What the largest radio galaxies are telling us, and why it may have important astrophysical consequences

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LANL Plasma Physics Summer School

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WHY GIANT RADIO GALAXIES ARE INTERESTING MAGNETO-PLASMA LABORATORIES

Faraday Rotation
(RM)

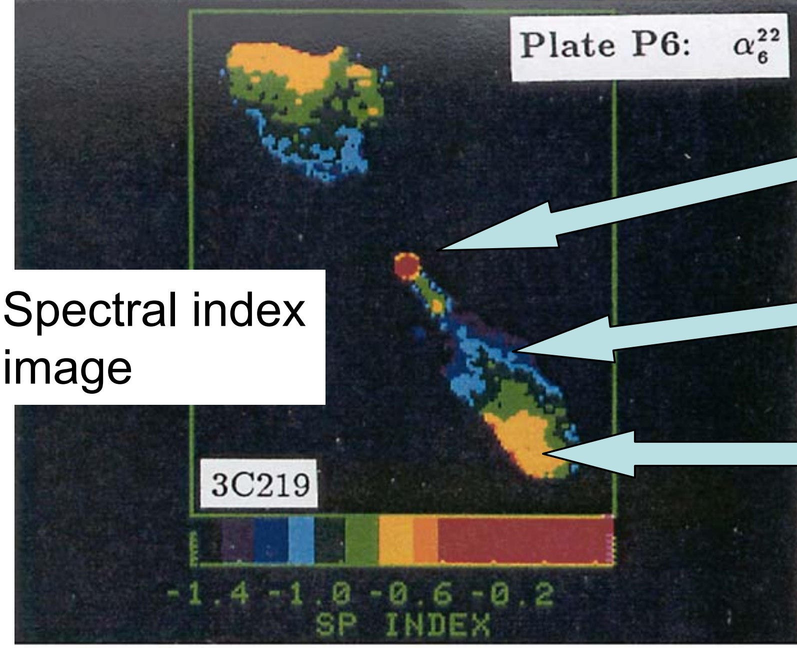
$$\frac{\Delta\chi}{\Delta\lambda^2} = 8.1\times10^5 \bullet \frac{n_{th}}{cm^{-3}} \bullet \frac{B}{\mu G} \bullet \frac{L}{Mpc}\ radians/m^2$$

Lowest measurable RM ≈ 1 radian/m^2

Galactic foreground RM ≈ 3 – 500 radians/m^2

RM meas't within a source limited by:

- ***variable ionospheric RM***
- ***galactic "foreground" removal***
- ***magneto-ionic environment of source***

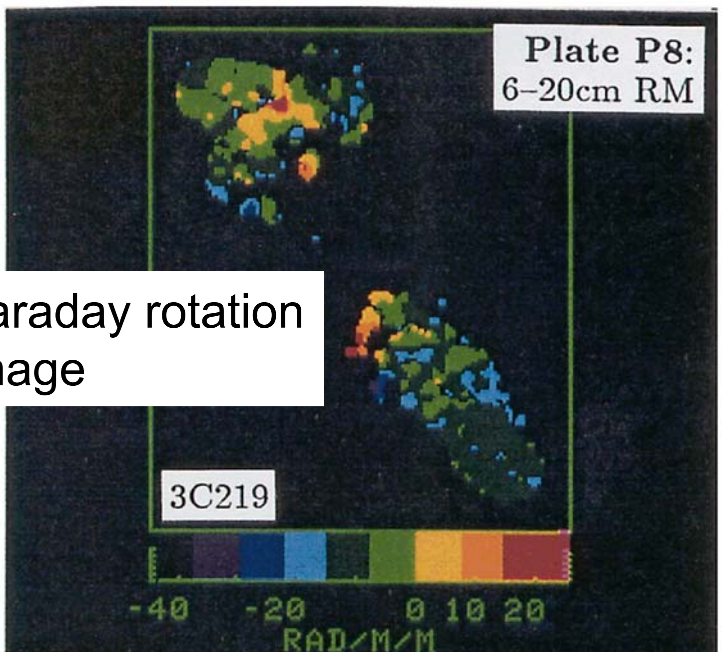


Spectral index image

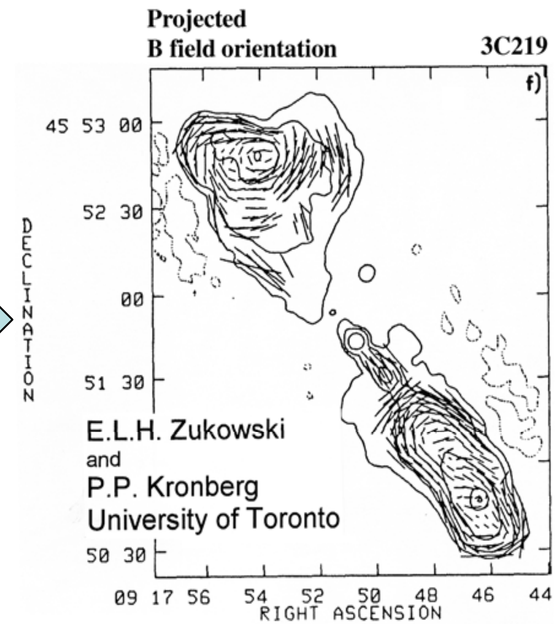
Galaxy nucleus (black hole)

Zone of “older” radiating electrons (steeper radio spectrum)

Zone of fresher acceleration (flatter synchrotron radio spectrum)



Faraday rotation image



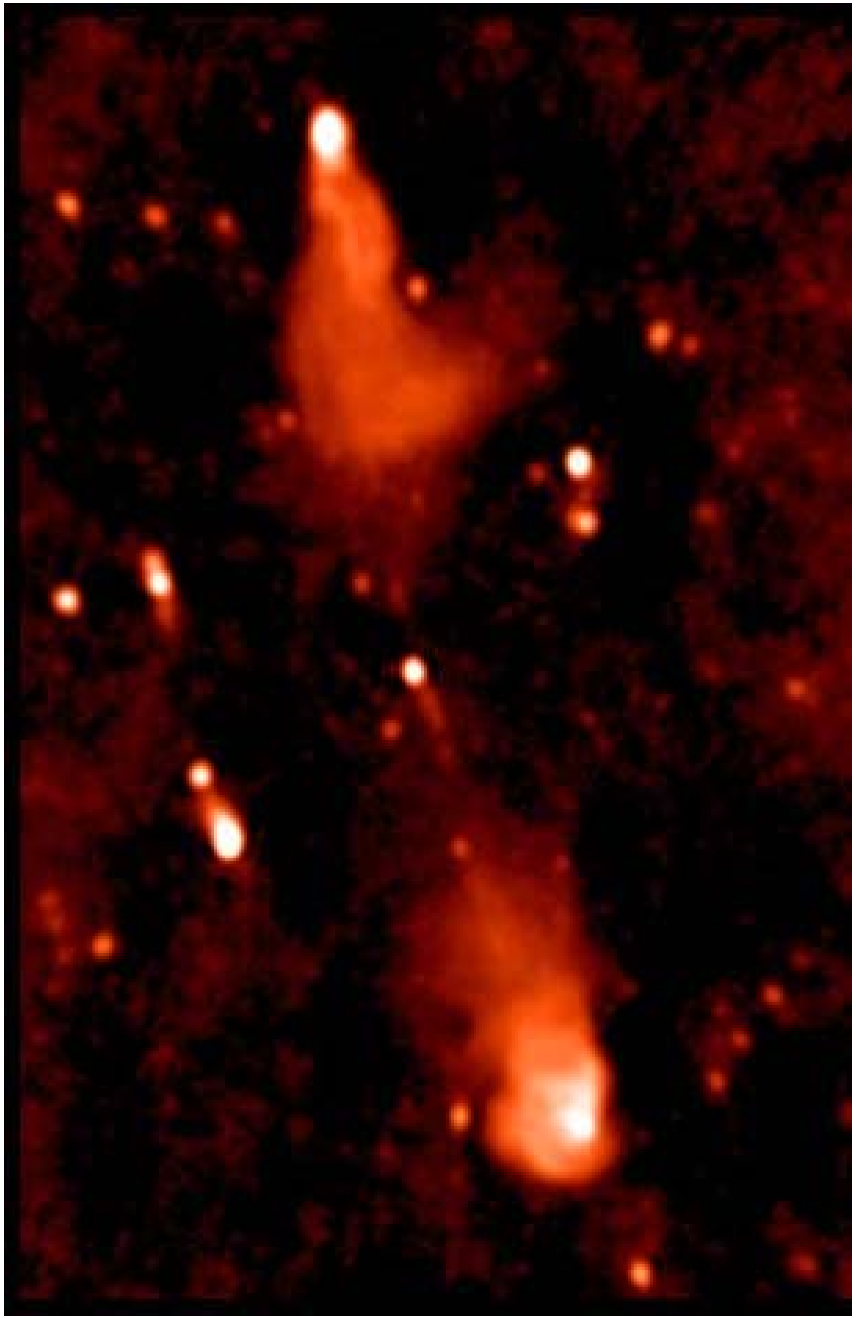
E.L.H. Zukowski and P.P. Kronberg
University of Toronto

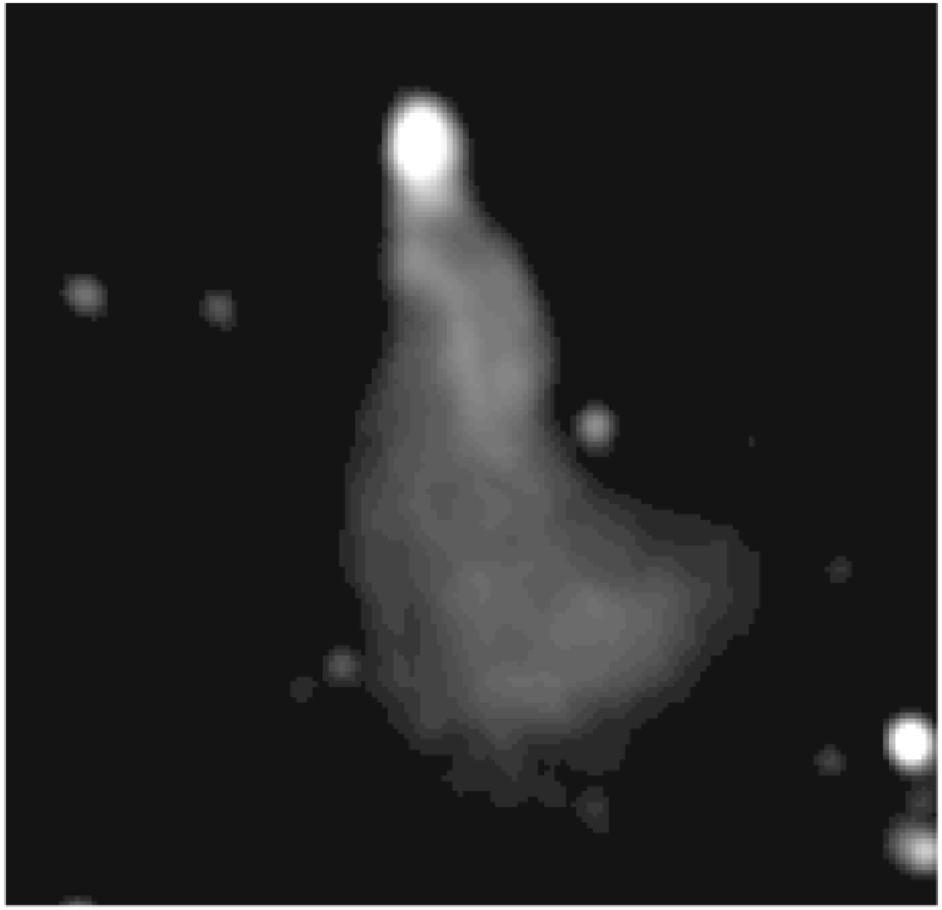
- **Flattest spectral index zones often not at lobe periphery (Mack et al 1998)**
  - **Most recently accelerated particles not accelerated in edge shocks (conventional wisdom)**
  - **This implies *in situ* CR particle acc'n --** first recognized 25 years ago (Willis & Strom 1978)
  - **New analysis & theory beginning to clarify the "in situ" process**

2147+816 giant radio galaxy

z=0.146

2.6 Mpc

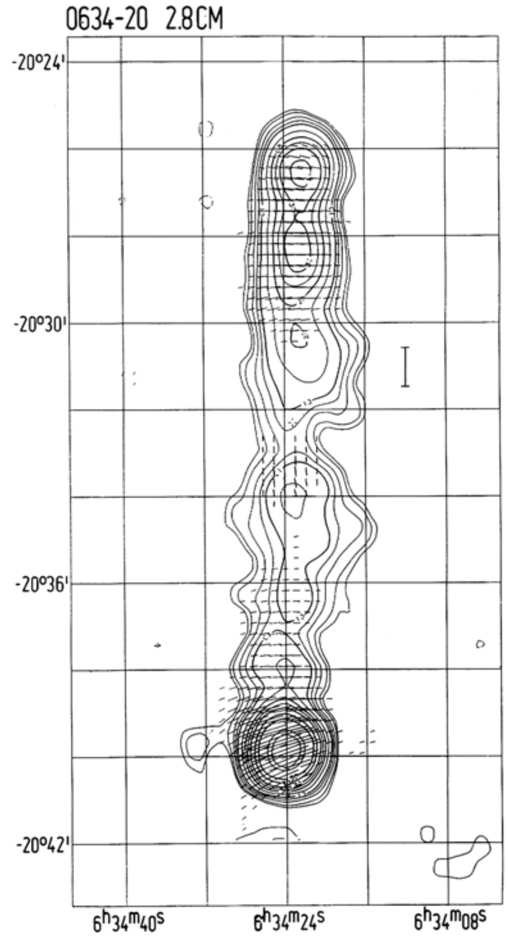




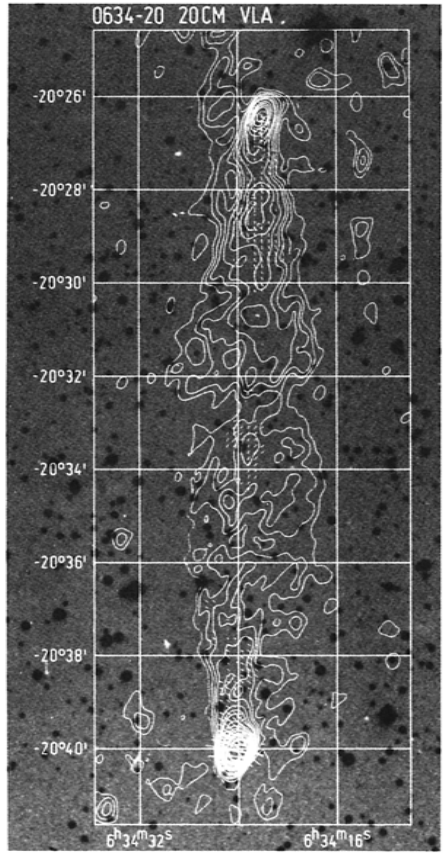
GRG 2147+816 at $z=0.146$ (Frame size=1.1x1.1 Mpc h_{75}^{-1})

No evidence for large scale lobe-internal shocks

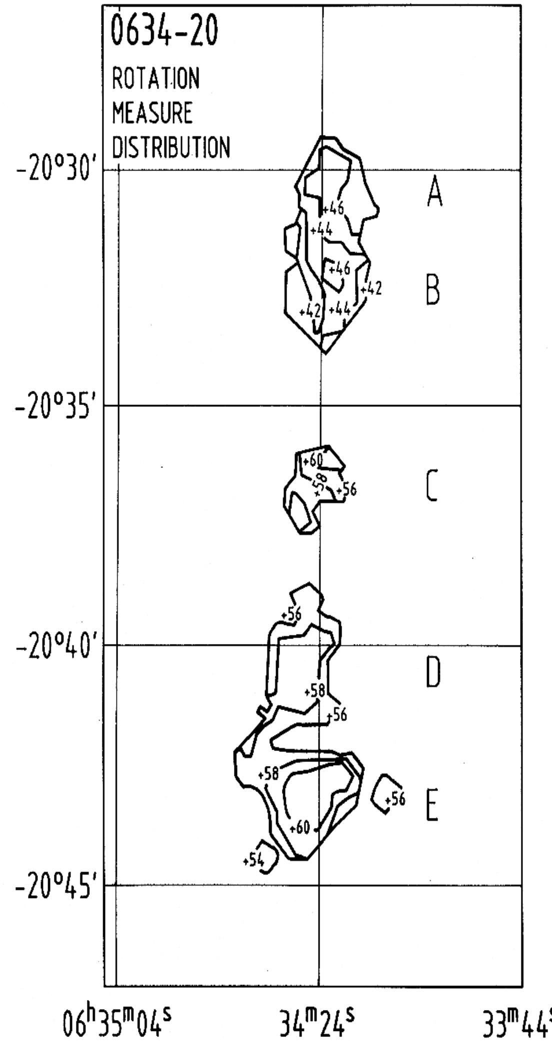
10 GHz



1.4 GHz



Faraday RM(radians/m^2)



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

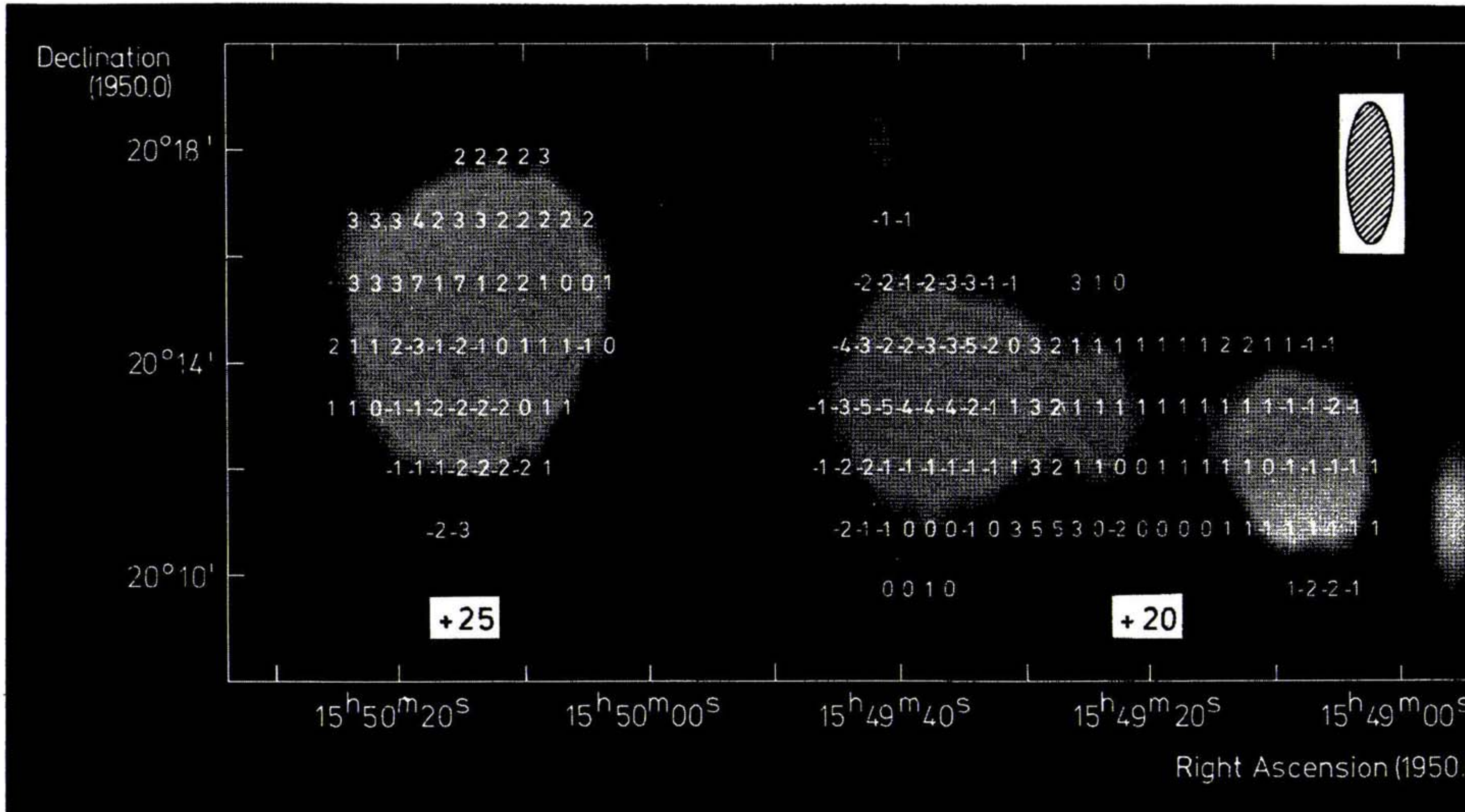


Fig. 8. The distribution of rotation measure over 3C 326 as computed from the 49 cm and 21 cm convolved data superposed upon photograph" of the 49 cm total intensity. Note that to produce a simple grid of single digit numbers we have subtracted integrated measures, whose derivation is described in the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

GRG's have

- **low *lobe vs. lobe* Rotation Measures**

1 □ Δ(RM) □ 10 rad/m²(lobe1 – lobe2)

►► ambient n^{ig}_{th} = 10^{-5} - 10^{-6} cm^{-3}

- **Usually even lower intra-lobe RM's**

0 □ Δ(RM) □ 5 rad/m²

Alfvén speeds in radio lobes

$$v_A = 696 \times \frac{B_{-6}^{L}(1+k)^{2/7}}{\sqrt{\rho_{10^{-5}}^{L}(1+k)^{-2/7}}} kms^{-1}$$

- ***k=Ep/Ee*** ***In Milky Way, k$\approx$100***

B_{-6}^{L} (G) assumes minimum total energy in field ρ+ relativistic particles (e^- + p^+)

- ***$\rho^{L}_{10^{-5}}$ derived from Faraday rotation limit ($\propto n_e^L.B^L.L$) in giant lobes***
- ***v_A depends on (unmeasured) relativistic proton energy $\propto (1+k)^{3/7}$***

Compare rad. Loss time with transport time

$$\tau^{e}_{rad} \leq \frac{5.4 \bullet 10^{7} B^{1/2}_{3.3\mu G}}{\left[B^{2}_{(cmb-equ)}(1+z)^{4} + B^{2}_{3.3\mu G}\right] \bullet \left[\upsilon_{10.6GHz}(1+z)^{1/2}\right]} yr$$

$$\tau_{T} \approx 5 \bullet 10^{8} \left\{\frac{d}{500pc}\right\} \bullet \left\{\frac{1000kms^{-1}}{v_{T}}\right\} yr$$

in GRG's τ_{rad} □ 0.1 τ_{transp} !!

- particle transport from outer hotspots (shock acc'n zones) cannot be the energizing mechanism of GRG lobes
- This question was less clear for 10x smaller radio galaxies & quasars

Important Characteristics of Mpc-scale radio sources.

- relaxed morphologies, no externally caused shape distortion.
- Little evidence for strong shocks around the lobes
- B-field parallel to lobe-igm interface
- Overpressured relative to surroundings
- Low lobe-internal Faraday rotation
- Sizes are of intergalactic dimensions!

  -> over time, can magnetize general igm

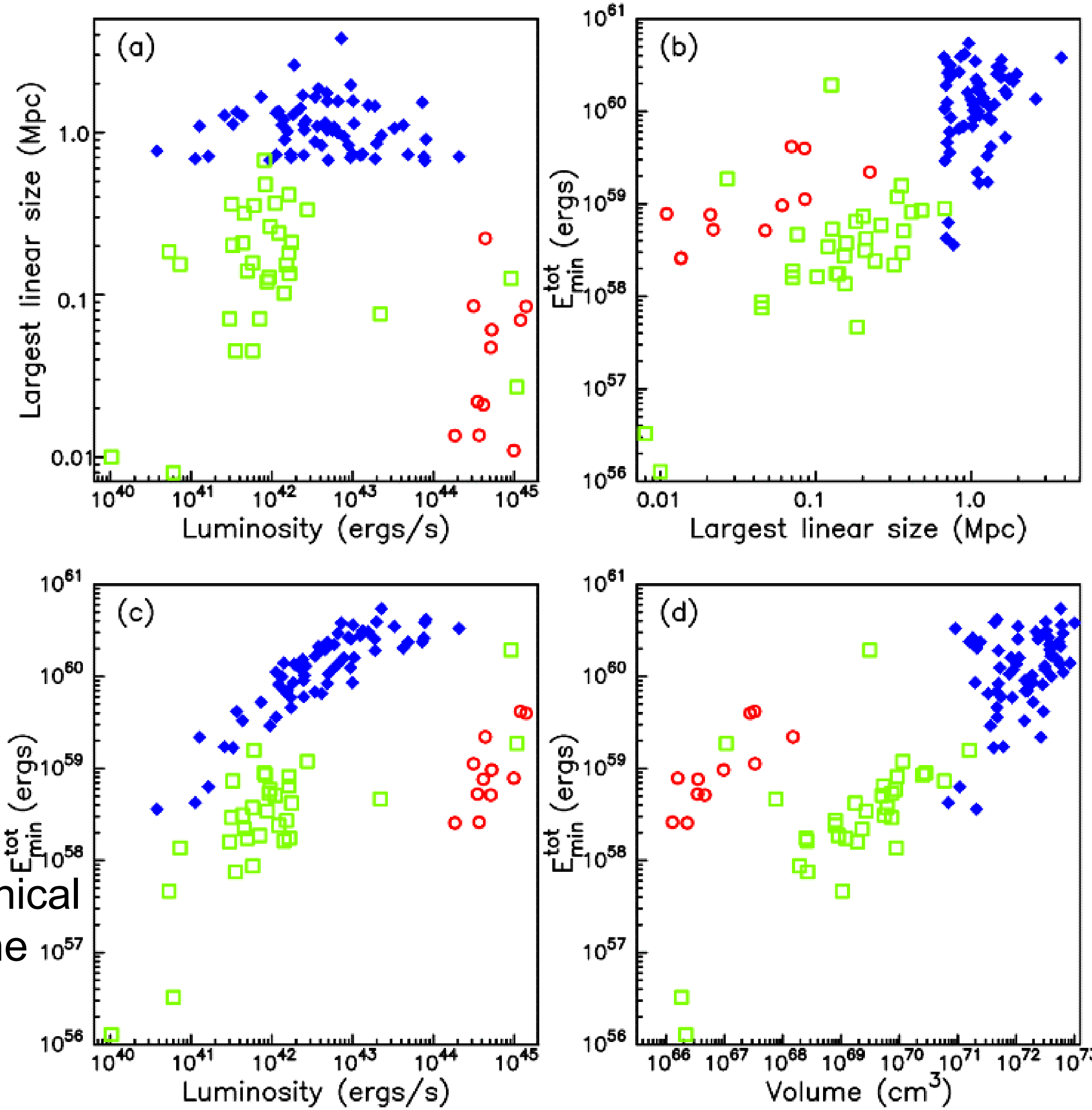
How much energy gets out and where does it go?

Test: Measure the energy content of egrs in different environments, and with differing luminosities

We have estimated E_{min}^{tot} for 3 groups of egrs:

1. All sources with projected size > 0.6 Mpc (GRG's)
2. Sources with the densest ambient environments (< 150 kpc of a galaxy cluster core)
3. Other sources with extremes of radio luminosity and distance

For GRG's, upper envelope of E_{min}^{tot} is close to the gravitational infall energy of a 10^8 M_ε BH!

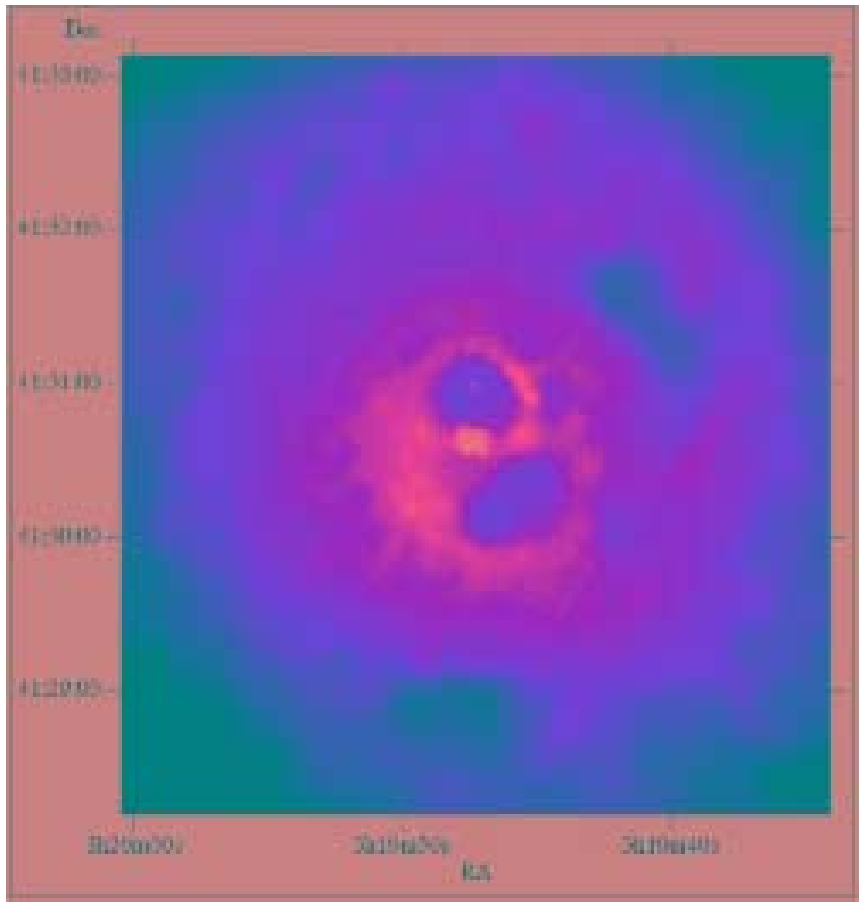


Cluster-embedded Sources have an energy content deficit of □ 10^{59} erg.

This is of order of the mechanical PdV work done to displace the hot ambient intracluster gas.

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

Radio lobes (X-ray holes) displacing hot gas (PdV work) in the Perseus cluster



Chandra image (A.C. Fabian et al.)

Etot (B + rel particles) is close to the maximum reservoir energy (*gravitational* -> requires very efficient acceleration process for the CR electrons.

(Kronberg Dufton Li & Colgate, ApJ 560, 178, 2001)

BH Energy into the IGM

- Infall energy onto galactic black holes

$$E_{\inf} = -\frac{GM_{BH}^2}{R_s}$$

- Schwarzschild Radius

$$R_s = \frac{GM_{BH}}{c^2}$$

- GRG's reveal that ***η*** is as much as 10%!!

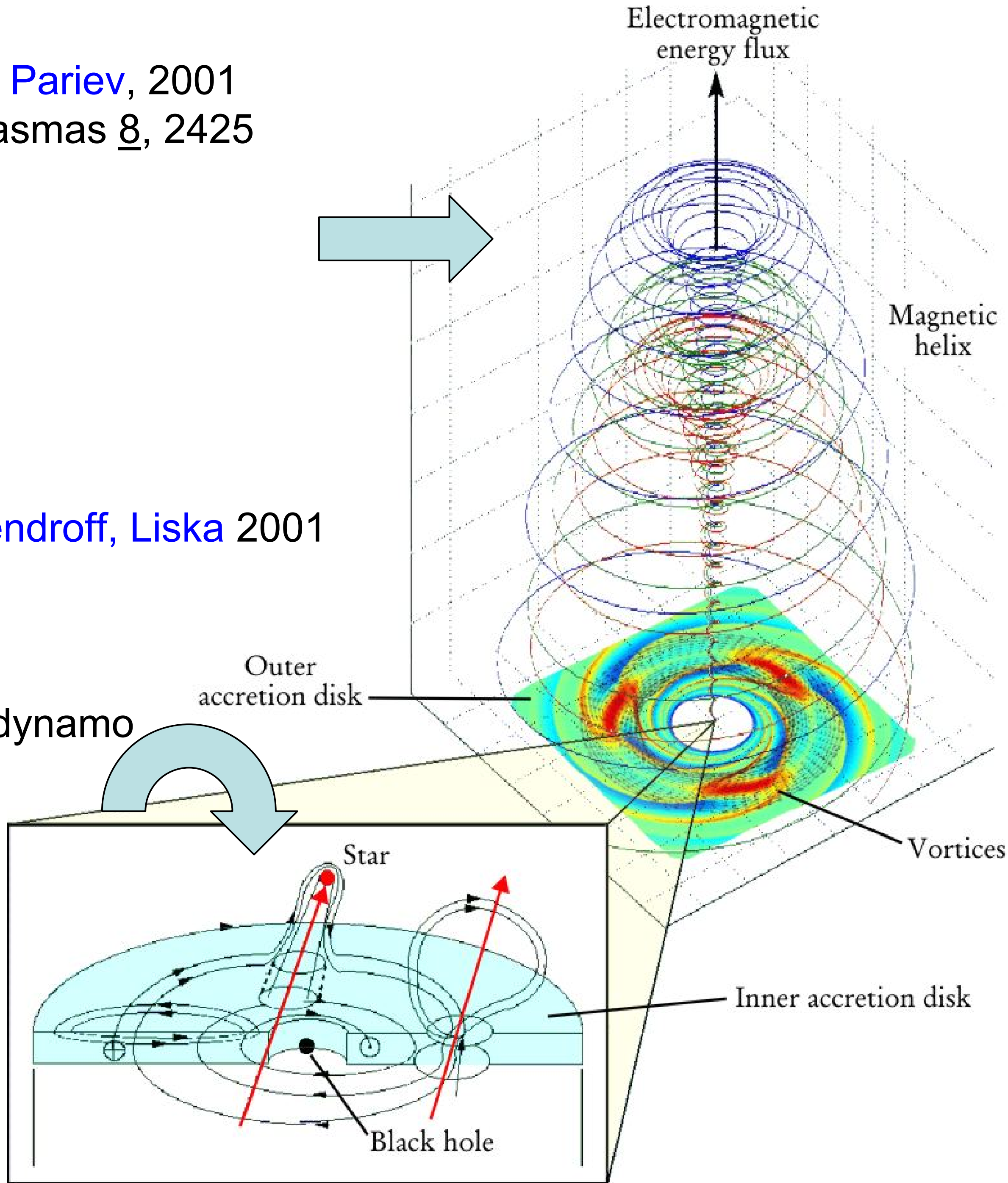
$$E_{released} = \eta E_{\inf.} = \eta M_{BH} c^2$$

- $E_{released}$ in magnetic fields and CR's $\approx$ photon energy release

Colgate, Li, Pariev, 2001
Phys. of Plasmas 8, 2425

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

Accretion disk dynamo
(S.A. Colgate)



Summary: physical constraints imposed by GRG’s

1. Mpc physical dimensions characteristic of inter-galaxy separations!

2. Outer extremes (hotspots) must advance at □ 6000 km/s, (□ 0.02c), but weak evidence for a supersonic shock at outer interface.

3. Internal Alfvén speeds are □ 2000 km/s (n_{th}^{L} is a lower limit)

4. CR electron radiative lifetimes much less than very long lobe-internal transport times (distances)

5. High acceleration efficiency required: (E_{min}^{tot})/(BH infall energy) ≈ 0.1

6. Classical shock theory (for CR electron acceleration) breaks down

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What’s the missing, efficient acceleration mechanism?

The very high Alfvén speeds, and highly ordered fields suggest acceleration by magnetic reconnection
(Li, Nishimura, Barnes, Gary, Colgate 2003)

The scenario:

- Collimated energy flow from BH is electromagnetic.
  10^{19} amps, energy initially in magnetic fields
- Electron CR’s energized by conversion of magnetic → particle energy
- Sheared B-fields evolve to a more relaxed state (Li et al. 2003)
- Magnetic reconnection a natural particle accelerator, esp. if V_A is high
- How this happens currently not understood

Magnetic reconnection in radio source lobes?

Standard reconnection models (too slow) seem not to apply in radio lobes.

The (resistive) reconnection layer width Δ in the Sweet-Parker model is:

$$\Delta_{s-p} \approx 1500 L_{kpc} \bullet n_{3.10^{-6}}^{\;1/4} \bullet \eta_4^{\;1/2} \bullet B^{-1/2}{}_{5.10^{-6}}\, km$$

L= length of the reconnection zone, η = resistivity (cm^2/sec)

Reconnection time scales

$$\tau_A \equiv L / v_A$$

Rate of magnetic energy dissipation

=rate of magnetic flux convection out of reconnection layer

Time scale for this $=(\tau_A \tau_\eta)^{1/2} \sim 6 \times 10^{26}$ yrs!

Standard Sweet-Parker doesn't work here!!

Recent insights on FAST reconnection

- GRG Radio lobe plasmas are collisionless
- Analagous conditions in Tokomaks(?) and the Earth's magnetotail
- A key parameter is the ion skin depth, d_i
- $di = c/\omega_{pi} \sim 1.3 \times 10^{10} n^{-1/2}{}_{3.10^{-6}}$ cm
- ω_{pi} = ion plasma frequency
- $d_i >> \Delta_{s-p}$ in radio lobes;
- This breaks the frozen-in flux condition

Application to force-free fields in radio lobes

- in a collisionless, and force free magnetoplasma reconnection rate → *x*% of v_A. (and *indep*. of plasma resistivity η)
- i.e. in GRG's v_{reconn} a fraction of *c*!

- Recent PIC simulations at LANL: H. Li *et al.* Phys. Plas. **10**, 2763, 2003
- A significant first step in facilitating particle acc'n by reconnection.

Reconnection acceleration?

– Reconnection acceleration not yet fully understood (C. Nodes *et al* Phys Plas. **10**,835, 2003), but can efficiently produce relativistic particles.

– Reconnection acceleration probably highly efficient – consistent with GRG lobe energy content.

– Converts magnetic to particle energy

– High V_A in GRG radio lobes is satisfied-- a key “prerequisite”.

Astrophysical implications

- *If* CR particles are accelerated by reconnection in GRG's, then:
- It is a universal mechanism in *all* egrs,
- Including radio lobes in galaxy clusters.
- Space – filling particle acceleration
- Candidate to explain UHECR's.
- Might explain optical/x-ray synchrotron
- radiation in diffuse radio lobes.

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Recent searches for faint intergalactic synchrotron radiation,

Intergalactic CR acceleration
and
why they point to some scientifically interesting SW-LWA (LOFAR) capabilities.

A project in progress

Smoothed-out density of galaxy black holes:

$$< \rho_{BH} > \approx 4 \times 10^5 M_\odot \; / Mpc^3$$

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

Average BH-ejected i.g. energy density ≈ 4×10^{-14} erg/cm^3

Equiv. average magnetic energy density = 1.1 microgauss!!

Current and past e.g.r.s. appear to supply a non-trivial fraction of that distributed energy – in B and CR's

Reason to expect 0.1-1 μG fields in LSS galaxy filaments

Low level radio searches at ν<450MHz (project I)

1. 74 MHz 15º field in Coma supercluster

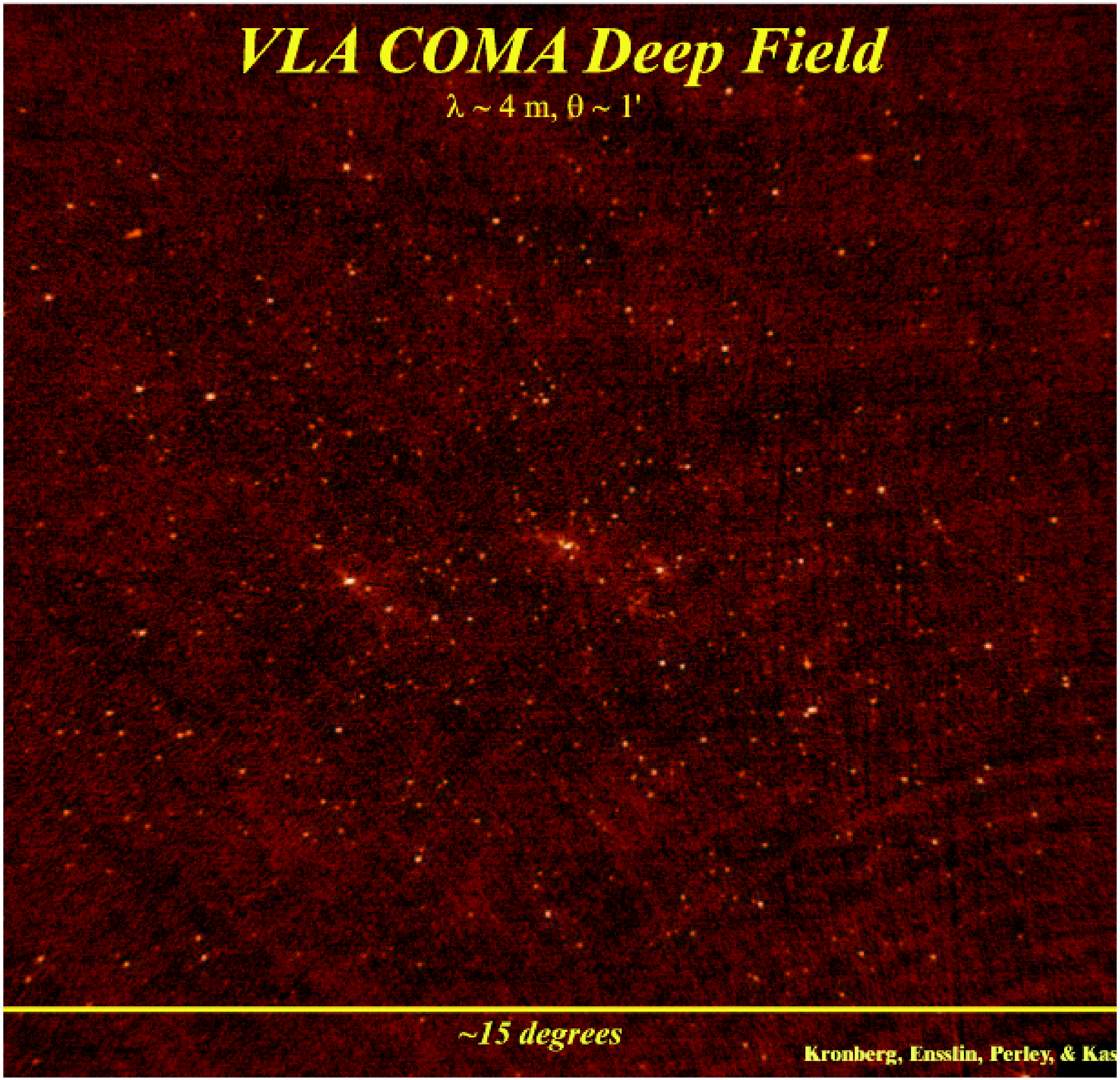
Philipp Kronberg (LANL)

Torsten Enβlin (MPA-Garching)

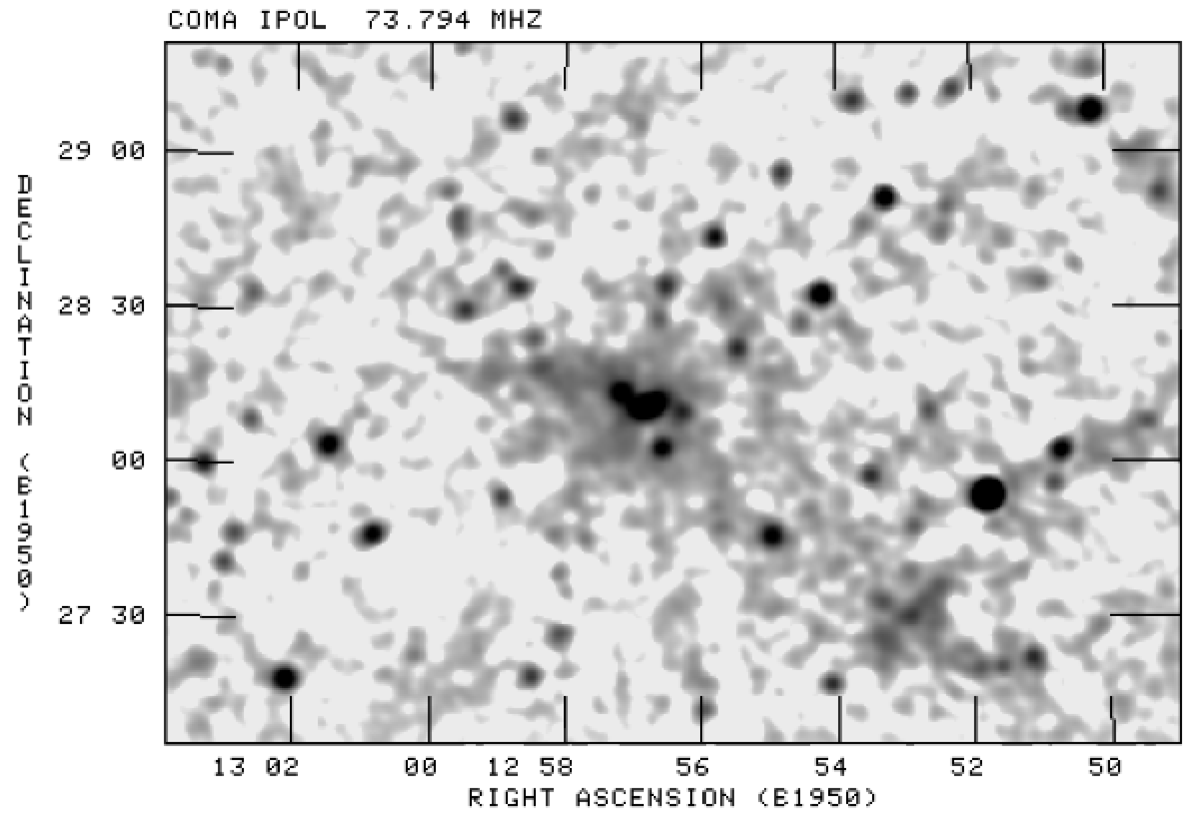
Richard Perley (NRAO)

Namir Kassim (NRL)

- VLA A+B+C+D configurations
- Full resolution ≈ 30”, full field 15 º



Interim image


COMA IPOL 73.794 MHZ
DECLINATION (B1950)
29 00
28 30
00
27 30
13 02
00
12 58
56
54
52
50
RIGHT ASCENSION (B1950)

Low level i.g. radio searches (Project II)

2. 410/430 MHz 8 °x 8° field in Coma supercluster

Philipp Kronberg (LANL)

Roland Kothes (DRAO – Penticton BC)

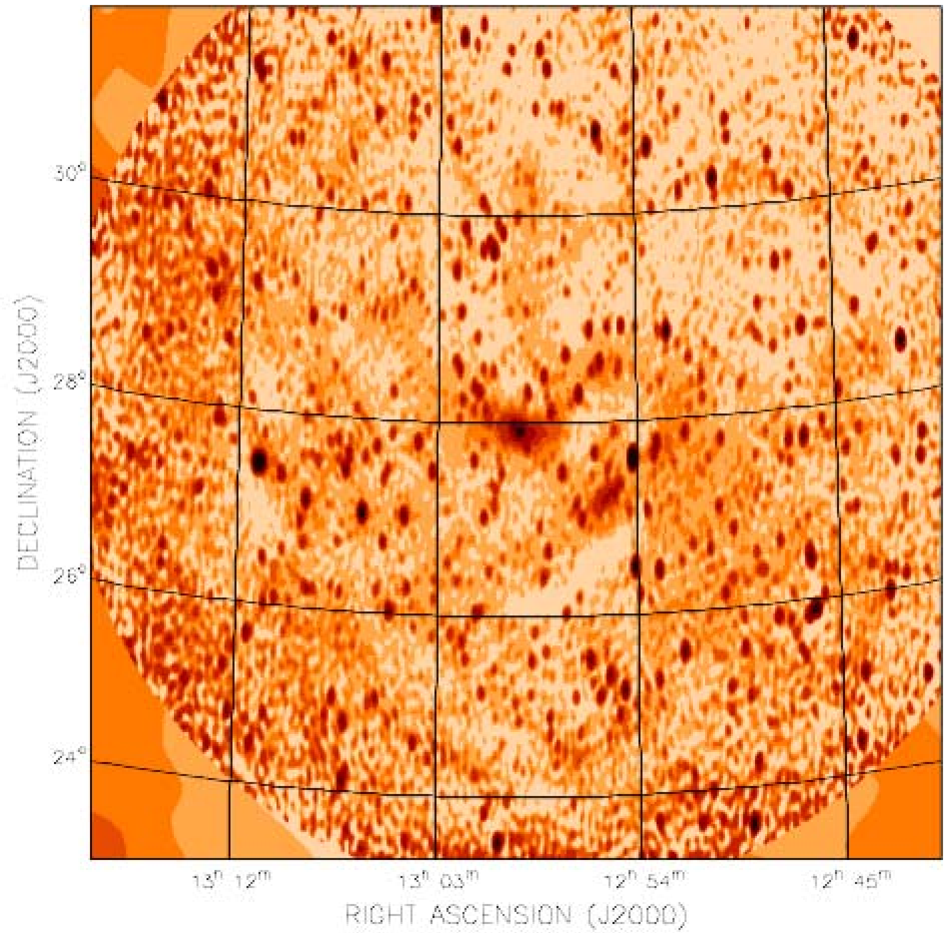
Chris Salter (Cornell-Arecibo)

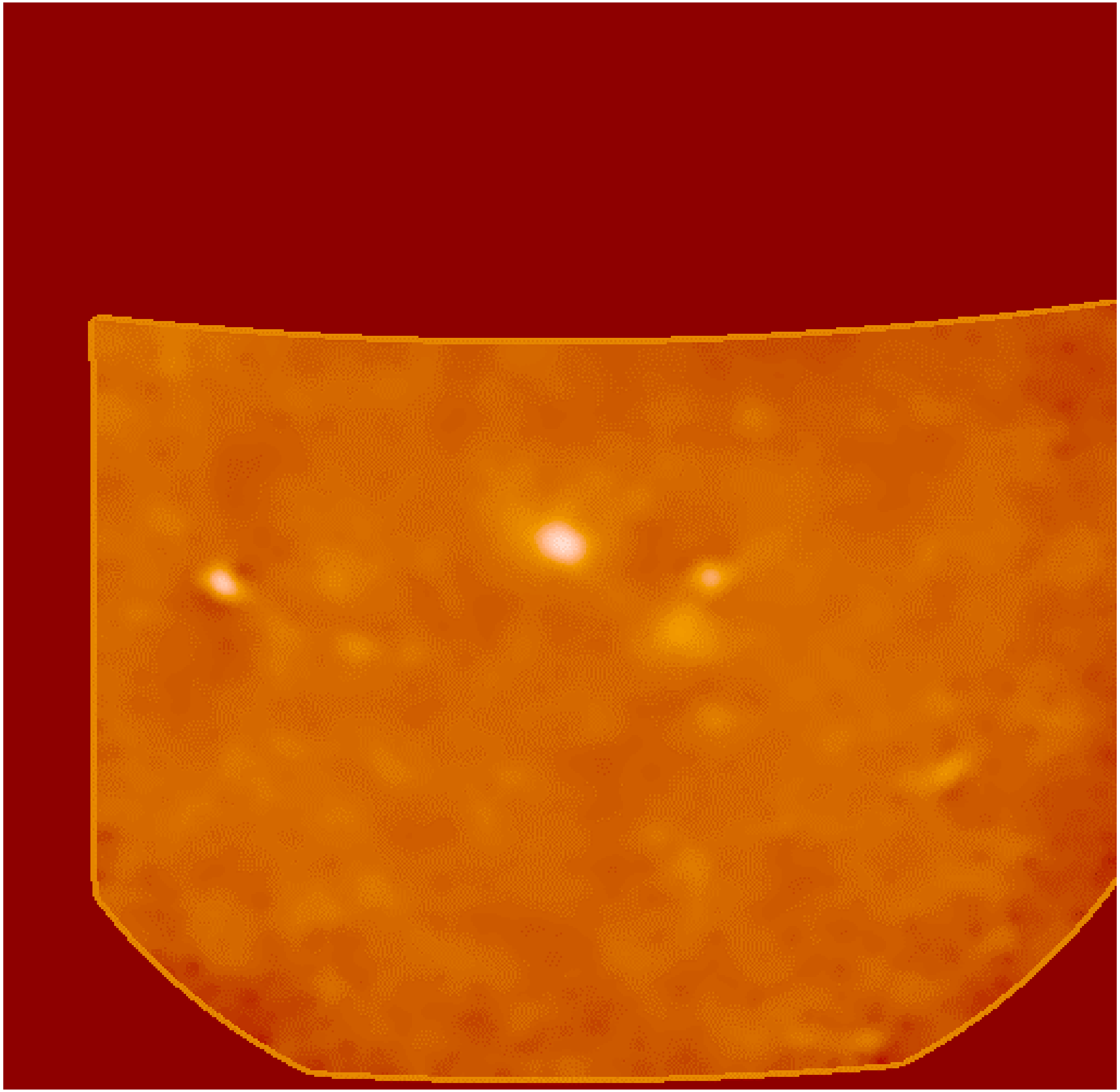
Phil Perillat (Cornell-Arecibo)

- Arecibo images at 430 MHz 2003/2004 (305m aperture) combined with:
- DRAO interferometer images (2x full synthesis) April 2003 (1600m aperture)

Dominion Radio Astrophysical Observatory
Penticton BC, Canada

DRAO: Combination of 2 full synthesis images





Low level extragalactic radio searches (Project III)

3. 327 MHz 2.5^{o} field in Coma supercluster

P. Kronberg (LANL)

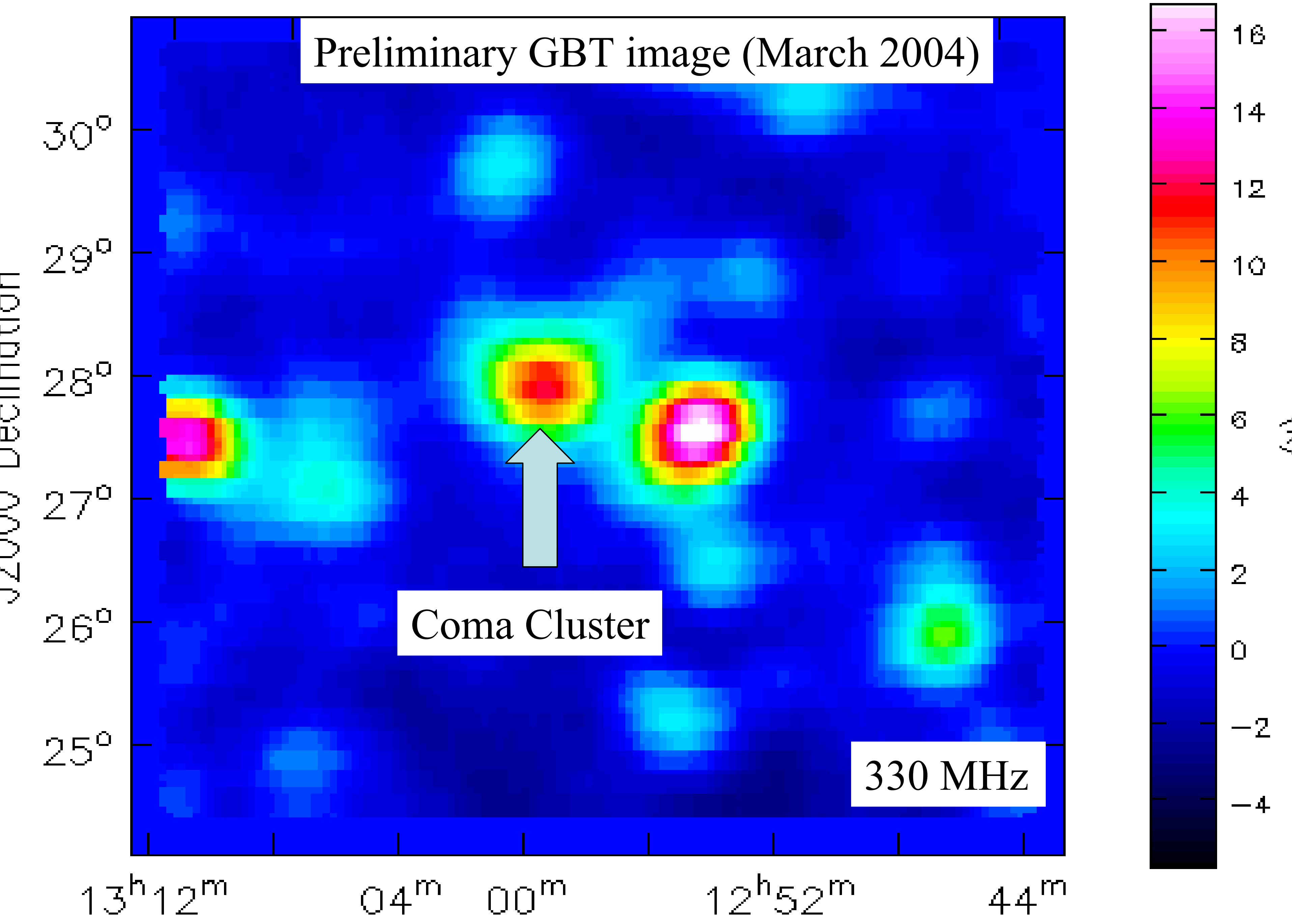
R.A. Perley (NRAO)

N. Kassim (NRL)

G. Giovannini (Bologna)

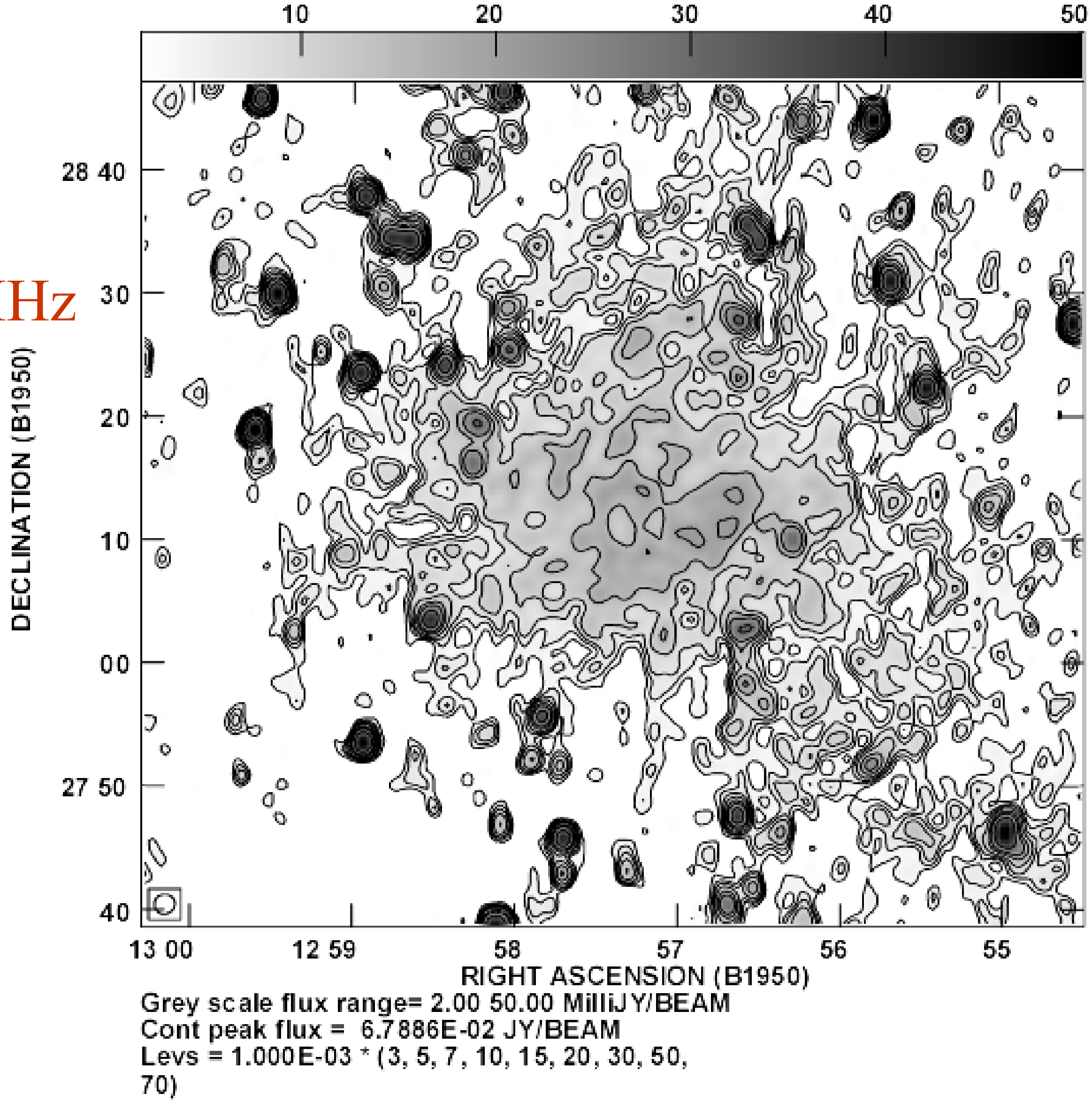
W. Cotton (NRAO)

- VLA A,B,C,D configurations at 330 MHz (35 km)
- Westerbork full synthesis at 326 MHz (1.6 km)
- GBT deep image at 330 MHz (110m)


Preliminary GBT image (March 2004)
Coma Cluster
330 MHz
30°
29°
28°
27°
26°
25°
J2000 Declination
13h12m
04m
00m
12h52m
44m
16
14
12
10
8
6
4
2
0
−2
−4

Combination of VLA (B+C+Dconfigs. + WSRT(all configs, 5 days)

326/330 MHz



TENTATIVE CONCLUSIONS

- Faint intergalactic synchrotron emission may be another tracer of large scale structure.
- Primary energy source may be coming from galactic black holes.
- “Energy feedback” into the IGM via conversion of ηE_{infall} into a magnetized plasma.

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