The Centaurus A Ultrahigh-Energy Cosmic Ray Excess

and

The Local Intergalactic Magnetic Field

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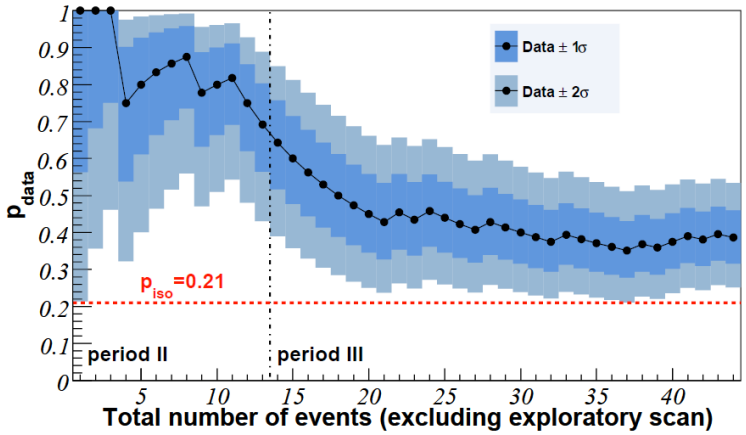
Two Unknowns

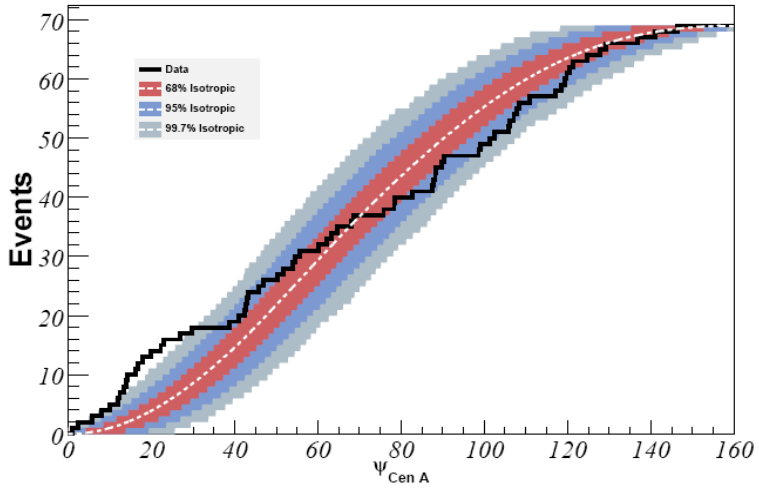
- The length of time that the origin of Ultra High Energy Cosmic Rays (UHECRs) has remained a mystery reflects the difficulty in definitively identifying their sources
  - The Pierre Auger Observatory has shown a prominent excess of events in the vicinity of Centaurus A, a nearby active radio galaxy possessing well-studied giant radio lobes
- The uncertain nature of the magnetic fields permeating the intergalactic space:
  - Magnetic fields in voids are exceedingly small
  - ~100 nG fields in filaments, ~ μG fields in galaxy clusters
  - Observations of several galaxy groups suggest ~100nG possible
- No particularly constraining measurements of magnetic fields in the vicinity of the Milky Way

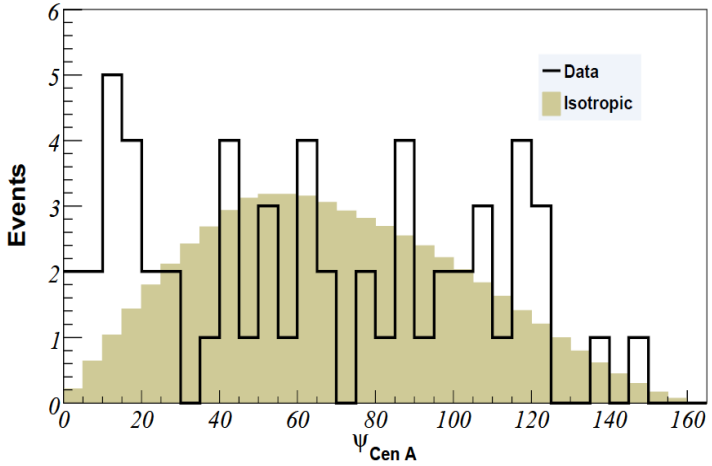
Centaurus A in the UHECR Sky

UHECRs from Cen A & Excess



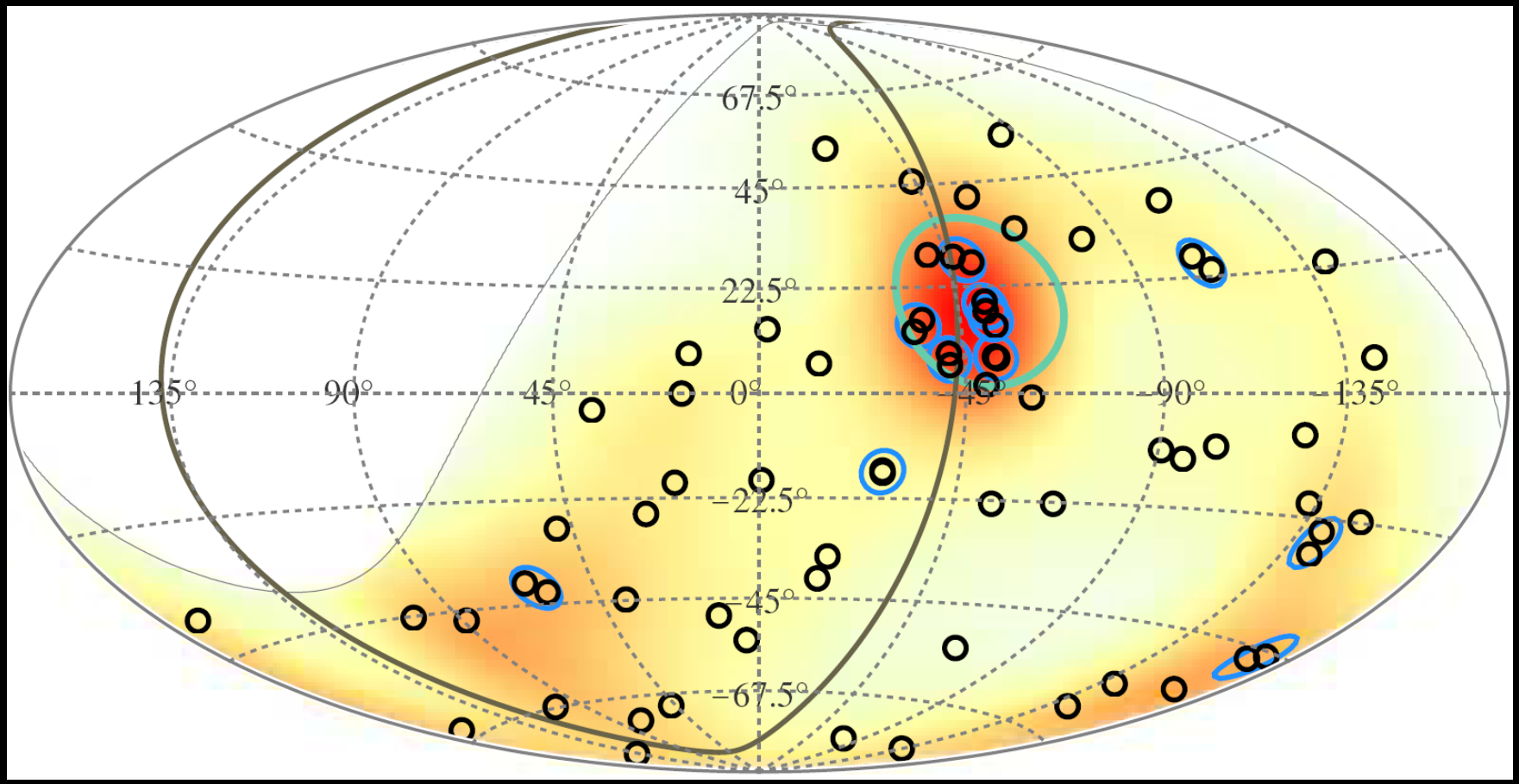
Period	Exposure	GP	N	k	$k_{\rm iso}$	P
I	4390	unmasked	14	9	2.9	
		masked	10	8	2.5	
II	4500	unmasked	13	9	2.7	2×10^{-4}
		masked	11	9	2.8	1×10^{-4}
III	8150	unmasked	31	8	6.5	0.33
		masked	24	8	6.0	0.22
II+III	12650	**unmasked**	**44**	**17**	**9.2**	$\mathbf{6 \times 10^{-3}}$
		masked	35	17	8.8	2×10^{-3}
I+II	8890	unmasked	27	18	5.7	
		masked	21	17	5.3	
I+II+III	17040	unmasked	58	26	12.2	
		masked	45	25	11.3	



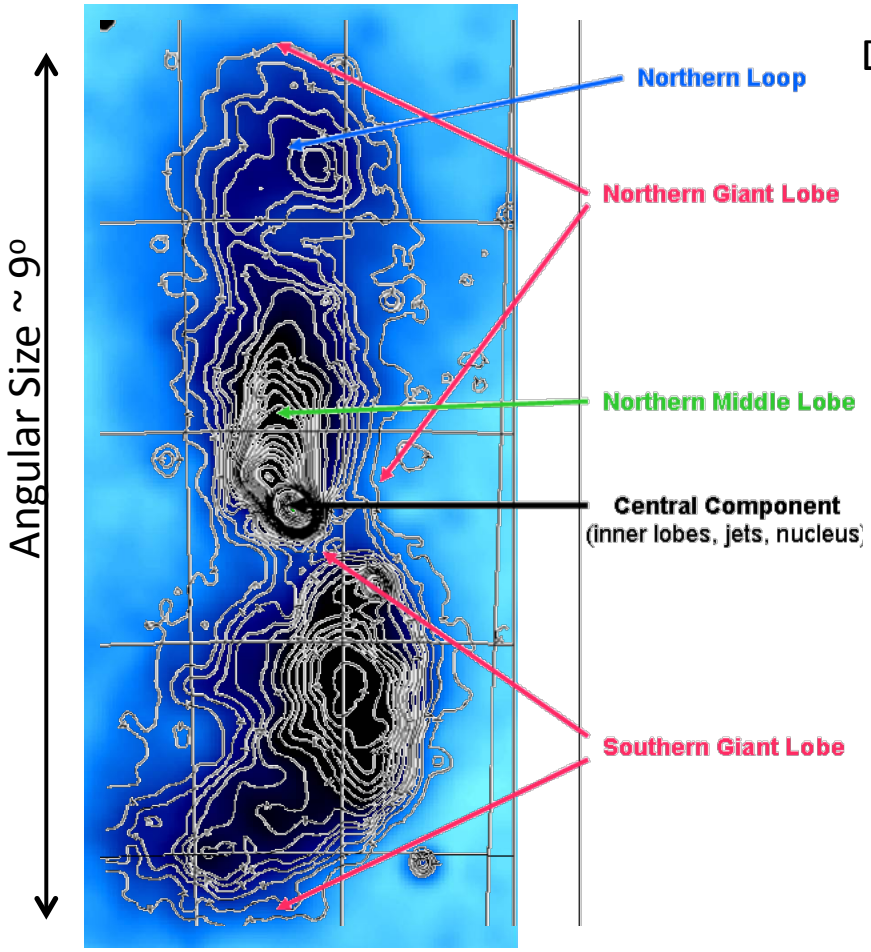


- 13 events are observed within 18 degree of Cen A while about 3 expected from isotropic expectations: Chance probability is less than 2%

- The arrival directions of 69 UHECR events detected by Auger (black circles) in Galactic coordinates. Pairs of events within 5 degree are shown with blue circles. A circle of 18 degree is shown around the radio galaxy Centaurus A. The estimated the density distribution of UHECR events are shown with colored contours. The excess of UHECR events from the direction of Centaurus A is evident.



Cen A Basics



l = 309.5° b = 19.4°

Distance : 3.8 ± 0.1 Mpc

Angular Size ~ 9°

Size ~ 0.6 Mpc

- The radio jets of Centaurus A extracts energy from the supermassive black hole at the center of the galaxy and are possibly accelerating UHECR particles to extreme energies

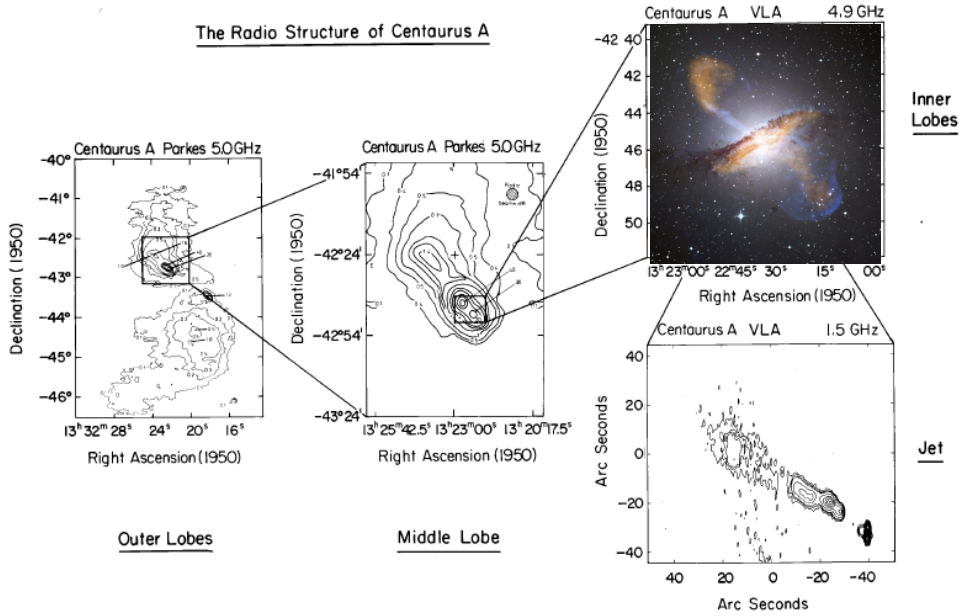
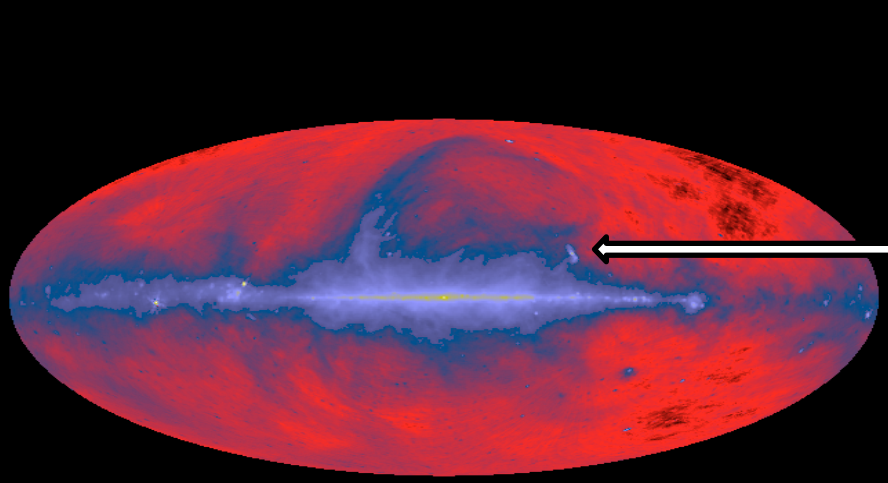
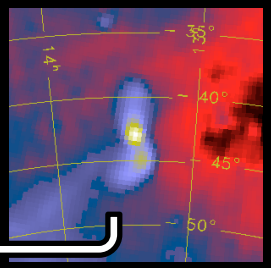


Fig. 3. Radio maps of Centaurus A, highlighting the various components of the radio source introduced in Sect. 2.1. From Burns et al. (1983).

Geometry: Cen A vs. Milky Way



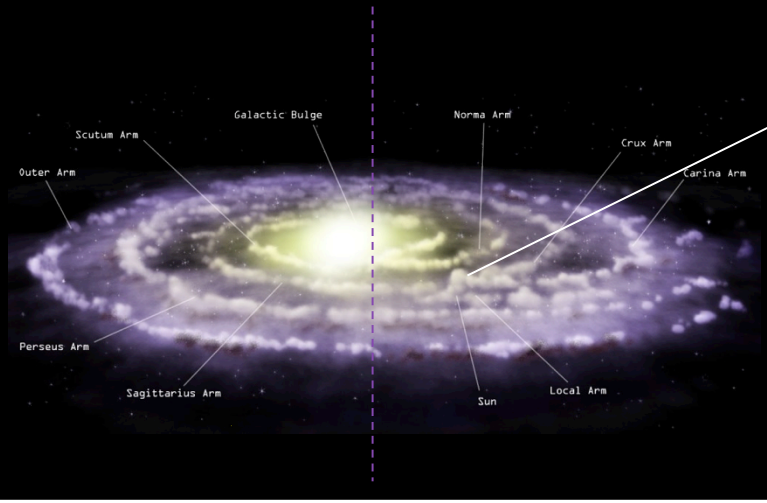


l ~ 310°

b ~ 20°

Size ~ 0.6 Mpc

Distance ~ 3.8 Mpc



Propagation of UHECR Particles

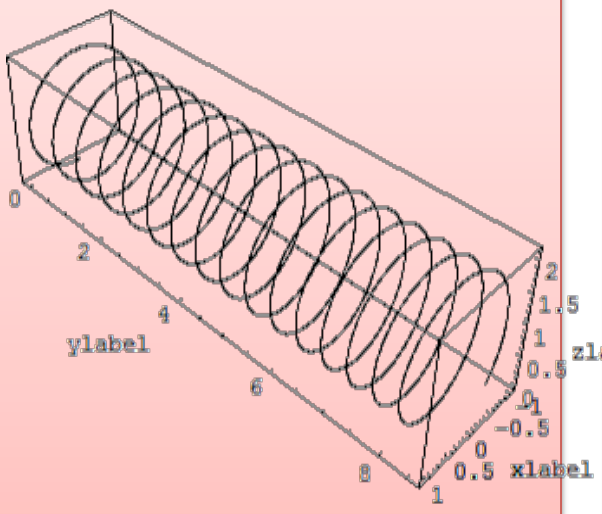
UHECRs in Magnetic Fields

- In units of:
  - E/EeV
  - R/(Z EeV)
  - B/ μG
  - D/kpc
  - v/c
- We have:

$$\frac{d\boldsymbol{\beta}}{dt} \simeq 0.925\,\frac{\boldsymbol{\beta}\times\mathbf{B}}{R}$$

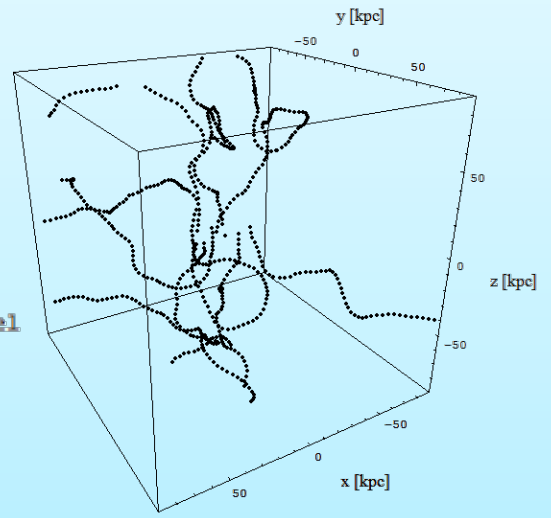
$$\boldsymbol{\beta} = \frac{d\mathbf{r}}{dt}$$

In Regular Field



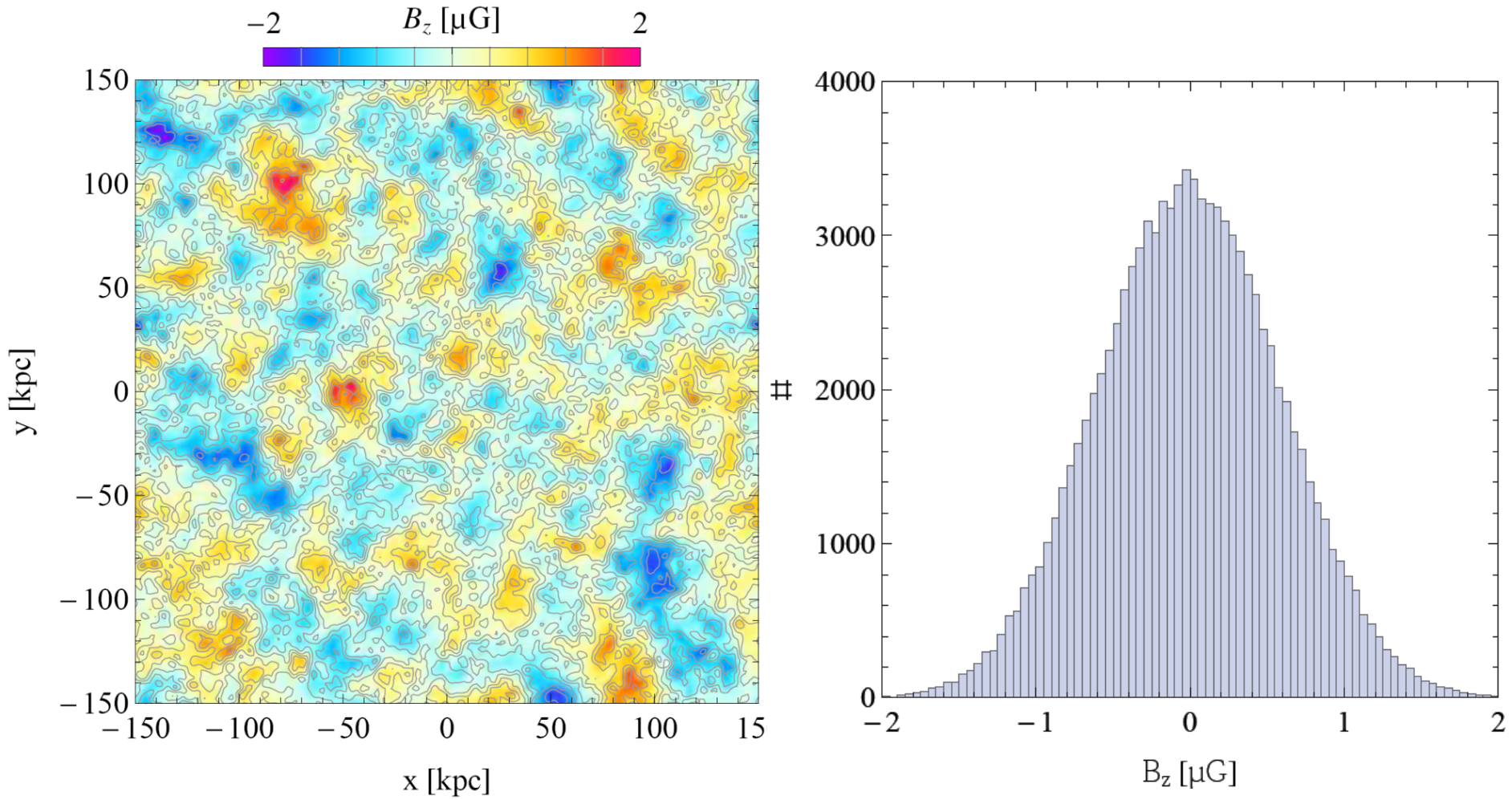
$$r_L \simeq 1.08\,R/B$$

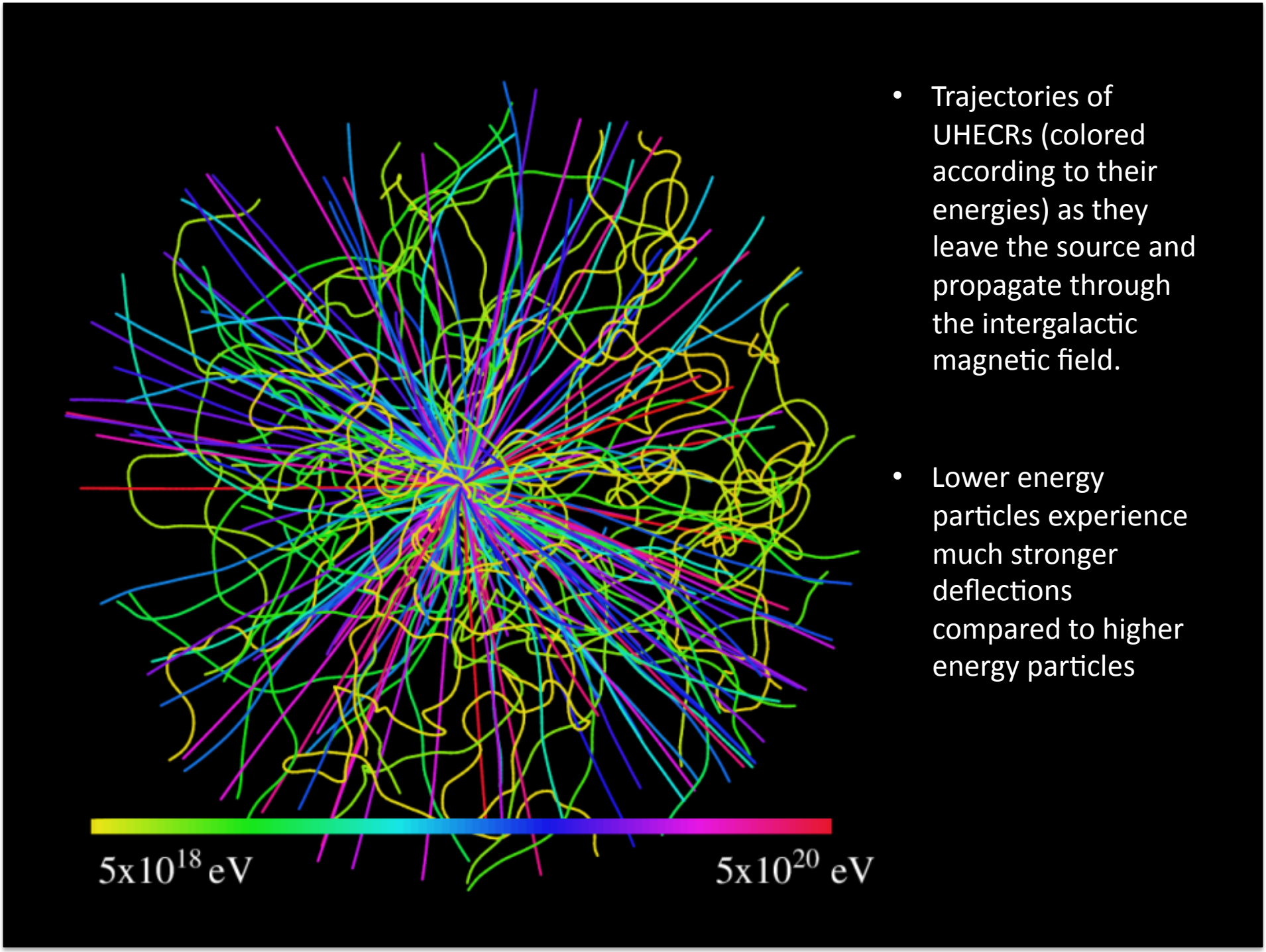
In Random Field



- The deflection of UHECR during propagation depends on their charge/momentum and any magnetic fields they encountered

- A slice from the magnetic field simulation, shown is the z component of the field in the x-y plane, obtained using a Kolmogorov turbulence spectrum within a cubic grid of size of 256^3

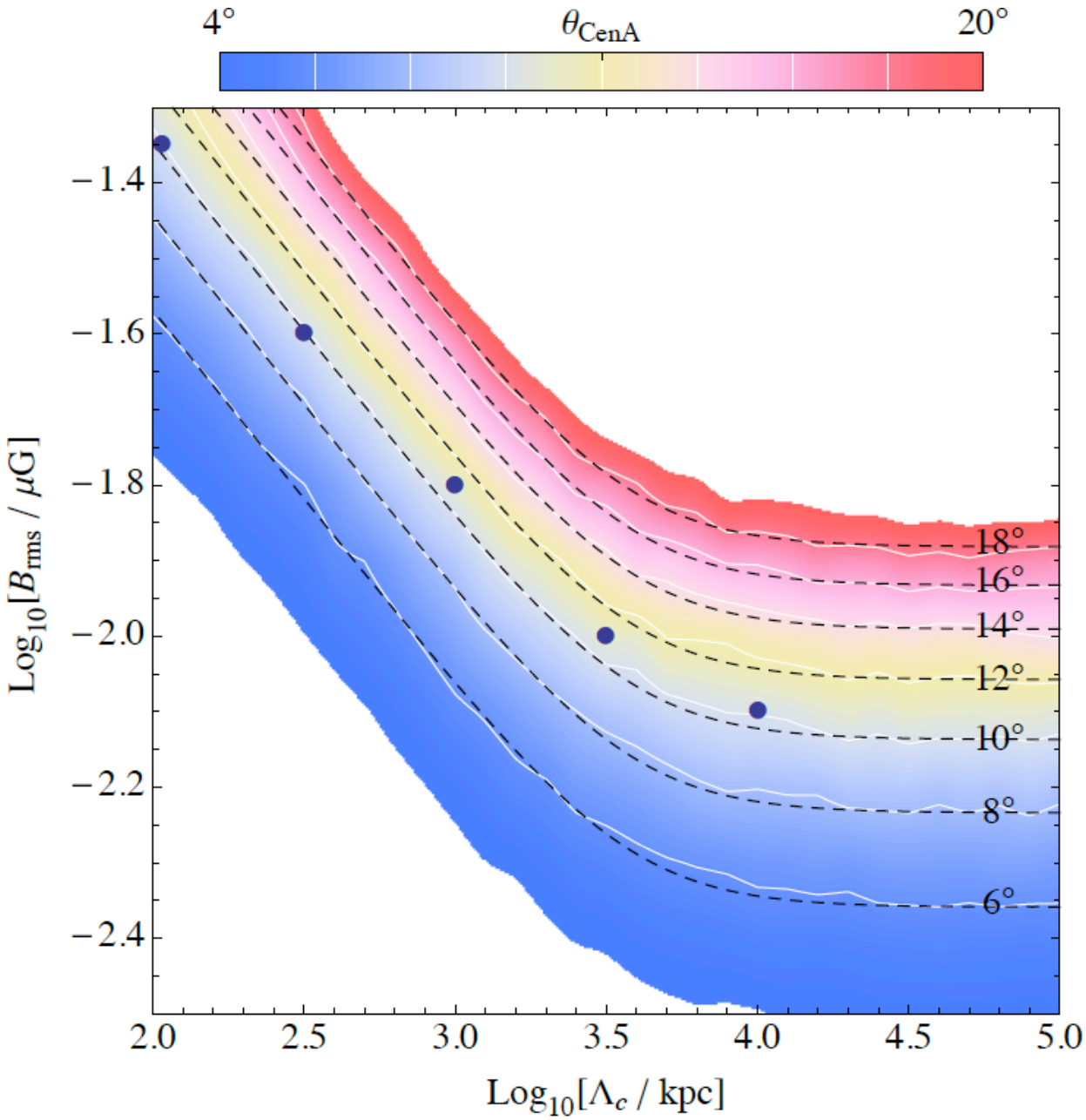




- Trajectories of UHECRs (colored according to their energies) as they leave the source and propagate through the intergalactic magnetic field.
- Lower energy particles experience much stronger deflections compared to higher energy particles

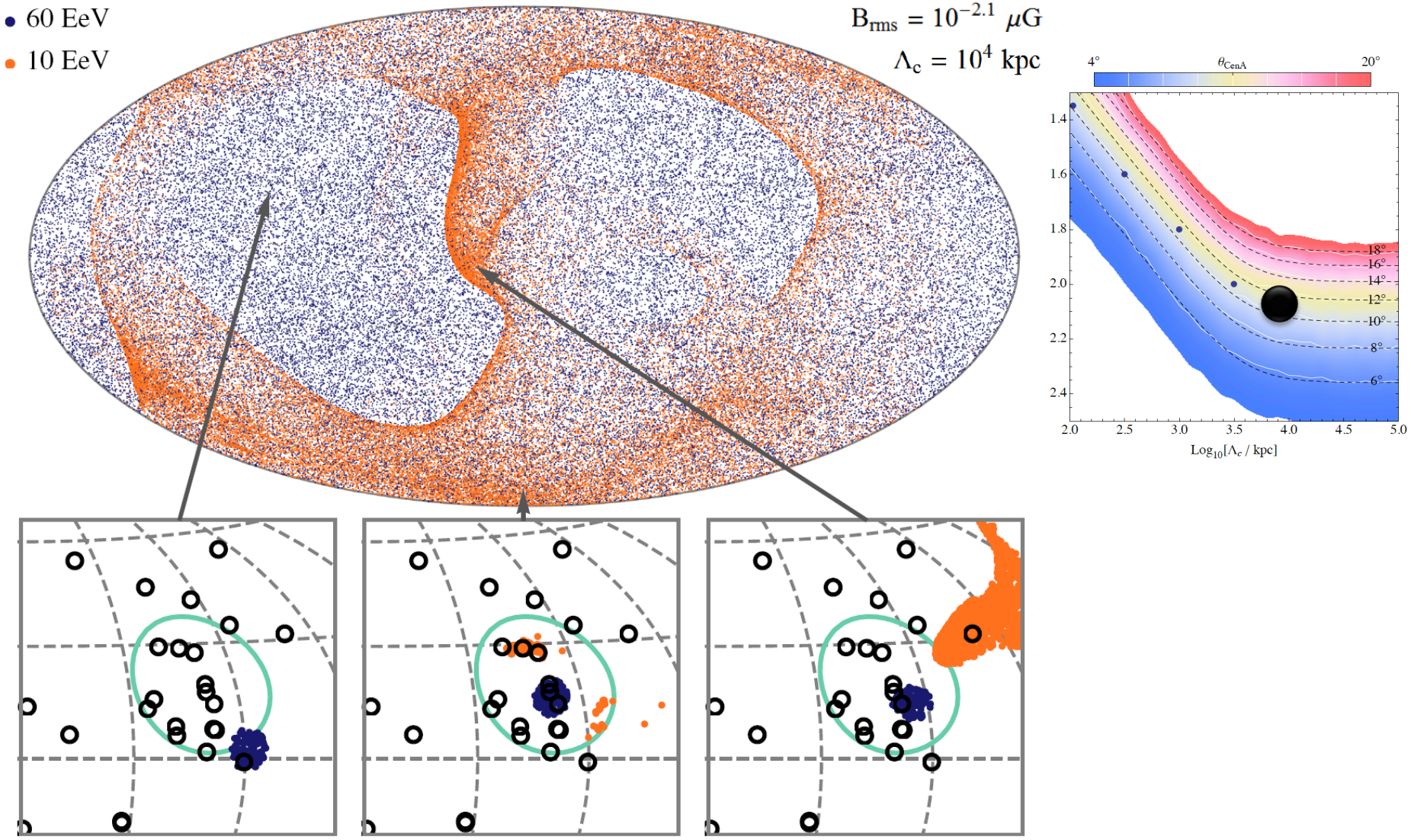
- The mean values of 60 EeV cosmic-ray angular distributions around Centaurus A as a function of field strength and coherence length

- Shown are the expectations from analytical expressions (dashed lines) compared to the our simulation (white lines)



Simulations & Scenarios

- Top: Particles from the viewpoint of Centaurus A obtained using our model of magnetic field structure for populations of cosmic rays with two different energies (blue and orange dots). Bottom: Three characteristic realizations of UHECR angular distributions arriving from Centaurus A, chosen from locations in the map above (as marked with arrows).



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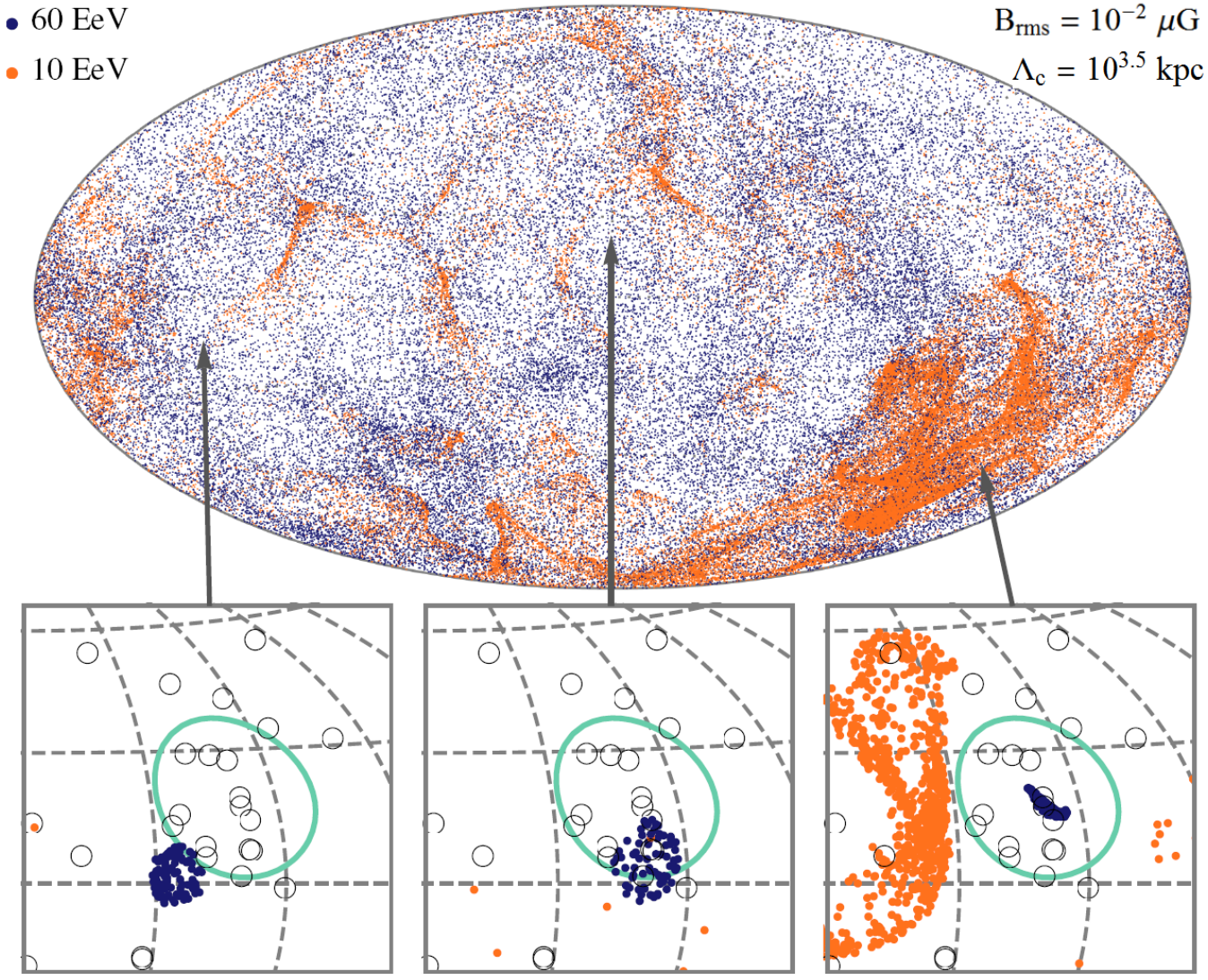

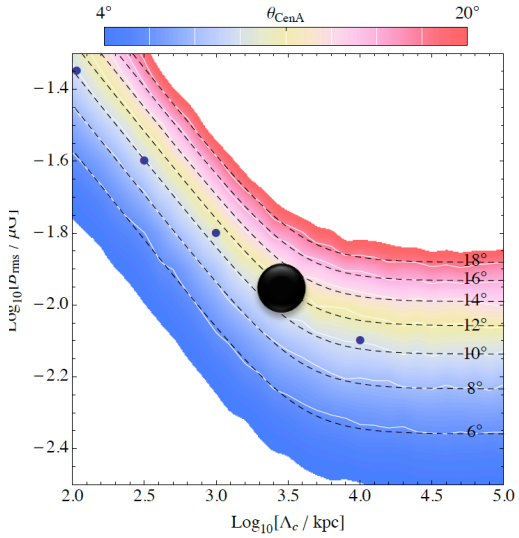

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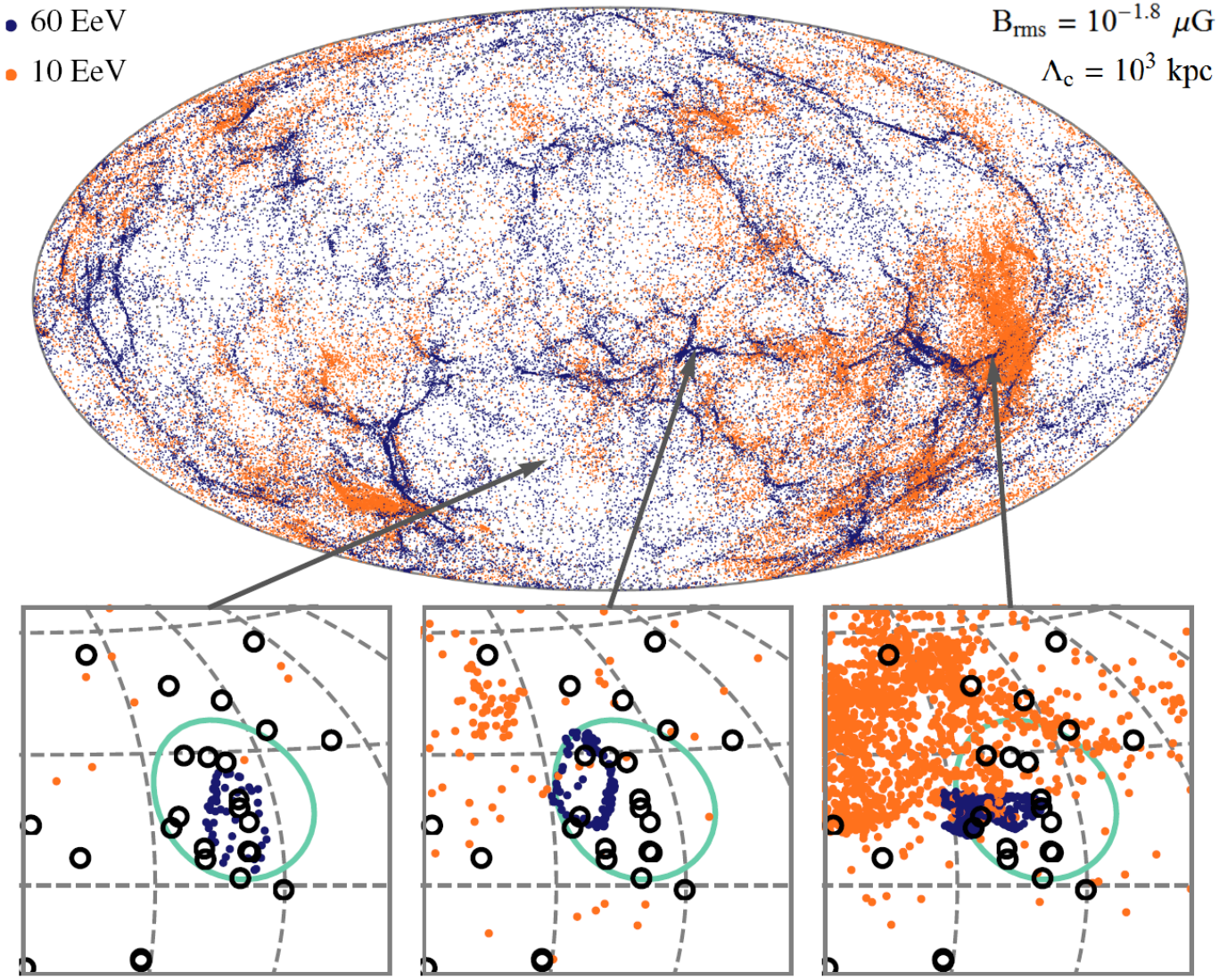

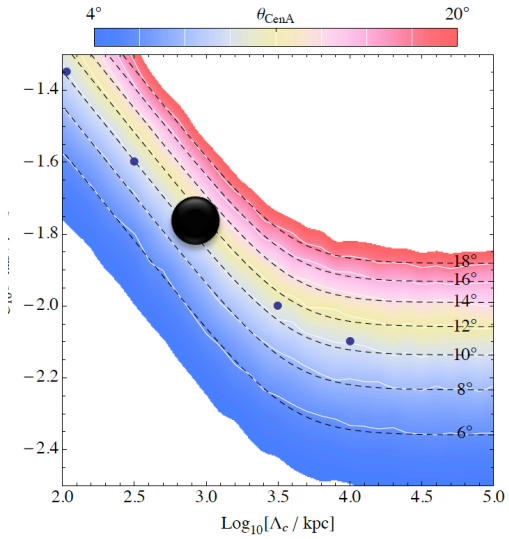

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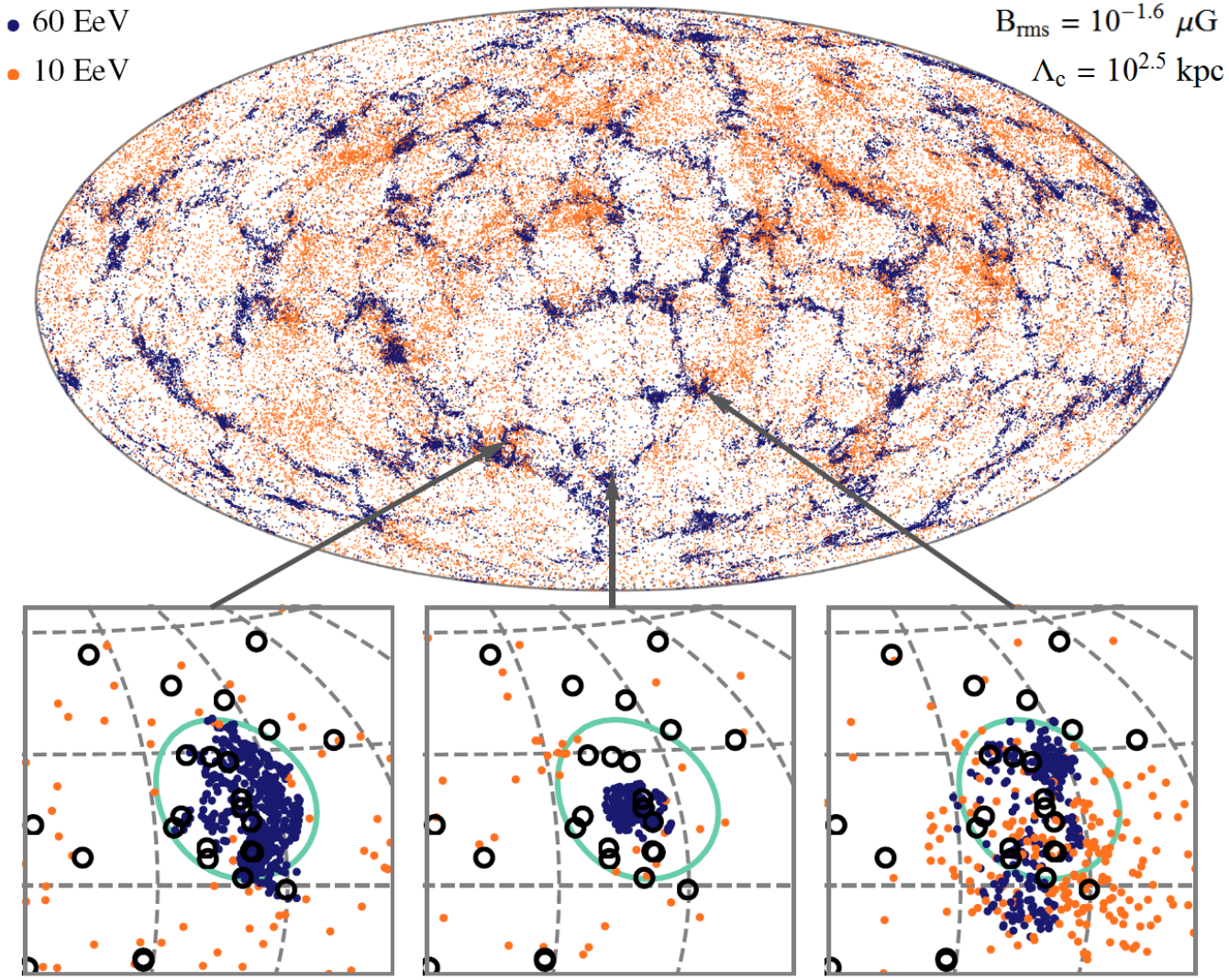

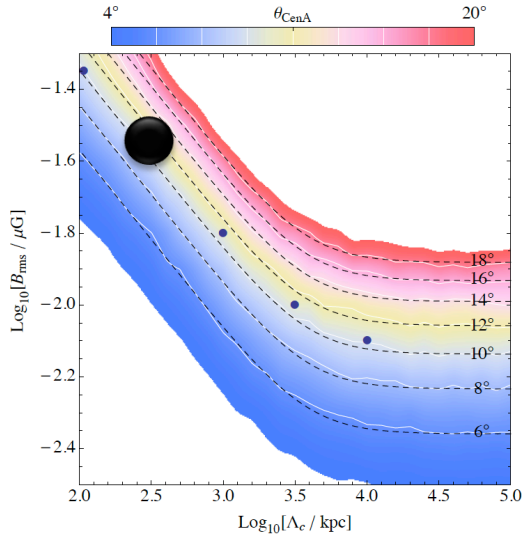

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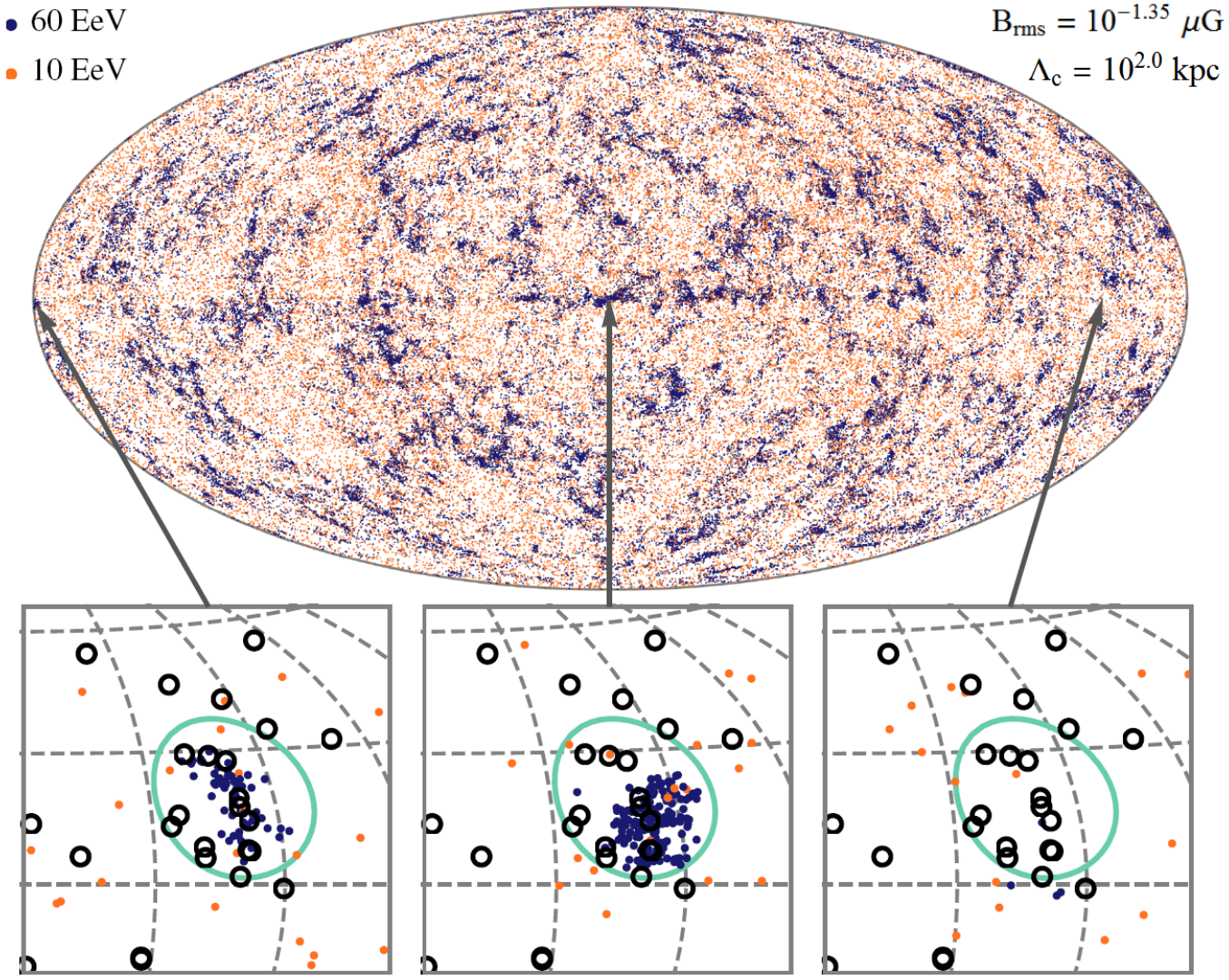
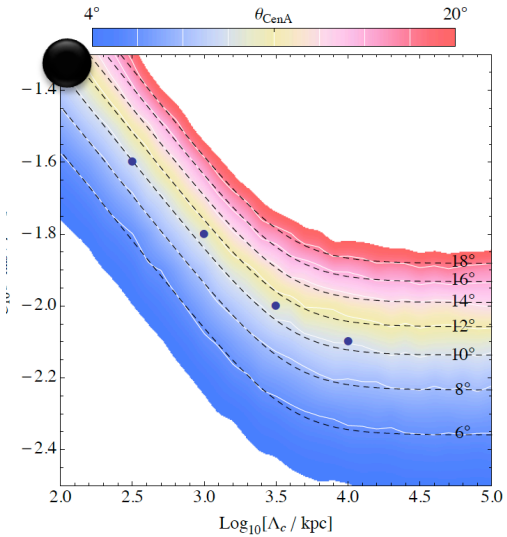
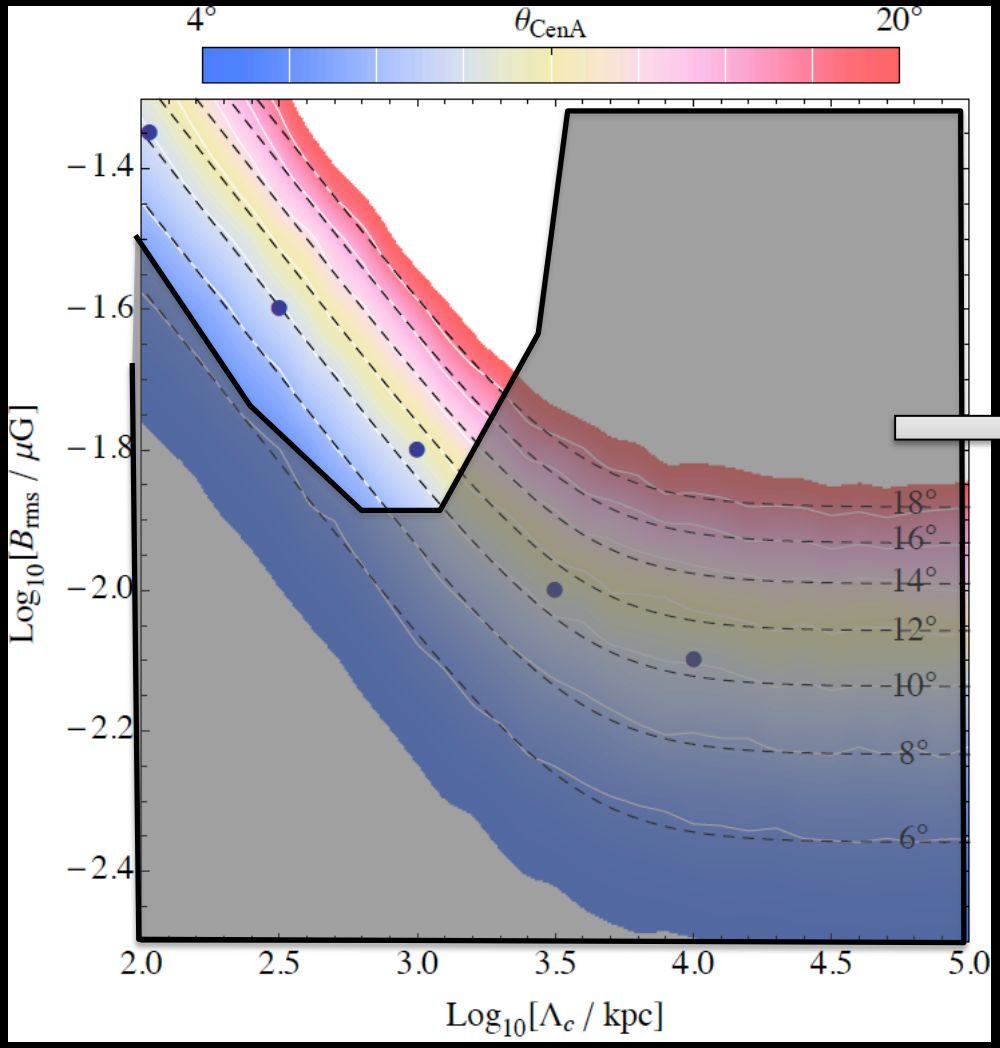




Local Intergalactic Magnetic Field



- We examine the parameter space of magnitude versus coherence length of the local intergalactic magnetic field
- The shaded region is ruled out at > XX % confidence using a simple Kolmogorov-Smirnov test comparing the observed and simulated angular distributions (preliminary)

Concluding Remarks

- Auger observed a significant excess of UHECRs around Cen A, we have performed several sophisticated simulations to understand the origin:
  - 13 UHECR events are distributed within ~18^{o} circle around Centaurus A while only 3 events are expected for an isotropic distribution
- Assuming Centaurus A is the source of the excess:
  - Local intergalactic magnetic fields strongly alter how Centaurus A will look in UHECRs
  - The overall angular distribution can be well reproduced for $|B| > 10$nG and coherence length in the range 100-1000 kpc
- We have developed a transport code that can handle propagation of charged particles with very high accuracy in variety of magnetic field configurations:
  - How long UHECRs stay in their source before they escape and reach us?
  - What is the preferred injection spectrum at the source
  - What are the additional neutrino & photon signatures?