

Investigating the filamentary emission of **radio phoenixes** and characterising their peculiarities

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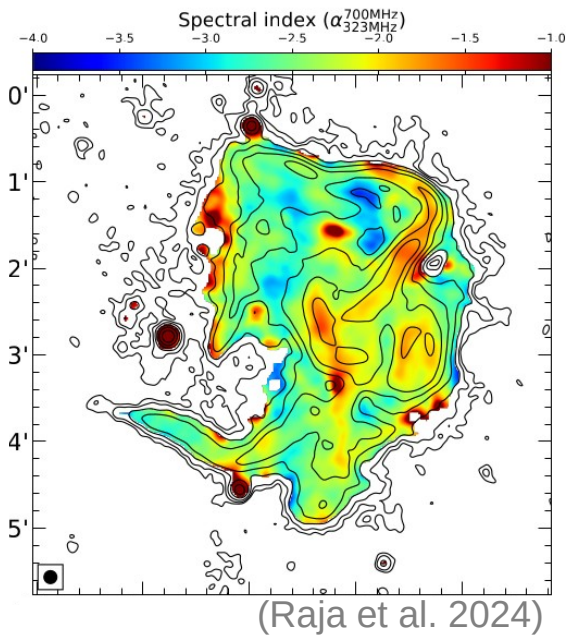
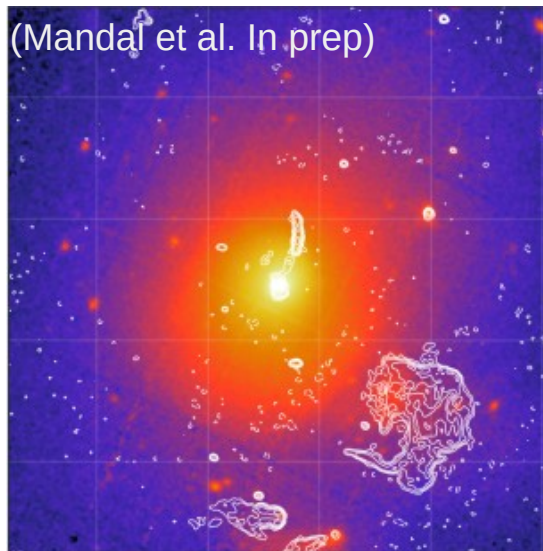
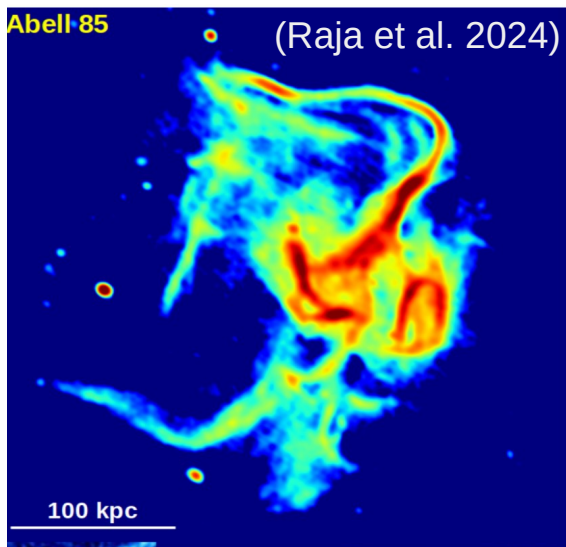


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Radio phoenix

“Filamentary” diffuse radio emission in galaxy clusters



- Irregular and filamentary morphology

- Typically located within R_{500}

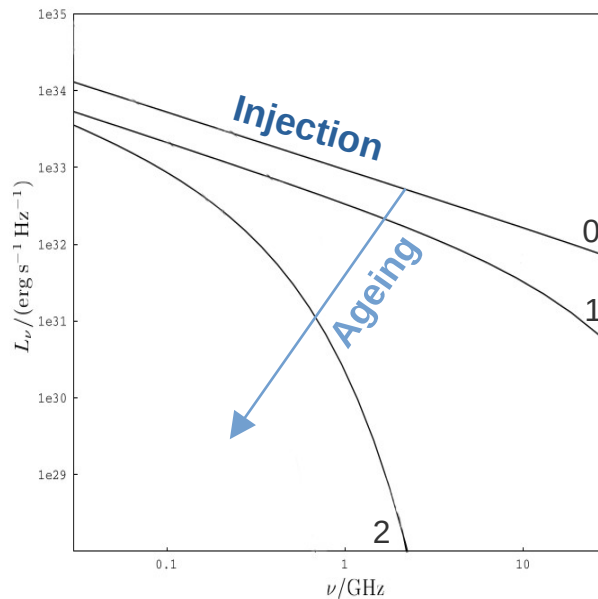
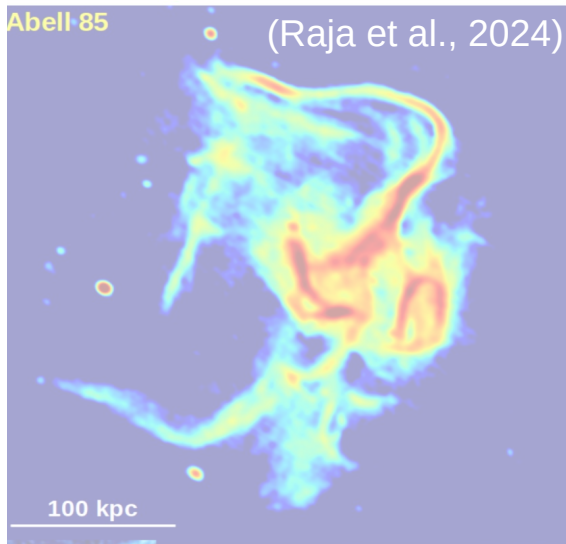
- Ultra-steep spectrum
 $-3.0 < \alpha < -1.5$

$$[S=S_0(\nu/\nu_0)^\alpha]$$

Radio phoenix

Theoretical model: AGN fossil plasma revived by shock wave adiabatic compression

(Enßlin and Gopal-Krishna 2001)

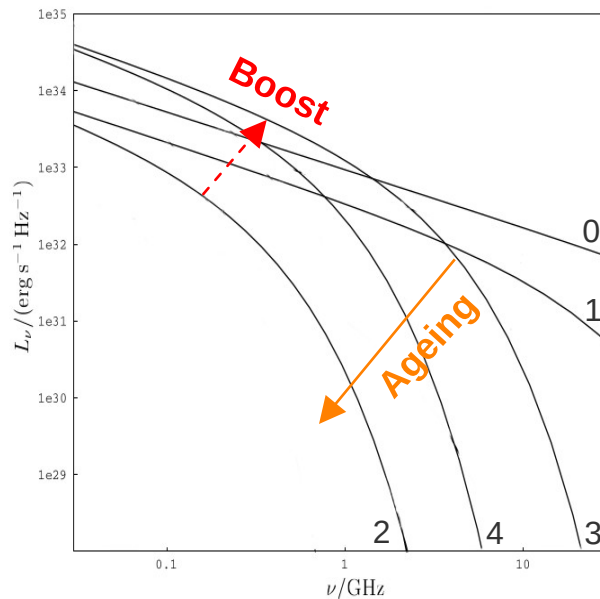
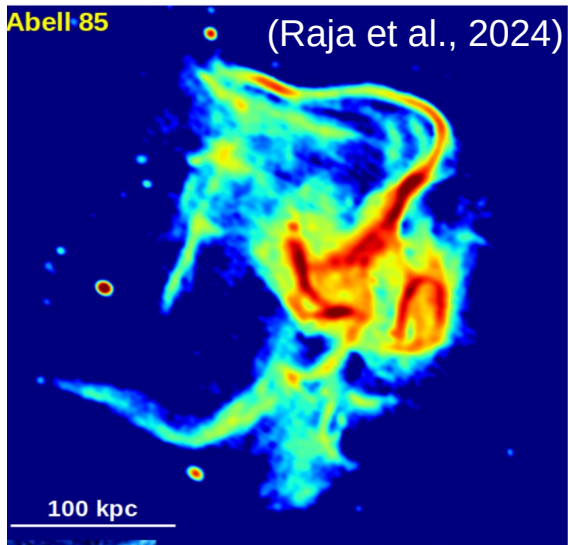


AGN activity can
enrich the ICM with a
population of mildly
relativistic electrons

Radio phoenix

Theoretical model: AGN fossil plasma revived by shock wave adiabatic compression

(Enßlin and Gopal-Krishna 2001)



- Ultra-steep spectrum ($\alpha \leq -1.5$)

Shock compression,
re-energise electrons
boosting their
emissivity

Radio phoenix

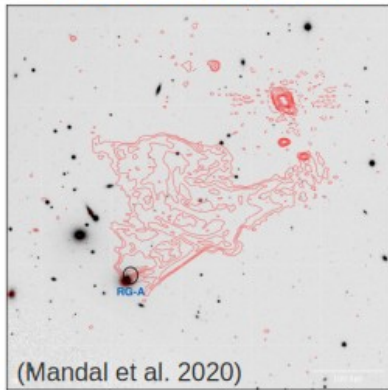
Theoretical model: AGN fossil plasma revived by shock wave adiabatic compression

(Enßlin and Gopal-Krishna 2001)

AGN origin of the plasma?

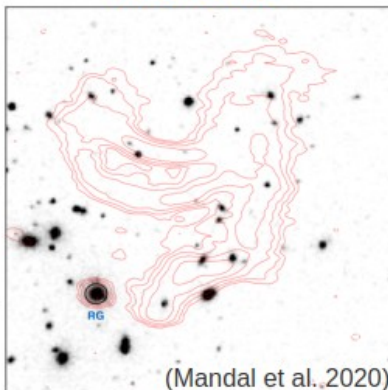
- Not always a clear connection with AGN optical counterpart

SDSS-C4-DR3-3088



(Mandal et al. 2020)

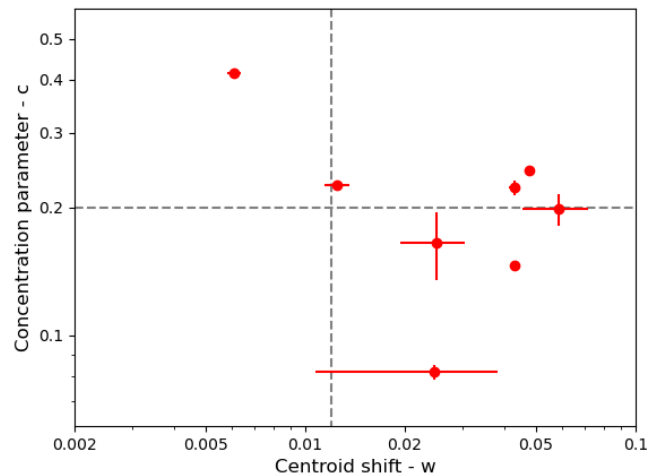
Abell 2048



(Mandal et al. 2020)

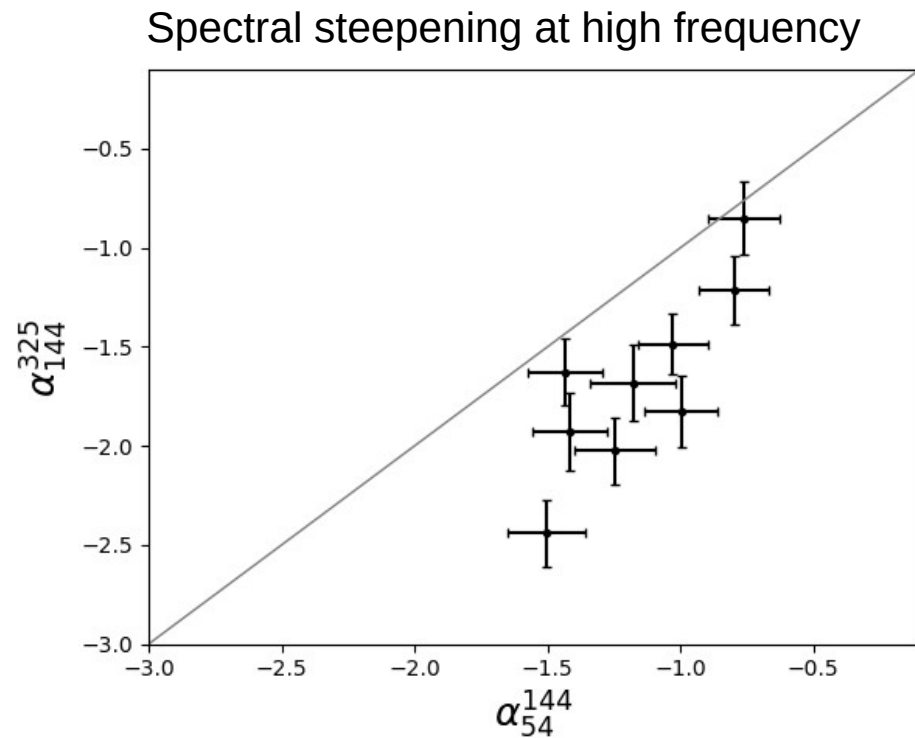
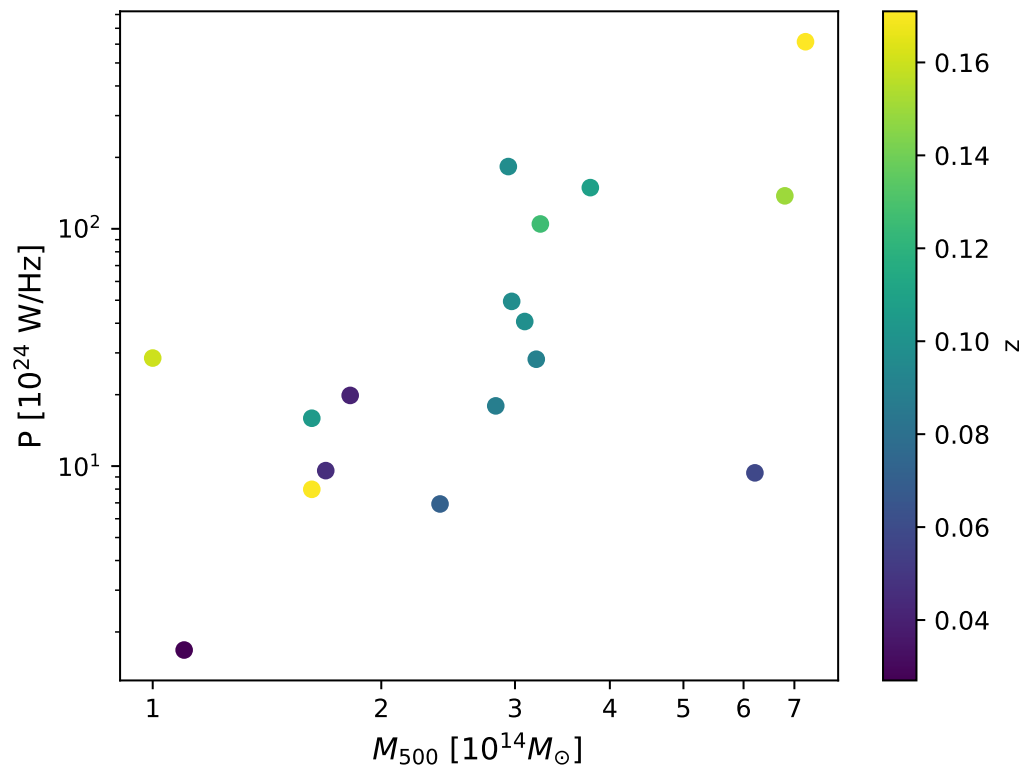
Re-energised plasma?

- No evidence of connection with shocks
- Mostly located in disturbed systems



Radio phoenix statistics

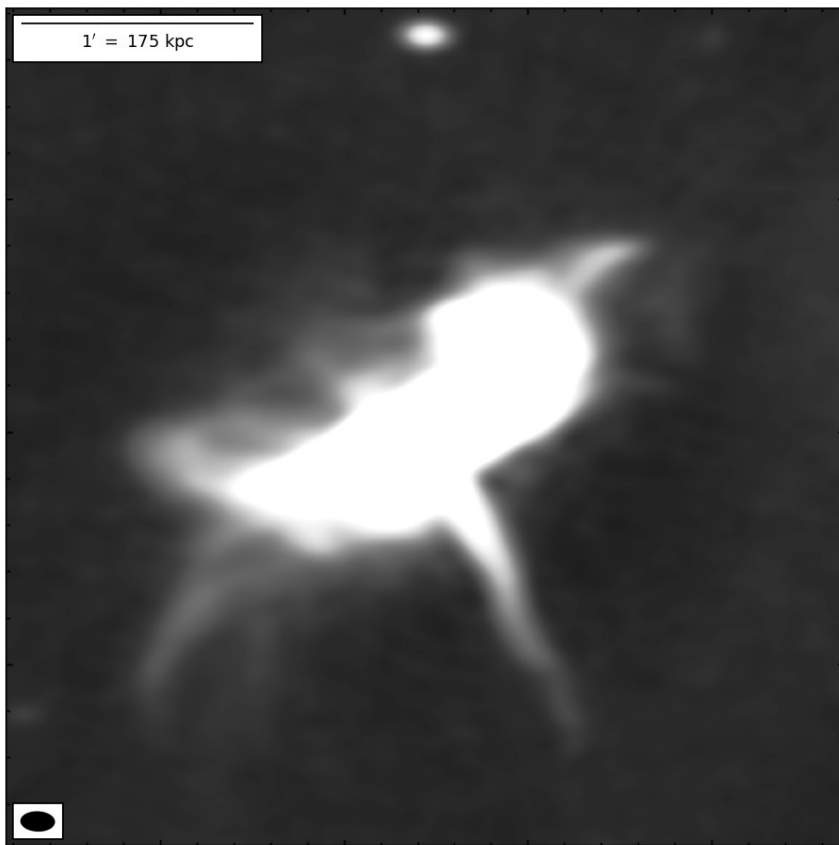
Known radio phoenixes in the northern hemisphere



Enlarge the sample combining LoTSS and LoLSS, looking for steep spectrum filamentary sources

Abell 1914

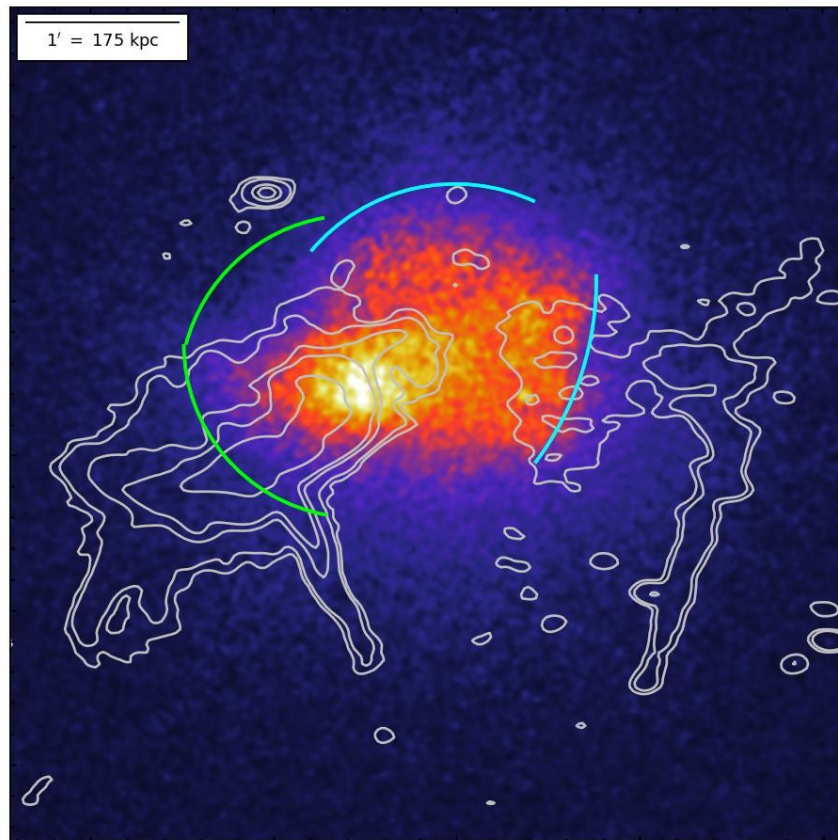
LOFAR 144 MHz - res = 9" x 6"



(Radio analysis in Mandal et al. 2019)

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

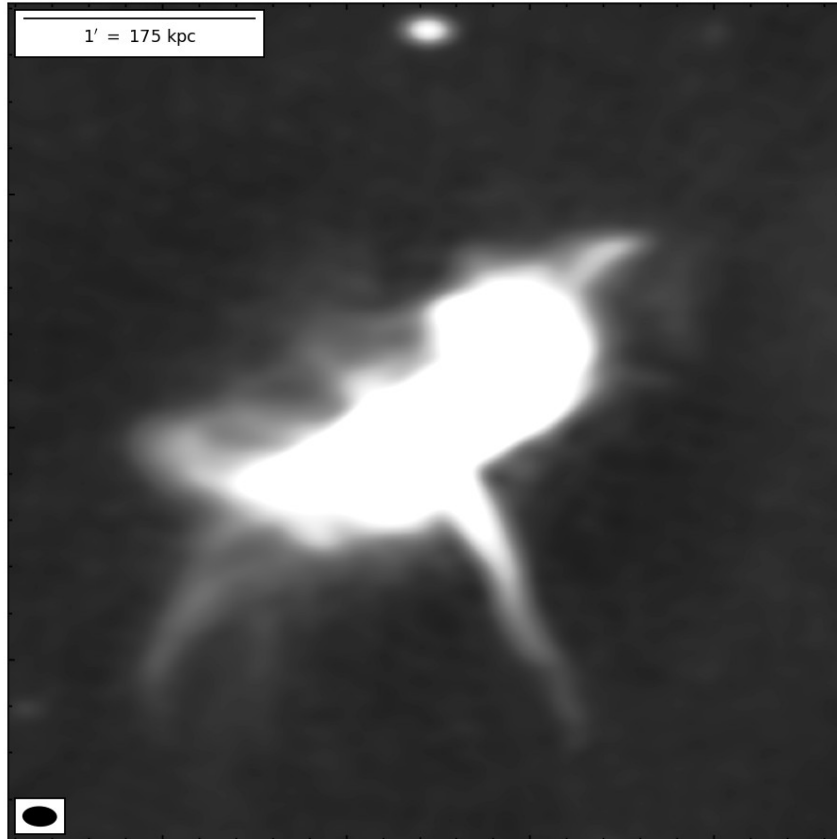
Chandra + LOFAR contours



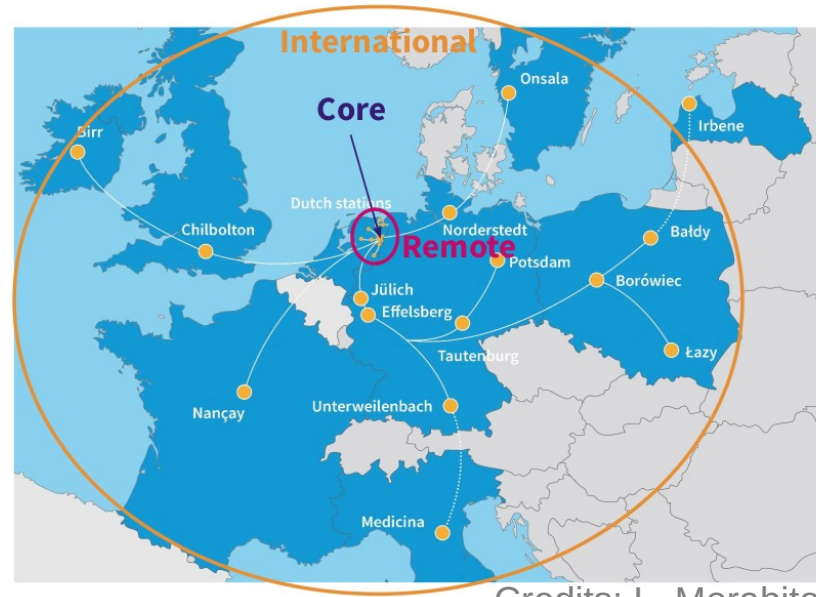
(X-ray analysis in Botteon et al. 2018)

Abell 1914

LOFAR: 144 MHz – res: 8" x 5"



Investigate phoenix at low frequency and high resolution with LOFAR international stations

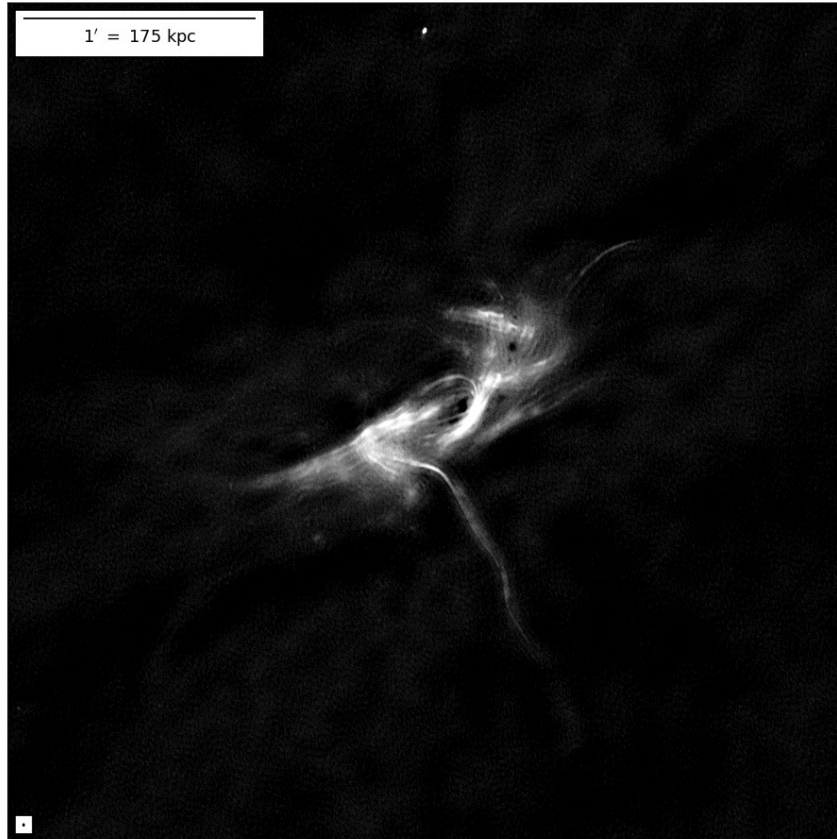


Credits: L. Morabito

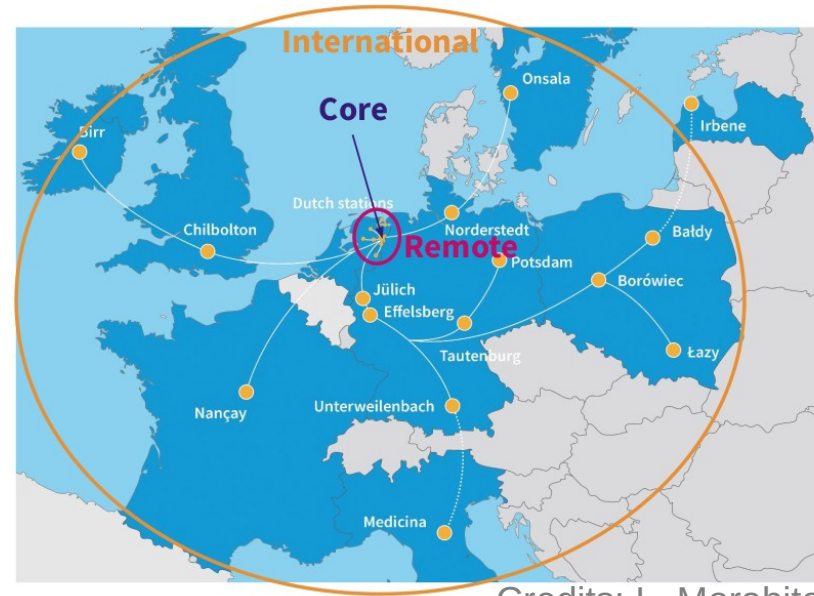
Abell 1914

(Biava et al. – in preparation)

LOFAR: 144 MHz – res: 0.5" x 0.2"



Investigate phoenix at low frequency and high resolution with LOFAR international stations

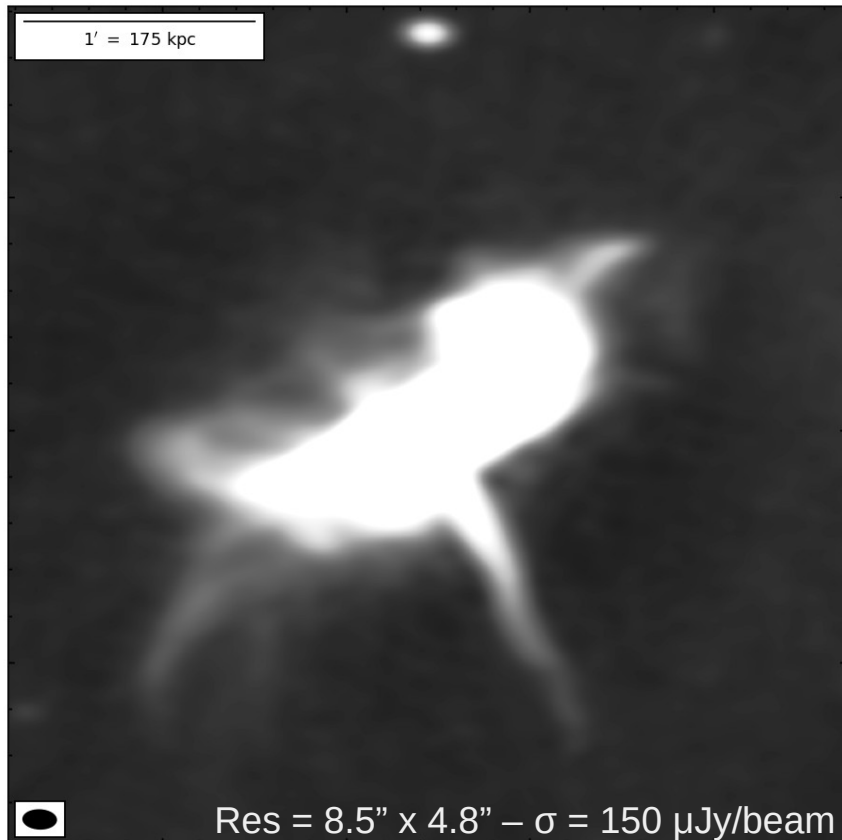


Credits: L. Morabito

Abell 1914

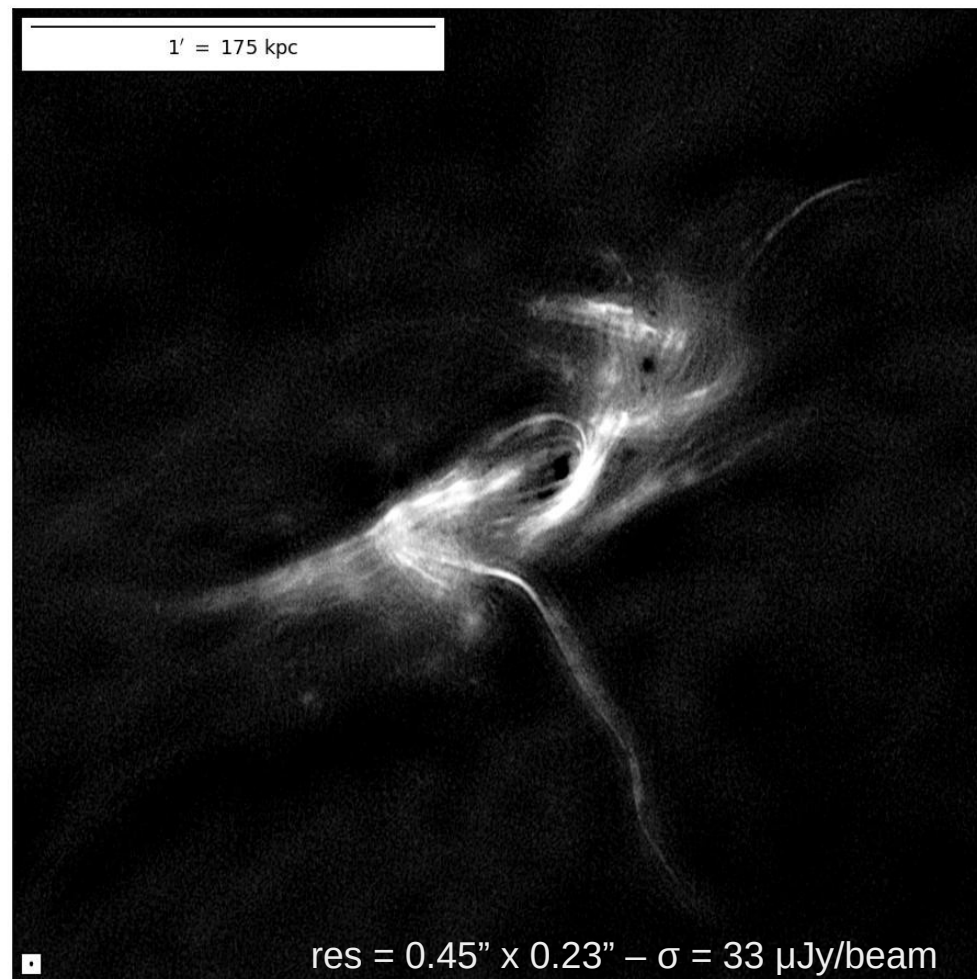
(Biava et al. – in preparation)

LOFAR 144 MHz



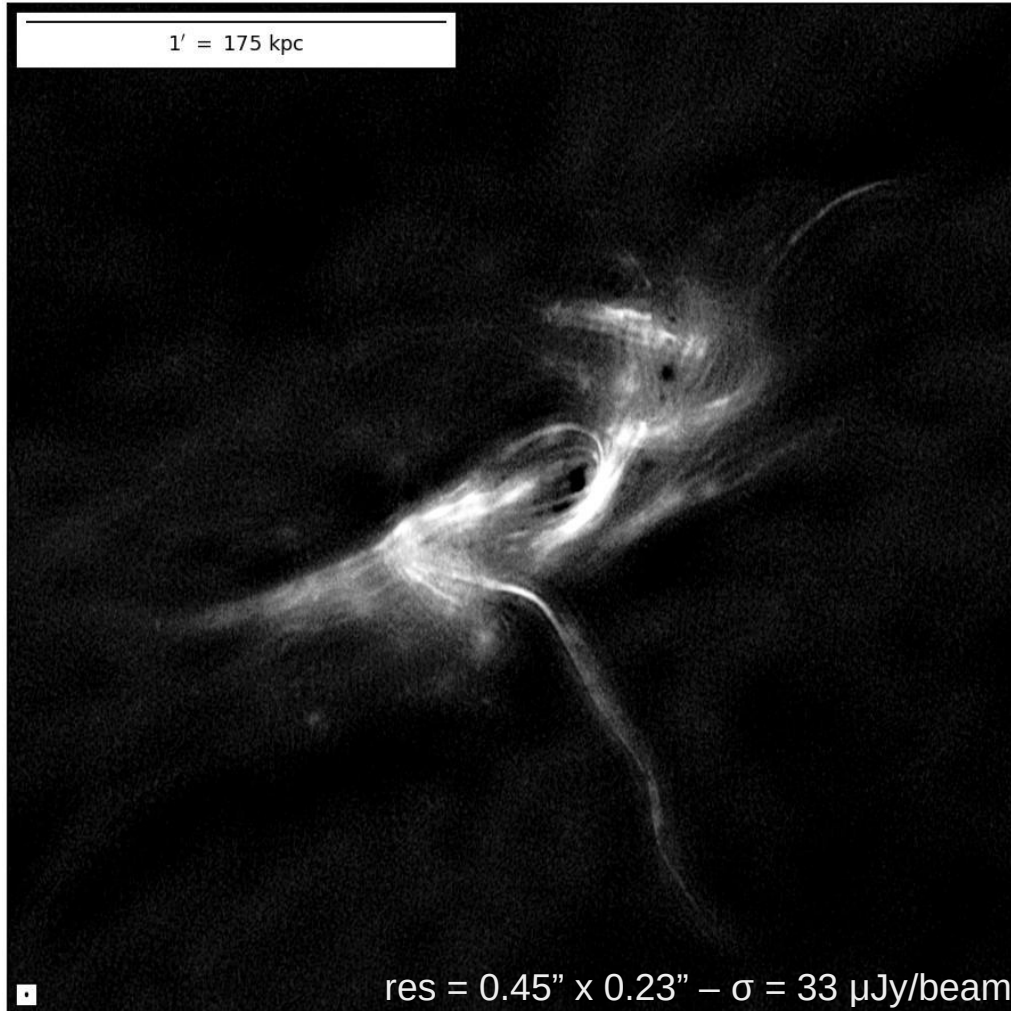
80% of total flux in filamentary structures

Filaments: length ~ 100 kpc, thickness 1-2 kpc



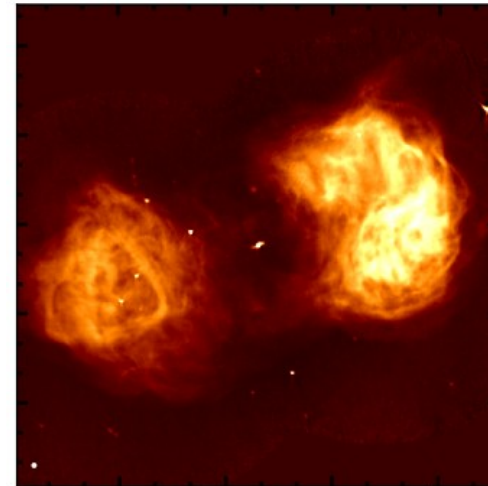
Abell 1914

(Biava et al. – in preparation)



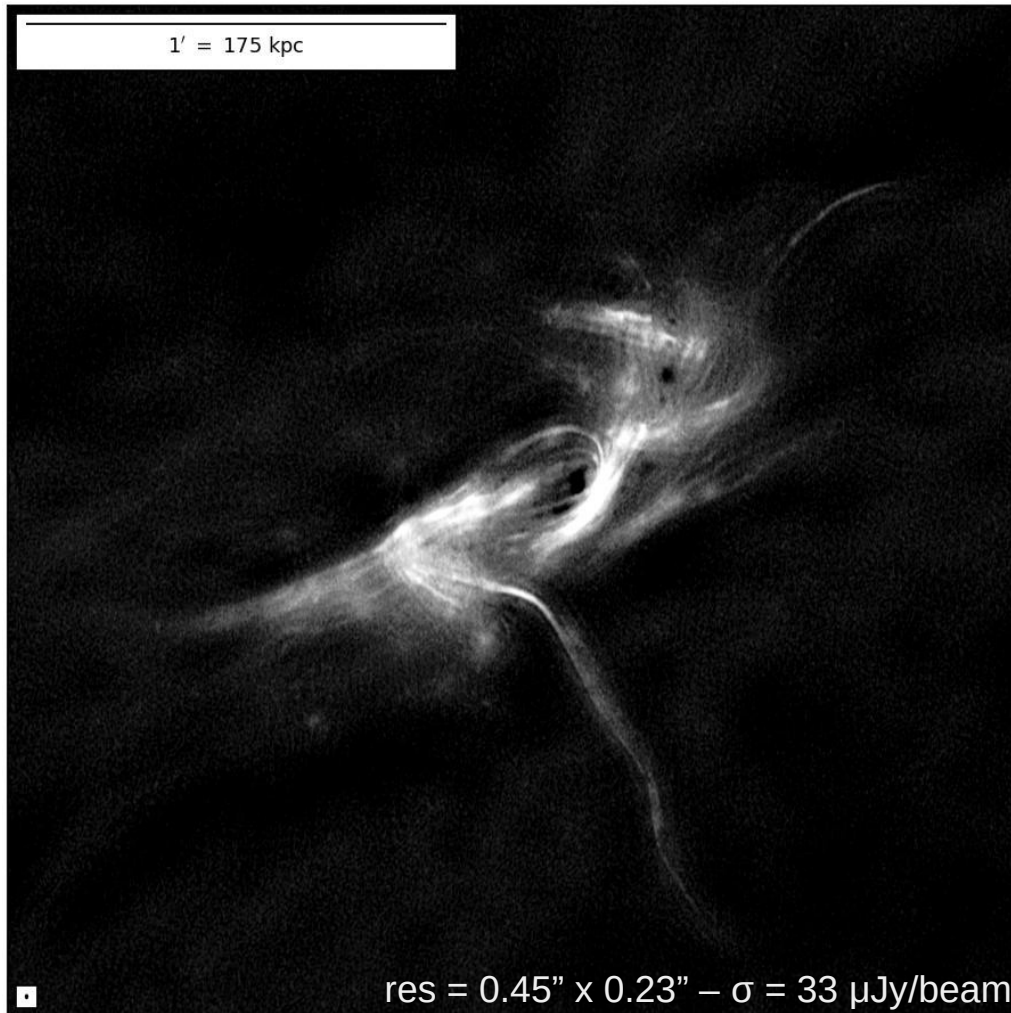
Filaments can reflect:

- Internal magnetic field structure of a remnant radio lobe:
 - filaments trace enhancements in the lobe magnetic field distribution (Hardcastle, 2013)
 - remnant plasma shredded into filaments under the influence of cluster dynamics (Vazza et al., 2021)



(Maccagni et al. 2020)

Abell 1914



Filaments can reflect:

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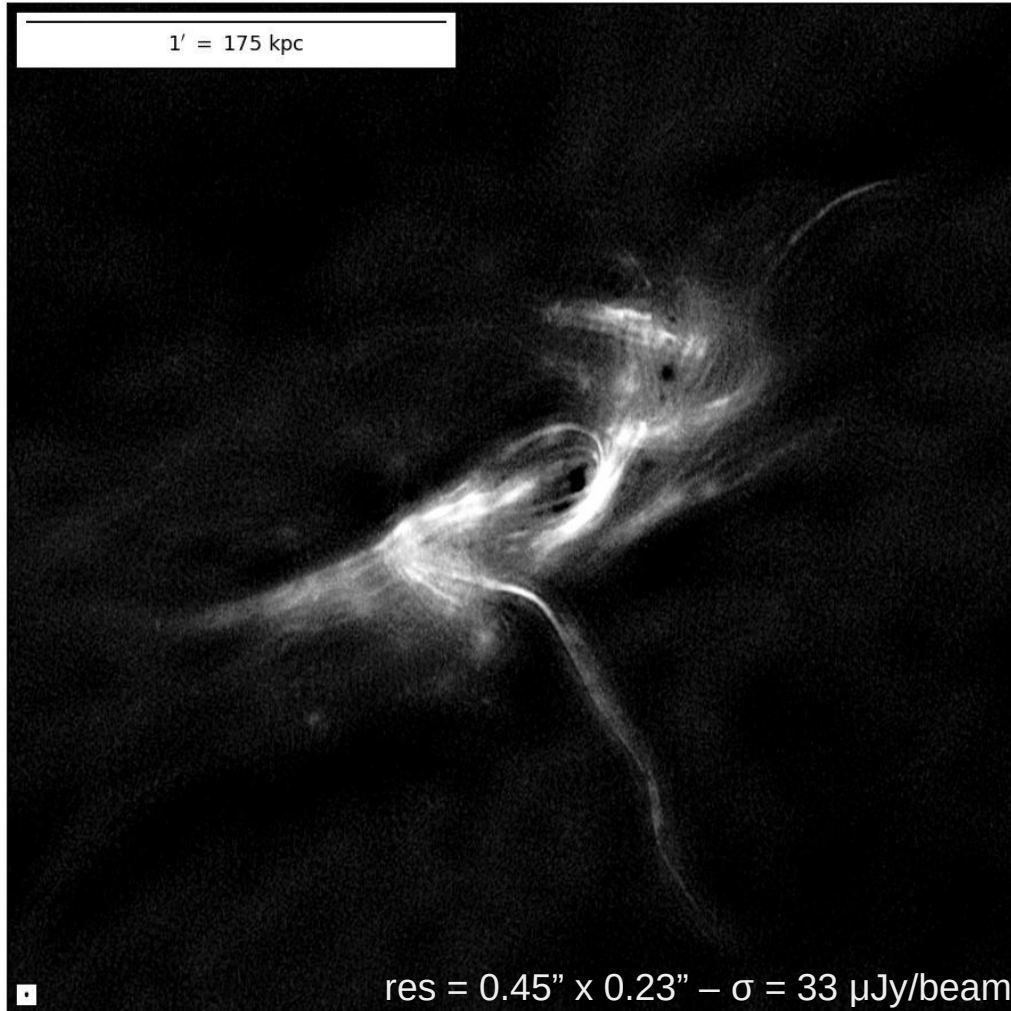
BUT

- No AGN
- Steep spectrum $\rightarrow$ old emission

without active injection of turbulence, filaments will decay to larger scale due to inverse cascade of energy

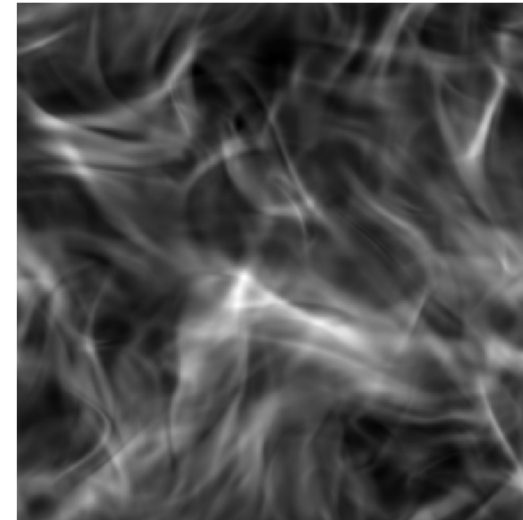
Abell 1914

(Biava et al. – in preparation)



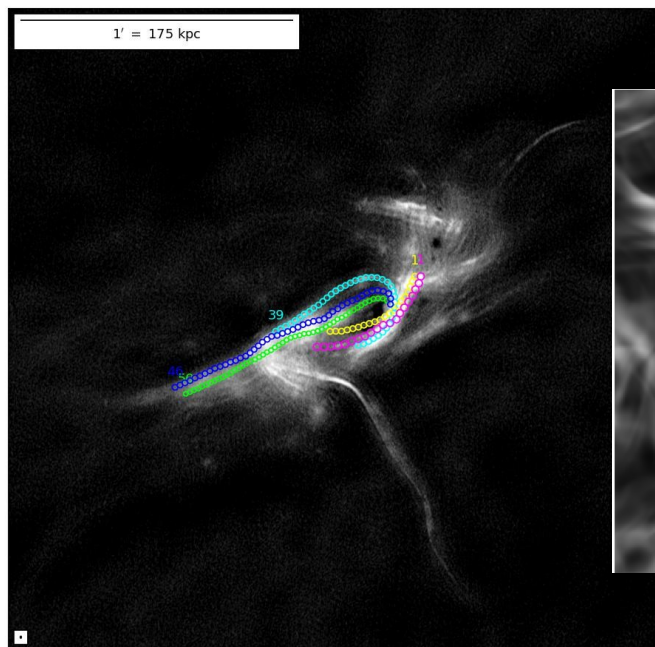
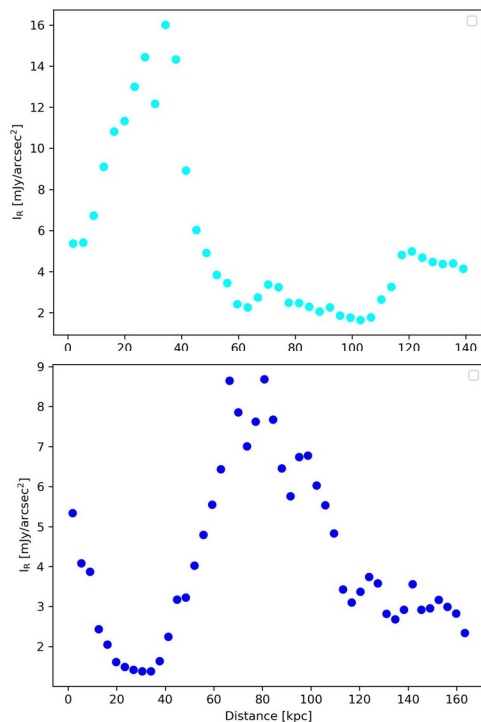
Filaments can reflect:

- Magnetic fields in the ICM:
 - magnetic filaments generated by action of turbulent dynamo (Basu & Sur, 2021)
 - Illuminated by Cosmic Rays

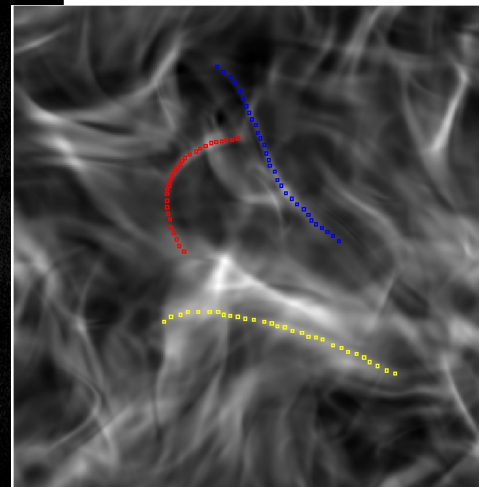


(Sur & Basu 2021)

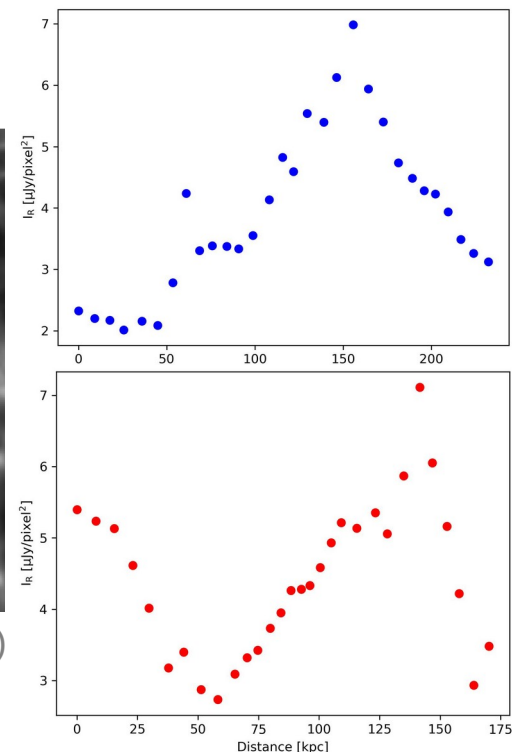
Observations vs simulations



MHD simulation



(Sur & Basu 2021)



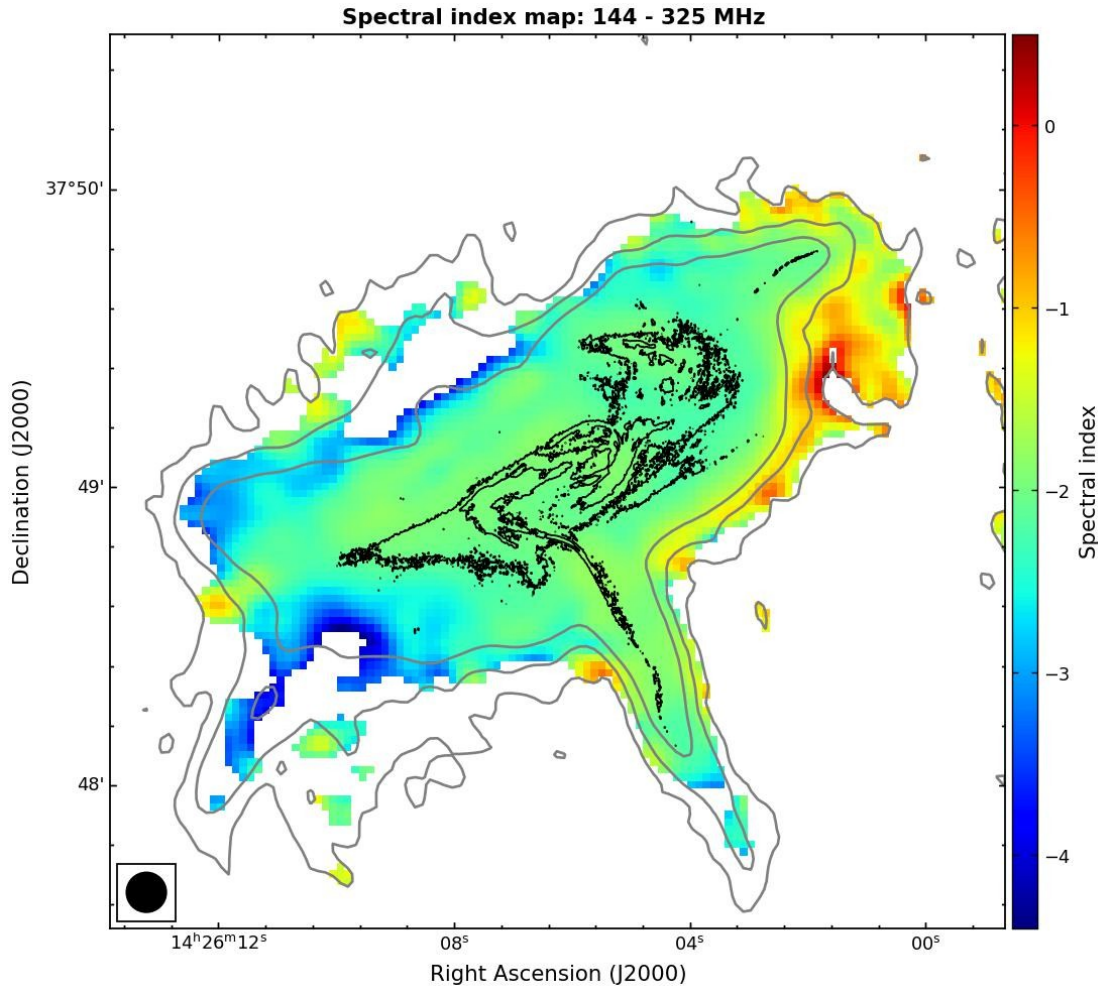
Observation do not show clear trend:

- Cosmic ray fluctuations ?
- Magnetic field fluctuations ?

Turbulent dynamo:

- Magnetic field fluctuations can produce the observed trend

Spectral informations

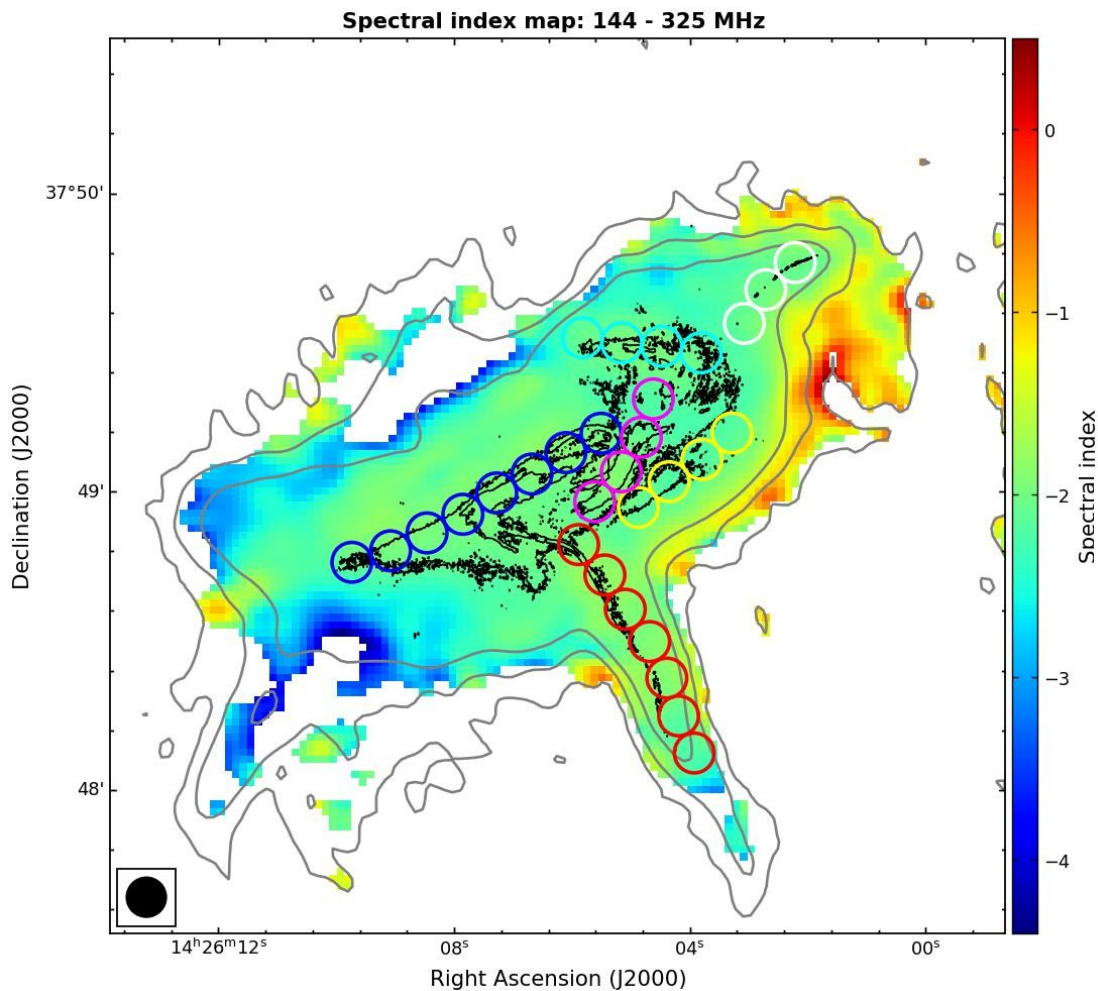


Radio Phoenix:

Fairly uniform spectral index distribution:

$$-2.4 < \alpha < -1.8$$

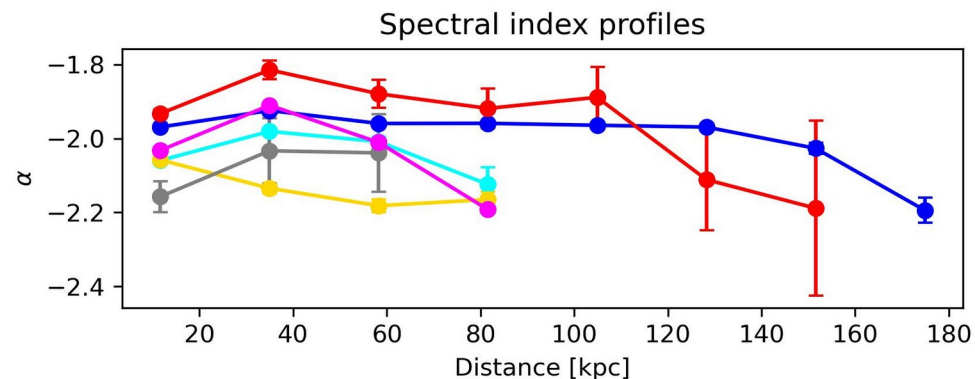
Spectral informations



Radio Phoenix:

Fairly uniform spectral index distribution:

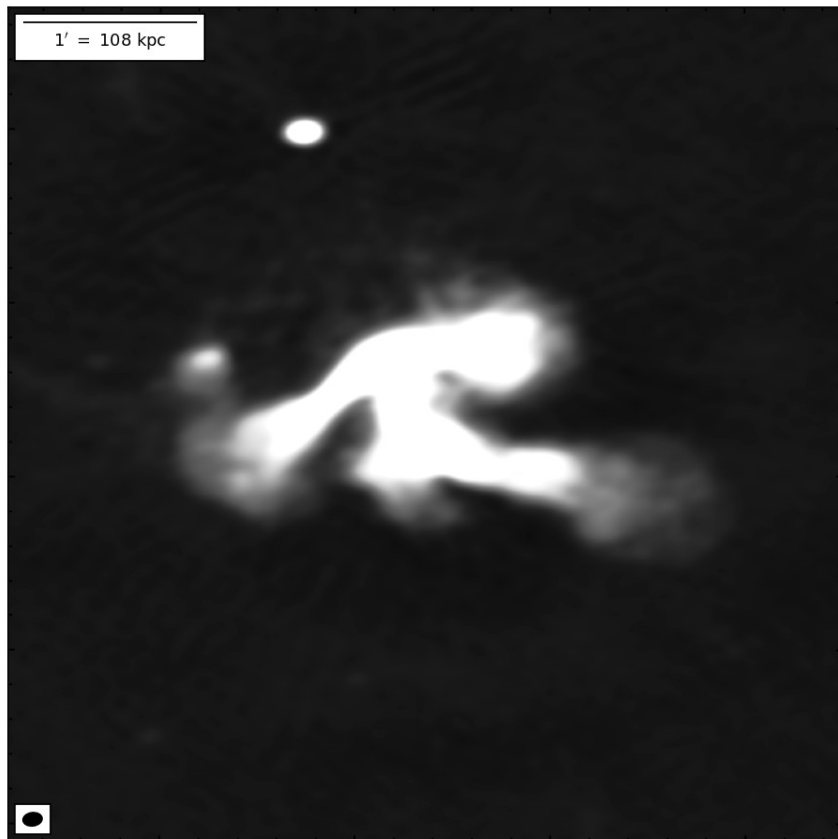
$$-2.4 < \alpha < -1.8$$



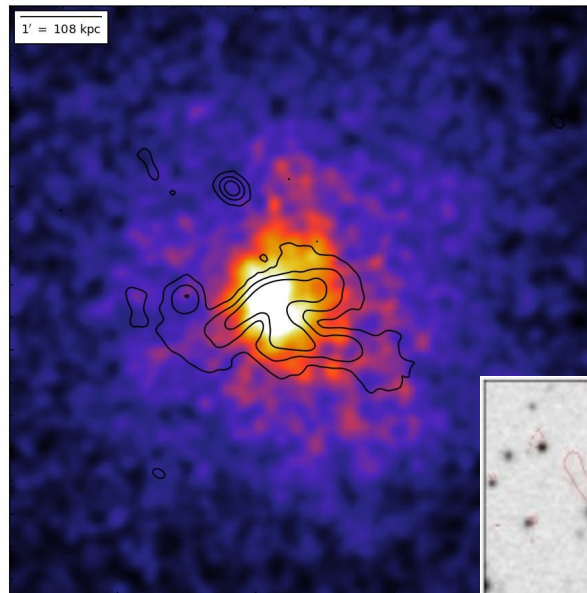
Abell 566

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

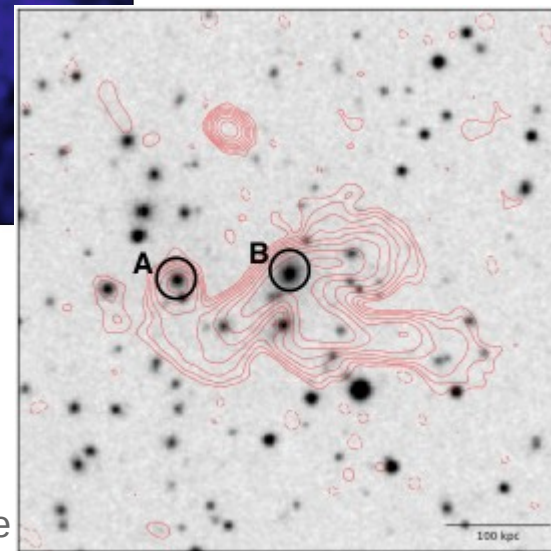
LOFAR 144 MHz – res 6.6" x 4.6"



XMM-Newton – EMOS1



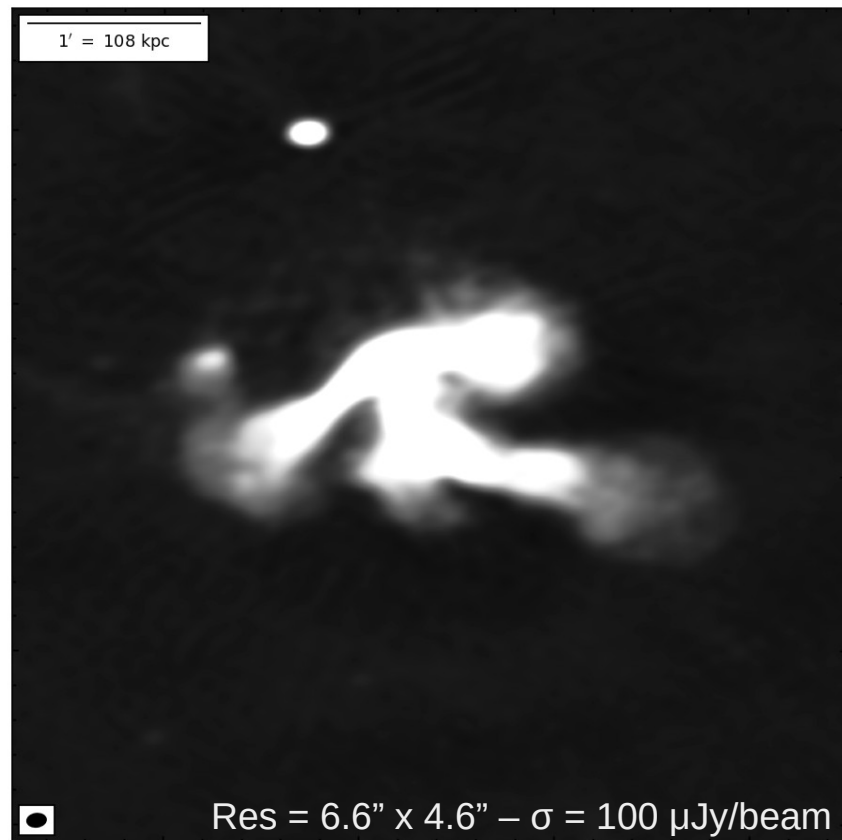
DSS r-band optical image



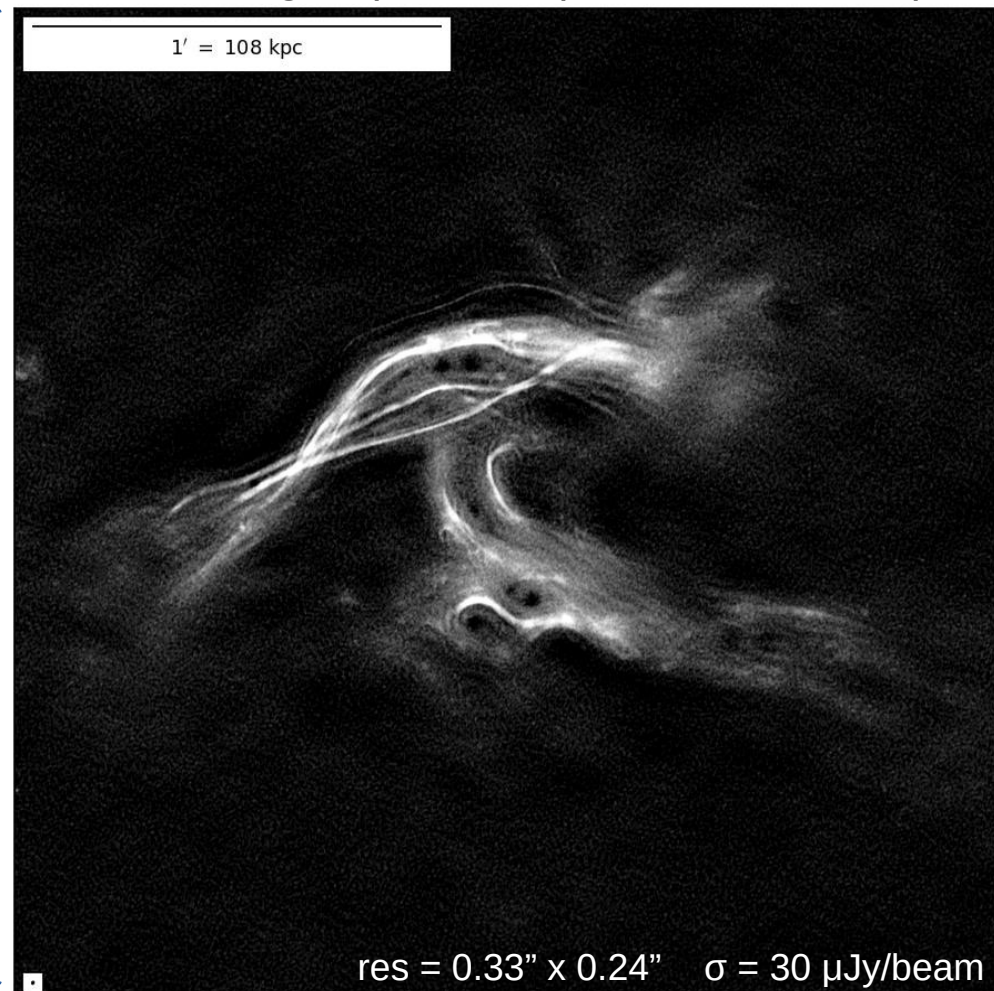
Abell 566

(Biava et al. – in preparation)

LOFAR 144 MHz

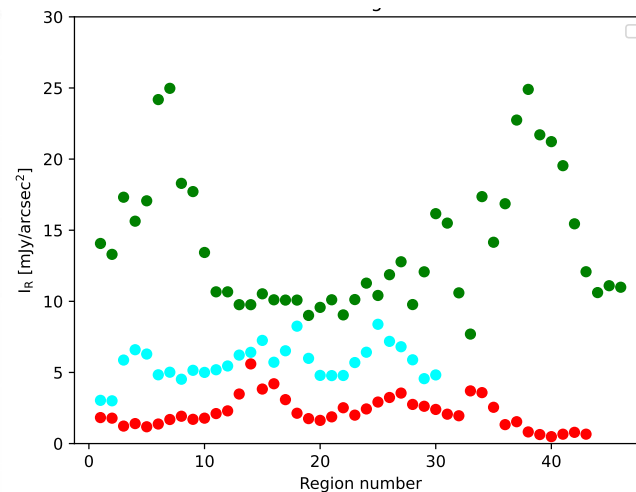
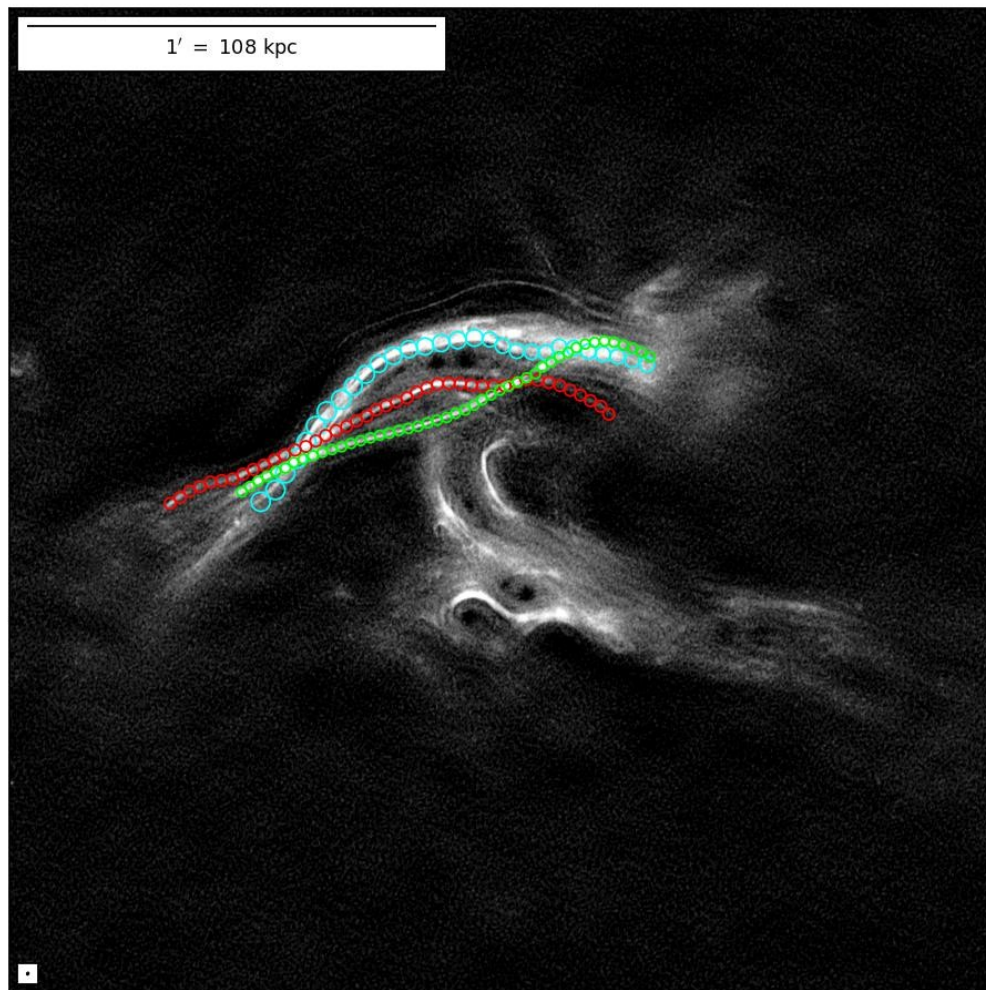


Filaments: length up to 150 kpc, thickness 1-2 kpc

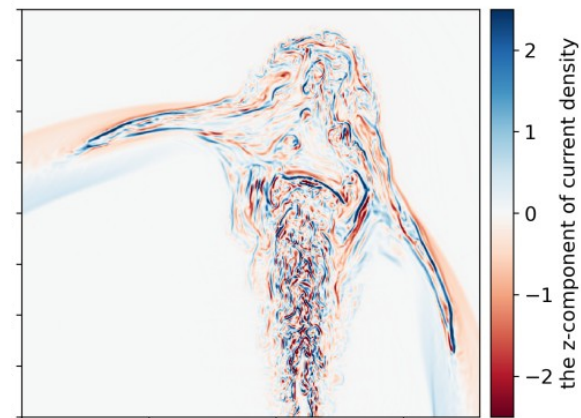


Abell 566

(Biava et al. – in preparation)

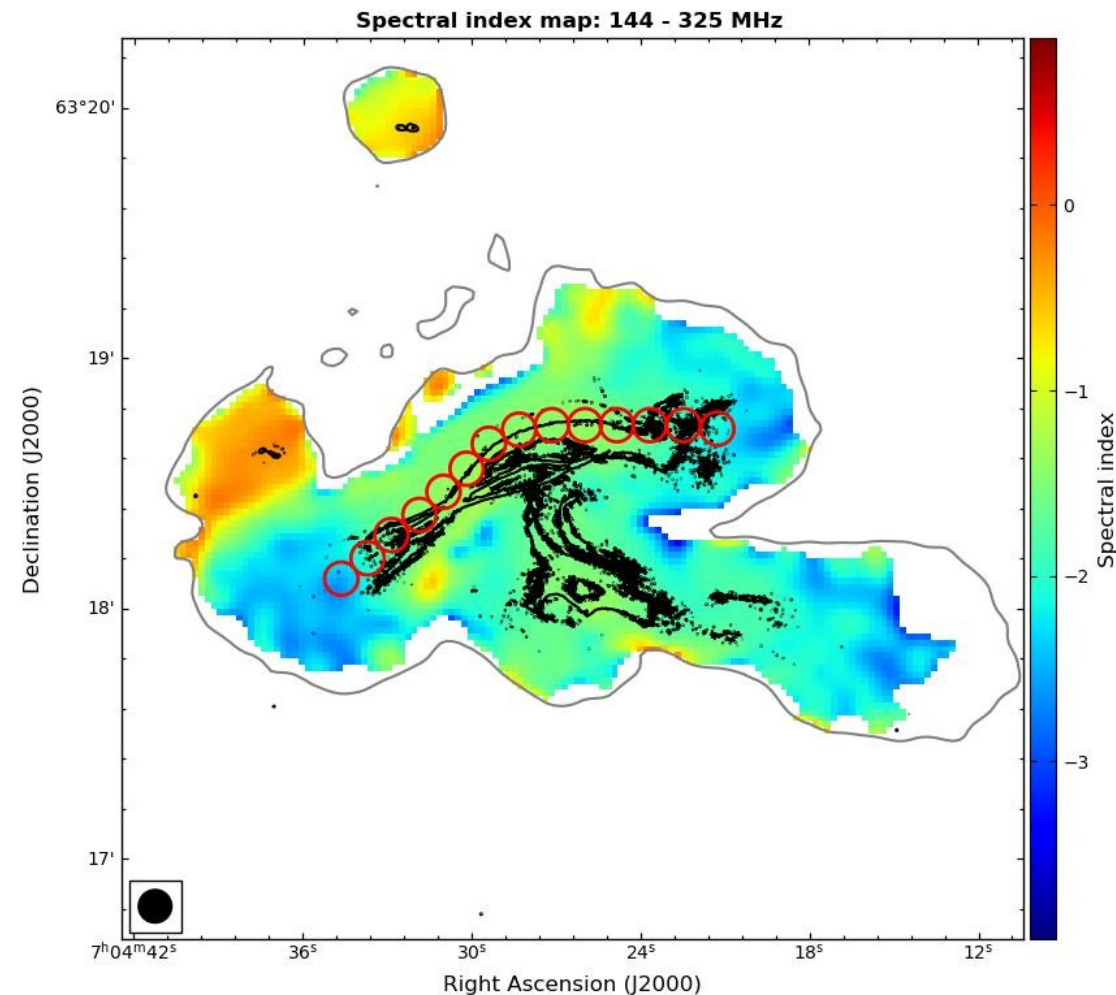


Possible scenario:
ICM magnetic
field stretched by
AGN lobe



(Chibueze et al. 2021)

Abell 566



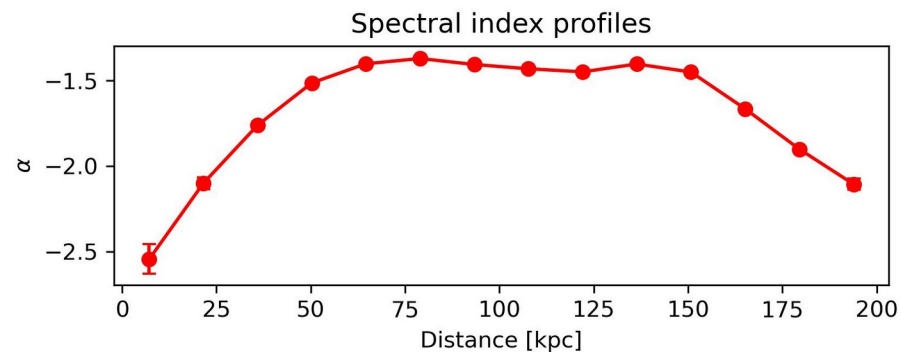
Radio phoenix:

- Main structure has a uniform spectral index

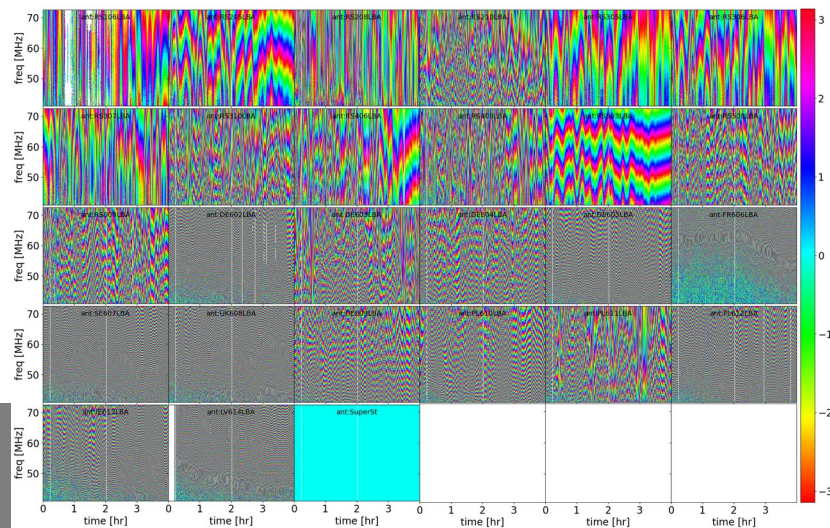
$$\alpha \sim -1.3$$

- Steepens only at extremities

$$\alpha \sim -2.0$$



Abell 566



Tried LBA-VLBI calibration

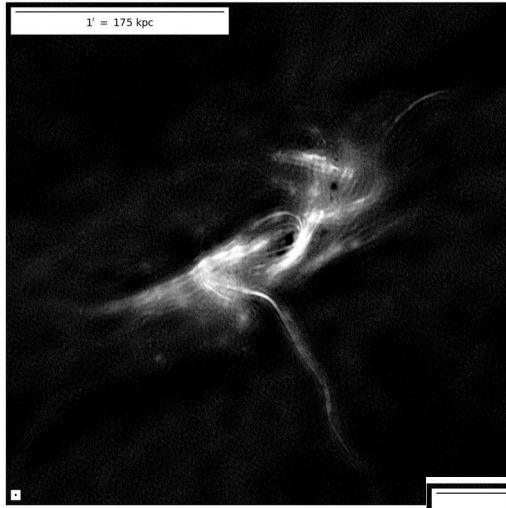
BUT:

- Observations taken during solar maximum
→ highly active ionosphere
- Infield calibrator not good enough
- No compact bright sources in the field

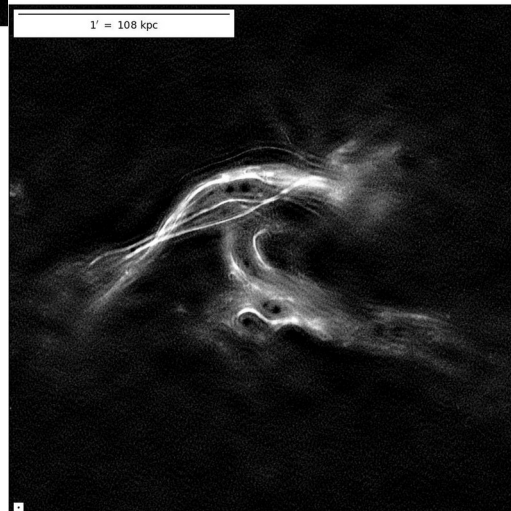
Choose carefully
the target

Hope for quiet
ionosphere

Future prospects



Old plasma +
ICM magnetic field ?



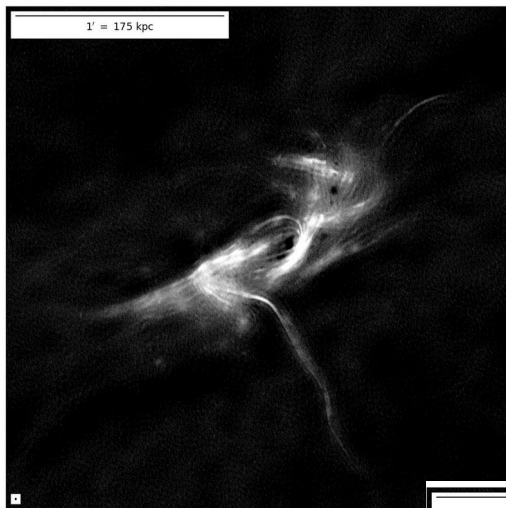
Energetic plasma
deforming ICM
magnetic field ?

To understand the nature of phoenixes:

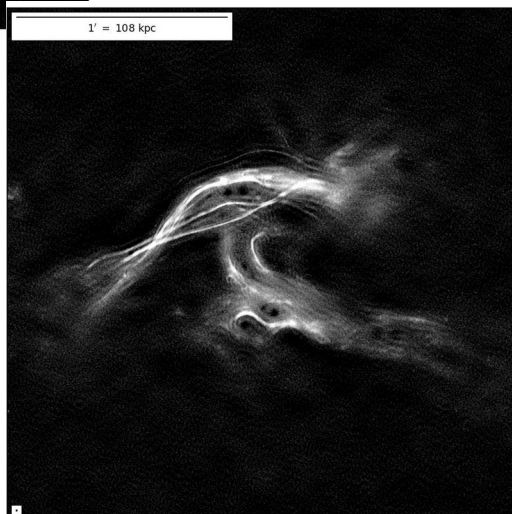
- **High-resolution spectral index profiles**
to track cosmic ray fluctuations
- **High-frequency spectral information**
to estimate the age of cosmic rays
- **Polarisation information**
to infer the magnetic field structure

Need for
LOFAR 2.0 & SKA-Mid
observations

Future prospects



Old plasma +
ICM magnetic field ?



Energetic plasma
deforming ICM
magnetic field ?

To understand the nature of phoenixes:

- **High-resolution spectral index profiles**
to identify cosmic ray fluctuations
- **High-frequency spectral information**
to estimate the age of cosmic rays
- **Polarisation information**
to infer the magnetic field structure

Need for
LOFAR 2.0 & SKA-Mid
observations

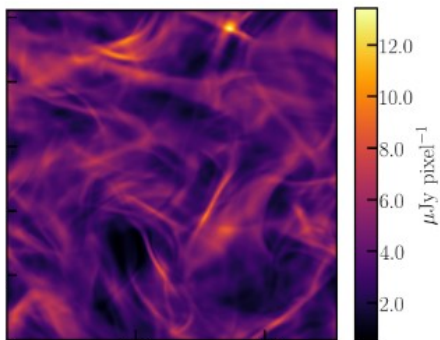
Thank you for the attention

Simulations*

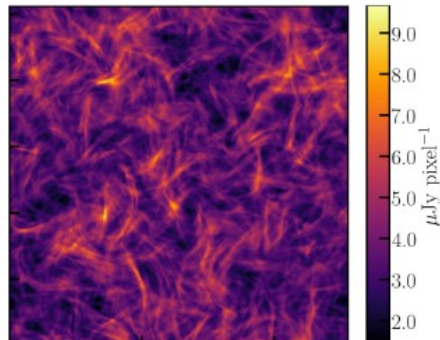
Basu & Sur 2021: Isothermal, sub-sonic simulations ($M \sim 0.2$)
Rms velocity $\sim 200 - 300$ km/s
Plasma $\beta = 10^6$

Turbulence driven on different scales

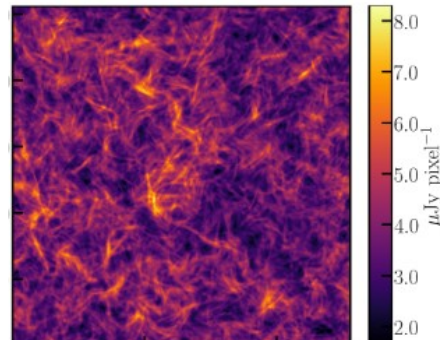
k2: $l_f = 76.8$ kpc



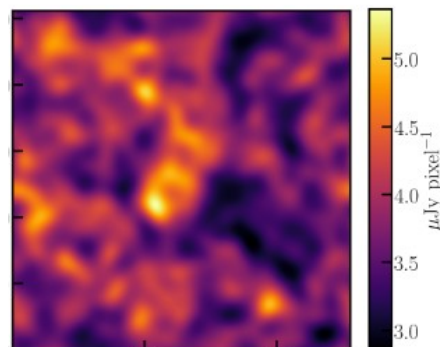
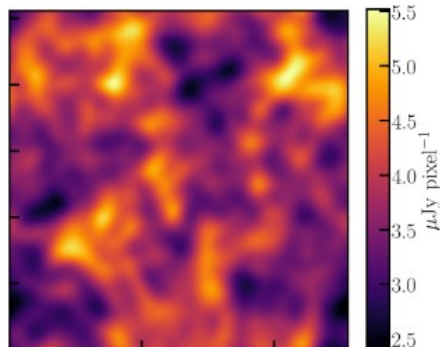
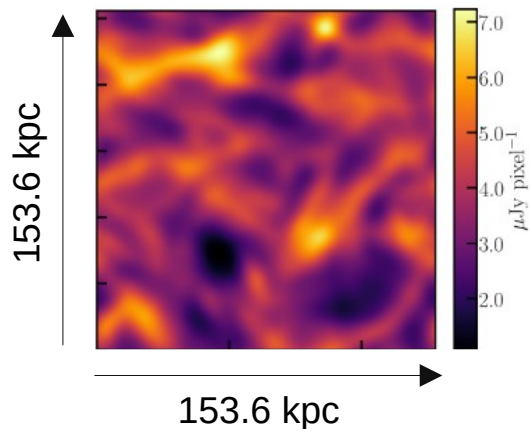
k5: $l_f = 30.7$ kpc



k8: $l_f = 19.2$ kpc



2D maps of surface
brightness of total
synchrotron
emission



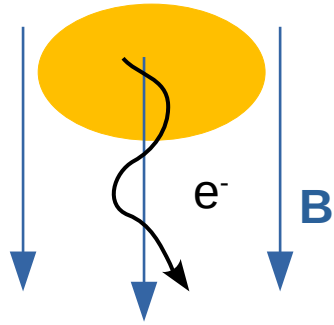
Smoothed maps of
total synchrotron
emission

*Simulations scaled to A1914 ICM properties and size

Abell 1914 – South filament

Investigating a possible scenario for the formation of the southern filament

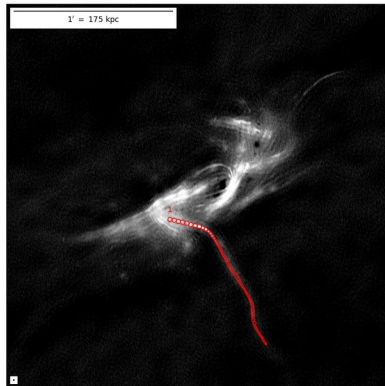
- Re-connection of ICM magnetic field line with remnant radio emission



CRe stream along magnetic field line with Alfvénic speed

$$v_A = \frac{B}{\sqrt{\mu_0 \rho}} \sim 270 \text{ km/s}$$

- $B_{\text{eq}} = 8.8 \mu\text{G}$
- ICM $n_e \sim 0.008 \text{ cm}^{-3}$ ($r = 140 \text{ kpc}$)



Filament length = 175 kpc



$$t_{\text{stream}} = 0.7 \text{ Gyr}$$

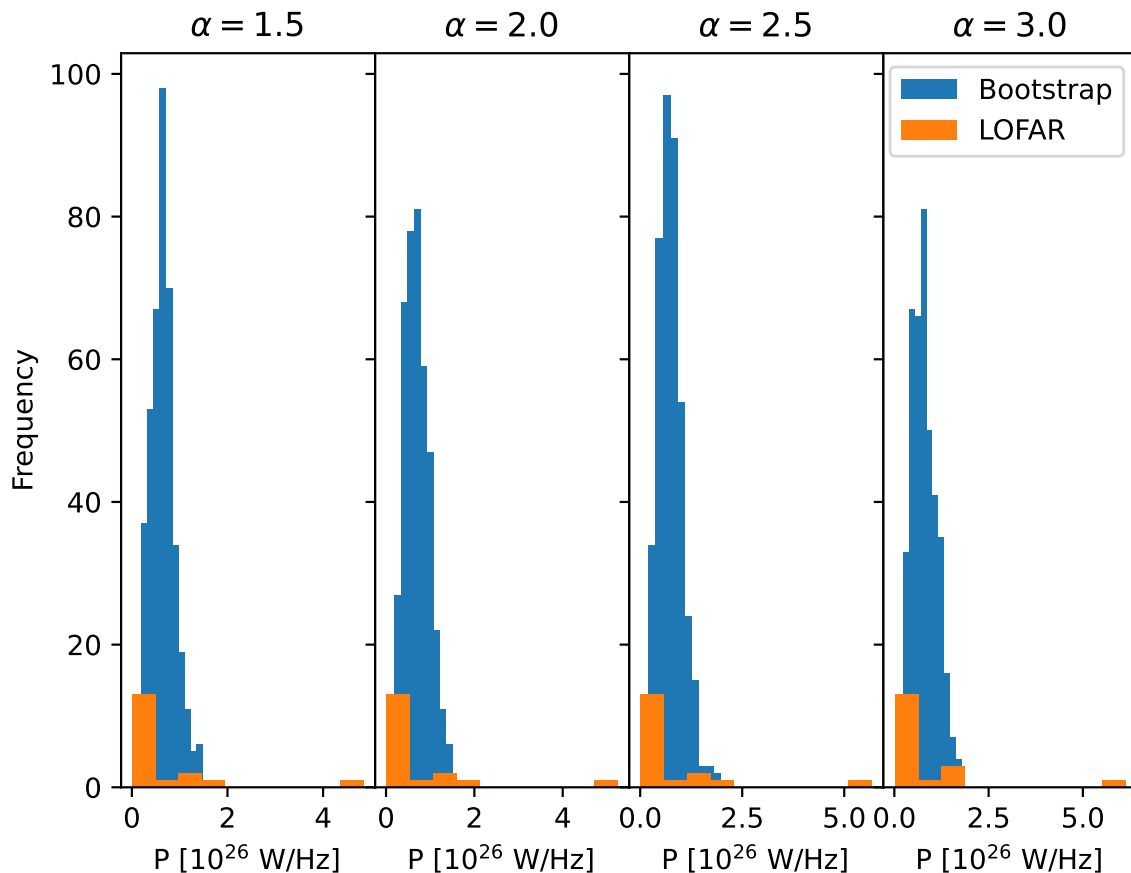
CRe energy loss timescale
IC + Synchrotron



$$t_{\text{loss}} = 0.1 \text{ Gyr}$$

$$v_e = 7 \times v_A \rightarrow n_e \ll \rightarrow r \gg 140 \text{ kpc}$$

Extrapolating LOFAR sample



18 candidate radio phoenixes
in the northern hemisphere

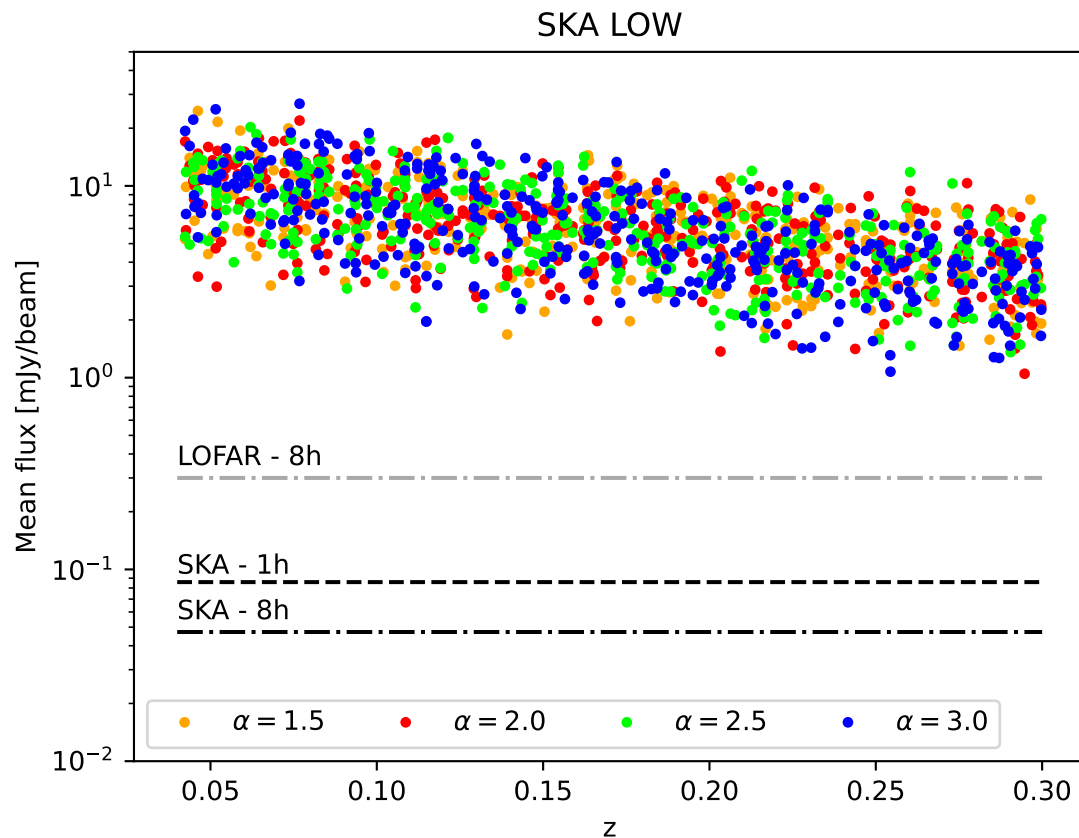
Total flux estimates from LoTSS

Computed the power at 144 MHz
considering different values of
spectral index: $1.5 < \alpha < 3.0$

Enlarged the sample using
bootstrap from LOFAR

SKA (AA*) estimates

SKA LOW



ν_0 : 144 MHz
 $\Delta\nu$: 48 MHz
Res: 6.95" x 6.24"

At comparable resolution and frequency coverage:

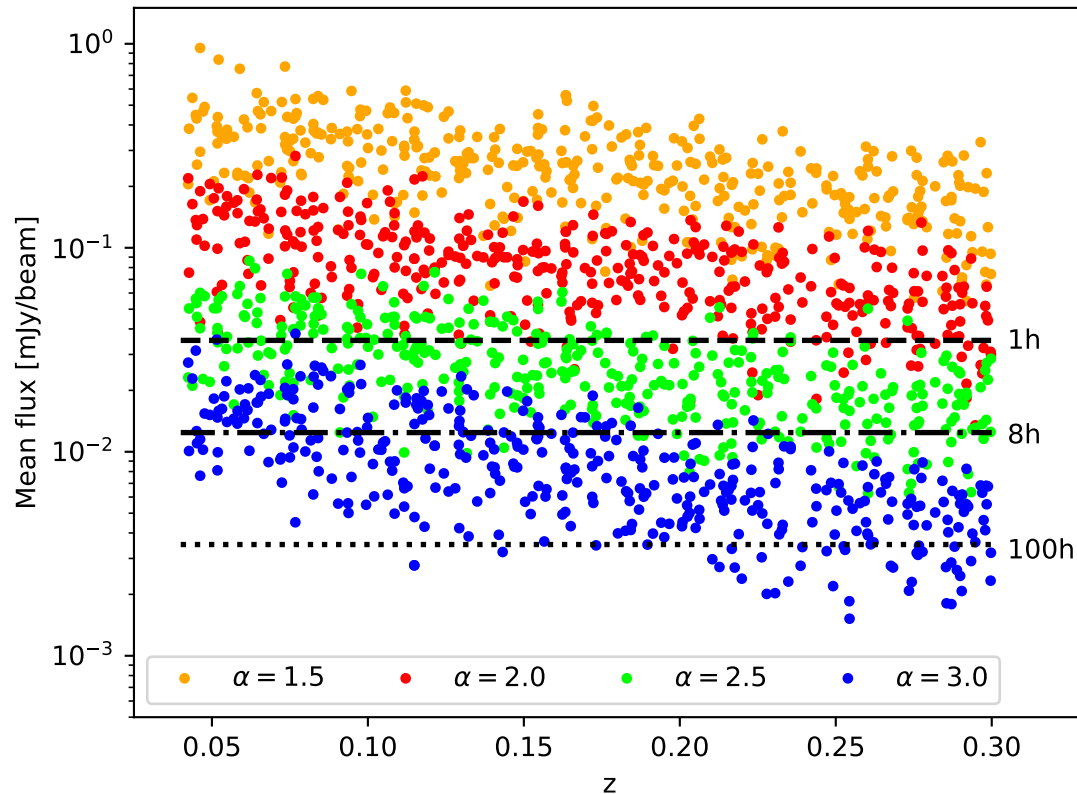
SKA sensitivity = 6 x LOFAR

Integration = 1h $\rightarrow$ 100% detection

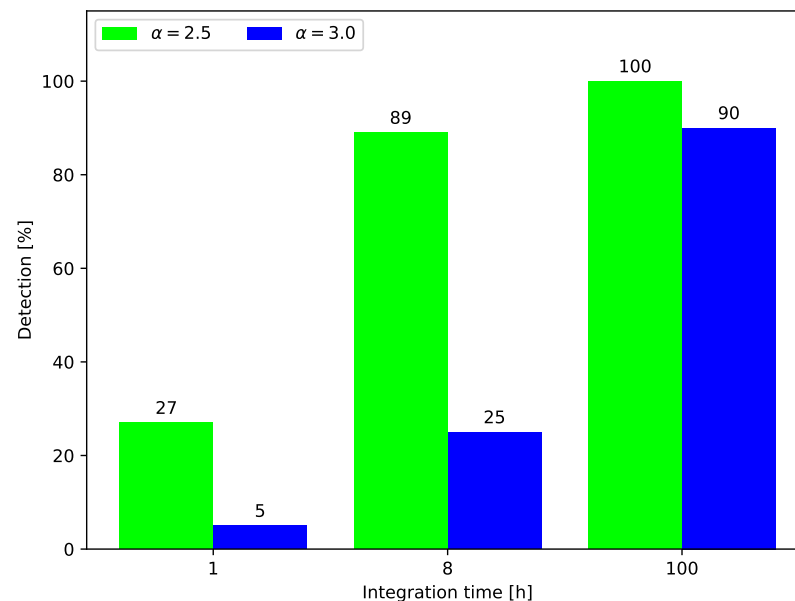
SKA (AA*) estimates

SKA MID - Band 2

SKA MID - Band 2



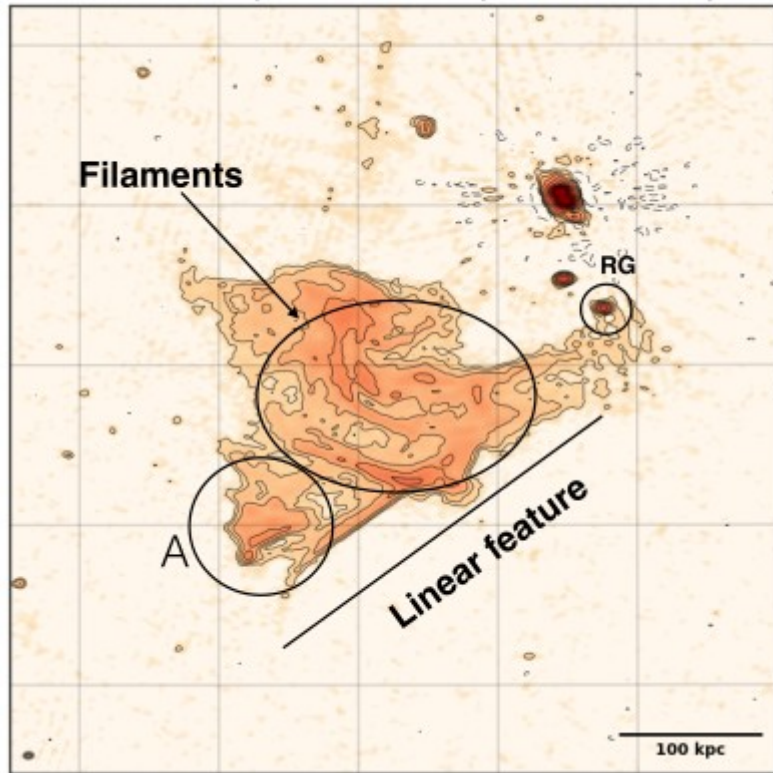
ν_0 : 1.31 GHz
 $\Delta\nu$: 0.72 GHz
Res: 0.76" x 0.27"



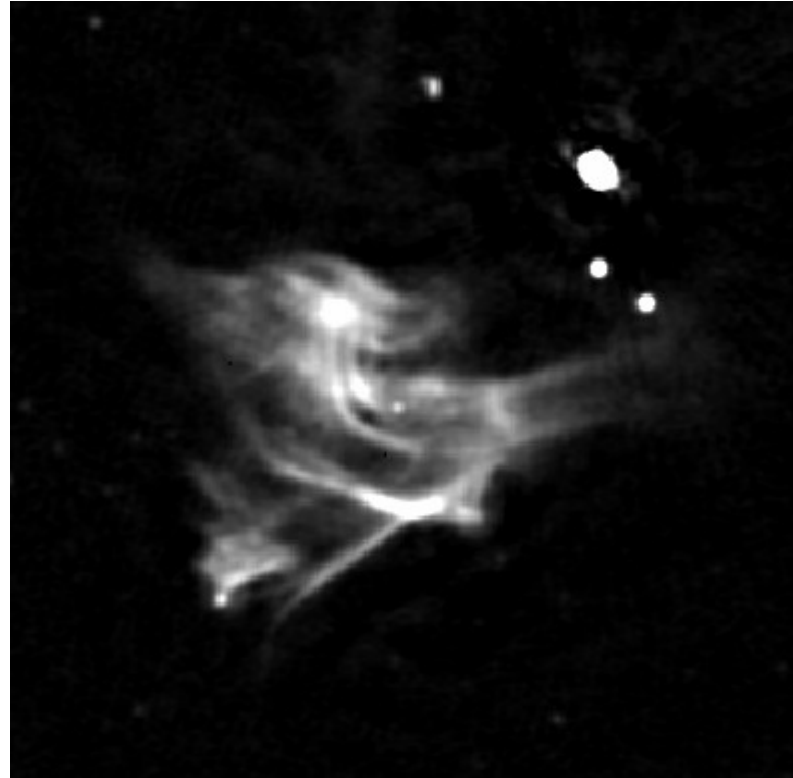
Need for dedicated observations

SDSS-C4-DR3-3088

$$M_{500} = 1.69 \times 10^{14} M_{\odot} \quad z = 0.046$$



(Mandal et al. 2020)



SDSS-C4-DR3-3088

