Magnetic Fields and Radio Observations in Galaxy Clusters

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Xu et al. 2012, "Comparisons of Cosmological MHD Galaxy Cluster Simulations to Radio Observations" ApJ. submitted;
Related talks: Andrey Beresnyak, Sam Skillman.

2nd ICM Theory & Computation Workshop
University of Michigan
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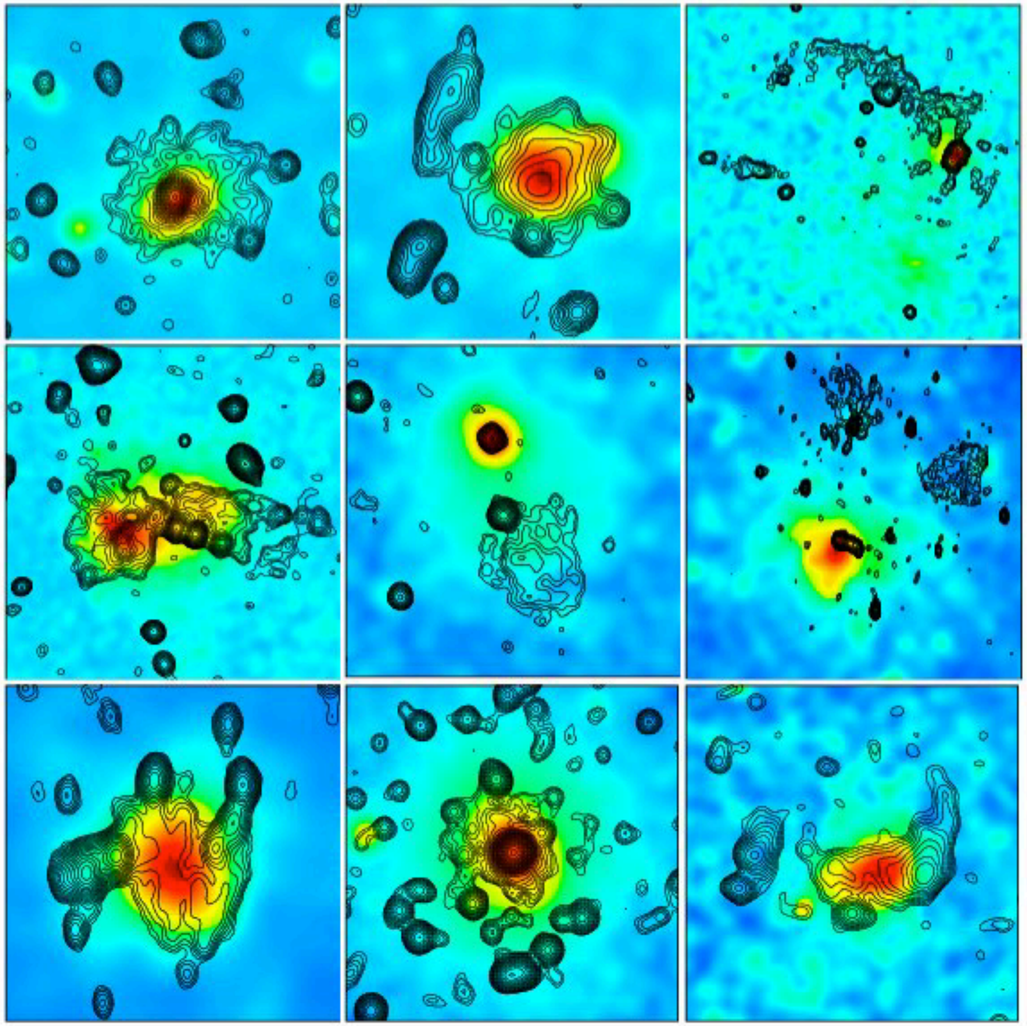
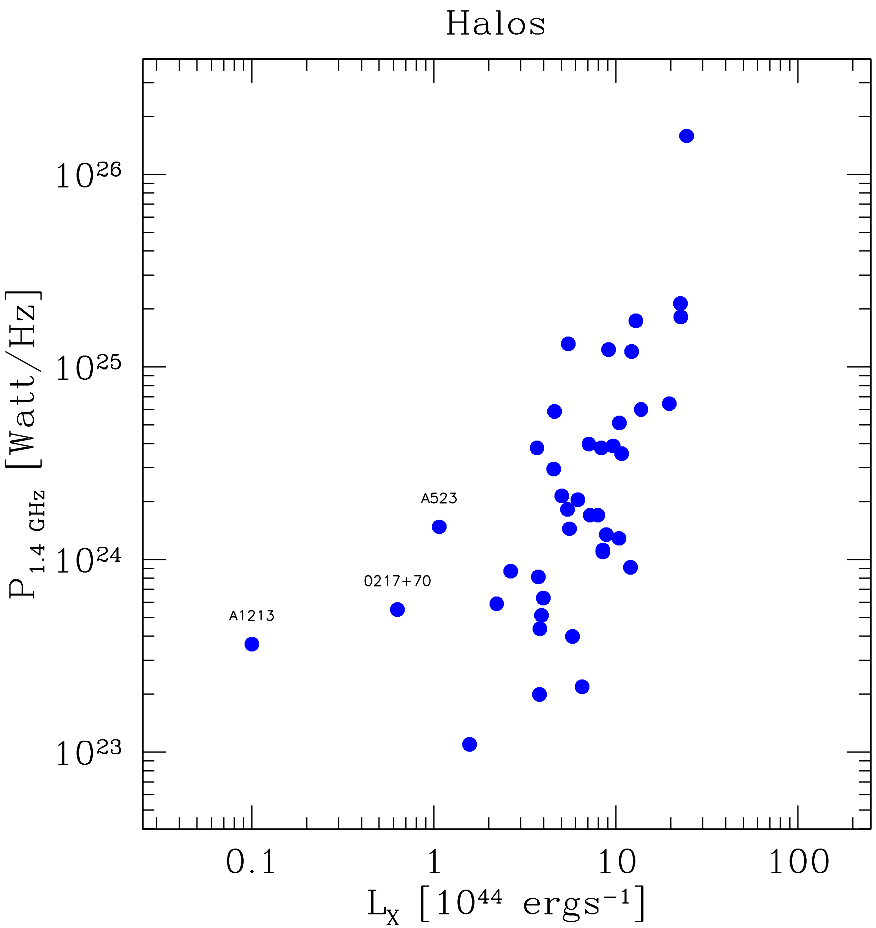
Evidence for Cluster Magnetic Fields: Radio Halos and Relics

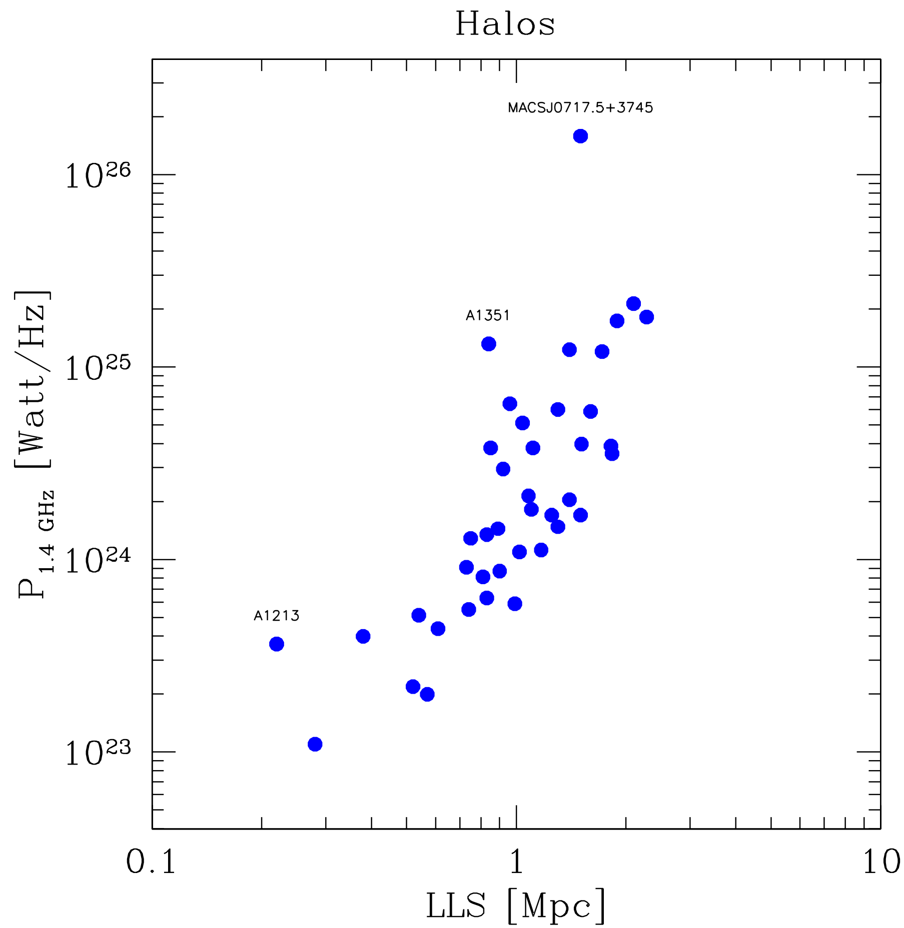
42 halos, 50 relics (39 clusters) ➔ cluster mergers



Collection of clusters showing several types of radio emission, shown in contours, overlaid onto
the X-ray emission, shown in *colors. Clusters are (from left to right and from top to bottom) A 2219 (halo),*
A 2744 (halo + relic), A 115 (relic), A 754 (complex, halo plus relic), A 1664 (relic), A 548b (relic), A 520
(halo), A 2029 (mini-halo), RXCJ1314.4−2515 (halo plus double relics). (Feretti et al. 2012).
Assuming equipartition conditions the corresponding equipartition magnetic field strengths range from 0.1 to 1 μG for halos.

Radio Halo Properties:





Left: Radio power of radio halos at 1.4 GHz versus X-ray luminosity between 0.1 and 2.4 keV, right: Radio power of halos versus their largest linear size (LLS) (Feretti et al. 2012).

Rotation Measure of Cluster Radio Sources

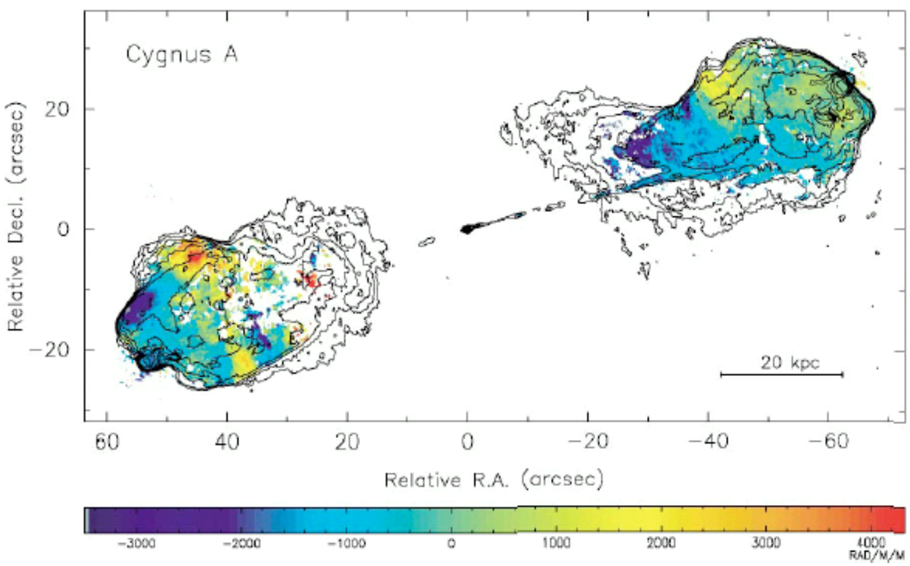
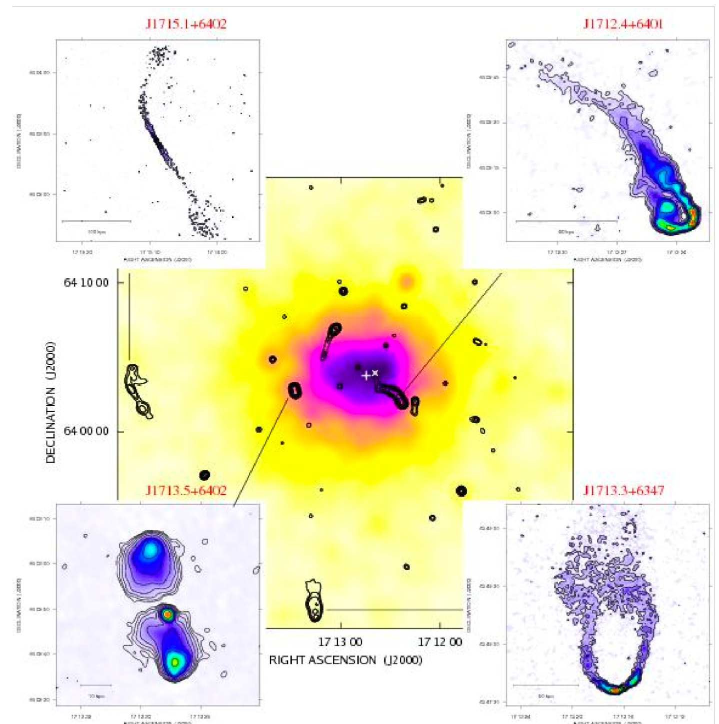


Figure 2 The RM distribution in Cygnus A based on multifrequency, multiconfiguration VLA observations. The resolution is 0.35″ (Dreher, Carilli & Perley 1987). The colorbar indicates the range in RMs from −3400 to +4300 rad m^{-2}. Note the undulations in RM on scales of 10–30 kpc. Contours are overlaid from a 5 GHz total intensity image. The RM was solved for by fitting for the change in polarization angle with frequency on a pixel-by-pixel basis (see Figure 4).



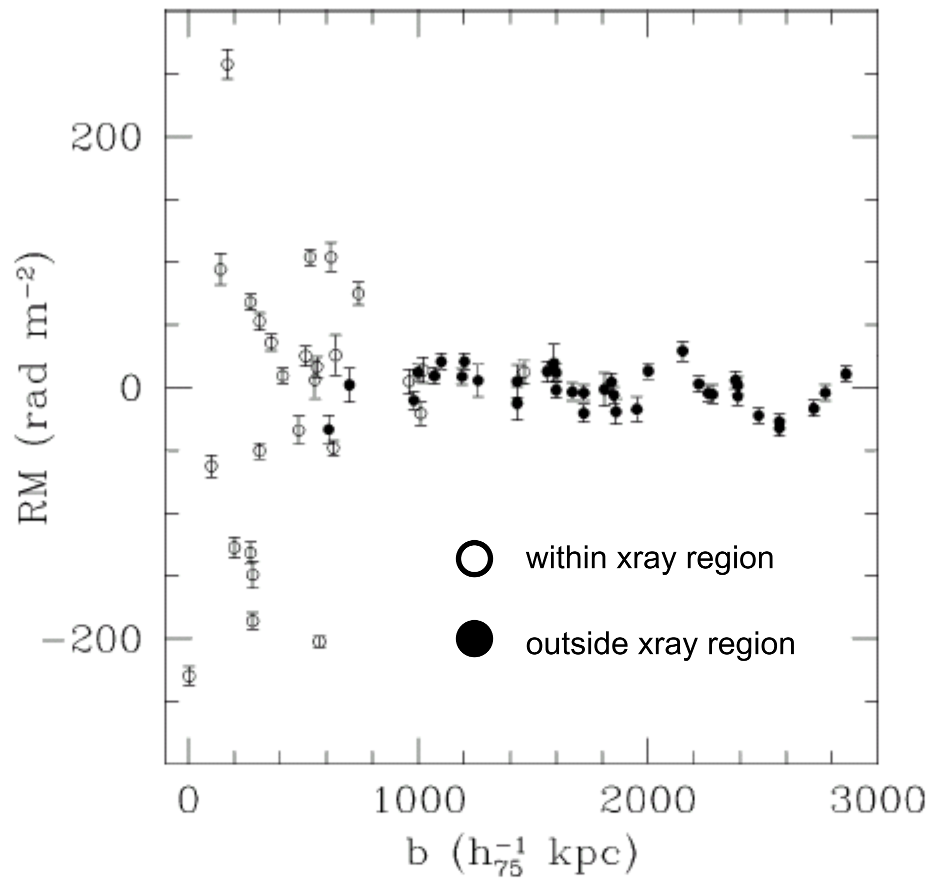
Radio contours of Abell 2255 overlaid ROSAT X-ray image (Govoni et al. 2006.)

Linear polarized radio sources (high quality):

- •Cluster central radio galaxies ➔ Magnetic fields in cluster center
- •Embedded or background radio galaxies (rare) ➔ Cluster wide magnetic fields

RM versus Radius

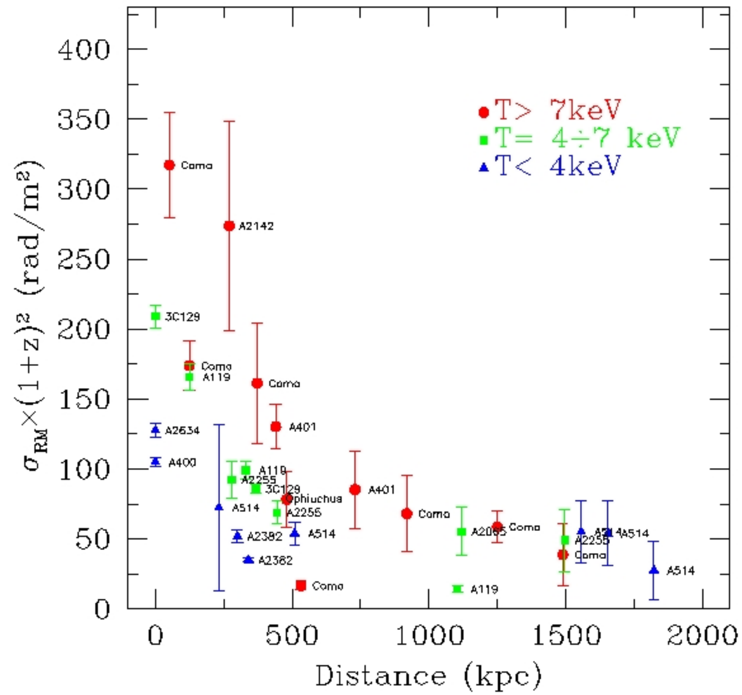
- Sample of 16 X-ray clusters;
- Measured RM due to background and embedded radio sources;
- All exhibit fields out to edge of X-ray emission ~1 Mpc;
- ~ 5 μG magnetic fields.

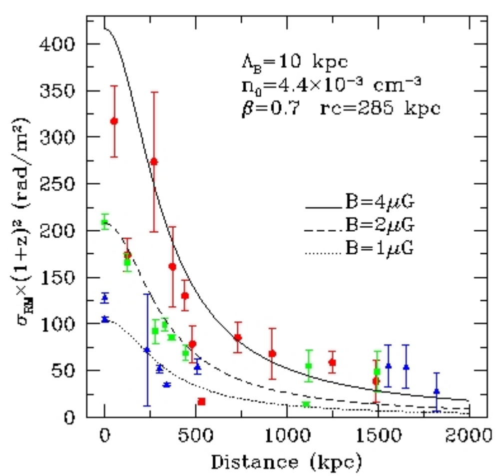


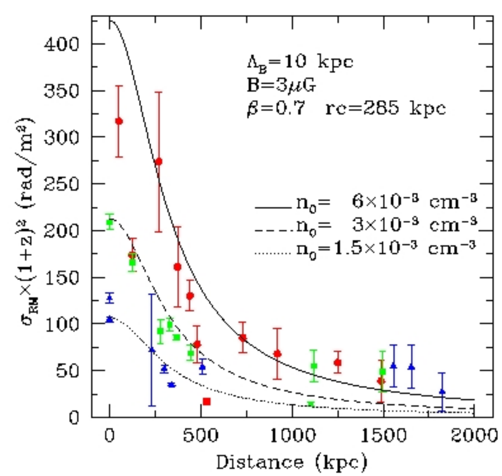
Clarke, Kronberg & Boehringer (2001)

σ_{RM} versus Radius

- Sample of 12 clusters, 29 galactic sources;
- statistically more stable;
- Insensitive to foreground RM of our galaxy;
- Fit by Micro Gauss fields (>1 μG), but hard to constrain B fields alone.







Govoni et al. 2010

Possible Origins for Cluster B-fields

- Magnetized jets and winds from galaxies and AGN
- Ram-pressure stripping of cluster galaxy interstellar fields
- Compression of intergalactic fields
- Biermann battery seed fields generated during structure formation, amplified by cluster turbulence

Previously Results: Magnetizing whole Cluster to micro Gauss by AGN Magnetic Fields

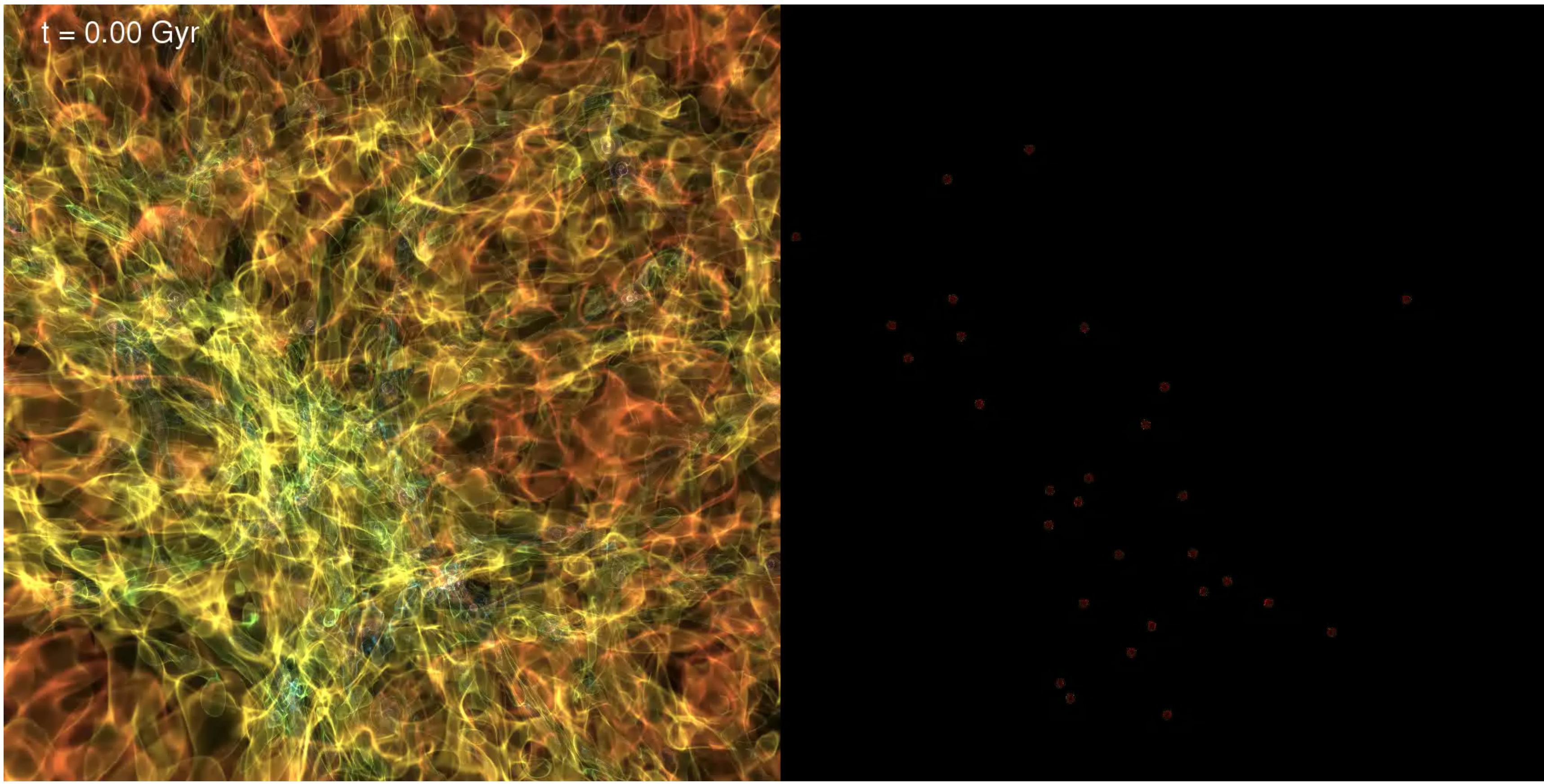
- Magnetic fields from a single powerful radio jet at high z can magnetize entire ICM to the observed micro Gauss, weakly sensitive on injected energy, and injection redshift between 2 to 3;
- Turbulent amplification and diffusion are the fundamental processes, Cluster-wide turbulence are maintained by mergers and accretion
- This magnetization process works with clusters with different properties and formation histories.

Multiple AGN magnetic field injections? Higher numerical resolution? Comparisons with observations?

What we did here

- Mock VLA observations of cosmological AMR MHD simulations of galaxy cluster formation with AGN fields performed by ENZO-MHD
  - 16 simulations with single AGN injection (Xu et al. 11)
  - One new simulation with 30 AGNs (Xu et al. 12)
  - Maintain uniform 11 kpc resolution throughout magnetized region wherever B> 5 x 10^{-8} G
  - Generated synthetic radio observations to compare with VLA observations: FRM and radio halos

Movies of Cluster Formation and Magnetic Fields Evolution

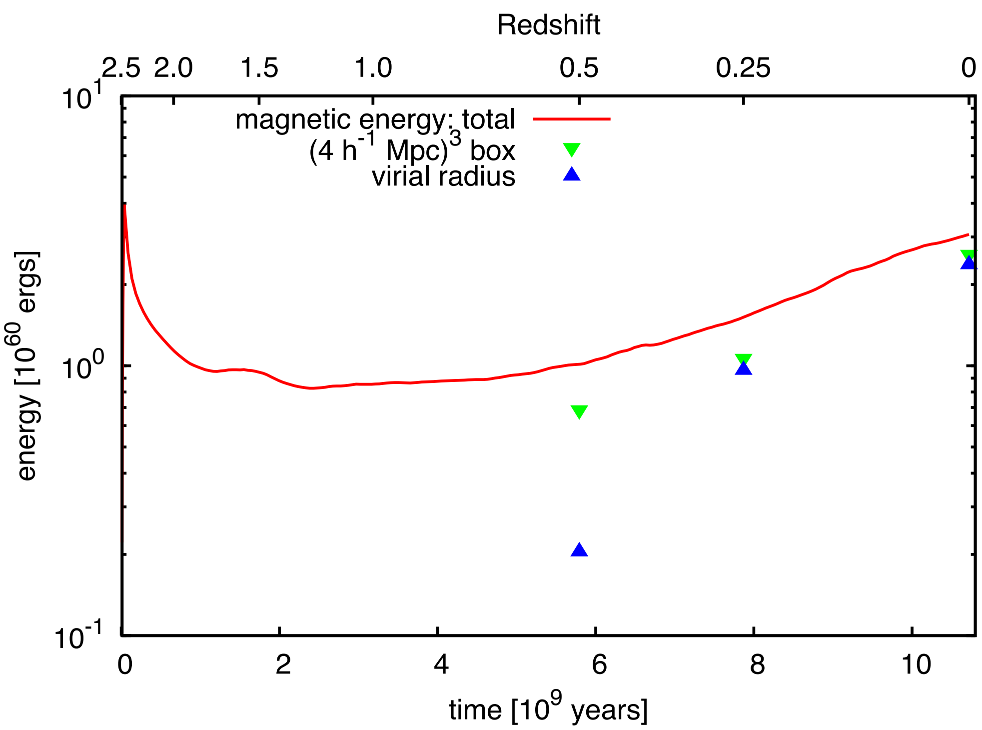


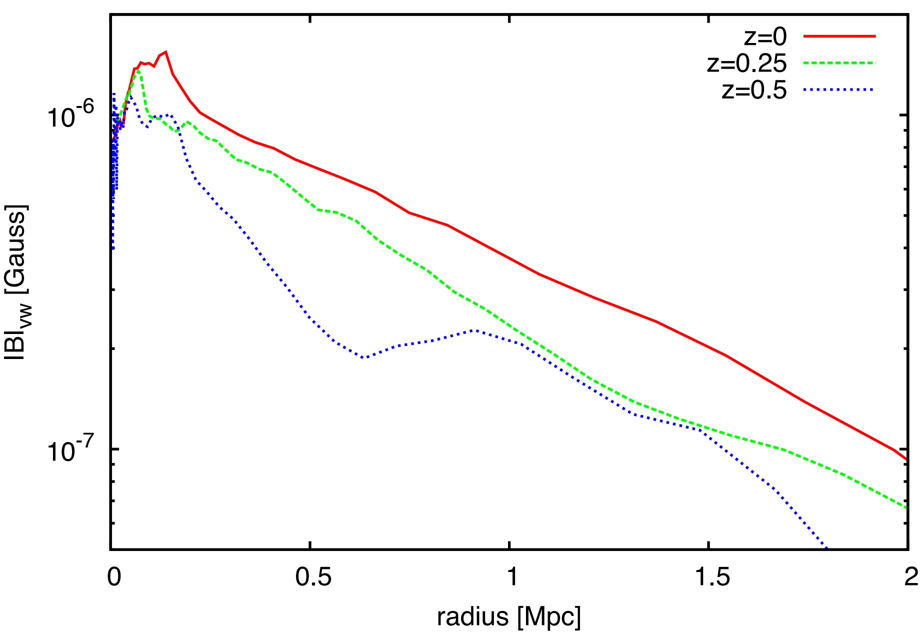
Gas Density

Magnetic Energy Density

Iso-contours of gas density and magnetic energy density are generated using volume rendering in yt tools (Turk et al 2011).

Magnetic Energy Evolution and Radial distributions of Multi-AGN Simulation





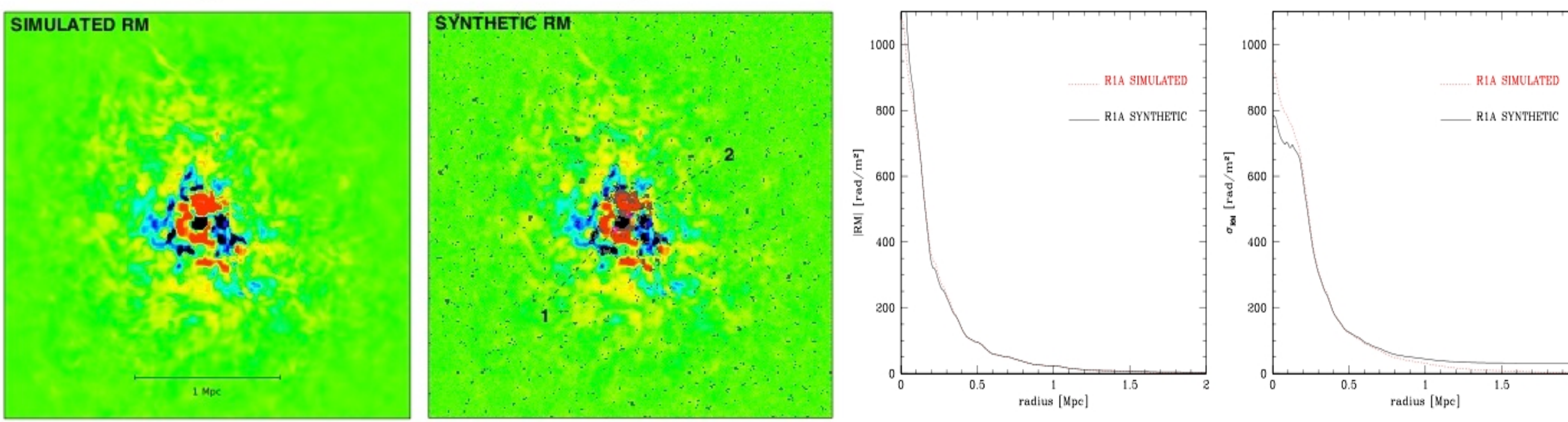
Magnetic energy inside the cluster is 2.4 x 10^{60} erg, the magnetic field is about 1 μG at the cluster center and decreases slowly with radius. These are similar to simulated clusters with single magnetic field source. M_{virial} ~ 6 x 10^{14} $M_{\odot}$ and R_{virial} ~ 1.6 Mpc.

Synthetic Faraday Rotation Images

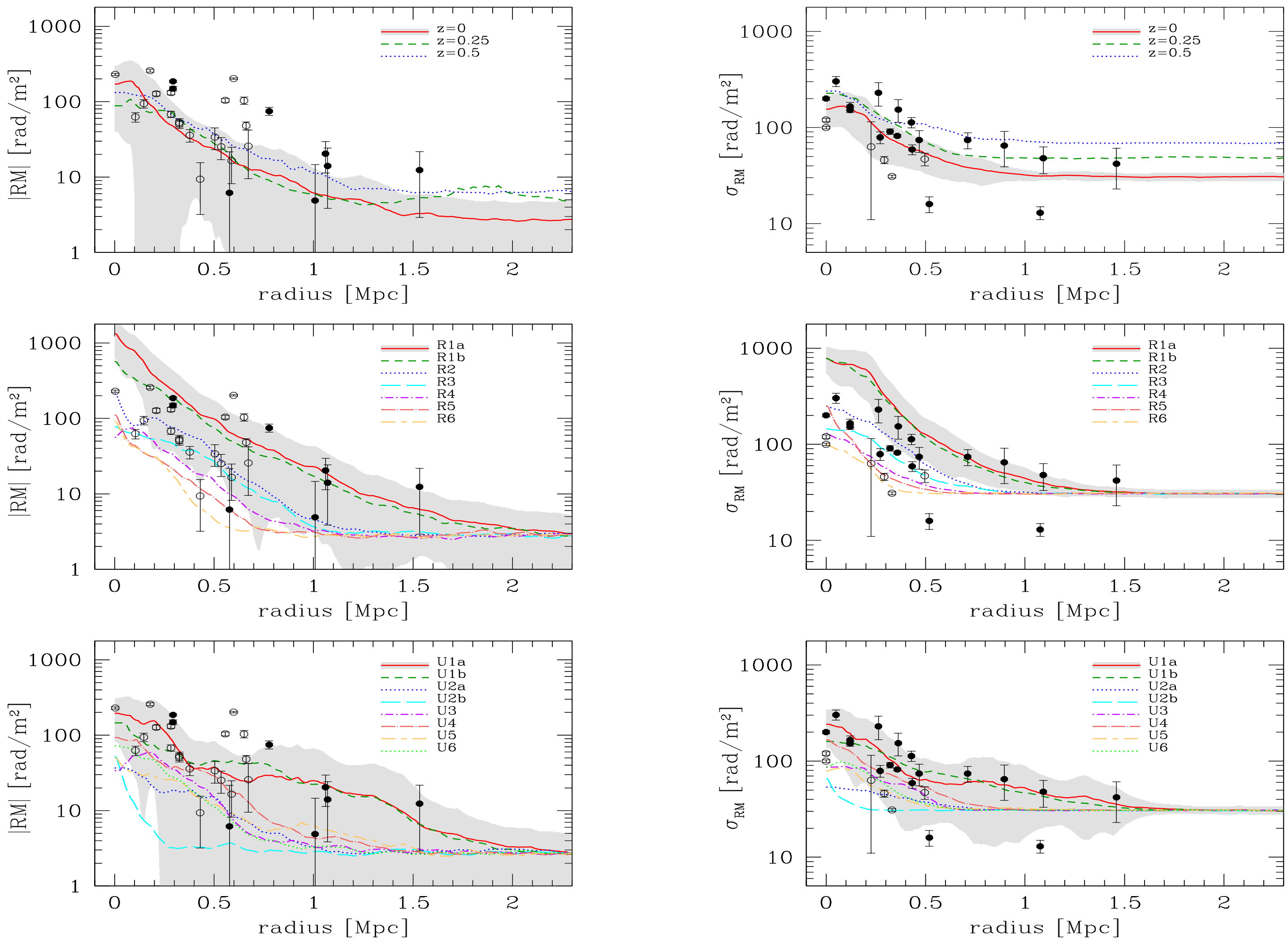
- Faraday Rotation Measure:

$$RM = \frac{\chi_{pol}}{\lambda^2} = 812\int\left(\frac{n_e}{cm^{-3}}\right)\left(\frac{\vec{B}}{\mu G}\right)\cdot\left(\frac{d\vec{\ell}}{kpc}\right)\text{rad/m}^2$$

- Simulated RM images calculated using n_e and B from simulations;
- Synthetic RM using FARADAY code (Murgia et al. 04), mock observation on five frequencies, considering bean depolarization, bandwidth depolarization, VLA noise, and then compute σ_{RM} over 100 kpc x 100 kpc boxes.



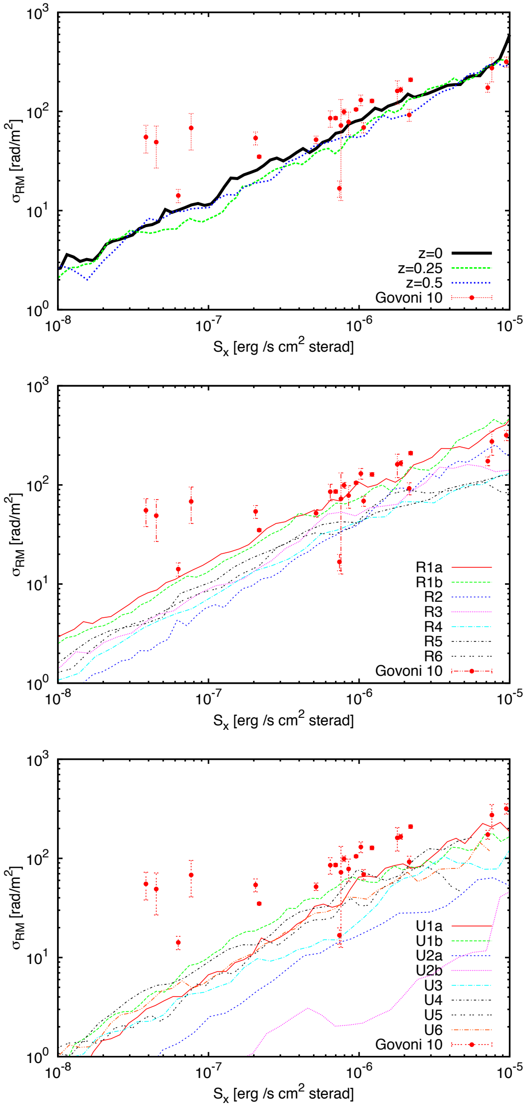
Faraday Rotation: Radial Profiles

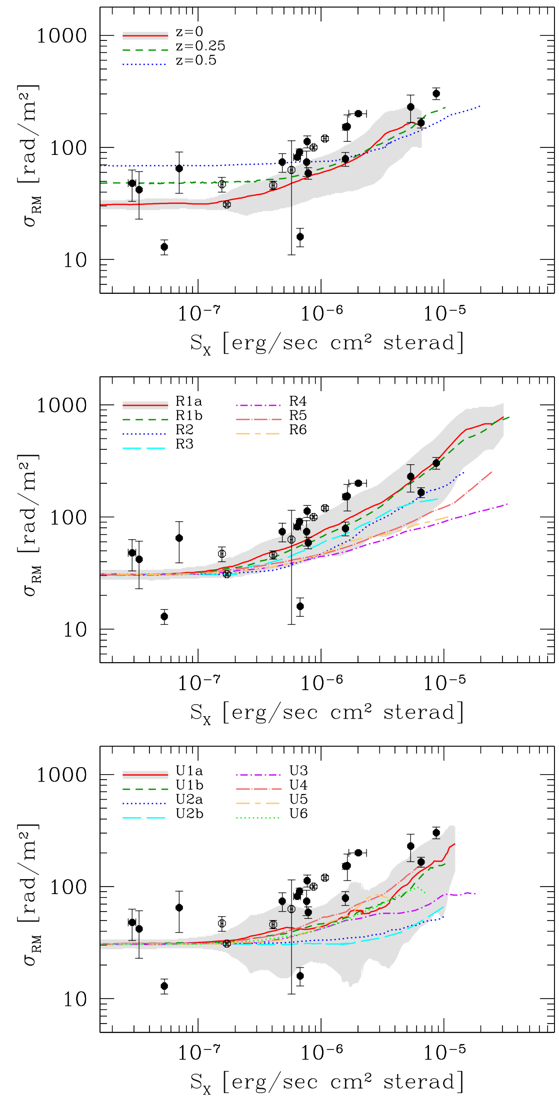


Radial profiles of synthetic RM distributions. Observations of |RM| and RM are taken from Clarke et al. 01 and Govoni et al. 10, respectively. The shaded regions represent the standard deviation for the average profiles of z=0, R1a and U1a.

Faraday Rotation Measure: σ_{RM} vs. S_x

Simulated





Synthetic

Observations data are taken from Govoni et al 10. The shaded regions represent the standard deviation for the σ_{RM} of z=0, R1a, and U1a .

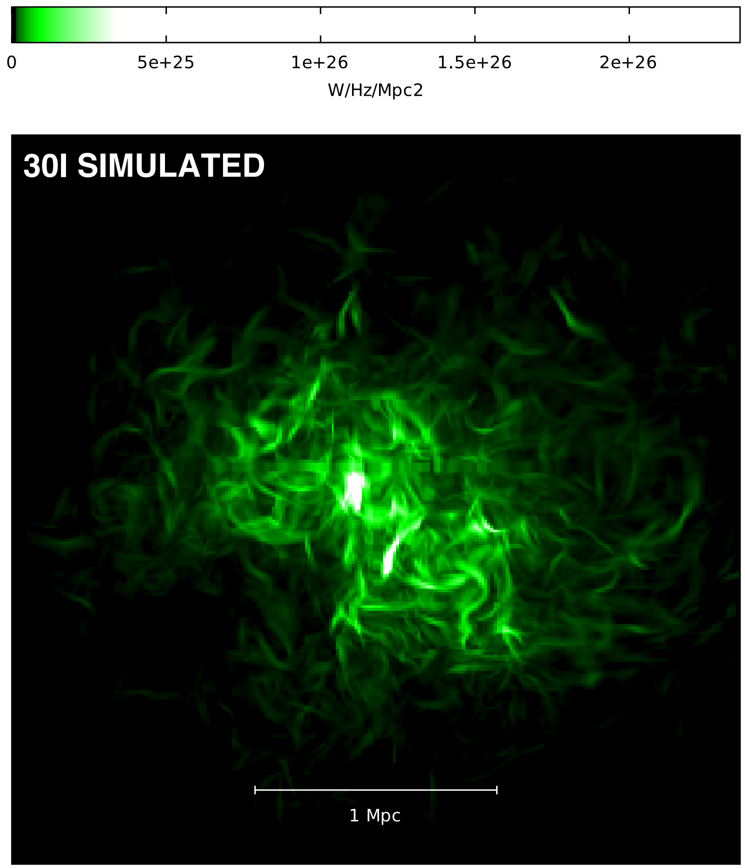
Mock Radio Halos

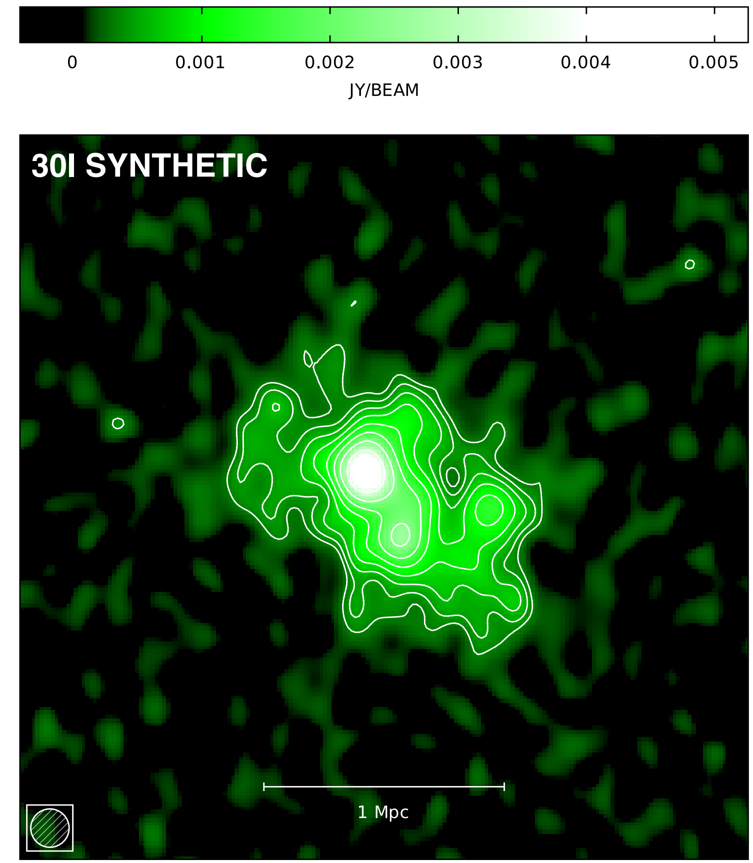
- Synchrotron emissivity from convolving the emission spectrum of a single relativistic electron;
- Population of relativistic electrons:

$$N(\gamma,\theta) = K_0\gamma^{-\delta}(\sin\theta)/2$$

- Energy equipartition between total non-thermal electron energy $U_{el} = m_e c^2 \int_{\gamma_{\min}}^{\gamma_{\max}} N(\gamma)\gamma d\gamma$ and magnetic energy;
- Electron energy spectral index $\delta = 2\alpha + 1$, typical spectral index $\alpha = 1.3$, $\Upsilon_{min} = 300$, $\Upsilon_{max} = 1.5\text{x}10^4$, K_0 varies to guarantee equipartition;
- Convert the images for a 2 hours observation with the VLA in D configuration using AIPS.

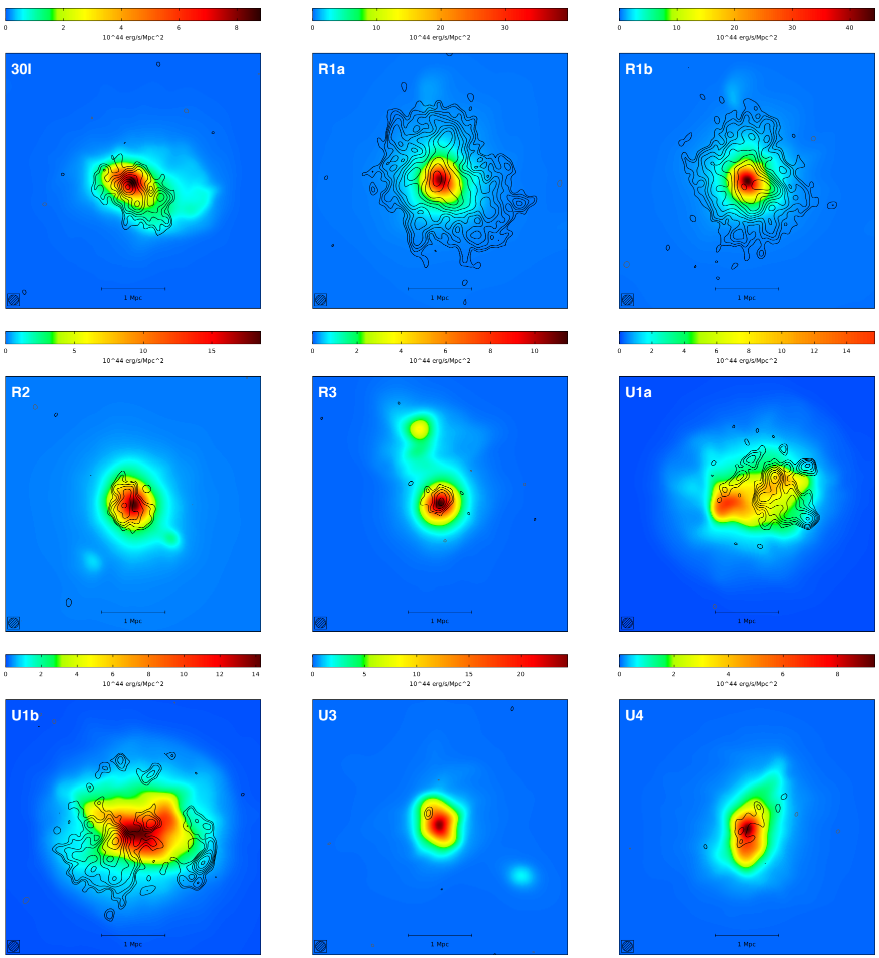
Simulated and Synthetic Radio Halos





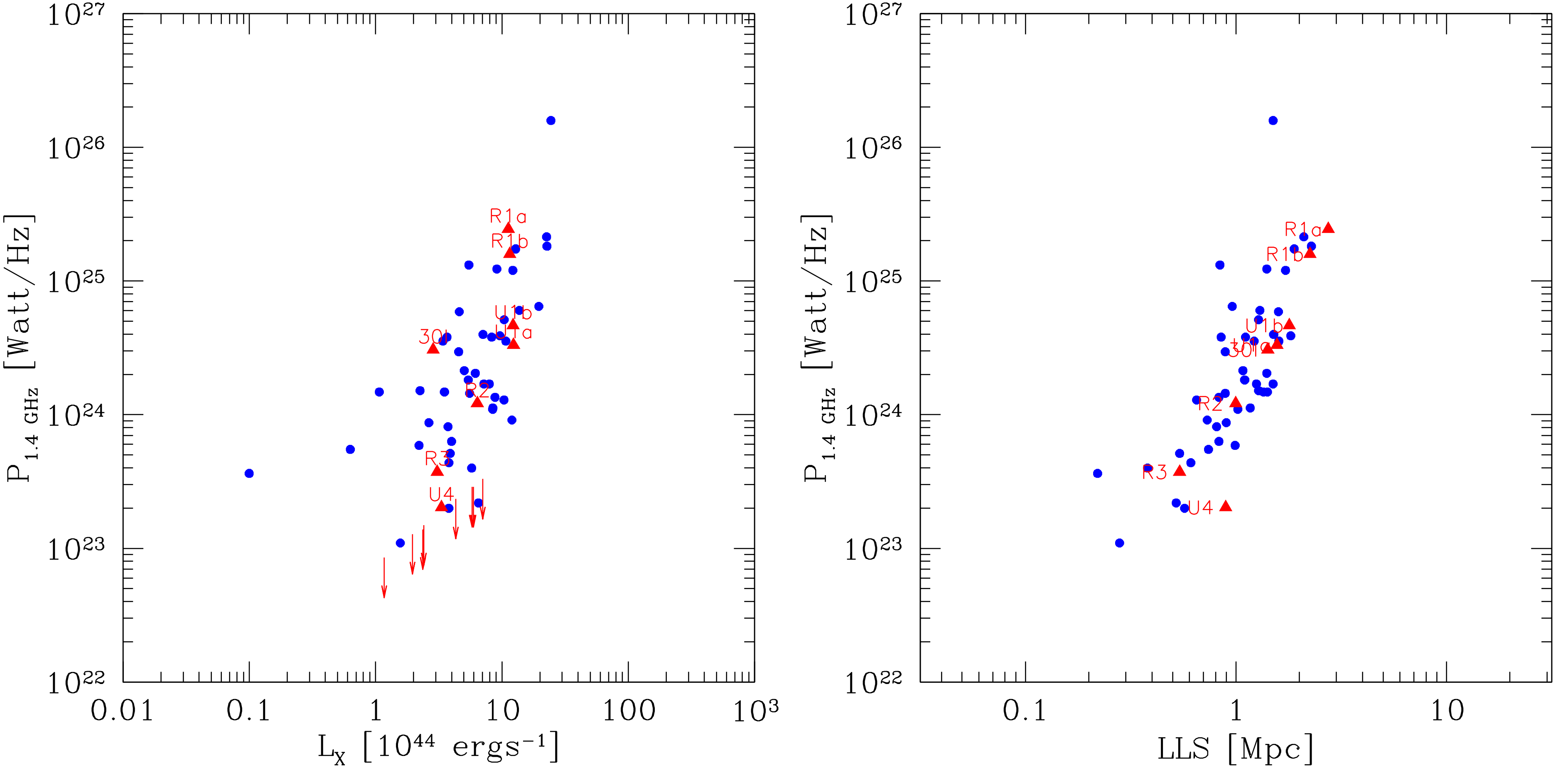
Most of the fine details of the halo structure are no long visible after VLA filtering, diffusive radio image is just like observations.

Radio Halos: Morphology



9 simulated (large) clusters have detectable radio emission. Contours of radio emission at 1.4 GHz are overlaid to the cluster X-ray emission in the 0.1-2.4 keV band. The radio contour levels start at 0.3 mJy/beam and increase by $\sqrt{2}$.

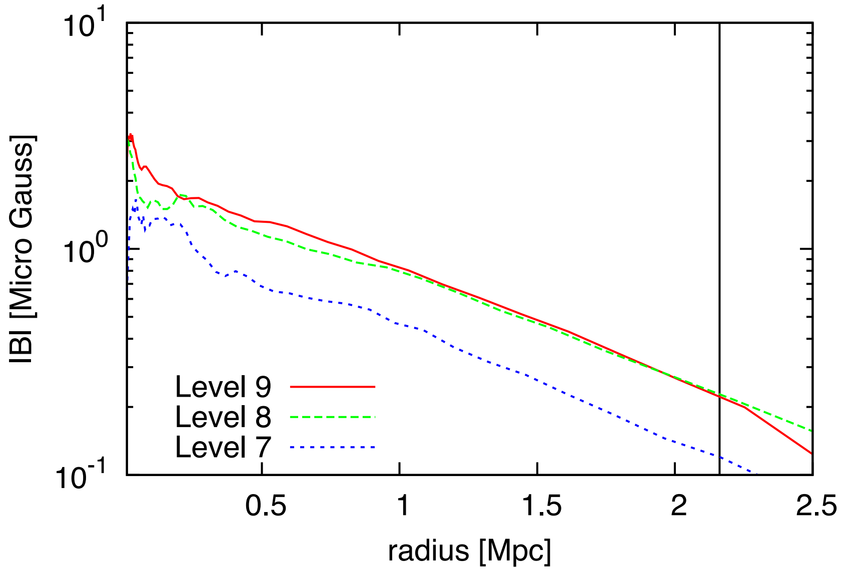
Radio Halos: Radio Power vs X-ray Luminosity and Largest Linear Size.



Synthetic radio halos agree with observations.

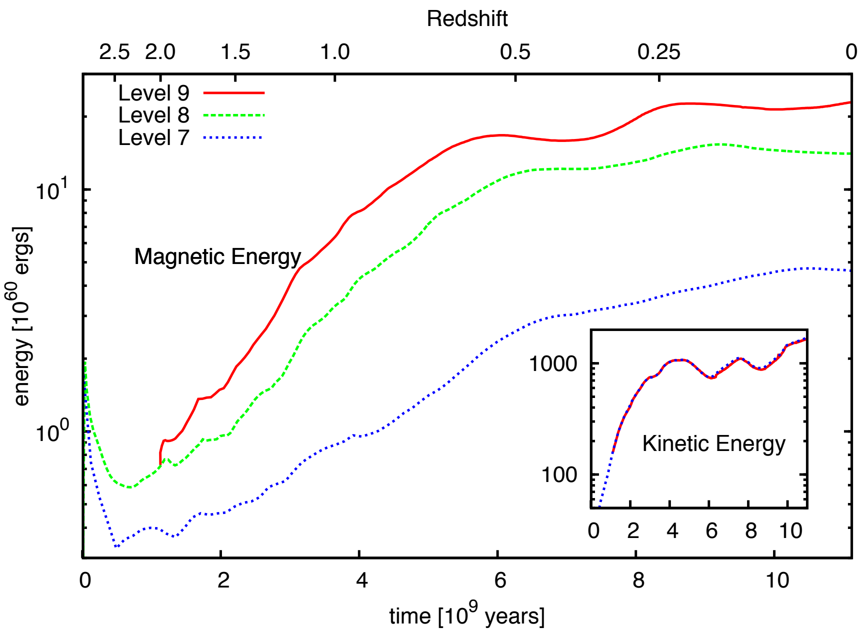
Resolution Effects

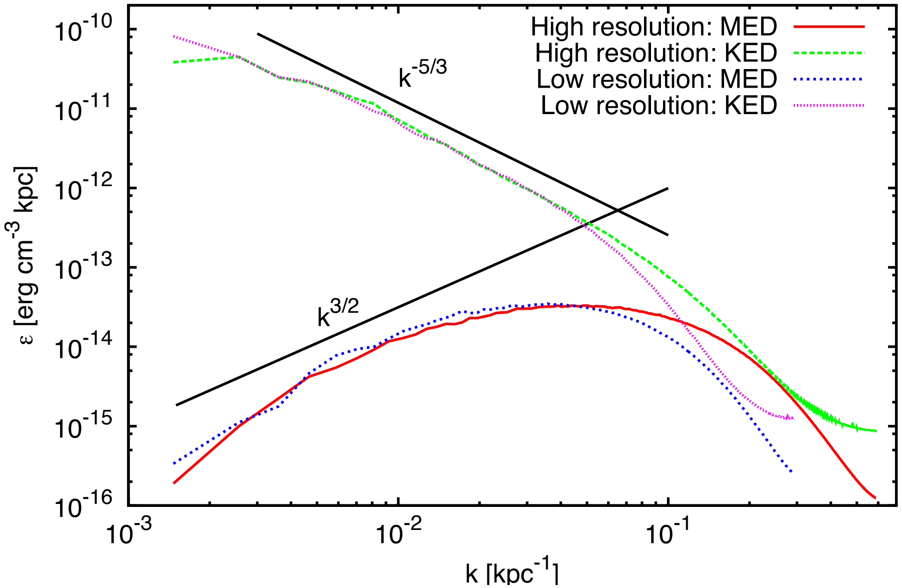
- Rerun one simulations with doubled highest resolution (~5.5 kpc);
- Same refinement criteria, all magnetized regions (> 5×10^{-8} G) refined to the highest resolution;
- ~ $(1000)^3$ grids tracking the whole cluster;
- 10 million CPU hours on Linux clusters at LANL;
- Few Impacts on gas distribution.



Radial profile of field strength: Slight stronger Magnetic field, yields higher peak B-fields but not RMS fields.

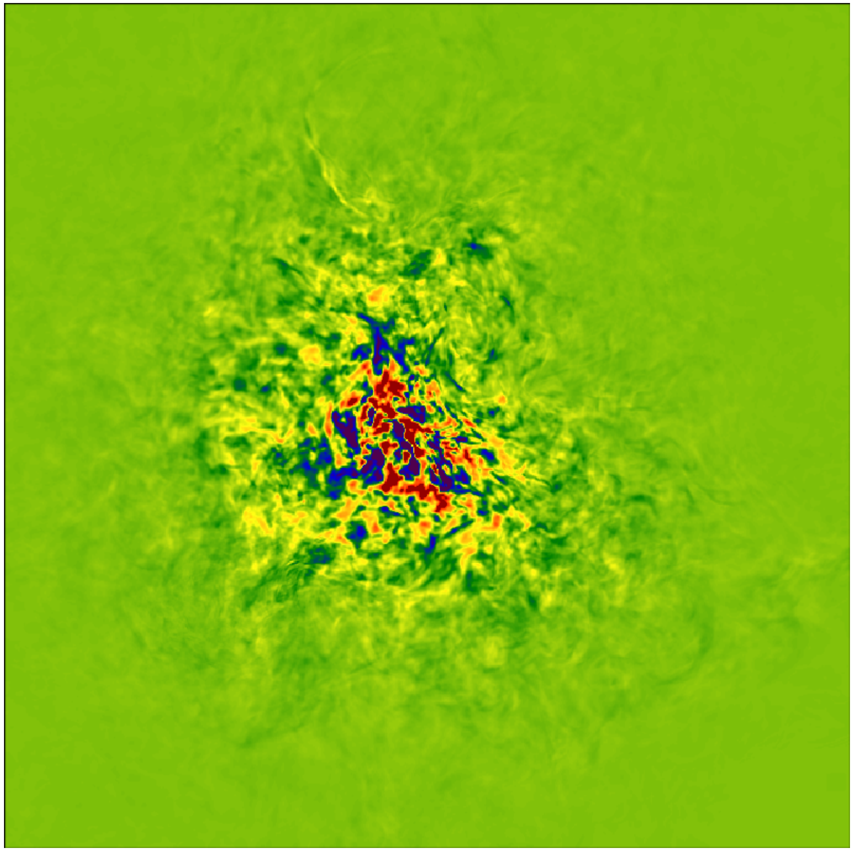
Resolution Effects: Magnetic Energy

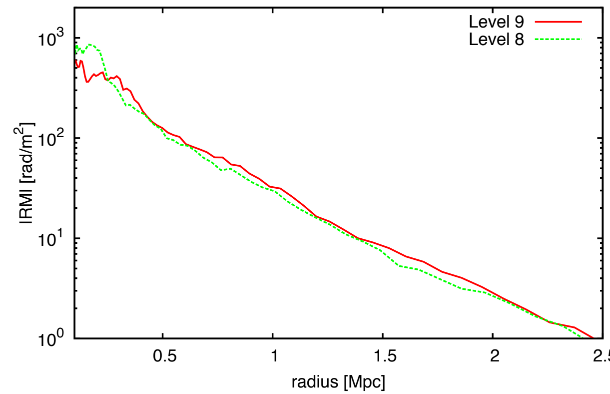


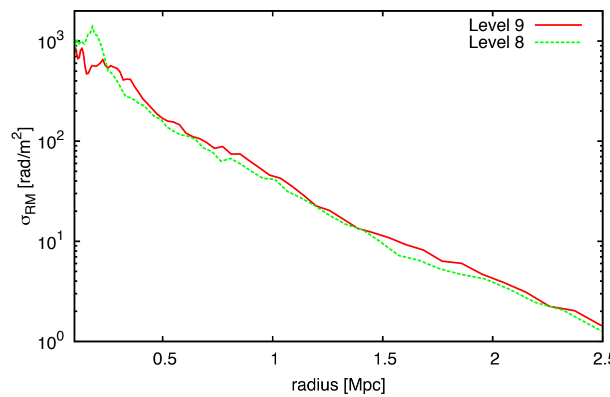


- Faster amplification of magnetic fields;
- 60% more magnetic energy, but still < 2% of kinetic energy;
- Spectra extent to small scales, saturation of magnetic and kinetic energy reached at small scales;
- Magnetic energy in large scale is a little less, since saturation at small scale reach faster.

Resolution Effects: FRM







Very similar RM distributions, more small scale structure (decreased magnetic fields reversal scale).
Conclusion: Though convergence is not reached, lower resolution, much cheaper simulations capture most of the physics of magnetic fields amplification and have “right” RMS magnetic field and RM distribution.

Conclusions

- Powerful radio jets at high z can magnetize entire ICM to μG through transportation and amplification by the turbulence;
- Final cluster B-field forgets its initial conditions and strength, hence results are insensitive to number of AGN and magnetic energy injected;
- Mock radio observations from our simulated clusters agree with VLA observations (Radio Halos, RM, as well as Radio relics);
- This magnetic field reconciles the equipartition magnetic fields in radio halos and the magnetic field derived from the RM;
- Resolutions have effects on magnetic field amplifications, but weakly impact radio observations.