Extragalactic Magnetic Fields

Luigina Feretti

IRA-INAF
Bologna Italy

Spiral galaxies: ~ 10 μG (average) ~ 30 μG (massive arms)
Starburst galaxies: ~ 50 μG

Radio galaxies: ~ μG

Clusters of galaxies: ~ 0.1-1 μG

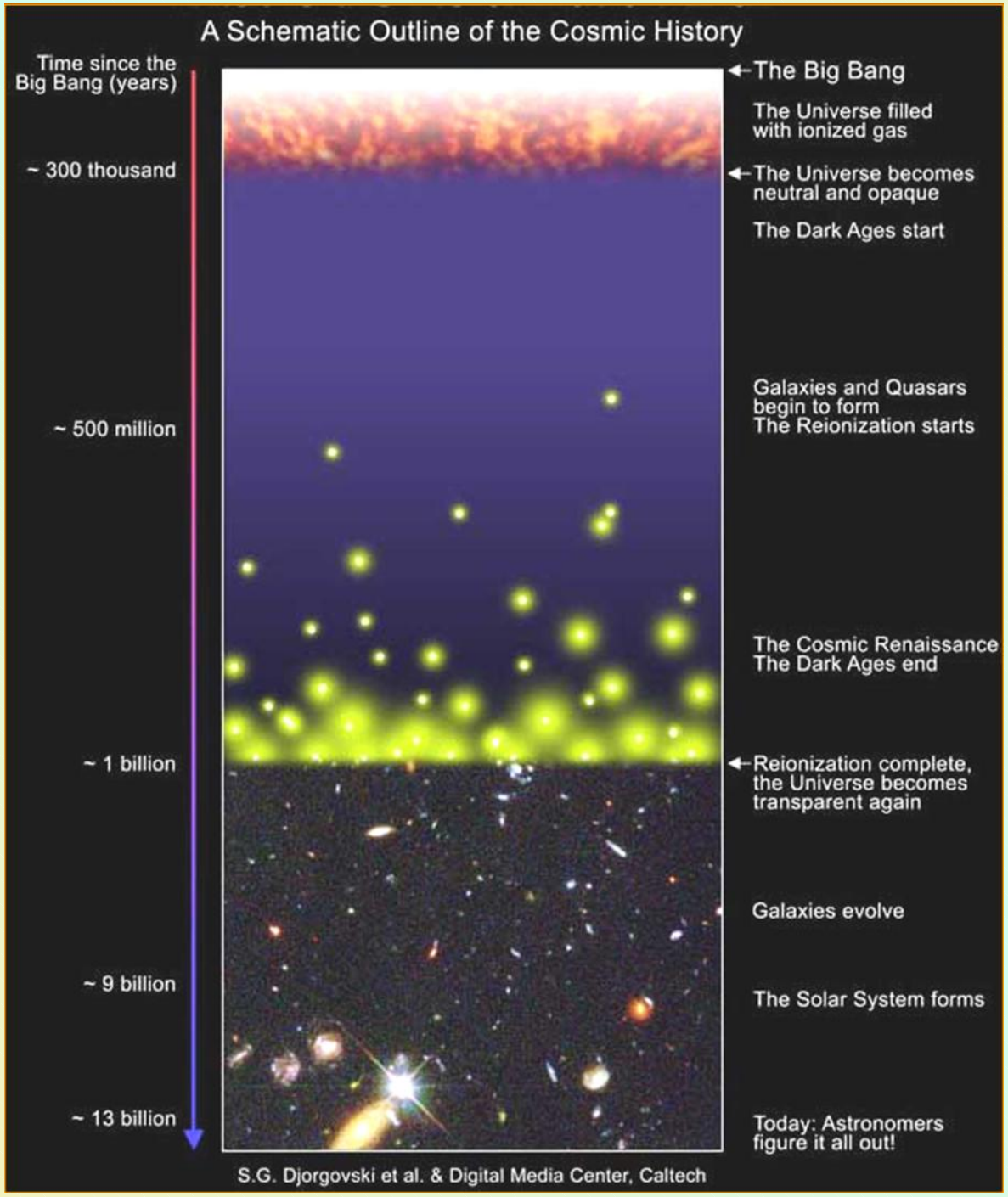
Intergalactic space: $\lesssim 10^{-2} - 10^{-3}$ μG

Large-scale fields
➔ Challenge to models

MAGNETIC FIELD

Primordial

RECOMBINATION



Early stars

z ~ 10

Protogalaxies

Galaxies
AGN

z ~ 5

z ~ 0.5

z ~ 0.1

Observational diagnostics

1 - Synchrotron emission (direct measurement)

total intensity ➔ field strength

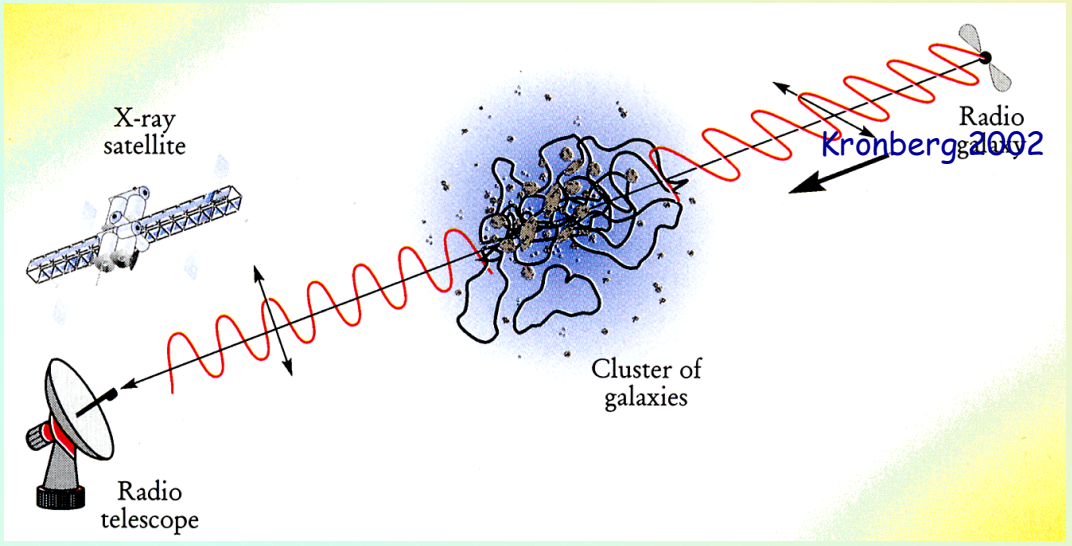
polarization ➔ field orientation and
degree of ordering

2 - Faraday rotation ➔ strength and structure of
the field along the l.o.s. (indirect measurement)

Faraday Rotation

rotation of the plane of polarization of linearly polarized emission as it passes through a magneto-ionic plasma

-- due to the different phase velocities of the orthogonal circular modes



$$\chi = \chi_o + RM\lambda^2$$

χ is the observed position angle of the emission at wavelength λ

χ_o is the intrinsic polarization position angle

Sources seen through magnetized medium:

$$RM = 811.9 \int_0^L n_e B_{||} d\ell \quad \mathrm{rad/m^2}$$

n_e is the electron density in cm^{-3}

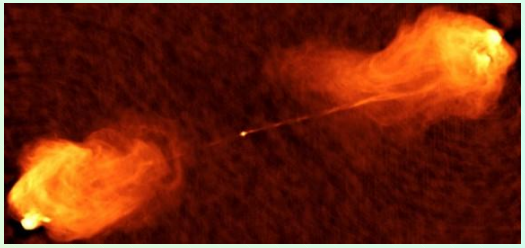
L is the path length in kpc

$B_{||}$ is the line of sight component of the field in μG

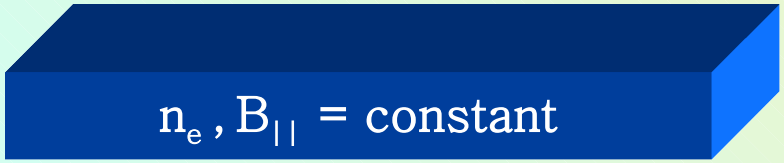
➔ infer B if n_e is known ⟹ X-Ray data

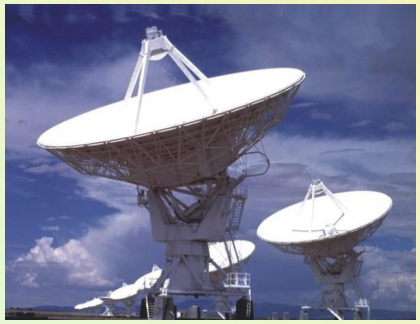
Inference of B, analytical approach:

ICM : uniform slab



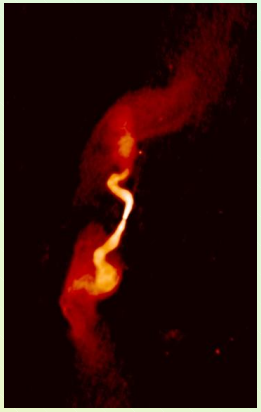
NRAO/AUI/NSF



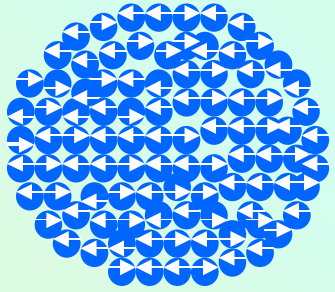


NRAO/AUI/NSF

ICM : single-scale cells



NRAO/AUI/NSF



n_e(r
$B_{||}$ random

NRAO/AUI/NSF

Caveats : embedded sources

power spectrum, B profile, complicated geometries:

➔ numerical techniques (Murgia, Govoni, 2004 - 2005)
semianalytical approach (Ensslin, Vogt 2004-2005)

Clusters of galaxies:

being the largest systems in the Universe, they represent an ideal laboratory to test theories for the origin of extragalactic magnetic fields

IMPORTANCE OF CLUSTER MAGNETIC FIELD KNOWLEDGE

e.g - cluster formation

- cluster evolution

- ICM energy budget

- effect on heat conduction

STRUCTURE - related to shocks and turbulence and shocks (Shukurov, Subramanian, Cassano,Brunetti)

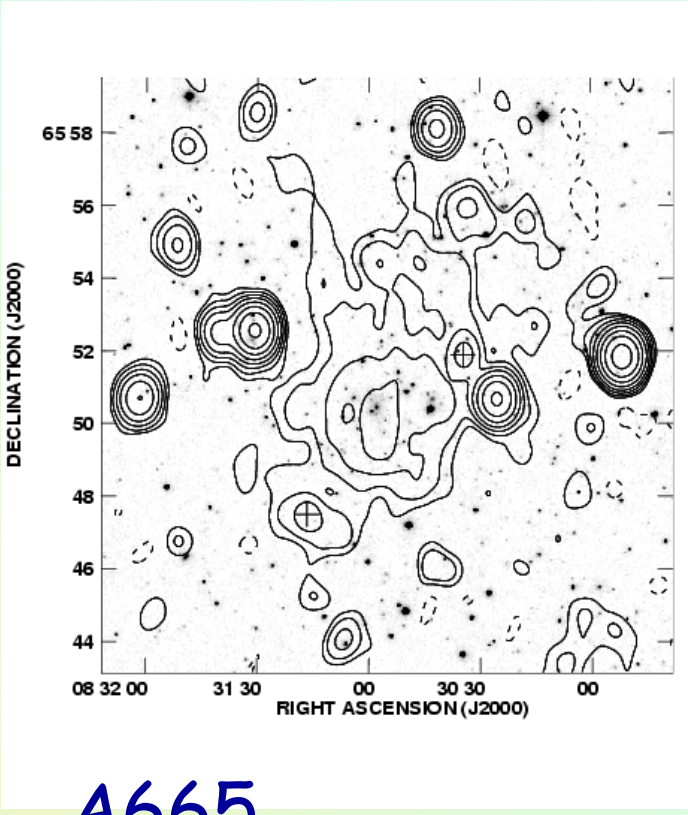
Current observational results:

merging clusters

cooling flow clusters

high z + intergalactic medium

Cluster radio halos



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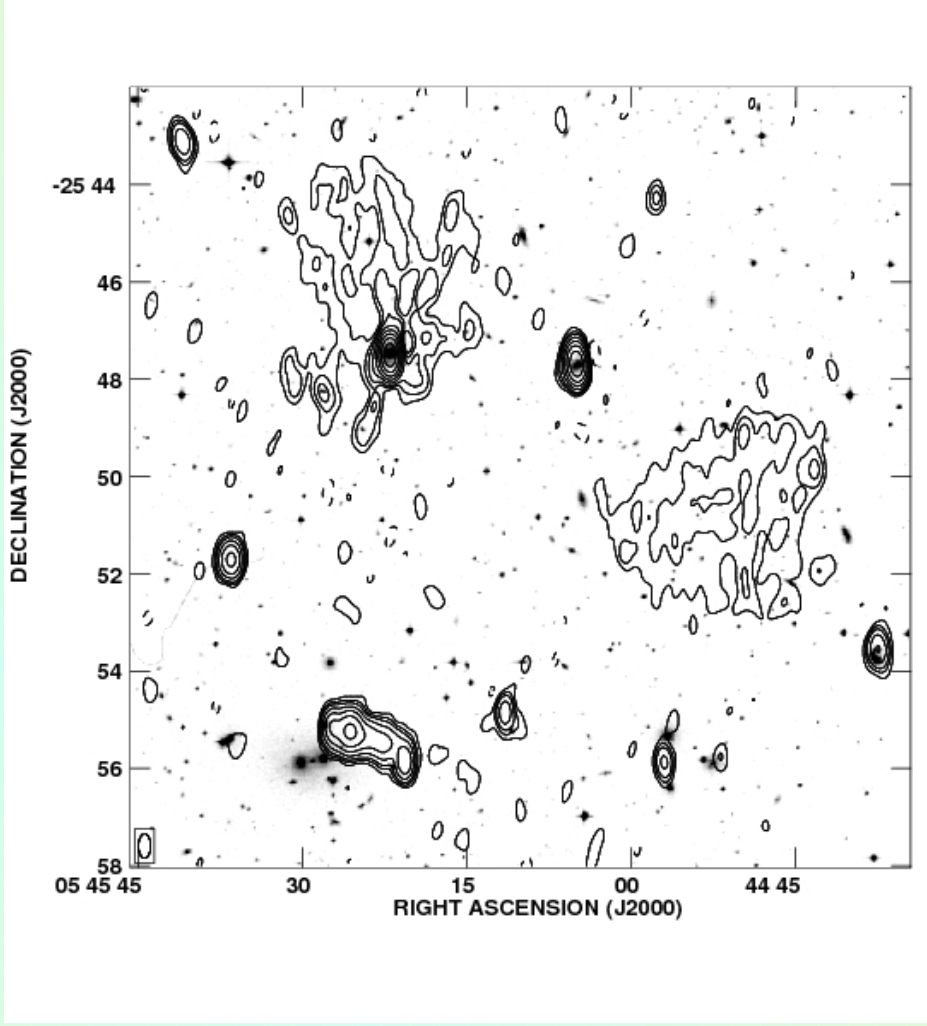
Cluster radio relics



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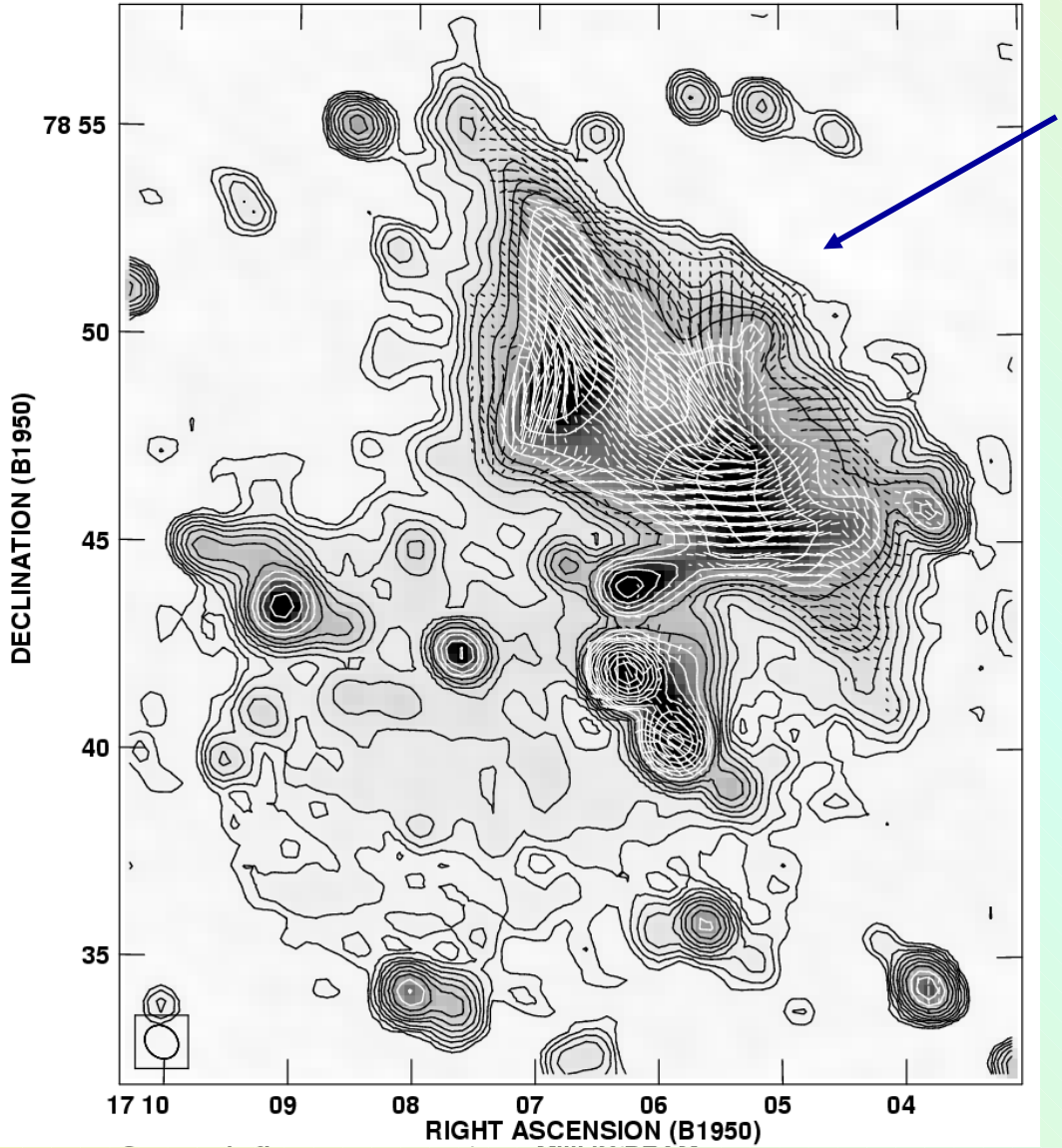
Equipartition Magnetic Fields 0.5–1μG
(consistent with IC hard X-ray studies)

Abell 2256

$I_{1.4}$ & B_0



Clarke et al. (2004)

Projected magnetic field direction

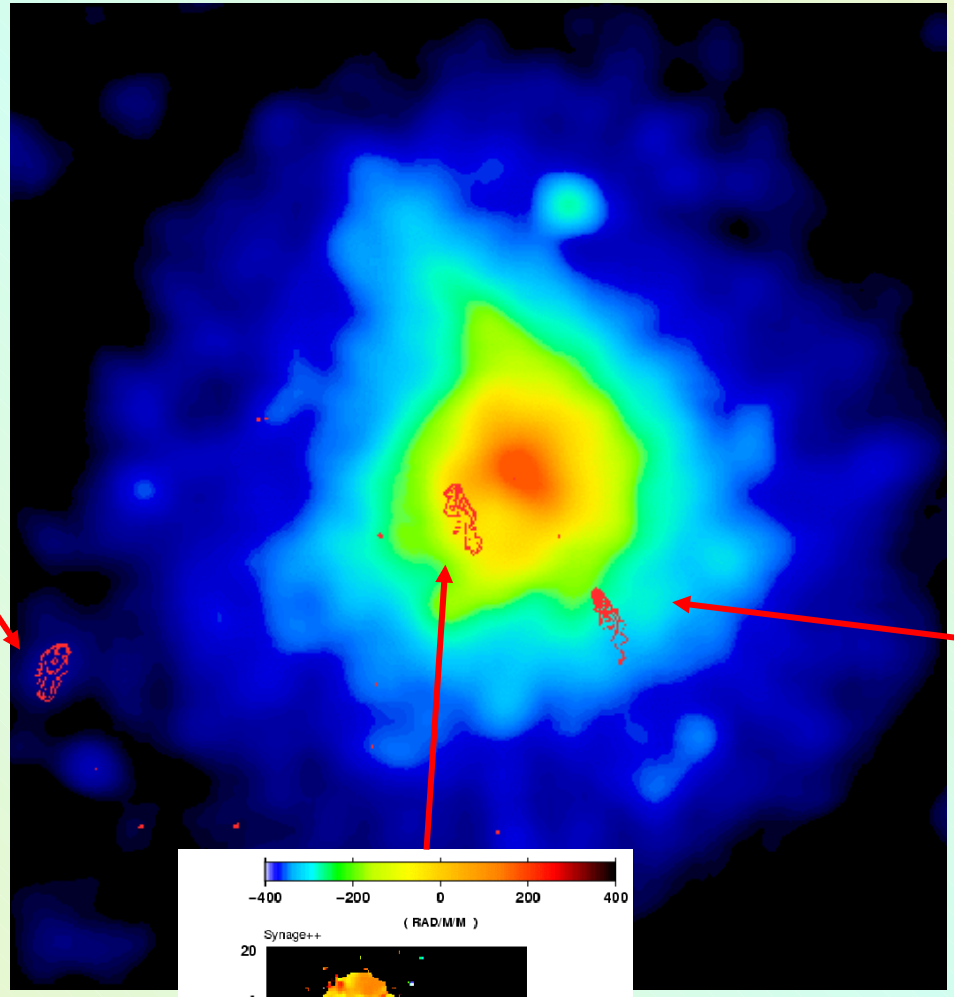
Polarization degree: 20%-40%
(at 1.4 GHz)

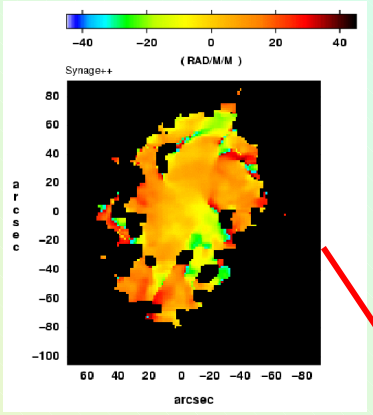
large scale order and generally follows the bright filaments

large regions (500 kpc) of fairly uniform magnetic field direction

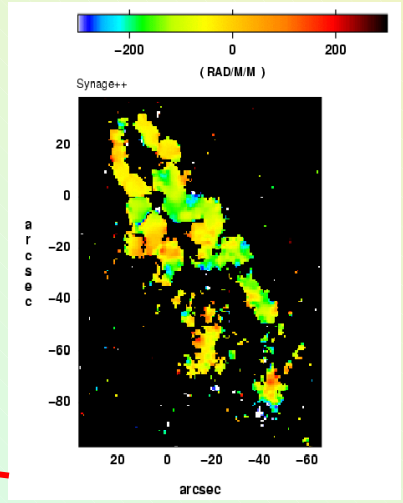
ABELL 119

merging cluster – no cool core

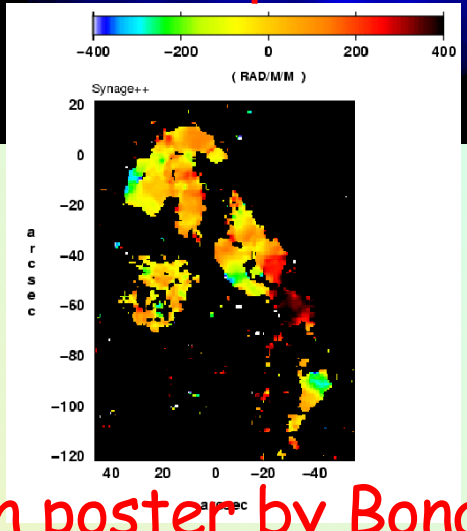




3C 29
<RM> = +4 rad m^{-2}
σ_{RM} = 13 rad m^{-2}



0053-016
<RM> = -79 rad m^{-2}
σ_{RM} = 91 rad m^{-2}



0053-015
<RM> = +28 rad m^{-2}
σ_{RM} = 152 rad m^{-2}

Tangled field ~ 5 kpc
B ~ 5μG Feretti et al. (1999)

Feretti et al. (1999)

See Coma cluster in poster by Bonafede et al.

Current observational results:

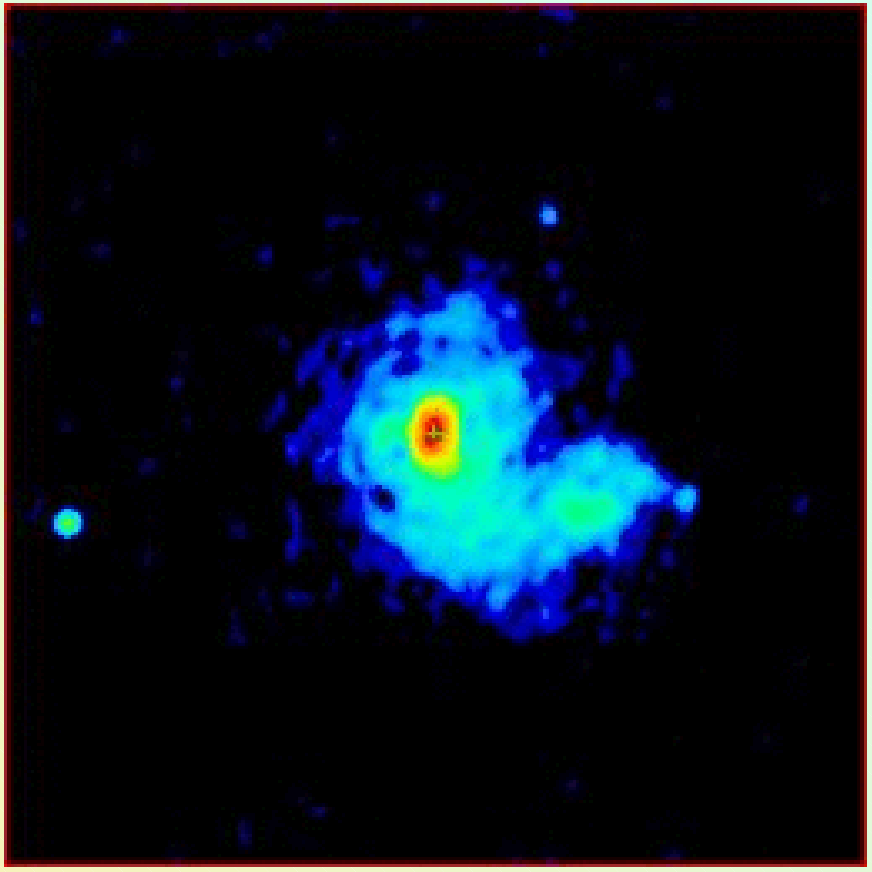
merging clusters

cooling flow clusters

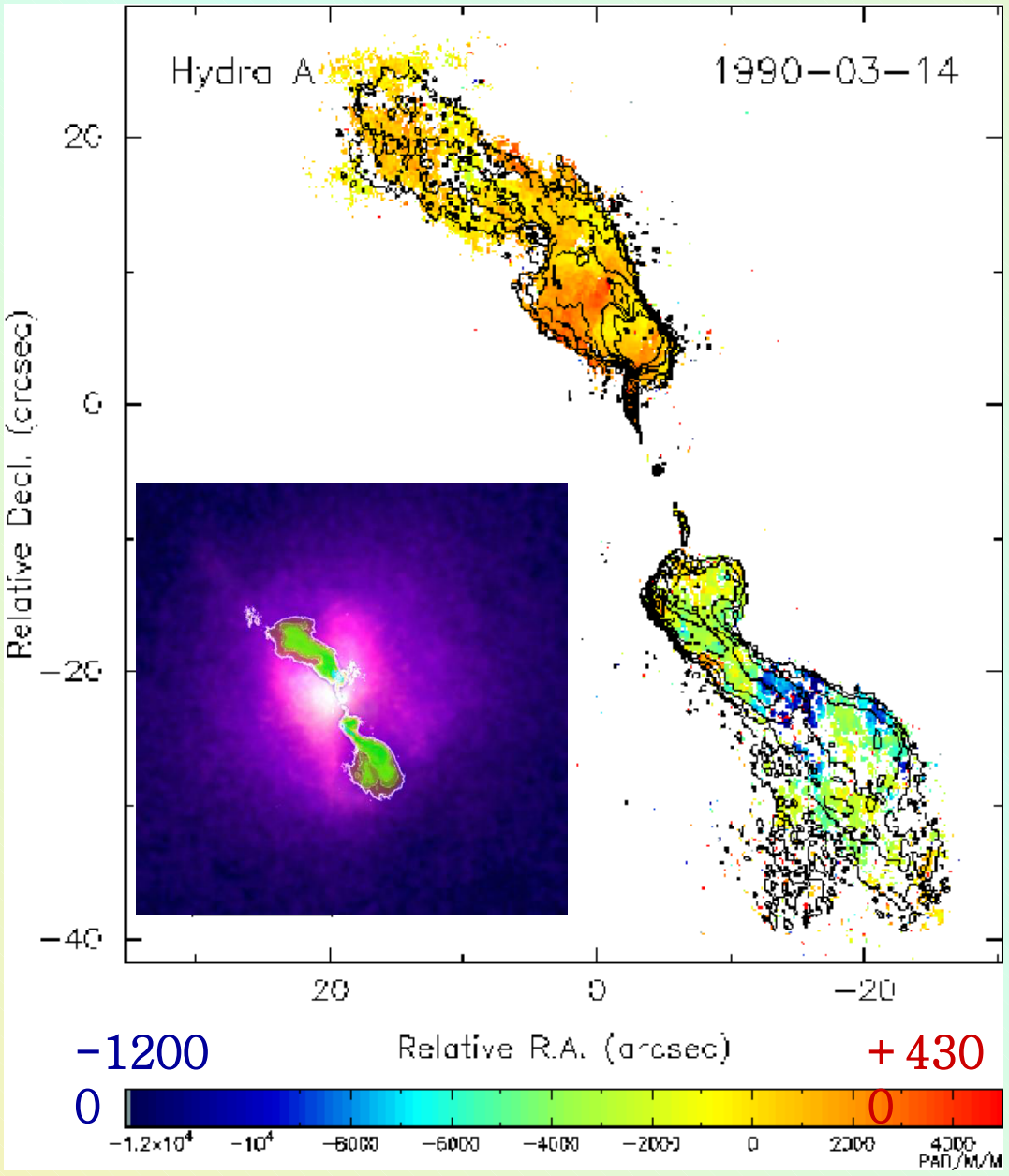
high z + intergalactic medium

Perseus

First cluster where a radio MINI-HALO was detected
Diffuse extended emission is developed around a
POWERFUL RADIO GALAXY – 3C 84 – in a COOLING CORE cluster



Radio, Size = 350 kpc
(Sijbring & De Bruyn 1993)



Taylor & Perley (1993)

Cluster with Strong Cooling Flow

- small scale fluctuations on scales of 5 kpc

$\langle RM \rangle_N = 820$ rad/m²

$\sigma_{RM} = 1200$ rad/m²

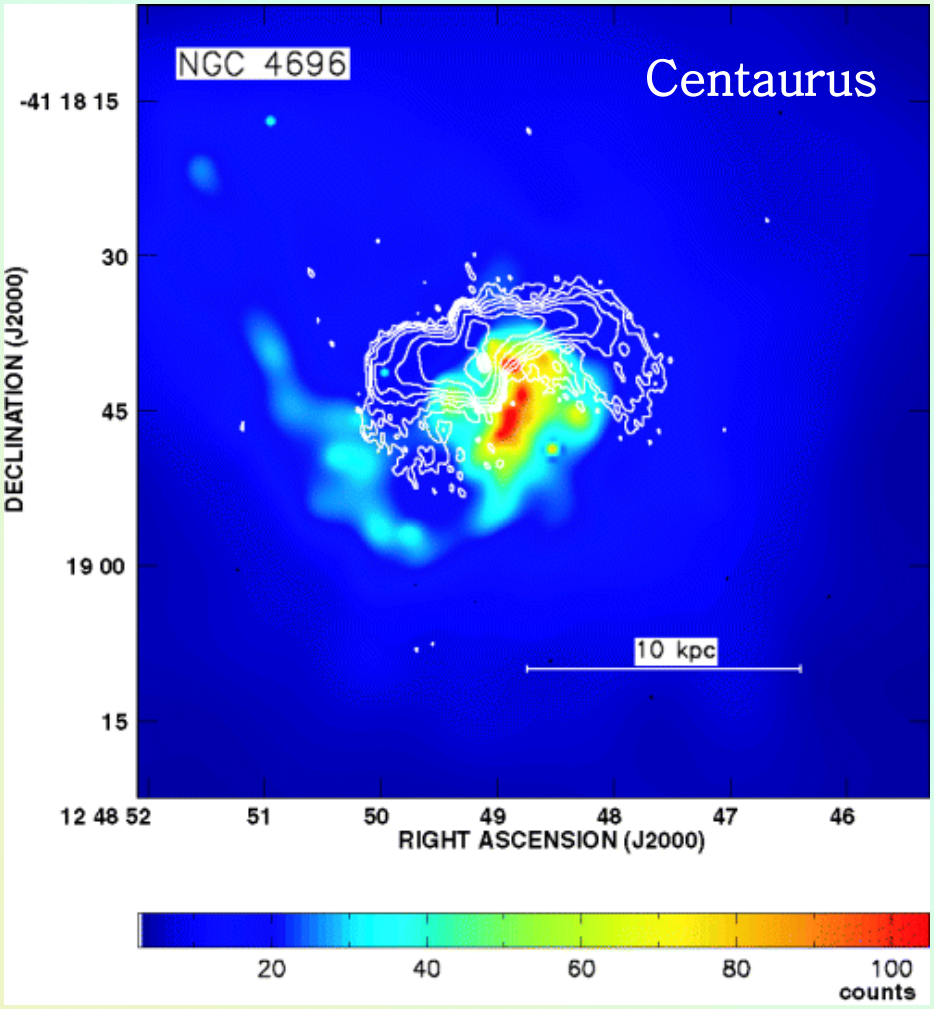
$\langle RM \rangle_S = -3450$ rad/m²

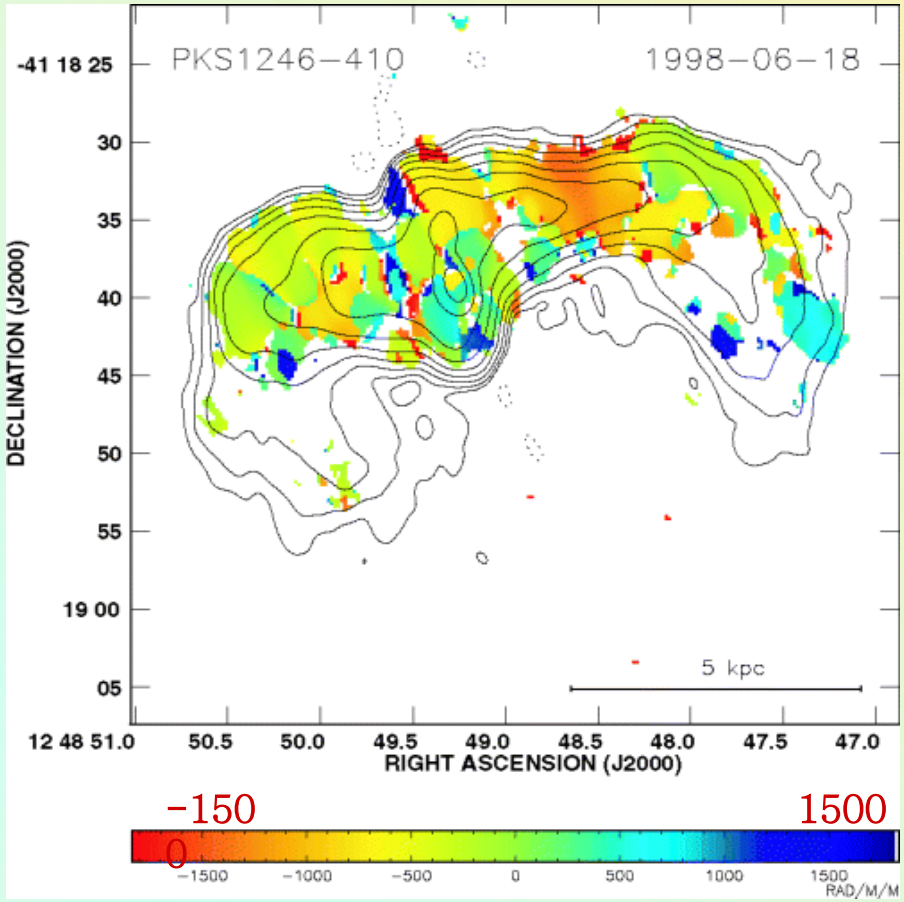
$\sigma_{RM} = 1500$ rad/m²

Combining with gas distribution:

$B_{Tang} \sim 40\ \mu G$

Cluster with moderate CF





Taylor et al. (2002)

Radio/Chandra

z=0.001

Fluctuations on small scales : l_{RM} ~ 1 kpc

➔ 0.5″ at z = 0.1

0.3″ at z= 0.2

Current observational results:

merging clusters

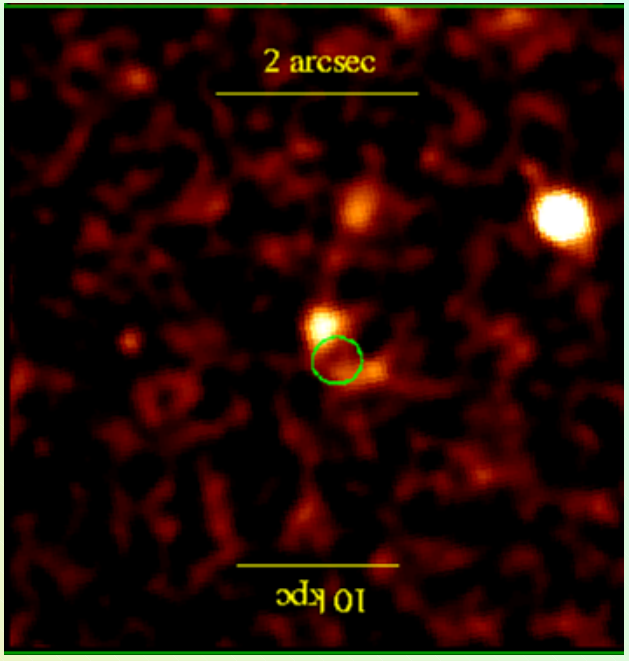
cooling flow clusters

high z + intergalactic medium

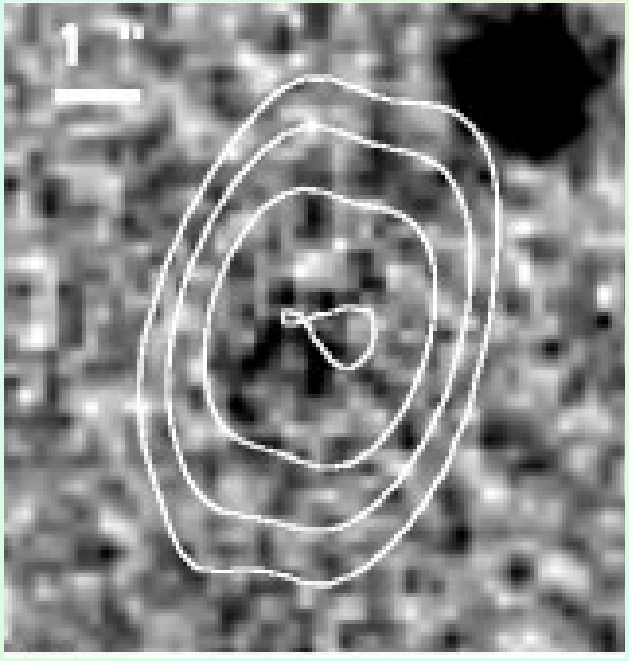
Search for Primordial Fields

Upper limits of intergalactic fields from existing studies:

$B_{IGM} < 10^{-9\ldots-8}$ G (model dependent)



GRB 000131 at z = 4.5
(Bloom et al 2001)

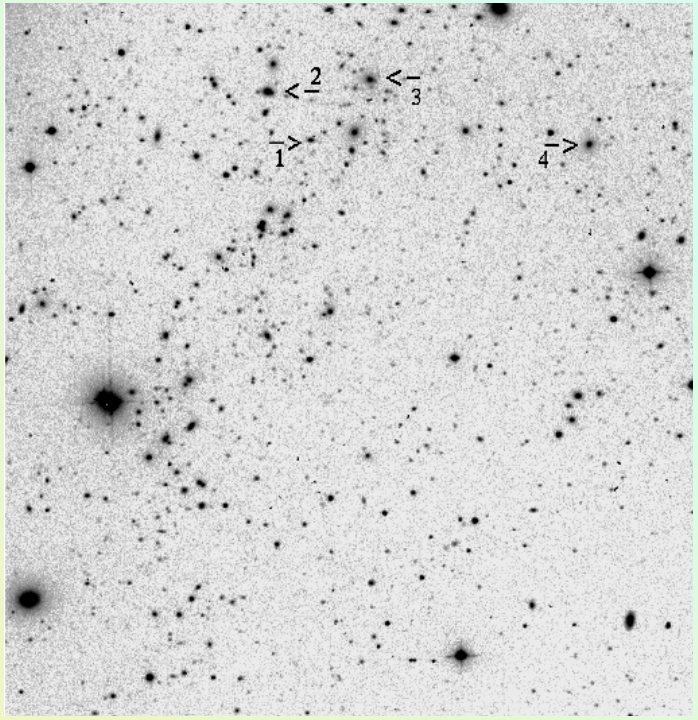


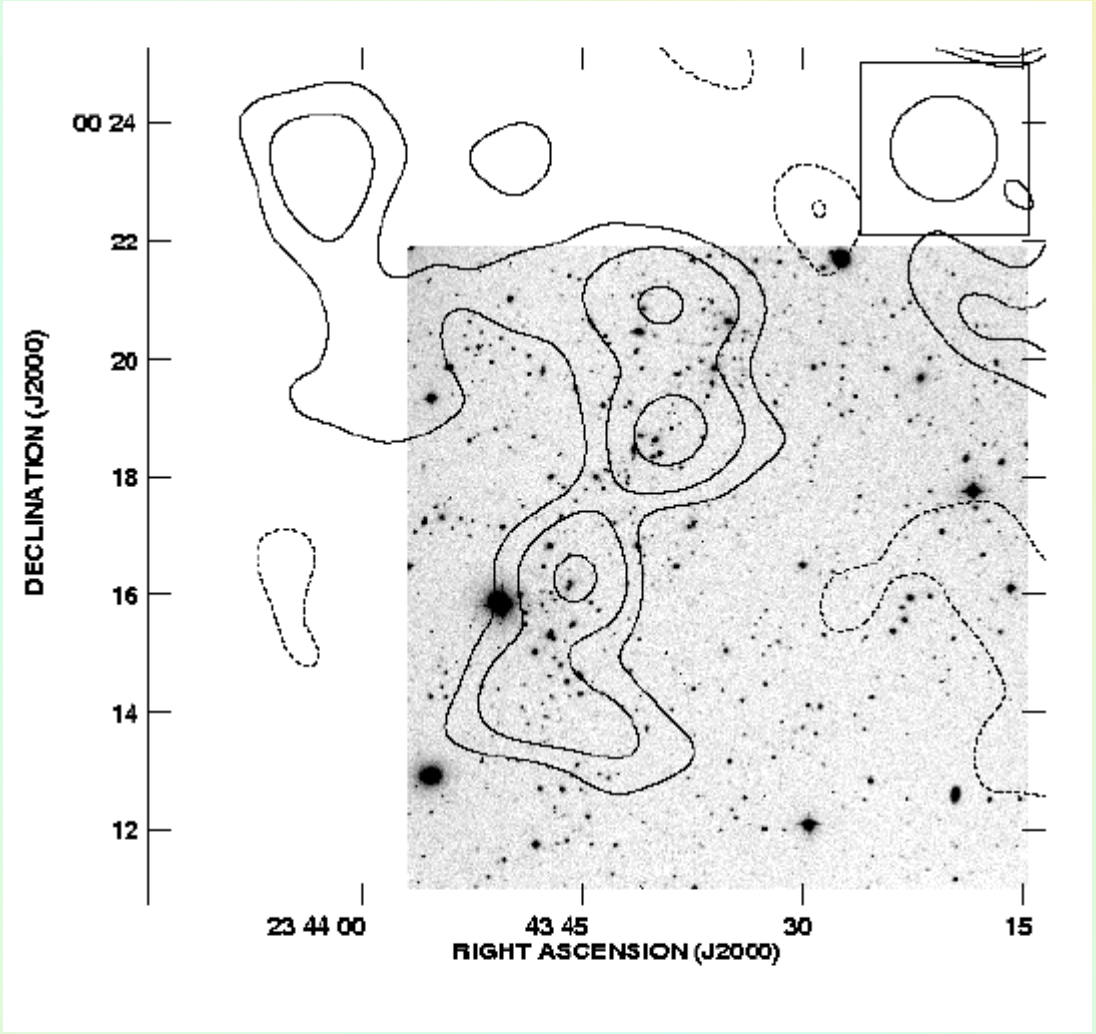
Radio galaxy at z = 5.2
(van Breugel et al 1999)

Filament of galaxies ZwCl 2341.1+0000

z ~ 0.3

Size ~ 4 Mpc





(Bagchi et al. 2002)

320 MHz VLA

Clusters

- Magnetic fields are common : few μG
  not only in clusters with halos

- In cooling flow clusters, magnetic fields are higher : 10-30μG

- Magnetic fields show structure:
  coherence length of 5-10 kpc (smaller in CF)
  possible filaments /flux-ropes
  radial profile : $B \propto n^{?}$

ICM

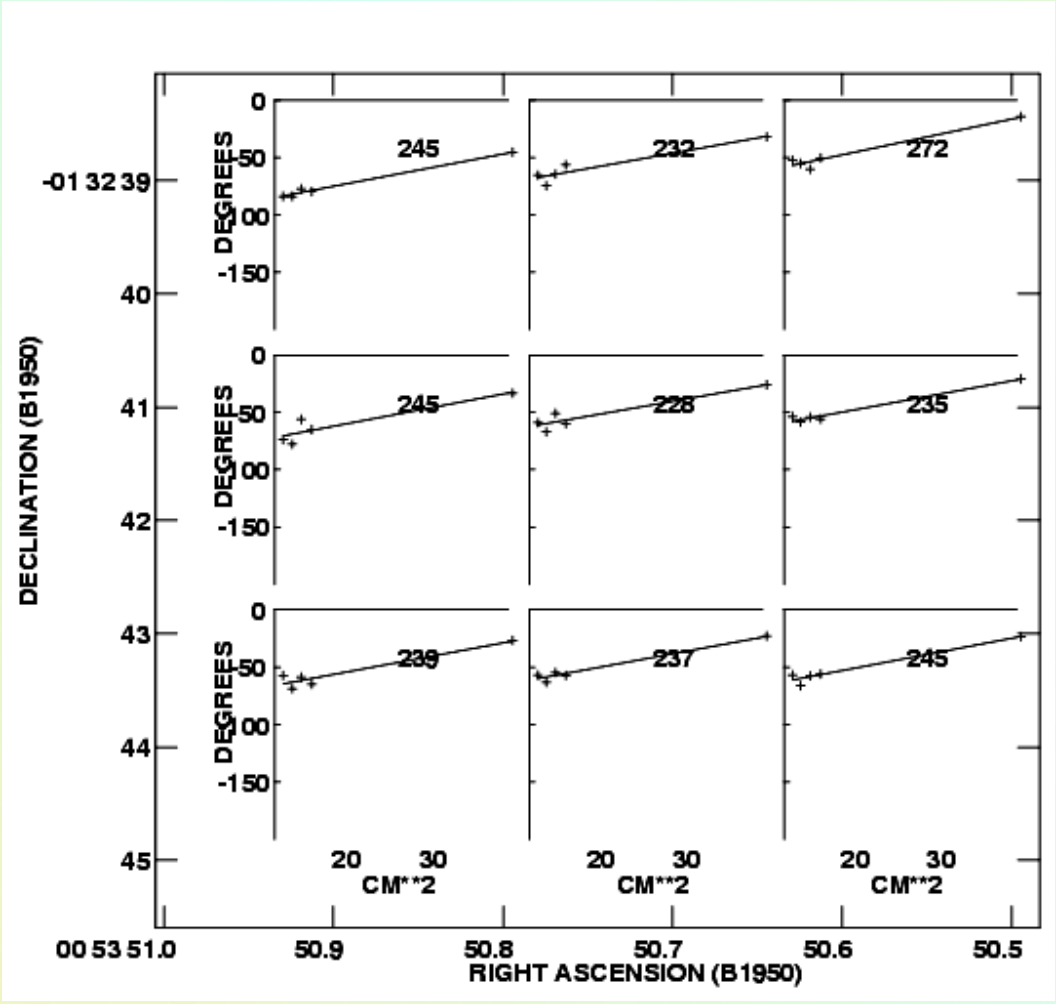
- Limits around 10^{-2} 10^{-3} μG

LOFAR

Low frequency ➔

- Diffuse synchrotron emission of steep spectrum

- Polarized emission
  sources of low RM
  ➔ weak magnetic fields



λ^2

$\Delta\theta = 10^o$

$\nu = 240$ MHz,
$\Delta\nu = 32$ MHz

RM = 0.4 rad/m^2

POLARIZATION

➔ NEED HIGH RESOLUTION TO

- reduce beam depolarization
- resolve foreground screens (? host galaxy,
  ? local turbulence,
  ? clouds ..)
- distinguish int/ext Faraday effect

➔ EXTENDED LOFAR

OPEN QUESTIONS ON EXTRAGALACTIC B FIELDS

Intensity: profile ?
correlation to cluster properties (e.g.temperature) ?
patches ?

Structure: degree of ordering ? (polarization of halos + RM)
filaments ?
existence of different coherence scales ?
field reversals ?

Origin: primordial ?
injected from galactic winds ?
injected from active galaxies ?
produced in shock waves of large scale structure formation?

THANK YOU