NON THERMAL PHENOMENA IN GALAXY CLUSTERS: OPEN QUESTIONS & FUTURE PERSPECTIVES

Seeing beyond the tip of the iceberg

→ *now*

Rossella Cassano

INAF-ORA, Bologna, ITALY

"THE MANY FACETS OF EXTRAGALACTIC RADIO SURVEYS: TOWARDS NEW SCIENTIFIC CHALLENGES"

Bologna, 20-23 October 2015

Outline of the talk

Setting the scene

✔ a multi-wavelength view of Galaxy Clusters →

Radio Halos and Radio Relics

✔ Cluster formation (mergers) → generation of NT-components

Origin of cluster-scale diffuse synchrotron radio emissions

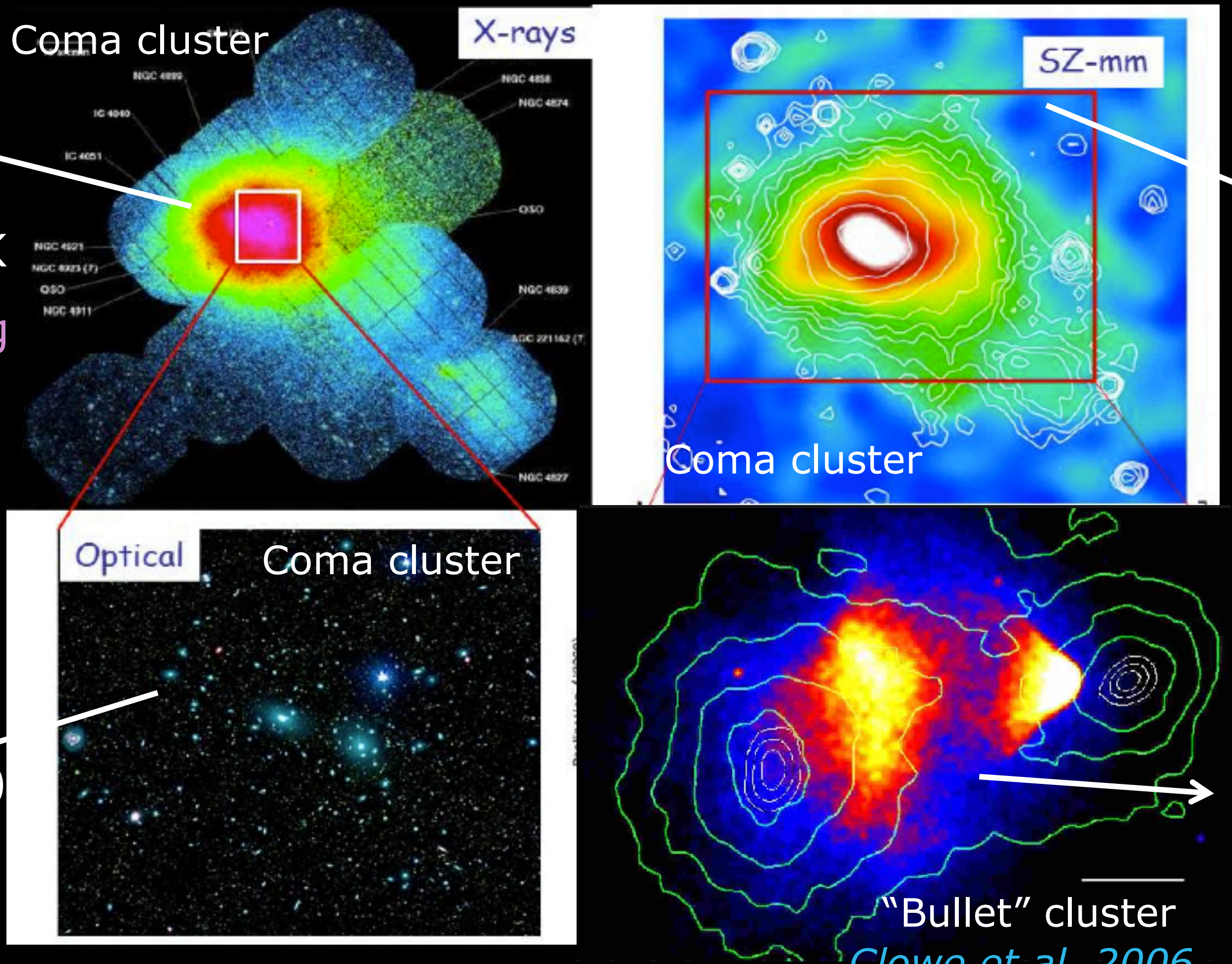
✔ basic theoretical models and open problems

Focus on giant Radio Halos

✔ Statistical models and expectations for future radio surveys with LOFAR, ASKAP, MeerKAT … SKA

A multi-wavelength view of galaxy clusters

Hot ICM
$n_e \sim 10^{-1}$-10^{-4} cm^{-3} , $T \sim 10^8$ °K
bremsstrahlung



Hot ICM
$n_e \sim 10^{-1}$-10^{-4} cm^{-3} , $T \sim 10^8$ °K
IC scattering of CMB photons

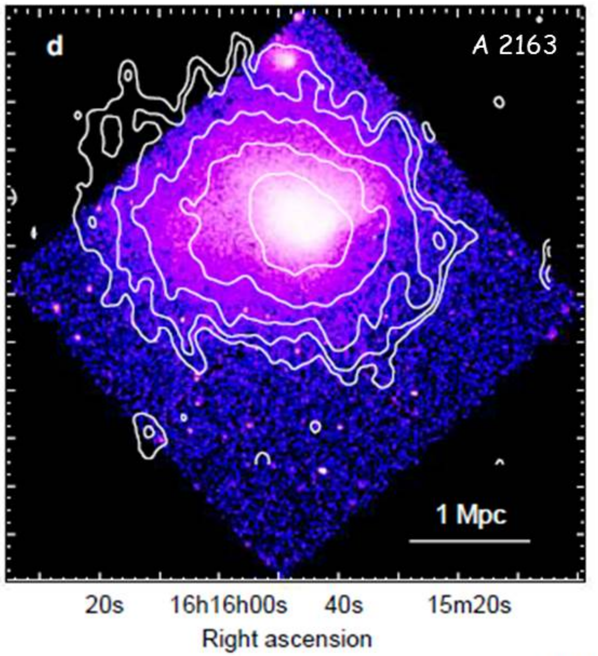
galaxies (stars)
+
DM (indirect)

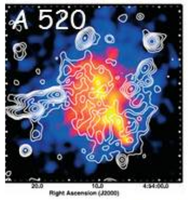
X-ray image + weak-lensing green contours
↓
DM mass

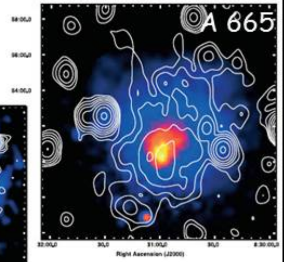
✓ Largest concentration of matter in the Universe:

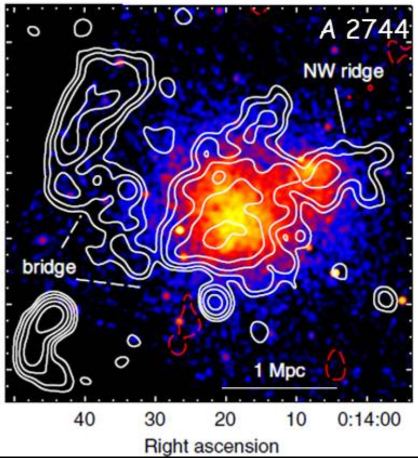
L~2-3 Mpc, $M \sim 10^{15} M_\odot$

✓ Made of : 70-80% of dark-matter
few % galaxies and 15-20% intra-cluster medium (ICM)









Diffuse synchrotron radiation from the ICM of merging clusters => GeV relativistic e⁻ and μG magnetic fields on Mpc-scale

(*e.g.; Ferrari et al. 08; Feretti et al. 12; Brunetti & Jones 2014, for a review*)

Fundamental questions…

- ➢ **ORIGIN ??**
- ➢ **IMPACT on thermal ICM ??** **(microphysics & dynamics)**

Giant Radio Halos

✔ Steep spectrum sources ($\alpha \sim 1.2$-1.4, $f(\nu) \sim \nu^{-\alpha}$)

✔ Low surface radio brightness

Radio Halos

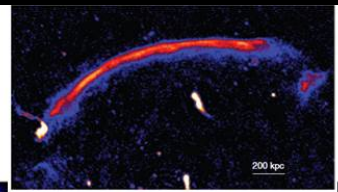
Unpolarised, follow the X-ray brightness

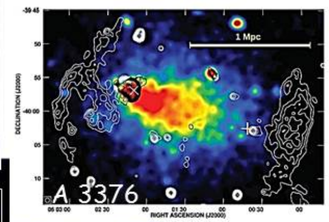
(originate from cluster central regions)

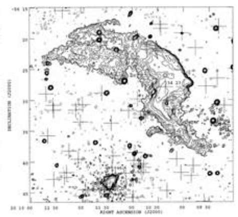
Radio Relics

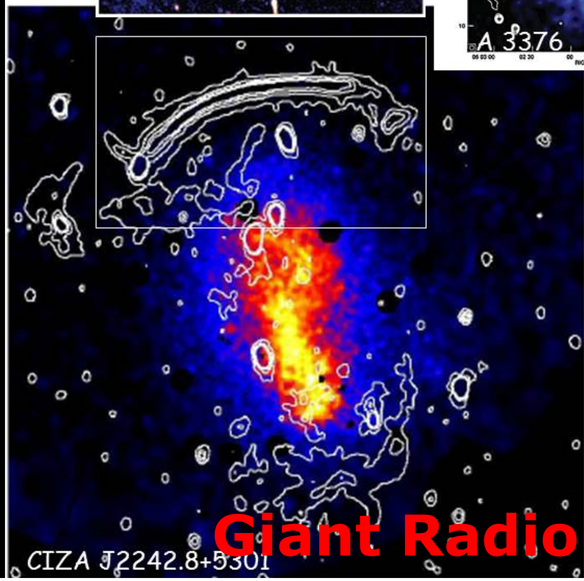
Polarised, no correlation with X-ray brightness

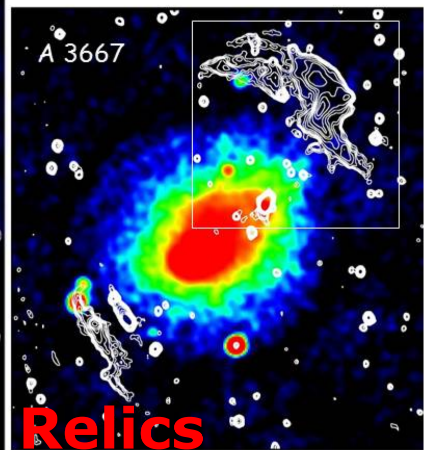
(form cluster outskirts)









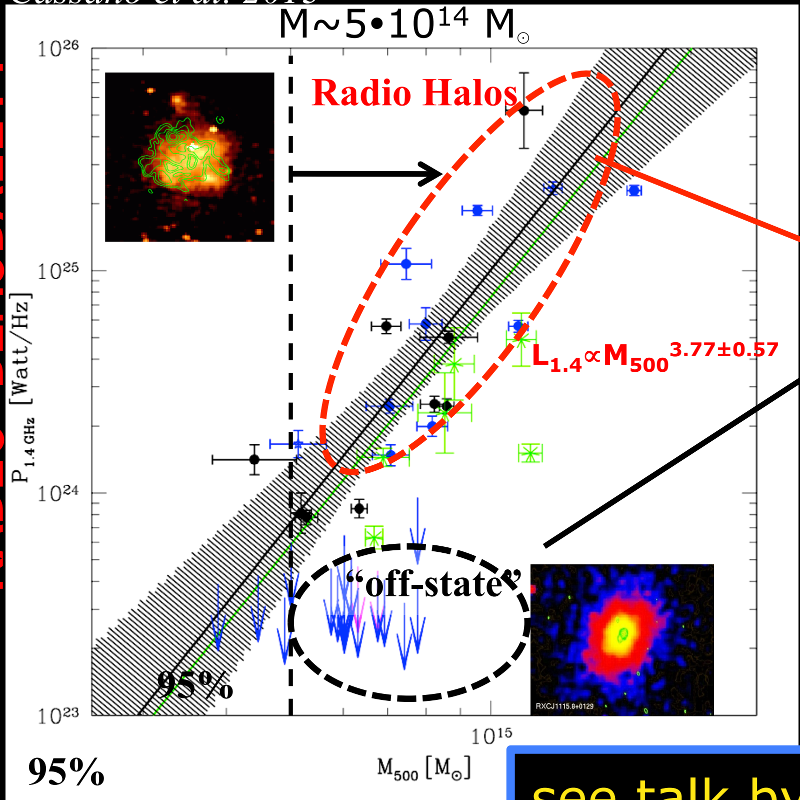


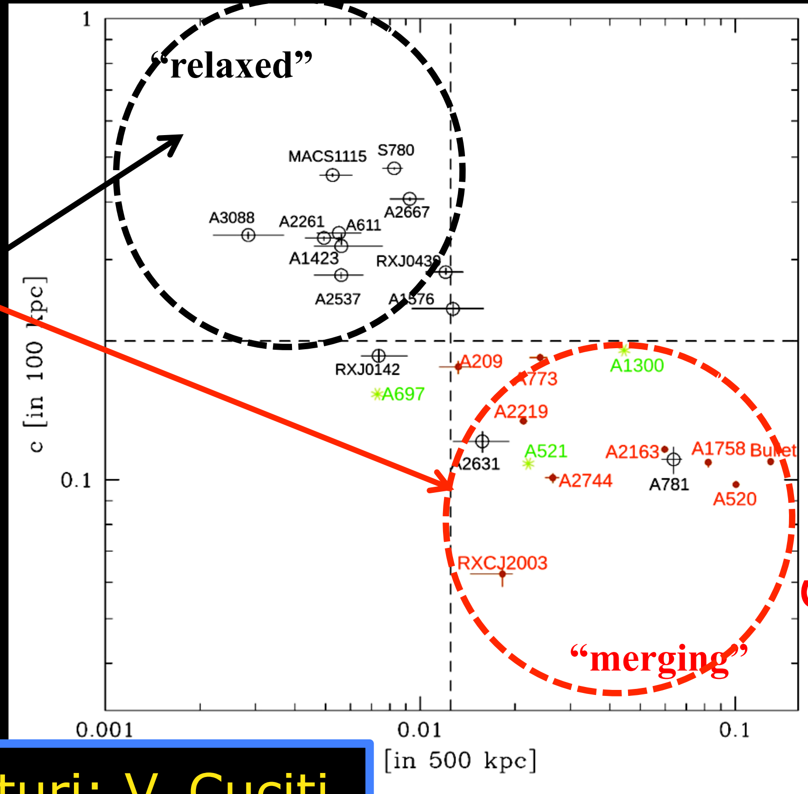
Giant Radio Relics

Observational Milestones: RH & cluster mergers

Cassano et al. 2013

RADIO BIMODALITY





Radio Halo-merger

see talk by T. Venturi; V. Cuciti

✓ The synchrotron power of radio halos ($P_{1.4}$) increases with the cluster mass L_X, T_X, Y_{SZ}; *e.g.; Colafrancesco 99; Liang et al 00, Feretti 00, 03; Ensslin & Röttgering 02; Cassano et al. 06, 13; Brunetti et al. 09; Giovannini et al. 09, Basu 12*)

✓ RHs are always found in merging clusters while clusters without RH are more "relaxed" (*Brunetti et al.07, Venturi et al. 07, 08; Cassano et al. 10, 13; Cuciti et al. 15*)

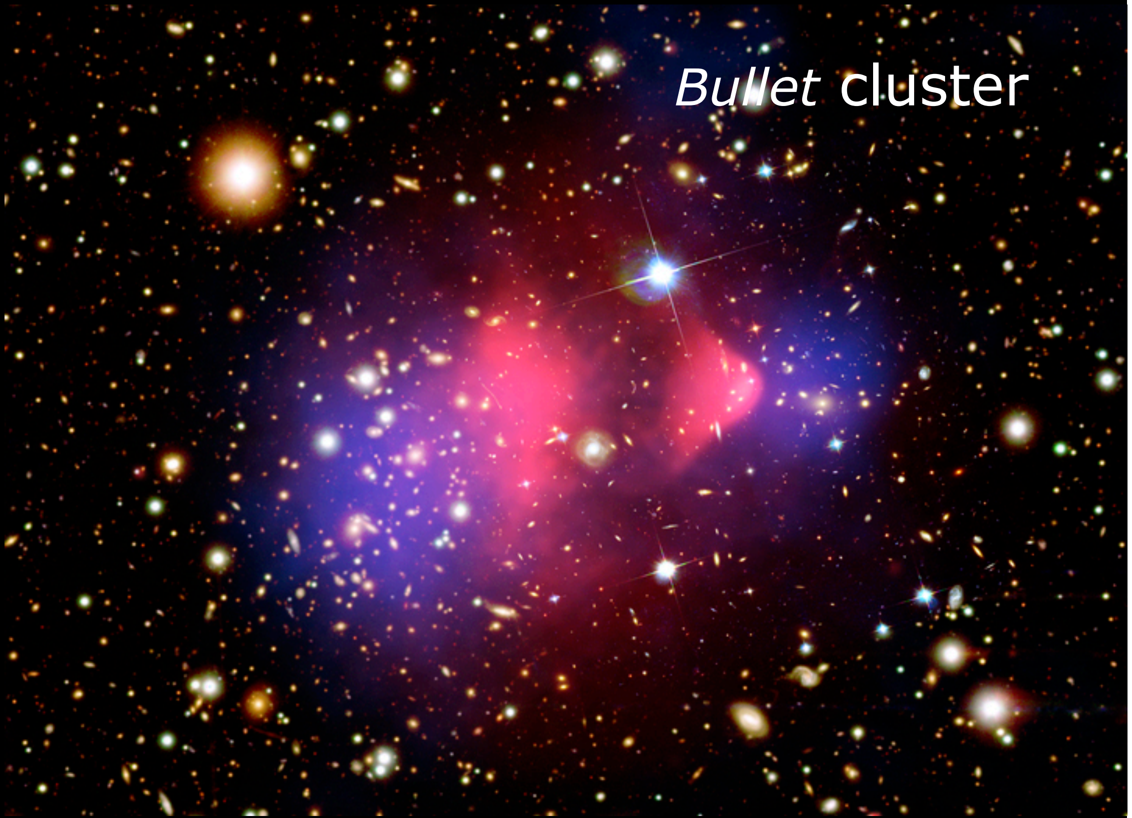
the generation of RHs is linked to the process of formation (mass growth) of galaxy clusters

How galaxy clusters form?

Galaxy clusters form via a hierarchical sequence of mergers and accretion of smaller systems driven by DM

Merger Energy ≈

$$\frac{GM_1M_2}{R} \simeq 4 \times 10^{64} \left(\frac{M_{1\,2}}{10^{15} M_\odot}\right)^2 \times \left(\frac{2Mpc}{R}\right) erg$$

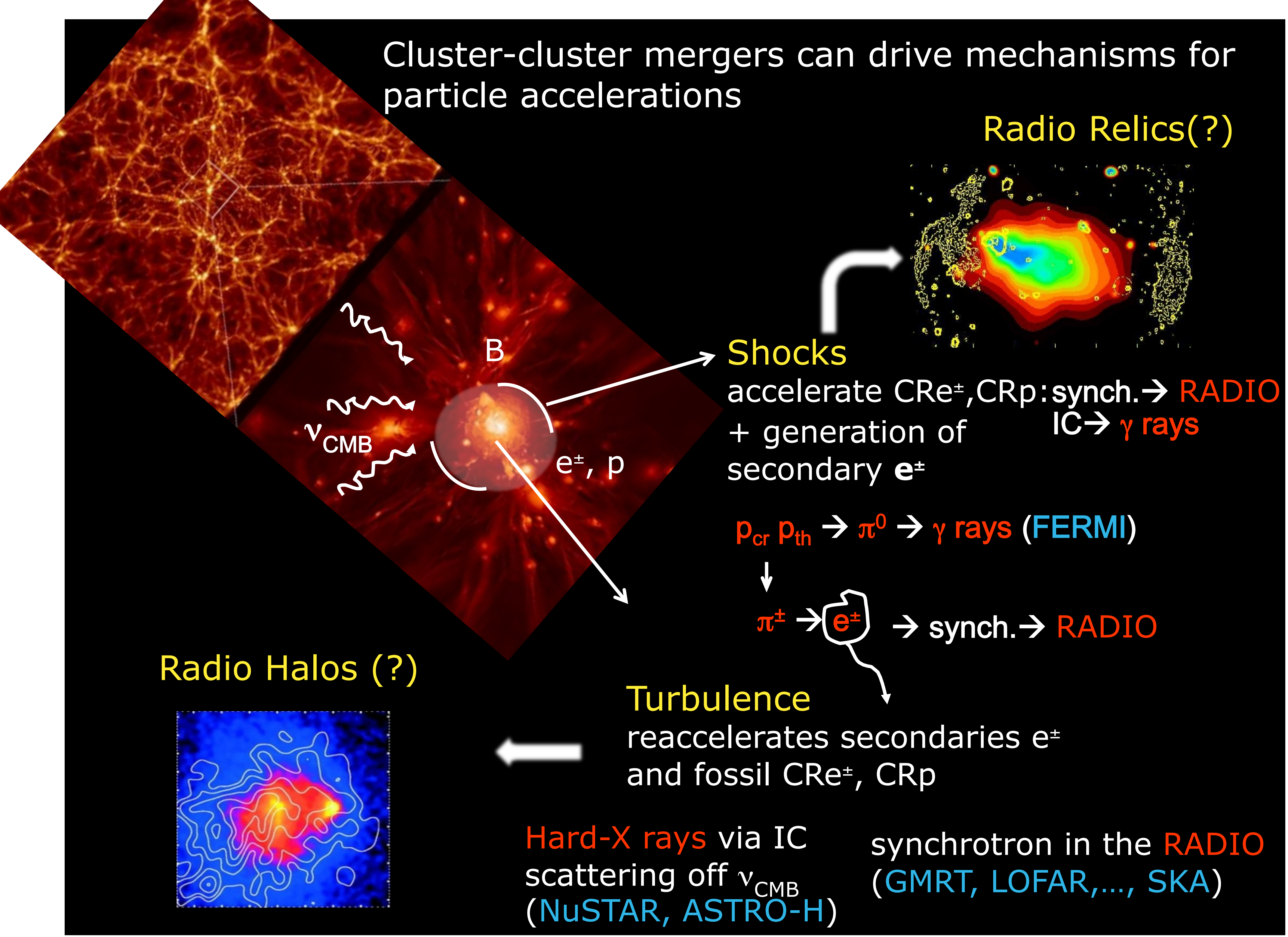


Clowe et al. 06

✓ Mergers dissipate up to 10^{63}-10^{64} ergs during one cluster crossing time (~1 Gyr)

✓ This huge energy is primarily dissipated at shocks into heating of the gas, but also through large-scale ICM motions

✓ A fraction of this energy can be channelled into NT plasma components: relativistic particles and magnetic fields in the ICM



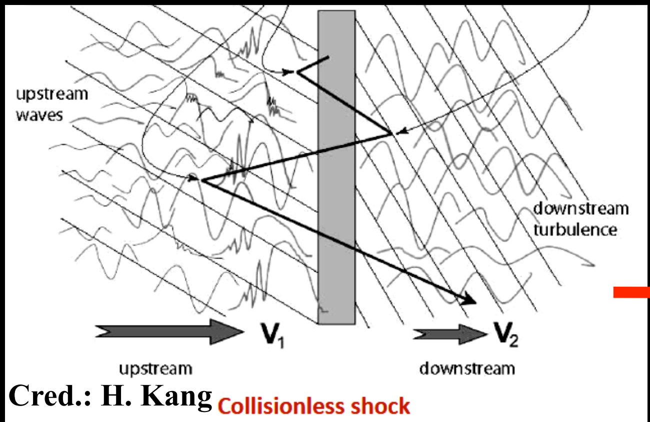
Cluster-cluster mergers can drive mechanisms for particle accelerations
Radio Relics(?)
B
ν CMB
e±, p
Shocks
accelerate CRe±,CRp: synch.→ RADIO
IC→ γ rays
+ generation of secondary e±
p cr p th → π0 → γ rays (FERMI)
π± → e± → synch.→ RADIO
Radio Halos (?)
Turbulence
reaccelerates secondaries e± and fossil CRe±, CRp
Hard-X rays via IC scattering off ν CMB
(NuSTAR, ASTRO-H)
synchrotron in the RADIO
(GMRT, LOFAR,…, SKA)

Giant Radio Relics

Diffuse Shock Acceleration (DSA) or first order Fermi mechanism

(e.g. Bell 1978; Drury 1983; Blandford & Eichler 1987; Jones & Ellison 1991)

✔ Relics trace regions where shocks accelerate (re-accelerate) electrons via Fermi I-type mechanisms *(e.g. Ensslin et al. 1998; Brüggen et al. 2011; Iapichino & Bruüggen 2012; Vazza et al. 2012; Skillman et al. 2013)*



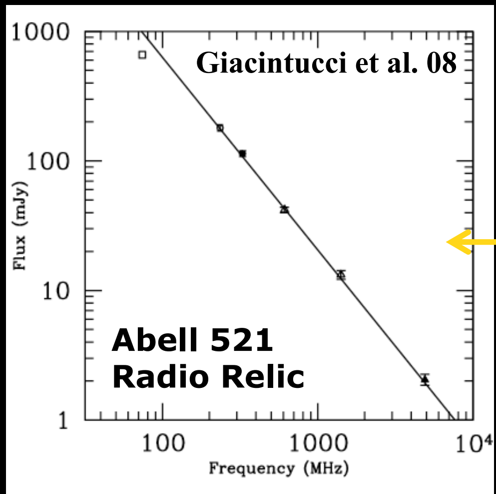
Power-law spectra

$$N(E) \propto E^{-\delta_{inj}}$$

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

Synchrotron spectra

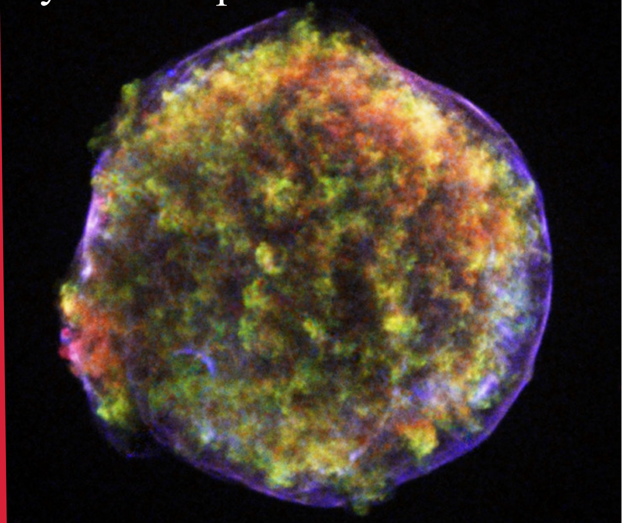
$$\Rightarrow \alpha_{inj} = \frac{\delta_{inj}-1}{2}$$



From radio spectral index => estimates of the shock Mach number

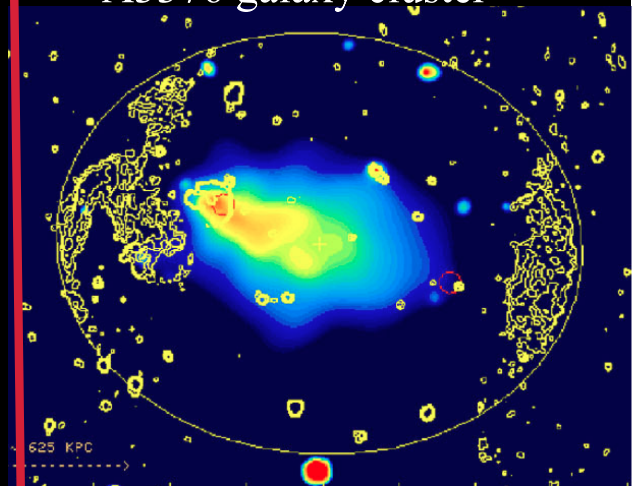
α=1.48 => $\mathcal{M}$~ 2.3

Tycho's Supernova Remnant



http://chandra.harvard.edu/photo/2005/tycho/

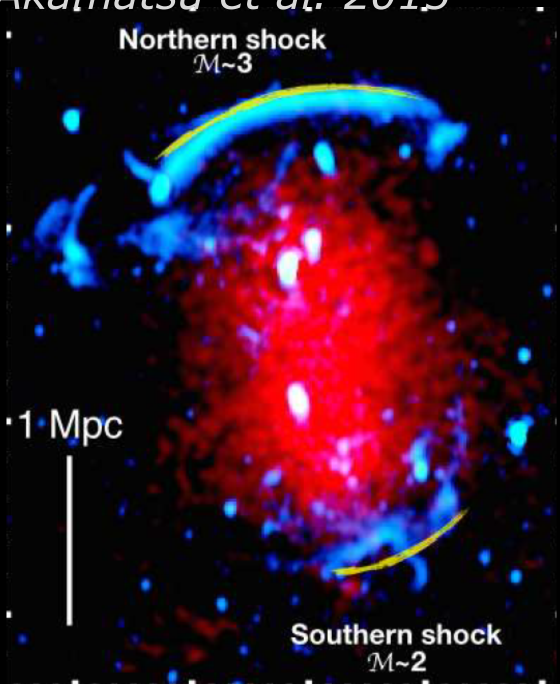
A3376 galaxy cluster



Bagchi et al. 2006

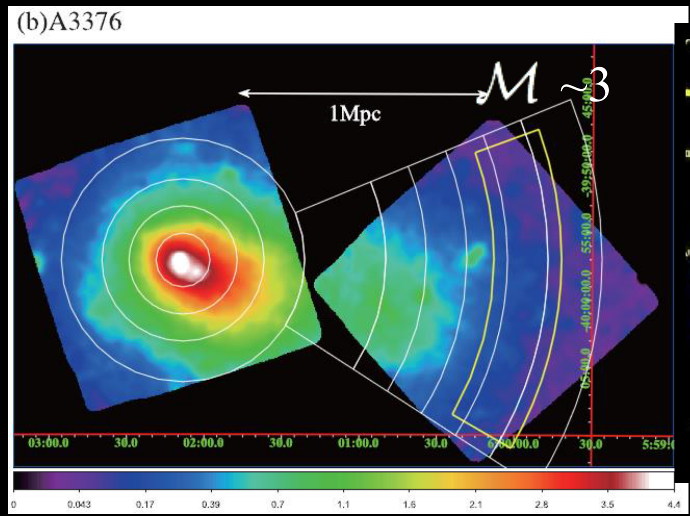
Giant Radio Relics – Shock connection

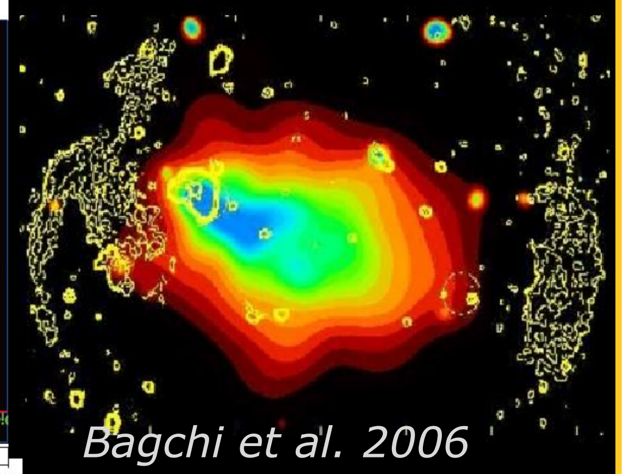
Akamatsu et al. 2015



"Sausage" Relic in CIZA J2242.8

Akamatsu & Kawahara 2013

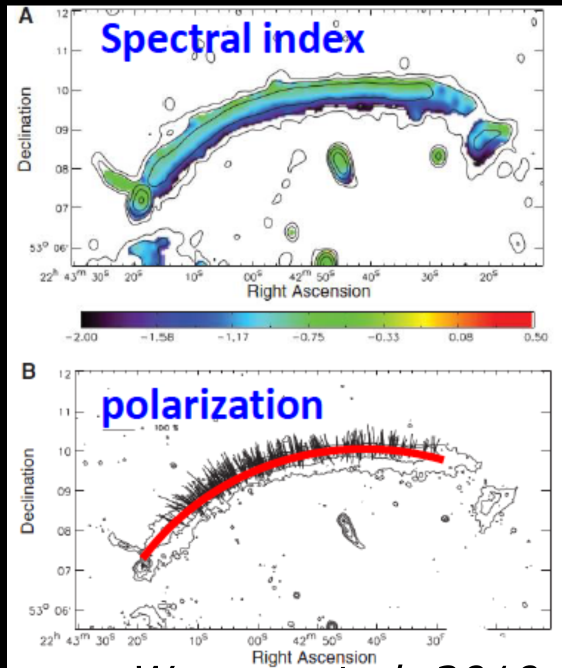




Observations in X-rays:
T, ρ and S_x jumps across the front =>
relatively weak shocks

$$\mathcal{M} \sim 1.5 - 3$$

(Markevitch & Vikhlinin 01,07)



DSA at the shock +
Radiative cooling
behind the shock

B line along the relic
→Quasi-perp. shock

van Weeren et al. 2010, Science, 330, 347

Radio Relics and shock acceleration: Open Problems

✔ Merger Shocks with $\mathcal{M}$ ~1.5-3 are relatively inefficient as particle accelerators

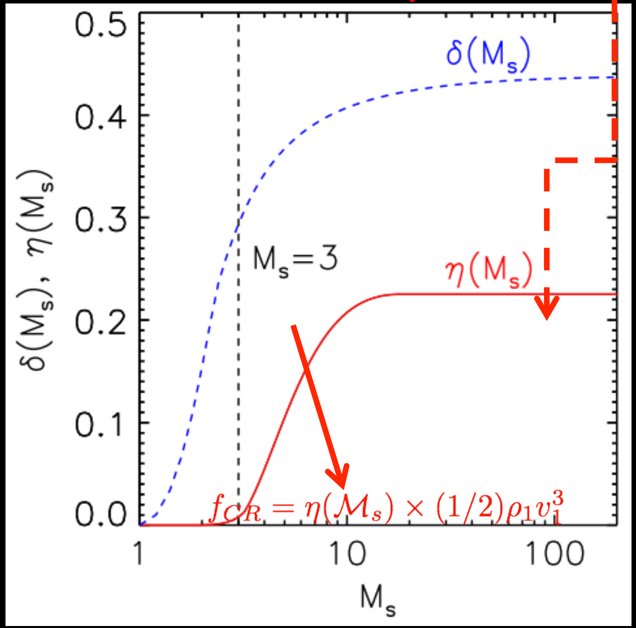
✔ explaining radio relics with standard DSA over-produce gamma-rays *(e.g.; Vazza & Bruggen 14; Brunetti & Jones 14; Griffin et al 14; Vazza et al. 15)*

To overcome these problems:

- *alternative* sources of CRe to be re-accelerated via DSA *(e.g.,Markevitch et al. 2005; Kang et al. 11)*

- *alternative* mechanism, e.g.; shock drift acceleration, SDA, *(e.g.; Guo, Sironi, Narayan 14a,b)* => Efficient CRe acceleration

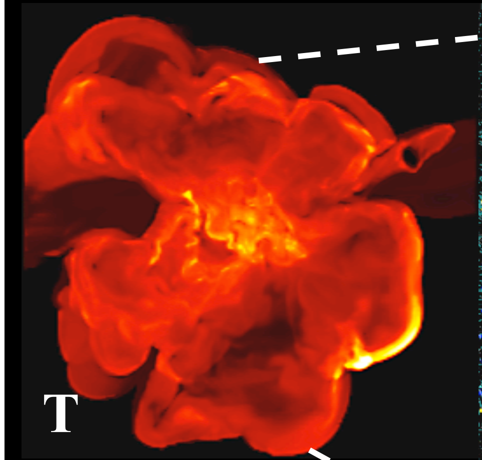
CRp acceleration efficiency at shocks



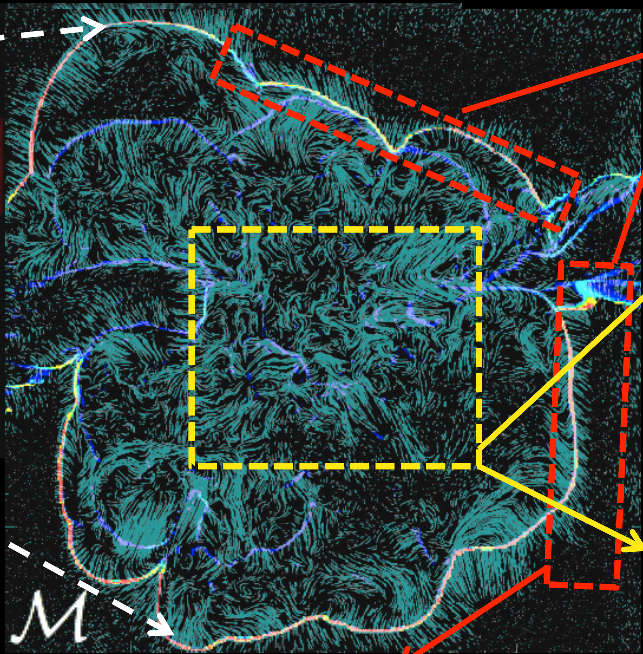
Kang & Ryu 13; Hong et al. 14

✔ $\mathcal{M}_{radio} > \mathcal{M}_{X-ray}$ *(e.g.; Akamatsu & Kawahara 2013; van Weeren et al. sub.)* => re-acceleration of fossil plasma (?); shocks with multiple $\mathcal{M}$ (?)

Cosmological Shocks and future radio Surveys



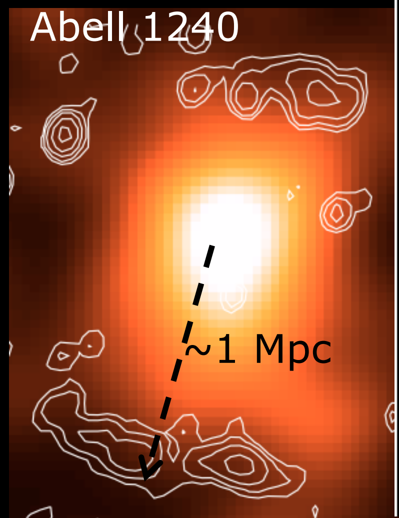
Vazza et al. 09

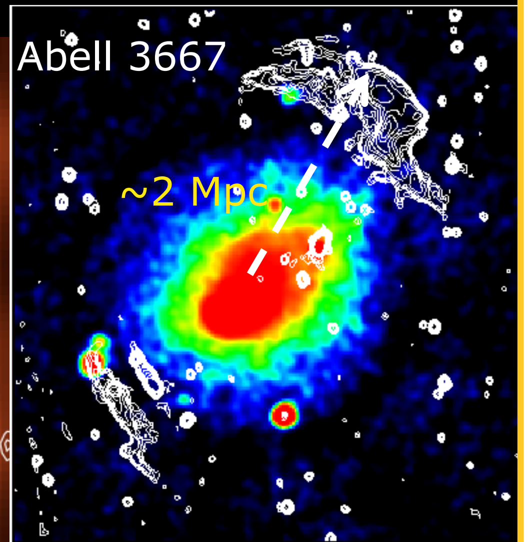


Strong External (accretion) shocks with $\mathcal{M}$ ~10-100

Weak internal (merger) shocks with $\mathcal{M}$ <3 dissipate more energy than external shocks

Present observations are only sensitive to “internal” (1-2 Mpc from the cluster centre) weak shocks

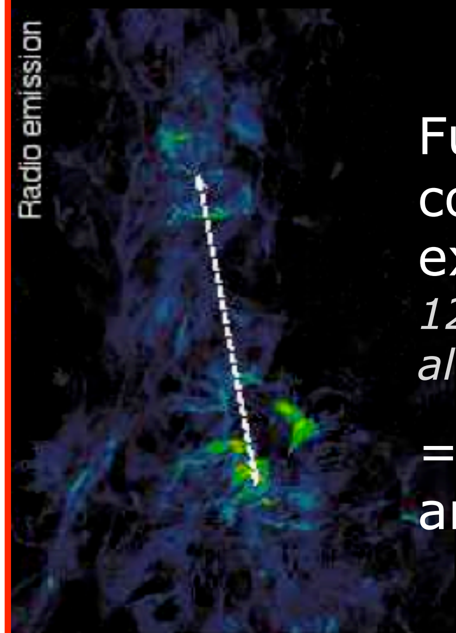




Bonafede et al. 09 *Bagchi et al. 06*

(see talk by R. van Weeren)

Vazza et al. 15



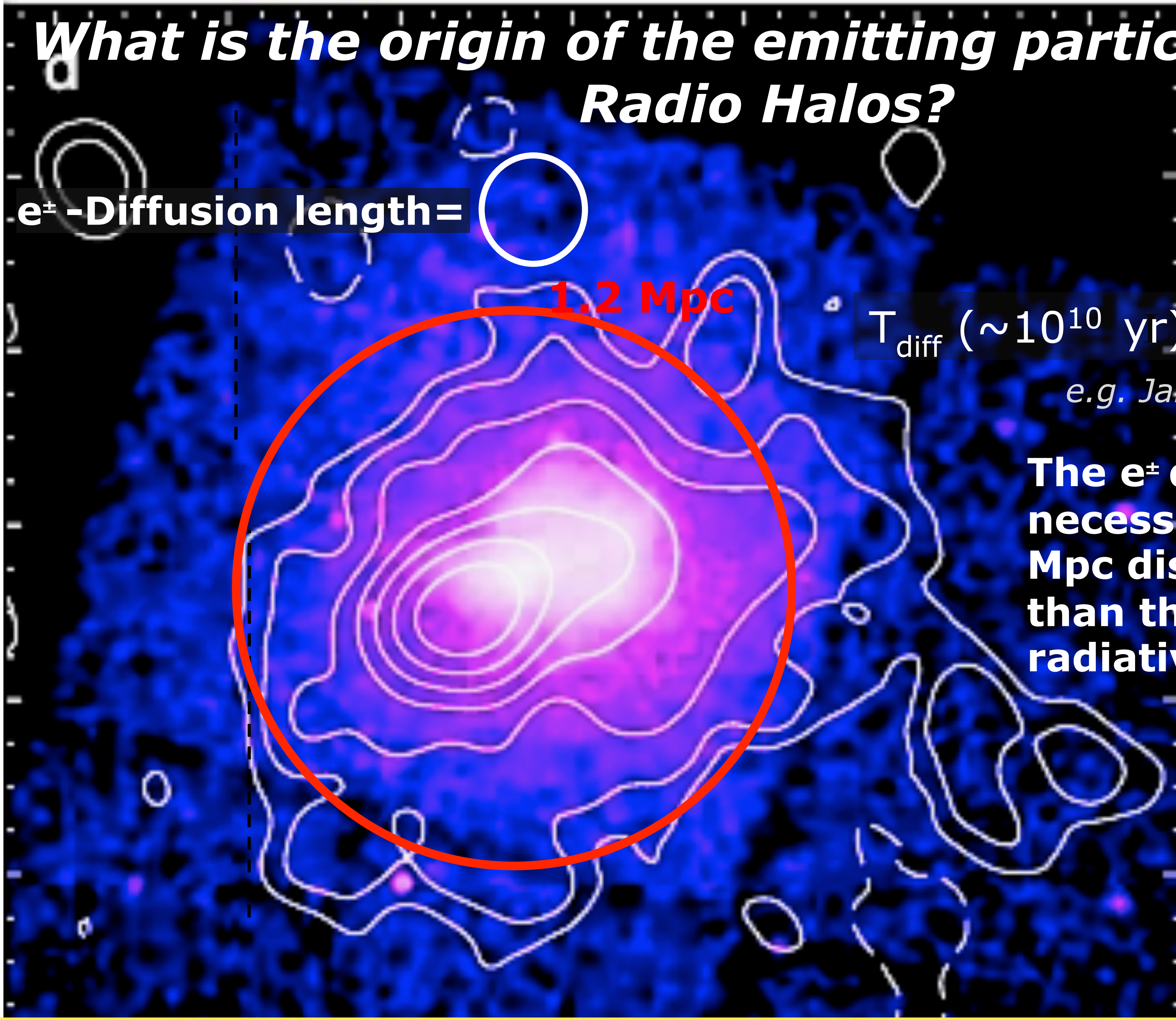
Future obs. (LOFAR, SKA) could be sensitive to more external shocks *(Nuza et al. 12; Skillman et al. 13; Vazza et al. 15)*

=> more external relics and intracluster filaments?

(see talk by F. Vazza)

Giant Radio Halos

What is the origin of the emitting particles in giant Radio Halos?



T_{diff} (~10^{10} yr) >> T_v (~10^8 yr)

e.g. Jaffe (1977)

The e± diffusion time necessary to cover Mpc distances is >> than the e± radiative life-time!

The very large scales implies the existence of mechanisms of "in situ" acceleration or injection of CRs on Mpc-scale

What is the origin of the emitting particles in giant Radio Halos?

- secondary models: relativistic electrons continuosly injected in the ICM by inelastic proton-proton collisions through productions and decay of charged pions *(e.g., Dennison 1980, Blasi & Colafrancesco 1999, Dolag & Ensslin 2000)*

$$p_{th} + p_{CR} \rightarrow \pi^{\pm} + \pi^{0} + \ldots \rightarrow \pi^{0} \rightarrow \gamma\,\gamma \rightarrow \text{gamma ray}$$

$$\pi^{\pm} \rightarrow e^{\pm} \rightarrow \text{synchrotron radio}$$

- CR protons are long living particles and are confined (*Voelk et al 1996; Berezinsky et al 1997*) → solution to the "diffusion problem" !

- Drawbacks of secondary models:

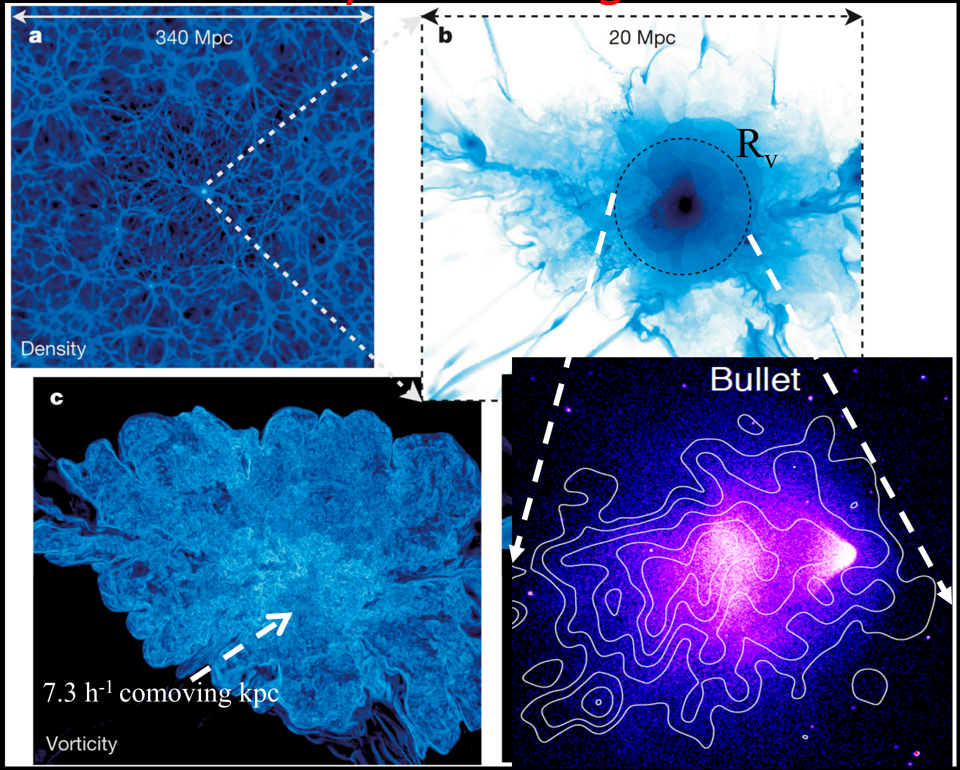
  - fail to explain halos with extremely steep spectra (α>1.5-1.6; *e.g., A521 Brunetti et al. 08; Dallacasa et al. 09; A697 Macario et al 10)*

  - not a "natural" explanation for rarity and connection with mergers *(see also Ensslin et al. 2012 for a different view)*

  - non-detection of galaxy clusters in the gamma-rays (by FERMI; Jeltema & Profumo 11, Brunetti et al. 12, Ackermann et al. 13, 15; Zandanel & Ando 14)

Need for another mechanism: turbulent re-acceleration?

High-resolution simulation of a galaxy cluster in fully cosmological context



Miniati & Beresnyak. Nature 523, 59-62 (2015)

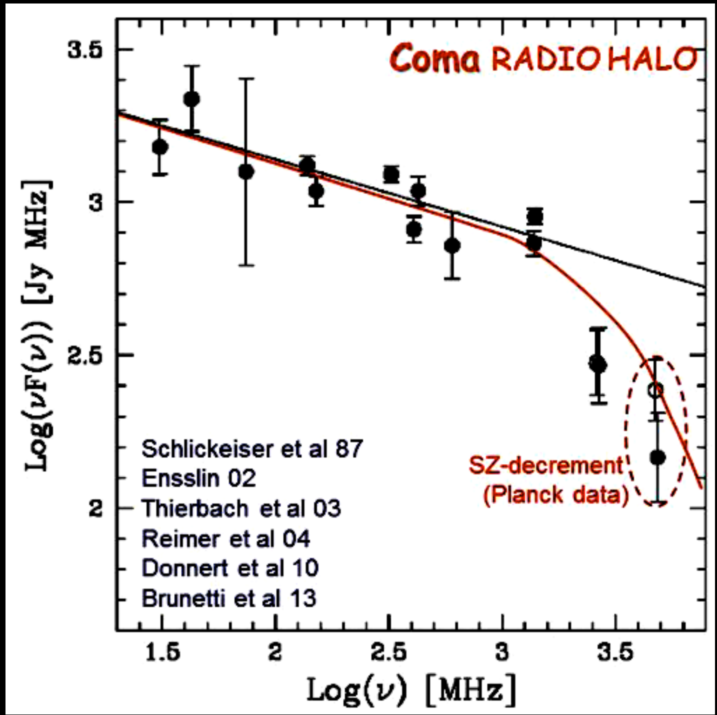
A popular idea to explain giant Radio Halos:

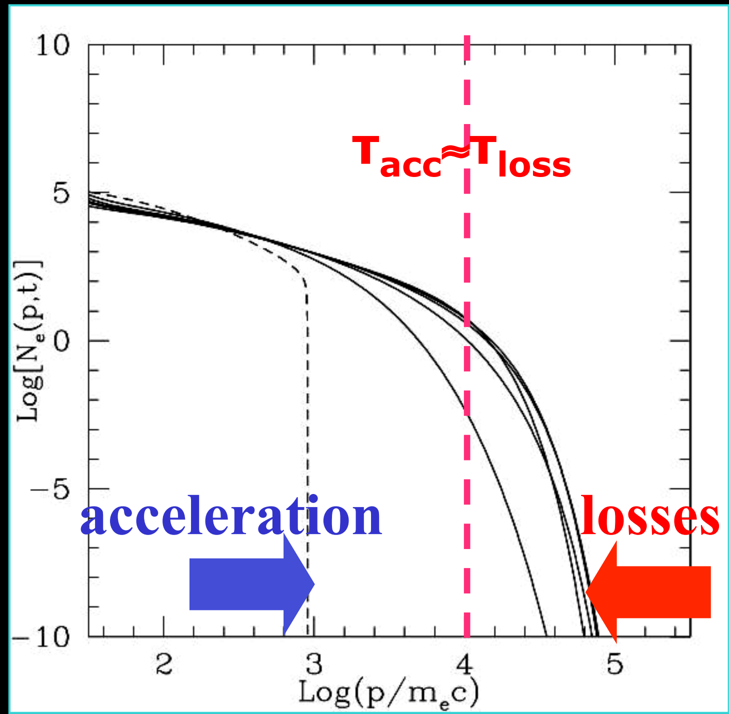
merger-driven turbulence injected at few 100 kpc scale cascades (without significant dissipation) to very small scale, ~100 pc, where stocastically re-accelerate CRe (fossil and secondaries) via Fermi II-type mechanisms

(Brunetti et al. 01, 04, Petrosian 01, Kuo et al 02, Fujita et al. 03, Cassano & Brunetti 05, Brunetti & Lazarian 07,11, Donnert et al 13, Beresnyak et al 13; Miniati 15)

Radio Halos : are they generated by "inefficient" mechanism of CRe acceleration ?

Synchrotron spectrum





Electron spectra

Evidence of break in the spectrum of the emitting electrons at energies of few GeV.

$$\tau_e(\mathrm{Gyr}) \sim 4 \times \left\{ \frac{1}{3}\left(\frac{\gamma}{300}\right)\left[\left(\frac{B_{\mu G}}{3.2}\right)^2 \frac{\sin^2\theta}{2/3} + (1+z)^4\right] + \left(\frac{n_{\rm th}}{10^{-3}}\right)\left(\frac{\gamma}{300}\right)^{-1}\left[1.2 + \frac{1}{75}\ln\left(\frac{\gamma/300}{n_{\rm th}/10^{-3}}\right)\right]\right\}^{-1}.$$

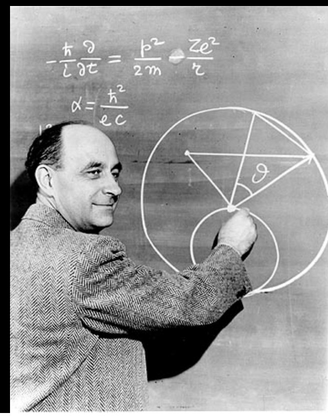
acceleration time-scale
≈10^8 years

Acceleration mechanism not efficient !

eg., "classical" Fermi II

$$\tau_{acc} \approx \frac{L_t\, c}{V_t^2}$$

> 10^7yrs

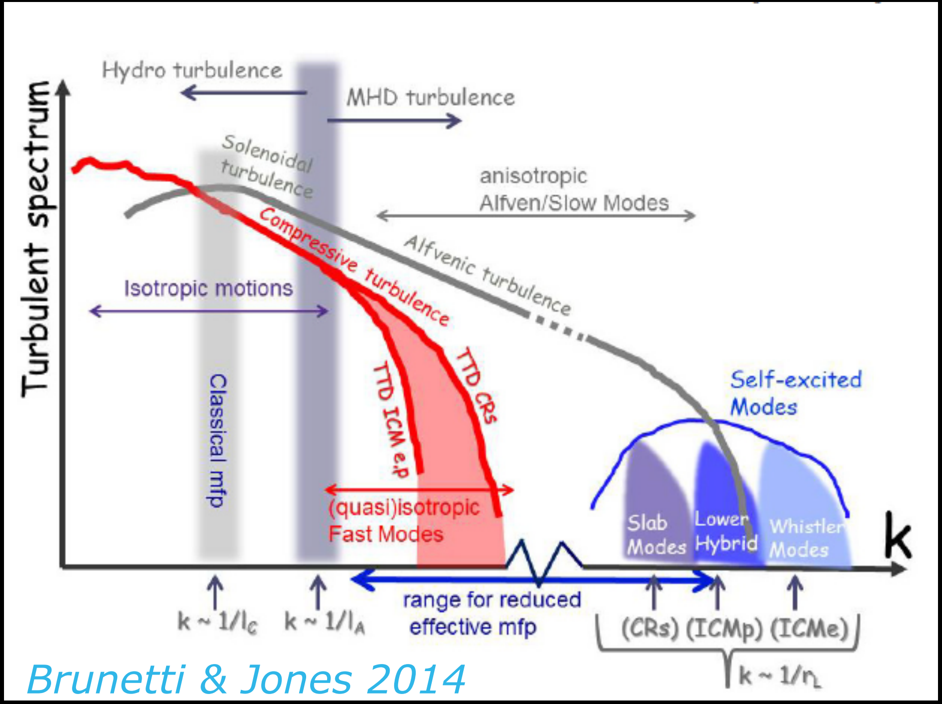


Radio Halos and turbulent re-acceleration: Open Problems

see Brunetti & Jones 2014, for a recent review

✔ Which is the role of secondaries?
Fermi γ-ray upper limits challenge a pure hadronic model => secondaries should be present at some level in the ICM (e.g.; Brunetti & Lazarian 11; Zandanel et al. 14)

✔ Composition and origin of seed particles? Relic electrons from AGN, galaxies and secondaries *(e.g.; Brunetti et al. 01,…Pinzke et al. 15)*

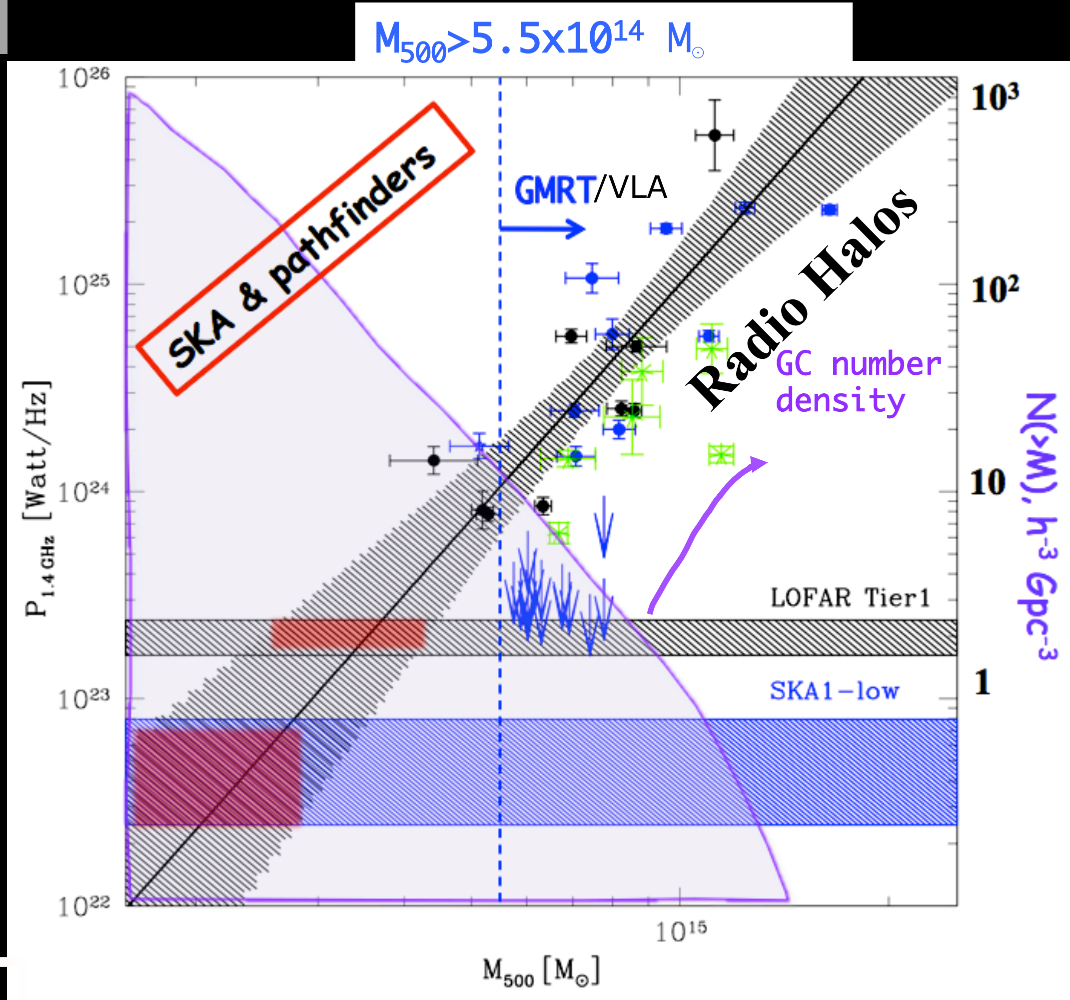


Brunetti & Jones 2014

✔ Physics of turbulent re-acceleration:
How merger-driven turbulence is transported to small scales?
How the the turbulent spectrum change with time on resonant scale?
(e.g., Brunetti & Lazarian 07; Miniati 15, Brunetti 15)

✔ Impact on the microphysics of the ICM?
(e.g., viscosity, conduction, heating of the plasma, plasma instabilities)
e.g.; Schekochihin et al 08,10, Lazarian & Beresniak 06, Brunetti & Lazarian11, Santos-Lima et al 14

Future prospects for RH



Are we seeing the tip of the iceberg?

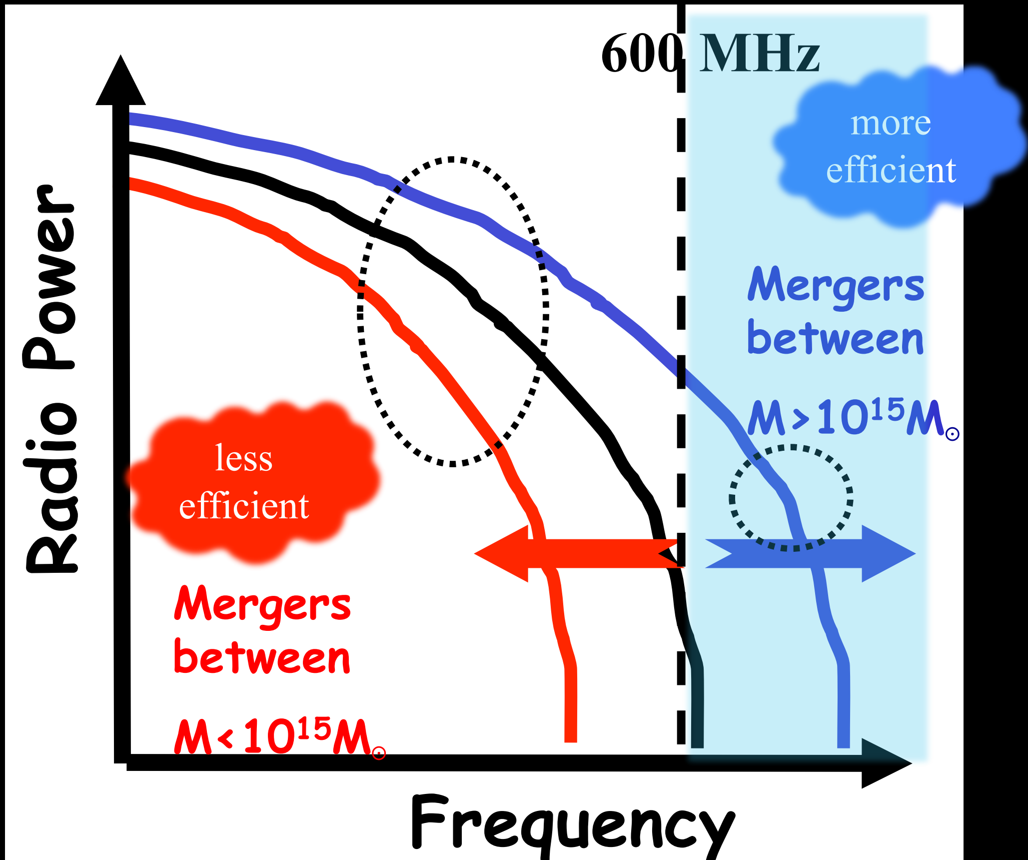
How many RH await discovery?

LOFAR and SKA1-LOW will explore low massive clusters (M_{500}~10^{14} $M_{\odot}$) that are ~100+ times more numerous than clusters observable by present facilities.

Going to smaller masses does not necessarily imply that more (much more) RHs will be found ! This depends on the occurrence of RH in smaller systems (MODELS!)

Basic theoretical expectations (turbulence)

Cassano & Brunetti 05; Cassano et al. 2006, 2010, 2012



Acceleration efficiency

$X \approx 1/\tau_{acc}$

Steepening frequency

$$\nu_s \propto \langle B \rangle \gamma^2_{max} \propto \frac{\langle B \rangle \chi^2}{\left(\langle B \rangle^2 + B^2_{cmb}\right)^2}$$

Radio Halos with very steep spectrum (**α>1.5, USSRH**) in the classical radio band must exist *(Cassano et al.06; Brunetti et al. 2008, Nature* ***455, 944****)*

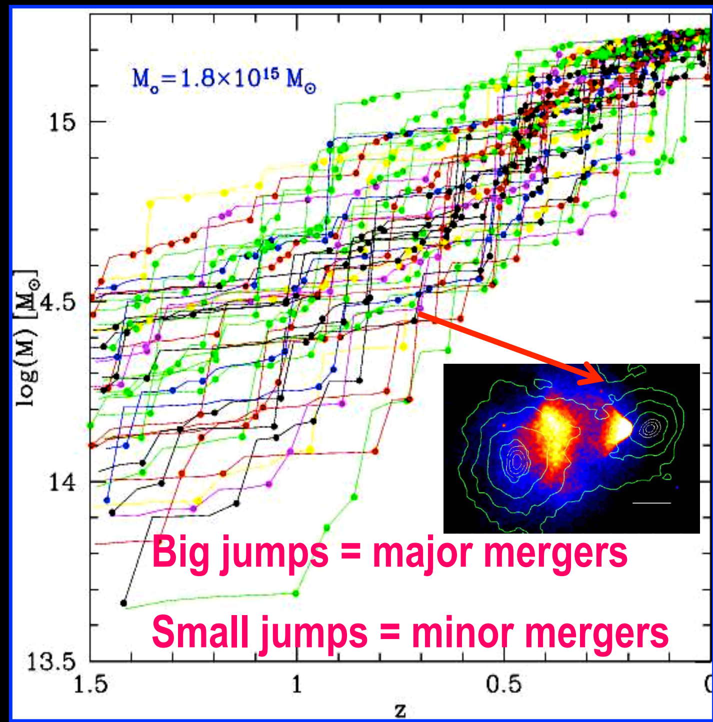
At **GHz frequency**:

✔ RH common in massive-merging GCs

✔ RH rare in less massive-merging GC

=> **drop of fraction of RHs at lower masses**

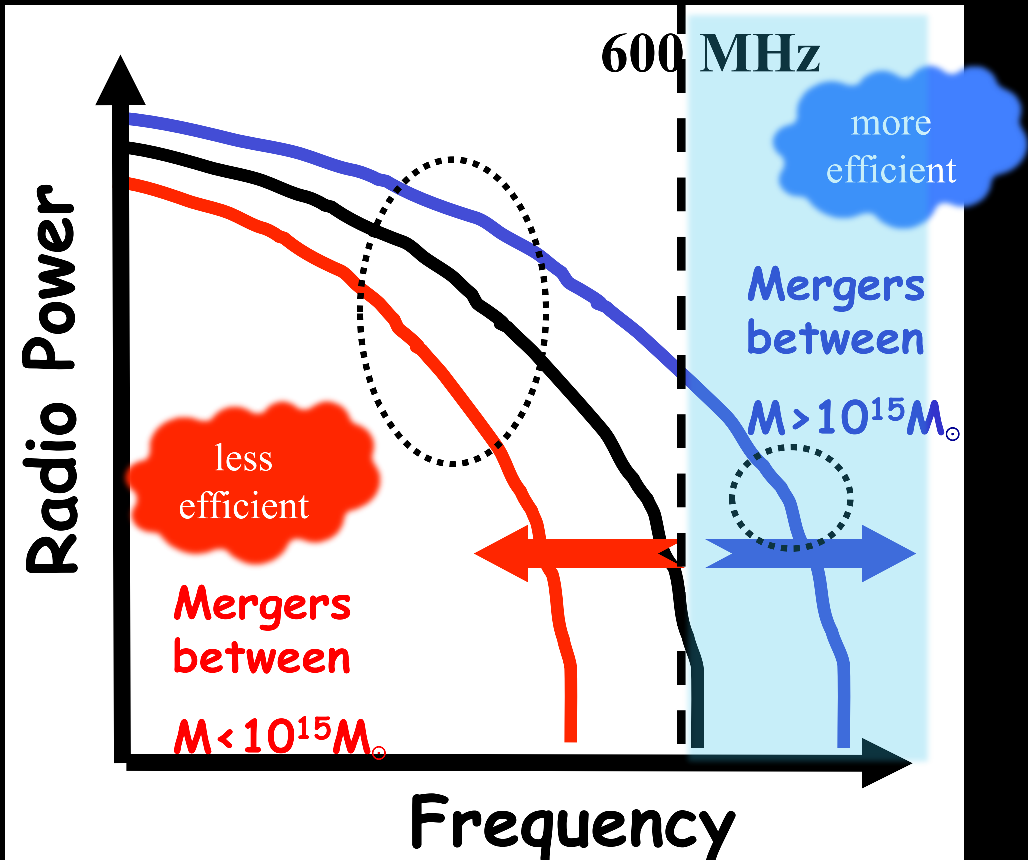
«mass sets the energy available»



Formation History of GCs

Basic theoretical expectations (turbulence)

Cassano & Brunetti 05; Cassano et al. 2006, 2010, 2012



Acceleration efficiency

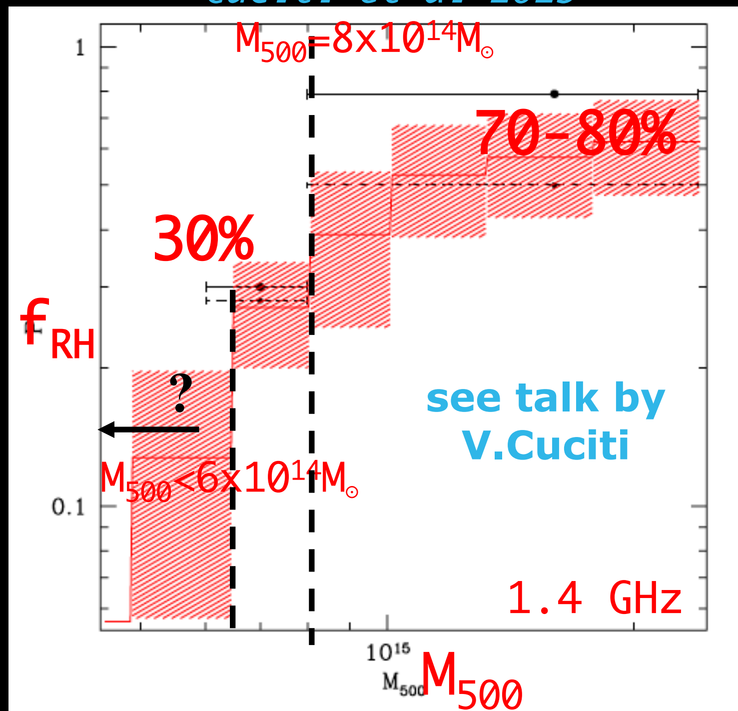
$X \approx 1/\tau_{acc}$

Steepening frequency

$$\nu_s \propto \langle B \rangle \gamma_{max}^2 \propto \frac{\langle B \rangle \chi^2}{\left(\langle B \rangle^2 + B_{cmb}^2\right)^2}$$

Radio Halos with very steep spectrum (**α>1.5, USSRH**) in the classical radio band must exist *(Cassano et al.06; Brunetti et al. 2008, Nature* ***455, 944****)*

Cuciti et al 2015



At **GHz frequency**:

✔ RH common in massive-merging GCs

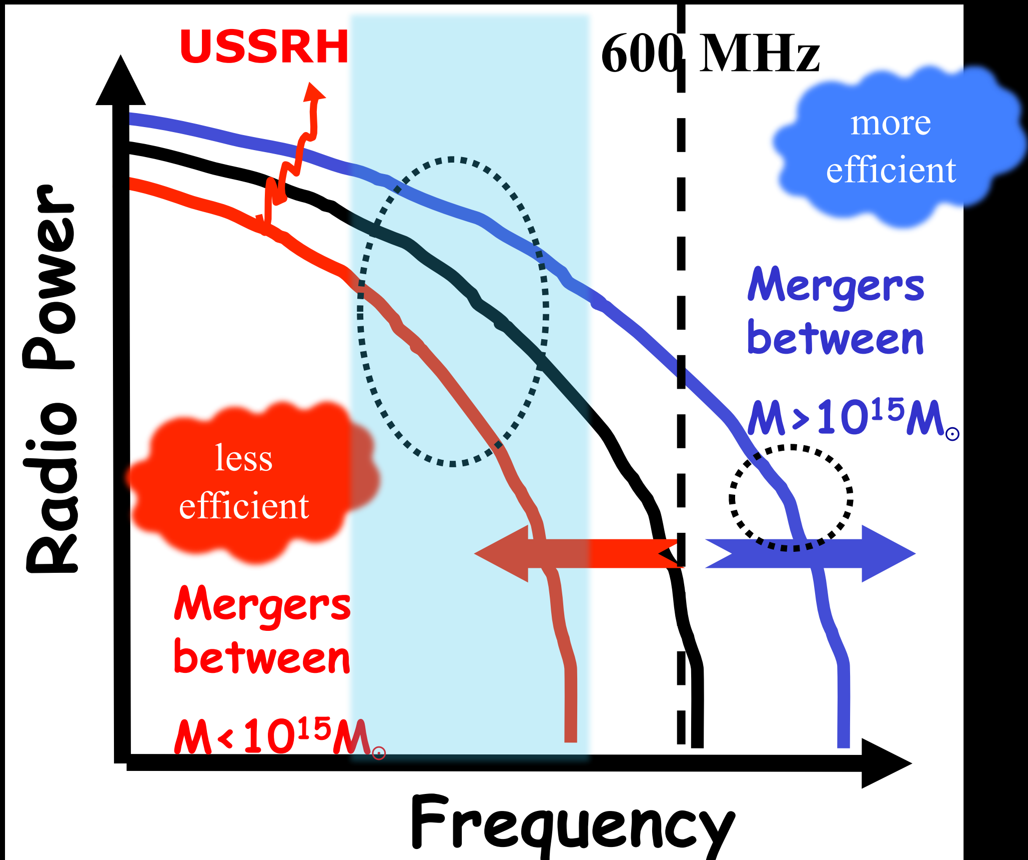
✔ RH rare in less massive-merging GC

=> **drop of fraction of RHs at lower masses**

«mass sets the energy available»

Basic theoretical expectations (turbulence)

Cassano & Brunetti 05; Cassano et al. 2006, 2010, 2012



Acceleration efficiency

$X \approx 1/\tau_{acc}$

Steepening frequency

$$\nu_s \propto \langle B \rangle \gamma_{max}^2 \propto \frac{\langle B \rangle \chi^2}{\left(\langle B \rangle^2 + B_{cmb}^2\right)^2}$$

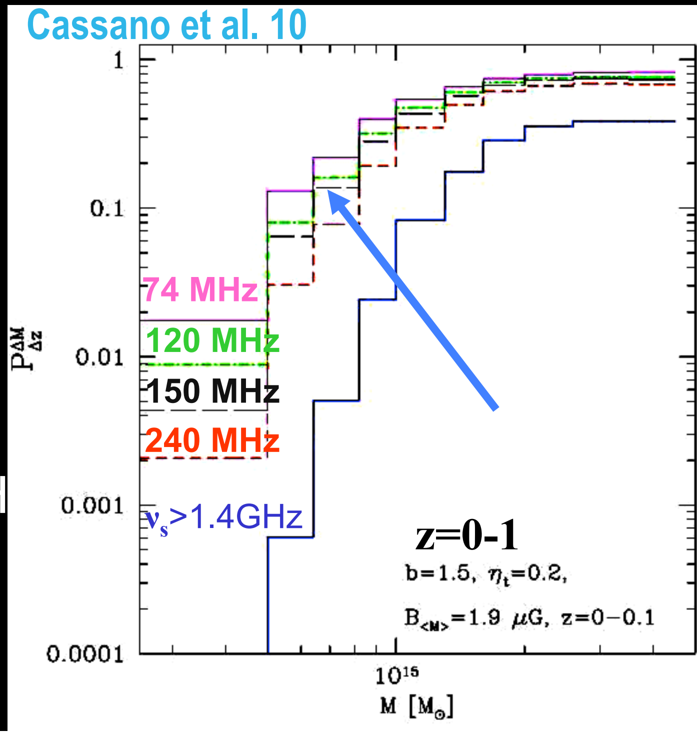
Radio Halos with very steep spectrum (**α>1.5, USSRH**) in the classical radio band must exist *(Cassano et al.06; Brunetti et al. 2008, Nature* ***455, 944****)*

At **low (<1 GHz) frequency**:

✔ A complex population of RH (different spectra)

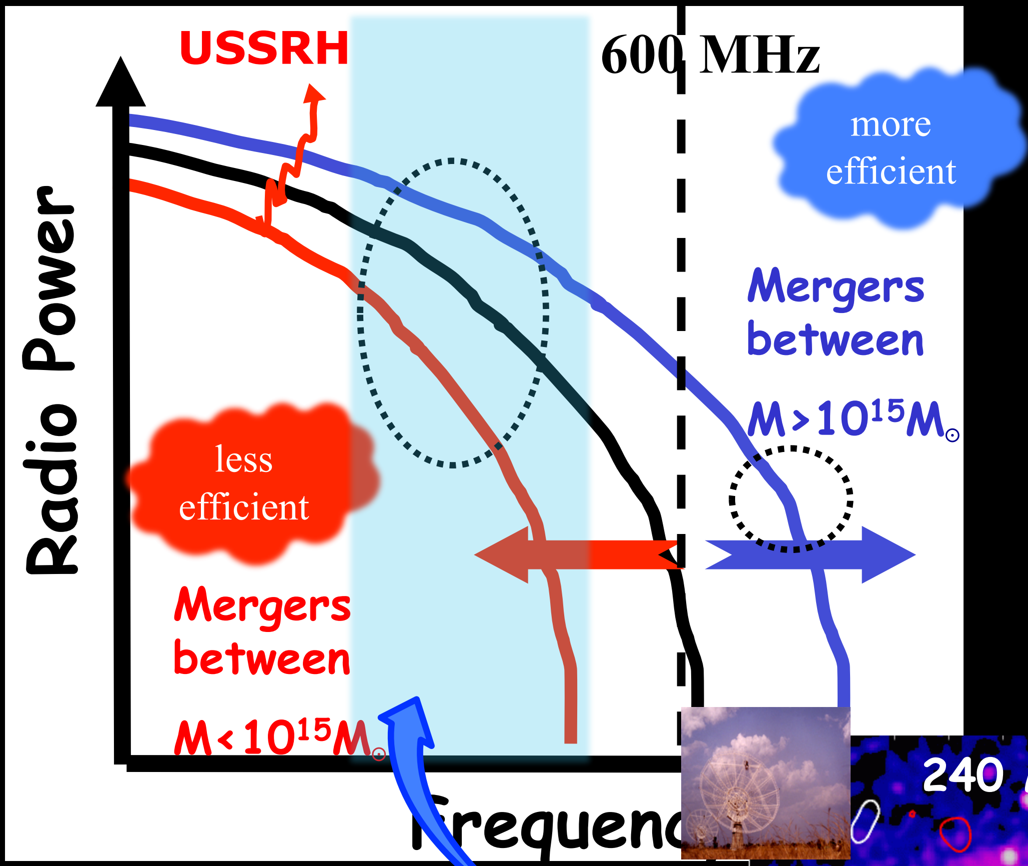
✔ RH more common, increase of the fraction of RH

✔ ultra-steep spectrum RH (USSRH, α>1.5)



Basic theoretical expectations (turbulence)

Cassano & Brunetti 05; Cassano et al. 2006, 2010, 2012



Acceleration efficiency

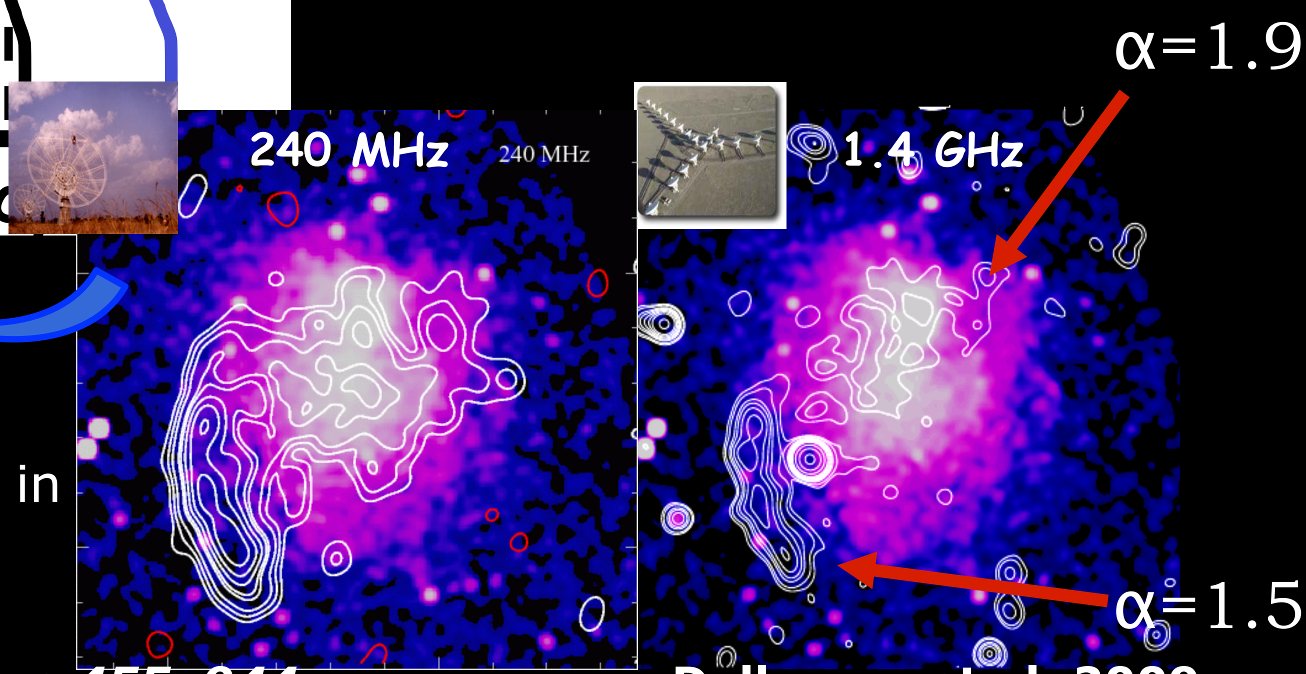
$\chi \approx 1/\tau_{acc}$

Steepening frequency

$$\nu_s \propto \langle B\rangle \gamma_{max}^2 \propto \frac{\langle B\rangle \chi^2}{\left(\langle B\rangle^2 + B_{cmb}^2\right)^2}$$

Radio Halos with very steep spectrum (**α>1.5, USSRH**) in the classical radio band must exist *(Cassano et al.06; Brunetti et al. 2008, Nature 455, 944)*

The prototype of these USSRHs was discovered in Abell 521



Brunetti +al. 2008, Nature 455, 944

Dallacasa et al. 2009

To summarize … (a message for observers!)

possible tests of this scenario can be done by finding:

✔ A DROP OF THE FRACTION OF CLUSTERS WITH RHS AT LOWER MASSES

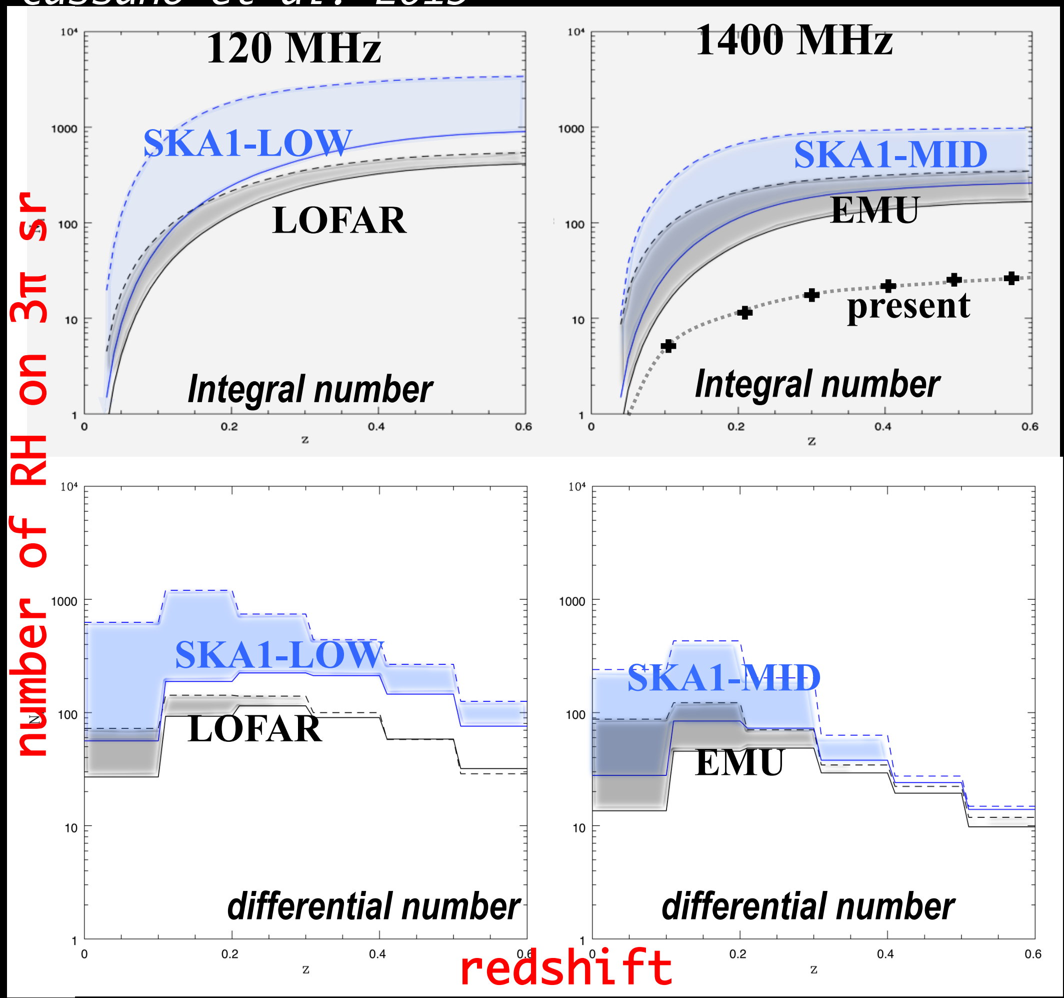
✔ AN INCREASE OF THE FRACTION OF CLUSTERS WITH RH TOWARDS LOW RADIO FREQUENCY

✔ THE EXISTENCE OF ULTRA-STEEP SPECTRUM RH (USSRH, $\alpha > 1.5$)

How many RHs await discovery in future radio surveys?

from Monte Carlo simulations (see also *Cassano et al. 10, 12, 15***)**

Cassano et al. 2015



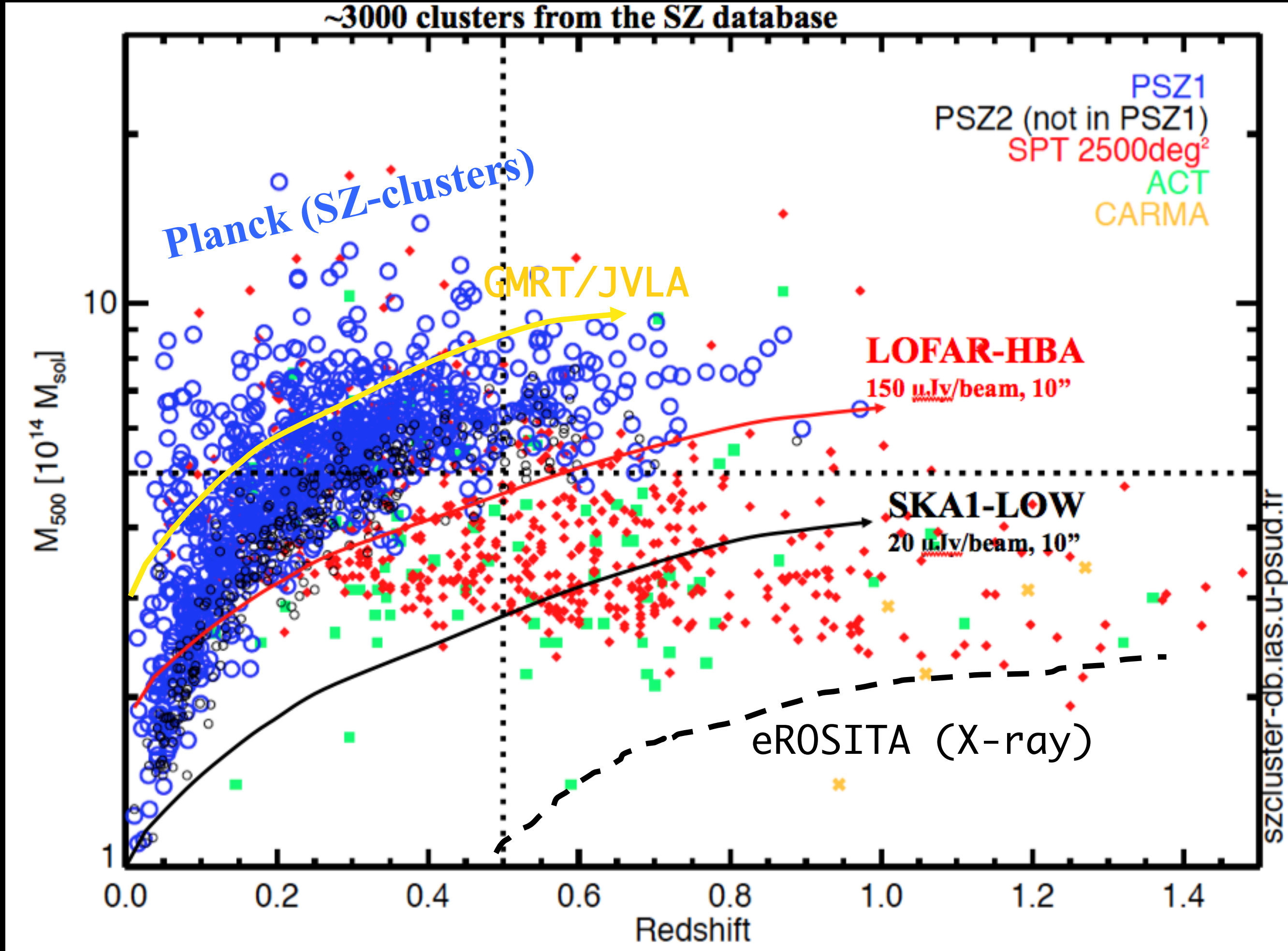
We know about 30 radio halos

ASKAP(EMU) => ~300
SKA1-MID => ~750
1-2 GHz

LOFAR => ~500
SKA1-LOW => ~2600
150-200 MHz

configurations	rms μJy/beam	θ_b arcesc
LOFAR (120 MHz)	400	25
SKA1-low (120 MHz)	20	10
EMU (1.4 GHz)	13	15
SKA1-MID (1.4 GHz)	5	15

RHs to detect galaxy clusters in radio survey



LOFAR-HBA (rms=150 μJy/beam) and SKA1-LOW (rms=20 μJy/beam) surveys:

- detection of clusters with RH up to high z
- competitive with X-ray and SZ-survey in the detection of galaxy clusters
- SKA1 will provide fundamental complementary information to the next-generation of multi-wavelength surveys (DES, LSST, Euclid, eROSITA)

Conclusions

Halos and Relics probe CRs and magnetic fields on Mpc-scale in ICM

Present scenario: Halos trace turbulent regions in the ICM where particles are trapped and accelerated during mergers, while Relics trace site of particle acceleration at merger shocks

Not a full understanding of turbulent and shock acceleration in the ICM

➡ **Impact on the ICM micro-physics !**

The future is bright: SKA pathfinders and precursors (LOFAR, MeerKAT, ASKAP), SKA1-LOW and SKA1-MID have the potential to test the present scenarios for Halos and Relics, possibly unveiling the *emergence of the iceberg of NT phenomena in Galaxy Clusters*

-Only a ~40 Halos and Relics are known so far:

1-2 GHz

SKA1-MID=> ~750

ASKAP(EMU)=> ~300

150-200 MHz

SKA1-LOW=> ~2600 RH

LOFAR=> ~500 RH