Origins and probes of cosmic magnetic fields

– *an introduction*

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and

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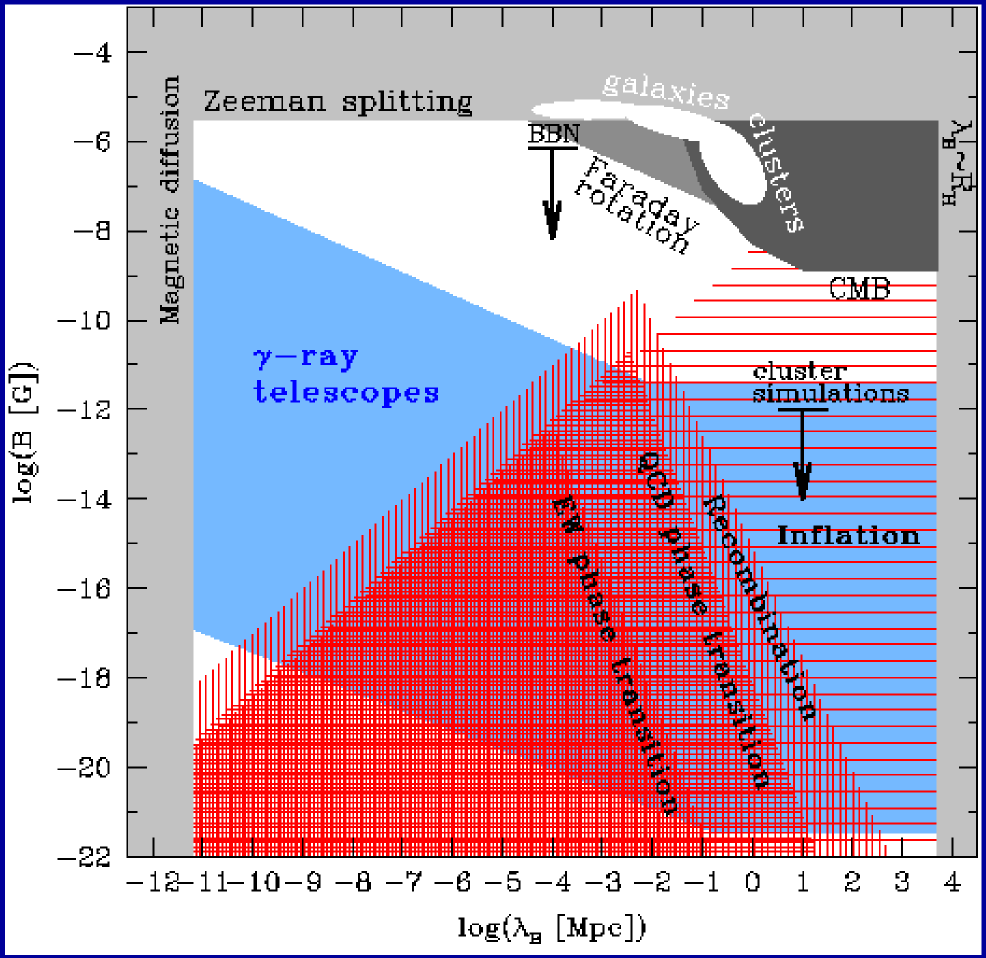
Paris, France, le 13 décembre, 2010

The CMF conference logo

D. Semikoz



Magnetic fields beyond the bounds of individual galaxies and clusters. Overview

- This talk mostly <u>excludes</u> B within galaxies and within galaxy clusters
- Local universe, filaments, voids, recombination era. ($z \approx 0$ to $\gtrsim 1500$).
- opportunities for next-generation observations
- Some guiding theory: modelling: energy, physics
- Synergies ***e.g.*** with high energy- & astroparticle phyics.

Comments on seed fields

Possibilties:

1. Primordial B
   – i.e. before the epoch of last scattering.

2. B seeded in baryonic plasmas, post-recombination, in stars/ galaxies/ IGM

Comments:

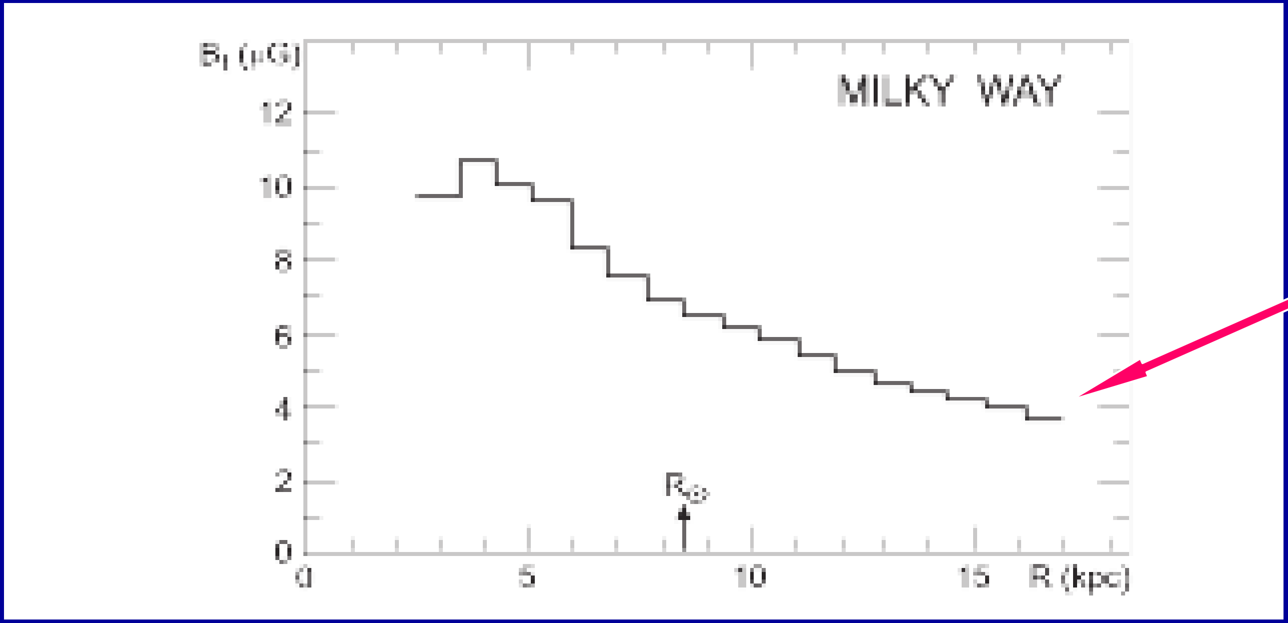
- Possibility 1 difficult to verify – but
  - important connections to physics, particle cosmology, and possibly string theory.
  - Possibilities start at the Planck scale
  - Iimportant test: $<|B|>$ in voids
  - (*reviews: e.g. Kronberg 1994, Widrow 2002, Grasso & Rubenstein 2004*)

- Possibility 2 is certain: Mechanisms experimentally verified
  - star + SN-driven outflow
  - Supermassive BH – produced fields
  - Subsequent regeneration mechanisms.

1.

B in the vicinity of galaxies

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



Connects to local B_{IGM} ?

E.M. Berkhuijsen, R, Wielebinski (MPIfR Bonn)

How galactic winds driven by stellar processes inject magnetic fields into the IGM

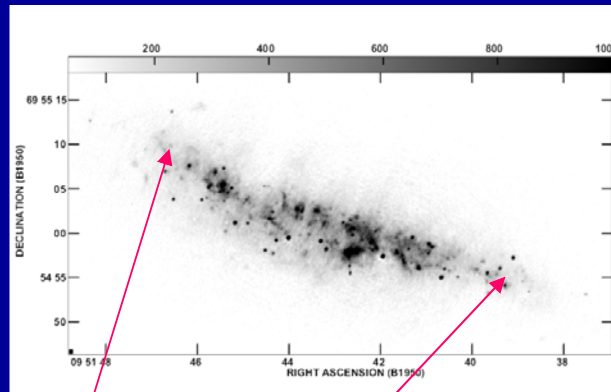
A. "quiescent", Milky Way – like galaxies
B. Starburst and dwarf galaxies

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

Outflow halo:

B_{halo} ~ 10μG

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.*

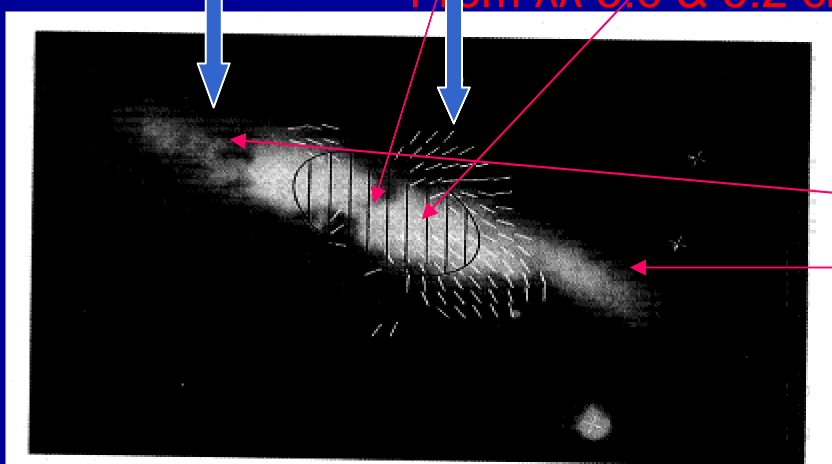
Allen & Kronberg, 8GHz

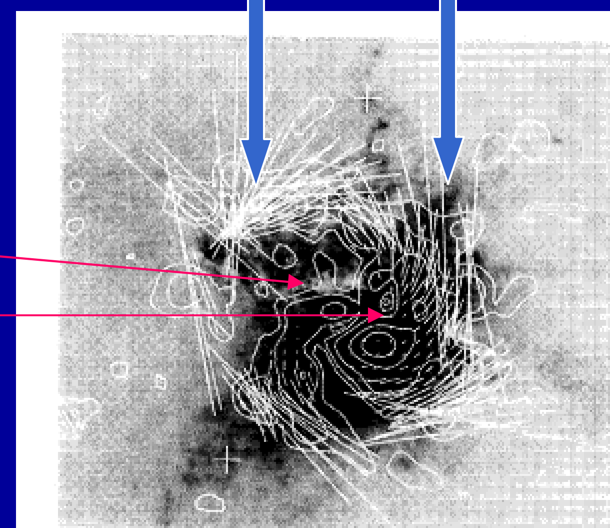
Optical image

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

Pol’n intensity

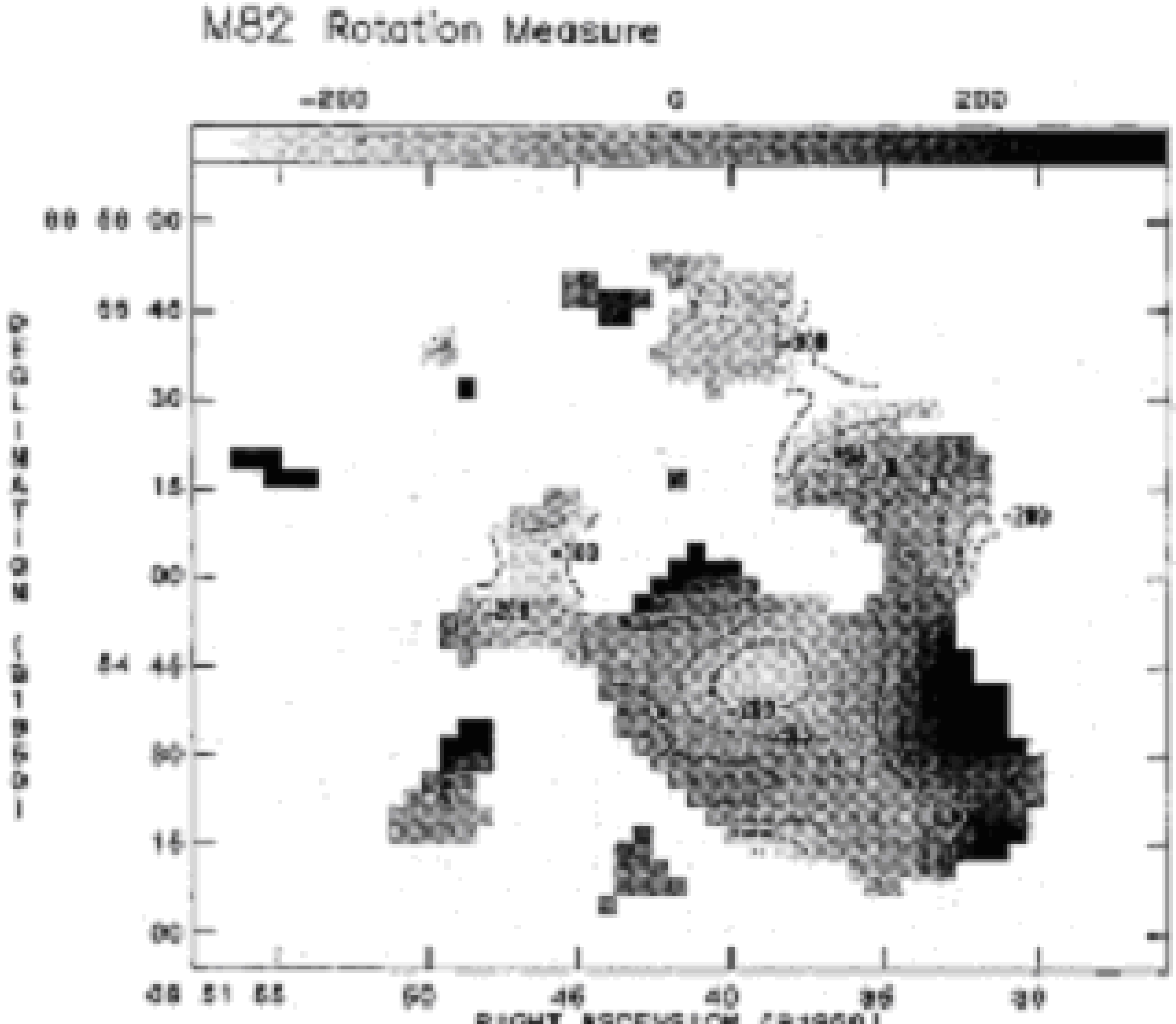
Hα emission



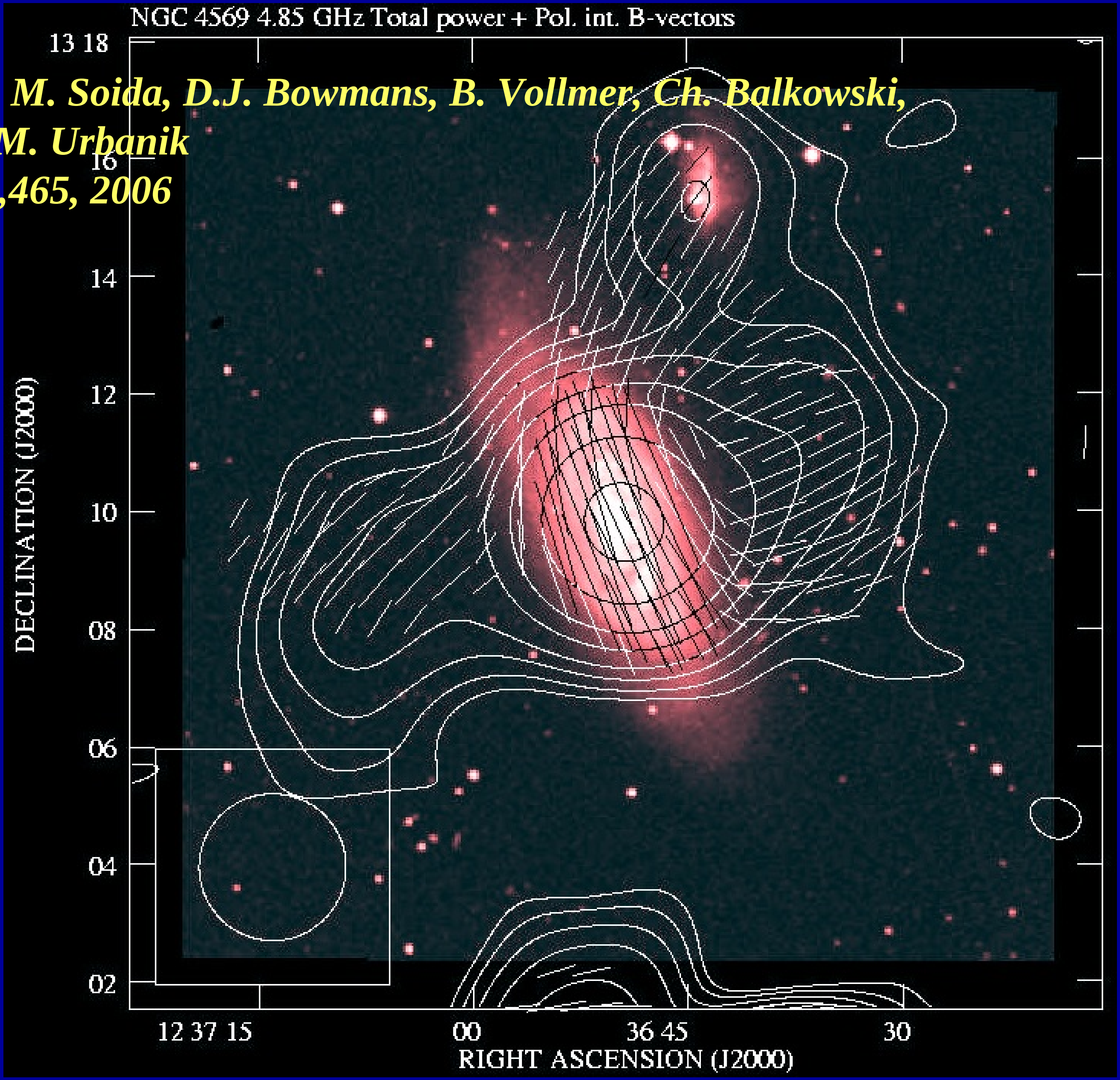


*Reuter, H.-P., et al.. A&A, **282**, 724, 1994, [A&A **293**, 287, 1995 - Figs. with corrected orientation].*

Reuter et al A&A 282, 724,1994



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



2.

Collective dwarf galaxy seeding of the IGM

MODEL INPUTS

- Outflow halo parameters at low z
- Dwarf galaxy counts, merging models
- Heirarchical merging scenarios since z ~15
- Embed in Hubble flow

RESULTS

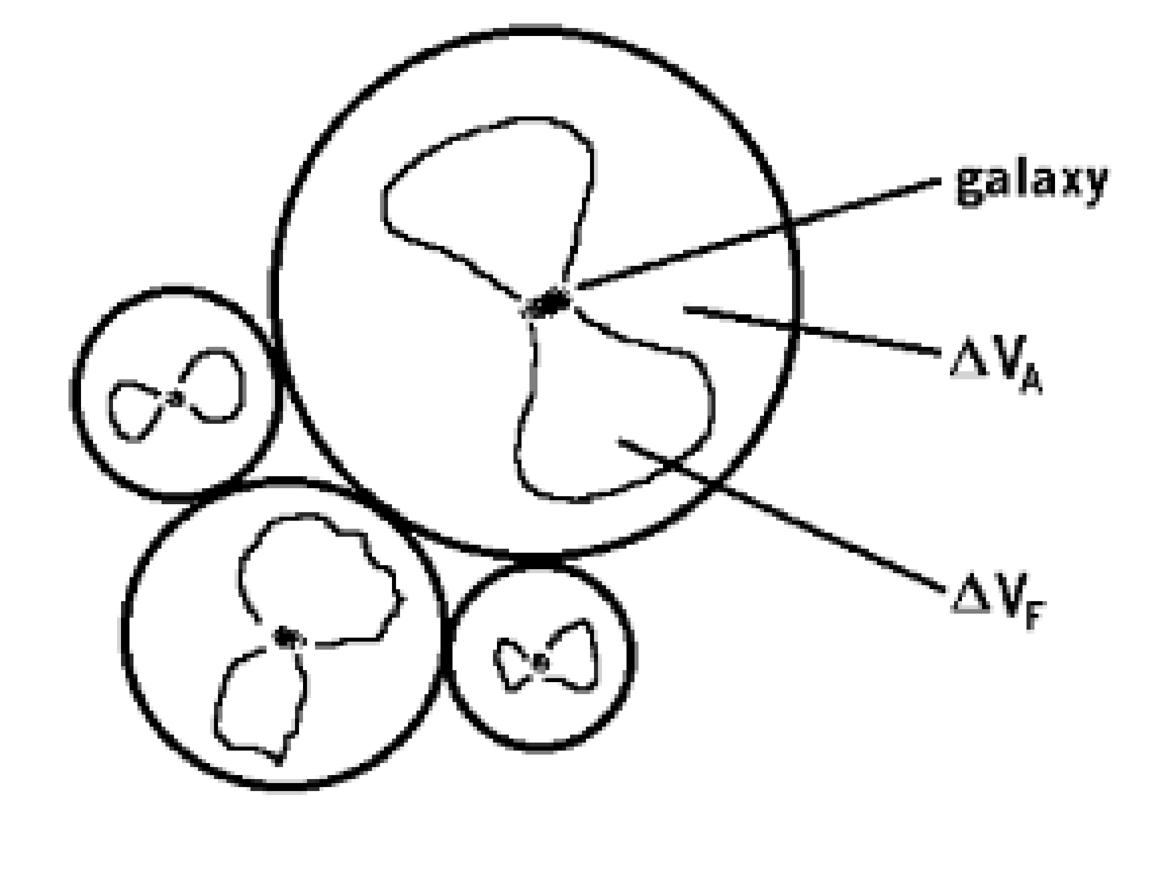
- Volume of intergalactic filaments at z ~0 is easily filled with magnetic fields at $\boldsymbol{B}_0 \sim 10^{-9}$ *before* any post-amplification --see below

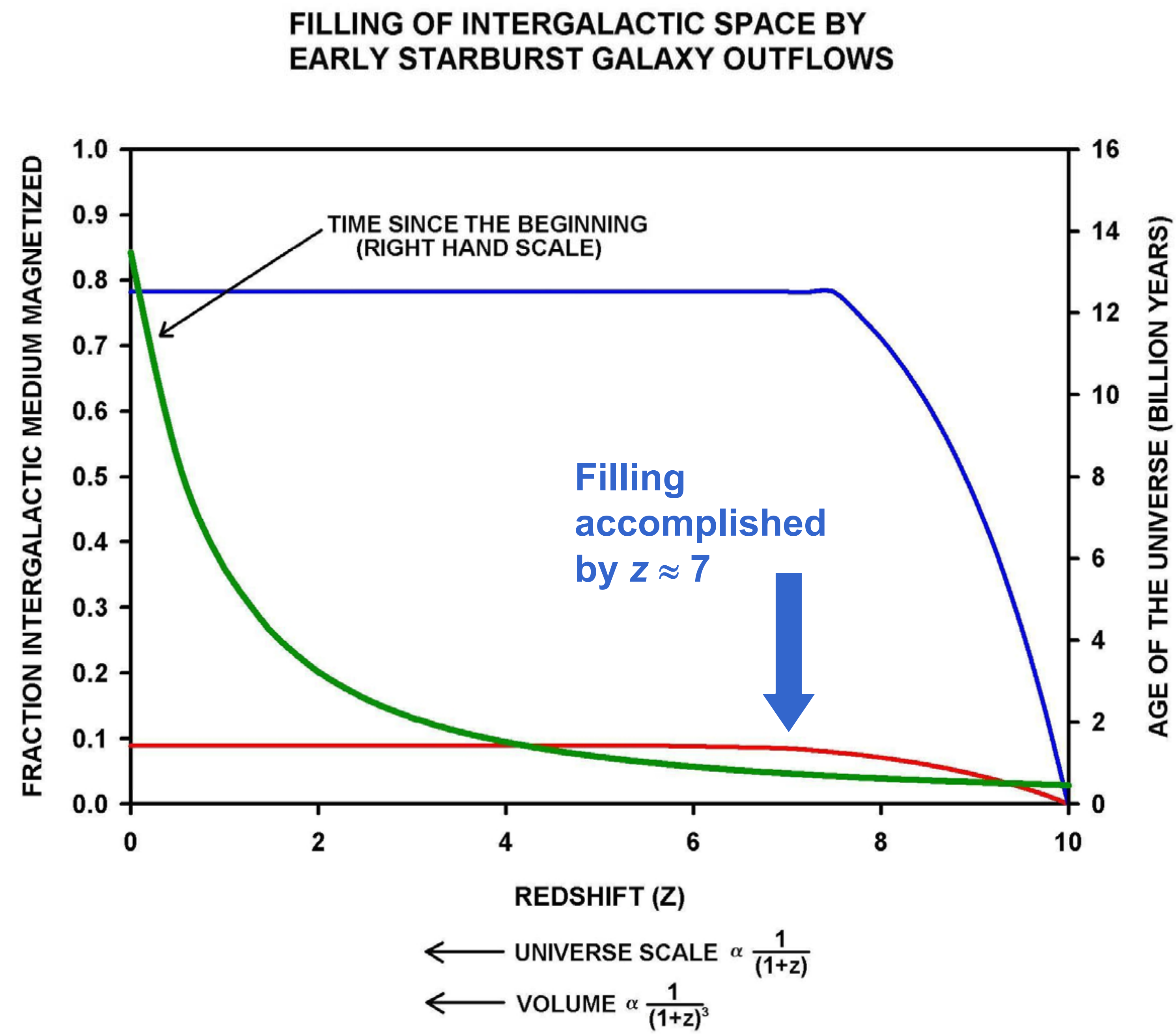
V_A = i.g. volume ``available'' to be filled with outflow
$V_F(t)$ = volume filled *with stellar/SN halo outflow*

$f(t)$, [or $f(z)$] = V_F/V_A fraction of available IGM (*i.e.* within galaxy filaments) that gets filled from $z \sim 10$ to $z = 0$

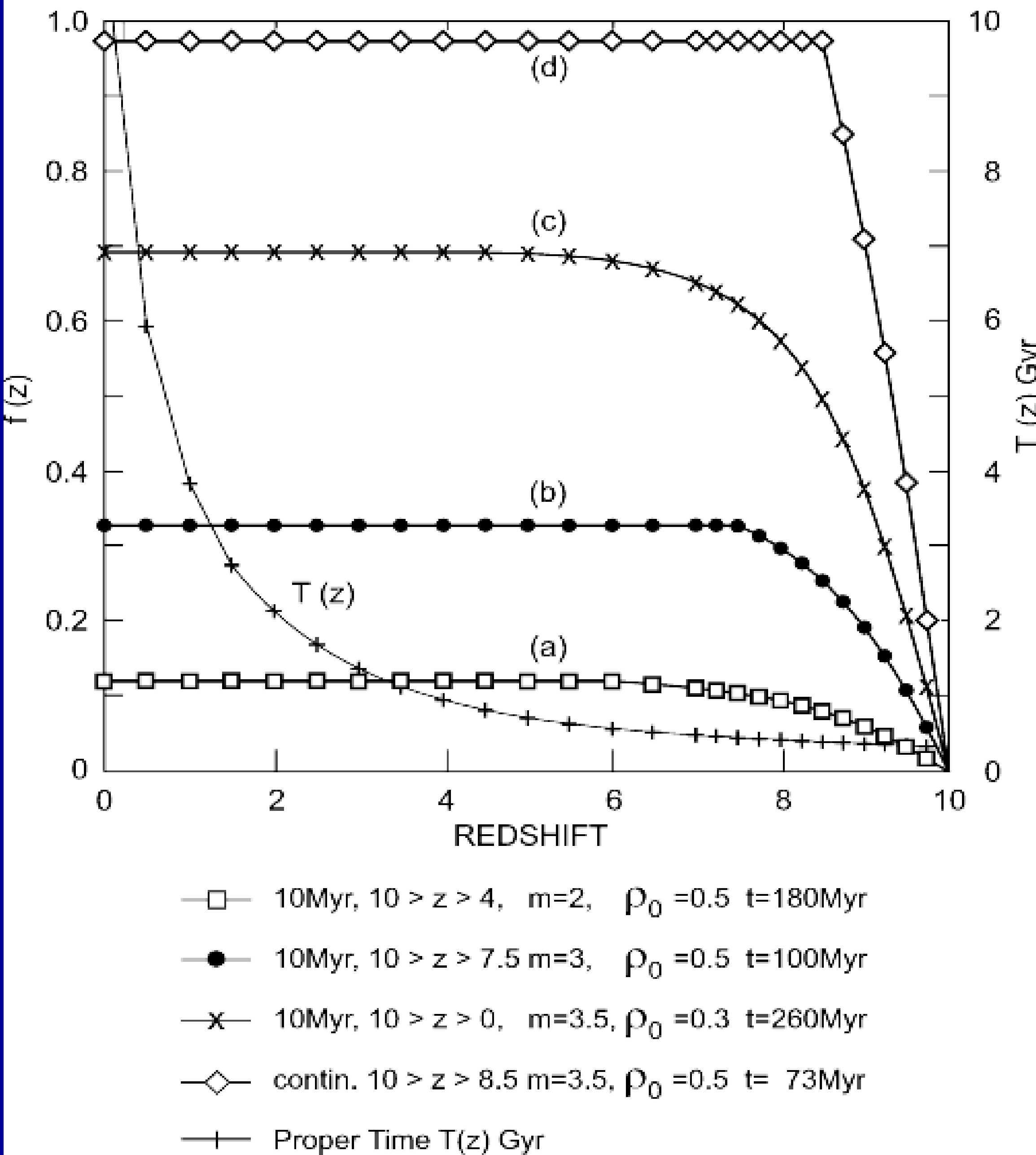
An analytical model for early starburst dwarf galaxy seeding of the IGM with magnetic fields

P.P. Kronberg, H. Lesch, and U. Hopp, ApJ , 511, 56-64, 1999




FILLING OF INTERGALACTIC SPACE BY
EARLY STARBURST GALAXY OUTFLOWS
FRACTION INTERGALACTIC MEDIUM MAGNETIZED
AGE OF THE UNIVERSE (BILLION YEARS)
TIME SINCE THE BEGINNING
(RIGHT HAND SCALE)
Filling
accomplished
by z ≈ 7
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
16
14
12
10
8
6
4
2
0
0
2
4
6
8
10
REDSHIFT (Z)
UNIVERSE SCALE α 1/(1+z)
VOLUME α 1/(1+z)3

I.G.M. MAGNETIC FIELD VOLUME FILLING FACTOR



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

Subsequent B - amplification of early galactic wind fields?

- $B_{i.g.}$ Subsequently amplified in vortices of shearing flows in LSS formation?
- up to ~ 10^{-7}G in LSS filaments?

*D. Ryu, H. Kang, & P. L. Biermann, A&A, **335**, 19, 1998,*
H. Kang, S. Das, D. Ryu, J. Cho, ICRC 2007,
*D. Ryu, Kang, H, Cho, J., Das, S.   Science, **320**, 909 2008:*

H. Kang, S. Das, D. Ryu, J. Cho
ICRC 2007 Proceedings, *and*
Science, 2008

earlier work: Ryu, Kang & Biermann ApJ 1998

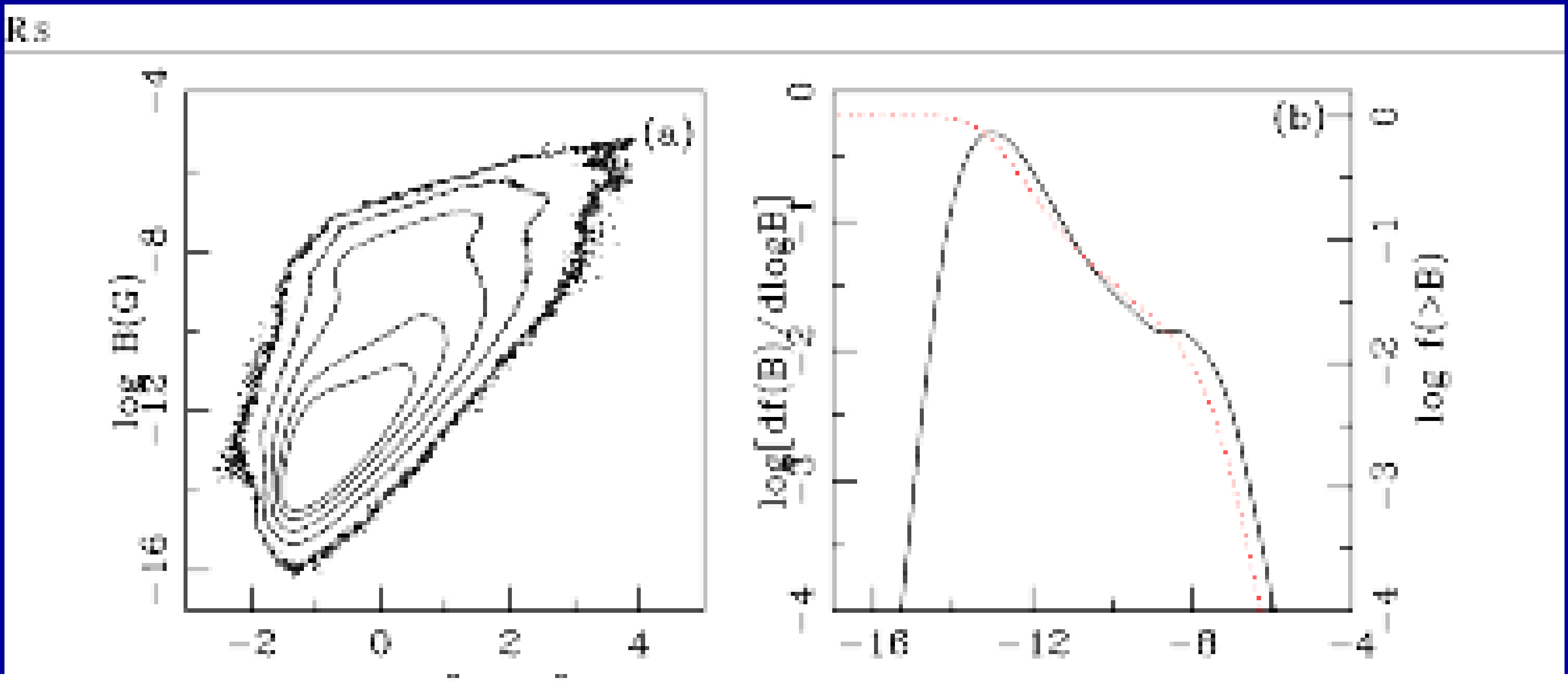


Figure 1: (a) Volume fraction in the gas density-EGMF strength plane with our model EGMF at $z = 0$. (b) Volume fraction, $df/d\log(B)$, (solid line) and its cumulative distribution, $f(> B)$, (dotted) as a function of EGMF strength.

3.

Central galactic black holes as a source of IGM magnetic energy

1. Energetics

2. Global consequences for IGM fields

3. Connections to fundamental plasma processes

IGM magnetic energy supplied by central galactic black holes

Can be globally quantified

A global, observation-based calculation:

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

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

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 .

if no B-dissipation over ~ a Hubble time

Smoothed out SMBH magnetic energy reservoir

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

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

- Initially captured within galaxy filaments

Conclusion:

IGM near galaxies should contain magnetic energy ≈ ε_B

- ***Next:***

Observational tests for ε_B in the IGM

4.

Two recent probes for magnetic fields in local cosmological LSS, *beyond* galaxy clusters

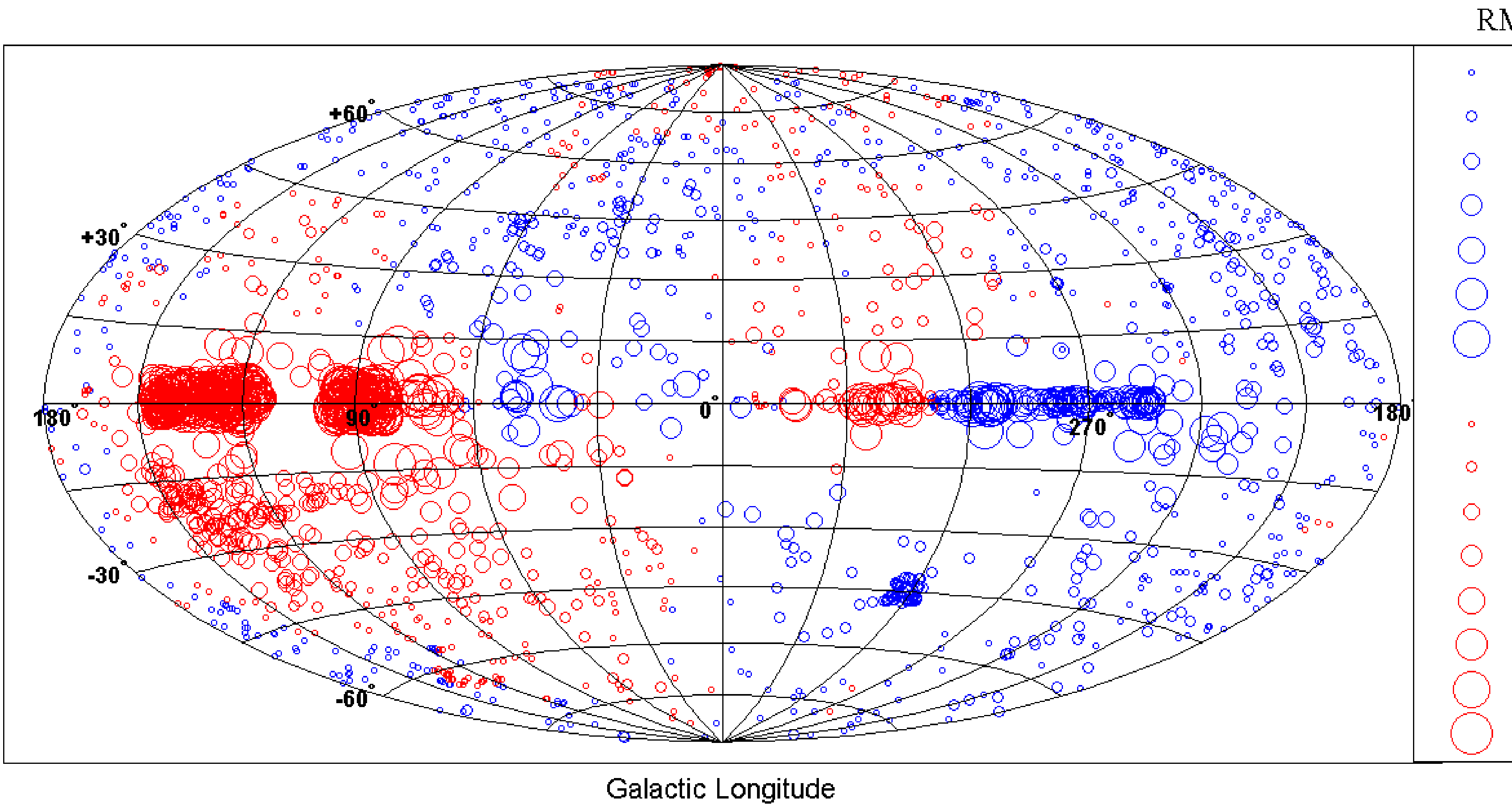
1. First Faraday RM probe for <|*B*|> in local universe LSS filaments of galaxies defined from (1) CfA2 and (2) 2MASS surveys

   Xu, Kronberg, Habib & Dufton ApJ ***637****, 19, 2006*

2. Search for unprecedented, faint, synchrotron radiation combining the 305m Arecibo telescope and the 1000m DRAO interferometer. Capable of ~ 0.1 μG – level B_{IGM} detection.

   Kronberg, Kothes, Salter, Perillat ApJ ***659****, 267, 2007*

New smoothed Galactic RM sky from 2250 egrs RM's

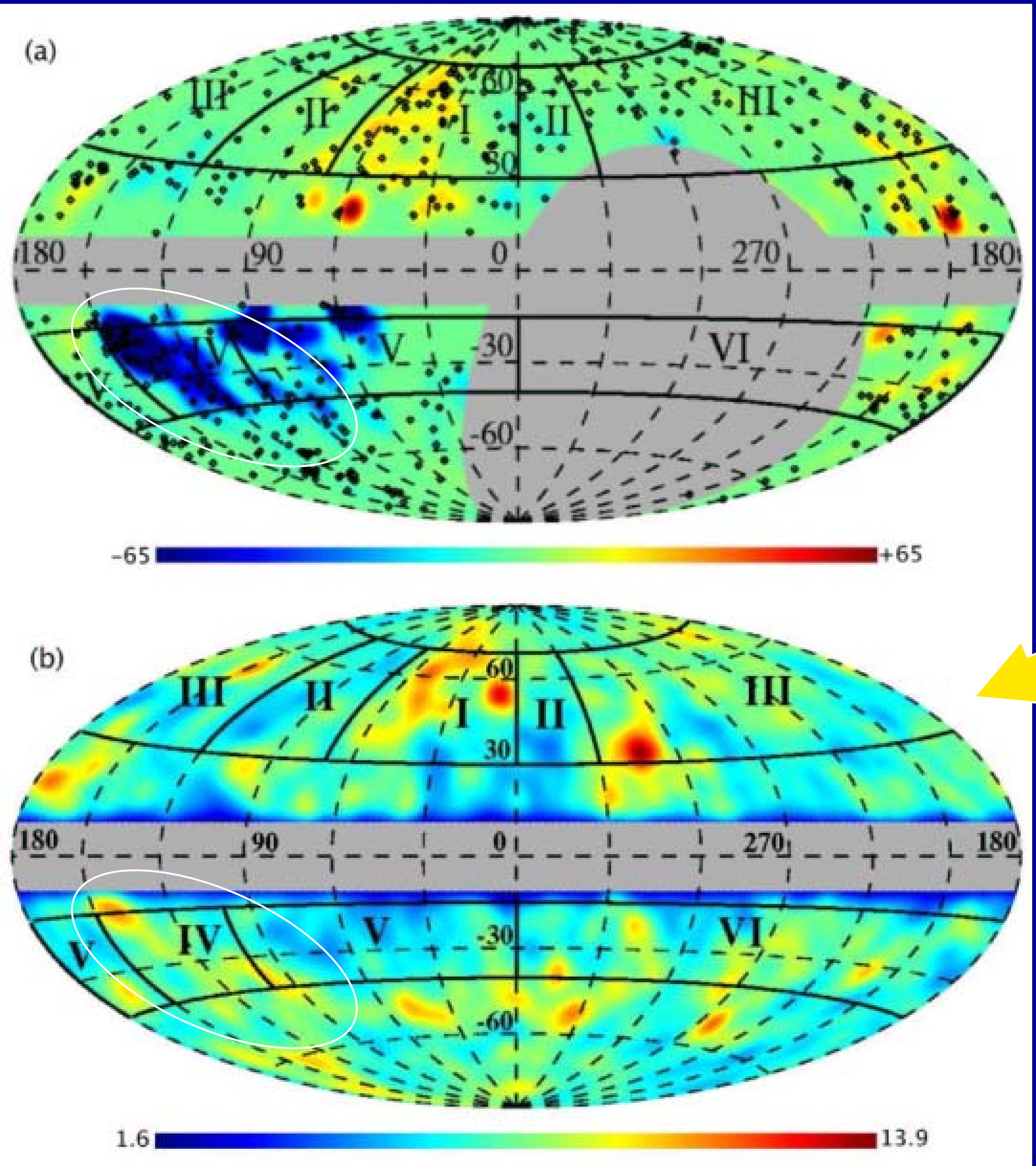


Kronberg & Newton-McGee 2009

Probe No.1

RM search for magnetized plasma beyond clusters

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



SMOOTHED FARADAY ROTATION

= Perseus-Pisces supercluster

rad/m²

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

galaxies per pixel (∝ column density)

Optical galaxy counts vs. RM plots
for the Perseus-Pisces supercluster chain
Two types of investigation

Xu et al. ApJ 2006

(a)

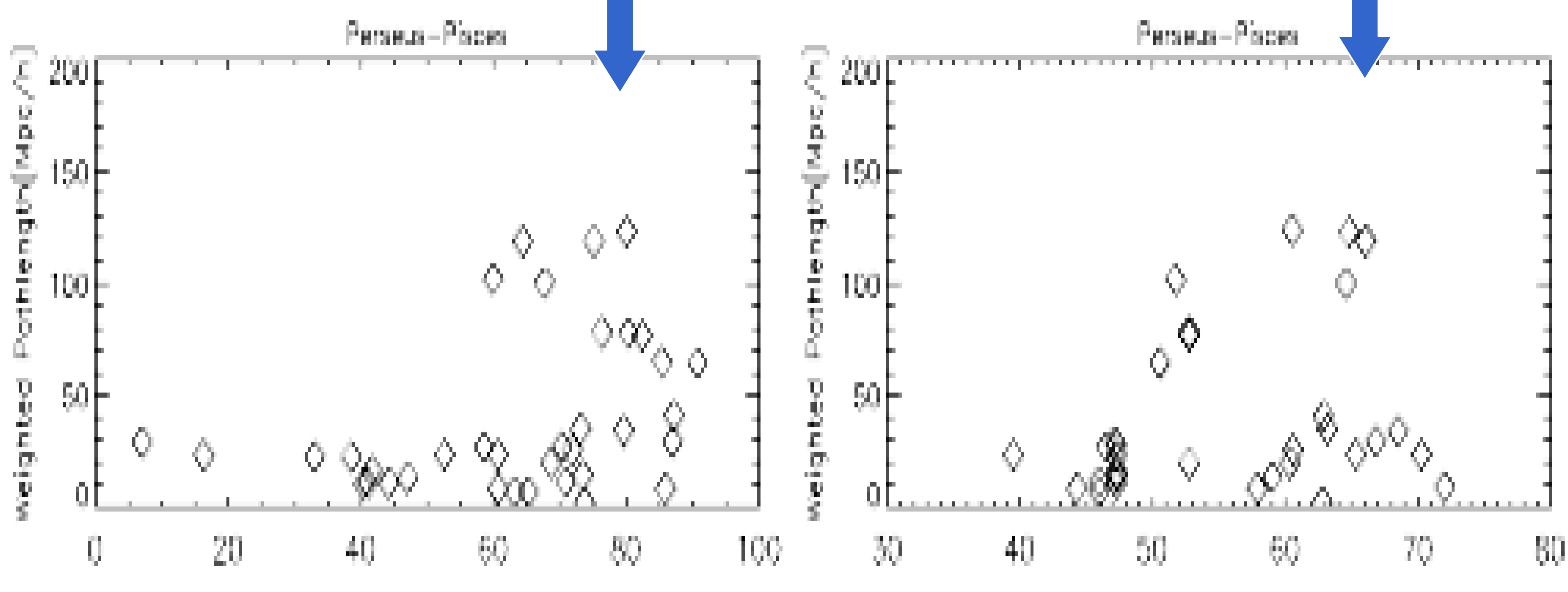
Galaxy column density *vs* RM
from 7°-smoothed data

(used the 2MASS galaxy survey)

(b)

Weighted path length *vs* RM
from 3-D Voronoi-tessilated IGM filament volumes
(∵ 3-D spectroscopic *z*'s are measured).
also from 7°-smoothed data

(Used the CfA2 galaxy survey)



Result *(Xu et al. ApJ* ***637****, 19, 2006)*

- Attempted 3 local superclusters Virgo, Hercules, Perseus-Pisces. **2 independent galaxy survey analyses + RM's**

1. CfA2 survey -spectroscopic *z*'s – 3D
2. 2MASS survey spectral z's – column densities

- Tentative result for B in Perseus-Pisces supercluster filament zones.

  ~ 10^{-7}G using both CfA2 and 2MASS

Probe No. 2

B_{IGM} from diffuse synchrotron radiation detection

A novel combination of :

The Arecibo radio telescope

(*largest single radio reflector*)

with

The DRAO interferometer

(*Wide-angle, precision-imaging interferometer*)

Astrophysical aims of Arecibo-DRAO radio images

- Detect weak magnetic fields in intergalactic space via diffuse synchrotron emission (at < 1GHz)
- Search possible radio foregrounds to the cosmic microwave background (CMB) on the scale of arcminutes (multipole scales, l, up to ~ 3000)
- Test for energy exchange from central black holes of galaxies to the intergalactic medium
- Can we detect a radio counterpart to the "Warm-hot intergalactic medium" (seen in soft X-rays)?
- Explore connections between the radio, and the X- and gamma-ray Universe)

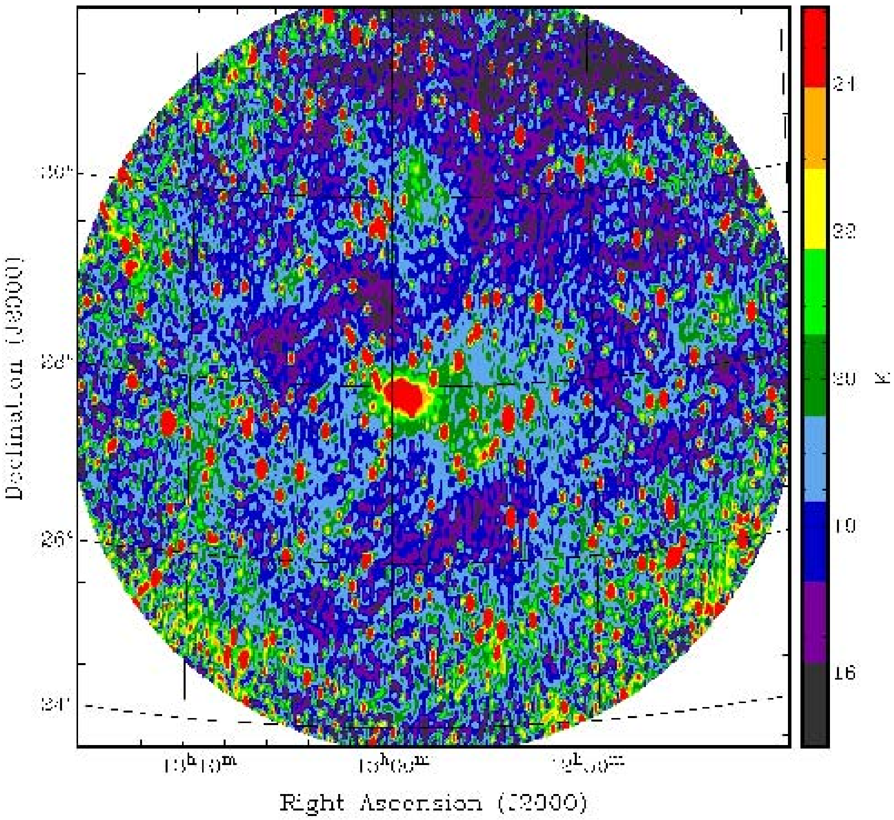

Arecibo 305m Telescope, PR
2 mm rms optics
illuminated area ≈ 200m
uv overlap with DRAO ≈ 200m

Dominion Radio Astrophysical Observatory
Penticton BC, Canada

Max. separation = 617m $\Rightarrow$ 1000m equiv. single dish resolution
Min. projected separation ≈ 18m

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

8° dia. Arecibo + DRAO image, at a resolution of 2.5’ x 6.5’ 0.4 GHz

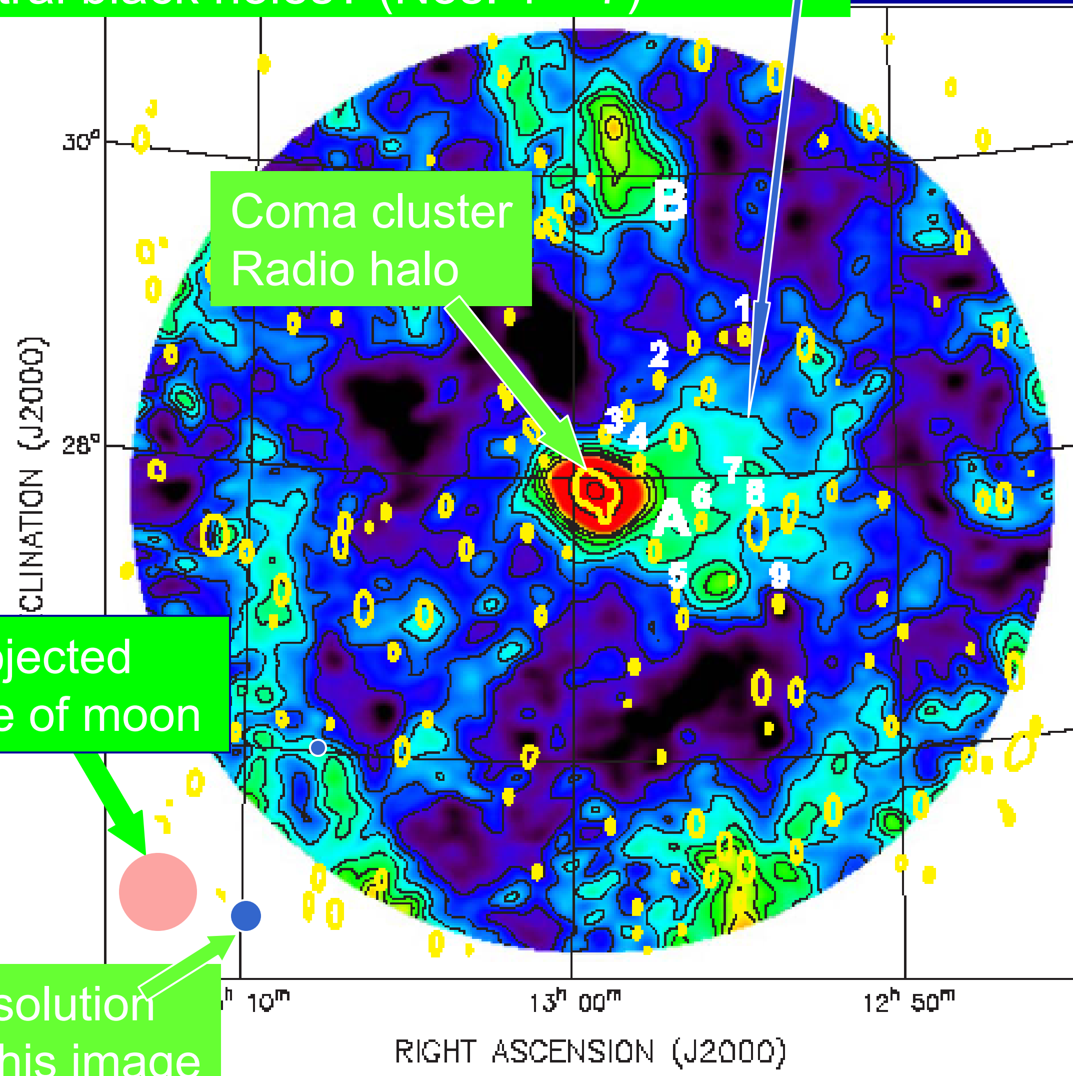


2.7K CMB background and galactic foregrounds (≈ 18K) are included

COMBINED Arecibo-DRAO image, 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.

Summary of signal detection

- In the hole zones, we have reached the absolute discrete source confusion limit.
- “diffuse” emission $\gtrsim$ 400 mK is detected at many locations over the 70 sq deg field

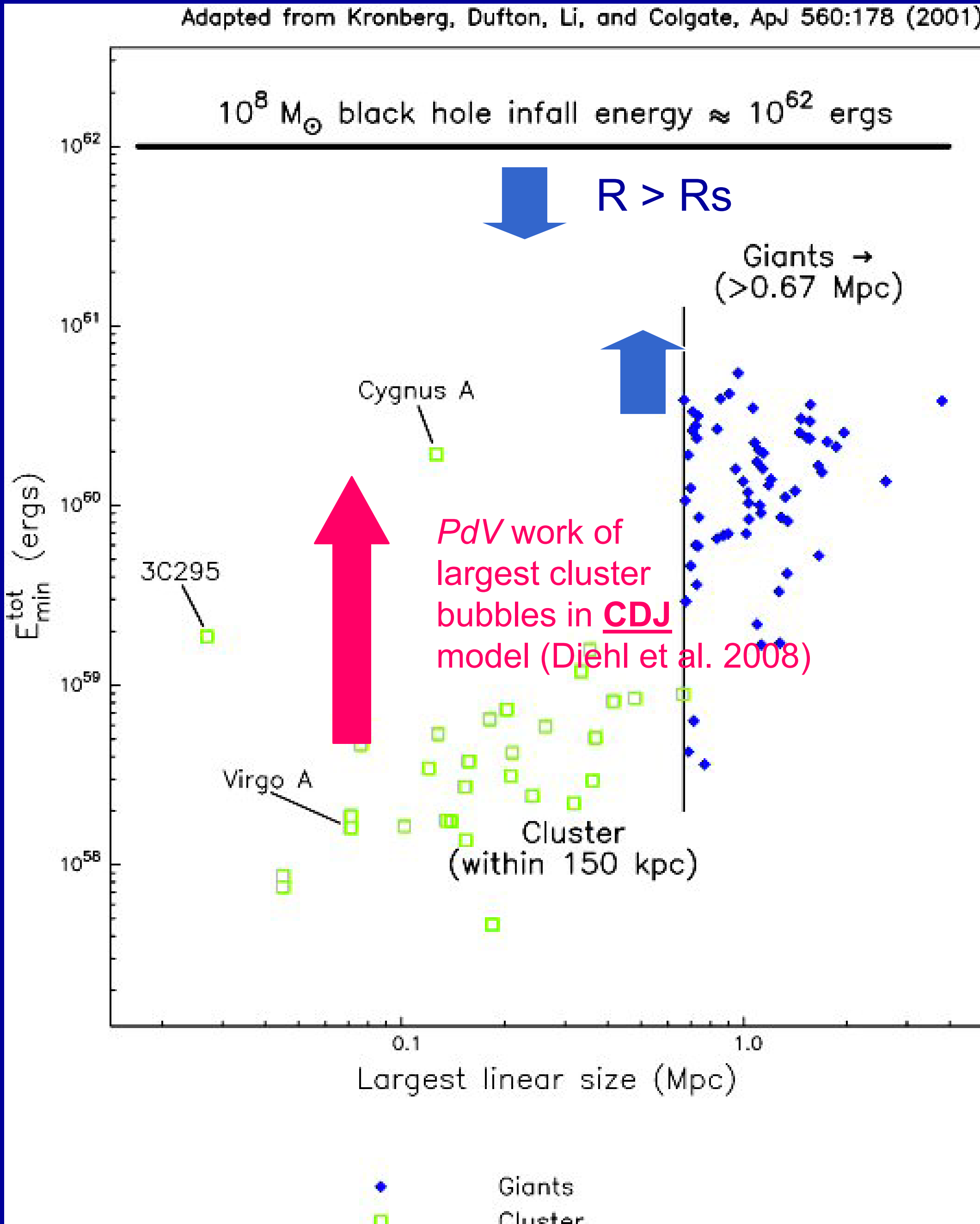
This is composed of:

1. Diffuse intergalactic emission (*e.g*. Regions A and B)
2. Galactic foreground (+ other extragalactic?), previously undetected on arcmin scales
3. Blends of faint discrete sources

5.

Energetics of intergalactic fields deriving from central BH's

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



$=M_{BH}c^2$

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*

Example of a GRG

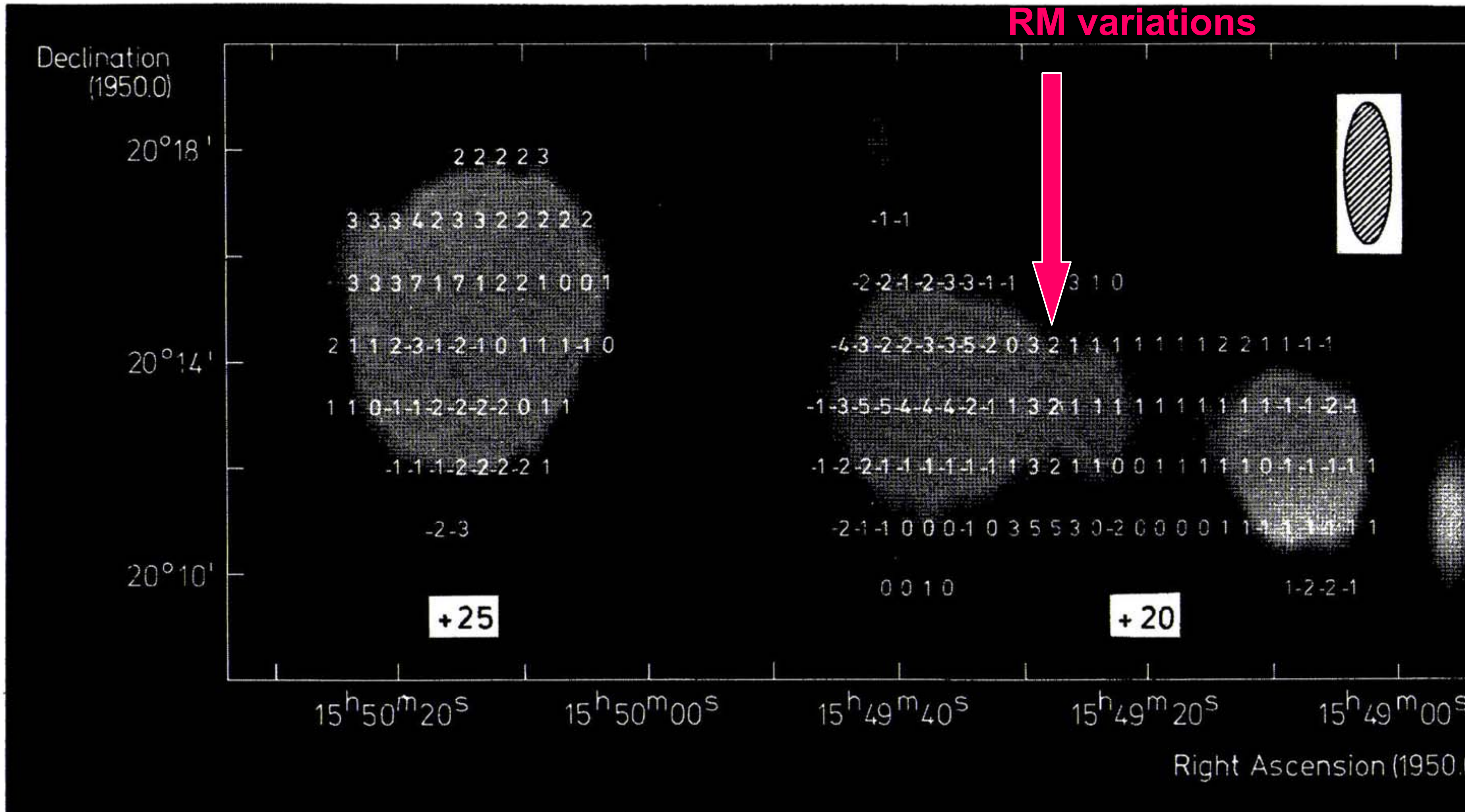
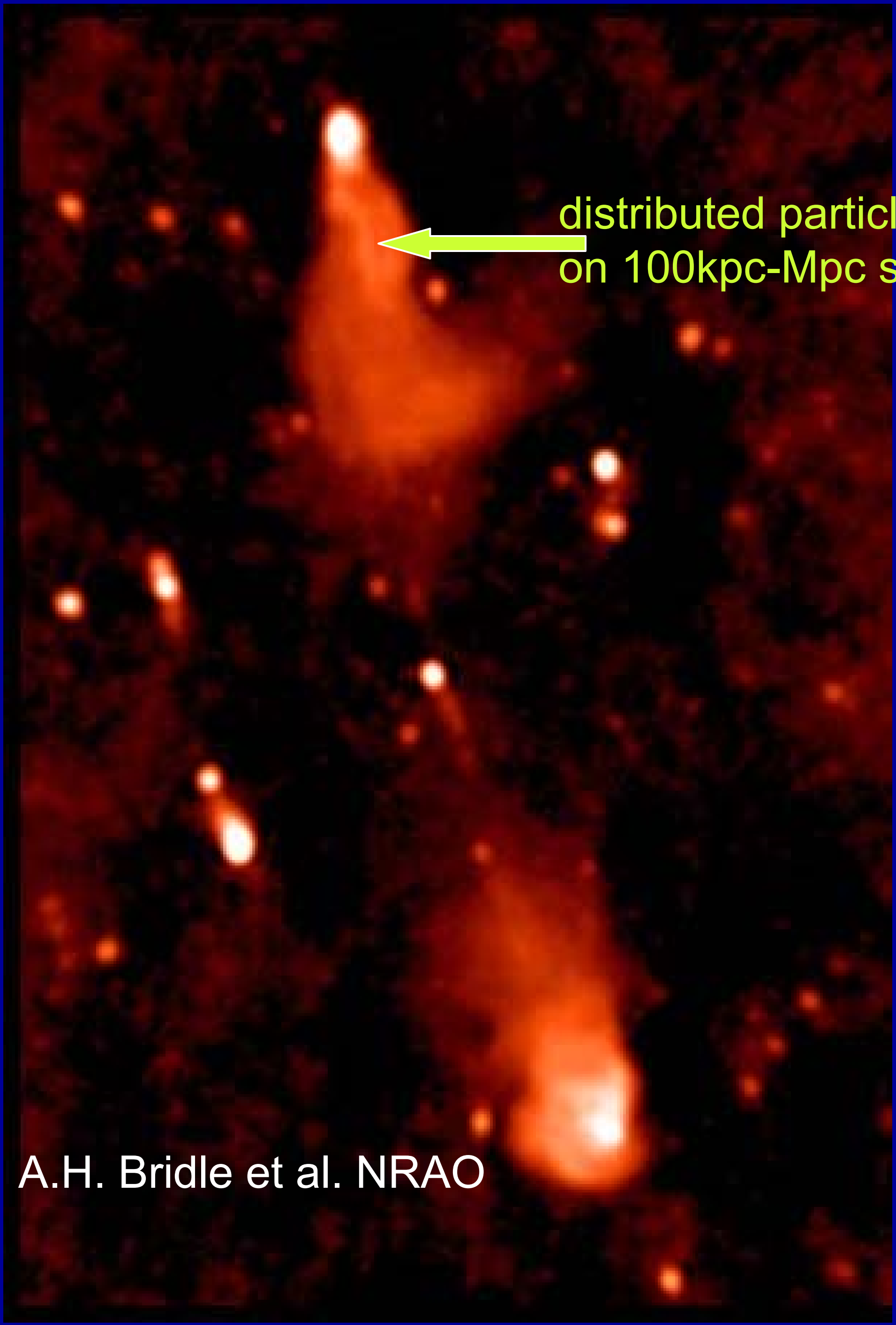
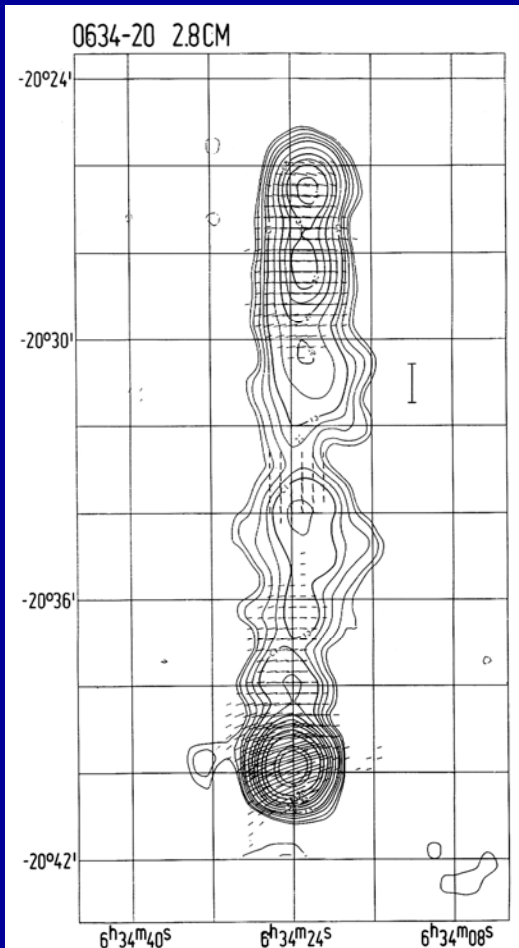


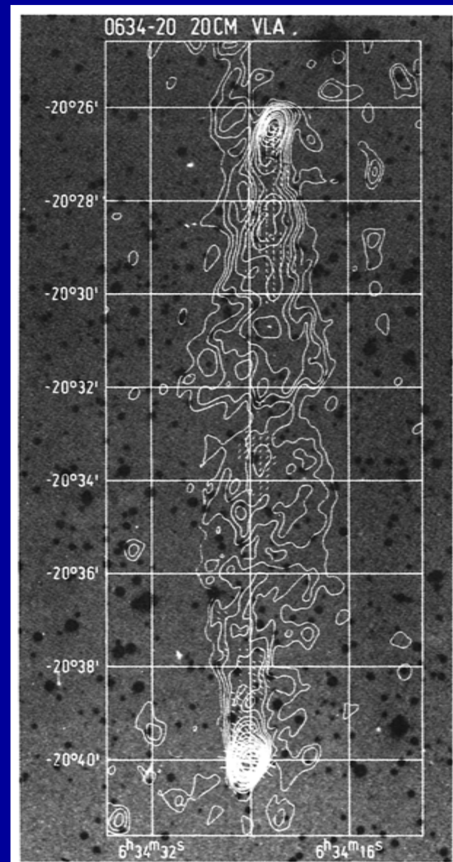
Fig. 8. The distribution of rotation measure over 3C 326 as computed from the 49 cm and 21 cm convolved data superposed upon
photograph" of the 49 cm total intensity. Note that to produce a simple grid of single digit numbers we have subtracted integrated
measures, whose derivation is described in the 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


distributed particle acceleration
on 100kpc-Mpc scales
A.H. Bridle et al. NRAO

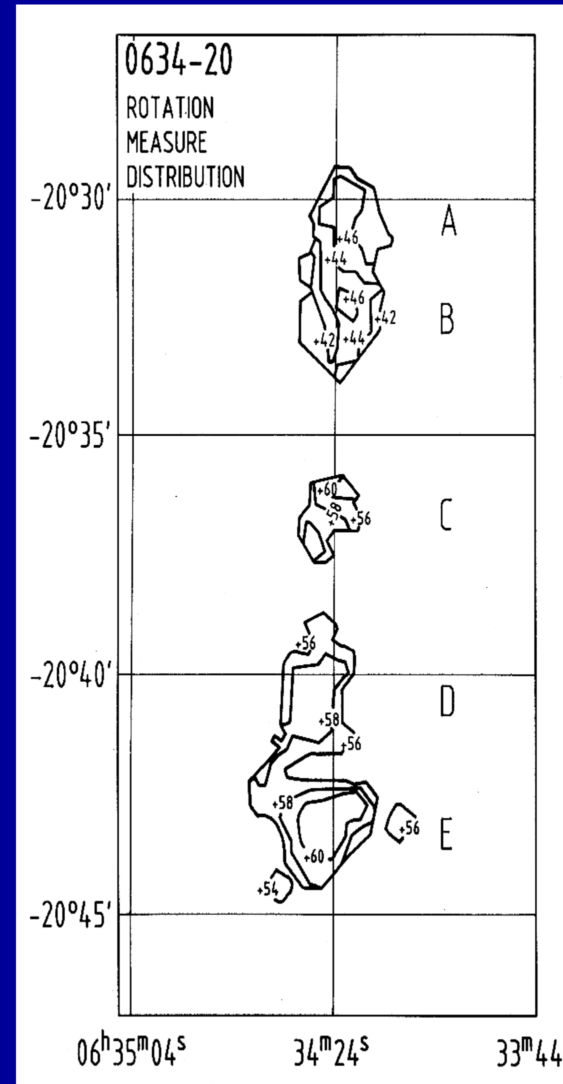
10 GHz



1.4 GHz



Faraday RM(radians/m^2)



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

General properties of BH – fed radio lobes

- Thermal gas density is < that of ambient IGM
- Easy to demonstrate within clusters,
- Appears also true of large radio lobes outside of clusters.
- Nicely demonstrated in WSRT GRG images of Strom & Willis 3C326, 3C236 A&A 1978, 1980, and others since

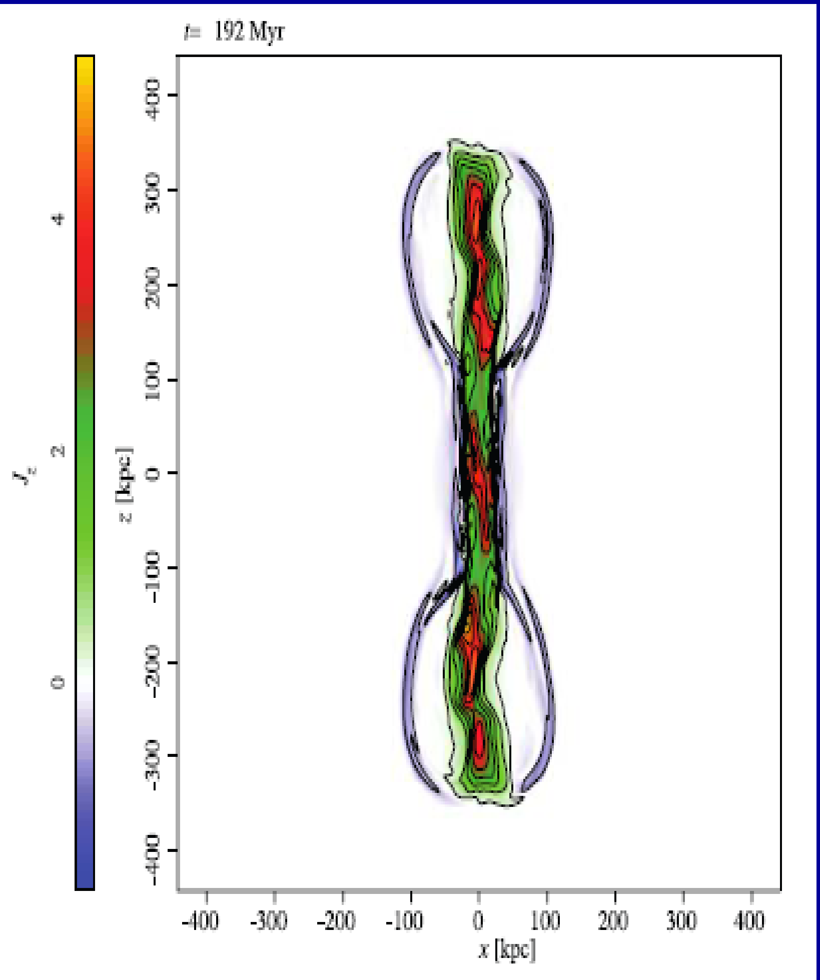
Opportunities for extending GRG observations with LOFAR and GMRT, incl. Faraday RM synthesis, at <u>1GHz $\gtrsim$ f $\gtrsim$ 150 MHz</u>

6. Evidence for dominance of magnetic structures in lobes and jets

- simulation of jet-lobe transition points in clusters
- jet/lobe systems as UHECR acceleration sites?
- cluster environment provide a ``controlled'' probe of lobe physics

Magnetic tower jet/lobe in a cluster environment

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



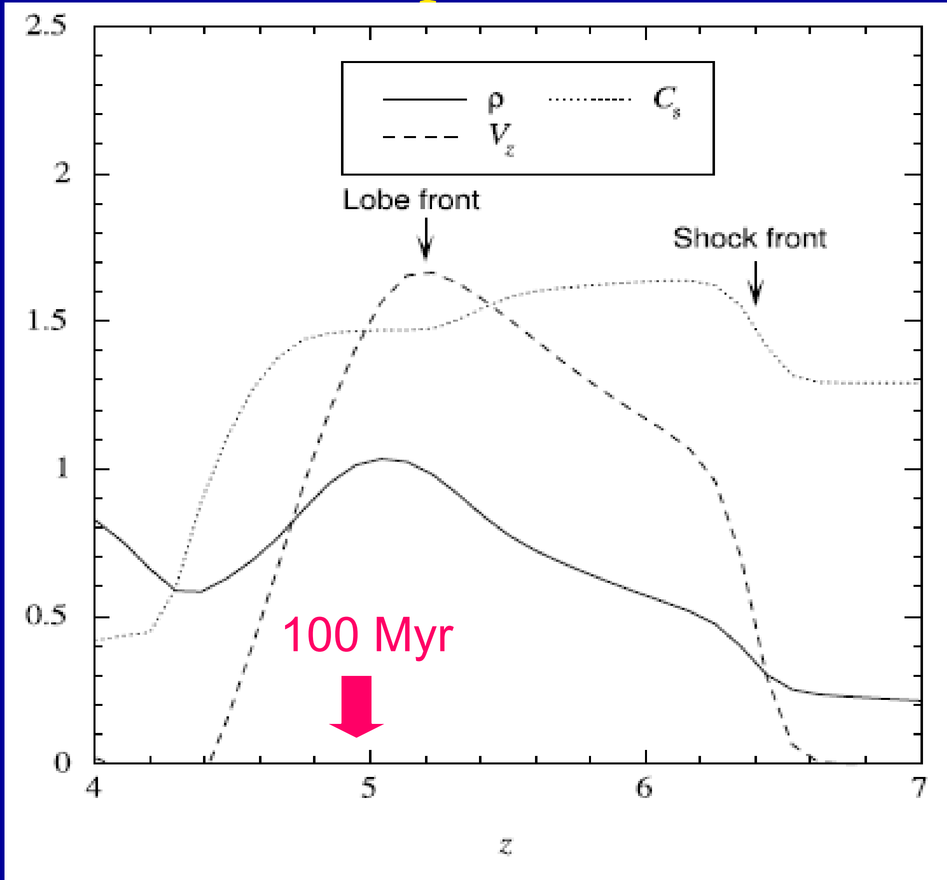


FIG. 2.—Axial profiles of physical quantities along the z-axis at $t = 3.0$ ($t =$ 72 Myr): density ρ, sound speed C_s, and the axial velocity component V_z. The positions of the expanding shock and lobe fronts are shown.

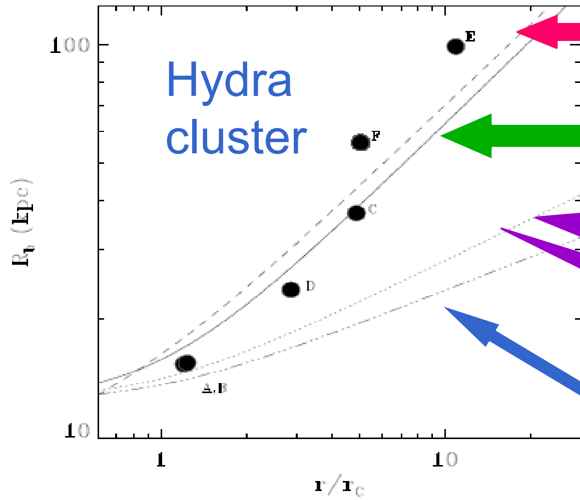
A recent galaxy cluster-environment test for the
for the relative dominance of magnetic BH/jet – energized lobes

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

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

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*



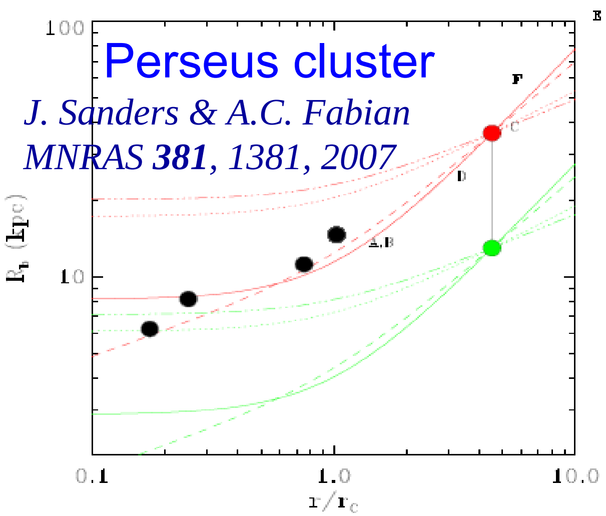
CIH continuous injection hydrodynamic model - - -

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.



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.

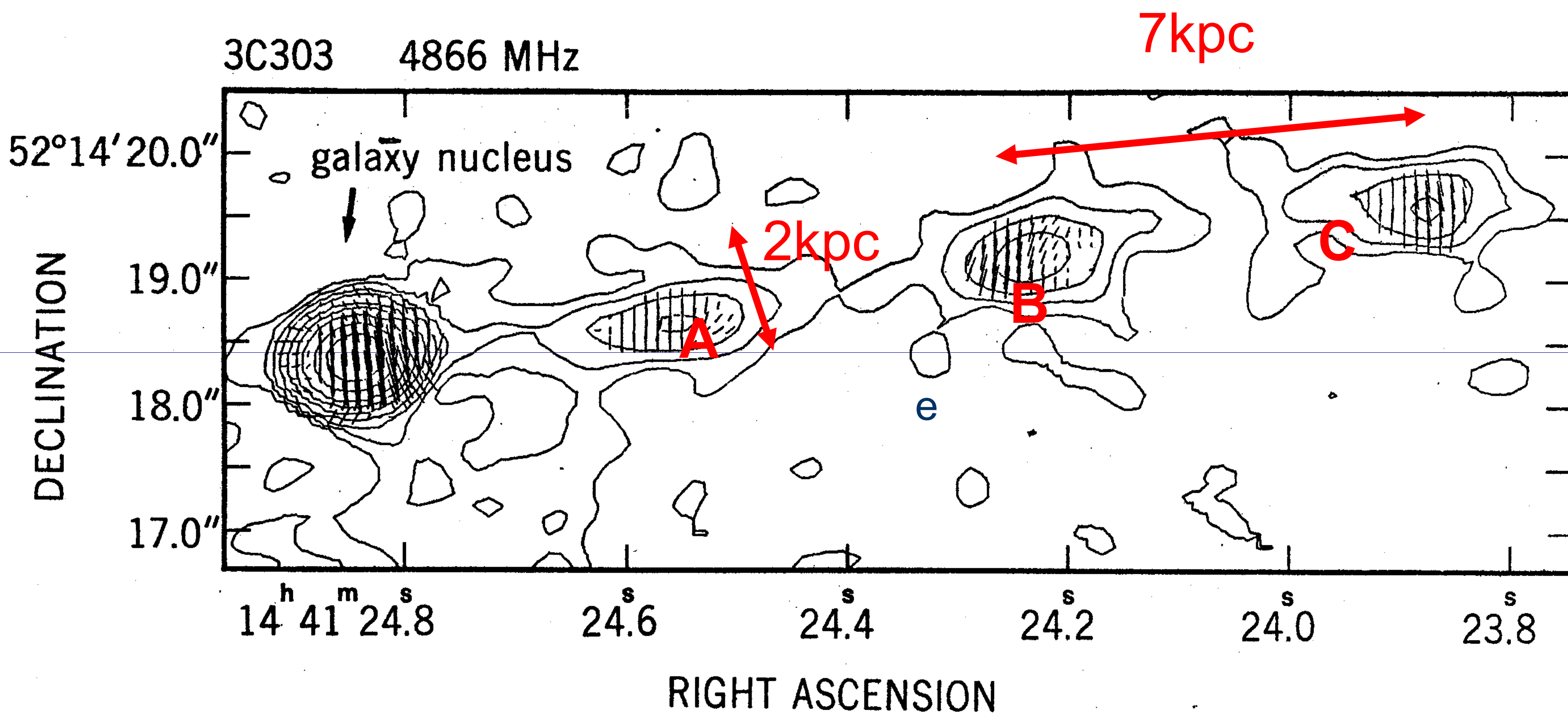
But there are more subtle effects that projection has on our data. As we do not have an automated tool to detect bubbles, one has to rely on human experience in finding and identifying these systems. This task is much more difficult, if the cavities overlap with the bright cluster center or the bubble 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*

7.
kpc jets as potential sites for UHECR acceleration

- The 3C303 jet

Jets as UHECR acccelerators?



$$E = \frac{B}{3\ \text{mG}} \times \frac{L}{1\ \text{kpc}} \Rightarrow 10^{19}\ \text{eV}$$

Plasma Diagnostics of the 3C303 jet

Lapenta & Kronberg ApJ 625, 37-50, 2005

(1) <(Energy flow rate)> $= E^{T}_{min}/\tau$ = **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 ≈10% of energy flow rate along jet!

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

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

→ **n_{th} in knots (*upper limit* for 3C303)** → $n_{th} \leq 1.4\times10^{-5}$ cm^{-3}

(3) & (4) → lower limit to 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***

- For knot "C", the RM image of 3C303 enables a measurement of the transverse ∇RM (radians/m^{-2}/m) over a knot. i.e. ∇RM is perpendicular to jet!

- *B* (RM) reverses sign on the jet axis. |*B*| is estimated from measured synchrotron emissivity ($\gtrsim$ 1mG)
- a galaxy-scale, current-carrying "wire"

- result for 3C303: $I = 7.5 \times 10^{17}$ (B^{G}_{-3}) [r= 0.5kpc] ampères

- *I* is directed AWAY from the galaxy AGN nucleus in this knot

- Intrinsic knot polarization consistent with low-ϕ jet helical field

H. Ji, P.P. Kronberg, S.C. Prager, D. Uzdensky, *Physics of Plasmas* **15**, *058302-8, 2008*

8.

Background RM probes of magnetic fields in galaxy systems to high z ($\lesssim$ 6)

- Striking correlations exist between RM & high column density absorption systems in quasars,-- to large z.

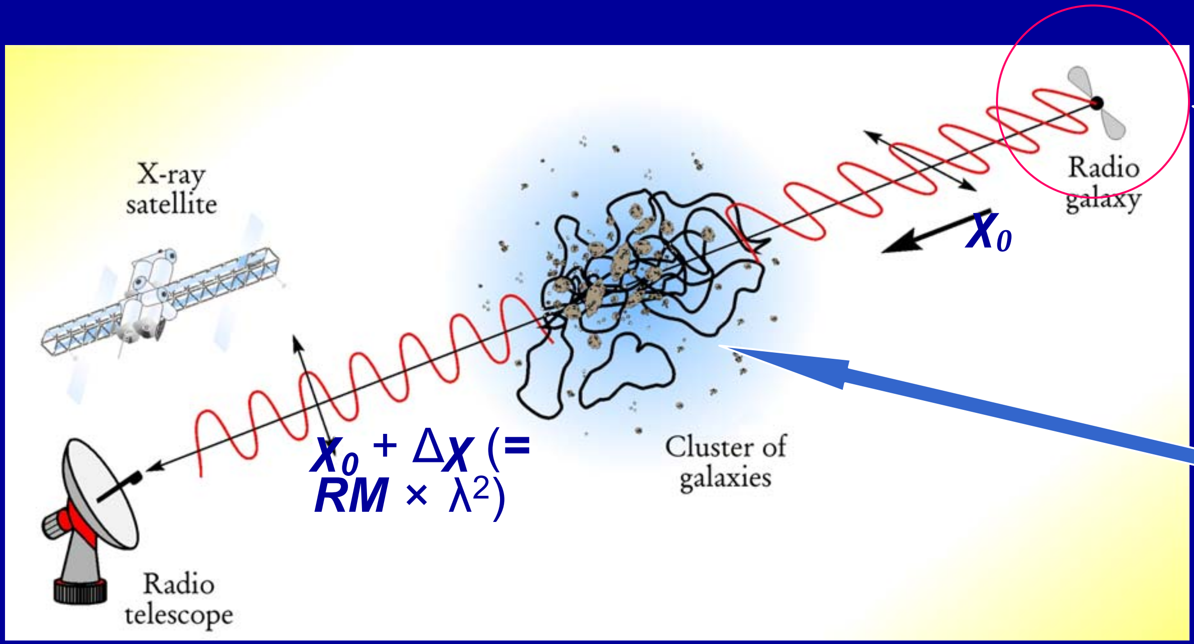
  Spectral resolution must be high enough to estimate W_{eq}. *Need 8+ meter optical telescopes* to explore spectra to large *z*! These now exist!

  Strong magnetic fields have been detected out to z $\gtrsim$ 3.5! Slow (10^9yr) galactic dynamos are not the explanation of |B| amplification in galaxy systems.

- RM due to a widespread, co-expanding B_{igm} ?

  No detections yet with current instruments

Faraday rotation at a distant EGRS, and at an intervenor



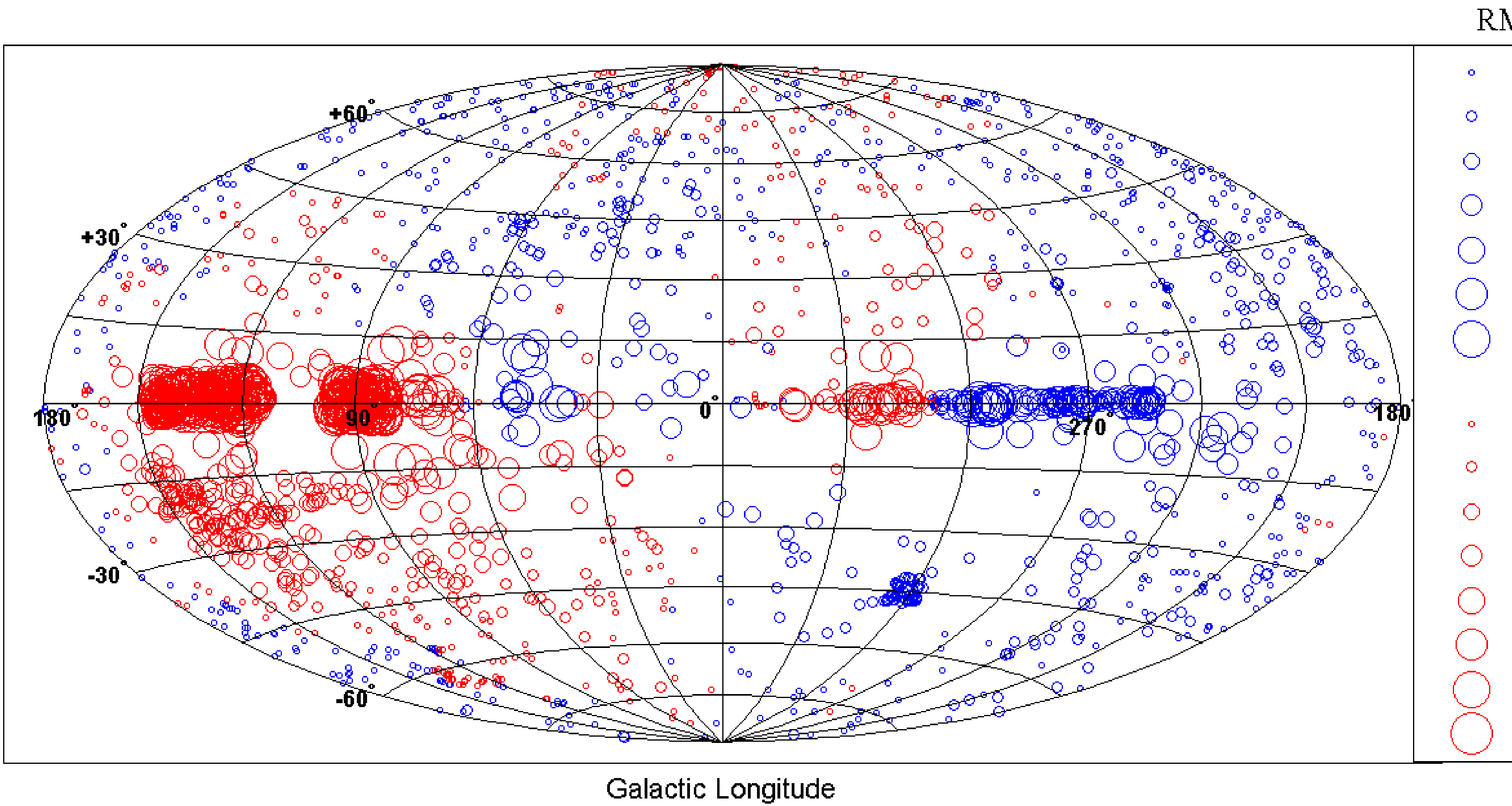
<u>host</u> galaxy system at z_e

<u>intervening</u> 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

New smoothed Galactic RM sky from 2250 egrs RM's

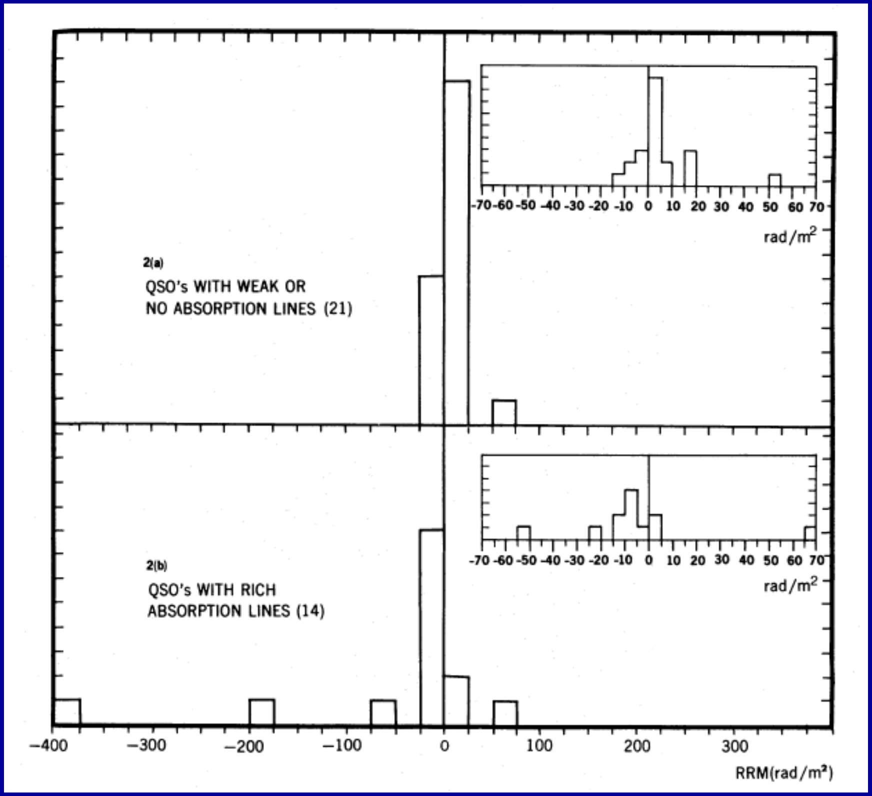


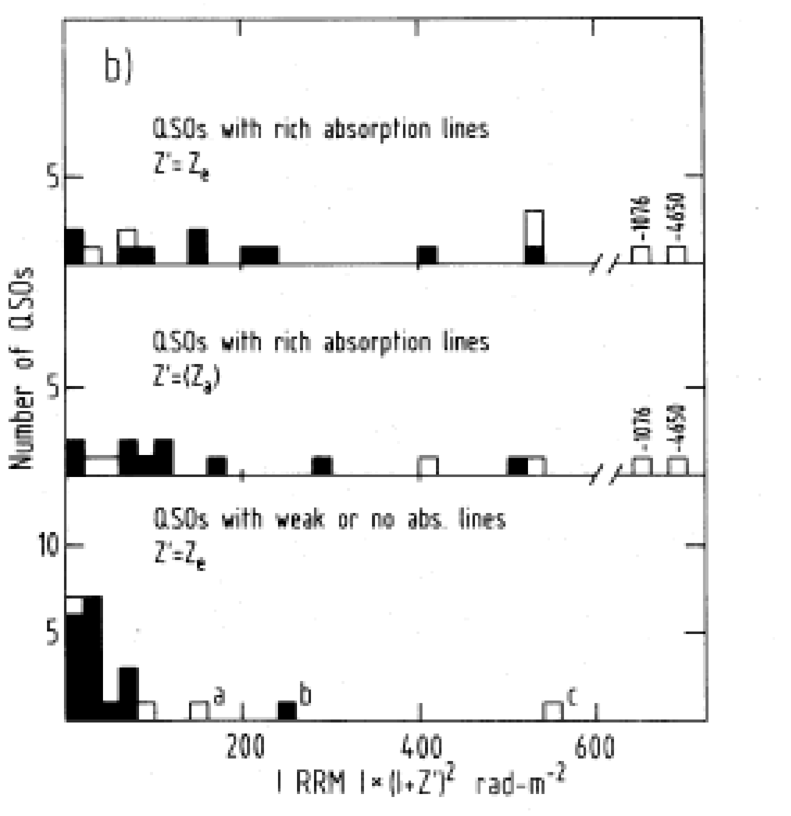
Kronberg & Newton-McGee ArXiv 0909.4753 2009

Detections of magnetized optical absorption line systems

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

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





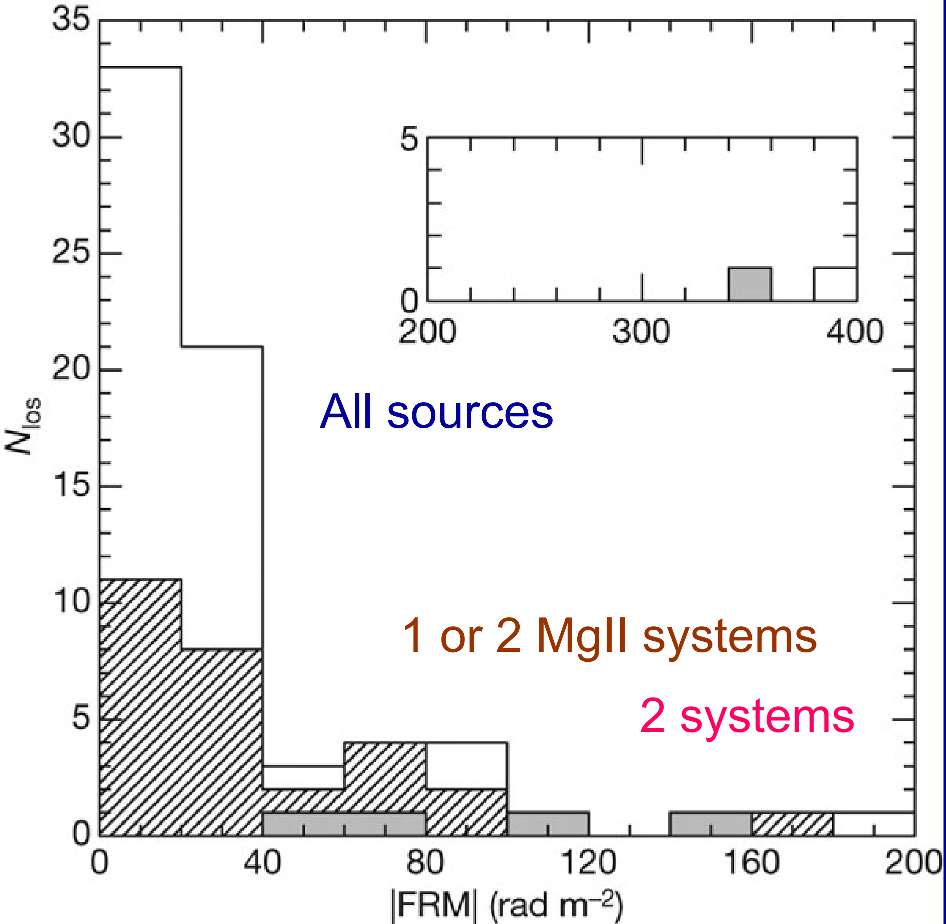
Effect of MgII absorption ($\lambda\lambda$2796.35, 2803.53 Å) on the RM's of quasars

$2.0 \geq z \geq 0.6$ $m_V < 19$, and $|b| > 30°$

M.L. Bernet, F. Miniati, S.J. Lilly, P.P. Kronberg, M. Dessauges-Zavadsky

*Nature **454**, 302-4, 2008 Jul18*

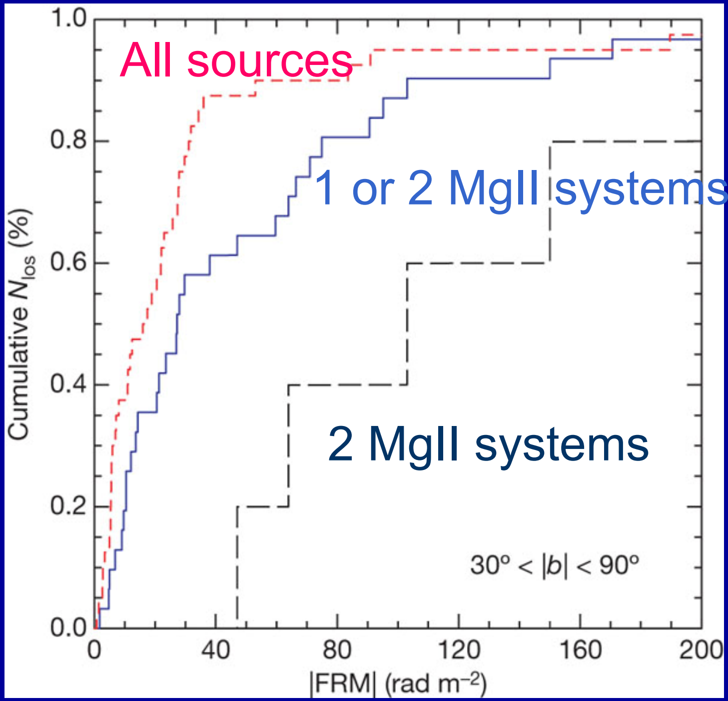
From new VLT observations in 2006-7.
UVES spectrograph



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*



9.
2-D magnetic probes of intervenors at high z

- High-z jets make promising probes of intervening galaxy systems.
- 2 systems described below

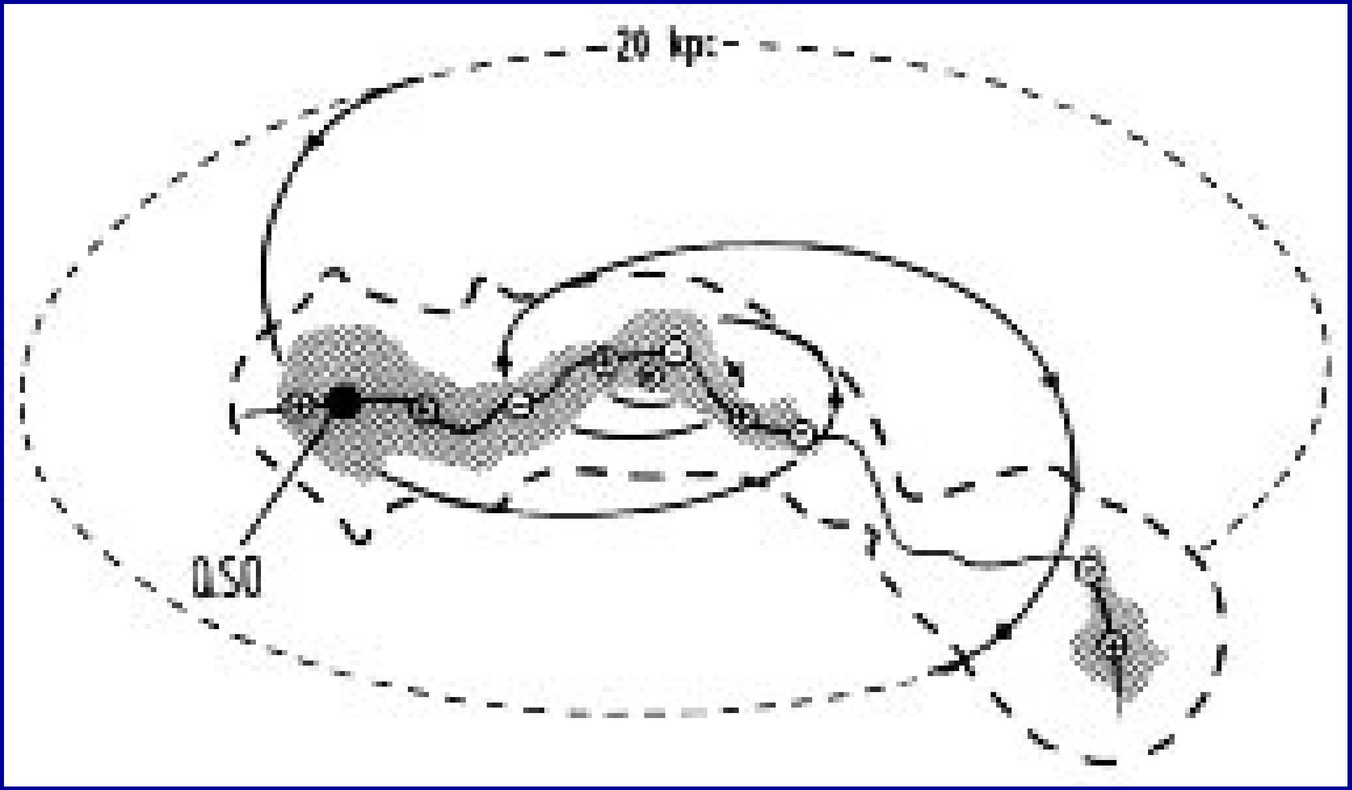
(1) – an intervening spiral-like galaxy (z = 0.38) in front of a z = 1 quasar jet

(2) -- an ``associated'' absorbing gas cloud at $z_{abs} \approx z_{emission}$ for 3C191 (z ~ 1.9)

- **Future: 3-D** using RM synthesis techniques

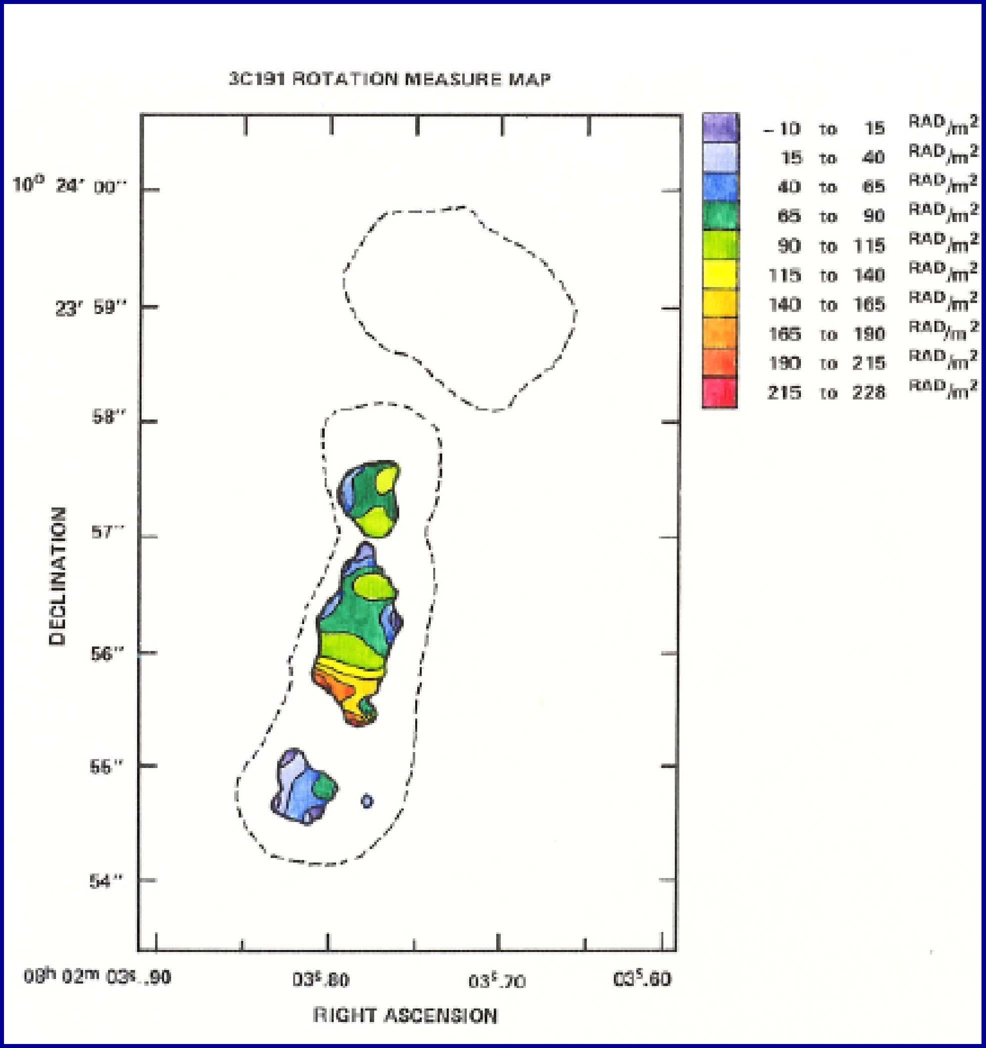
PKS 1229-021 a jet quasar at z = 1.03 behind a spiral galaxy at z = 0.4

Kronberg, Perry & Zukowski ApJ ***387****, 528-535, 1992*



3C191 a quasar jet (z = 1.95) with an ``associated'' intervenor with rich absorption lines

P.P Kronberg,
J.J.Perry &
E.L.H. Zukowski
*ApJL **355**, L31, 1990*



RM measured

between

5GHz and 15 GHz

Principle conclusion from both analyses of (1) all sources, and (2) MgII absorbers

- Magnetic field strengths in galaxy <u>systems</u> ($N_e \gtrsim 10^{20}$ cm^{-2}) up to $\gtrsim$ 80% of a Hubble time ago are at least comparable to those at $z = 0$.
- *i.e*. confirms lack of evidence for a slow galactic dynamo field amplification over cosmic time

10.

Can we detect $|B| \neq 0$ before the epoch of recombination?

Currently, few possibilities to detect B at $\tau < \tau_{RECOMB}$.

Best(?) one: look for a Faraday RM signal in the polarized CMB over the a appropriate range of multipole scales (*l*). ***(Kosowsky & Loeb ApJ 469, 1 1996)***

$RM = \Delta\chi/(\Delta\lambda)^2$ (radians/m^2) $= k\int neB_{//}dl$

- *$\Delta\chi$ must be a detectable angle rotation*

- *Longest λ in $\Delta\lambda$ range must be short enough to be free of all polarized foregrounds at $z \lesssim 1000$*

- *Need to evolve n_e profile as scattering τ increases through the recombination redshift.*

  *(W. Hu, D. Scott, N. Sugiyama & M. White, Phys Rev. D **52**, 5498, 1995)*

Illustrative result

$$\langle \Delta\chi_{\nu_1,\nu_2}{}^2 \rangle^{1/2} = 1.1^\circ \left(1 - \frac{\nu_1{}^2}{\nu_2{}^2}\right)\left(\frac{B_0}{10^{-9}G}\right)\left(\frac{30GHz}{\nu_1}\right)$$

Kosowsky & Loeb ApJ 469, 1 1996

i.e. 1.1º rotation at 30 GHz (λ 1cm) ⇒ RM 195 rad m^{-2} at z = 0

ν must be *<u>high</u> enough to be beyond* all foreground polarized rad'n
(e.g. synchrotron, polarized dust, etc. at any $z \lesssim$ 1000)

ν must be *<u>low</u> enough* to detect rotation

ν_1~ 30 GHz is ~ the only possible window, and even there $\Delta\chi$ *is* only ~ 1º

A direct, but difficult measurement. May be possible in future

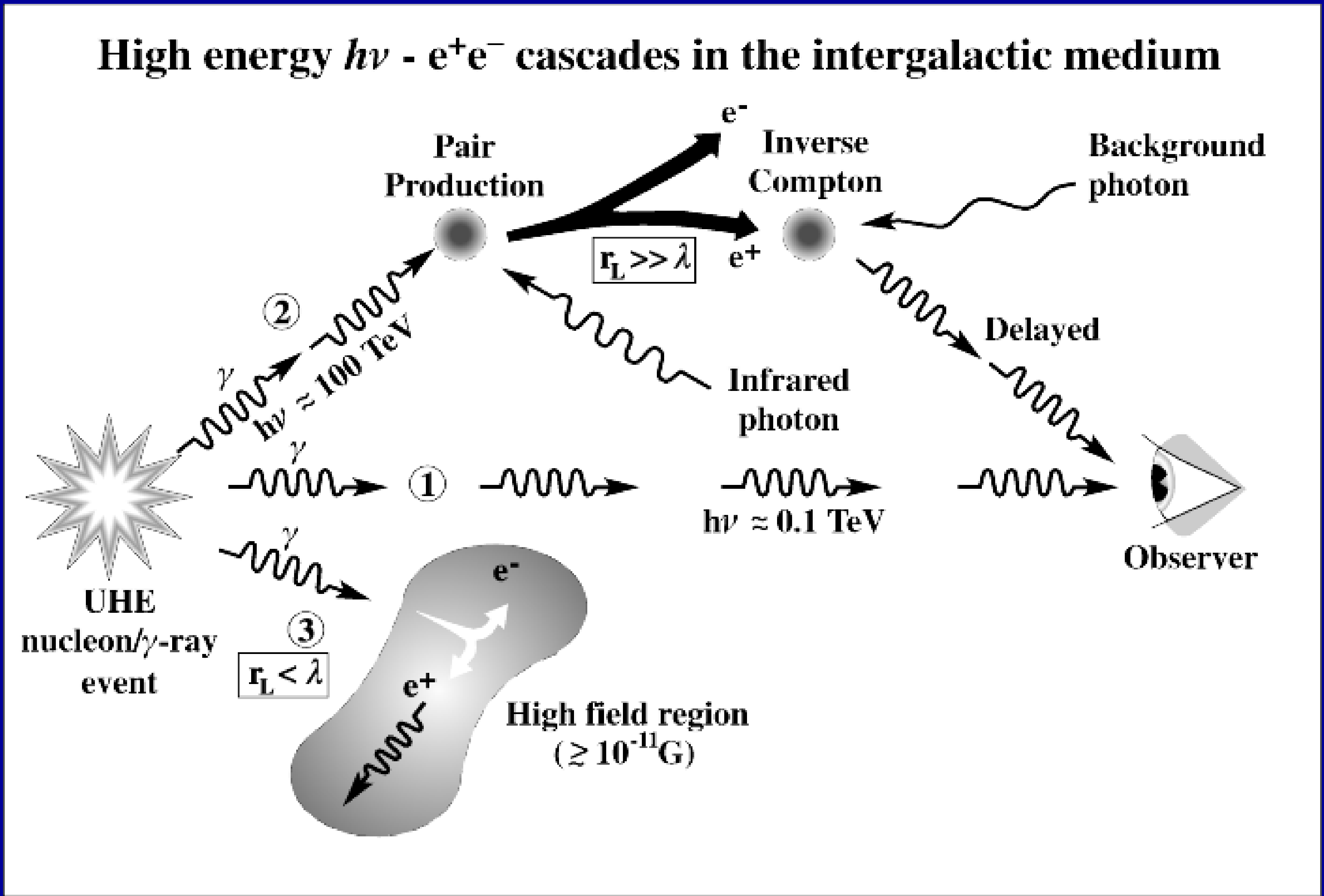
11.
How to detect Magnetic fields in cosmic voids?

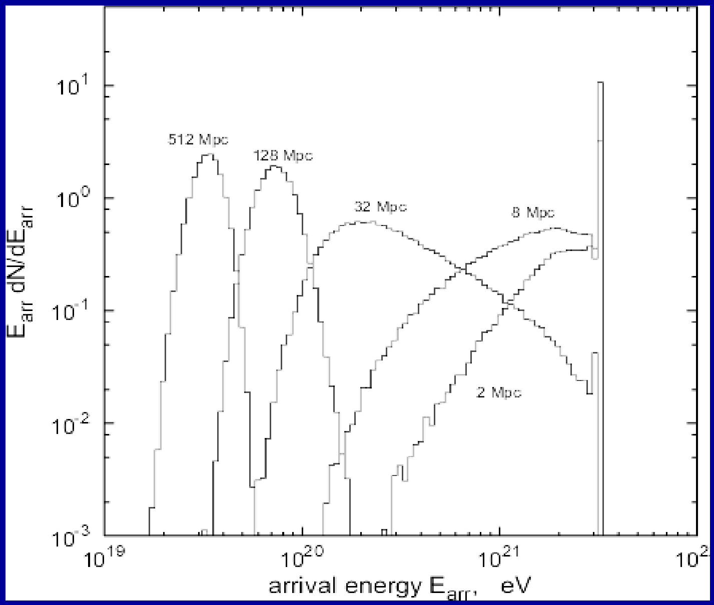
- Diffusion out of the walls and filaments?
- Relic of a pre-galactic field?

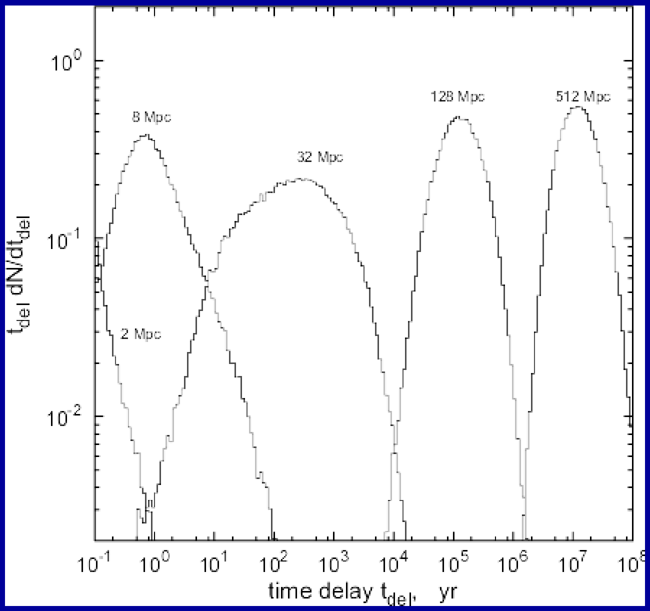
(these two need to be independently verified)

- Propagation of both high energy particles & photons
- Time of arrival, deflection, energy and composition

Energy dependent cascade of a broadband γ-ray burst might probe a very weak IGM field







Stanev T., Engel, R., Mücke, A., Protheroe, R. J., Rachen, J. Phys Rev. D, 62, 0930052000

(**left**)

The <u>received CR energy distribution</u> on Earth for a monoenergetically injected proton energy of $10^{21.5}$ eV for a randomly orientated B_{IG} = 10^{-9} G at progessively larger distances, up to 512 Mpc. The energy is reduced by the GZK effect (most severe), B-H pair production losses, and adiabatic losses.

(**right**)

The <u>relative time delay for protons</u> injected at the same distance, when propagated through a randomly oriented magnetic field of 10^{-9} G, where l_0 = 1Mpc.

Limitations in current observational diagnostics = opportunities!

- Need better resolution and frequency coverage for AGN jet and lobe RM images – for synergy w. simulations
- Deeper X-ray observations of jets ($\lesssim$ 1” res.)
- X-ray and EUV observations in the IGM
- γ- ray obervations
- Milky Way foregrounds in more deep synchrotron surveys
- More discrete source Faraday rotation observations needed

End

P.P. Kronberg