Recent plasma and particle experiments on the sky:

Wider implications and future directions

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I. Energy transfer from an AGN Supermassive Black Hole to the IGM, and how to measure it – i.e. from an appropriate calorimeter

II. First measurement of a kpc-scale electric current in an extragalactic Black-Hole powered jet *LA-UR 11-10885*

III. Propagation of CR's through a magnetised intergalactic medium

Authors

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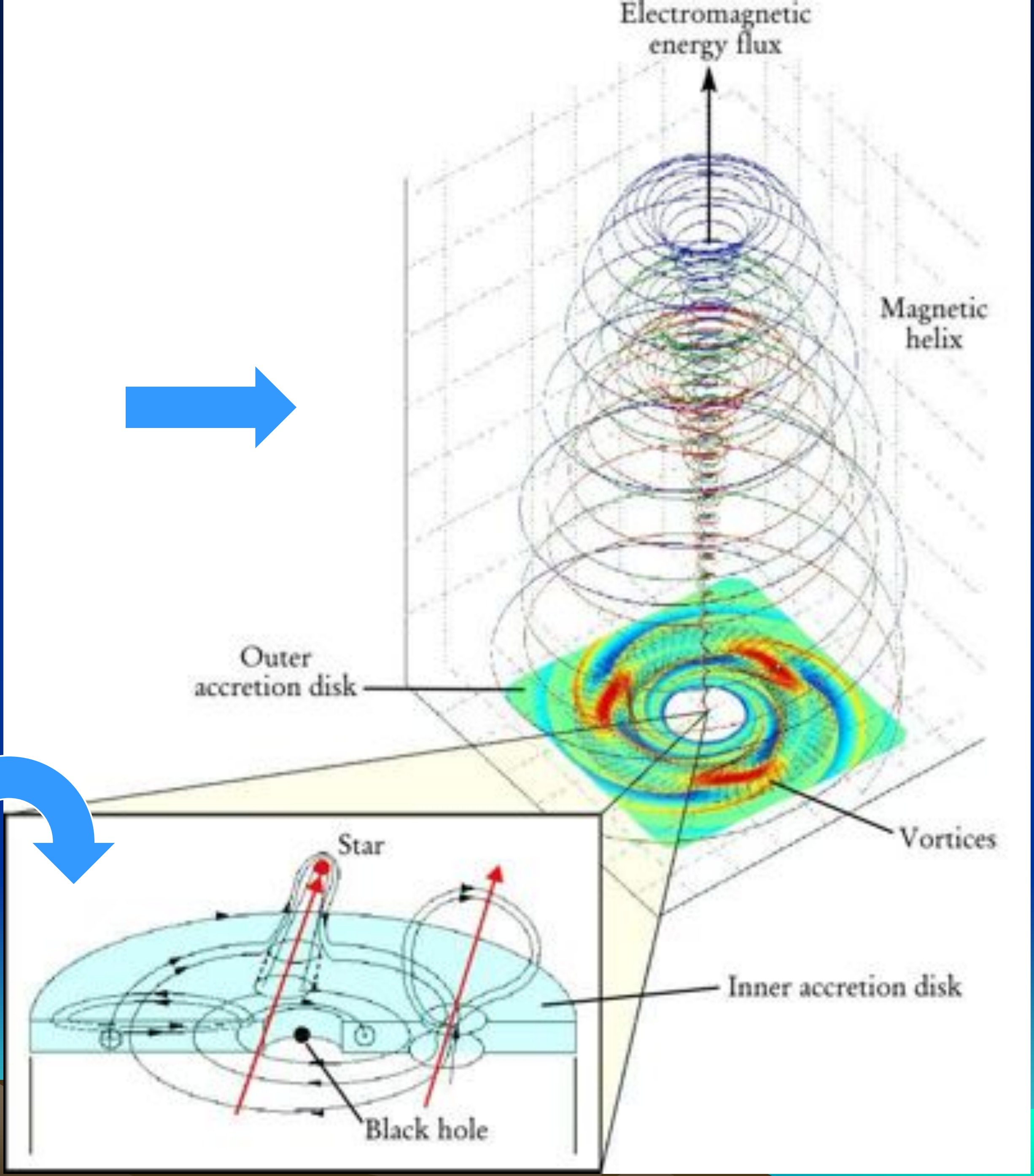
Philipp Kronberg, *LANL. Univ. of Toronto*

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

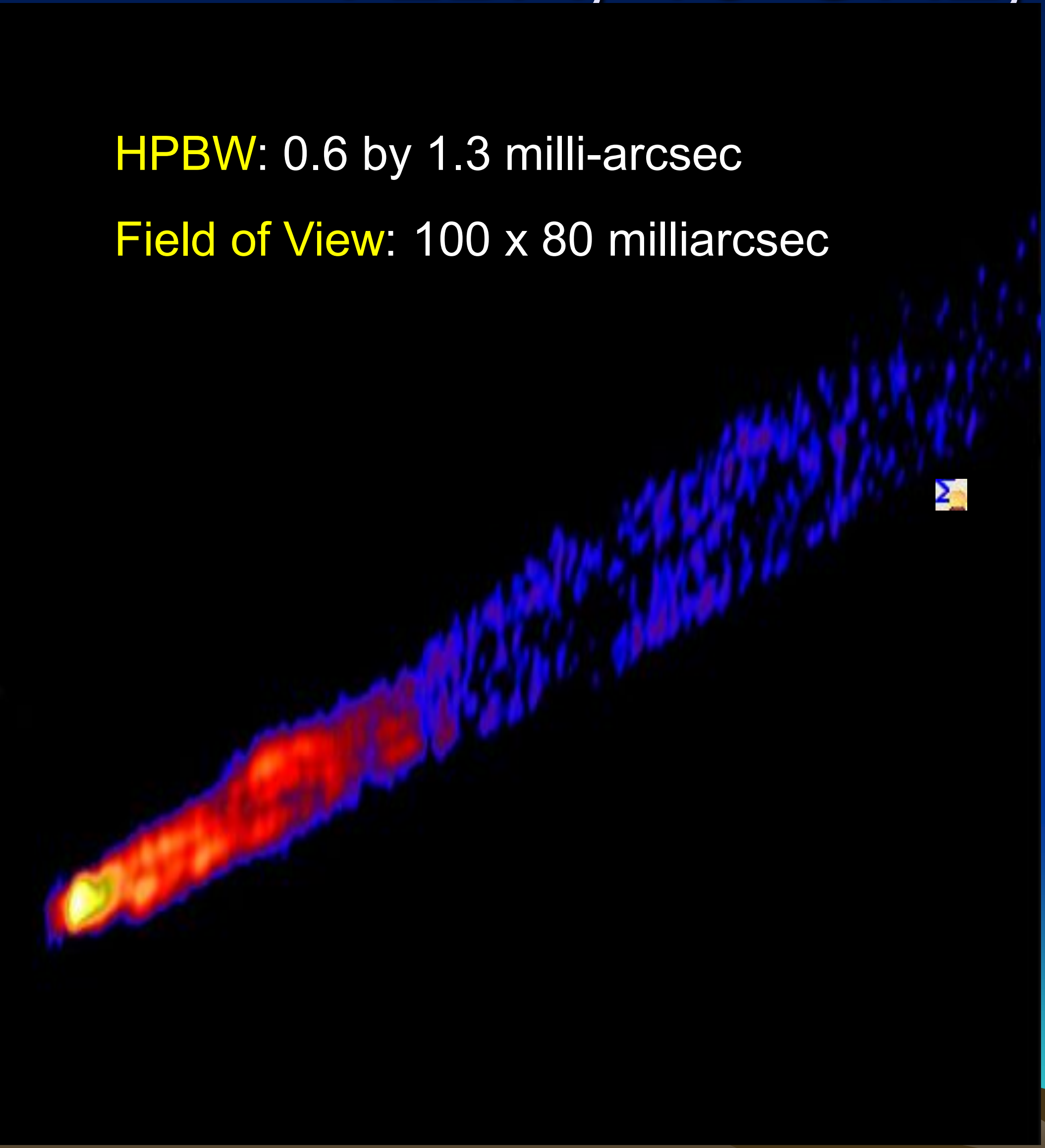
S. Colgate, H. Li,
V. Pariev, 2001
Phys. of Plasmas
8, 2425

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

Accretion disk
dynamo
(S.A. Colgate)



Virgo A jet at high resolution: VLBA, 15 GHz, epoch 2000



HPBW: 0.6 by 1.3 milli-arcsec

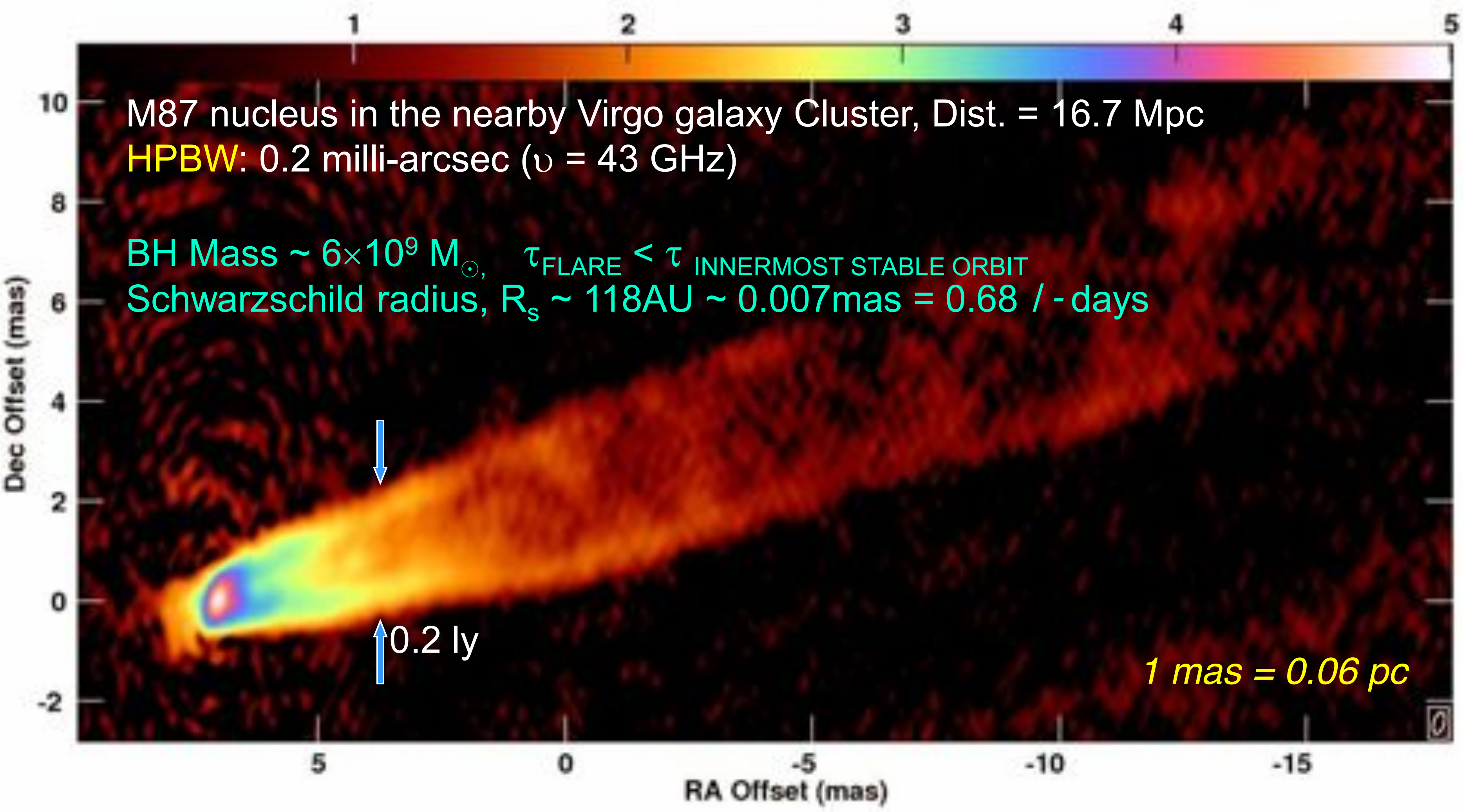
Field of View: 100 x 80 milliarcsec

Y. Y. Kovalev (MPIfR & ASC Lebedev),
M. L. Lister (Purdue U.),
D. C. Homan (Denison U.),
K. I. Kellermann (NRAO)

Sum of 23 VLBA images at 43 GHz

Veritas Collab,
NRAO VLBA M87 Monitoring Team,

H.E.S.S. Collab. & MAGIC Collab., Science, 325, 444, 2009



M87 nucleus in the nearby Virgo galaxy Cluster, Dist. = 16.7 Mpc
HPBW: 0.2 milli-arcsec (υ = 43 GHz)

BH Mass ~ $6\times10^{9}\ M_{\odot}$, $\tau_{FLARE} < \tau_{\text{INNERMOST STABLE ORBIT}}$
Schwarzschild radius, R_s ~ 118AU ~ 0.007mas = 0.68 / - days

0.2 ly

1 mas = 0.06 pc

Energetics of intergalactic fields deriving from central BH’s

and

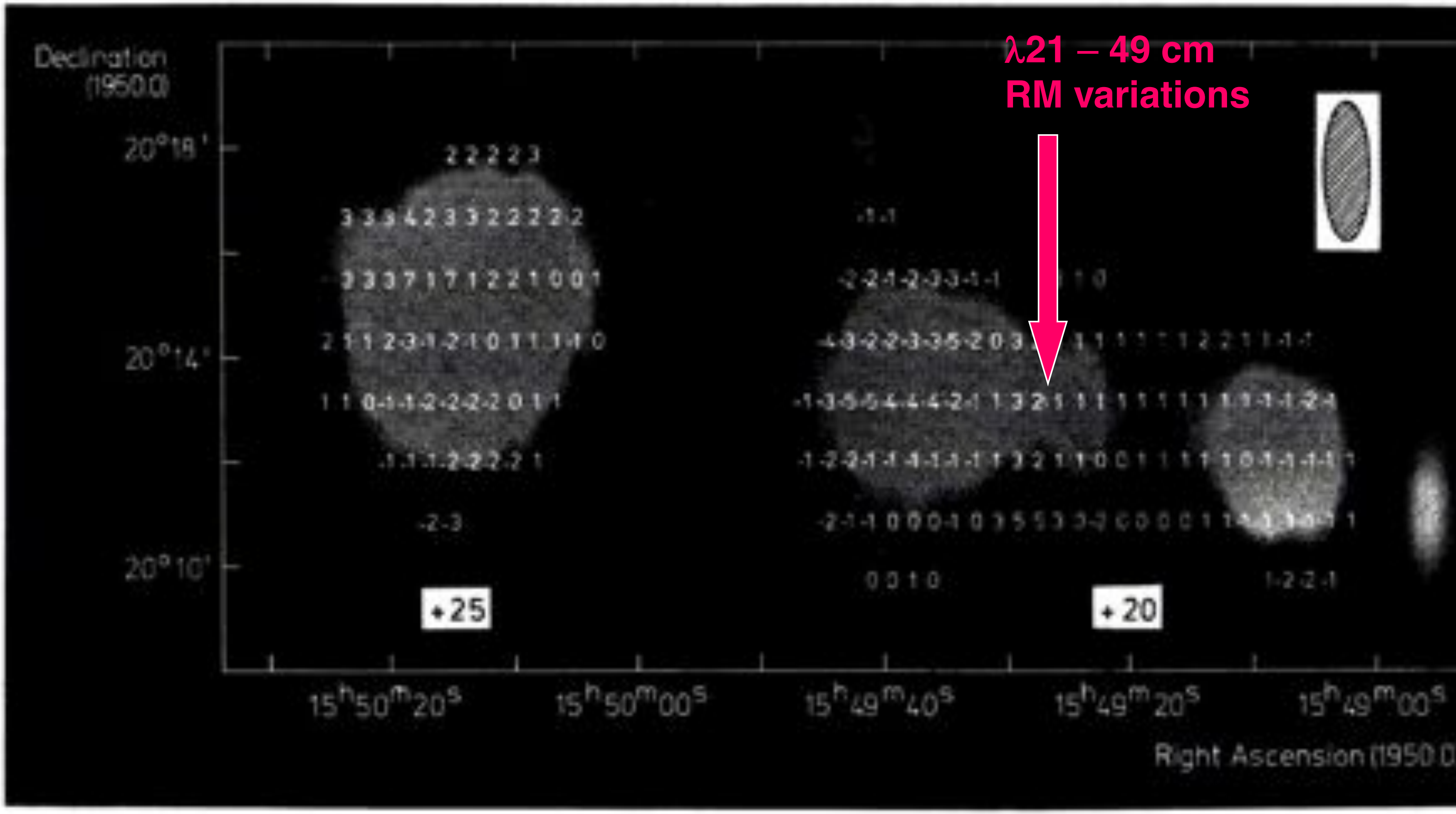
Probes of the thermal gas content of the giant lobes

Giant radio galaxies are the best calibrators of BH energy input to the IGM (magnetic + CR)

Example of a GRG – 3C326

Willis, A.G., & Strom, A.G. A & A 62, 375, 1978

A. G. Willis and R. G. Strom: Multifrequency Observations of 3C 326



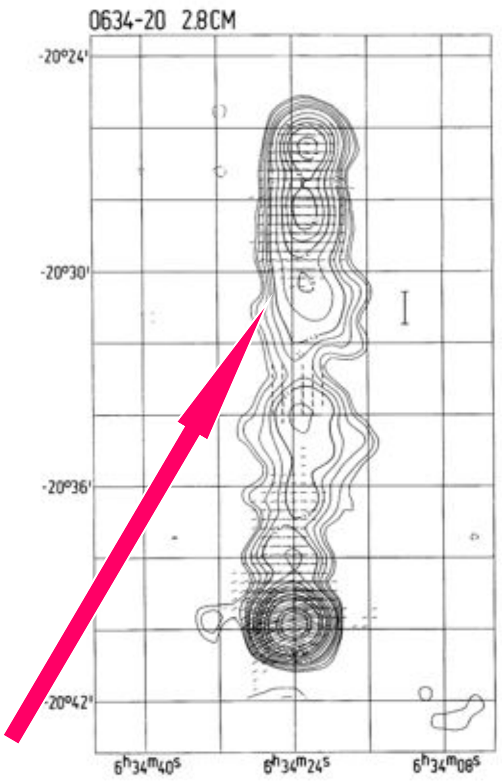
λ21 – 49 cm
RM variations

Fig. 8. The distribution of rotation measure over 3C 326 as computed from the 49 cm and 21 cm convolved data superposed upon photograph" of the 49 cm total intensity. Note that to produce a simple grid of single digit numbers we have subtracted integrated measures, whose derivation is described in the text, of $+25$ rad m^{-2} and $+20$ rad m^{-2} from the values measured at individual sample the east and west components respectively. For reference, these integrated values are displayed under each component

Indications for distributed acceleration of CR's within Mpc-sized (intergalactic) radio lobe volumes *Kronberg, Colgate, Li & Dufton ApJ 2004*

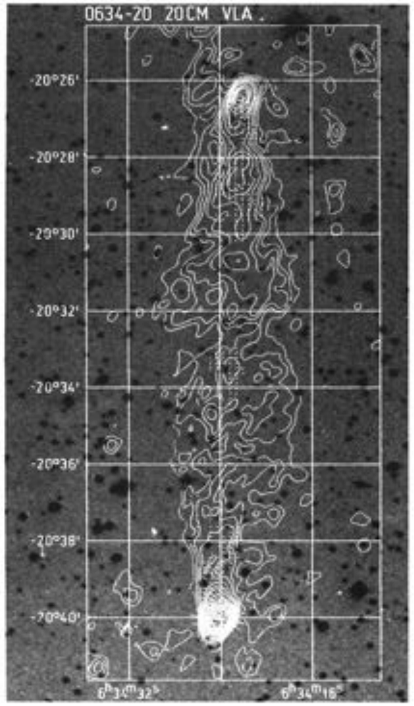
a "template" for widespread IGM CR acceleration??

10 GHz



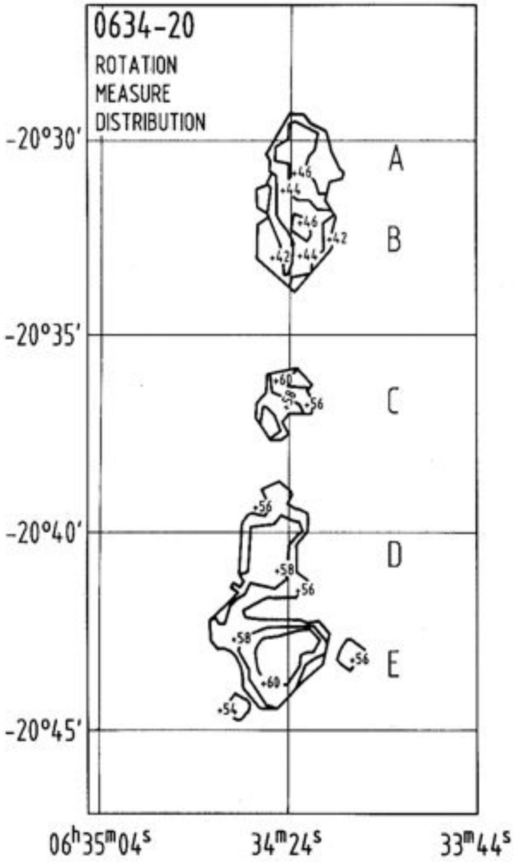
Effelsberg 100m.
Telescope 10.6 GHz

1.4 GHz



VLA 1.4GHz

Faraday RM(radians/m^2)



Kronberg, Wielebinski & Graham
***A&A* 169**, 63, 1986

Freshly accelerated, starved of thermal plasma?

→UHECR acceleration source?

$$E \approx 10^{19}\left(\frac{B}{3\,\mu\mathrm{G}}\right)\left(\frac{L}{1\ \mathrm{Mpc}}\right)\ \mathrm{eV}$$

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

BH (magnetic + CR) energy output ($\gtrsim 10^{60}$ ergs) is "captured" within a few Mpc, *compare with efficiency of* η (photons), $\approx$ 10%of $M_{BH}c^2$ (<u>not</u> captured) appears comparable to η (CR + B),

2147+816 giant radio galaxy

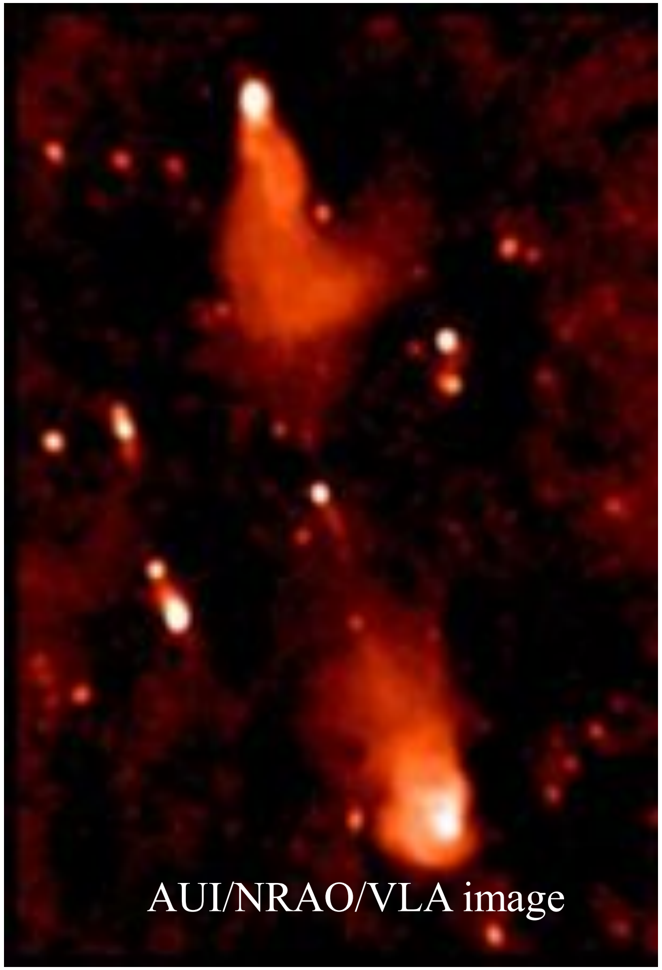
Analysis of ≈ 70 GRG images
Kronberg, Dufon, Li, Colgate
ApJ 2001

z=0.146

2.6 Mpc

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

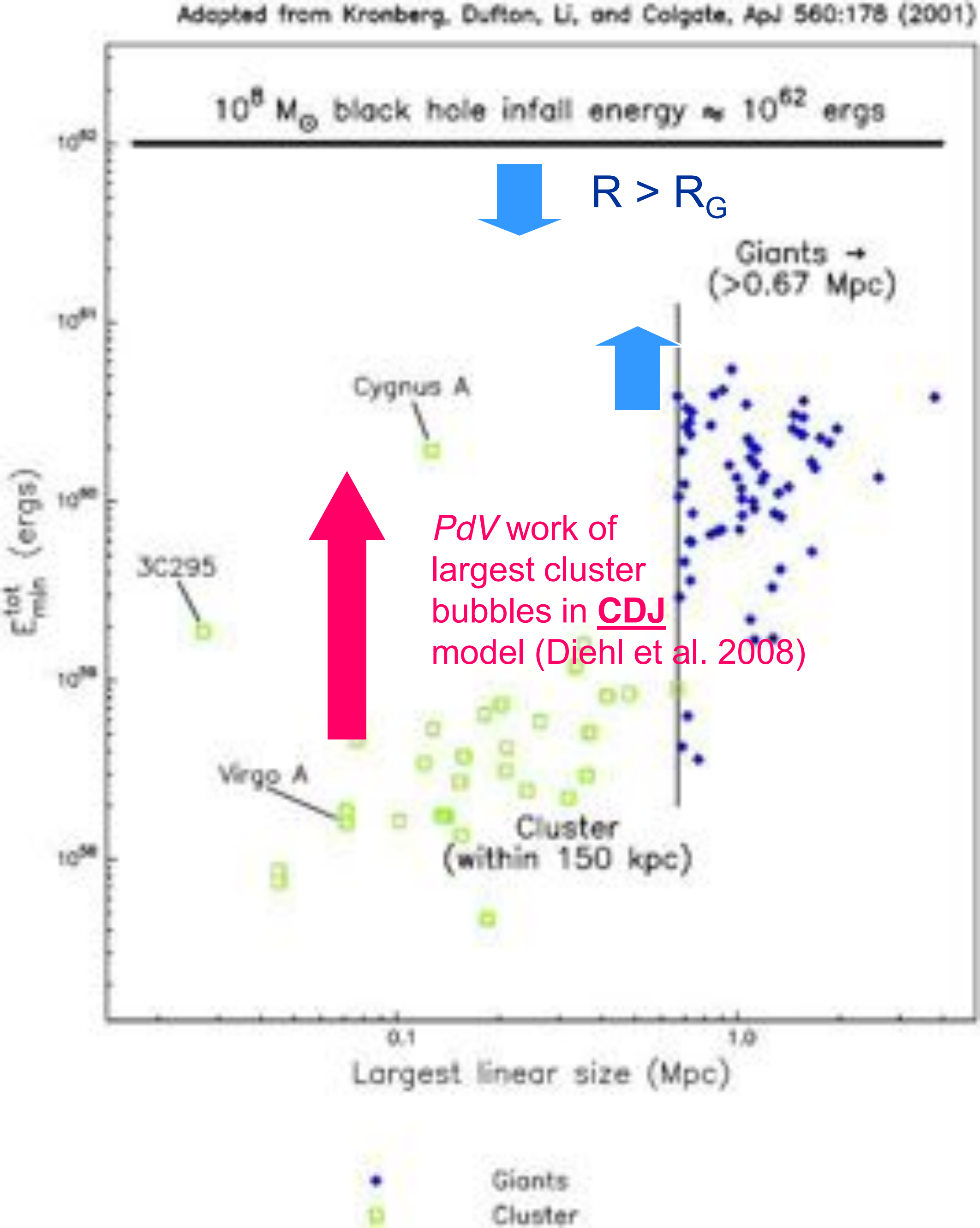
- Willis & Strom, 1978,80
- Kronberg, Wielebinski & Graham.1986,
- Mack *et al.* A&A 329, 431, 1998
- Schoenmakers *et al.* 1998,2000
- Subrahmanian *et al*. 1996
- Feretti *et al* 1999
- Lara *et al*. 2000
- Palma *et al*. 2000



AUI/NRAO/VLA image

The energy story

Adapted from Kronberg, Dufton, Li, and Colgate, ApJ 560:178 (2001)



$R > R_G$

PdV work of largest cluster bubbles in **CDJ** model (Diehl et al. 2008)

$= M_{BH}c^2$

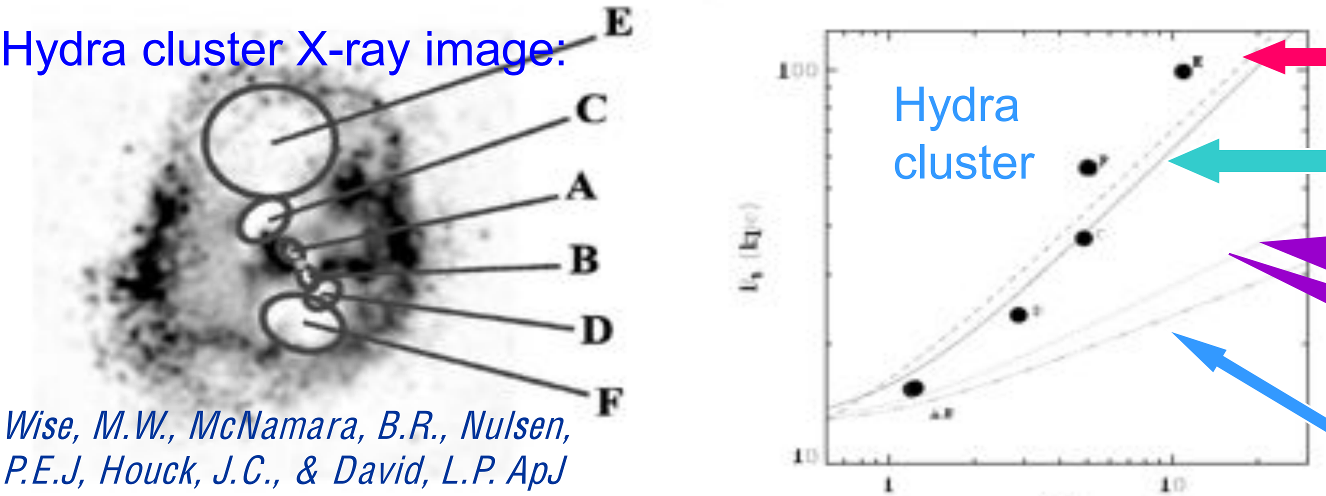
Mind the gap!!

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

Hydra cluster

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

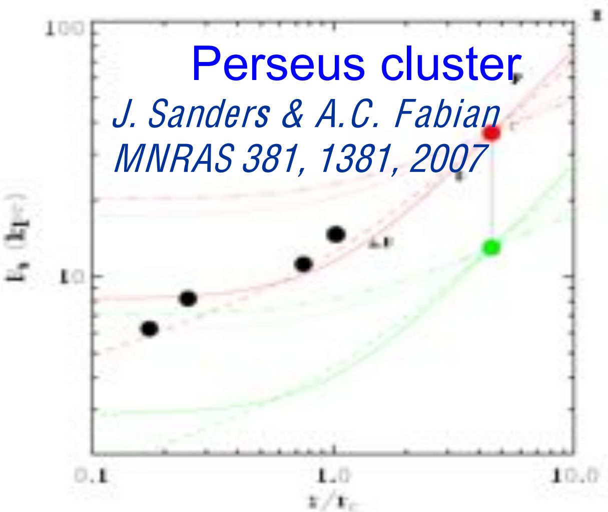
CIH continuous injection hydrodynamic model - - -

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.



Perseus cluster

J. Sanders & A.C. Fabian MNRAS 381, 1381, 2007

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.

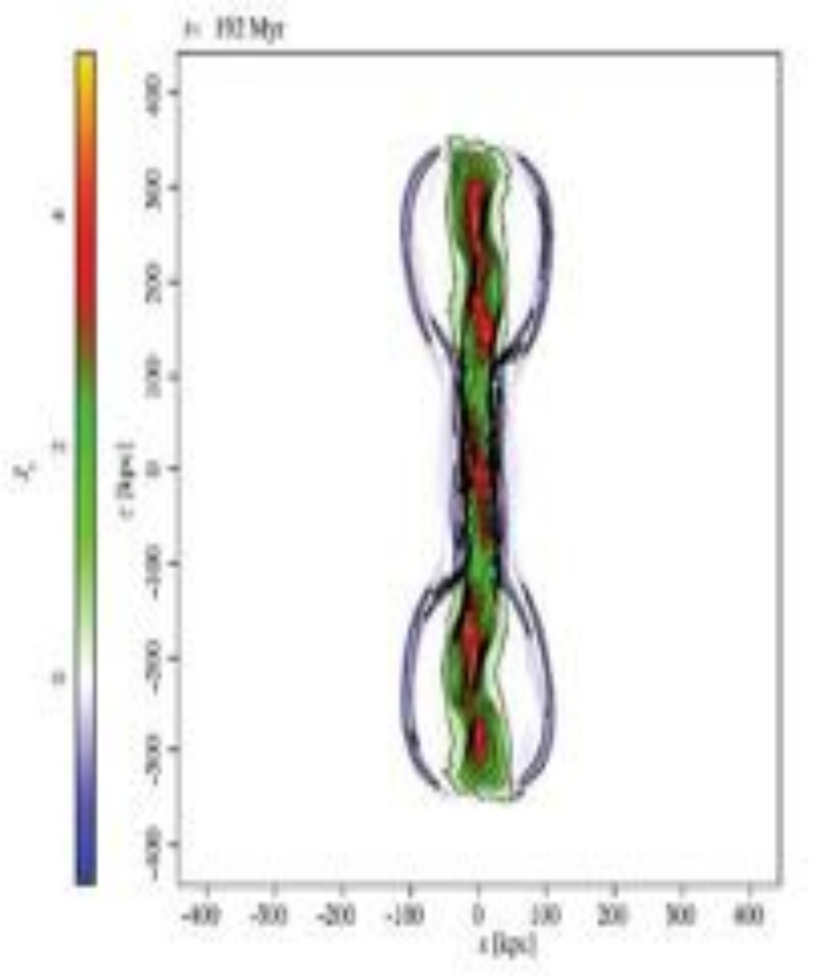
limits to the true location of the bubbles. This will not only affect the radii themselves, but also the point at which other quantities are evaluated at, like density, temperature and pressure. In general the temperature rises outward in these systems, thus the temperature at the location of the bubble 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*

Simulated magnetic tower jet/lobe in a cluster environment

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



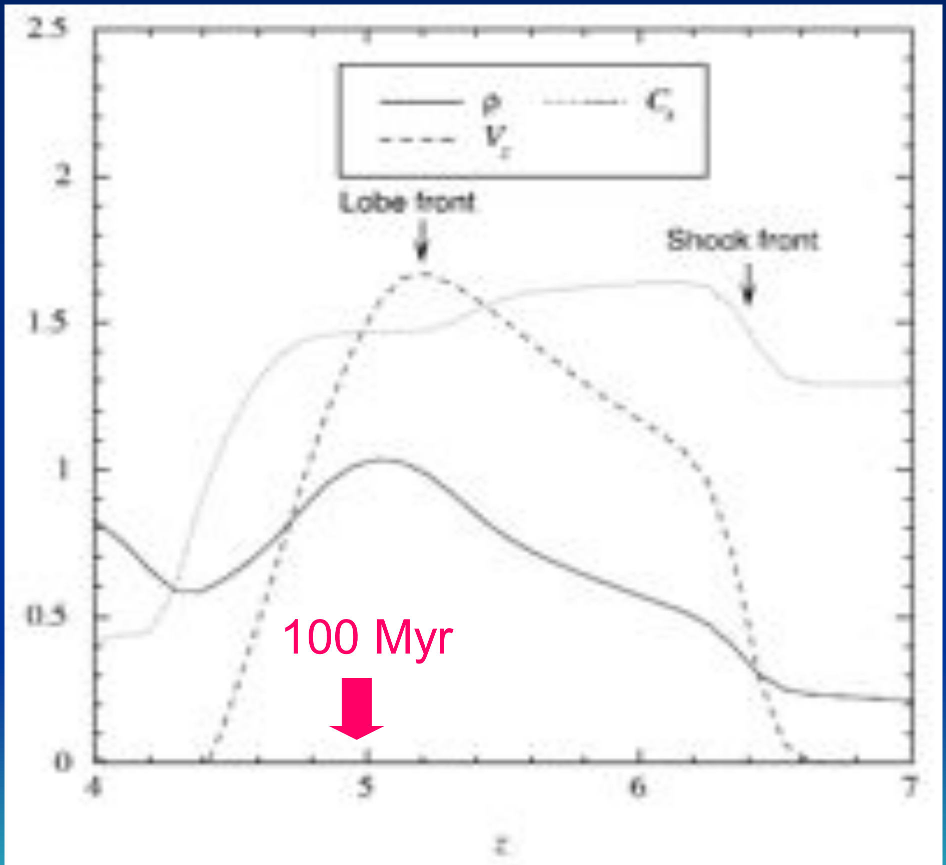


Fig. 2.—Axial profiles of physical quantities along the z-axis at $t = 3.0$ ($t =$ 72 Myr): density ρ, sound speed C_s, and the axial velocity component V_z. The positions of the expanding shock and lobe fronts are shown.

IGM magnetic energy supplied by central galactic black holes

Can be (globally) quantified

A global, observation-based calculation:

Average BH density (for $M_{BH} \gtrsim 10^6 M_\odot$)

$$< \rho_{BH} \geq 2\times10^5\, M_\odot / Mpc^3$$

Gravitational energy reservoir per BH (scaled for infall to R_G)

$$M_{BH}c^2 = 1.8\times10^{62}\,\frac{M_{BH}}{10^8\, M_\odot}\, ergs$$

This leads to an average magnetic energy density, ε_B supplied to the IGM

from supermassive black holes (SMBH).

if no *B*-dissipation over ~ a Hubble time

Smoothed-out SMBH magnetic energy reservoir

$$\varepsilon_{\mathrm{B}} = 1.36\times10^{-15}\left(\frac{\eta_{\mathrm{B}}}{0.1}\right)\times\left(\frac{f_{\mathrm{RG}}}{0.1}\right)\times\left(\frac{f^{VOL}{}_{\mathrm{FILAMENTS}}}{0.1}\right)^{-1}\times\left(\frac{M_{\mathrm{BH}}}{10^{8}M_{\odot}}\right)\ \mathrm{erg\ cm^{-3}}$$

Gives $$B^{\mathrm{BH}}_{\mathrm{IG}} = \sqrt{8\pi\varepsilon_{\mathrm{B}}} = 1.8\times10^{-7}\ \mathrm{G}$$

- Magnetic energy initially captured within galaxy filaments of LSS

Conclusion:

i.e. IGM near galaxies should contain magnetic energy ≈ ε_B

- ***Next:***

Other observational tests for ε_B in the IGM

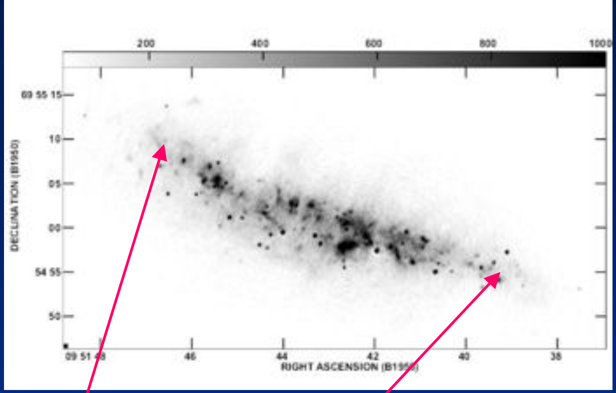
Stellar/SN-driven galaxy outflows

Outflow to IGM from the M82 starburst galaxy (3 Mpc distant)

Outflow halo:

$B_{halo} \sim 10\mu G$

coherence scale
1 – 2 kpc

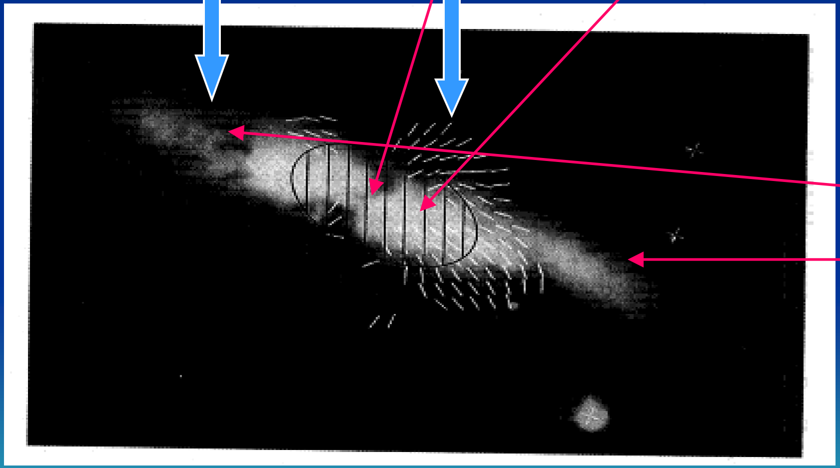


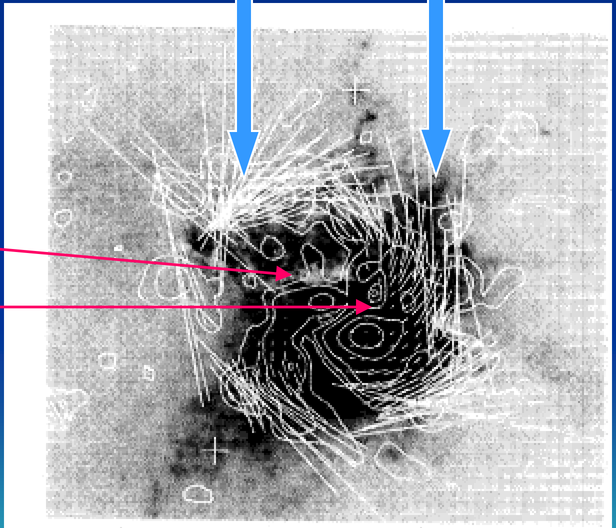
VLA, All-config, 5 & 8 GHz, ~0.3" resolution
*Kronberg, P.P. Biermann, P.L. Schwab, F.R. ApJ **246**, 751, 1981.*
and
Allen & Kronberg, 8GHz shown

Optical image

De-Faraday rotated, projected magnetic field lines From λλ 3.6 & 6.2 cm

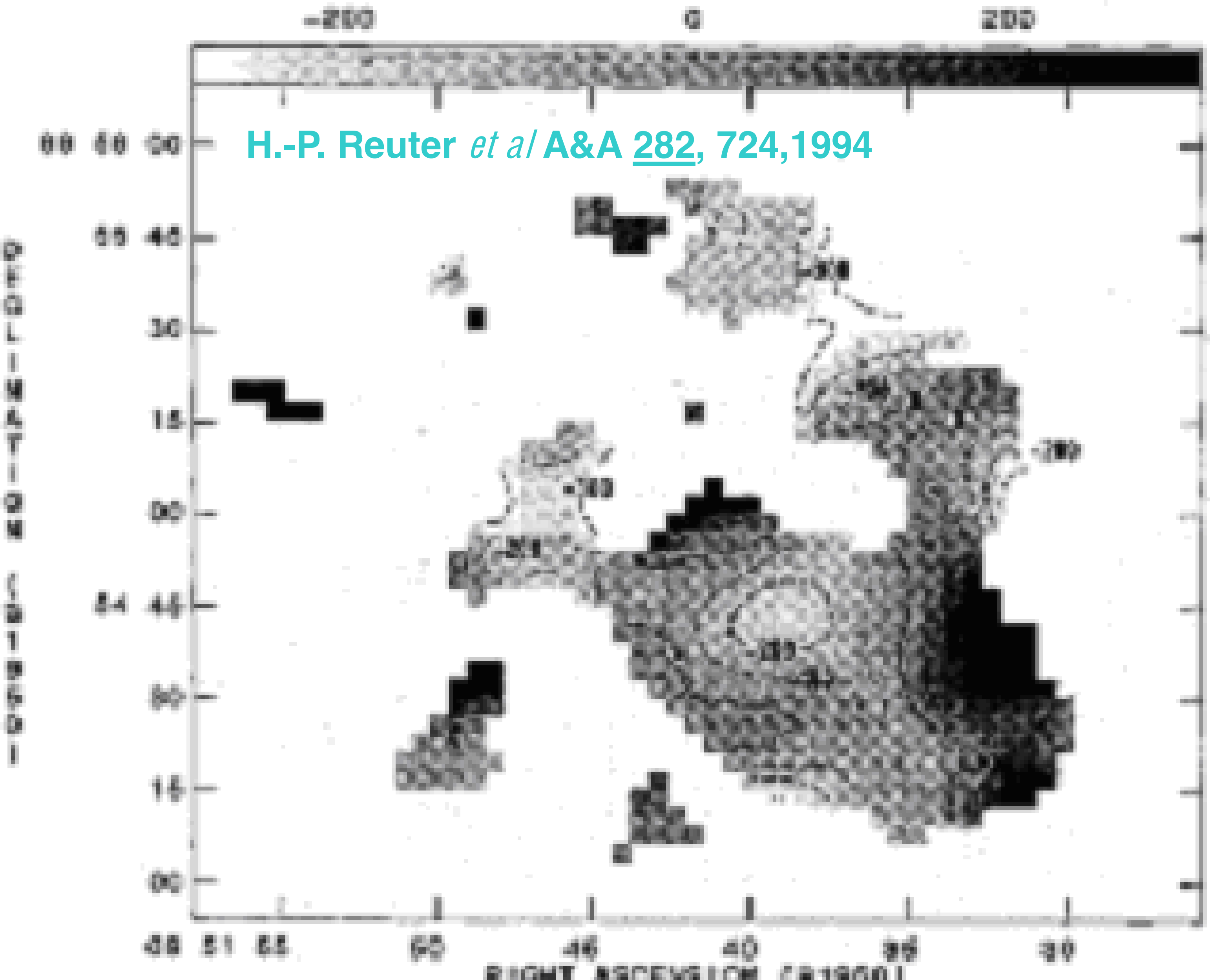
Pol'n intensity Hα emission





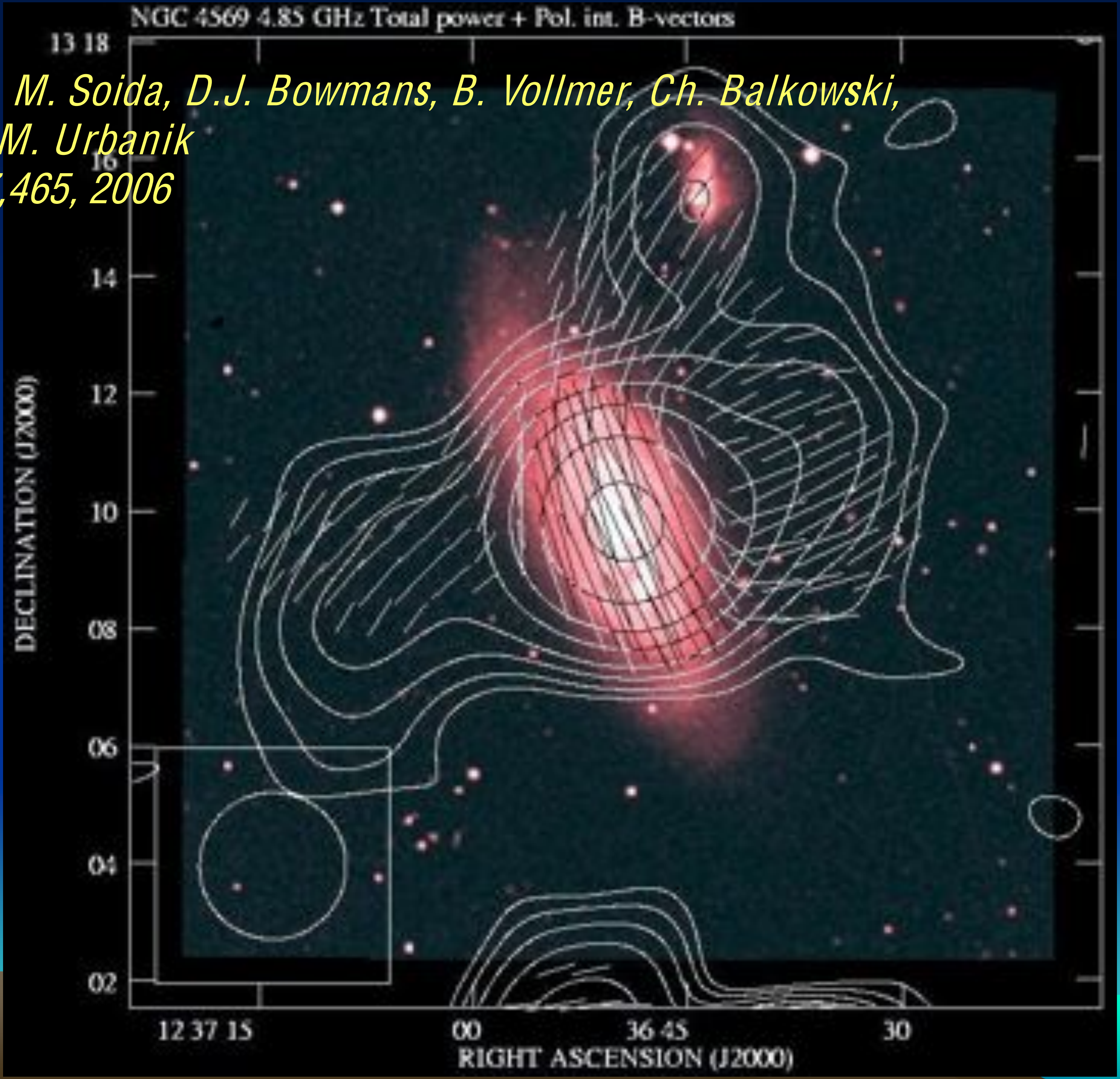
*Reuter, H.-P., et al.. A&A, **282**, 724, 1994, [A&A **293**, 287, 1995 - Figs. with corrected orientation].*

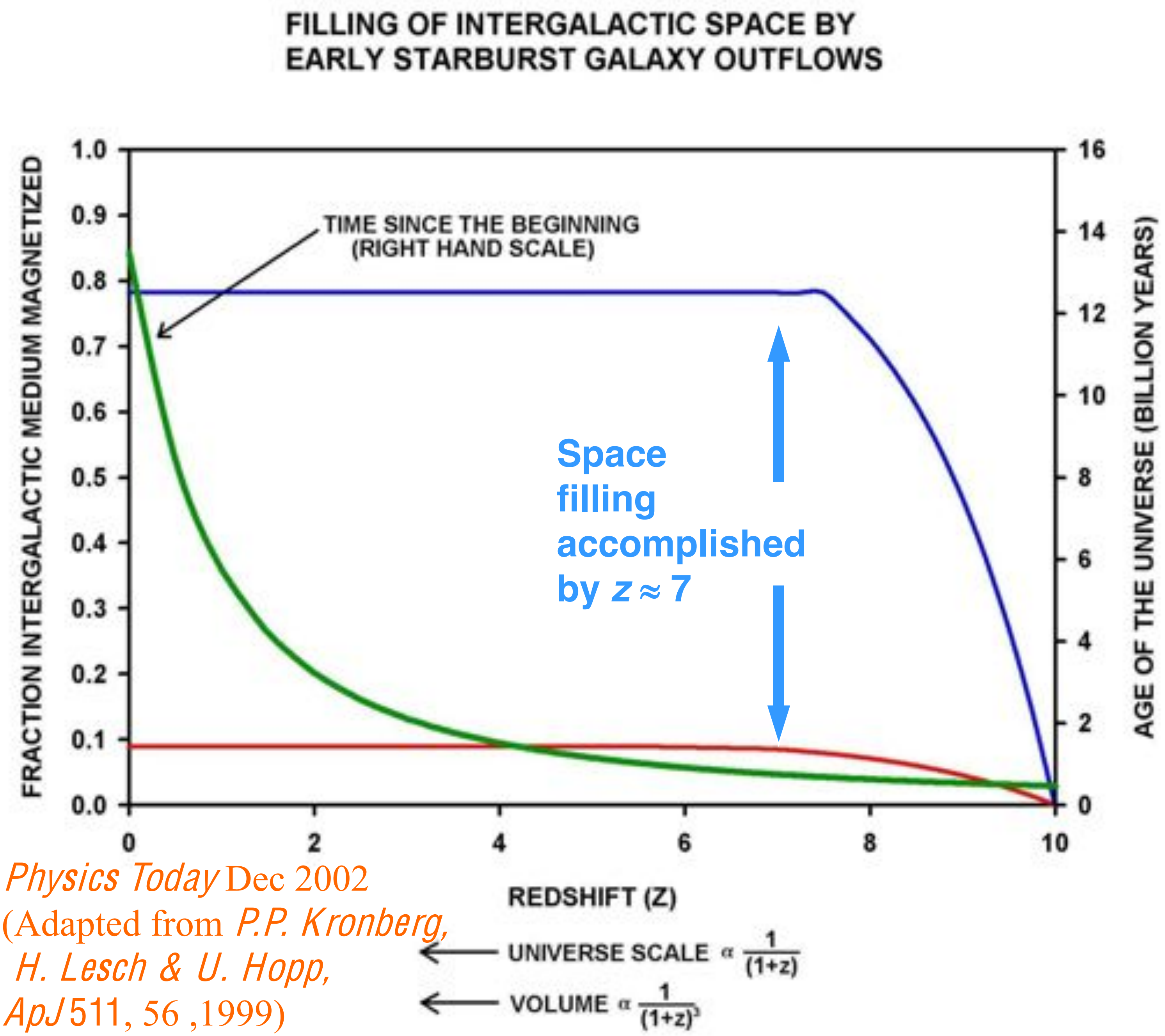
M82 Rotation Measure image in M82's halo



H.-P. Reuter *et al* **A&A <u>282</u>, 724,1994**

K. Chyzy, M. Soida, D.J. Bowmans, B. Vollmer, Ch. Balkowski,
R. Beck, M. Urbanik
A&A 347,465, 2006

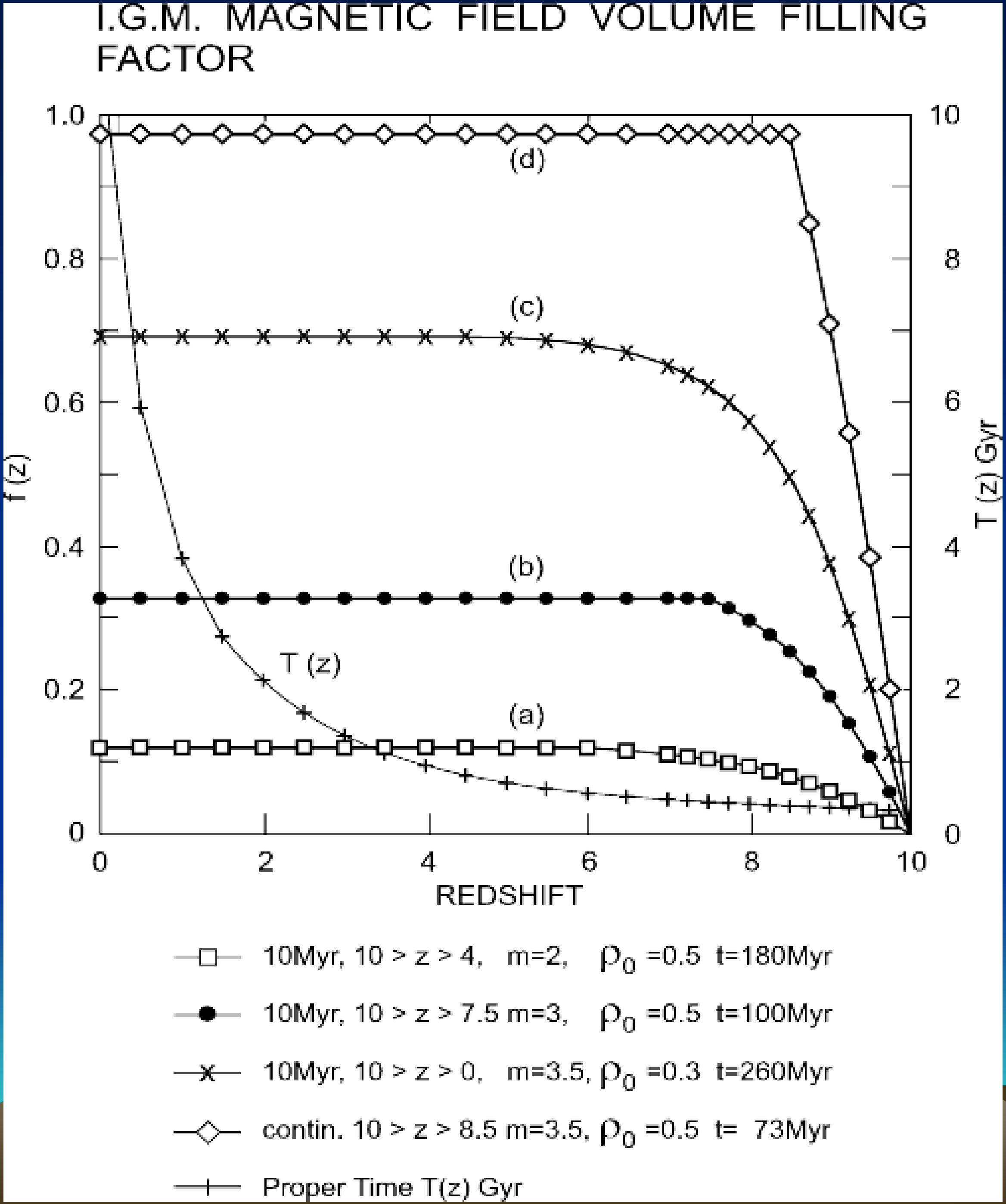




Space filling accomplished by $z \approx 7$

Physics Today Dec 2002
(Adapted from *P.P. Kronberg, H. Lesch & U. Hopp, ApJ* 511, 56 ,1999)

RESULTS & CONCLUSIONS



IGM MAG FIELD
SEEDED
by
STARBURSTING
PRIMEVAL GALAXIES

Figure from:
P. Kronberg, H. Lesch & U. Hopp ApJ , 511, 56-64, 1999

A starting
template for
full simulations

Conclusion:

Galactic star/SN driven outflows *alone*
can magnetize a significant
fraction of the IGM from $z \sim 12 \rightarrow 0$

Dwarf galaxies at large z are significant contributors

Supermassive BH-driven magnetization of the IGM

Posterior indicators of AGN –produced intergalactic <B>

Deep imaging of diffuse synchrotron radiation

Arecibo telescope (USA)

+

DRAO synthesis telescope
(Canada)

Arecibo 305m Telescope, PR

2 mm rms optics

illuminated area ≈ 200m

uv overlap with DRAO ≈ 200m

Dominion Radio Astrophysical Observatory
Penticton BC, Canada

Precision track (E-W)

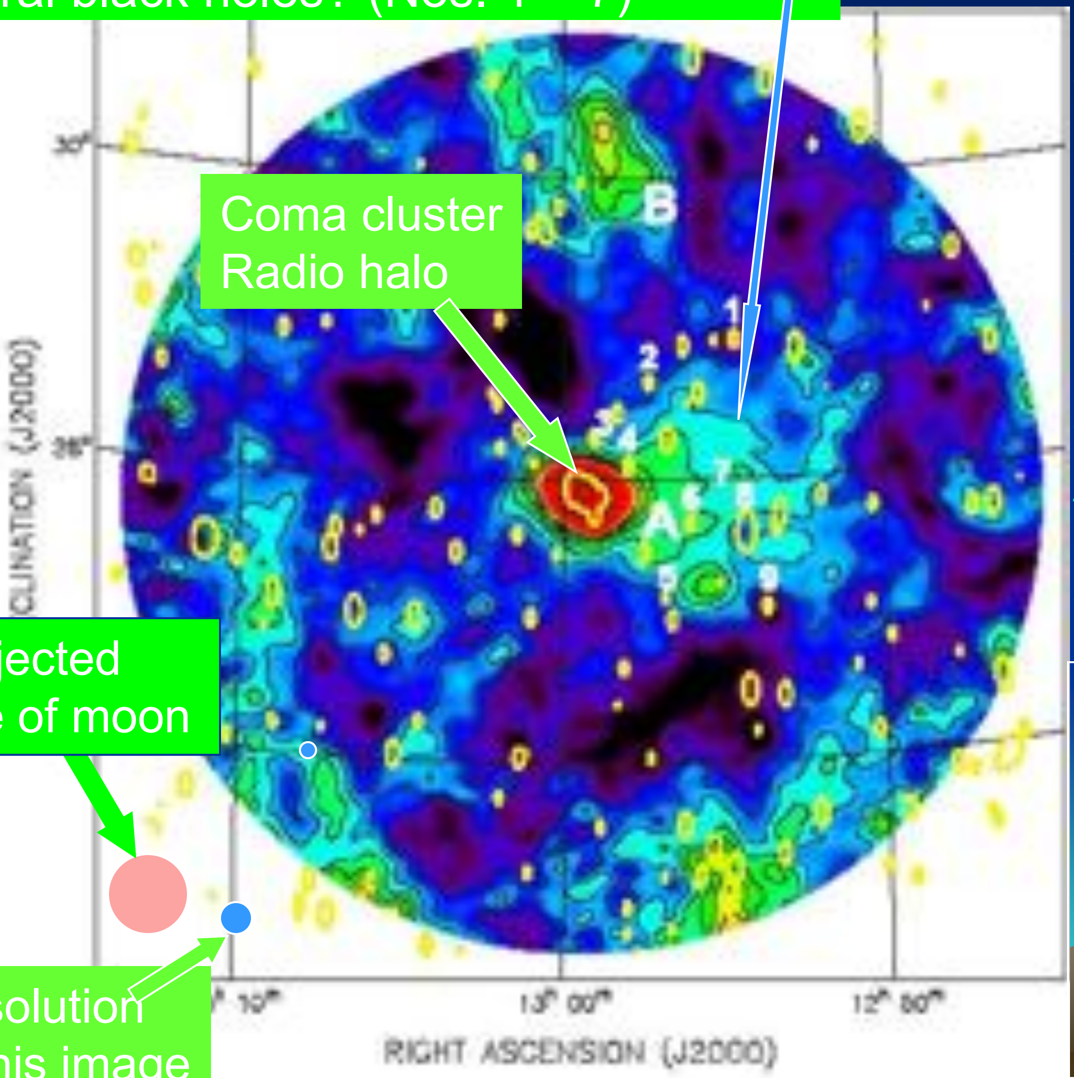
seven 9m dishes

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)

Coma cluster Radio halo

Projected size of moon

Resolution of this image

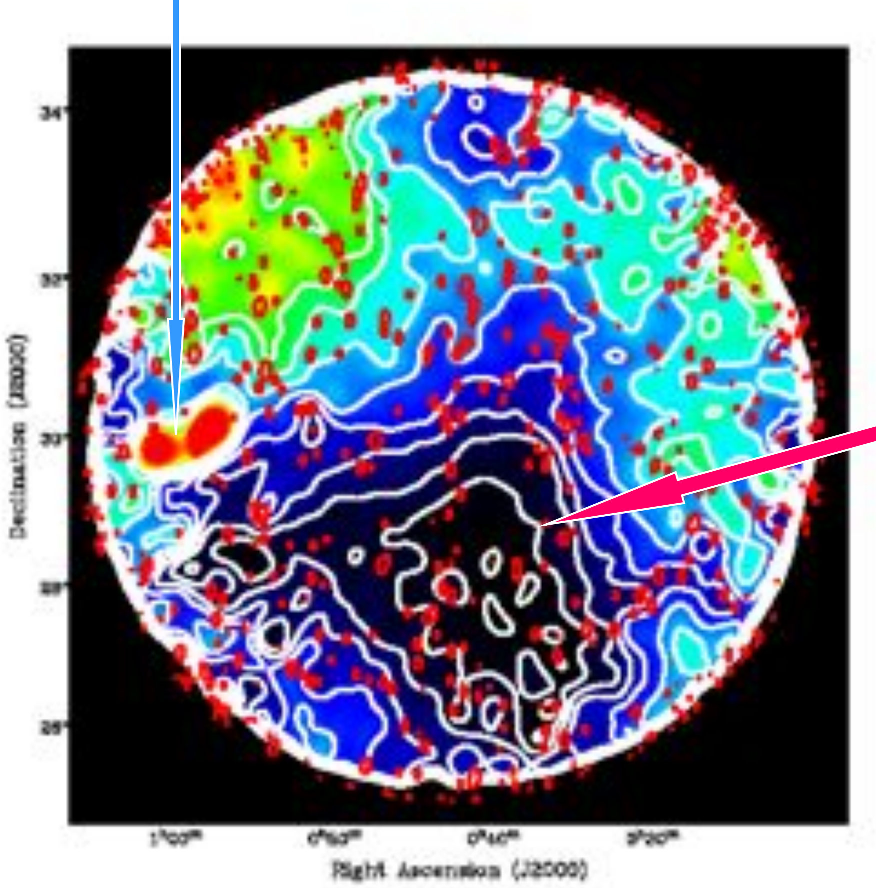
- *Discrete sources removed,*
- *CMB + linear plane Milky Way foreground removed*
- *Strongest discrete sources re-overlaid (yellow ellipses)*
- *Black contours at 1.4, 1.9, 2.4, 2.9, 3.4, 3.9, 4.4, 10, 40K*
- *σ ≈ 250mK at 430 MHz*

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

Another DRAO-Arecibo field in the Perseus-Pisces Supercluster

Kothes, Kronberg, Perillat, Salter (to be published)

(Giant radio source NGC315)



- rms noise ~250 mK
  (limit is set by
  DRAO resolution)

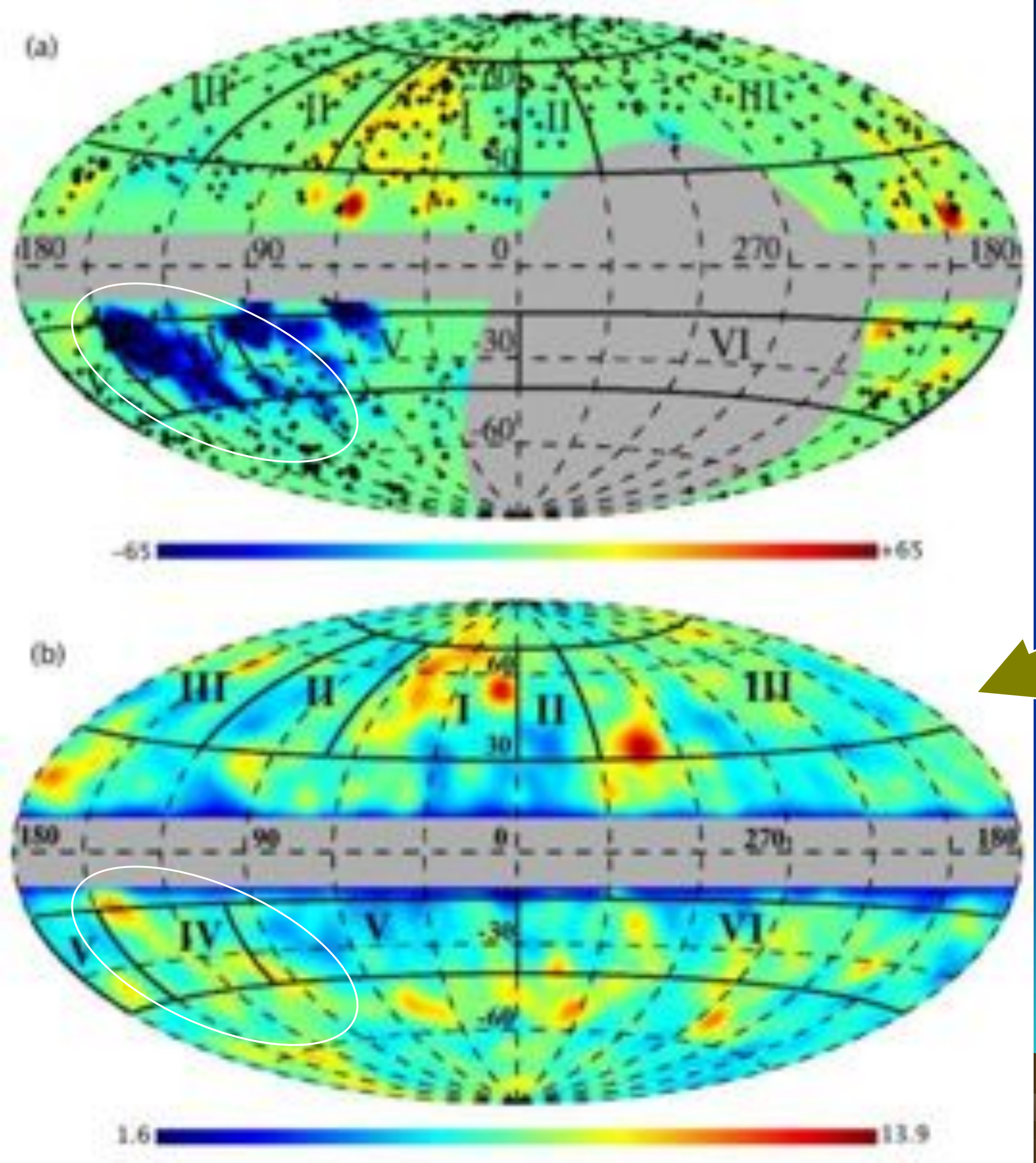
- Newly discovered deep “holes” for CMB investigations at $l \gtrsim 1000$

- Red DRAO Int. beamshapes show removed discrete sources

- (Note: no trace of residual diffraction lobes!)

RM search for beyond clusters: <B> in LSS filaments

Xu, Kronberg, Habib, Dufton: ApJ 2006, 637, 19



SMOOTHED
FARADAY
ROTATION

= Perseus-Pisces
supercluster

rad/m^2

GALAXY COLUMN
DENSITY
(Method #2:
2MASS, HEALPix)

galaxies
per pixel
($\propto$ column density)

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*

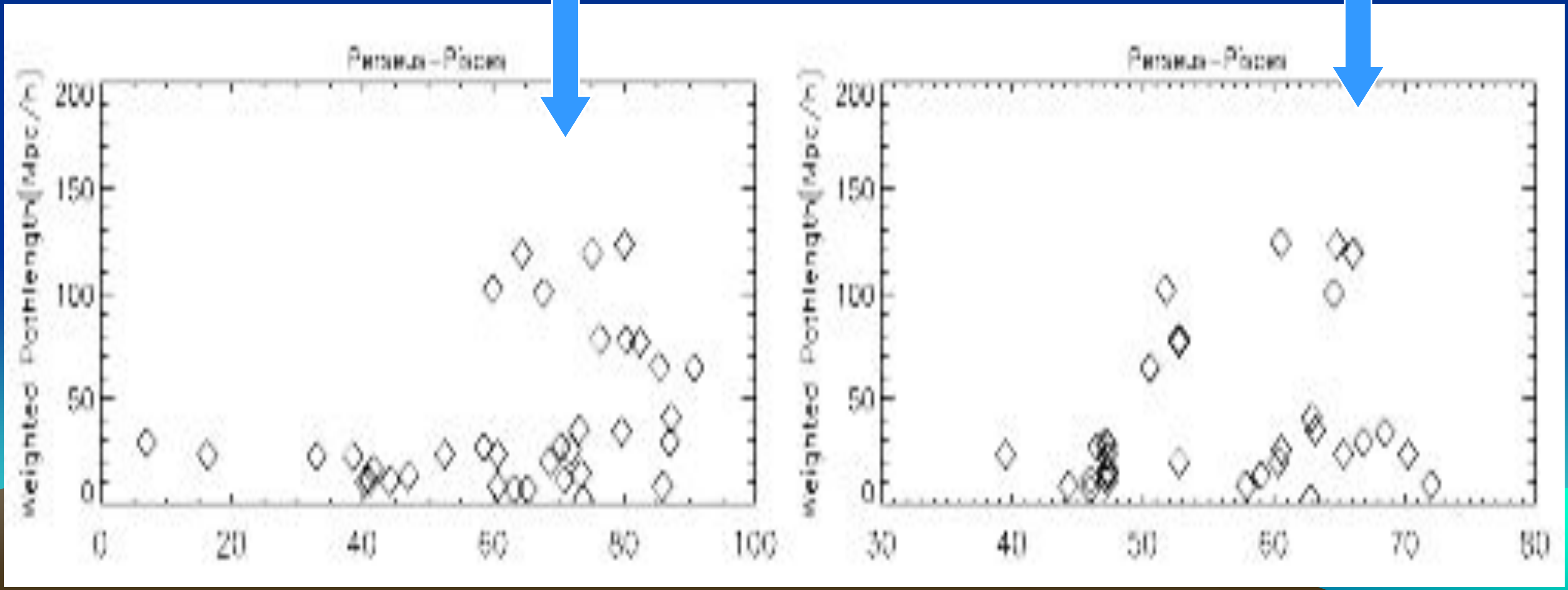
(a)

7°-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 7°-smoothed data



Plasma experiments on the largest accessible scales

- Plasma parameters in a radio galaxy (3C303), and the first jet current measurement

- particle acceleration sites on large scales

- Magnetic organization on kpc-Mpc scales

- Jets & Lobes as electrical circuits

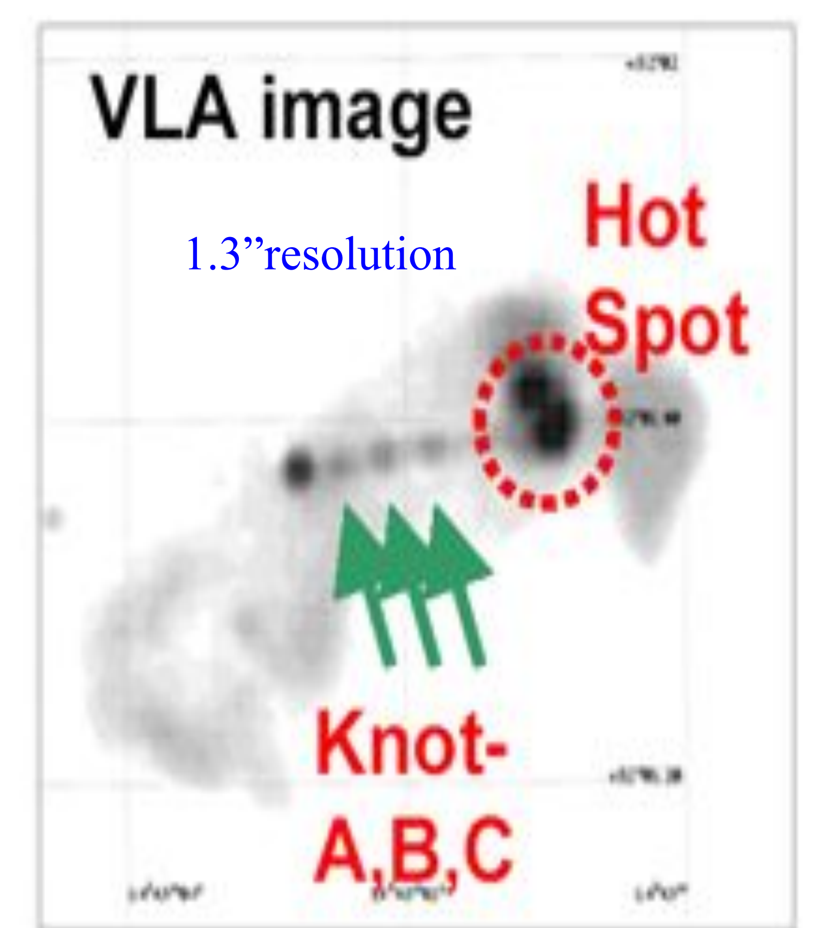
Knots and Hotspots of 3C303 (z=0.141)

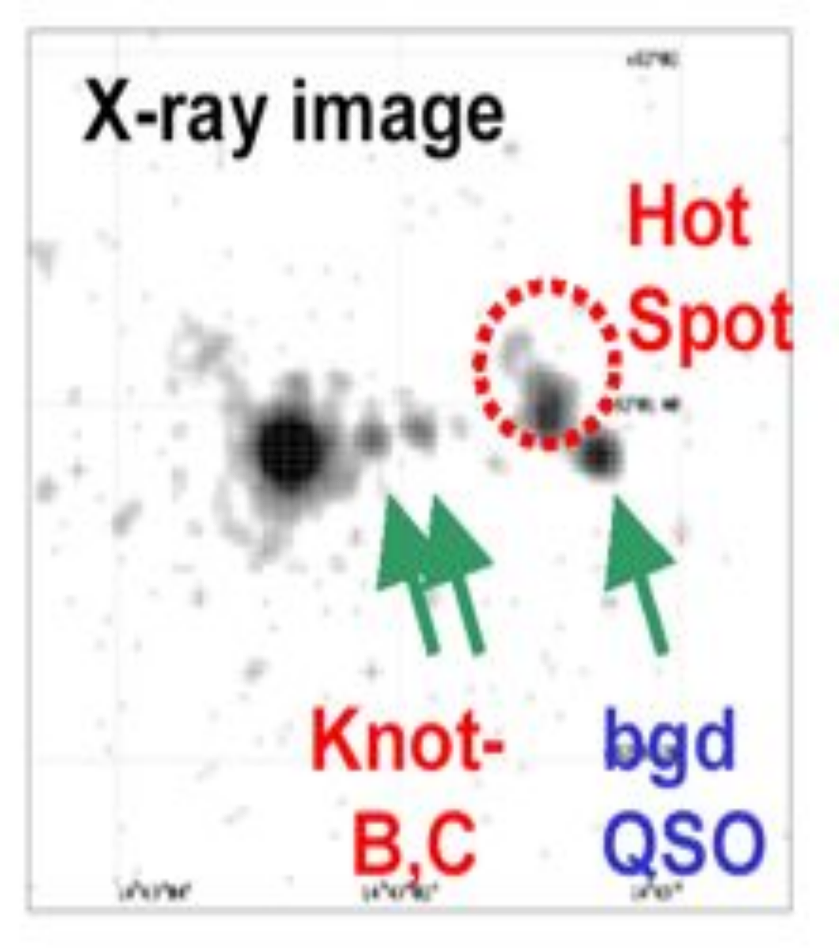
Radio (VLA) and X-Ray (CHANDRA)

P. Kronberg, Can.J. Phys 64, 449, 1986

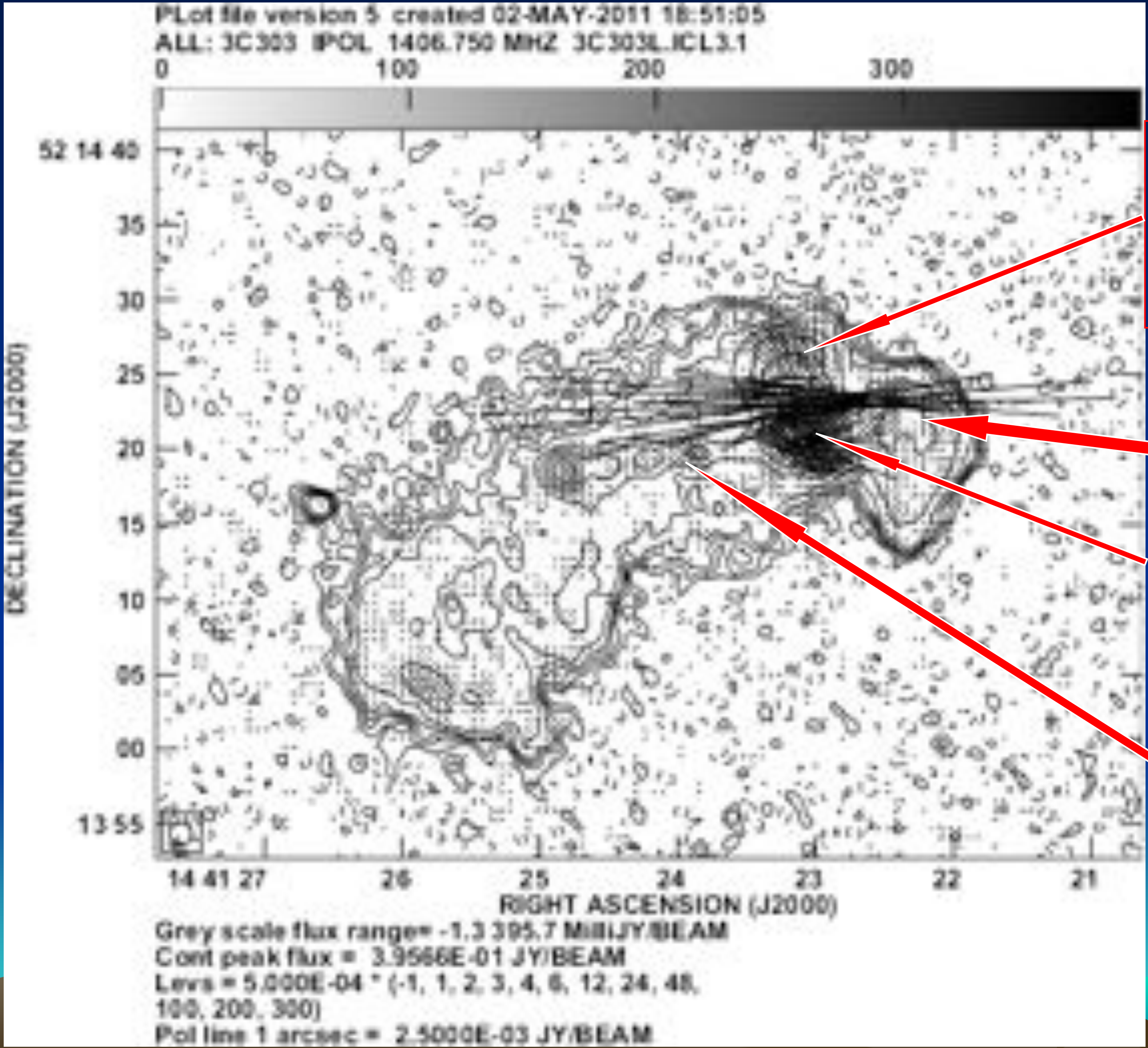
P. Leahy & R. Perley, Astr. J. 102, 537, 1991

J. Kataoka, P. Edwards,
M. Georganopoulos, F. Takahara,
& S. Wagner A&A 399, 91, 2003





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

How to estimate the jet current? -- *required measurements:*

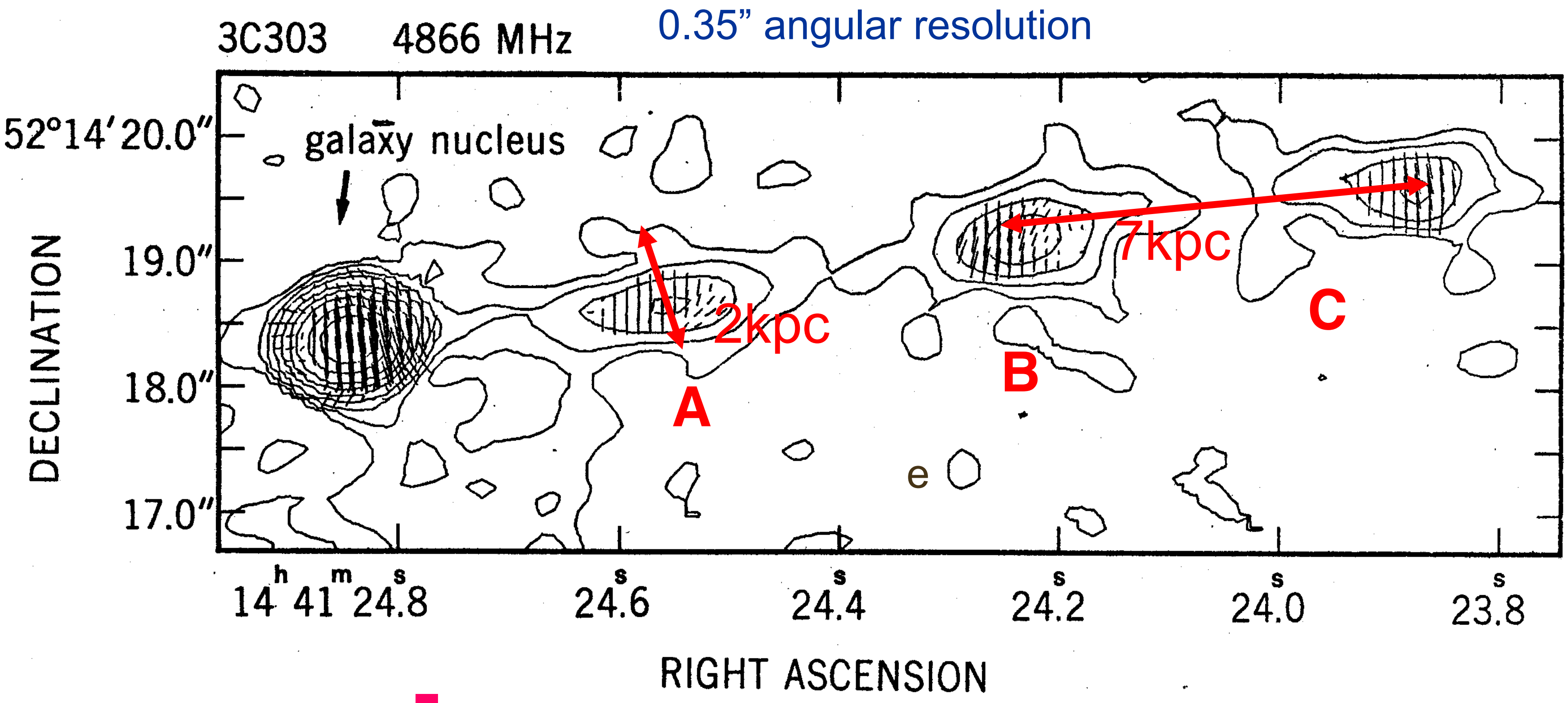
1. $\lesssim$ arcsec resolution, sensitive images at ν_1, ν_2, ν_3

2. Faraday RM image of the jet -- at a common angular resolution

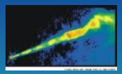
3. X-ray image ~ kev range –gives n_e^{th}

4. Need the surrounding sky RM's to establish the RM zero-level
i.e. subtract $<\mathrm{RM}_{\text{backgnd sources}}>$ from the RM's in the jet image
(*normally only possible outside a galaxy cluster*)

VLA image



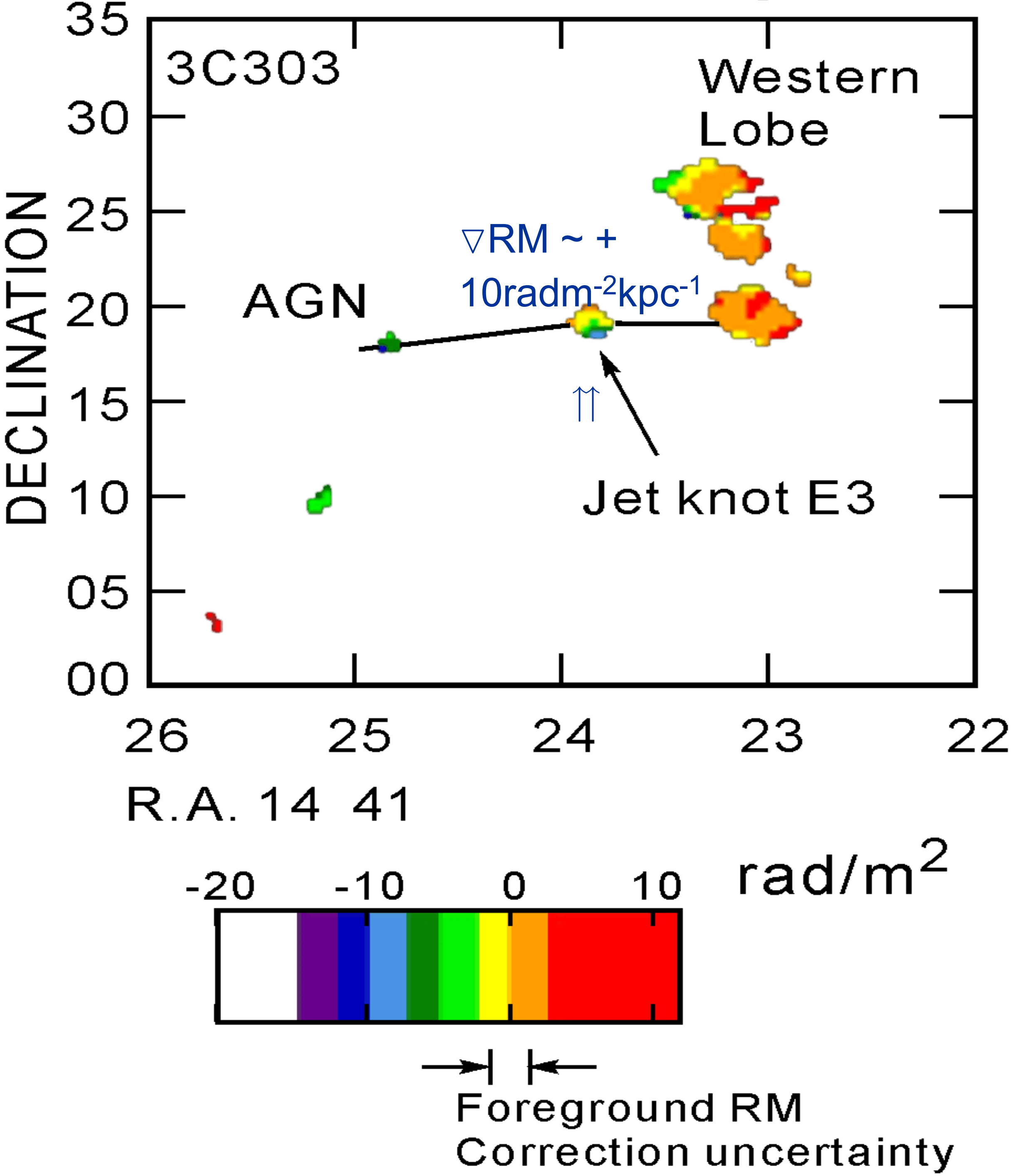
Compare scales!



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!



∇RM ~ + 10radm^{-2}kpc^{-1}

⇈

Plasma Diagnostics of the 3C303 jet

Lapenta & Kronberg ApJ 625, 37-50, 2005

(1) <(Total energy flow rate)> = E^T_{min}/τ = **$2.8\text{x}10^{43}$** τ_7^{-1} erg/s

(2) Total radio → X-ray luminosity of the jet = **$1.7 \text{ x } 10^{42}$** erg s^{-1}

$$\frac{(2)}{(1)}$$ → Radiative dissipation from the jet is ≈10% of the energy flow rate along jet!

(3) Measure knots' synchrotron luminosity & size (D_{knot}) → **$B^{knot}_{int}=10^{-3}$G**

(4) From the Faraday rotation isolated in the knots, **RM** $\propto n_{th} \times B^{knot}_{int} \times D_{knot}$

gives n_{th} in knots for 3C303) → $n_{th} \approx 1.4\times10^{-5}$ cm^{-3} (an extragalactic density!)

(3) & (4) → estimate of V_A within knots : $V_A^{knot} \propto B^{knot}_{int} / (n_{th})^{1/2}$

RESULT: $V_A^{knot} \approx 1.9c$. i.e. close to *c*, or *near relativistic* V_A^{rel}

Plasma parameters in the 3C303 jet

- With $|B|$ and n_{th} measured in the 3C303 jet,
- Plasma $\beta = \dfrac{nkT}{\left\{ B^2 / 8\pi \right\}} \approx 10^{-5}\, T_8$, *confirms very little thermal plasma – an intergalactic level density!*
- $|B| \sim 1$ mG *in the synch. radiating jet knots (cocoons),* over ~ 1kpc

Lapenta & Kronberg ApJ 2005

- *Consistent with a magnetically confined, Poynting flux driven jet:* Absence of evidence for mass-loading, -- which is otherwise required to carry a particle beam energy flow.

Analysis leads to straightforward electrical circuit analogues to describe BH energy transfer into ``empty'' space

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

calculations for 3C303:

- $P \sim 10^{37}$ watts of directed e.m. power

  → $I = 3.3 \times 10^{18}$ ampères of axial current

  ∇RM sign gives I direction – in this case *away* from the BH

- Jet's electrical properties:

$V_0 = 2.7 \times 10^{20}$ V (MKS)

$I_0 = 3 \times 10^{18}$ A (MKS)

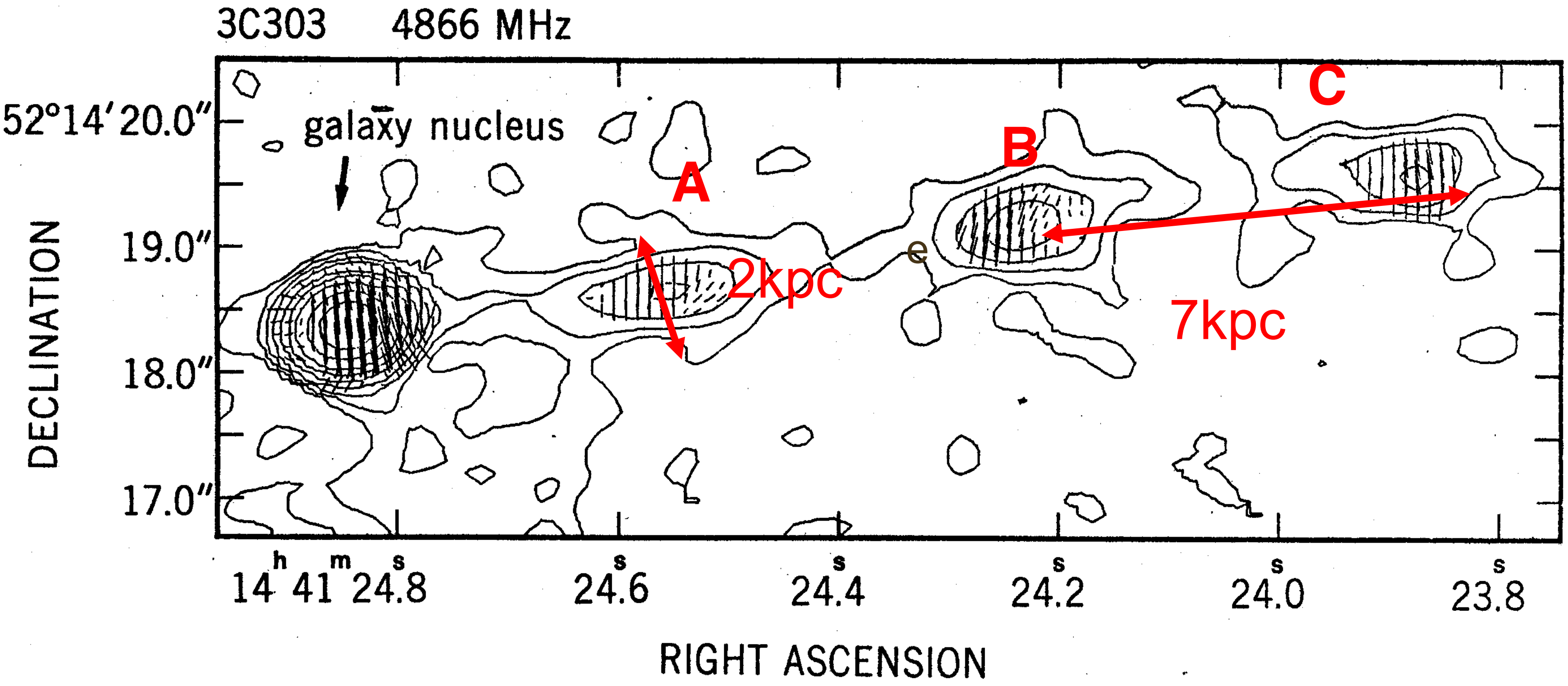
$Z_0 = 30\beta$ ohms (MKS)

where $\beta = U_{z/c} \lesssim 1$, and r_1, r_2 are the inner & outer transmission line radii.

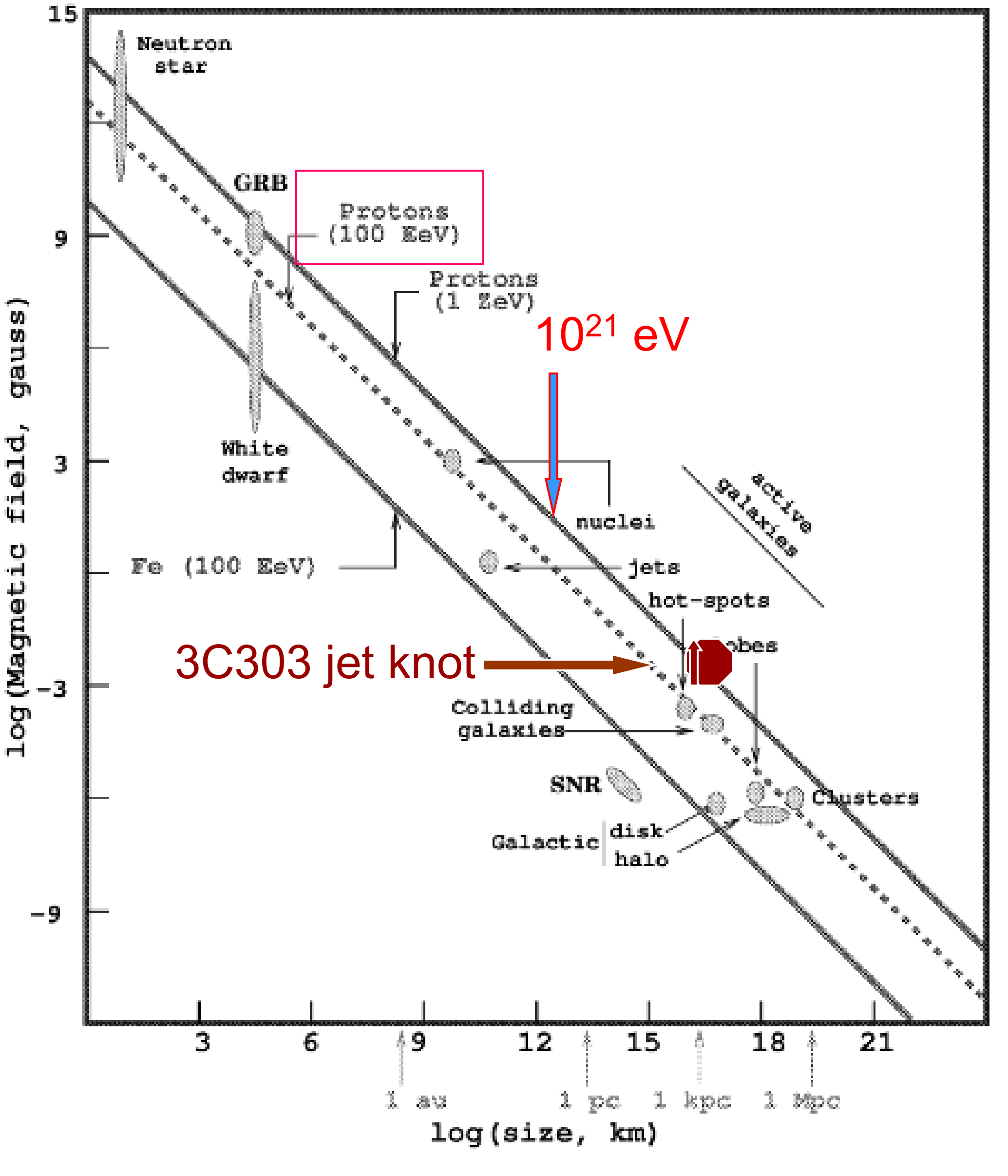
(*Lovelace & Ruchi, 1983*)

VLA image

AGN jets
viewed as VHE particle acceleration machines



UHECR acceleration in the 3C303 jet?



B·L (“Hillas”) plot

(*A.M. Hillas AnnRevAstAp 1984*)

knot parameters make the jet a potential acceleration site for CR nuclei up to ~ 10^{21} eV

Future
Opportunities for diagnosing jet magneto-plasmas

- 1. On pc scales near r_{G} of the SMBH

  VLBI up to Earth's dia & beyond

- 2. On kpc-Mpc scales Interferometers up to n00 km

  i.e. beyond the EVLA !!

Future instrumental directions and opportunities

Essential improvements required

For both (1) VLBI and (2) VLA-scale arrays:

- Need angular resolution 6x to 50x better, with optimum sensitivity
- Need Multi-frequency polarimetry & good frequency coverage
- ALL OF THESE ARE POTENTIALLY REALIZEABLE

1. PARSEC SCALE jet launching regions

-- $\gtrsim$ 6 x more better VLBI resolution OFTEN REQUIRES SATELLITE-BASED VLBI

-- increase observing frequency to 90GHz (3mm) and 120GHz (1.8mm)

-- more large radio telescopes in the array, longer baselines

--extend bandwidths

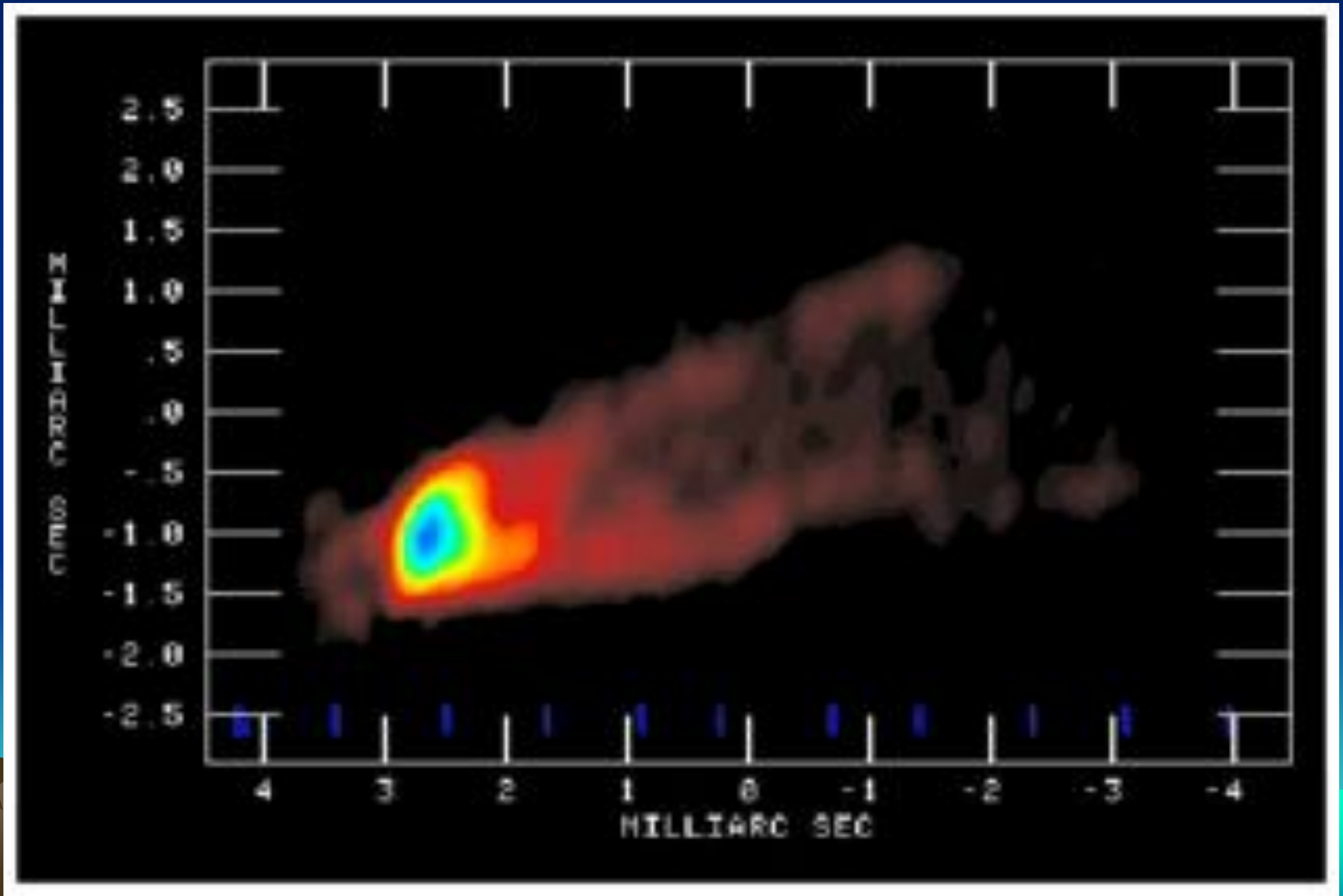
--measure and calibrate all Stokes’ parameters

--explore time-evolution – a new capability. -- next slide

M87 jet 23-frame time sequence

Craig Walker et al., J. Phys Conf Ser. 131, 012053

http:iopscience.iop.org/1742-6596/131/1/012053



2. KPC SCALE jets: (e.g. 3C303)

1. $\gtrsim$15x more resolution needed transverse to the jets
i.e. 35km EVLA needs to be ~ 500km, to the "EVLA-**2**"
not yet implemented

2. Wide freq coverage at much greater sensitivity – now achieved
(The new EVLA "WIDAR", post-2011, correlator)

---

1. would be possible with the proposed EVLA-**2**,
-- ``The New Mexico Array"-- 6 – 10 more EVLA dishes covering several hundred km, Cost: ~ $150-200M)

The EVLA-**2** proposal was recently shelved or withdrawn

-- For Faraday RM imaging, we also need $\upsilon \lesssim$ 1 GHz, probably down to
~300MHz, to explore 3-D magnetic field structures in lobes
at "Faraday depths"(RM) $\lesssim$ 10rad m^{-2}.

-- At low Faraday depths the current, insufficient, resolution is not solved by simply going to higher frequencies!! Illustrated by the case of 3C303

Near-future instrumental capabilities are in good shape

(EXCEPT FOR ANGULAR RESOLUTION).

- Enhanced VLA,
- Upgraded Arecibo telescope,
- LOFAR
- X-ray telescopes (Chandra and successors)
- TeV γ-ray telescopes

Cen –A, AUGER + HiRes

A new analysis and conclusions on:

nearby EGMF strength & structure

UHECR composition

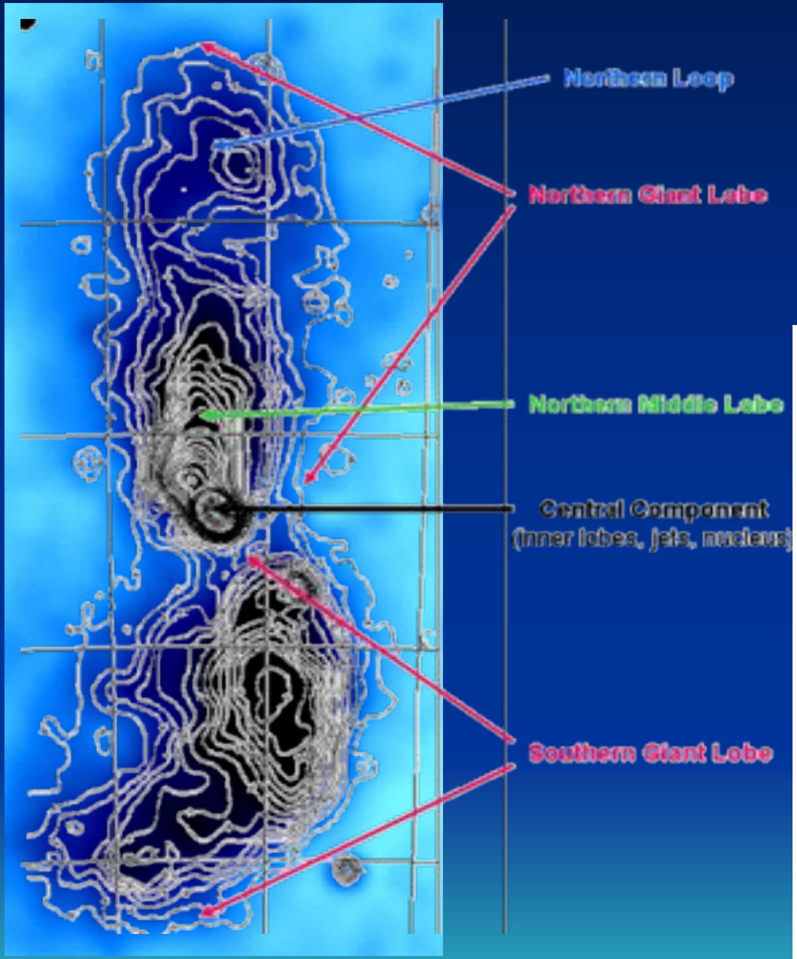
Cen A Basics

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

Angular Size ~ 8°
Size ~ 0.6 Mpc

- The radio jets of Centaurus A extracts energy from the supermassive black hole at the center of the galaxy and also possibly accelerates UHECR particles.

Angular Size ~ 8°



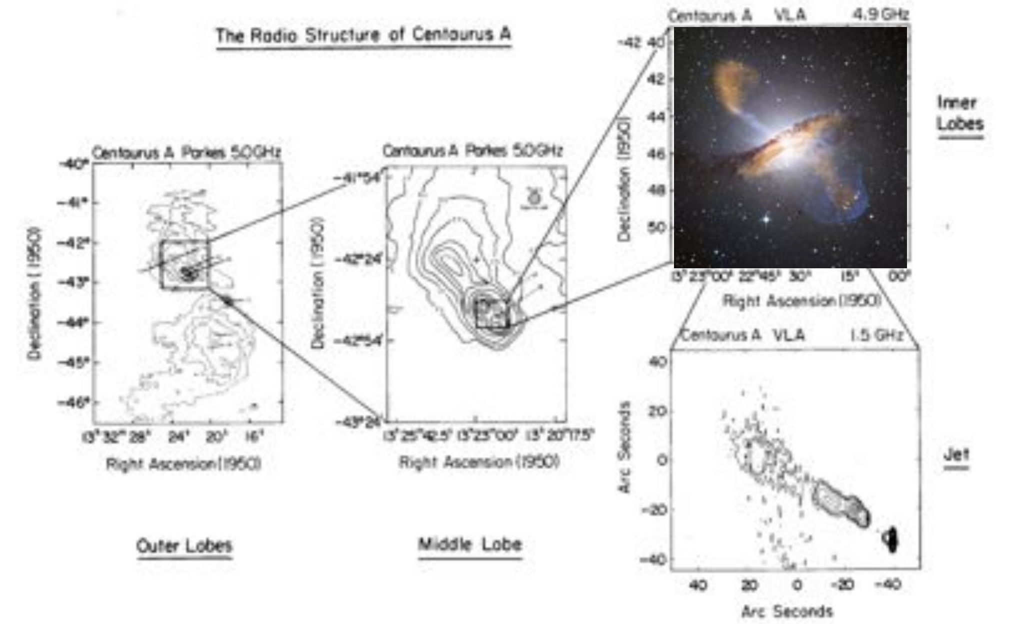
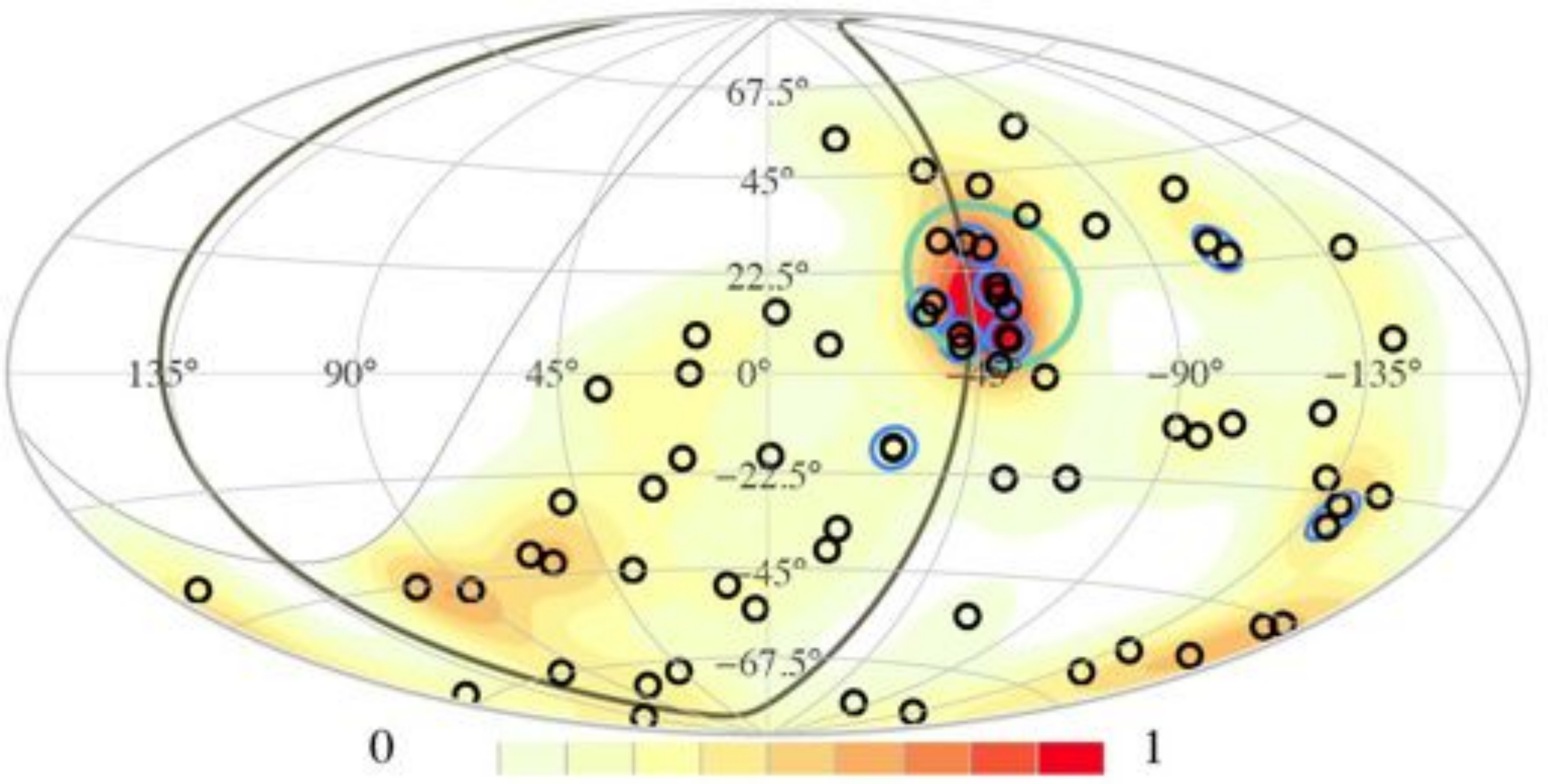


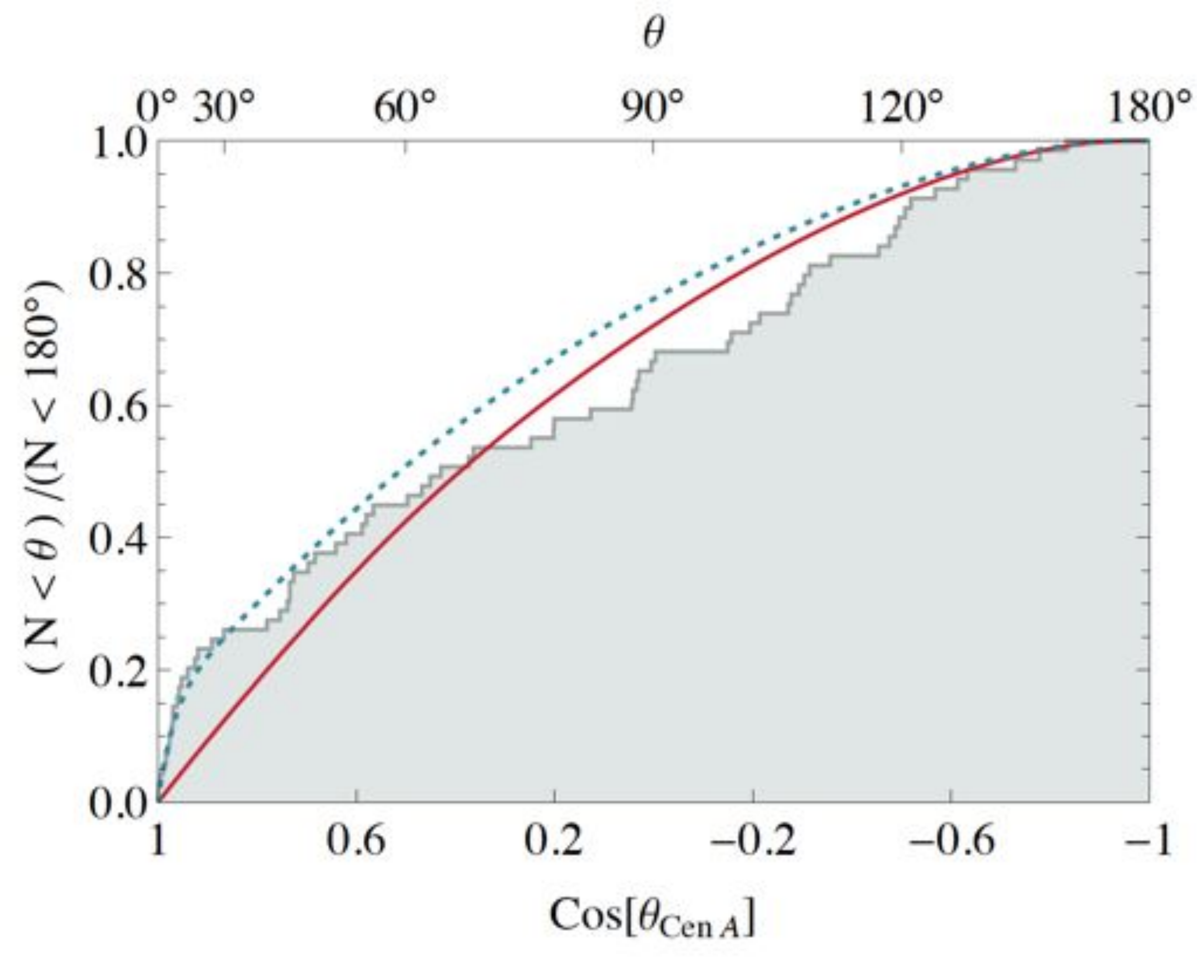
Fig. 3. Radio maps of Centaurus A, highlighting the various components of the radio source introduced in Sect. 2.1. From Burns et al. (1983).

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 colored contours



Cumulative angular distribution of events around Cen A

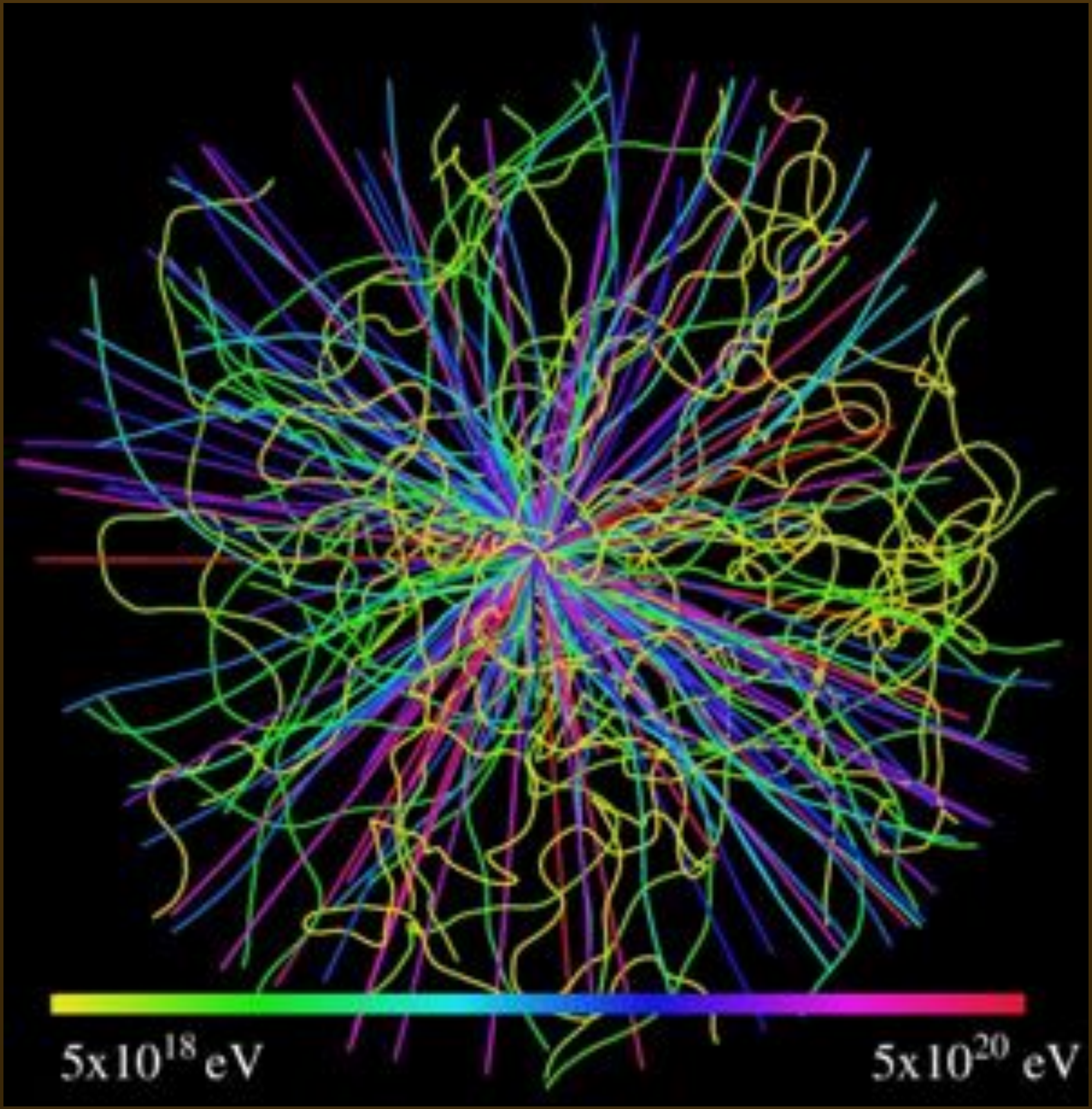


After weighting for exposure, the expectations for

- A purely isotropic distribution of all events (solid)

- A model of 10 events from Cen A, following a 10 degree Gaussian distribution around Cen A -- plus an isotropically distributed 59 events (dotted blue)

Even with 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.

- Lower energy particles experience much stronger deflections compared to higher energy particles

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

Analytically:

$$\Lambda_c \ll d$$

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

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

$$\Lambda_c \gg d$$

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

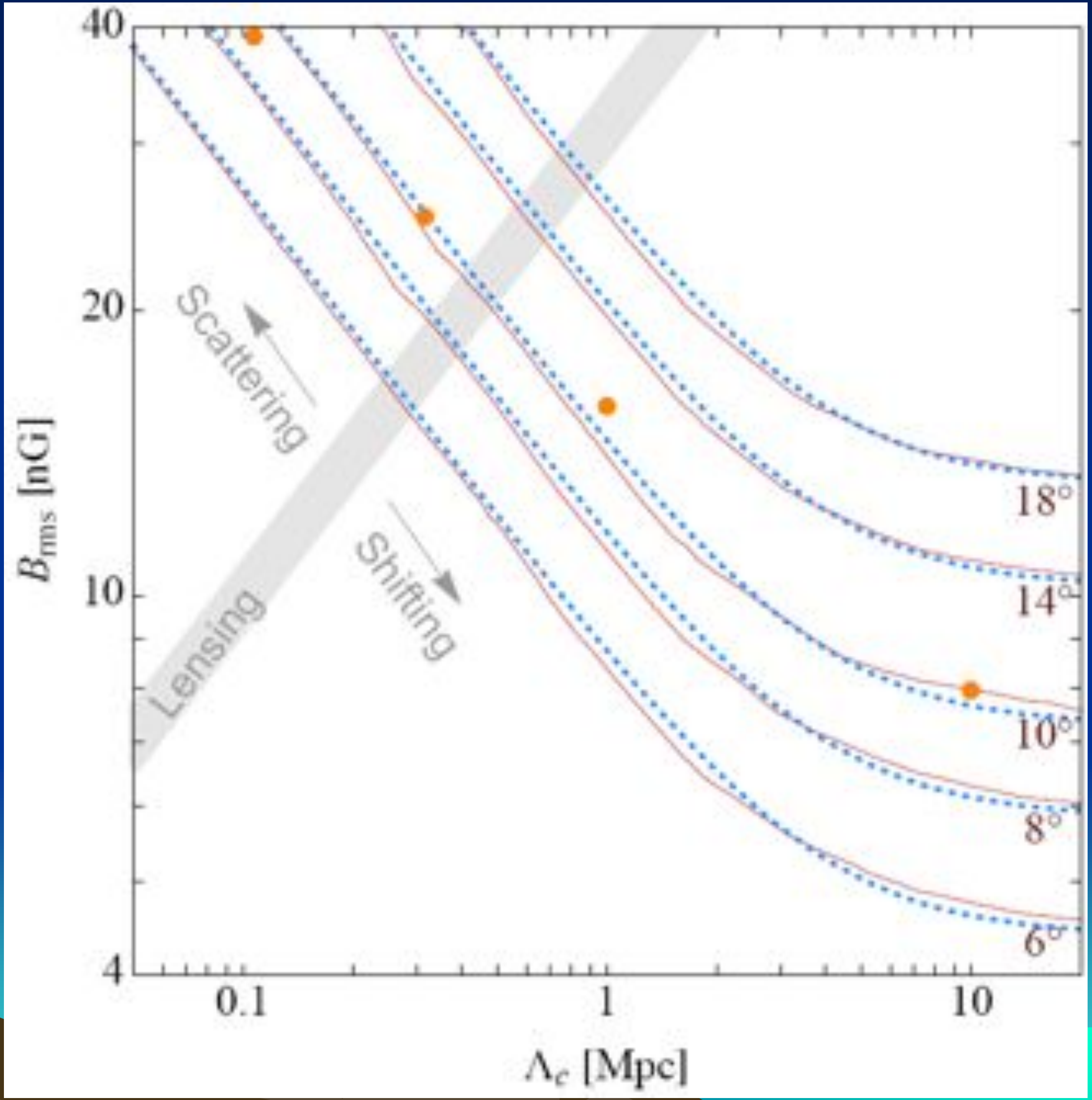
$$\theta_{\rm av} = \delta_{\rm av}/2$$

$$\theta \simeq \left(\theta_{av}^{\eta} + \theta_{rms}^{\eta}\right)^{1/\eta} \qquad \eta \to -4$$

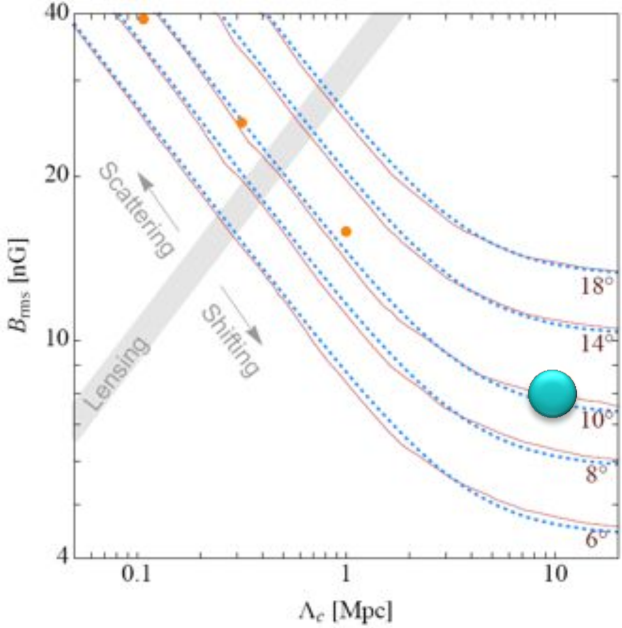
$$\simeq 53^\circ \sqrt{1/6}\, B_{\rm rms}\, (d/E) \left((\Lambda_c/d)^{\eta/2} + 1 \right)^{1/\eta}$$

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

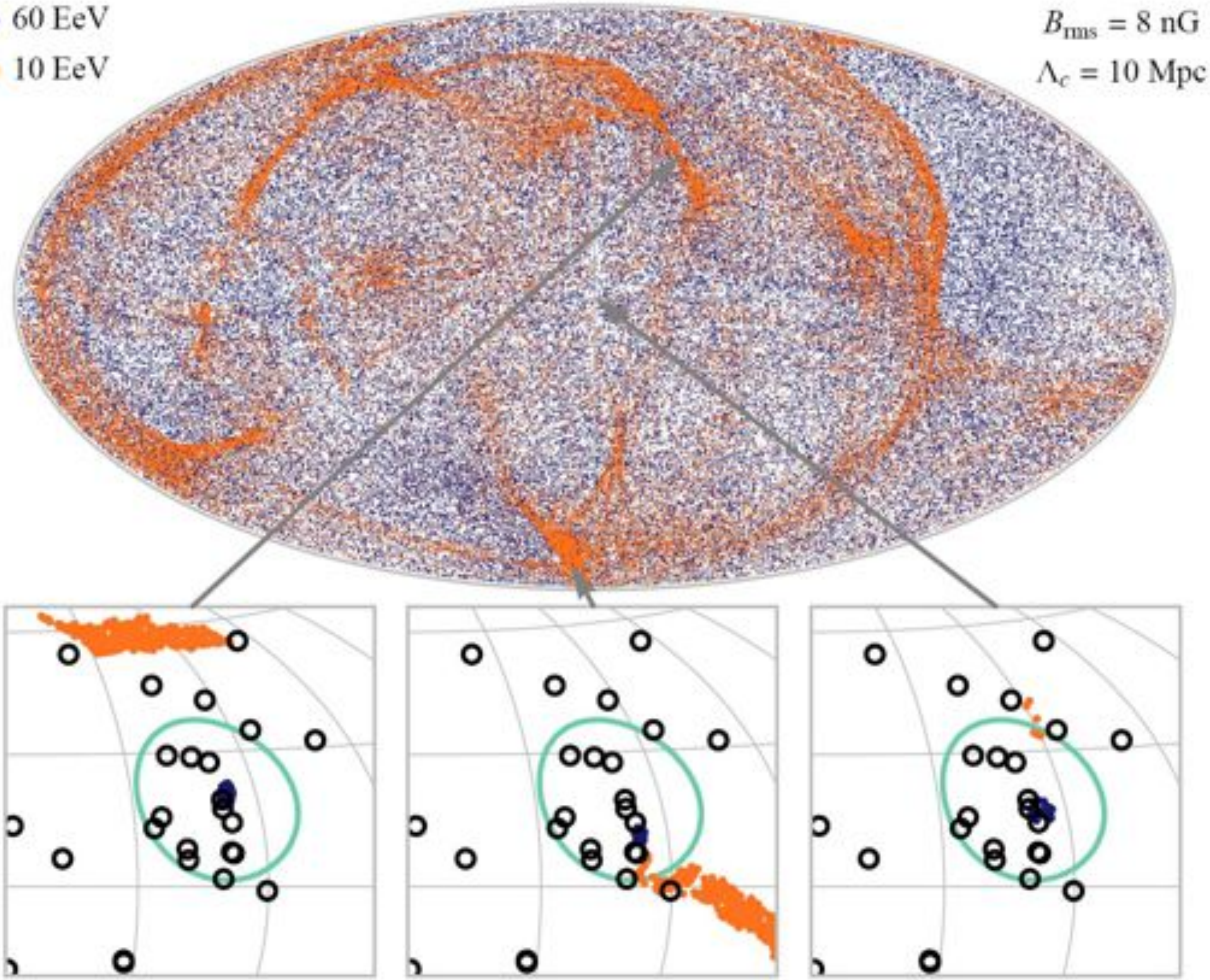
The mean values of 60 EeV cosmic-ray angular distributions around Centaurus A as a function of field strength and coherence length



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



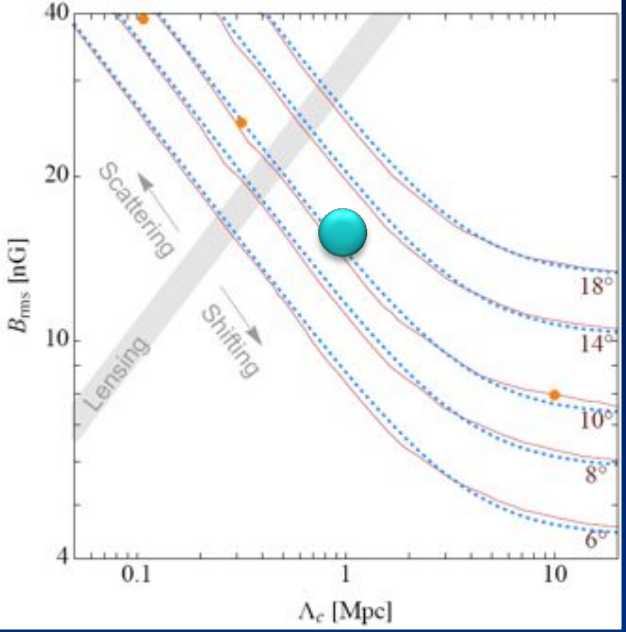
The sky as seen from Cen A
-- projected on a 3.8 Mpc radius screen

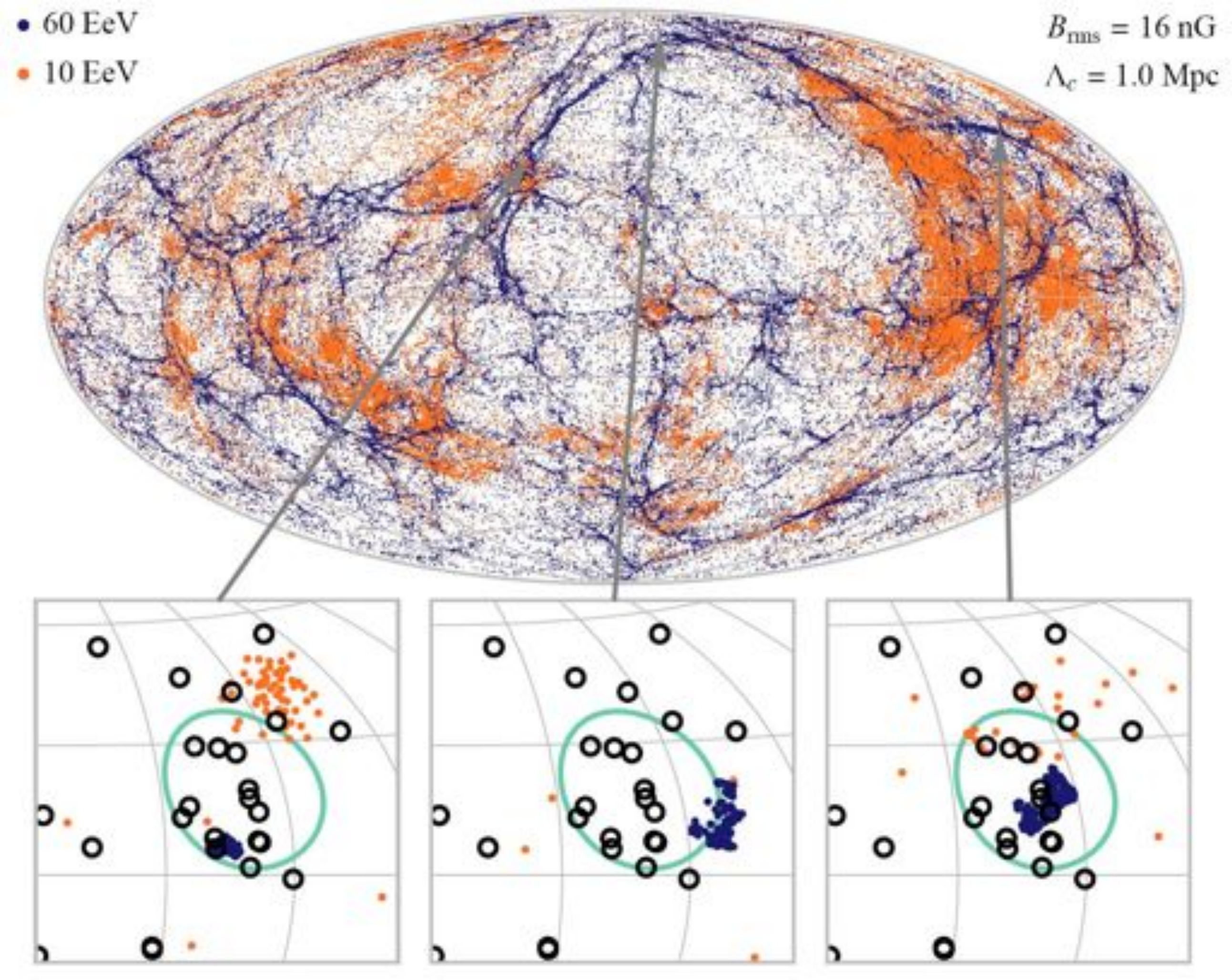


A piece of the (l.b) sky, centered on the (l.b) of Cen A

b

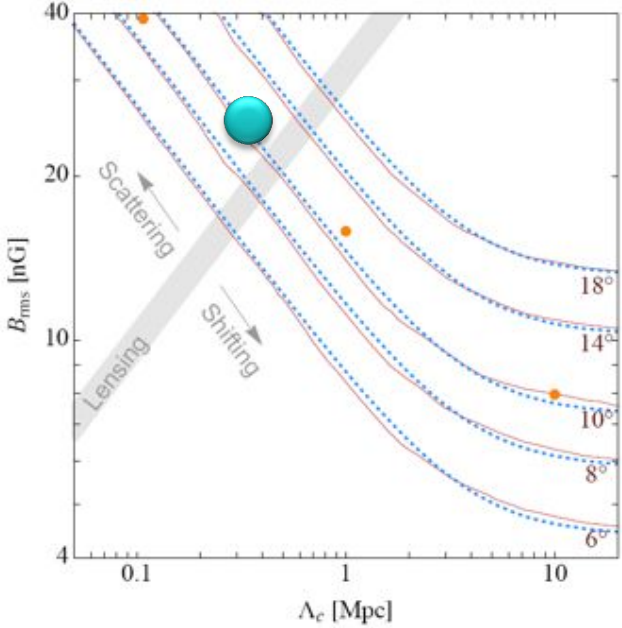
l

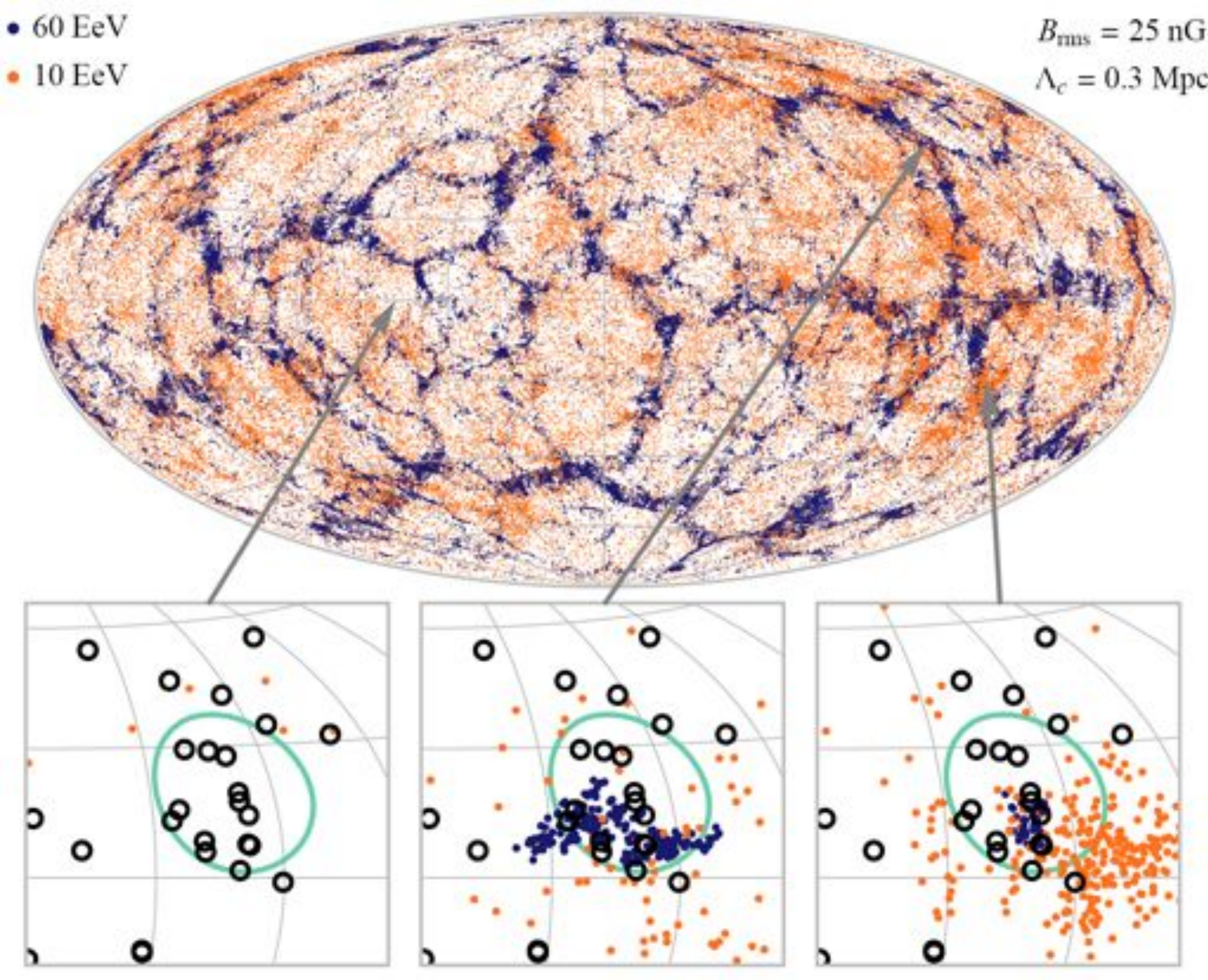

40
20
10
4
B_{rms} [nG]
0.1
1
10
Λ_c [Mpc]
18°
14°
10°
8°
6°
Scattering
Shifting
Lensing


● 60 EeV
● 10 EeV
$B_{\mathrm{rms}} = 16$ nG
$\Lambda_c = 1.0$ Mpc

b

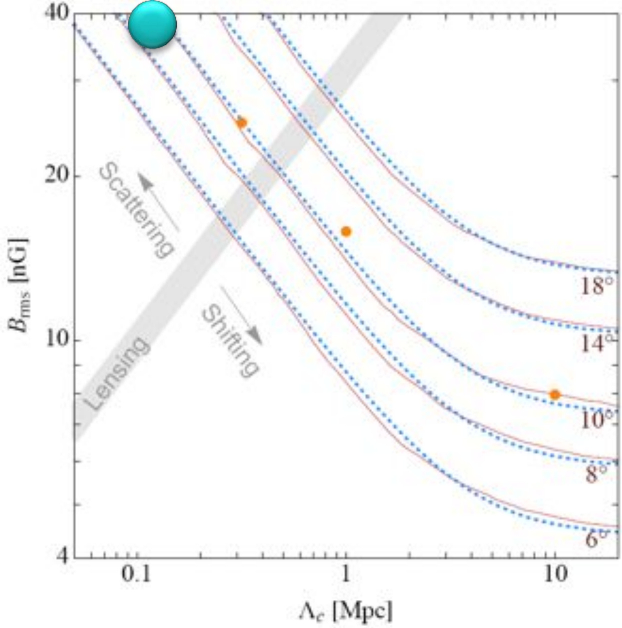
l

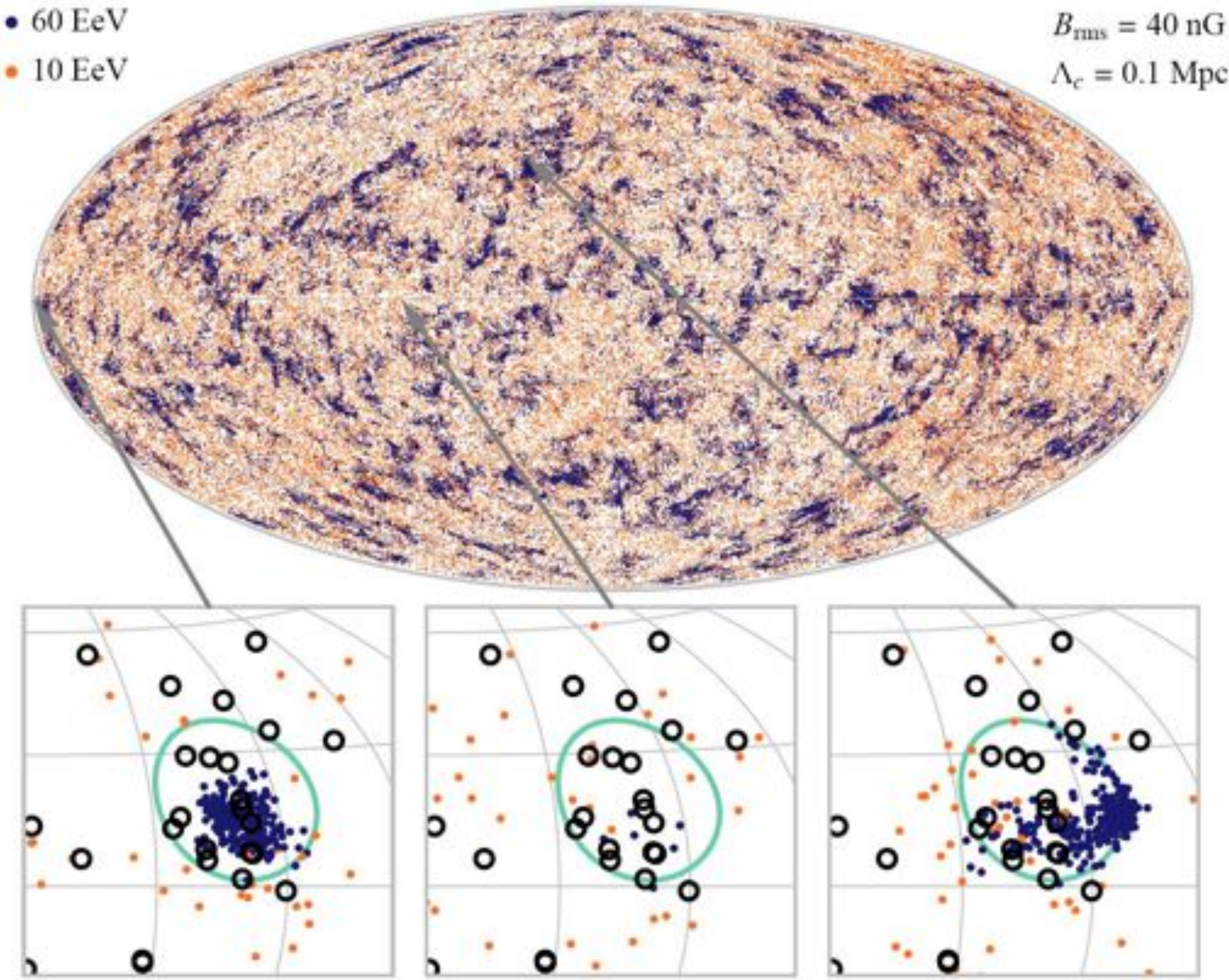

40
20
10
4
$B_{\rm rms}$ [nG]
0.1
1
10
Λ_c [Mpc]
18°
14°
10°
8°
6°
Scattering
Shifting
Lensing


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

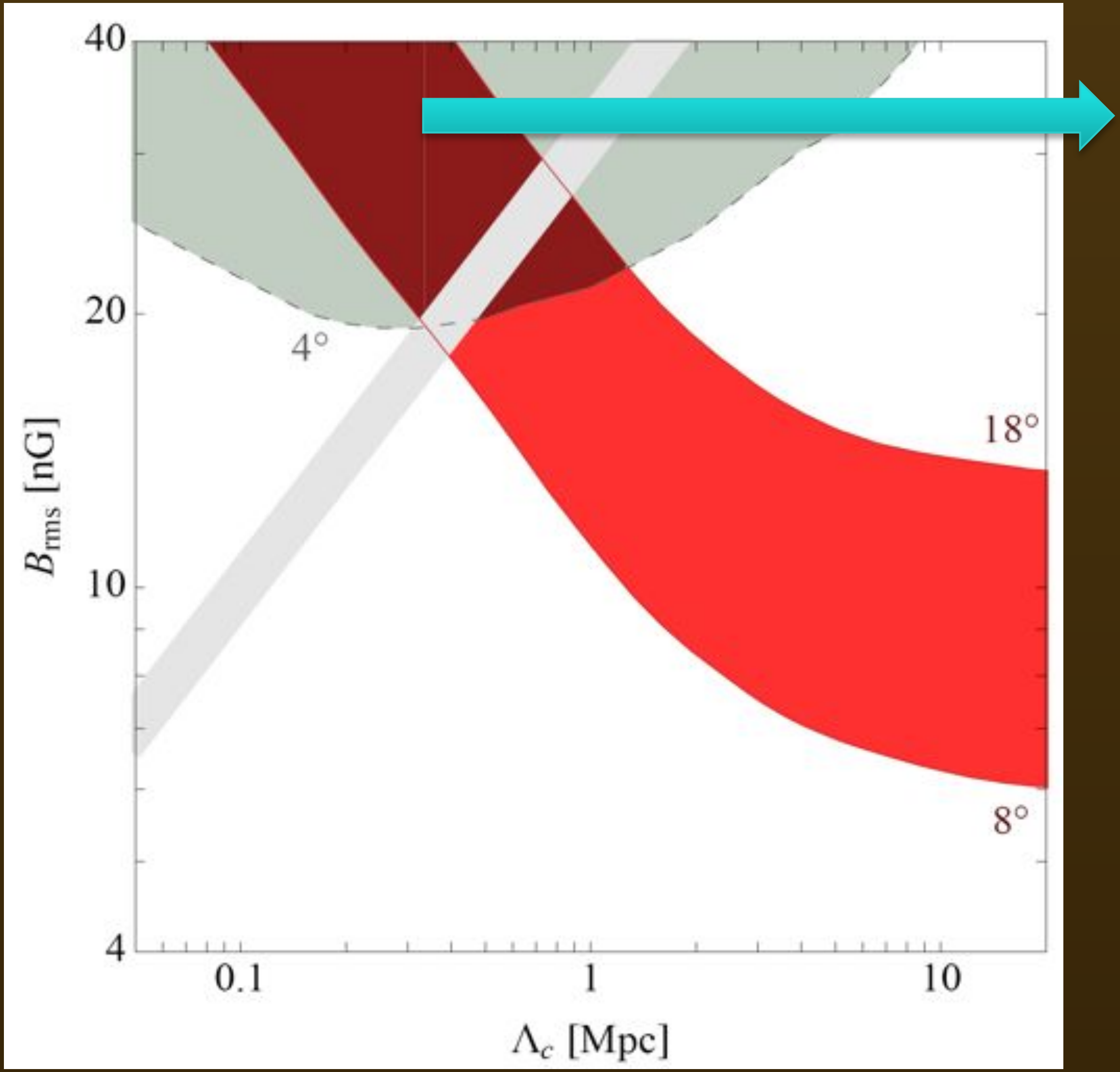
b

/


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


● 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)

- *The latter condition disfavors scenarios in which events are shifted from the source position, yet remain tightly clustered*

Some Implications:

- A > 10 nG field extending at a few Mpc around the Milky Way results in a ``screen'' scattering all UHECRs 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
  - this would introduce a minimum time dispersion, important for transient sources, such as gamma-ray bursts
- Even if protons dominate the composition at high energies, heavier nuclei may still be present:
  - with a solar composition and acceleration based on nuclear charge, the number of events near Cen A would suggest 1 or 2 He nuclei in the excess
  - the highest energy event seen by Auger (142 EeV) is within 30 degree of Cen A, which is in rough agreement with the high total energy and greater scattering expected for a heavier He nuclei

Concluding Remarks

- The UHECR anisotropies discovered by the Pierre Auger Observatory give the potential to finally address both the particles' origins and properties of the nearby extragalactic magnetic field (EGMF)

- We examine the implications of the excess of >60 EeV events seen towards the nearby radio galaxy Centaurus A

- *If* Cen A is the source of these cosmic rays, the angular distribution of events constrains the EGMF strength within several Mpc of the Milky Way >10 nG. This is important for:

  - UHECR scattering from more distant sources
  - time delays from transient sources
  - The use of *magnetic lensing* signatures to attain tighter constraints

- Our conclusions suggest that the observed excess is either

  - a statistical anomaly

    or
  - the local EGMF must be much stronger then previously thought

End

Philipp Kronberg