A new analysis method for high energy CR hadron arrival directions

Philipp P. Kronberg

Dept of Physics, University of Toronto,

and

T2 Division, LANL

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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 ~ 4Mpc, 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 $\gtrsim$ 20nG out to D ~ 4Mpc, based on recent AUGER data.

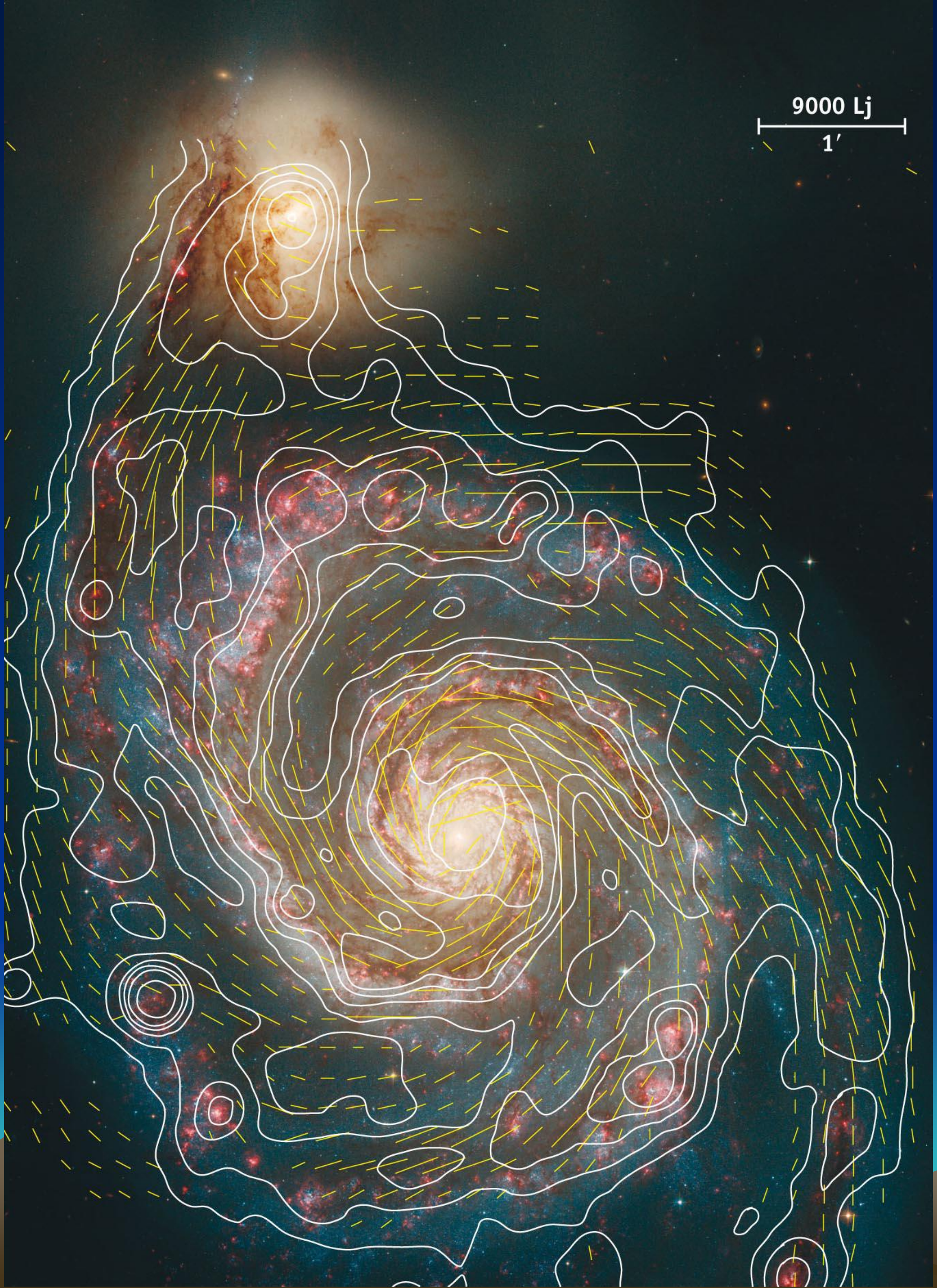
This is "new territory" for IGM magnetic field probes, and also the first VHECR sky-based probe of B_{IGM} on supra-galactic scales. It is a potentially powerful template for the understanding, and future modeling of VHECR/UHECR propagation at greater distances.

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

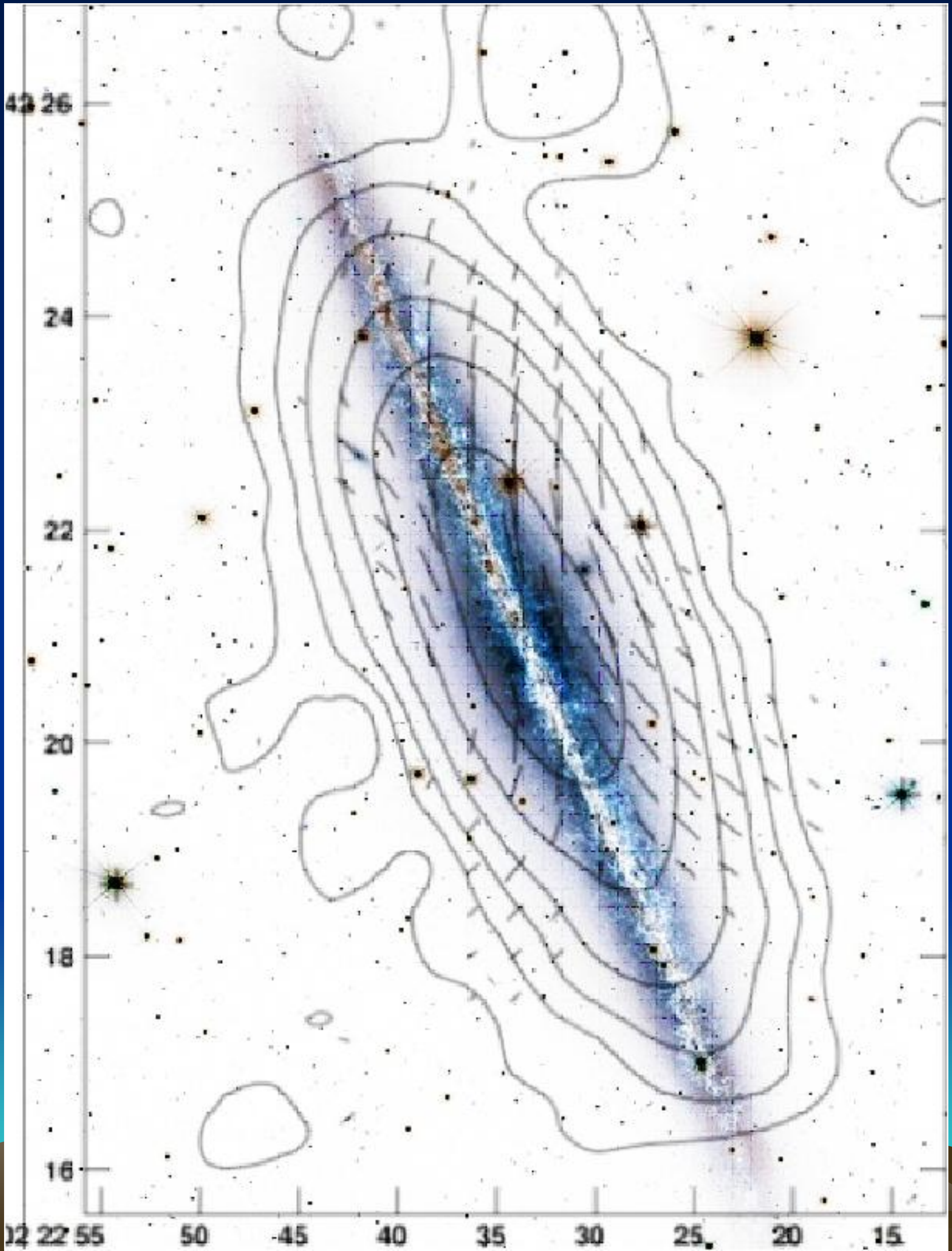
Projected Magnetic field
In a "grand design" galaxy

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, $\boldsymbol{l}$,$\boldsymbol{b}$)

1
The Milky Way field structure

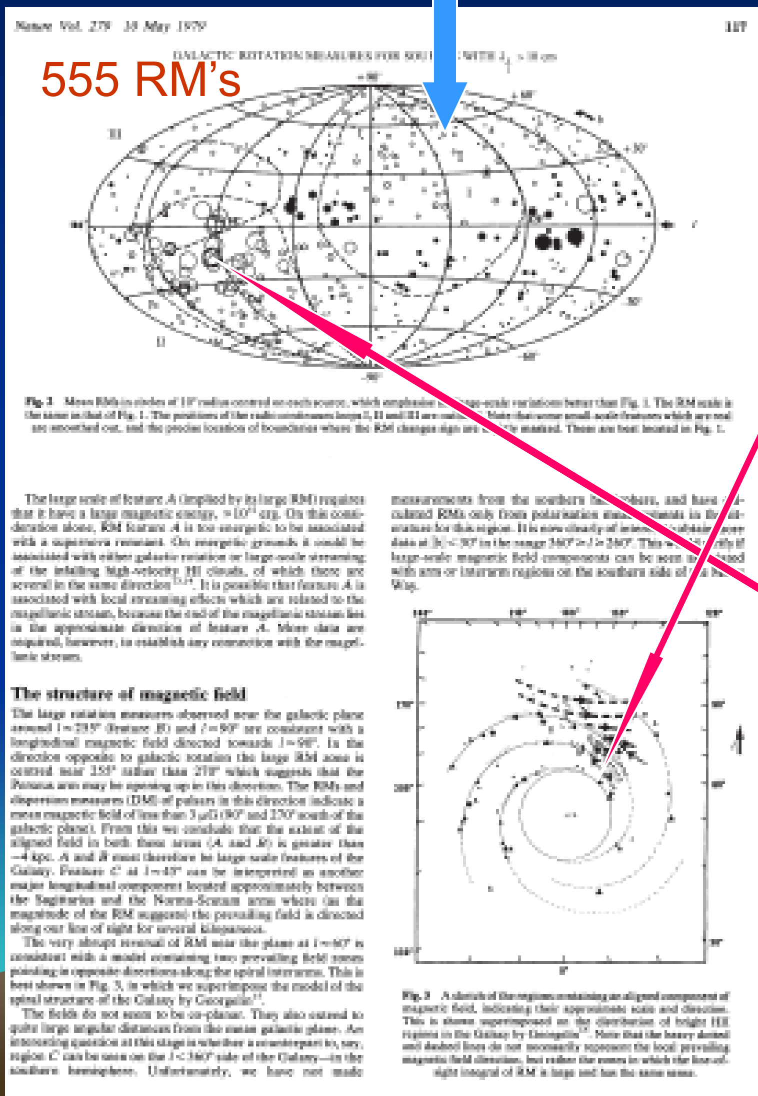
Begin with Simard-Normandin & Kronberg

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, *<u>Nature</u>*, ***279***, *115,1979*.



<u>Summary of conclusions in 1980</u>:

Simard-Normandin & Kronberg

<u>ApJ</u> ***242***, *74, 1980*

1. Bisymmetric field pattern

2. Off-plane angular <u>autocorrelation scale</u> of RM <u>sign</u> ≈ 30º

3. Magneto-ionic scale height ≈ 1.8 kpc

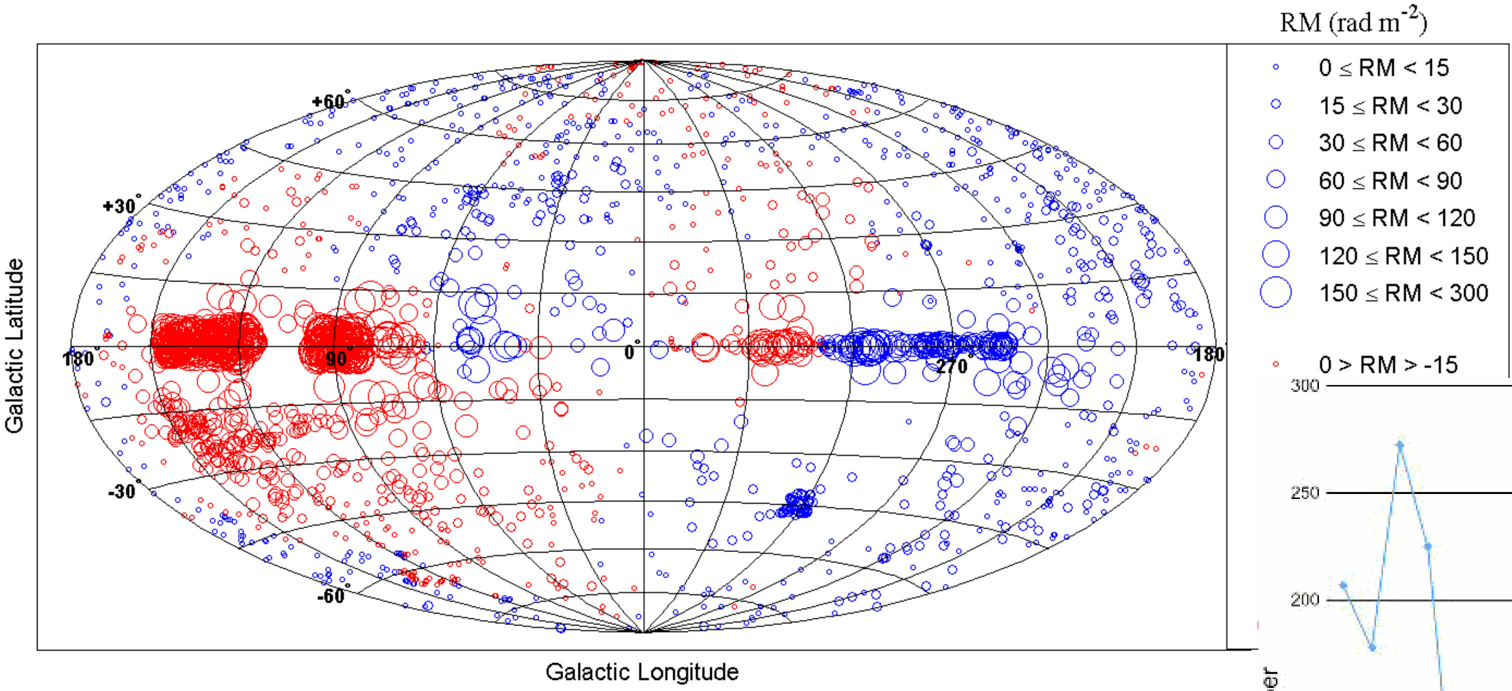
4. (Still mysterious) off-plane, high-RM zone at l ~ 100º, b ~ -25º (region "A")

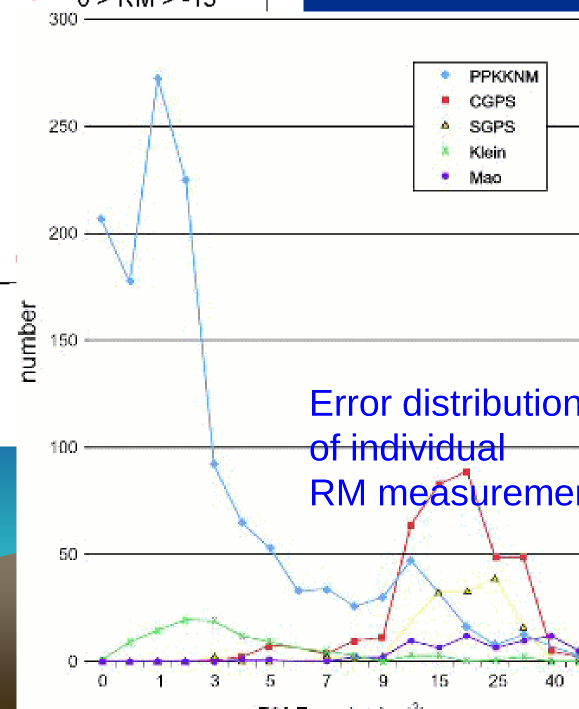
5. Spiral with -15º (from tangential) pitch angle (*now -5º*)

Updated RM probe of the Milky Way disk

New evidence

New smoothed Galactic RM sky from 2250 egrs RM's





Error distribution
of individual
RM measurements

Kronberg & Newton-McGee 2009, 2011

Inside the plane of the Milky way disk:

a view between $b \pm 4°$

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 (~ 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± 2º. 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/m^2

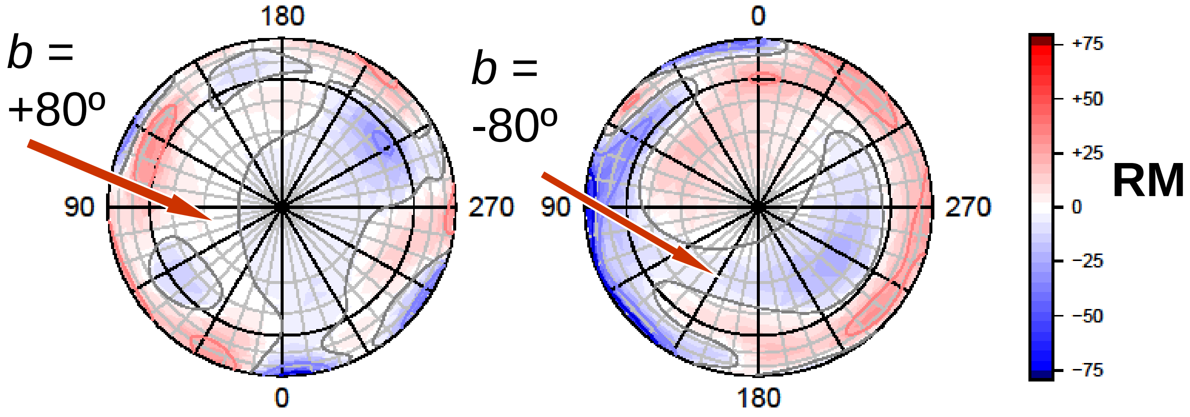
In the SGH: medium RM = $+6.3 \pm 0.7$ rad/m^2

$\sigma = 9$ rad/m^2 indep. of angular scale up to 25° -> $\sigma_B \sim 1\mu G$

Bayesian smoothed RM's in the Galactic caps |*b*|>30º
(a different analysis method)

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

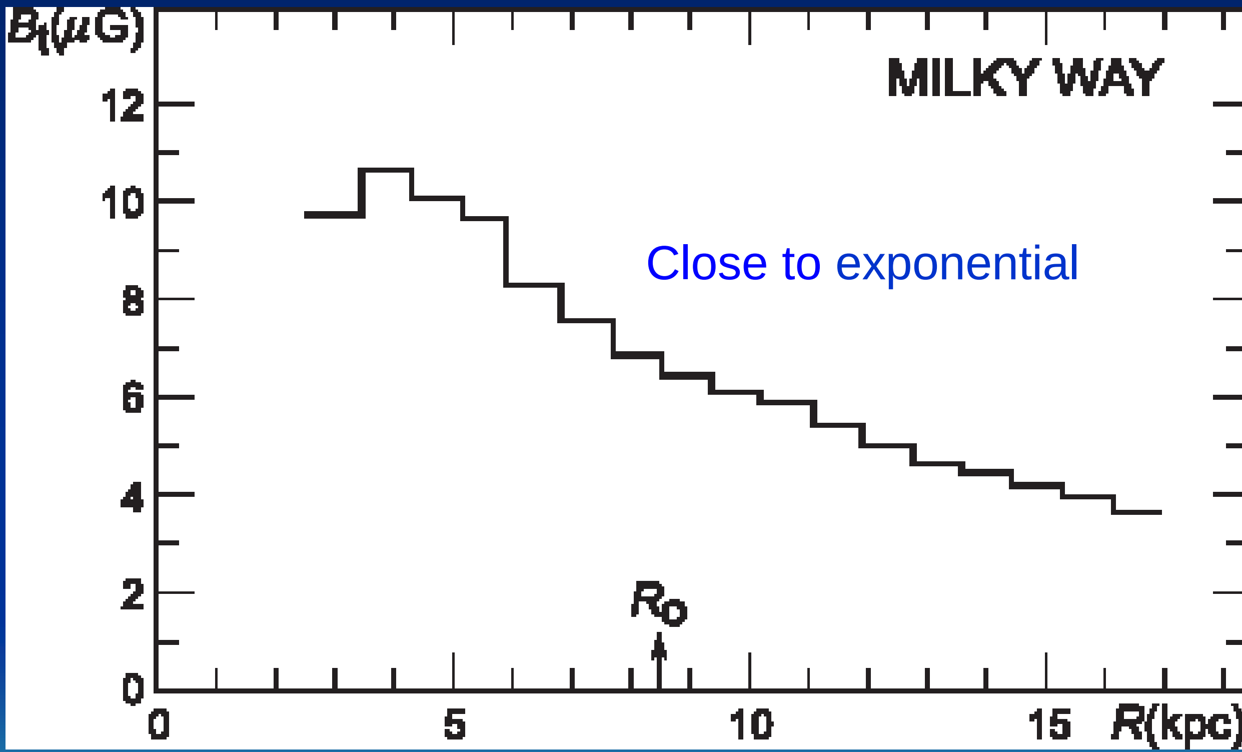
North Gal. H. South Gal.H



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 <|***B***|> vs *R*, modelled from all-sky continuum radiation at 0.4GHz (Haslam *et al*.) and 1.4 GHz (Reich et al.)



~10^{-8}G? at *r*=100kpc

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

LSS out to ≈ 110 Mpc

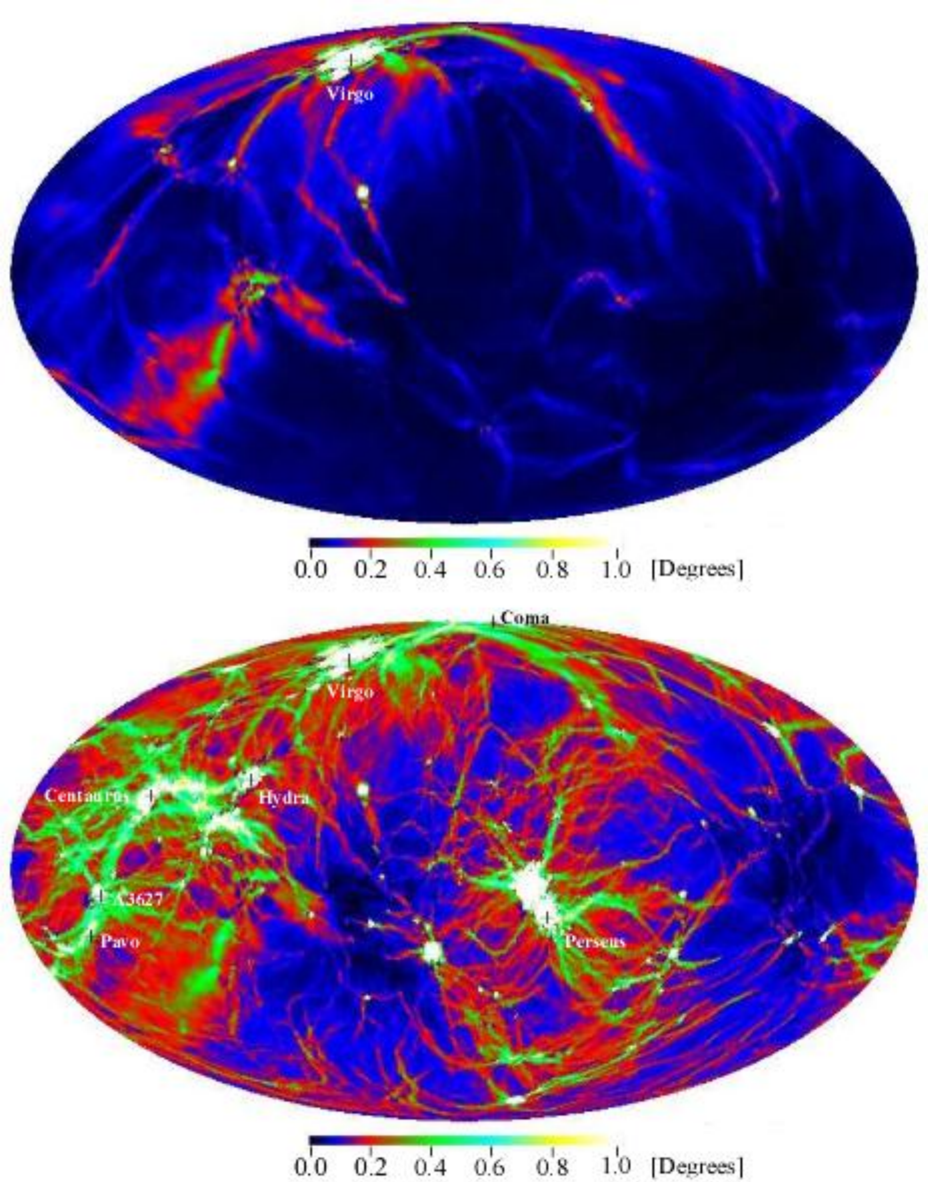


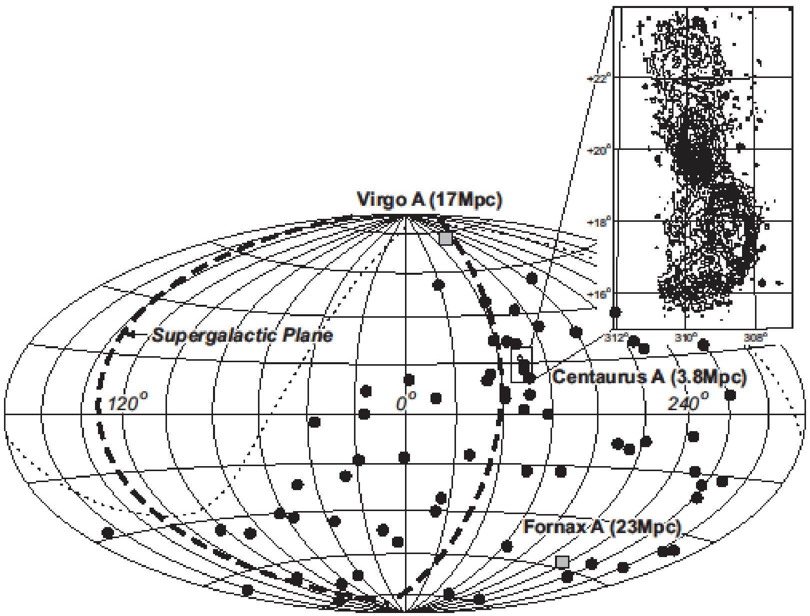
Fig. 14.—Full sky maps of expected deflection angles for protons with the arrival energy $E = 4 \times 10^{19}$ eV. The upper panel is restricted to the 25 Mpc propagation distance, while in the lower panel the whole simulation volume within a radius of 110 Mpc around the position of the Galaxy was used.

23

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 x 10^{-6} G(Clusters)



CENTAURUS A??

69 events above 6×10^{19}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.)

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

(3.8Mpc distance)

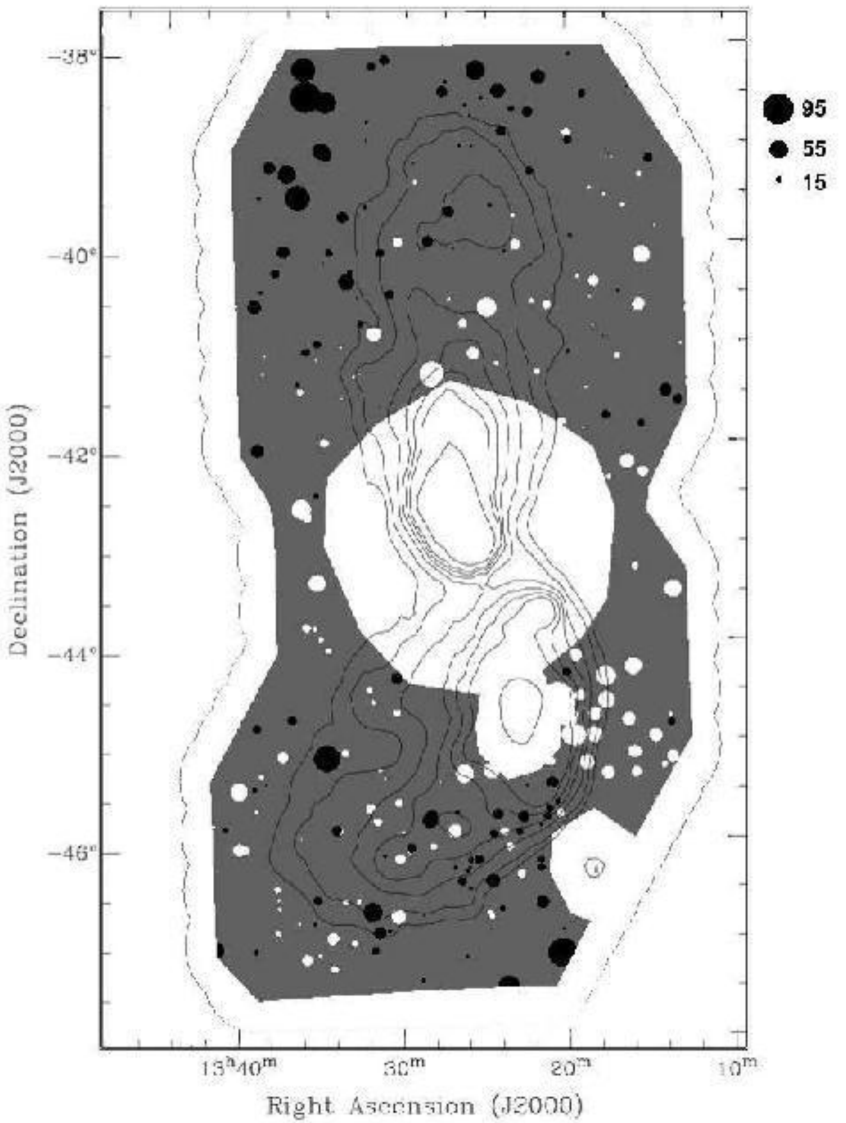


FIG. 7.— Locations and RMs of the 281 sources in Table 3. To better highlight the variations, the diameter of the sources represent the amplitude of their residual RM after the mean RM of the whole distribution (-57 rad m^{-2}) has been subtracted. Black and white sources are those with positive and 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}.

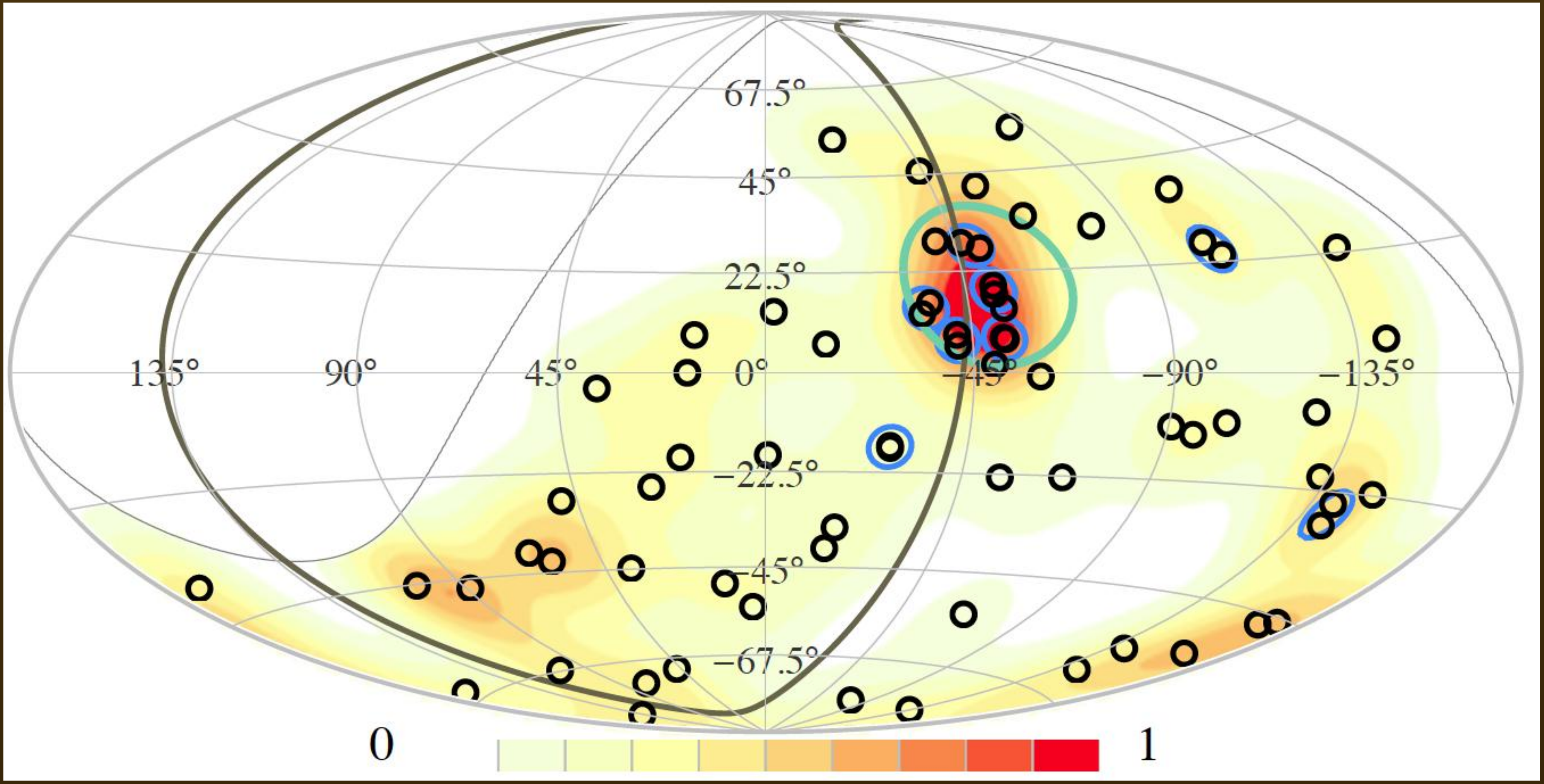
RM Image:

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

ApJ **707**,114, 2009

- Arrival directions of the same <u>**69**</u> Auger UHECR events (black circles), in (l,b).
- Blue circles show event pairs within 5°
- 18° degree circle shown around Centaurus A.
- Coloured shading → The smoothed angular density distribution of events

- *Yüksel et al ApJ Aug. 2012*.



Deflection of UHE CR trajectories through the local universe

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

Sigl et al. Phys Rev. D 043002, 2003

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

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

$\theta = 3.4^\circ$

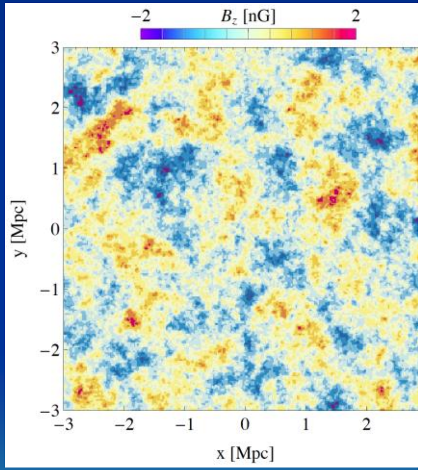
Plausible distributions of CR's for selected extragalactic magnetic field parametrizations

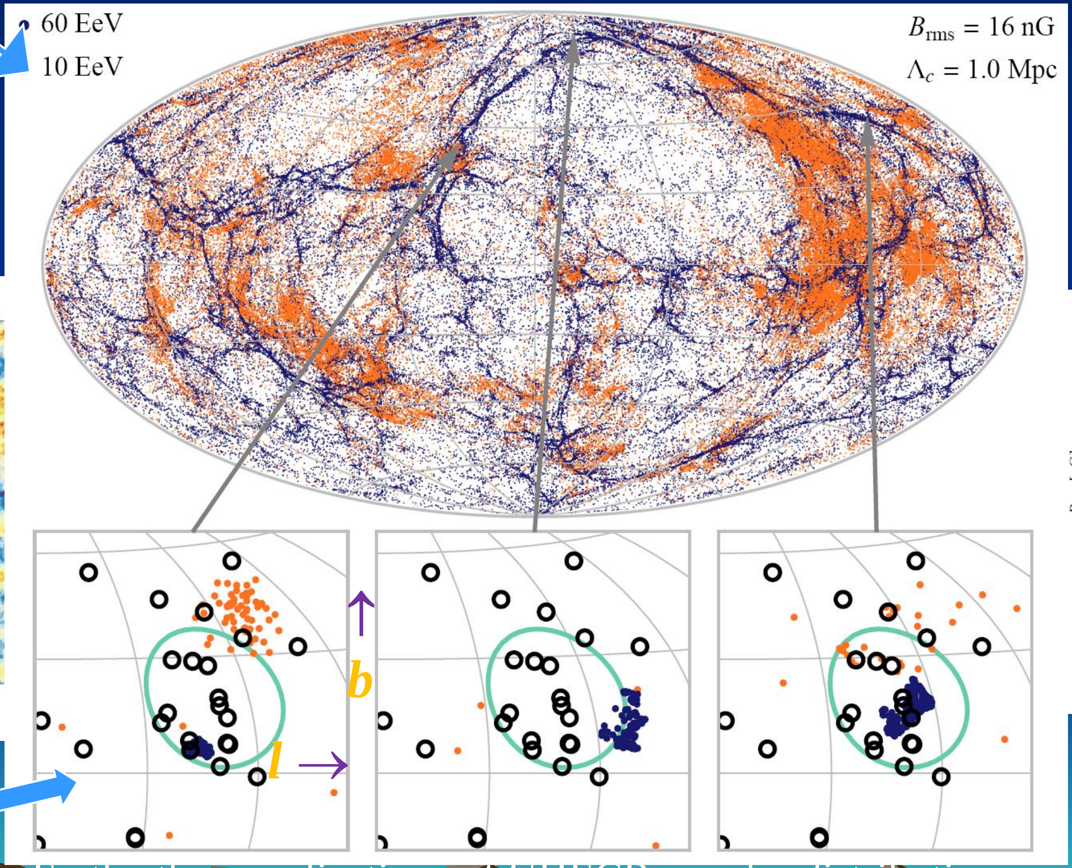
CR energies **of 60 EeV (blue) and 10 EeV (orange) → next 4 slides**

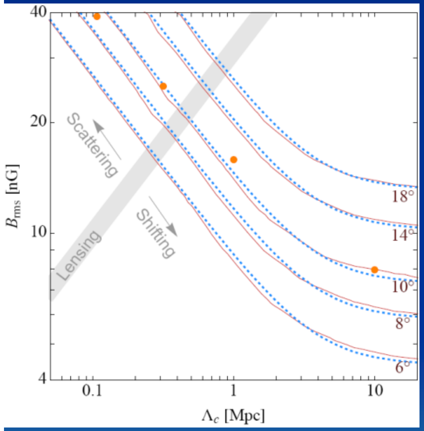
Top: As seen by an observer located at Cen A, Final positions of particles at 3.8 Mpc from Cen A (100,000 particles are shown for each energy)

ASSUMES PROTONS ONLY

2-D slice of 3-D Kolmogorov
l max=2Mpc, *l* min=0.04Mpc

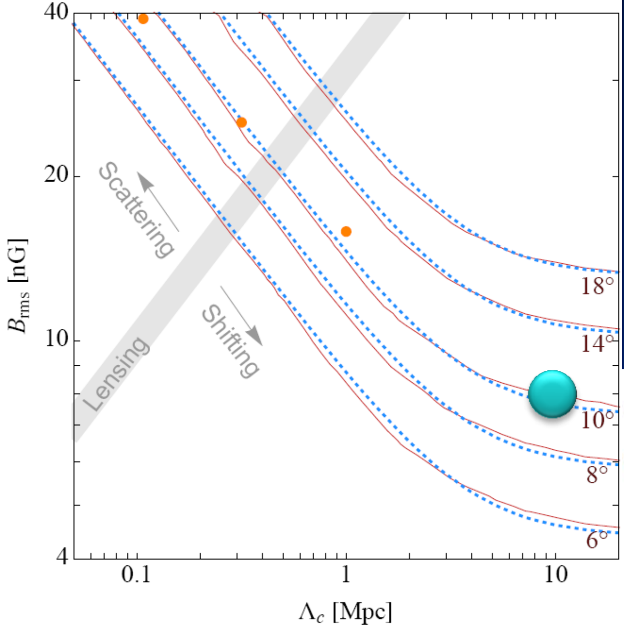






Bottom: As seen from Earth . three realizations of UHECR angular distributions arriving from Cen (ASSUMED an ISOTROPIC EMITTER) chosen from the 3 locations above

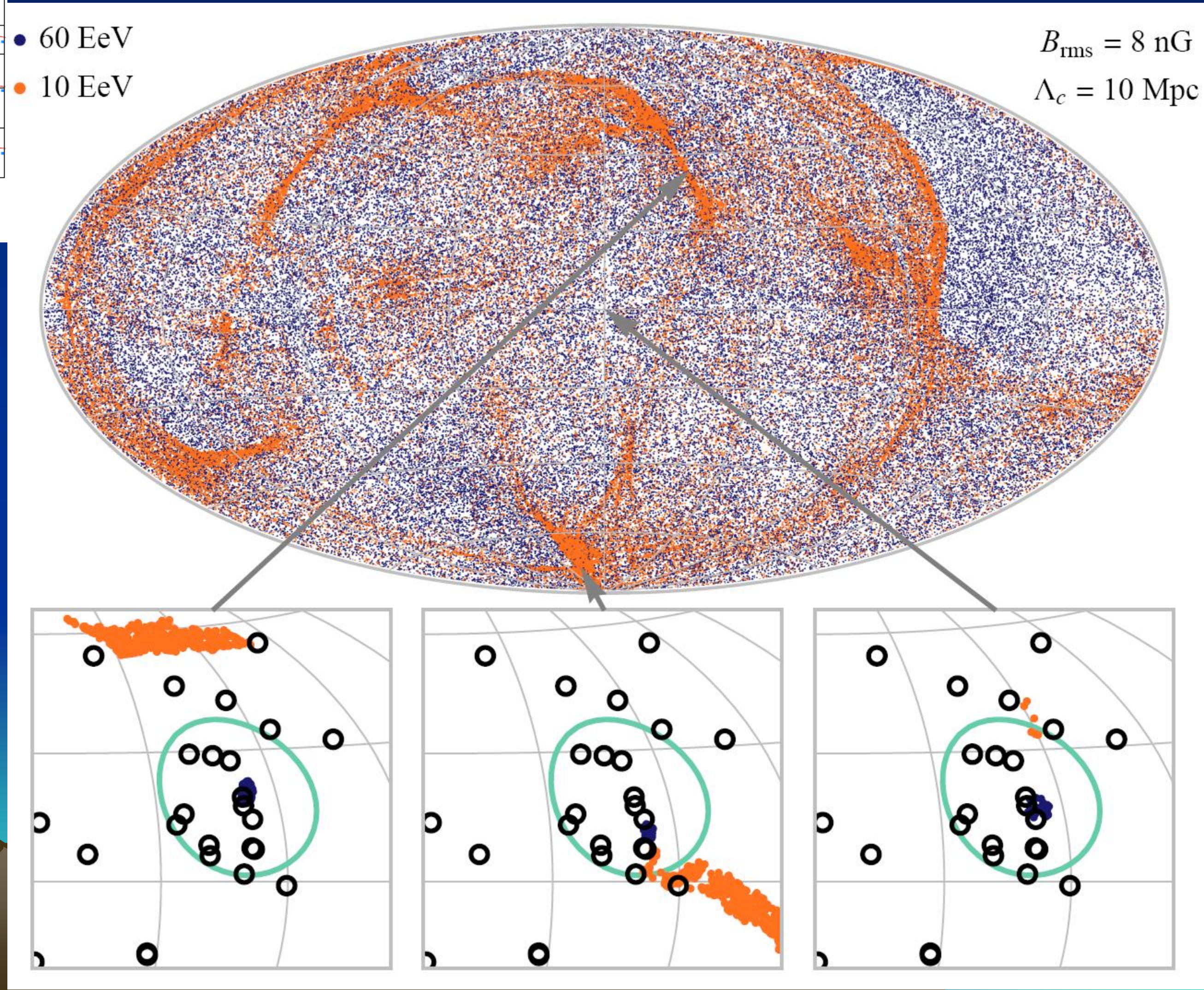
H.Yüksel, T. Stanev, M. Kistler, & P. Kronberg Astrophys J accepted August 2012

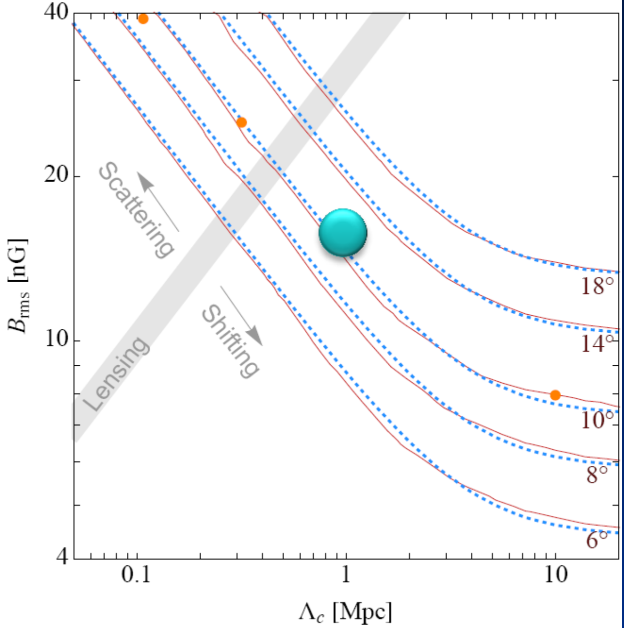


H. Yüksel, T. Stanev, M. Kistler, P. Kronberg
Astrophys J. Aug 2012

fixed

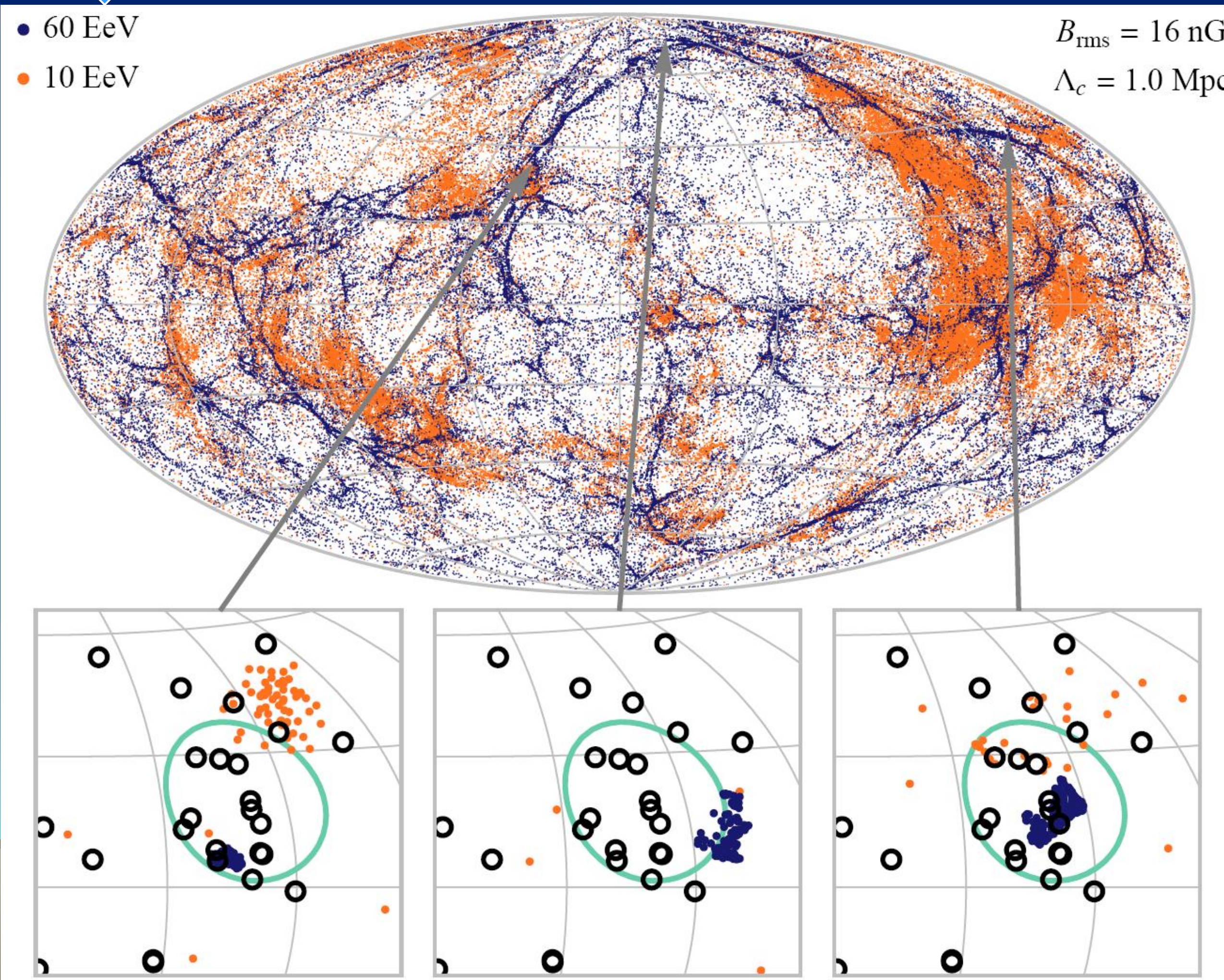
variable

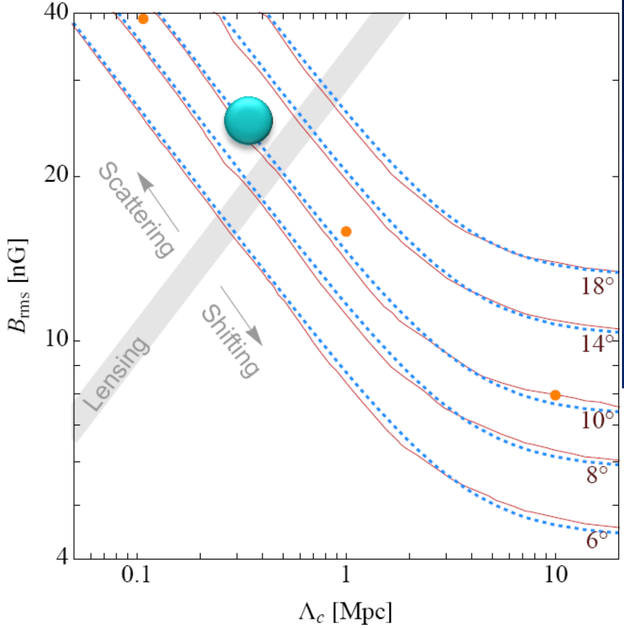


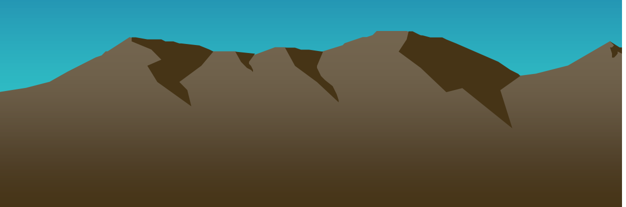


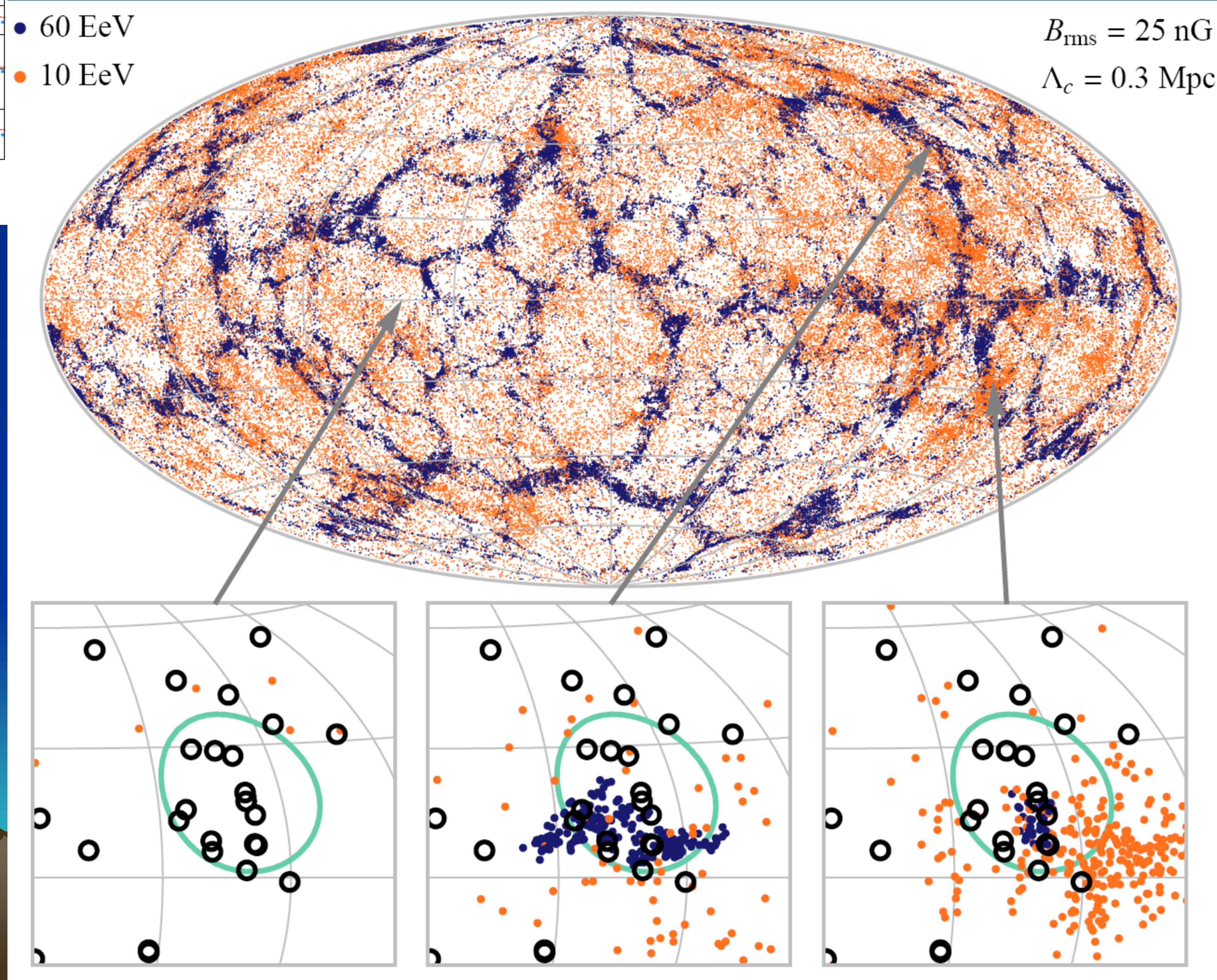
Fixed

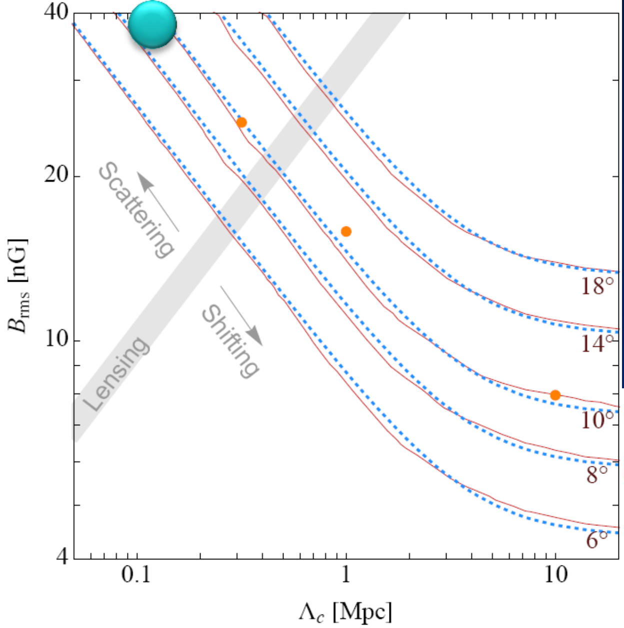
variable




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




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



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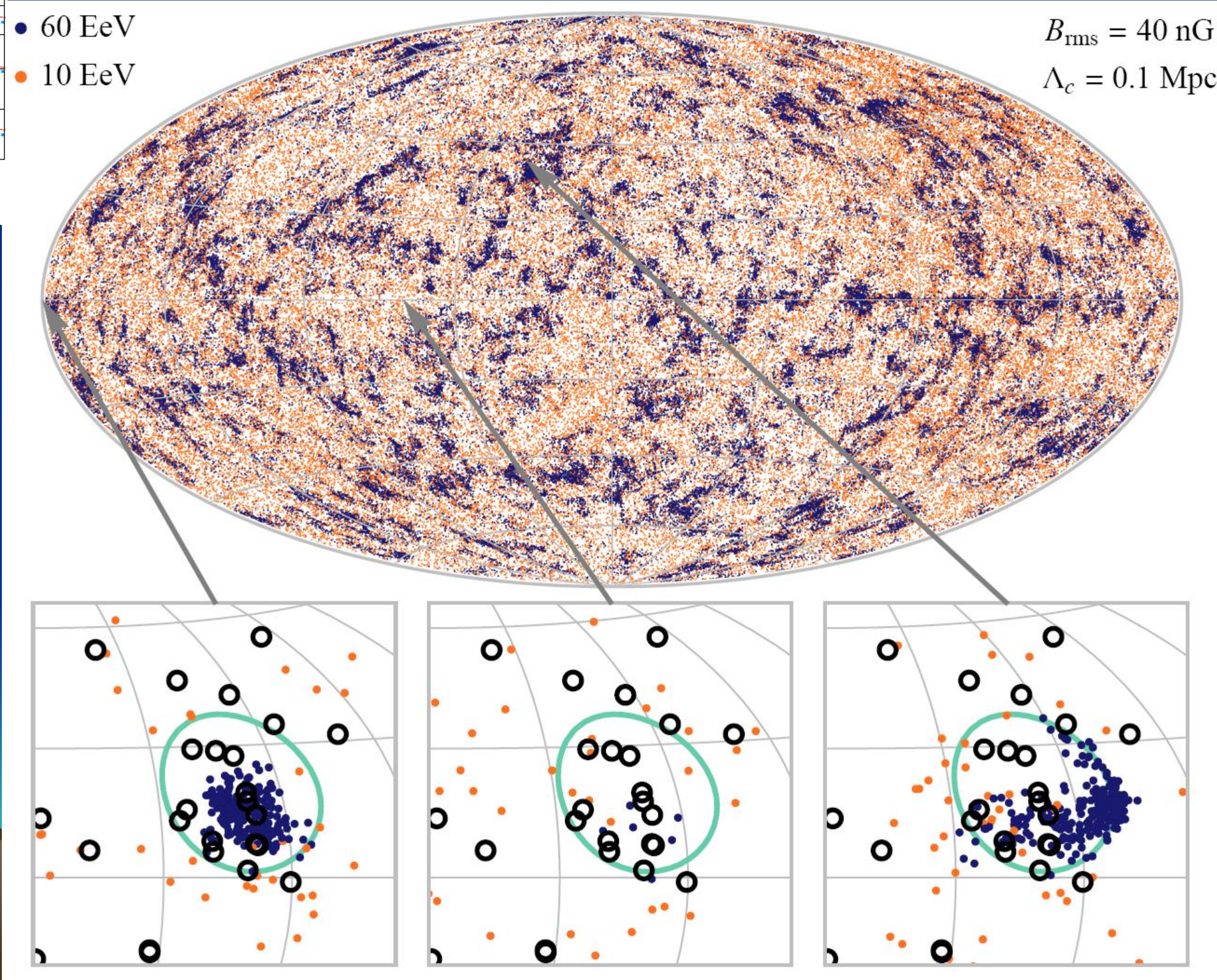
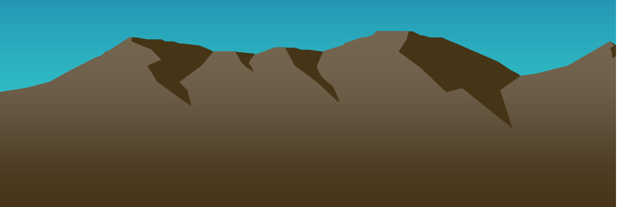
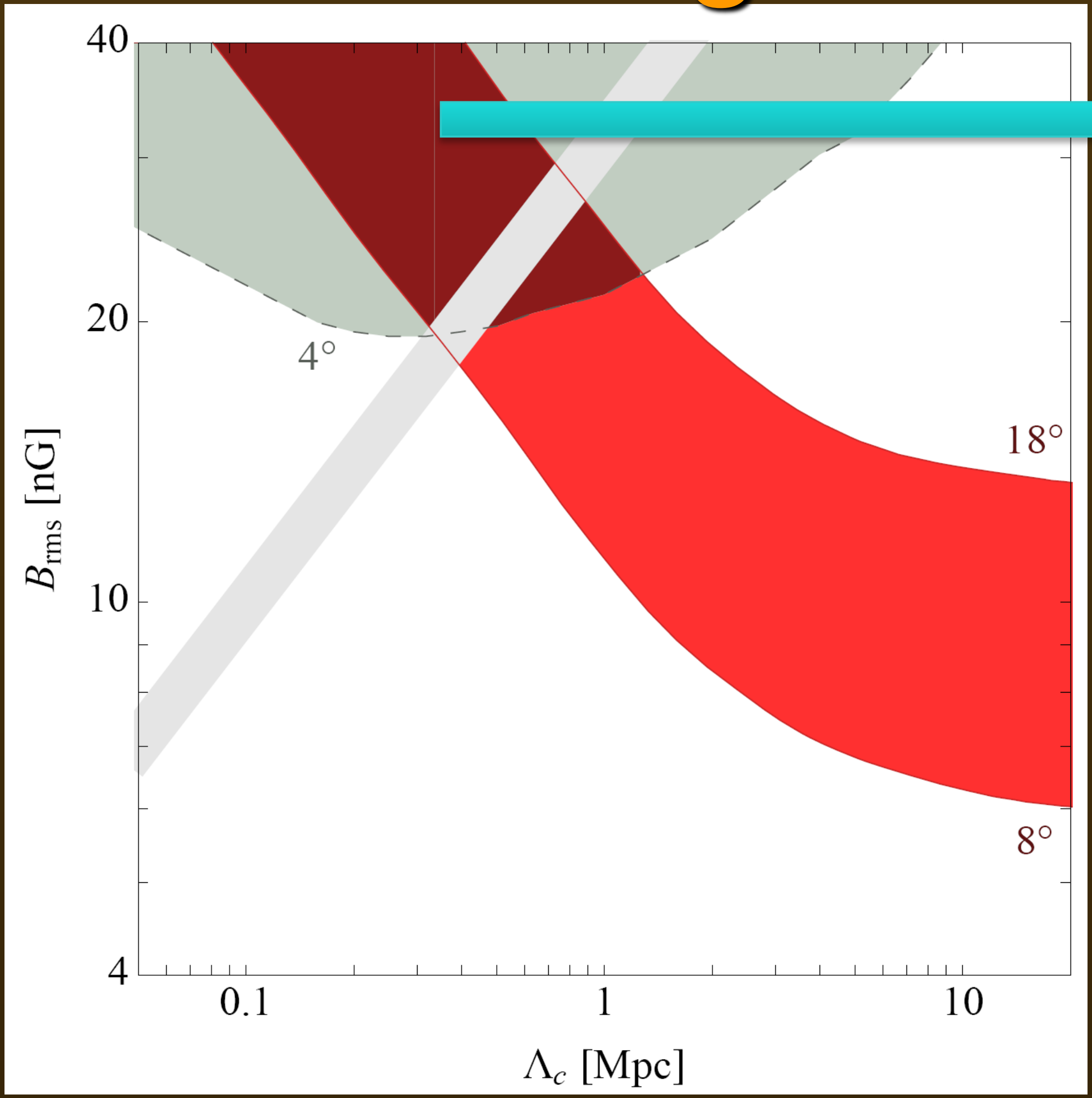


60 EeV
10 EeV
$B_{\rm rms}$ = 40 nG
Λ_c = 0.1 Mpc



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 + scales741, L15 2011
R.V.E. Lovelace & P.P. Kronberg, MNRAS April 2013 Jets as transmission lines

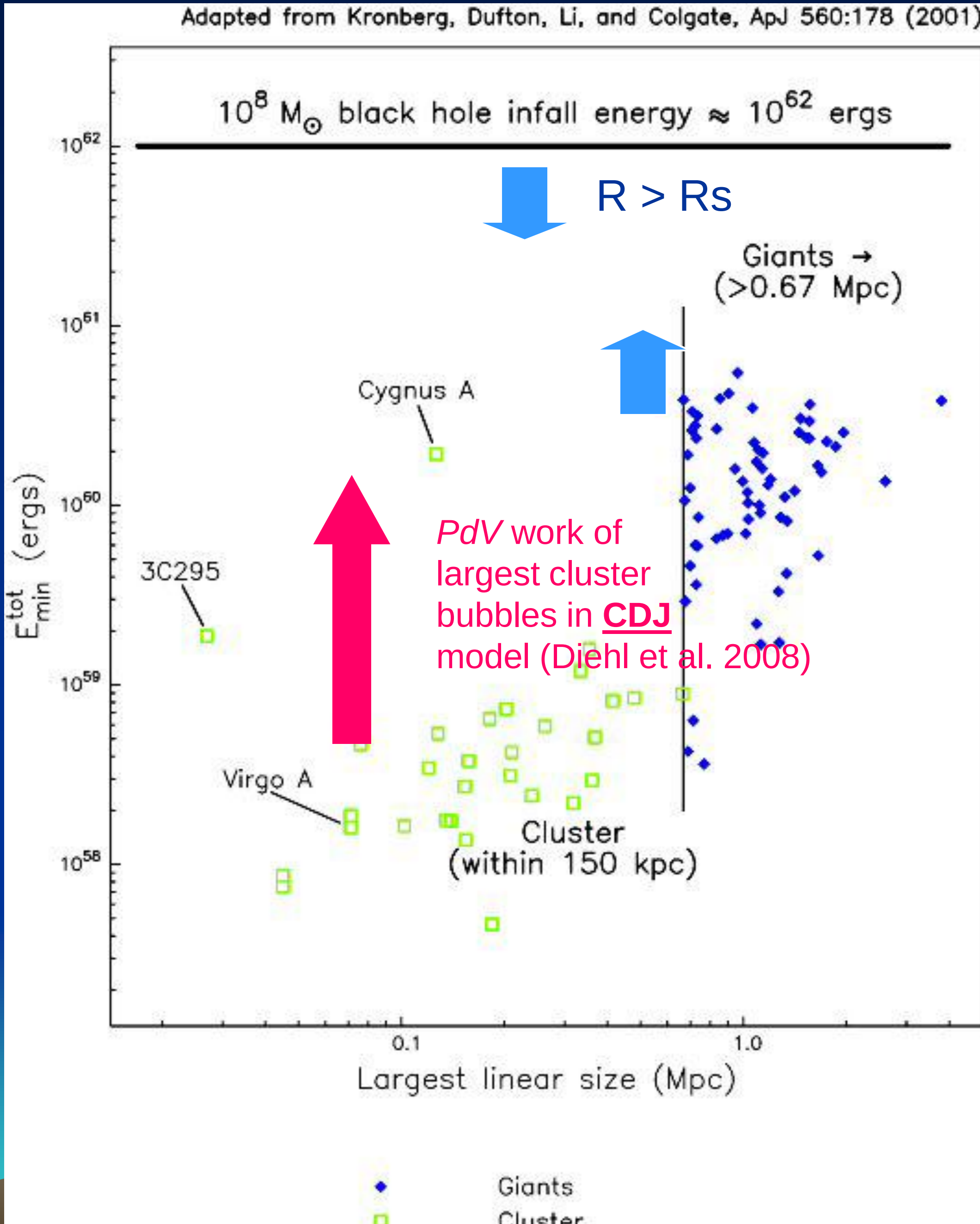
- ***Low thermal density around knots confirms dominance of a Poynting flux***
- ***P*** ~ 10^{37} watts of directed e.m. power, and ***I*** =3.3×10^{18} ampères of axial current.
  Sign of ∇RM gives ***I*** direction – in the case of 3C303, away from the BH
- **POYNTING jet's electrical properties: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

$$I_0 = c r_2 B_{\phi(r_2)} = \frac{V_0}{Z_0} \approx 3\times10^{18}\ \text{Amps (MKS)}$$

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

$$V_0 = \frac{r_0 B_0}{3^{1/4}\sqrt{R}} = 2.7\times10^{20}\ \text{Volts(MKS)}$$

$\beta = \frac{U_z}{c} \lesssim 1$, where *r1*, *r2* are the inner & outer transmission line radii (*Lovelace & Ruchi, 1983*)



ENERGETICS

$=M_{BH}c^2$

and calorimetry of large radio lobes:

Mind the gap!!

Accumulated energy ($B^2/8\pi + \varepsilon_{CR}$) x (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*

* * *