The high resolution view of radio phoenices

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INAF IRA

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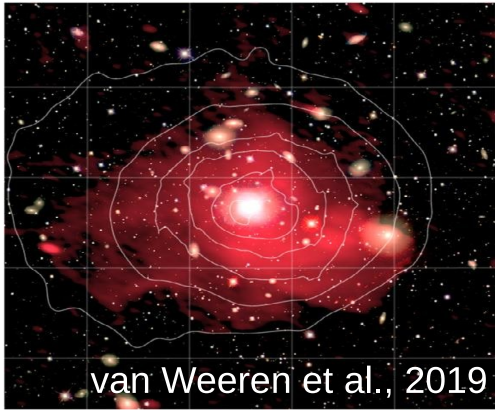
TLS

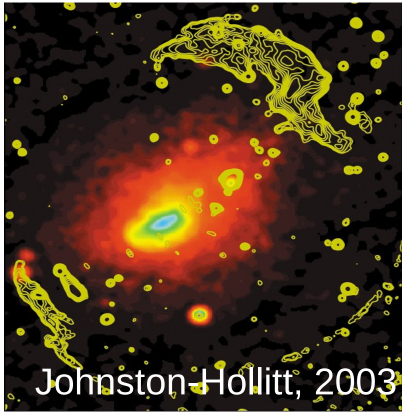
Diffuse radio emission

Radio halos



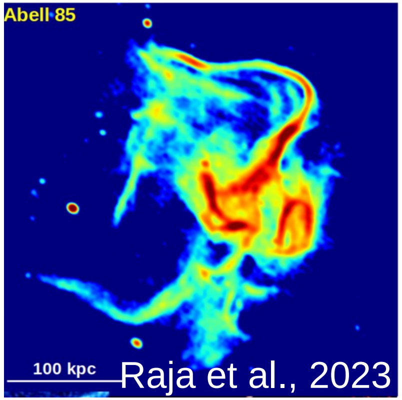
- Extended sources that follow the ICM distribution
- In relaxed/merging cluster
- Particle re-acceleration by turbulence and/or secondary electrons

Radio relics



- Extended sources tracing particles (re-)accelerated at ICM shock waves
- Mostly located at cluster periphery
- Highly polarised

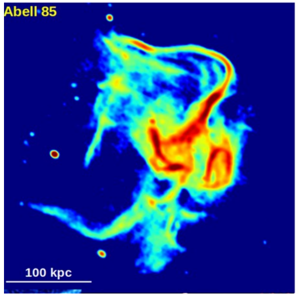
Revived fossil plasma



- Sources tracing AGN plasma re-energized through processes in the ICM, unrelated to galaxy
- Ultra-steep spectrum
- Uncertain origin

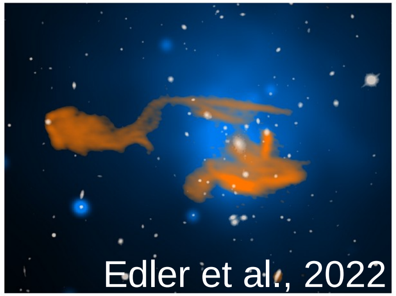
Diffuse radio emission

Radio phoenix



- Irregular and filamentary morphology
- Trace fossil lobes re-energised by shock wave adiabatic compression

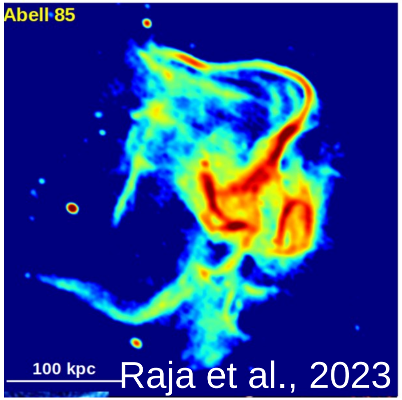
Greet



Edler et al., 2022

- Tails of radio galaxies that are somehow revived
- Unexpected spectral flattening

Revived fossil plasma



Raja et al., 2023

- Sources tracing AGN plasma re-energized through processes in the ICM, unrelated to galaxy
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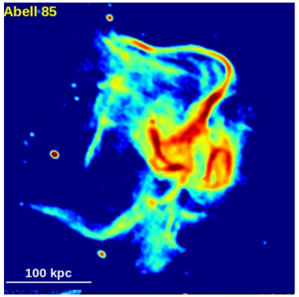
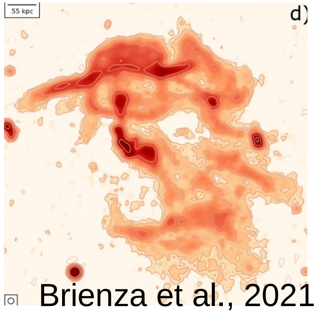
Diffuse radio emission

Radio phoenix



- Irregular and filamentary morphology
- Trace fossil lobes re-energised by shock wave adiabatic compression

AGN remnant

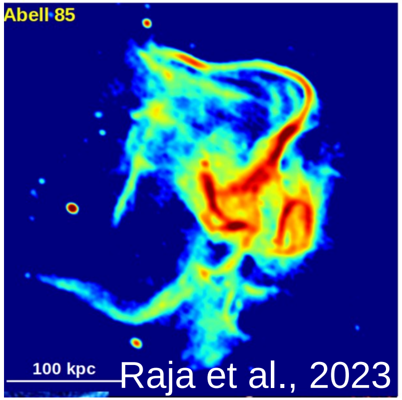


Brienza et al., 2021

- Dying AGN radio lobes, where the central engine has stopped, looking like separate radio source
- Steep spectrum due to ageing of electrons

Shock connection uncertain

Revived fossil plasma



Raja et al., 2023

- Sources tracing AGN plasma re-energized through processes in the ICM, unrelated to galaxy
- Ultra-steep spectrum
- Uncertain origin

Source selection

Exploit the high resolution of LOFAR VLBI observations to study radio phoenixes

Source selection:

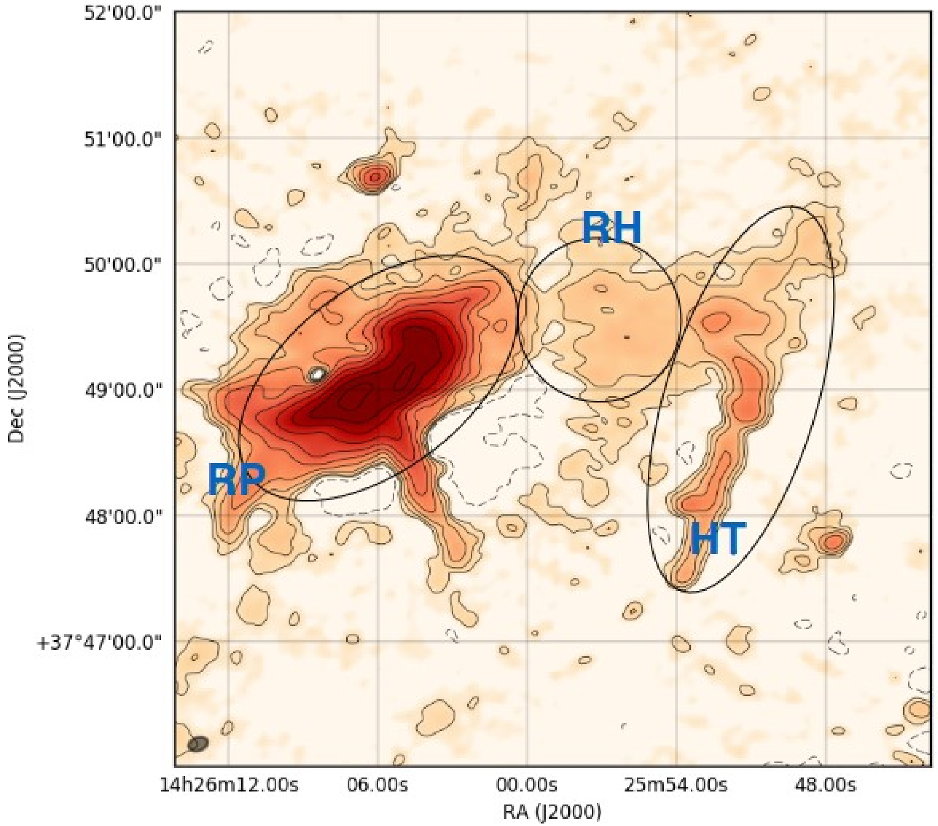
- Mandal et al. (in prep) sample of radio phoenix candidates (25)
  - Brightest sources (peak at 6” > 10 mJy/beam) in the northern hemisphere (15)
    - Close to the center of LoTSS field (r < 1°) or with pointed obs with IS (5)
      - Presence of a good in-field calibrator

→ 3 sources: A1914, A566, MKW8

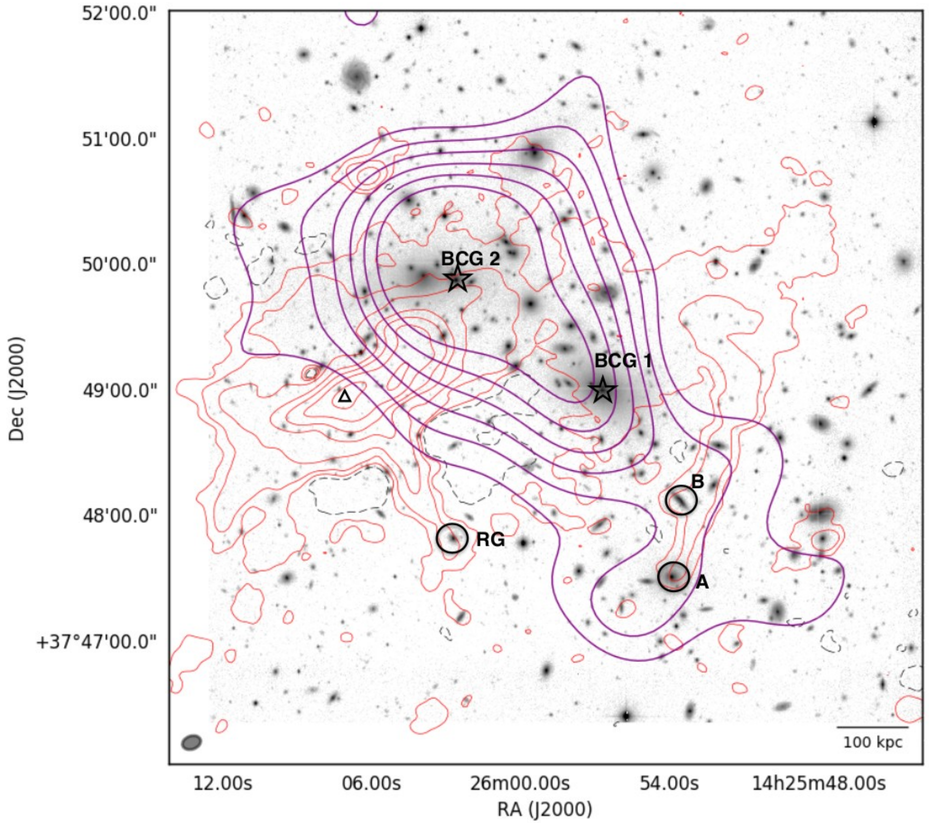
Abell 1914

(Mandal et al. 2019)

$M_{500} = 7.2 \times 10^{14}\, M_\odot$ $z = 0.17$



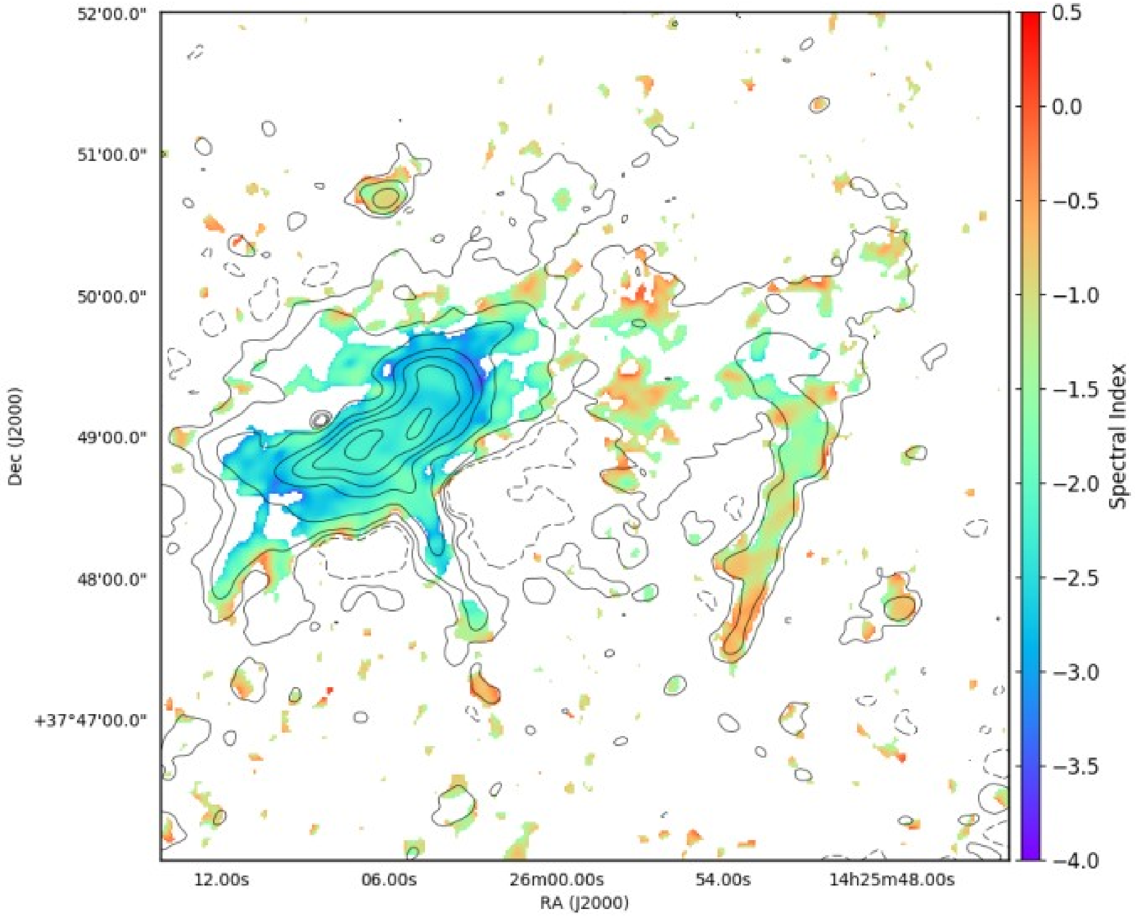
LOFAR 144 MHz - res = 9” x 6”



CFHT r-band image
+ weak lensing (purple)+ radio (red) contours

Abell 1914

(Mandal et al. 2019)



LOFAR 144 MHz – GMRT 610 MHz - res = 6”

Head-tail galaxy:

- Flat head (α~0.5)
- Steepening along the tail

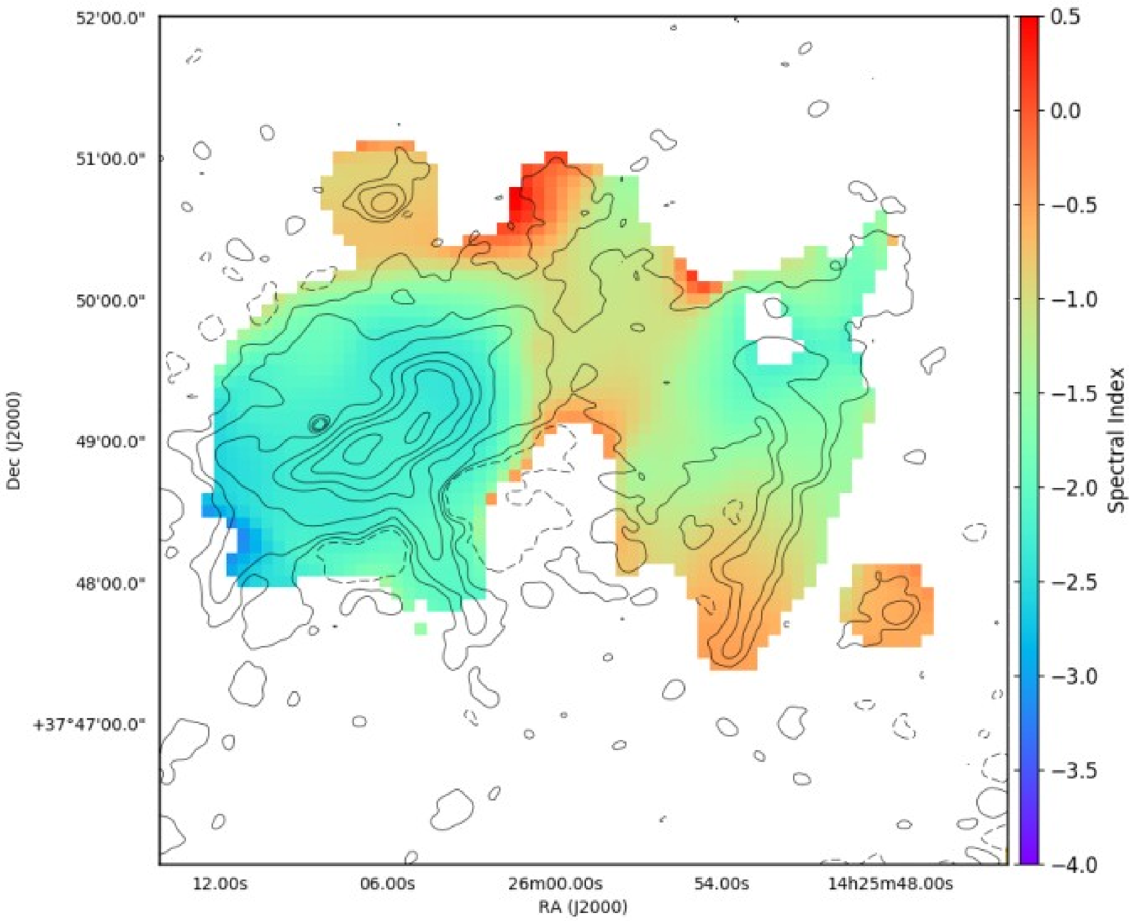
Radio Phoenix:

- Fairly uniform spectral index with small variations

$-1.9 < \alpha < -2.3$

Abell 1914

(Mandal et al. 2019)



LOFAR 144 MHz – GMRT 610 MHz - res = 30”

Head-tail galaxy:

- Flat head (α~0.5)
- Steepening along the tail

Radio Phoenix:

- Fairly uniform spectral index with small variations

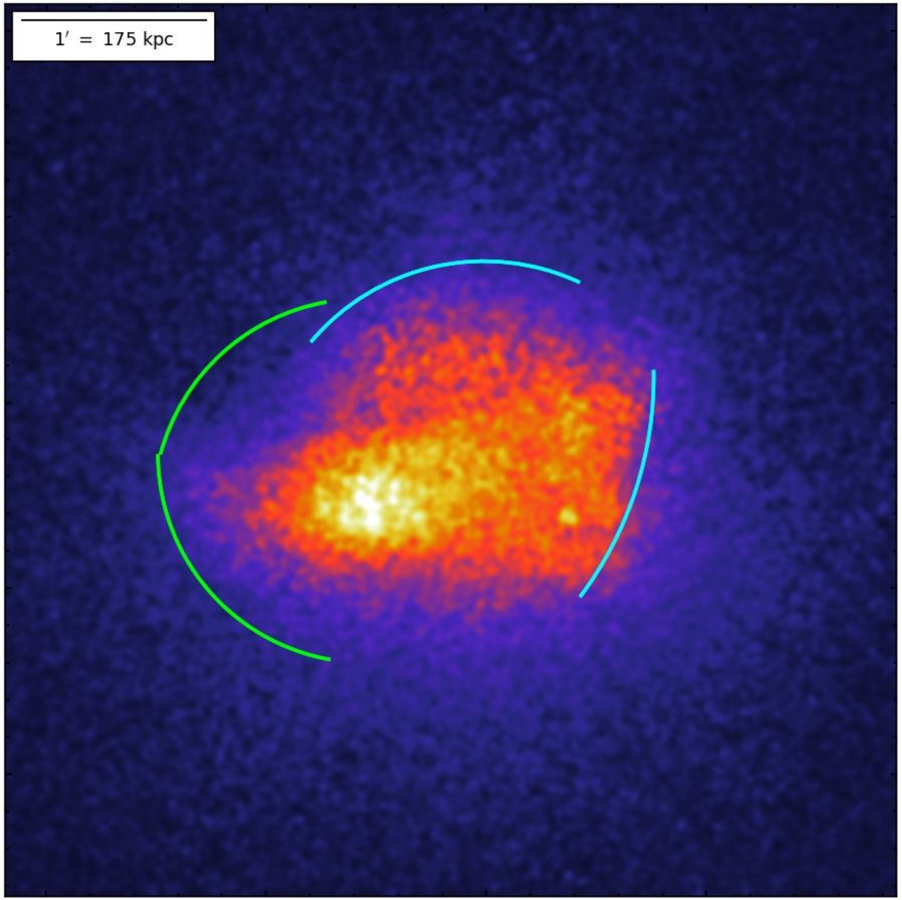
  -1.9 < α < -2.3

Radio halo:

- Mean spectral index: α~1.15
- Contaminated by other sources

Abell 1914

(Botteon et al. 2018)
(Rahaman et al. 2022)



Chandra – tot exposure 113 ks

Chandra observations

Disturbed cluster

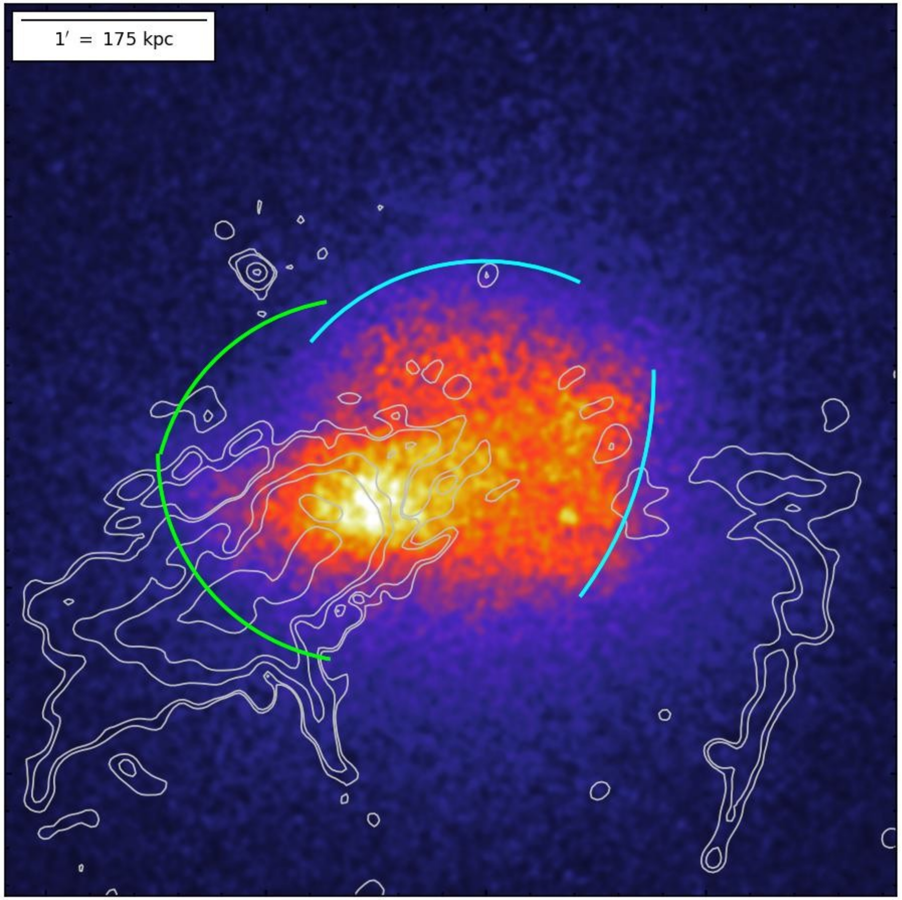
Complex merger state

Surrounded by multiple fronts

- Possible cold fronts on E
- Shock fronts on N and W

Abell 1914

(Botteon et al. 2018)
(Rahaman et al. 2022)



Chandra + HBA contours

Chandra observations

Disturbed cluster

Complex merger state

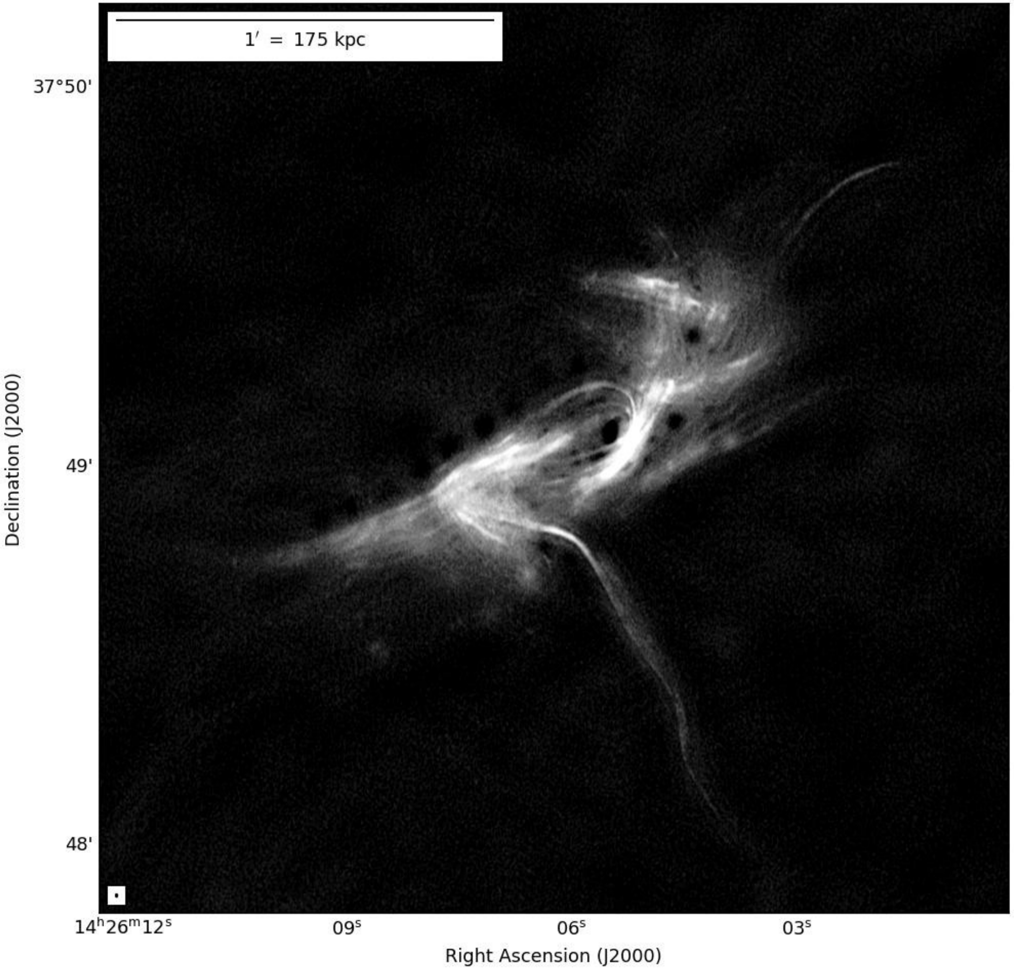
Surrounded by multiple fronts

- Possible cold fronts on E
- Shock fronts on N and W

Radio Phoenix

- located SE of cluster centre
- Close in projection to the front

Abell 1914

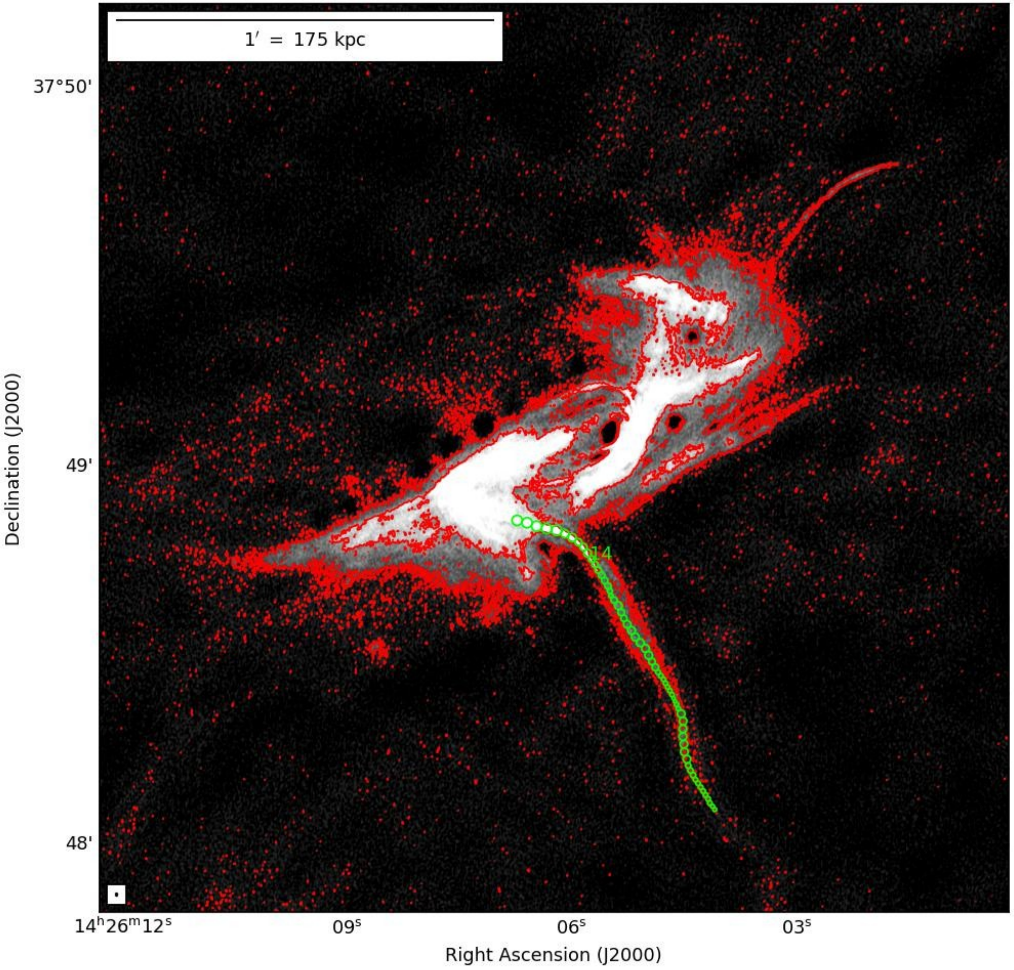


res = 0.45” x 0.24” – σ = 33 μJy/beam

LOFAR HBA - VLBI data

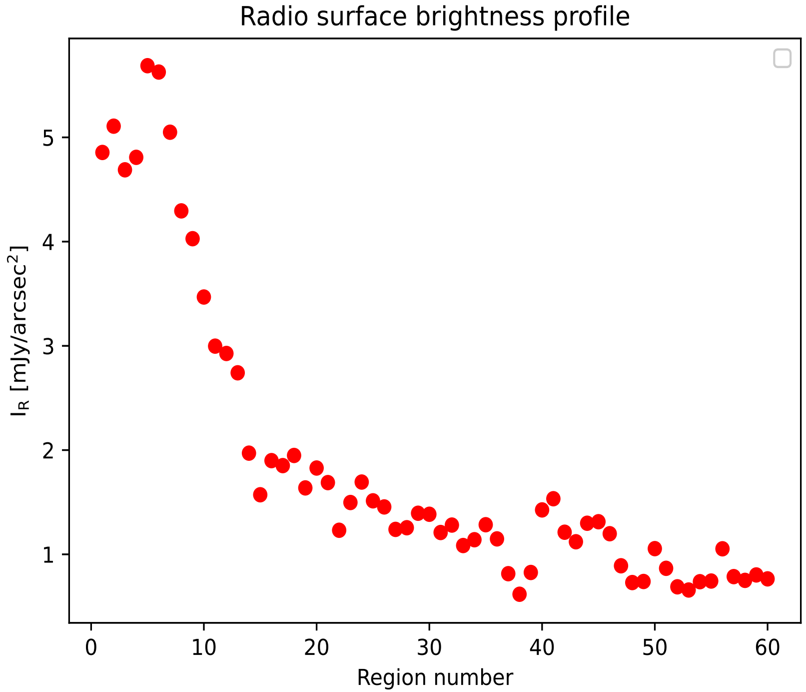
- LoTSS observation, target 0.5° from field centre
- Detected only radio phoenix:
  - Made of two substructures, could be remnant radio lobes
  - Different filaments connect the two components or branch out from them
  - Longest filament 1’ = 175 kpc

Abell 1914



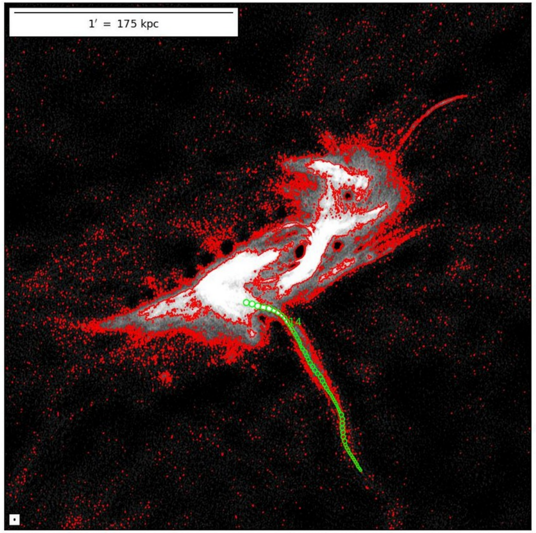
Southern filament:

- Lenght: 1’ = 180 kpc
- Width: 0.7 – 4 kpc
- α ~ - 2.0



Abell 1914

Investigating a possible scenario for the formation of the southern filament



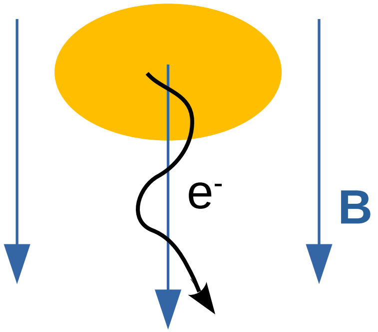
Southern filament:

- Lenght: 1’ = 175 kpc
- Width: 0.7 – 4 kpc
- α ~ - 2.0

Eastern lobe:

- r ~ 140 kpc
- α ~ - 2.0

Hp: re-connection of ICM magnetic field line with AGN lobe



CRe stream along magnetic field line with Alfvenic speed

$$v_A = \frac{B}{\sqrt{\mu_0 \rho}}$$

Magnetic field in the lobe:
B_{eq} ~ 8.8 μG

Distance from cluster centre:
r ~ 140 kpc
ICM : n_e ~ 0.008 cm^{-3}
v_A ~ 270 km/s

Hp: $v_e = v_A$
d = 175 kpc → t_{stream} = 0.7 Gyr

CRe loss timescale IC + Synchrotron
t_{loss} = 0.1 Gyr

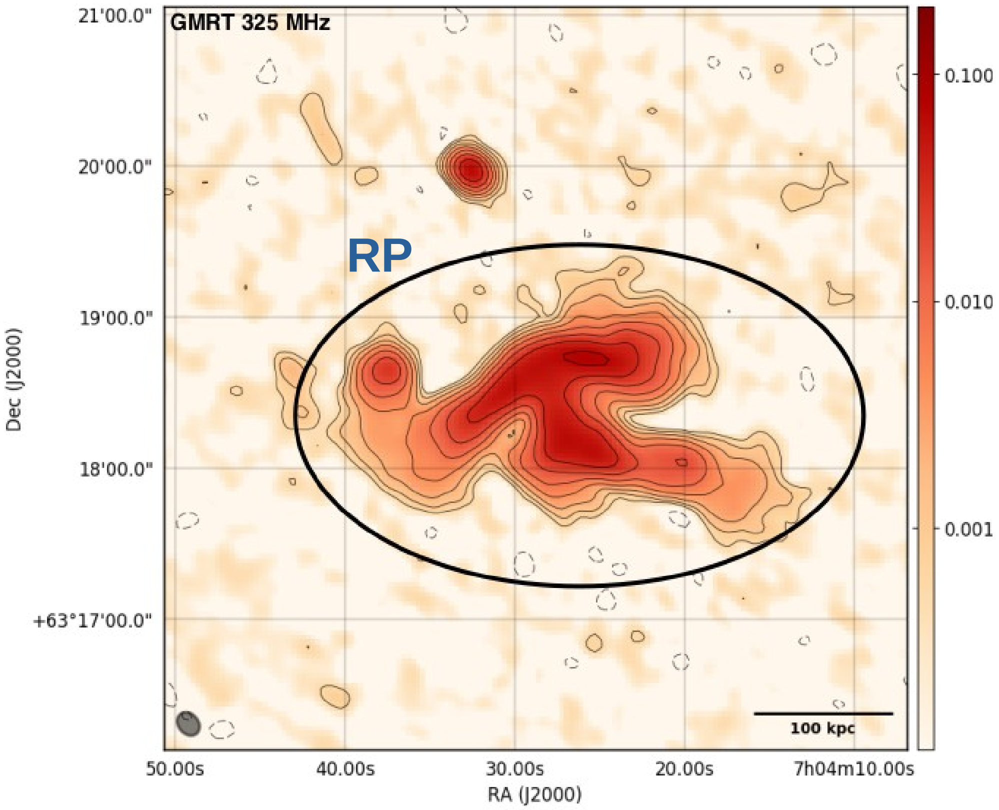
$V_e = 7 \times V_A$ → n_e << → **r >> 140 kpc**

Abell 566

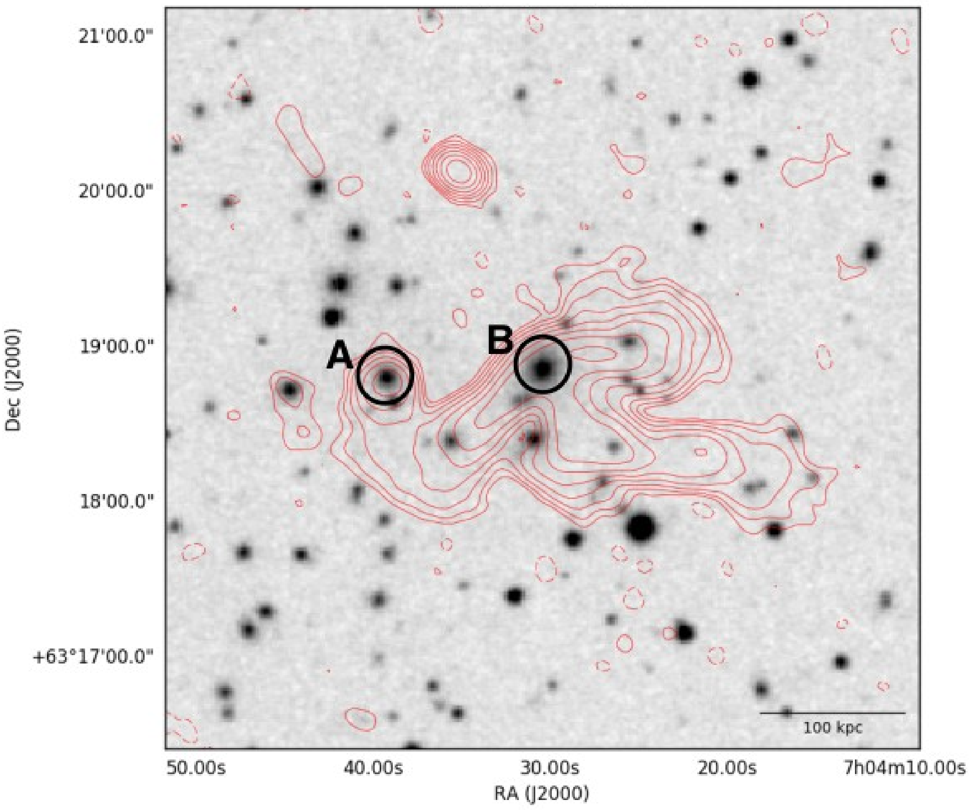
(Mandal et al. - in prep)

$\alpha_{150\text{-}325\ \mathrm{MHz}} = -1.88$ $\alpha_{325\text{-}1400\ \mathrm{MHz}} = -2.32$

$M_{500} = 2.95 \times 10^{14}\ M_\odot$ z = 0.097

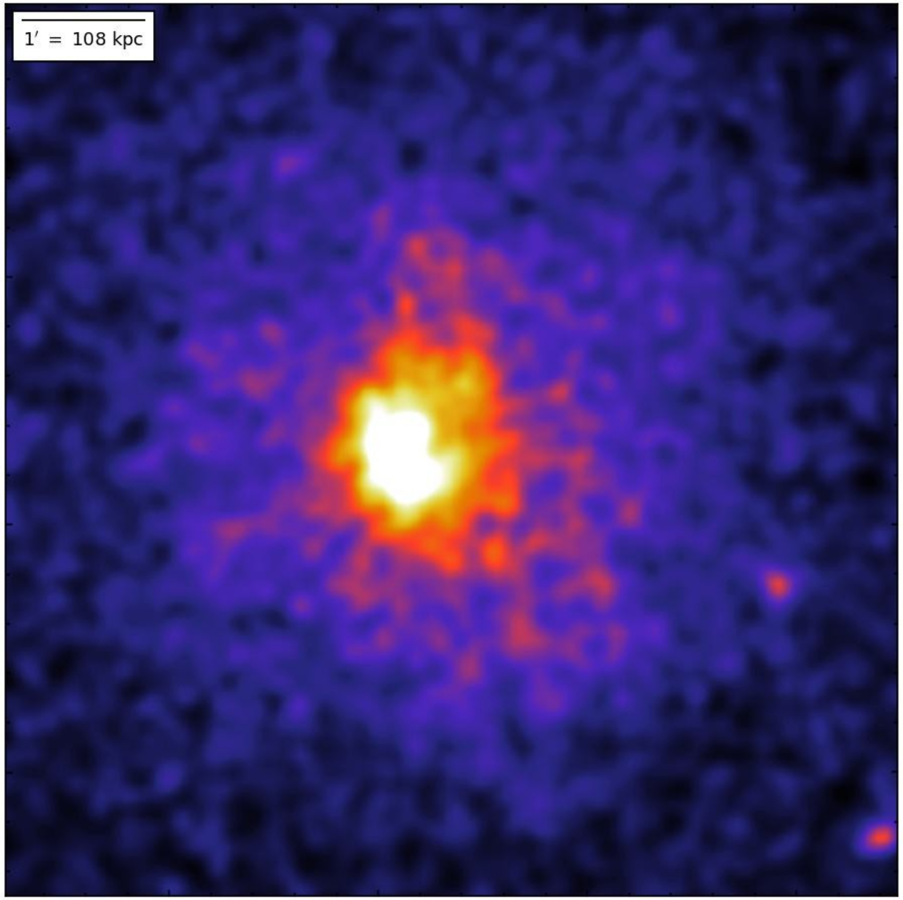


GMRT 325 MHz – res 9”x6”



DSS r-band optical image

Abell 566

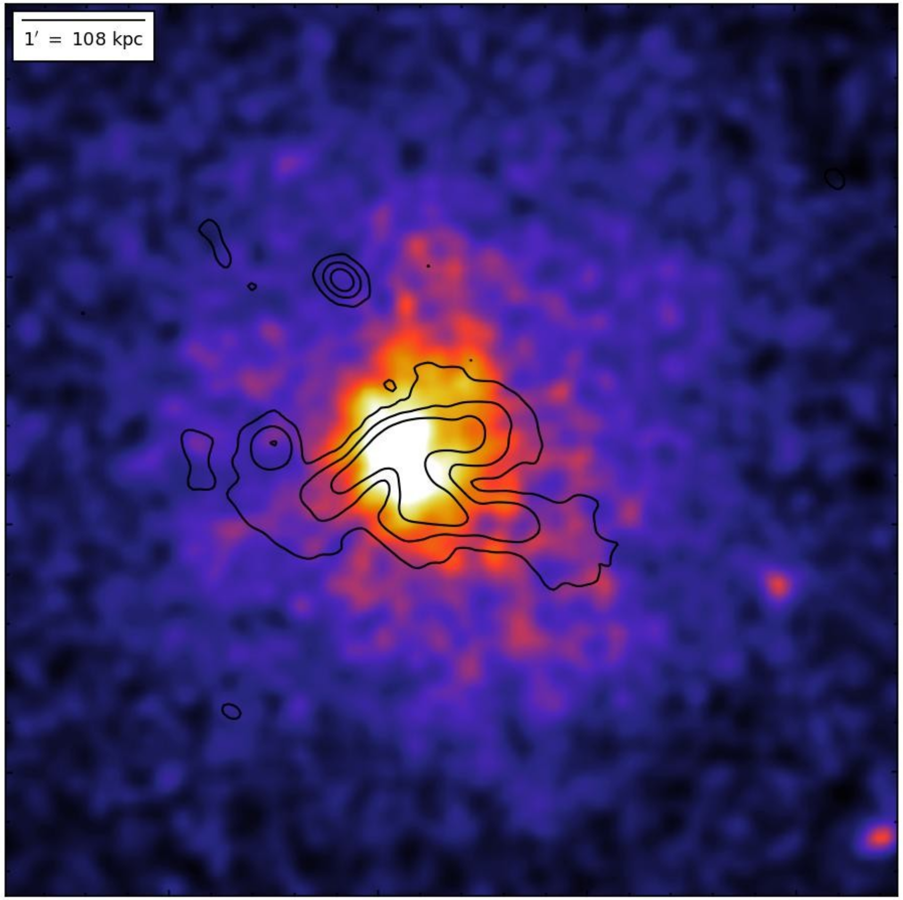


XMM-Newton – EMOS1

XMM-Newton observation

Not spherical distribution of gas
X-ray peak decentralised

Abell 566



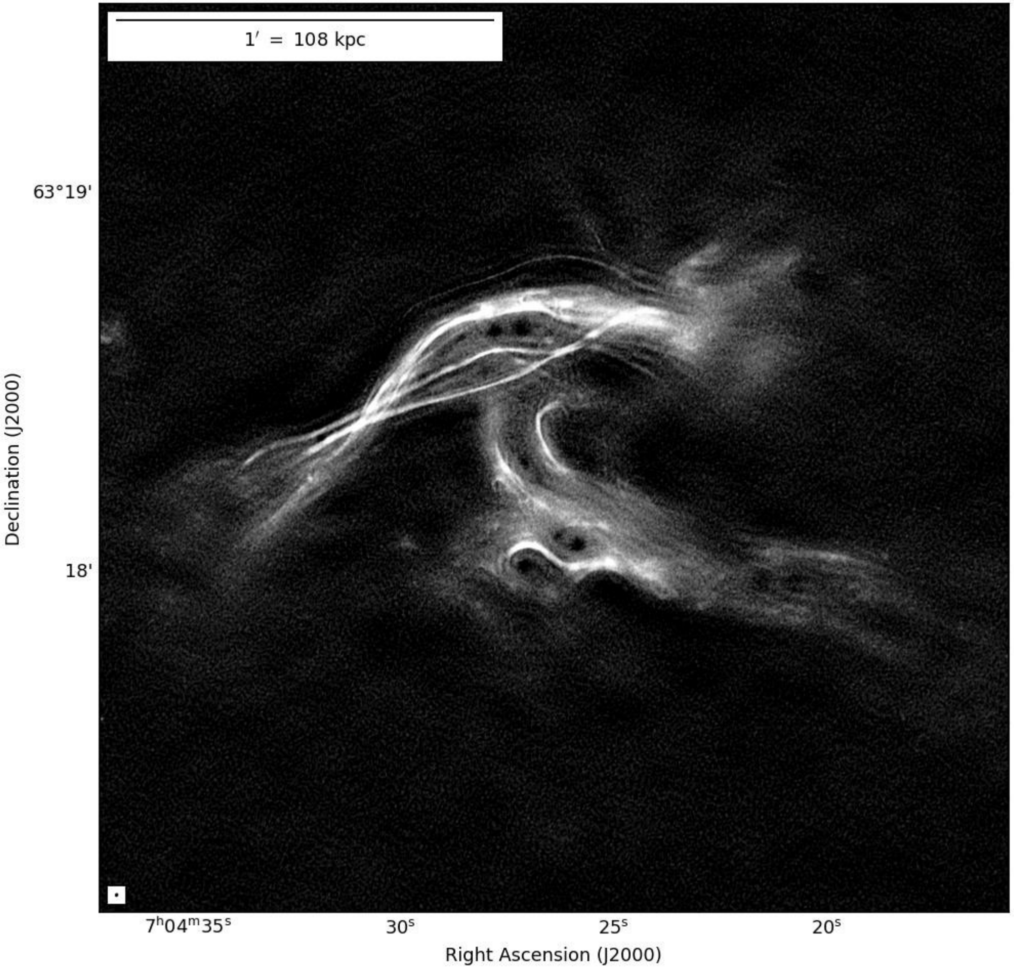
XMM-Newton – EMOS1 + GMRT 325 MHz contours

XMM-Newton observation

Not spherical distribution of gas
X-ray peak decentralised

Candidate radio phoenix localised
at cluster centre

Abell 566

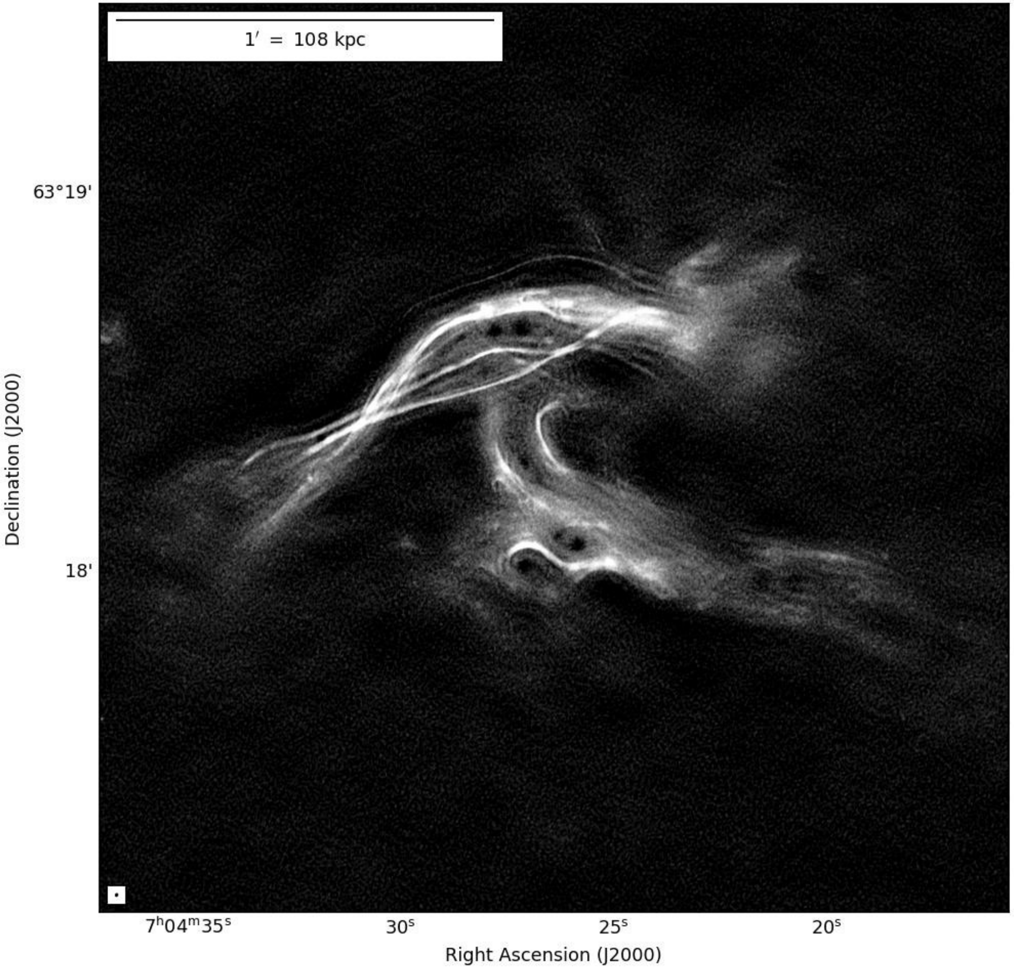


LOFAR HBA - VLBI data

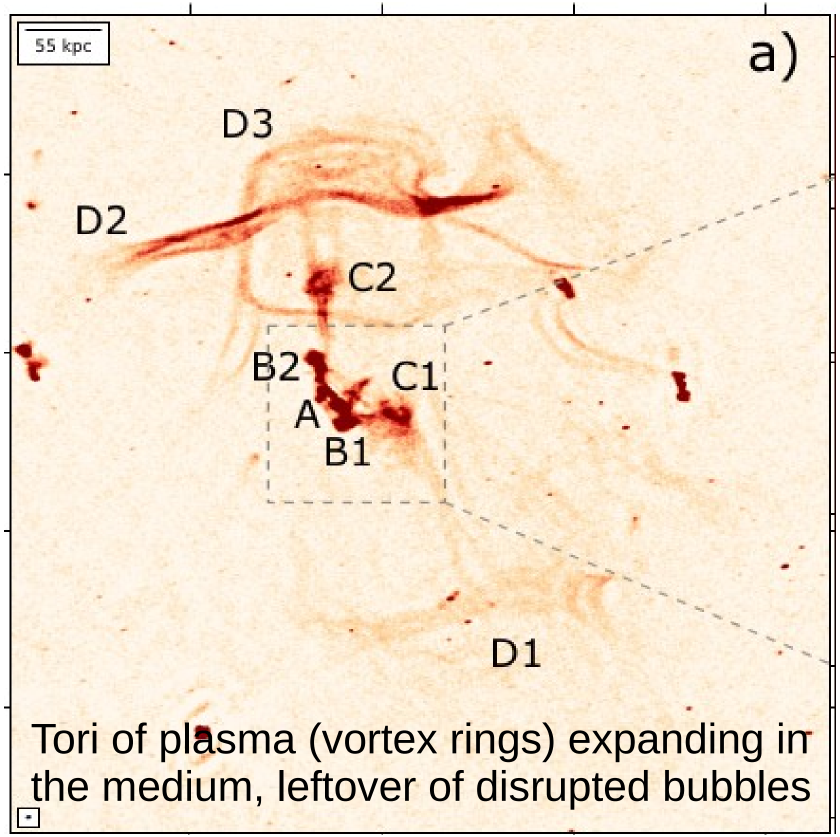
- Pointed observation
- Radio morphology:
  - Filamentary emission
  - Not detected a radio source associated to the BCG (source B in optical image)
  - Toroidal structure, resembling a mushroom

res = 0.33” x 0.24” σ = 30 μJy/beam

Abell 566

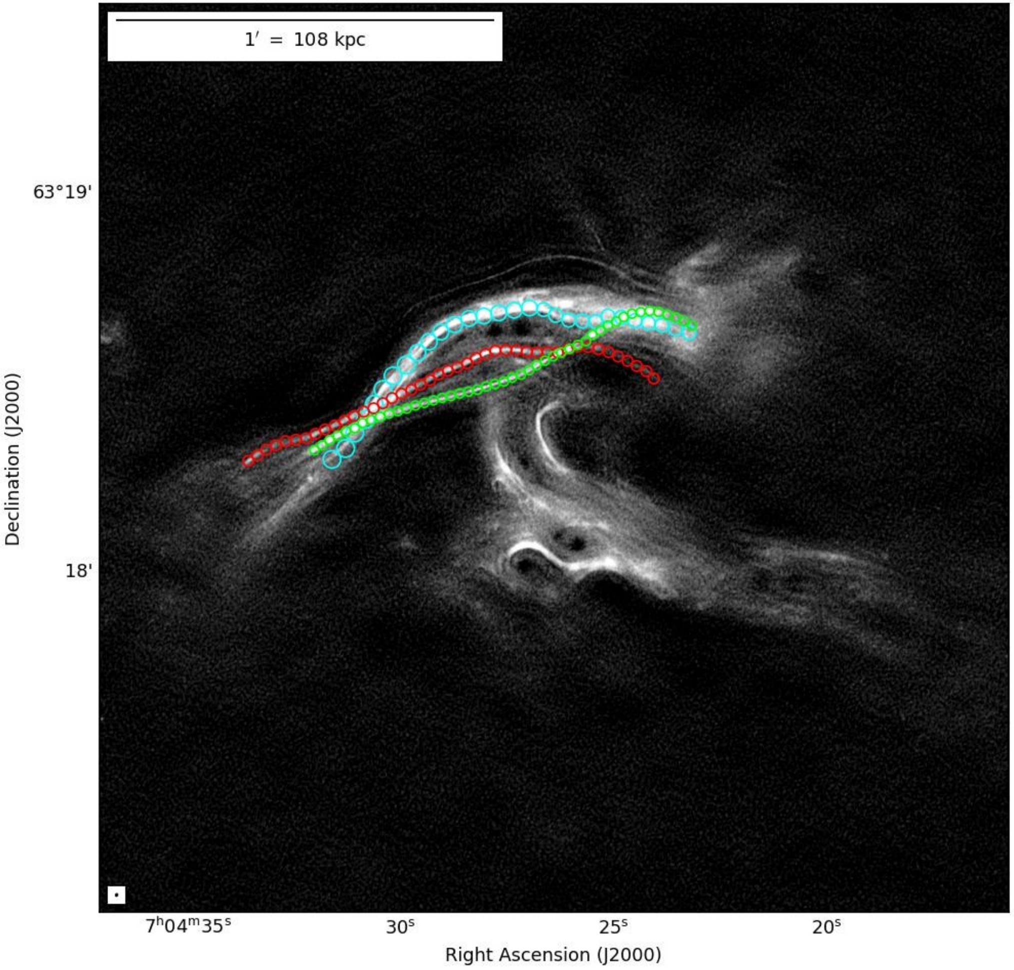


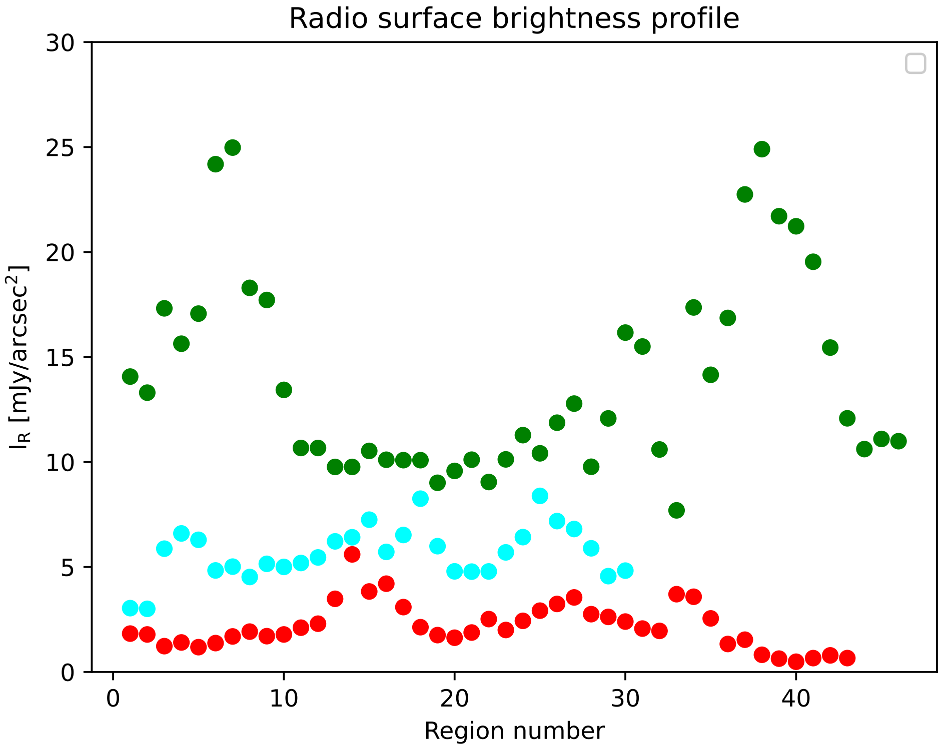
Nest200047 galaxy group – Brienza et al. 2021



Tori of plasma (vortex rings) expanding in the medium, leftover of disrupted bubbles

Abell 566

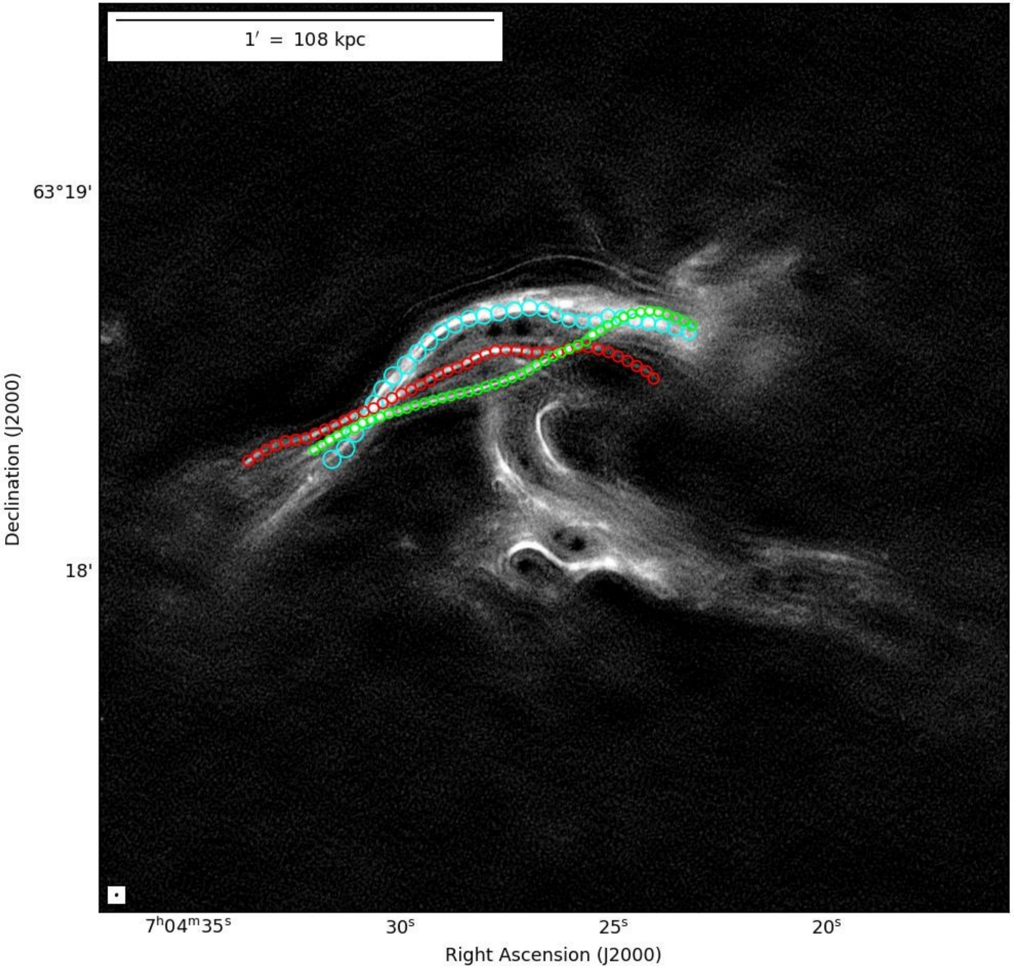




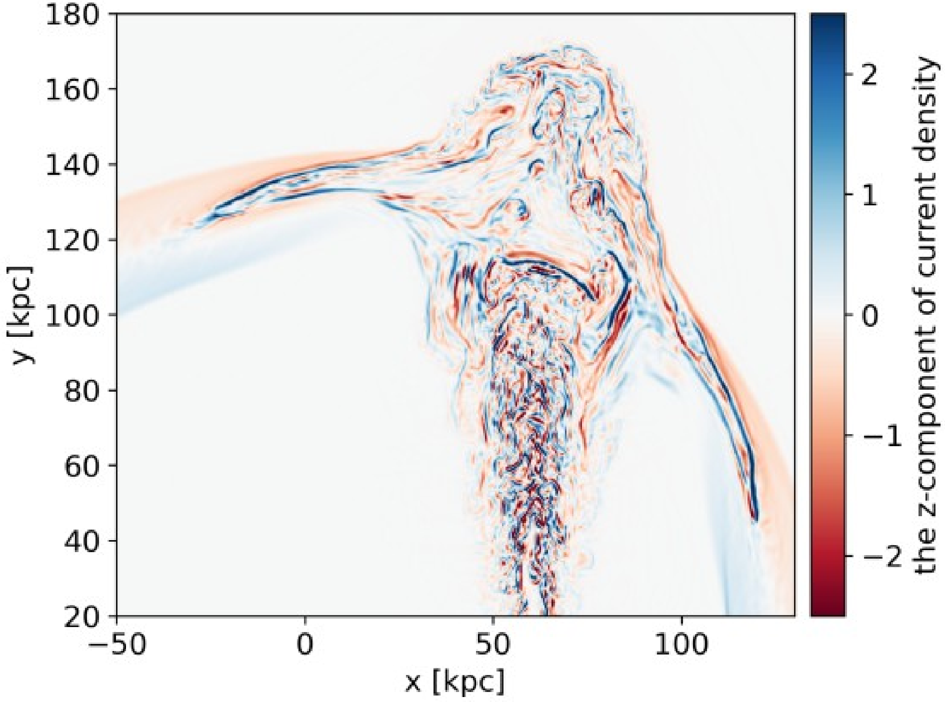
No clear pattern

→ Compression of B field lines by the AGN jet

Abell 566



Chibueze et al. 2021



No clear pattern
→ Compression of B field lines by the AGN jet

Conclusions

- The detection of filaments within radio sources is becoming frequent thanks to the high resolution and sensitivity observations available nowadays
- Importance of LOFAR VLBI observations to study steep spectrum radio sources
  - Not detectable at subarcsec resolution at high frequency with available instruments
- LOFAR 2.0 to observe candidate radio phoenices with both LBA and HBA international stations
  - To trace the spectral index profile along the filaments
  - Try to understand the nature of radio phoenixes

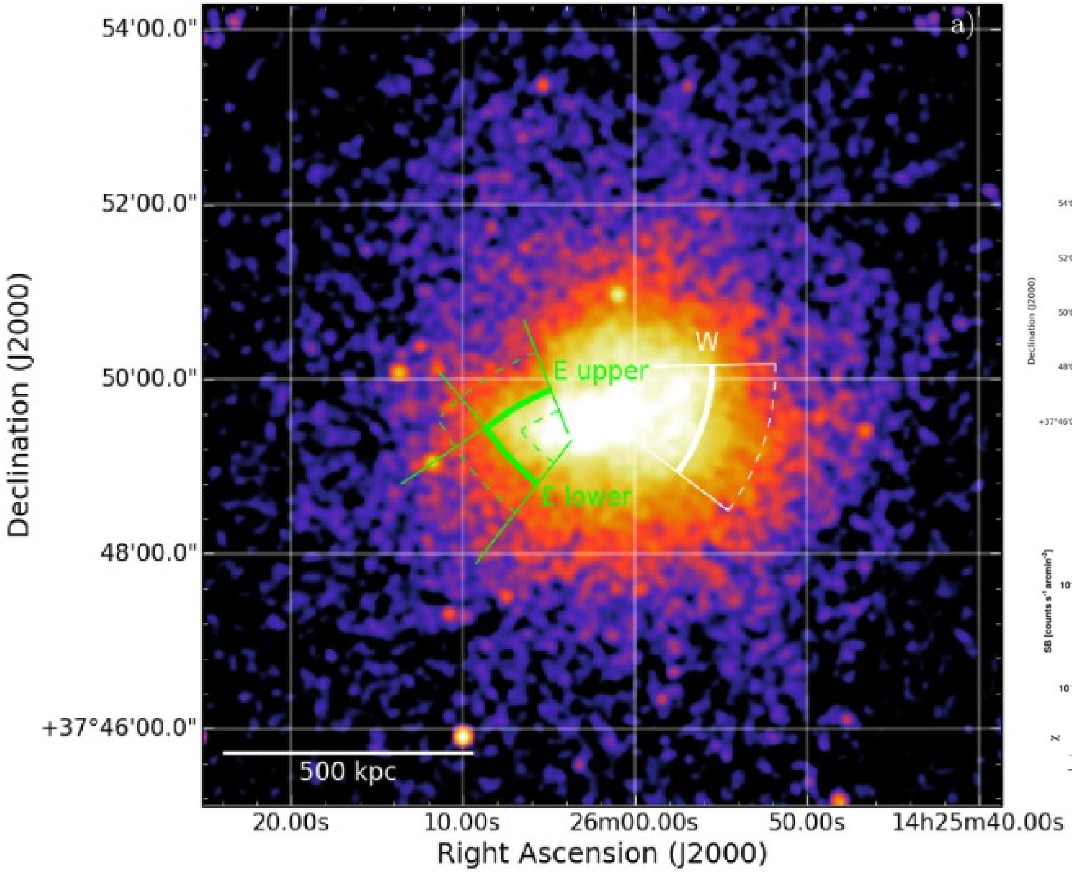
Thank you for the attention

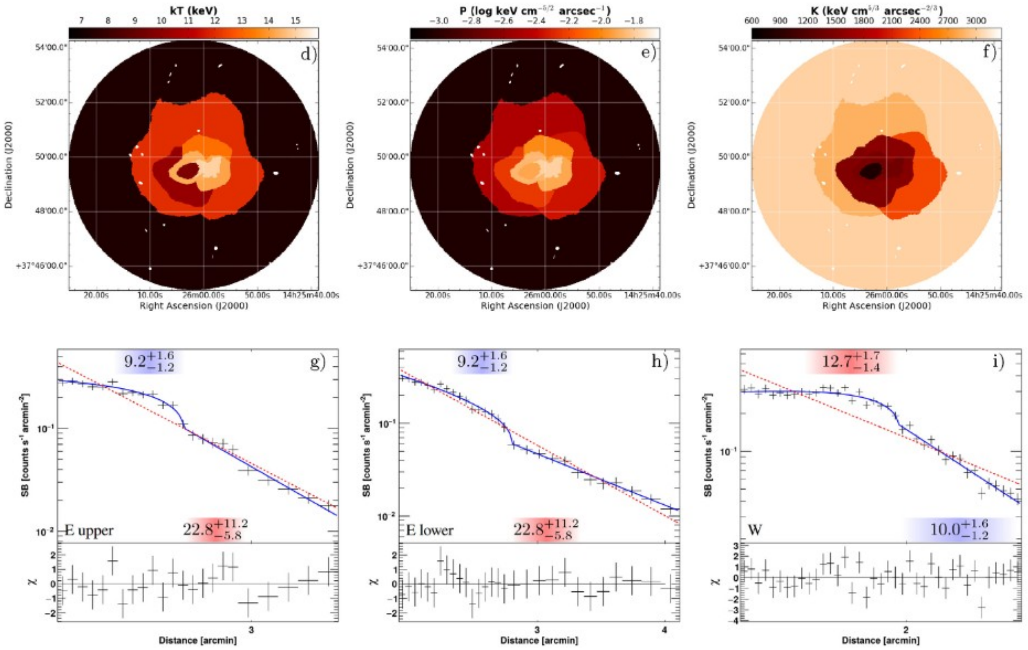
Abell 1914

(Botteon et al. 2018)

Chandra X-ray observation
Exposure time: 20ks

- East: Cold Front (green) + possible outern shock-heated region
- West: Shock Front (white – M=1.2)

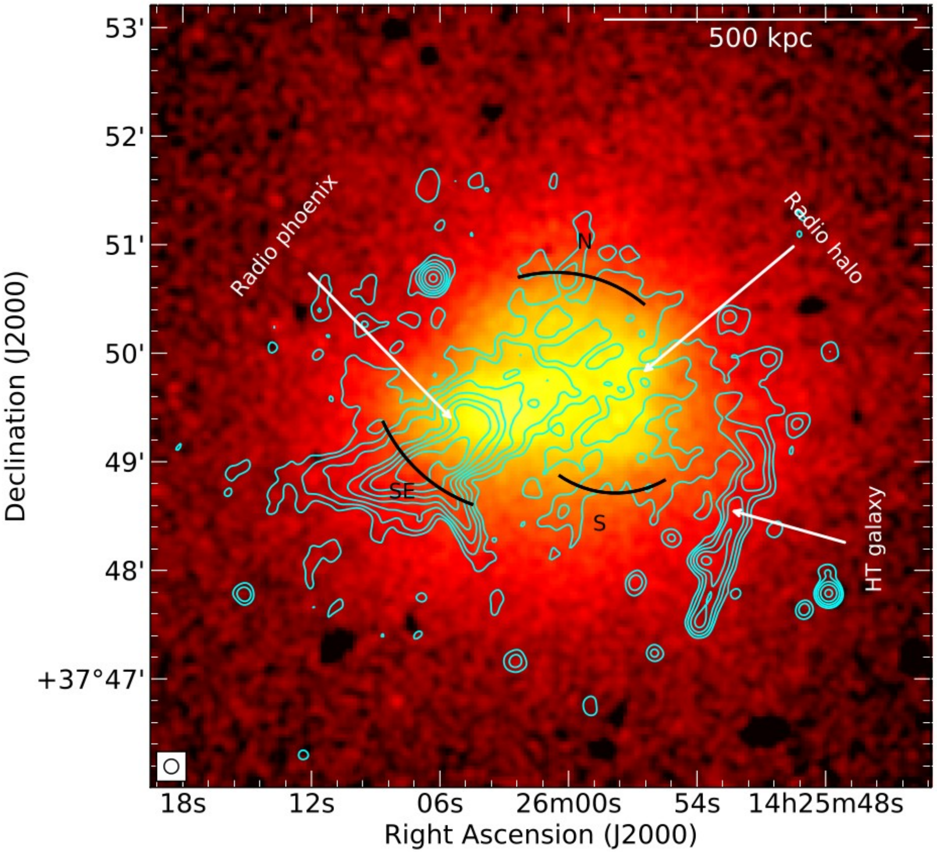




Abell 1914

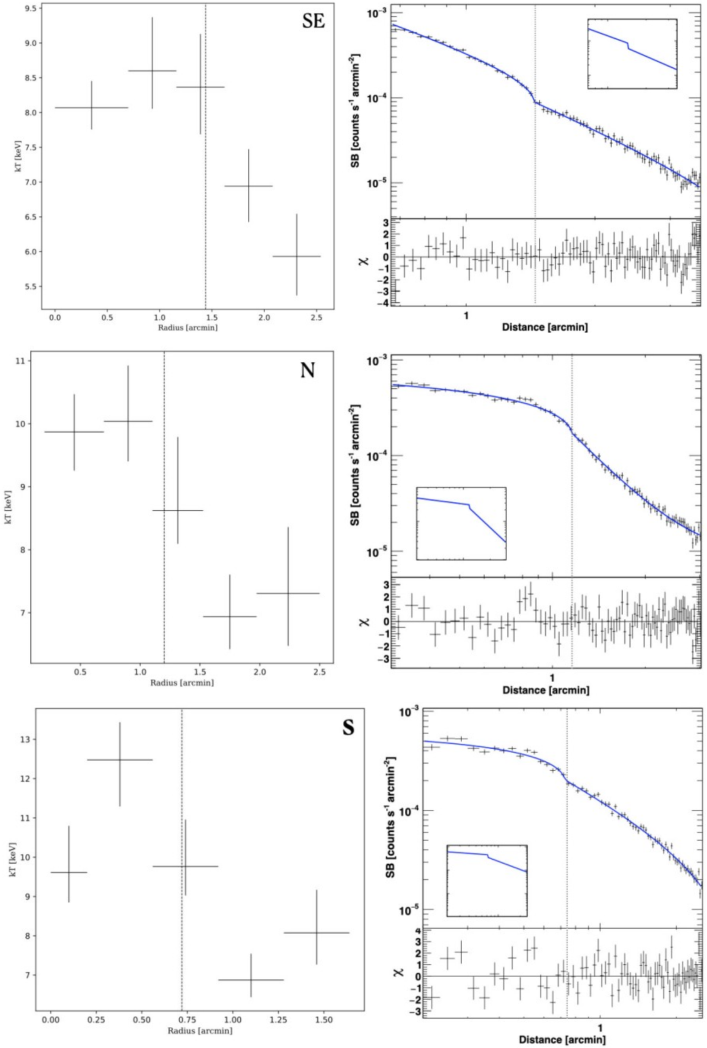
(Rahaman et al. 2022)

6 Chandra X-ray observations
Exposure time: 140ks

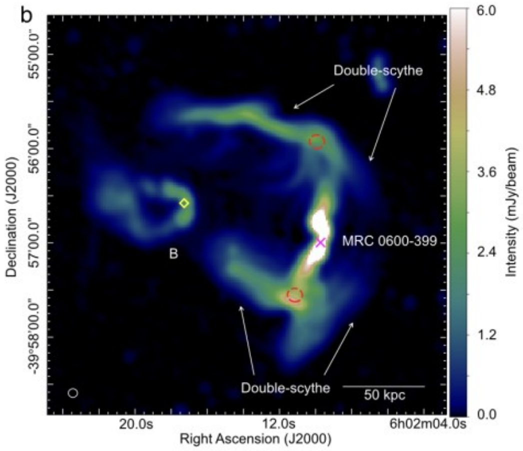


Detected 3 shock fronts:

- South-east
  r = 1.44’
- North
  r = 1.15’
- South
  r = 0.72’



Similarities



Chibueze et al. 2021 – Bent jets in the cluster Abell 3376

A jet travels straight with supersonic speed and hits a magnetic layer. The motion of the jet across the arch is suppressed due to the arch's magnetic tension. The jet flow diverges along with the magnetic layer. Because the magnetic field in the AGN jet reconnects the magnetic layer, non-thermal particles accelerated by the magnetic reconnection propagate along with the magnetic layer.