14. Clusters of Galaxies

a. Feretti, Giovannini, Govoni & Murgia, 2012, A&ARev. 20, 54

"Clusters of galaxies: observational properties of the diffuse radio emission"

a'. van Weeren & al. 2019, Space Sci Rev (2019) 215:16

" Diffuse Radio Emission from Galaxy Clusters"

b. Bykov & al., 2015 SSRv, 188,141 .... or.... https://arxiv.org/pdf/1512.01456.pdf

"Structures and components in galaxy clusters: observations and models"

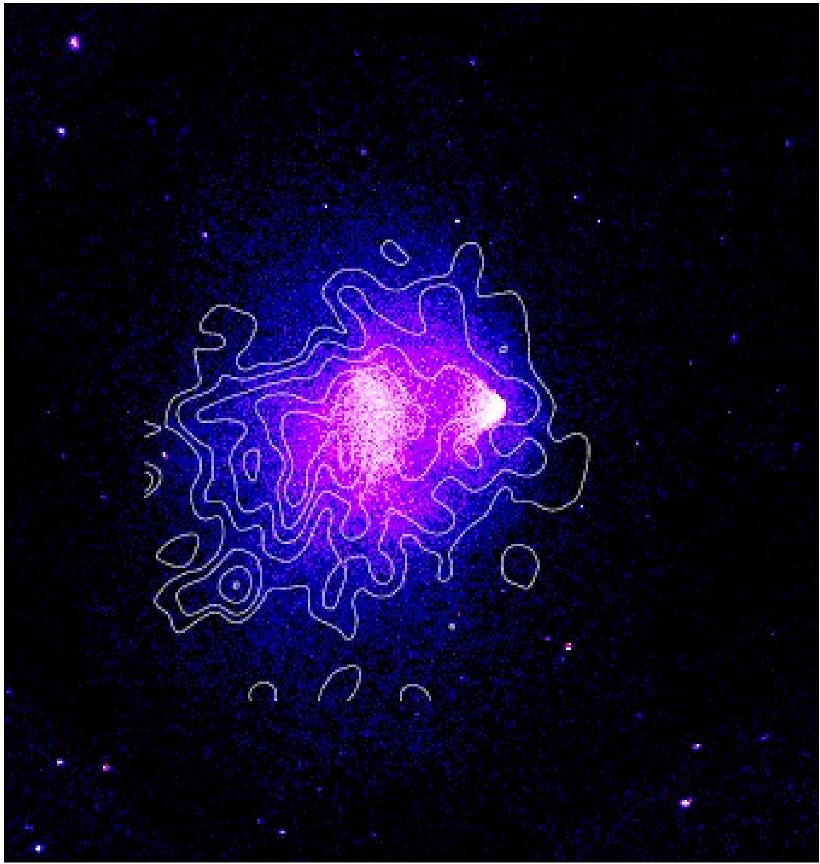
c. Brunetti & Jones, 2014, Int. J. of Mod. Phys D. 23, 30007-30083

"Cosmic Rays in Galaxy Clusters and their Non-Thermal Emission"

a. observational point of view

c. theory & astrophysics

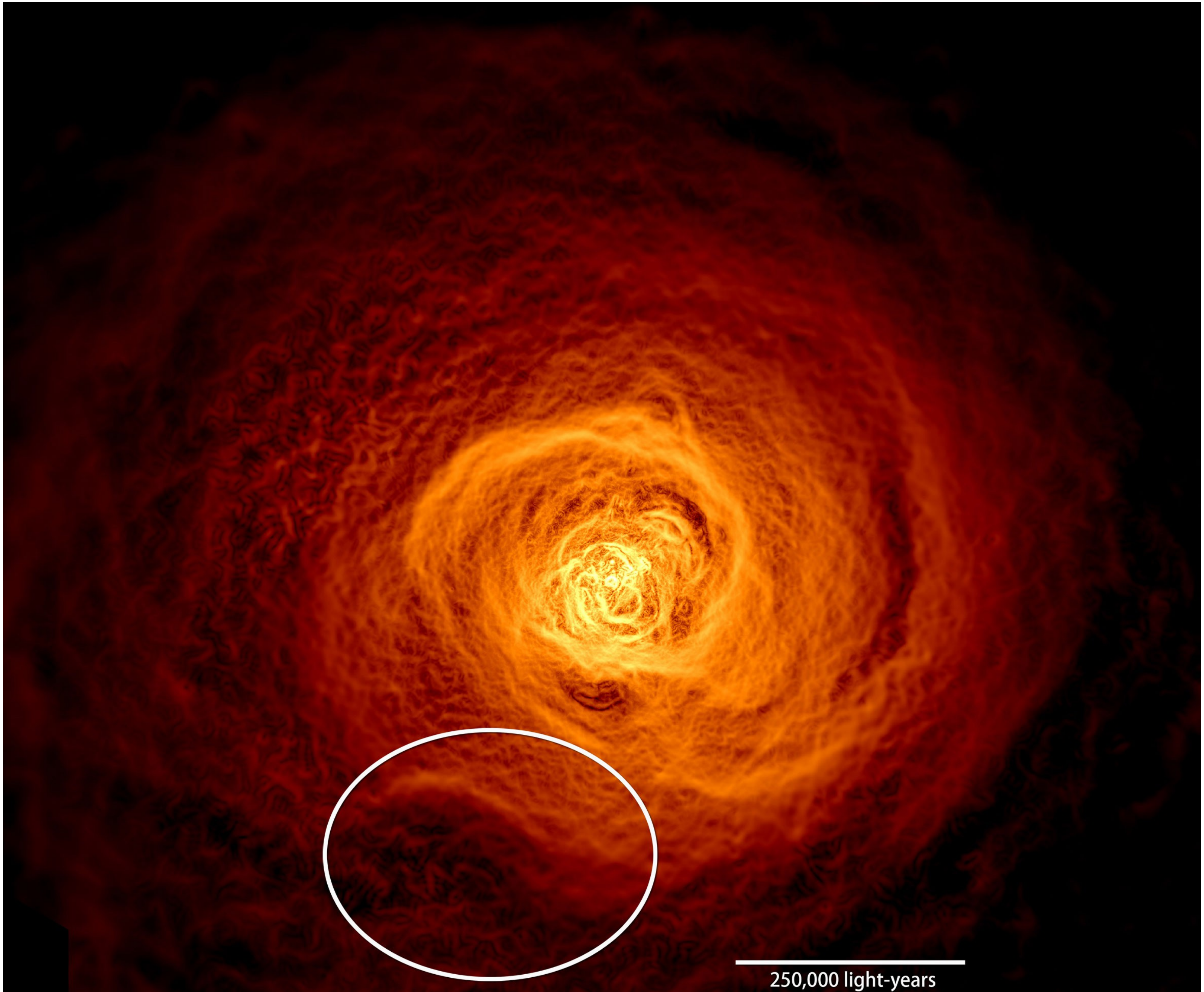
b. link between a and c.



Optical view of Clusters of Galaxies (Hubble) ⇨ STARS (3-5% of the total mass)

Abell 2218, @ z = 0.17

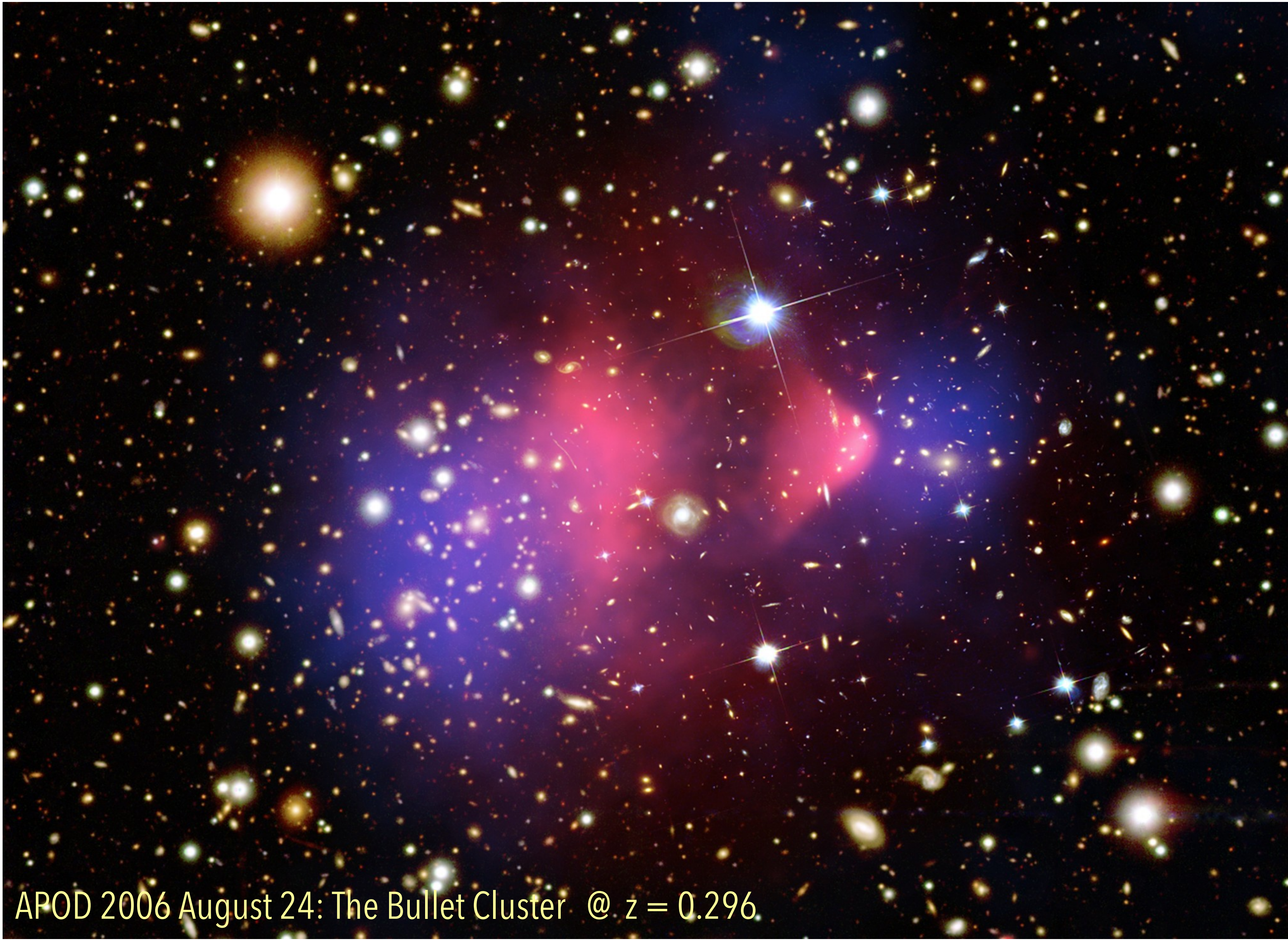
X-ray view of Clusters of Galaxies (Chandra) ➪ GAS (12-15% of the total mass)



Chandra X-ray view of the Perseus cluster

https://scitechdaily.com/astronomers-discover-a-giant-wave-of-hot-gas-rolling-through-the-perseus-galaxy-cluster/

~Full view of Clusters of Galaxies ⇨ Dark matter, gas and stars



Some facts:

Sizes: roundish, about a few Mpc in radius

Masses: $10^{14} - 10^{15}\ M_{\odot}$

Galaxies: 100s to 1000s (definition of either "individual" or "satellite" galaxy for the smallest ones)

Mostly ellipticals, then spirals, generally "ISM deficient"

Gas: hot (several KeV) and tenuous ($n_e \sim 10^{-1} - 10^{-4}\ cm^{-3}$)

Dark Matter: 70/80% of total mass, gravitational effects (weak/strong gravitational lensing, σ_v)

Tracers: Gas ⇨ X-rays (Bremsstrahlung) + SZ with CMB in mm, Galaxies ⇨ optical (BB),

Dark Matter ⇨ image distortion on background objects

ASSEMBLY via merger-trees: very massive clusters at z=0 were much lighter at z=1 or beyond

⇨ the effects of mergers may be used to test a lot of physics

All clusters are X-ray emitting extended sources (IGM gas cooling time longer than the Hubble time)

Classified as: RELAXED: hydrostatic equilibrium with spherical distribution, very efficient cooling where the gas is denser (Cool Core Clusters), producing enhanced X-ray emission at the center

UNRELAXED: a recent perturbation (minor/major merger) broke the equilibrium heating the gas. About 1 Gyr required to settle down again. X-ray emission is affected

ASSEMBLY via merger-trees: very massive clusters at z=0 were much lighter at z=1 or beyond

⇨ the effects of **mergers** may be used to test a lot of physics

Disrupt relaxed structures

Very energetic processes, can dump a lot of kinetic energy 10^{63} erg to be transferred (in a crossing time of ~ 1 Gyr) to various elements, including relativistic particles and magnetic field amplification

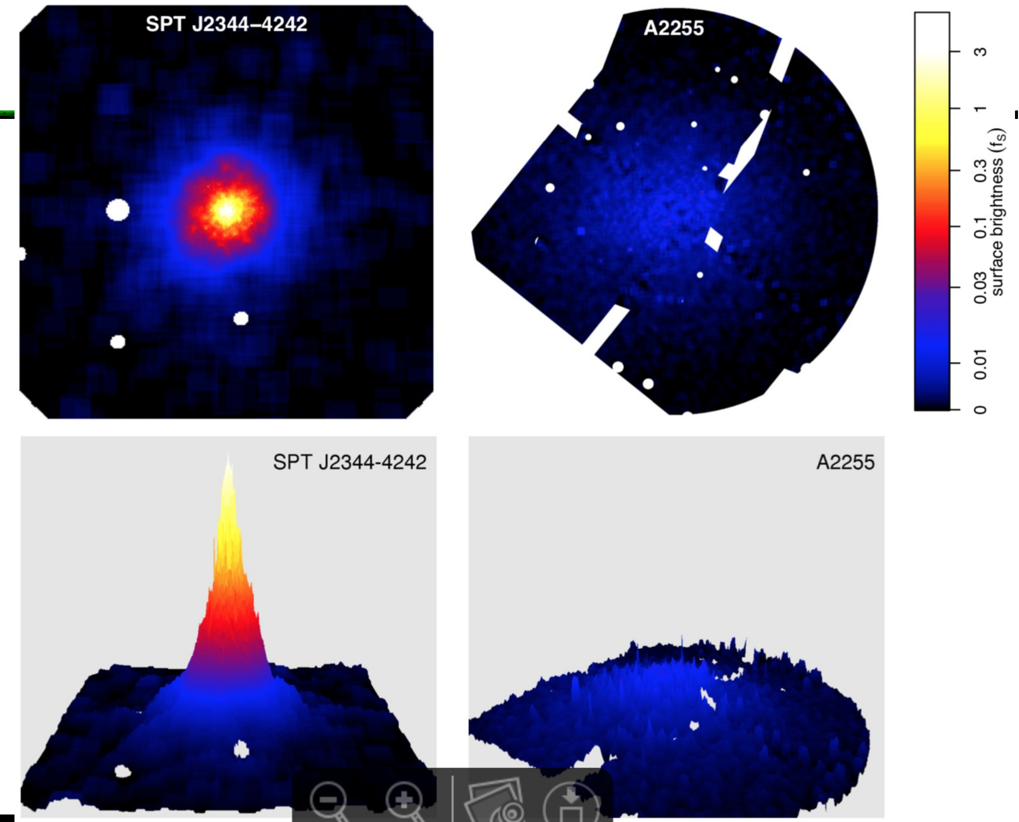
Clusters of Galaxies

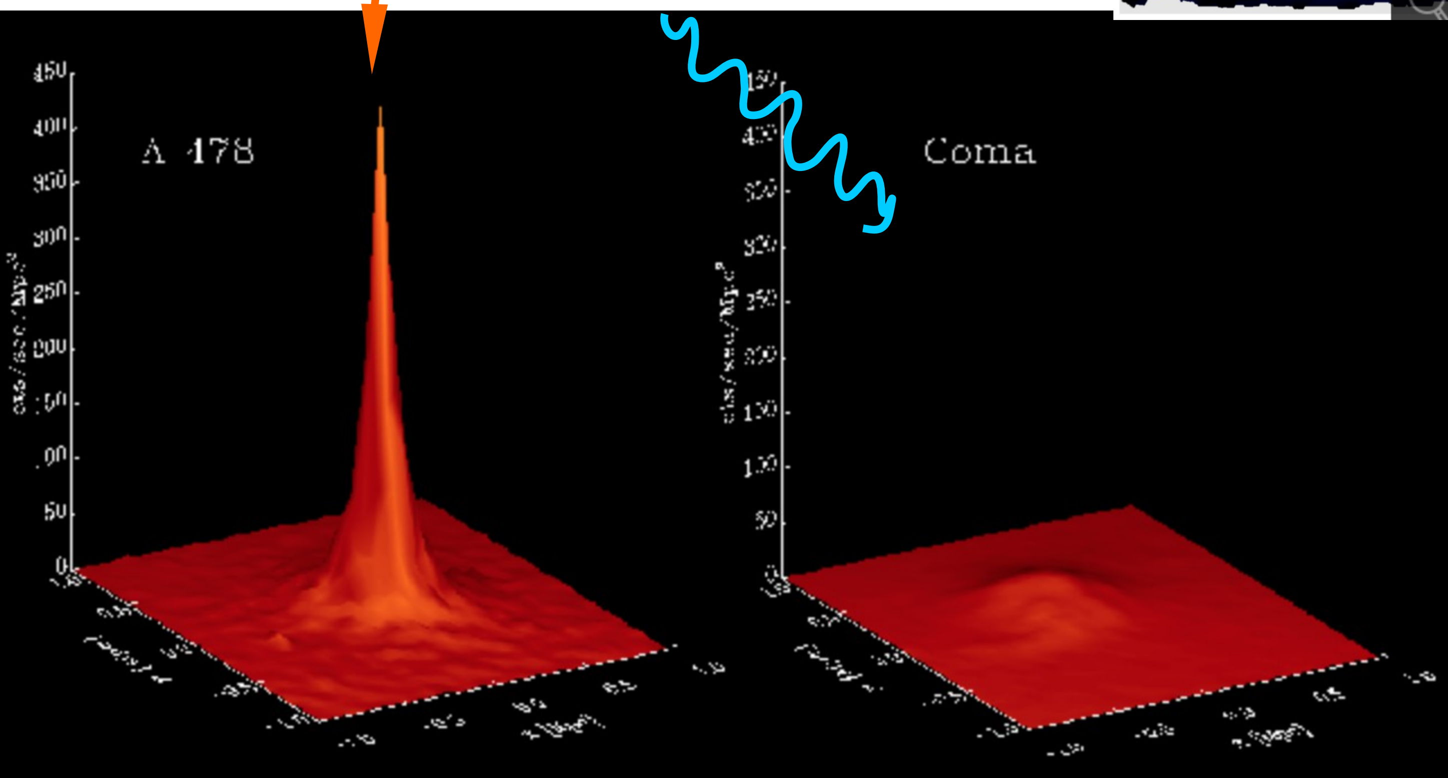
RELAXED:

hydrostatic equilibrium with spherical distribution, very efficient cooling where the gas is denser (CCCs) producing enhanced X-ray emission at the center

UNRELAXED:

a recent perturbation (minor/major merger) broke the equilibrium heating the gas. About 1 Gyr required to settle down again. X-ray emission is affected





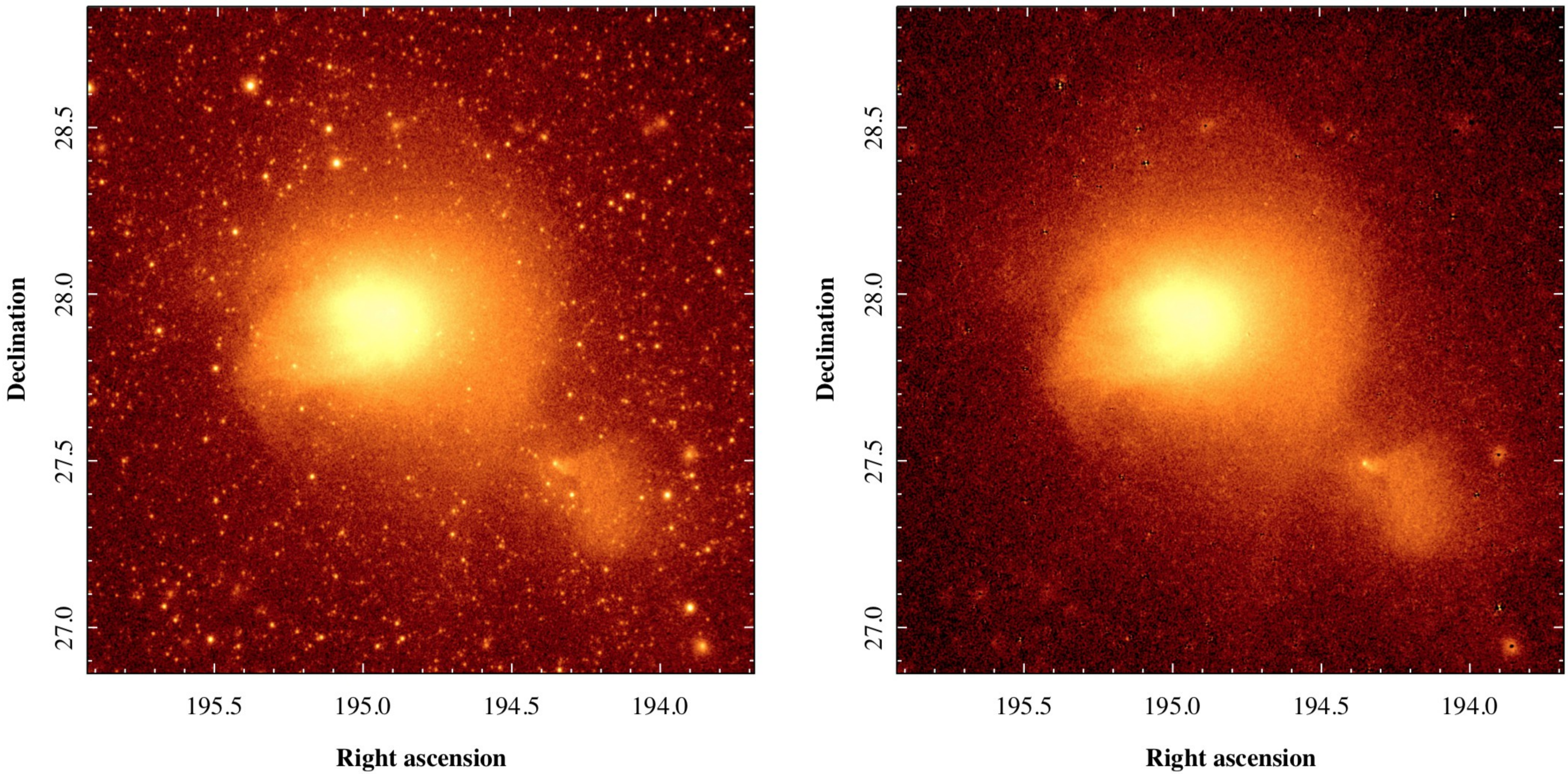


Fig. 4. X-ray image of the central ~ 2 × 2 degrees of the field showing 0.4-2 keV surface brightness on a a logarithmic scale. The left panel shows the original image without subtraction of the multitude of foreground, background and Coma-related sources. The right panel shows the map of the diffuse emission obtained after modeling and subtraction of the confidently detected point-like and mildly-extended sources using the β-profile approximation of the PSF described in Appendix B.

Clusters of Galaxies:

The sharp view of the Coma cluster by e-Rosita.
Deviations from a "relaxed structure"

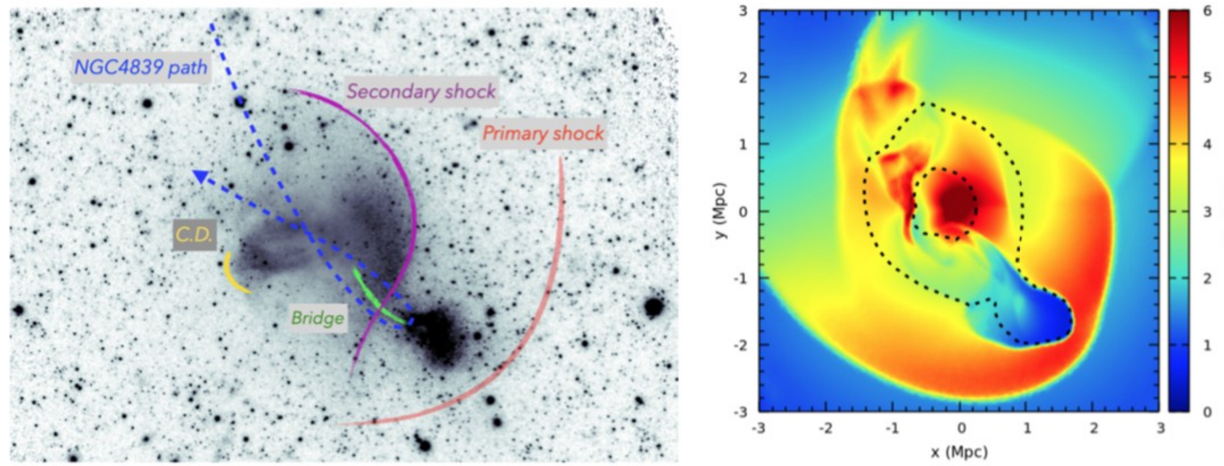


Fig. 11. Left: Flattened image of the Coma cluster field with labels schematically marking some of the features associated with the merger with the NGC4839 group. The blue dashed line is the suggested trajectory of the group (Lyskova et al. 2019; Sheardown et al. 2019; Zhang et al. 2019), which enters the Coma cluster from NE, and is currently close to the apocenter. The presumed position of the primary shock is shown with the red curve so that it goes through the radio relic SW from the NGC4839 group. The purple curve marks the secondary shock caused by settling the displaced ICM back to the hydrostatic equilibrium. This is the most salient feature directly seen in the image as the surface brightness edge. The green line shows the fain X-ray "bridge" connecting NGC4839 and the main cluster, which is a possible trace of the group through the Coma cluster. **Right:** Projected temperature map from simulations (Zhang, Churazov, & Zhuravleva 2021, see their fig.8 for the original version of the figure). The simulations qualitatively reproduce the morphology of the cold gas and the positions of the primary and secondary shocks. In the simulations, the inner region is a complex mixture of shocks and contact discontinuities. It is, therefore, not surprising that real observations have both types of structures.

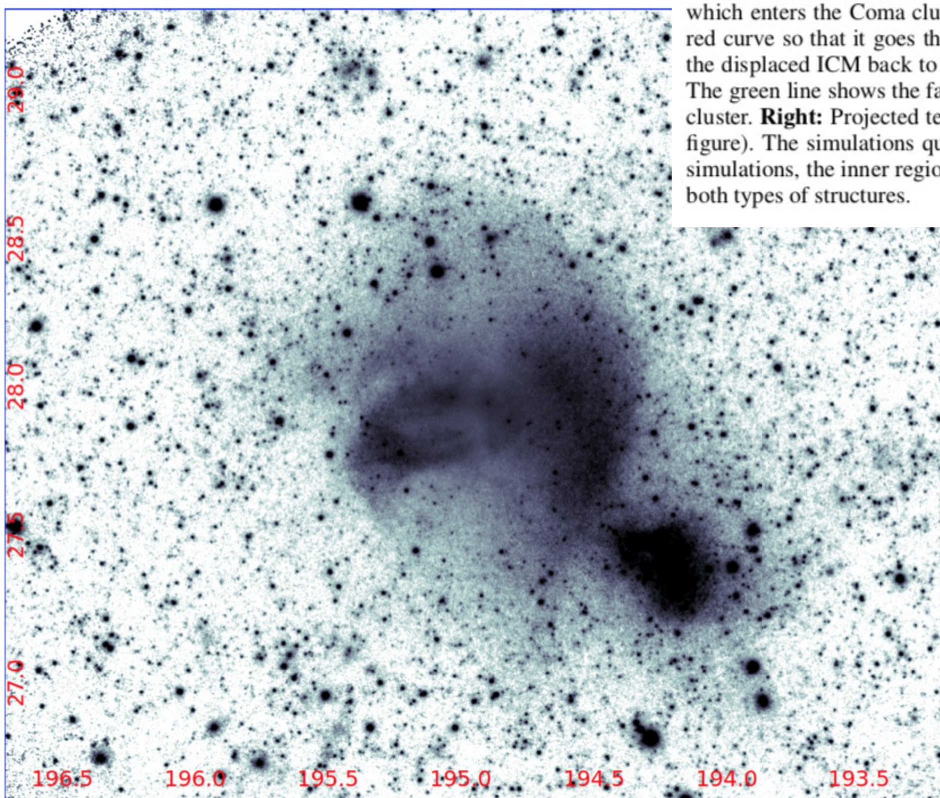


Fig. 6. Flat-fielded 3.5 × 2.4 degrees X-ray image of the Coma cluster. Flat-fielding procedure (see Eq. 1) emphasizes departures from a smooth purely radial profile. The most spectacular is the bow-like sharp feature to the West from the core, which extends over ~ 3 Mpc from the North to the South. To the East from the core, there is another very sharp feature (~500 kpc in size), which turns out to be a contact discontinuity (see below). The NGC4839 (a dark spot to the SW from the core) appears to be connected with the main cluster via a rather faint "bridge". In addition, one can spot a number of fainter filaments/extensions, which will be discussed in the forthcoming studies.

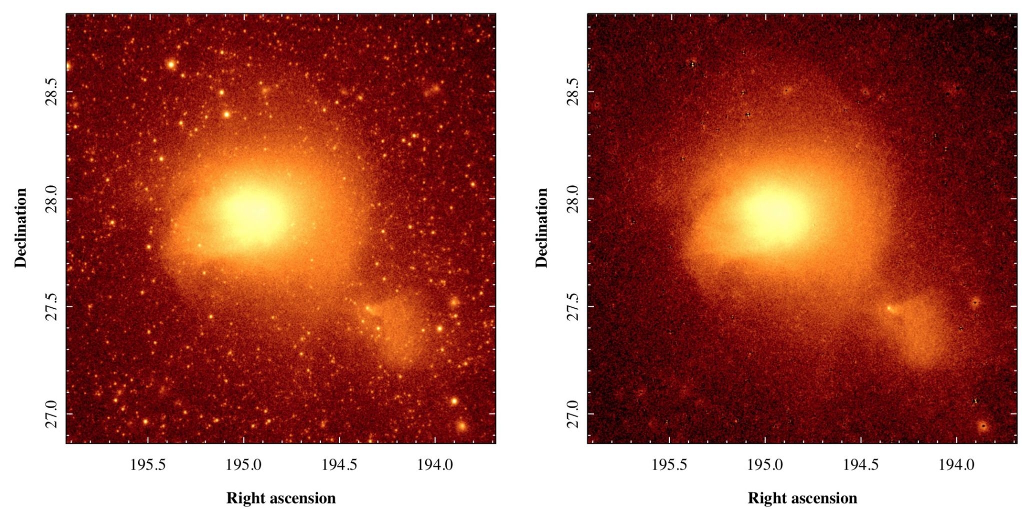
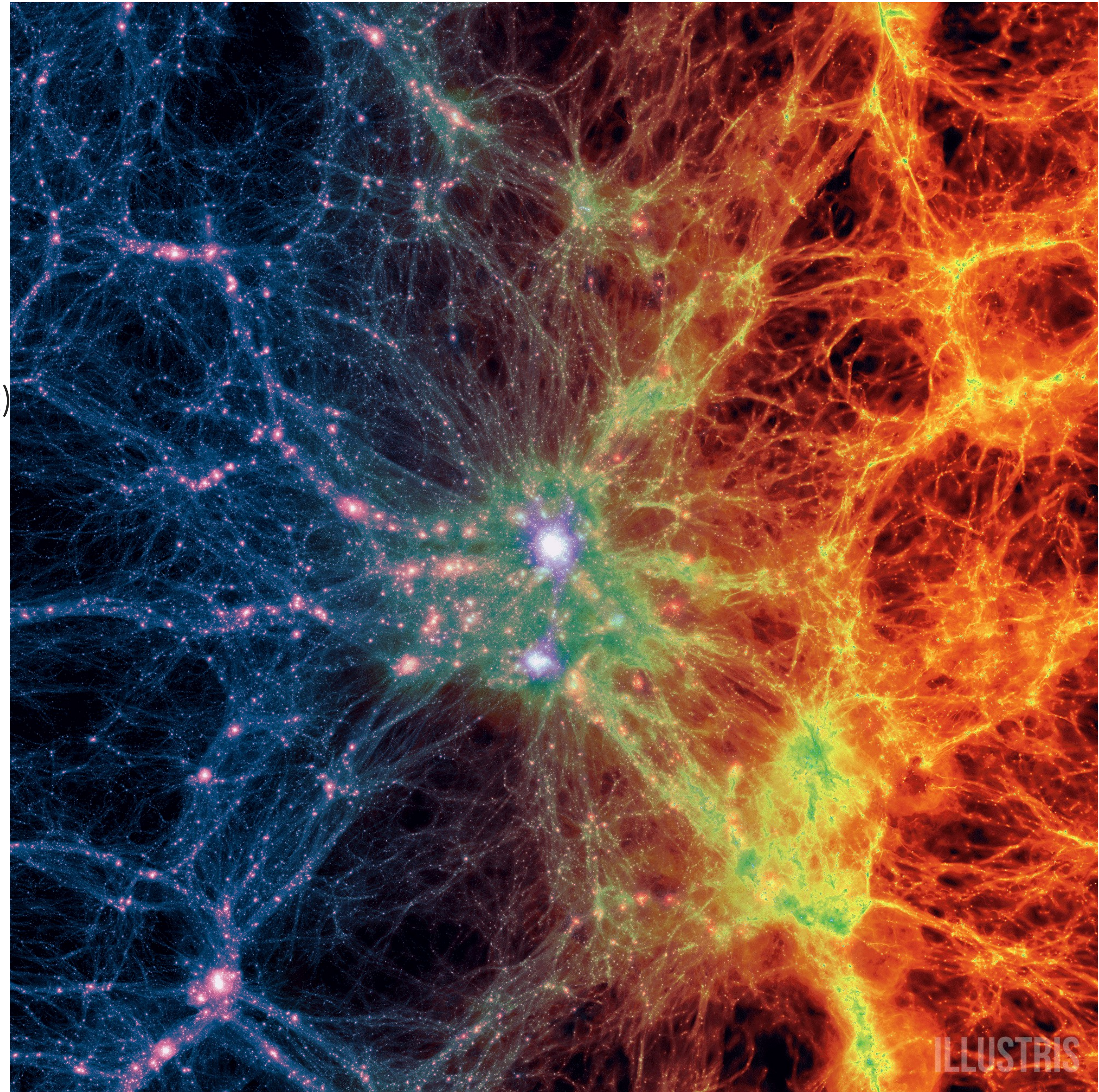


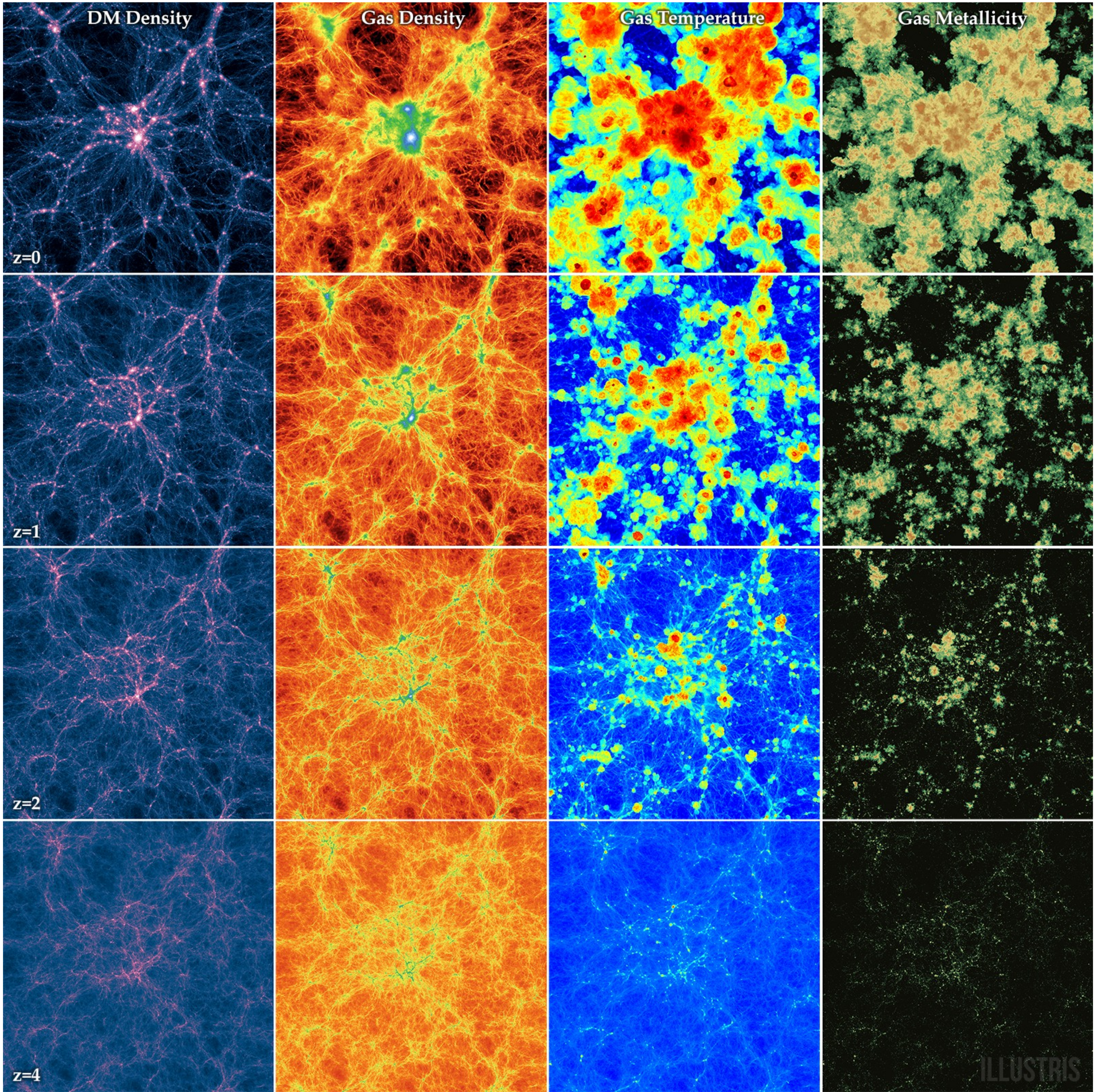
Fig. 4. X-ray image of the central ~ 2 × 2 degrees of the field showing 0.4-2 keV surface brightness on a a logarithmic scale. The left panel shows the original image without subtraction of the multitude of foreground, background and Coma-related sources. The right panel shows the map of the diffuse emission obtained after modeling and subtraction of the confidently detected point-like and mildly-extended sources using the β-profile approximation of the PSF described in Appendix B.

ILLUSTRIS view of Clusters of Galaxies

Large scale projection through the Illustris volume at z=0, centered on the most massive cluster, 15 Mpc/h deep. Shows dark matter density (left) transitioning to gas density (right).



ILLUSTRIS view of Clusters of Galaxies ⇓



Another example:

Simulation of a merger:

https://vimeo.com/307848975

by F. Vazza

Radio view of Clusters of Galaxies: ~ *local people involved in "radio science "*

Prof. Dr. Annalisa Bonafede – DRA...

Andrea Botteon's home...
home.strw.leidenuniv.nl

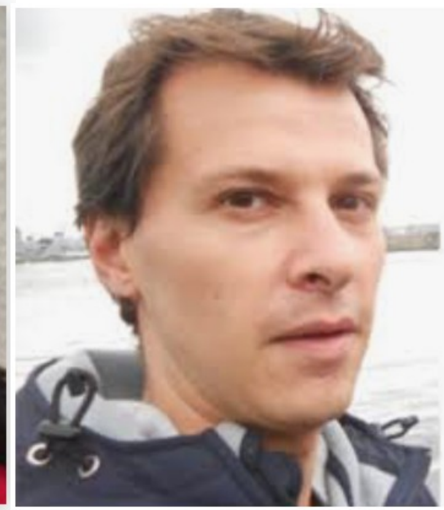
Gianfranco Brunetti ...

Rossella Cassano - Ricerc...

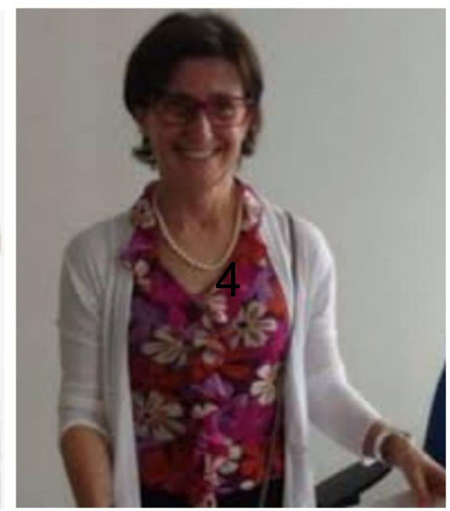
Dr. Virginia Cuciti : Tea...
physik.uni-hamburg.de

Myriam Gitti | IAU

Ruta KALE | National Centre For ...



Franco Vazza – AstroFIt2



Tiziana Venturi INAF, Istituto ...

Simona Giacintucci (Naval Research Lab),

Matteo Angelinelli, Serena Banfi, Nadia Biava, Luca Bruno, Alessandro Igniesti, Nicola Locatelli, Chiara Stuardi (PhD)

Kamlesh Rajpurohit, Chris Riseley, Gianadrea Inchingolo, Marisa Brienza, Etienne Bonnassieux (posdoc)

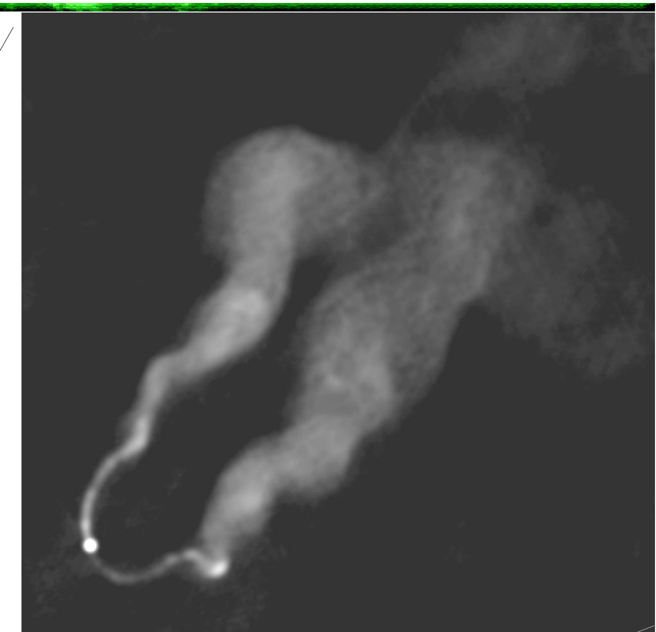
+ Xrays.....

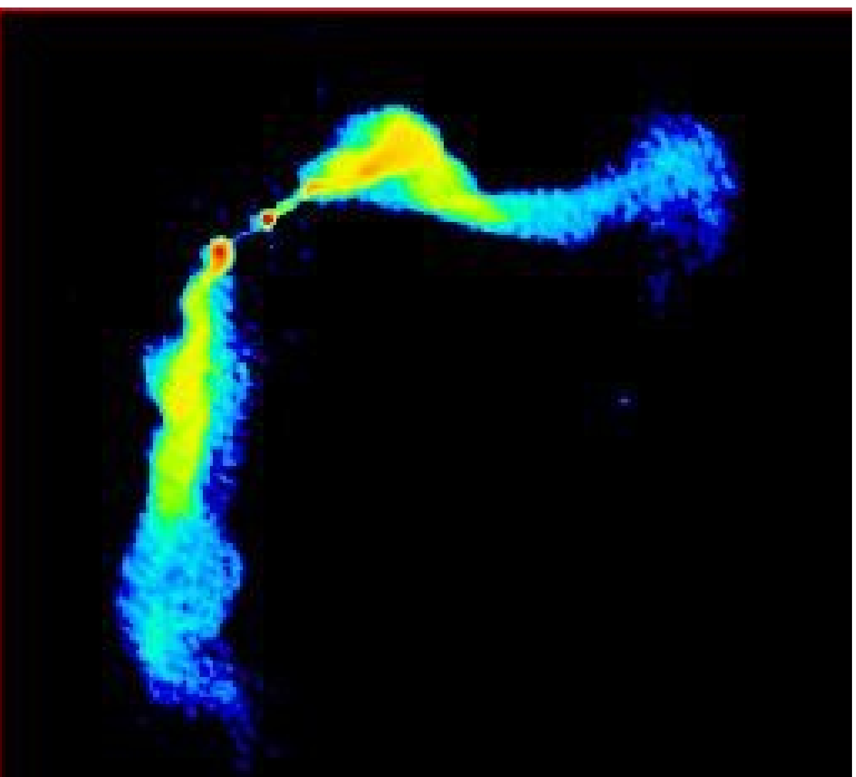
Radio emission from: *Individual galaxies*

(+ Diffuse sources)

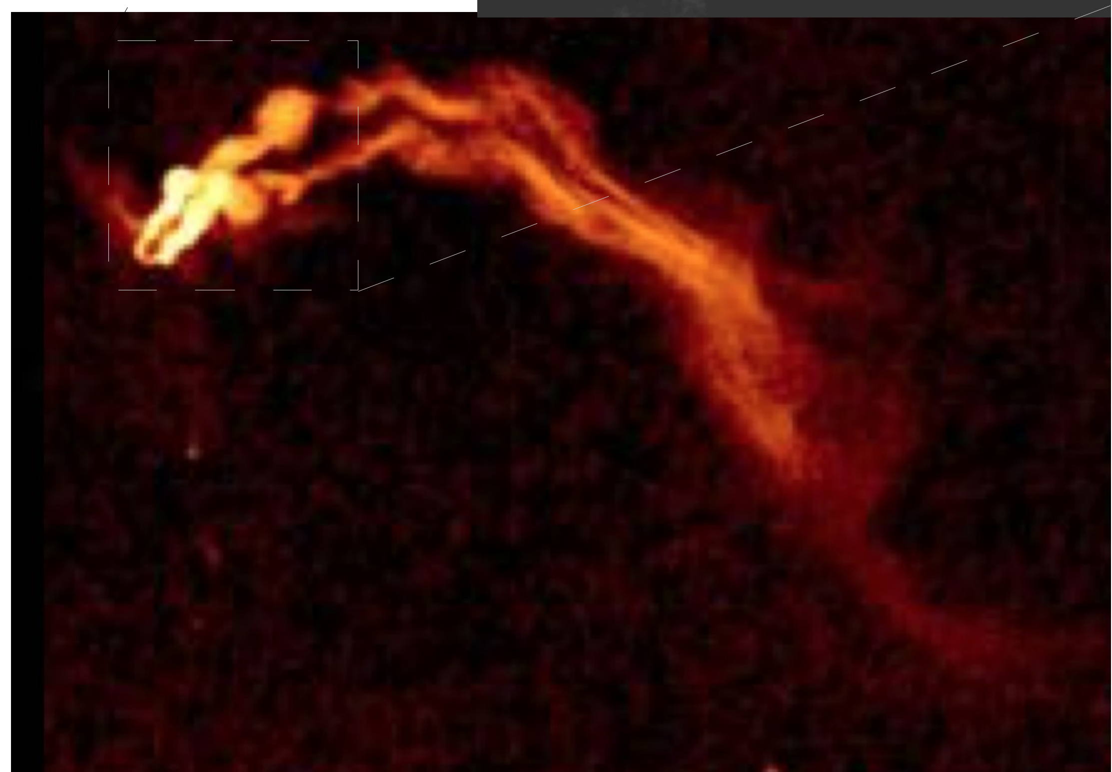
Radio Galaxies:

- *A number of "compact radio sources"*
- ***Extended objects are typically FR – I radio galaxies with distorted morphology (cluster weather)***





3C465 a Wide Angle Tailed (WAT) radio source



3C129 a Narrow Angle Tailed (NAT radio source) [Lane + 2002]

Radio emission from: Individual galaxies (+ Diffuse sources)

Radio Galaxies:

- *A number of "compact radio sources"*
  ⟹ debate whether the cluster triggers/quenches the radio activity

- ***Extended objects** are typically FR – I radio galaxies with distorted morphology (cluster weather)*
  Radio power determines the FR-type, as well as the lack of hot-spots

- *Often the **BCG** has substantial radio emission (despite it might not be the brightest radio source of the cluster)*

- ***AGN feedback:***
  Interaction between thermal and non-thermal plasma
  Heating the ICM

- *There is a well established influence of the dynamical status of the cluster on what we observe*

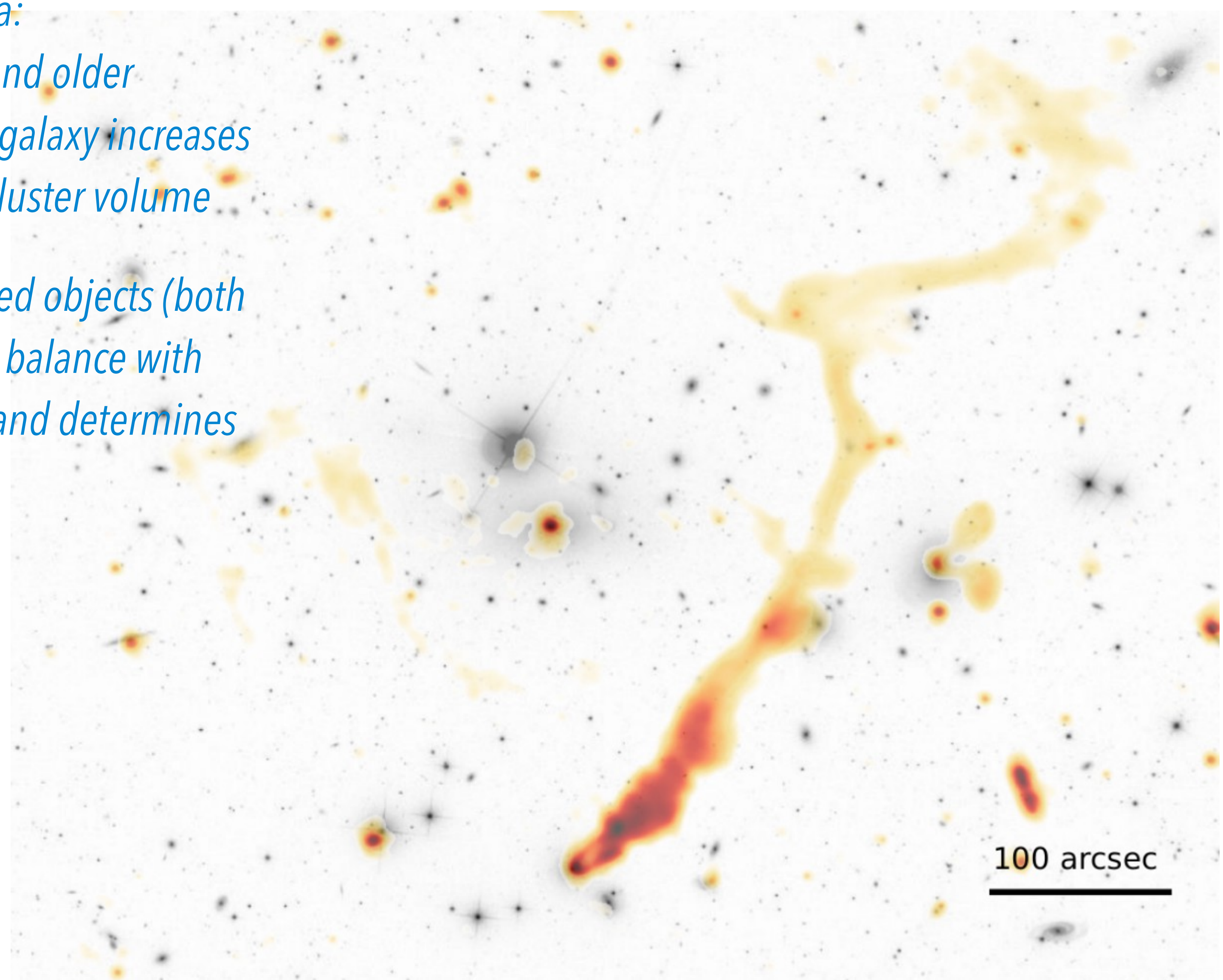
- *Remember that we stated that **spiral galaxies** in clusters are **HI deficient** (e.g. Haynes & Giovannelli 1984)*

Radio emission from: Individual galaxies

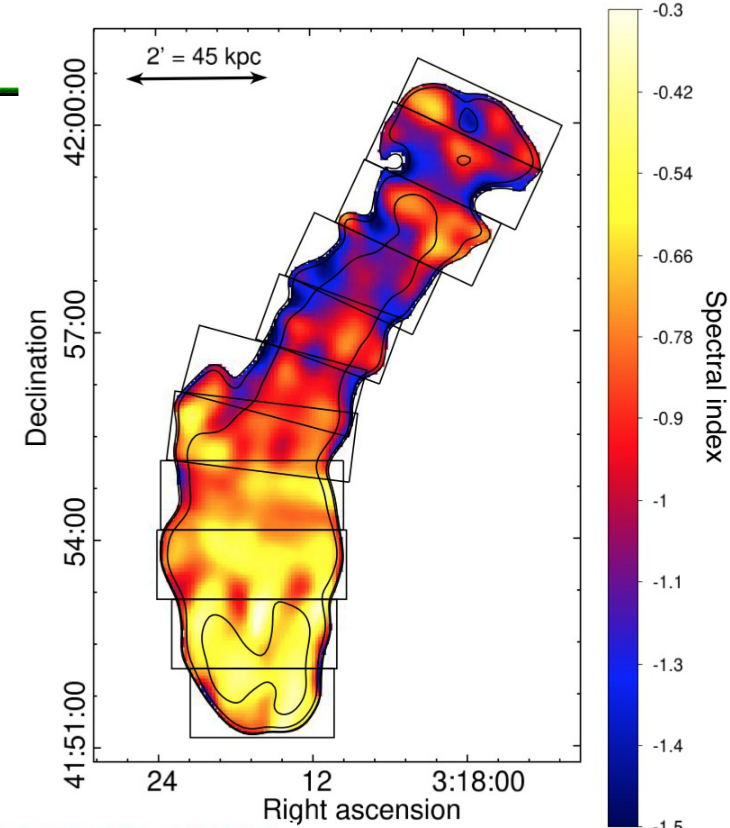
NAT radio galaxies *can provide info about*

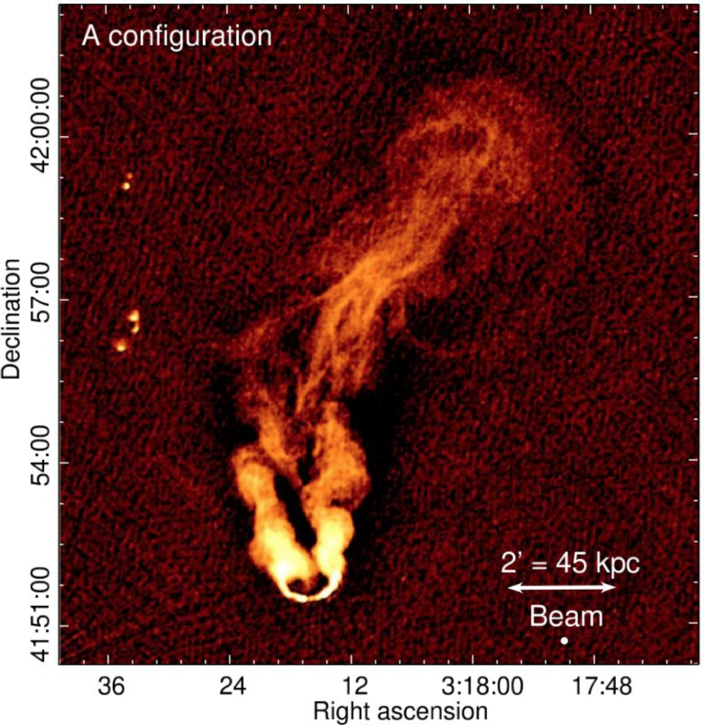
- *radiative age of relativistic plasma: the emitting electrons are older and older as their distance from the parent galaxy increases*
- *(projected) trajectory within the cluster volume*

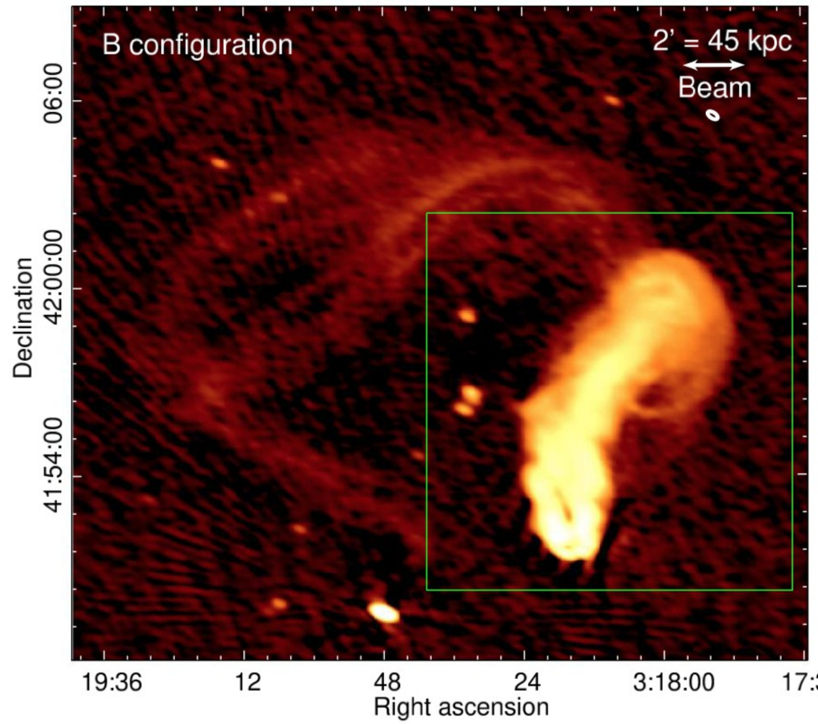
- *Radio emitting plasma in extended objects (both NATs nd WATs) tests the pressure balance with the ambient (thermal) medium, and determines the plasma expansion speed.*



Radiative age:
older electrons have steeper spectra

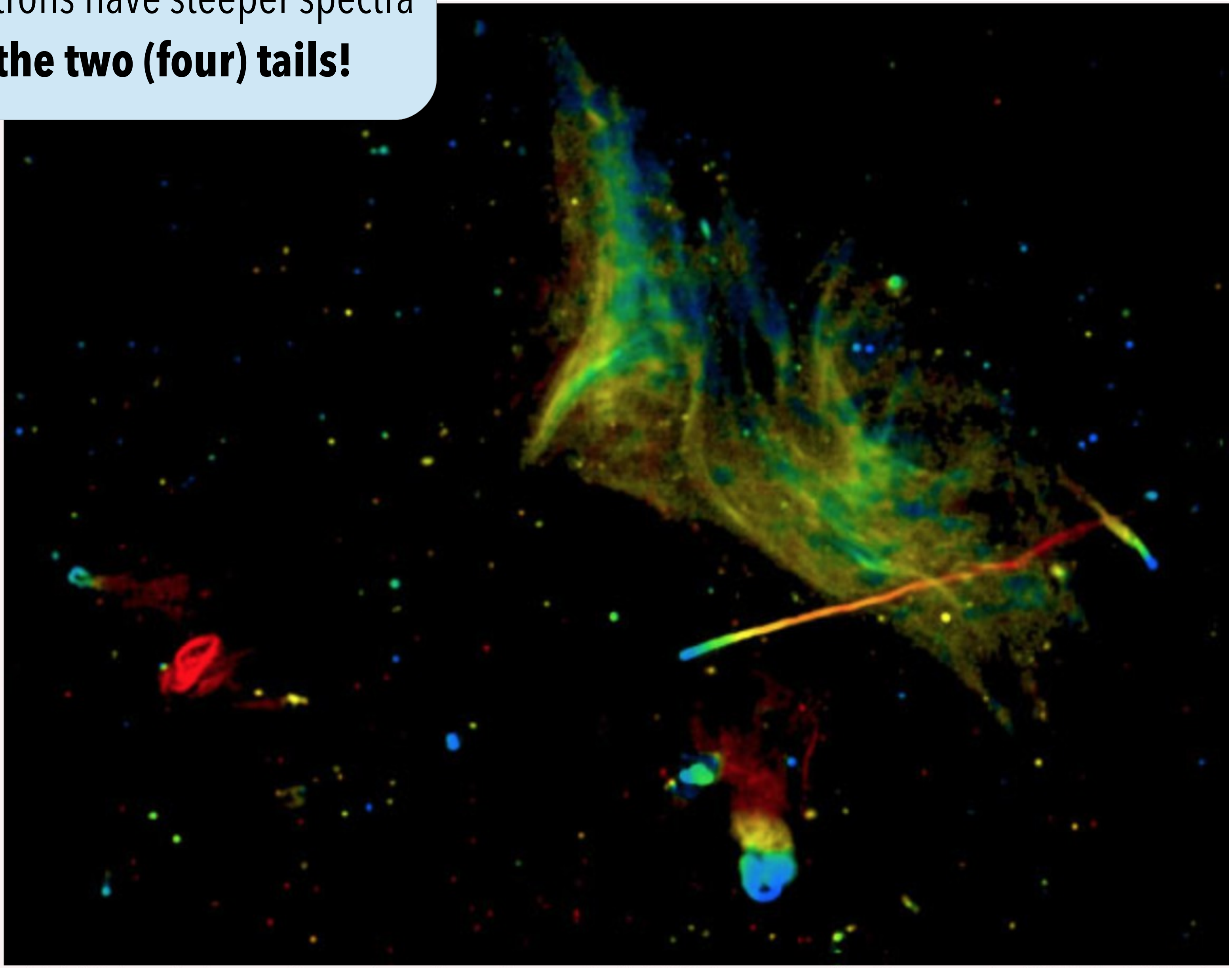




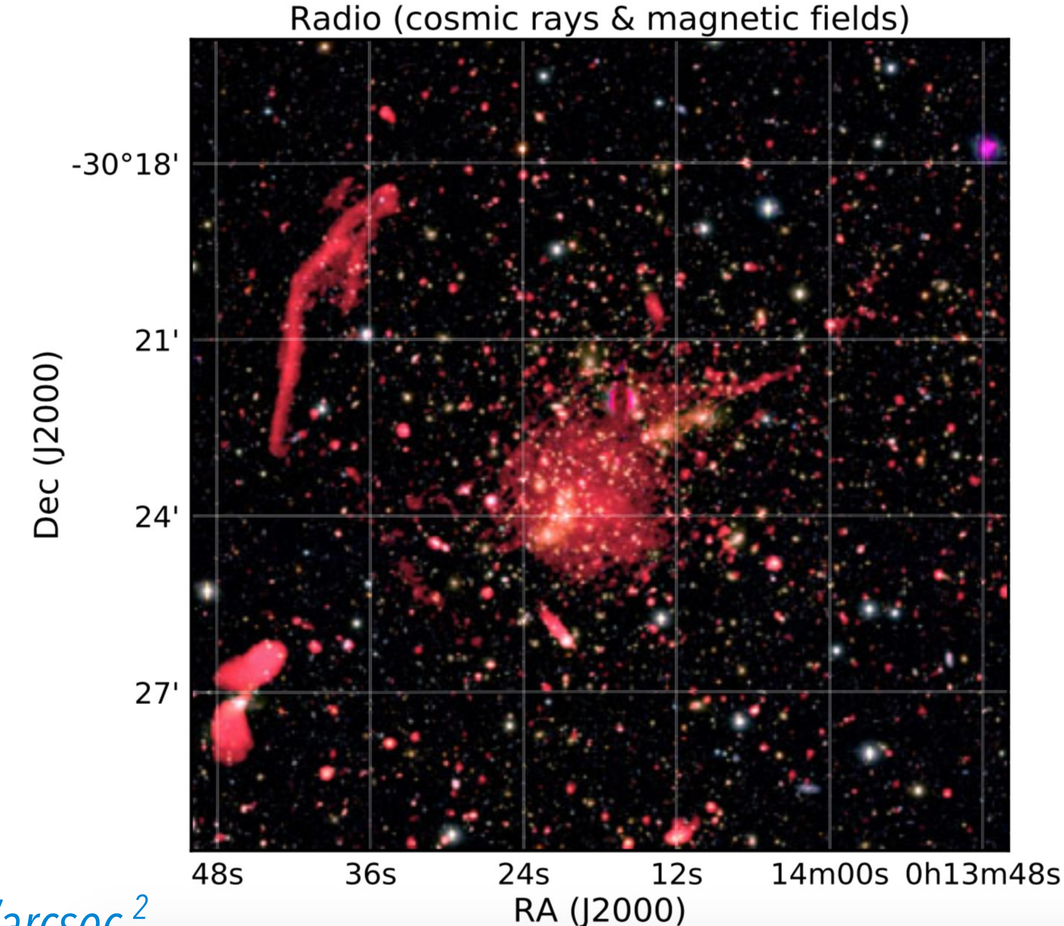


Gendron-Marsolais + 2021

Radiative age:
older electrons have steeper spectra
Note the two (four) tails!



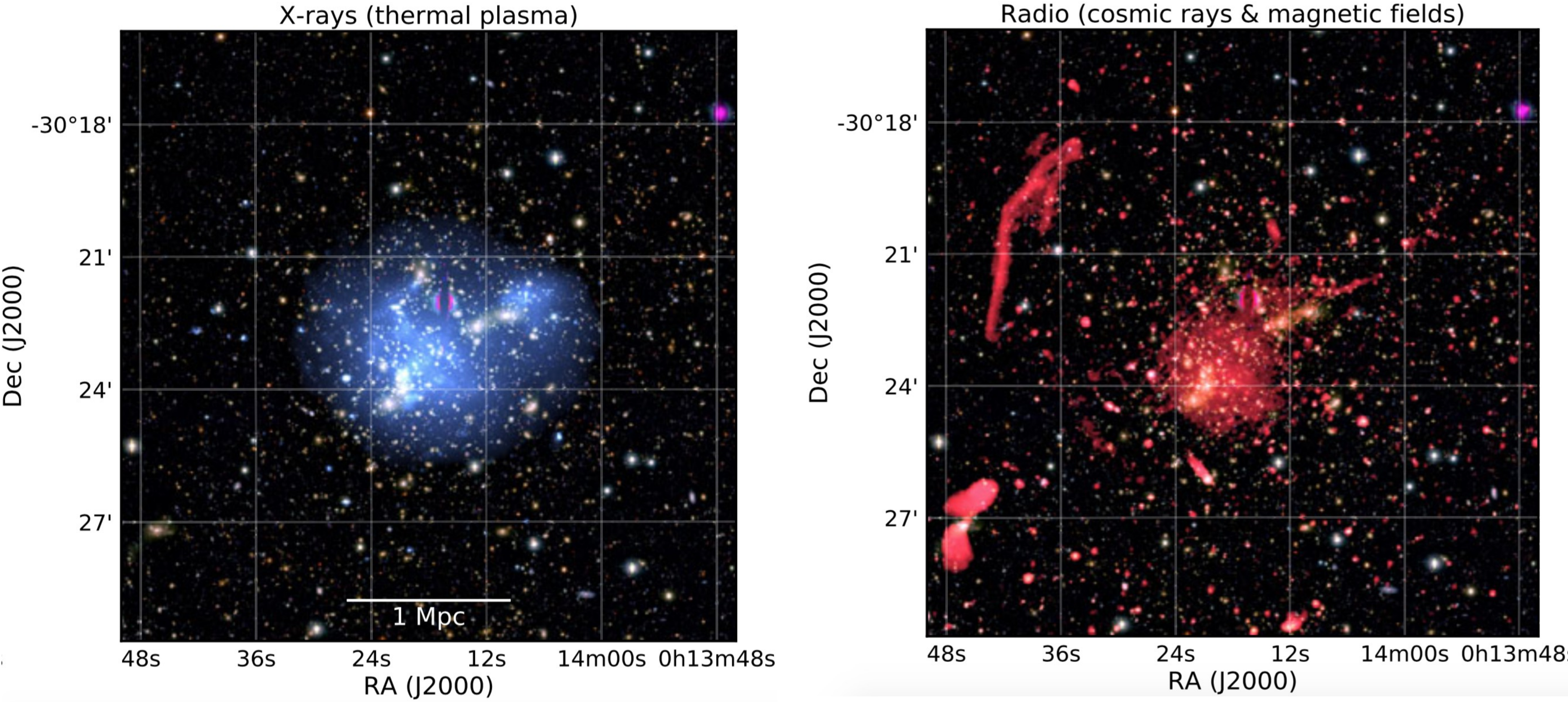
This VLA radio image shows the galaxy cluster Abell 2256. Image credit: Owen et al. / NRAO / AUI / NSF.



Diffuse sources *(definition & properties)*

- *Not associated to an optical host*
- *Rather large*
  (LS ≥ 100s kpc, sometimes exceeding the Mpc)
- *Steep radio spectrum ($\alpha \geq 1.2 - 1.3$)*
- *Typical surface brightness @ 1.4 GHz is ~ 1 μJy/arcsec^2*
  (i.e. their large (LLS & LAS) and the relatively weak flux density give low surface brightness)

- *They can be in the form of radio …*
- ***…HALO**s,*
- ***…mini-HALO**s,*
- ***…RELIC**s (shocks, phoenices, GReETs)*



ABELL 2744

Left: X-ray (Chandra 0.5-2.0 keV) and optical (Subaru) photons

Right: Radio (JVLA 1 – 4 GHz) and optical emission

(picture from van Weeren +2019)

The linear sizes of diffuse radio sources cannot be covered by (relativistic) plasma transfer (diffusion) during the radiative lifetime of the particles.

$t_{syn} \sim 10^7 - 10^8$ yr

With particles bulk motions of ***v ~ 0.1 c*** *they could travel* $10^6 - 10^7$ *light-yr (max 10s of kpc)*

Re-acceleration *processes are required :* ***IN – SITU***

Mechanisms should produce a large number of "fresh" relativistic electrons

(and processes providing energy should be found):

Shocks, Turbulence, DSA *in general*

Details of re-acceleration mechanisms in Brunetti & Jones (2014)

(first / second order Fermi acceleration; "secondary models"), (adiabatic) compression ...

- ***Radio Mini-Halo***
- *a few hundreds of kpc in size, roundish, centrally located*
- *likely associated with the cD galaxy*
- *in Cool Core Clusters (CCC)*

AGN feedback:

- *Heating the ICM*
- *Interaction between thermal and non-thermal plasma*

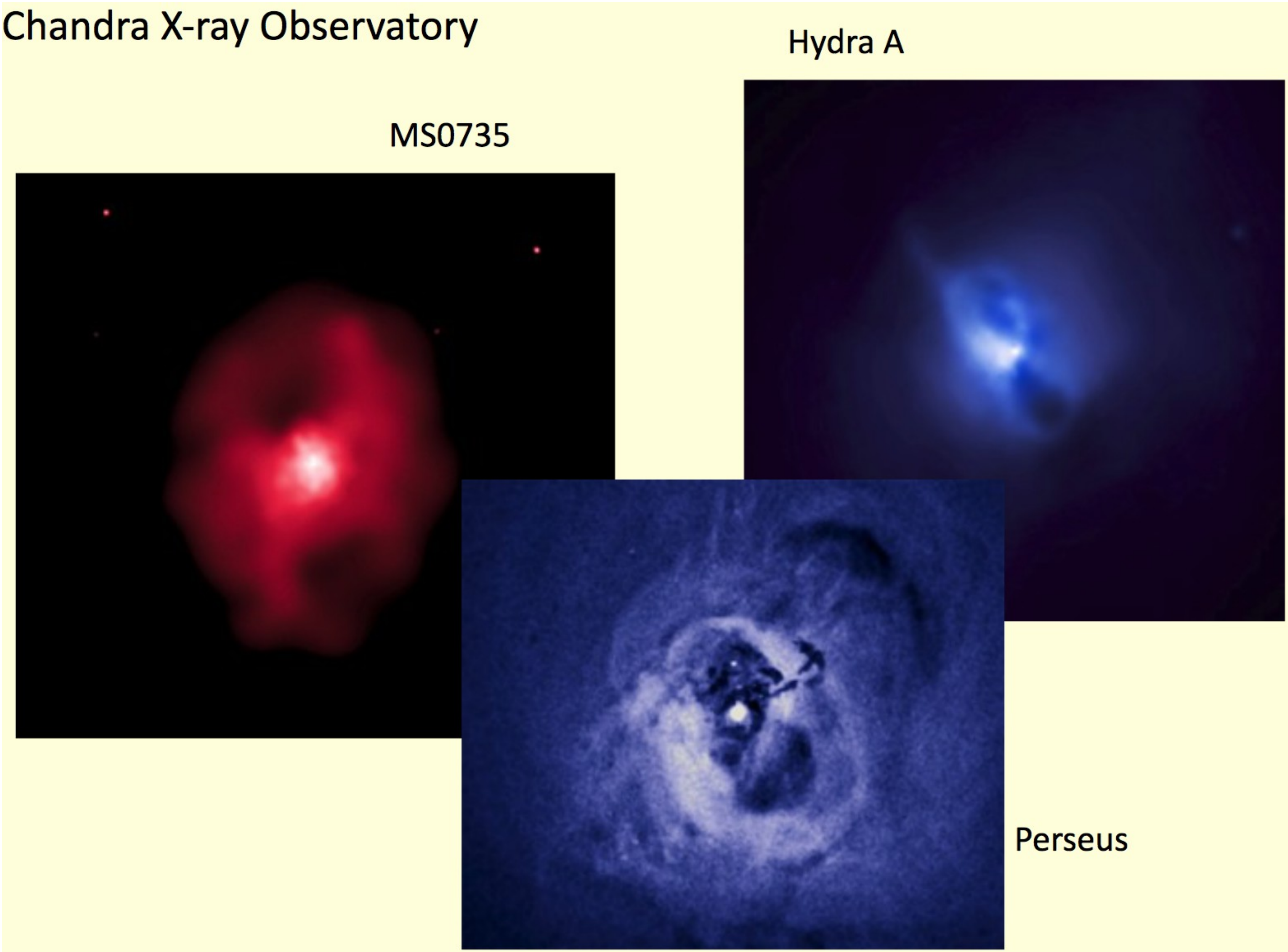
- ***(Giant) Radio Halo***
- *cluster wide, 1-2 Mpc in size*
- *smooth and roughly centered on the galaxy distribution & X-ray emission*
- $P_{1.4\,GHz} \sim 3.1\,x10^{23} \leftrightarrow 1.6\ 10^{26}$ W Hz^{-1}
- *unpolarized, generally (very) steep spectrum (Á ≥ 1.3), uniformly distributed*
- *in dynamically "active"/"disturbed" clusters*
- *"El Gordo", at z=0.87 is the most distant*

- ***Radio Relic***
- ***Shock*** *(elongated, up to ~ Mpc long, peripheral regions, often substantially polarized)*
- ***Phoenix*** *(elongated, up to ~ Mpc long, central regions, often substantially polarized)*
- ***GReET*** *(Gently Re-Energized Tail)*

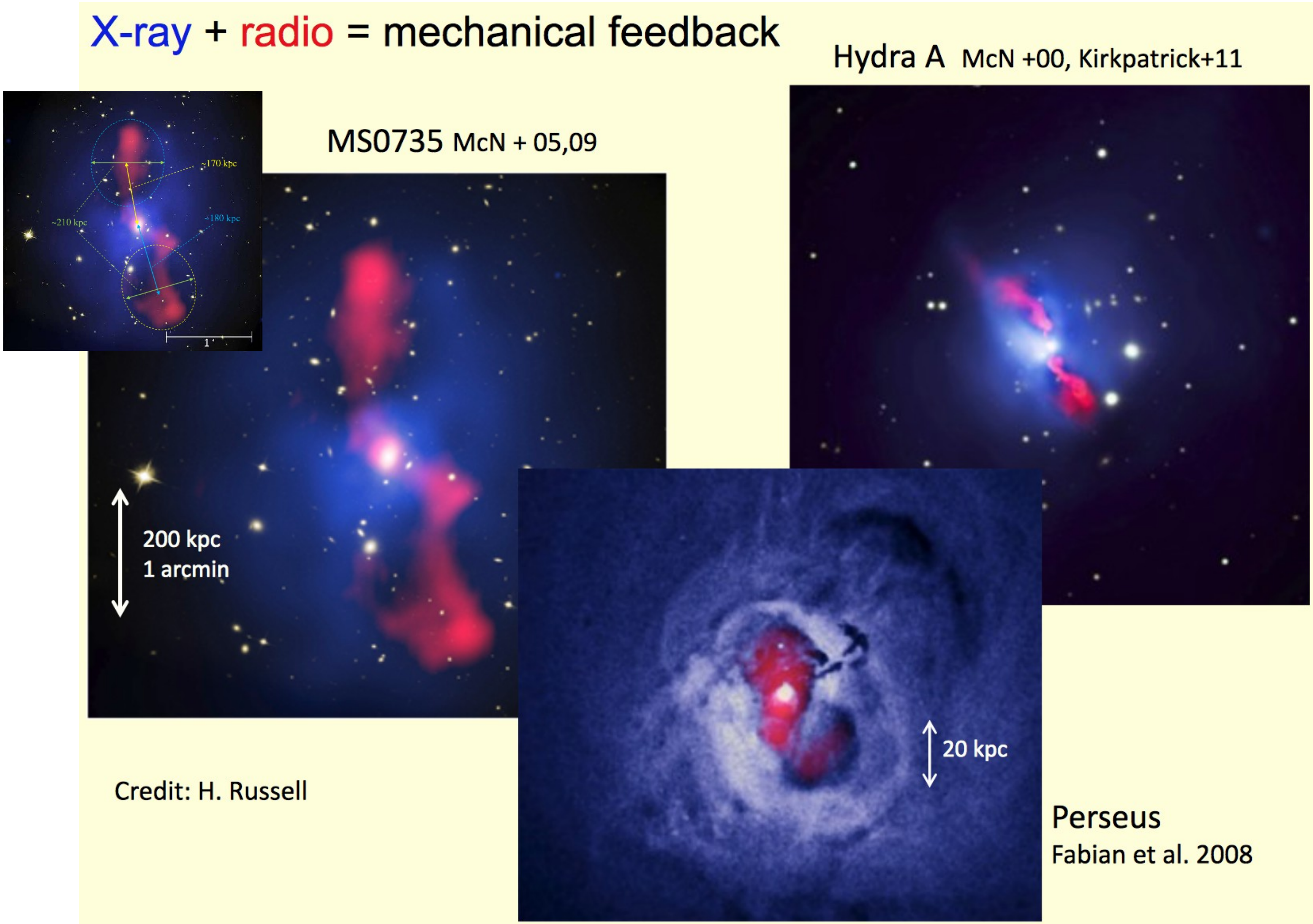
- a few hundreds of kpc in size, roundish, centrally located, sometimes difficult to be classified
- in Cool Core Clusters (80 % of CCC host a mini-halo, 0% in non CCC)
- in ~50 % of X-ray luminous clusters $L_{X\,(0.1\text{-}2.4\,keV)} > 5 \times 10^{44}$ erg s^{-1}) at $0.2 < z < 0.4$
- likely associated with the cD galaxy (AGN contribution may be difficult to be highlighted)
- Often "cavities" in the IGM/ICM
- $P_{1.4\,GHz} \sim 10^{23} \leftrightarrow 10^{25}$ W Hz^{-1}
- the most distant at z=0.805 (uncertain)
- emissivity higher than in Giant RH (emissivity mostly confined to the X-ray cooling region)
- local spectral index quite uniform (very incomplete info), integrated ~ power-law
- unknown polarization properties
- origin from gas sloshing in the cluster core (fossil electrons from the central AGN)

- Radio emission with a spiral-shape like tail and hints of steepening along the tail in RXJ1720.1+2638 (Giacintucci + 2014)

*Feedback: interaction between relativistic and thermal plasmas – **Cavities in the IGM***

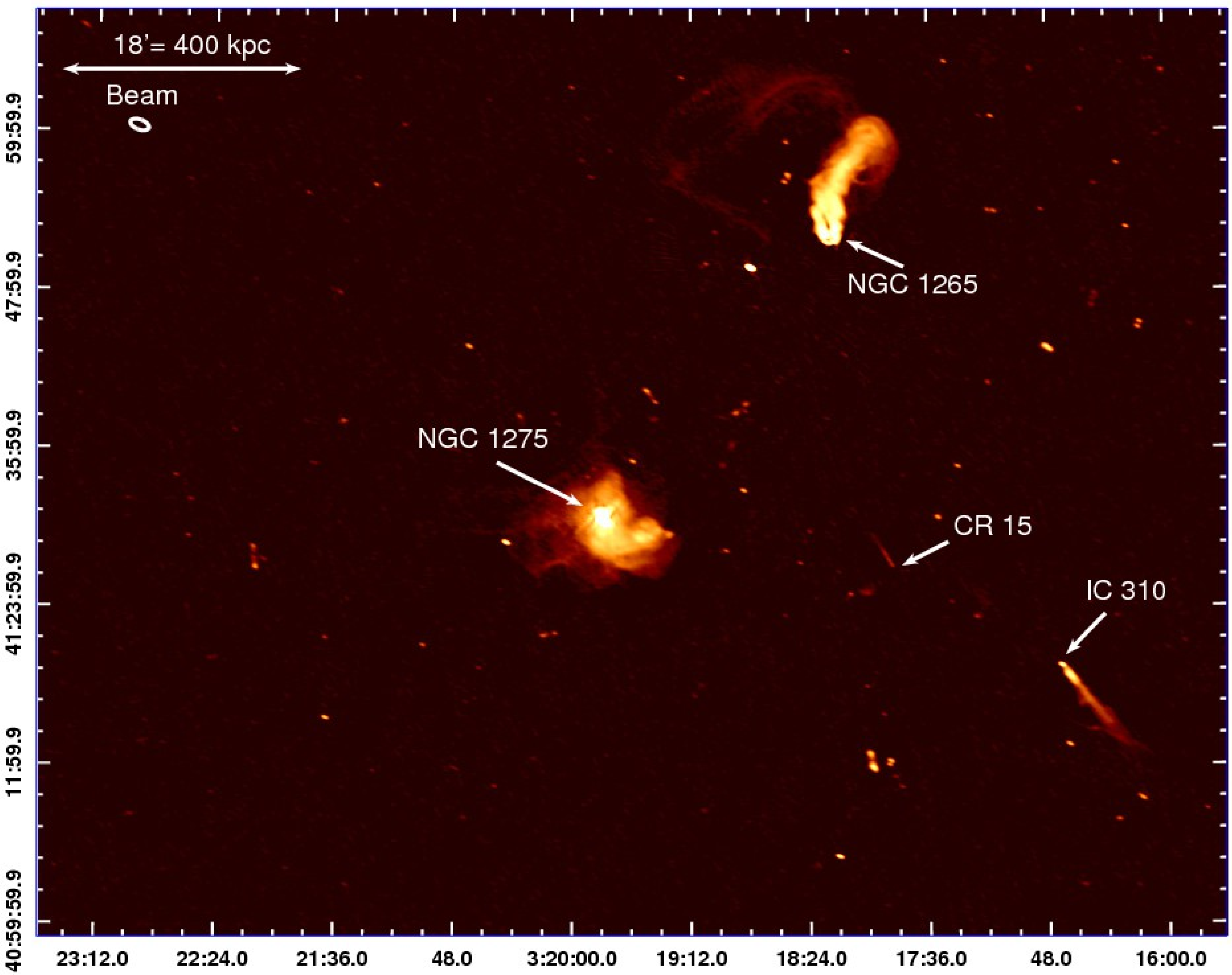


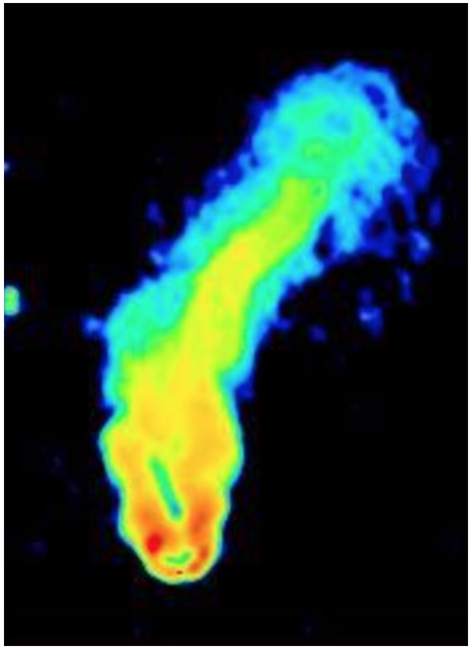
*Feedback: interaction between relativistic and thermal plasmas – **Cavities in the IGM***



Radio view of Clusters of Galaxies: Diffuse sources can be:

Radio Mini-Halo (a few hundreds of kpc in size, likely associated with the cD galaxy)





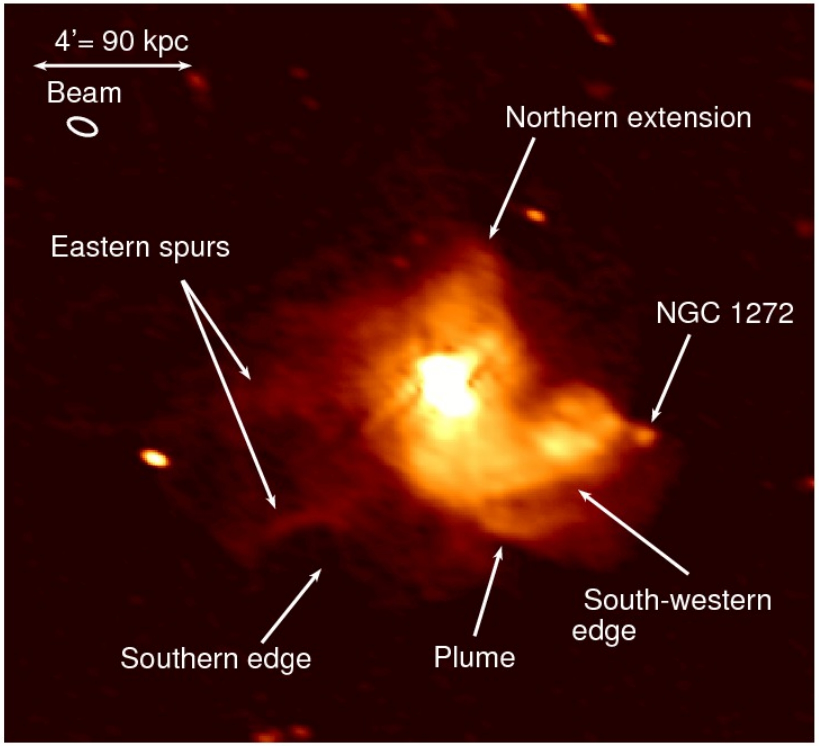
AGN feedback:

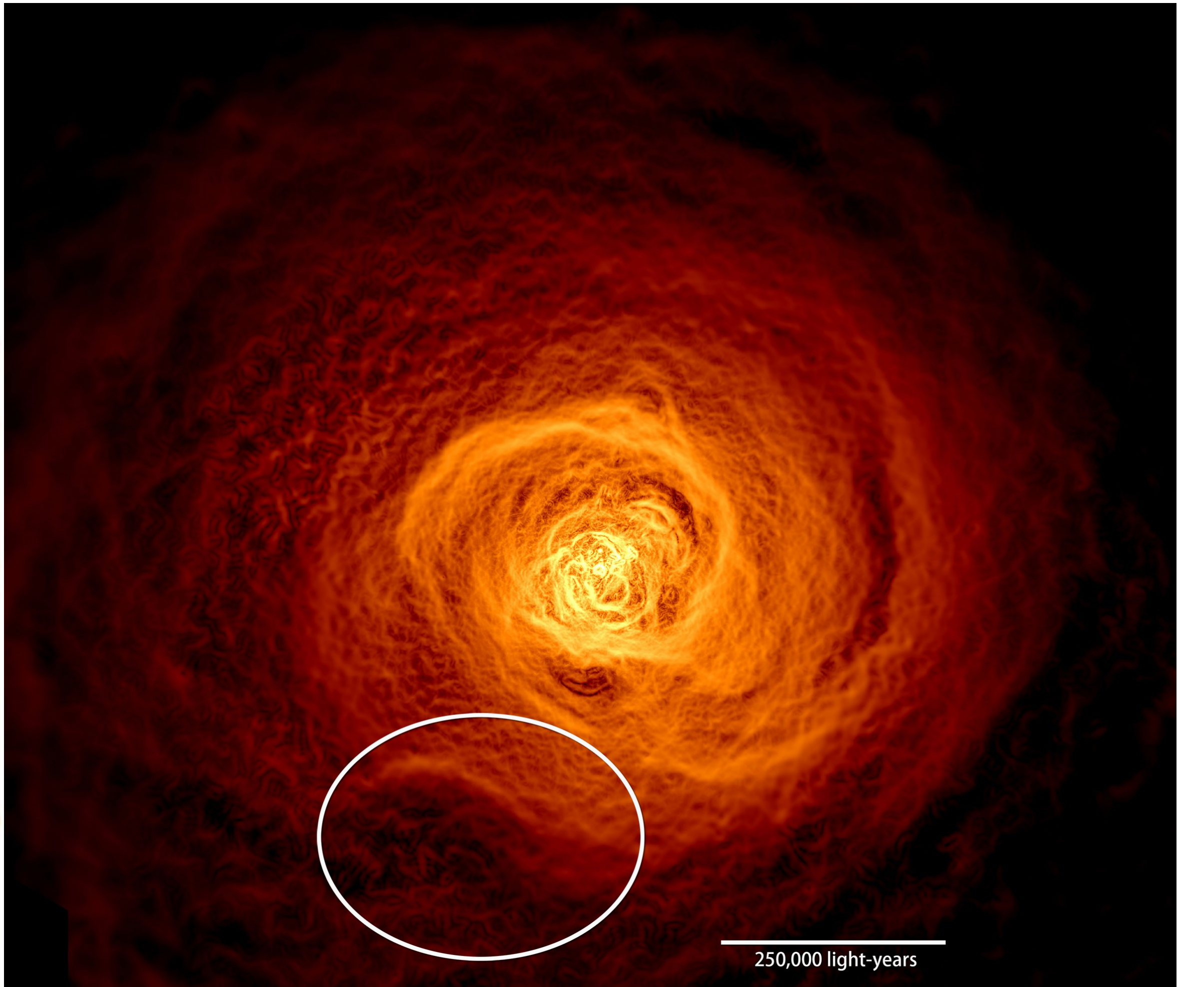
- Heating the ICM
- Interaction between thermal and non-thermal plasma

Gendron-Marsolais + 2017, VLA image 230-470 MHz, beam ~22x11"

Radio view of Clusters of Galaxies: Diffuse sources can be:

Radio Mini-Halo (a few hundreds of kpc in size, likely associated with the cD galaxy)





Chandra X-ray view of the Perseus cluster
https://scitechdaily.com/astronomers-discover-a-giant-wave-of-hot-gas-rolling-through-the-perseus-galaxy-cluster/

https://www.nasa.gov/feature/goddard/2017/scientists-find-giant-wave-rolling-through-the-perseus-galaxy-cluster

Detailed information and a movie from numerical simulation on how the "spiral like structure" is formed.

CCC may be disrupted by [major) merger (unclear how long the CCC may survive after the start of the merging)

[minor merger might not be able to a full disruption]

The same applies to the Radio Mini-Halo (?)

Particles may be transported outer regions and reaccelerated (Giant RH)

In minor merger both mH and GRH may coexist

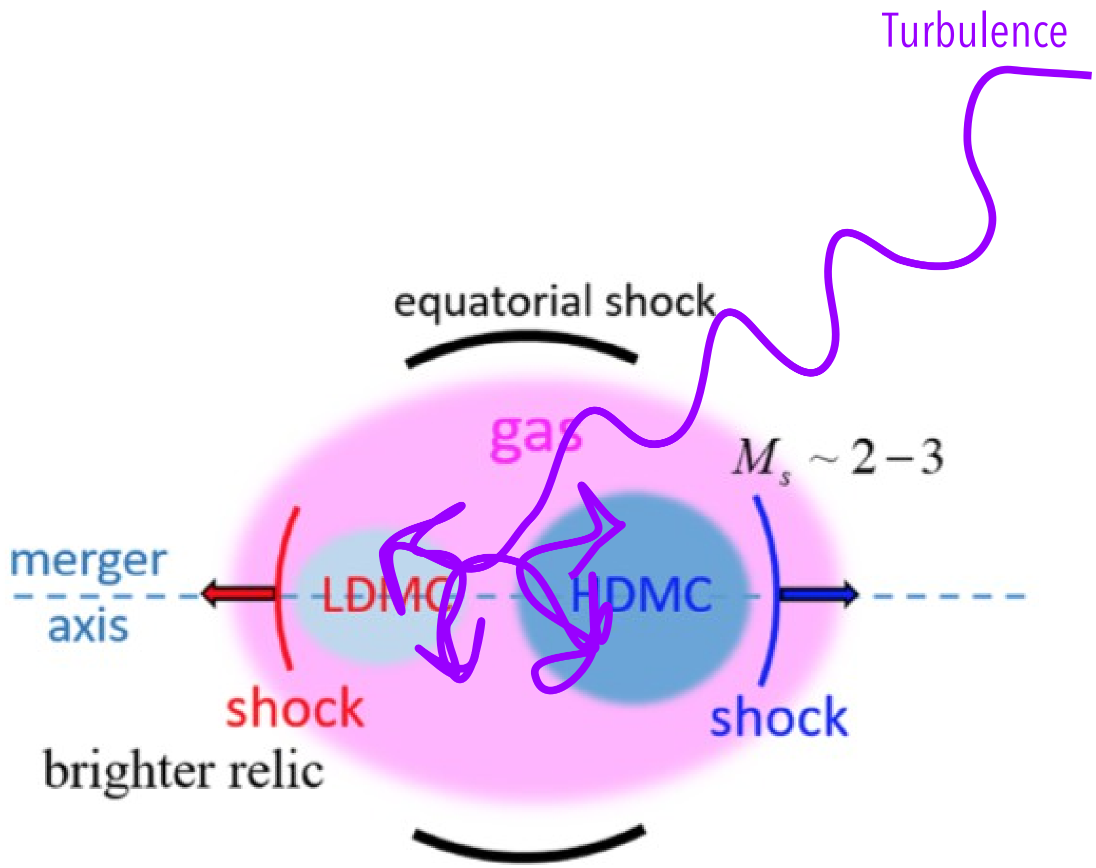
A handful of objects may be interpreted as mH + GRH

Strong cosmological evolution

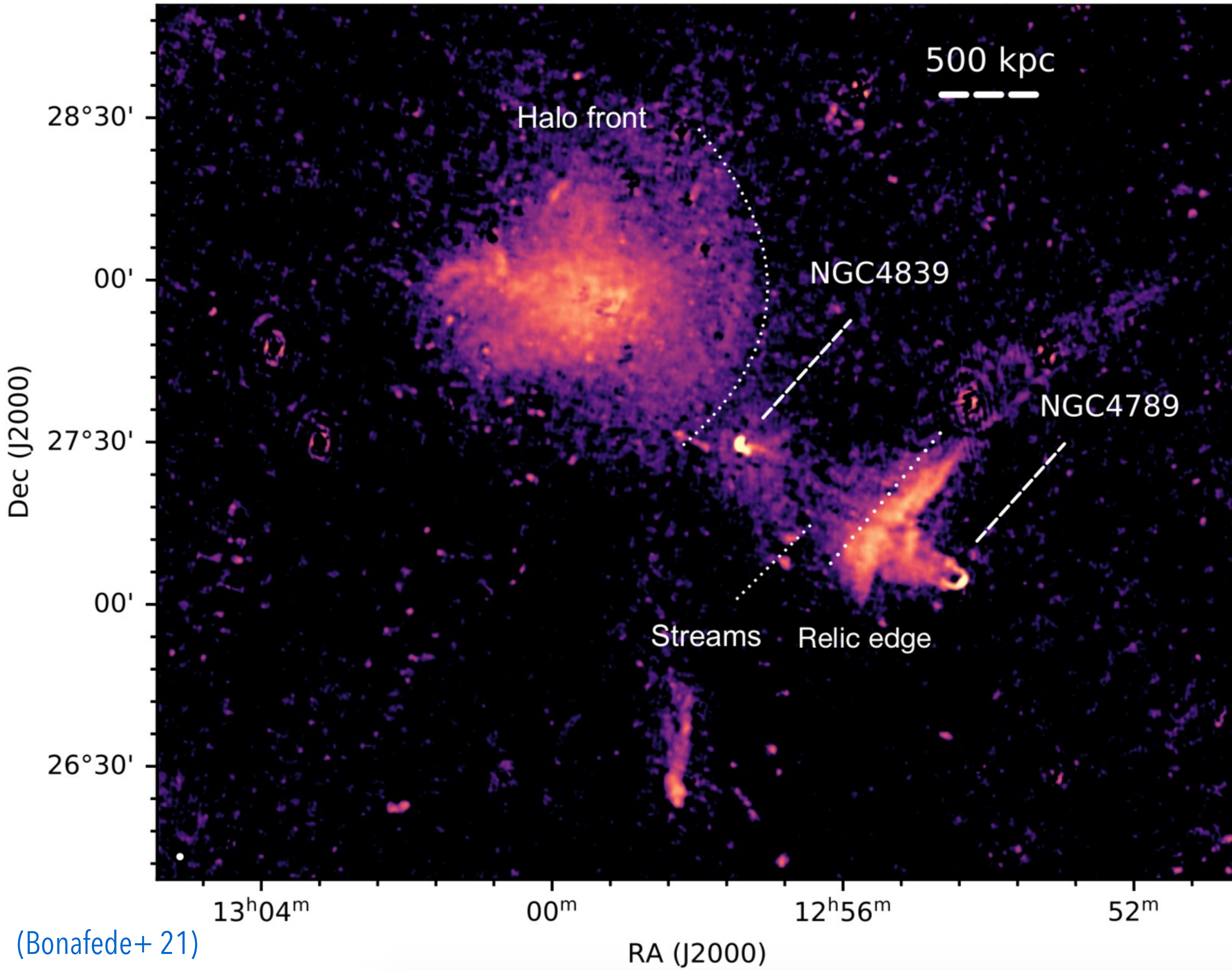
- The merger history is very time-dependent: big clusters are more easily found at z~0 since the mass assembly proceeds as the Universe evolves
- For diffuse radio emission from relativistic electrons, the IC with CMB photons is getting more and more relevant [" H_{CMB} " ~ $3.28\,(1+z)^2\,\mu G$]

Numerical simulations show that an equatorial shock is formed first when there is the first passage at the barycenter. This is a "belt", best visible at the edges where the LoS intercepts a larger layer of particles

Subsequently,



Radio view of Clusters of Galaxies: *example of cluster merger*



(Bonafede+ 21)

Radio view of Clusters of Galaxies: Abell 2255 (from Botteon+ 2020)

LOFAR @ 144 MHz *WSRT @ 1.2 GHz* *Chandra @ 0.5 – 2.0 keV*

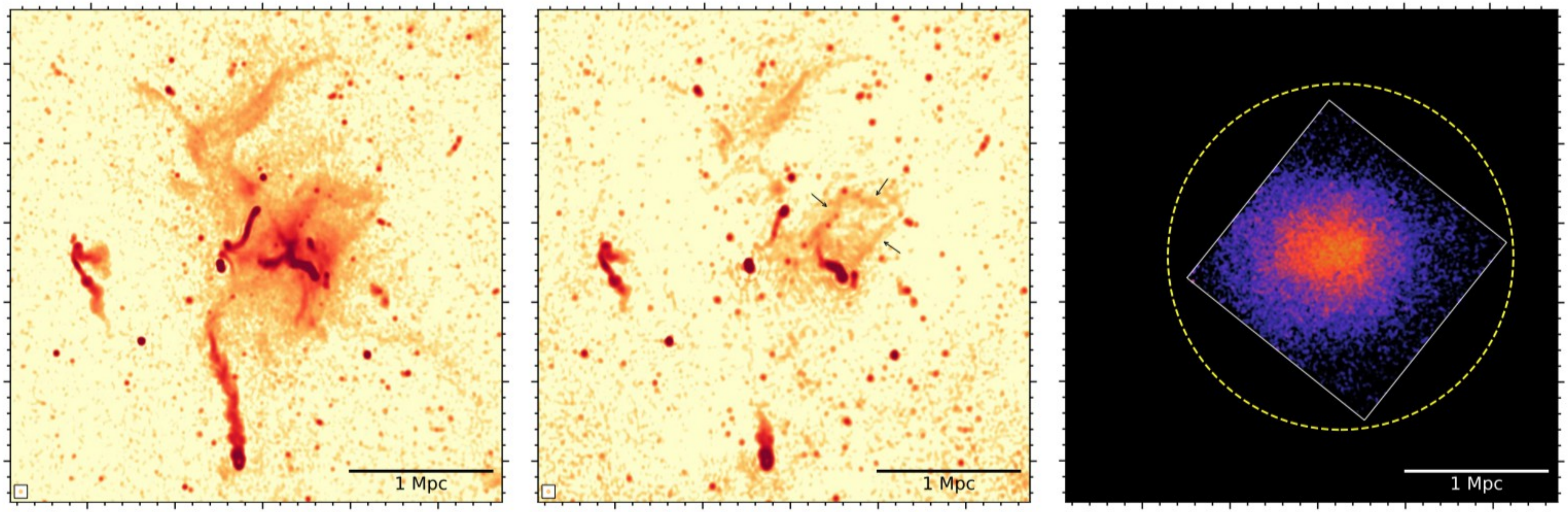
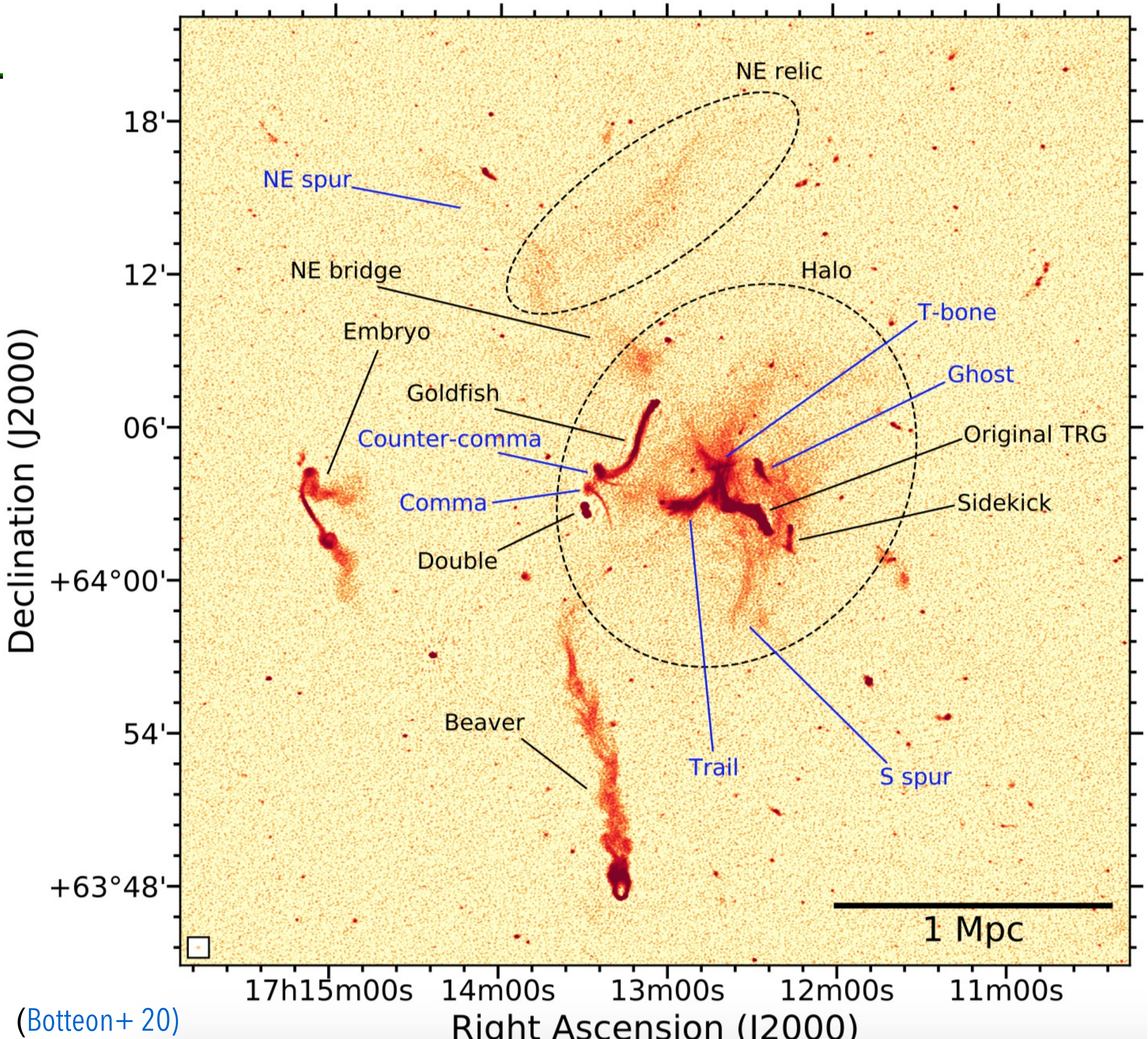


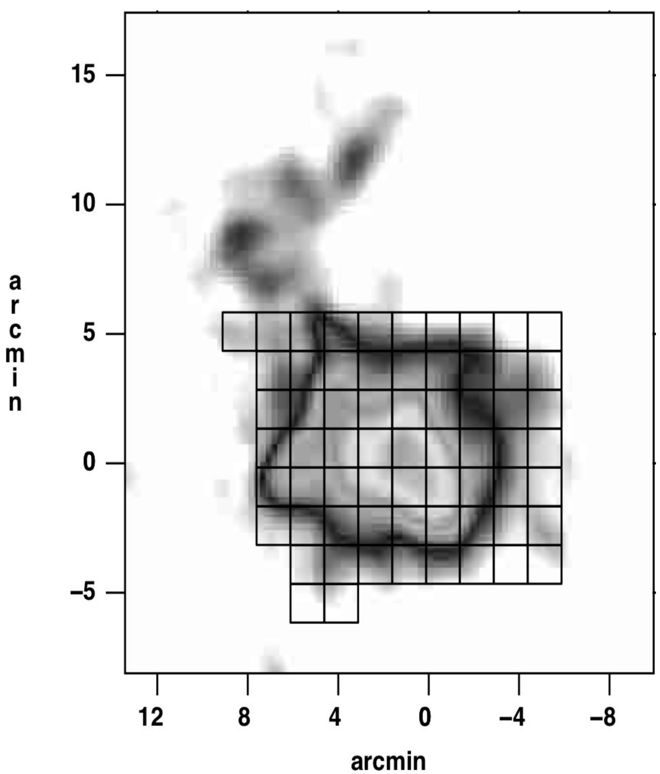
Figure 3. LOFAR 144 MHz (*left*) and WSRT 1.2 GHz (*center*, from Pizzo & de Bruyn 2009) images of A2255 at the same resolution of $15'' \times 14''$. The noise levels in the images are 120 μJy beam^{-1} and 10 μJy beam^{-1} for LOFAR and WSRT, respectively. The arrows in the WSRT image indicate the three straight (polarized) filaments reported in Govoni et al. (2005) and Pizzo et al. (2011). The *Chandra* image of the cluster in the 0.5 – 2.0 keV band (*right*) has been smoothed to a resolution of $\sim 5''$ for visualization purposes. The white region denotes the ACIS-I FoV while the yellow circle indicates the approximate location of r_{500}.

Note diffuse & filamentary emission as well as radio tails

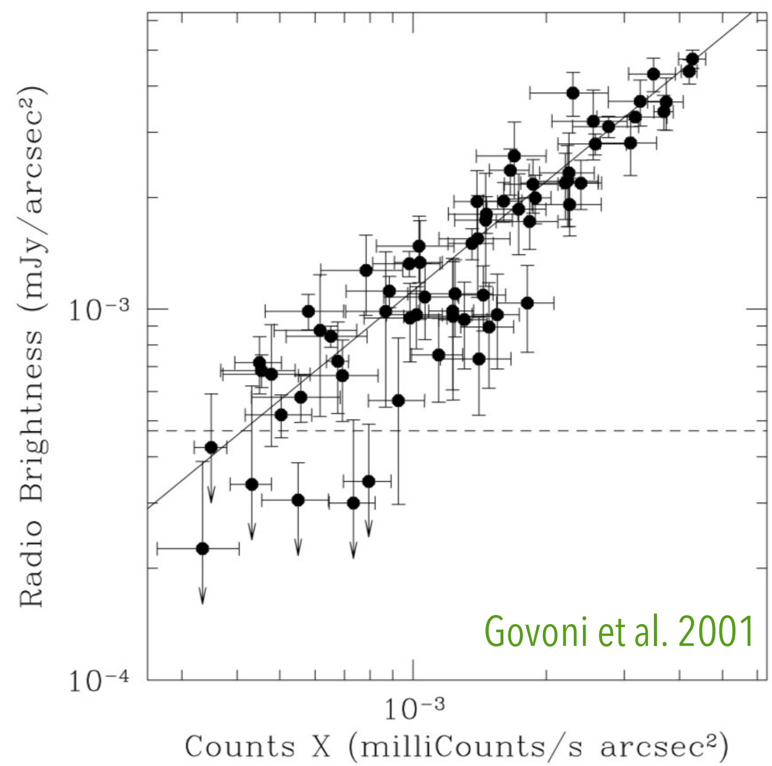


(Botteon+ 20)

- *cluster wide, 1-2 Mpc in size*
- *smooth and roughly centered on the galaxy distribution & X-ray emission*
- $P_{1.4\,GHz} \sim 3.1 \times 10^{23} \leftrightarrow 1.6 \times 10^{26}$ W Hz^{-1}
- *unpolarized, generally (very) steep spectrum (1.1 ≤ Á ≤ 1.4), uniformly distributed*
- *in dynamically "active"/"disturbed" clusters*
- *"El Gordo", at z=0.87 is the most distant*
- *about 75 GRHs are known to date (may 2020)*



Abell 2255
(point source subtracted)
Radio image and grid
[relic non included]



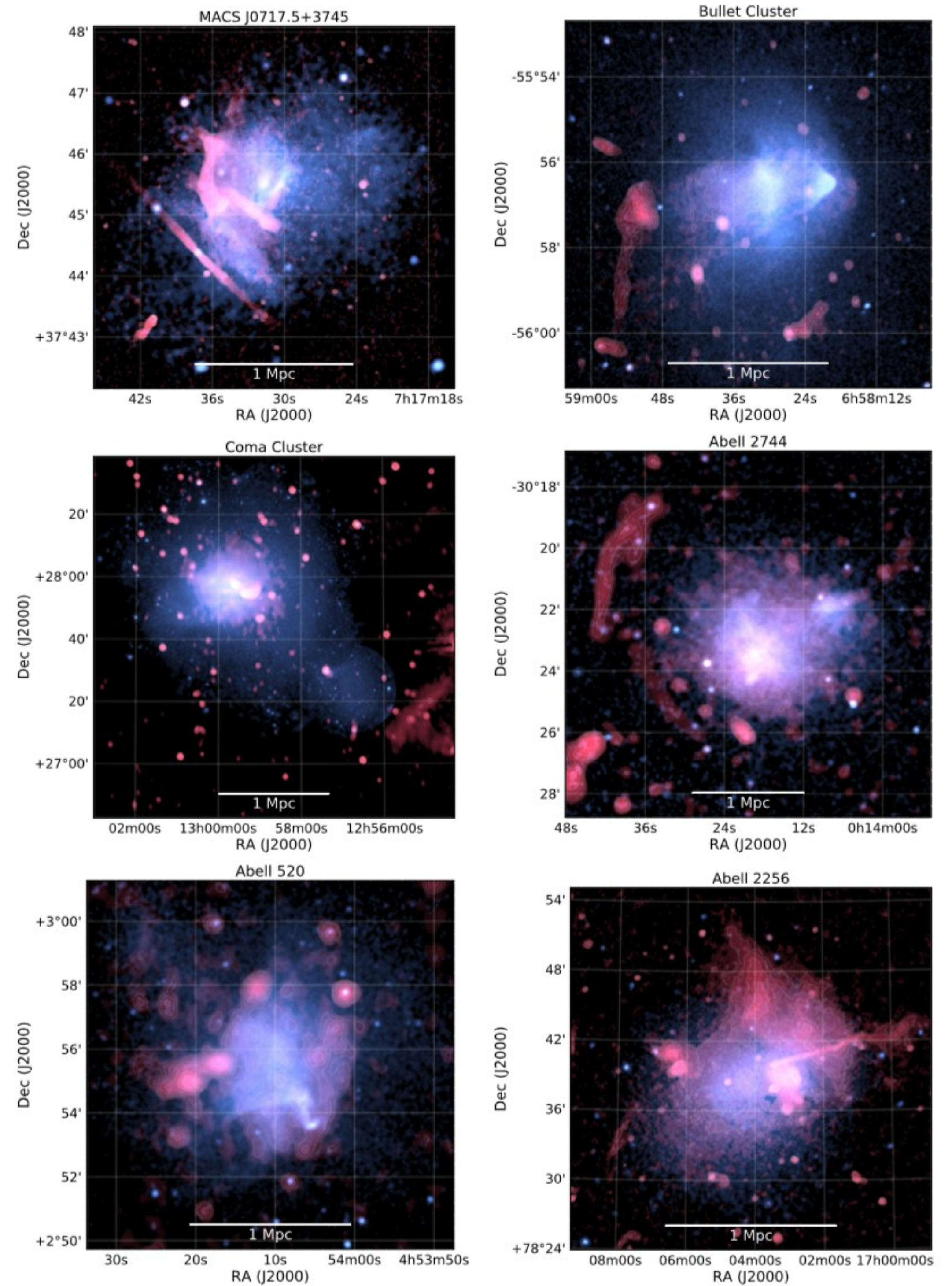
Radio view of Clusters of Galaxies: Diffuse sources: **(Giant) Radio Halos**

Blue: X ray emission

Red: radio emission

Excluding individual (and foreground/background) radio sources, the diffuse emission is co-spatial to thermal plasma

Often the foreground/background radio sources are difficult to disentangle from the extended radio emission, leading to uncertainties in the determination of the properties of each class.

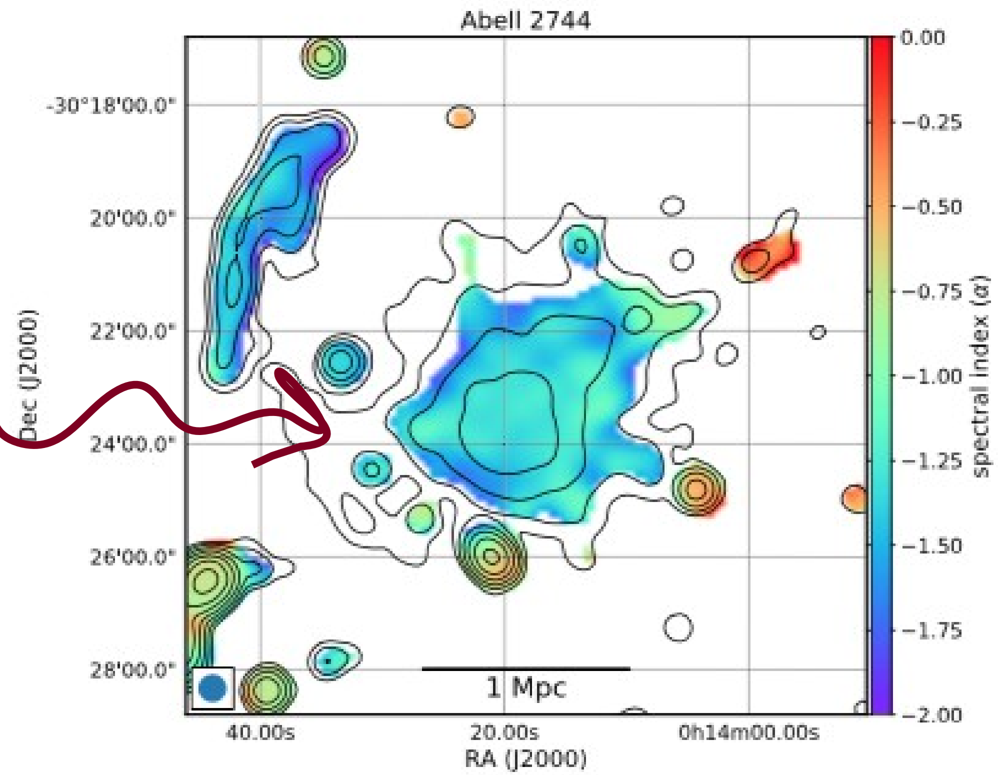


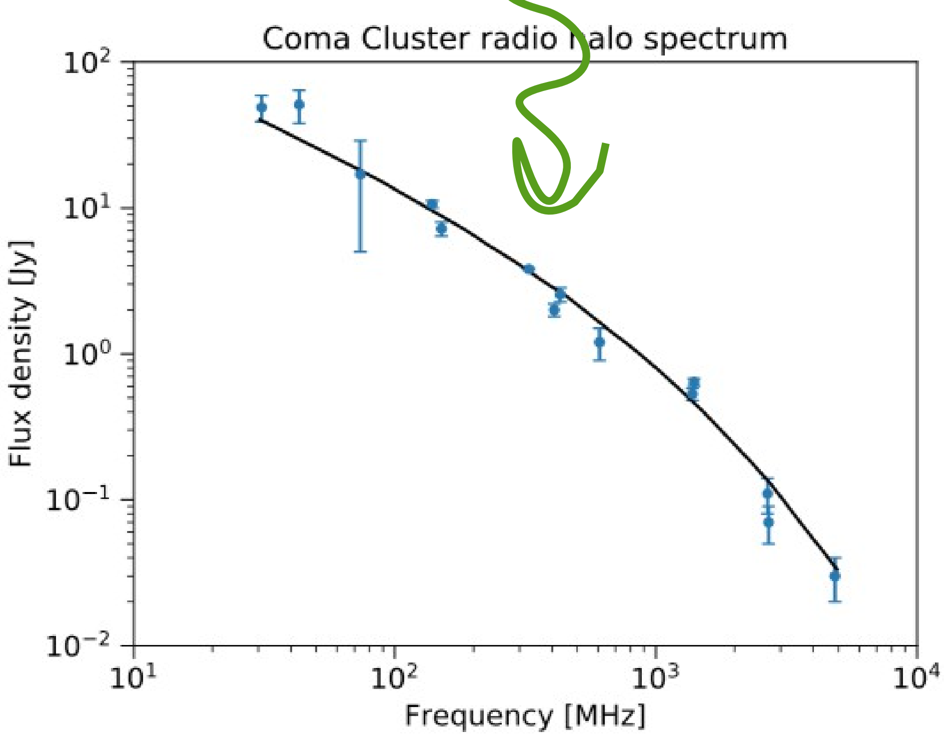
Spectral index:

Local (in situ) distribution [uniform]

&

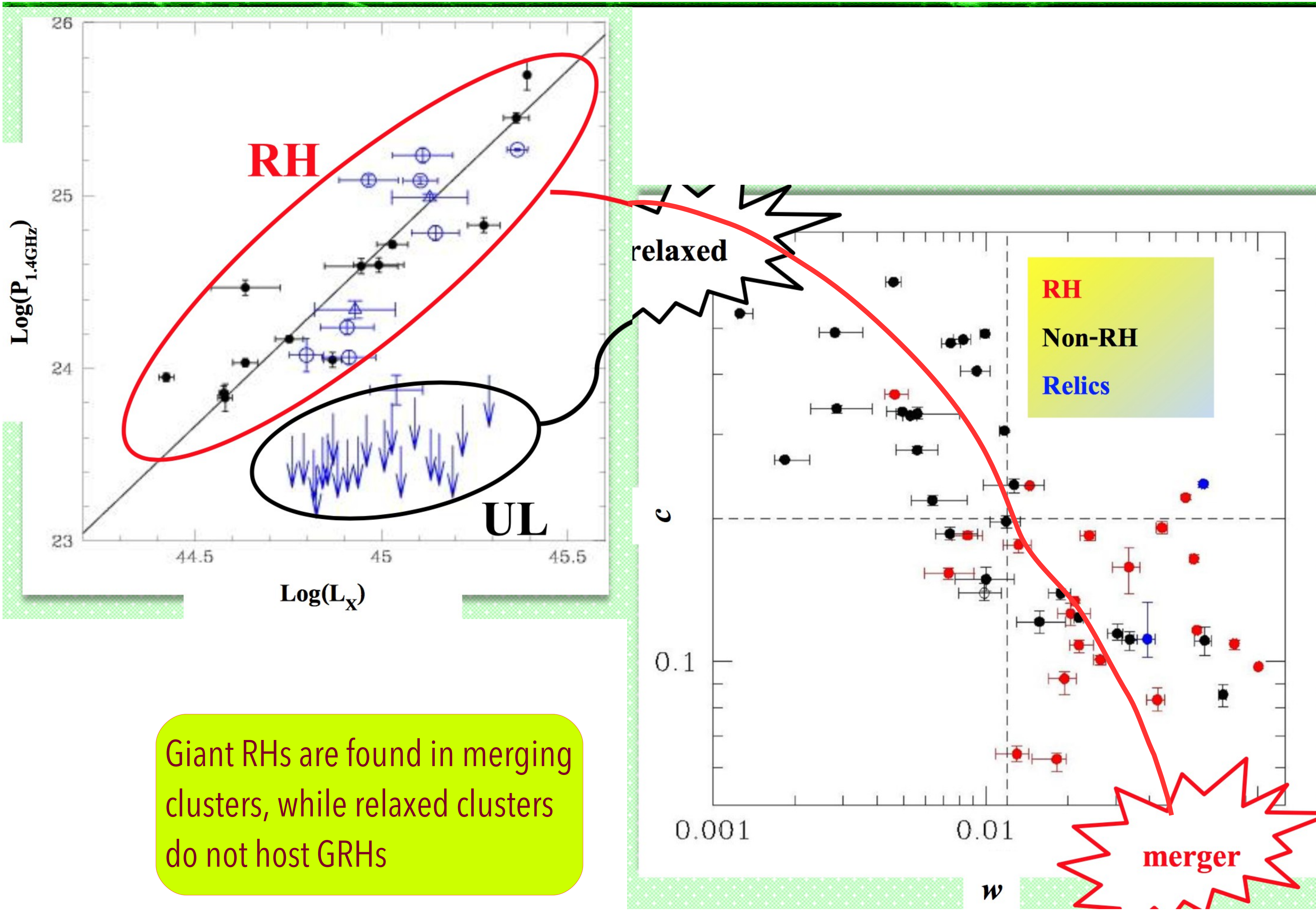
Integrated spectrum [steepening]





Models predict that a USSRH population should exist (see further)

Clusters of Galaxies :Radio Halo sources: Radio .vs. X-ray Luminosity Correlation (Radio Luminosity .vs. Mass)



Giant RHs are found in merging clusters, while relaxed clusters do not host GRHs

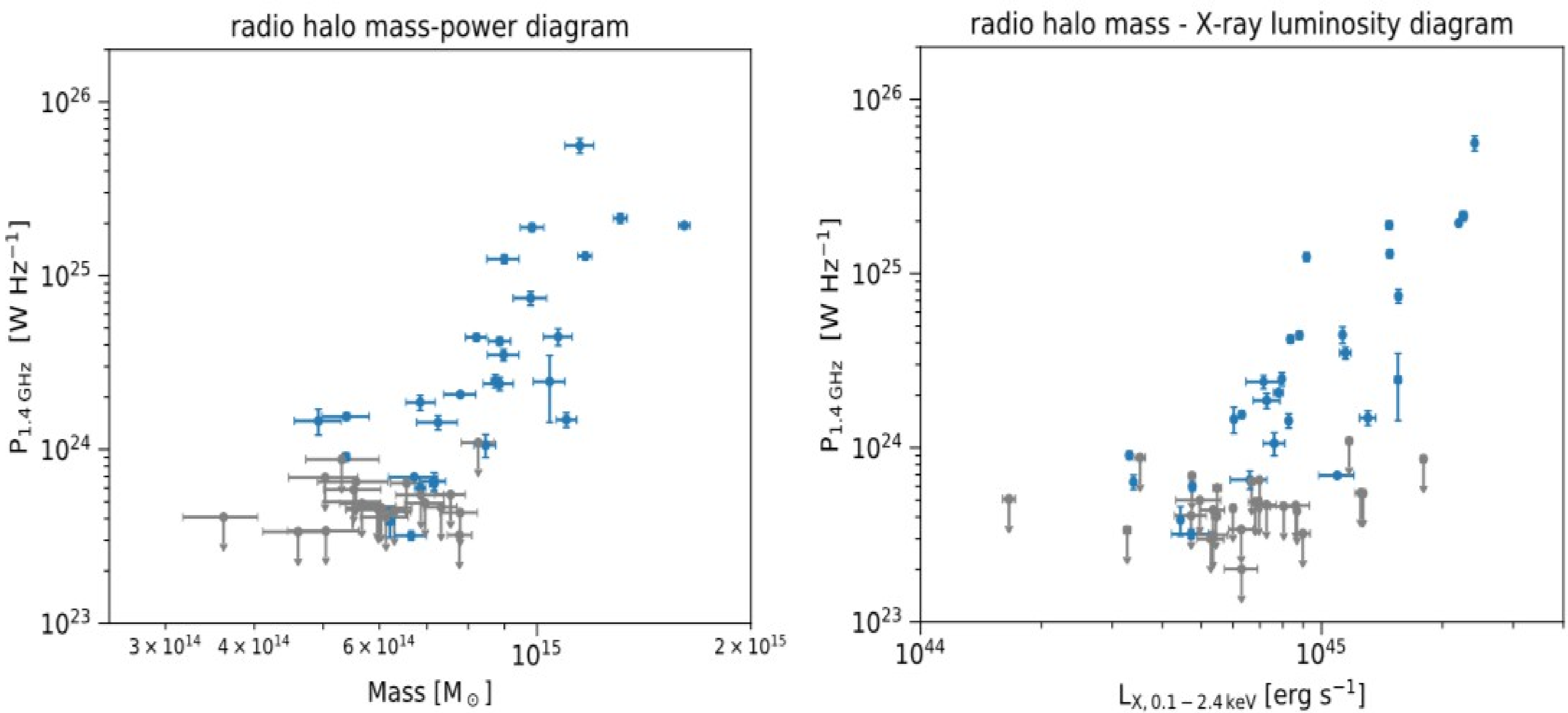
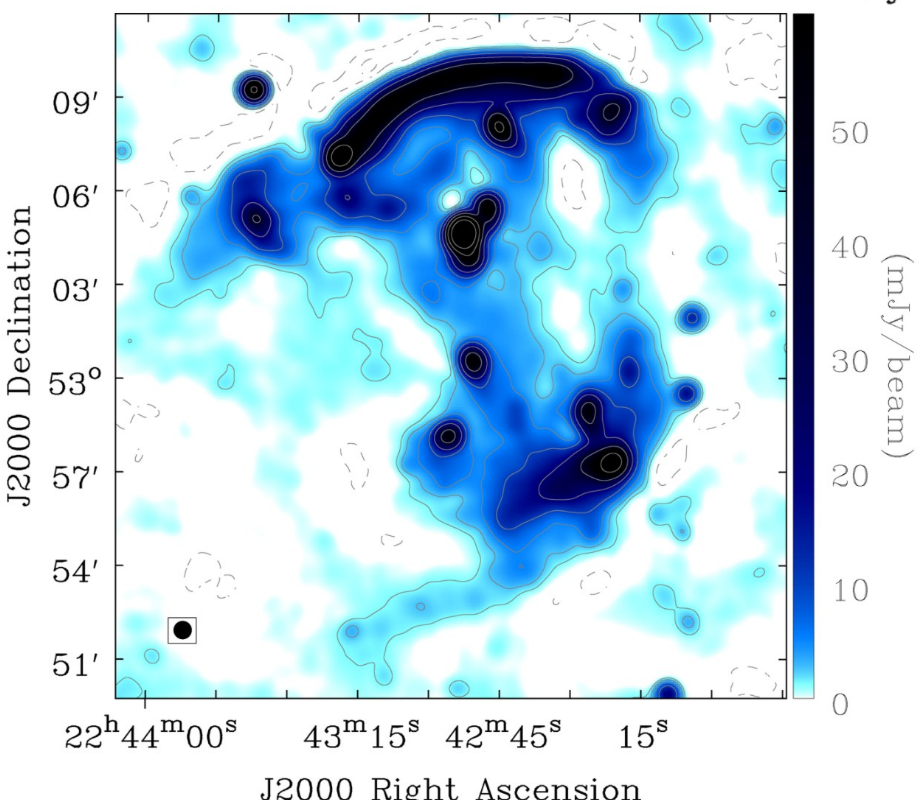
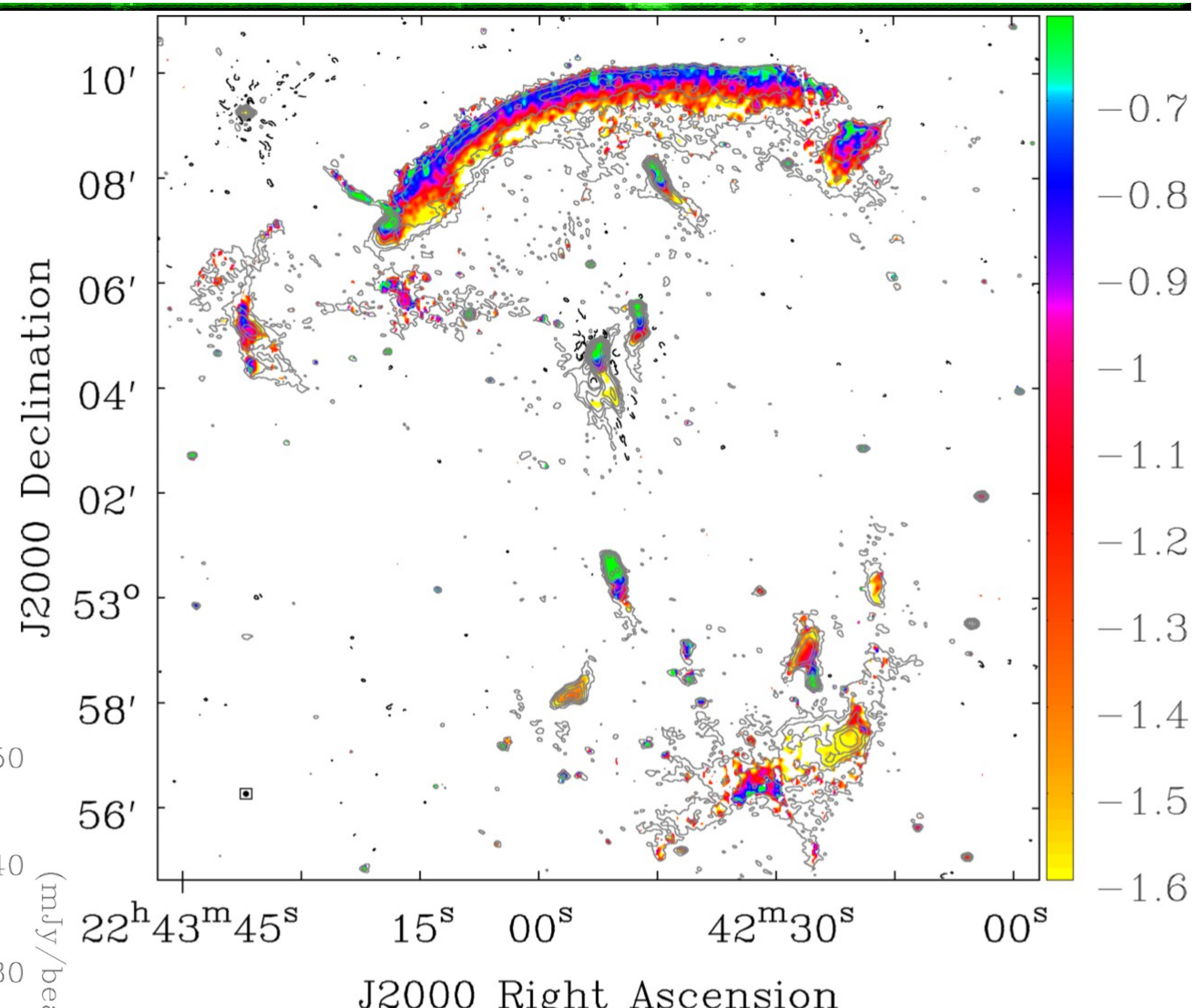


Fig. 9 Radio halos in the mass (*left panel*) and L_X (*right panel*)—radio power diagrams. Radio halos are taken from Cassano et al. (2013), Kale et al. (2015), Cuciti et al. (2018) and references therein. Cluster masses are taken from the Planck PSZ2 catalog (Planck Collaboration et al. 2016)

Radio Relic *(elongated, up to ~ Mpc long, peripheral regions, often substantially polarized)*





⇐ Relic(s) and Giant Radio Halo may coexist and may be overlapping (bridged)

Shocks traced by the outer limb

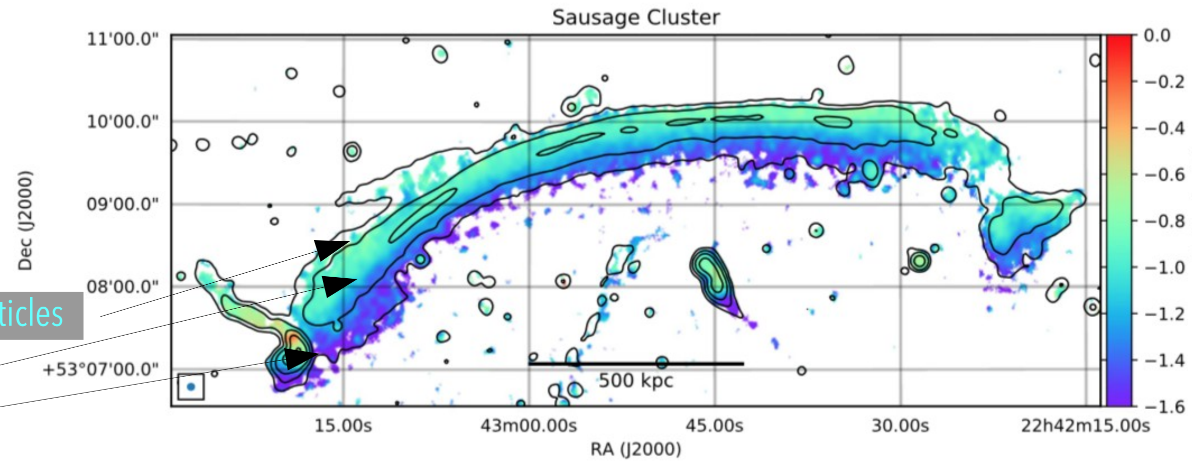
Steepening due to ageing

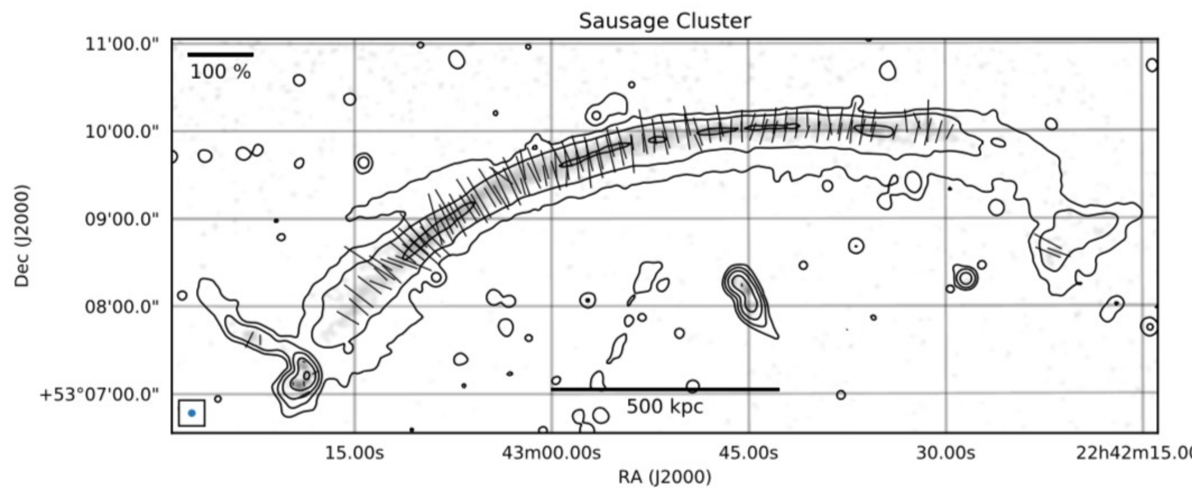
Polarization!

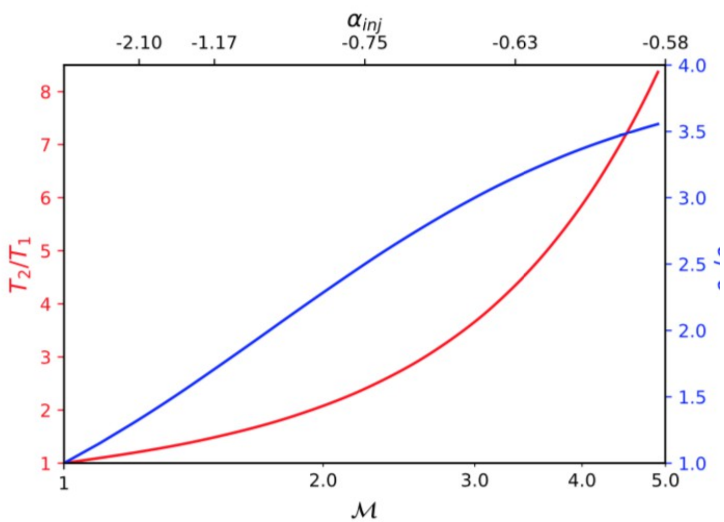
Actively accelerated particles

Ageing particles

Aged particles







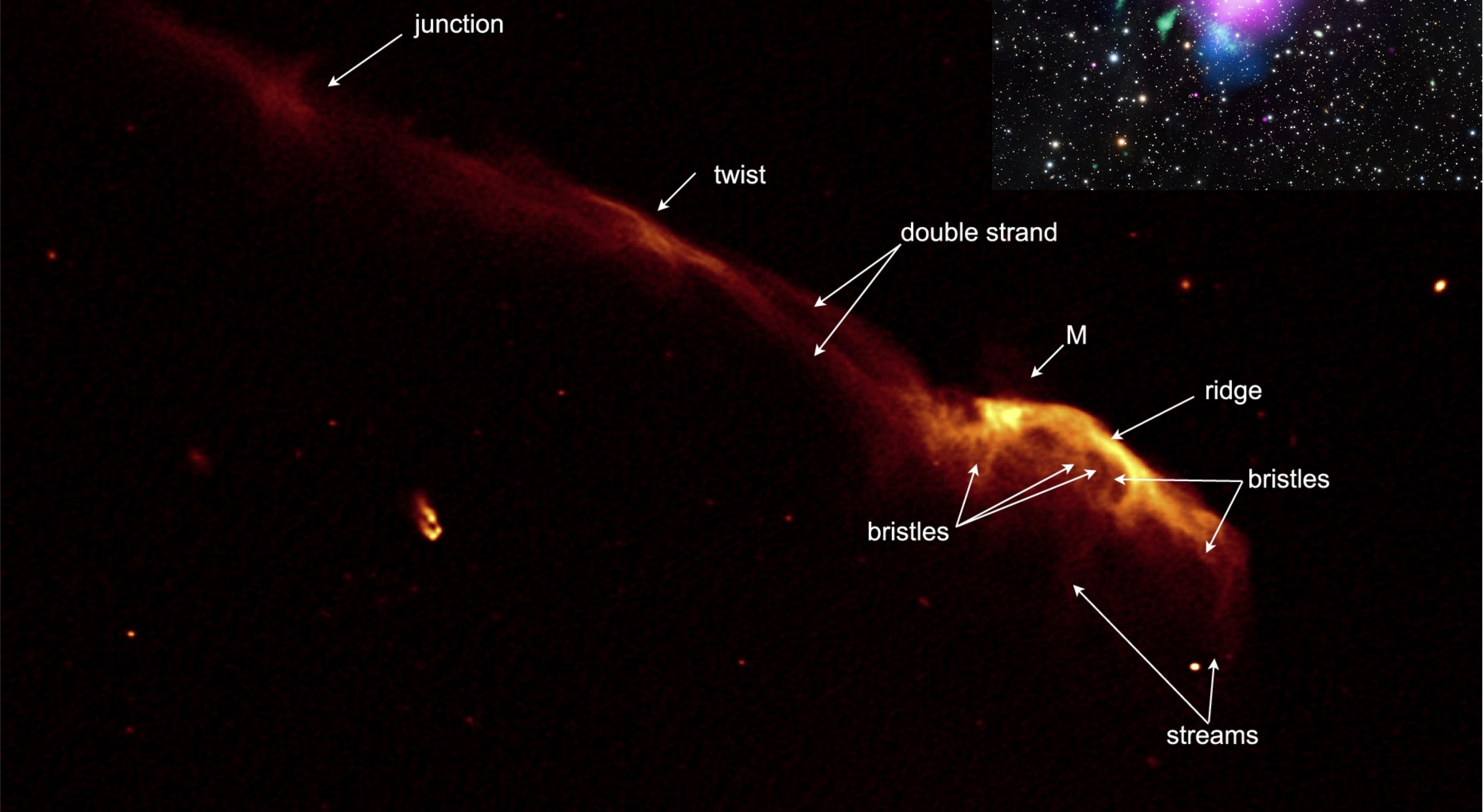
Mach number from α_{inj}

$$M = \sqrt{\frac{2\alpha_{inj} - 3}{2\alpha_{inj} + 1}} = \sqrt{\frac{2\alpha_{inj} + 3}{2\alpha_{inj} - 1}}$$

for $S(\nu) \approx \nu^{\alpha}$ \\===// $S(\nu) \approx \nu^{-\alpha}$ respectively

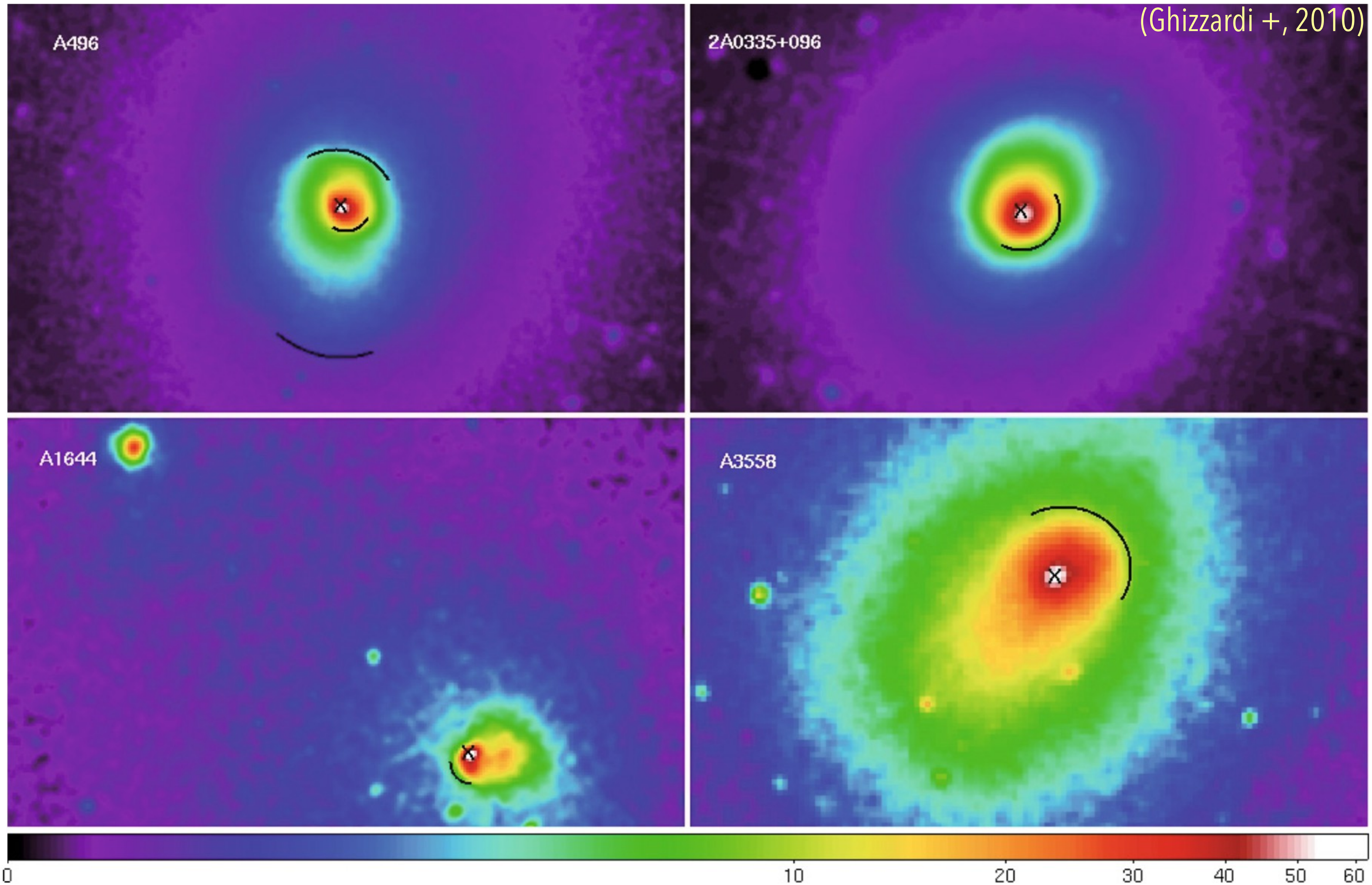
Searching for a "hot topic" in radio astronomy

Detailed morphological/polarization studies of individual relics
Toothbrush: filamentary structure: why? Changes in B?



X-ray view of Clusters of Galaxies: signatures of dynamical activity

Jumps in Surface Brightness, T, n_e ⇨ SHOCKS



A. Botteon, G. Brunetti, D. Ryu, S. Roh: Shock acceleration efficiency in radio relics

How to detect discontinuities:

Jumps in

Surface Brightness, T, n_e

⇨ *SHOCKS*

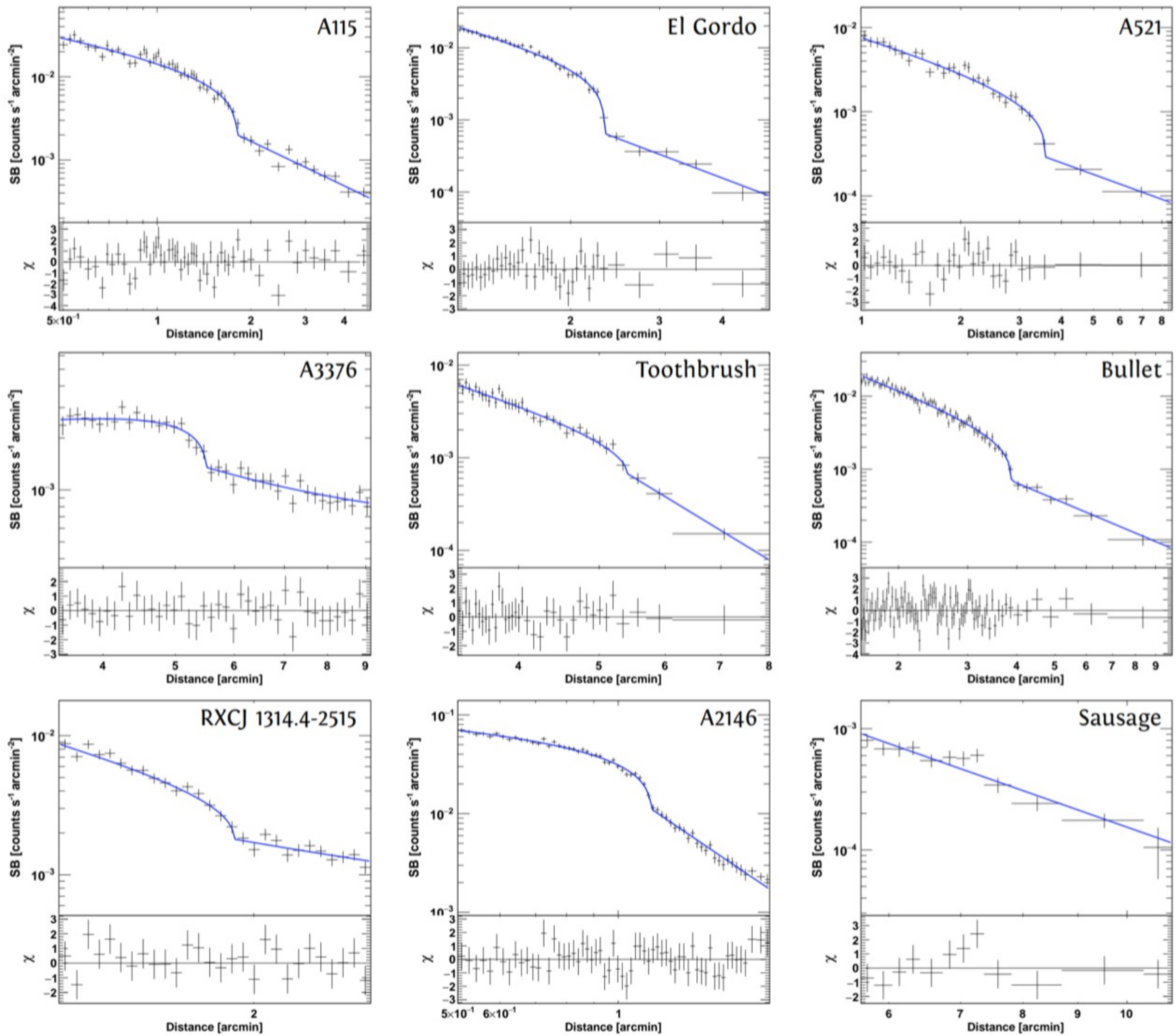
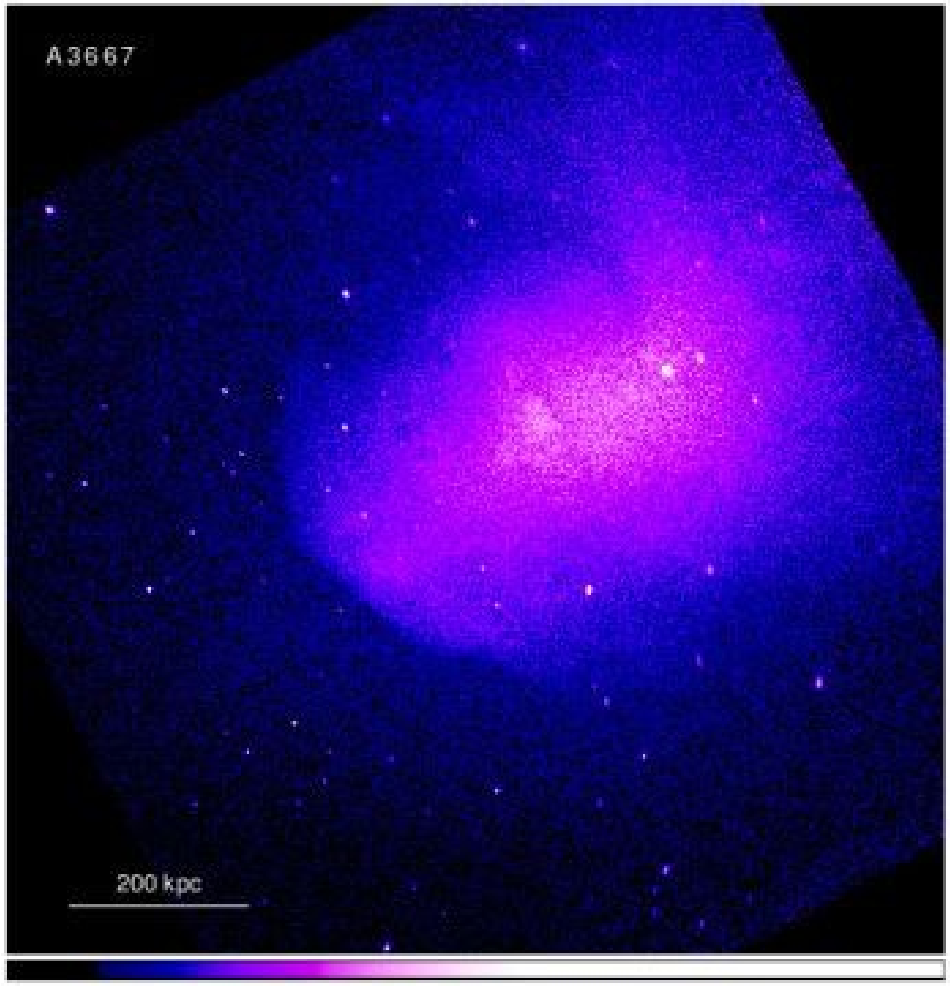
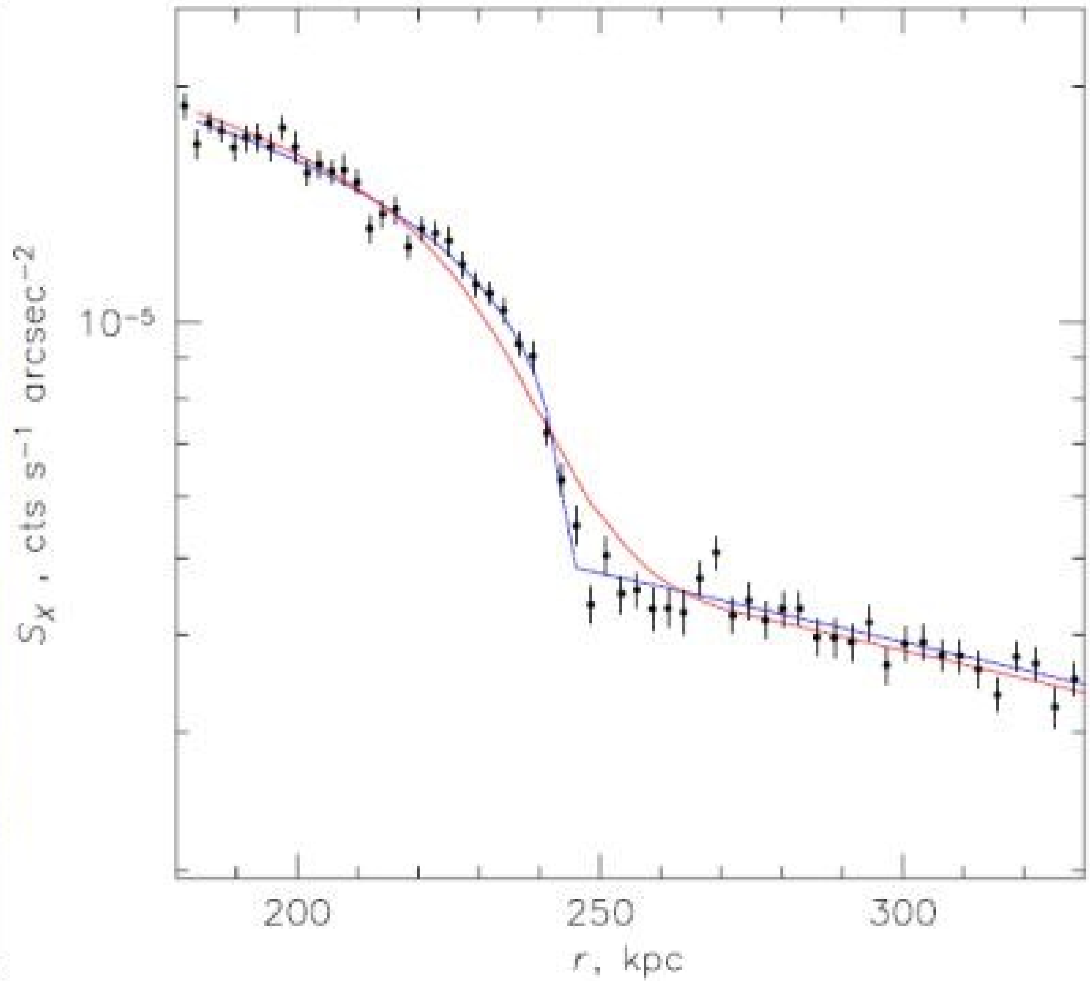


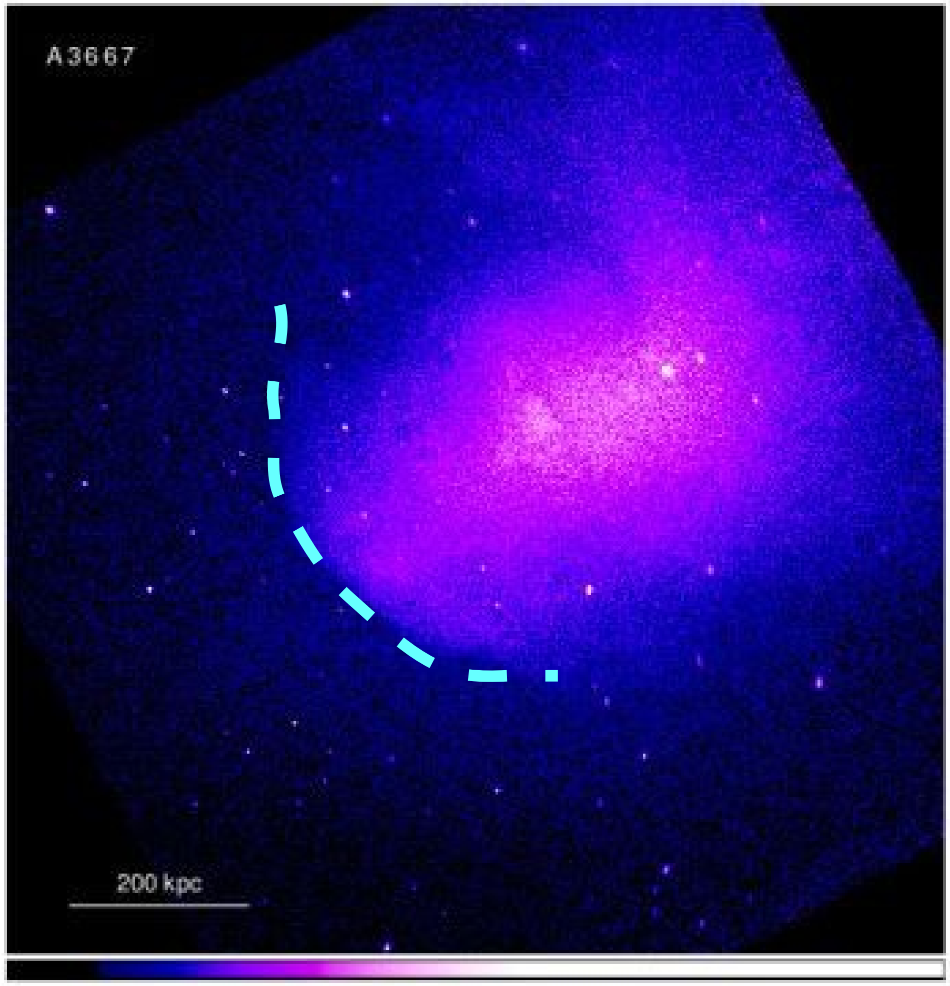
Fig. A.2. X-ray surface brightness profiles extracted across the relics in the sample. A broken power-law model was used to fit the data for all the relics but the Sausage.

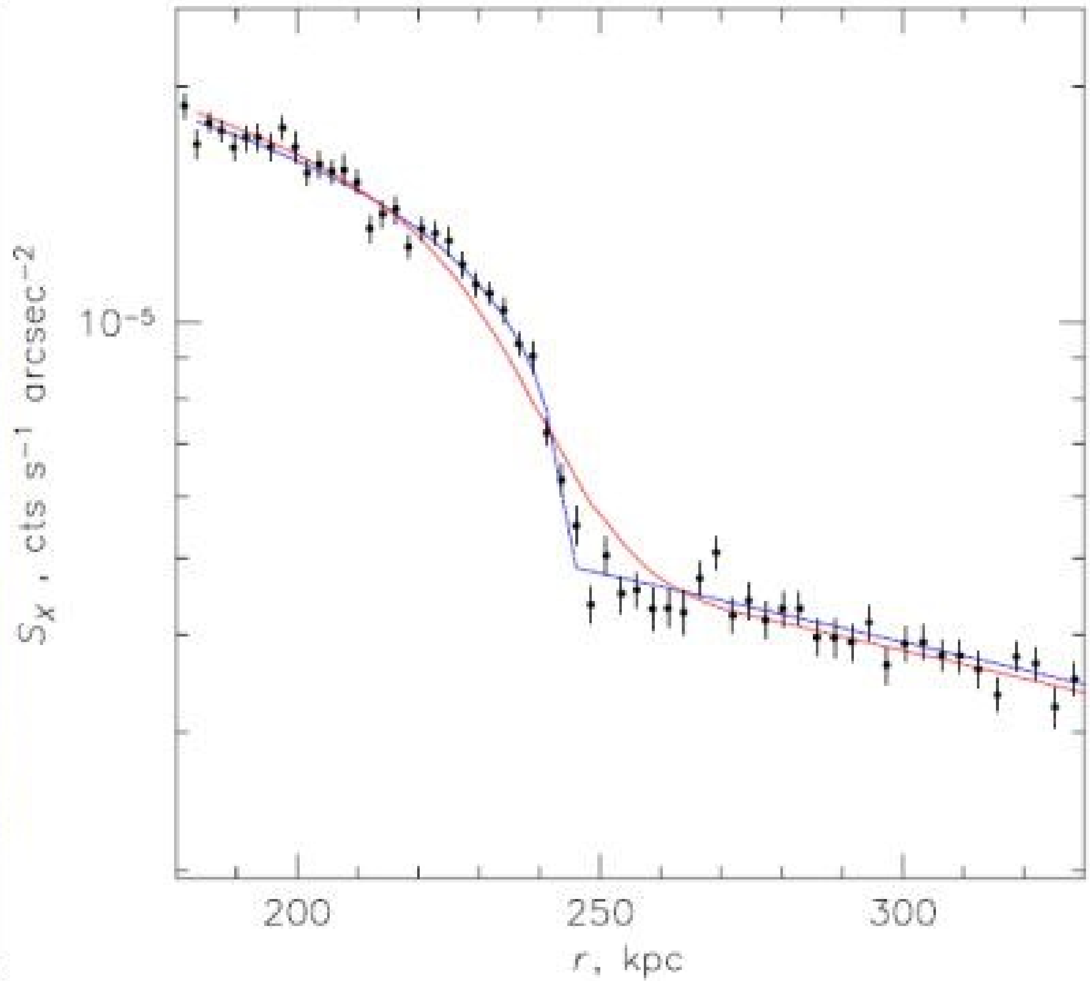
Jumps in Surface Brightness, T, n_e ⇨ SHOCKS





Jumps in Surface Brightness, T, n_e ⇨ SHOCKS





from Rankine-Hugoniot conditions

$$\frac{T_d}{T_u} = \frac{5M^4 + 14M^2 - 3}{16M^2} \qquad \frac{\rho_d}{\rho_u} = C = \frac{4M^2}{M^2 + 3}$$

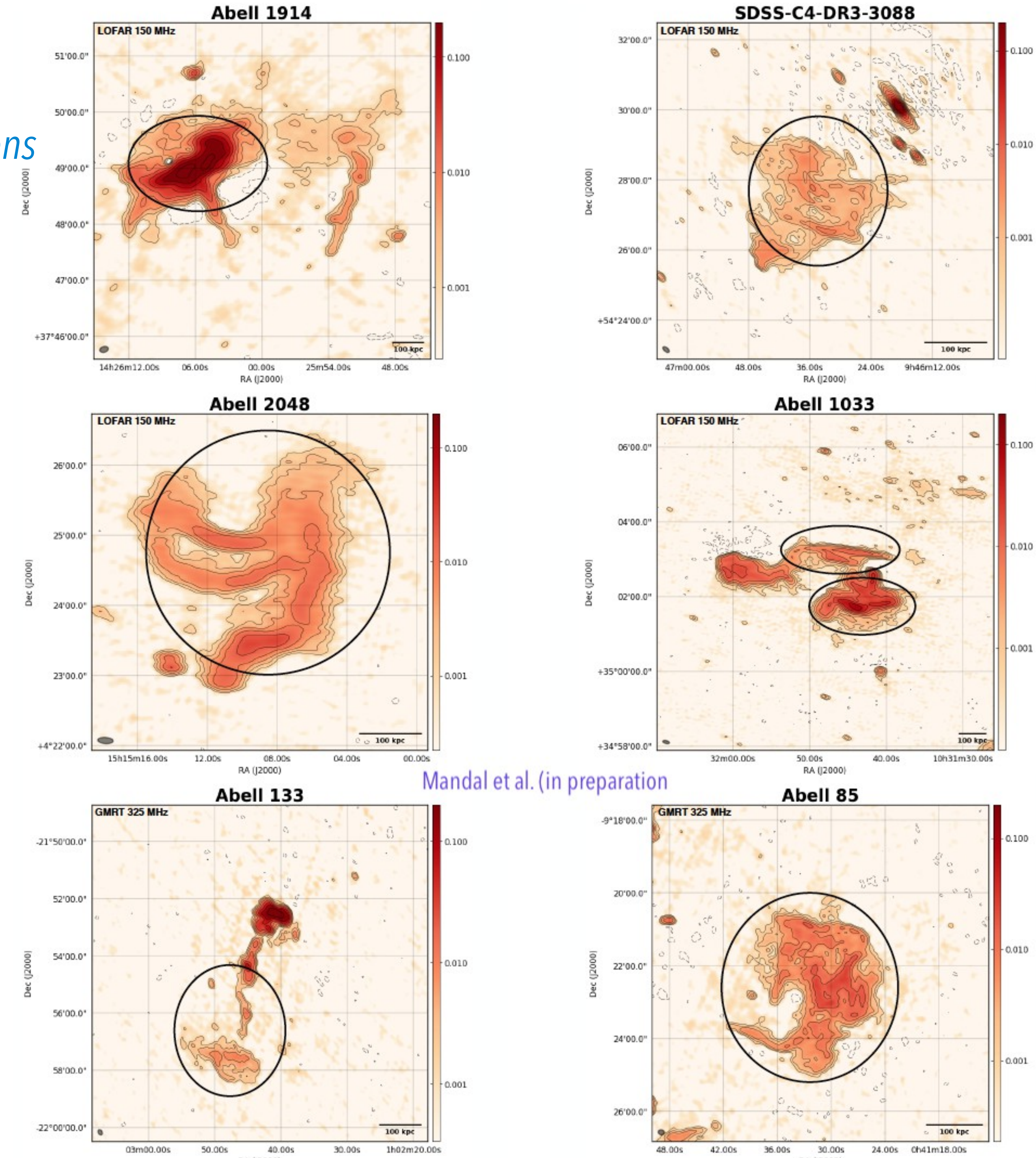
M is the Mach number

“Hot topic”: newly discovered UUSS radio sources: Phoenices

Low frequencies sample “long living” electrons with relatively modest Ä .

Sources visible below 200 MHz
Must have a sharp cutoff

Old population of “dying” electrons ?
Fossil electrons revived by some process?



Mandal et al. (in preparation

"Hot topic": newly discovered UUSS radio sources: Gently ReEnergized Tailed sources [GreETs]

Low frequencies sample "long living" electrons with relatively modest γ .

These particles are border-line with being insterted into the CR travelling in the cluster

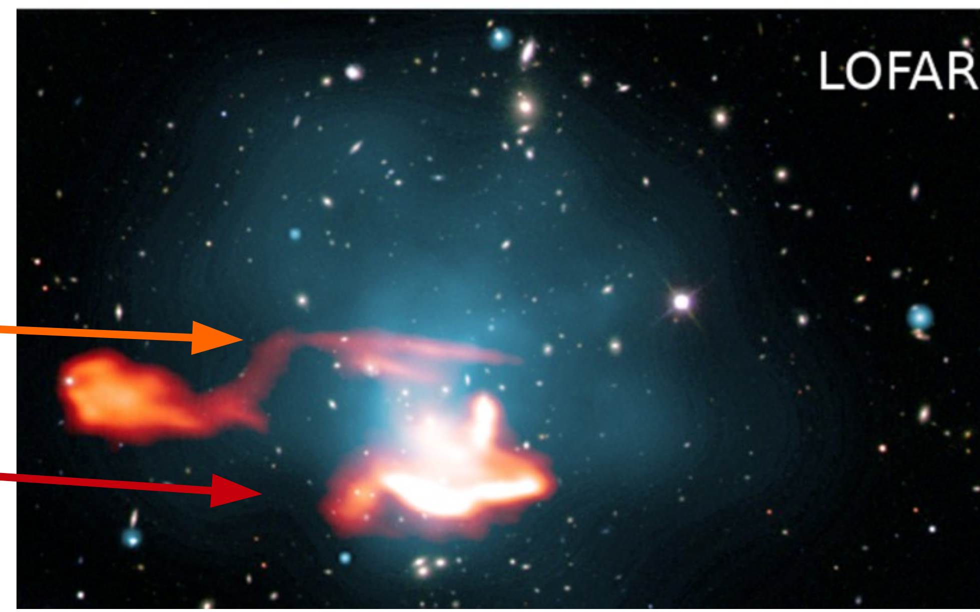
Some may be the seed particles to be accelerated

Example of

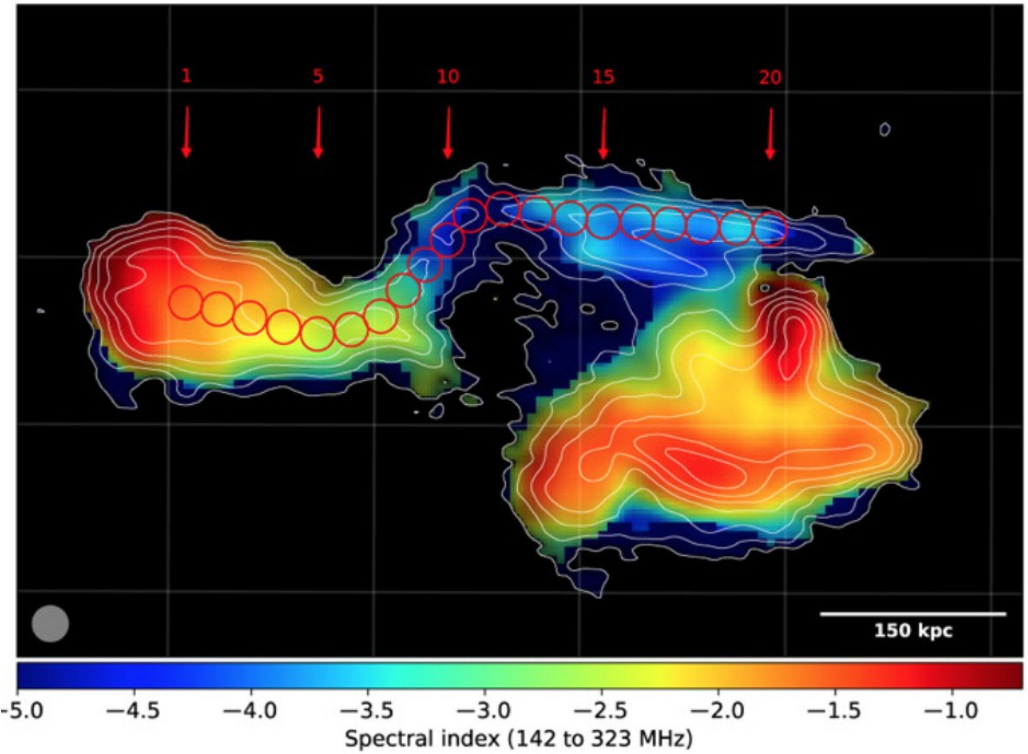
a **GReET**

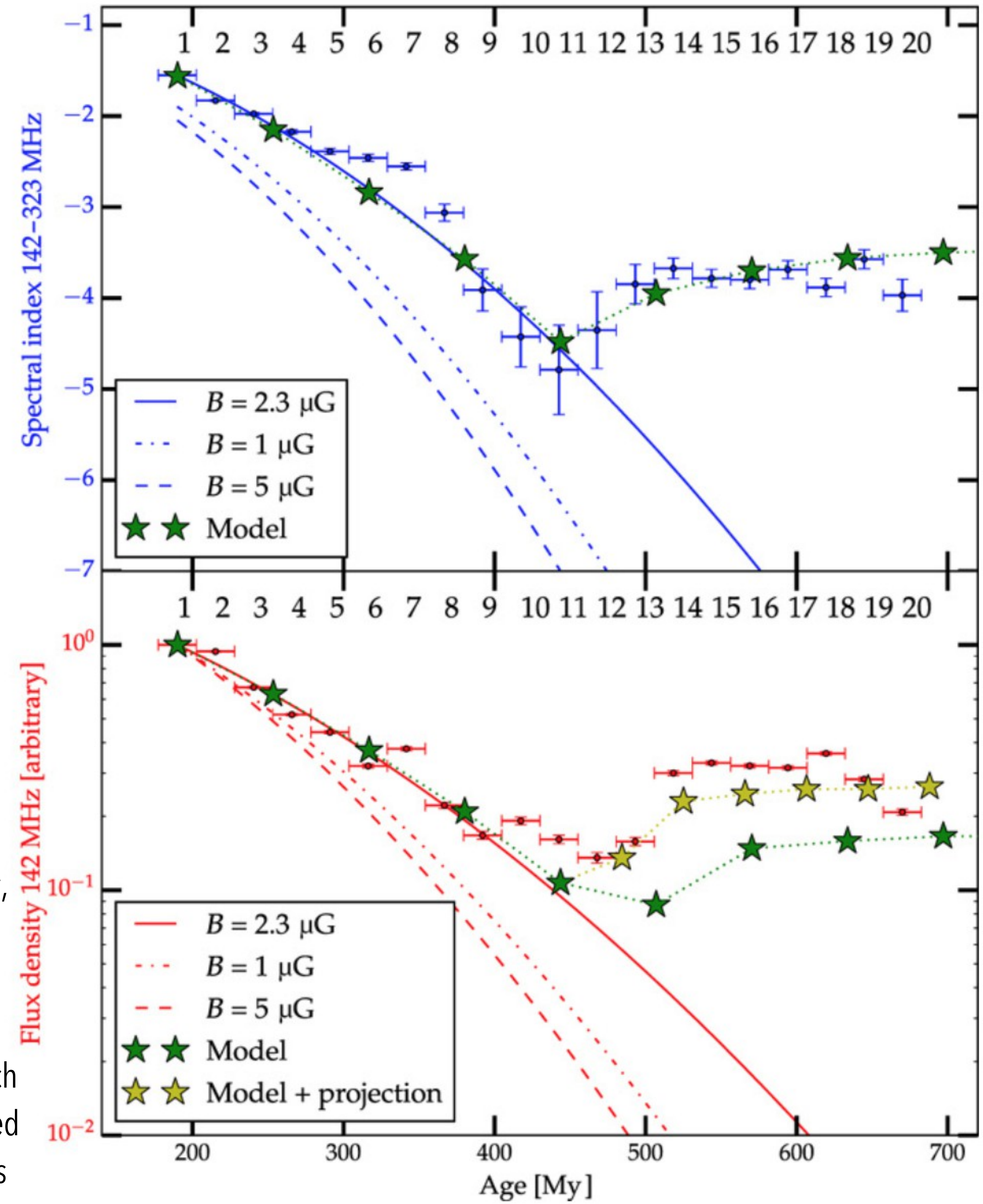
and

a **Phoenix**



“Hot topic“: newly discovered UUSS radio sources: Gently ReEnergized Tailed sources [GreETs]





Spectral index map of the radio emission in Abell 1033.

(**Left**) Spectral index values (142 to 323 MHz) of the radio emission.
To trace the evolution of the spectral index along the tail of the WAT radio galaxy, we defined 20 beam-sized regions. (**Right**) Each point in the plot is associated with one region defined in the left panel. Lines show the spectral index and the 142-MHz flux density predicted by a model, assuming three possible values for the magnetic field. The position of point 1 has been shifted on the *x* axis to match the model spectral index for the 2.3-ÕG case, and the age axis has been stretched to fit the spectral index data (reflecting the unknown galaxy speed). Star markers in the plot show the expected spectral index and flux density if a gentle reacceleration starts at 450 My. Green stars assume no projection effect, while yellow stars assume a 40° inclination of the tail with respect to the line of sight. (from De Gasperin et al. 2017)

A. – Acceleration of seed electrons

1. from the "thermal pool"
2. pre-esisting CRs
3. fossil plasma

Via Shocks (i.e. mainly Fermi – I) and Turbulence (mainly Fermi - II)

***B. – Secondary electrons** (+ positrons)*

Gamma rays from π^0 particles decay are expected but not observed so far.
Upper limits in FERMI and ground based observations imply at most a few % in terms of their contribution to the total energy content.

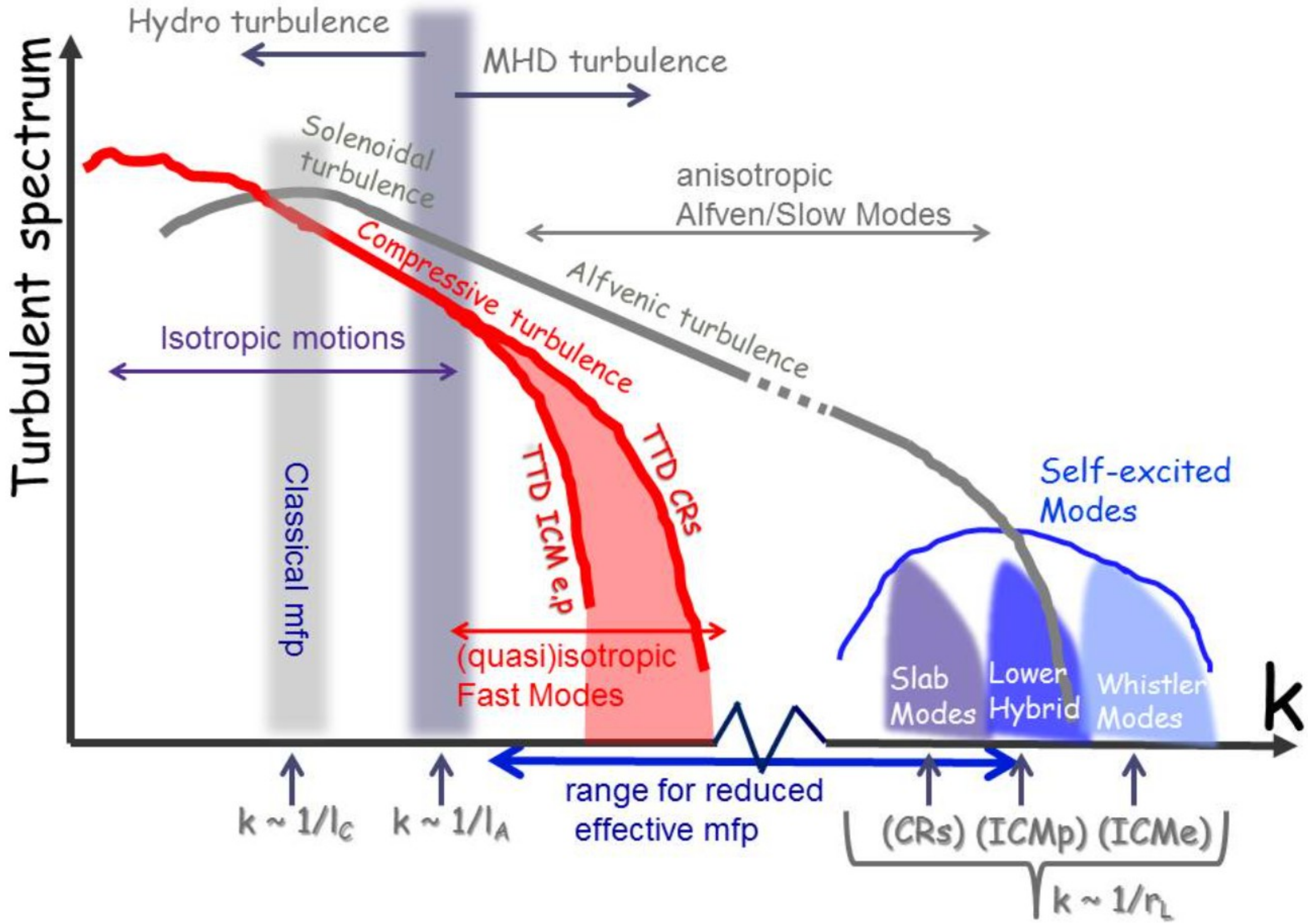


Fig. 6. A schematic view of turbulence in the ICM. The transition from hydro- to MHD turbulence is marked (see text). The expected spectral features of both solenoidal and compressive turbulence generated at large scales are illustrated : solenoidal turbulence develops an Alfvénic cascade at small (micro-) scales whereas the compressible part (fast modes in the MHD regime) is presumebly dissipated via TTD resonance with electrons and protons in the ICM (or eventually via TTD resonance with CRs in case of reduced effective mean free path, see text). A schematic illustration of relevant examples of "self-excited" modes, excited via CRs- or turbulent-induced instabilities, is also shown together with the relevant scales: slab modes, lower hybrid electrostatic waves, and whistler waves (see text). A schematic illustration of the scales of the Alfvén scale, l_A, classical mean-free-path due to Coulomb ion-ion collisions, l_C, and reduced particles mean-free-path is also given.

Brunetti & Jones (2014)

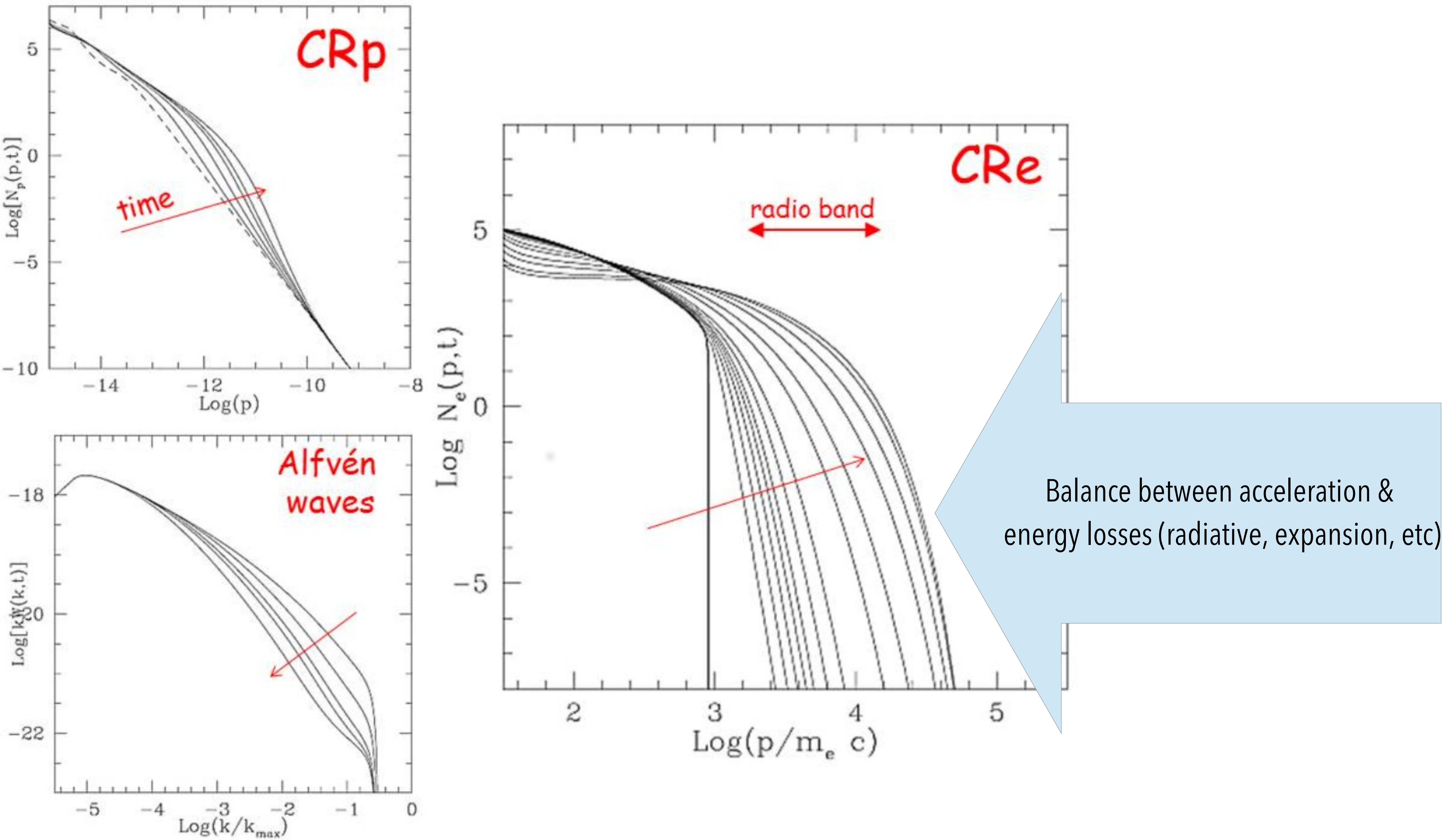
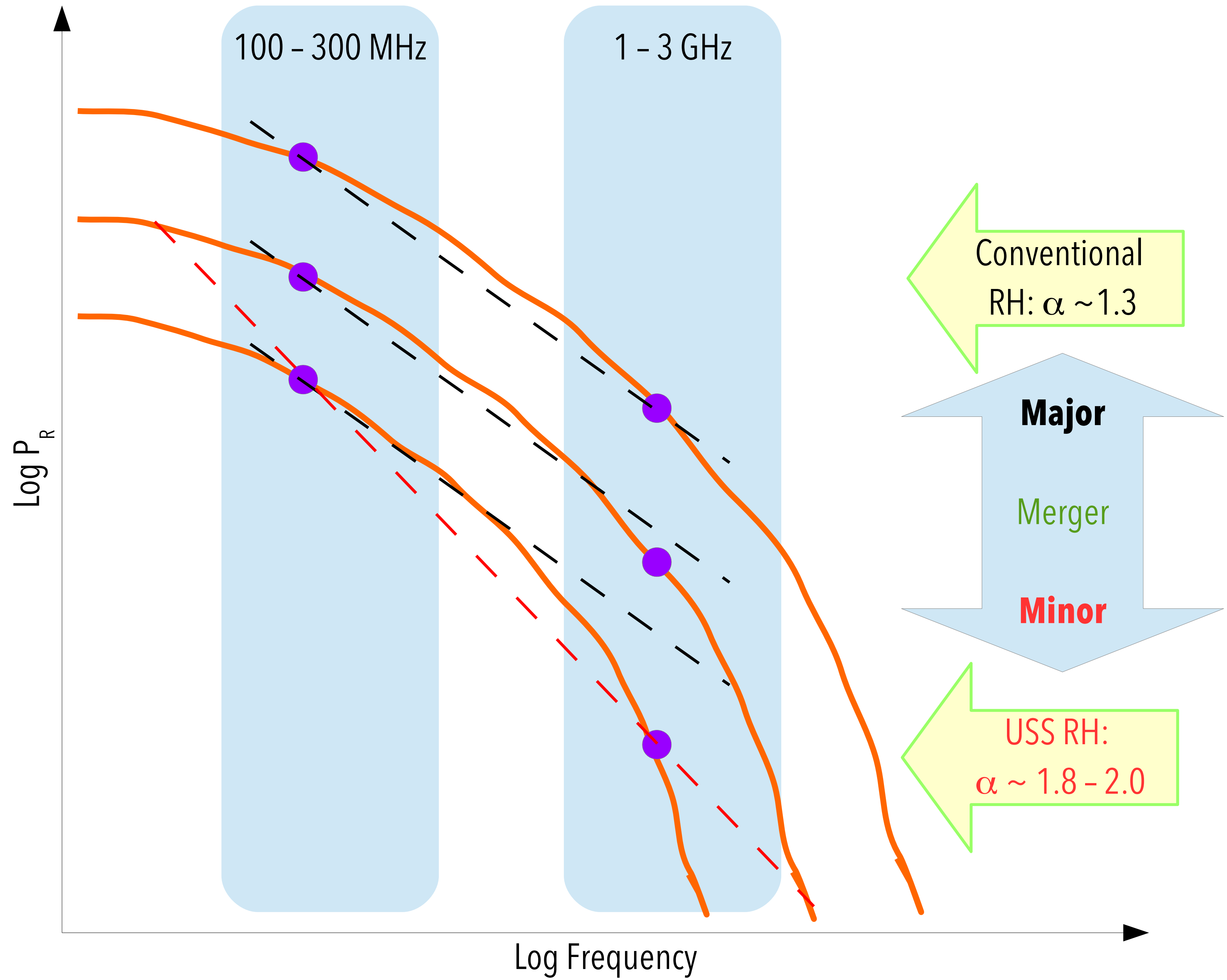


Fig. 7. The coupled evolution with time of the spectra of CRp (upper-left; p is in cgs units), CRe (right) and Alfvén waves (bottom-left); Alfvén waves are continuously injected assuing an external source (adapted from[174]). Panels highlight the non-linear interplay between the acceleration of CRs and the evolution of waves that, indeed, are increasingly damped with time as they transfer an increasing amount of energy to CRs. Saturation of CRe acceleration at later times is due to the combination of radiative losses and the damping of the waves that limits acceleration efficiency.

Brunetti & Jones (2014)

Clusters of Galaxies :Radio Halo sources: standard and Ultra Steep – Spectrum (Brunetti + 2008, Nature)



Mini-Halo: electrons from AGN (cD); sloshing possibly plays a role

Radio Halo: turbulent acceleration as from mergers

Radio Relic: low M shock acceleration of fossil plasma

- *Diffusion time (e.g. for CR) is ~ 10^9 yr, exceeding the radiative lifetime (~ 10^8 yr)*

- *Need for: in situ (re –) acceleration of electrons*
- *What about their origin? Primary/Secondary e– ? Fossil plasma? ... implications (see Brunetti & Jones)*

  ... Longstanding debate, many questions still open

- *Relaxed clusters may host a mini-halo*
- *Merging clusters may host a radio-halo and/or radio relic(s)*

- *Energy from mergers converted into particle acceleration via low M shocks*
- *Spectral index of the halo depending on the mass ratio and total energy (Normal .vs. USS RH)*

Radio Halo sources

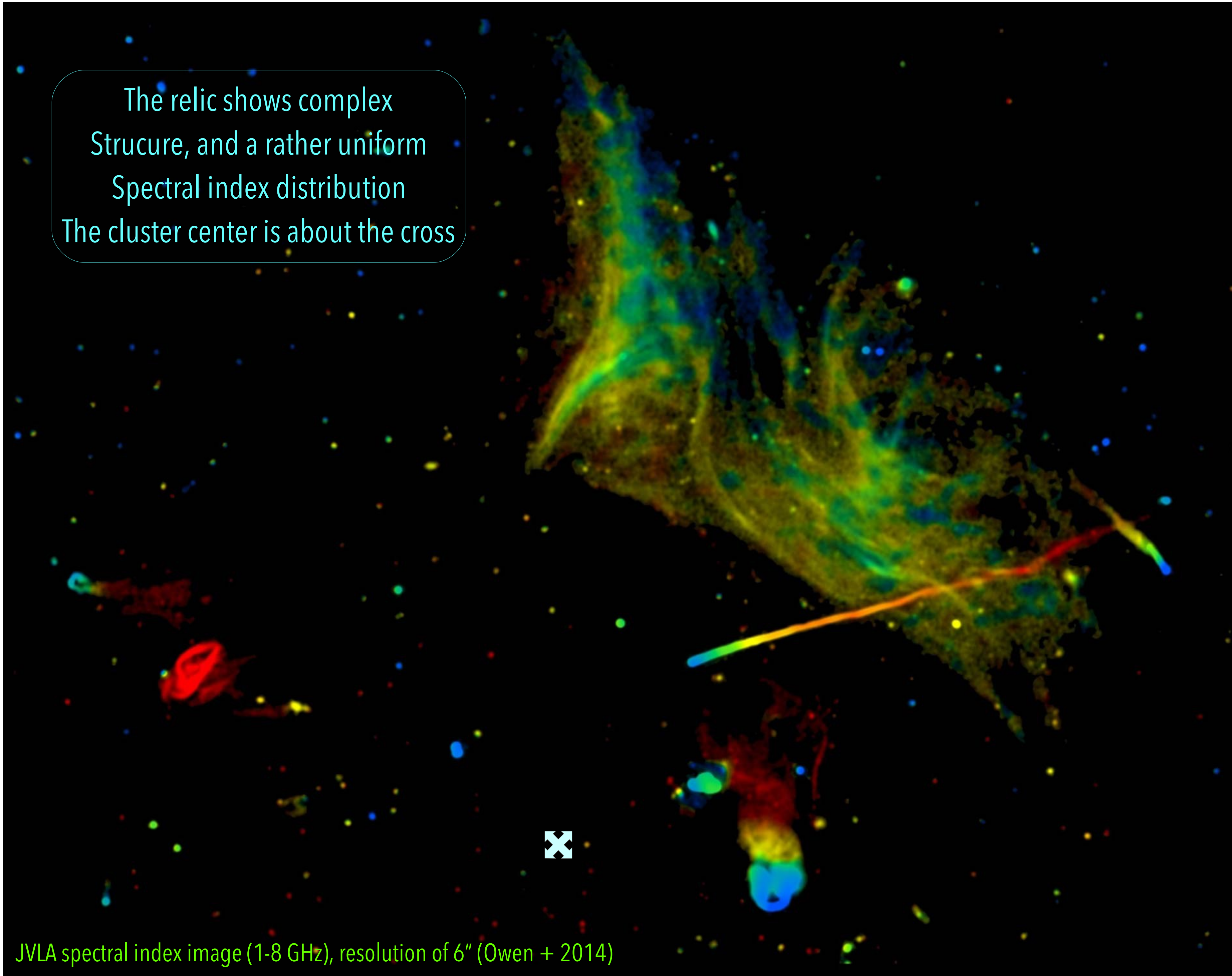
- Low surface brightness
- Steep spectral index (~ 1.3, but also 1.8-2.0 -> USSRH), relatively uniform across the whole radio emitting region
- No polarization

Relic radio sources

- Elongated, at peripheral regions of clusters. Active acceleration surface best visible.
- SPIX gradient from ~1.0 to 1.5 and more.
- Polarized!

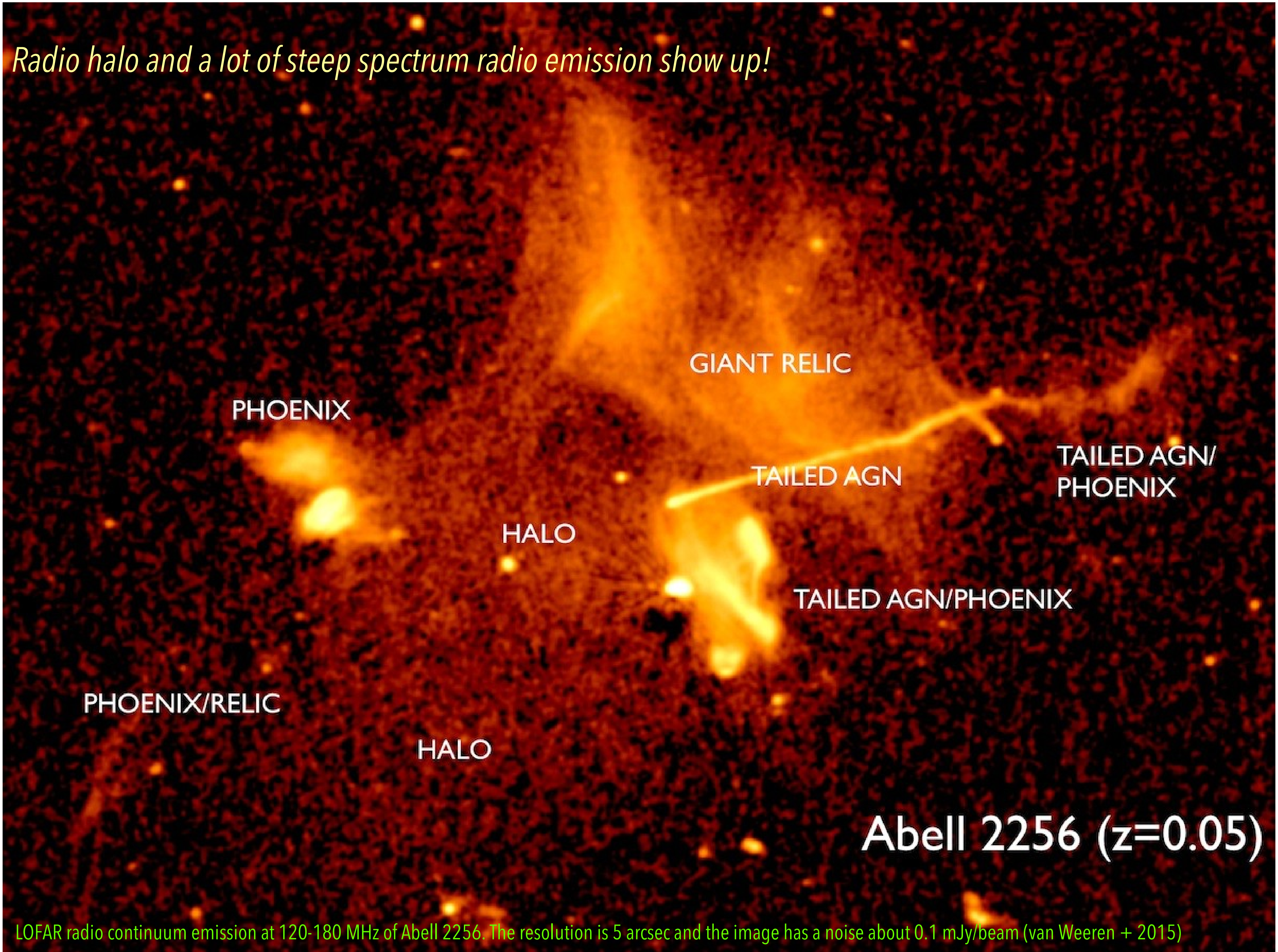
Steep synchrotron radio spectrum: ALL are best studied at low frequencies (e.g. LOFAR!) given the steep spectral index and uv-coverage of Interferometric observations.

Abell 2256: A relic which is not seen edge on?



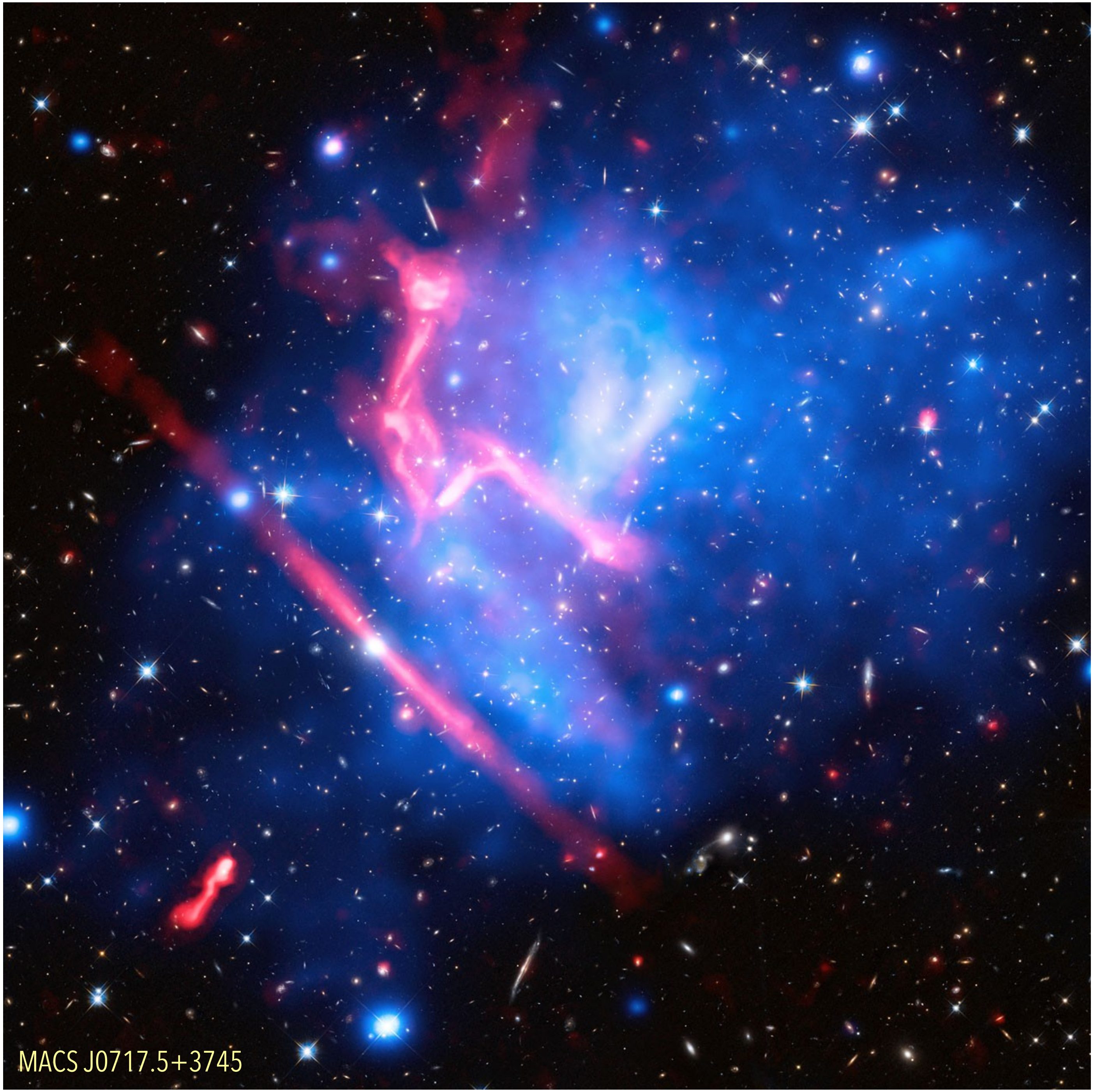
 Extended time! Abell 2256: A relic which is not seen edge on?

Radio halo and a lot of steep spectrum radio emission show up!



LOFAR radio continuum emission at 120-180 MHz of Abell 2256. The resolution is 5 arcsec and the image has a noise about 0.1 mJy/beam (van Weeren + 2015)

Searching for a "hot topic" in radio astronomy (1)



Searching for a “hot topic” in radio astronomy (2)

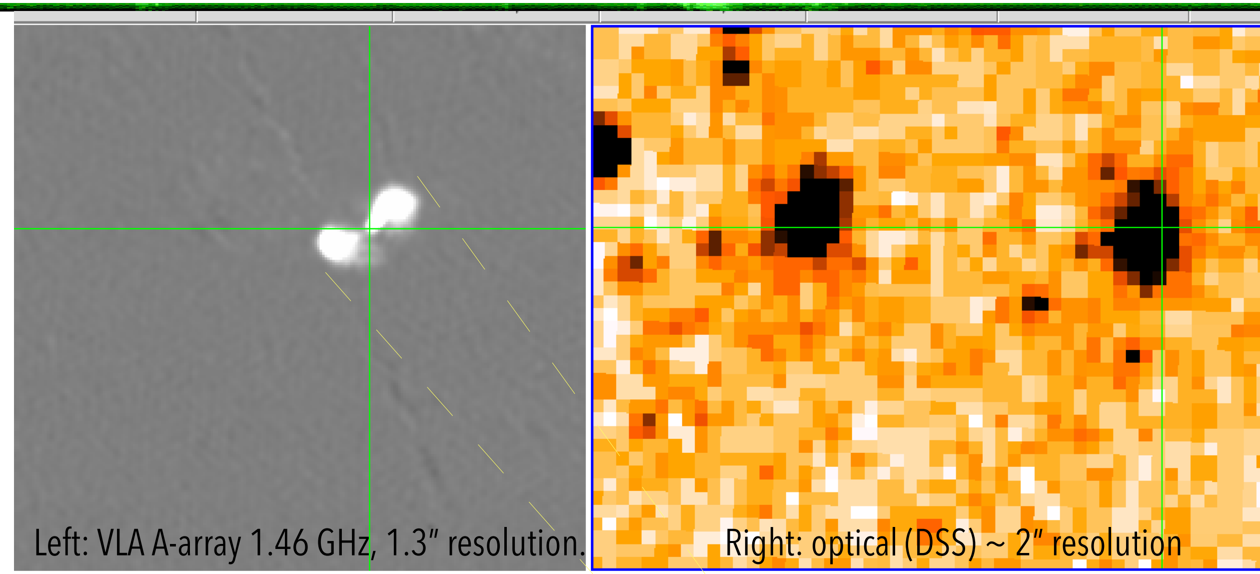
Abell 1682 @ z = 0.2259

Individual radio galaxies & diffuse emission

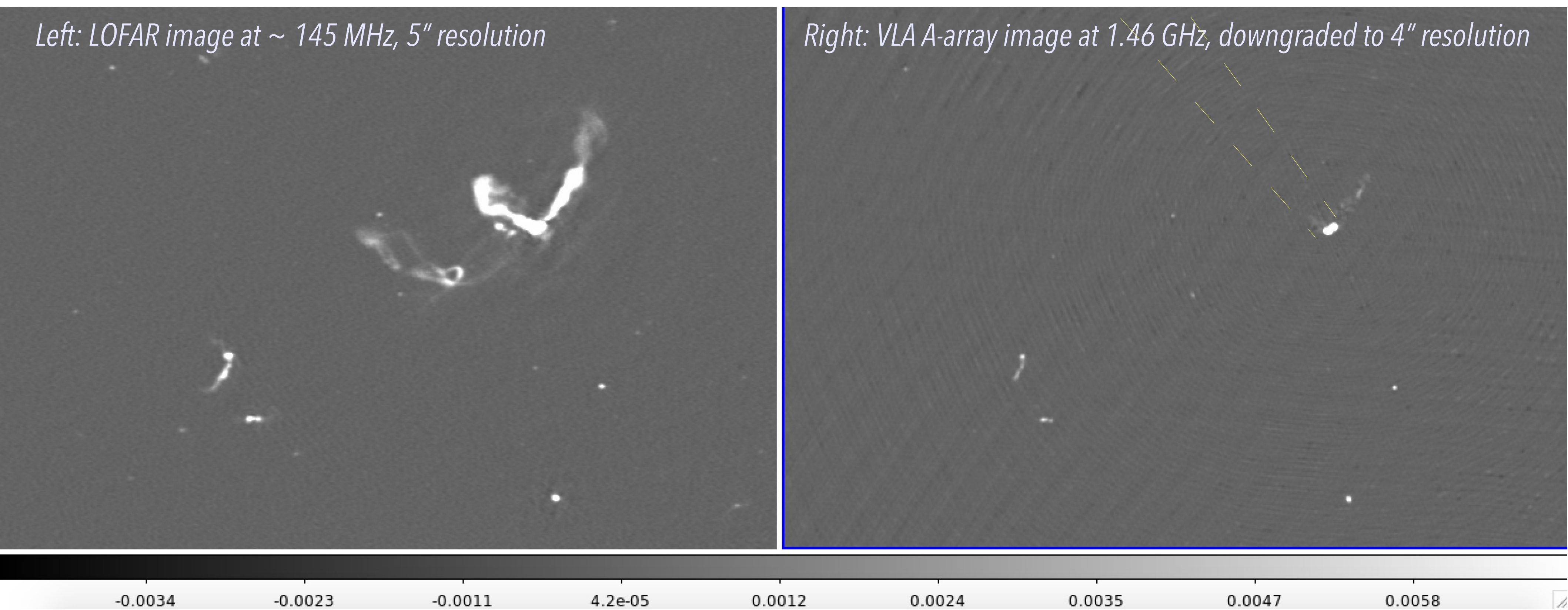
Low-frequency tails are relic emission?

A new active cycle has begun in the AGN?

Fossil plasma accelerated by turbulence?



Left: VLA A-array 1.46 GHz, 1.3″ resolution. Right: optical (DSS) ~ 2″ resolution

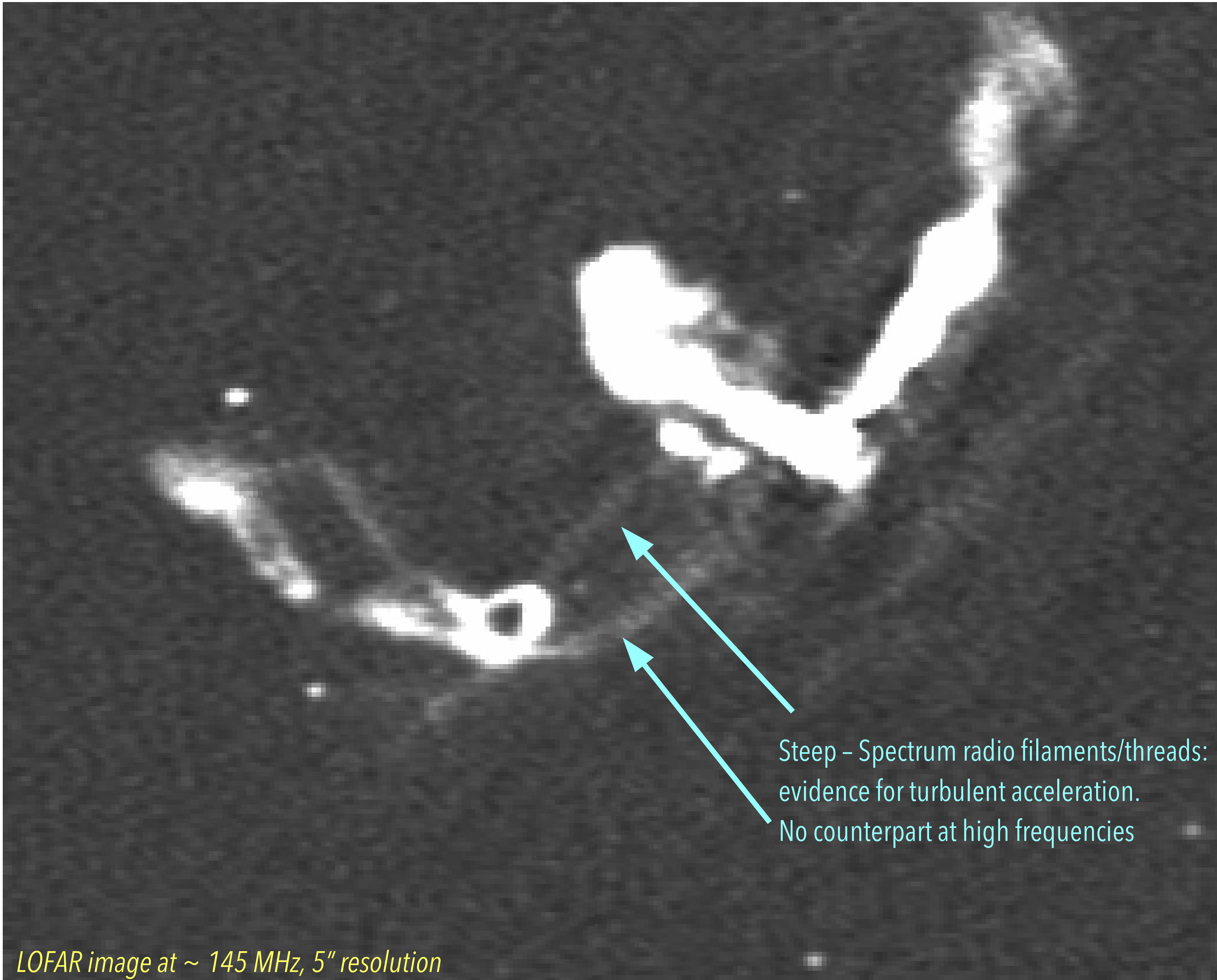


Left: LOFAR image at ~ 145 MHz, 5″ resolution

Right: VLA A-array image at 1.46 GHz, downgraded to 4″ resolution

Radio view of Clusters of Galaxies

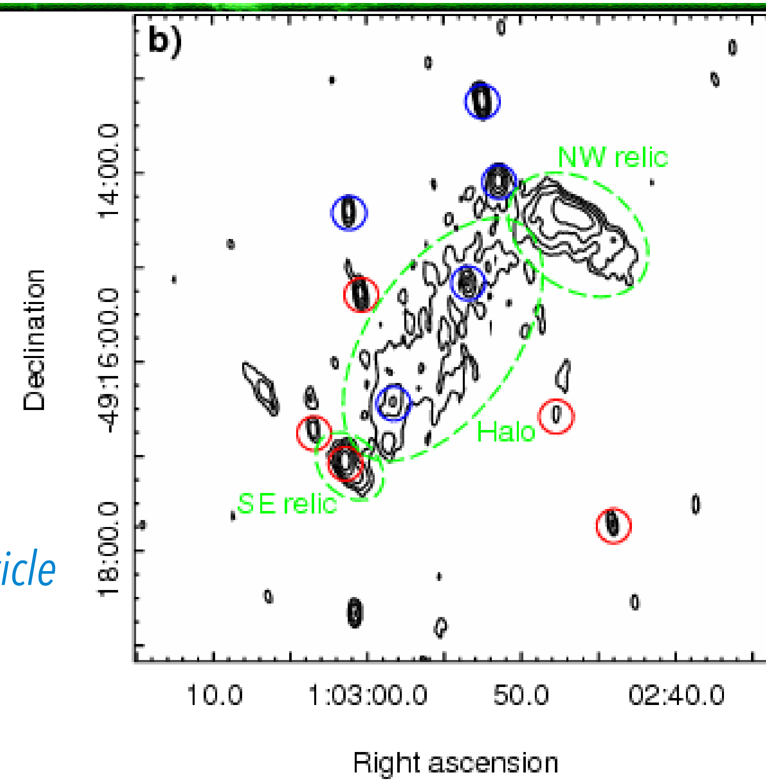
Abell 1682
@ z =0.2259

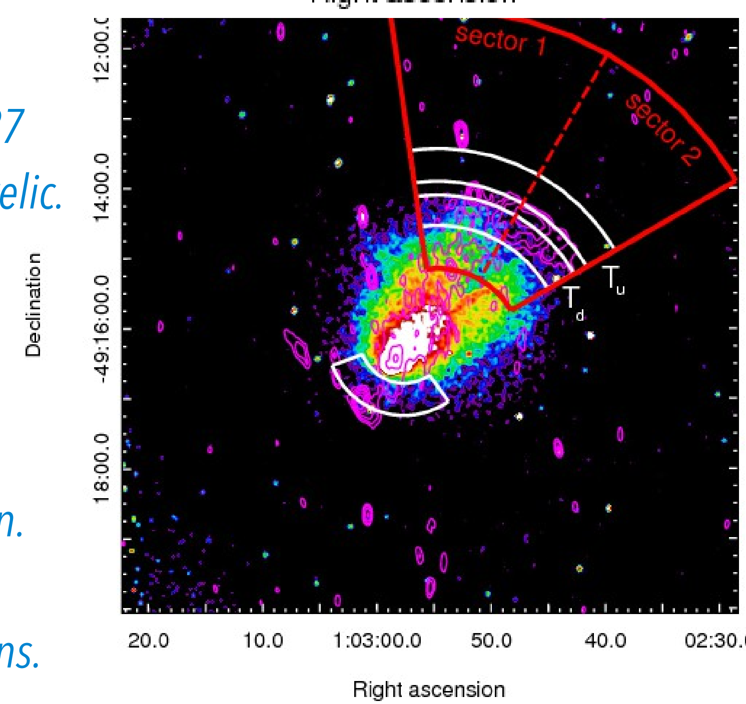


EXAMPLE: of “hot topic” in radio astronomy: El Gordo cluster at z=0.87, and relic – shock connection

Botteon et al. 2016

The X-ray SB profile abruptly drops at the relic location.
The density compression factor C ~ 3 and the high downstream temperature provide the indication of a strong shock (M ~ 3) in the ICM.
This is one of the three strongest shocks detected in galaxy clusters and the most distant (z = 0.87) observed so far.
The detection of a shock co-spatially located with a relic strongly supports the relic–shock connection. The NW shock in ‘El Gordo’ cluster allows to study particle acceleration in a rare regime of strong shock.
DSA of thermal electrons is consistent with measured synchrotron spectrum. Nonetheless, only shocks with M > 3.5 appear energetically viable while for weaker shocks re-acceleration models would be preferred.
The presence of relativistic particles emitting a bright synchrotron relic at z = 0.87 makes ‘El Gordo’ a suitable cluster candidate to search for IC emission from the relic.
From the X-ray spectral analysis we obtained possible hints for IC emission from the relic, however we could not firmly conclude the presence of IC excess and conservatively we derived only lower limits to the downstream magnetic field that have been used to improve constraints on particle acceleration. However, we also found hints of an excess in the 0.5-2 keV SB profile across the relic region.
The combination of a possible IC excess in the spectral analysis with the hints of excess in the SB is tantalizing and certainly deserves deeper Chandra observations.





Summary of the summary.

- *Definition/Composition*
  Dark matter, galaxies, gas (thermal & relativistic components), magnetic field

- *Relevant parameters*
  Mass & Luminosity
  Morphological Classification (Relaxed .vs. Unrelaxed. Radio galaxies, environmental influence, BGC emission, NAT & WAT)

- *Astrophysical problems:*
  Diffusion time for relativistic particles
  Total energy content (CR, H, Thermal)

- *Particle acceleration (low Mach numbers, large regions: DSA .vs. Reacceleration) and shocks (cold fronts)*

- *Beyond the suggested literature for the exams, search for the papers by Bonafede, Botteon, Brunetti, Cassano, Cuciti, Vazza, (LOFAR), etc*

Possible topics for a thesis in radio astronomy (partial selection, incomplete list of local people)

- *Masers (@Arcetri, J. Brand)*
- *Radio stars (@Catania, G. Umana, C. Trigilio)*
- *Pulsars, **FRB** (@Cagliari, A. Possenti, M. Burgay, M. Pilia, G. Bernardi)*
- *SNR*
- *Microquasars (G. Migliori)*
- ***AGN** (M. Orienti, M.Giroletti, F. D'Ammando, M. Bondi)*
- *ALMA (V. Casasola, F. Pozzi, A. Cimatti, R. Paladino, E. Liuzzo, M. Massardi --- Star formation @Arcetri)*
- ***Radio galaxies** (T. Venturi)*
- ***Clusters of Galaxies** (A. Bonafede, G. Brunetti, R. Cassano, T. Venturi, M. Gitti, F. Brighenti, F. Vazza, S. Ettori, F. De Gasperin)*
- *Survey & radio counts (I. Prandoni, M. Bondi)*
- *Instrumentaton & software tools (@ Medicina)*