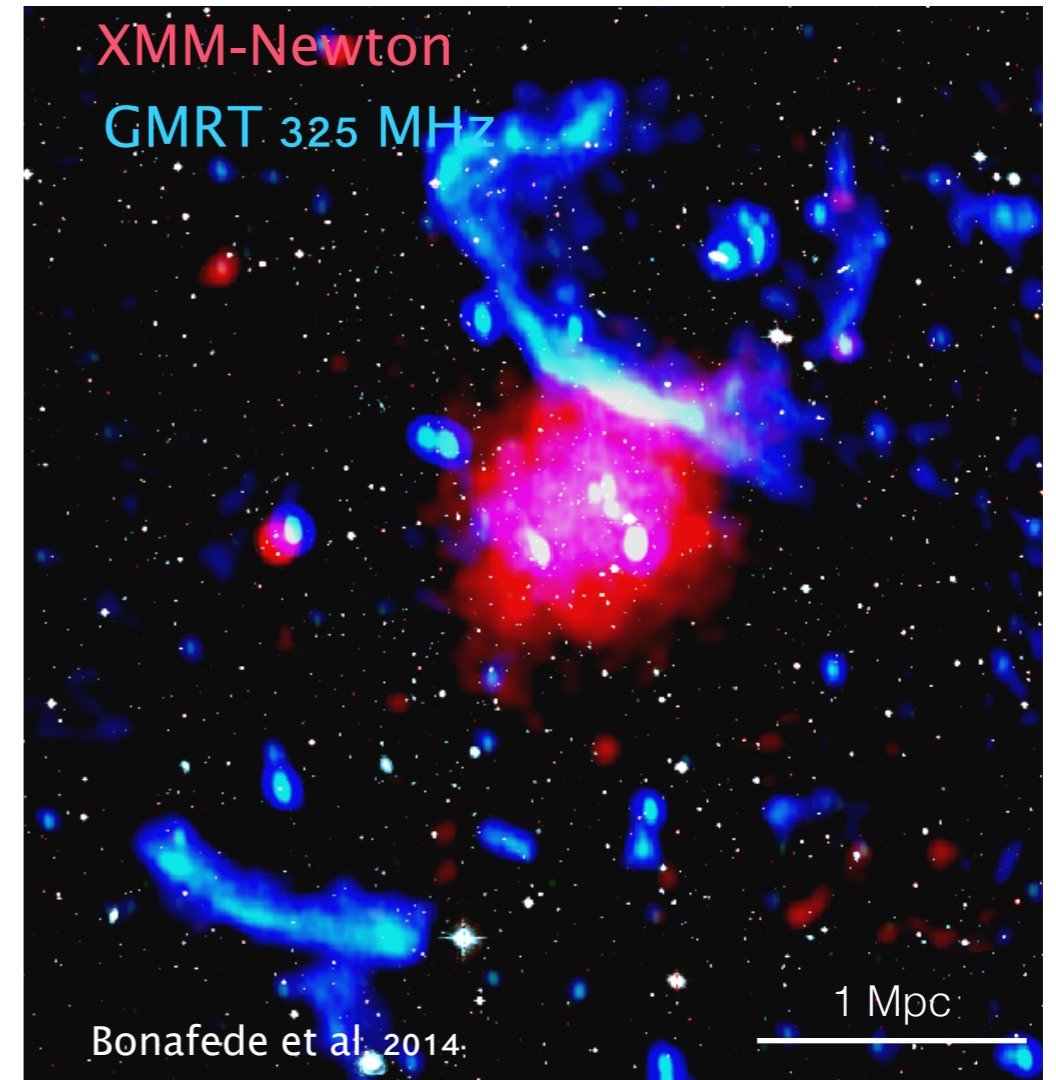
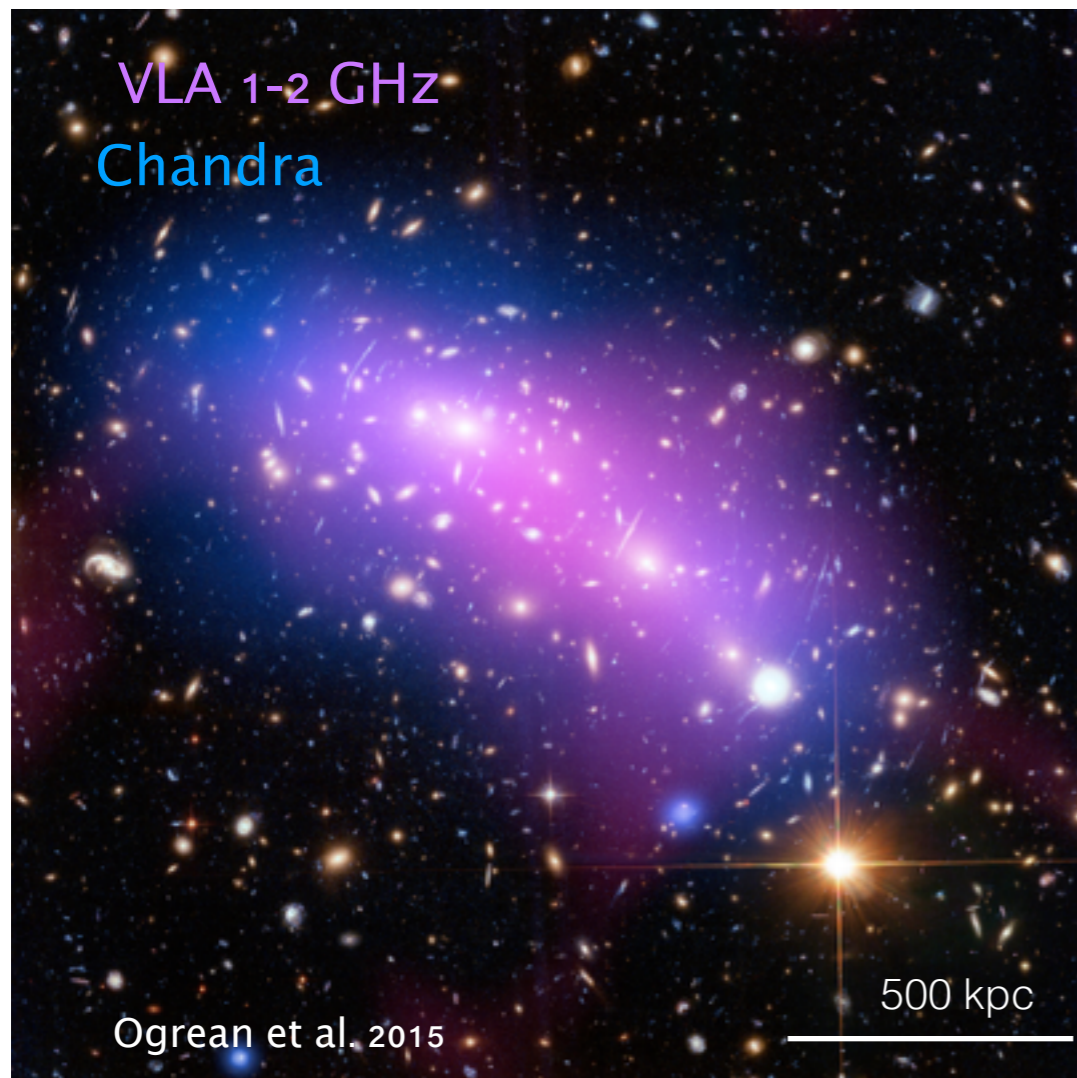


Non-thermal phenomena in the ICM: insights from radio observations

Annalisa Bonafede
Hamburg University

M. Bruggen, R. van Weeren, G. Ogrean, F. de Gasperin, F. Vazza, R. Cassano

Radio emission from the ICM



Synchrotron emission on Mpc scale
-> Ultra relativistic electrons + magnetic fields
only in a fraction of clusters

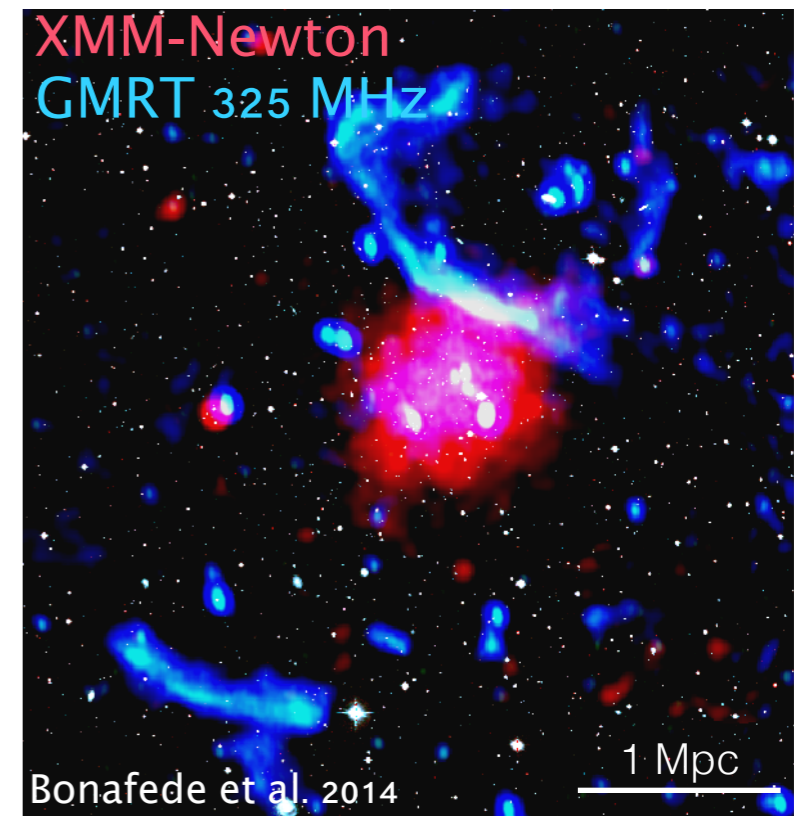
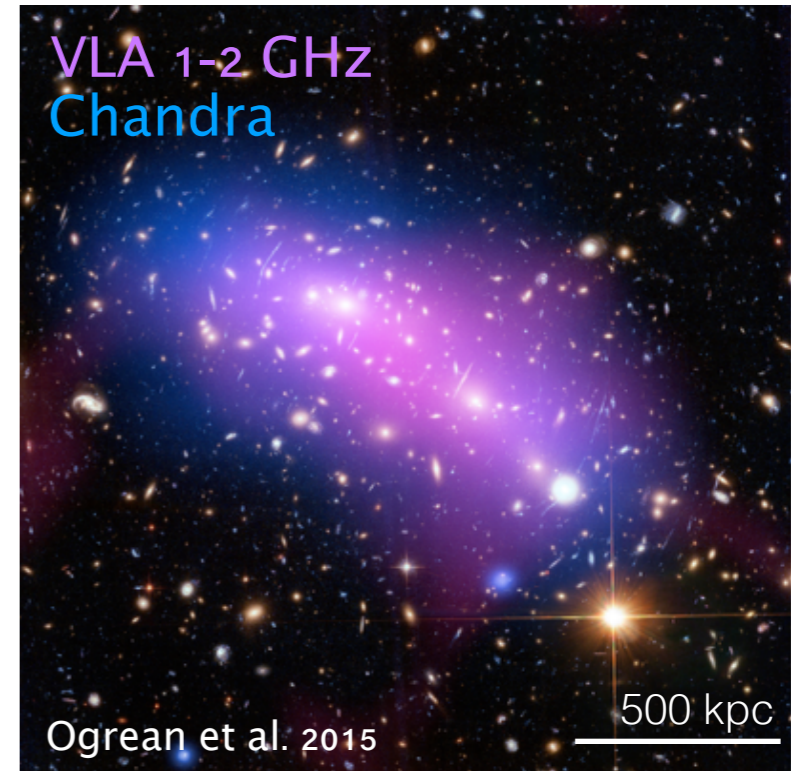
Radio emission & mergers

Cluster-cluster merger

$$E \sim 10^{64} \text{ erg}$$



Credits: Markevitch, Clowe



Radio emission & mergers

Cluster-cluster merger

$E \sim 10^{64}$ erg



Credits: Markevitch, Clowe

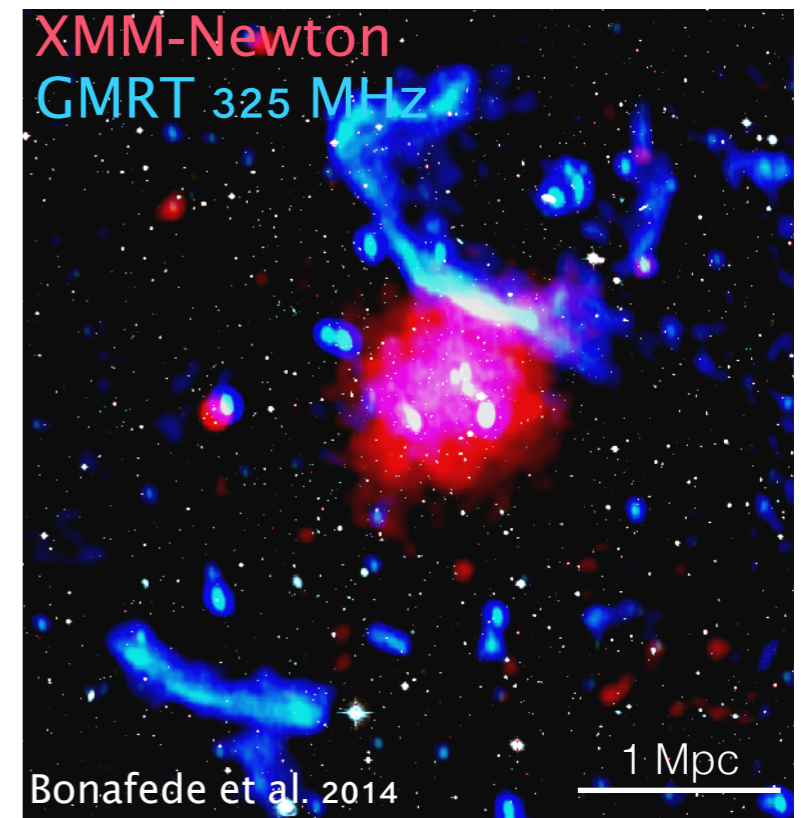
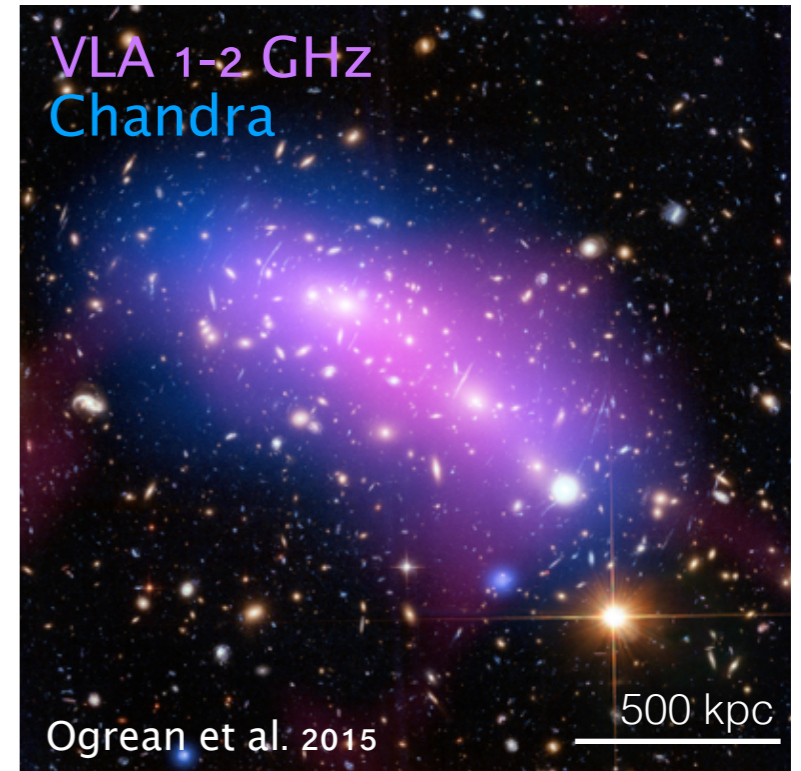
Turbulence
(e.g. Brunetti et al 2001)

Halos



Shocks
(e.g. Ensslin et al. 1998)

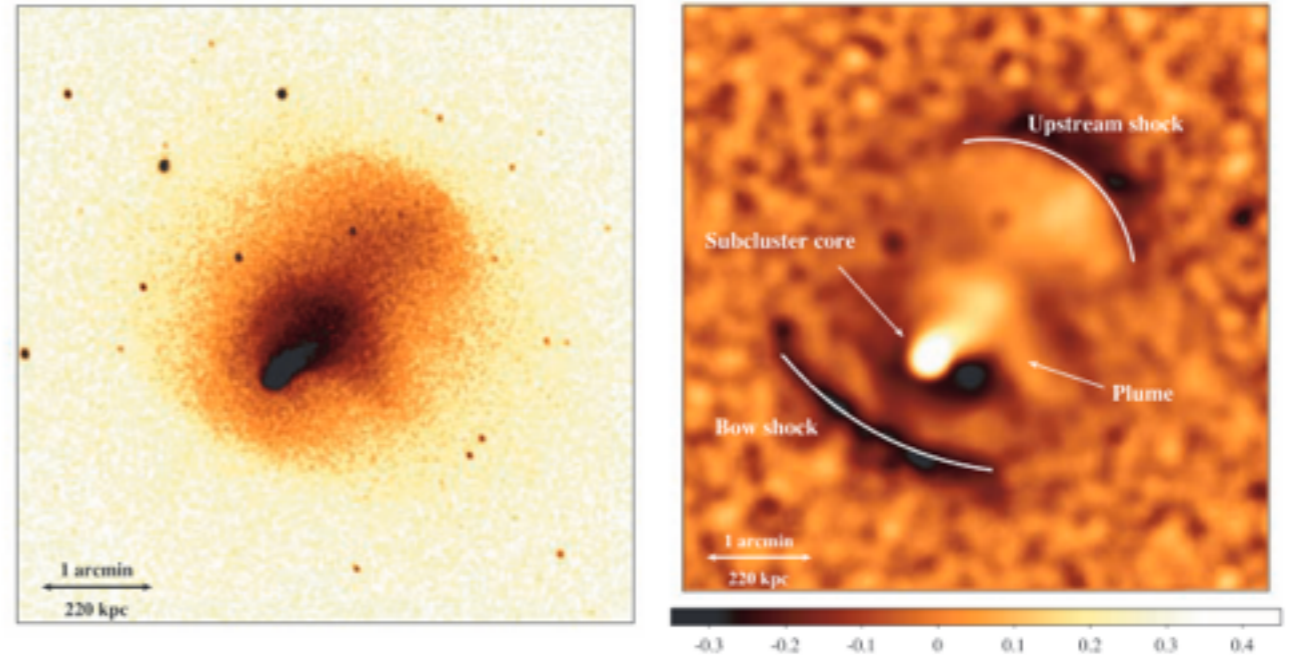
Relics



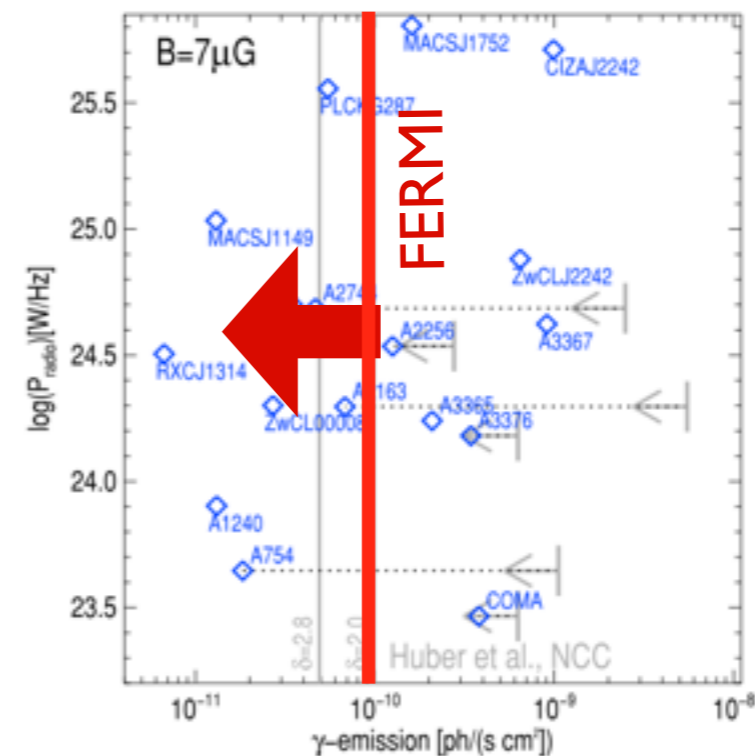
Radio relics & shocks

- “Injection problem” - low Mach number 2-5
 - > re-acceleration of energetic electrons (e.g. Kang & Ryu 2011)

- Shock waves
but no relic associated
(Russell et al. 2011)



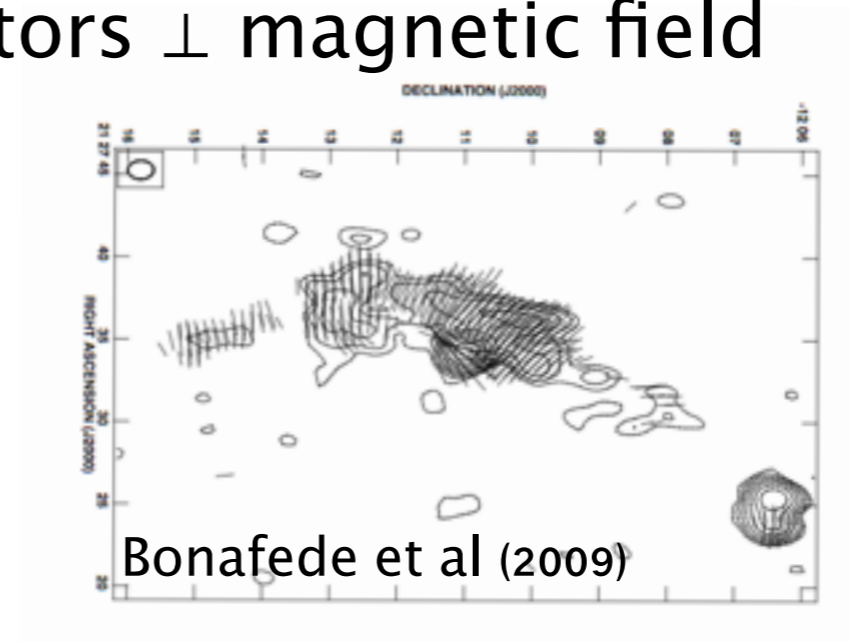
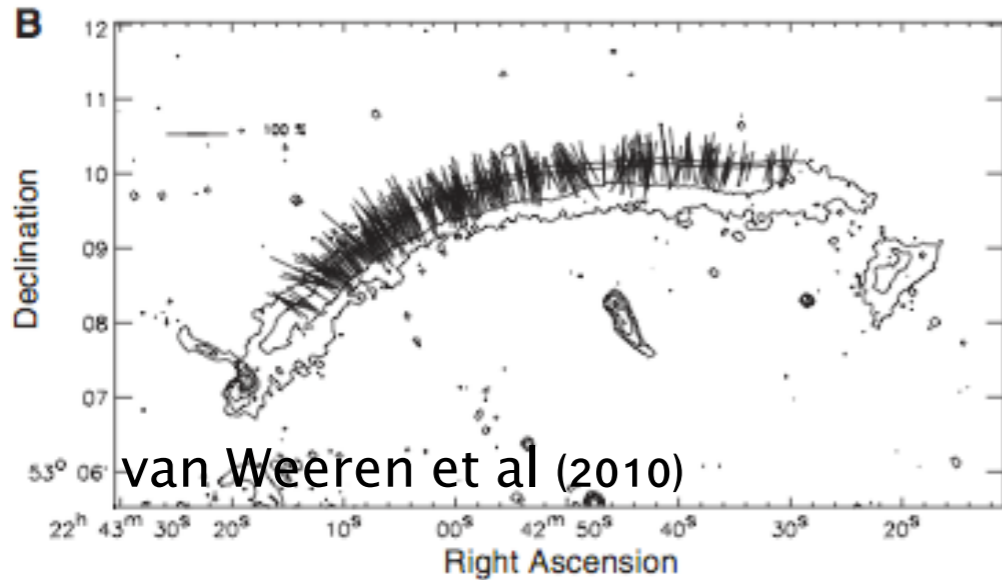
- No Gamma-ray emission
(Vazza & Brüggen 2013)



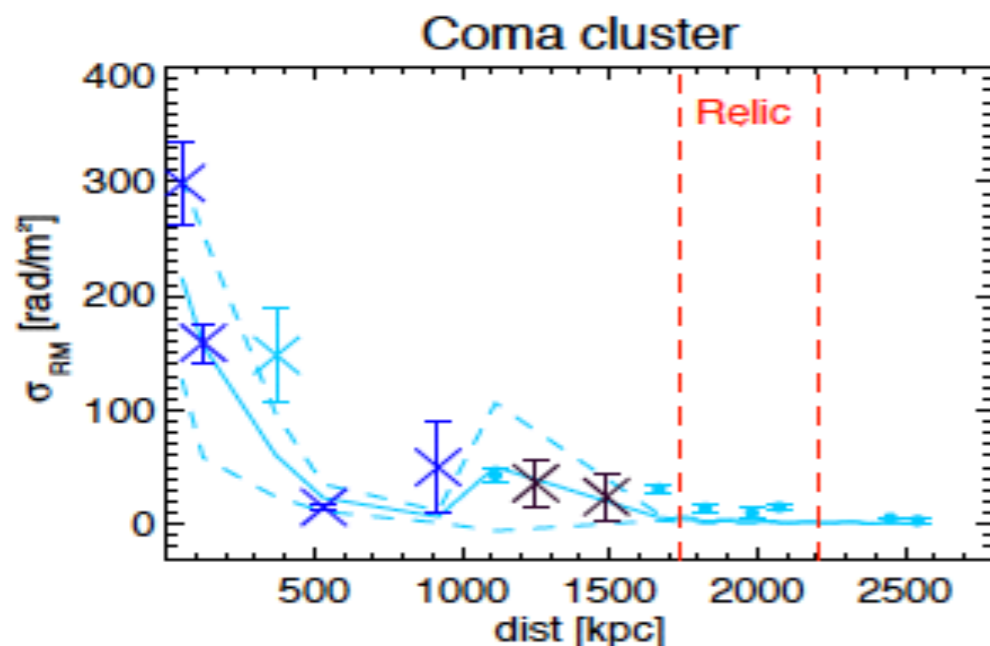
Radio relics & shocks

What we can learn from radio: 1) Magnetic field

Polarisation: E vectors \perp magnetic field



Rotation Measure analysis



Coma magnetic field profile (Bonafede et al 2010)

X RM of sources in Coma

X RM of sources in the relic quadrant

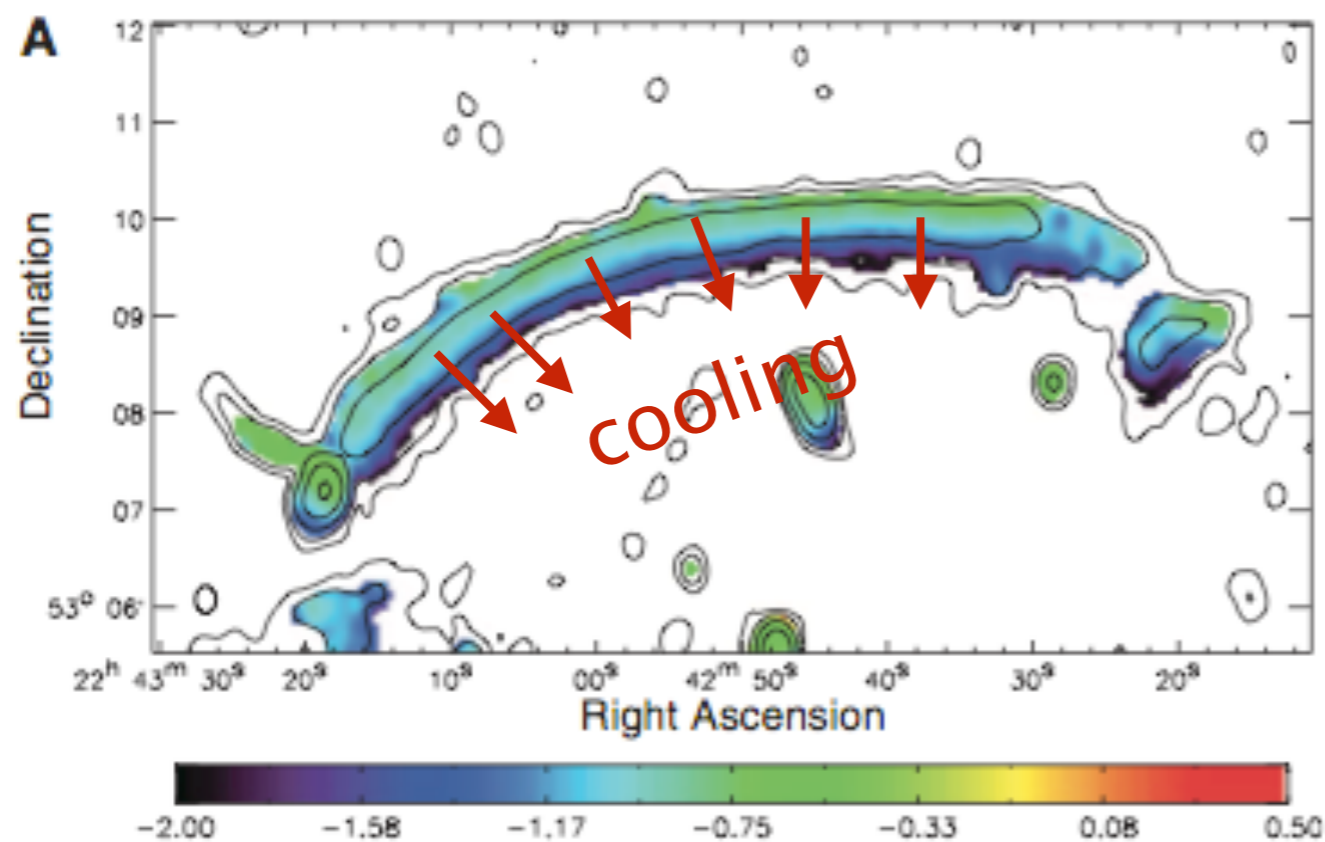
Magnetic field amplified by a factor ~ 3

Bonafede et al (2013)

Radio relics & shocks

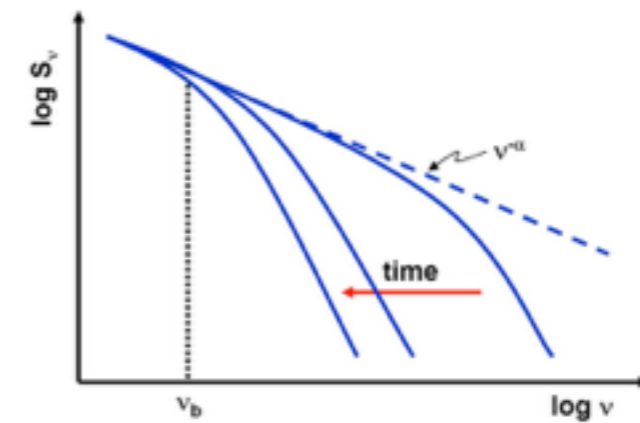
What we can learn from radio:

2) Mach number



Spectral index

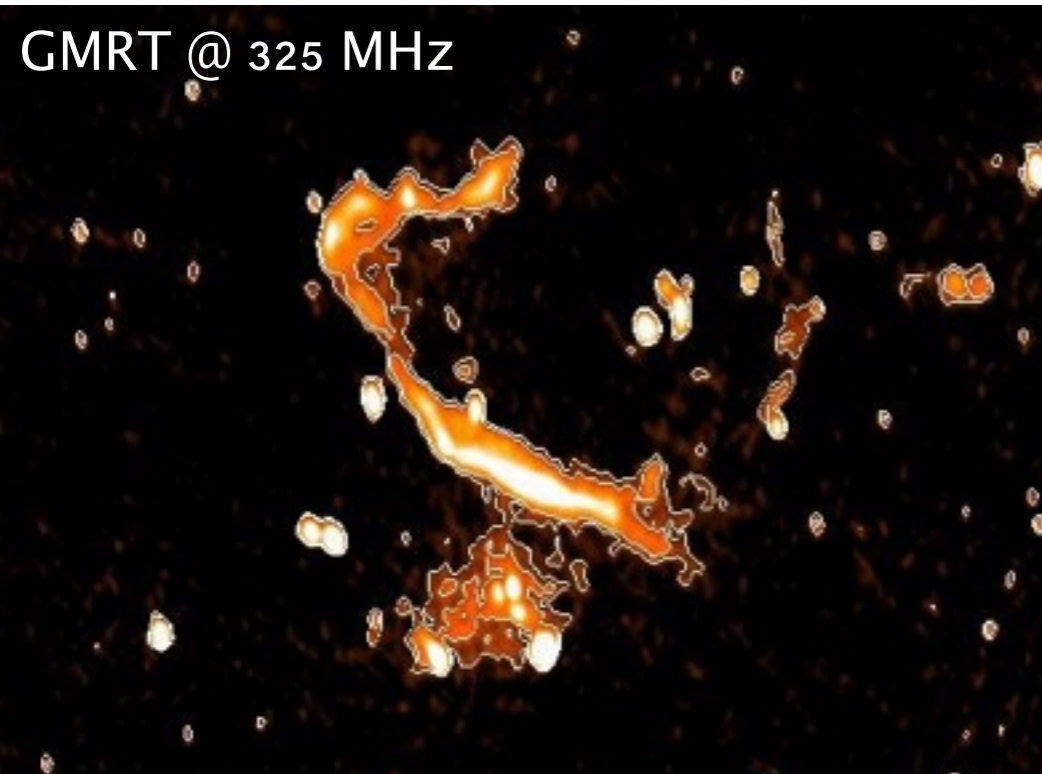
van Weeren et al (2010)



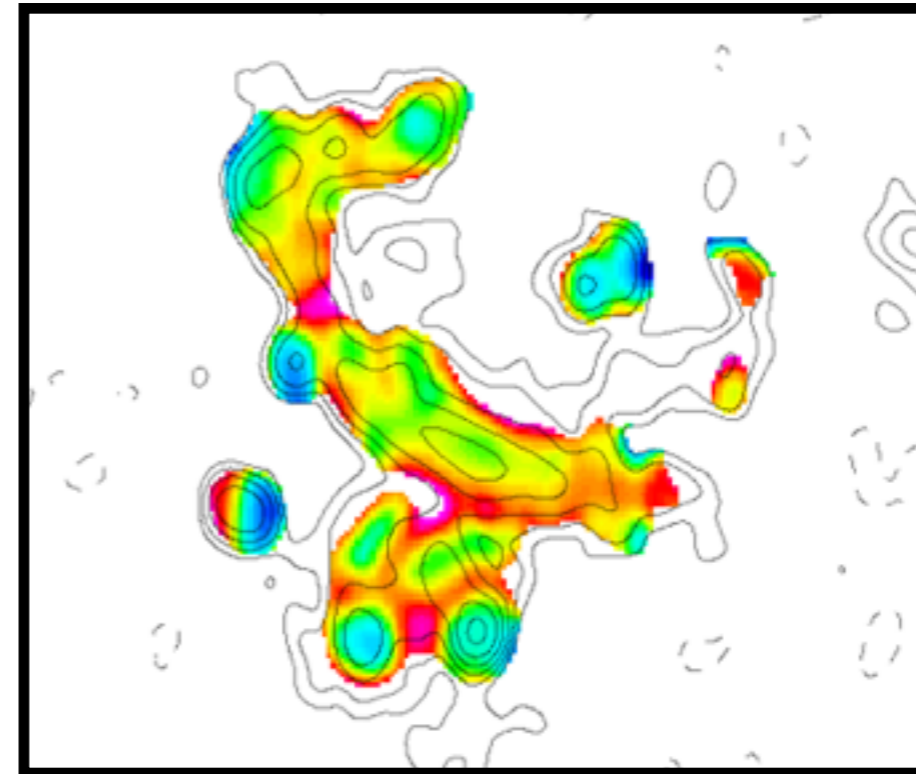
$$\alpha_{inj} = -\frac{1}{2} + \frac{M^2 + 1}{M^2 - 1}$$

First evidence of particle re-acceleration

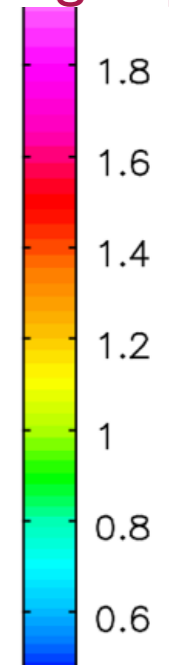
The cluster PLCK G287



Spectral index map



steep spectrum -
aged particles



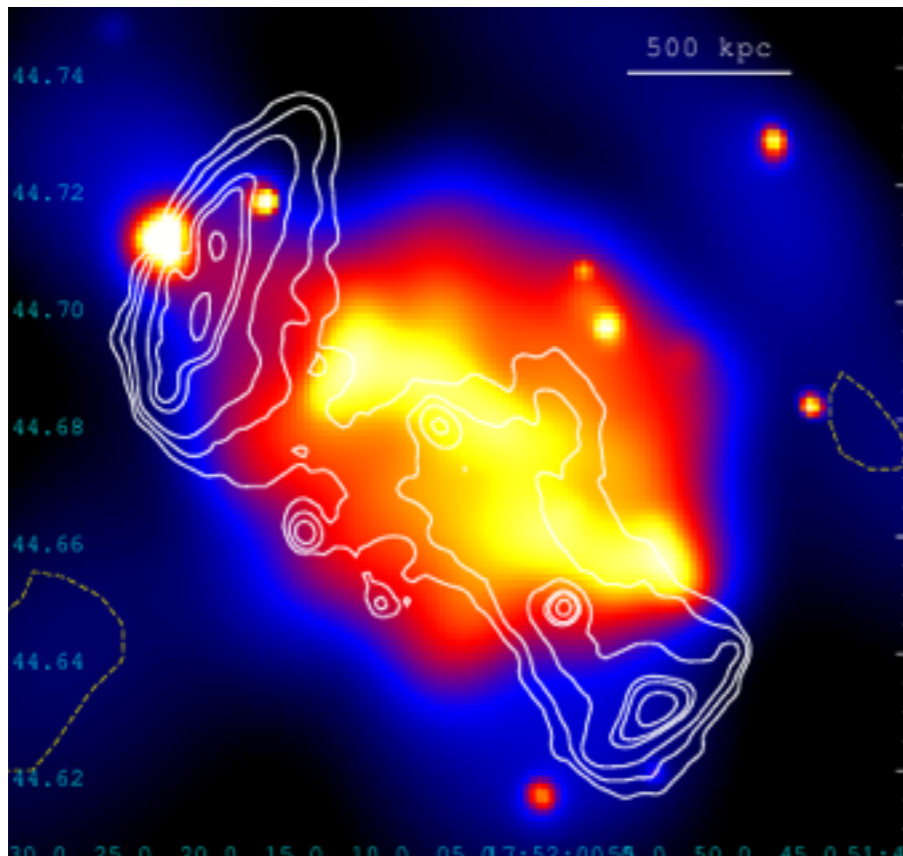
flat spectrum -
young particles

AGN injecting electrons in the ICM

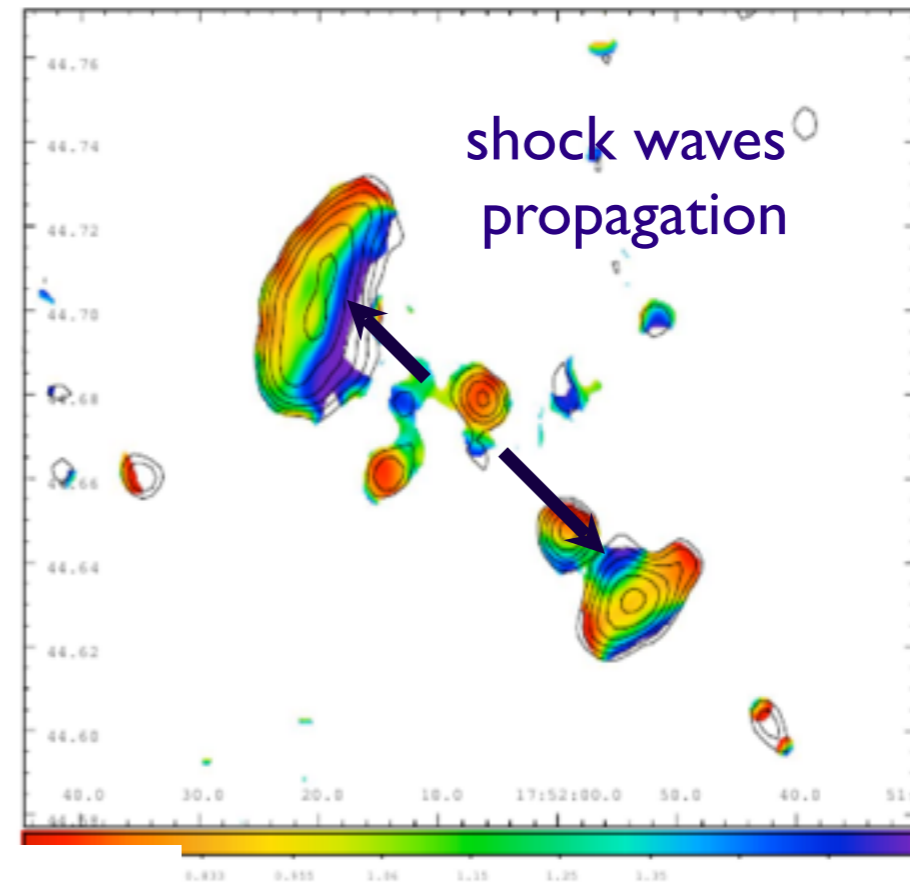
(Bonafede et al. 2014)

The cluster MACSJ1752.0+0000

Double radio relics and halo - Bonafede et al. (2012)



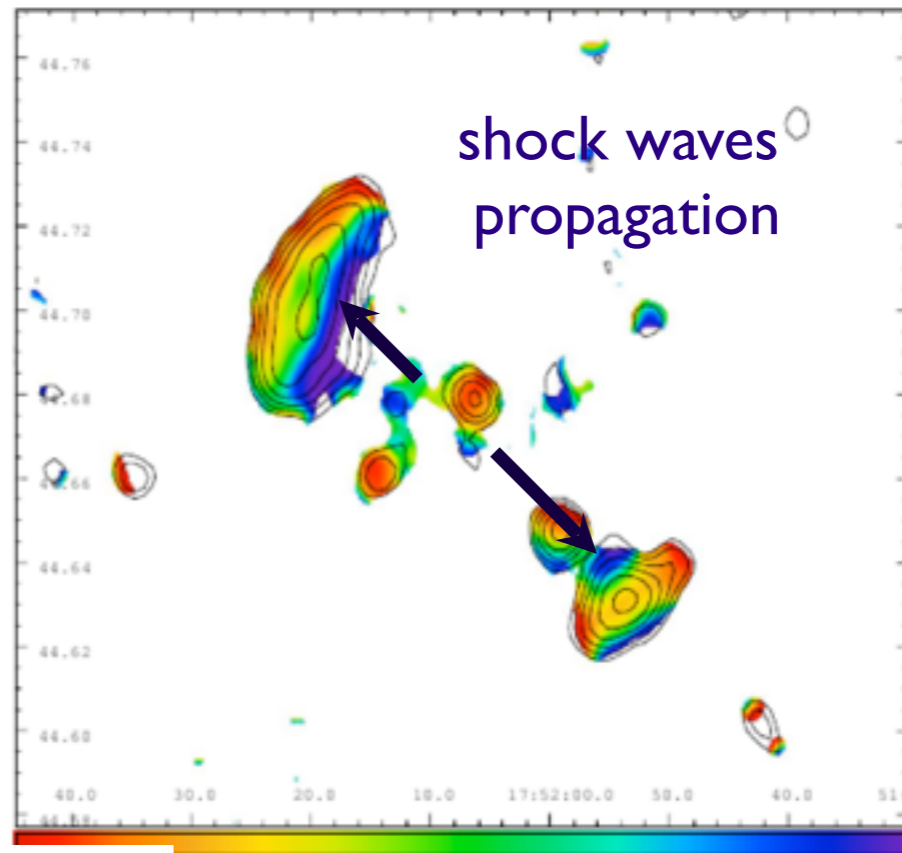
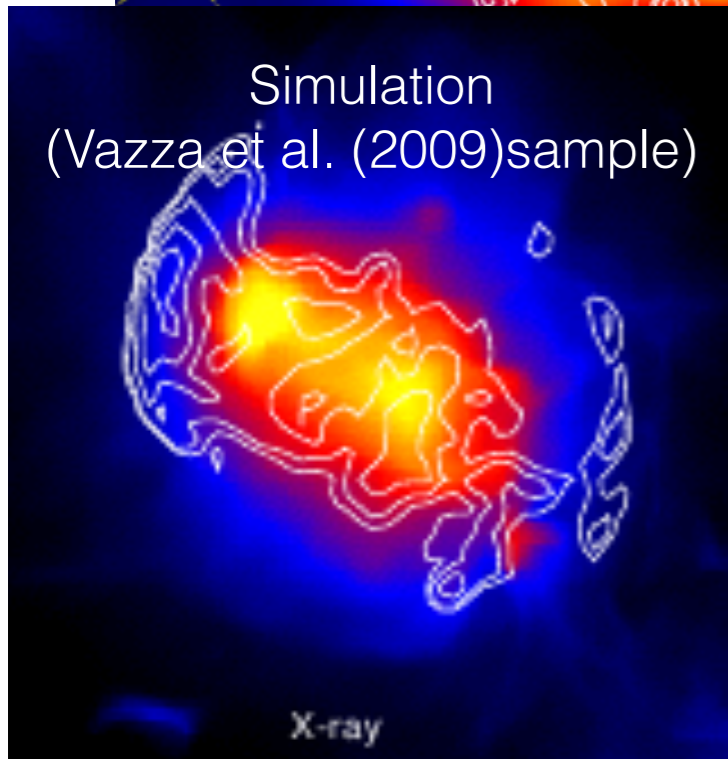
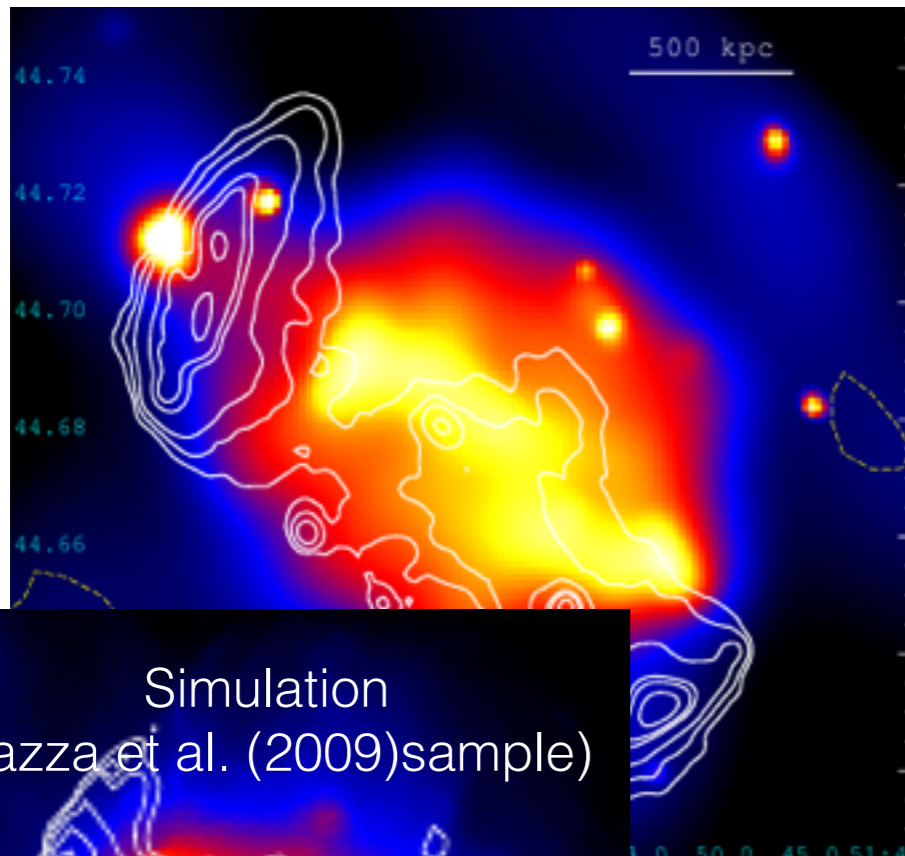
Flat spectrum
young particles



Steep spectrum
old particles

The cluster MACSJ1752.0+0000

Double radio relics and halo - Bonafede et al. (2012)



Flat spectrum
young particles

Steep spectrum
old particles

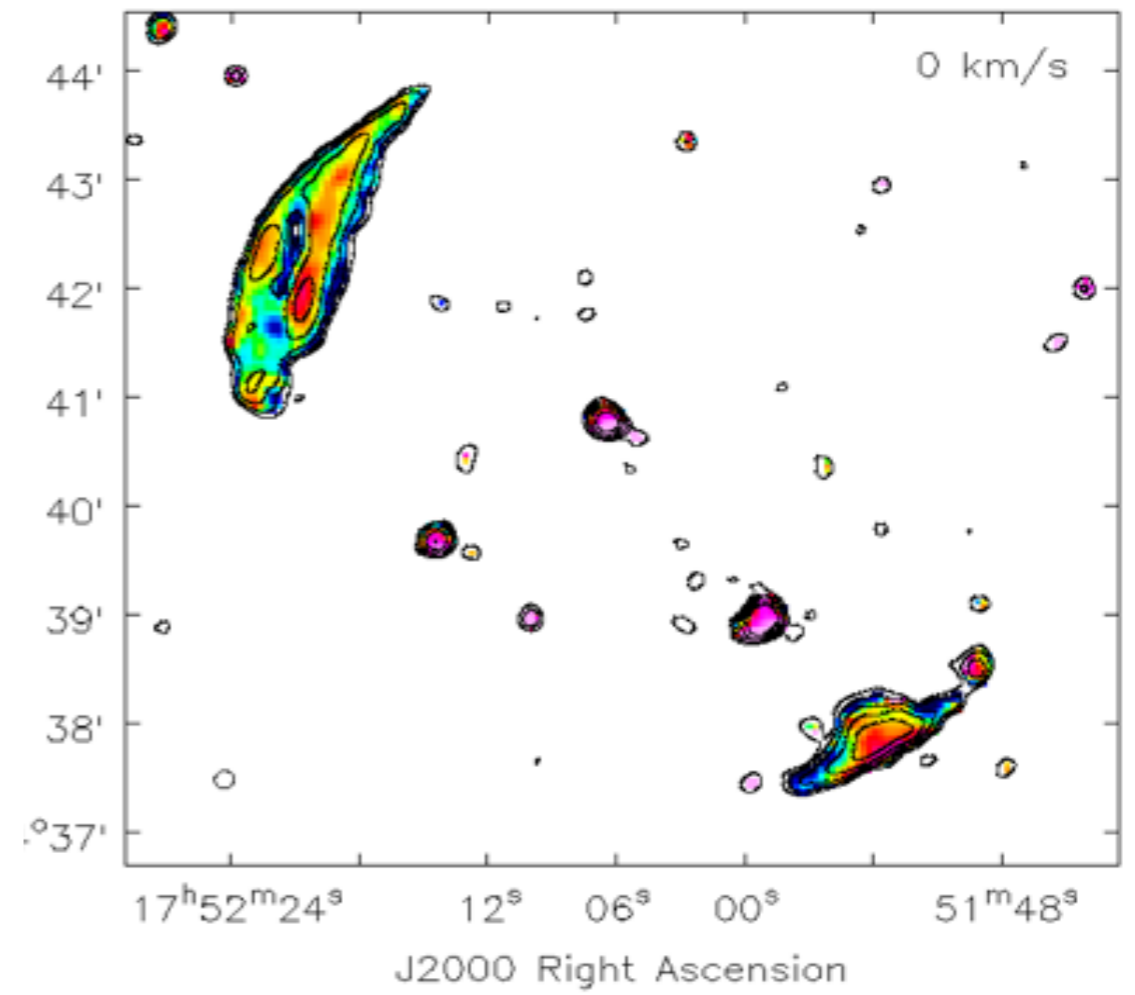
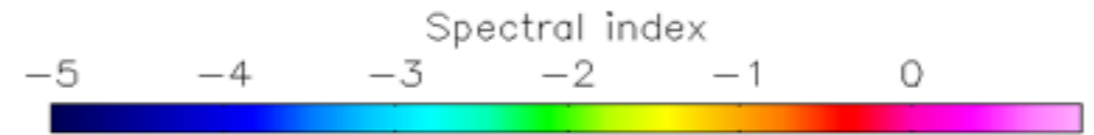
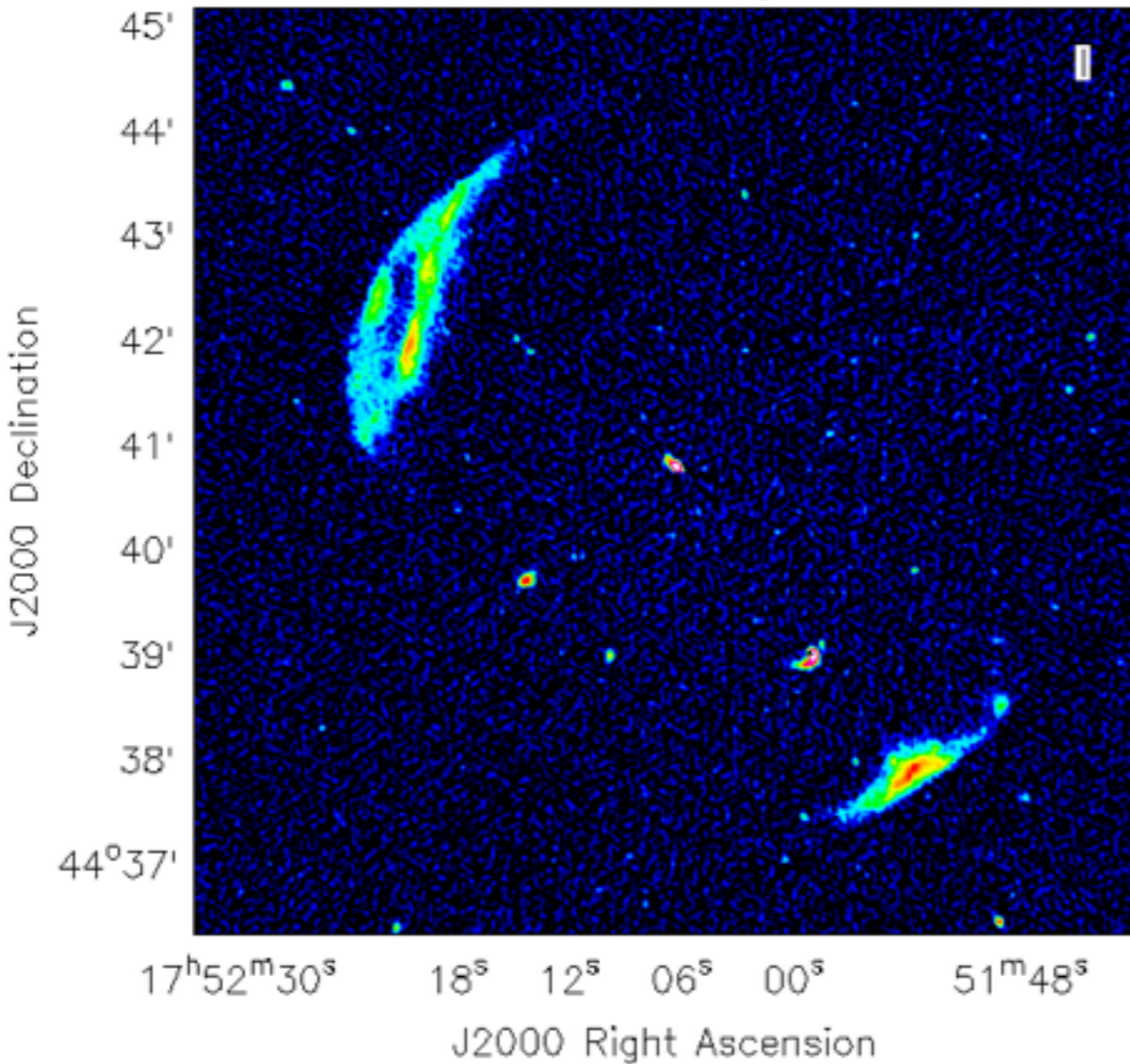
-> constraints of acceleration efficiency

$$P_{\text{radio}} = \epsilon \Phi_{\text{shock}} \quad \epsilon \sim 10^{-5} \text{ agreement with theoretical works}$$

More data, more troubles

MAcs J1752 : double radio relics and halo

J1752_B_C_R-1.5.image.tt0-raster



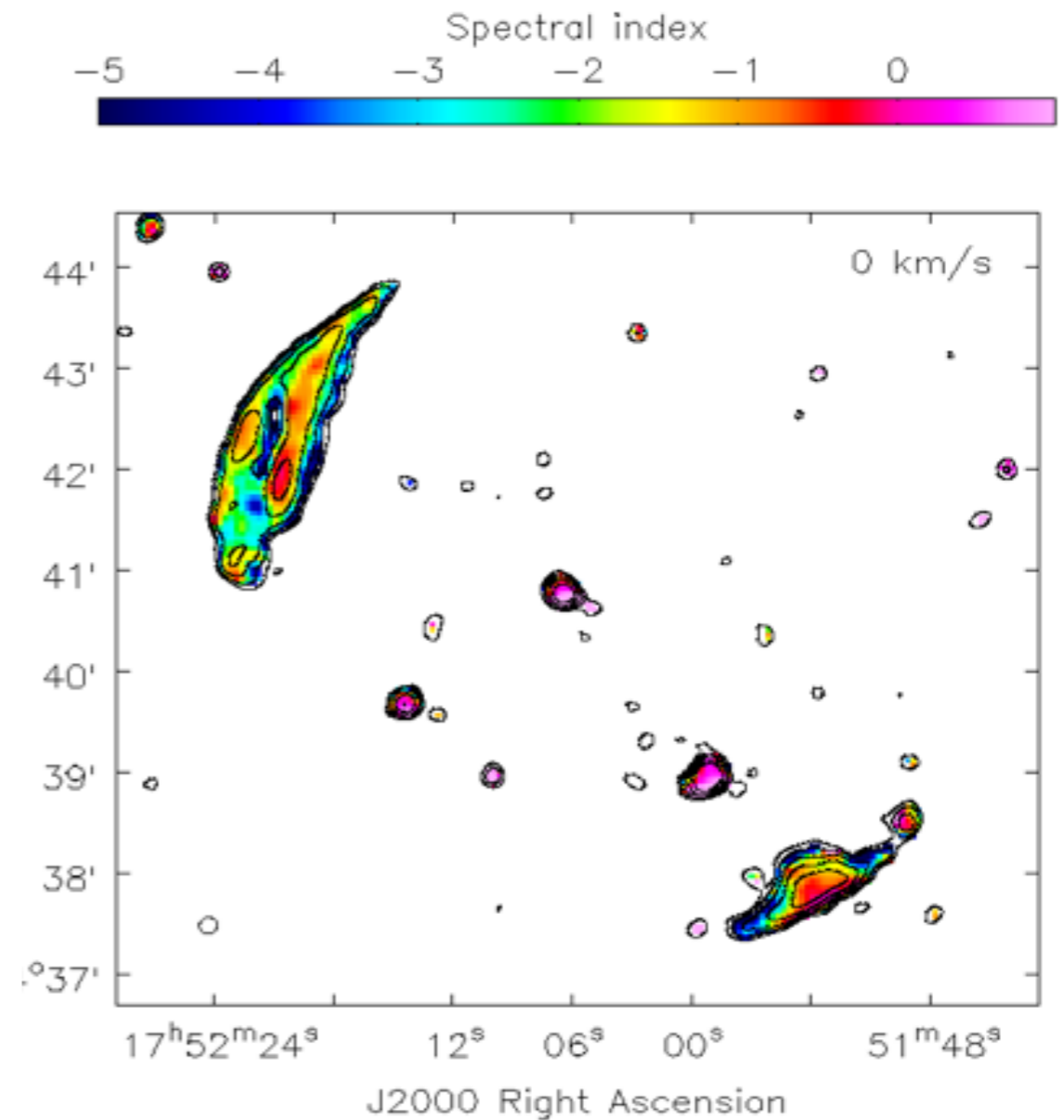
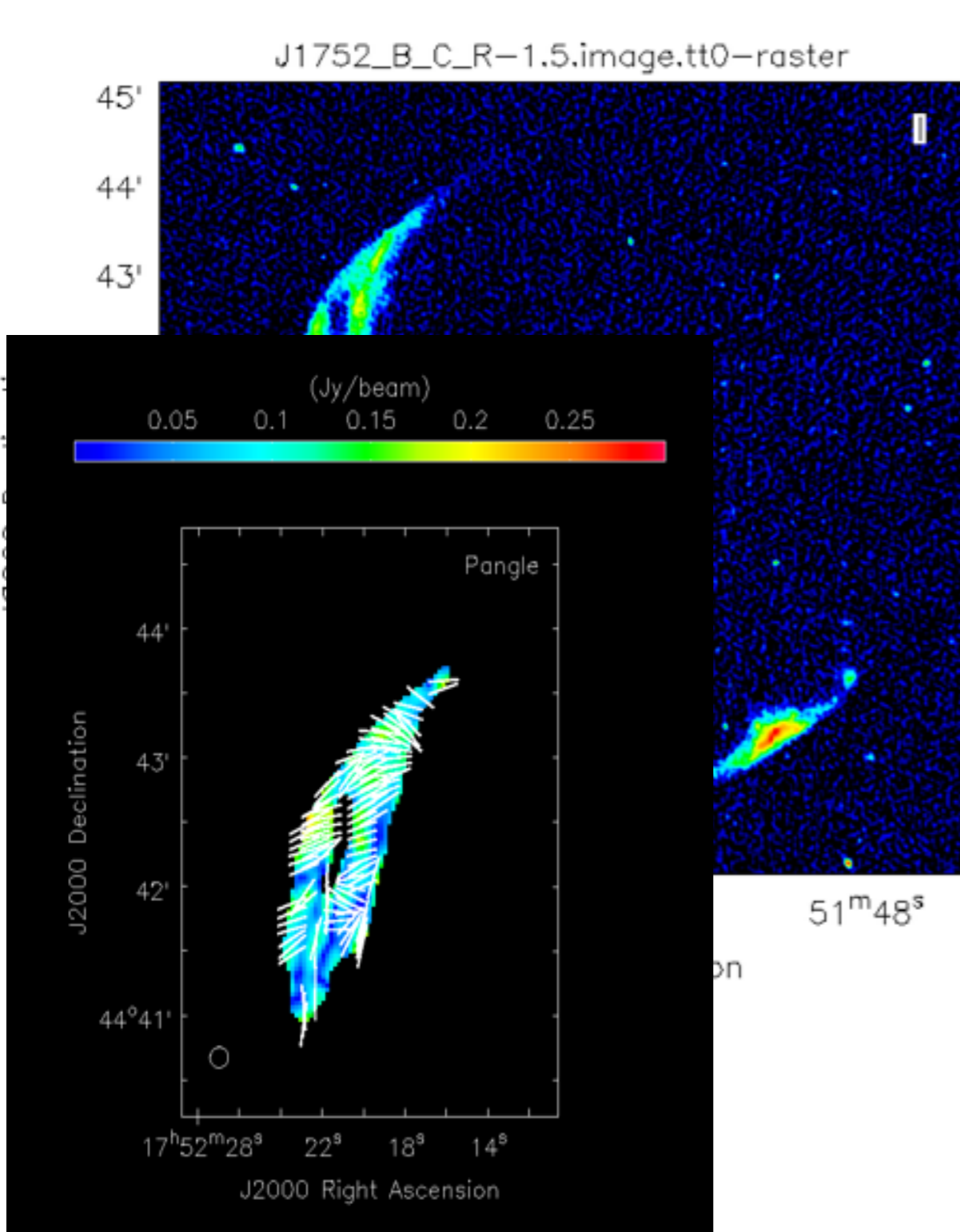
1-2 GHz VLA observations

beam $\sim 3''$

-> Mach number variation within the shock front?
(Skillman et al. 2008)

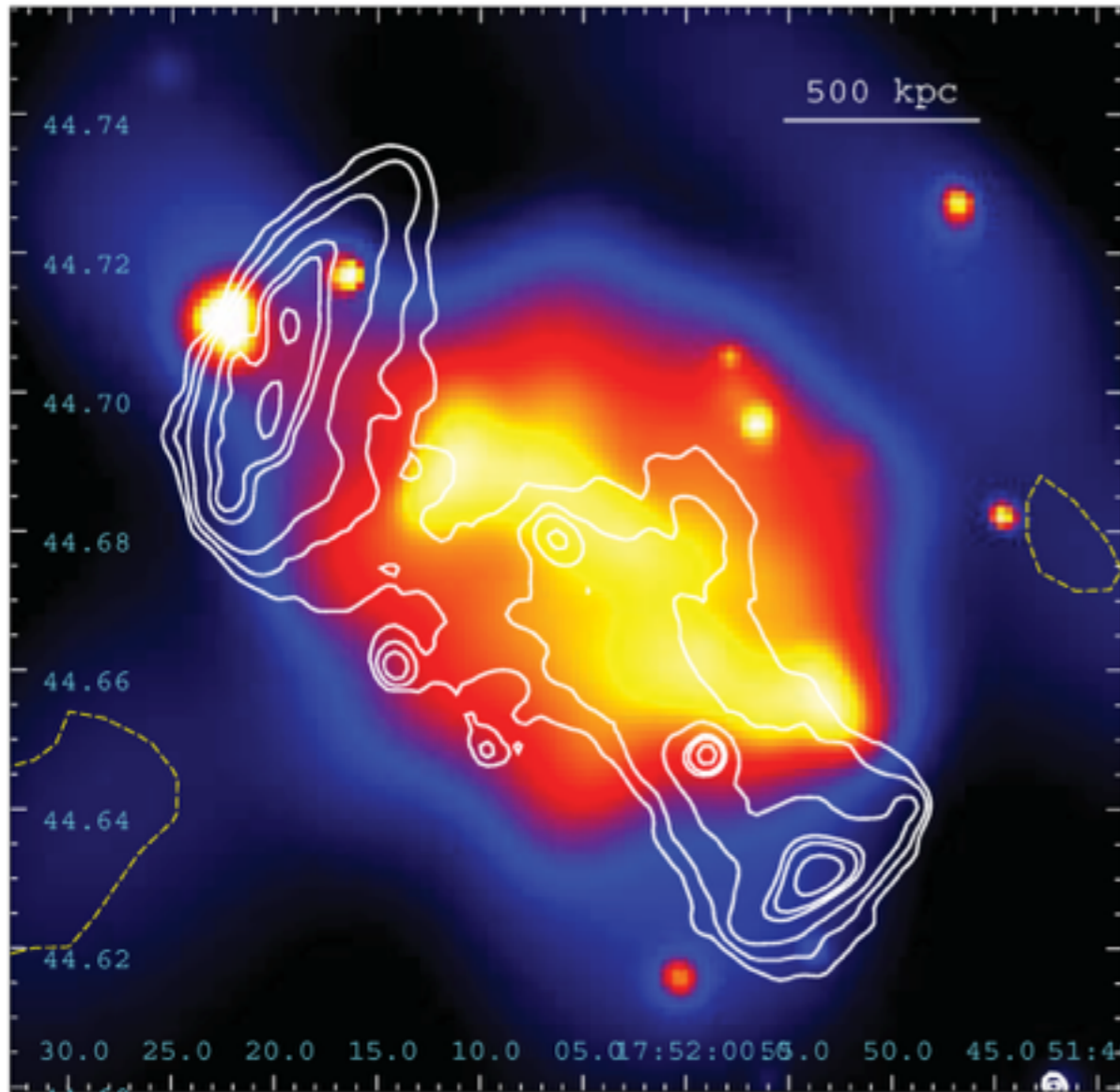
More data, more troubles

MAcs J1752 : double radio relics and halo



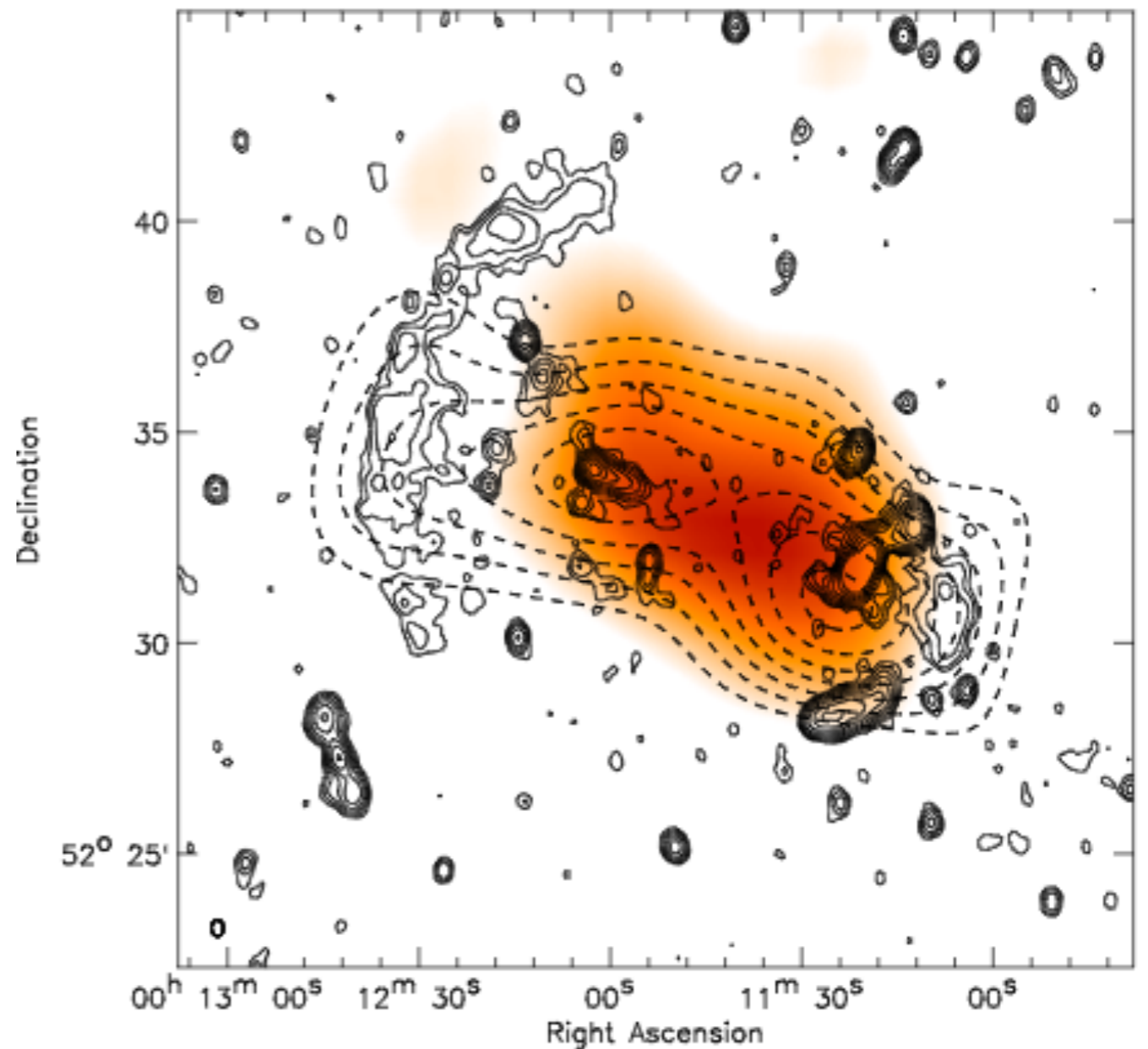
-> Mach number variation within the shock front?
(Skillman et al. 2008)

Clusters with double relics



Bonafede et al. (2012)

Double relics + halo



van Weeren et al (2011)

Double relics, no halo

Why no radio halo?

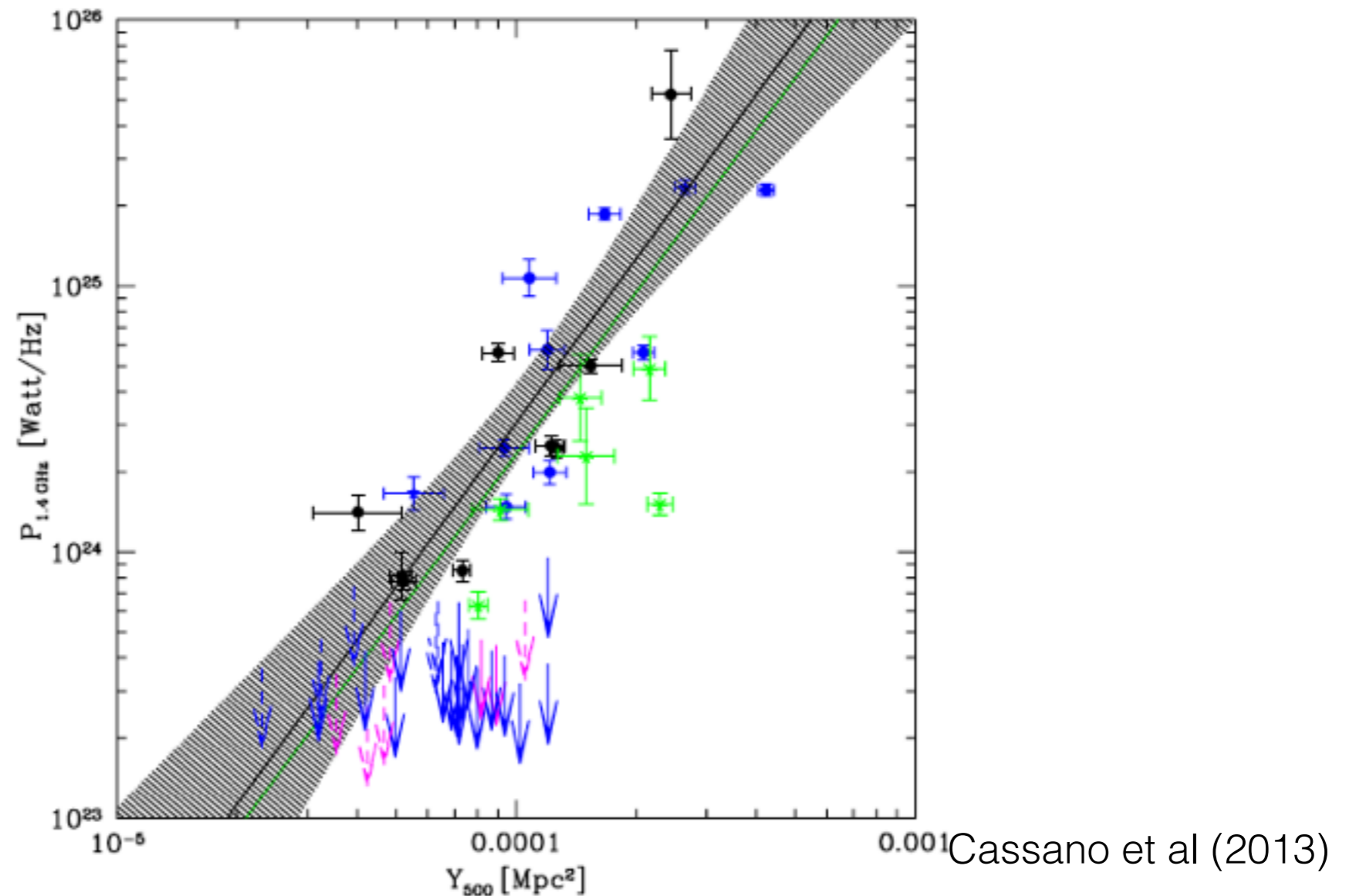
So far we know of:

15 clusters with double relics
7 have no radio halo
7 have a radio halo
(1 is debated)

Is a radio halo really missing?

Upper limits

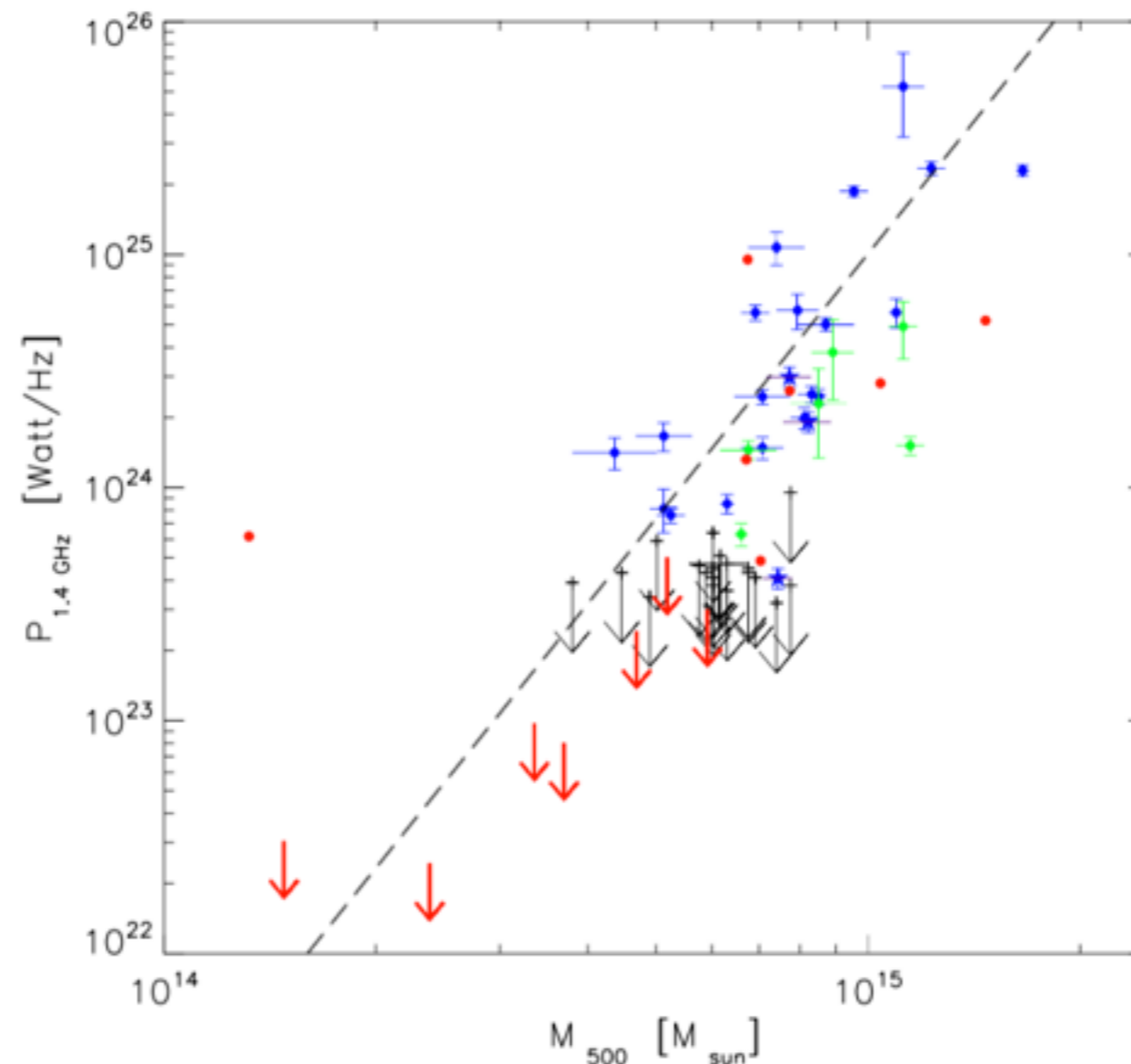
- Injection of fake halos in the UV data (following Venturi et al 2008)
- Realistic models for the fake radio halo:
 - 1) fluctuations of the radio brightness
 - 2) average exponential profile - as observed



Is a radio halo really missing?

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- Injection of fake halos in the UV data (following Venturi et al 2008)
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Bonafede et al (in prep)

Why is radio halo missing?

- 1) Radio halo is really missing in 6 cases

Should we expect a halo?

X-ray morphological analysis

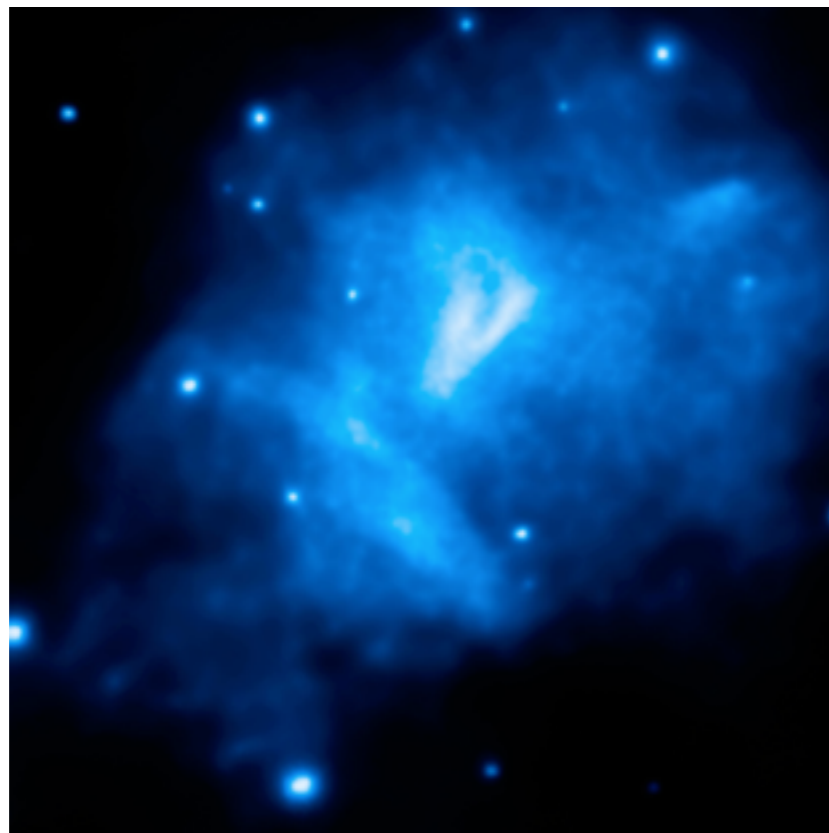
Chandra archival observations - 10 clusters

X-ray indicators of cluster dynamical status:

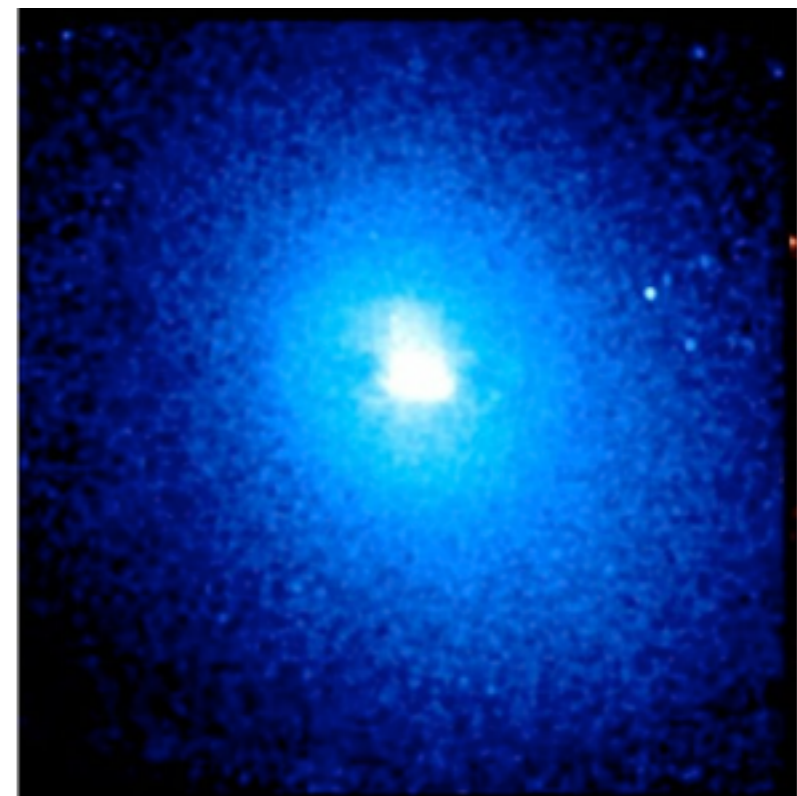
P_3/P_0 ~ amount of substructures

$c \sim S_x(100 \text{ kpc})/S_x(500 \text{ kpc})$

$w \sim$ asymmetry



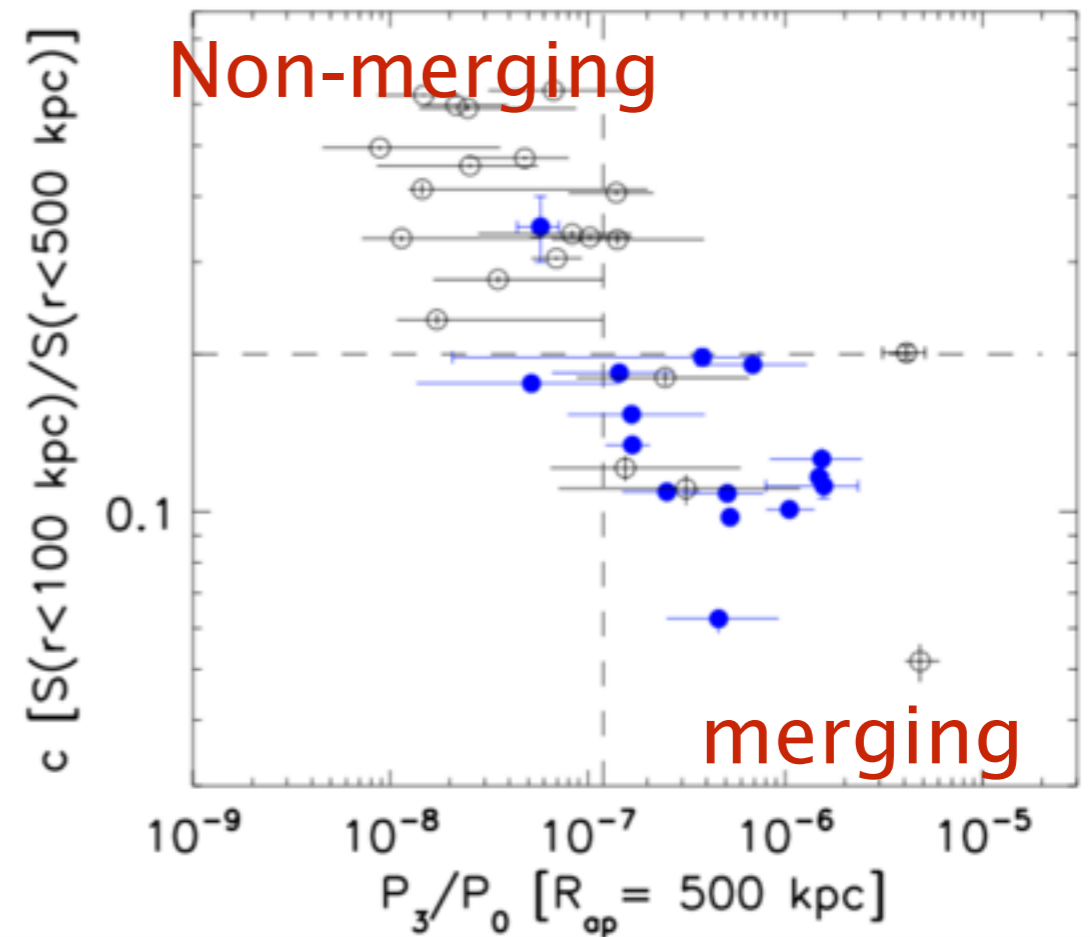
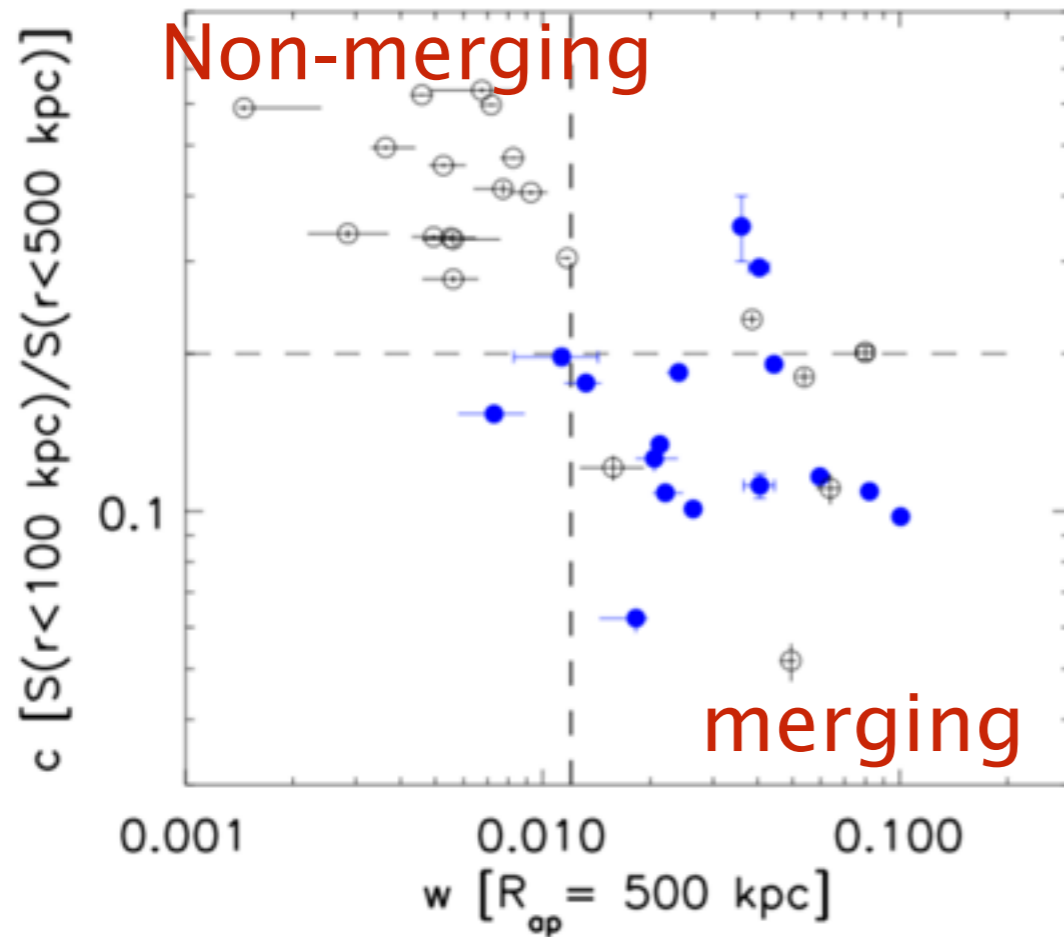
Credits: G. Ogrean



Credits: P. Nulsen

Merger?

Should we expect a halo?

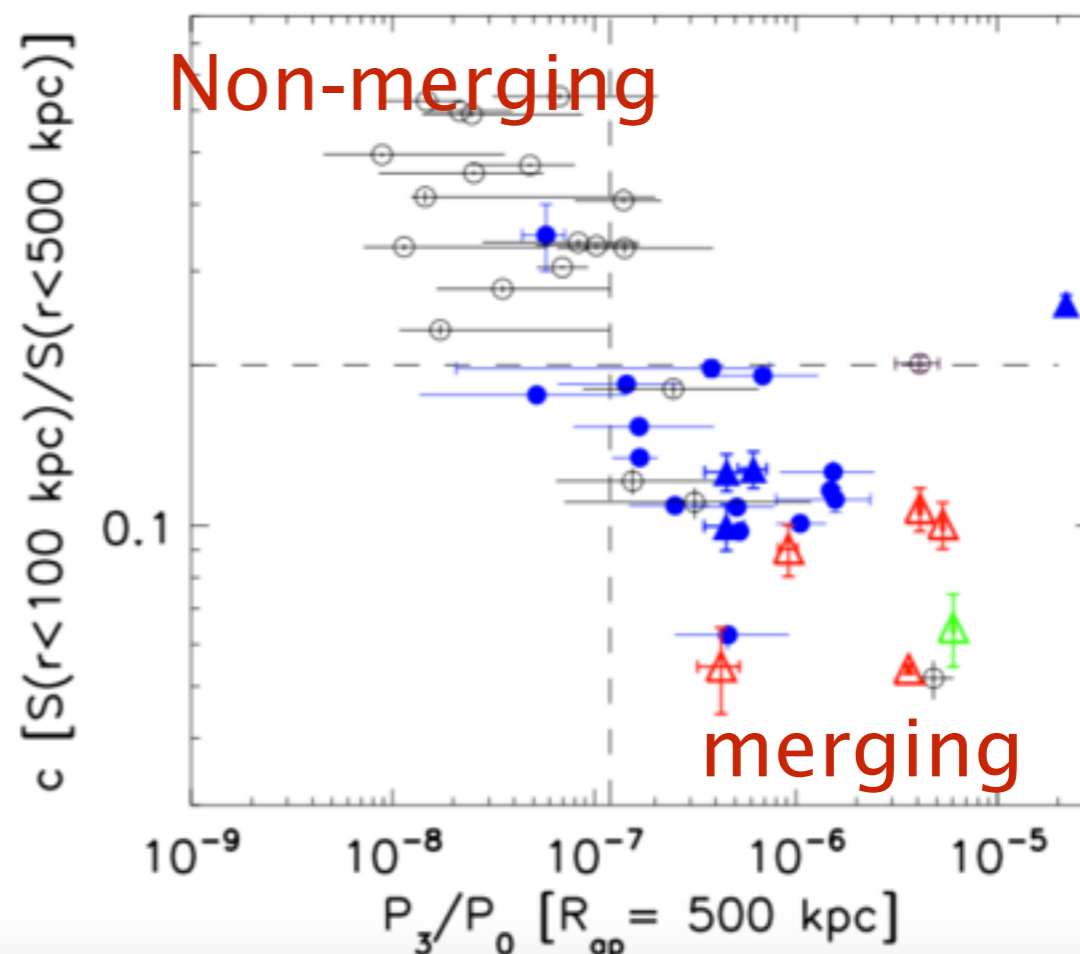
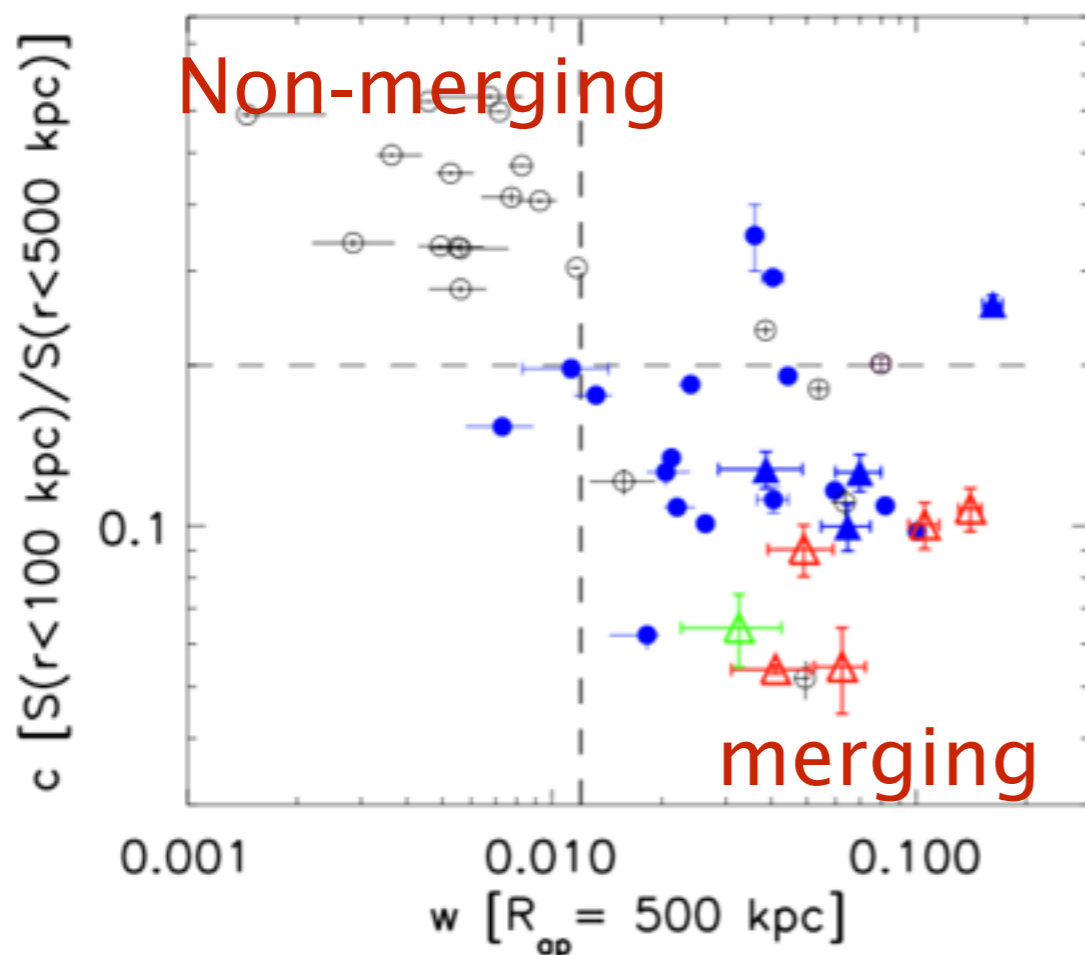


Cassano et al (2010), Bonafede et al (2015)

- clusters with halo
- clusters with no halo (below the correlation)

Merger?

Should we expect a halo?



Cassano et al (2010), Bonafede et al (2015)

- clusters with halo
- clusters with no halo (below the correlation)
- ▲ clusters with double relics and halo
- ▲ clusters with double relics and NO halo
- ▲ debated case

Why is radio halo missing?

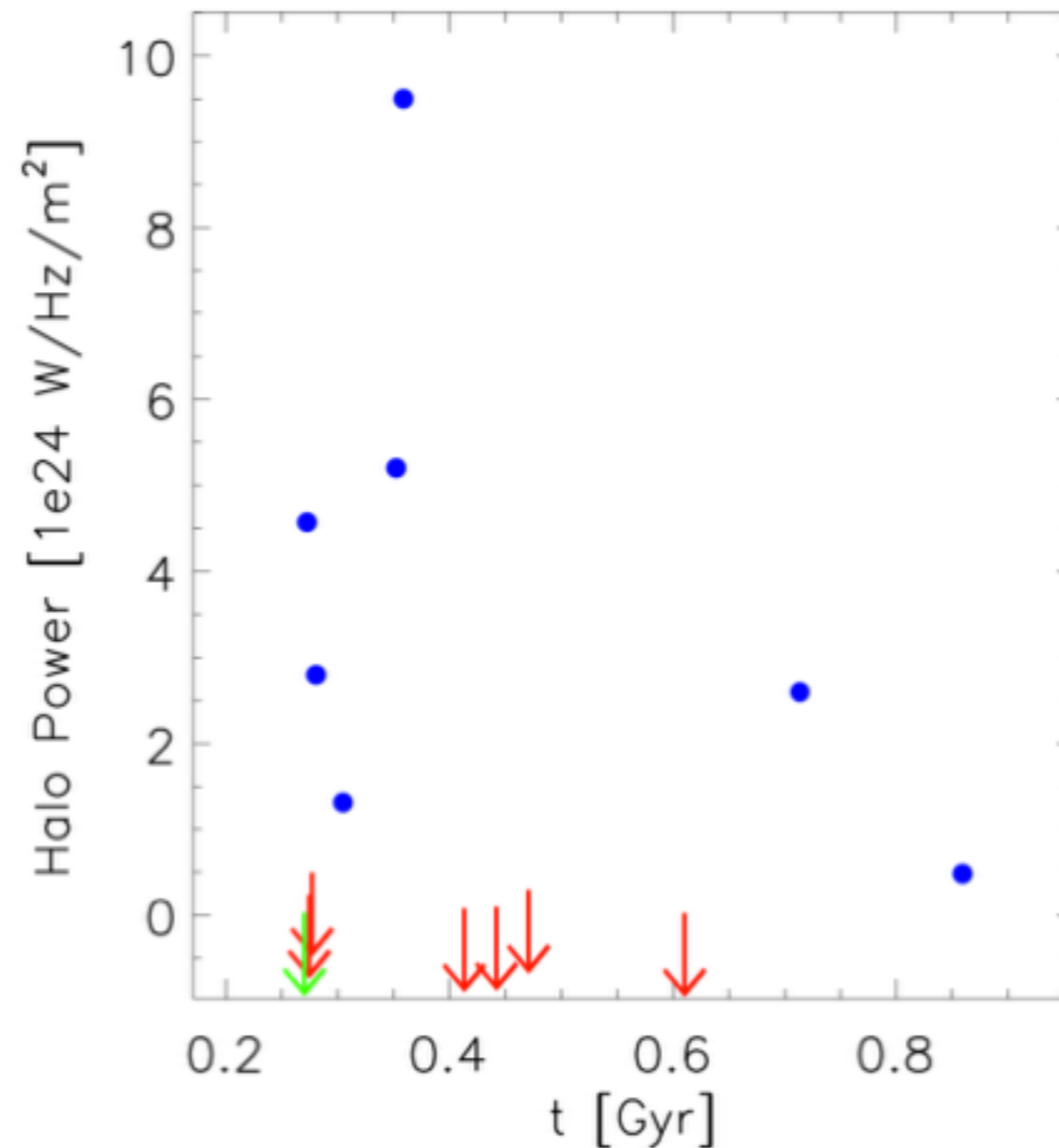
- 1) Radio halo is really missing in 6 cases
- 2) We should expect a halo

Time-scale issue?

- Distance of relic from the cluster centre
- Mach number from radio spectral index/Xray
- v from Mach number - assumed constant

Time-scale issue?

- Distance of relic from the cluster centre
- Mach number from radio spectral index/Xray
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Why is radio halo missing?

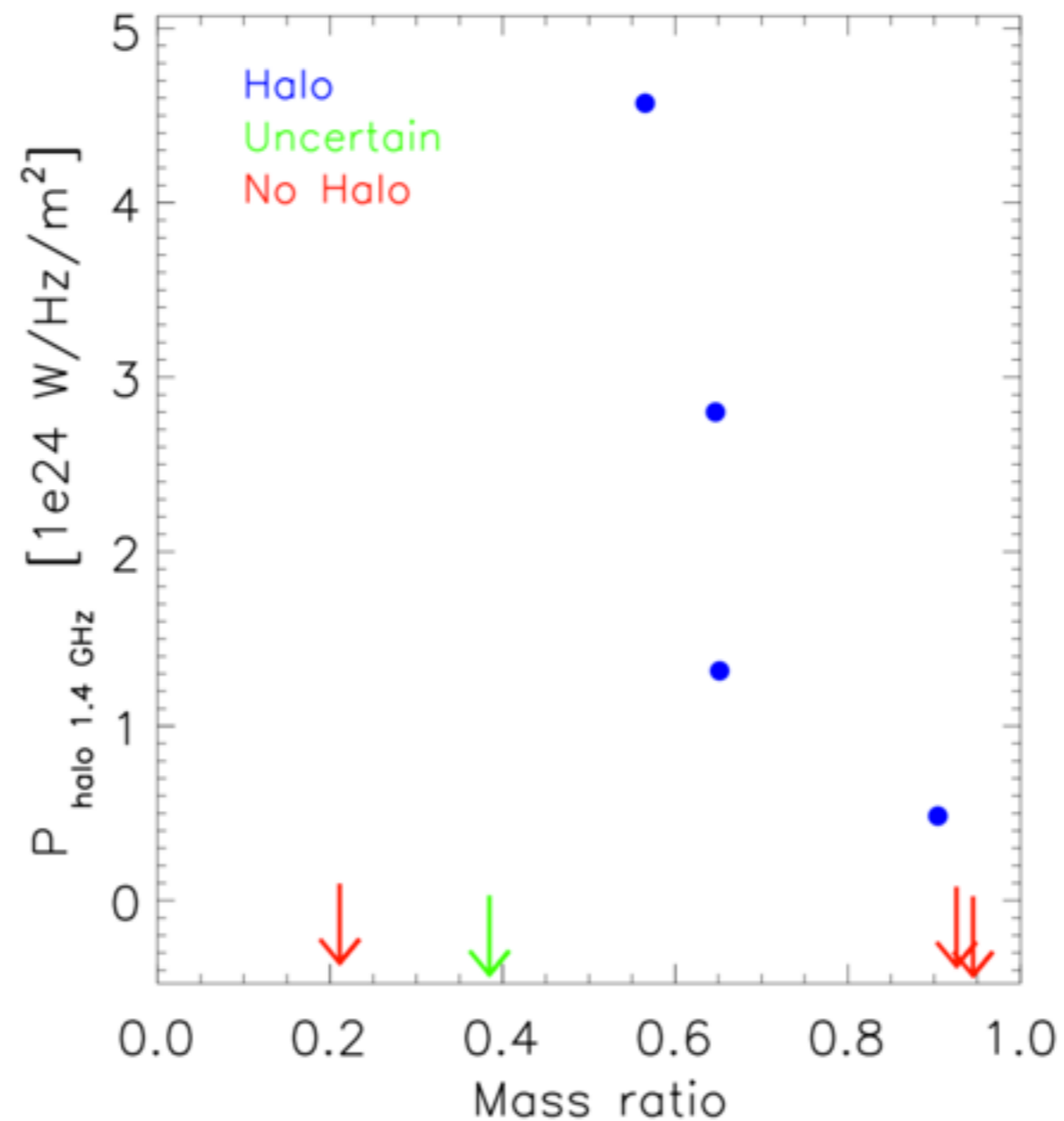
- 1) Radio halo is really missing in 6 cases
- 2) All clusters are in extreme merger state
- 3) Time-scale unlikely plays a role

Mass ratio?

Weak lensing analysis - mass reconstruction (by N. Golovich, MCC collaboration)
Mass of the 2 merging sub-clusters - 8 systems

Mass ratio?

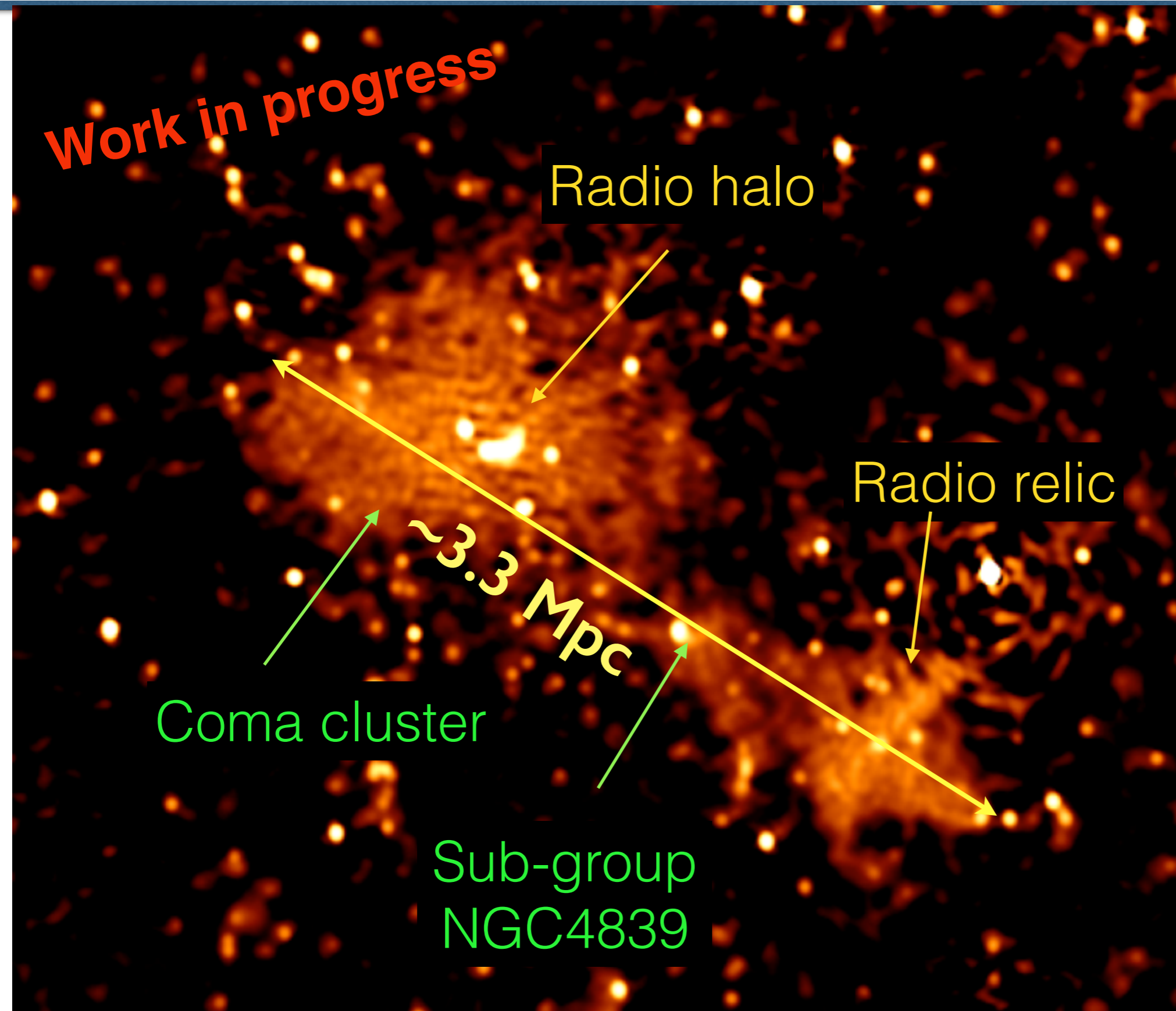
Weak lensing analysis - mass reconstruction (by N. Golovich, MCC collaboration)
Mass of the 2 merging sub-clusters - 8 systems



Why is radio halo missing?

- 1) Radio halo is really missing in 6 cases
- 2) All clusters are in extreme merger state
- 3) Time-scale unlikely plays a role
- 4) Mass ratio unlikely plays a role - but very low statistics

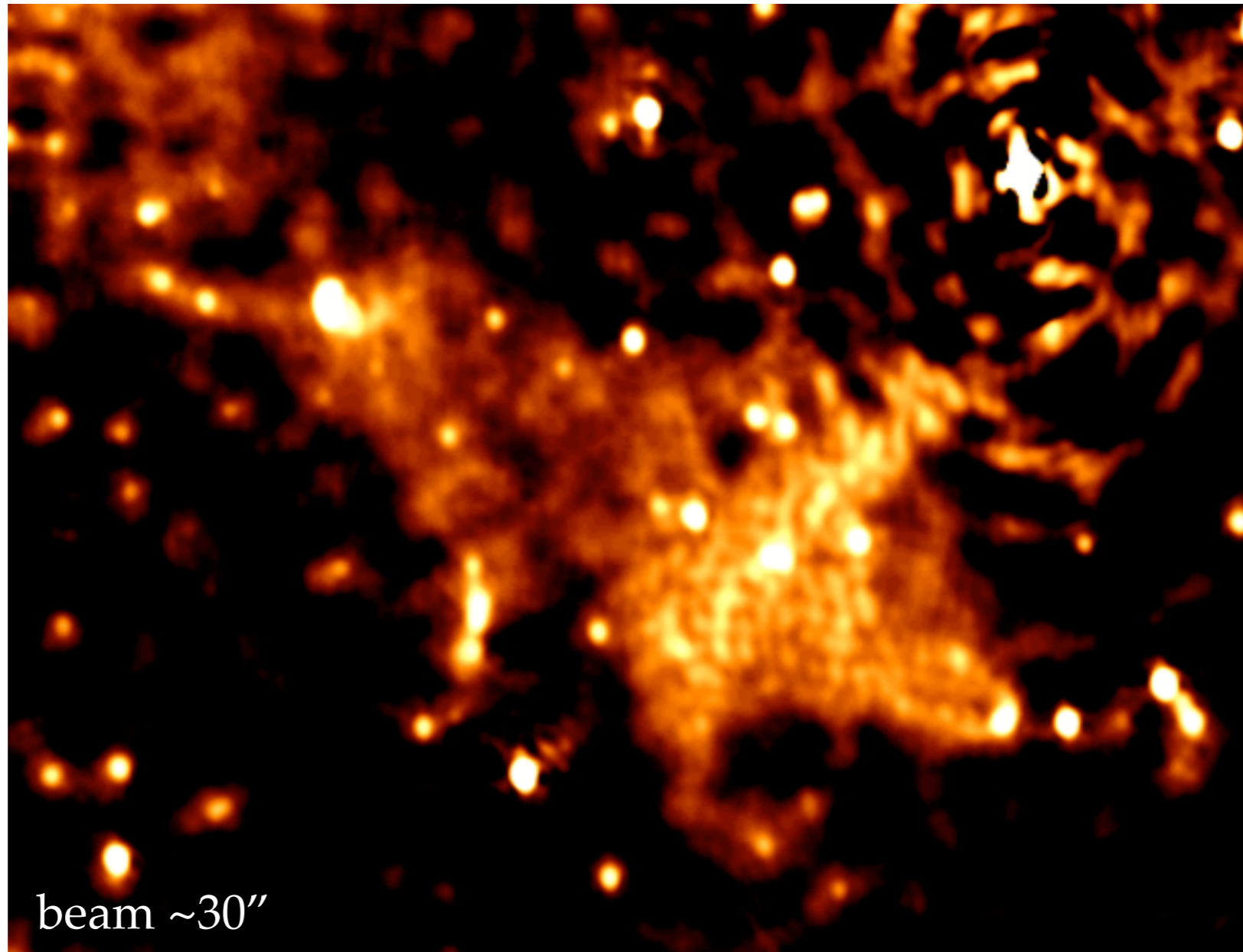
The Coma cluster



LOFAR image
at 140 MHz

30 arcsec resolution

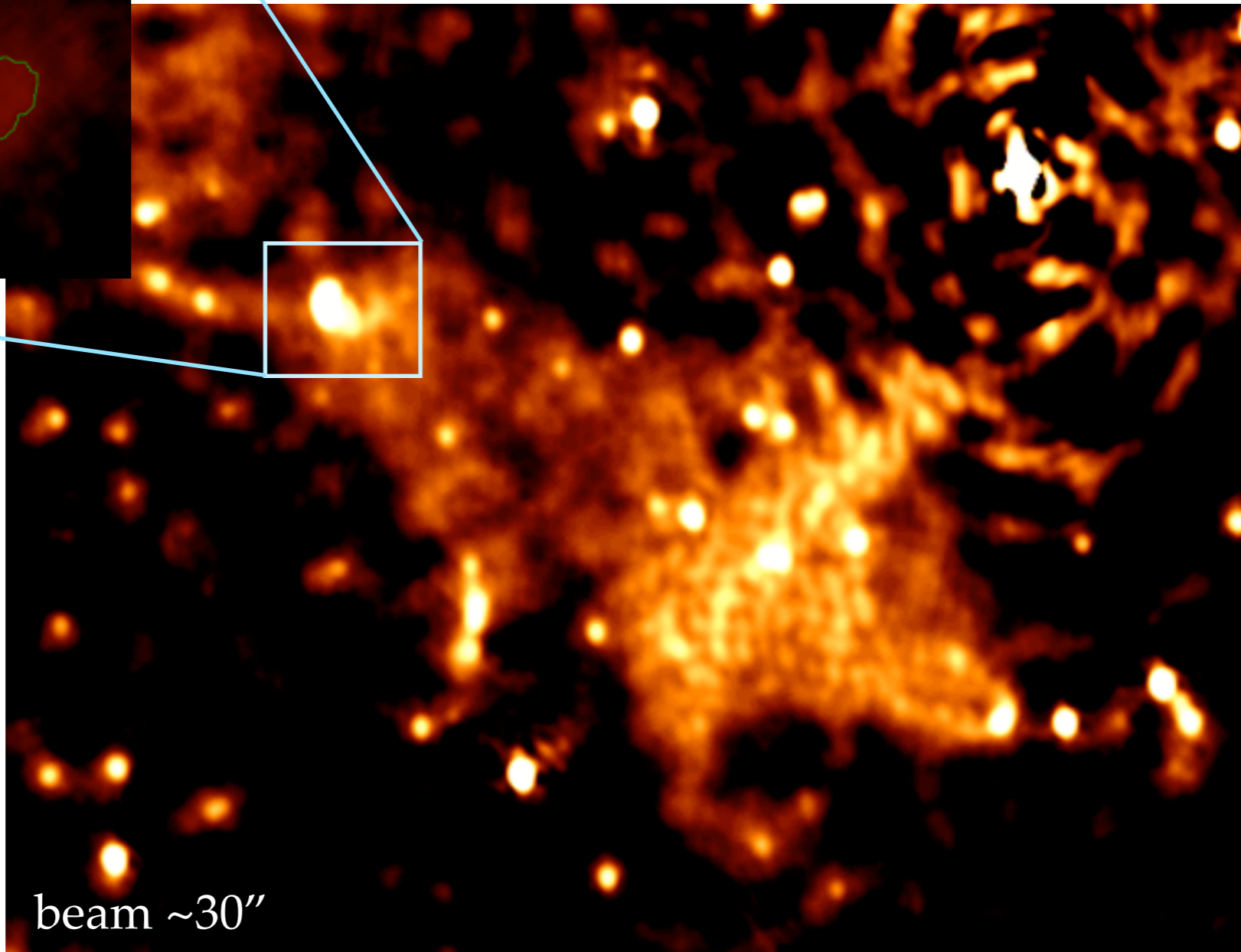
The Bridges



The Bridges

NGC 4839

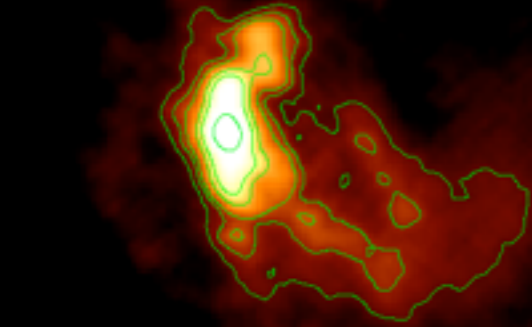
beam $\sim 5''$



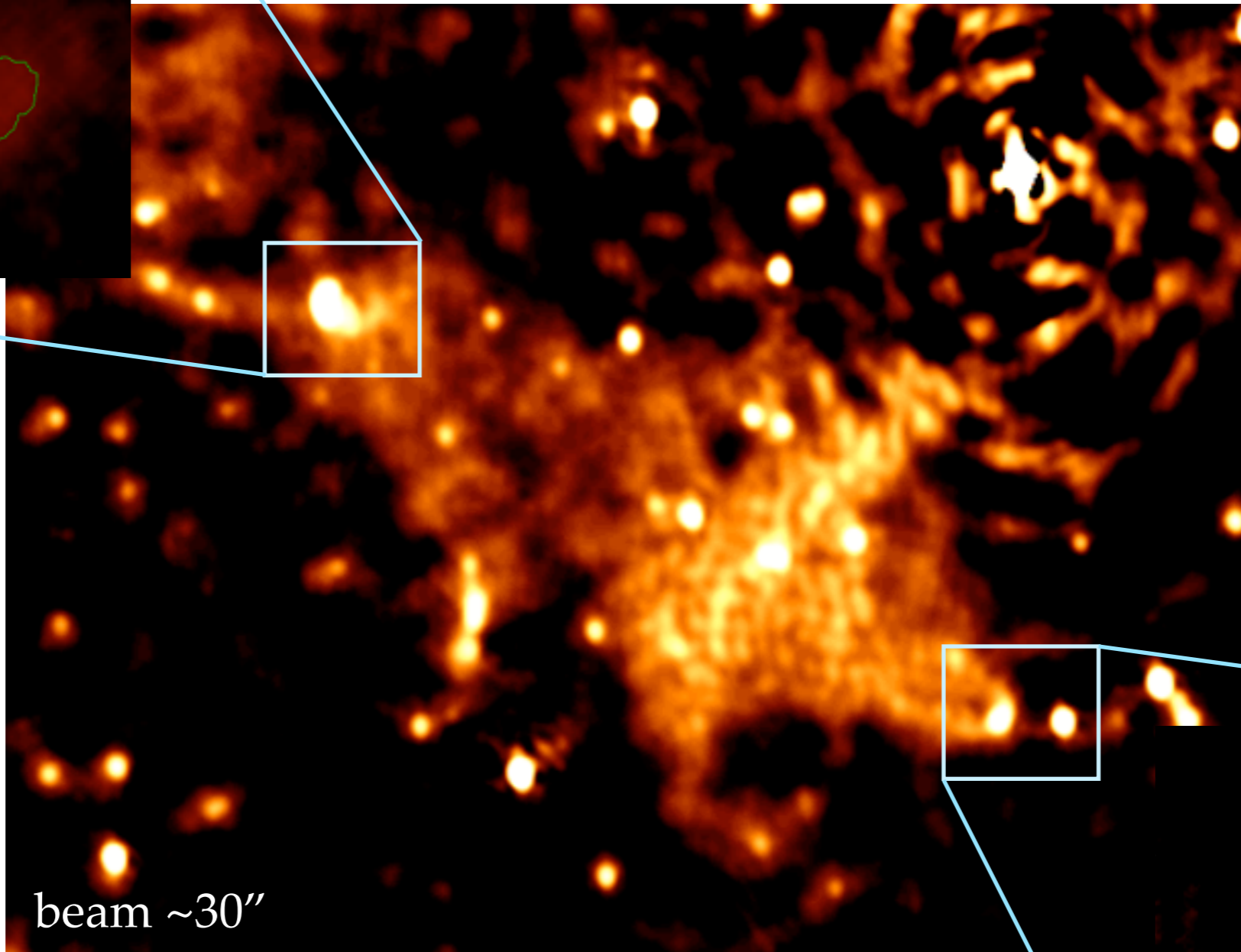
beam $\sim 30''$

The Bridges

NGC 4839

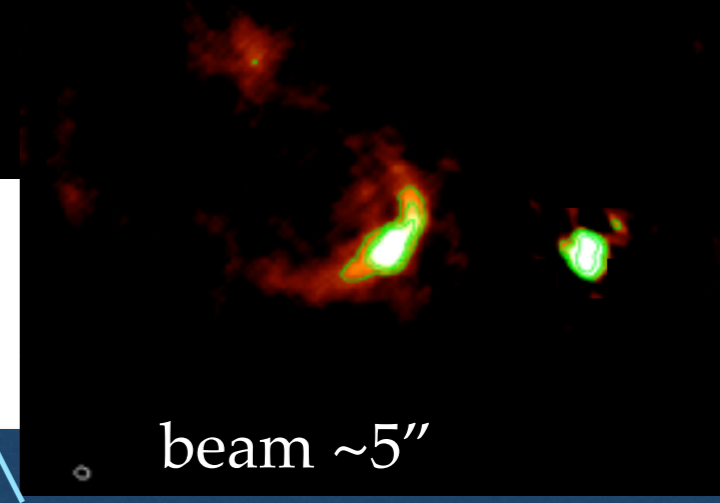


beam $\sim 5''$



beam $\sim 30''$

NGC4789



beam $\sim 5''$

New technique: facet calibration

LOFAR HBA: 140 MHz

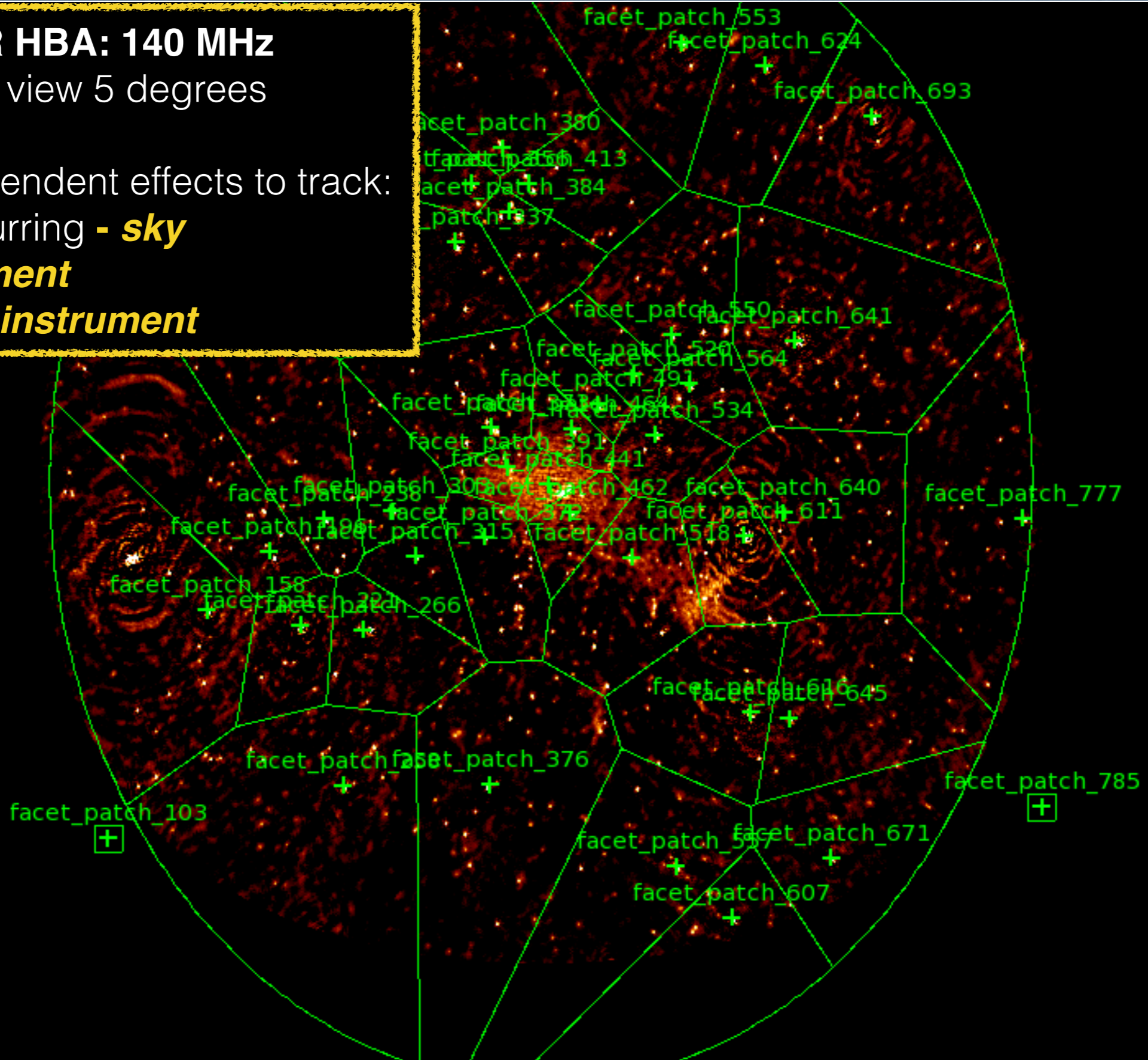
field of view 5 degrees

directional dependent effects to track:

ionospheric blurring - **sky**

gains - **instrument**

station beam - **instrument**

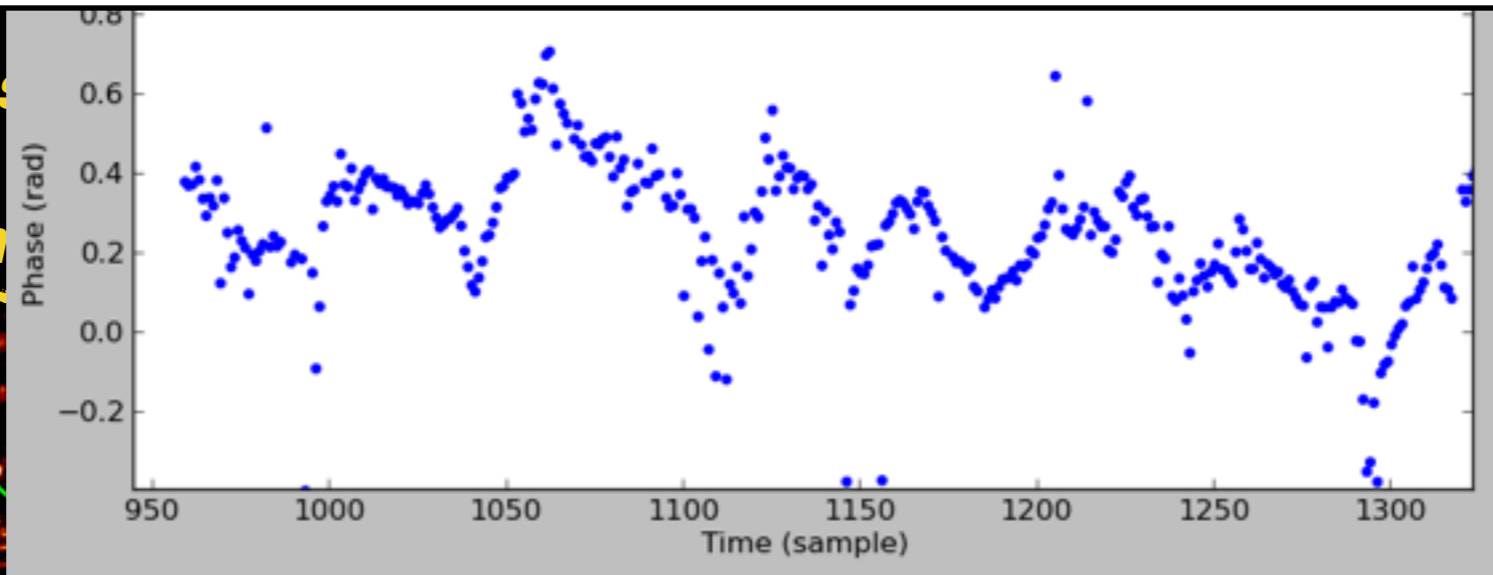


New technique: facet calibration

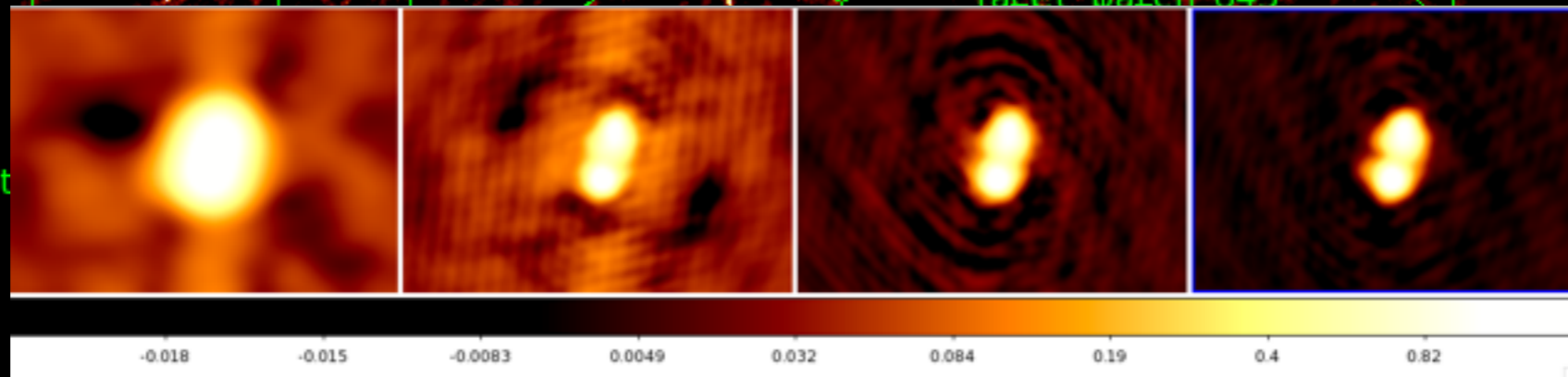
LOFAR HBA: 140 MHz

field of view 5

Tracking the variation in total electron content in the atmosphere on 5-sec scale

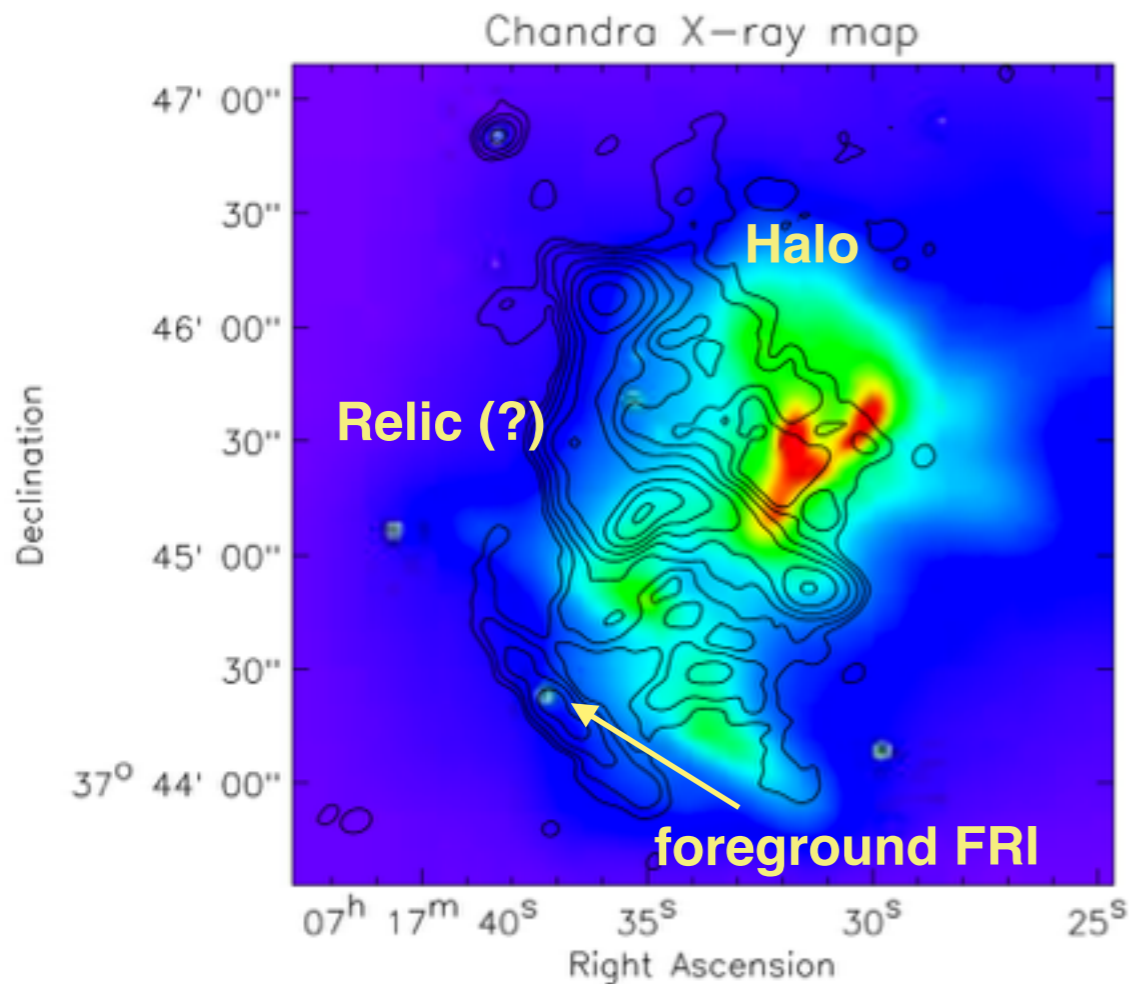


directional dependent
ionospheric blurring -
gains - **instrument**
station beam - **instrum**



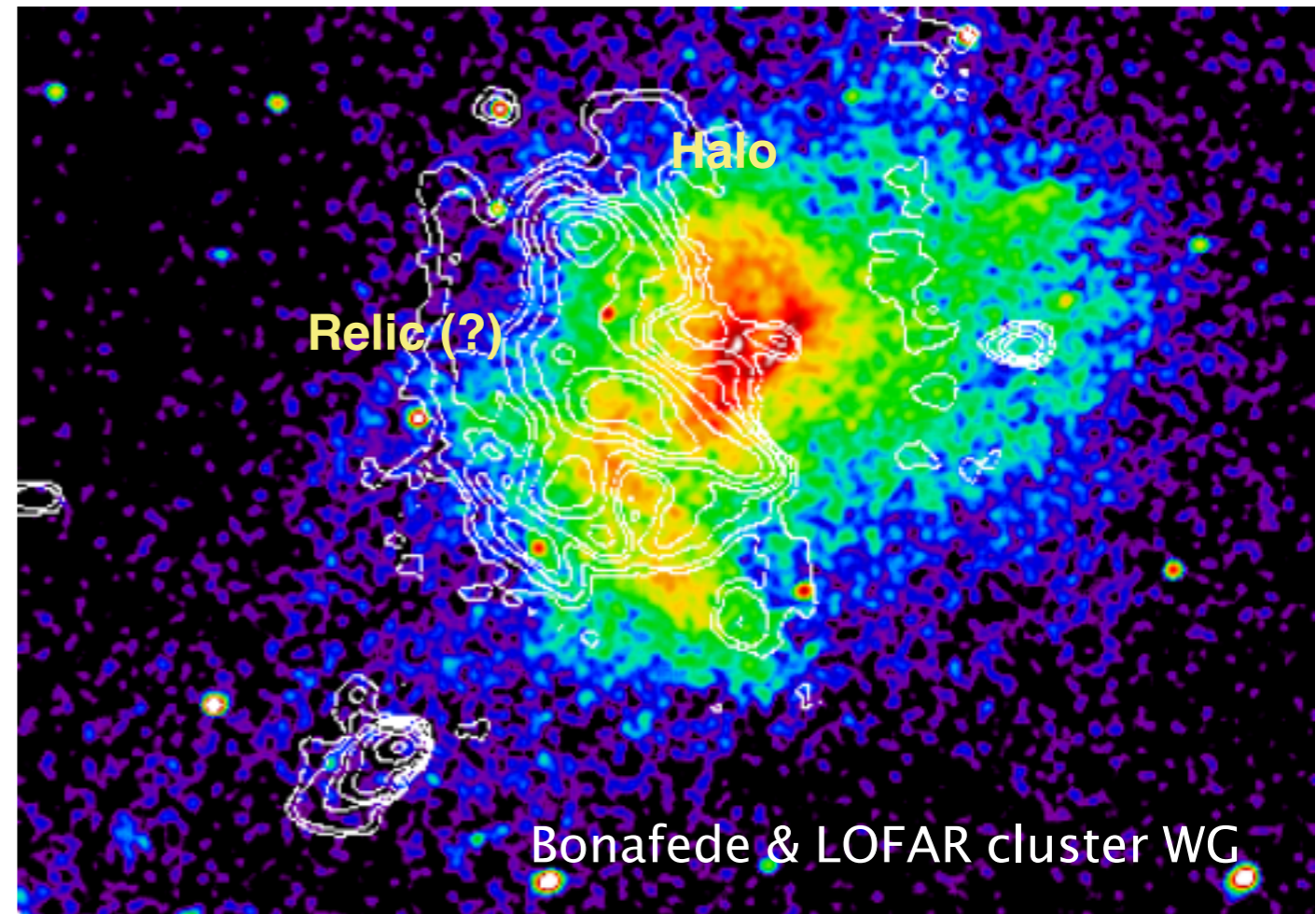
10x sensitivity improvement!

LOFAR High Band observations



van Weeren et al (2009)
GMRT @ 610 MHz
beam ~7"

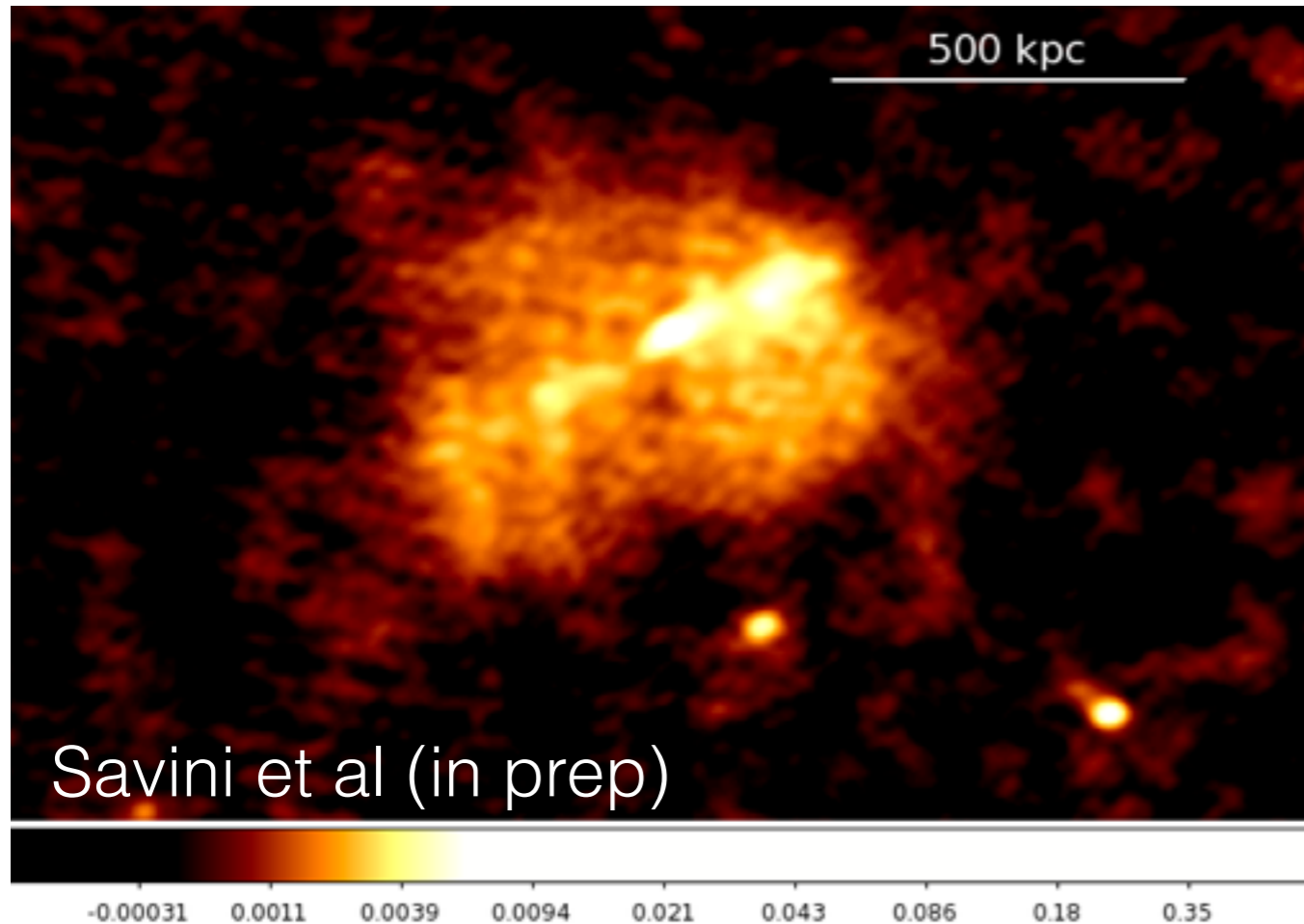
Colors: Chandra
Contours: radio



LOFAR @ 148 MHz
thermal noise reached!
beam ~ 7"

More LOFAR results

2MASX J13171639+5143303, $Z=0.188$

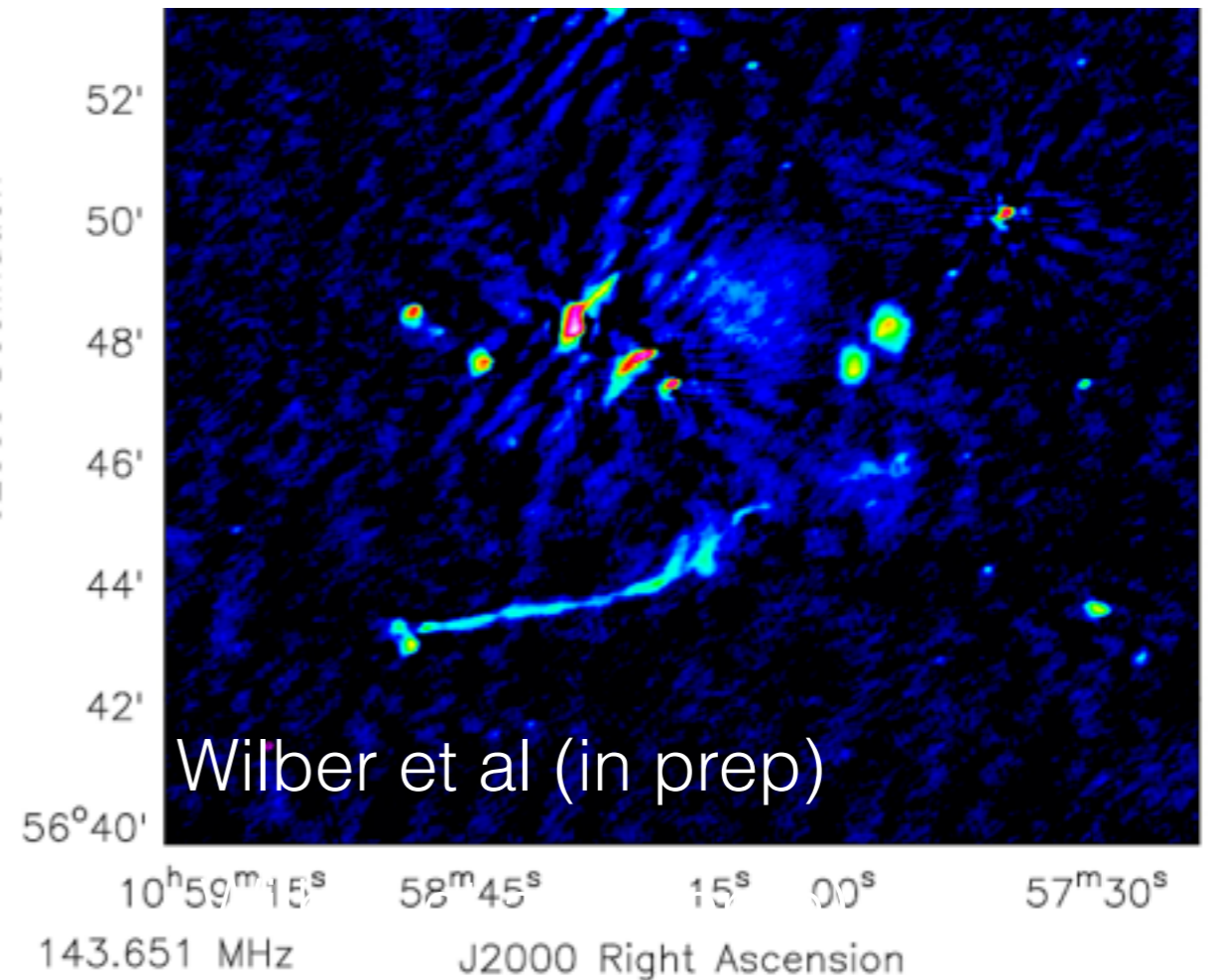


Savini et al (in prep)

Low-mass cluster ($M_{500} \sim 3 \cdot 10^{13} M_{\text{sun}}$)
 $R_{200} \sim 550 \text{ kpc}$

Radio emission $\sim 650 \text{ kpc}$
average $\alpha^{1.4} \text{ GHz}_{148 \text{ MHz}} \sim 1.5$

Abell 1132, $Z=0.1363$



Wilber et al (in prep)

Head tail? 1.5 Mpc long!