

A new analysis method for high energy CR
hadron arrival directions

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A new analysis of high energy CR hadron arrival directions

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A new approach to understanding the VHECR/UHECR sky is presented. I describe a multi-parameter analysis that is based on the observed CR arrival directions and energy. The sky plot origin can be any chosen reference source of Cosmic rays. This *source-centred* sky (unlike (l,b) , or (α,δ) etc.) displays simulated energy-species-direction data. I discuss a preliminary UHECR-determined estimate of the intergalactic magnetic field out to $\sim 4\text{Mpc}$, on the assumption that Cen A is the principal UHECR source. Other assumptions and models can be applied within this conceptual framework.

The analysis method, (Yüksel, Stanev, Kistler & Kronberg ApJ 2012) can be applied to data from AUGER, HiRes, TA, and their successors. A specific example shows, within our reference assumptions, how the strength and structure of B_{IGM} is approximately constrained at $\gtrsim 20\text{nG}$ out to $D \sim 4\text{Mpc}$, based on recent AUGER data.

This is “new territory” for IGM magnetic field probes, and also the first VHECR sky-based probe of B_{IGM} on supra-galactic scales. It is a potentially powerful template for the understanding, and future modeling of VHECR/UHECR propagation at greater distances.

Themes

1. Magnetic field environment of the Milky Way, and CR propagation to us (brief)
2. UHECR propagation in the “local” Universe within a GZK radius
3. Sites of UHECR acceleration (very brief)



a top (plan) view

Projected Magnetic field
In a “grand design” galaxy

M51

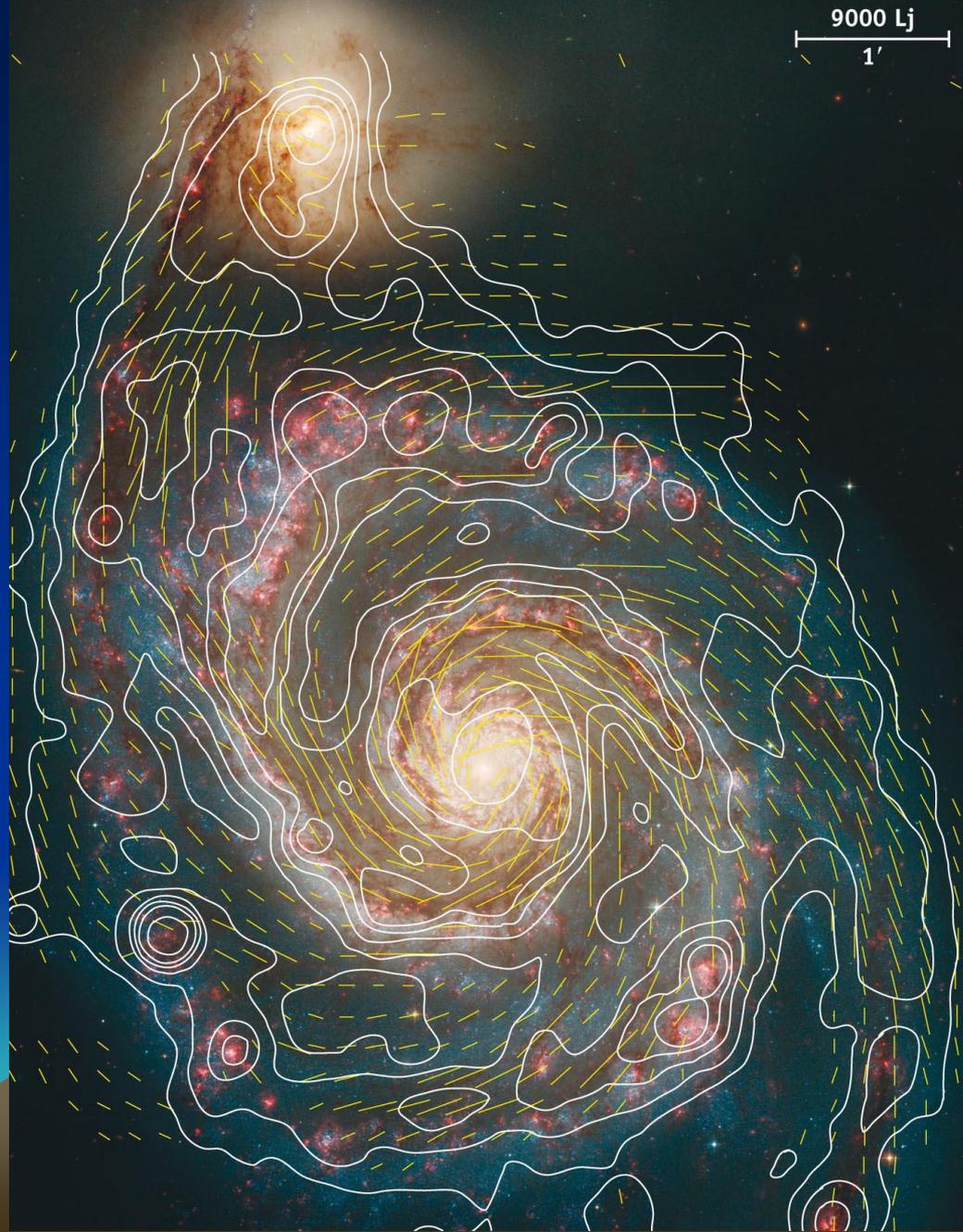
R. Beck

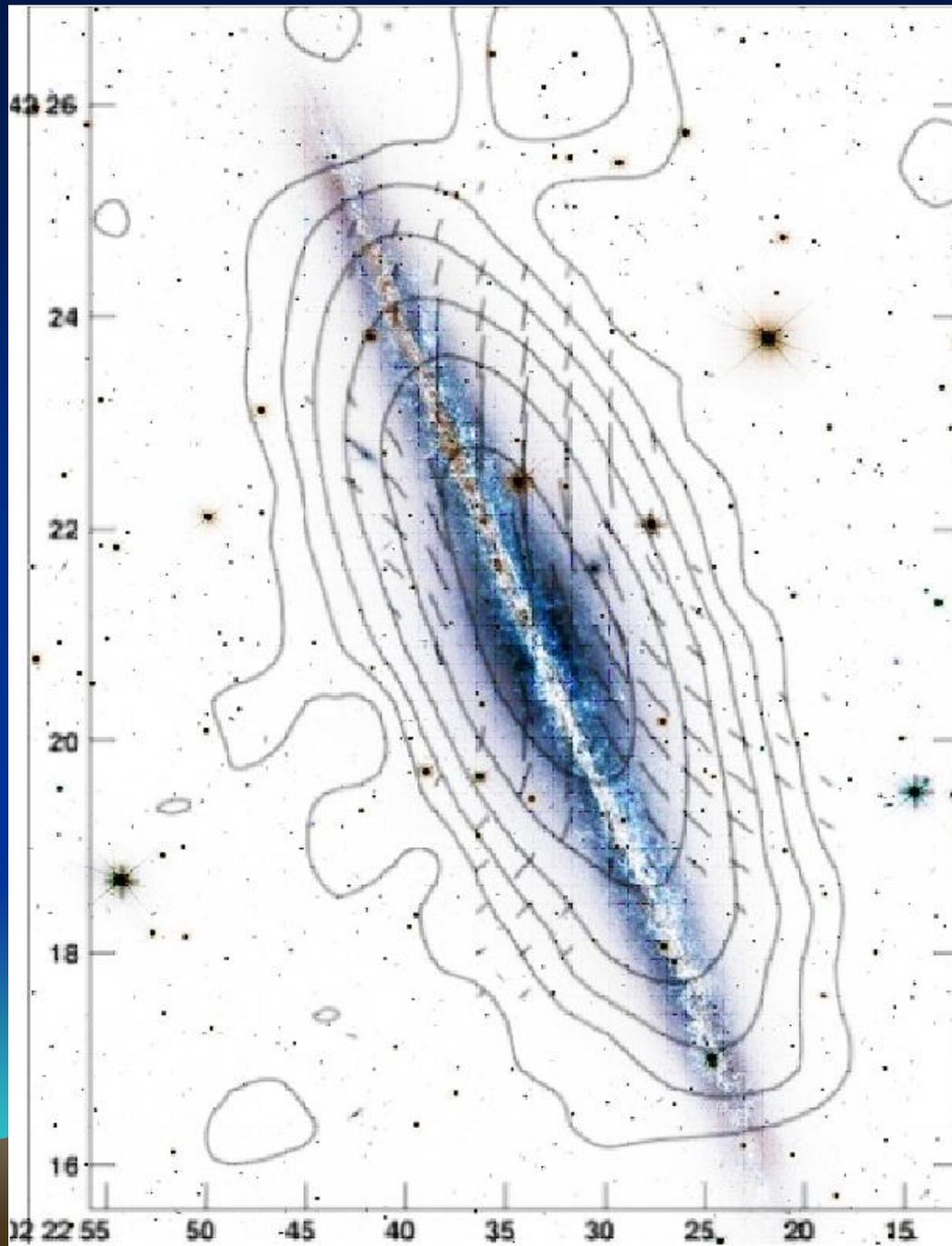
in

*Sterne und Weltraum,
September 2006.*

Question: To an extragalactic observer, does the Milky Way present a clear and beautiful magnetic grand design, like this one and others?

New results suggest **yes**





Edge-on view of the
(2-D projected)
halo magnetic field of
NGC891
(Similar to the Milky Way)

Goal for the Milky Way: obtain
a similar, and 3-D halo magnetic
field model for mapping CR
deflections

i.e.

$\Delta\theta$ (species, energy, l, b)

1

The Milky Way field structure

Begin with Simard-Normandin & Kronberg
Nature **279**,115,1979, *ApJ* **242**,74, 1980



Faraday Rotation measure studies of the Milky

“New Large Scale Magnetic Features of the Milky Way”
 Simard-Normandin & Kronberg, *Nature*, 279, 115, 1979.

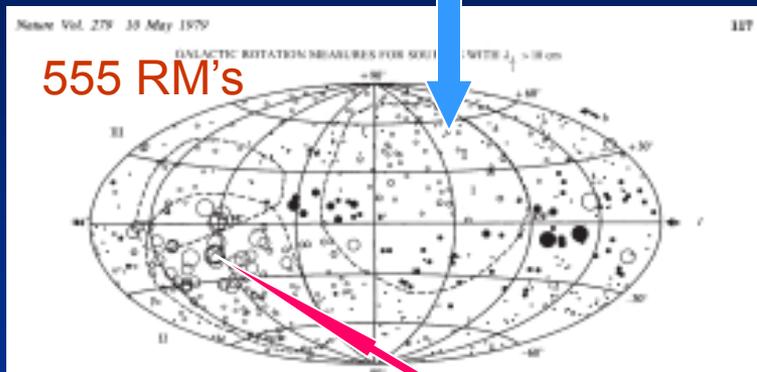


Fig. 1. Mean RM's in circles of 10° radius centered on each source, which emphasize large-scale variations better than Fig. 1. The RM scale is the same as that of Fig. 1. The positions of the radio continuum arms I, II and III are shown. Note that some small-scale features which are not smoothed out, and the precise location of boundaries where the RM changes sign are clearly marked. These are best located in Fig. 1.

The large scale of feature A (implied by its large RM) requires that it have a large magnetic energy, $\approx 10^{47}$ erg. On this consideration alone, RM feature A is too energetic to be associated with a supersonic filament. On energetic grounds it could be associated with either galactic rotation or large-scale streaming of the infalling high-velocity HI clouds, of which there are several in the same direction^{11,12}. It is possible that feature A is associated with local streaming effects which are related to the magellanic stream, because the end of the magellanic stream lies in the approximate direction of feature A. More data are required, however, to establish any connection with the magellanic stream.

The structure of magnetic field
 The large rotation measures observed near the galactic plane around $l \approx 215^\circ$ (feature B) and $l \approx 90^\circ$ are consistent with a longitudinal magnetic field directed towards $l \approx 90^\circ$. In the direction opposite to galactic rotation the large RM zone is centered near 155° rather than 215° which suggests that the Perseus arm may be opening up in this direction. The RMs and dispersion measures (DM) of pulsars in this direction indicate a mean magnetic field of less than $3 \mu\text{G}$ (90° and 120° south of the galactic plane). From this we conclude that the extent of the aligned field in both these arms (A and B) is greater than $\sim 4 \text{ kpc}$. A and B must therefore be large-scale features of the Galaxy. Feature C at $l \approx 10^\circ$ can be interpreted as another major longitudinal component located approximately between the Sagittarius and the Norma-Scutum arms where (on the magnitude of the RM) suggests the prevailing field is directed along our line of sight for several kiloparsecs.
 The very abrupt reversal of RM near the plane at $l \approx 90^\circ$ is consistent with a model consisting two prevailing field zones pointing in opposite directions along the spiral interarms. This is best shown in Fig. 3, in which we superimpose the model of the spiral structure of the Galaxy by Georgakopoulos¹³.
 The fields do not seem to be one-phase. They also extend to quite large angular distances from the mean galactic plane. An interesting question at this stage is whether a counterpart, very region C can be seen on the $l < 360^\circ$ side of the Galaxy—in the southern hemisphere. Unfortunately, we have not made

measurements from the southern hemisphere, and have calculated RMs only from polarization measurements in the northern hemisphere for this region. It is now clearly of interest to obtain more data at $|b| < 30^\circ$ in the range $160^\circ > l > 280^\circ$. This would identify if large-scale magnetic field components can be seen associated with arm or interarm regions on the southern side of the Galaxy.

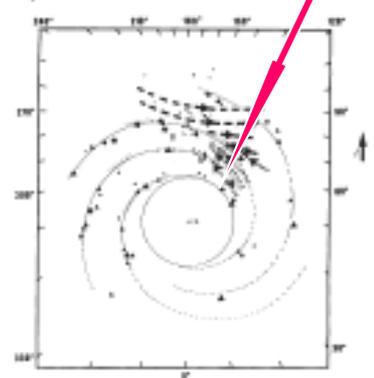


Fig. 3. A sketch of the regions containing an aligned component of magnetic field, indicating their approximate size and direction. This is shown superimposed on the distribution of bright HII regions in the Galaxy by Georgakopoulos¹³. Note that the heavy dotted and dashed lines do not necessarily represent the local prevailing magnetic field directions, but rather the zones in which the line-of-sight integral of RM is large and has the same sign.

Summary of conclusions in 1980:

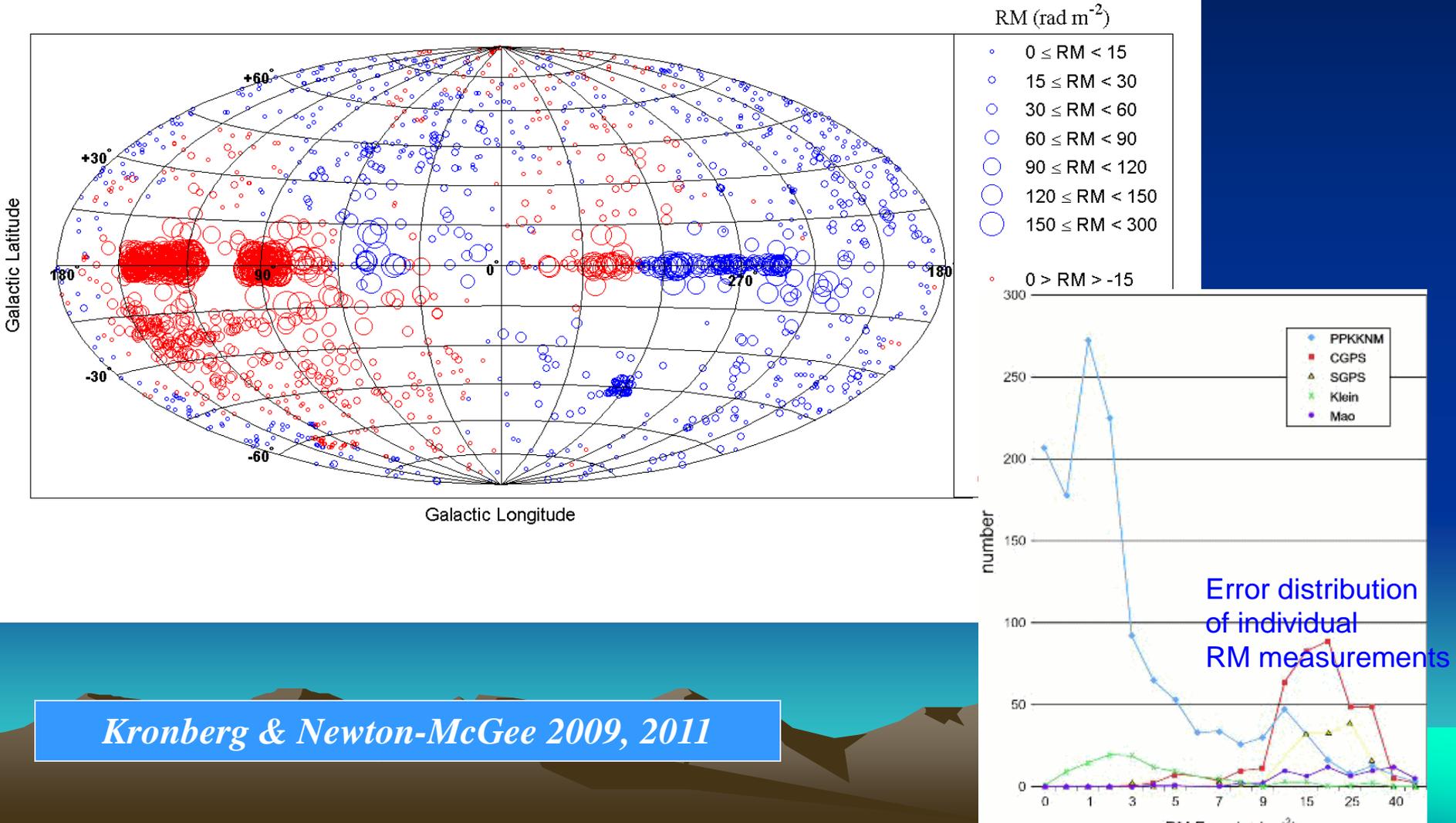
Simard-Normandin & Kronberg
ApJ 242, 74, 1980

1. Bisymmetric field pattern
2. Off-plane angular autocorrelation scale of RM sign $\approx 30^\circ$
3. Magneto-ionic scale height $\approx 1.8 \text{ kpc}$
4. (Still mysterious) off-plane, high-RM zone at $l \sim 100^\circ, b \sim -25^\circ$ (region “A”)
5. Spiral with -15° (from tangential) pitch angle (*now* -5°)

Updated RM probe of the Milky Way disk

New evidence

New smoothed Galactic RM sky from 2250 egrs RM's



Kronberg & Newton-McGee 2009, 2011

Inside the plane of the Milky way disk:

a view between $b \pm 4^\circ$

A segment of the Canadian Galactic Plane survey (CGPS) at 1.4 GHz



MW disc results – quick summary

P.P. Kronberg & K. J. Newton-McGee, 2011

Pub. Astr. Soc. Australia 28, 171-176

1. RM smoothing resolution is comparable with (1) the galactic z -height (~ 1.5 kpc), and (2) inter-arm spacing ($\sim 1 - 2$ kpc).
Smaller-scale B reversals are averaged out.
(may be unimportant for most VHECR propagation on larger scales)
2. *Spiral pitch angle is $-5.5 \pm 2^\circ$. Similar to recent Han et al RM result, and Heiles (1996), based on local interstellar polarization data (indep. of RM's).*
(note: all this is confirmed only on our side of MW disk, Where CR deflections are mostly registered).
3. *Average B aligns closely with the stellar spiral structure –like many other nearby spirals*
4. *To an extragalactic observer, magnetic Milky Way is a highly patterned, “grand design” spiral galaxy, similar to M51, etc. –look at the forest, not the trees*

B in the galactic Halo?

*Mao , S.A., Gaensler, B. M., Haverkorn, M., Zweibel, E.G.,
Madsen, G. J., McClure-Griffiths, N. M., Shukurov, A.,
Kronberg, P. P. ApJ **714**, 1170, 2010*

In the NGH: median RM = 0 ± 0.5 rad/m²

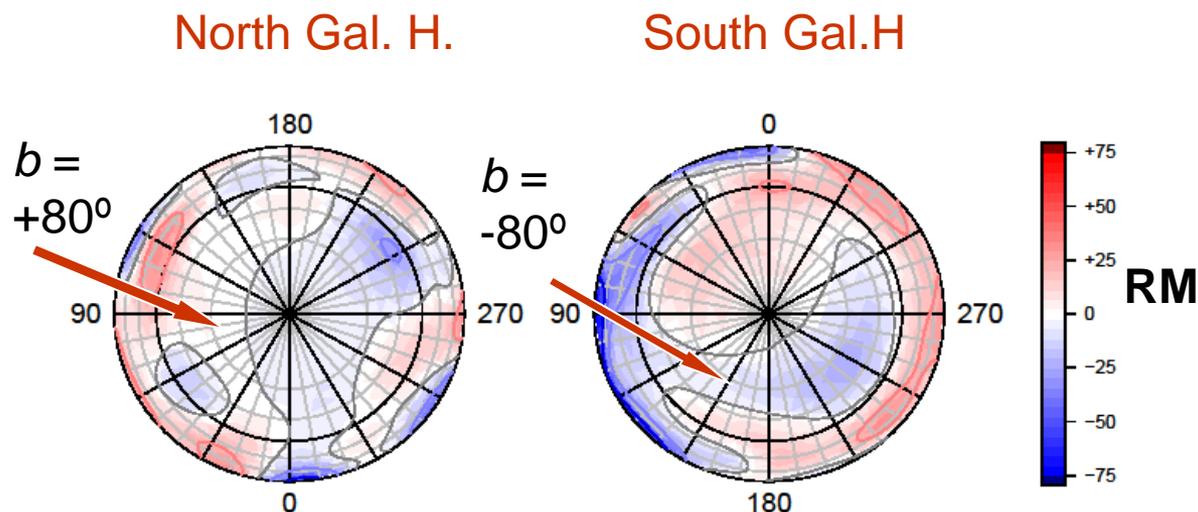
In the SGH: median RM = $+6.3 \pm 0.7$ rad/m²

$\sigma = 9$ rad/m² indep. of angular scale up to 25° -> $\sigma_B \sim 1\mu\text{G}$



Bayesian smoothed RM's in the Galactic caps $|b| > 30^\circ$ (a different analysis method)

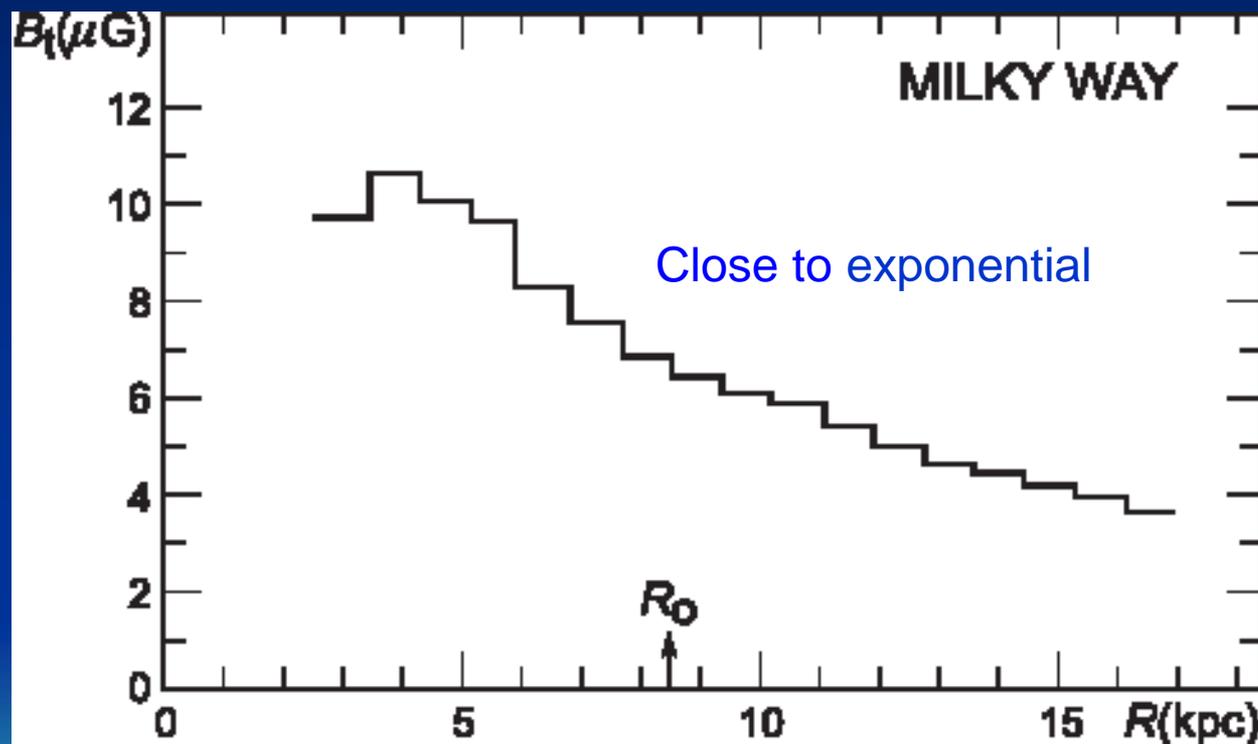
M.B. Short, D.M. Higdon & P.P. Kronberg
Bayesian Analysis 2, 665, 2007



Better data and more refined analysis are underway

$|B|(R)$ in the outer Milky Way disk – does it merge with the intergalactic medium?

Galactic disk field $\langle |B| \rangle$ vs R , modelled from all-sky continuum radiation at 0.4GHz (Haslam *et al.*) and 1.4 GHz (Reich *et al.*)



$\sim 10^{-8}\text{G?}$ at $r=100\text{kpc}$

(*E.M Berkhuijsen, W. Reich 2005, 2009*)

LSS out to ≈ 110 Mpc

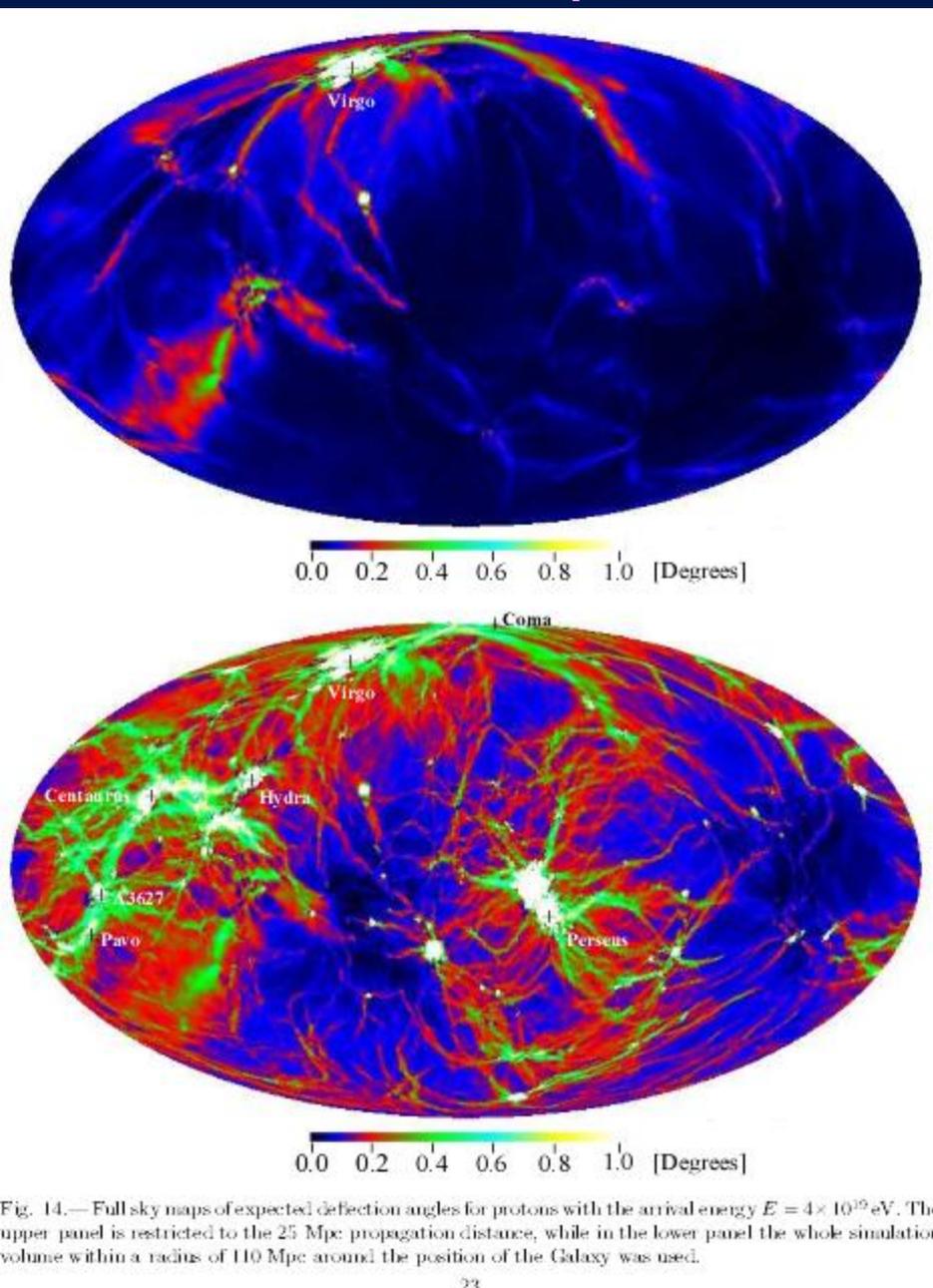


Fig. 14.— Full sky maps of expected deflection angles for protons with the arrival energy $E = 4 \times 10^{19}$ eV. The upper panel is restricted to the 25 Mpc propagation distance, while in the lower panel the whole simulation volume within a radius of 110 Mpc around the position of the Galaxy was used.

B_{IGM} in the local Universe and UHECR propagation

*K. Dolag, D. Grasso, V. Springel
& I. Tkachev*

J. Cosm. & Astroph. Phys. 1:009, 2005

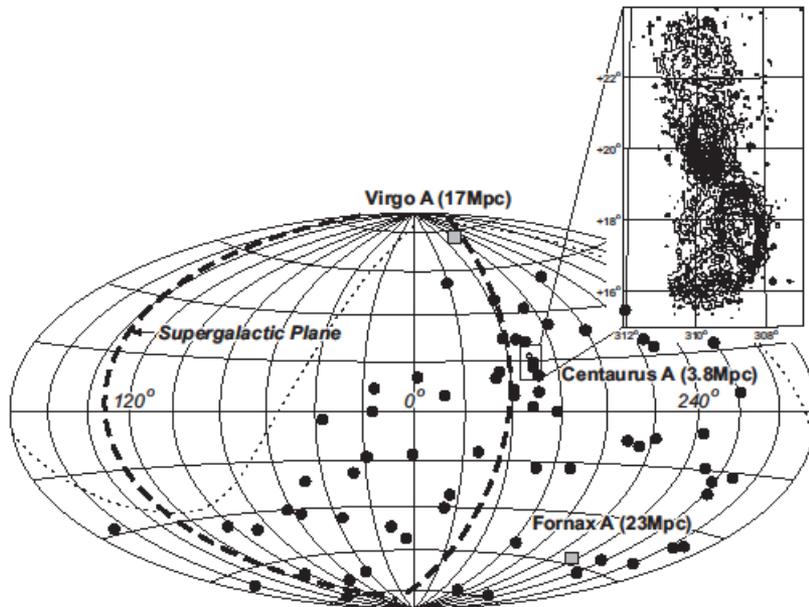
- Seed field at high redshift
- $|B|$ growth driven by LSS formation (gravity)
- MHD field amplification
- $\lesssim 10^{-12}$ G (voids) – few $\times 10^{-6}$ G (Clusters)

CENTAURUS A??

69 events above $6 \times 10^{19} \text{eV}$
detected by the
Auger collaboration

Inset:
Centaurus A at 3.8 Mpc

*N. Junkes et al. A&A, 269, 29,
2003
and
Patricia Reich (priv. comm.)*



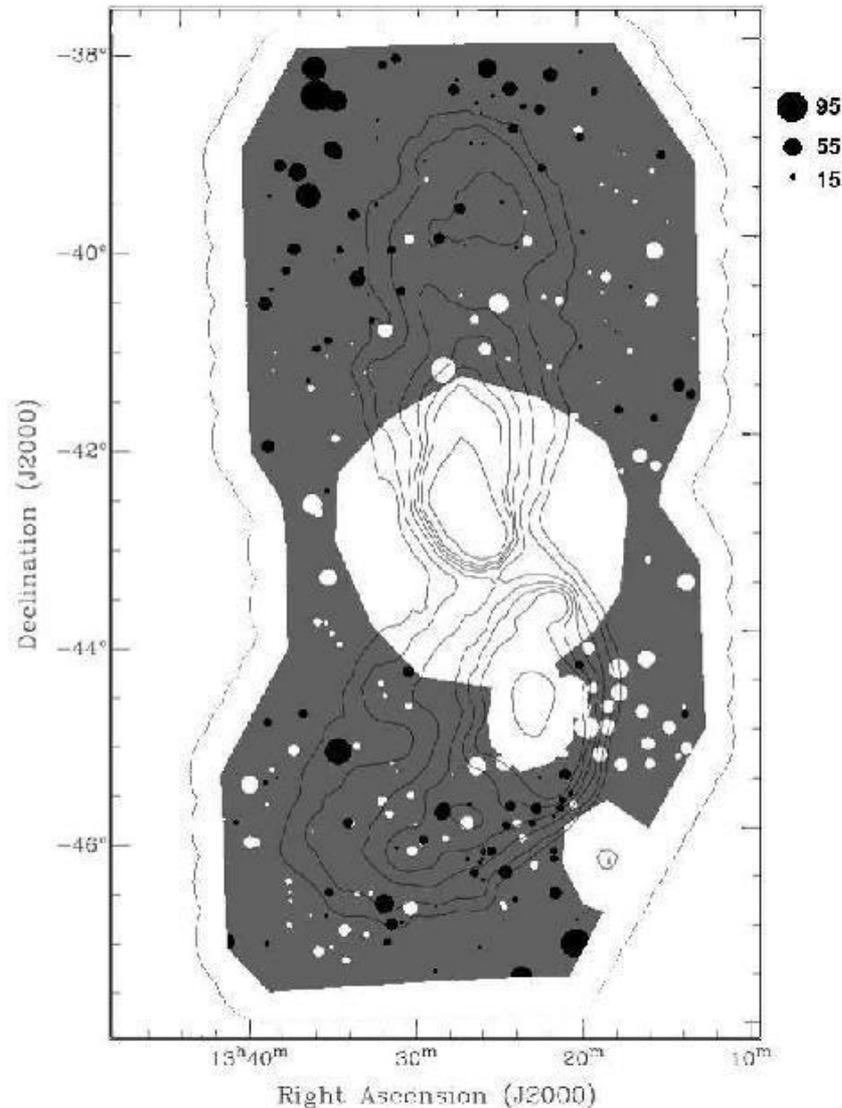


FIG. 7.— Locations and RMs of the 281 sources in Table 3. To better highlight the variations, the diameter of the sources represent the amplitude of their residual RM after the mean RM of the whole distribution (-57 rad m^{-2}) has been subtracted. Black and white sources are those with positive and negative residuals from the mean, respectively. Overlaid are Parkes 1.4 GHz radio continuum contours of Centaurus A. Contour levels are 1.5, 2, 3, 4, 5, 6, 10, 100 Jy beam^{-1} . The legend on the right hand side of the figure shows the relation between the source diameter and the absolute value of the mean-subtracted RM in units of rad m^{-2} .

Does the environment of Centaurus A itself perturb Faraday Rotation Measures?

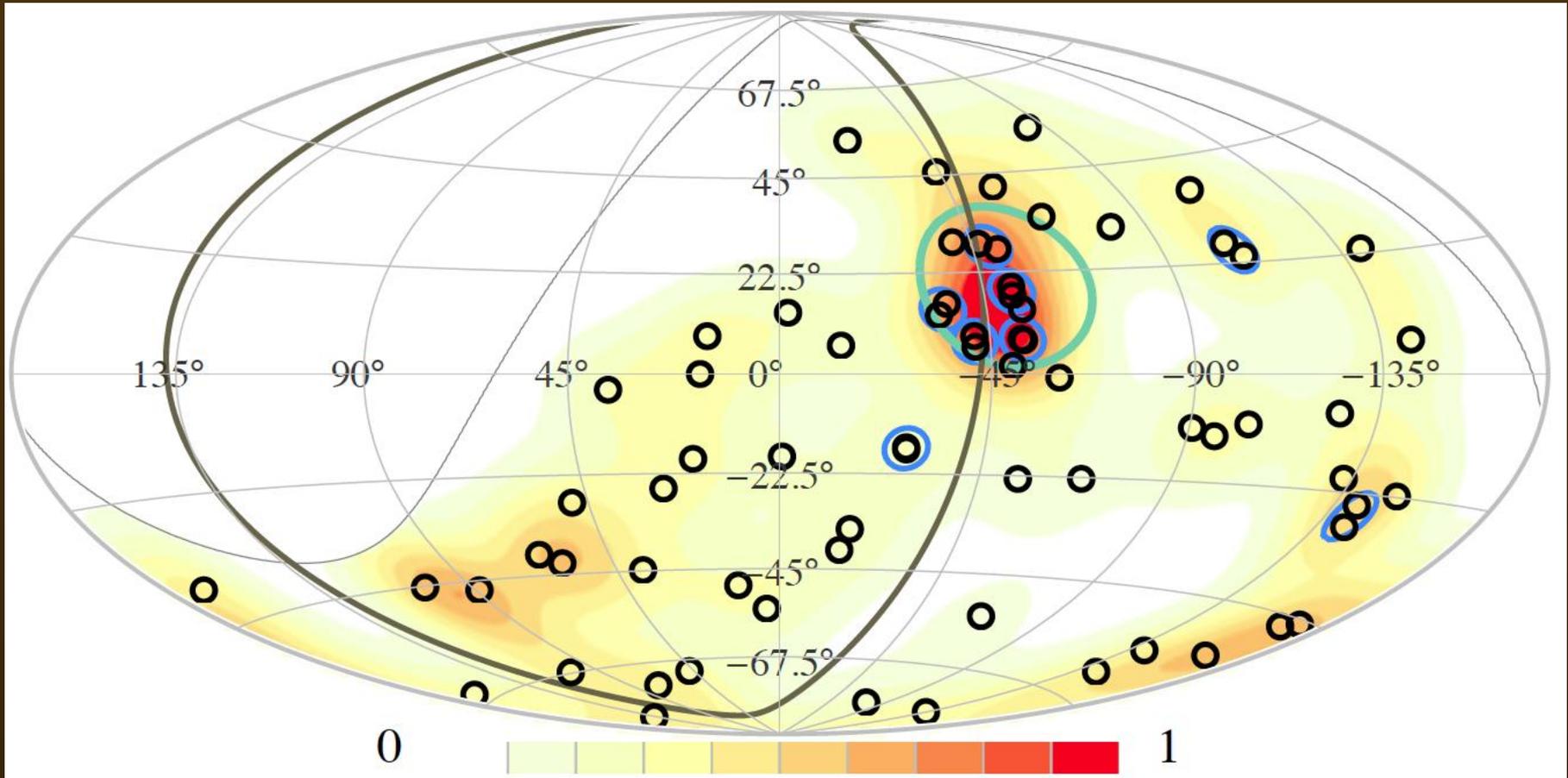
(3.8 Mpc distance)

RM Image:

Feain, I., J. Ekers, R.D.,
 Murphy, T., Gaensler, B.M.,
 Marquart, J-P, Norris, R.P.,
 Cornwell, T.J., Johnson-Hollitt, M.,
 J. Ott, & Middelberg, E.

ApJ 707,114, 2009

- Arrival directions of the same **69** Auger UHECR events (black circles), in (l,b) .
 - Blue circles show event pairs within 5°
 - 18° degree circle shown around Centaurus A.
 - Coloured shading \rightarrow The smoothed angular density distribution of events
- *Yüksel et al ApJ Aug. 2012.*



Deflection of UHE CR trajectories through the local universe

$$\theta \simeq 8^\circ Z \left(\frac{l}{10 \text{ Mpc}} \right)^{0.5} \left(\frac{l_0}{1 \text{ Mpc}} \right)^{0.5} \left(\frac{E}{10^{20} \text{ eV}} \right)^{-1} \left(\frac{B}{10^{-8} \text{ G}} \right)$$

Sigl et al. Phys Rev. D 043002, 2003

Sample calculation relevant to Centaurus A ($l_0 < l$):

For protons ($Z = 1$), $l = 3.8 \text{ Mpc}$, $l_0 = 300 \text{ kpc}$, $E = 10^{20} \text{ eV}$, $B = 10^{-7} \text{ G}$

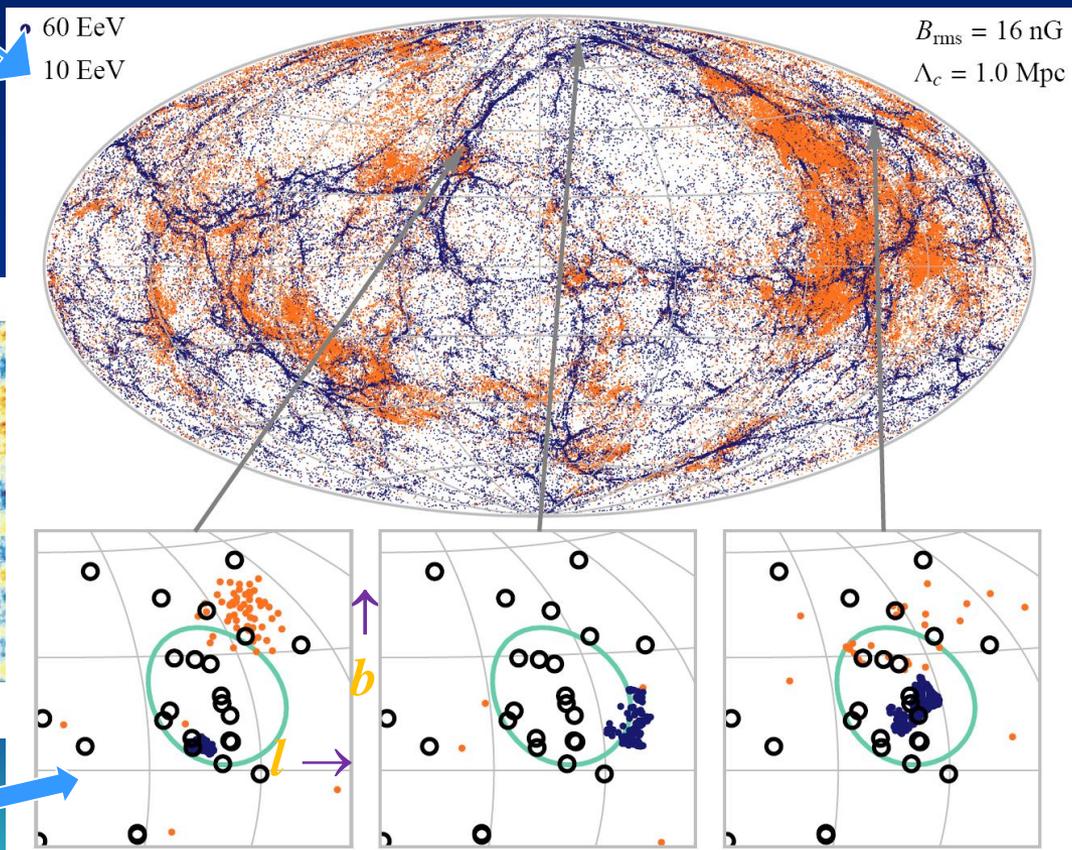
$$\theta = 3.4^\circ$$

Plausible distributions of CR's for selected extragalactic magnetic field parametrizations

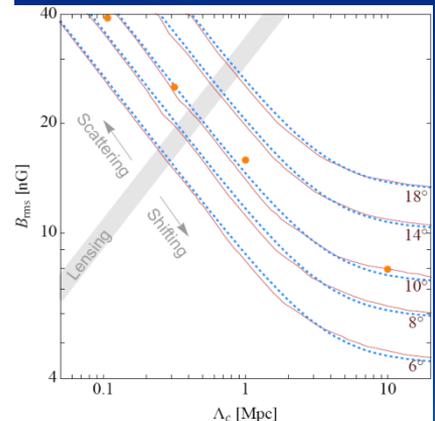
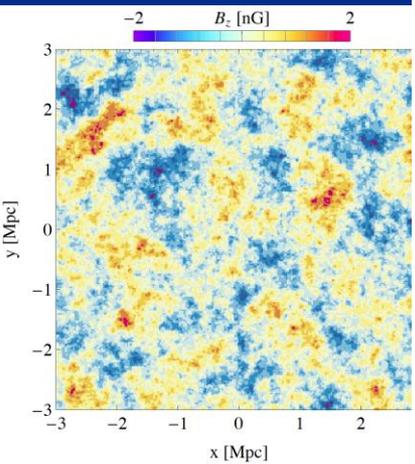
CR energies of 60 EeV (blue) and 10 EeV (orange) → next 4 slides

Top: As seen by an observer located at Cen A, Final positions of particles at 3.8 Mpc from Cen A (100,000 particles are shown for each energy)

ASSUMES PROTONS ONLY



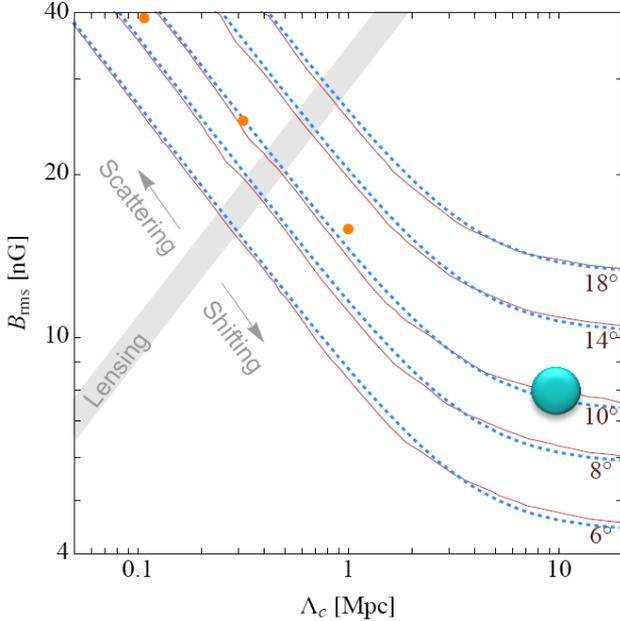
2-D slice of 3-D Kolmogorov
 $l_{max}=2\text{Mpc}$, $l_{min}=0.04\text{Mpc}$



Bottom: As seen from Earth, three realizations of UHECR angular distributions arriving from Cen (ASSUMED an ISOTROPIC EMITTER) chosen from the 3 locations above

H.Yüksel, T. Stanev, M. Kistler, & P. Kronberg Astrophys J accepted August 2012

H. Yüksel, T. Stanev, M. Kistler, P. Kronberg
Astrophys J. Aug 2012

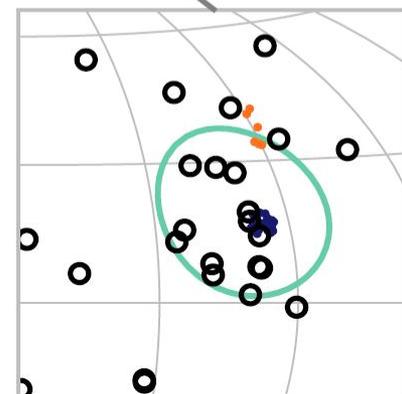
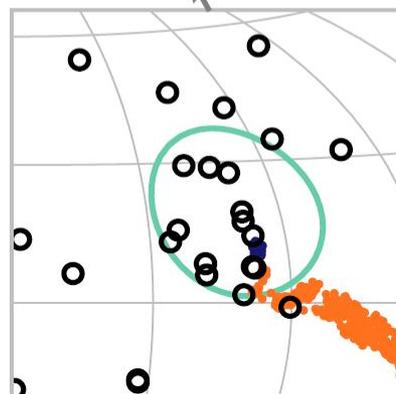
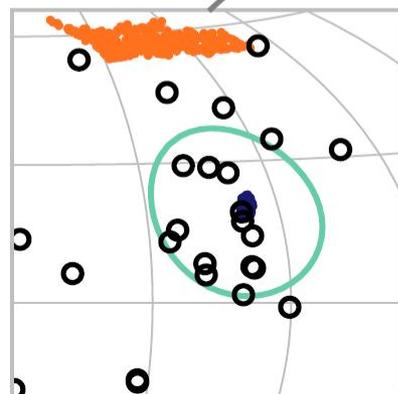
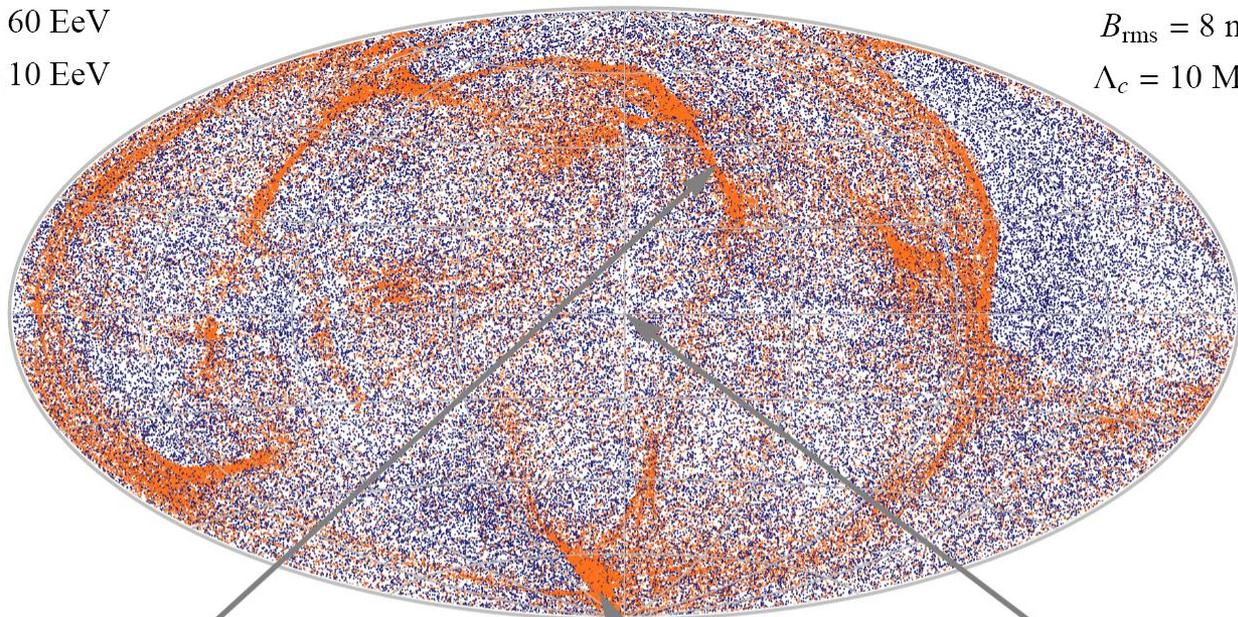


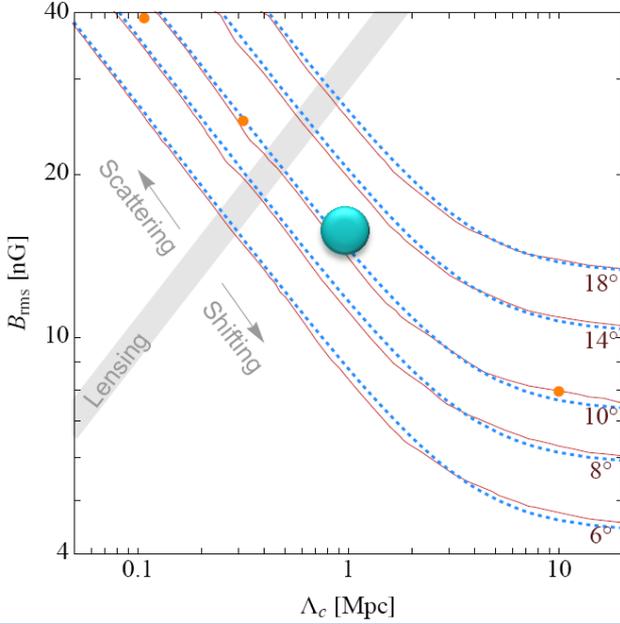
fixed

- 60 EeV
- 10 EeV

variable

$B_{\text{rms}} = 8$ nG
 $\Lambda_c = 10$ Mpc





Fixed

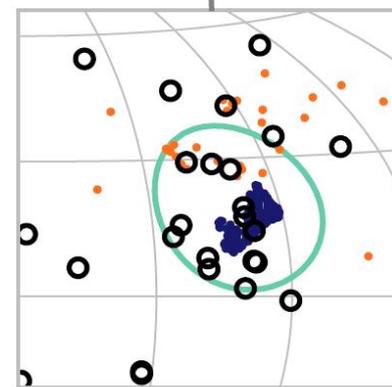
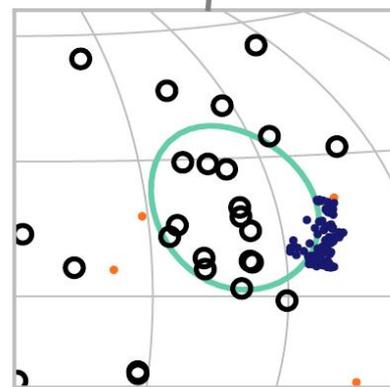
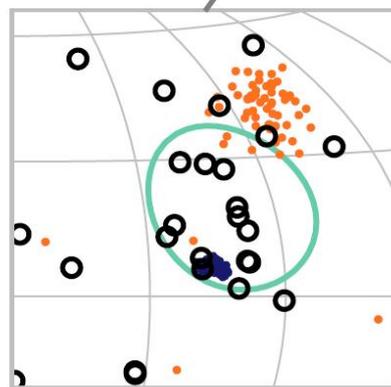
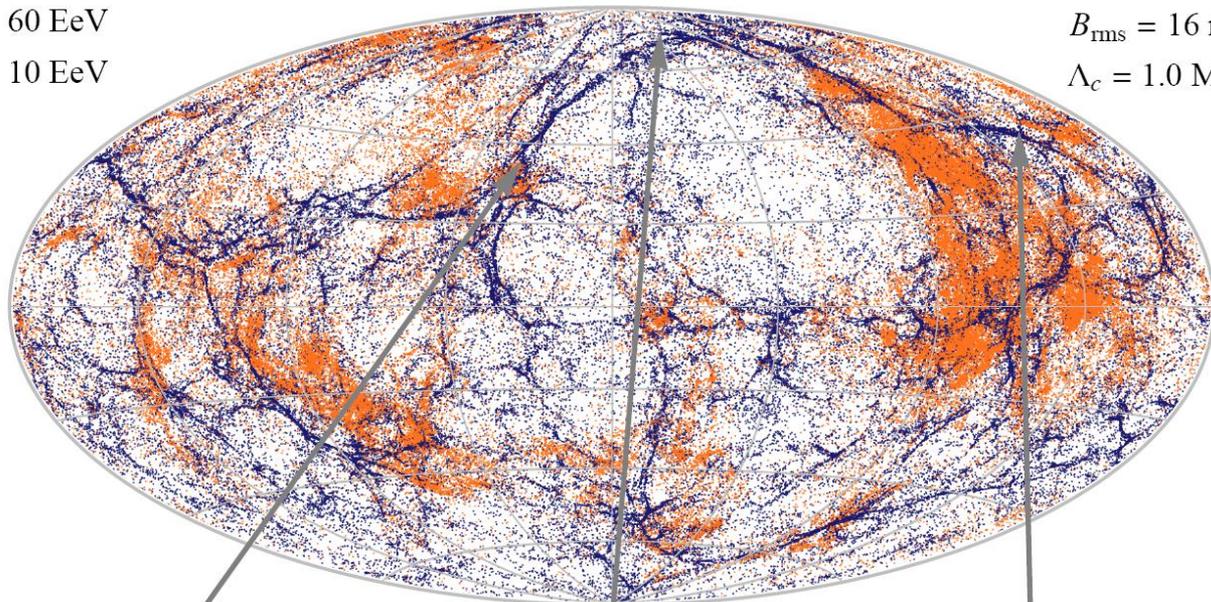


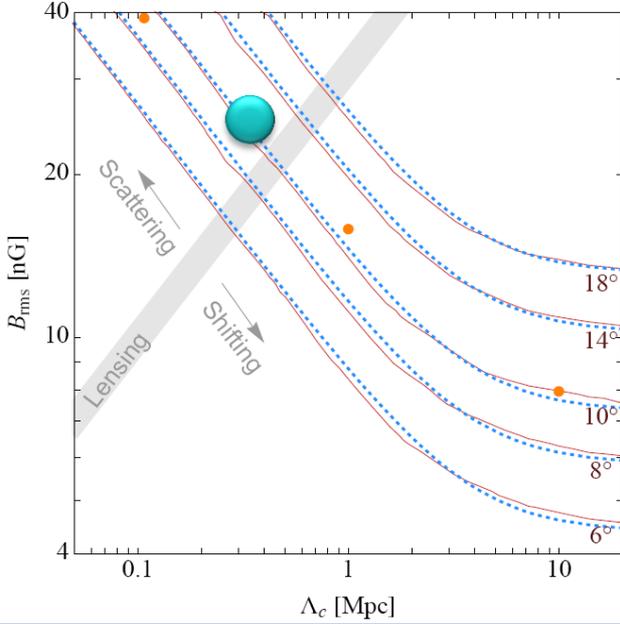
- 60 EeV
- 10 EeV

variable

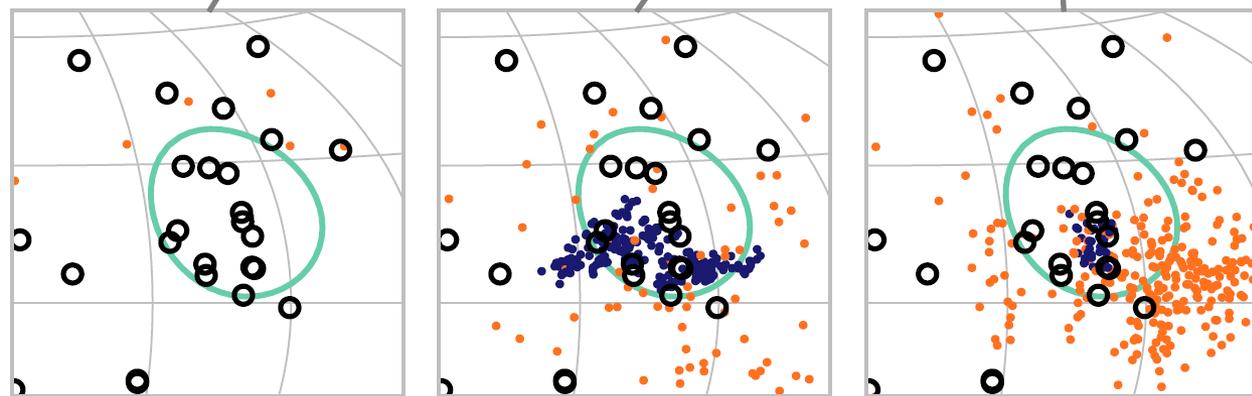
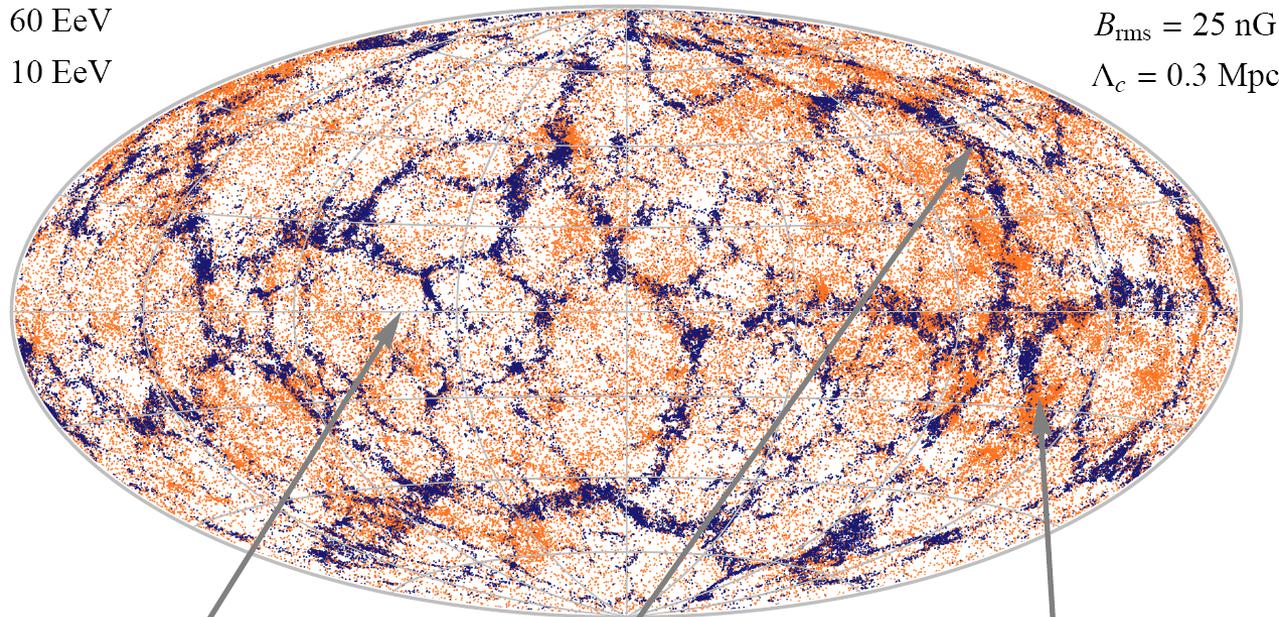


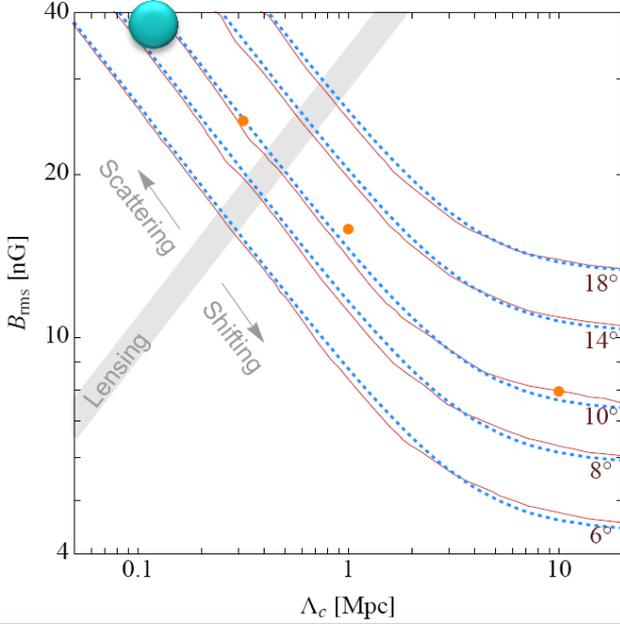
- $B_{\text{rms}} = 16$ nG
- $\Lambda_c = 1.0$ Mpc



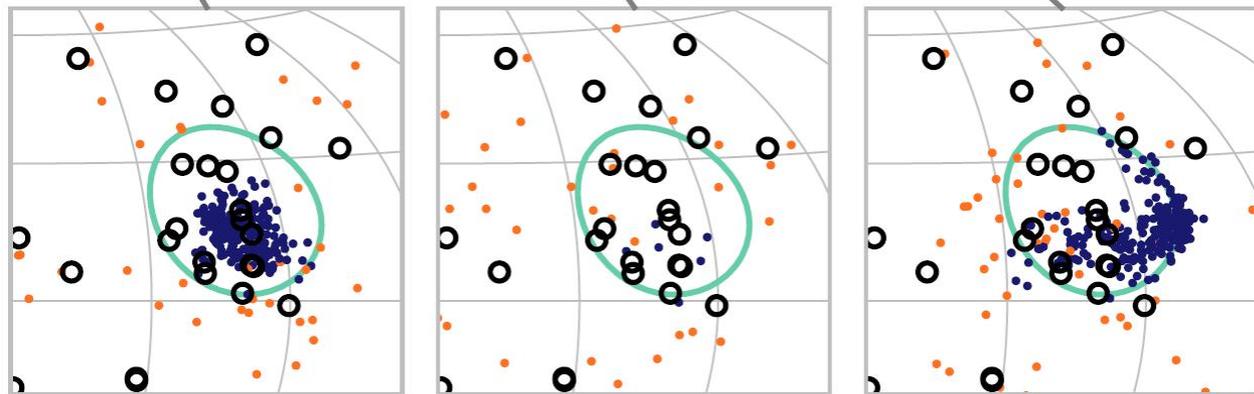


- 60 EeV
- 10 EeV

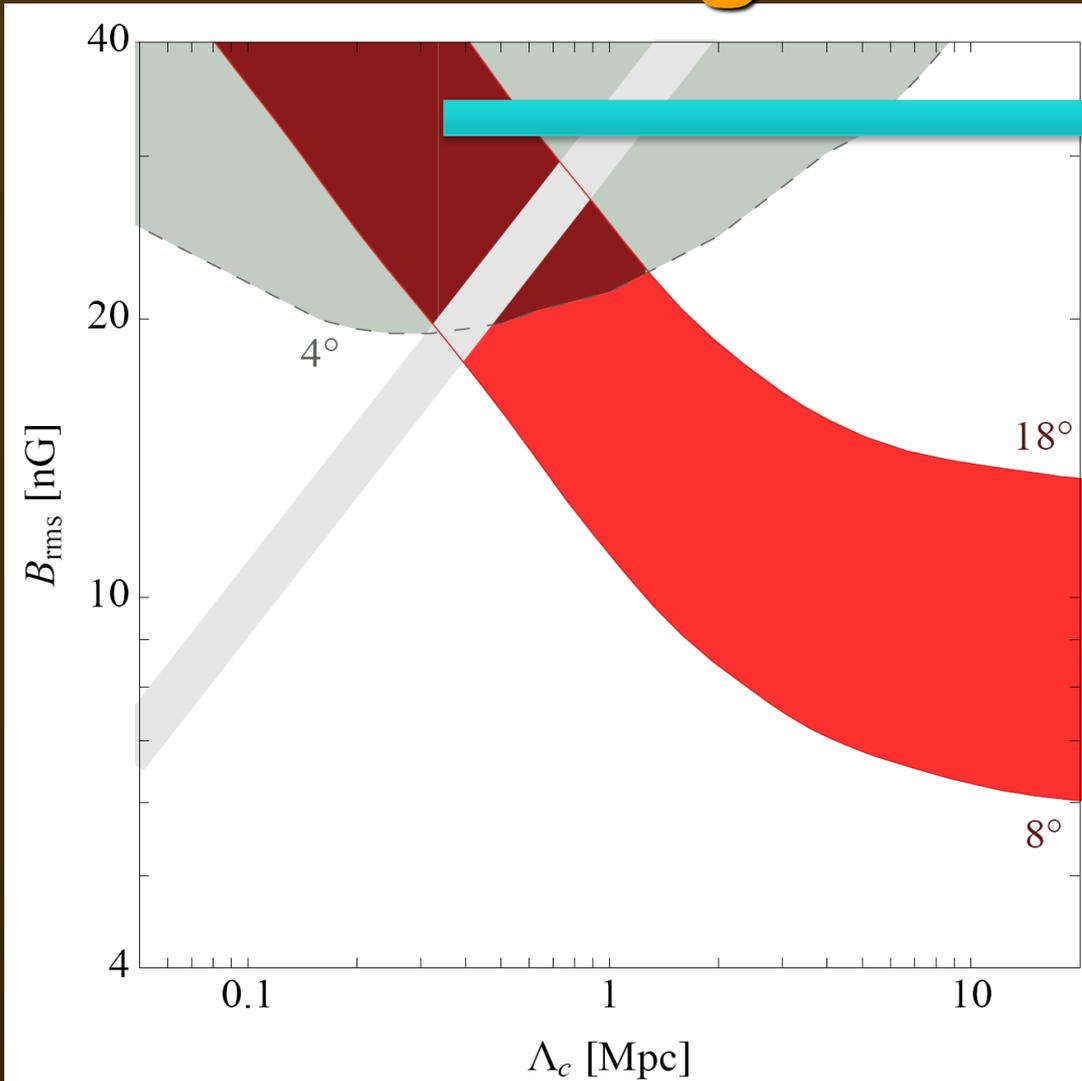




- 60 EeV
- 10 EeV



What is the Local Intergalactic Magnetic Field?



Inferred range of extragalactic magnetic field parameters is compatible with:

1. the average angular distribution of 8-18 degrees from Cen A (solid lines)
2. the spread of events among themselves being less than 4° (dashed line)

Condition 2 implies events are not much shifted from the source position.

VHECR / UHECR
acceleration in
electromagnetically powered jet and lobes of
e.g.r.s. with central SMBH's

Seems inevitable,
(though not the only candidate site)



A straightforward electrical circuit analogue for BH energy transfer into ``empty'' space

P.P. Kronberg, R.V.E. Lovelace, G. Lapenta & S.A. Colgate ApJL 2011 Electric current (I) on kpc + scales 7-41, L15 2011

R.V.E. Lovelace & P.P. Kronberg, MNRAS April 2013 Jets as transmission lines

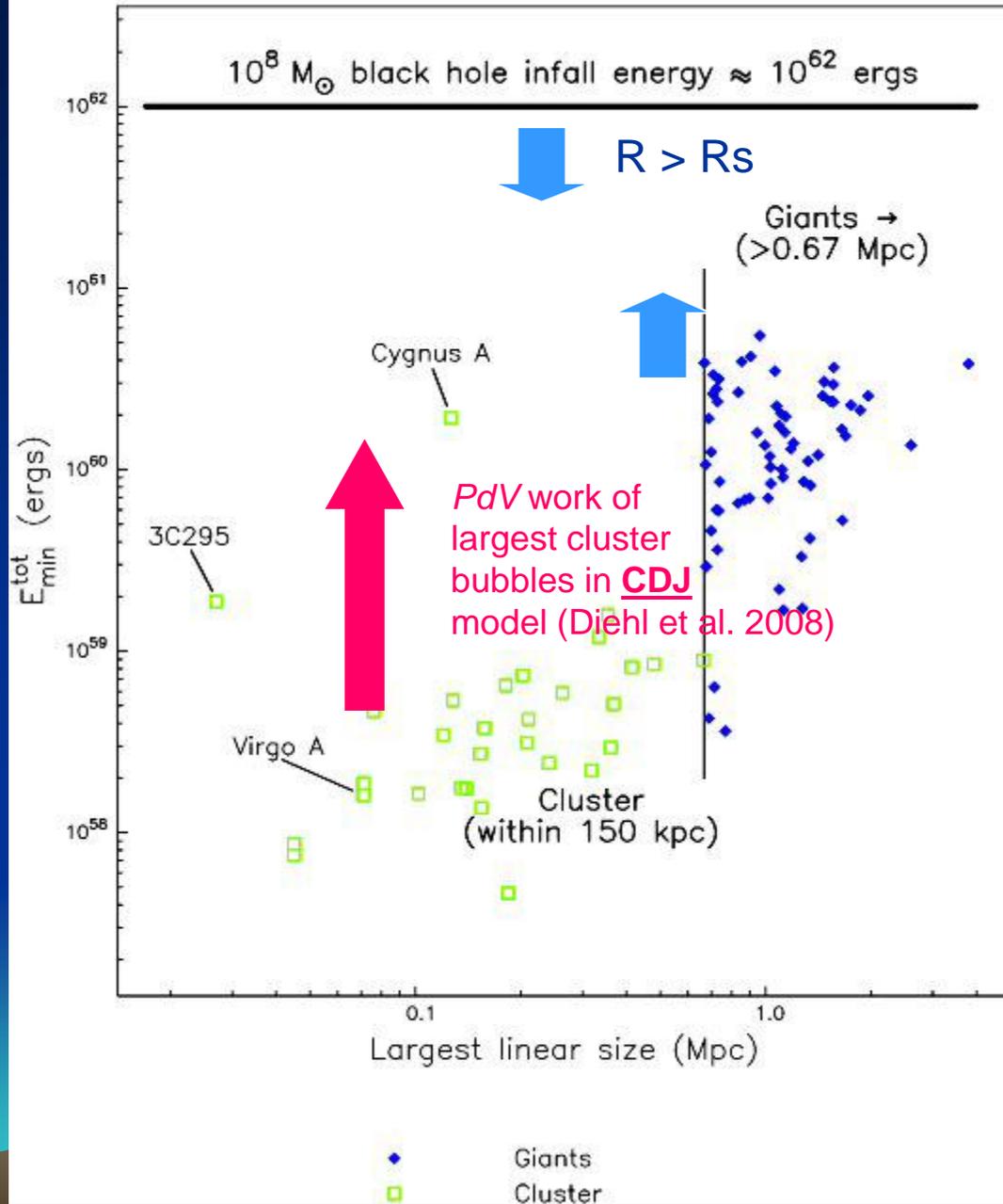
- *Low thermal density around knots confirms dominance of a Poynting flux*
- $P \sim 10^{37}$ watts of directed e.m. power, and $I = 3.3 \times 10^{18}$ ampères of axial current.
Sign of ∇RM gives I direction – in the case of 3C303, away from the BH
- **POYNTING jet's electrical properties: (voltage, impedance, current):**

$$I_0 = cr_2 B_{\phi(r_2)} = \frac{V_0}{Z_0} \approx 3 \times 10^{18} \text{ Amps (MKS)}$$

$$Z_0 = \frac{3}{c} \beta \text{ (cgs)} = 90 \beta \text{ Ohms (MKS)}$$

$$V_0 = \frac{r_0 B_0}{3^{1/4} \sqrt{R}} = 2.7 \times 10^{20} \text{ Volts (MKS)}$$

$\beta = \frac{U}{c} \lesssim 1$, where r_1, r_2 are the inner & outer transmission line radii (Lovelace & Ruchi, 1983)



ENERGETICS

$\rightarrow =M_{\text{BH}}c^2$
and calorimetry of large radio lobes:

Mind the gap!!

Accumulated energy
 $(B^2/8\pi + \epsilon_{\text{CR}}) \times (\text{volume})$
 from "mature" BH-powered
 radio source lobes

Giant Radio Galaxies
 capture the highest fraction
 of the magnetic energy
 released to the IGM

*Kronberg, Dufton, Li, & Colgate,
 ApJ 560, 178, 2001*

