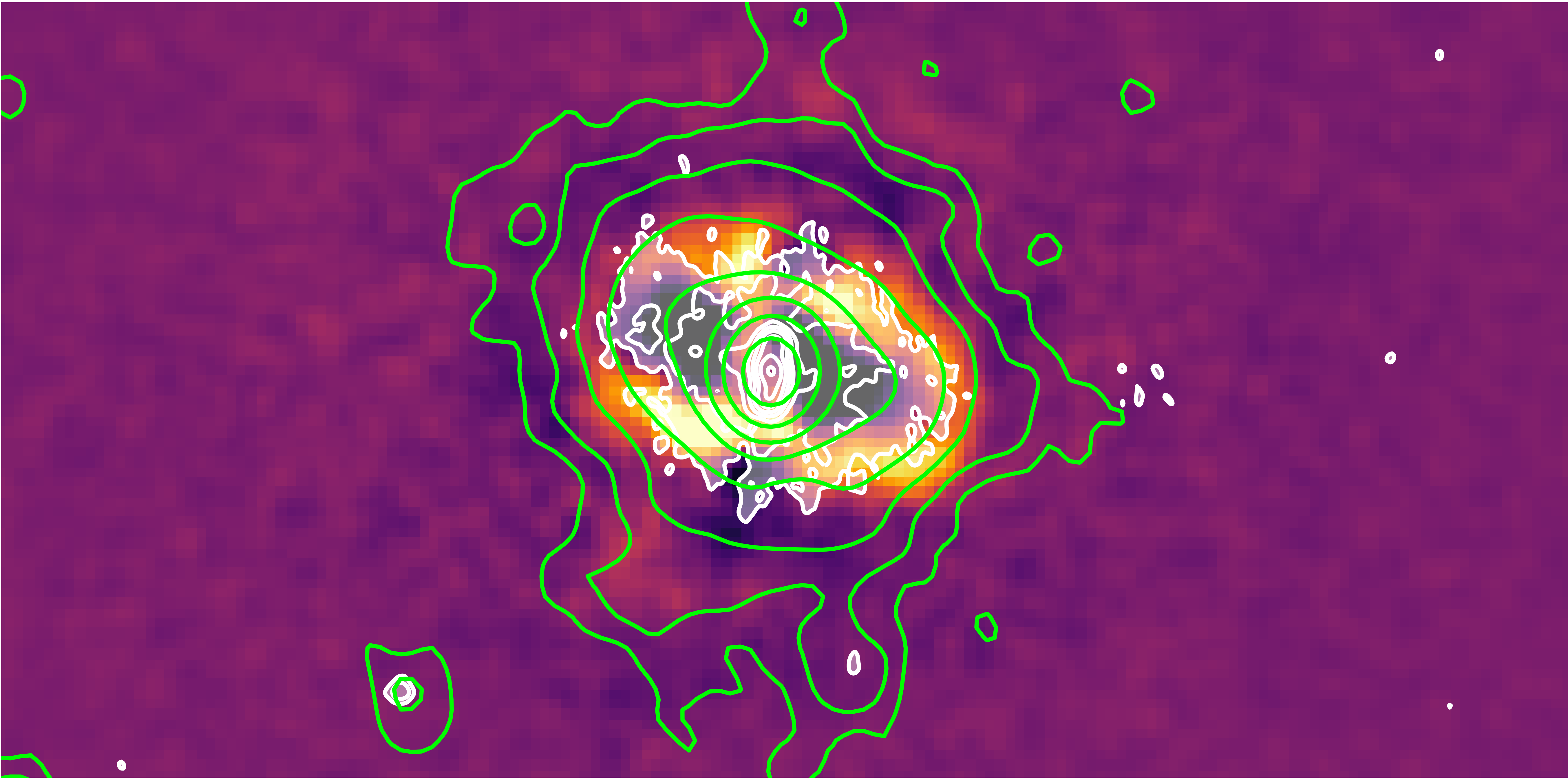
AGN FEEDBACK IN THE MOST MASSIVE STRUCTURES

THE SKA PERSPECTIVE ON HOW RADIO JETS HEAT GALAXY GROUPS AND CLUSTERS



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INAF ISTITUTO NAZIONALE DI ASTROFISICA

Finanziato dall'Unione europea NextGenerationEU

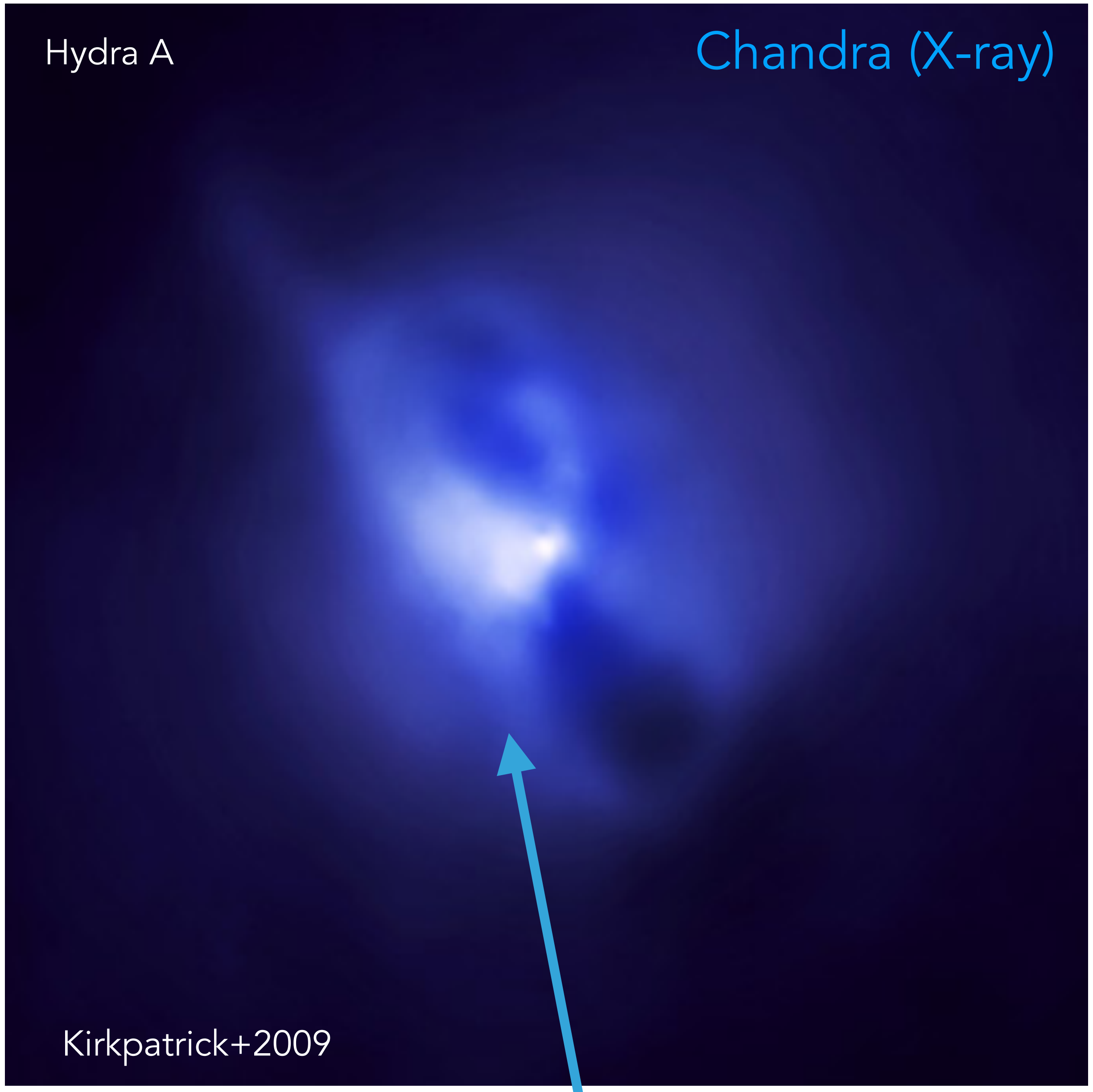
Ministero dell'Università e della Ricerca

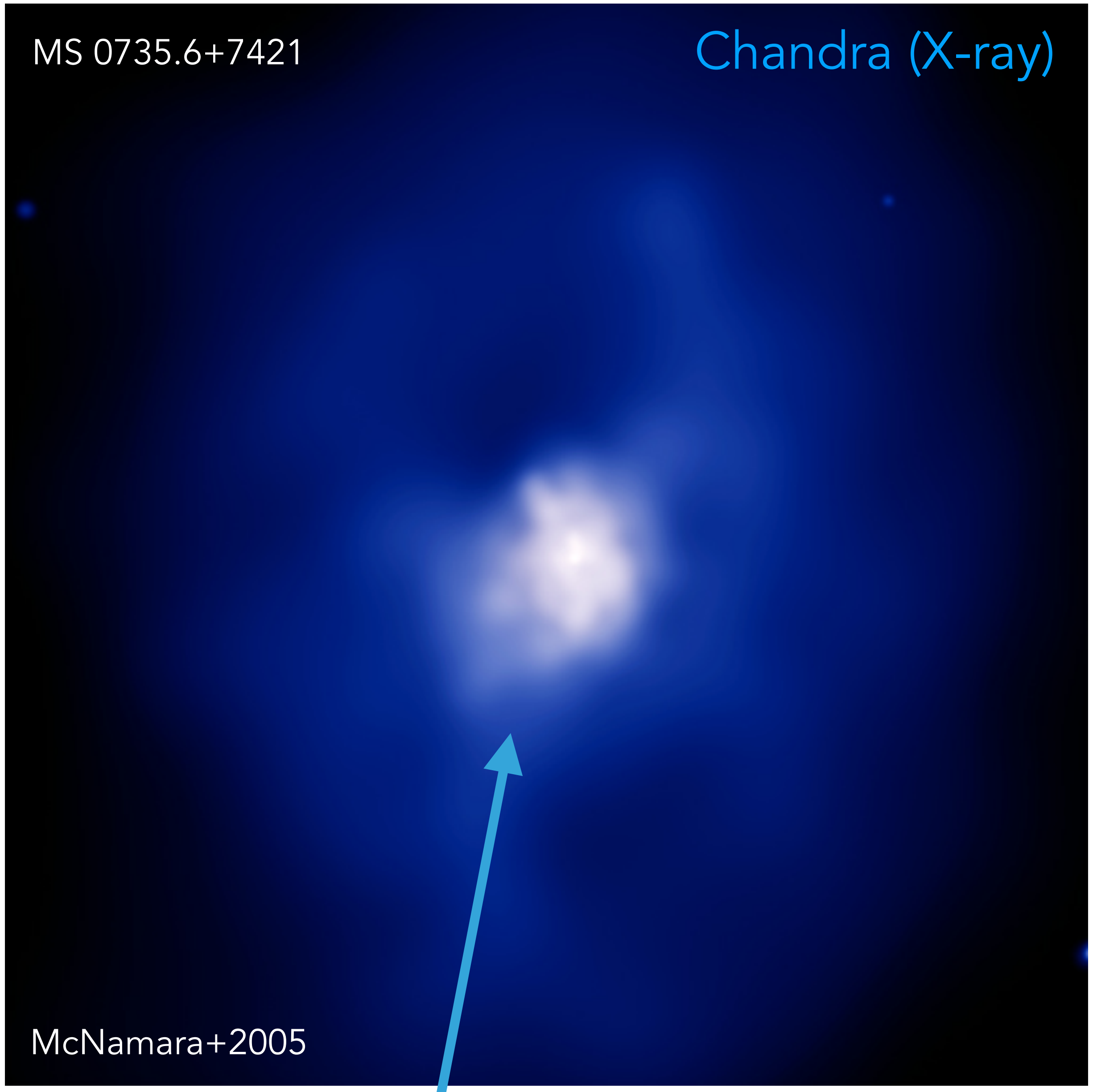
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

INAF ISTITUTO NAZIONALE DI ASTROFISICA

AGN Feedback in Galaxy Clusters

Introduction



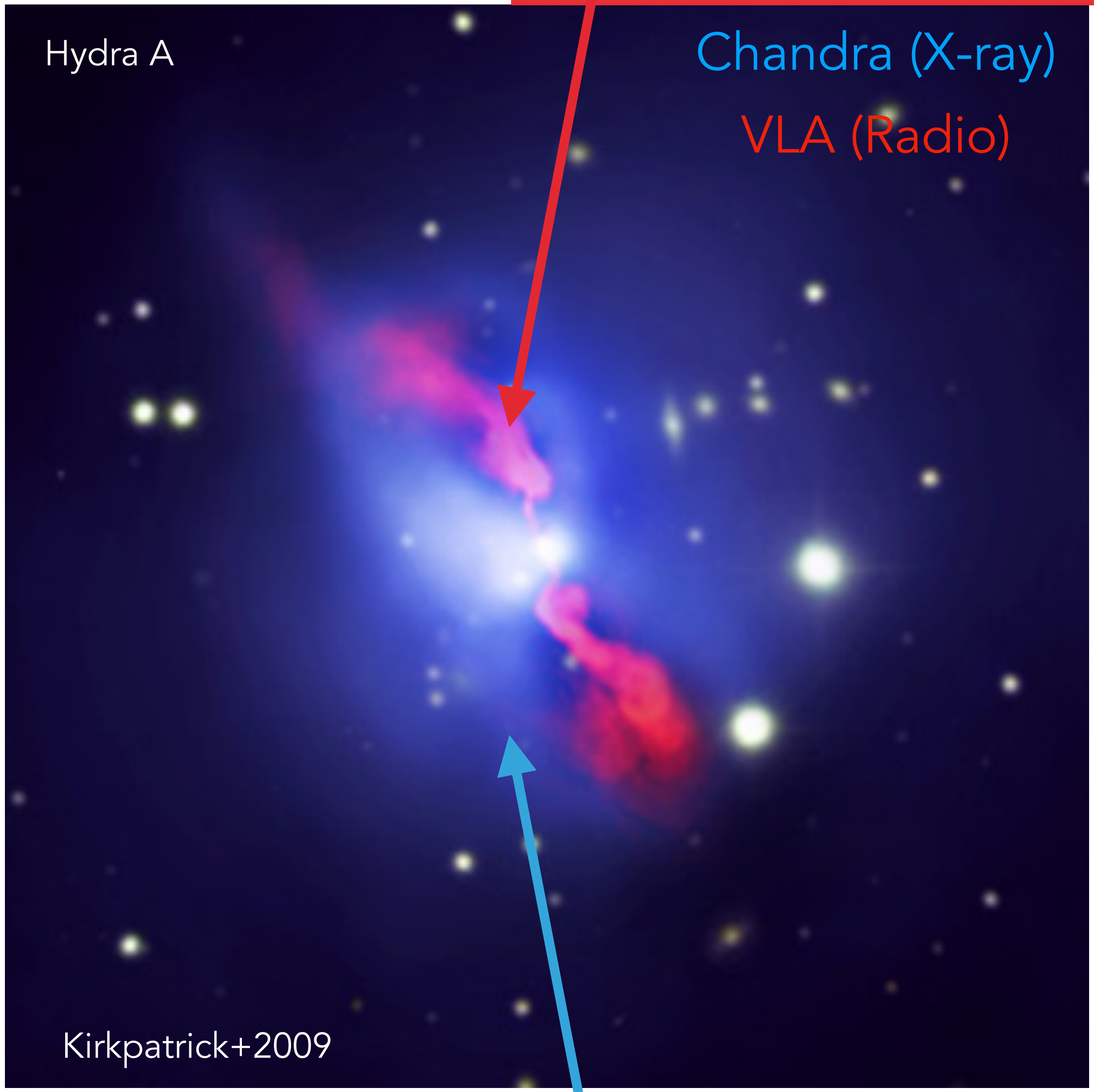


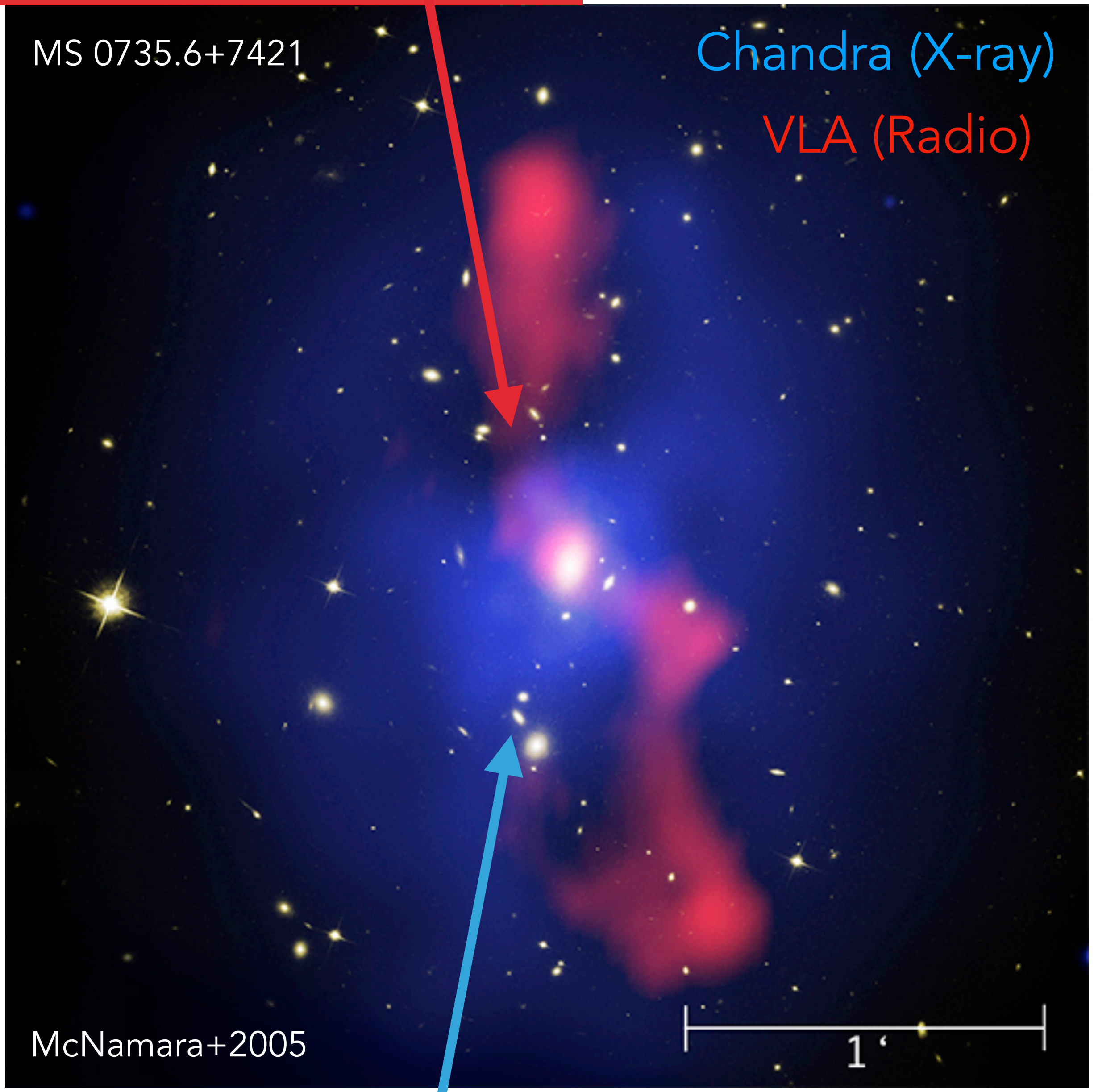
Cooling of the intracluster medium

AGN Feedback in Galaxy Clusters

Introduction

Heating the gas with relativistic jets



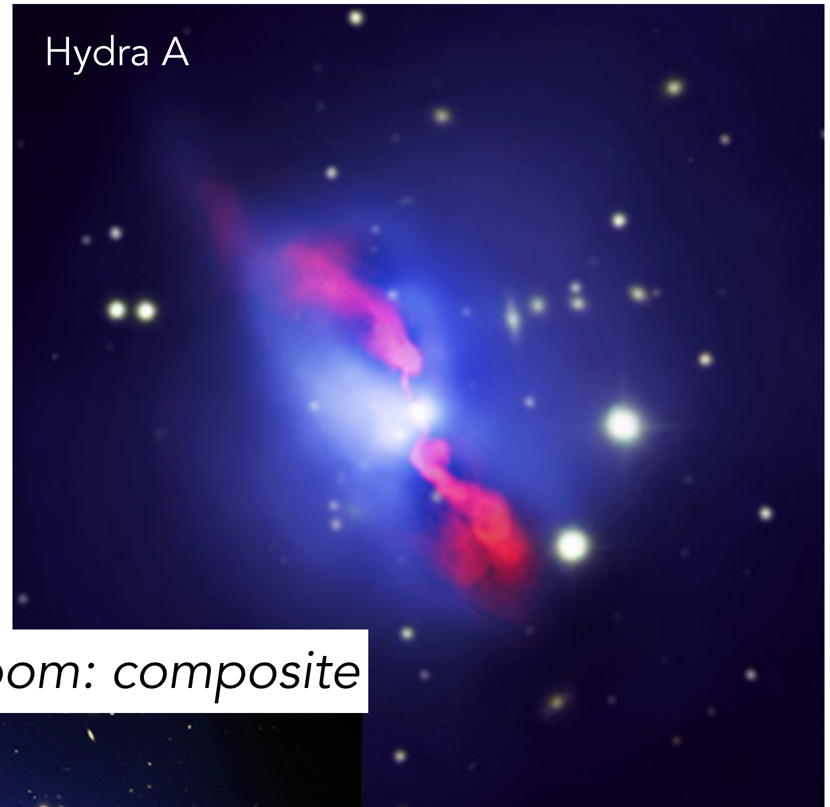


Cooling of the intracluster medium

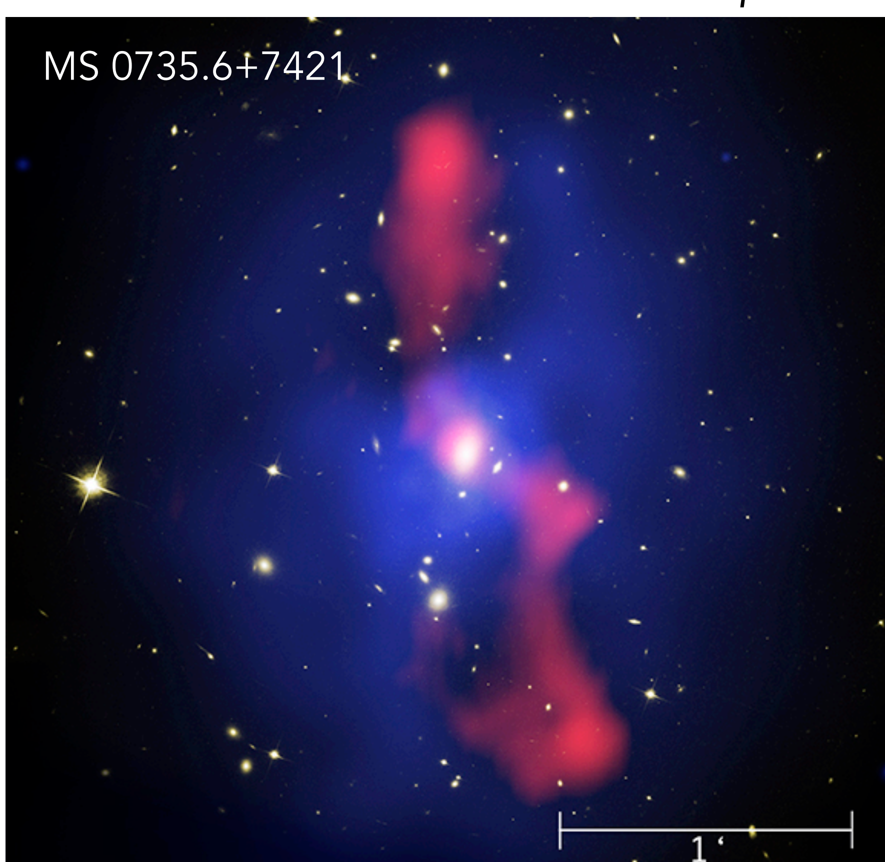
AGN Feedback in Galaxy Clusters

Introduction

e.g. Tozzi+01, Voit+05, Pratt+06, Iqbal+17, Babyk+18, Zhu+21, Donahue&Voit 22, McNamara & Nulsen 2007, 2012; Gitti+2012; Fabian+2012; Eckert+2021



Credits: CXC Press Room: composite



Understanding AGN feedback in massive structures

Physics of relativistic jets and black holes

$$P_{jet} \propto B_{acc} \times a_s \times M_{BH}$$

(Blandford & Znajek 1977)

BH - Galaxy - Environment coevolution

$$P_{jet} \propto L_{ICM}$$

$$\propto \dot{M}_{cool}$$

(e.g., McNamara&Nulsen 2007)

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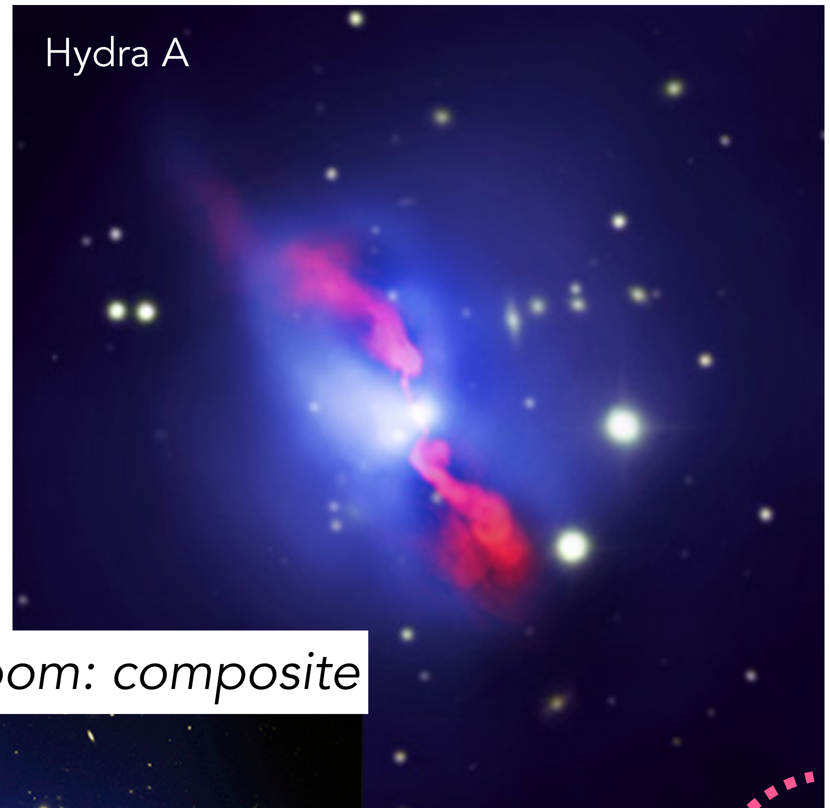

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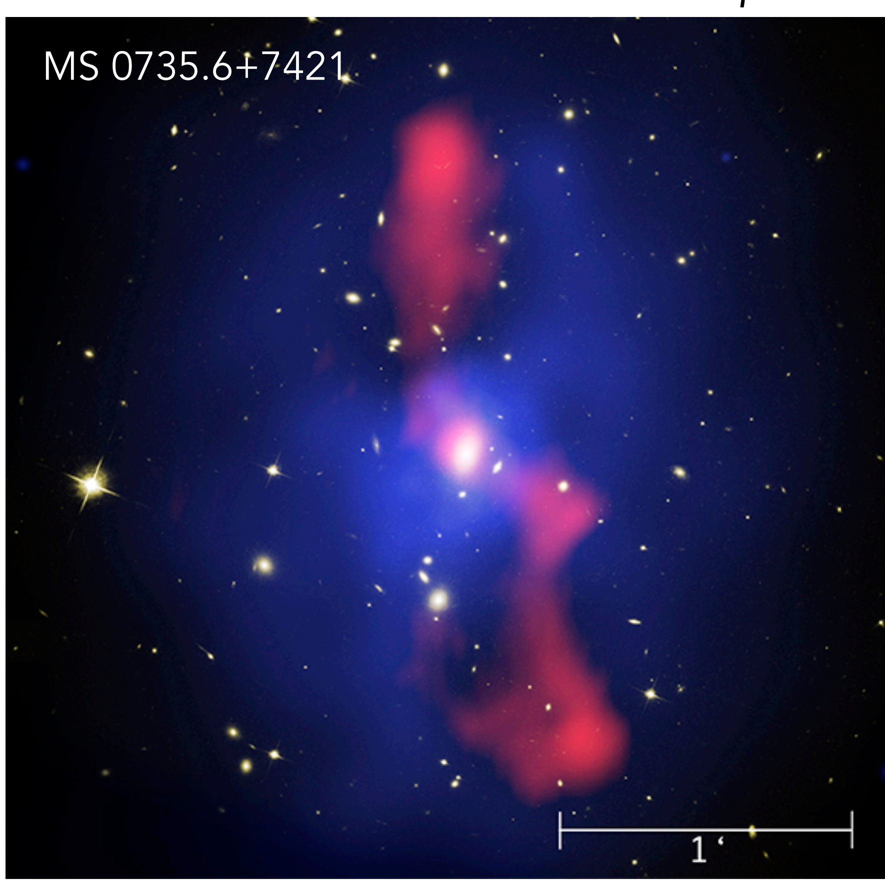

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$\propto \dot{M}_{cool}$

(e.g., McNamara&Nulsen 2007)

A WIDE RANGE OF SPATIAL SCALES!
Sub-parsec - parsec - kpc - Mpc

AGN Feedback in Galaxy Clusters

How To Connect the Different Scales of AGN Jets?

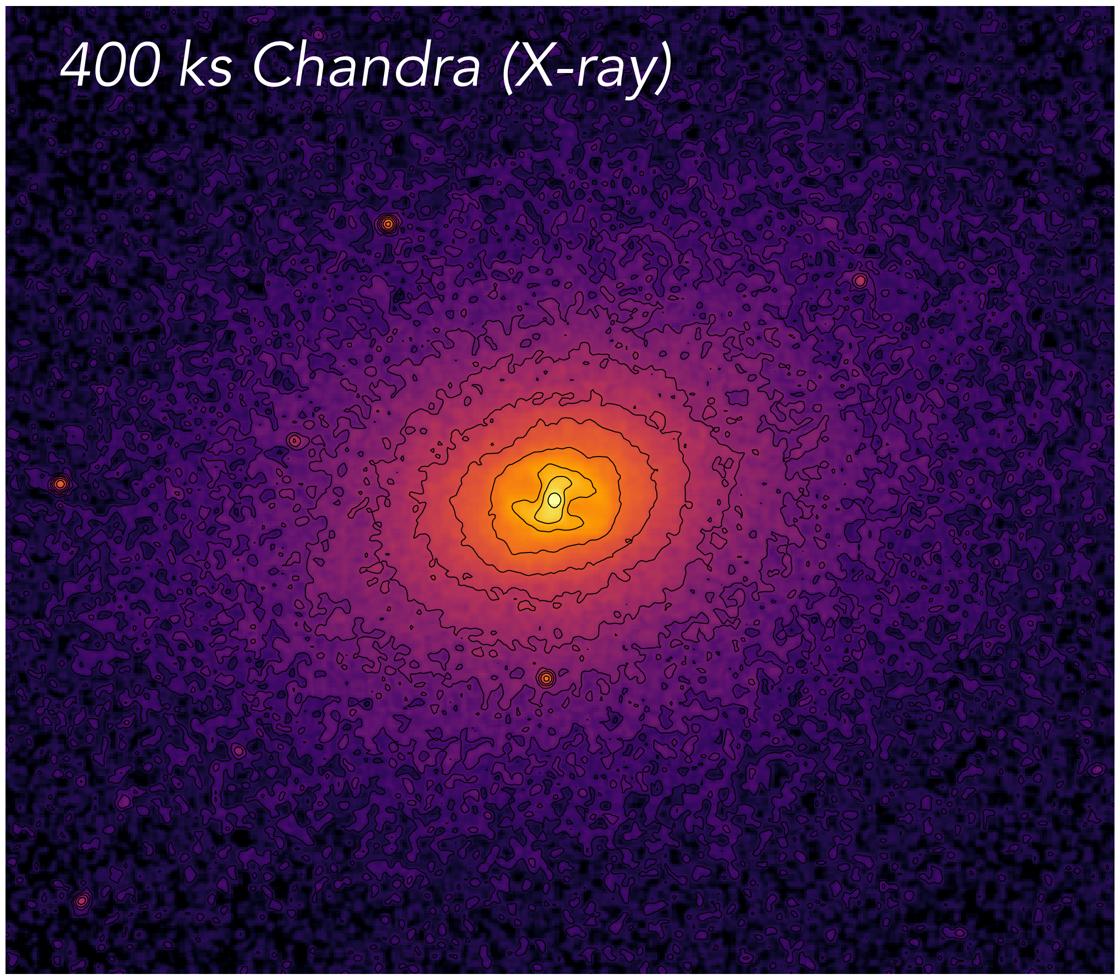
How To Connect the Different Scales of AGN Jets?

We combine several radio telescopes!

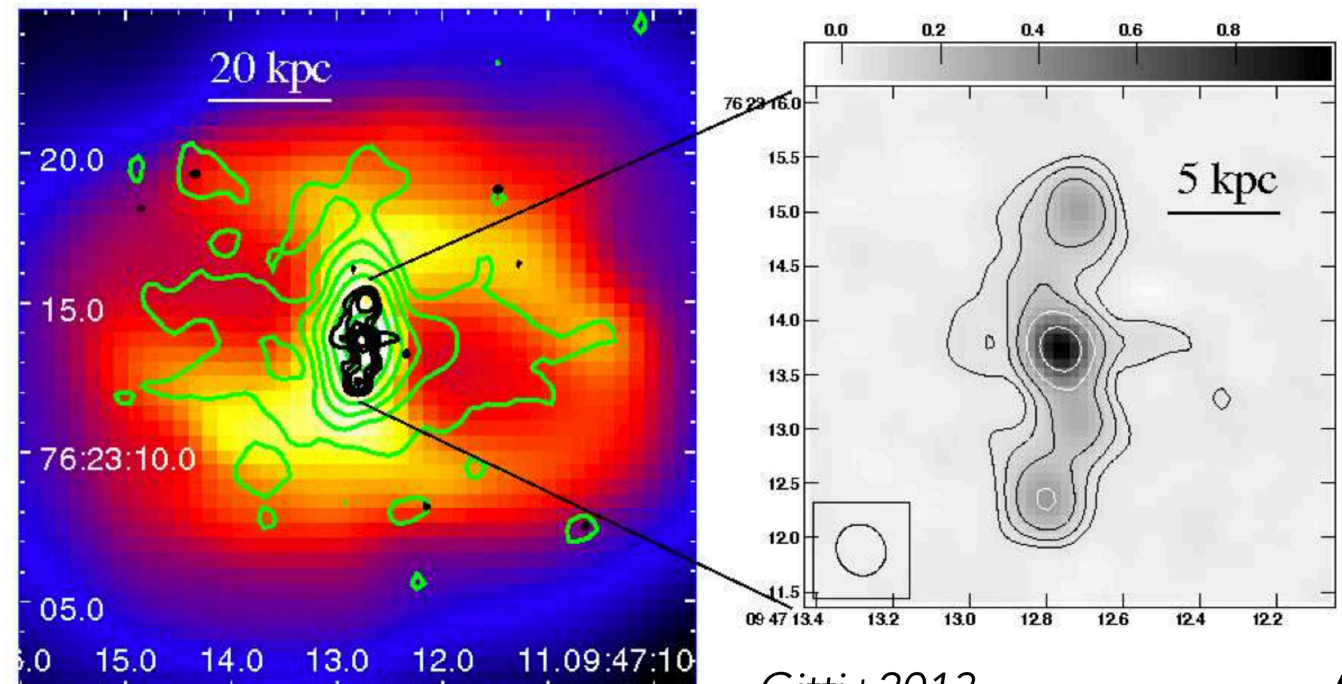
AGN Feedback in Galaxy Clusters

How To Connect the Different Scales of AGN Jets?

AGN feedback in the remarkable cool core cluster RBS 797



VLA (radio)



Gitti+2013

We combine several radio telescopes!

AGN Feedback in Galaxy Clusters

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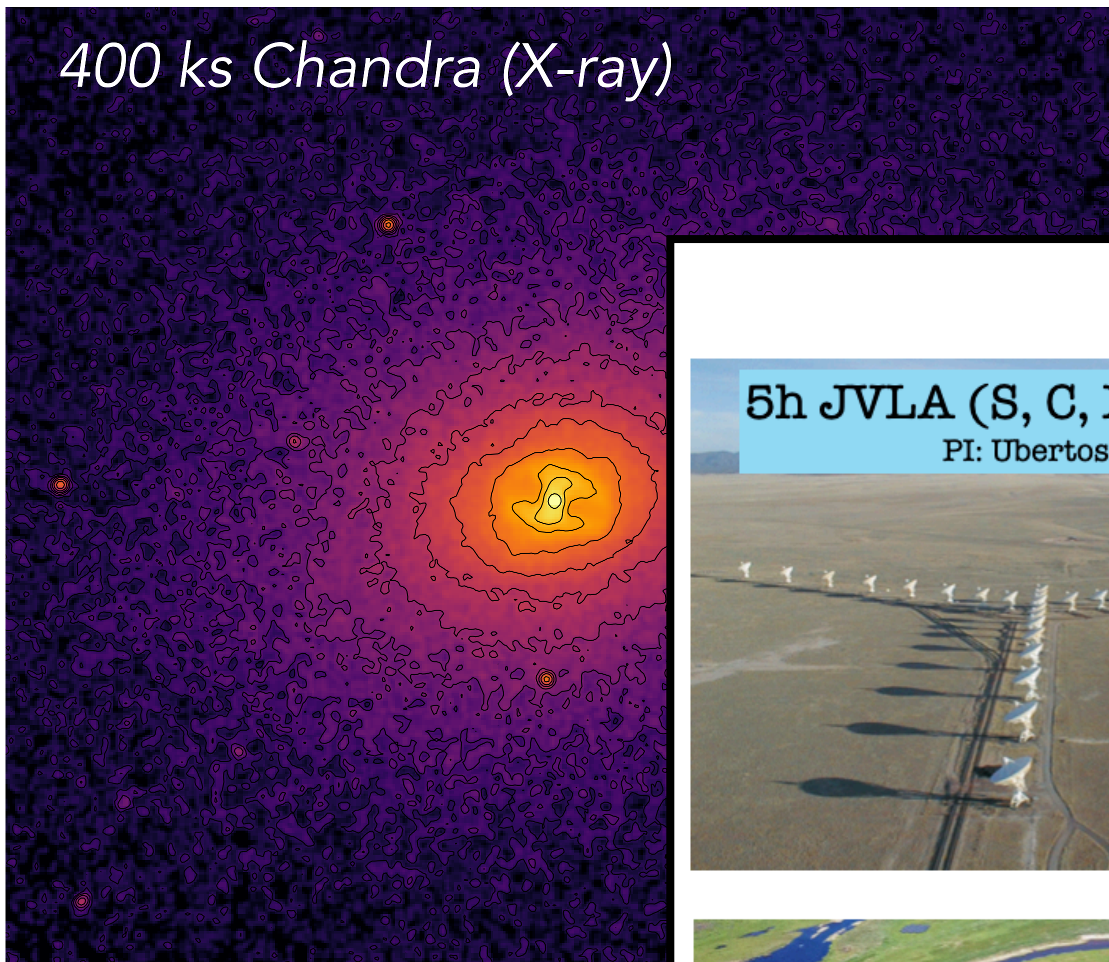

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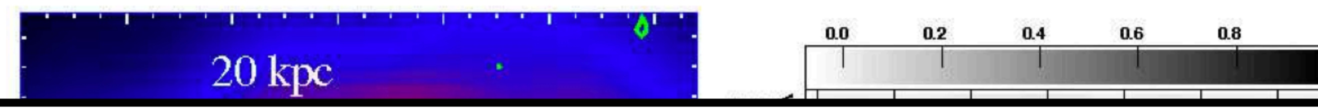

We combine several radio telescopes!

Ubertosi et al. 2021, 2023b, 2024b

AGN Feedback in Galaxy Clusters

How To Connect the Different Scales of AGN Jets?

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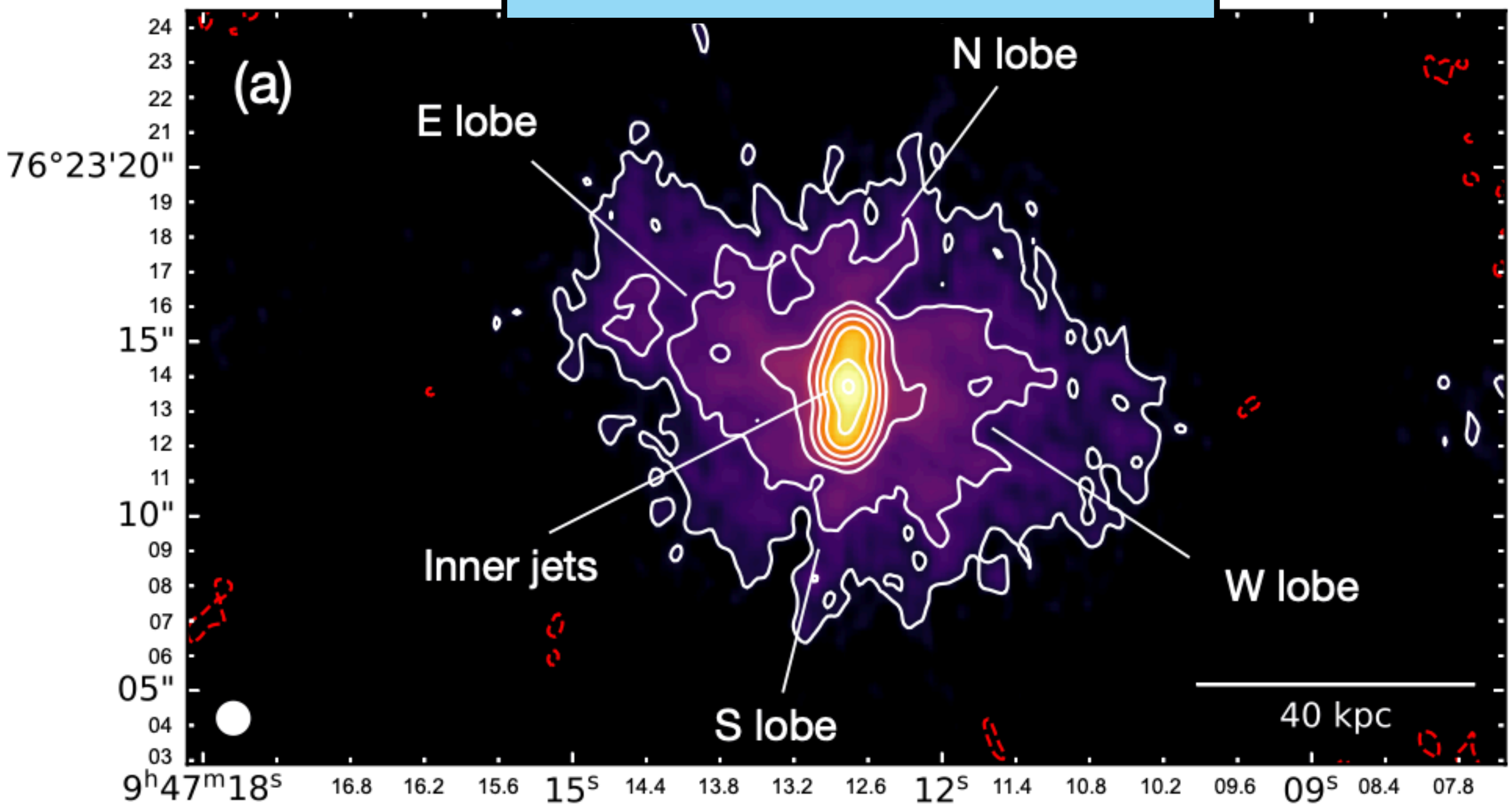
JVLA S band



Ubertosi et al.* *2021*, *2023b*, *2024b

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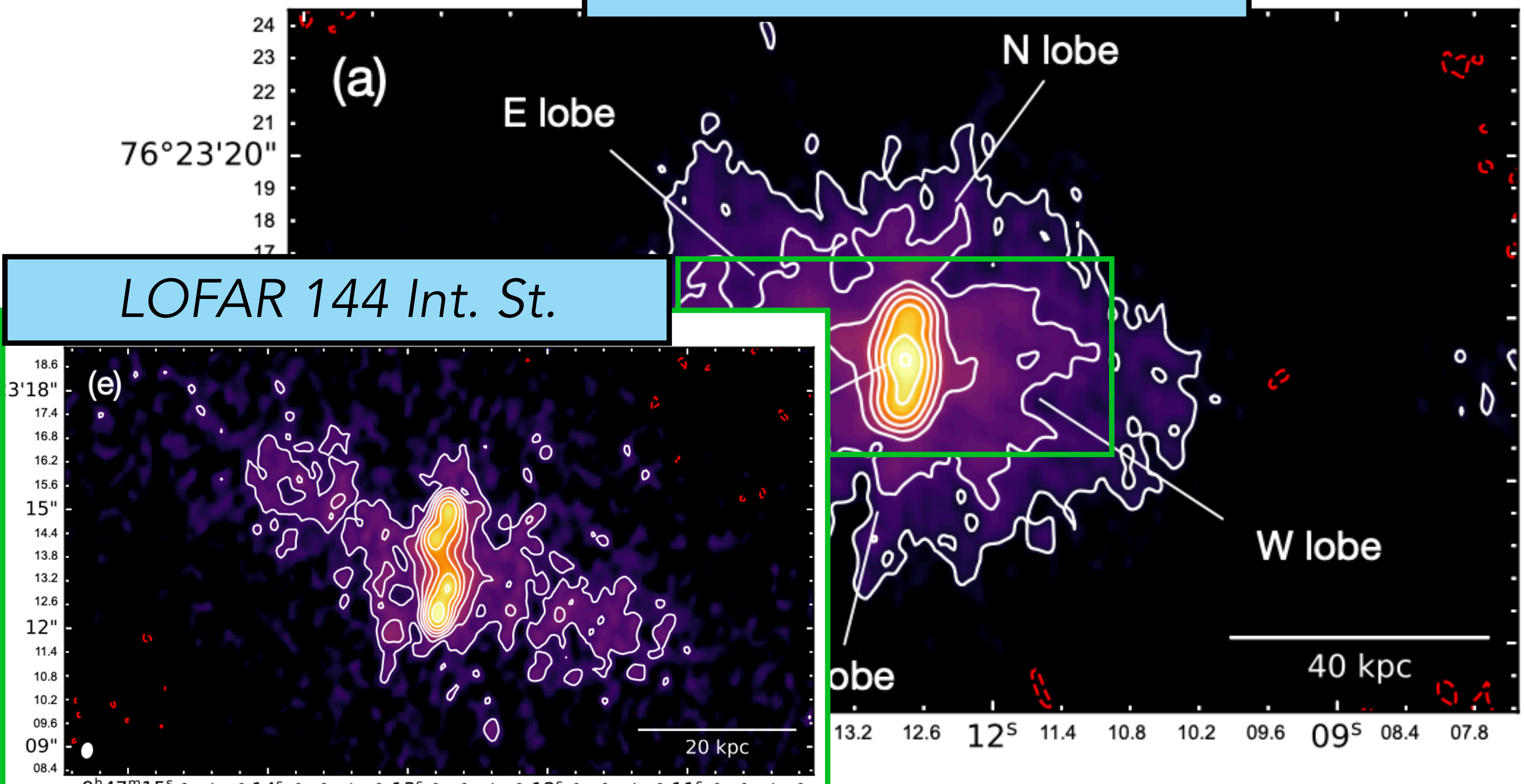
We combine several radio telescopes!

JVLA S band

LOFAR 144 Int. St.

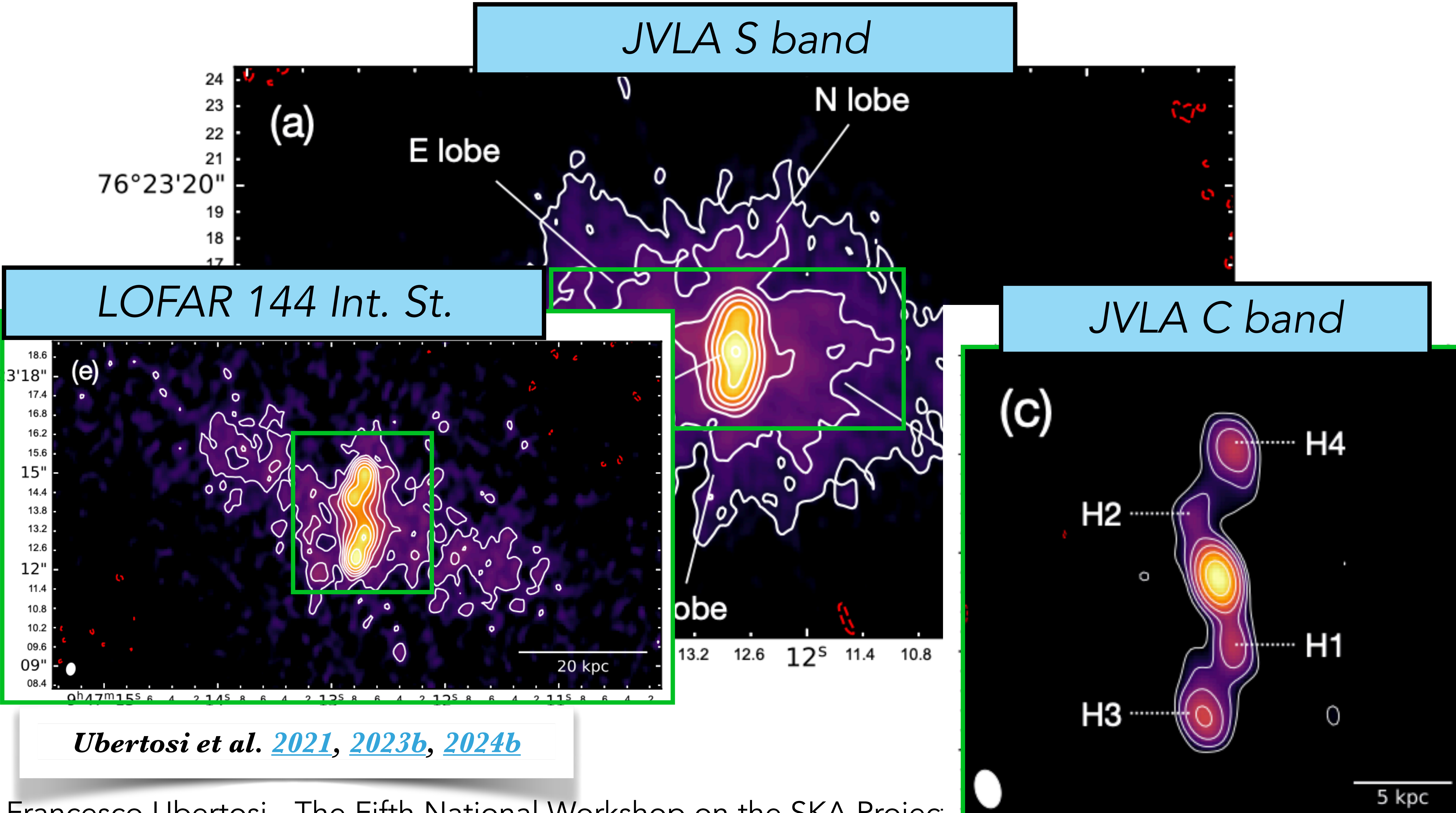


Ubertosi et al. 2021, 2023b, 2024b

AGN Feedback in Galaxy Clusters

How To Connect the Different Scales of AGN Jets?

We combine several radio telescopes!



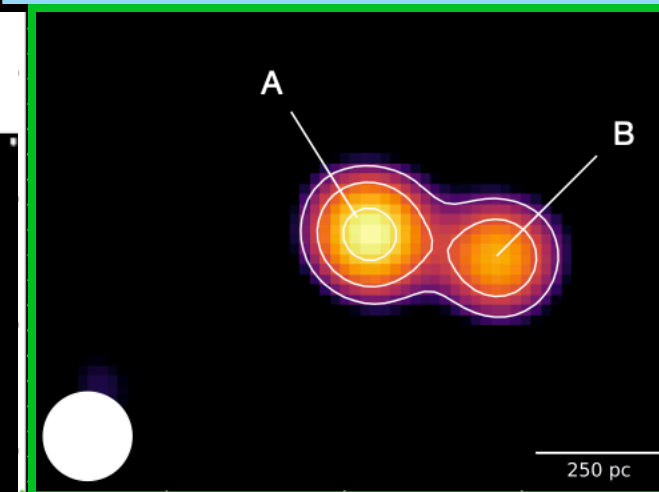
***Ubertosi et al.* 2021, 2023b, 2024b**

AGN Feedback in Galaxy Clusters

How To Connect the Different Scales of AGN Jets?

We combine several radio teles

e-MERLIN C band



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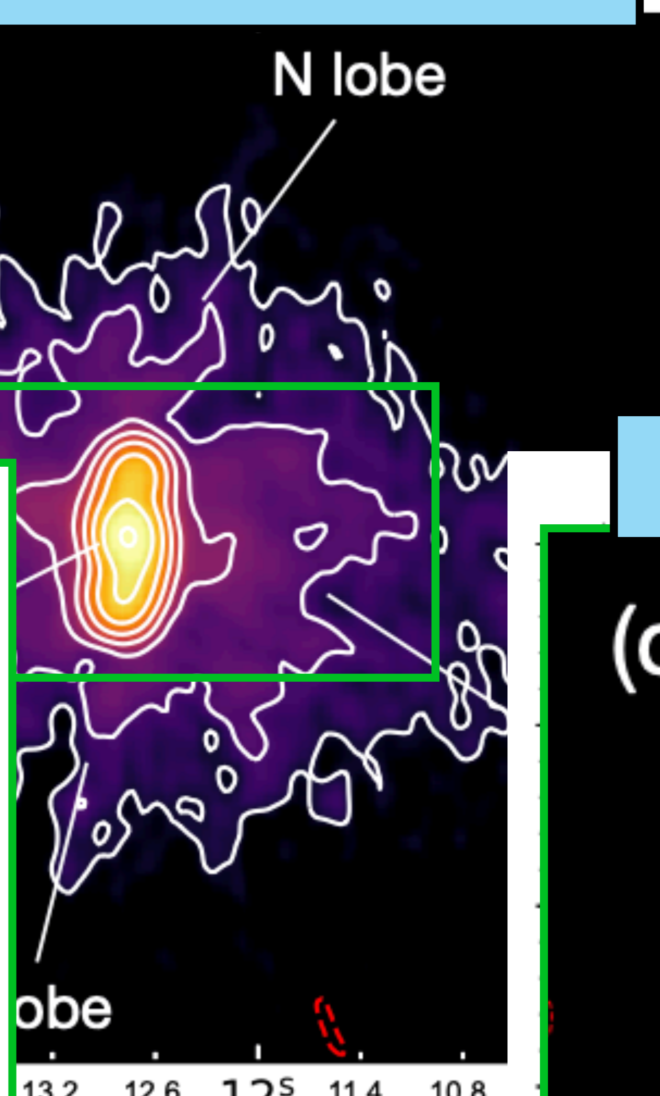

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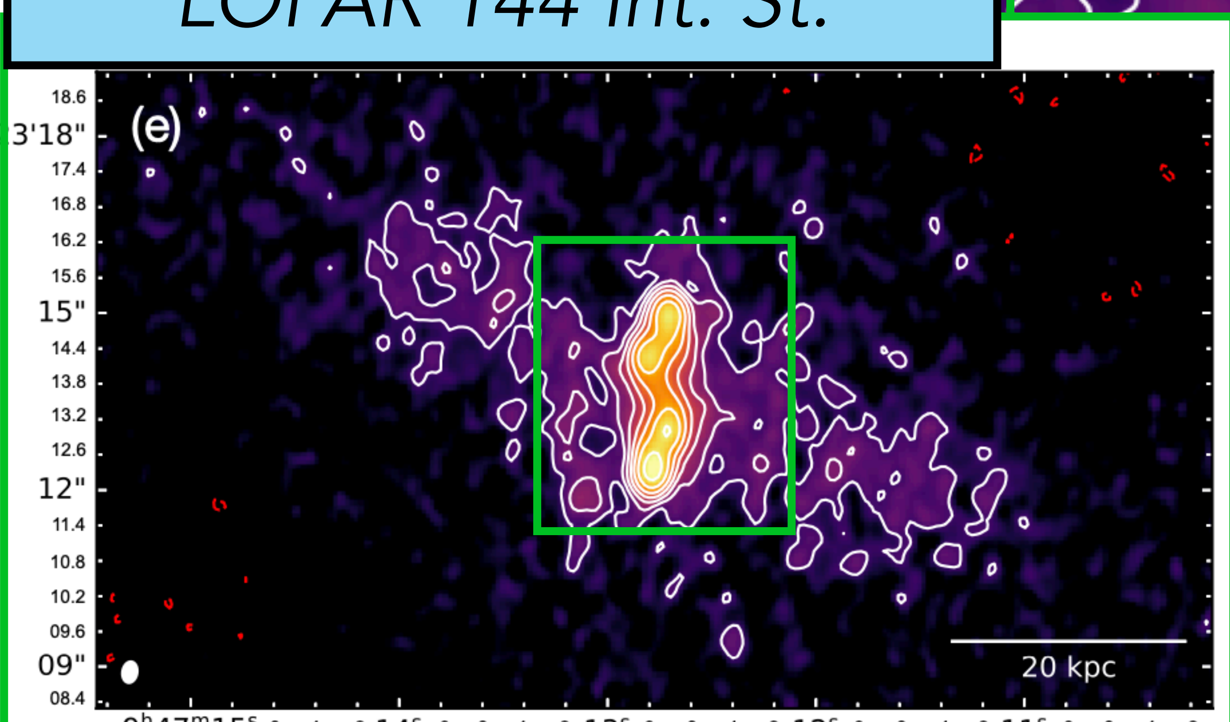

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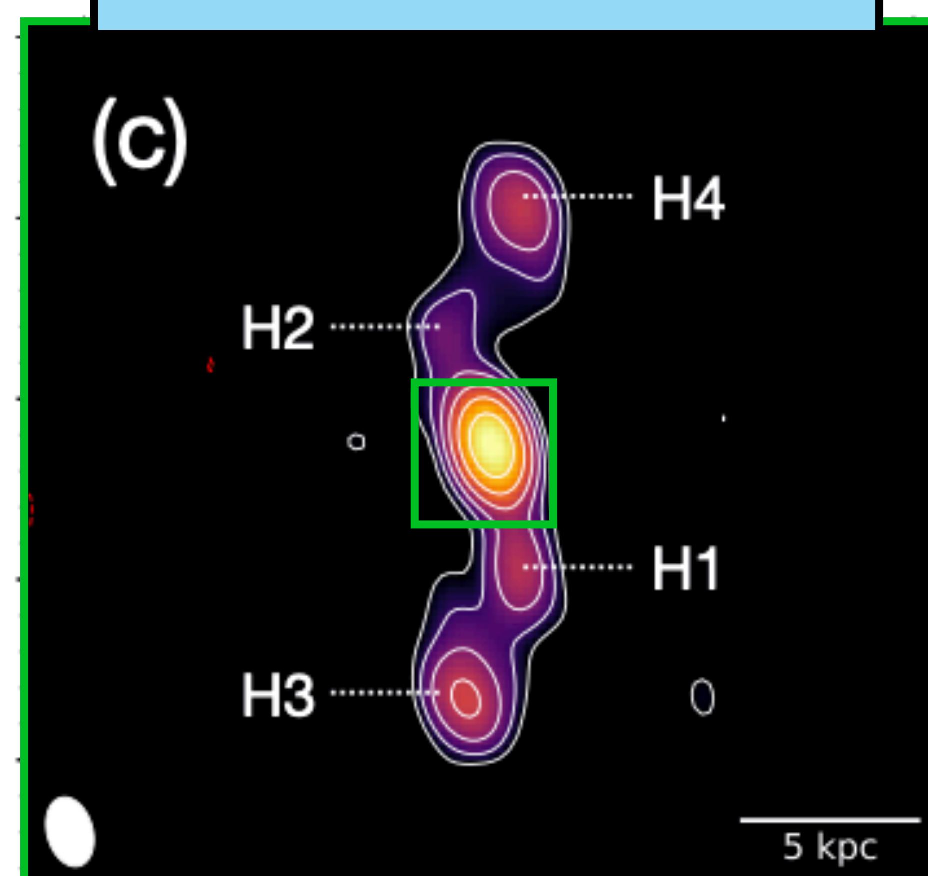


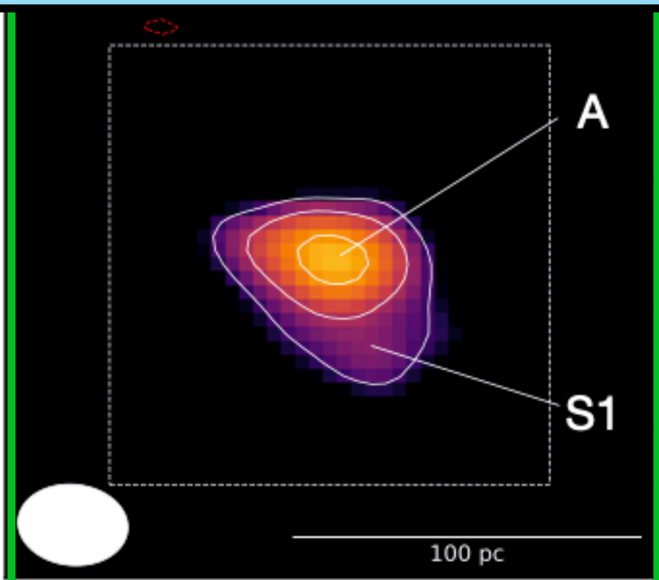
Ubertosi et al. ***2021***, ***2023b***, ***2024b***

AGN Feedback in Galaxy Clusters

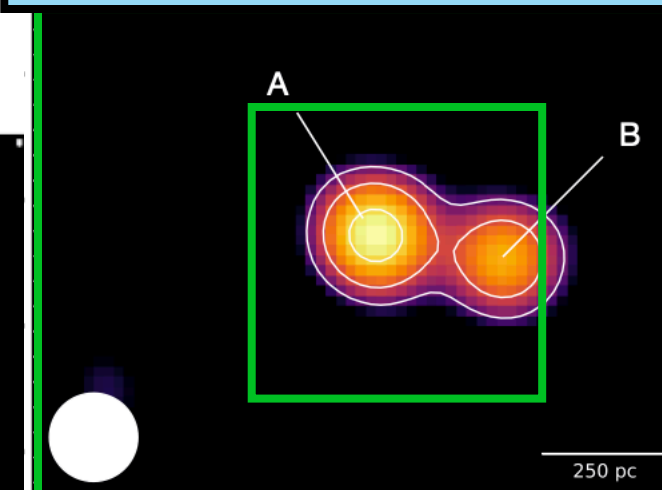
ect the Different Scales of AGN Jets?

combine several radio teles

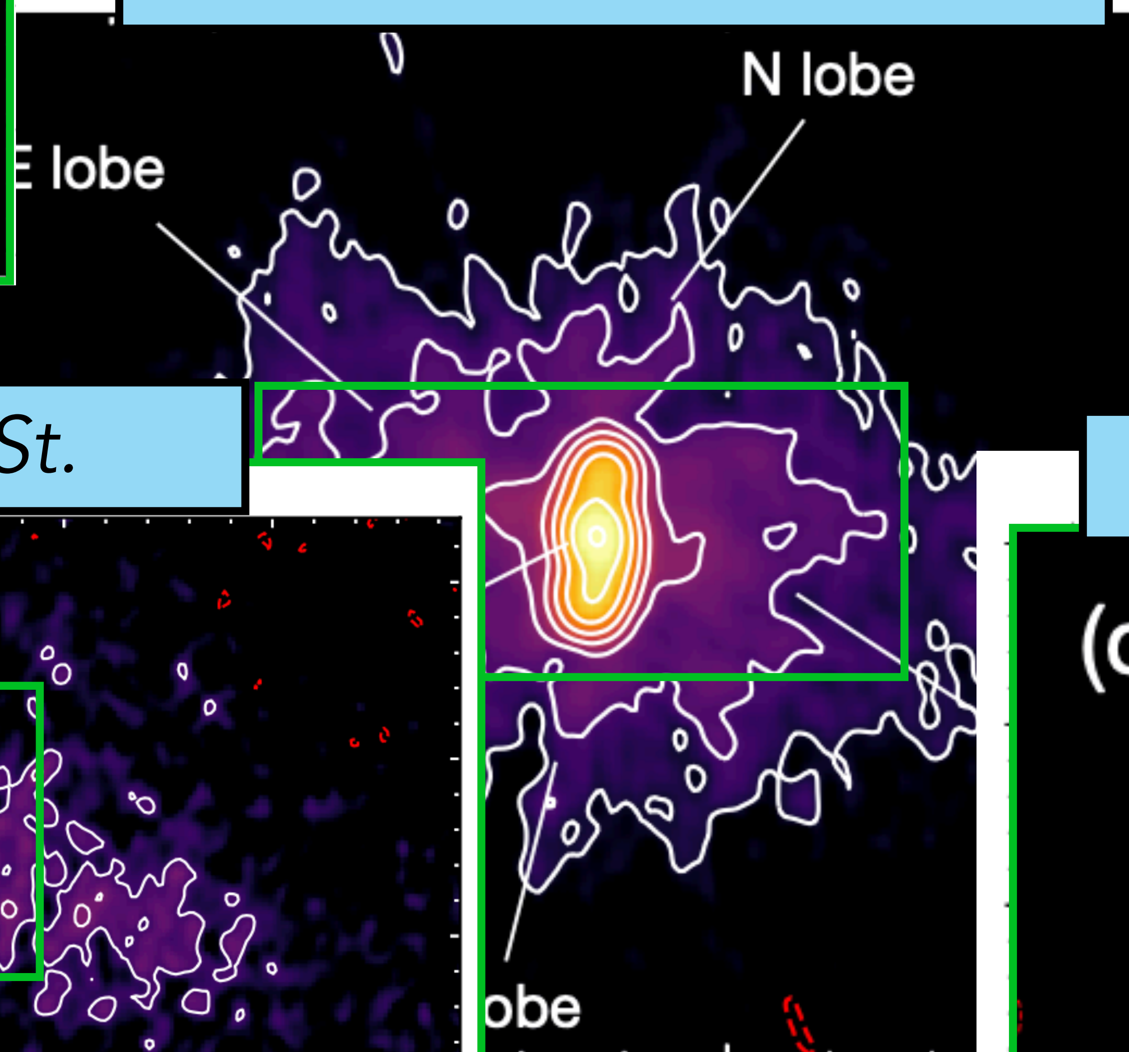
VLBA L band



e-MERLIN C band



JVLA S band



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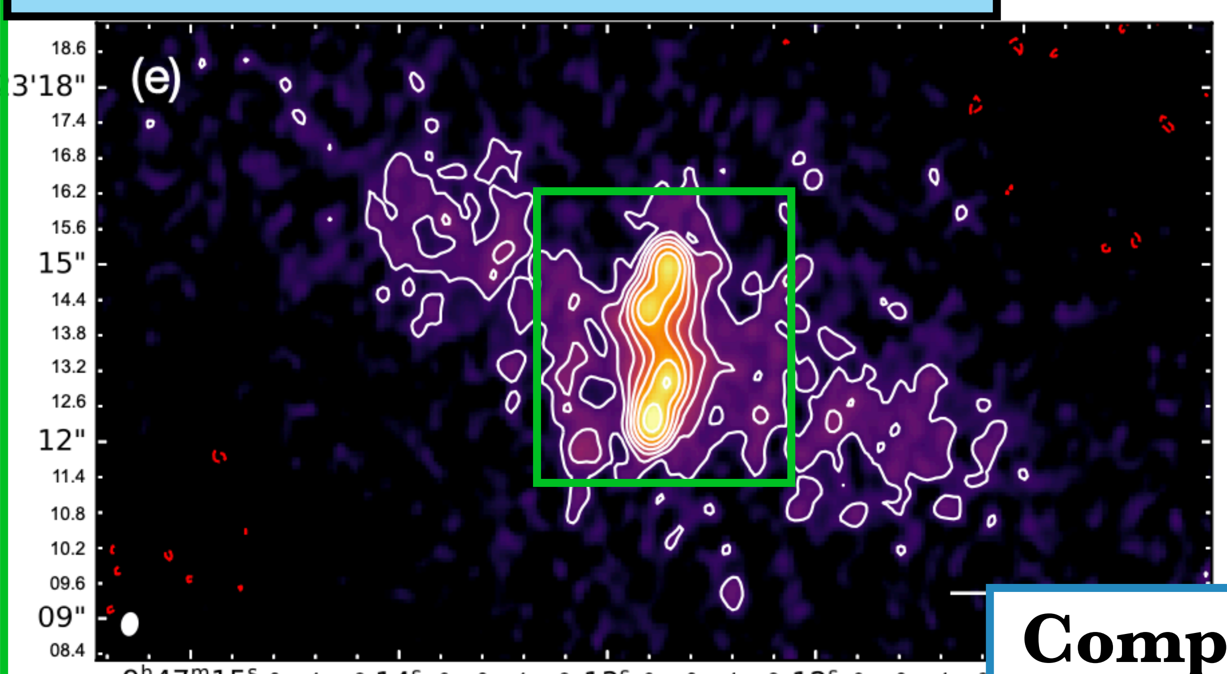
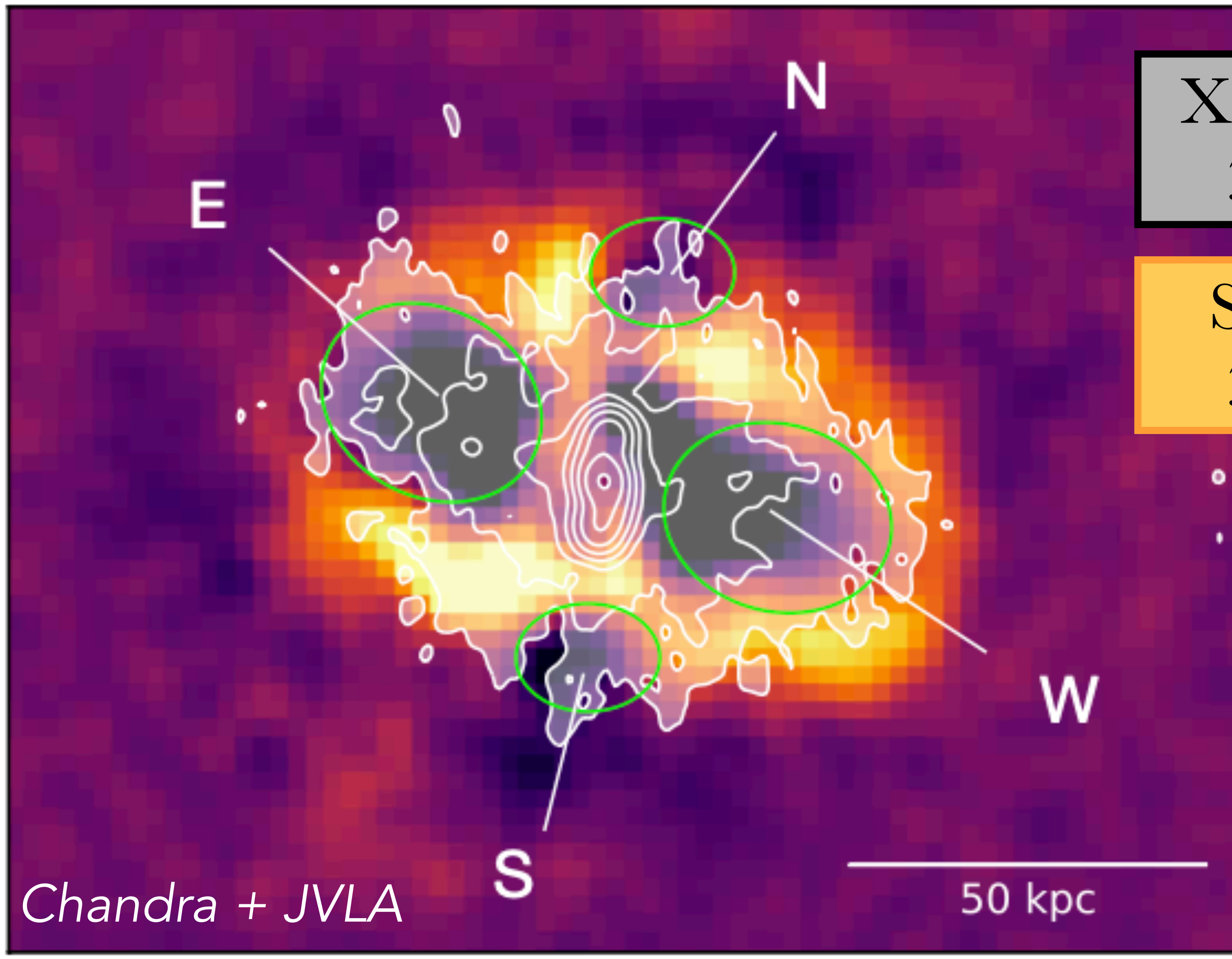


JVLA C band

Complex precession + reorientation

***Ubertosi et al.* 2021, 2023b, 2024b**

Radio Observations of the Cool Core Cluster RBS 797



X-ray cavities:
30 ± 9 Myr

Shock front:
33 ± 2 Myr

Timescales of AGN Feedback

Ubertosi et al. ***2021, 2023b, 2024b***

AGN Feedback in Galaxy Clusters

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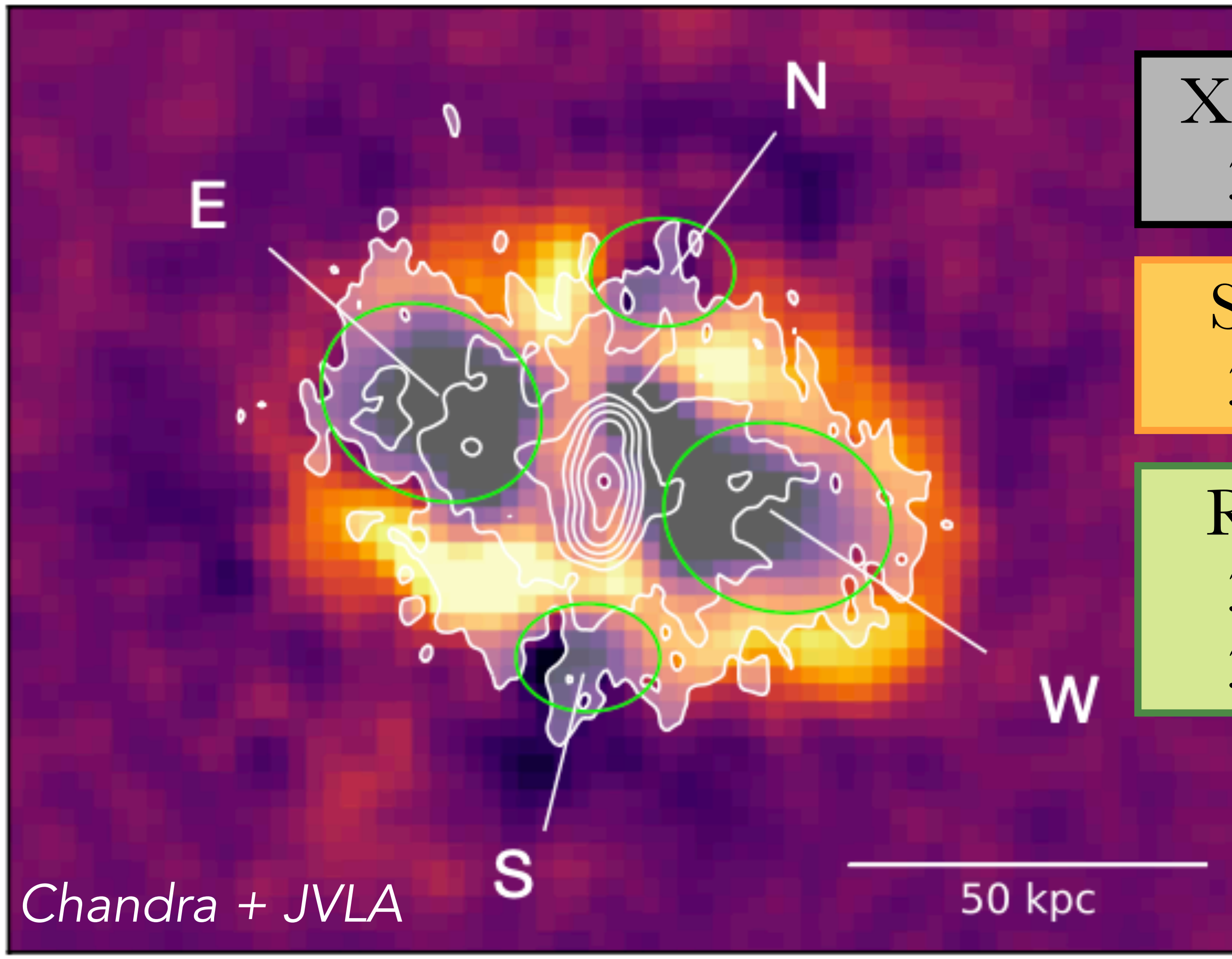


X-ray cavities: 30 ± 9 Myr

Shock front: 33 ± 2 Myr

Radio lobes: 31 ± 7 Myr, 32 ± 8 Myr

Timescales of AGN Feedback

$$t_{synchro} \propto \frac{B^{0.5}}{(B^2 + B^2_{\mathrm{CMB}})} \frac{1}{[\nu_b \times (1+z)]^{0.5}}$$

Ubertosi et al. 2021, 2023b, 2024b

AGN Feedback in Galaxy Clusters

The SKA Perspective

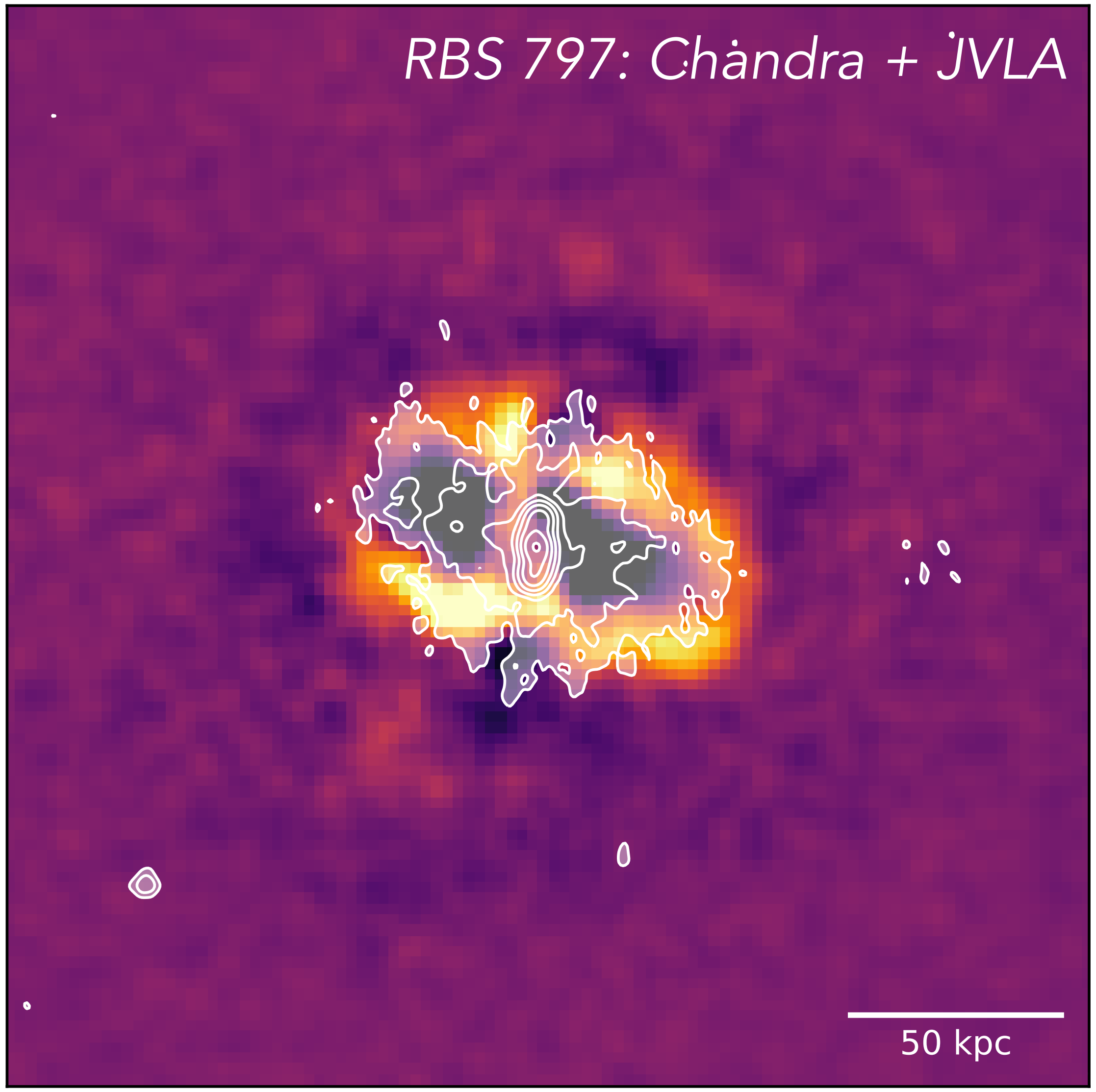
Systems such as RBS 797 are not rare:

*Krause+19: 70% of 3CR sample shows precession

*Ubertosi+24a: 30% cluster central galaxies show >45° changes in jet axis

*Horton+25: 28% of LoTSS radio galaxies show precession

… they are just "expensive" for current radio telescopes!



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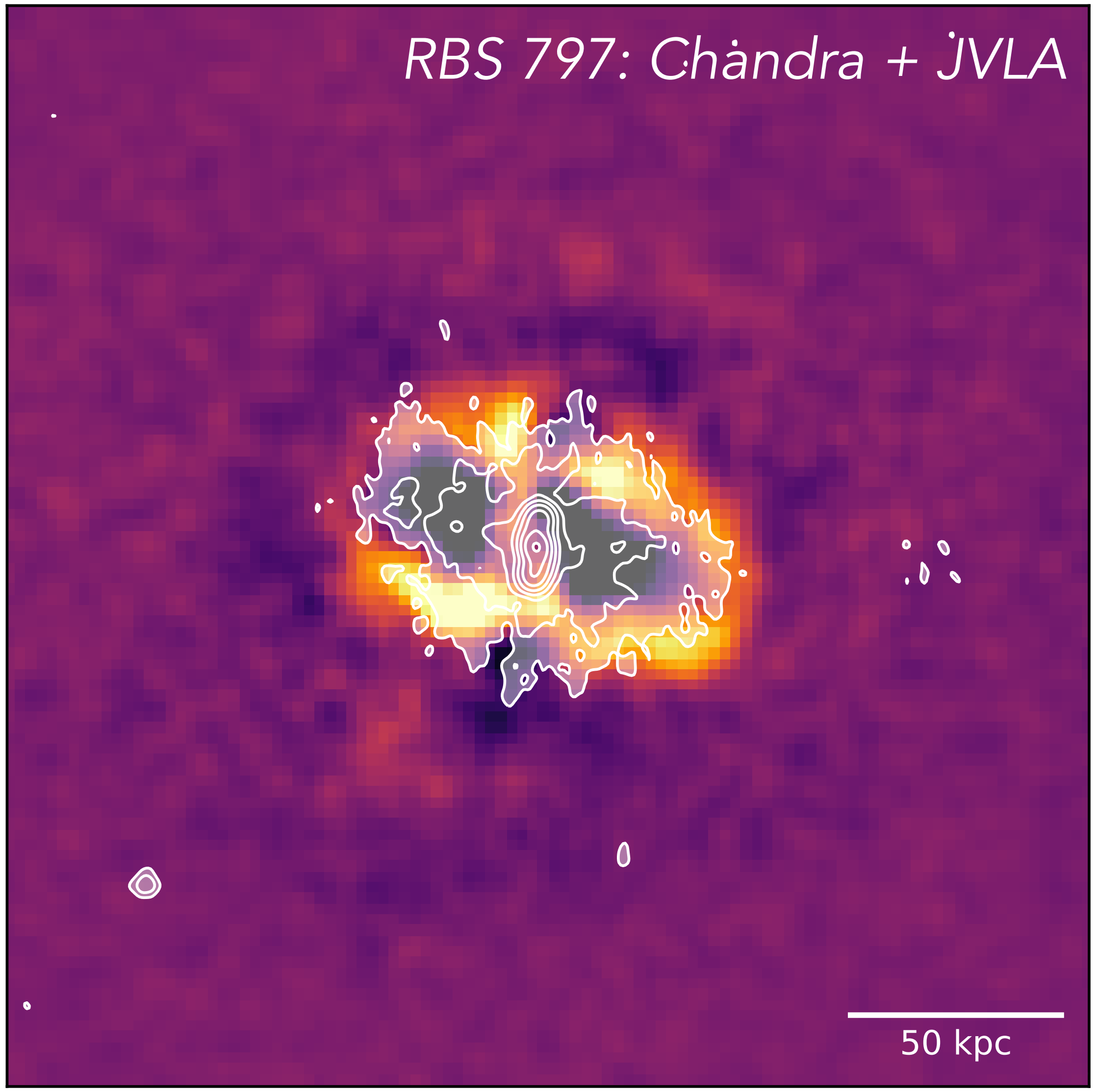


Gitti+submitted (SKA Chapter)

a SKA-MID survey will detect every central radio galaxy of cool cores down to 10^{23} W/Hz up to $z \sim 2$

$[> 10^3 - 10^4$ at $z > 0.5]$

SKA-MID Surveys

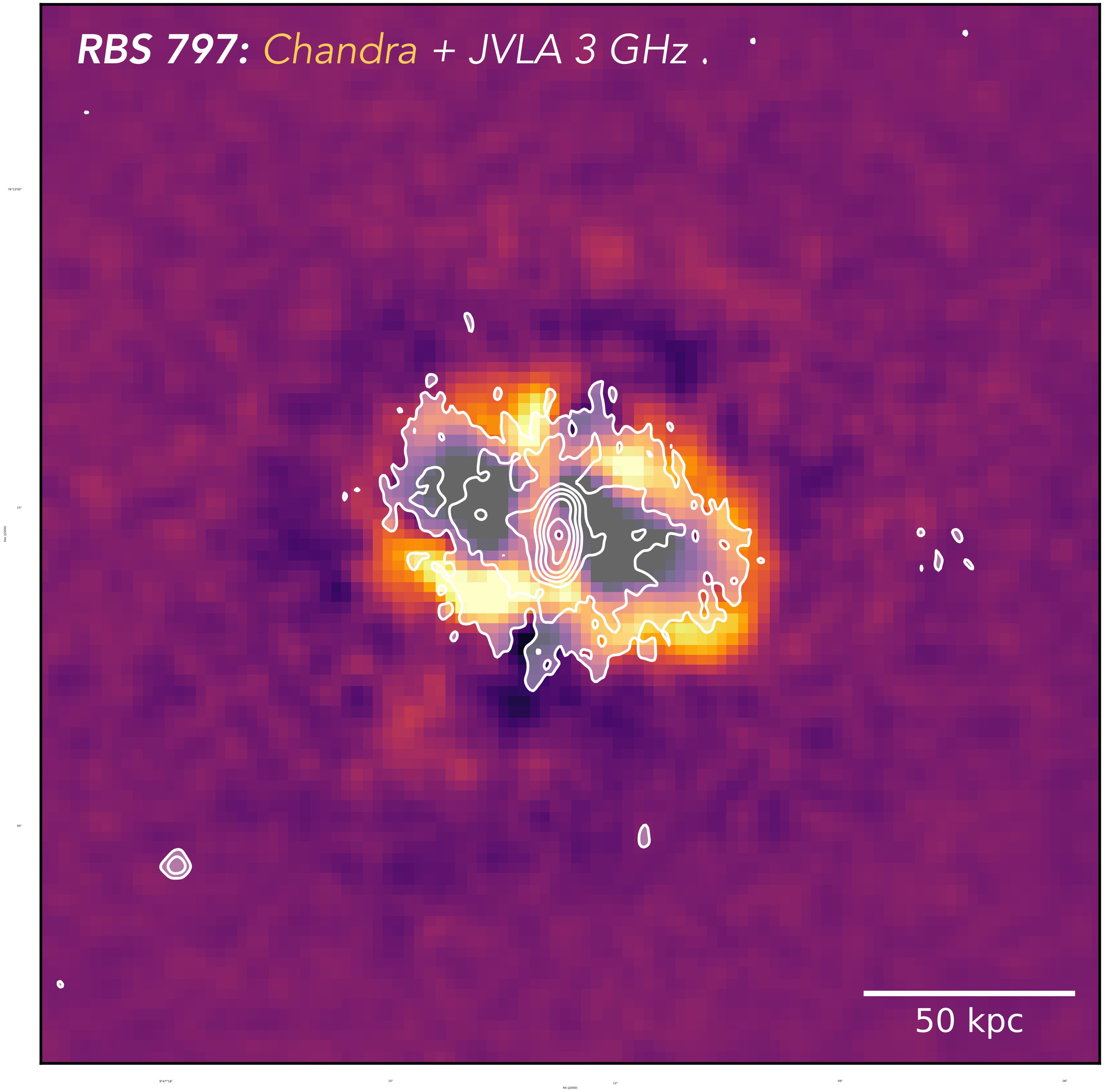
(Prandoni & Seymour 2015):

1.3" - 0.03" resolution

Sensitivity (1h): 1 - 4 μJy/beam

AGN Feedback Is Not Everything…

Large-Scale Diffuse Radio Emission in Cool Cores



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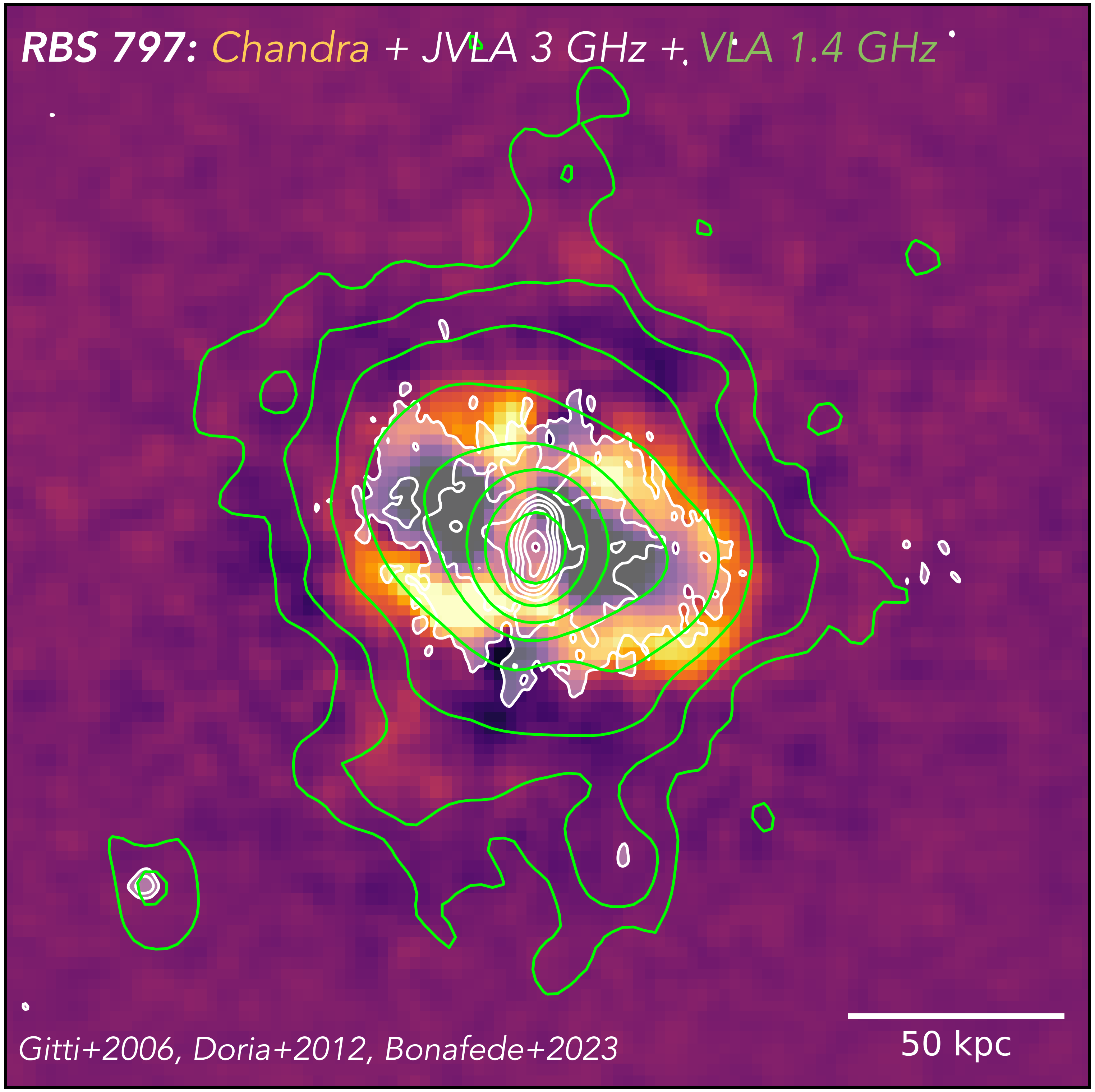
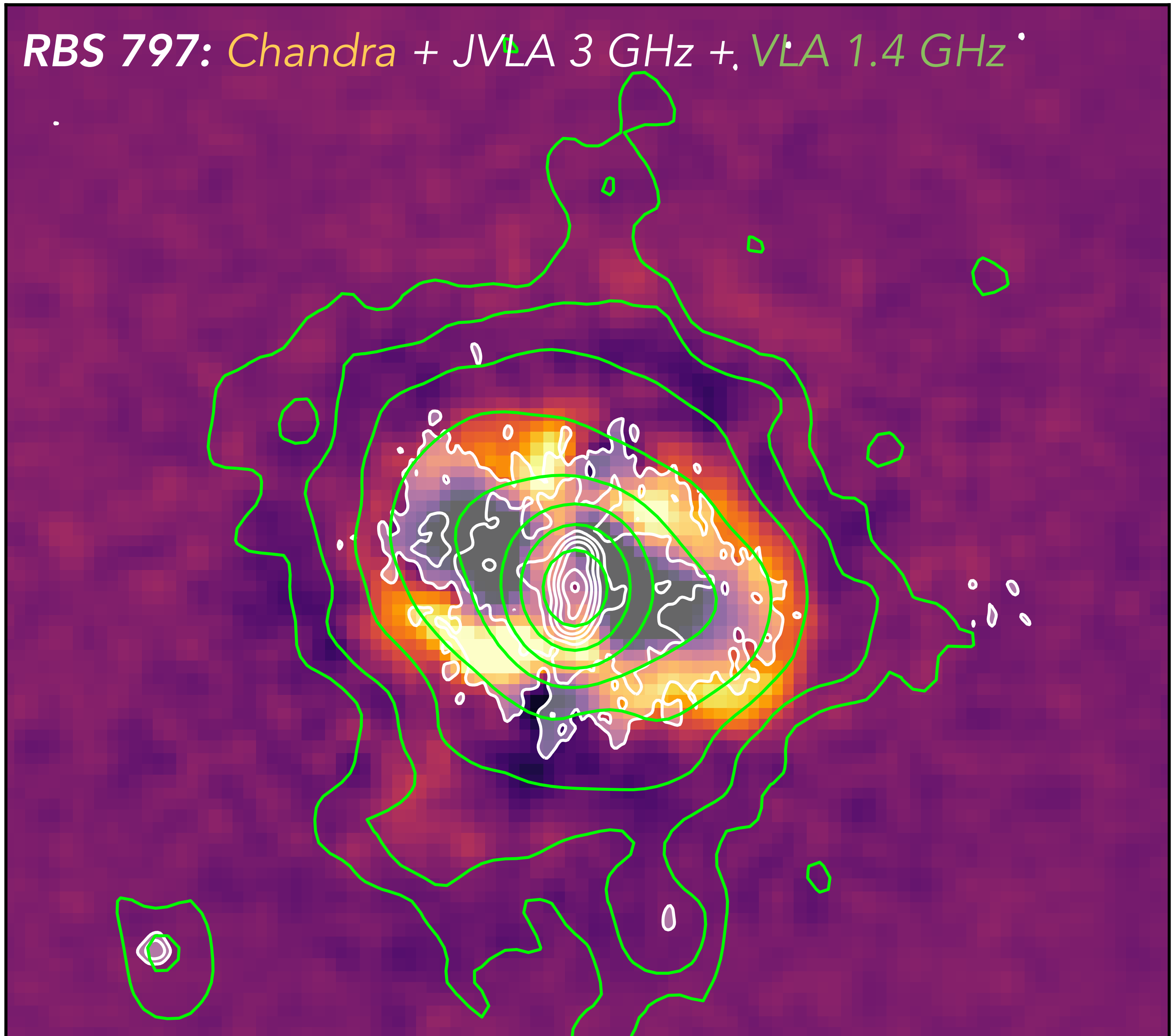


Mini-halos

diffuse synchro-sources, in **cool core clusters**, spectral index $\alpha \approx -1$, $R_{MH} \lessapprox 300\,\mathrm{kpc}$

AGN Feedback Is Not Everything…

Large-Scale Diffuse Radio Emission in Cool Cores



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diffuse synchro-sources, in **cool core clusters**, spectral index $\alpha \approx -1$, $R_{MH} \lessapprox 300\,\mathrm{kpc}$

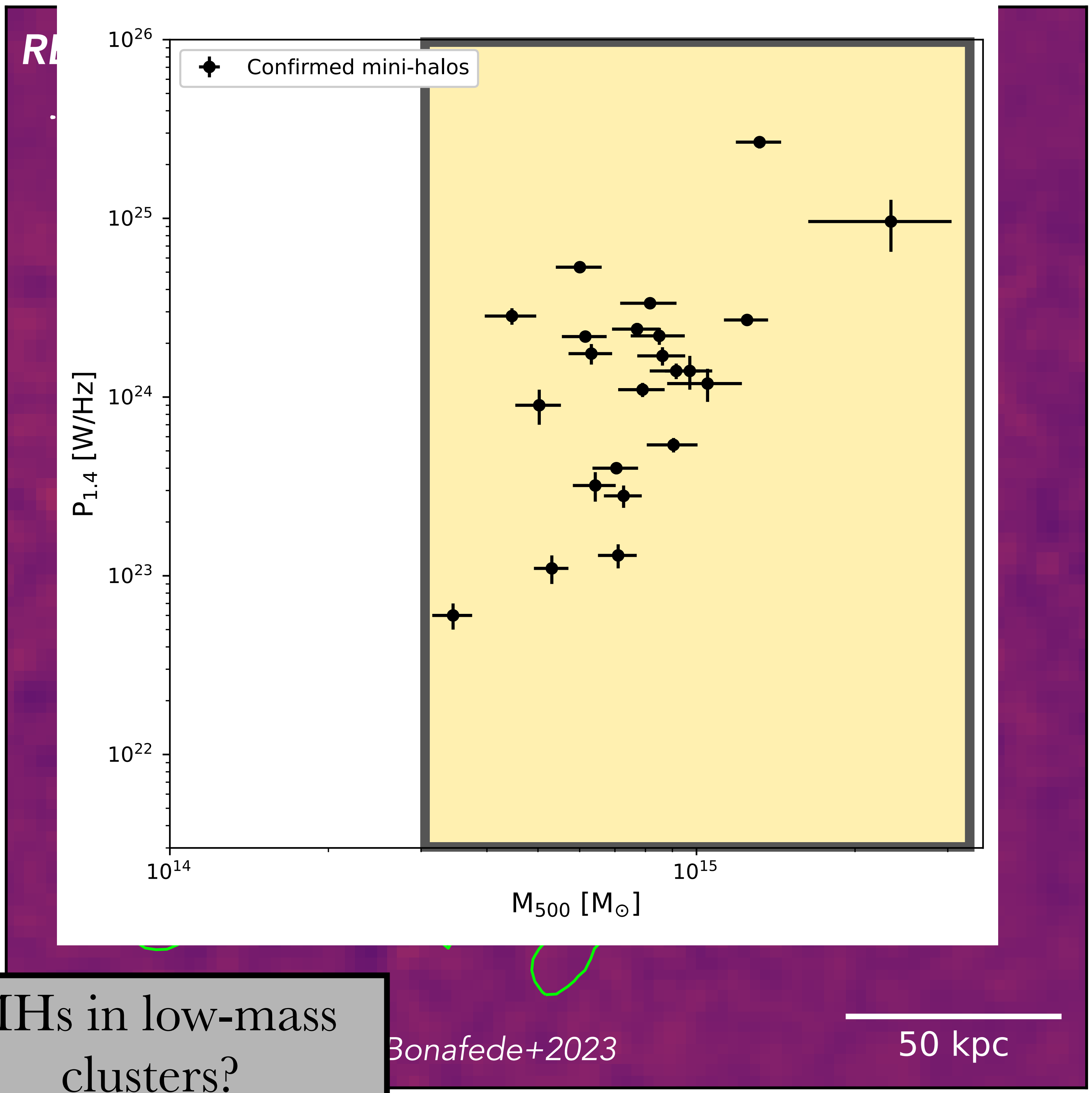
Less than 40 confirmed cases

(e.g., Giacintucci+2019, Trehaeven+2023, Kolokythas+2025)

MHs in low-mass clusters?	Origin of relativistic electrons?	Magnetic fields in relaxed clusters?	Role of AGN feedback?

AGN Feedback Is Not Everything…

Large-Scale Diffuse Radio Emission in Cool Cores



MHs in low-mass clusters?

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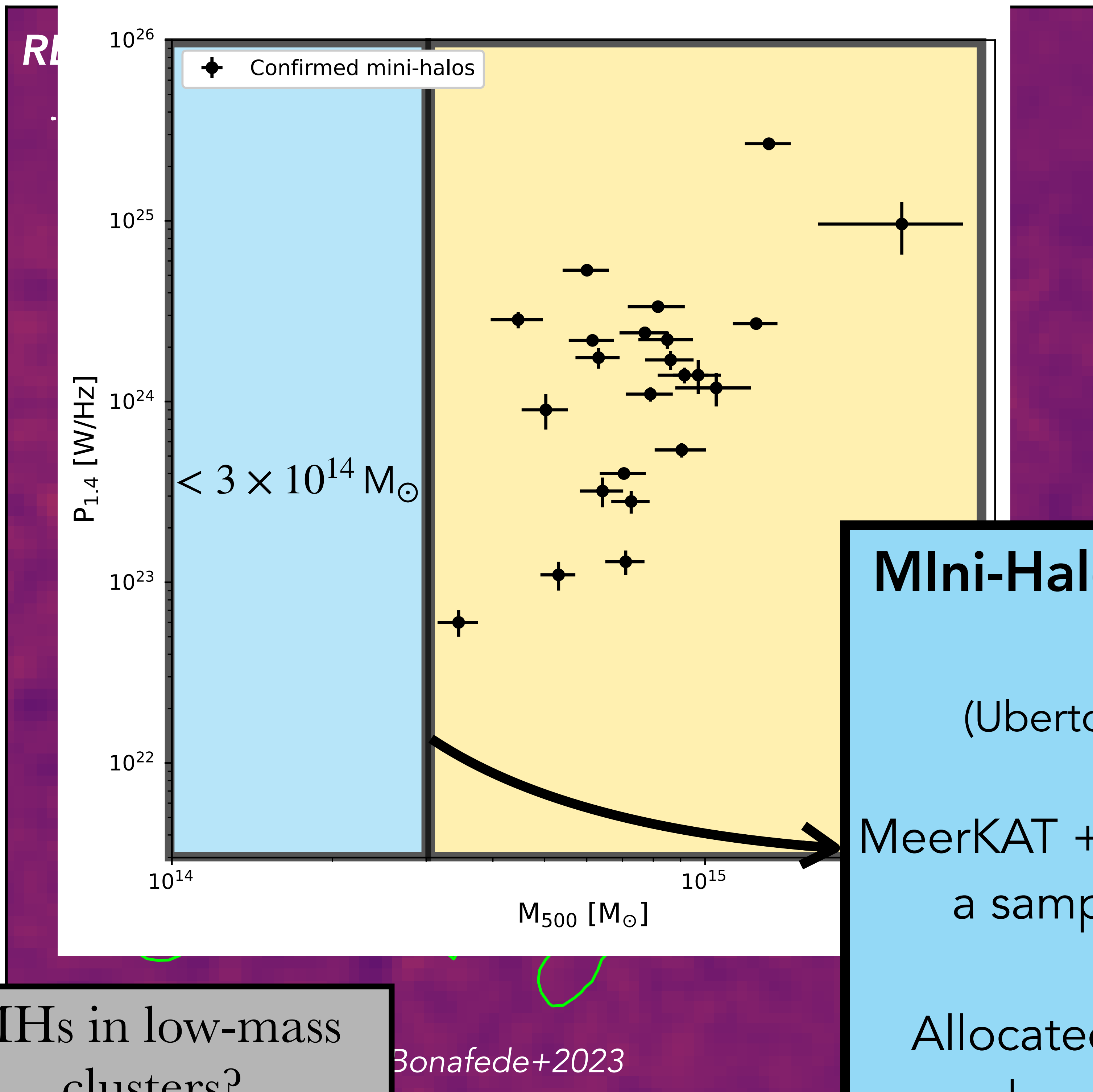


Mini-halos

diffuse synchro-sources, in **cool core clusters**, spectral index $\alpha \approx -1$, $R_{MH} \lesssim 300\,\mathrm{kpc}$

MHs in low-mass clusters?

MIni-Halos in MIni-Clusters (MIMICs) project

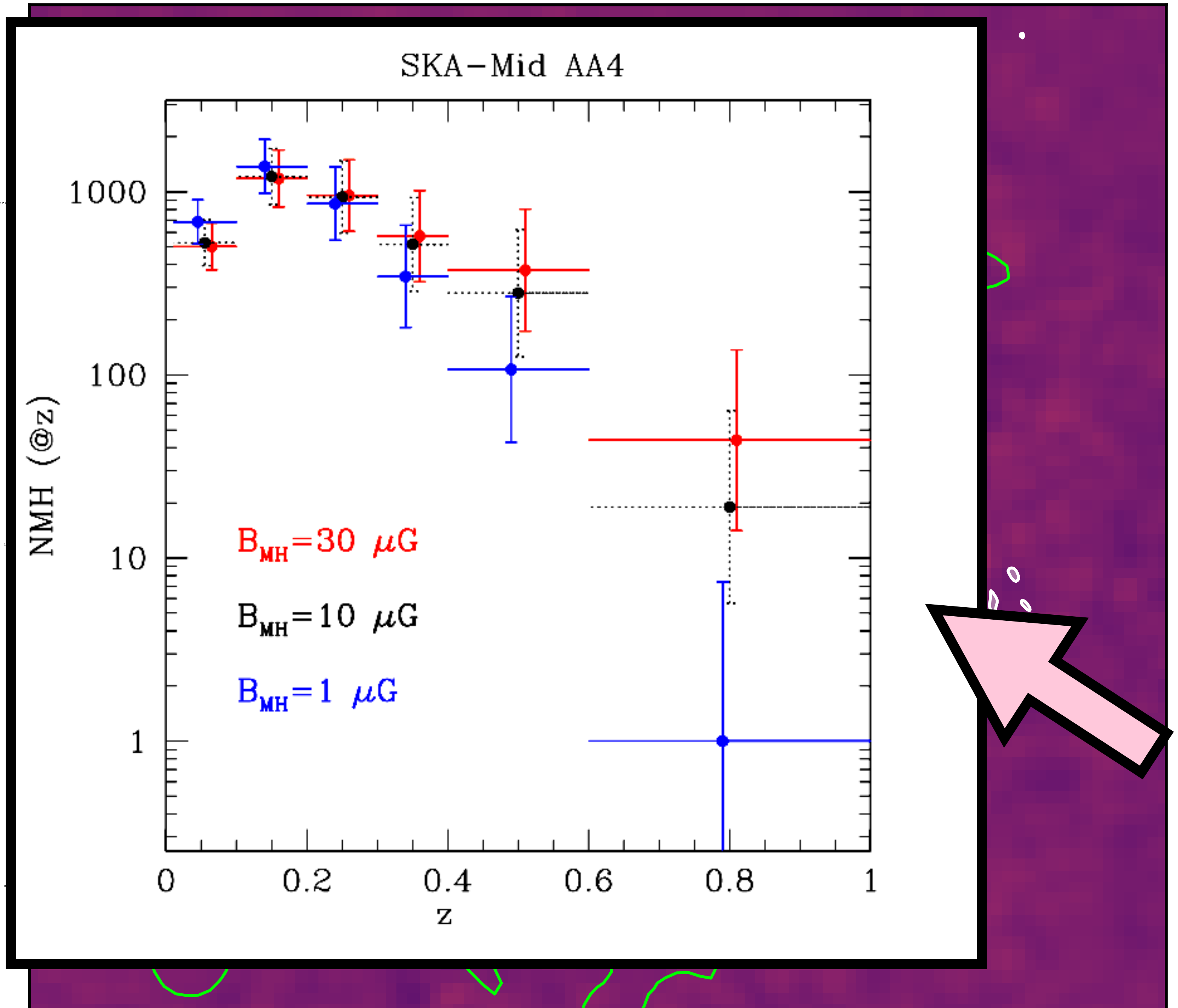
(Ubertosi, Giacintucci, Botteon+in prep.)

MeerKAT + LOFAR + uGMRT observations of a sample of low-mass galaxy clusters

Allocated **40 hours of MeerKAT L band** observations in 2026 (PI: Ubertosi)

AGN Feedback Is Not Everything…

Large-Scale Diffuse Radio Emission in Cool Cores



Mini-halos

diffuse synchro-sources, in **cool core clusters**, spectral index $\alpha \approx -1$, $R_{MH} \lessapprox 300\,\mathrm{kpc}$

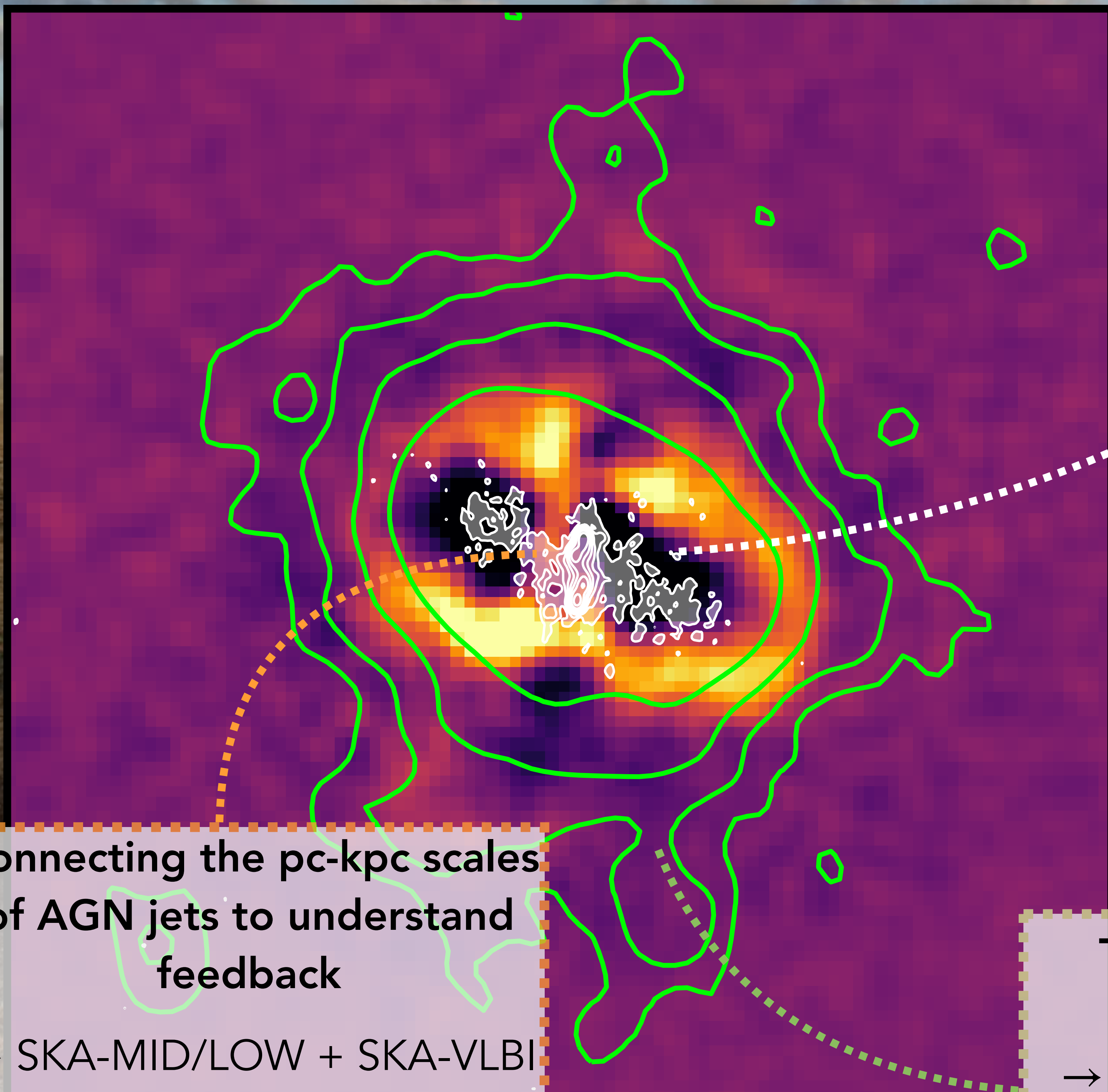
Gitti+submitted (SKA Chapter)

a SKA-MID survey will detect ~3500 mini-halos, up to z = 1

MHs in low-mass clusters?	Origin of relativistic electrons?	Magnetic fields in relaxed clusters?	Role of AGN feedback?

The SKA View of Relaxed Galaxy Clusters

Conclusions



Understanding jet dynamics & isotropic heating of the ICM

→ SKA-MID surveys to image cluster-central radio galaxies up to z~2

Connecting the pc-kpc scales of AGN jets to understand feedback

→ SKA-MID/LOW + SKA-VLBI synergy

Tracing particle re-acceleration & magnetic fields with mini-halos

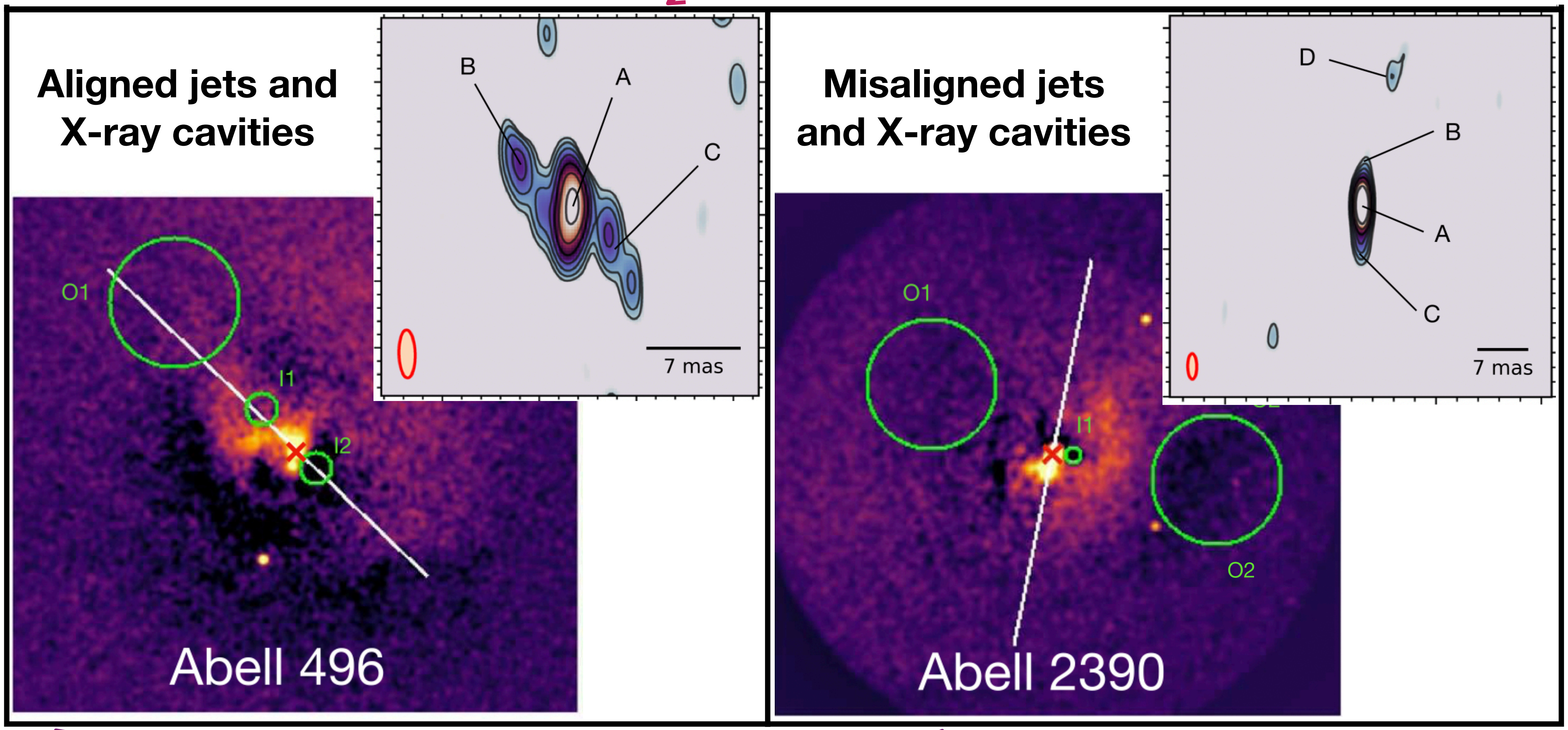
→ SKA-MID/LOW surveys will improve MH statistics by a factor of 100!

Backup slides

AGN Feedback in Galaxy Clusters

Jet Reorientation in the Most Massive Galaxies

VLBA 5 GHz



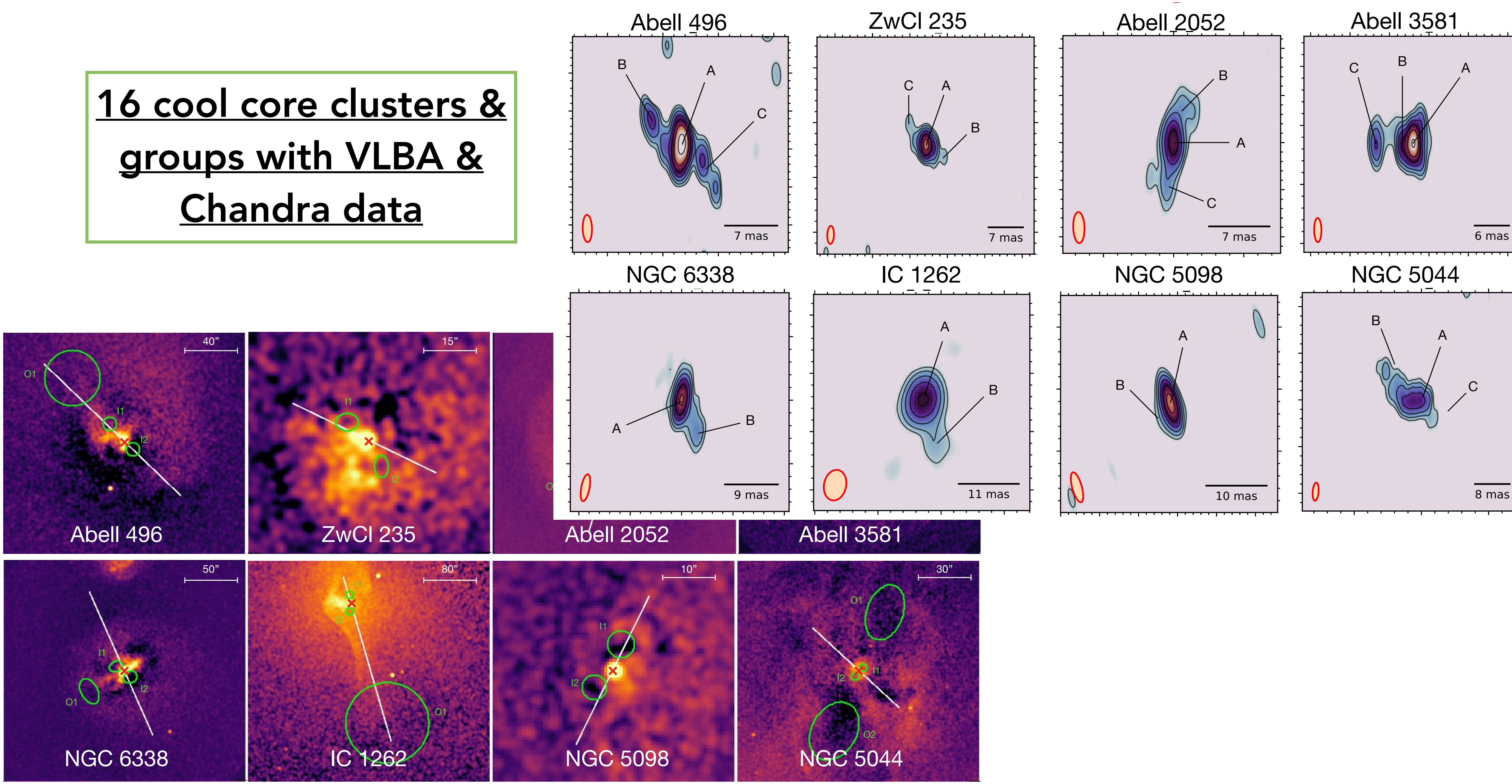
Chandra (residual image)

radio jets in VLBA data and X-ray cavities in *Chandra* data

Ubertosi et al. (2024b)

AGN Feedback in Galaxy Clusters
Jet Reorientation in the Most Massive Galaxies

16 cool core clusters & groups with VLBA & Chandra data



Ubertosi et al. (2024b)

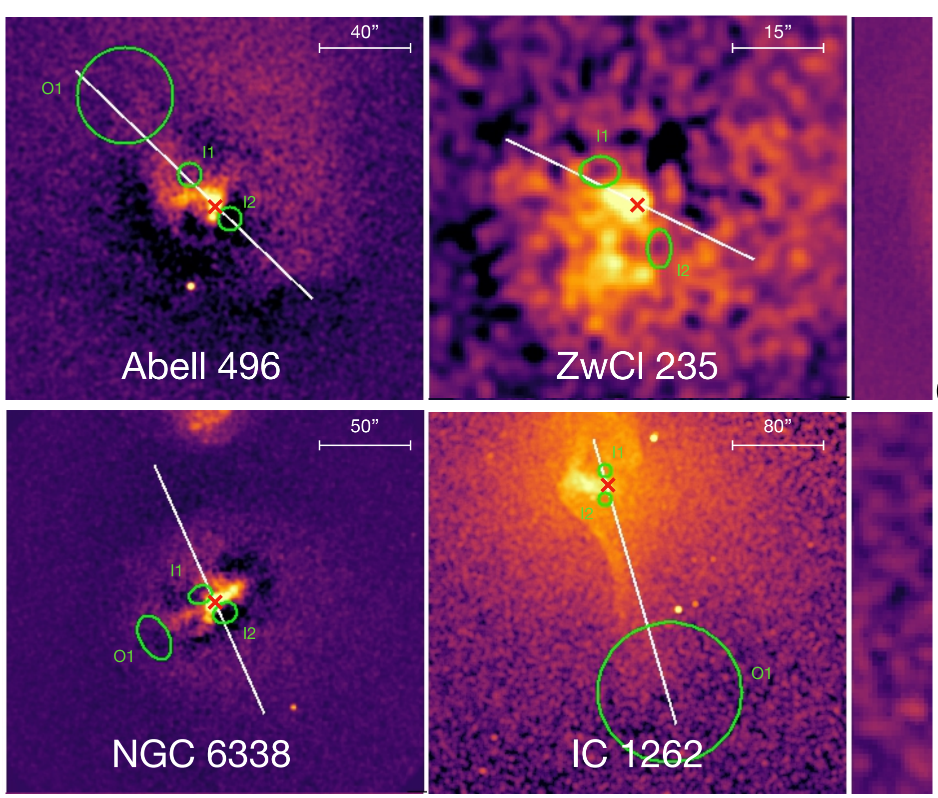
AGN Feedback in Galaxy Clusters

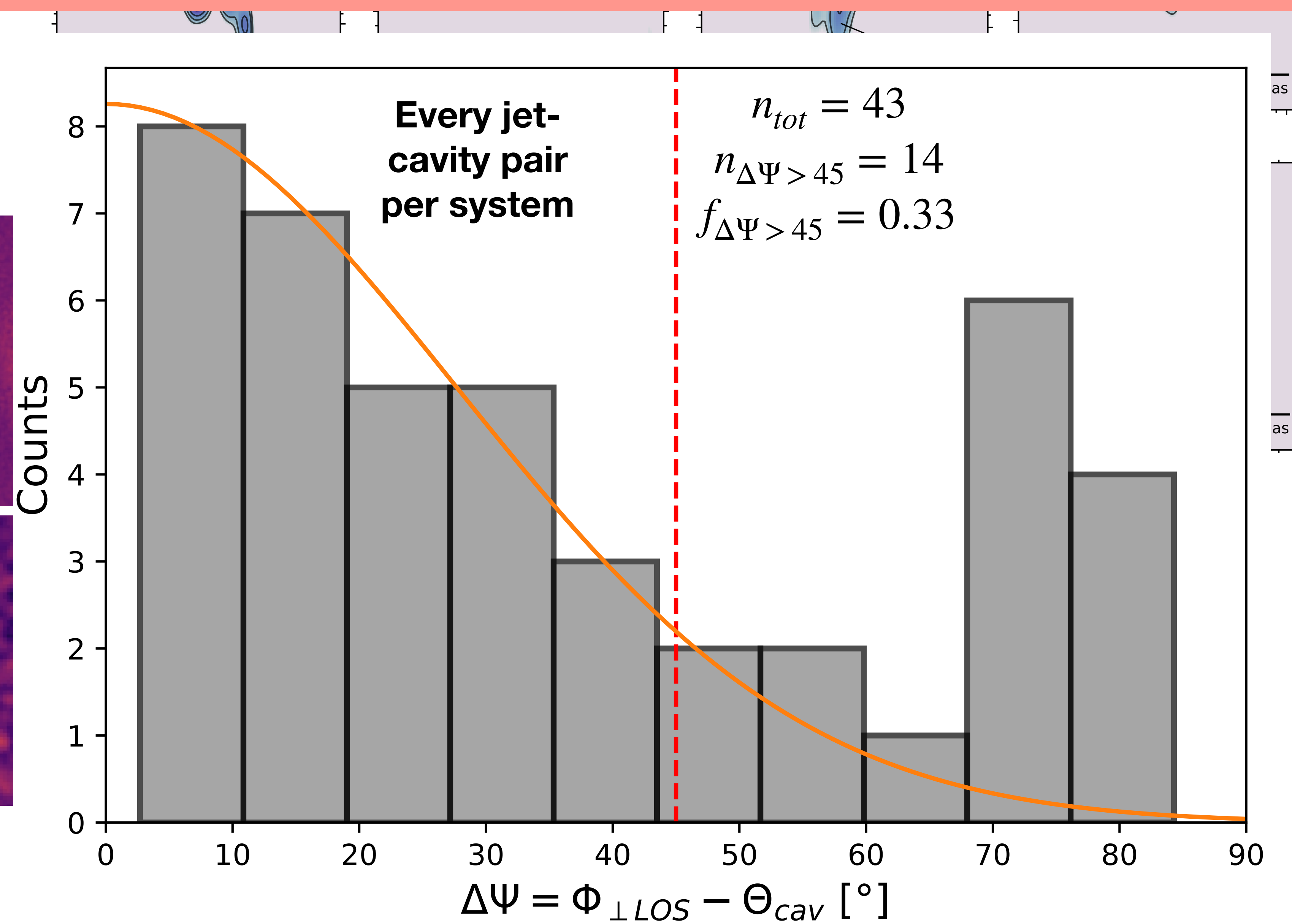
Jet Reorientation in the Most Massive Galaxies

$$f_{\Delta\Psi > 45^\circ} = 30\% - 38\ \%$$

Jet reorientation is common!

16 cool core cl
groups with V
Chandra data





Ubertosi et al. (2024b)

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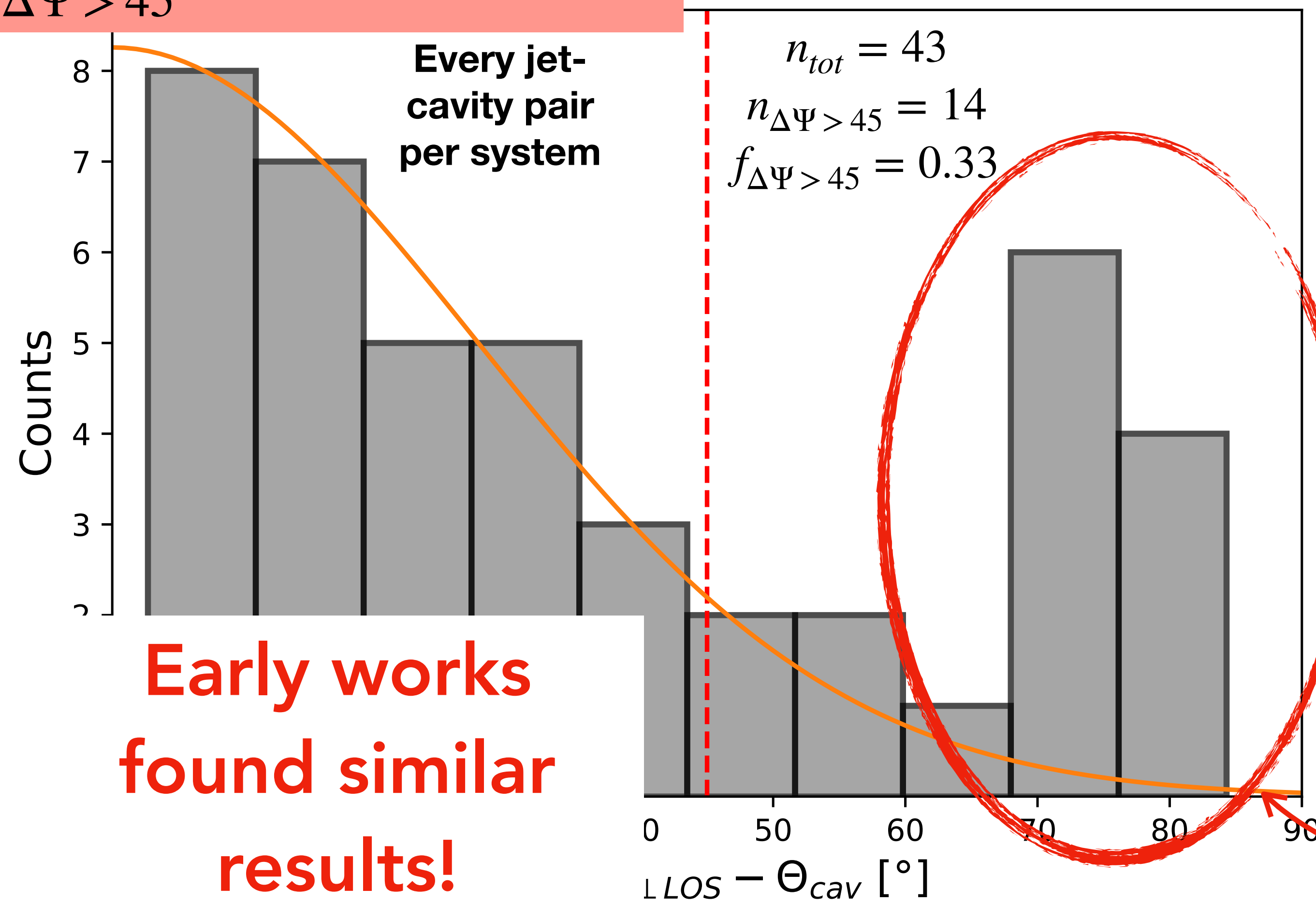
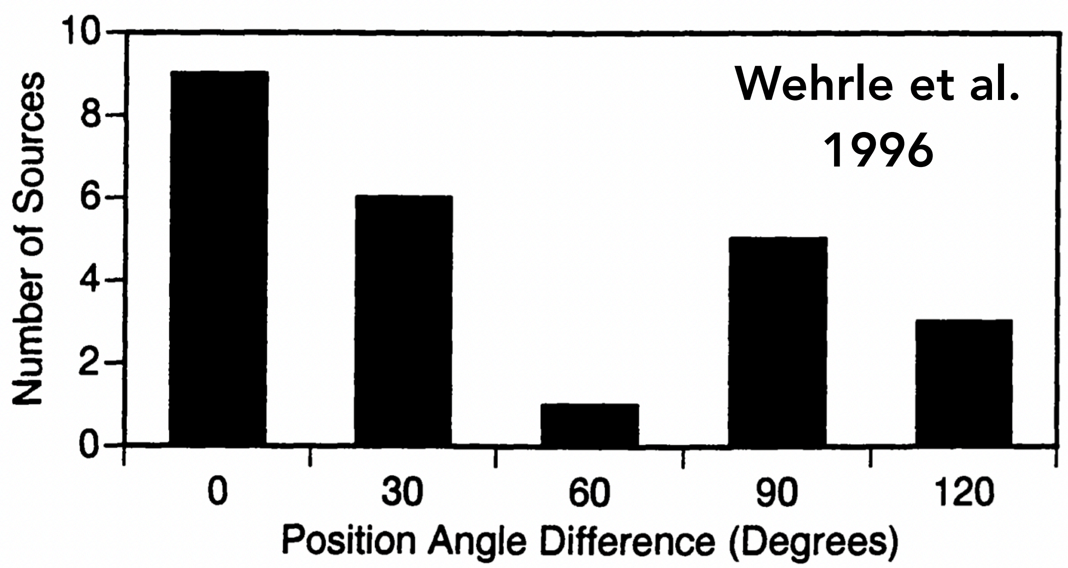


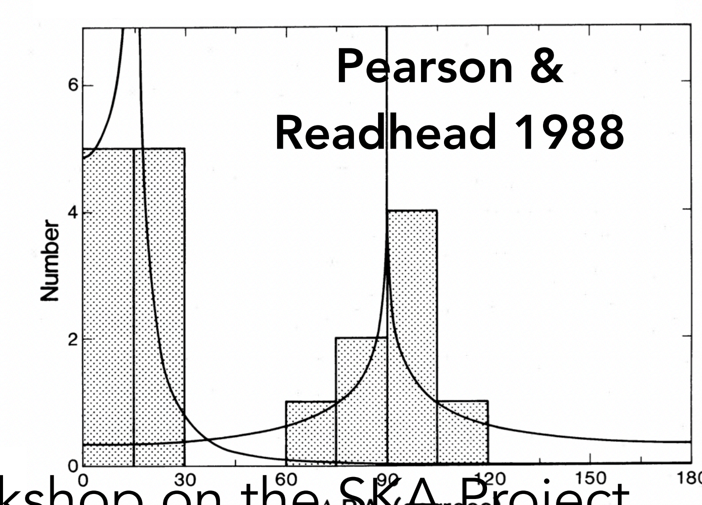
Early works found similar results!

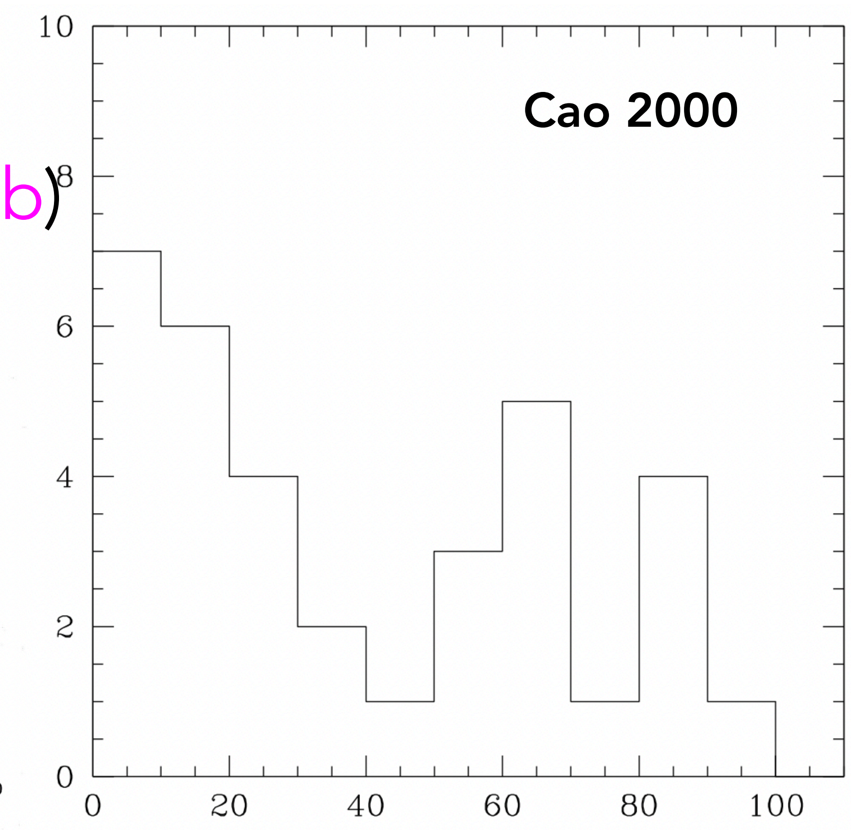
If jet reorientation was a random mechanism, we would expect a uniform distribution at $\Delta\Psi > 45^\circ$

The peak at 75° is significant at 98.4% confidence

Ubertosi et al. (2024b)

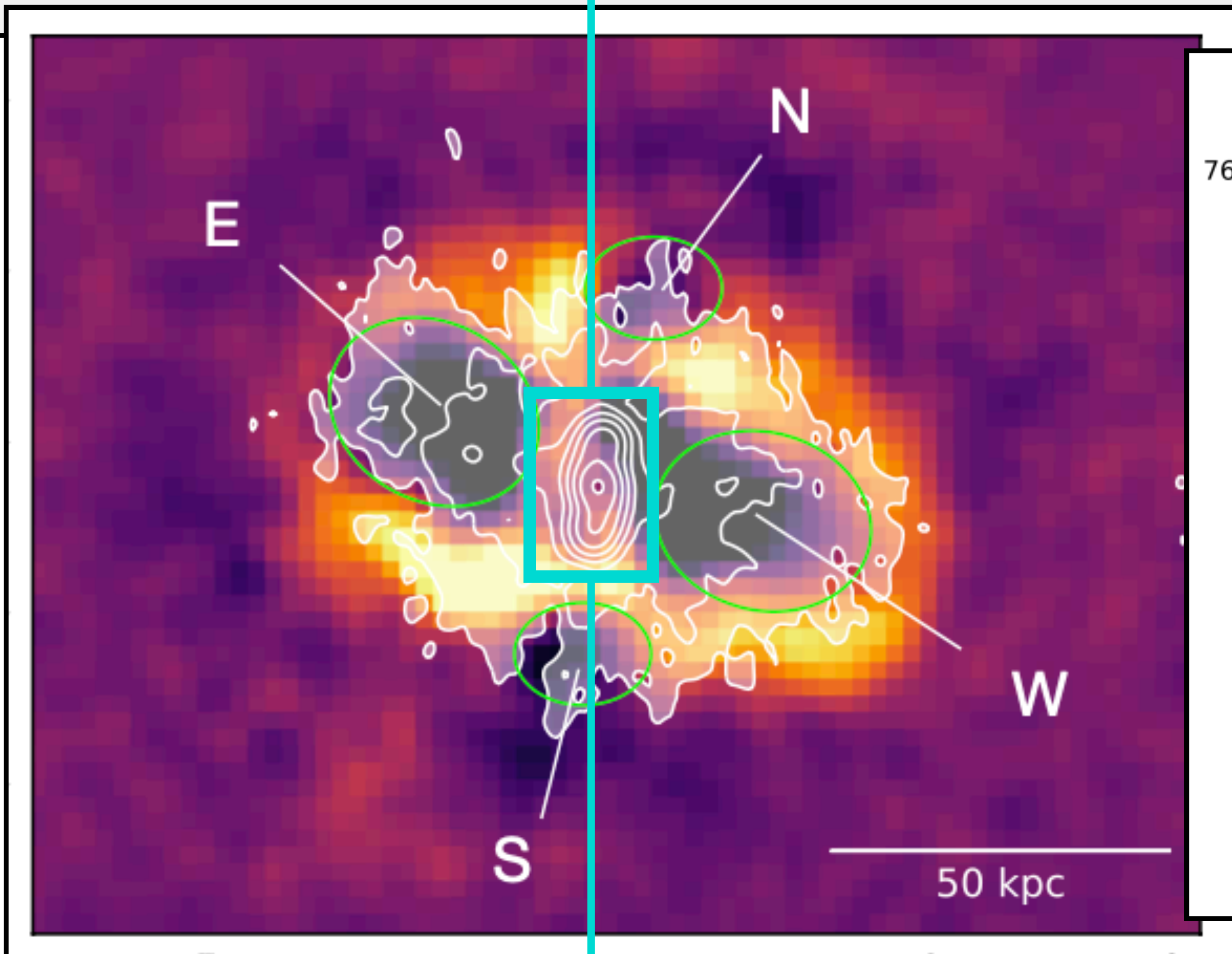


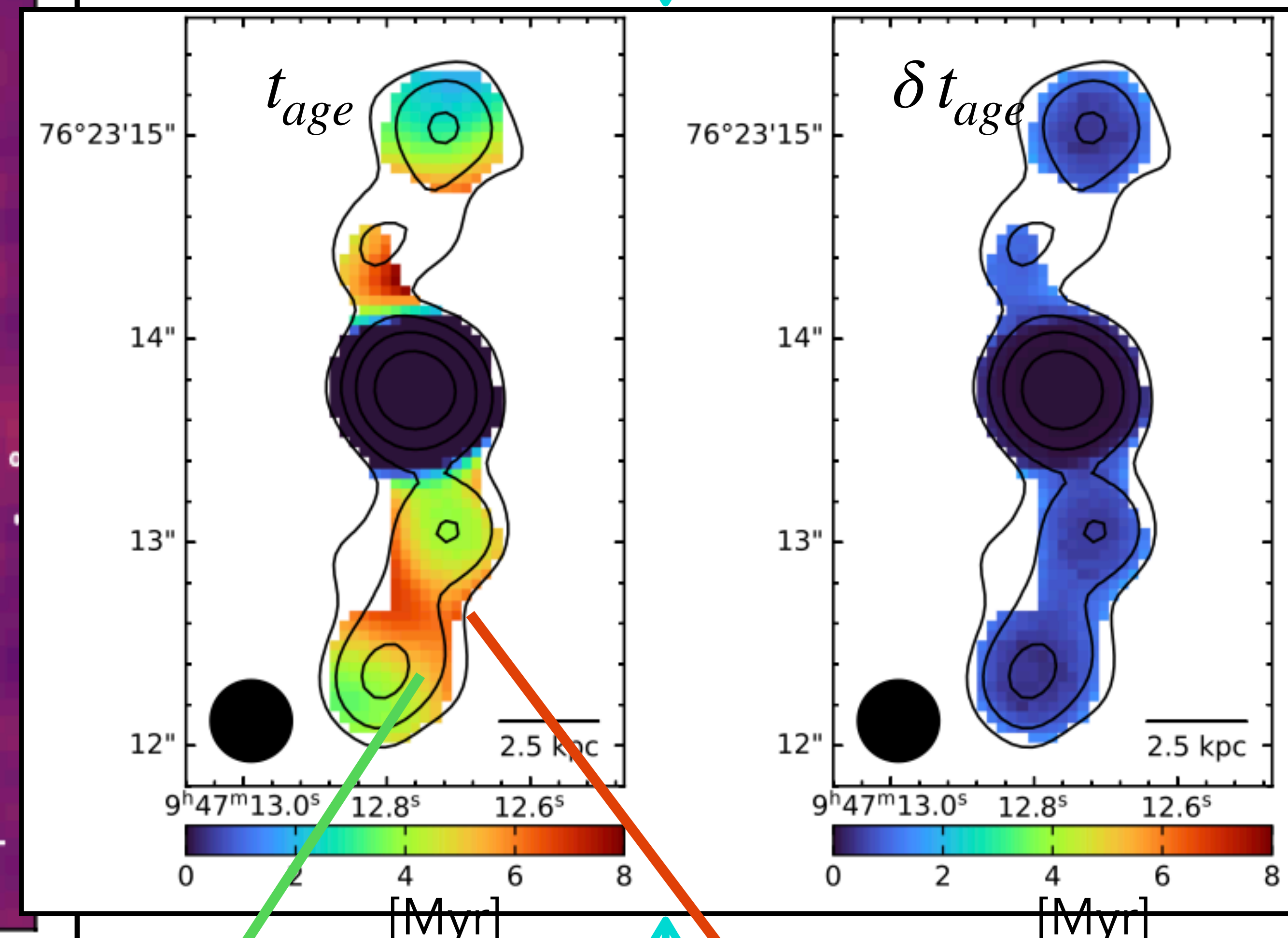




AGN Feedback in Galaxy Clusters

Radio Observations of the Cool Core Cluster RBS 797





Maps of radiative age

Twisted morphology, multiple hotspots:

precession signatures

Hotspots:

$t_{age} = 4.4 \pm 0.5$ Myr

Trailing plasma

$t_{age} = 5.8 \pm 0.3$ Myr

AGN Feedback in Galaxy Clusters

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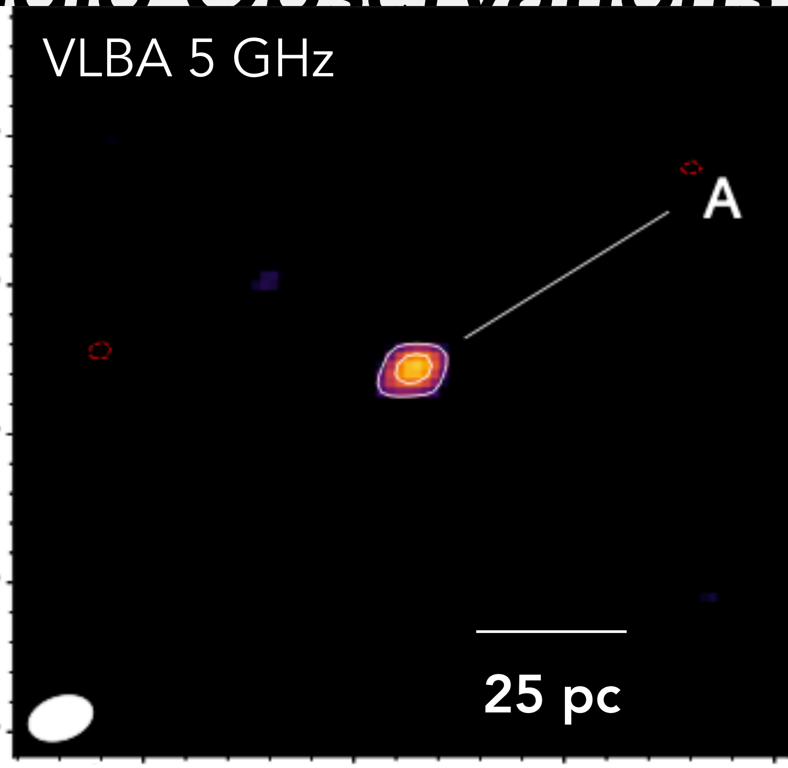


The detection of a single component in VLBI data is still consistent with the binary interpretation!

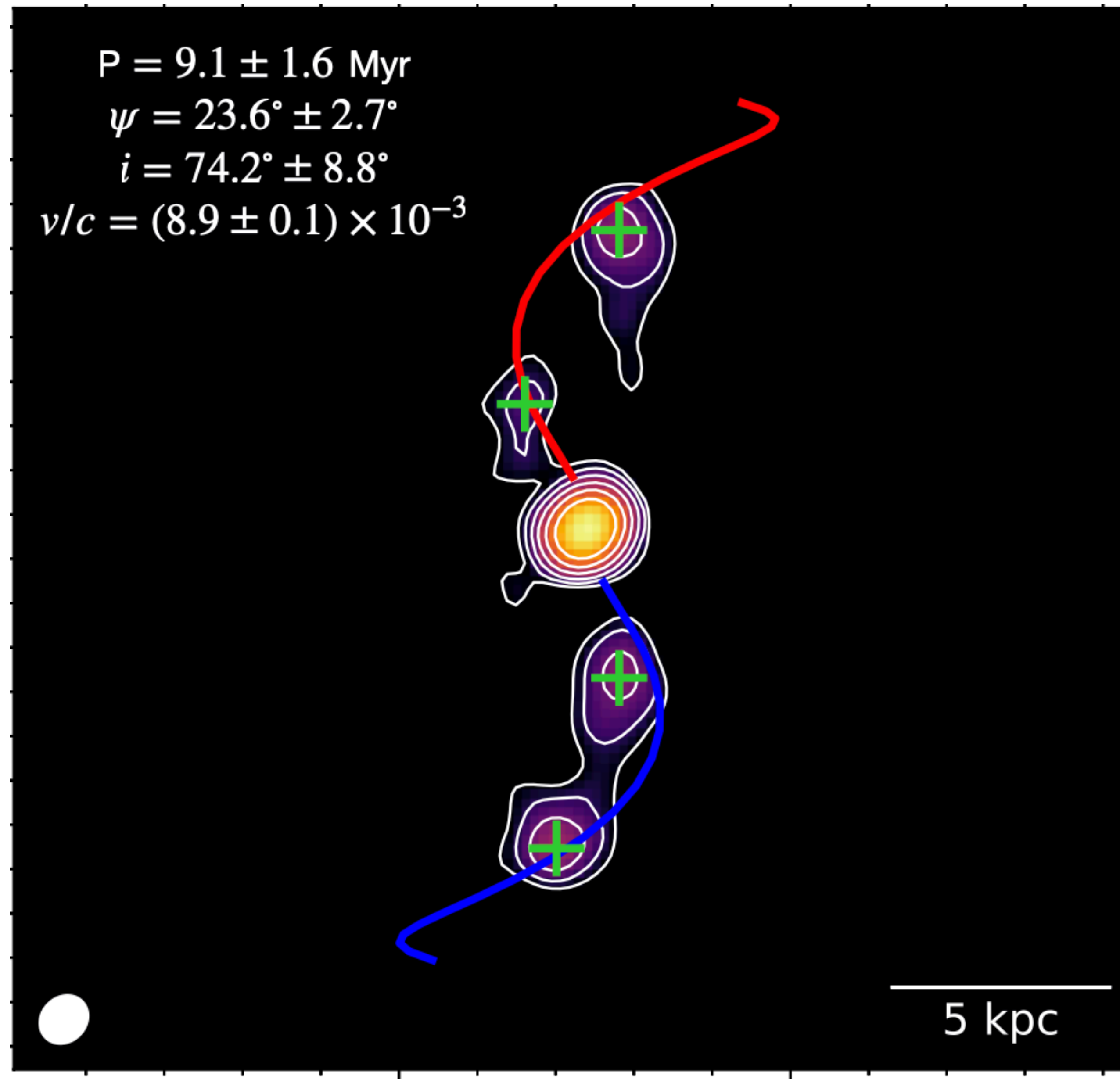
Binary separation from jet precession model:

e.g., Krause et al. (2019); Horton et al. (2020, 2023)

$$d_{sep} \lesssim 0.6 \text{ pc}$$

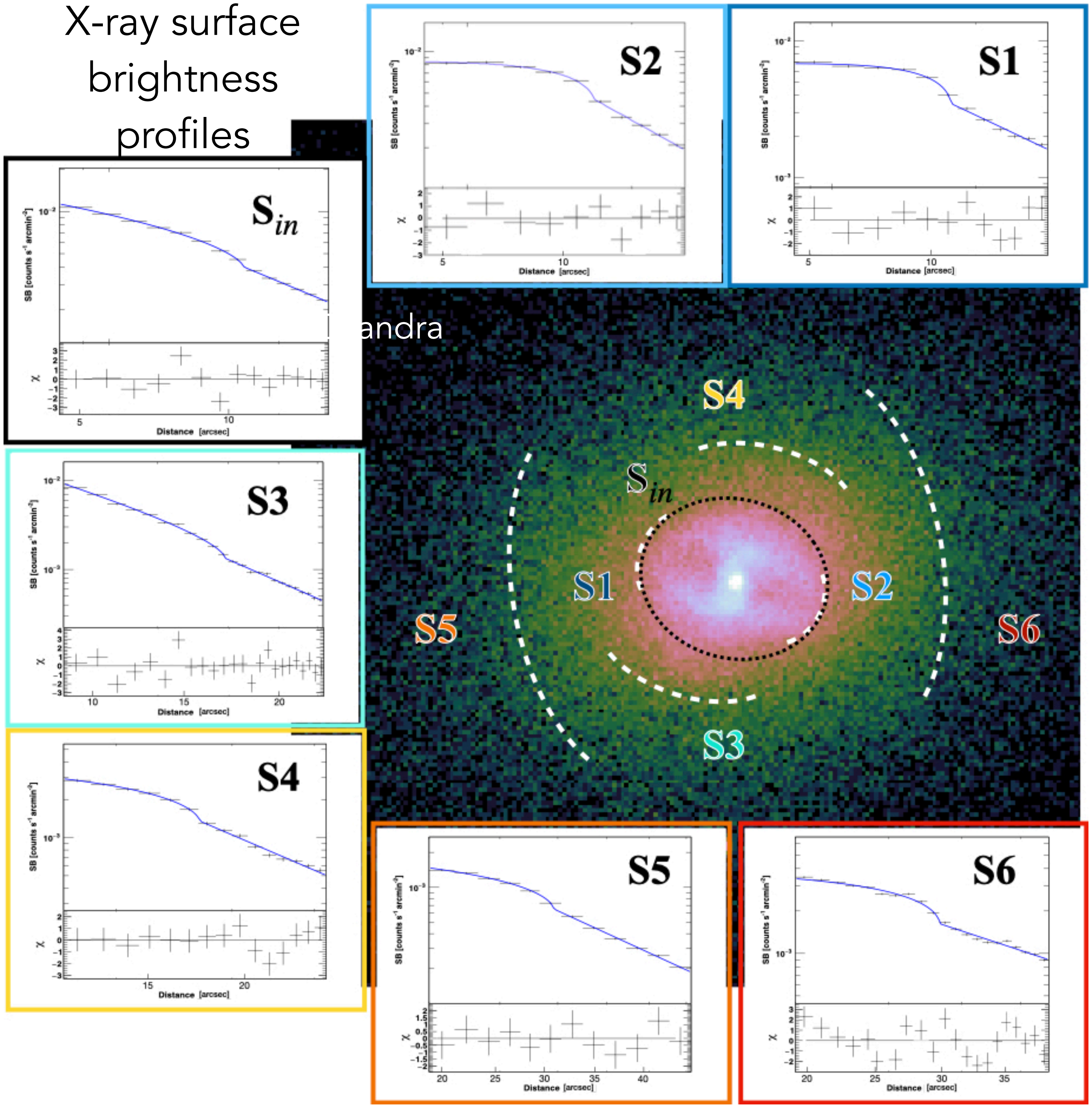
↓

An order of magnitude smaller than our best VLBI resolution (5 pc)!



Shock Fronts in the Cool Core Cluster RBS 797

X-ray surface brightness profiles

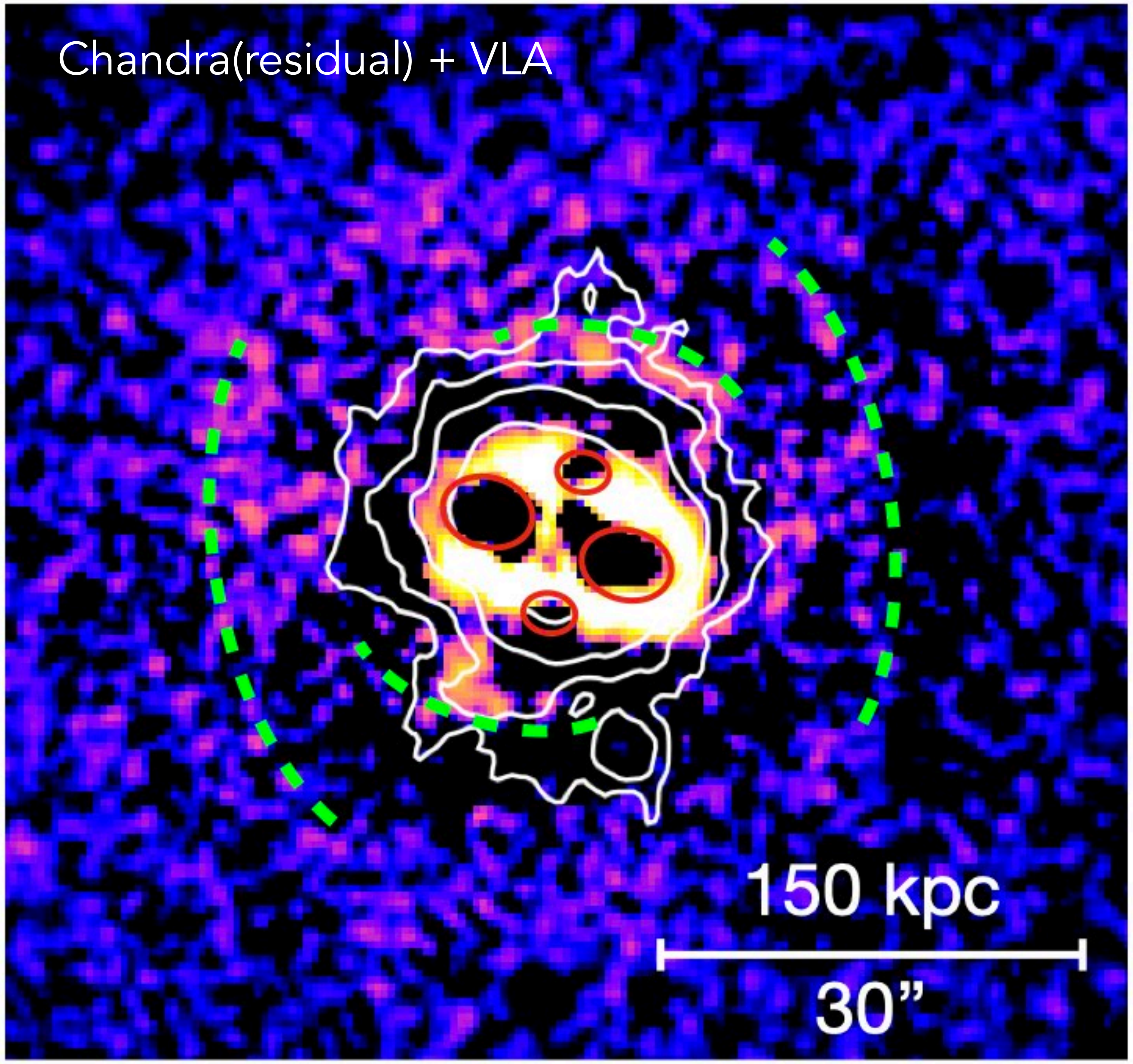


Ubertosi et al. (2021b) and Ubertosi et al. (2023b)

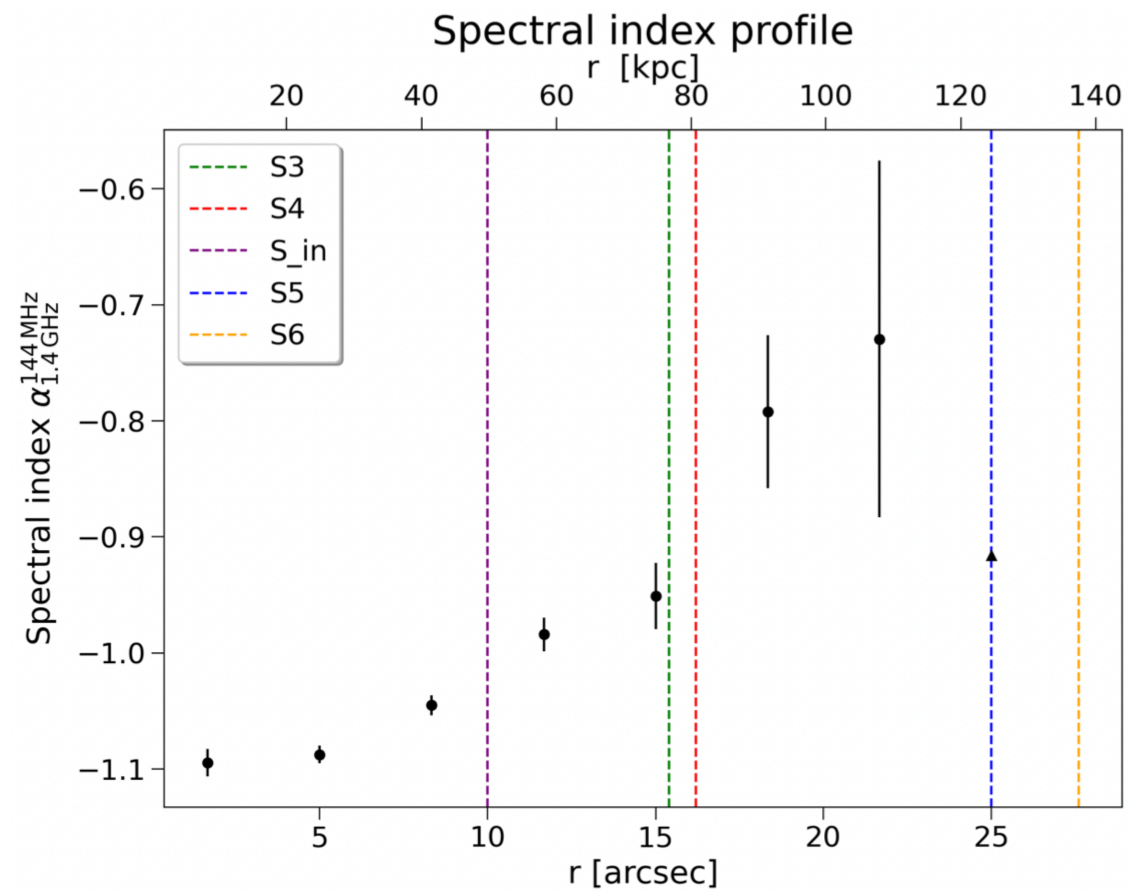
In RBS 797 there are **three pairs of nested shock fronts** centered on the AGN, with Mach numbers in the range $1.1 \leq \mathscr{M} \leq 1.2$

→ weak shocks **driven by AGN jet** expansion in the ICM

Shocks-mini halo connection in RBS 797



The radio emission appears "caged" within the middle shock front

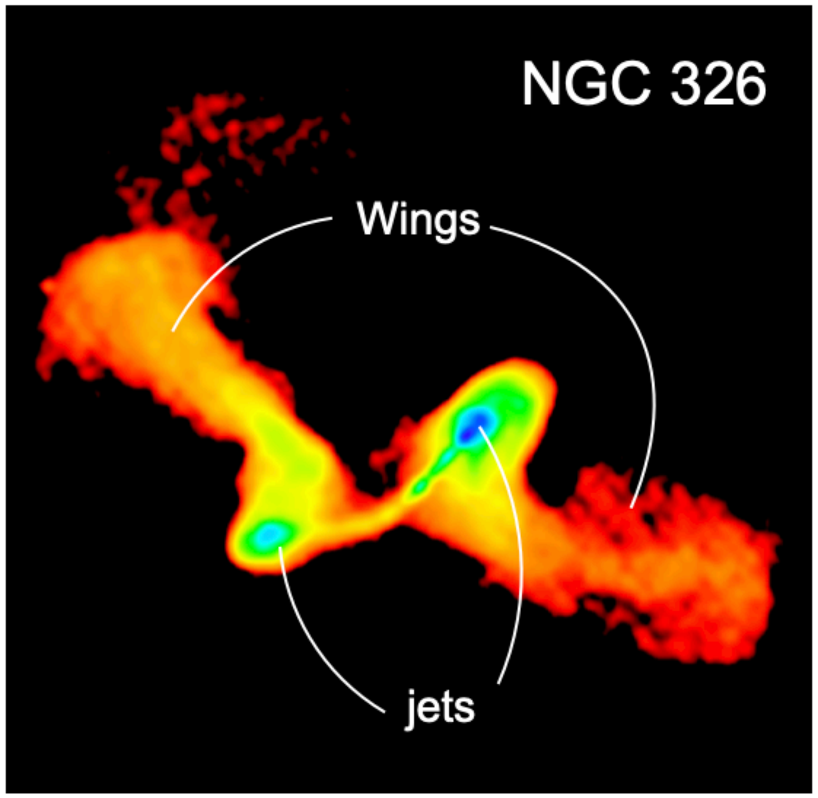


Bonafede et al. (2023)

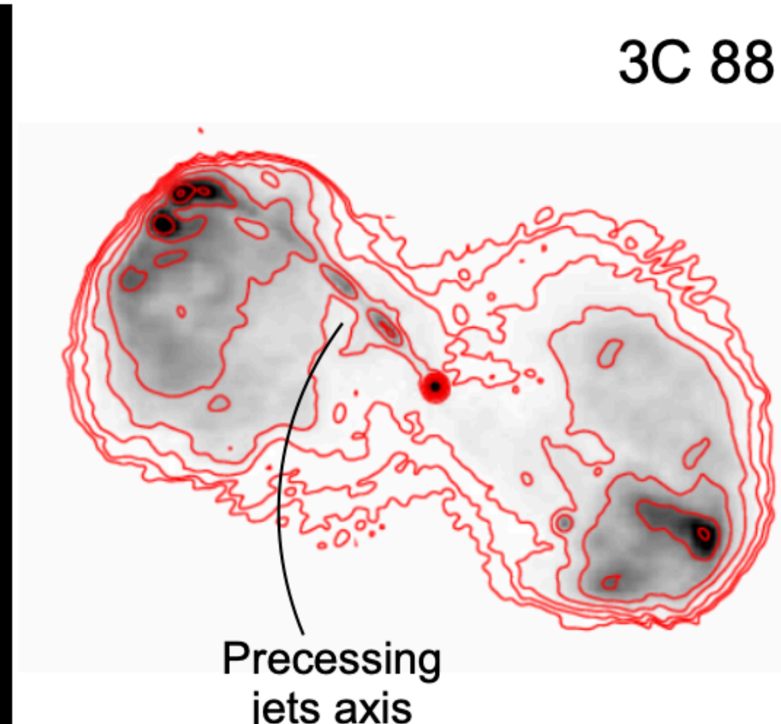
A connection between the shock fronts and the diffuse radio emission in the cluster?

Changing the Axis of AGN Relativisti Jets

Jets from a single active SMBH

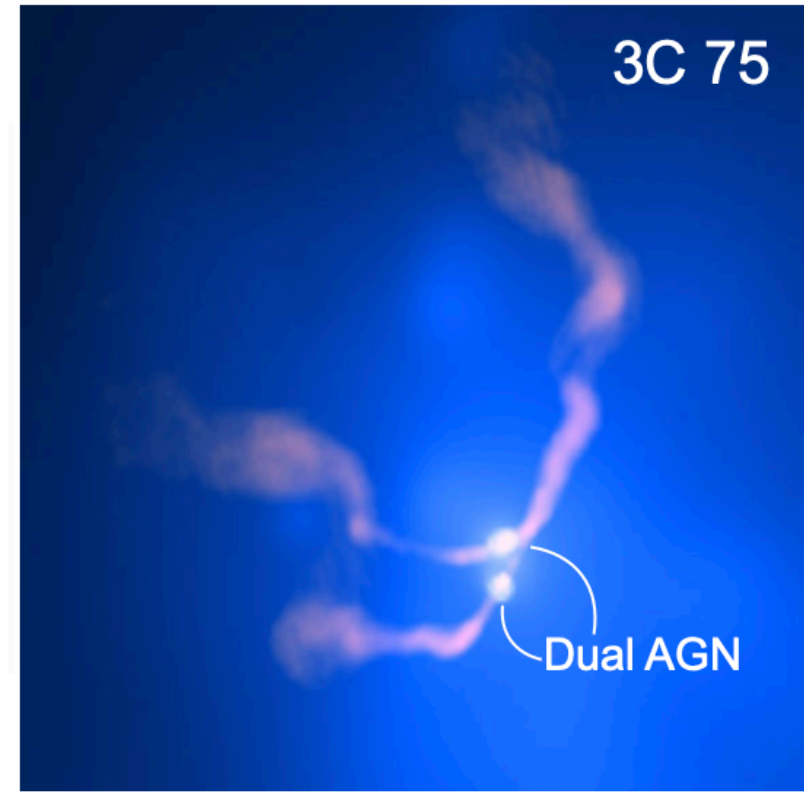


Murgia et al. 2001

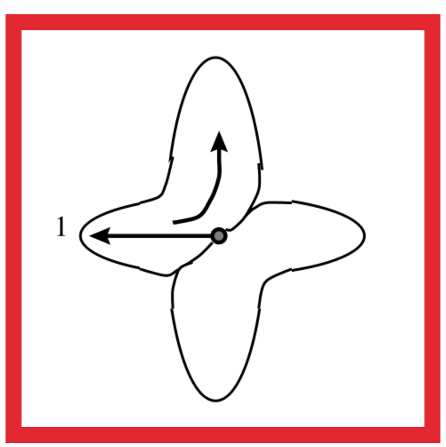


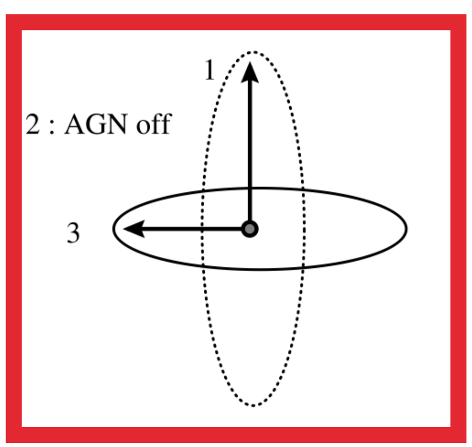
Liu et al. 2019

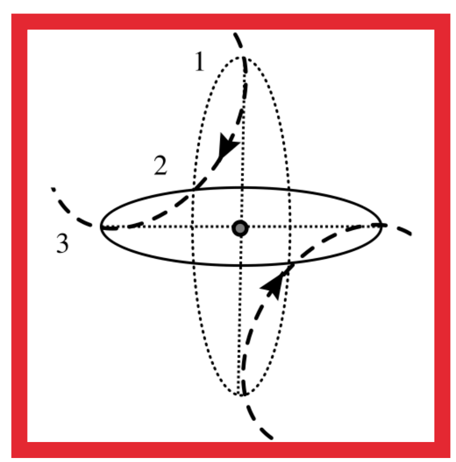
Jets from binary active SMBH



Hudson et al. 2006







Some of these models require a secondary (inactive) binary SMBH