Magnetic fields in the Universe

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The Milky Way field structure

Begin with M. Simard-Normandin & Kronberg

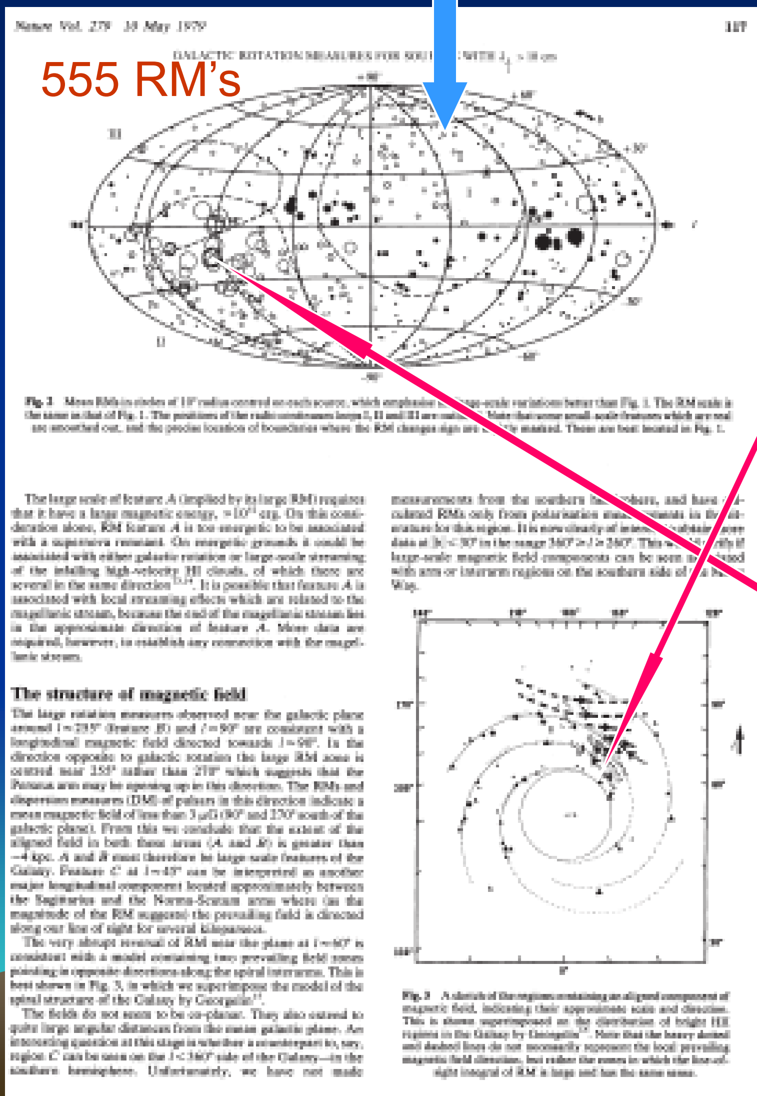
Nature **279**,*115,1979,*

and

ApJ **242**,*74, 1980*

Faraday Rotation measure studies of the Milky

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



Summary of conclusions in 1980:

Simard-Normandin & Kronberg
*ApJ **242**, 74, 1980*

1. Bisymmetric field pattern

2. Off-plane angular autocorrelation scale of RM sign ≈ 30º

3. Magneto-ionic scale height ≈ 1.8 kpc

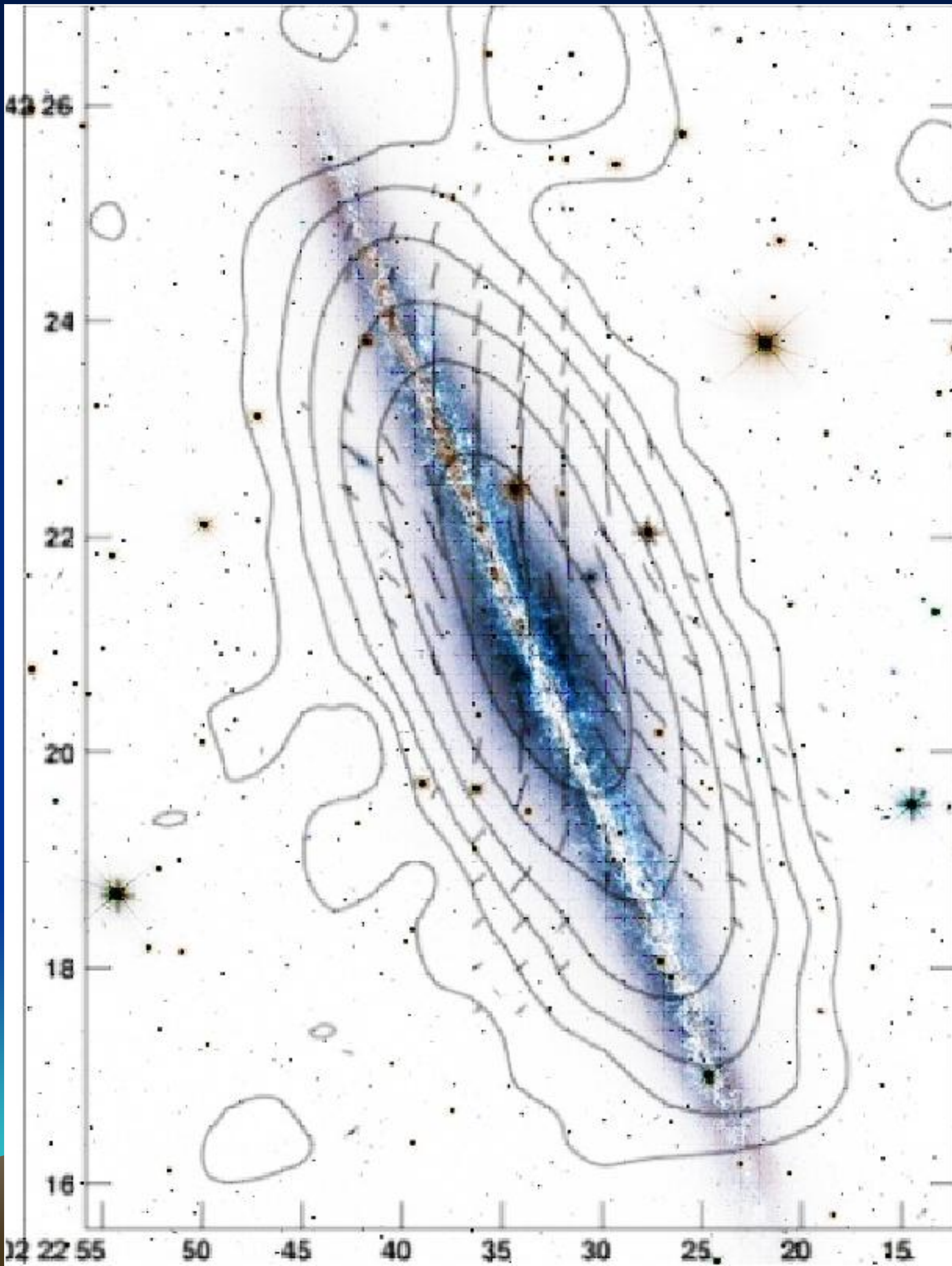
4. (Still mysterious) off-plane, high-RM zone at *l* ~ 100º, *b* ~ -25º (region "A")

5. Spiral with -25º pitch angle (from tangential) (now - 5 °)

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

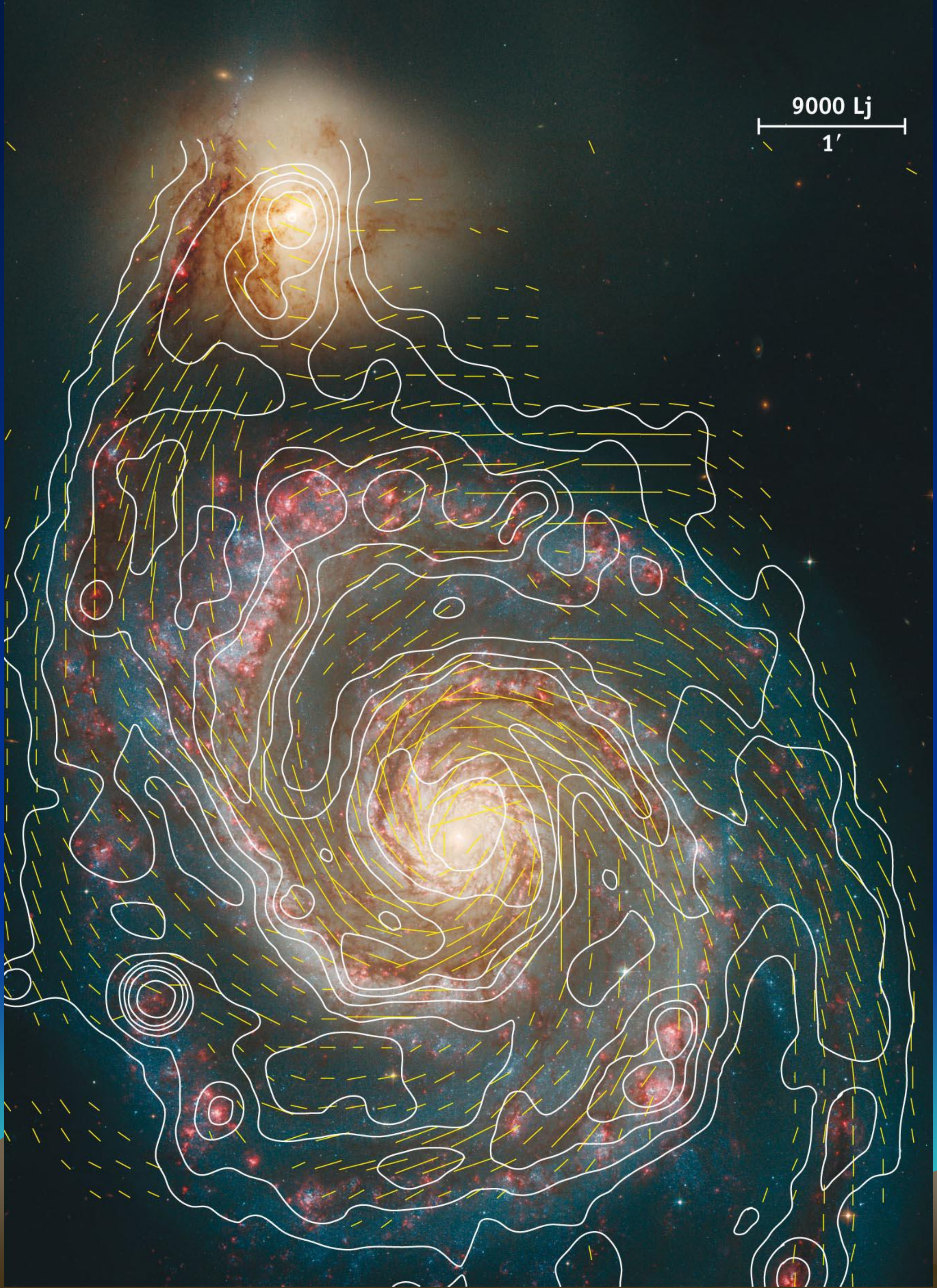


Edge-on view of the (2-D projected) halo magnetic field of NGC891

(*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. $\Delta\theta$ (atomic species, energy, $\boldsymbol{l}$,$\boldsymbol{b}$)



a top (plan) view

Projected Magnetic field
In a "grand design" galaxy

M51

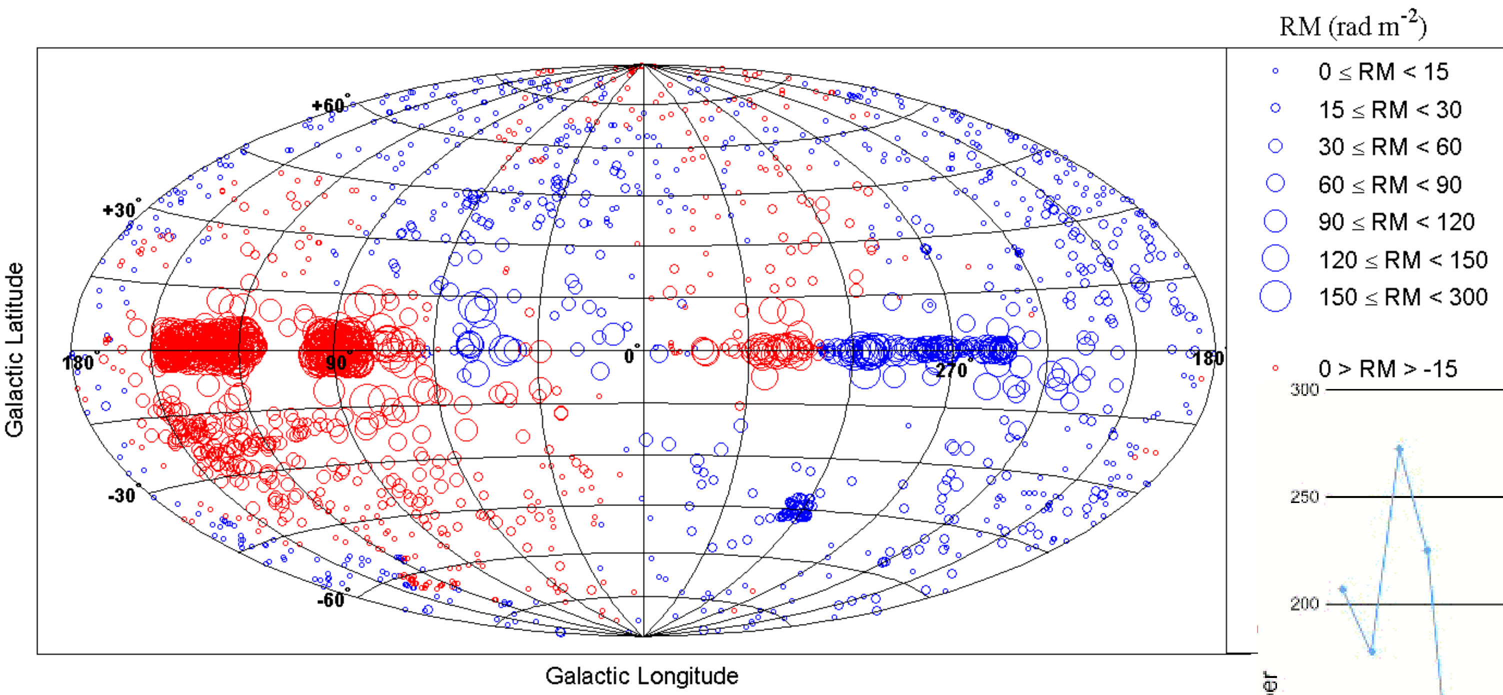
R. Beck
in
Sterne und Weltraum,
September 2006.

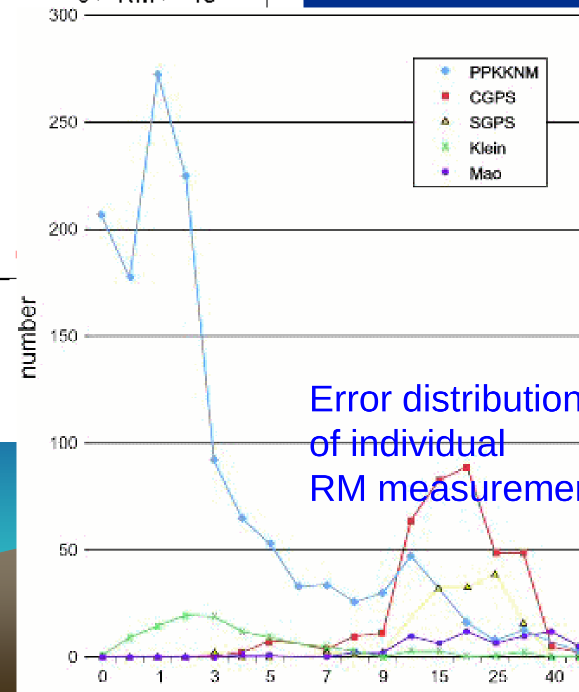
Question: To an extragalactic observer, does the Milky Way present a clear and beautiful magnetic grand design, like this one and others?

New results suggest **yes**

A recent RM probe of the Milky Way disk

New smoothed Galactic RM sky from 2250 egrs RM's



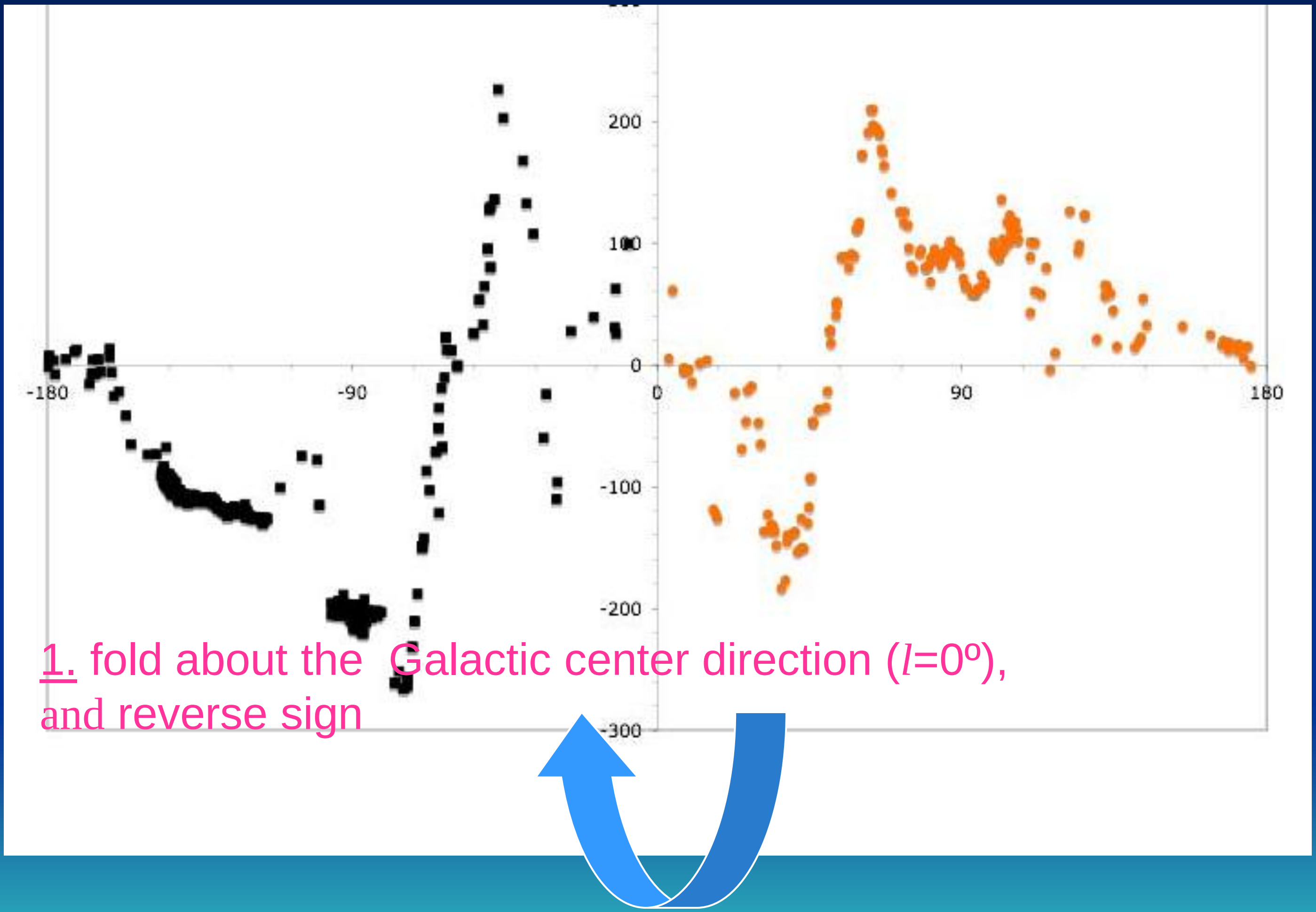


Error distribution
of individual
RM measurements

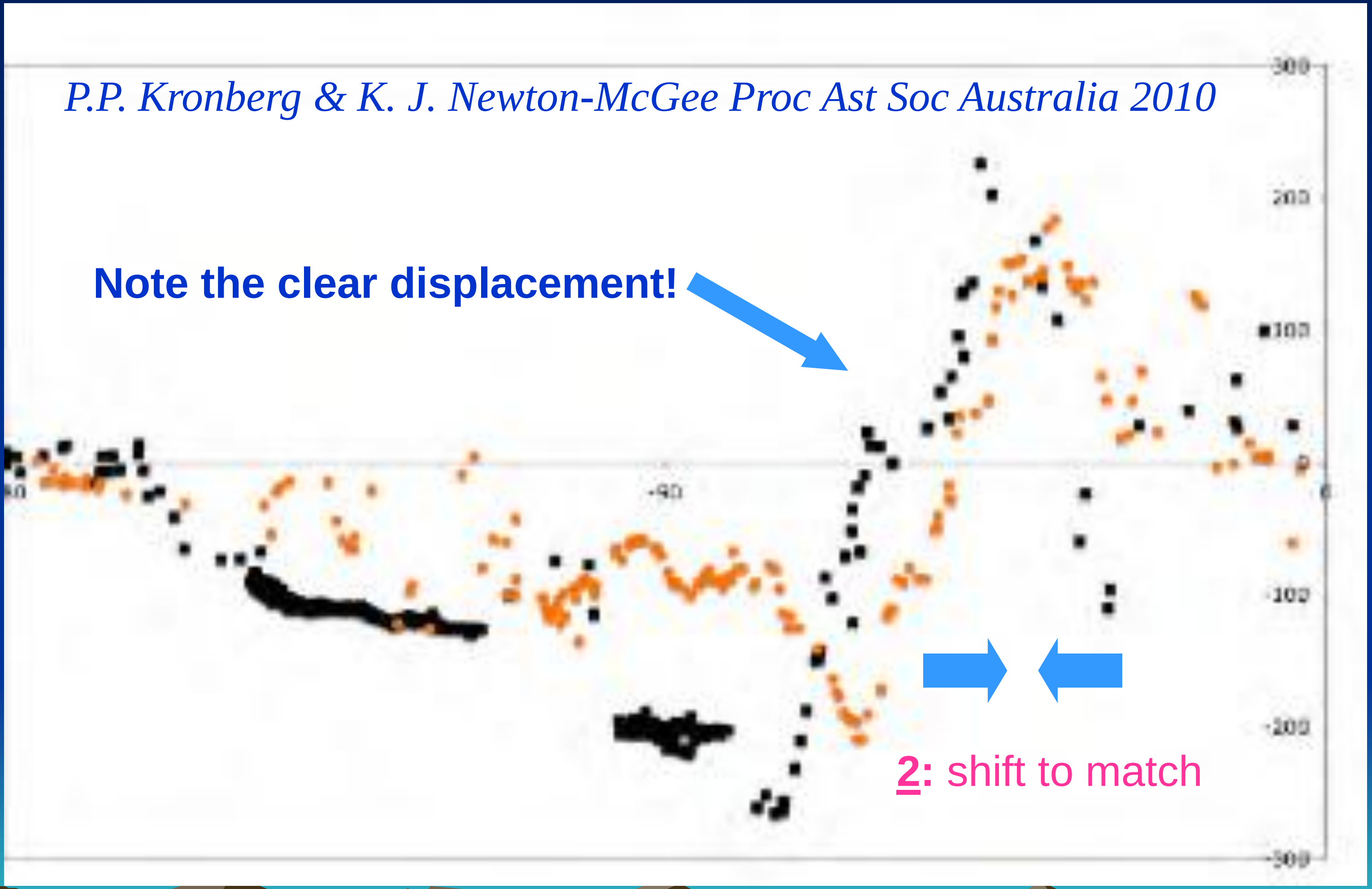
P.P. Kronberg &** K.J. **Newton-McGee
***Pub. Ast. Soc.Australia v28,** 171,2011*

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

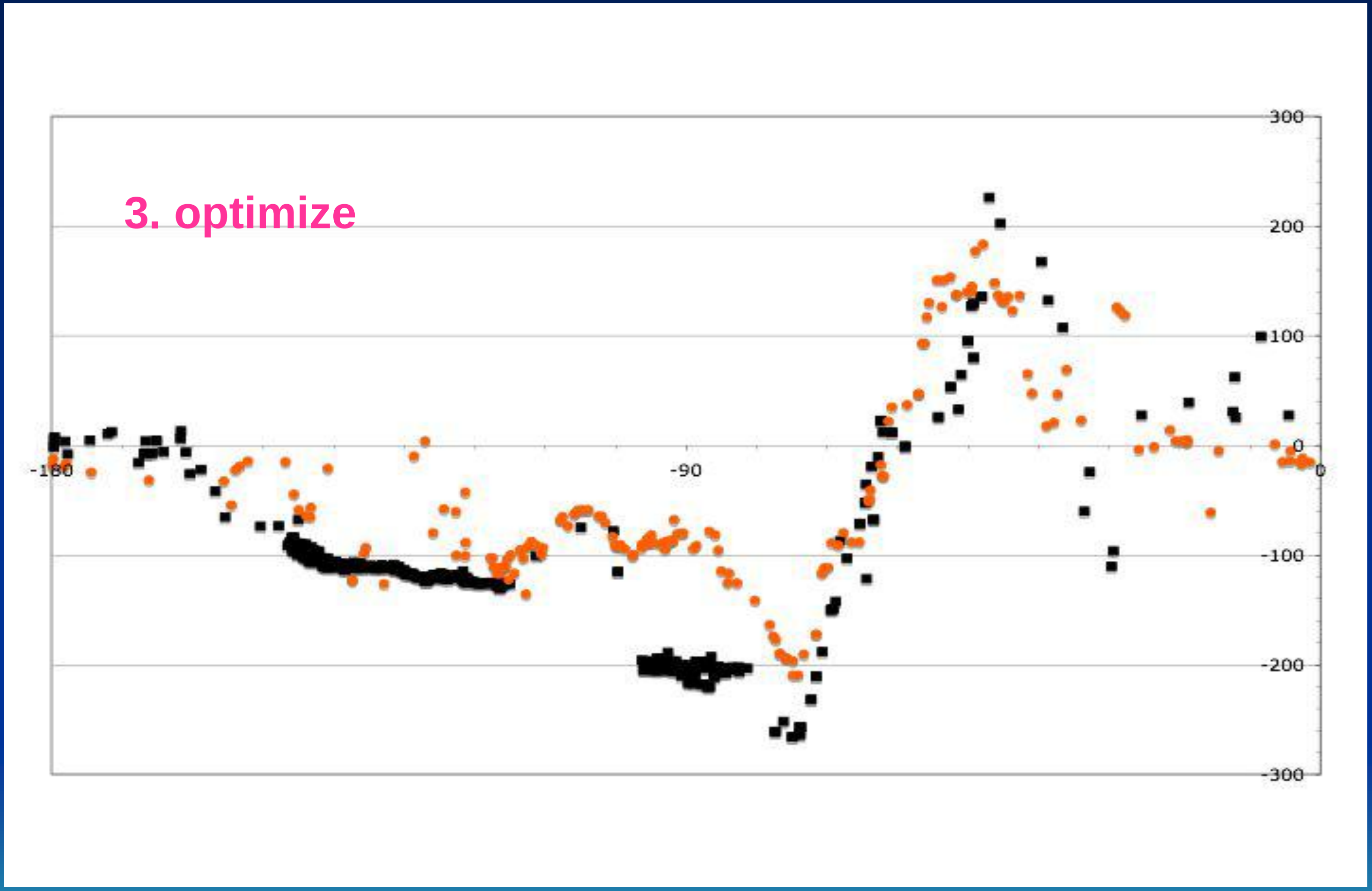
P.P. Kronberg & K. J. Newton-McGee Pub Ast Soc Aus 2011



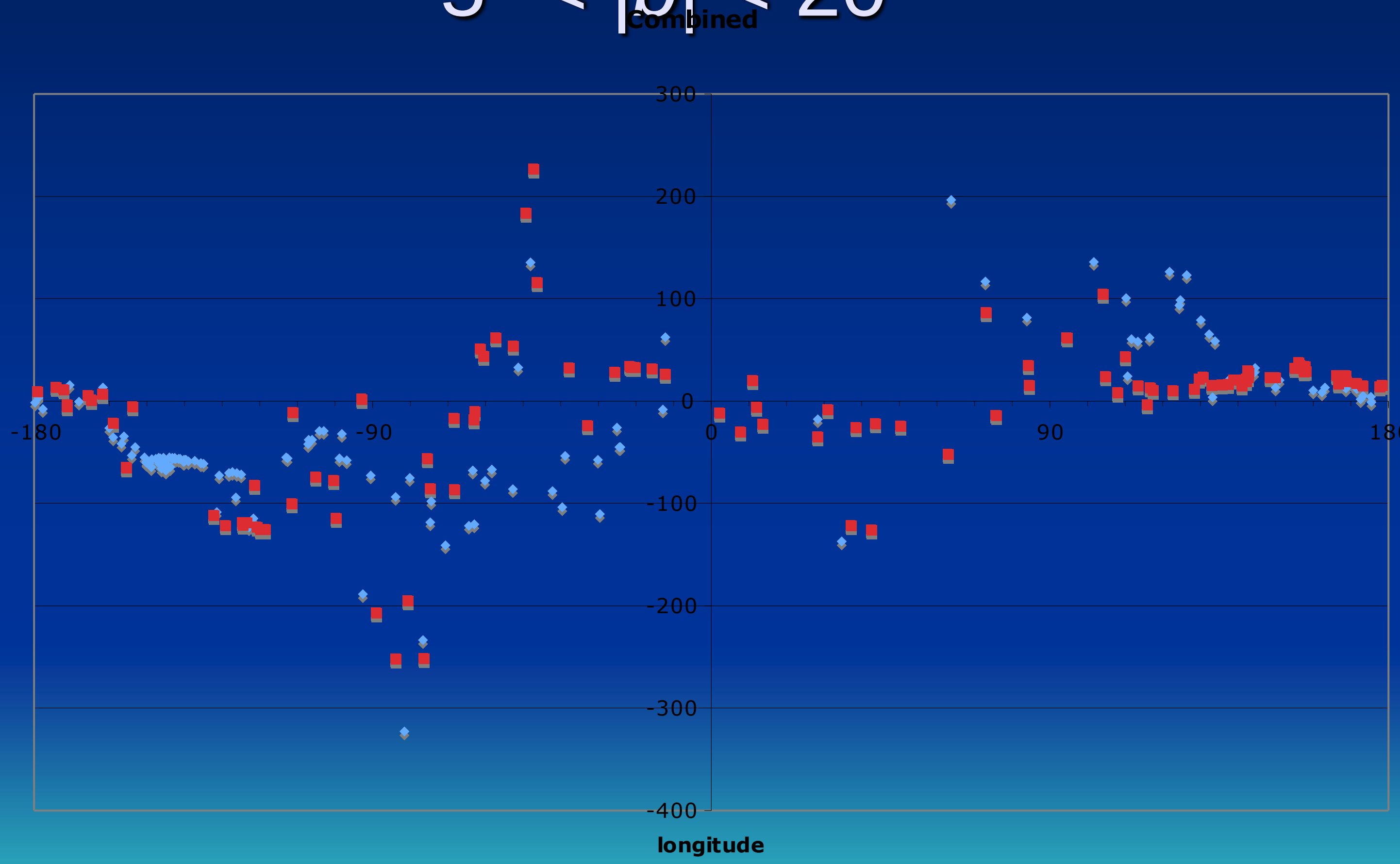
Fold RM's about *l*=0, then **reverse the sign** of RM's at 360° > *l* > 180° (orange points)



RM's *after* an 11º (± 2º) shift



Now, migrate further away from the Galactic plane
5º < |*b*| < 20º



Quick summary of results

*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).*

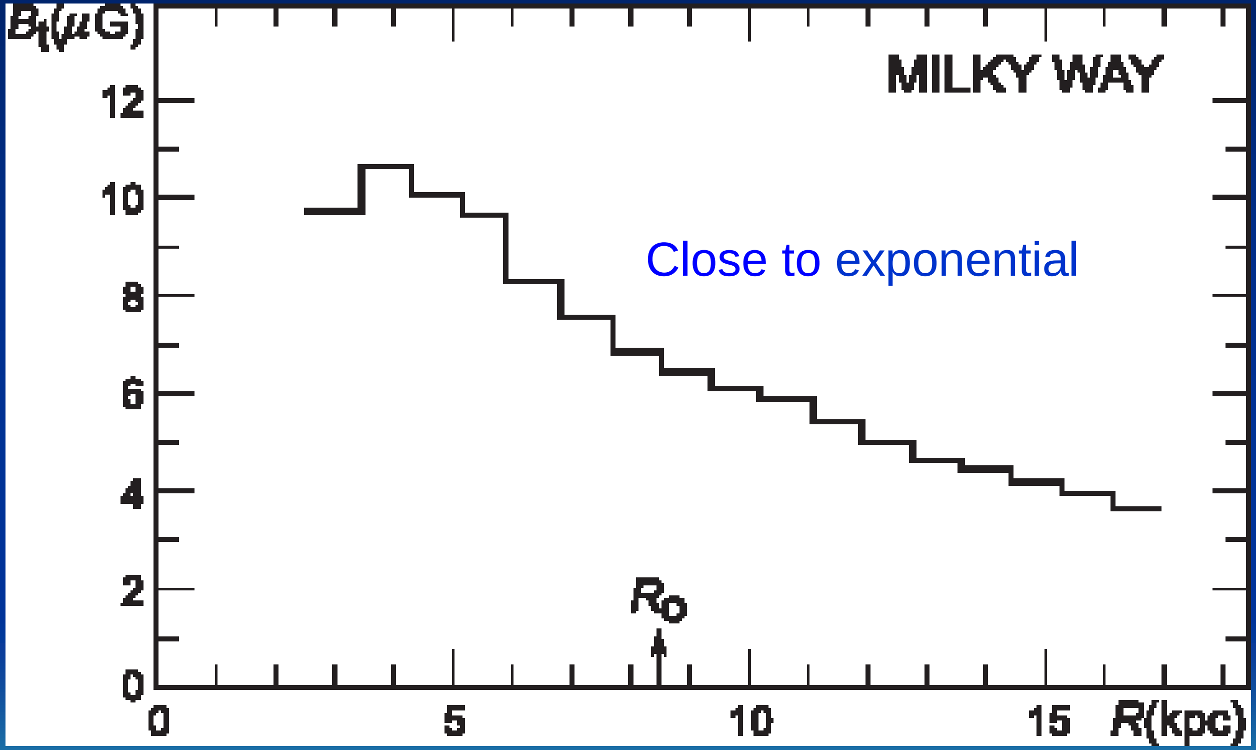
   Smaller-scale B reversals are averaged out: Not important for most VHECR propagation on larger scales)

2. *Average B aligns closely with the stellar spiral structure –like many other nearby spirals*

3. *To an extragalactic observer, the magnetic Milky Way is a highly patterned, "grand design" spiral galaxy, just like M51, etc. – **when we look at the forest, not the trees***

|*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*)

B in the galactic Halo?

not so easy to define!

One recent RM-based result:

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

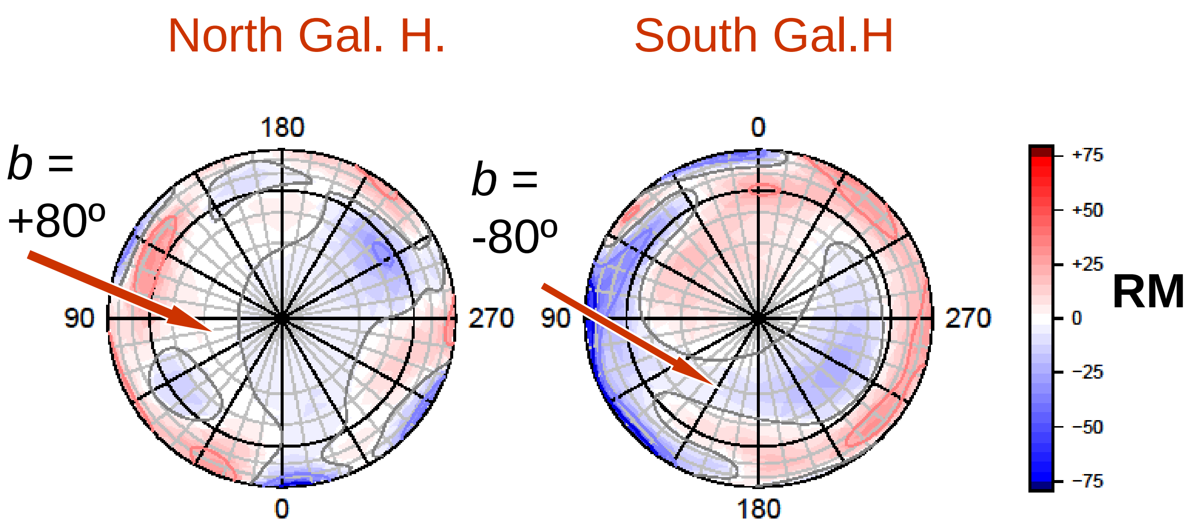
In the NGH: median RM = 0 ± 0.5 rad/m^2

In the SGH: medium RM = +6.3 ± 0.7 rad/m^2

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

Another attempt: Bayesian-smoothed RM's in the Galactic caps |b|>30°
from the 2250-RM all-sky sample above

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



How to measure/model the 3-D magnetic structure of a galaxy halo?

Use the Fourier transform relation between measured *P*(λ^2) and the Faraday depth (ϕ) – relates to the 3rd (depth) dimension

B.J. Burn MNRAS 1966

Note (below): for redshift (*z*) = 0, as in this case,

n(*z*), *B*(z) become *n*(*l*), *B*(*l*)

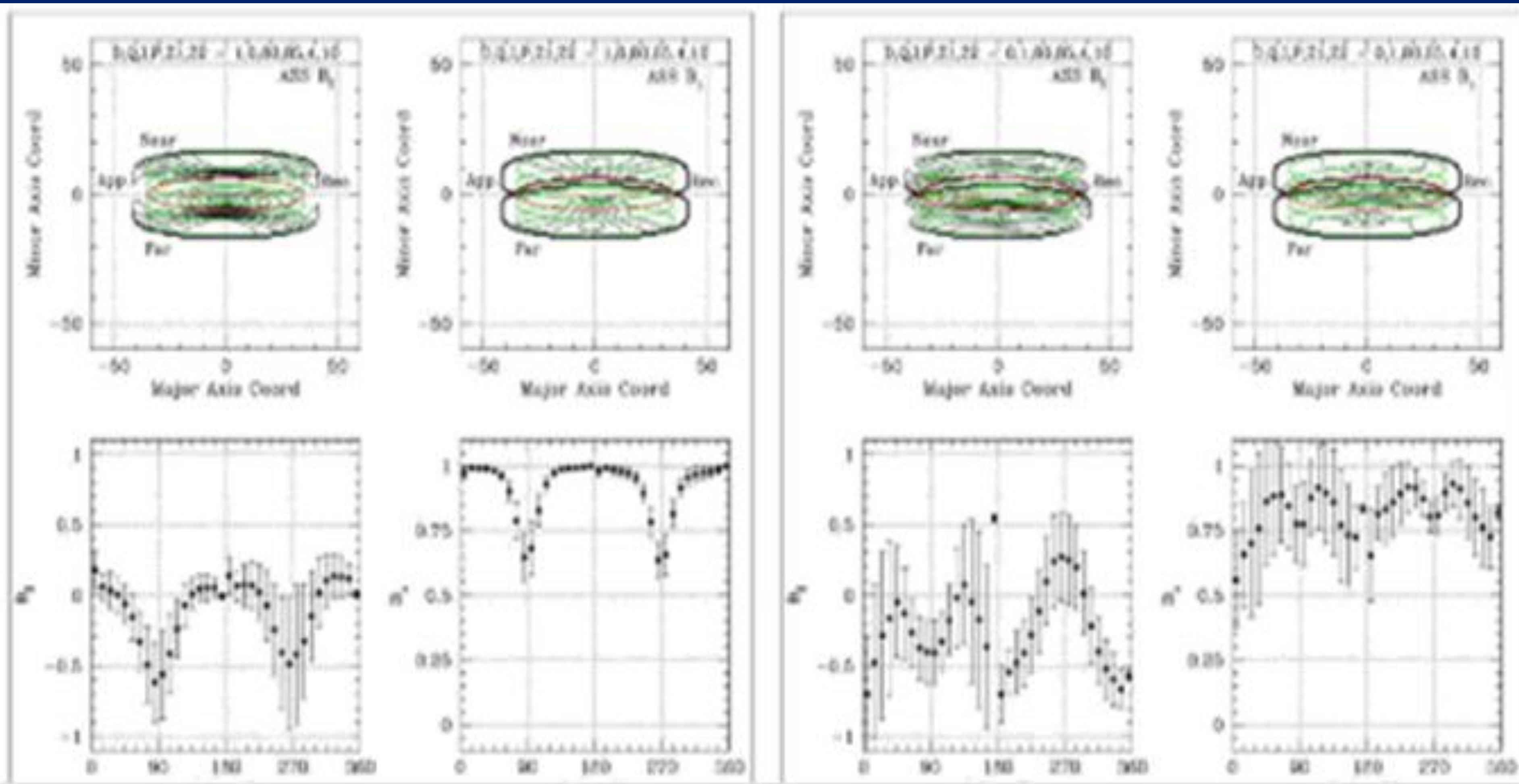
$$\phi(\lambda^2) \propto RM = \frac{\Delta\chi}{\Delta\lambda^2} = 8.12 \times 10^5 \int_0^{z_s} (1+z)^{-2} n_e(z) B_{||}(z) dl(z) \quad \frac{\mathrm{rad}}{\mathrm{m}^2}$$

Conversion of measured polarizations (below) into a derived 3-D halo field geometry (above) for an inclined spiral galaxy

R. Braun, G.W. Heald & R Beck

"The WSRT SINGS Survey III: Global magnetic field topology"

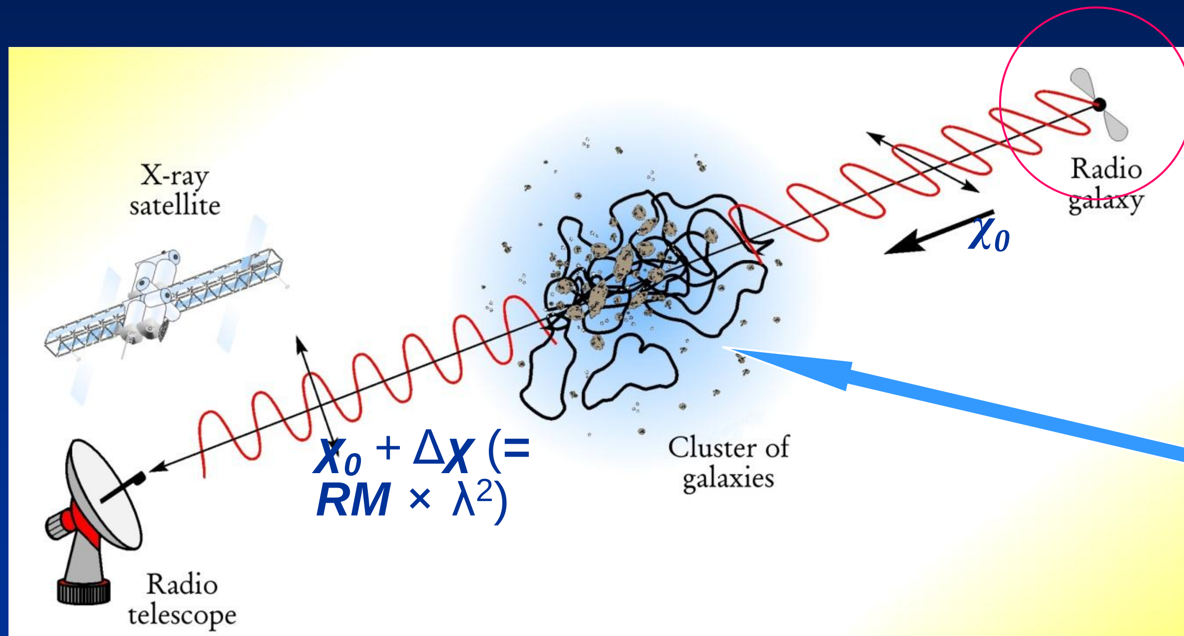
Astron & Astrophys. ***514****, 42, 2010*



Magnetic fields within galaxy clusters

$$n_{ICM} = 10^{-1} - 10^{-4} cm^{-3}, \quad T = 10^{6} - 10^{8} K$$

Illustration of Faraday rotation, including z dependencies



source galaxy system at z_e

intervening galaxy system at z_a

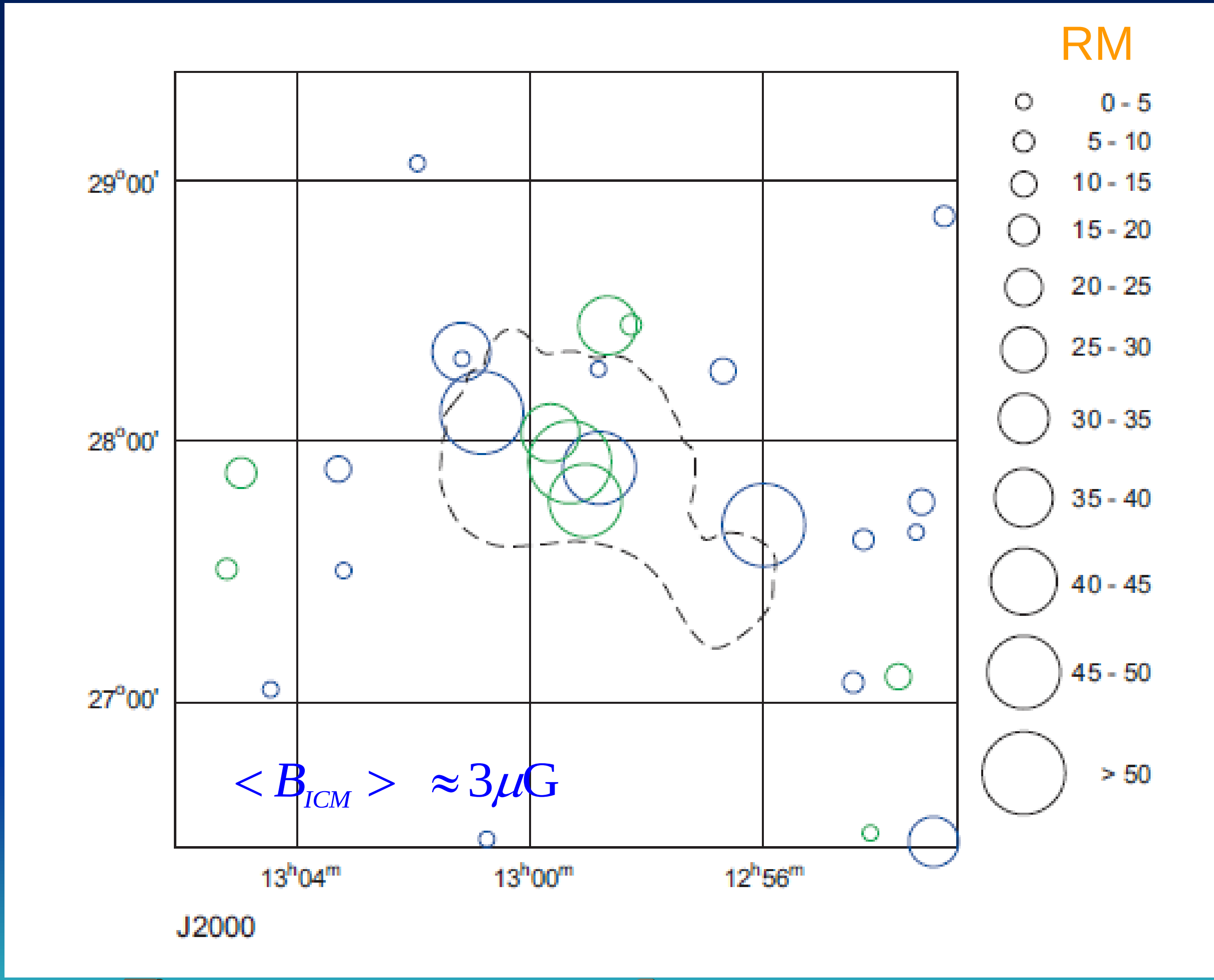
$$RM = \frac{\Delta\chi}{\Delta\lambda^2} = 8.12\times10^5 \int_0^{z_s} (1+z)^{-2} n_e(z) B_{||}(z) dl(z) \quad \frac{\text{rad}}{\text{m}^2}$$

B in Gauss, n_e in cm^{-3}, l in pc

Philipp P. Kronberg

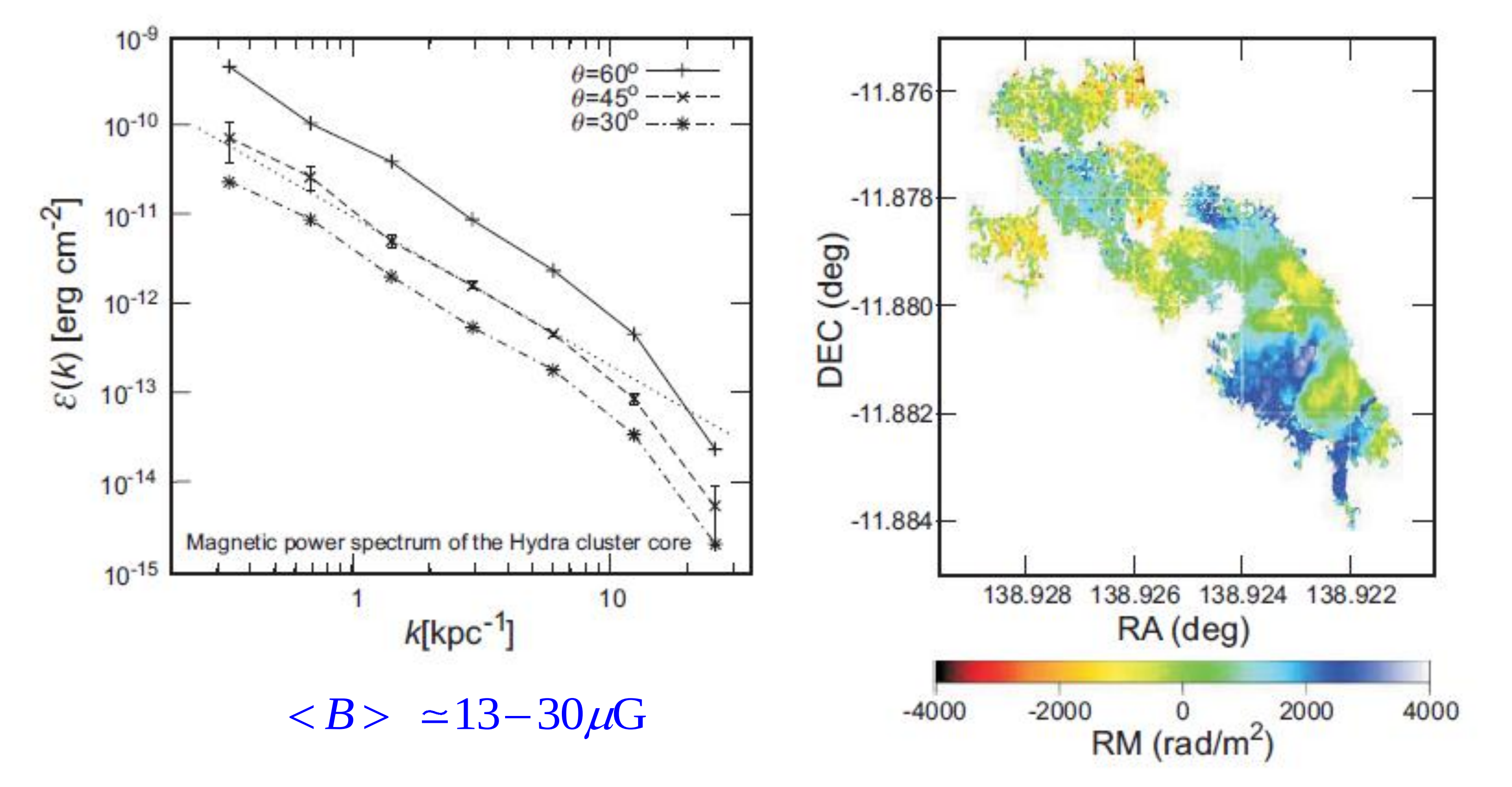
Faraday rotation relative to the Coma Cluster X-ray image

dashed lines → outer Rosat X-ray boundary



Kim, K.T., Kronberg, P.P. Dewdney, P.E., & Landecker, T.L. Astrophys. J 1990
(augmented 2010 with 8 new RM's by E. Fürst, R. Kothes, P. Kronberg, & R. Wielebinski)

RM image in the inner Hercules Cluster cluster “cool zone”– showing embedded radio source Hydra A



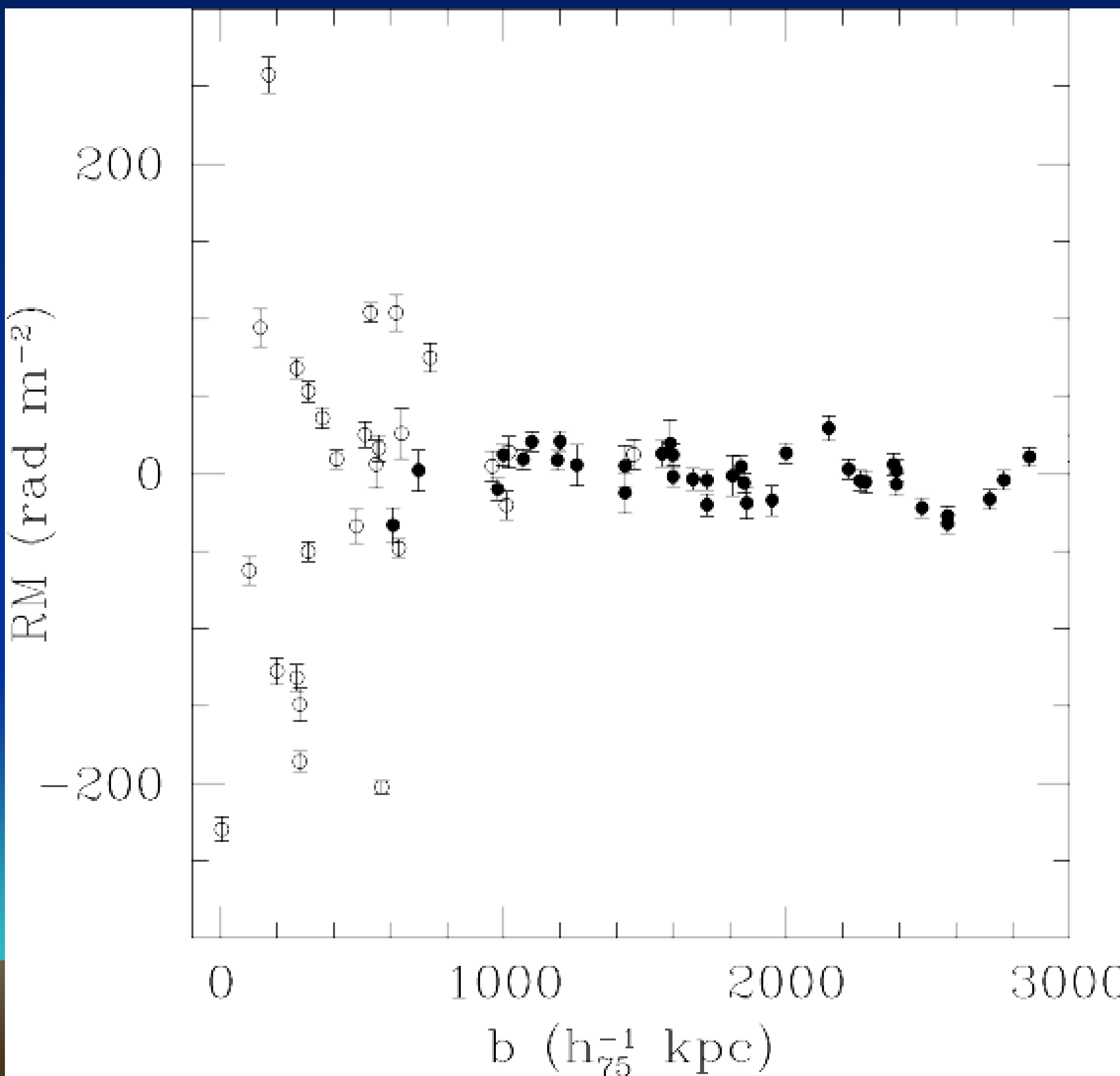
$$<B> \simeq 13-30\mu G$$

Taylor, G.B., & Perley, R.A. ApJ 416,554, 1993 (original RM image)
Enßlin, T.A. Vogt, C., Pfrommer, C., & other authors from 2003-2006
e.g. A&A 401, 835, 2003

Is an ICM magnetic field a universal property of galaxy clusters?

RM of radio sources mostly behind a collectivity of (ROSAT X-ray-selected) **galaxy clusters**

RM Plotted against impact parameter to the cluster center Clusters are scaled, and stacked



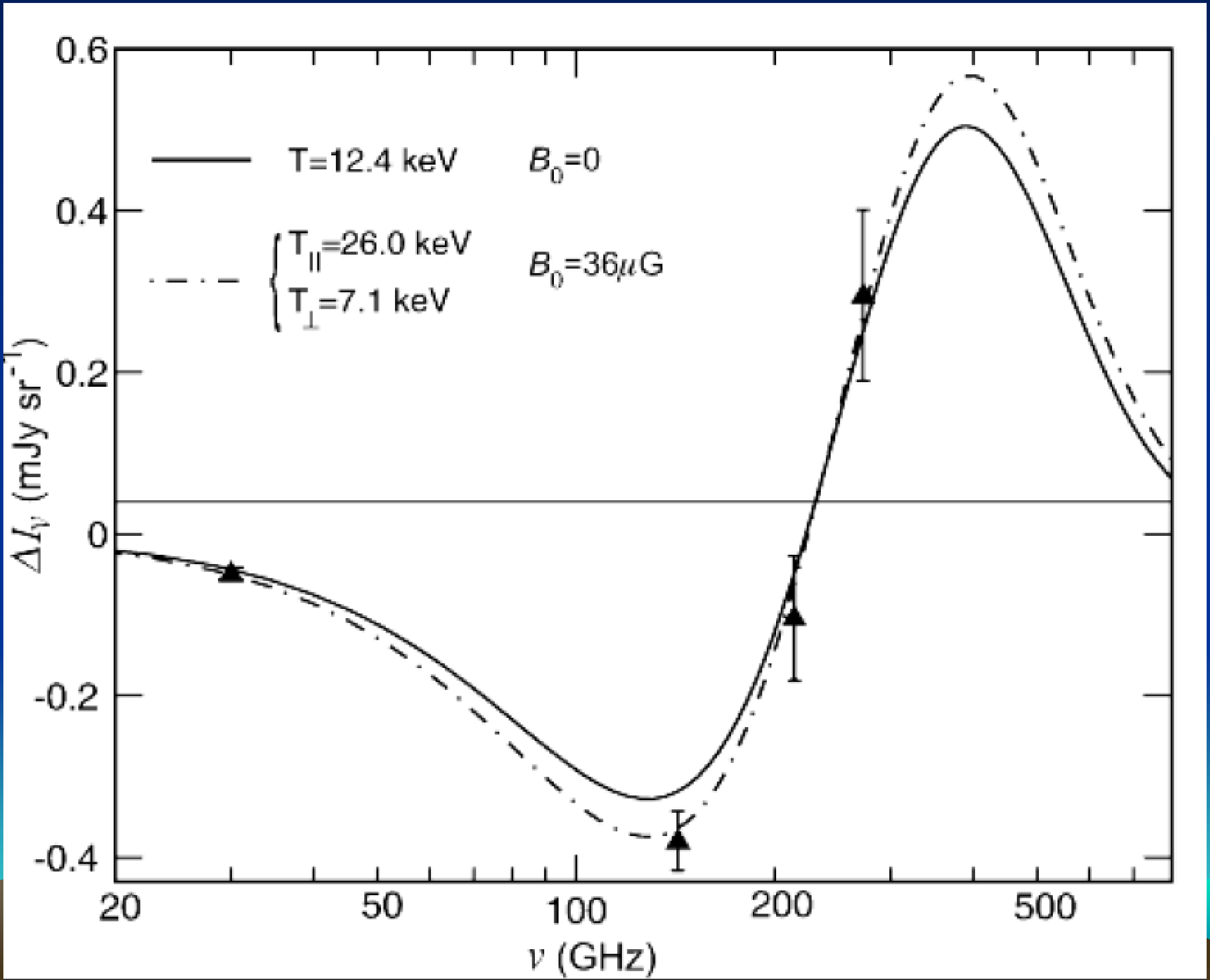
- cluster redshifts are typically < 0.2
- Selected to have no radio halo.
- X-ray (baryonic mass) distribution smooth and nearly symmetrical. (i.e. no recent mergers/collisions)

$$< B_{ICM} > = 5 \rightarrow 10 \left(\frac{10\text{kpc}}{l_0}\right)\left(h_{75}^{1/2}\right) \mu\text{G}$$

T.E.Clarke, P.P. Kronberg, & H. Böhringer
ApJLett 547, L111, 2001

A magnetic S-Z effect in the central cool zone?

*J. Hu, & Q-Y Lou ApJ **606**, L1 2004*



Intergalactic magnetic fields beyond clusters, but still in the "nearby" universe at z $\lesssim$ 0.1

using

1. Combine Faraday rotations with galaxy surveys

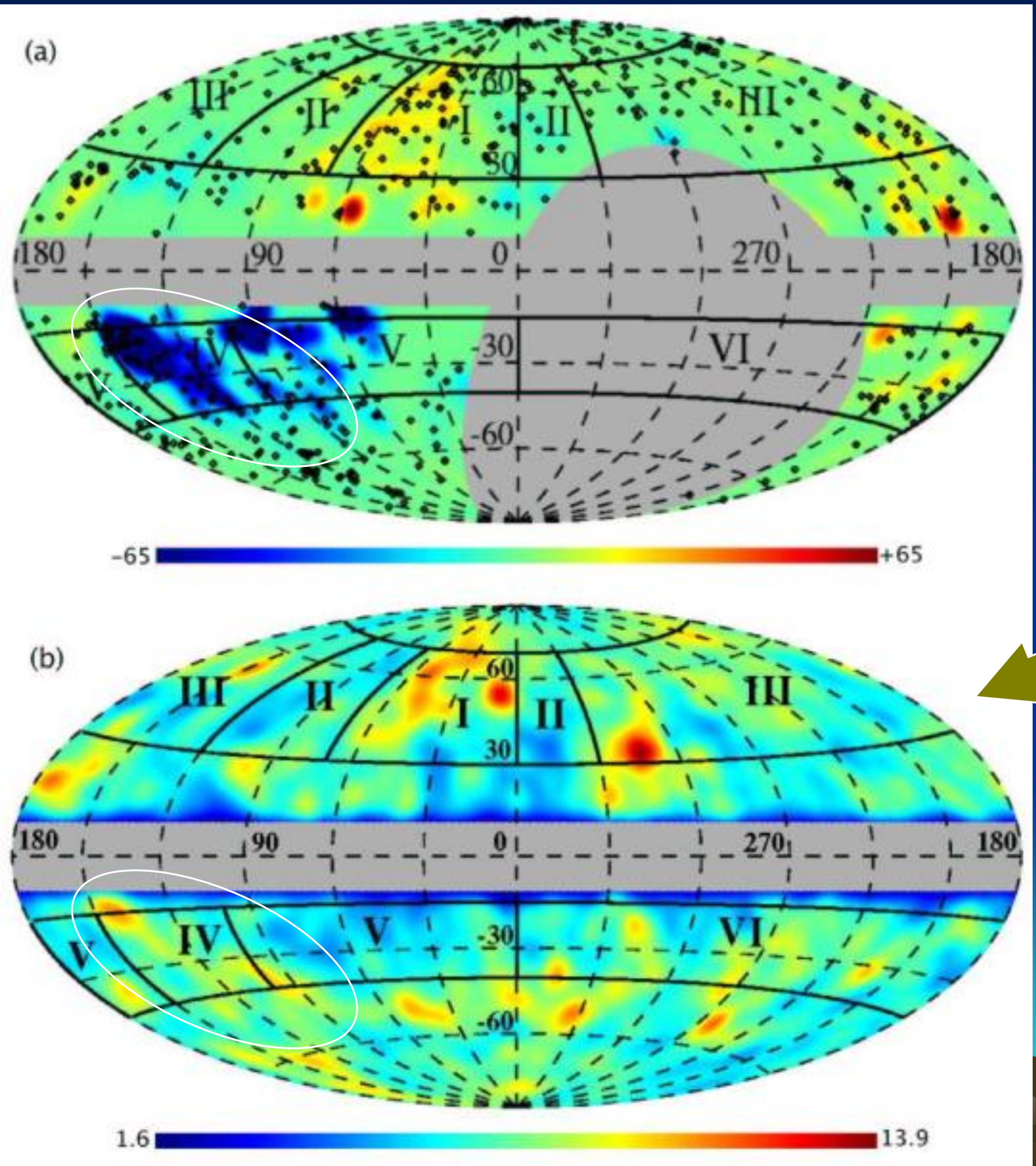
2. Ultra-faint imaging of diffuse metre wave synchrotron emission

- If $\langle|B_{\mathrm{IGM}}|\rangle \approx 10^{-7}$G on scales of few $\times$100 kpc, it has a chance of being detectable in RM

- First test for $\langle|B_{\mathrm{IGM}}|\rangle$ in nearby galaxy supercluster filaments --

Y. Xu, P. Kronberg, S. Habib, & Q. Dufton ApJ ***637****, 19, 2006*

Y. Xu, P. Kronberg, S. Habib, Q. Dufton: ApJ 2006, 637, 19



SMOOTHED FARADAY ROTATION

Region containing the Perseus-Pisces supercluster

rad/m^2

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

galaxies per pixel ($\propto$ column density)

RM + galaxy survey data (CfA2, 2MASS)

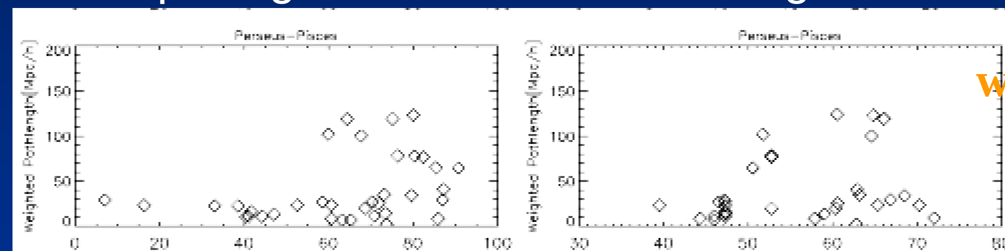
2 methods of IGM *B* analysis for the Perseus-Pisces supercluster

for the Perseus-Pisces supercluster:

Col. density **2MASS** HEALpix algorithm

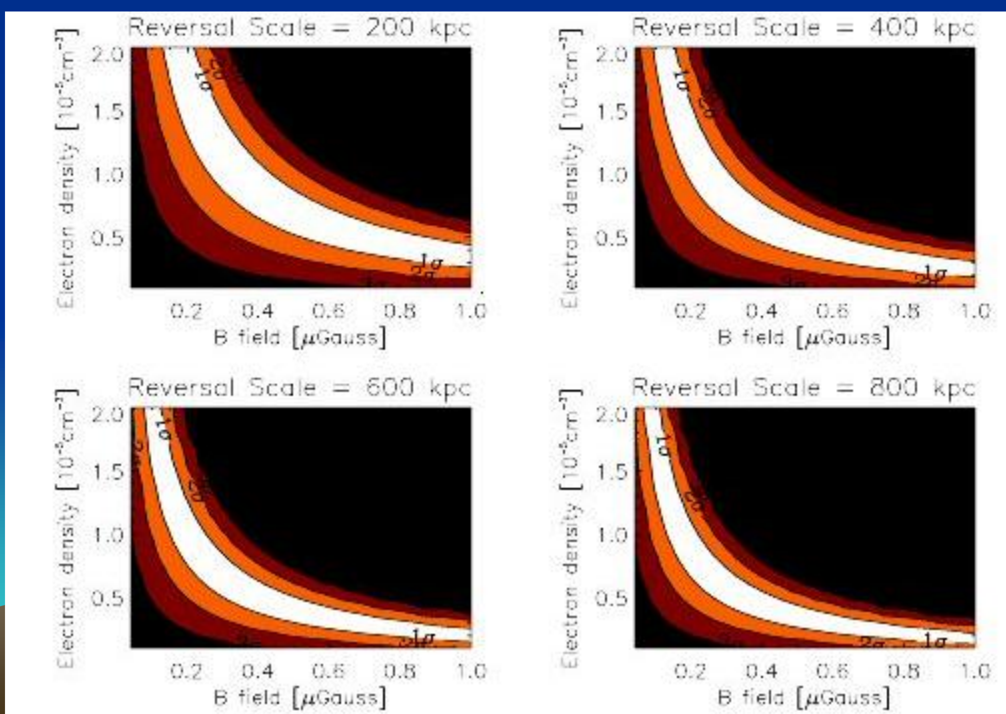
Weighted path *l*. **CfA2** Voronoi diagrams.

2 independ. measures of pathlength through the intergalactic filament →



w.p.l. ↑

RM →



Estimate: few $\times 10^{-7}$ G

Y. Xu, P. P. Kronberg, S. Habib & Q.W. Dufton ApJ 637, 19 2006

"A Faraday rotation search for magnetic fields in Large Scale Structure"

Intergalactic diffuse synchrotron emission as a probe of B_$_{IG}$

current relevant instruments:

LOFAR, and Arecibo + DRAO interferometer

B_IG estimates from diffuse synchrotron emission

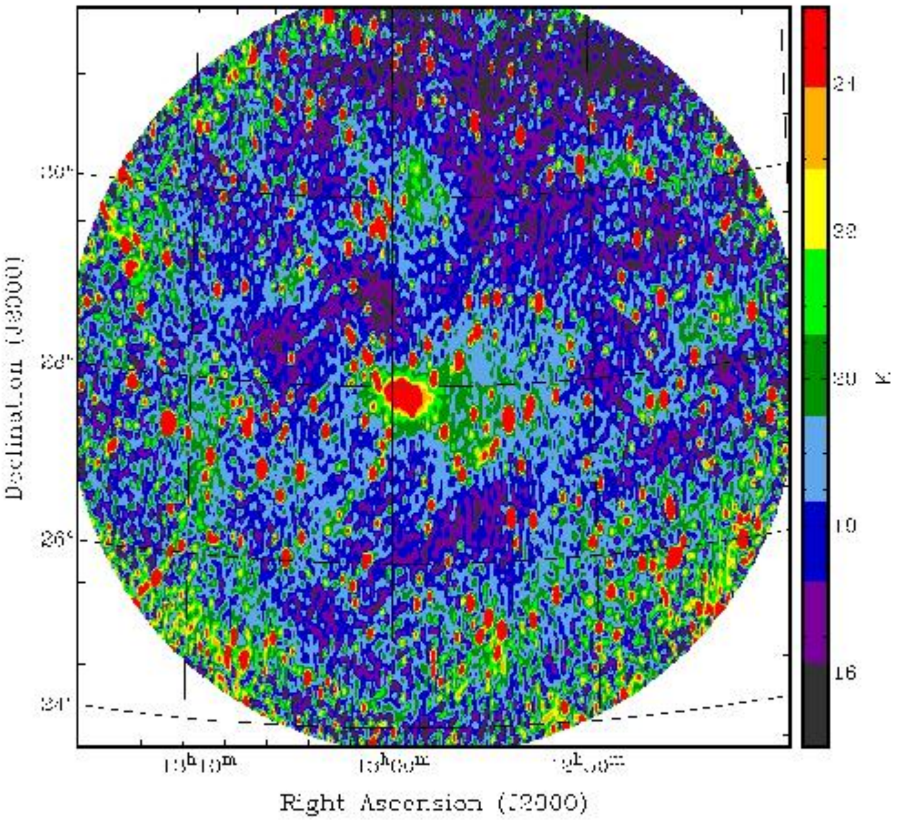
Recent combination of two unique instruments:
DRAO synthesis telescope and Arecibo telescope
at 0.4 GHz

7 x 9m dishes overall length= 617m Min. projected separation ≈ 18m

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


Arecibo 305m Telescope, PR
2 mm rms optics
illuminated area ≈ 225m
uv overlap with DRAO ≈ 200m

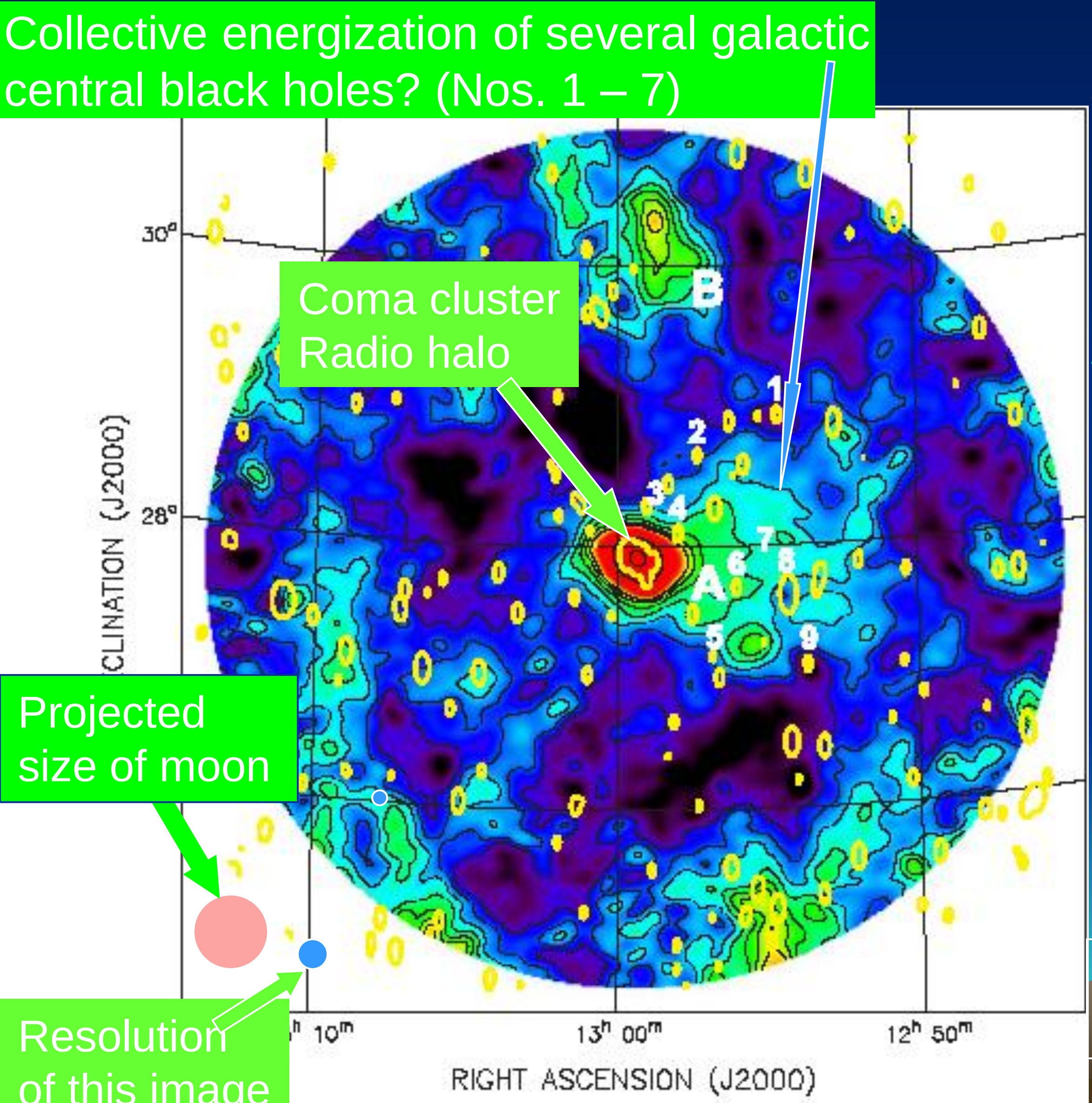
8° dia. Field containing combined Arecibo + DRAO + Effelsberg 100m data, at a resolution of 2.5’ x 6.5’ 0.4 GHz



- 2.7K CMB background and galactic foregrounds (≈ 18K) are included

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

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



REMOVED:

- *Discrete sources*
- *CMB + linear plane Milky Way foreground*

Strongest discrete sources re-overlaid as 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.

RESULT:

<|*B*|> ≈ 10^{-7}G over 2 – 3 Mpc

Intergalactic magnetic fields from UHECR's in the wider IGM out to ~ 4 Mpc

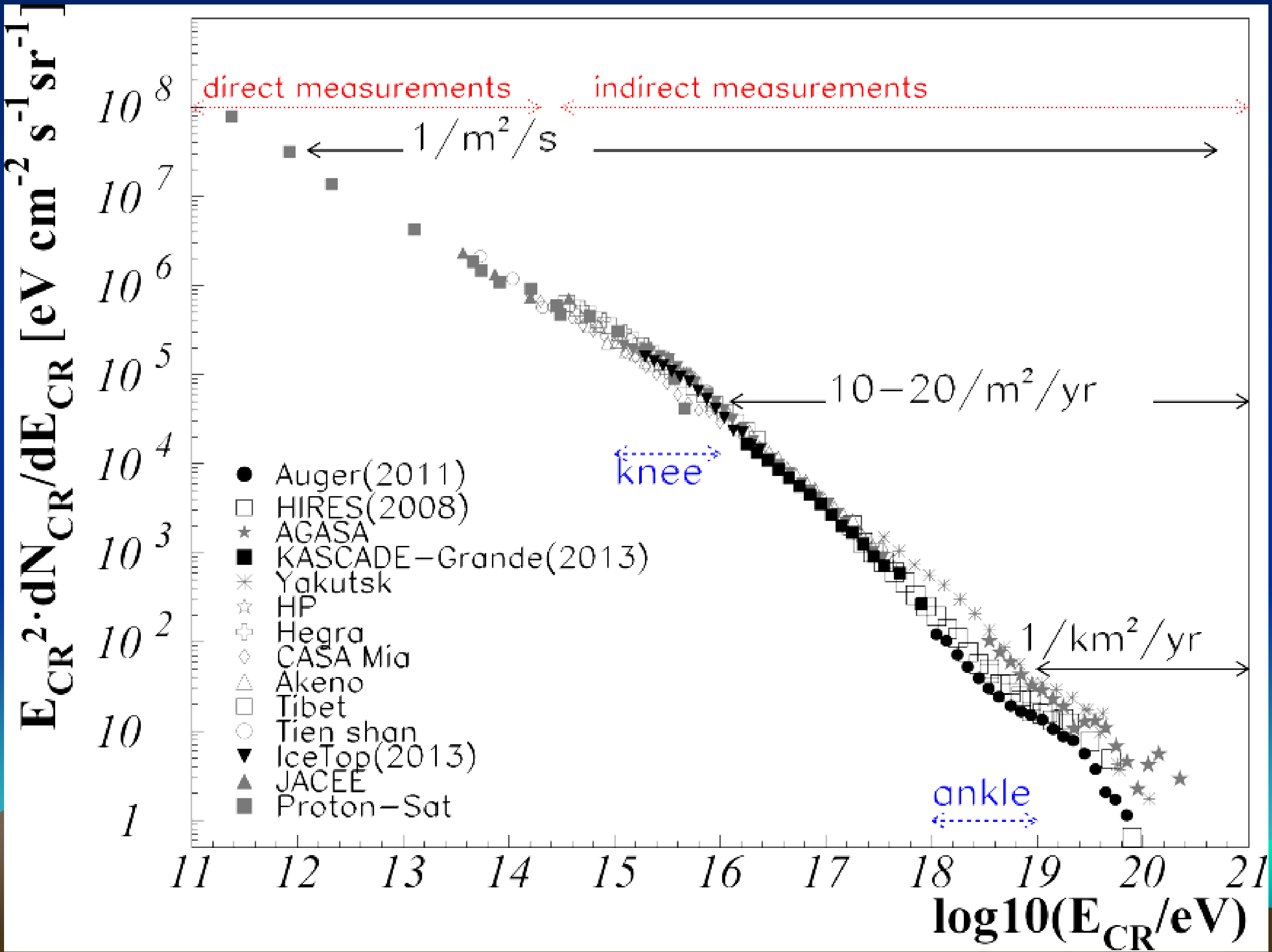
Note: A new method,

and

in a previously unexplored IGM distance range

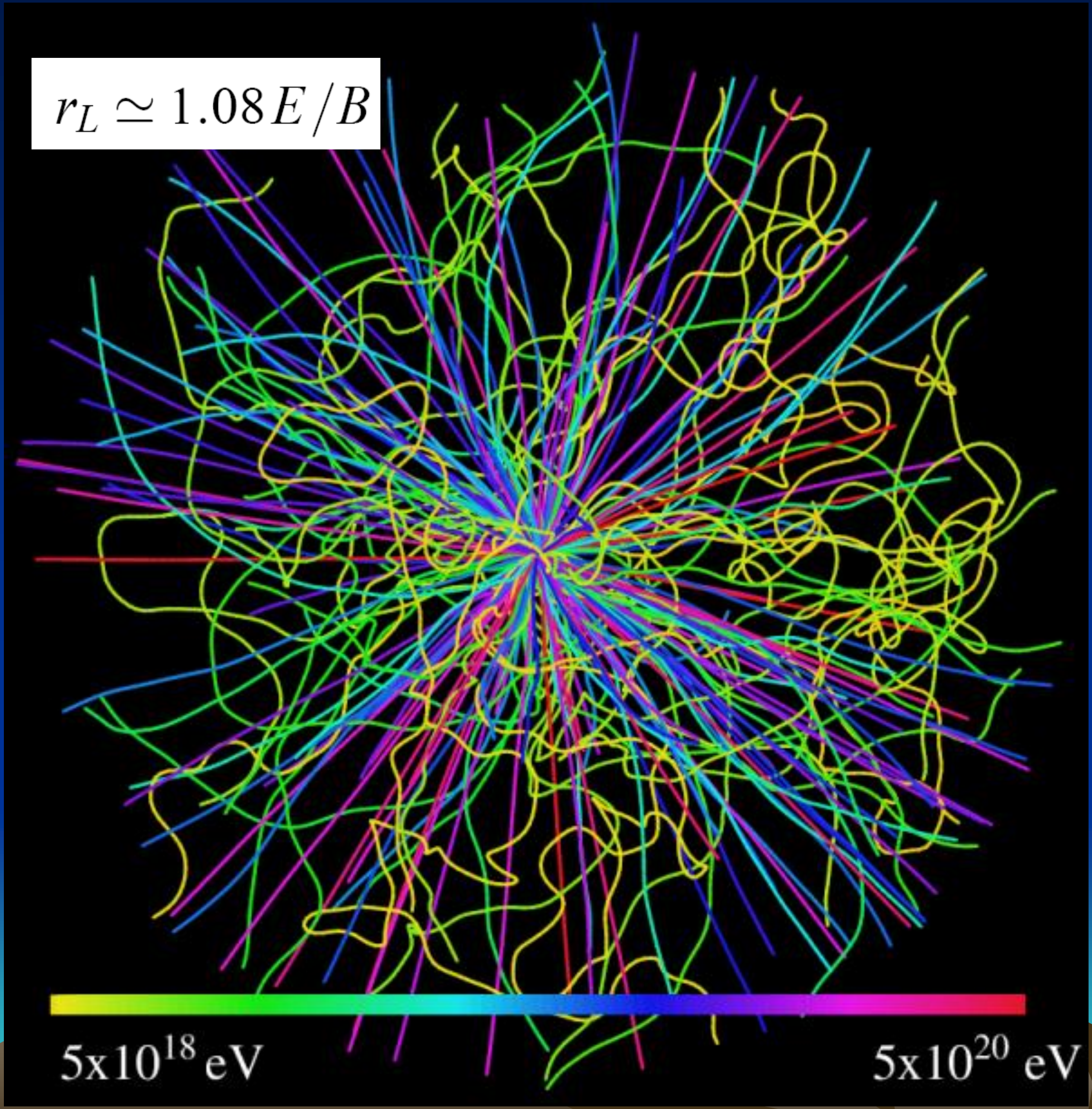
Setting the context: The measured CR spectrum out to 100EeV

*Julia Becker, Phys Rep. **458**,173B, 2008 + updates in 2013*



GZK dist. "limit"
≈ 100 Mpc

CR propagation in the IGM



Hasan Yüksel 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

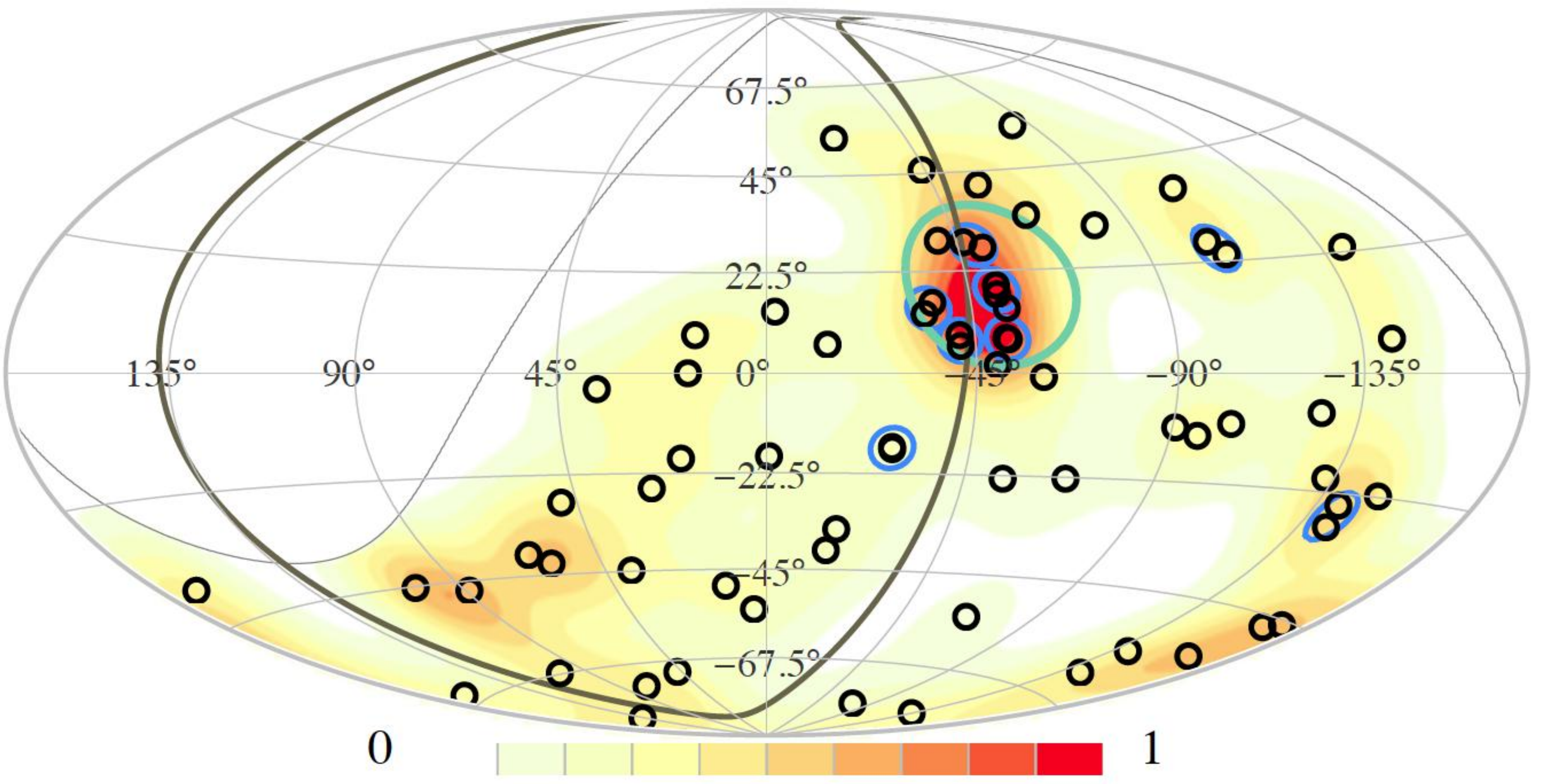
Sample calculation relevant to Centaurus A ($l_0 < l$):

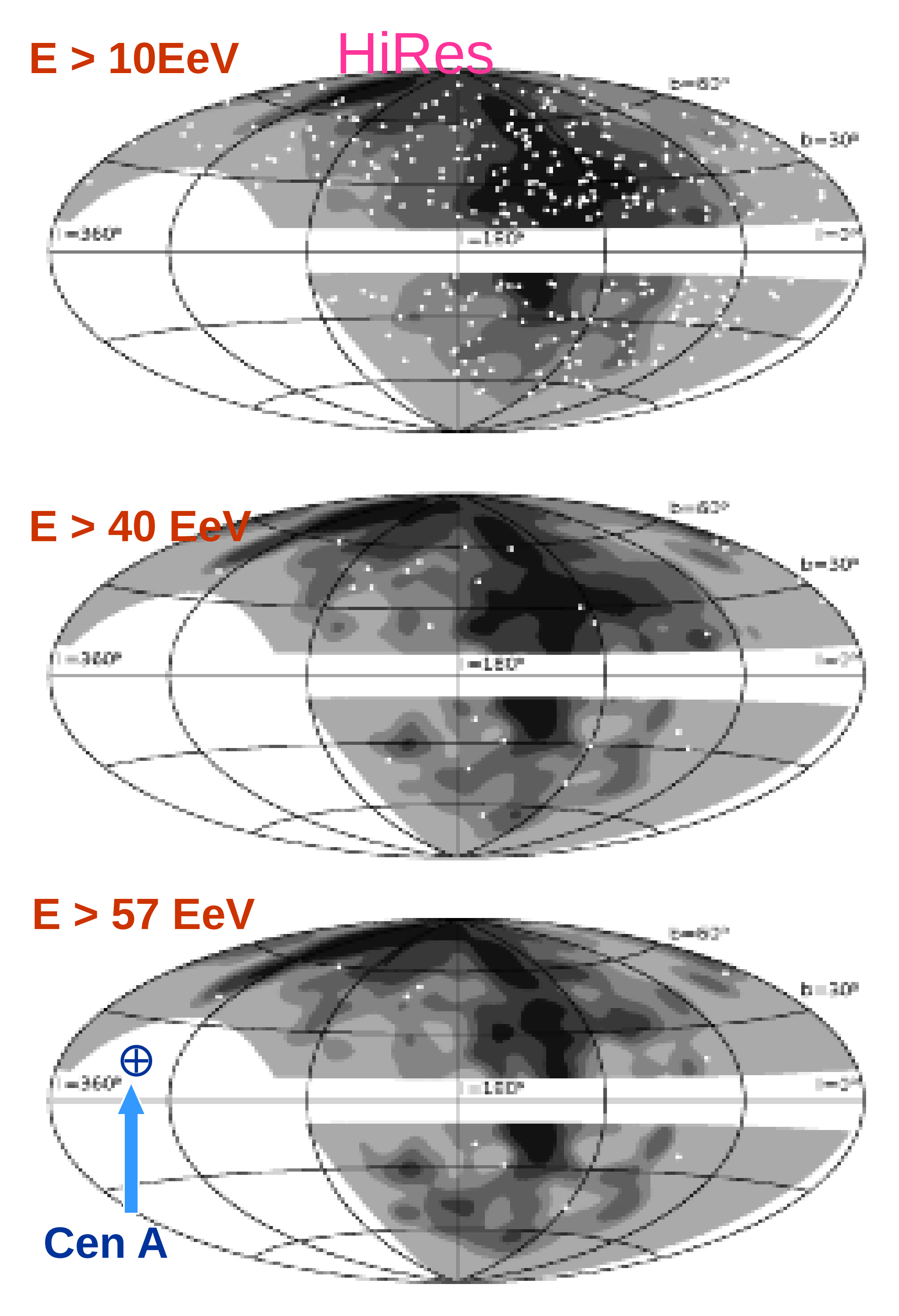
For protons (Z = 1), l = 3.8Mpc, l_0 = 300kpc, E = 10^{20}eV, B = 10^{-7}G

$\theta = 3.4^{\circ}$

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

- *Version of Yüksel et al ApJ 758,16, 2012*.





Abbasi et al. arXiv:1002.1444
ApJL ***713****, 64, 2010*

Search for large scale anisotropy of UHECR's in HiRes data"

Grey scale steps display

$$\mathit{\Phi} = \Phi \cdot \Xi$$

Exposure function

model mass distr. function (with 9°smearing)

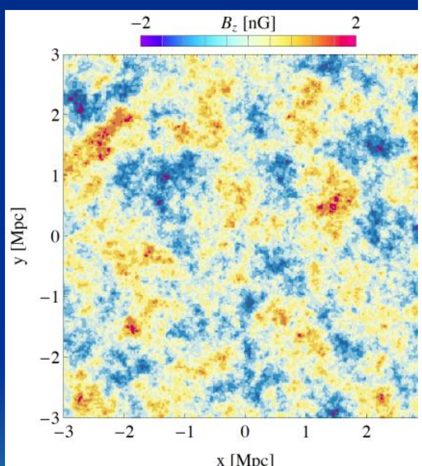
Plausible distributions of CR's for selected extragalactic magnetic field parametrizations

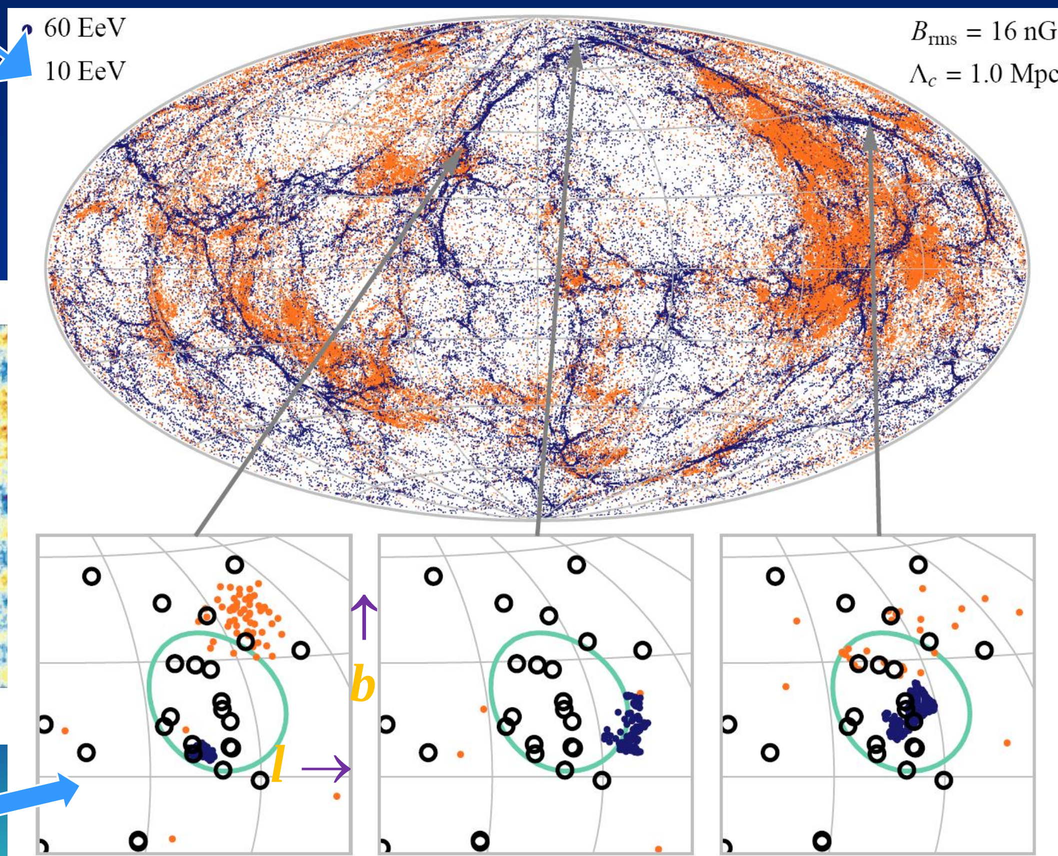
CR energies **of 60** EeV (blue) and **10** EeV (orange) → next 4 slides

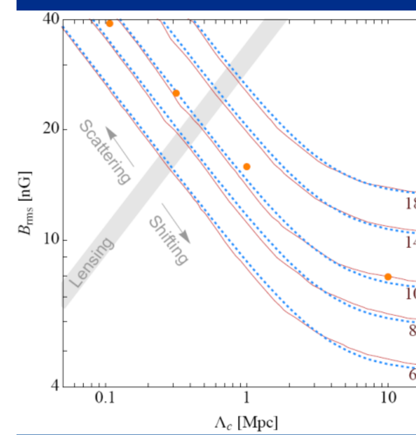
Top: As seen by an observer located at Cen A, Final positions of particles at 3.8 Mpc from Cen A (100,000 particles are shown for each energy)

ASSUMES PROTONS ONLY

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

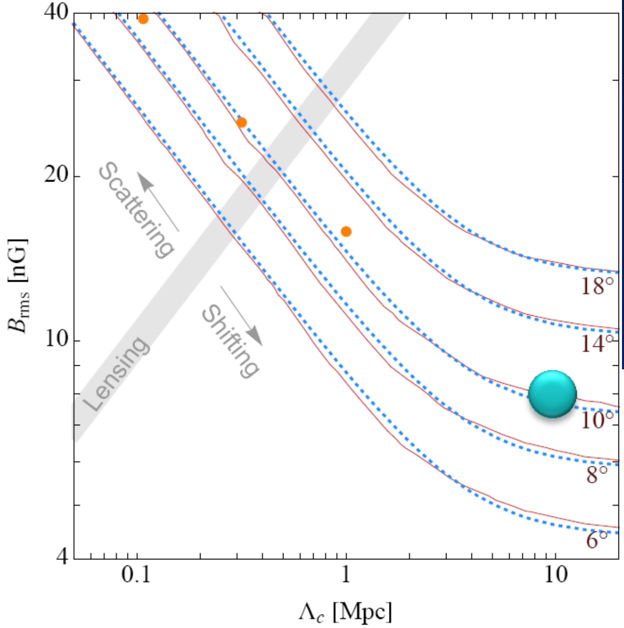






Bottom: As seen from Earth . three realizations of UHECR angular distributions arriving from Cen (ASSUMED an ISOTROPIC EMITTER) chosen from the 3 locations above

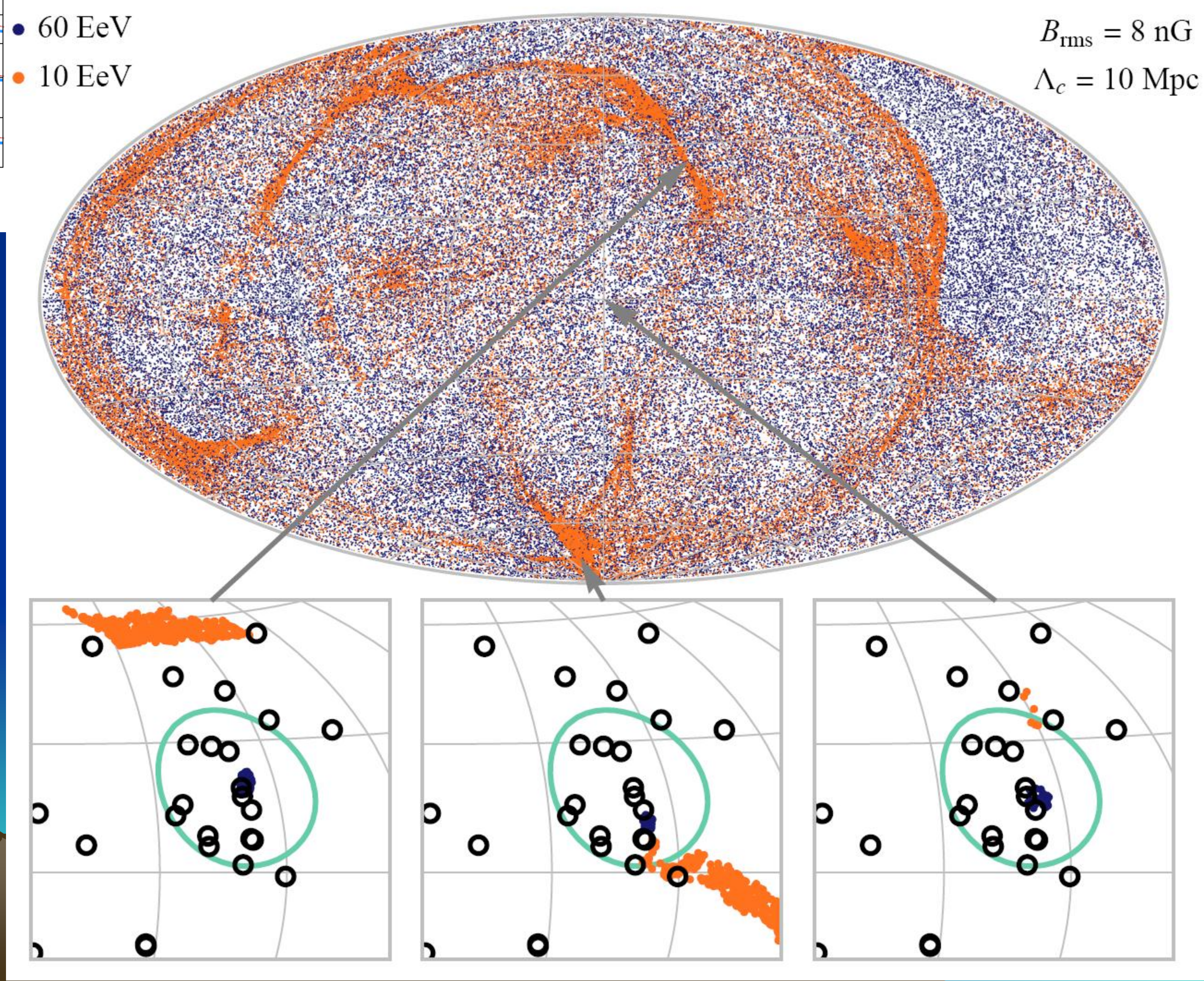
H.Yüksel, T. Stanev, M. Kistler, & P. Kronberg *Astrophys J* **758**, *16, 2012*

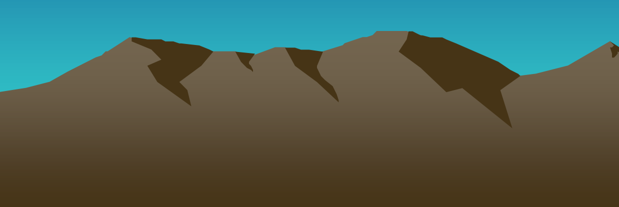


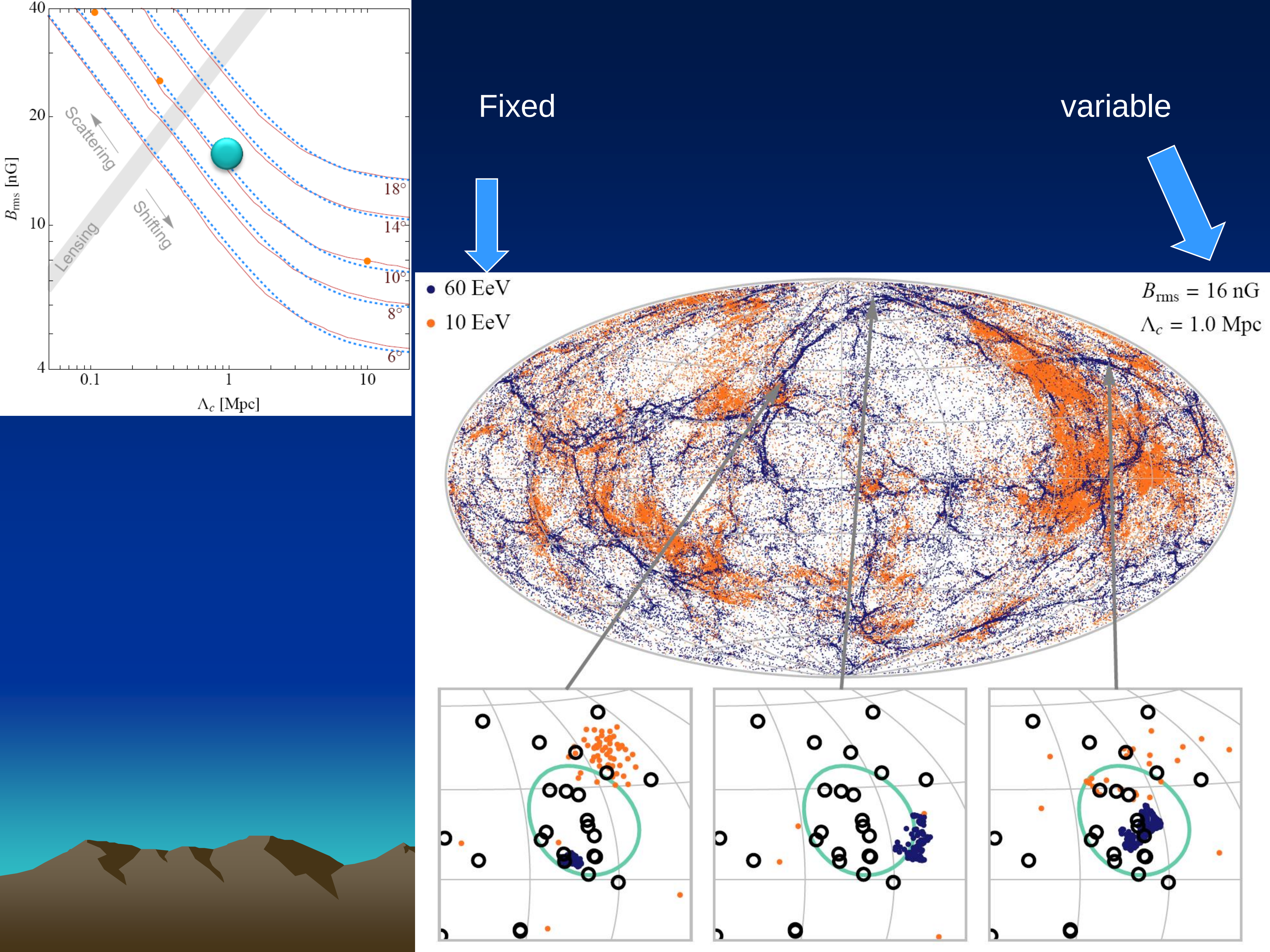
H. Yüksel, T. Stanev, M. Kistler, P. Kronberg
Astrophys J. ***758****, 16, 2012*

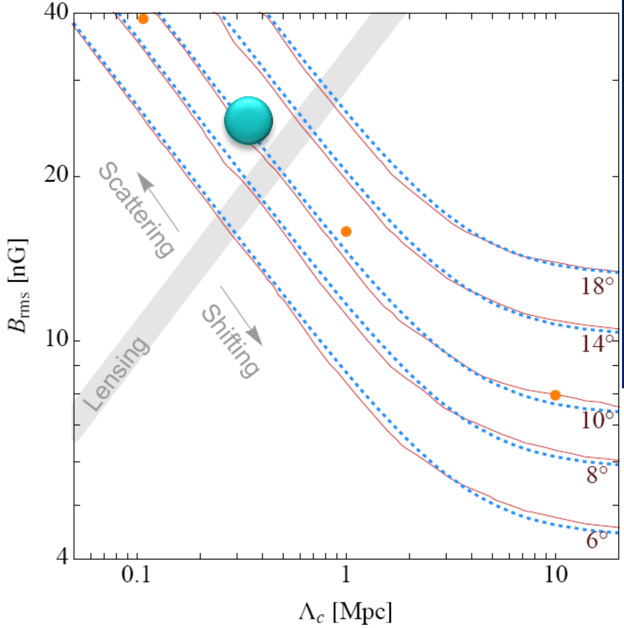
fixed

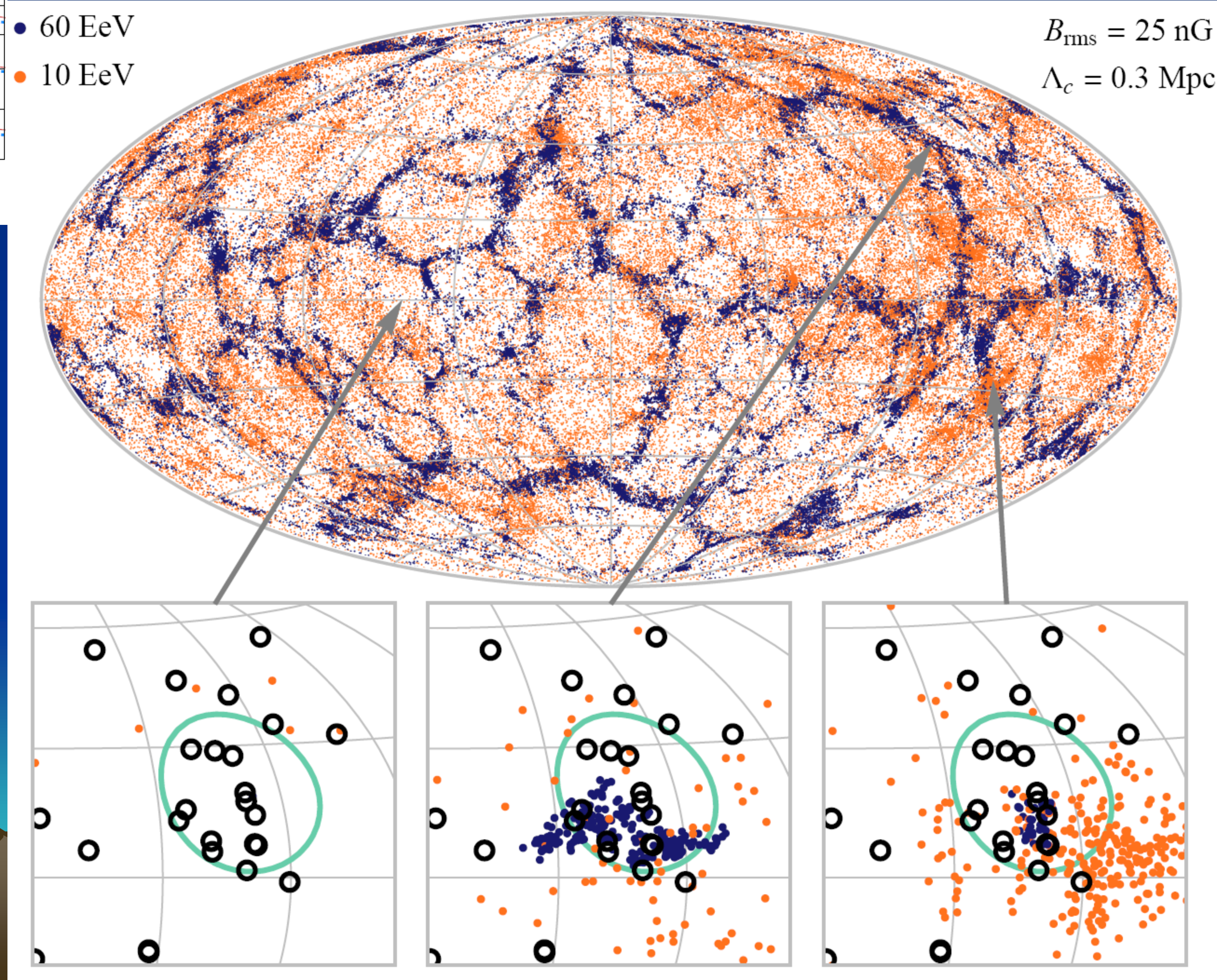
variable

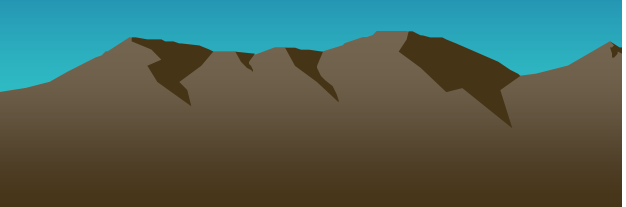


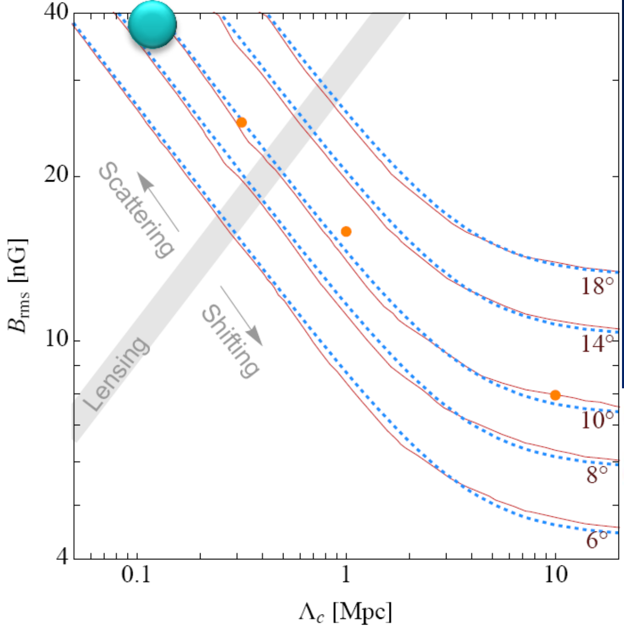


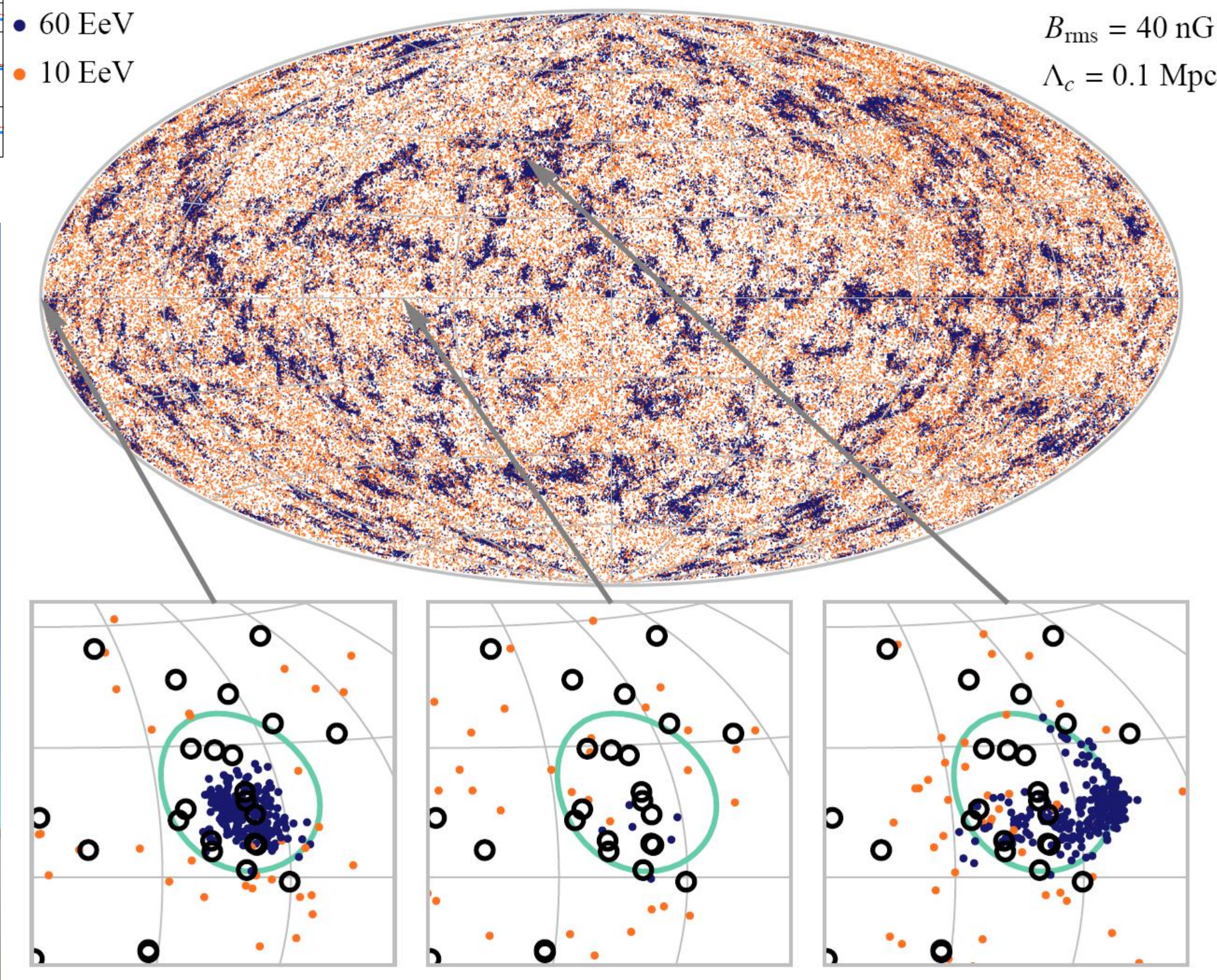

Fixed
variable
B_{rms} [nG]
Λ_c [Mpc]
Scattering
Shifting
Lensing
18°
14°
10°
8°
6°
60 EeV
10 EeV
B_{rms} = 16 nG
Λ_c = 1.0 Mpc


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

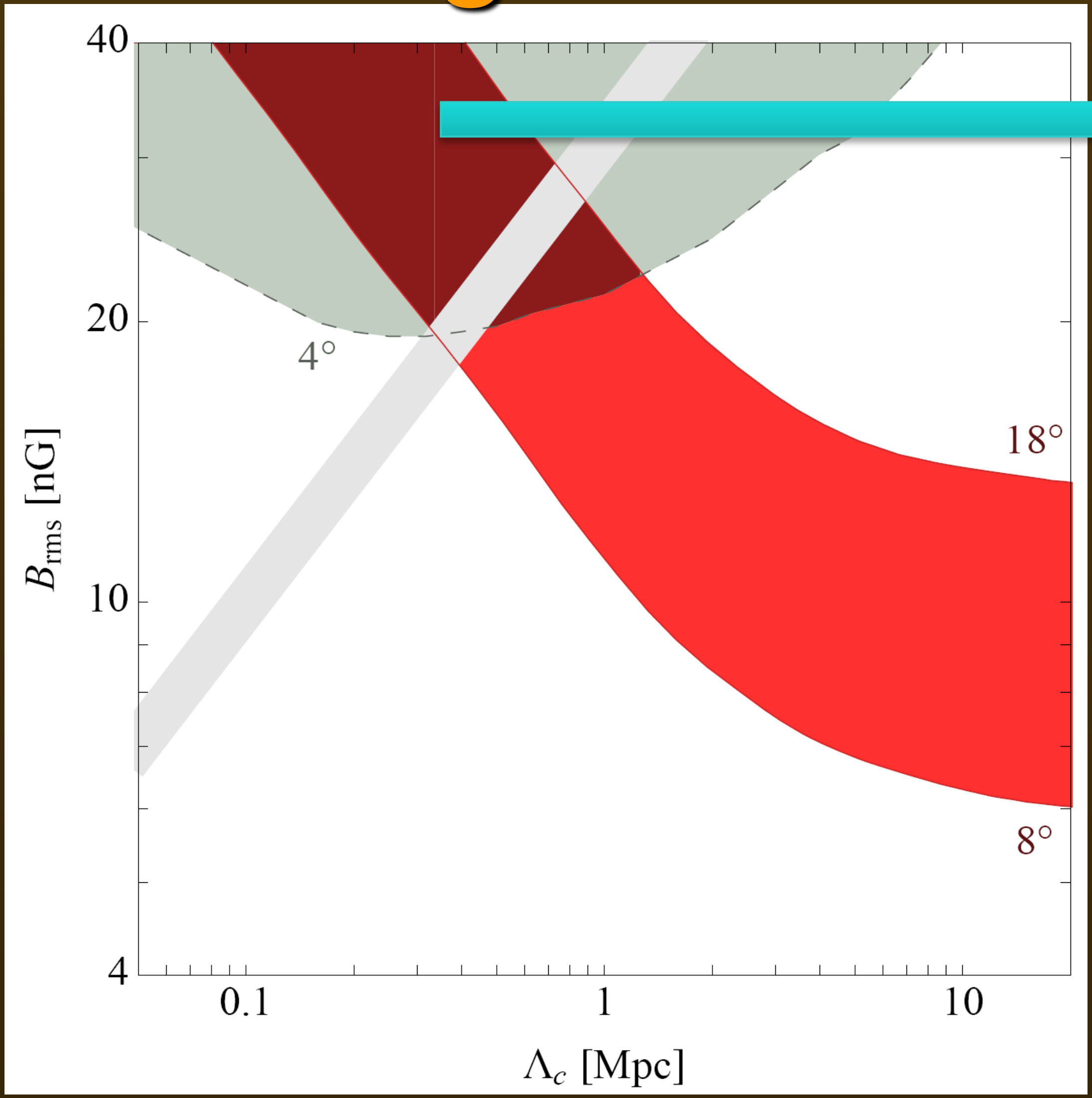

60 EeV
10 EeV
B_{rms} = 25 nG
Λ_c = 0.3 Mpc




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


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

UHECR estimates of 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 is less than 4° (dashed line)

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

H. Yüksel et al. 2012

Some desirable enhancements of the model described here
(*see H. Yüksel,T. Stanev, M.Kistler & P. Kronberg ApJ* ***758****, 16, 2012*)

(some are in progress)

1. Variations in particle composition
2. Variations in the fluctuation spectrum of the IGMF within 4Mpc of Centaurus A
3. Explore non-Kolmogorov models – e.g. include very large scale B components
4. Scaling of the IGM magnetic field strength
5. (future, with more data?) Study the detailed energy dependence of VHECR arrivals, to explore the transition between Galactic and extragalactic deflections
6. Add other discrete CR sources -- besides CenA

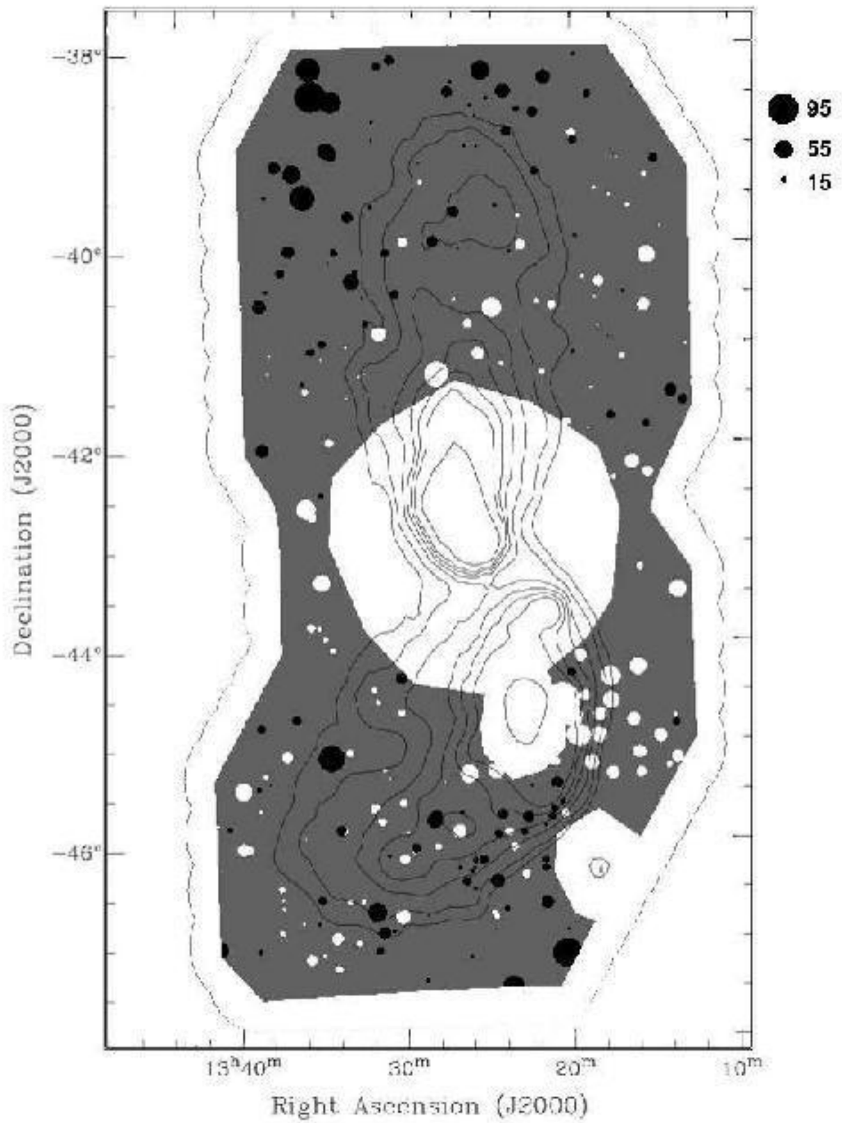


FIG. 7.— Locations and RMs of the 281 sources in Table 3. To better highlight the variations, the diameter of the sources represent the amplitude of their residual RM after the mean RM of the whole distribution (-57 rad m^{-2}) has been subtracted. Black and white sources are those with positive and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

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

(3.8Mpc distance)

Answer: apparently not

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

Candidate UHECR acceleration sites in jets and lobes

- Nearby jet/lobe candidate: Cen A
- Diagnosable “test” jet: 3C303 at $z = 0.14$

Extragalactic plasma experiments at larger distances

PARSEC SCALE jet launching regions

Future directions for observations

-- $\gtrsim$ 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 arrays, longer baselines

--extend bandwidths

--measure and calibrate all Stokes’ parameters

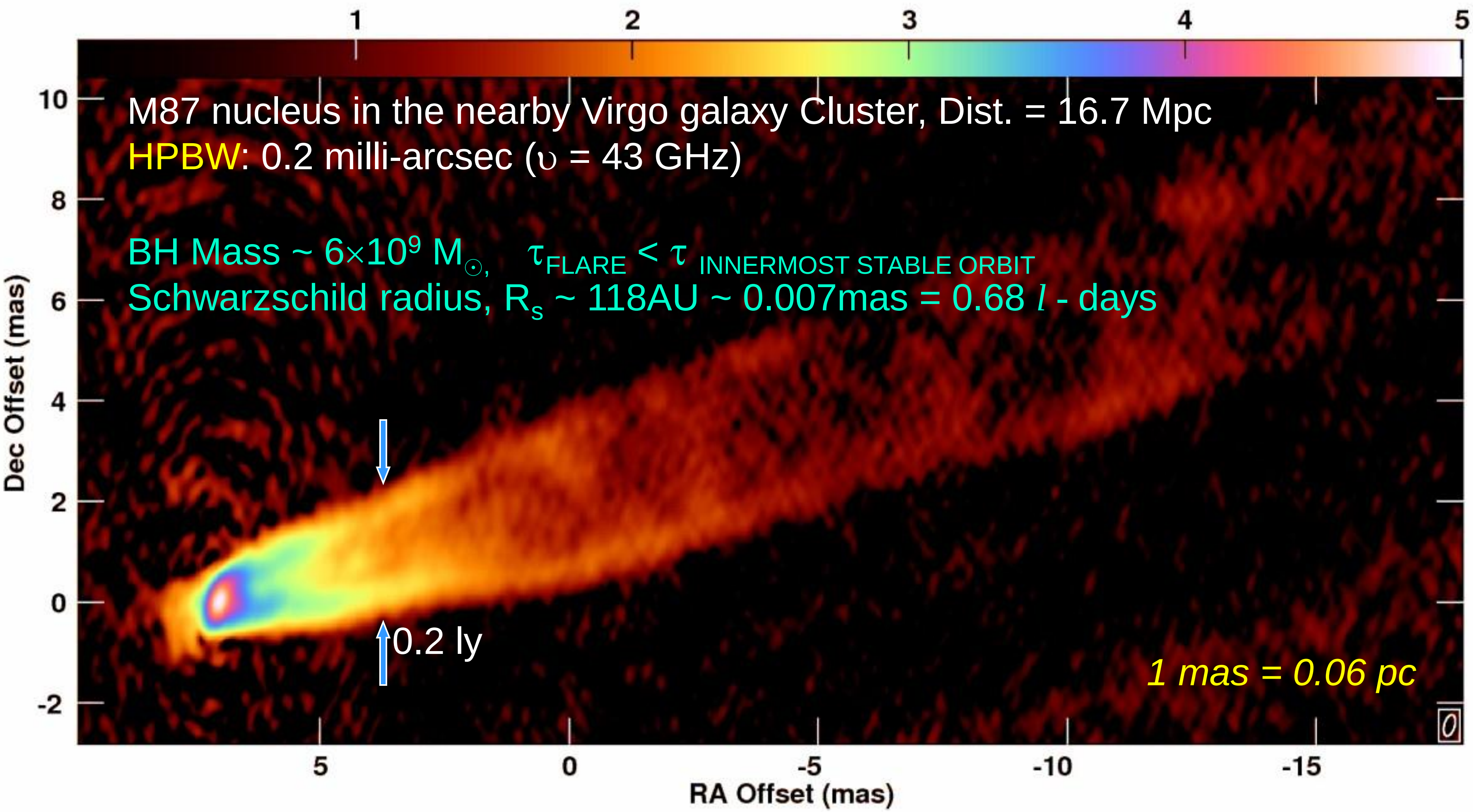
--explore in time-evolution – a new capability. -- next slide

Sum of 23 VLBA images of M87 at 43 GHz

Veritas Collab,

NRAO VLBA M87 Monitoring Team,

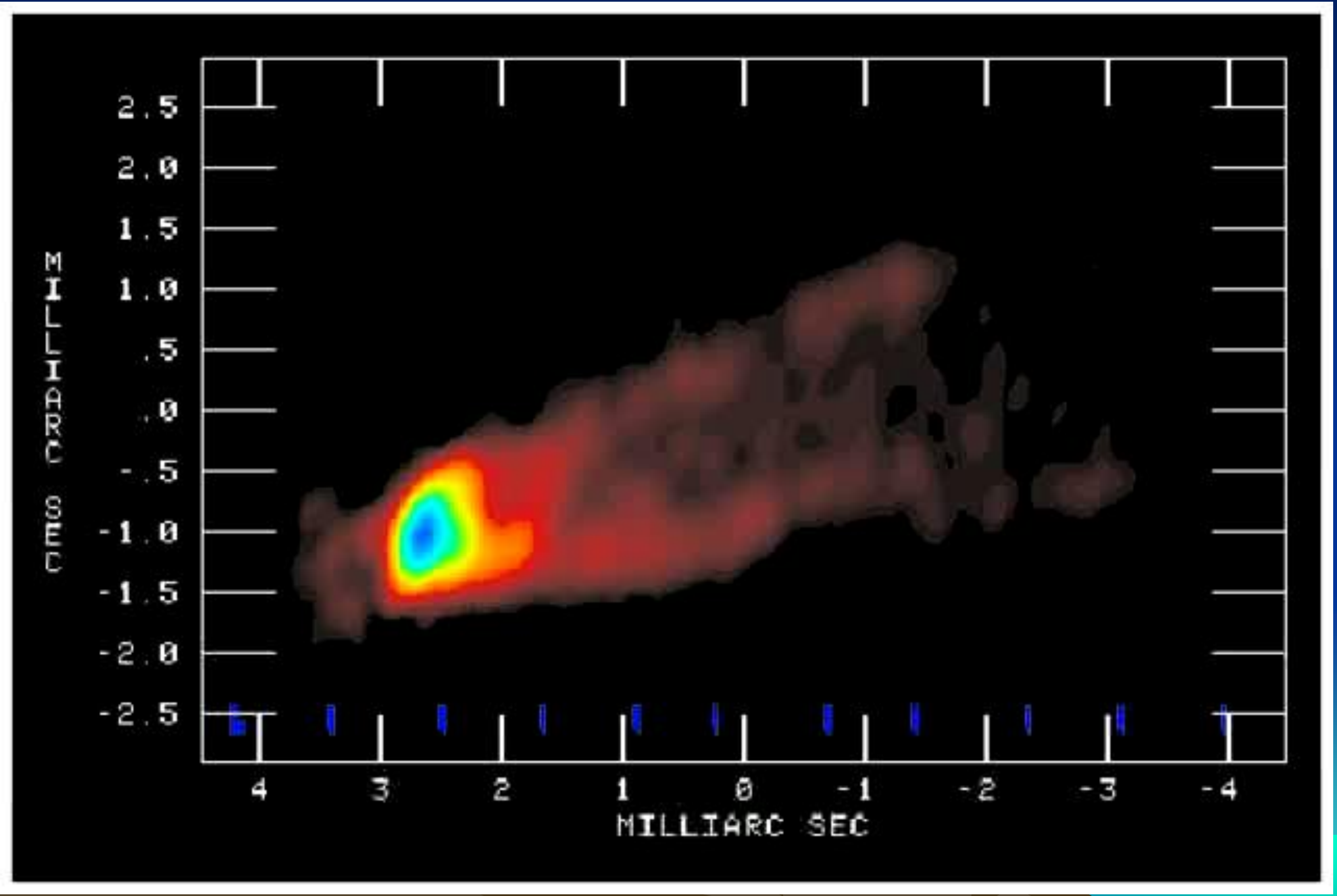
H.E.S.S. Collab. & MAGIC Collab., **Science**, **325**, 444, 2009



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



Next topics

- Giant radio sources, plasma parameters and energies
  and Comparison with cluster-embedded radio sources
- 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

A&A 1978 (+ 7 following, related papers

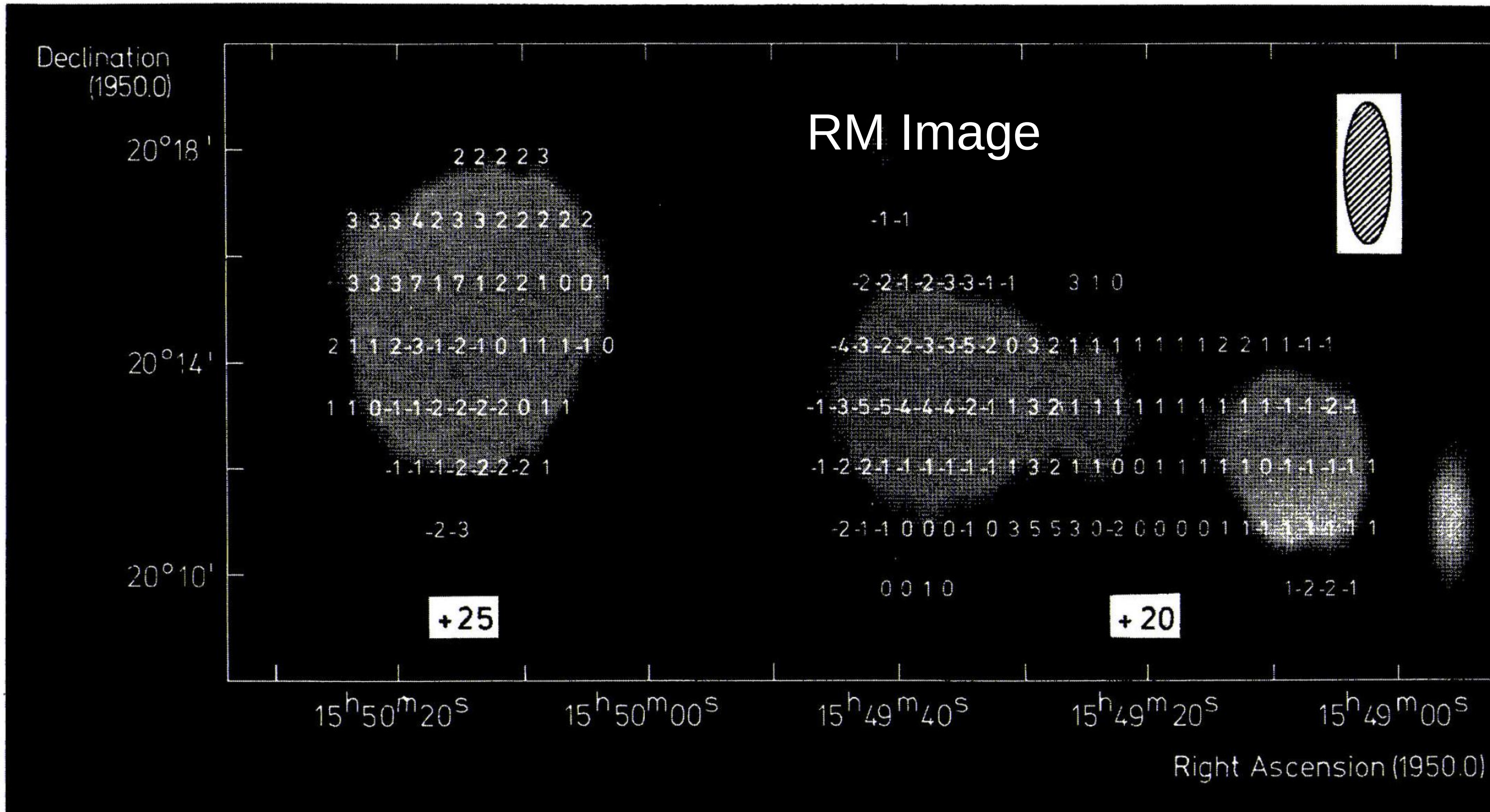


Fig. 8. The distribution of rotation measure over 3C 326 as computed from the 49 cm and 21 cm convolved data superposed upon a " photograph" of the 49 cm total intensity. Note that to produce a simple grid of single digit numbers we have subtracted integrated ro measures, whose derivation is described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

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

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

compare with

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

2147+816 giant radio galaxy

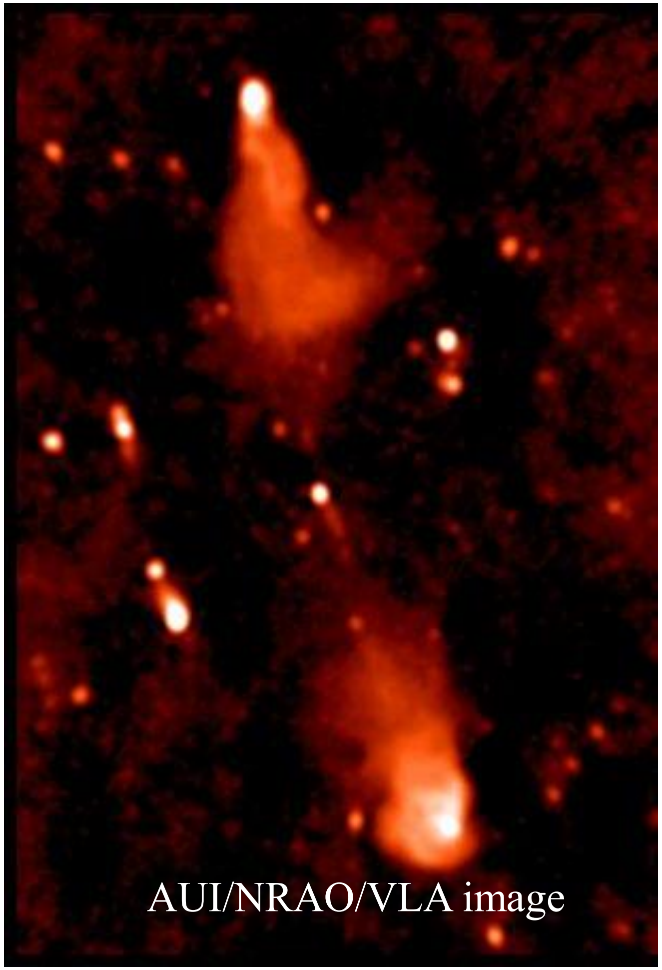
Analysis of ≈ 70 GRG images
Kronberg, Dufon, Li, Colgate
ApJ 2001

z=0.146

2.6 Mpc

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

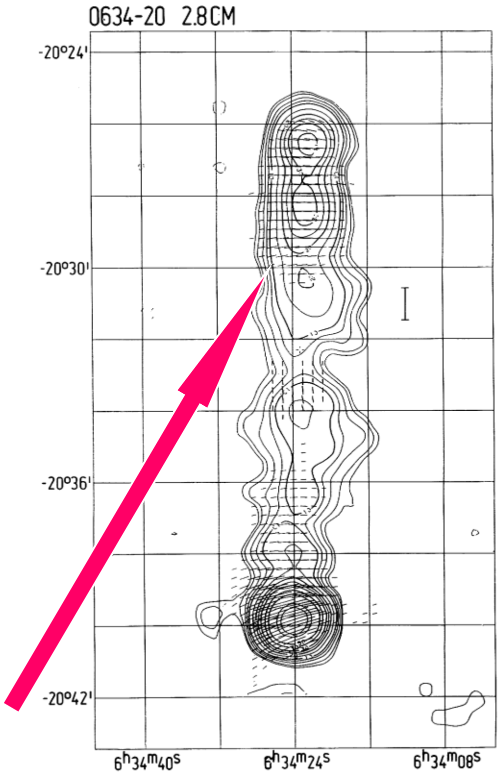
- •Willis & Strom, 1978,80
- •Kronberg, Wielebinski & Graham.1986,
- •Mack *et al.* A&A 329, 431, 1998
- •Schoenmakers *et al.* 1998,2000
- •Subrahmanian *et al*. 1996
- •Feretti *et al* 1999
- •Lara *et al*. 2000
- •Palma *et al*. 2000



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

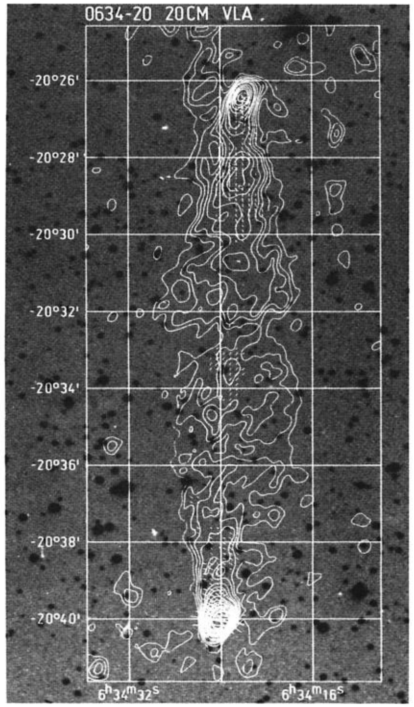
a “template” for widespread IGM CR acceleration??

10 GHz



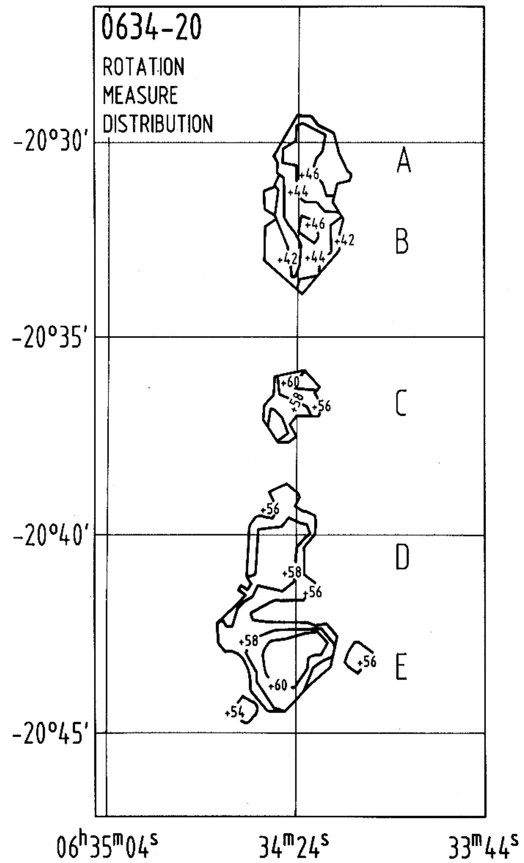
Effelsberg 100m. Telescope 10.6 GHz

1.4 GHz



VLA 1.4GHz

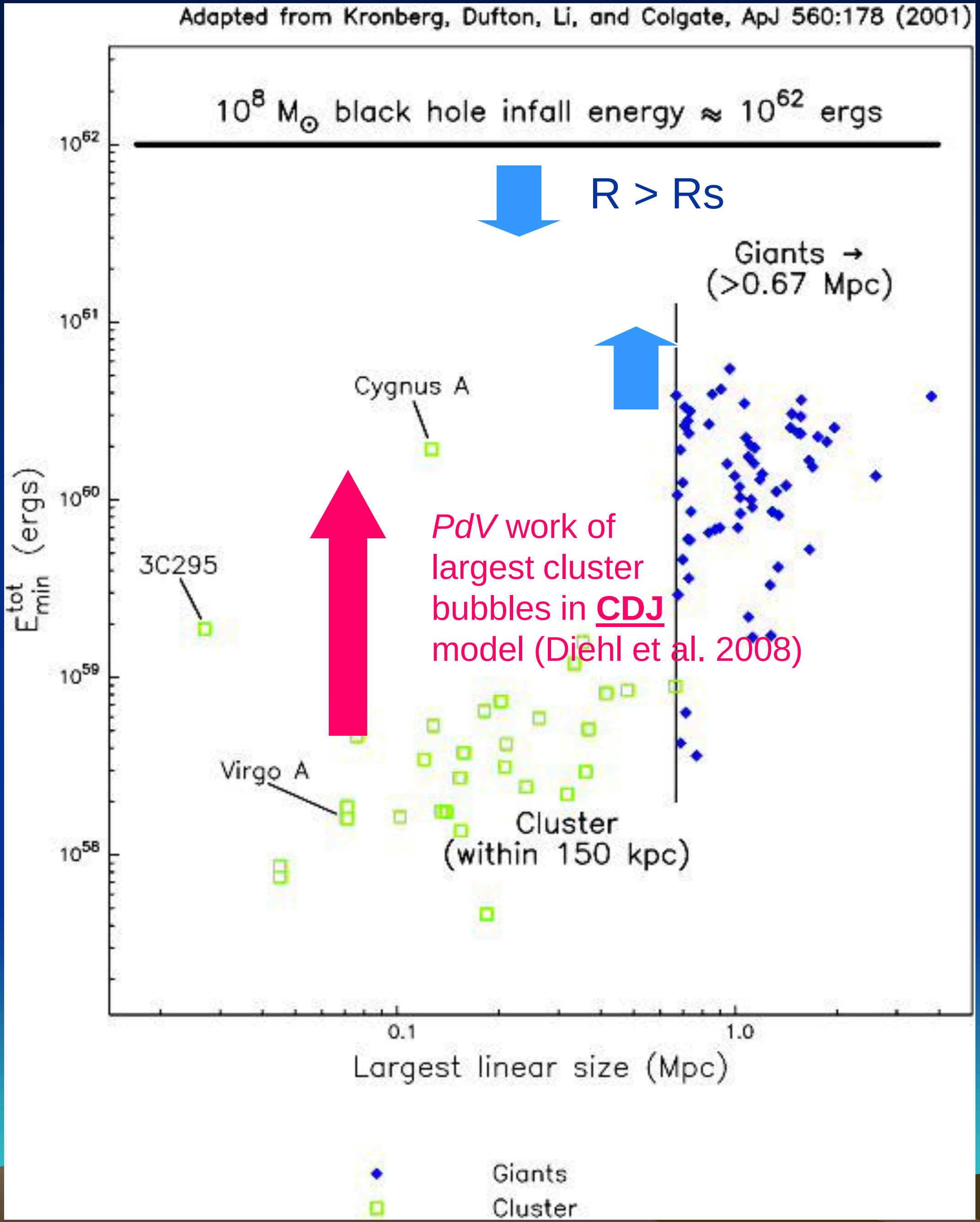
Faraday RM(radians/m²)



Freshly accelerated, starved of thermal plasma?

Kronberg, Wielebinski & Graham
***A&A* 169**, 63, 1986
→UHECR acceleration source?

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



ENERGETICS:

$=M_{BH}c^2$

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

P. Kronberg, Q. Dufton, H. Li, & S. Colgate, ApJ ***560****, 178, 2001*

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

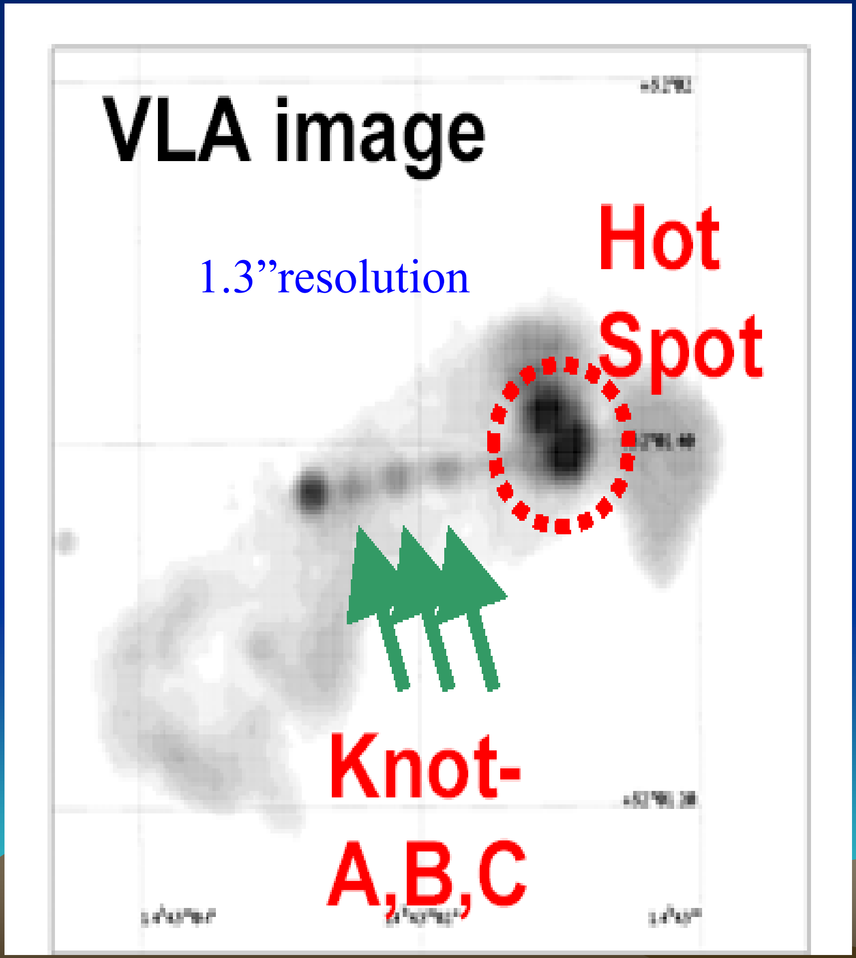
Knots and Hotspots of 3C303 (z=0.141)

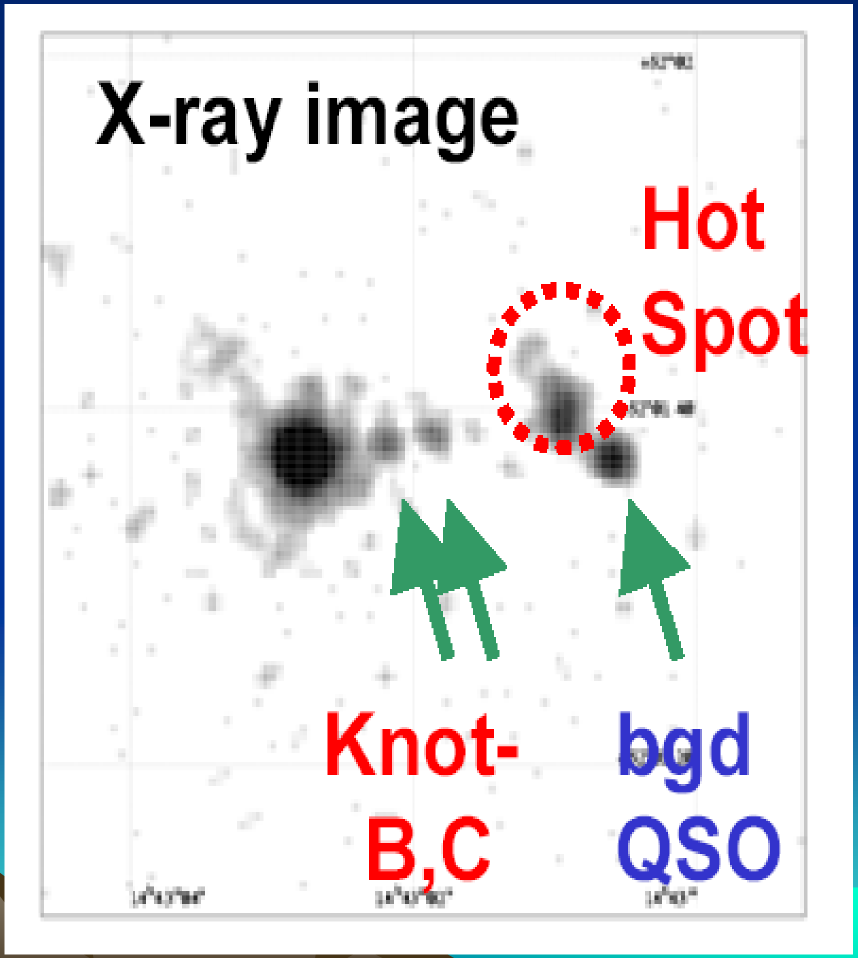
Radio (VLA) and X-Ray (CHANDRA)

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

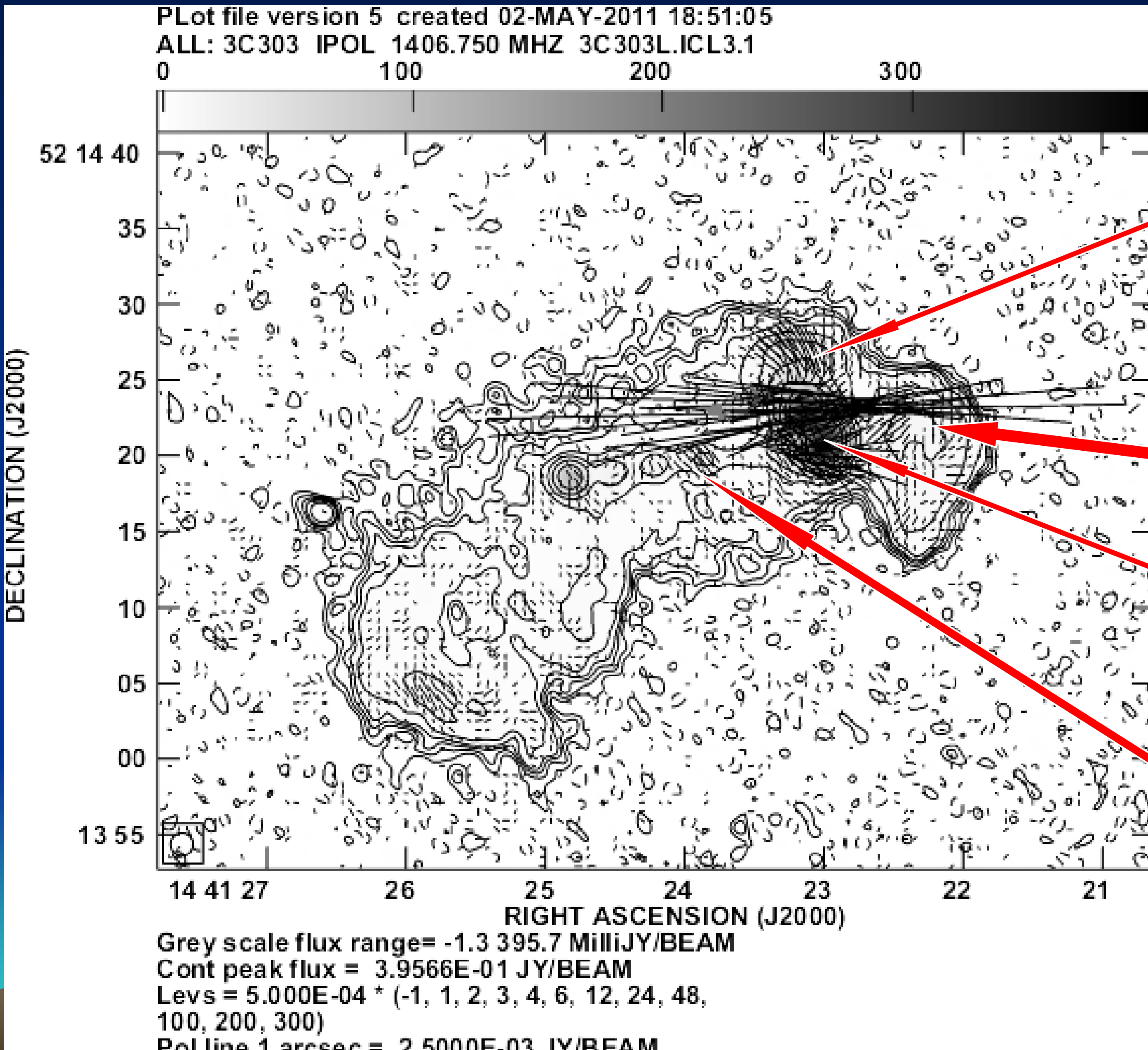
*P. Leahy & R. Perley, Astr. J. **102**, 537, 1991*

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





3C303 1.4GHz



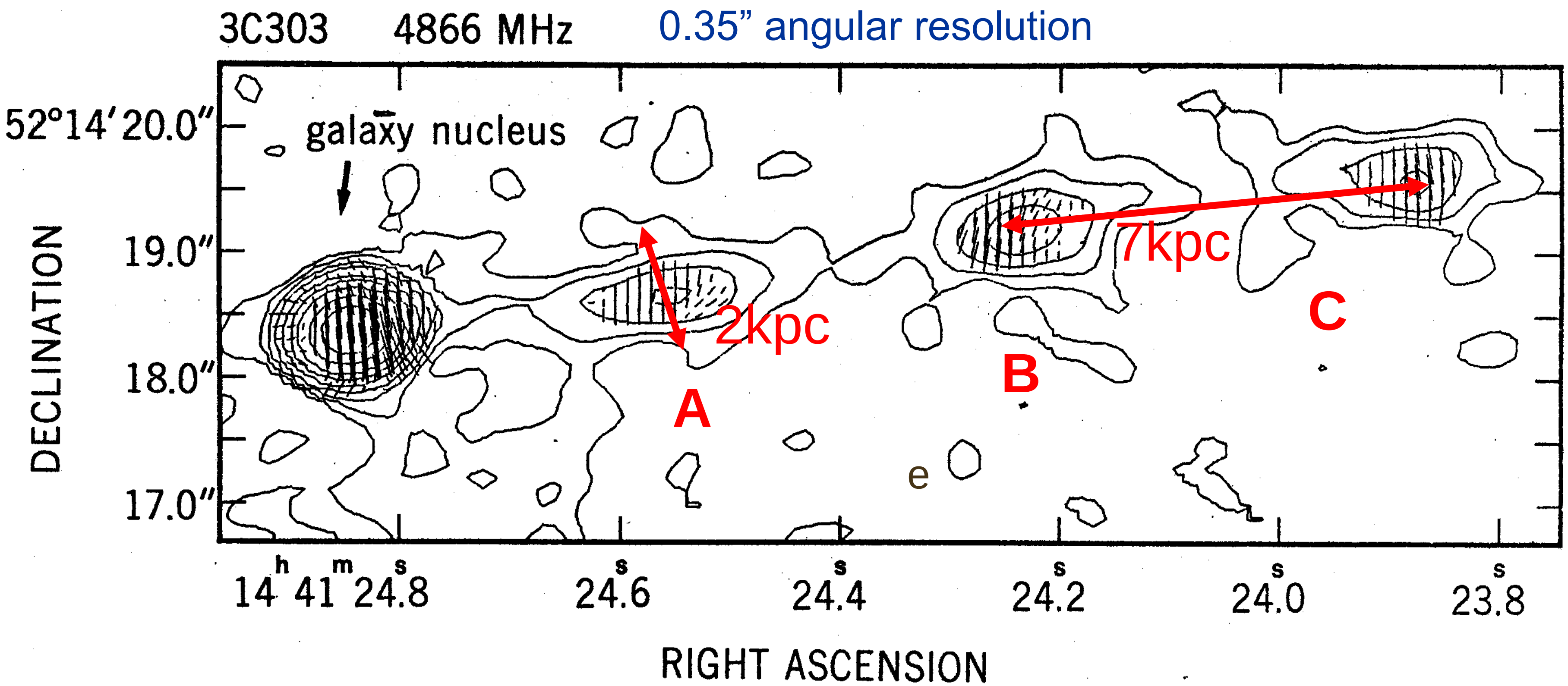
3 spheroid ``islands''
Each has high
Mag field– ordering
& current signatures

jet continues
undeflected
to here

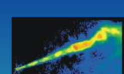
jet disruption
point

Knot ``E3' has a
measured ∇RM
vector

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!

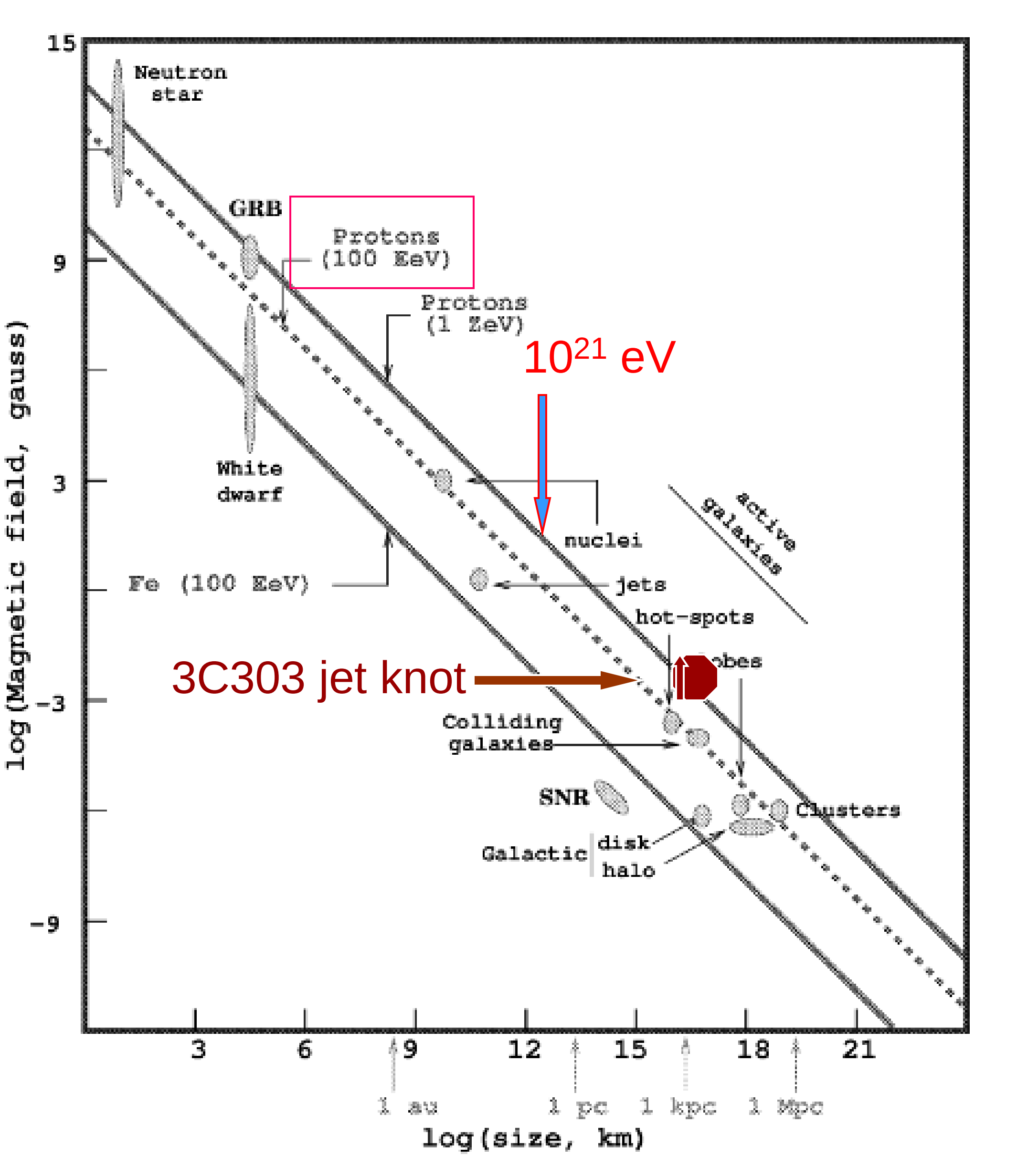
(3) Measure knots' synchrotron luminosity & size (D_{knot}) → B^{knot}_{int}=10^{-3}G

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

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. in the *relativistic range V_A^{rel}*



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

How to estimate the <u>jet current</u>? --
what are the required measurements:

1. arcsec resolutionl, sensitive images at ν_1, ν_2, ν_3

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

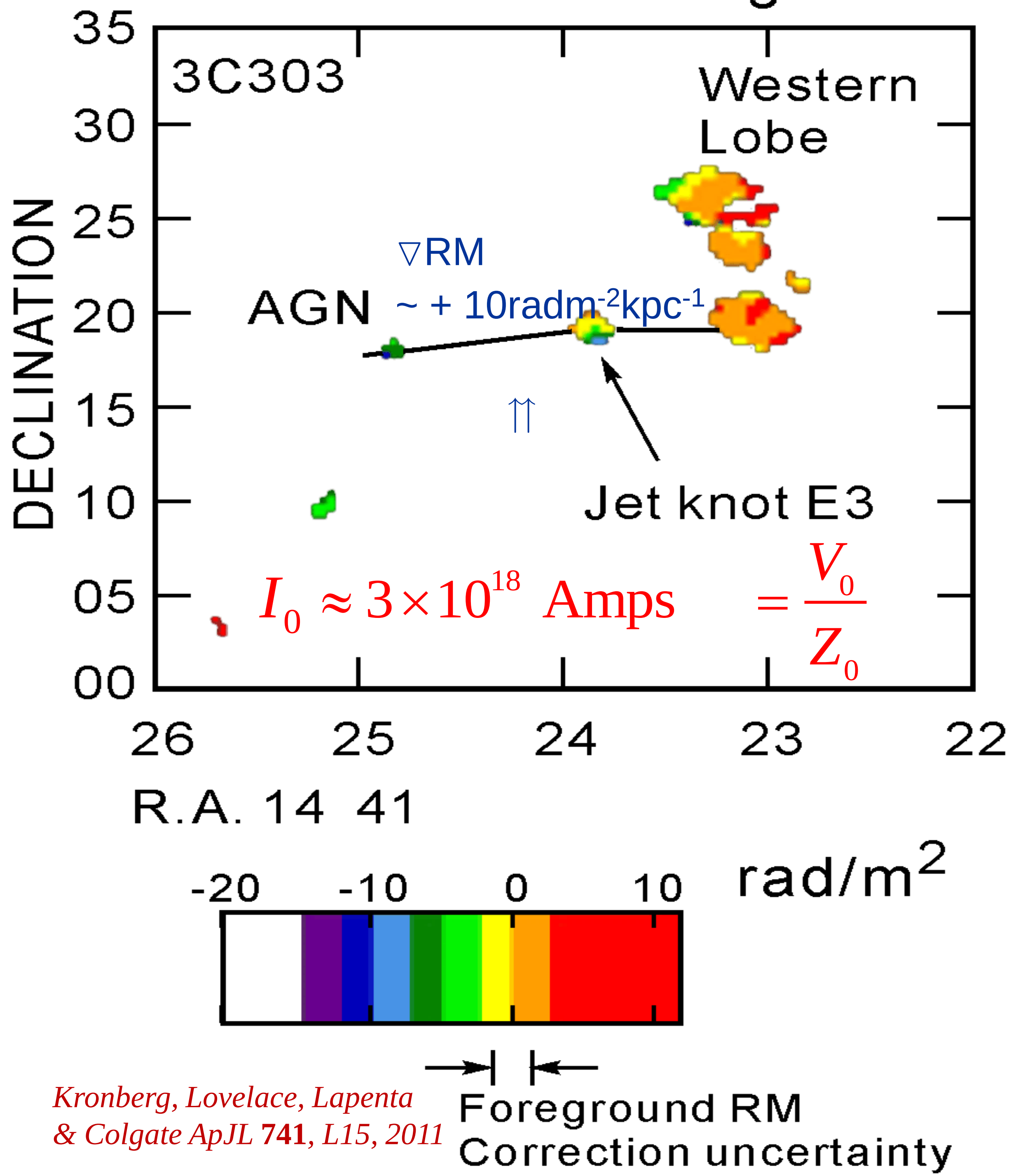
3. X-ray image ~ kev range

4. Need surrounding sky RM's to establish the <u>RM</u> zero-level

   i.e. subtract $<RM_{\text{backgnd sources}}>$ from the RM's in the jet image

   (*normally only feasible outside a galaxy cluster*)

P.P. Kronberg, R.V.E. Lovelace, G. Lapenta, & S.A. Colgate, ApJL **741**, *L15, 2011*



Kronberg, Lovelace, Lapenta & Colgate ApJL ***741****, L15, 2011*

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*** $=3.3\times10^{18}$ ampères of axial current.
  sign of ∇RM gives ***I*** direction – in this case away from the BH
- Jet's electrical properties: (voltage, impedance, current).

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

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

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

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

Some near-future or existing instrumental capabilities

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

Further comments on extragalactic CR accelerator candidates

M87 and Centaurus A are both in a galaxy cluster or galaxy group environment.

- problems of separating source effects from the local environment.

Truly giant radio sources, <u>outside</u> of clusters make the best calibrators of SMBH energy output

3C303 is intermediate in scale between M87 (small), and Giant radio galaxies

B- input to the IGM from galaxies can be due to:

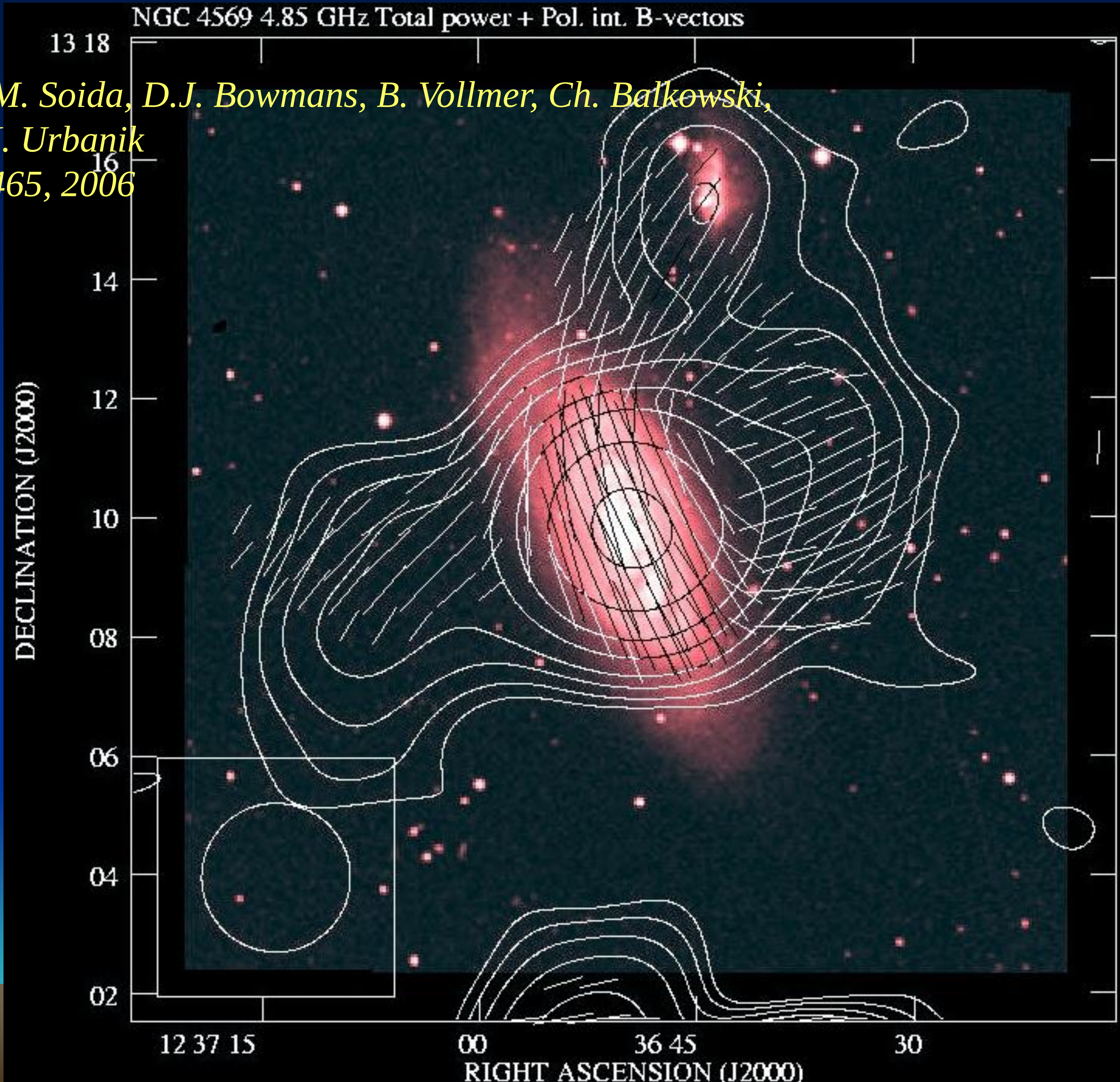
1.

Galaxies with strong starburst-driven outflows

(see 2 examples)

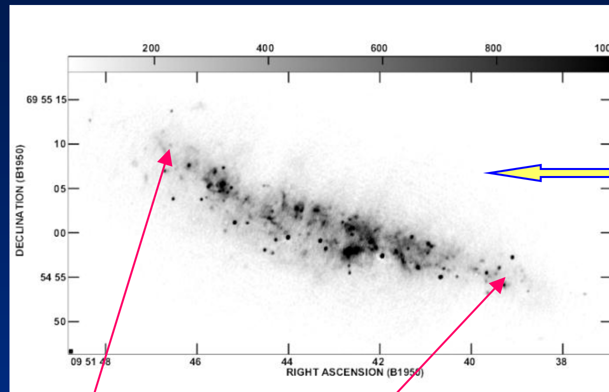
A

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



B. Supernova etc. – driven outflow from the M82 starburst galaxy (at 3 Mpc)

Kronberg, P.P. Biermann, P.L. Schwab, F.R.
*ApJ **246**, 751, 1981.*
VLA, 5 GHz, 0.3" resolution
M.L. Allen, Ph.D. Thesis 8GHz

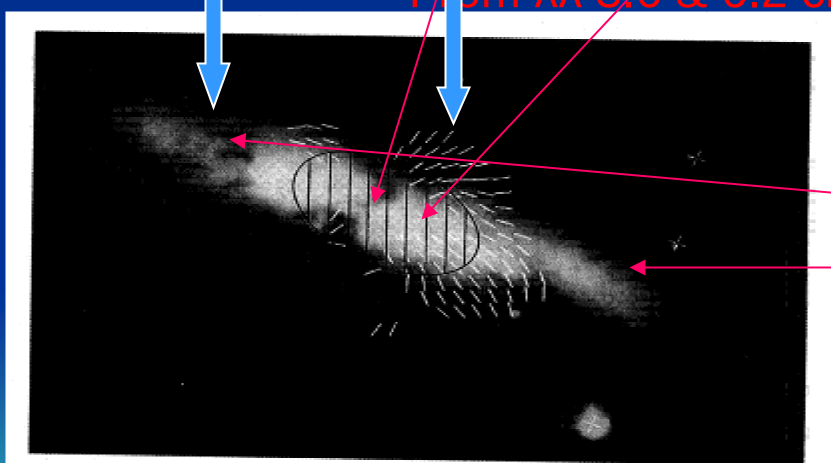


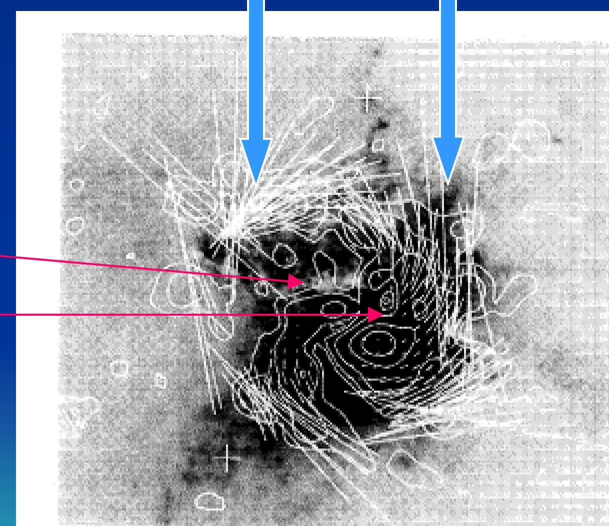
Optical image

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

Pol'n intensity

Hα emission





*Reuter, H.-P., Klein, U., Lesch, H., Wielebinski, R., and Kronberg, P.P. A&A, **282**, 724, 1994, [A&A **293**, 287, 1995 - Figs. with corrected orientation].*

2.

Intergalactic fields from supermassive Black holes, producing jets, which feed and inflate intergalactic scale lobes

Electromagnetic extraction of accretion energy from a supermassive black hole

Lovelace, R.V.E. Nature, 1976
Blandford, R.D., & Znayek, R.L., MNRAS 179, 433,1977
Pariev, V., & Colgate, S.A.

Expectation of the average intergalactic field seeded by supermassive black holes: A global calculation

Average galactic BH density ($M_{\rm BH} \gtrsim 10^{6.5} M_\odot$)

$$< \rho_{BH} > \approx 2 \times 10^5 M_\odot / Mpc^3$$

Gravitational energy reservoir per BH (scaled to infall to R_S)

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

Gives a global magnetic energy density, $\varepsilon_{\rm B}$

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

Gives $B^{\rm BH}_{\rm IG} = \sqrt{8\pi\varepsilon_{\rm B}} = 1.8 \times 10^{-7}$ G

- Initially captured within galaxy filaments
- Intergalactic medium near large galaxies should contain significant magnetic energy that originates in central BH's

~ $10^{-7\text{-}8}$G in galaxy filaments
roughly consistent with:

1. Globally calculated, space –averaged, supermassive ($\gtrapprox 10^7 M_\odot$)BH magnetic energy ($B^2/8\pi \times Vol.$) output (shown above)

2. Computer simulation predictions of LSS filament fields amplified by LSS gravitational infall.

   (*H.Kang, D.Ryu & P.L.Biermann ApJ* **335**, *19, 1998* + others since.

   More recent: *J. Cho & D.Ryu, ApJL*, **705**, *90, 2009* predict:

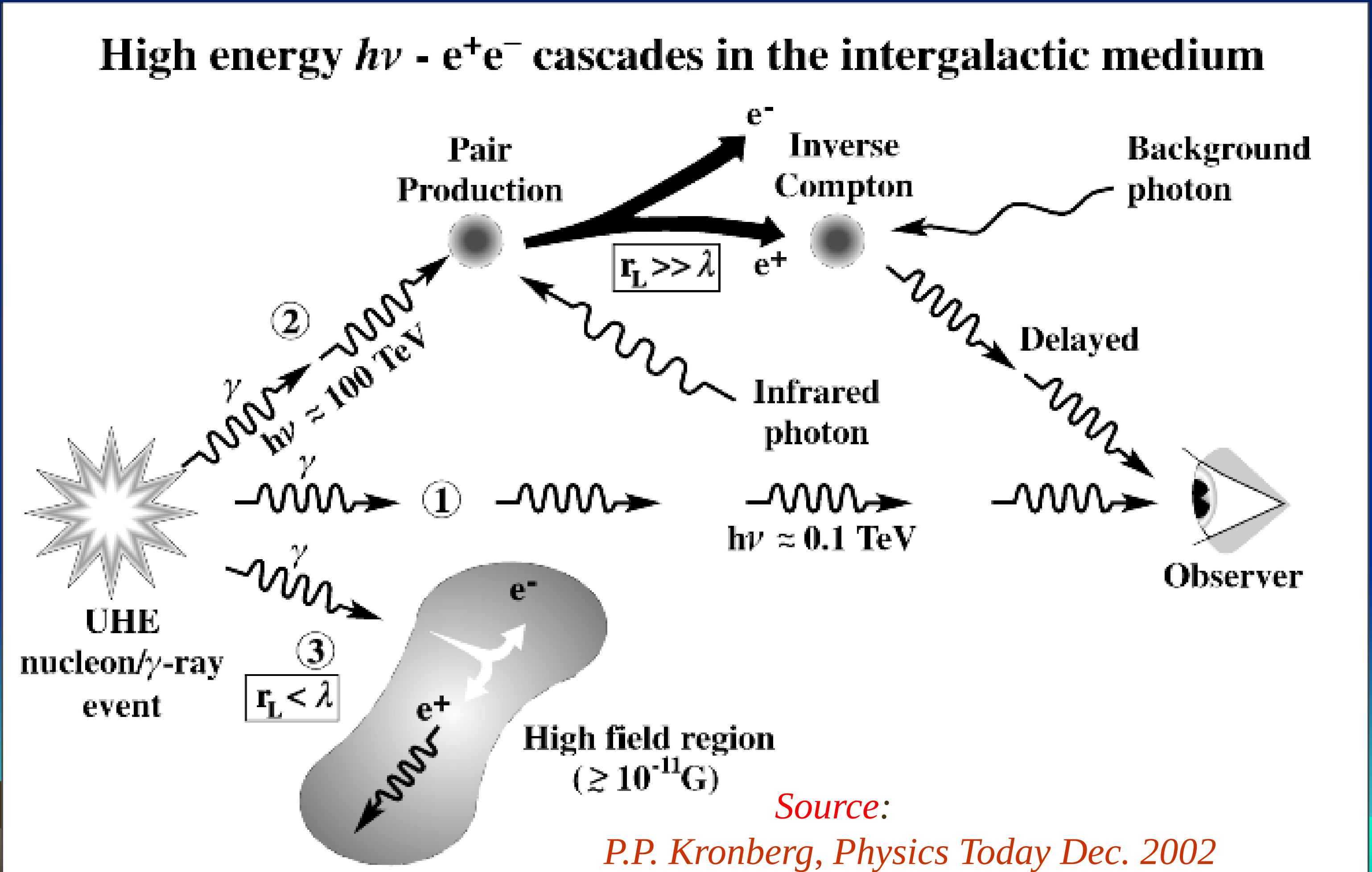
$$\sigma_{RM} \sim 15 \left(\frac{n_e}{10^{-4}\,\mathbf{cm}^{-3}} \right) \left(\frac{<|B|>}{3\times10^{-7}\,\mathbf{G}} \right) \left(\frac{l}{300\mathbf{kpc}} \cdot \frac{L}{5\mathbf{Mpc}} \right)^{0.5} \mathbf{rad\,m}^{-2}$$

Magnetic fields in cosmic voids? from where? how to detect them?

- Diffusion out of the walls and filaments? (galaxy-supplied)
- Relic of a pre-galactic, or primordial field?
- B measurements still mainly ***Gedanken-Experiments*,**
- Most involve high energy particle & photon propagation
- Time of arrival, deflection, energy and composition

At $E \gtrapprox 10^{18}$ eV, all of ``empty" i.g. space becomes a (passive) particle physics laboratory!!

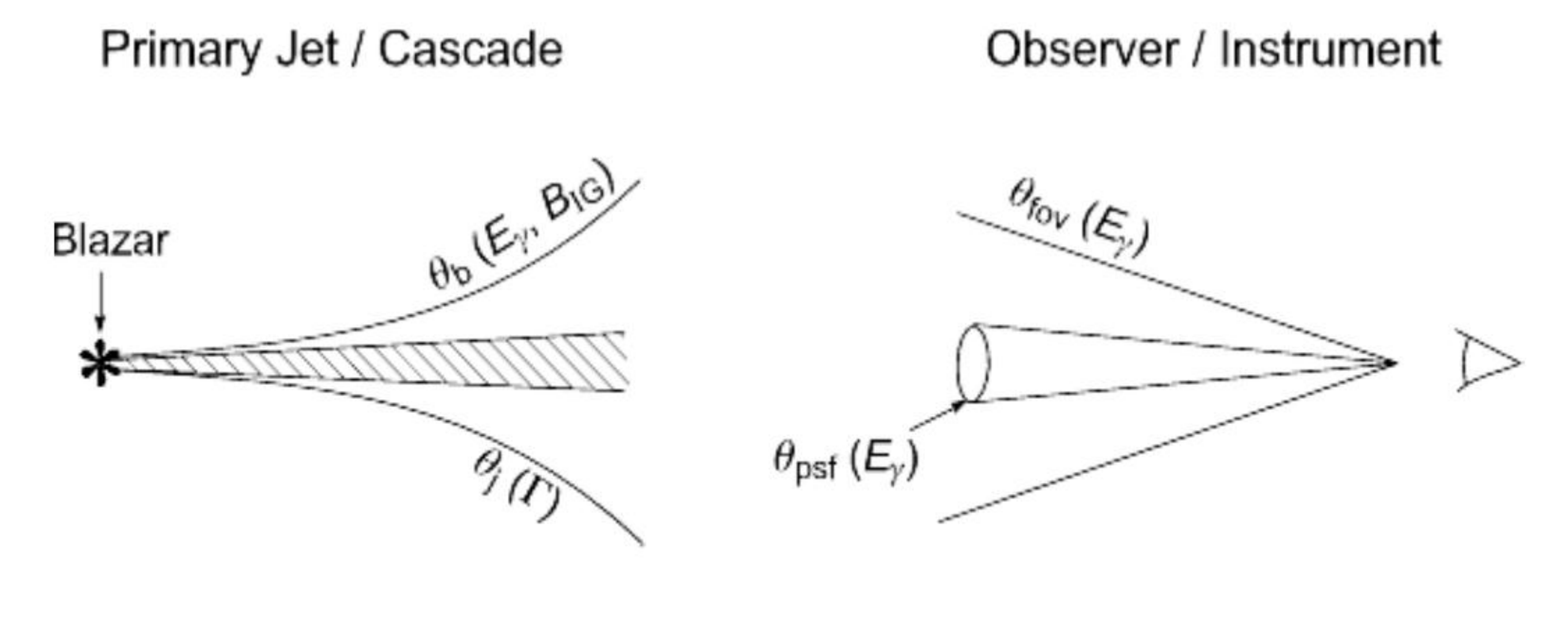
Energy cascade cartoon of a broadband γ-ray burst could probe a very weak IGM field



Source:
P.P. Kronberg, Physics Today Dec. 2002
adapted from R. Plaga Nature 374, 430, 1994

Very weak i.g. fields from γ-ray cascades

degrees



P.P. Kronberg

Magnetism in the widespread IGM to the largest measurable redshifts

1. Optimally remove the galactic foreground $RM \rightarrow$ evaluate *residual RM* (RRM)

2. Test for $\sigma^2(RRM)$ vs. z

RM search at high *z* for a widespread B_{IGM}

- Began in 1970's *Papers by M. Rees, M. Reinhardt, P. Kronberg M. Simard-Normandin, A. Nelson , J.P. Vallée*

- Why was it of interest?
  - **Then** Ω_B was thought $\simeq 1$, $\therefore n_e(z)$ is high enough to "illluminate'' B_{IG} to high z !
  - **Now**, $\Omega_B \simeq 0.04$; too little to detect a significant RM_{IGM}

  BUT

  - high energy extragalactic events can probe/limit $|\boldsymbol{B}|$ to ~ 10 orders of magnitude fainter.

774 P. P. Kronberg et al

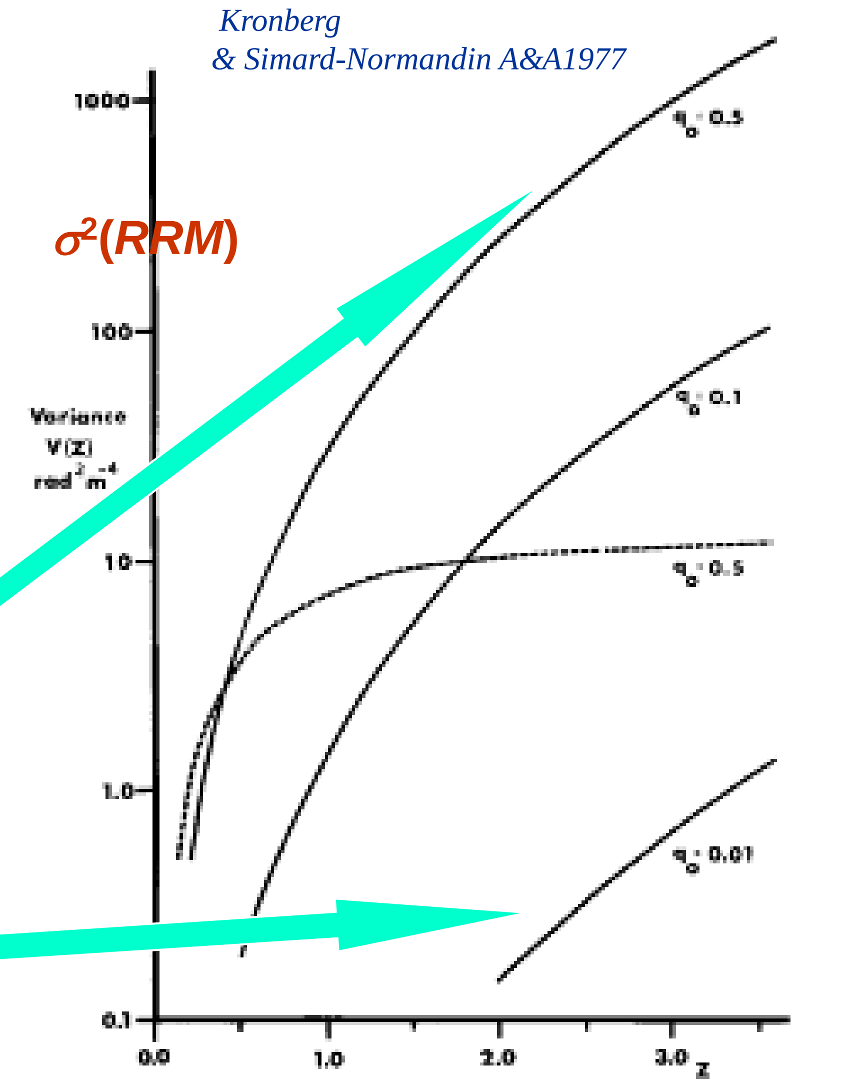


Fig. 1. The calculated variation of $V(z)$ for models 1 (solid lines) and 2 (dashed line) over the redshift range $0 < z < 3.6$. The following values were assumed: $B_0 = 1.8\ 10^{-8}$ Gauss, $\eta = 1$, $H_0 = 75$ km s^{-1} Mpc^{-1}, $l_0 = 1$ Mpc, and $f = 1/64$ for model 2. Model 1 is shown for q_0 ($= \Omega/2$) values of 0.5, 0.1 and 0.01

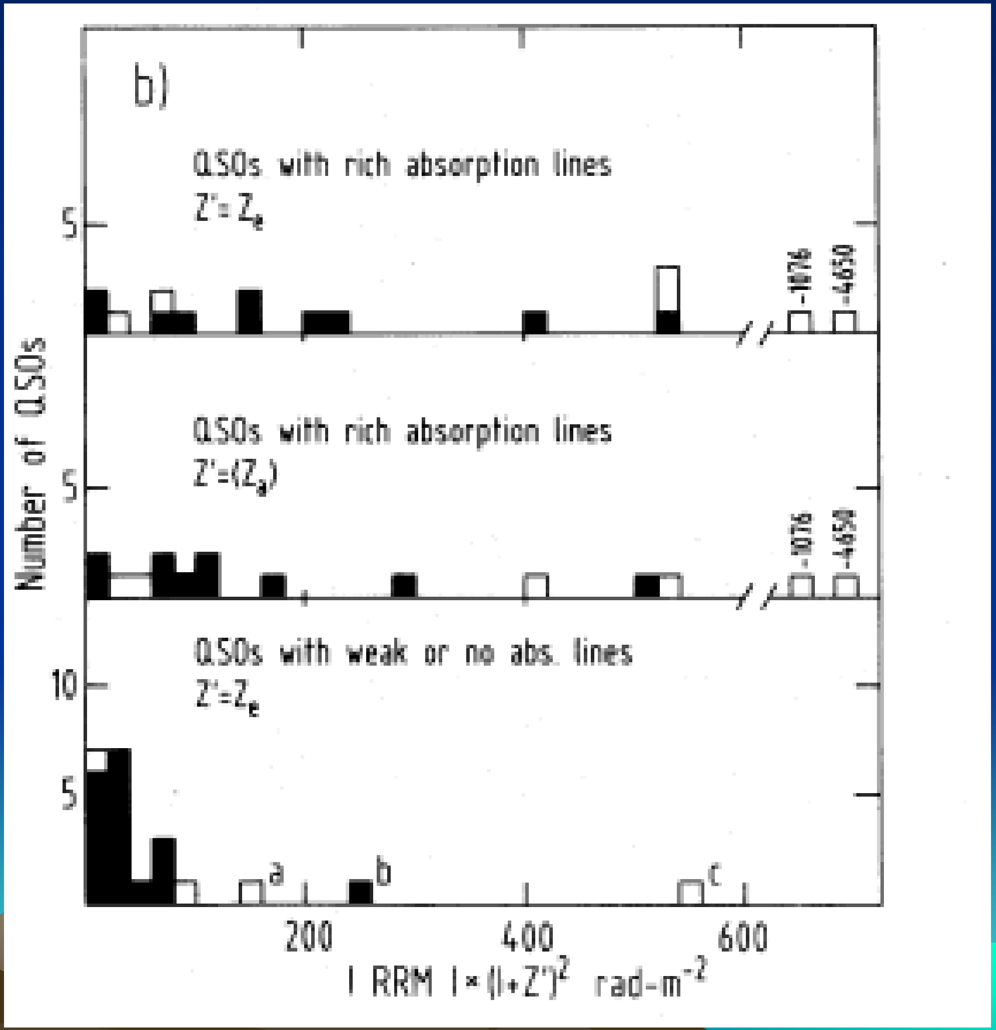
Discrete magnetized *intervenors* in the universe

Note:

globally, galaxy clusters barely count here! $\rightarrow \rho(z) \cdot \sigma(z)$ is too small relative to that of galaxies

detections of magnetized optical absorption line systems in sightlines to quasars

G.L. Welter, J.J. Perry, & P.P. Kronberg
ApJ 279, 19, 1984
(119 RM sample, 40 had spectra with strong optical absorption lines)

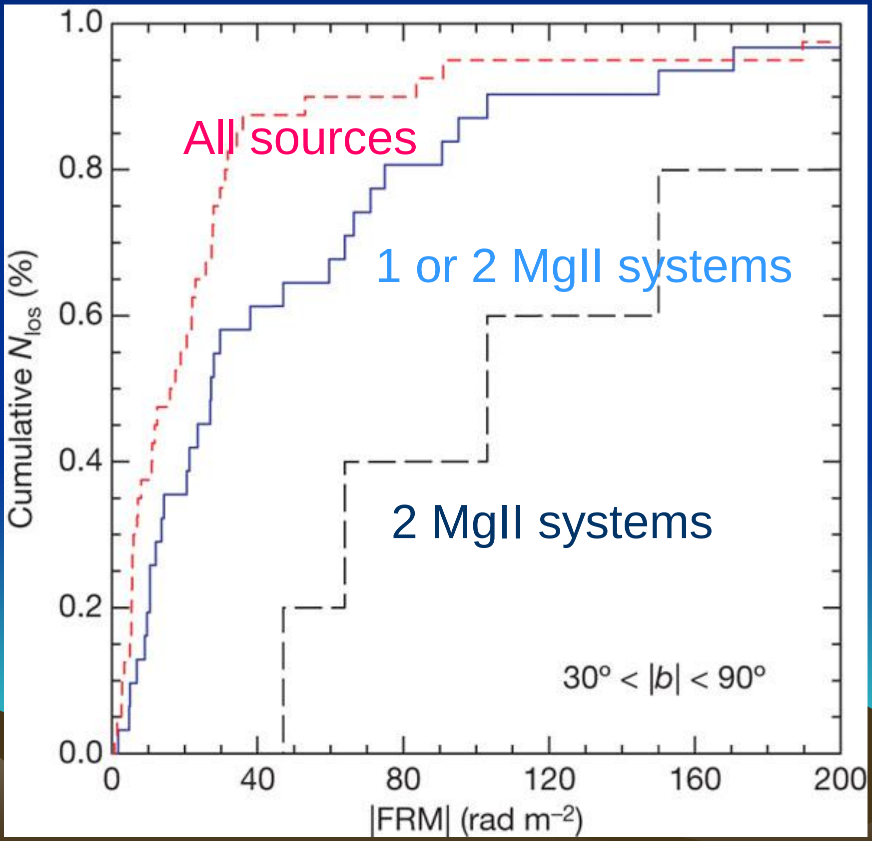


P.P.Kronberg & J.J. Perry,
ApJ 263, 518, 1982
(37 RM + Abs. spectrum QSO's)

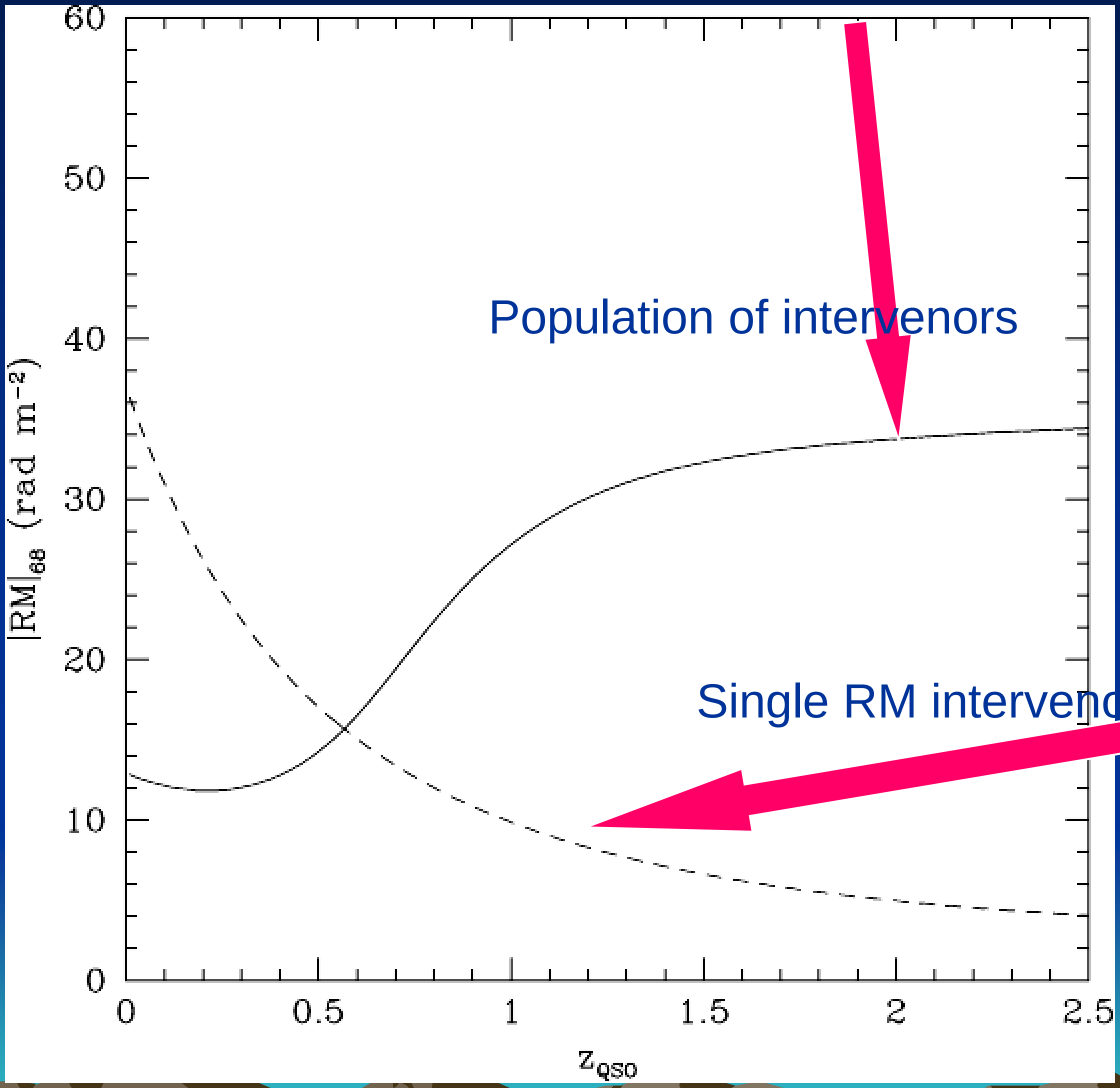
Cumulative plots of RM for 3 different MgII absorption line groups

M.L. Bernet, F. Miniati, S.J. Lilly, P.P. Kronberg, M. Dessauges-Zavadsky Nature **454**, *302-4, 2008*

Method: G.L. Welter, J.J. Perry & P.P. Kronberg ApJ **279**, *19, 1984*



Observed RM increase through a population of intrinsically similar Faraday intervenors (galaxy systems) out to $z = 2.5$



Σ (RM_i) for a population of discrete magnetized *L** galaxy intervenors

RM_0 of a 37 rad m^{-2} intrinsic Faraday rotation at z_{qso} --illustrates **(1 + *z*)$^{-2}$** decease of RM with z

M. L. Bernet and P. P. Kronberg

N(*RRM*, *z*) is a complex, multivariate distribution!

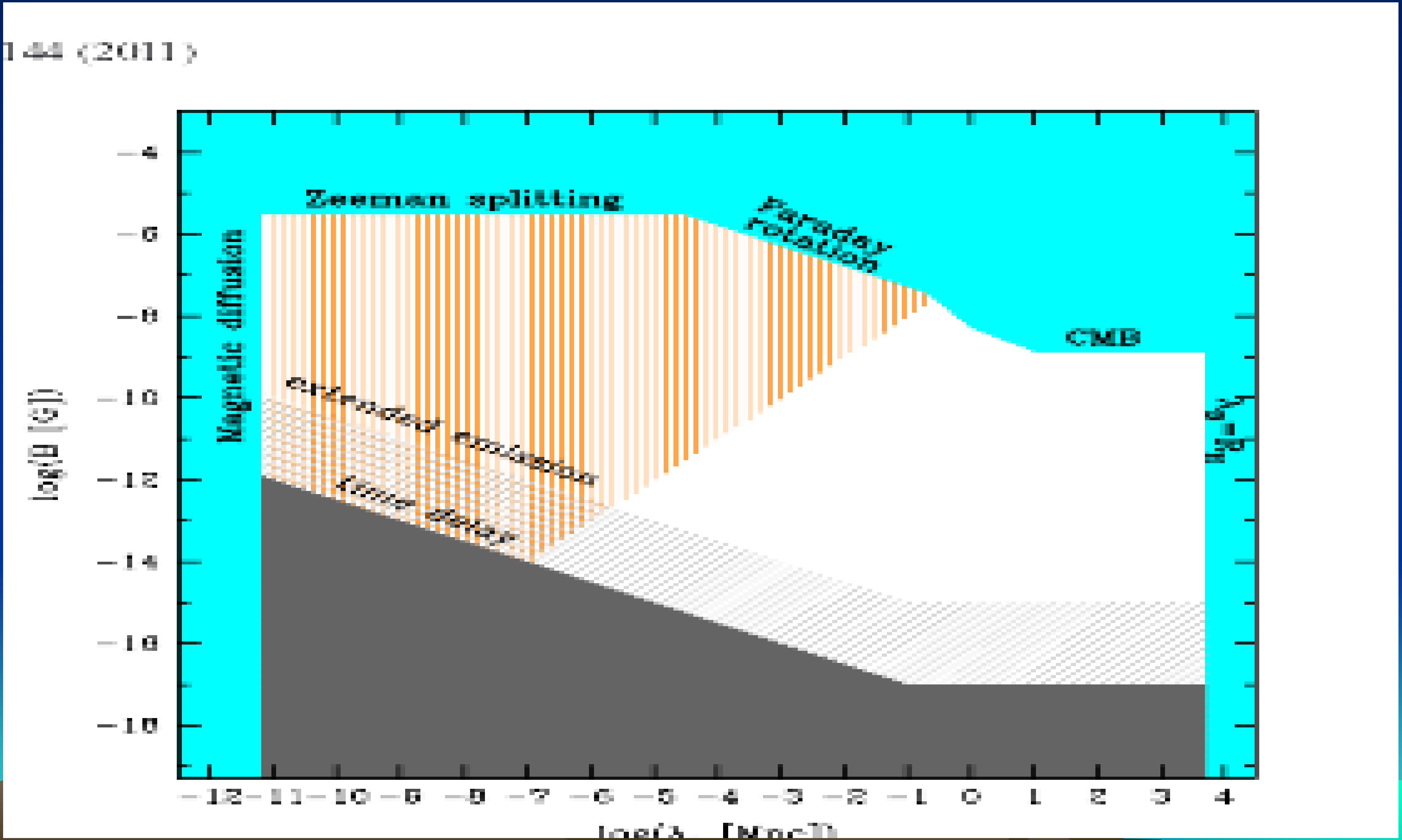
It contains:

- a strong $(1+z)^{-2}$ factor (only $0.06 \times RRM_0$ at z = 3!)
- varying fraction of real RRM< “outliers”
- RM outliers have different causes
- multiple populations of galaxy and halo intervenors
- galaxy groups and (fewer) galaxy clusters
- small subset of high intrinsic (& evolving?) RM’s
- Cross-section evolution
- etc.

Philipp Kronberg

Approximate current limits on intergalactic magnetic fields (referred to current epoch)

A.M., Taylor, A. Noronov & Vovk, I, 2011



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