High energy processes in low-z intergalactic space

Philipp Kronberg

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I. The Cen A UHECR excess and the local Extragalactic magnetic field
LA-UR 12-10321

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

Université libre de Bruxelles, Belgique,
2 May 2012

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Cen –A, AUGER + HiRes

A new analysis and conclusions on:

nearby EGMF strength & structure

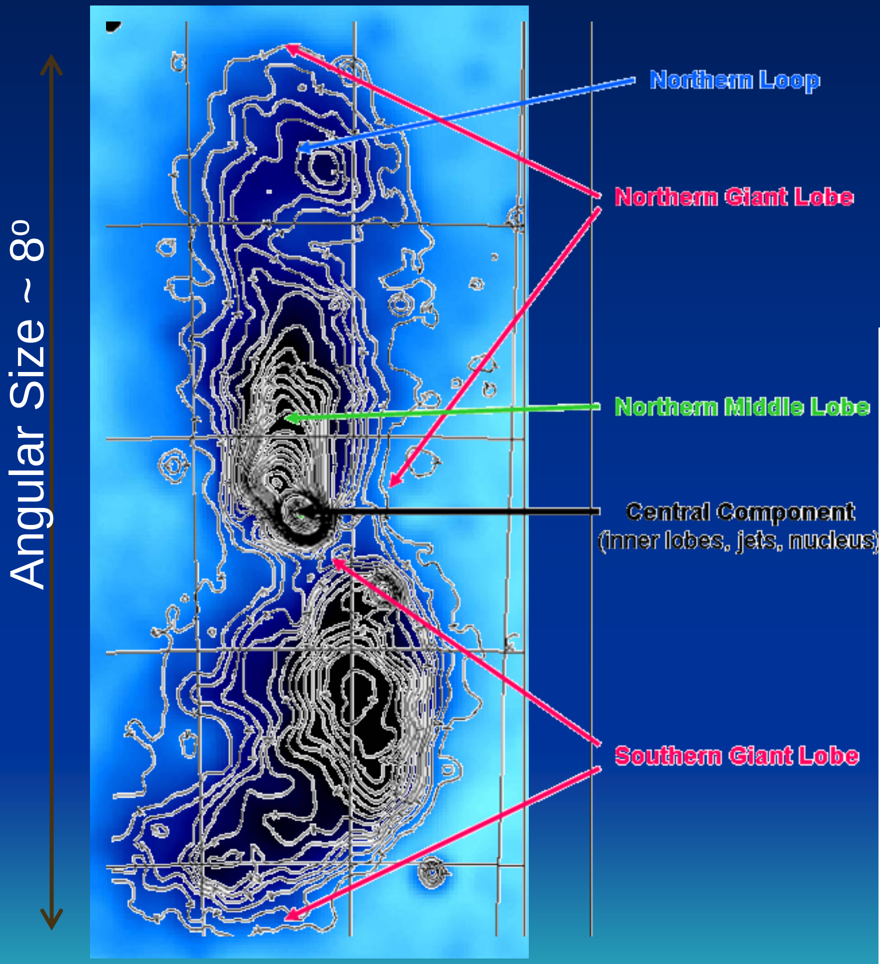
UHECR composition

Cen A Basics

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

Angular Size ~ 8º
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 accelerate UHECR particles.



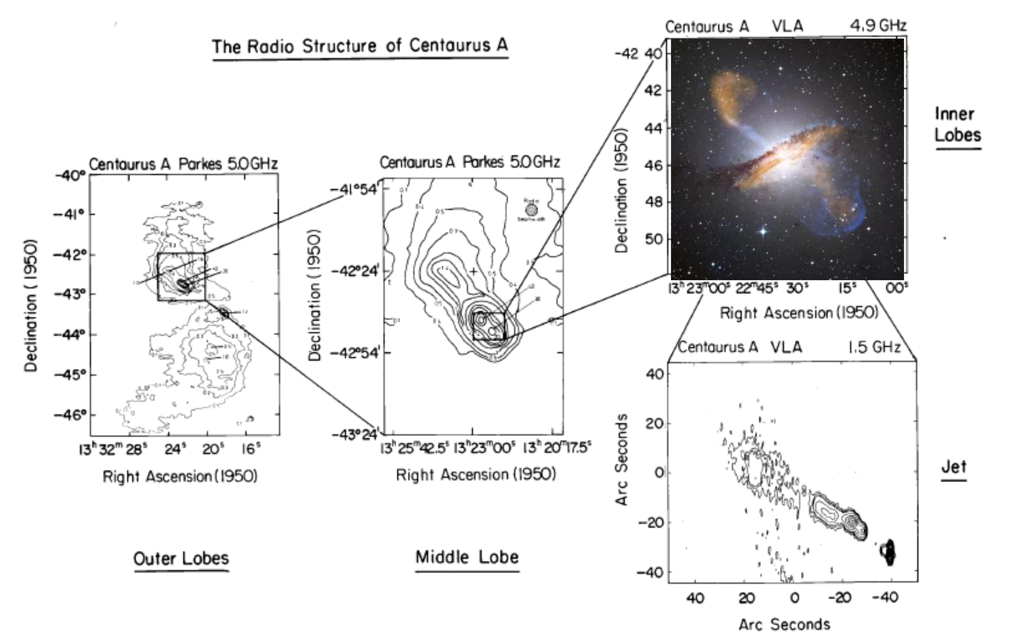
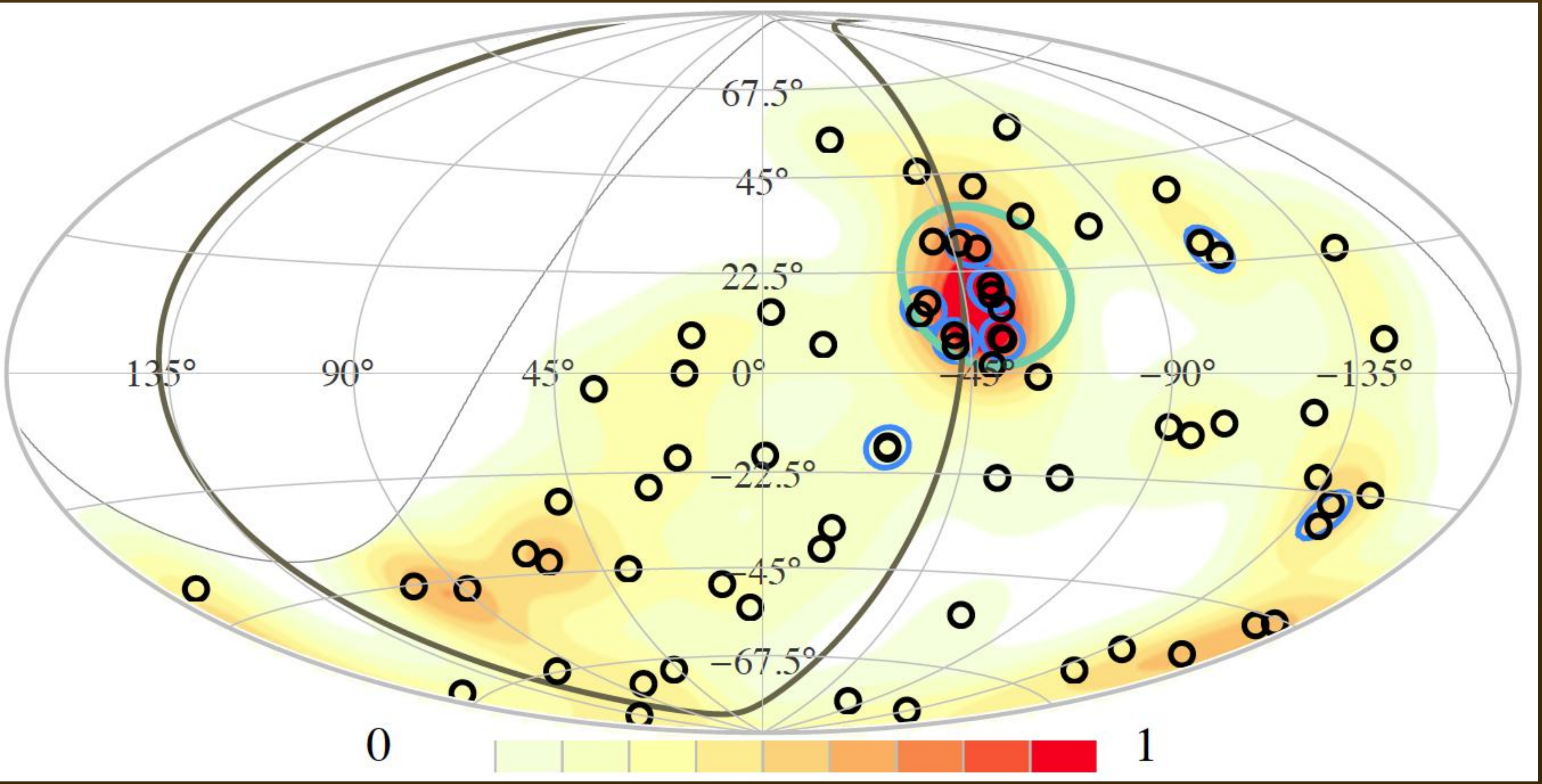


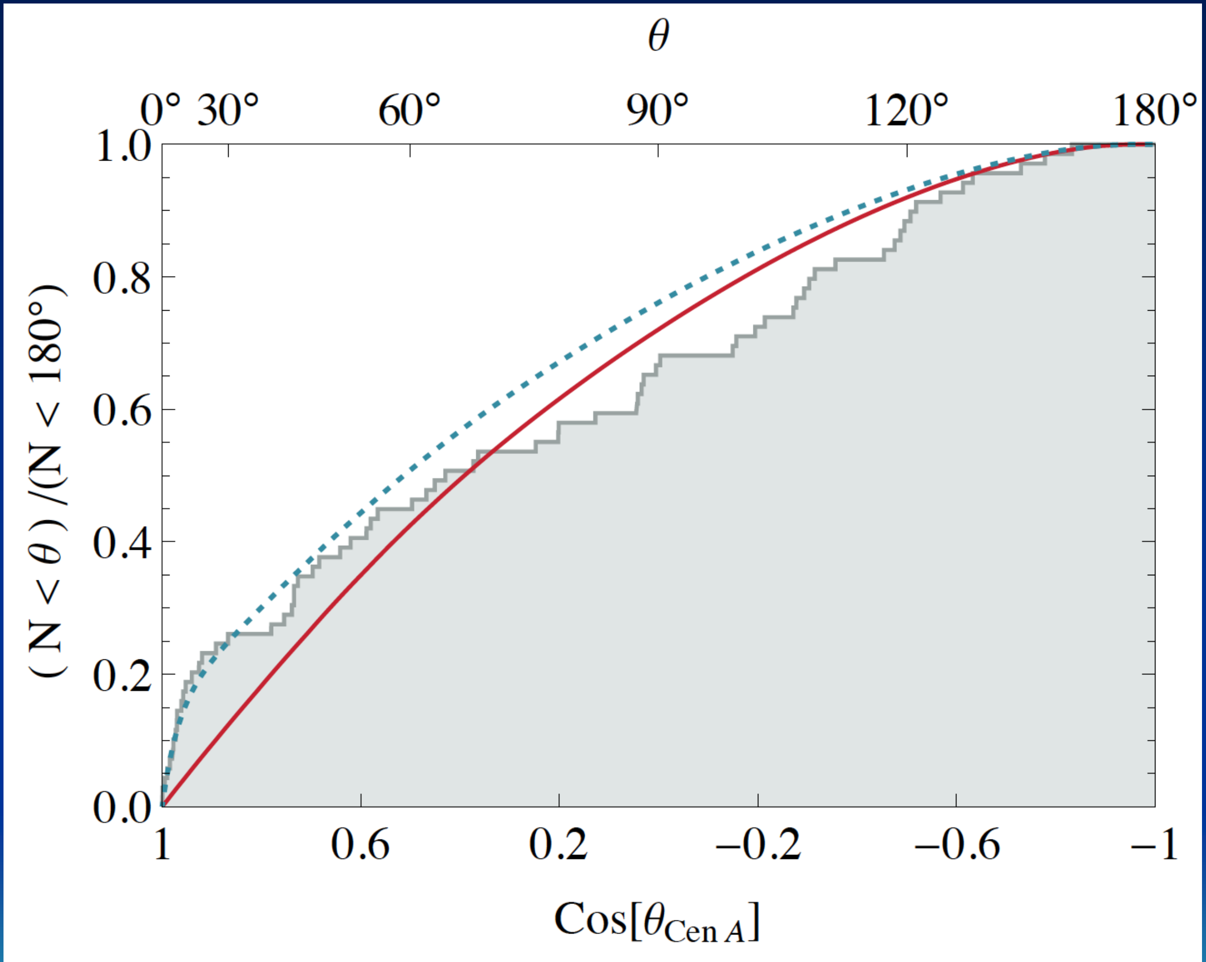
Fig. 3. Radio maps of Centaurus A, highlighting the various components of the radio source introduced in Sect. 2.1. From Burns et al. (1983).

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

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



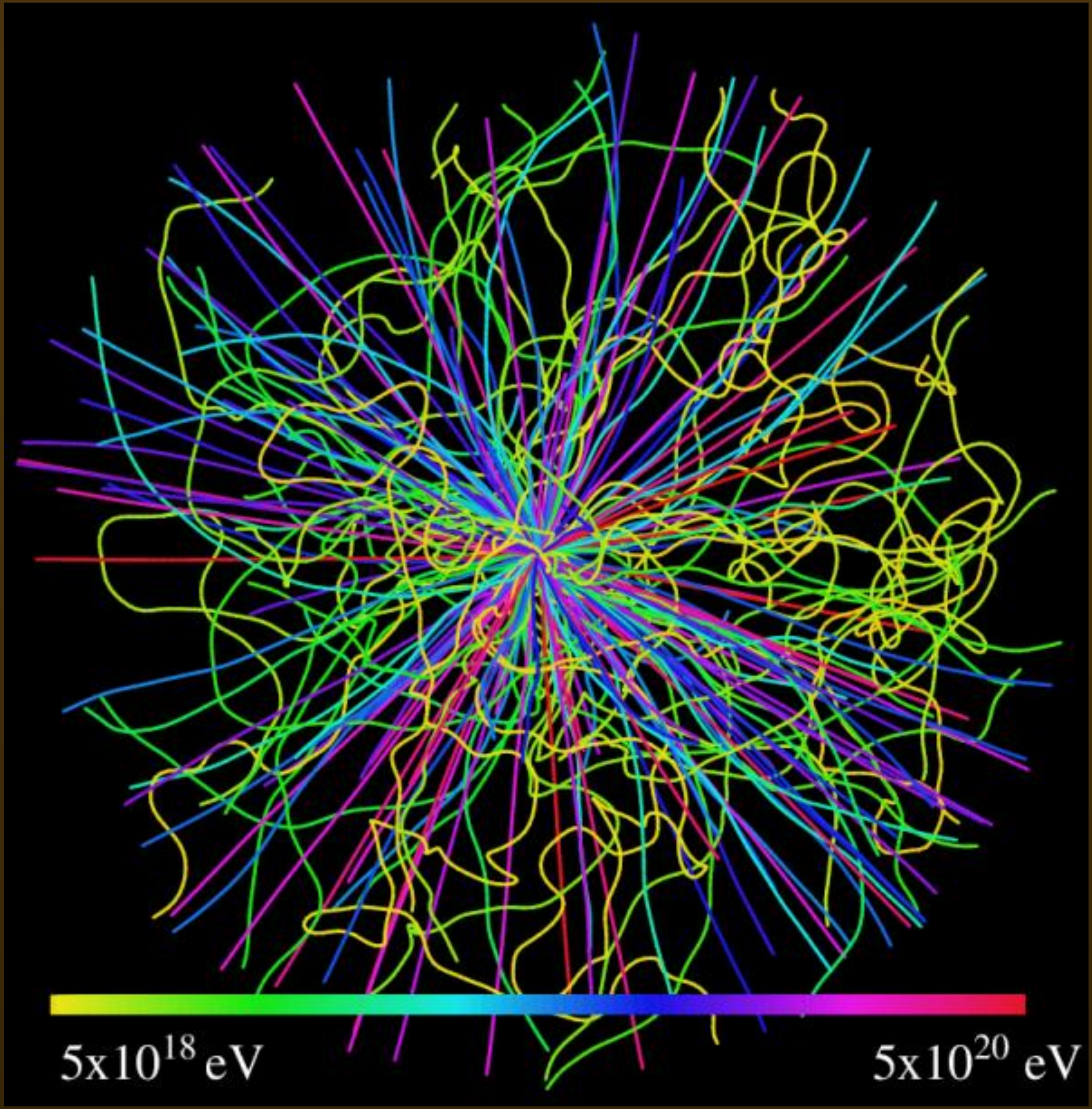
Cumulative angular distribution of events around Cen A



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 (colored 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:

$\Lambda_c \ll d$

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

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

$\Lambda_c \gg d$

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

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

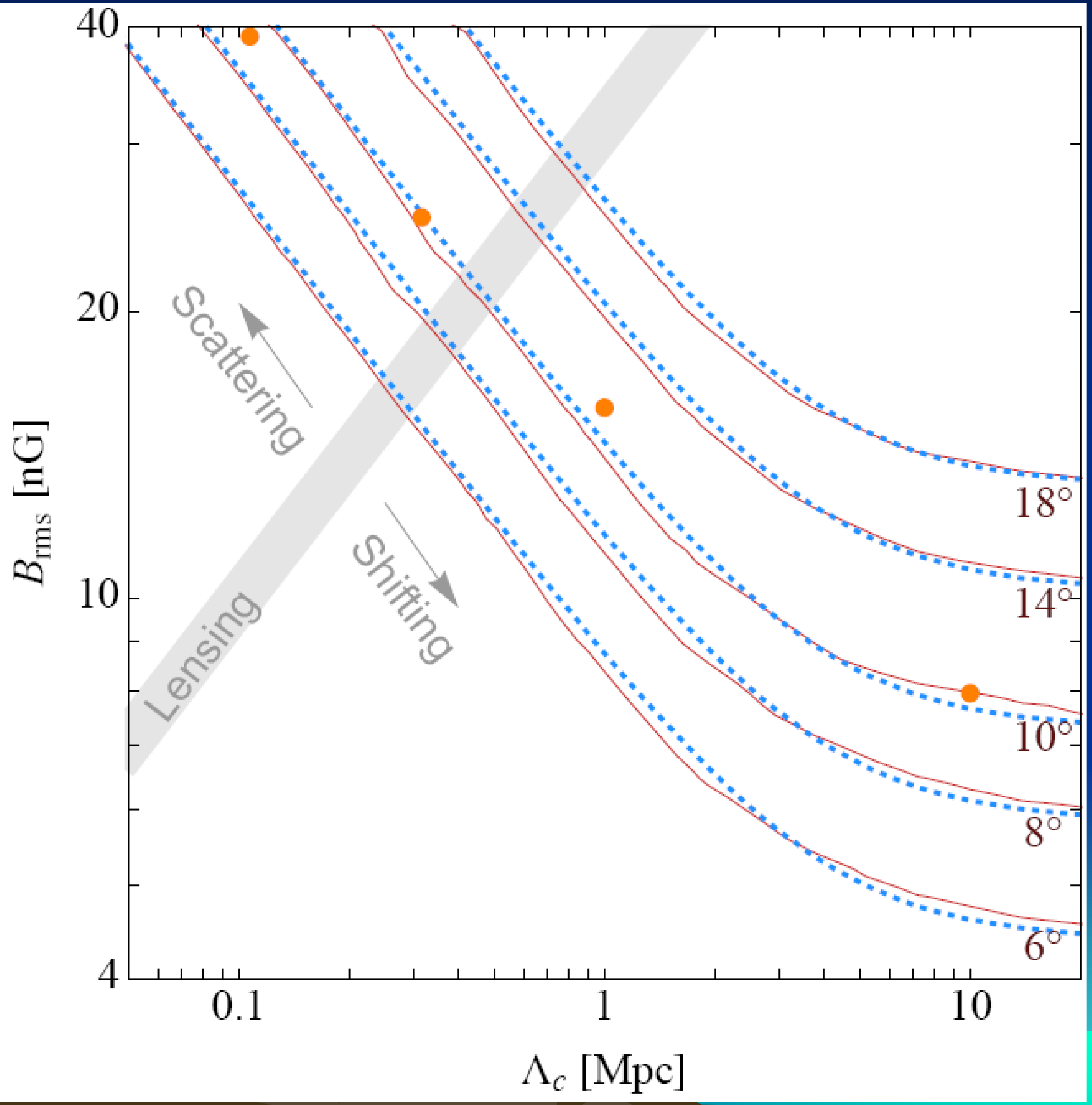
$$\theta \simeq \left(\theta_{av}^\eta + \theta_{rms}^\eta\right)^{1/\eta} \qquad \eta \to -4$$

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

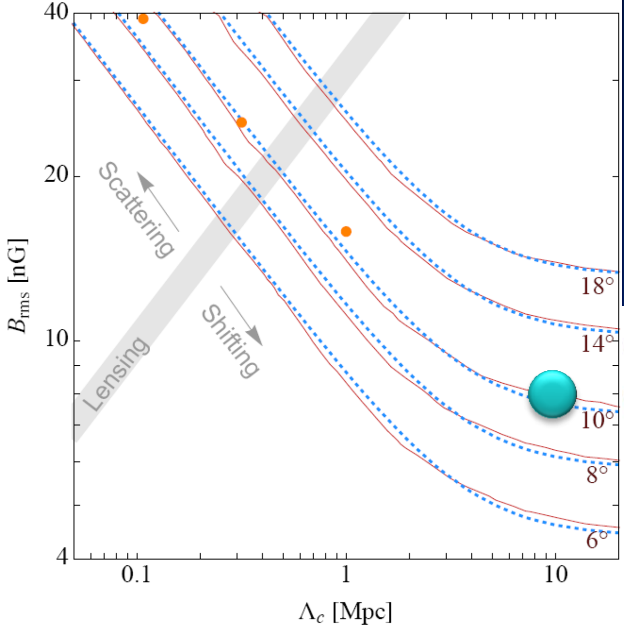
we compute θ numerically, utilizing a fourth-order Runga-Kutta method to solve equation of motion, keeping the step size small in comparison to both the minimum scale of magnetic field variation, and Larmor radius

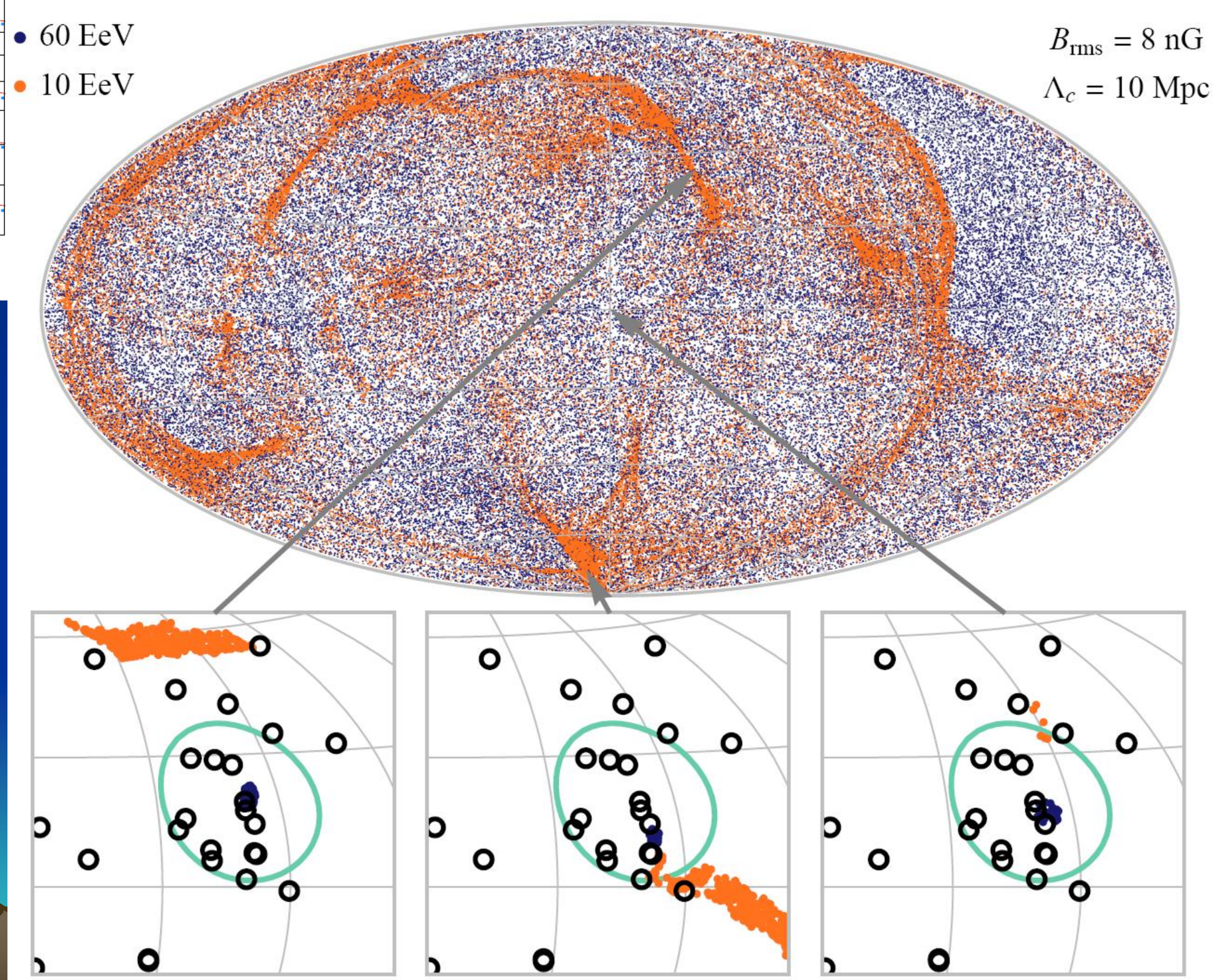
The mean values of 60 EeV cosmic-ray angular distributions around Centaurus A as a function of field strength and coherence length

- 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

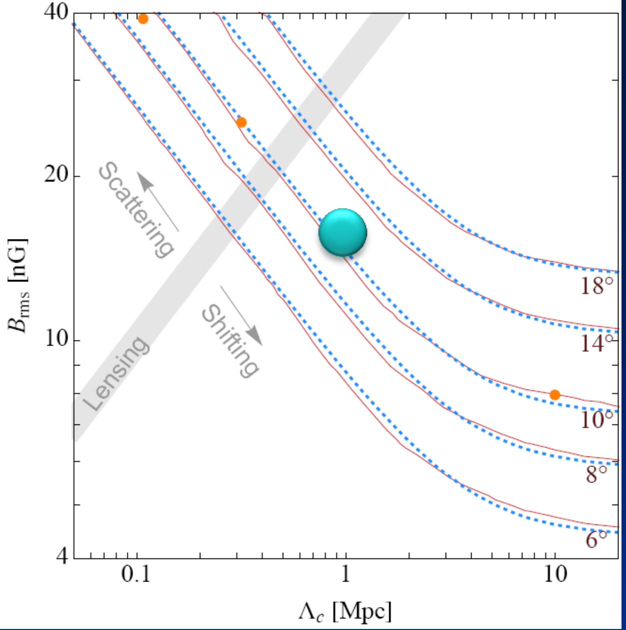




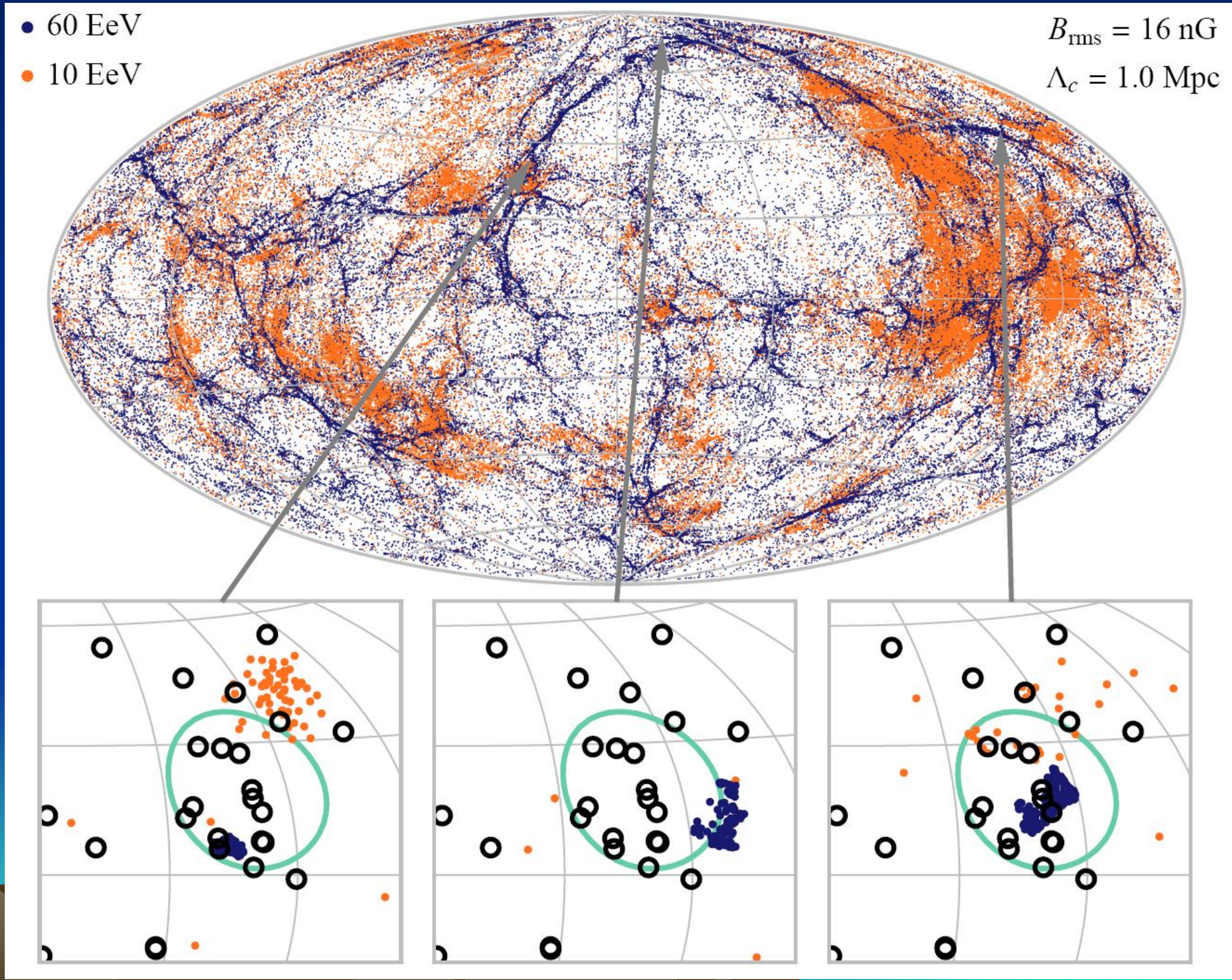
A piece of the (l.b) sky, centered on the (l.b) of Cen A

b

l



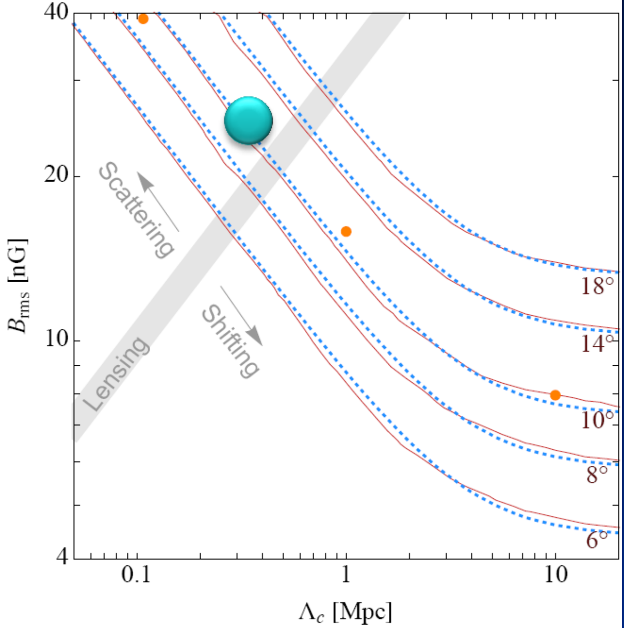
40
20
10
4
0.1
1
10
B_{rms} [nG]
Λ_c [Mpc]
Scattering
Shifting
Lensing
18°
14°
10°
8°
6°



60 EeV
10 EeV
B_{rms} = 16 nG
Λ_c = 1.0 Mpc

b

l


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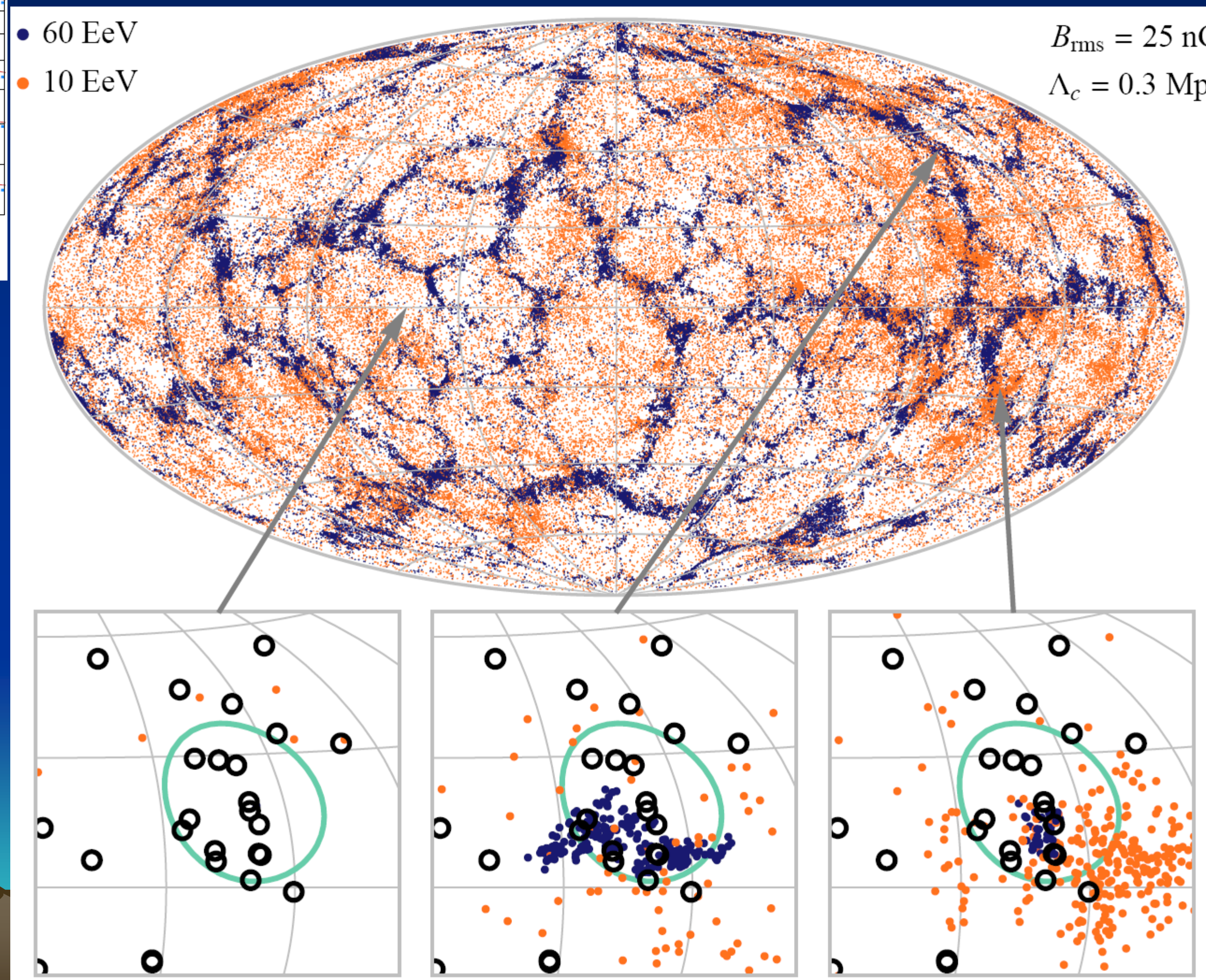
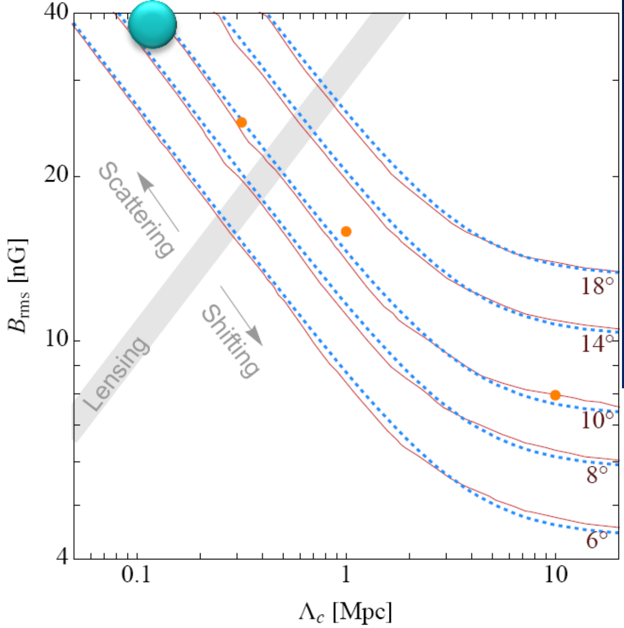
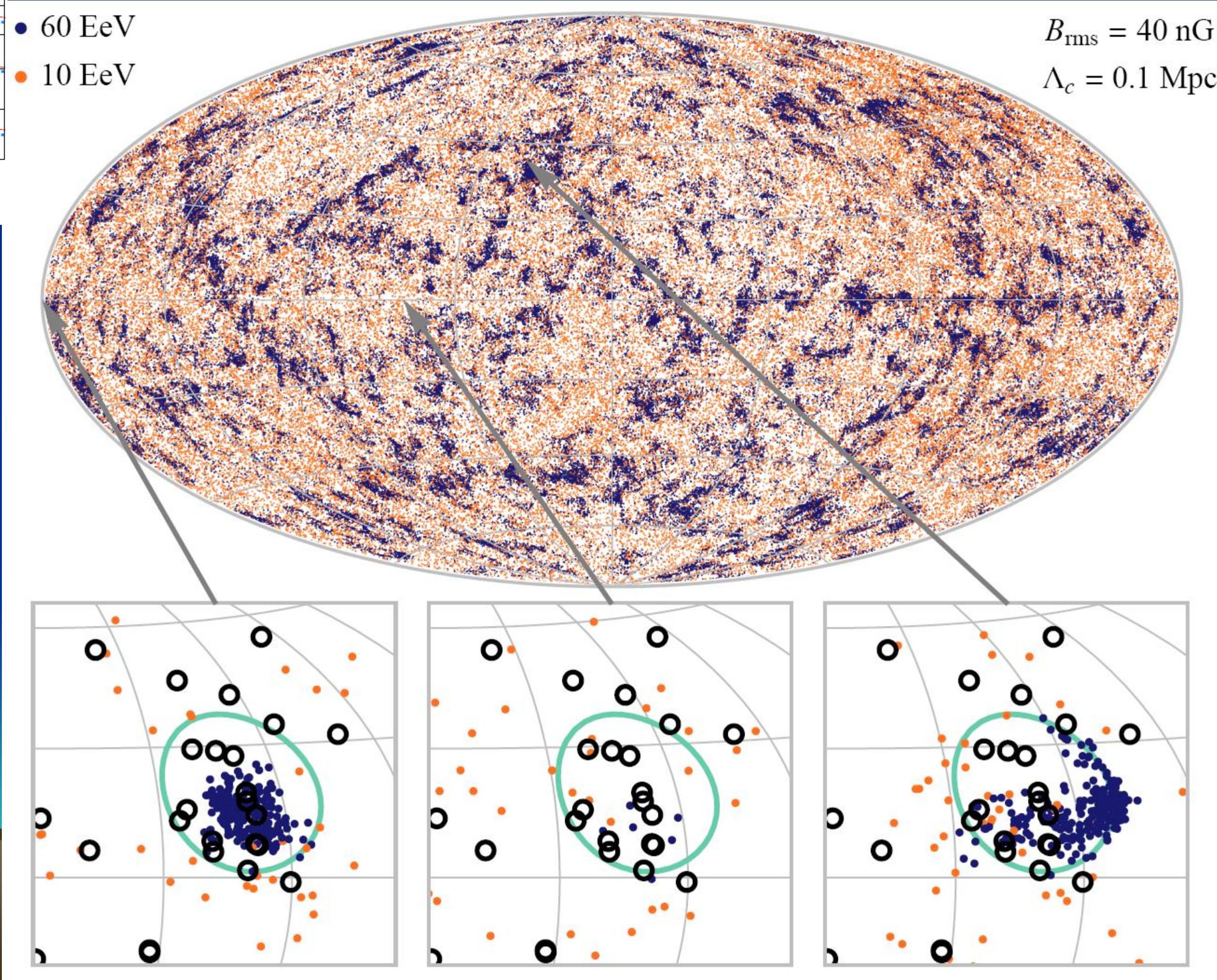
Λ_c [Mpc]
Scattering
Shifting
Lensing
18°
14°
10°
8°
6°


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

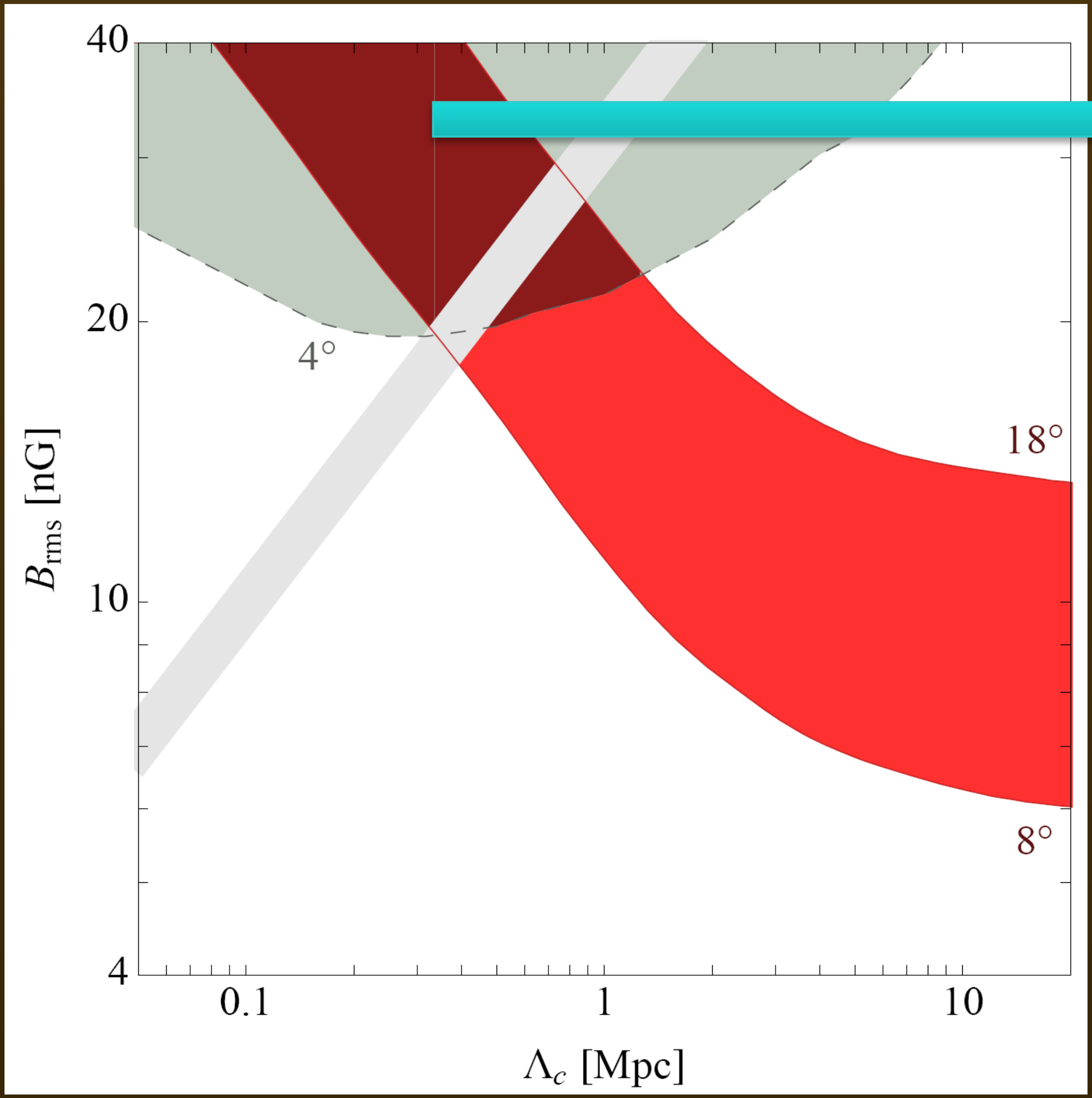
b

l


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
$\Lambda_c = 0.1$ Mpc

The local Intergalactic Magnetic Field



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

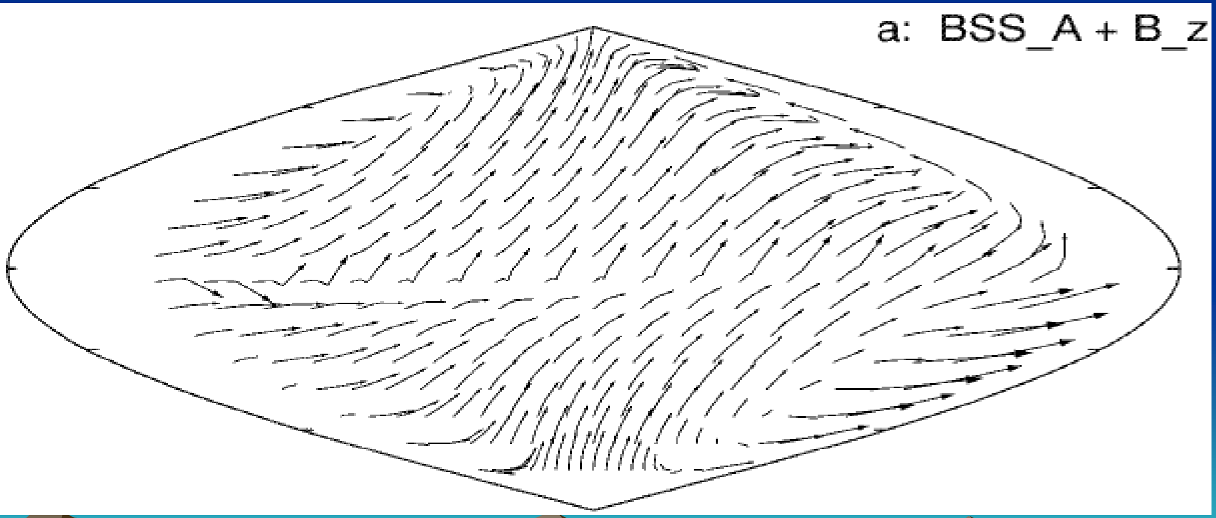
  1. *the average angular distribution of events 8-18 ° from Cen A (solid lines)*
  2. *the spread of events among themselves is < 4 ° (dashed line)*

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

What about the Galactic (Milky Way)magnetic fields?

- The GMF consists 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

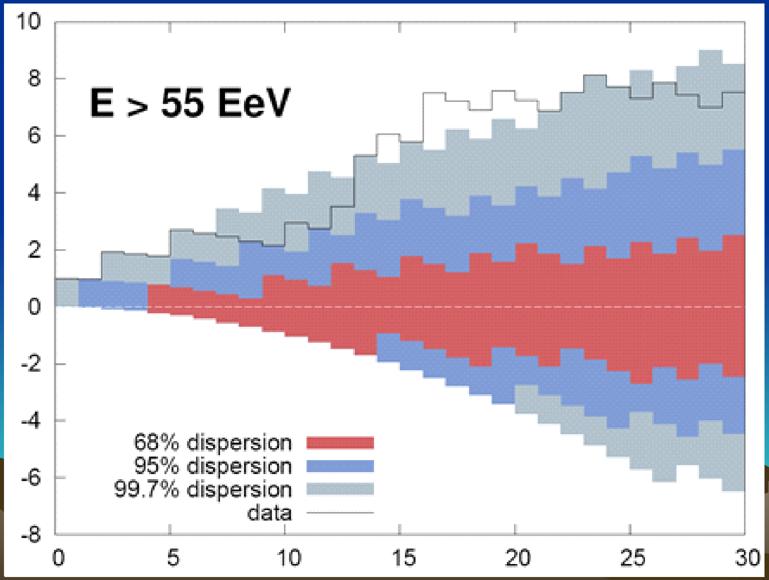
- Protons with energies of 60 EeV expected to be scattered by only about a degree (smaller than the uncertainty of UHECR detectors)
- The regular *B*-component tends to produce only a coherent shift in the position of the source:

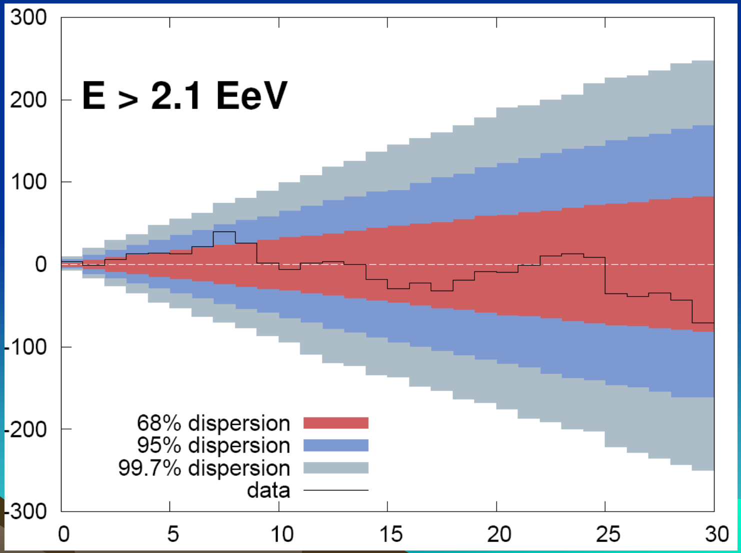


- We thus expect the GMF to have only a small effect on protons at the energies examined here and not to impact our conclusions

What about heavy Nuclei?

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





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 either the observed excess is either

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

End

I. Centaurus A

Philipp Kronberg

I. A kpc –scale electric current in 3C303

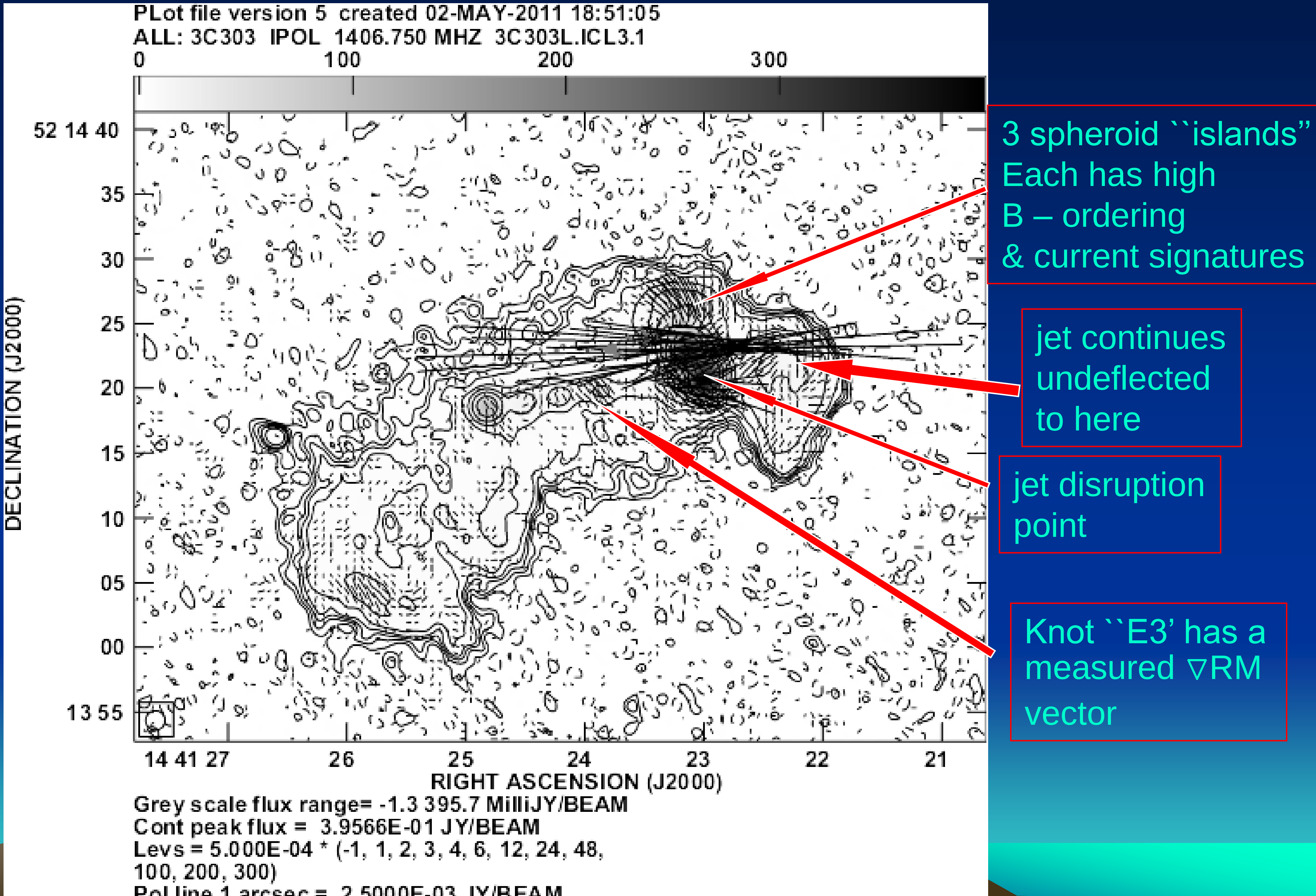
- VLA images at three radio frequencies were used to define
  (1) the morphology, (2) polarization and (3) the Faraday rotation structure, over 50kpc of the jet.

- These combined with (4) accurate background source Faraday rotations and (5) arcsec-level
  Chandra X-ray images, to analyse the jet's plasma parameters and deduce the current, and its direction
- Result -- ~3.3x1018 ampères, directed *away* from the central Black Hole.
- Firmly supports the theory of extragalactic jet power flow mainly by a Poynting flux.
- Implications, and why such kpc-scale currents have not been measured before,
- Future instrumental developments needed to cover "measurement parameter space"
  in extragalactic jets and lobes"

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

3C303 1.4GHz


PLot file version 5 created 02-MAY-2011 18:51:05
ALL: 3C303 IPOL 1406.750 MHZ 3C303L.ICL3.1
0
100
200
300
52 14 40
35
30
25
20
15
10
05
00
13 55
DECLINATION (J2000)
14 41 27
26
25
24
23
22
21
RIGHT ASCENSION (J2000)
Grey scale flux range= -1.3 395.7 MilliJY/BEAM
Cont peak flux = 3.9566E-01 JY/BEAM
Levs = 5.000E-04 * (-1, 1, 2, 3, 4, 6, 12, 24, 48, 100, 200, 300)
Pol line 1 arcsec = 2.5000E-03 JY/BEAM
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

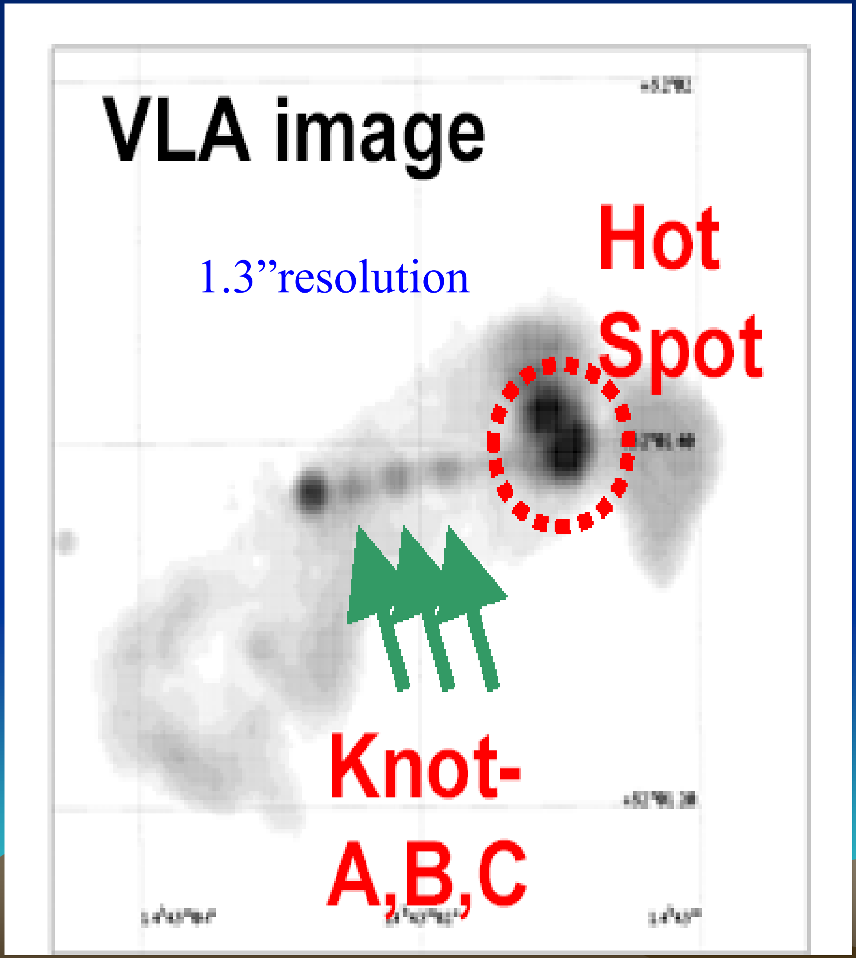
Knots and Hotspots of 3C303 (z=0.141)

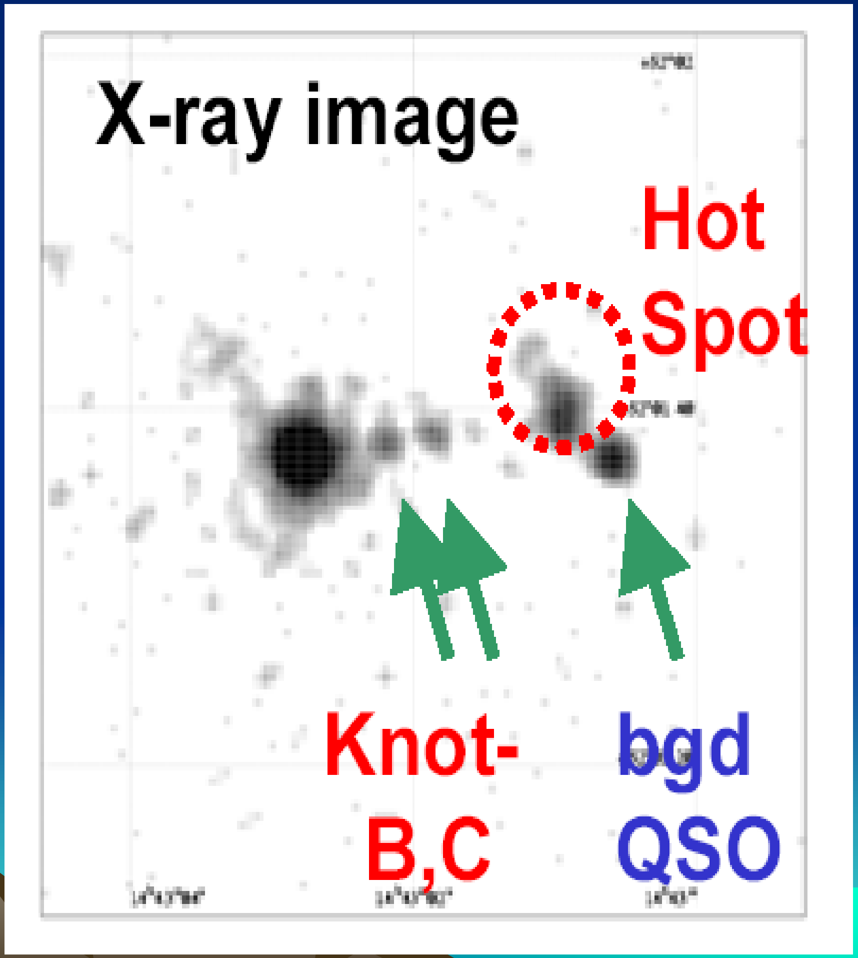
Radio (VLA) and X-Ray (CHANDRA)

*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*





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

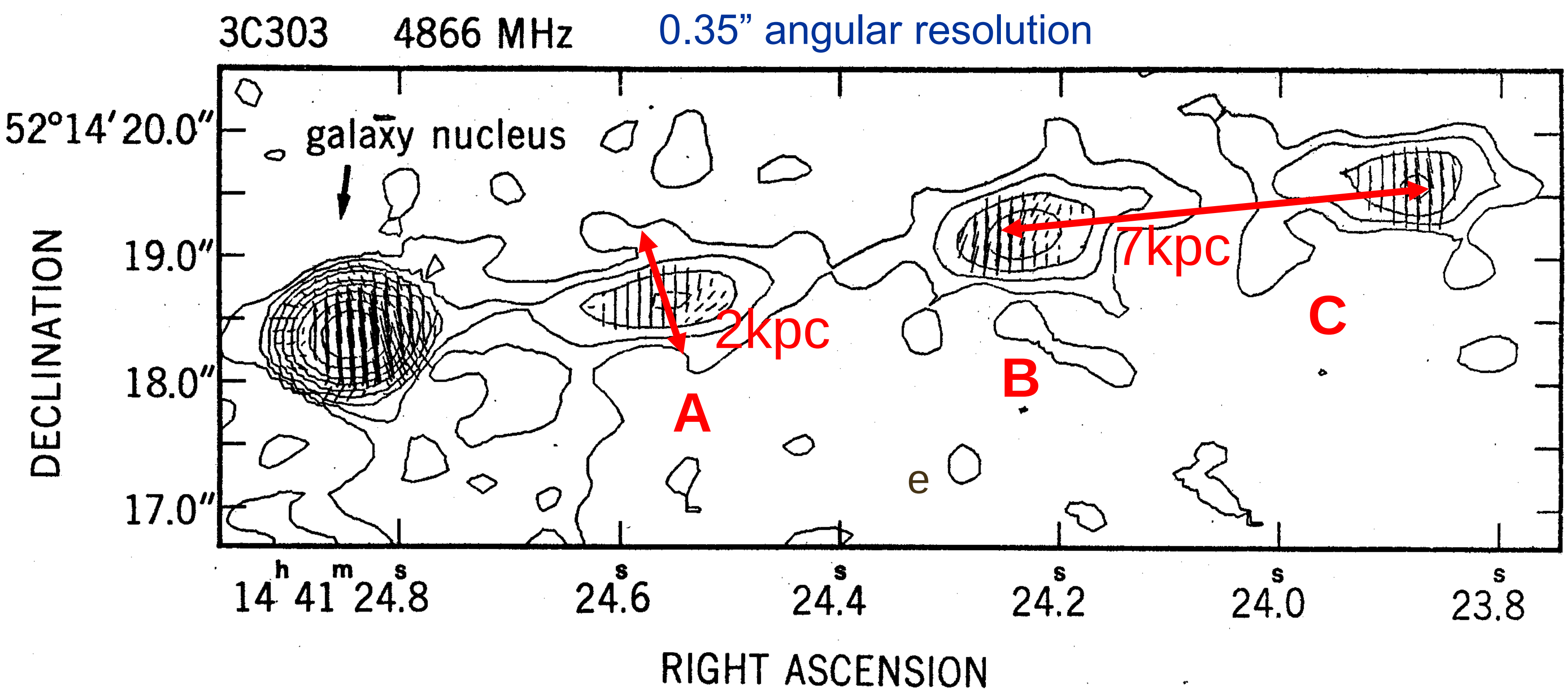
1. Sensitive images at $\nu_1, \nu_{2,}\ \nu_3$

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

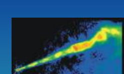
3. X-ray image ~ kev range

4. Need surrounding sky RM's to establish the RM zero-level
i.e. subtract <$\text{RM}_{\text{backgnd sources}}$> 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!

Plasma Diagnostics of the 3C303 jet

Lapenta & Kronberg ApJ 625, 37-50, 2005

(1) <(Total energy flow rate)> = E^T_{min}/τ = **2.8x10^{43}** τ_7^{-1} erg/s

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

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

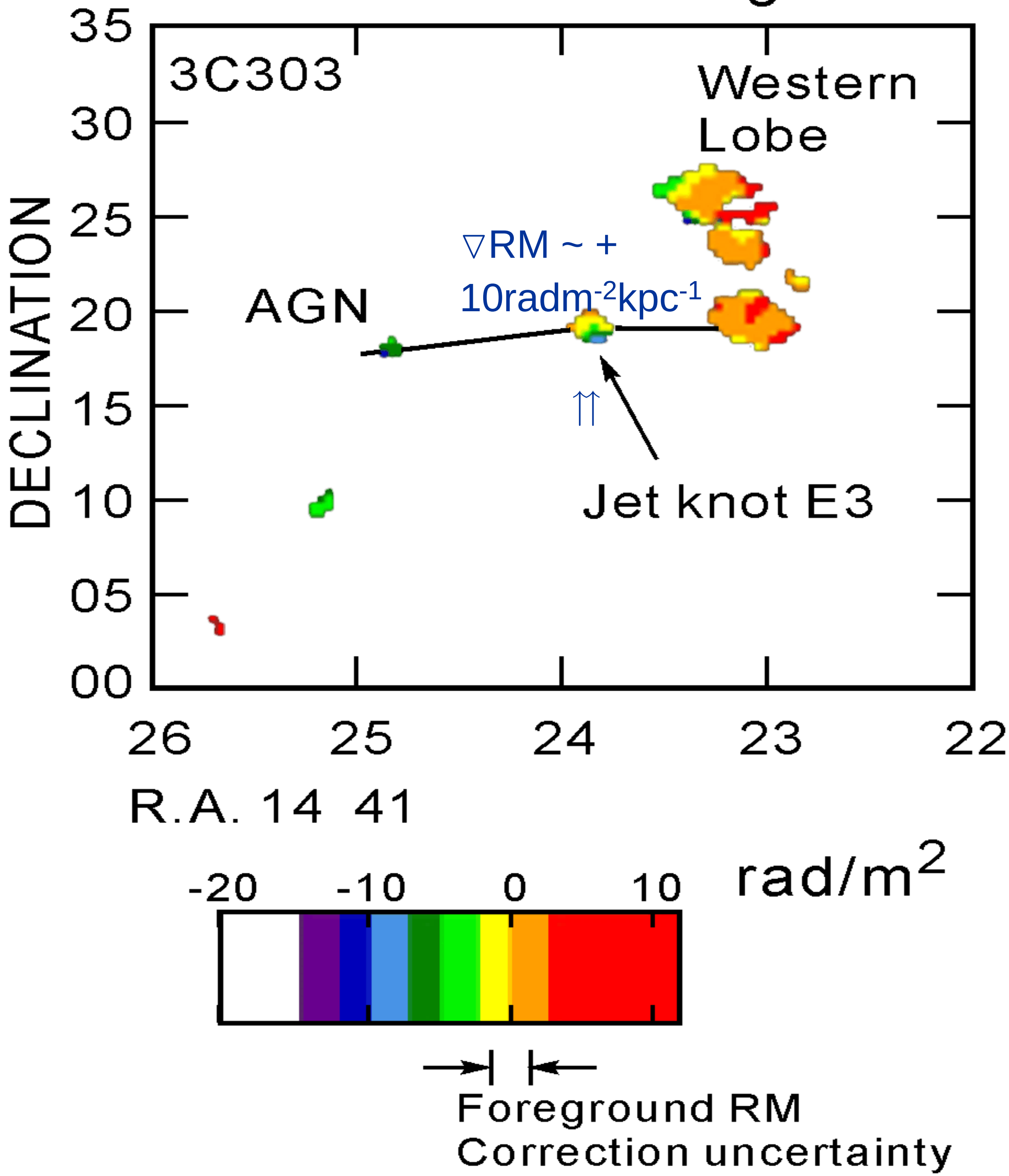
(3) Measure knots' synchrotron luminosity & size (D_{knot}) → **B^{knot}_{int}=10^{-3}G**

(4) From the Faraday rotation isolated in the knots, **RM** ∝ n_{th} × B^{knot}_{int} × D_{knot}

gives n_{th} in knots for 3C303) → n_{th} ≈ 1.4×10^{-5} cm^{-3} (an extragalactic density!)

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

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


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

Plasma parameters in the 3C303 jet

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

  Lapenta & Kronberg ApJ 2005
- *Consistent with a magnetically confined, Poynting flux driven jet:* Absence of evidence for mass-loading, -- otherwise required to carry a <u>particle beam</u> 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*** ~ 10^{37} watts of directed e.m. power
  - → ***I*** $=3.3\times10^{18}$ ampères of axial current
  - ▽RM sign gives ***I*** direction – in this case away from the BH
- Jet's electrical properties:

V_0 = r_0B_0/(3^1/4 sqrt(R) (c.g.s.) = 2.7 x 10^20 V (MKS)

I_0 = c r_2B_phi(r_2) = V_0/Z_0 (c.g.s.) = 3 x 10^18 A (MKS)

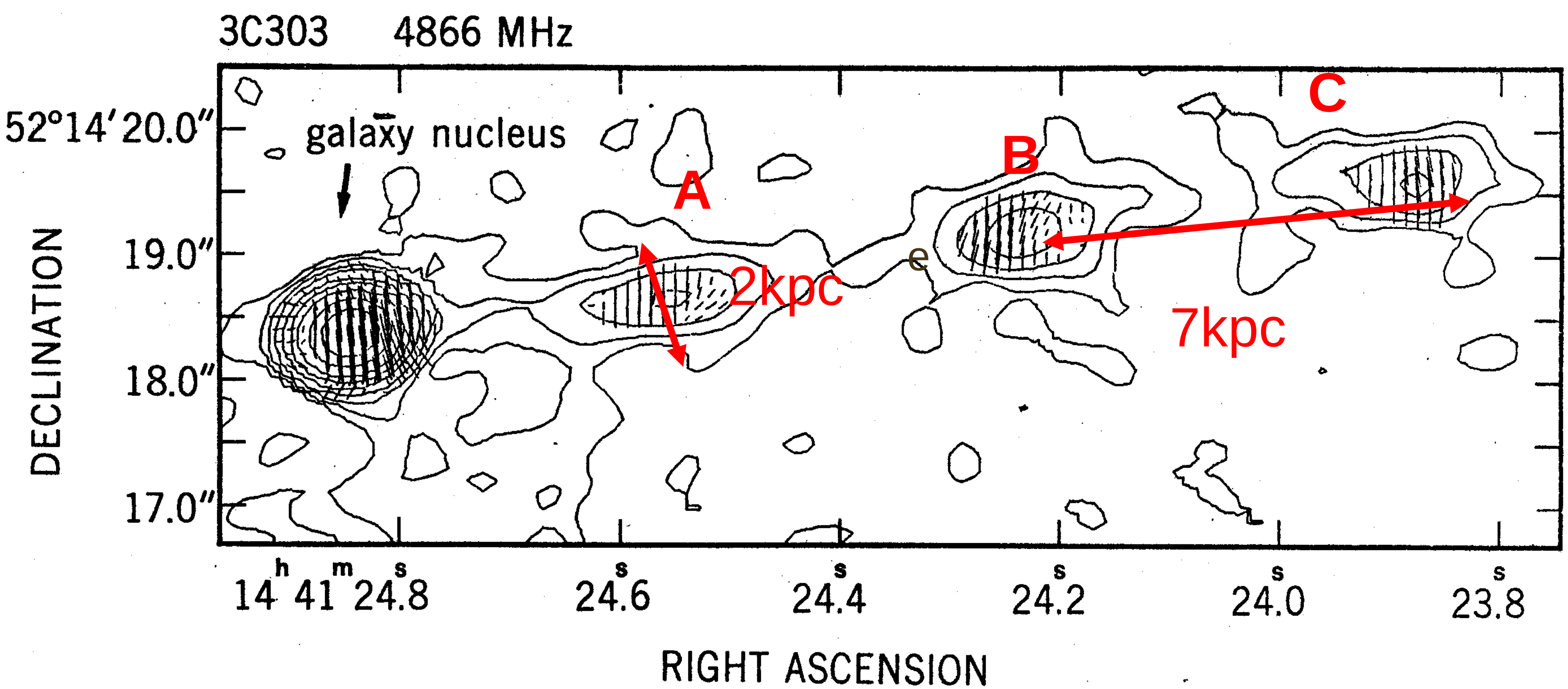
Z_0 = (3/c) beta (c.g.s.) = 30beta ohms (MKS)

where beta = *U_z/c* $\lesssim$ 1, and *r*_1, *r*_2 are inner & outer transmission line radii

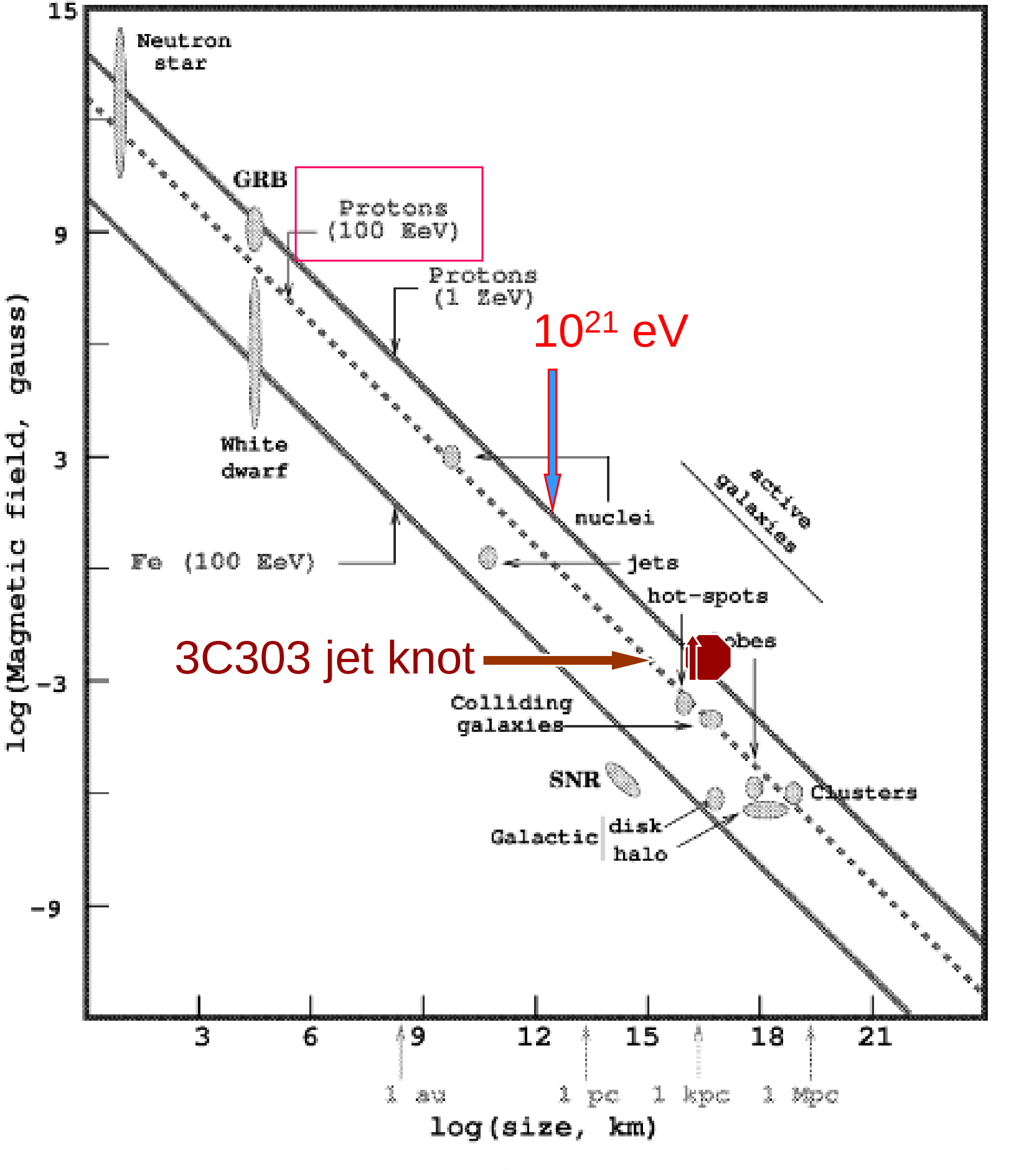
(*Lovelace & Ruchi, 1983*)

VLA image

AGN jets
viewed as VHE particle acceleration machines



UHECR acceleration in the 3C303 jet?



<u>*B·L* ("Hillas") plot</u>

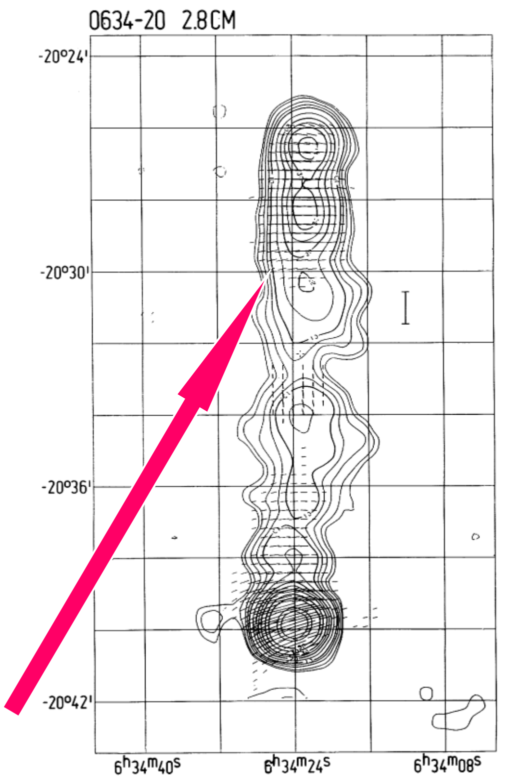
(*A.M. Hillas AnnRevAstAp 1984*)

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

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

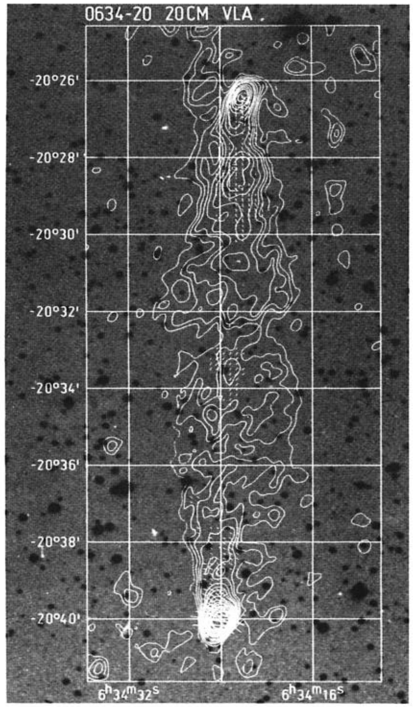
a "template" for widespread IGM CR acceleration??

10 GHz



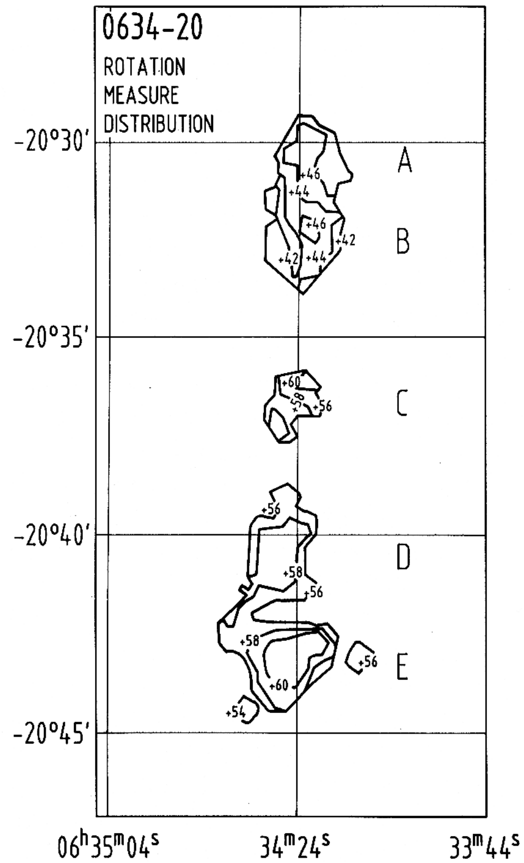
Effelsberg 100m. Telescope 10.6 GHz

1.4 GHz



VLA 1.4GHz

Faraday RM(radians/m^2)



Freshly accelerated, starved of thermal plasma?

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

→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

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

2147+816 giant radio galaxy

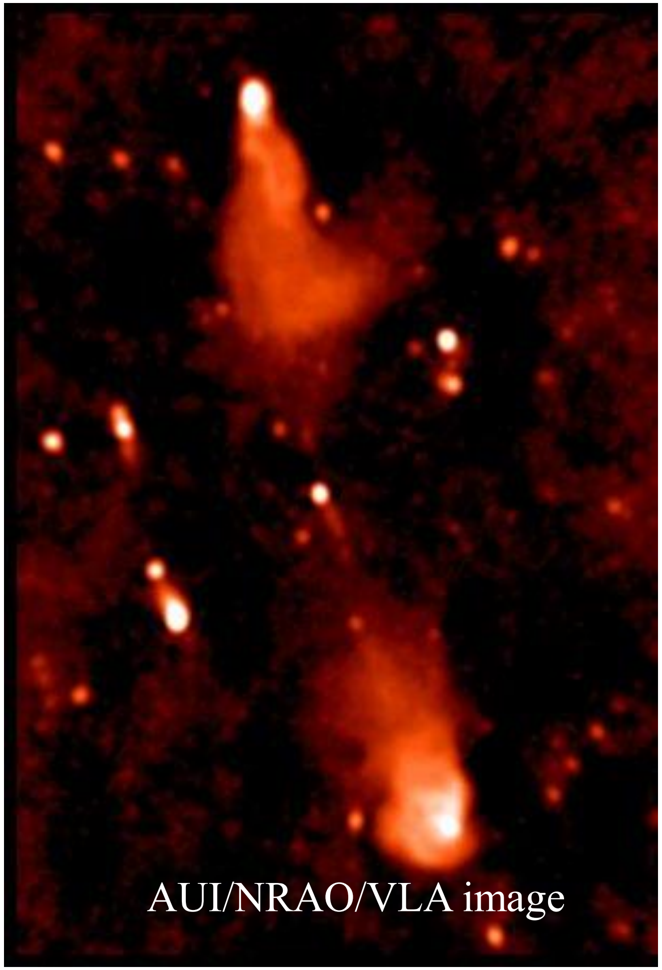
Analysis of ≈ 70 GRG images
Kronberg, Dufon, Li, Colgate
ApJ 2001

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



Future
Opportunities for diagnosing jet magneto-plasmas

- 1. On pc scales near r_G of the SMBH

  VLBI up to to Earth's dia & beyond

- 2. On kpc-Mpc scales Interferometers up to *n*00 km

Future instrumental directions and opportunities

Essential improvements required

For both (1) VLBI and (2) VLA-type 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

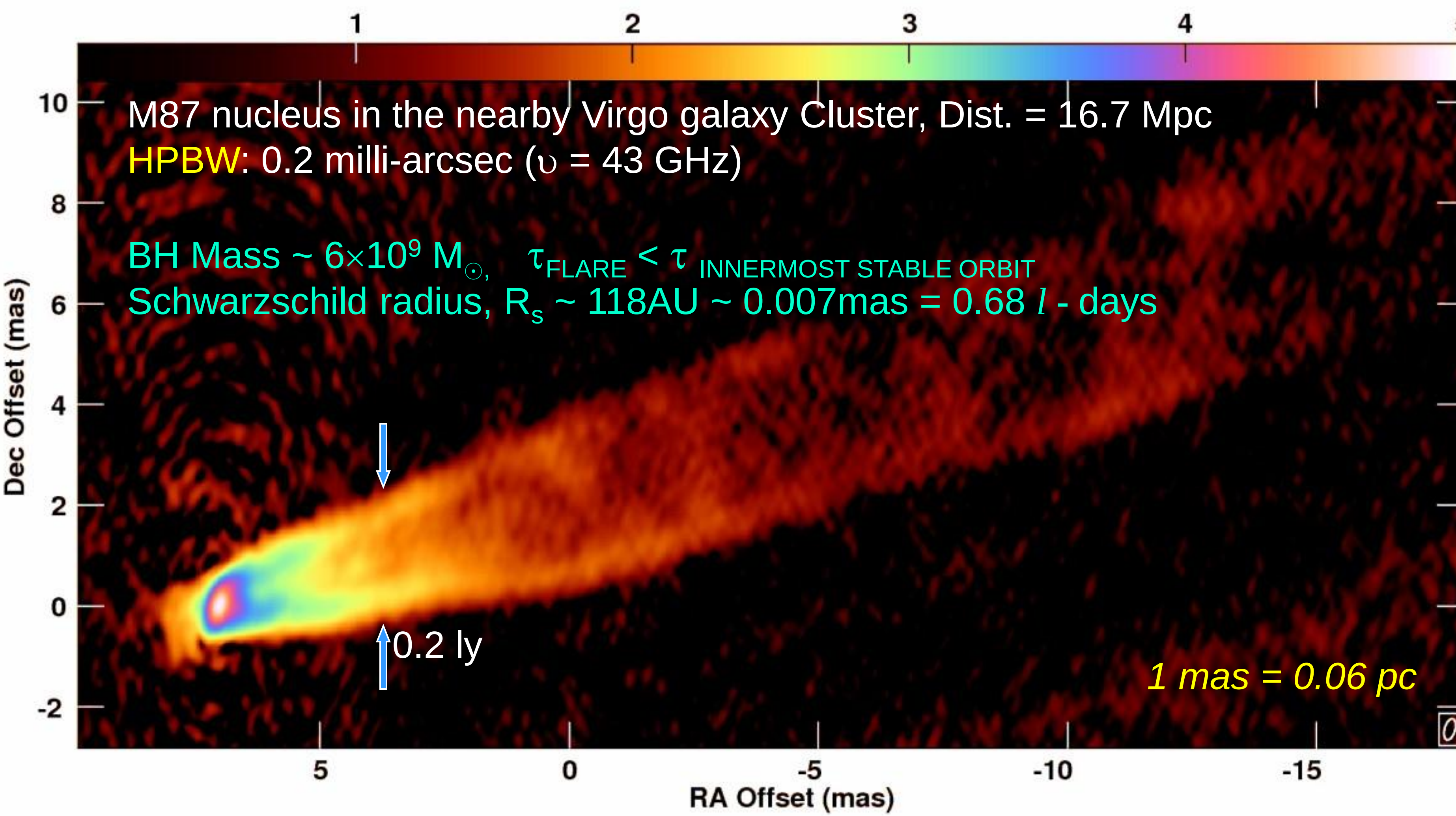
--explore in time-evolution – a new capability. -- next slide

Sum of 23 VLBA images at 43 GHz

Veritas Collab,

NRAO VLBA M87 Monitoring Team,

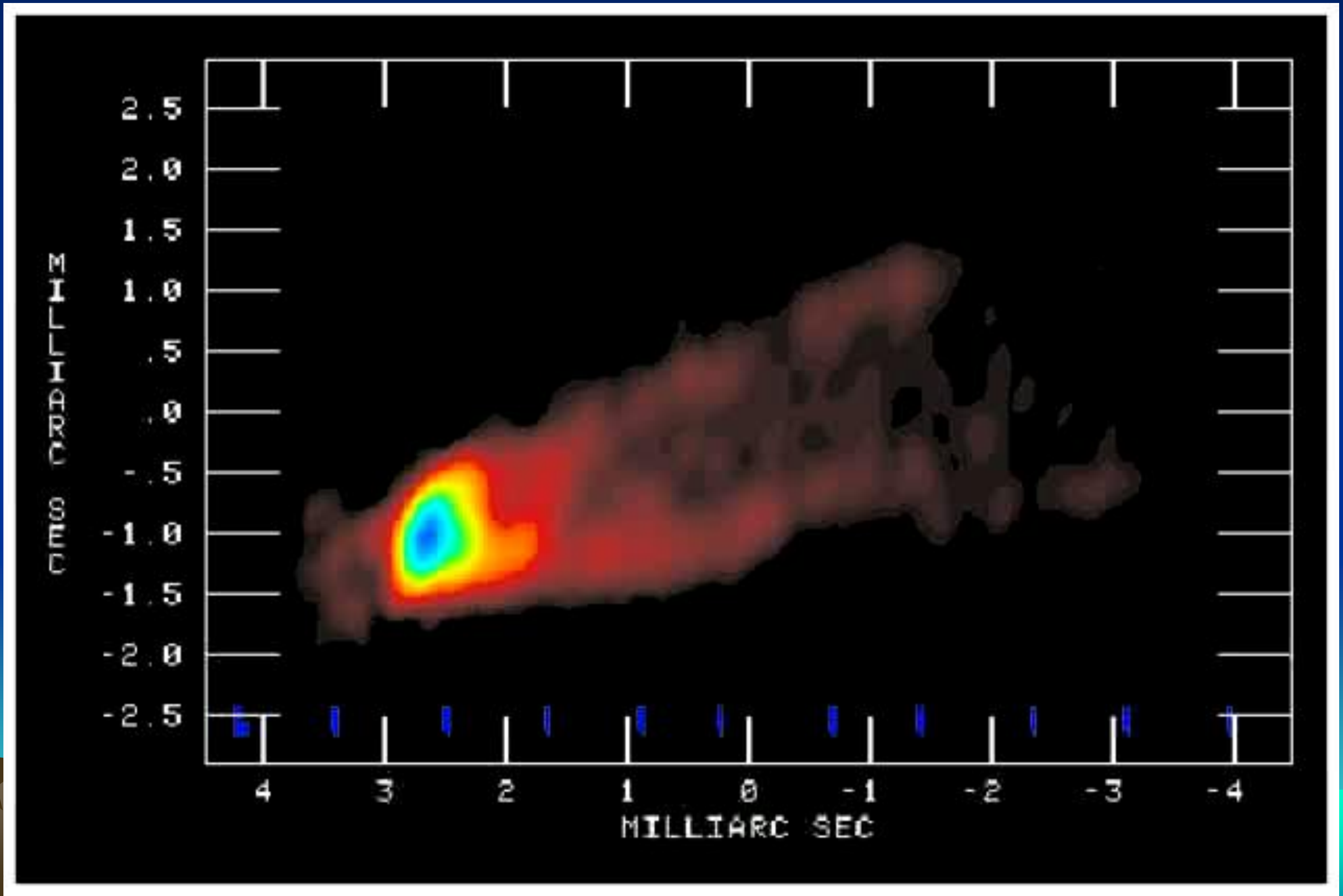
H.E.S.S. Collab. & MAGIC Collab., **Science**, **325**, 444, 2009



M87 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)

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1. is 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}.

-- 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

End

Ⅱ. 3C303 as an electrical circuit