Magnetic fields in clusters: measurements and future

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Clusters of galaxies

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

Knowledge of cluster magnetic field important for

- cluster formation
- cluster evolution
- ICM energy budget
- effect on heat conduction
- relation to shocks and turbulence

Observational diagnostics of B

What we know about magnetic fields derives from radio observations

1 - Synchrotron emission: cosmic rays illuminate magnetic fields at the μG level in the ICM (direct measurement)

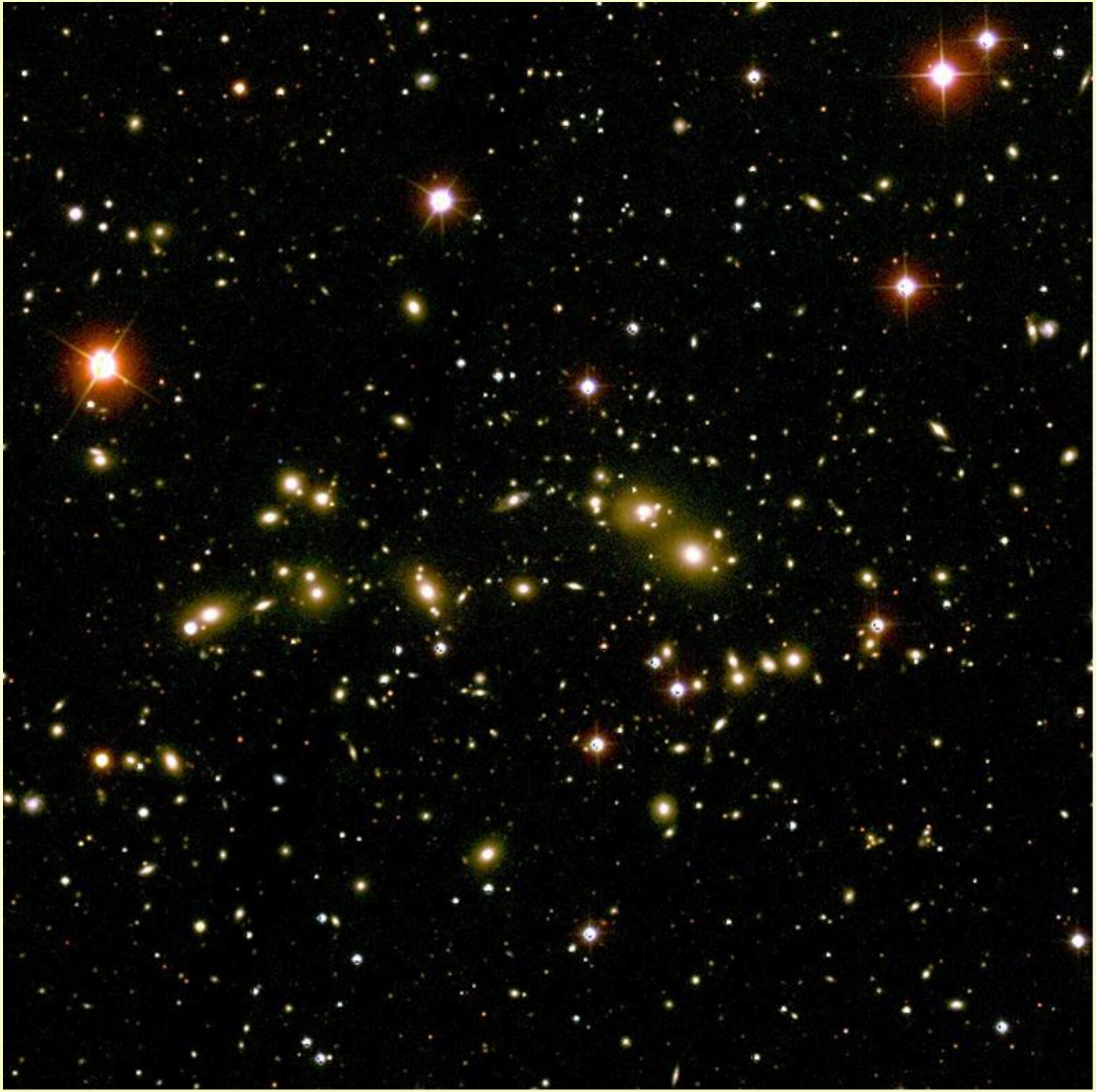
a- total intensity ➔ field strength ⊥ - equipartition

b- polarization ➔ field orientation and degree of ordering

2 – Rotation Measure of imbedded or background radio sources (indirect measurement)

➔ field strength ∥ and structure

A2255



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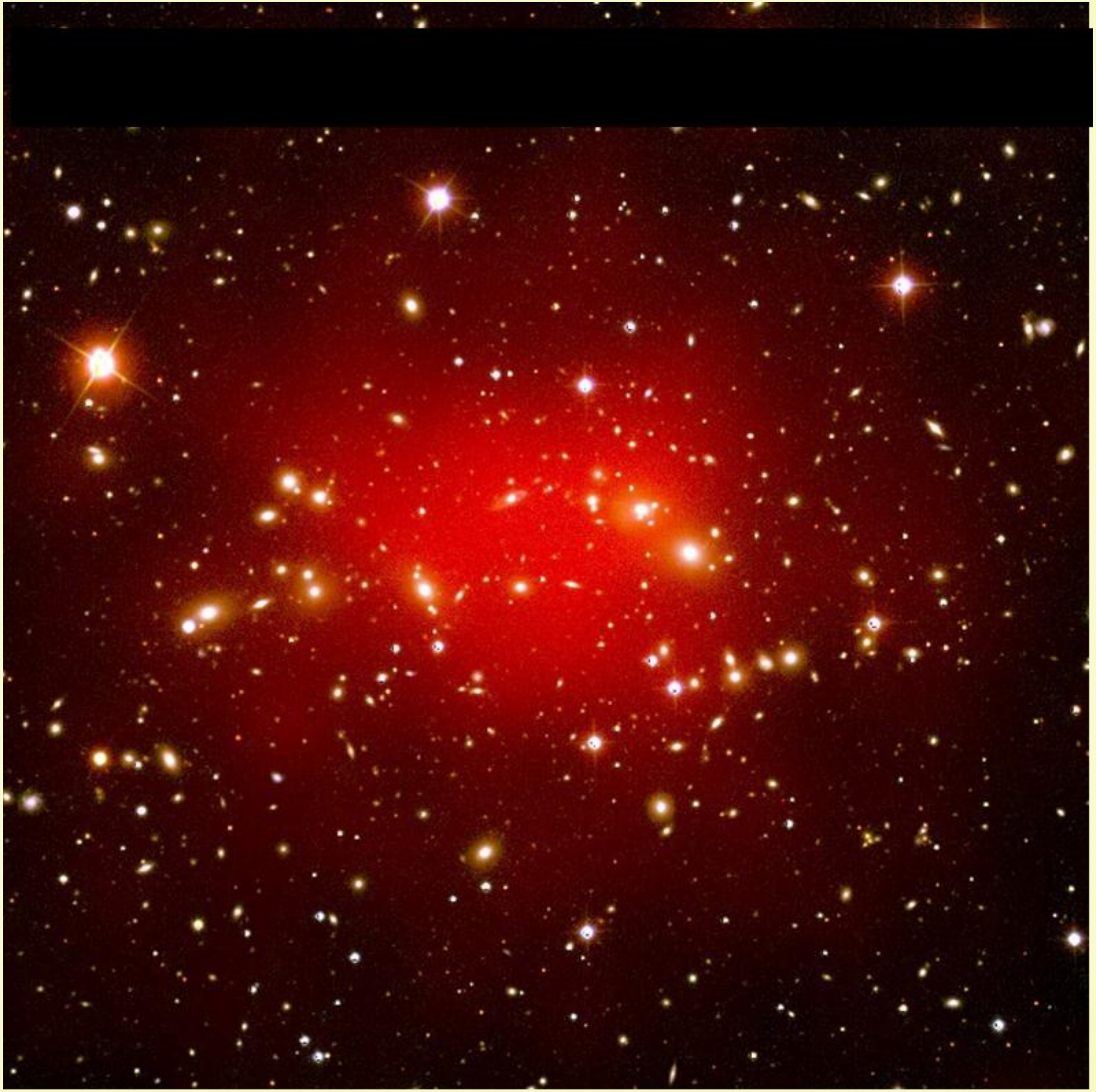
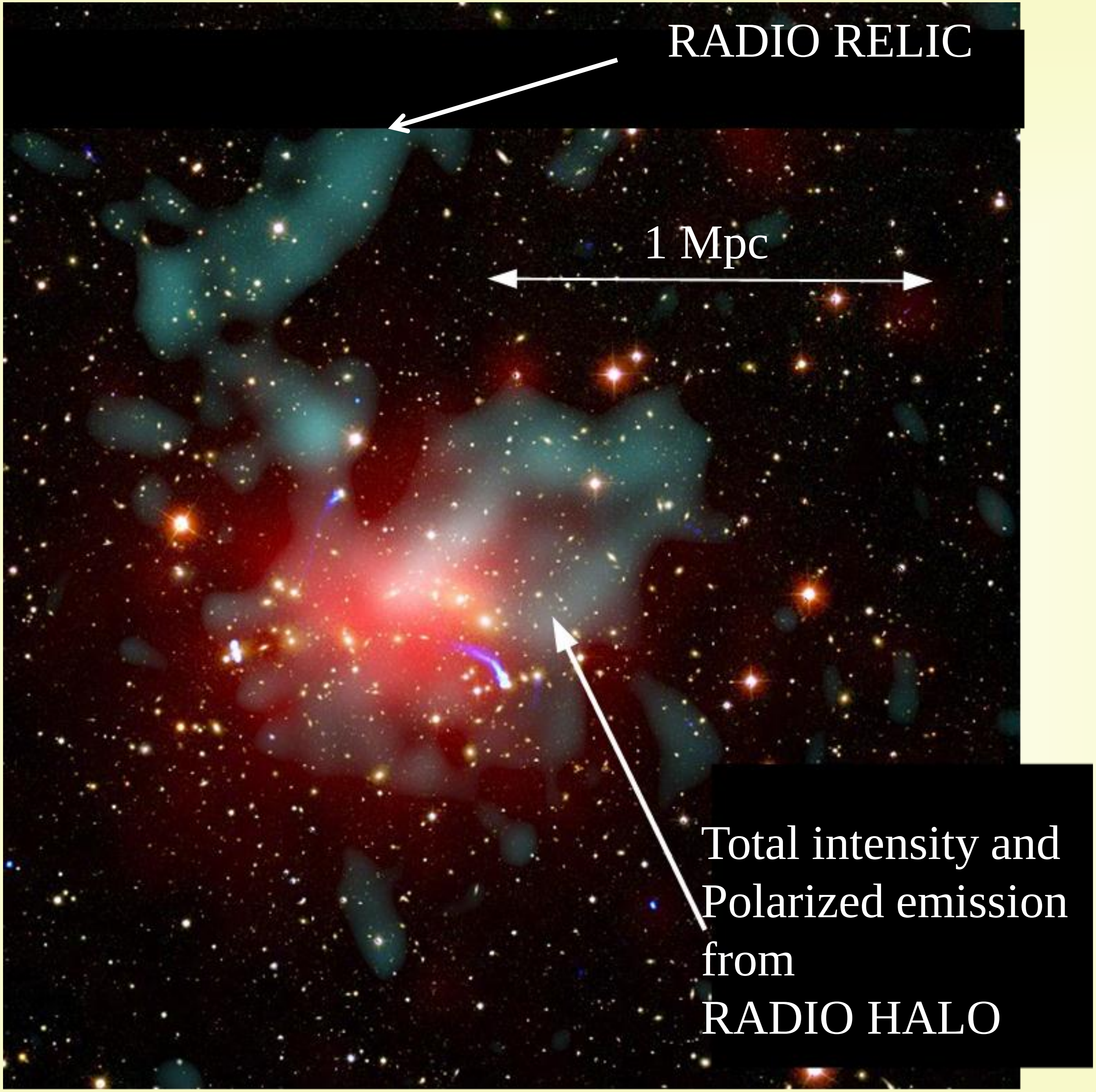
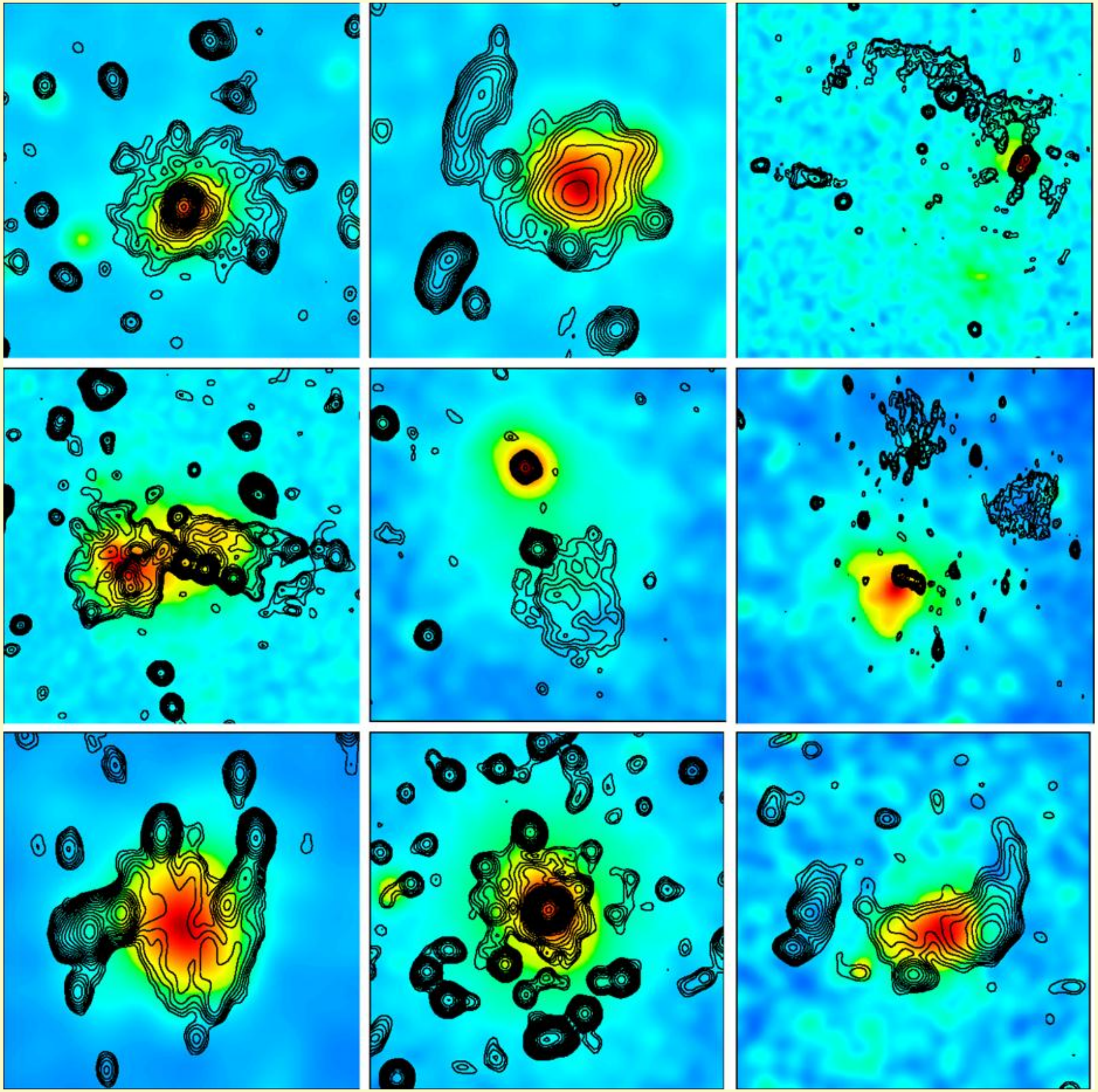



RADIO RELIC
1 Mpc
Total intensity and
Polarized emission
from
RADIO HALO

A2255

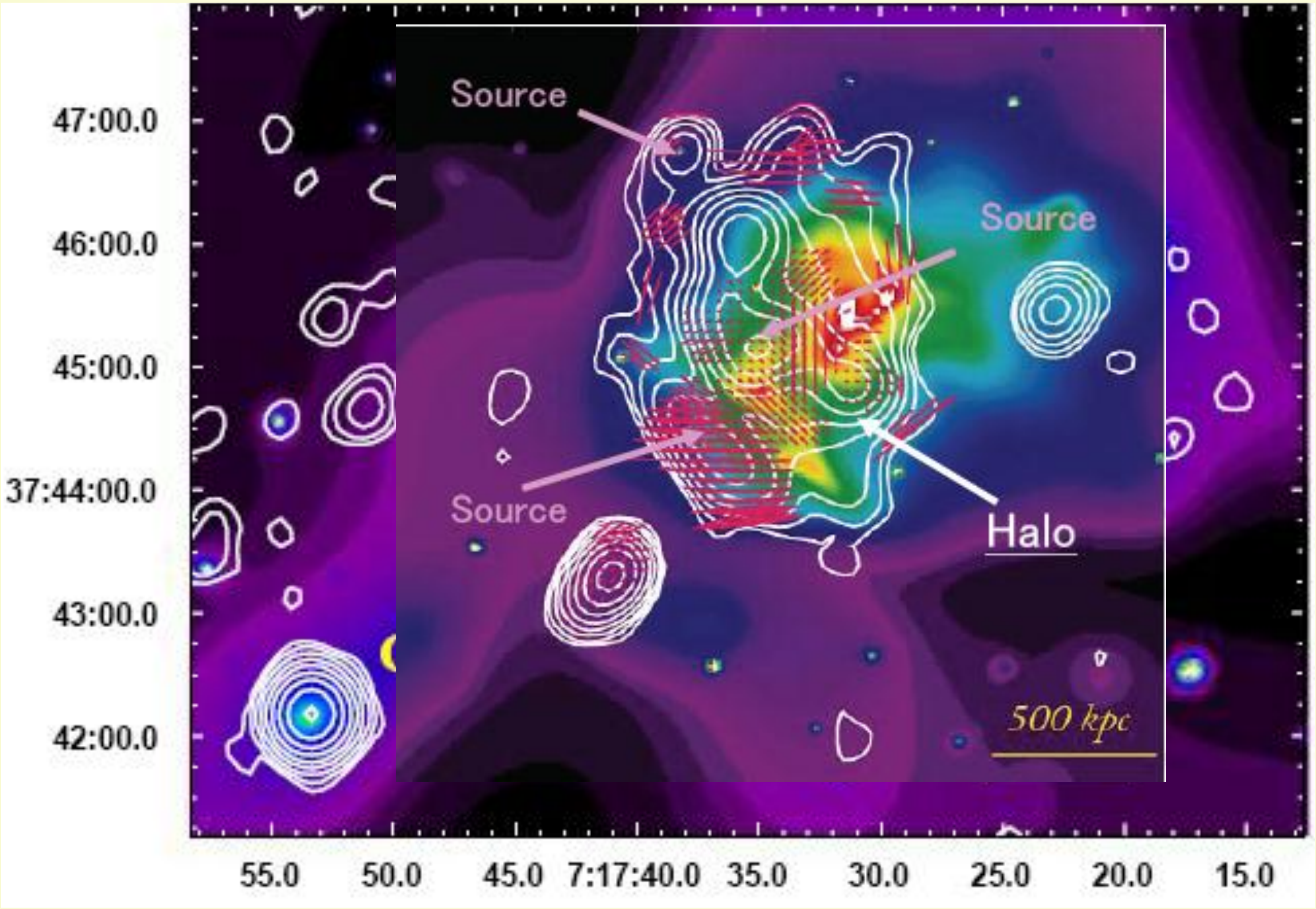
Synchrotron emission



Halos (merging cl)
Relics (“)
Minihalos (cool core)

Feretti et al. 2012

The cluster Macs J0717+3745



(Bonafede et al 2009)

One of most distant & most powerful radio halo, , z= 0.55, $P_{1.4\ GHz}$~1.6 10^{26} W/Hz

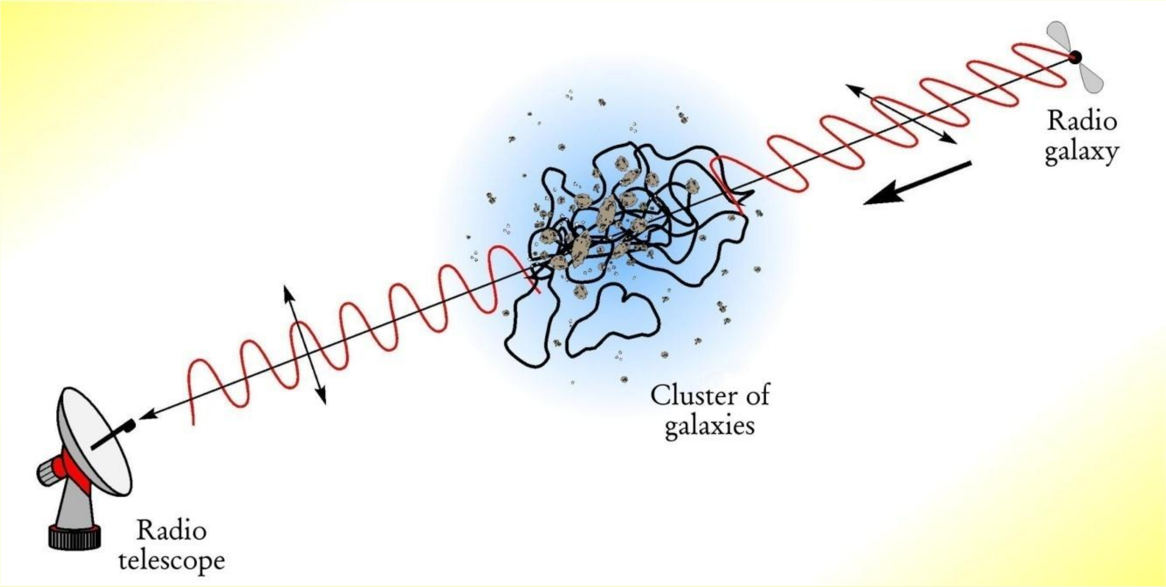
also showing polarization at ~5 %

Faraday Rotation:

SOURCES SEEN THROUGH A MAGNETIZED MEDIUM

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

$$\propto \lambda^2$$

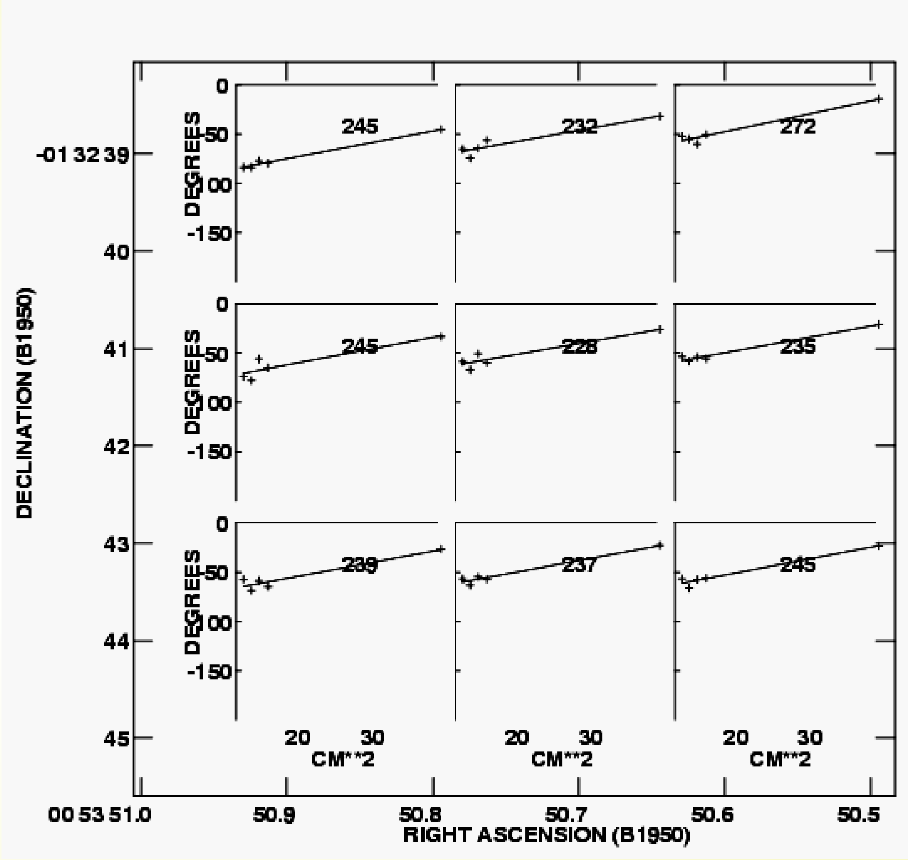


Kronberg 2002

polarized radio sources are mapped at several frequencies

to derive RM / produce RM maps

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



Use radio sources imbedded in a cluster of galaxies or beyond

RM is *the* PARAMETER THAT IS OBSERVED

RM SYNTHESIS to recover the polarized signal

(Brentjens and De Bruyn 2005)

$$RM = 812 \int_0^L n_e B_z \, dl \ (\mathrm{rad\,m^{-2}})$$

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

L is the path length in kpc

B_z is the line of sight component of the field in μG

Values derived for B are model dependent

- analytical solution only for simplest models of the Faraday screen

$$\sigma_{\mathrm{RM}}^2 = 812 \Lambda_C \int_0^L (n_e B_z)^2 \, dl \ (\mathrm{rad^2\,m^{-4}}).$$

Λ_C is the magnetic field coherence length in kpc

A sigle cell model is not suitable.

Realistic cases: B structure, B profile, n profile, complicated geometries

Power spectrum

obtained with semianalytical approach, or numerical techniques
(Ensslin & Vogt 2003, Vogt & Ensslin 2003,2005, Murgia et al. 2004, Govoni et al 2006, Guidetti et al. 2008, Bonafede et al. 2010)

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

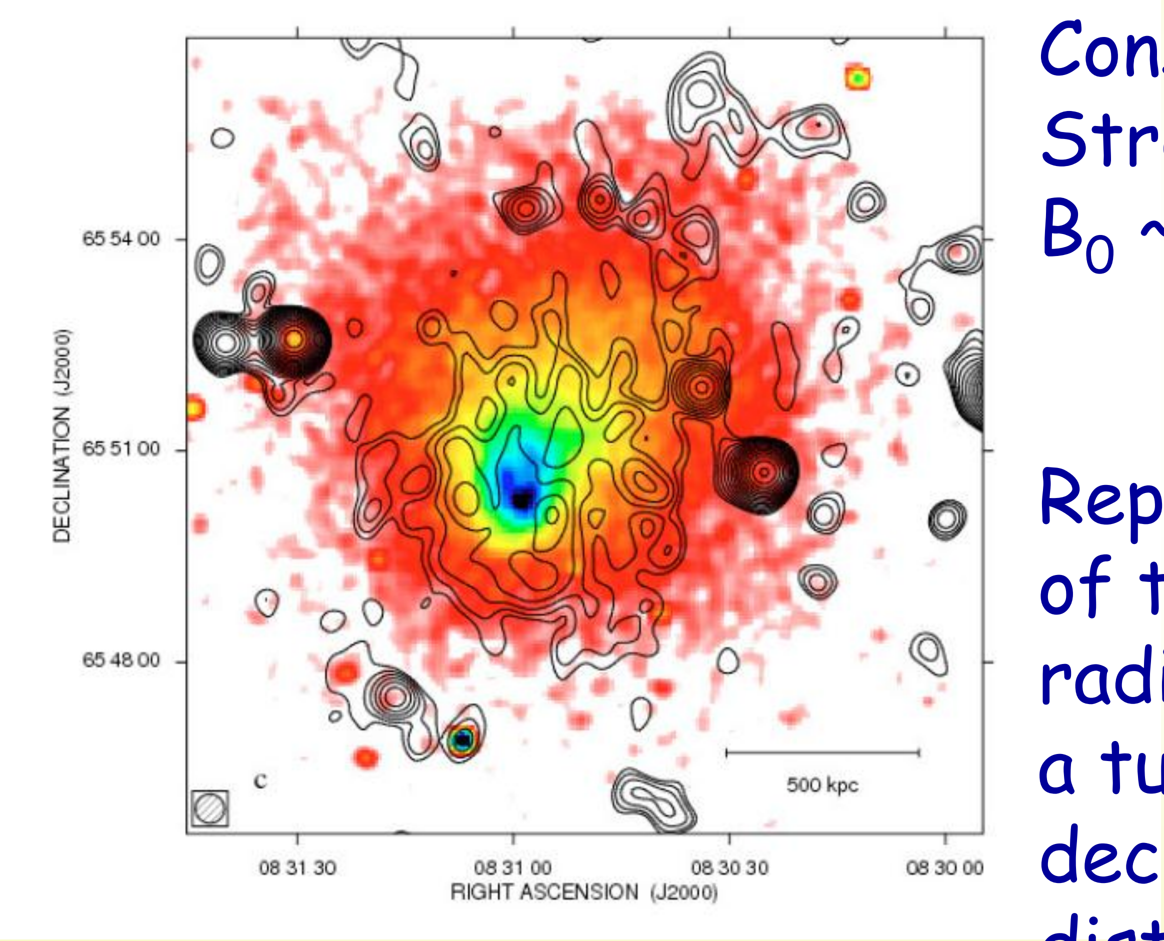
Index n = 2 – 4, Spatial scale in range 30 – 500 kpc

Autocorrelation length Λ_B ➔ Λ_C

The intracluster magnetic field power spectrum in Abell 665

V. Vacca[1,2], M. Murgia[2,3], F. Govoni[2], L. Feretti[3], G. Giovannini[3,4], E. Orrù[5], and A. Bonafede[3,4]

A&A 2010



Constrain Magnetic field Strength and Structure

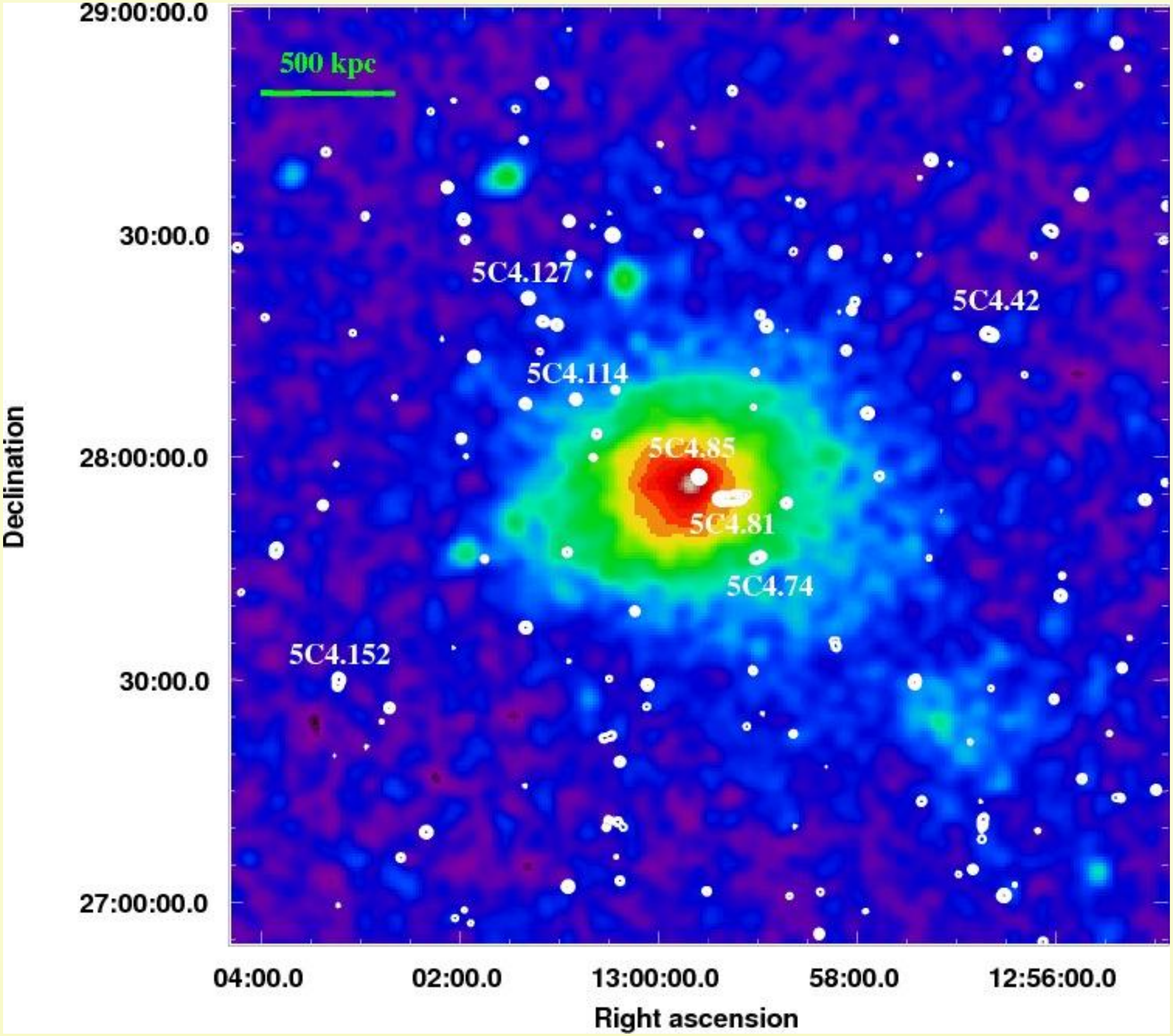
$B_0 \sim 1.3\ \mu G$

Reproduce fluctuations of the total intensity radio emission from a turbulent B field declining with radial distance

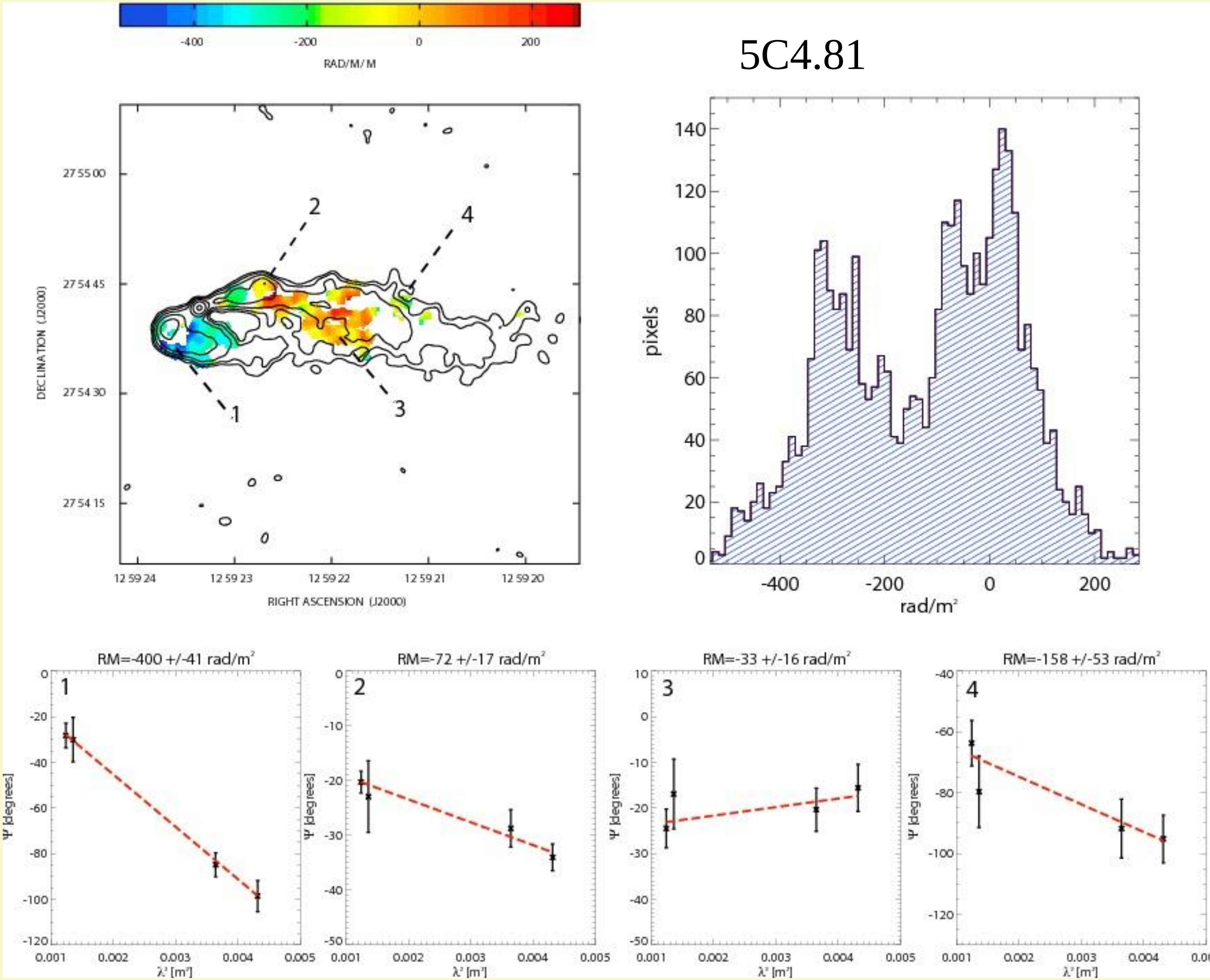
VLA C+D 1.4 GHz

Coma cluster

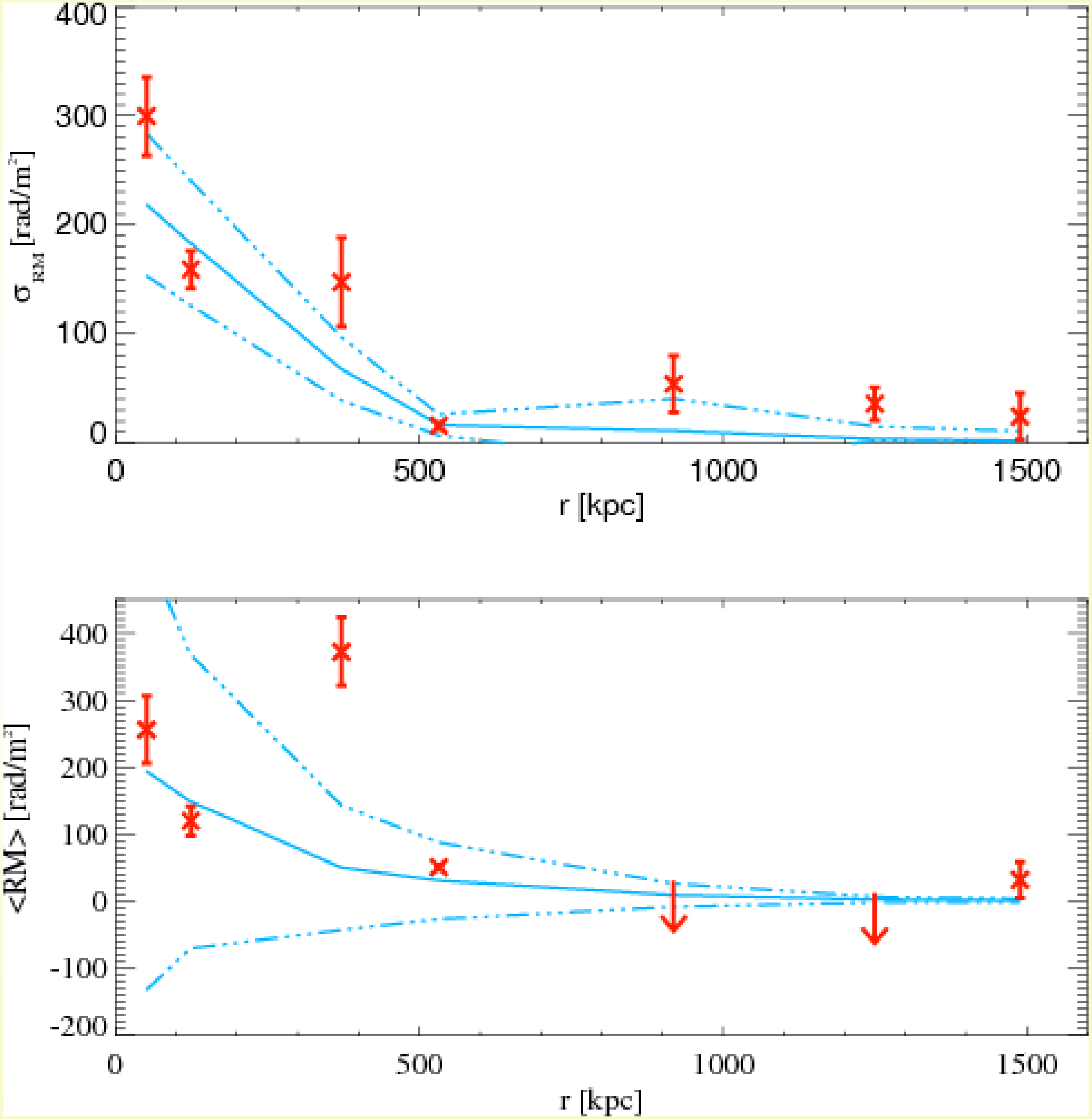
Bonafede et al 2010

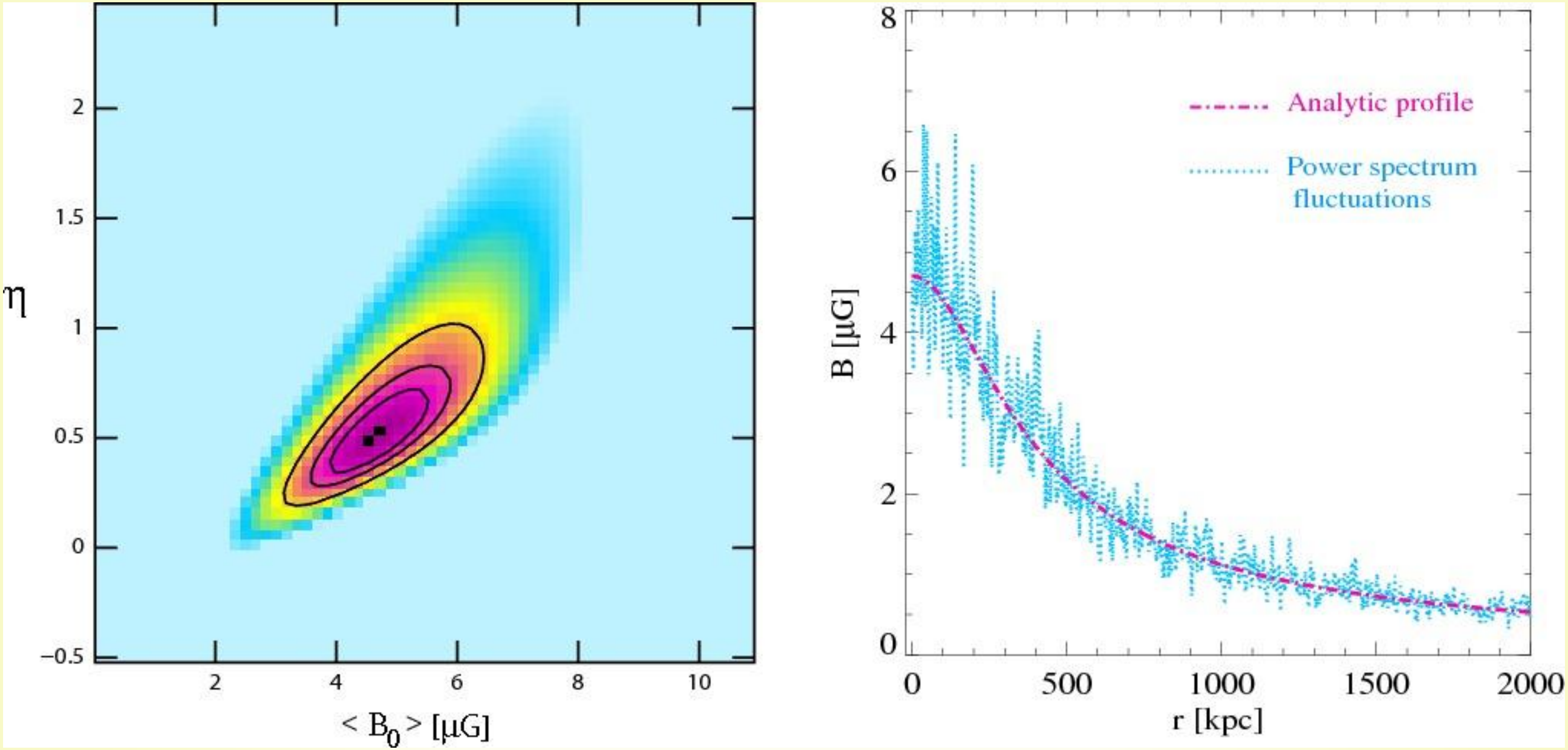


5C4.81


RAD/M/M
-400
-200
0
200
DECLINATION (J2000)
RIGHT ASCENSION (J2000)
27 55 00
27 54 45
27 54 30
27 54 15
12 59 24
12 59 23
12 59 22
12 59 21
12 59 20
1
2
3
4
pixels
rad/m²
RM=-400 +/-41 rad/m²
RM=-72 +/-17 rad/m²
RM=-33 +/-16 rad/m²
RM=-158 +/-53 rad/m²
Ψ [degrees]
λ² [m²]

σ_{RM} and <RM> for the best model (continuous line), dispersion (dotted lines), and observed points (red)





Left: χ^2 plane for the central B intensity and the index of scaling with n. Right: profile of the best magnetic field model. Magenta line refers to the analytic profile. Power spectrum fluctuations on the profile are shown.

Magnetic field parameters that reproduce RM values :

-Kolmogorov power spectrum

- coherence scale from ~2 kpc to ~34 kpc

- central intensity B_0 in the range 3.9 – 5.4 μG

- B profile scaling as thermal gas density with as n^η
with index η = 0.4 - 0.7

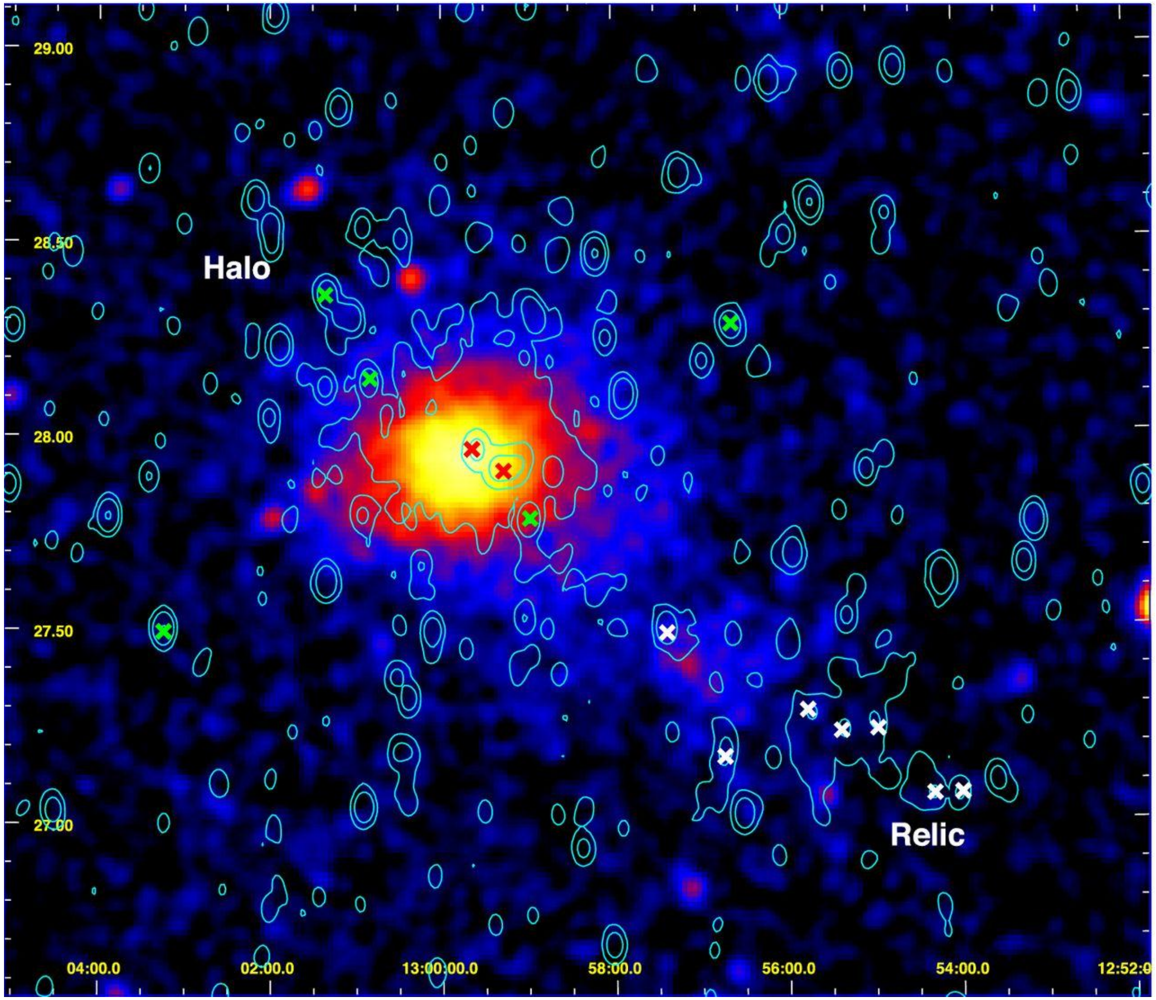
Best agreement between observations and simulations is achieved for B_0 = 4.7 μG and η = 0.5.

Values of B_0 > 7 μG and <3 μG as well as η < 0.2 and η > 1.0 are incompatible with RM data at 99% confidence level.

(Bonafede et al. 2010)

B field in the Coma cluster periphery

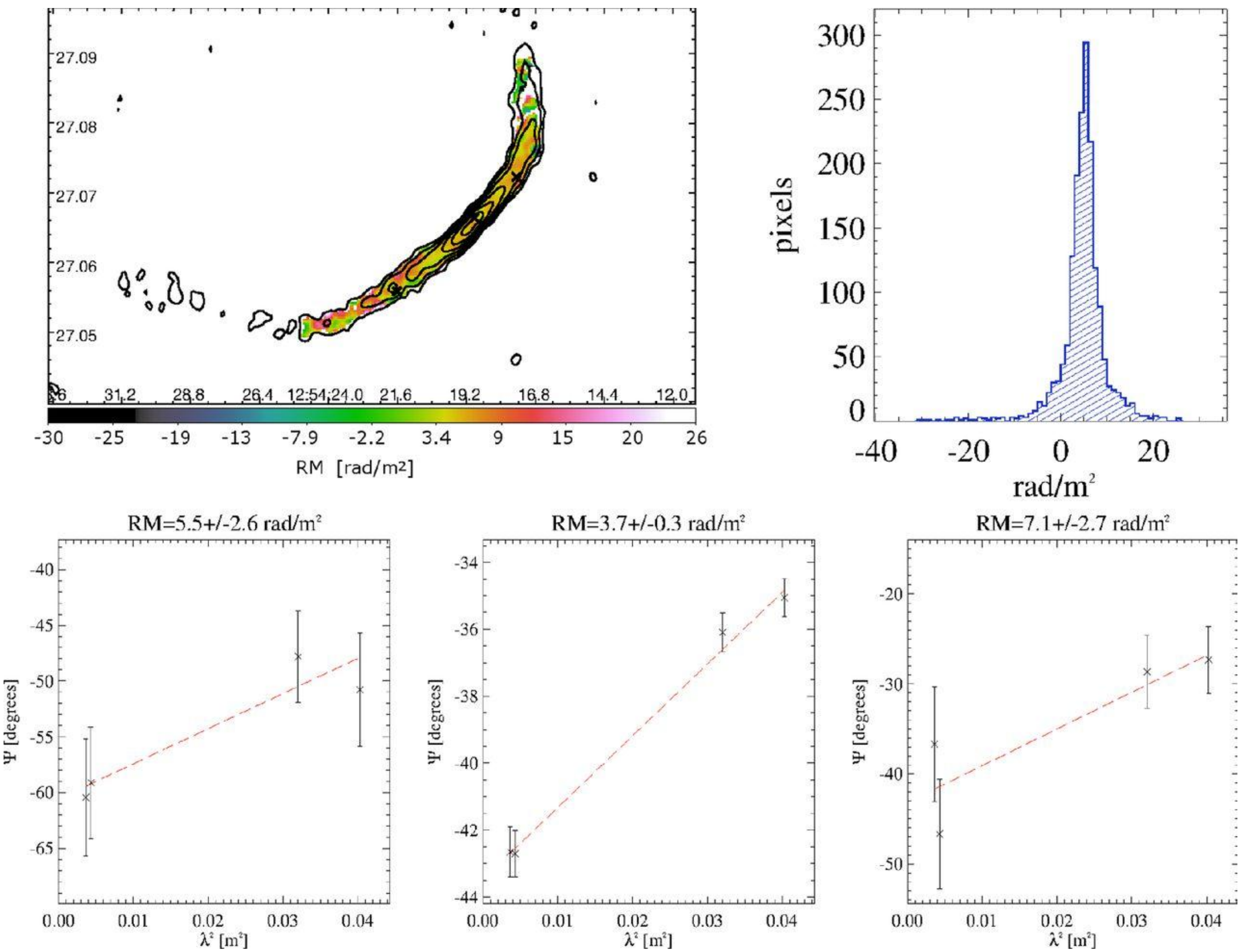
Colours: X-ray emission from the Coma cluster and the NGC 4839 group from the ROSAT All Sky Survey (Briel, Henry & Boehringer 1992).



Bonafede A et al. MNRAS 2013;433:3208-3226

MONTHLY NOTICES of the Royal Astronomical Society

5C4.20 – Top left: the RM fit is shown in colour along with total intensity radio contours at 1.4 GHz.



Bonafede A et al. MNRAS 2013;433:3208-3226

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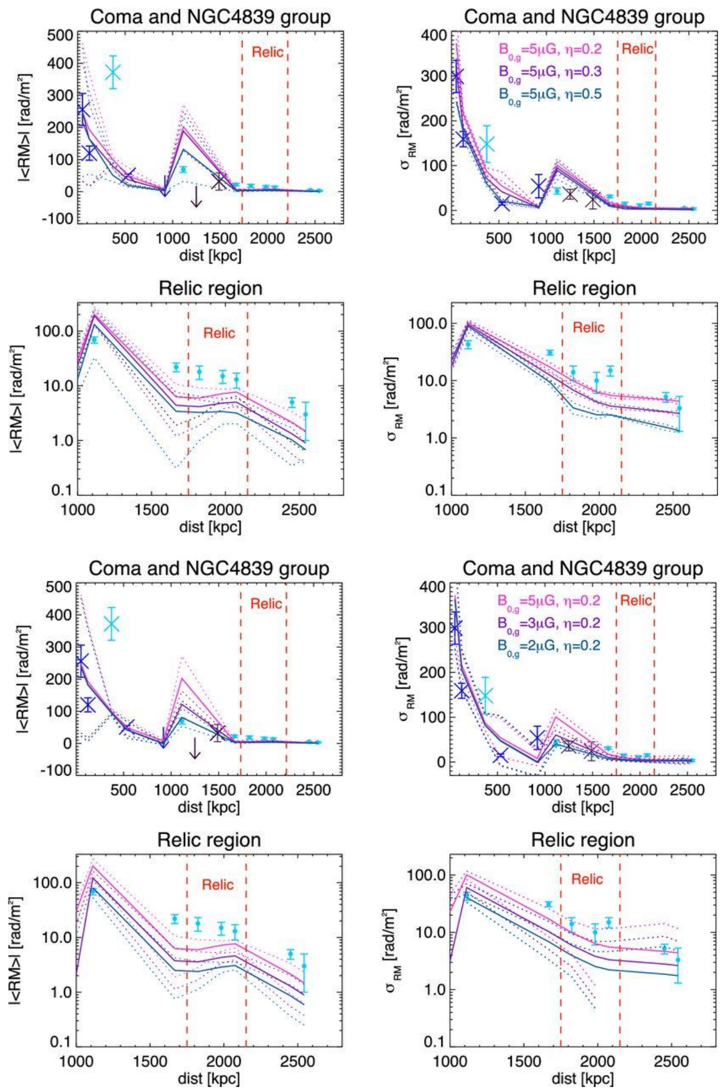
$\langle|RM|\rangle$ and σRM trend versus the projected distance from the cluster centre.



Bonafede A et al. MNRAS 2013;433:3208-3226

MONTHLY NOTICES of the Royal Astronomical Society

The magnetic field model that gives the best fit to the Coma central region underestimates the RM in the south-west region by a factor of ~ 6

Magnetic field in the relic region is $\sim 2\ \mu G$

An amplification of the magnetic field along the south-west sector is inferred

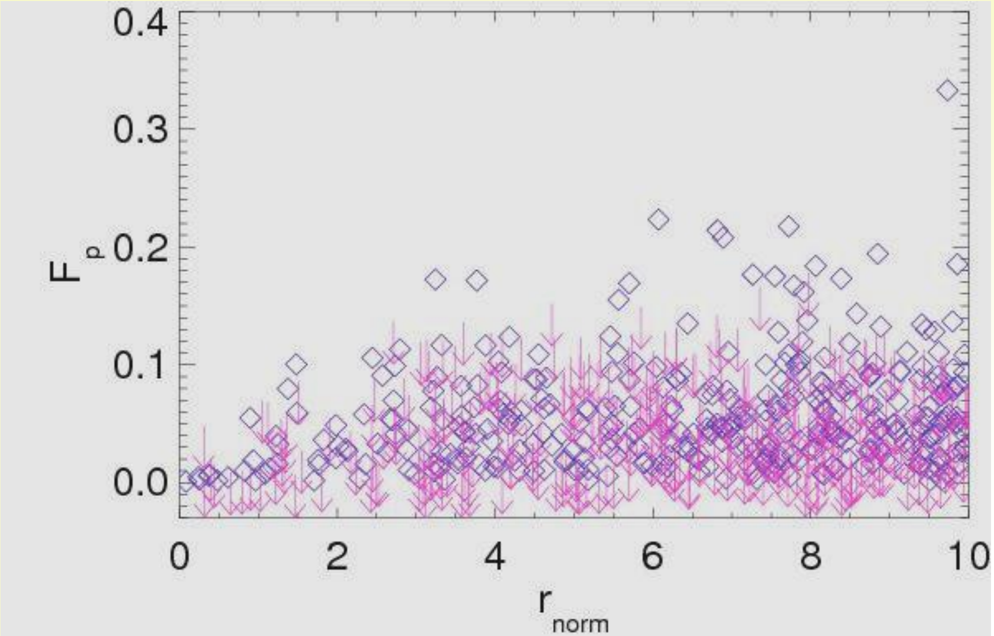
This is consistent with gas density values and inverse Compton limits obtained in X-ray with Suzaku

Use of RM is the most efficient way to probe ICM magnetic field and derive its parameters

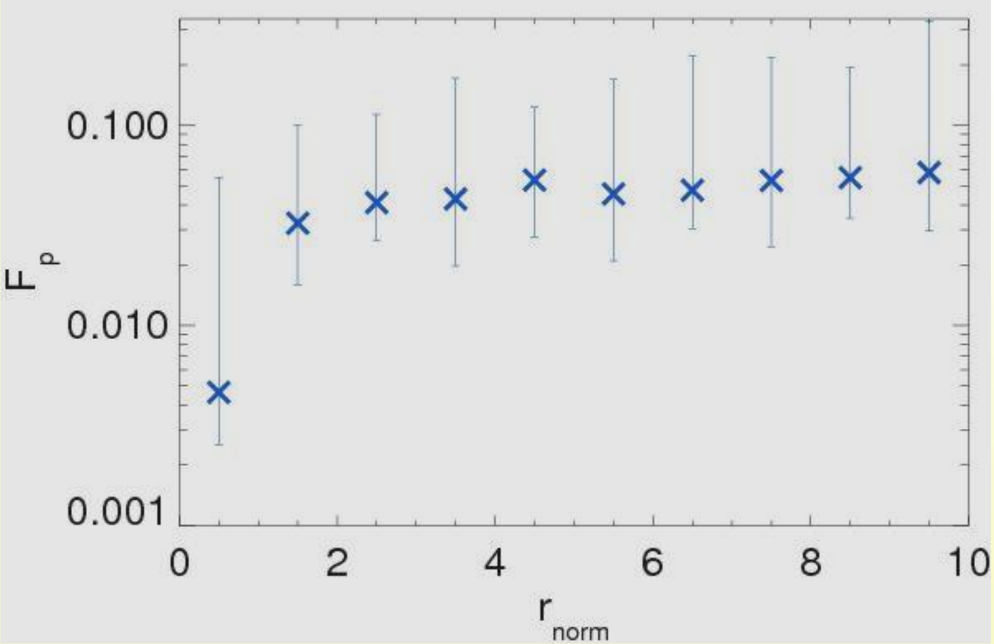
But also Fractional polarization can be used

➔imbedded or background sources are depolarized due to the ICM B field, because of large observing beam and bandwidth which mixes regions with different RM

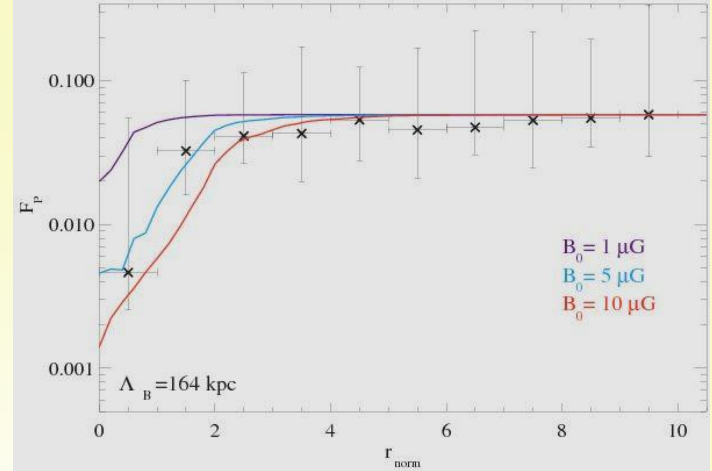
Bonafede et al. 2011: trend of fractional polarization vs the cluster impact parameter



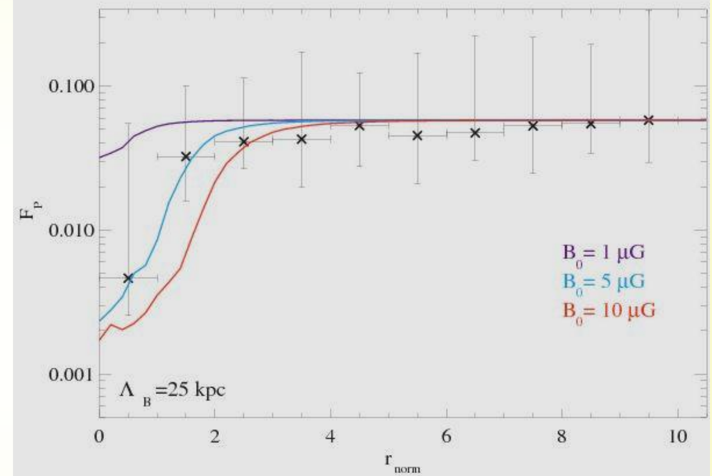
0.4
0.3
0.2
0.1
0.0
F_p
0
2
4
6
8
10
r_{norm}



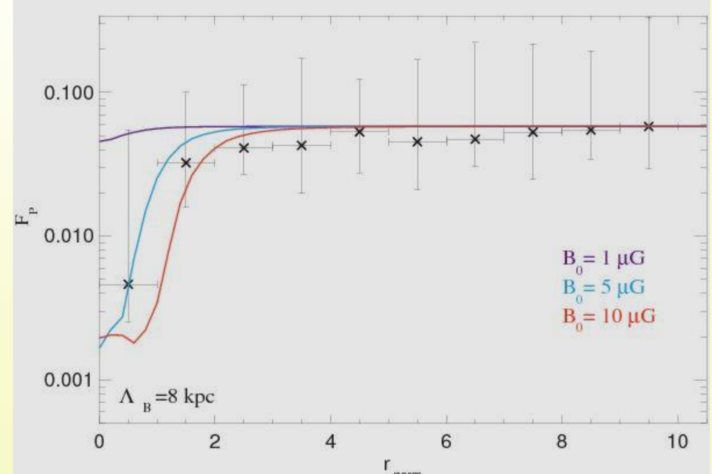
0.100
0.010
0.001
F_p
0
2
4
6
8
10
r_{norm}



0.100
0.010
0.001
F_p
$B_0 = 1\ \mu G$
$B_0 = 5\ \mu G$
$B_0 = 10\ \mu G$
$\Lambda_B = 164$ kpc
0
2
4
6
8
10
r_{norm}



0.100
0.010
0.001
F_p
$B_0 = 1\ \mu G$
$B_0 = 5\ \mu G$
$B_0 = 10\ \mu G$
$\Lambda_B = 25$ kpc
0
2
4
6
8
10
r_{norm}

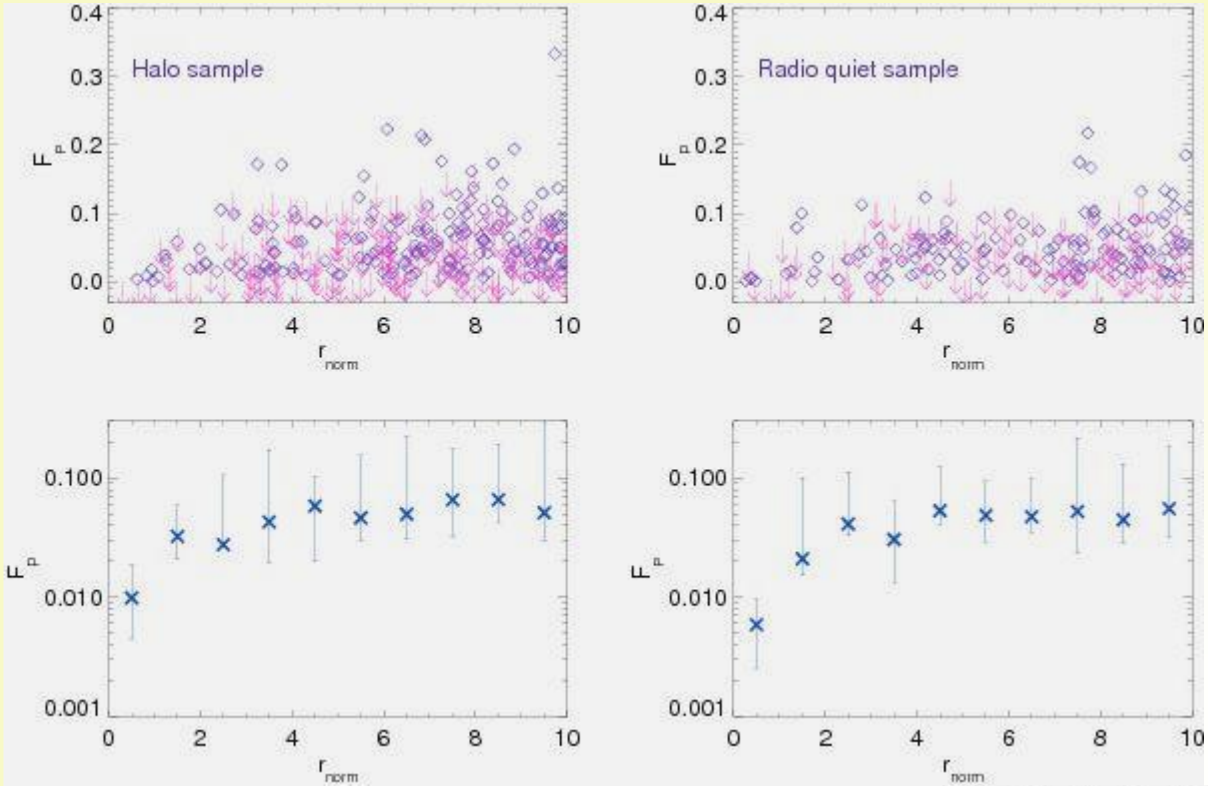


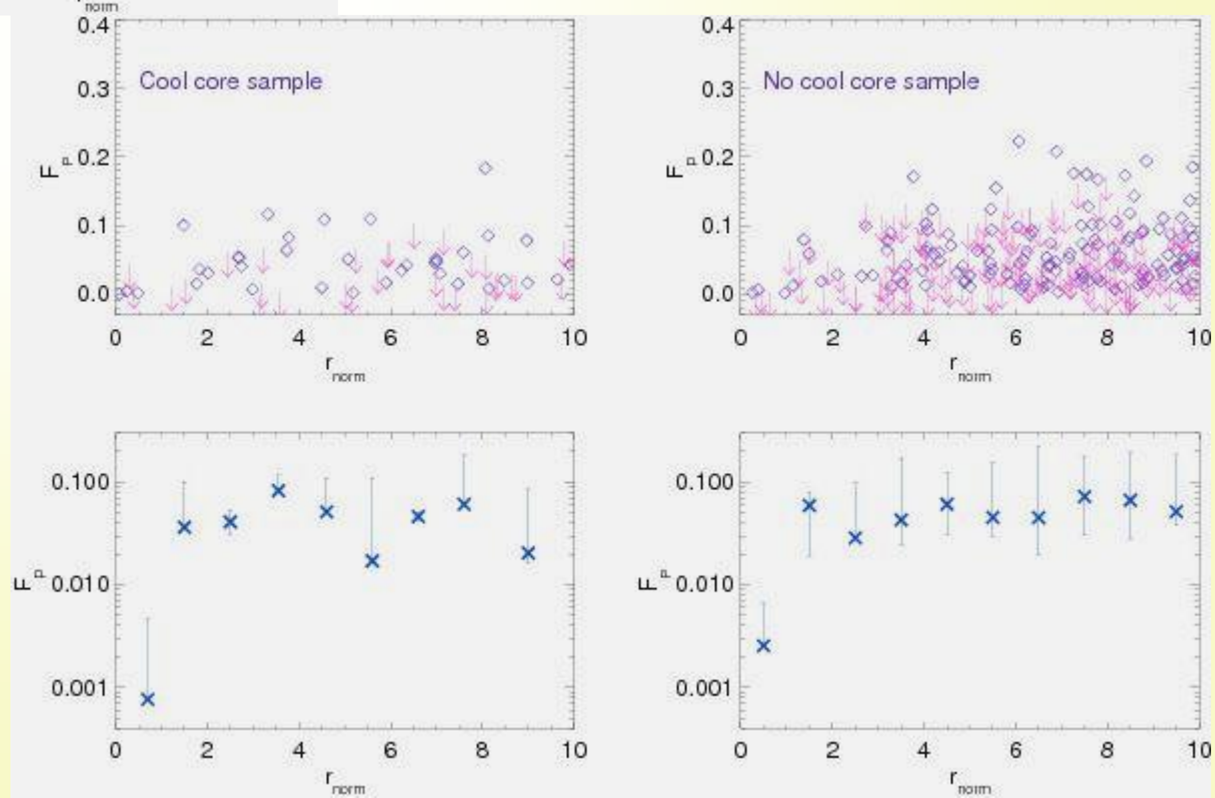
0.100
0.010
0.001
F_p
$B_0 = 1\ \mu G$
$B_0 = 5\ \mu G$
$B_0 = 10\ \mu G$
$\Lambda_B = 8$ kpc
0
2
4
6
8
10
r_{norm}

fractional polarization increases at the cluster periphery
(decreases toward the cluster center)

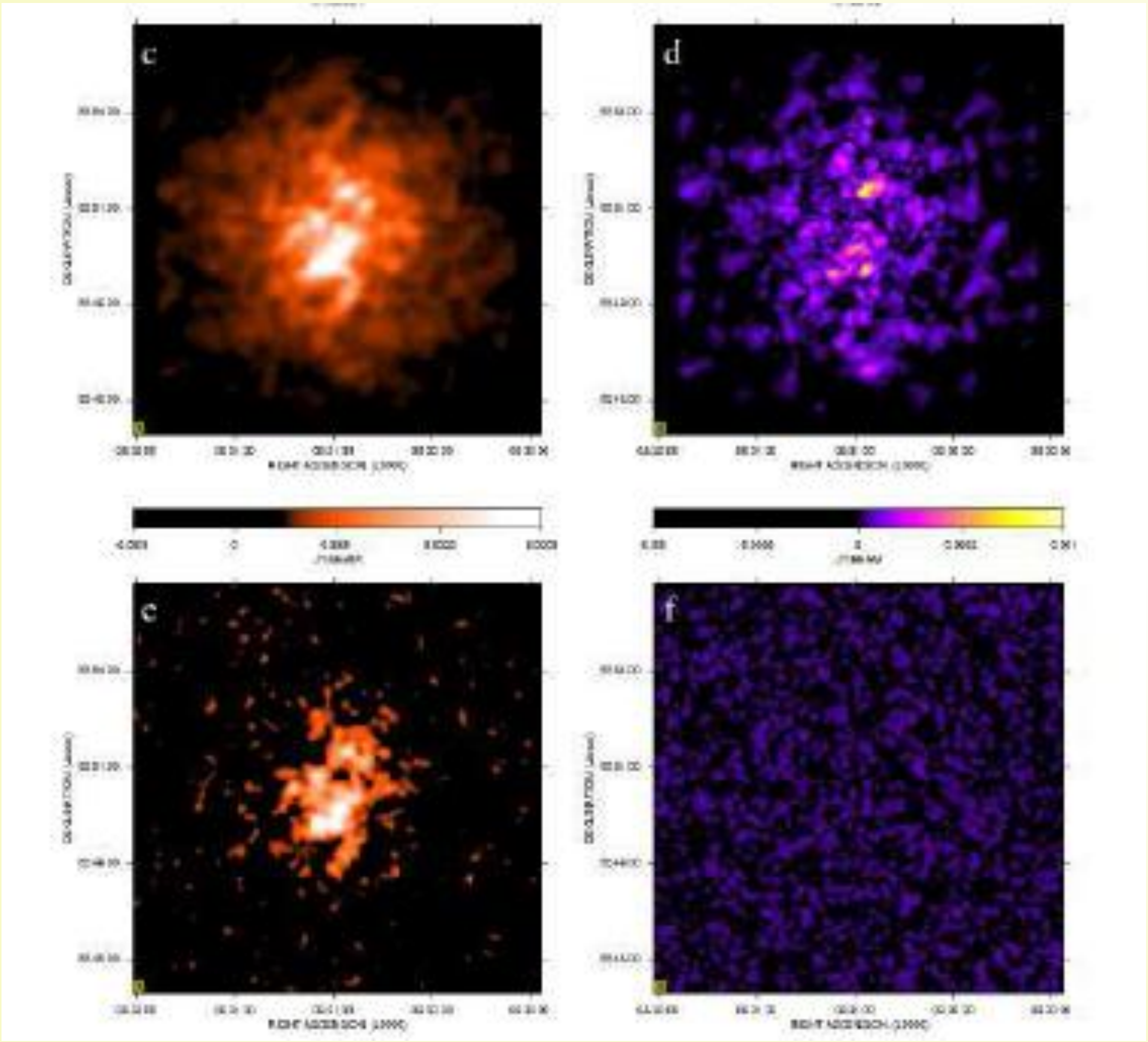
Such trend can be reproduced by a magnetic field model with a central value of few μG

Statistical test indicates
-no significant differences in the depolarization trend between clusters with and without a radio halo
-possible differences - marginal - between clusters with and without cool core


Halo sample
Radio quiet sample
F_p
r_norm


Cool core sample
No cool core sample
F_p
r_norm

Polarization in Radio Halos :
expected with turbulent magnetic field



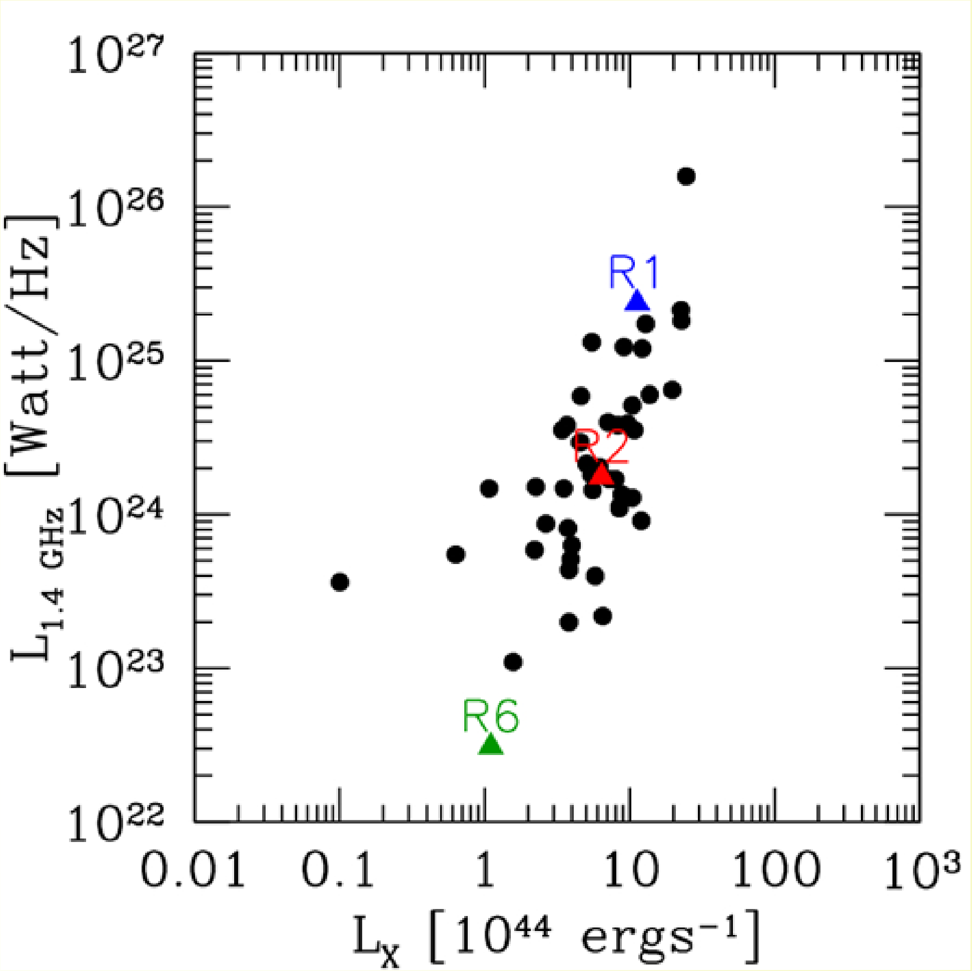
15" resolution, for cluster at z=0.2 expected pol 7%

Noise added

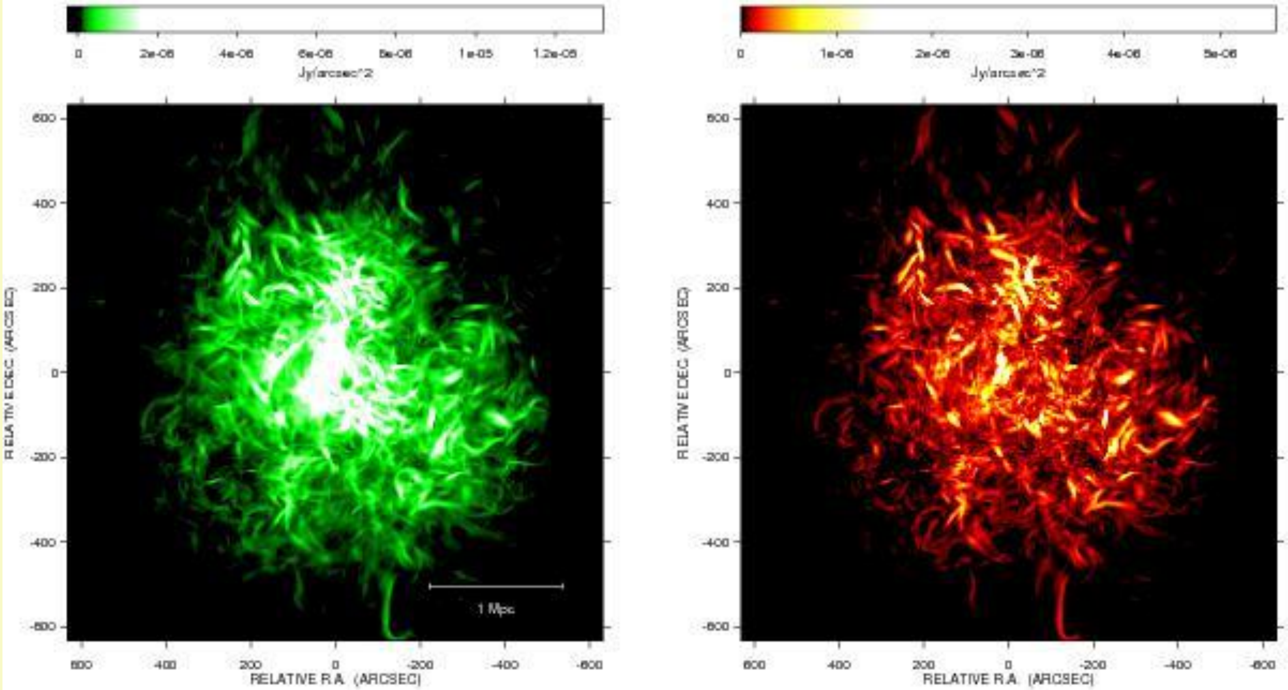
Simulations by Vacca et al. 2010 – A665

Recent studies

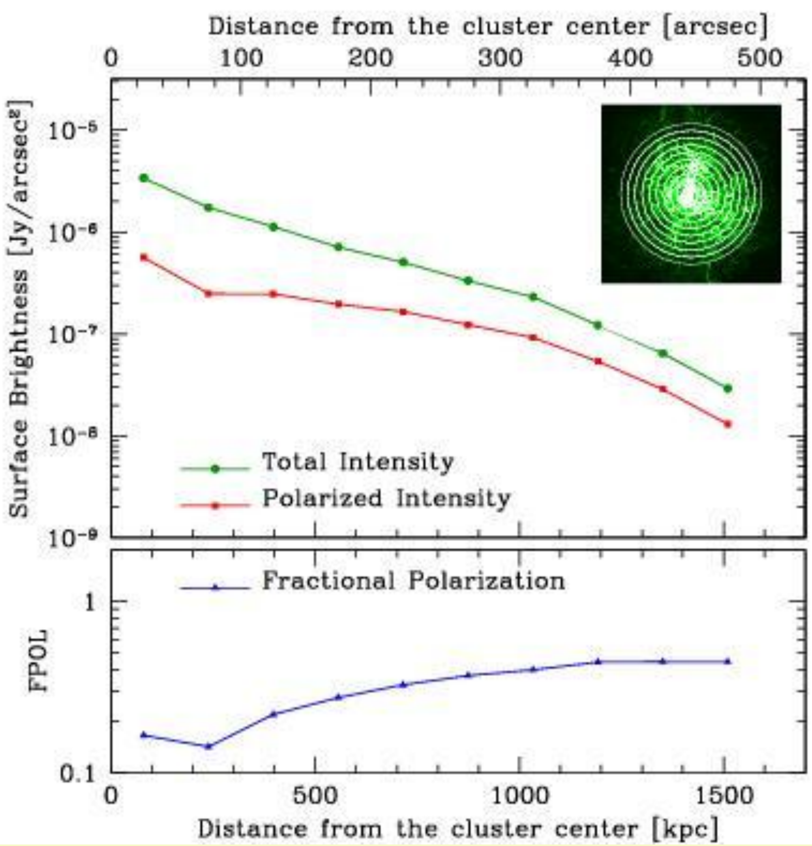
On the basis of cosmological MHD simulations, with initial magnetic fields injected by active galactic nuclei, and amplified by cluster turbulence, we obtained synthetic halo clusters at different powers, showing global properties in line with the observations (magnetic field strenght and structure, radio – X-ray correlation.
(Xu et al. 2012)



As a second step, we predict the expected degree of polarization of a radio halo (Govoni et al. 2013)



Radio halo in a simulated Cluster in total intensity and polarization



Azimuthally averaged halo Brightness profile in total Intensity and polarization

and fractional polarization

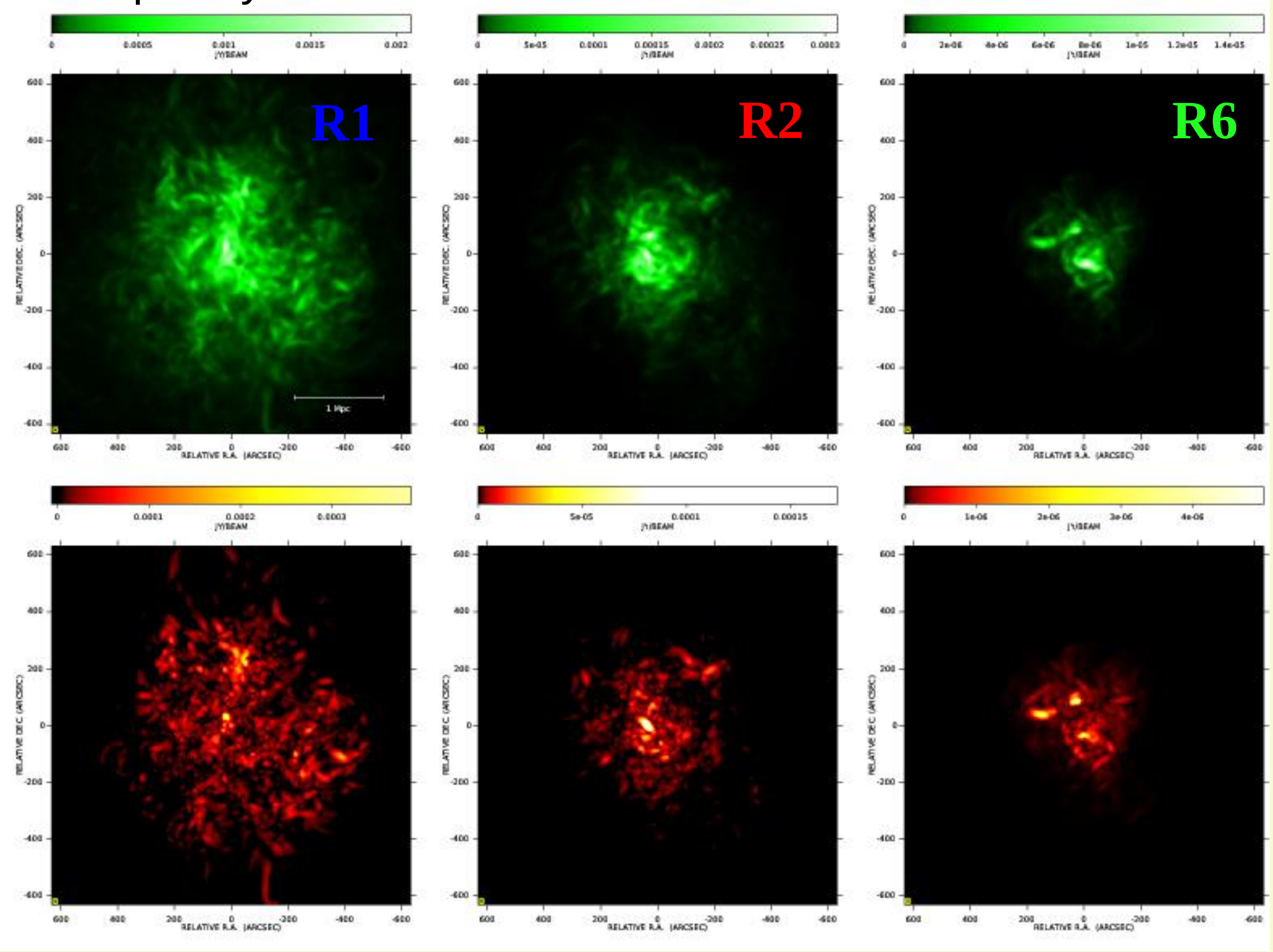
Govoni et al. 2013

Mock radio halos Govoni et al. 2013

Frequency 1.4 GHz - Bandwidth 300 MHz - Resolution 15''

Total Intensity

Polarized Intensity

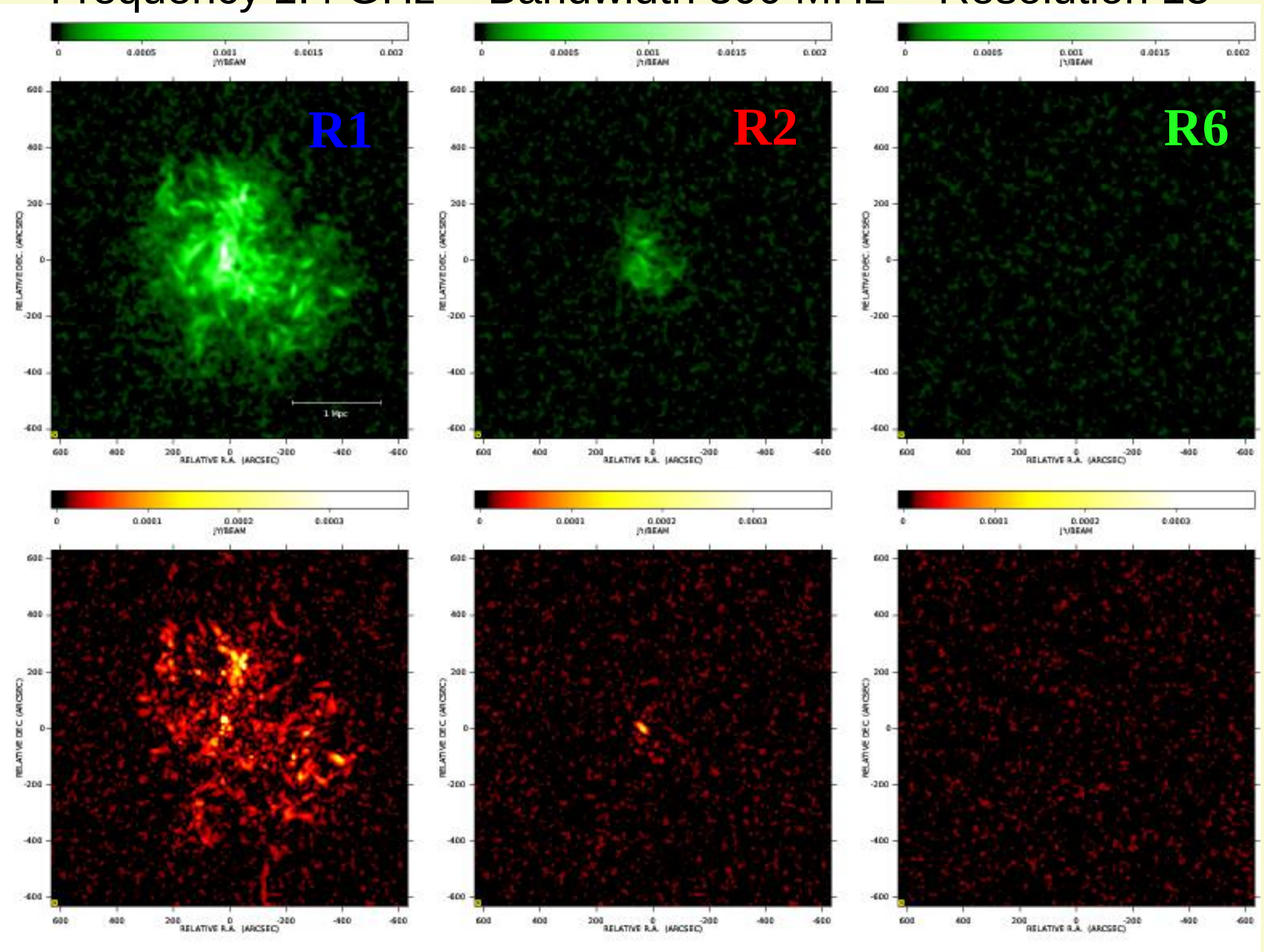


Mock radio halos Govoni et al. 2013

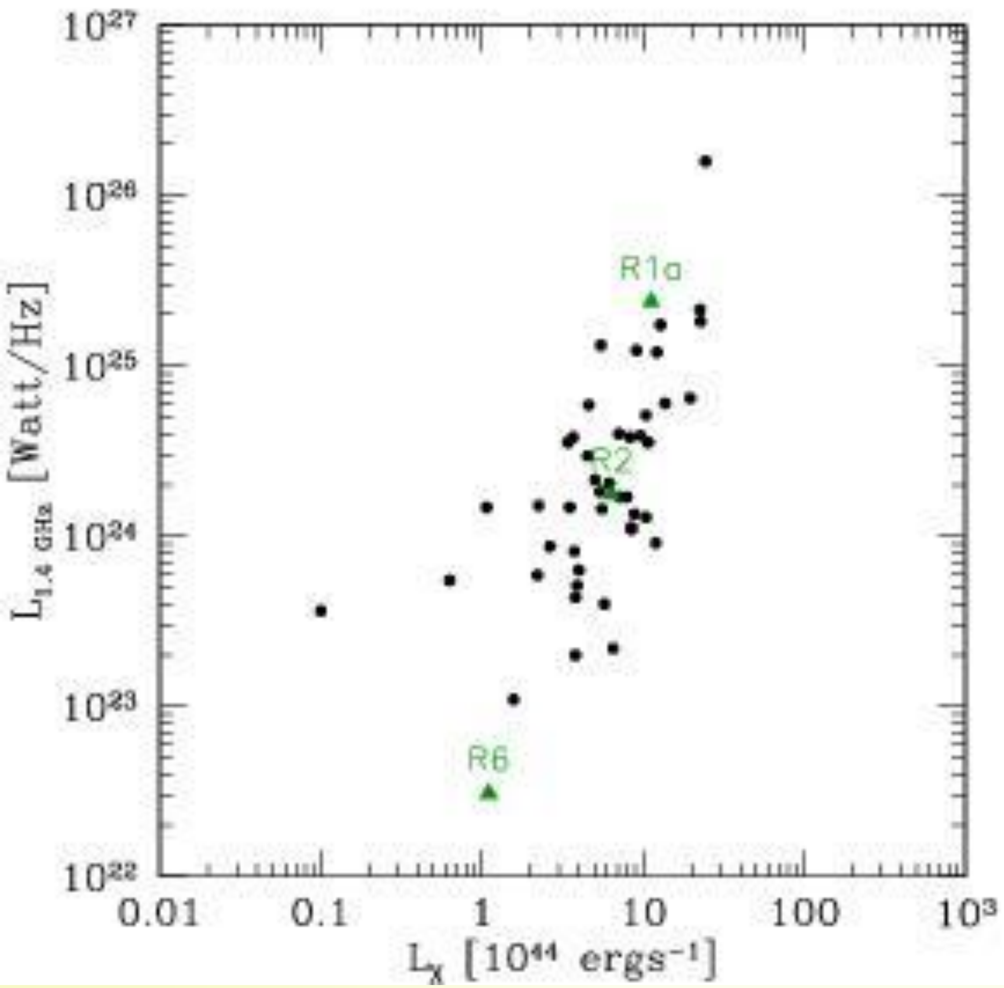
Frequency 1.4 GHz - Bandwidth 300 MHz - Resolution 15"

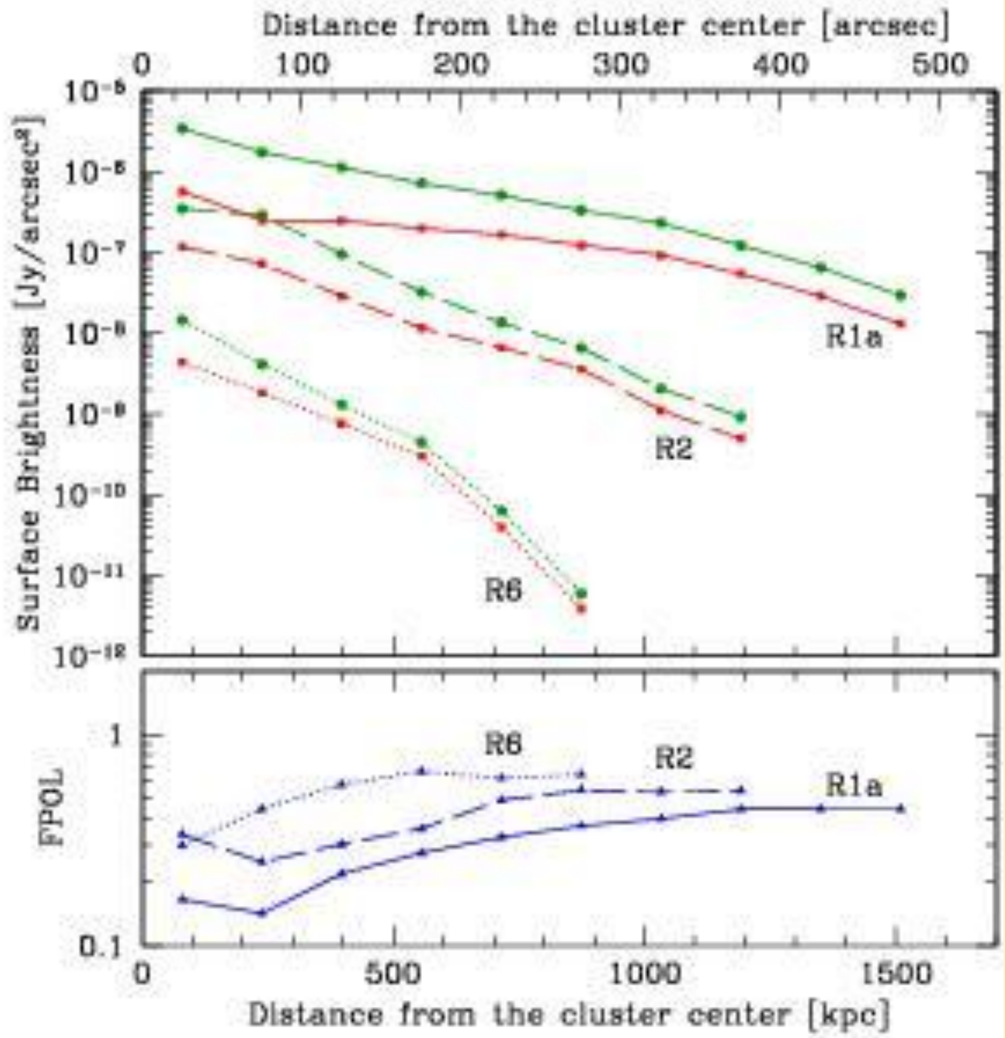
Total Intensity

Polarized Intensity



Noise added : σI = 10 μJy/beam, σP = 5 μJy/beam (confusion)



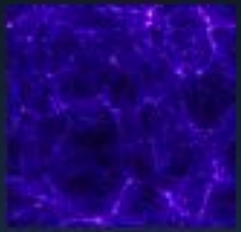


P-Lx observed + simulated clusters
R1a R2 R6

Averaged brightness profiles in
I and P and FPOL

➔ **need SKA**

www.skatelescope.org



Probing the Dark Ages and the Epoch of Reionization

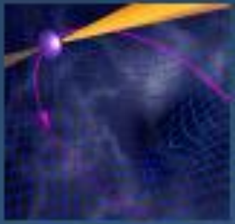
The SKA will provide detailed pictures of the early "cosmic web" of neutral gas and observe the very first black holes, stars and galaxies that shaped the development of the Universe.

Galaxy Evolution, Cosmology and Dark Energy

A neutral-hydrogen sky survey will detect 1 billion galaxies and enable us to understand their formation and evolution. The SKA will measure the geometry of the Universe to probe the nature of dark energy.

The Origin and Evolution of Cosmic Magnetism

By measuring Faraday rotation in the radio emission of tens of milions of distant galaxies, the SKA will detect magnetic fields throughout the Universe and reveal their role in its evolution.



Strong-Field tests of Gravity using Pulsars and Black Holes

Pulsars orbiting black holes will test Einstein's description of these enigmatic objects, whilst those discovered and monitored across the galaxy will act as a cosmic gravitational wave detector.

The Cradle of Life

The great sensitivity of the SKA will enable it to search for complex molecules in space. It will detect planets by observing their effects on the motion of their suns and could search for signals from other civilisations.

Deep polarization surveys are under way or planned with new or newly upgraded radio telescopes :

WODAN with APERTIF (Westerbork) - Röttgering et al. 2011
POSSUM with ASKAP – Gaensler et al. 2010
GALFACT with Arecibo – Taylor & Salter 2010
LOFAR
MeerKAT
JVLA

Instrument	Frequency Range MHz
SKA1-low	50-350
SKA1-mid	350-1050 (Band 1)
	950-1760 (Band2)
SKA1-survey	650-1670 (PAFBand2)
SKA1	50-1760 (full coverage)

Improvement in

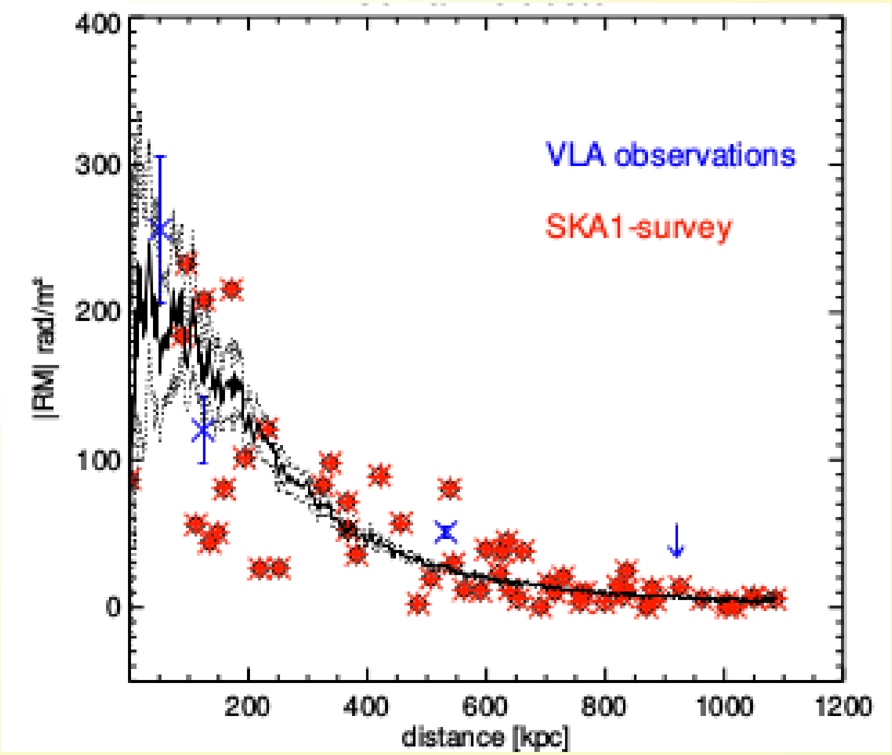
Frequency coverage : broadband to properly interpret the data
Angular resolution : calibration, confusion limit, beam depolarization
Field of view : largest angular scale
Sensitivity
Polarization purity
Survey speed

All-sky polarization survey at ~1 GHz

Instrument	Frequency	Field of View	Resolution	Sensitivity
SKA1-survey PAFBand2	~1-1.5 GHz	All sky	~ 2"	~2 µJy/beam

10 000 deg2,
grid of Faraday RM 300 – 1000 times denser than the most accurate all-sky map currently available
(about 1 source/deg2, Taylor et al. 2009)

100 – 1000 sources per cluster



Coma cluster

Deep polarization surveys at ~ 1- 3 GHz

Instrument	Frequency	Field of View	Resolution	Sensitivity
SKA1-mid Band2	~1-2 GHz	~10 deg^2	~ 0.5-1"	~0.1 μJy/beam
SKA1-mid Band3	~2-3 GHz	~3 deg^2	~ 0.5-1"	~0.1 μJy/beam

High redshift objects,
Faint objects

Targeted observations at all frequencies

Conclusions

Magnetic fields are common in clusters
Detected so far up to high redshift

complex structure (power spectrum)
radial decline
linked to gas density

polarization of radio halos predicted at
15 – 35 % levels

breakthrough from SKA

THANK YOU

Cluster Magnetic field vs Temperature

Comparison RM - X-ray surface brightness
(Dolag et al. 2001)

$S_X \propto \int n^2 T^{1/2} dx$

$\sigma_{RM} \propto \int n B \, dx$

➔

σ_{RM} vs S_X reflects the trend of B vs n

(if the $T^{1/2}$ dependance is taken into account)

any further relation of B to T would be enhanced

Rotation measures of radio sources in hot galaxy clusters★

F. Govoni[1], K. Dolag[2], M. Murgia[1], L. Feretti[3], S. Schindler[4], G. Giovannini[3,5], W. Boschin[6,7], V. Vacca[1,8], and A. Bonafede[3,5]

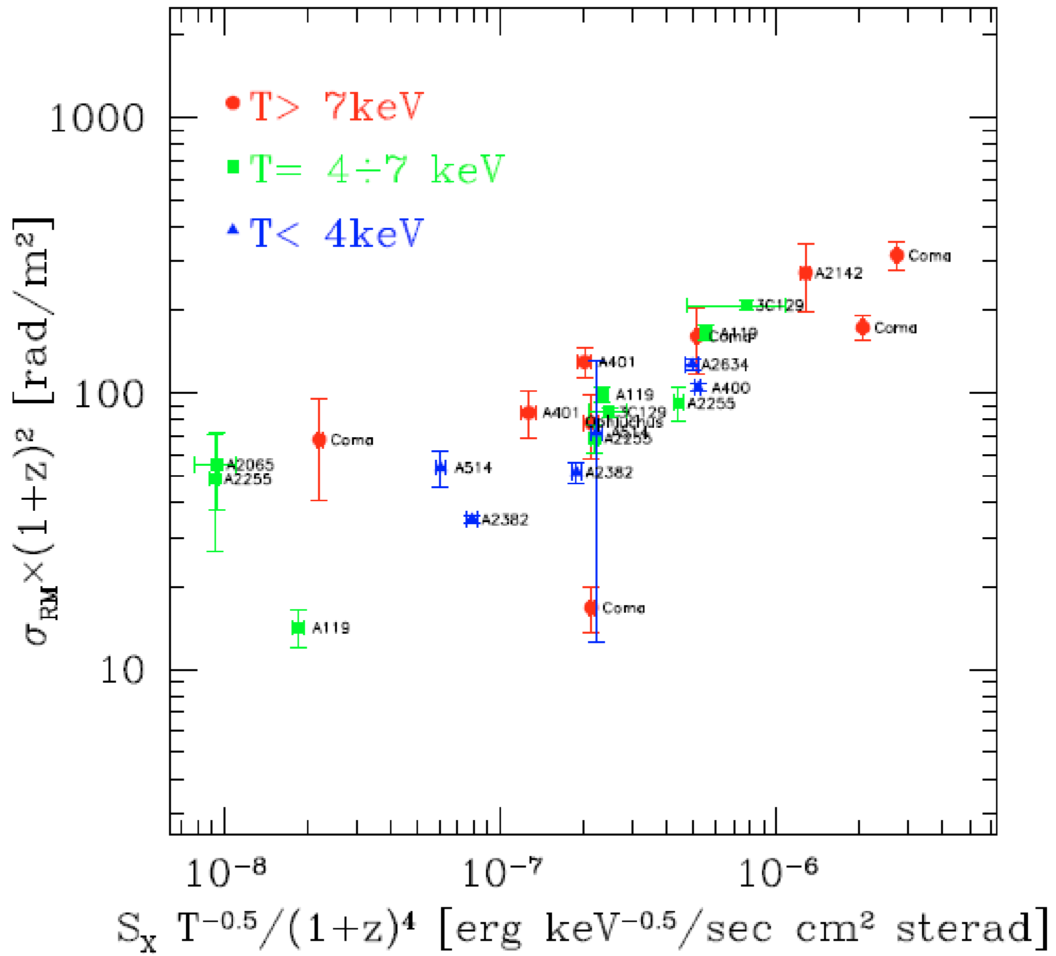
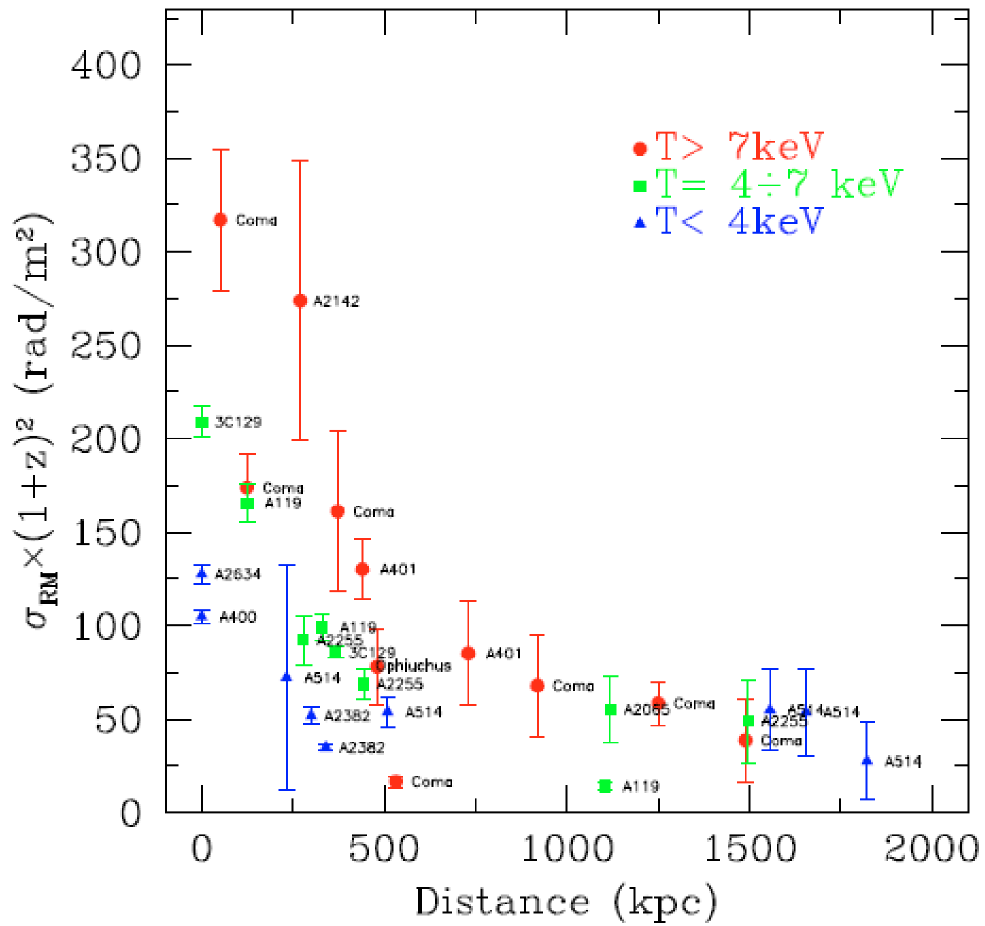


Fig. 18. Dispersion of the rotation measure distribution as a function of the X-ray surface brightness of the intracluster gas in the source location. The different symbols represent the cluster temperature taken from the literature (red >7 keV, green 4–7 keV, blue <4 keV).

(A&A 2010)

Govoni et al. A&A 522, A105 (2010)



For a fixed projected distance, clusters with high T show a higher RM dispersion

➔Either B linked to n
or B linked to T