Polarization of Cluster Radio Halos with Upcoming Radio Interferometers

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LOFAR Workshop

Sant'Antioco 13-17 May 2013

Outline of the Talk

1) The intracluster medium is magnetized

-Evidence from RM of embedded or back-ground radio galaxies (kpc-scale fluctuations)
-Evidence from extended radio halos at cluster center (Mpc-scale fluctuations)

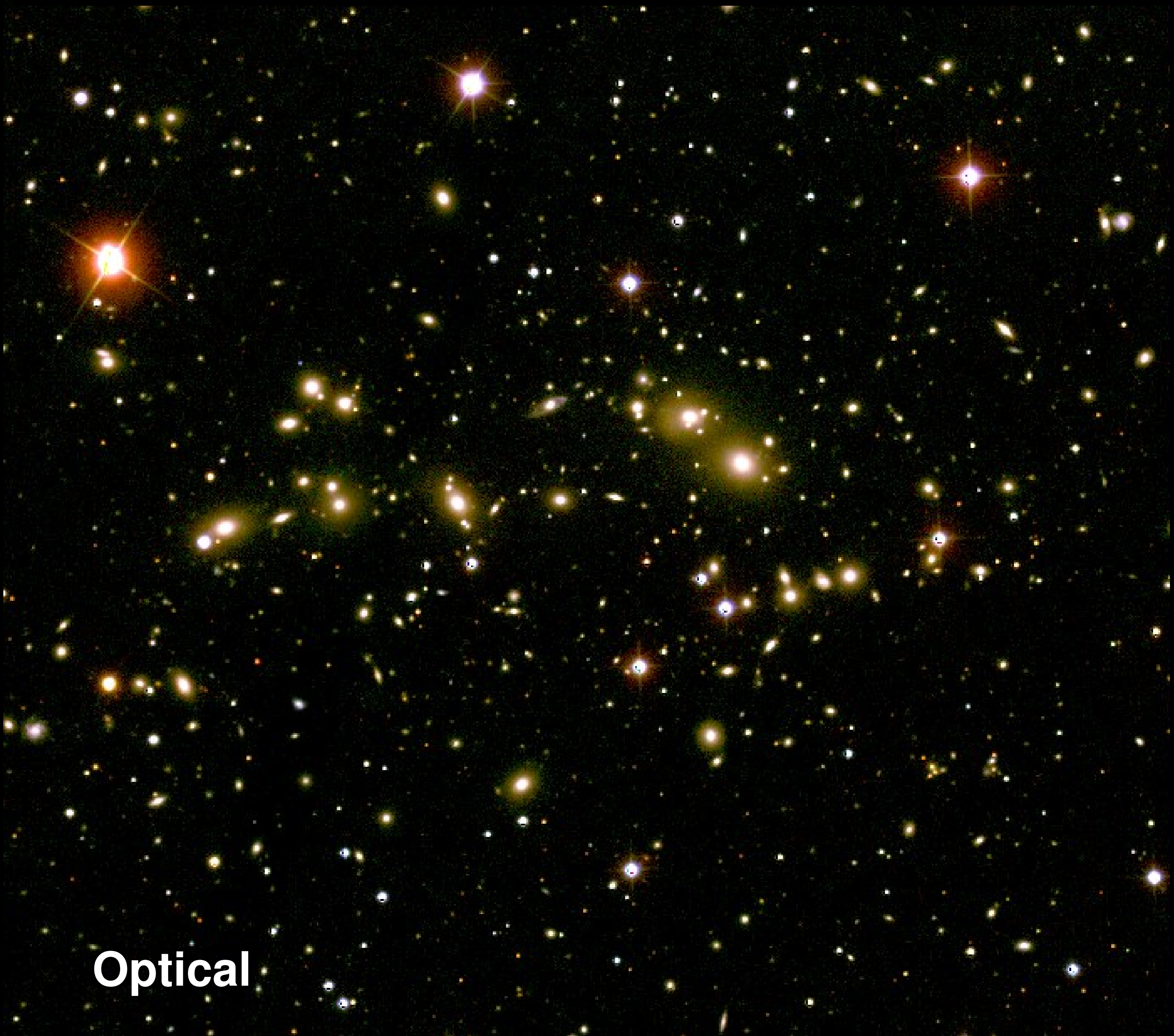
2) Numerical simulations and comparison with data

-Examples of RM images from MHD simulations and comparison with data
-Examples of total intensity radio halo images from MHD simulations and comparison with data

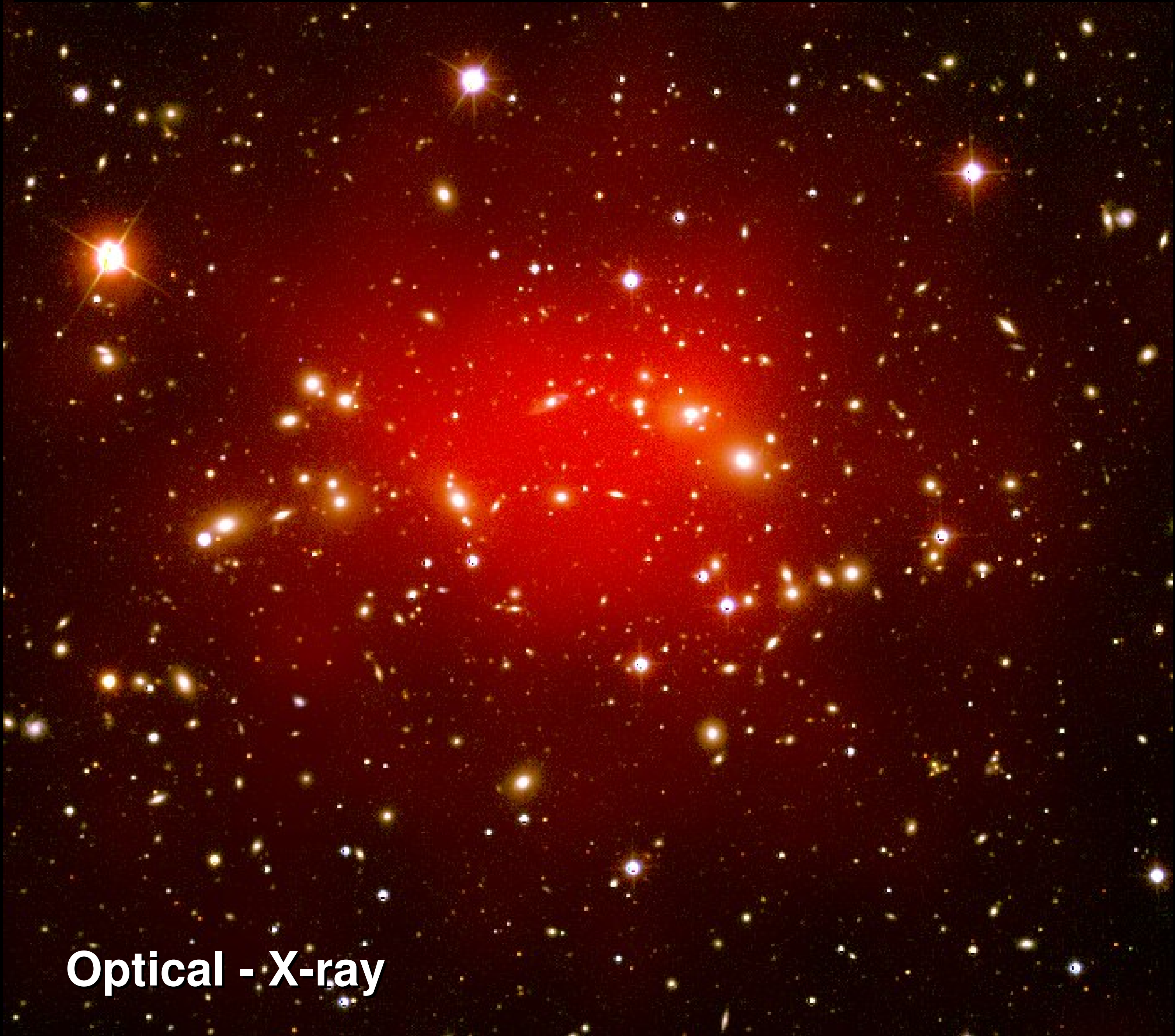
3) Polarization of radio halos with upcoming radio interferometers

-Radio halo polarization powerful tool to investigate field strength and structure but very hard to measure with current instruments
-Perspectives at GHz frequencies for JVLA, ASKAP, APERTIF, and SKA

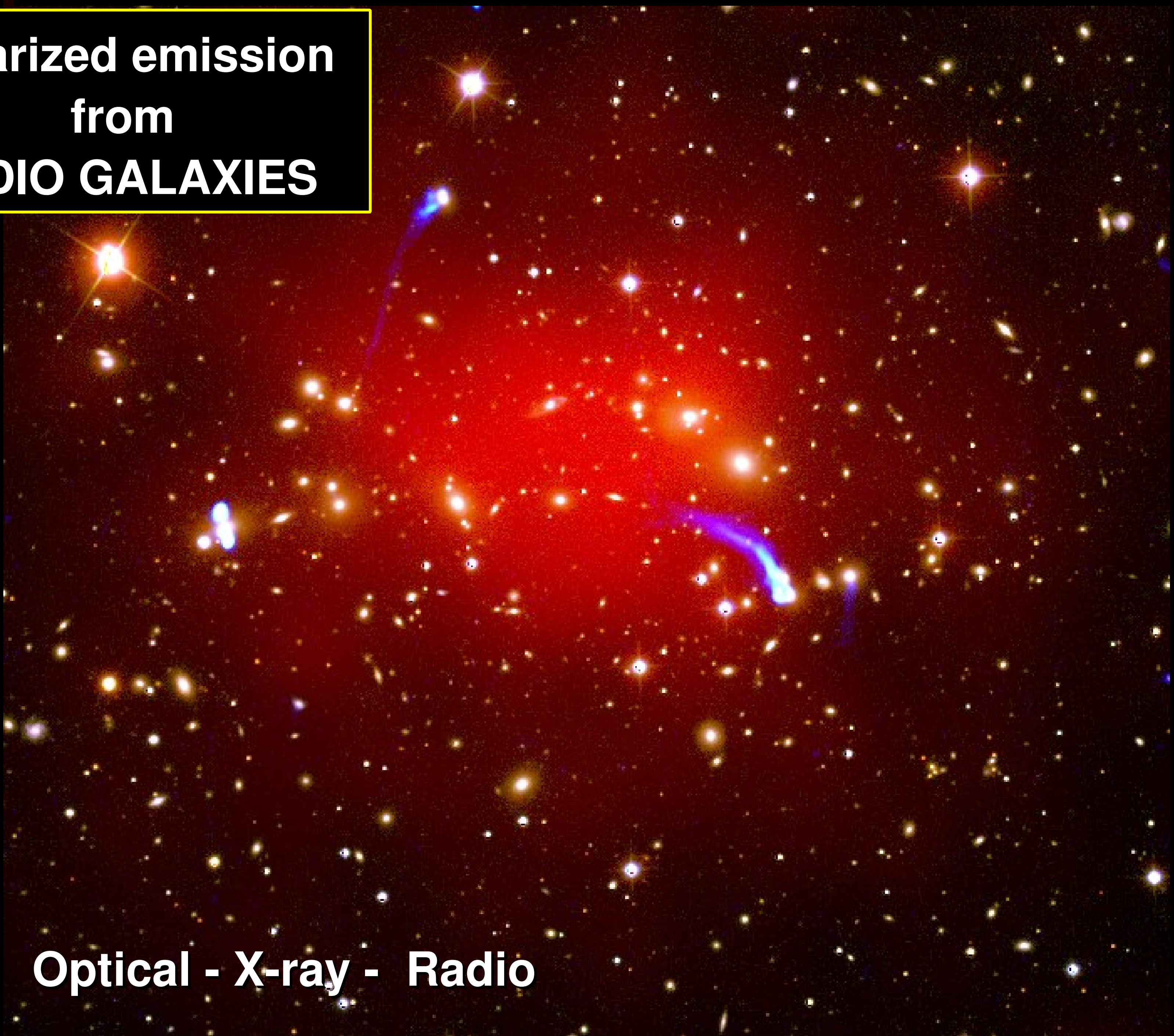
Magnetic Fields in Galaxy Clusters



Magnetic Fields in Galaxy Clusters



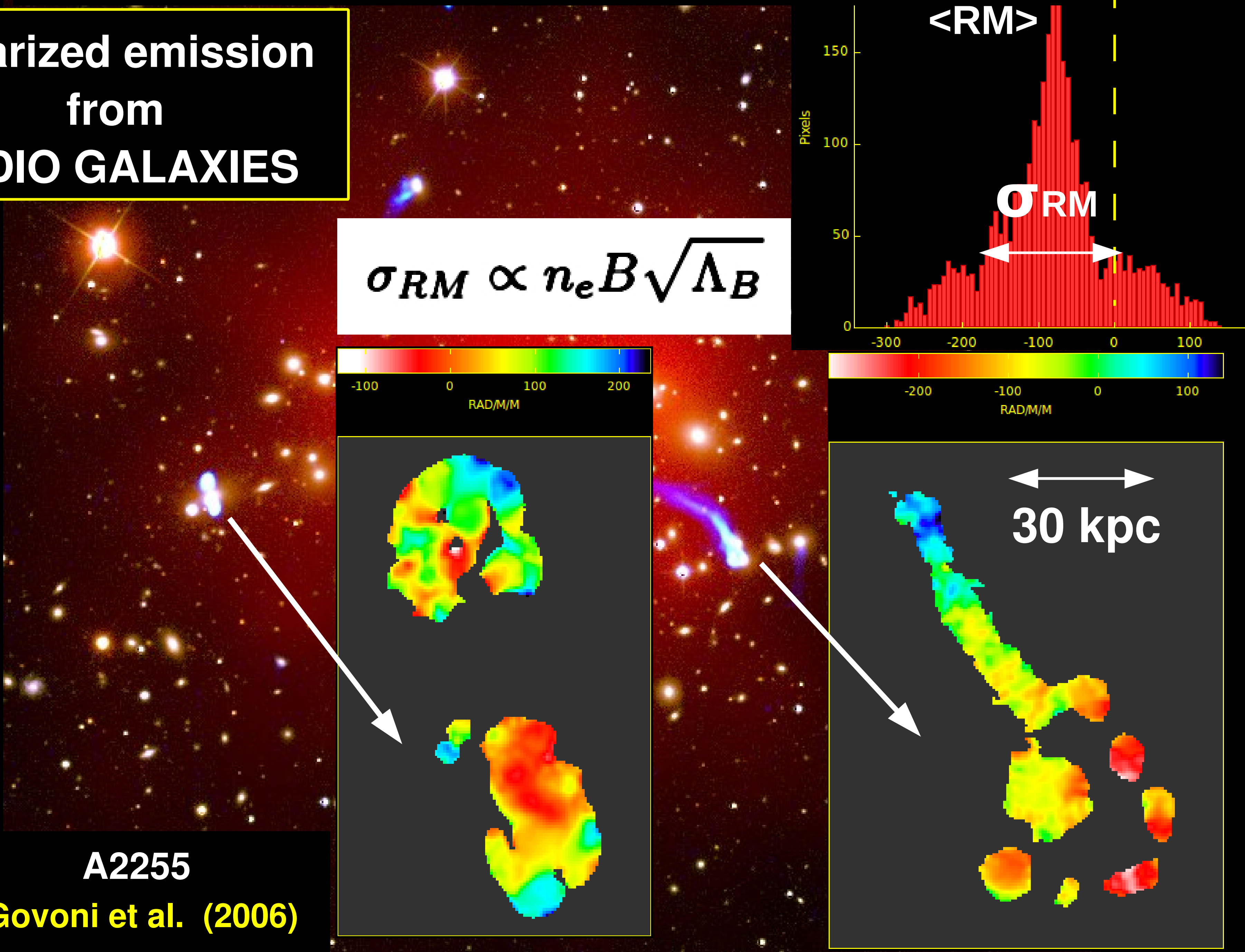
Magnetic Fields in Galaxy Clusters



Magnetic Fields in Galaxy Clusters

Polarized emission from RADIO GALAXIES

$$\sigma_{RM} \propto n_e B \sqrt{\Lambda_B}$$



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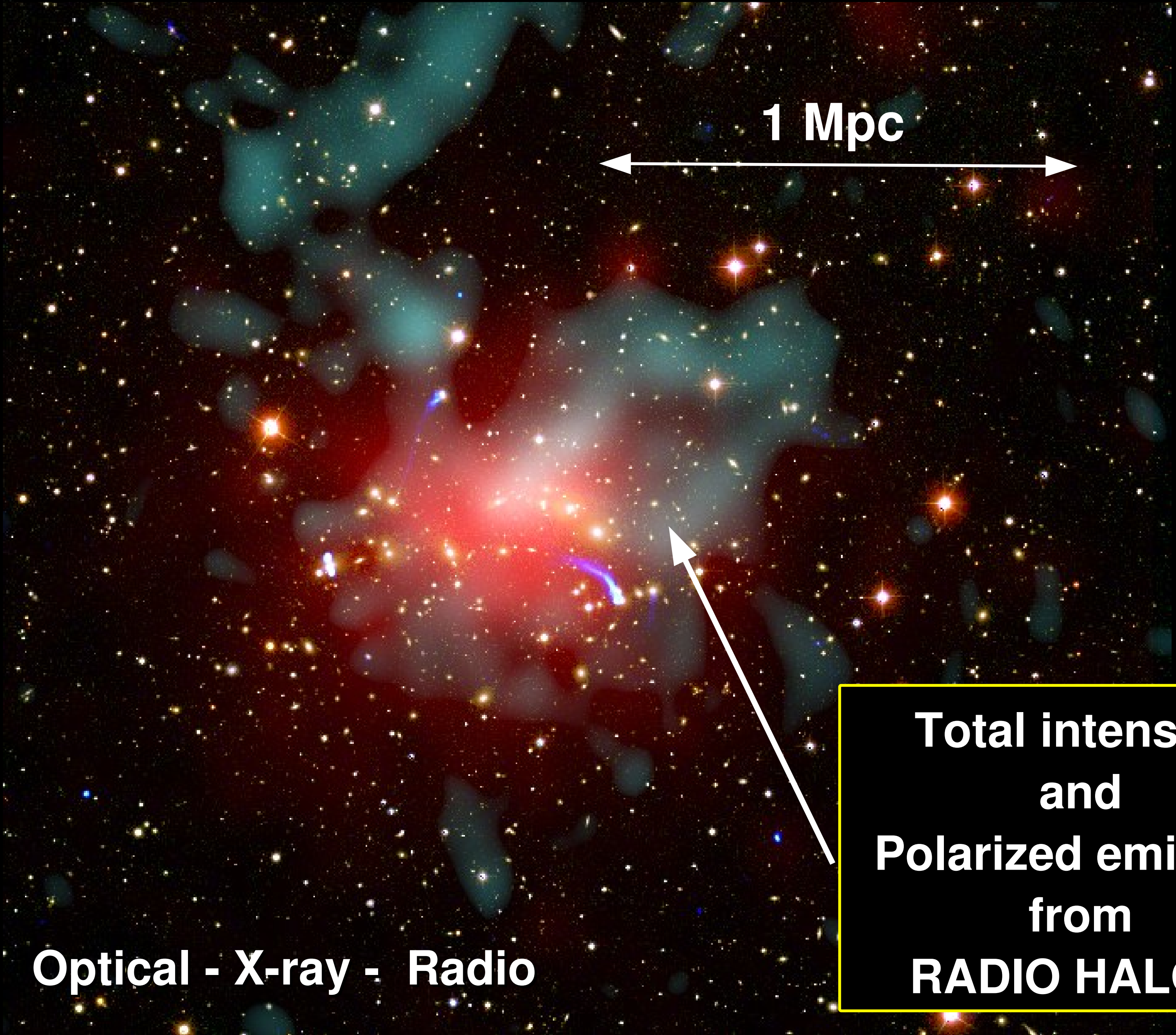
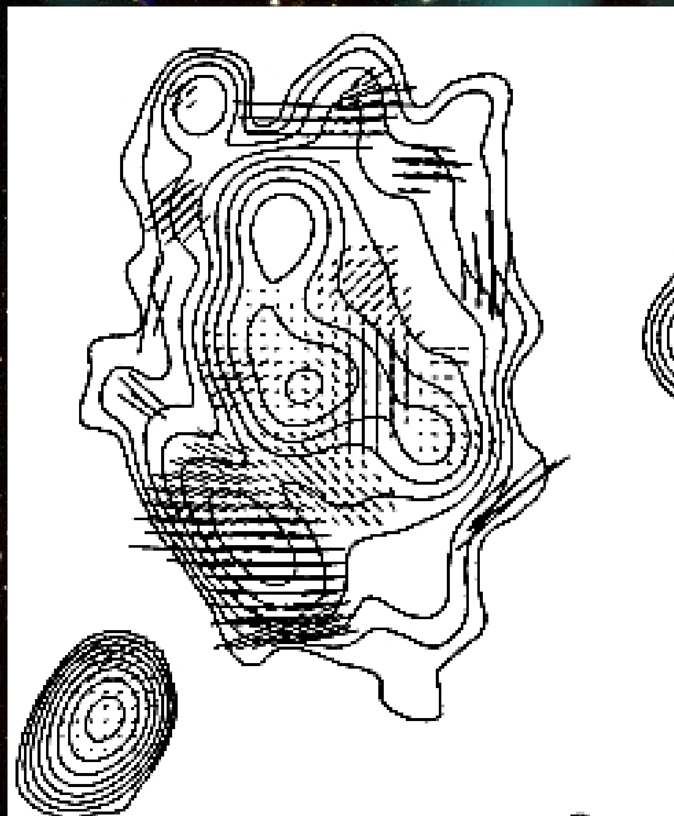
Govoni et al. (2006)

Magnetic Fields in Galaxy Clusters



Magnetic Fields in Galaxy Clusters

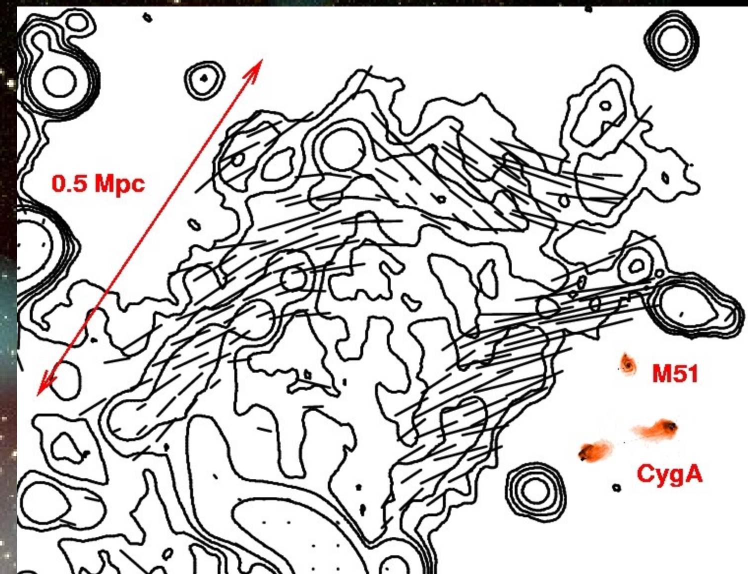


MACS J0717.5+3745
Bonafede et al. (2009)

$$\Lambda_B = \frac{3\pi}{2} \frac{\int |B_k|^2 k dk}{\int |B_k|^2 k^2 dk}$$

Ensslin et al. (2003)

A2255
Govoni et al. (2005), Pizzo et al. (2009)



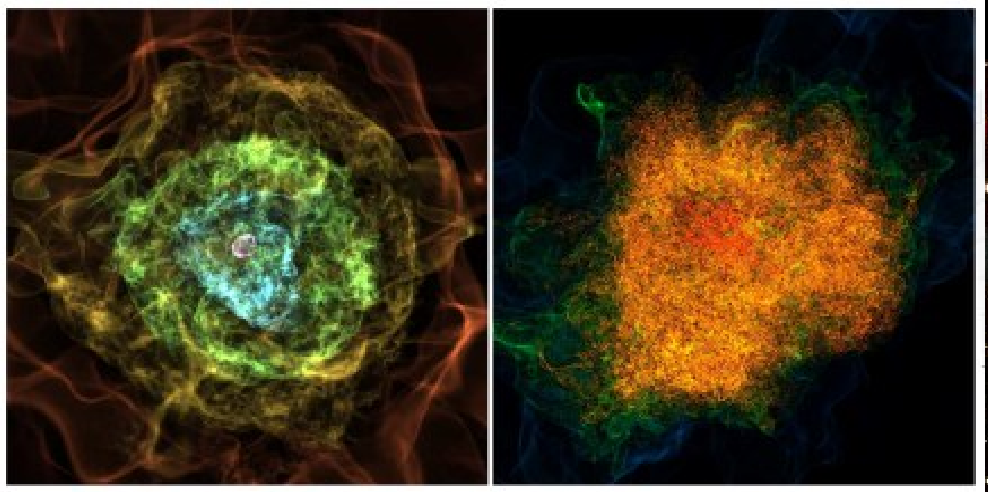
**Total intensity
and
Polarized emission
from
RADIO HALOS**

Cosmological Simulations

Cosmological MHD simulations have been playing an important part in studying cluster magnetic fields (e.g. Dolag et al. 1999, Bruggen et al. 2005, Donnert et al. 2009, Bonafede et al. 2011).

MHD cluster simulations have been performed with different initial magnetic fields, including:

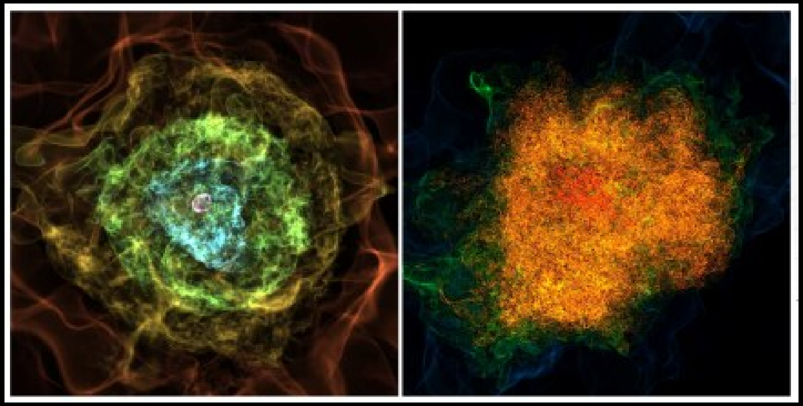
- Random or uniform fields from high redshift (Dolag et al. 2002, Dubois & Teyssier 2009)
- Outflows of normal galaxies (Donnert et al. 2009)
- AGN (Xu et al. 2009, 2010, 2011, 2012)



Seed magnetic fields injected by high-z AGNs are spread and amplified to micro-Gauss level by the intracluster turbulence caused by mergers during the cluster formation process.

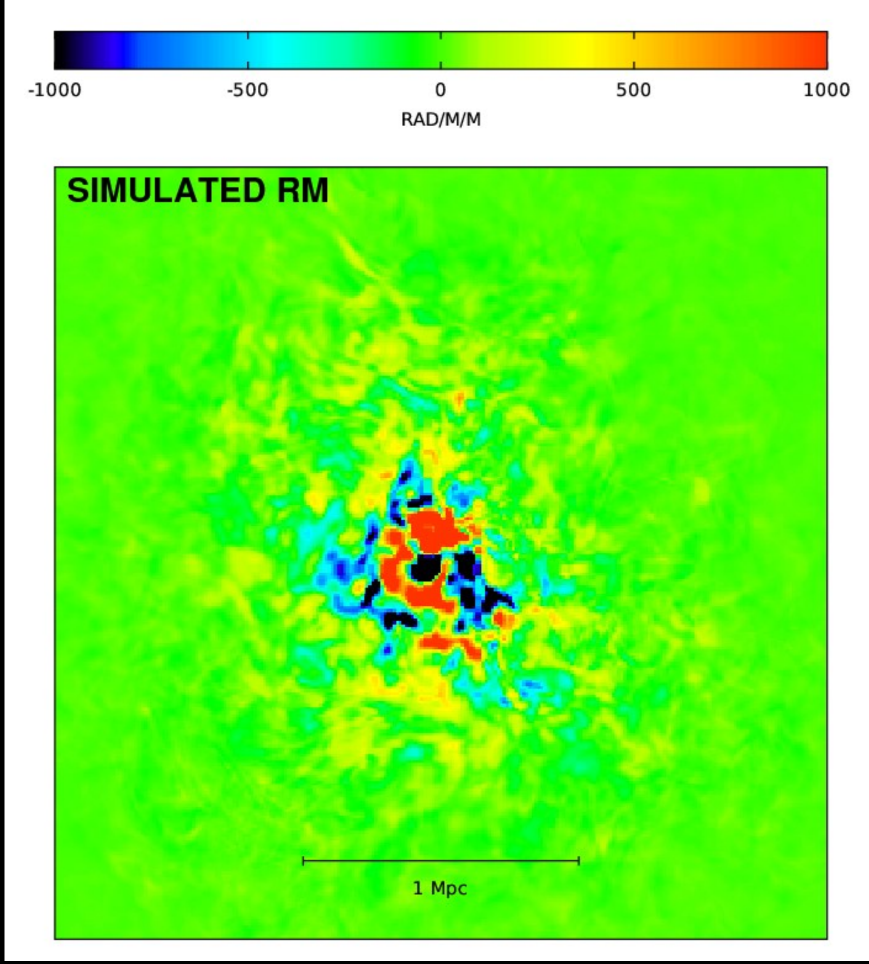
Simulated Rotation Measure

Xu et al. (2012)



Gas density Magnetic fields

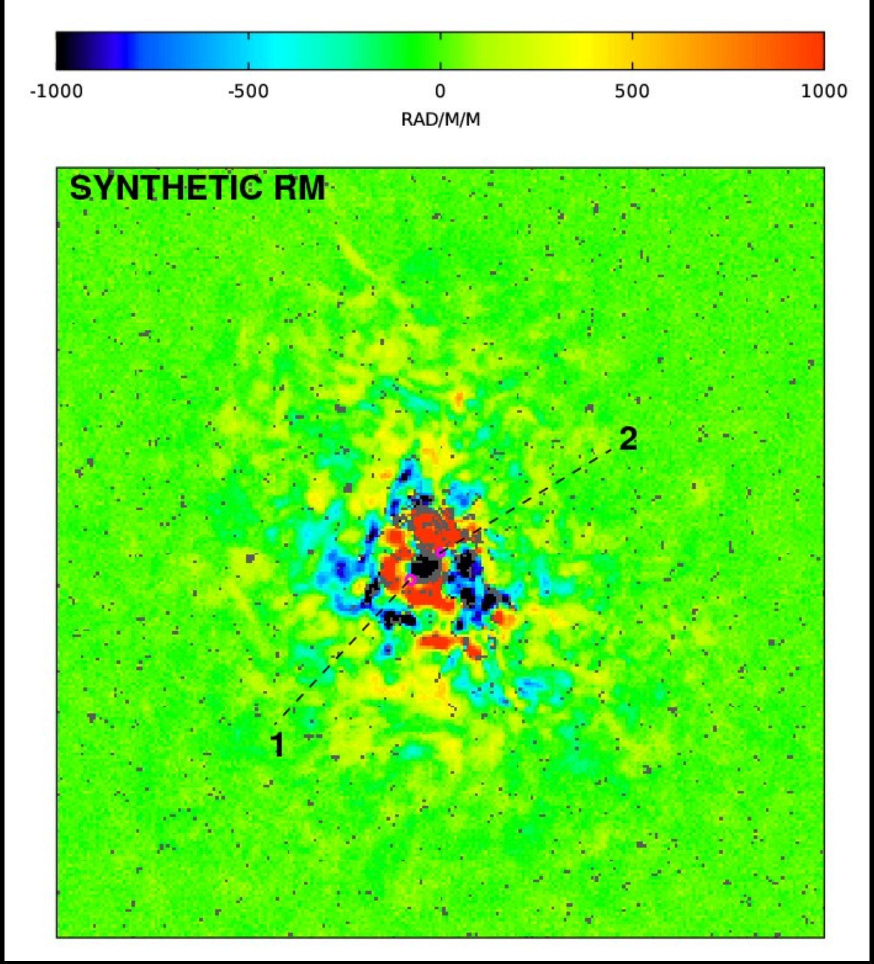
$$RM = 812 \int_0^{L_{[kpc]}} n_{e\ [cm^{-3}]} B_{||\ [\mu G]} dl \quad (\mathrm{rad\ m^{-2}})$$



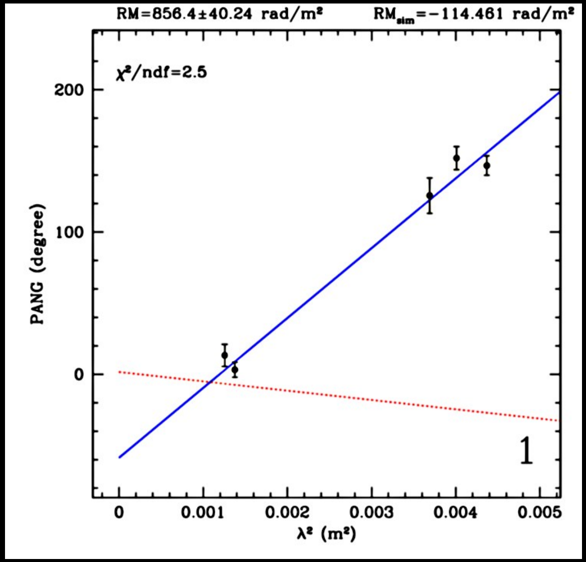
When comparing the expectation of numerical simulations of cluster Faraday rotation images with data one must take into account of the instrumental filtering affecting the observed RM images.

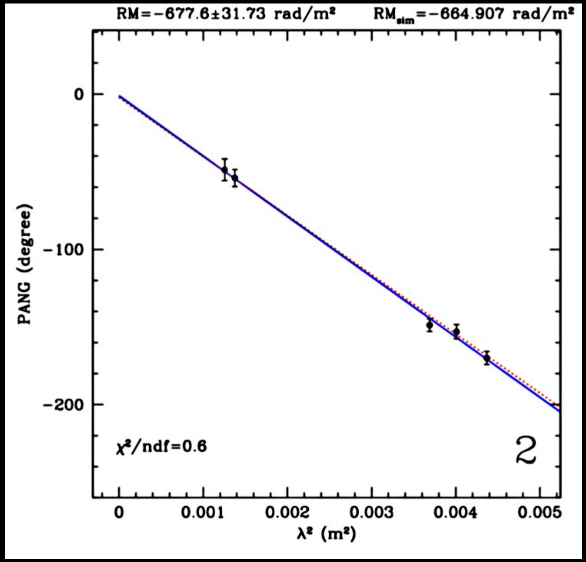
Synthetic Rotation Measure

- Mock images of intrinsic polarization intensity and angle.
- Polarization intensity and angle images at different frequencires 4-8 GHz
- Synthetic Stokes images U and Q at each Frequency
- Noise - Beam - Bandwidth
- Synthetic RM image created pixel by pixel by fitting the “observed” polarization angles images for all frequencies.



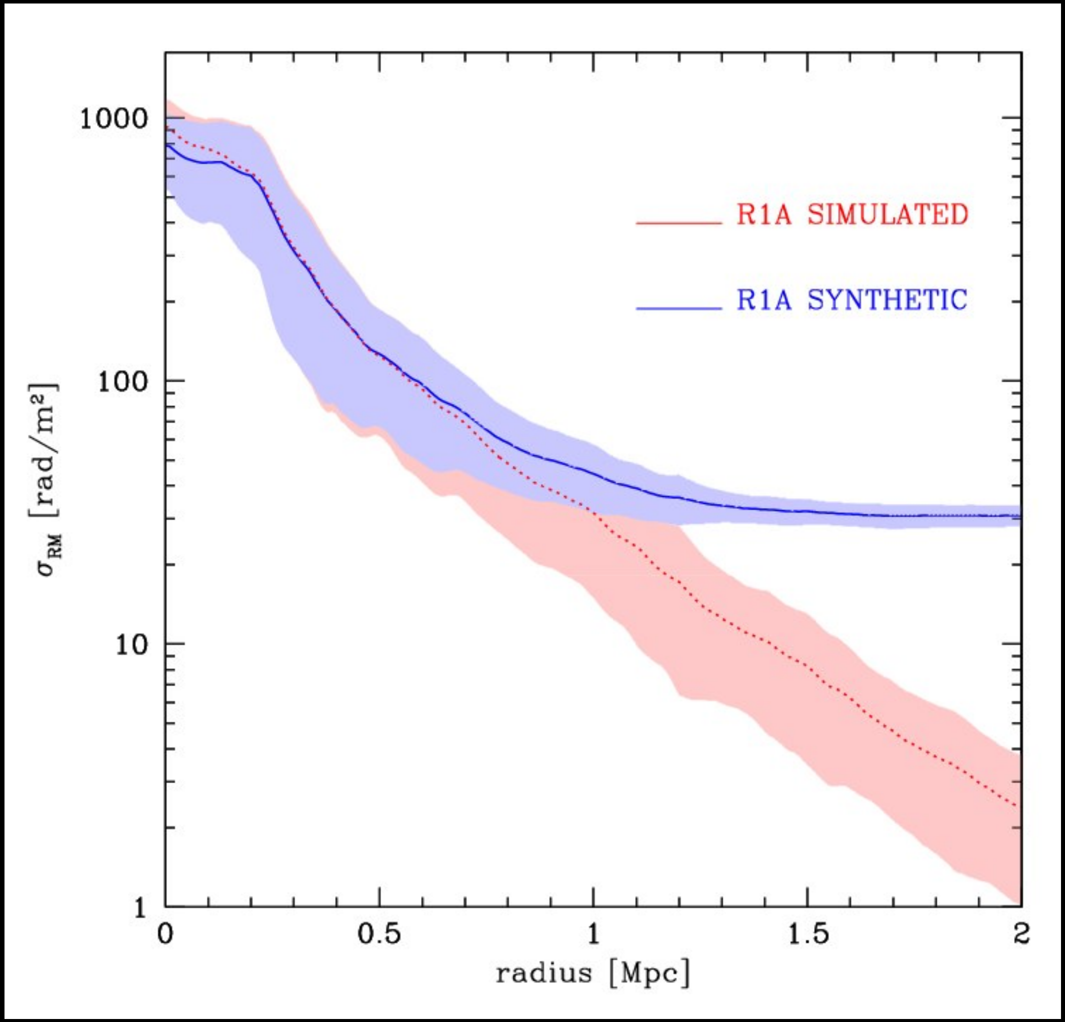
$$\chi=\chi_0+\lambda^2 x RM$$

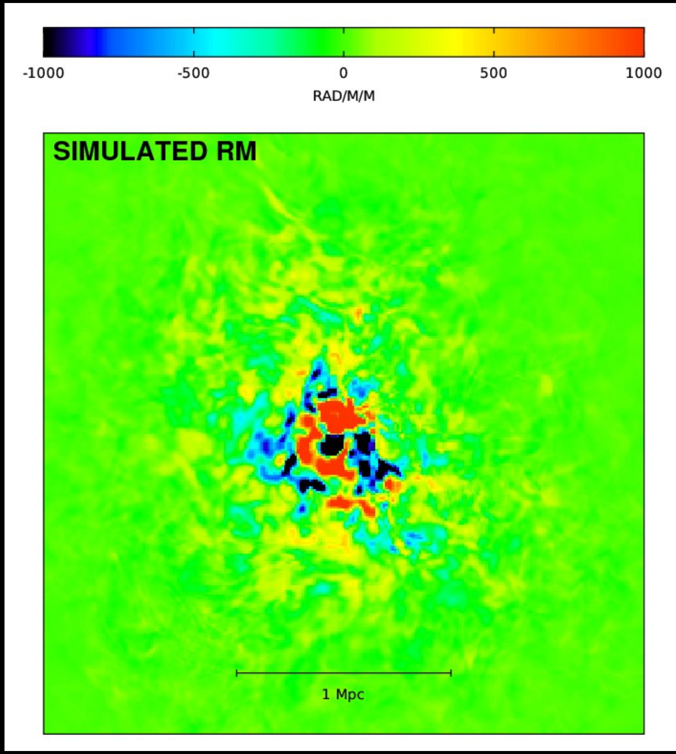


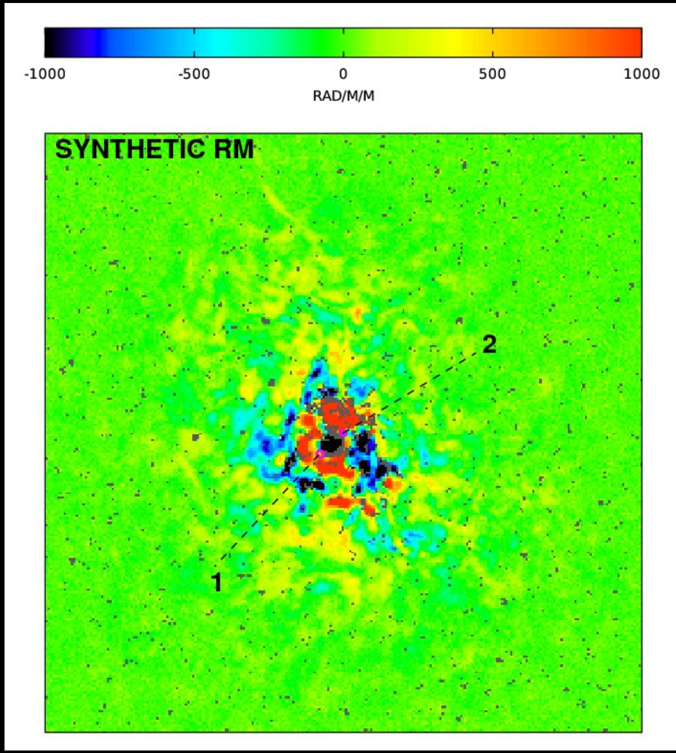


Fit of the λ^2-law (blue solid line). The red dotted lines correspond to the trend expected without instrumental filtering.

Synthetic Rotation Measure





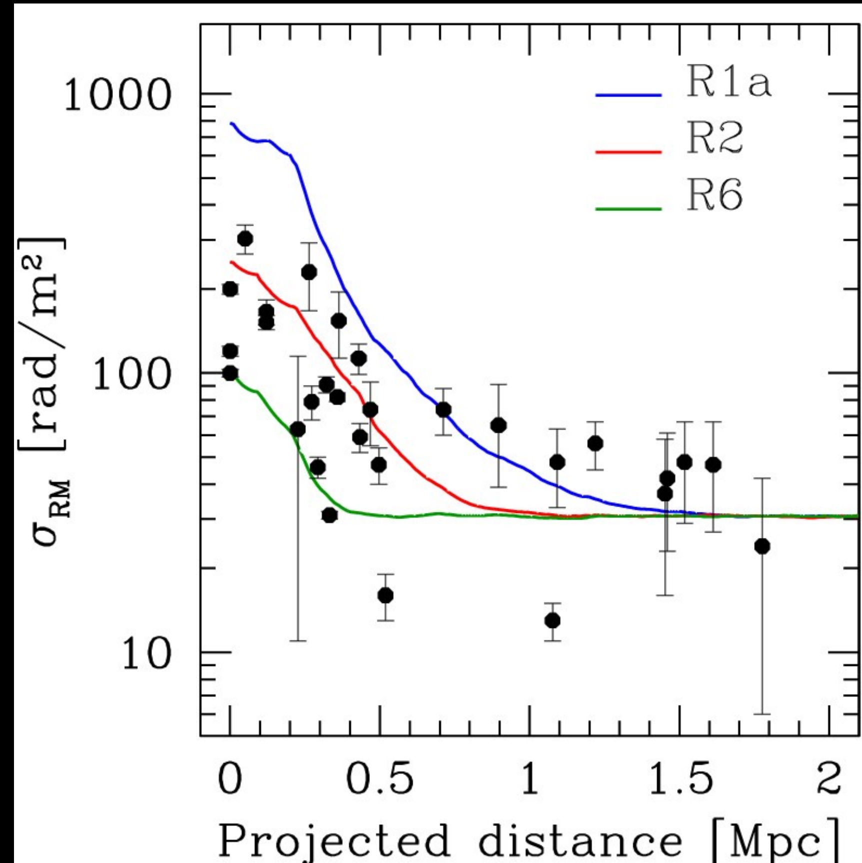


Simulated and synthetic σRM profiles.

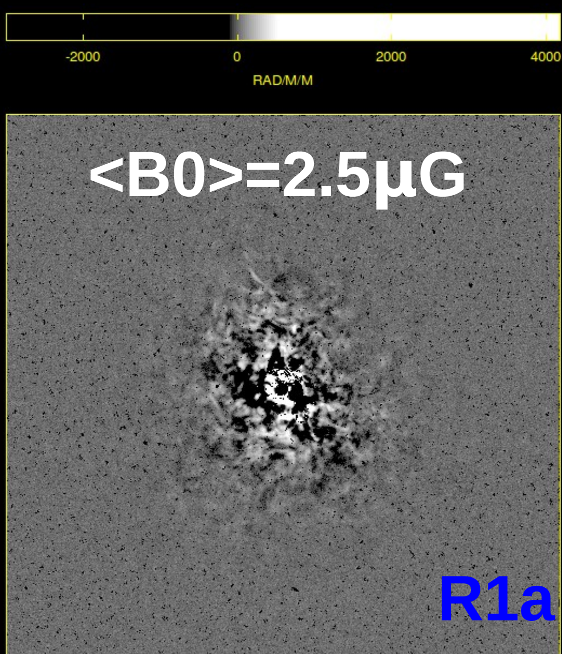
Comparison between observations and synthetic RM

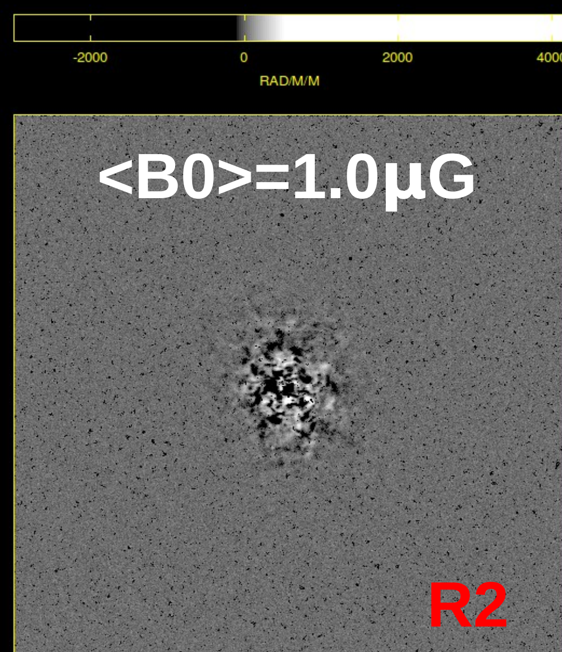
ROTATION MEASURE as a function of the projected distance from the cluster center

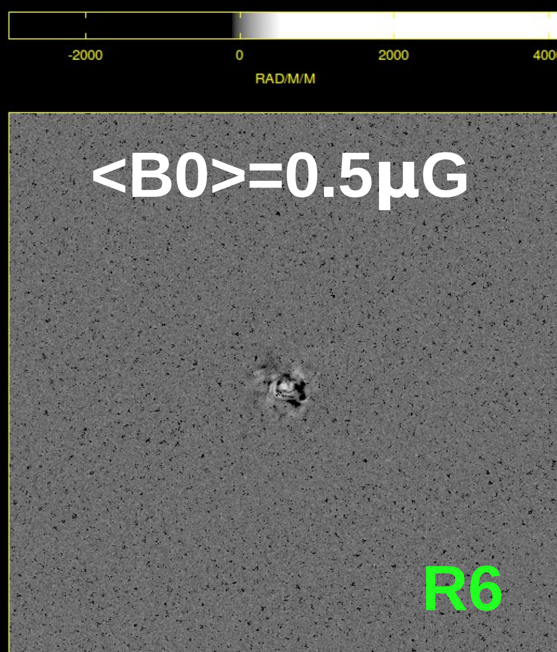
Govoni et al. 2010
(see also Clarke et al. 2004)



RM Images

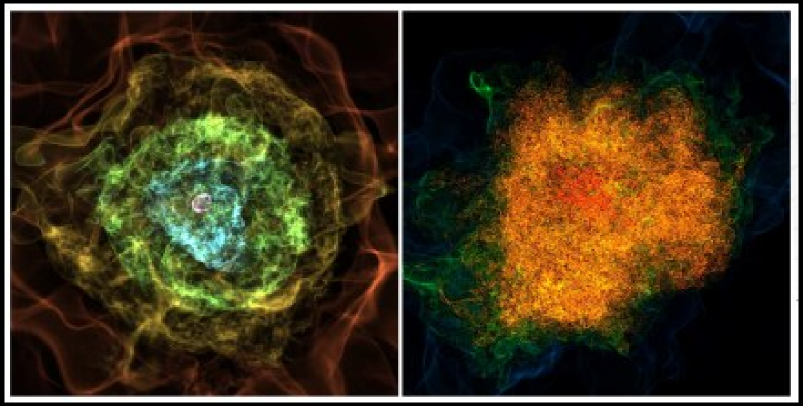






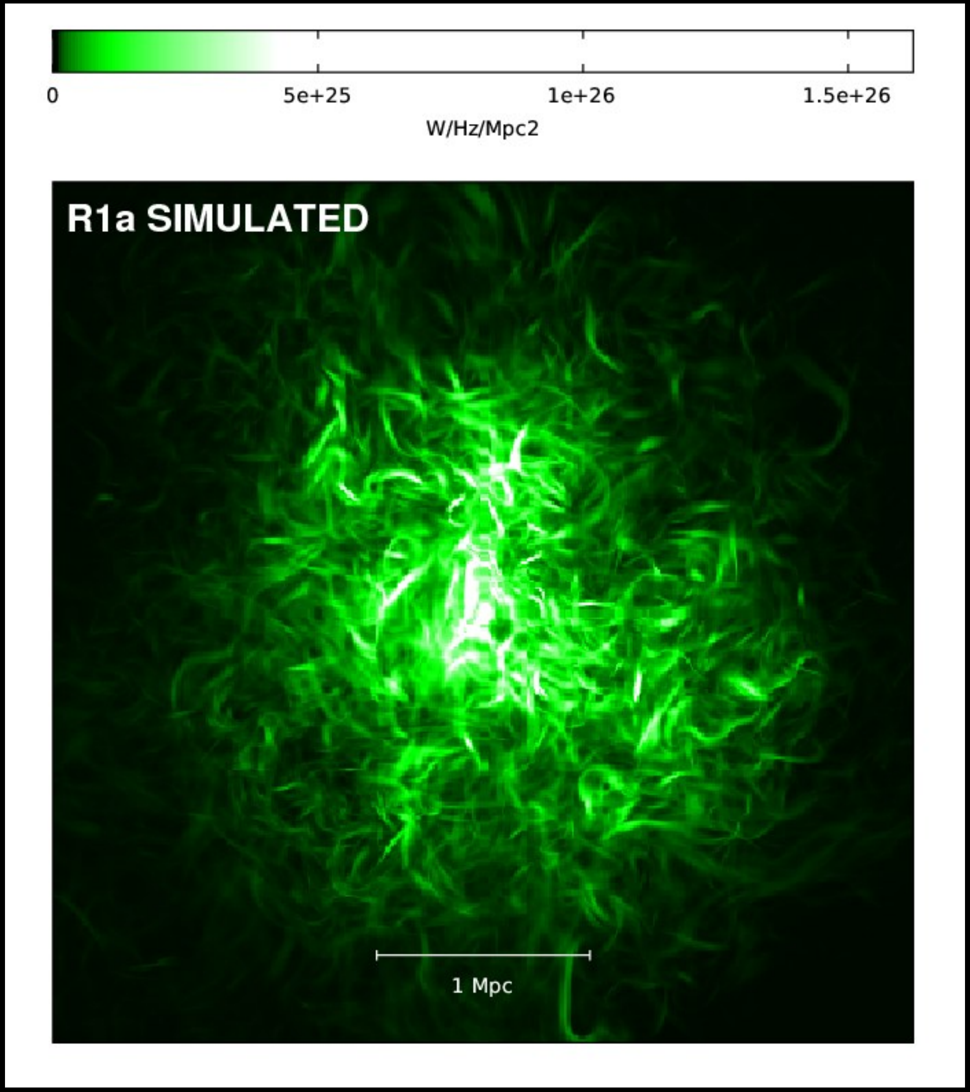
Simulated Radio Halos

Xu et al. (2012)



Gas density Magnetic fields

Frequency 1.4 GHz

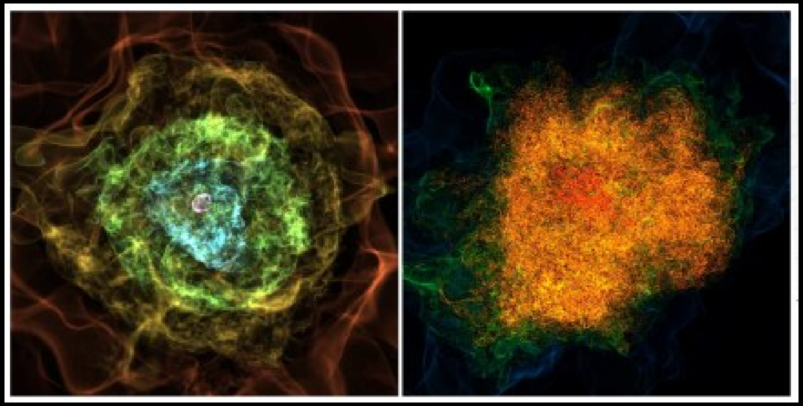


Simulated radio halo images by Illuminating the cosmological magnetic fields with a population of relativistic electrons.

1) Resonable energy spectrum for the synchrotron electrons.
2) Energy equipartition between magnetic fields and relativistic electrons.

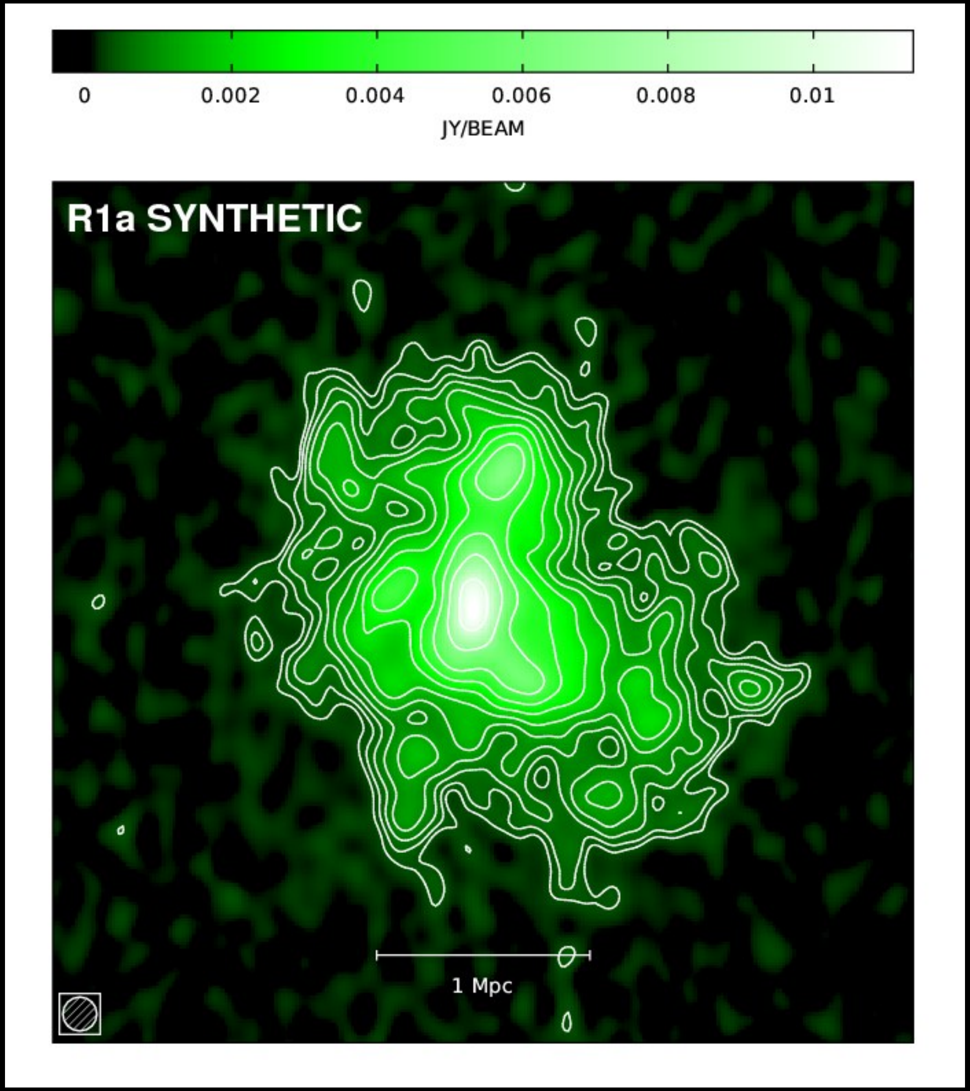
Synthetic Radio Halos

Xu et al. (2012)

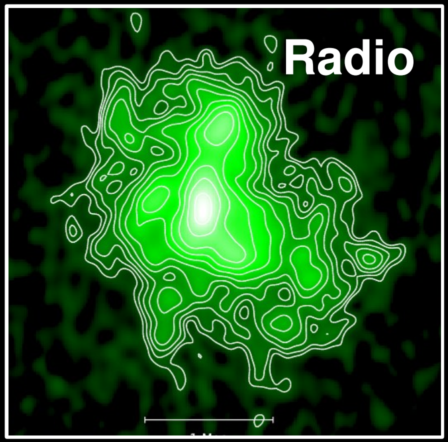


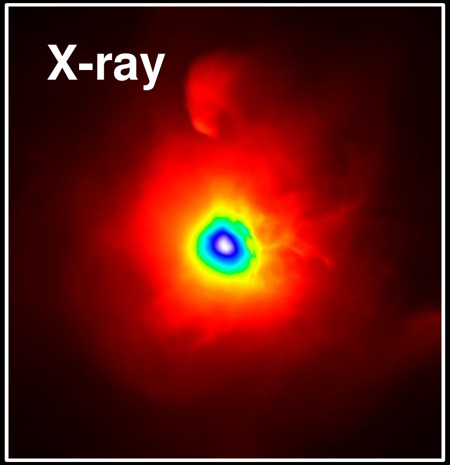
Gas density Magnetic fields

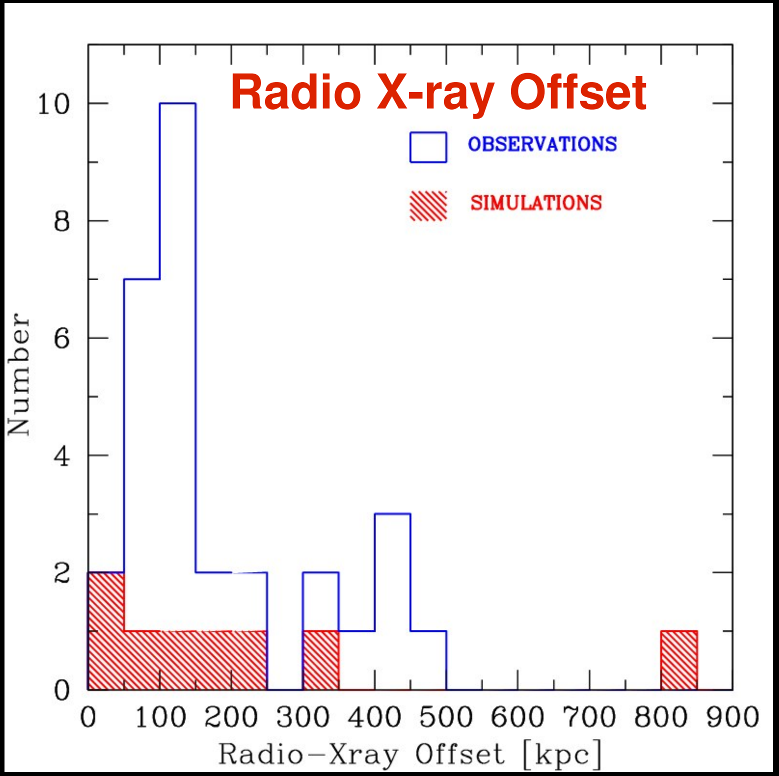
Frequency 1.4 GHz
Bandwidth 25 MHz
Resolution 50''
σ_I=0.1 mJy/beam

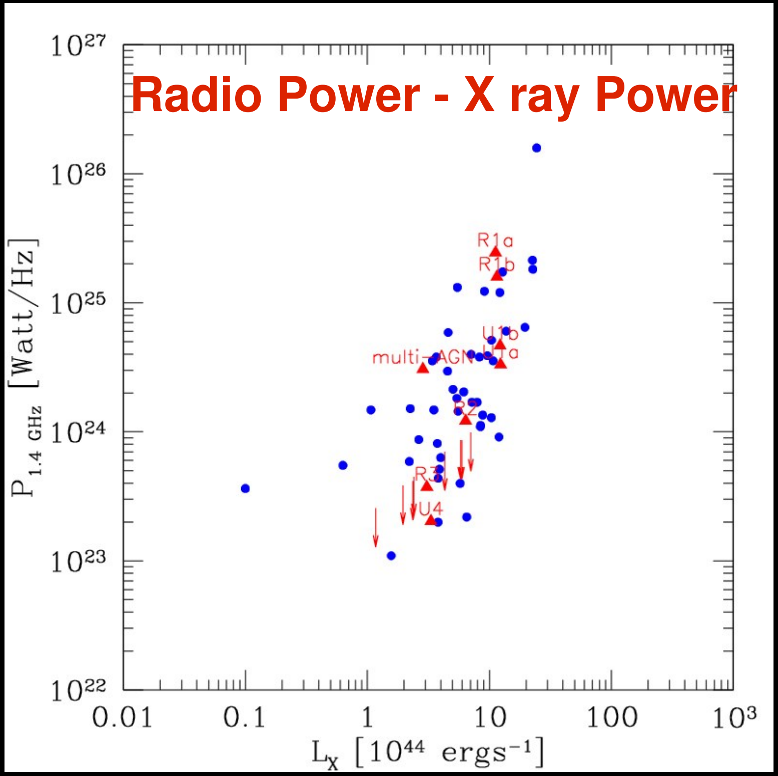


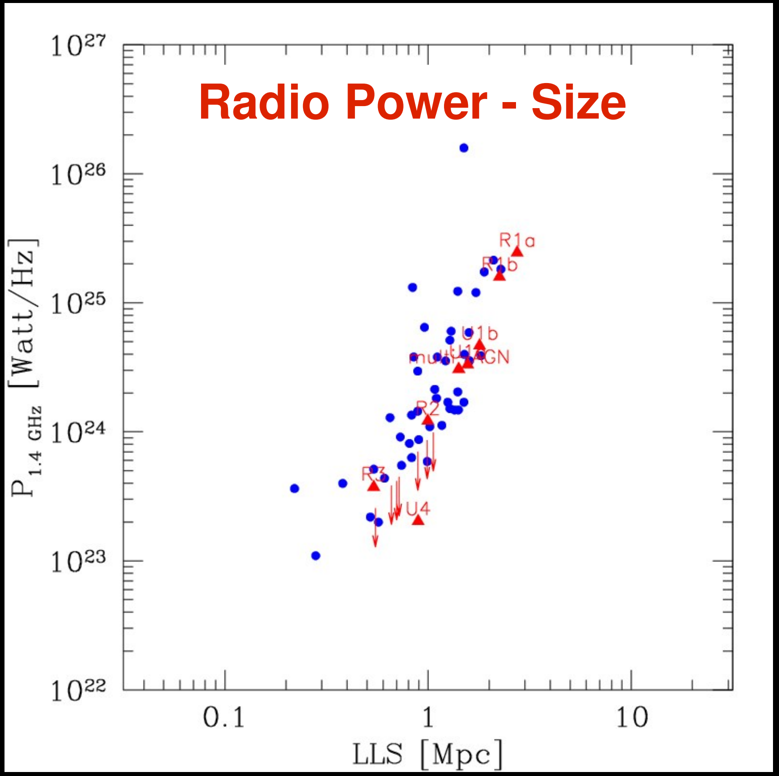
Comparison between observations and synthetic radio halos





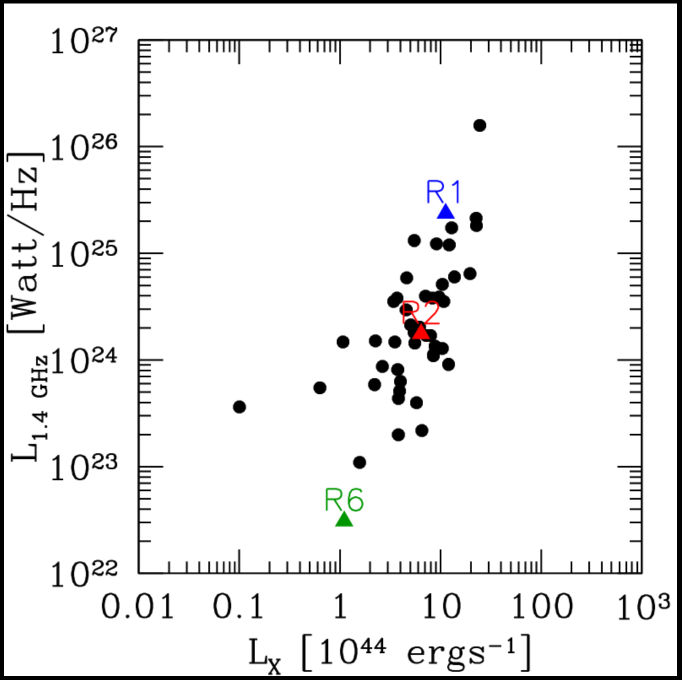






Polarization of Radio Halos

The synthetic Faraday Rotation Measure and total intensity radio halo images presented by Xu et al. (2012) have global properties in line with observations.



The study of polarized emission from radio halos has been shown to be extremely important to constrain the properties of intra-cluster magnetic fields.
Murgia et al. (2004), Govoni et al. (2006), Vacca et al. (2010)

On the basis of cosmological magnetohydrodynamical simulations, with initial magnetic fields injected by active galactic nuclei by Xy et al. (2012) we predict the expected radio halo polarized signal at 1.4 GHz.

1) We compare these expectations with the limits of current radio facilities

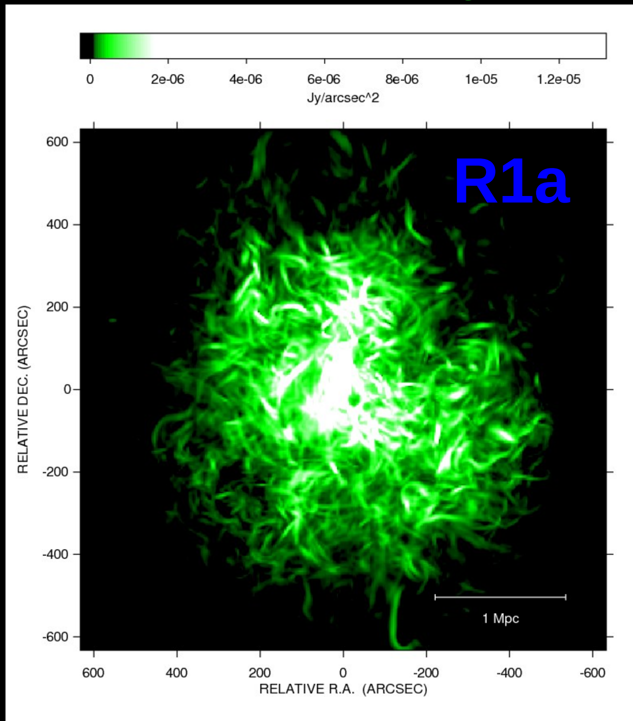
2) We explore the potential of the upcoming radio interferometers to detect the polarized emission from radio halos.

Govoni et al. (2013), In press.

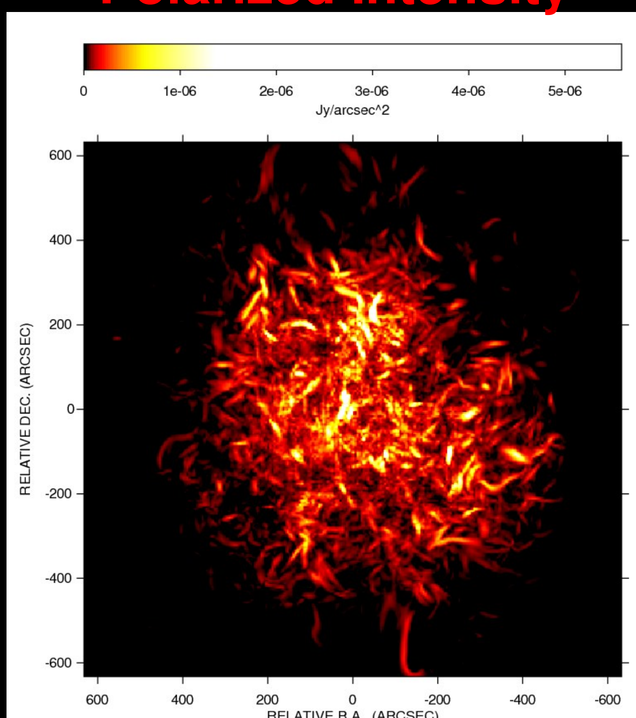
Polarization of Radio Halos

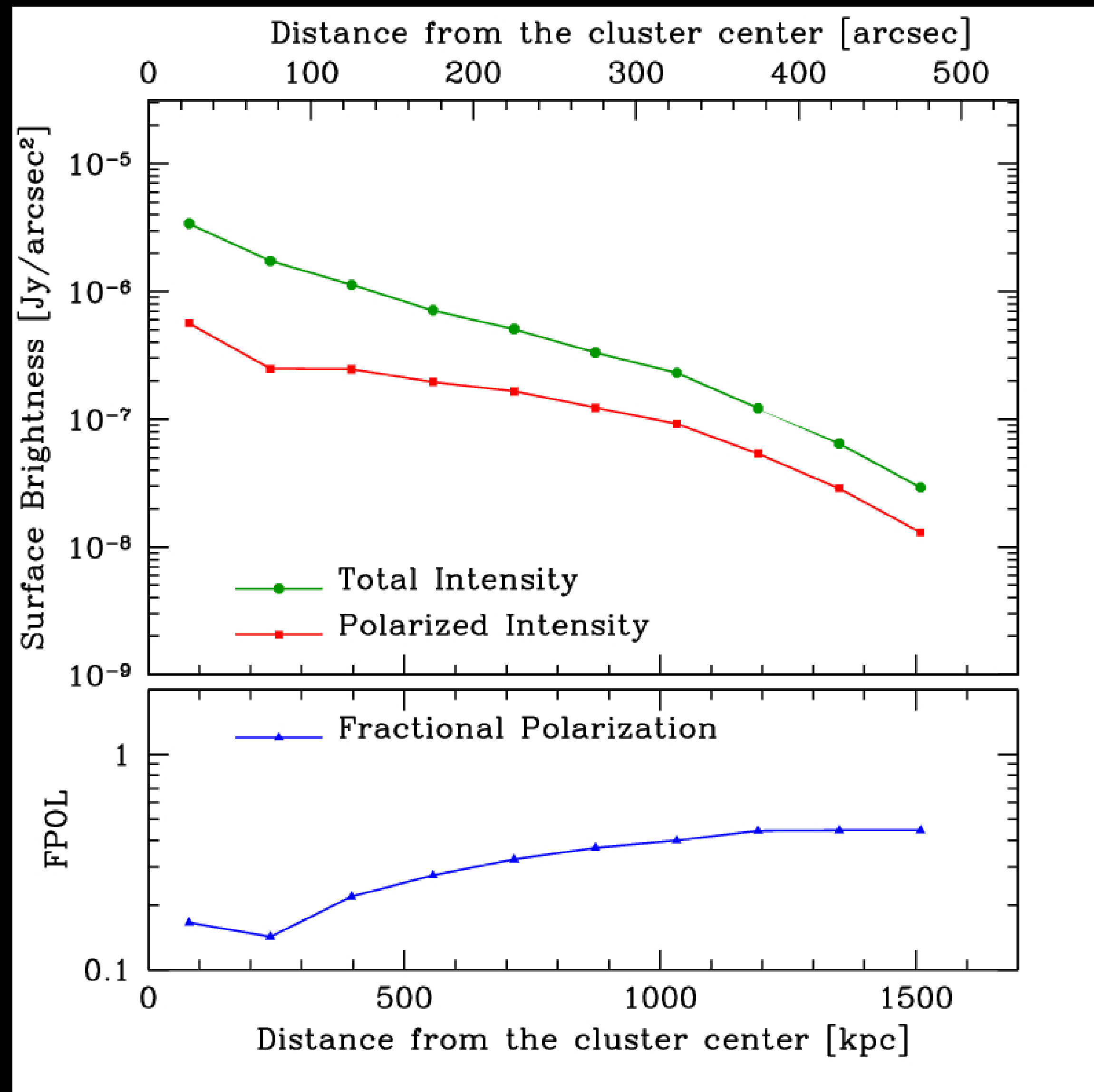
Full resolution radio halo emission
Frequency 1.4 GHz
Bandwidth 25 MHz

Total Intensity



Polarized Intensity

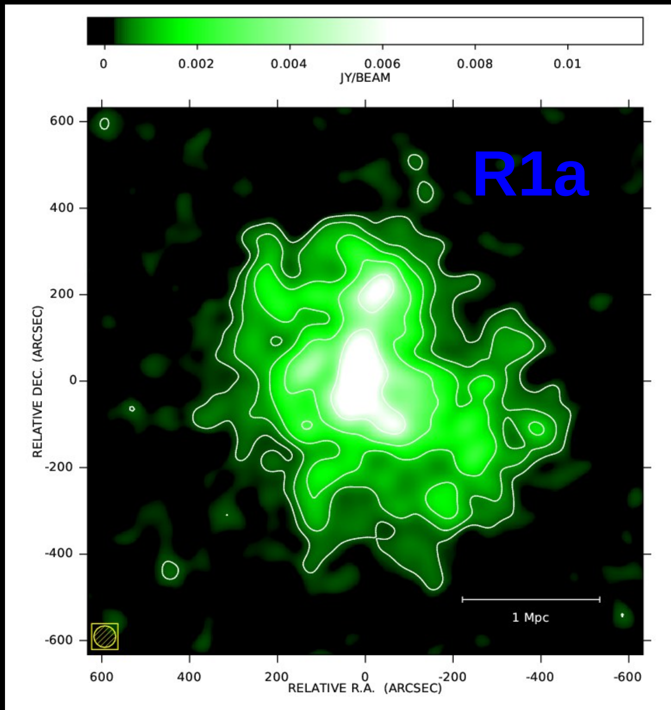




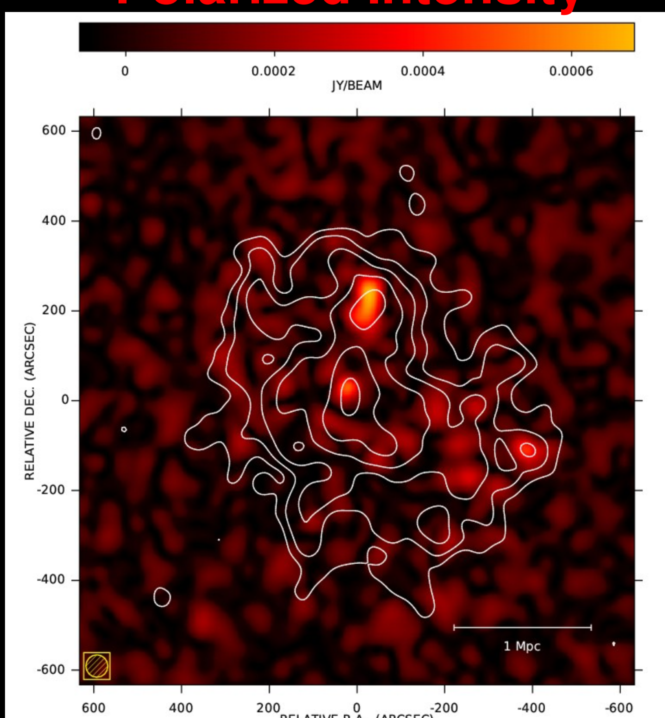
Polarization of Radio Halos

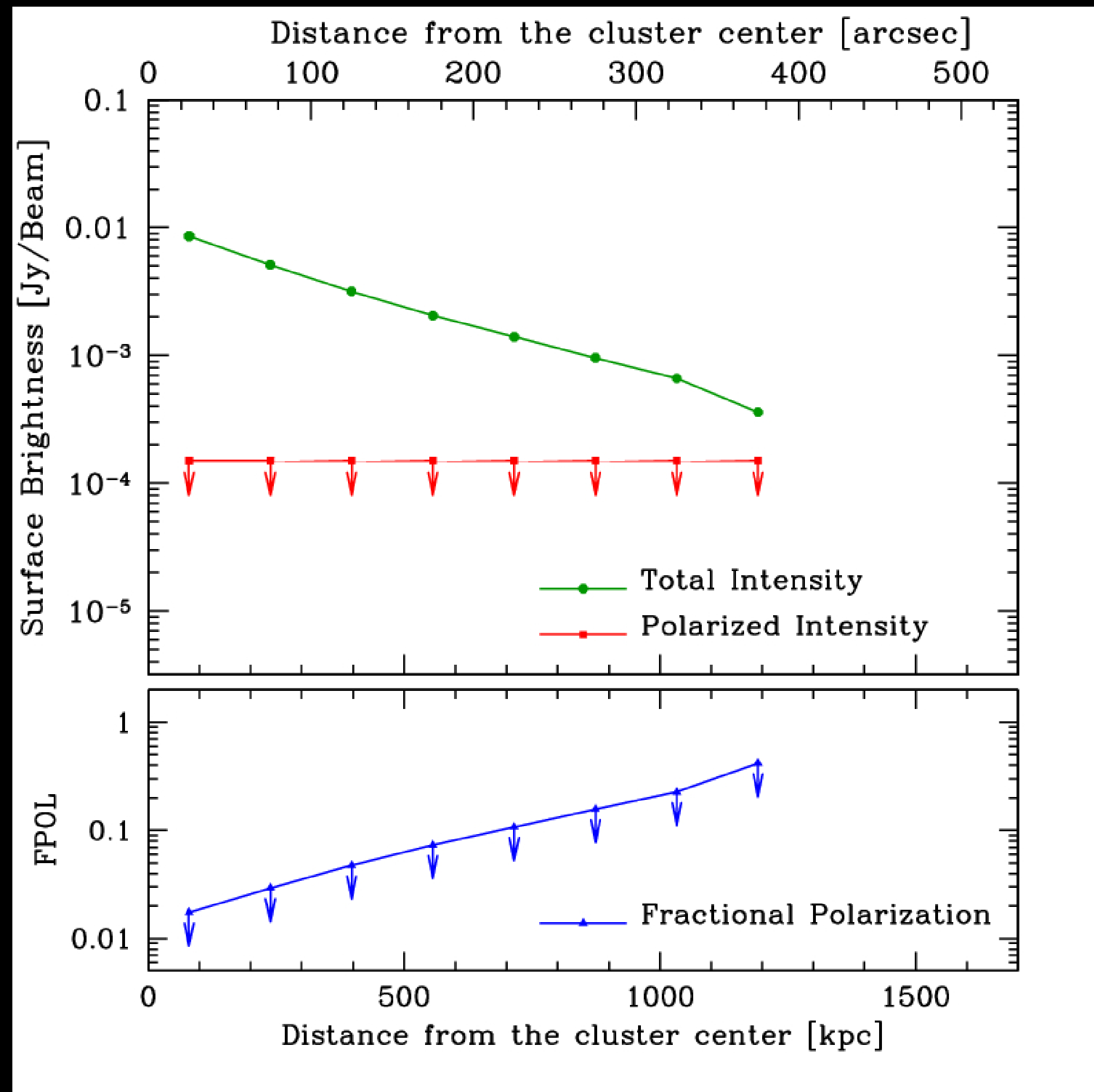
Frequency 1.4 GHz
Bandwidth 25 MHz
Resolution 50''
σI=0.1 mJy/beam   σU,Q=0.05mjy/beam

Total Intensity



Polarized Intensity



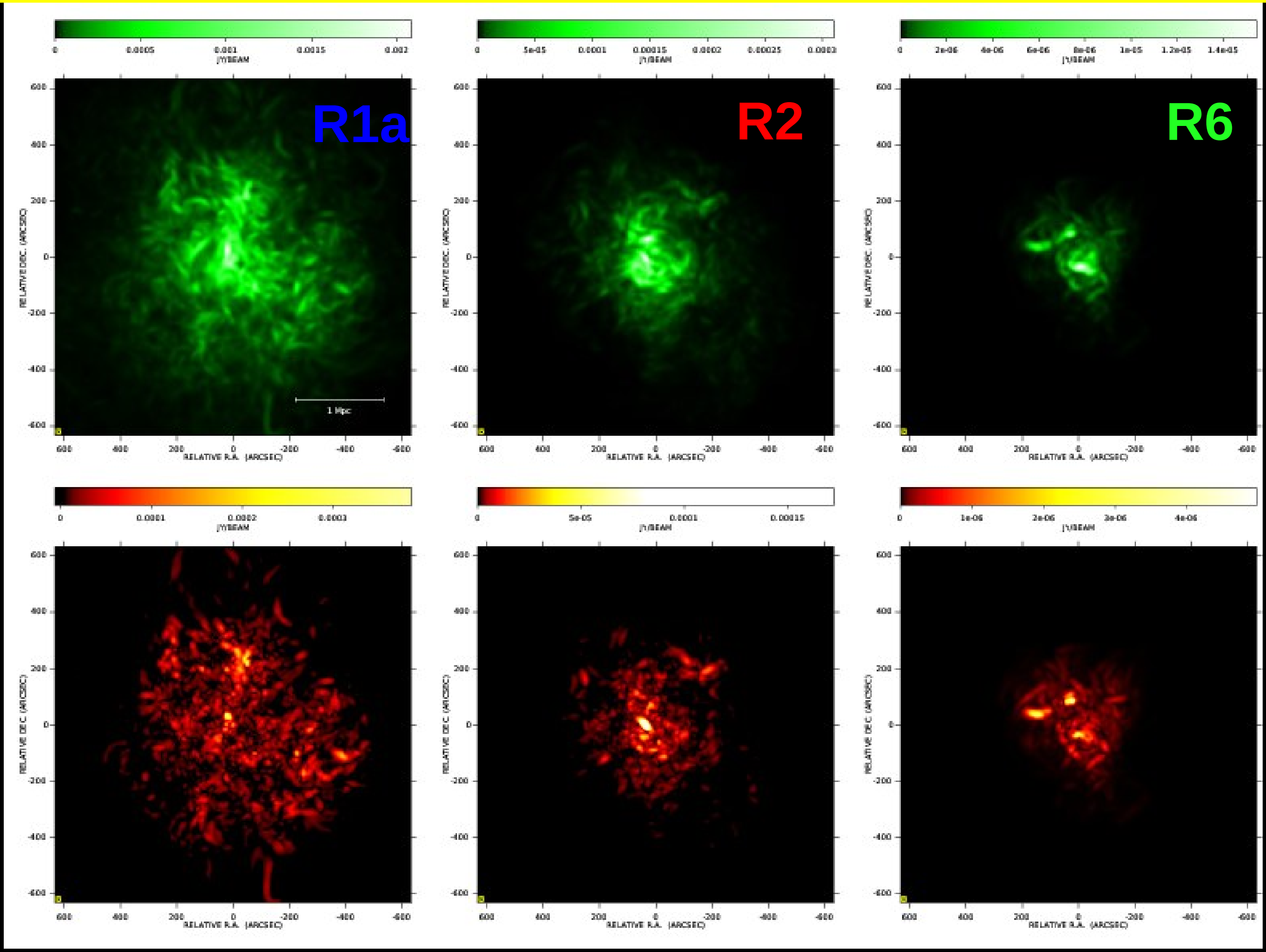


Polarization of Radio Halos

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

Total Intensity

Polarized Intensity



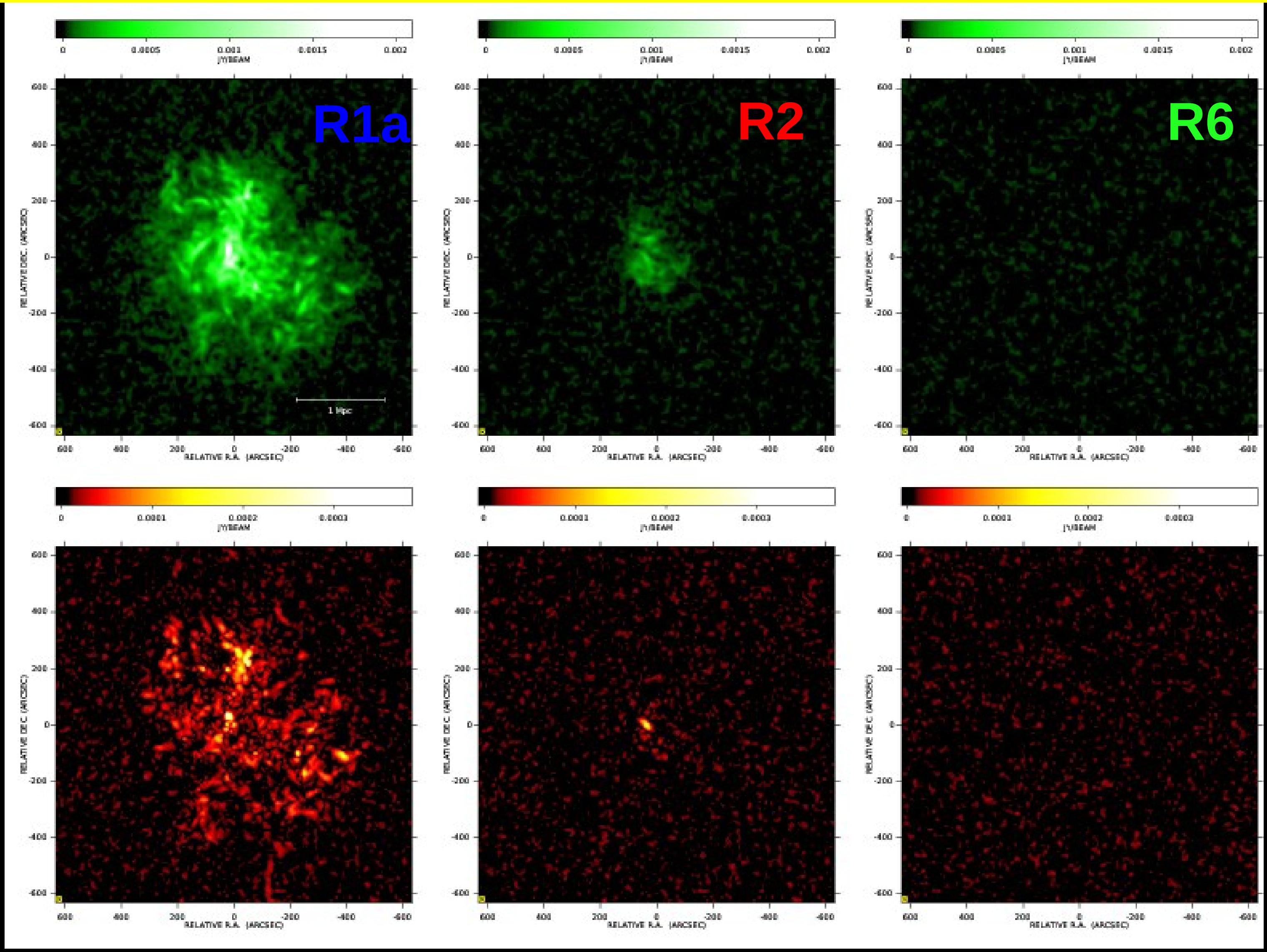
In these simulations we applied the RM-synthesis to recover polarized signal reduced by the bandwidth depolarization Brentjens & de Bruyn (2005) Pizzo et al. (2011)

Polarization of Radio Halos

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

Total Intensity

Polarized Intensity

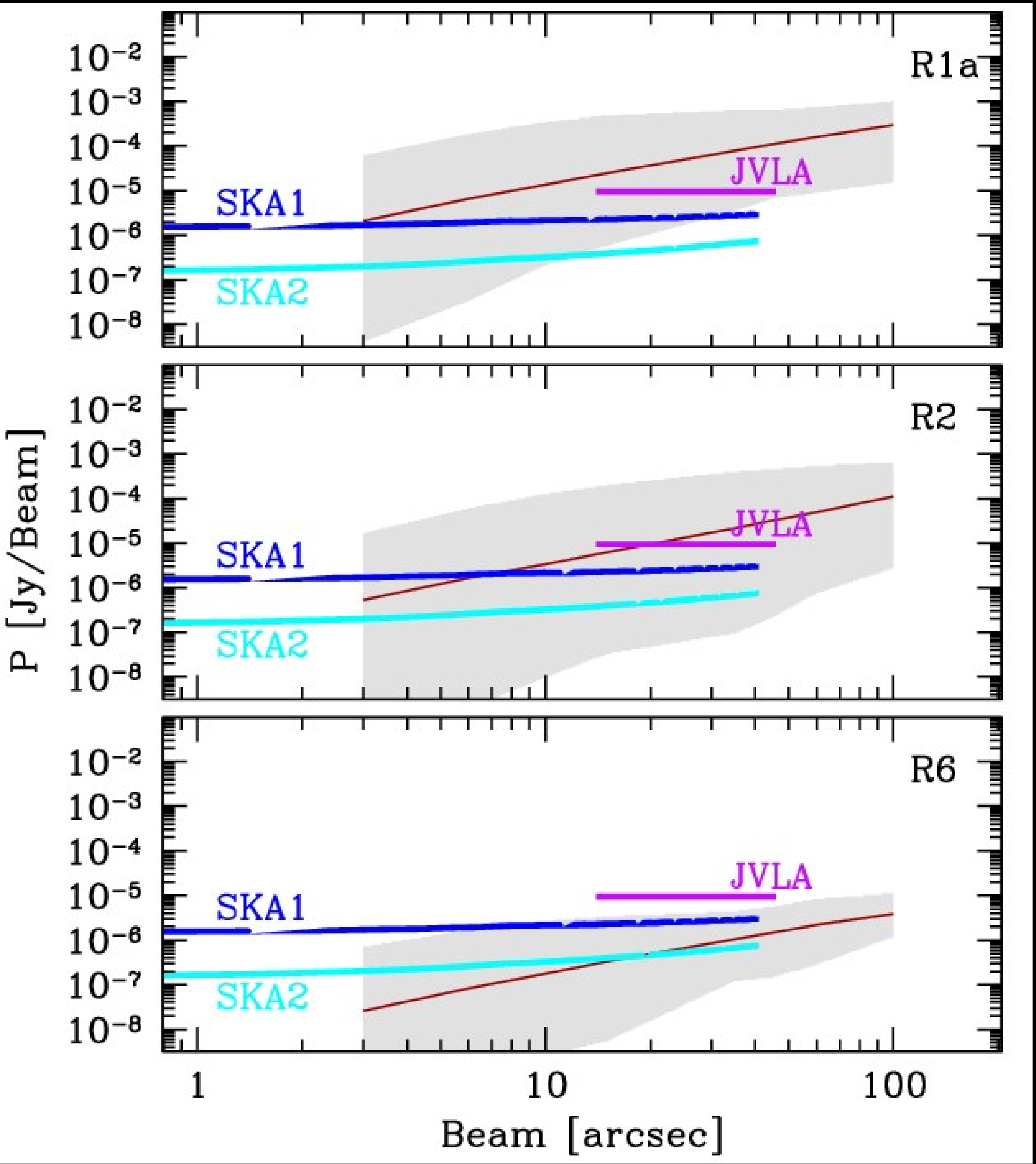


Survey WODAN with APERTIF
Survey POSSUM with ASKAP

σI = 10 μJy/beam
σU,Q = 5 μJy/beam

Polarized Intensity of Radio Halos

Frequency 1.4 GHz - Bandwidth 1 GHz



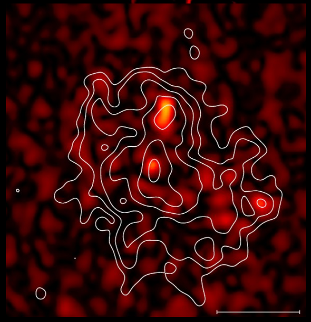
Polarized intensity surface brightness as a function of the beam size

The simulated surface brightness is compared with the sensitivity of wide band instruments (SKA Phase-1, SKA Phase-2, JVLA) to explore their potential in detecting the polarized intensity emission of halos at different radio power. The sensitivity refers to the 3σ limit for 1 hour of integration time.

Conclusions

Frequency 1.4 GHz

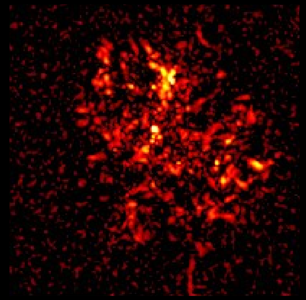
Radio halos are intrinsically polarized at full resolution.



Polarized signal is undetectable if observed with the resolution and sensitivity of current interferometes.

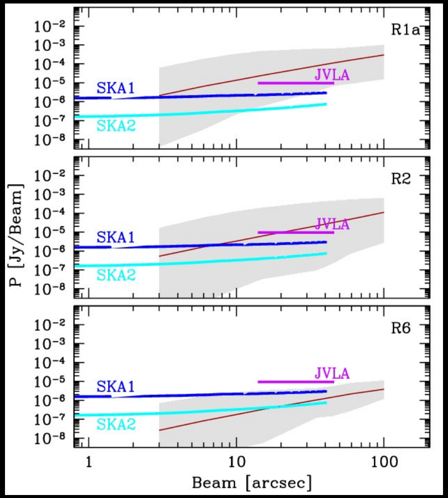
Bandwidth 25 MHz
Resolution 50''

σI=0.1 mJy/beam



Surveys planned with the SKA precursors (WODAN, POSSUM) will be in principle able to detect the polarized emission in the most luminous halos known.

Bandwidth 300 MHz
Resolution 15''
σI=10 μJy/beam

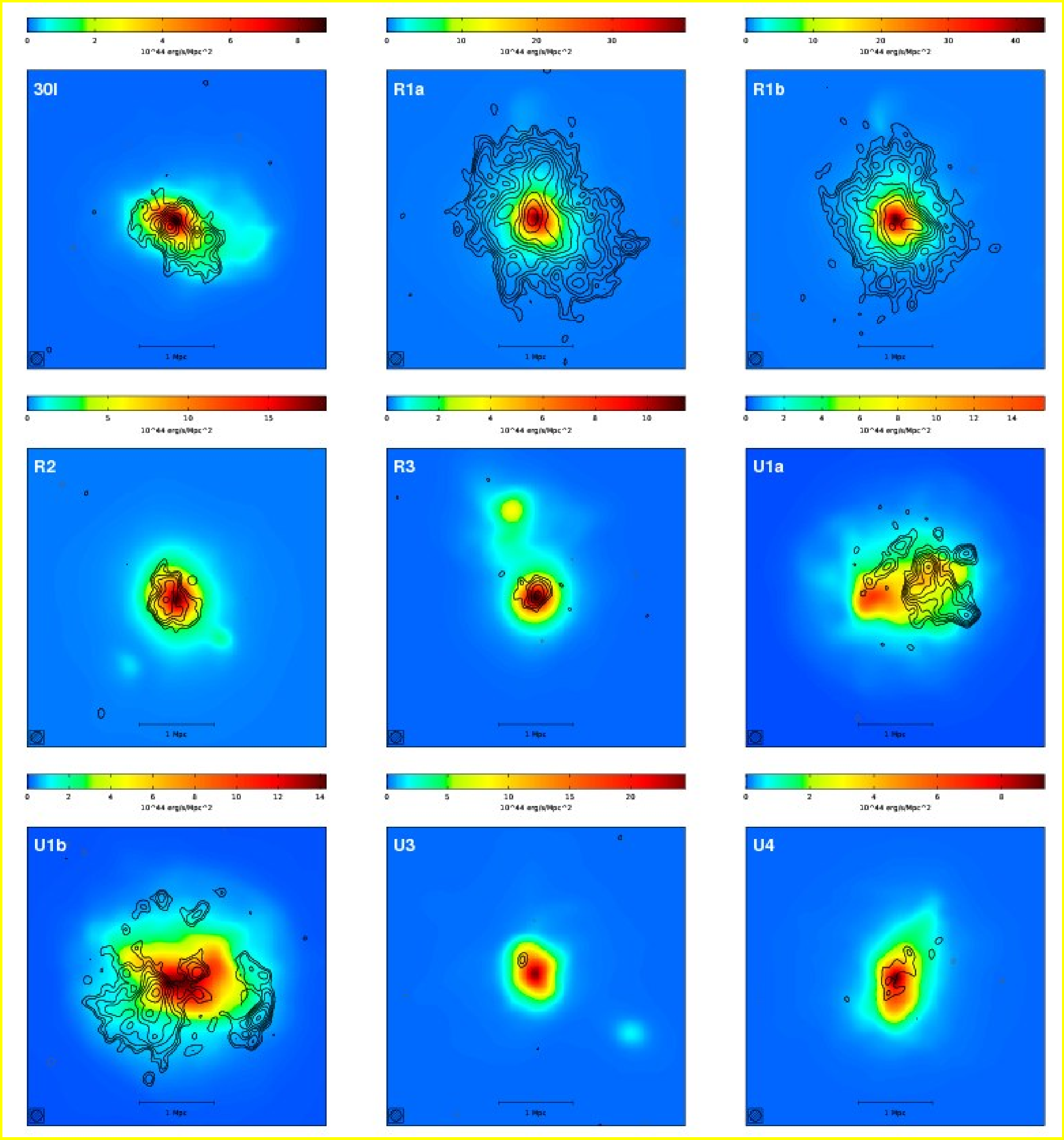


SKA could have the sufficient sensitivity to detect the polarized emission of strong and intermediate radio halos at high resolution

Bandwidth 1 GHz
Resolution 1''

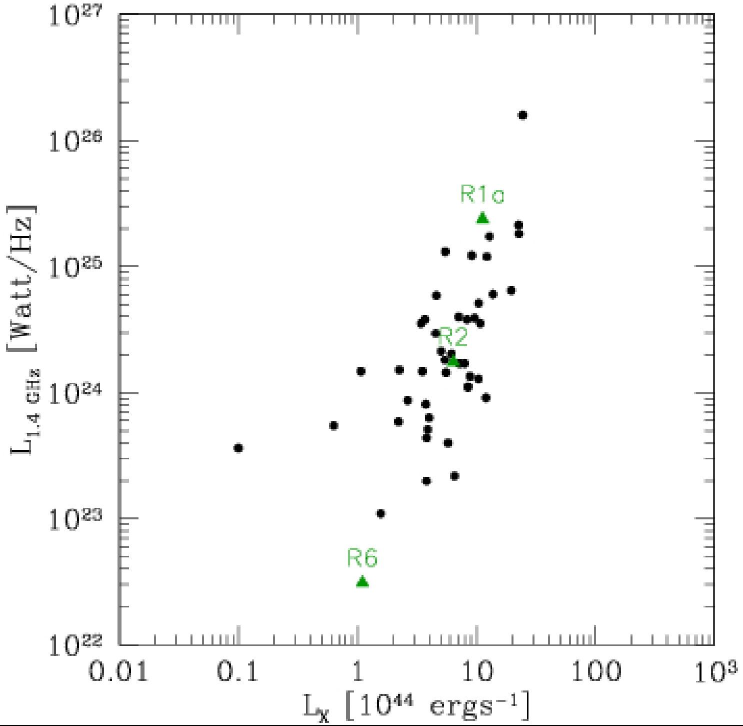
σI=1-0.1 μJy/beam

Synthetic Radio Halos

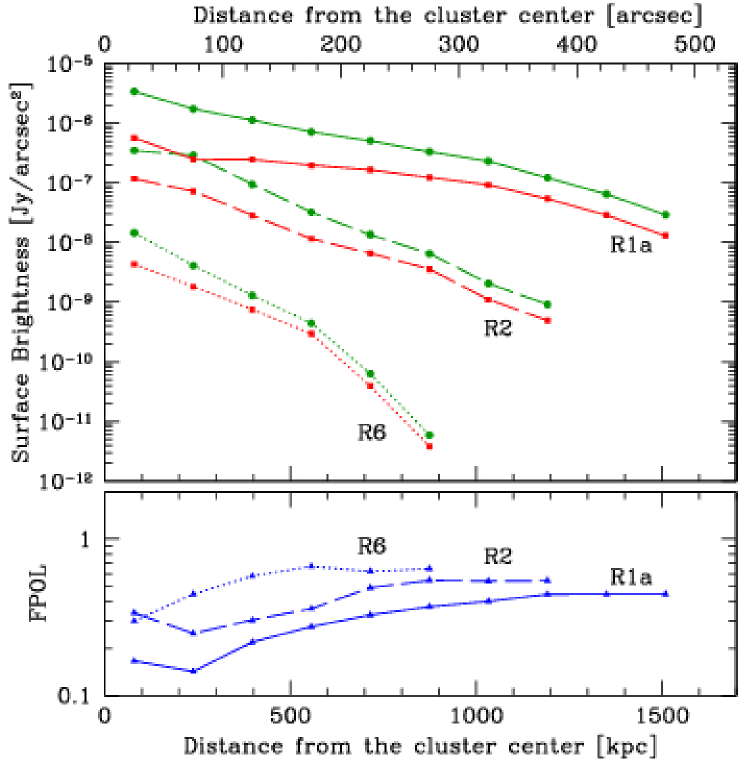


Radio contours levels are overlaid to the cluster X-ray emission in the 0.1-2.4 keV band

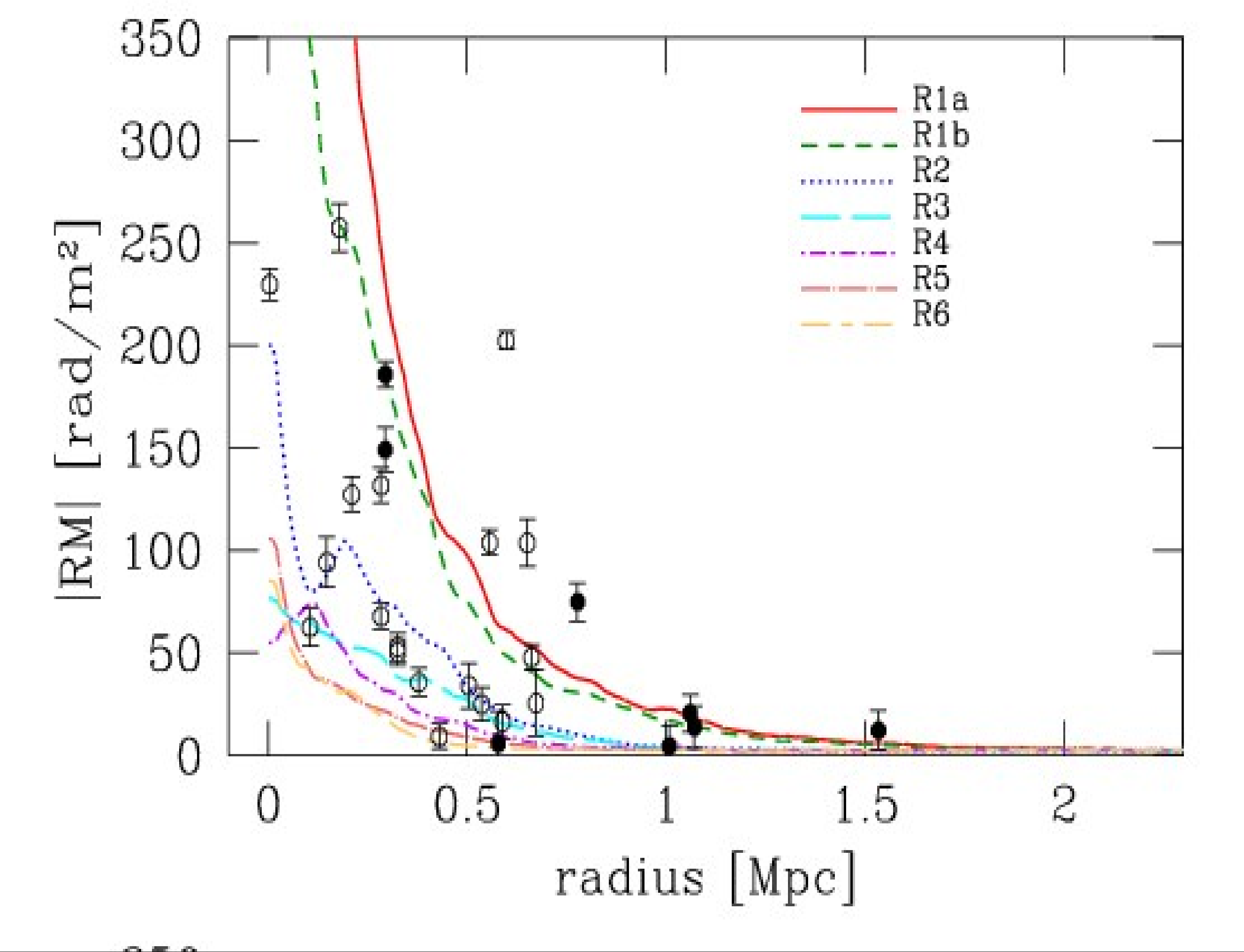
Xu et al. (2012)



10^{27}
10^{26}
10^{25}
10^{24}
10^{23}
10^{22}
$L_{1.4\ GHz}$ [Watt/Hz]
R1a
R2
R6
0.01
0.1
1
10
100
10^3
L_X [10^{44} ergs^{-1}]



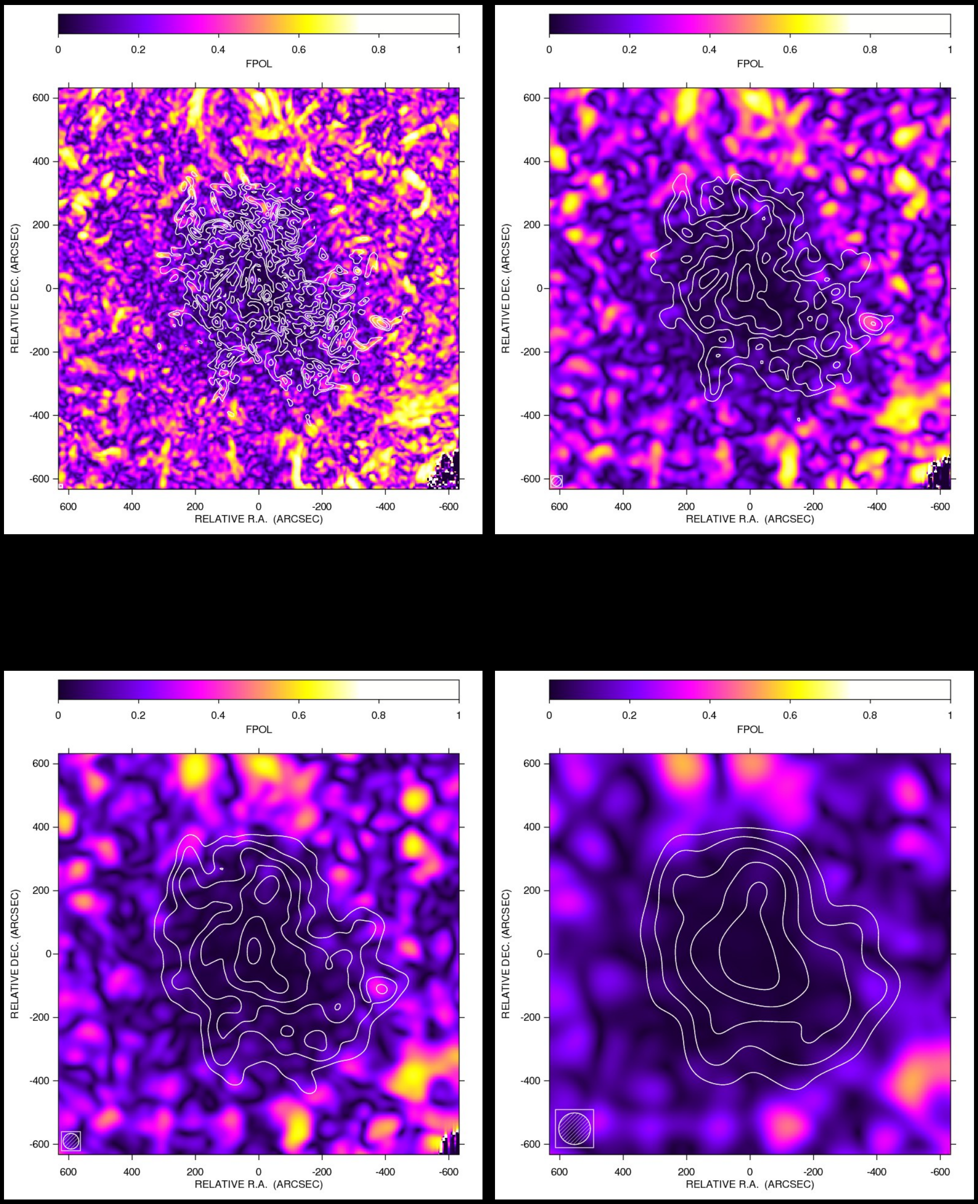
Distance from the cluster center [arcsec]
0
100
200
300
400
500
Surface Brightness [Jy/arcsec^2]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
R1a
R2
R6
FPOL
1
0.1
0
500
1000
1500
Distance from the cluster center [kpc]

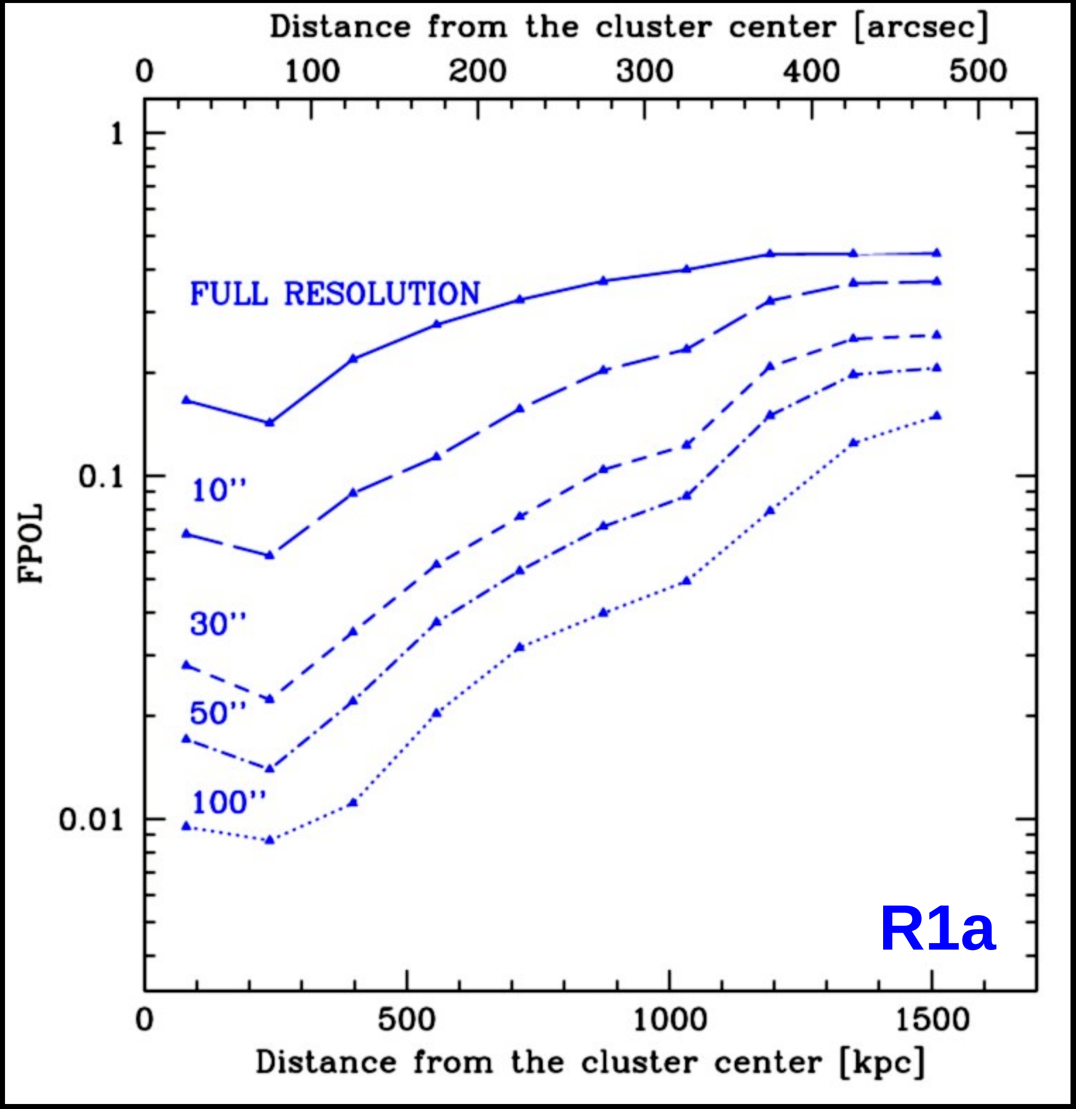


R1a
R1b
R2
R3
R4
R5
R6
|RM| [rad/m²]
radius [Mpc]
0
50
100
150
200
250
300
350
0
0.5
1
1.5
2

Polarization of Radio Halos

FPOL=P/I





Fractional polarization images at different resolutions.

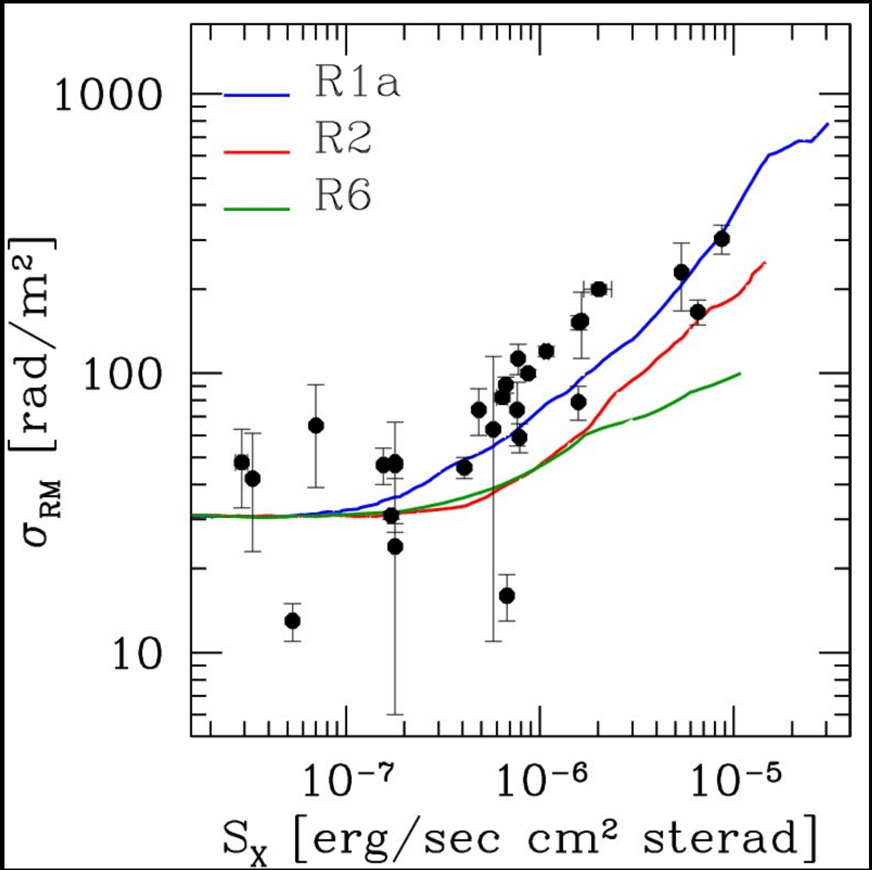
Comparison between observations and synthetic RM

ROTATION MEASURE – X Ray relation
In the radiogalaxy location.

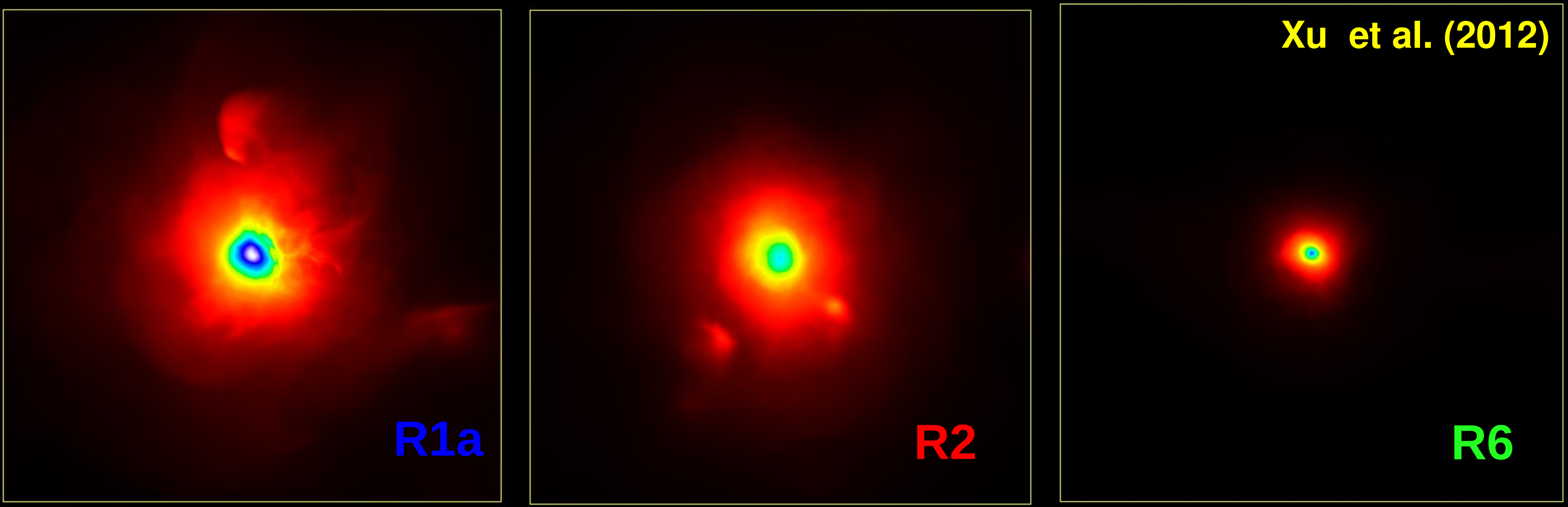
Govoni et al. 2010
(see also Dolag et al. 2001, Dolag 2006)

$$\sigma_{RM} = B\, n_e \sqrt{(\Lambda_B L)}$$

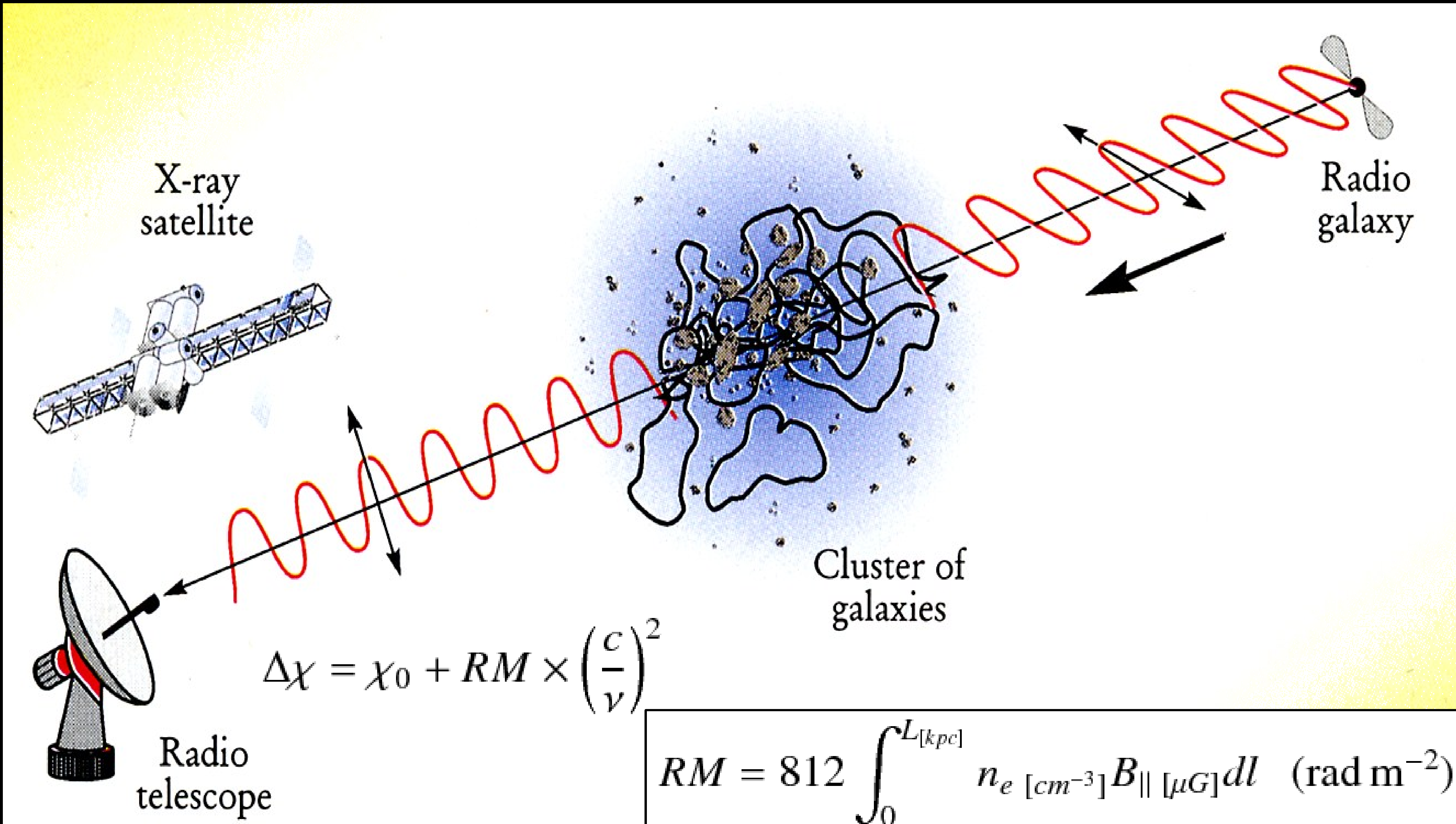
$$S_x = n_e^2 \sqrt{T}\ L$$



X-ray Images



The Faraday rotation effect in galaxy clusters



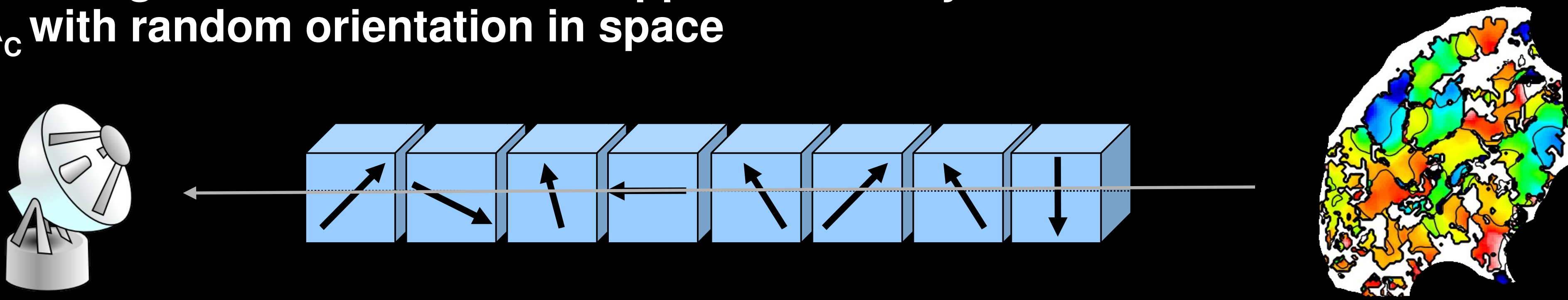
$$\Delta\chi = \chi_0 + RM \times \left(\frac{c}{\nu}\right)^2$$

$$RM = 812 \int_0^{L_{[kpc]}} n_{e\ [cm^{-3}]} B_{||\ [\mu G]} dl \quad (\mathrm{rad\ m^{-2}})$$

see e.g. Burn (1966)

Interpretation of Faraday rotation effect

The magneto-ionic medium is approximated by uniform cells of size Λ_c with random orientation in space



The Faraday rotation from a physical depth L (>>Λ_c) is expected to be a Gaussian with zero mean and dispersion given by:

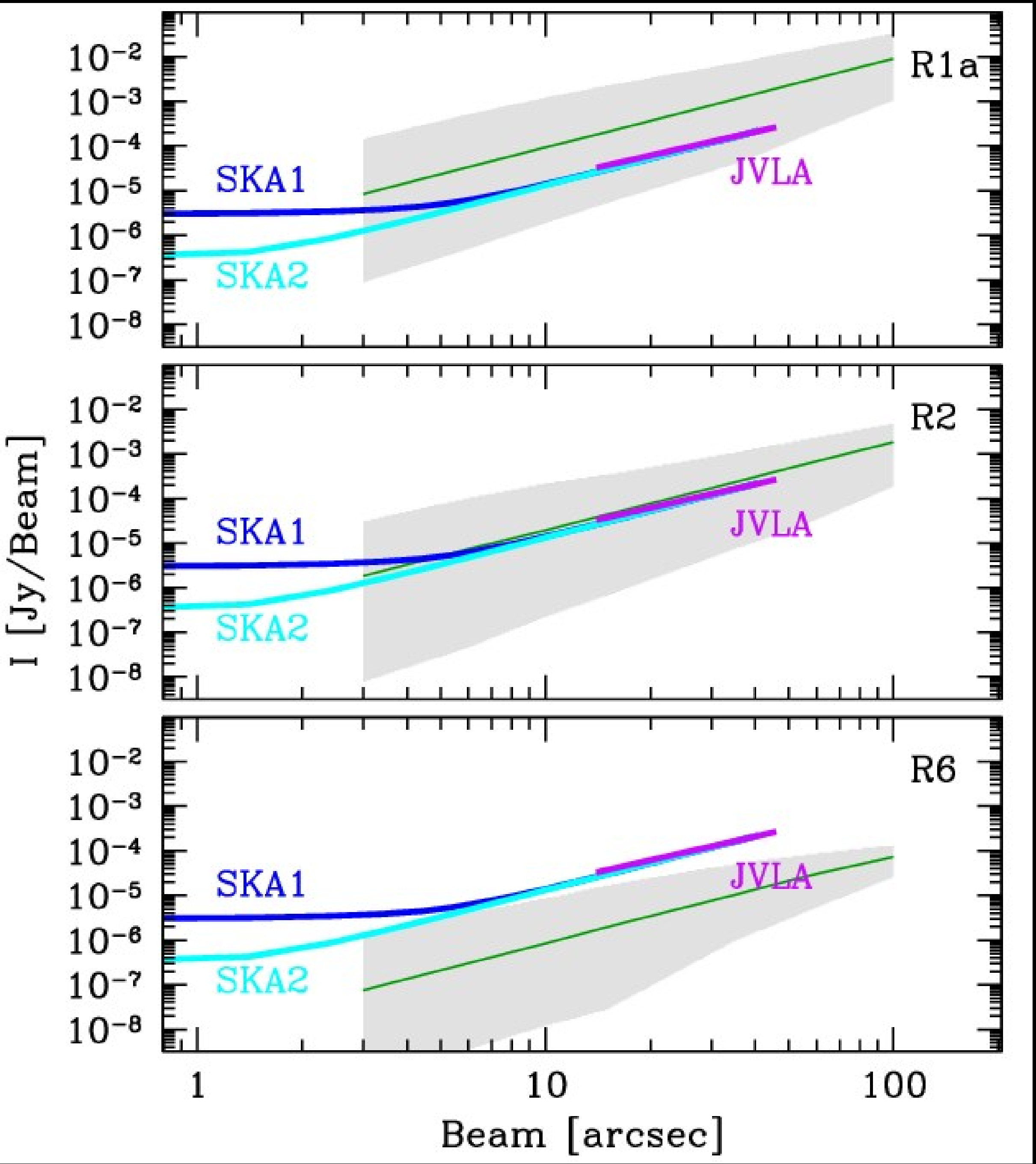
$$\sigma^2_{RM} = \langle RM^2 \rangle = 812^2 \Lambda_c \int_L (n_e B_{\|})^2 dl \quad (\mathrm{rad^2 m^{-4}})$$

$$\sigma_{RM} = 812 \sqrt{\Lambda_c}\, \sqrt{L}\, n_e\, \sigma_{B_{\|}}$$

See e.g. Lawler & Dennison (1982), Tribble (1991), Feretti et al. (1995), Felten (1996), Sokoloff et al. (1998)

Total Intensity of Radio Halos

Frequency 1.4 GHz - Bandwidth 1 GHz

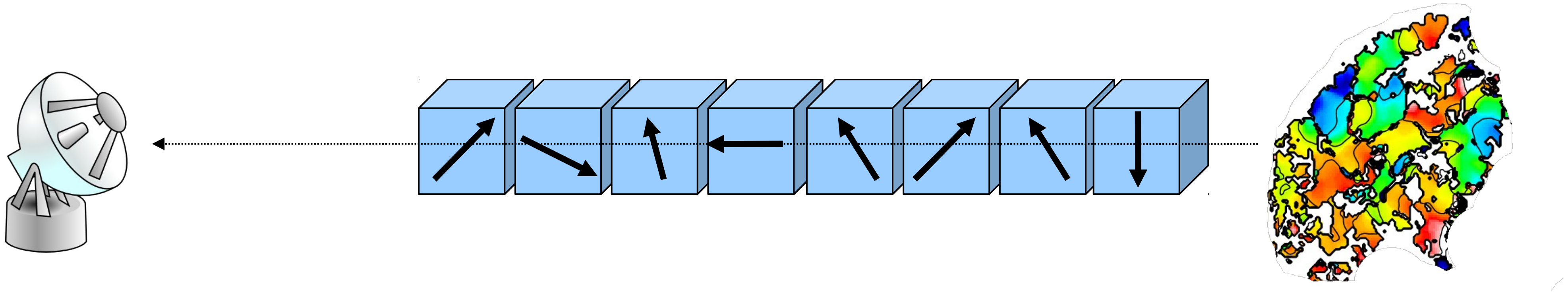


Total intensity surface brightness as a function of the beam size

The simulated surface brightness is compared with the sensitivity of wide band instruments (SKA Phase-1, SKA Phase-2, JVLA) to explore their potential in detecting the total intensity emission of halos at different radio power. The sensitivity refers to the 3σ limit for 1 hour of integration time.

Single-scale model

The magneto-ionic medium is approximated by uniform cells of size Λ_c with random orientation in space



The Faraday rotation from a physical depth L ($>>\Lambda_c$) is expected to be a Gaussian with zero mean and dispersion given by:

$$\sigma^2_{RM} = \langle RM^2 \rangle = 812^2 \Lambda_c \int_L (n_e B_{\|})^2 dl \quad (\mathrm{rad^2 m^{-4}})$$

(e.g. Lawler & Dennison 1982; Tribble 1991; Feretti et al. 1995; Felten 1996)

Single-scale model

$$\sigma_{RM} = 812\sqrt{\Lambda_c}\ \sqrt{L}\, n_e\, \sigma_{B_{||}}$$

If the thermal gas n_e is known (e.g. from X-ray data), then by measuring the RM dispersion we can estimate B if we know Λ_c

OK, but what exactly is Λ_c and how can we find it?

It turns out that the correct value for Λ_c is the field autocorrelation length, Λ_B, which can be calculated if the magnetic field power spectrum is known.

The intra-cluster magnetic field power spectrum

For an *isotropic* random magnetic field, the autocorrelation function and the power spectrum, $|B_k|^2$, are related by the Hankel transform:

$$C_{B_z}(\Delta r) = 4\pi \int_0^\infty |B_k|^2 k^2 \frac{1}{(k\Delta r)^2} \left(\frac{\sin(k\Delta r)}{k\Delta r} - \cos(k\Delta r) \right) dk$$

and similarly for the RM autocorrelation and the 2D power spectrum, $|RM_k|^2$:

$$C_{RM}(\Delta r_\perp) = 2\pi \int_0^\infty |RM_k|^2 J_0(k\Delta r_\perp) k dk$$

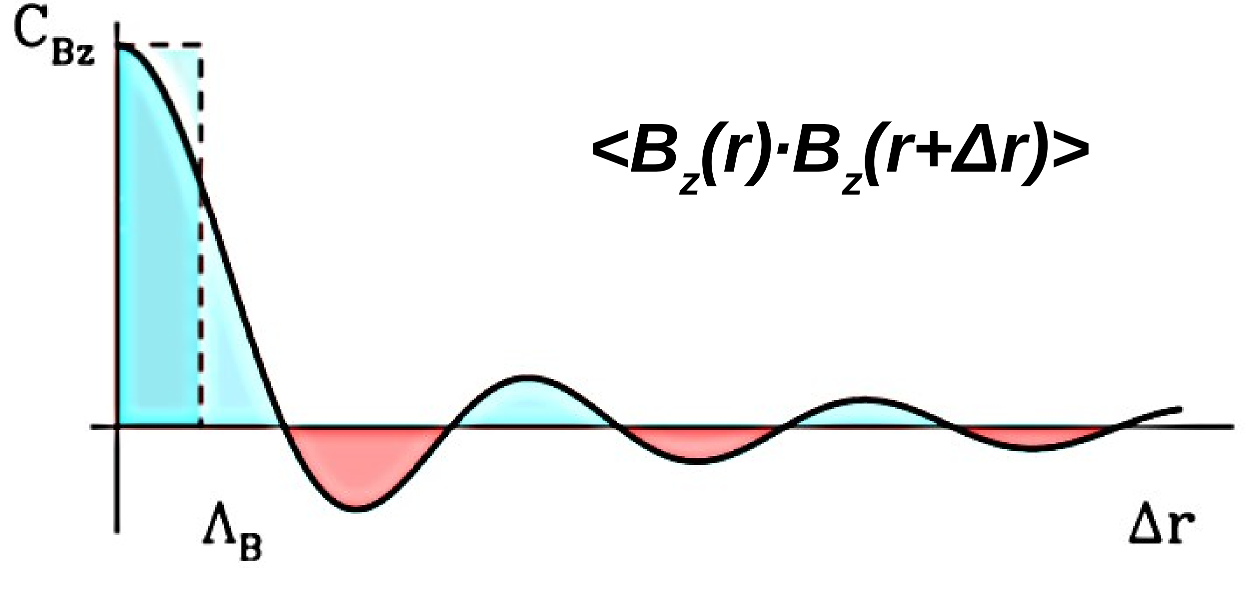
Ensslin & Vogt (2003), Vogt & Ensslin (2003), Vogt & Ensslin (2005)

The intra-cluster magnetic field power spectrum

For $L \gg 2\pi/k_{min}$, we can assume that $C_{RM}(0) \rightarrow \sigma^2_{RM}$, and derive:

$$\sigma^2_{RM} = 812^2 n_e^2 L \left(\frac{3\pi}{2} \frac{\int |B_k|^2 k dk}{\int |B_k|^2 k^2 dk} \right) \sigma^2_{B_\parallel}$$

This is exactly the single-scale model formula with $\Lambda_C = \Lambda_B$, i.e. the “cell size” has to be the magnetic field autocorrelation length.



The intra-cluster magnetic field power spectrum

Note that, although the RM and magnetic field power spectra are proportional:

$$|RM_k|^2 \propto n_e^2 \, L \, |B_k|^2$$

the corresponding autocorrelation lengths are different

$$\Lambda_{RM} = 2 \frac{\int |RM_k|^2 dk}{\int |RM_k|^2 k dk} \qquad \Lambda_B = \frac{3\pi}{2} \frac{\int |B_k|^2 k dk}{\int |B_k|^2 k^2 dk}$$

In particular, $\boldsymbol{\Lambda_{RM}} >> \boldsymbol{\Lambda_B}$.

Magnetic fields in Galaxy Clusters

The intracluster medium is magnetized

-Evidence from RM of embedded or back-ground radio galaxies (kpc-scale fluctuations)
-Evidence from extended radio halos at cluster center (Mpc-scale fluctuations)
-The magnetic field is likely turbulent (we want to measure power spectra)
-Increase the statistics to determine how the magnetic field power spectra varies with The dynamical state of the galaxy clusters

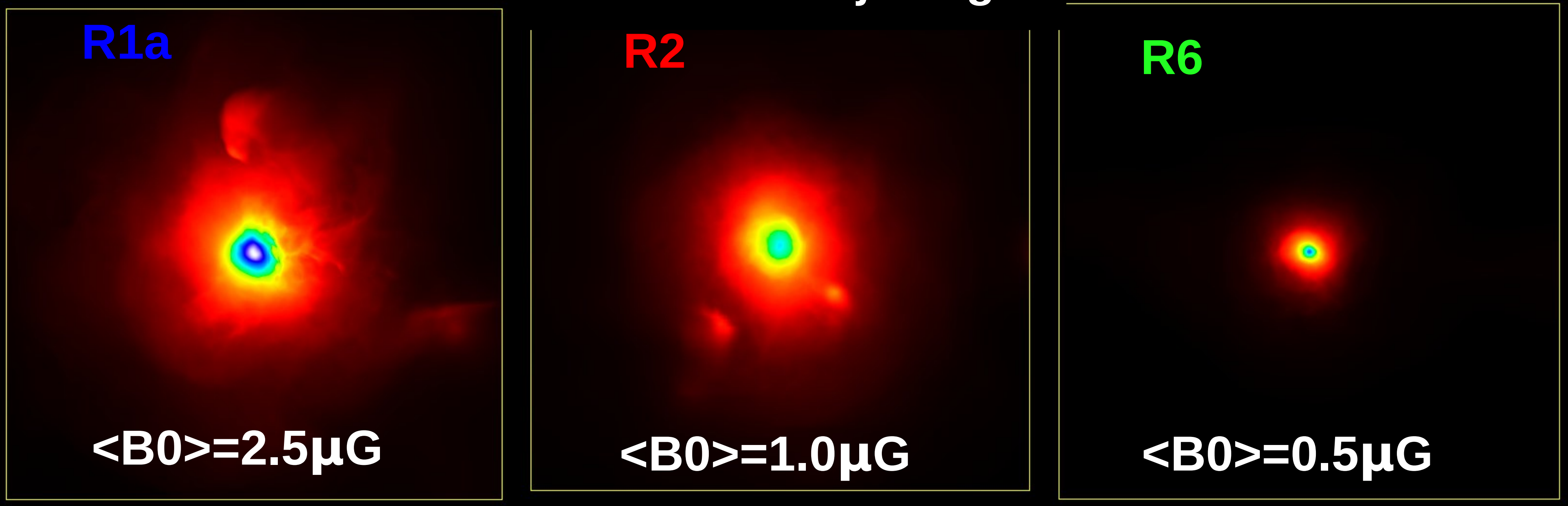
Numerical simulations and comparison with data

-Examples of synthetic RM images from MHD simulations and their comparison with statistical data (RM-Sx relation)
-Examples of synthetic total intensity radio halo images and their comparison with observed Lradio-Lx, Lradio-LLS corralations and Lradio-Lx offsets

Polarization of radio halos with upcoming radio interferometers

-Radio halo polarization powerful tool to investigate field strength and structure but very hard to measure with current instruments
-Perspectives at GHz frequencies for JVLA, ASKAP, APERTIF and SKA
-Perspectives at low-frequencies for LOFAR

Simulated X-ray Images



Simulated total intensity radio halo images at 1.4 GHz