Magnetic fields and Cosmic Rays in galaxy clusters: … from LOFAR to SKA

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Clusters of galaxies: the largest gravitational structures in the Universe

($M \approx 10^{14}-10^{15} M_{sun}$,

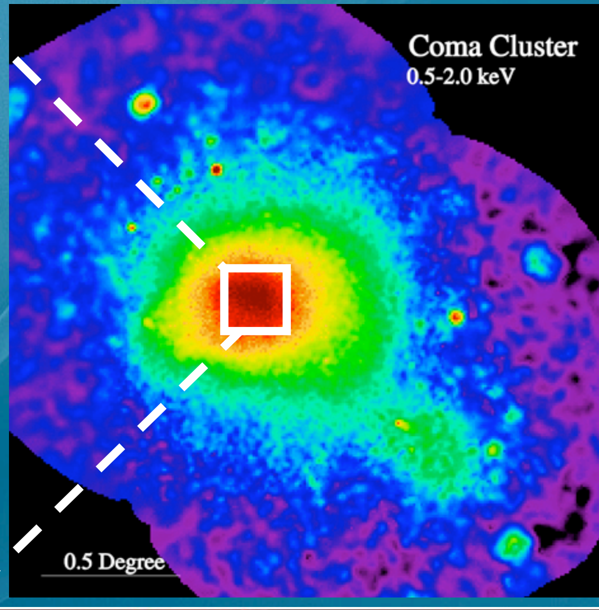
$R_V \approx$ 2-3 Mpc)

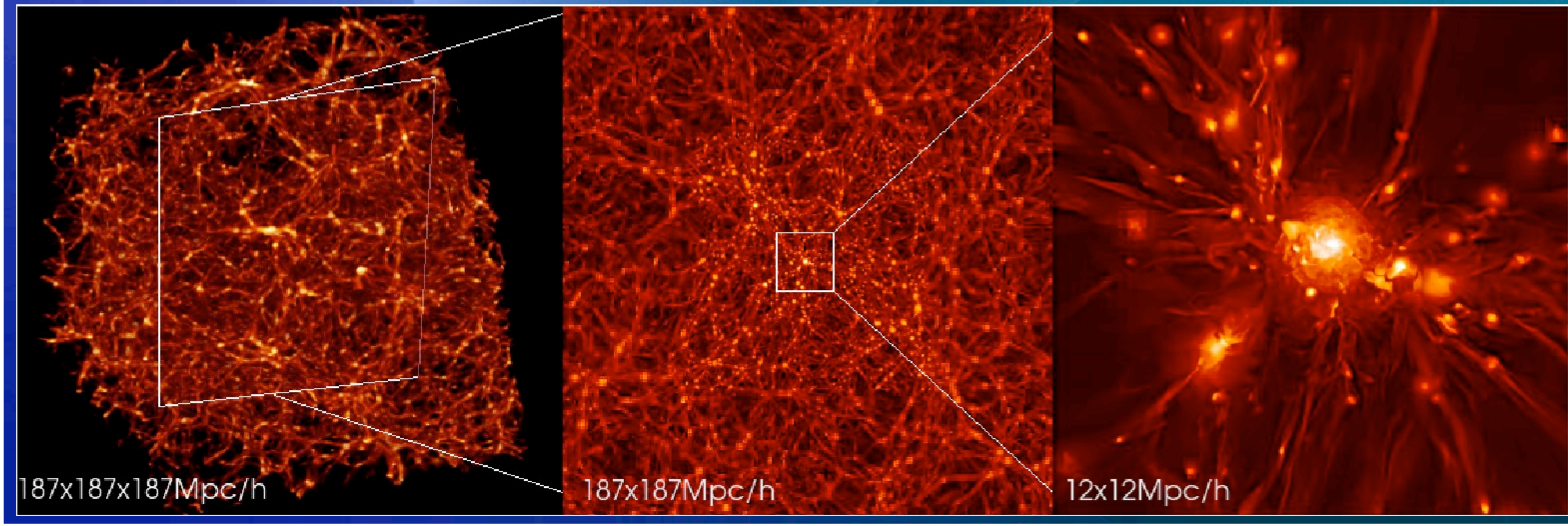
Galaxy cluster mass:

Barions **10%** of stars in galaxies

15-20% of hot diffuse gas

Dark Matter 70%



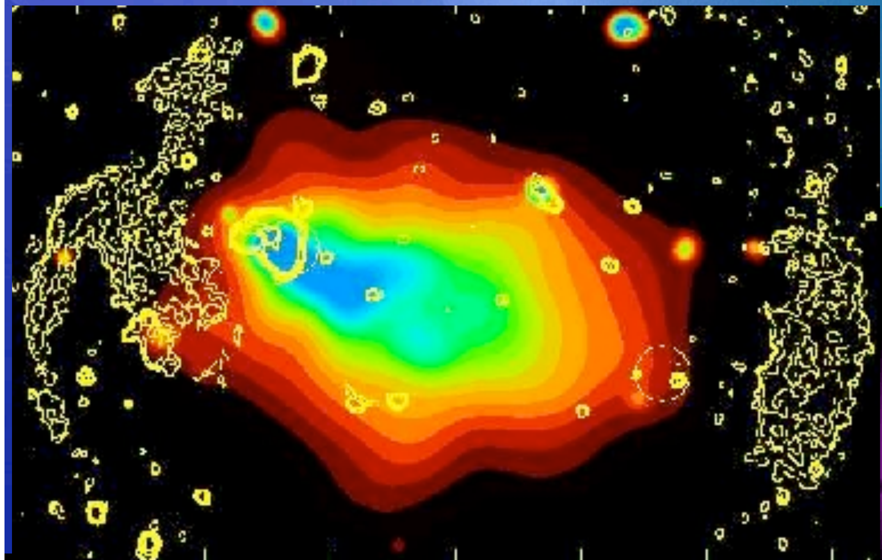


Cosmic rays & B in galaxy clusters

Diffuse synchrotron emission is detected in a fraction of galaxy clusters.
This demonstrates the presence of (at least) CRe and B.

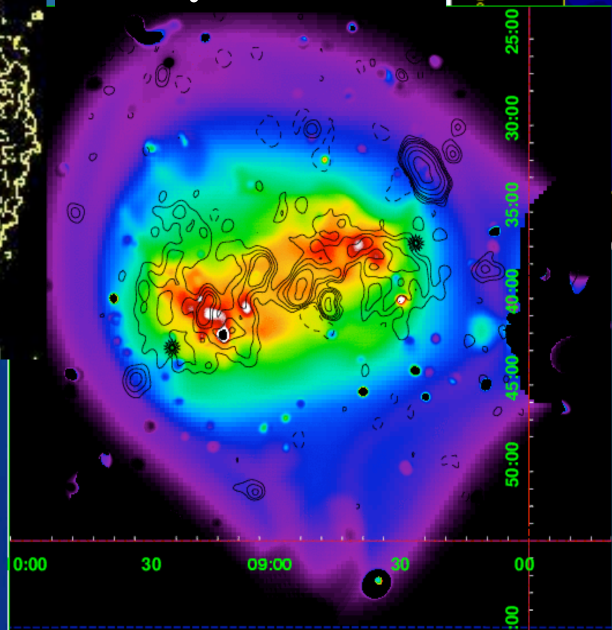
Unpolarised, follow the X-ray brightness
(originate from cluster central regions)

Polarised, no correlation with X-ray brightness
(form in cluster outskirts)

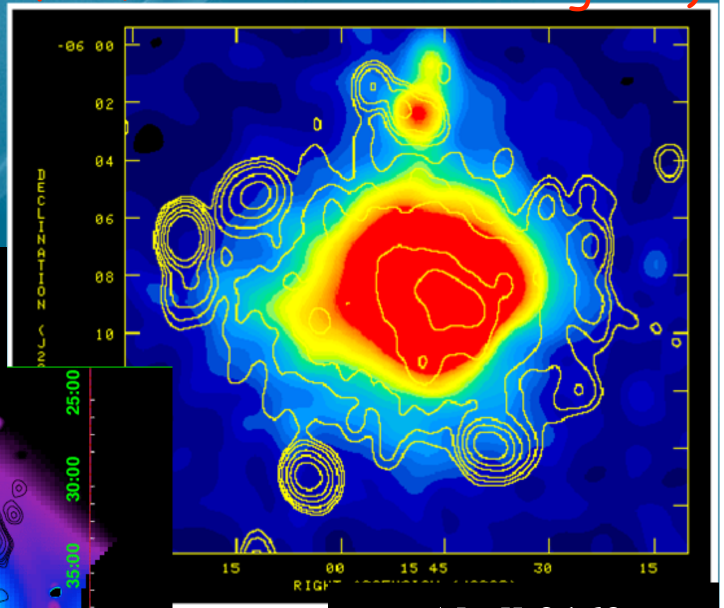


Abell 3376
Bagchi et al. 2002

Radio Relics



Abell 754
Henry et al. 2004



Abell 2163
Feretti et al. 2001

Radio Halos

CR+B : important not only for NT-physics ….

Thermal conduction, kin. Viscosity, "collisionality" in the ICM
(Schekochihin et al 05,08, Lazarian & Brunetti 11, Brunetti & Lazarian 11)

Diffusion and transport of metals in the ICM
(Voigt & Fabian 04, Rebusco et al. 05, Cho et al. 06, Vazza et al 10..)

Impact on clusters dynamics, scalings and evolution
(Ryu et al 04, Colafrancesco et al., …)

Heating of the ICM and "cooling flow" problem
(Fujita, Matsumoto, Weda 04, Guo & Oh 08, …)

Diffusion and scattering of HE & UHECR in the Universe
(Sigl et al. 05; Dolag et al. 05, …)

Important (open) questions

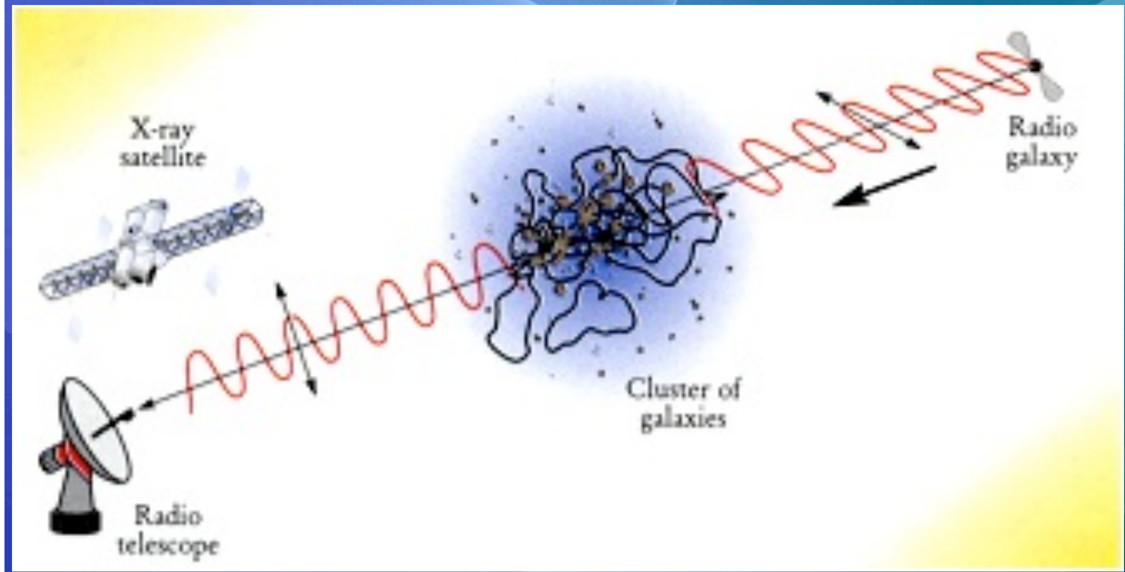
- Are CR and B common or not ?

- Energy budget of B and CRp,e ?

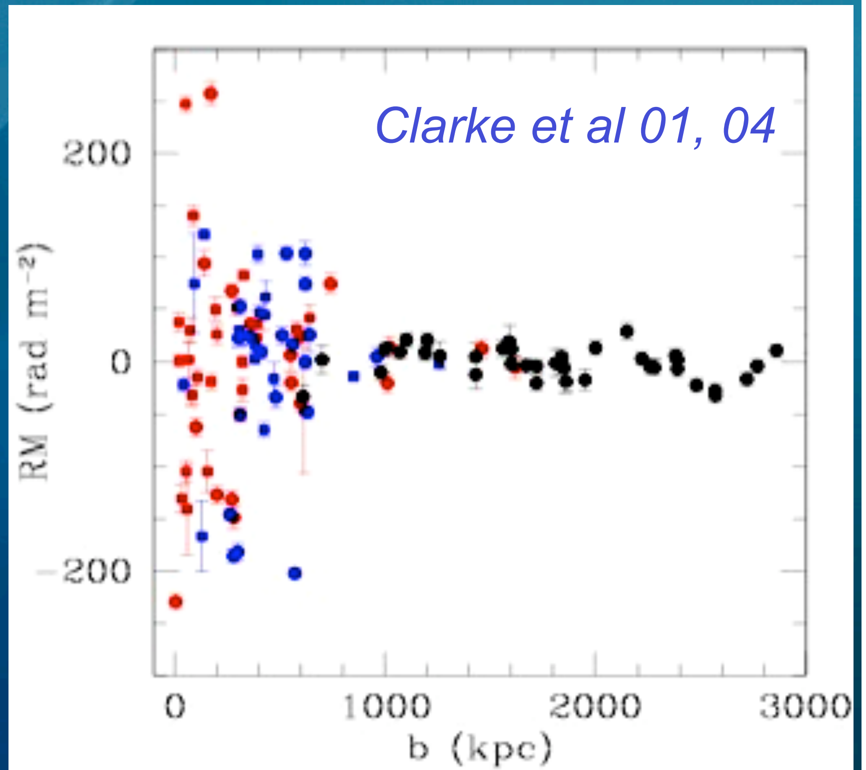
- Impact on the physics of the ICM

- Origin of CR and B

How to measure B ? - Faraday Rotation



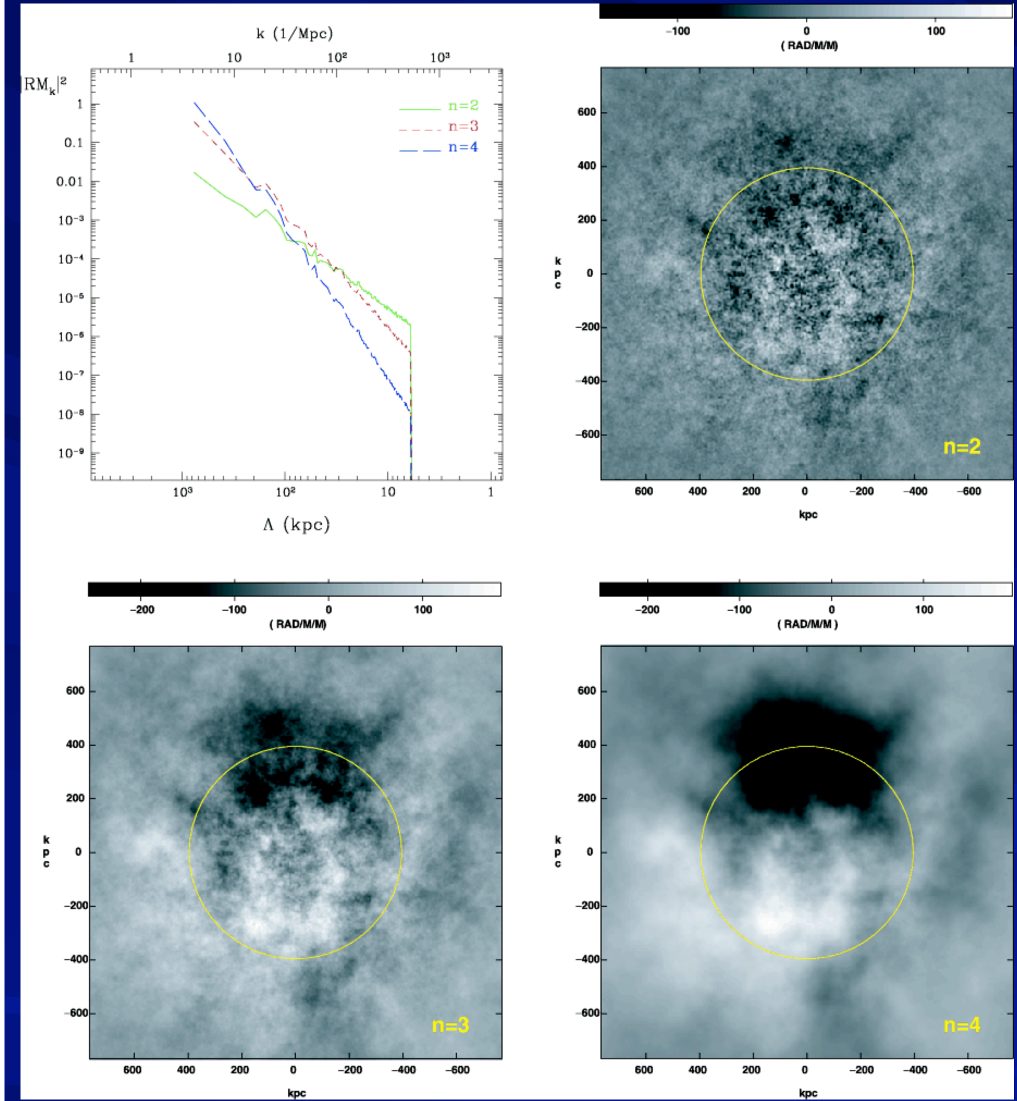
Observations of background (or in clusters) polarised radio sources in a clusters sample: RM increases in the clusters central regions where thermal electron density and B are larger.



$$\mathrm{RM} = \frac{\Delta\chi}{\Delta\lambda^2} = 811.9 \int_0^L n_e B_\parallel \, d\ell \ \ \mathrm{rad\ m^{-2}},$$

Magnetic fields are **common** in galaxy clusters, regardless of the presence of diffuse Syn emission.

Murgia et al 2004

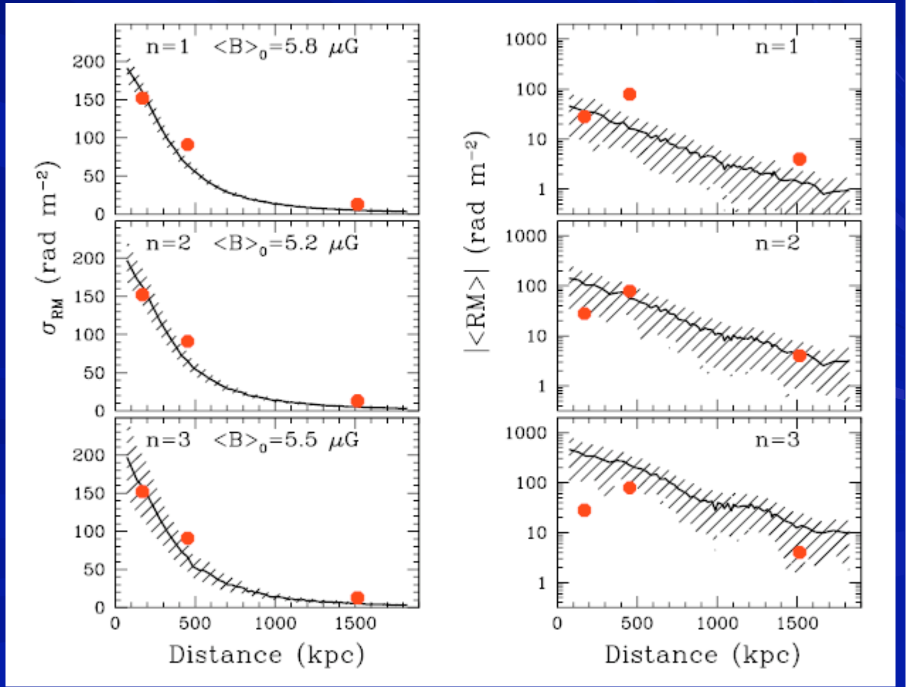


B in Galaxy Clusters

B ≈ few μG
Λc ≈ few-50 kpc

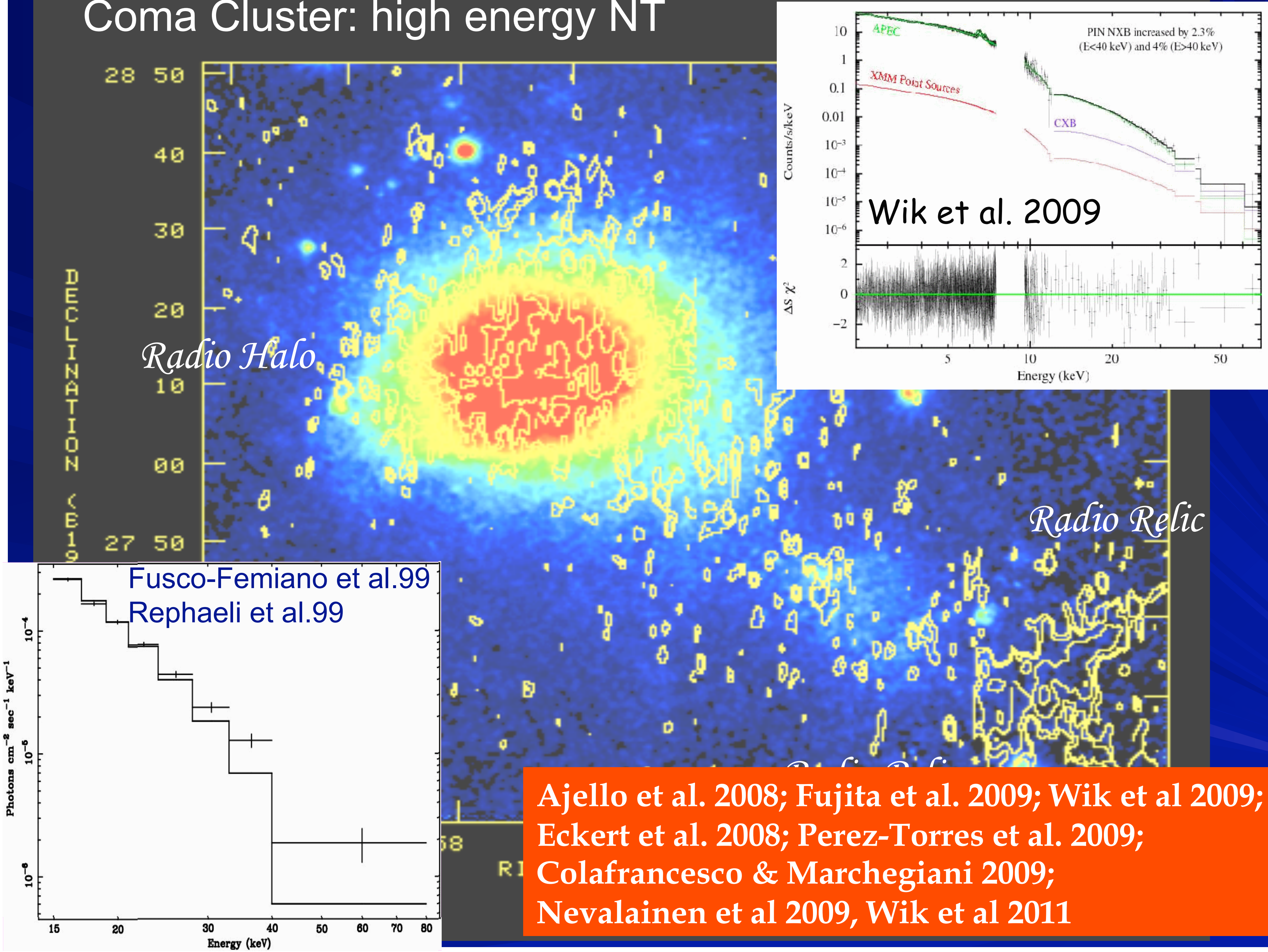
RM probe turbulent motions in the ICM

$$\sigma^2_{RM} = \langle RM^2 \rangle = 812^2 \Lambda_c \int (n_e B_{\parallel})^2 dl \; .$$



RM depends on the combination of magnetic field strength & topology (and its coherent scales) with electron density along the line of sight, implying Strong degeneracy

Coma Cluster: high energy NT



Ajello et al. 2008; Fujita et al. 2009; Wik et al 2009;
Eckert et al. 2008; Perez-Torres et al. 2009;
Colafrancesco & Marchegiani 2009;
Nevalainen et al 2009, Wik et al 2011

Controversial… but (at least!) lower limits on B

$L_{rad} \to (U_e\ , U_B) \to K_e B^2$
$L_{HE} \to (U_e\ , U_{ph}) \to K_e U_{ph}$

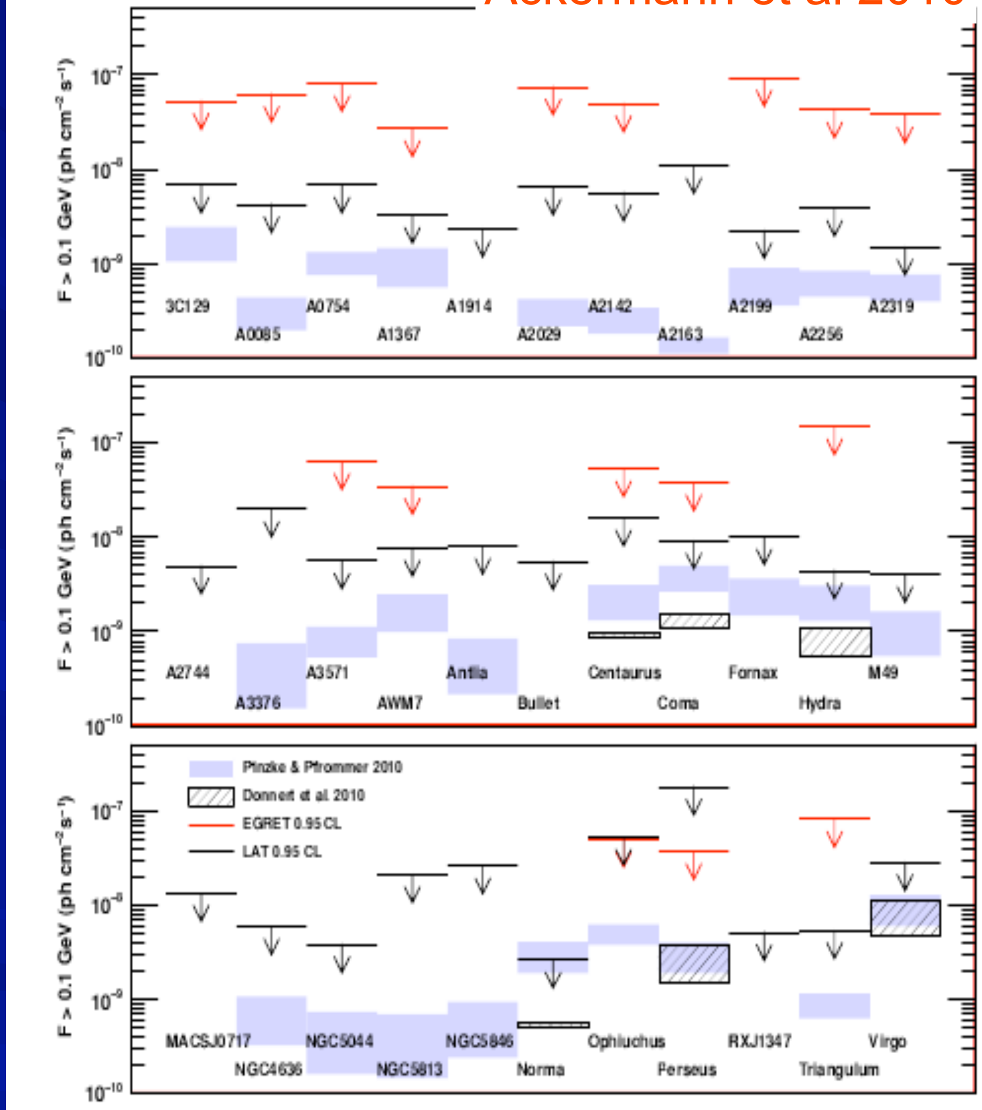
$L_{rad} / L_{HE} \approx U_B / U_{ph} \to B$

Ajello et al 2010

om Combined *XMM-Newton* and BAT Data

Name	$F_{50-100\,\mathrm{keV}}$[a] (10^{-12} erg cm^2 s^{-1})	B[b] (μG)
A85	<2.51	~0.6
A401	<0.22	~0.4
Bullet	$1.58^{+0.43}_{-0.47}$	~0.16
PKS 0745-19	<1.6	~0.5
A1795	<1.38	/
A1914	<1.08	~0.3
A2256	<0.19	~0.6
A3667	$2.98^{+4.17}_{-0.73}$	/
A2390	<0.25	~0.8

Ackermann et al 2010



B > 0.3-0.5 μG

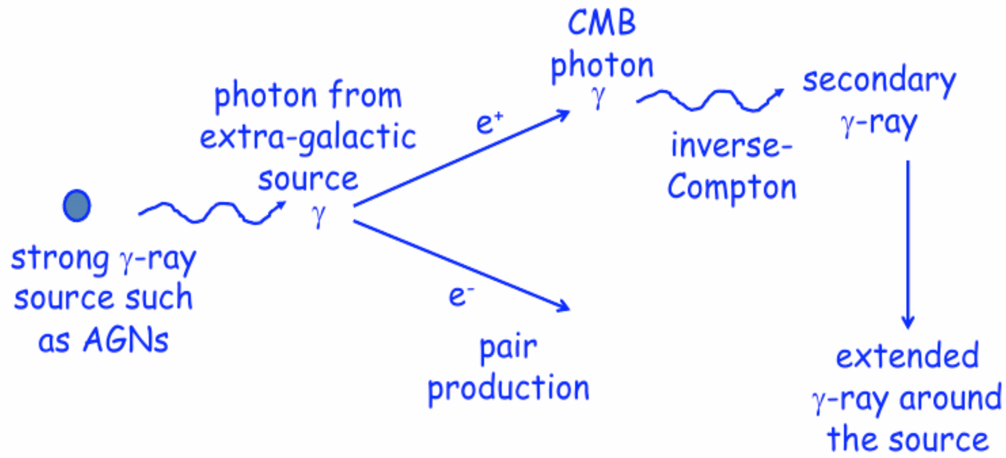
B > 0.15 μG

Constraints on magnetic fields "outside" clusters

Void regions - magnetic fields

Lack of extended γ-ray emission around AGNs

-> $B >\sim 10^{-16}$ G



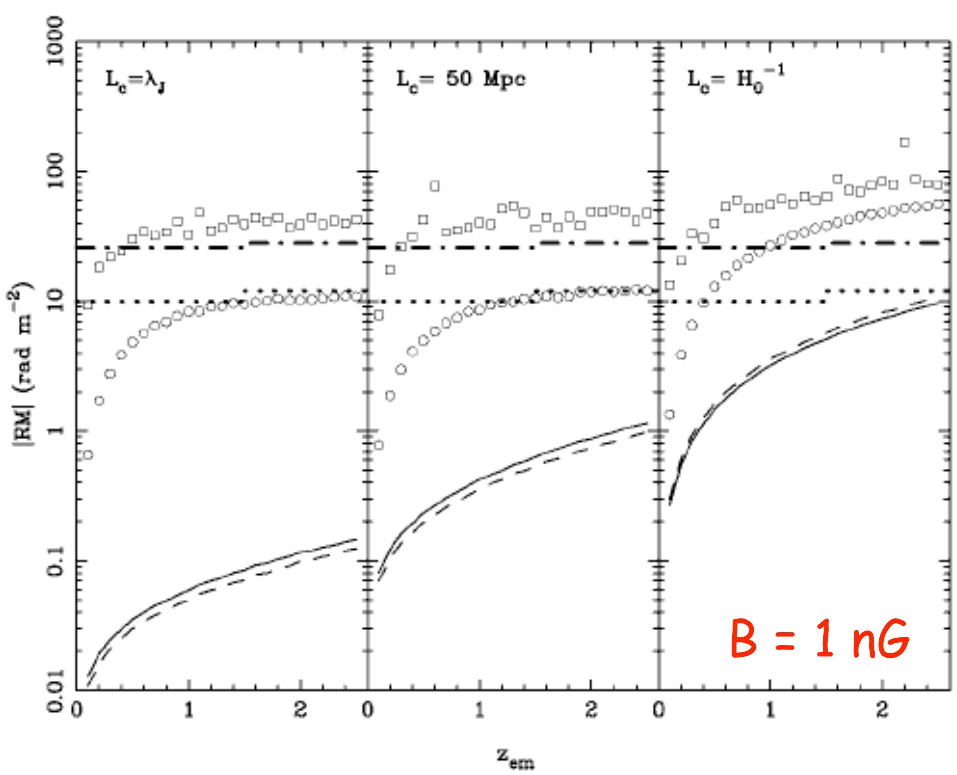
no observation of extended γ-ray around sources

-> evidence of magnetic defection along the path from the source to the observer

$B >\sim 10^{-16}$ G in void regions!

Neronov 10
Aleksic et al 10

Blasi et al 99



Combining constraints from the lack of gamma-ray halos (Neronov et al 10, Aleksic et al 10), from RMs of QSO (Blasi et al 99), and from isotropy of the CMB (Barrow et al 97) the magnetic field in "voids" is in the range 10^{-7}-1 nG.

Magnetic fields in the LSS of the universe

Seed magnetic fields

Origin of seeds for comic magnetic fields is uncertain.

some suggestions:

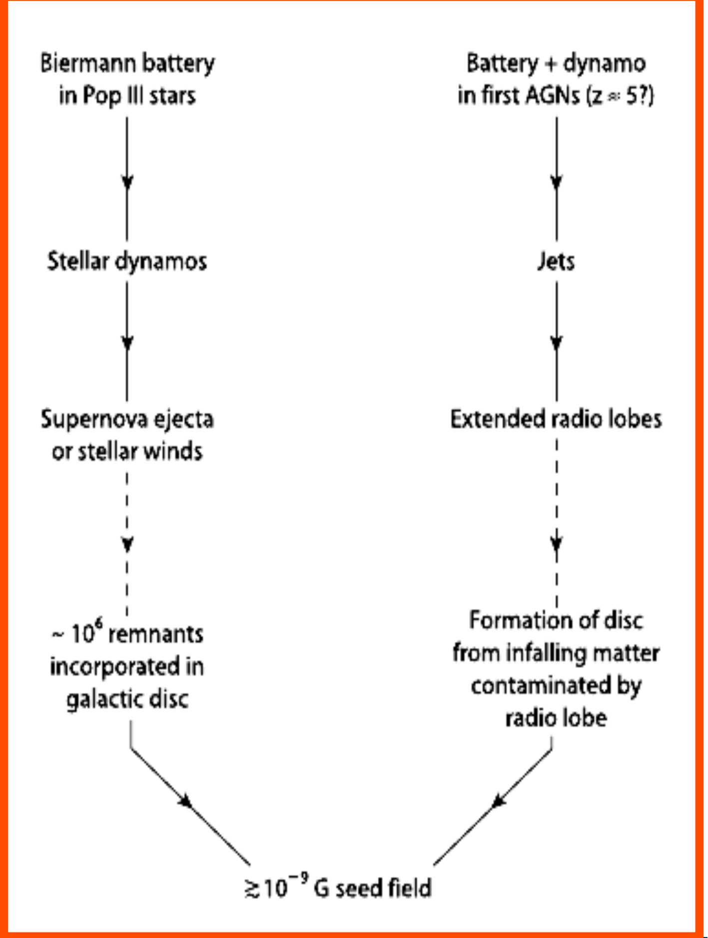
1. generation in the early universe
   e.g.) during the electroweak phase transition ($t \sim 10^{-12}$sec)?
   during the quark-hadron transition ($t \sim 10^{-5}$sec)?
2. generation before cluster formation
   e.g.) plasma processes such as thermal fluctuations or at shocks
3. magnetic fields from the first stars and active galaxies

...

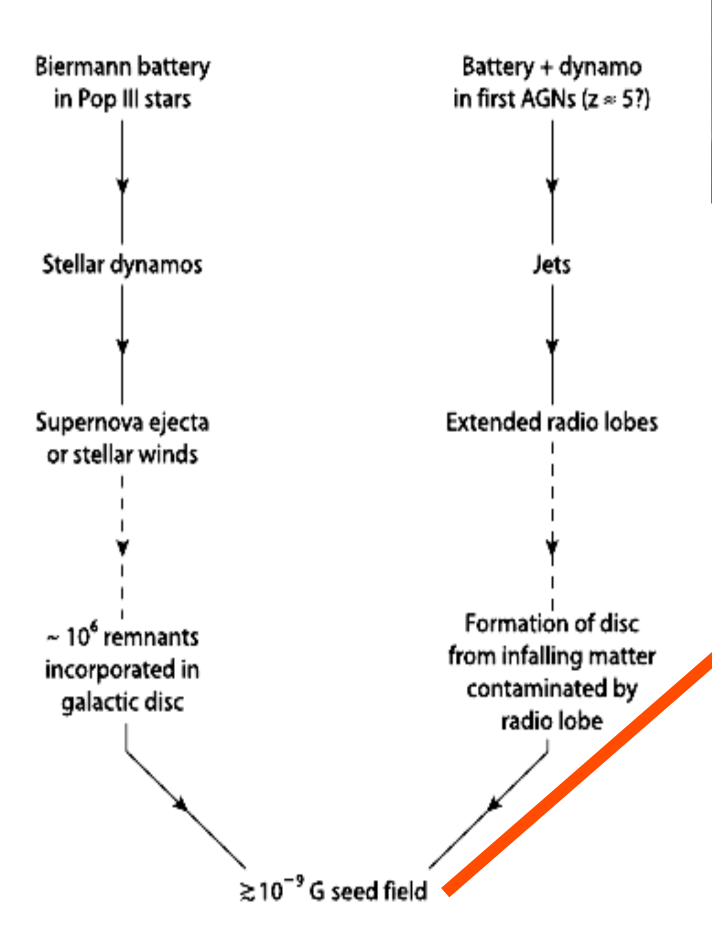
-> expected to be very weak

Amplification through turbulence dynamo ?

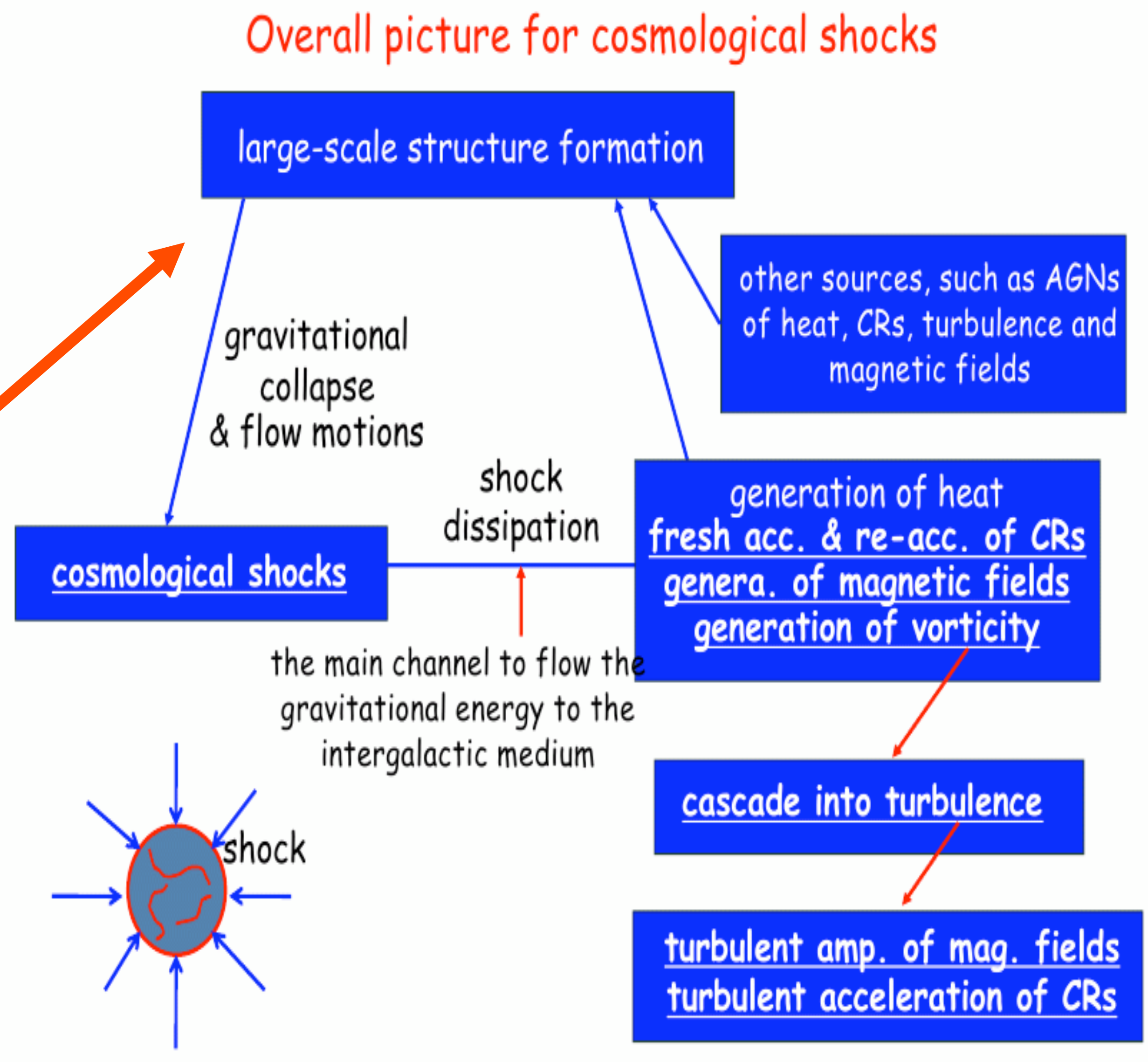
Rees 04
Gaensler et al 04



Origin of LS Magnetic Fields

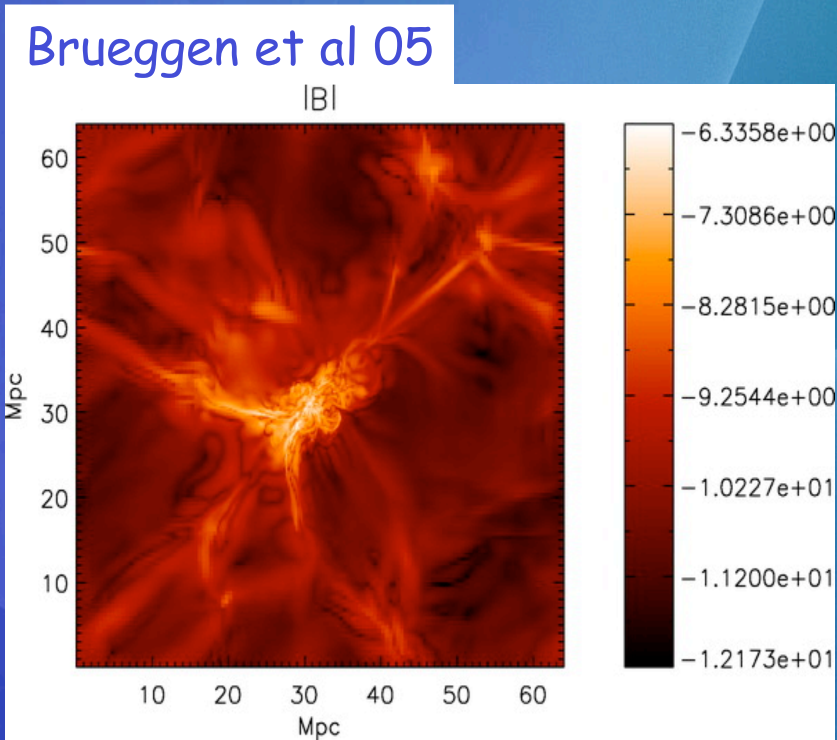


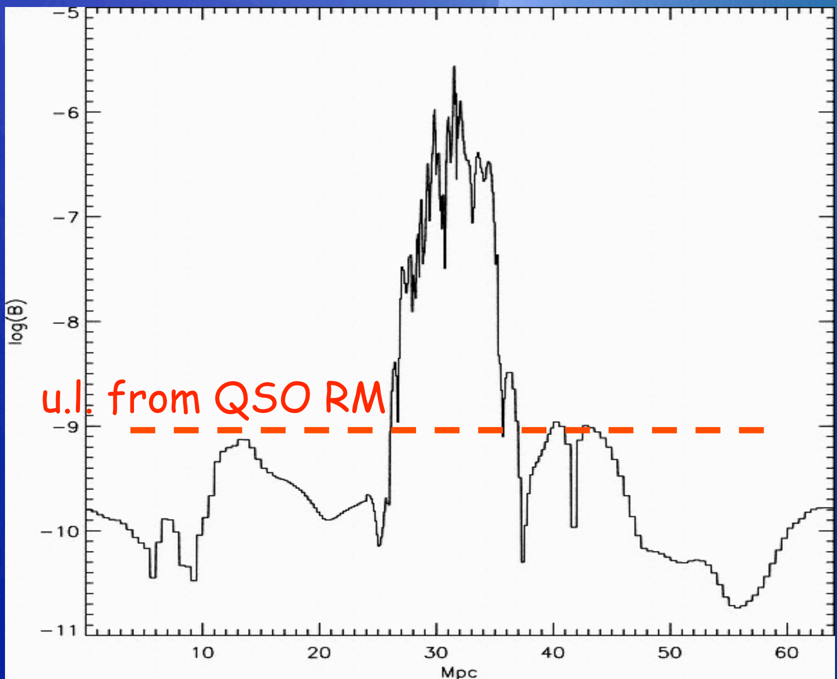
Rees 04
Gaensler et al 04

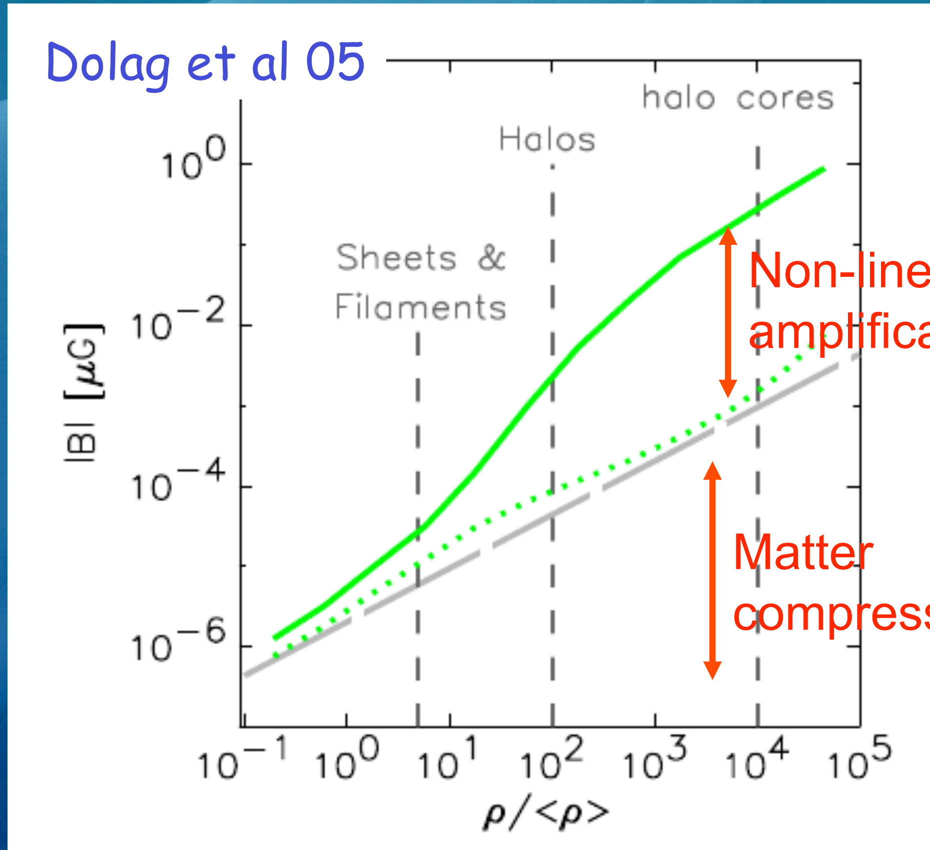


Dolag et al 05, Subramanian et al 06, Ryu et al 08, …

Origin of LS Magnetic Fields



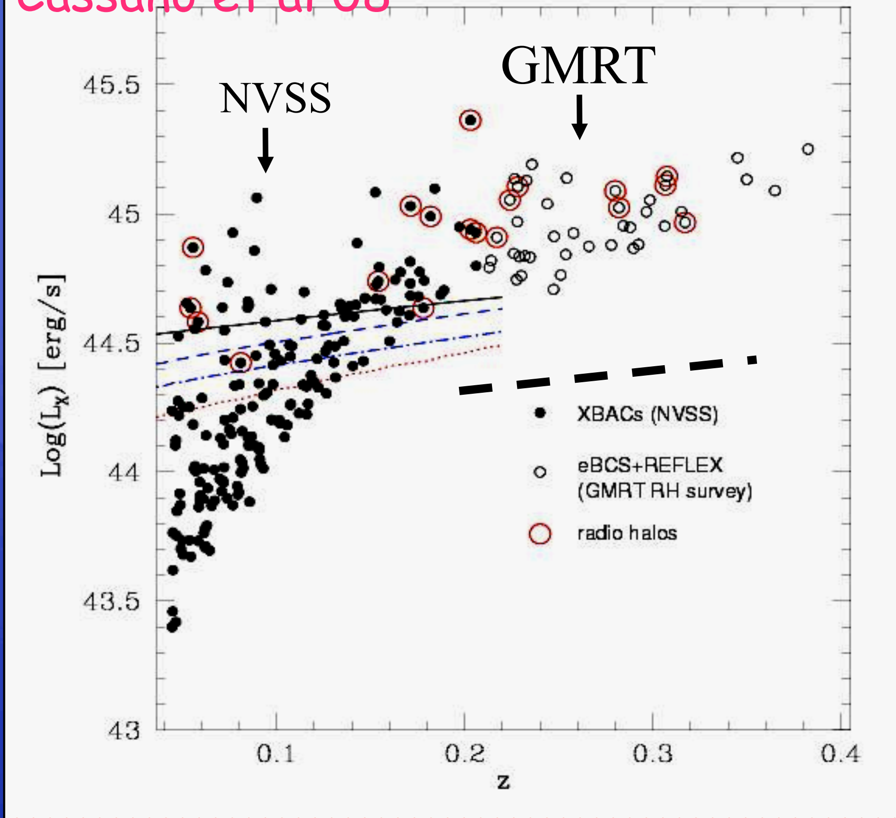




Shear flows and turbulent/kinetic dynamos amplify the magnetic field in the clusters internal regions. The amplification process increases B energy by 4 orders of magnitude (with respect to matter compression).

Synchrotron from LSS : combined info on CR(e) and B

Cassano et al 08



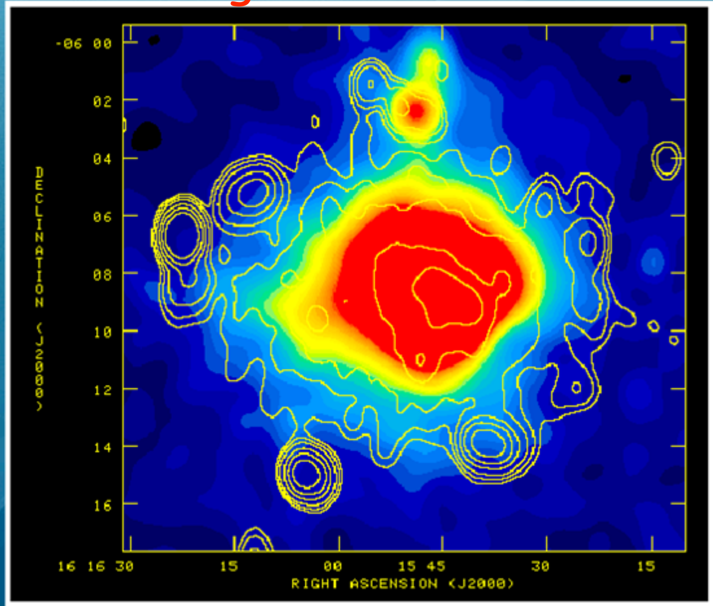
NVSS data (from *Giovannini et al. 1999)* and deep **GMRT observations.**

0.41±0.11 for $L_x > 10^{44.9}$ erg/s ≈ 1/3

0.08±0.04 for $L_x < 10^{44.9}$ erg/s ≈ 1/10

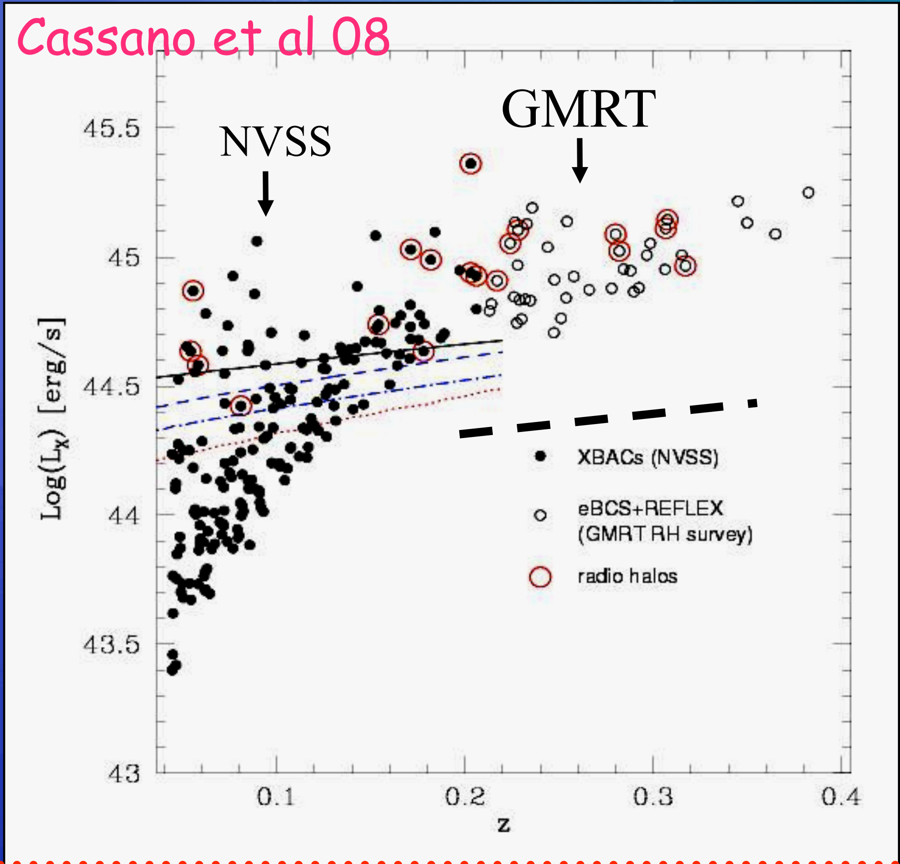
(Venturi et al. 2007, 2008; Cassano et al.2008)

Radio halos probes B and CR in gigantic Mpc-scale regions



Contrary to magnetic fields, Mpc-scale synchrotron emission is not (very) common in galaxy clusters.
Present data suggest that the fraction of clusters with radio halos increases with clusters mass.
Lack of sensitivity of present radiotel does not allow to detect halos in less massive (sub-Coma..) clusters and to firmly address their evolution with z.

Synchrotron from LSS : combined info on CR(e) and B



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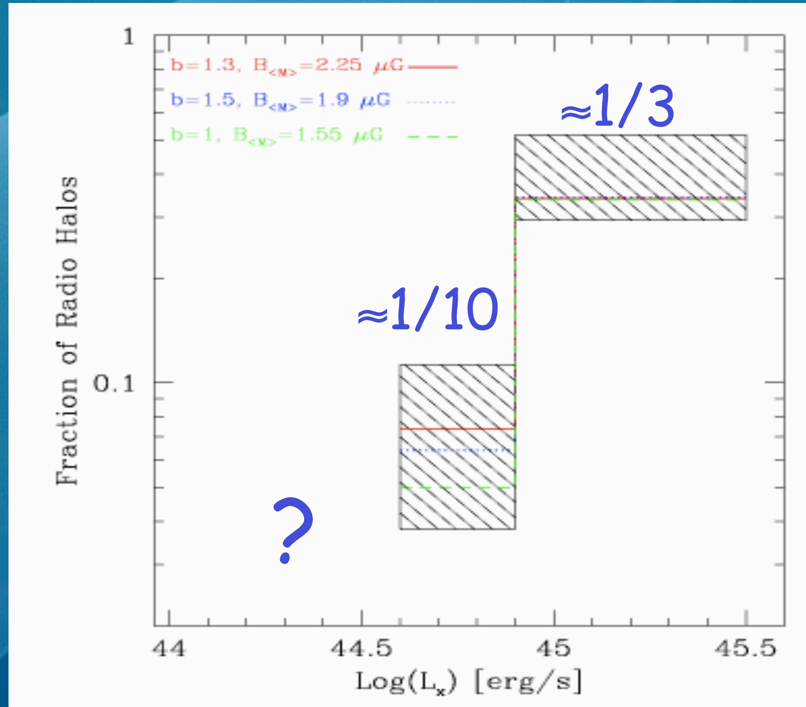

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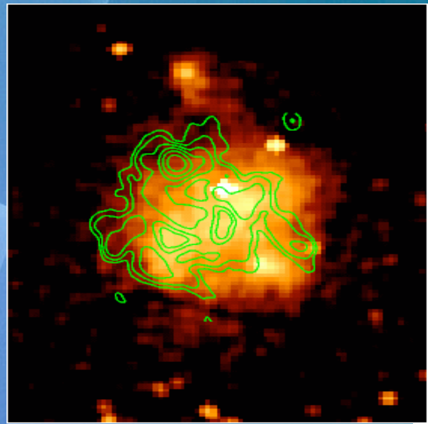
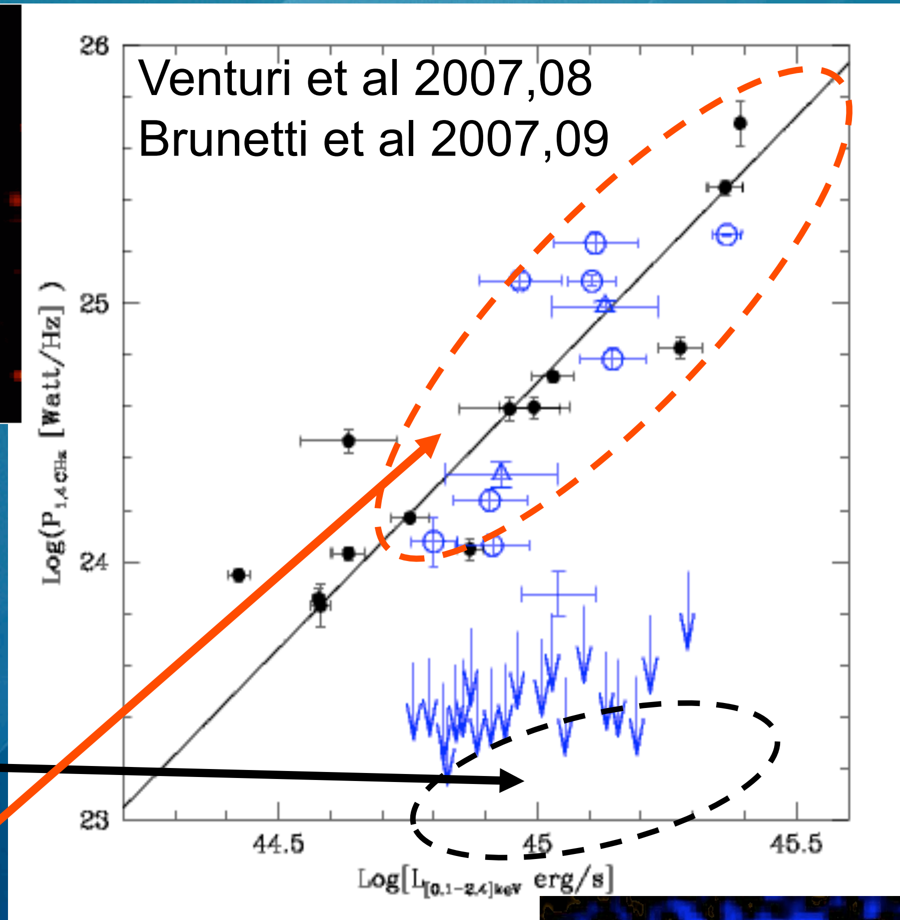
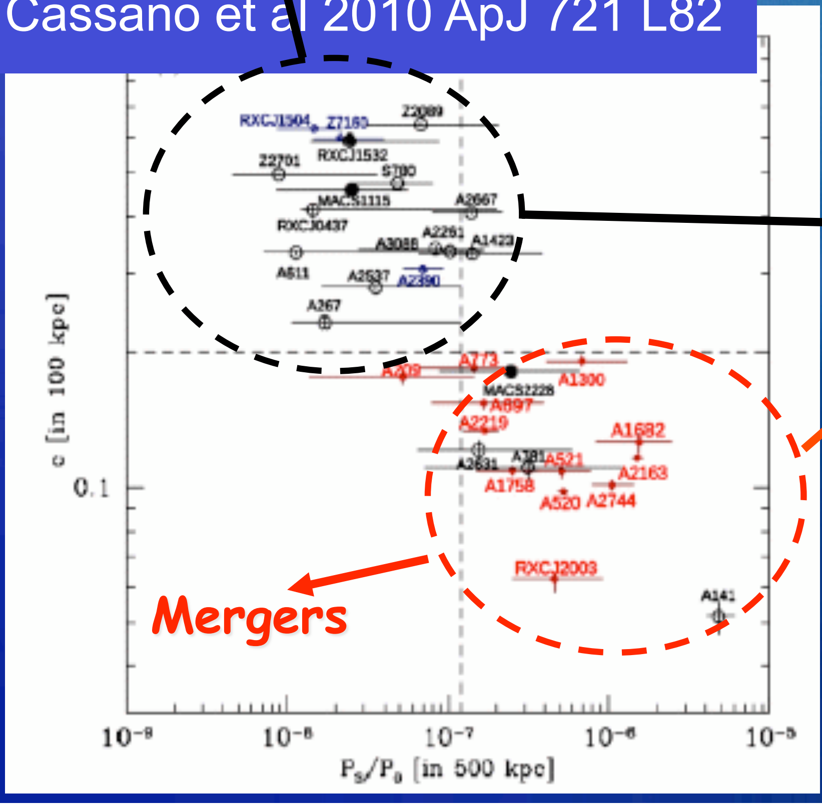
Cluster mergers - radio halos connection



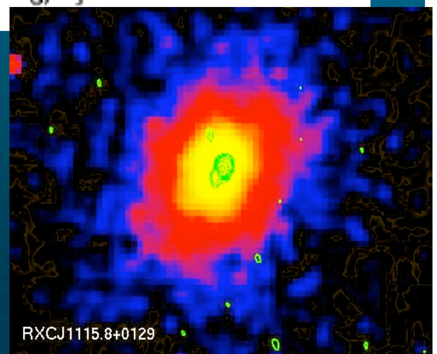


Relaxed

Cassano et al 2010 ApJ 721 L82



Mergers



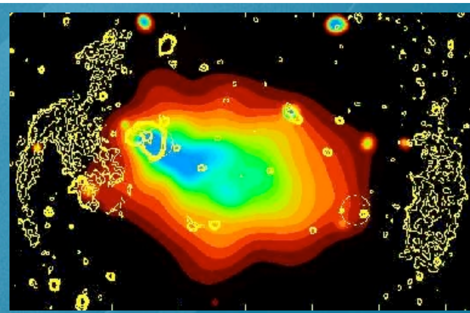
The radio bimodality has a correspondence in terms of dynamical segregation : particle acceleration and B amplification in meregrs

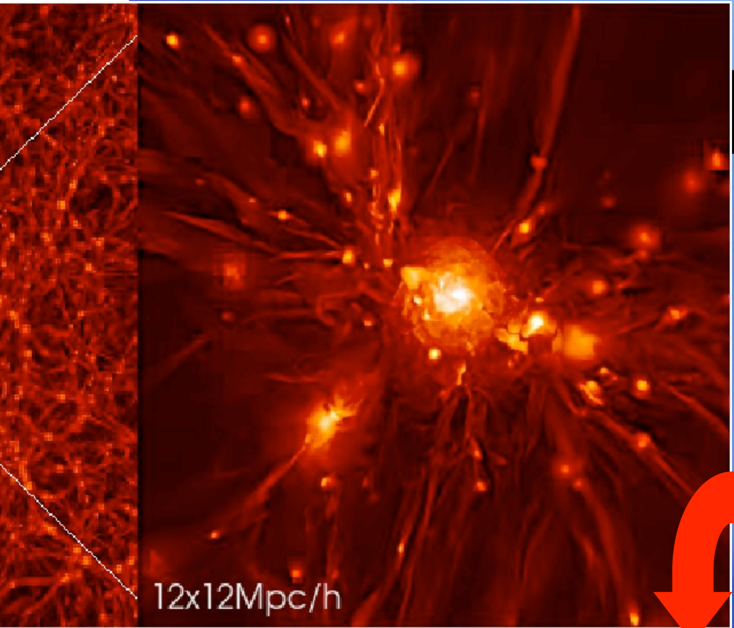
(Brunetti et al 07, 09, Kushnir et al09, Keshet & Loeb 10)

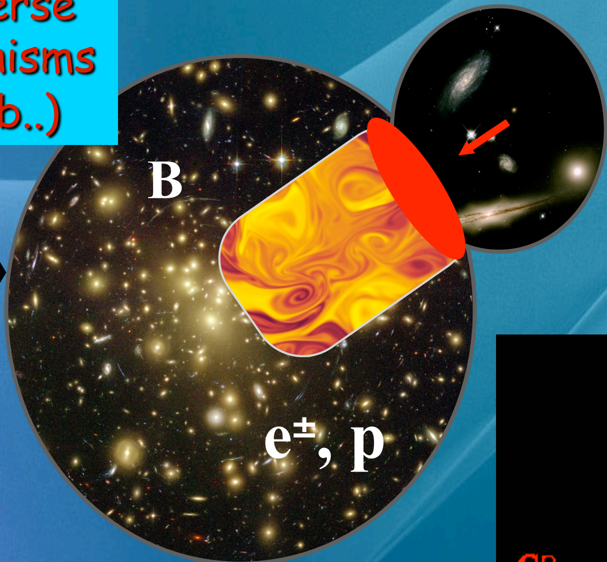
Mergers & CR-acceleration

(eg Brunetti 11, rev)

Cluster-cluster mergers are the most energetic events in the present Universe (10^{64}erg/Gyr). They can drive mechanisms for particle acceleration (shocks, turb..)

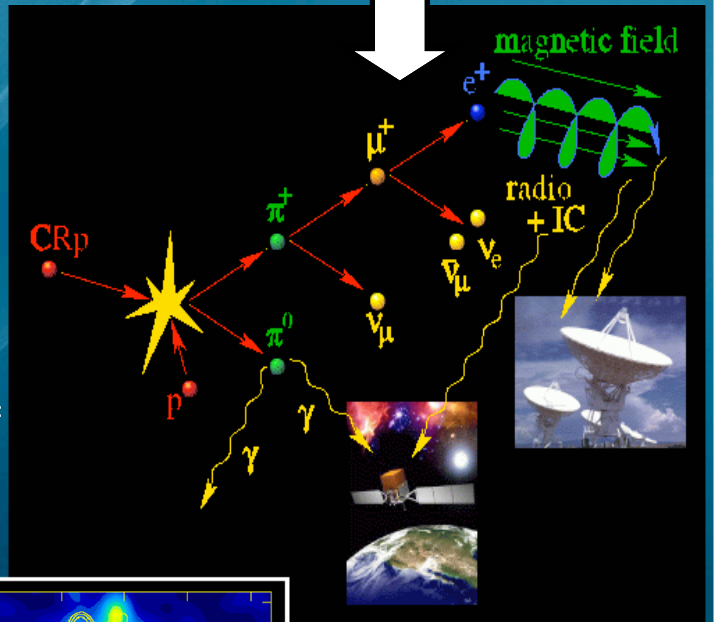






SHOCKS

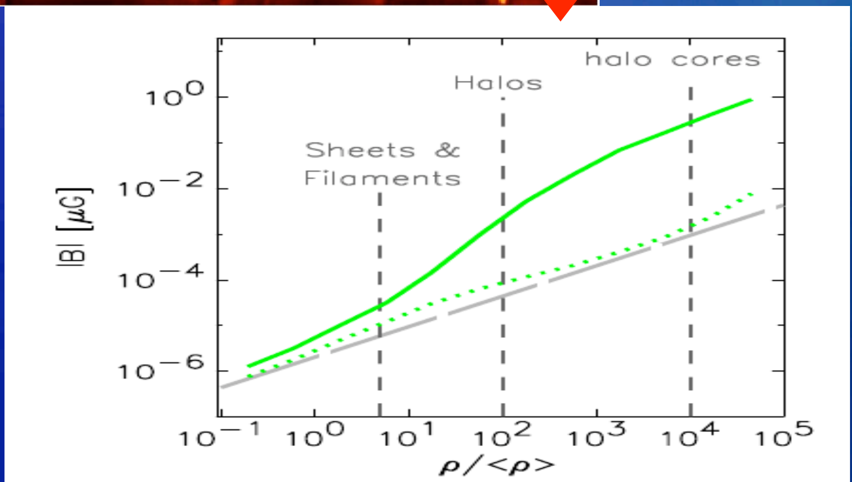
accelerate CRe±,CRp

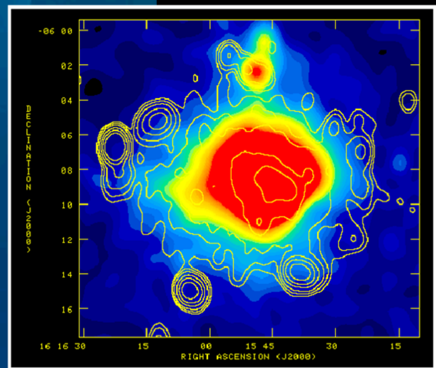


TURBULENCE

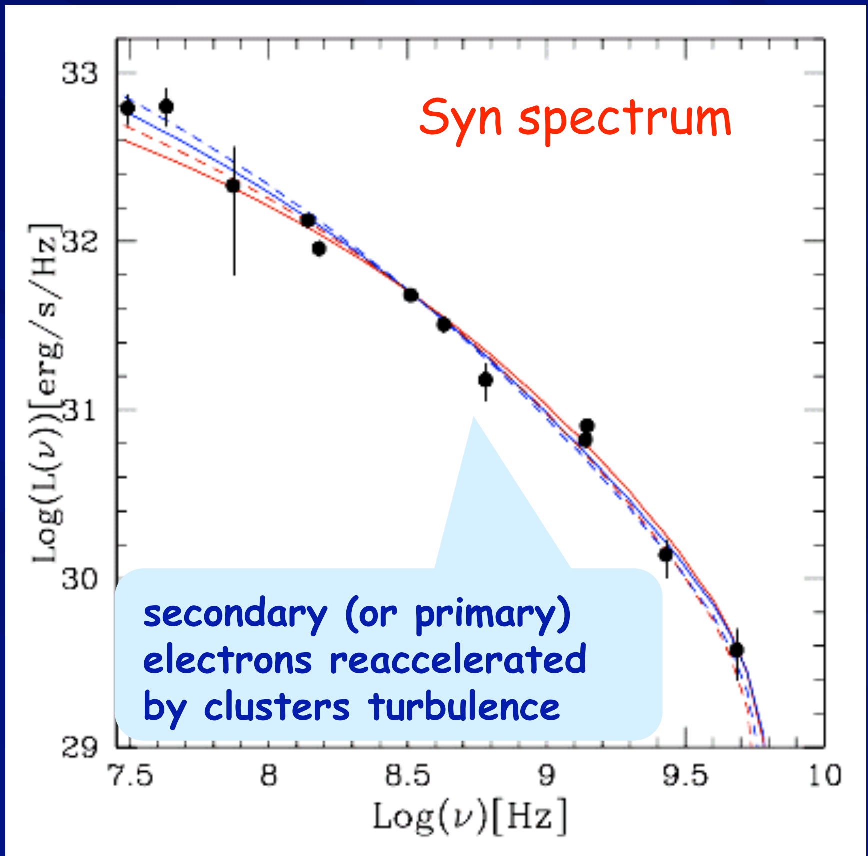
reaccelerates fossil CRe±

CRp and secondaries CRe±

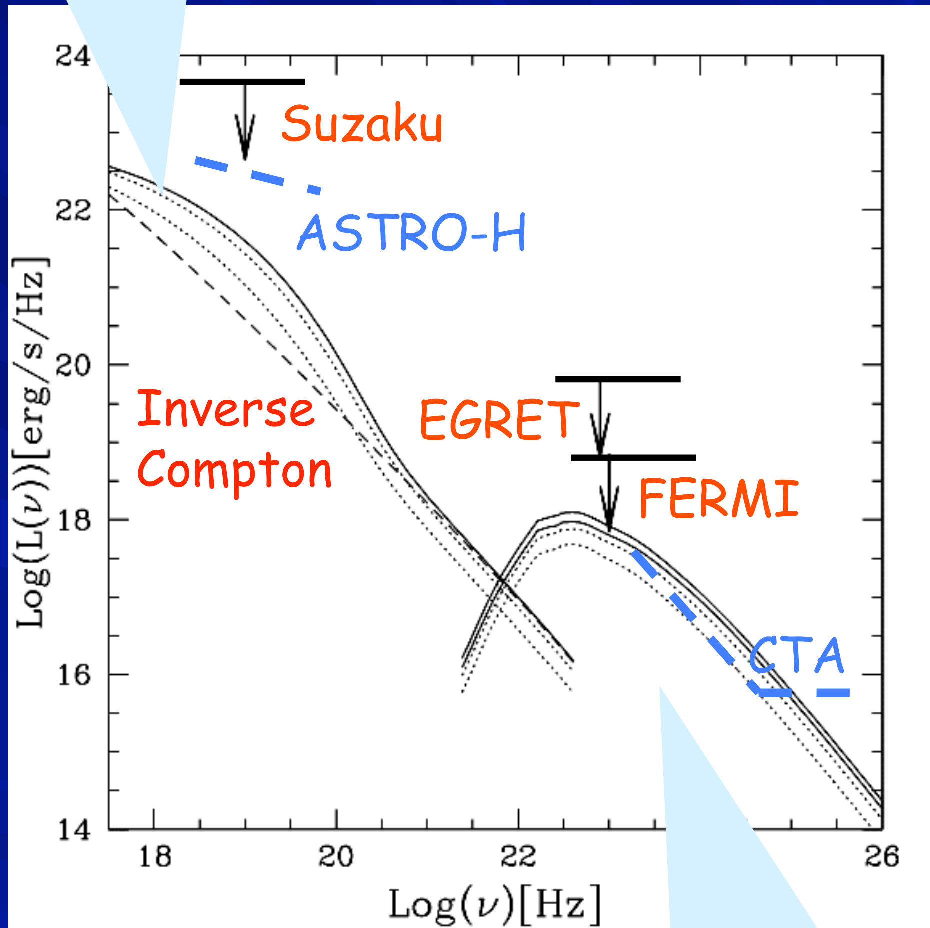




Radiation from CR in clusters (Brunetti & Lazarian 11)



secondary (or primary) electrons reaccelerated by clusters turbulence



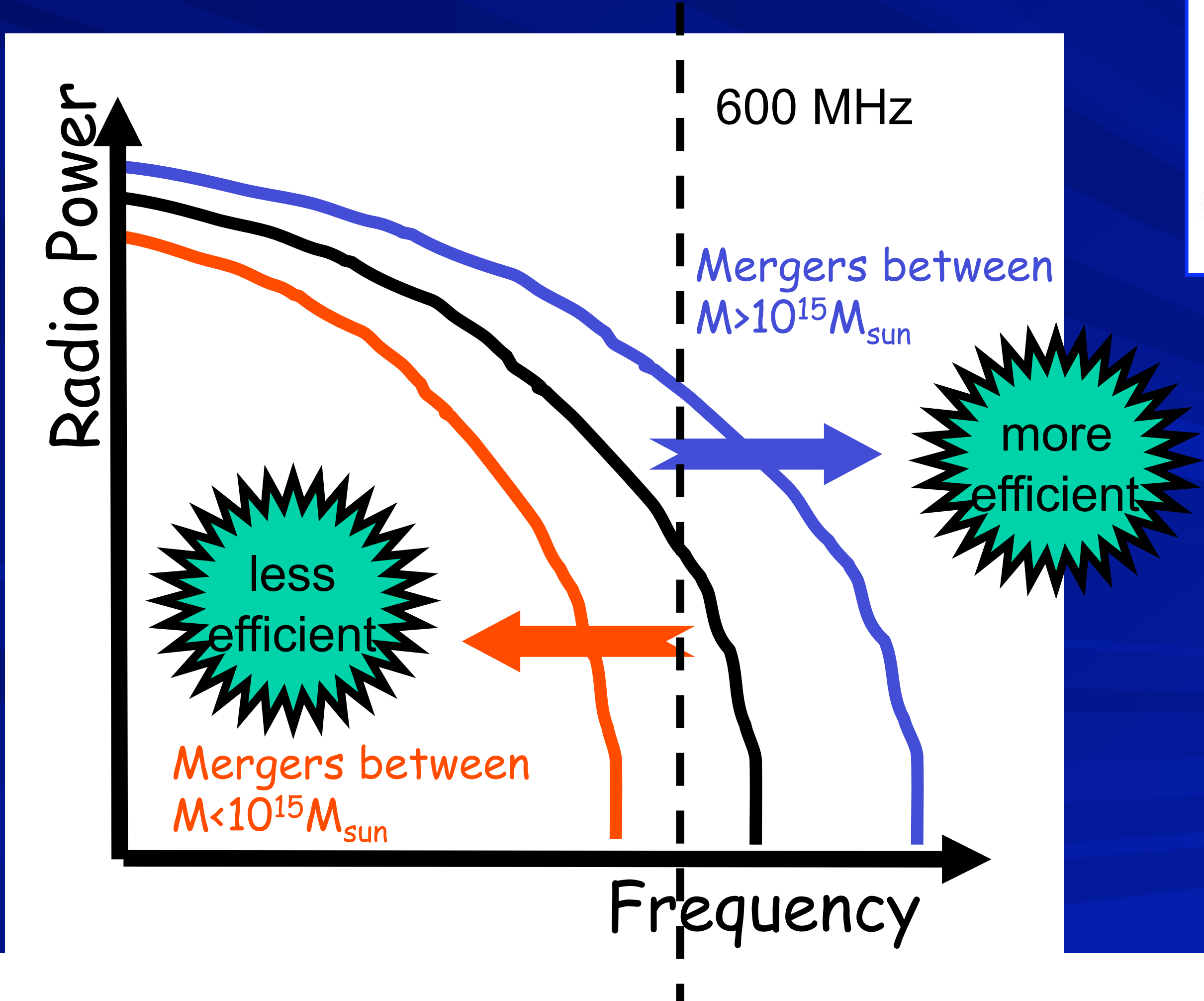
Gamma rays from decay of π^0 from CRp-p collisions

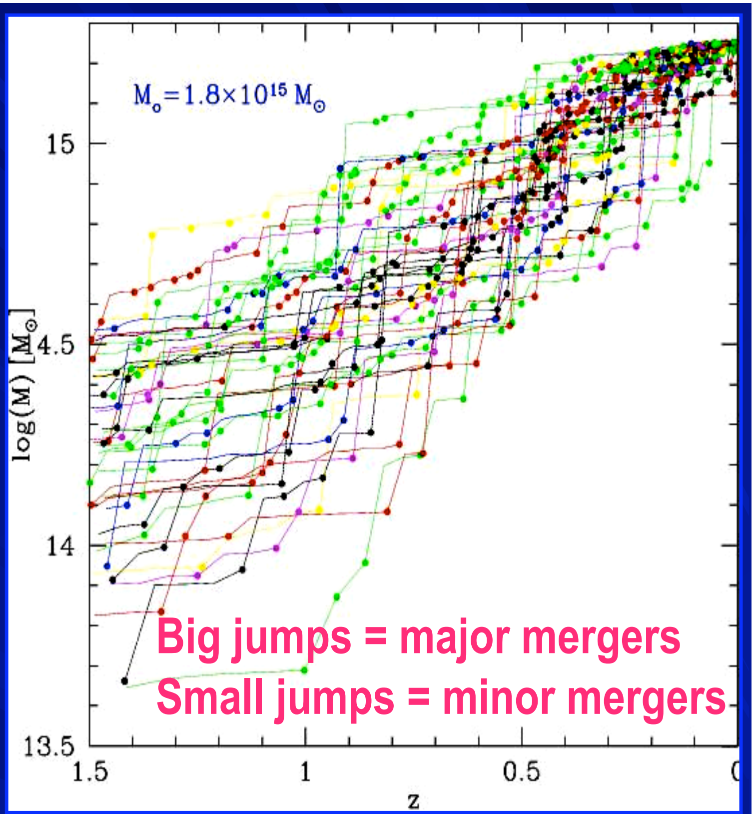
Observations in different bands provide constraints on different processes …

Probing CRe acceleration models

It is difficult to test/constrain theories of particle acceleration in very inhomegeneus and distant regions…

TURBULENCE is the potential source of CRparticle reacceleration in clusters environments, in this case high frequency radio observations can detect only the "tip-of-the-iceberg", while the majority of Mpc-scale radio sources should glow up at lower radio frequencies.



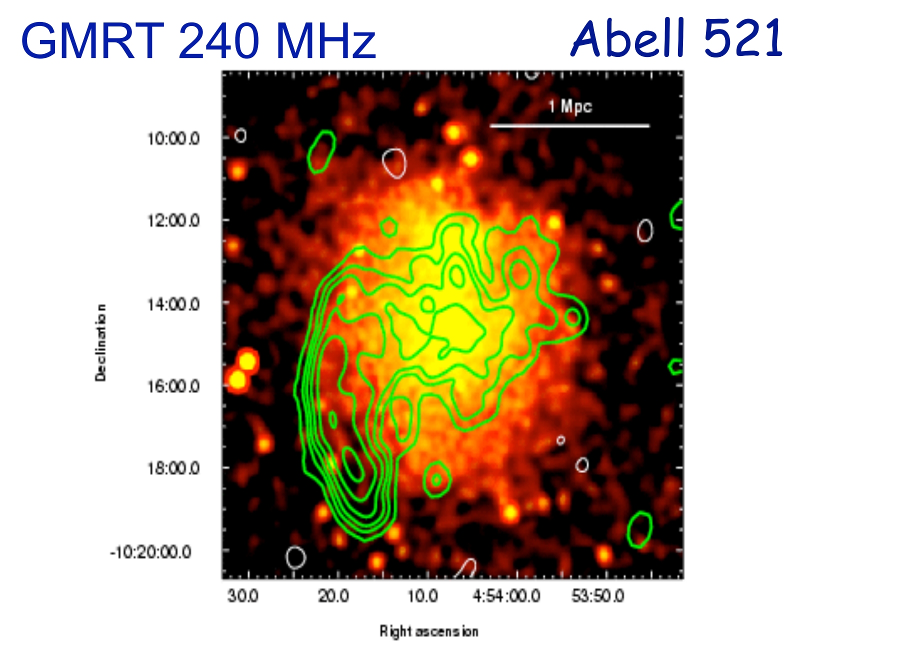


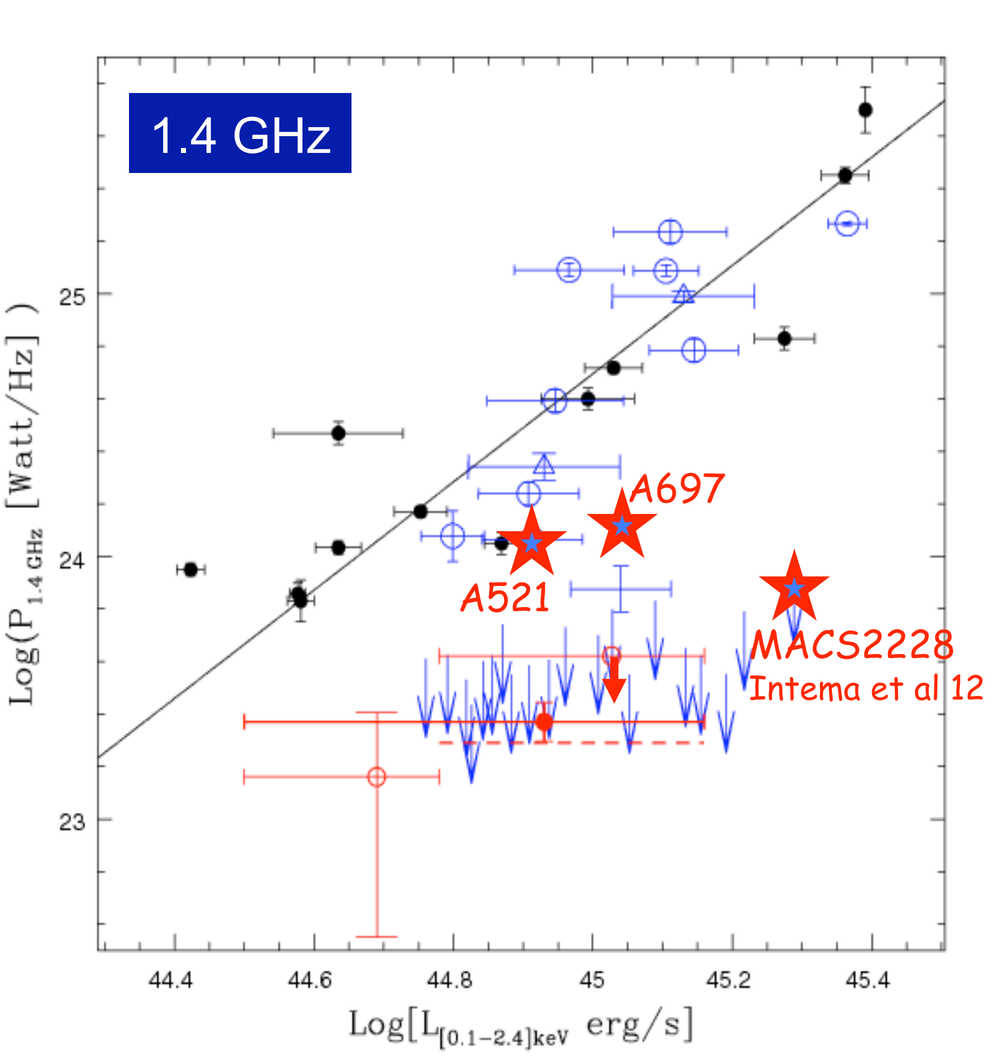
Radio Halos with very steep spectrum in the classical radio band must exist

(Cassano, GB, Setti 06)

Turbulent acceleration?

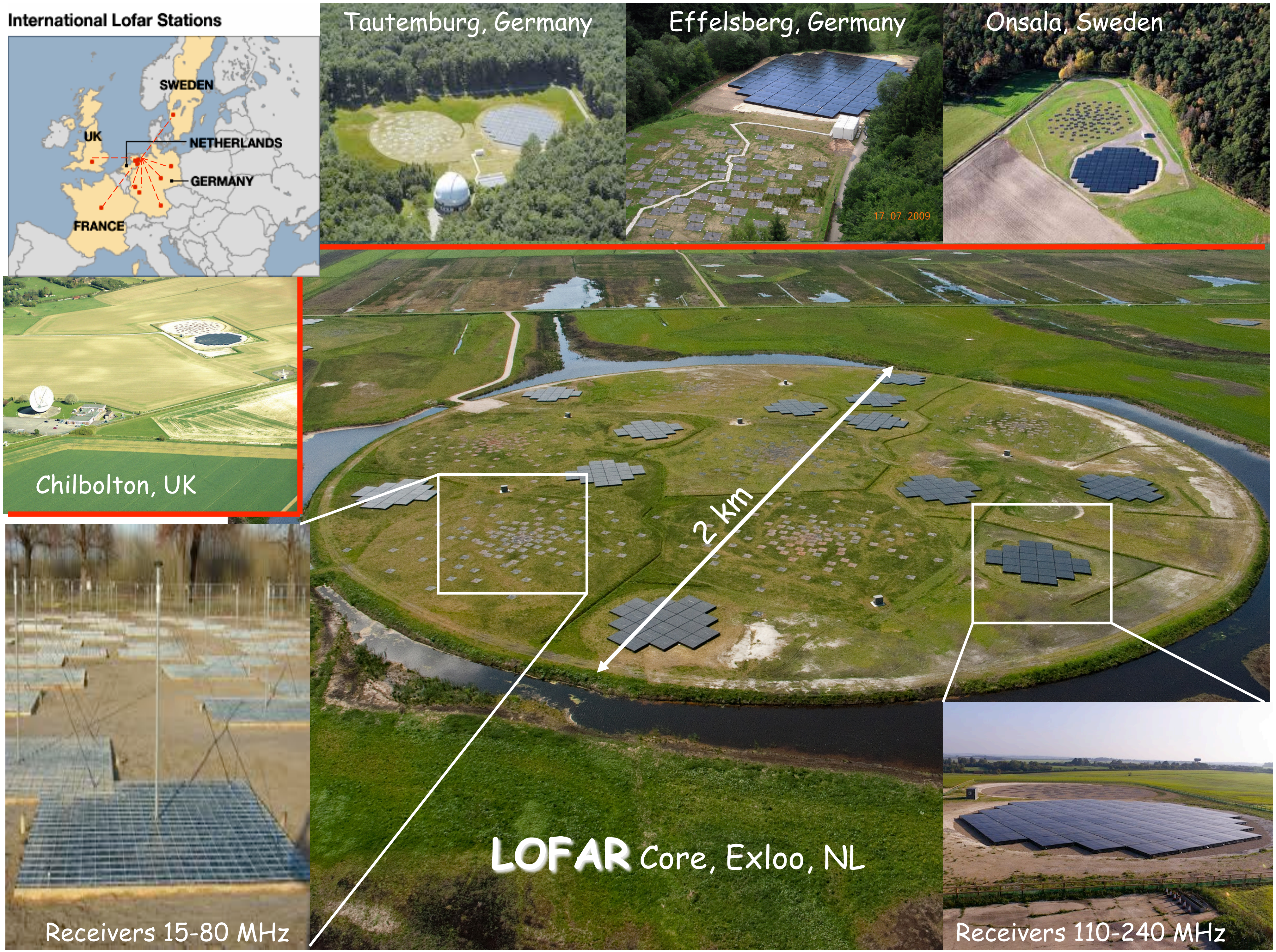
Brunetti +al 2008, *Nature 455, 944*



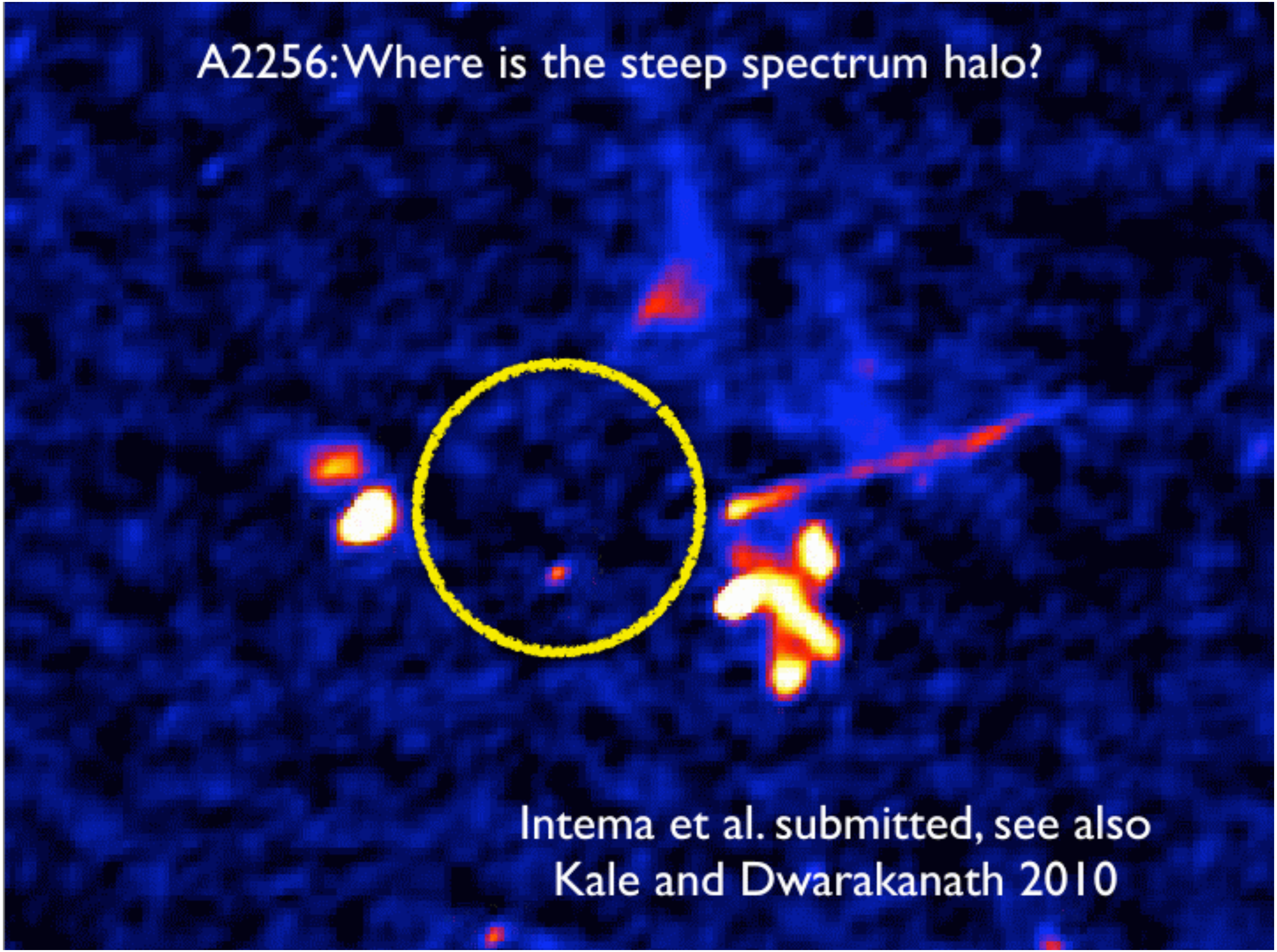


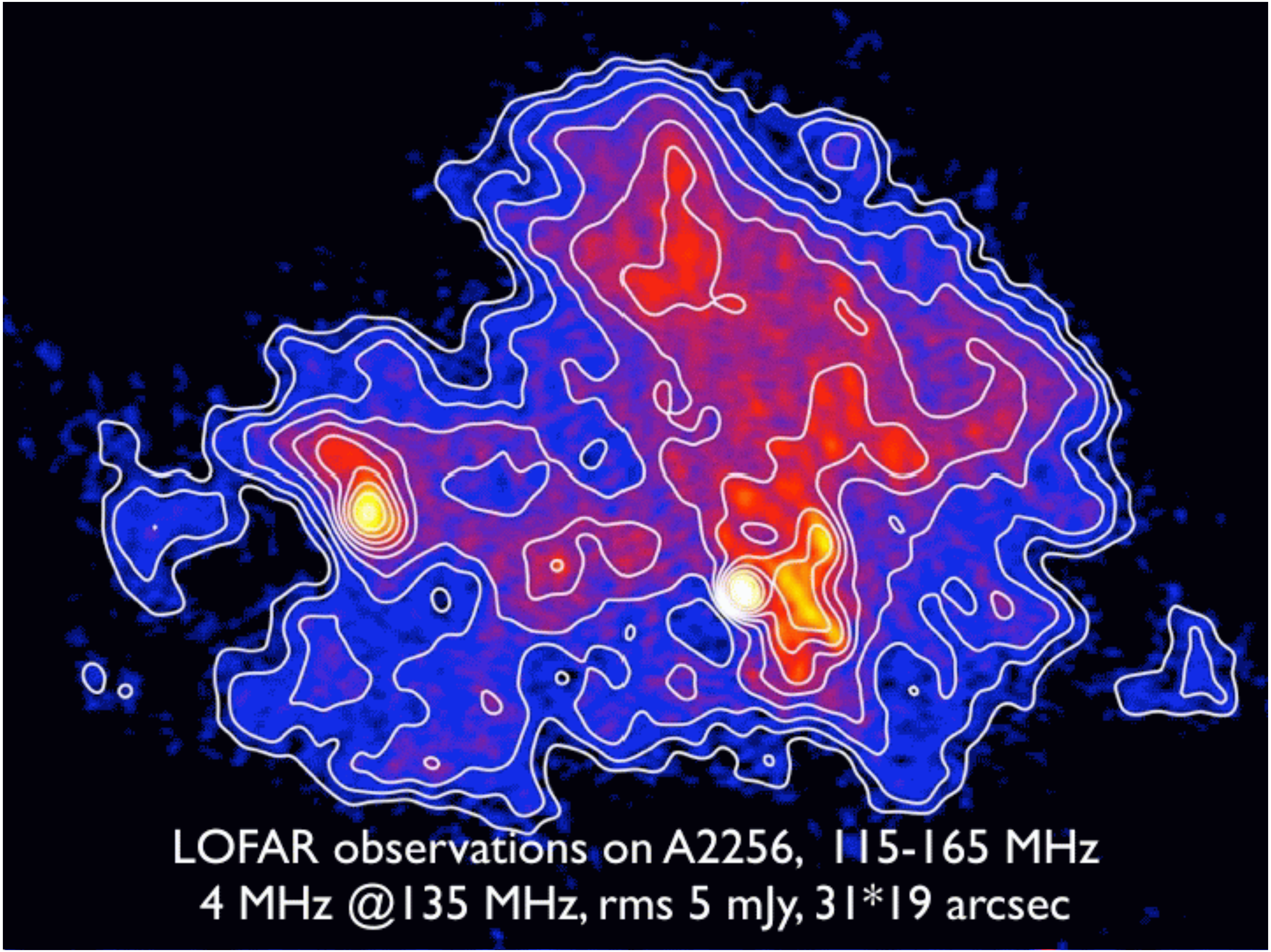
Several giant radio halos with ultra-steep spectrum have been discovered so far, they fill the transition region in the Psyn-Px diagram as expected by the reacceleration model .

Radio observations/surveys at low radio frequencies with unprecedented sensitivity are required to unveil the majority of halos in the Universe…



International Lofar Stations
SWEDEN
UK
NETHERLANDS
GERMANY
FRANCE
Tautemburg, Germany
Effelsberg, Germany
17.07.2009
Onsala, Sweden
Chilbolton, UK
2 km
LOFAR Core, Exloo, NL
Receivers 15-80 MHz
Receivers 110-240 MHz

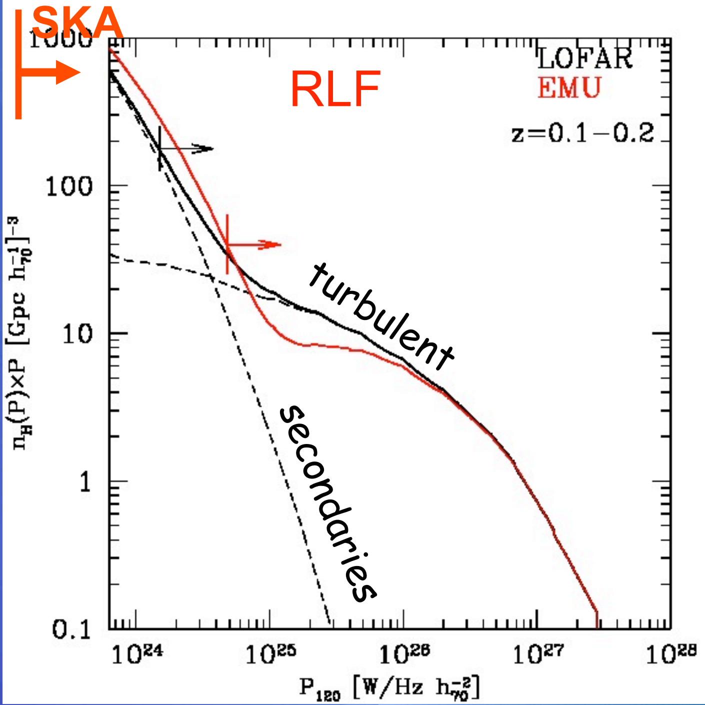

A2256: Where is the steep spectrum halo?
Intema et al. submitted, see also
Kale and Dwarakanath 2010

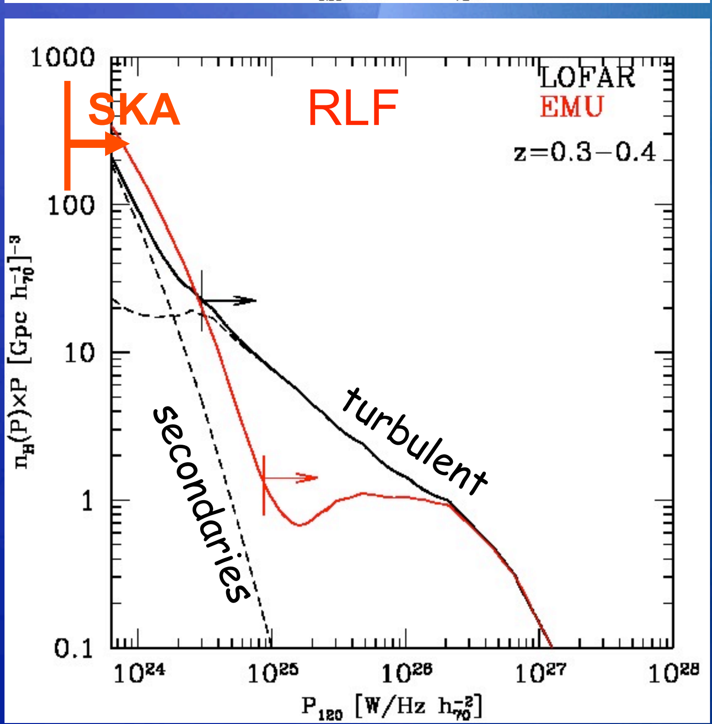

LOFAR observations on A2256, 115-165 MHz
4 MHz @135 MHz, rms 5 mJy, 31*19 arcsec

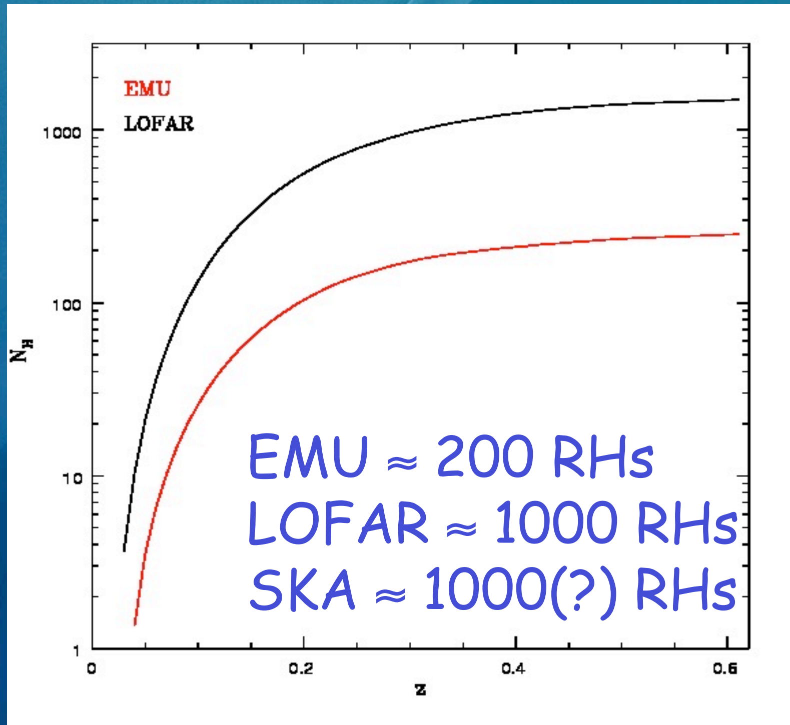
How many radio halos can be discovered ??

Results from MonteCarlo calculations including (turbulence) reaccelerated and secondary electrons
(Cassano,GB, Johnston-Hollit, Norris, Rottgering, Trasatti 12)

LF at 1.4 GHz (EMU,SKA) are shifted at 120 MHz assuming =1.2





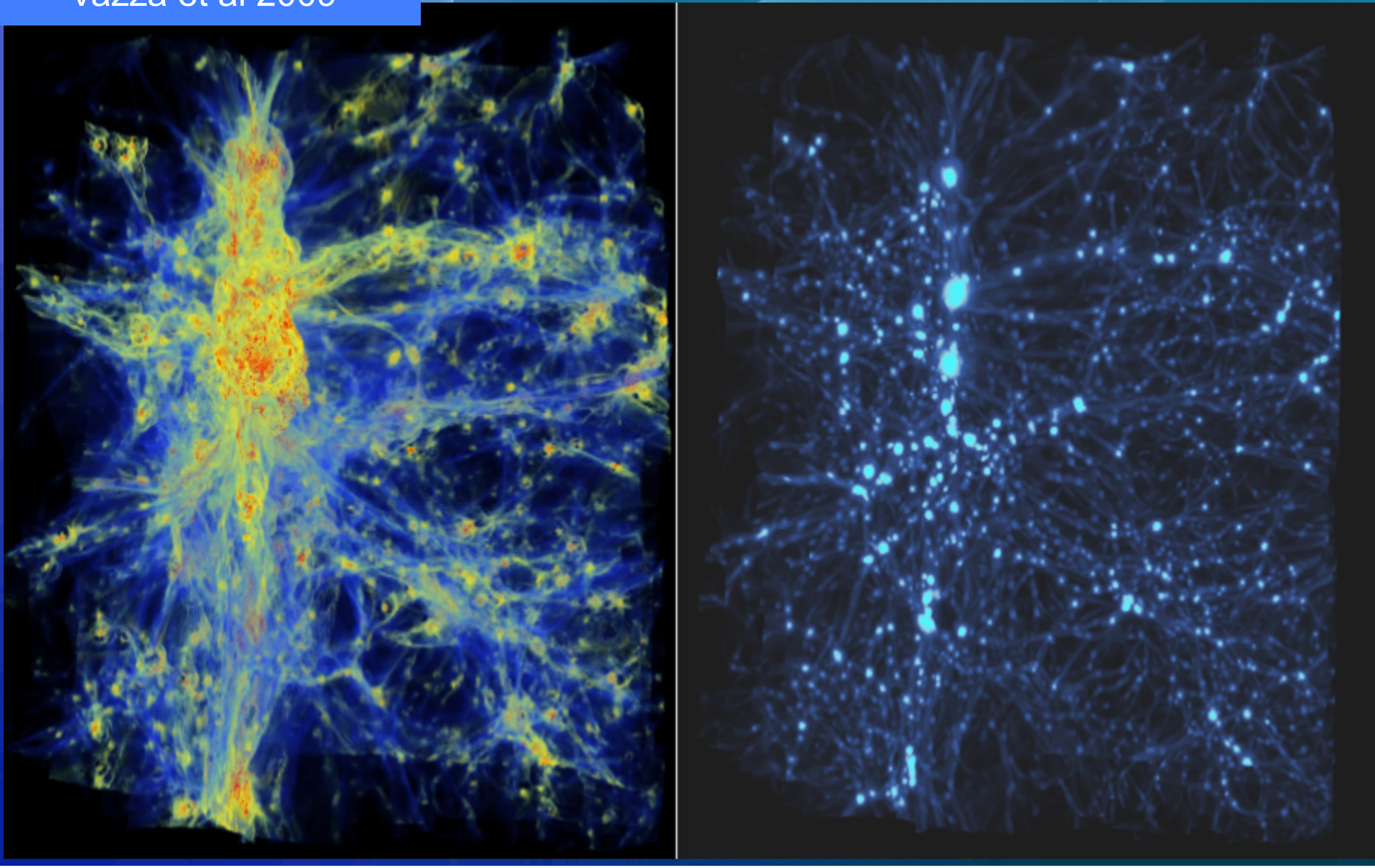


Constrain B amplification and CR acceleration up to z=1, with impact on Cosmology …

Cosmological Shocks

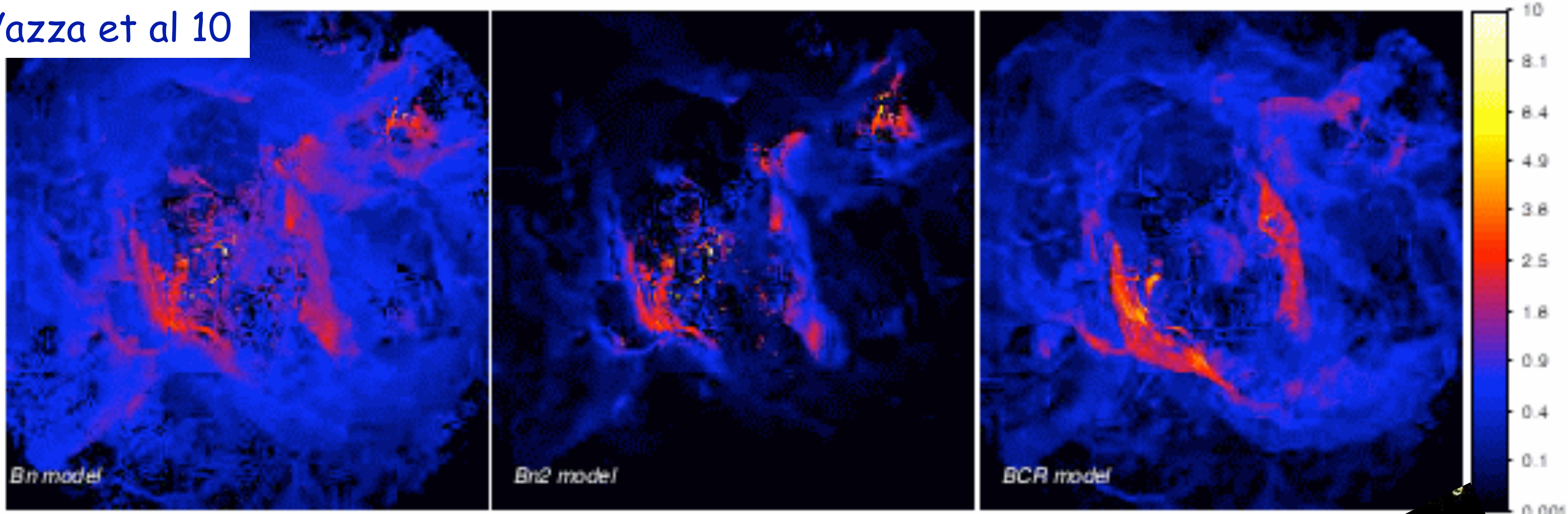
Natural consequence of the hierarchical process of LSS formation

Vazza et al 2009

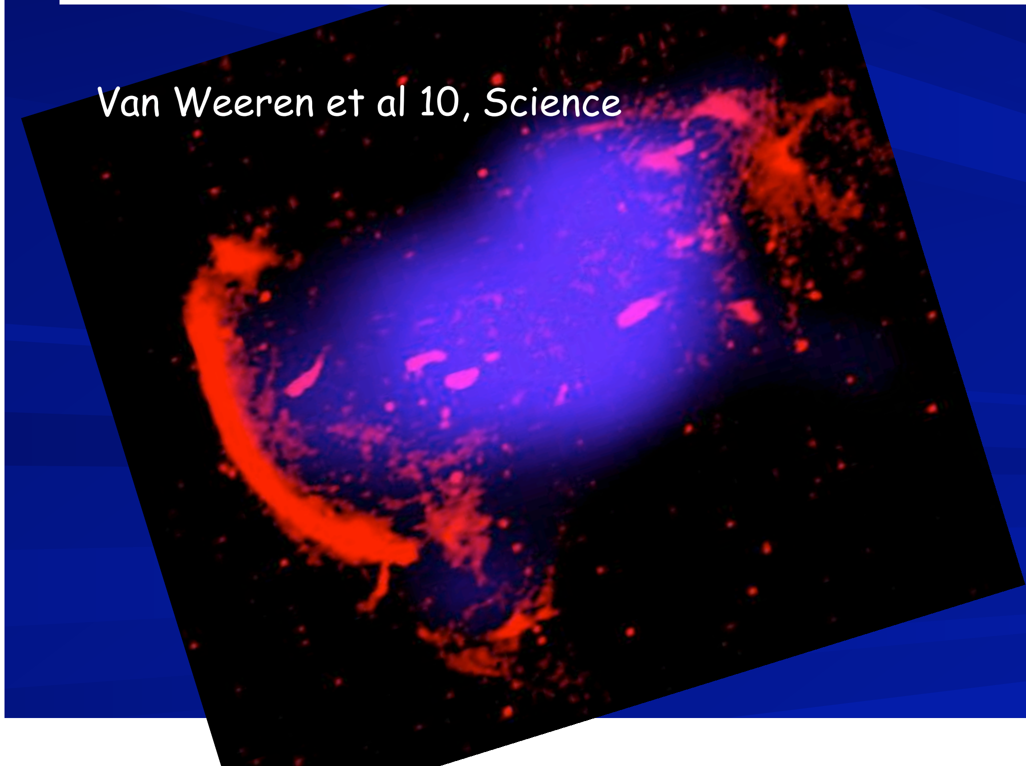


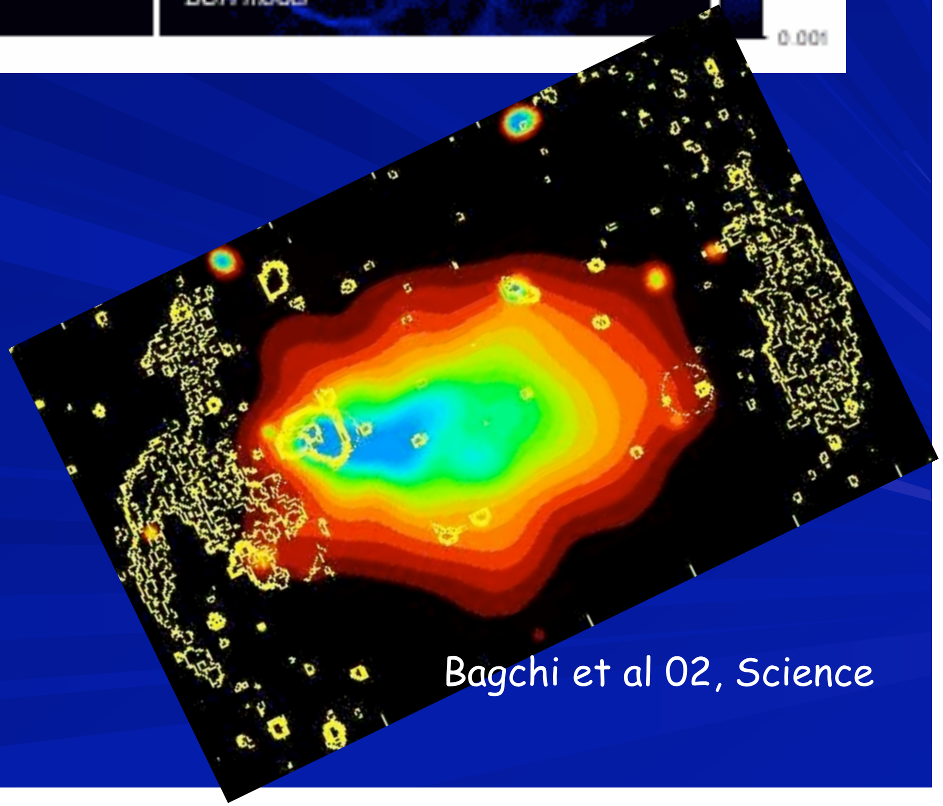
Syn diffuse emission beyond clusters

Vazza et al 10



Van Weeren et al 10, Science

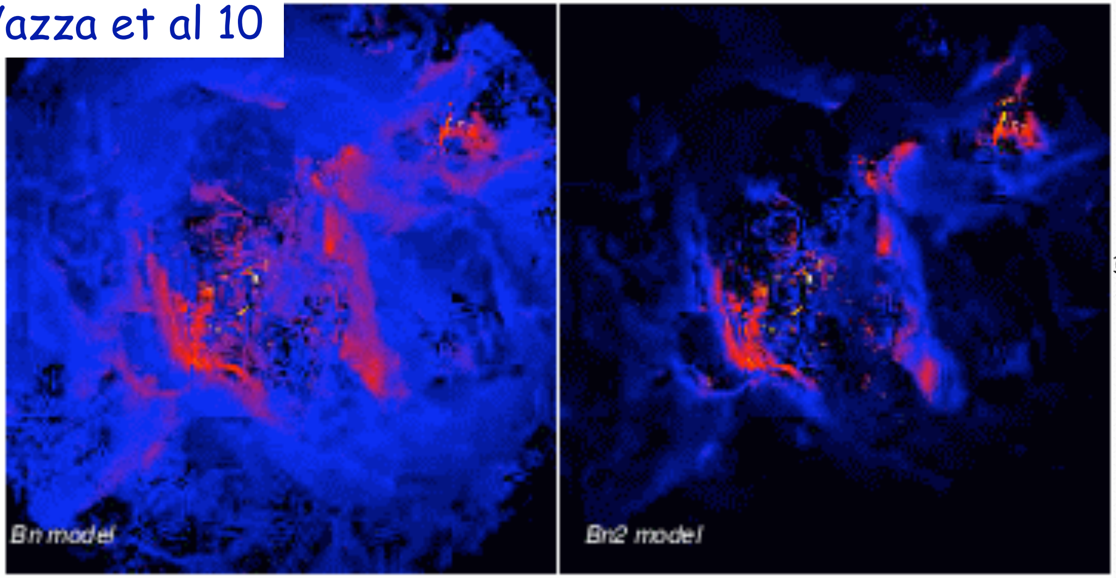


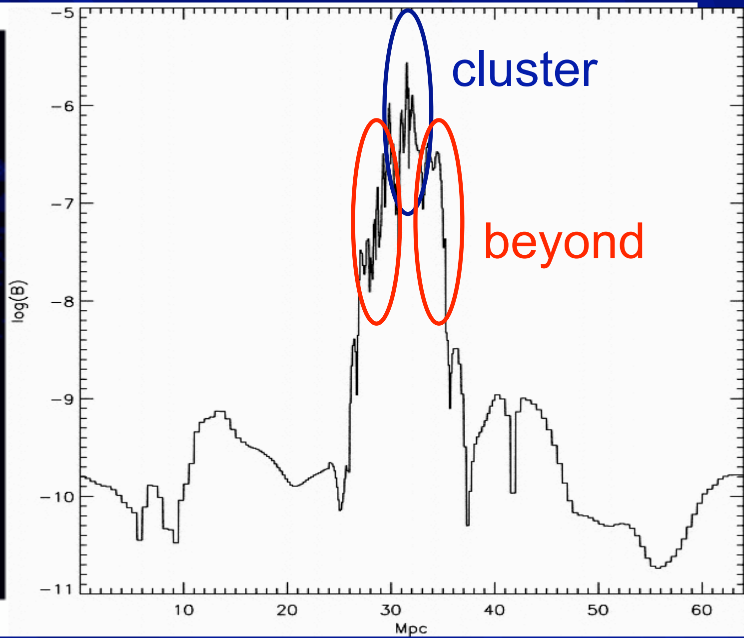


Bagchi et al 02, Science

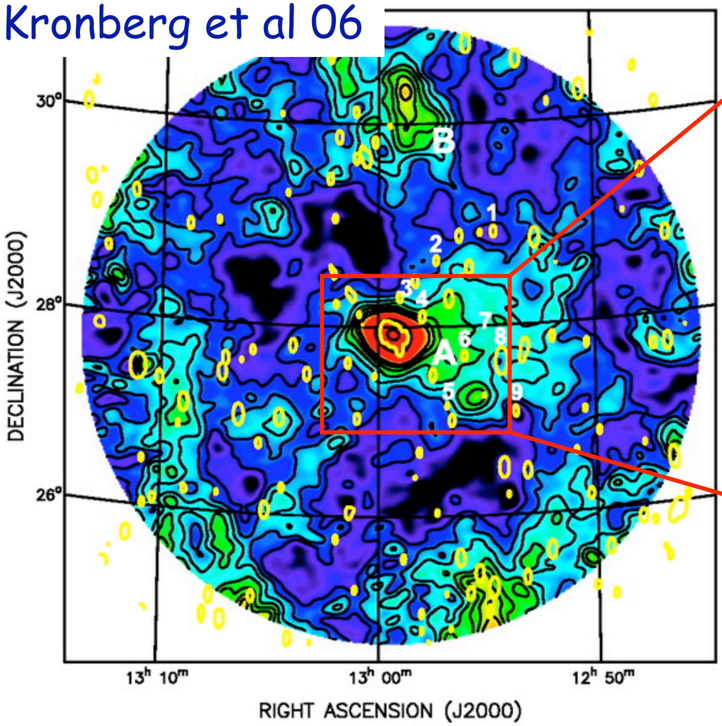
Syn diffuse emission beyond clusters

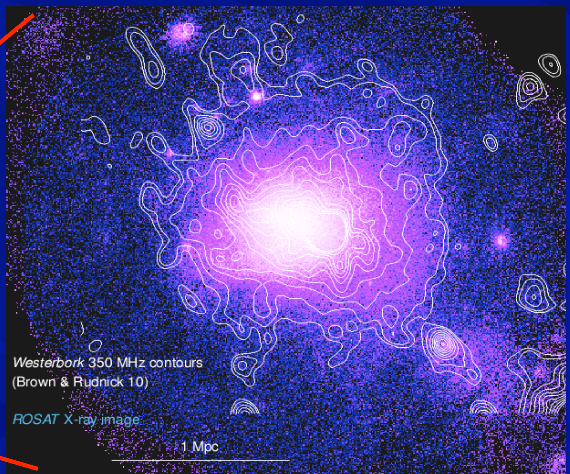
Vazza et al 10





Kronberg et al 06



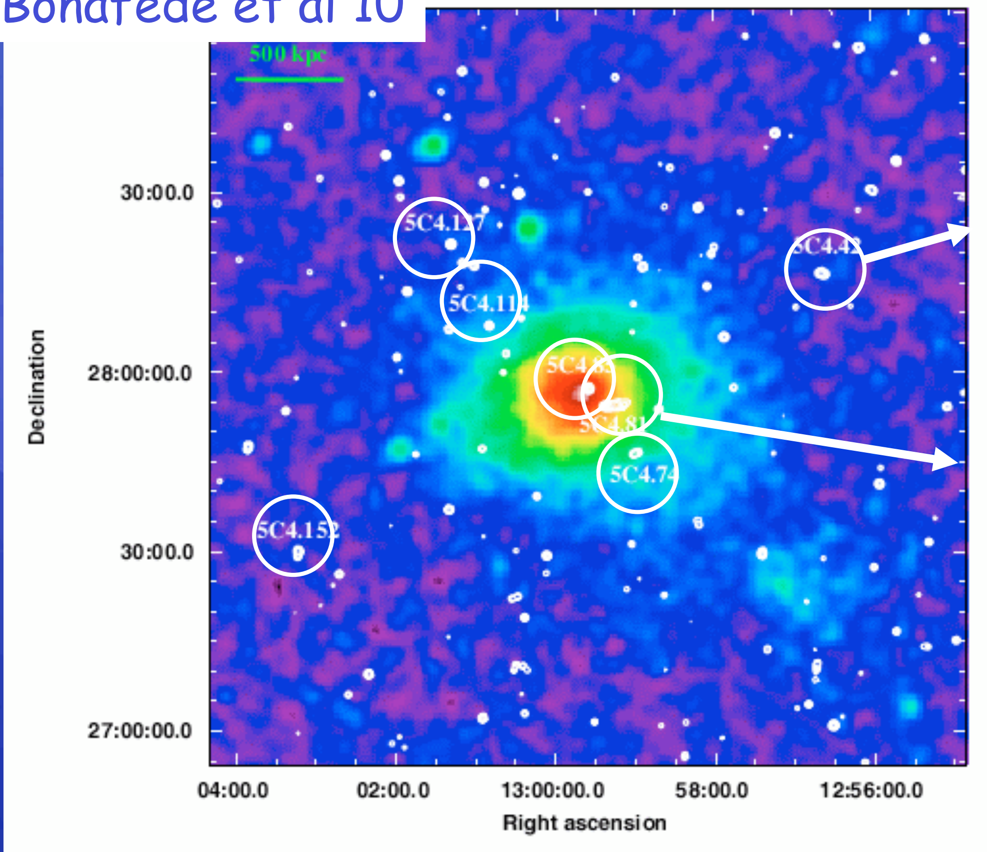


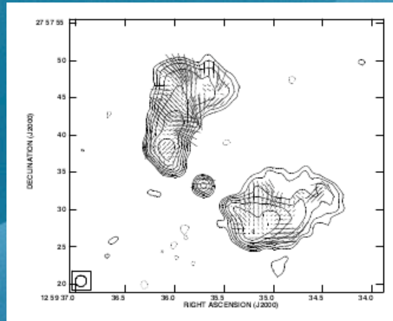
Depending on plasma physics and B amplification mechanisms, observations at GHz-frequencies with sensitivity 10-30 times better than present should be able to probe a totally unexplored territory …

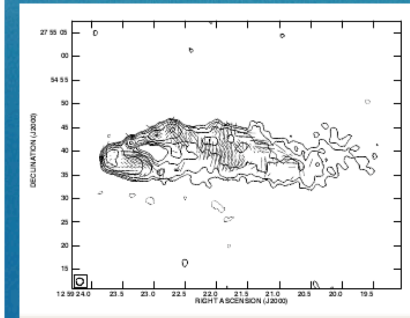
Territory for the SKA

Leap forward in RM-science with SKA

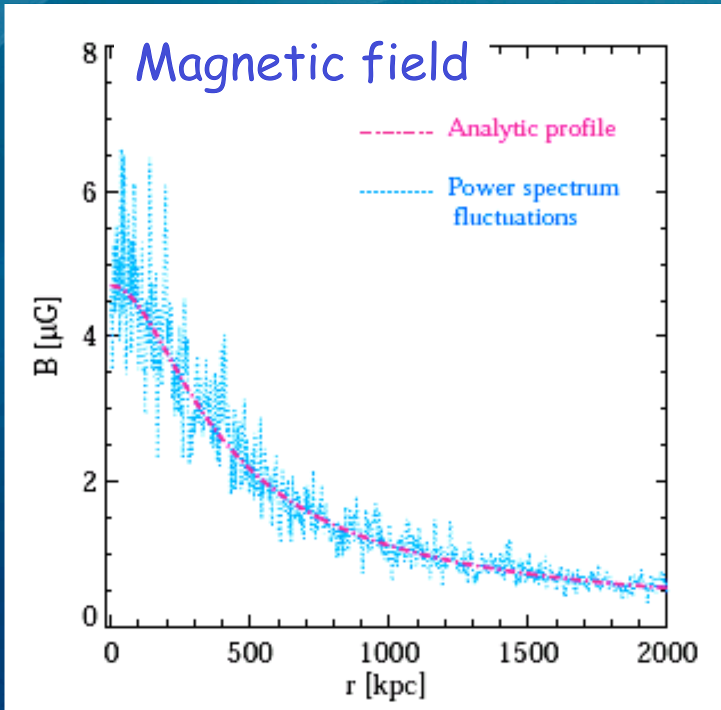
Bonafede et al 10





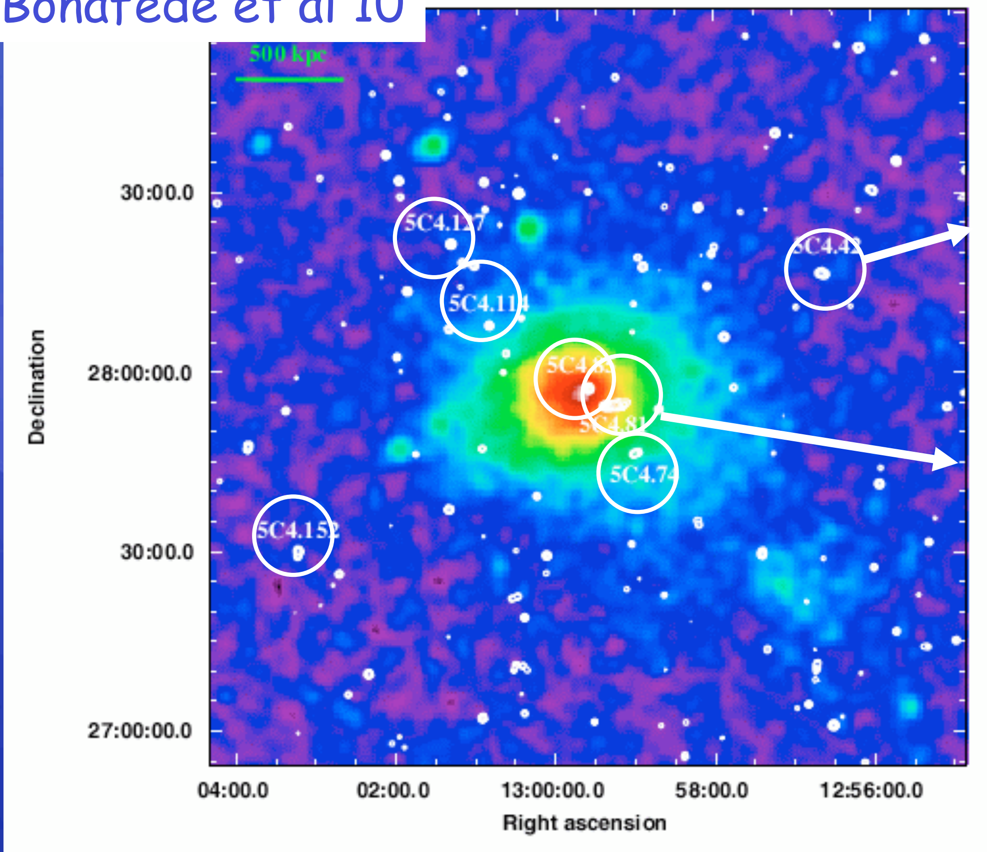


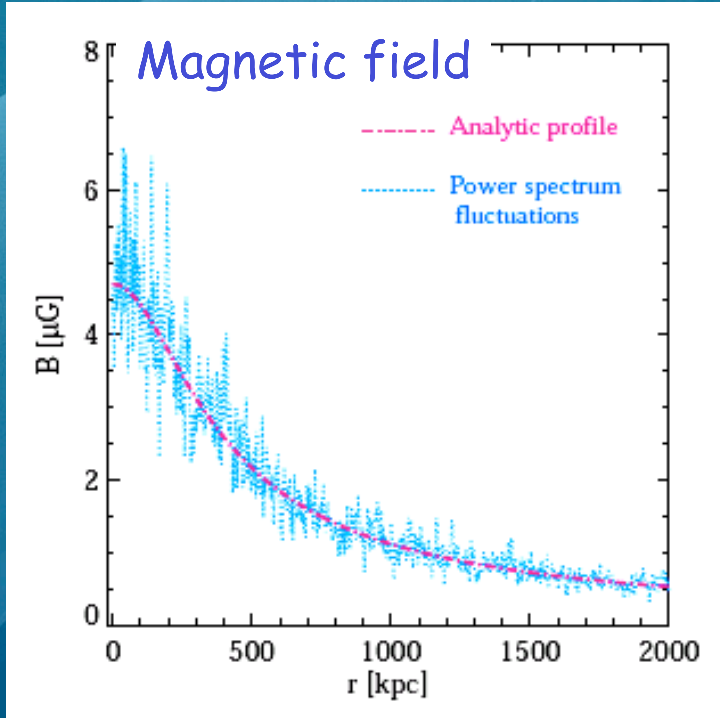
“State of the Art” results are based on few (3-8) backgroud sources/line of sight.
Variance and assumptions (geometry) are major problems for a reliable measure of B and its spatial profile.
Limitations are due to the poor sensitivity of radiotel… few sources “available” per deg2



Leap forward in RM-science with SKA

Bonafede et al 10



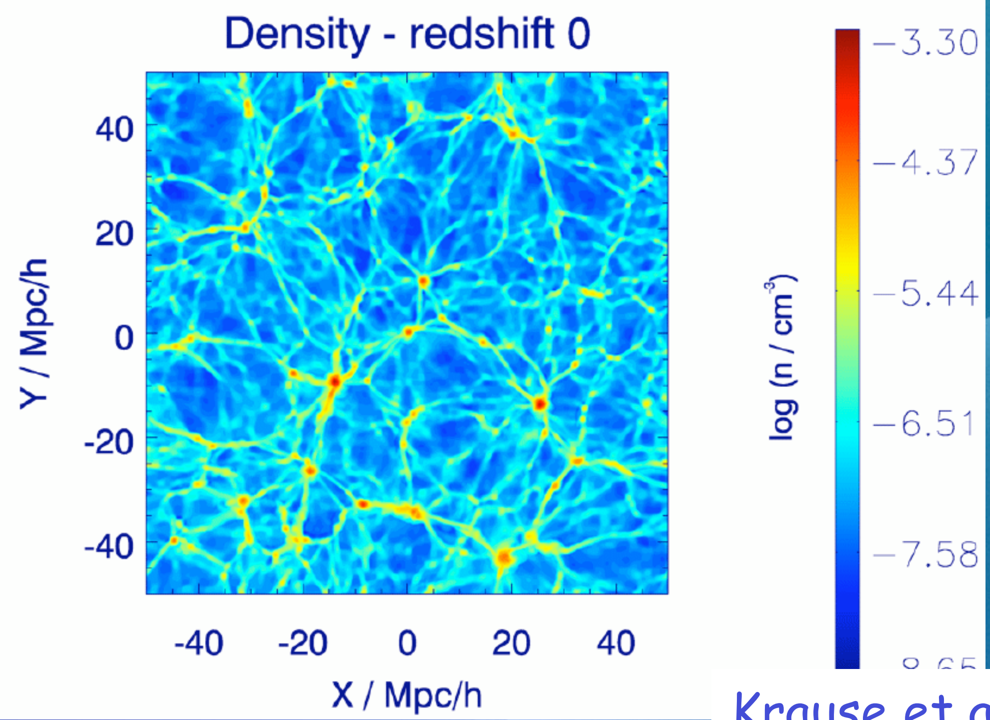


The SKA Magnetism Key Science Project plans to observe large regions in the sky with a sensitivity (GHz) 0.5-1 μJy flux density allowing for 1500 RMs deg^{-2} .

In a nearby cluster field there will be up to 100-1000 background sources/lines of sight to sample … compared to a few in present studies .

This will allow firm measurements of magnetic field in clusters, its evolution and connection with clusters dynamics.

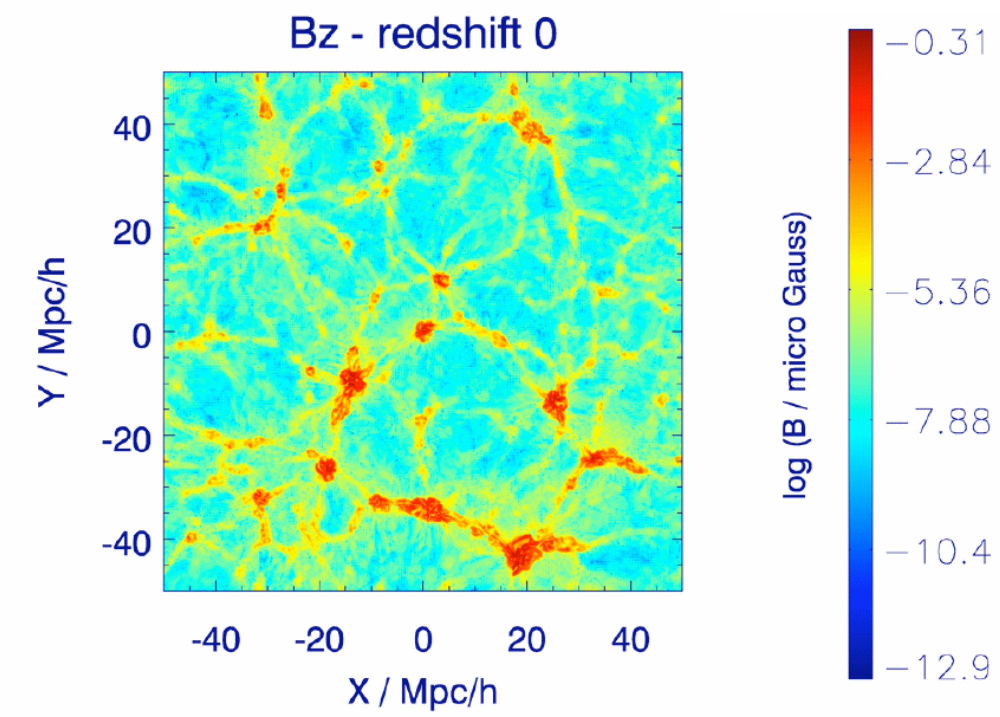
Clusters and beyond … ??

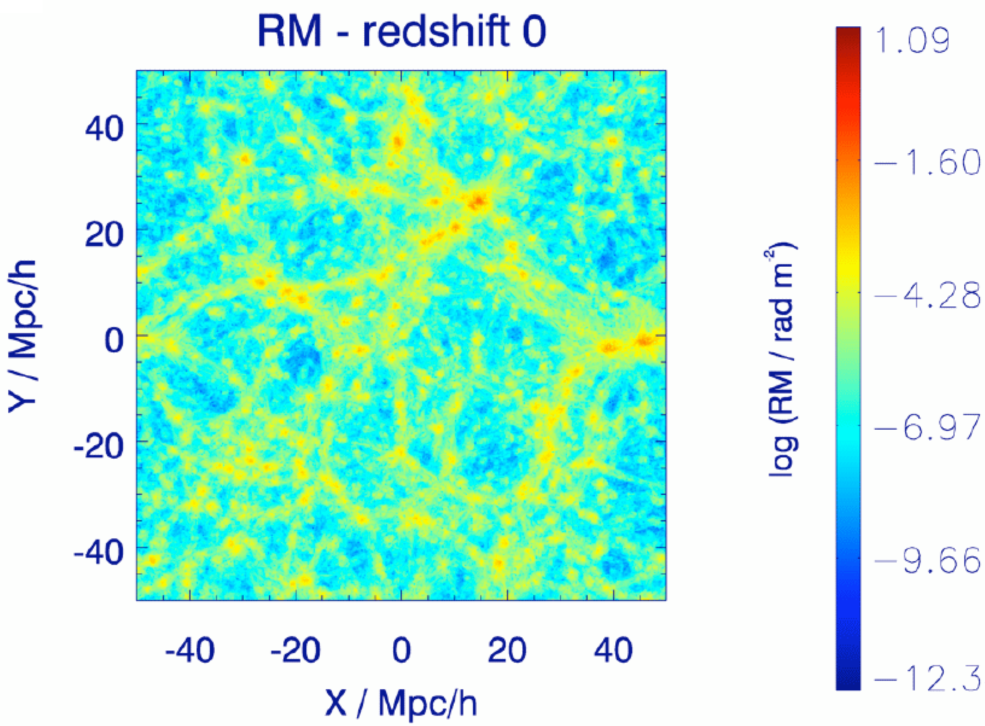


The SKA sensitivity (RMs) will be 10-100 times better than present radiotelescopes.

SKA will explore regions where $\langle n_e B \rangle$ = 0.1-0.01 $\langle n_e B \rangle$_(clusters cores)

Krause et al





Conclusions

Non-thermal components in GC are probed by radio observations

Non-thermal components may strongly affect the physics of the ICM

Origin of B and CR in GC is still a open question, yet a promising theoretical picture suggests a connection between the acceleration of CR (turbulence, shocks, secondaries), the amplification of seed B (turbulent dynamos / shocks) and the formation of GC (mergers)

LOFAR and SKA-pathfinders will shortly start testing this theoretical picture.
LOFAR **in particular** will enter into the unexplored territory of low-radio frequencies where synchrotron emission from merging clusters "must" be common

SKA will allow firm measurements of B in galaxy clusters and its evolution
SKA will enter into the unexplored territory (also in 20 years!) of the exploration of non-thermal (and plasma physics!) properties of clusters outskirts and beyond