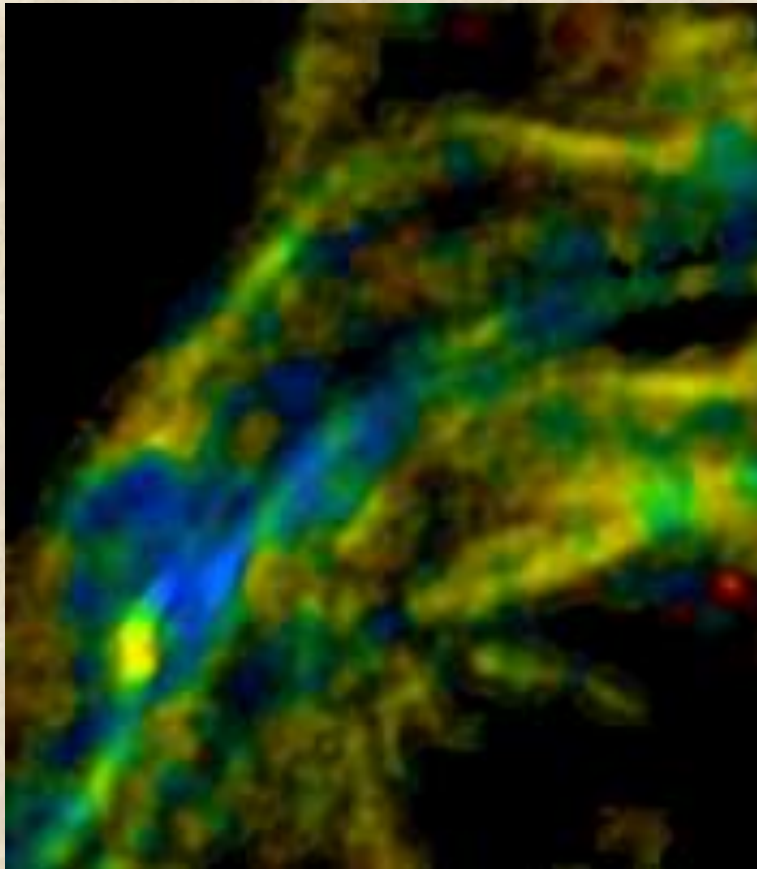


# Cluster magnetic fields: *patterns and prospects*



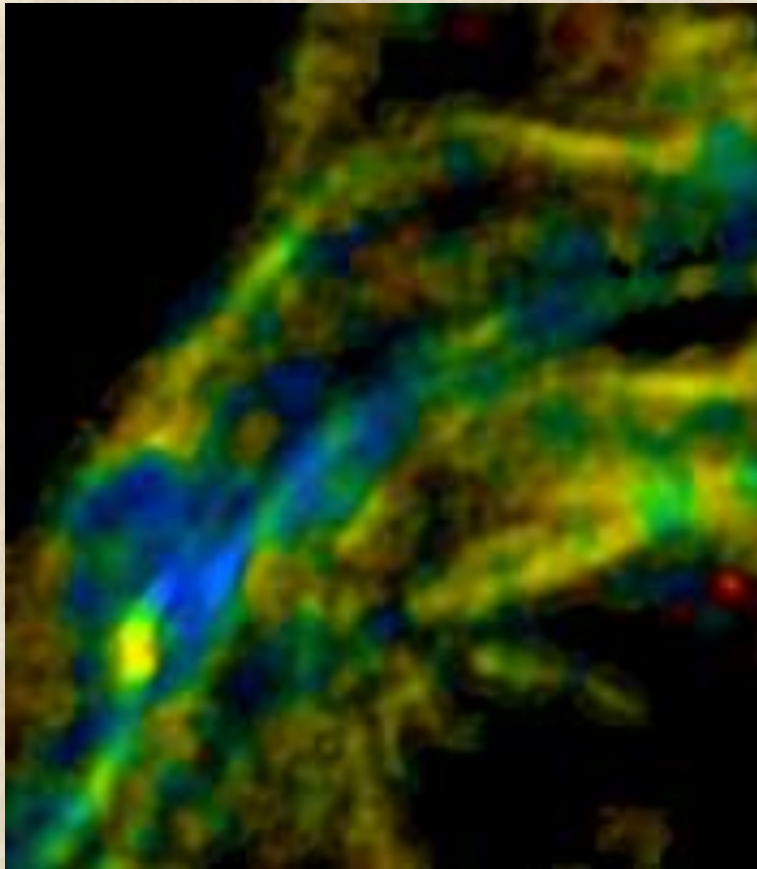
**L. Rudnick**  
**MN Inst. for Astrophysics**

**Magnetic Fields in the Universe 2015**

**Collaborators:** F. Owen (NRAO), J. Eilek (NMIMT) Brandon Bergerud, Avery Garon (UMN undergrads), Kyle Willett (UMN), T. W. Jones (Guru)

**With support from NSF: AST 1211595**

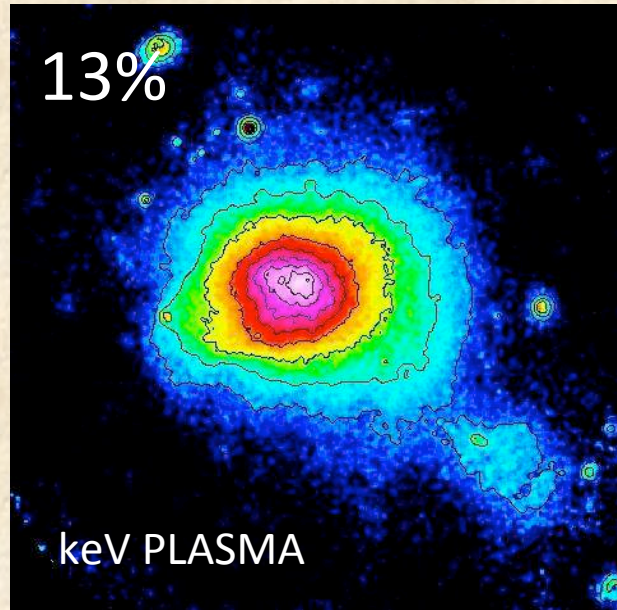
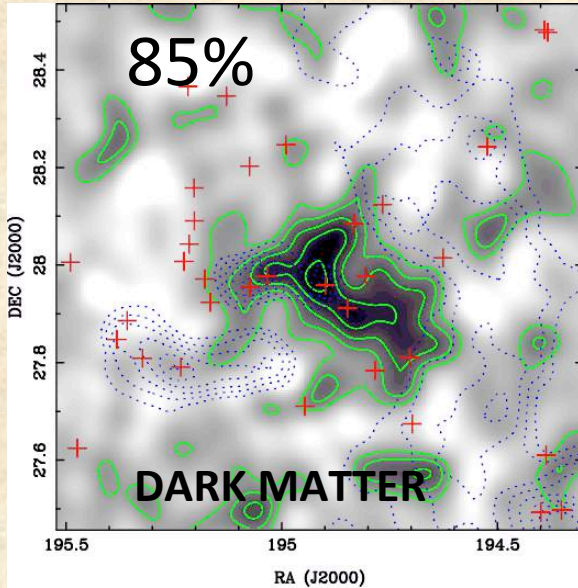
# Cluster magnetic fields: *patterns and prospects*



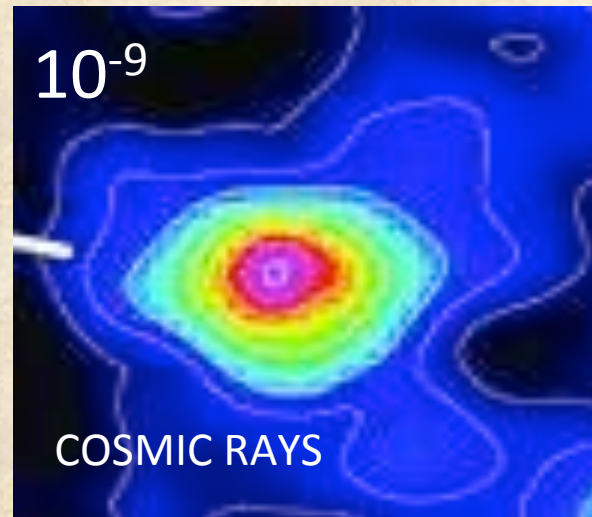
L. Rudnick  
MN Inst. for Astrophysics

$$\beta_{\text{comprehensibility}} = \frac{\rho_{\text{pictures}}}{\rho_{\text{equations}}}$$

# What is a cluster?



- $10^{15}$  Msun
- + ICM
  - + Galaxies
  - + CRs & fields
- 



# Plasma physical parameters

## Thermal plasma: X-rays & Sunyaev-Zeldovich

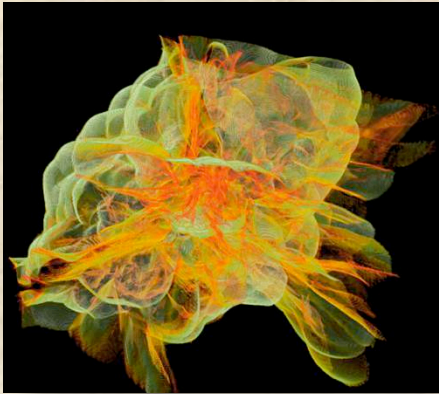
- $n \sim 10^{-3}$  to  $10^{-1}$
- $T \sim 10^8$  K      $c_s \sim 1500$  km/s
- $M_s \sim 0.2-0.5$  (turbulence) , 1-3 (shocks)  
*(continued driving from accretion)*

## Magnetic fields: Diffuse radio & Faraday Rotation

- $B \sim 0.1 - 3 \mu\text{G}$
- $M_A \sim 20$
- particle mfp  $\sim l_A \sim (0.3 \text{ kpc})$  *(scale for acceleration)*
- plasma  $\beta \sim 10^{2-3}$ , pressure ratio (thermal/magnetic)

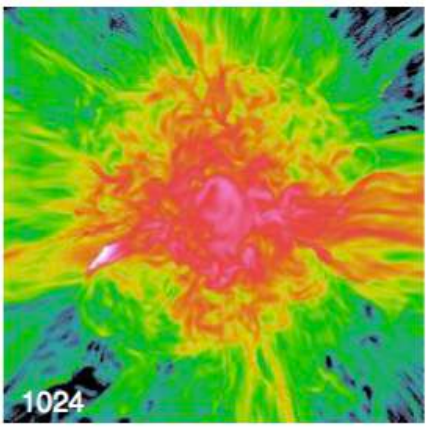
# Cluster Fields: (*CR electrons*)

probe scales  $\sim 1$  kpc to 1 Mpc



20kpc resolution over 6.4 Mpc  
Courtesy T. W. Jones & F. Vazza

Mach # Red (1-3) White (20)

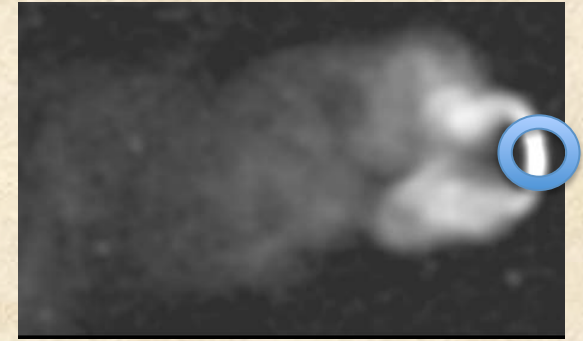


Magnetic field

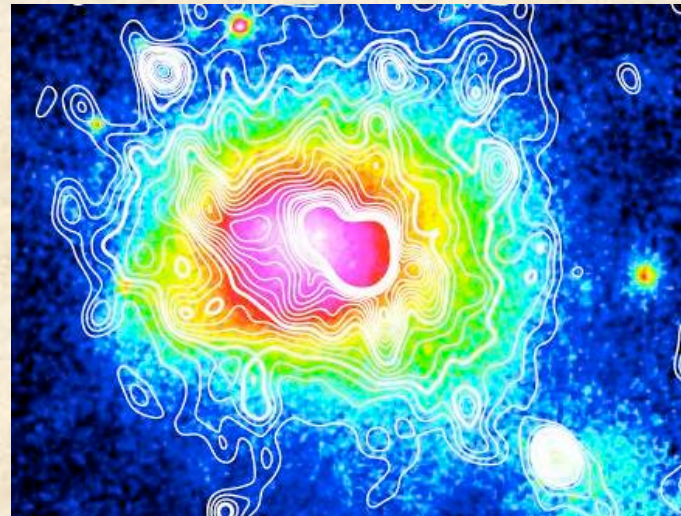
Vazza, Bruggen+14

Extended  
AGN

Tailed  
Radio  
Galaxy



Coma: Mpc scale,  $\sim \mu\text{G}$



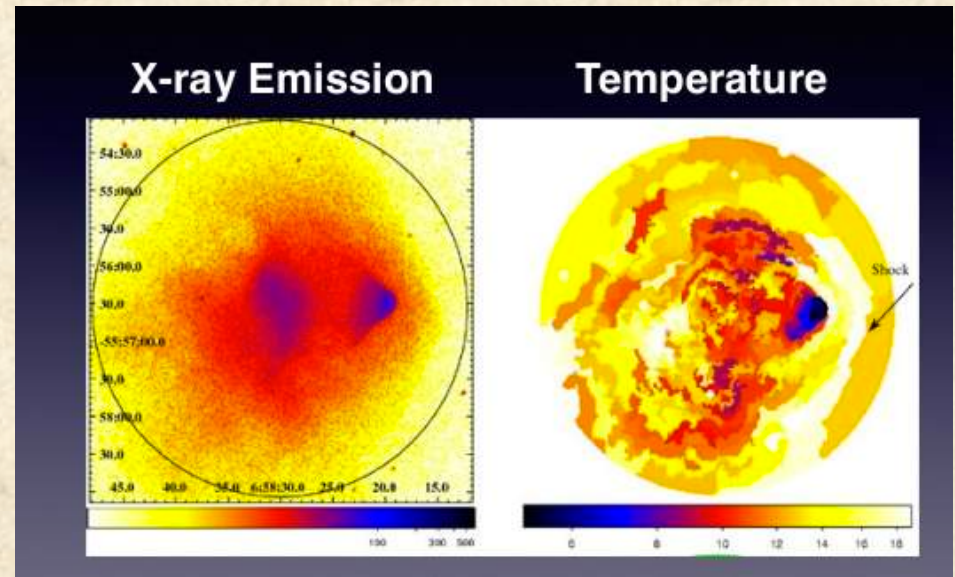
color ROSAT, contours WSRT 325 MHz  
Brown & Rudnick, 2011

Cluster-wide  
emission

# Questions, questions...

- Can we measure the strength and structure of cluster magnetic fields?
  - large scales  $\rightarrow$  driving
  - small scales  $\rightarrow$  CRe acceleration

B fields -- for ICM,  
energetics/pressure small,  
but important for  
thermal conduction



Needed,  
a magnetic guide...



Needed,  
a magnetic guide...



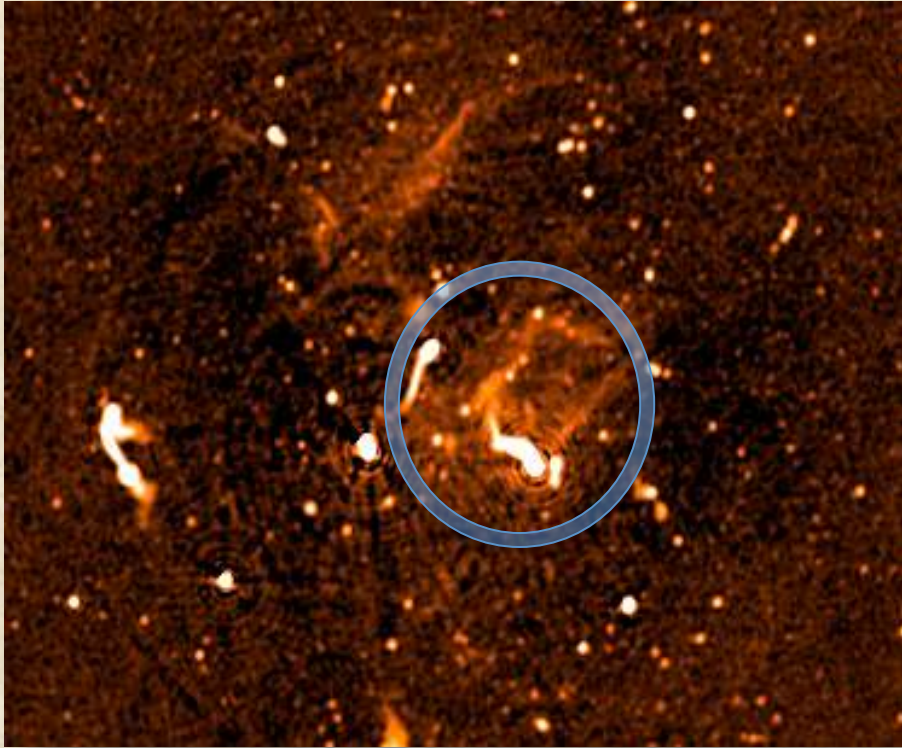




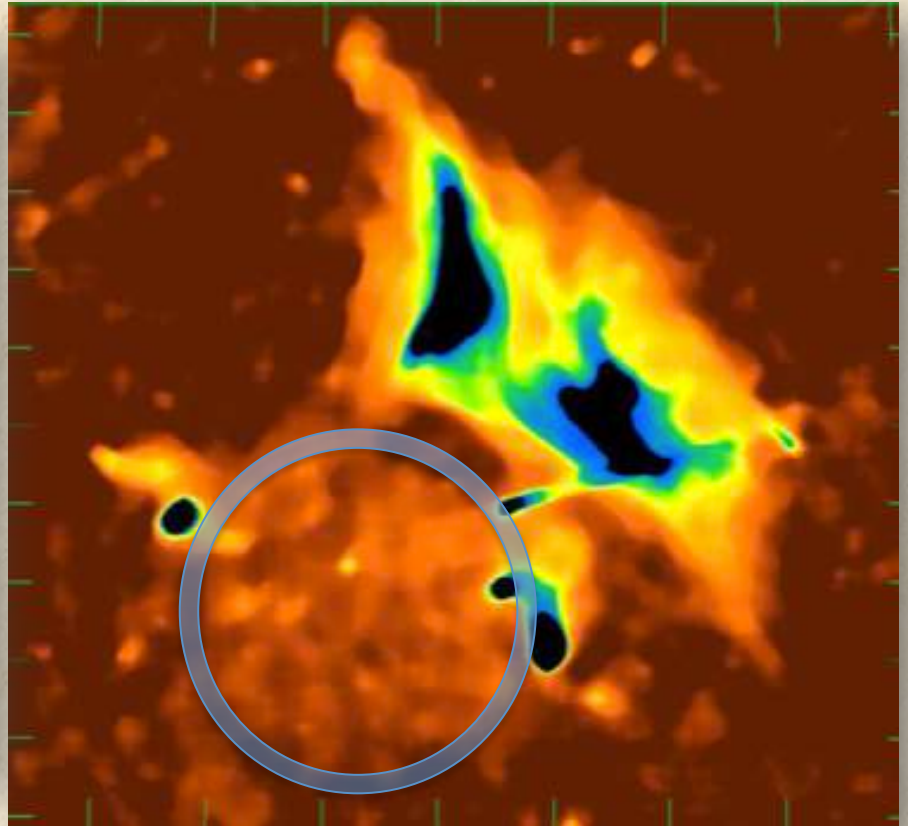
# Take home messages

- Network of likely ICM weak shocks now becoming visible → *can we invert to diagnose ICM?*
- $\mu\text{G}$  fields found  $> \text{Mpc}$  from centers, wide variety of structures  
→ *what are the field and particle origins?*
- Faraday rotation & filaments in A2256, very large scale fields (0.5 Mpc) in ICM  
→ *will RMS give us turbulent ICM scales?*

# Finding the halos (Mpc scales)

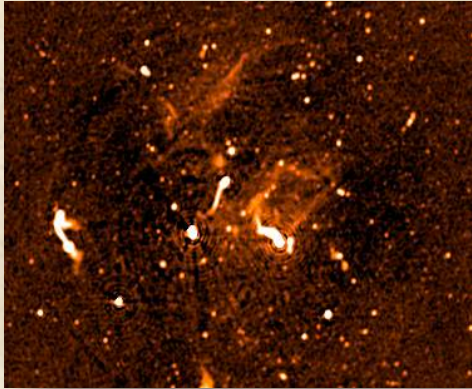


Abell 2255  
Pizzo+



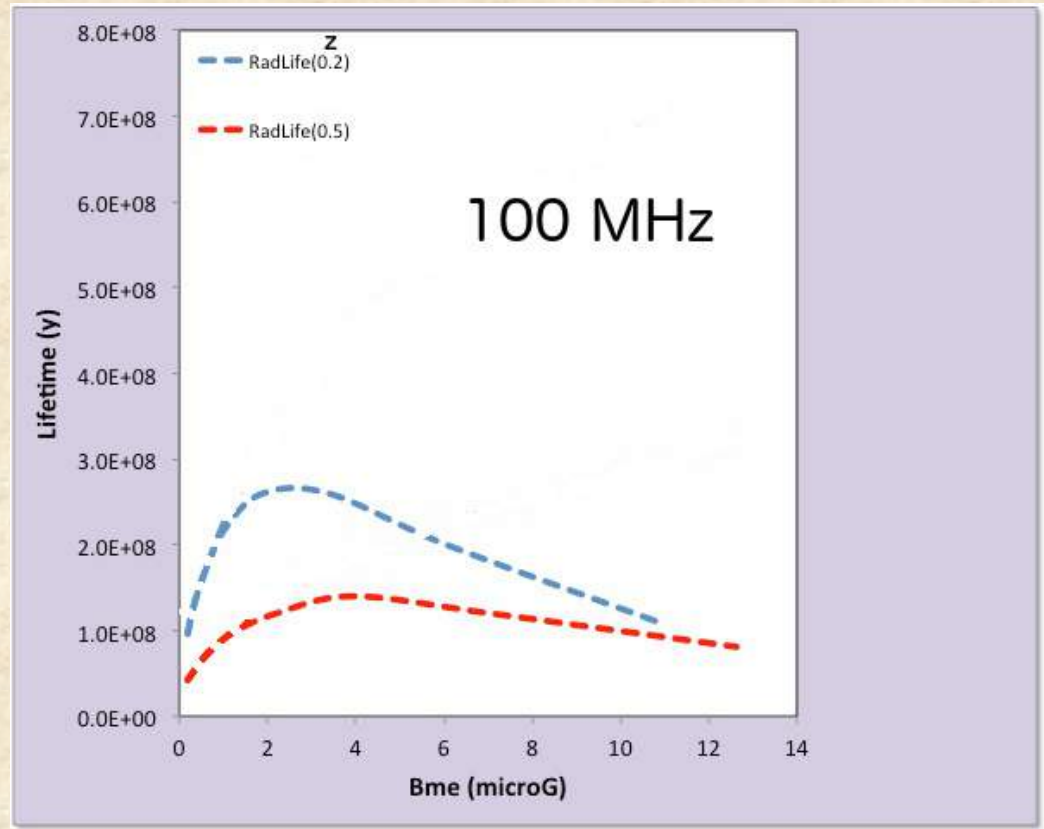
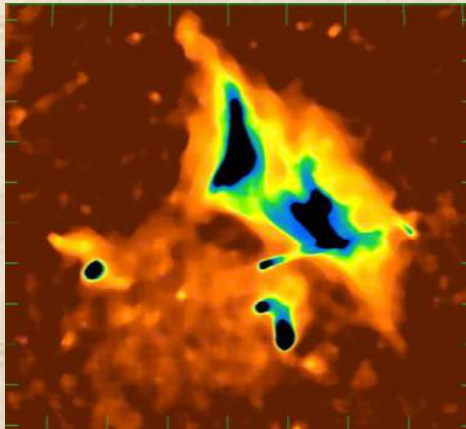
Abell 2256  
Owen+14

# Finding the halos (Mpc scales)



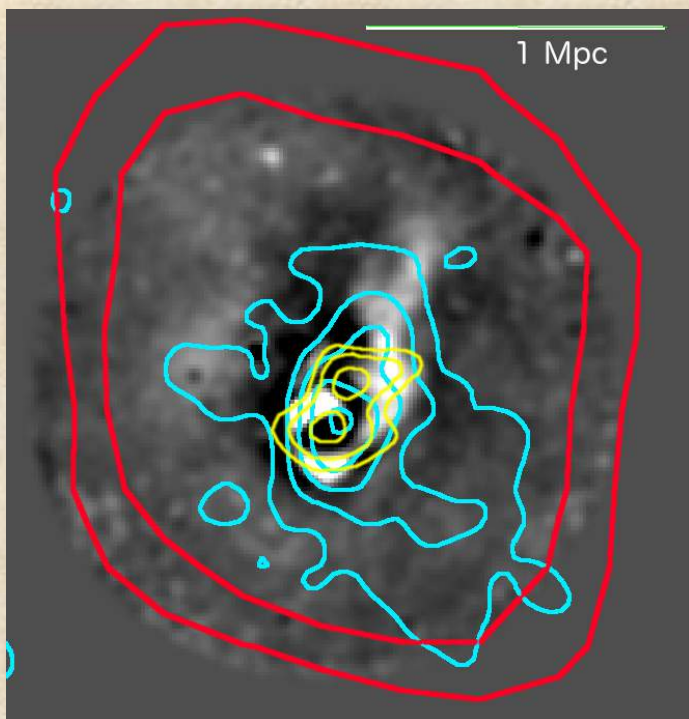
Abell 2255

Abell 2256

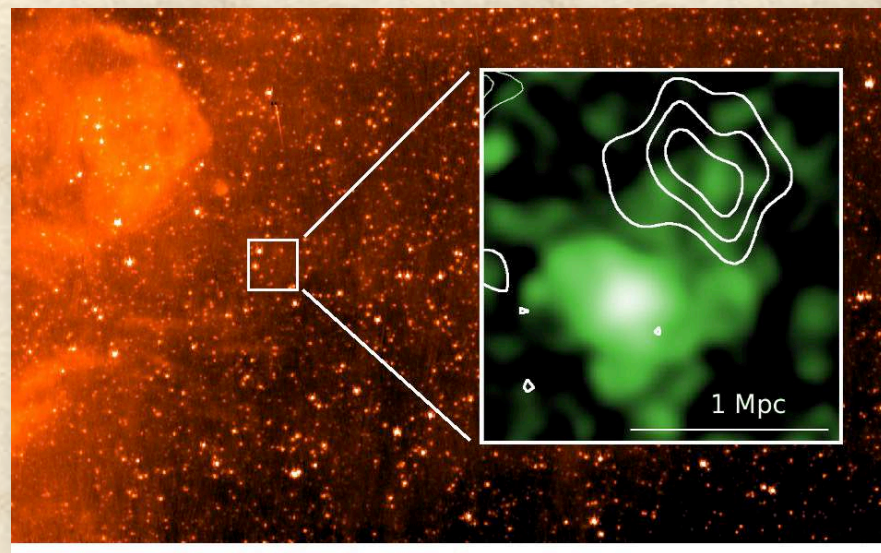


High fields -- shortened lifetime,  
requires faster acceleration  
Low fields -- fainter, higher energy particles (IC loss)

# *Pushing the brightness limits =pushing to lower fields → (single dish)*



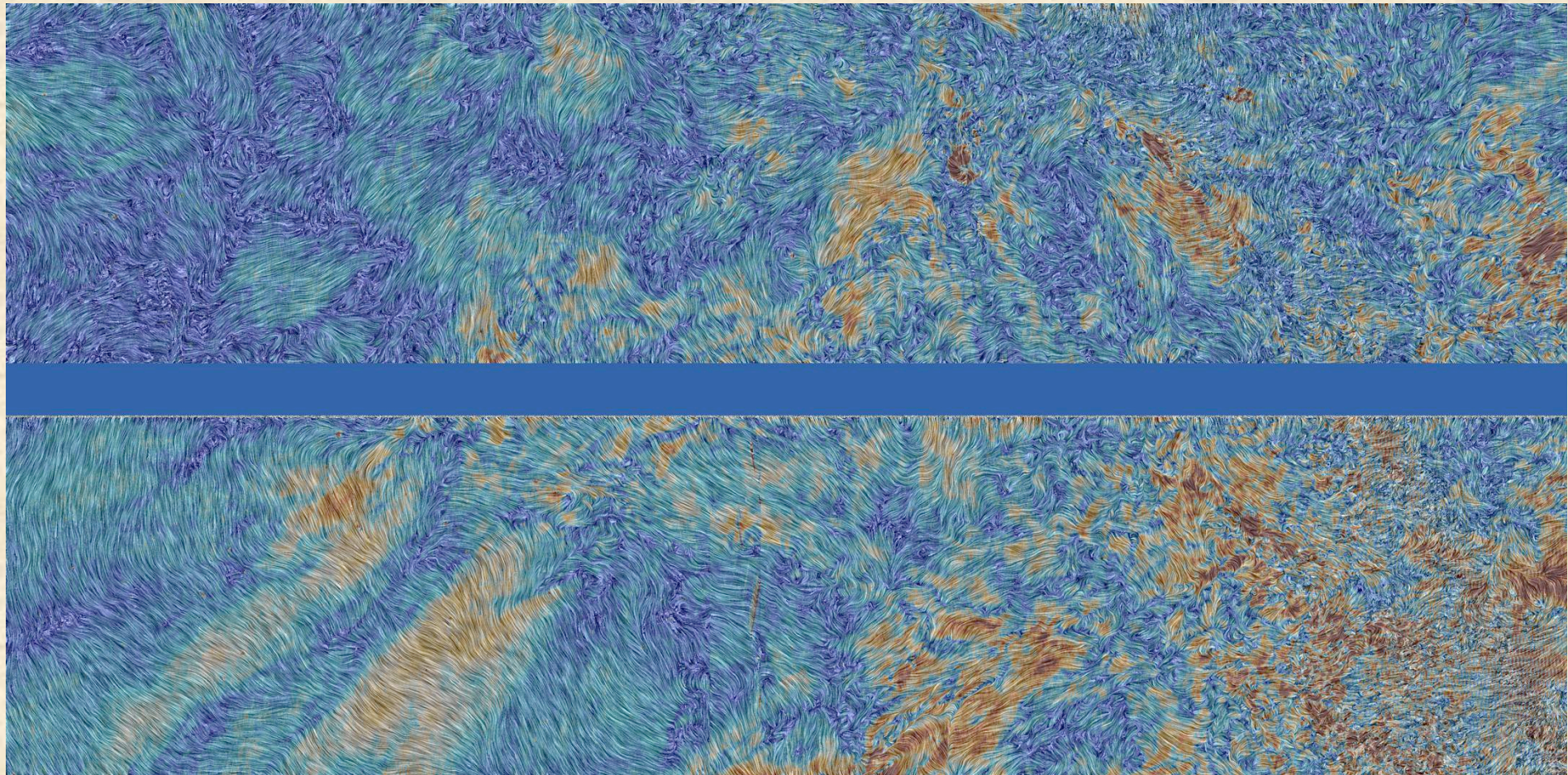
Abell 2319: GBT+XMM( $\beta$ -sub)+AMI  
Farnsworth+



Abell 539: GALFACTS + ROSAT

*+ Lifetime problem! (magnetic field sweet spot, few  $\mu$ G)*

# More to come... GALFACTS



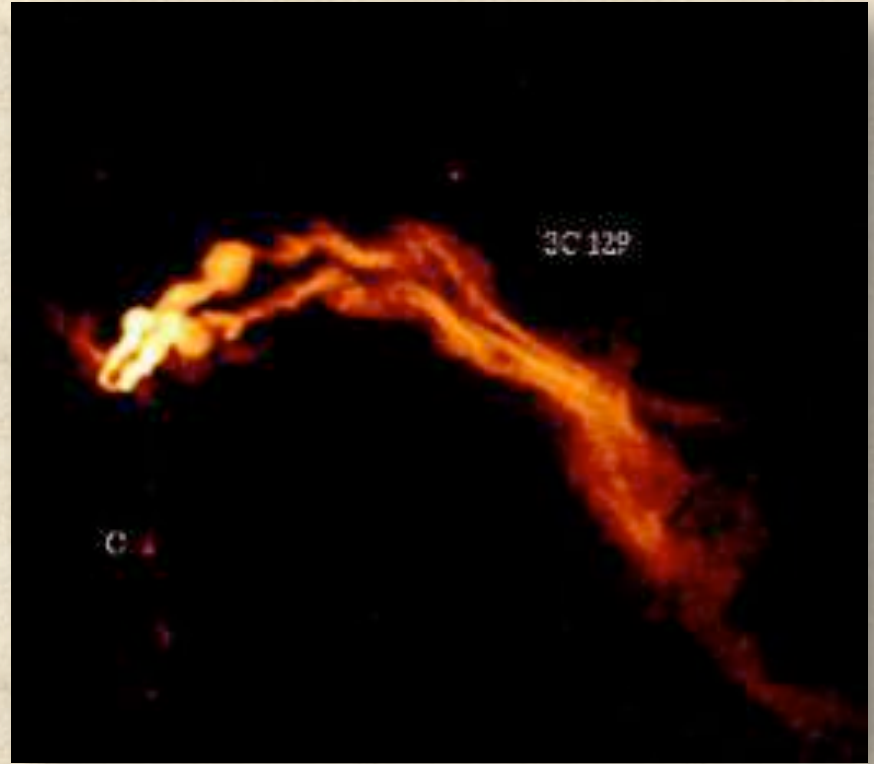
GALFACTS 13,000 sq deg, 21cm, 3.4': Imaging, Russ Taylor; Visualization, Jamie Farnes

# Filling the ICM: Mpc scales

*Field origins: primordial? pre-galactic? galactic? AGN?*



*active transport*



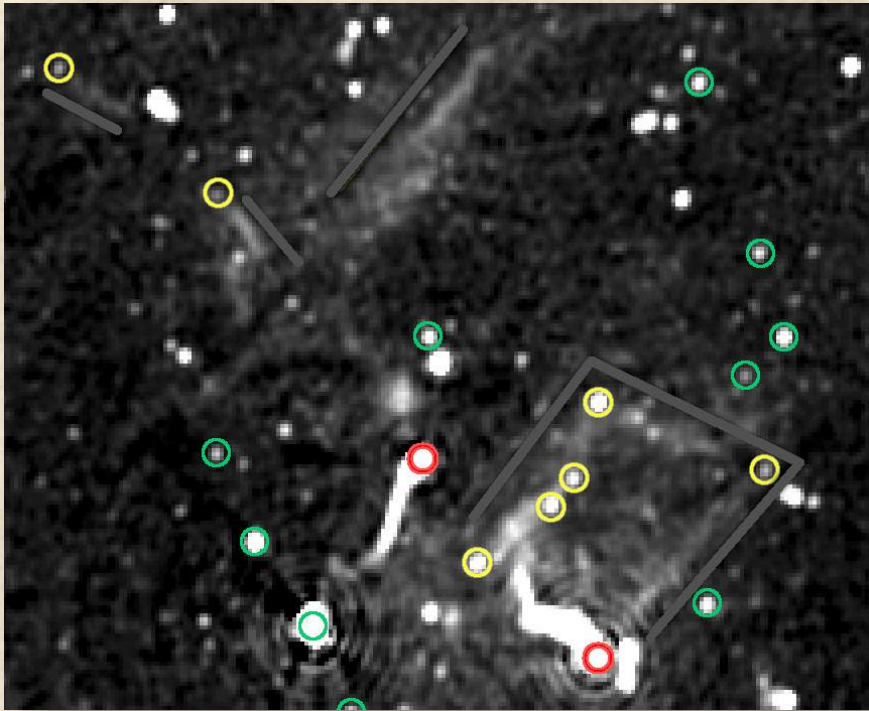
*passive deposition*

HYDRA A:  
X-ray: NASA/CXC/U.Waterloo/C.Kirkpatrick et al.;  
Radio: NSF/NRAO/VLA;  
Optical: Canada-France-Hawaii-Telescope/DSS

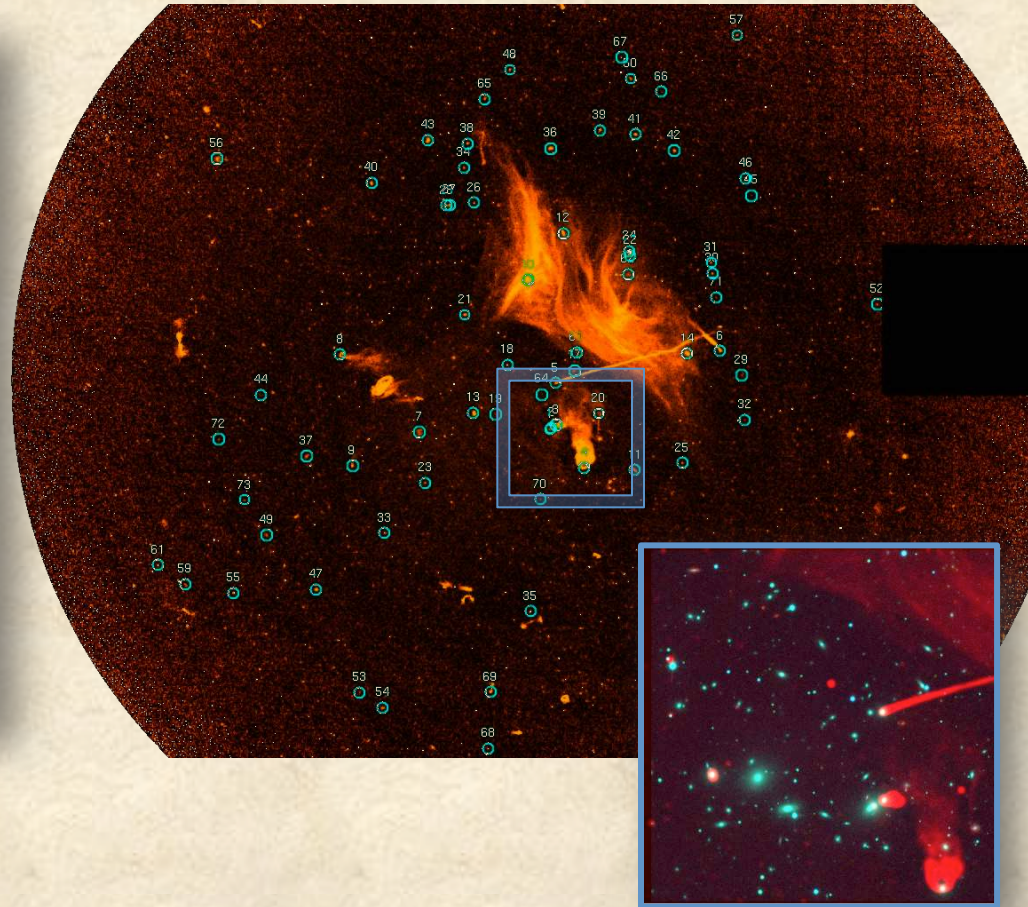
Lane et al., AJ, 123, 2985, 2002.

# Filling the cluster:

*lots of AGN+ ← what's the history?*  
*+ energy from continued accretion, mergers*

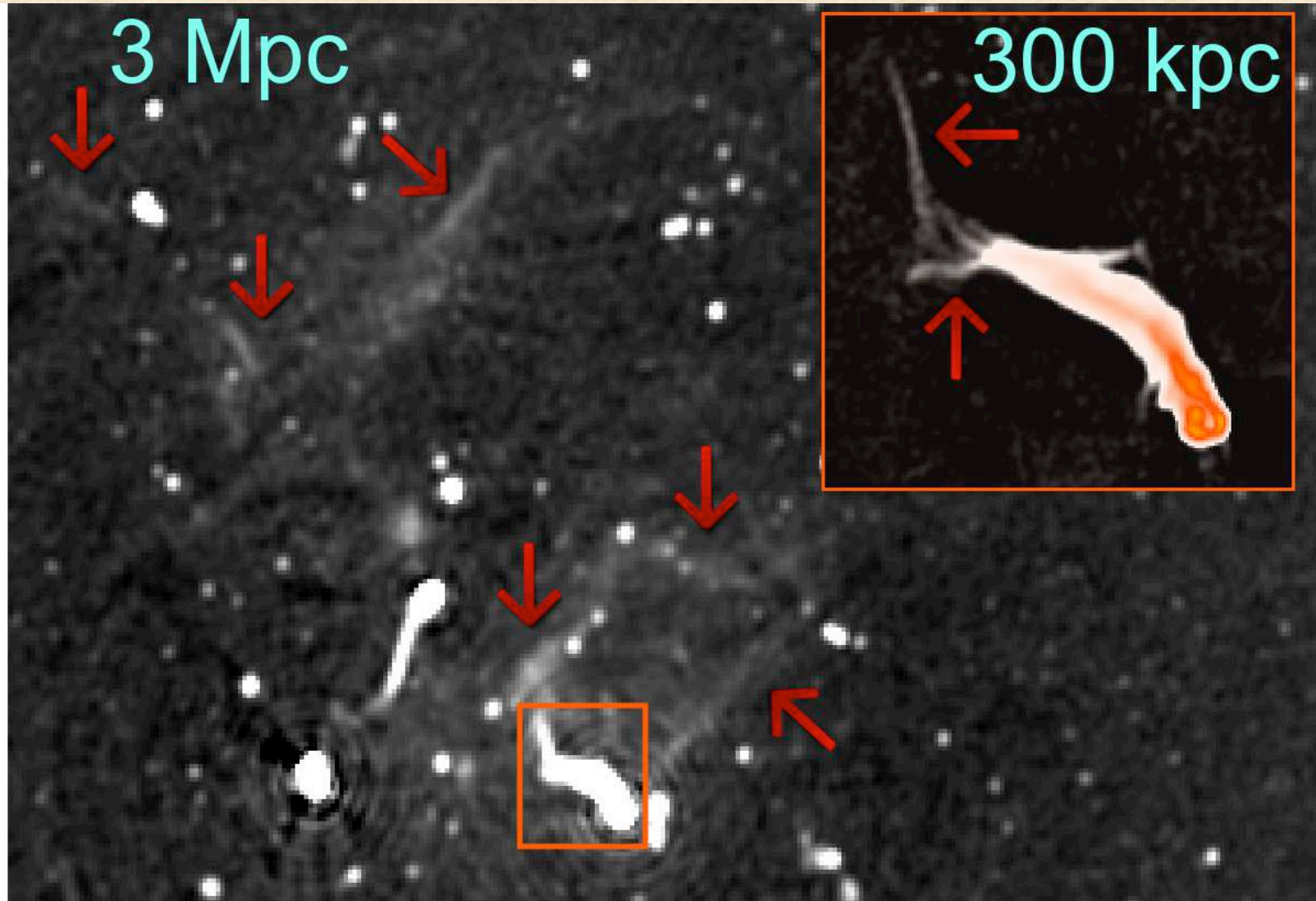


A2255: Pizzo & de Bruyn



A2256: Forootaninia, Rudnick, Owen, in prep

# The weak shock population (perhaps down to $M \sim 1.5$ ? AGN connection?)

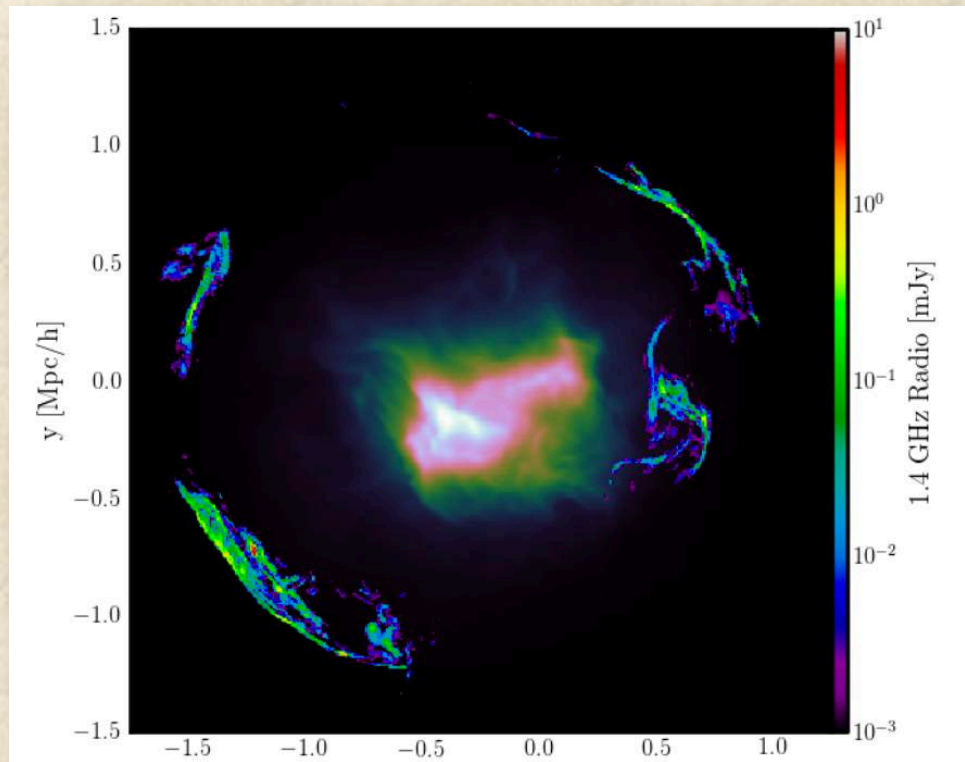




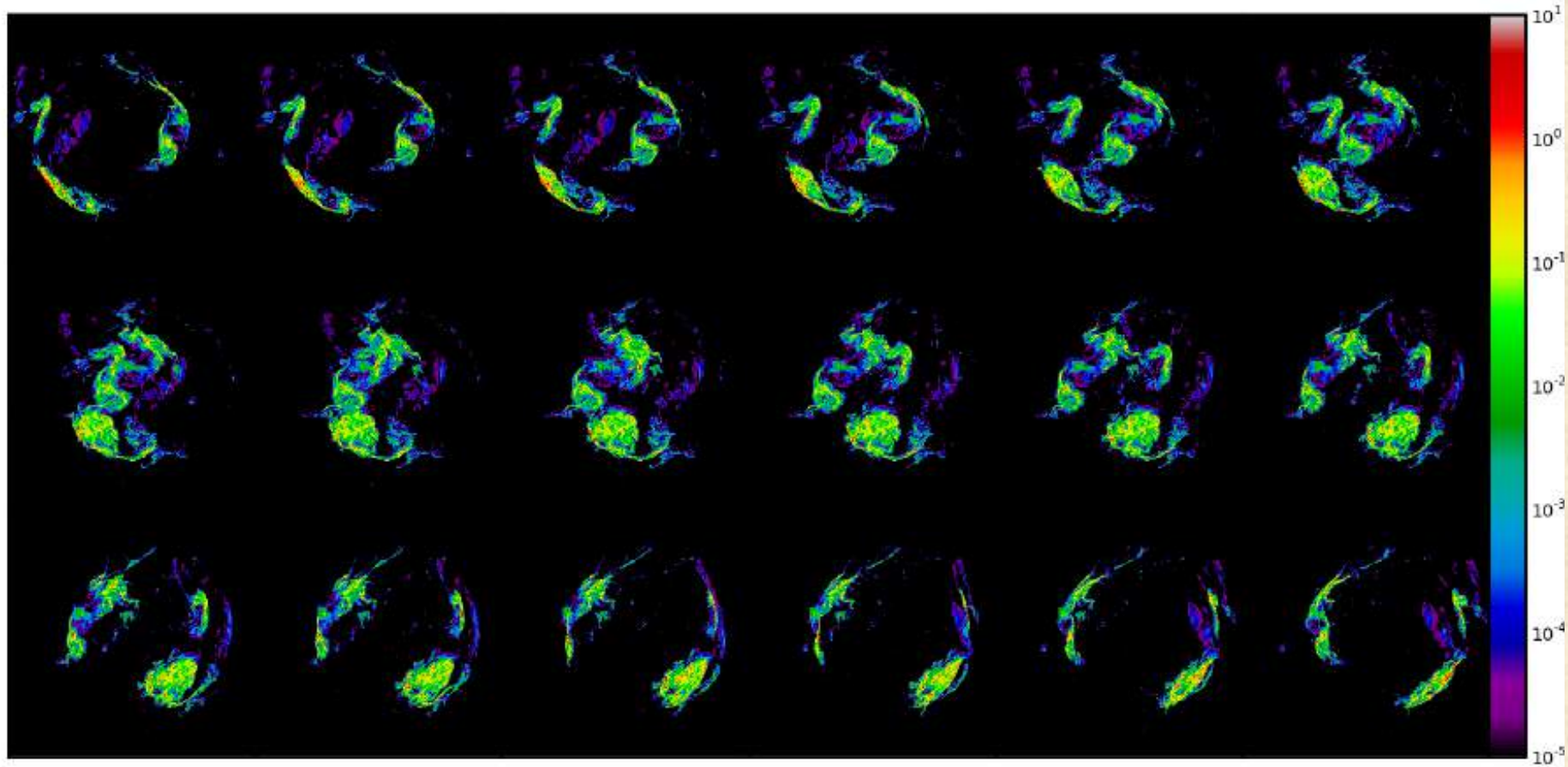
# $\mu\text{G}$ fields in cluster outskirts

“Peripheral relics”

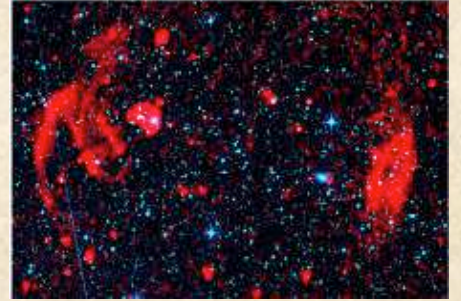
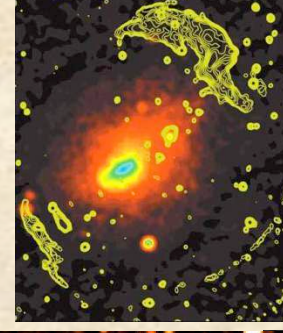
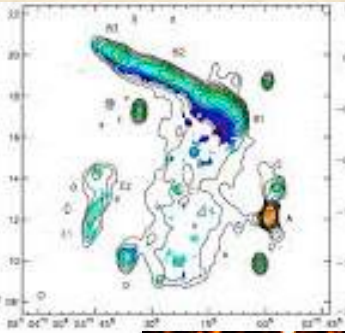
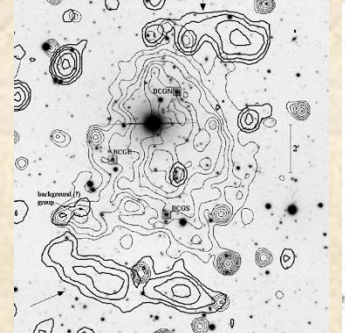
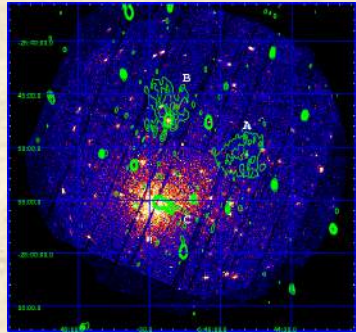
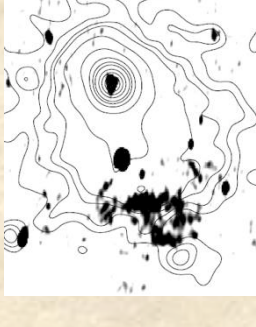
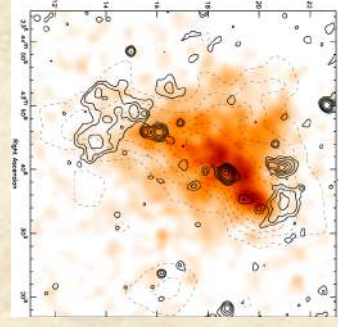
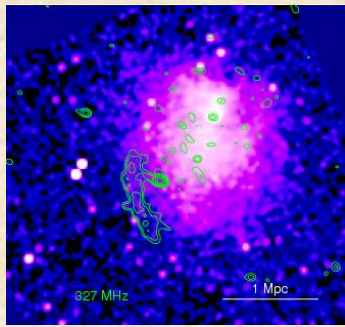
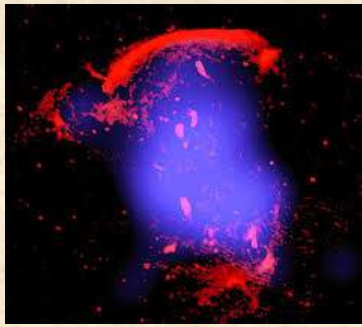
What do we expect to see?



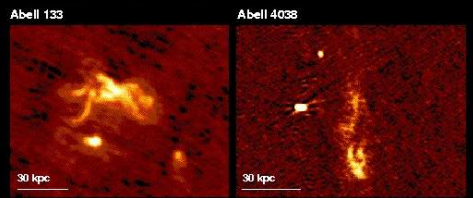
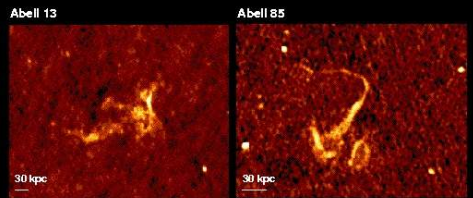
# $\mu\text{G}$ fields in cluster outskirts



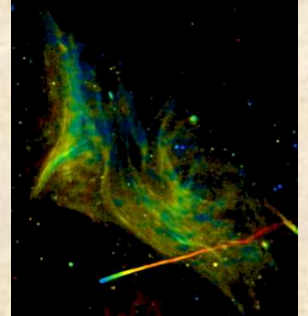
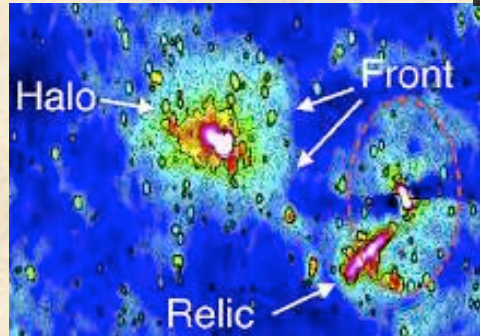
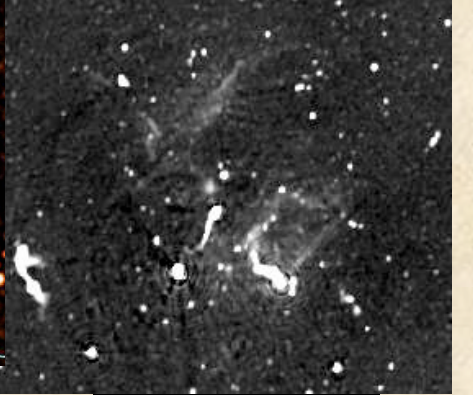
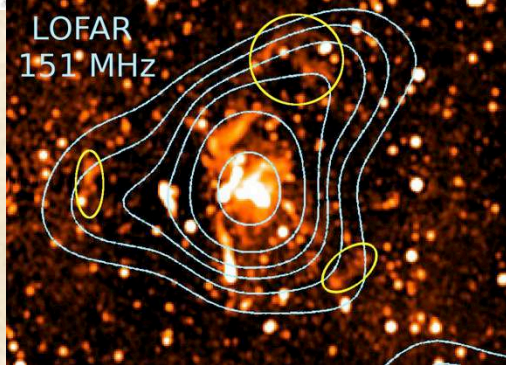
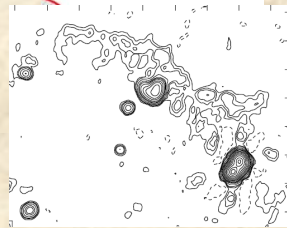
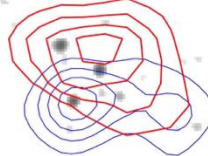
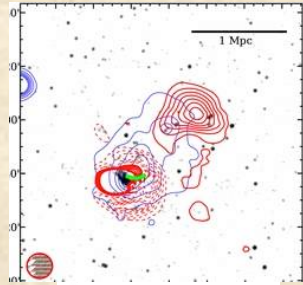
Challenges: Field origins/amplification  
CRe origins/amplification



Cluster Relic Radio Sources VLA 1.4 GHz



Slee, Roy, Murgia, Andernach & Ehle 2001



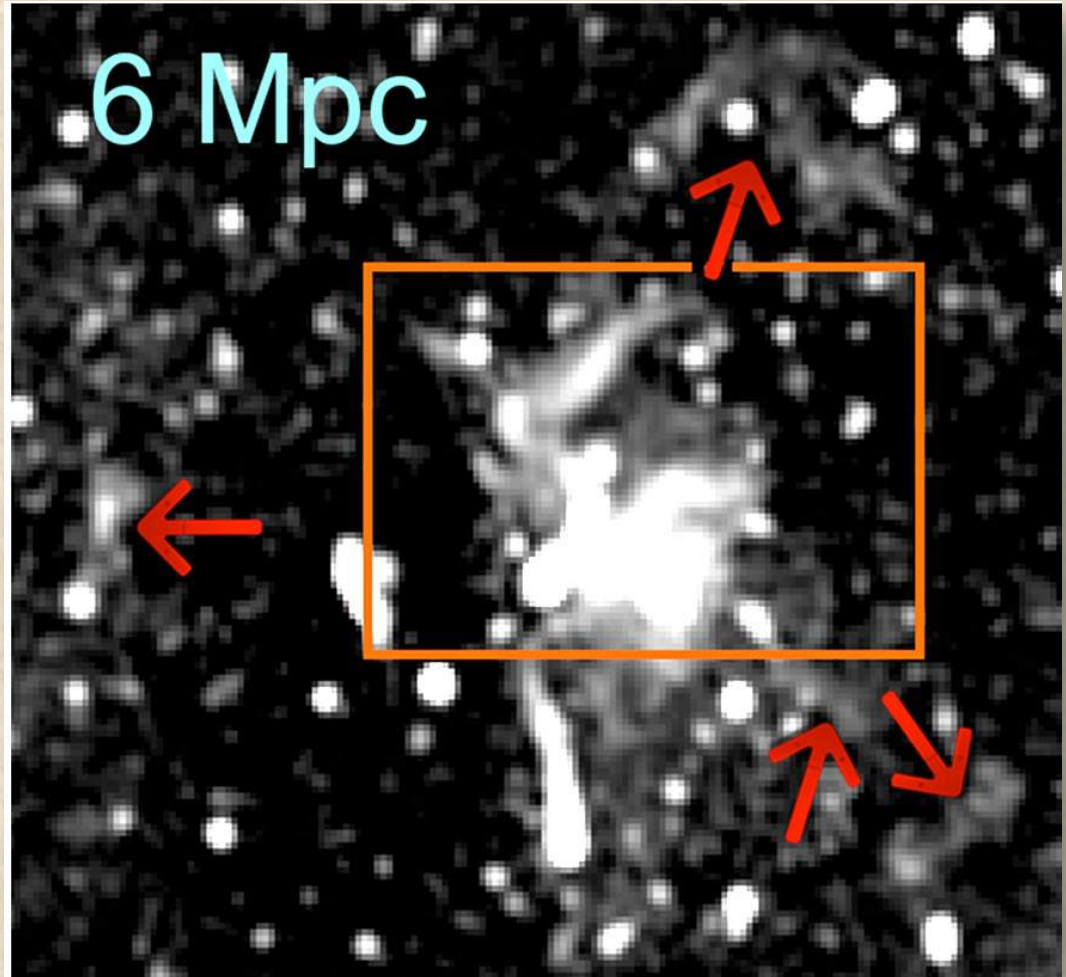
A not quite random collection of radio relics (LR 6/15)



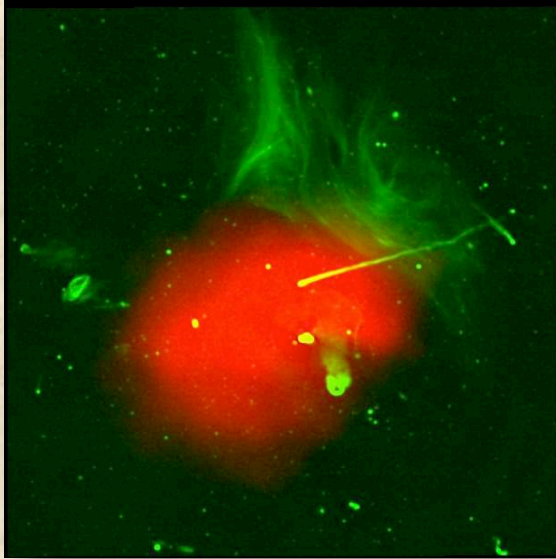
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“Peripheral relics”

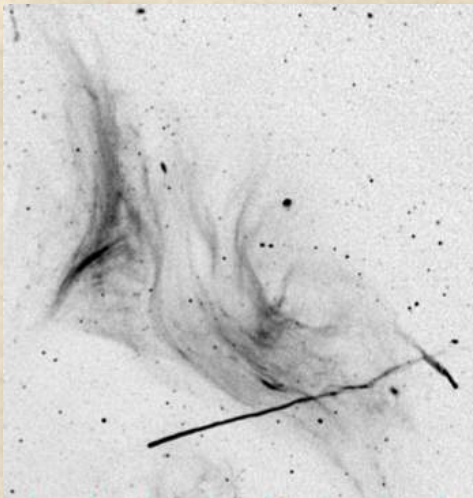
Abell 2255  
R. Pizzo, G. de Bruyn 2011



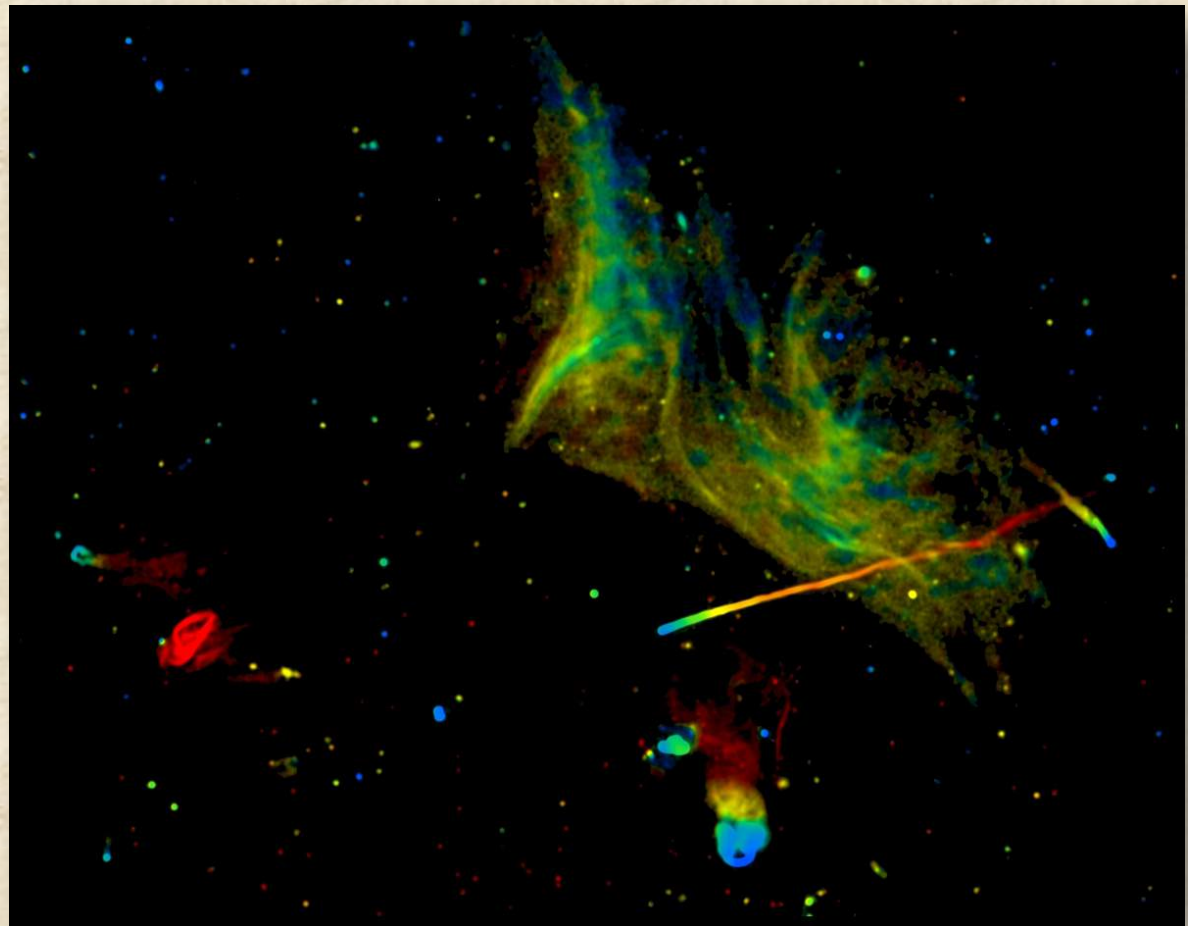
# Abell 2256: Magnetic ropes?



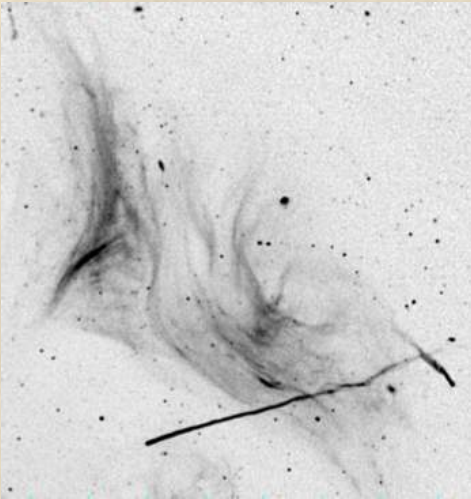
X-ray (ROSAT) + VLA



VLA Observations: Abell 2256  
(Owen, Rudnick, Eilek et al. 2014)



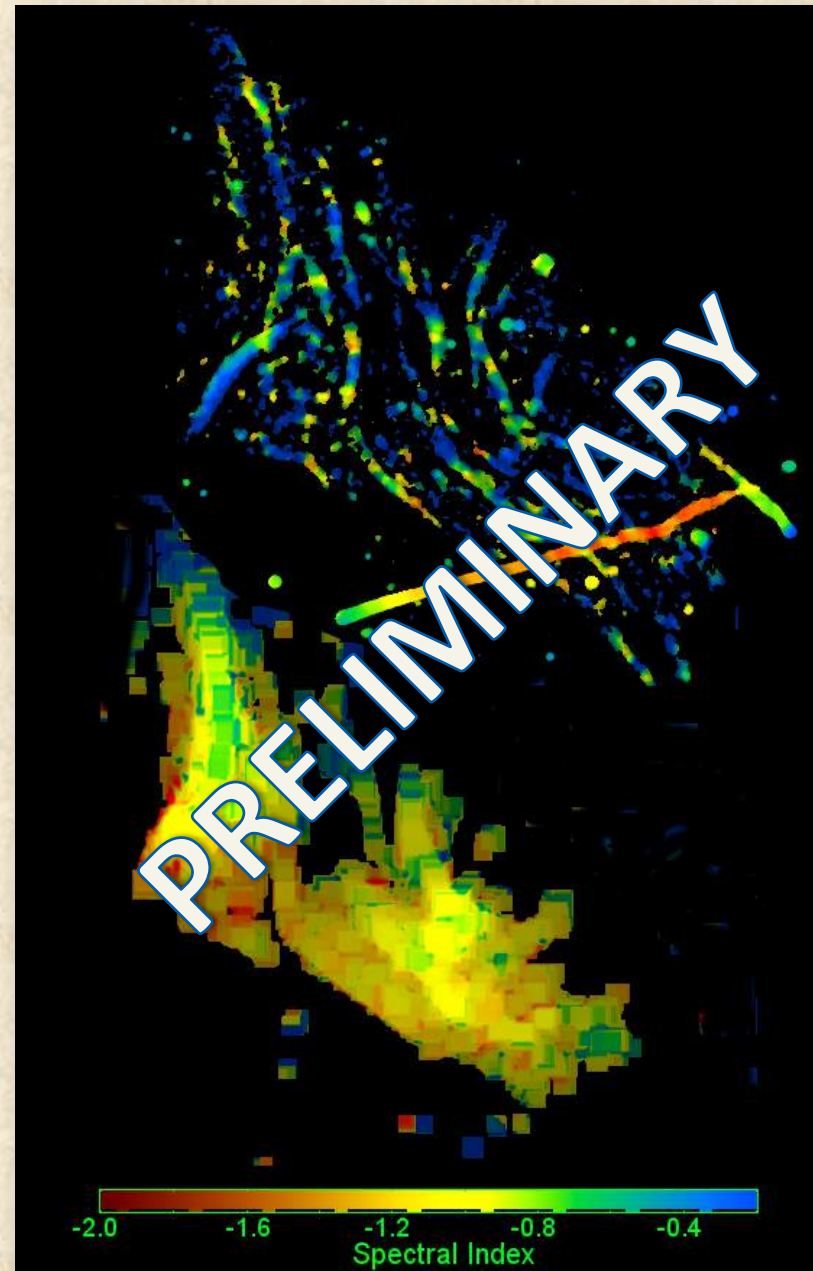
# Abell 2256: Magnetic ropes?



- *Localized CRe acceleration?*

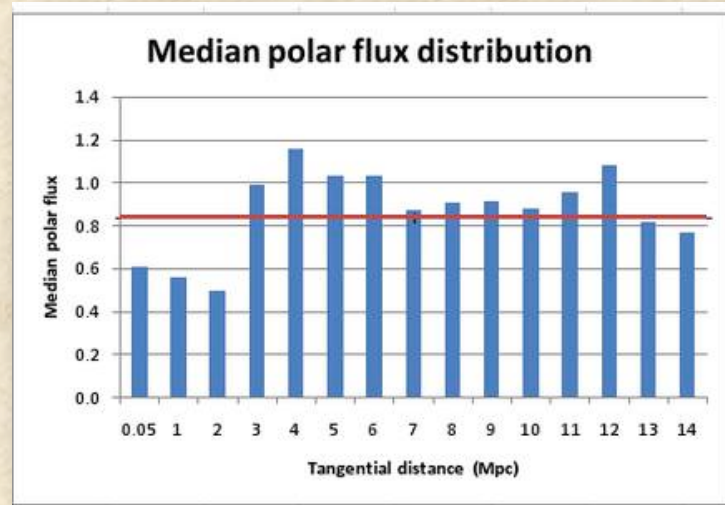
$\langle \alpha \text{ (filaments)} \rangle = \text{flat}$

$\langle \alpha \text{ (diffuse)} \rangle = \text{steep}$



# Cluster Fields: (*Thermal electrons*)

- Radio galaxies **in clusters** have lower polarizations



Avery Garon, UMN

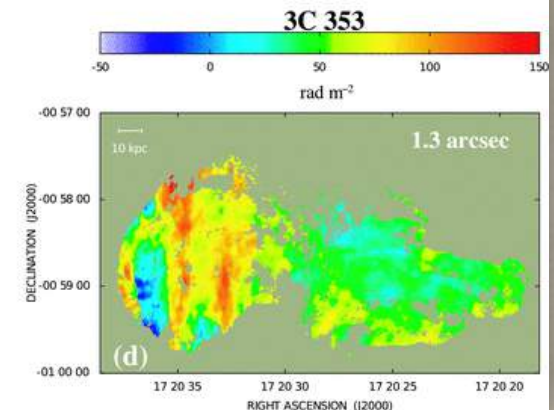
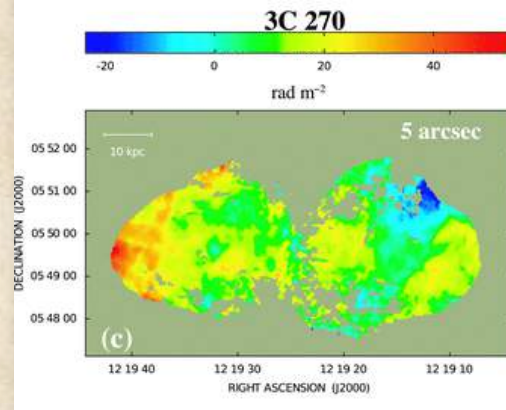
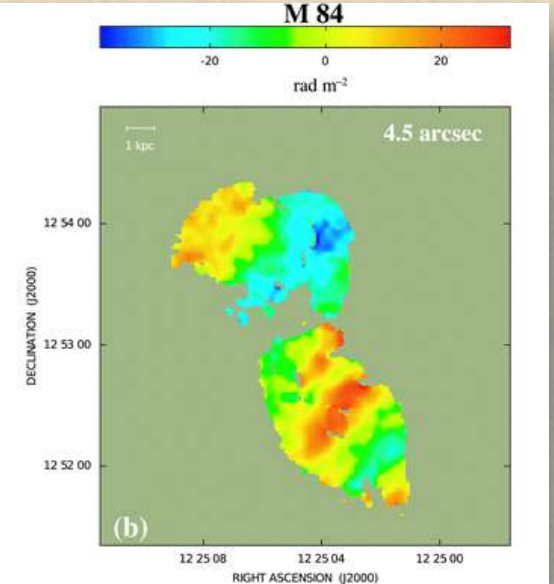
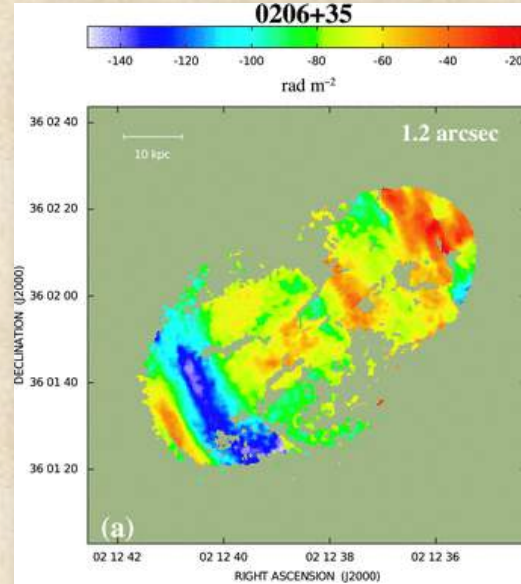
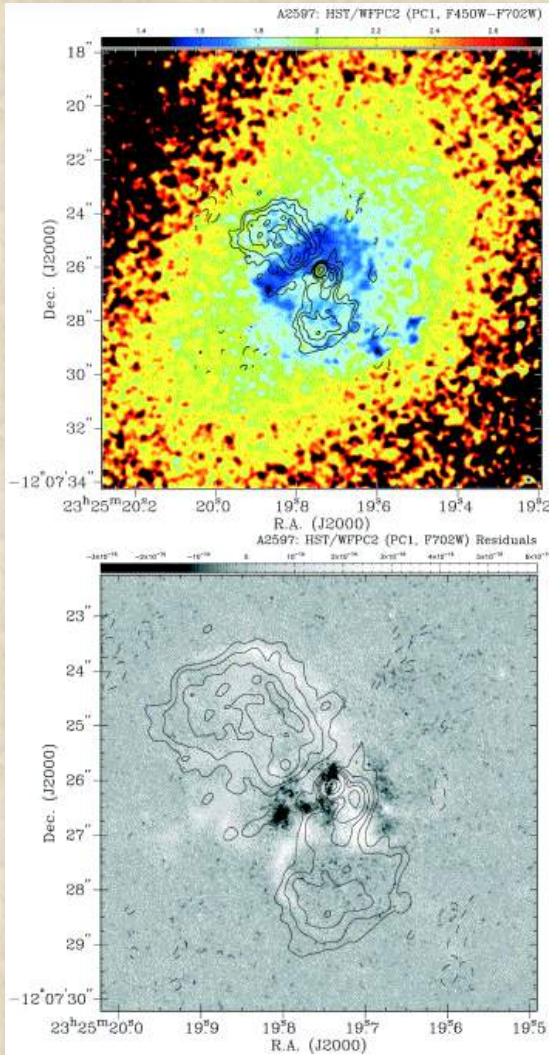
If **DEPOLARIZATION** from small scale variations in Faraday rotation

$$\Delta\chi = \frac{e^3 \lambda^2}{2\pi (mc^2)^2} \int_{LOS} n_e(z) B_{\parallel}(z) dz$$

then use these variations to measure magnetic field strength and structure

$$\Delta\chi = \mathbf{RM} * \lambda^2$$

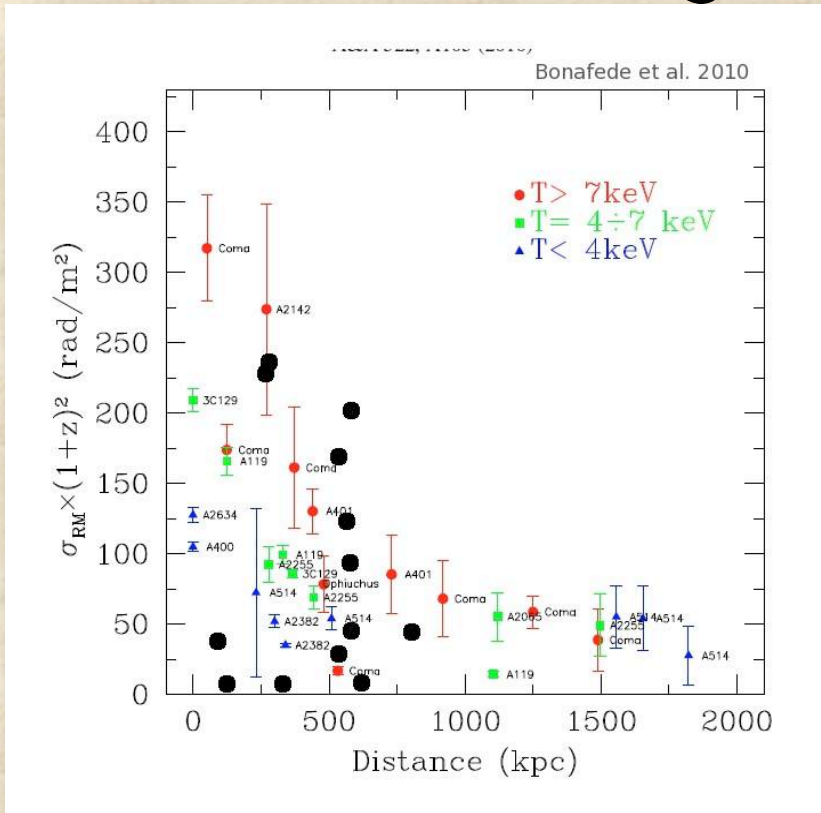
# Local effects or cluster-wide?



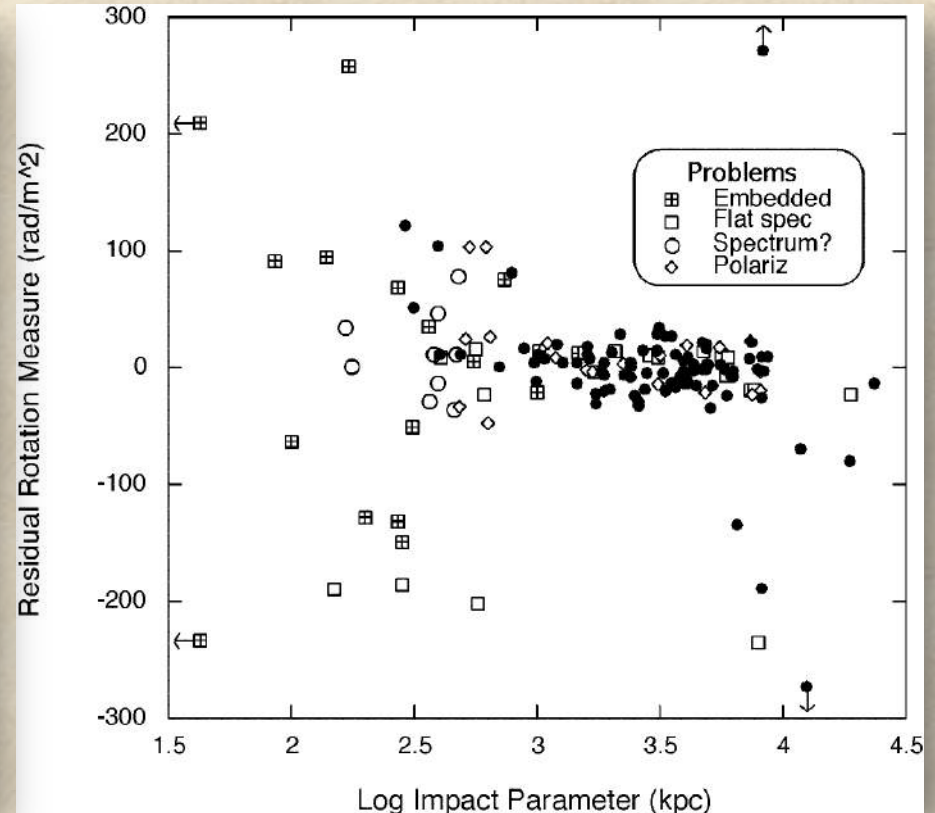


# GOLD STANDARD: Polarized Background Sources

2015: there are NO reliable cluster background studies



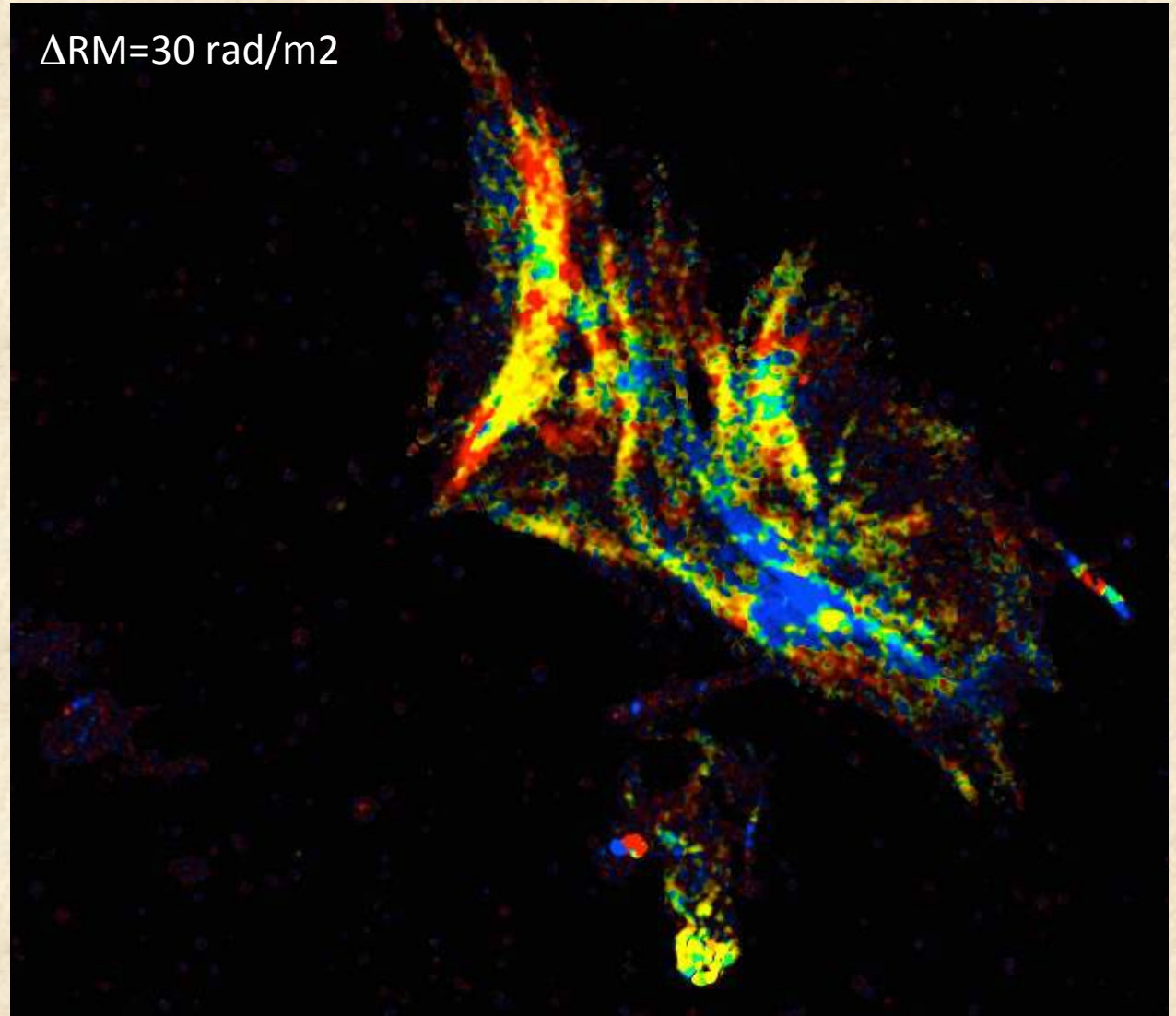
Bonafede+10 (plus 2256 data)



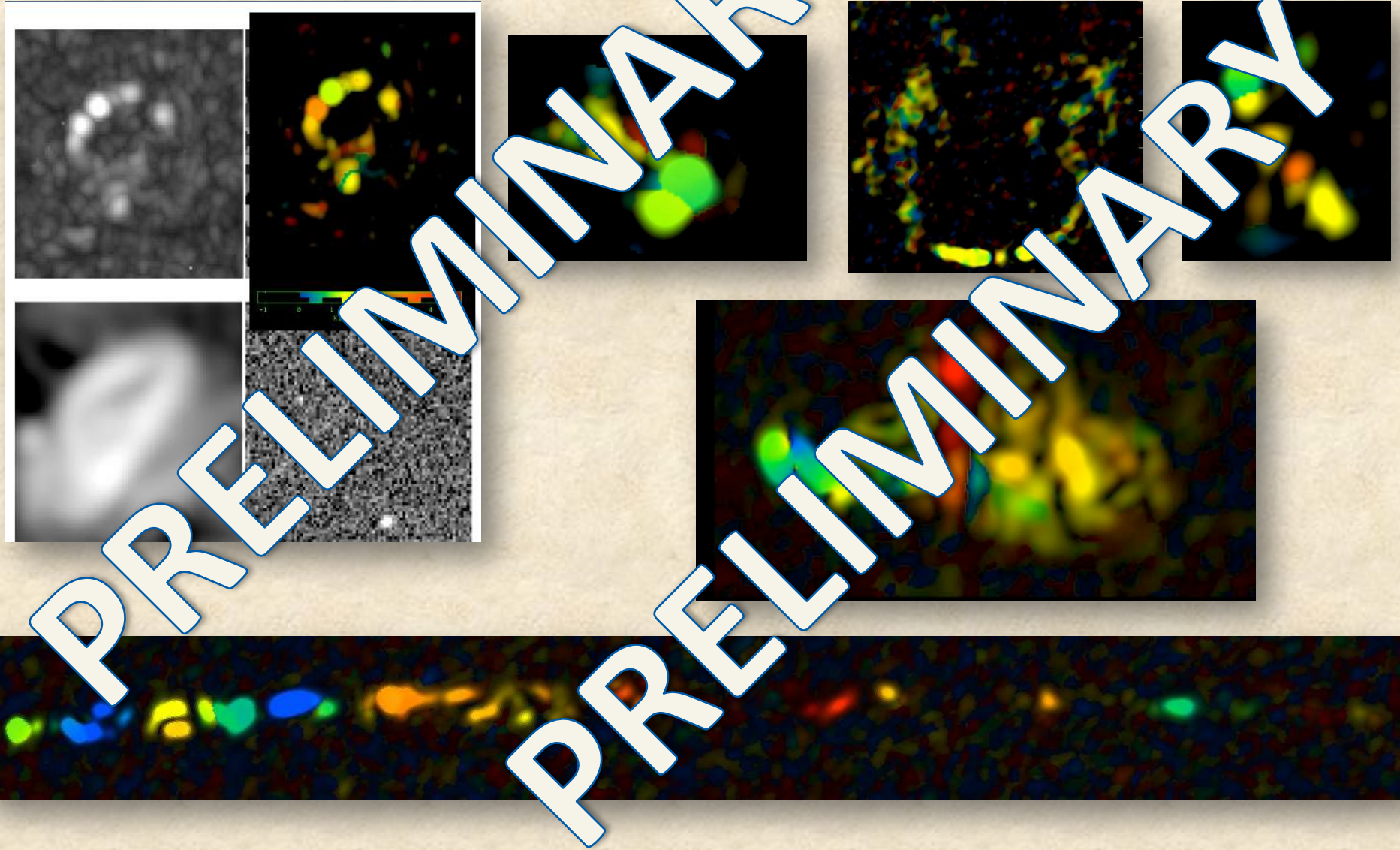
Rudnick & Blundell '04, from Clarke+01

# RM variations in Abell 2256

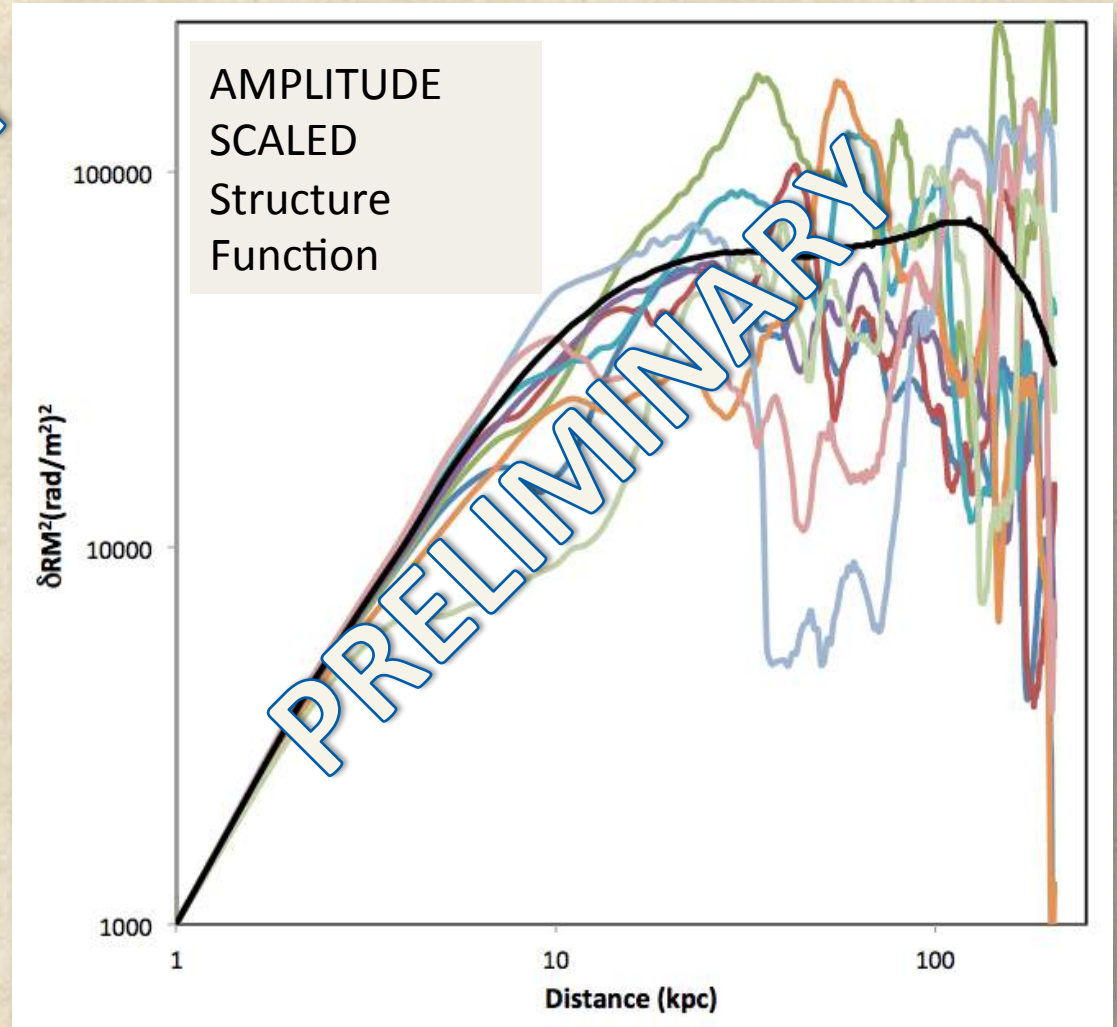
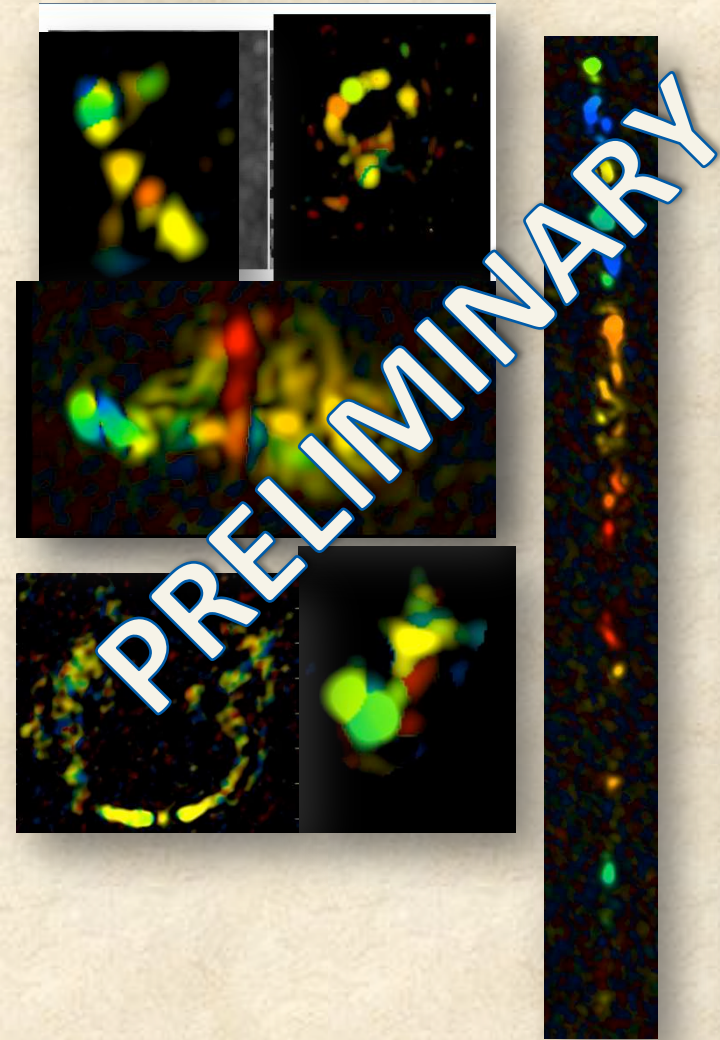
→ results: ***no characteristic  $\Delta RM$***



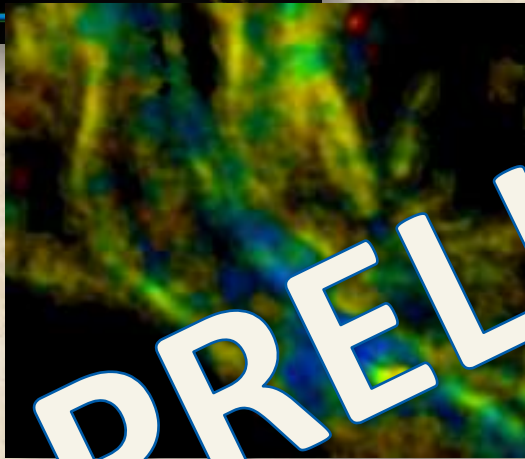
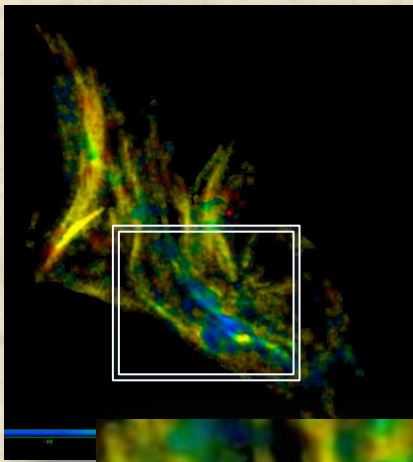
# RM variations



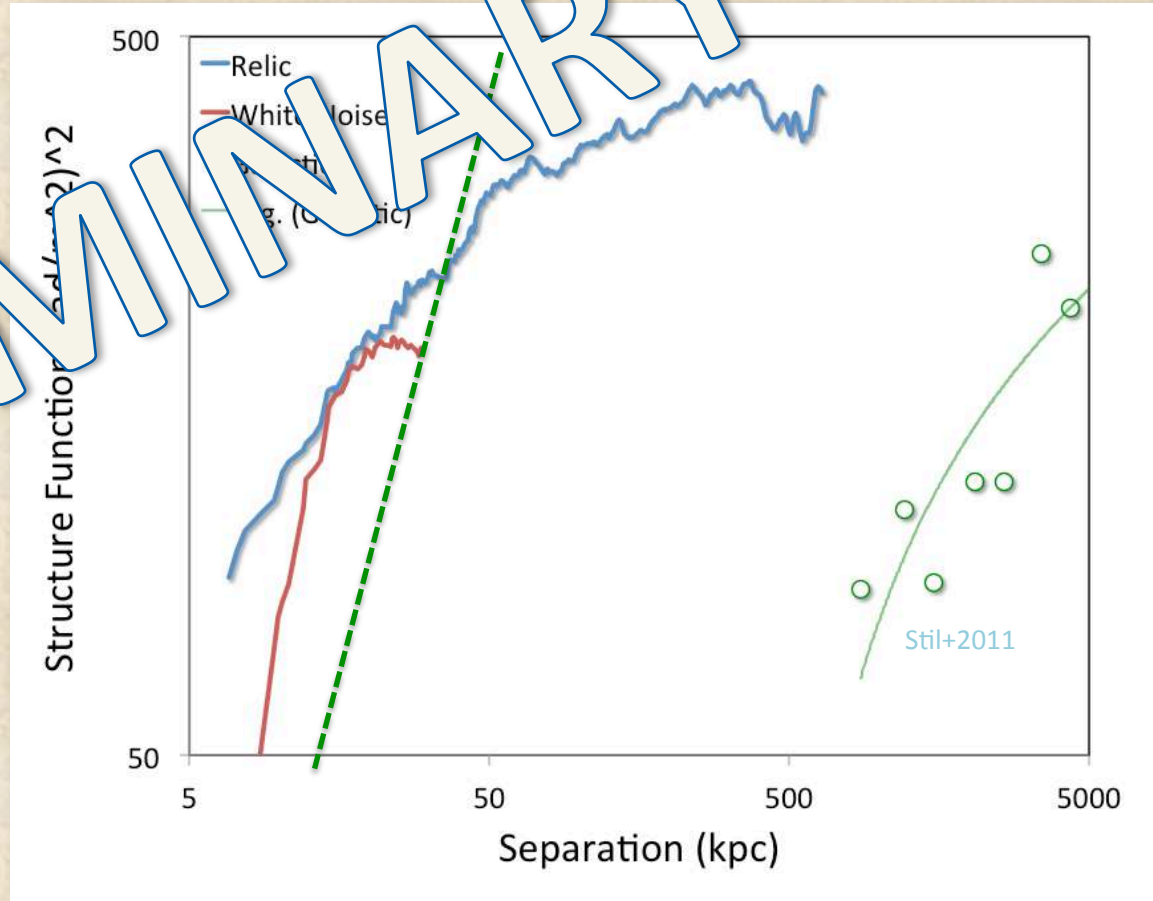
# Structure Functions



# RELIC: 10- 500 kpc magnetic patches



PRELIMINARY



**Coherent field ~ 500 kpc**

- not Galactic
- not 10kpc as in cluster core
- **evidence for large scale ordering of ICM, at least local to relic?**

# Coming attractions

*other exciting new surveys*

## LOFAR



## ASKAP/APERTIF



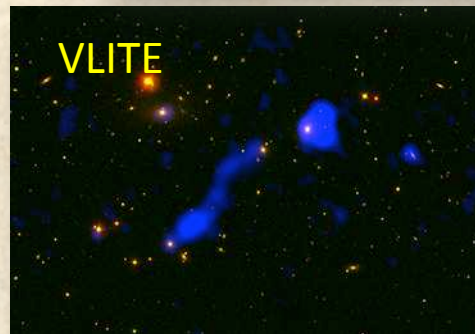
## MWA



## VLASS



## VLITE



## MEERKAT





# Take home messages

- Network of likely ICM weak shocks now becoming visible → *can we invert to diagnose ICM?*
- $\mu\text{G}$  fields found  $> \text{Mpc}$  from centers, wide variety of structures  
→ *what are the field and particle origins?*
- Faraday rotation & filaments in A2256, very large scale fields (0.5 Mpc) in ICM  
→ *will RMS give us turbulent ICM scales?*