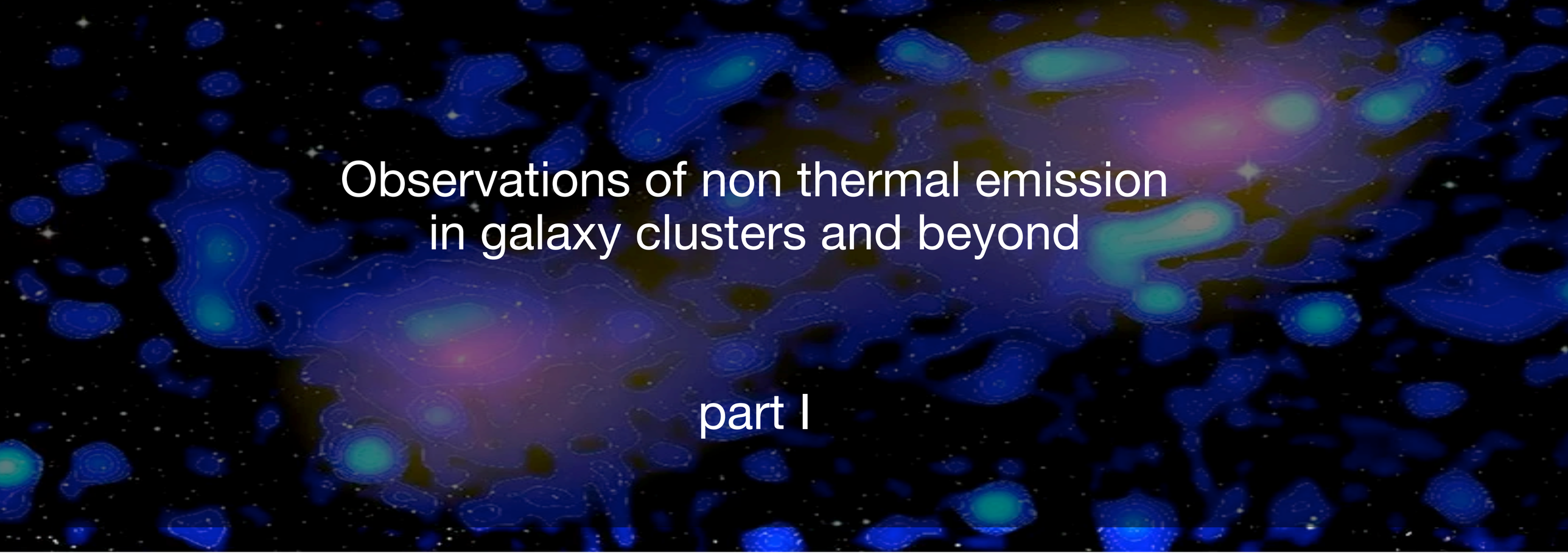


Observations of non thermal emission in galaxy clusters and beyond

part I

Annalisa Bonafede

Università di Bologna

&

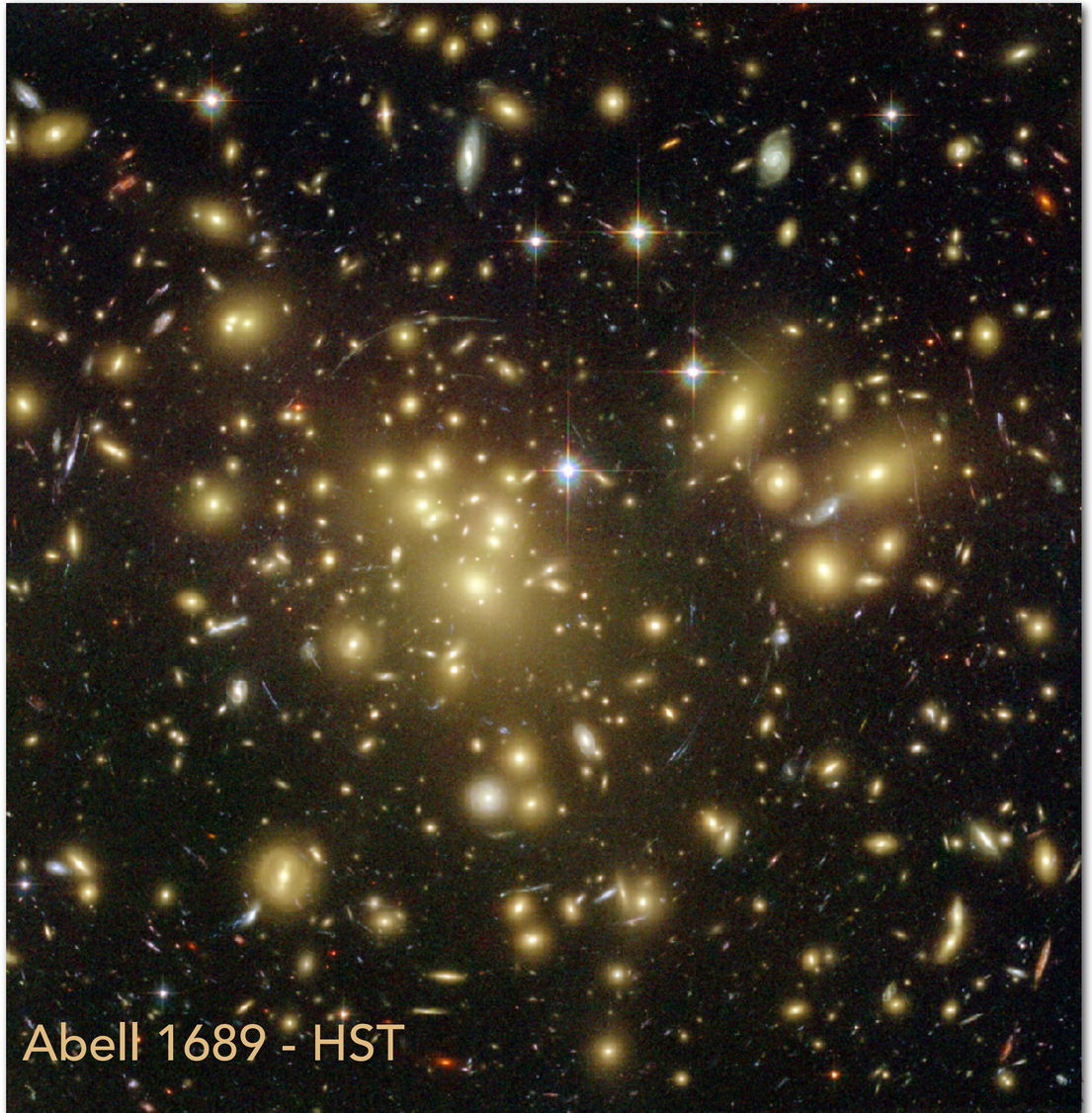
IRA INAF

Outline

- Galaxy clusters
- Radio emission in clusters and the energetic problem
- Radio halos, radio relics, mini halos - the classical view
- New discoveries and open challenges

GALAXY CLUSTERS

- Largest gravitationally bounded objects $M \approx 10^{14} - 10^{15} M_{\odot}$
-
  - Dark matter dominates ~80%
  - 100-1000s of galaxies



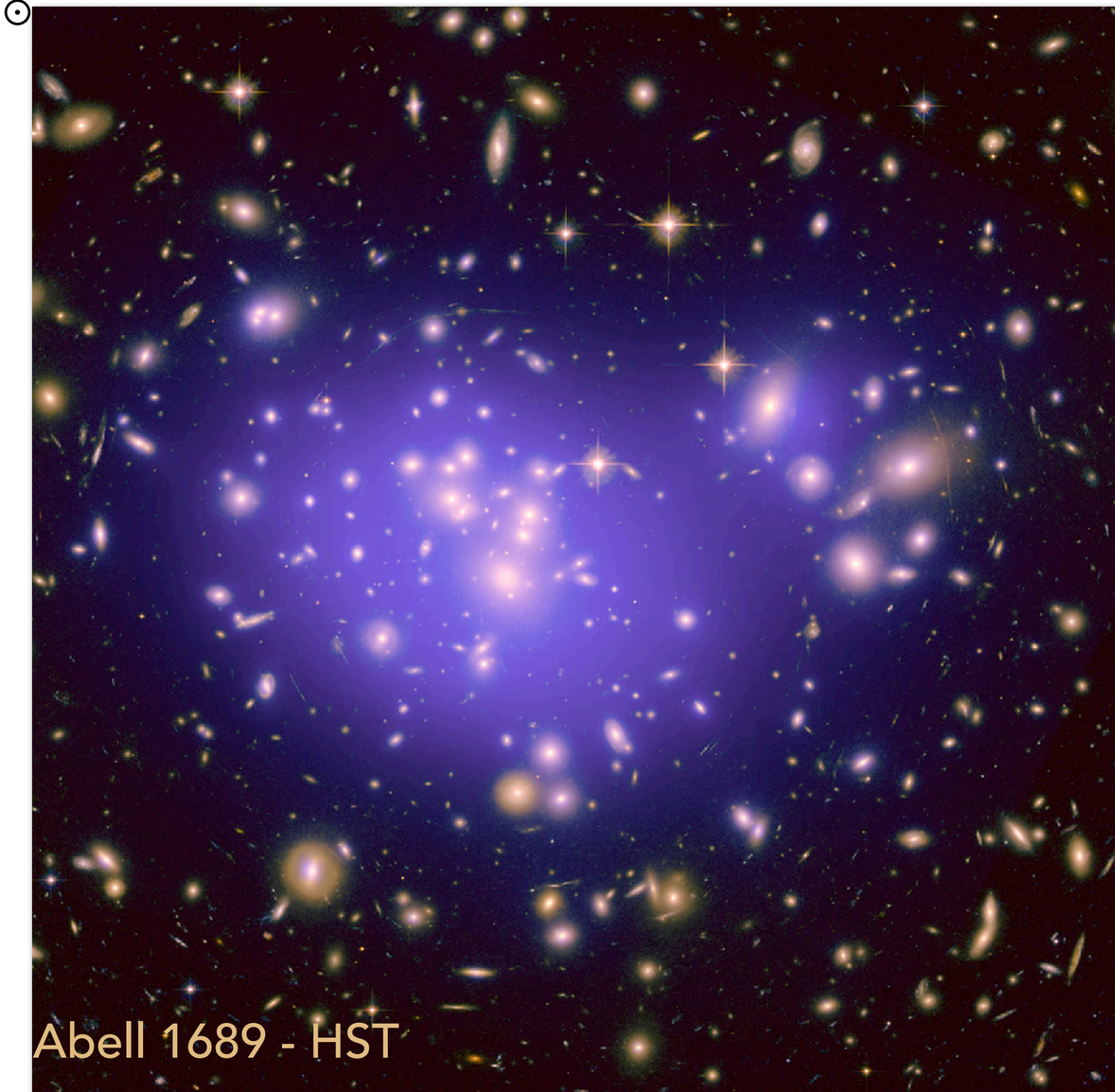
NASA, ESA, E. Jullo (JPL/LAM), P. Natarajan (Yale) and J-P. Kneib (LAM).

GALAXY CLUSTERS

- Largest gravitationally bounded objects $M \approx 10^{14} - 10^{15} M_{\odot}$
  - Dark matter dominates ~80%
  - 100-1000s of galaxies
  - The space in between galaxies: hot rarefied gas

$$T \sim 10^{7} - 10^{8} \mathrm{K}$$
$$n_e \sim 10^{-3} \mathrm{cm}^{-3}$$

Thermal emission: optically thin
bremsstrahlung
X-ray band (soft X)



Abell 1689 - HST

NASA, ESA, E. Jullo (JPL/LAM), P. Natarajan (Yale) and J-P. Kneib (LAM).

GALAXY CLUSTERS

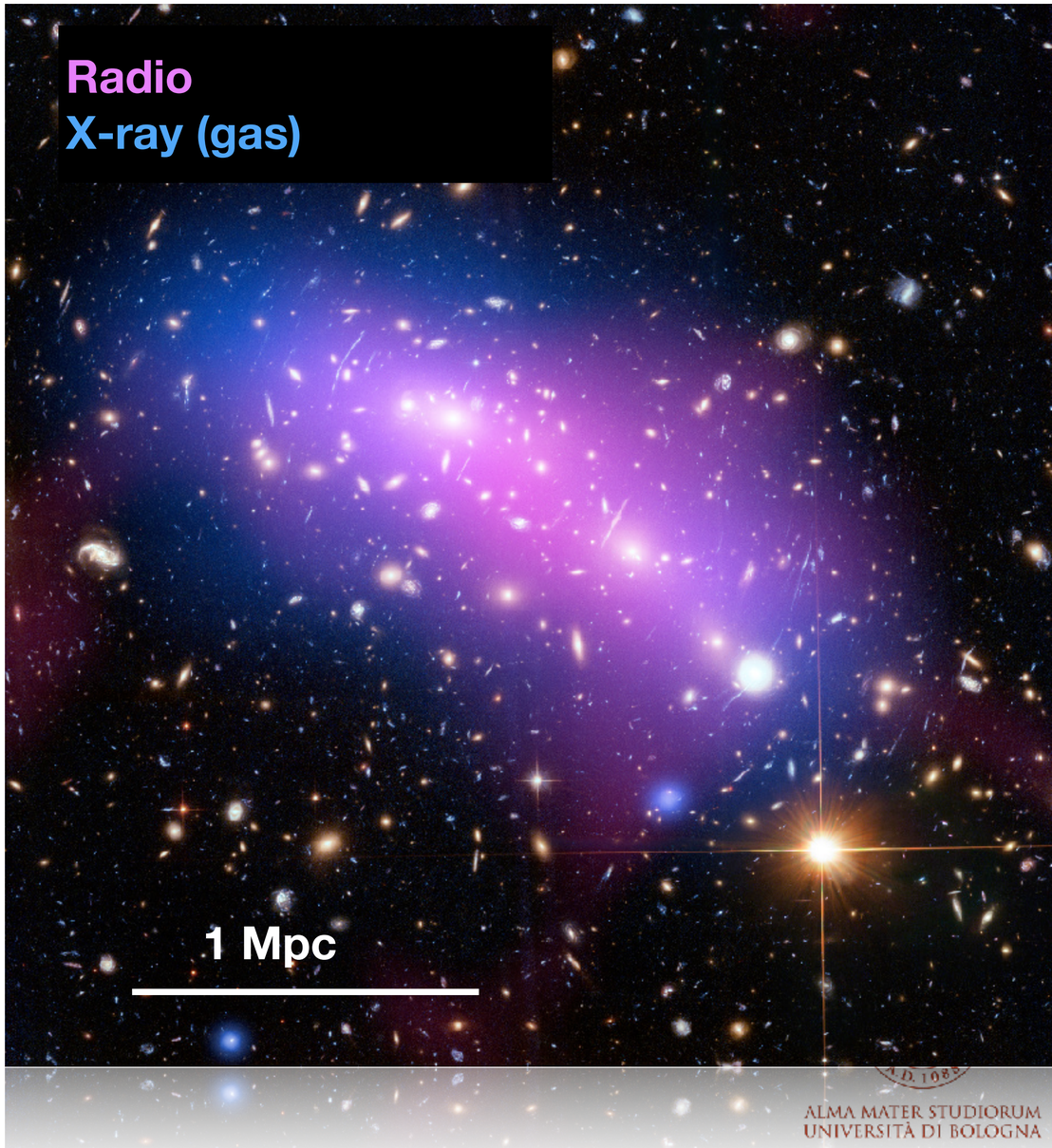
- In some cases Mpc-scale synchrotron emission seen in radio
- Synchrotron:

Relativistic electrons + **Magnetic fields**

We'll see tomorrow that B ~μG

Magnetic fields are not dynamically important

Tomorrow's lecture



GALAXY CLUSTERS: BASIC NUMBERS

- The virial radius $R_{\rm vir} = \sqrt{\dfrac{GM_{\rm vir}}{\sigma_v^2}}$
- the sound speed $c_s = \sqrt{\dfrac{5k_BT}{3m_p}}$
- the collisional mean free path is
- the gyroradius of thermal protons: $r_L = \dfrac{mv}{qB}$

$R_{\rm vir} \sim 1 - 3$ Mpc

$c_s \sim 10^3\,{\rm km/s}$

$\lambda_{mfp} \sim 20{\rm kpc}$

$r_L \sim 10^8{\rm cm} \sim 10^{-10}{\rm pc}$

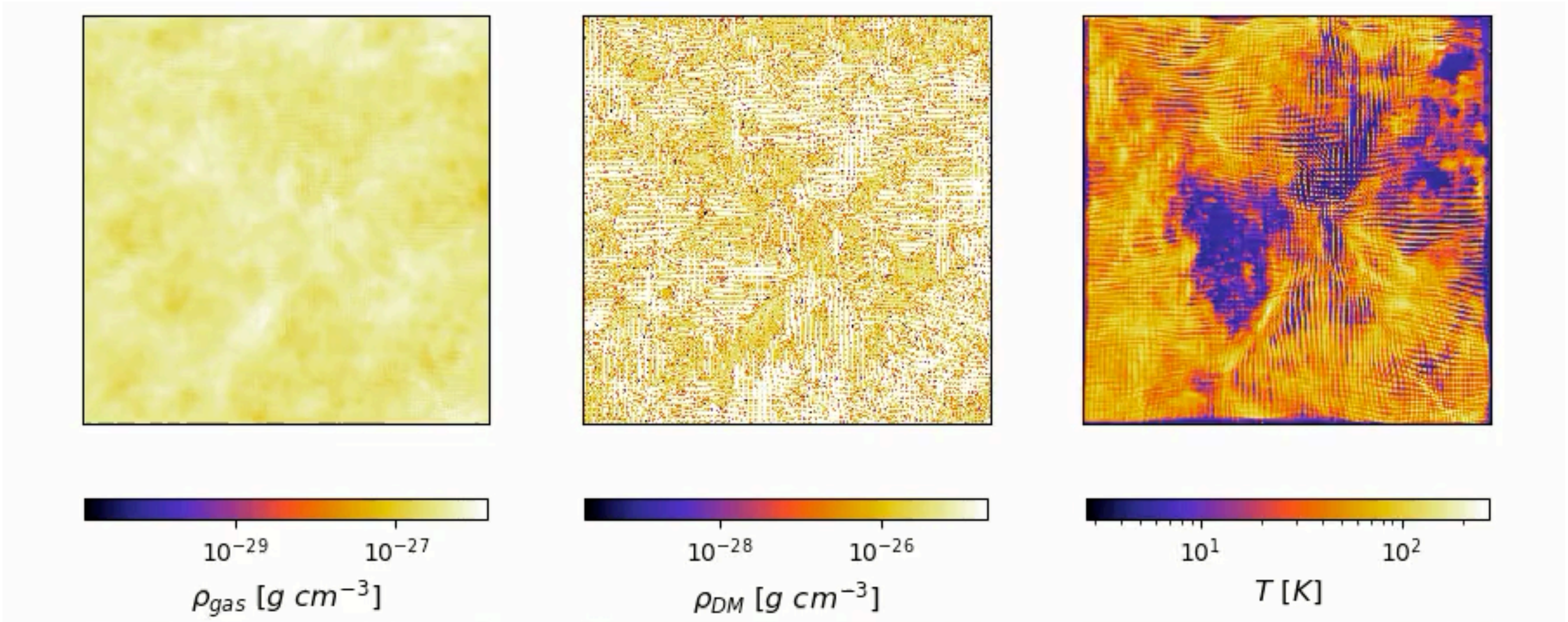
The plasma is only very weakly collisional:

$$\tau_{\rm coll} \sim \lambda_{mfp}/c_s \sim 20{\rm Myr}\ ,$$

while get scattered by the magnetic fields every $\tau_L \sim 2\pi r_L/c_s \sim 10s.$

Collective processes mediated by magnetic fields make the intra-cluster medium the most perfect plasma

FORMATION OF GALAXY CLUSTERS



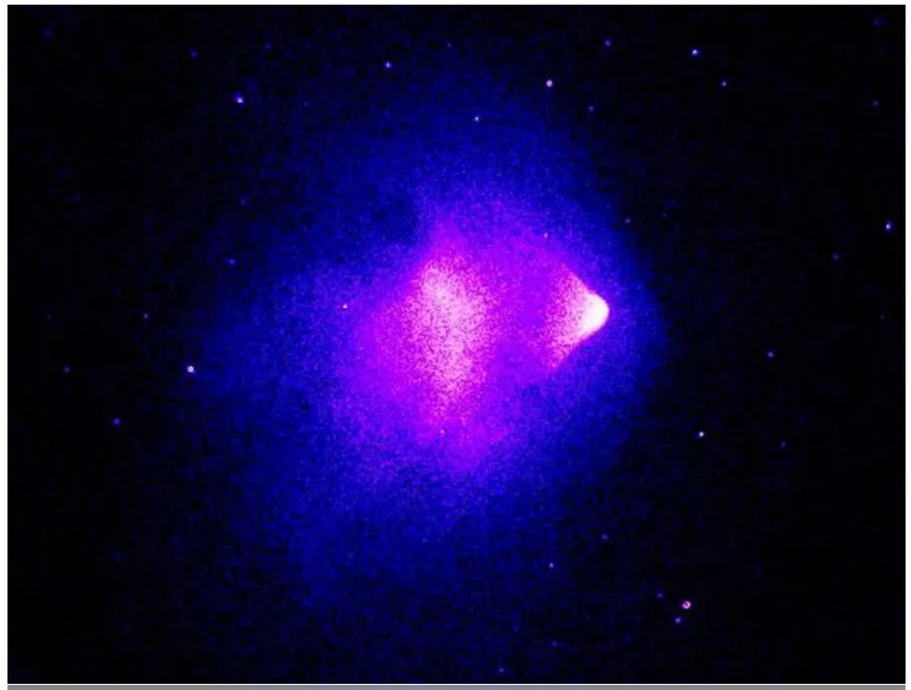
Credits: Angelinelli et al. 2020

HOW DO THEY LOOK LIKE?

X-ray emission:
tracing the gas



“Relaxed” clusters
i.e. virialized after merger



Merging clusters

Credits: Chandra

MERGERS BETWEEN CLUSTERS

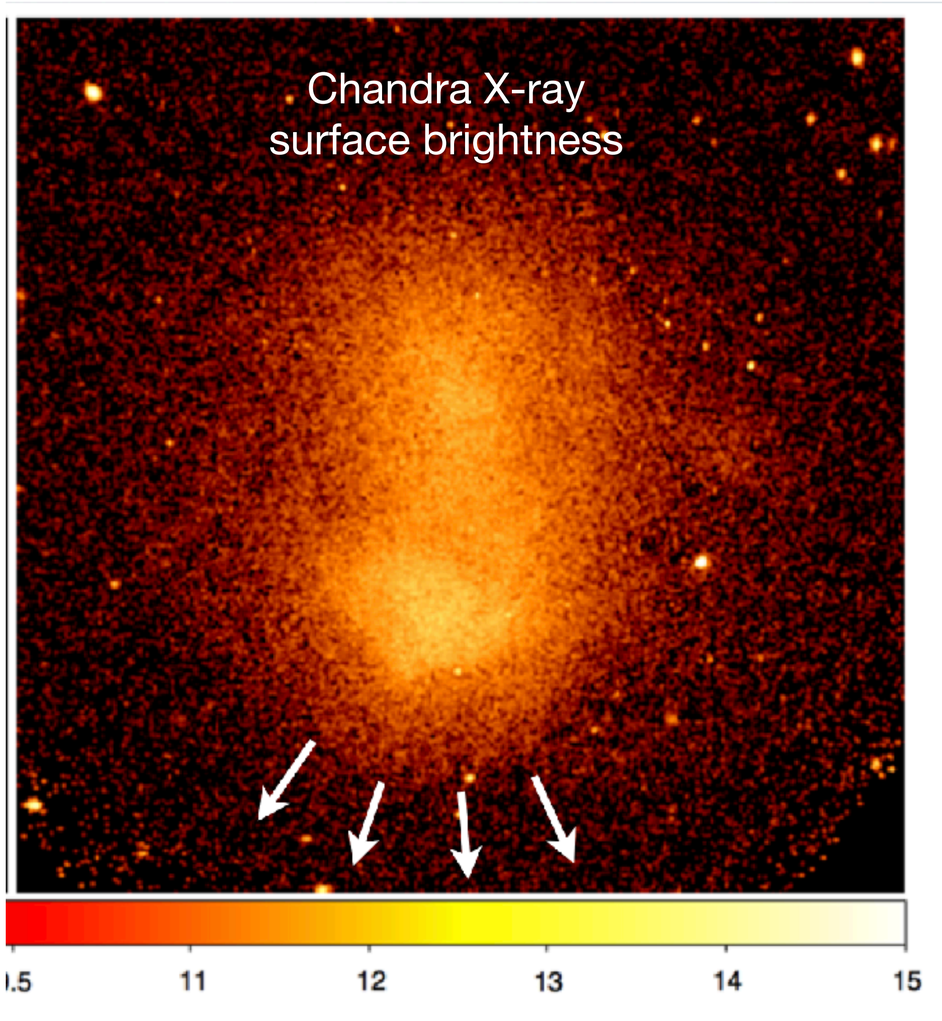
- Major mergers: the most energetic events since the Big Bang $E \sim 10^{63-64}$ erg

- Collision velocity - free-fall velocity

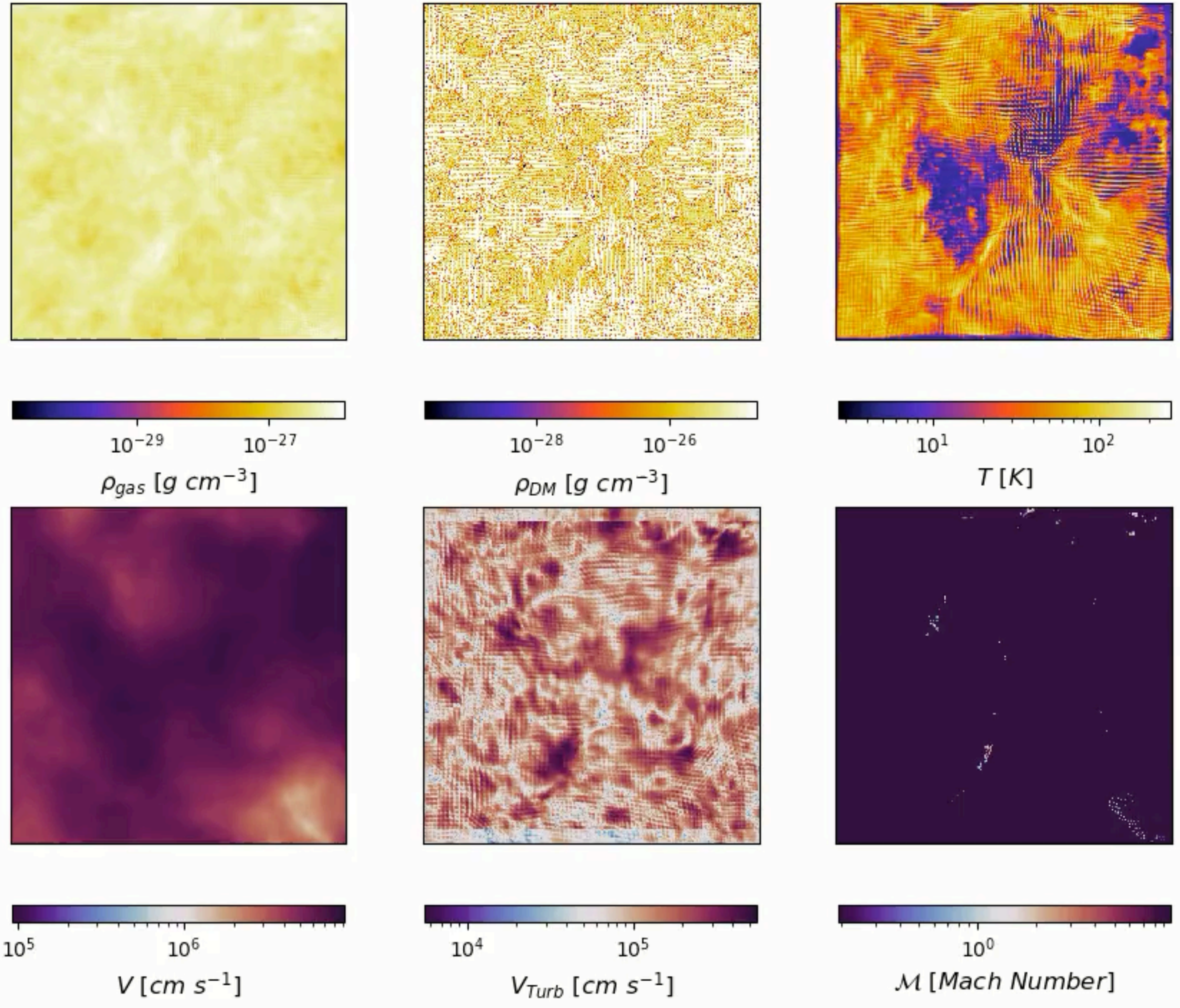
$$v_{ff} \sim \sqrt{\frac{2GM}{R}} \sim 10^3 \text{ km/s}$$

- Infall velocity similar to sound speed in the ICM —> induced gas motions are transonic, low Mach numbers

$$\mathcal{M} \approx \frac{v_{ff}}{c_s} \sim \sqrt{2}$$



FORMATION OF GALAXY CLUSTERS

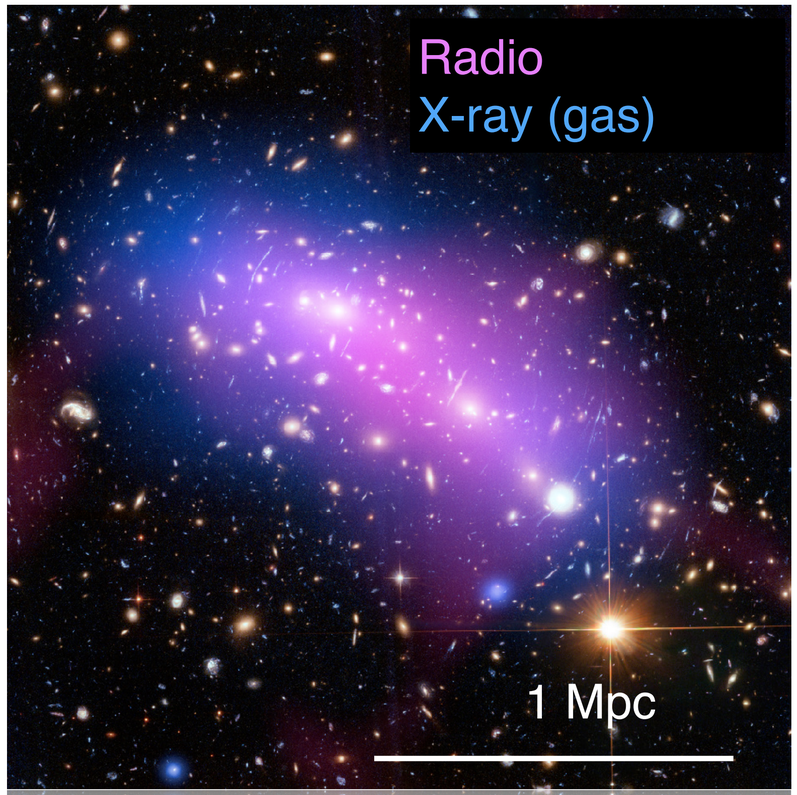


Credits: Angelinelli et al. 2020

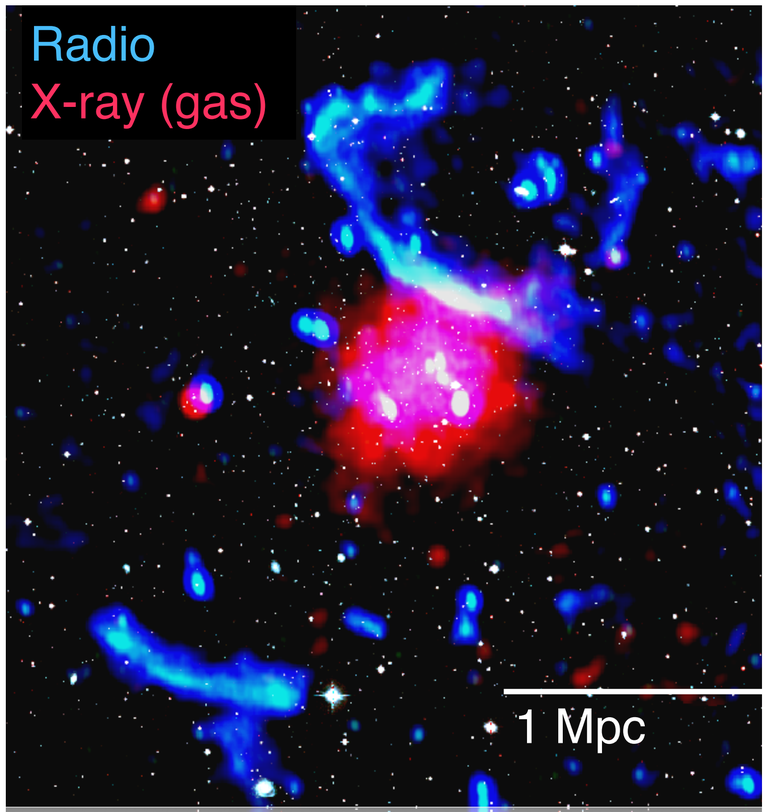
RADIO EMISSION IN GALAXY CLUSTERS

Merging systems

Radio halos

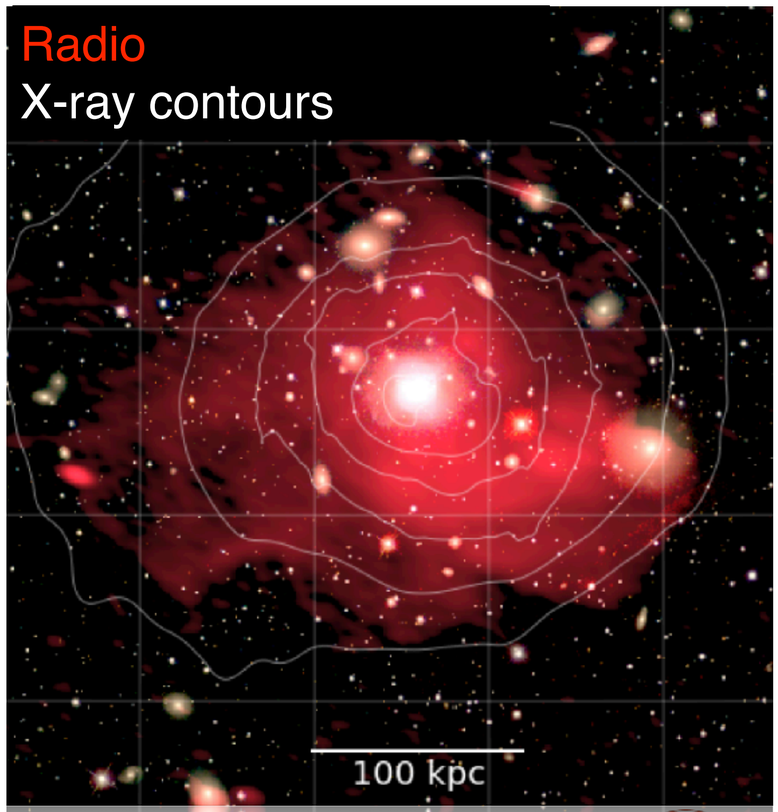


Radio relics



Virialized systems

Mini halos



Credits: Orgean et al. 2015, Bonfede et al 2014, van Weren et al 2019

THE ENERGETIC PROBLEM

Life-time of GeV electrons in a ~μG magnetic field

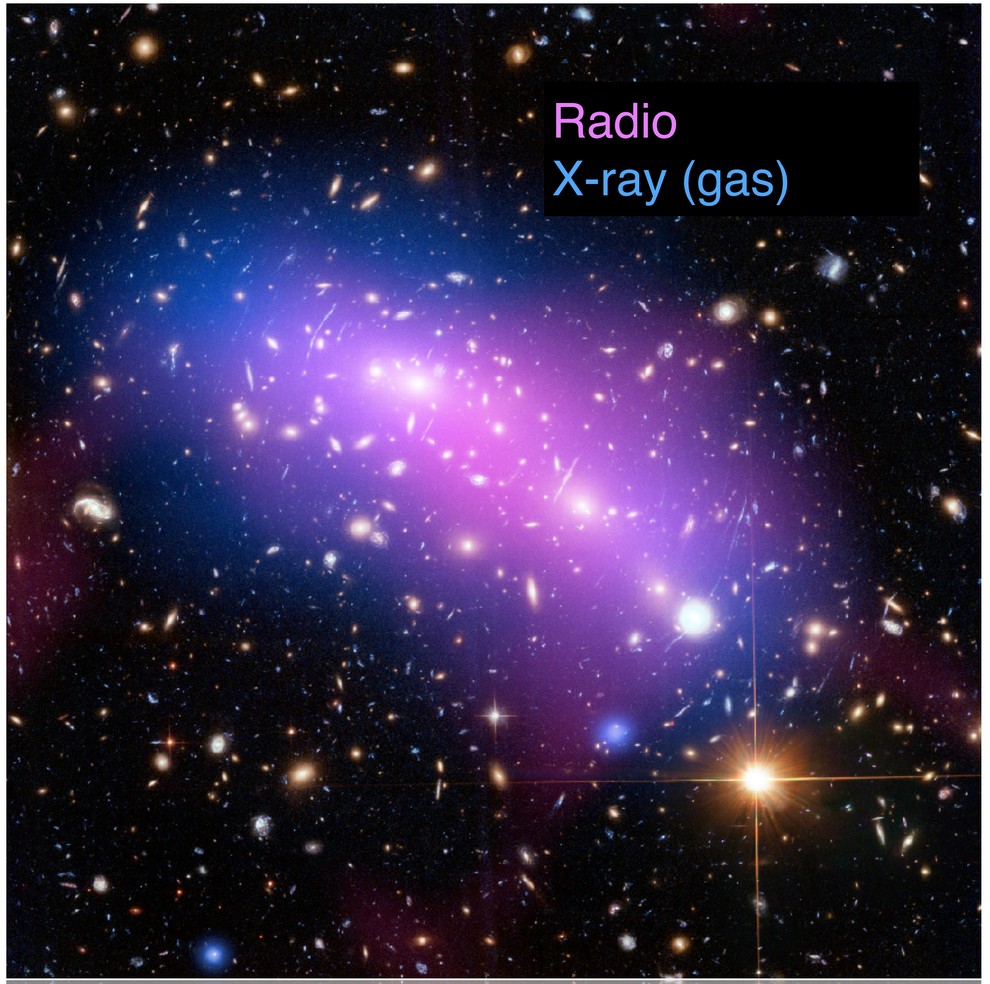
$t \sim 10^8$ years

Diffusion velocity

$v \sim 100$ km/s

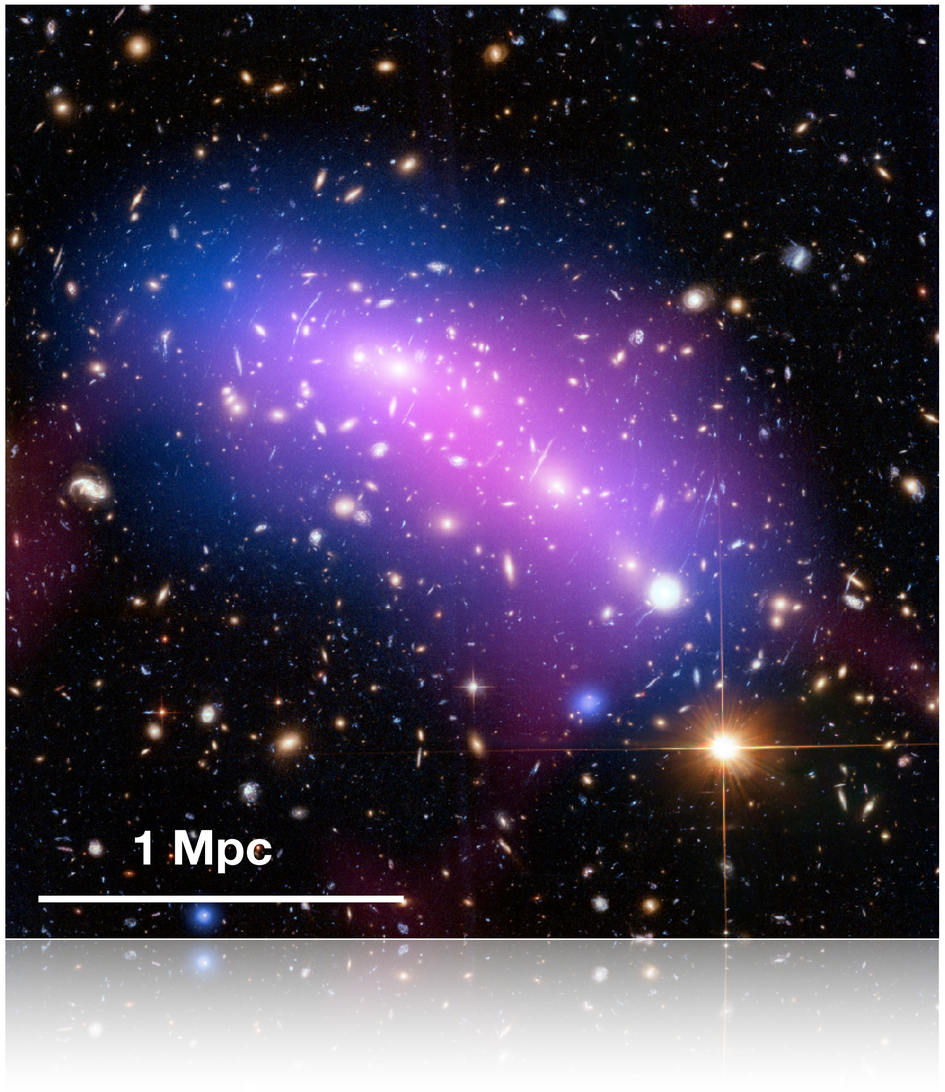
L_{max} ~30 kpc
Radio emission ~Mpc

Electrons need to be continuously injected or accelerated



What is accelerating the electrons/injecting them in the Intra Cluster Medium?

RADIO HALOS

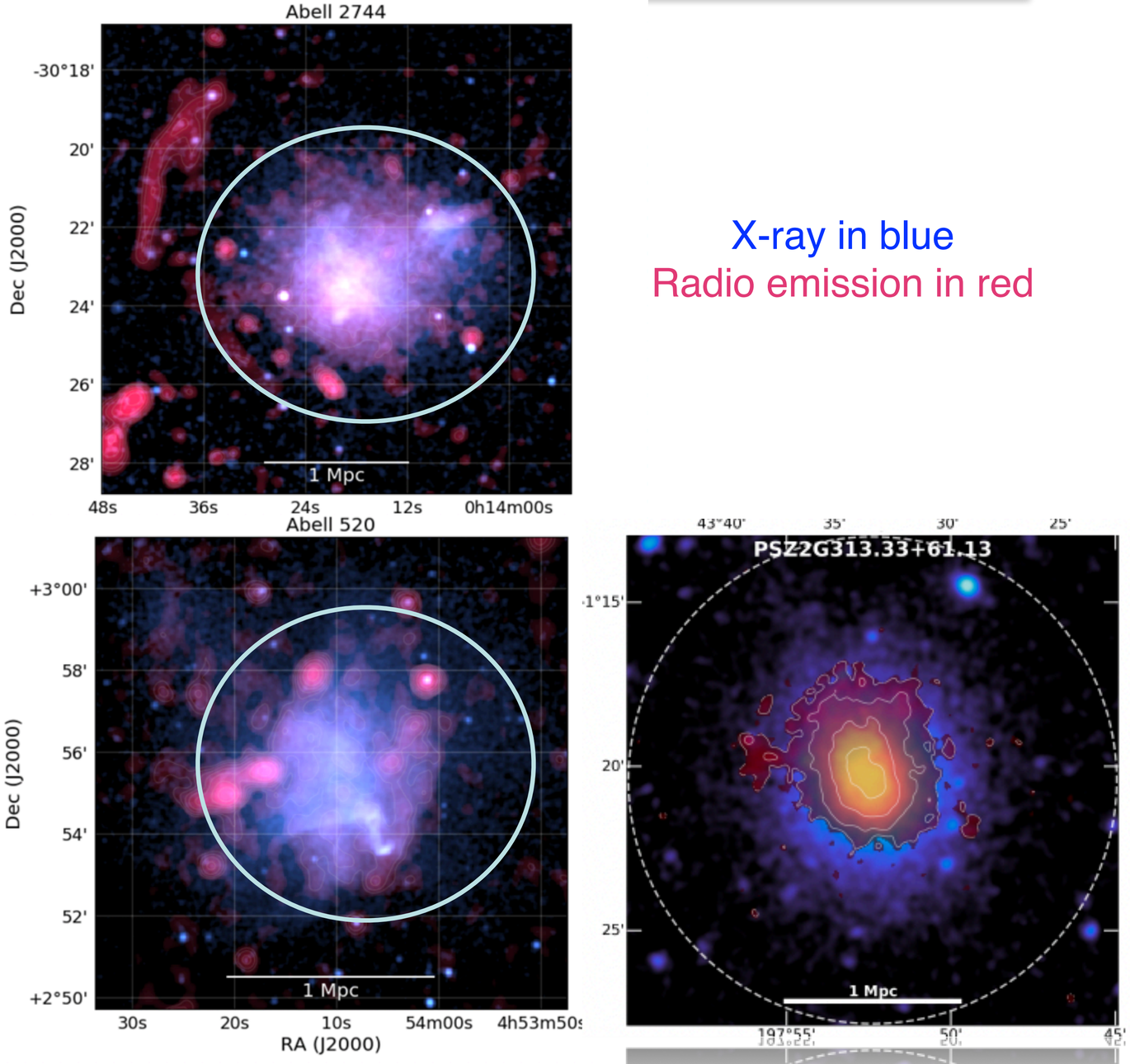


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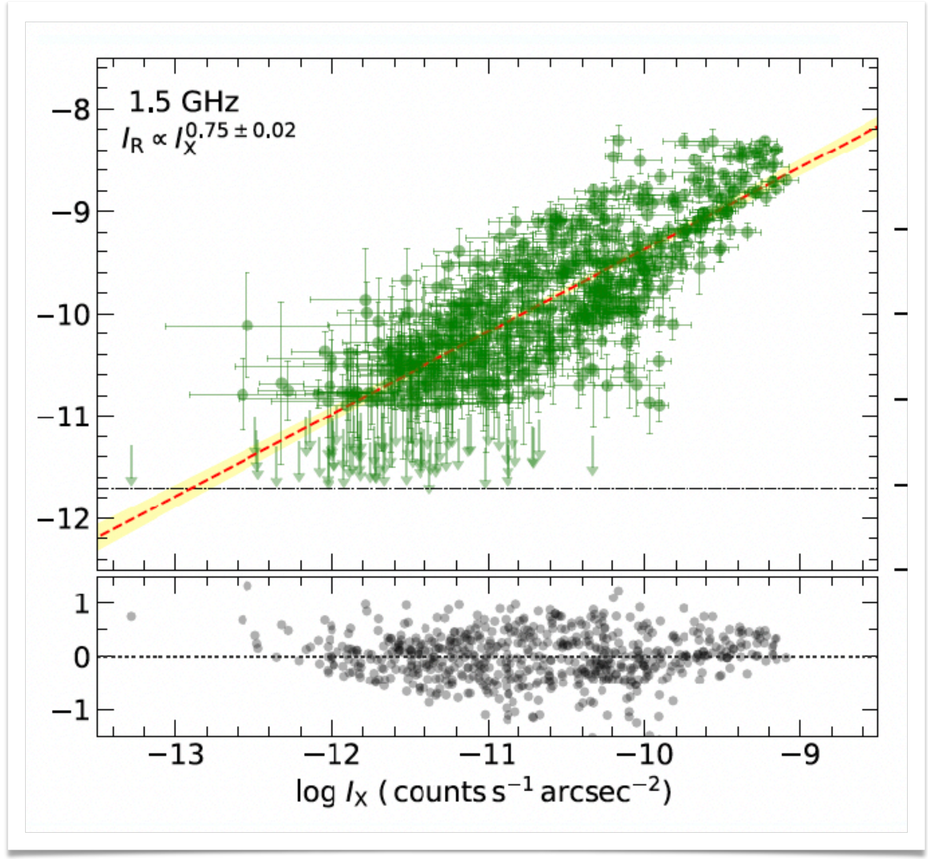
- Mpc-scale emission in Merging clusters
- Found only in a fraction of clusters

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THE RADIO EMISSION "KNOWS" ABOUT THE THERMAL EMISSION



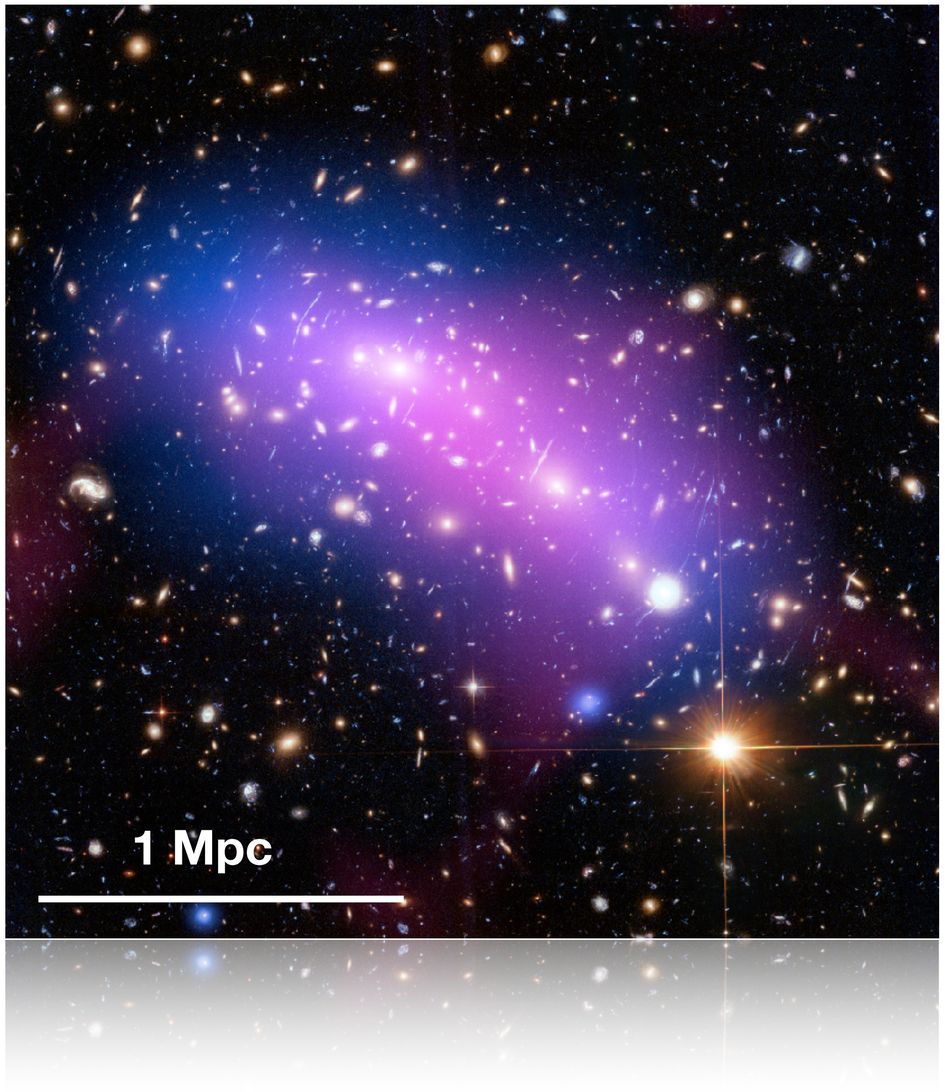
X-ray in blue
Radio emission in red



Credits: van Weeeren et al 19,
Balboni et al 26, Rajpurohiit et al 24

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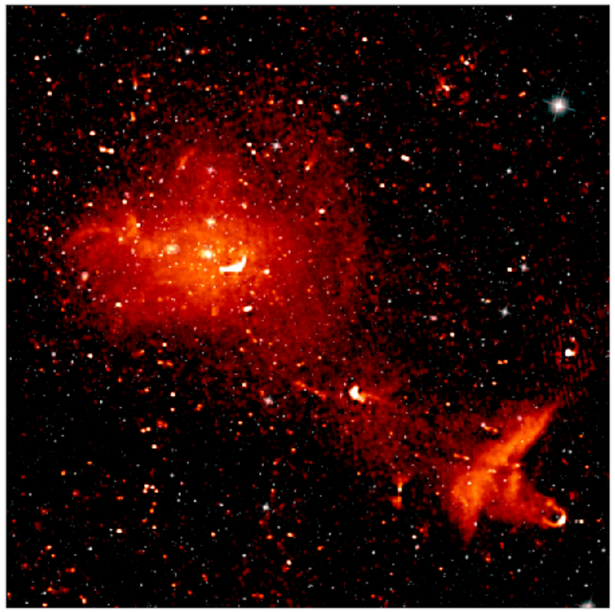
RADIO HALOS

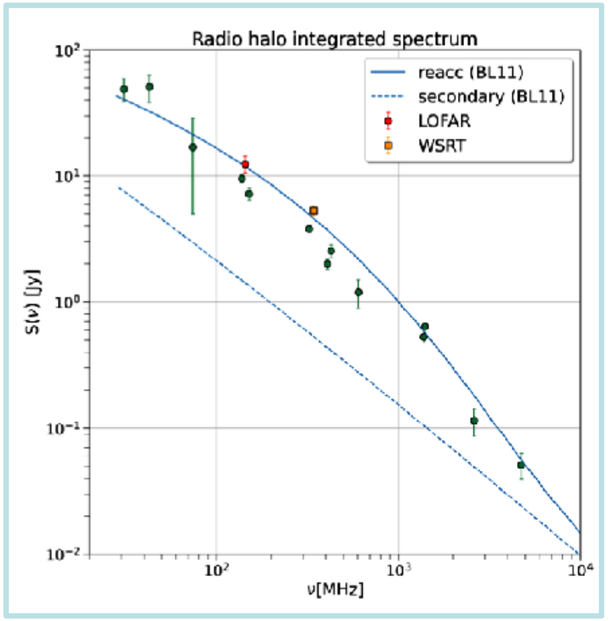


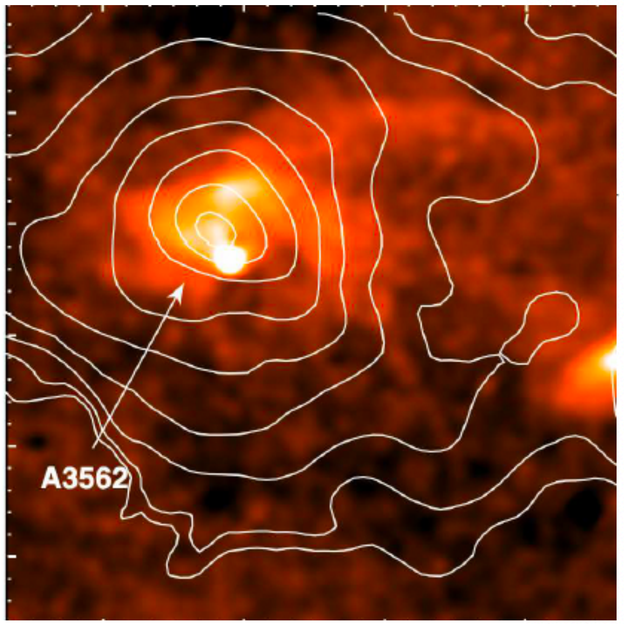
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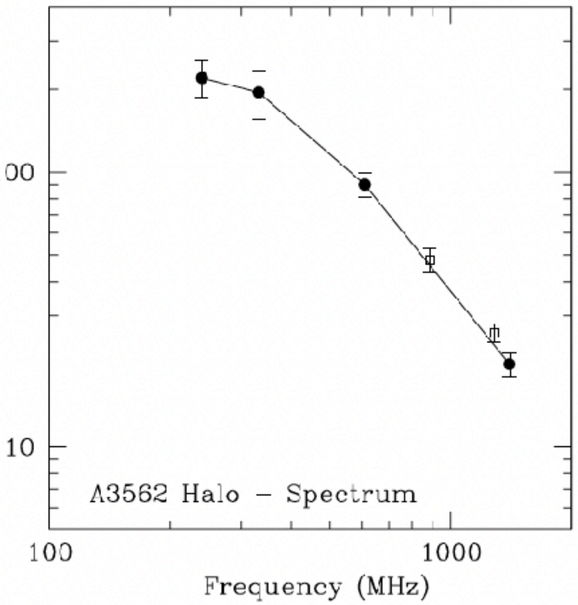
- Mpc-scale emission in Merging clusters
- Found only in a fraction of clusters
- Radio emission co-spatial with X-ray emission

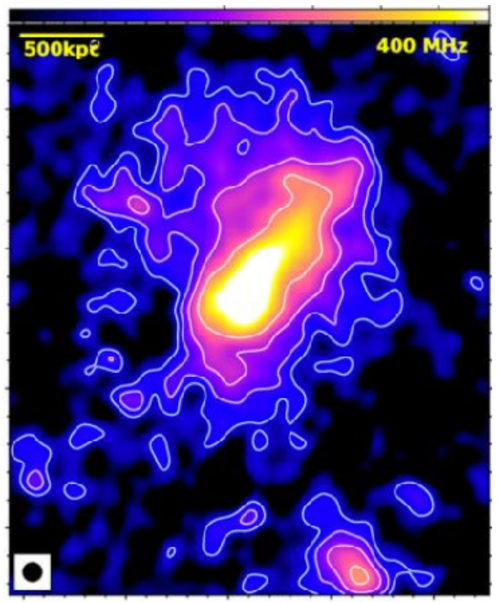
RADIO HALOS: SPECTRAL PROPERTIES

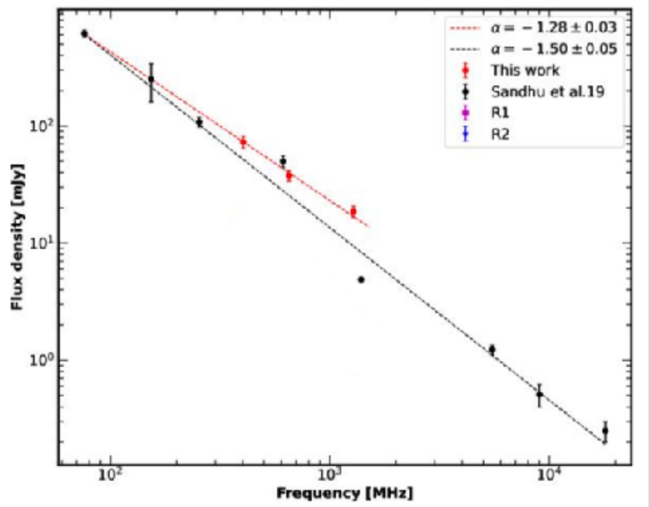












Steep spectrum,
$S(\nu) \propto \nu^{-\alpha}, \alpha \sim 1 - 1.5 \rightarrow$ non thermal!

Hints of curvature
few cases studied at more than 2 frequencies

Credits: Bonafede et al 22, Venturi et al 22, Santra et al 26

RADIO HALOS



Properties:

- Mpc scale emission in Merging clusters
- Found only in a fraction of clusters
- Radio emission co-spatial with X-ray emission
- Steep spectrum emission $S(\nu) \propto \nu^{-\alpha}$, $\alpha = 1 - 2$, but few cases with large frequency coverage

RADIO HALOS: TURBULENCE ?

- Reynolds number ($R_e = \sigma_v L/\nu$) of the ICM is very large ($\gg 10^3 - \ldots 10^{20}$) indicating that perturbations will induce fluid turbulence
- The typical rms velocities are $\sigma_v \sim (0.1 - 0.5) c_s \sim 100 - 1000\,\mathrm{km/s}$ on $L \leq$ Mpc scales.
- This environment seems suitable to host Fermi II acceleration of particles (electrons) for a few billion years.





Proposed by Brunetti et al(2001) Petrosian et al (2001)

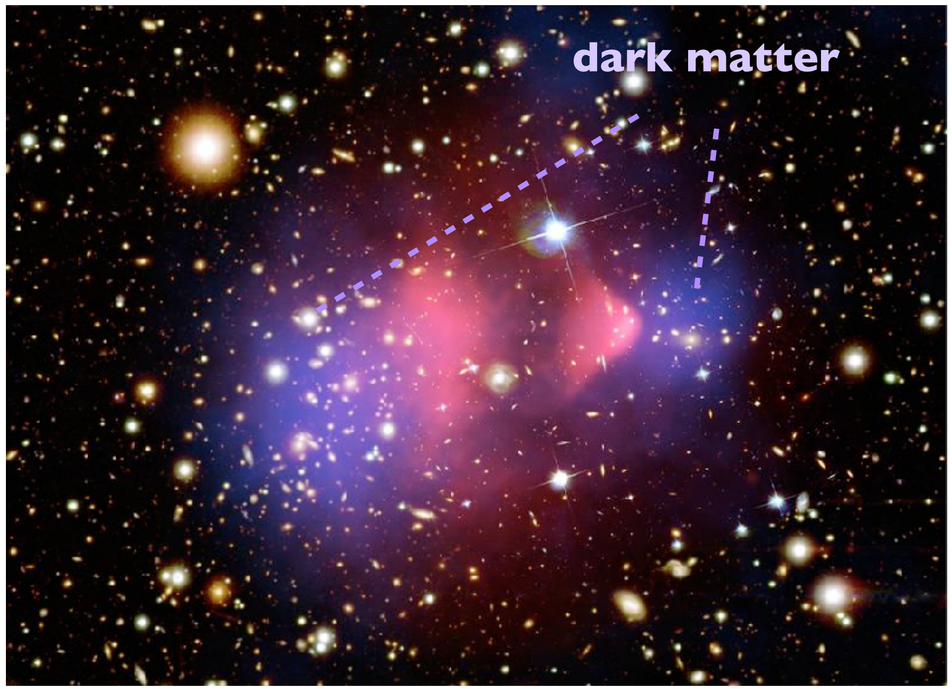
Credits: Vazza

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RADIO EMISSION IN CLUSTERS: THE "CLASSIC VIEW"

Cluster-cluster merger

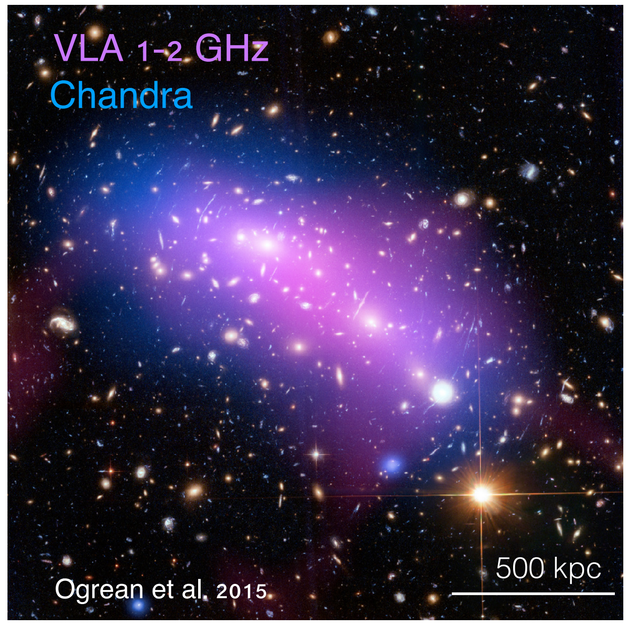
E ~10^{64} ergs



Turbulence
(e.g. Brunetti et al 2001)

Halos

?



Challenges

(R. Cassano lecture tomorrow)

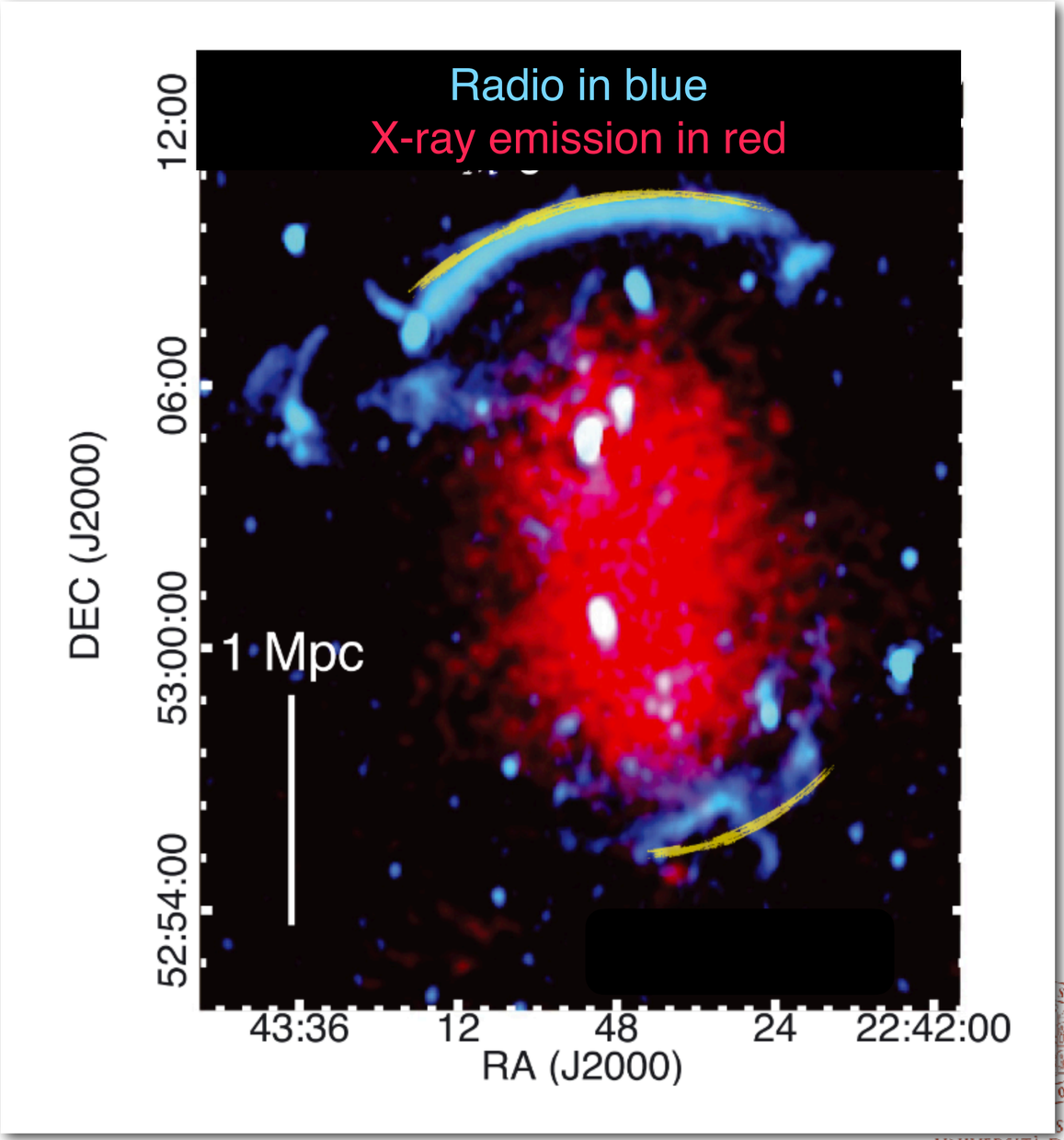
- Low efficiency $\eta_t \sim 0.01$
- Turbulence is hard to measure
- Process happening at plasma-scale

Credits:Markevitch, Clowe, Ogrean, Bonafede

RADIO RELICS

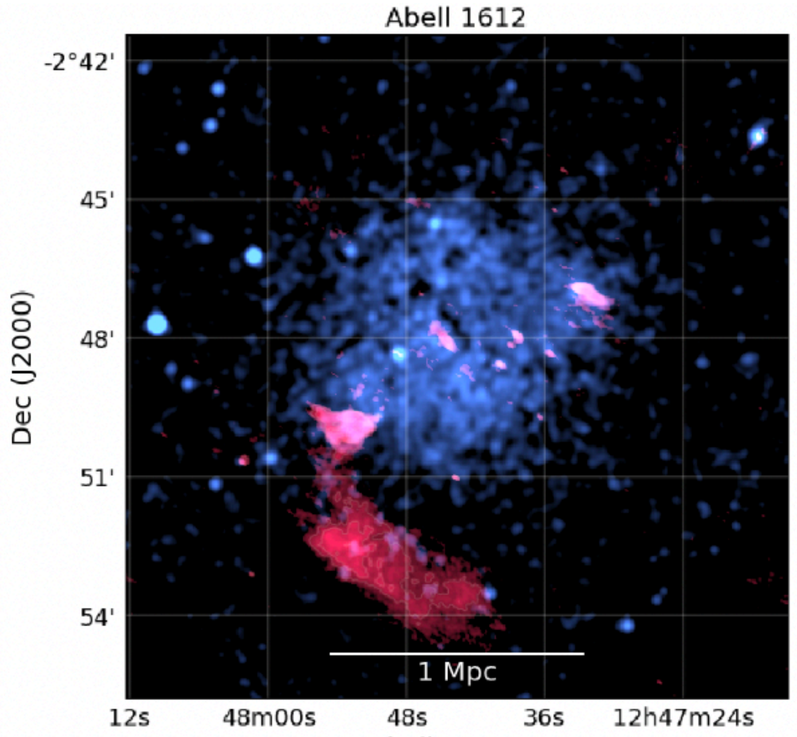
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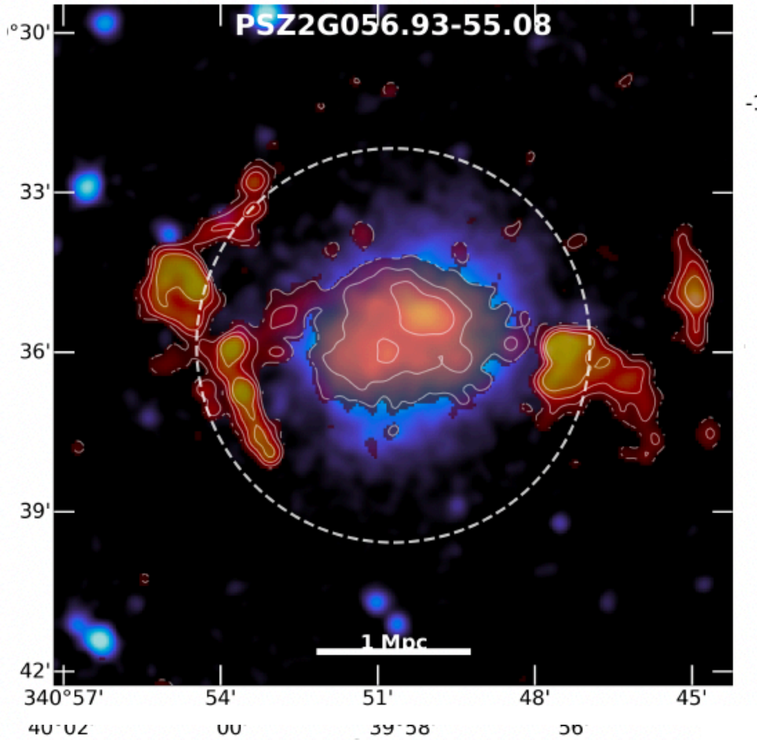
- Mpc-scale emission in Merging clusters



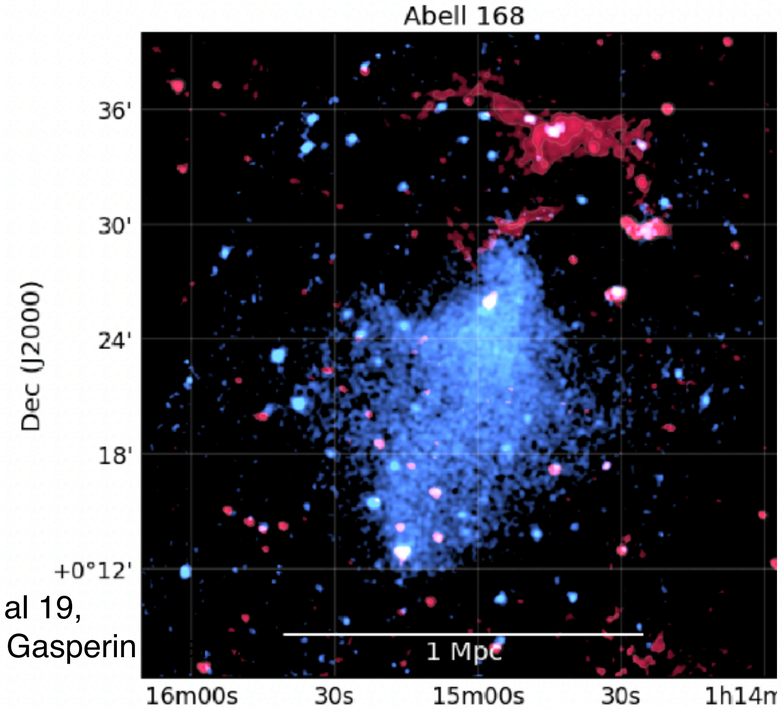
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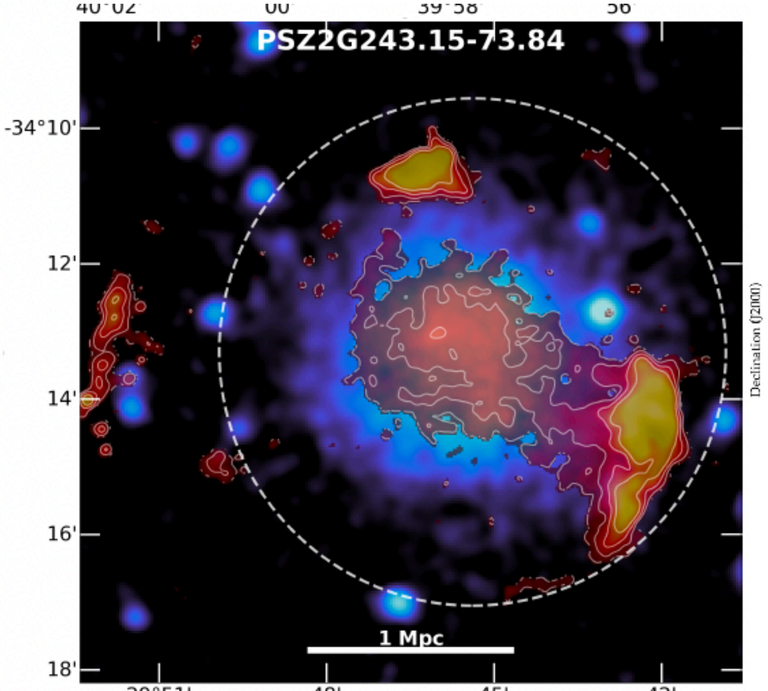
X-ray in blue
Radio emission in red

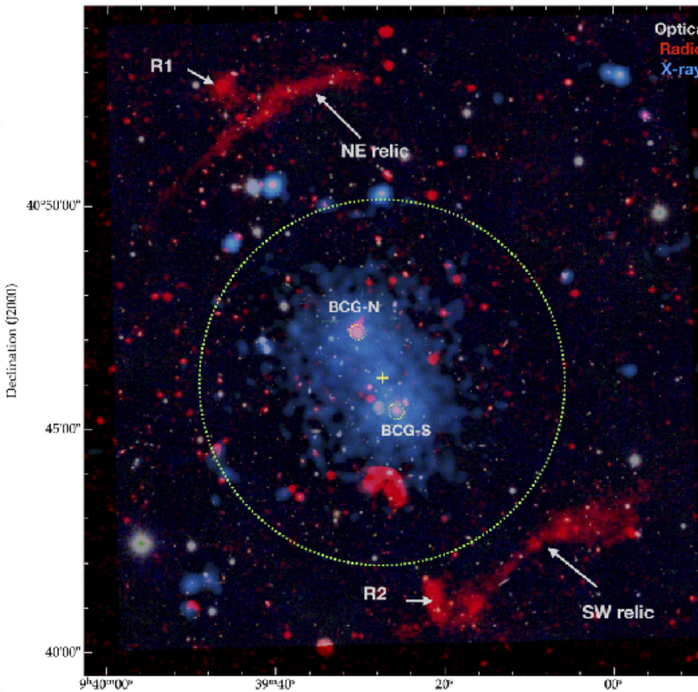










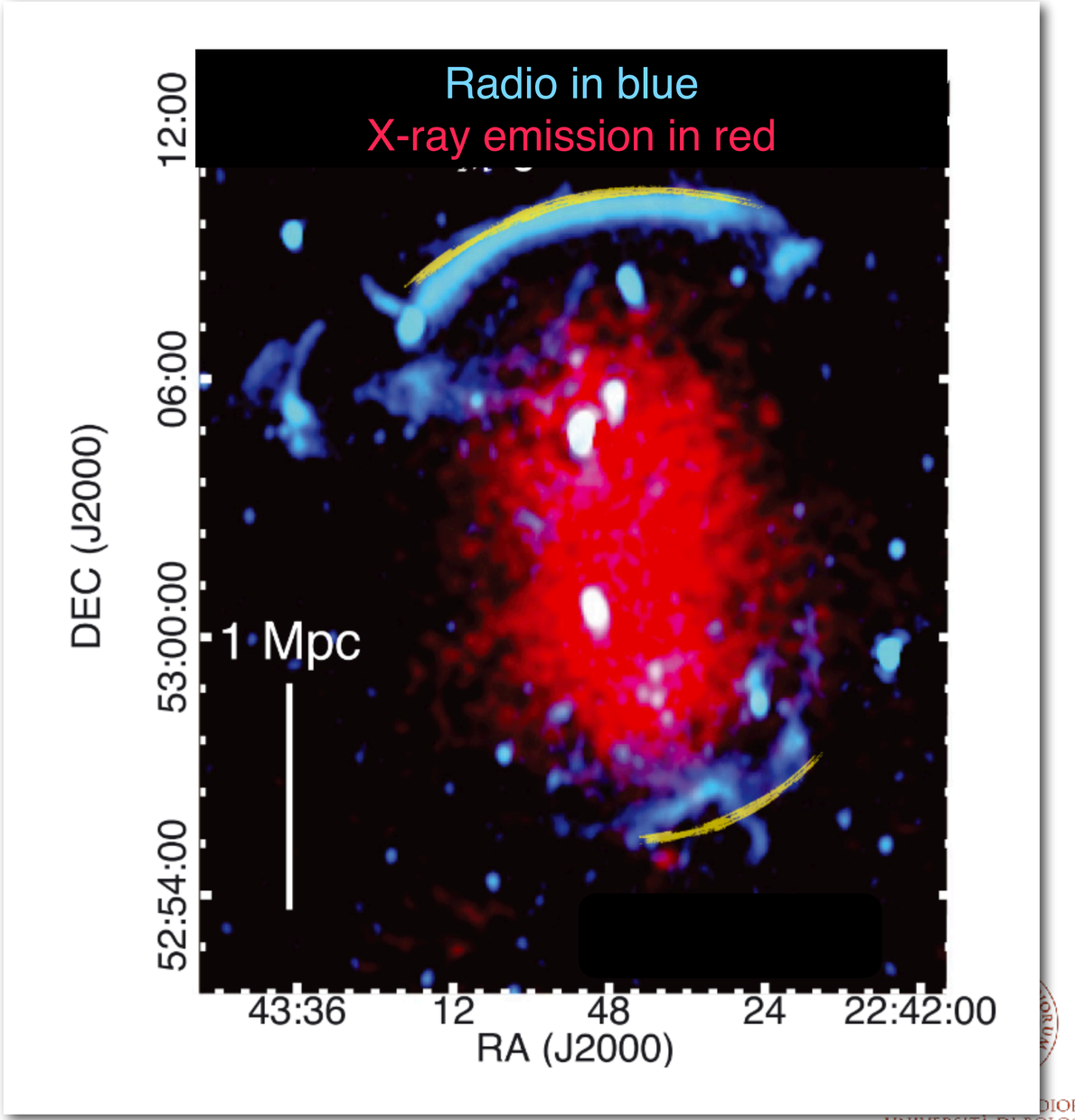


credits: van Weeren et al 19, Rajpurohit et al 25, de Gasperin Balboni et al 26

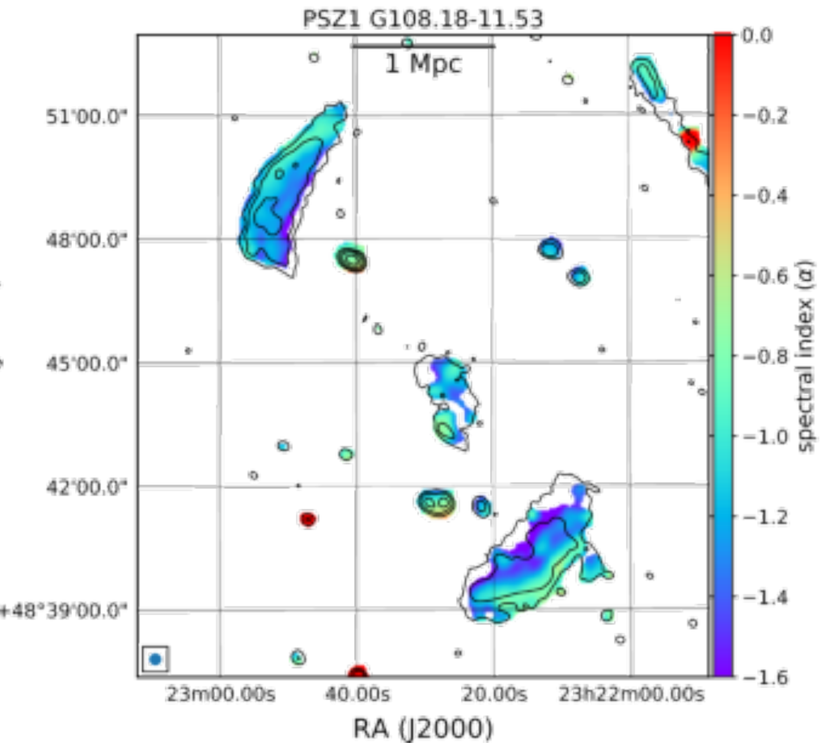
RADIO RELICS

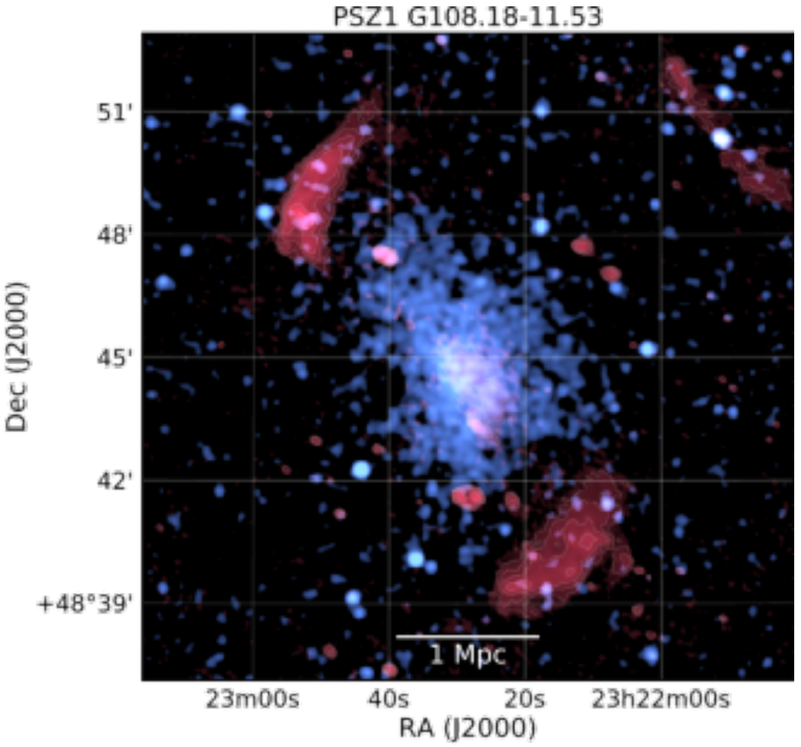
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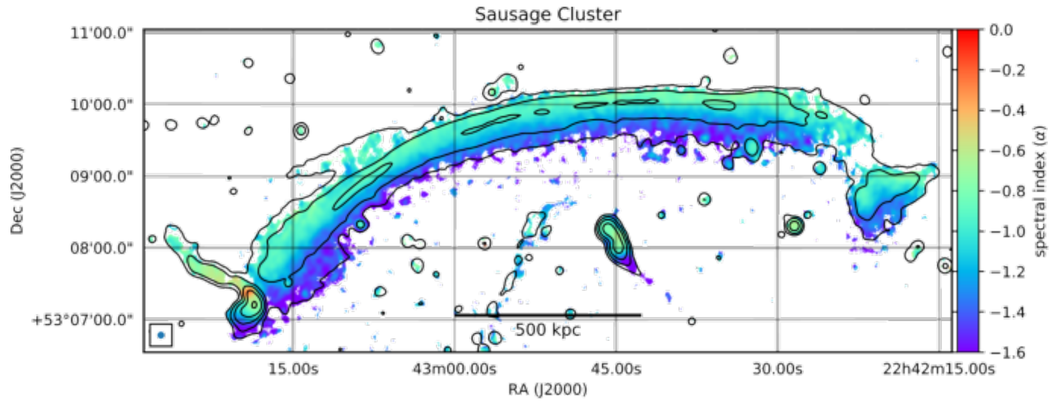
- Mpc-scale emission in Merging clusters
- At the cluster periphery, perpendicular to the merging axis
- can co-exist with radio halos and appear single or in pairs



RADIO RELICS: SPECTRAL PROPERTIES







Steep spectrum

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

Spectral steepening often observed
transverse to the relic main axes

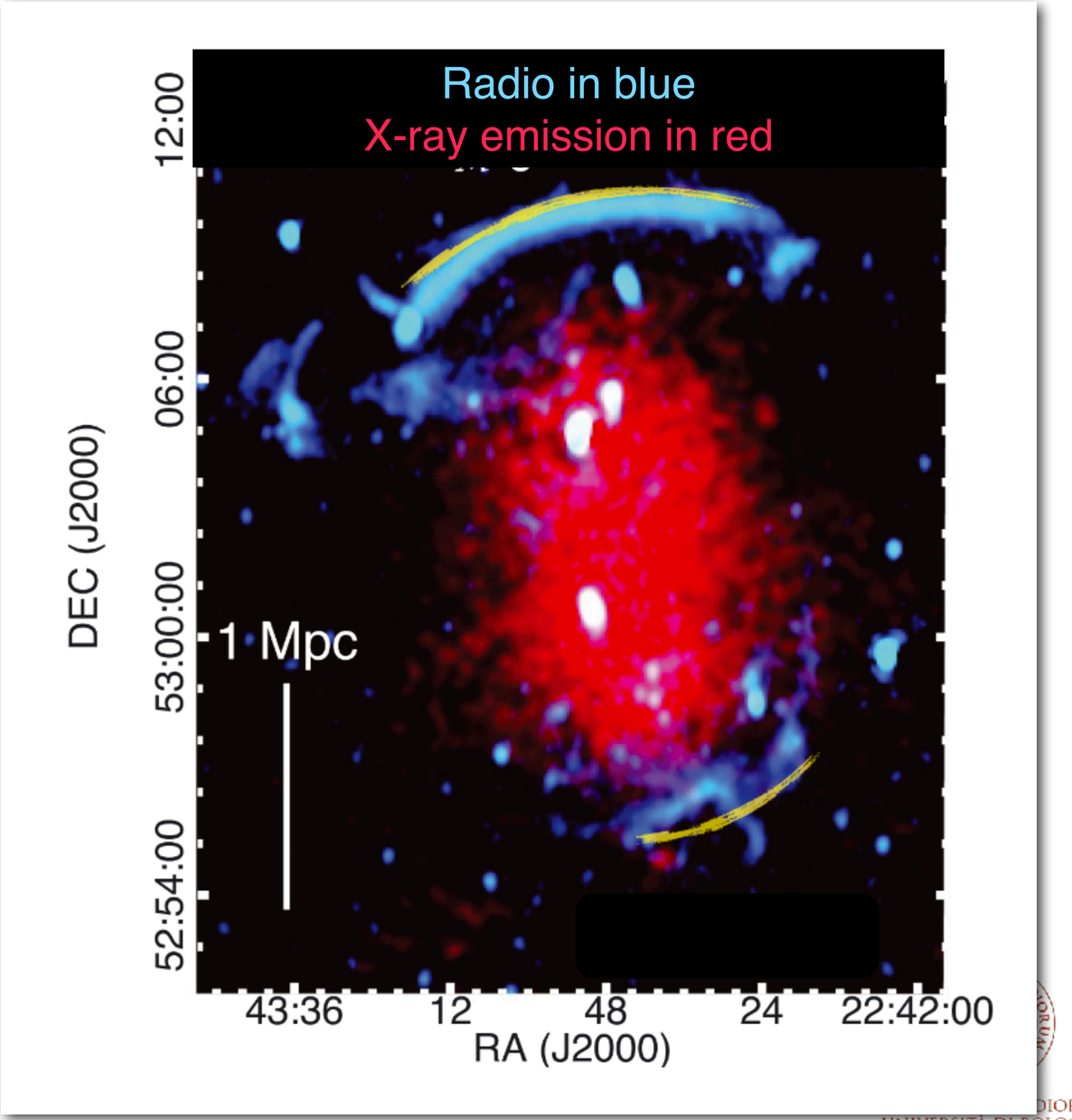
Remember: flat spectrum: fresh/ young particle
steep spectrum: aged particles

RADIO RELICS

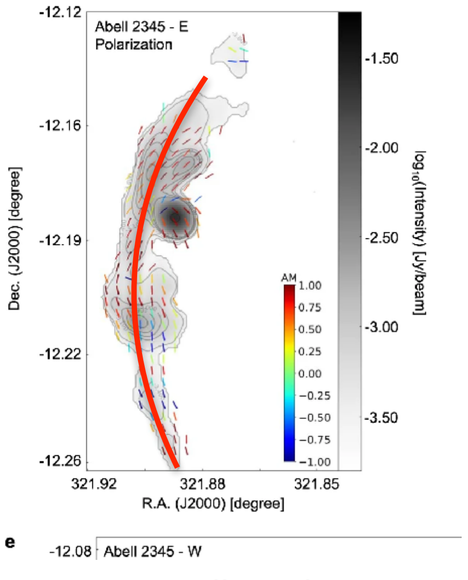
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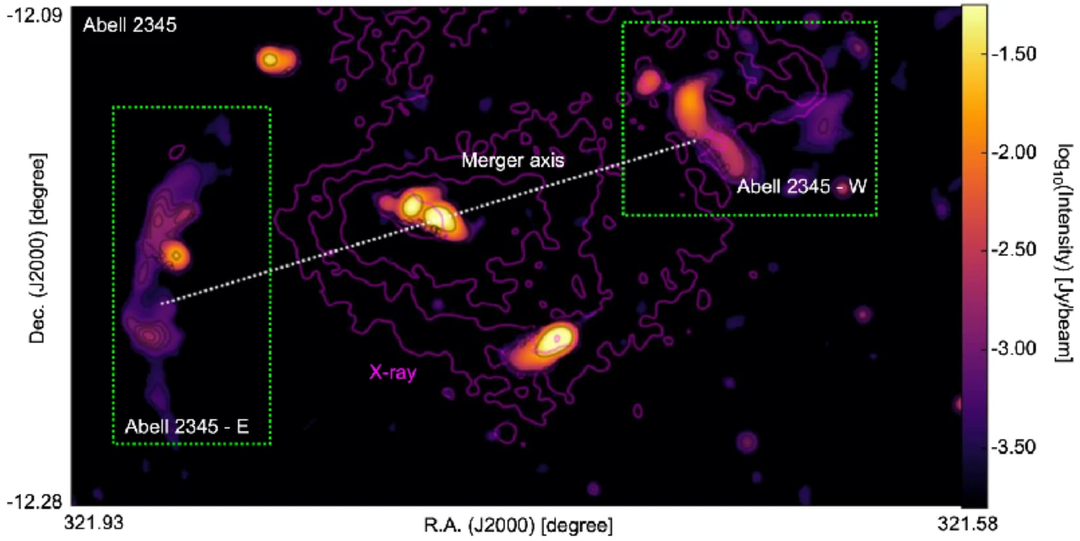
- Merging clusters
- At the cluster periphery, perpendicular to the merging axis
- can co-exist with radio halos and appear single or in pairs
- steep spectrum $S(\nu) \propto \nu^{-\alpha}, \alpha \approx 1$

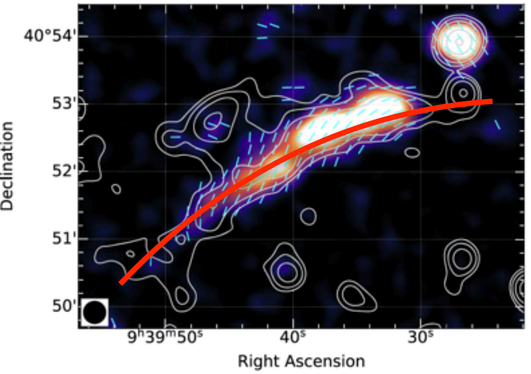
and spectral trend often observed

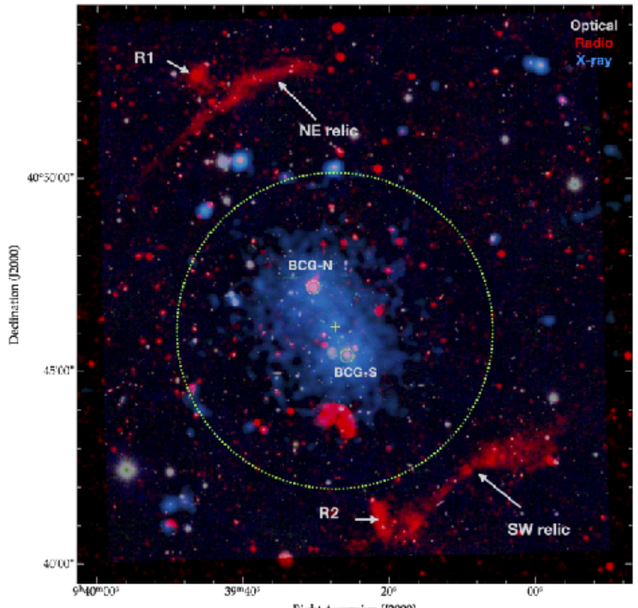


RADIO RELICS: POLARIZATION









Polarisation reveals magnetic fields oriented along the relic main axis

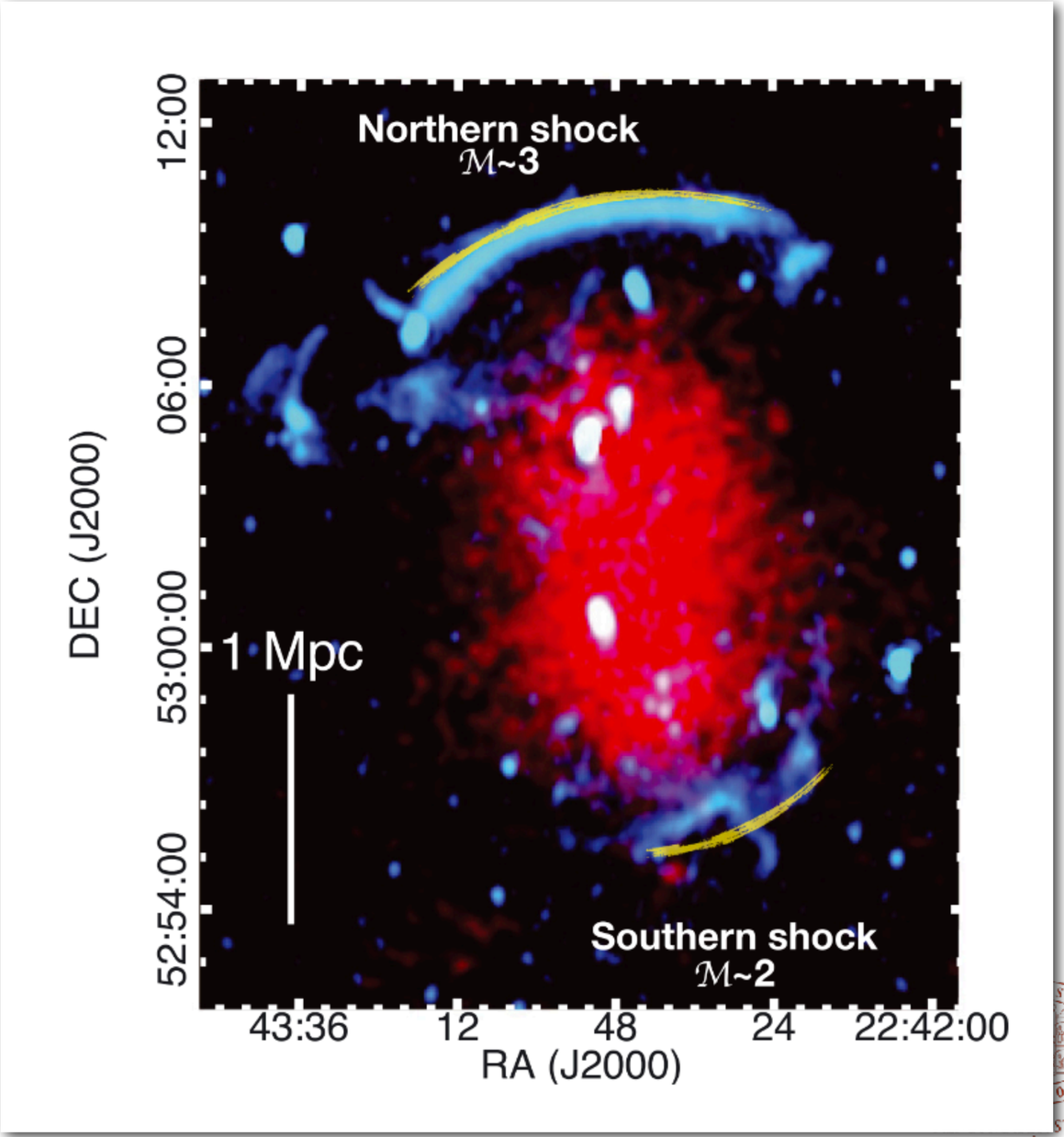
credits: Rajpurohit et a; 25, Stuardi et al 21, Hu et al 24

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RADIO RELICS

Properties:

- Mpc-scale emission in Merging clusters
- At the cluster periphery, perpendicular to the merging axis
- can co-exist with radio halos and appear single or in pairs
- steep spectrum $S(\nu) \propto \nu^{-\alpha}$, $\alpha \approx 1 - 1.3$and spectral trend often observed
- Polarised (20-30% at 1.4 GHz)

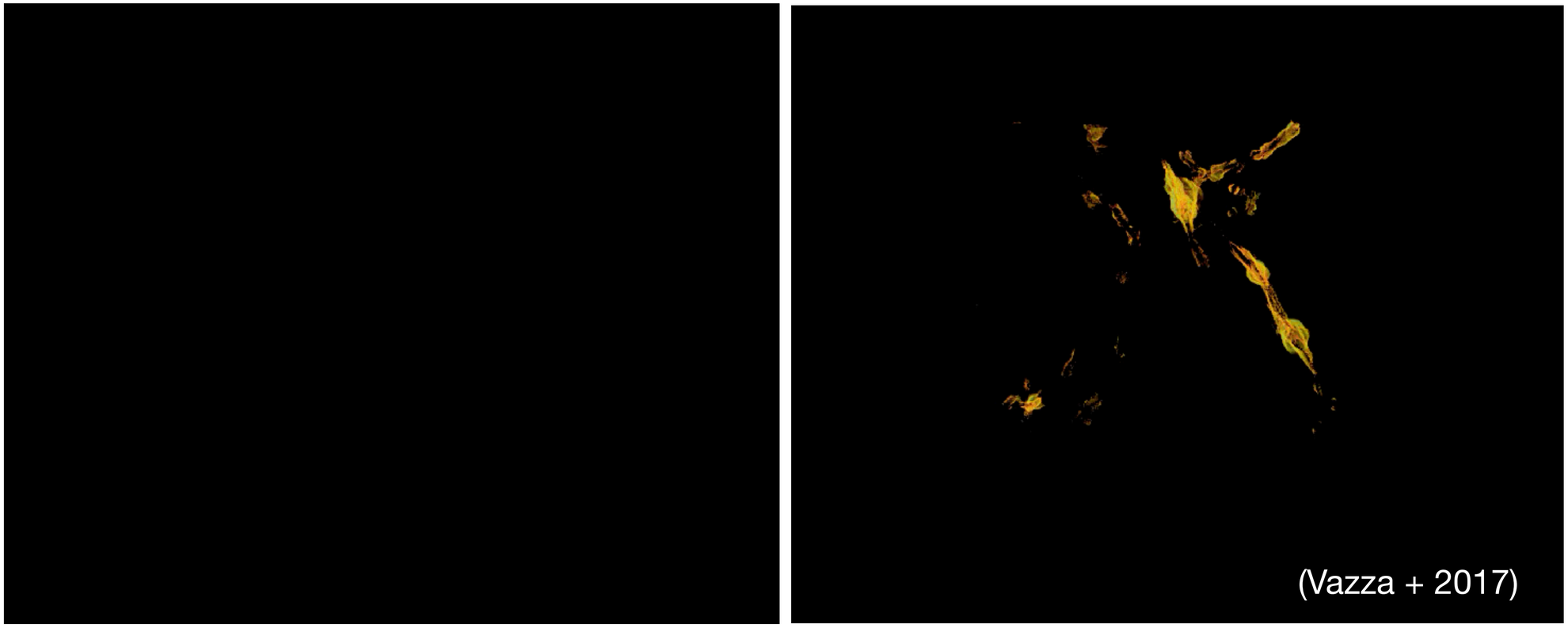


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SHOCKS IN COSMOLOGICAL SIMULATIONS

Gas density

Shocks [log(Mach number)]

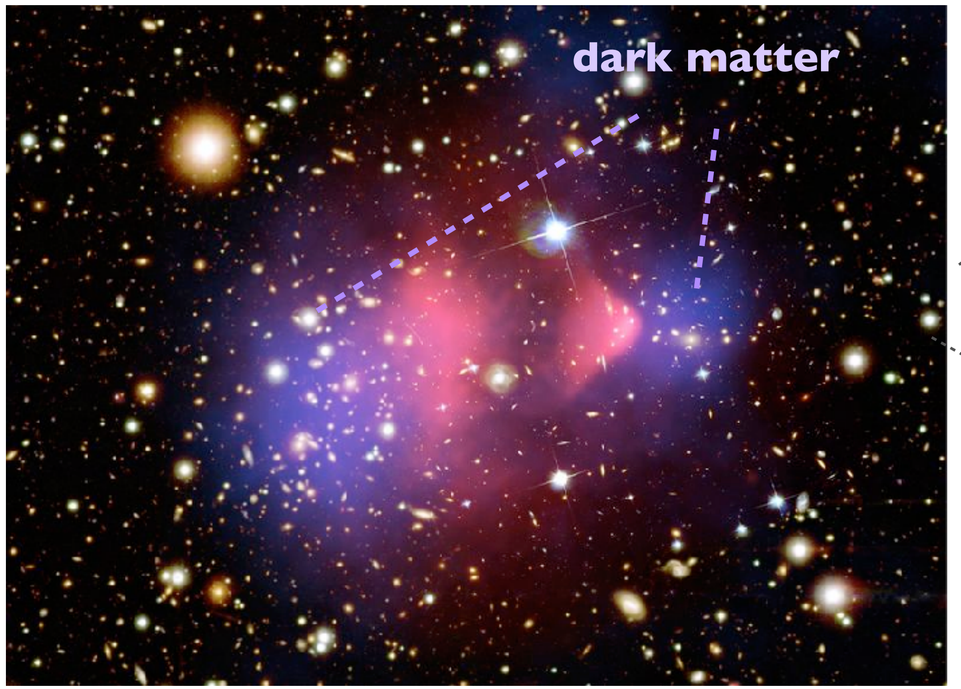


Accretion on several scales → shock waves with a range of Mach numbers and kinetic power

RADIO EMISSION IN CLUSTERS: THE "CLASSIC VIEW"

Cluster-cluster merger

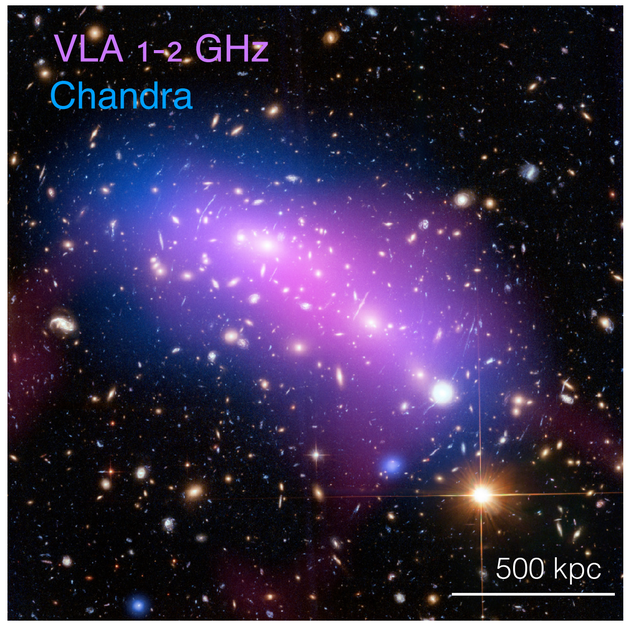
E ~10^{64} ergs



Turbulence
(e.g. Brunetti et al 2001)

Halos

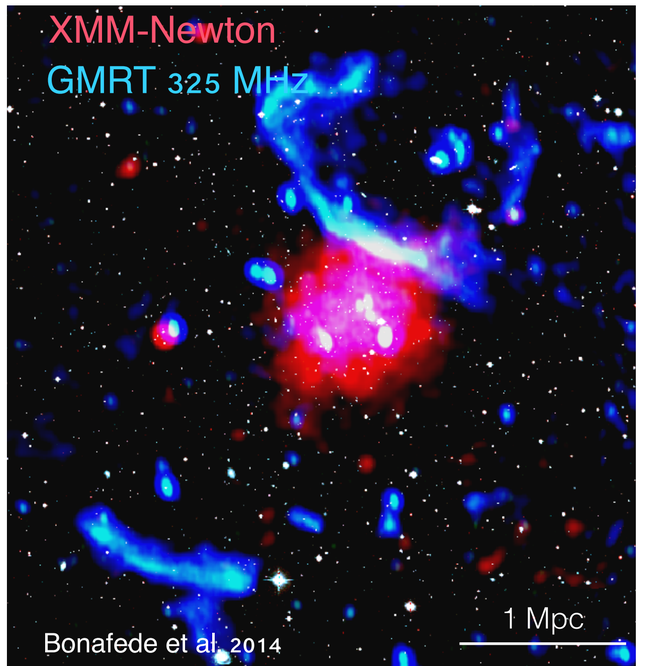
?



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

Relics

?



Credits:Markevitch, Clowe, Ogrean, Bonafede

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RELICS - SHOCK CONNECTION

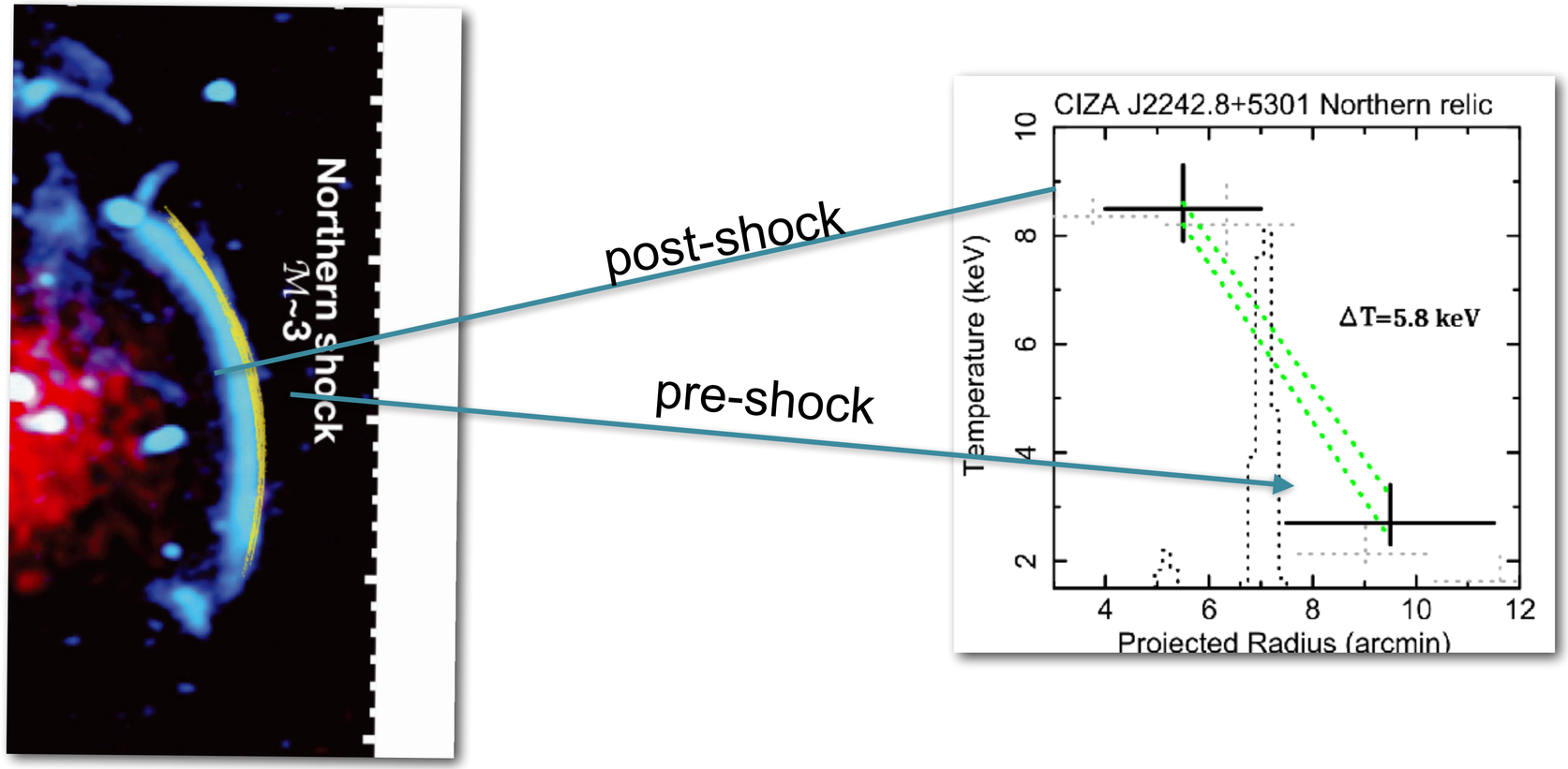
Rankine-Hugoniot jump conditions

$$\frac{T_2}{T_1} = \frac{(5\ \mathcal{M}^2 - 1)(\mathcal{M}^2 + 3)}{16\mathcal{M}^2}$$

$$\frac{n_2}{n_1} = \frac{4\ \mathcal{M}^2}{\mathcal{M}^2 + 3}$$

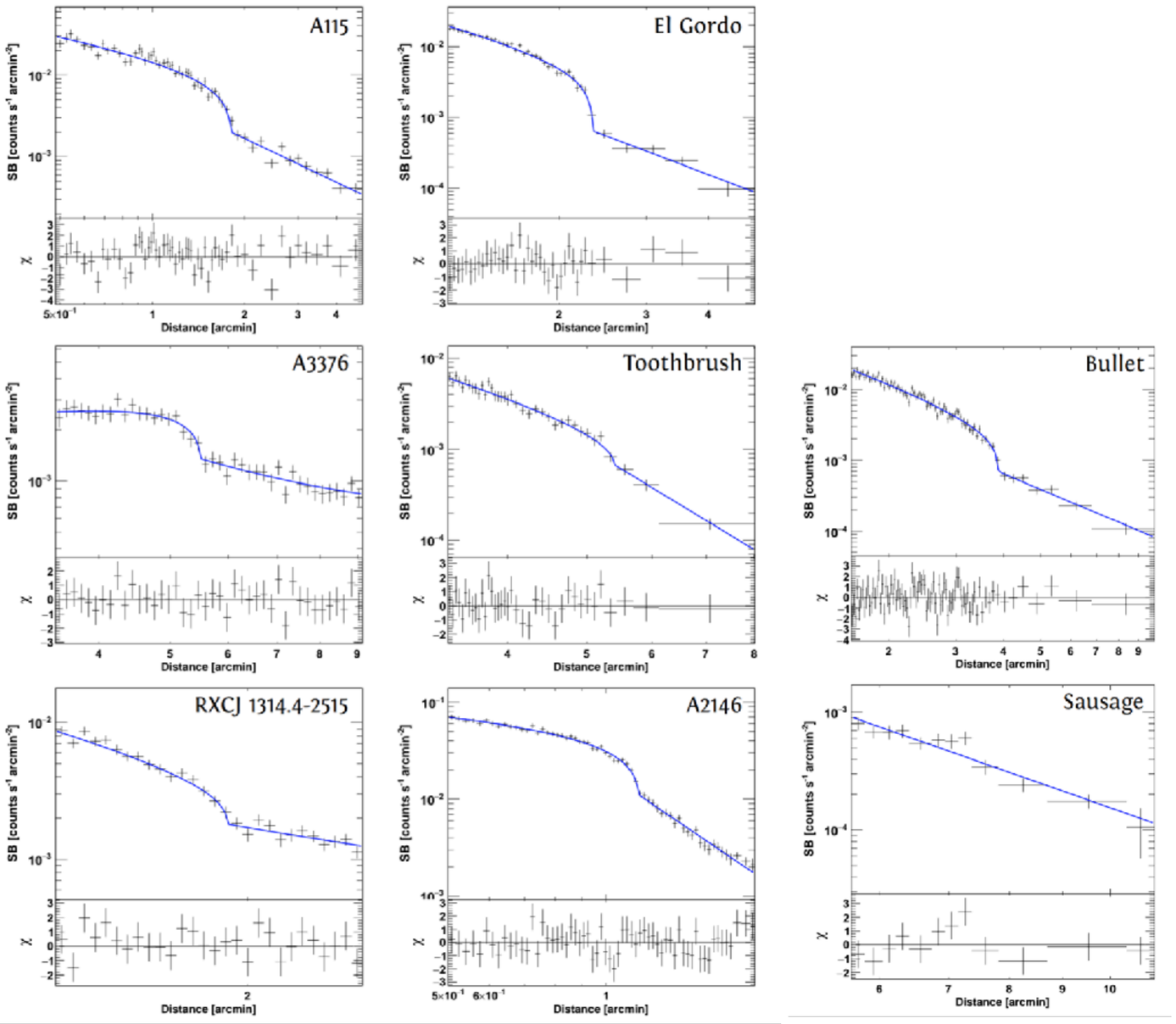
Xray brightness $S_x \propto n^2\sqrt{T}$

→shocks should leave an imprint also on the X-ray emission



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RELICS - SHOCK CONNECTION



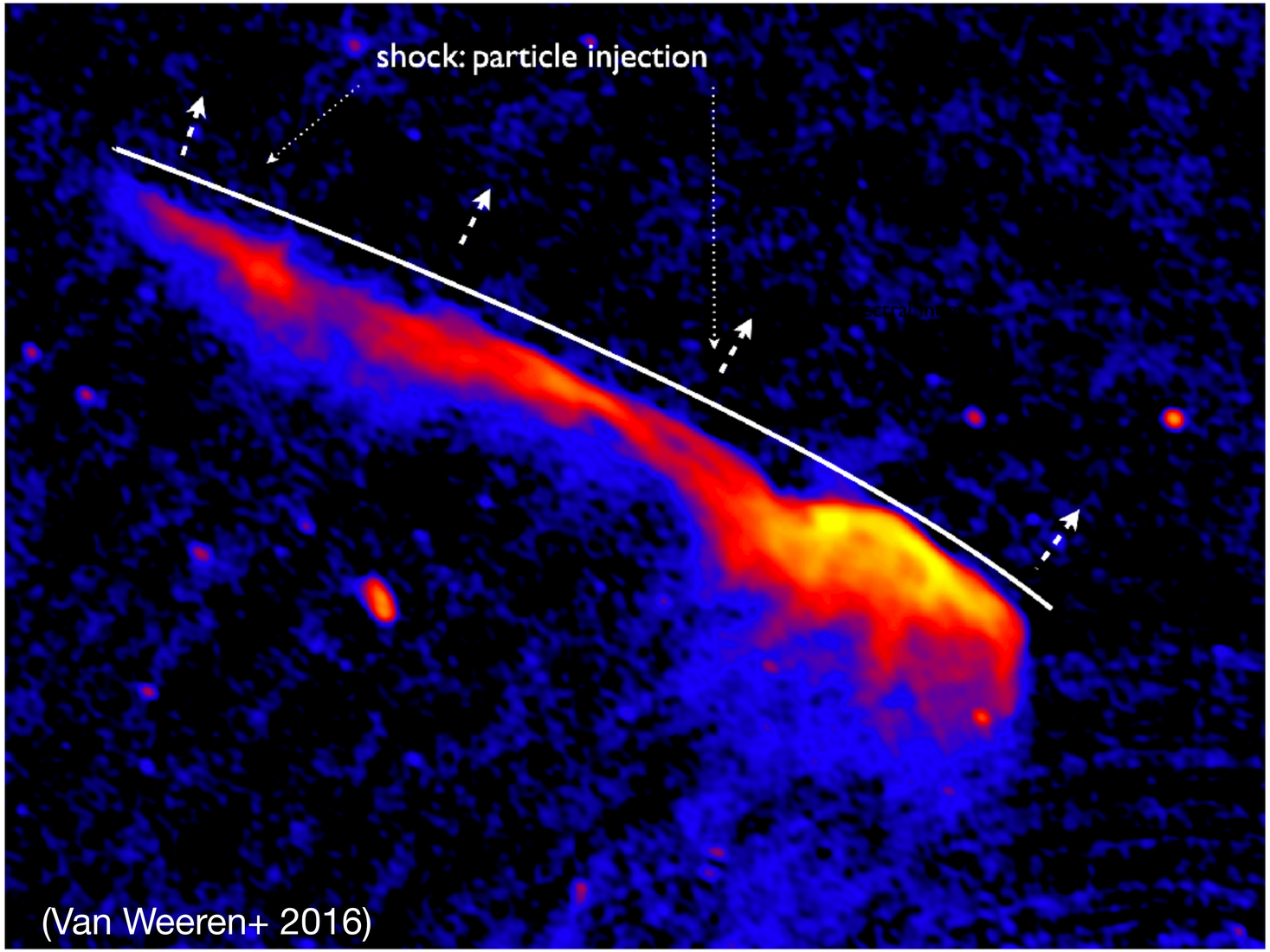
X-ray jumps in S_x (and often also in spectroscopic temperature) are detected in several clusters with radio relics.

The Mach numbers obtained from X-ray analysis typically are $1.2 \leq \mathscr{M} \leq 3$

(Botteon et al. 2019)

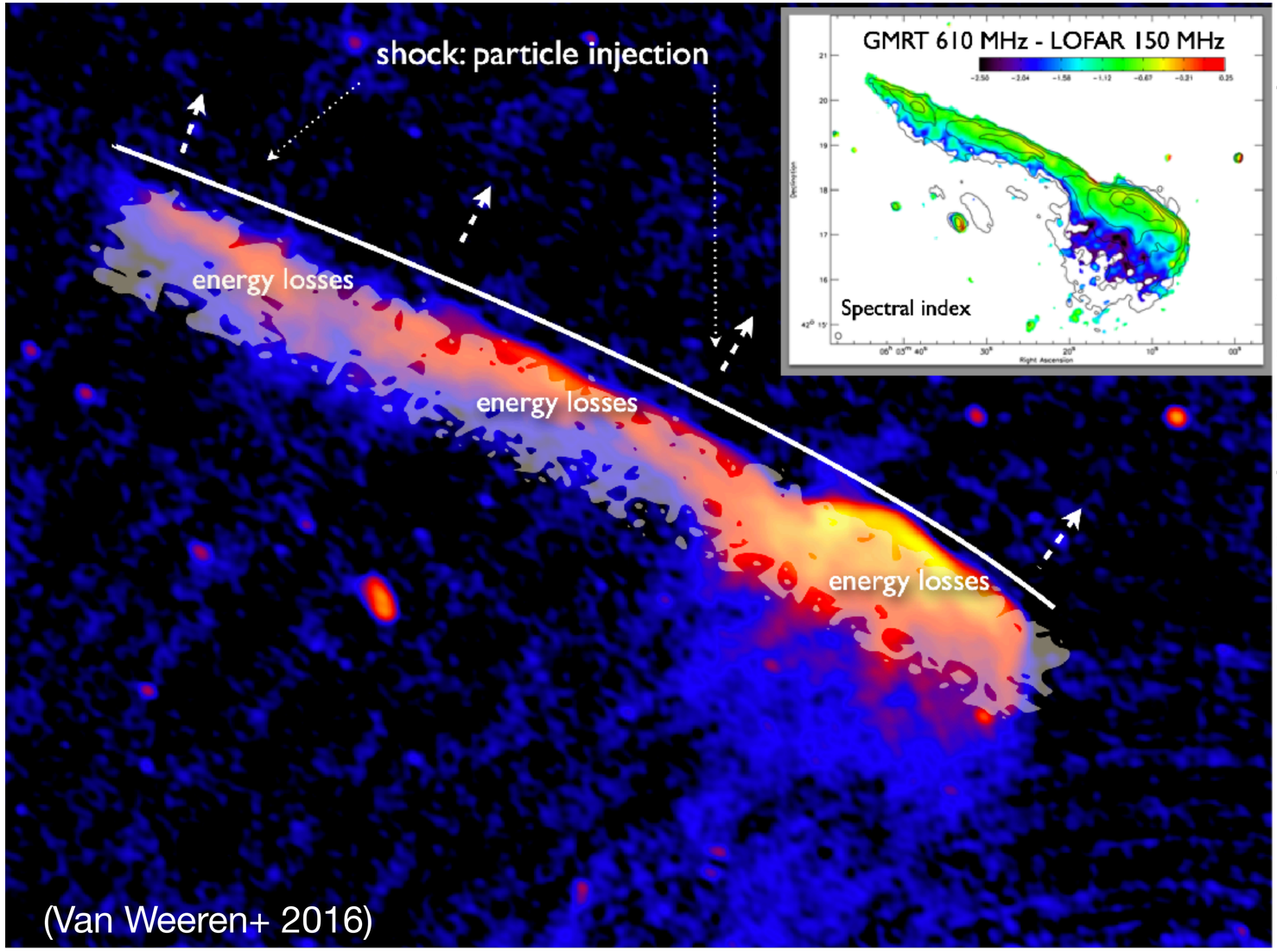
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1) particles are injected at the shock front

RELICS - SHOCK CONNECTION

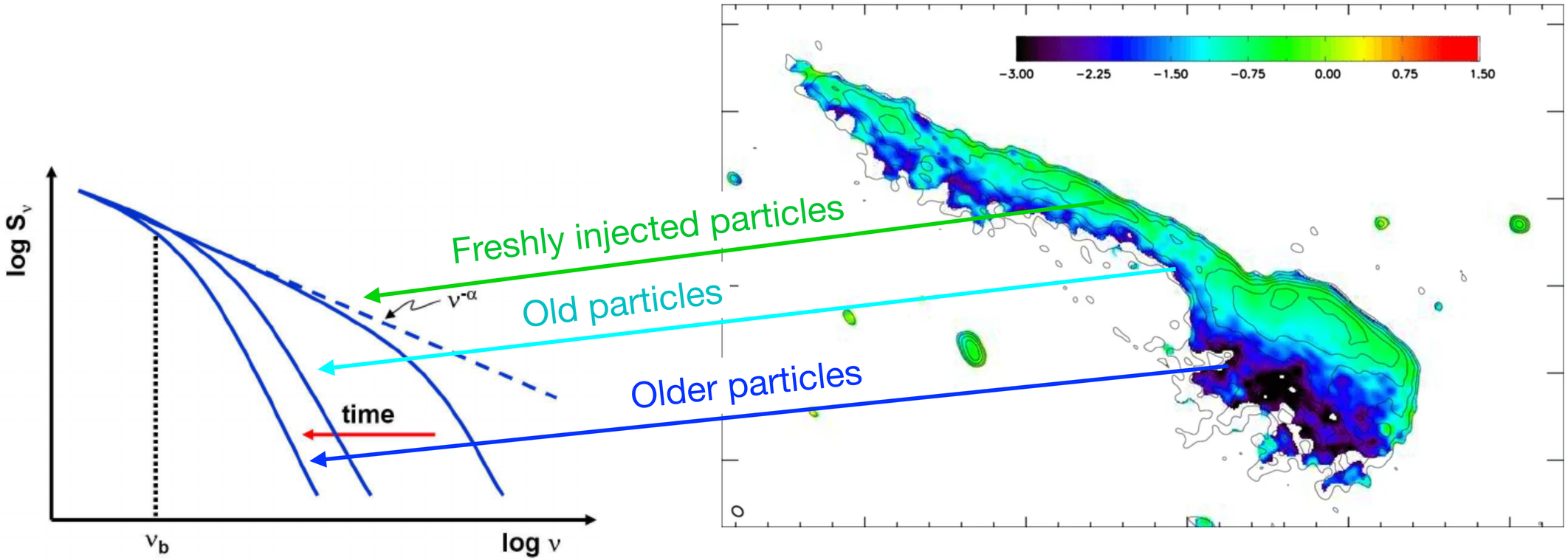


1) particles are injected at the shock front

2) as the shock front advances ($v_s \sim 10^3 \mathrm{km/s}$) the electrons downstream cool down ($\tau_{loss,GeV} \leq 10^8 \mathrm{yr}$)

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RELICS - SHOCK CONNECTION

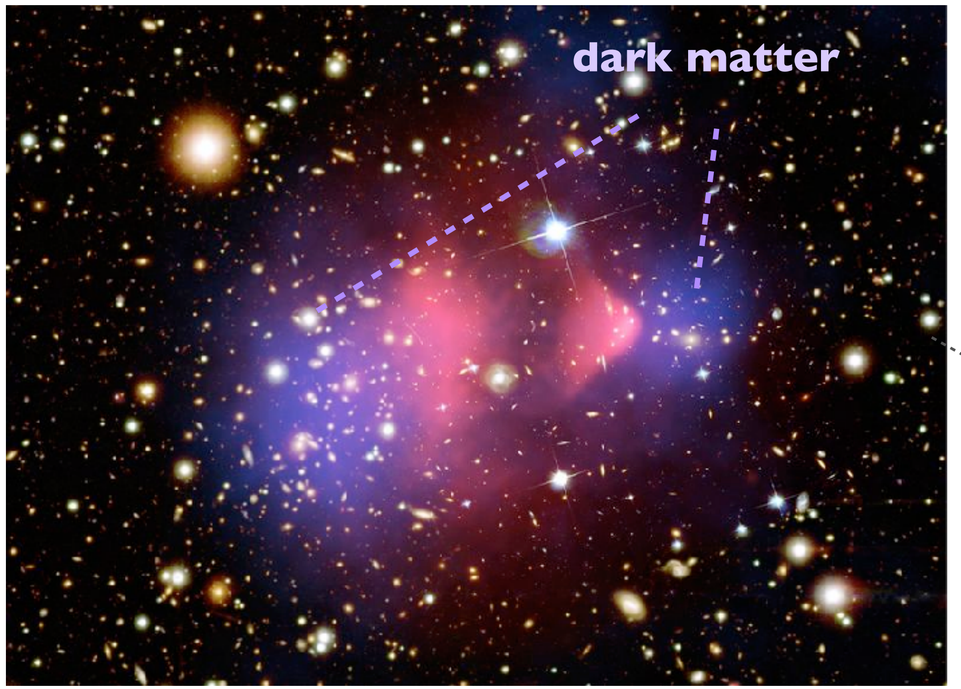


3) different parts of the relic show increasingly steeper spectra moving further away from the advancing shock edge

RADIO EMISSION IN CLUSTERS: THE "CLASSIC VIEW"

Cluster-cluster merger

E ~10^{64} ergs



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

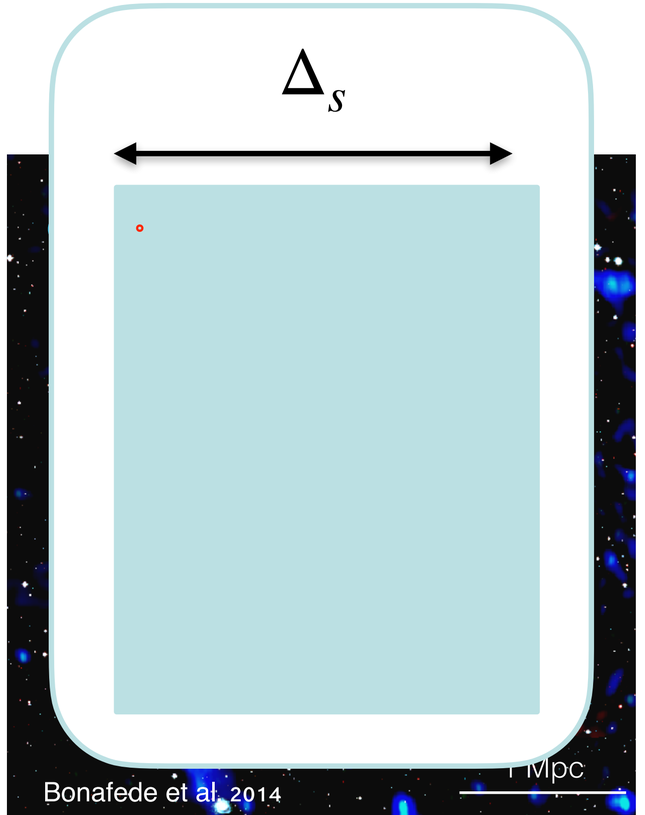
Relics

?

Challenges

(R. Cassano lecture tomorrow)

- Low Mach number, low efficiency
- Injection problem the electron Larmor radius is much smaller than the shock width



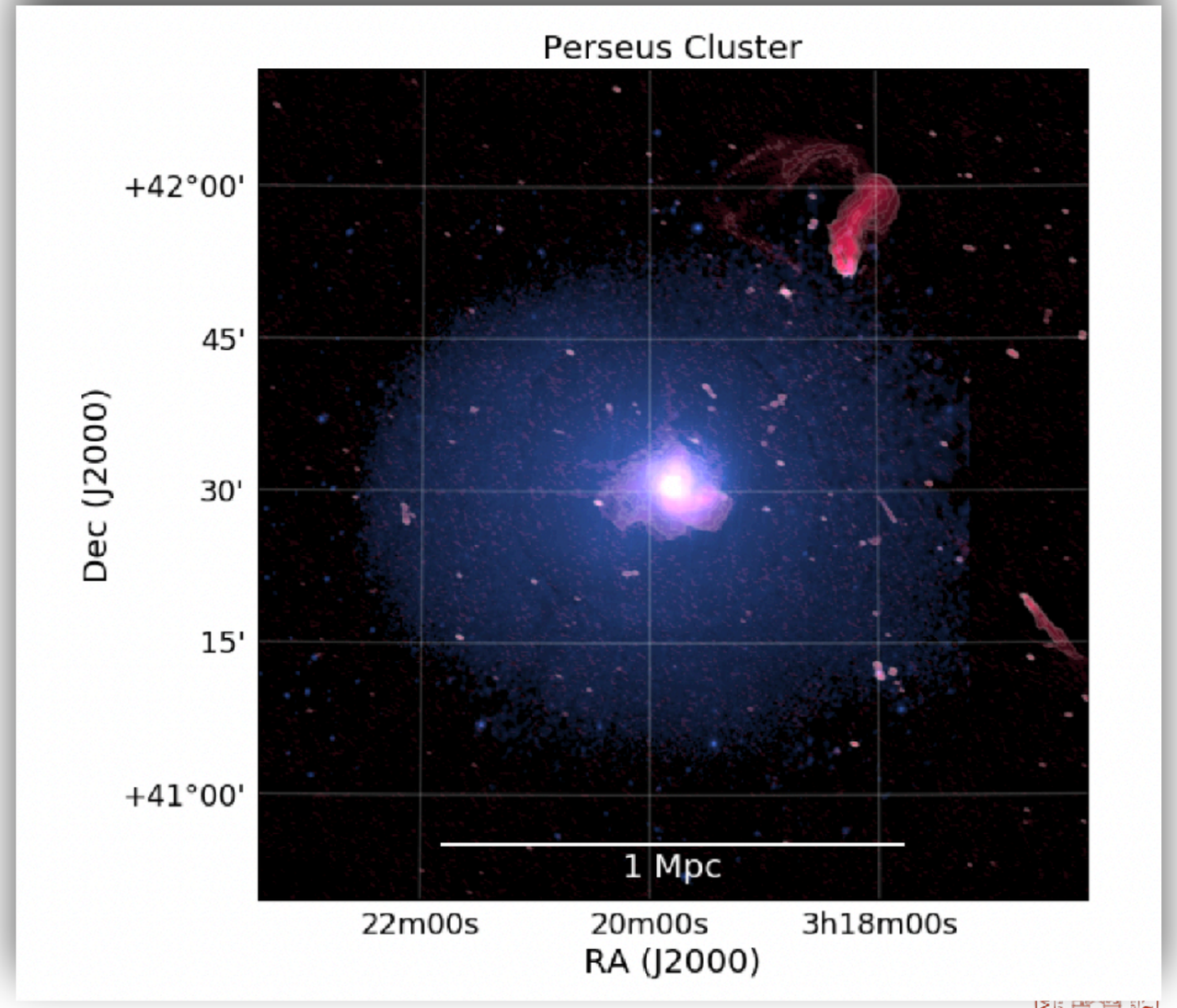
Credits:Markevitch, Clowe, Ogrean, Bonafede

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MINI HALOS

Properties:

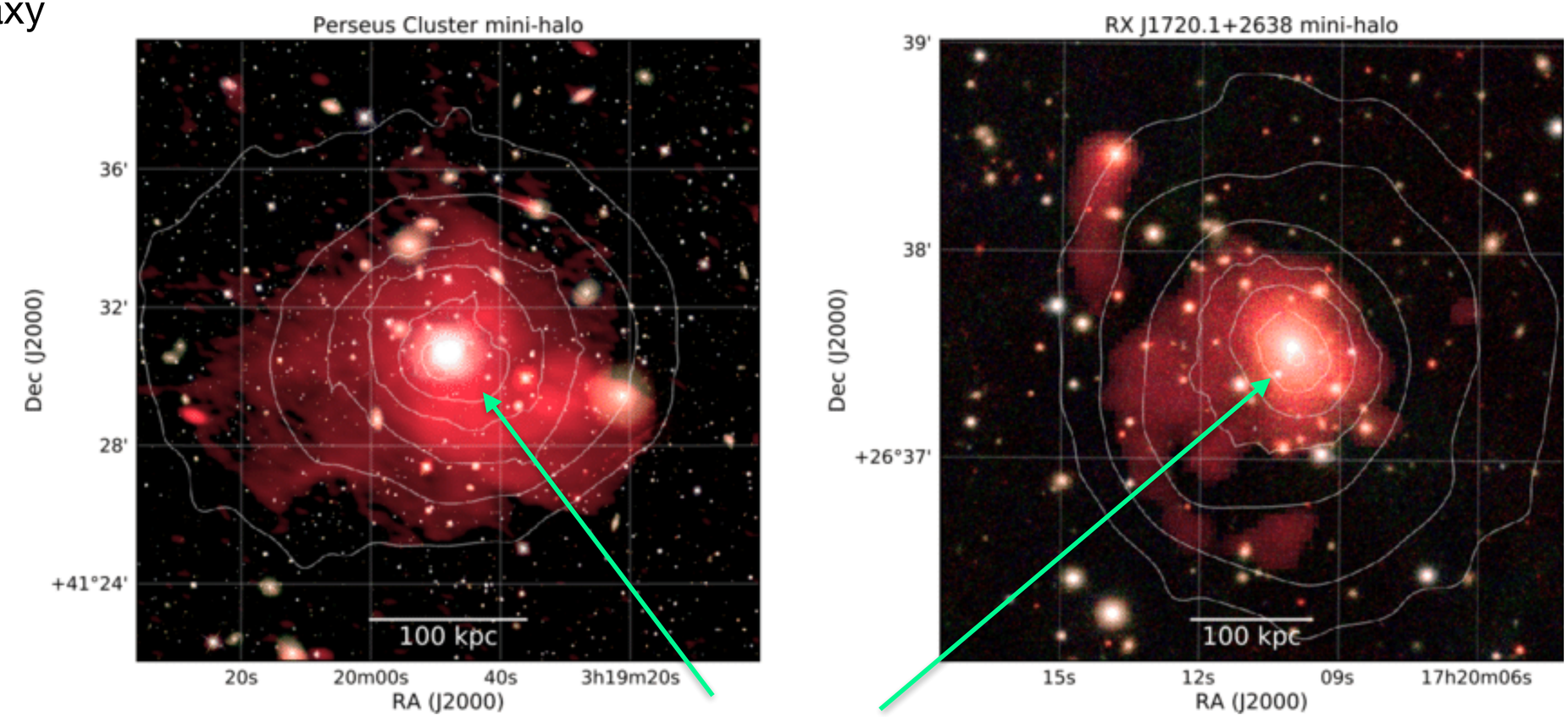
- Relaxed clusters, only found in cool core systems (we know about 30)
- located in the cluster center size ~100-300 kpc
-



Credits: can Weeren

MINI HALOS

Diffuse emission around the central radio galaxy



Central radio galaxy (BCG)

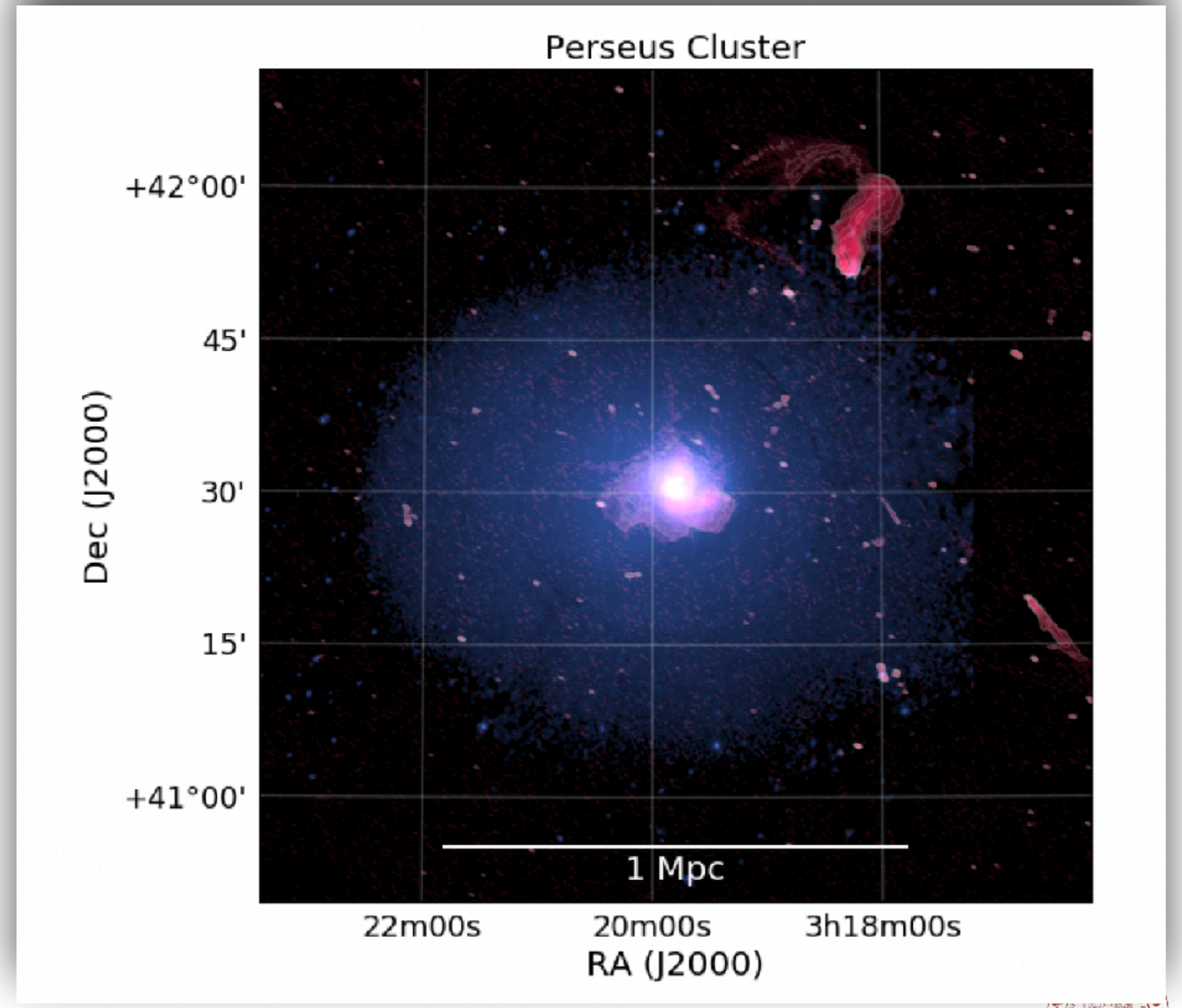
Credits:Giacintucci, van Weeren

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MINI HALOS

Properties:

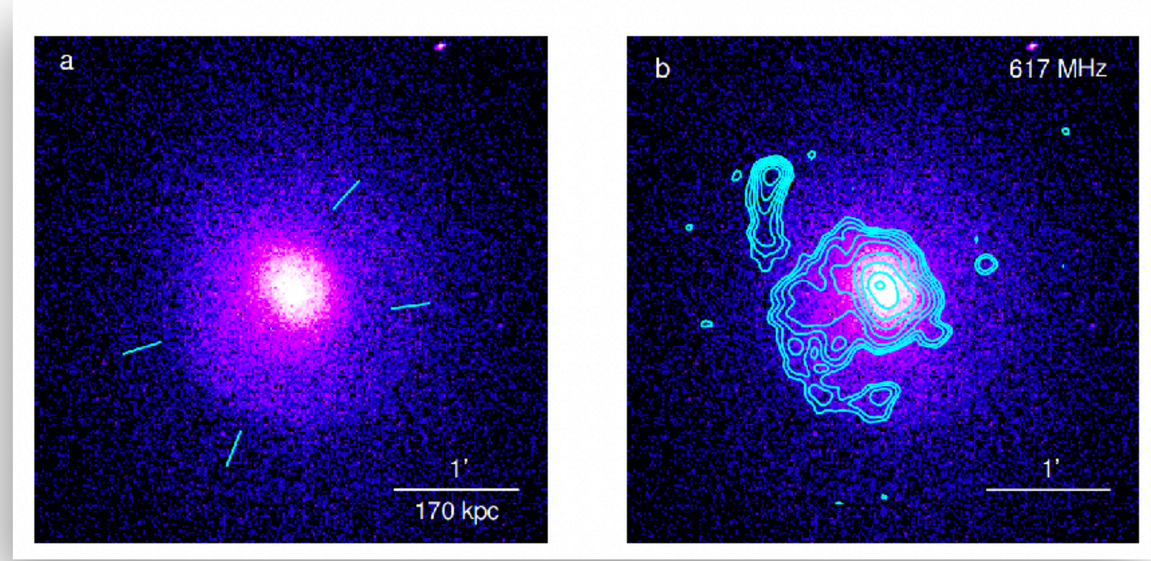
- Relaxed clusters, only found in cool core systems
- located in the cluster center size ~100-300 kpc
- emission surrounding the central radiogalaxy

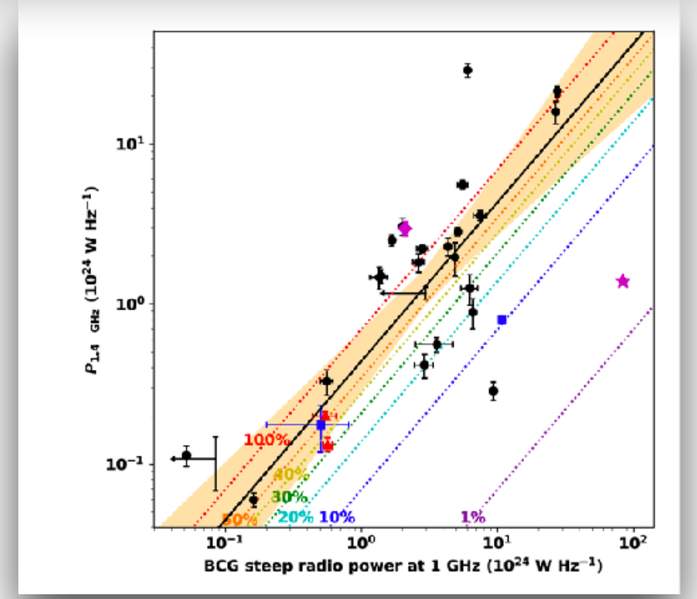


Credits: can Weeren

MINI HALOS: CONNECTION TO X-RAY and AGN

- Correlation with X-ray surface brightness (like halos)
- In some cases, surrounded by “cold fronts” discontinuities in the gas, which is denser and colder
- The radio power knows about the past AGN activity →connection between AGN feedback and mini halo emission





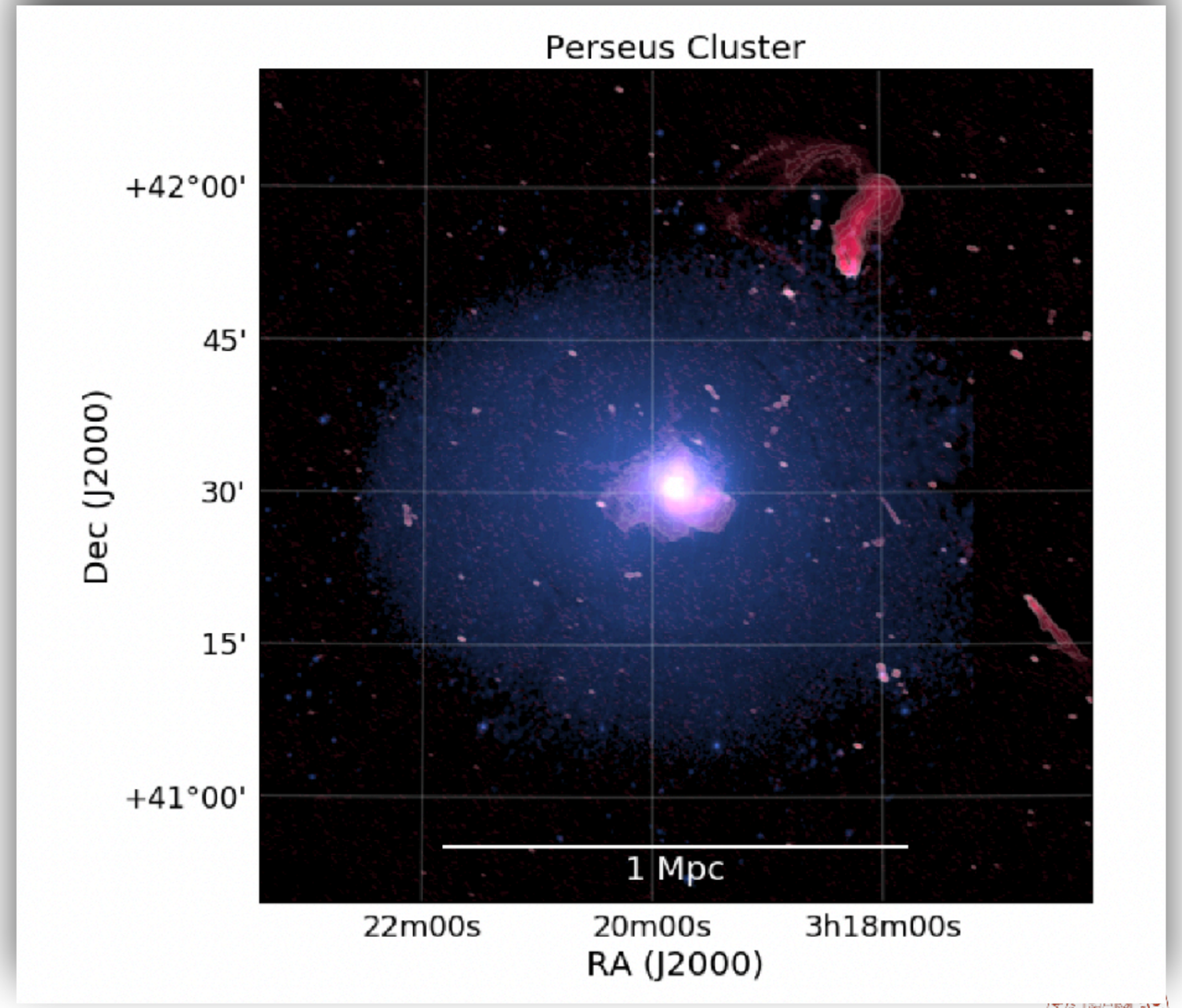
Credits:Giancintucci et al 14, Richard-Laferriere et al. 20

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MINI HALOS

Properties:

- Relaxed clusters, only found in cool core systems
- located in the cluster center size ~100-300 kpc
- emission surrounding the central radiogalaxy
- Connection with the central AGN and with the X-ray properties of the cluster core



Credits: can Weeren

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MINI HALOS: ORIGIN?

Turbulence?

- injected by AGN activity
- Turbulence due to minor/off-axis mergers

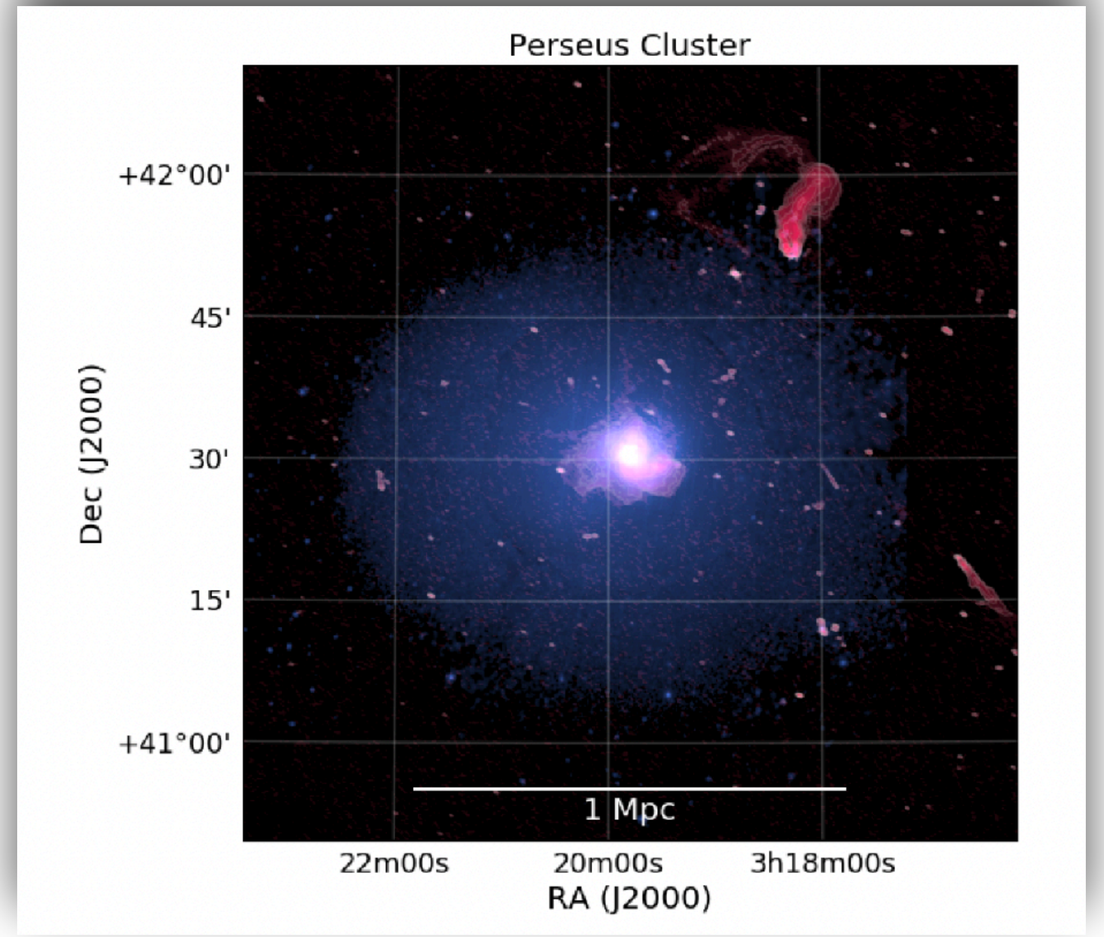
Gitti et al 2002
Zu Hone et al 2013

Relativistic electrons due to hadronic process?

- thermal protons in the Intra Cluster Medium + Cosmic Ray protons

$$p_{th} + p_{CR} \rightarrow \ldots. \rightarrow e^{+} + e^{-} + \gamma$$

Pfrommer and Ensslin 2004

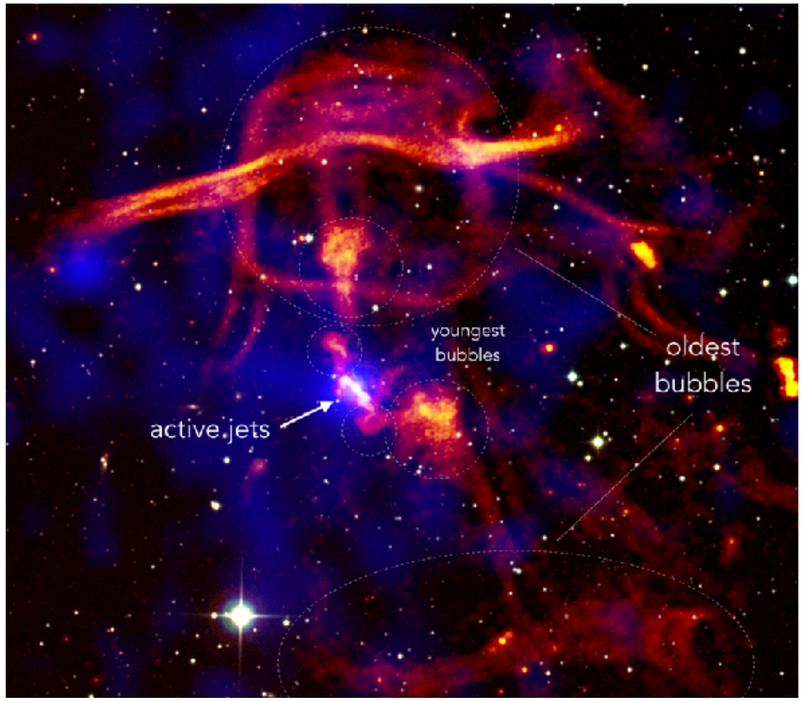


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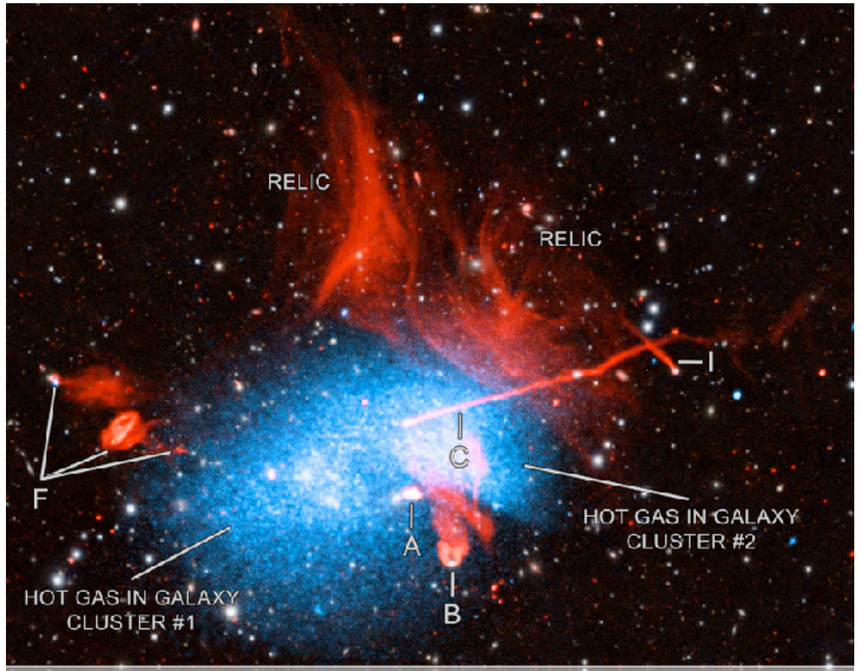
RECENT DISCOVERIES
MORE DATA = MORE CHALLENGES

FILAMENTS AND SUBSTRUCTURES

- The new generation of low-frequency (<200 MHz) radio surveys keeps discovering surprisingly complex patterns of CRe circulating from radio galaxies in the ICM



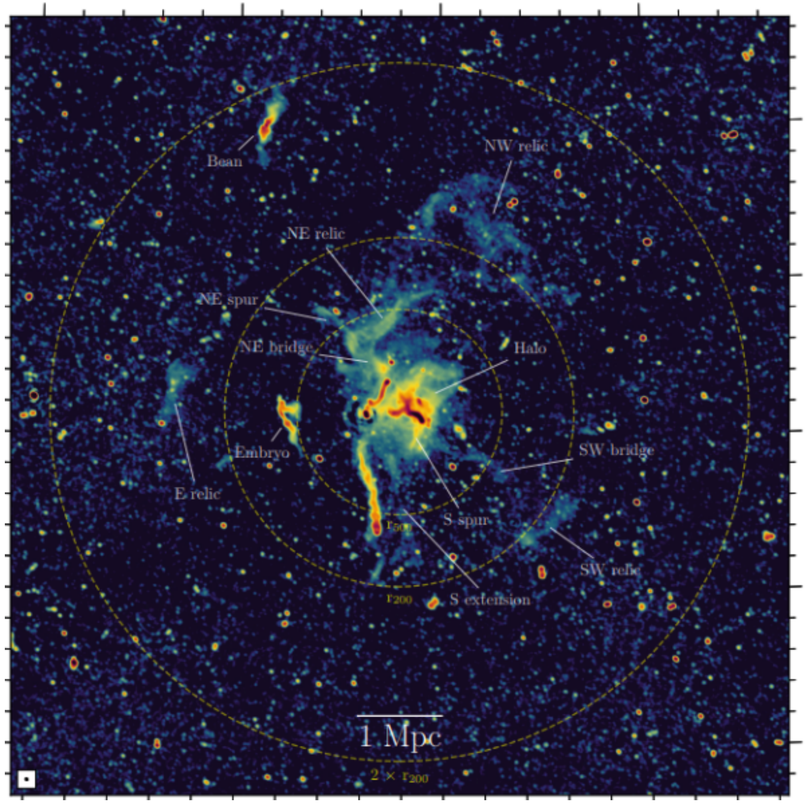
(Brienza et al. 21).



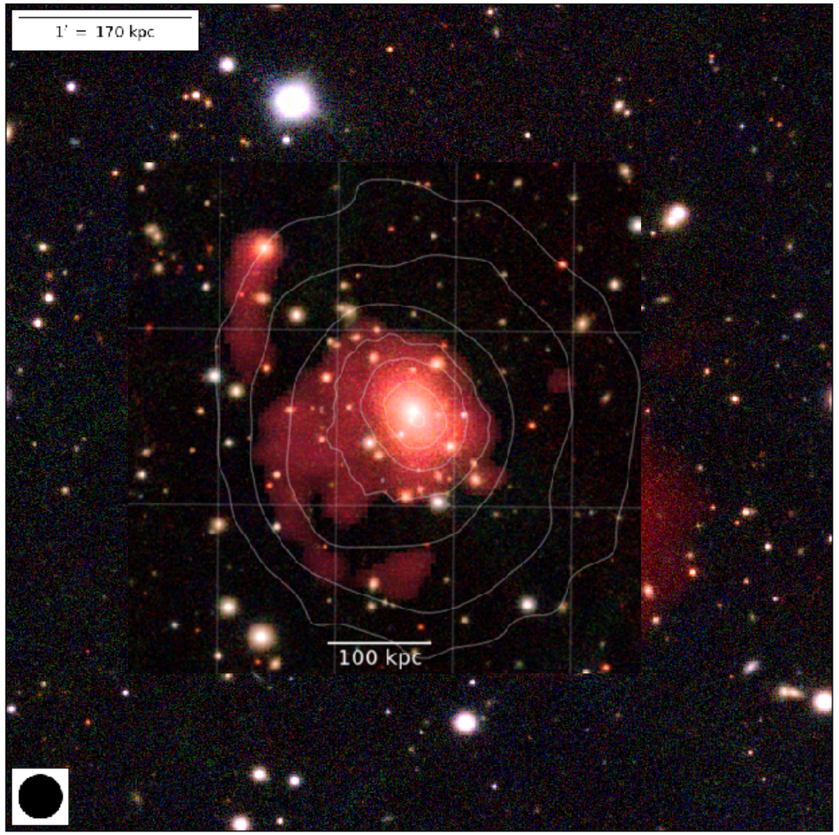
Rajpurohit et al (22)

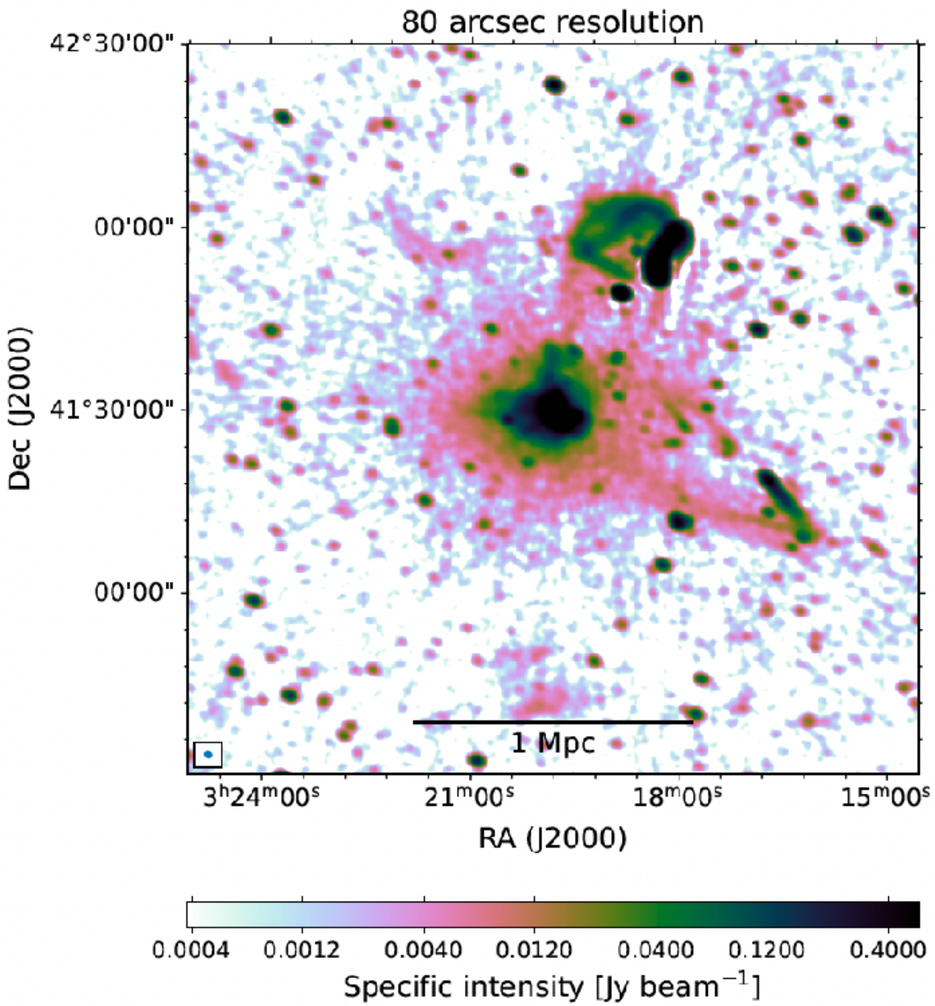
- Zooming in: radio diffuse emission is not smooth!

Botteon et al (26)



MINI (?) HALOS





Mpc-scale emission visible al low (~150 MHz) around mini halos

→ energetic problem even more severe

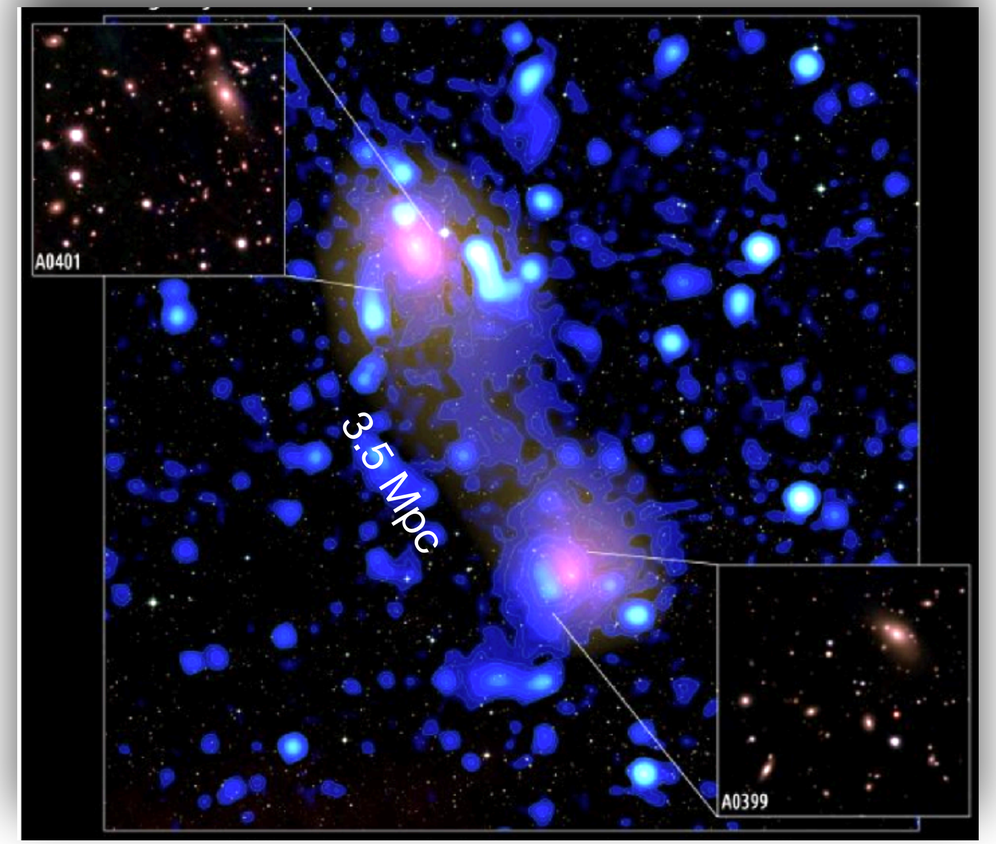
Credits: Biava et al 24, van Weeren et al 26

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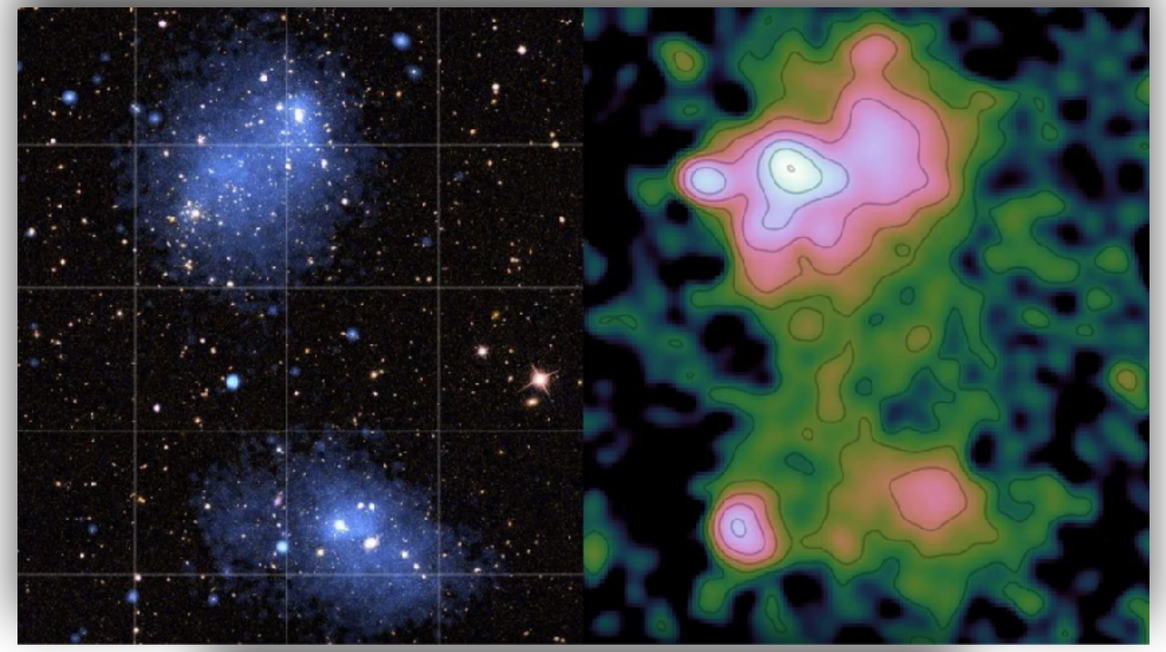
INTRACLUSTER BRIDGES

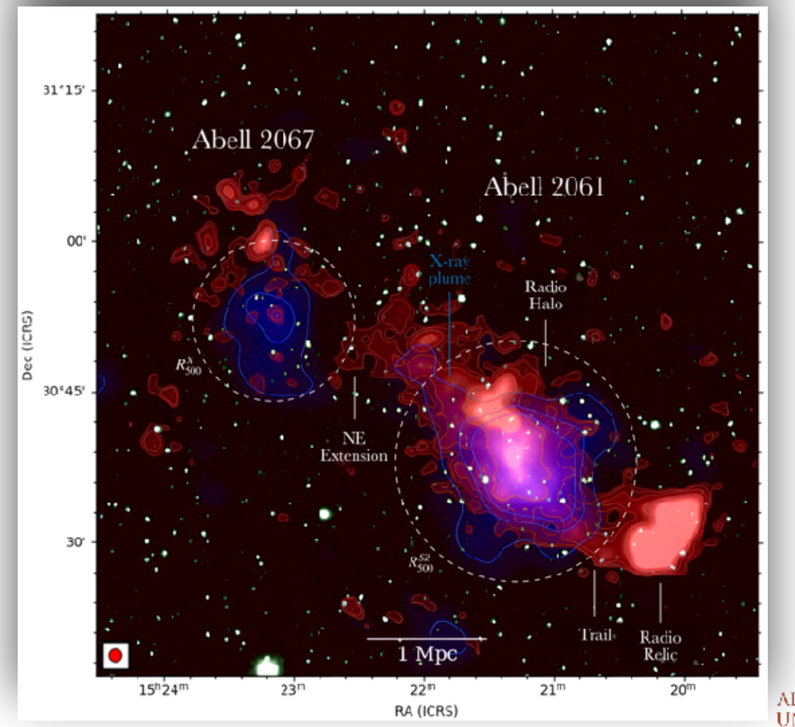
- LOFAR has discovered a few ~3 Mpc long “bridges” in between pre-merging clusters of galaxies.

2 - 3 cases found so far



credits: Govoni, Botteon, Pigantaro

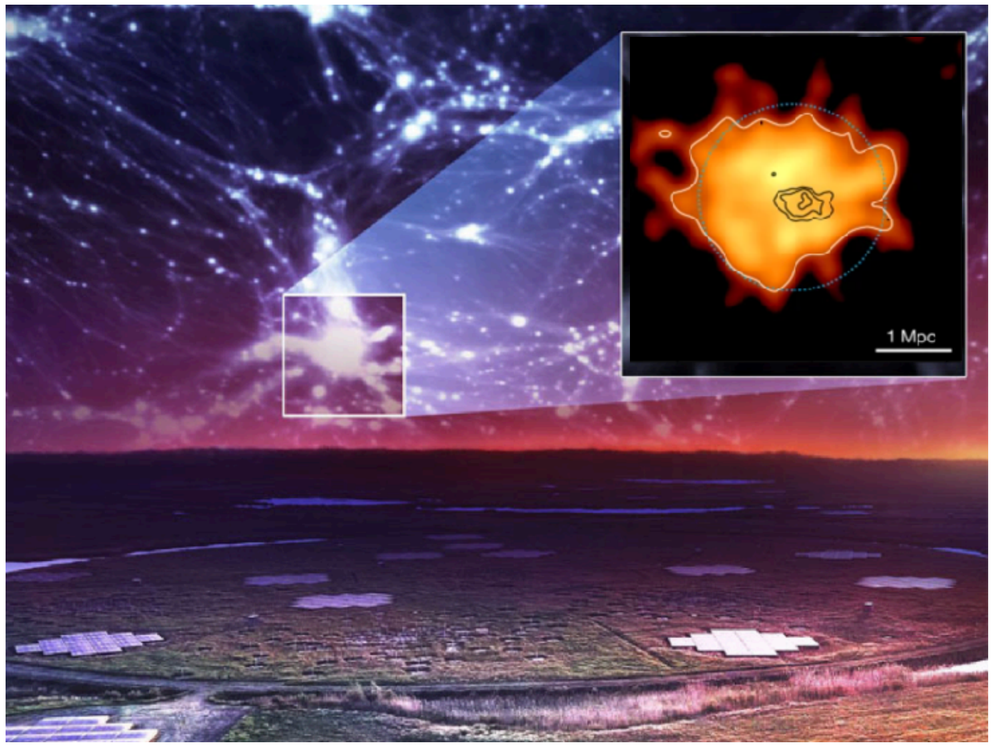


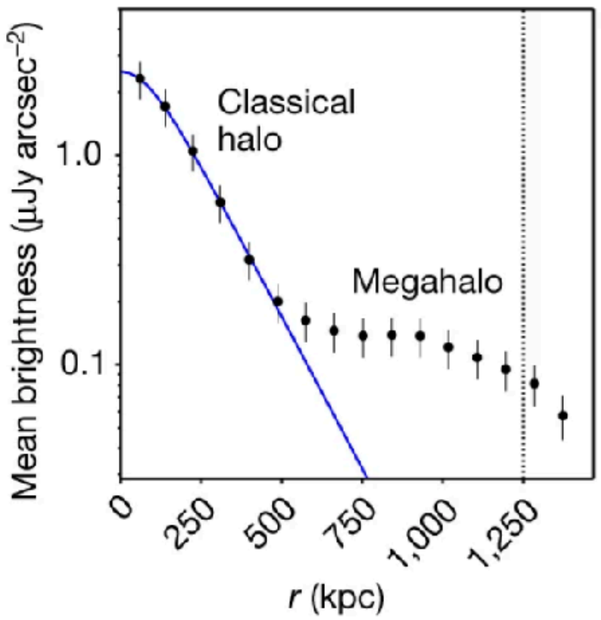


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RADIO MEGA HALOS

- New LOFAR detection of very low surfacer brightness emission in 4 galaxy clusters (so far) originating from a $\times 30$ larger volume than the one of classical radio halos





→ energetic problem even more severe

Cuciti et al. 2021 Nature

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SUMMARY

- Radio synchrotron emission on Mpc scale found in more and more clusters
- Radio halos and relics in merging clusters, mini halos in relaxed clusters - classic view
- Emission is connected to relativistic electrons: energetic problem!
- Recent observations are showing even larger scale emission, also in relaxed clusters and in-between clusters with a more complex morphology, which pose further challenges to our understanding of the phenomena

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