Ultra High Energy Cosmic Rays and the study of Cosmic Magnetism

Bachelor Thesis by Stefan Hackstein

Goals

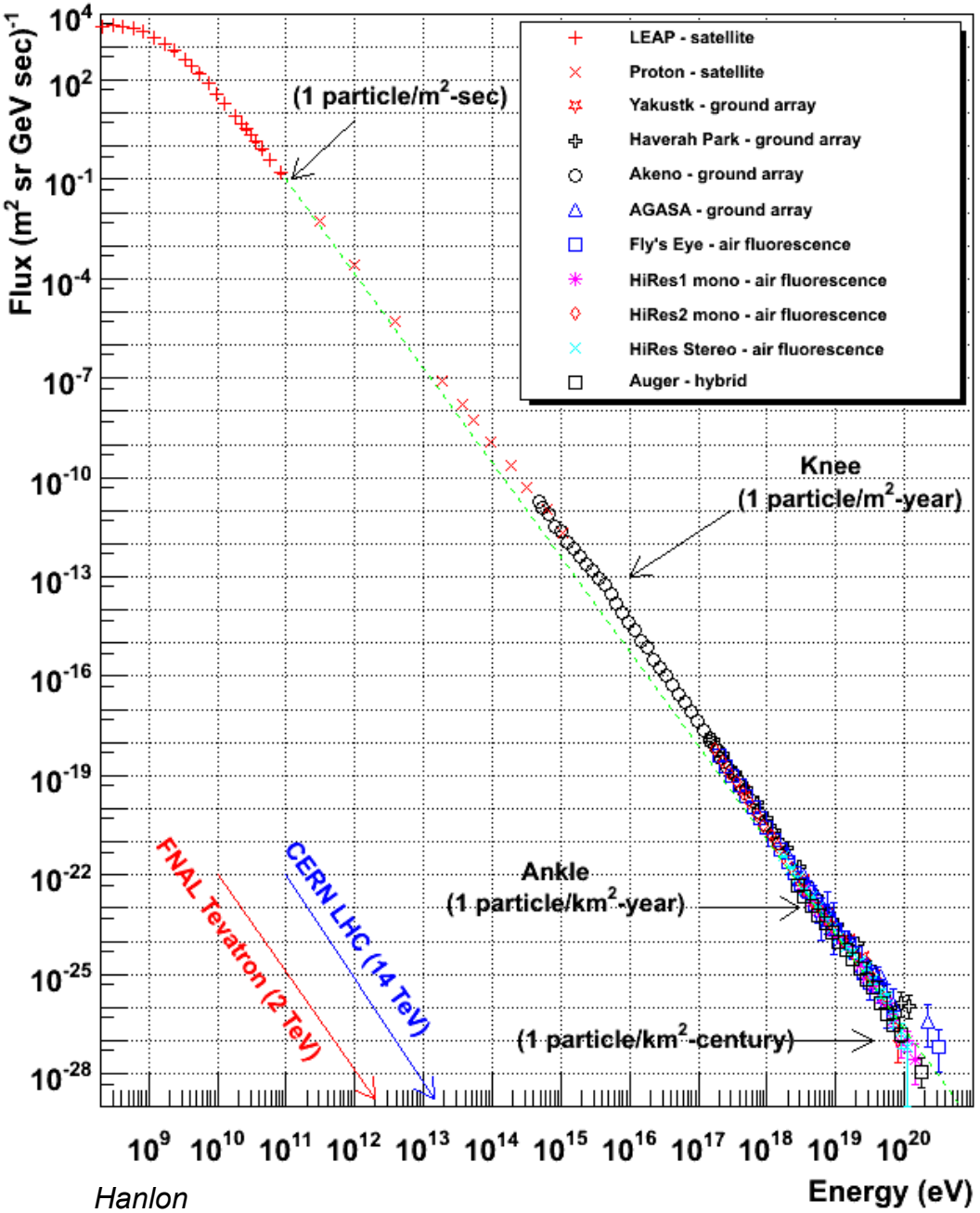
Magnetic Field Seeding model

UHECRs Injection scenario

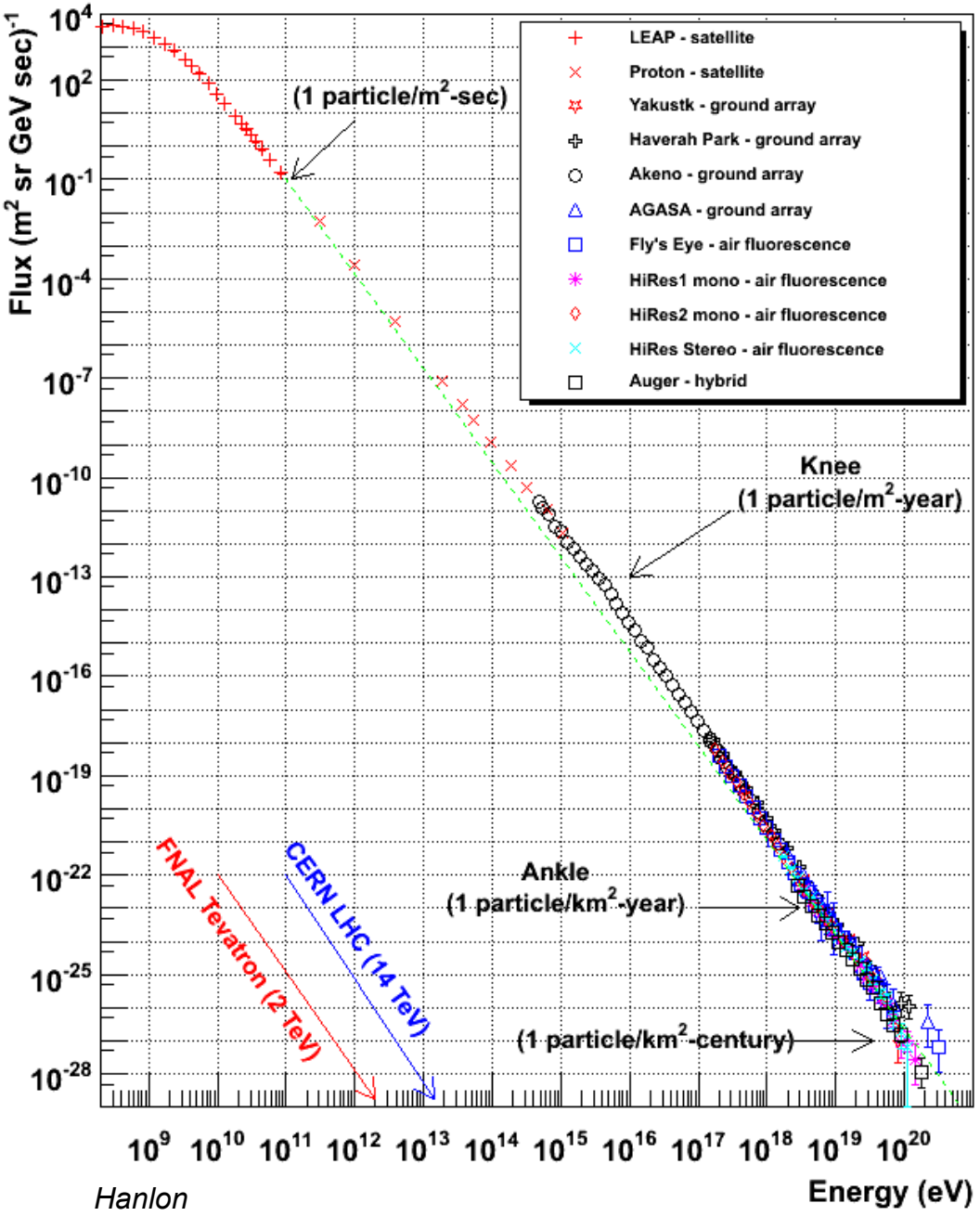
random vs. cluster center

effects on energy spectrum & anisotropy

Cosmic Rays

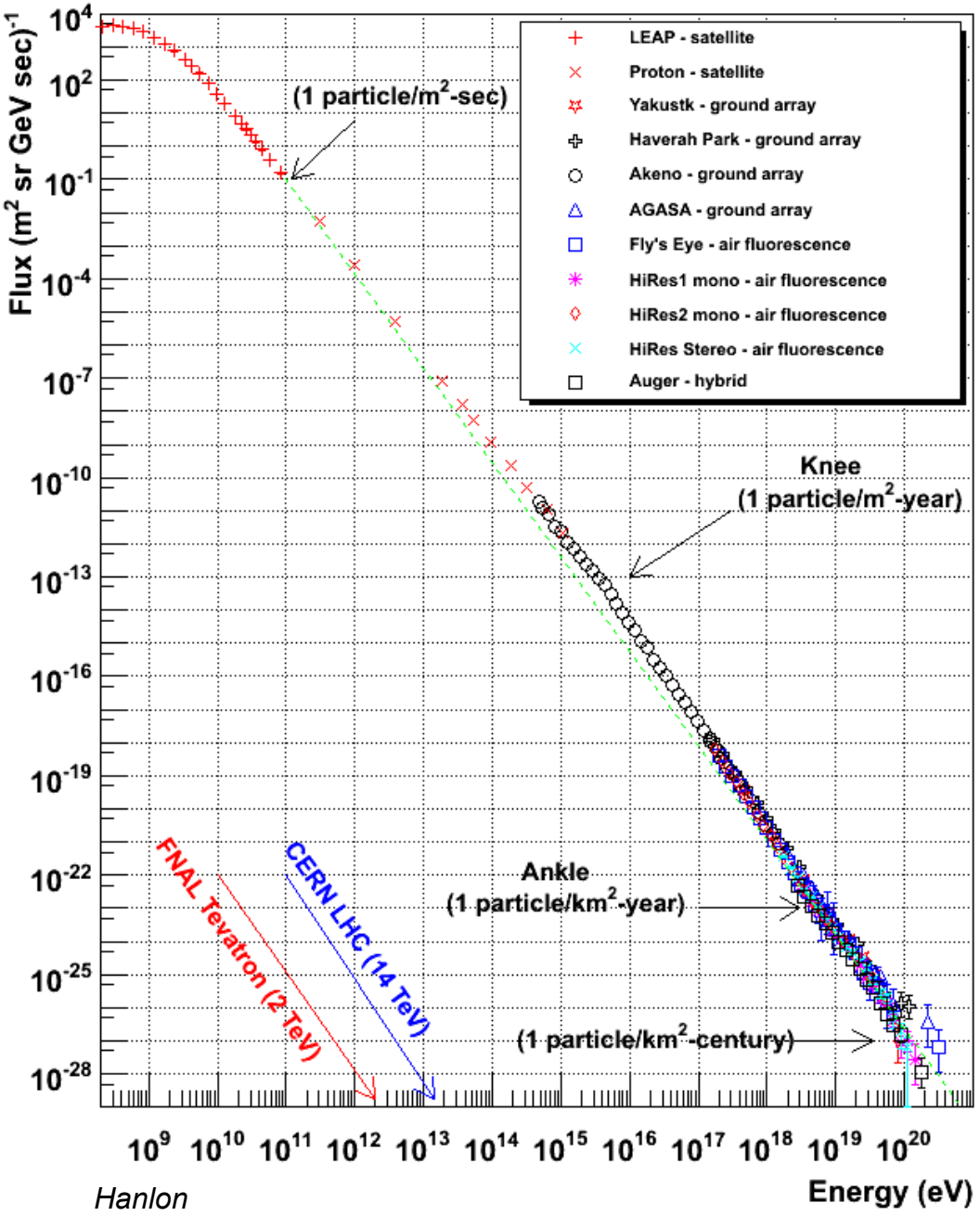

LEAP - satellite
Proton - satellite
Yakustk - ground array
Haverah Park - ground array
Akeno - ground array
AGASA - ground array
Fly's Eye - air fluorescence
HiRes1 mono - air fluorescence
HiRes2 mono - air fluorescence
HiRes Stereo - air fluorescence
Auger - hybrid
(1 particle/m²-sec)
Knee
(1 particle/m²-year)
Ankle
(1 particle/km²-year)
(1 particle/km²-century)
FNAL Tevatron (2 TeV)
CERN LHC (14 TeV)
Flux (m² sr GeV sec)⁻¹
Energy (eV)

Cosmic Rays



Power law

Cosmic Rays

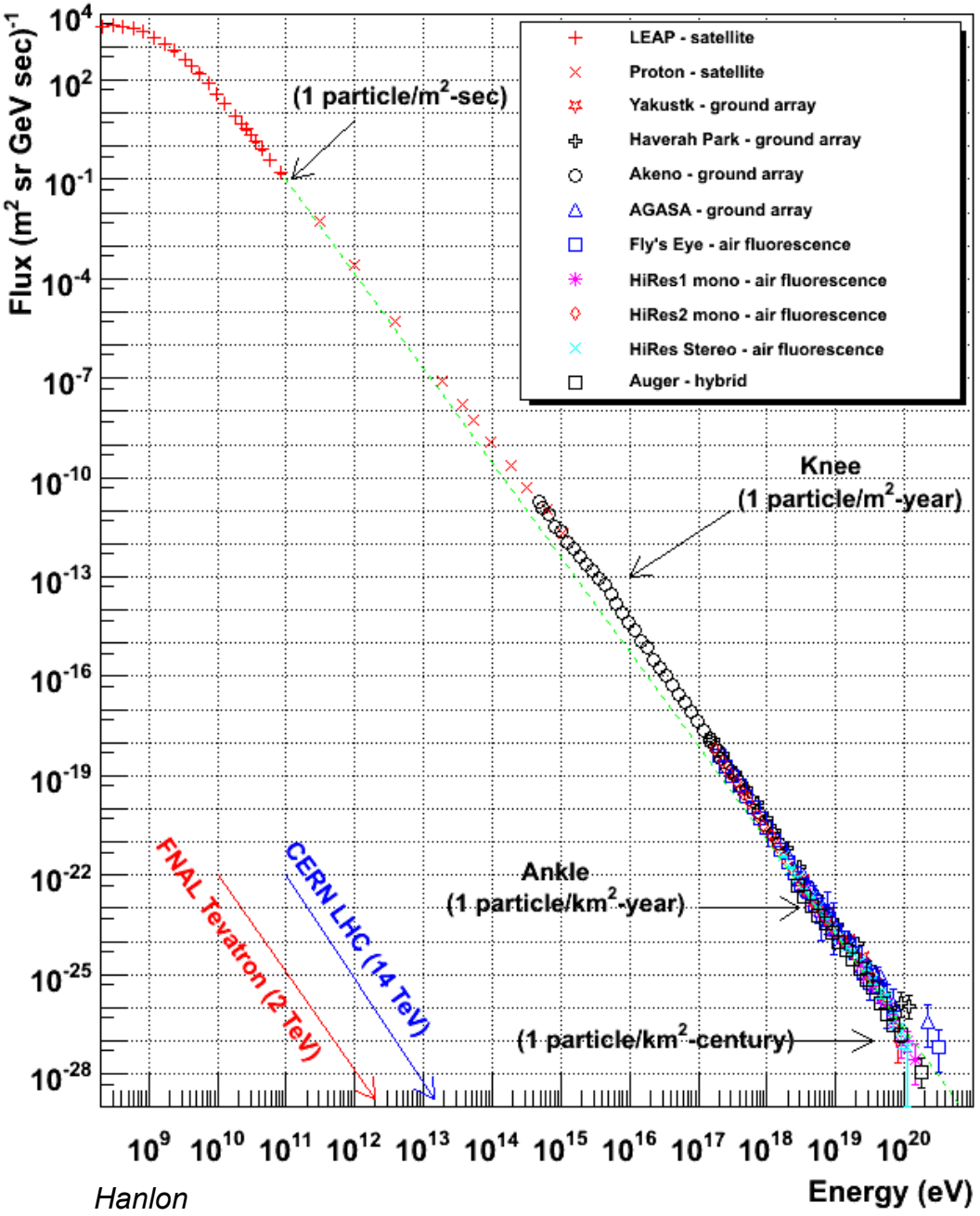


Power law

Larmor Radius

$$r_L = \left(\frac{E/Z}{\mathrm{EeV}}\right)\left(\frac{B}{\mu\mathrm{G}}\right)^{-1} \mathrm{kpc}$$

Cosmic Rays



Power law

Larmor Radius

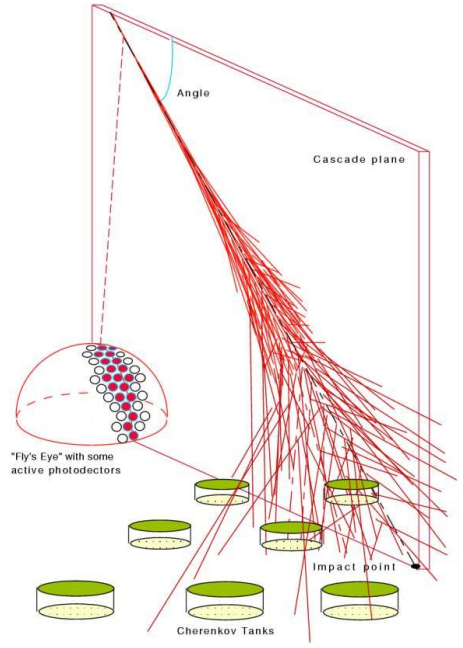
$$r_L = \left(\frac{E/Z}{\mathrm{EeV}}\right)\left(\frac{B}{\mu\mathrm{G}}\right)^{-1} \mathrm{kpc}$$

=> Extragalactic sources

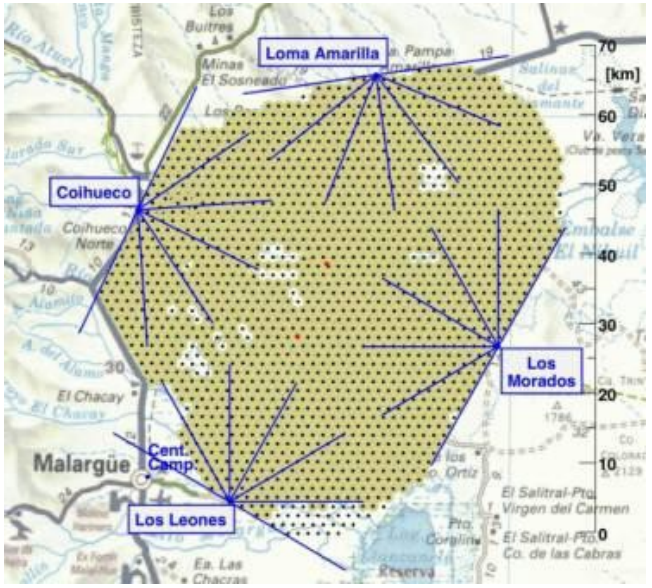
$$> 10^{18}\ \mathrm{eV}$$

UHECR Observatories

Airshower
-Particle detectors
(surface)



Necesal 2010

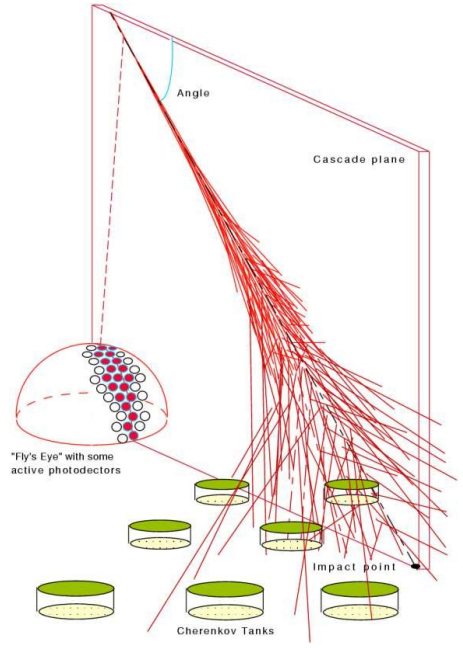


Auger Observatory - Dawson 2007

UHECR Observatories

Airshower
-Particle detectors
(surface)

cause Fluorescence Light
-Photo detectors
“Fly's Eye“ (around)



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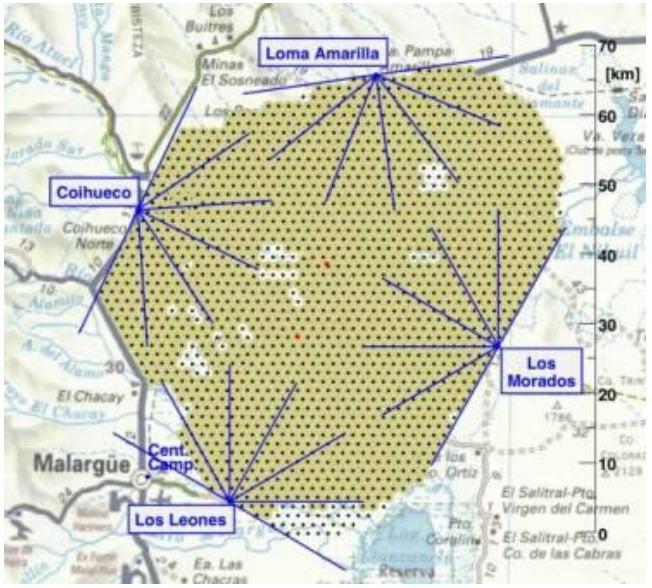


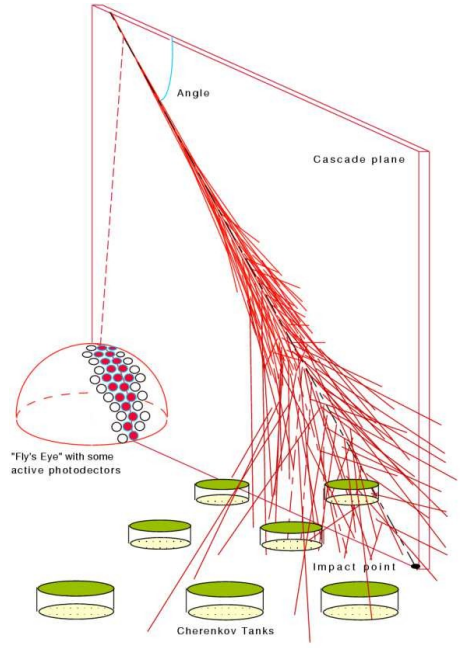
Auger Observatory - Dawson 2007

UHECR Observatories

Airshower
-Particle detectors
(surface)

cause Fluorescence Light
-Photo detectors
“Fly's Eye“ (around)

=> Arrival Direction,
Energy & Composition



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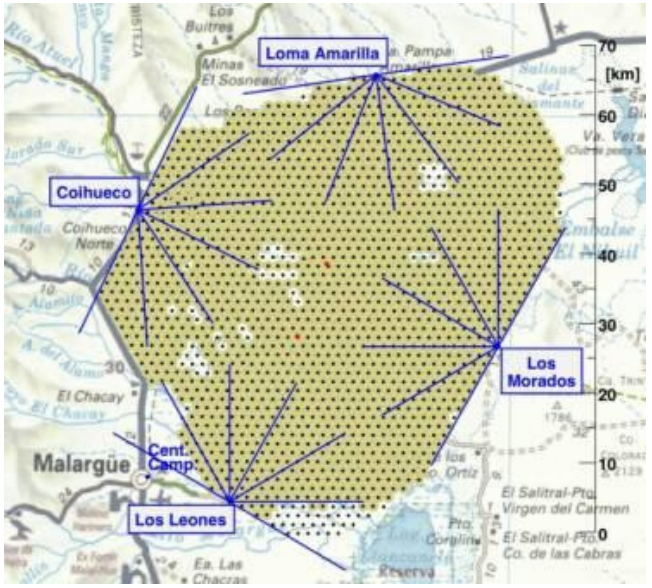


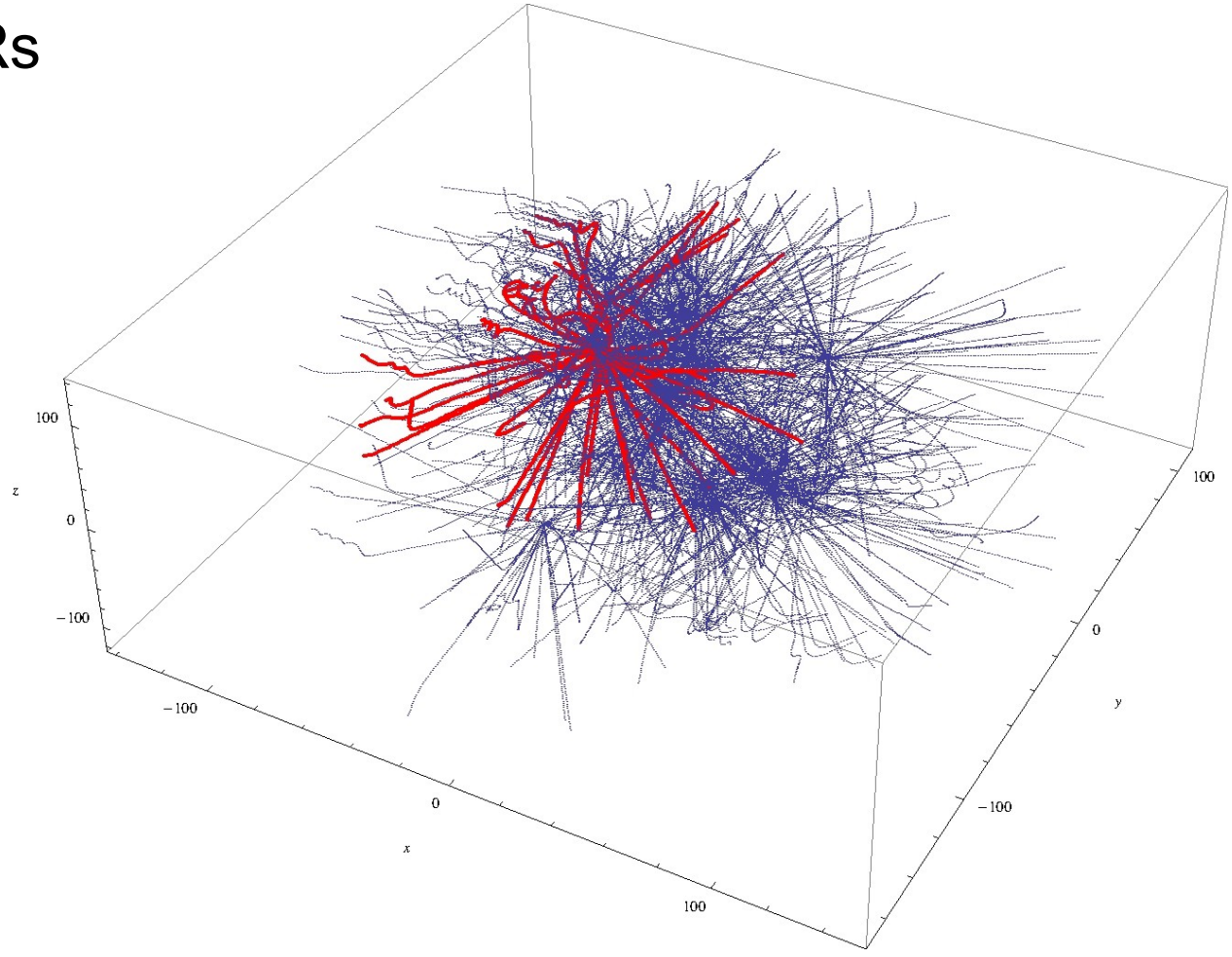
Auger Observatory - Dawson 2007

CRPropa

by Sigl *et al.*, DESY

https://crpropa.desy.de

Simulates Propagation of CRs



Dutan & Caramete 2014

CRPropa

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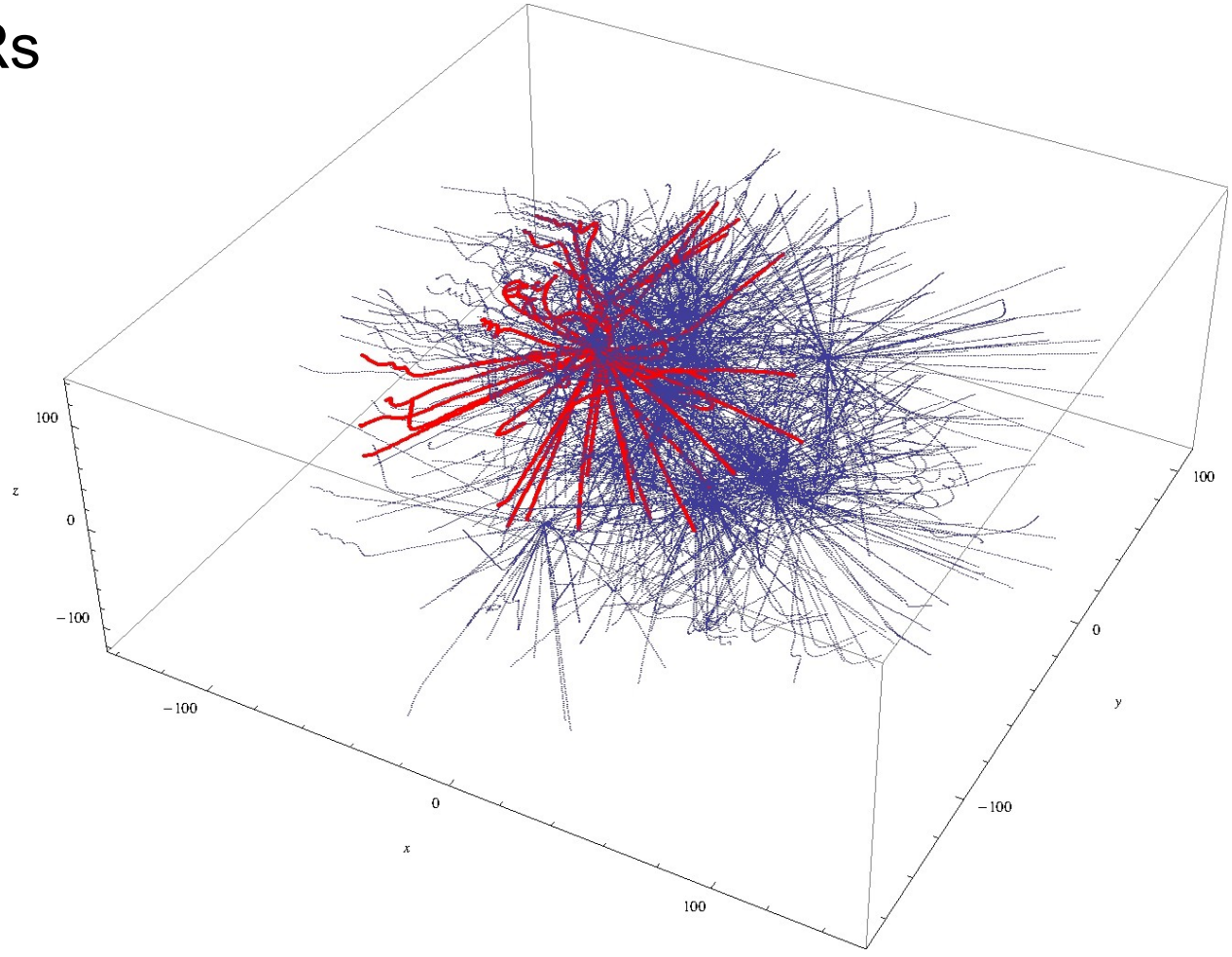
Simulates Propagation of CRs

Energy Spectrum,
Composition,
Injection Sources



Dutan & Caramete 2014

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Simulates Propagation of CRs

Energy Spectrum,
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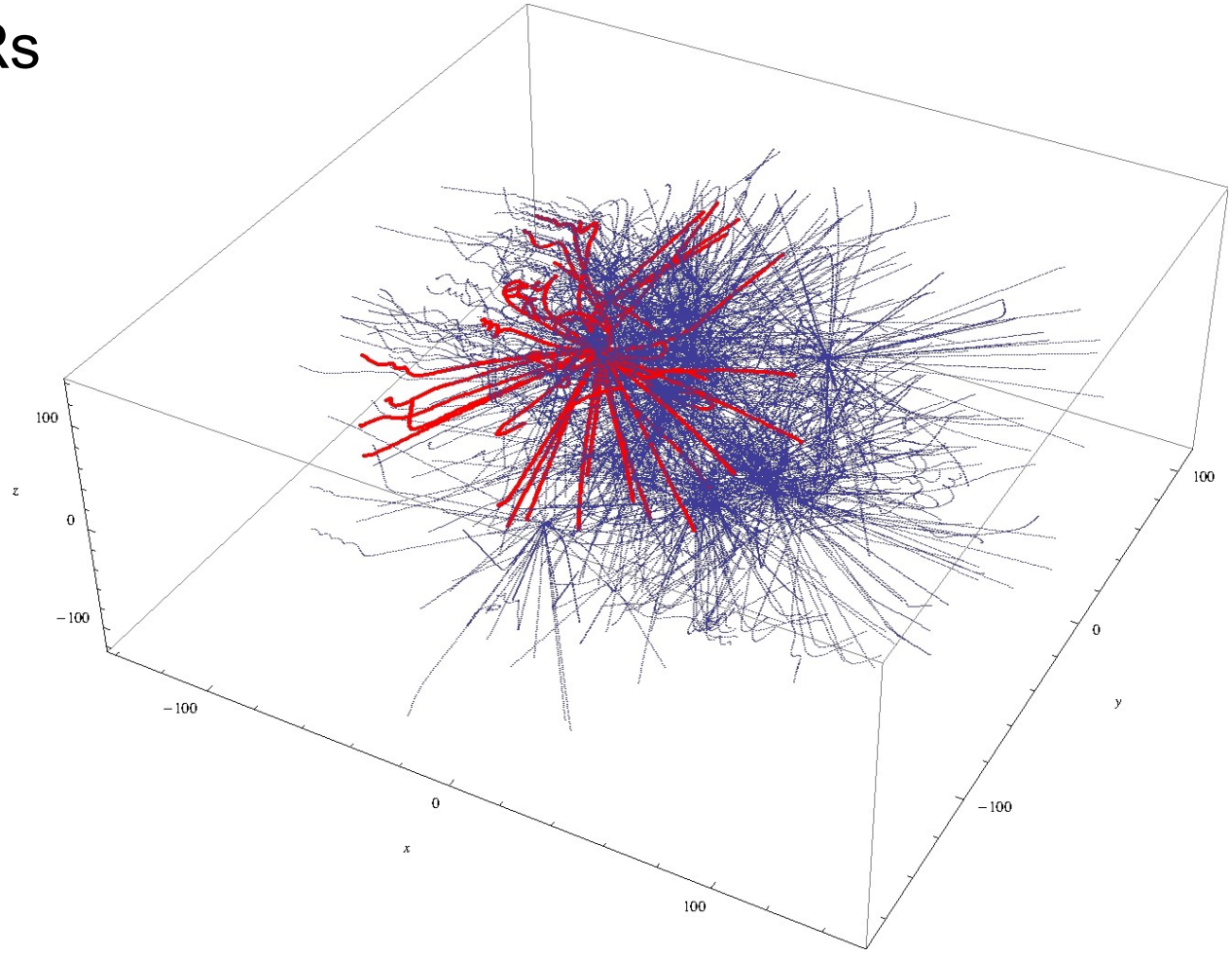
Injection Sources

-Low energy ambient Photon fields (IRB, CMB)



Dutan & Caramete 2014

CRPropa

by Sigl *et al.*, DESY

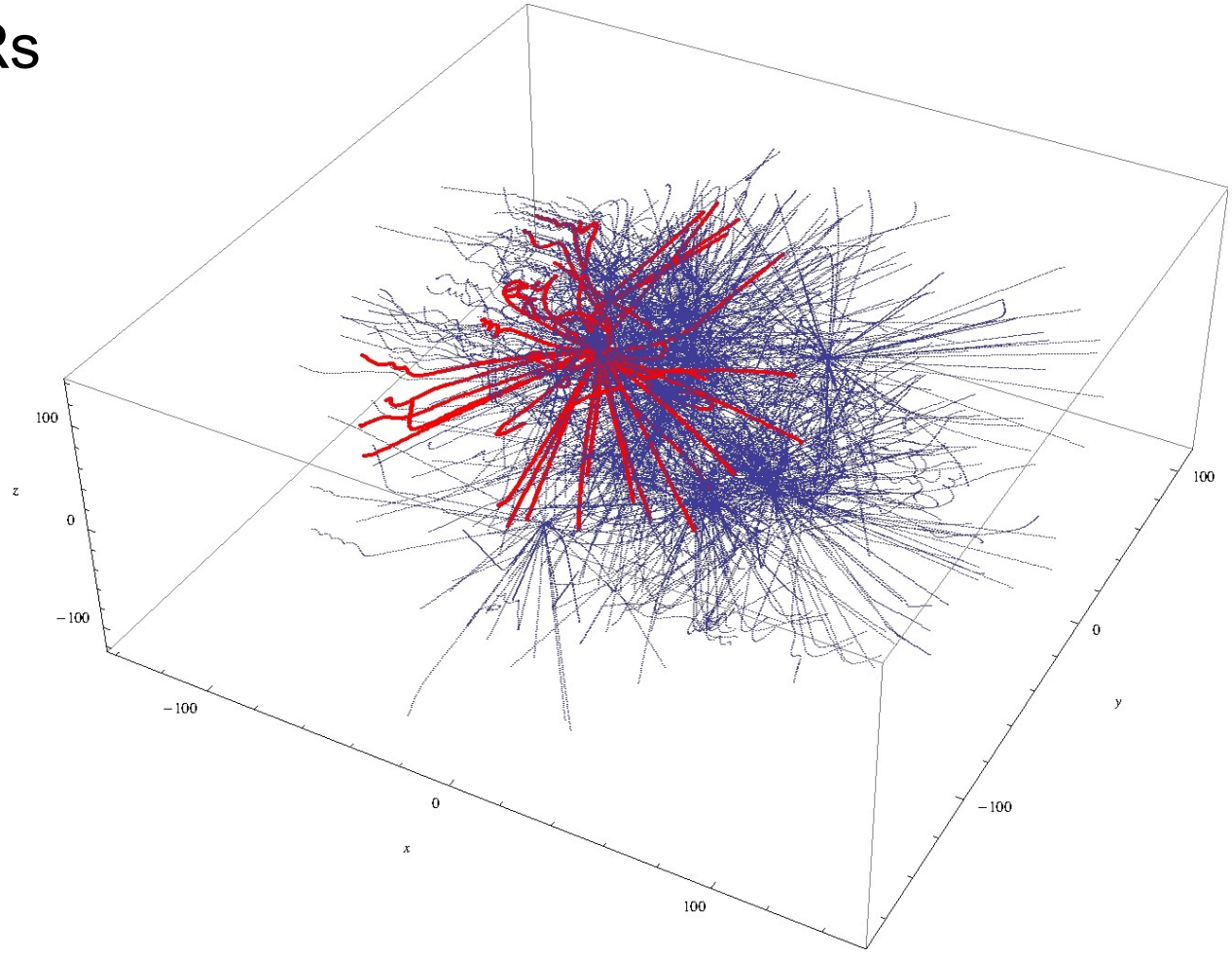
https://crpropa.desy.de

Simulates Propagation of CRs

Energy Spectrum,
Composition,
Injection Sources

-Low energy ambient Photon fields (IRB, CMB)

-Deflection
Uniform or simulated Magnetic Field



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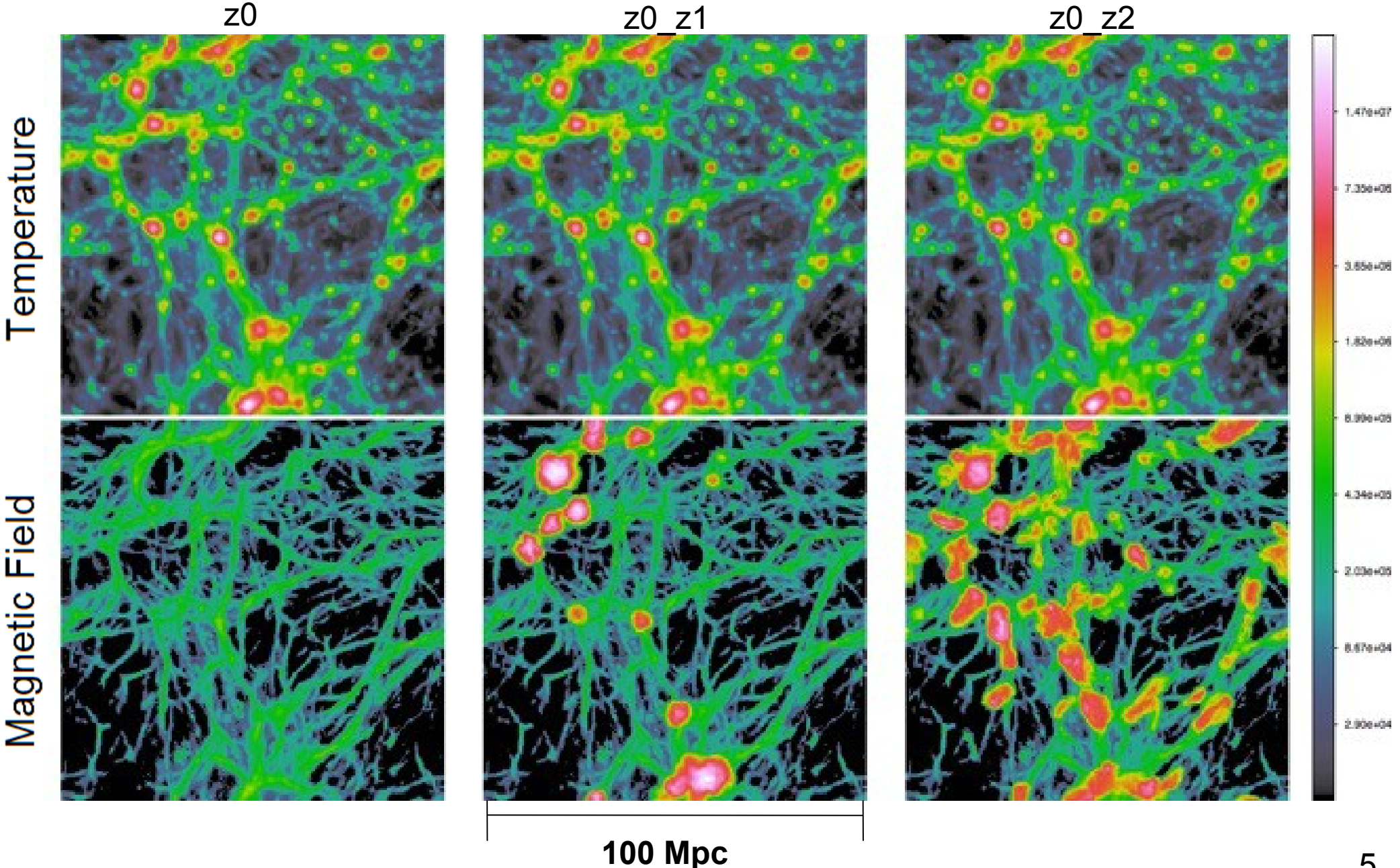
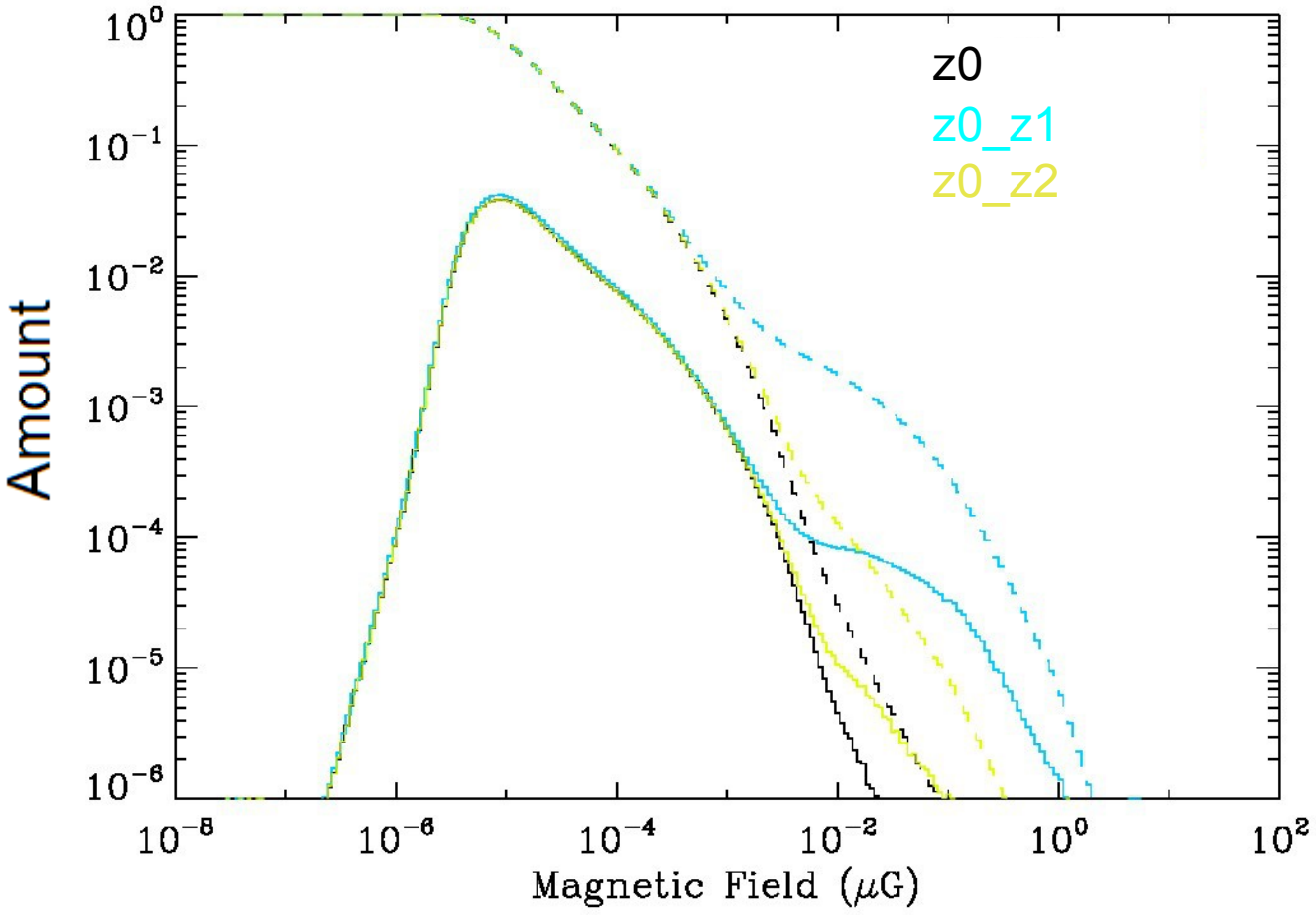
ENZO Magnetic Field Models



ENZO Magnetic Field Models



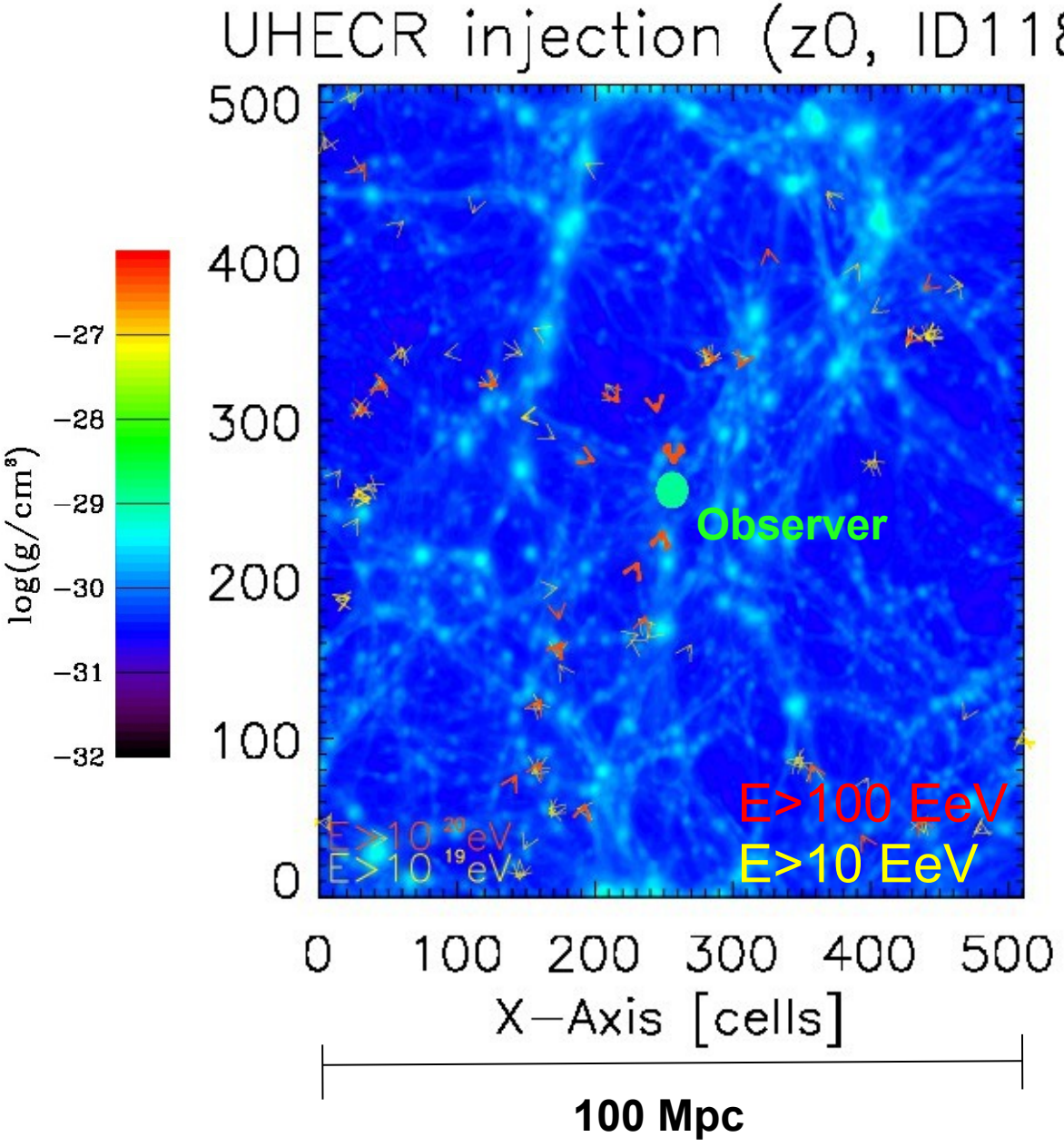
Primordial Seed Field

$(10^{-4}\mu G \text{ at } z=30)$

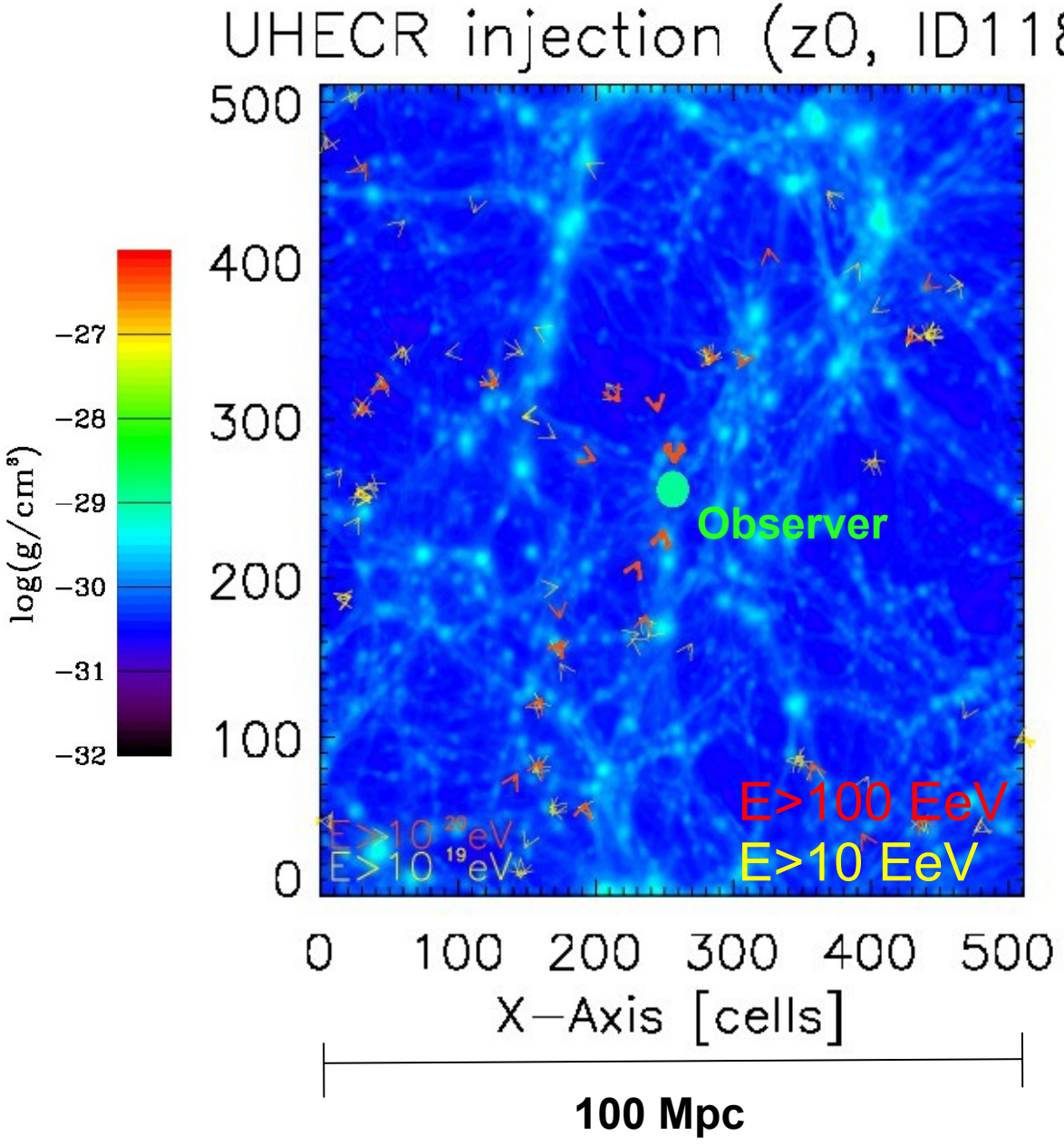
Galactic Outflow at

$z = 1$ & $z = 2$

CRPropa & ENZO



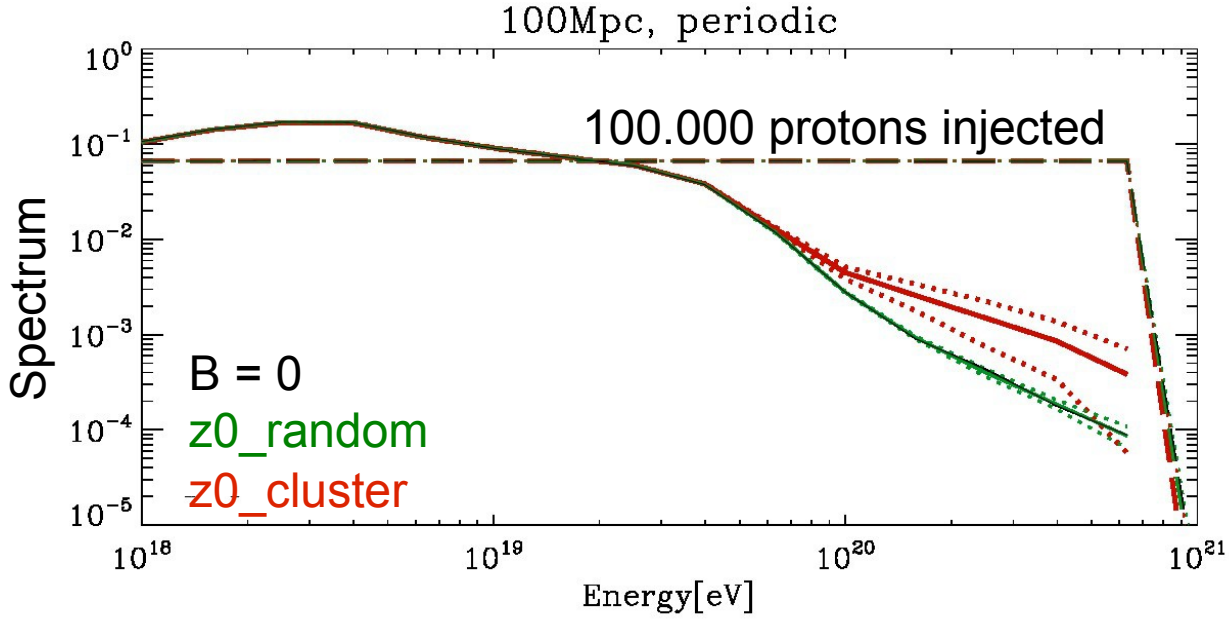
CRPropa & ENZO



High energy Particles originate within 100 Mpc (GZK-Effect)

Distribution of closeby UHECR Sources affects Spectrum and Anisotropy

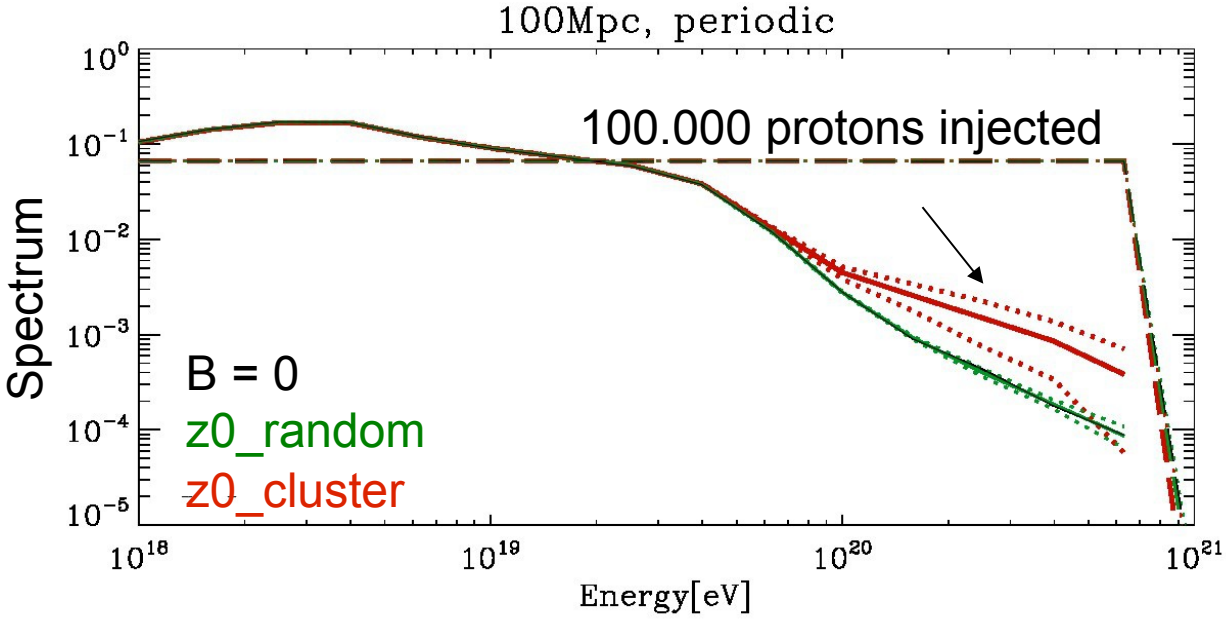
Random vs. Cluster Injection



Random vs. Cluster Injection

Spectrum:

- Random: consistent with B = 0 case
- Cluster: ~2 times larger



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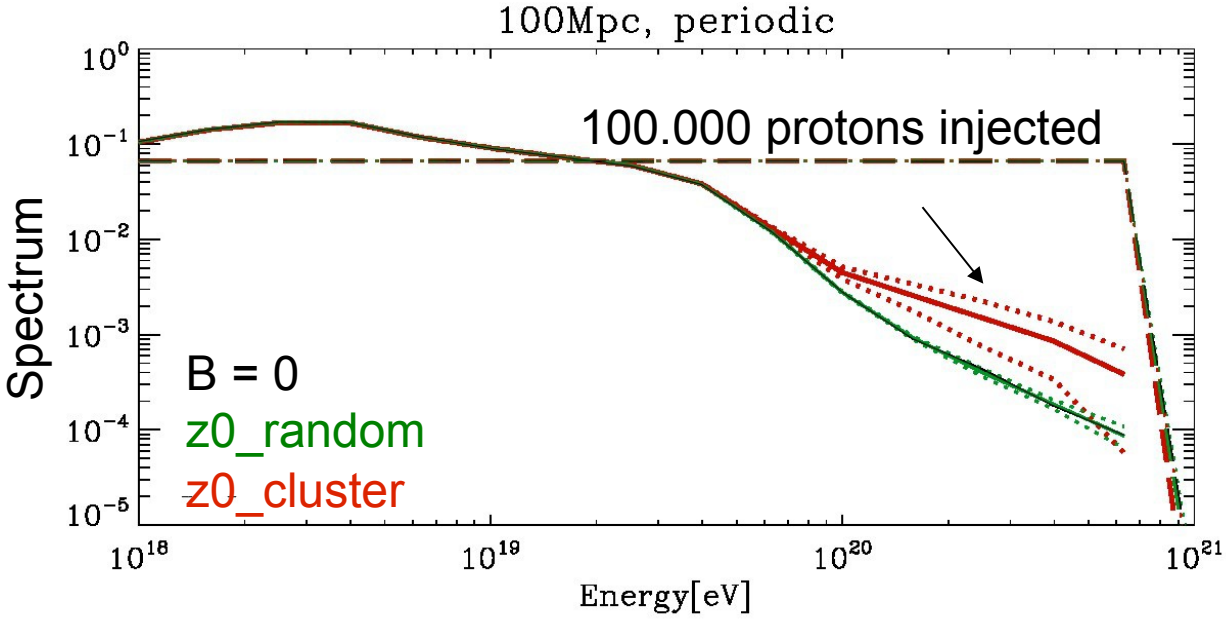

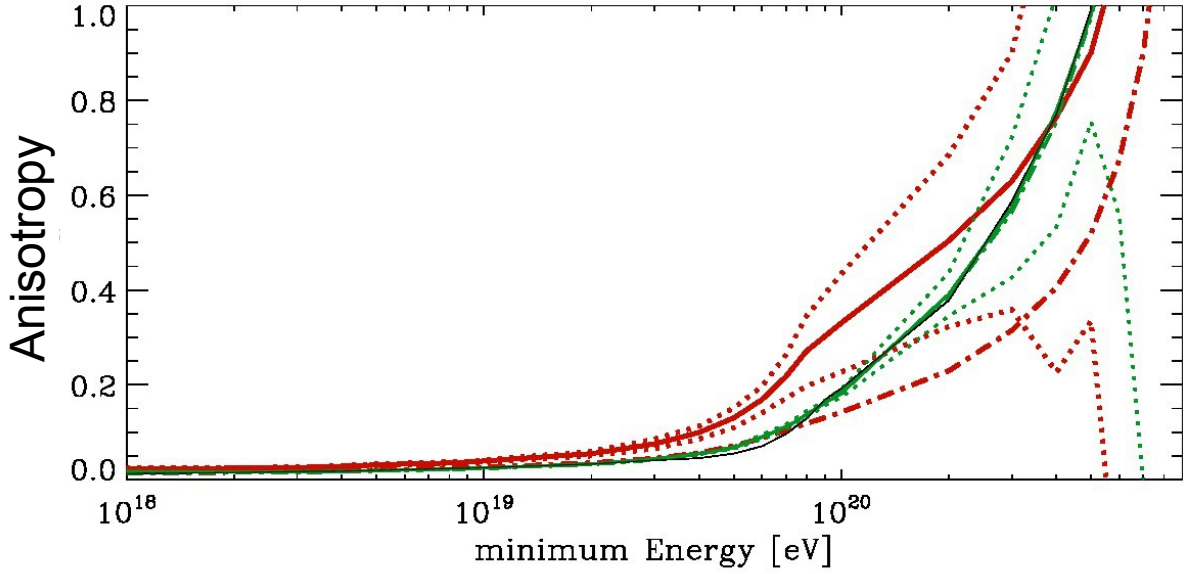

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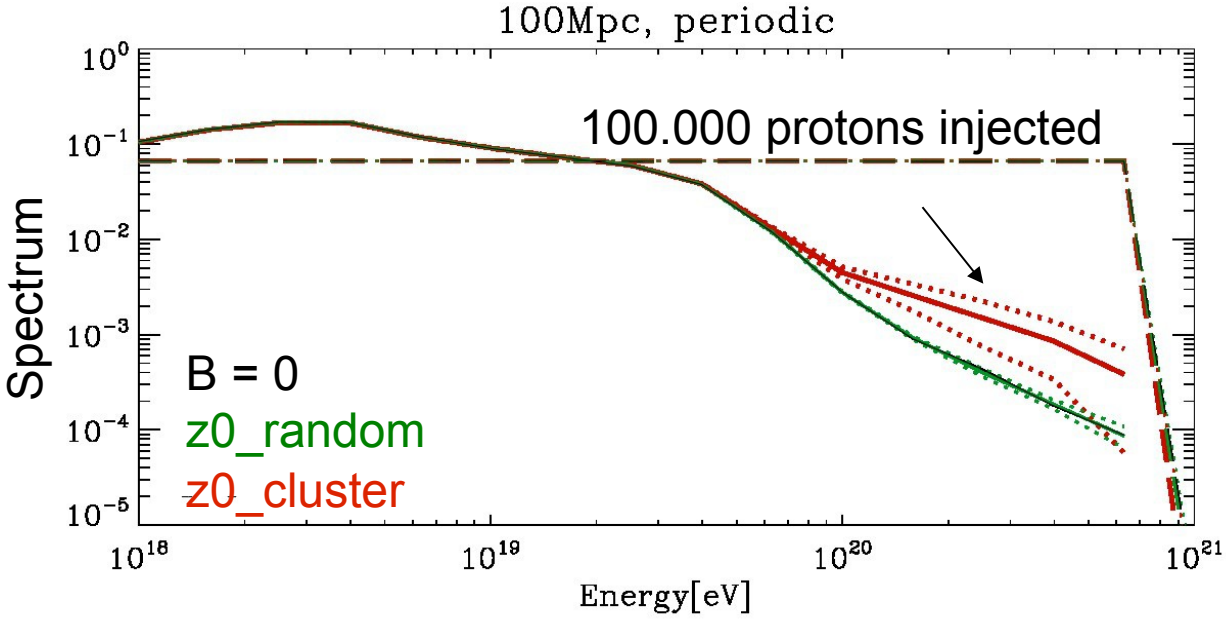
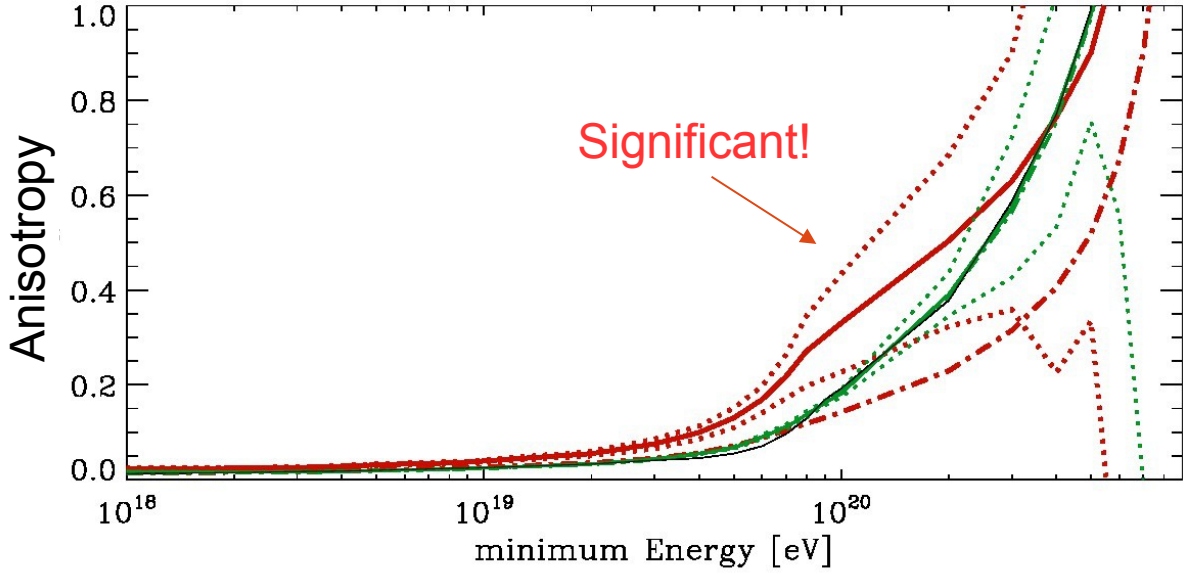


Anisotropy:

- Random: consistent with statistical noise
- Cluster: exceeds statistical noise



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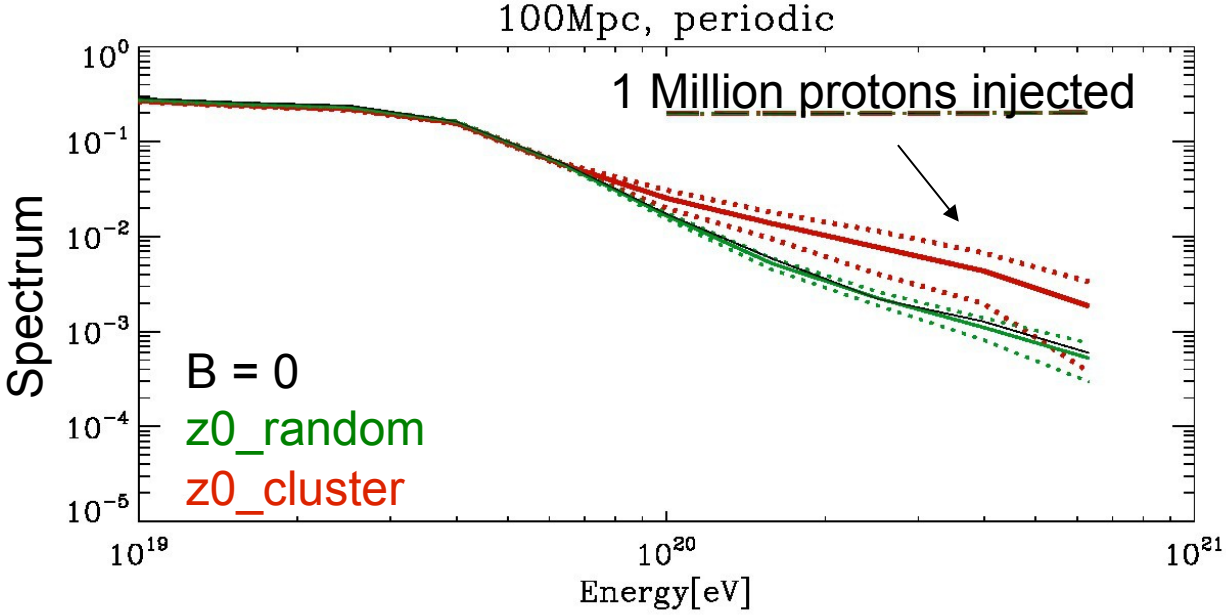

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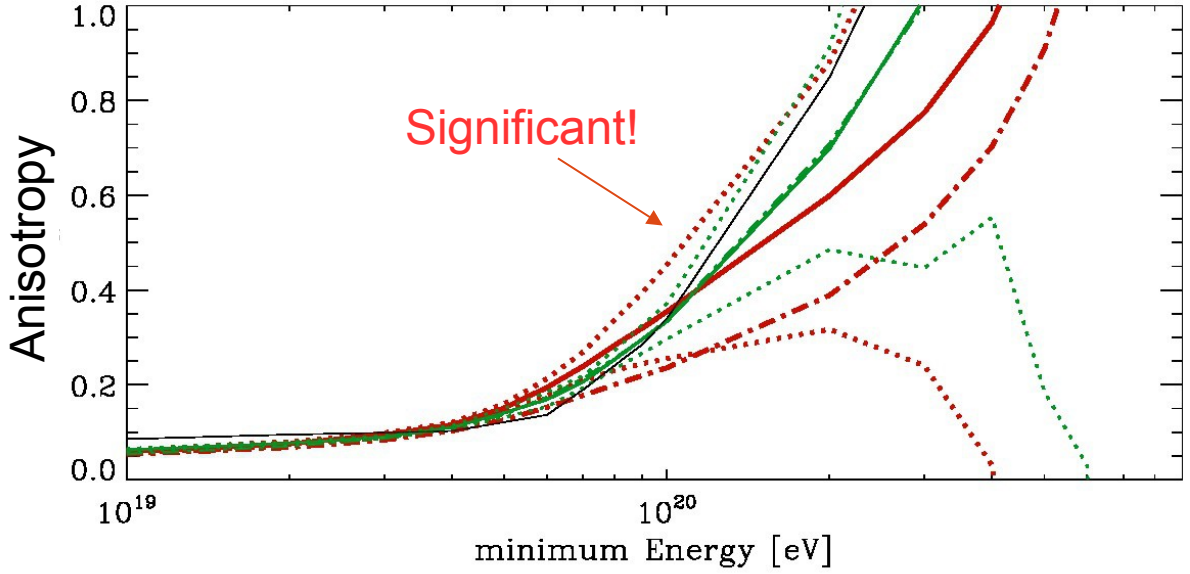

Additional Magnetic Field Seeding

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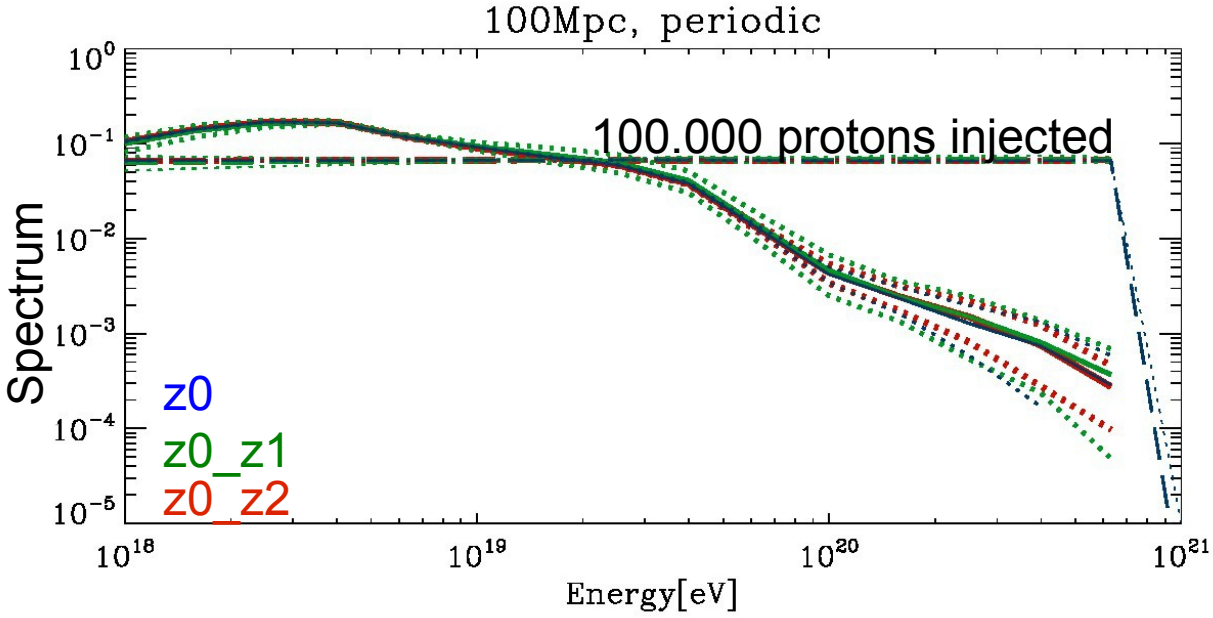
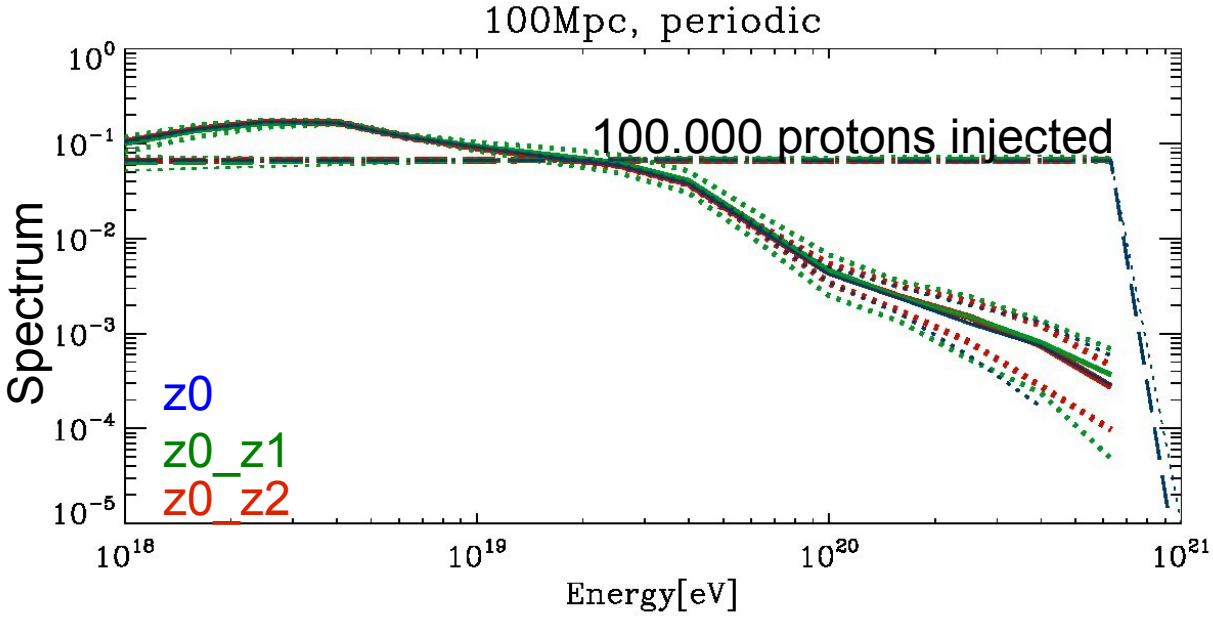


Additional Magnetic Field Seeding

No effect on Spectrum



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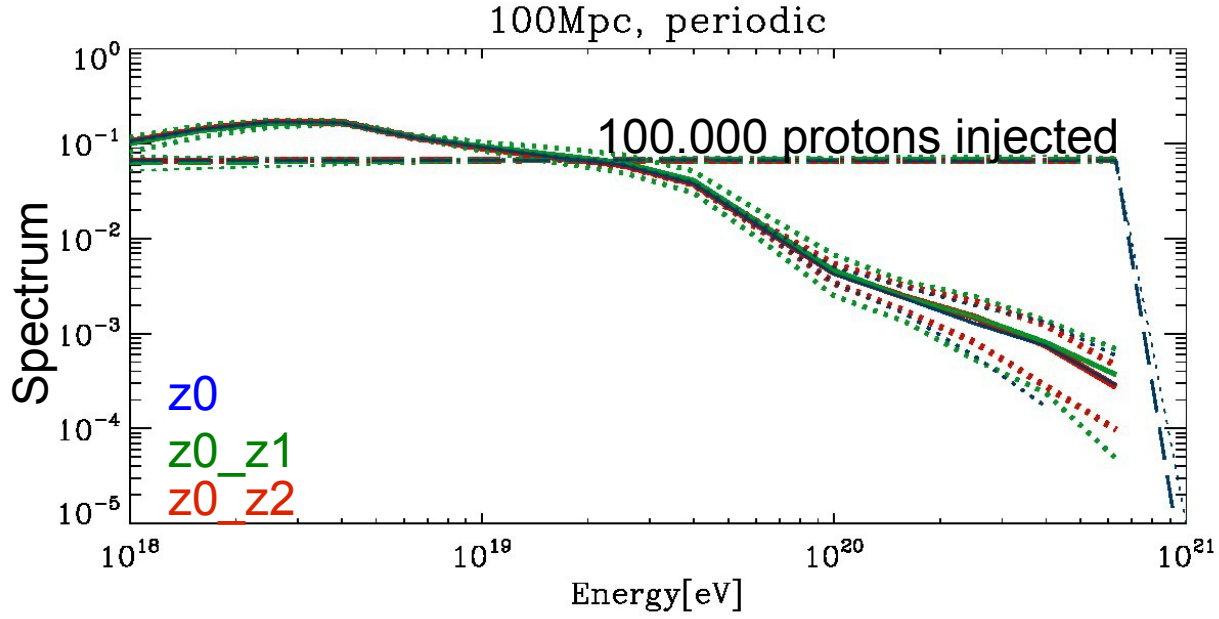

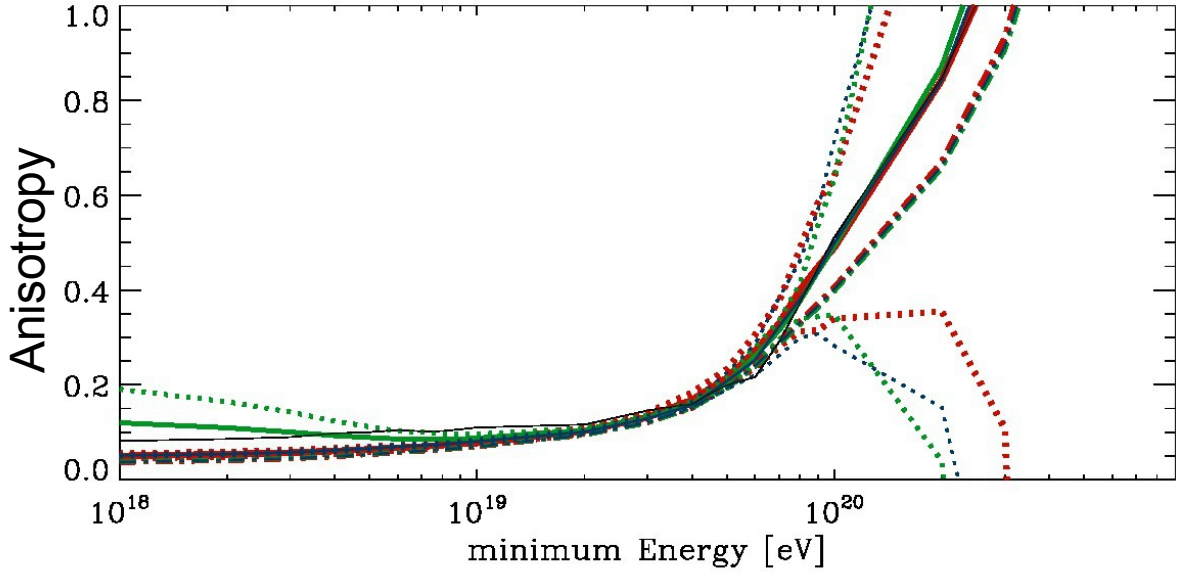

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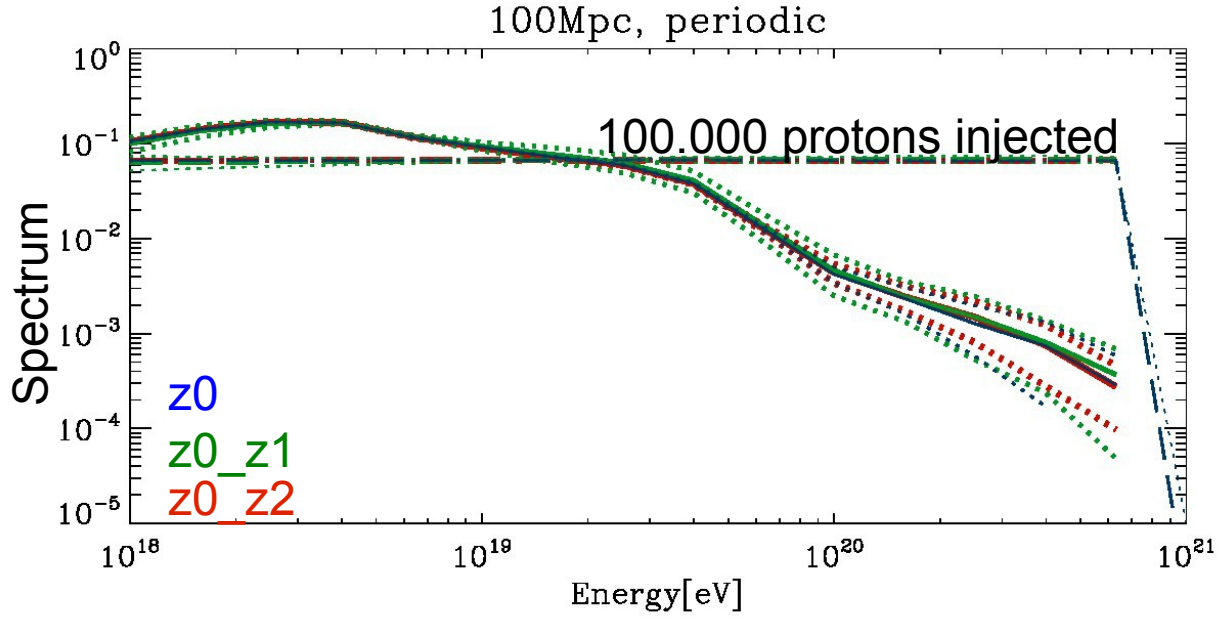
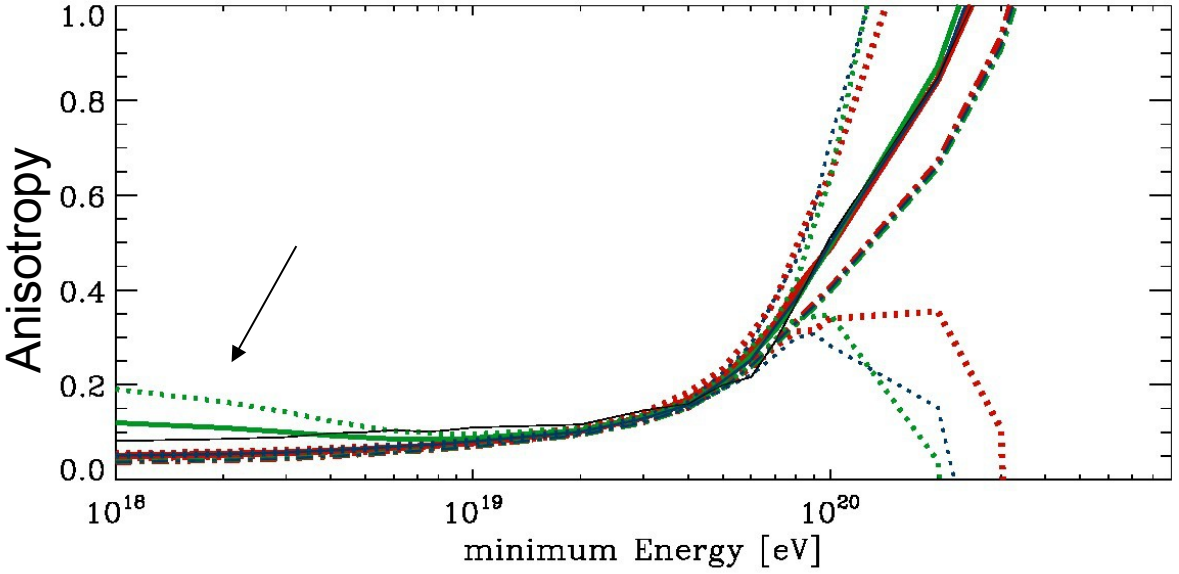
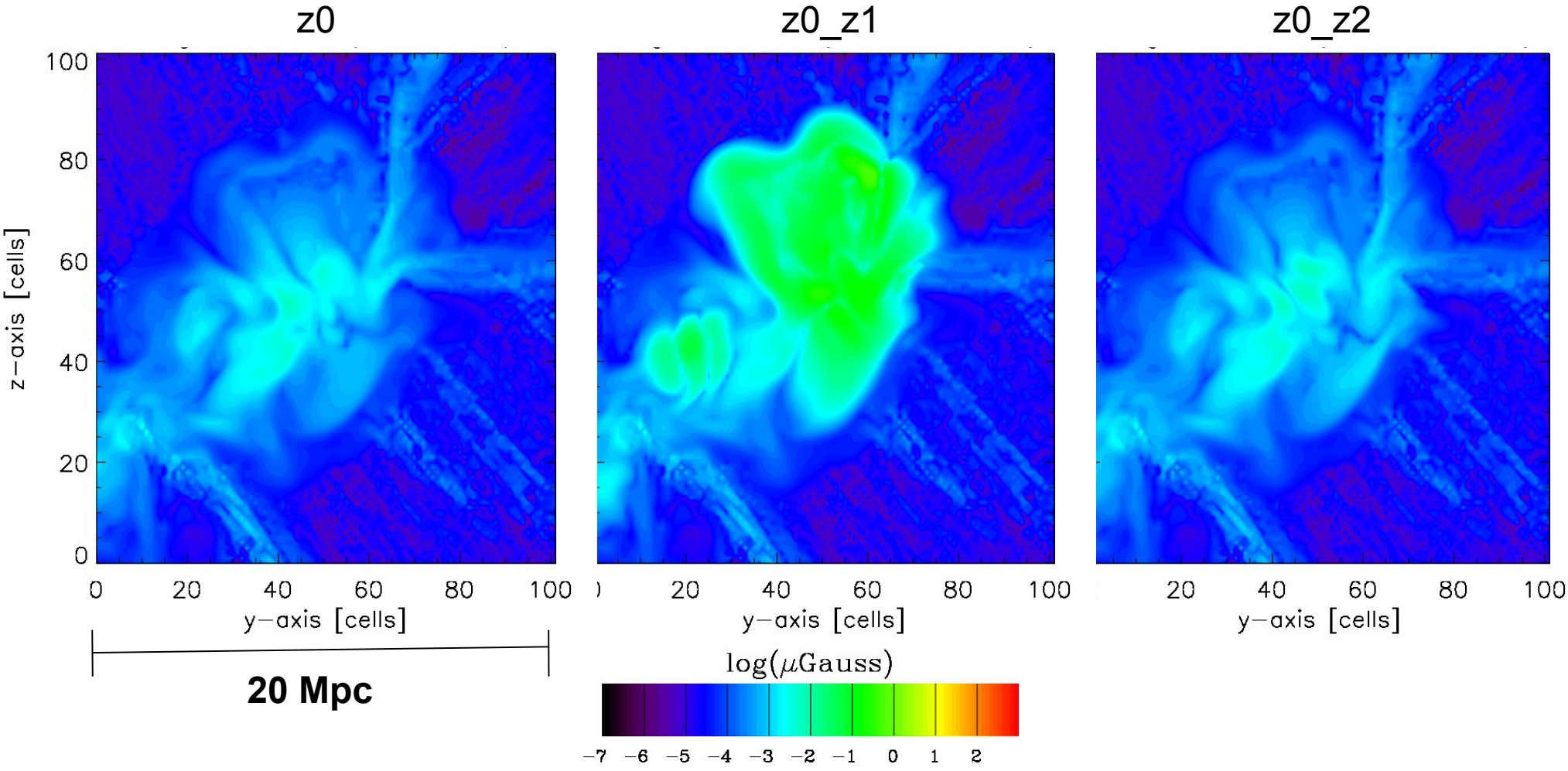


Anisotropy at low Energies

(Additional Seeding at z = 1)



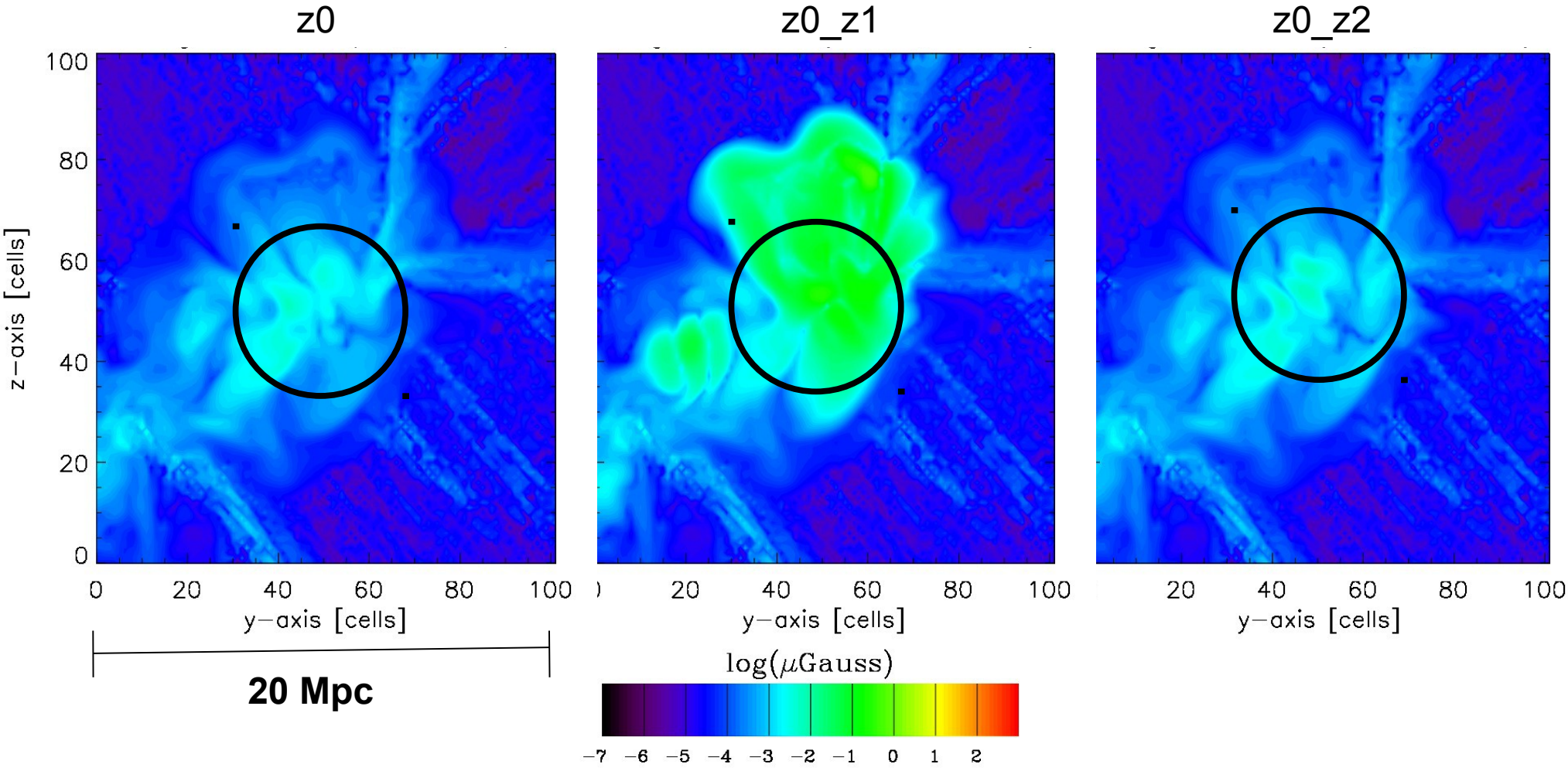
Cluster Magnetic Field



Very strong Field added to Environment

=> More UHECRs are deflected

Cluster Magnetic Field



Very strong Field added to Environment

=> More UHECRs are deflected

Conclusions

Cluster Injection:

- More events at high energies (2 times >100 EeV)
- Anisotropy exceeds statistical noise at high energies (1 – 2 σ)

Additional Magnetic Field Seeding:

- Anisotropy exceeds statistical noise at lower Energies (> 2 σ)

Conclusions

Cluster Injection:

- More events at high energies (2 times >100 EeV)
- Anisotropy exceeds statistical noise at high energies (1 – 2 σ)

Additional Magnetic Field Seeding:

- Anisotropy exceeds statistical noise at lower Energies (> 2 σ)

Future plans:

- Increased Statistics, Smaller Observer
- Composition
- More Magnetic Field Seeding Models

List of Figures

W. F. Hanlon, Cosmic Ray Spectra of Various Experiments http://www.physics.utah.edu/~whanlon/spectrum.html Aug 2014

P. Necesal, The Fluorescence Detector of the Pierre Auger Observatory arXiv:1011.6523v1 [astro-ph.IM] 30 Nov 2010

P. R Dawson, Hybrid Performance of the Pierre Auger Observatory arXiv:0706.1105v1 [astro-ph] 8 Jun 2007

I. Dutan & L.I. Caramete, Ultra-High-Energy Cosmic Rays from Low-Luminosity Active Galactic Nuclei arXiv:1409.8162v1 [astro-ph.HE] 29 Sep 2014

Composition

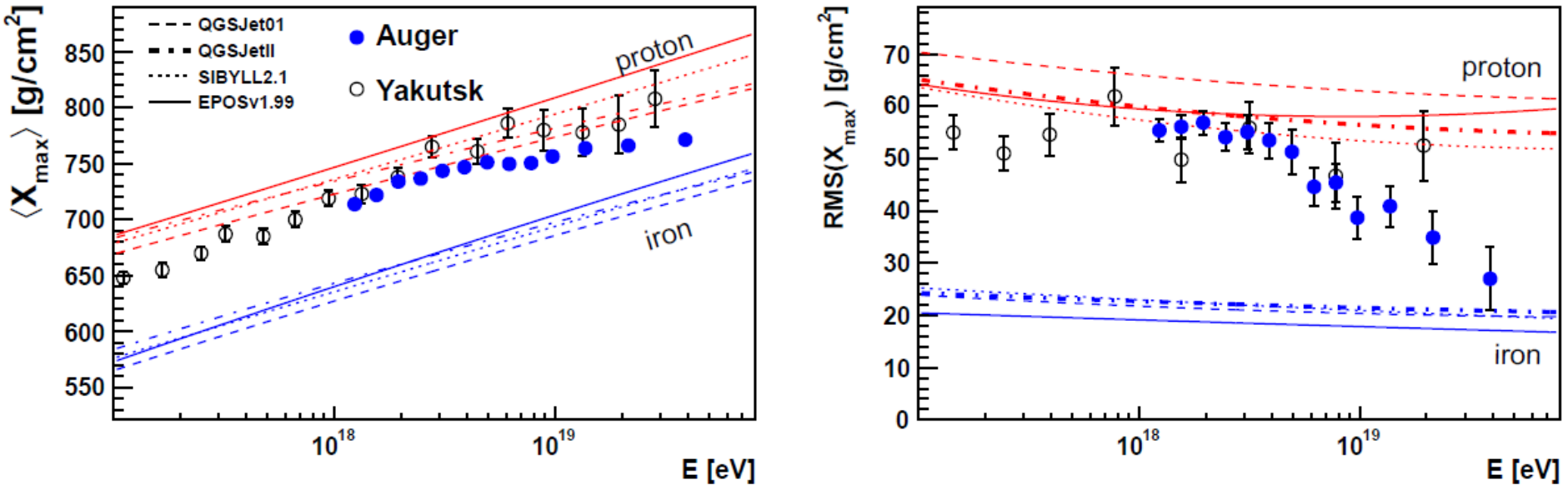


Fig. 3. Measured $\langle X_{\max} \rangle$ (left) and RMS($X_{\max}$) (right) for the Auger and Yakutsk experiments. The lines indicate the $\langle X_{\max} \rangle$ expectations for proton and iron compositions using different hadronic interaction models. Notice that the highest energy bin for Yakutsk contains **only 3** events (Fig. 6).

J. Bellido et. al., Mass Composition Working Group Report - 19 Jun 2013

Composition

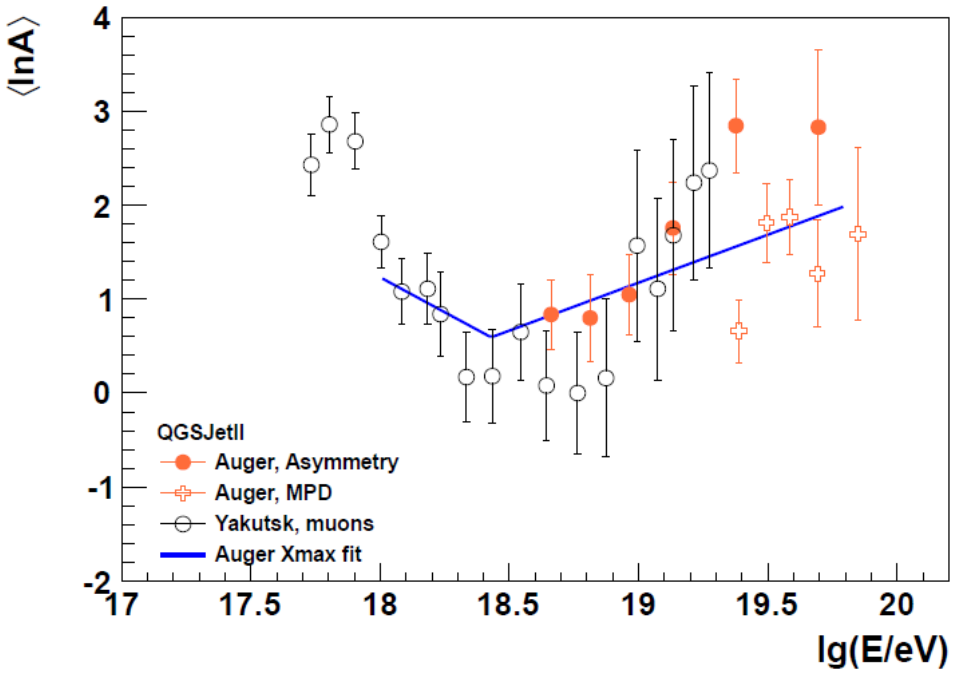


Fig. 13. Average composition estimated using other (other than $X_{\max}$) shower observables. Open circles are using muon detectors from the Yakutsk experiment [5], solid circles use the observed shower asymmetries around the core with the Auger SD [21], and open crosses are using the estimated muon production depth maximum with the Auger SD.

J. Bellido et. al., Mass Composition Working Group Report - 19 Jun 2013