Unravelling particle acceleration and magnetic field amplification in galaxy clusters through radio observation

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European Research Council
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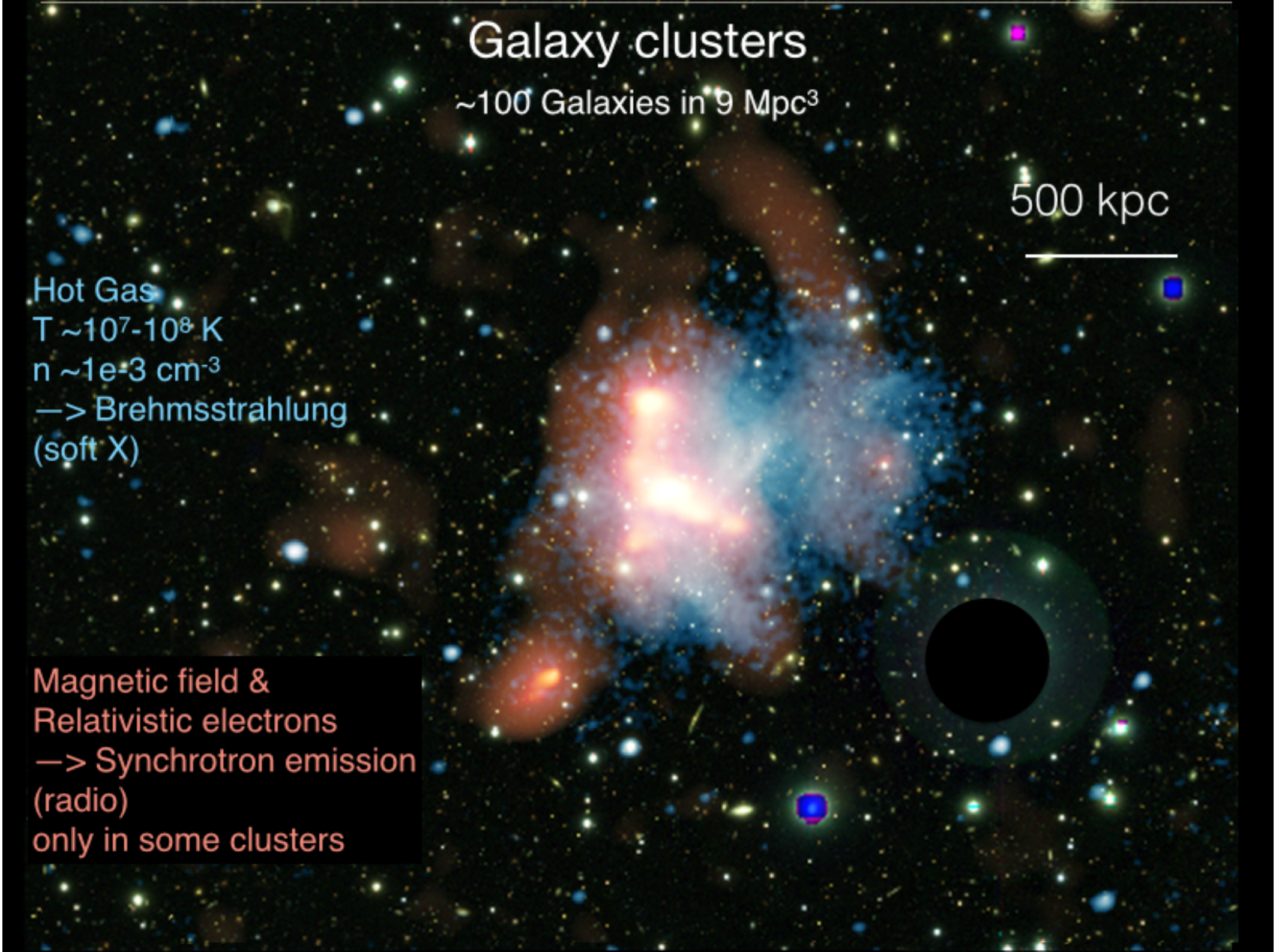
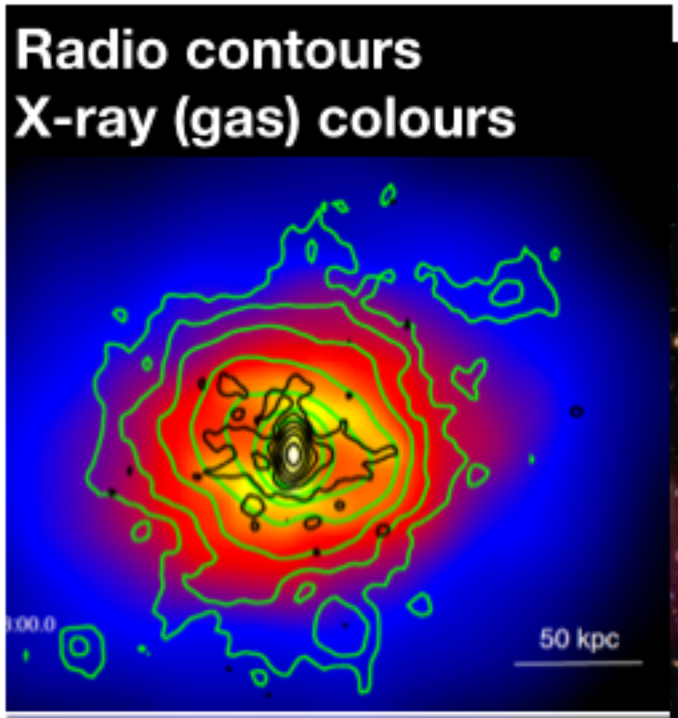
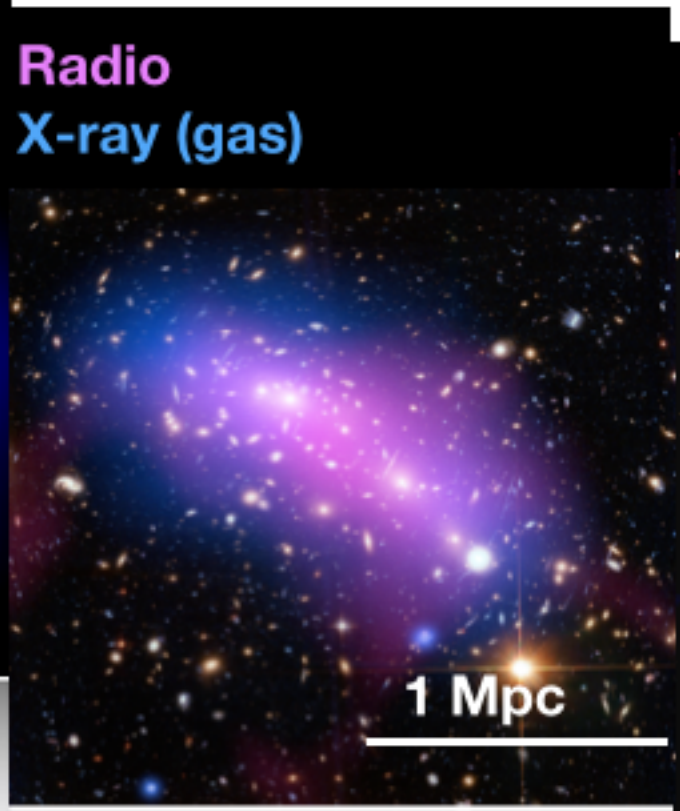
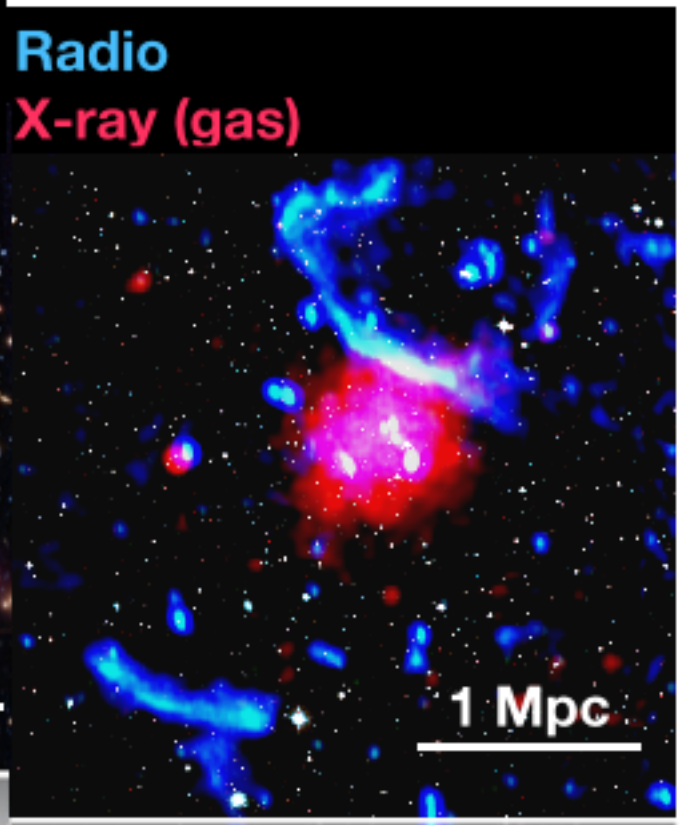

Galaxy clusters
~100 Galaxies in 9 Mpc3
500 kpc
Hot Gas
T ~10^7-10^8 K
n ~1e-3 cm^-3
—> Brehmsstrahlung
(soft X)
Magnetic field &
Relativistic electrons
—> Synchrotron emission
(radio)
only in some clusters

RADIO SOURCES IN CLUSTERS







Virialized systems

Merging systems

Tracing **co-evolution** of non-thermal component with **cluster dynamics**

ENERGETIC PROBLEM

Life-time of electrons
(E~10 GeV)
$t \sim 10^8$ years

Diffusion velocity
v ~ 100 km/s

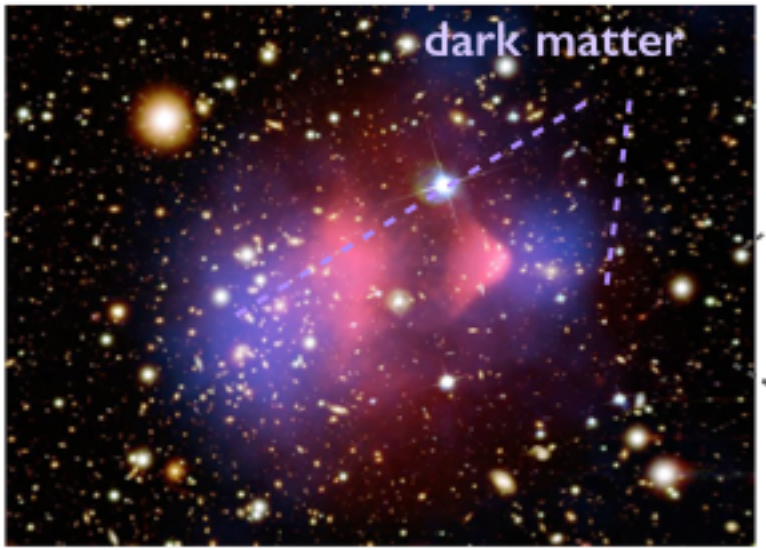
L_{max} ~30 kpc
Radio emission ~Mpc

Electrons need to be continuously injected or accelerated

RADIO EMISSION & CLUSTER MERGERS

Cluster-cluster merger

E ~10^{64} erg



Credits:Markevitch, Clowe

Turbulence
(e.g. Brunetti et al 2001)

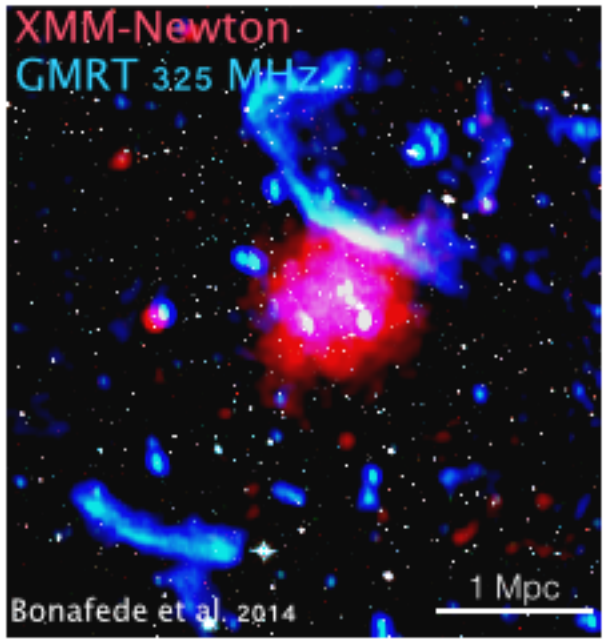
Halos

?

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

Relics

?



OPEN QUESTIONS (I will discuss in this talk)

- Shock and turbulent acceleration → Seed population of mildly relativistic CR e

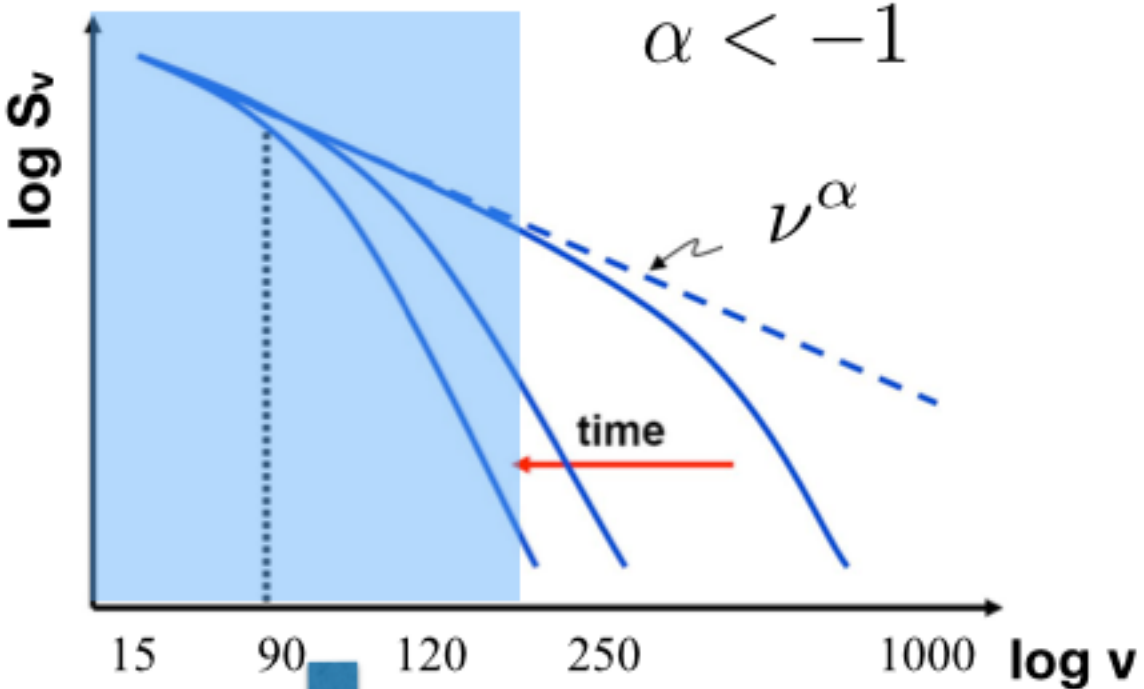
- Is there a connection between these sources?

- Role of the magnetic field?

Why low frequencies?

- Low surface brightness at ν~GHz
- The spectrum is steep

$$S(\nu) \propto \nu^{\alpha}$$
$$\alpha < -1$$



Old population of CR electrons

Low efficiency acceleration mechanisms

Why low frequencies?

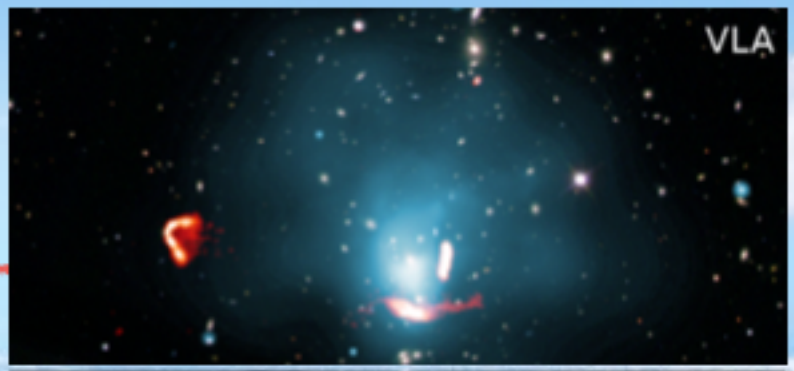
Most energetic events

Emission at 1.4 GHz

Emission at 300 MHz

Observing frequency

Long living Cosmic ray electrons



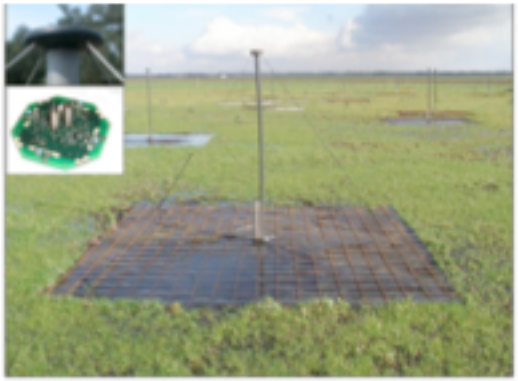
Less energetic events

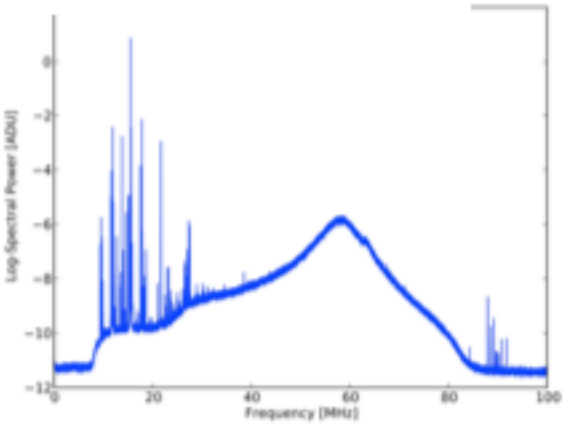
The LOw Frequency ARray

- 24 Core stations (<2 km)
- 14 Remote stations (<120 km)
- 12 International stations (<1600 km)

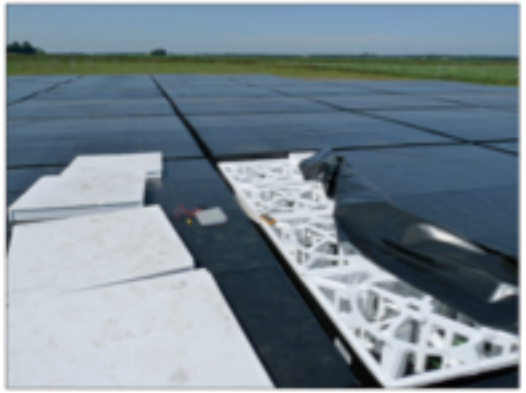
Opening up a new window in the electromagnetic spectrum

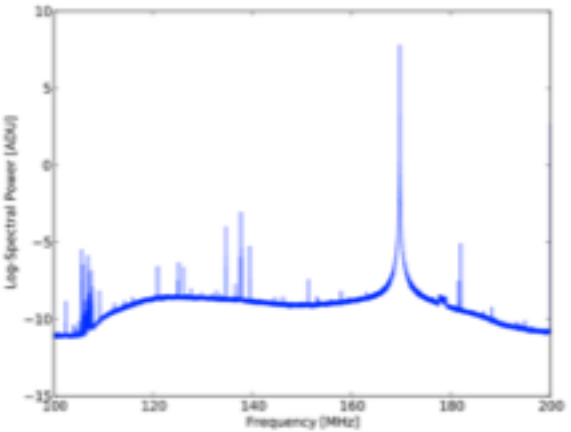
Low- Band Antennas 10-90 MHz



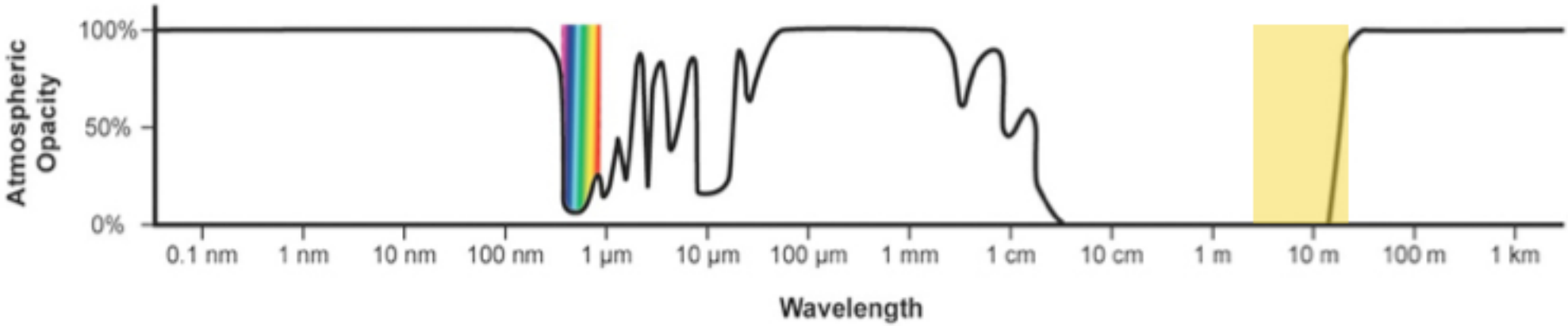


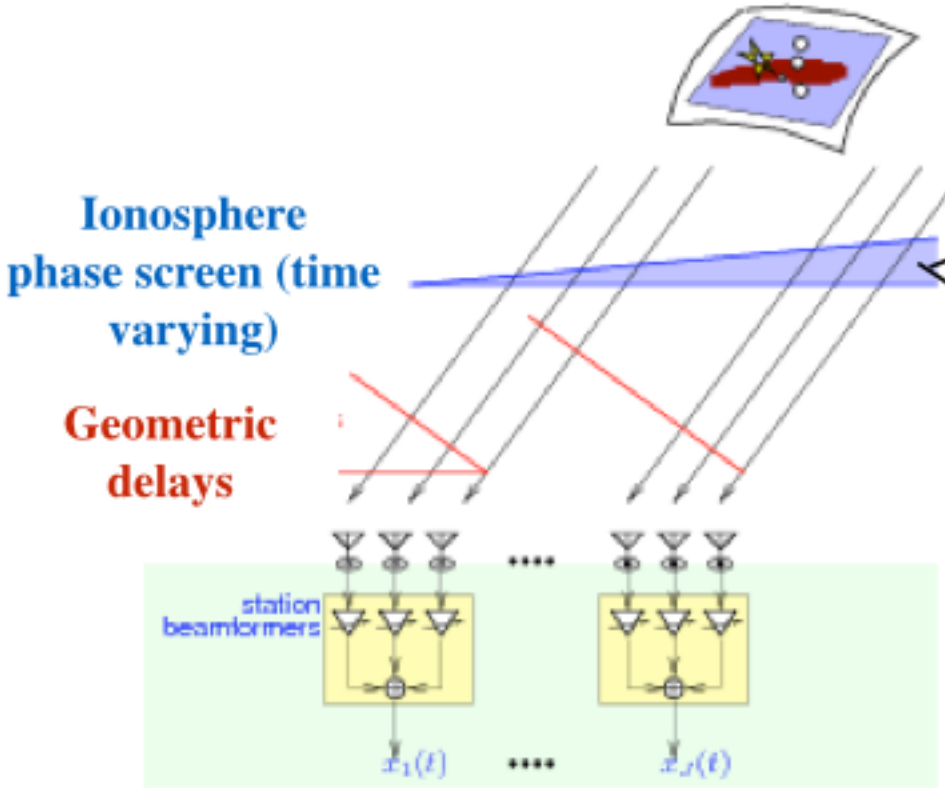
High- Band Antennas 120 - 200 MHz





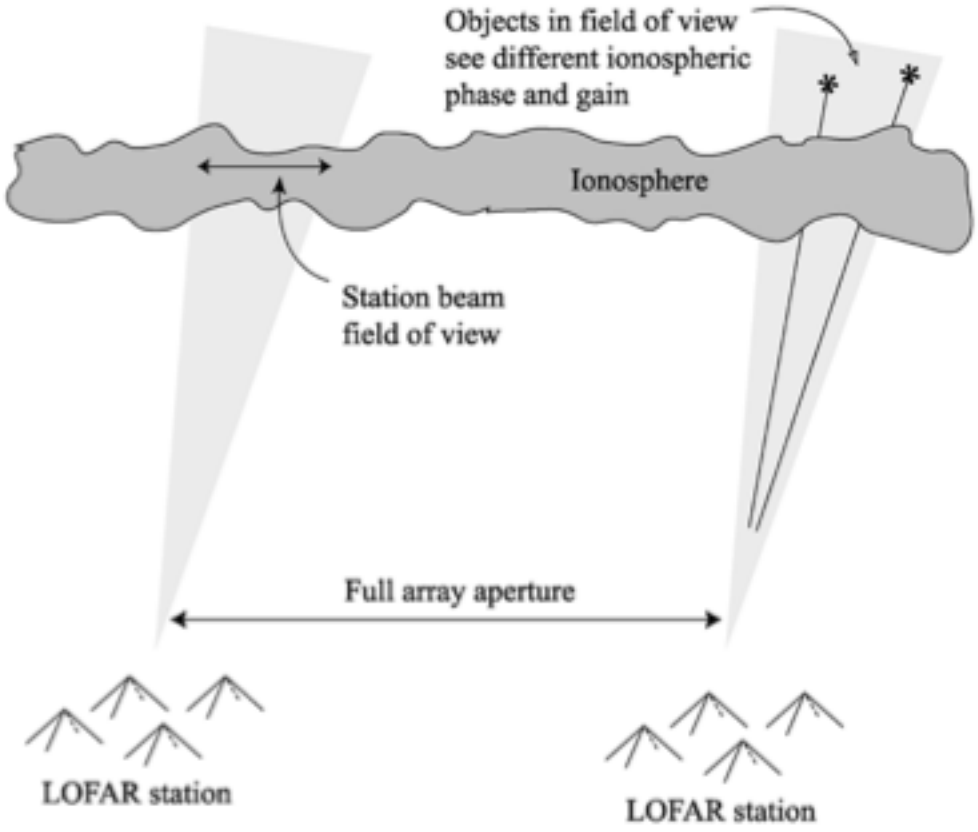
The radio window & the ionosphere





- "weak plasma" (1% neutral atoms)
- ionisation controlled by UV and X-rays emitted by the Sun

The ionosphere



n_e

Phase error:

$$\Phi^{\text{ion}} = -\frac{2\pi\nu}{c}\int_{\text{LoS}}(n-1)\,\mathrm{d}l$$

Refractive index expansion:

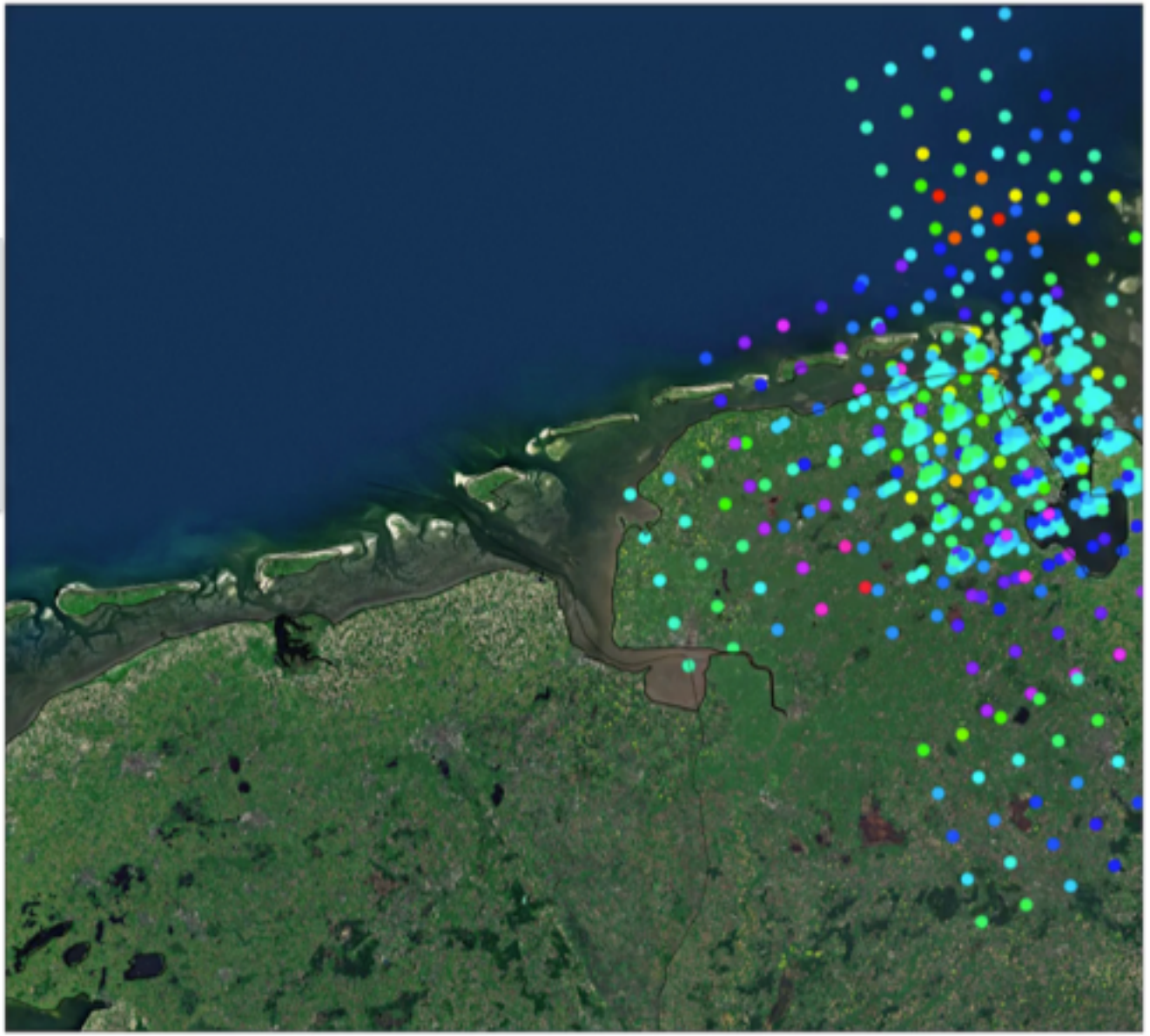
$$n = 1 - \frac{q^2}{8\pi^2 m_e \varepsilon_0}\cdot\frac{n_e}{\nu^2} \pm \frac{q^3}{16\pi^3 m_e^2 \varepsilon_0}\cdot\frac{n_e B\cos\theta}{\nu^3} - \frac{q^4}{128\pi^4 m_e^2 \varepsilon_0^2}\cdot\frac{n_e^2}{\nu^4} - \frac{q^4}{64\pi^4 m_e^3 \varepsilon_0}\cdot\frac{n_e B^2(1+\cos^2\theta)}{\nu^4},$$

n_e depends on ionisation state
changing with
time (sec), position (few arcmin), solar activity

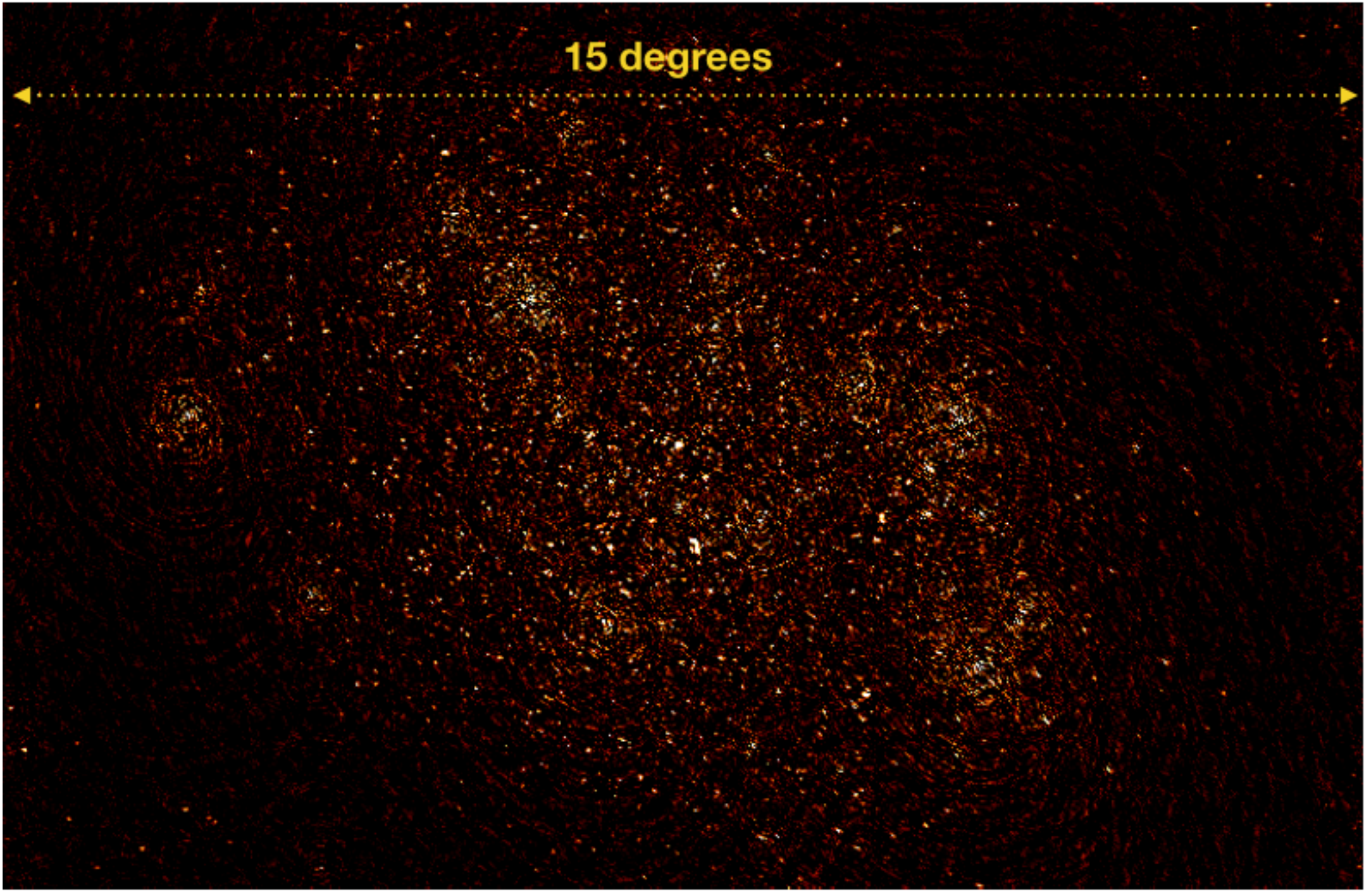
The ionosphere

-2π 2π

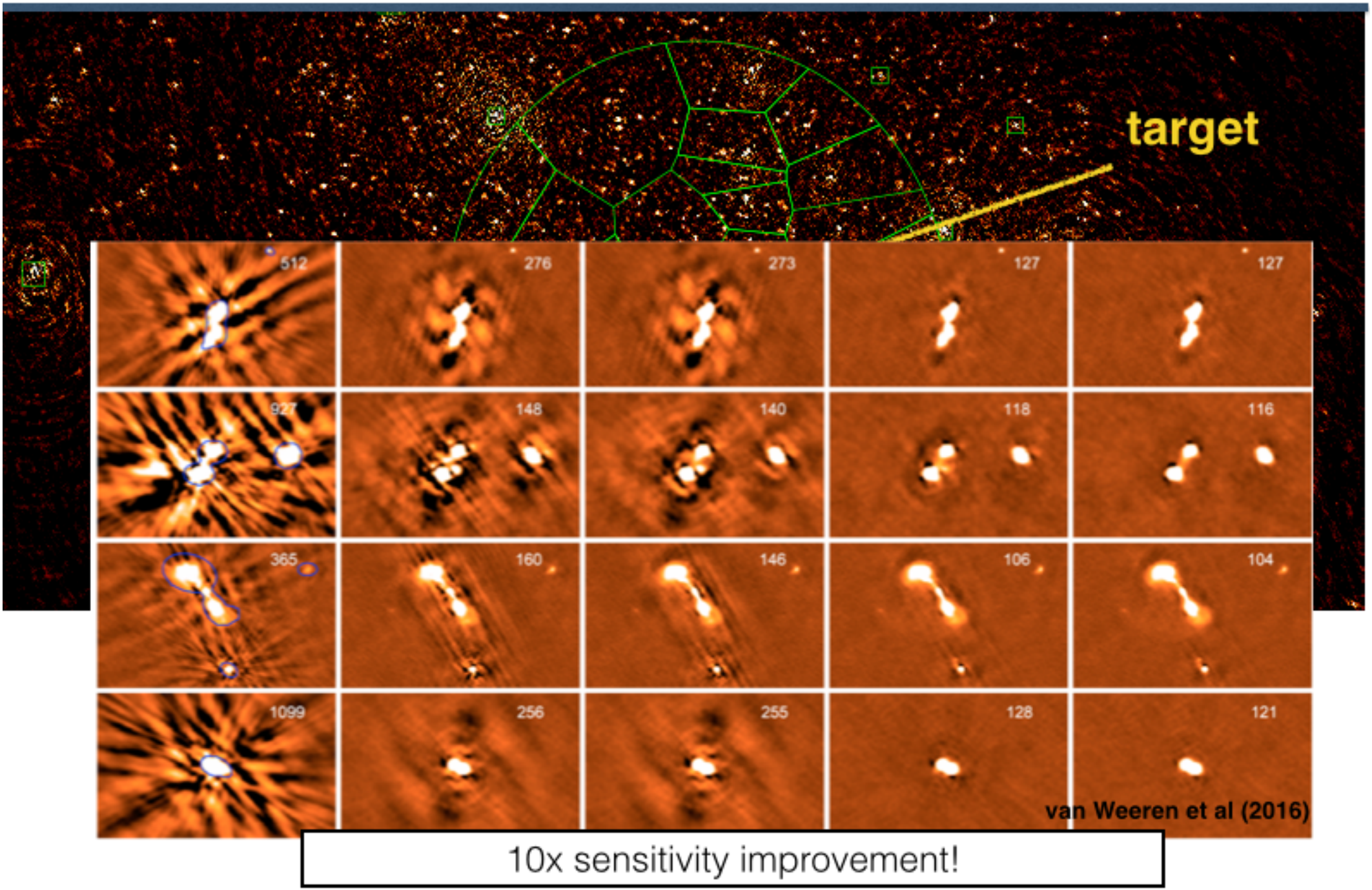
Phase corrections
58 stations
42 directions
1 solution every 10 sec



Credits: Maaijke Mevius, R. van Weeren and EoR LOFAR KSP

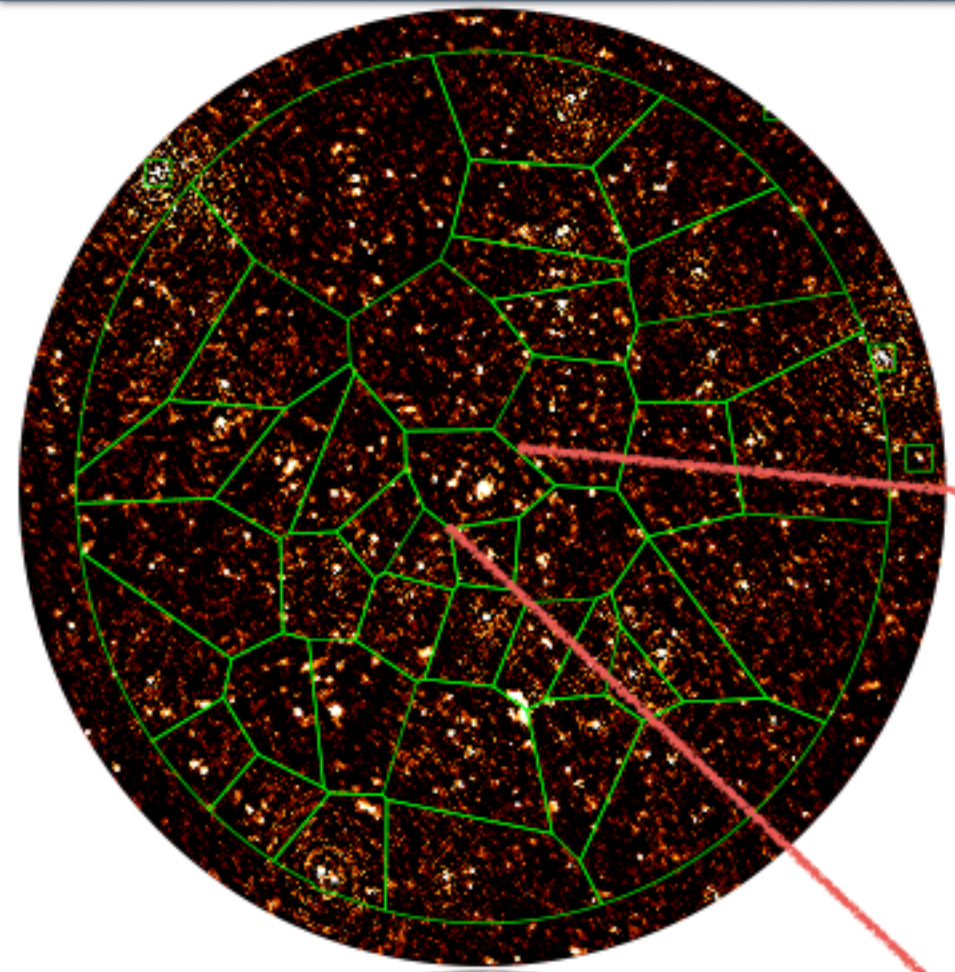

15 degrees

New technique: Facet calibration



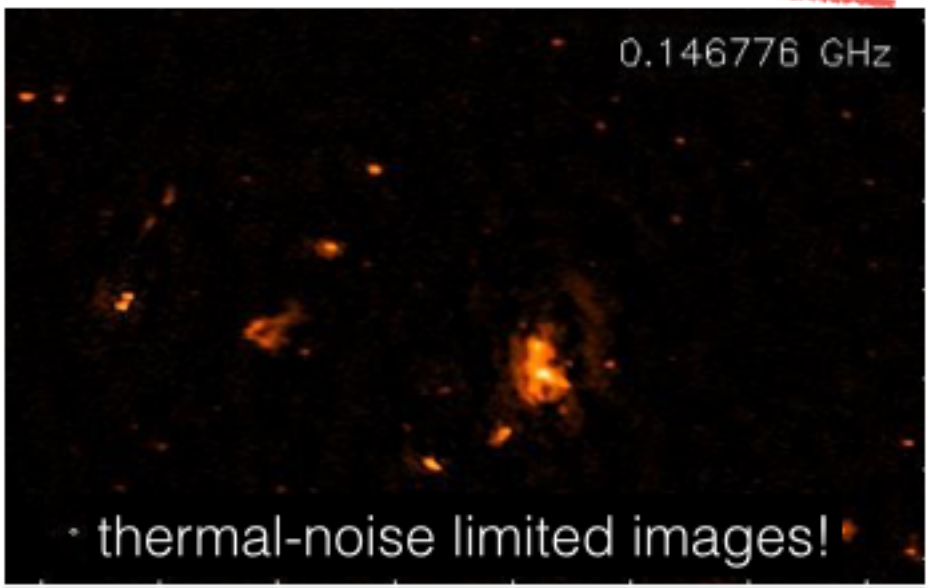
10x sensitivity improvement!

New technique: Facet calibration



LOFAR HBA: 120-190 MHz
field of view 5 degrees

directional dependent effects to track:
ionosphere - ***sky***
gains - ***instrument***
station beam - ***instrument***



keep data at 1s res
0.1 KHz res
Typical dataset (8h obs time) ~33 TB

Low Frequency **technical** take-home message

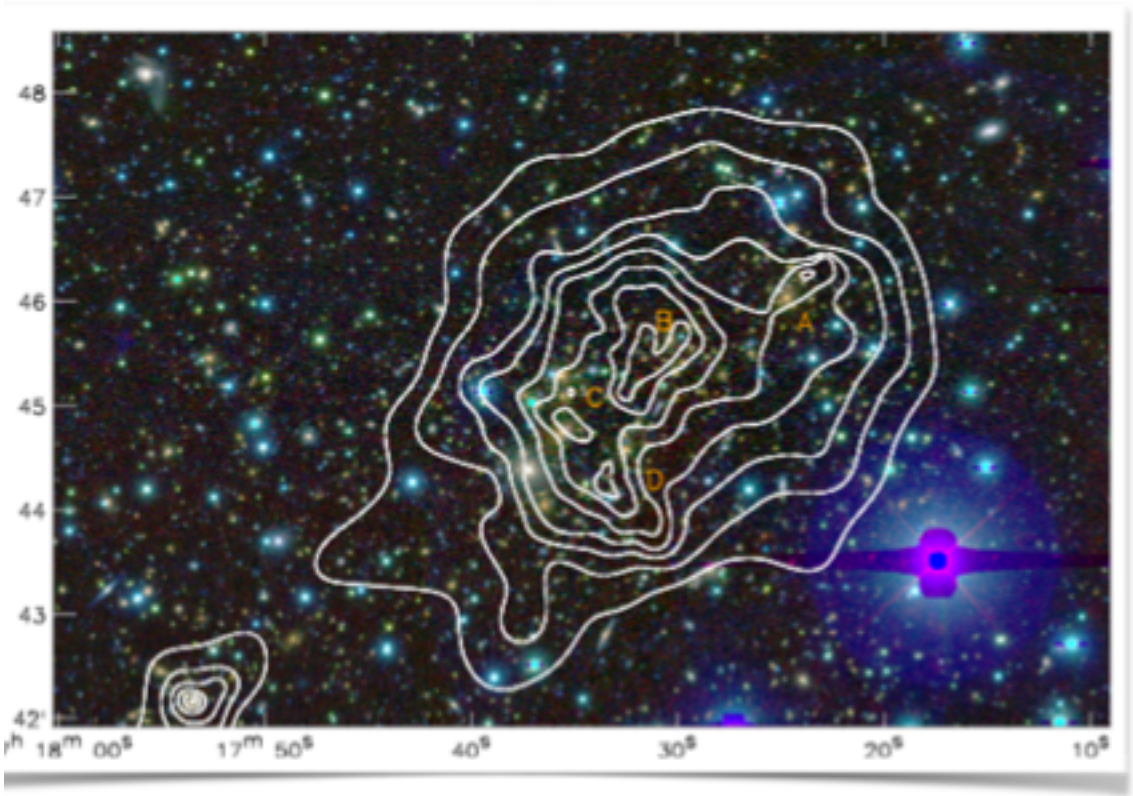
✔ Stepping into a **new era** - supercomputing resources

In **2015:**
Facet calibration on the full field of view:
24 core (two 12-core Xeon E5-2695v2.4 CPUs) machine with 256 GB RAM.
net processing time ~ **4 months**.

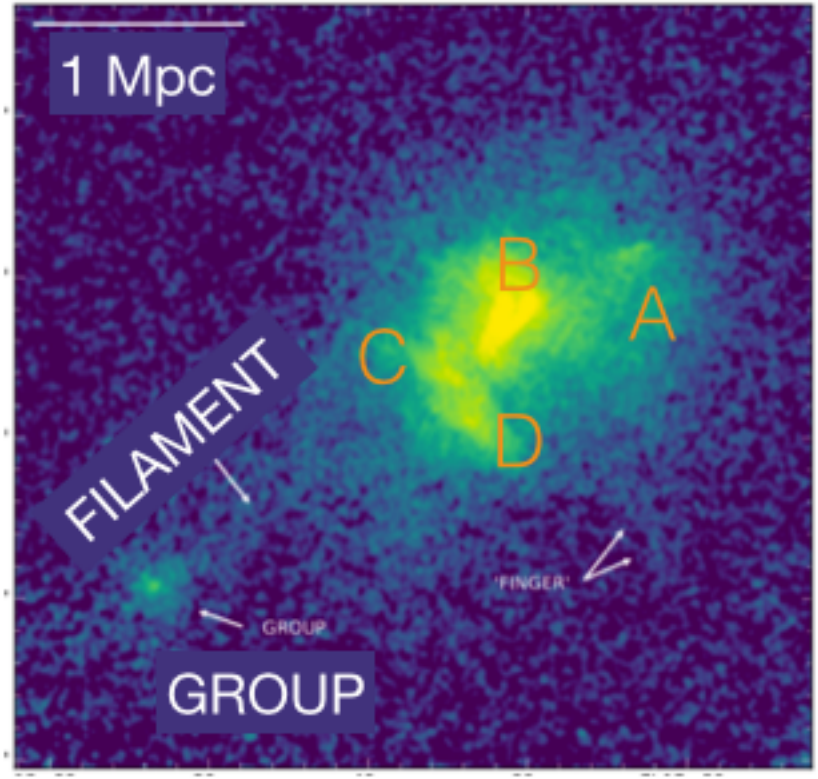
Now reduced to **~3-4 weeks**

✔ **crucial step towards the SKA**

MACSJ0717+3745, z=0.546



SUBARU gri Umetsu et al (2014)
Contours: Chandra 0.5 - 4 keV (Ebeling et al 2006)

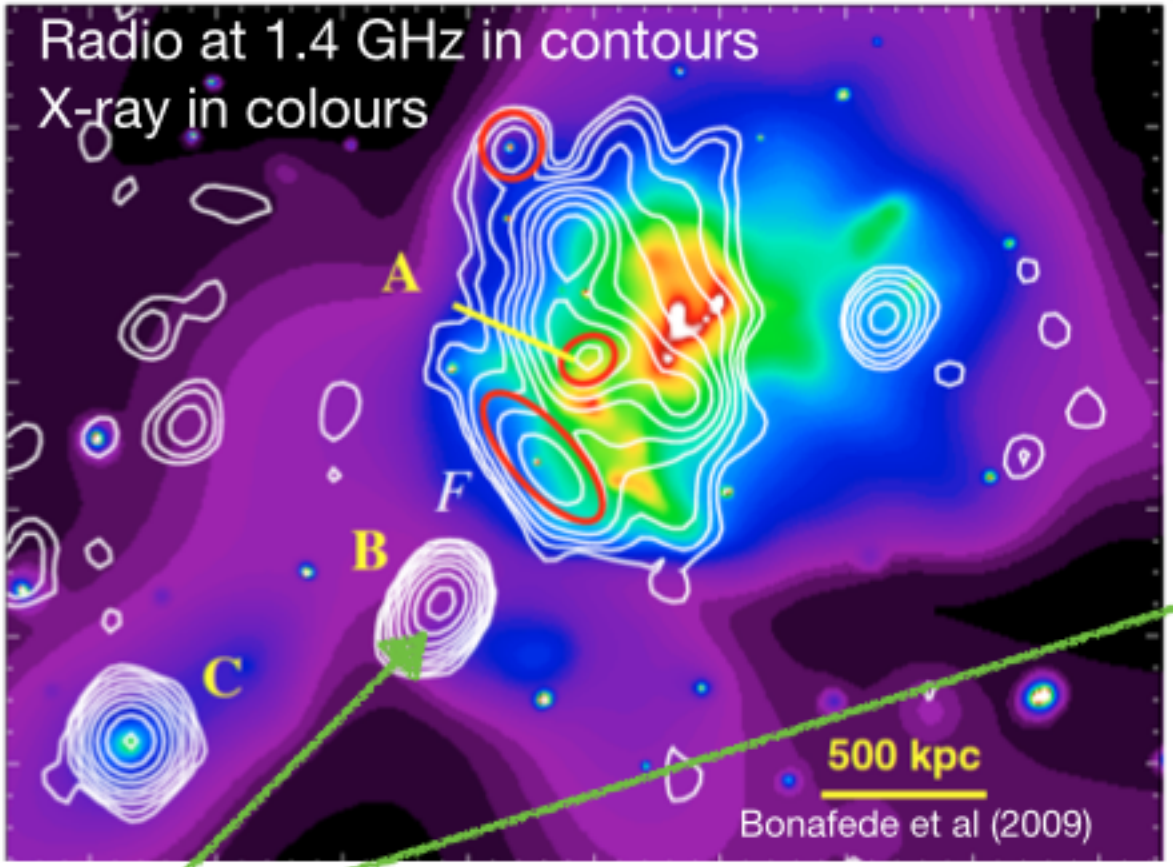


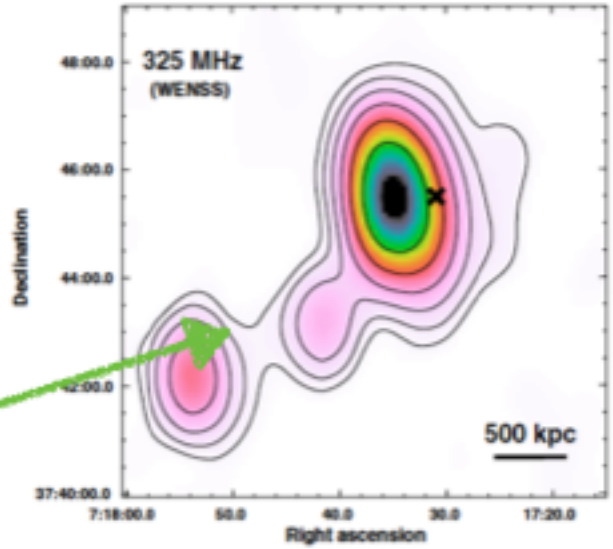
Chandra 0.5 - 4 keV (Ogrean et al submitted)

M_{500} ~11.5 10^{14} Msun
Four subclusters merger

- 19 Mpc long filament (Jauzac et al 2012)
- X-ray emission from the filament

MACSJ0717+3745

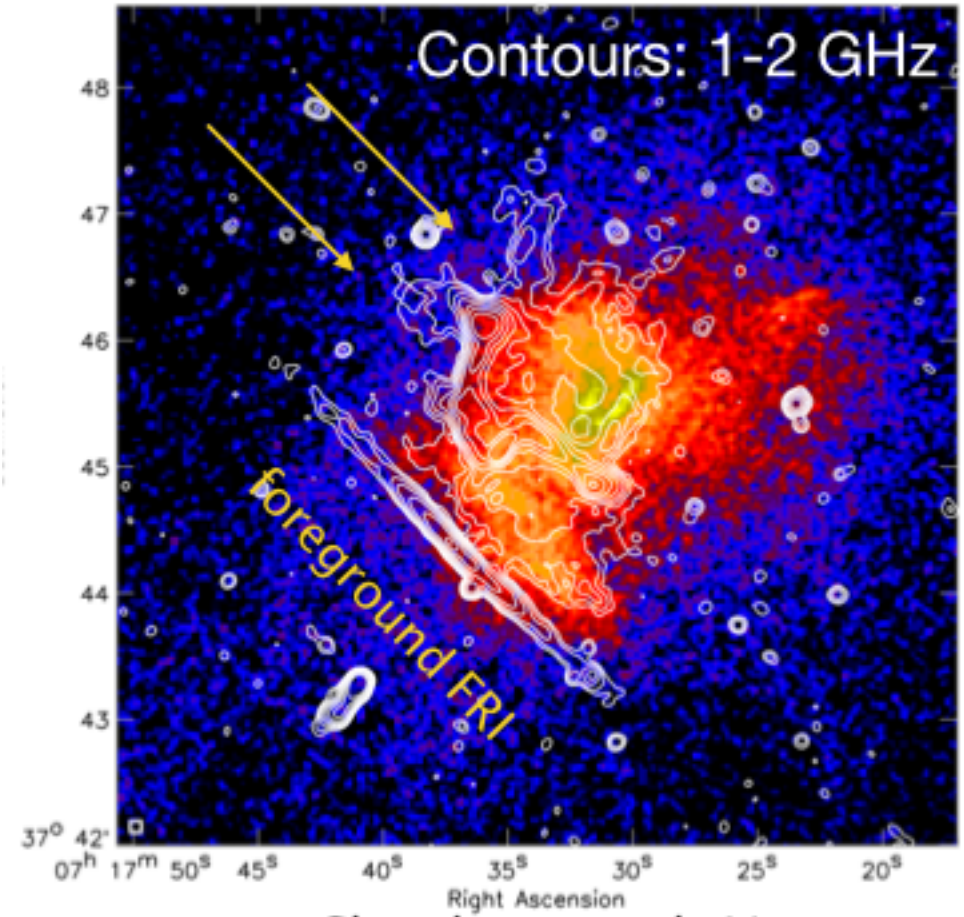




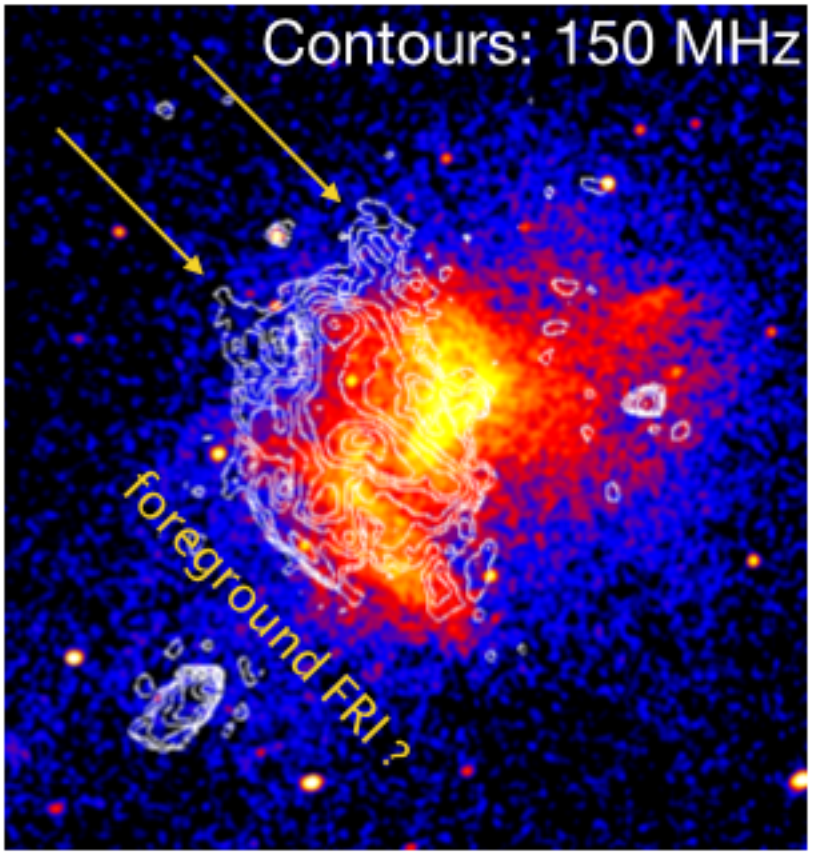
In-falling Group

Radio emission not spatially correlated with X-ray
Emission from the filament?

Comparison with Jansky VLA observations



Chandra [0.5 - 4 keV]
Jansky VLA L band - 5"
(van Weeren et al 2017)



Chandra [0.5 - 4 keV]
LOFAR HBA 4"x6"
first contour at 0.4 mJy/beam

MACSJ0717+3745

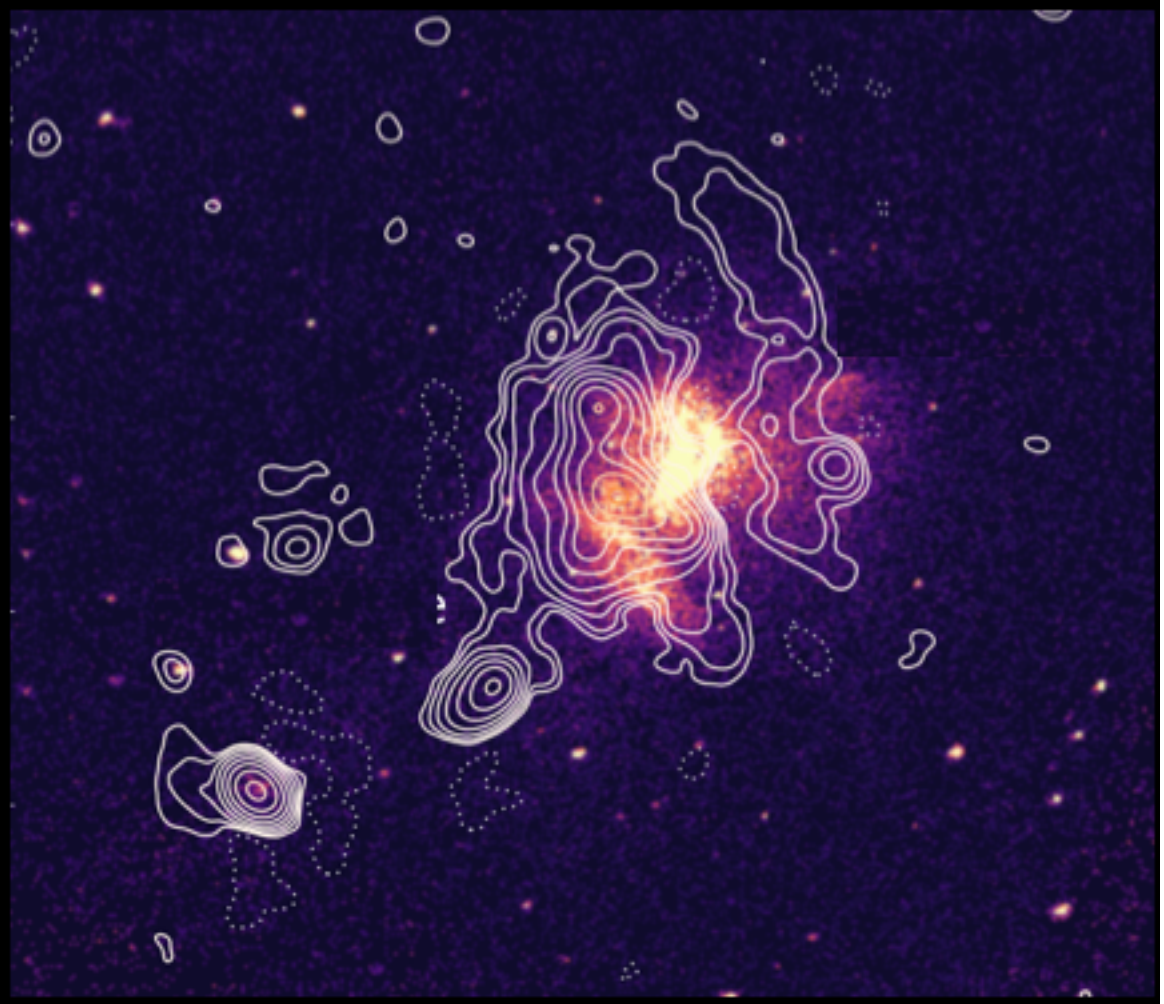
Radio arc - 1.7 Mpc

$\alpha_{[150MHz - 1.4\ GHz]} < -1.3$

Bridge - emission along the accreting filament ~600 kpc

$\alpha_{[150MHz - 1.4\ GHz]} < -1.4$

Radio emission does not correlate with X-ray

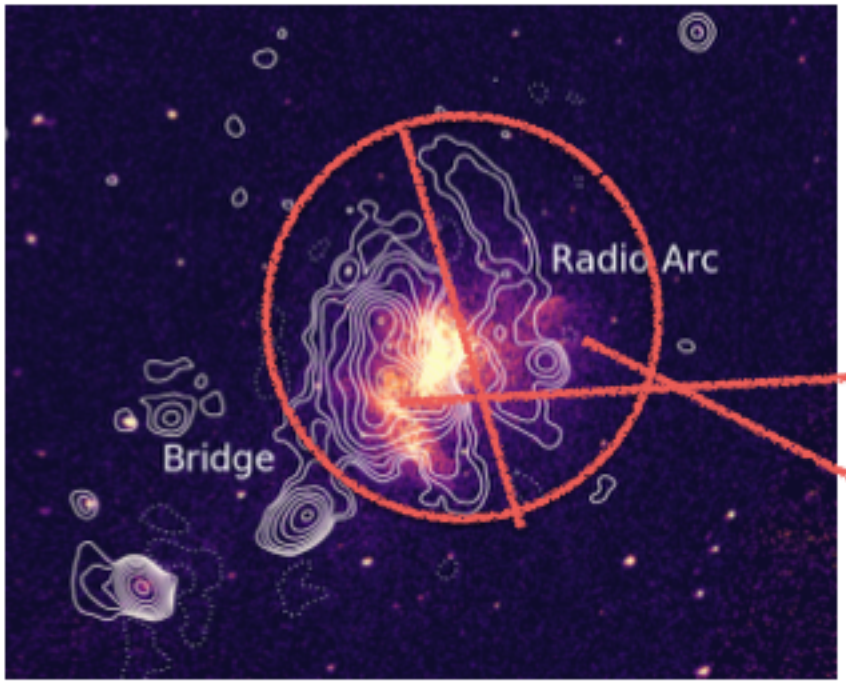


LOFAR emission at 146 MHz in contours
rms noise ~150 Jy/beam, resolution 18”

Chandra X-ray emission in colours

Bonafede & LOFAR cluster collaboration

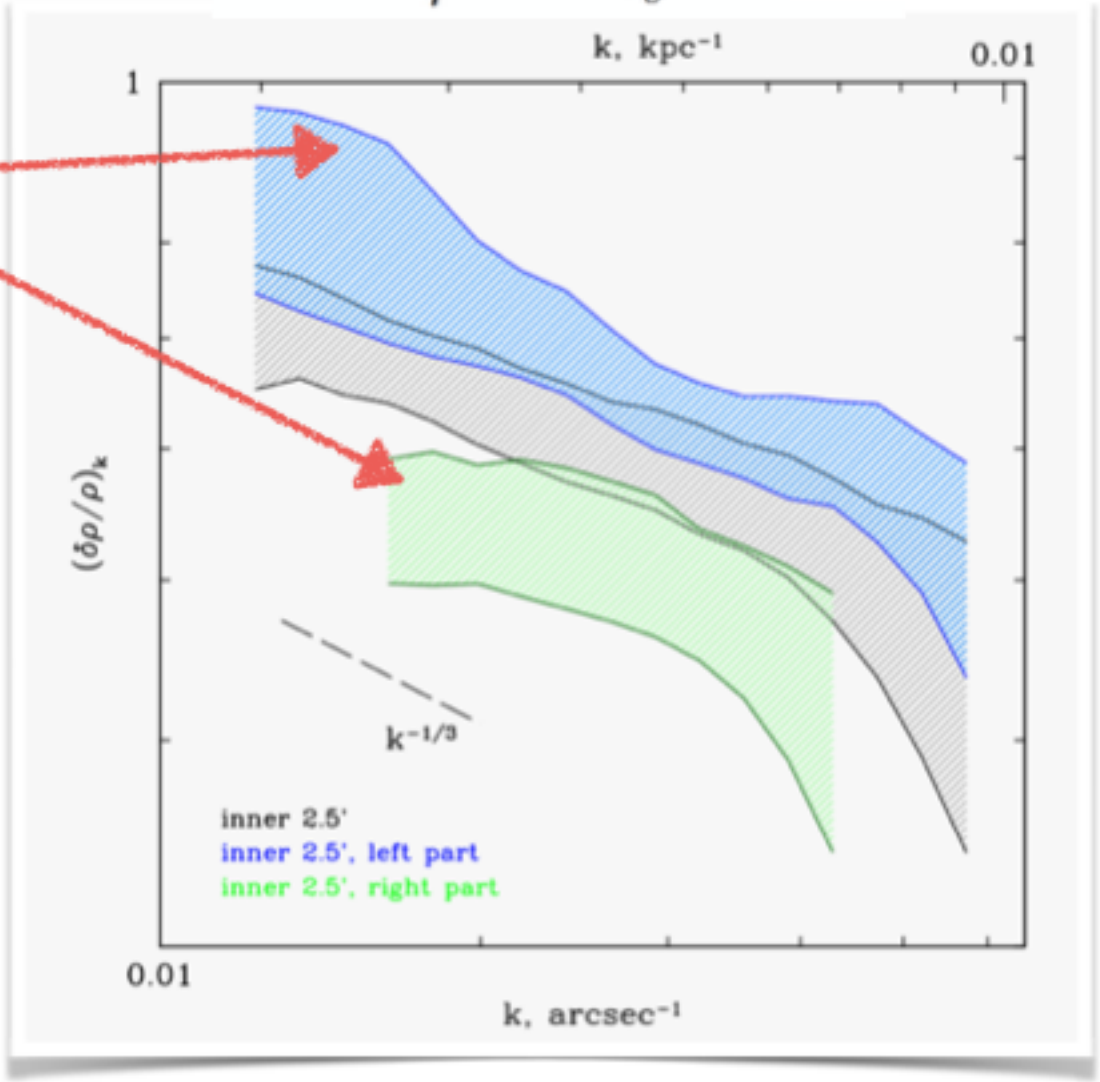
Interplay radio plasma - thermal gas



Gas density fluctuations

$$\frac{\delta\rho_k}{\rho} = \eta\frac{V_k}{c_s}$$

Zhuravleva et al. 2014,
Gaspari et al 2014



E_kin/E_therm twice larger in the left region

Radio Power > 30 times higher

Conclusions (so far)

✔ LOFAR observations → additional emission discovered!
→ emission ahead of the infalling group

✔ Radio emission in regions of higher E_{kin}/E_{therm}

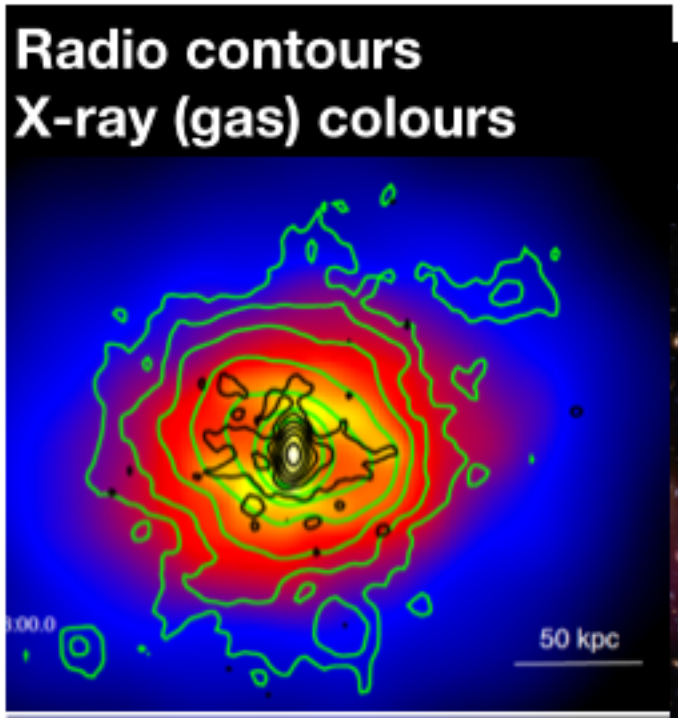
OPEN QUESTIONS (I will discuss in this talk)

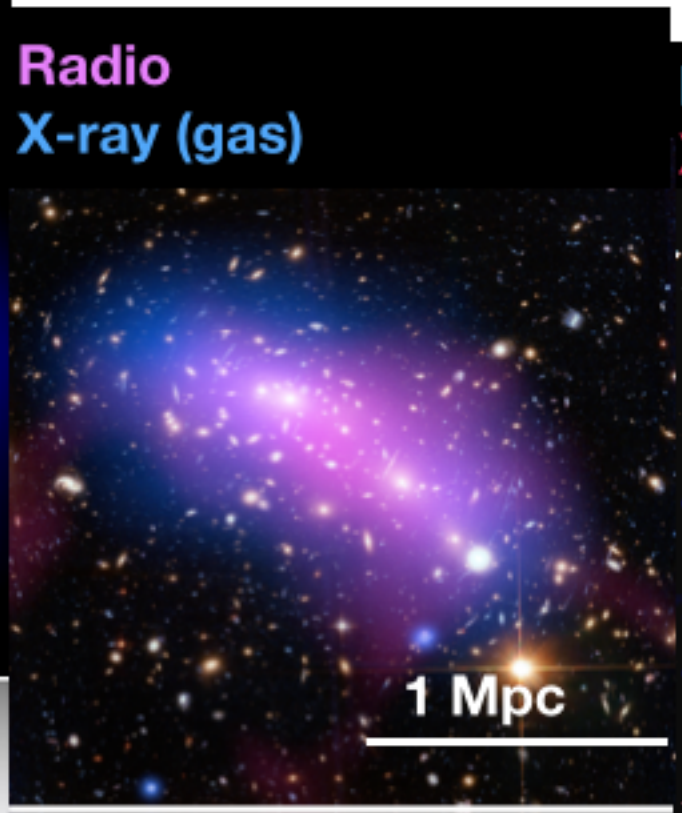
- Shock and turbulent acceleration —>Seed population of mildly relativistic CR e emitting al low freq?

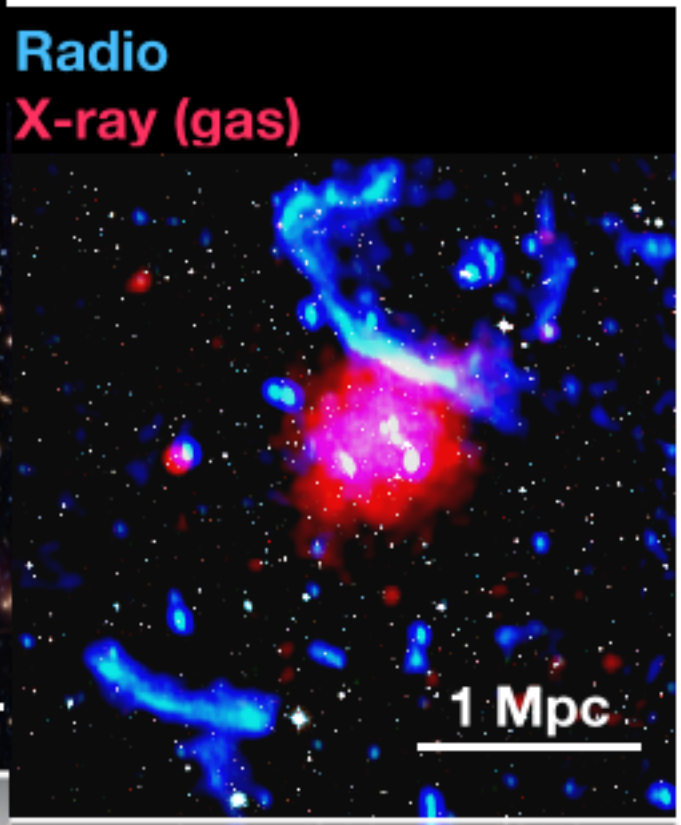
- Is there a connection between these sources?

- Role of the magnetic field?

RADIO SOURCES IN CLUSTERS







Virialized systems
~100 kpc

Merging systems
~1 Mpc

Tracing **co-evolution** of non-thermal component with **cluster dynamics**

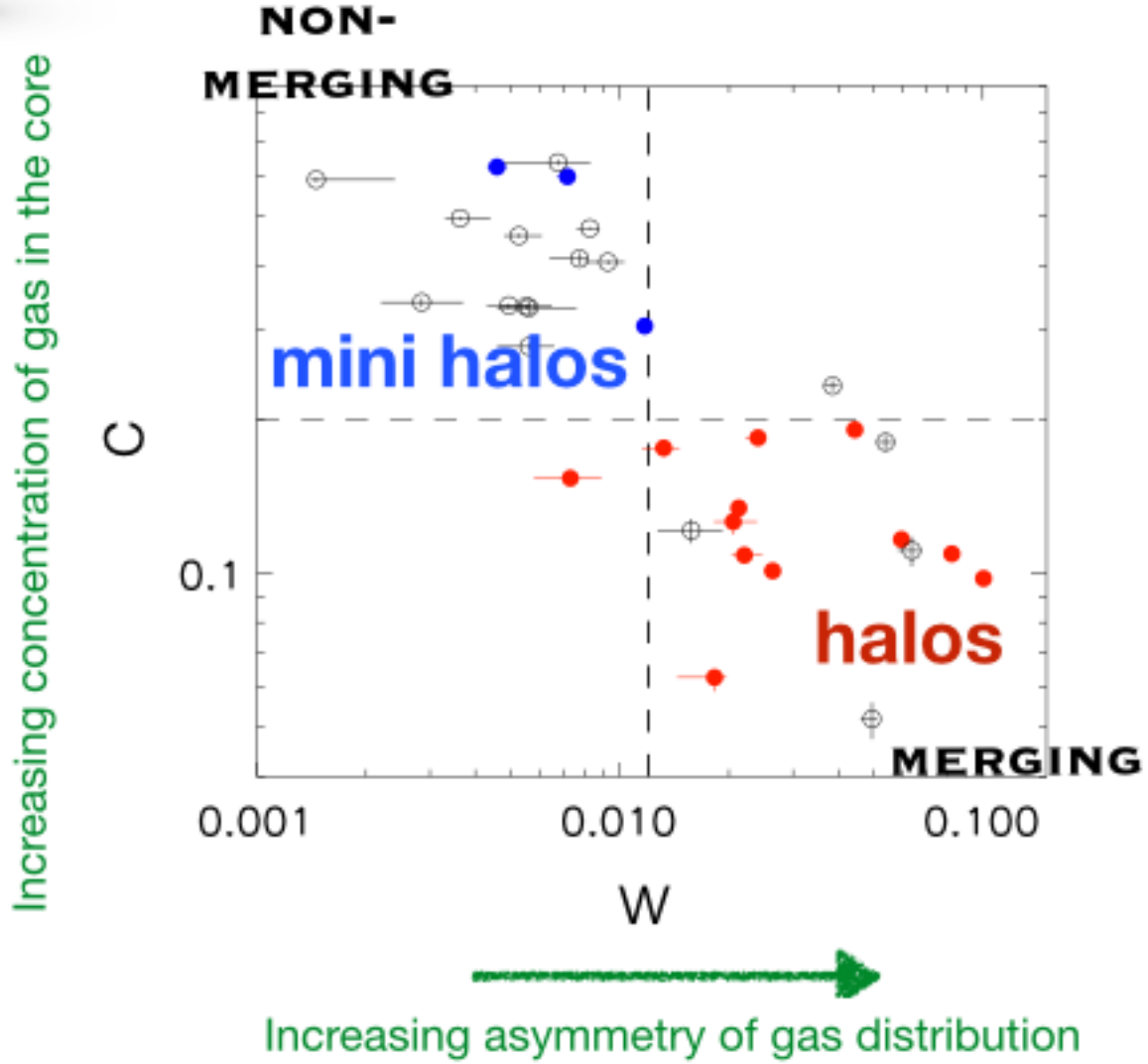
Halos and Mini halos

Correlation with cluster dynamical status

X-ray indicators of cluster dynamical status:

$$c = \frac{S(r < 100\,kpc)}{S(r < 500\,kpc)}$$

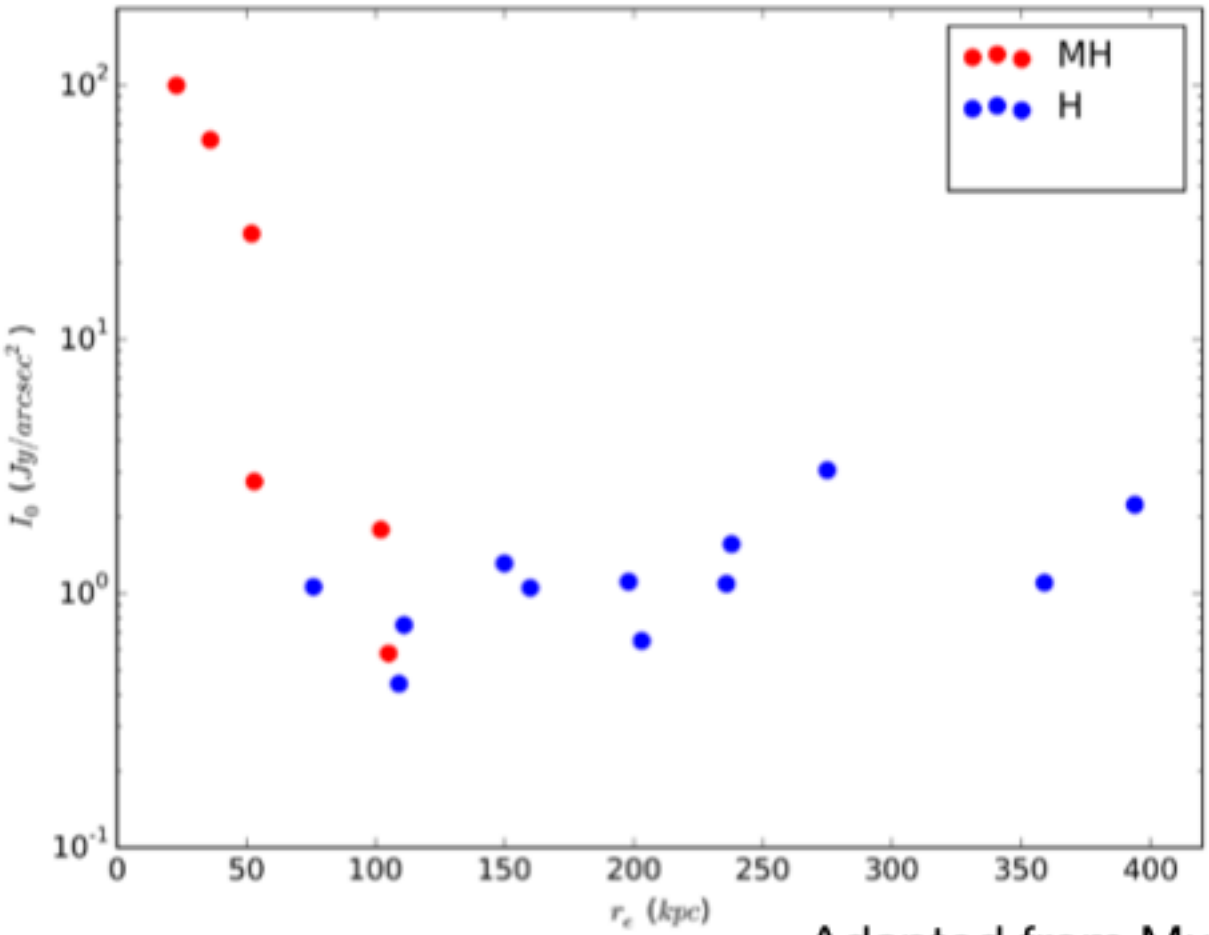
$$w = \frac{1}{R_{max}} \sqrt{\frac{\Sigma\,(\Delta_i - <\Delta>)^2}{N-1}}$$



Cassano et al. (2010)

Halos and Mini halos

$$I(r) = I_0 e^{-r/r_e}$$

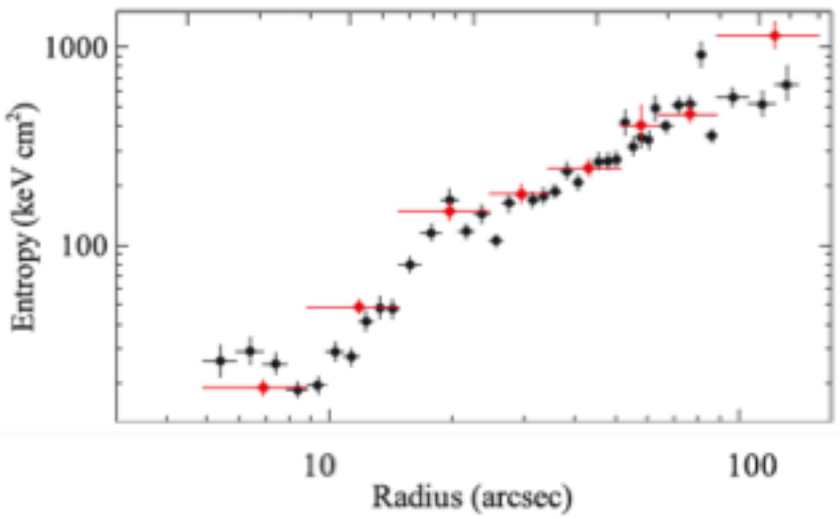


Adapted from Murgia et al (2009)

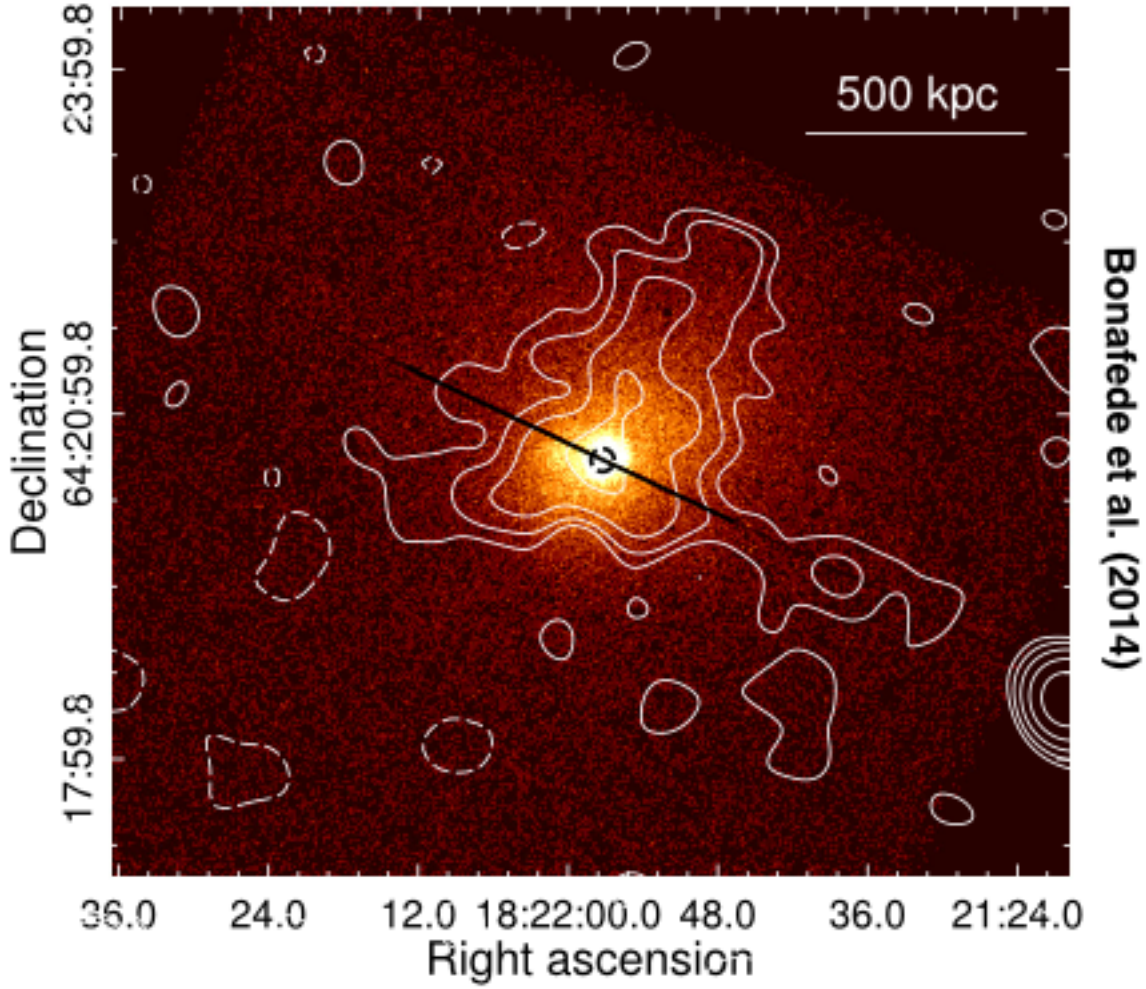
OPEN ISSUES: no major merger + halos

Cluster: CL1821+643

M_{500} ~6.3 10^{14} Msun
Strong cool-core t_{cool}~1 Gyr



Russell et al. (2010)



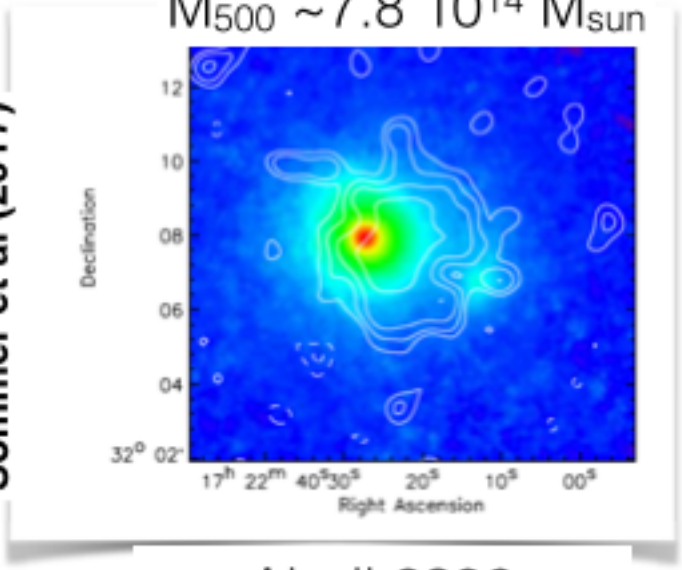
Bonafede et al. (2014)

Radio emission at 325 MHZ in contours
X-ray emission in colours

TWO MORE CASES

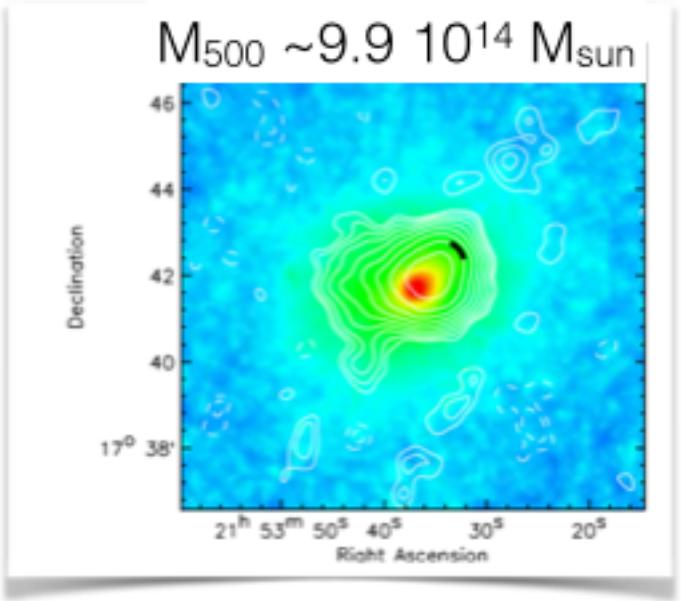
Abell 2261

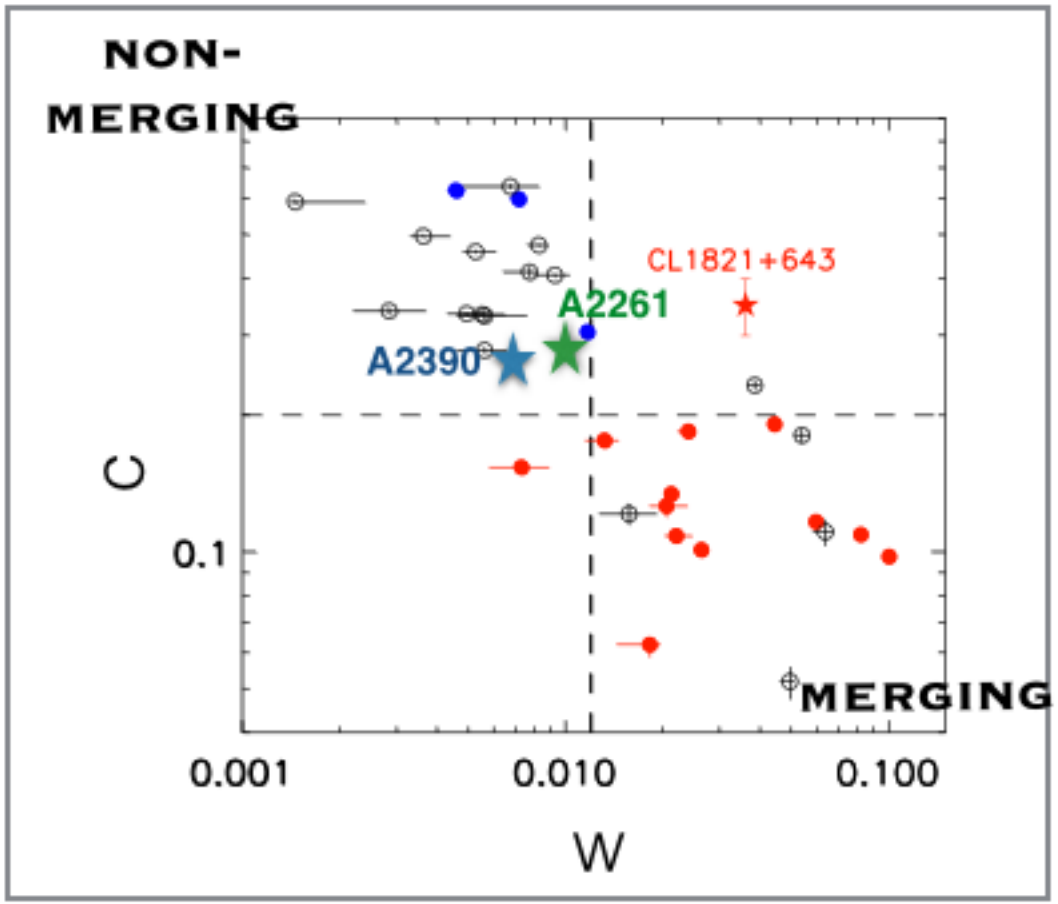
M_{500} ~7.8 10^{14} M_{sun}



Abell 2390

M_{500} ~9.9 10^{14} M_{sun}

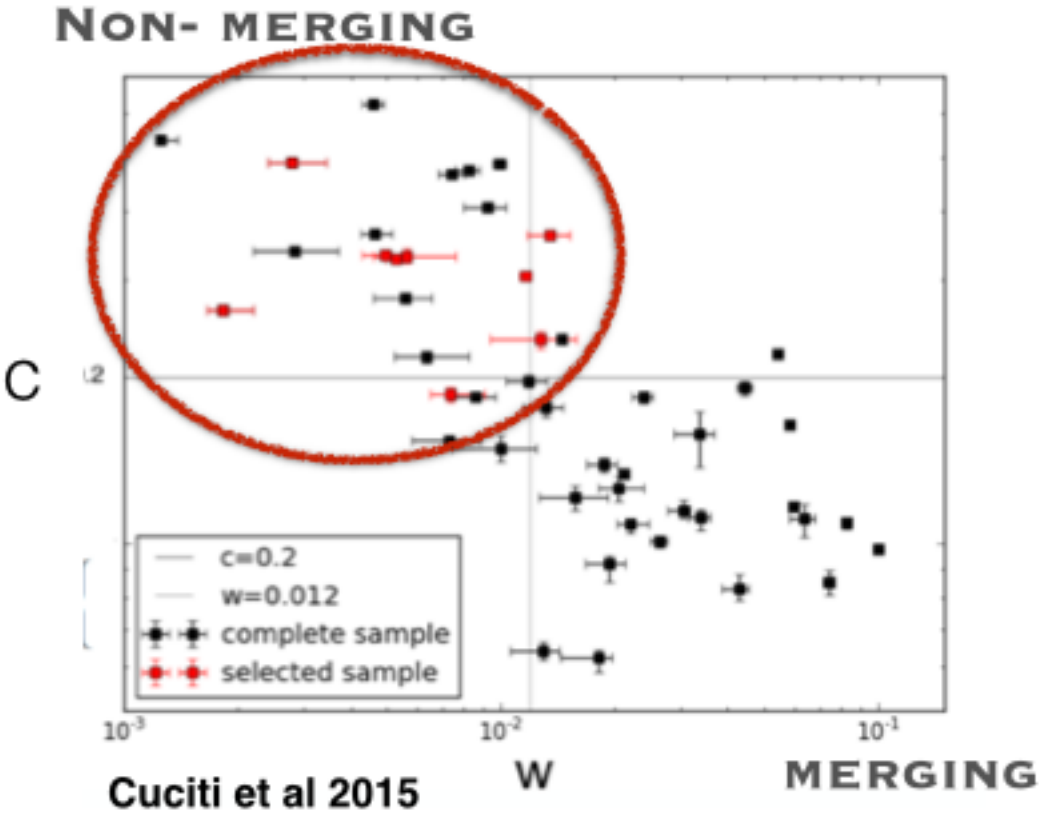




X-ray in colours, radio in contours

RADIO MINI HALOS AND RADIO HALOS

Mini halos and halos are at the extreme ends of a whole spectrum of sources?

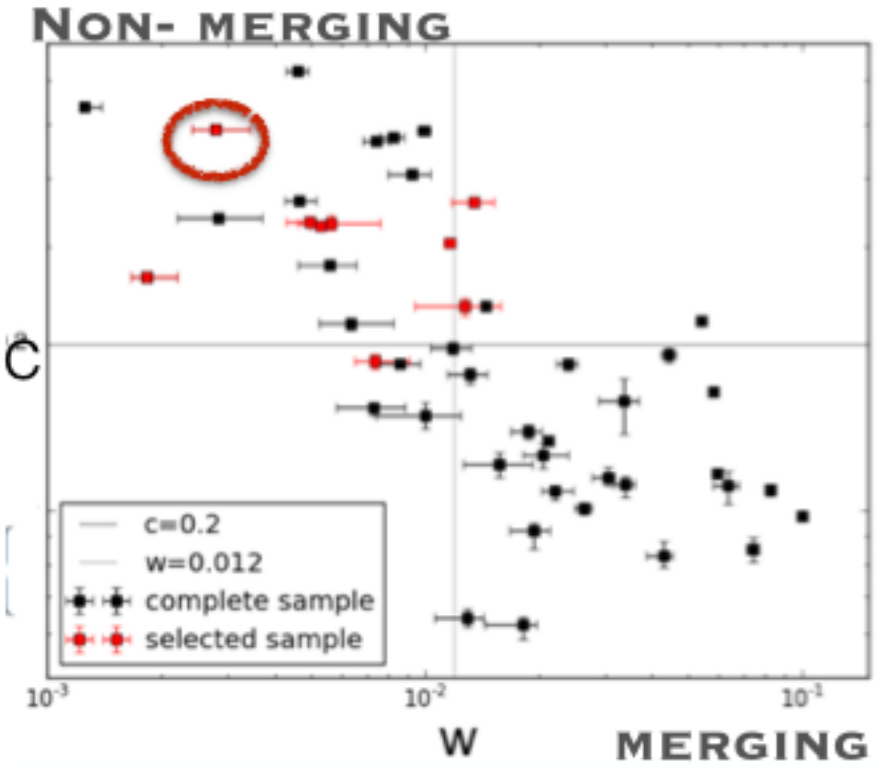


Cuciti et al 2015

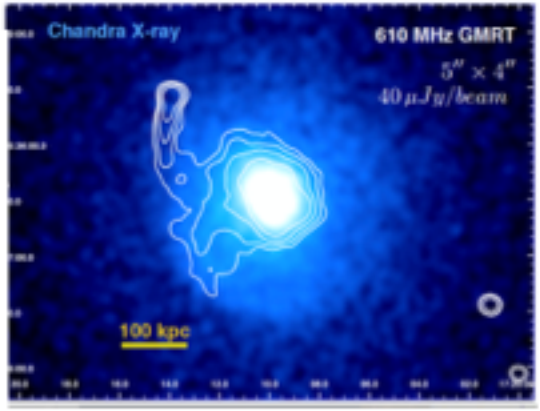
LOFAR observations

PhD thesis - Federica Savini
(Hamburg University)

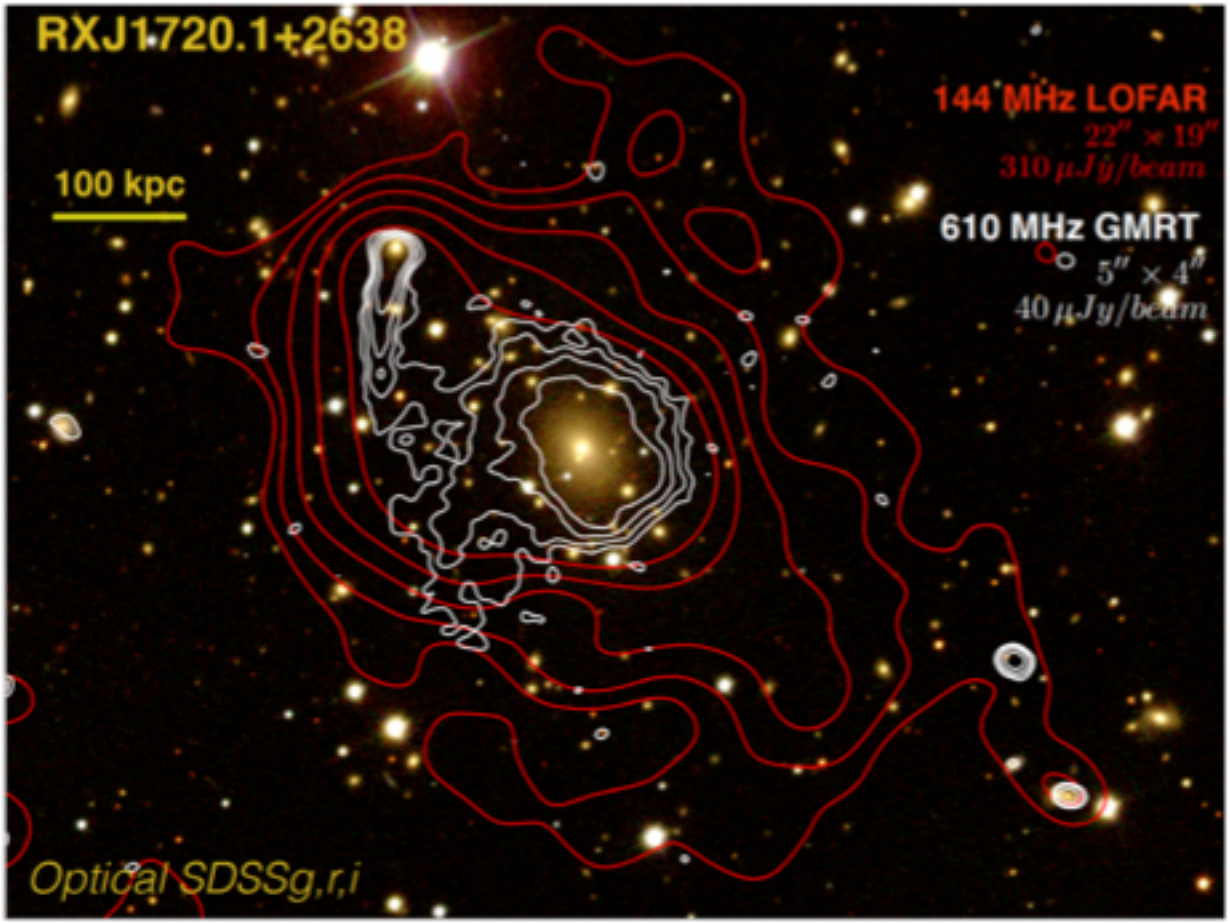
NO MAJOR MERGER + HALO



Cuciti et al 2015

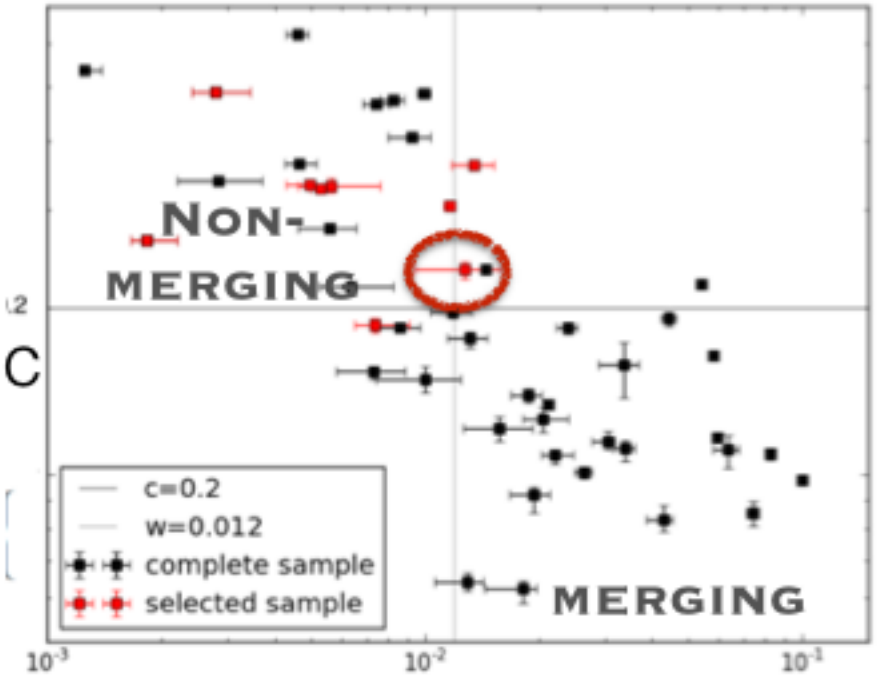


Mini-halo
Giacintucci et al 2014



F. Savini, AB + in prep

NO MAJOR MERGER + HALO



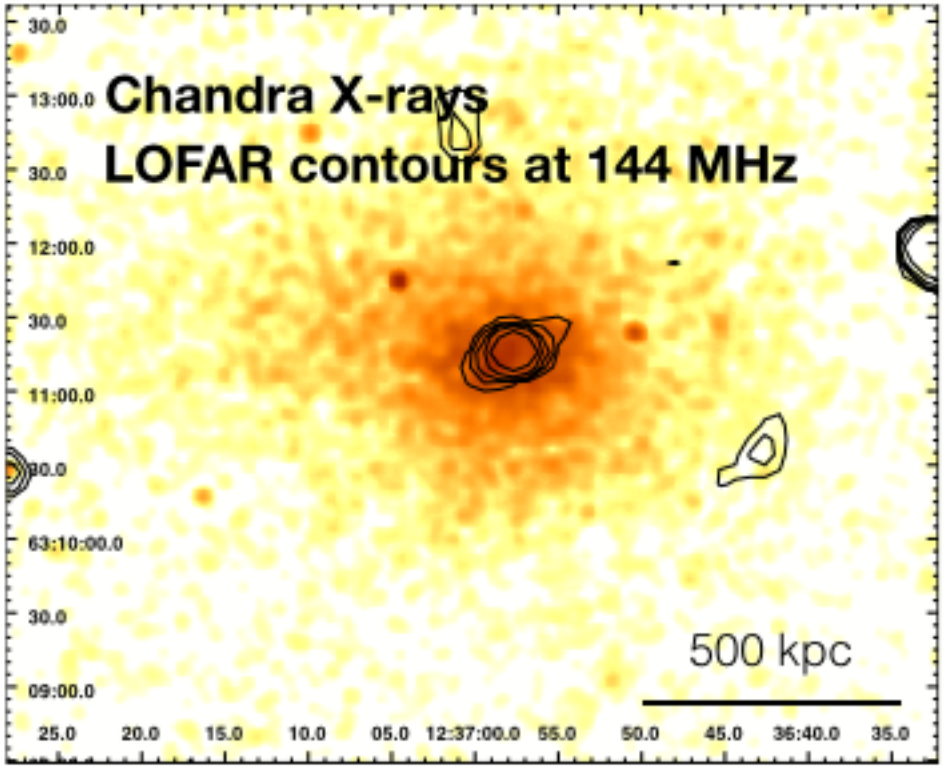
Cuciti et al 2015

A1576

$M_{500} = 5.98\ 10^{14}$ Msun

No diffuse emission at 610 MHz

(Venturi et al 2007)



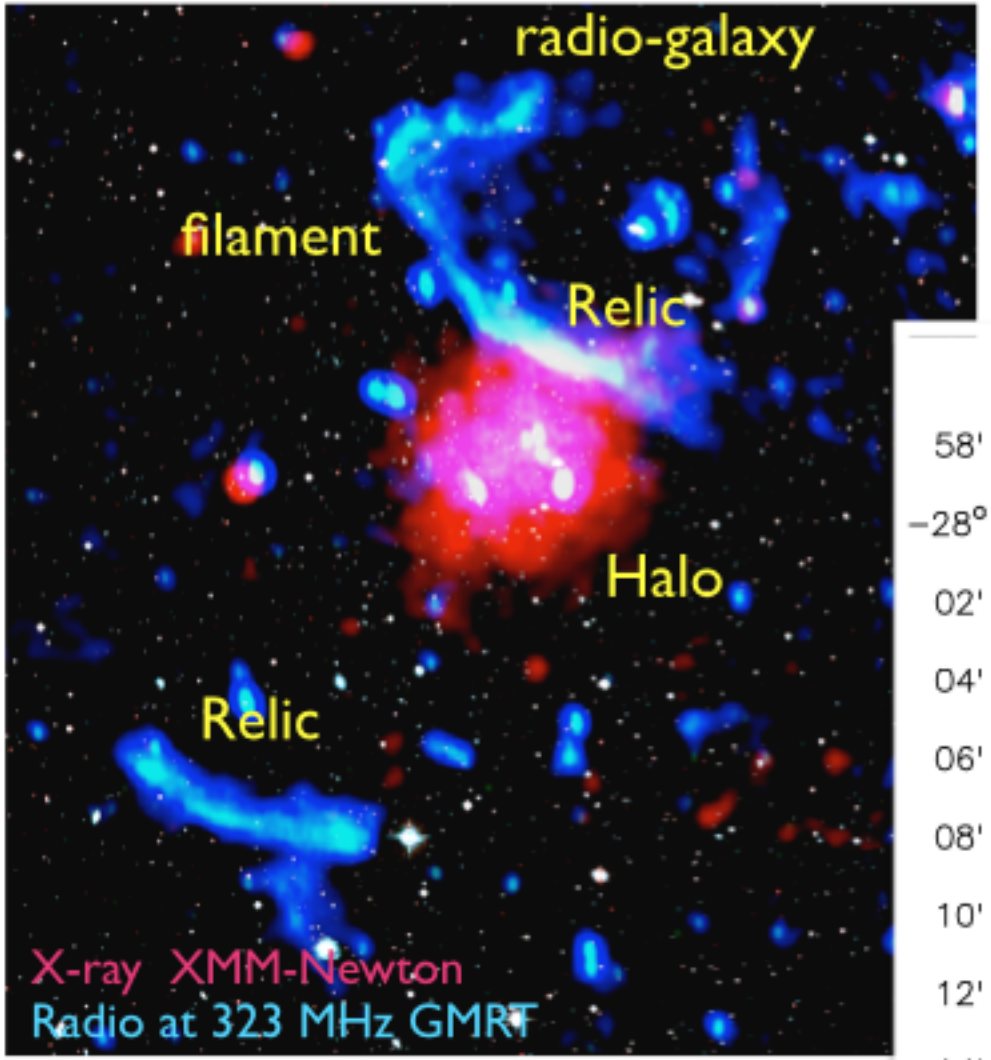
No diffuse emission detected by LOFAR

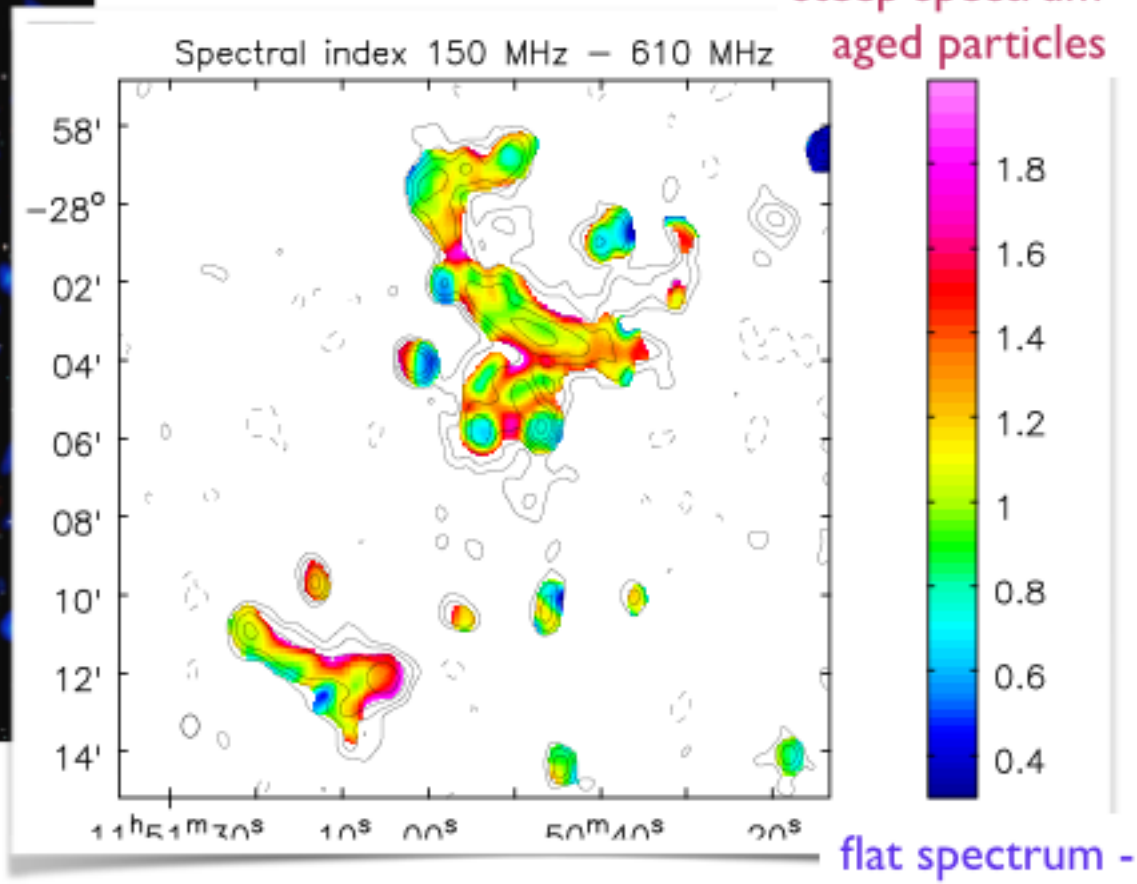
F. Savini, AB + in prep

Conclusions (so far)

- ✔ LOFAR observations → additional emission discovered!
  → emission ahead of the infalling group
- ✔ Radio emission in regions of higher E_{kin}/E_{therm}
- ✔ Found 1st case of mini halo turning into a radio halo
- ✔ How/when radio emission is switched on?

ROLE OF SEED ELECTRONS FROM AGN? RELICS



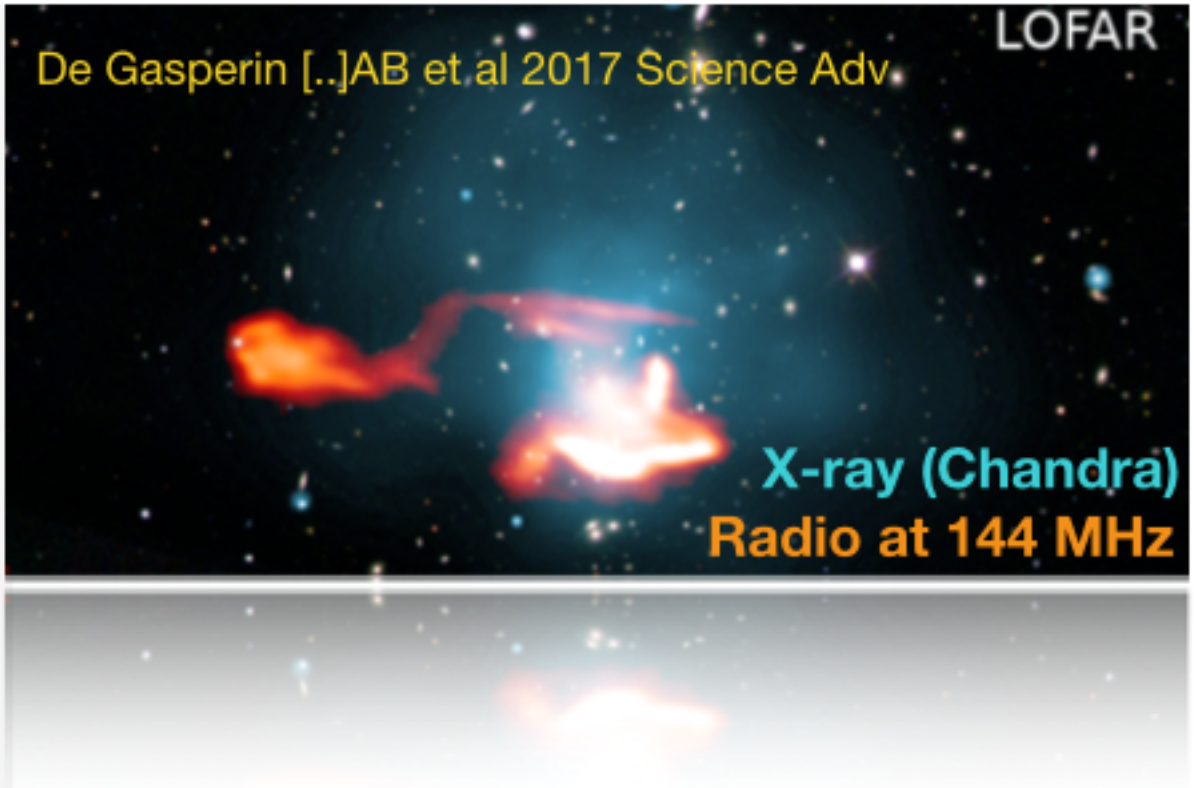


steep spectrum - aged particles

flat spectrum - young particles

Bonafede et al. (2014)

ROLE OF SEED ELECTRONS FROM AGN in HALOS?



1-2 Mpc-Long radio tails observed at low frequencies

—> New paradigm for CR e life-cycle in the ICM

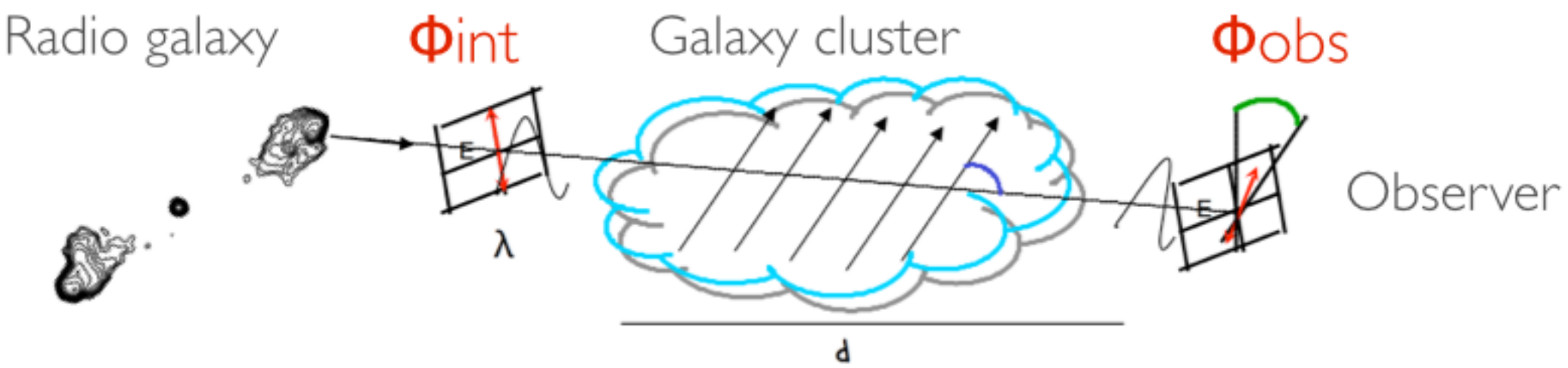
OPEN QUESTIONS (I will discuss in this talk)

- Shock and turbulent acceleration —>Seed population of mildly relativistic CR e emitting al low freq?

- Is there a connection between these sources?

- Role of the magnetic field?

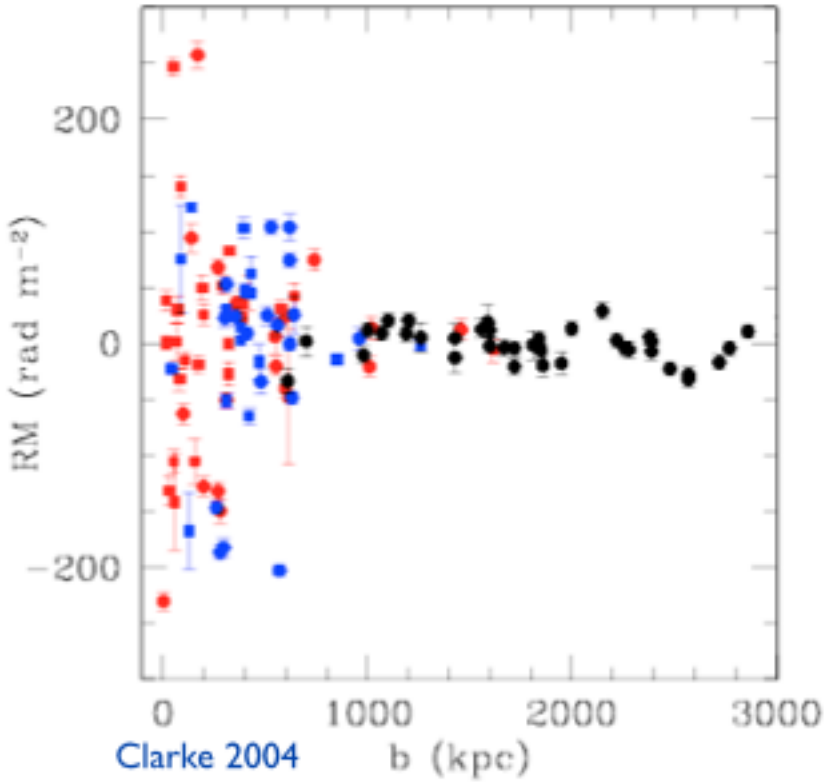
The Faraday Rotation



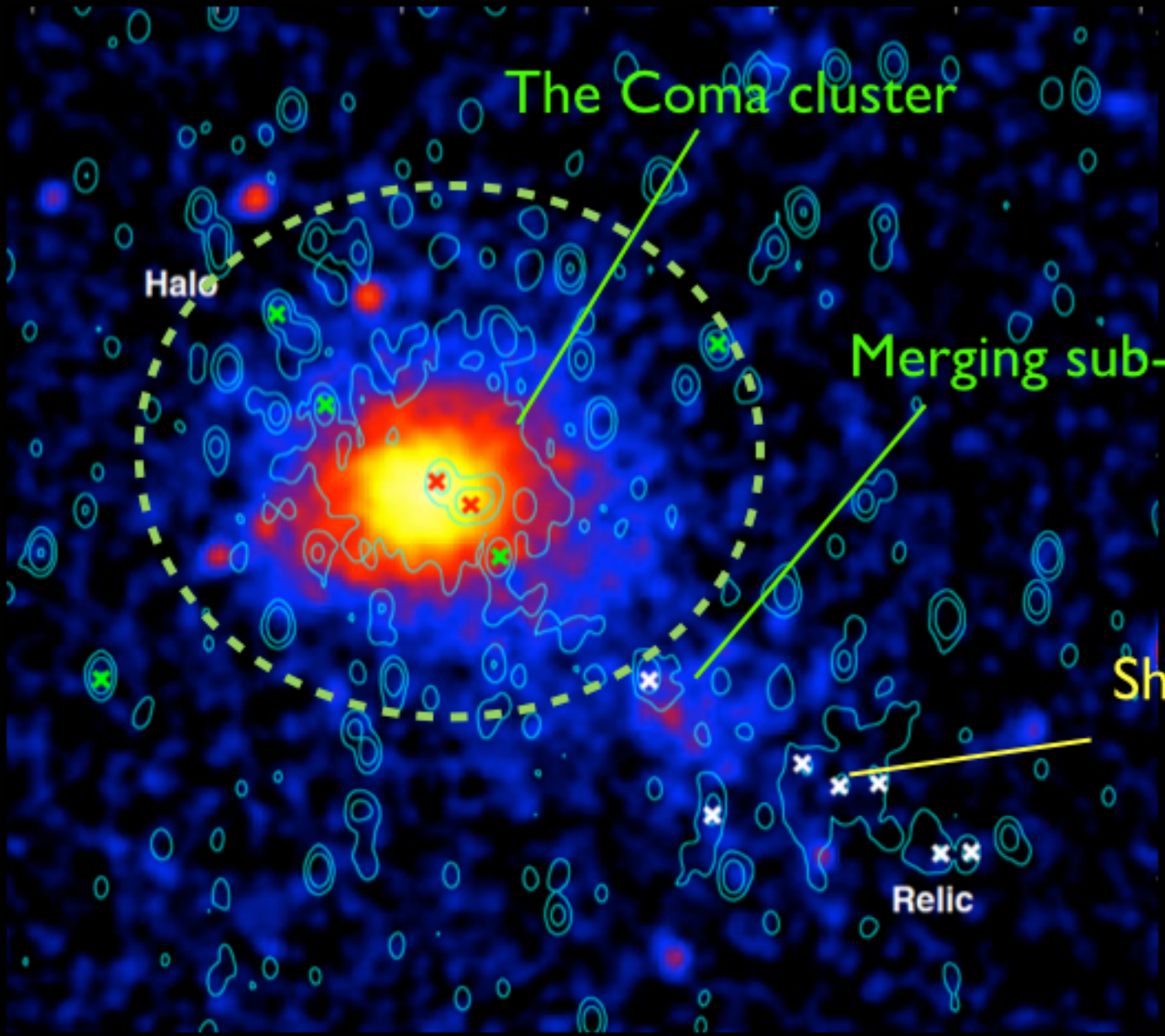
Rotation Measure
RM

$$\Phi_{obs} = \Phi_{int} + RM\lambda^2$$

$$RM = \int_0^d B_{los} n dl$$



HOW CAN WE CONSTRAIN THE MAGNETIC FIELD?



Ogrean & Brüggen 2013
Akamatsu et al. 2013

ROSAT All Sky Survey in colorsRadio at 300 MHz in contours

OBTAINING MOCK ROTATION MEASURE IMAGES

observed $RM = \int_0^d B_{los} n dl$

model for gas distribution

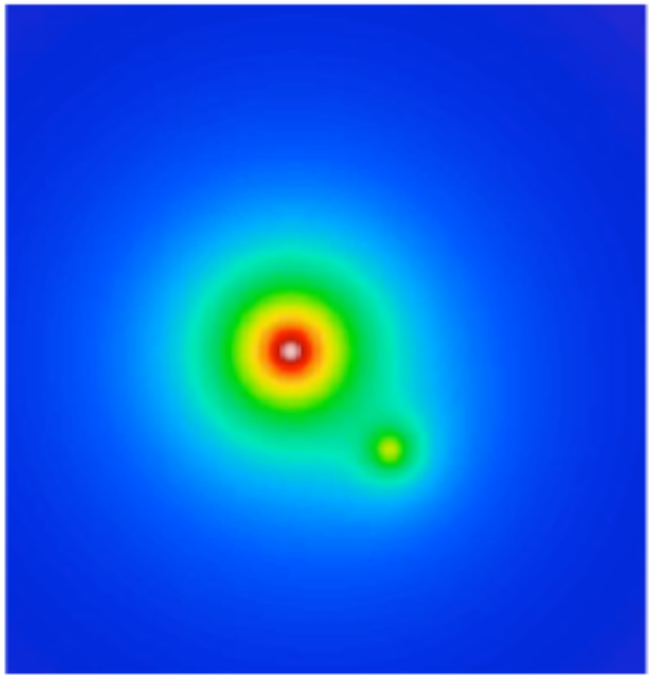
MiRo' code (Bonafede et al 2013)

3D model for the magnetic field

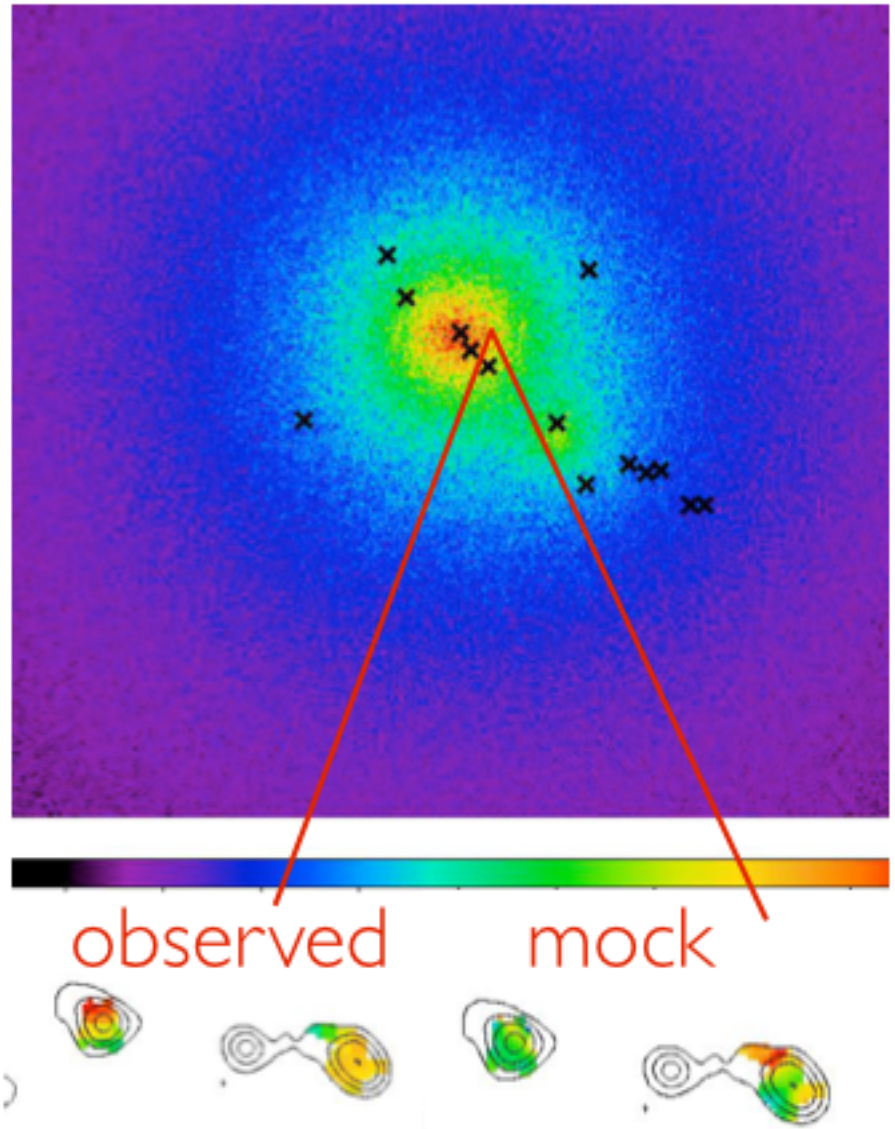
2 Isothermal gas spheres matching X-ray observations

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

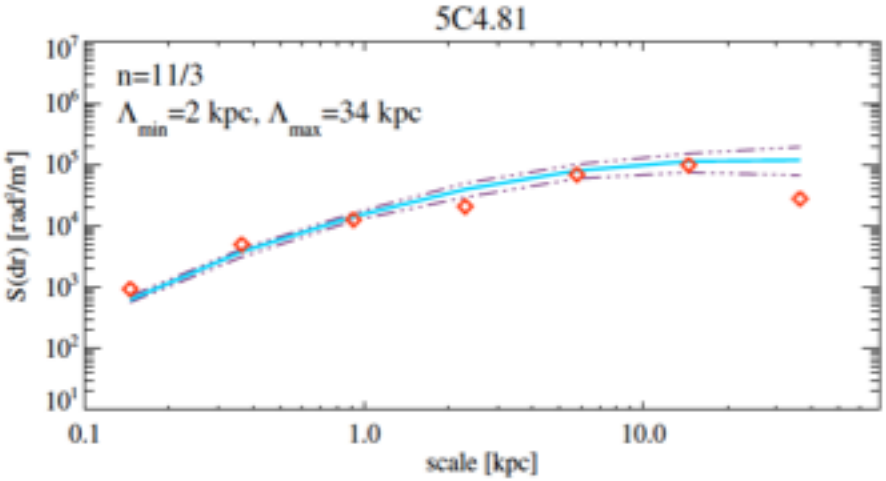
$$B(r) = B_0 \left(\frac{n_e}{n_0} \right)^{\eta}$$

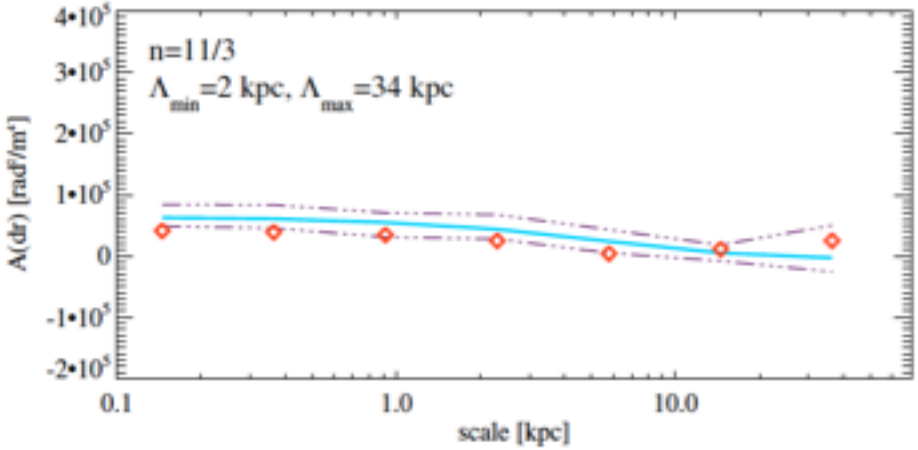


Mock observations of Rotation Measures

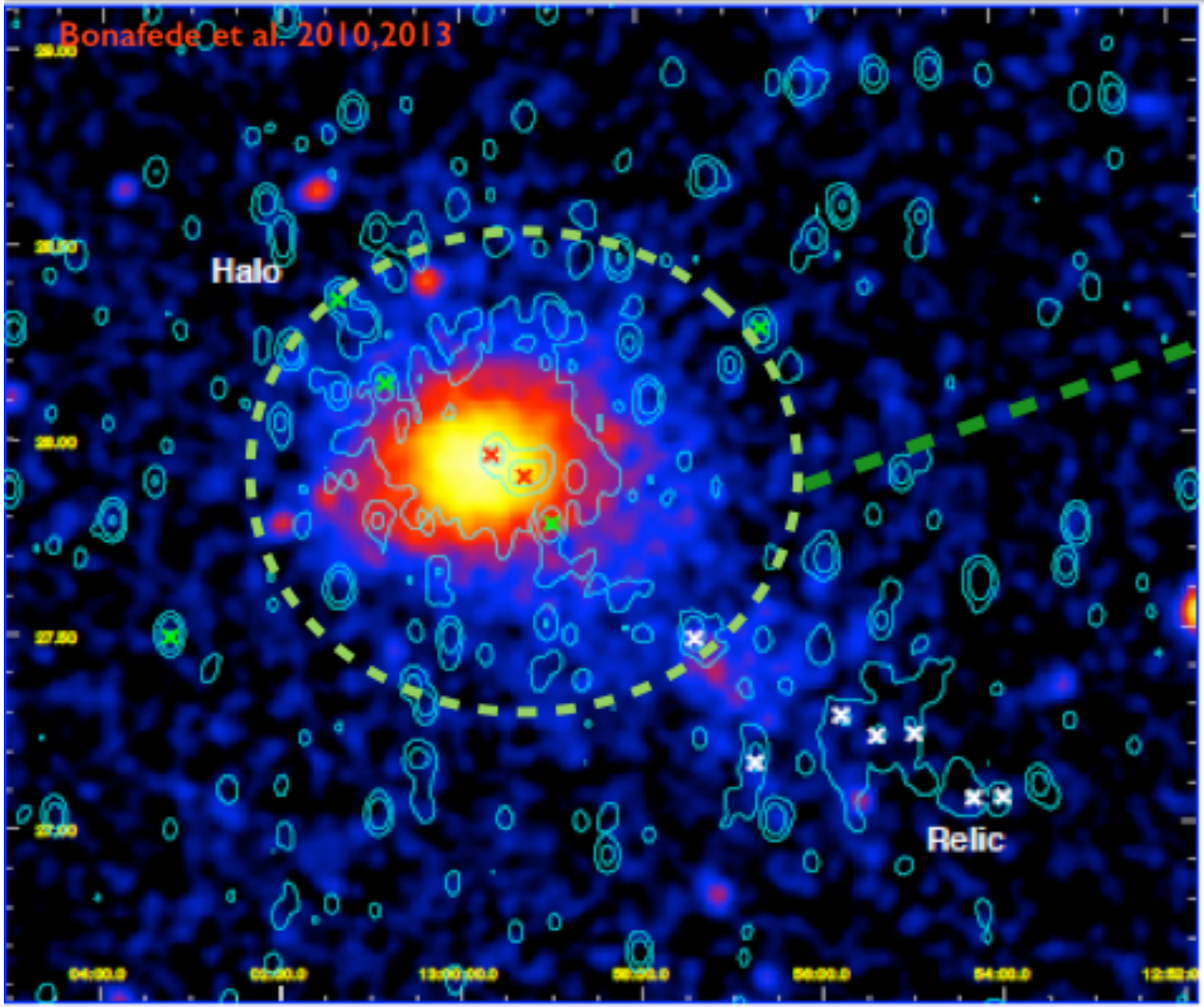


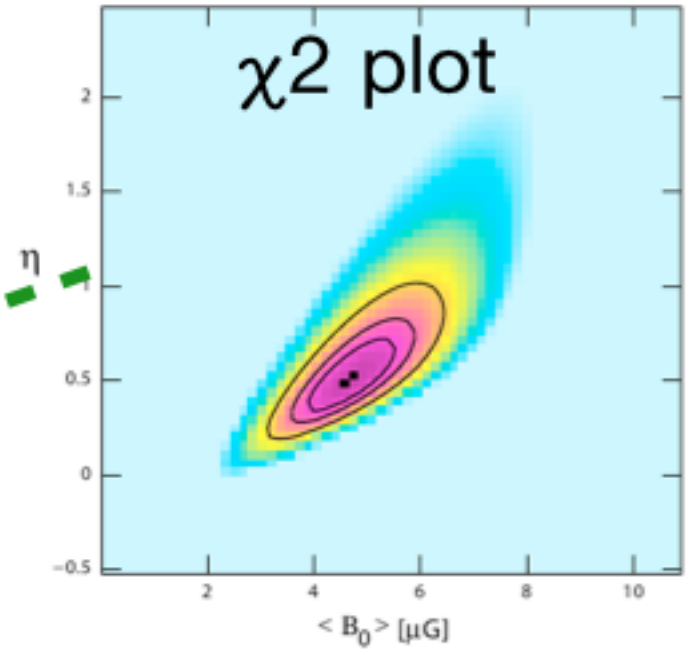
Fit of Structure function
and
autocorrelation function

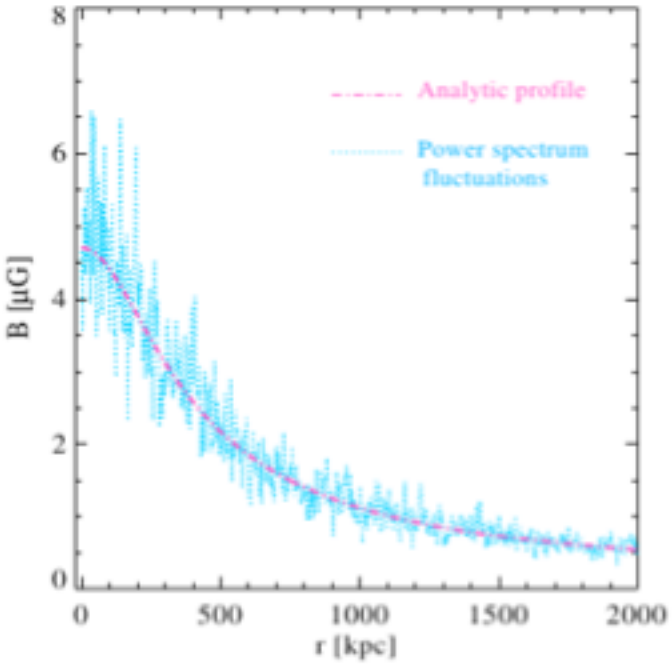




MAGNETIC FIELD IN THE COMA CLUSTER



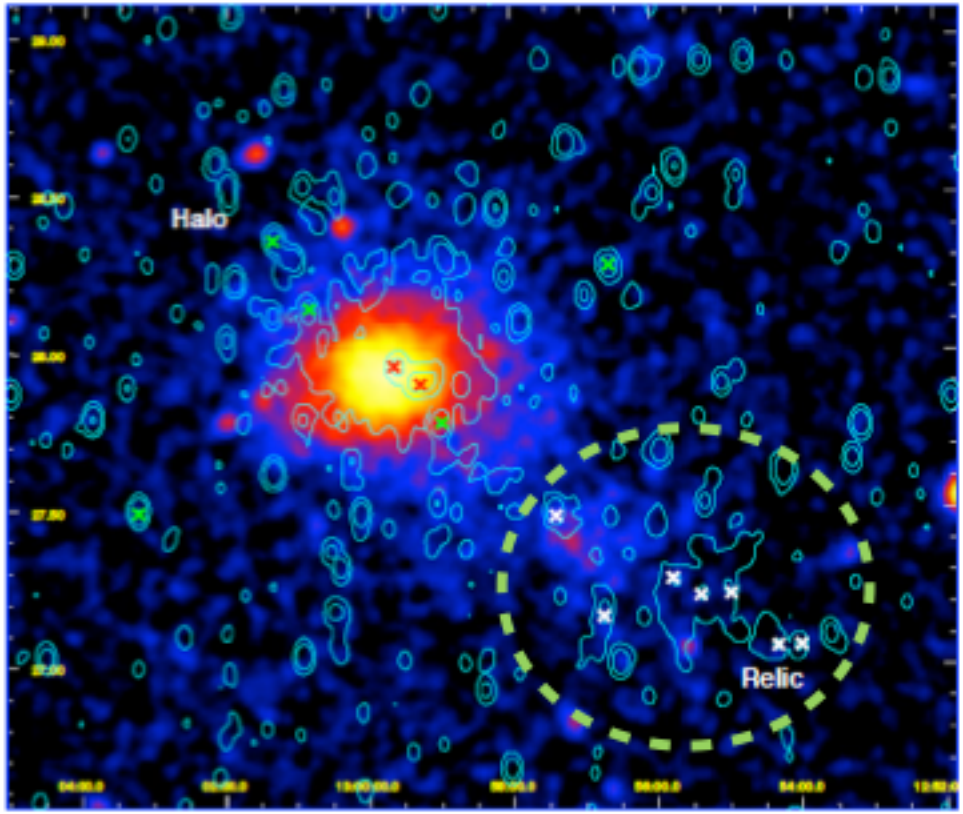


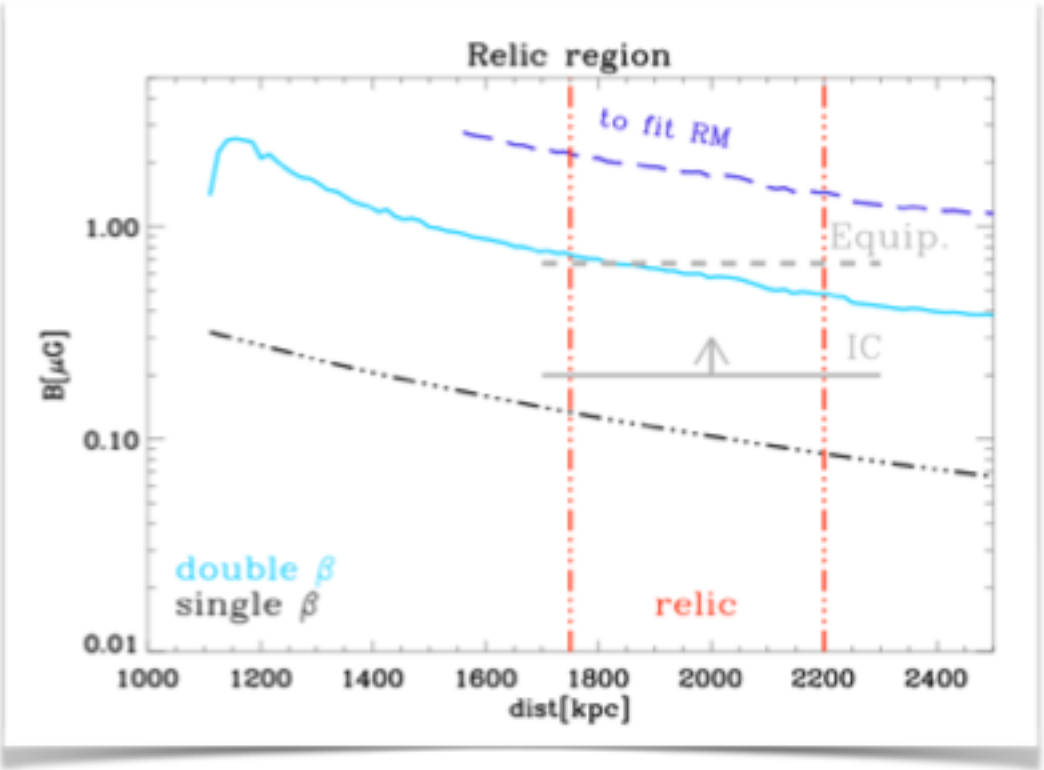


$$B \propto B_0 n_{gas}^{\eta}$$

Best fit: B_0 ~5 μG, η ~0.5

B amplification in the relic?





- Magnetic field amplified by a factor 3 in the relic region
- no Jump at the relic (shock)

80h JVLA time to study RM across relics
Chiara Stuardi PhD Thesis (Bologna)

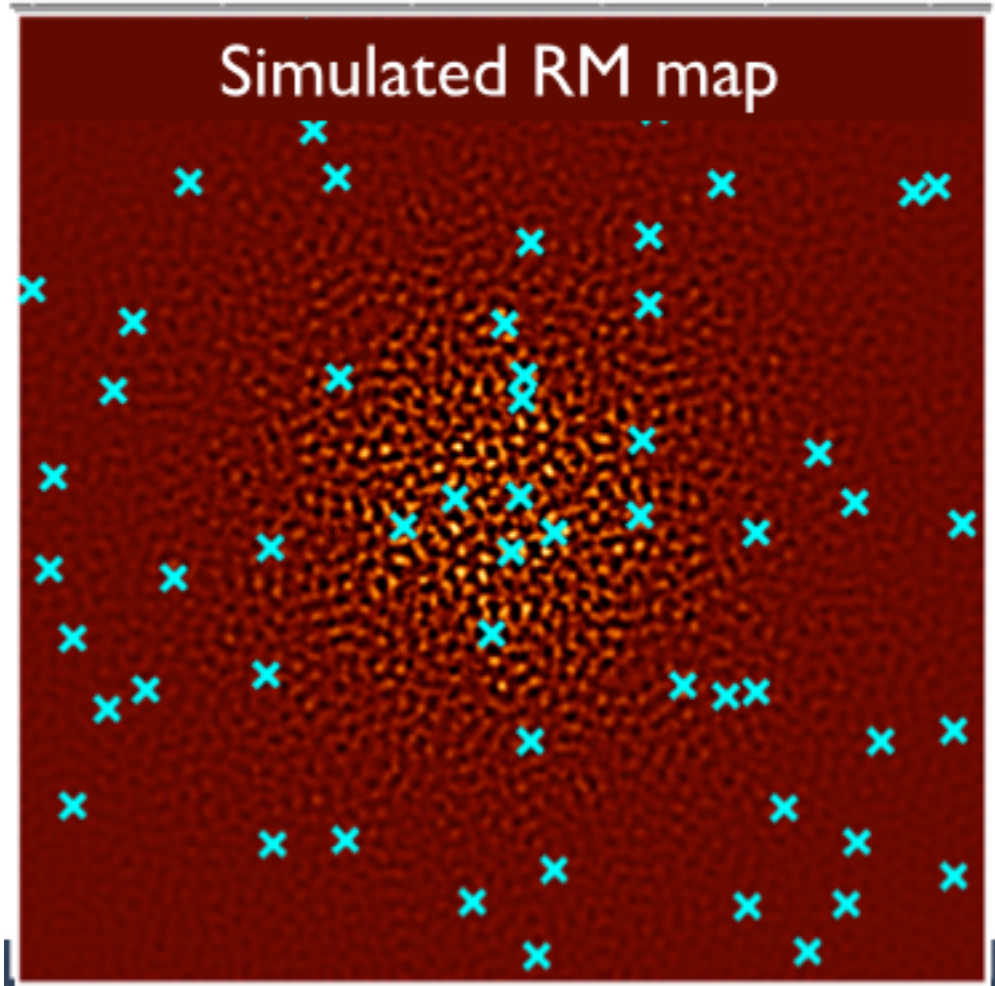
Bonafede et al. 2013

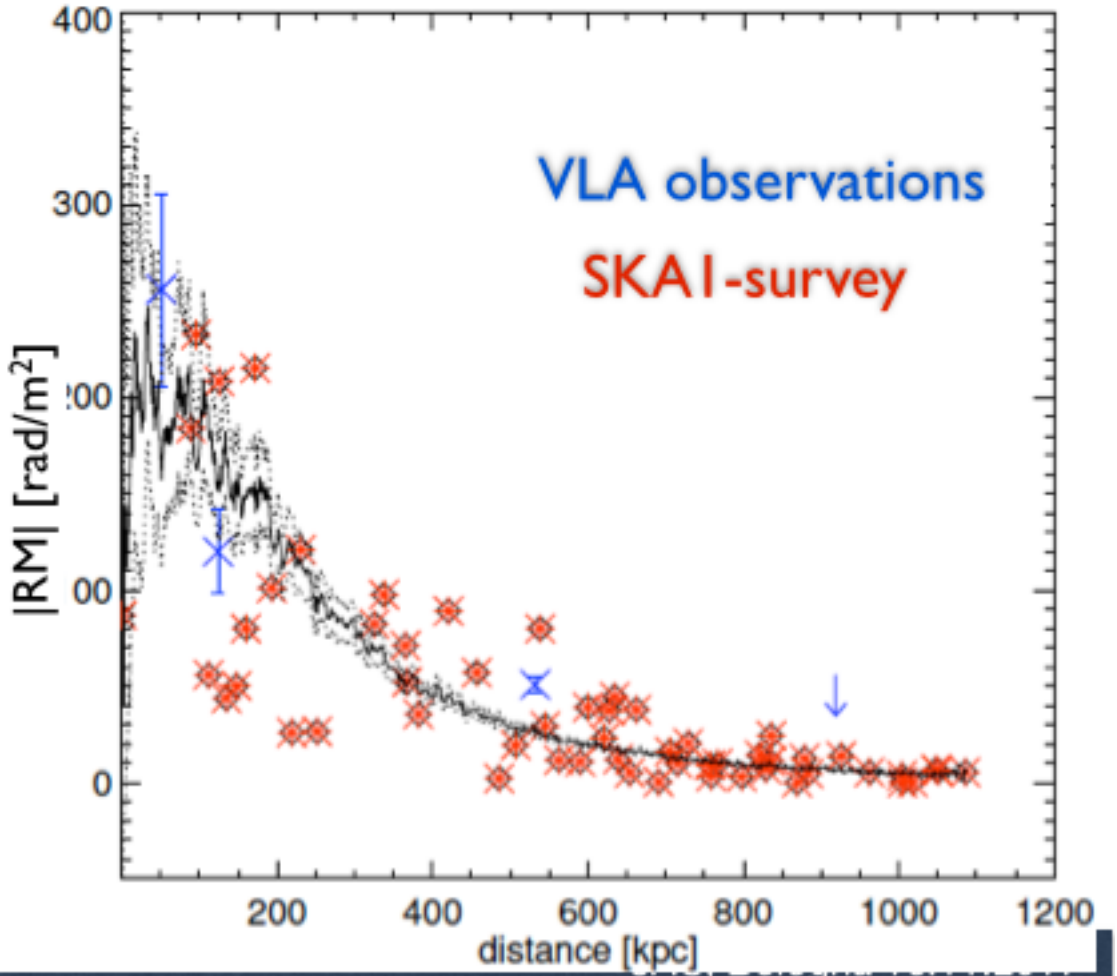
A Coma-like cluster as seen by the SKA

$$B \propto B_0 n_{gas}^{\eta}$$

$$B_0 = 5\mu G$$
$$\eta = 0.5$$

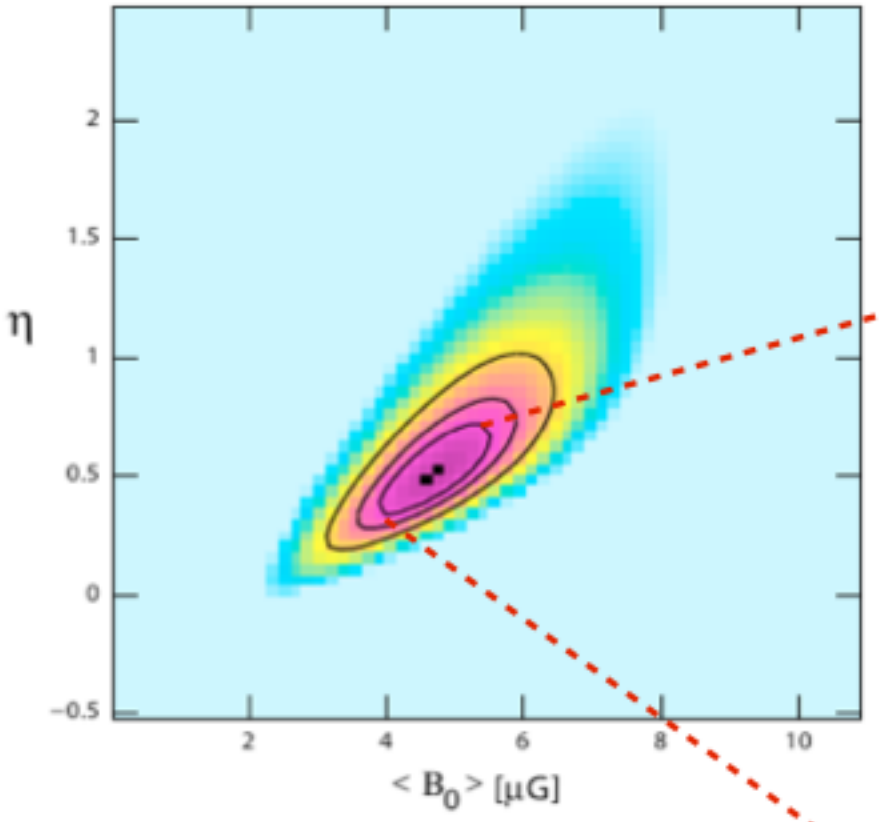
Bonafede et al. 2015 SKA white book

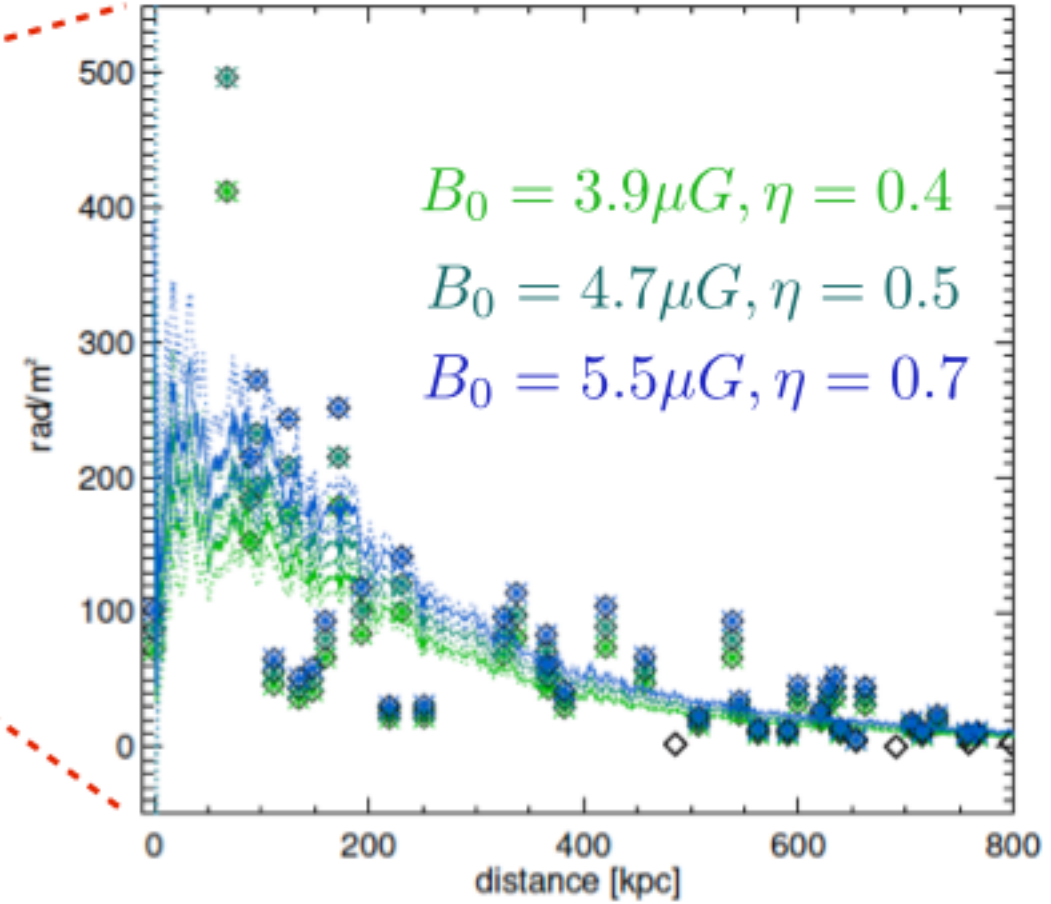




A Coma-like cluster as seen by the SKA

VLA data -> χ^2 plane

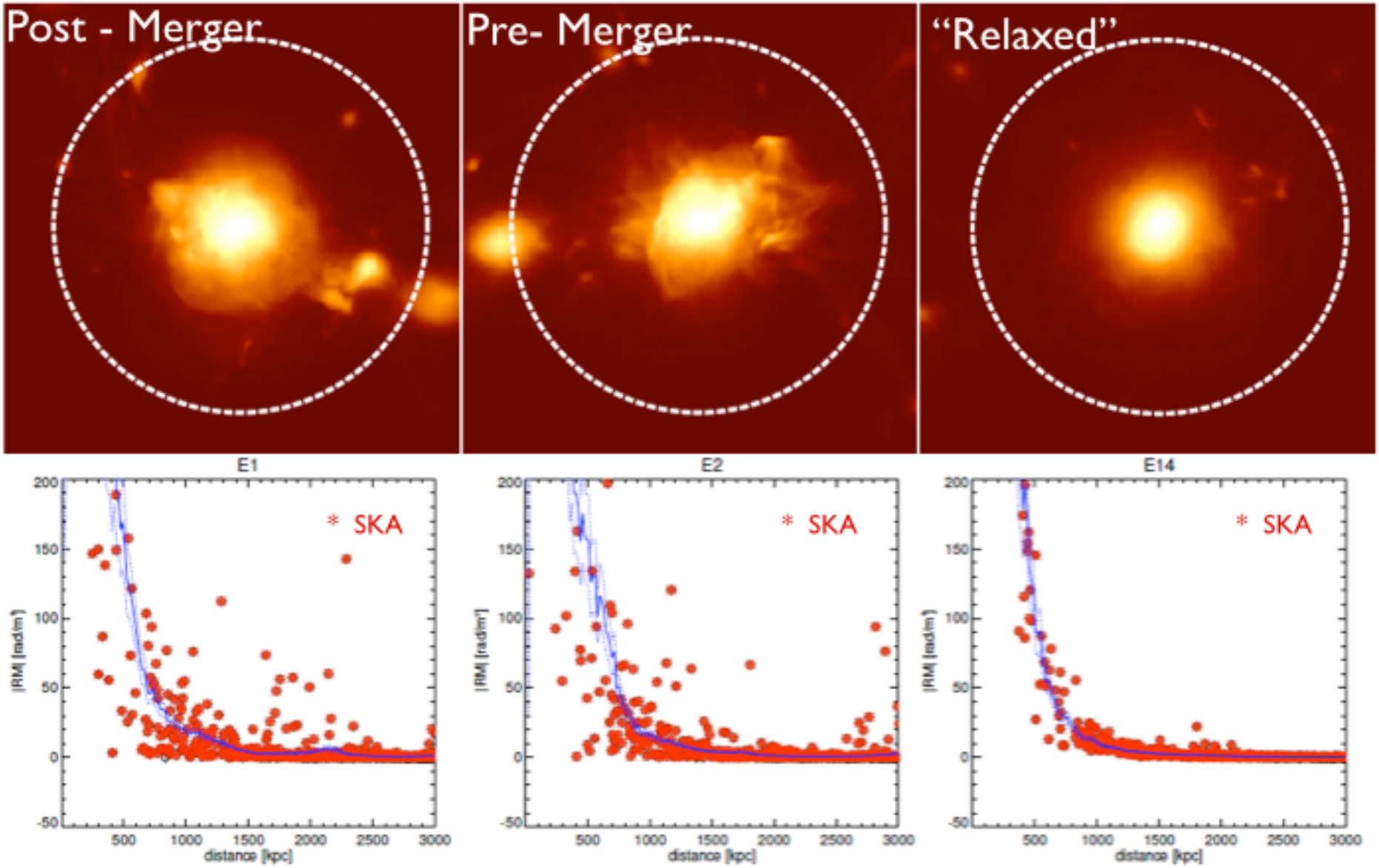




Bonafede et al. 2015 SKA white book

More realistic cluster models

20 Massive clusters Cosmological simulations (Vazza et al. 2010)
Resolution 25 kpc/h, resampled at 12 kpc/h



Bonafede et al. 2015 SKA white book

Conclusions

✔ LOFAR observations → additional emission discovered!
→ emission ahead of the infalling group

✔ Radio emission in regions of higher E_{kin}/E_{therm}

✔ Found 1st case of mini halo turning into a radio halo

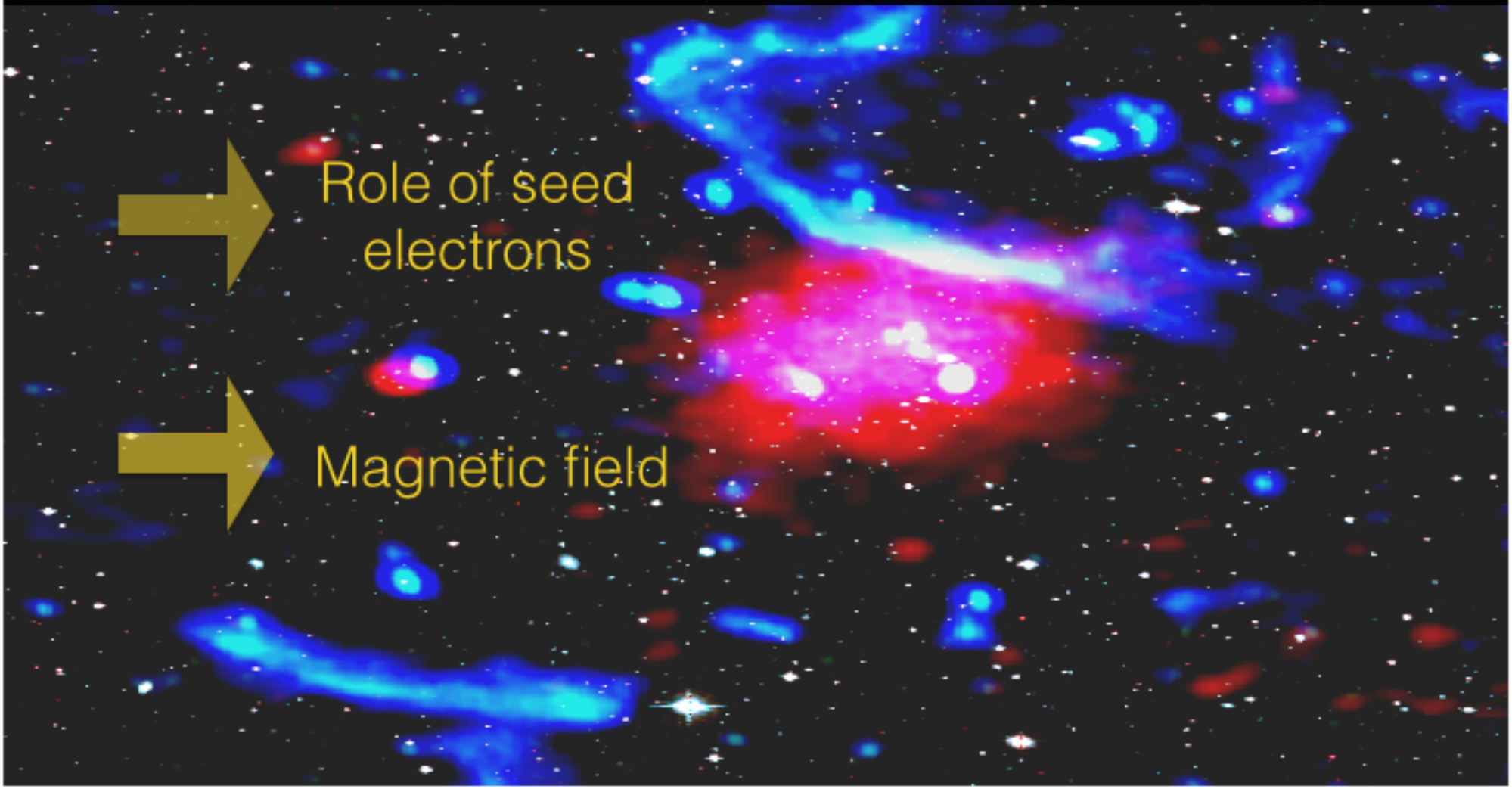
✔ How/when radio emission is switched on?

Magnetic field yet poorly constrained.

✔ JVLA (and SKA later) → Understand the role of B in particle acceleration

ERC Stg

Deciphering RAdio NOn-thermal Emission on the Largest scale



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