Cosmic magnetic fields

connections to particle astrophysics

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University of Toronto

CTA Link Symposium,
Buenos Aires, Argentina,

21 November 2012

1.
CR propagation models based on one, or a few prominent UHECR sources

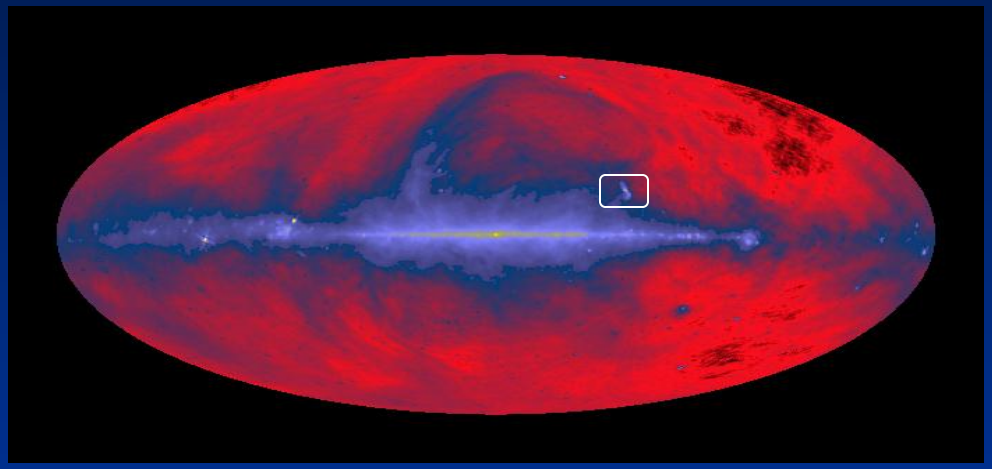
New conceptual for analysis of UHECR propagation.

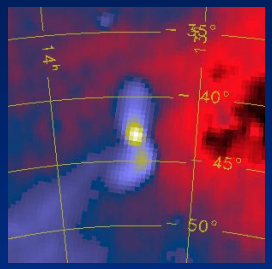
Initially assume that Cen A is the sole prominent (and isotropically emitting), local UHECR source)

H. Yüksel, T. Stanev, M. Kistler & P. Kronberg

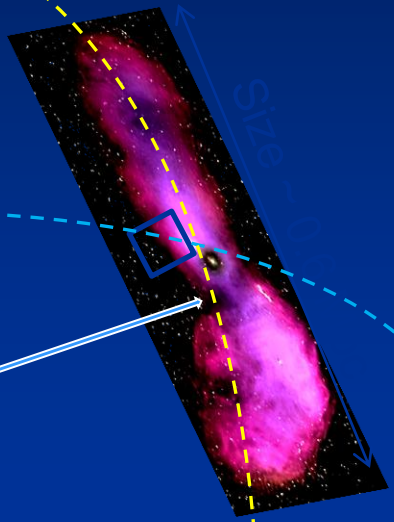
Astrophysical Journal **758**, *16, 2012 October 10*

Geometry: Cen A vs. Milky Way



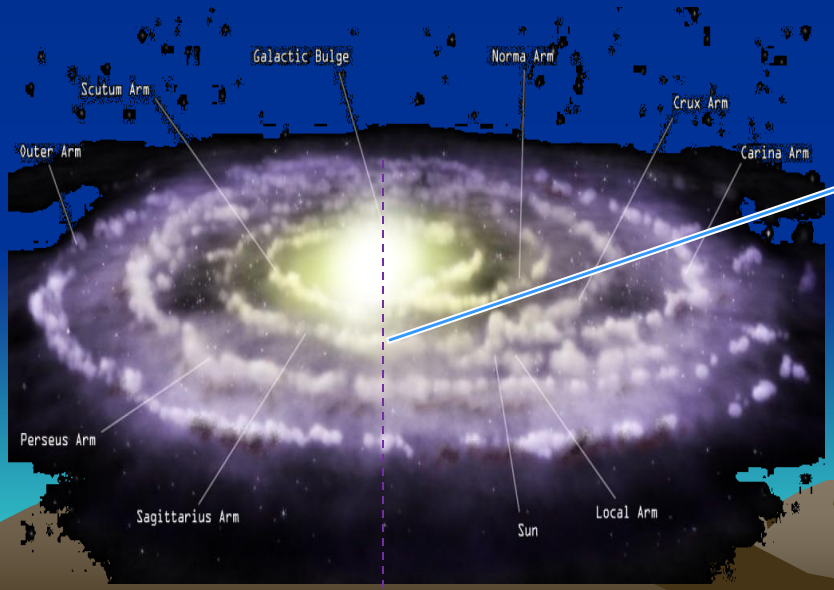


l ~ 310°



Size ~ 8°

3.8Mpc



b ~ 20°

Cen –A, AUGER + HiRes

A new analysis and conclusions on:

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

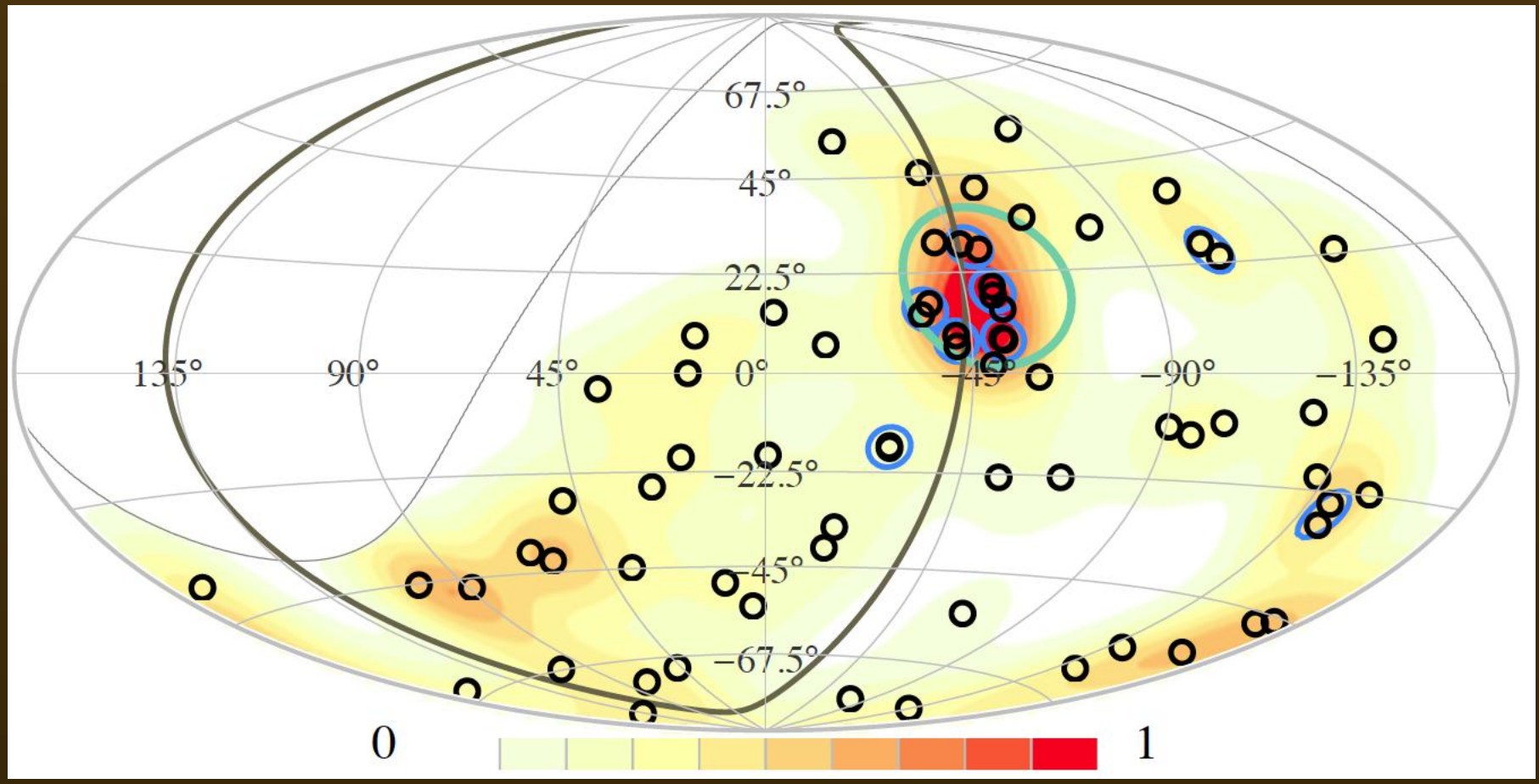
A comparison of
UHECR simulation and measurement at 1 and 6 x10^{19} eV

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

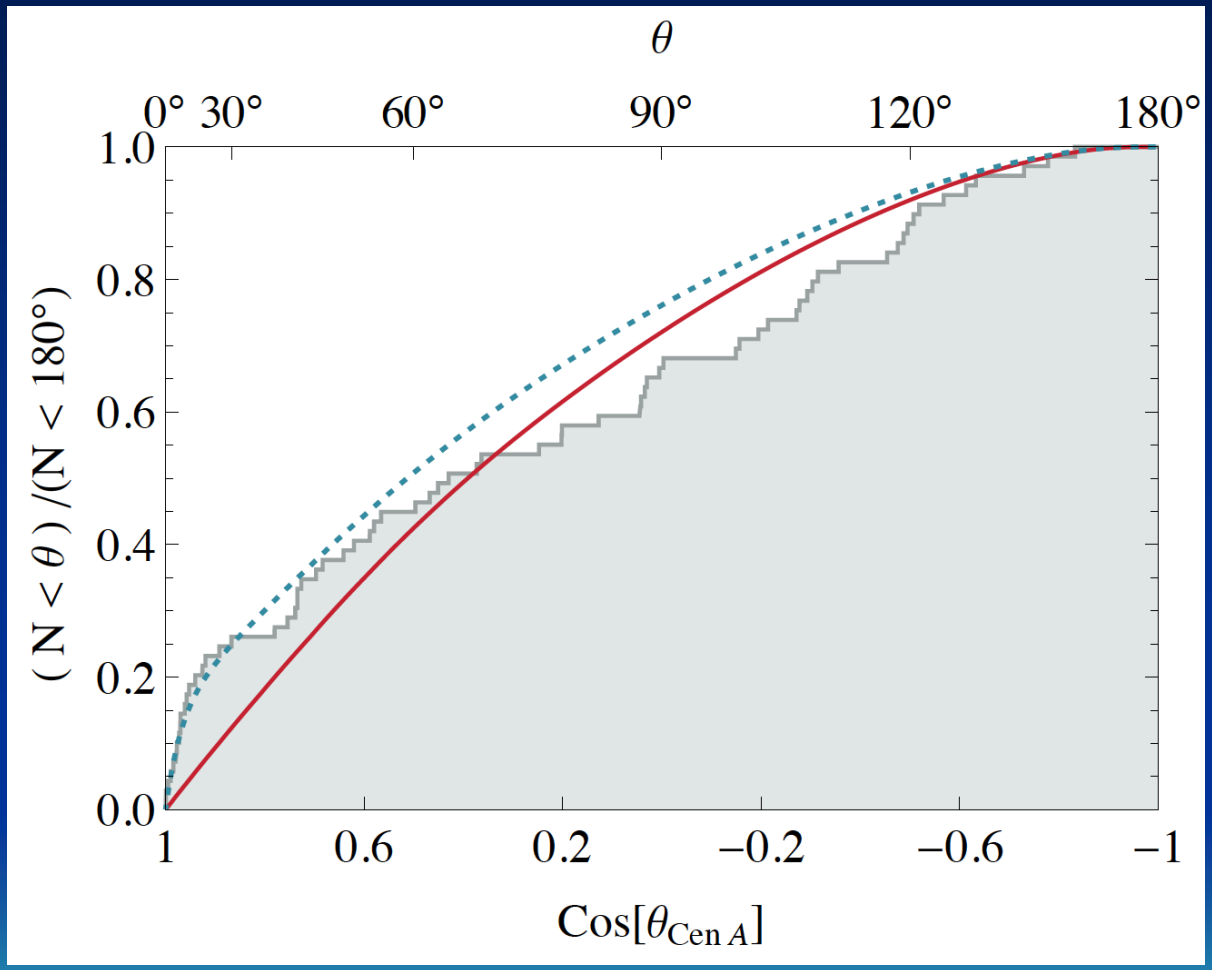
Input UHECR data are from 2010 published data:
AUGER UHECR data: (Argentina)
Abreu *et al. Astroparticle. Phys.* **34**, 314, 2010
HiRes/TA UHECR data: (Utah)
Abbasi R.U. *et al., ApJL* **713**, L64, 2010

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

For a first-order understanding of 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:

$$\delta_{\rm rms} \simeq 53^\circ \sqrt{1/2}\, B_{\rm rms} \sqrt{d\,\Lambda_c}\,/E$$
$$\theta_{\rm rms} = \delta_{\rm rms}/\sqrt{3}$$

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

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

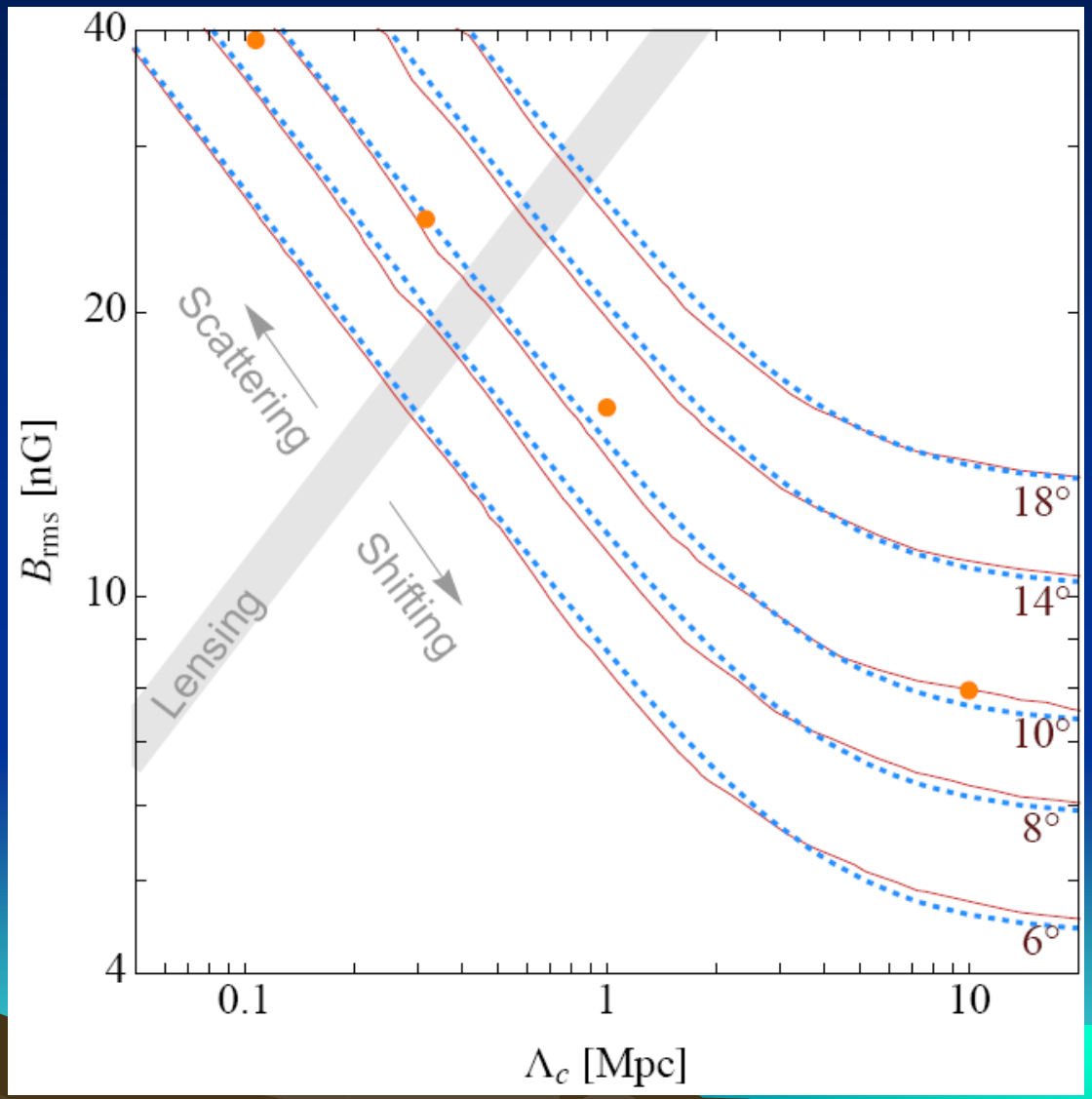
$\eta \to -4$

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

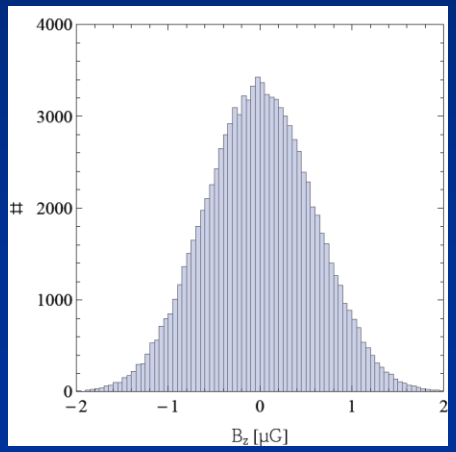
Mean values of cosmic-ray angular distributions for 60 EeV around Centaurus A as a function of field strength and coherence length

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

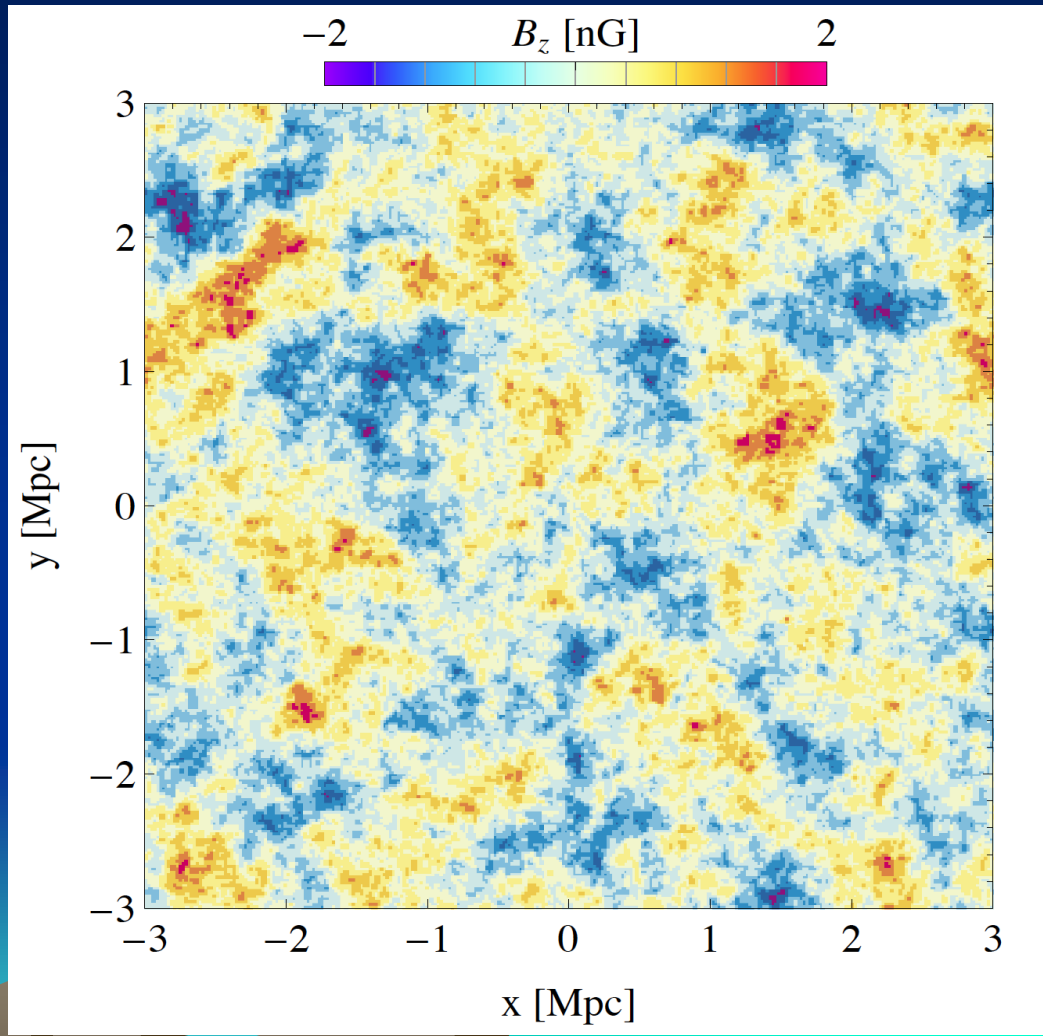


Magnetic Fields

- We generate a divergence free, random magnetic field model whose components have a Gaussian distribution and follow Kolmogorov spectrum



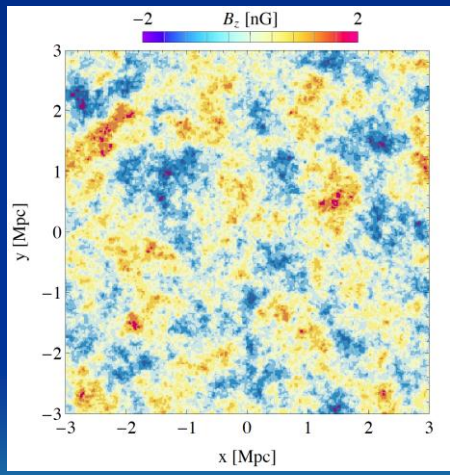
- A slice from the magnetic field simulation. Displays the z component of the field in the x-y plane within a cubic grid of size of 512^3:

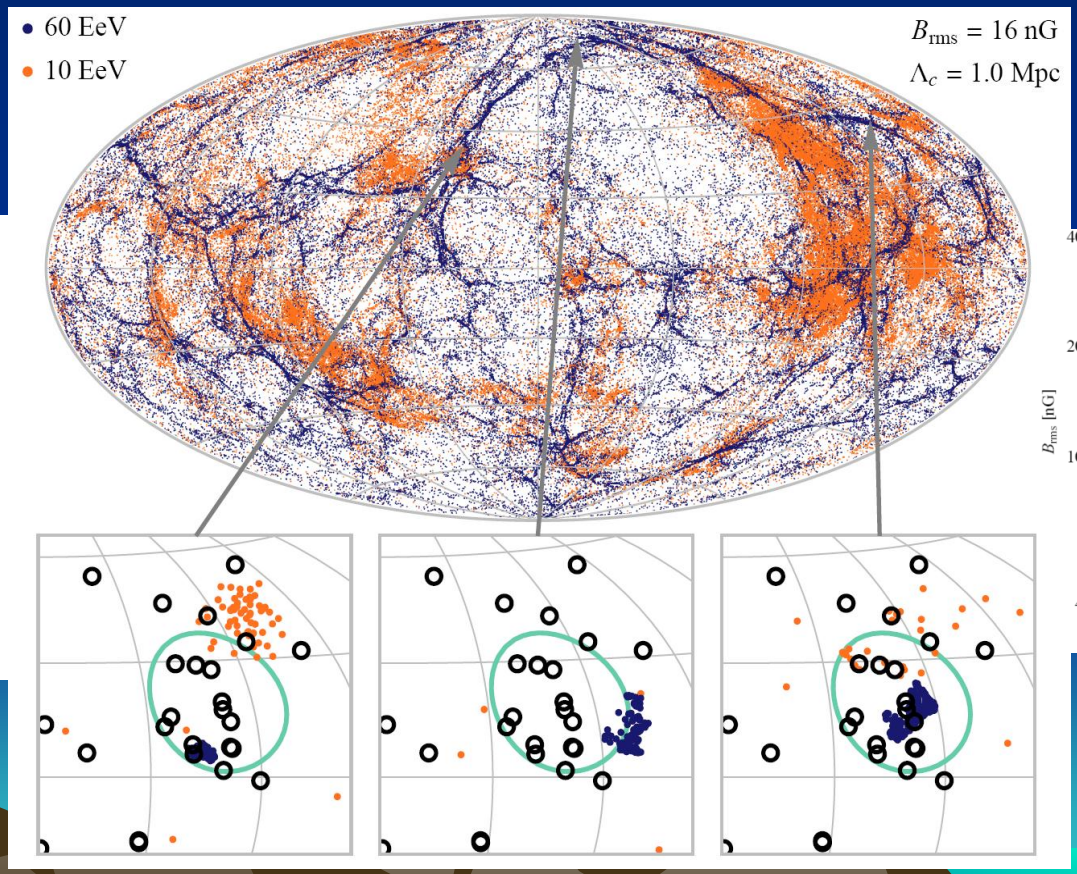


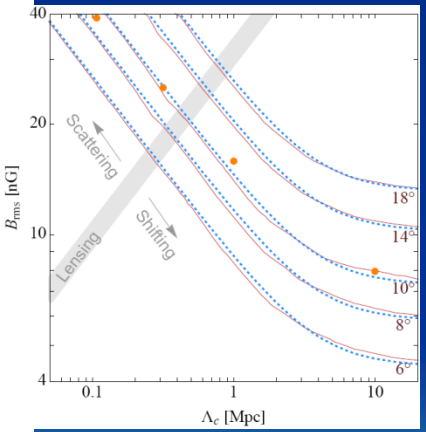
Plausible distributions of cosmic rays are illustrated for a variety of extragalactic magnetic field parametrizations (cosmic rays with energies of **60** EeV (blue) and **10** EeV (orange)

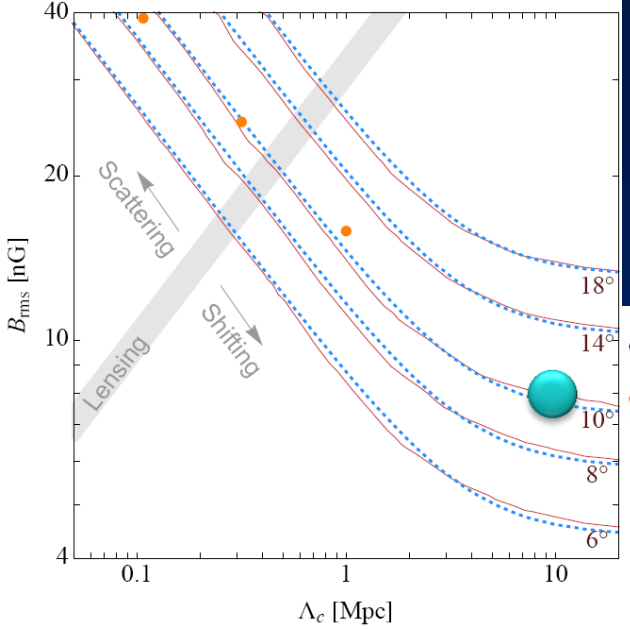
Upper: As seen by an observer located at Cen A, final positions of particles at a distance 3.8 Mpc from the source(100,000 particles are shown for each energy)

Lower: As seen by an Earth-based observer, three characteristic realizations of UHECR angular distributions arriving from Cen A, chosen from locations in the map above

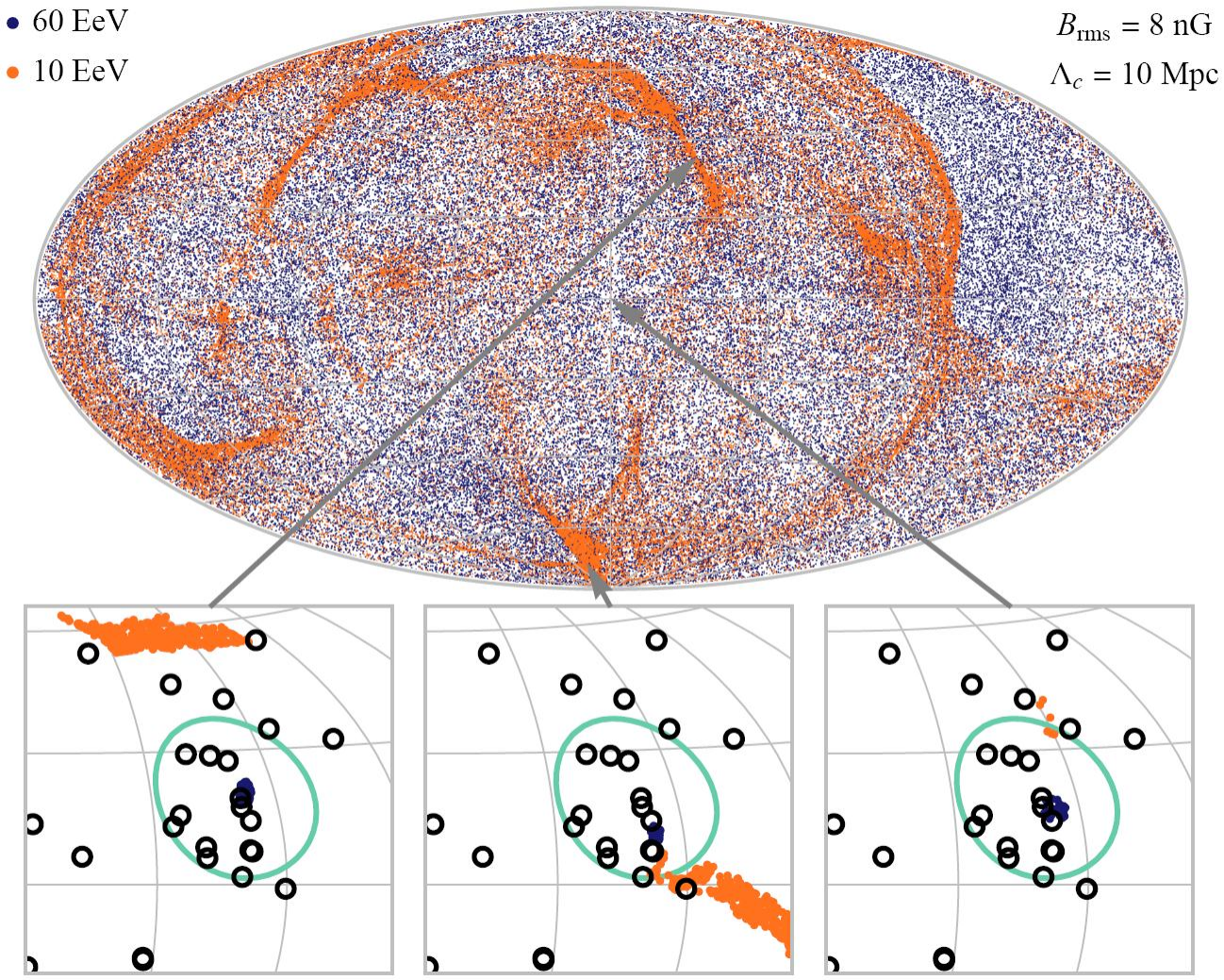






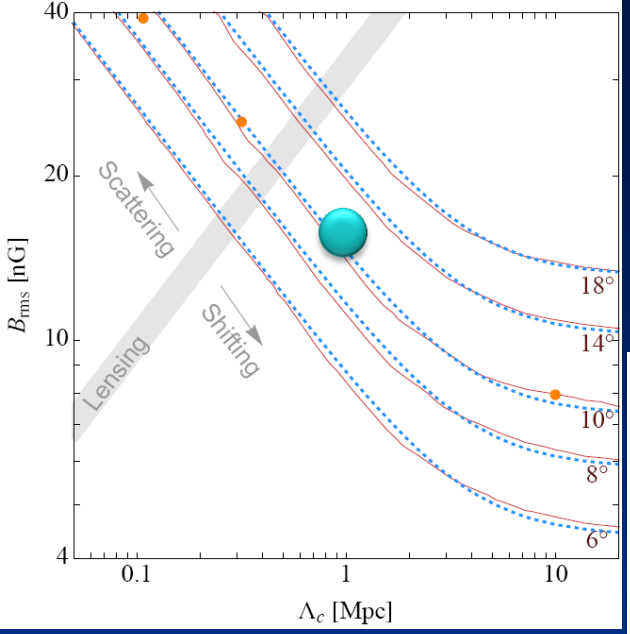


The sky as seen from Cen A (upper plots)
-- projected on a 3.8 Mpc radius screen



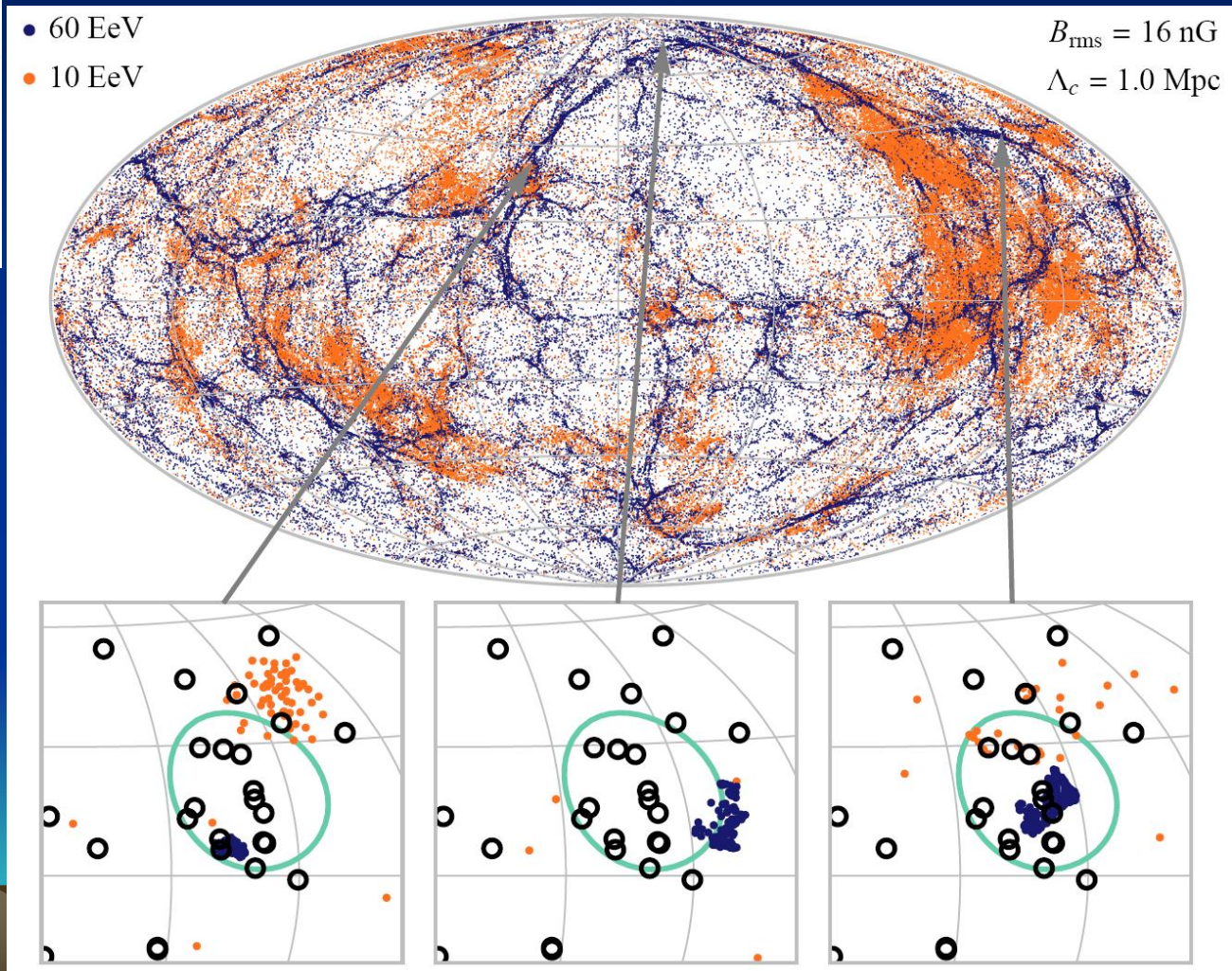
Lower plots:

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



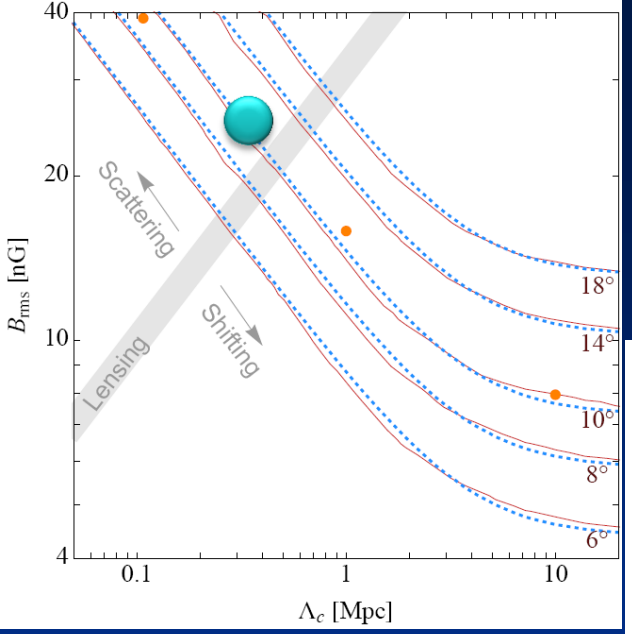
Note the clearly delineated "caustic" zones, here for *E*=60 EeV protons.

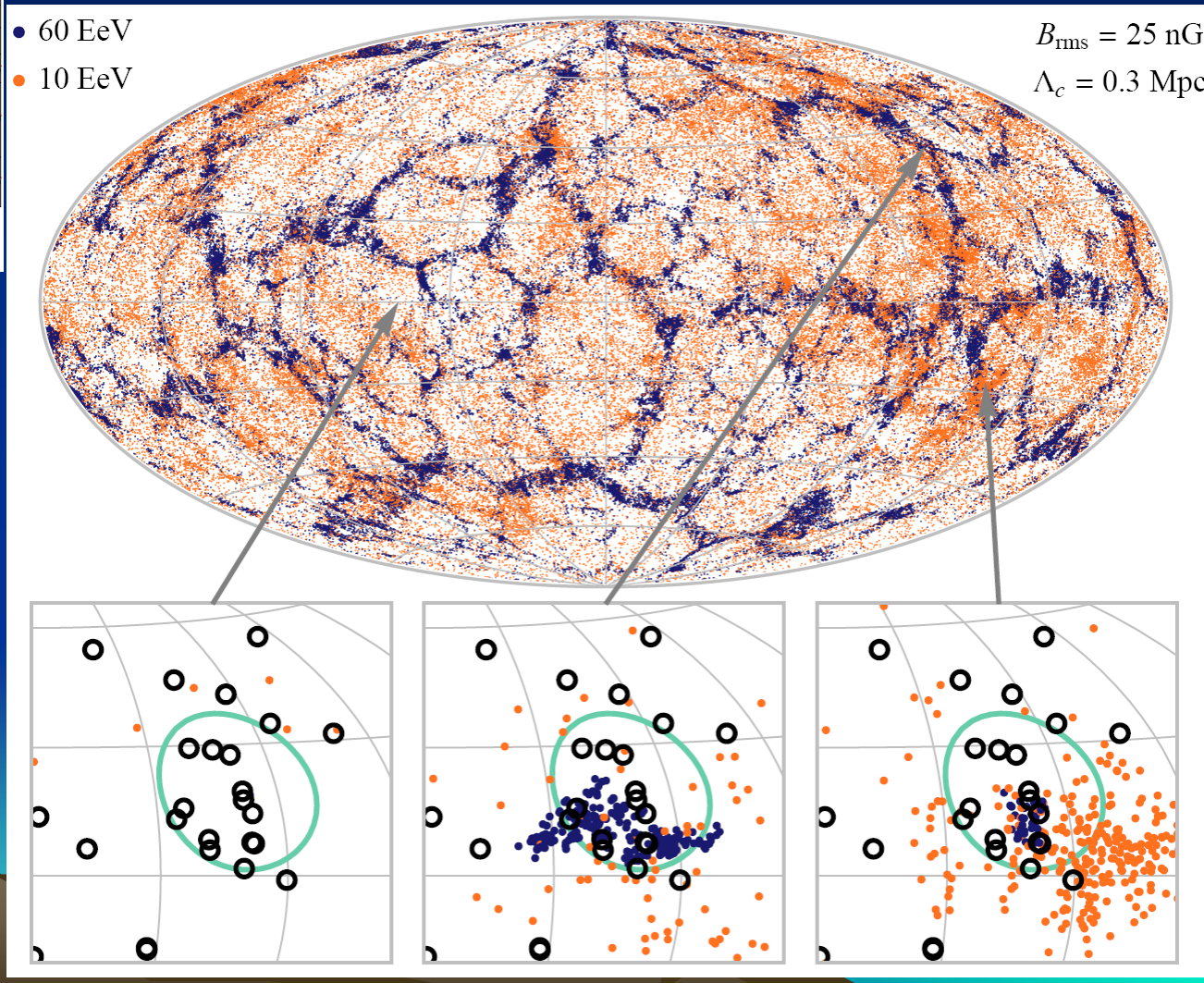
These correspond to the gray-shaded "lensing"zone in the upper left inset. They lead to a relatively model - insensitive $\langle B_{IG} \rangle$



b

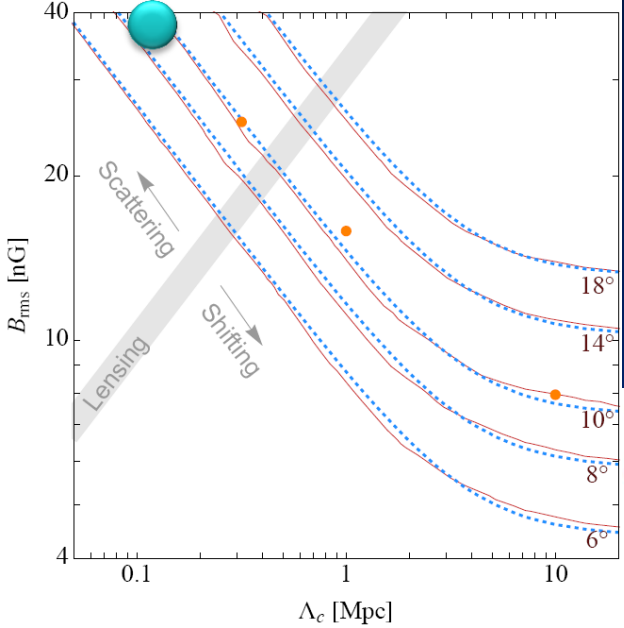
Details in *ApJ* ***758****, 16, (Oct 10) 2012 (Yüksel, Stanev, Kistler & Kronberg)*

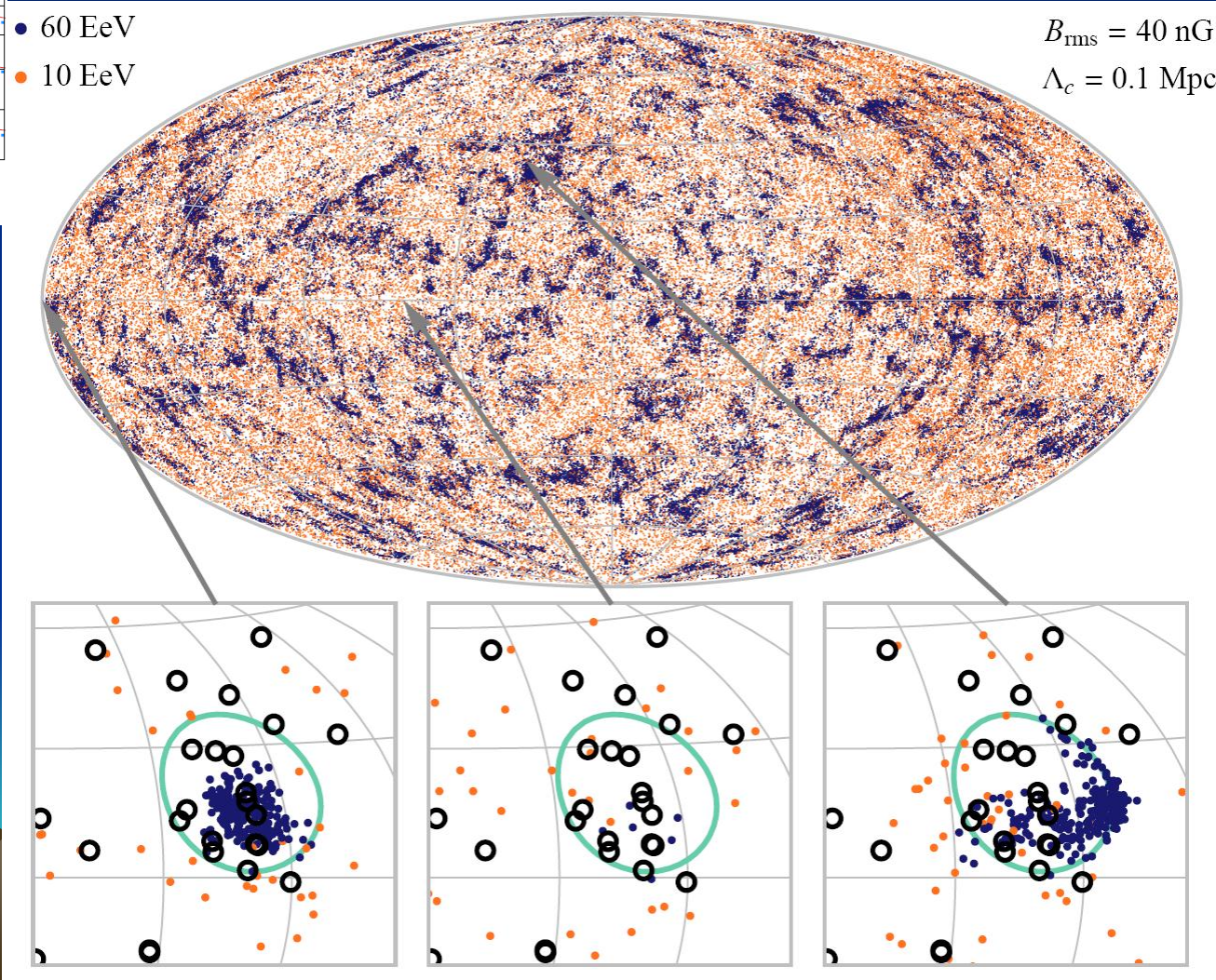

40
20
10
4
$B_{\rm rms}$ [nG]
Scattering
Shifting
Lensing
18°
14°
10°
8°
6°
0.1
1
10
Λ_c [Mpc]


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

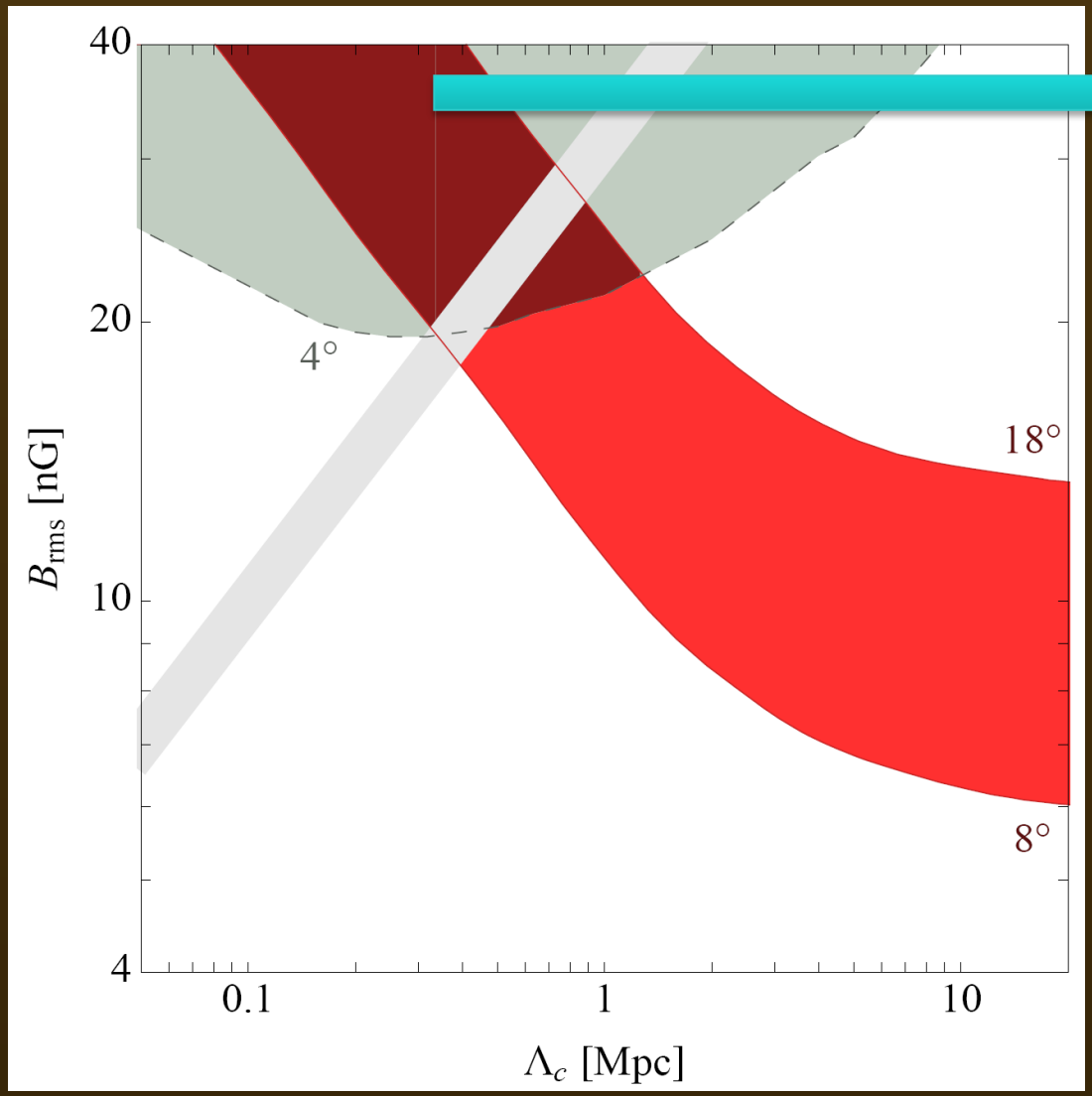
b

l


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


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

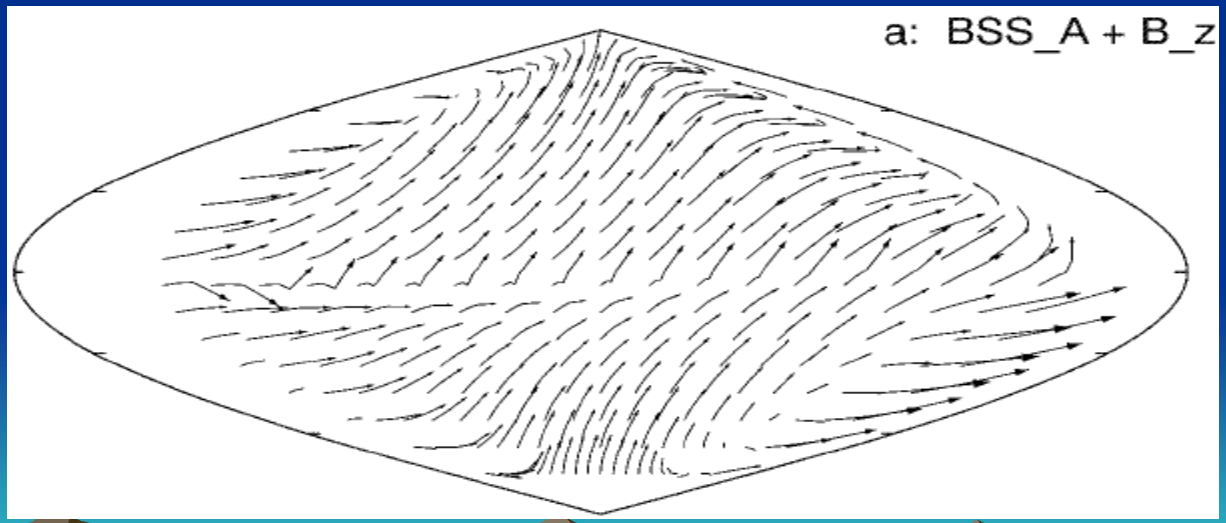
  2. the spread of events among themselves is < 4 ° (dashed line)

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?
Not visible in our AUGER UHECR analysis

- 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 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. 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 difficulty of making associations with more distant sources
  - it would also introduce a minimum time dispersion, important for transient sources, such as gamma-ray bursts

  Heavier nuclei plausibly present at the highest obs'd energies

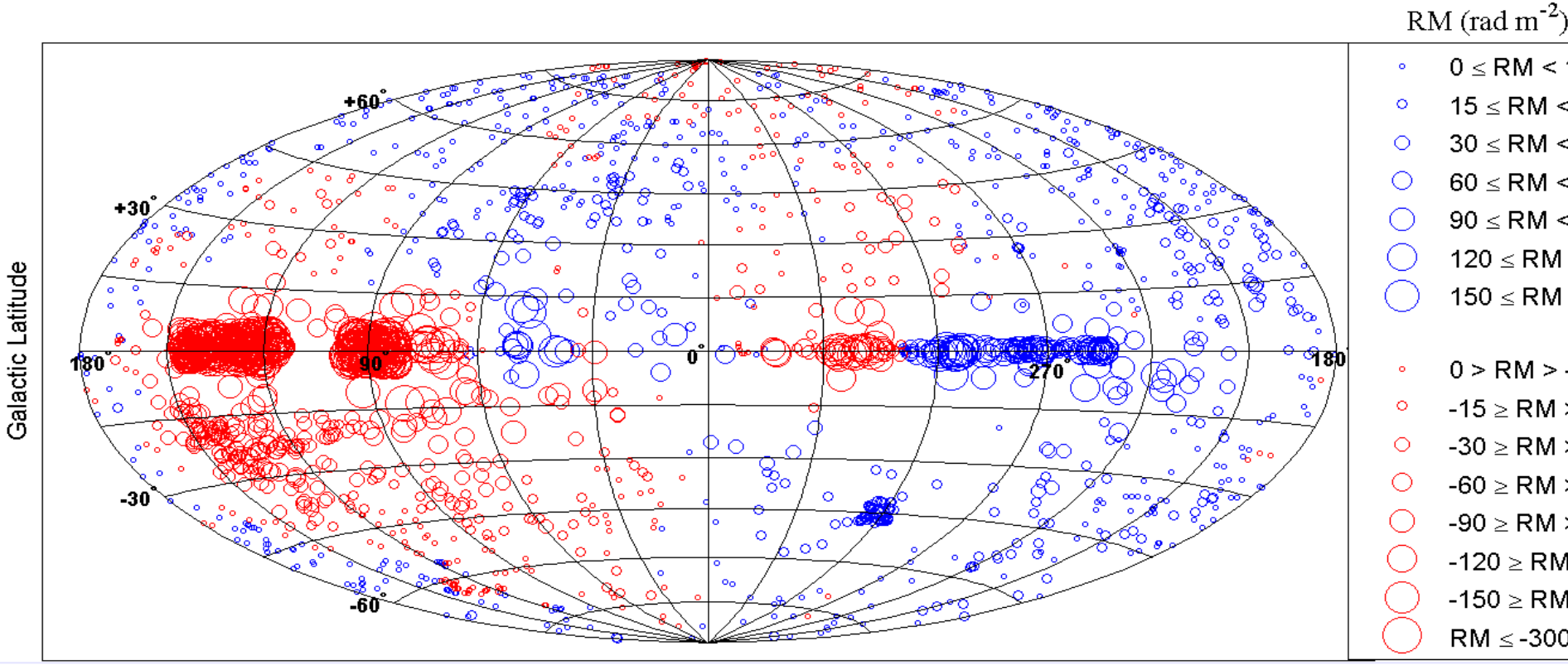
  - If it is a solar composition, and acceleration is based on nuclear charge, the observed events near Cen A would suggest 1 or 2 He nuclei in the observed excess.
  - *NOTE: The highest energy event seen by Auger --142 EeV and within 30 degree of Cen A, --- is in rough agreement with the high total energy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

- The Milky way is a magnetic “grand design” galaxy

Smoothed Galactic RM sky from 2250 egrs RM's

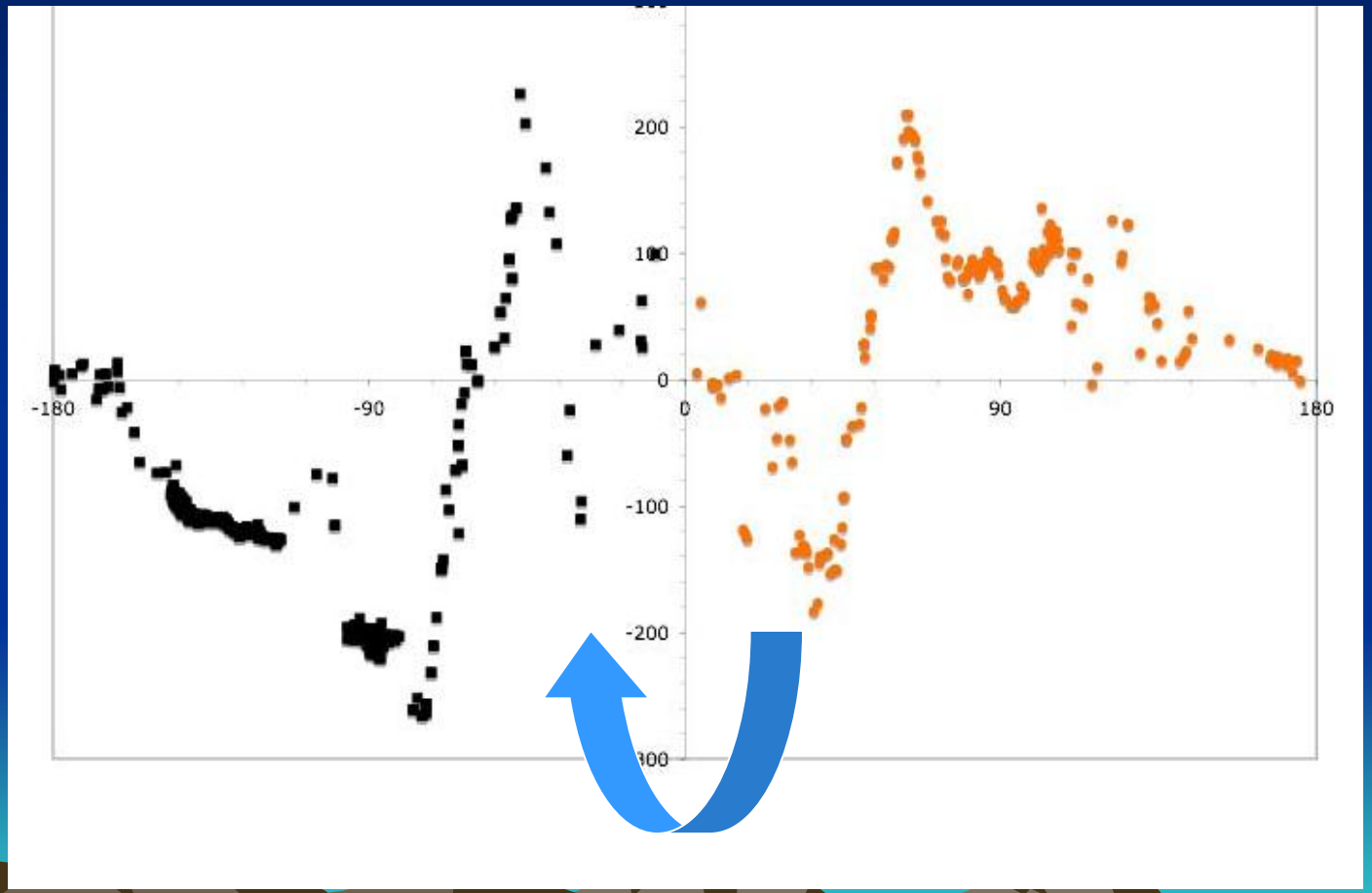


P. Kronberg &Katherine J. Newton-McGee, Proc. Ast Soc. Australia 82, 2011

Further analysis: M.S.Pshirkov, Tinyakov, Kronberg, Newton-McGee (ApJ 2011)

Smoothed RM's around the Galactic plane at $|b| \preceq 10^{o}$ *New evidence for <B> in the disk*

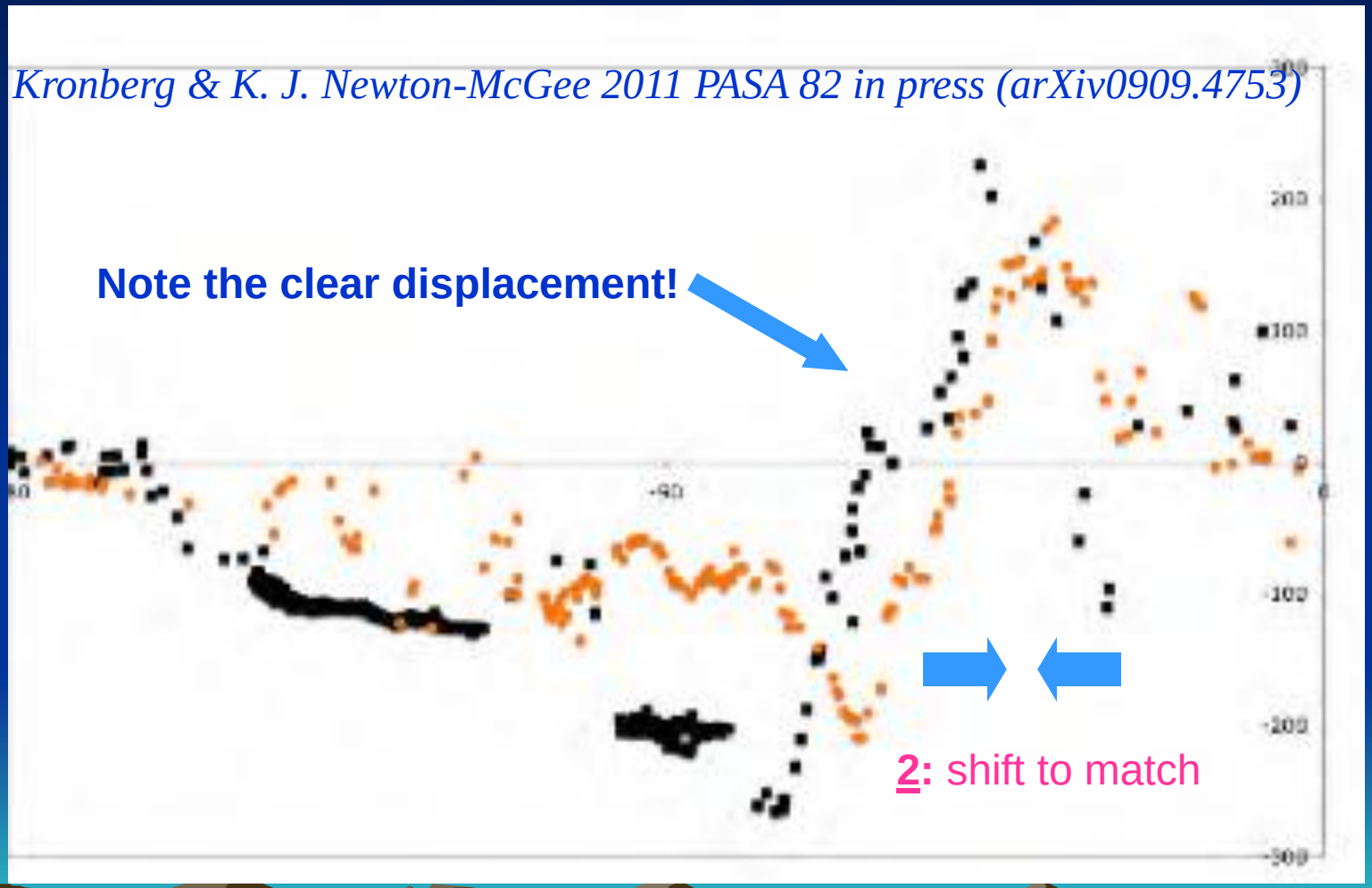
P.P. Kronberg & K. J. Newton-McGee PASP 2011 (arXiv:0909.4753)



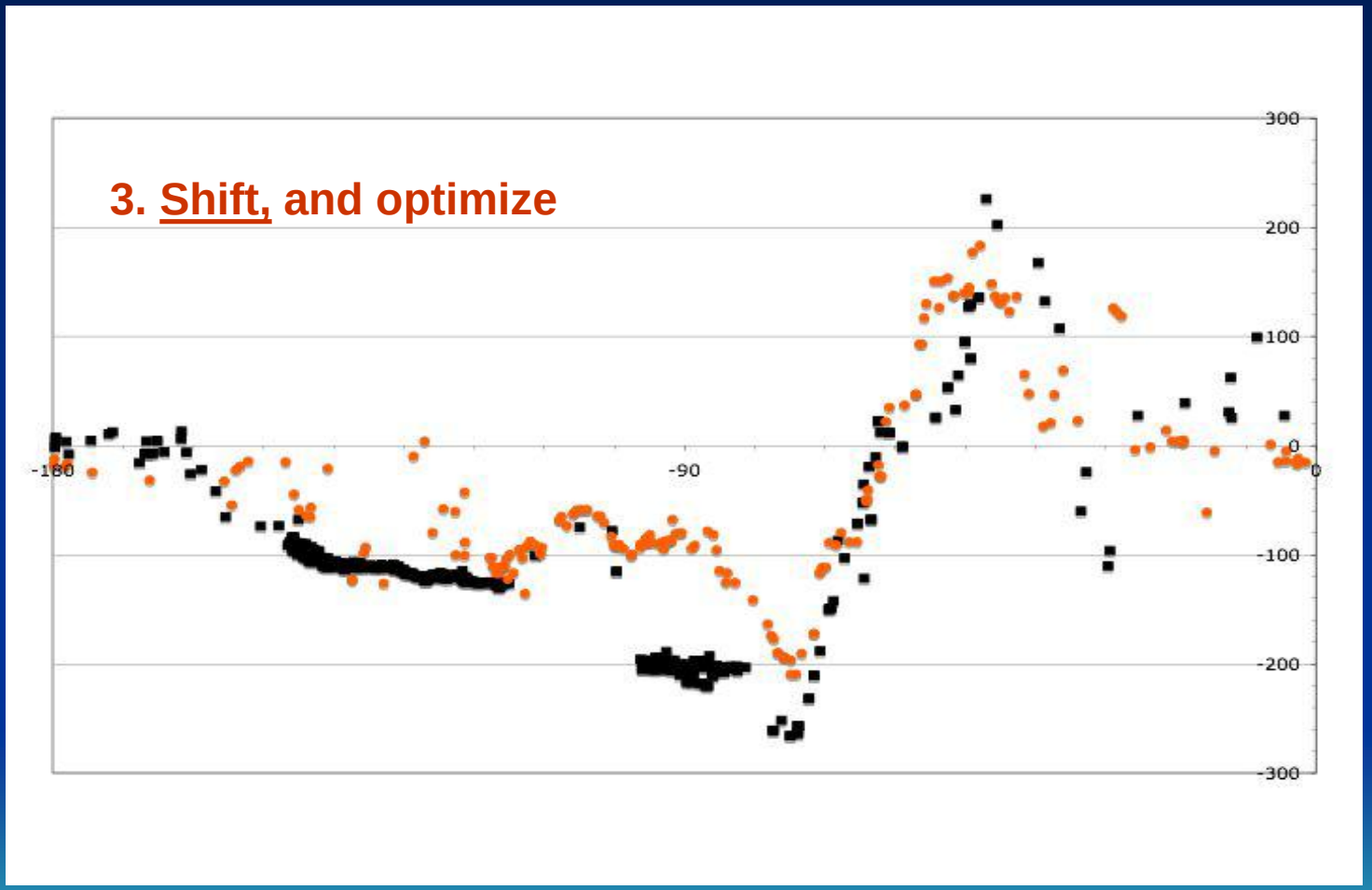
1. fold about the Galactic center direction (l=0º), and reverse sign

Fold RM's about l=0, then **reverse the sign** of RM's at 360° > l > 180° (orange points)

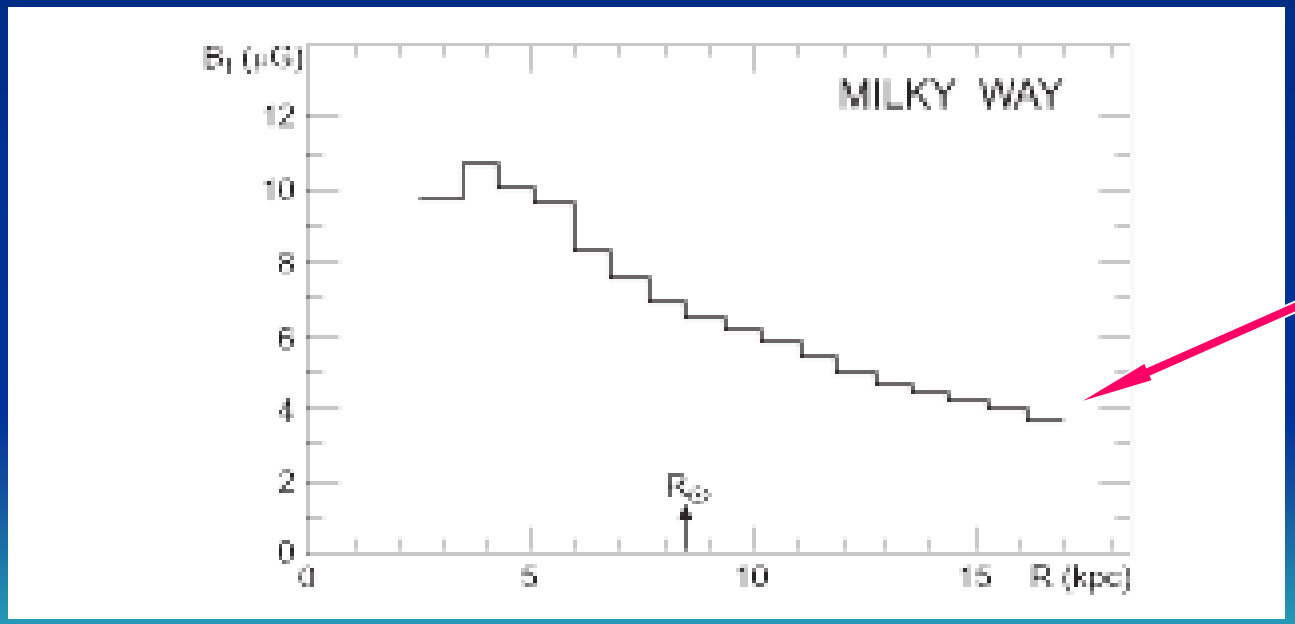
P.P. Kronberg & K. J. Newton-McGee 2011 PASA 82 in press (arXiv0909.4753)



RM's *after* an 11º (± 2º) shift



Model of the Galactic |*B*| vs. *r*.
from all-sky, 0.4 GHz synchrotron emissivity
(Haslam, Salter, et al.)
confirmed by γ - ray observations
(Strong et al.)



Connects to local B_{IGM} ?

Faraday RM probe of magnetic fields in filaments of cosmological LSS

Well-defined Perseus-Pisces supercluster filament

Optical galaxy counts vs. RM plots
for the Perseus-Pisces supercluster chain

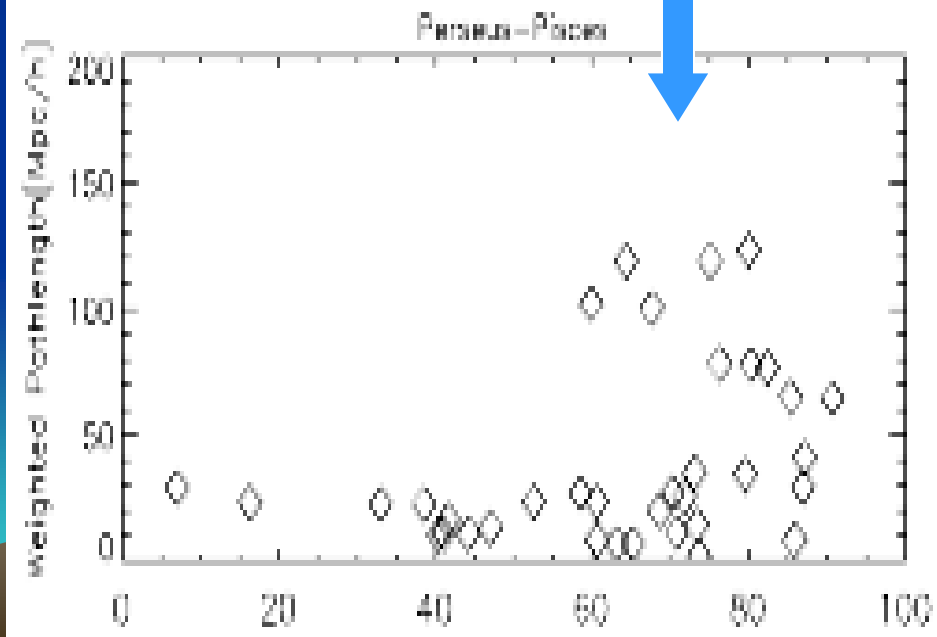
Two optical methods used: *Y. Xu, P. Kronberg, S. Habib & Q. Dufton ApJ 2006*

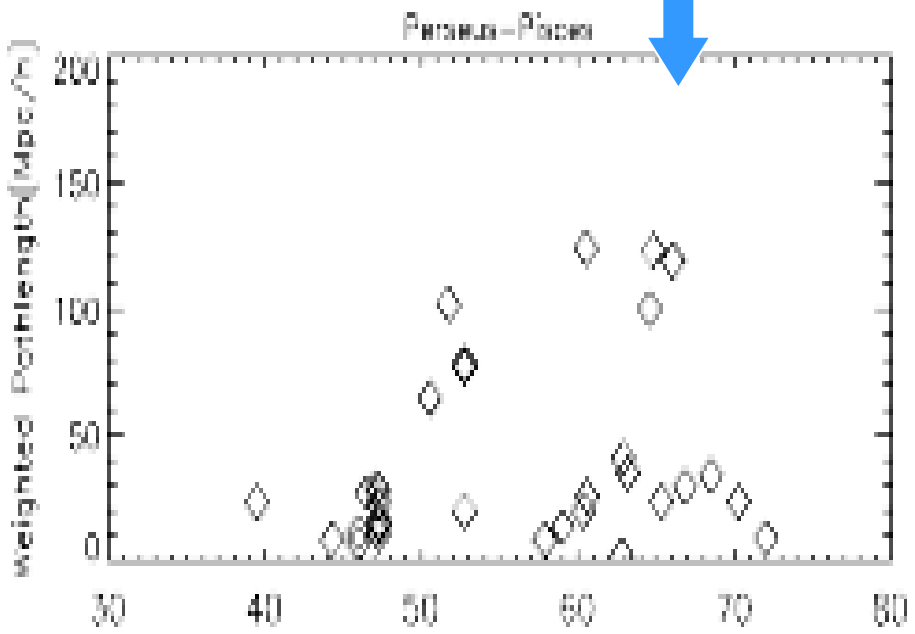
(a)

7º-smoothed galaxy column density *vs* RM

(used the 2MASS galaxy survey)

(b) Weighted path length *vs* RM
(This used the CfA2 galaxy survey)
from 3-D Voronoi-tessilated IGM filament volumes
(∵ 3-D spectroscopic *z*'s are measured).
also from 7º-smoothed data






Arecibo 305m Telescope, PR
2 mm rms optics
illuminated area ≈ 200m
uv overlap with DRAO ≈ 200m

Dominion Radio Astrophysical Observatory
Penticton BC, Canada

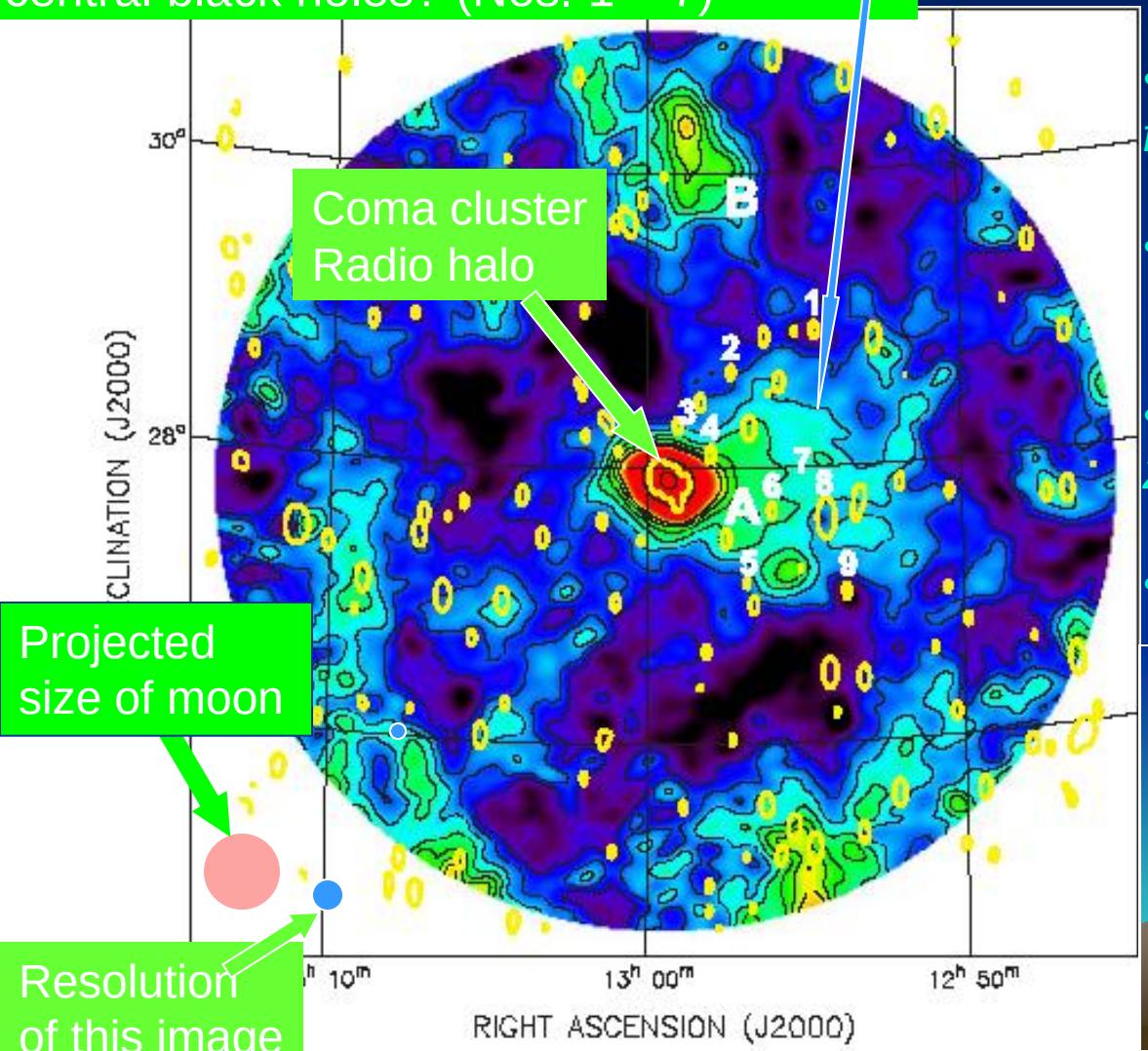
Max. separation = 617m ⇒ resolution equiv. to 1000m single dish. *Min. projected separation ≈ 18m*

In 12 days, 1 full image within 9° circle at 408 MHz

COMBINED Arecibo-DRAO image, now smoothed to *10' (Arecibo) resolution*

P. Kronberg, R. Kothes, C. Salter, & P. Perillat ApJ 659, 267, 2007

Collective energization of several galactic central black holes? (Nos. 1 – 7)



- *Discrete sources removed,*
- *CMB + linear plane Milky Way foreground removed*
- *Strongest discrete sources re-overlaid (yellow ellipses)*
- *Black contours at 1.4, 1.9, 2.4, 2.9, 3.4, 3.9, 4.4, 10, 40K*
- *σ ≈ 250mK at 430 MHz*

Region A (2 – 3 Mpc in extent) requires a distributed "fresh" energy source – plausibly provided by the ~ 7 embedded, radio galaxies.

$Z_0 = \frac{3}{c}\beta$

BH (magnetic + CR) energy output ($\gtrsim 10^{60}$ ergs) is "captured" within a few Mpc,

compare with

η (photons), $\approx$ 10%of $M_{BH}c^2$ (not captured) appears comparable to η (CR + B),

2147+816 giant radio galaxy

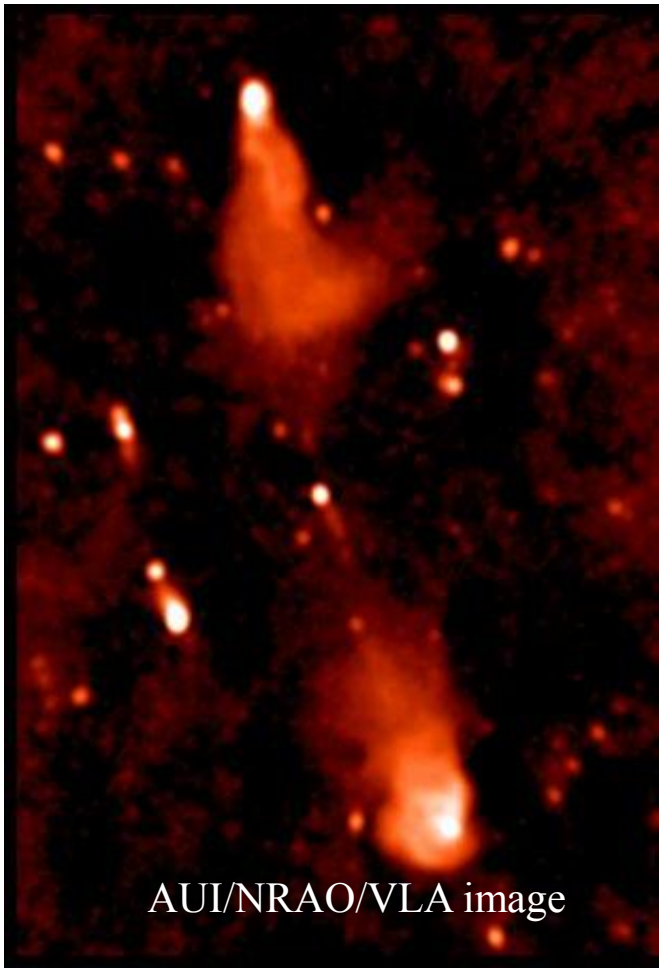
Analysis of ≈ 70 GRG images
Kronberg, Dufon, Li, Colgate
ApJ 2001

z=0.146

2.6 Mpc

8 FRII-like GRG's, w. detailed, multi-λ obs. & analysis
Kronberg, Colgate, Li, Dufton ApJL 2004

- Willis & Strom, 1978,80
- Kronberg, Wielebinski & Graham.1986,
- Mack *et al.* A&A 329, 431, 1998
- Schoenmakers *et al.* 1998,2000
- Subrahmanian *et al*. 1996
- Feretti *et al* 1999
- Lara *et al*. 2000
- Palma *et al*. 2000



Magnetic fields in cosmic voids

1. Gamma ray cascades

Papers by: A. Noronov,

I. Vovk,

A.M. Taylor,

Elyiv

2009- 2012

2. Magnetoplasma diffusion from void galaxies, and from surrounding "filament" galaxies

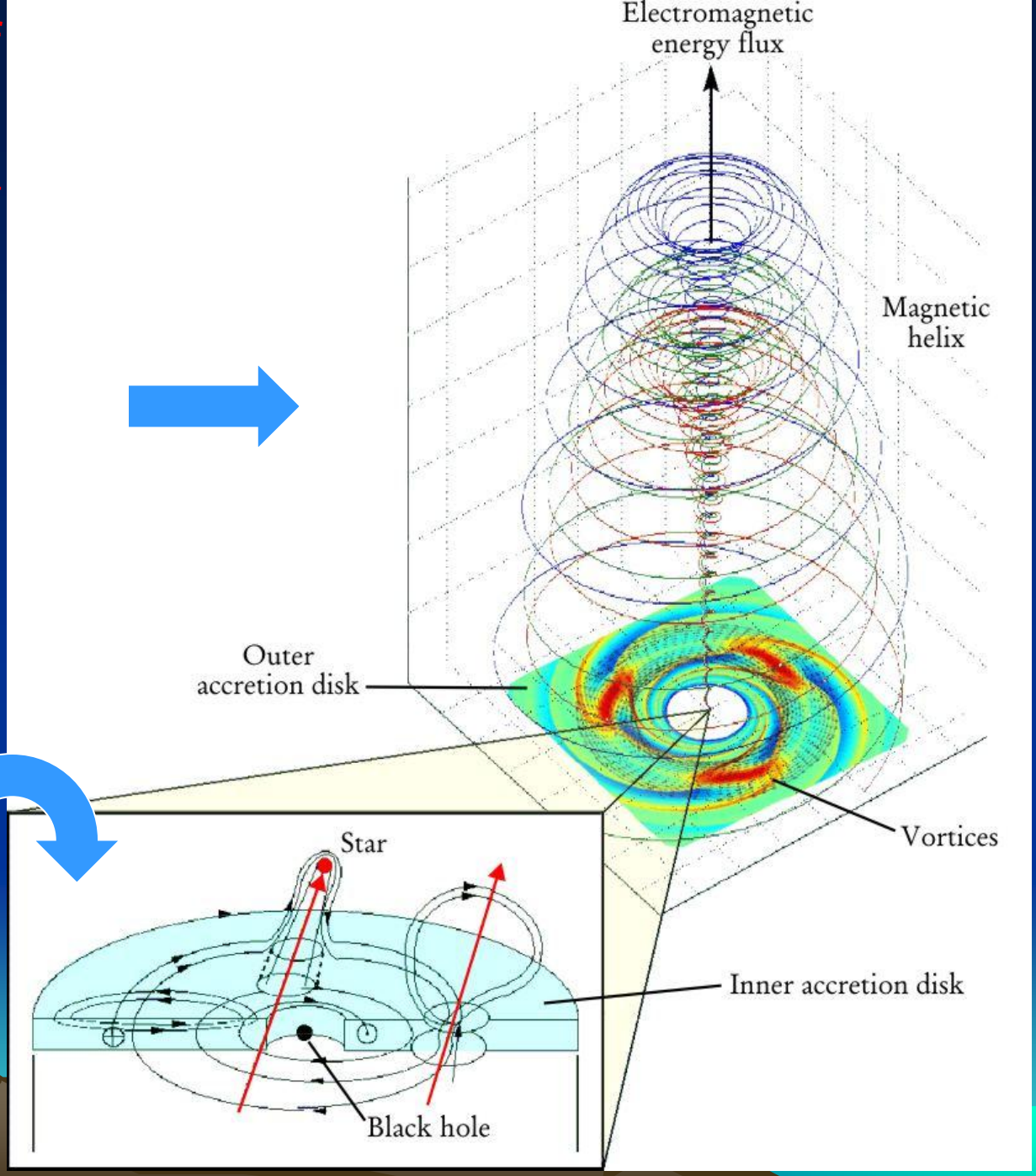
A.M. Beck, H. Lesch et al. A&A 2013, in press

“Los Alamos” suite of models for BH infall energy release into a Poynting flux-dominated jet

S. Colgate, H. Li, V. Pariev, 2001 Phys. of Plasmas 8, 2425

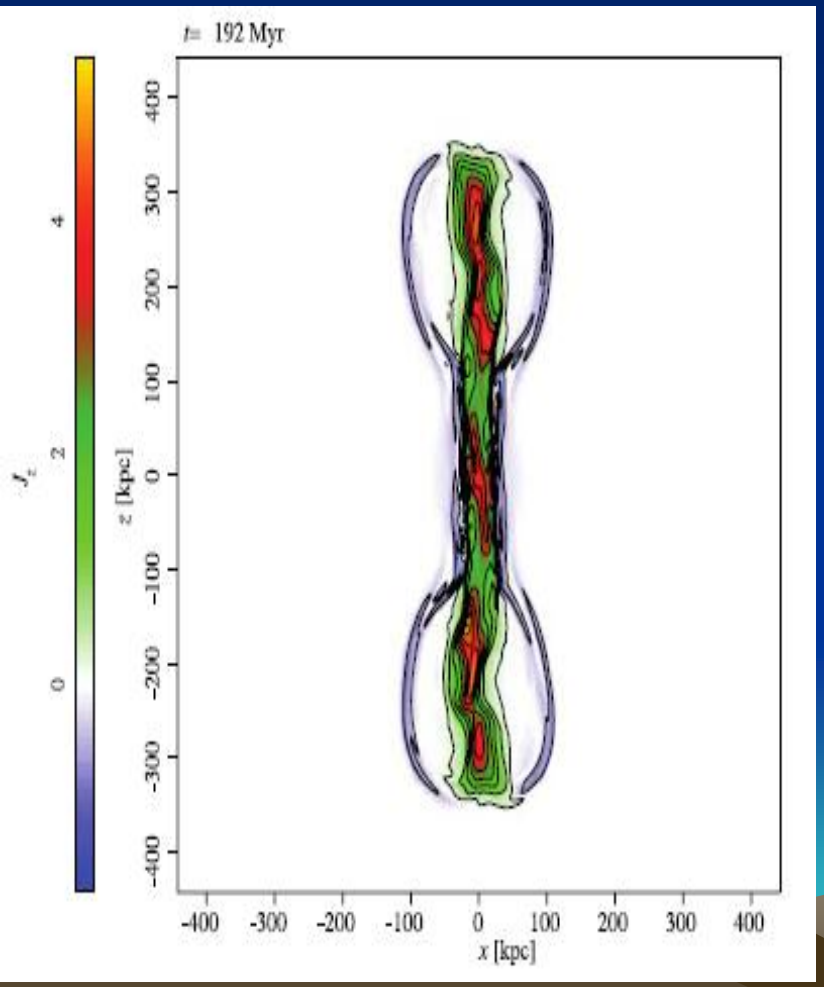
Li, Colgate, Wendroff, Liska 2001 ApJ 551, 874

Accretion disk dynamo (S.A. Colgate)



Simulated magnetic tower jet/lobe in a cluster environment

M. Nakamura, I.A. Tregillis, H. Li, S. Li ApJ **686** *843, 2008*



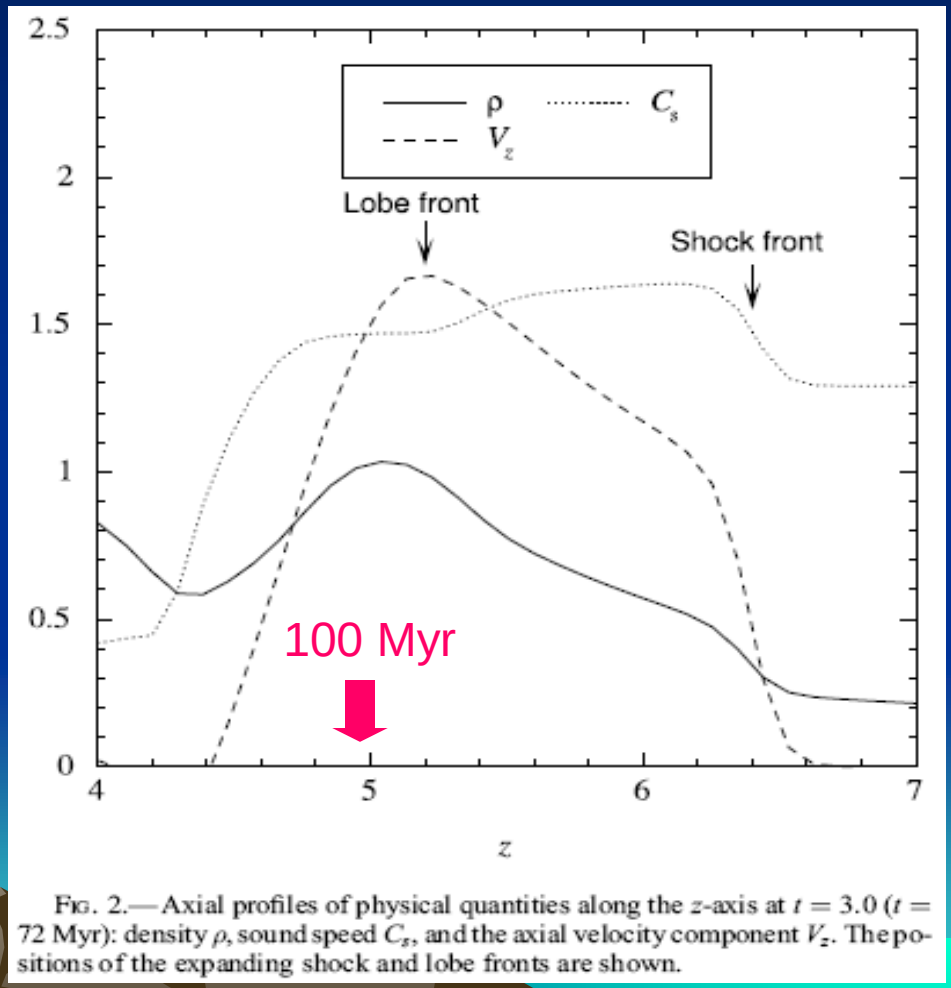
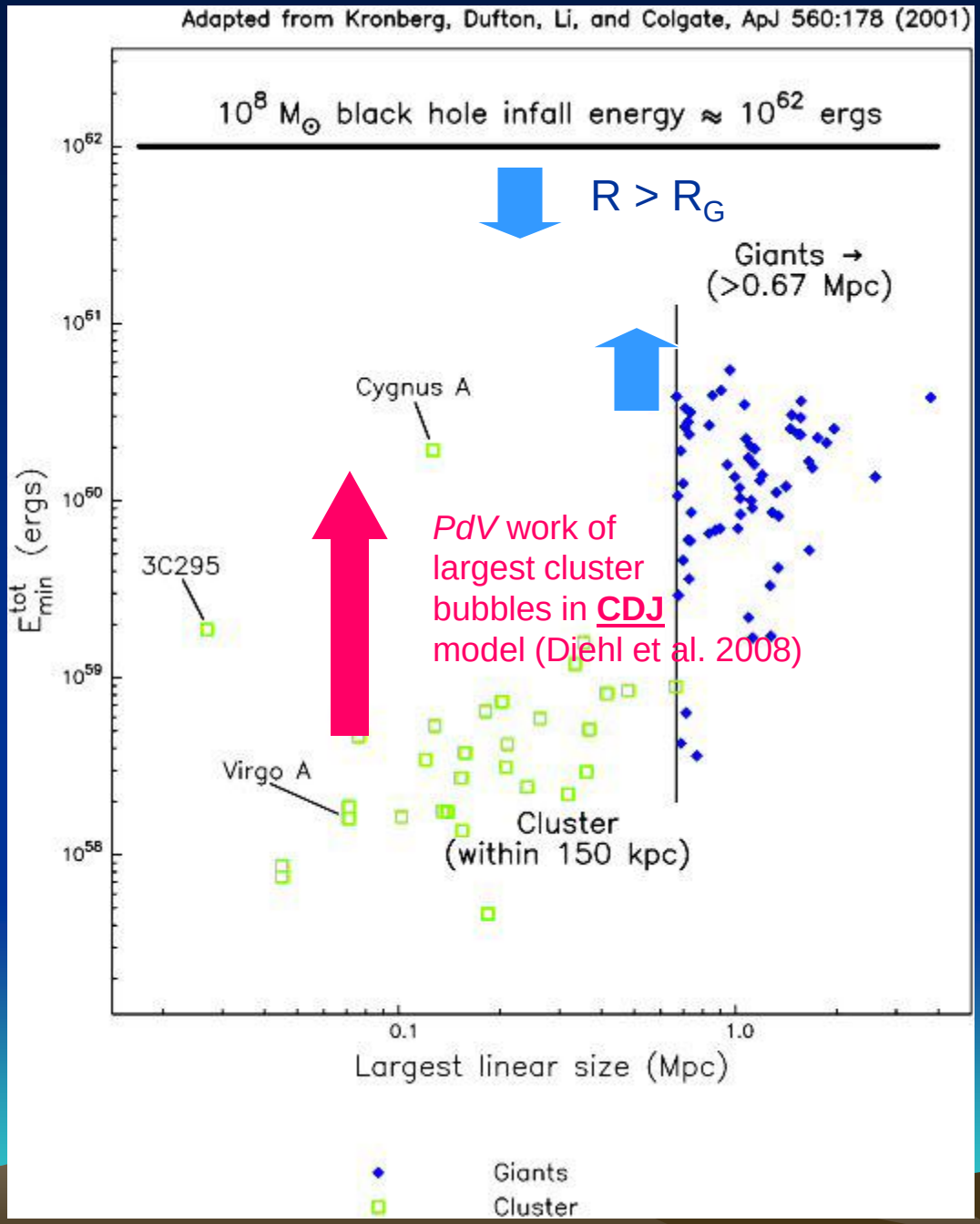


FIG. 2.—Axial profiles of physical quantities along the z-axis at $t = 3.0$ ($t = 72$ Myr): density ρ, sound speed C_s, and the axial velocity component V_z. The positions of the expanding shock and lobe fronts are shown.



$=M_{BH}c^2$

Mind the gap!!

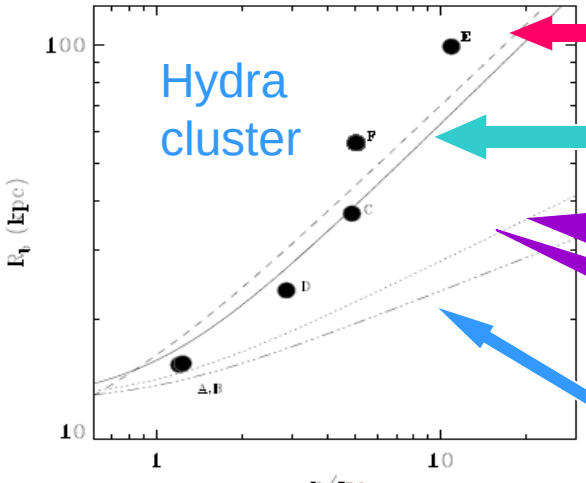
Accumulated energy $(B^2/8\pi + \varepsilon_{CR})$ x (volume) from ``mature'' BH-powered radio source lobes

GRG's
capture the highest fraction of the magnetic energy released to the IGM

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

Hydra cluster X-ray image:

Wise, M.W., McNamara, B.R., Nulsen, P.E.J, Houck, J.C., & David, L.P. ApJ ***659****, 1153, 2007*



S.Diehl, H. Li, C.Fryer, D. Rafferty 2008 ApJ

CIH continuous injection hydrodynamic model - - -

CDJ current-dominated MHD jet model

FML Bubbles contain frozen-in mag. loops

AD Γ=5/3, **AD Γ=4/3** Adiabatically expanding hydrodynamic models

FIG. 6.— *Left:* The multi-cavity system in Hydra A, reproduced from Wise et al. (2007) with permission from the authors. The black area is excess X-ray emission left-over after an elliptical surface brightness model has been subtracted. *Right:* Data Points: Bubble sizes for Hydra A as a function of distance to the center, taken from Wise et al. (2007); Lines show predictions from the AD53 (triple-dot dashed line), AD43 (dotted line), FML (also dotted line), CIH (dashed line), as well as the CDJ model (solid line). The cavity labels are the same in both plots.

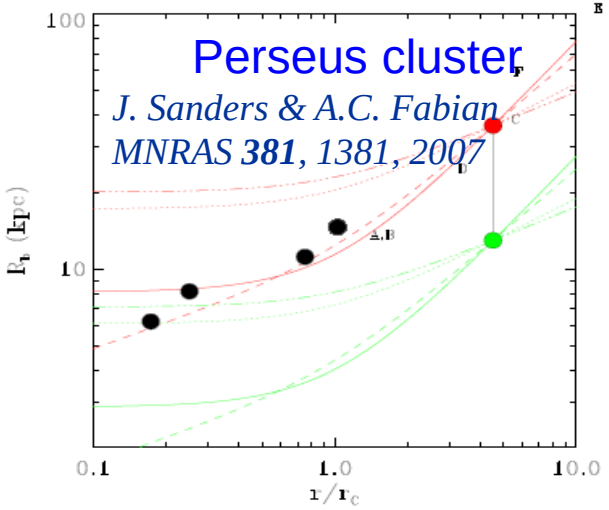


FIG. 7.— Bubble sizes for Perseus as a function of distance to the center. Lines as in Figure 6. The red data point shows the upper limit for the new bubble size estimate, the green data shows a lower limit. The correct answer will likely lie somewhere in between these two extremes.

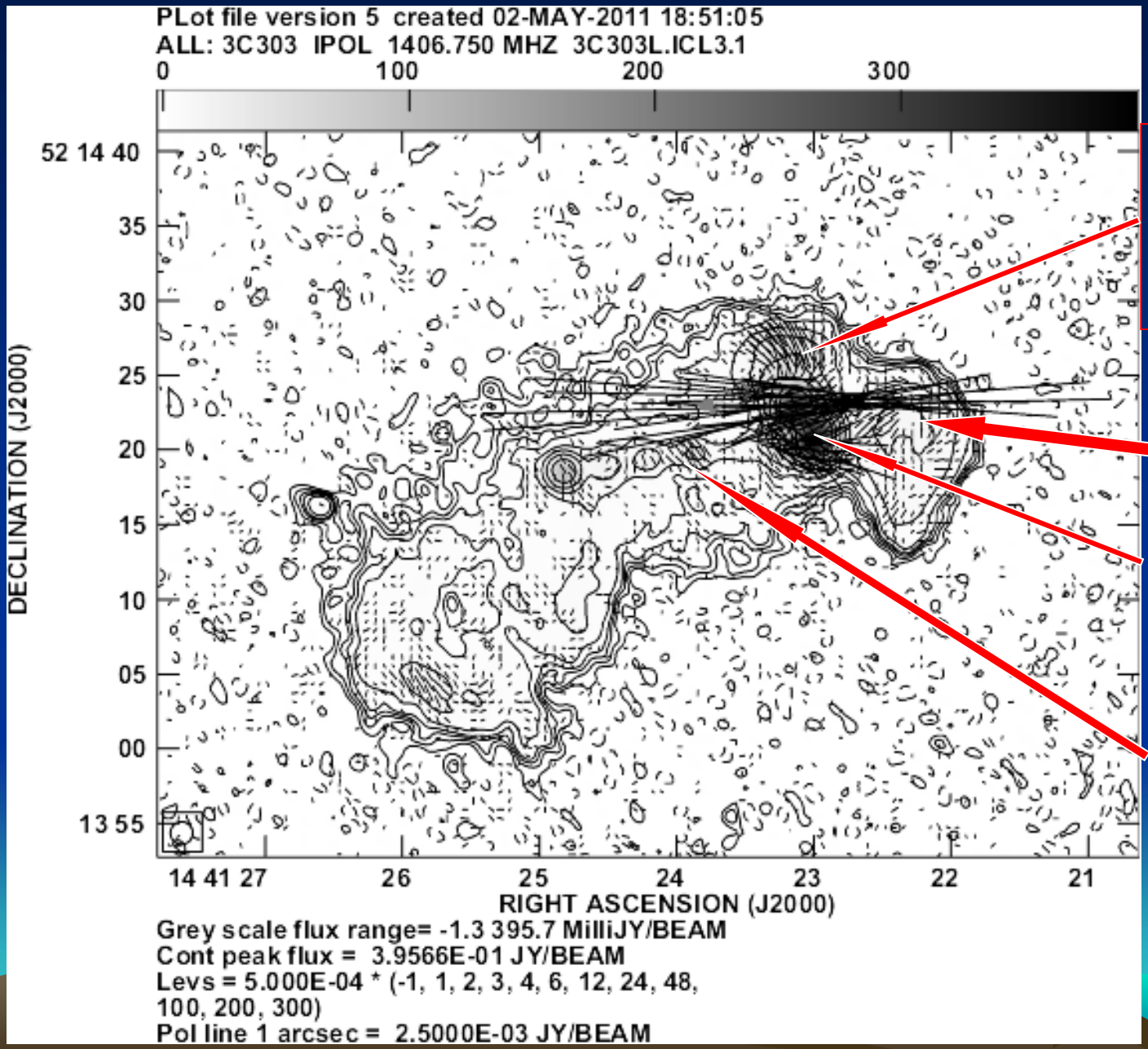
limits to the true location of the bubbles. This will not only affect the radii themselves, but also the point at which other quantities are evaluated at, like density, temperature and pressure. In general the temperature rises outward in these systems, thus the temperature at the location of the bubble is likely to be systematically underestimated. The density and ambient pressure on the other hand will always be overestimated. This also means that any rise times derived from using the projected radius rather than the true distance to the center will result in estimates for the rise times that are systematically too low. We also note that the smaller the observed radius is, the higher the probability that it is due to an effect caused by projection.

But there are more subtle effects that projection has on our data. As we do not have an automated tool to detect bubbles, one has to rely on human experience in finding and identifying these systems. This task is much more difficult, if the cavities overlap with the bright cluster center or the bubble on the opposite side of the cluster. In fact, our sample does not contain *any* cavity system in which the bubble size exceeds the projected distance to the center, the slope of which is shown by the black solid line in Figure 8, even though this is statistically very improbable. This suggests that our sample is affected by what we will refer to as a "geometric" selection effect, introduced by our manual detection process.

Effects of Sig/Noise and projection effects;
Enßlin & Heinz
A&A **384**, *L27, 2002*

Extragalactic jets as (V/U)HECR accelerators

3C303 1.4GHz

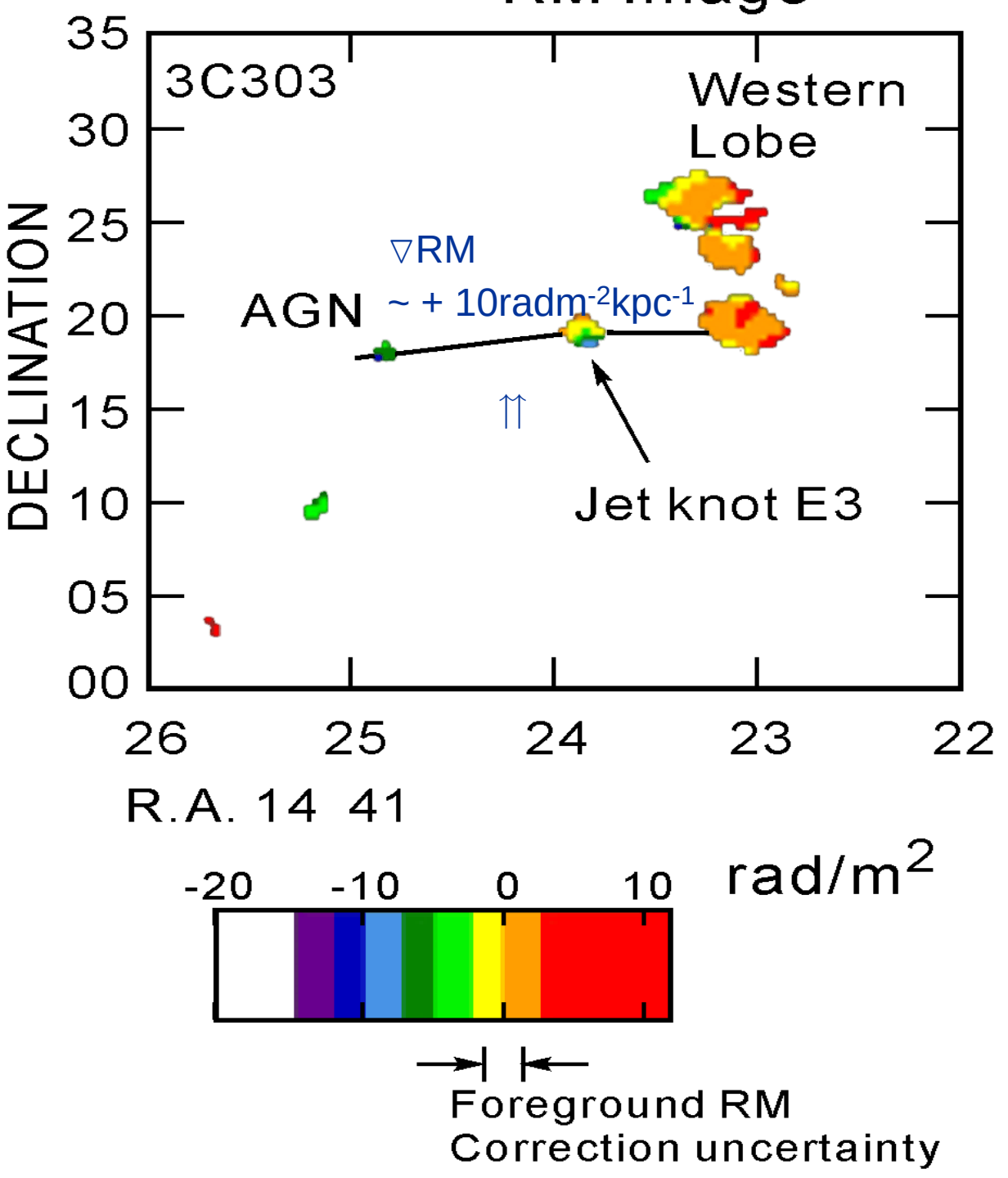


3 spheroid ``islands'' Each has high B – ordering & current signatures

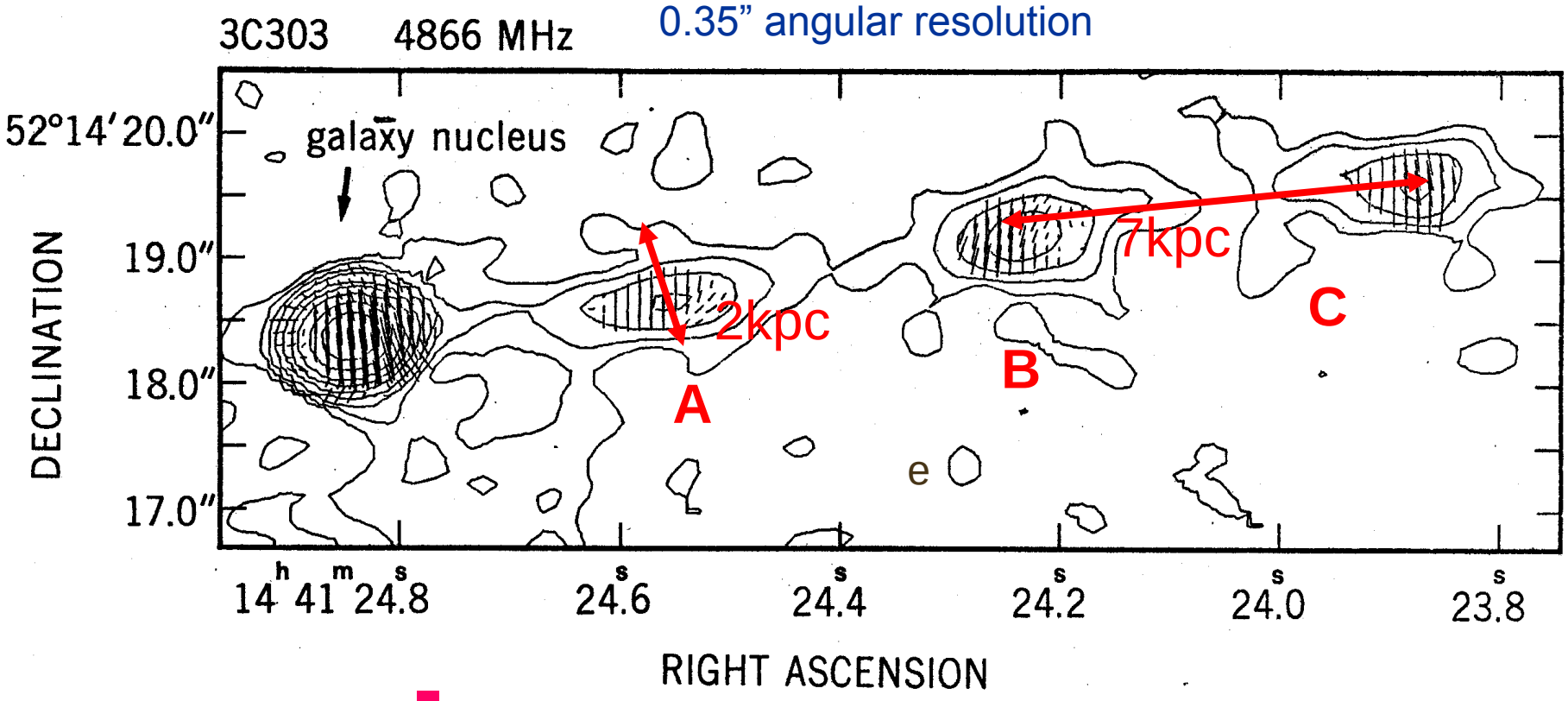
jet continues undeflected to here

jet disruption point

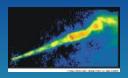
Knot ``E3' has a measured ∇RM vector


3C303
Western Lobe
AGN
▽RM
~ + 10radm-2kpc-1
Jet knot E3
DECLINATION
35
30
25
20
15
10
05
00
26
25
24
23
22
R.A. 14 41
-20
-10
0
10
rad/m2
Foreground RM
Correction uncertainty

VLA image



Compare scales!



M87 jet on the physical scale of 3C303

M87 knot cocoons are ~ 12,000 times smaller than those in 3C303!

SMBH-powered jets are very scale-independent systems!

Analysis gives straightforward electrical circuit analogues for BH energy transfer into ``empty'' space

P.P. Kronberg. R.V.E. Lovelace, G. Lapenta & S.A. Colgate
*ApJL **741**, L15 2011*
and
R.V.E. Lovelace, S. Dyda & P.P. Kronberg
Proc. Xth International Conf.on Gravitation, Astrophysics, and Cosmology: Ed. Roland Triay 2012 *LA-UR 12-01129*

- ***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 this case away from the BH
- Jet's electrical properties: (voltage, impedance, current)

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

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

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

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

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 These point 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.
- These results serve as pathfinders to future extensions of the above analyses:
  e.g.
  - **UHECR scattering from much more distant sources**
  - **Propagation time delays (~ 10^{4-5} yr to Cen A) for transient sources**
  - **The use of CR *magnetic lensing* signatures to attain tighter B_{IGM} constraints**
  - **Others**

Extragalactic jet-lobe sources as electrical circuit analogues

Kronberg, Lovelace, Colgate ApJL 2011

Upcoming papers:

Lovelace & Kronberg *MNRAS submitted*

Lovelace & Richardson *in prep*

End

Philipp Kronberg