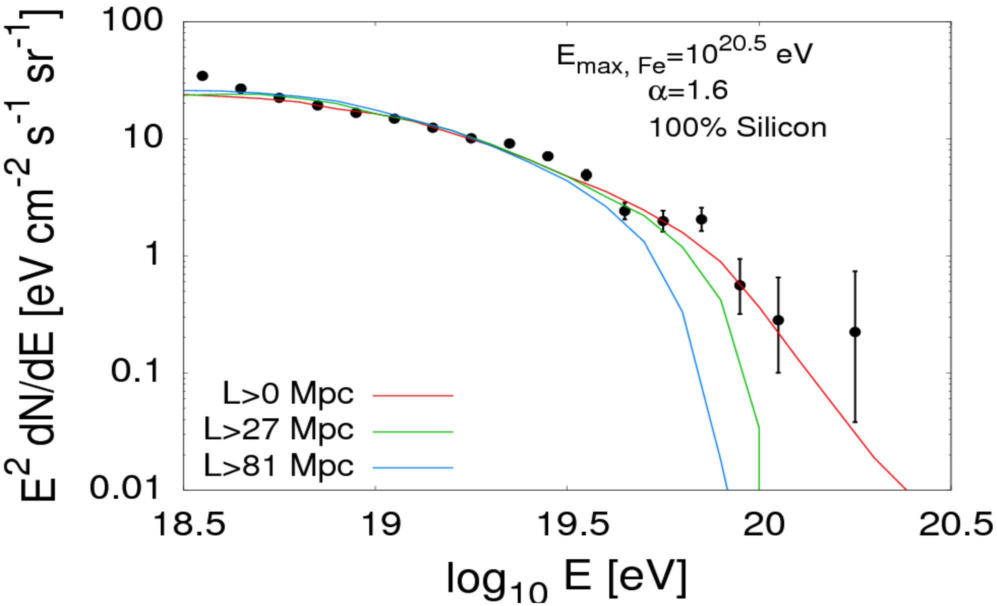
# The High Energy Part of the Extragalactic Spectrum

# Composition Interpretation

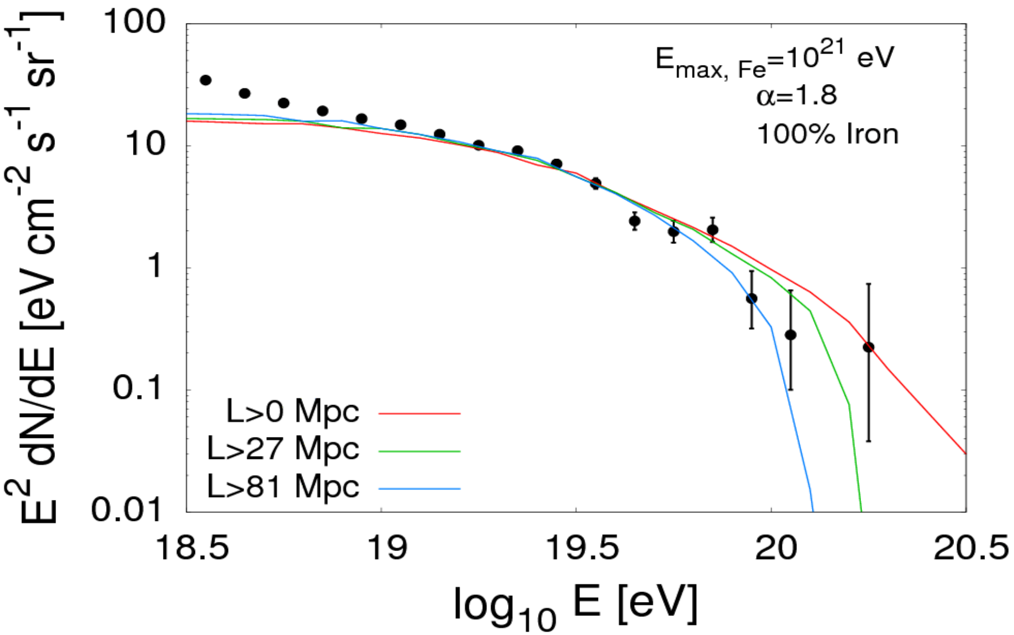


# How Far is the Nearest Source?

**Silicon- L<60 Mpc**




**Iron- L<80 Mpc**




**De Marco et al. (2006), 0603615**

**Taylor et al. (2011), 1107.2055**

**Fargion et al. (2015), 1412.1573**

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# What is the Source Composition?

**Keep It Simple**

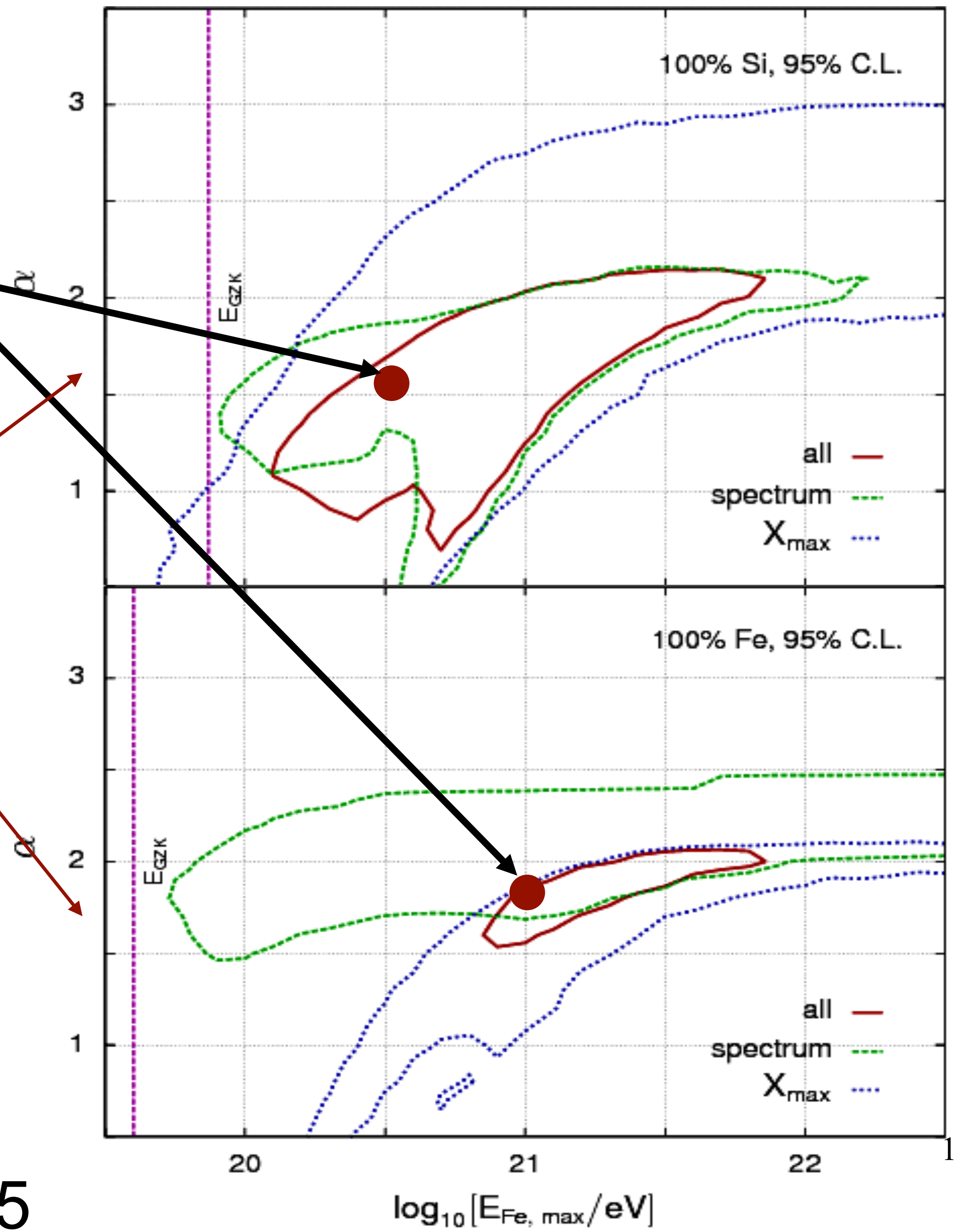
**- Single Composition**

**Example Best-Fit Models**

**Silicon**

**Iron**

**Hard Spectra preferred**



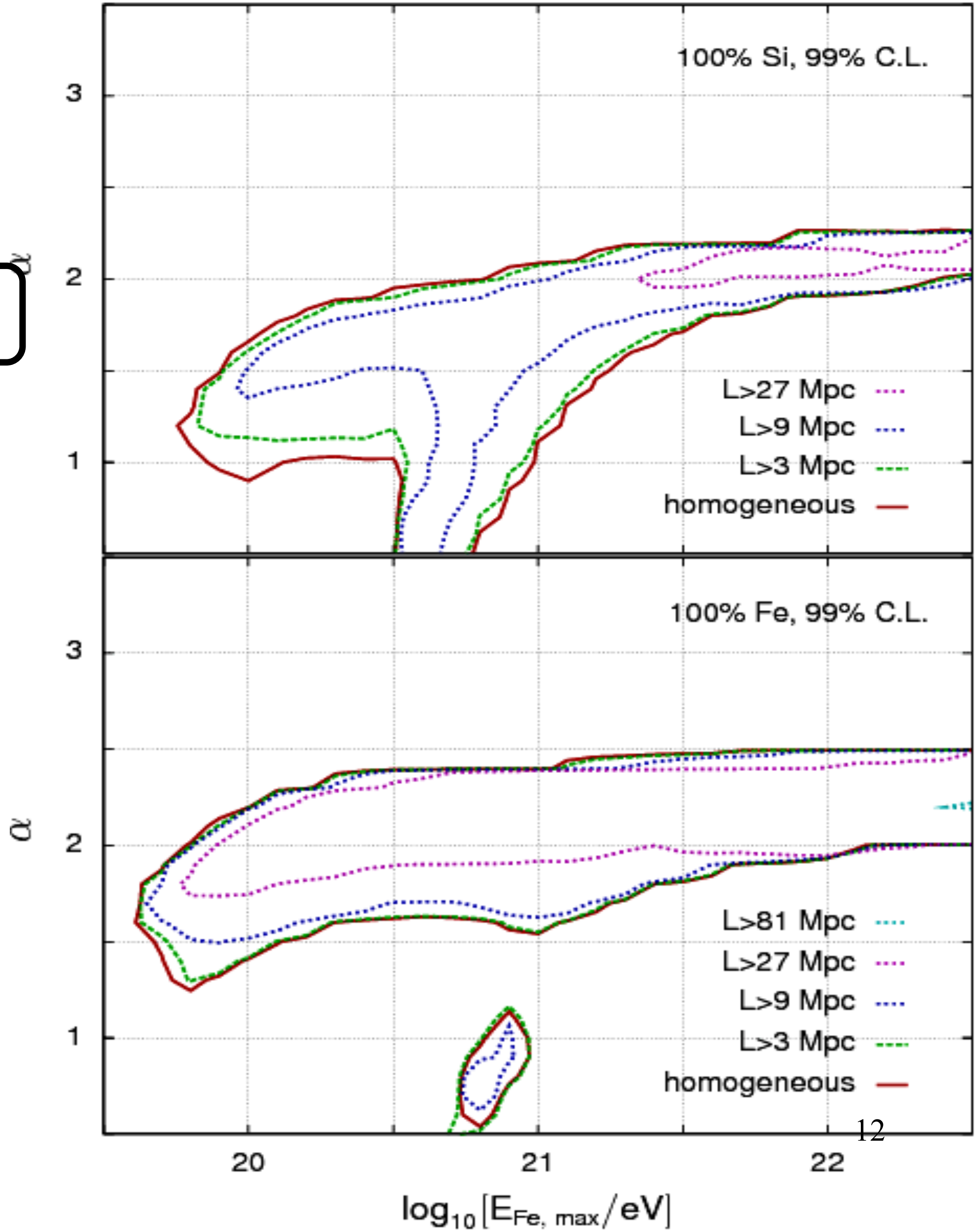

astro-ph/1107.2055

# How Far is the Nearest Source?

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

**Silicon- D<60 Mpc**

**Iron- D<80 Mpc**




astro-ph/1107.2055

# MCMC Parameter Constraints

False minima

<u>Metropolis-Hastings Algorithm</u>

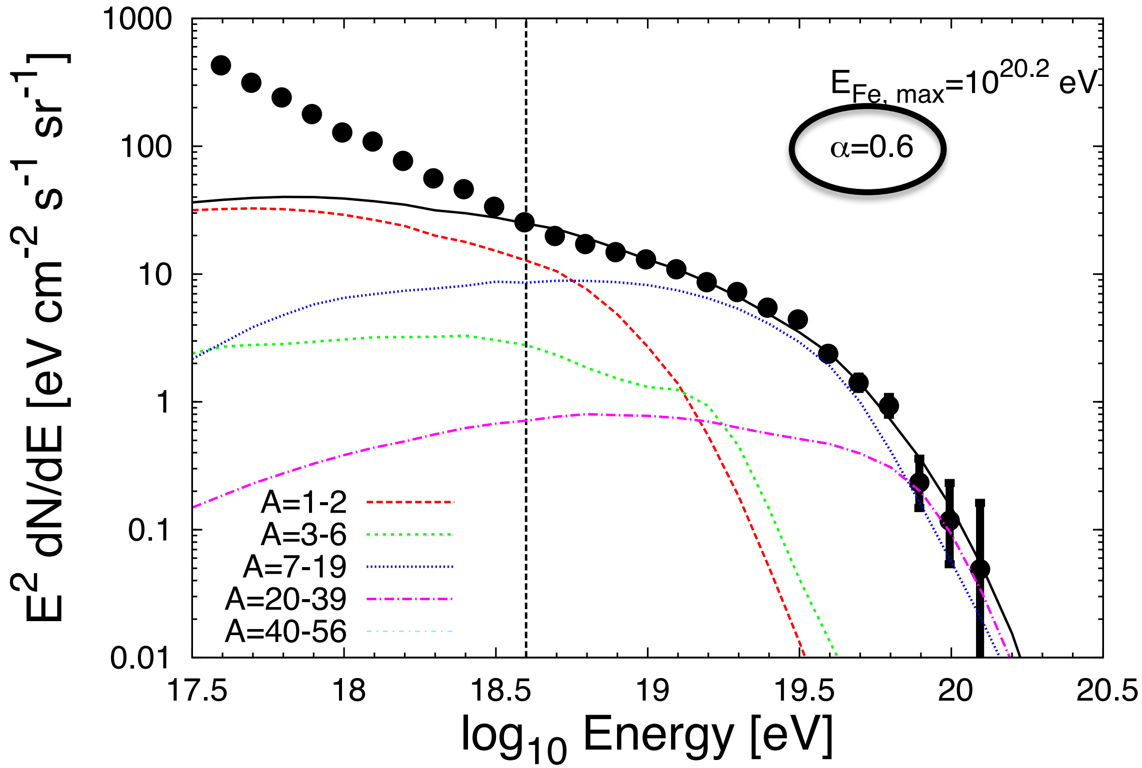
Steps:

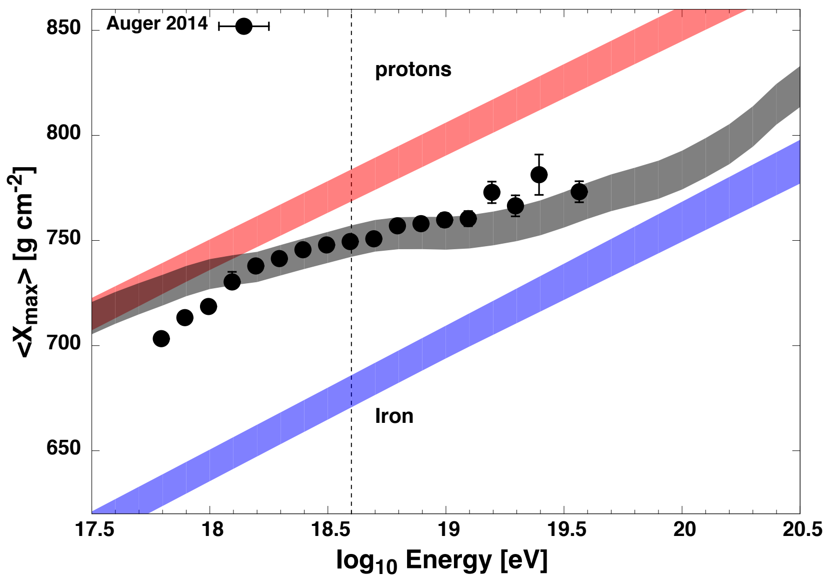
- Perturb one of the model parameters using a symmetric function about the present position (eg. Gaussian or Flat distribution)
- Evaluate the change in the fit following this change
- Accept the new model parameter if fit improved
- Accept/reject the new model parameter if fit is worse on a probabilistic basis, with rejection probability being larger when decrease in fit is larger
- History of where walker has been in landscape can provide histograms of parameter distributions

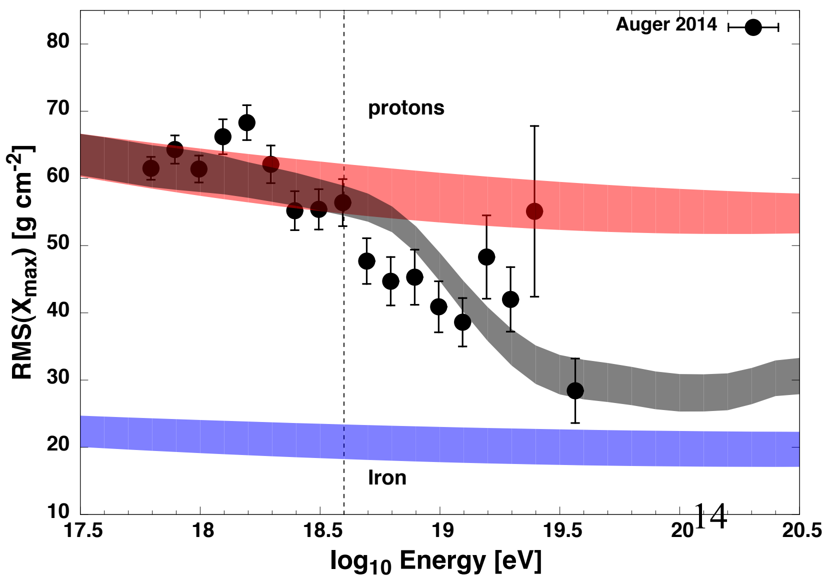
# MCMC Likelihood Scan: Spectral + Composition Fits

$$\mathbf{L}(\mathbf{f_p}, \mathbf{f_{He}}, \mathbf{f_N}, \mathbf{f_{Si}}, \mathbf{E_{max}}, \alpha) \propto \exp(-\chi^2/2)$$

n=3 evolution result




**Taylor et al. (2015), 1505.06090**
**Aloisio et al. (2014), 1312.7459**
**Di Matteo et al. (2015), ICRC 2015**
**Zirakashvili et al. (2017), 1701.00820**

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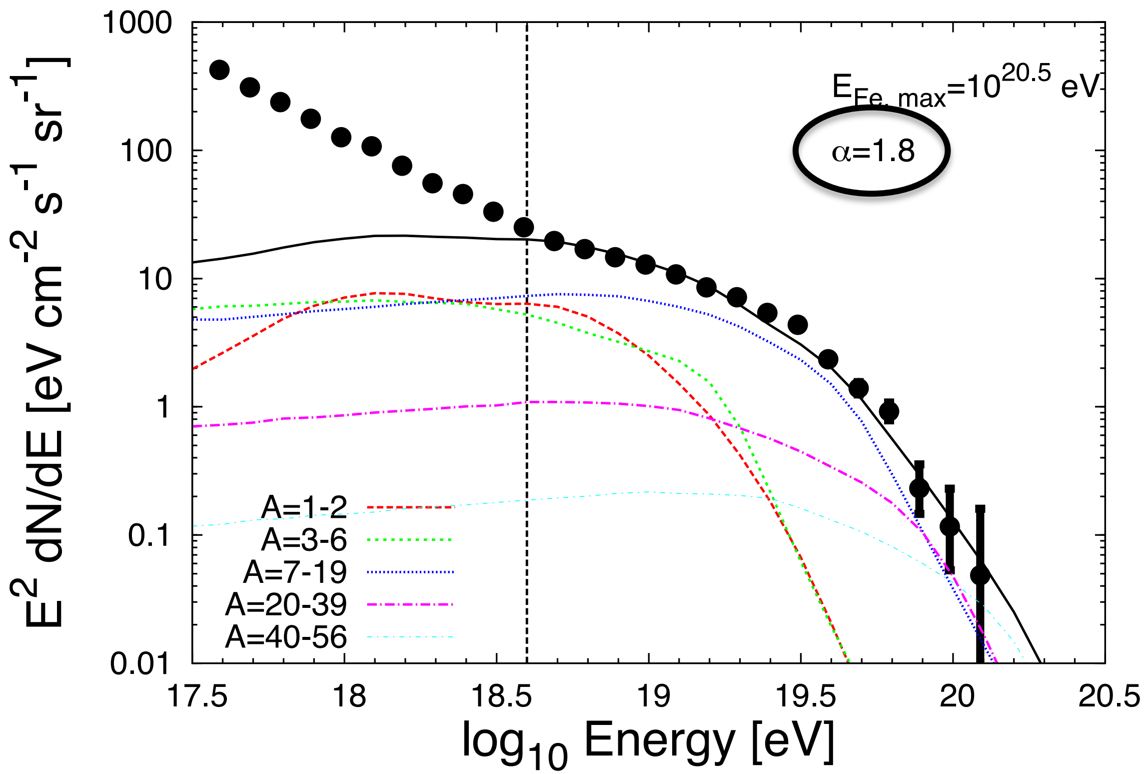
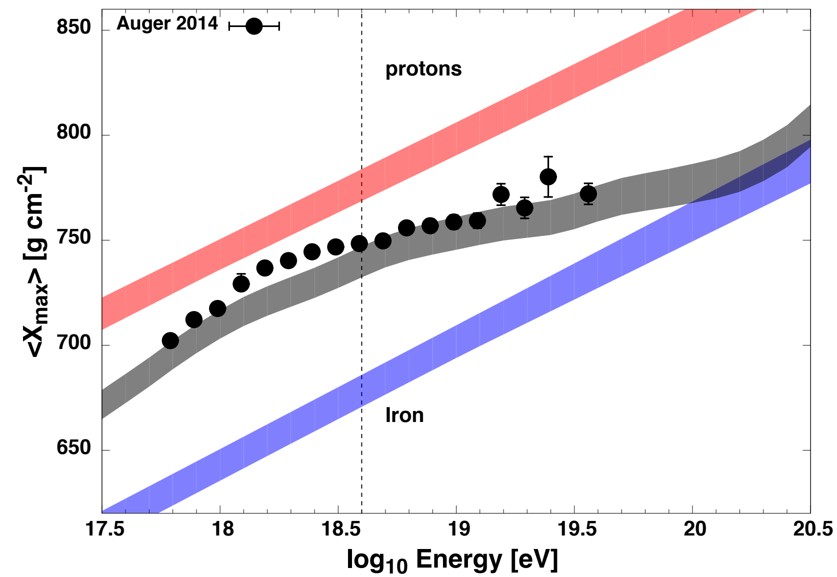
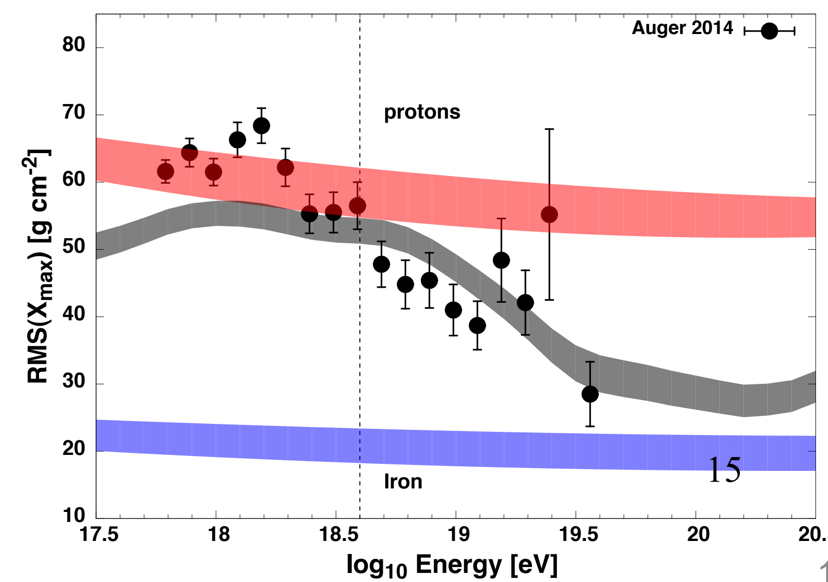
# MCMC Likelihood Scan: Soft Spectra Solutions

$$L(f_p, f_{He}, f_N, f_{Si}, E_{max}, \alpha) \propto \exp(-\chi^2/2)$$

n=-6 evolution result

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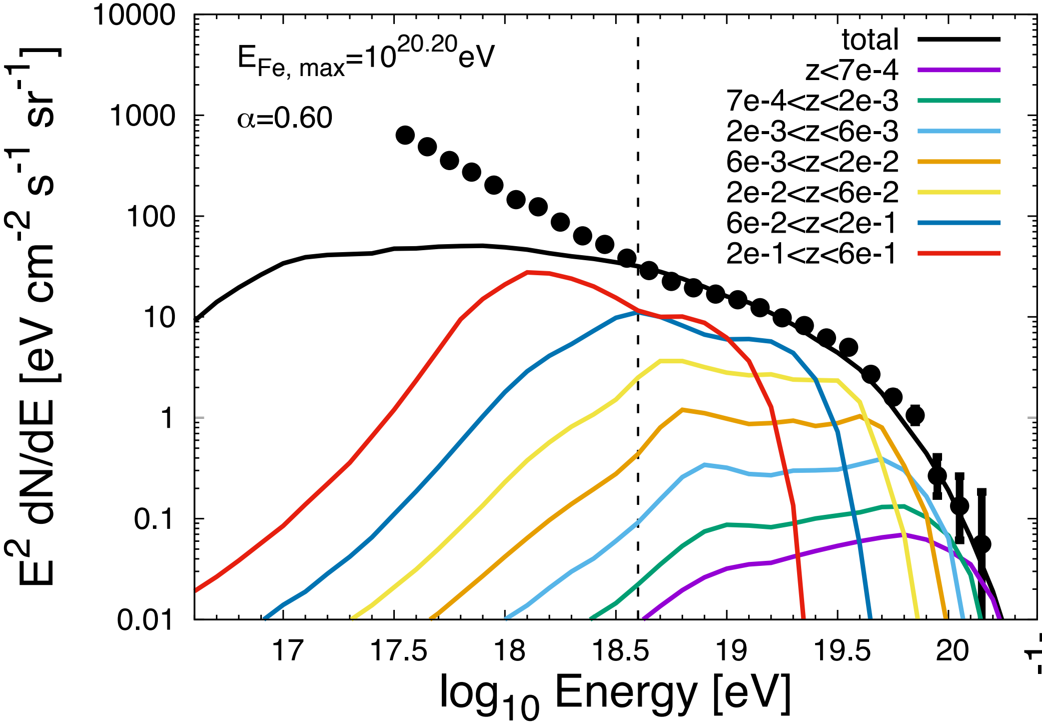
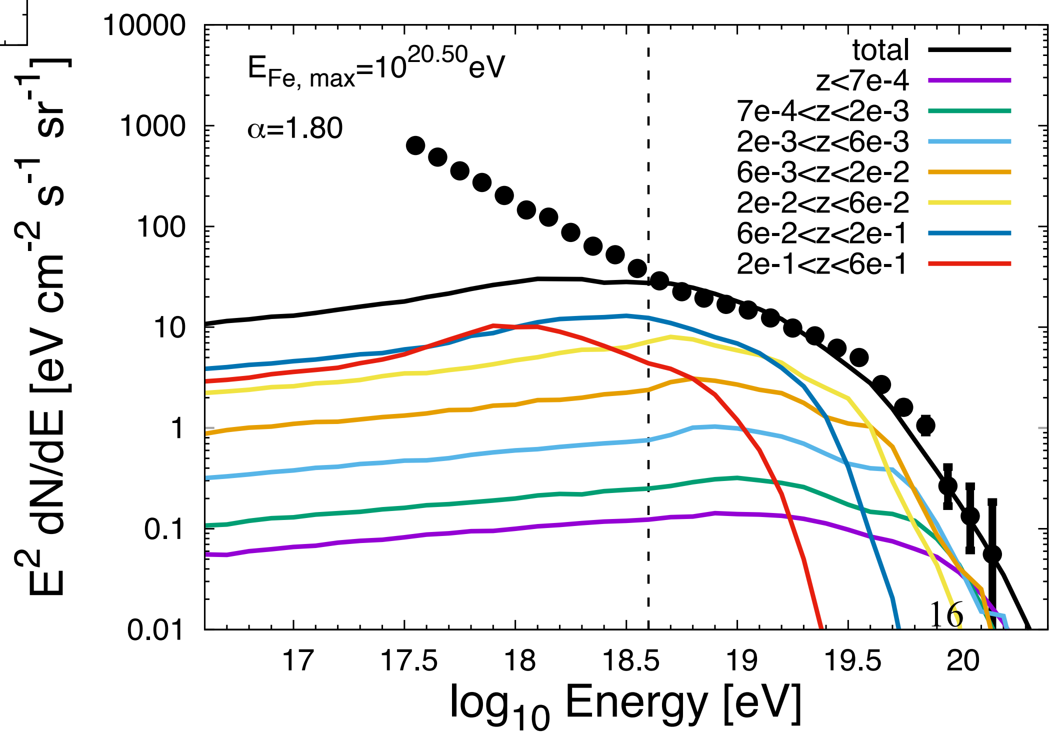
**Taylor et al. (2015), 1505.06090**

# Source Redshifts Contributing to Arriving Flux



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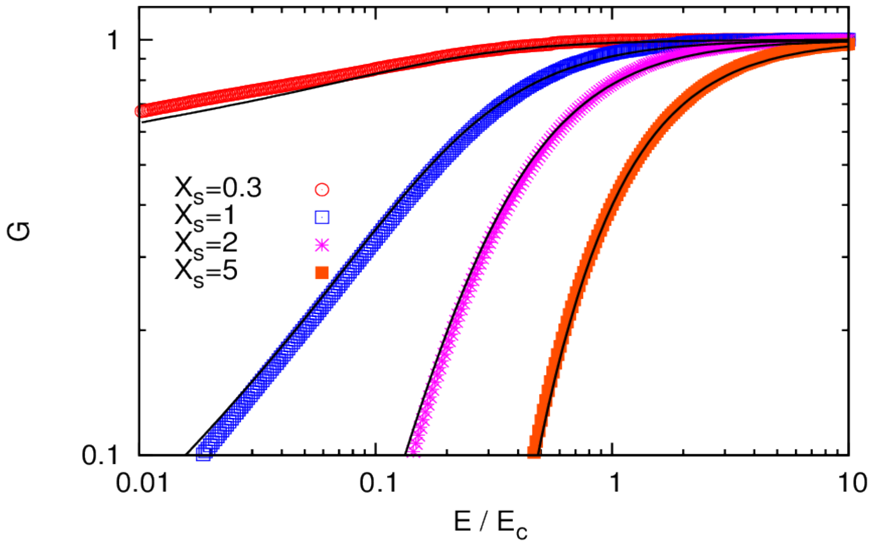



# Hard Spectra Problem

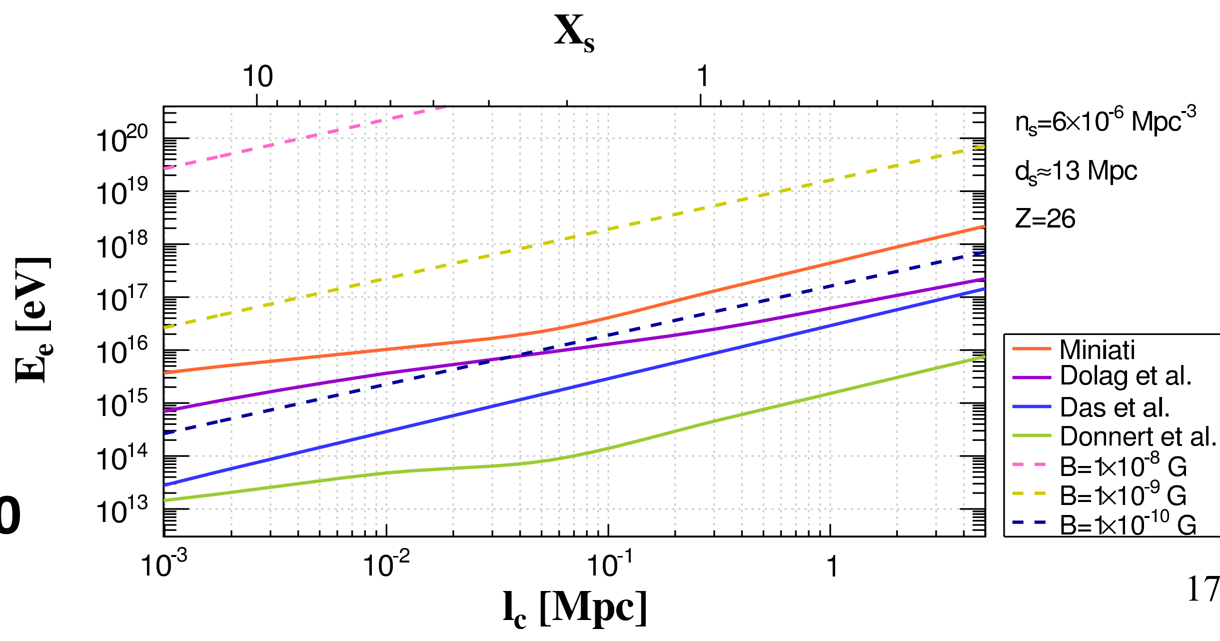
Magnetic horizon suppression suggested to resolve “hardness” issue,
**Mollerach et al. (2013), 1305.6519**

| | Miniati | Dolag *et al.* | Das *et al.* | Donnert *et al.* |
|---|---|---|---|---|
| $\langle B \rangle$ [G] | $1.8 \times 10^{-8}$ | $5.5 \times 10^{-11}$ | $1.2 \times 10^{-9}$ | $6.3 \times 10^{-11}$ |
| $B_{rms}$ [G] | $1.7 \times 10^{-7}$ | $1.5 \times 10^{-8}$ | $5.7 \times 10^{-8}$ | $1.7 \times 10^{-8}$ |

$$X_s = \frac{d_s}{(ct_H l_c)^{1/2}}$$

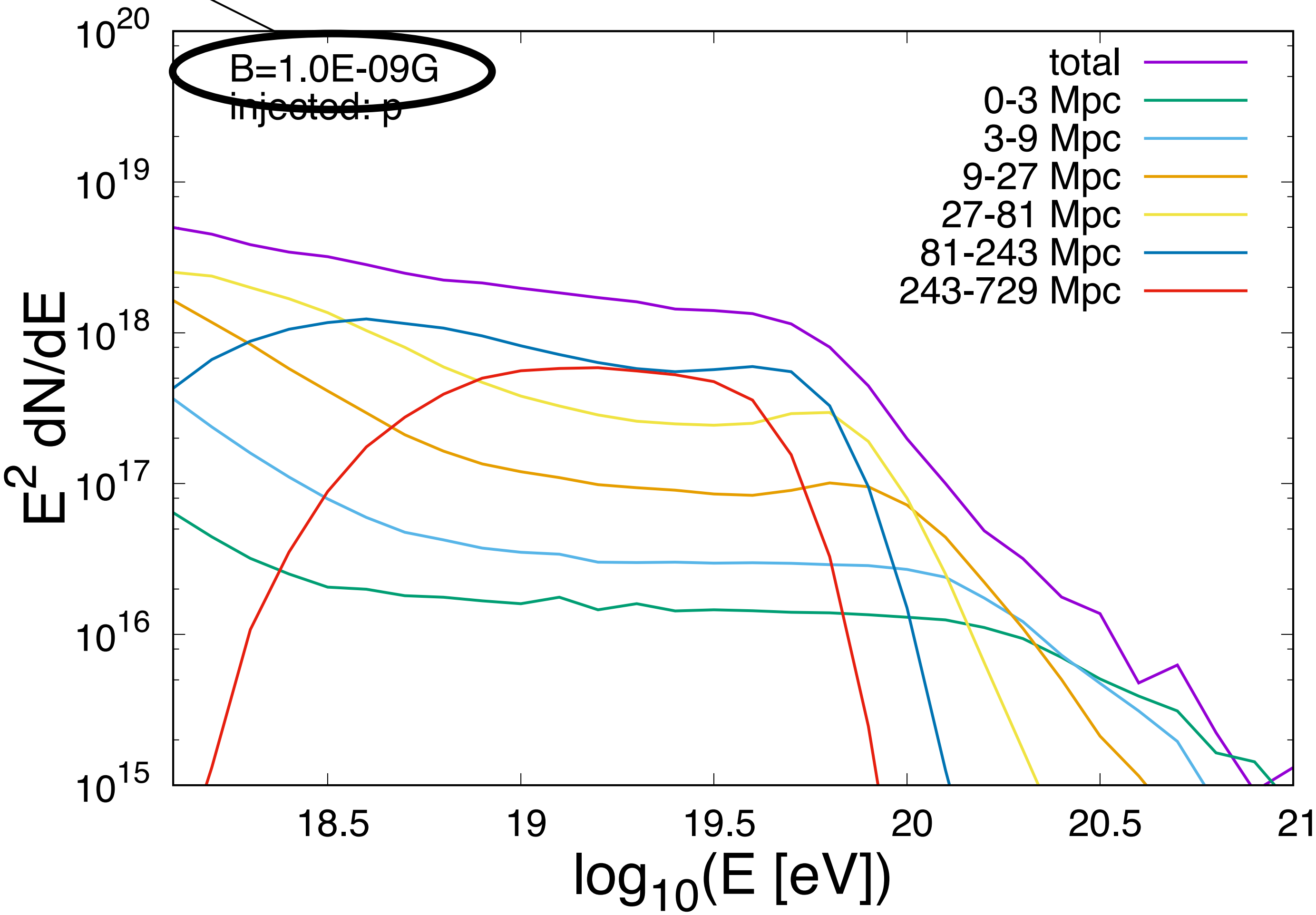
$$= 0.1 \left(\frac{d_s}{10\ \mathrm{Mpc}}\right)\left(\frac{1\ \mathrm{Mpc}}{l_c}\right)^{1/2}$$

“Realistic” field structures/strengths, however, don't provide sufficient suppression,
**Alves Batista et al. (2014), 1407.6150**



# Magnetic Horizon Effect

Note strong B-field strength considered



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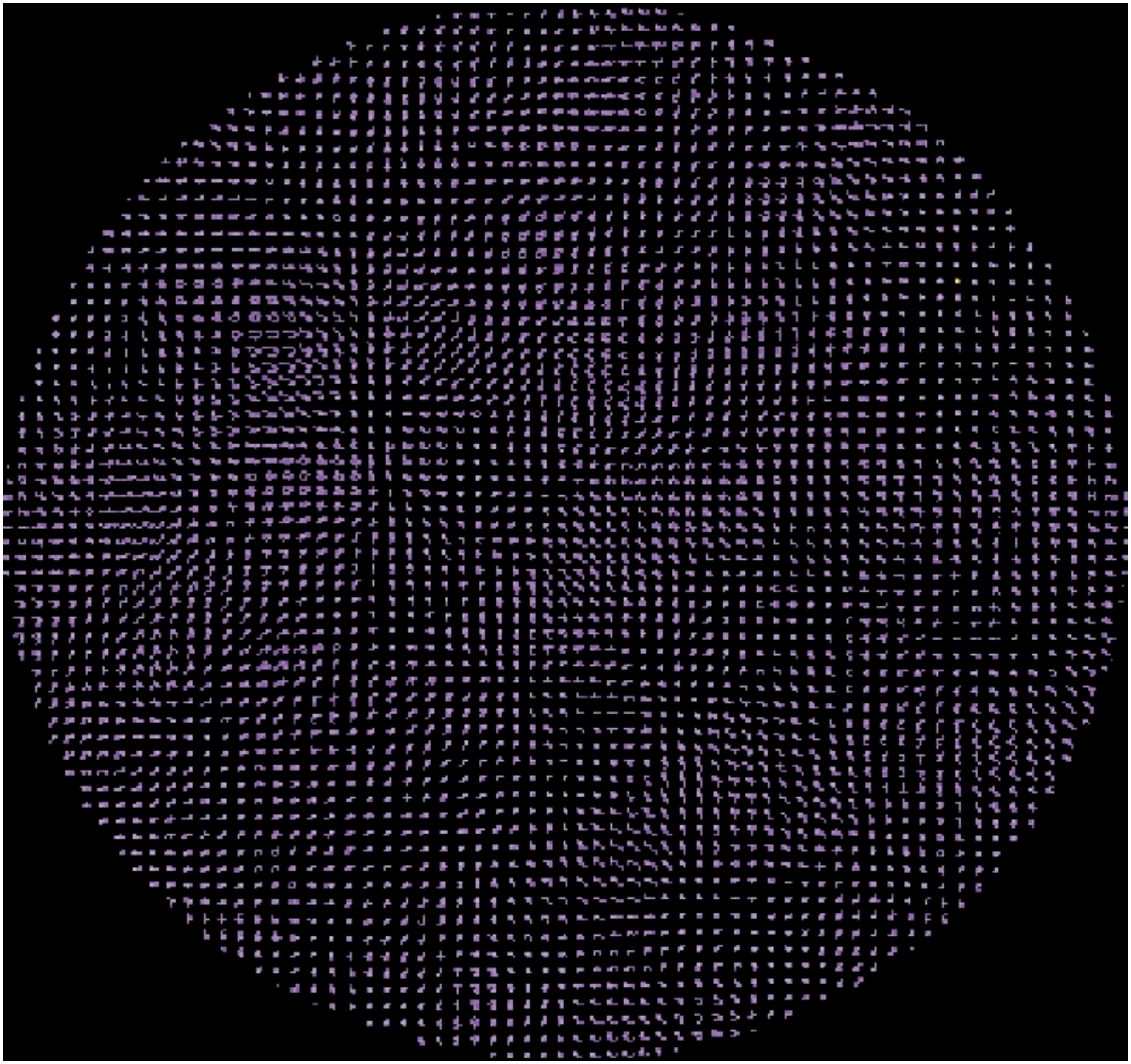
# The Uncertainty in the Extragalactic Magnetic Field Strength

# Extragalactic Magnetic Fields



$$z = 40$$

Is the EGMF already present?



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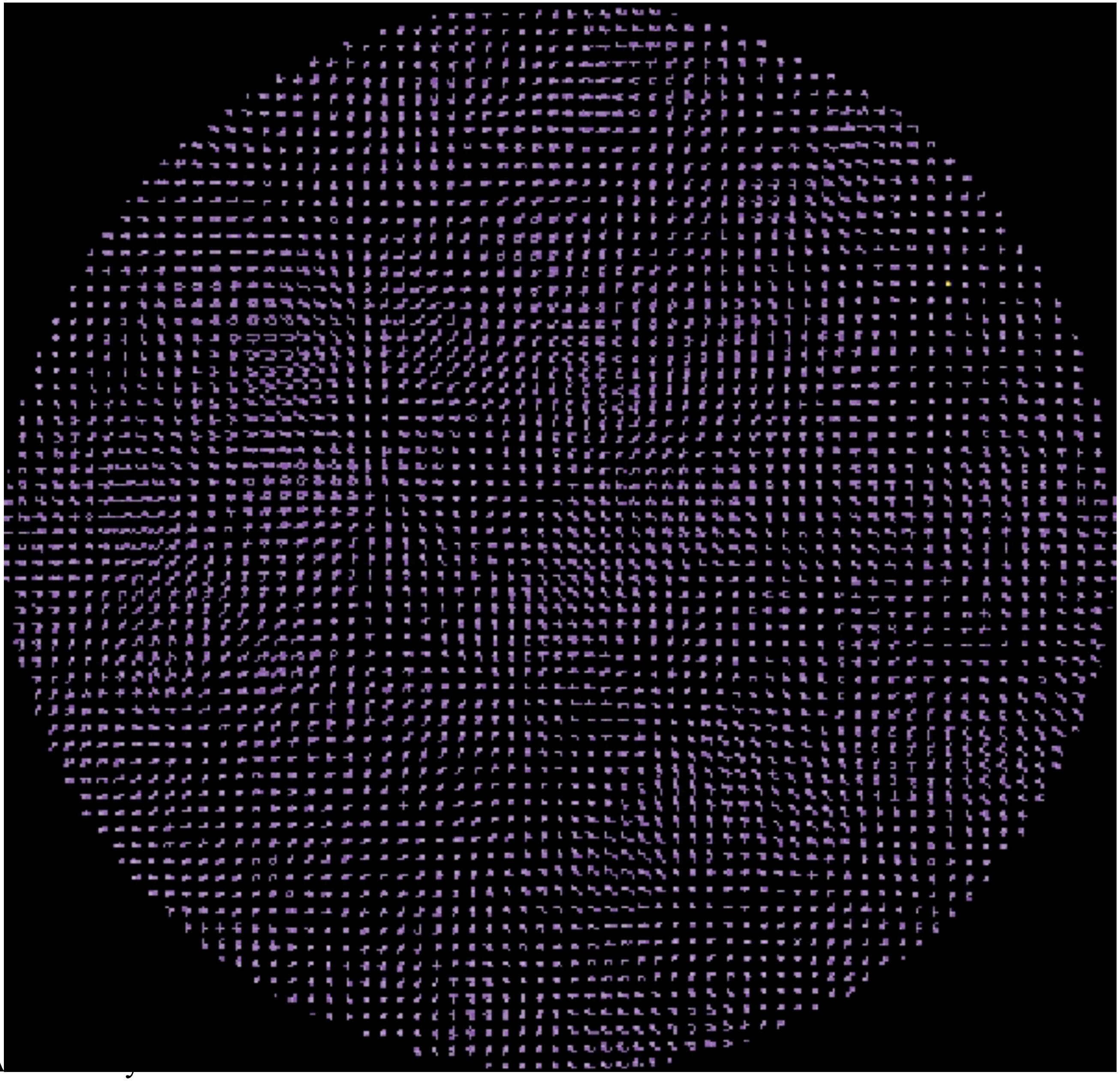
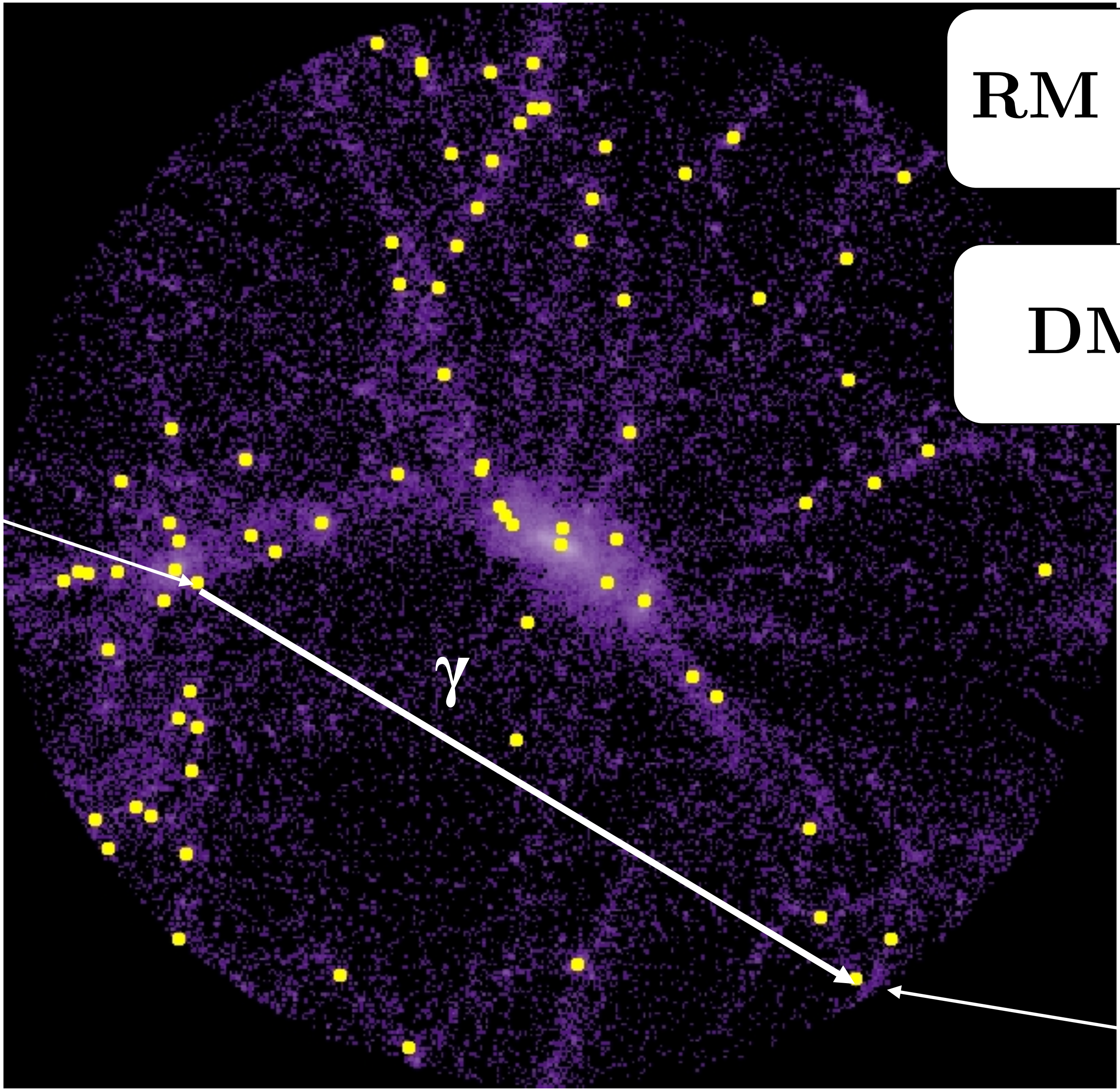
# Extragalactic Magnetic Fields



...or is the EGMF generated during structure formation?

# A Radio Probe




$$\mathbf{RM} = \int \mathbf{n_e B_{\parallel} dl}$$

$$\mathbf{DM} = \int \mathbf{n_e dl}$$

AGN

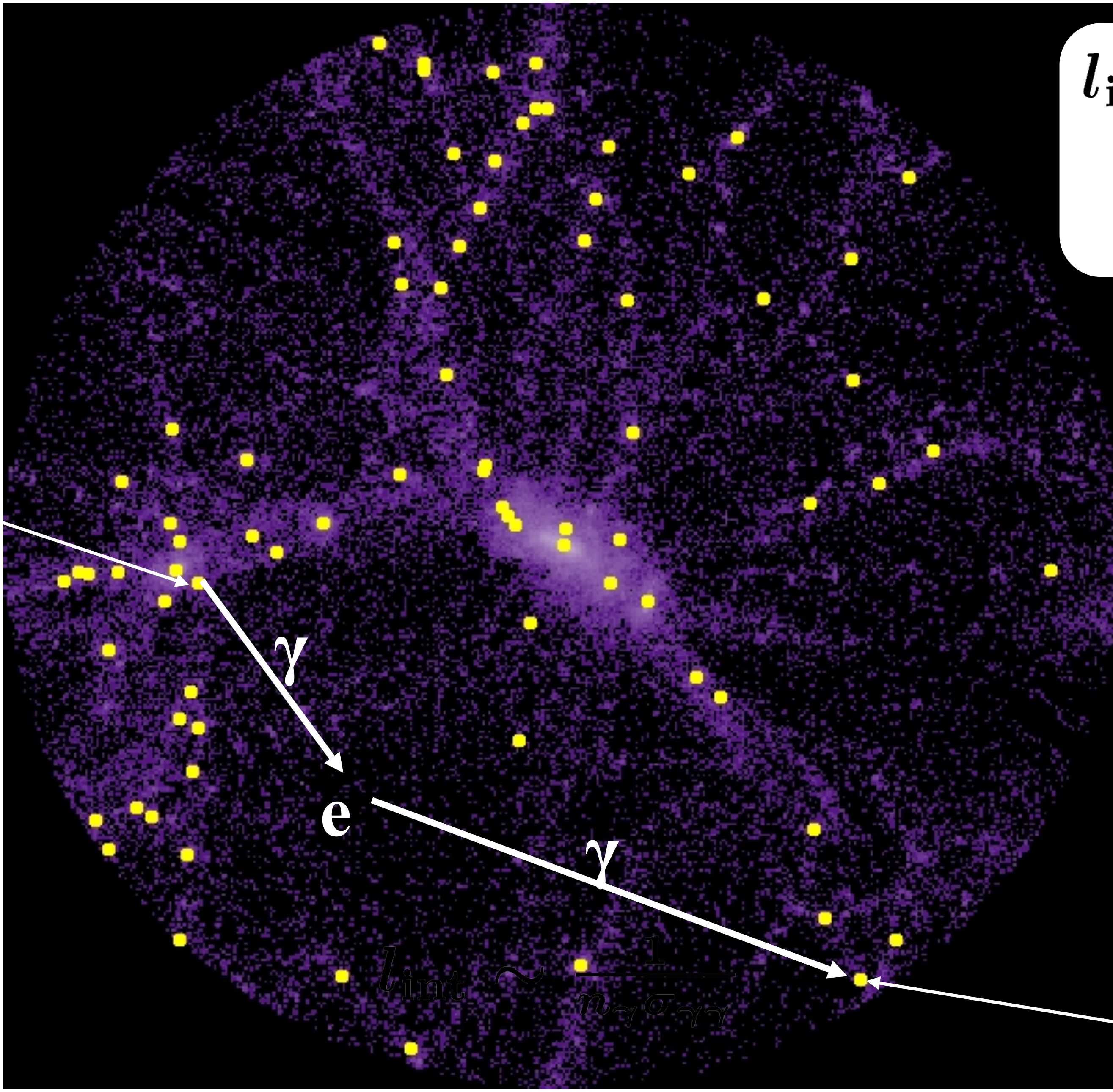
Milky Way



DESY.

# A Gamma-Ray Probe

AGN

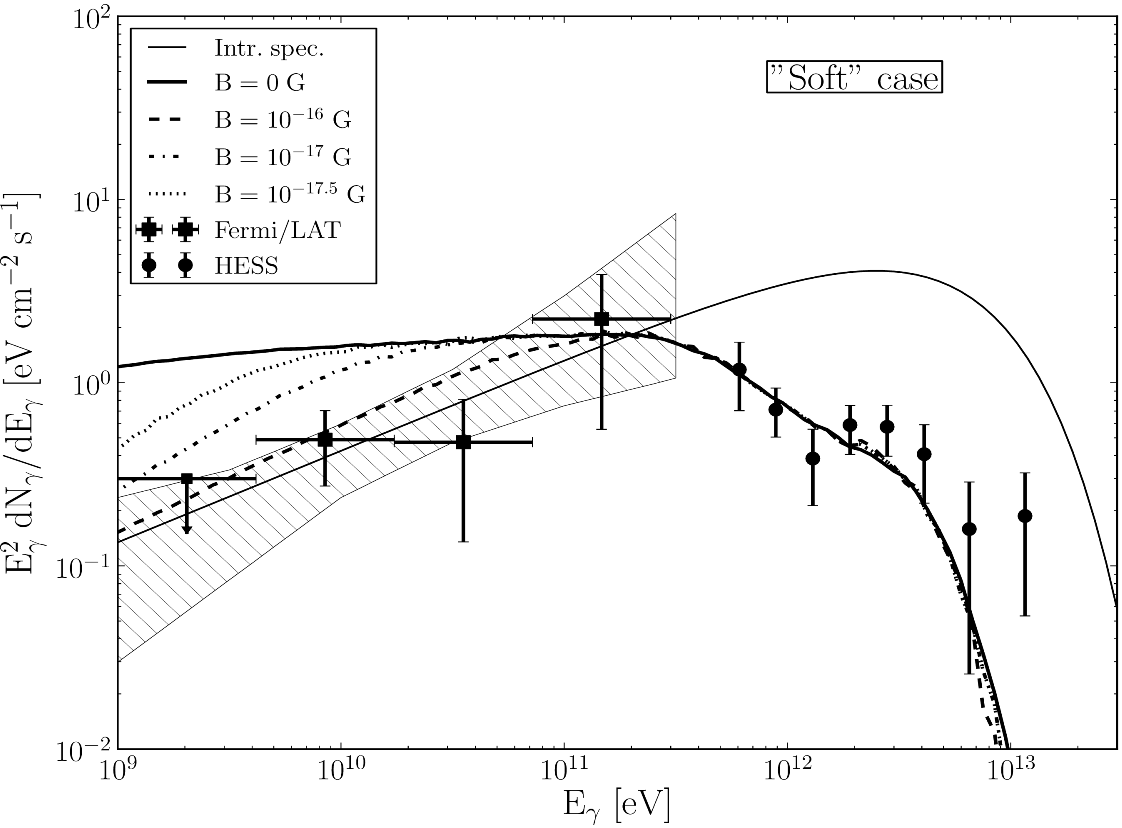


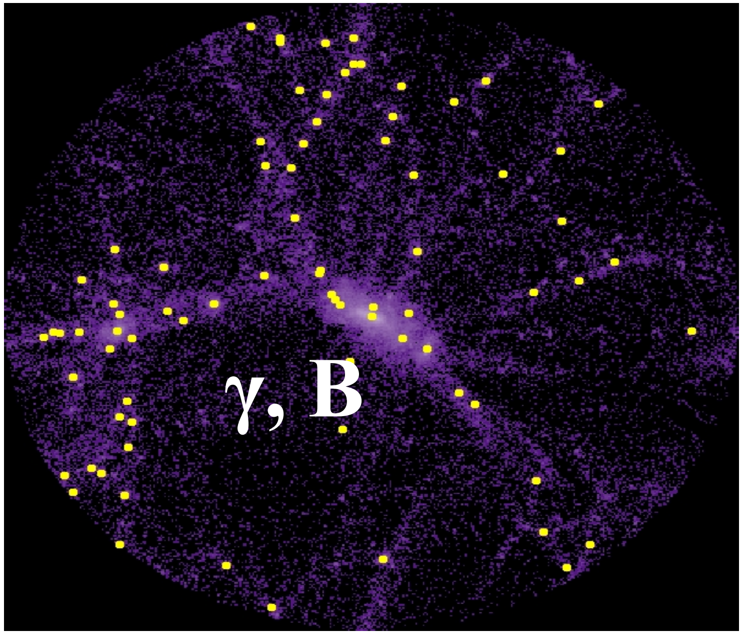

$$l_{\rm int} \sim \frac{1}{n_\gamma \sigma_{\gamma\gamma}}$$

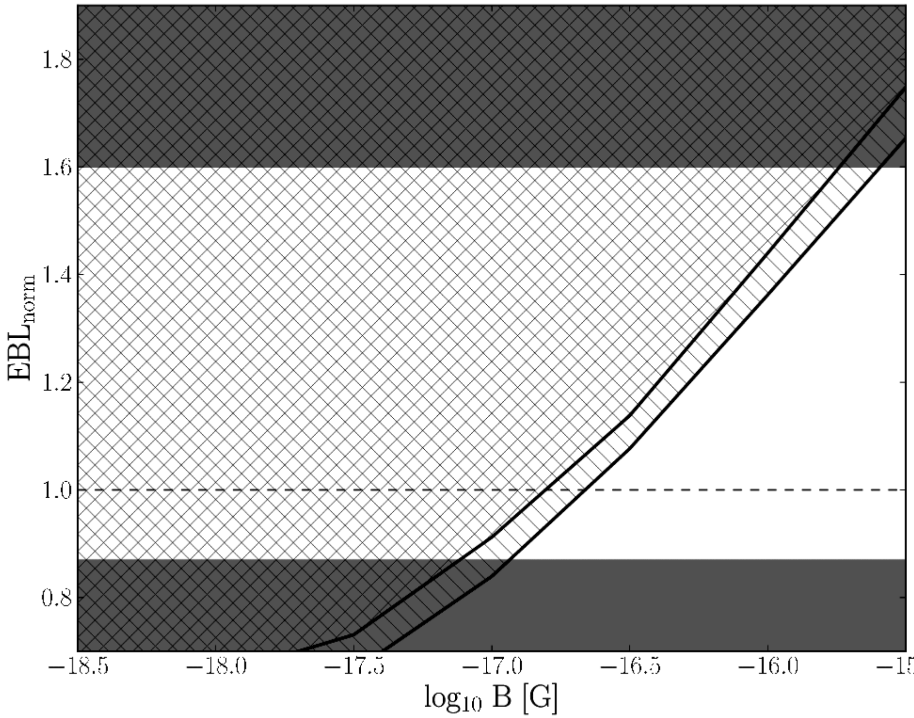
$$\sim 30 \text{ Mpc}$$

Milky Way

# Probing Extragalactic Radiation + Magnetic Fields?



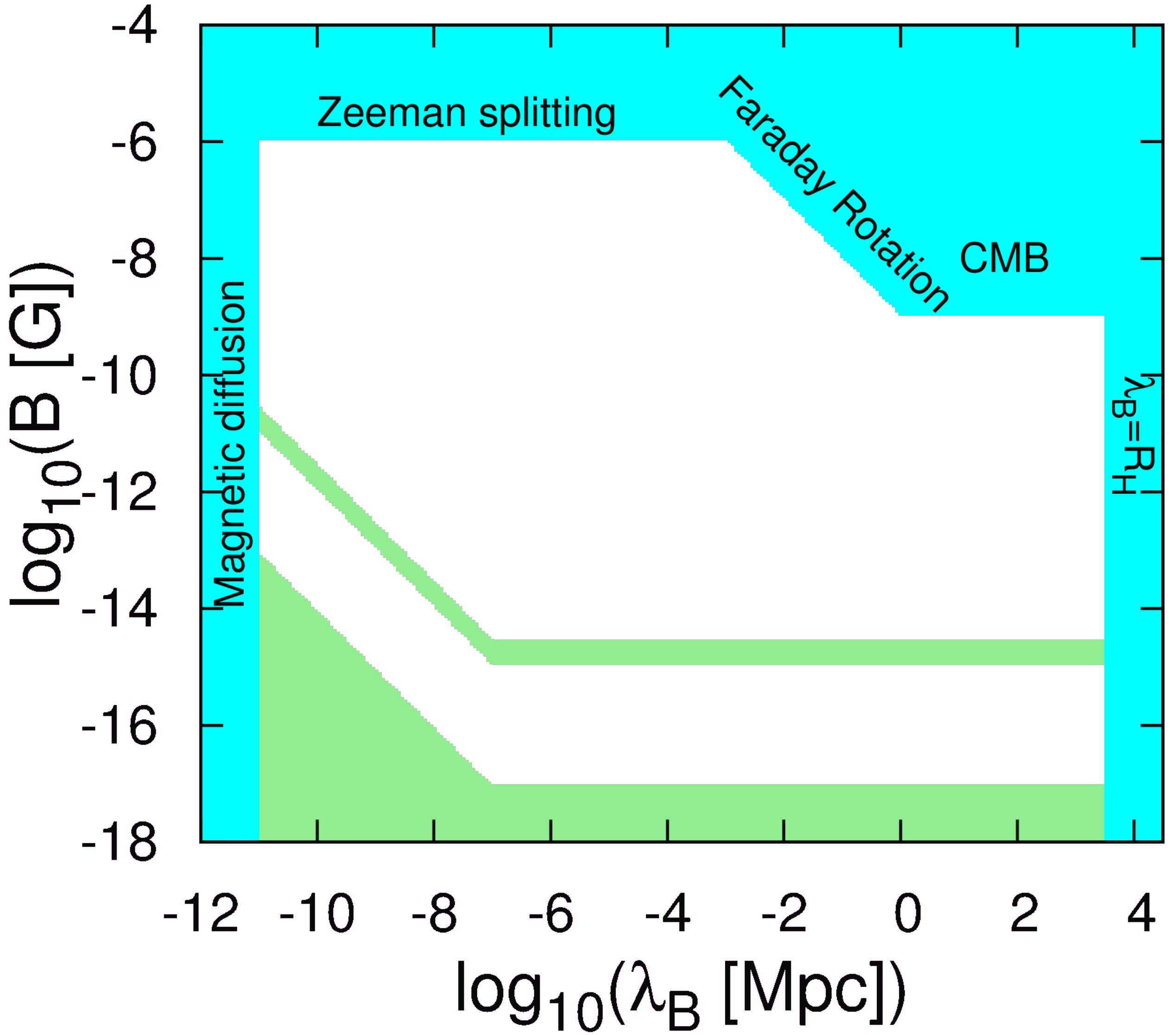




astro-ph/1101.0932 Taylor et al.

astro-ph/1112.2534 Vovk et al.

# Extragalactic Magnetic Field is Hugely Uncertain



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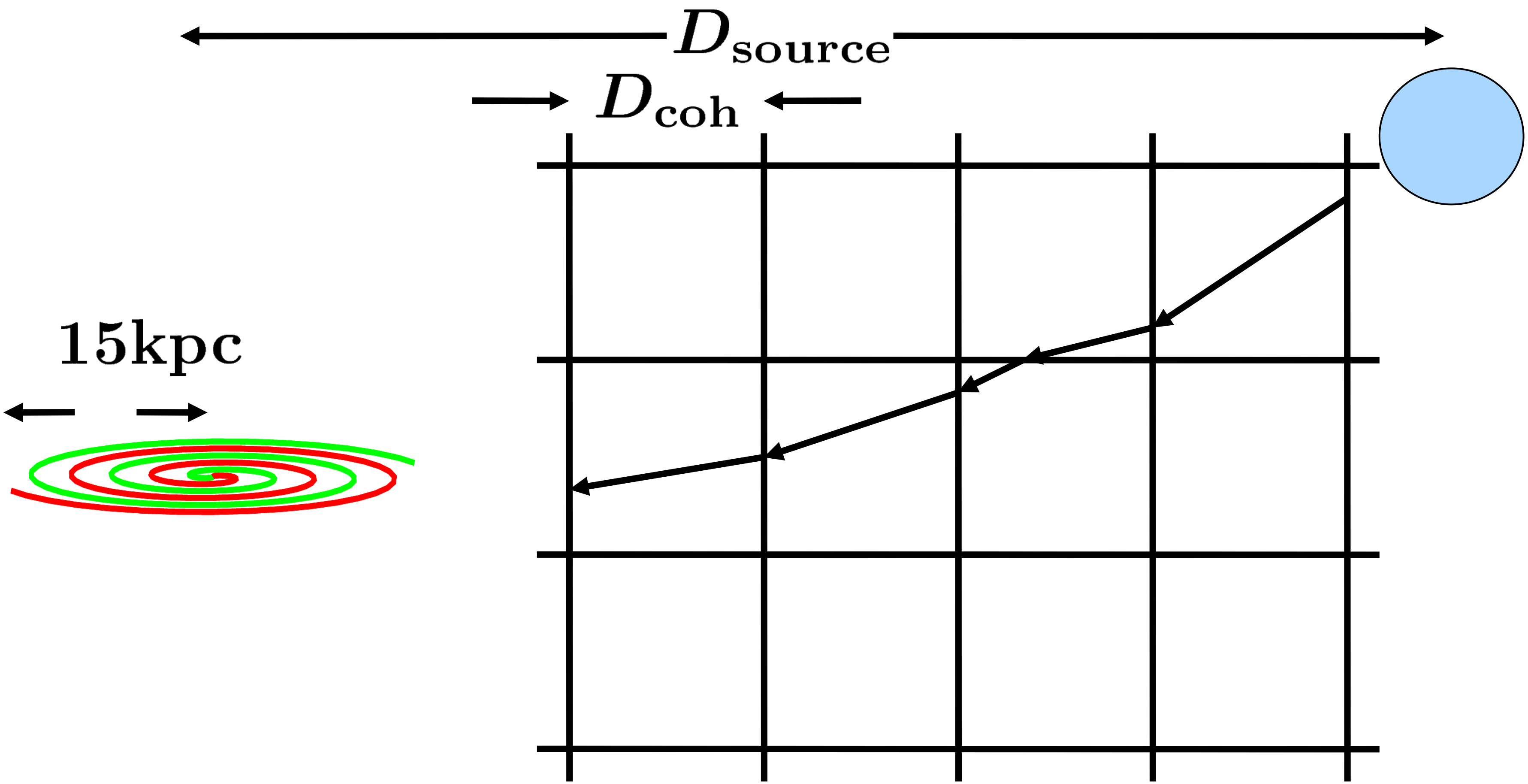
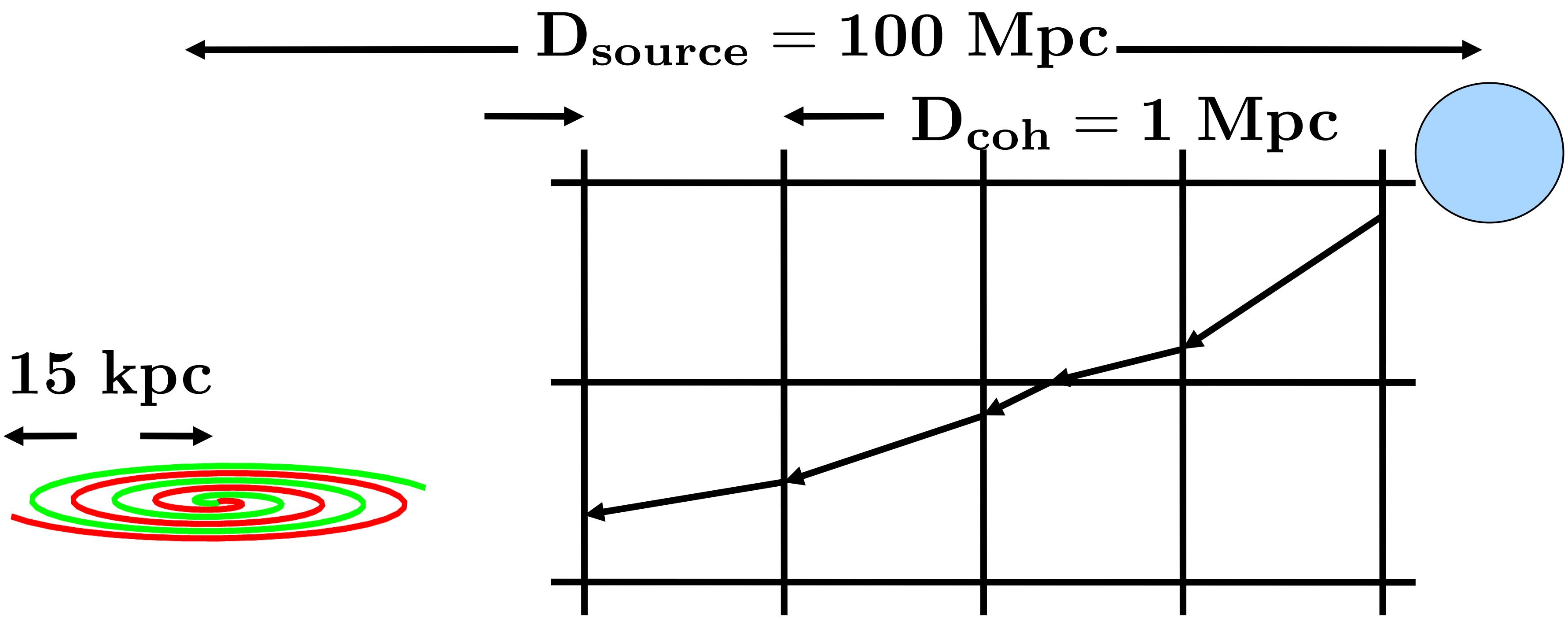
# Extragalactic Deflections

# 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



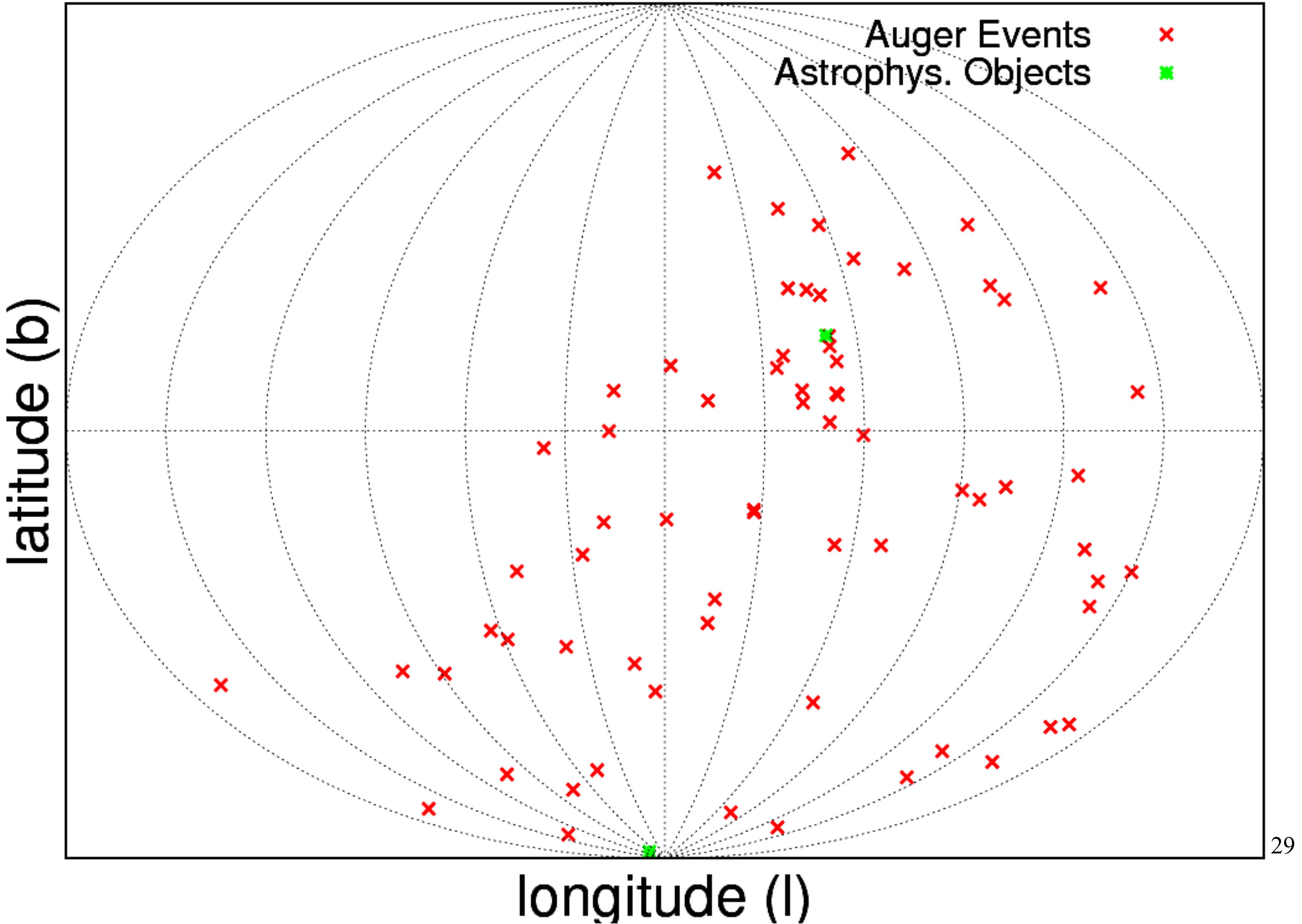

$$R_{Larmor} = 1\ \text{Gpc} \left(\frac{1}{Z}\right)\left(\frac{E}{10^{20}\ \text{eV}}\right)\left(\frac{0.01\ \text{nG}}{B}\right)$$

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

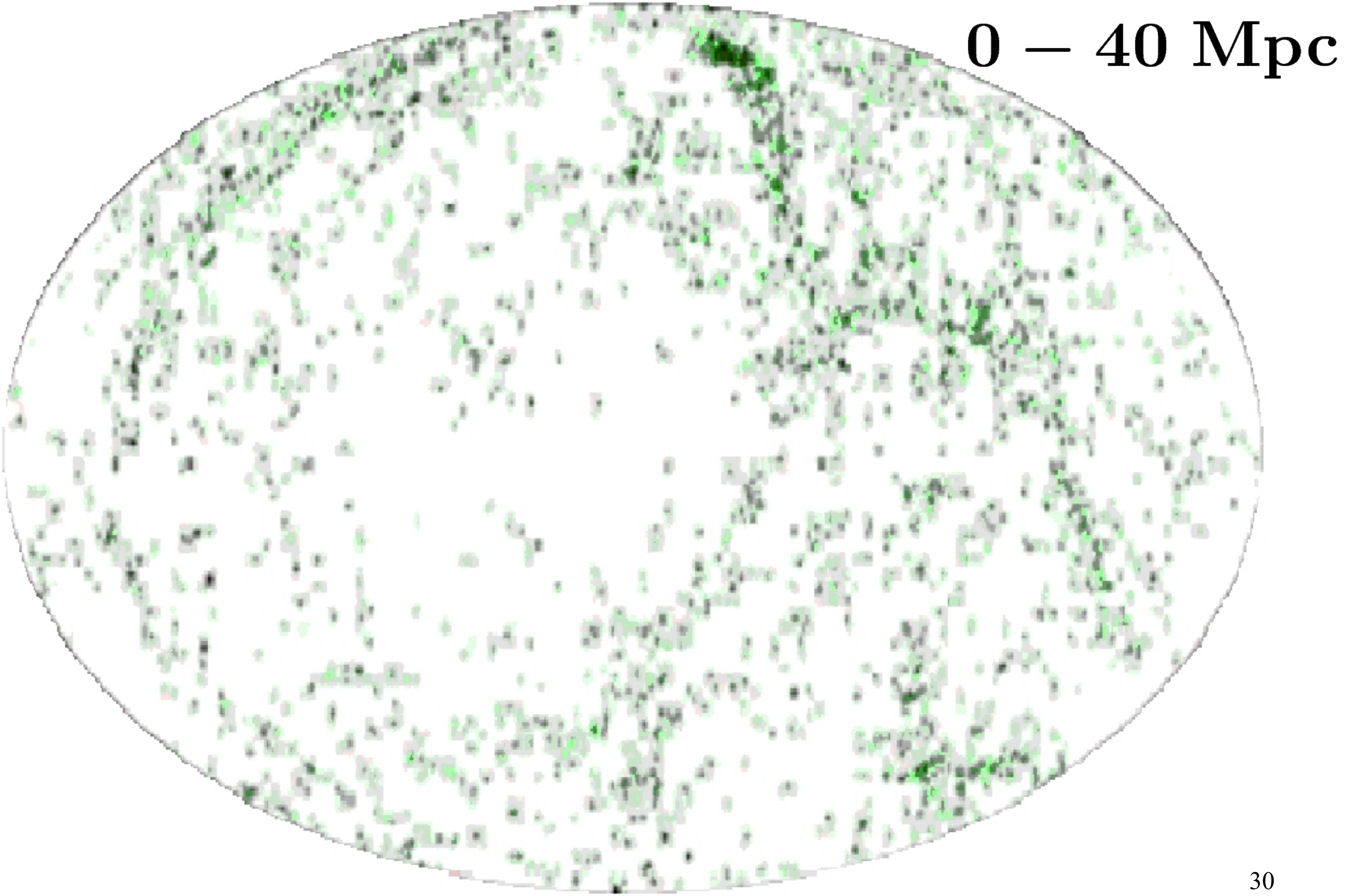
For $10^{20}$ eV protons: $\Delta\theta_{tot} = 0.01$ rad. (ie. $0.6^\circ$)

For $10^{20}$ eV iron: $\Delta\theta_{tot} = 0.26$ rad. (ie. $15^\circ$)

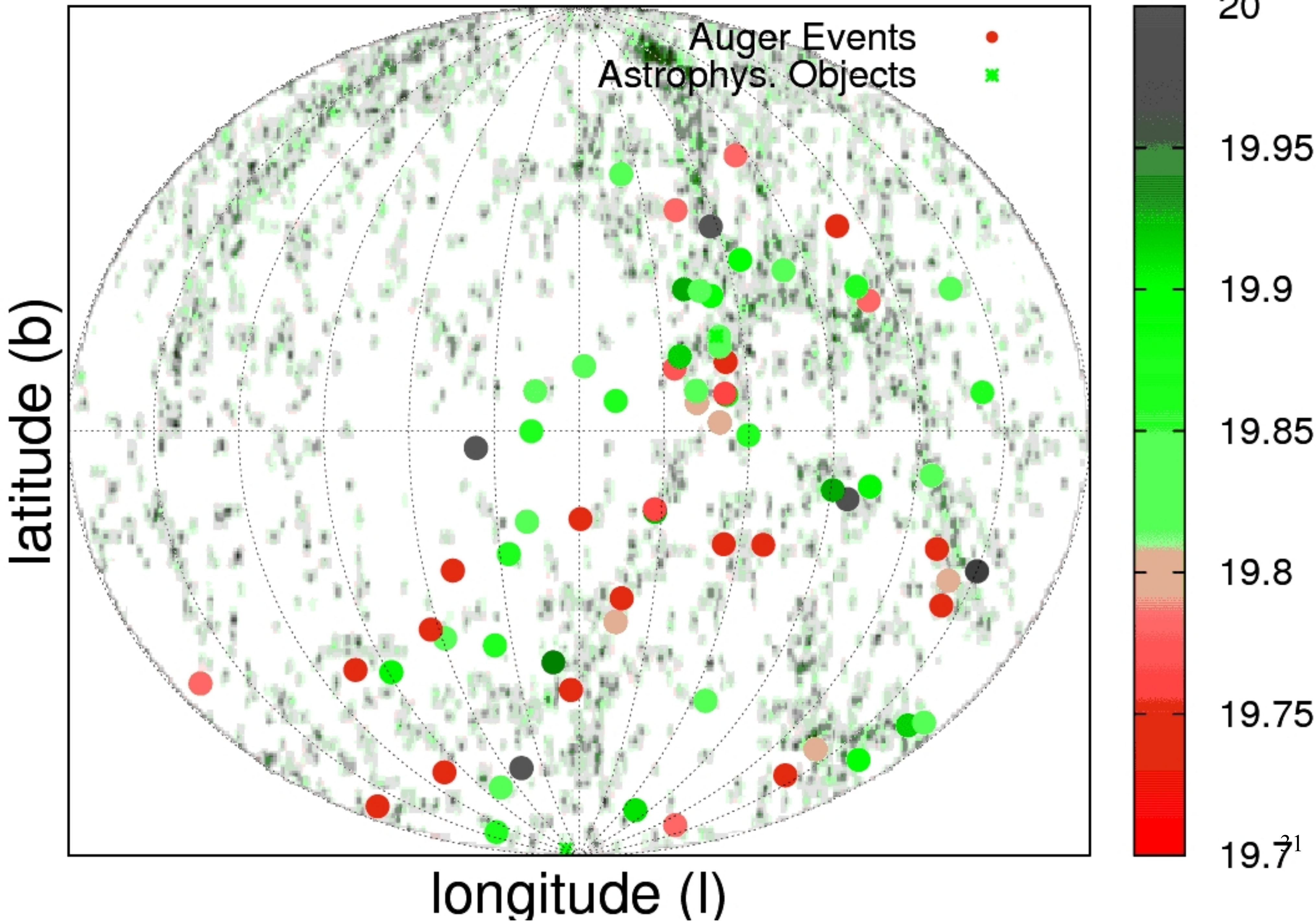
# Can We See UHECR Sources Directly?



# Our Local Extragalactic Neighbourhood



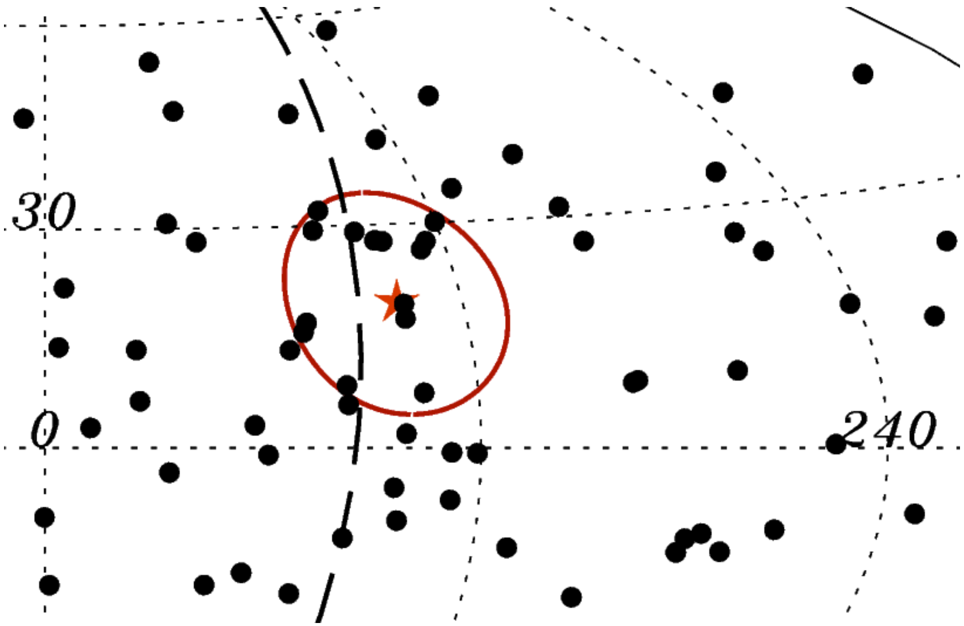
# Can We See UHECR Sources Directly?



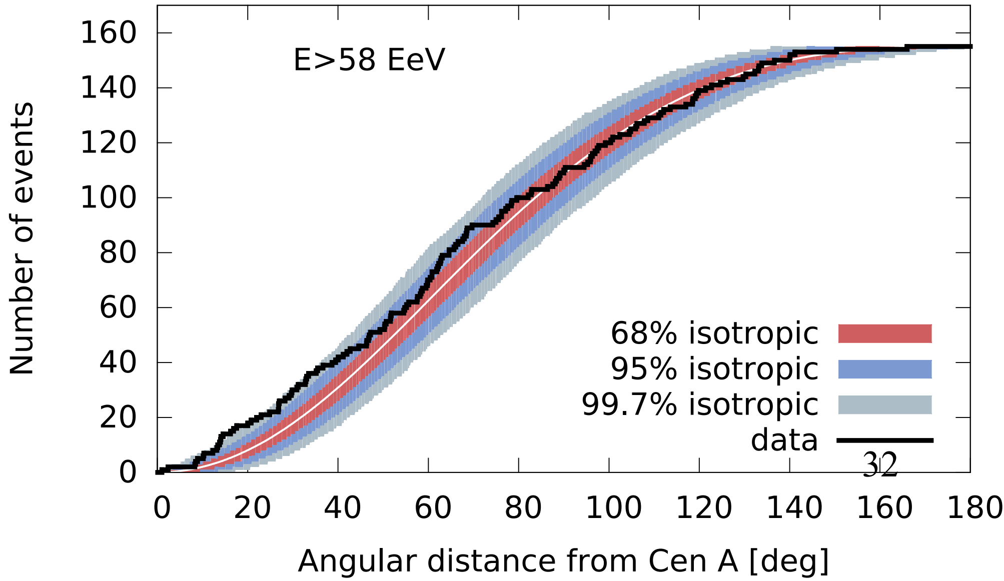
# Can We See UHECR Sources Directly? No....so we resort to statistics!

**Auger analysis archiv: 1411.6111**

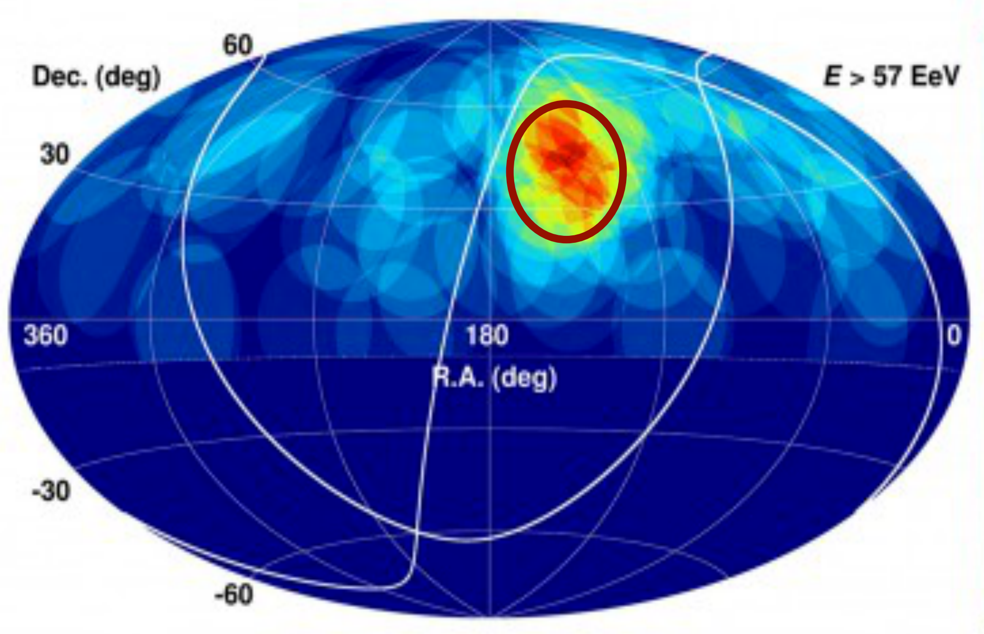
"The most significant excess observed in a blind search over the exposed sky with the present data set is also a region close to the direction of Cen A"



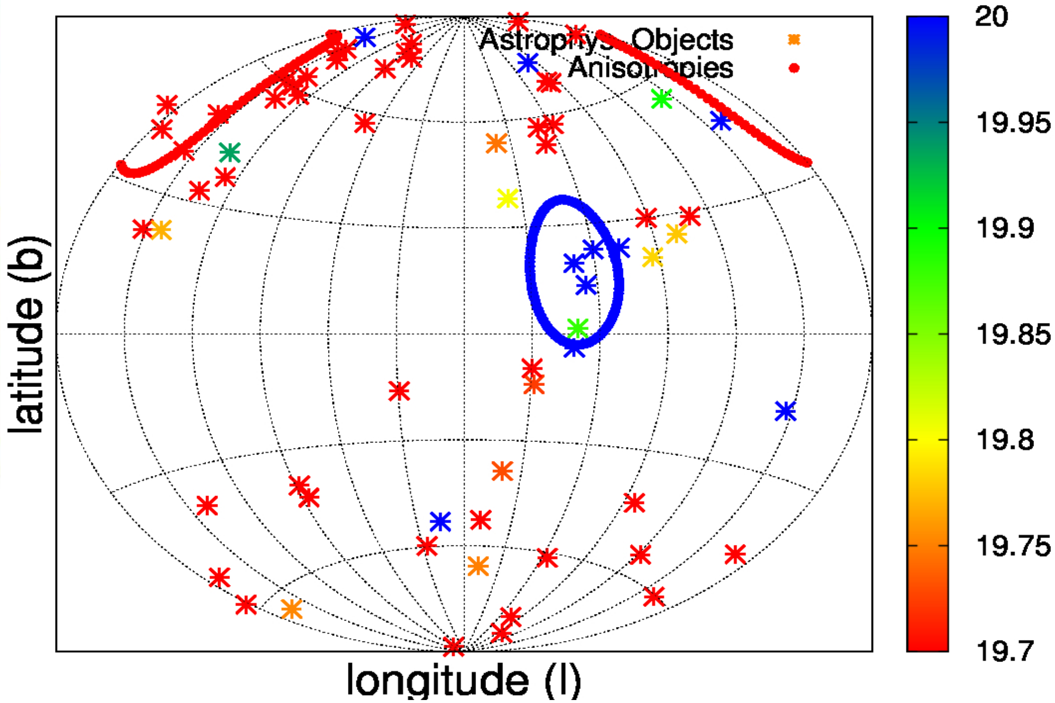

14 events correlate with Cen A, whilst 4.5 expected by chance



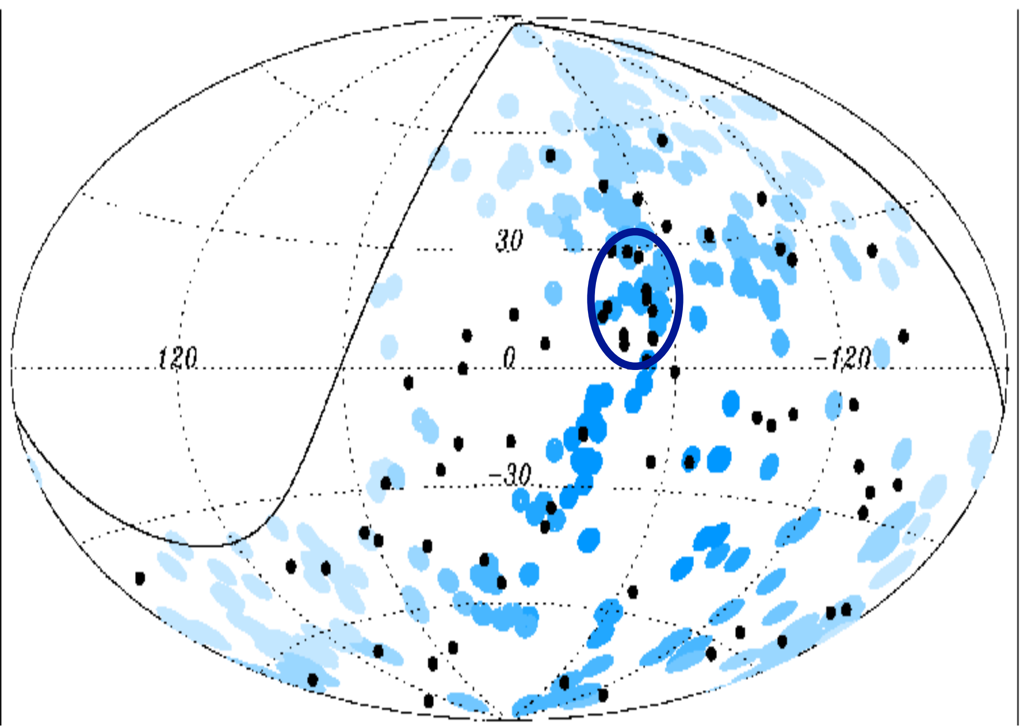
# A UHECR – X-ray Bright AGN Connection



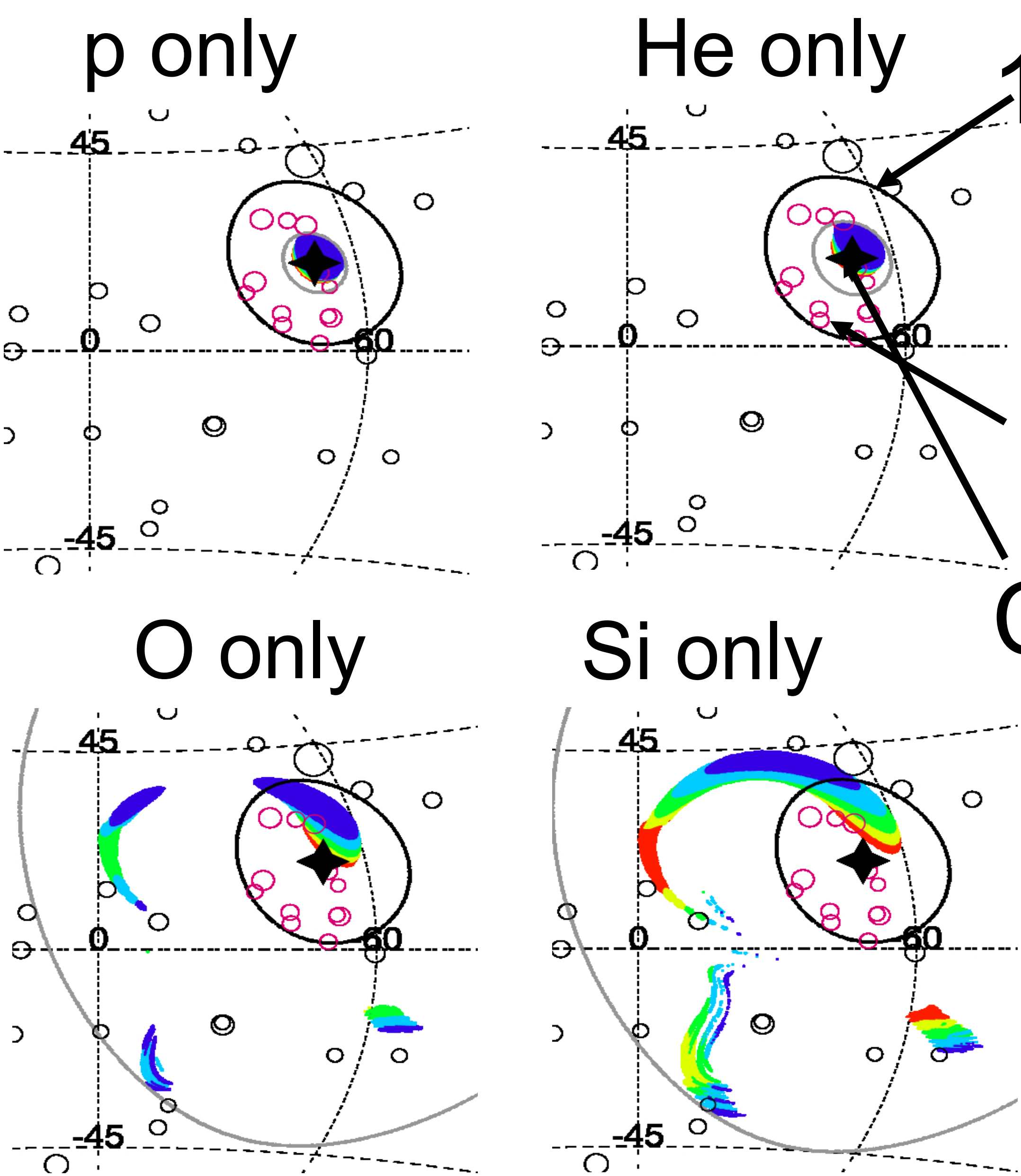

($L_X > 10^{42}$ erg s$^{-1}$, D<60 Mpc)

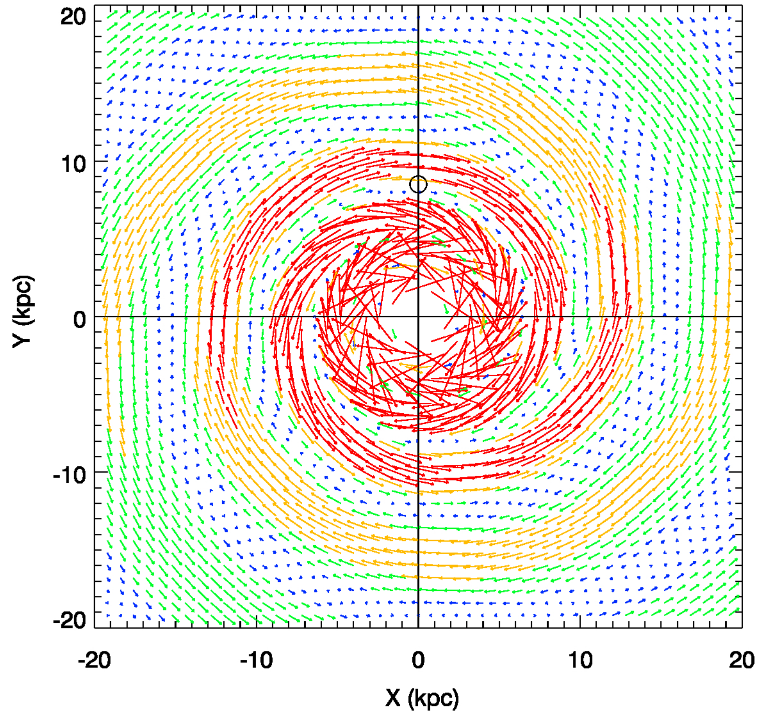



$$s = log_{10}(L_X/z^2) - 27.5$$



# Anisotropy Signatures of UHECR From Cen A?




astro-ph/1206.3907

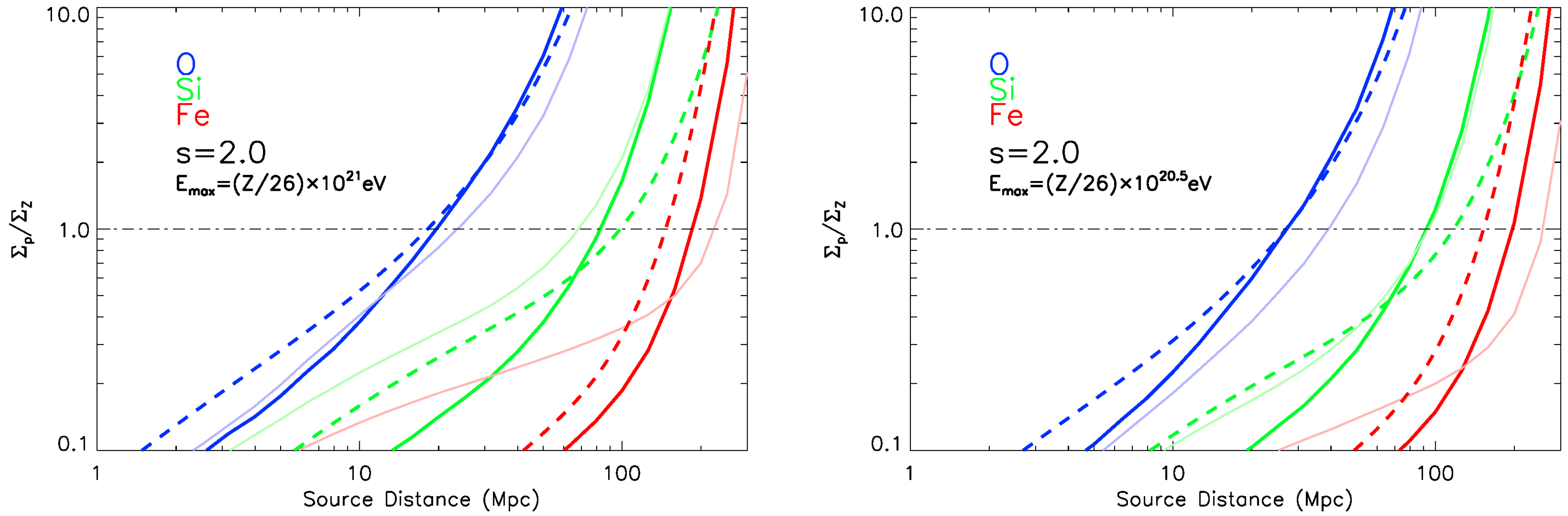
Giacinti et al.astro-ph/1006.5416

Yuksel et al. astro-ph/1203.3197

# Anisotropy Signatures of UHECR Sources?

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

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




astro-ph/1308.5699



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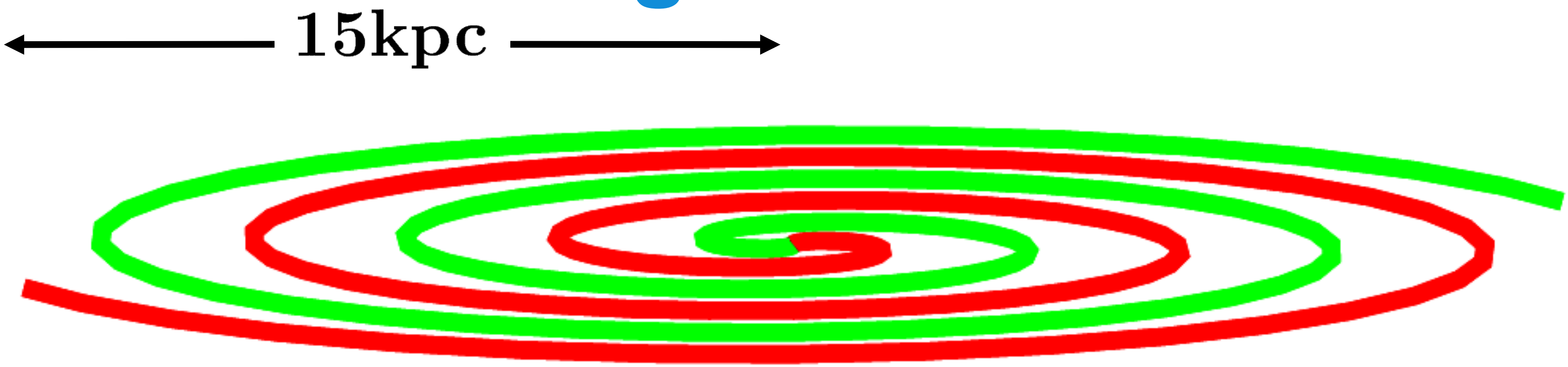
# The Effect of Galactic Magnetic Fields on Arriving Extragalactic Cosmic Rays

# Our Knowledge of the Galactic Magnetic Field




**Galactic Bfield Probes:**

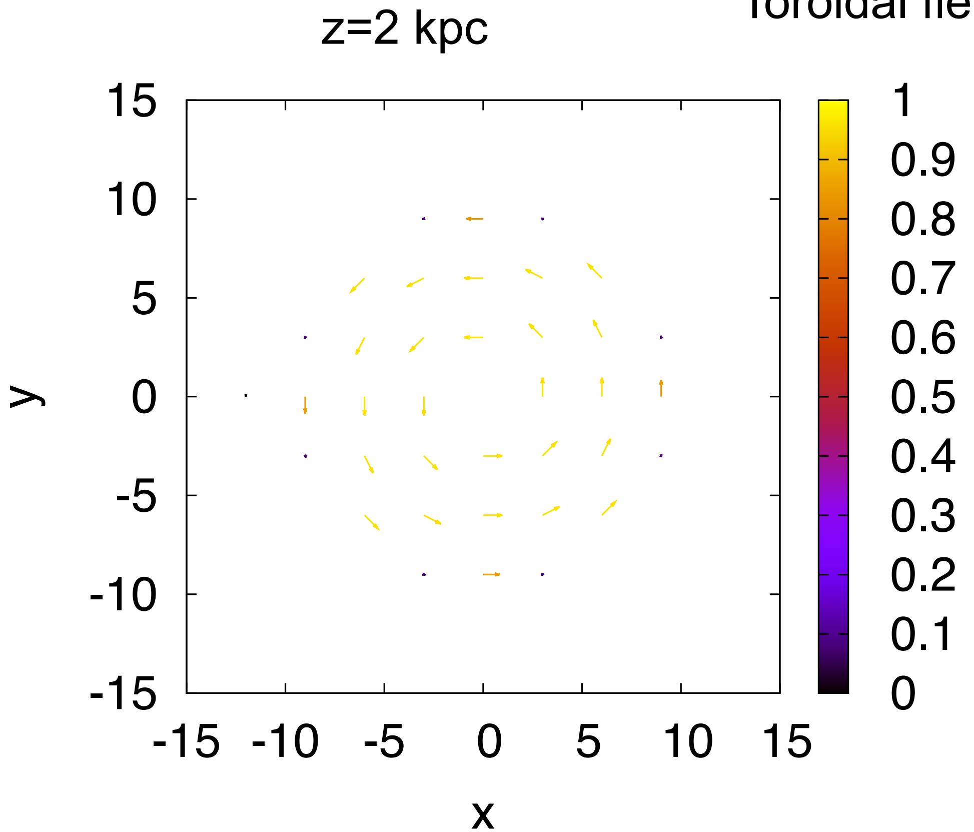
- Radio Pulsar Rotation/Dispersion Measure
- Radio Zeeman splitting of Hydrogen
- Radio Synchrotron

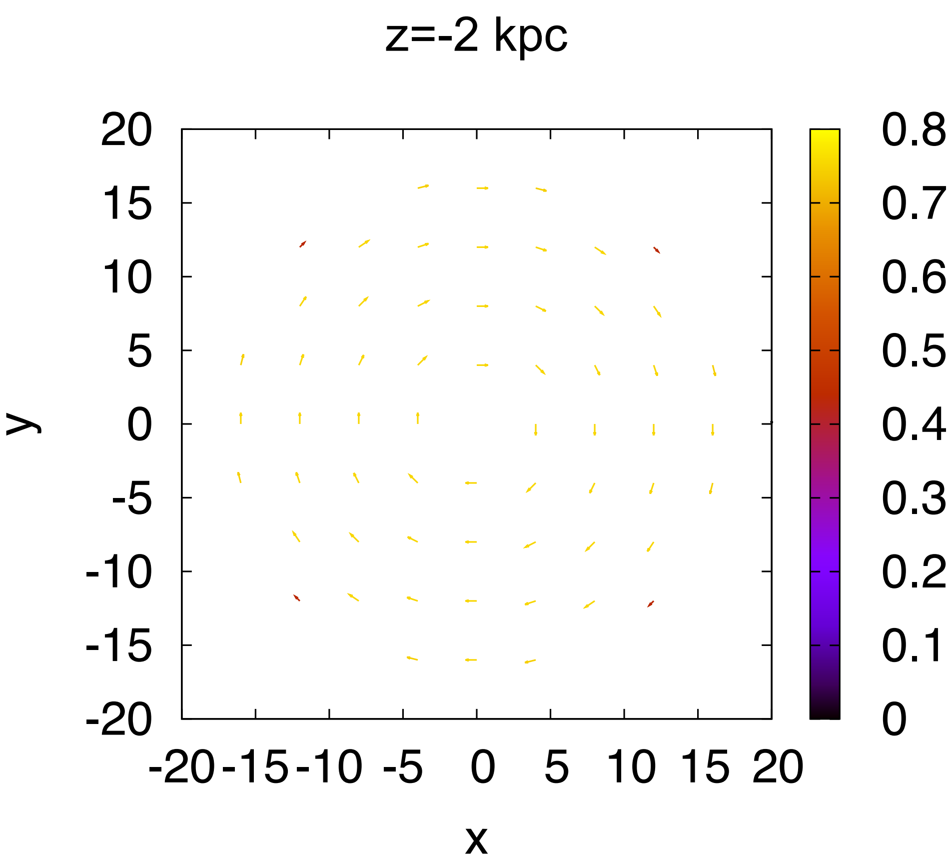
↳ $B_{\mathrm{Gal.}} \approx 3\mu\mathrm{G}$

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

# Galactic B-field Interaction with Cen A CR Flux

Toroidal field component



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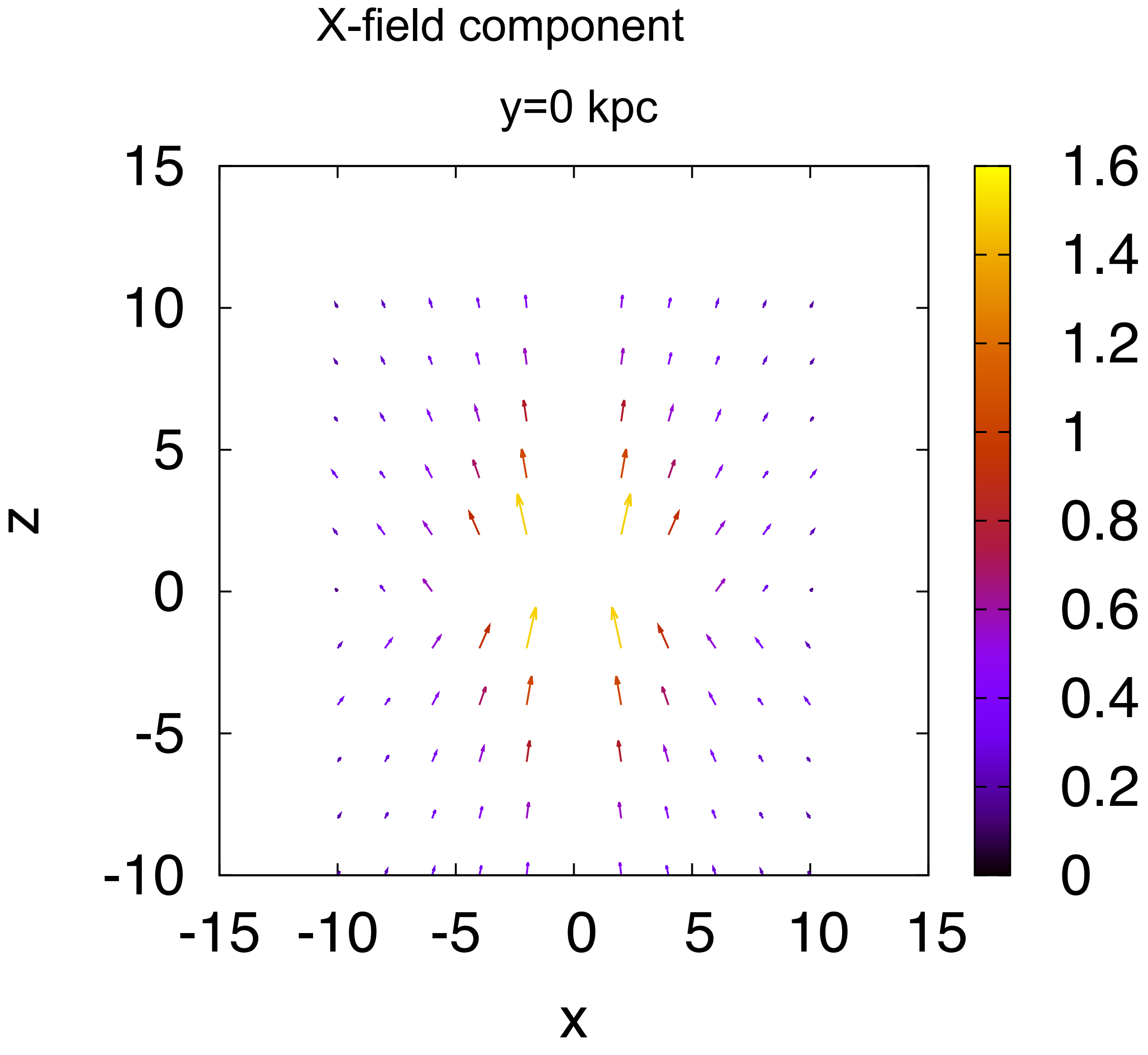
# Galactic B-field Interaction with Cen A CR Flux



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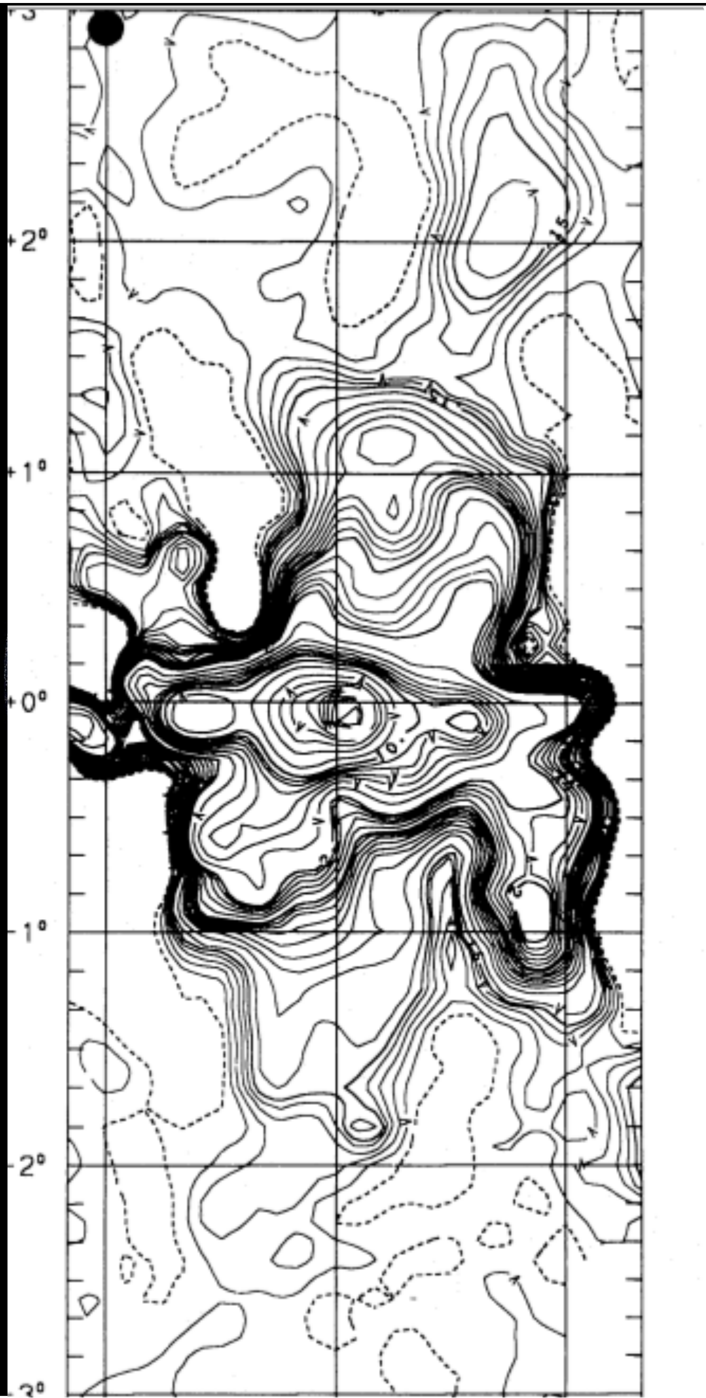
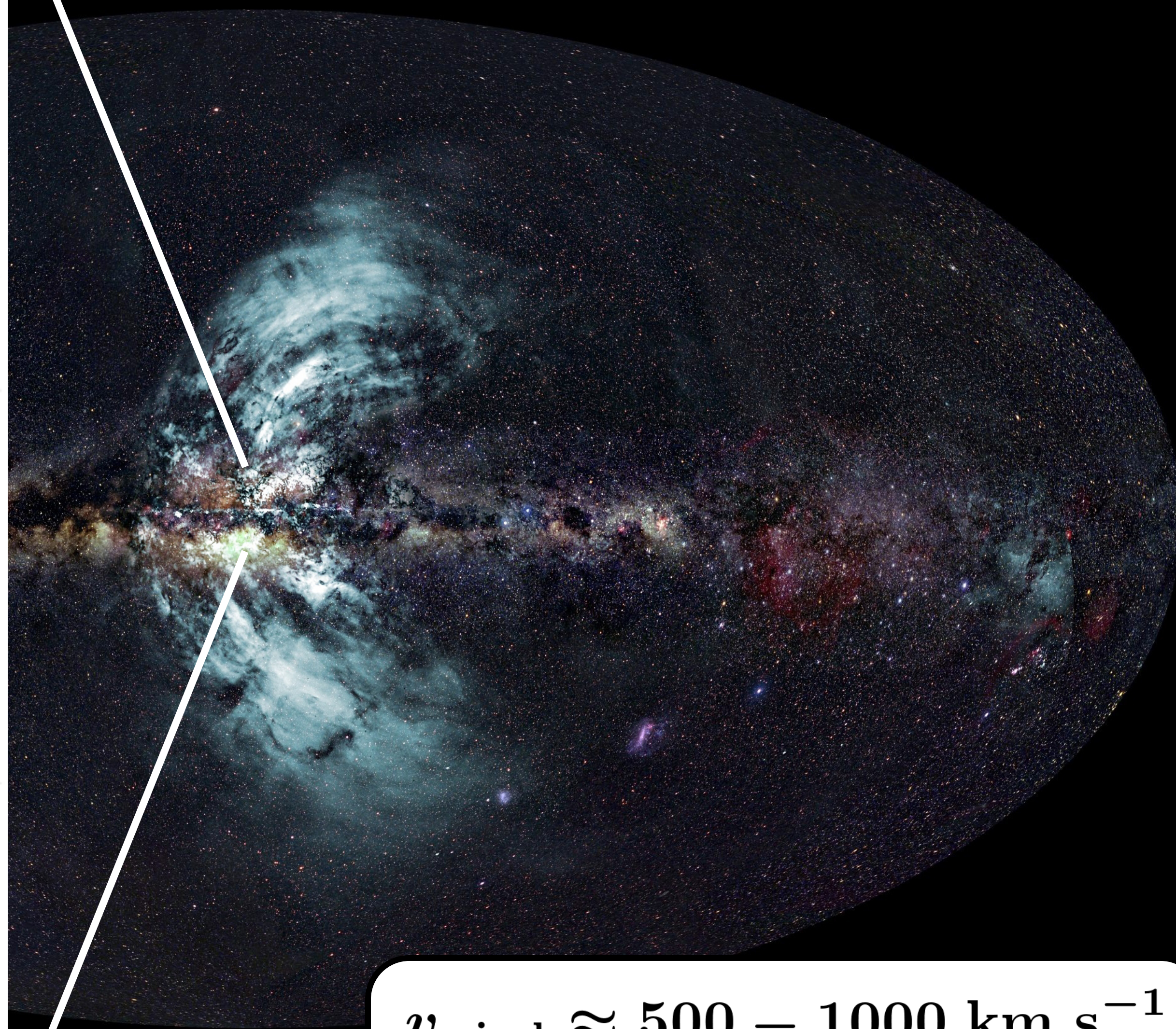
# Galactic Diffuse Radio Emission

Pohl+, A&A 262 441 1992

Carretti+, *Nature* **volume 493**, 2013



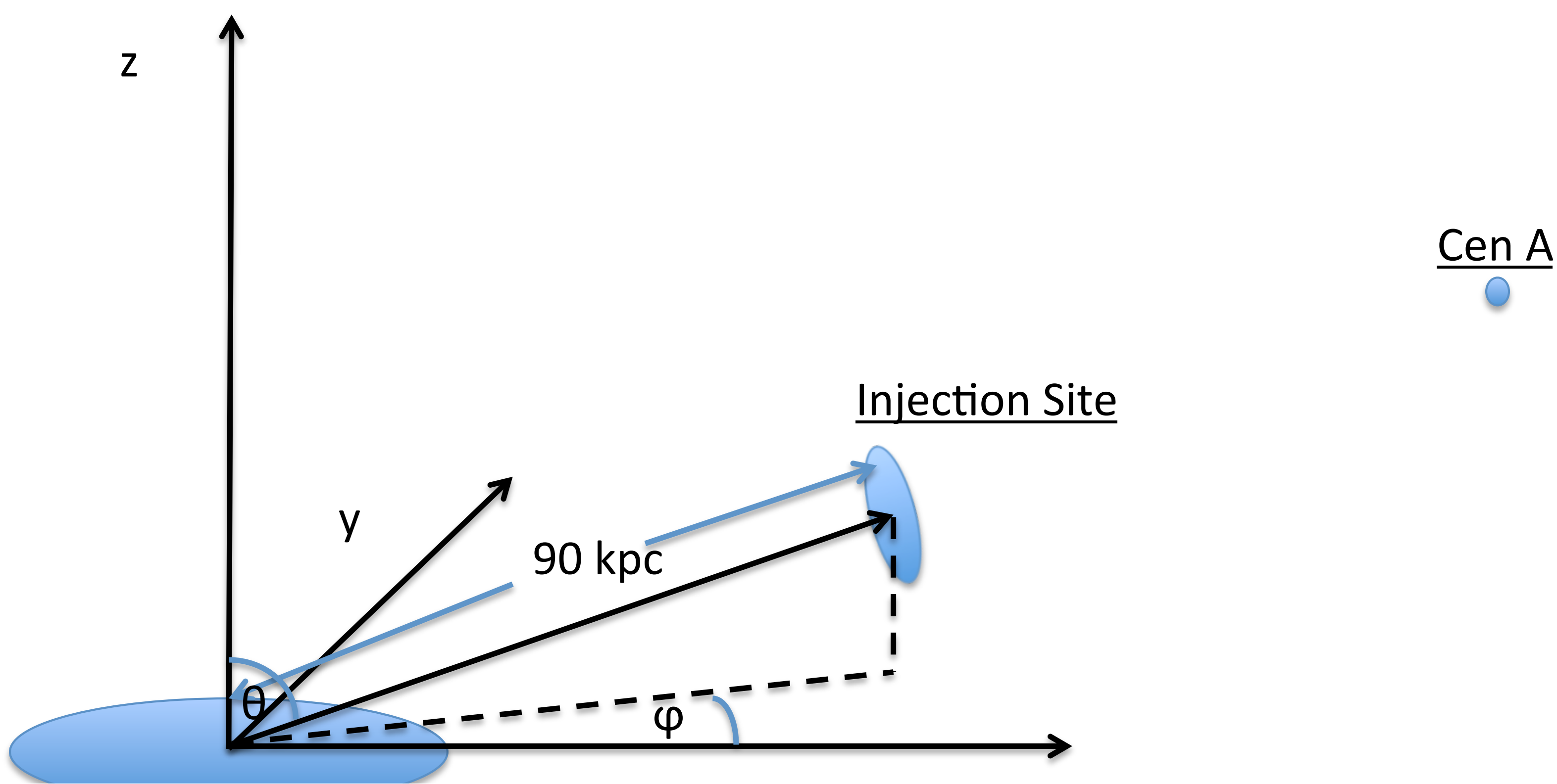



$$\boldsymbol{v_{\mathrm{wind}} \approx 500 - 1000\ \mathrm{km\ s^{-1}}}$$

$$\boldsymbol{\dot{E}_{\mathrm{wind}} \approx 3 \times 10^{40}\ \mathrm{erg\ s^{-1}}}$$

# "Low Energy" Spectral Suppression of CR from Cen A

## System Setup



# Galactic Magnetic Field "Shadowing"

$$U_B^{disk} = 8 \times 10^{53} \text{ erg}$$

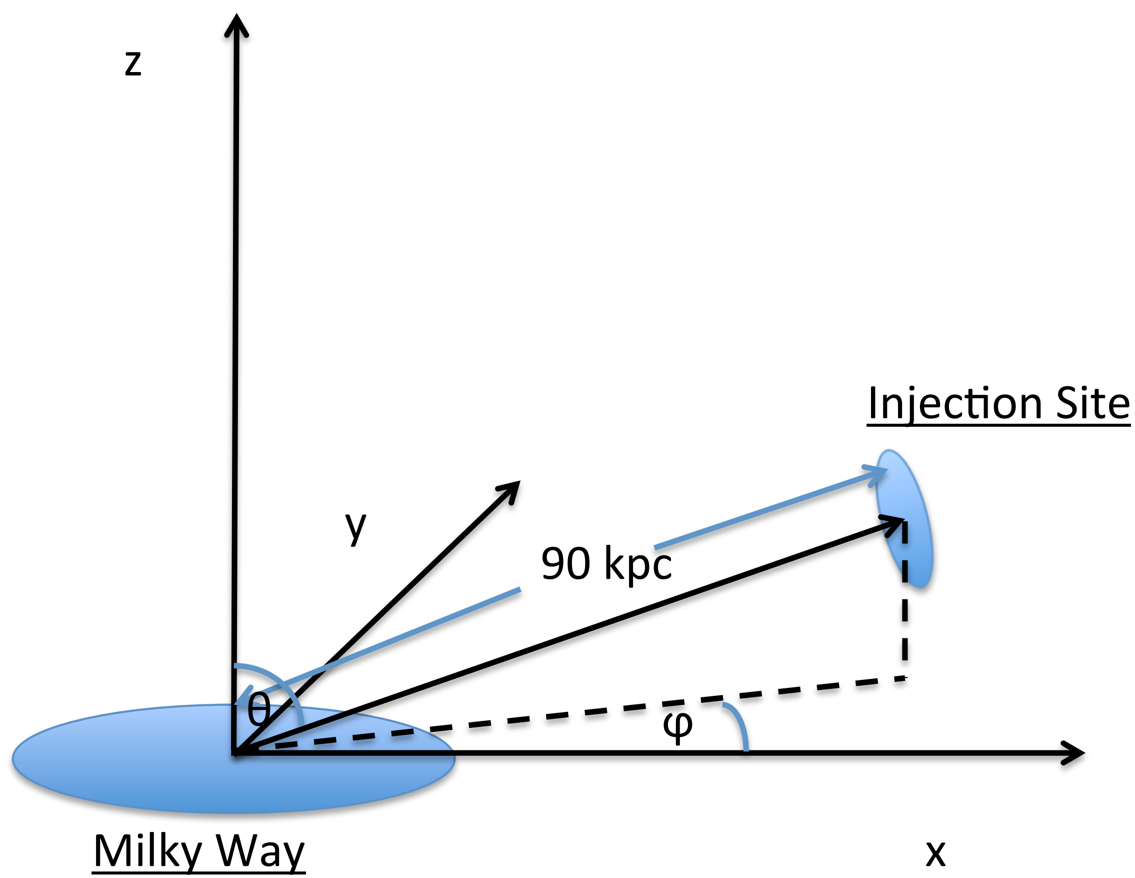
$$U_B^{toroid} = 4 \times 10^{54} \text{ erg}$$

$$U_B^{X-field} = 3 \times 10^{54} \text{ erg}$$

$$U_{CR} \approx 10^{55} \text{ erg}$$

$$E_p = 3 \times 10^{18} \text{ eV}$$

**System Setup**



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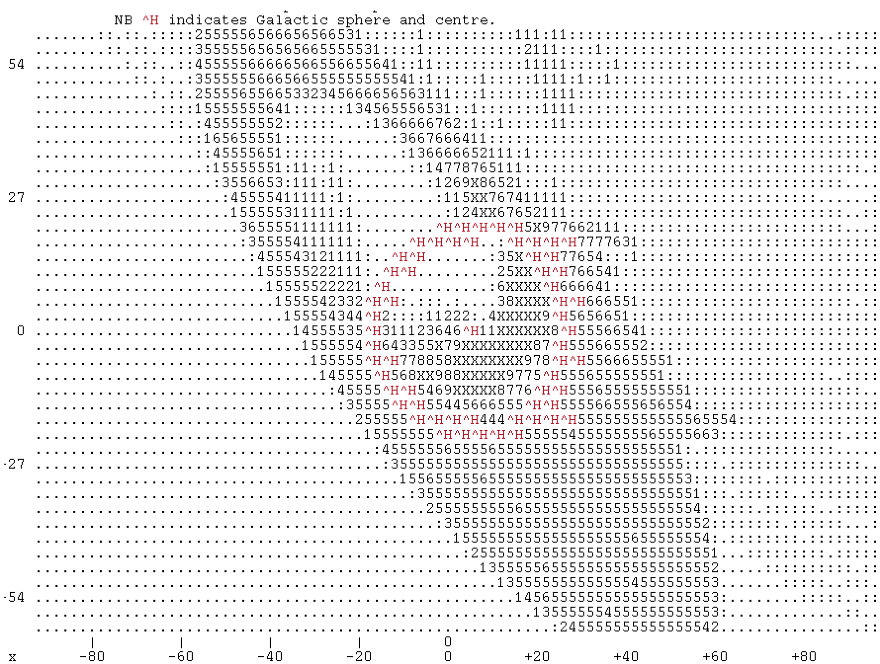


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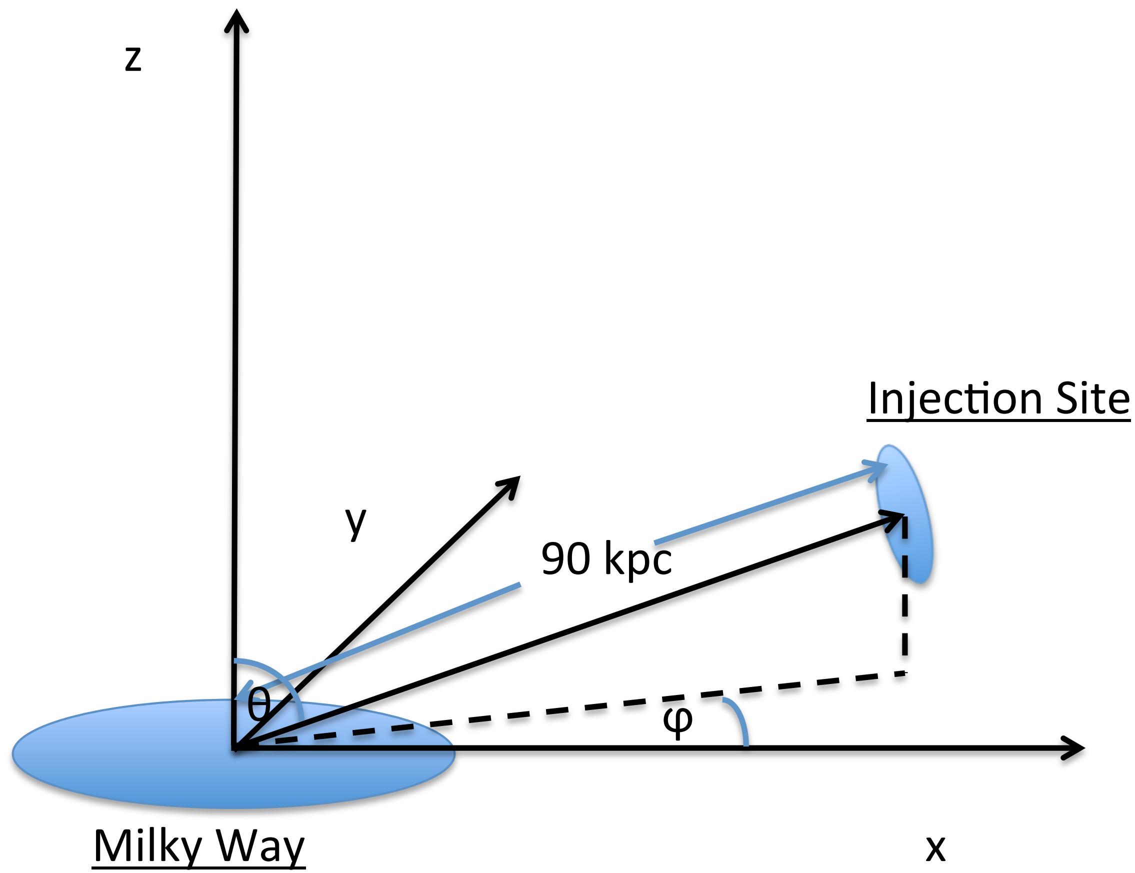


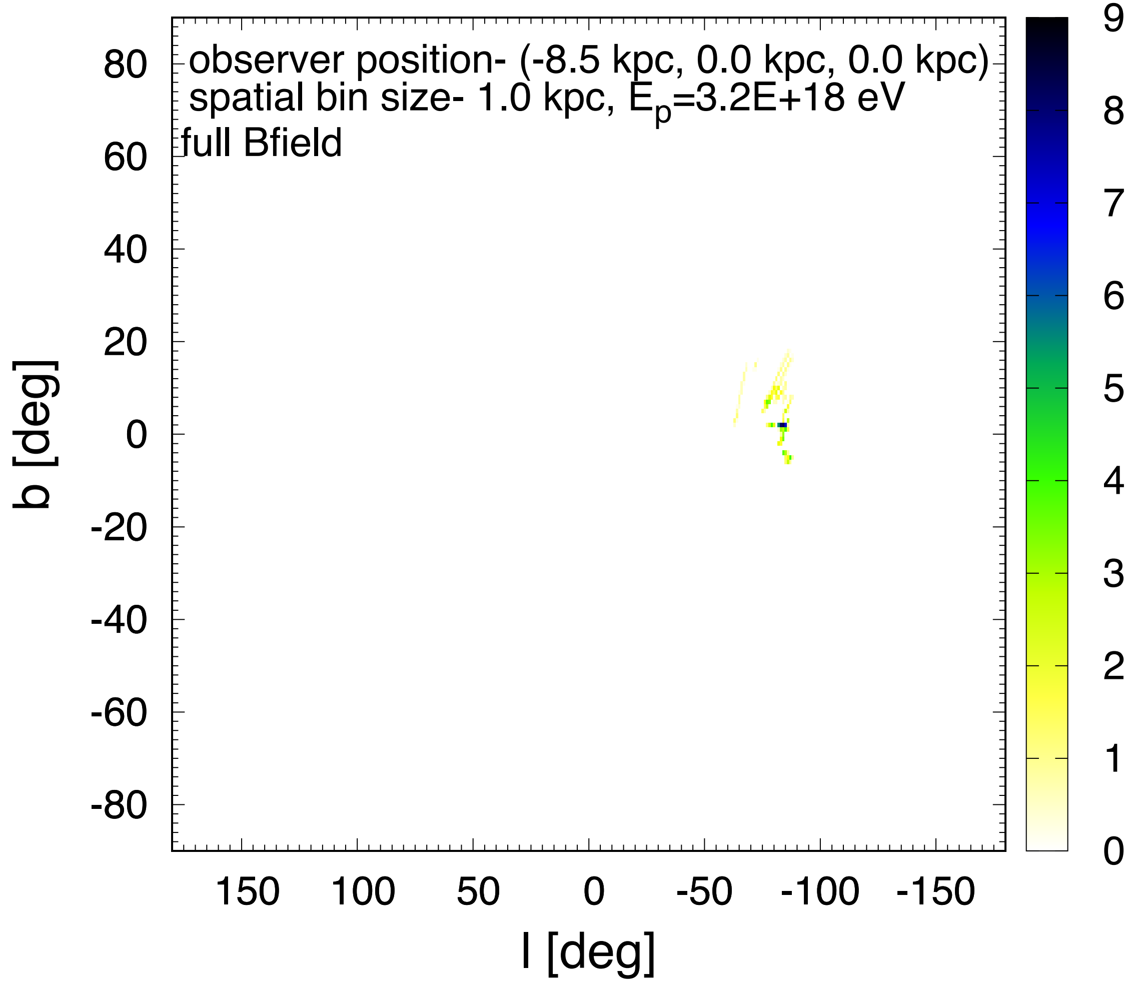

Michael & I had intended to produce a short paper on this "shadowing" effect



DESY.

# Cosmic Ray Anisotropy from Cen A?

Angular arrival distribution of parallel beam from Cen A fired at Galactic magnetic field



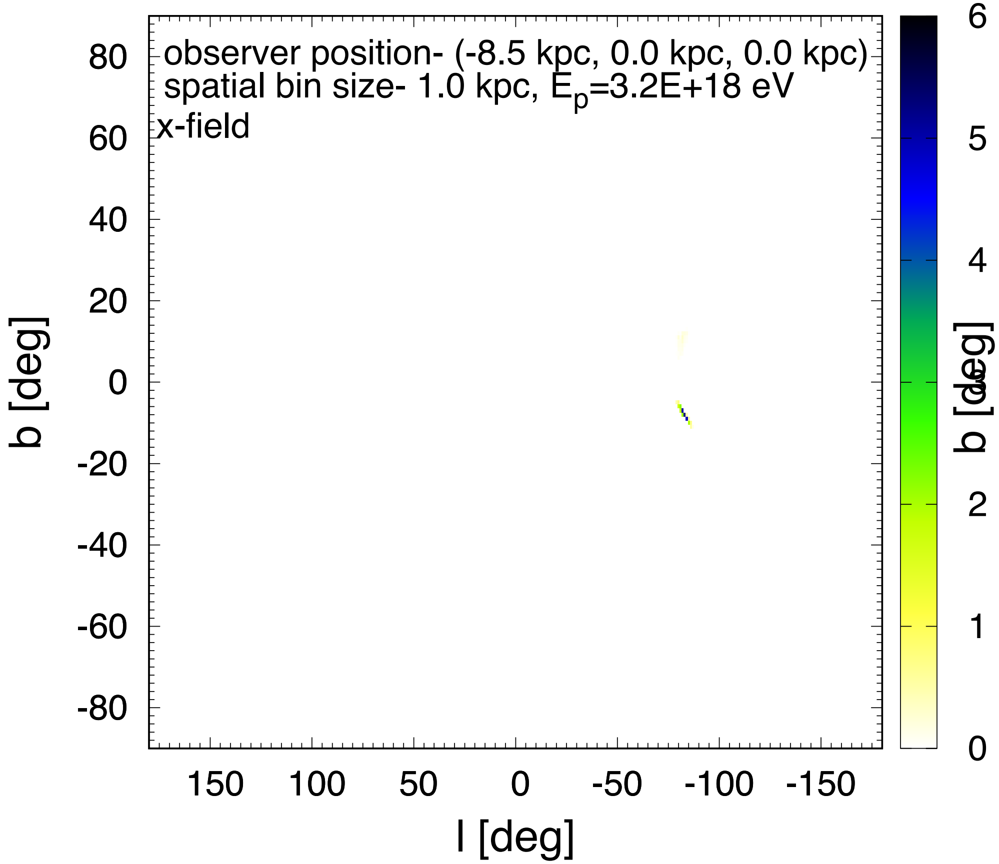



DESY.

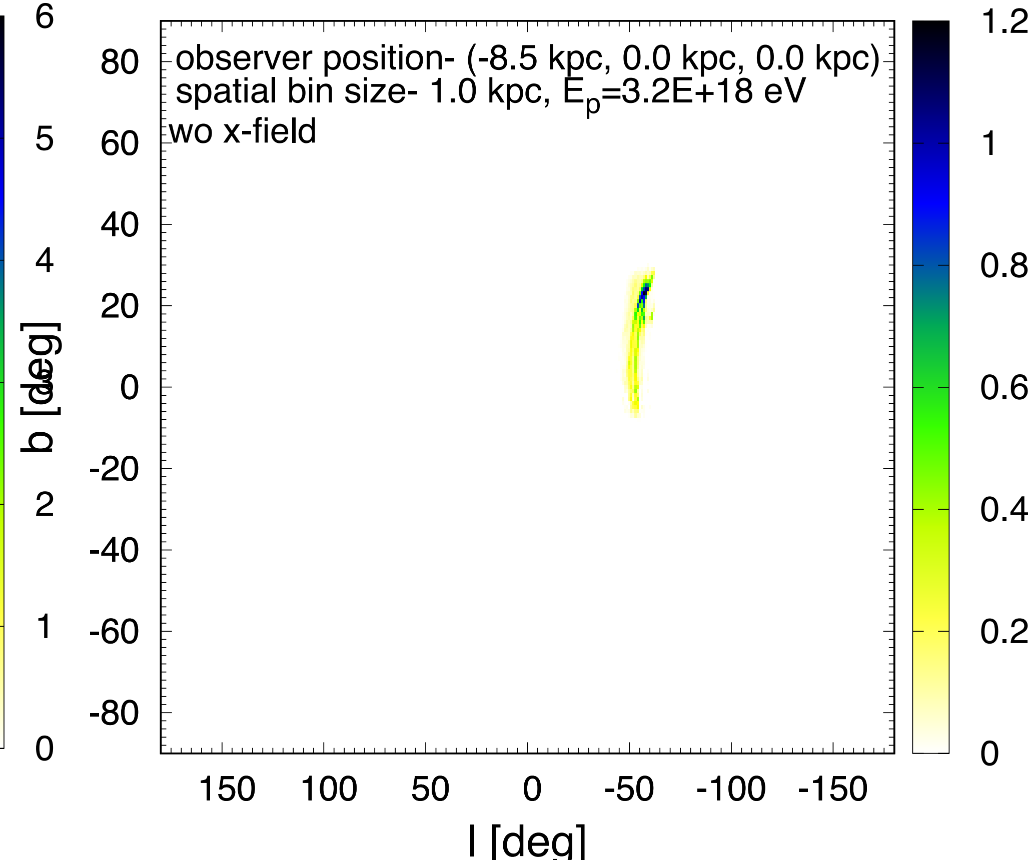
# Cosmic Ray Anisotropy from Cen A?

Importance in role of X-field component of the Galactic Magnetic in shifting position of Cen A in arriving flux from beam injected

Only X-field




Only Toroidal + Disk Fields



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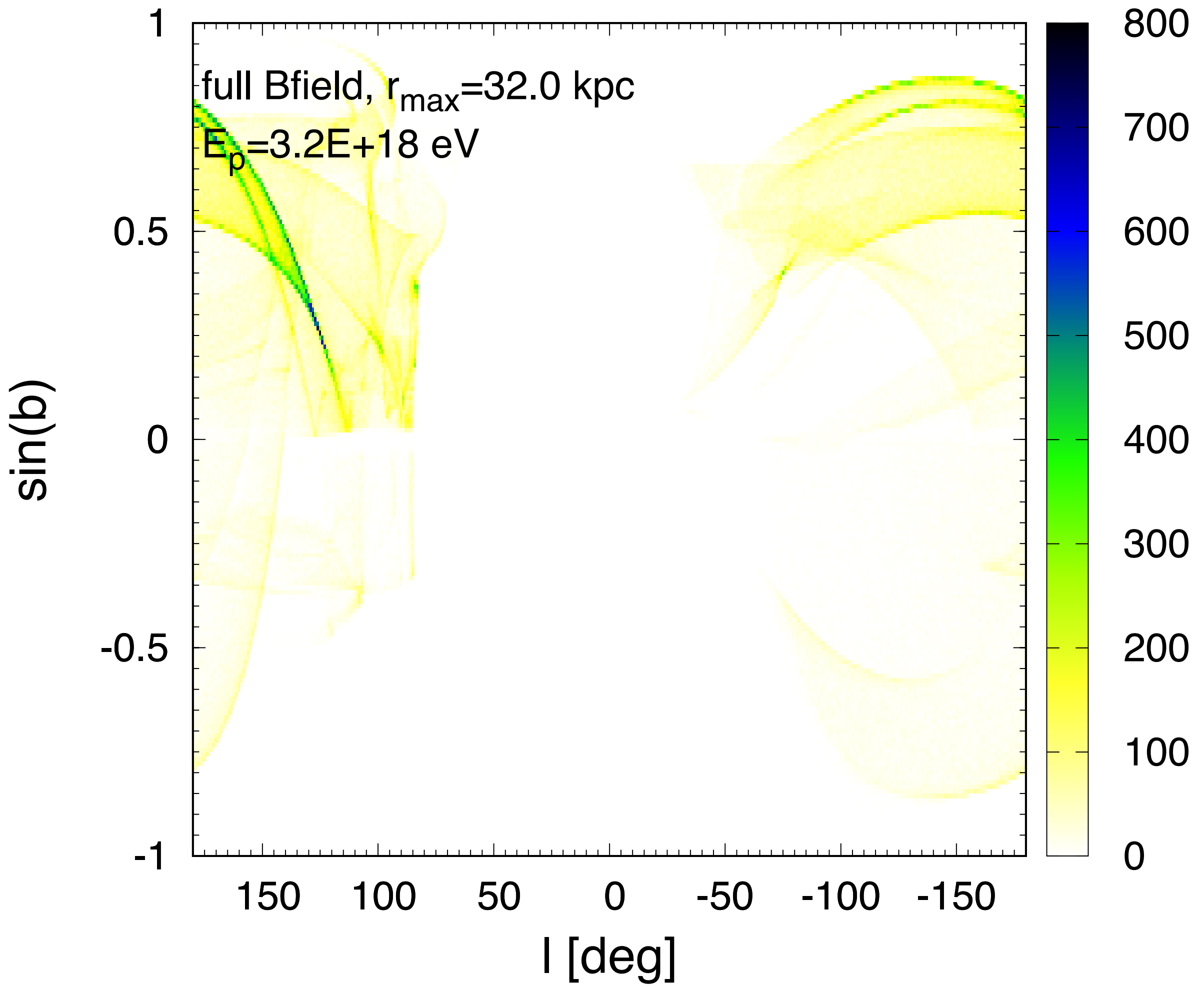
# How Isotropic Cosmic Rays at Earth Sample the Isotropic Extragalactic Sky

⋯.and lastly, back-tracking isotropic particles from Earth to see which parts of extragalactic sky are preferentially sampled at these energies



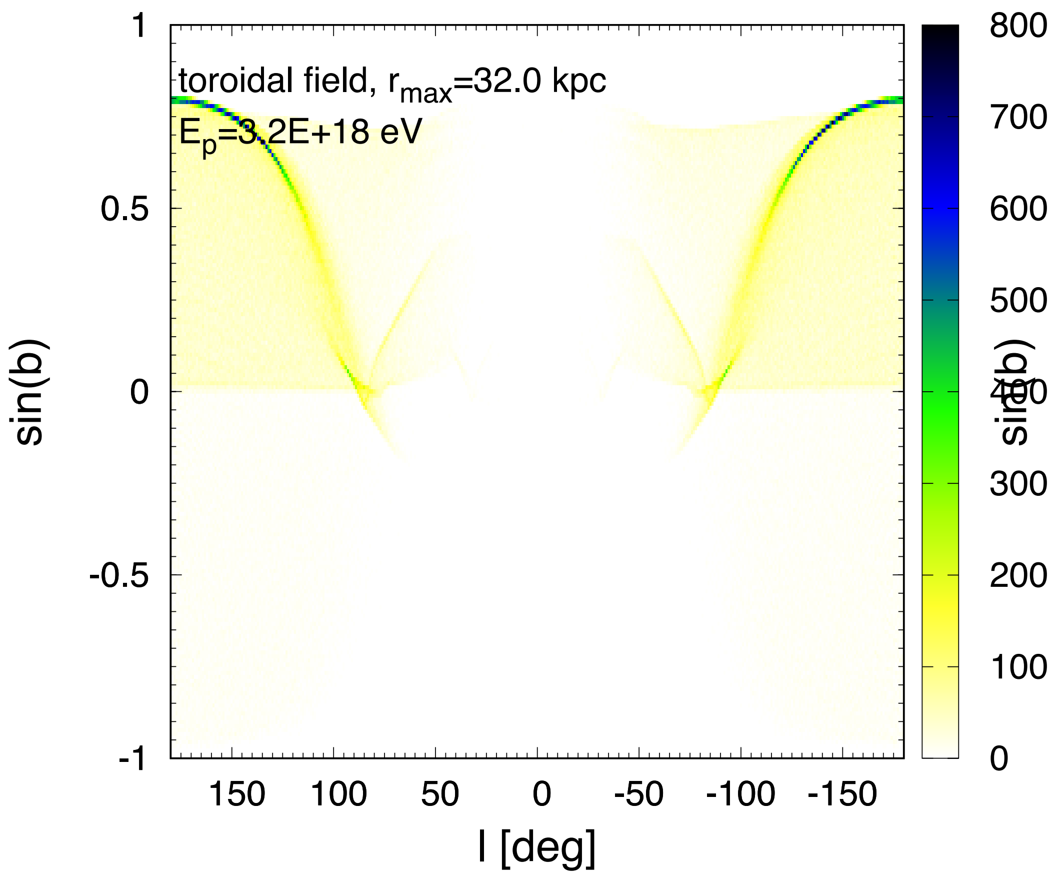

Michael named this effect “tunnel vision”!

DESY.

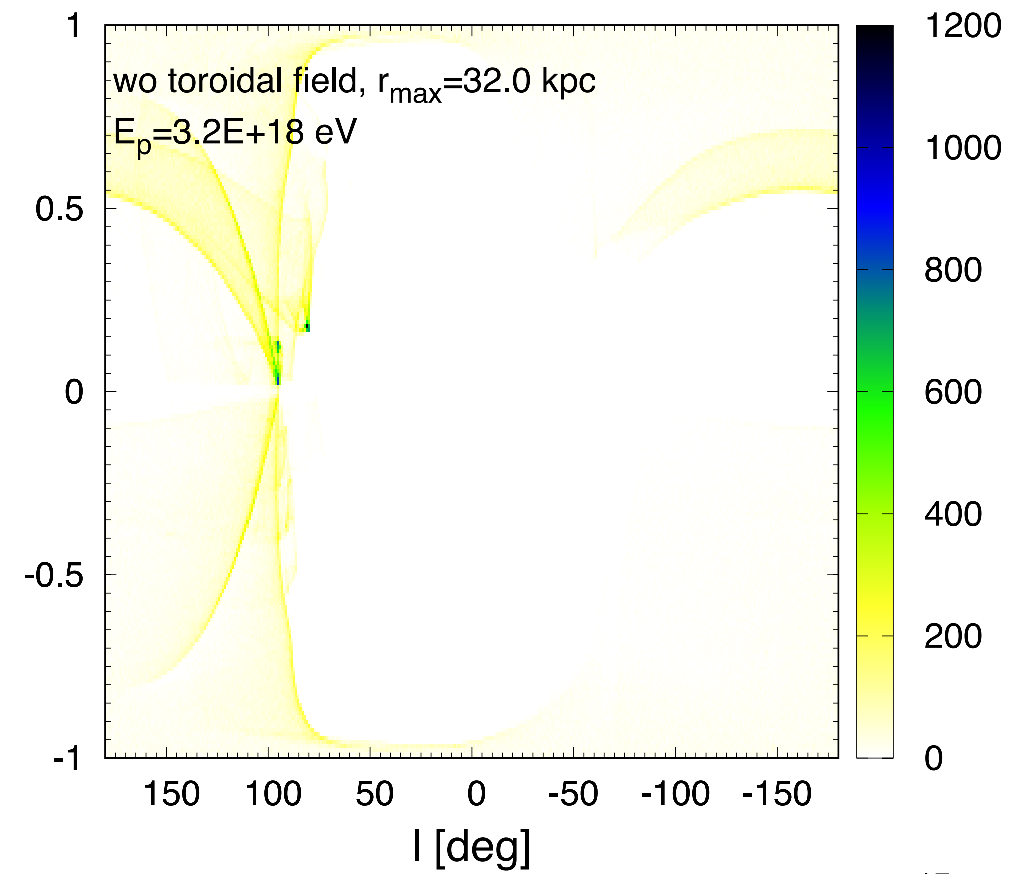
# How Isotropic Cosmic Rays at Earth Sample the Isotropic Extragalactic Sky

Importance in role of Toroidal Field in Selecting Extragalactic Regions Probed

Only Toroidal Field




Only Disk + X-Field






DESY.

# End of Third Lecture

# 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

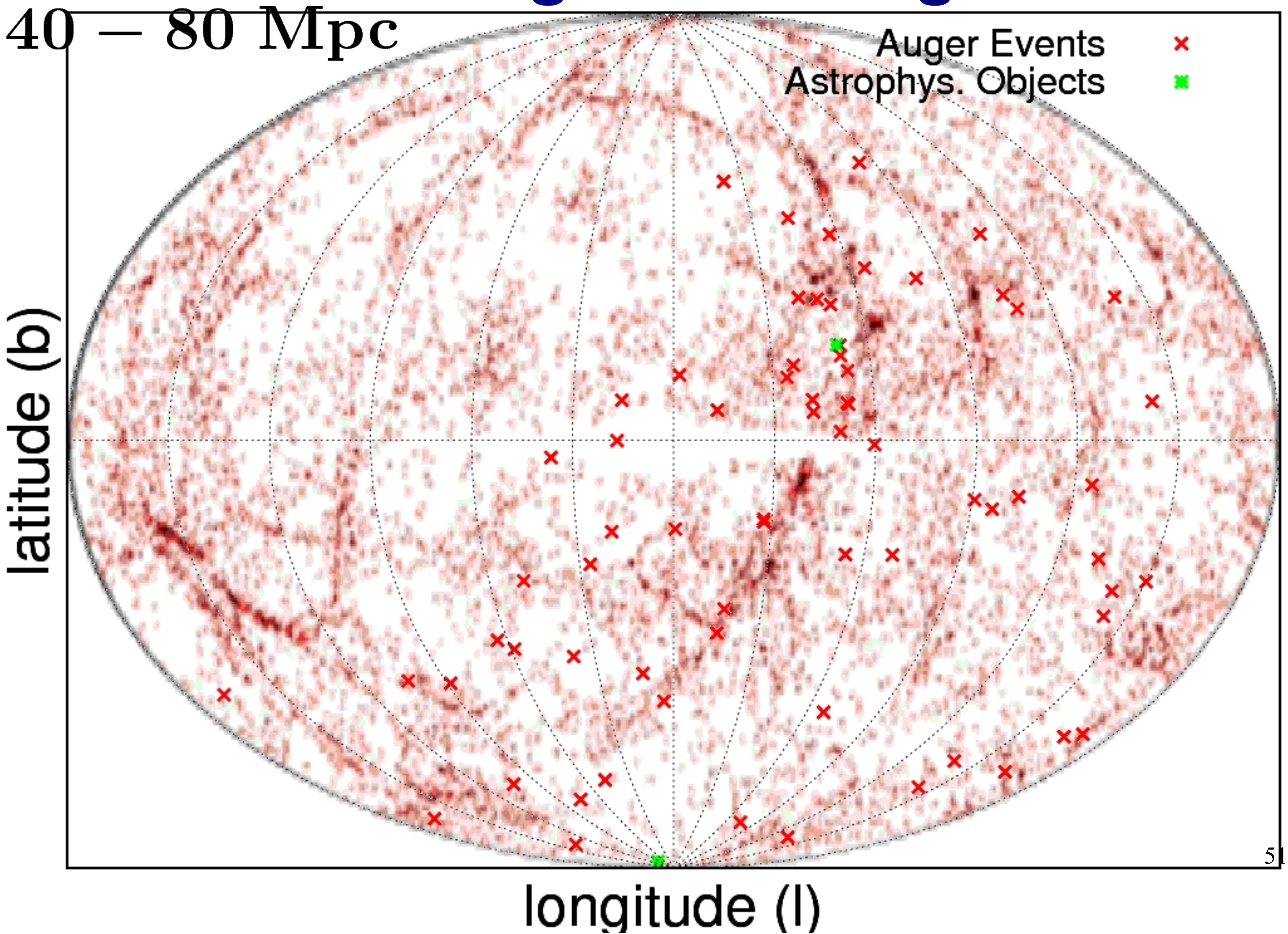
Regions close to luminous objects are excluded as UHECR sources, favouring slow/non-compact accelerators



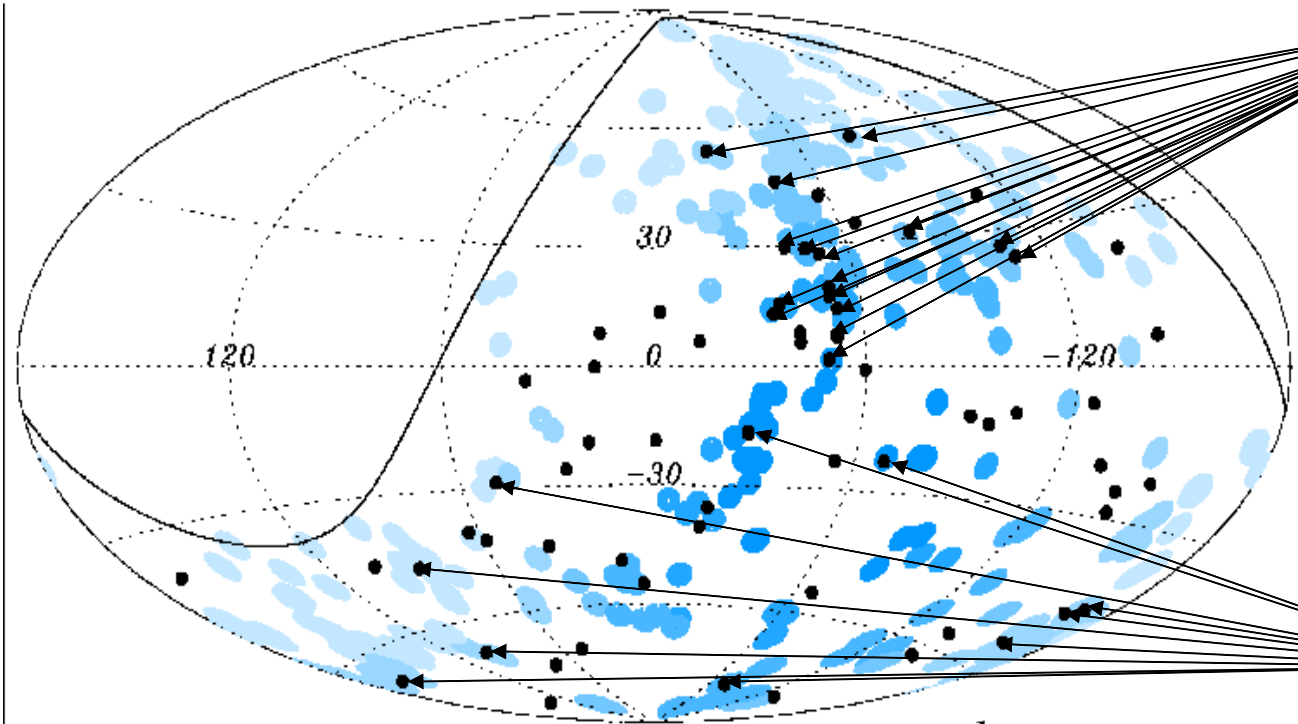
DESY.

# Extra Slides

# Our Local Extragalactic Neighbourhood



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

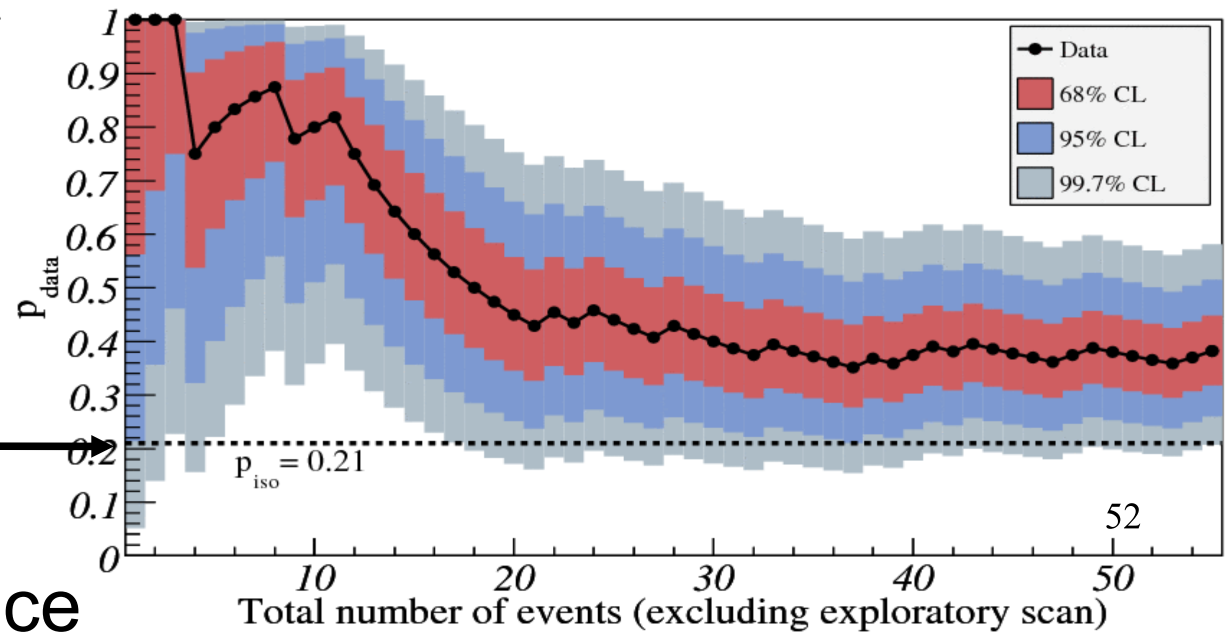



16 correlated events

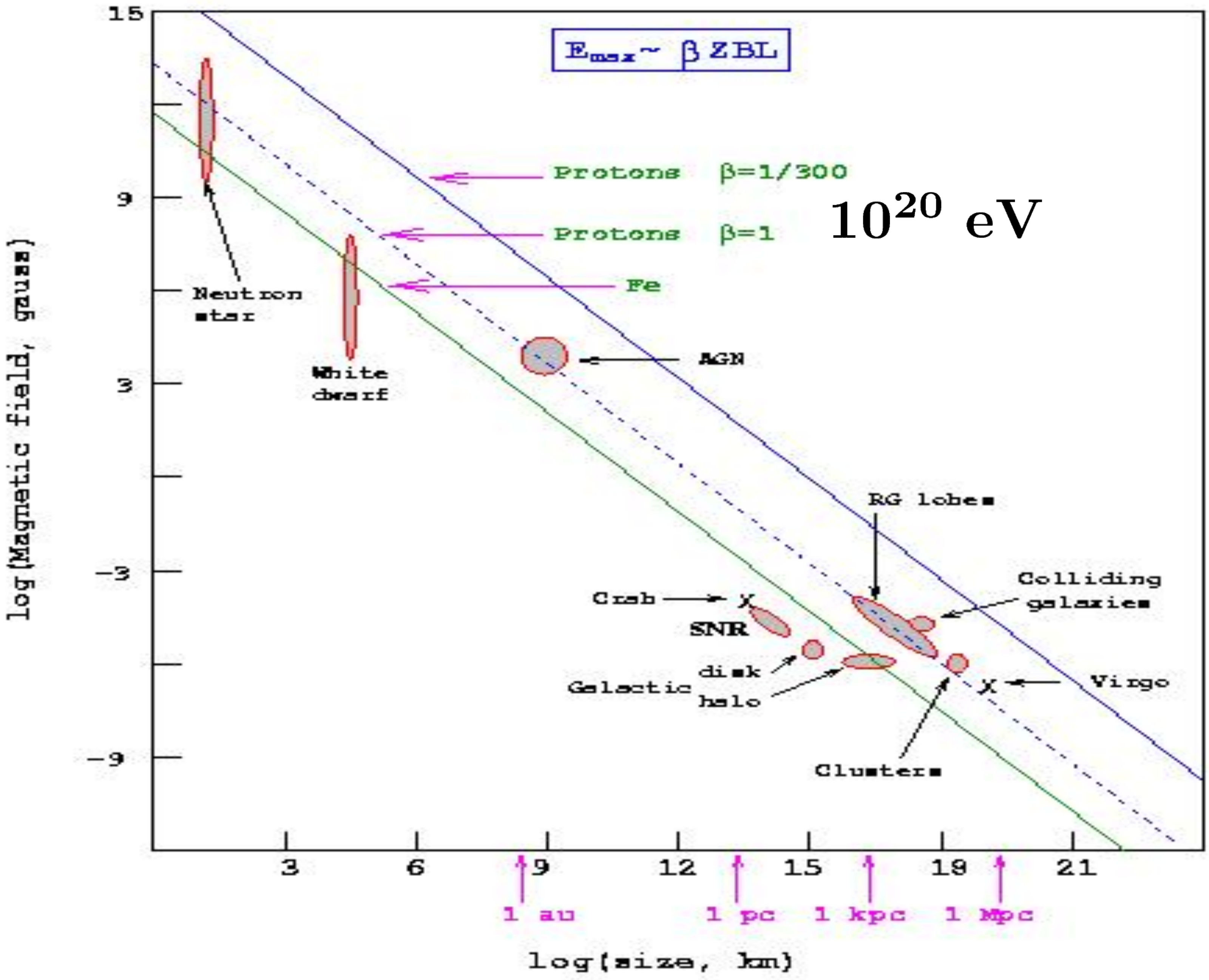
10 correlated events

~26 of the events correlate with an AGN

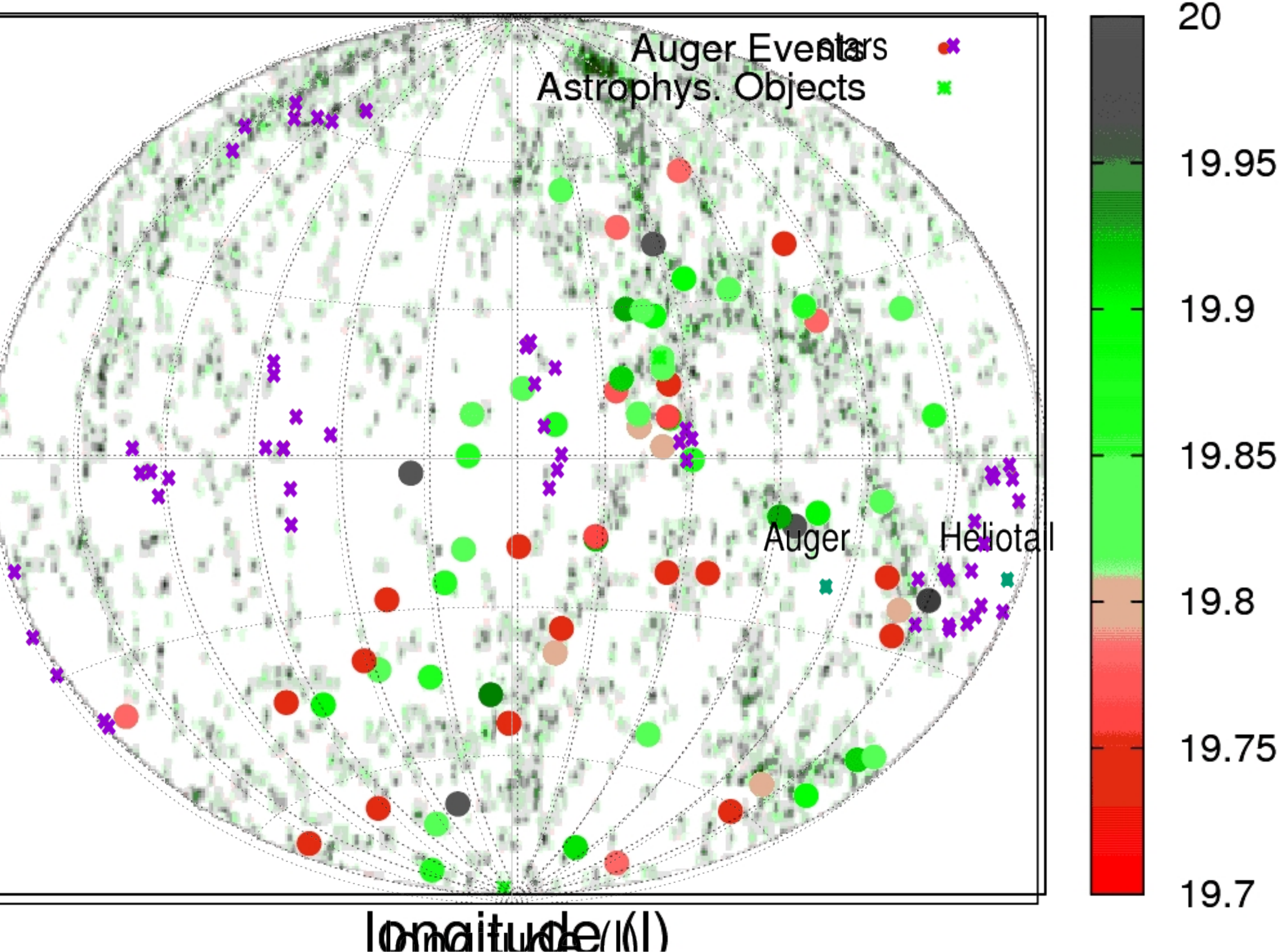
ie. ~11 events expected to correlate by chance



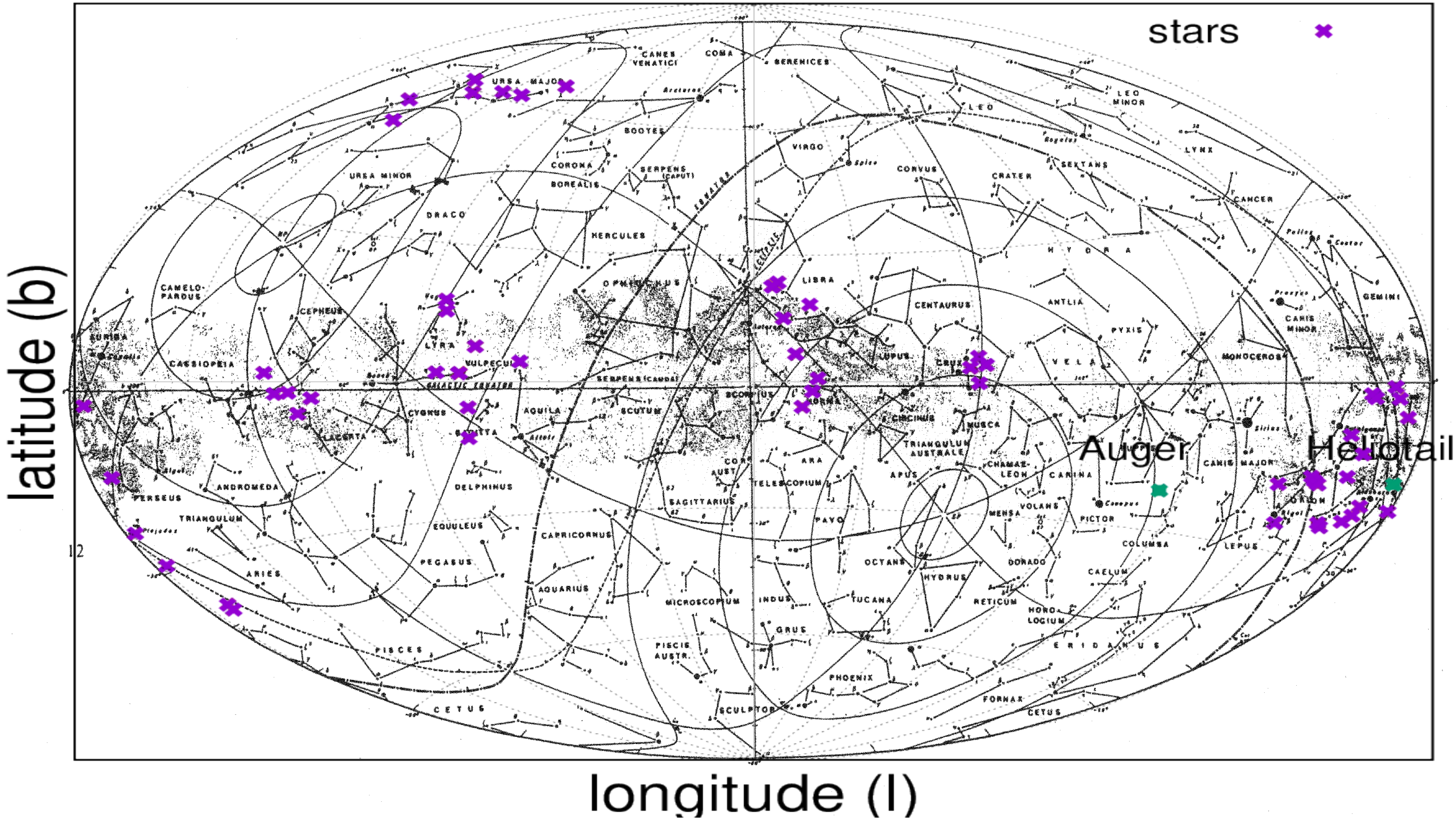
# Hillas' Hillas Plot



# Can We See UHECR Sources Directly?



# Can We See UHECR Sources Directly?






tre :
ette carte présente, en détail, la position des constellations
s par rapport au plan de notre Galaxie. Ici, toute la Voie lactée