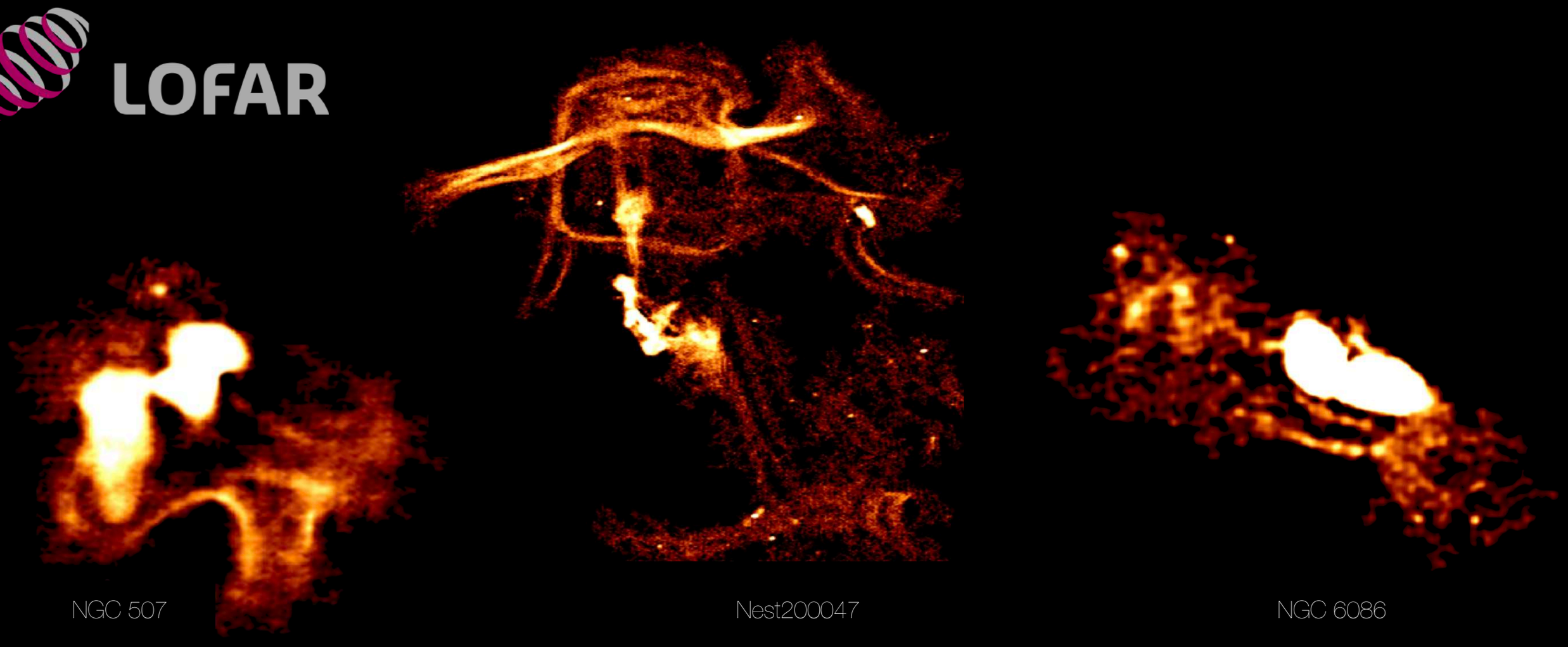
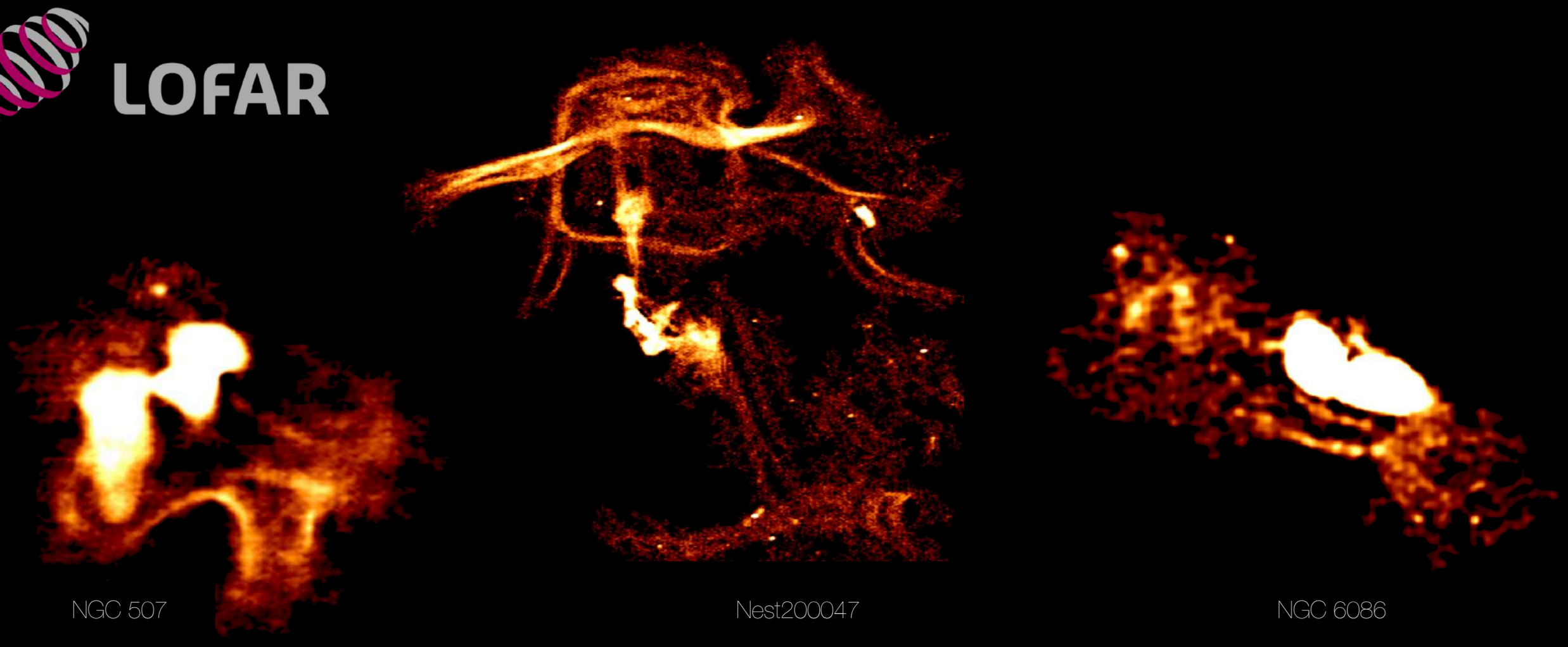


AGN fossil plasma in galaxy groups

Marisa Brienza

Vazza, Bonafede, Morganti, Lovisari, **Gastaldello**, Churazov, Rajpurohit, Murgia
Biava, Bikmaev, Bonnassieux, Botteon, Brunetti, Brüggen, Burenin, Capetti, de Gasperin, Drabent
Hardcastle, Khabibullin, Lyskova, Mandal, Pasini, Purser, Riseley, Röttgering, Shimwell,
Simionescu, Sunyaev, Tasse, van Weeren



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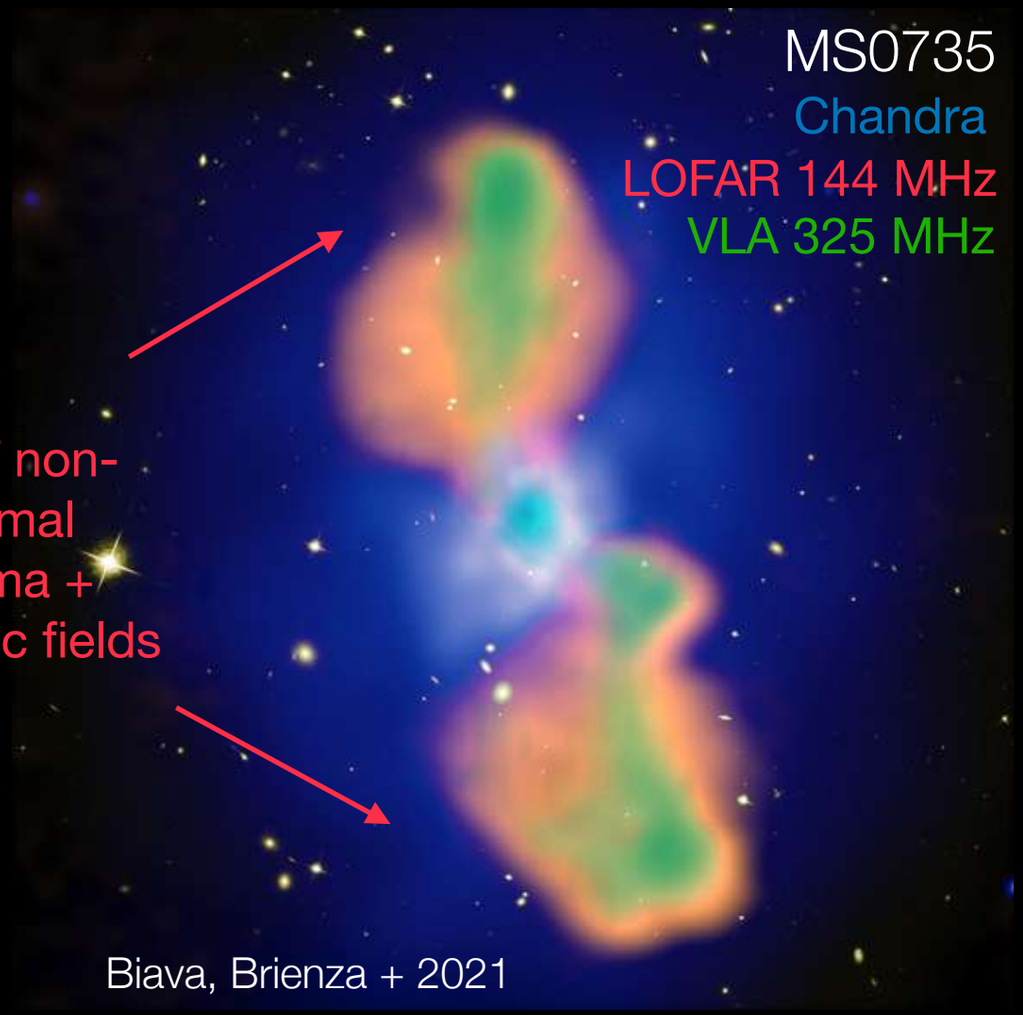
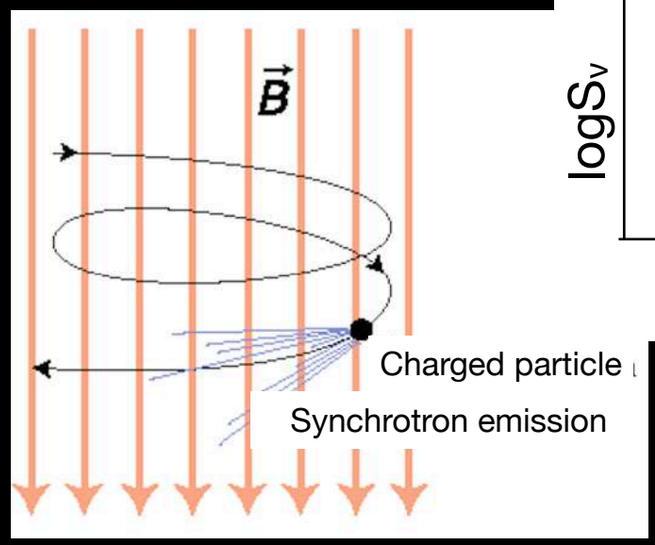
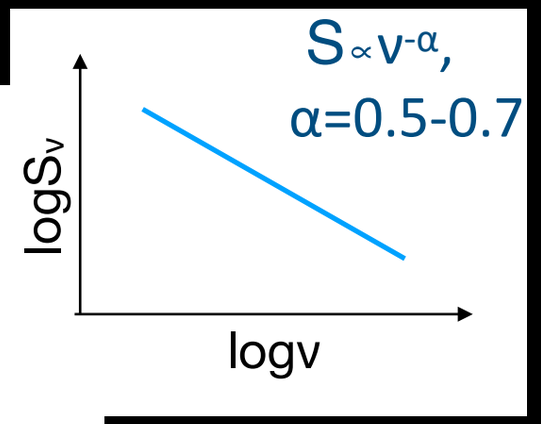
AGN jets



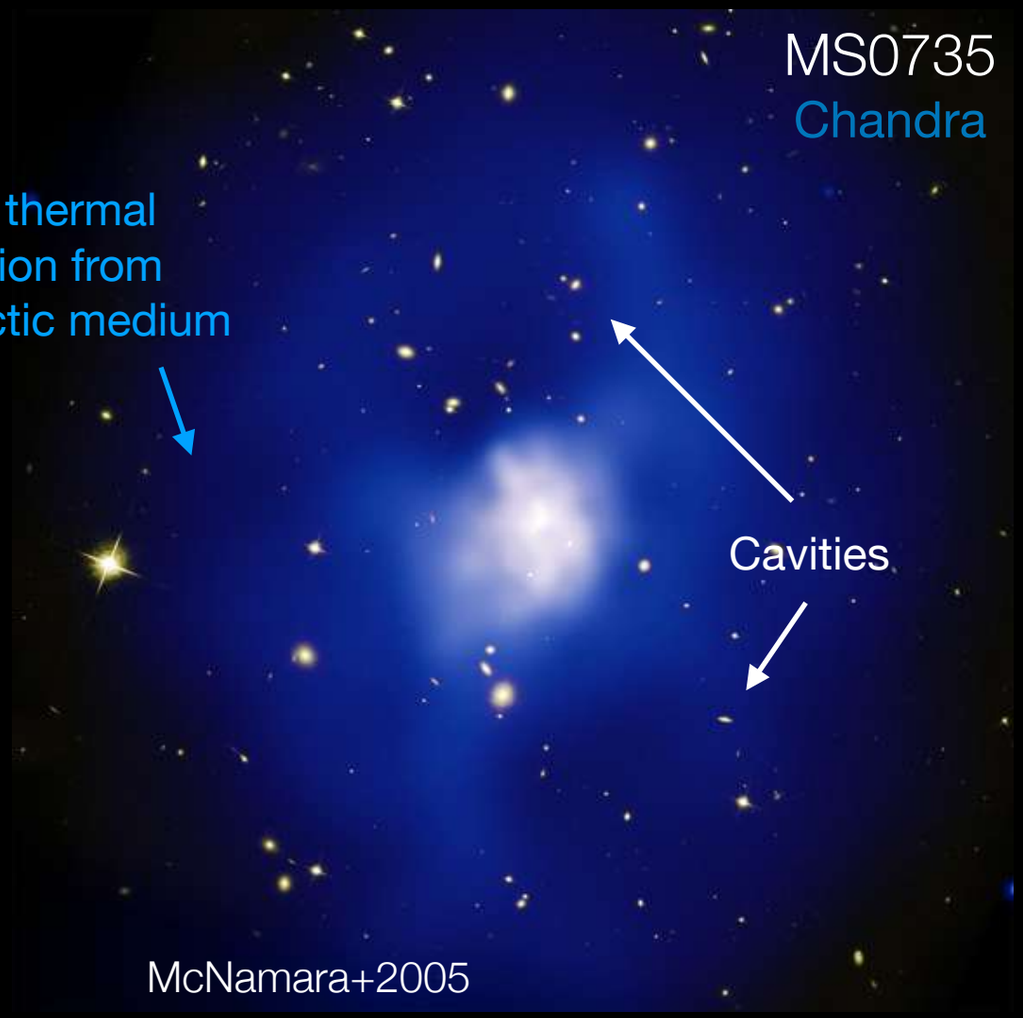

Simulation
Heinz+2016

buoyancy velocity > jet expansion velocity
bubble starts rising into the ICM





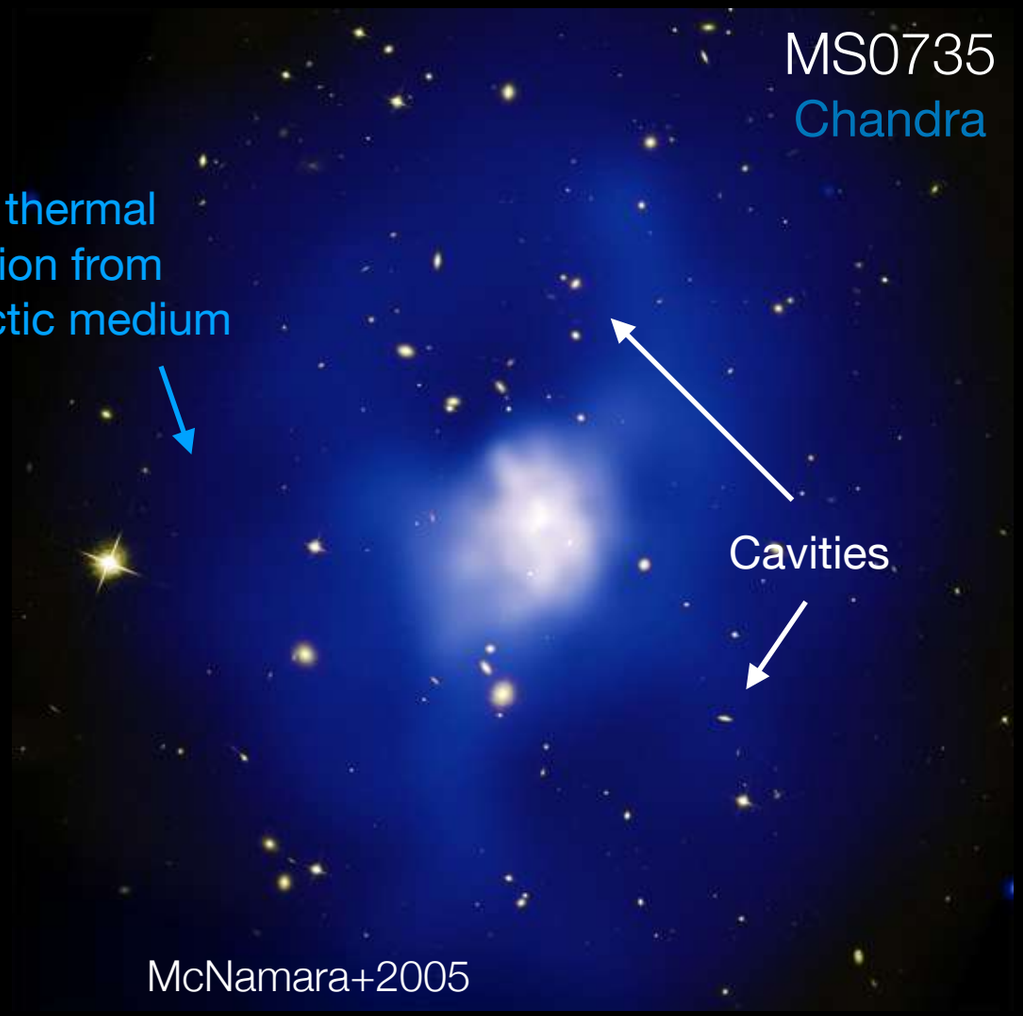
AGN jets and mechanical feedback

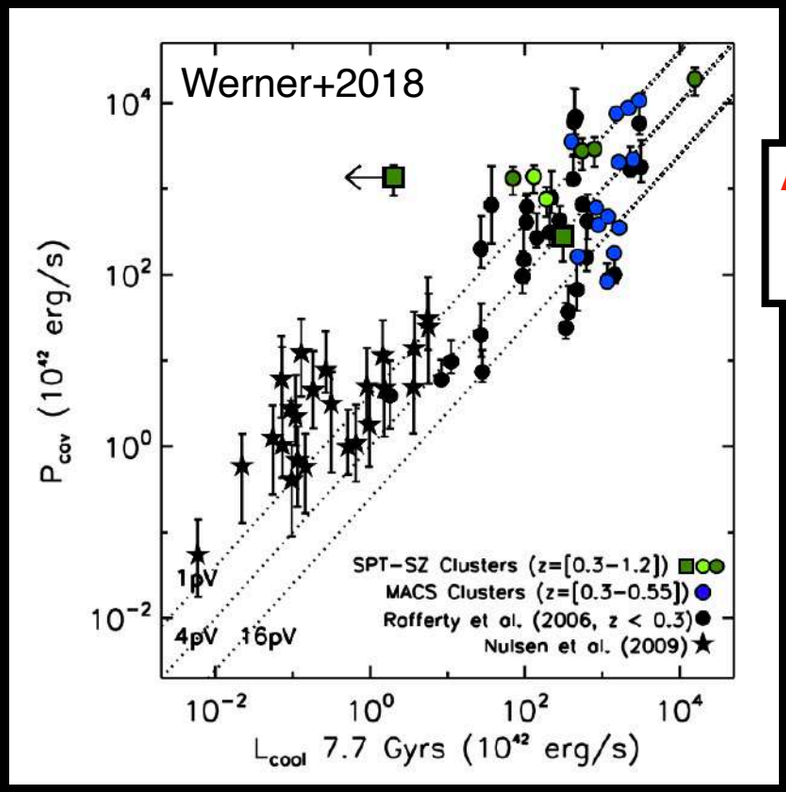


- Displace and heat ICM/IGrM

We know

AGN jets and mechanical feedback





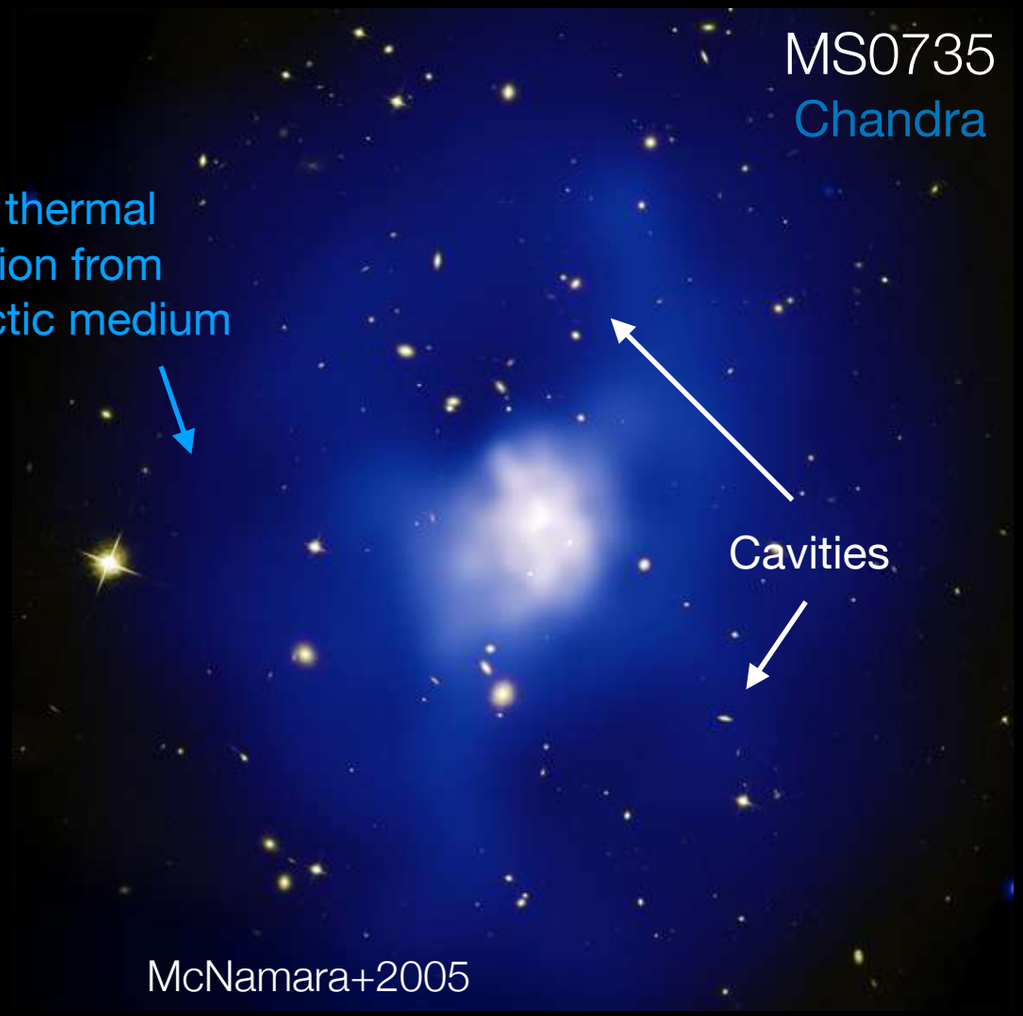
P_{cav} vs L_X

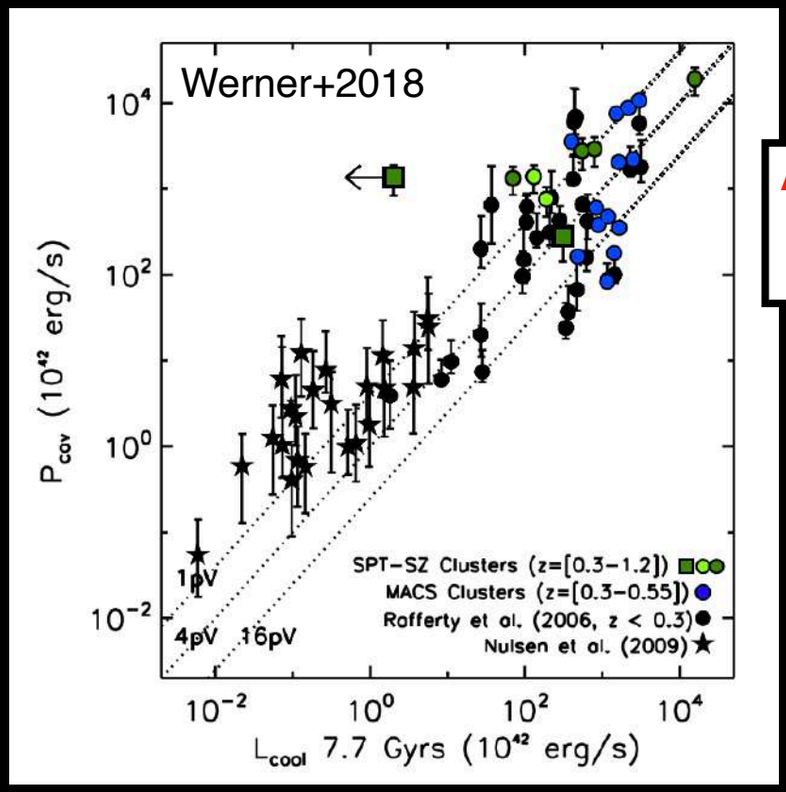
AGN jets output vs ICM cooling

- Displace and heat ICM/IGrM
- Bubble power matches the X-ray luminosity

We know

AGN jets and mechanical feedback





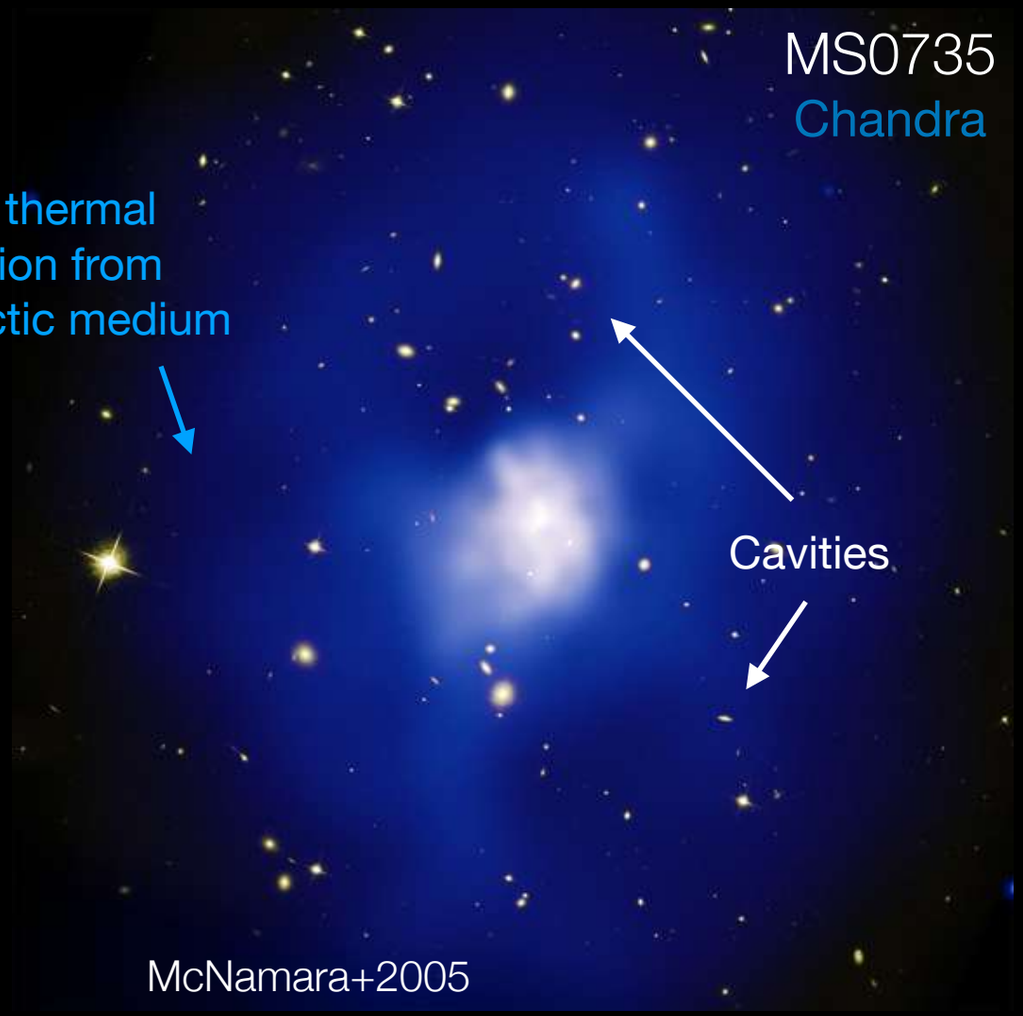
P_{cav} vs L_X

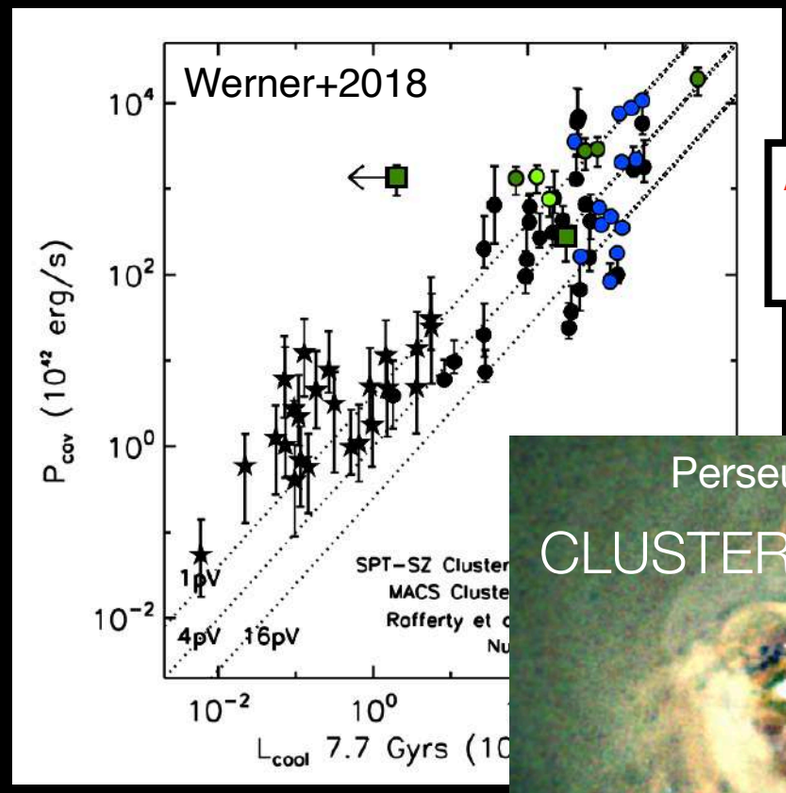
AGN jets output vs ICM cooling

We know

- Displace and heat ICM/IGrM
- Bubble power matches the X-ray luminosity
- Weak shocks / Sound waves
- Turbulence
- Uplift gas from the central regions of the galaxy

AGN jets and mechanical feedback





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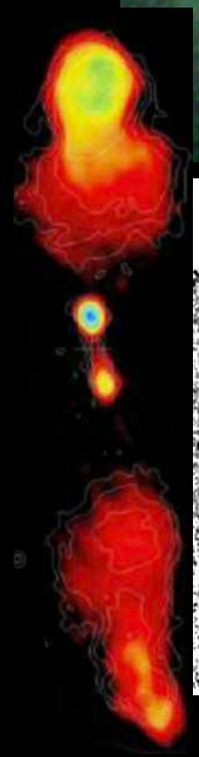
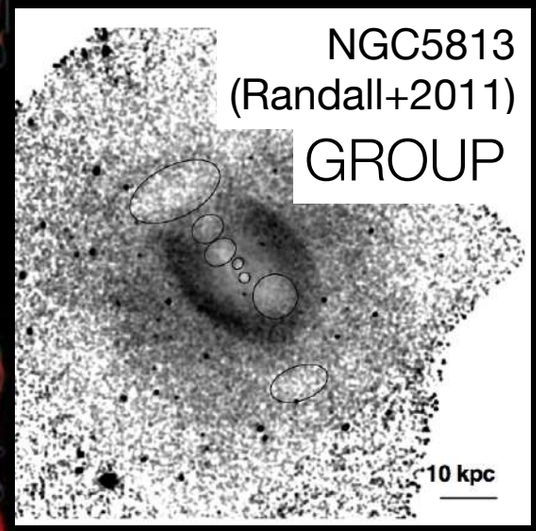
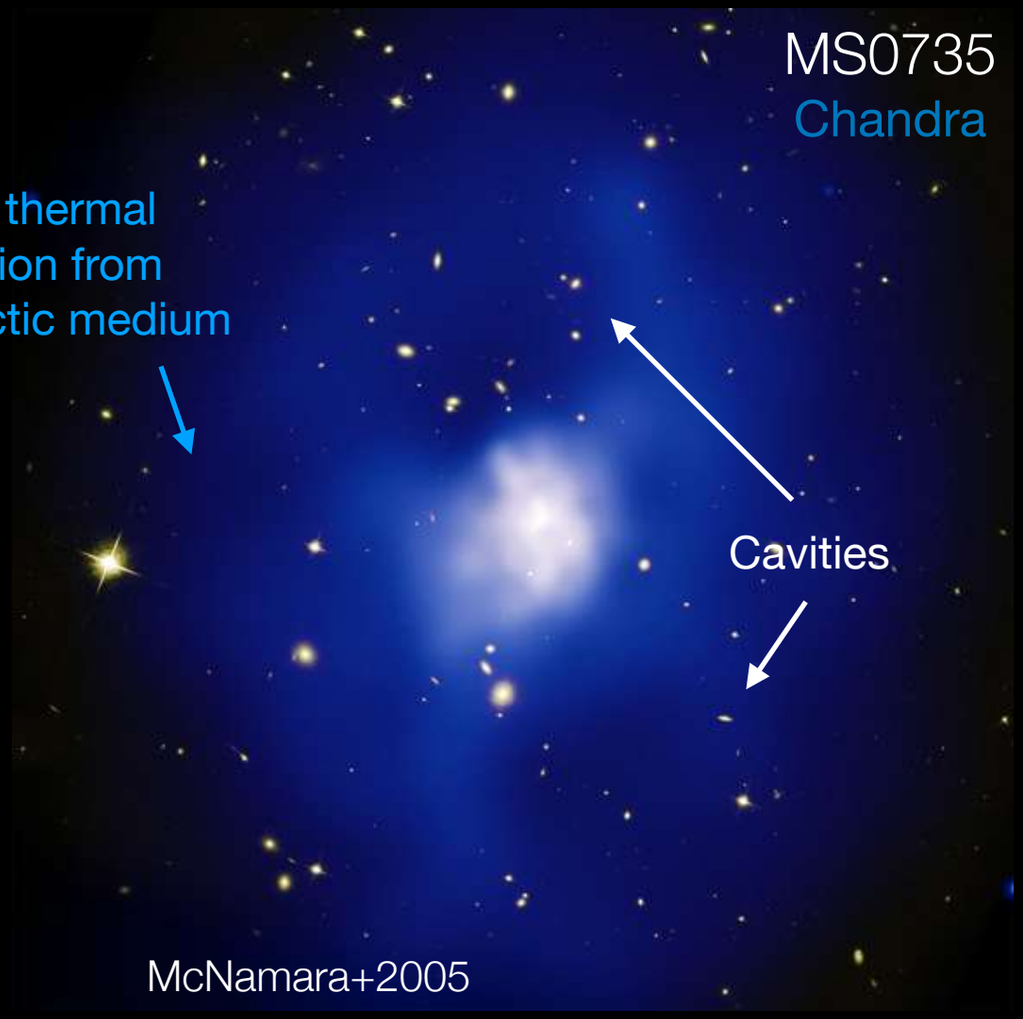
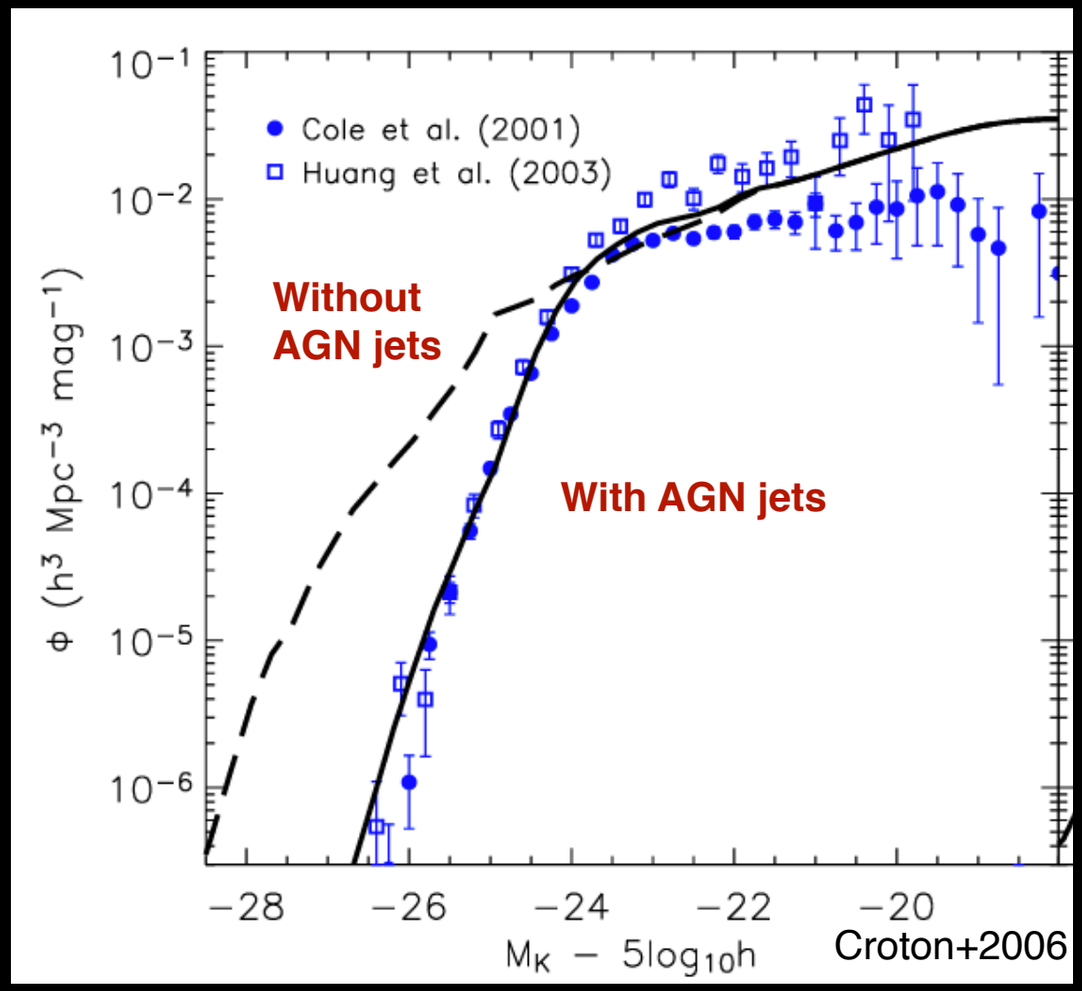
MULTIPLE TIMES!





AGN jets and mechanical feedback





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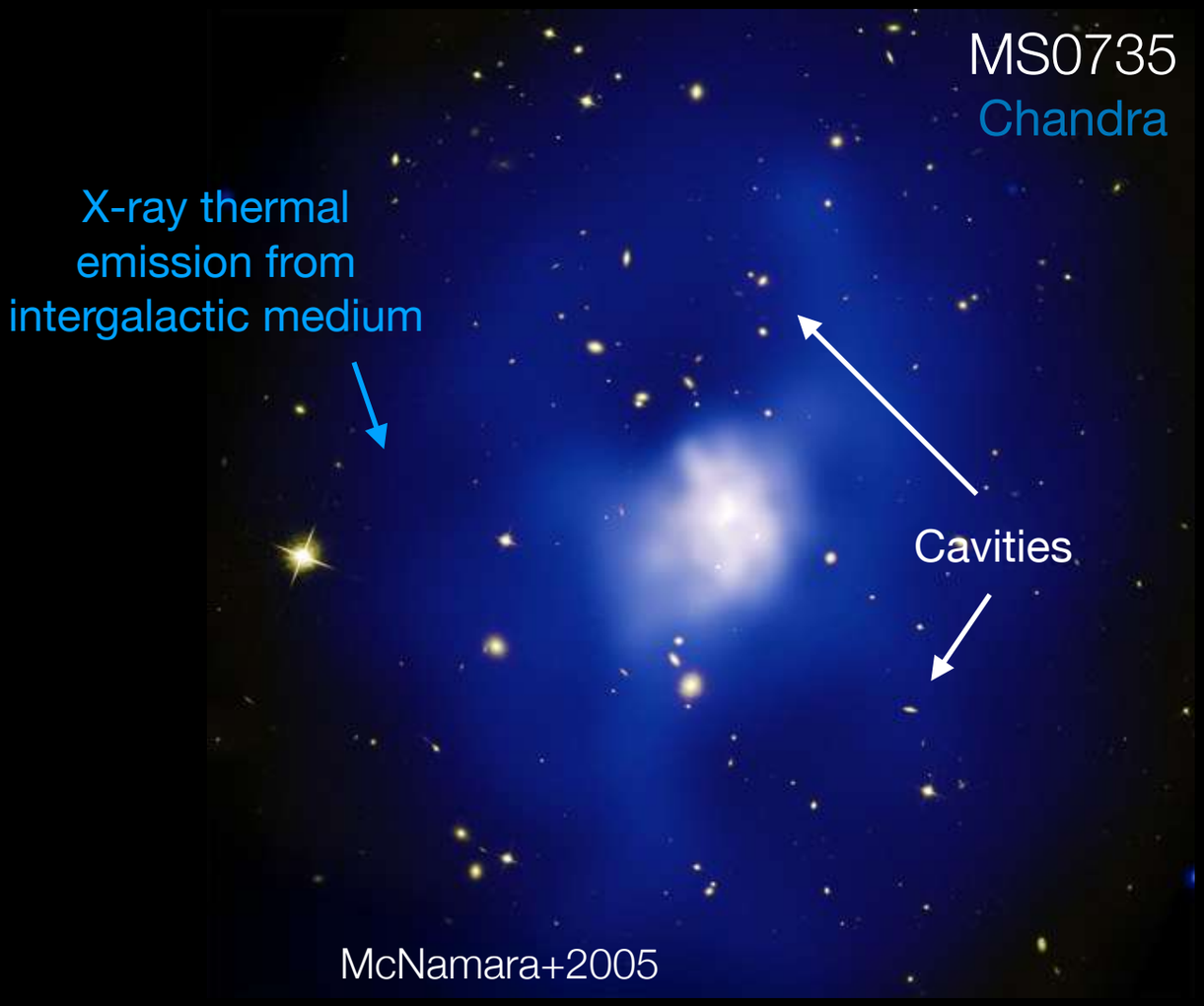
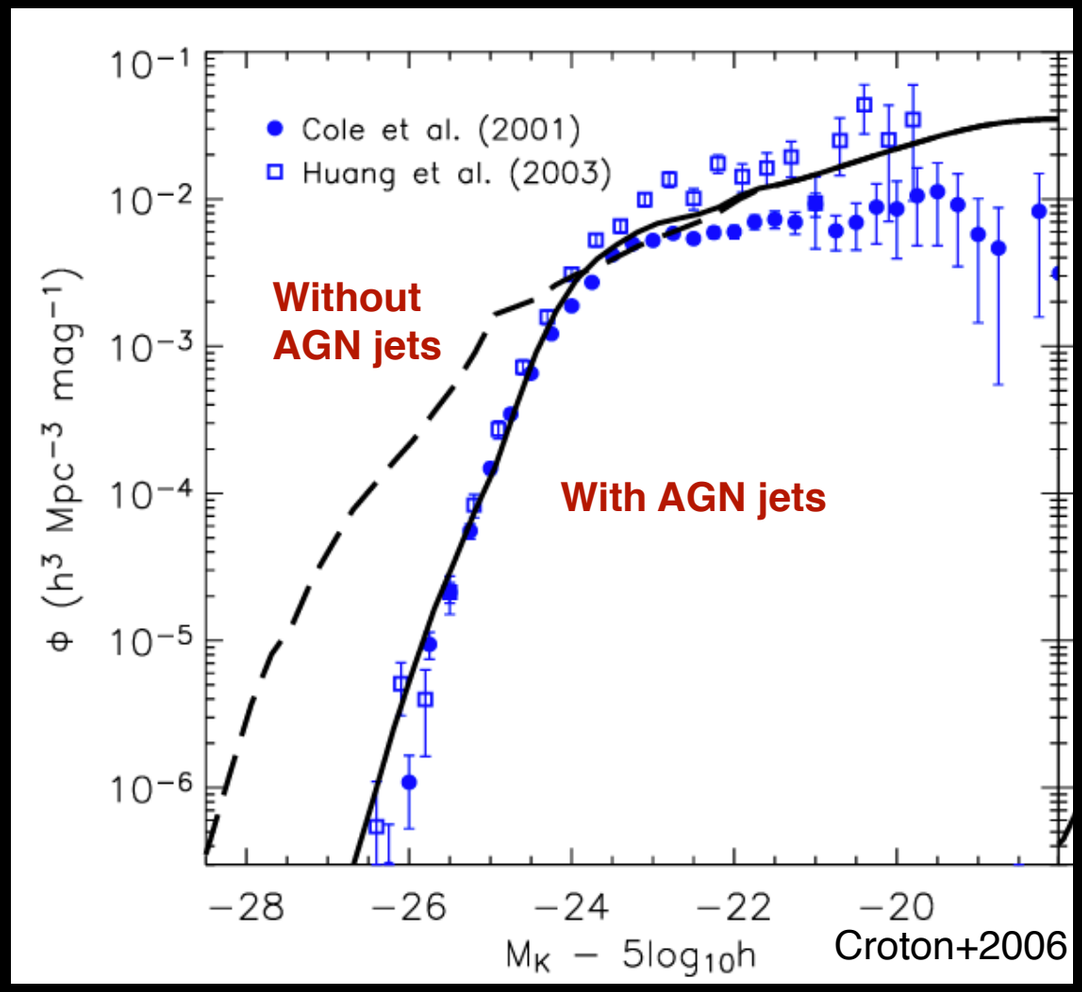
AGN jets and mechanical feedback

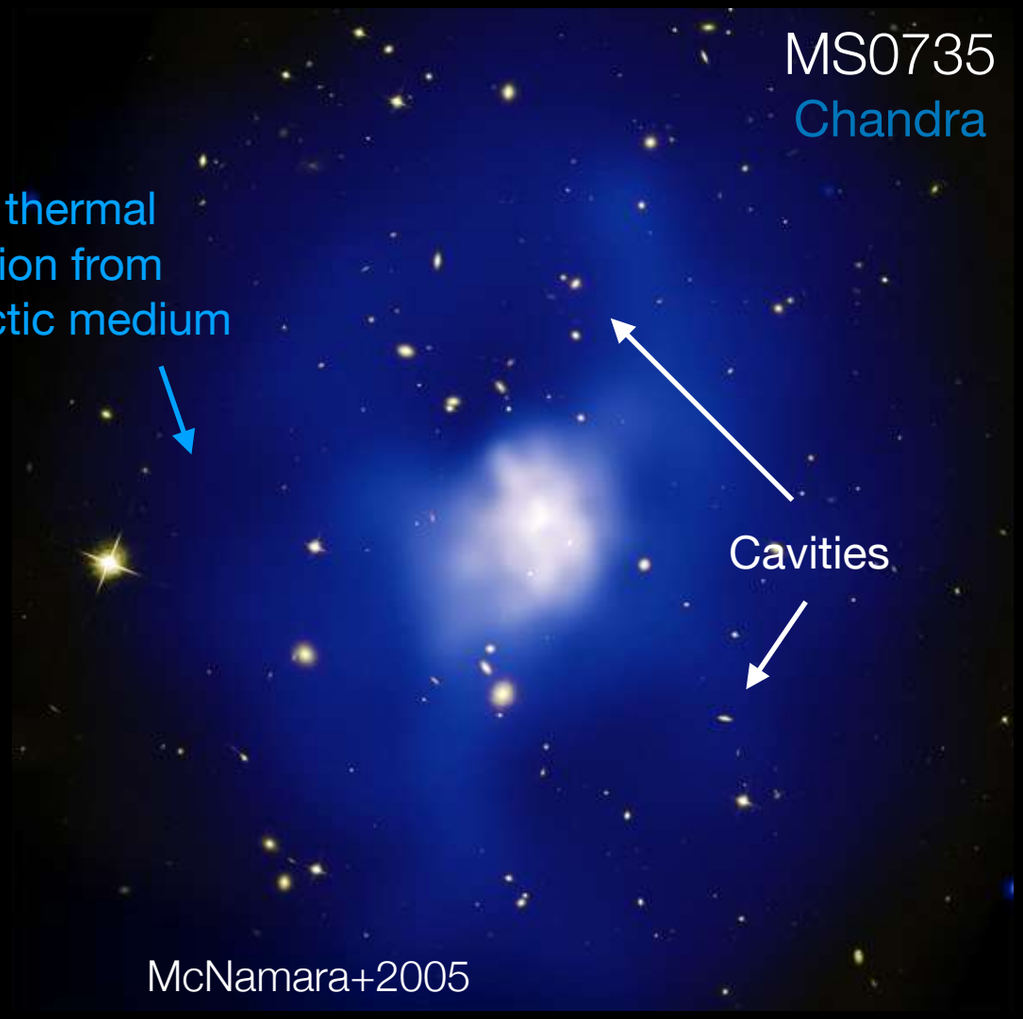


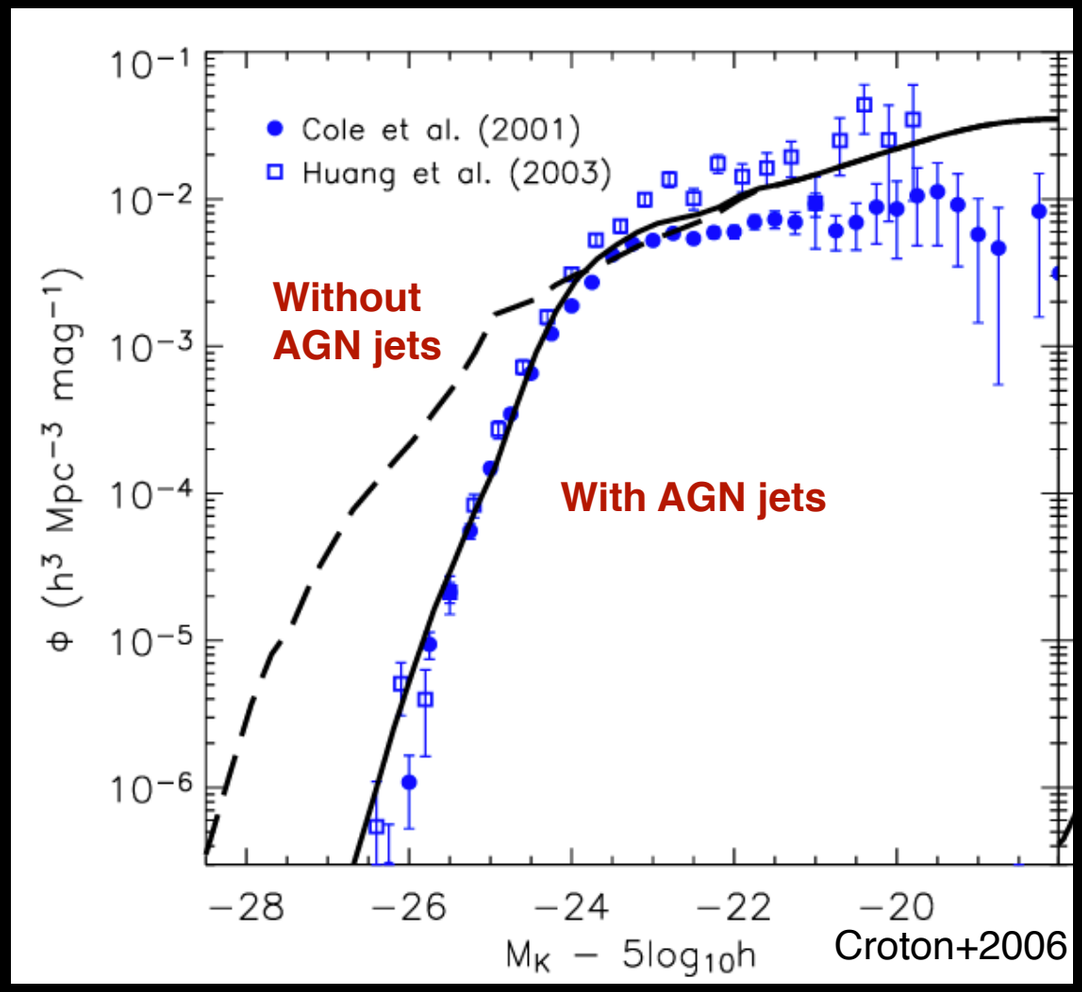


We know less

- The duty cycle of jets
- Bubble exact composition
- Bubble evolution and mixing with surrounding medium (role of magnetic fields, viscosity..)
- Conversion bubble's power into heat

AGN jets and mechanical feedback





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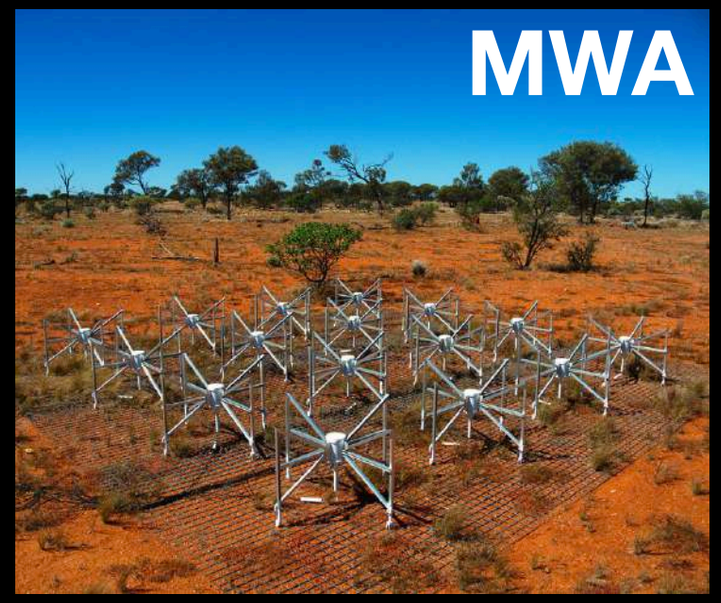
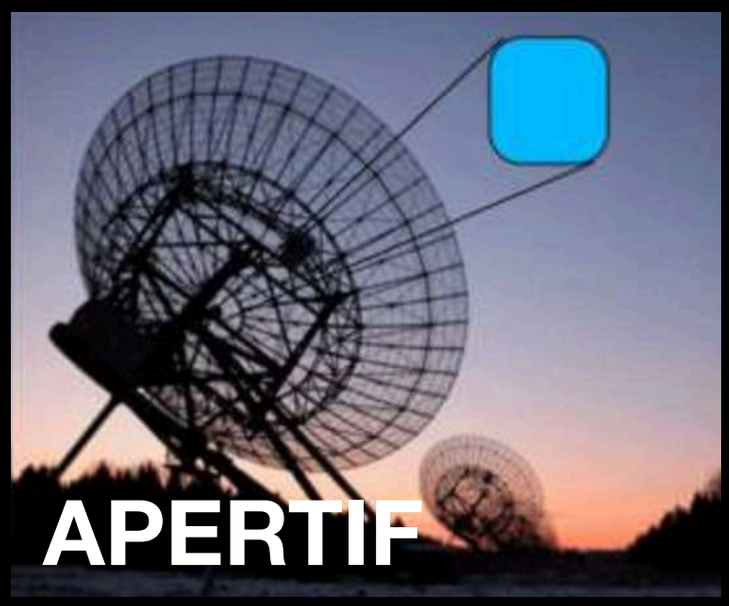
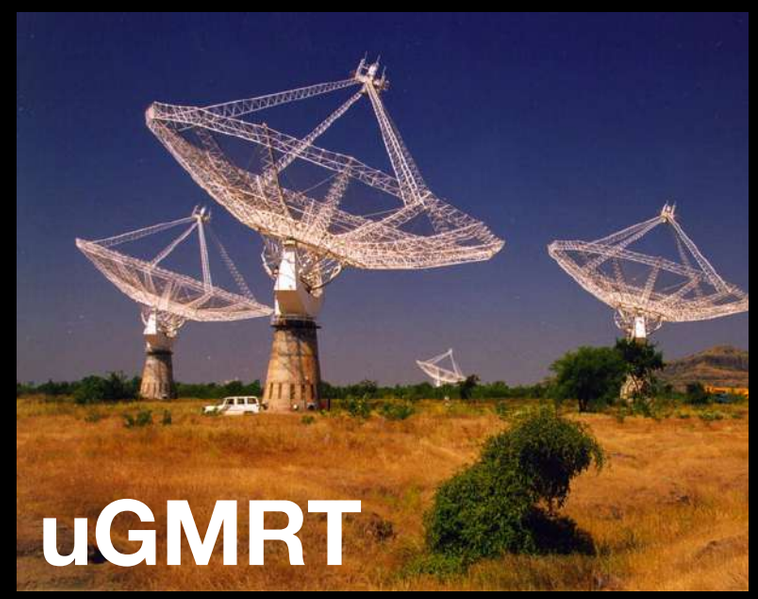
- …n (role of magnetic …osity..)
- Conversion bubble's power into heat

Observations difficult!



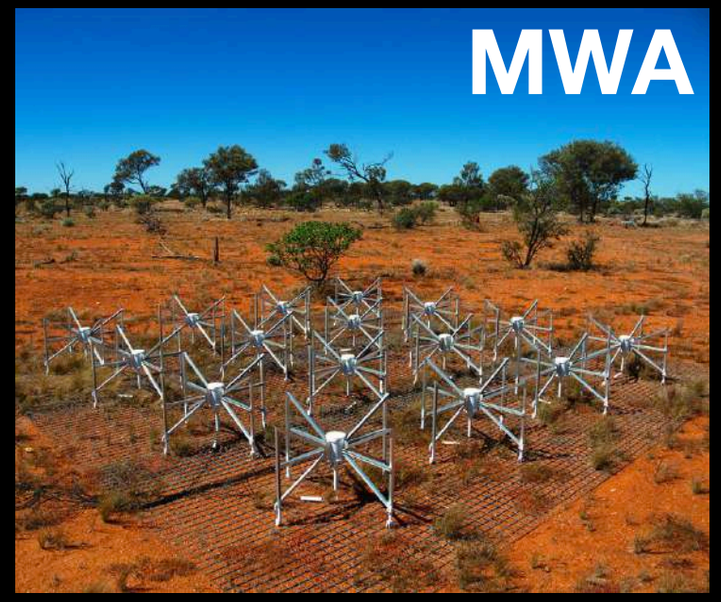
Observations with NEW GENERATION RADIO INSTRUMENTS

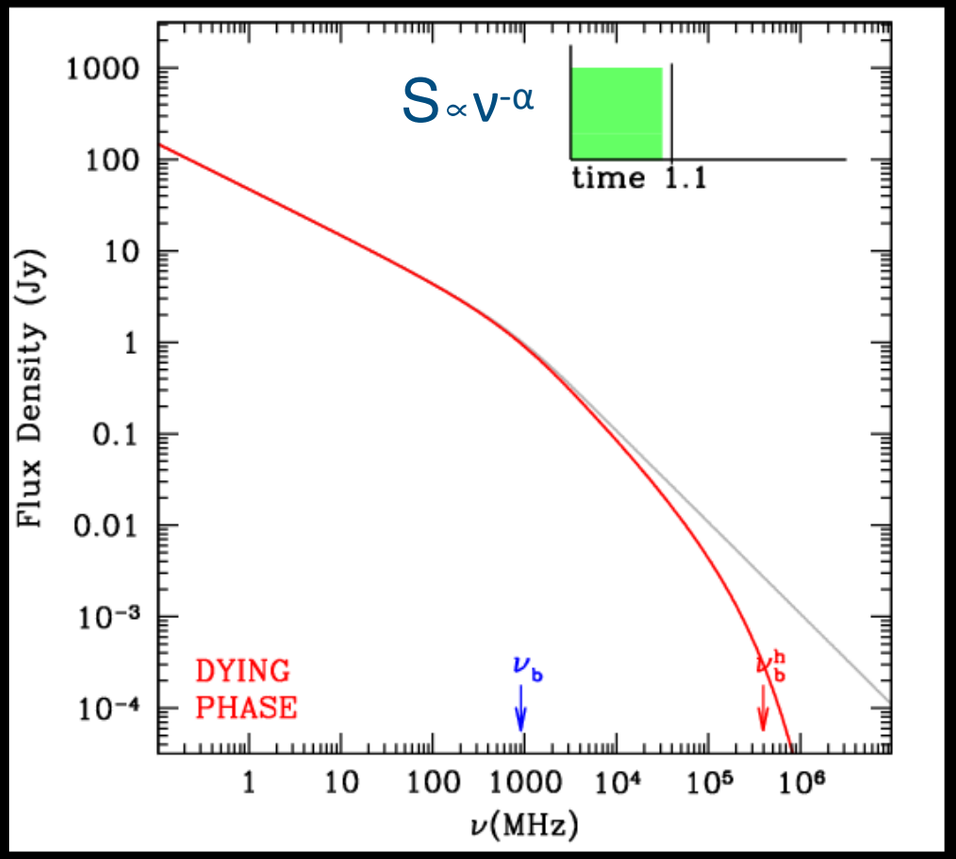




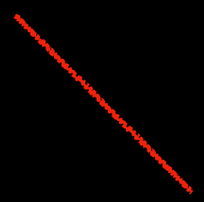
Low radio frequencies (<1 GHz)

to detect the oldest populations of emitting particles

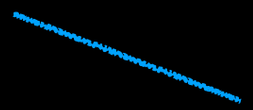




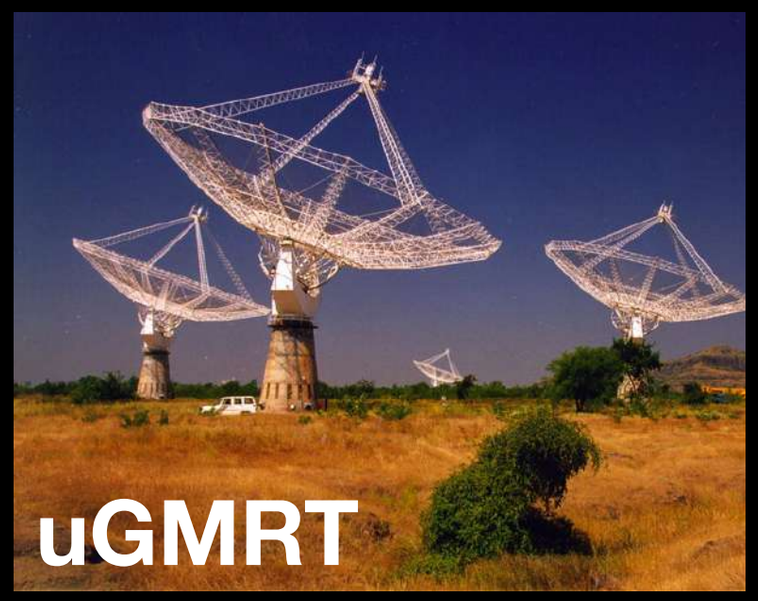
Courtesy of Murgia M.



STEEPER=OLDER



FLATTER=YOUGER



Remnant radio galaxies: the classical view

B2 0924+30, LOFAR 150 MHz

Jamrozy+2004,Shulevski+15

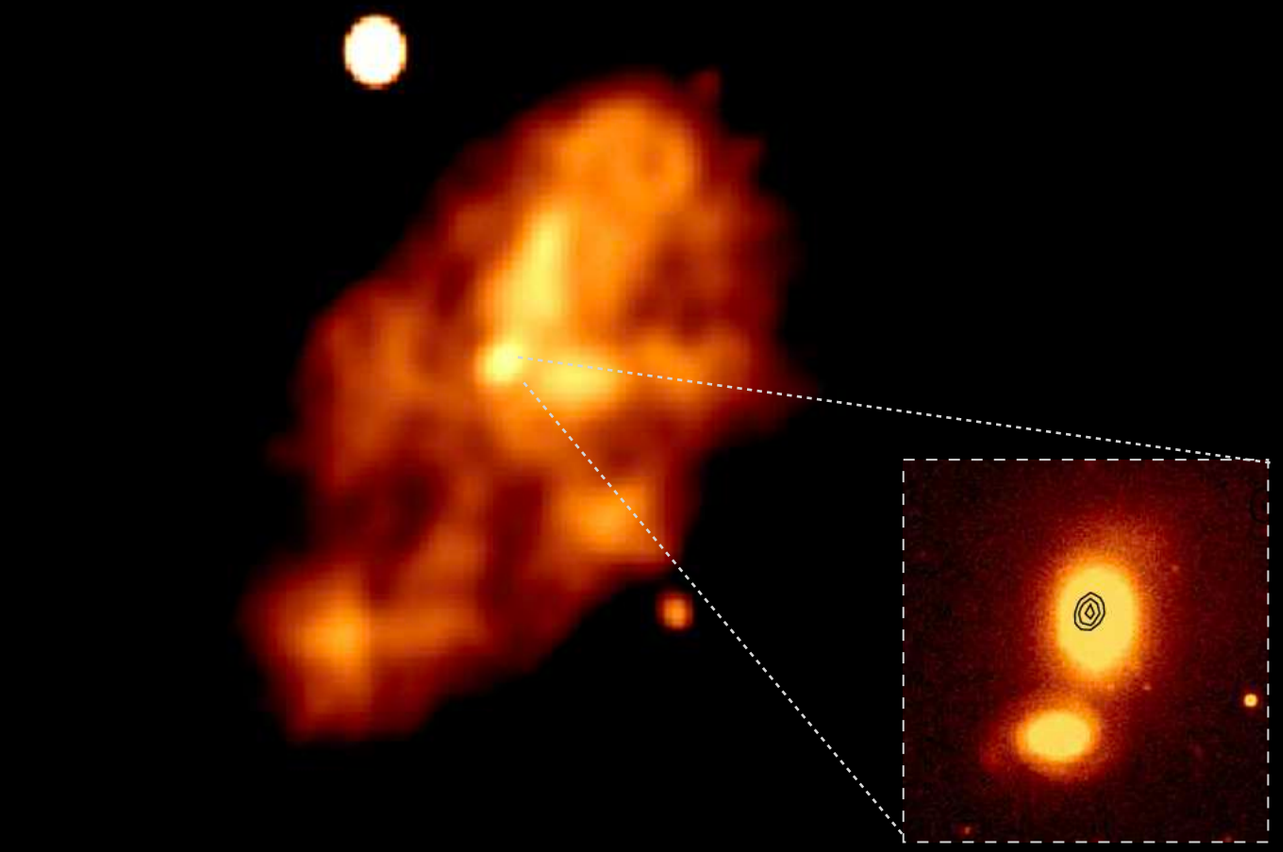
-> understand what happens to the jet plasma after switch off

-> constrain the length of the jet activity

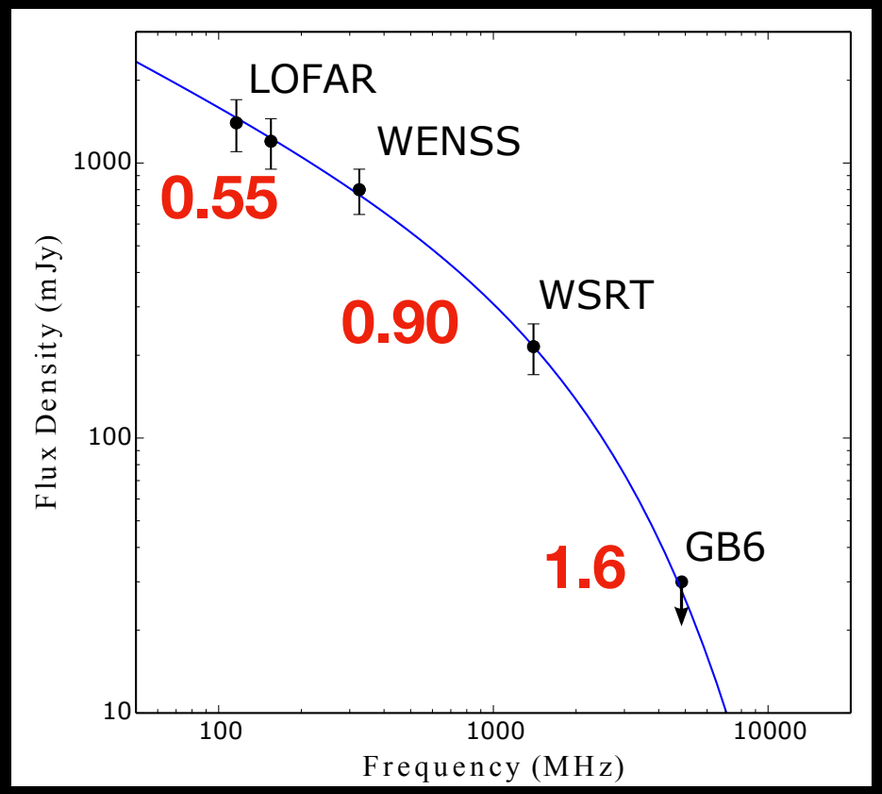
CLASSICAL PROPERTIES
(and selection criteria)

- Relaxed morphology (no compact features like core/jets/hotspots)
- Very curved/steep spectrum $\alpha>1.2$

Remnant radio galaxies: the new view



Brienza+2016



But also..
e.g.
Hurley-Walker+2015
Tamhane+2015
Duchesne&Jhonston-Hollit+2019
Randriamanakoto+2020
Lal+2021

no ultra-steep spectral index at MHz frequencies!

Core prominence=

$$\frac{\text{Core flux density}}{\text{Total flux density}}$$

=1e-4

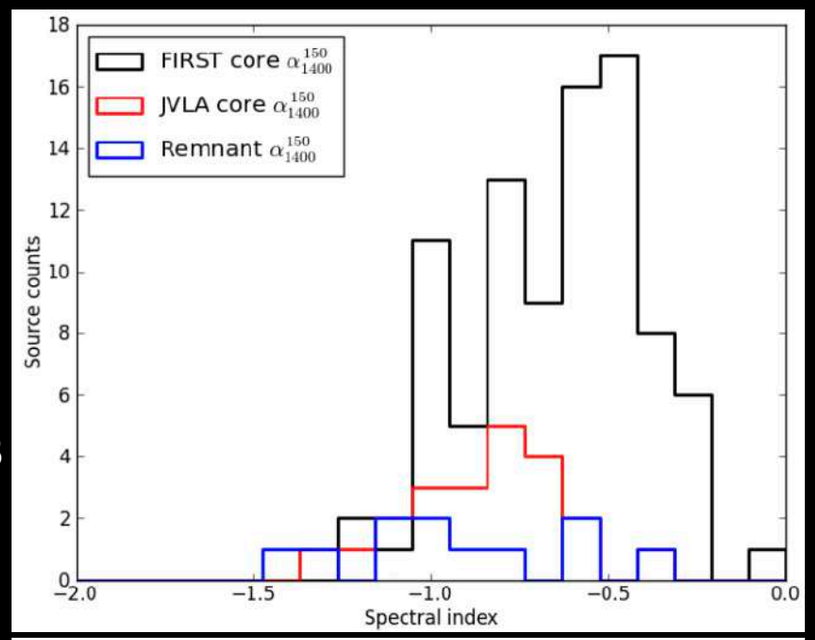
Remnant radio galaxies: samples!

Godfrey+2017
Brienza+2017,
Mahatma et al. 2018
Jurlin+2020, 2021
Quici+2021

Spectral index <1GHz

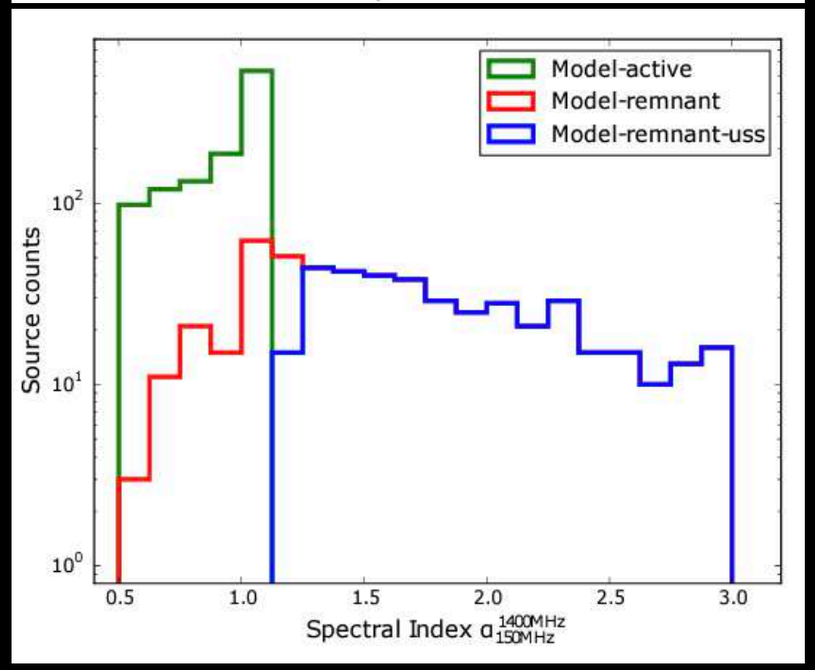
OBS

Mahatma et al. 2018



MODEL

Brienza+2017



Remnant radio galaxies: samples!

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Brienza+2017,
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Jurlin+2020, 2021
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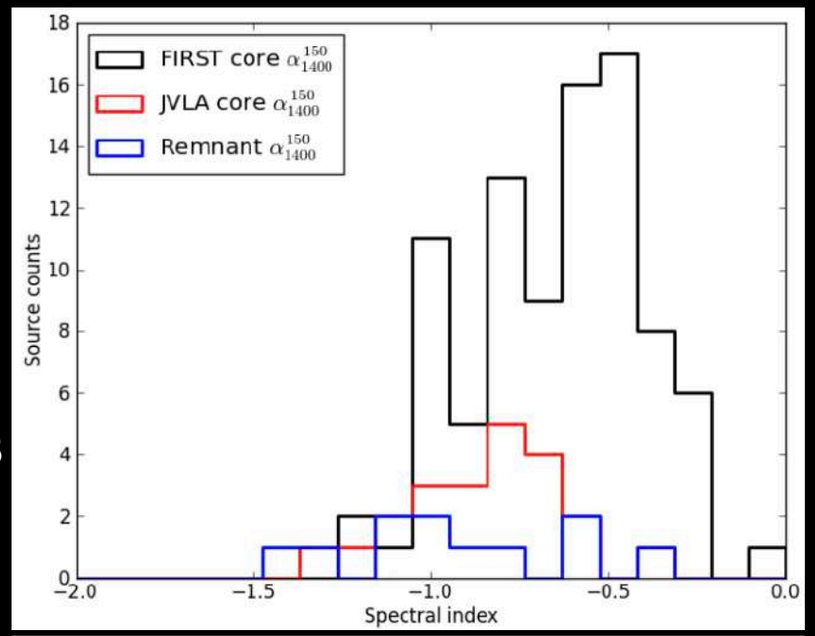
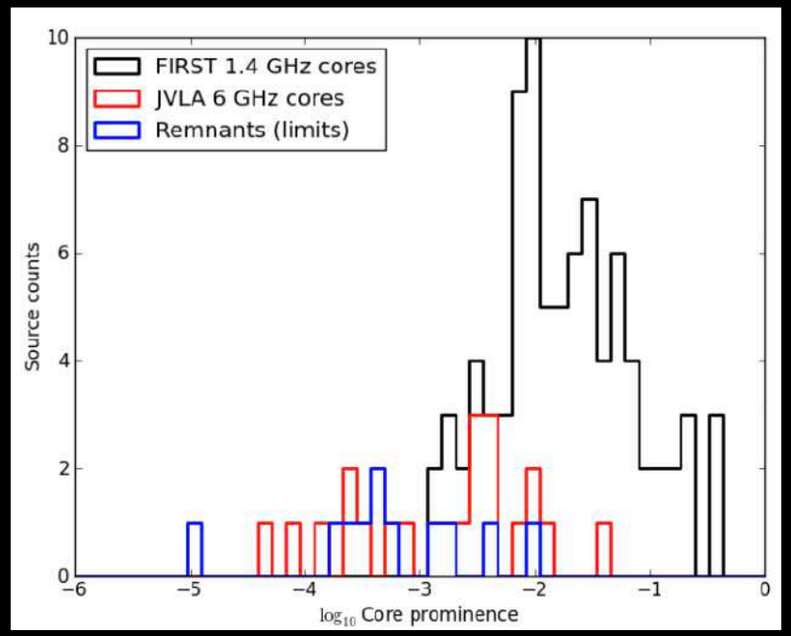


Cores

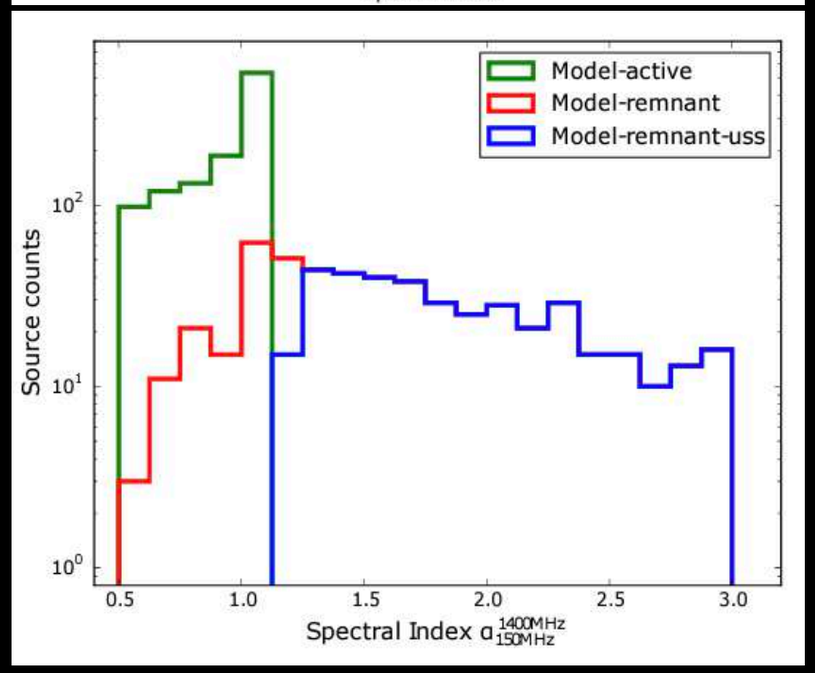


OBS

Mahatma et al. 2018

MODEL

Brienza+2017



Not all remnants have ultra-steep spectra!

Remnants can have weak cores!

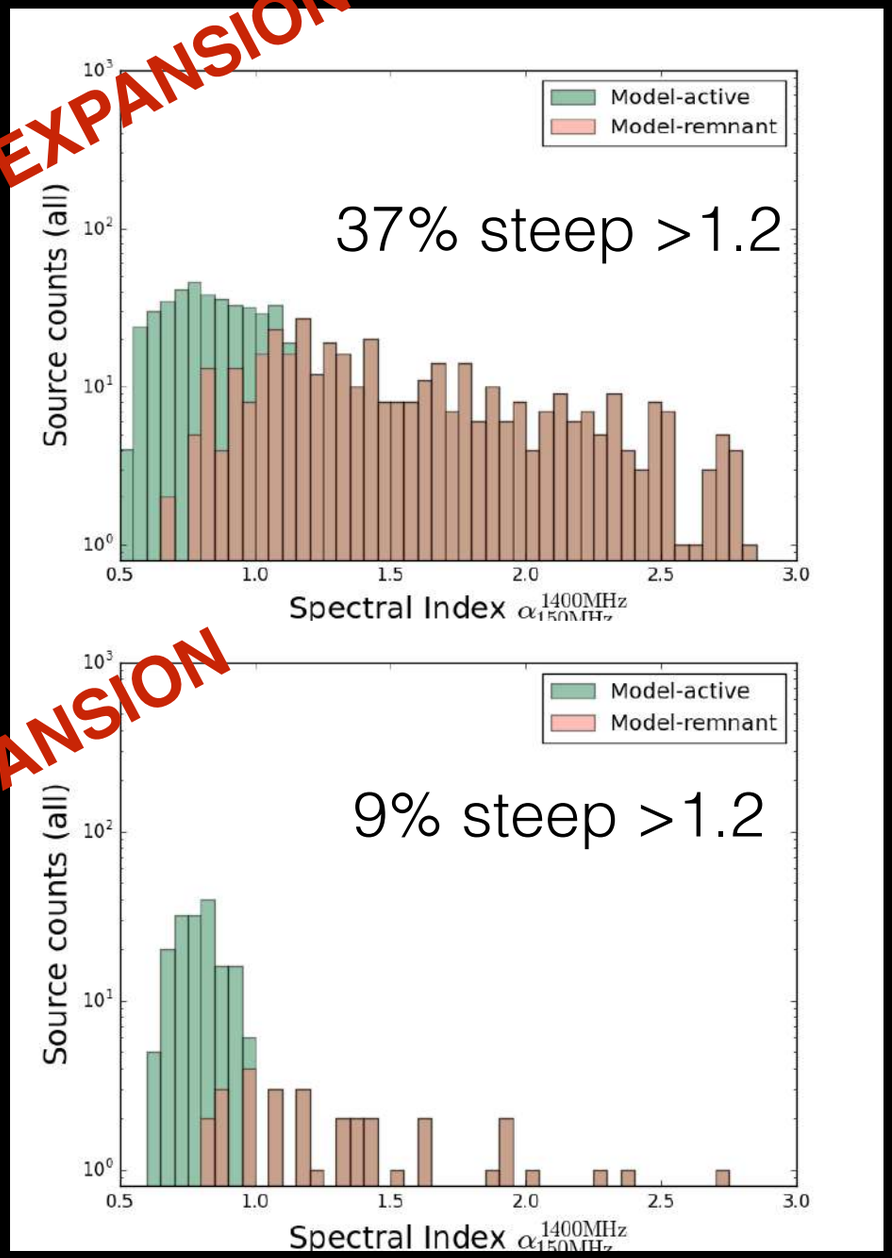
Remnant radio galaxies: statistics

Godfrey+2017
Brienza+2017,
Mahatma et al. 2018
Jurlin+2020, 2021
Quici+2021

FRACTION OF REMNANTS with respect to the active radio galaxy population 5-15%

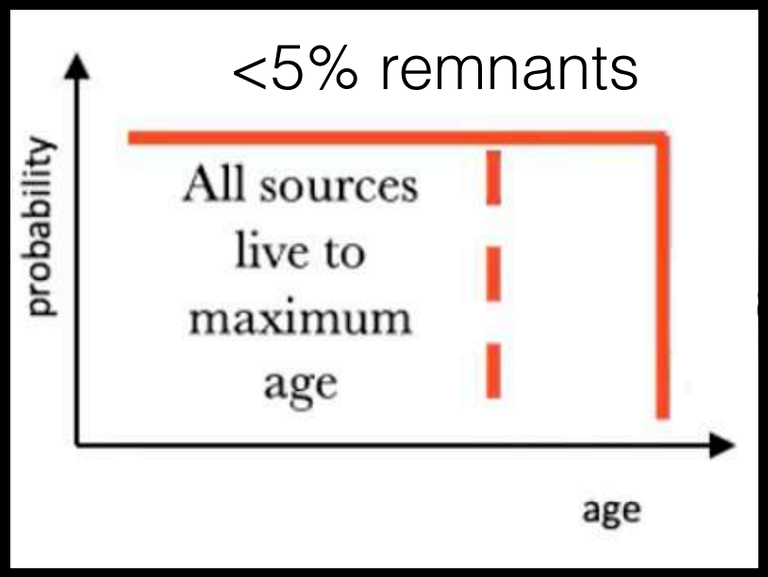
Brienza+2017

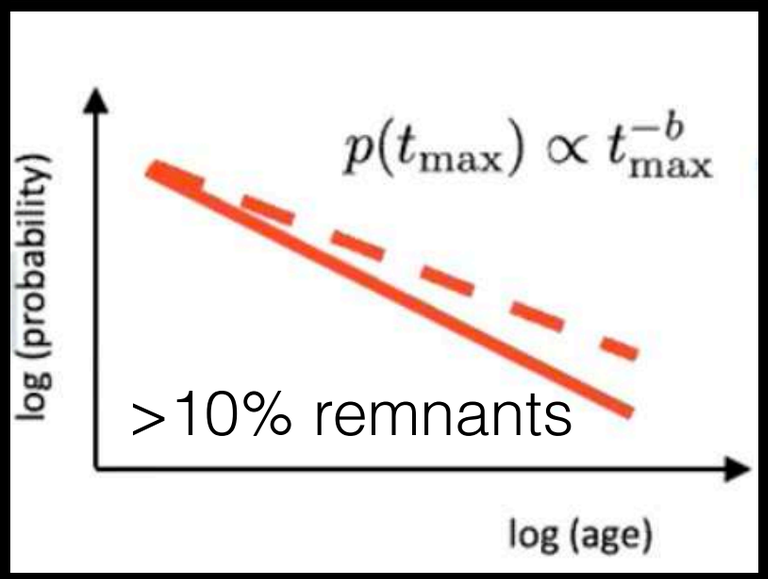
NO EXPANSION



Constraining RG evolution models

Shabala+2020

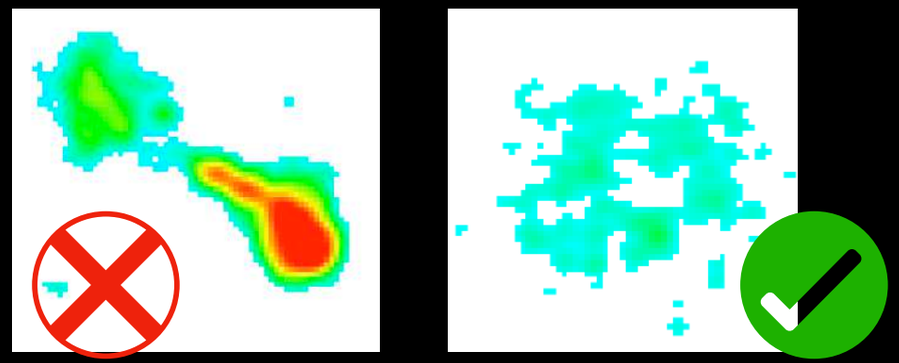




Remnant radio galaxies: automatic selection for large samples

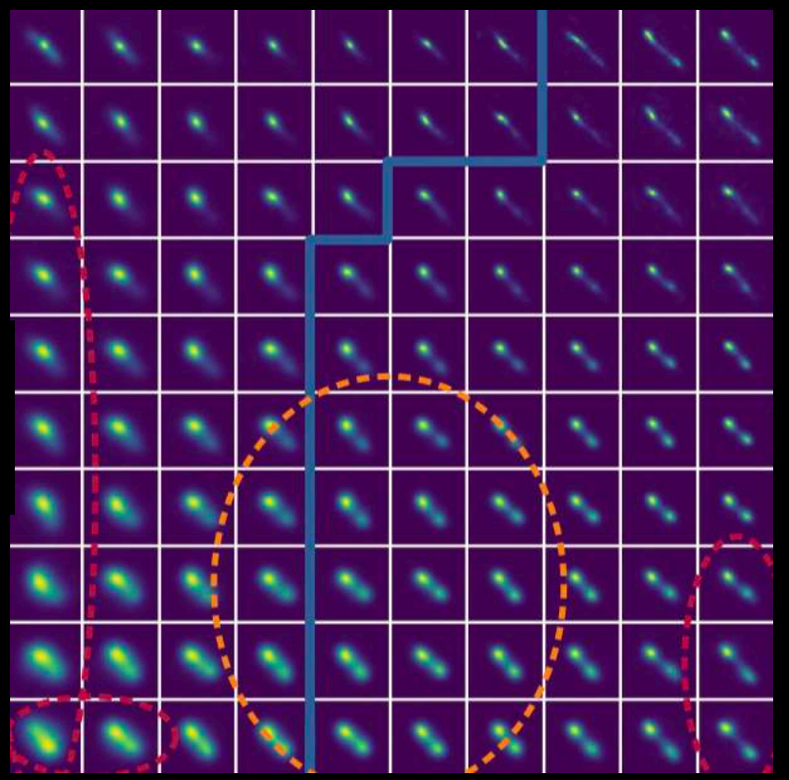
Morphology selection from the LOFAR Two Meter Sky Survey at 150MHz

Pixel statistics
Max/Mean
Brienza+in prep



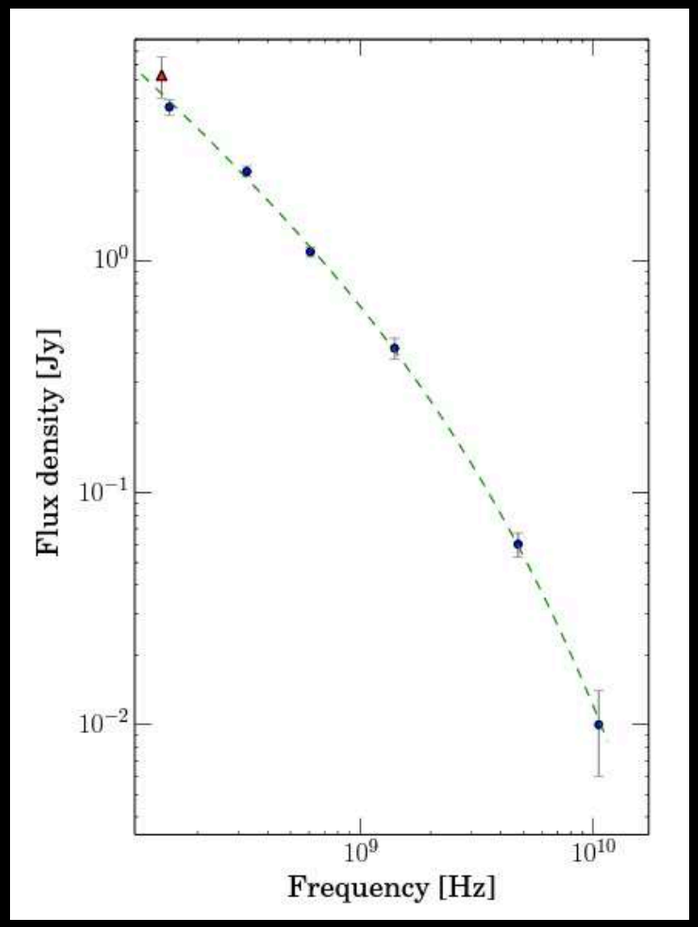
Tens/hundreds of good remnant candidates!

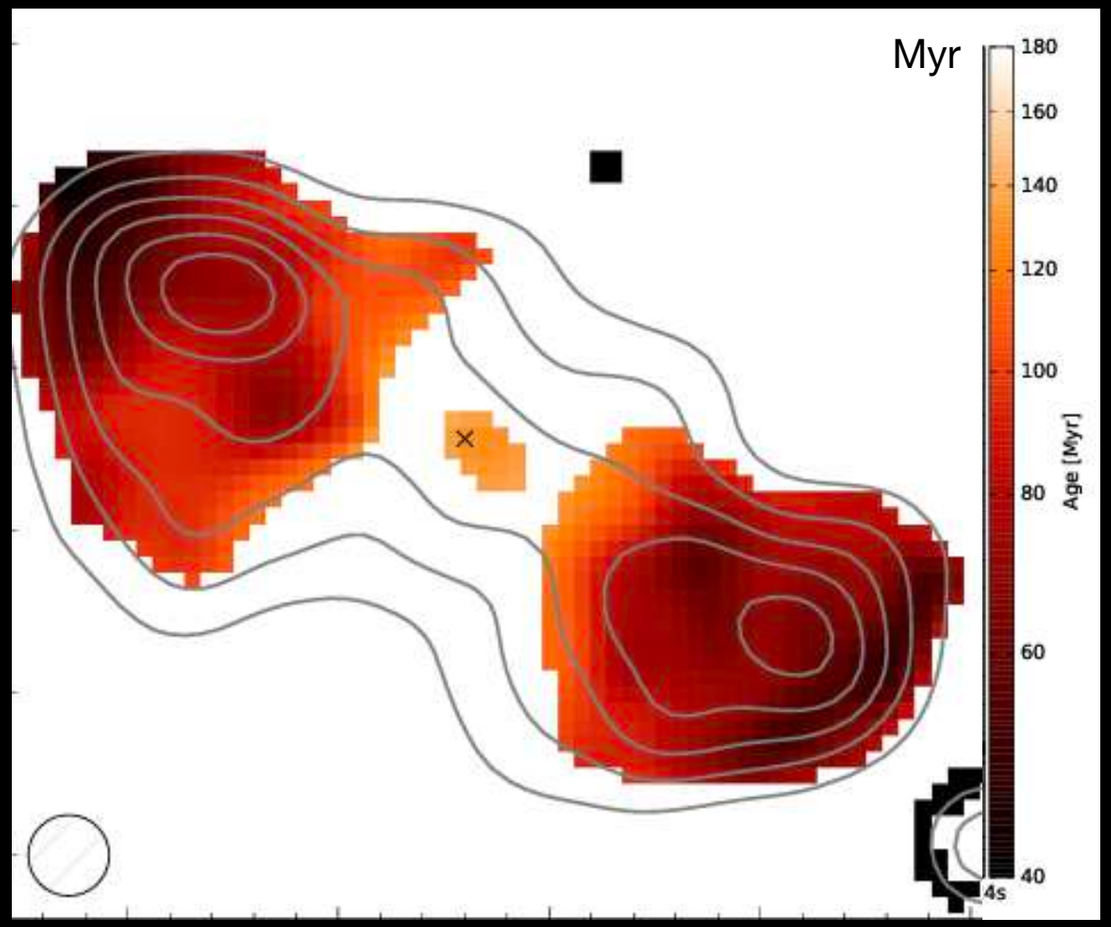
Self-organized maps
Mostert+in prep



Remnant radio galaxies: spectral ages

Shulevski+15





$$t_{\rm s} = 1590 \frac{B_{\rm eq}^{0.5}}{(B_{\rm eq}^2 + B_{\rm CMB}^2)\sqrt{\nu_{\rm b}(1+z)}},$$

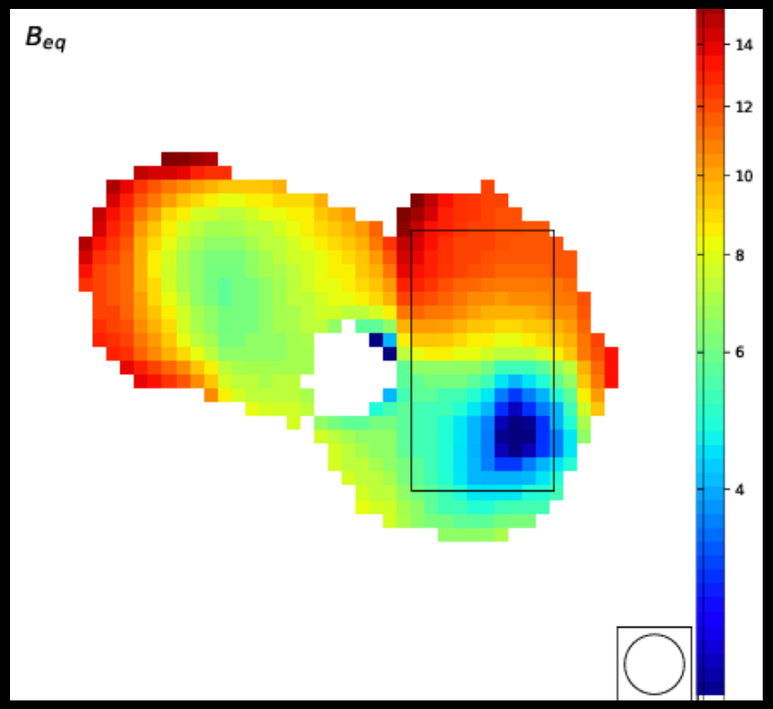
B=magnetic field
v=break frequency

Radiative evolution models
(Jaffe&Perola1974, Komissarov&Gubanov1994)

ACTIVE TIMES tens of Myr put to a few hundreds

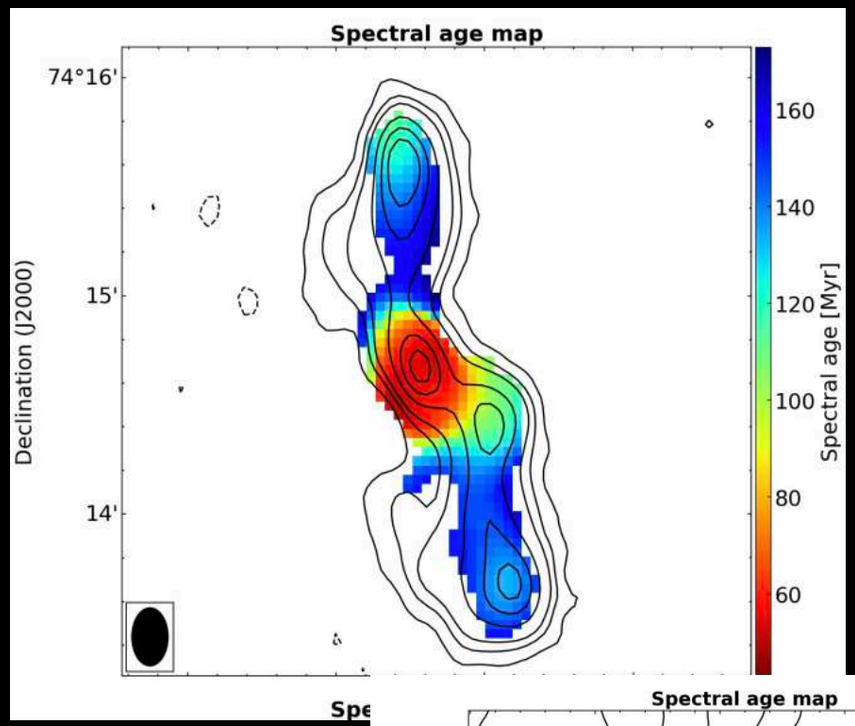
Resolved spectral age analysis of restarted radio galaxies

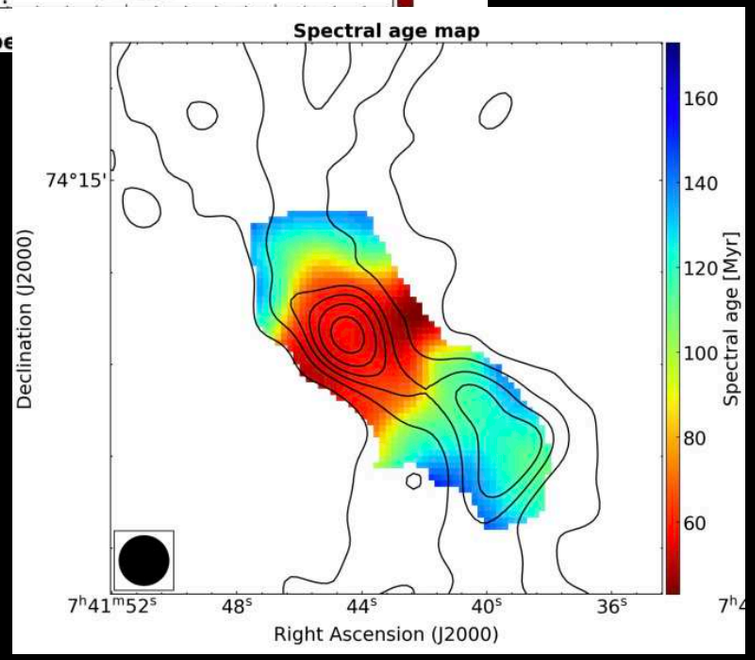
3C388



Brienza + 2020

MS0735





Studying age of the outer lobes and inner lobes at the same time

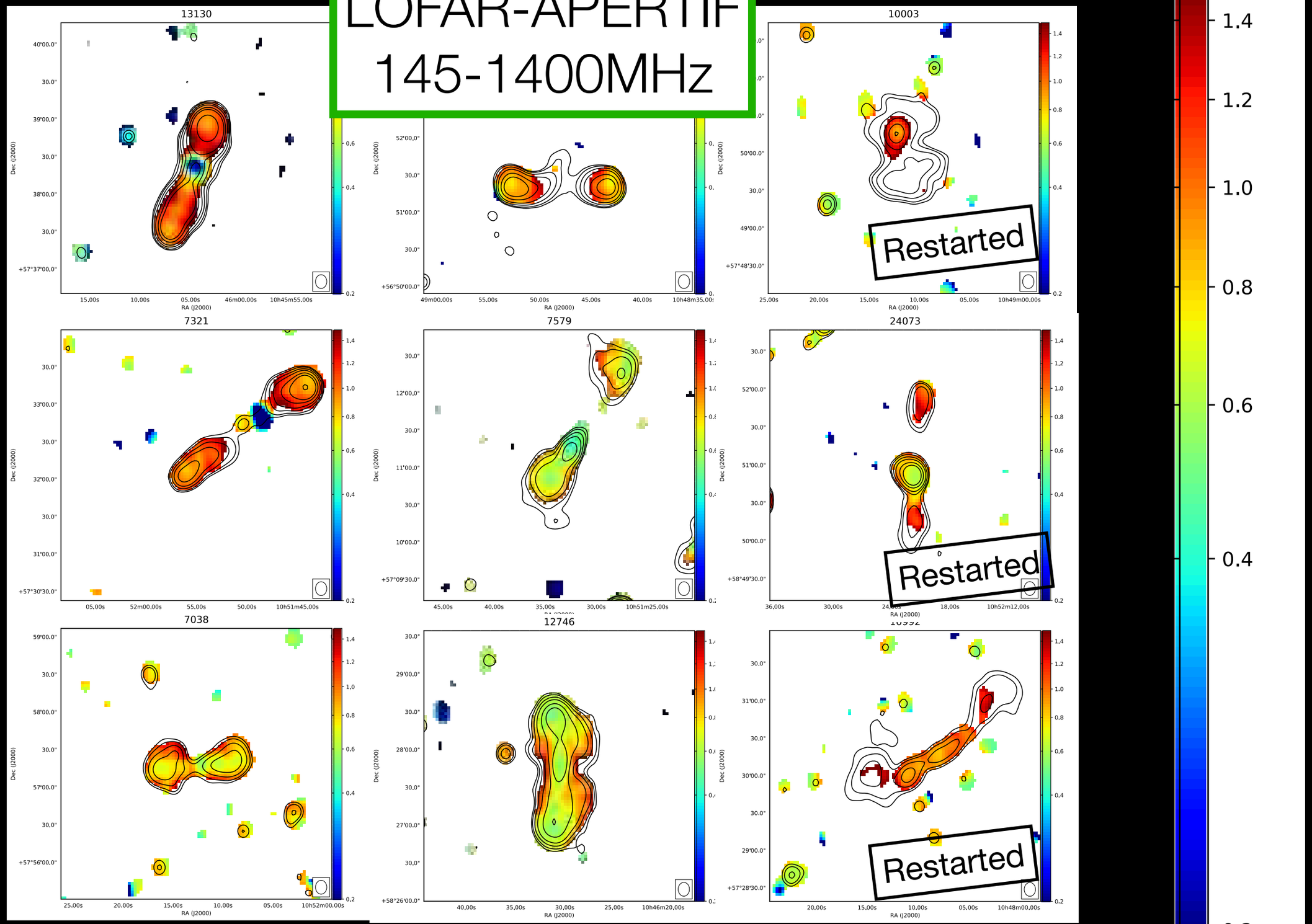
Very fast duty cycle! Inactive phase/Active phase <30%

Biava, Brienza + 2021

Resolved spectral index maps: large samples

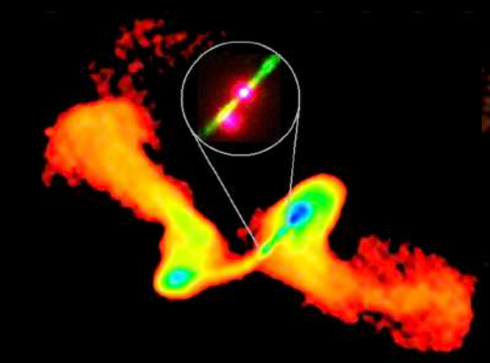
Morganti, Oosterloo, Brienza+2020

LOFAR-APERTIF
145-1400MHz

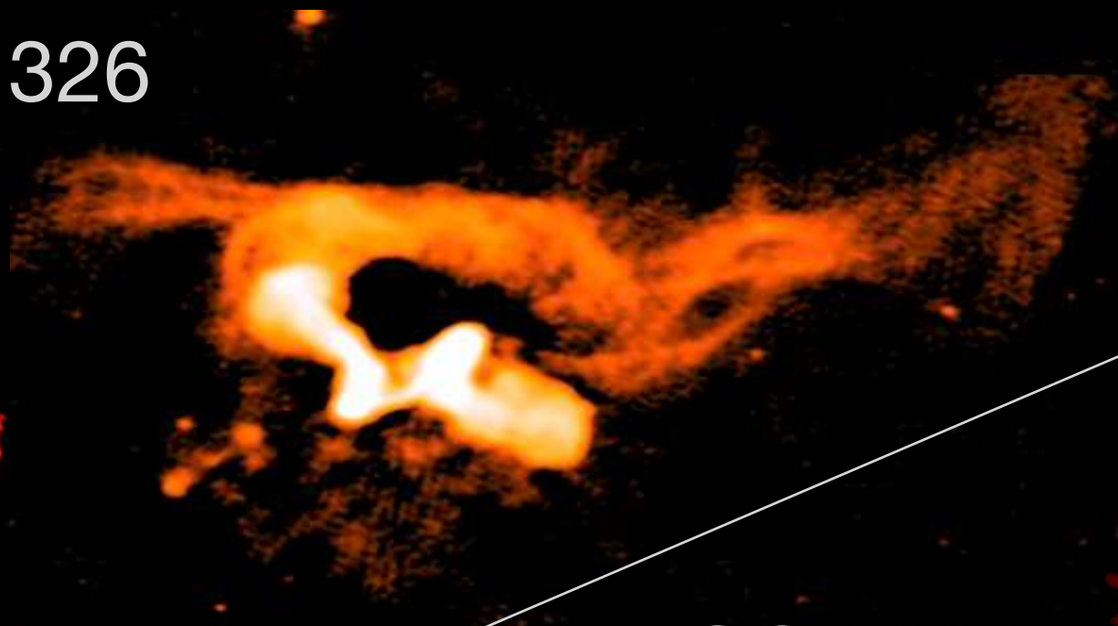


Interaction between AGN remnant plasma and external environment

NGC 326



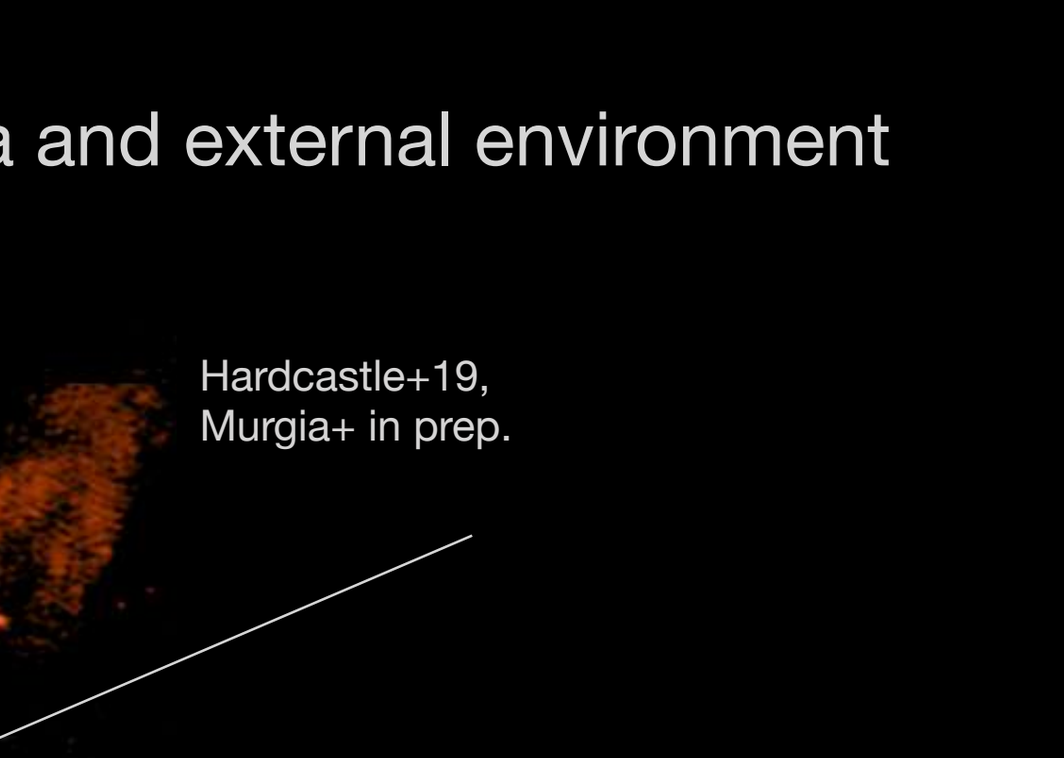
Murgia et al. 2001



Hardcastle+19,
Murgia+ in prep.

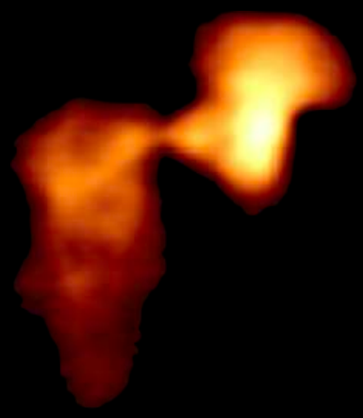
NGC 6086

Murgia et al. 2011

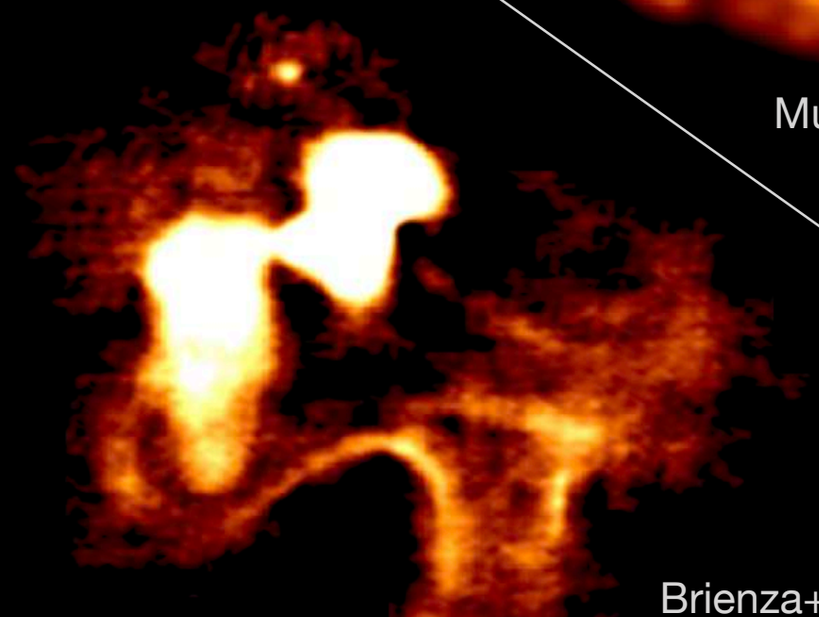


Brienza+in prep

NGC 507

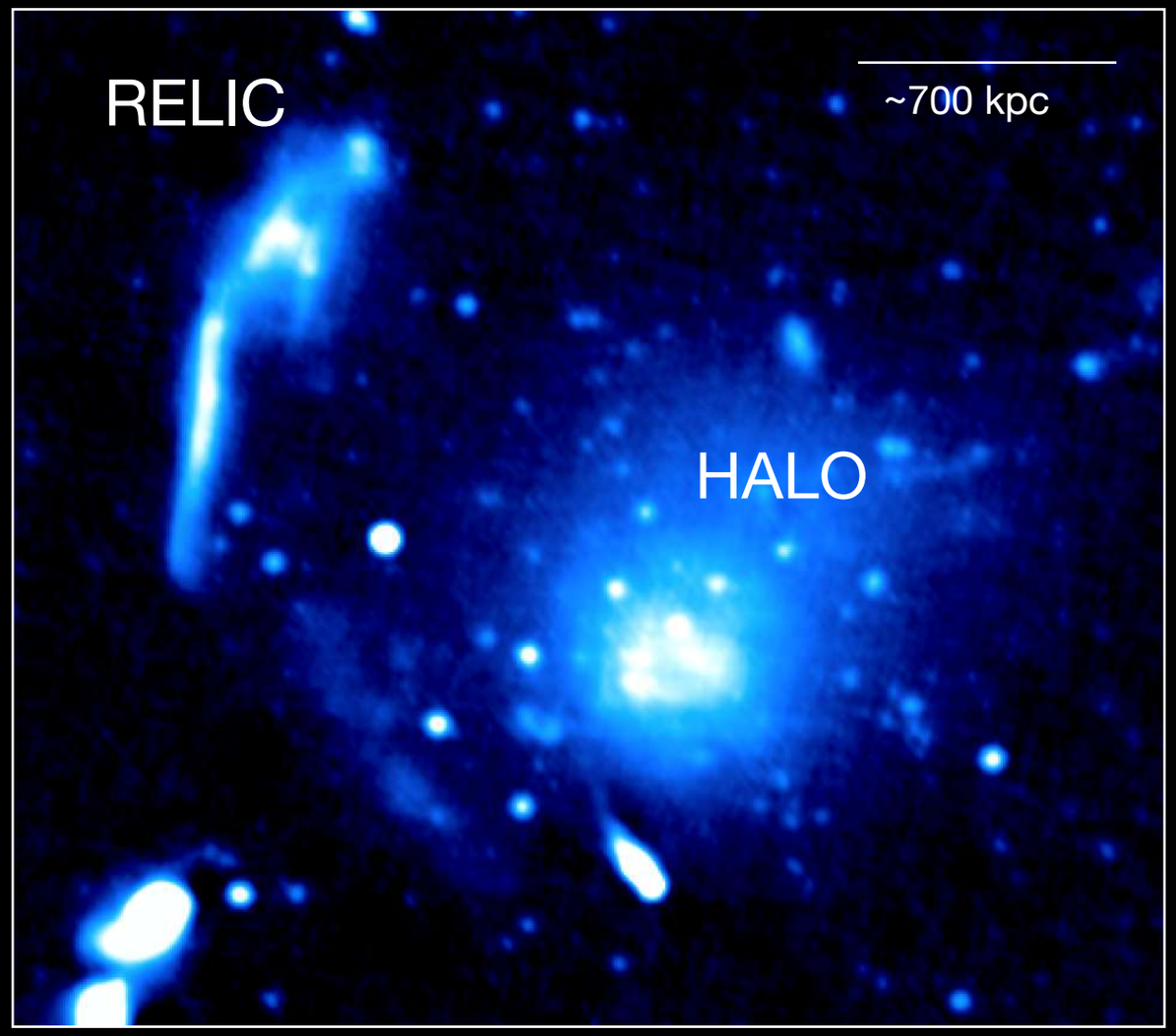


Murgia et al. 2011

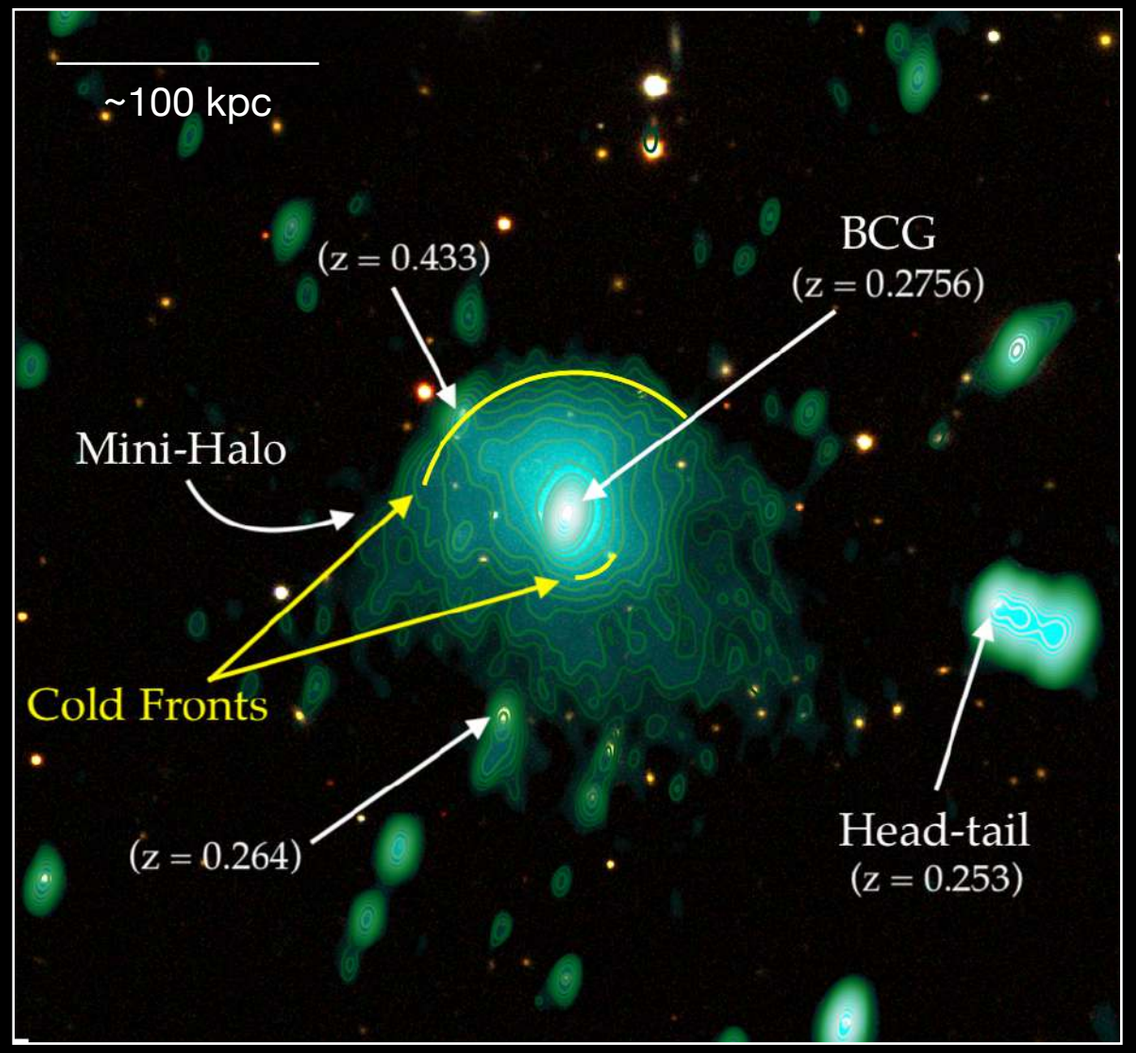


Brienza+22

AGN remnant plasma seeding diffuse radio sources in clusters of galaxies

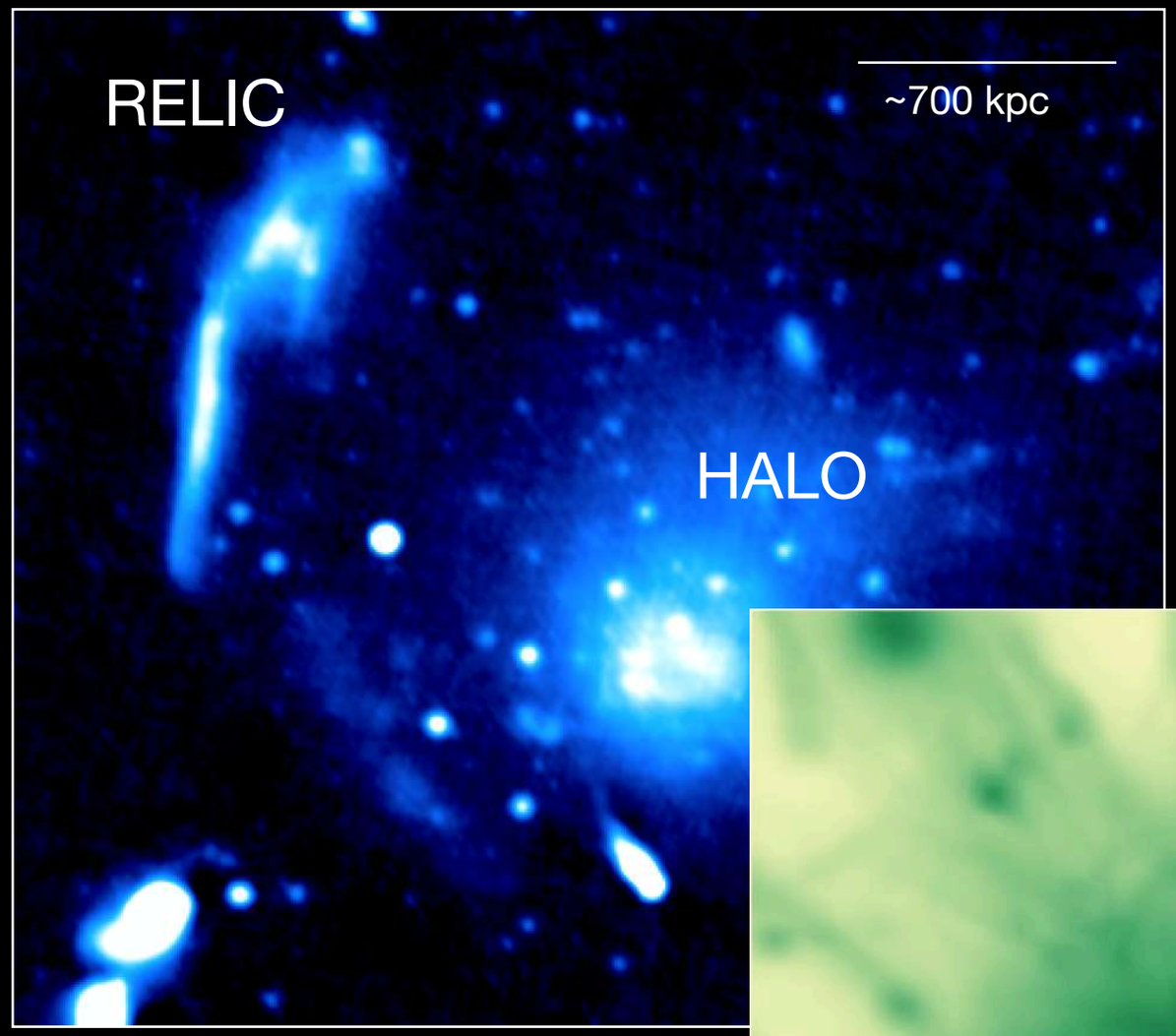


A2744
RELIC+HALO
Rajpurohit+2021

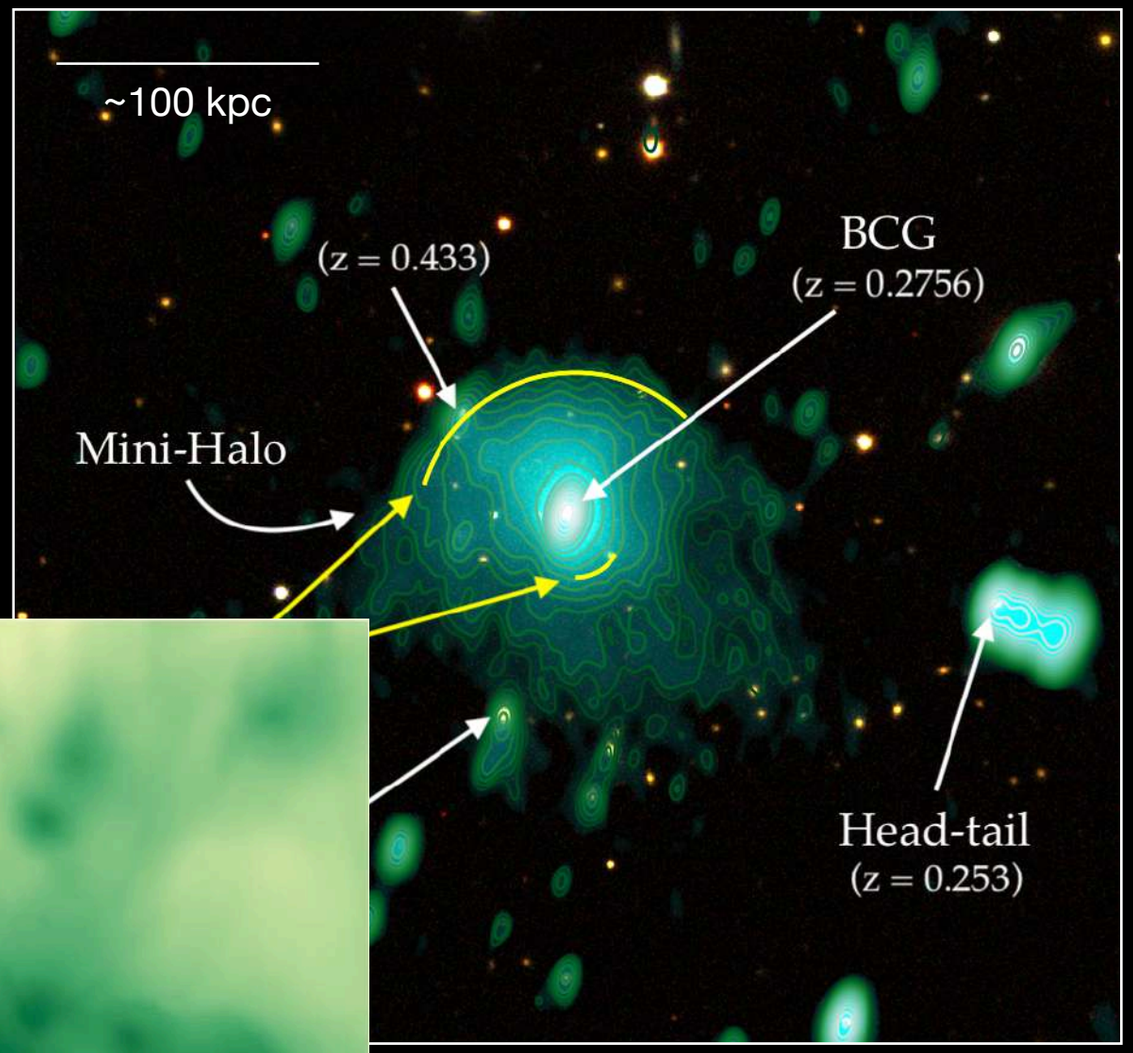


MS1455+2232
MINI-HALO
Riseley+submitted

AGN remnant plasma seeding diffuse radio sources in clusters of galaxies



A2744
RELIC+HALO
Rajpurohit+2021



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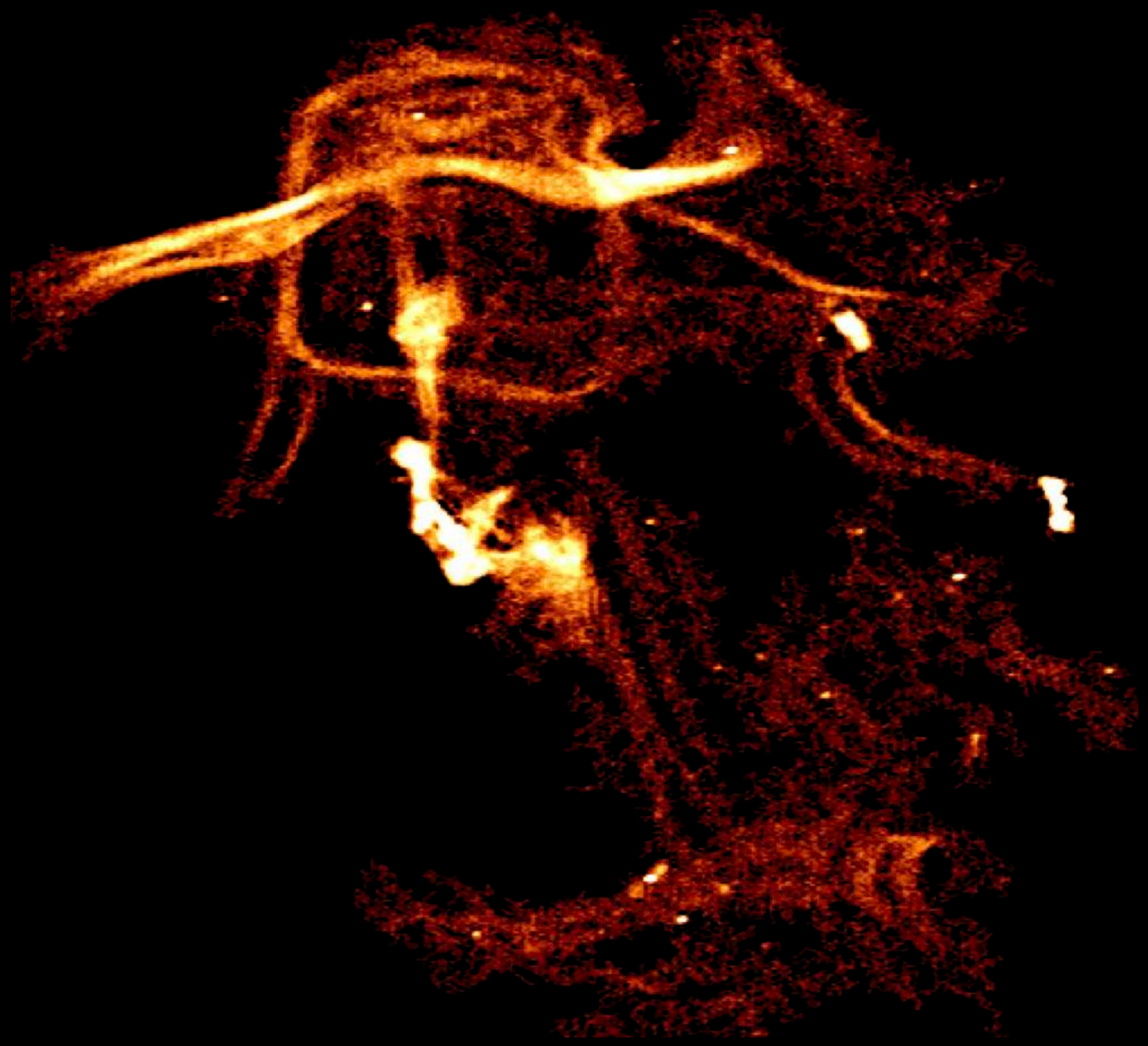
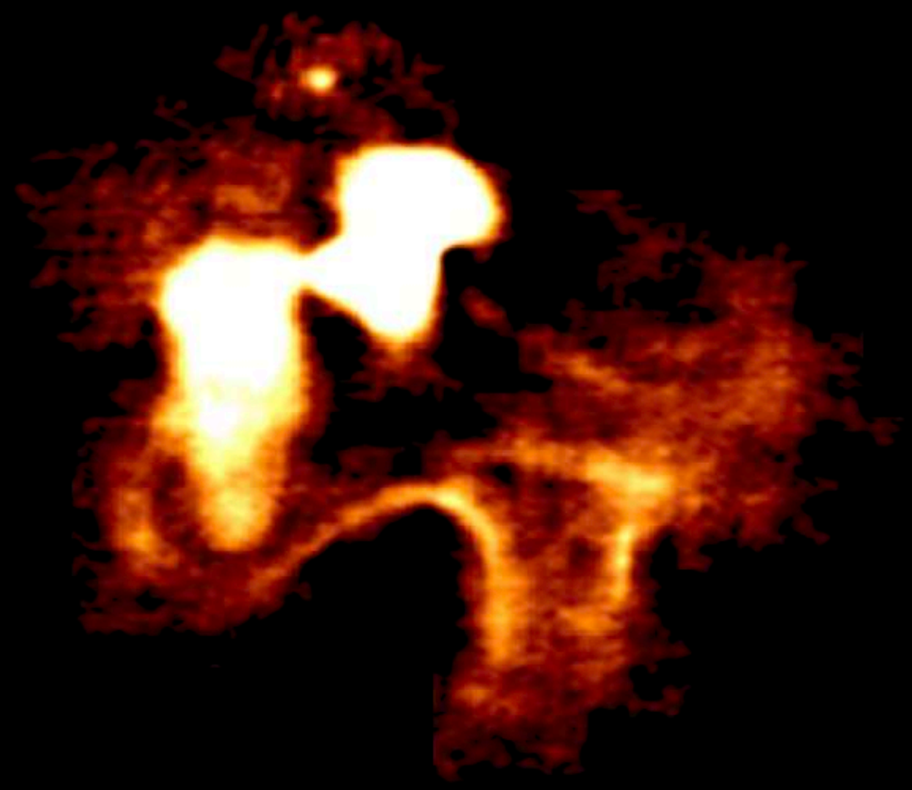


Nest200047

Brienza+21

NGC 507

Brienza+22



6’ / 100 kpc

LOFAR 144 MHz
6” 0.2mJy/b

Nest200047
galaxy group 17 galaxies
based on 2MASS (Tully+15)
sigma=421 km/s
1.5×10^{14} M_{sun} (K_s luminosity)

BCG z=0.018
$\log(M_{star}/M_{sun})=11.56$
Low excitation radio galaxy

6’ / 100 kpc

LOFAR 144 MHz
6” 0.2mJy/b

multiple pairs of lobes
AGN recurrent activity

outer lobes/bubbles

Inner jets
25 kpc

6’ / 100 kpc

LOFAR 144 MHz
6” 0.2mJy/b

main filament

bridge

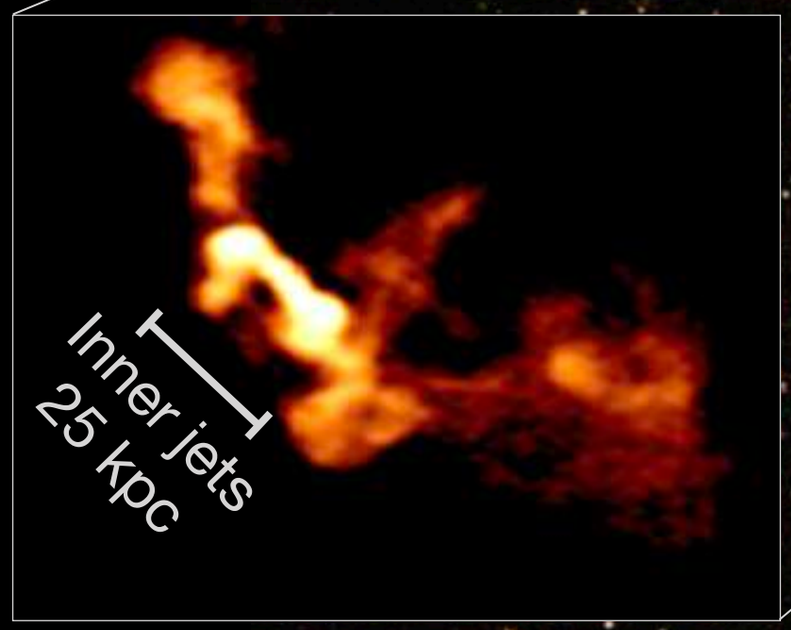
outer
lobes/bubbles

diffuse
emission

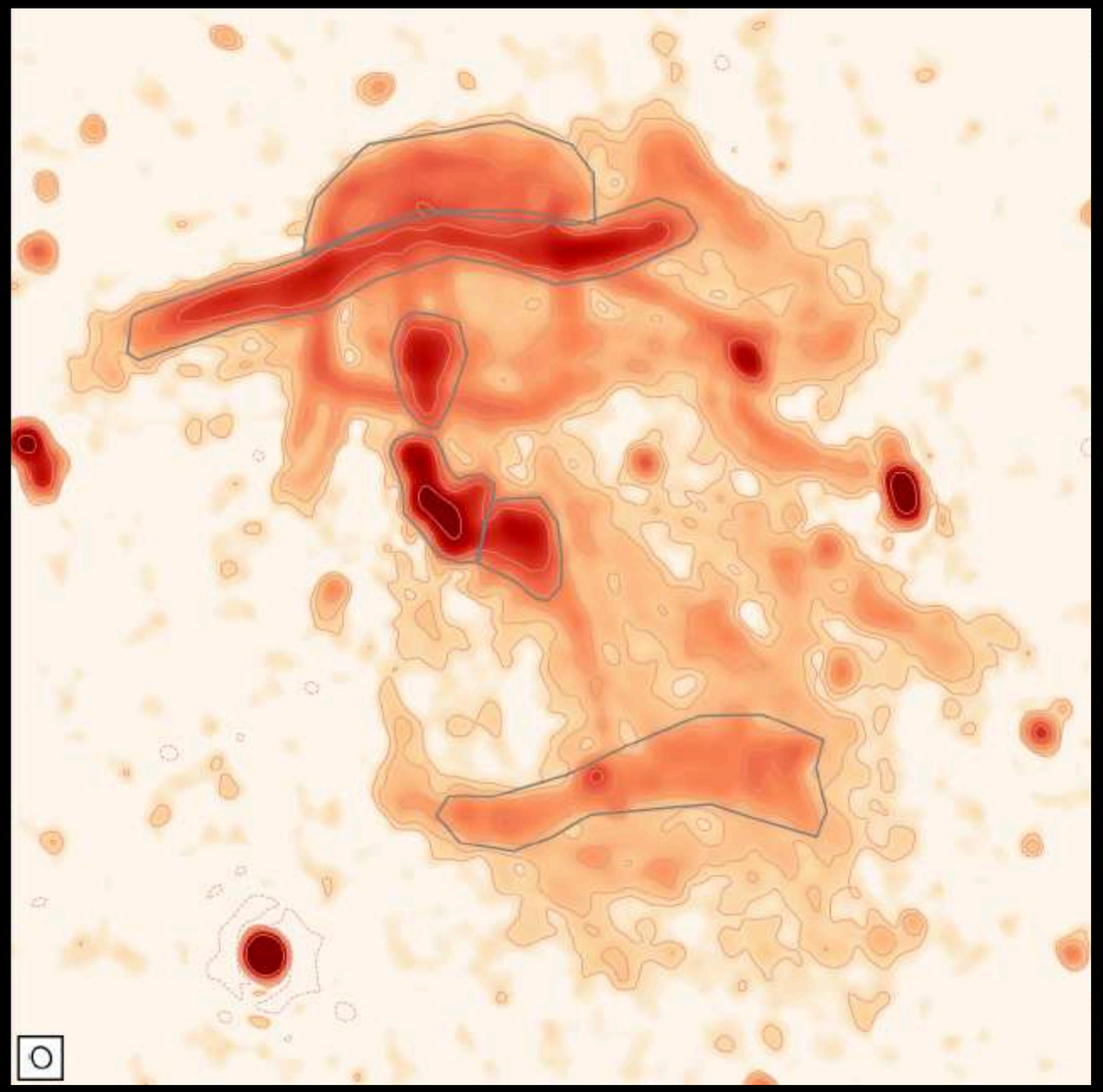
bridge

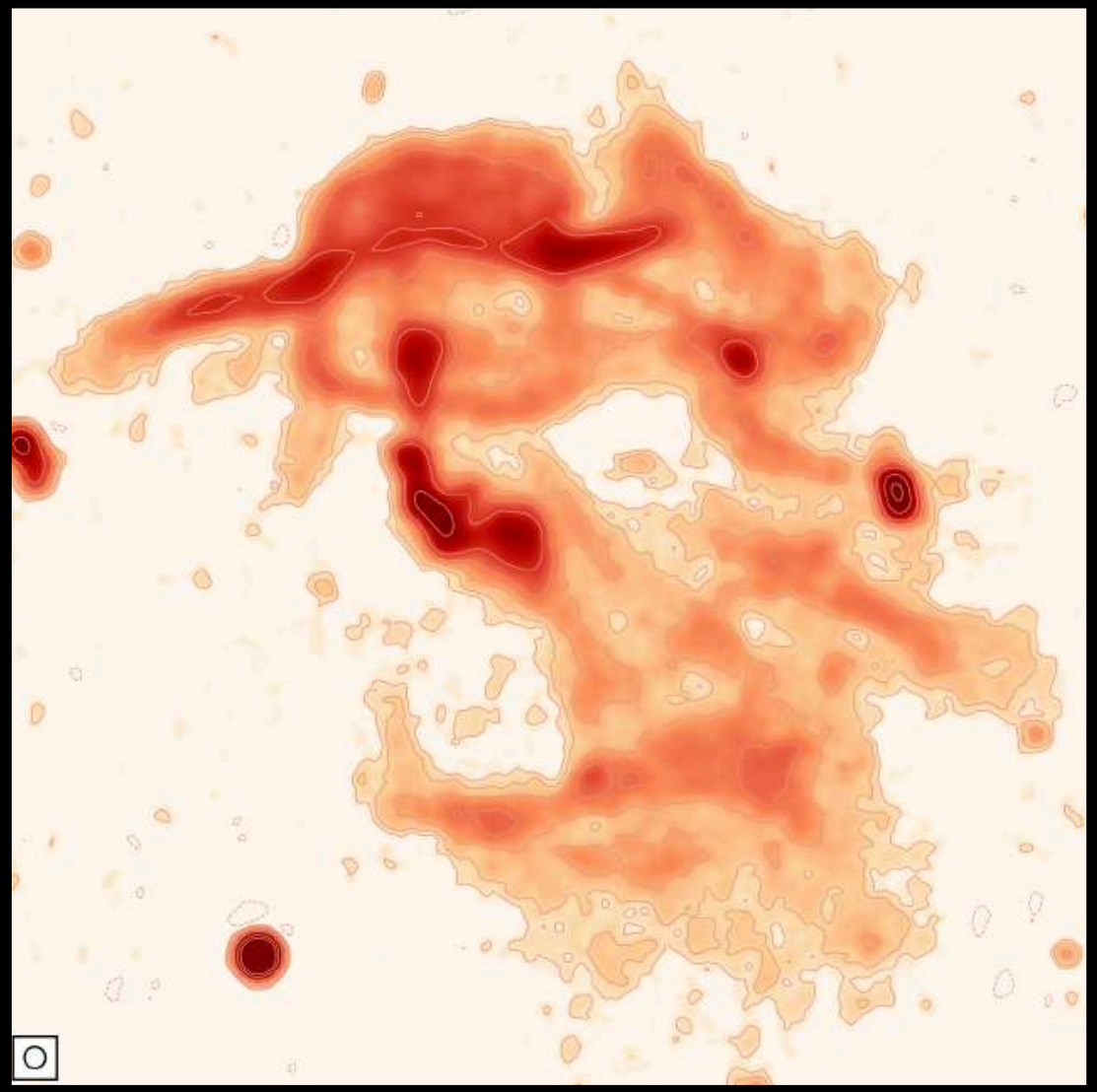
multiple pairs of lobes
AGN recurrent activity

filaments of relativistic plasma and magnetic fields
few kpc wide and
up to 350 kpc long



A lot of extended, low surface brightness emission..



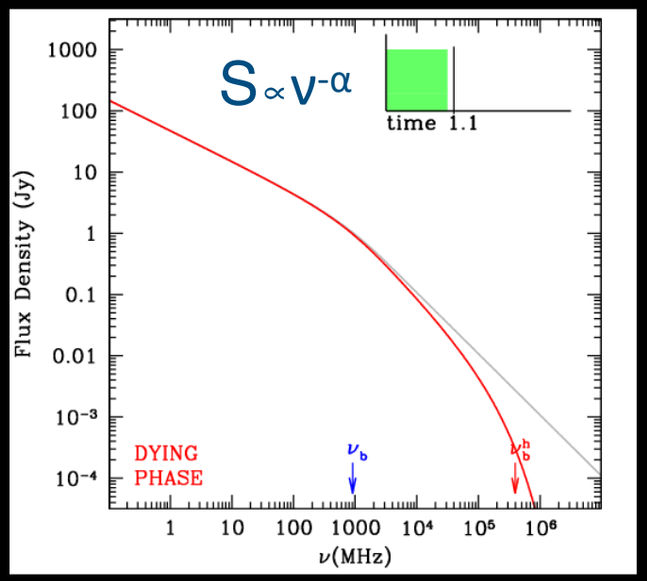


High band antennas
144MHz (16hr)
0.8 mJy/b 25”

Low-band antennas
54MHz (8h)
1.5 mJy/b 25”

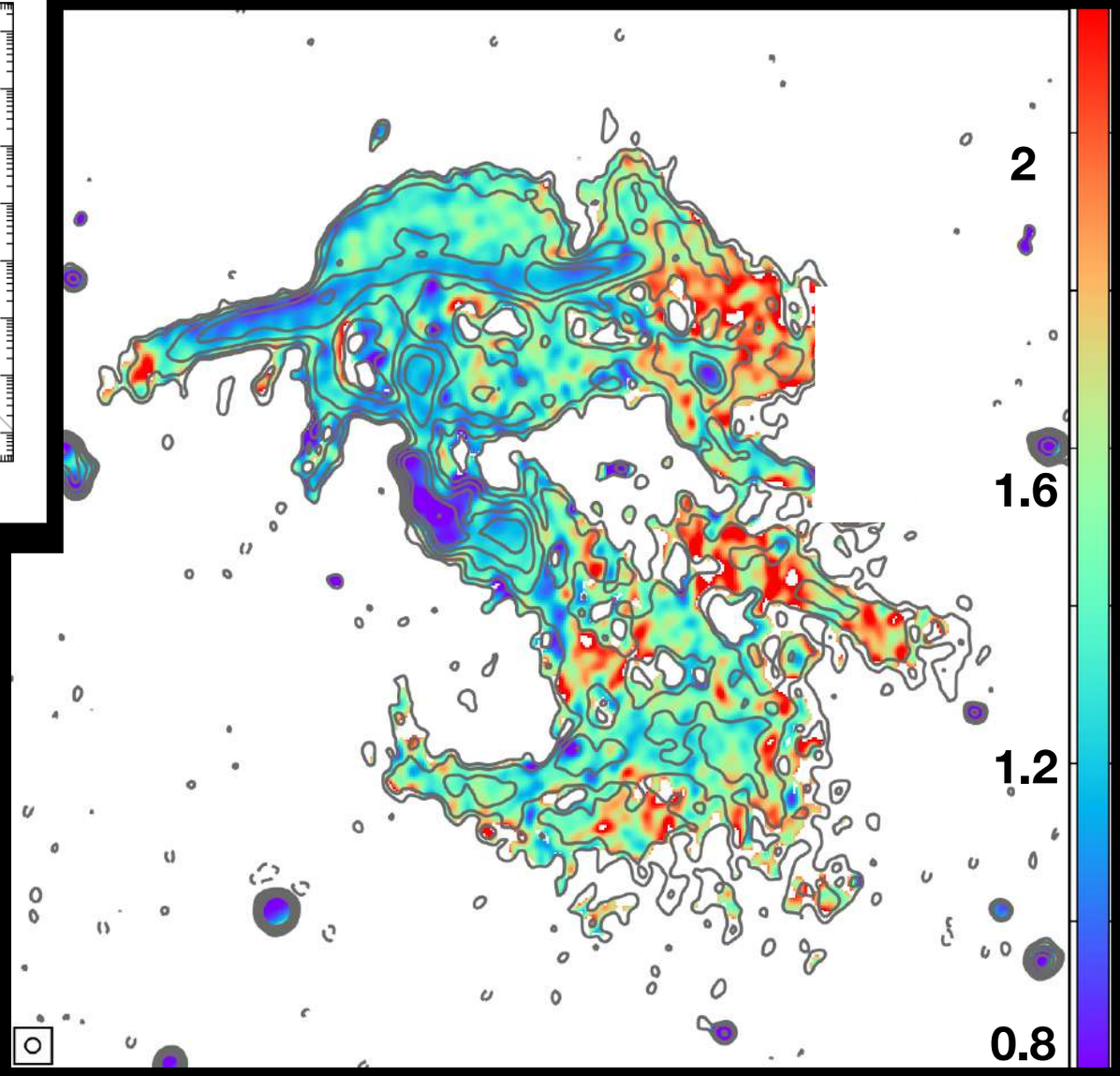
Spectral index α(53-144 MHz)

Flux vs freq



FLATTER=YOUGER

STEEPER=OLDER



central AGN
α =0.6-0.7
typical of active jets

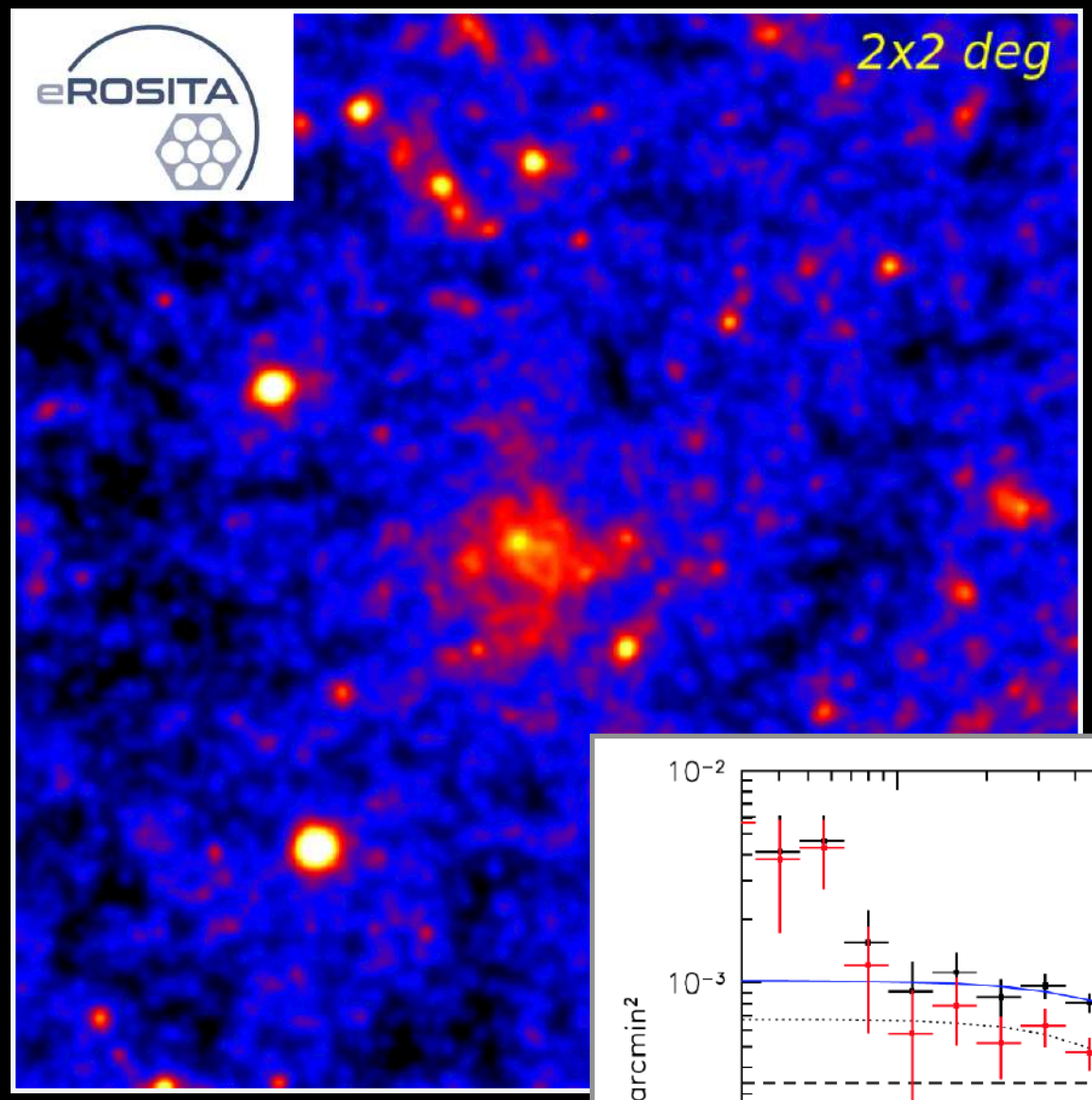
spectrum steepens
moving away from the central AGN

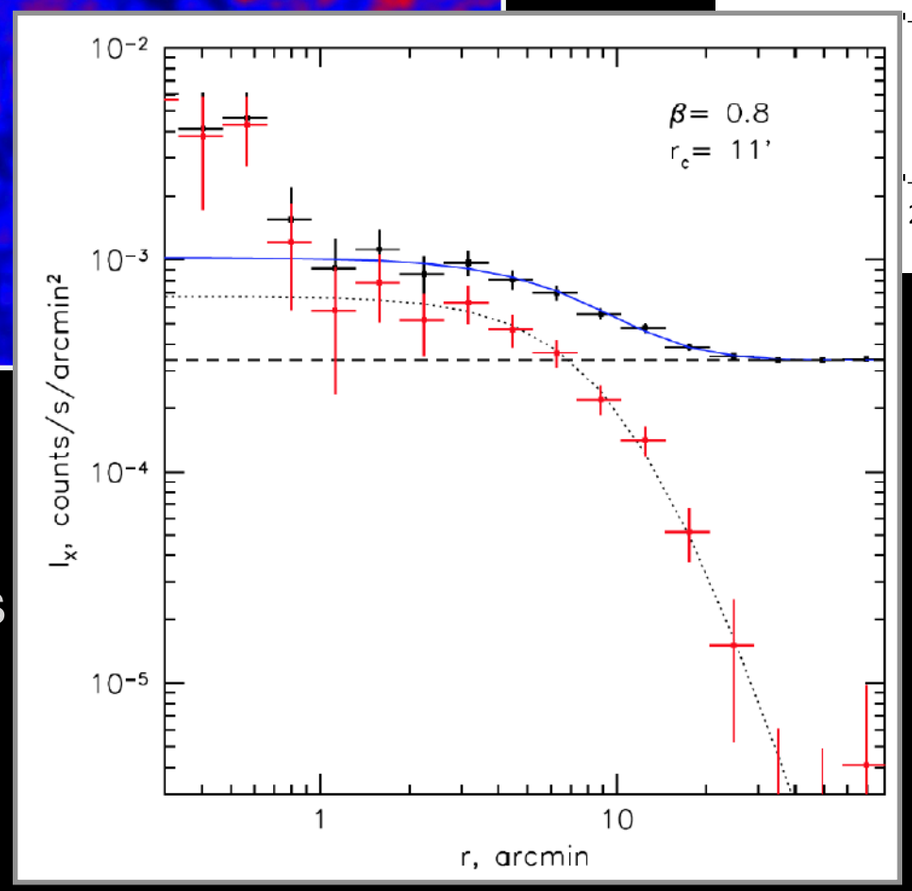
no clear gradient

diffuse emission
ultra-steep α=1.4~2.5

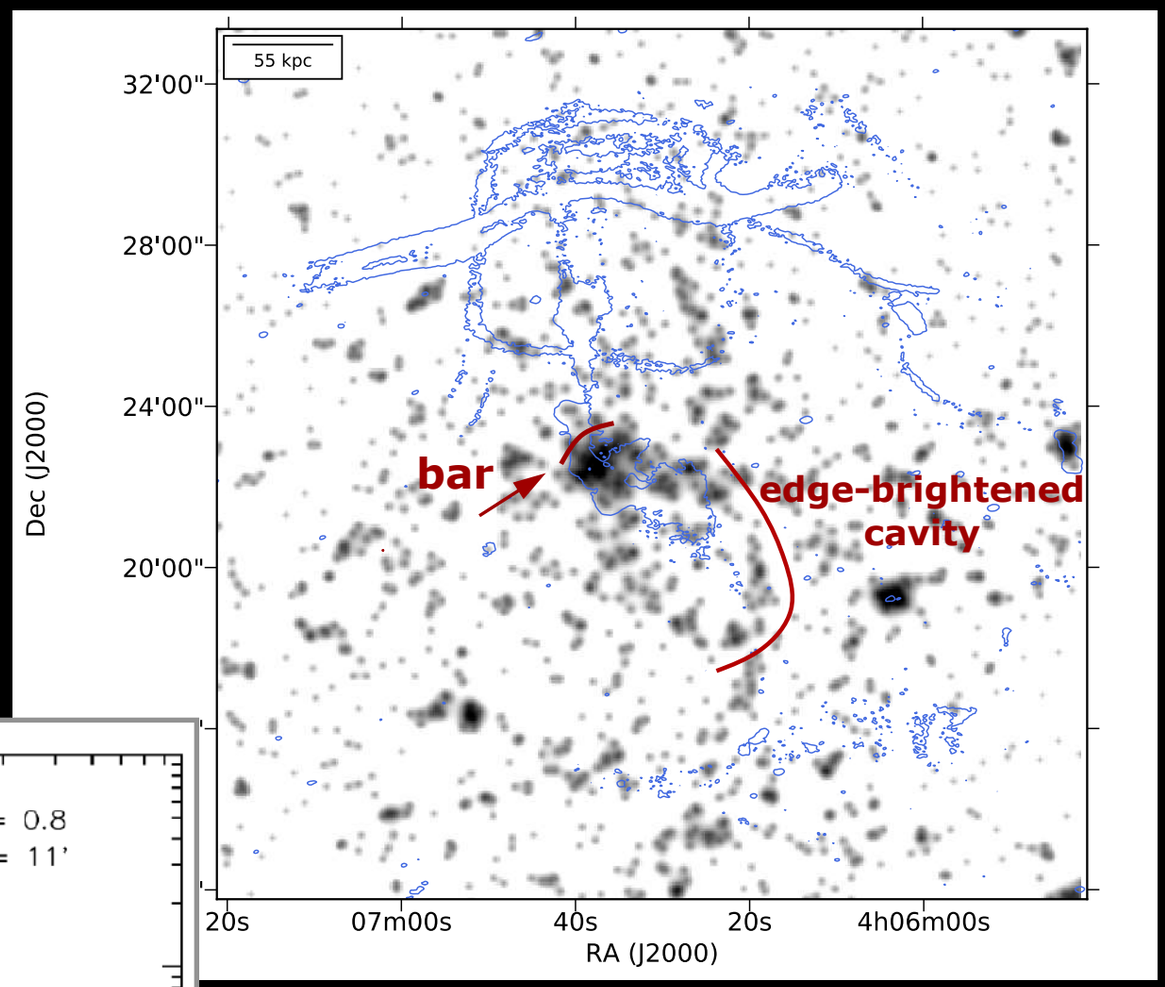
main filament in the North
shows a flatter α than what expected at that distance (down to 0.75-0.9)
Compression?

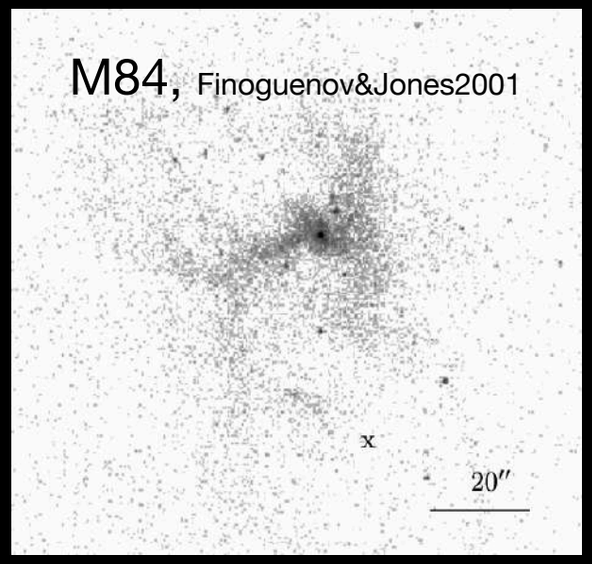
SRG/eRosita 0.5-2.3 keV (645s)





T_x = 2 keV
L_x = 5-10x10^{42} erg/s
M_x =~3-7x10^{13} M_{sun}





Evolution of AGN jet-driven bubbles

buoyancy velocity > jet expansion velocity
bubble starts rising into the ICM

Pressure gradient present around the bubble transforms a roughly spherical bubble into a torus (vortex ring)

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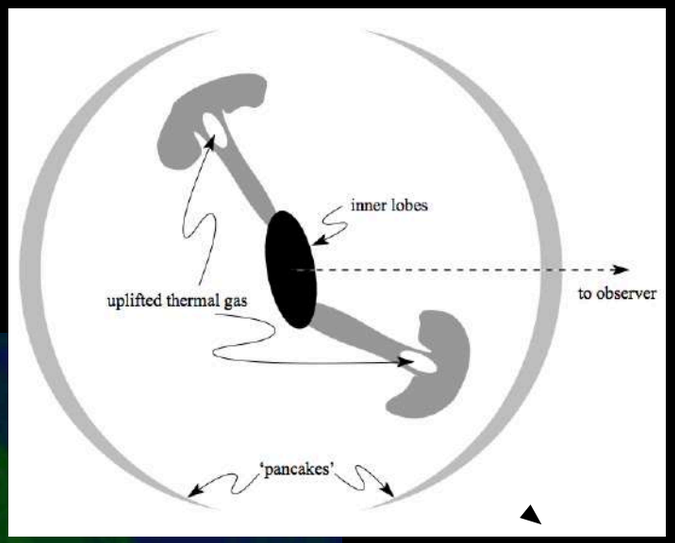
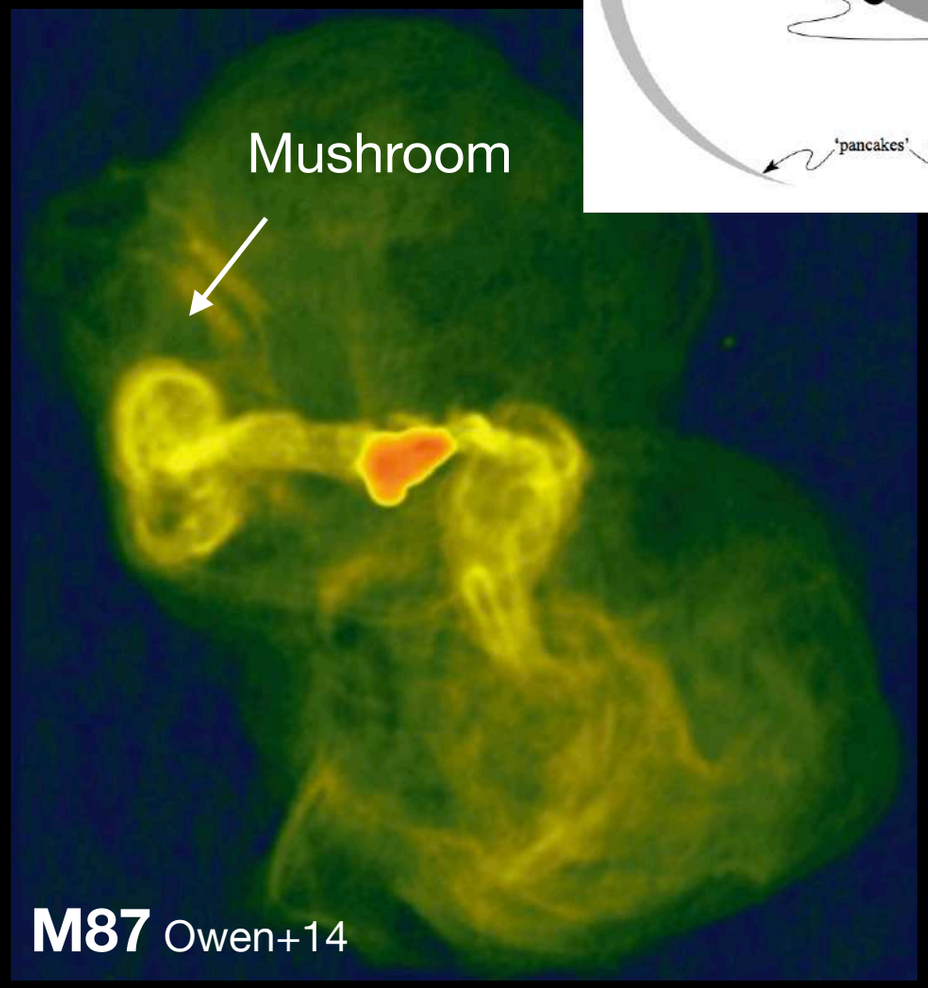


Churazov+2001

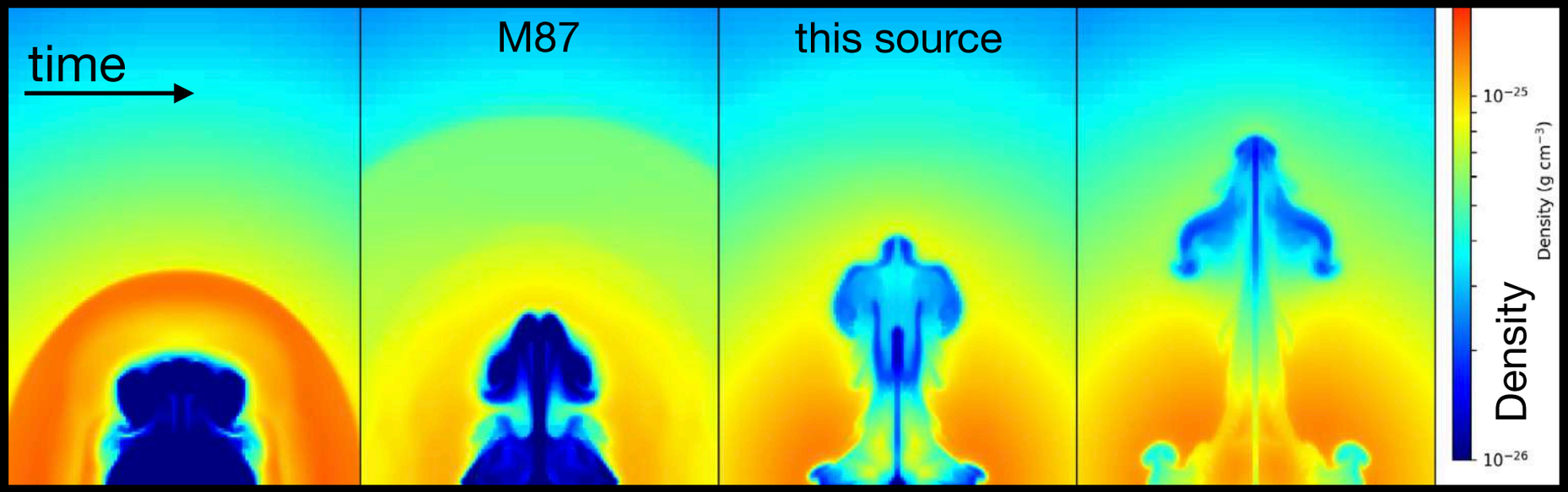


M87 Owen+14

Very late phases of bubble evolution

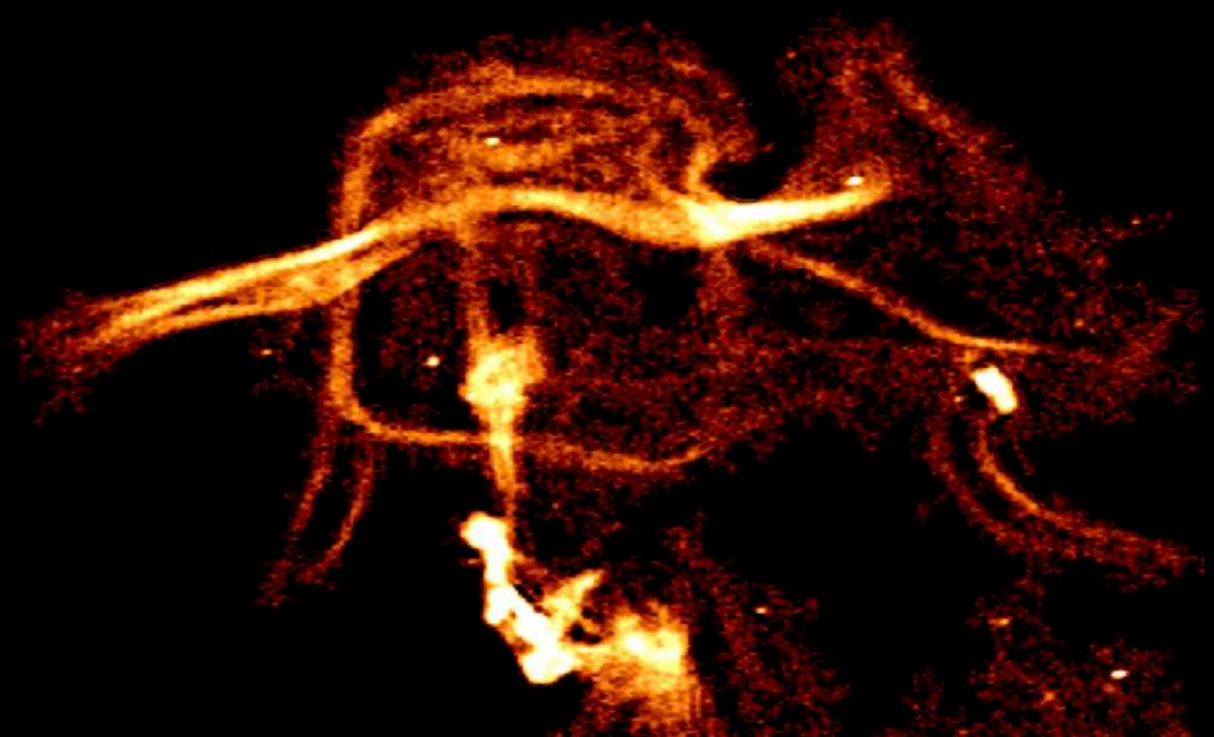
…much older than M87!

Yang+2019



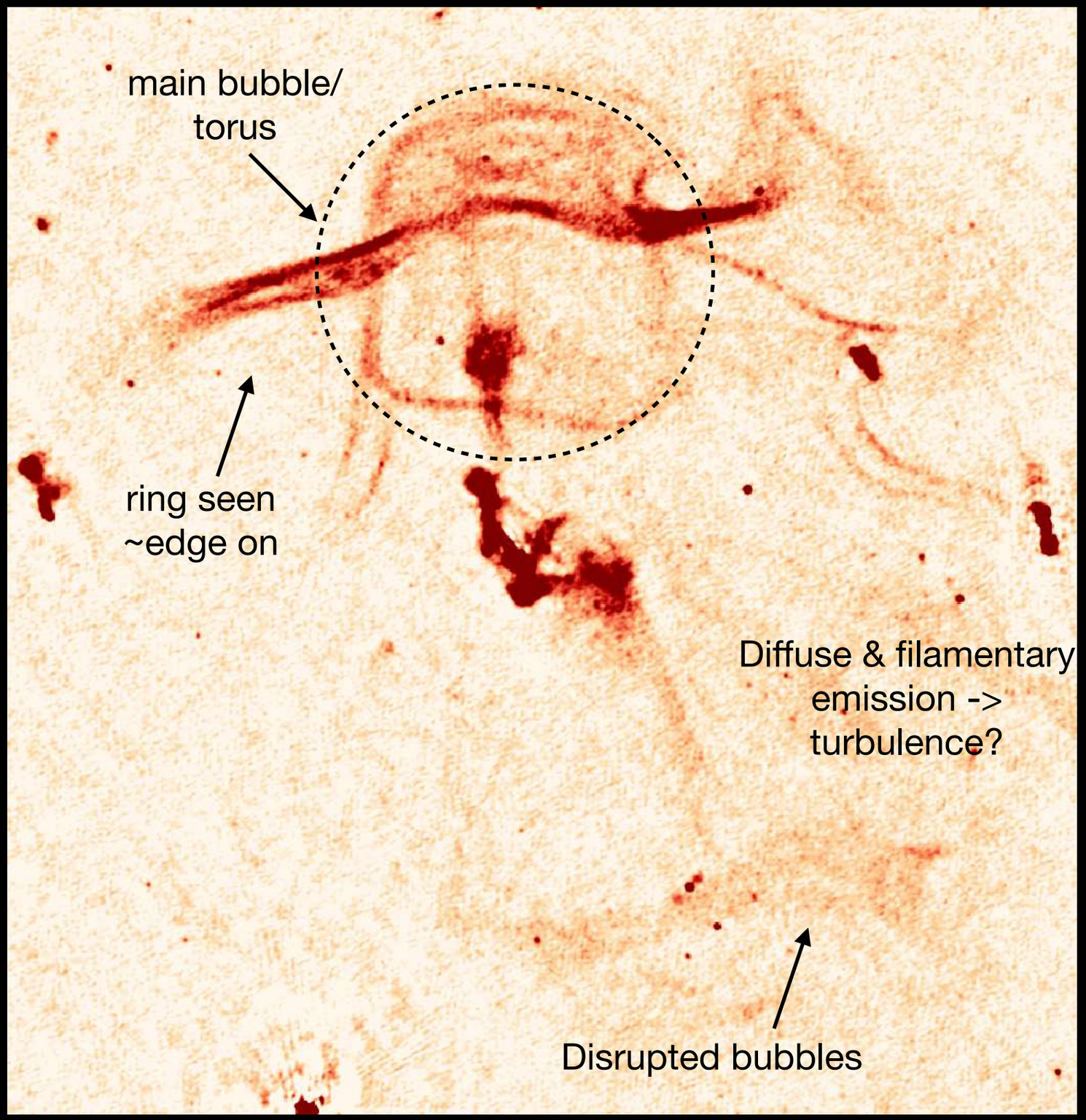
e.g.
Brüggen et al. 2002, 2003,
Robinson et al. 2004;
Jones & De Young 2005;
Gardini 2007;
Dong & Stone 2009;
Ogiya et al. 2018;
Ehlert et al. 2018;
Zhang et al. 2018;
Candelaresi
& Del Sordo 2020

And many more!



Very late phases of bubble evolution

…much older than M87!



- Age of oldest bubble based on dynamics **~200-300 Myr and** consistent with radiative age

$$v_{c_s} = \sqrt{\Gamma \frac{kT}{\mu m_p}}, \quad v_{buoy} = \sqrt{\frac{2gV}{SC}},$$

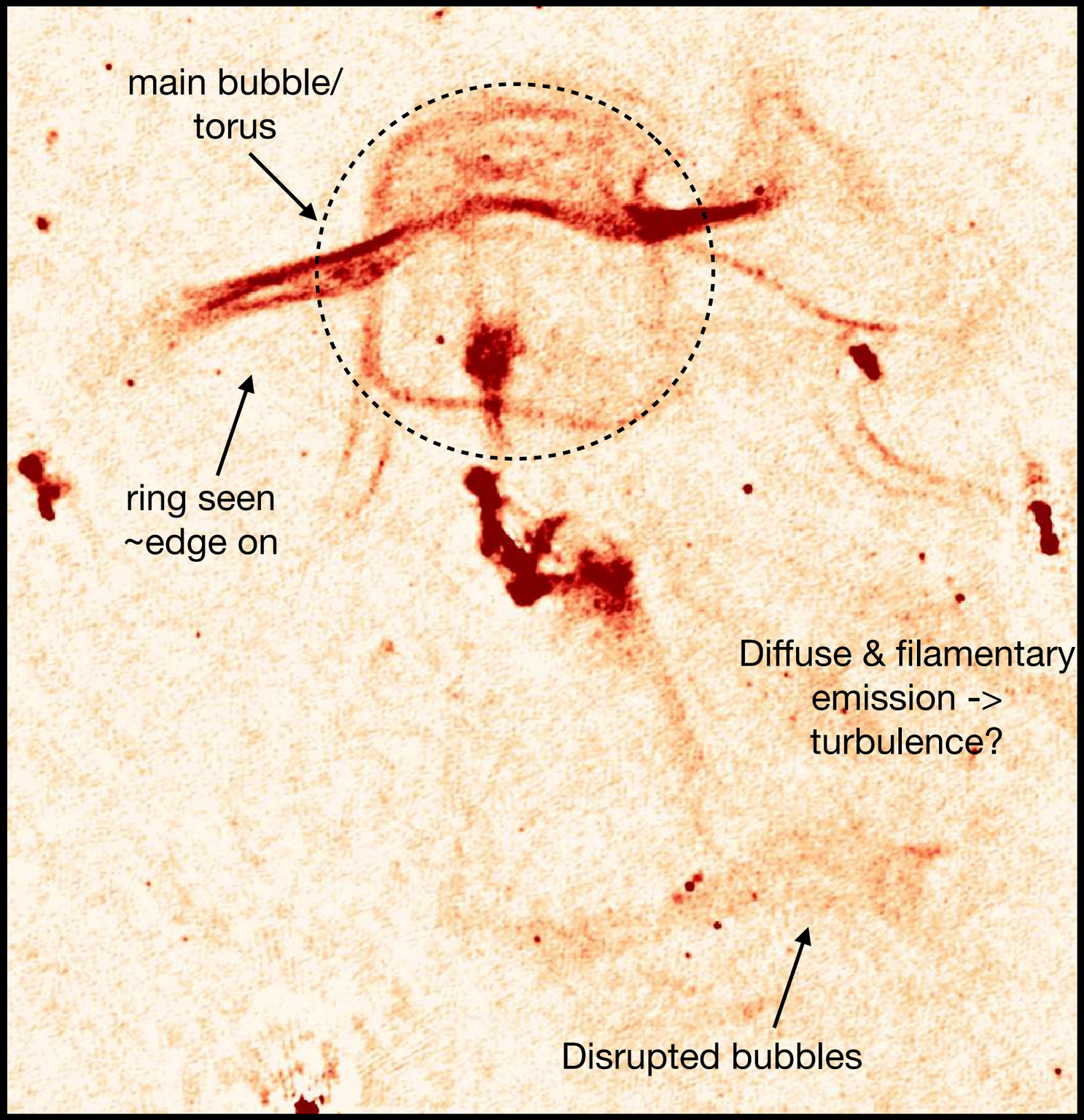
S=cross section, C=drag coefficient

- Bubble power = pV/t ~4 x10^{42} erg/s
  Compatible with
  Lx ~ 5-10x10^{42} erg/s

-> **effective in offsetting cooling**
even without complete mixing

Very late phases of bubble evolution

…much older than M87!



External pressure ~ p=1.9nkT=2-4x10^{-12} dyne/cm^2

Internal pressure ~ equipartition= 2-4x10^{-13} dyne/cm^2

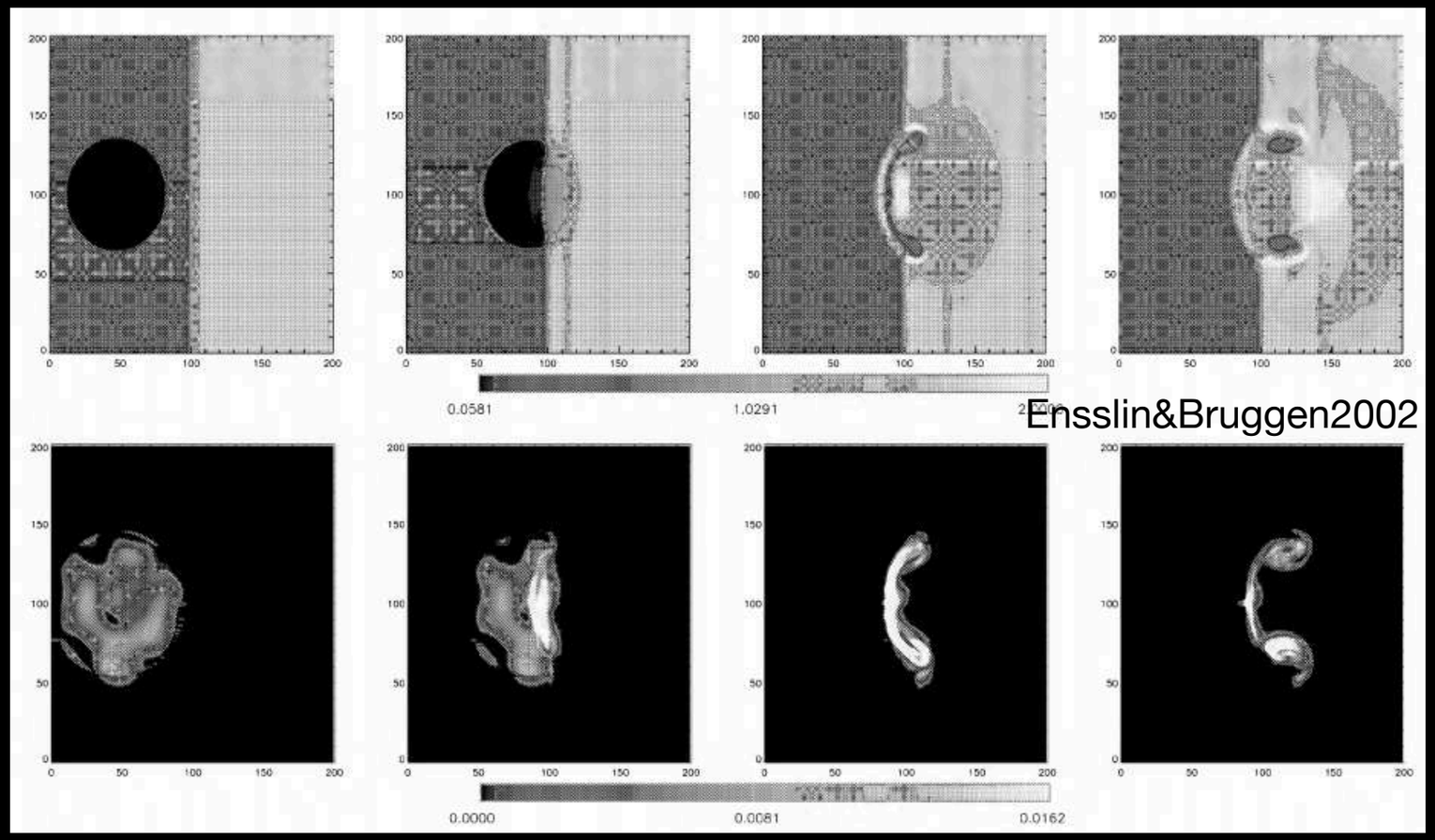
- -> **non-negligible contribution of cosmic-ray protons (np/ne<10)**

assuming pressure balance and smaller if not in pressure balance

- **-> impressive stability!** K-H and R-T instabilities would be expected to disrupt the bubbles and filaments on shorter timescales… but magnetic fields might prevent them

-> Alfven scale = 5-15 kpc = filaments width!

Alternative/complementary scenario



Ensslin&Bruggen2002

Weak shock waves through hot bubbles of remnant plasma can also alter the radio morphology.

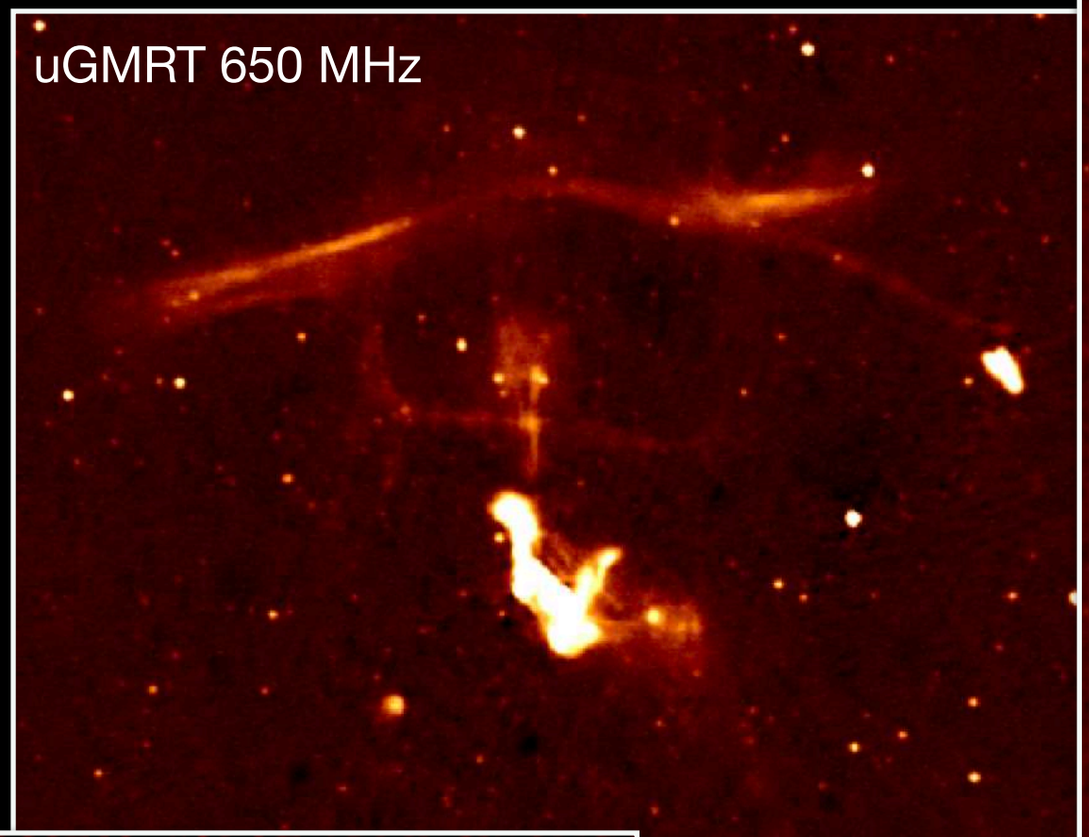
Different sound speeds inside and outside the remnant plasma = transformation of the bubble into a torus + filaments, rings, eddies

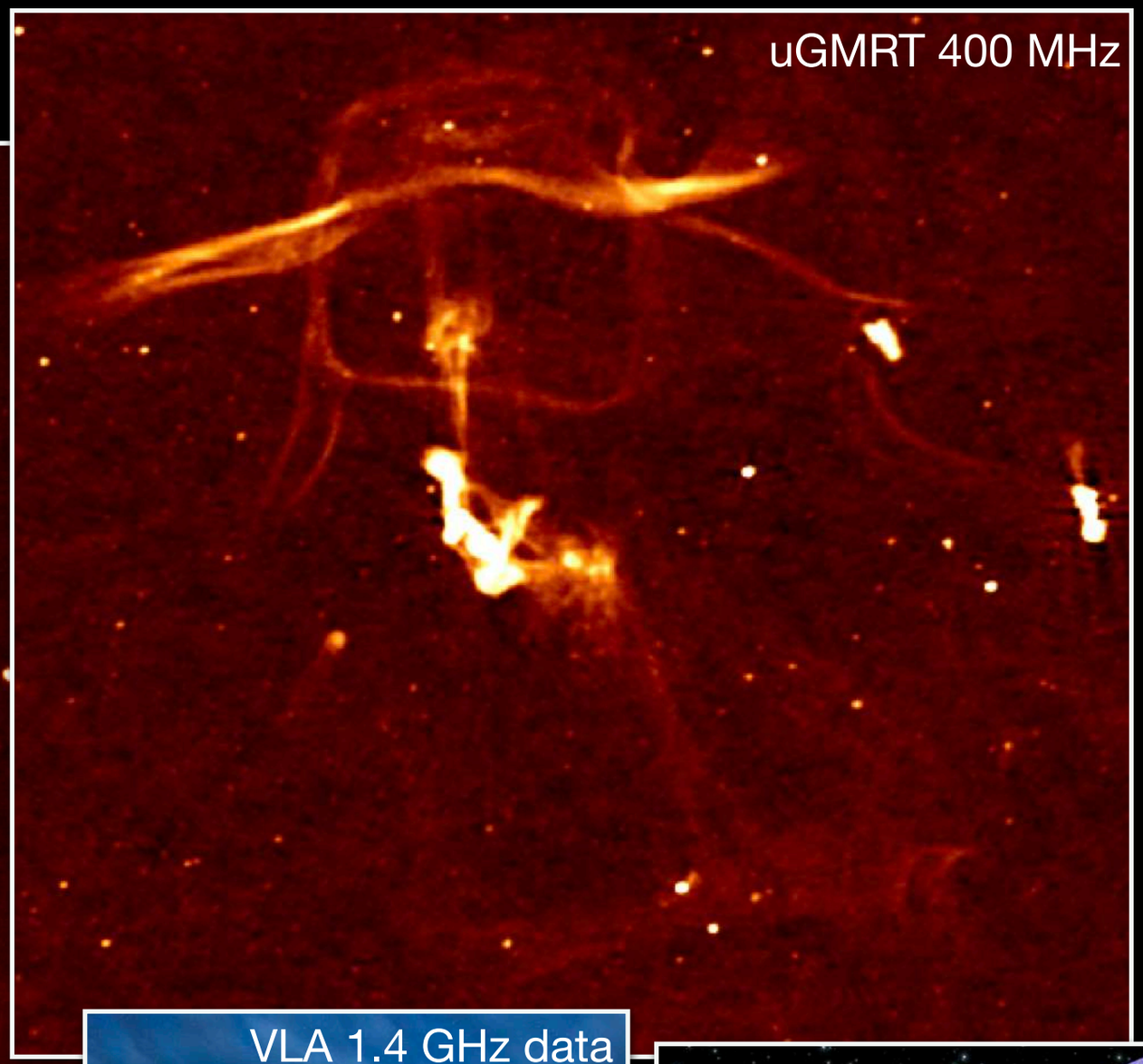
(proposed scenario for formation of radio relics and phoenices Enßlin & Brüggen 2002; Heinz & Churazov 2005)

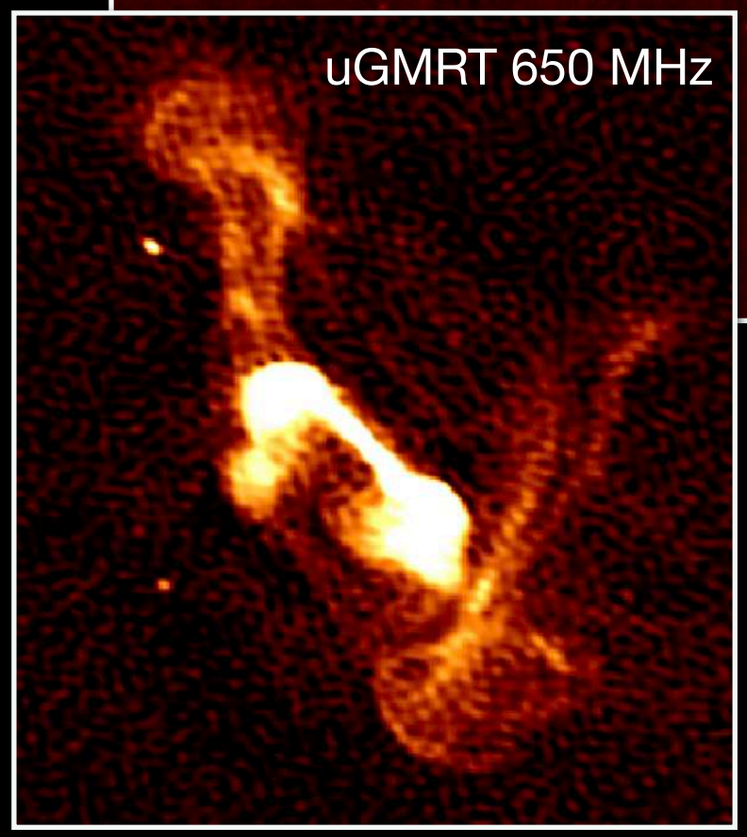
1) group dynamics?

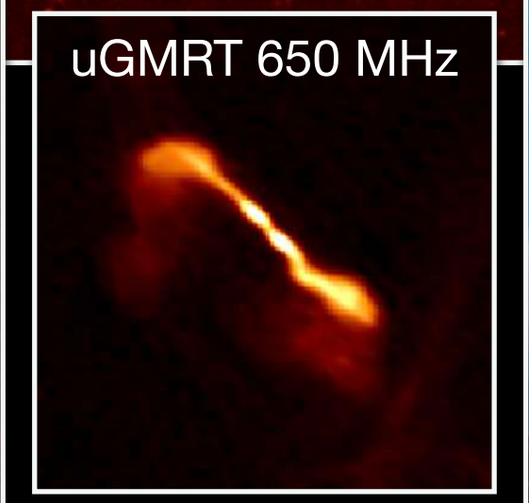
2) second AGN outbursts?

More to come!

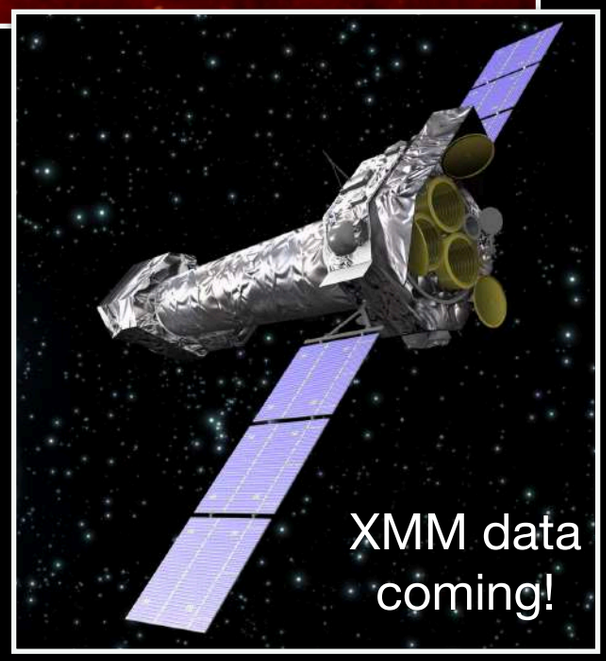

uGMRT 650 MHz


uGMRT 400 MHz


uGMRT 650 MHz

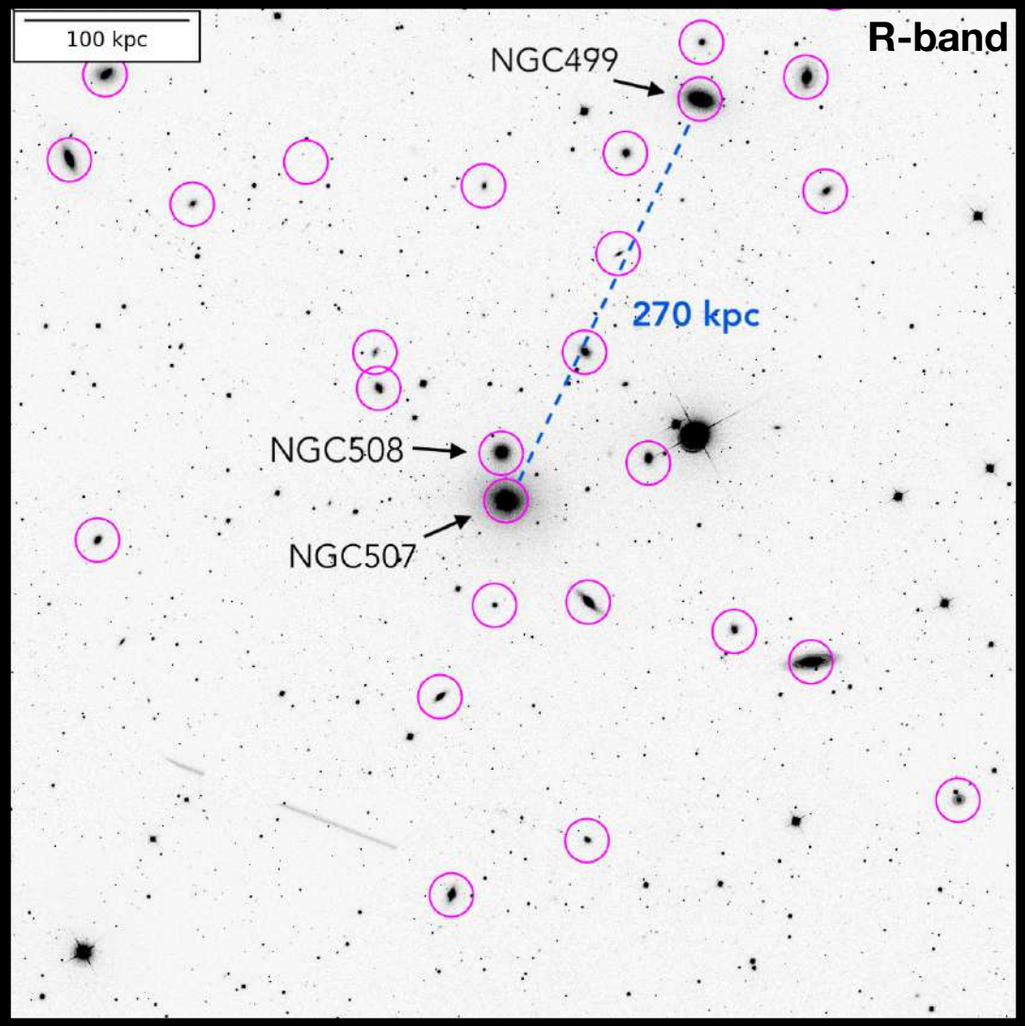

uGMRT 650 MHz


VLA 1.4 GHz data
coming!


XMM data
coming!

The galaxy (group) NGC 507

- z=0.01646
- Pisces supercluster
- 76 galaxies with magnitude mZw<16:4 within1 Mpc
- Velocity dispersion of 658 km/s
- M500 = 6x10^{13} M_{sun} (within R500 = 596 kpc)



Mulchaey et al. 2003; O'Sullivan et al. 2003
Jeltema et al. 2008; Barton et al. 1998
Piffaretti et al. 2011; Kim et al. 2019

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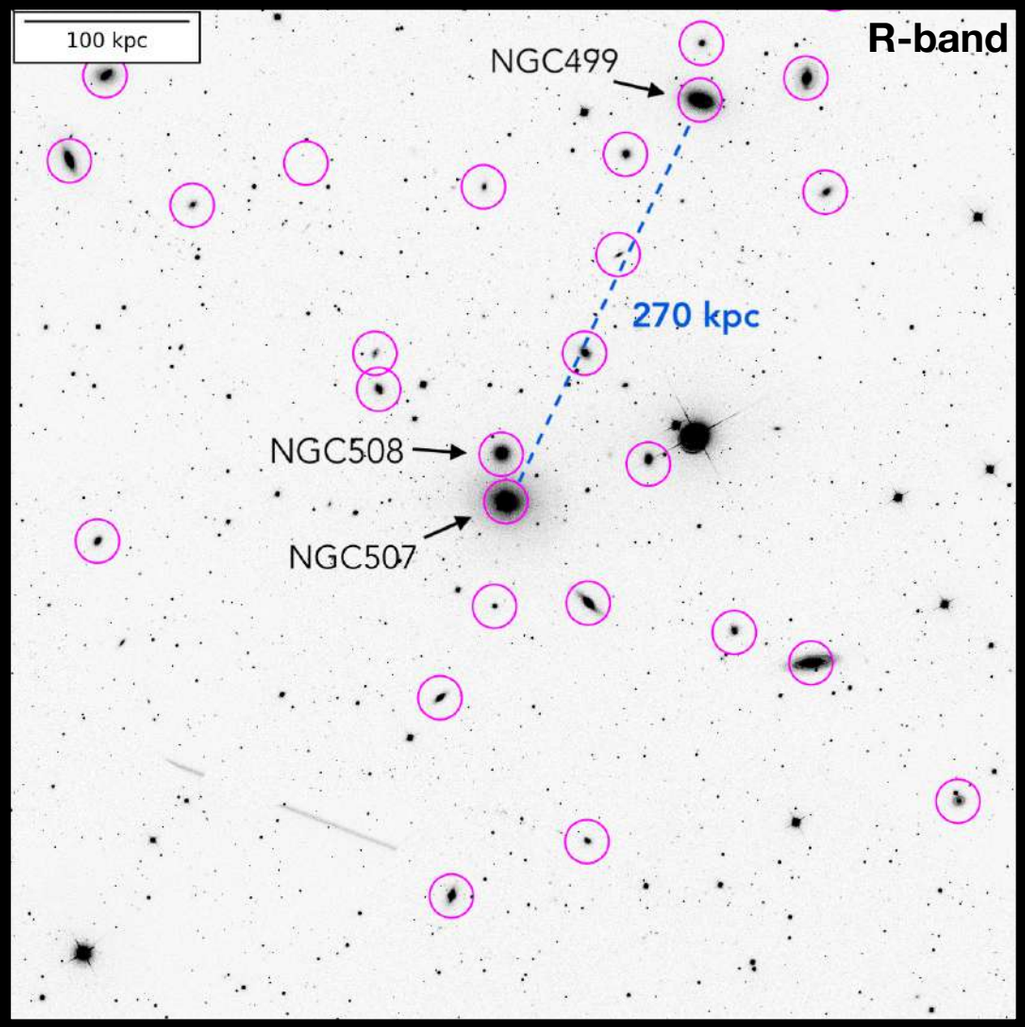
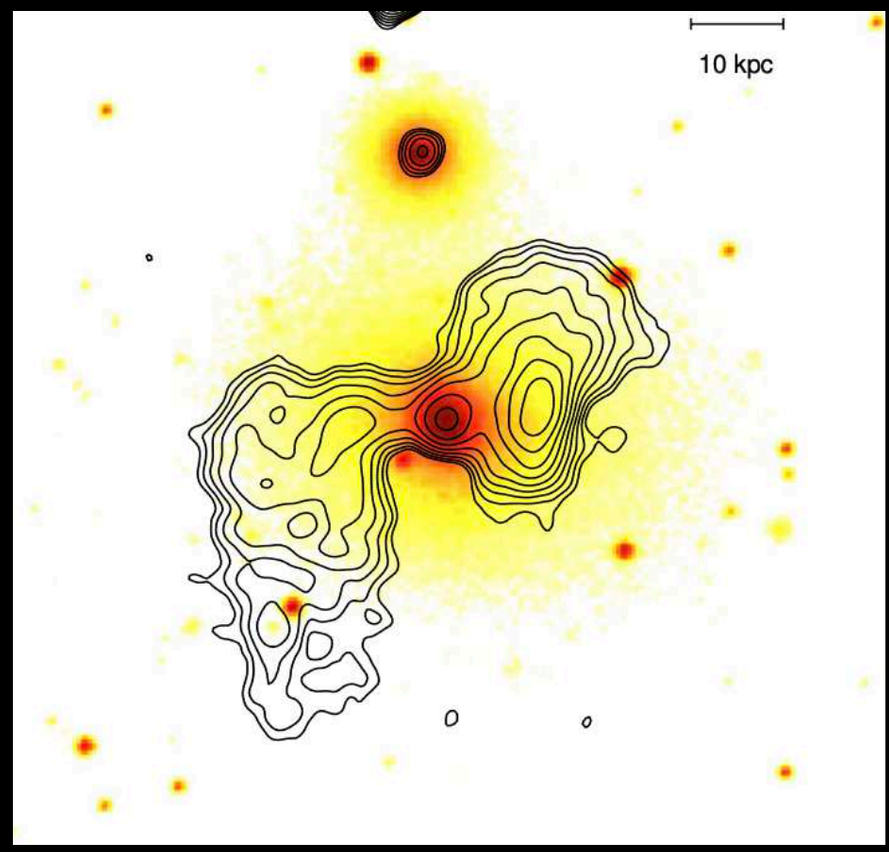


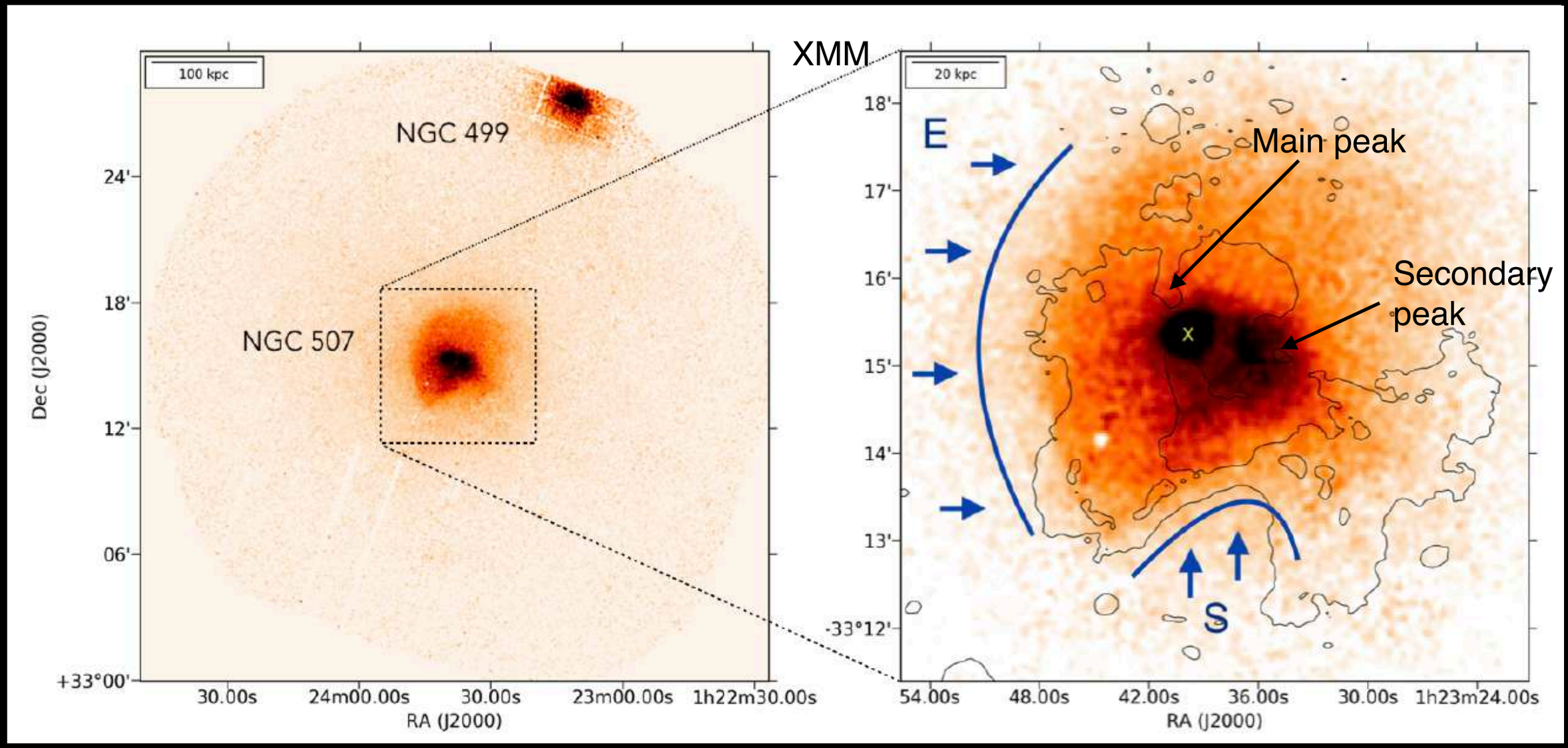
Mulchaey et al. 2003; O'Sullivan et al. 2003
Jeltema et al. 2008; Barton et al. 1998
Piffaretti et al. 2011; Kim et al. 2019

- L(150MHz) ~10^{24} W/Hz
- FRI radio galaxy (B2 0120+33)
- 70 kpc
- Remnant/Dying radio galaxy
  -> No jets/very curved spectrum SPC=1.5
  -> Low core prominence
- Total age <140 Myr
  Jets switch off 50 Myr ago



Parma+1986
Murgia+2011
Giacintucci+2011

NGC 507 in the X-rays



- Lx= 1.43e10^43 erg/s (0.1-2 keV band)
- X-ray morphology -> two components -> INNER= two main peaks
  OUTER= asymmetric halo
- Two discontinuities in surface brightness -> E (abundance front?) + S (not characterized)

(Paolillo et al. 2003; Kim & Fabbiano 2004; Kraft et al. 2004; Sato et al. 2009; Piffaretti+2011, Lovisari & Reiprich 2019; Islam et al. 2021)

SDSS
LOFAR 144 MHz - 6”
XMM 0.7-2 keV

2′ = 35.7 kpc

asymmetric X-ray halo

primary
X-ray peak

X-ray E
discontinuity

Western lobe

secondary
X-ray peak

Eastern lobe

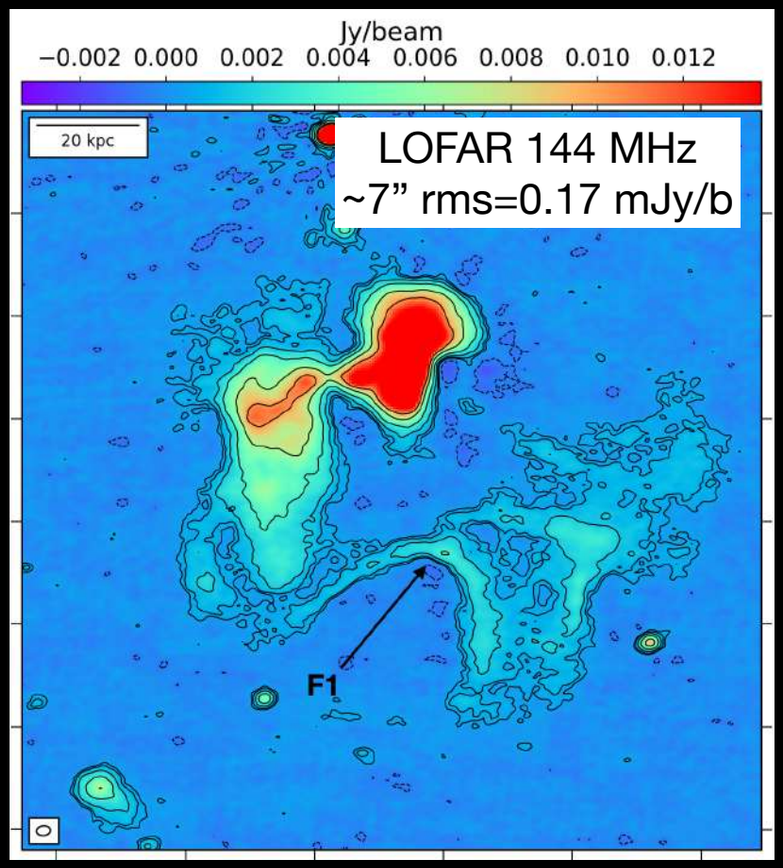
NEW

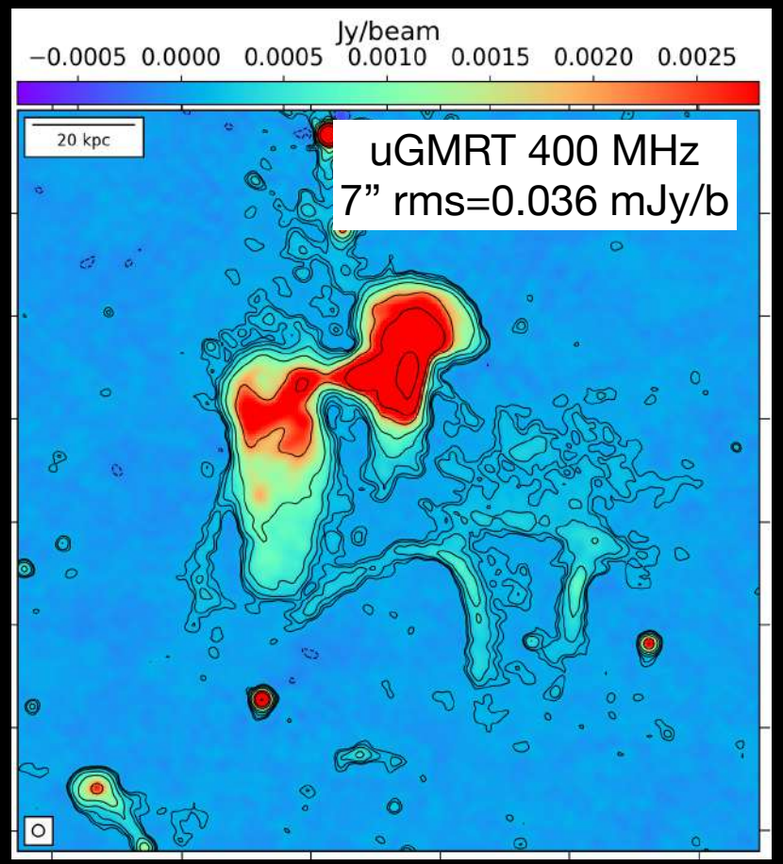
AGN remnant
emission

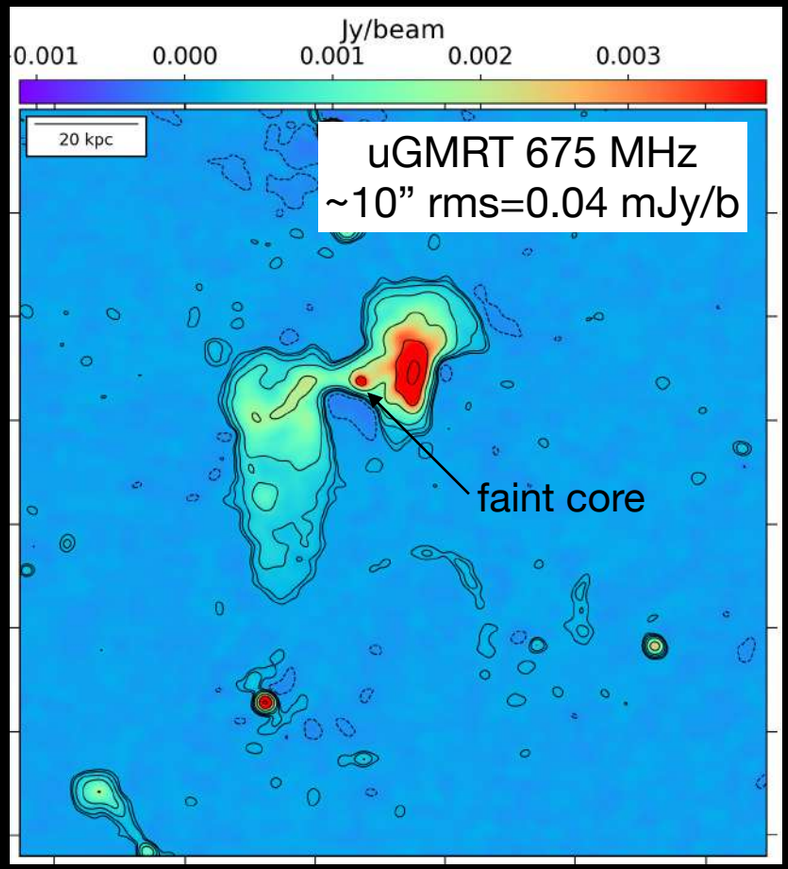
Multiple
Outbursts!

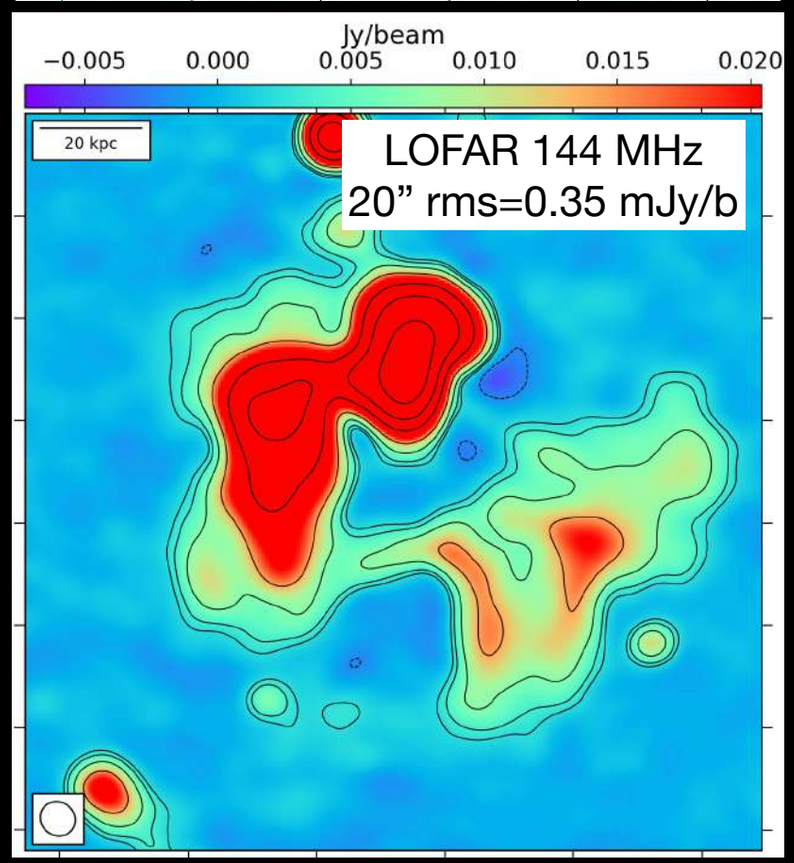
X-ray S discontinuity &
radio arc-shaped filament

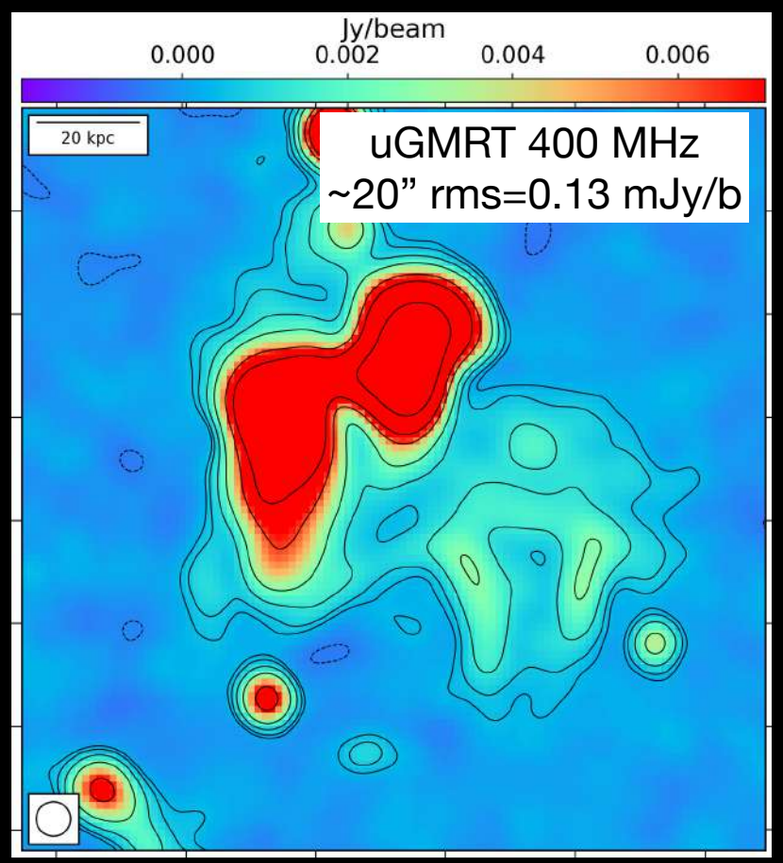
NGC 507: multi-frequency radio images

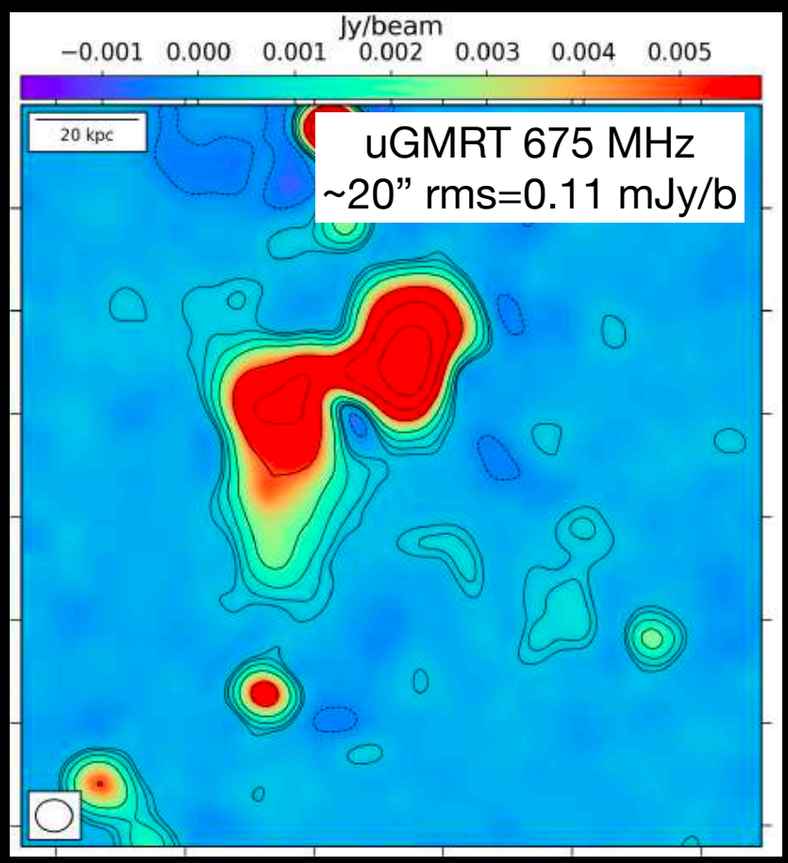




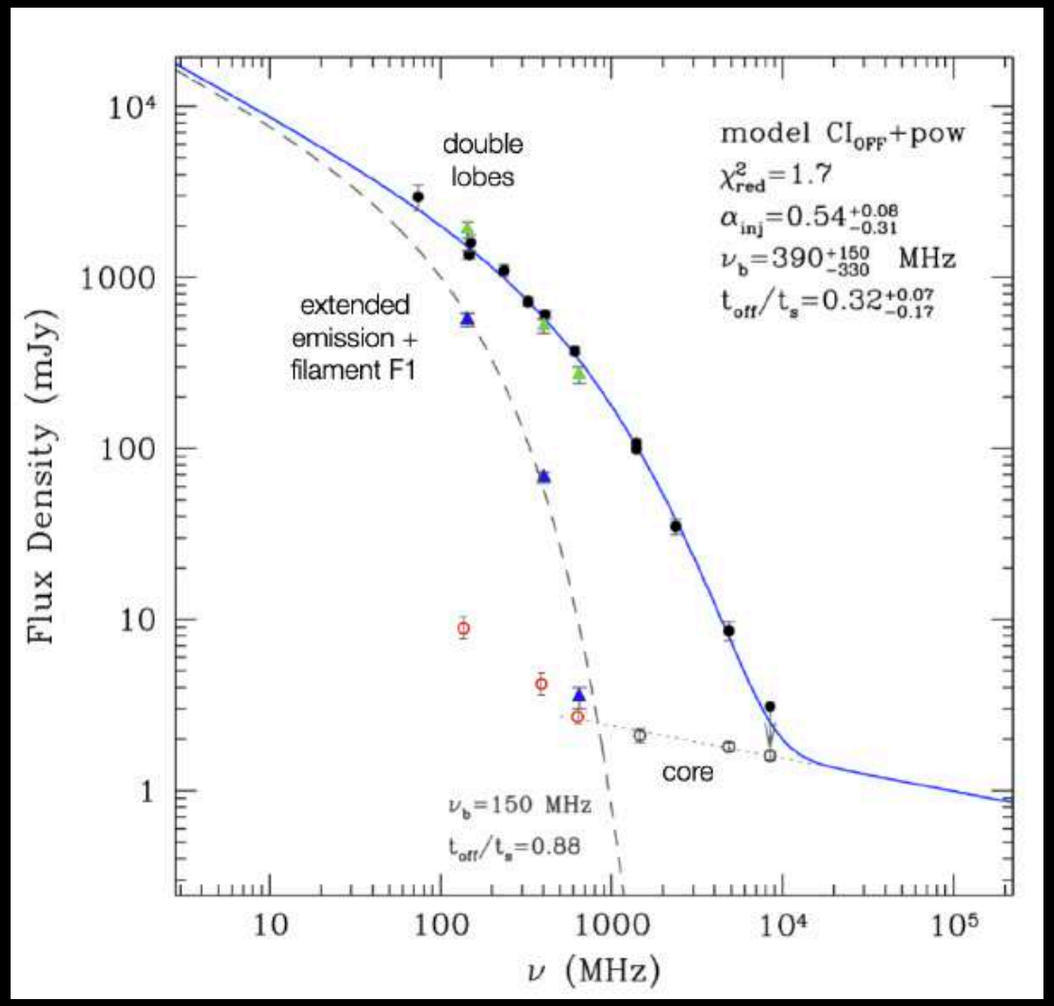








NGC 507: radio spectral analysis



$S \propto \nu^{-\alpha}$

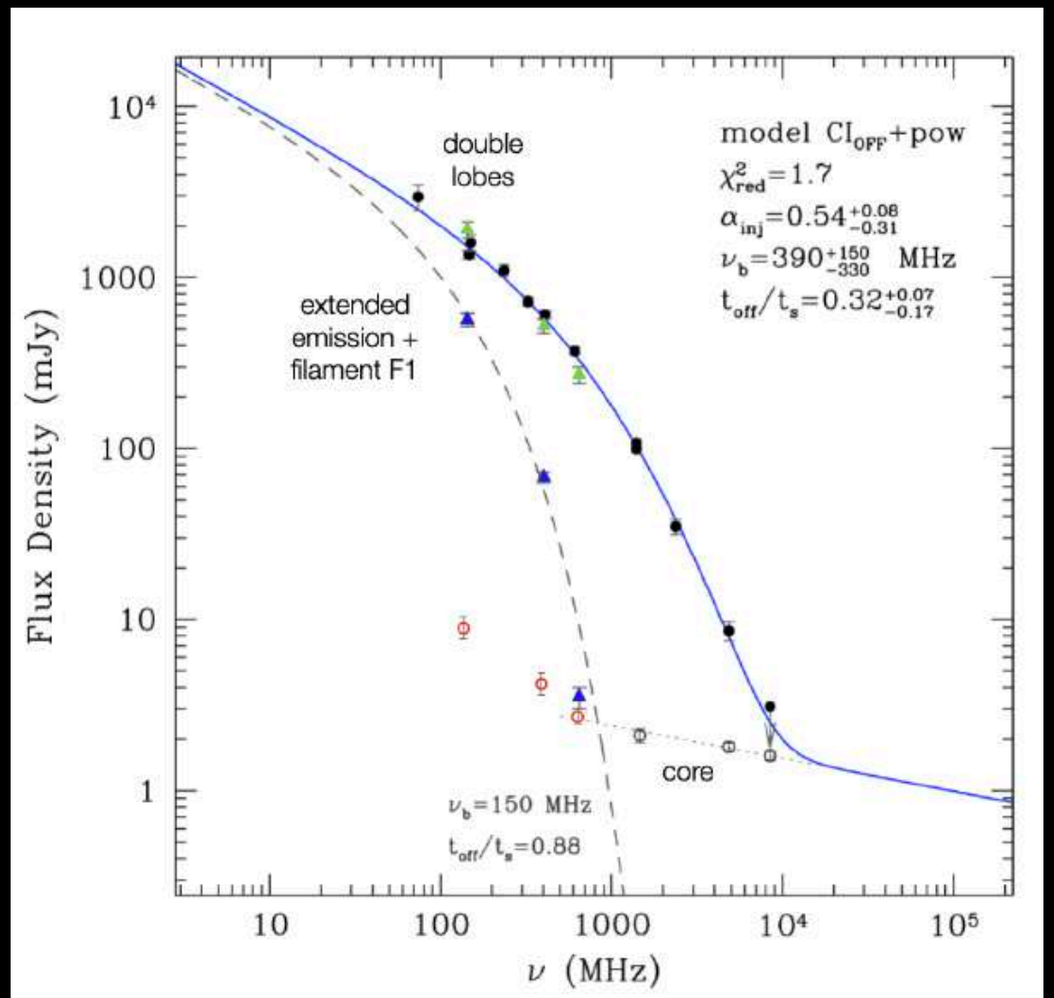
DOUBLE LOBES

t_tot=150 Myr (t_on=102 Myr+t_off = 48 Myr)

EXTENDED REMNANT PLASMA

t_tot~300 Myr (t_on~30 Myr+t_off ~ 270 Myr)

NGC 507: radio spectral analysis



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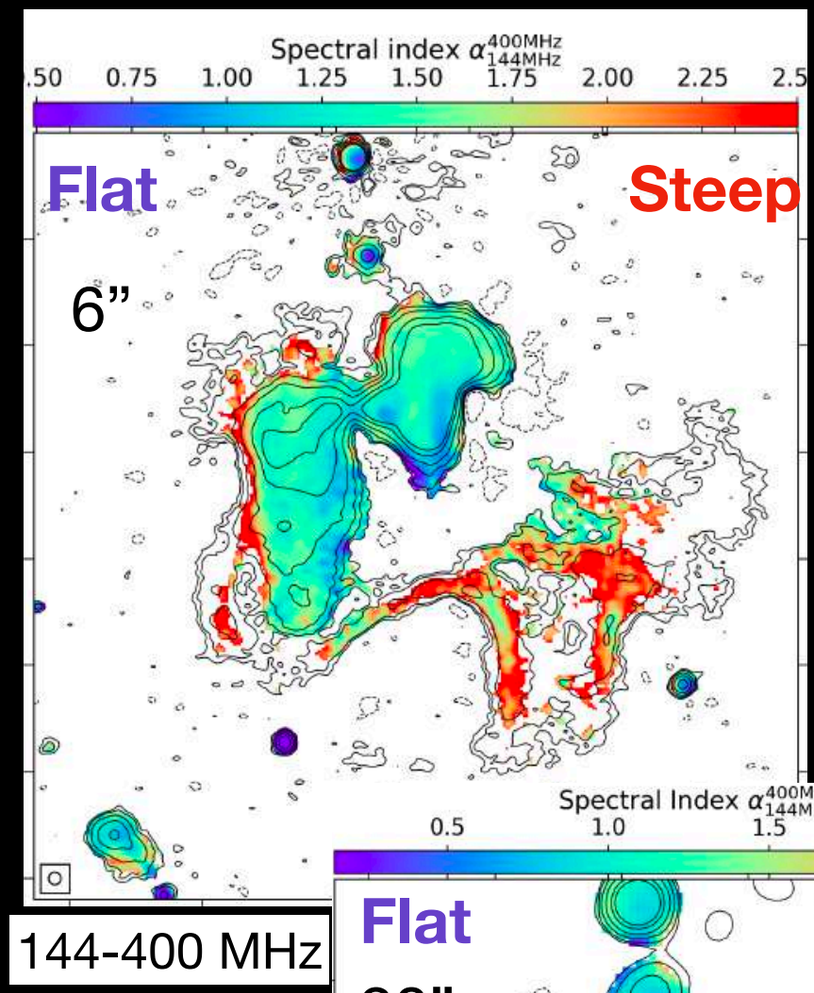

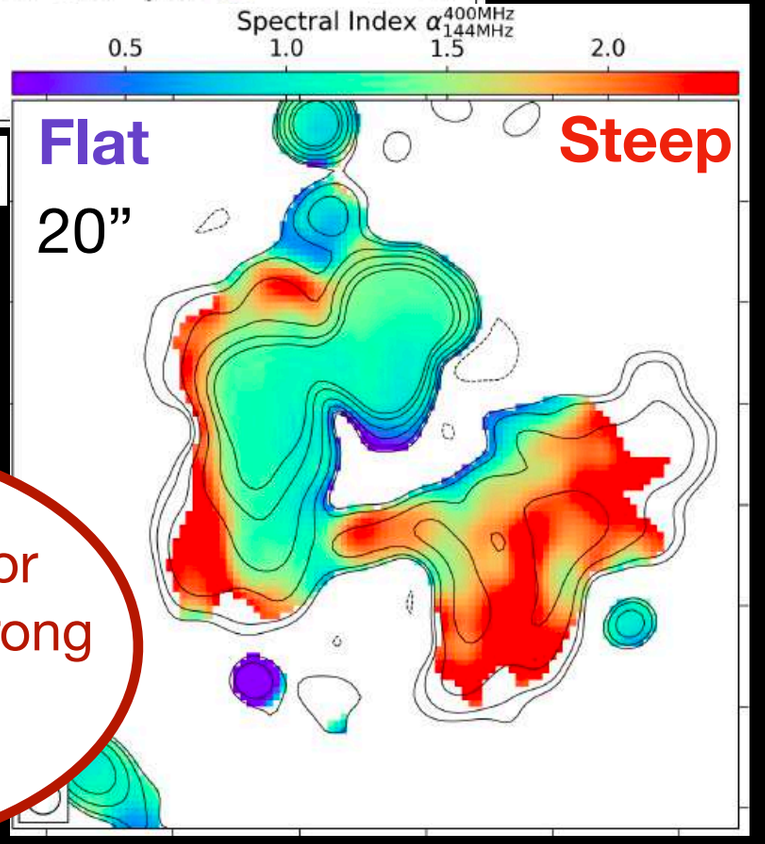

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t_tot=150 Myr (t_on=102 Myr+t_off = 48 Myr)

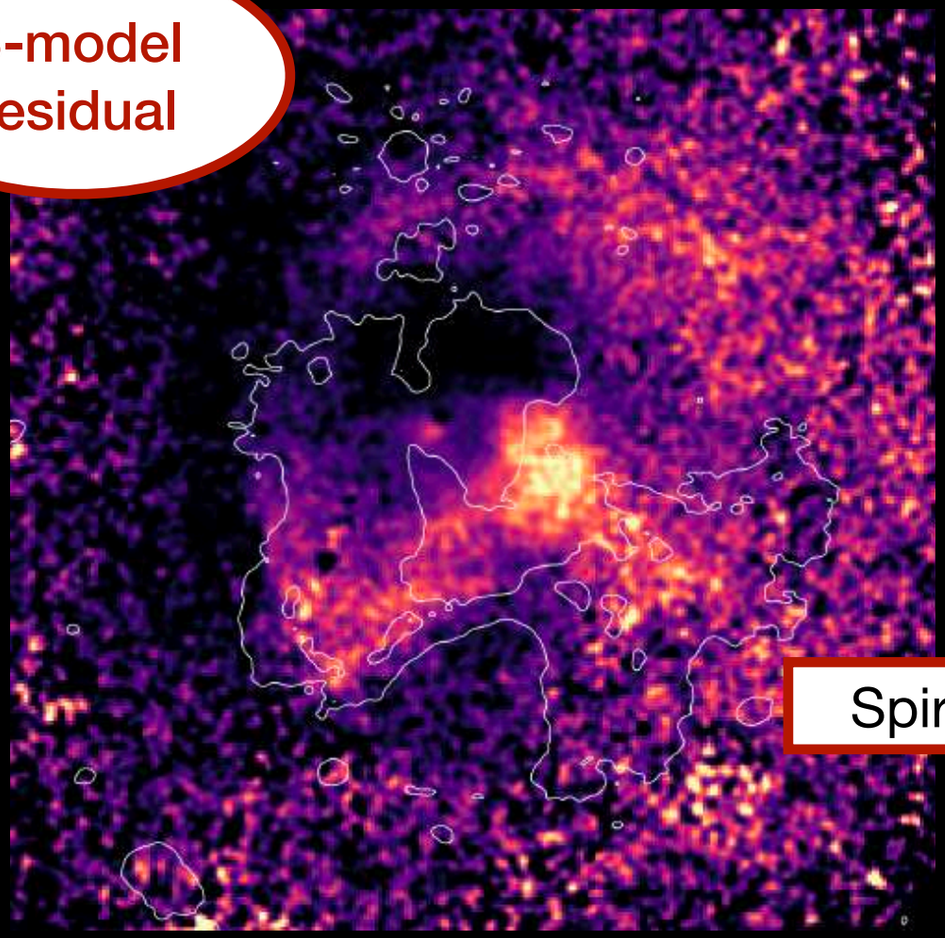
EXTENDED REMNANT PLASMA

t_tot~300 Myr (t_on~30 Myr+t_off ~ 270 Myr)

No clear trend or flattening = no strong compression ongoing

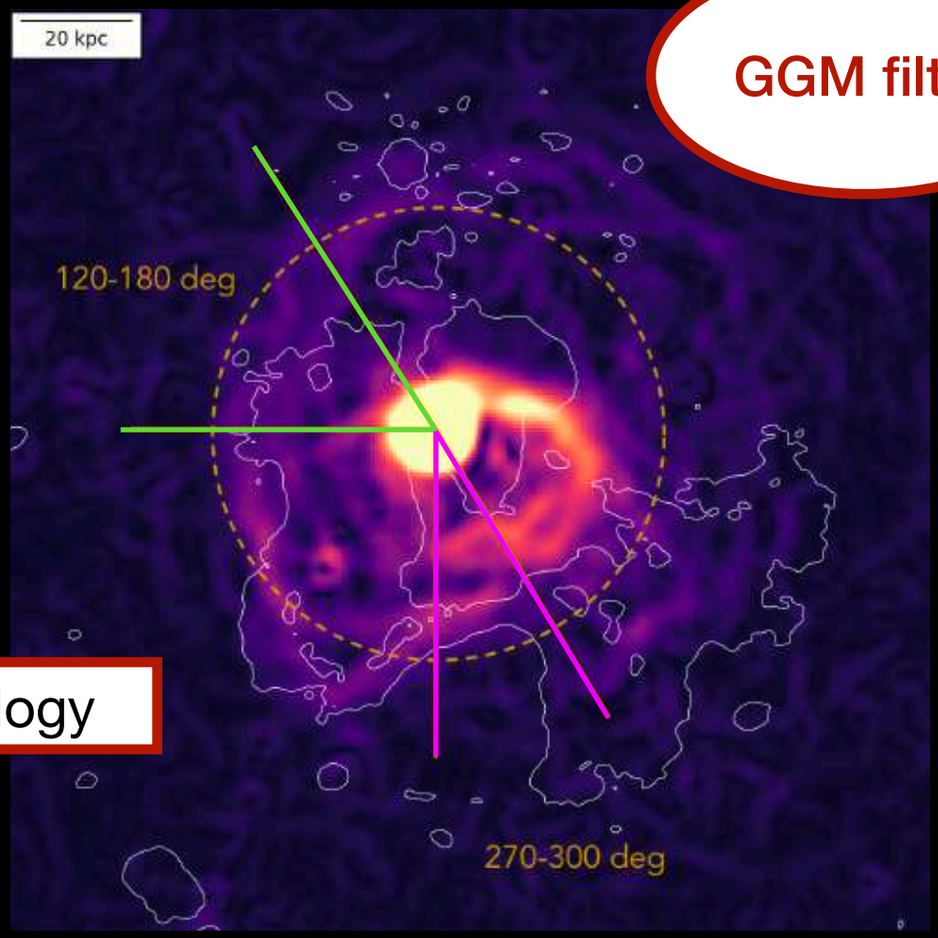
NGC 507: X-ray morphology (XMM 0.5-02 keV)

β-model residual



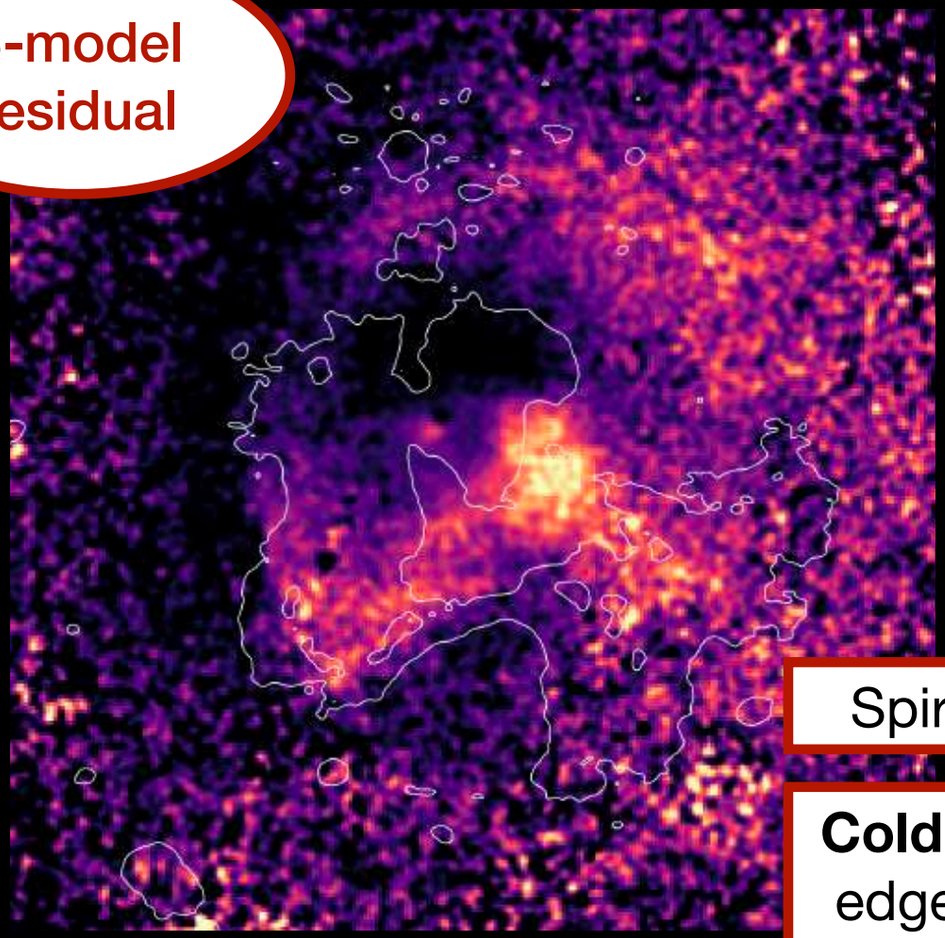
Spiral morphology

GGM filter

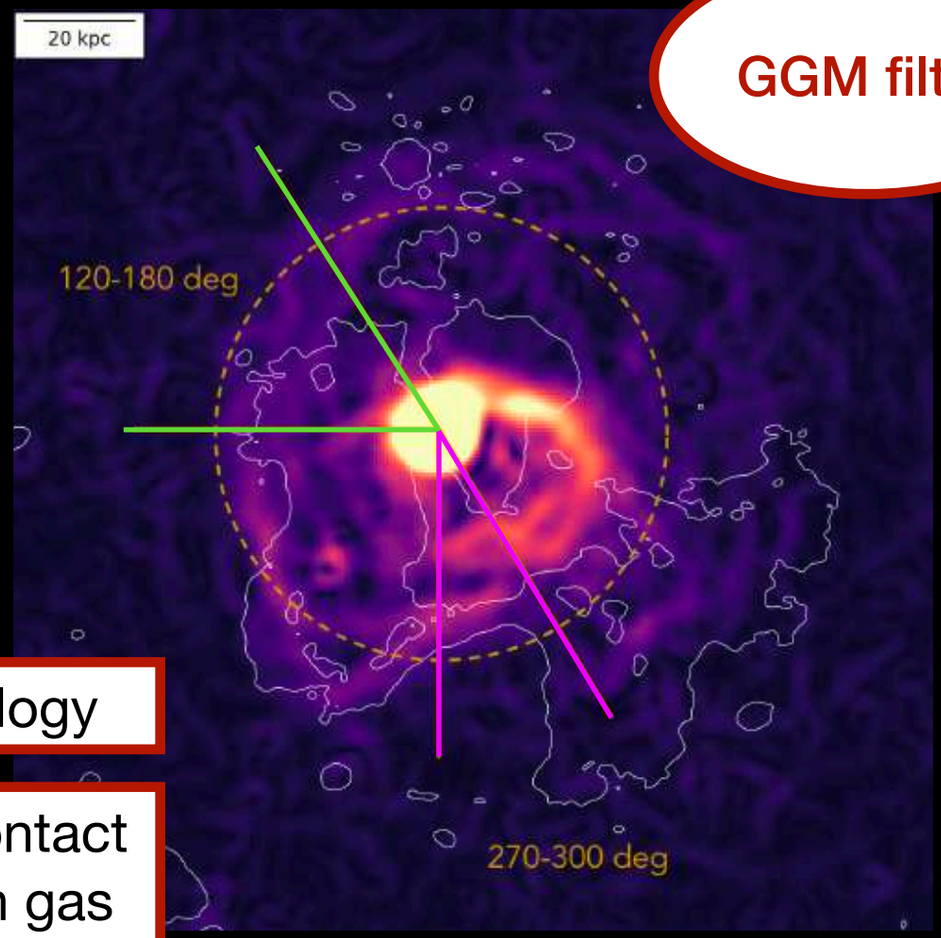


NGC 507: X-ray morphology (XMM 0.5-02 keV)

β-model residual

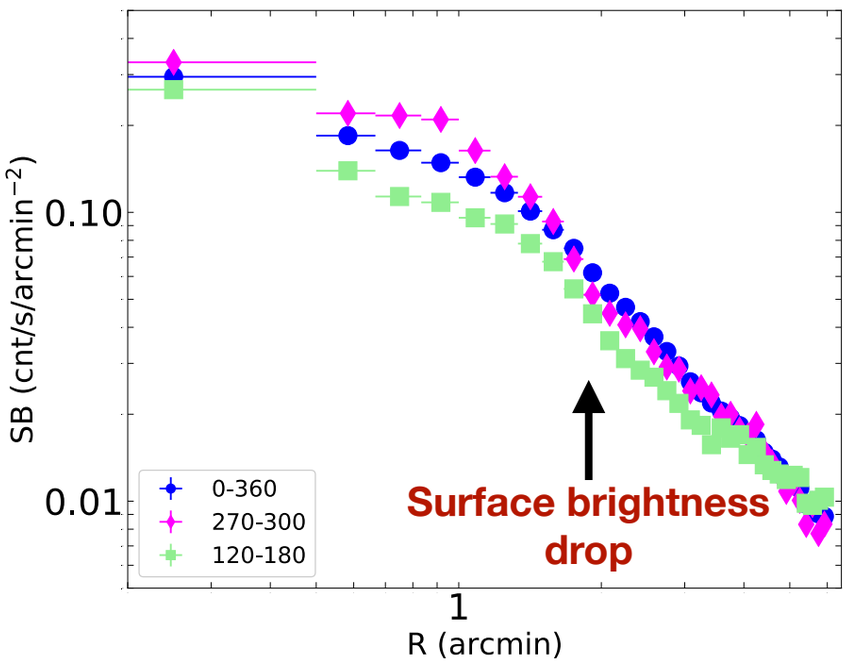


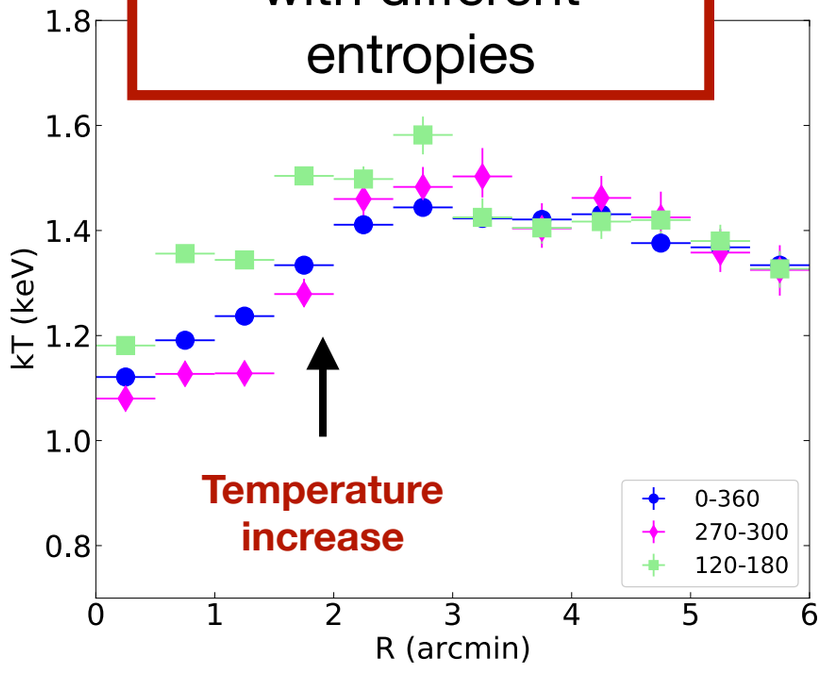
GGM filter

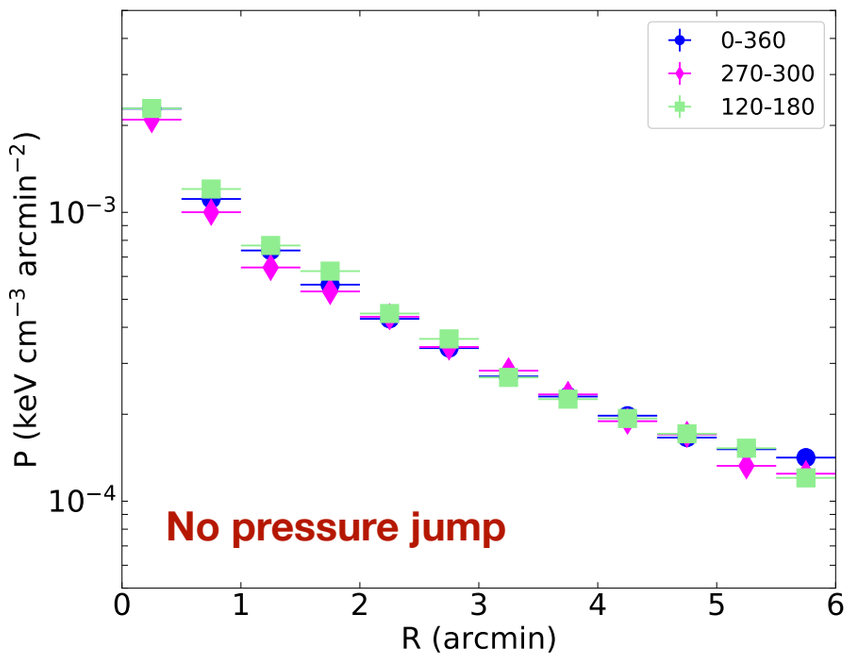


Spiral morphology

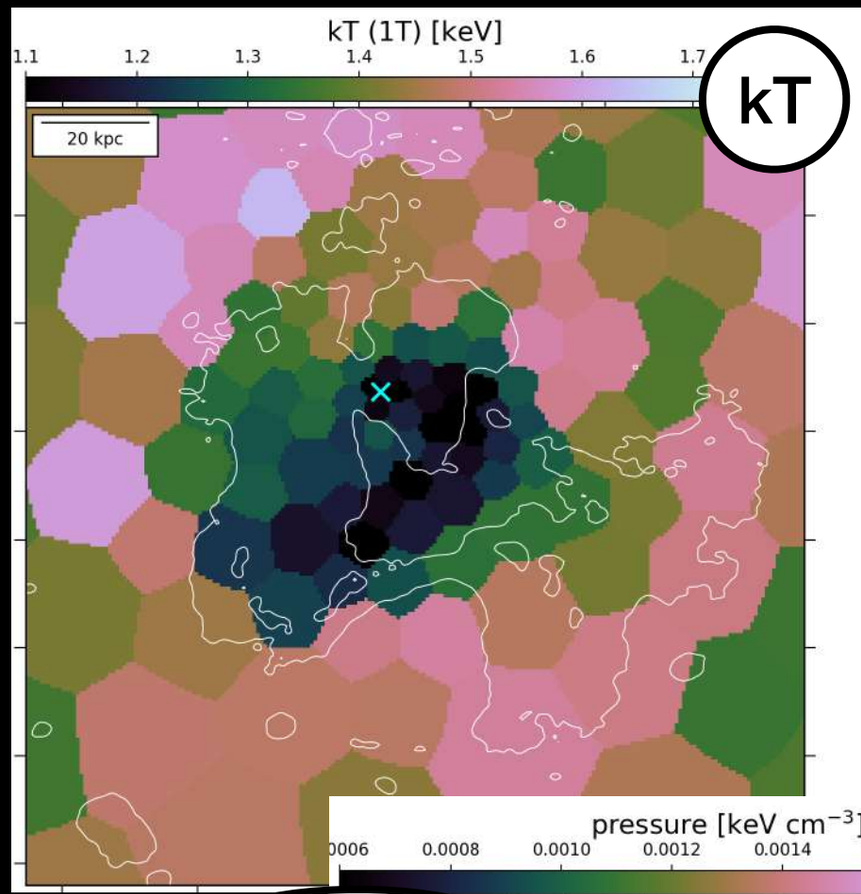
Cold fronts=contact edges between gas with different entropies



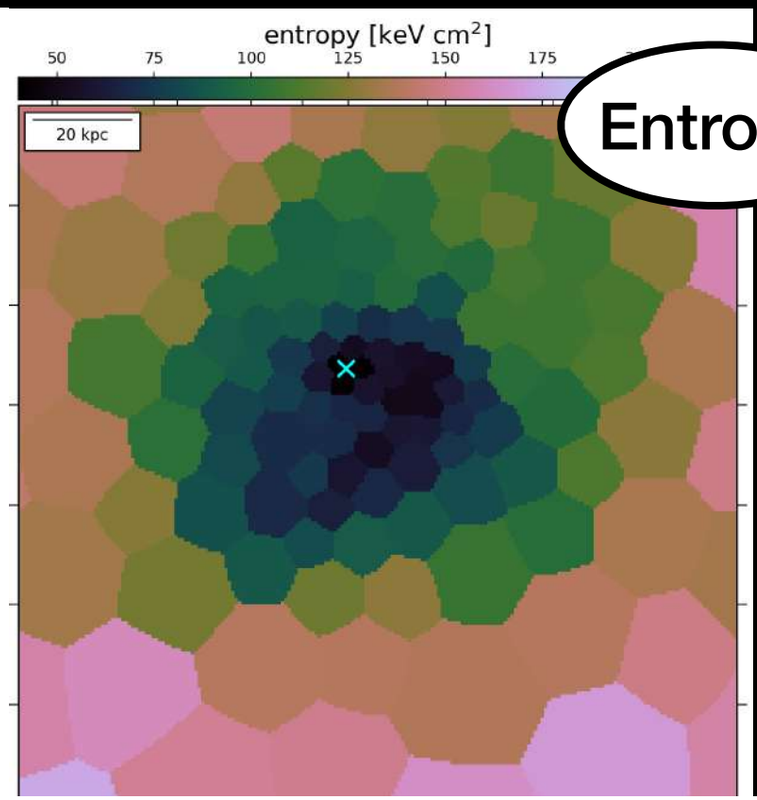




NGC 507: X-ray spectral maps



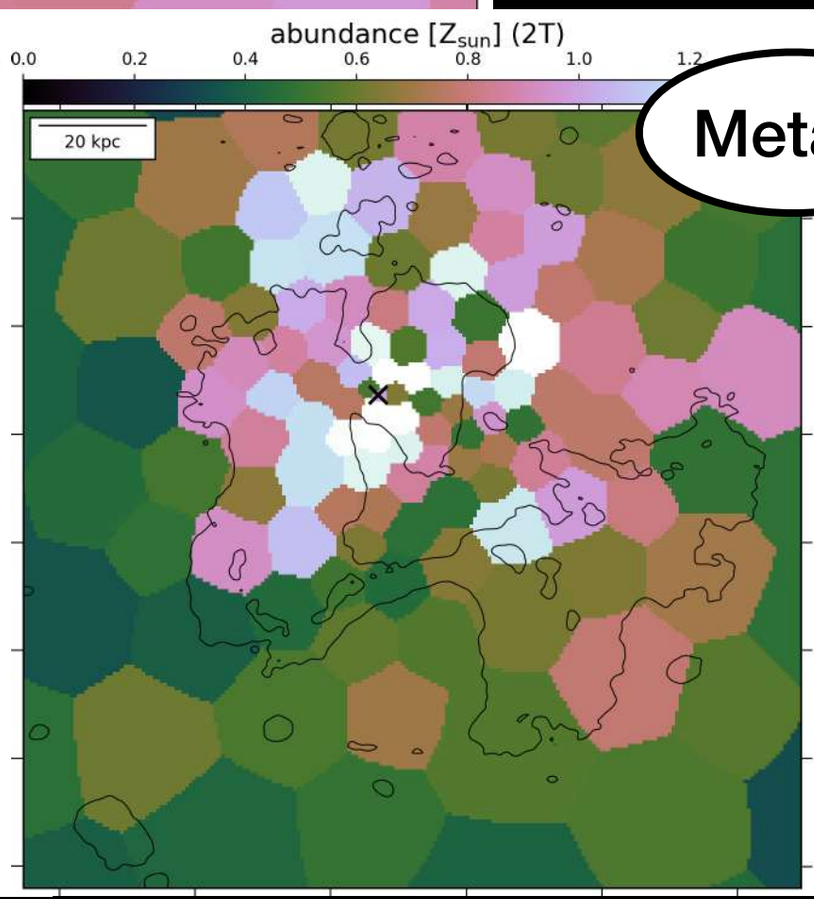
kT



Entropy

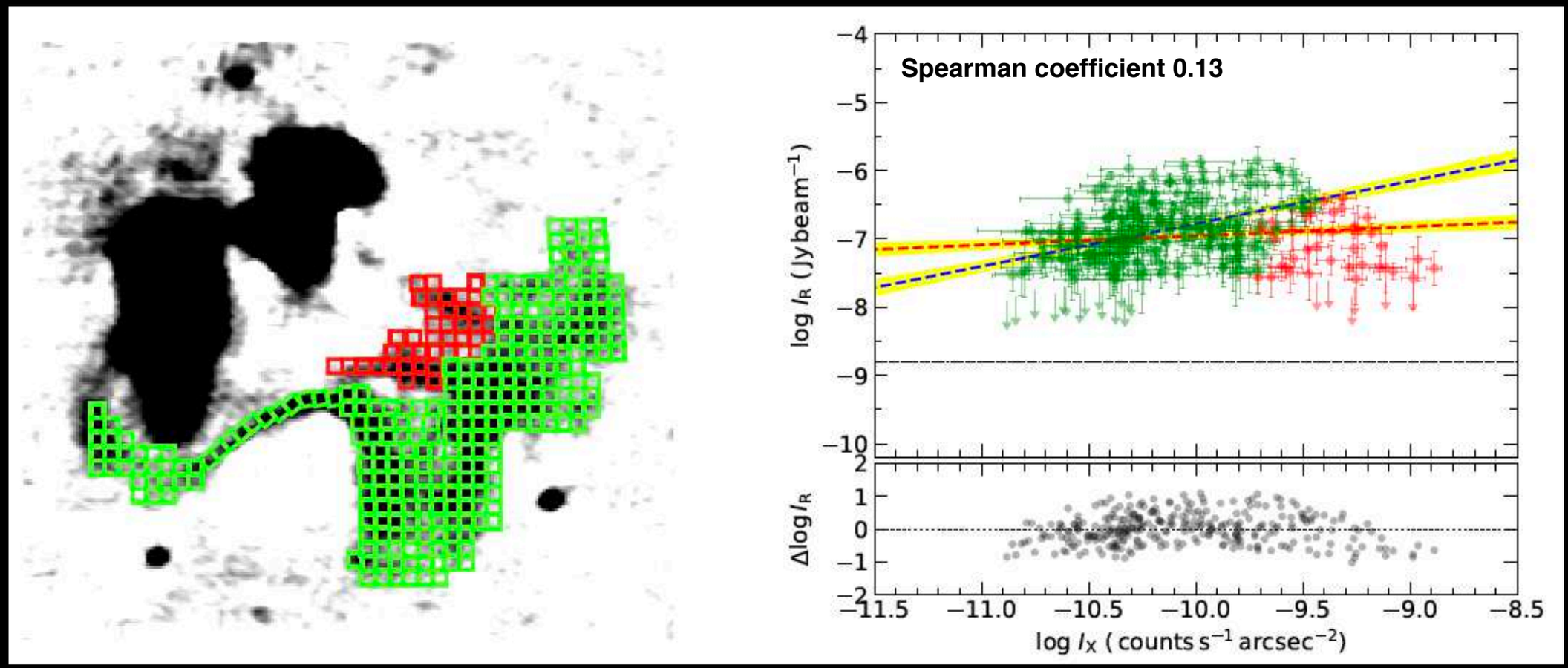
- Asymmetrical distribution
- Spiral pattern in entropy and T
- Temperature discontinuities
- Not unusual abundance front!

Pressure



Metals

NGC 507: X-ray vs radio correlation

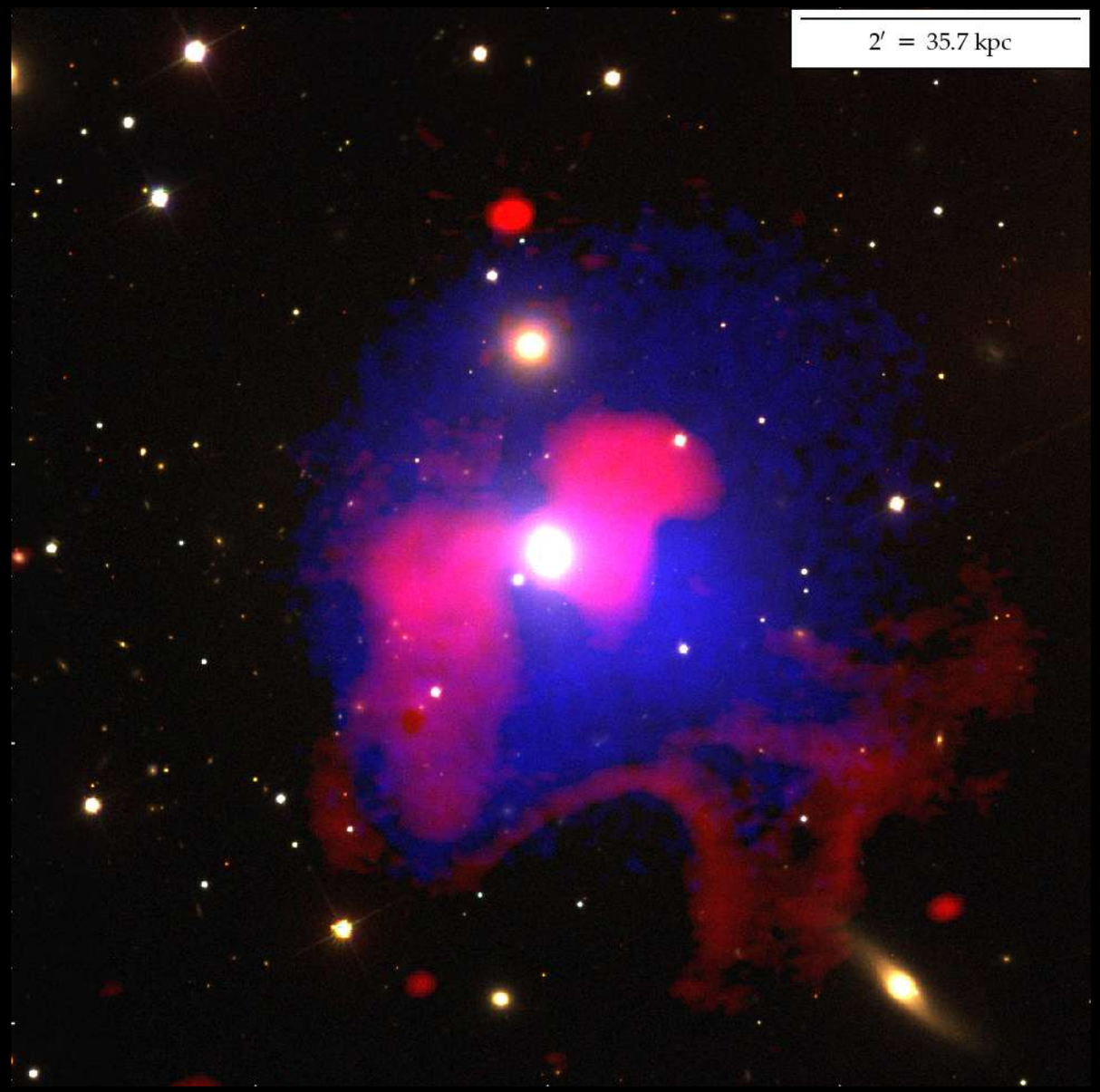


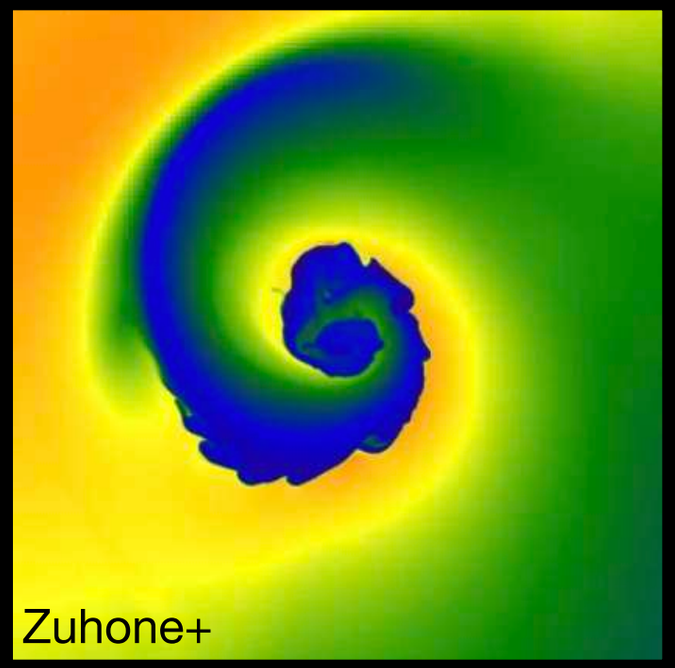
No correlation = non-thermal plasma still not mixed up with external medium

Correlation typically observed in the case of halos and mini-halos in galaxy clusters

e.g. Ignesti+20, Rajpurohit+

NGC 507: interpretation

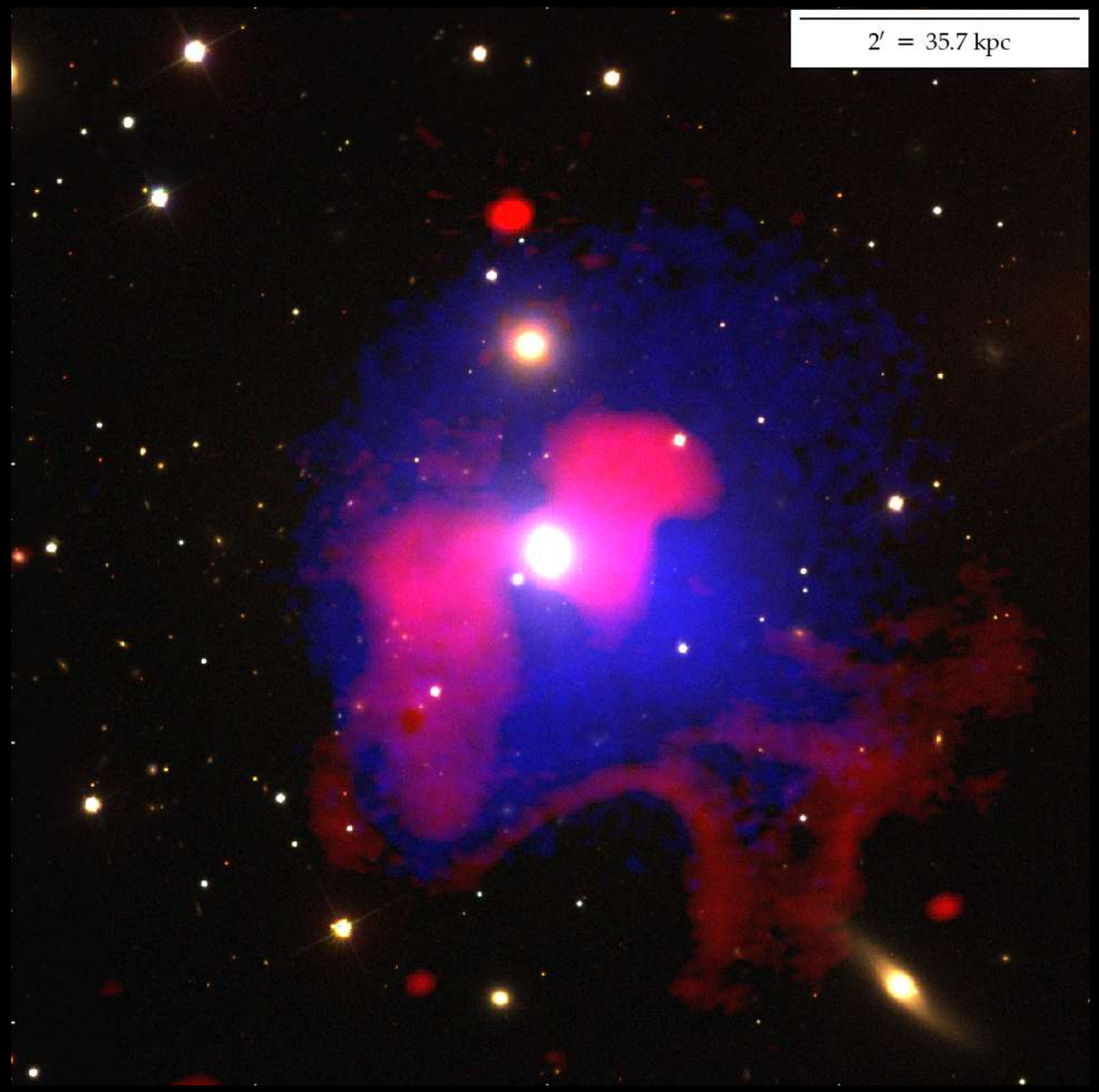




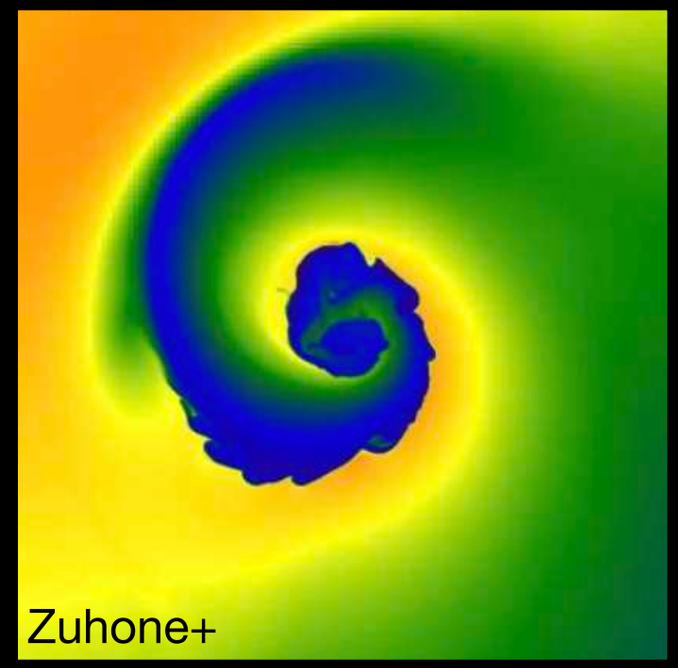
Remnant AGN plasma transported by **SLOSHING** motions during its buoyant rise in the group atmosphere,
still not mixed with the IGrM (with perturber in the plane of the sky
e.g. Roediger et al. 2011)

Timescales
Sloshing ~145 Myr
vs
Remnant plasma ~300 Myr

NGC 507: interpretation



NGC 5044 (Gastaldello et al. 2013; O'Sullivan et al. 2014) NGC 5098 (Randall et al. 2009) NGC 5846 (Machacek et al. 2011; Gastaldello et al. 2013) **IC 1860** (Gastaldello et al. 2013) NGC 7618 (Roediger et al. 2012, Sheardown et al. 2019) NGC 1550 (Kolokythas et al. 2020)



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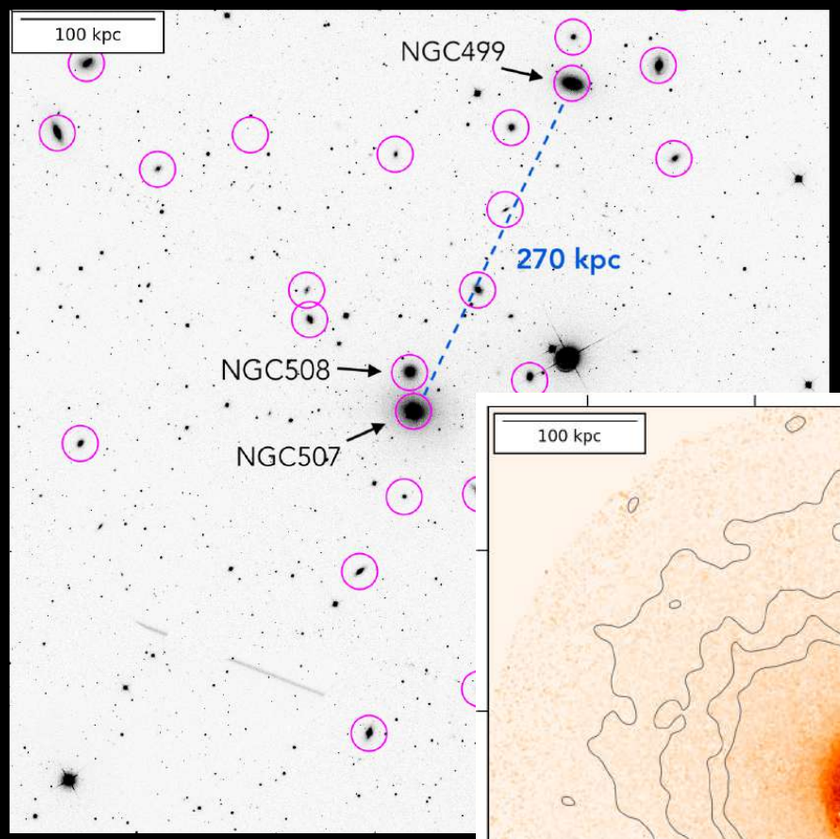
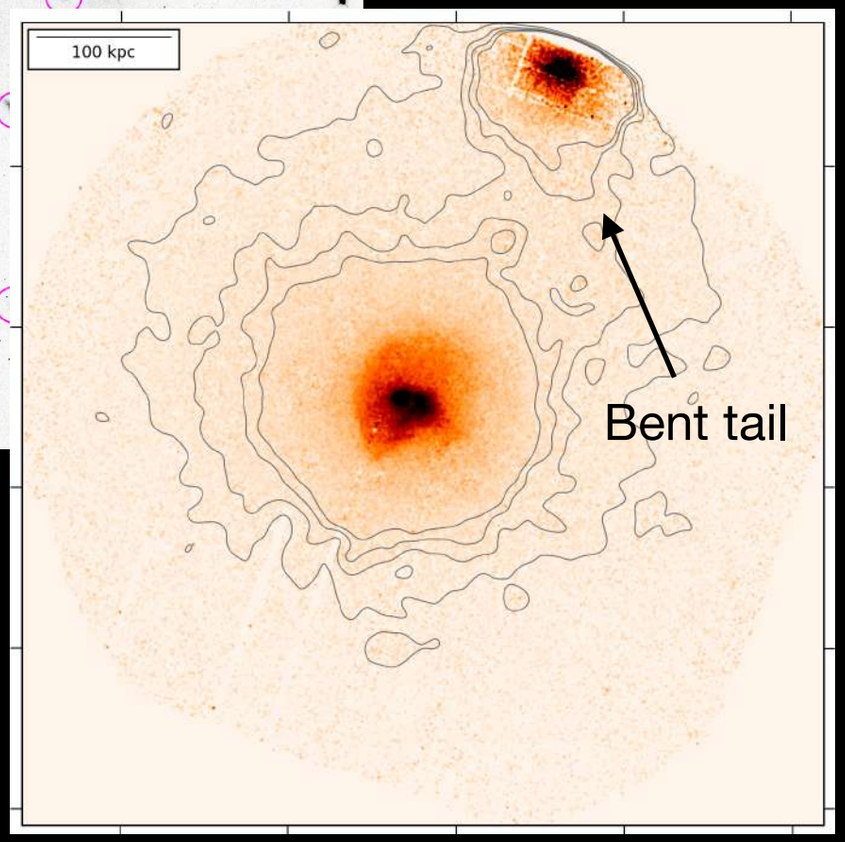
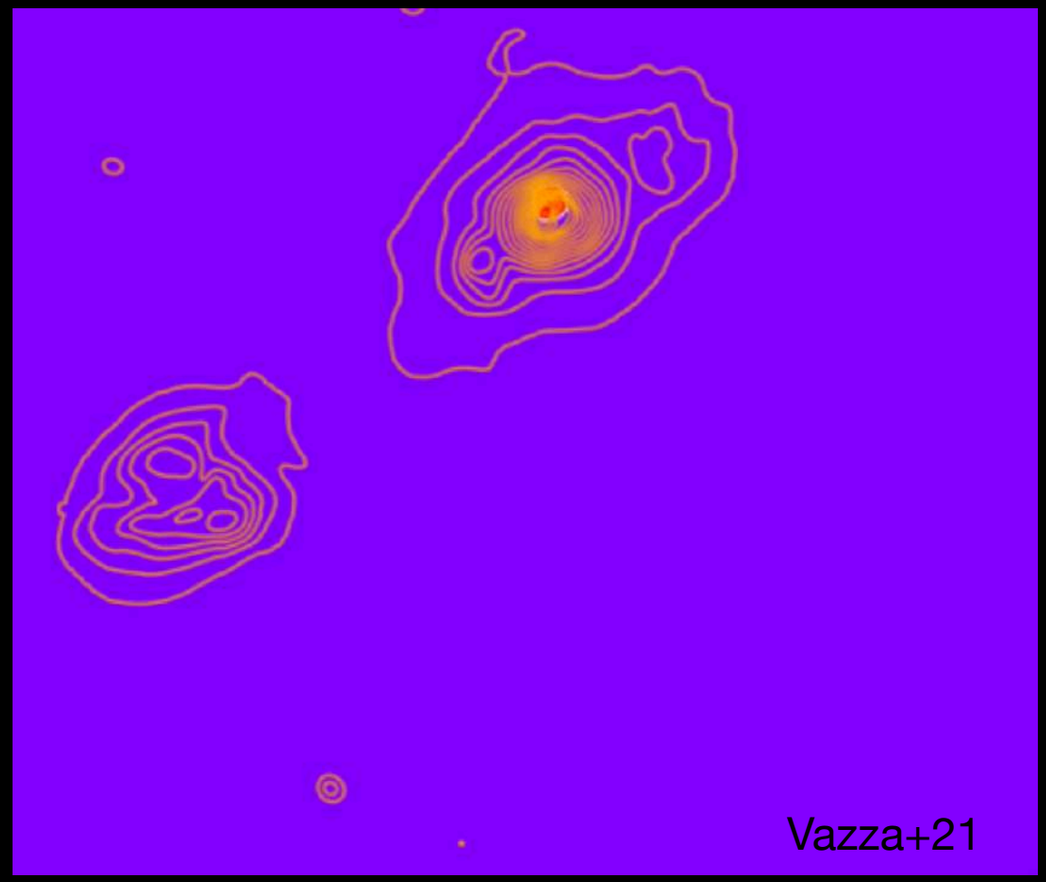
NGC 507: interpretation

Sloshing perturber?
NGC 499 - low mag difference
NGC 508 - extended tails of X-ray emission (Jeltema+2008)





Arc-shape non thermal filament and X-ray discontinuity?



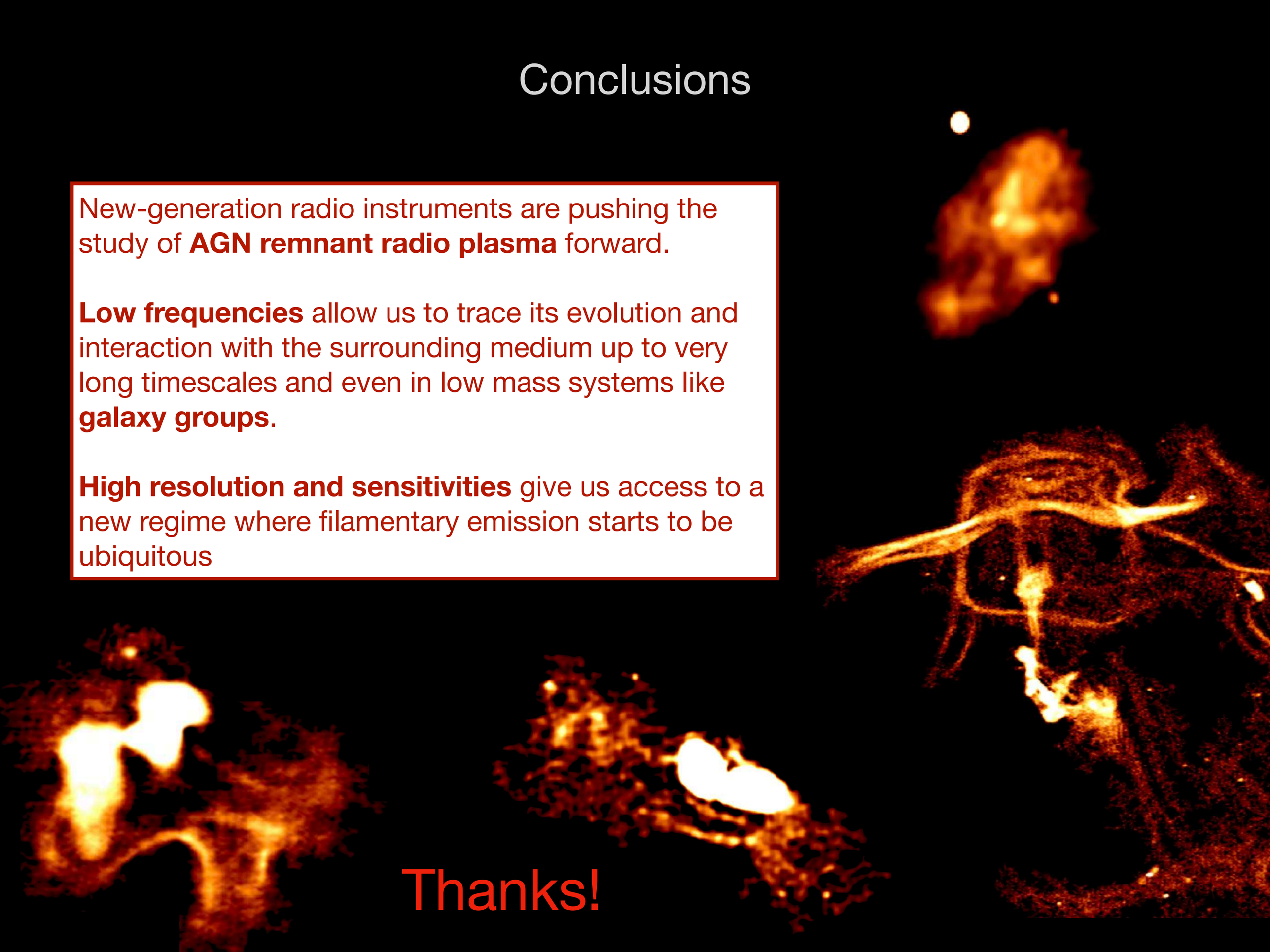
Filament likely created by particles accumulated following velocity fluctuations of IGrM after minor interaction.

Conclusions

New-generation radio instruments are pushing the study of **AGN remnant radio plasma** forward.

Low frequencies allow us to trace its evolution and interaction with the surrounding medium up to very long timescales and even in low mass systems like **galaxy groups**.

High resolution and sensitivities give us access to a new regime where filamentary emission starts to be ubiquitous



Thanks!