The Centaurus A UHECR excess and the local extragalactic magnetic field

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The low-metallicity ISM: chemistry, turbulence and magnetic fields

8 – 12 October 2012

Göttingen, Germany

Co-workers

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Cen –A, AUGER + HiRes

A new analysis and conclusions on:

The strength & structure of the nearby EGMF out to ~5 Mpc

A comparison of

UHECR simulation and measurement at 1 and 6 x10^{19} eV

Yüksel, Stanev, Kistler & Kronberg *ApJ* **758**, 16, Oct 10 2012

Source data are from 2010 published data:

AUGER UHECR data: (Argentina)

Abreu *et al. Astroparticle. Phys*. **34**, 314, 2010

HiRes/TA UHECR data: (Utah)

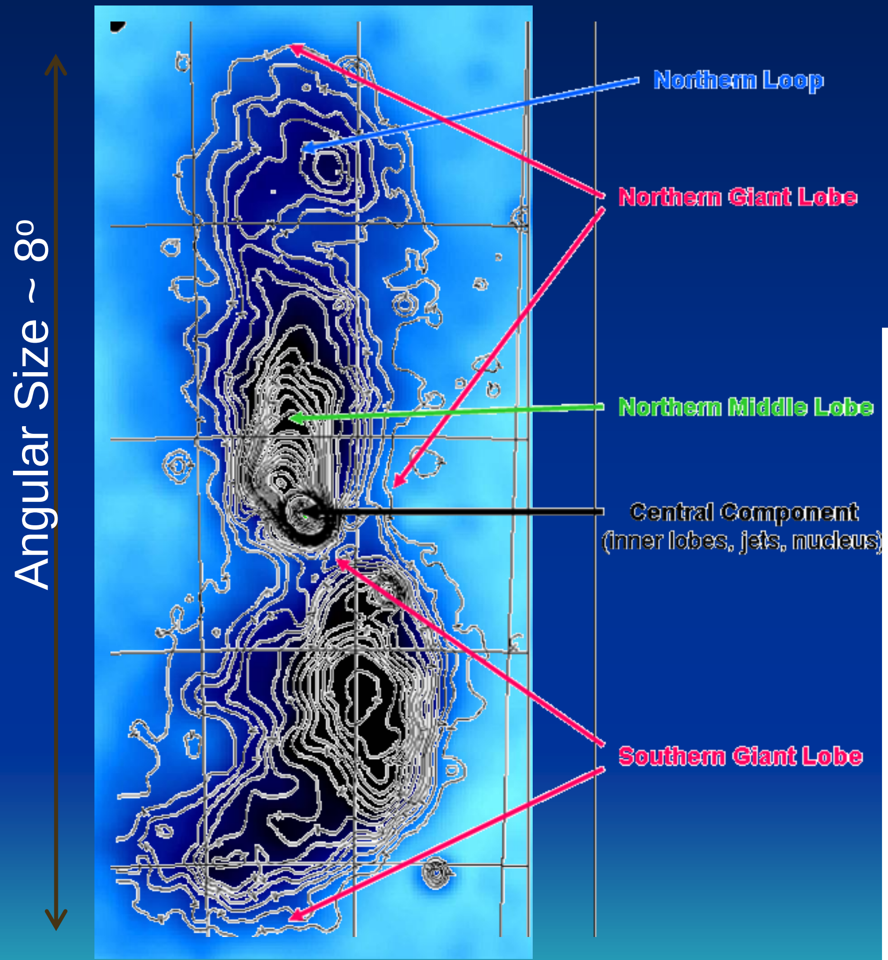
Abbasi R.U. *et al., ApJL* **713**, L64, 2010

Cen A Basics

l = 309.5º b = 19.4º
Distance : 3.8 ± 0.1 Mpc

Angular Size ~ 8º
Projected size ~ 0.6 Mpc

- The radio jets of Centaurus A assumed to extract energy from the central SMBH, and also accelerate UHECR particles.



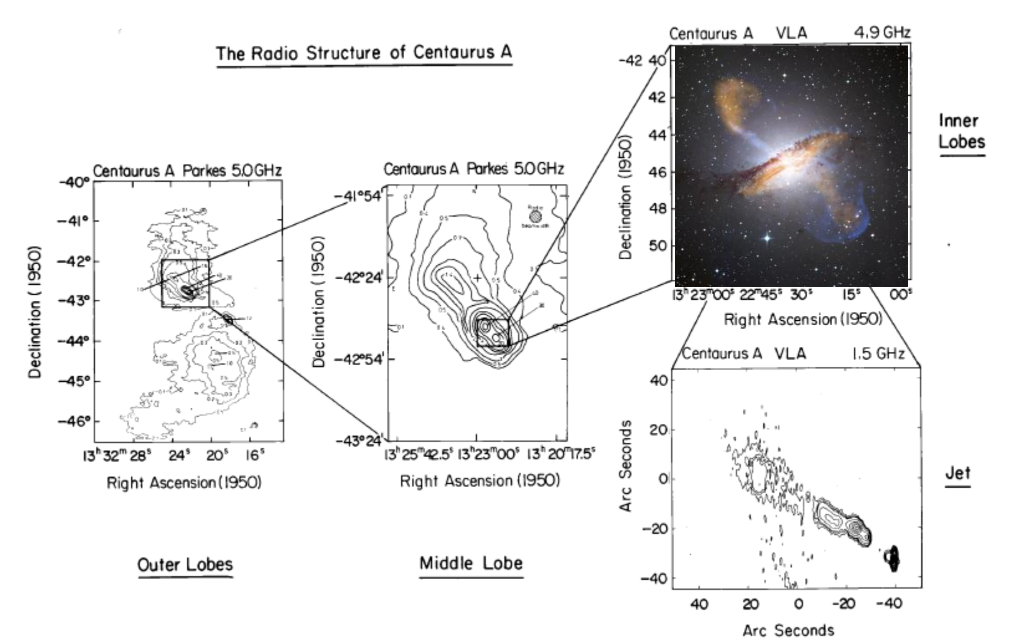
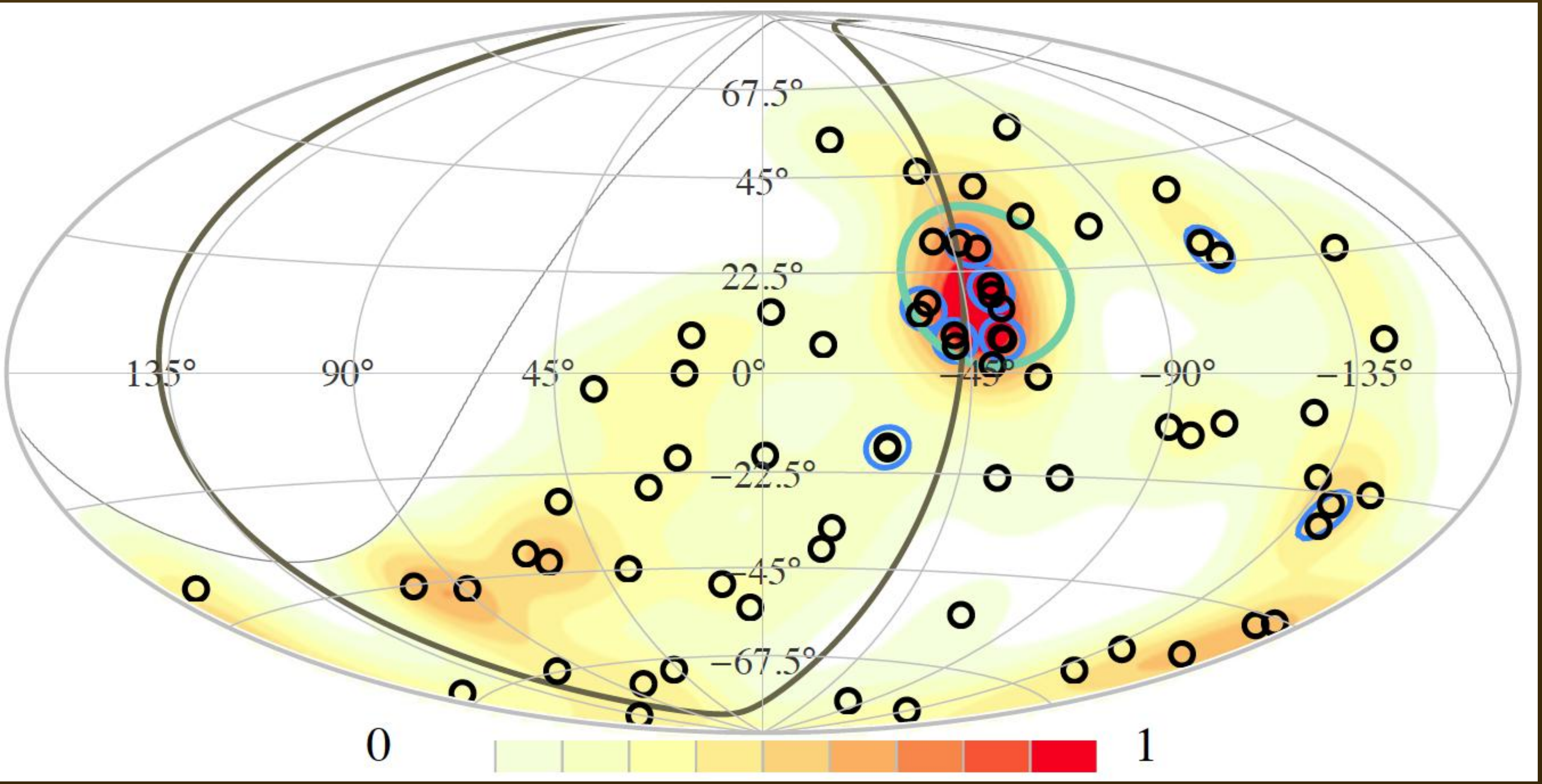


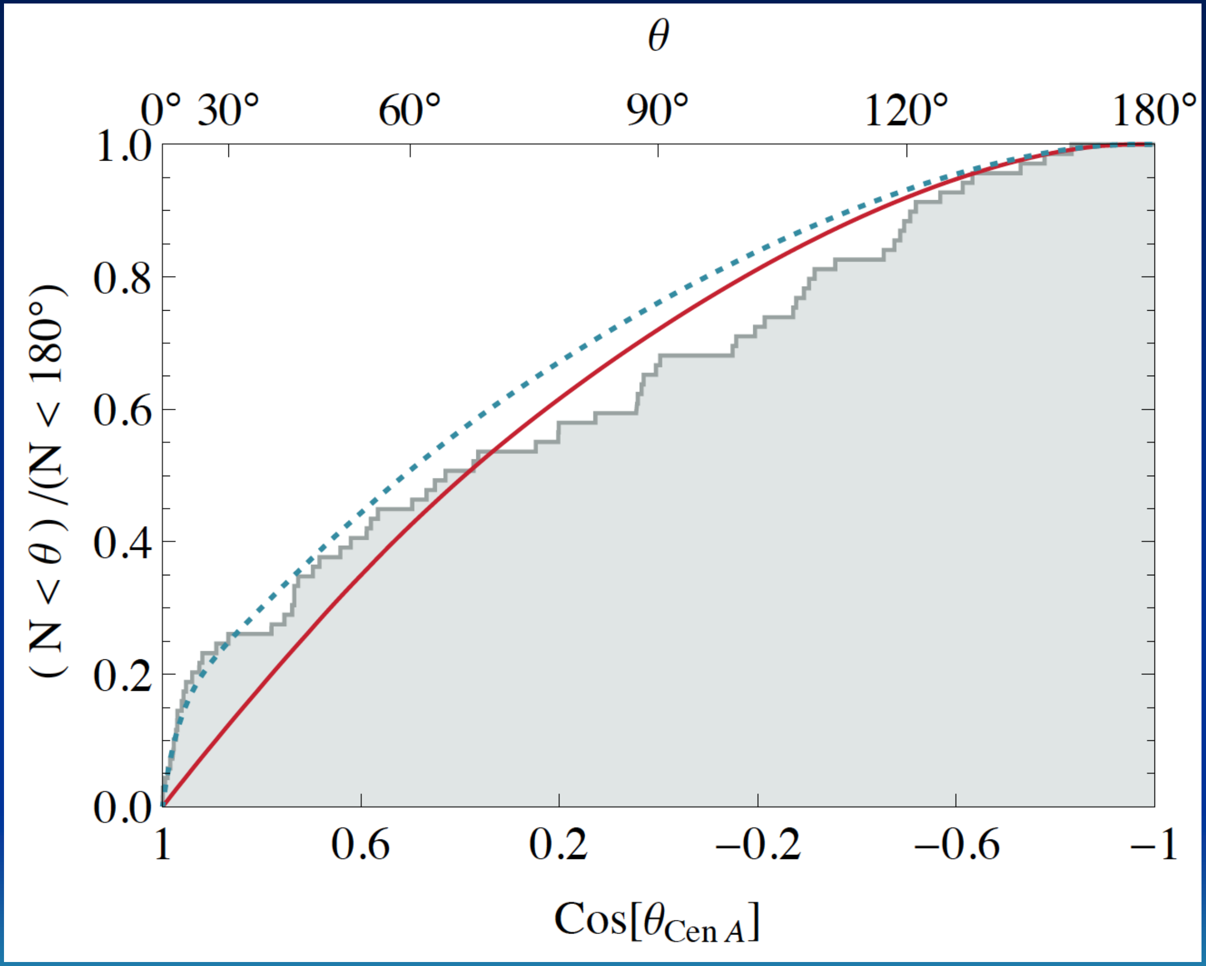
Fig. 3. Radio maps of Centaurus A, highlighting the various components of the radio source introduced in Sect. 2.1. From Burns et al. (1983).

The arrival directions of 69 UHECR events detected by Auger (black circles) in Galactic coordinates. Pairs of events within 5° are shown with blue circles.

A circle of 18° is shown around the radio galaxy Centaurus A. The estimated density distribution of UHECR events are shown with coloured contours



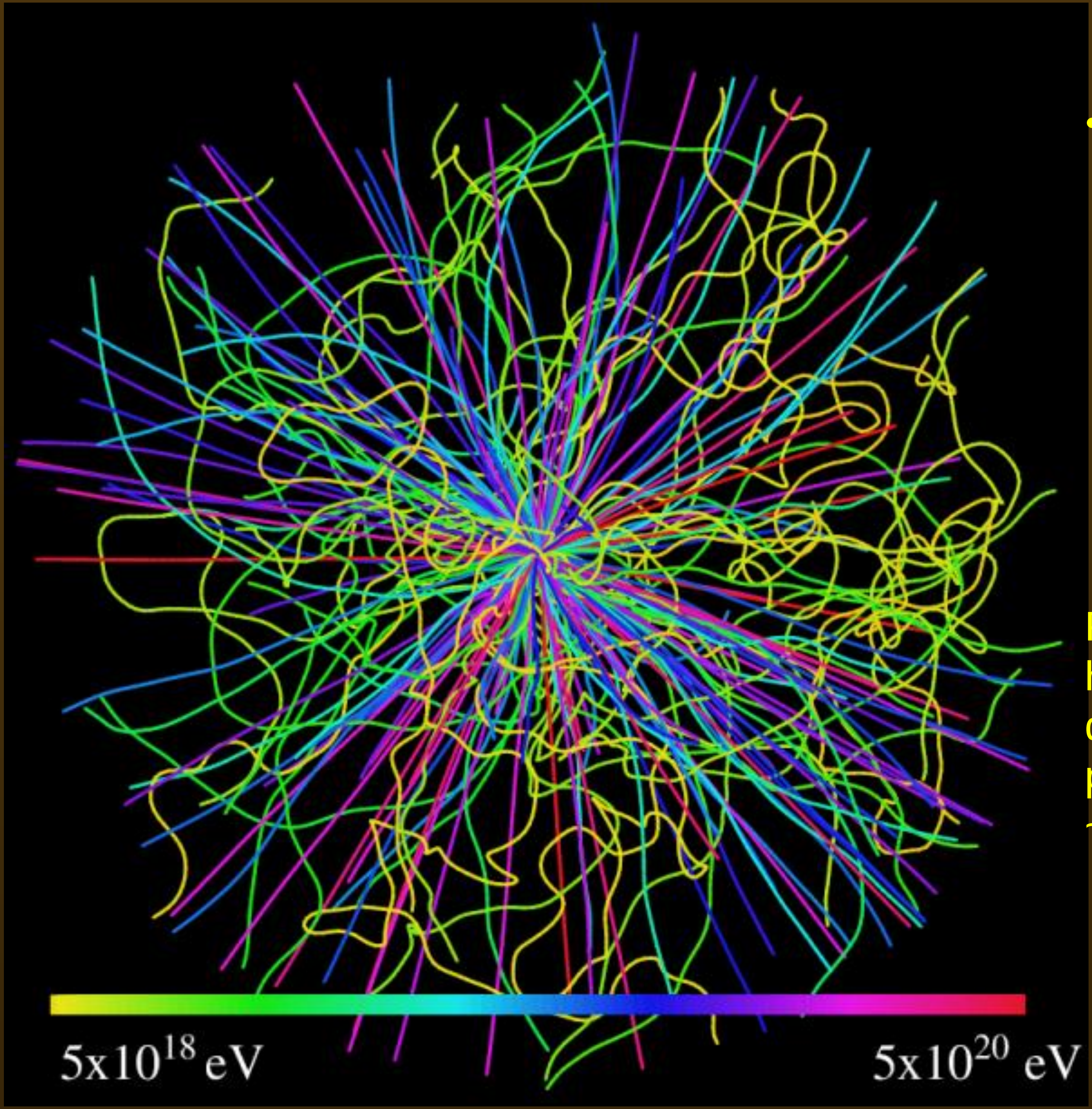
Cumulative angular distribution of events around Cen A



After weighting for exposure, the expectations for

- (solid line)
A purely isotropic distribution of all events
- (dotted blue line)
A model of 10 events from Cen A, smoothed by a 10 degree Gaussian distribution around Cen A -- plus an isotropically distributed 59 events

Even without an excess from the direction of Cen A, the all-sky distribution of events is anisotropic



- Trajectories of UHECRs (coloured according to their energies) as they leave the source and propagate through the intergalactic magnetic field.

Particles below $5x10^{19}$eV have much stronger deflections compared to particles above ~$5x10^{19}$eV

To understand the angular distribution of events seen by Auger, first look for a range of EGMF parameters that can produce the observed spread of ~ 10° for UHECRs around Cen A's location:

i.e. decide on a useful model framework

Propagation pathlength = d , particle deflection = δ

B_{IG} coherence length = Λ_c shift in arrival direction = θ_{AV} $\theta_{AV} = \frac{\delta_{AV}}{2}$

A: $\Lambda_c \ll d$ B: $\Lambda_c \gg d$

Analytically:

$$\delta_{\rm rms} \simeq 53^\circ \sqrt{1/2}\, B_{\rm rms} \sqrt{d\, \Lambda_c}\, / E$$

$$\theta_{\rm rms} = \delta_{\rm rms} / \sqrt{3}$$

$$\delta_{\rm av} \simeq 53^\circ \sqrt{2/3}\, B_{\rm rms}\, d\, / E$$

$$\theta_{\rm av} = \delta_{\rm av} / 2$$

$$\theta \simeq (\theta_{av}^{\eta} + \theta_{rms}^{\eta})^{1/\eta}$$
$$\simeq 53^\circ \sqrt{1/6}\, B_{\rm rms}\, (d/E) \left((\Lambda_c/d)^{\eta/2} + 1 \right)^{1/\eta}$$

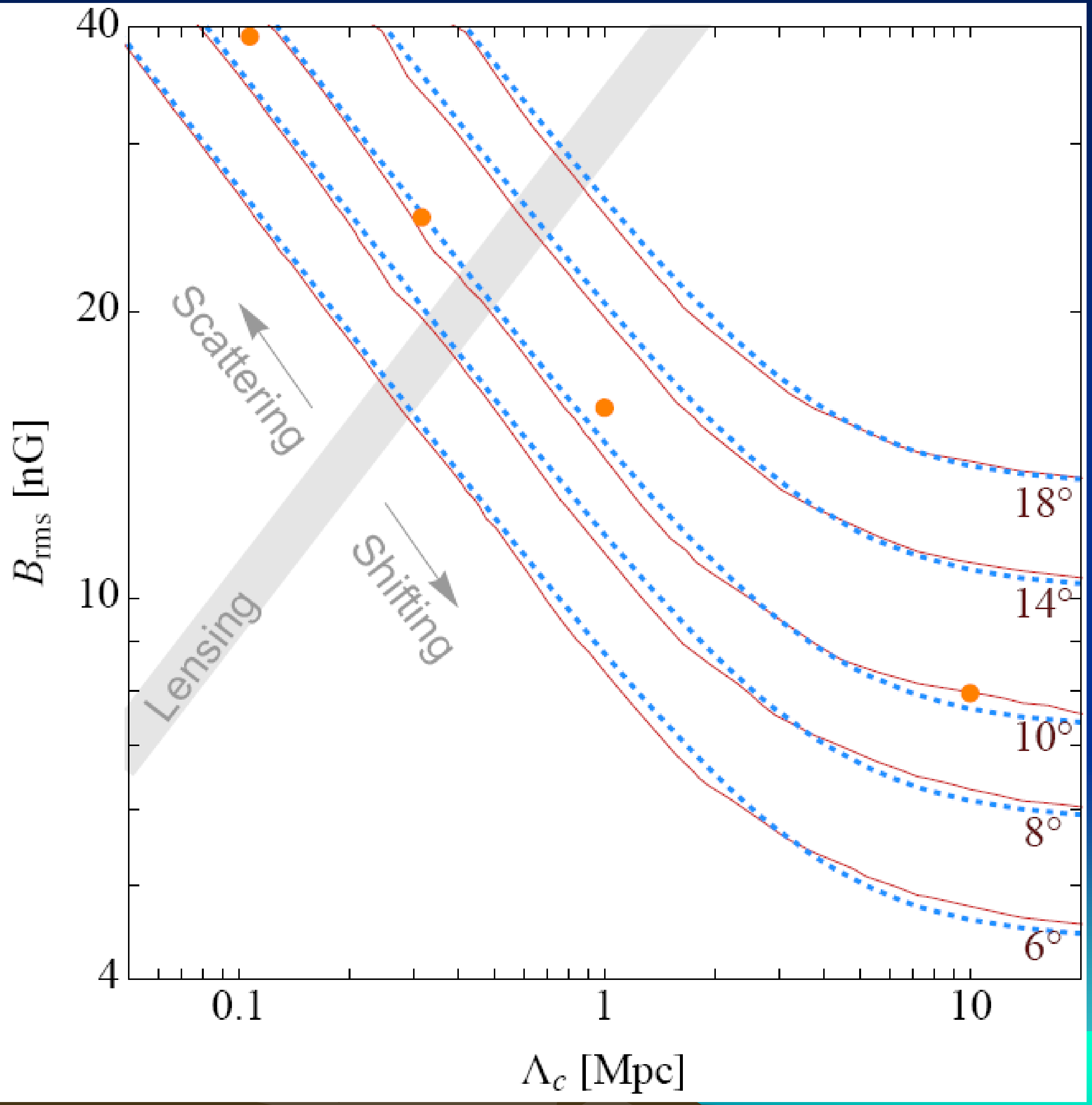
$\eta \to -4$

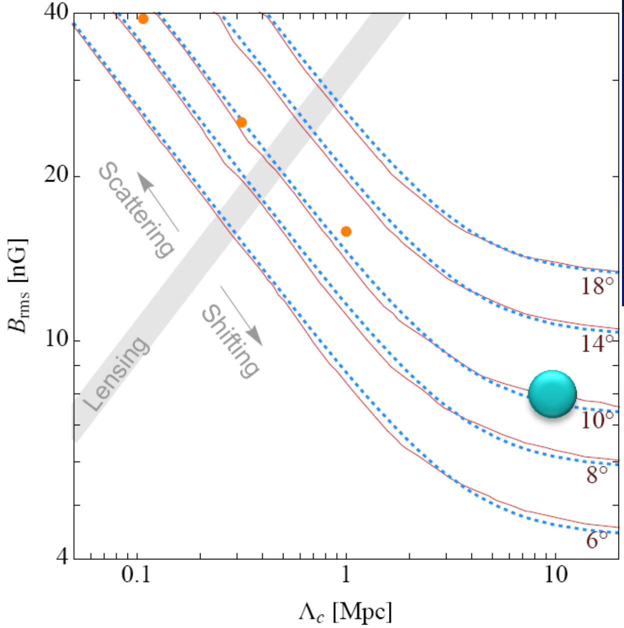
η parmeterizes smoothness of transition from A ->B

We compute θ numerically, utilizing a fourth-order Runga-Kutta method to solve equation of motion, keeping the step size small in comparison to both the minimum scale of magnetic field variation, and Larmor radius

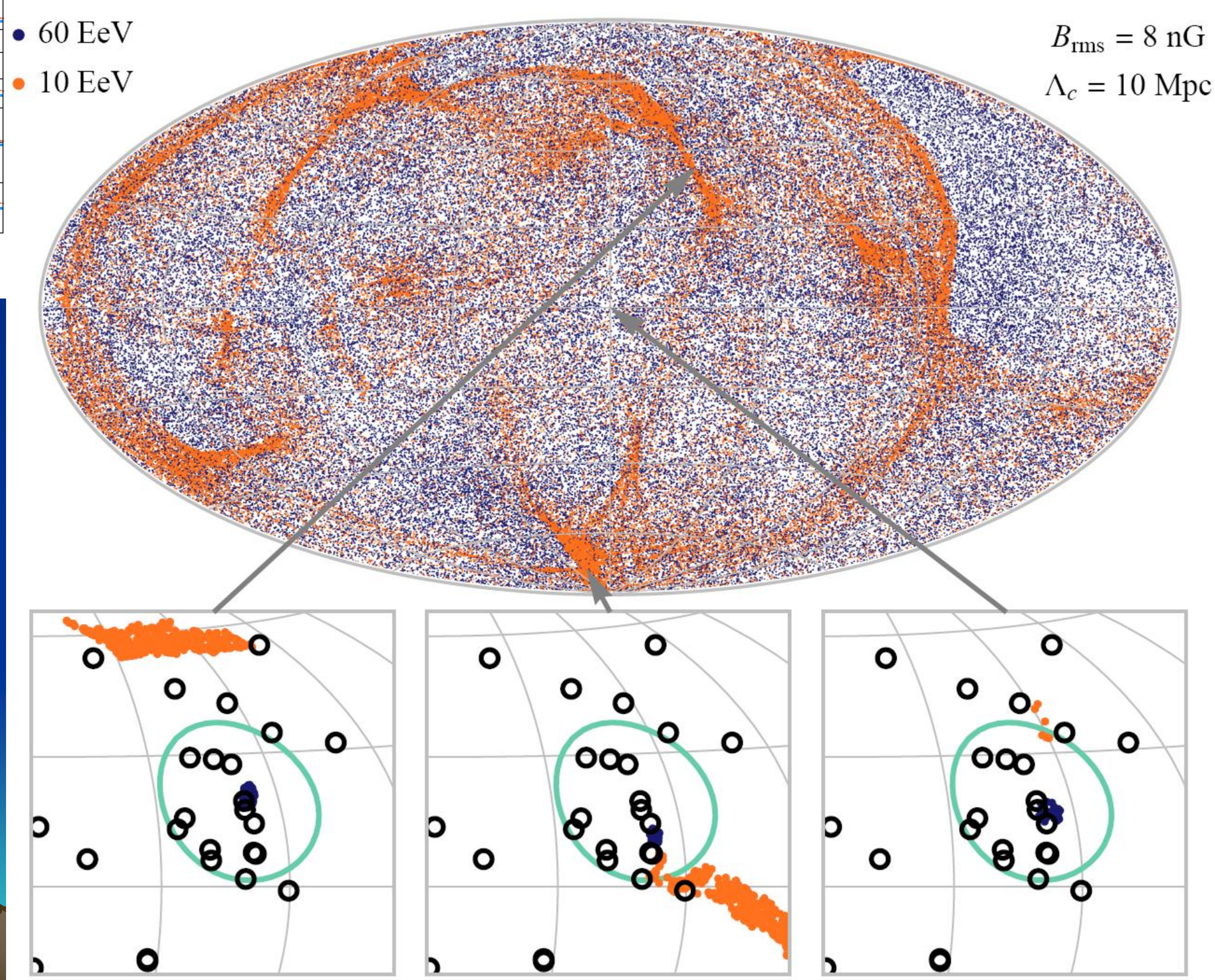
The mean values of cosmic-ray angular distributions for 60 EeV around Centaurus A as a function of field strength and coherence length

- Shown are the expectations from analytical expressions (dotted lines) compared to the our simulation (solid lines)
- Maximum lensing appears in the shaded band





The sky as seen from Cen A (upper plots)
-- projected on a 3.8 Mpc radius screen

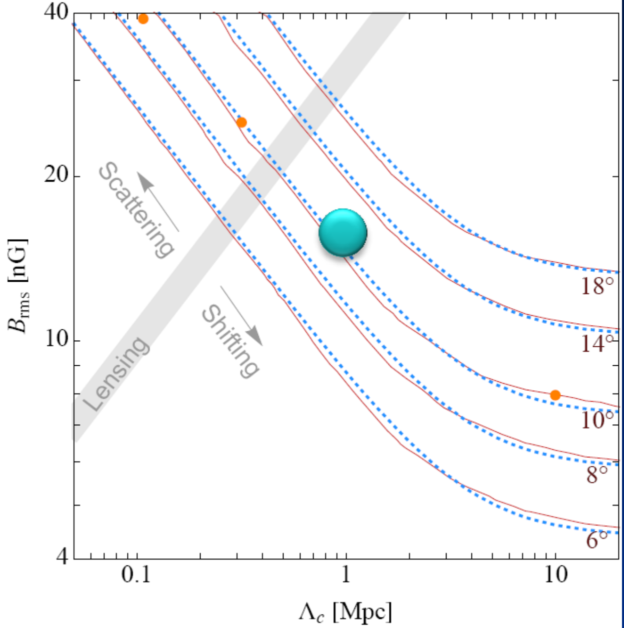


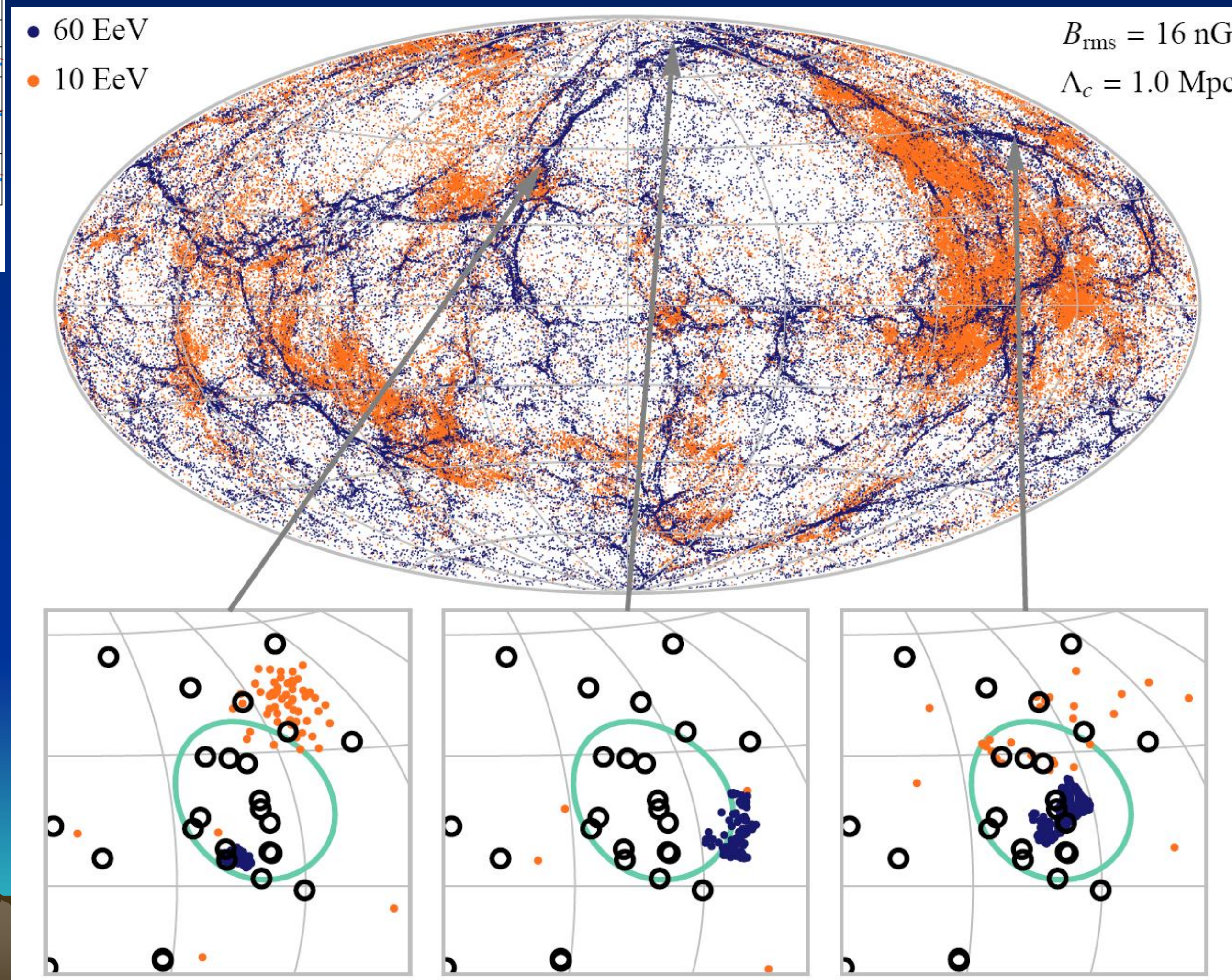
Lower plots:

Observed events
vs. (l,b) for the 3 Earth
locations on the
Cen A-centred sphere
above

b

l

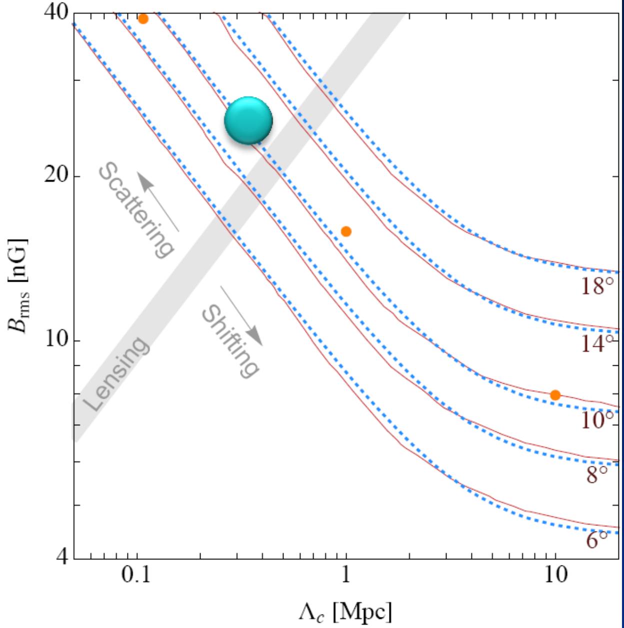




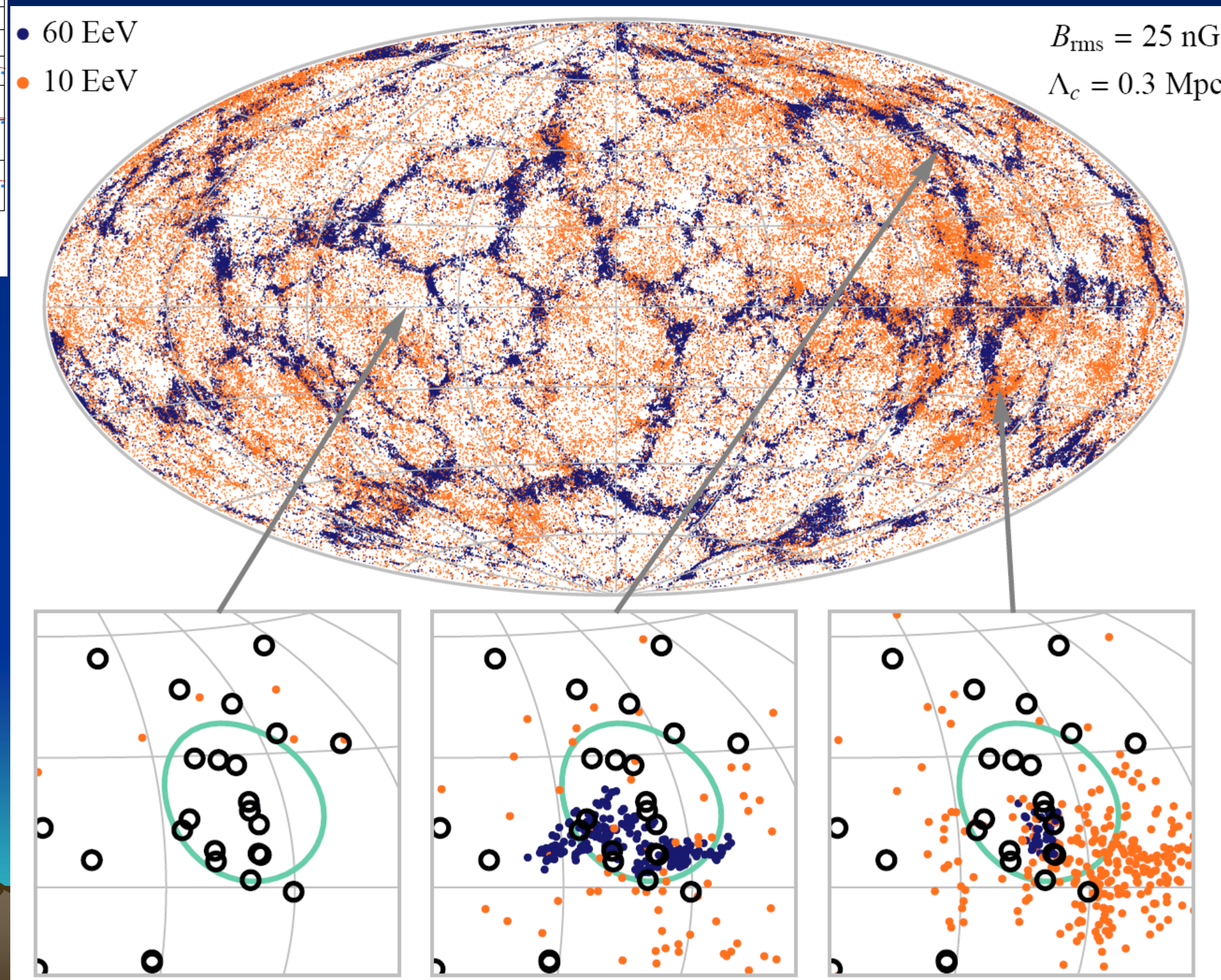
Note the clearly delineated "caustic" zones for E=60 EeV protons. These correspond to the gray-shaded "lensing"zone in the upper left inset. They lead to a relatively model - insensitive $\langle B_{IG} \rangle$

Details in *ApJ* ***758***, *16, (Oct 10) 2012 (Yüksel, Stanev, Kistler & Kronberg)*

b



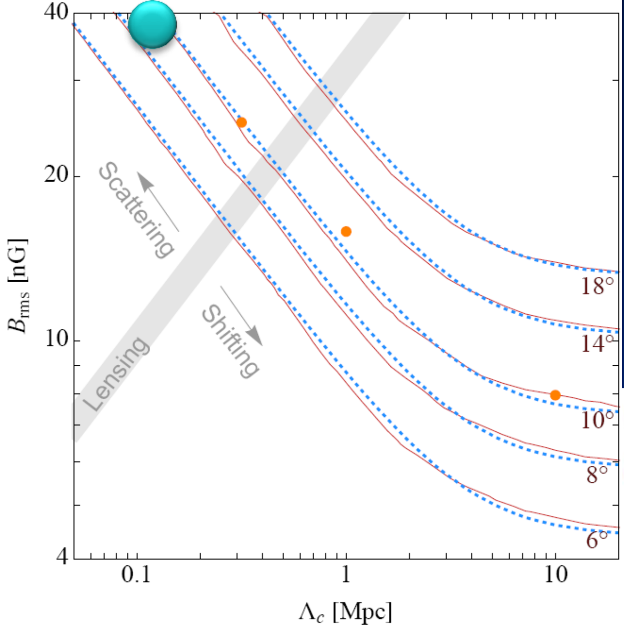
40
20
10
4
$B_{\rm rms}$ [nG]
0.1
1
10
Λ_c [Mpc]
Scattering
Lensing
Shifting
18°
14°
10°
8°
6°



60 EeV
10 EeV
$B_{\rm rms}$ = 25 nG
Λ_c = 0.3 Mpc

b

l



40
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10
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B_rms [nG]
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Λc [Mpc]
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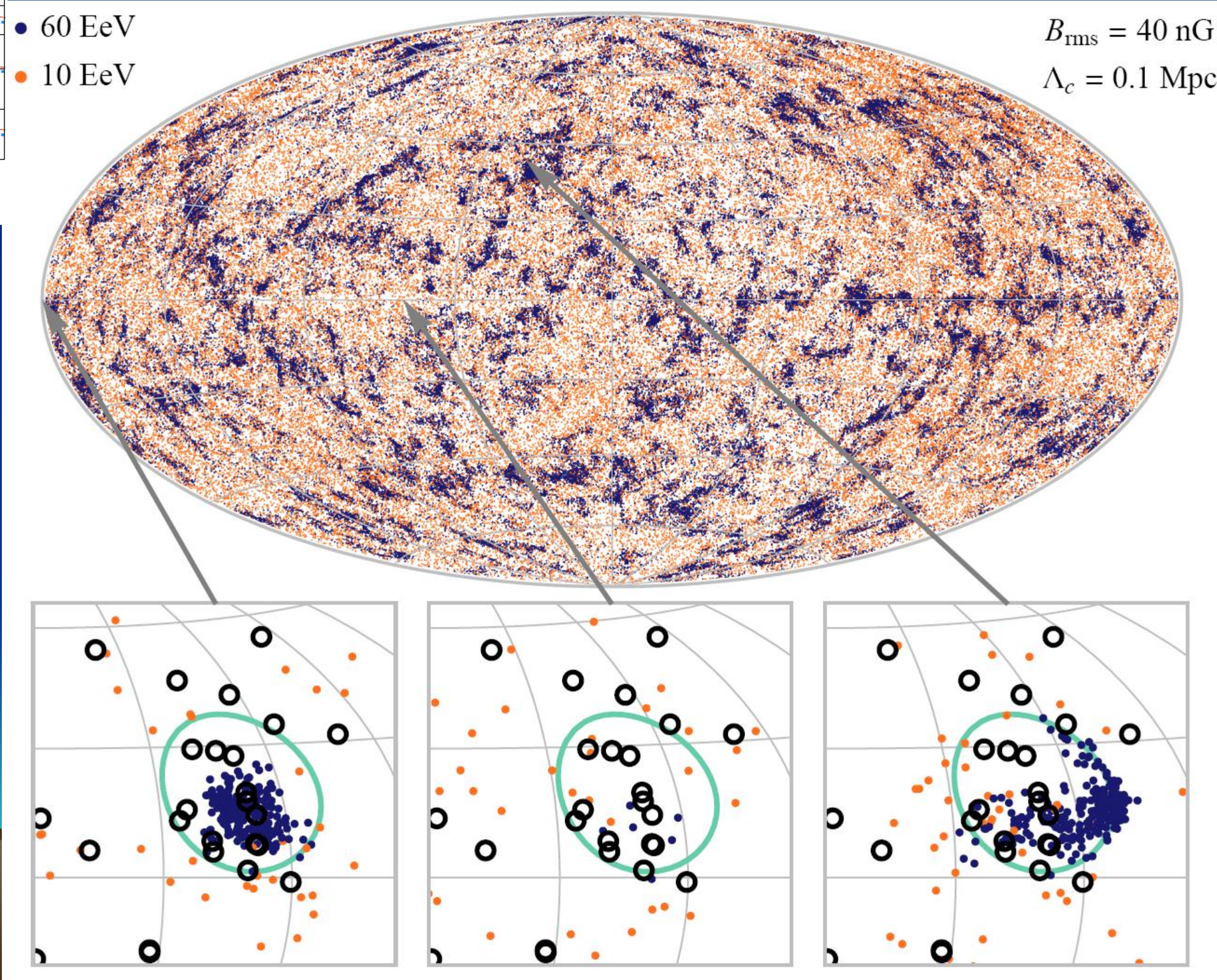
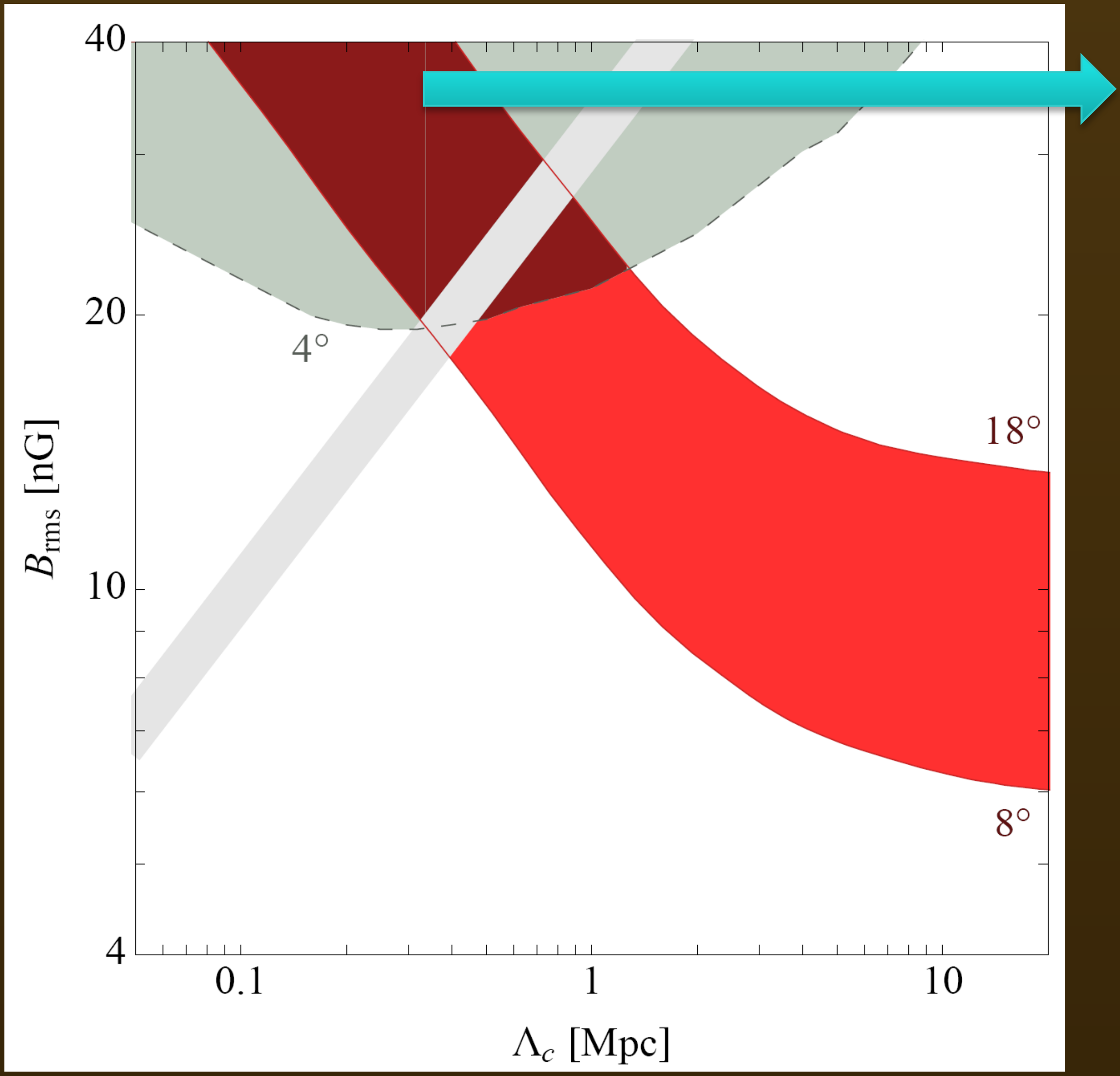


60 EeV
10 EeV
B_rms = 40 nG
Λc = 0.1 Mpc

The local Intergalactic Magnetic Field



- *Inferred range of extragalactic magnetic field parameters that are compatible with:*

    1. *the average angular distribution of events 8-18 ° from Cen A (solid lines)*

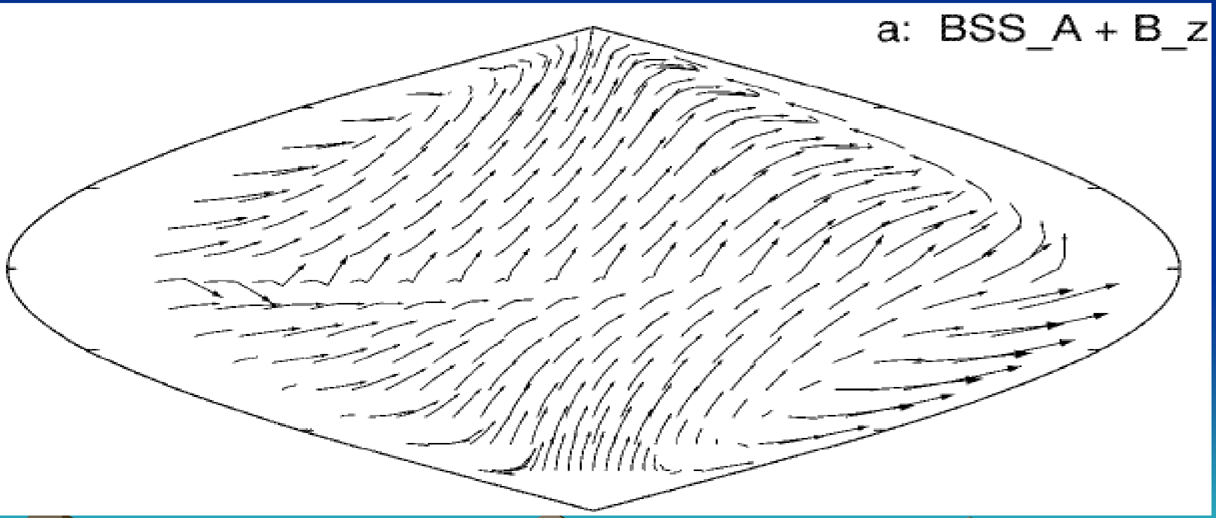
    2. *the spread of events among themselves is < 4 ° (dashed line)*

Condition 2 disfavors scenarios in which events are shifted from the source position, yet remain tightly clustered

What about the Galactic (Milky Way)magnetic fields?

- GMF in the disk modelled as consisting of two ~μG strength components :
  - a regular component with reversals in the <*B*> direction between neighboring arms of the galaxy
  - a turbulent component with coherence length of ~ 0.1 kpc

- Protons with energies of 60 EeV expected to be scattered by only about a degree (smaller than the uncertainty of UHECR detectors)
- The regular *B*-component tends to produce only a coherent shift in the source position:



- We thus expect the Galactic MF to have only a small effect on protons at the energies examined here and minimally impact our conclusions

What about heavy Nuclei CR's?

- A heavy composition at these energies would imply a flux of protons of the same rigidity for the same trajectories
- We would expect an excess at lower energies, though not as prominent,
- This excess was not seen in the Auger data, so the simplest interpretation is a dominant proton component. This was also suggested by the HiRes measurements from the depth of maximum of the HiRes UHECR showers:

Some Implications:

- A > 10 nG field extending at a few Mpc around the Milky Way results in a ``screen" scattering all UHECR's that eventually reach Earth:

  - each UHECR would then be expected to have a minimum amount of deflection due to this field alone
  - it would increase the difficultly of making associations with more distant sources
  - it would introduce a minimum <u>time dispersion</u>, important for transient sources, such as gamma-ray bursts

Even if protons dominate the composition at high energies, heavier nuclei may plausibly be present:

  - If it is a solar composition, and acceleration is based on nuclear charge, the observed events near Cen A would suggest <u>1 or 2 He nuclei in the excess</u>.
  - *NOTE: The highest energy event seen by Auger --142 EeV <u>and</u> within 30 degree of Cen A, --- is in rough agreement with the high total energy and greater scattering expected for a <u>heavier</u> , e.g. He nucleus*

Variables that can be further explored (resolved) as more UHECR data accumulate in future

- Better resolution in CR energy – CR lensing $\rightarrow$ tighter constraints on strength and structure of B_{IG}
- Model with different mixes of CR nucleus composition e.g. Solar, Fe-dominated,etc.
- Milky Way halo field deflection at lower CR energies
- etc.

Concluding Remarks

- We examine the implications of the excess of events seen towards the nearby radio galaxy Centaurus A, ASSUMING 1. ALL PROTONS, and 2. THAT ALL ORIGINATE AT CEN A
- OUR MODEL FRAMEWORK IS A "TIP OF THE ICEBERG" ANALYSIS, WHICH IS SET UP TO PRODUCE A VARIETY OF OTHER MODELS WITH ASSUMPTIONS OTHER THAN 1. AND 2. ABOVE
- OTHER, LARGE SCALE, ISOTROPIES ALSO APPEAR TO EXIST IN THE CURRENT AUGER DATA

  They add to the potential to finally address both the particles' origins, and properties of the nearby EGMF
- The angular distribution of events constrains the EGMF strength within several Mpc of the Milky Way, and implies that $<B_{IG}> 10$ nG.
- This is important for several other important projects::

  e.g.
  - **UHECR scattering from much more distant sources**
  - **Propagation time delays (~ $10^{4\text{--}5}$ yr to Cen A) from transient sources**
  - **The use of CR *magnetic lensing* signatures to attain tighter B_{IGM} constraints**
  - **Others**

End

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