Radio Observations of Magnetic fields

in galaxy clusters

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Galaxy Clusters

Hot Gas (10^7 - 10^8 °K)

Optically-thin bremsstrahlung emission

Soft X

~15% of the Mass

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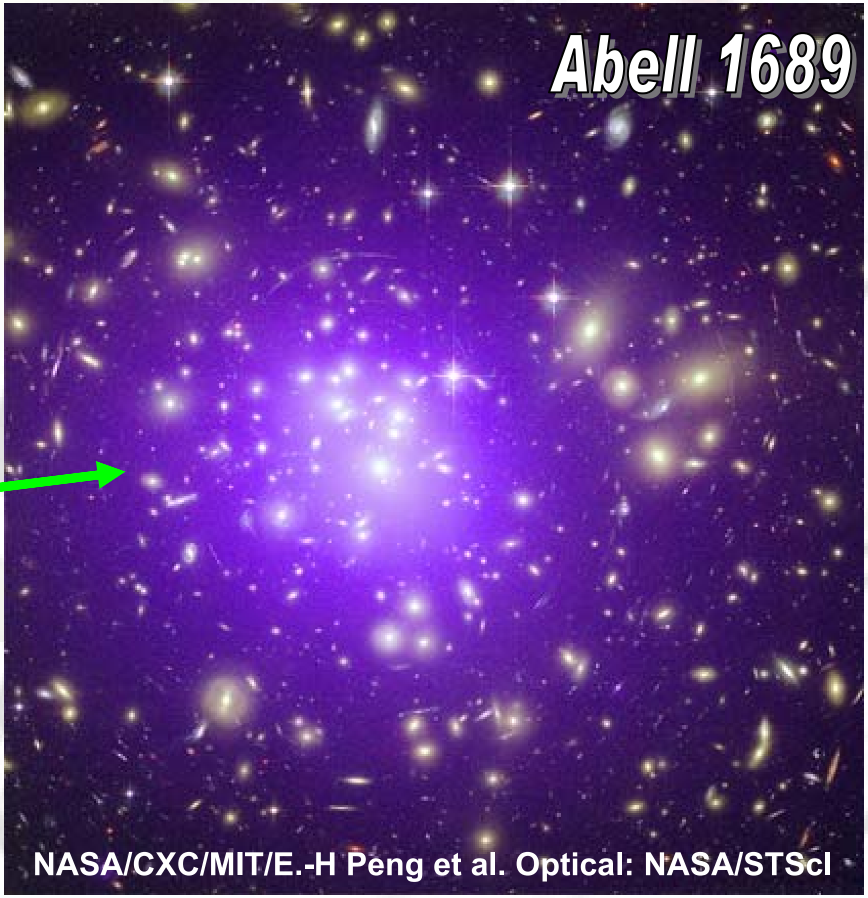
Dark Matter

Revealed by gravitational lensing

~80% of the Mass



Galaxy Clusters

Hot Gas (10^7 - 10^8 °K)

Optically-thin bremsstrahlung emission

Soft X

~15% of the Mass

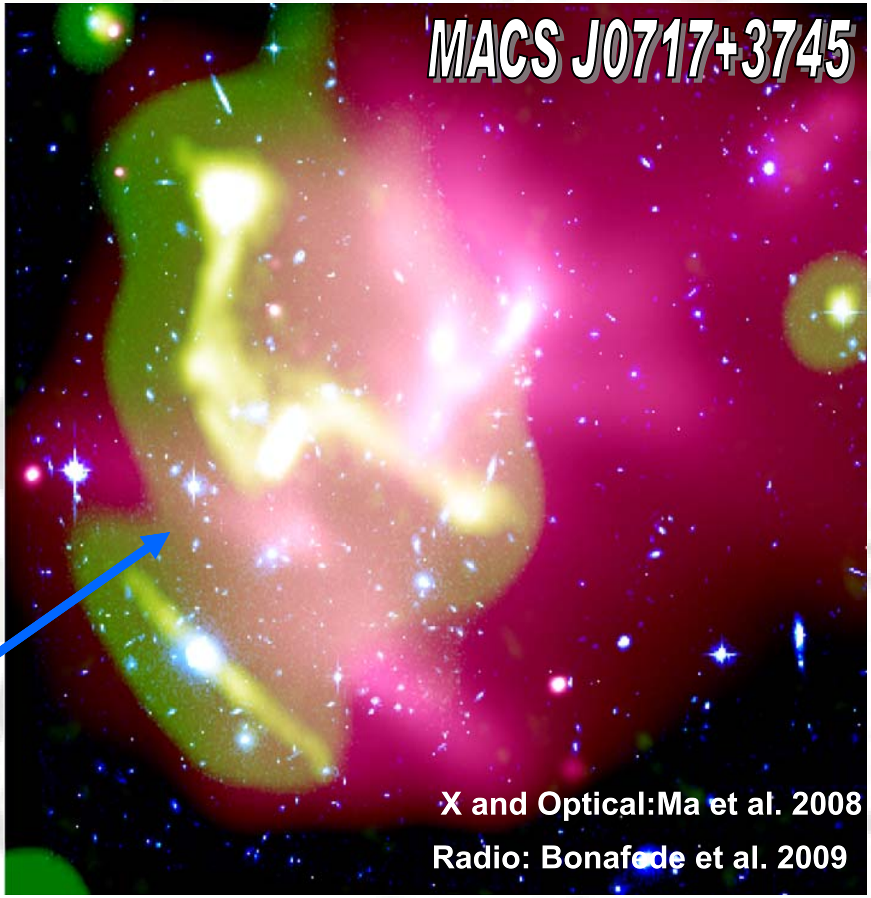
Dark Matter

Revealed by gravitational lensing

~80% of the Mass

Magnetic fields

Revealed by radio emission



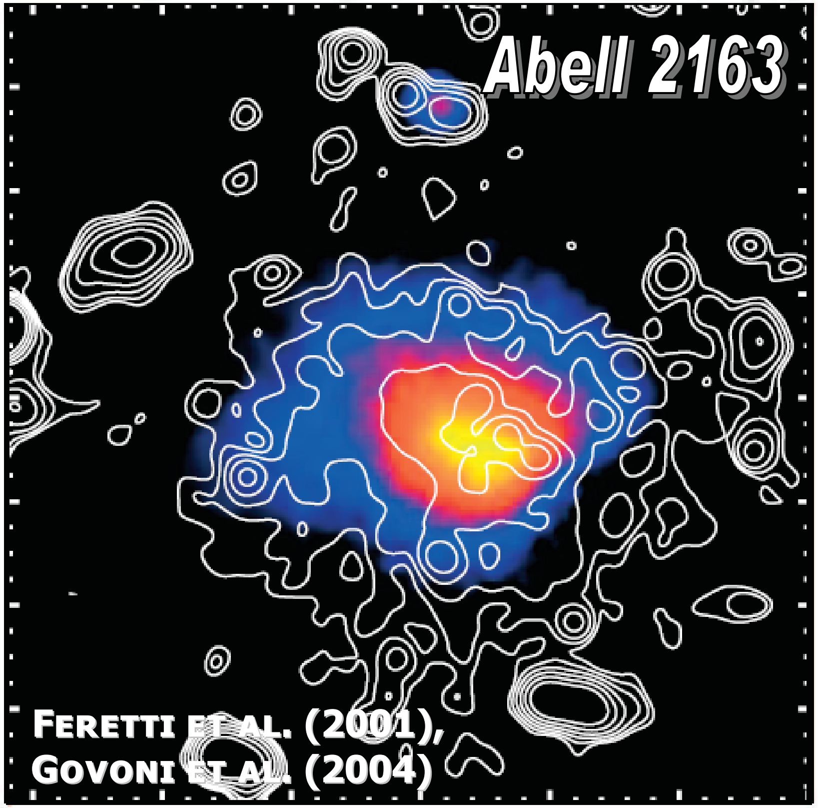
Radio Halos

Synchrotron emission on Mpc scale

Low surface brightness
~ 1 μJy/arcsec^2 at 1.4 GHz

Steep spectrum ($\alpha > 1$)

Usually un-polarized



Origin of the emitting particles?

Particles generated or accelerated everywhere in the cluster

Turbulence? (e.g. Petrosian 2001, Brunetti 2001)

Secondary origin from p-p collisions? (e.g. Dennison 1980, Blasi & Colafrancesco 1999)
Difficult to reconcile with present radio and gamma observations

Polarized emission from Radio Halos

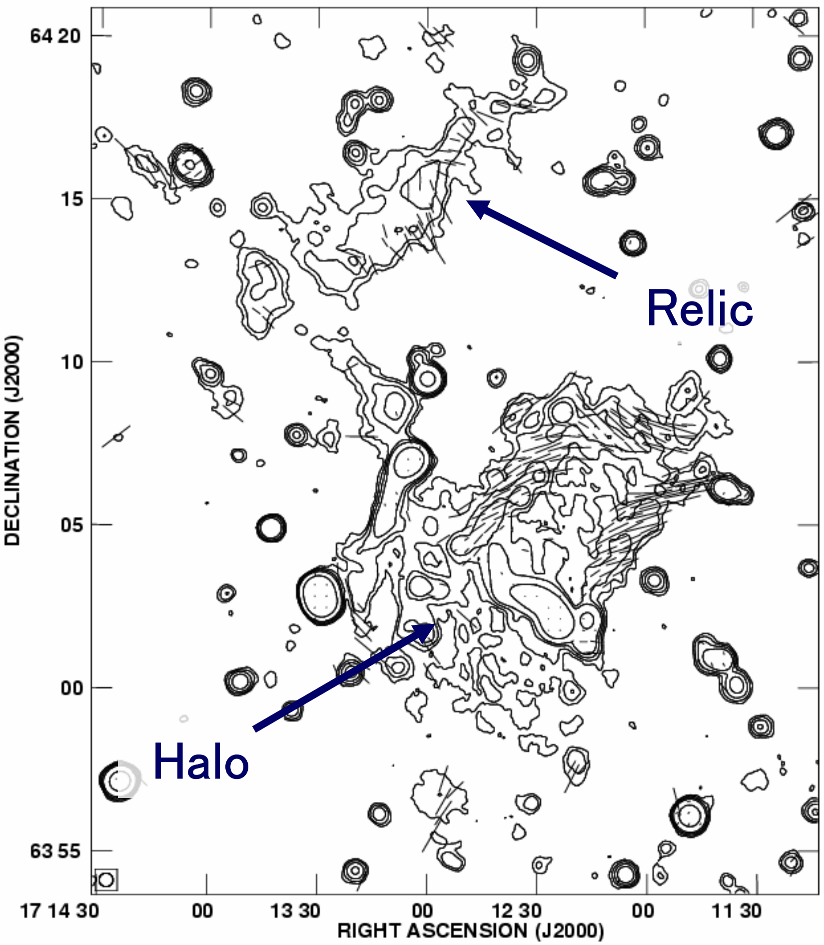
Only two clusters so far:

A2255

z=0.08

Govoni et al. 2005

See also Pizzo et al. 2010



VLA 1.4 GHz, Beam FWHM 25”

Polarized emission from Radio Halos

Only two clusters so far:

A2255

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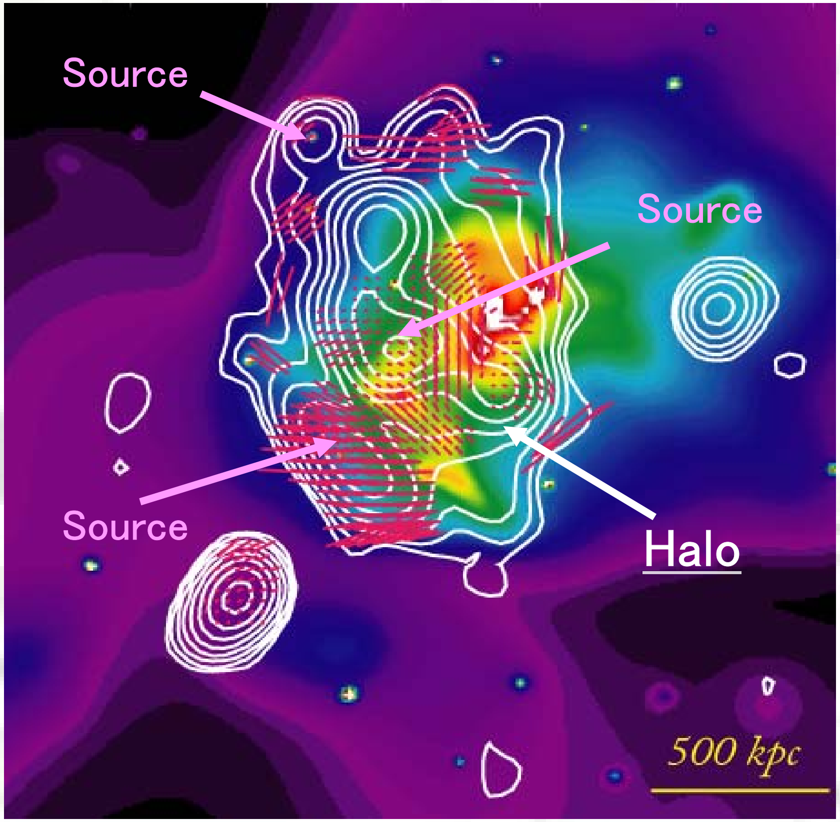
Macs J0717 + 3745

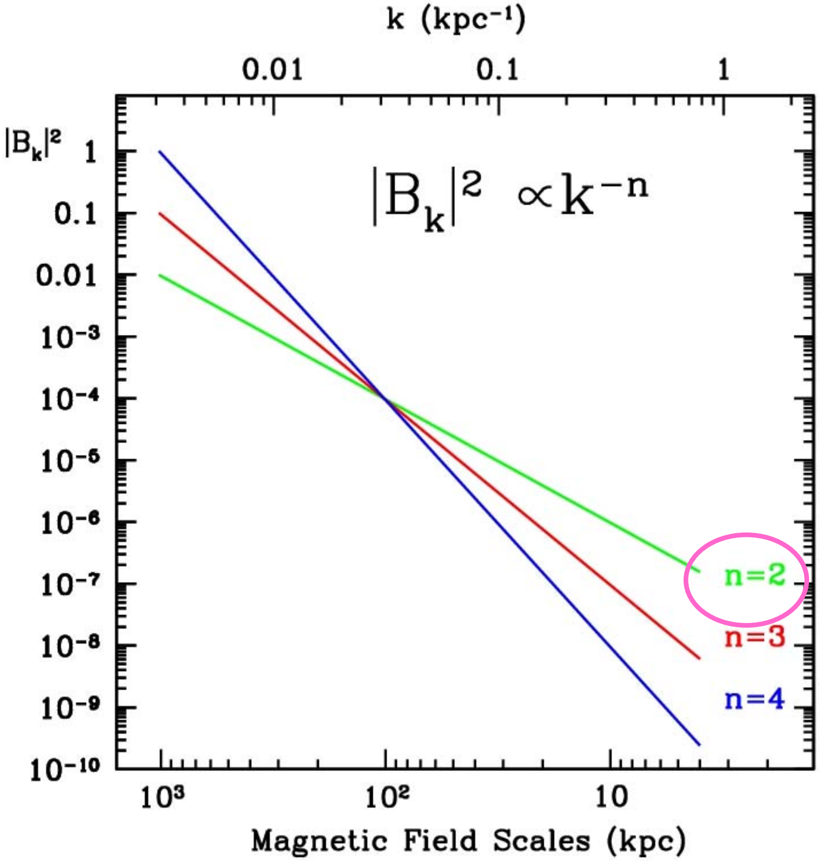
z=0.545
Bonafede et al. 2009
See also ***van Weeren et al. 2009***

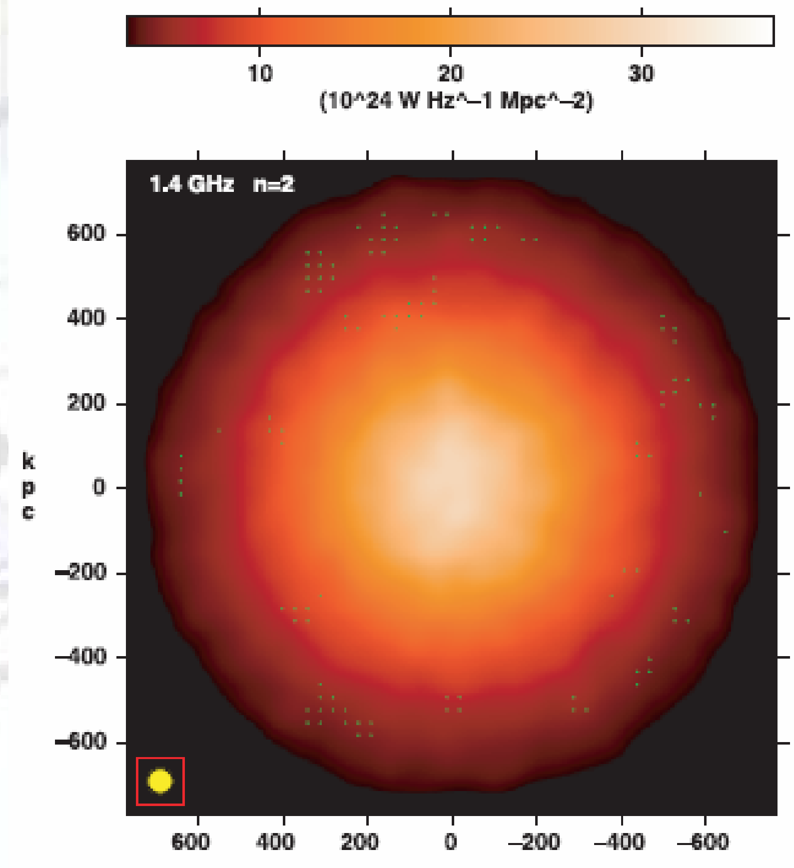


Chandra [0.1 –2.4 keV] ad VLA 1.4 GHz, Beam FWHM 25”

Polarized emission from Radio Halos

The magnetic field power spectrum:
simple model: single power–law



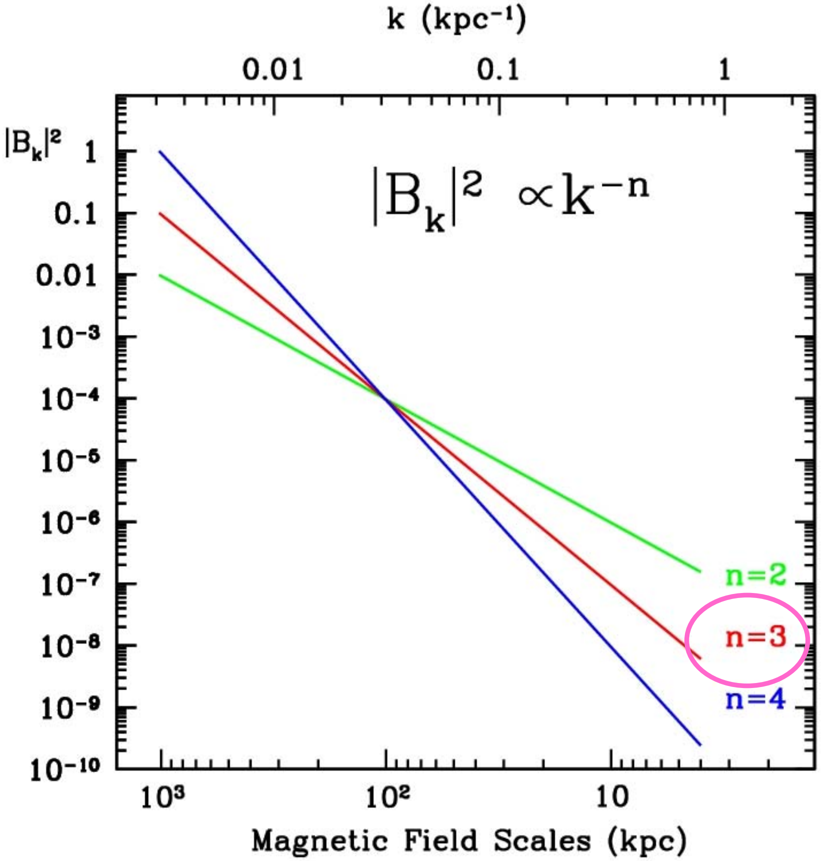


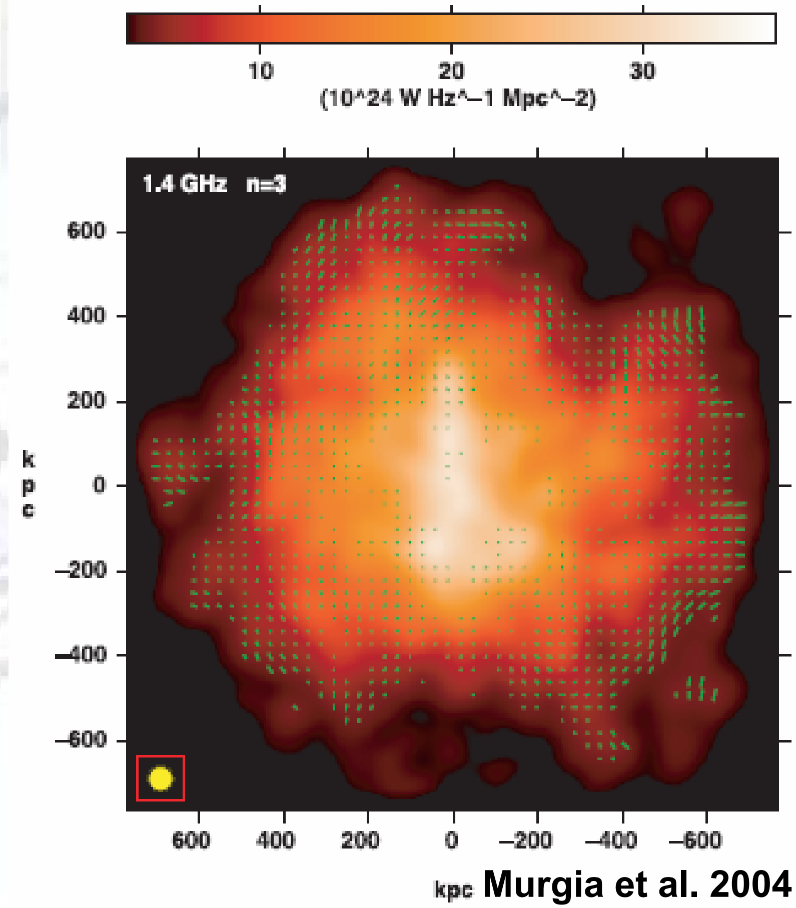
Murgia et al. 2004

$P_{200\text{kpc}} < 1\%$
(at 1.4 GHz)

Polarized emission from Radio Halos

The magnetic field power spectrum:
simple model: single power-law



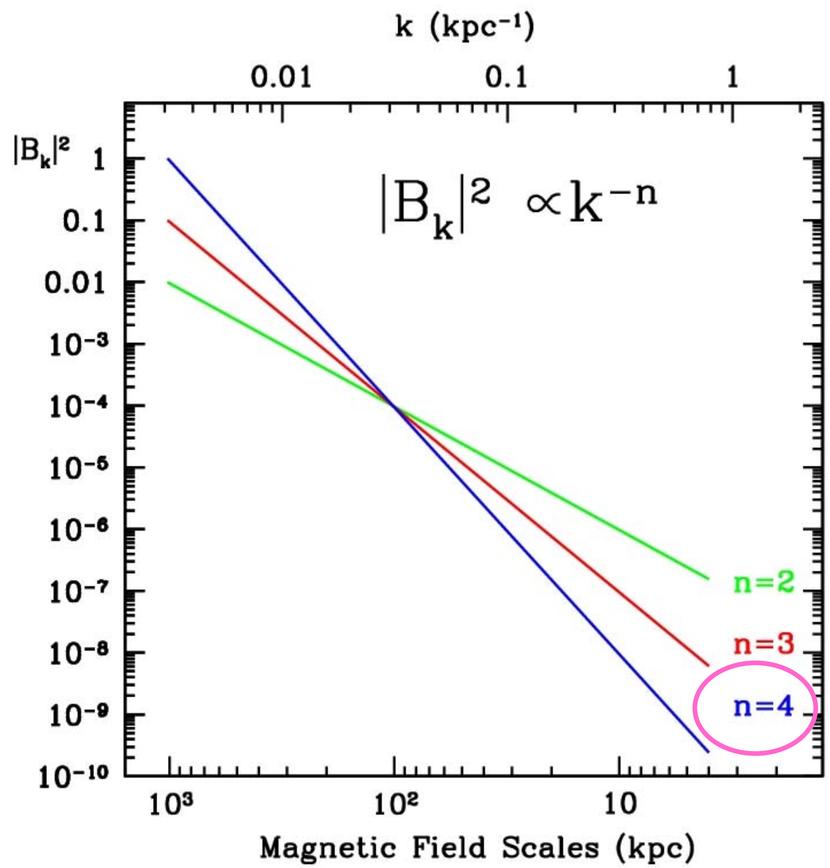


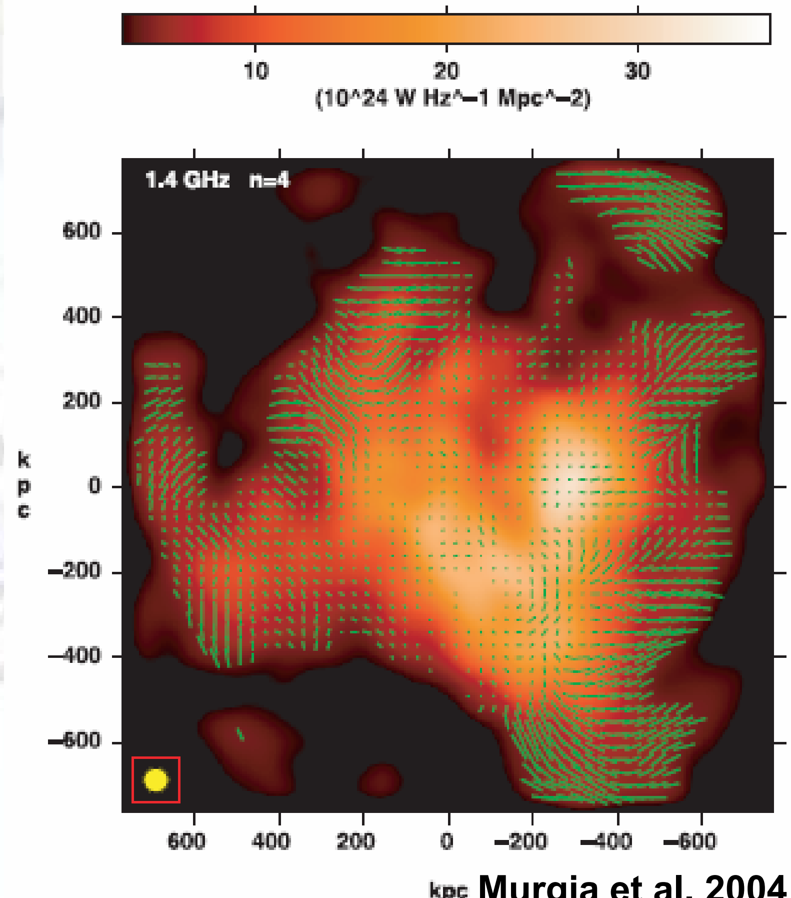
Murgia et al. 2004

P_{200kpc} ~ 3%
(at 1.4 GHz)

Polarized emission from Radio Halos

The magnetic field power spectrum:
simple model: single power-law





Murgia et al. 2004

P_{200kpc} ~7%
(at 1.4 GHz)

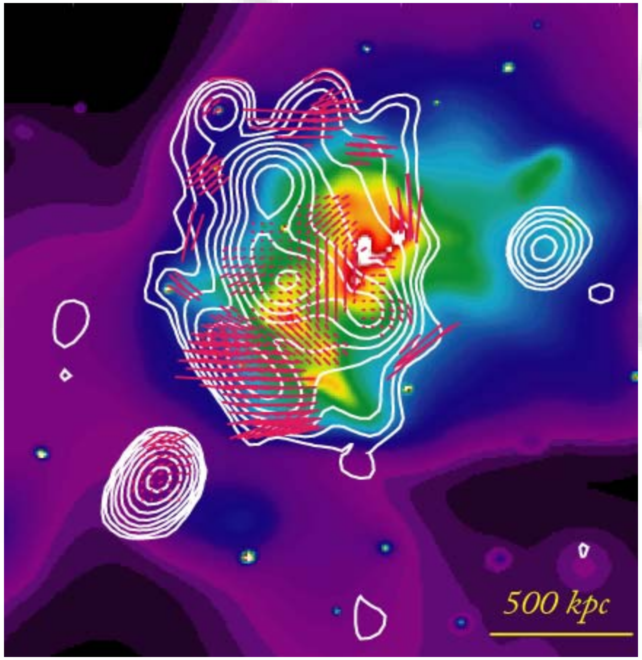
Polarized emission from Radio Halos

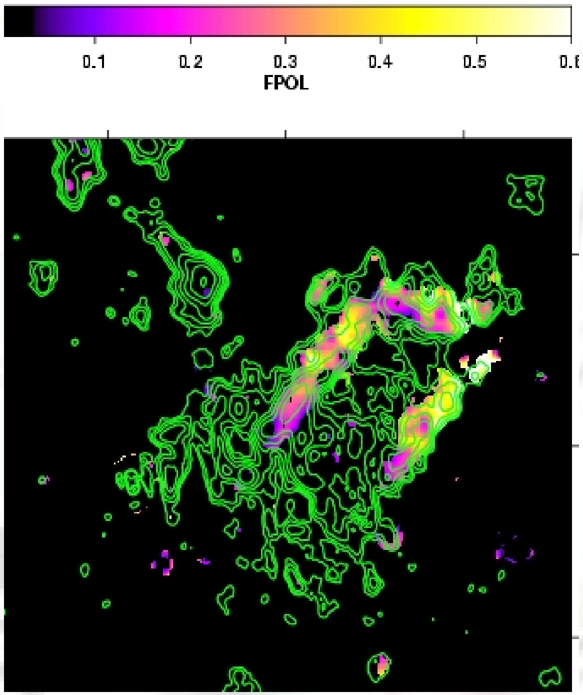
$$|B_k|^2 \propto k^{-n}$$

A2255

Govoni et al. 2006

-Power spectrum spectral index:
n=2 at the cluster center
n=4 at the cluster periphery





MACS J0717 + 3745

Bonafede et al. 2009

-Power spectrum spectral index:
n> 3

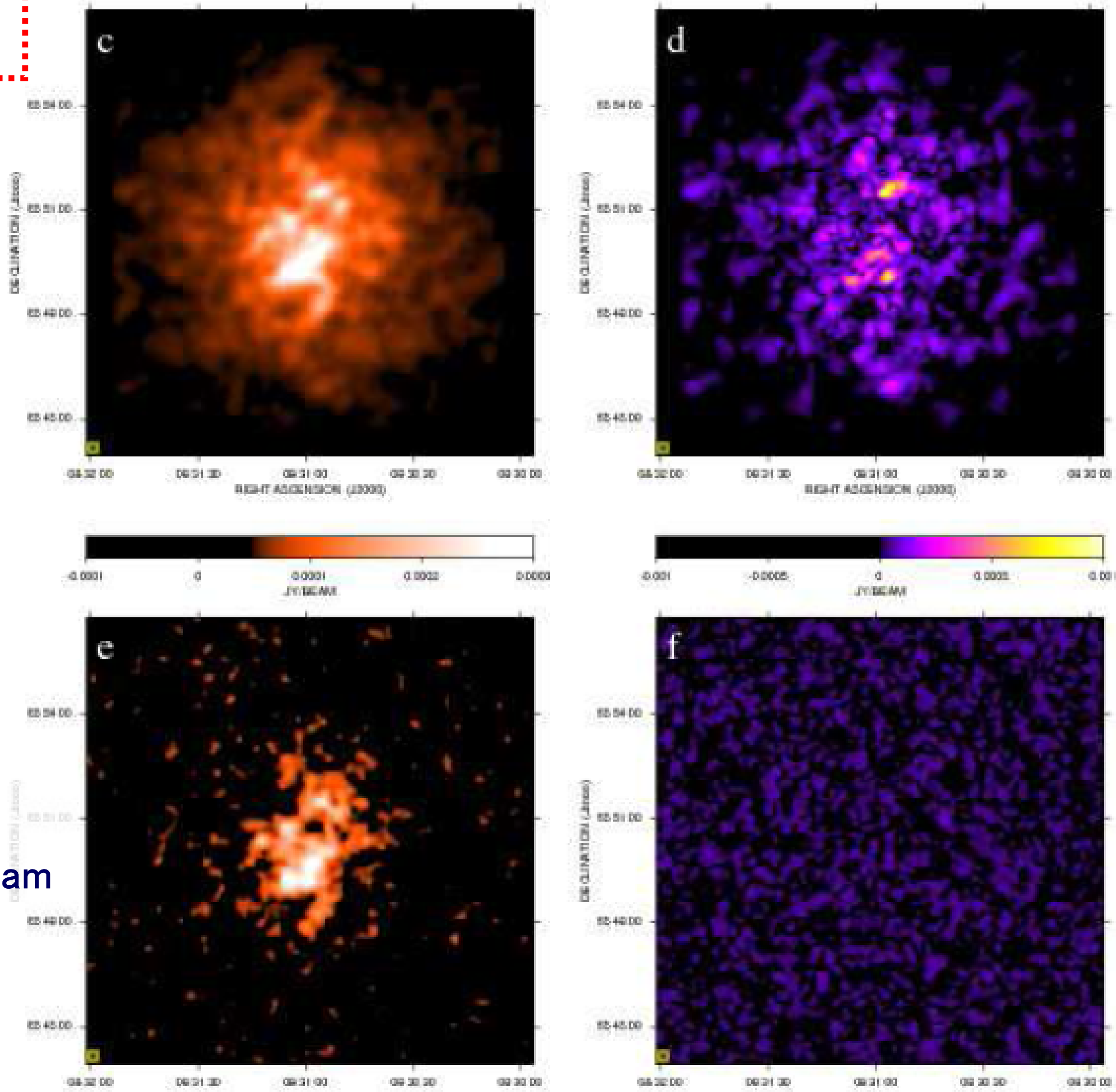
Polarized emission from radio halos

1.4 GHz

15 arcsec resolution for a cluster at z~0.2

Total intensity | Polarized intensity

Intrinsic

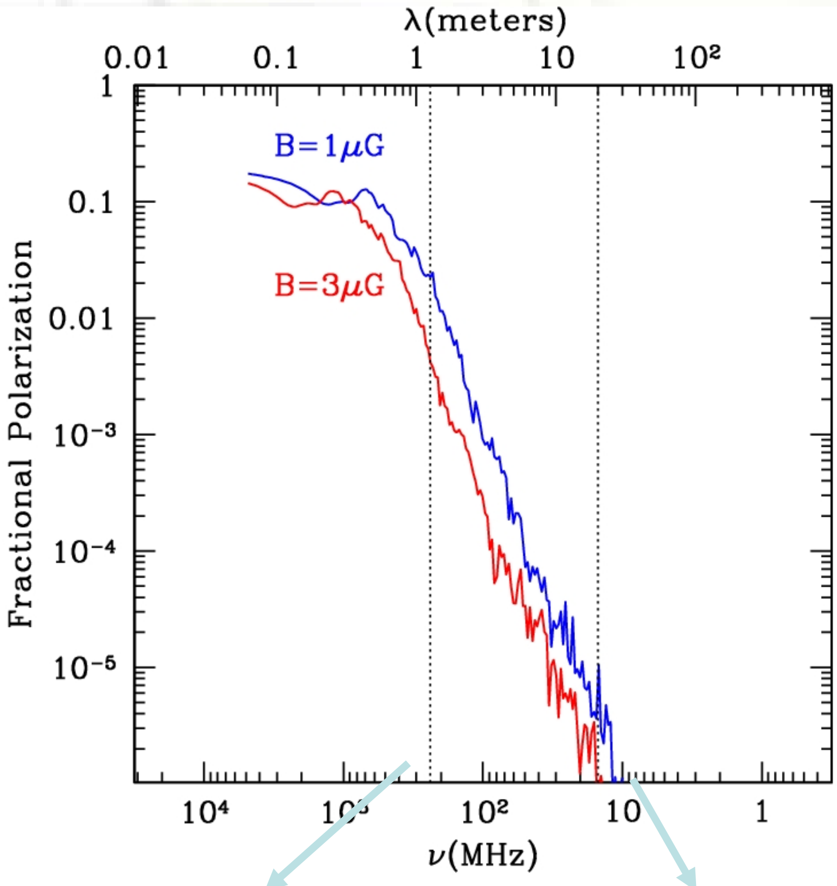


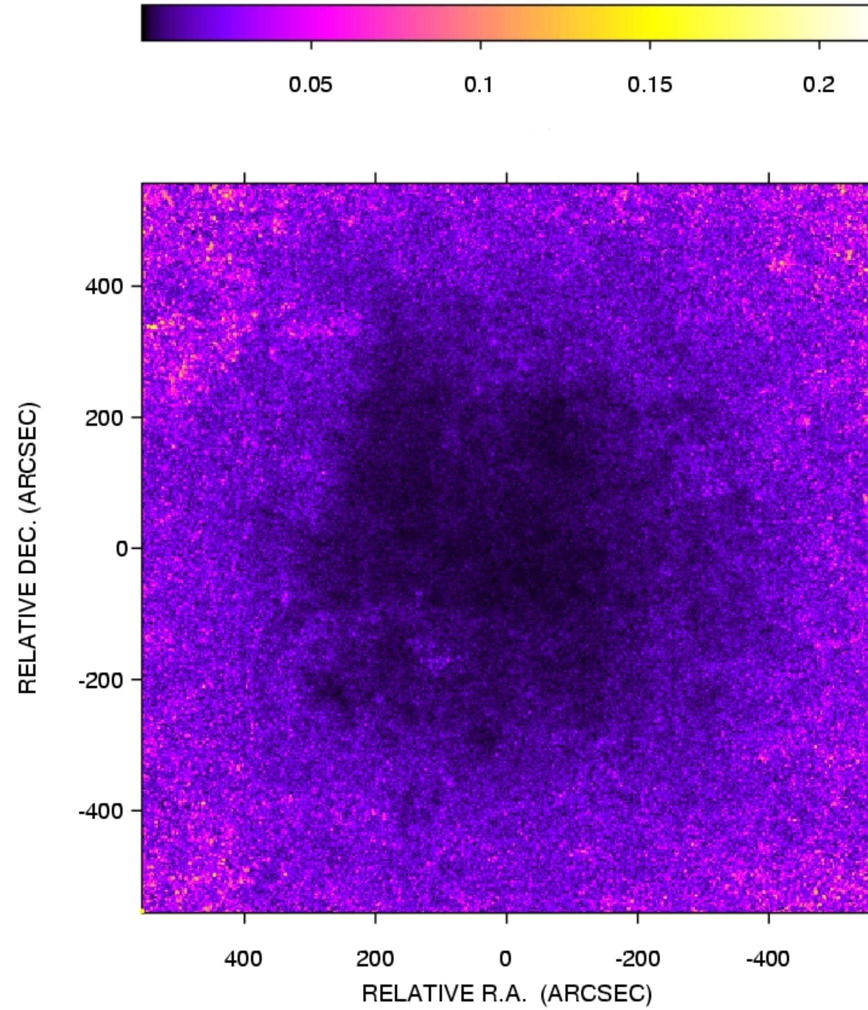
Noise added

Noise rms ~ 25 μJy/beam

Vacca et al. 2010

LOFAR: Polarized emission from Radio Halos ?





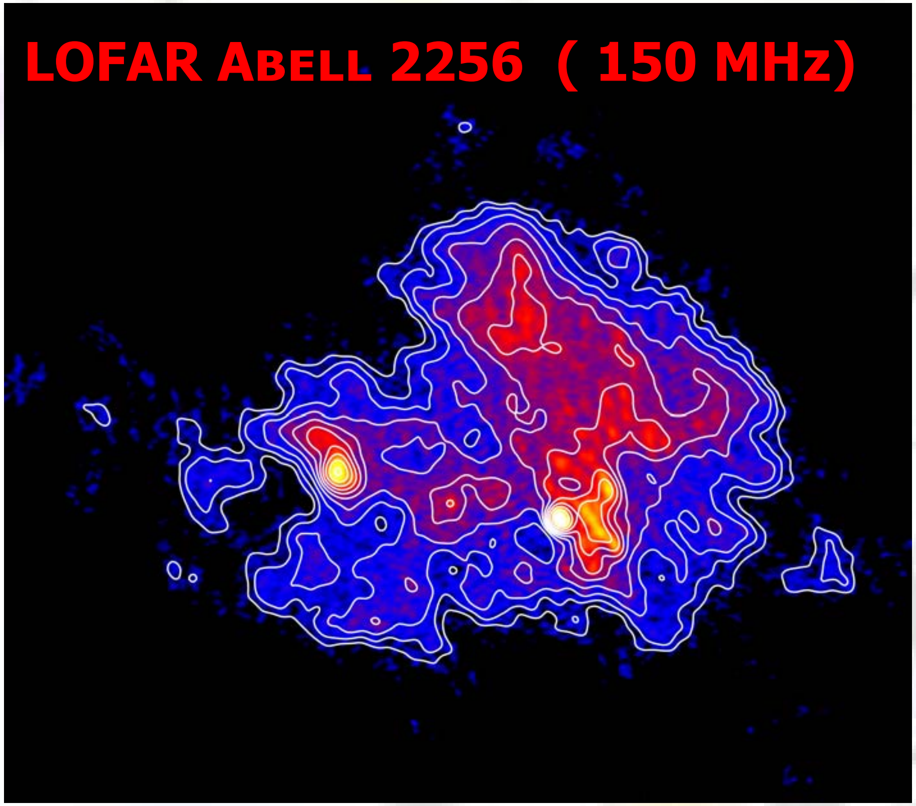
Frequency=240 MHz
Beam=3.1″
Sensitivity=0.076 mJy/beam

Frequency=15 MHz
Beam=50″
Sensitivity=11 mJy/beam

Courtesy of F. Govoni

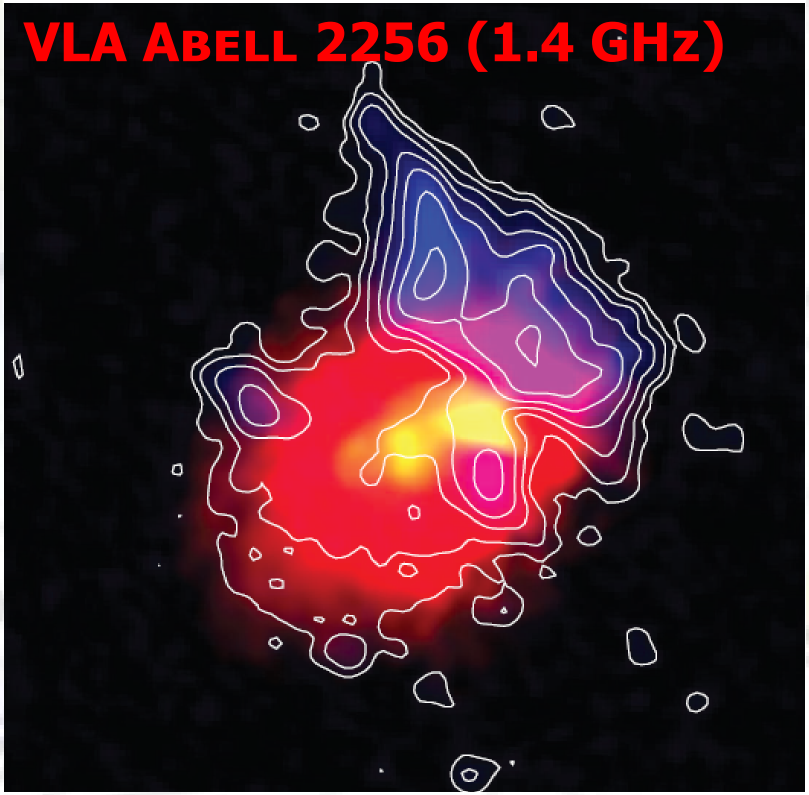
Chance of detecting polarization at level of few % at least at the higher frequencies

Radio Halos: importance of low frequency observations



van Weeren, Shulevski , van der Tol, Pizzo,
Orrù , Bonafede, Ferrari, Macario

and the survey key project team



Clarke & Ensslin 2004

LOFAR → spectrum over a wide frequency range – radio halo statistics

test of the formation scenarios

Radio Relics:

Synchrotron emission on Mpc scale in the cluster outskirts

Low surface brightness ~ 1 μJy/arcsec^2 at 1.4 GHz

Steep radio spectrum (α >1)

Polarized ~ 20% at 1.4 GHz

Origin of the emission?

Bonafede et al. 2009

different models, they all require shock waves

Radio Relics

❖ Radio ghost:
aged radio plasma revived by merger or shock wave through adiabatic compression
(Ensslin & Gopal Krishna 2001)

→ **Curved radio spectrum**

→ **Filamentary or toroidal morphology**

→ **Polarization vectors perpendicular to the filamentary structure**

❖ "Radio gischt"[1]:

Diffusive Shock Acceleration energize cosmic ray electrons that emit synchrotron in magnetic field amplified by shock
(Ensslin et al. 98)

→ **Straight radio spectrum**

→ **Arc-like**

→ **Polarization vectors perpendicular to the relic main axis**

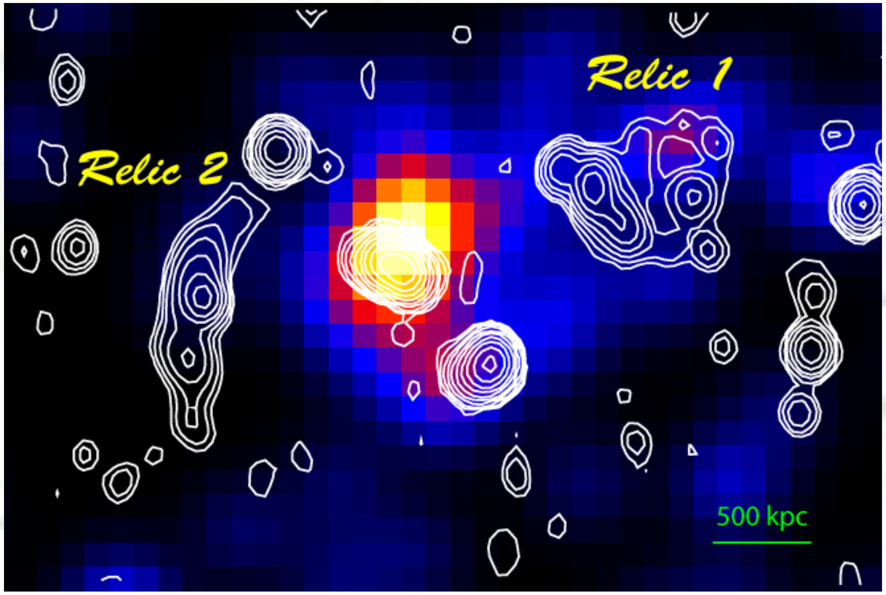
1 Definition by Kempner et al. (2004)

Cluster with double Radio Relics

A2345

z=0.177

Bonafede et al. 2009



VLA at 1.4 GH, Beam FWHM = 50″

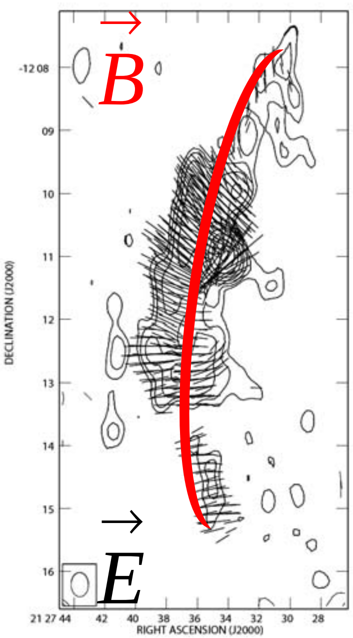
ROSAT PSPC 0.1 -2 keV band

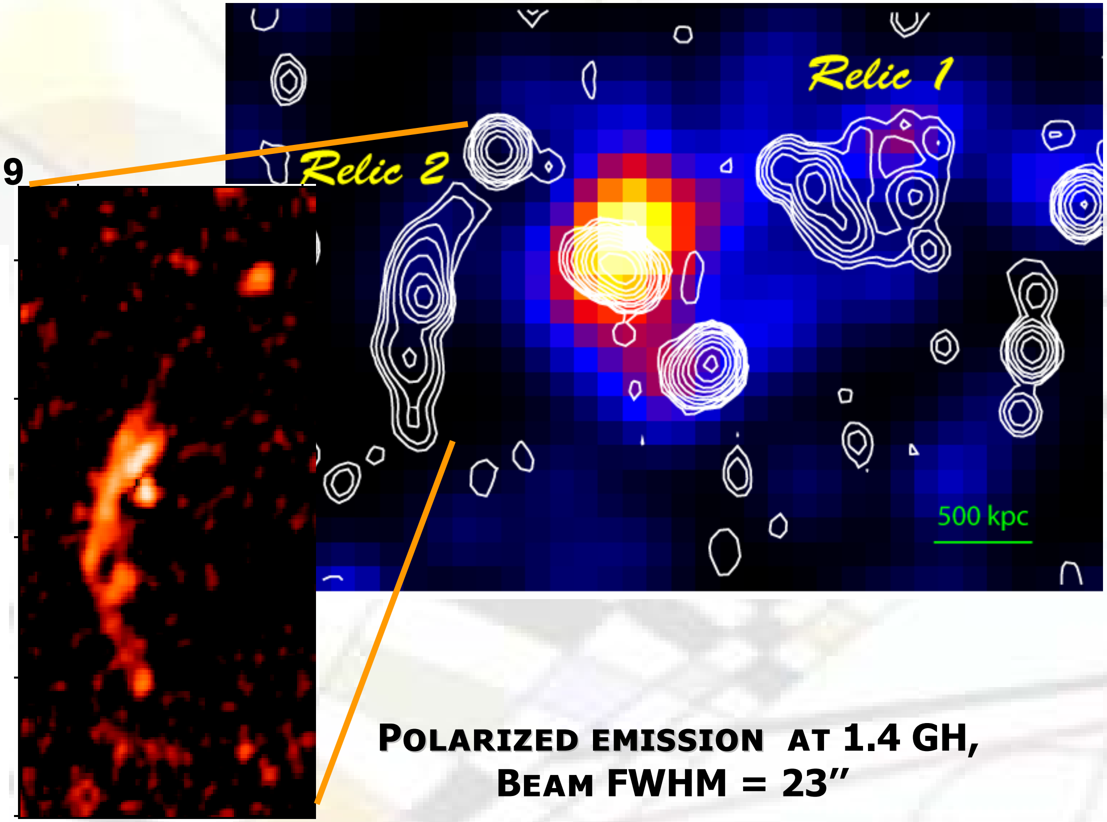
Cluster with double Radio Relics

A2345

z=0.177

Bonafede et al. 2009





Polarized emission at 1.4 GH,
Beam FWHM = 23″

Mean fractional polarization 24%

Arc-like structure of the relic

"Radio gischt" prediction

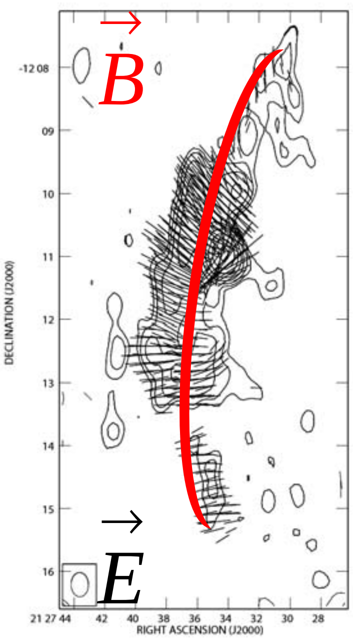
Magnetic field aligned with the relic main axis

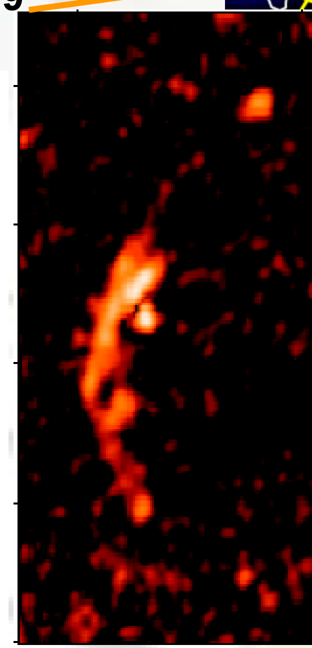
Cluster with double Radio Relics

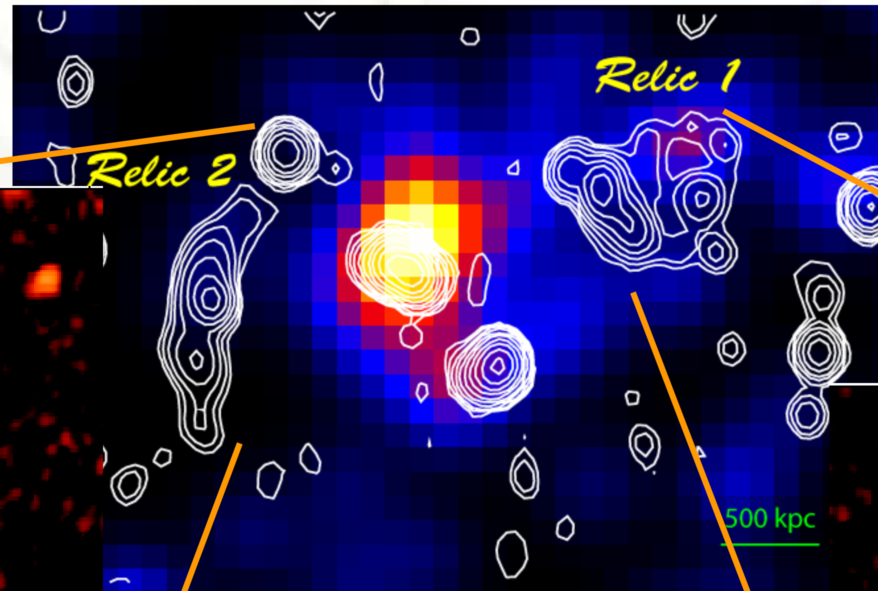
A2345

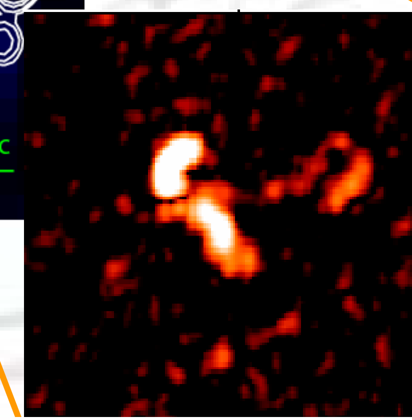
z=0.177

Bonafede et al. 2009









Polarized emission at 1.4 GH,
Beam FWHM = 23''

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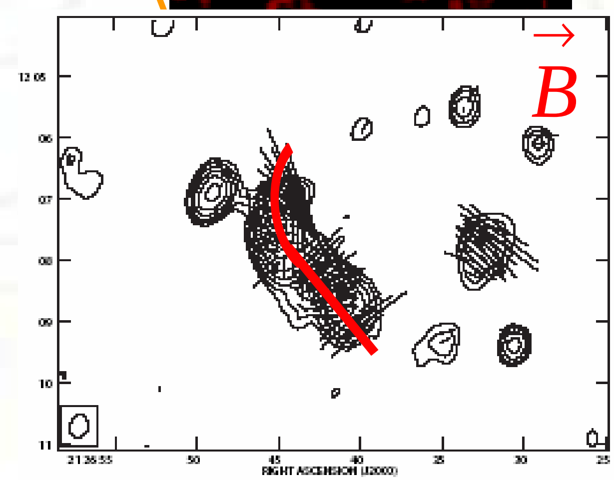


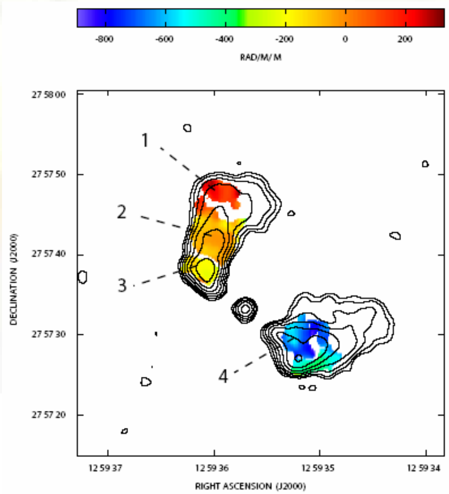
Mean fractional polarization 20%

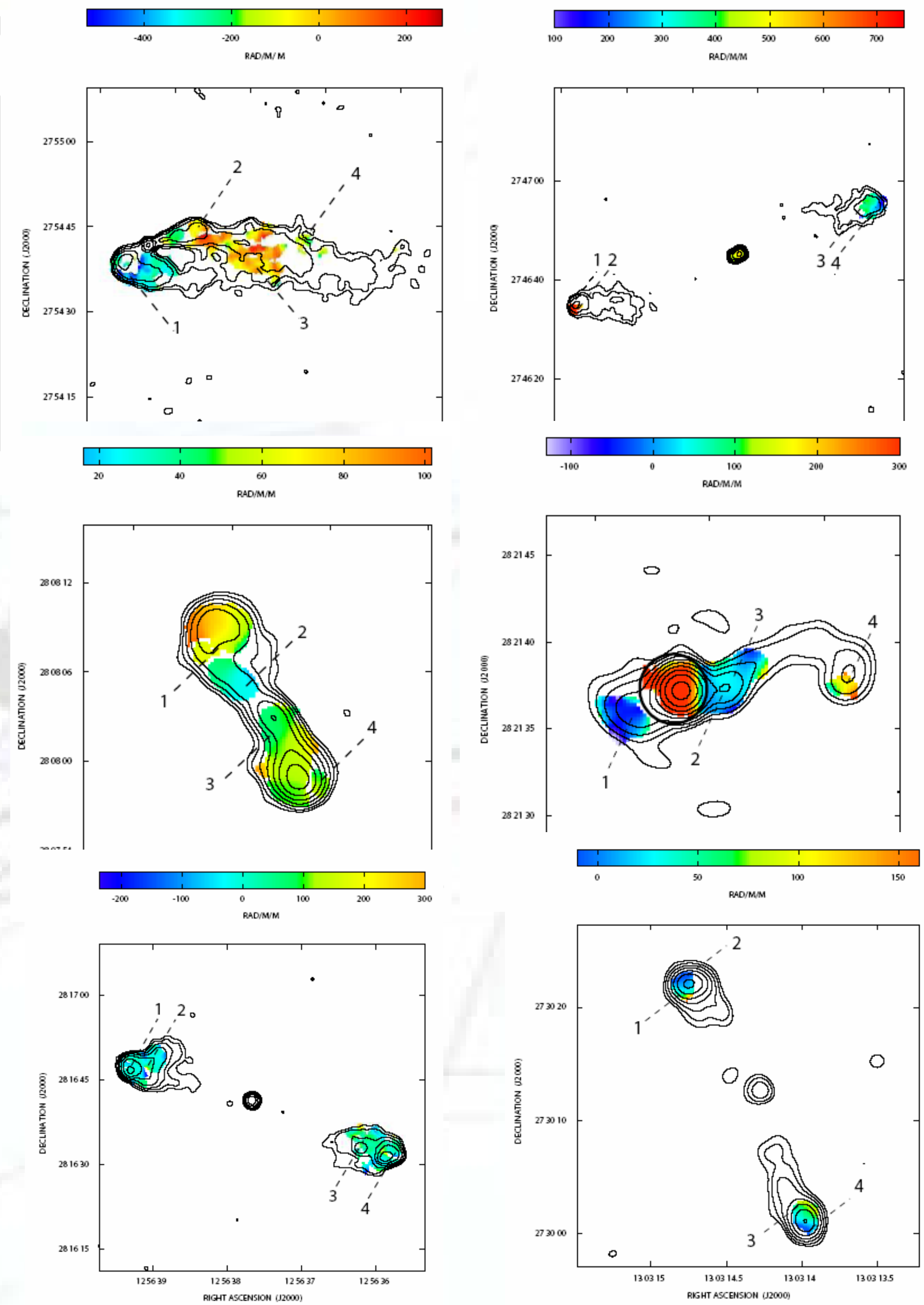
Magnetic fields from Faraday RM

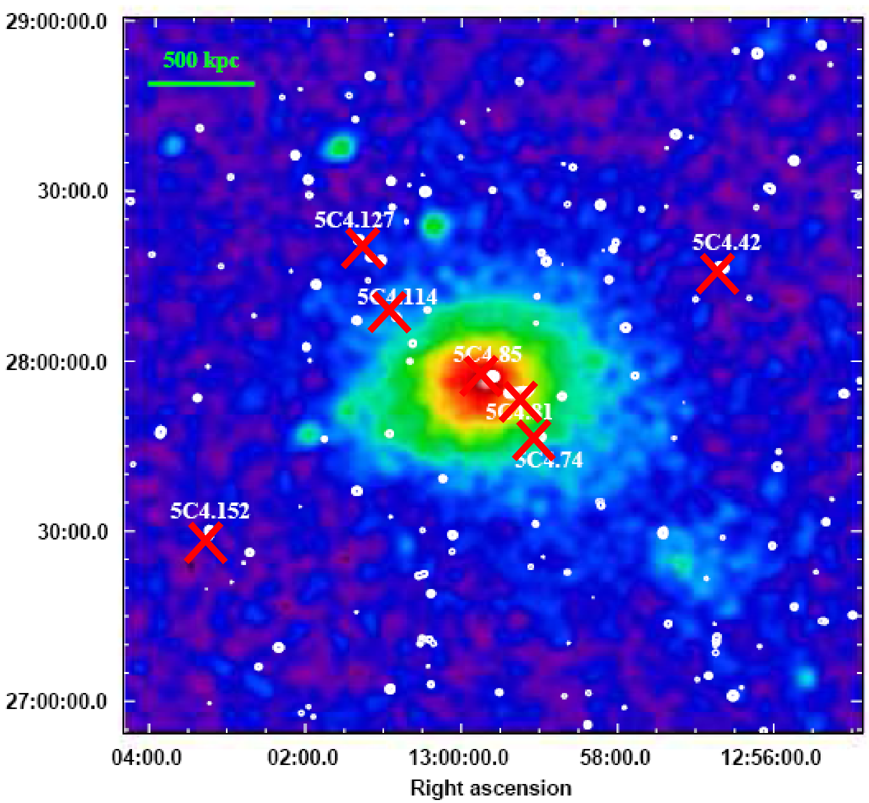
Coma

z=0.023
Bonafede et al. 2010

7 sources observed at
4-5 freq.
(from 1.4 to 8.9 GHz)
Resolution= 0.7 kpc







Modeling the magnetic field power spectrum

- **The vector potential A(k)** with a given **power spectrum**

$$|A_k|^2 \propto k^{-\zeta}$$

Fourier components A(k)

Rayleigh distribution

phases random

- **The magnetic field** $\tilde{B}_k = ik \times \tilde{A}_k$

FFT → B_z in the real space

$$\nabla \cdot \vec{B} = 0$$

$$|B_k|^2 \propto k^{-n}$$

Power spectrum degeneracy
(higher n, lower k_{min})

Schuecker et al 04
from pseudo-pressure map
KOLMOGOROV POWER SPECTRUM n=11/3

COMA

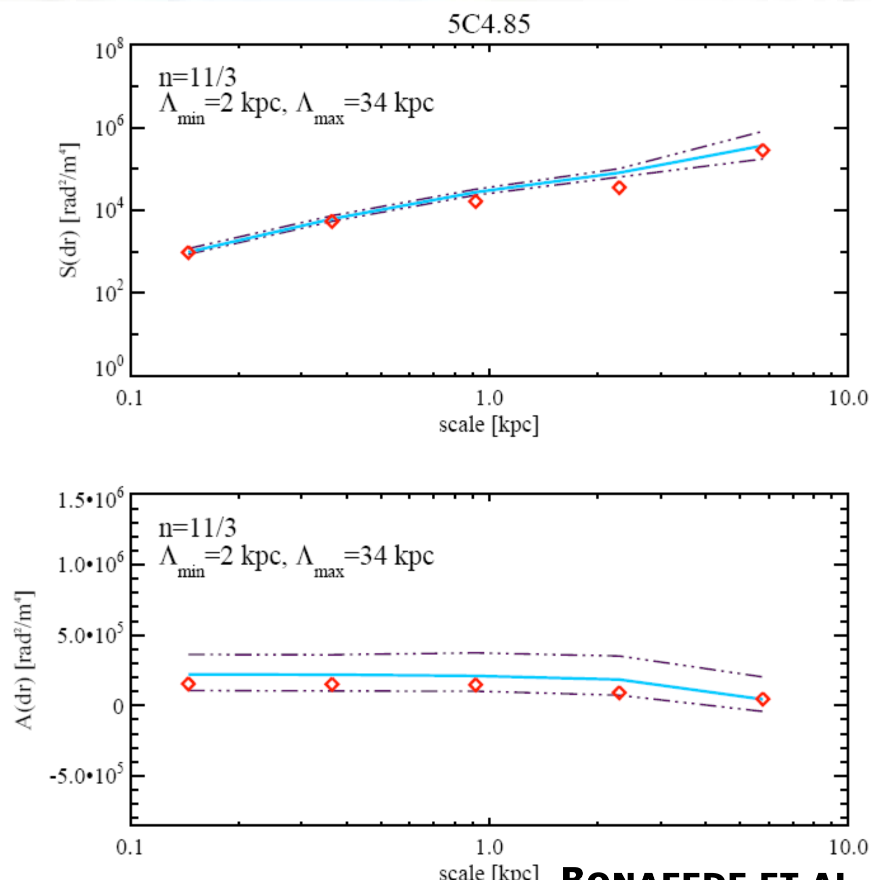
The magnetic field power spectrum

Simulated and observed RM
structure function and auto-correlation function

$$|B_k|^2 \propto k^{-n}$$

Observed

Expected for Kolmogorov Power spectrum, with scales from 2 to 35 kpc



BONAFEDE ET AL. 2010

Magnetic fields Power spectrum from Faraday RM

Coma

Bonafede et al. 2010

n = 11/3 Kolmogorov PS
Scales up to 30 kpc

A2255

Govoni et al. 2006

n = 2 (center) 4 (periphery)
Scales up to 100s kpc

A2382

Guidetti et al. 2008

n = 11/3 Kolmogorov PS
Scales up to 35 kpc

Other works based on different approaches

Hydra A

Kuchar & Ensslin 2009

Consistent with Kolmogorov PS
Single Power law from 0.3 - 8 kpc with no turnover on the large scales

A400

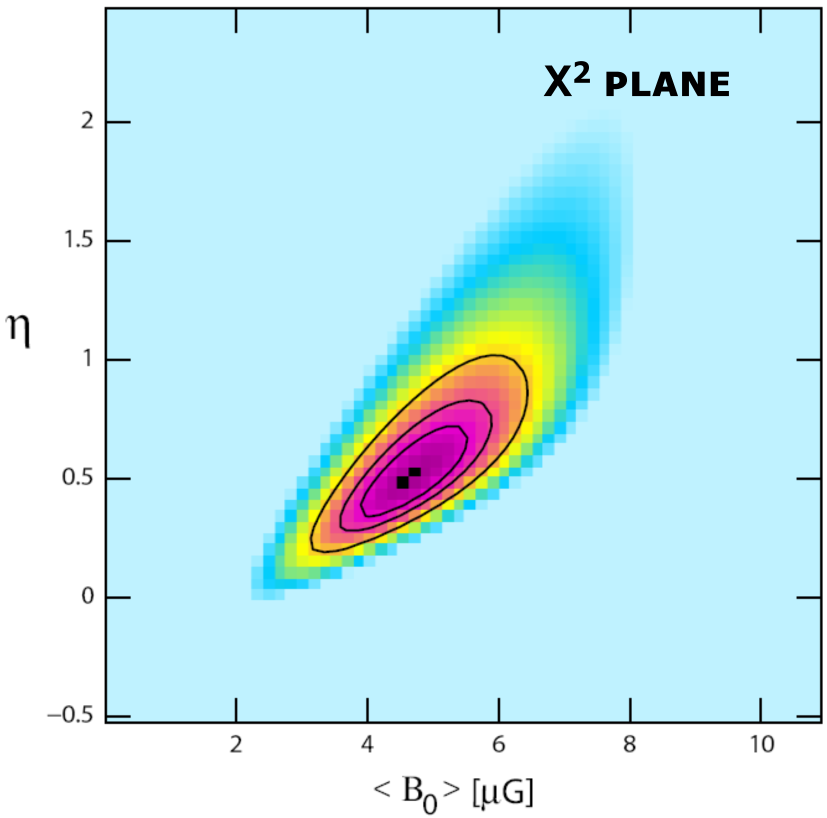
A2634

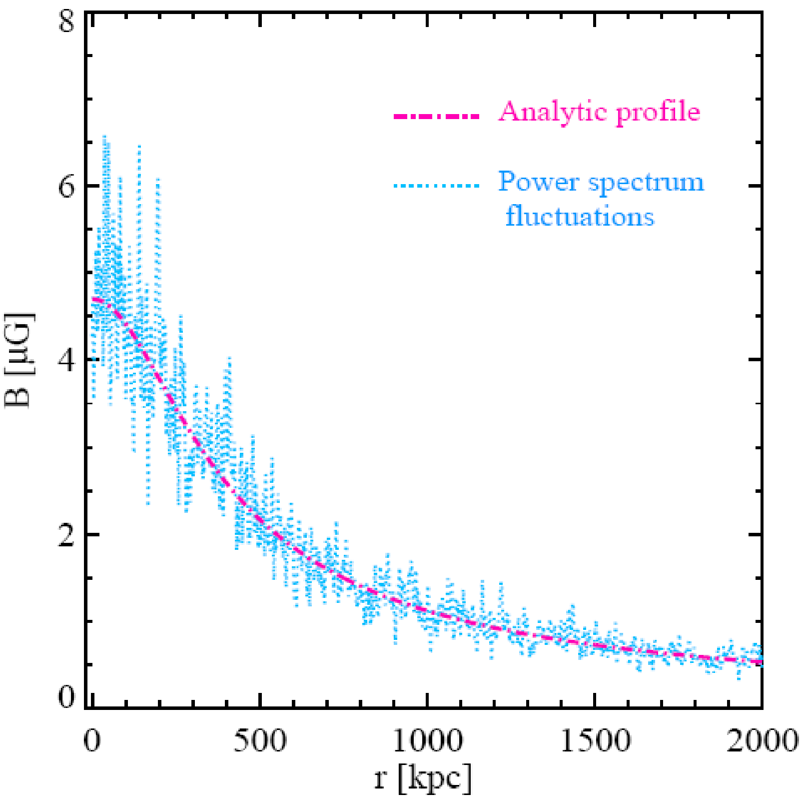
Vogt & Ensslin 2003

Consistent with Kolmogorov PS

RM observations – 3D magnetic field numerical simulations (Faraday code, Murgia et al. 2004)

$$< B > (r) = B_0 \left(\frac{n_e}{n_0} \right)^{\eta}$$





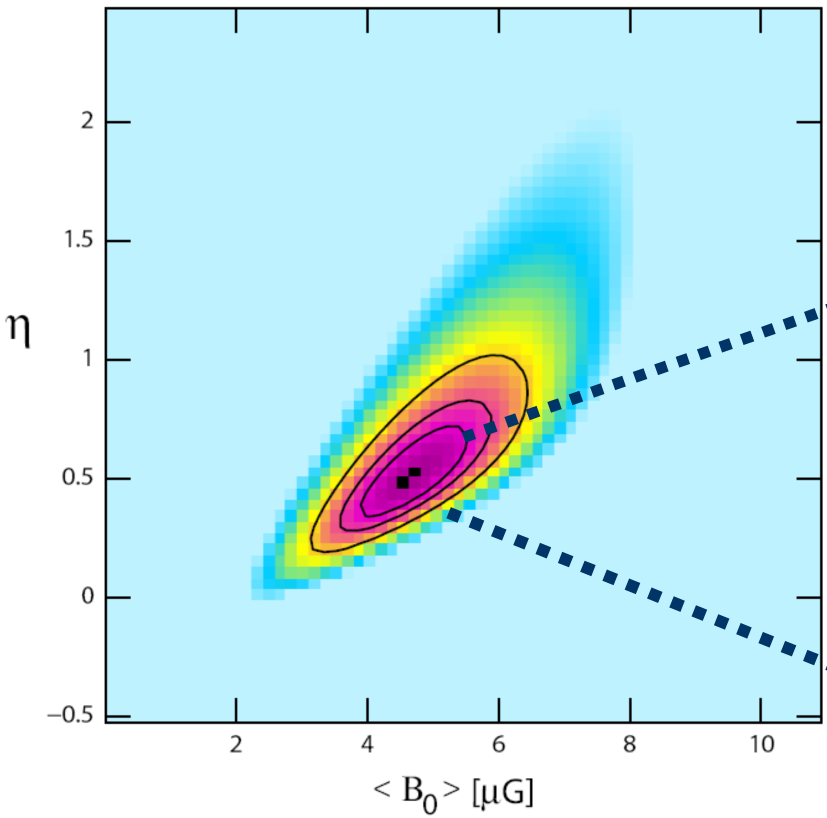
COMA CLUSTER

BONAFEDE ET AL. 2010

Best model:
B0=4.7 μG, η=0.5

RM observations – 3D magnetic field numerical simulations (Faraday code, Murgia et al. 2004)

$$< B > (r) = B_0 \left(\frac{n_e}{n_0} \right)^{\eta}$$



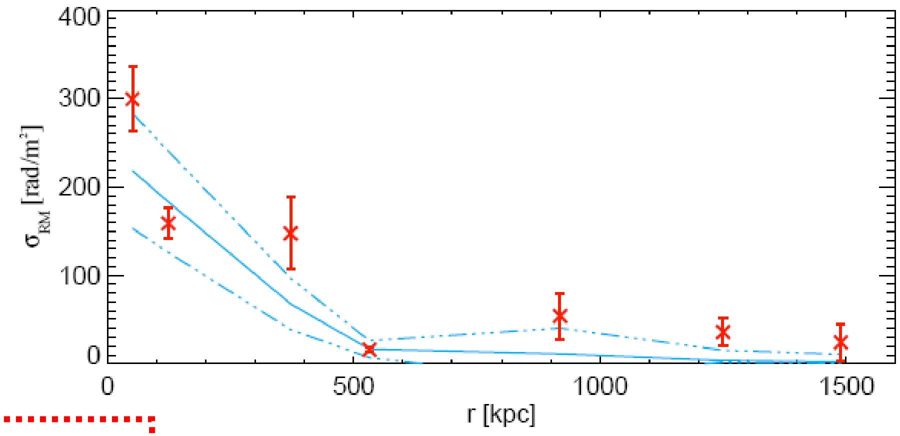
Inside **68% confidence** level
η=0.67
Magnetic field frozen into the gas

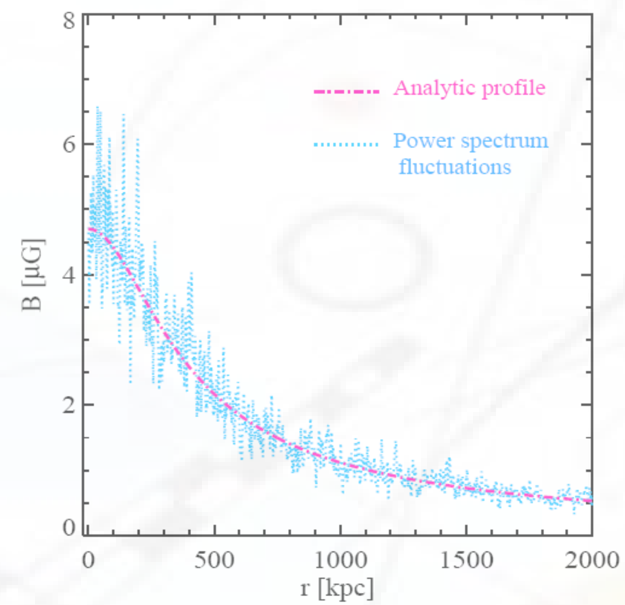
B_0>7 μG or <3μG
η>1 or < 0.2
excluded at **99%** confidence level

COMA CLUSTER
BONAFEDE ET AL. 2010

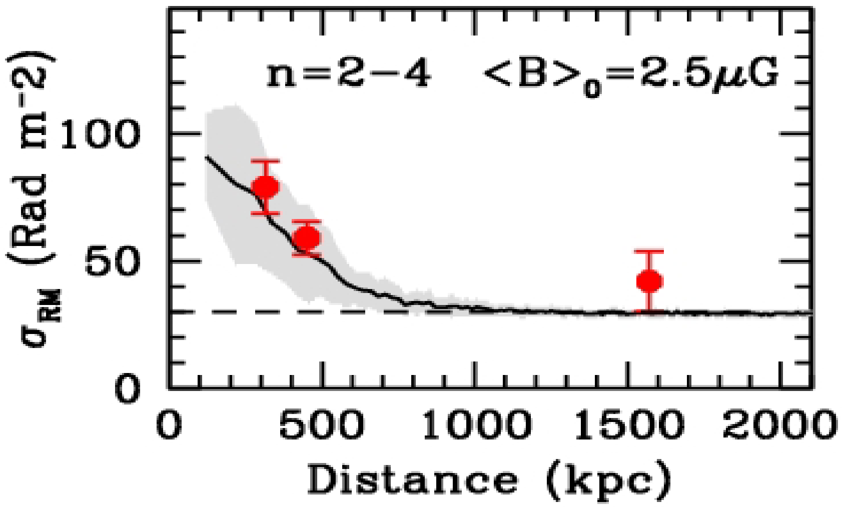
RM observations – Main limitation: number of EXTENDED sources

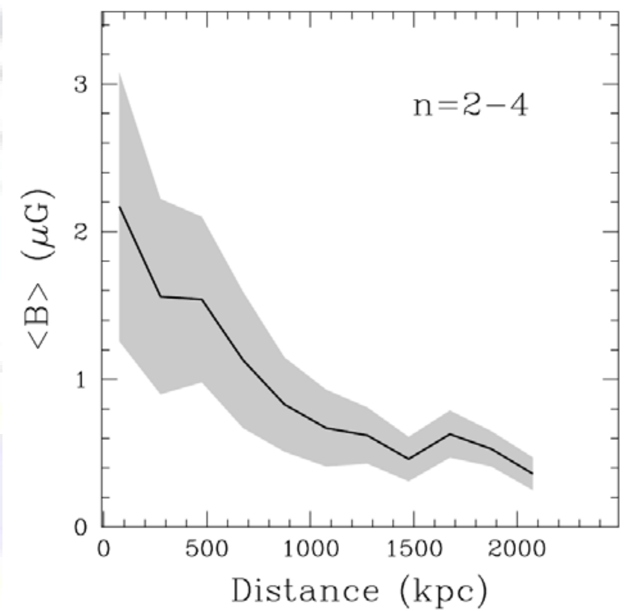
COMA **BONAFEDE ET AL. 2010**





A2255 **GOVONI ET AL. 2006**





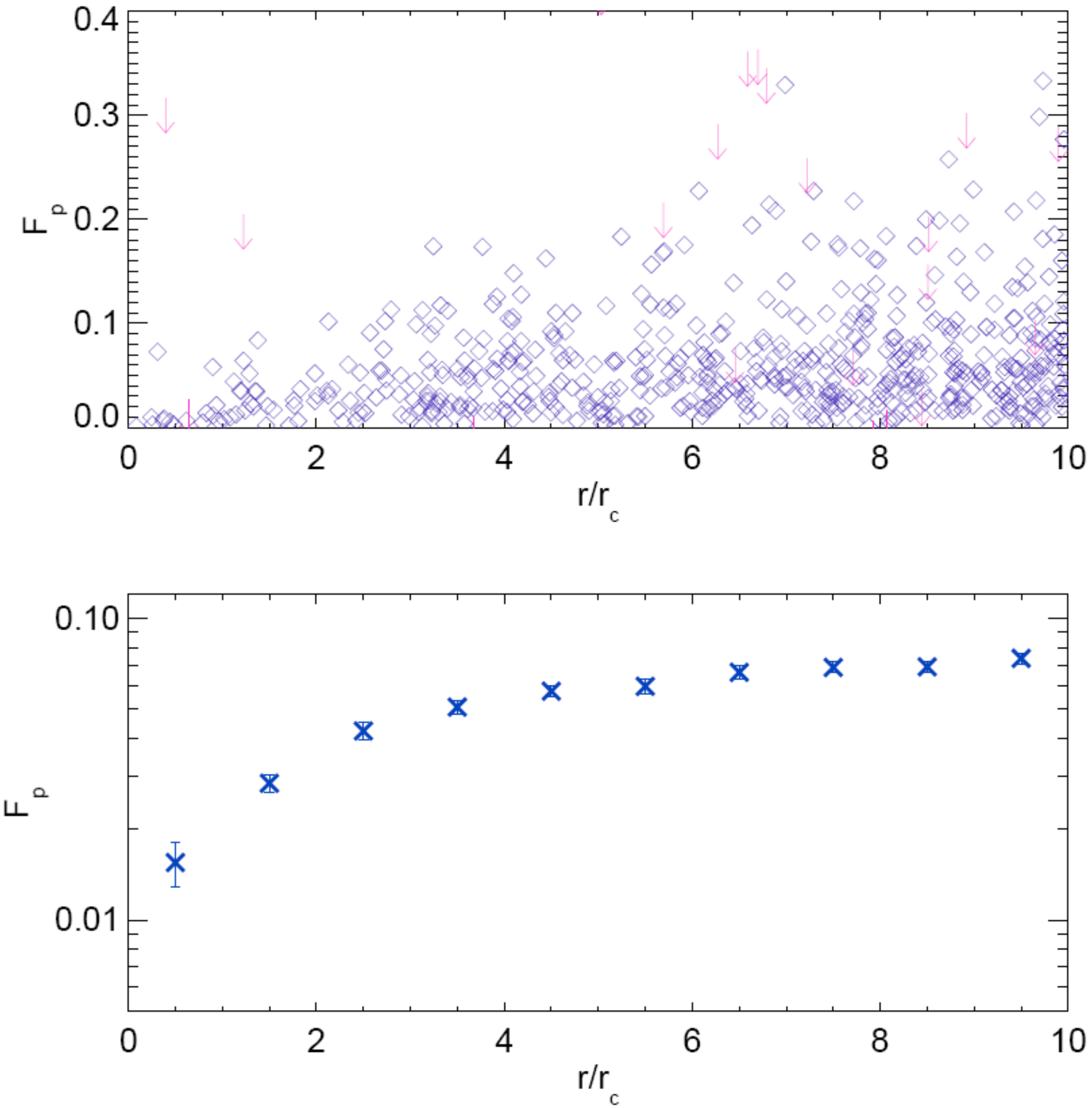
Magnetic field from Depolarization of radio sources

32 clusters

The most luminous from HIFLUGCS catalog

NVSS data

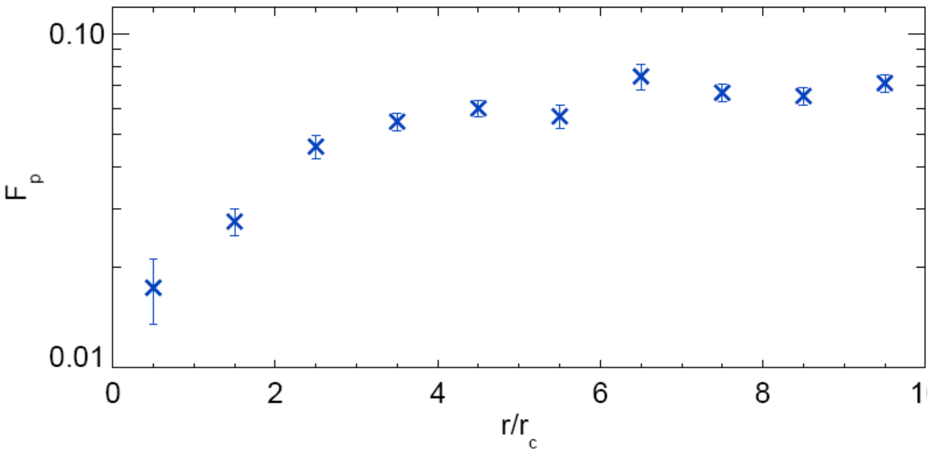
Fractional polarization vs cluster projected distance



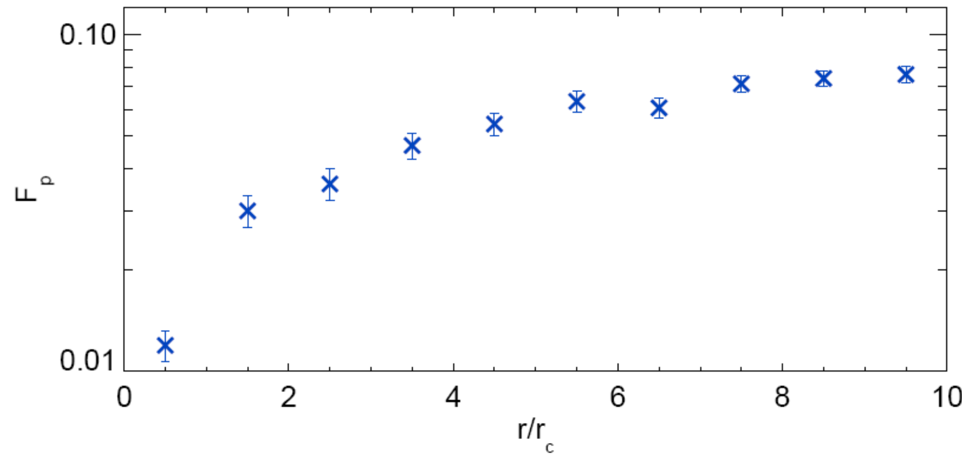
Cluster center
→ higher B and gas density
→ higher RM
→ lower fractional polarization

Bonafede et al. in prep

Magnetic field from Depolarization of radio sources



Radio-halo sub-sample



No Radio-halo sub-sample

K S test: P = 0.9

Magnetic field is ubiquitous in galaxy clusters

→No significant difference from this analysis for clusters with and without radio halo

Bonafede et al. in prep

Conclusions

Magnetic field in galaxy clusters are revealed by radio emission
Polarization maps + Farday Rotation allow a reconstruction of the 3D magnetic field

Magnetic field is ubiquitous in galaxy clusters

farthest detection: z=0.55 (Bonafede et al 2009, van Weeren et al. 2009)

Magnetic field strength: 2-5 μG in non cool-core clusters (central regions)

Profile: $B \sim n_e^{\eta}$ $\eta \sim 0.5$ Coma cluster (Bonafede et al. 2010)

Power spectrum: general agreement with Kolmogorov power-law ,
scales going to few to 10s 100s kpc

In the next Future:

Possibility of studying polarized emission from radio halos (EVLA and possibly LOFAR)

Magnetic field in low density environments will be revealed by LOFAR HB observations