AGN jet feedback & life cycle

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INAF PhD School “Franchesco Lucchin”, Bertinoro, October 2026

AGN (jet) feedback

i.e. impact of energy release on external medium

Needed to explain evolution of galaxies and large-scale structure:

- Explain correlation bewteen BH and host galaxy properties
- Suppress star formation in the most massive galaxies to reproduce the high-mass end of the galaxy luminosity function
- Prevent cooling flows in galaxy clusters
- Explain the baryon content of galaxy groups/clusters

e.g. McNamara & Nulsen (2012) , Fabian (2012) Hardcastle & Croston (2020), Harrison & Ramos Almeida (2024)

AGN (jet) feedback

i.e. impact of energy release on external medium



Winds vs jets



Gas winds driven by radiative pressure from the accretion disk

<u>High accretion rate AGN</u>

Jets of relativistic particles

<u>(Mostly) Low accretion rate AGN</u>

AGN (jet) feedback

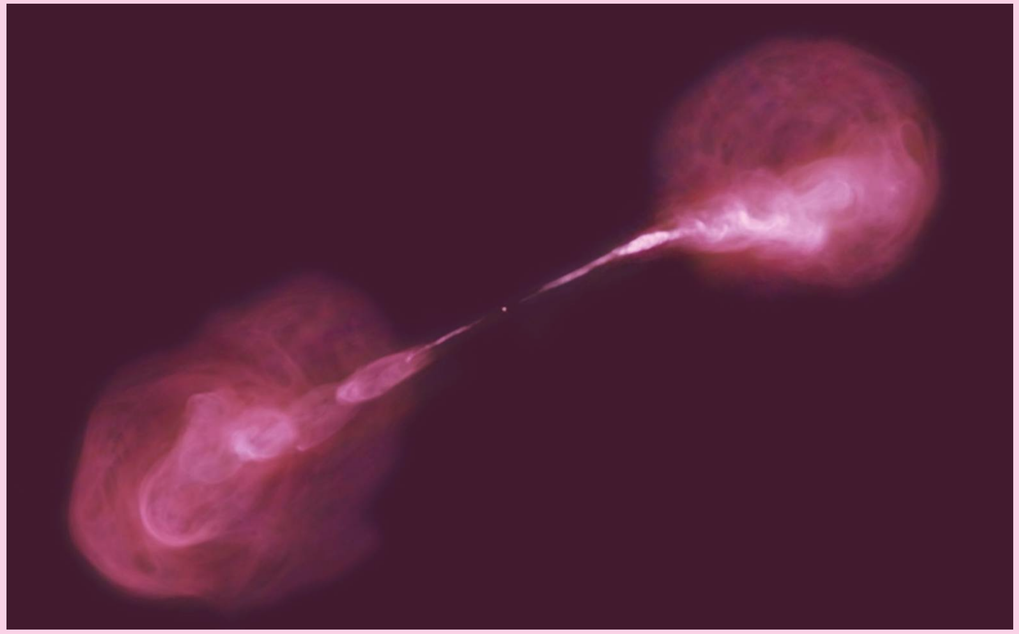
i.e. impact of energy release on external medium



Gas winds driven by radiative pressure from the accretion disk

High accretion rate AGN

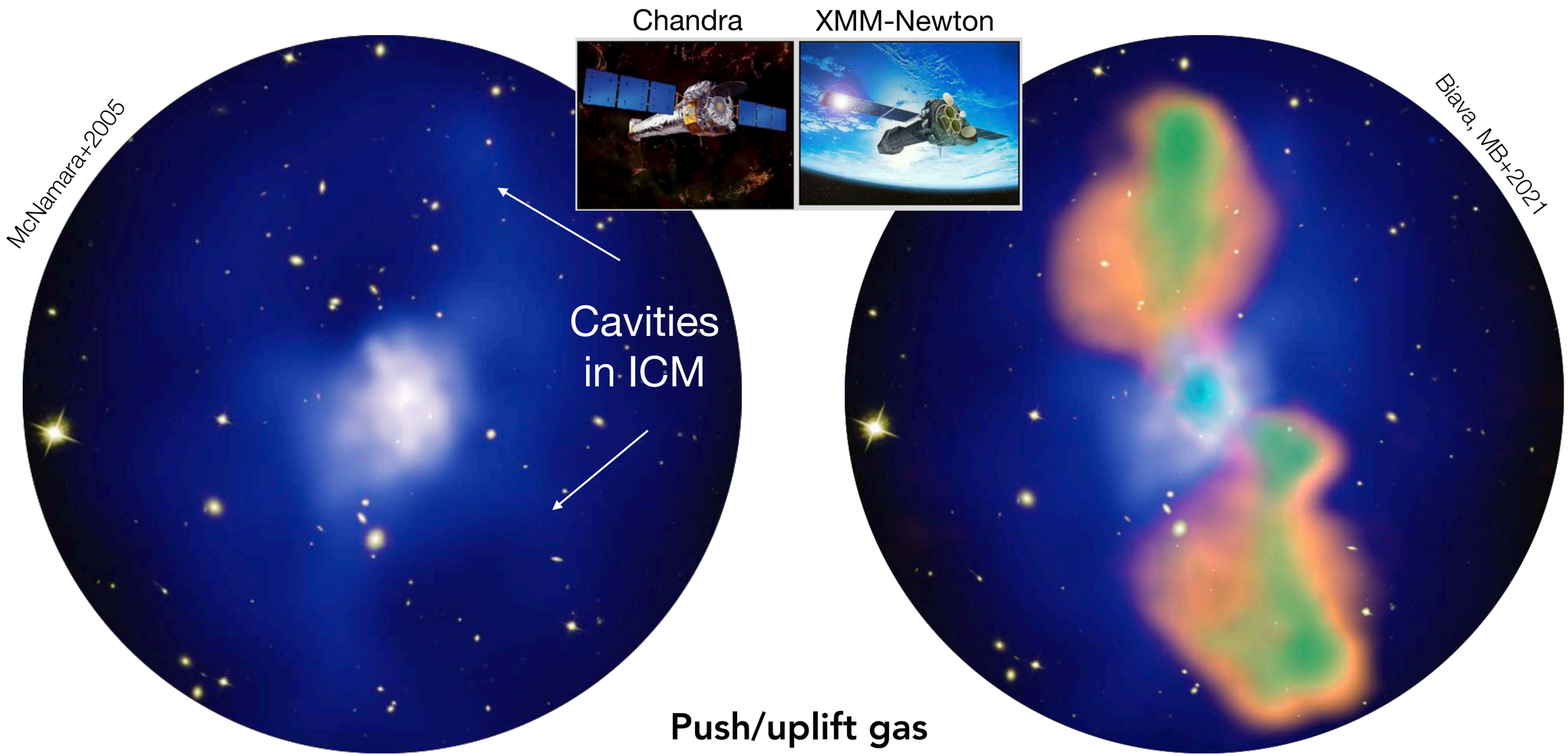
Winds vs jets



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AGN jet feedback in galaxy groups and clusters



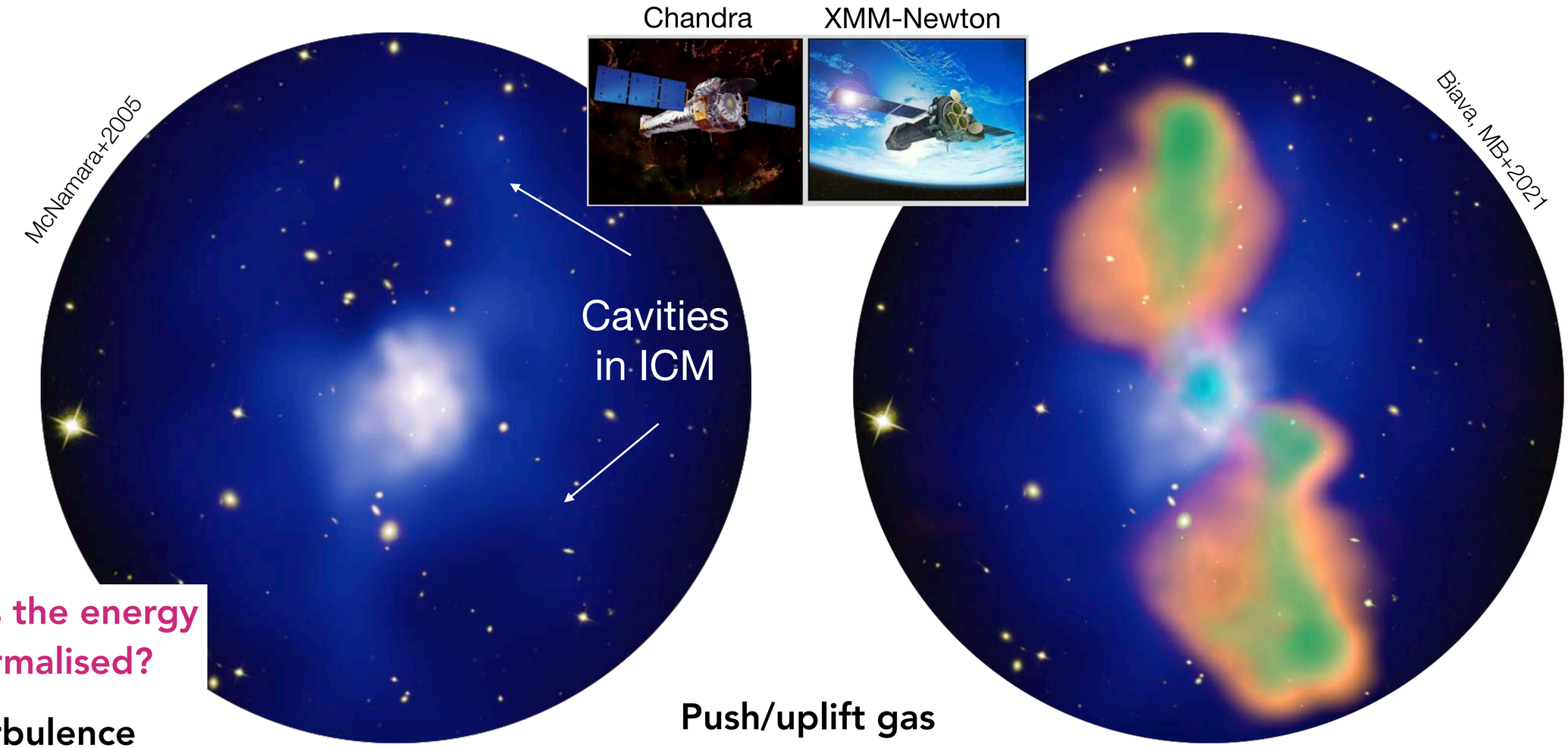
Push/uplift gas

<u>Also when jets switch off!</u>

Mechanical power can be inferred…

see next lecture! Spoiler…Power= 1e40-1e46 erg/s

AGN jet feedback in galaxy groups and clusters



How is the energy thermalised?

Turbulence
Shocks/soundwaves
Mixing

Push/uplift gas

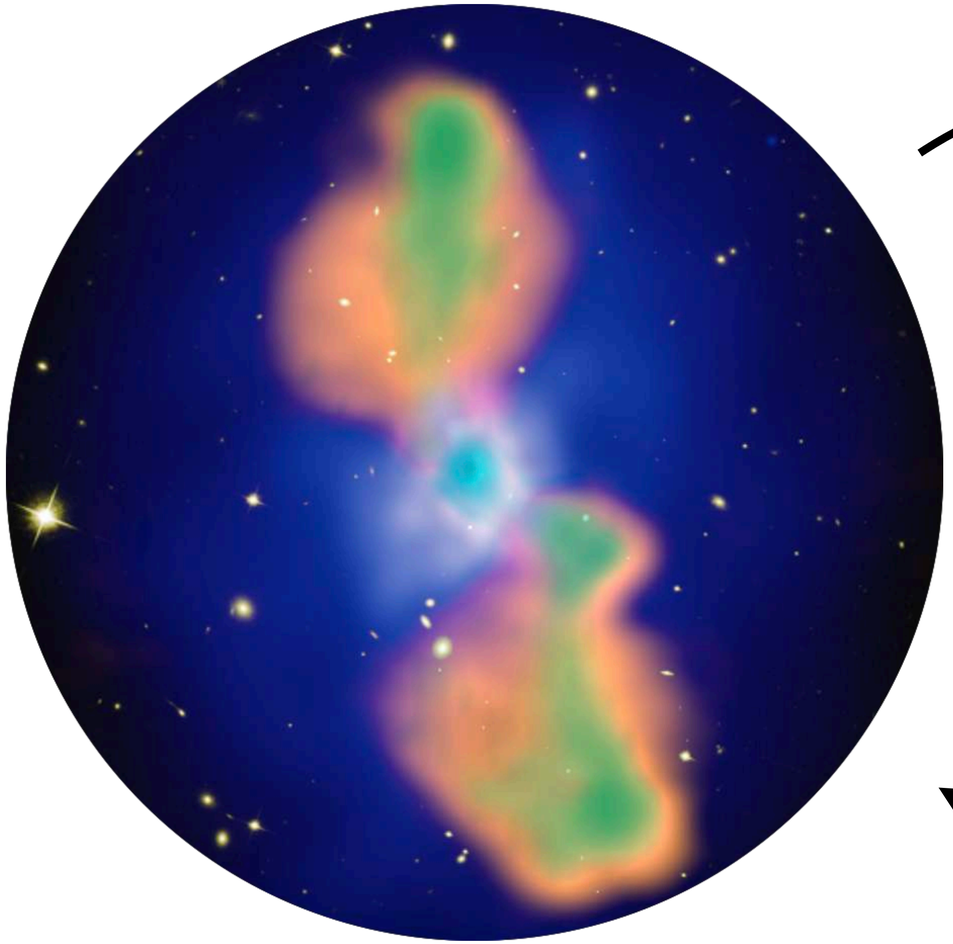
<u>Also when jets switch off!</u>

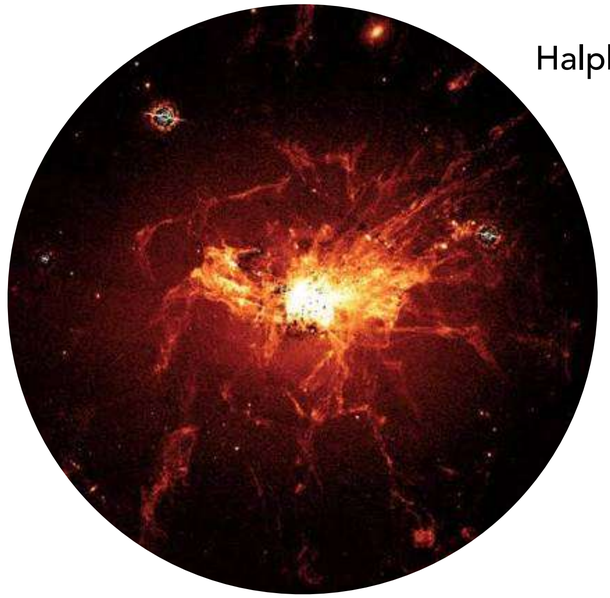
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see next lecture! **Spoiler…Power= 1e40-1e46 erg/s**

AGN jet feedback in galaxy groups and clusters

Autoregulated Feeding - Feedback loop



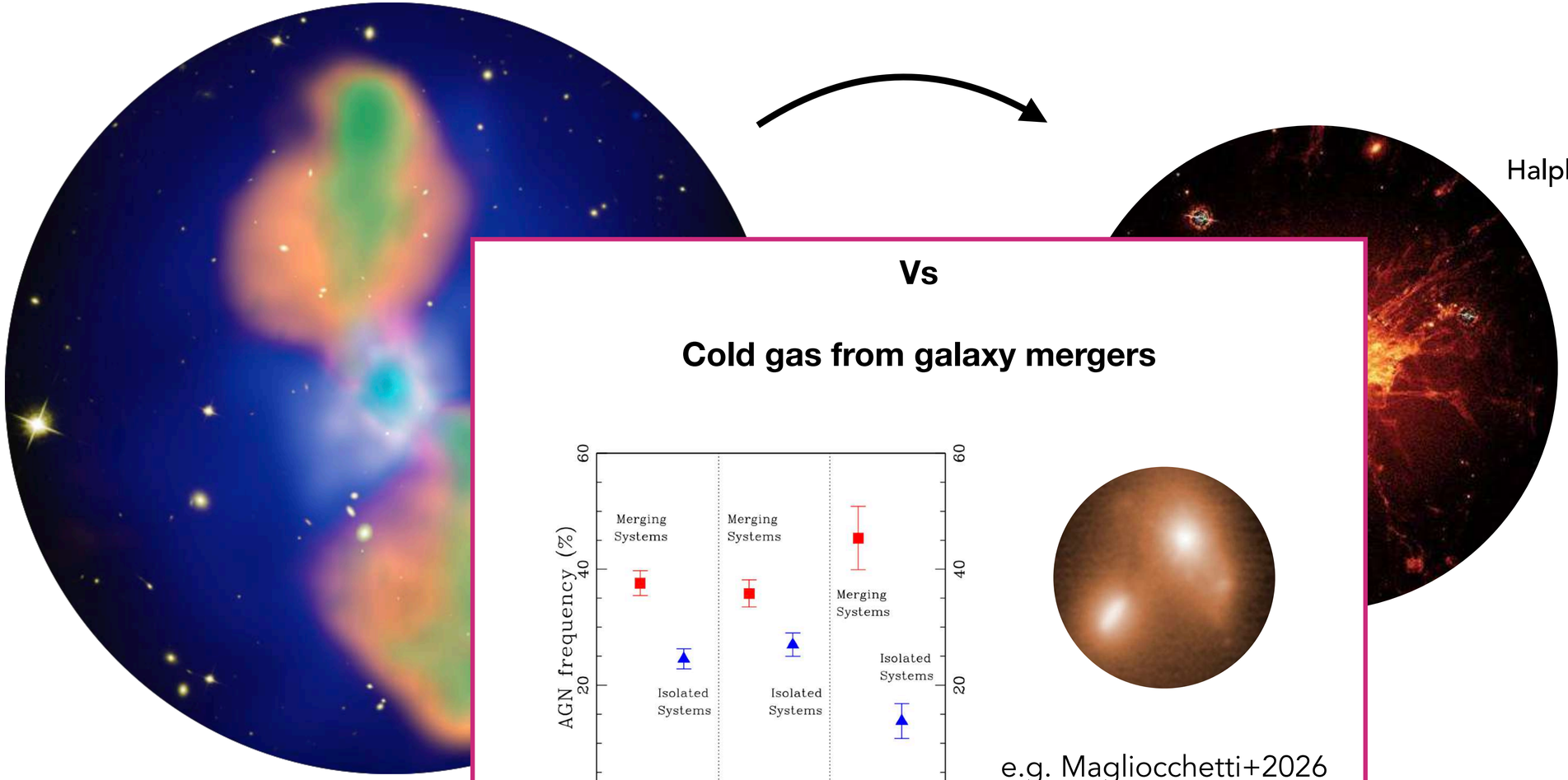


Fabian+2008
Halpha, Perseus cluster

SMBH accretes gas from hot halo forming jets until heating stops cooling,
jets switches off -> cooling can restart

AGN jet feedback in galaxy groups and clusters

Autoregulated Feeding - Feedback loop



Fabian+2008
Halpha, Perseus cluster

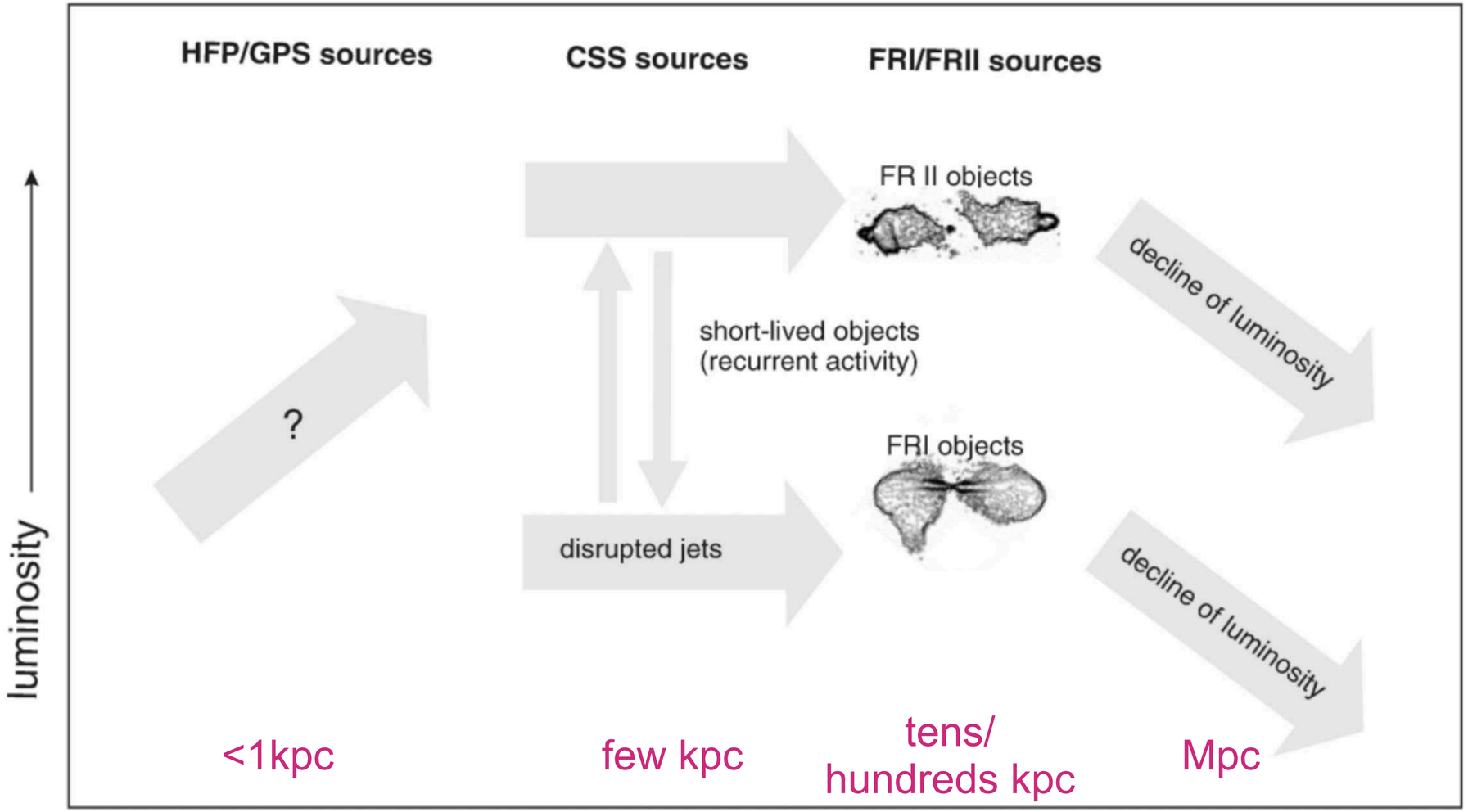
SMBH accre ting stops cooling,

Vs

Cold gas from galaxy mergers

e.g. Magliocchetti+2026
LOFAR+Euclid

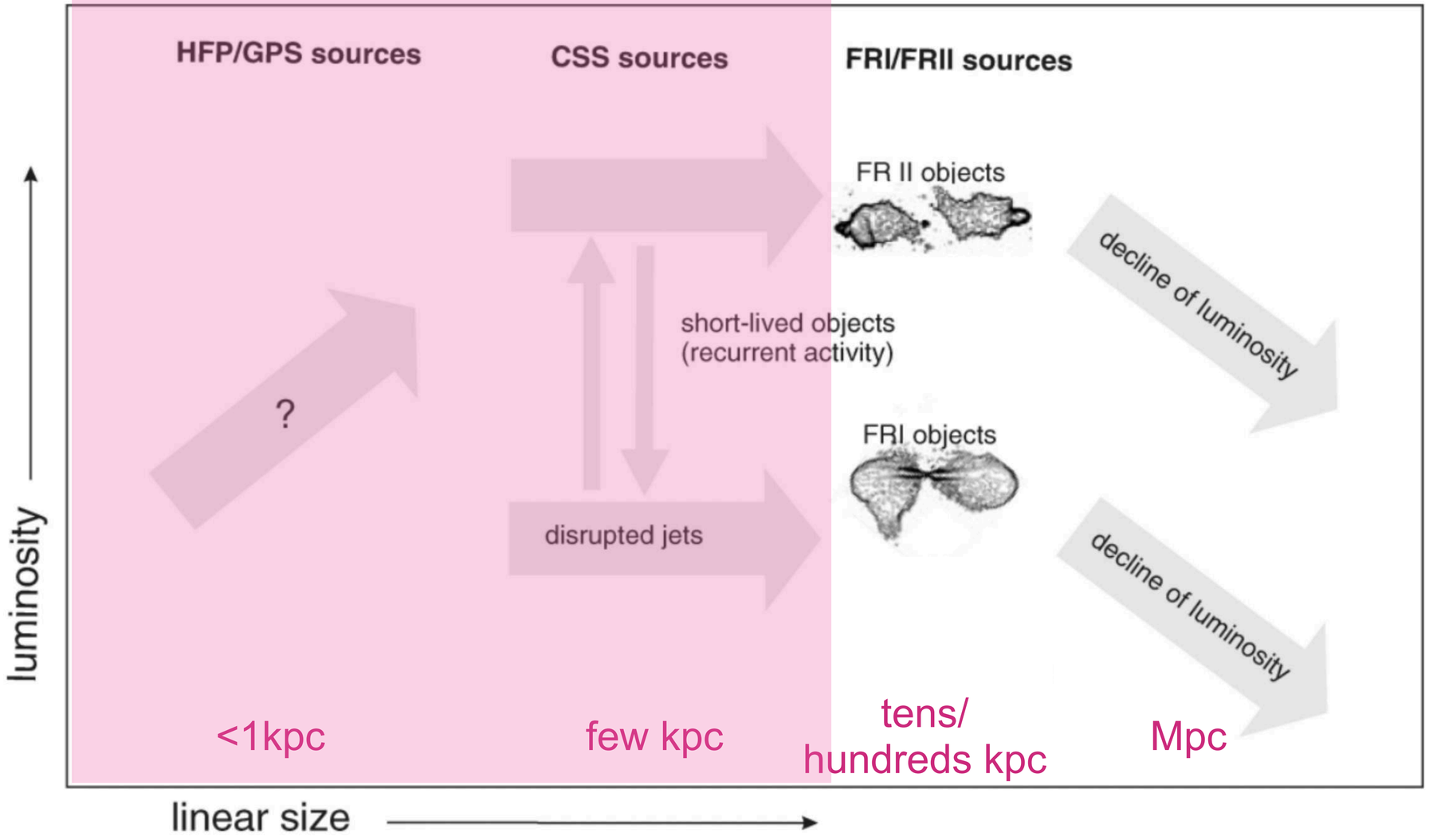
AGN jet release energy on galaxy scale (kpc)



Kunert-Bajraszewska et al. (2010)

AGN jet release energy on galaxy scale (kpc)

Most jets in the Universe!

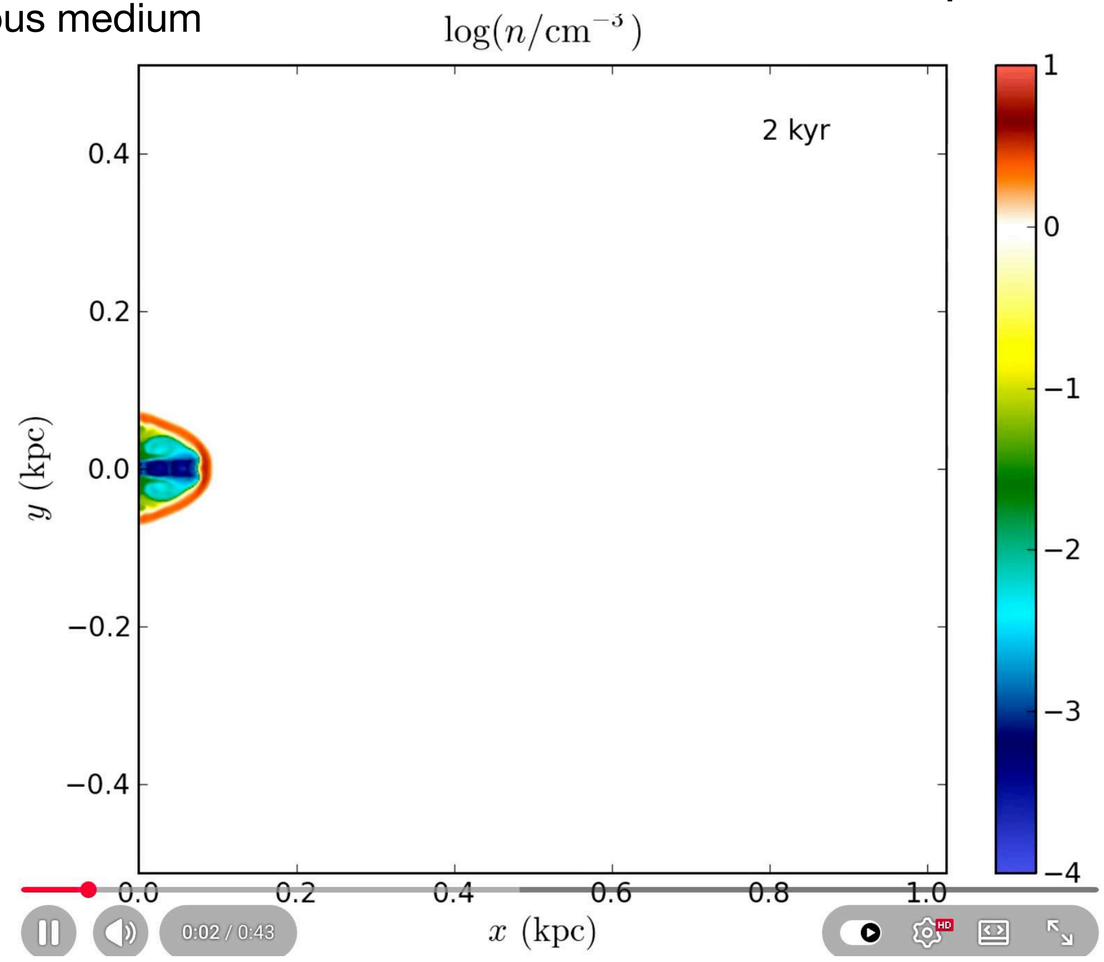


Kunert-Bajraszewska et al. (2010)

AGN jet release energy on galaxy scale (kpc)

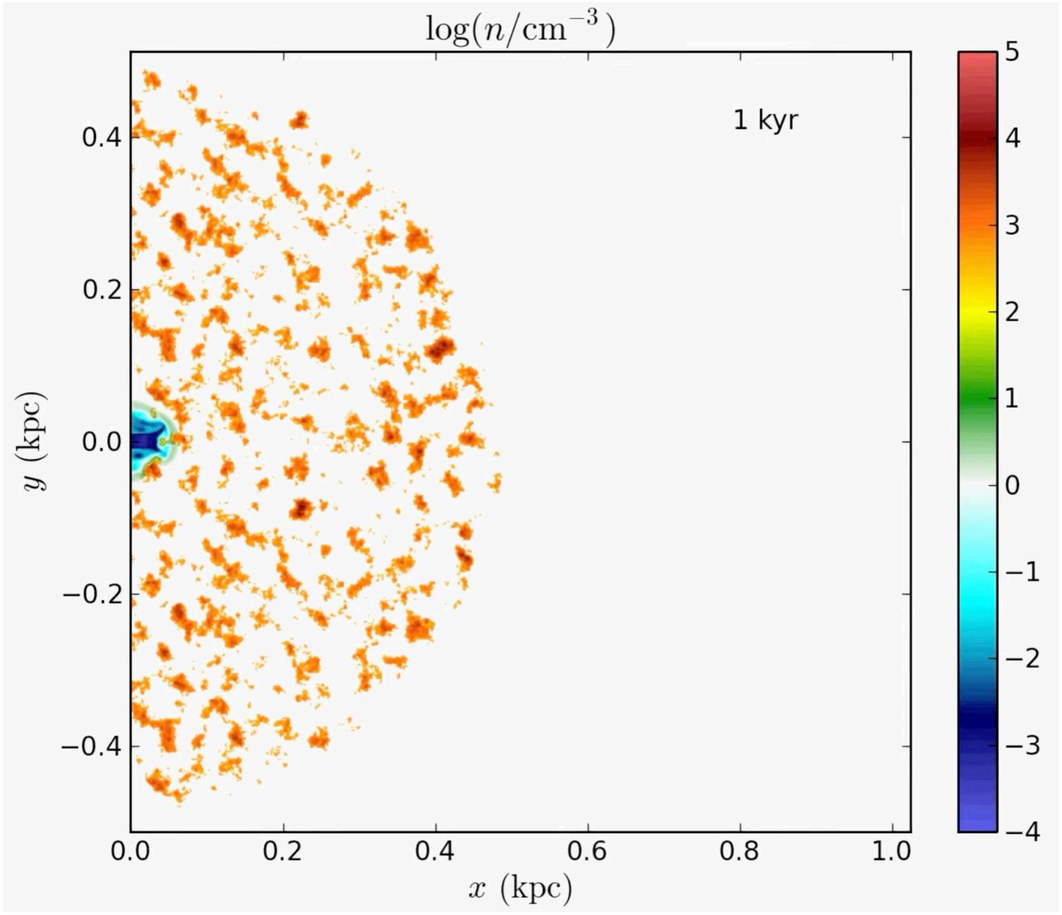
Jet power = 1e45 erg/s

Homogeneous medium



Clumpy medium

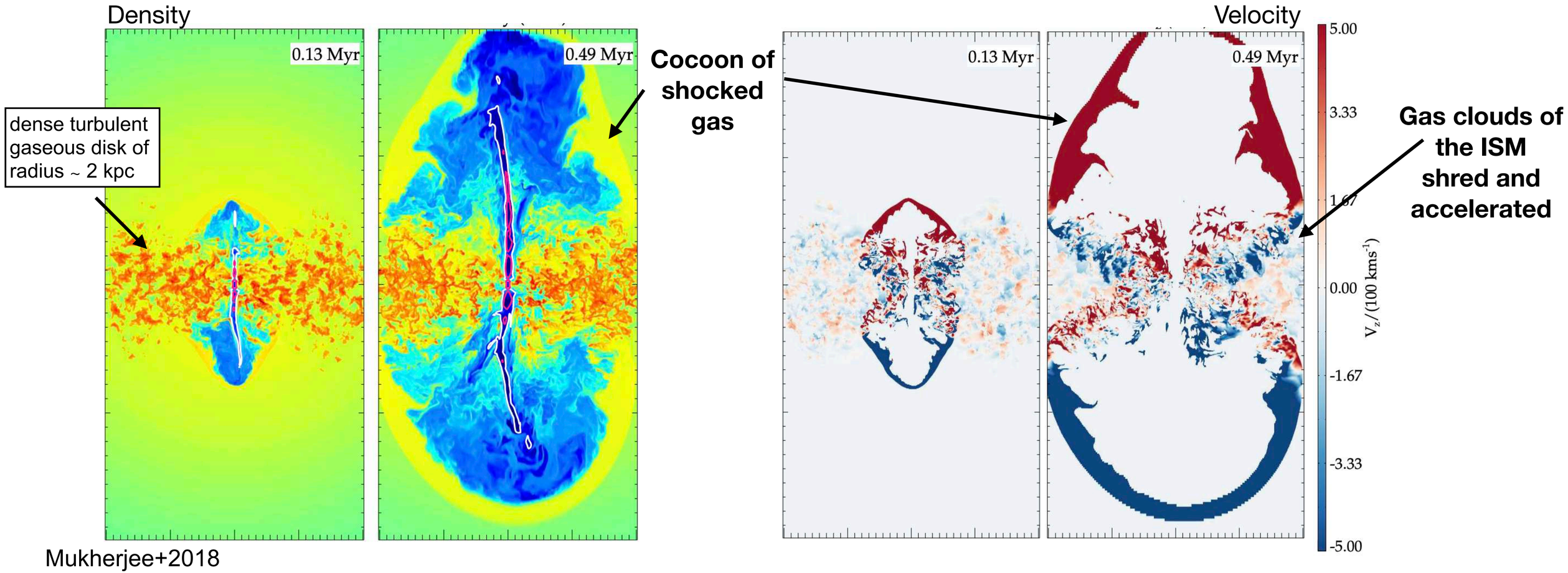
Hot halo 1e7 K + clouds 1e4 K



Jets with powers in the range of 1e43–1e46 erg/s can inhibit star formation through the dispersal of dense gas in the galaxy core

Wagner+2011

AGN jet release energy on galaxy scale (kpc)



Mukherjee+2018

Simulations predict that even low power jets expanding in a clumpy medium (ISM) can efficiently couple to it as they are trapped for longer time

-> feedback even stronger if jet axis in the disk plane

AGN jet release energy on galaxy scale (kpc)

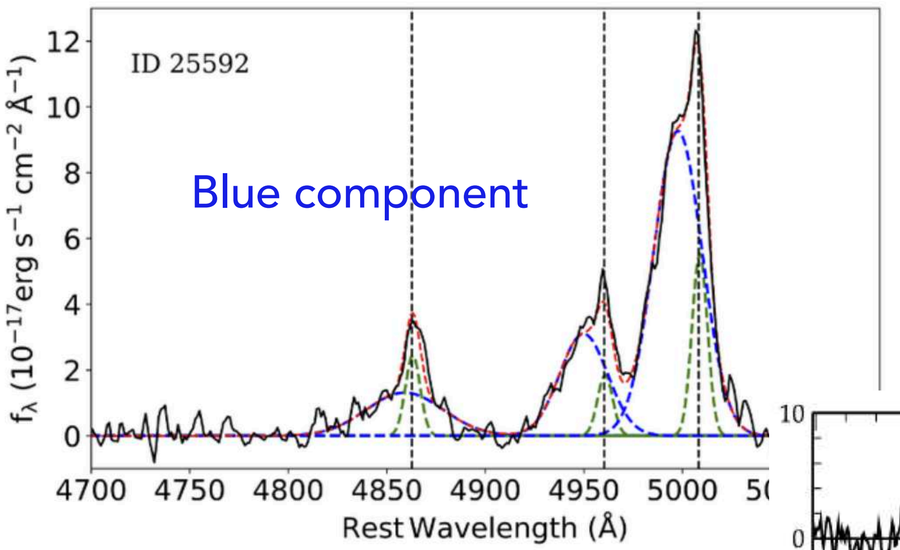
MULTI-SCALE & MULTI-PHASE

IONISED, ATOMIC, MOLECULAR OUTFLOWS

kpc scale or beyond

mass outflow rates 10-100s M⊙/yr

vout ~ 500 – 2000 km/s



OIII emission

Musiimenta et al. 2023

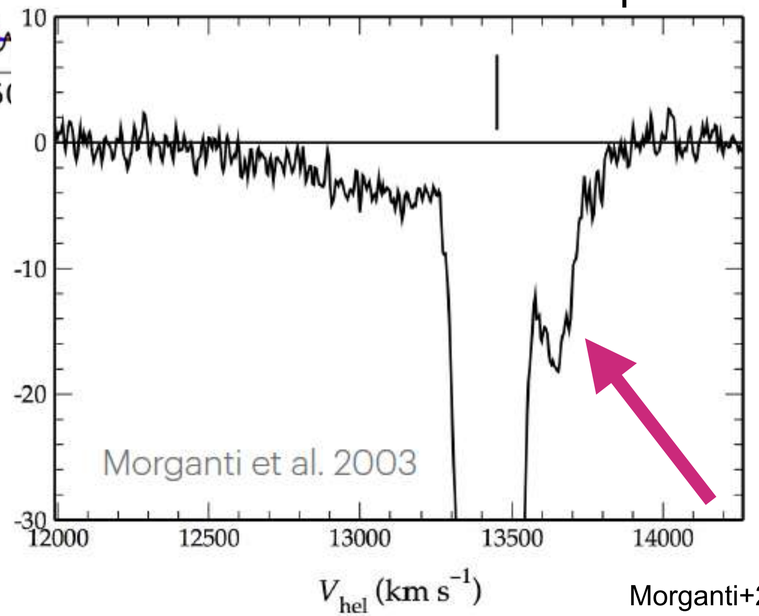
Outflows

Wings with respect to systemic velocity

Turbulence

Large velocity dispersions

HI absorption



Morganti+2005

AGN jet release energy on galaxy scale (kpc)

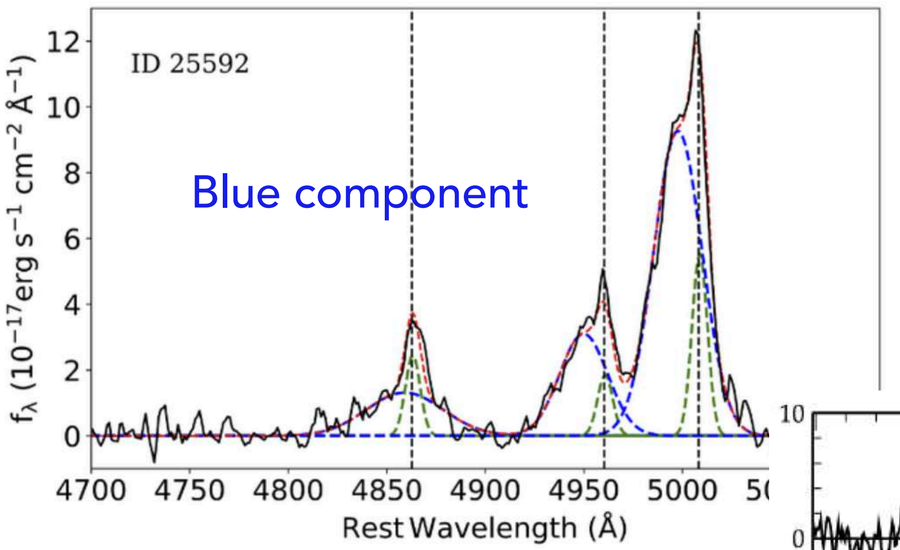
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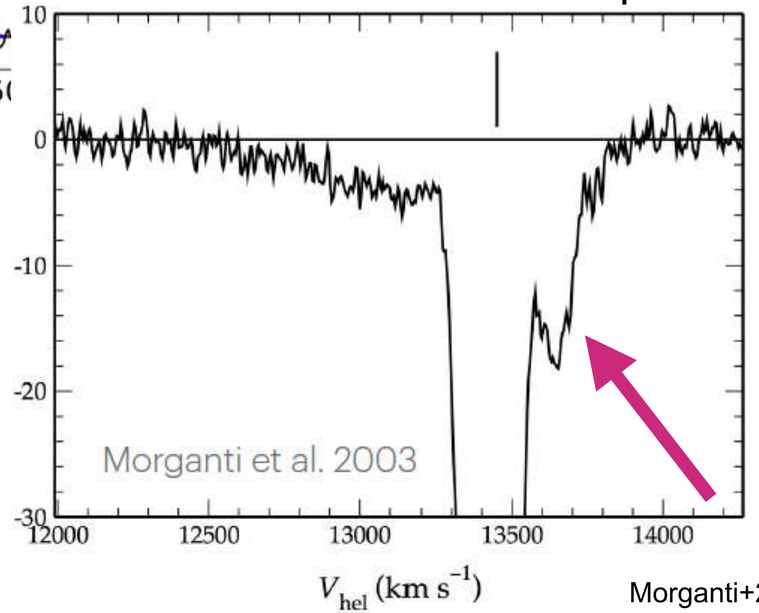
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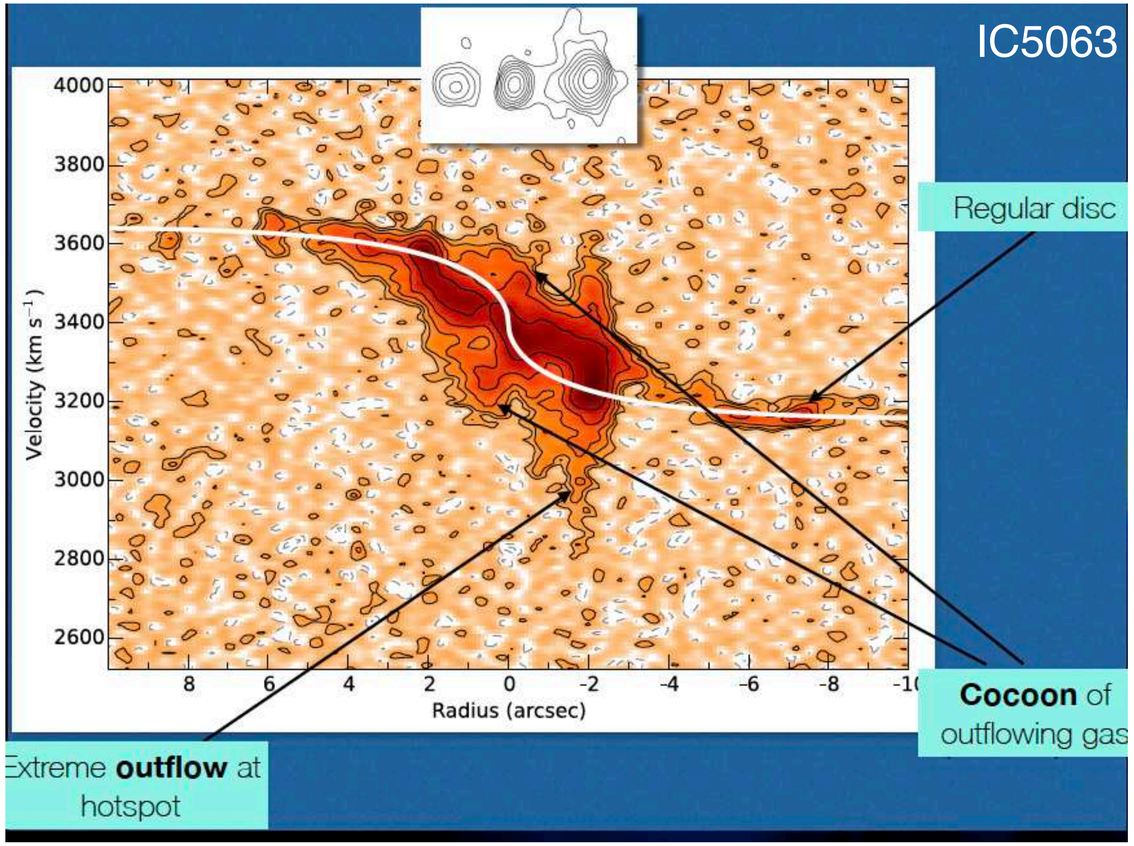
An ocean of literature!

What is driving these galaxy scale outflows?

AGN jet release energy on galaxy scale (kpc)

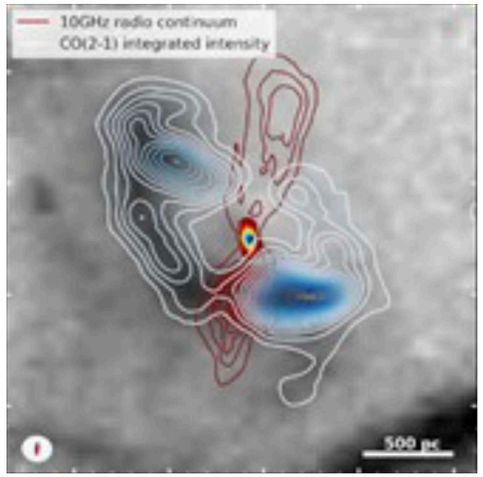
Outflows + turbulence

CO



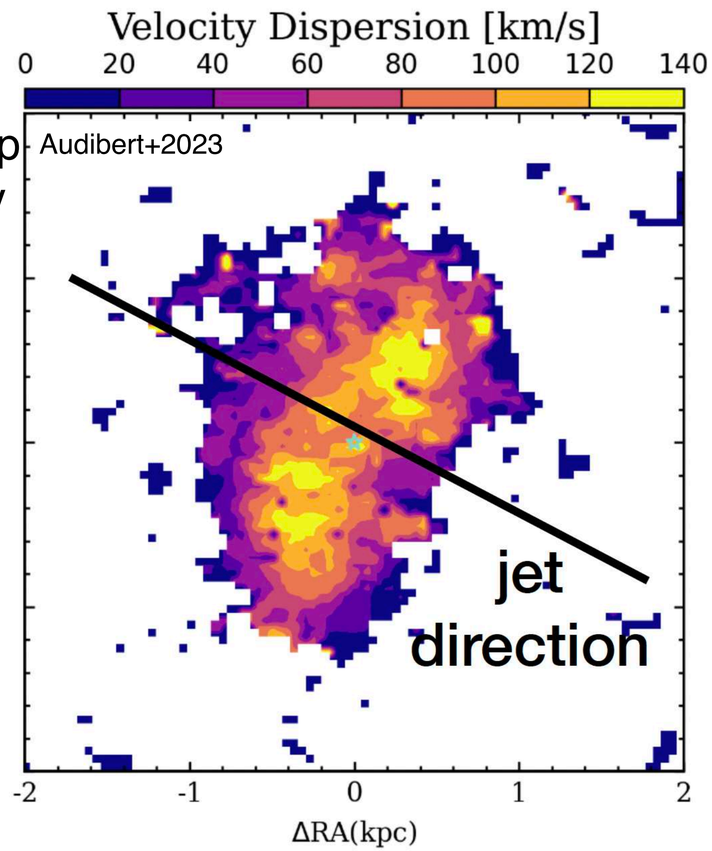
Morganti +15, Tadhunter+14, Dasyra+16
Oosterloo +17, Nesvadba+ 2021, Murthy+2019 and many others

White = CO, red = jet



Ruffa+2022

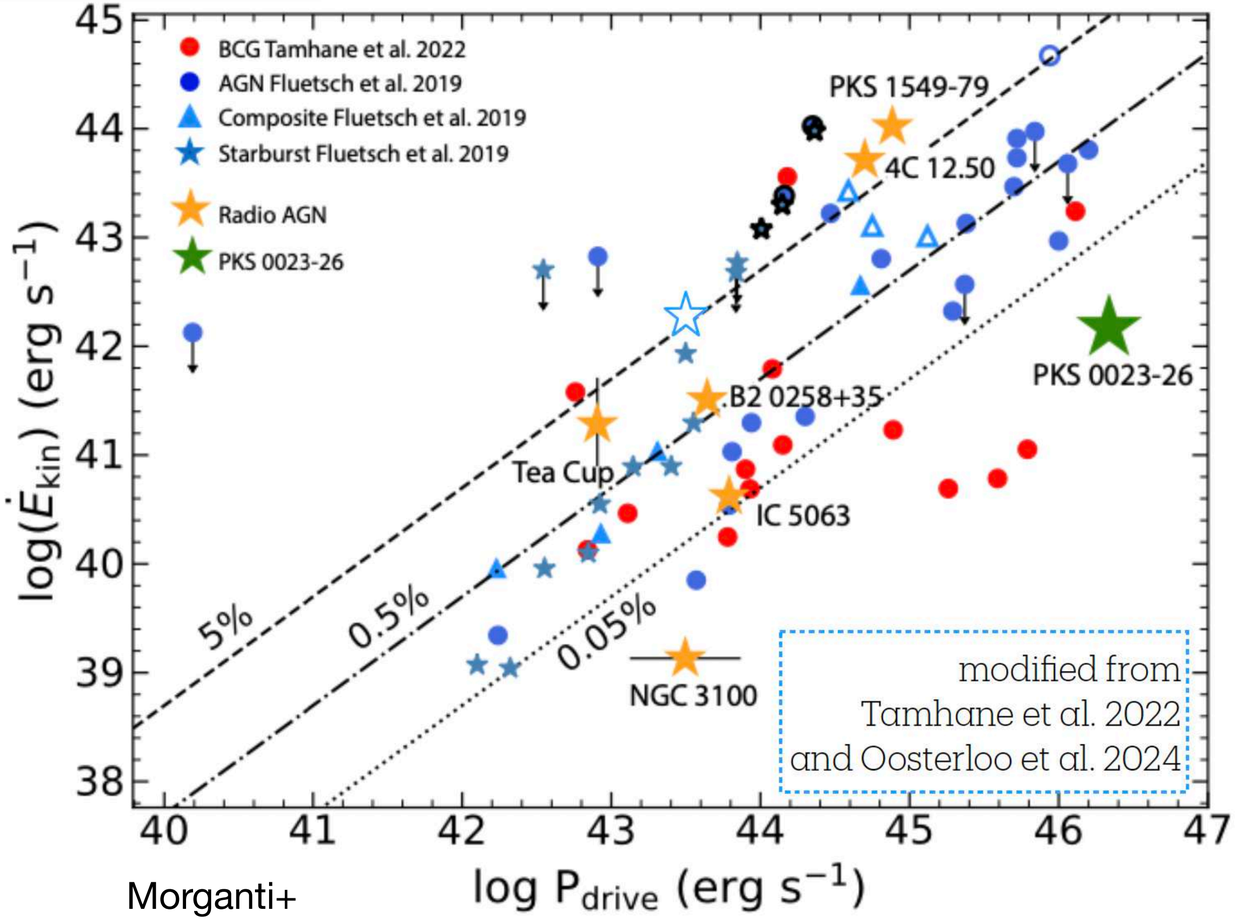
Teacup galaxy



Distribution of the gas perpendicular to jet direction with high velocity dispersion = turbulence!

AGN jet release energy on galaxy scale (kpc)

$$\dot{E}_{\rm kin} = \frac{1}{2}\dot{M}v^2$$



Morganti+

$\dot{E}_{kin}/P_{jet}$ between ~5% and <0.5% = a small fraction of the jet power goes into accelerating the gas BUT rest is dissipated as heat or contributes to turbulent motions within the ISM (prevents gas from cooling)

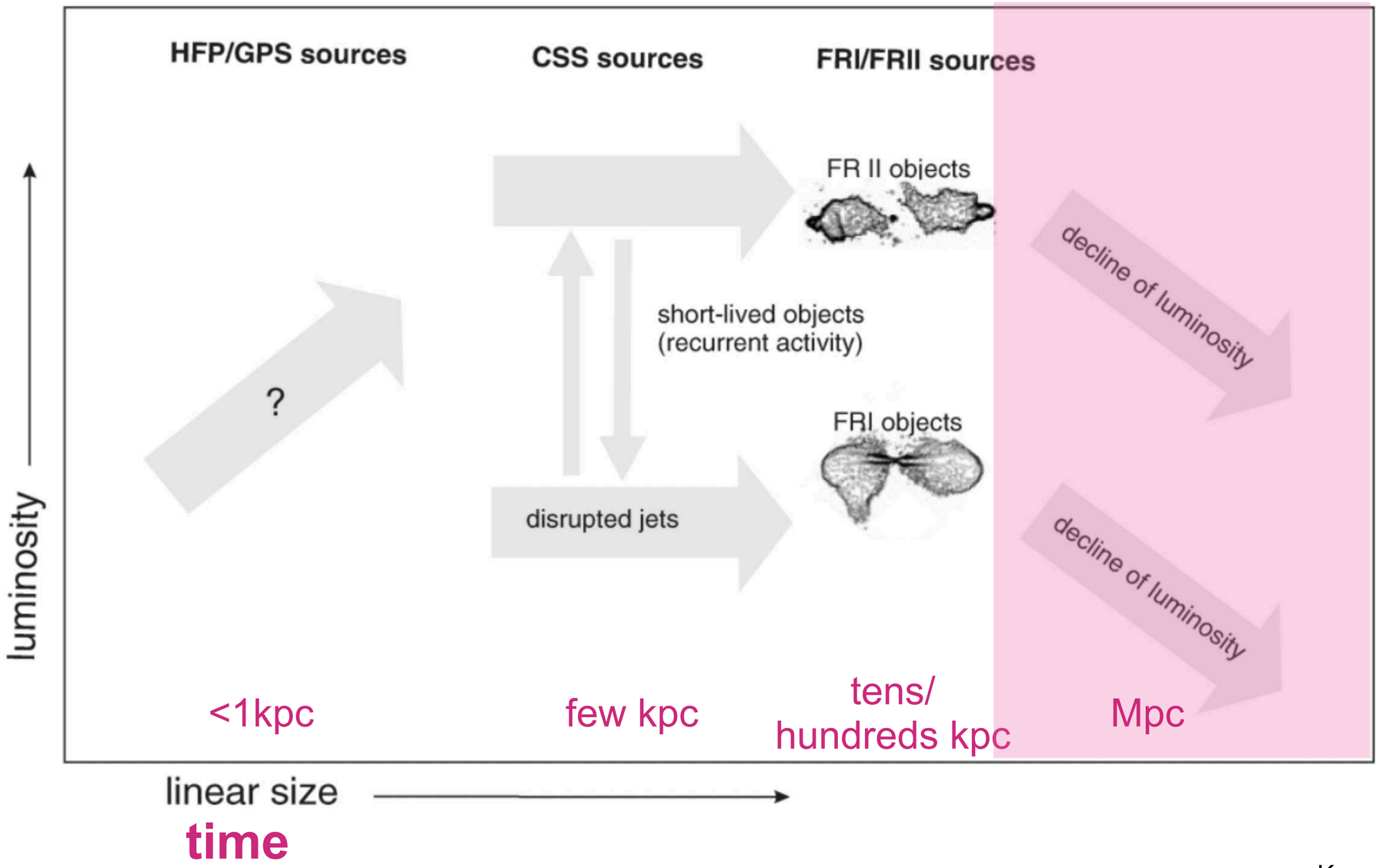
Impact on star formation in the host galaxy difficult to quantify:

- different time scales and cumulative effects possibly dominating

- outflows relatively short living -> small fraction of mass leaving the galaxy

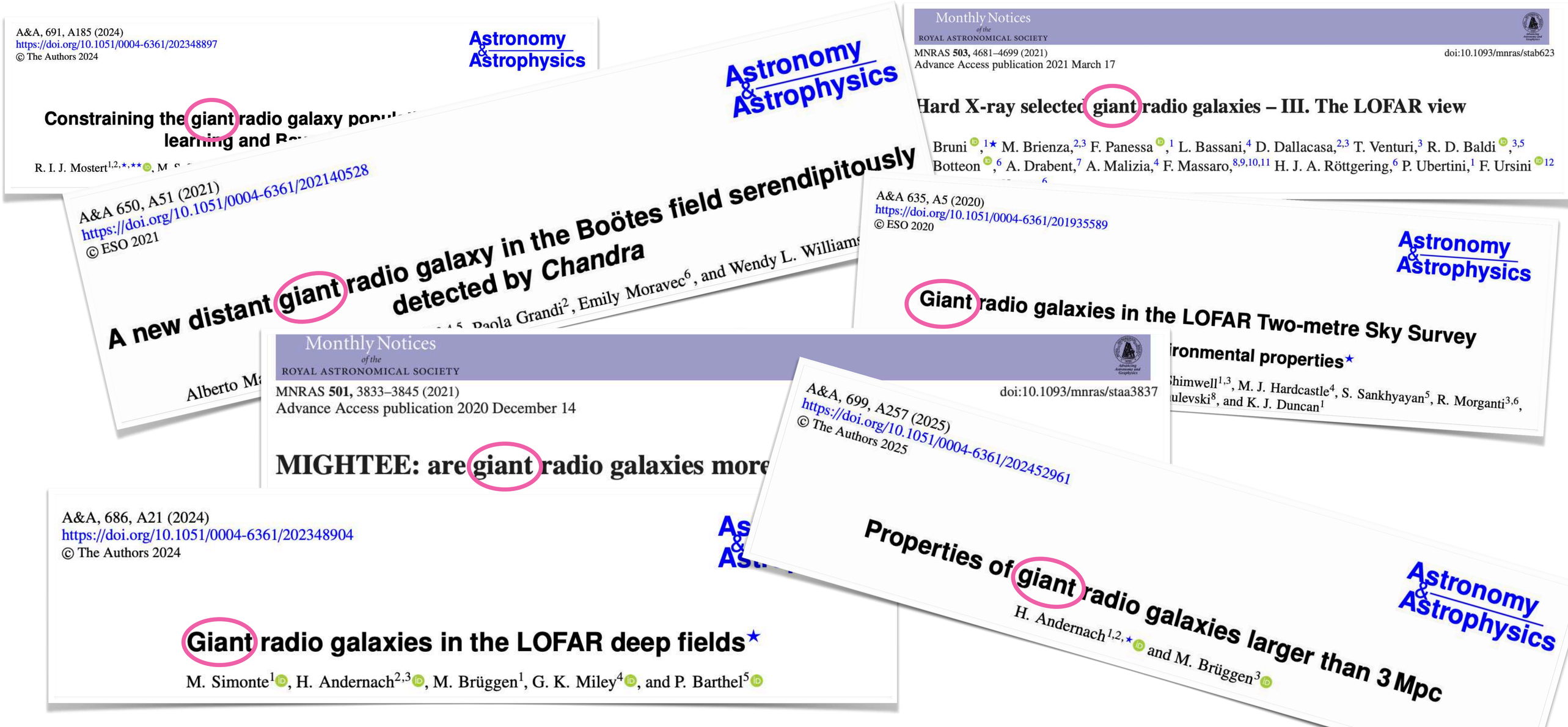
Outflow power vs Power of jet/wind/SF $P_{drive} = P_{mech}$ for jets

AGN jet release energy on the scale of the cosmic web (Mpc)



Kunert-Bajraszewska et al. (2010)

AGN jet release energy on the scale of the cosmic web (Mpc)



A&A, 691, A185 (2024)
https://doi.org/10.1051/0004-6361/202348897
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Astronomy & Astrophysics

Constraining the giant radio galaxy popu… learning and Ba…

R. I. J. Mostert[1,2,★,★★], M. S…

A&A 650, A51 (2021)
https://doi.org/10.1051/0004-6361/202140528
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Astronomy & Astrophysics

A new distant giant radio galaxy in the Boötes field serendipitously detected by Chandra

Alberto Ma… Paola Grandi[2], Emily Moravec[6], and Wendy L. Williams

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS 501, 3833–3845 (2021)
Advance Access publication 2020 December 14
doi:10.1093/mnras/staa3837

MIGHTEE: are giant radio galaxies more…

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS 503, 4681–4699 (2021)
Advance Access publication 2021 March 17
doi:10.1093/mnras/stab623

Hard X-ray selected giant radio galaxies – III. The LOFAR view

…Bruni[1★], M. Brienza[2,3], F. Panessa[1], L. Bassani[4], D. Dallacasa[2,3], T. Venturi[3], R. D. Baldi[3,5], …Botteon[6], A. Drabent[7], A. Malizia[4], F. Massaro[8,9,10,11], H. J. A. Röttgering[6], P. Ubertini[1], F. Ursini[12]

A&A 635, A5 (2020)
https://doi.org/10.1051/0004-6361/201935589
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Astronomy & Astrophysics

Giant radio galaxies in the LOFAR Two-metre Sky Survey

…ironmental properties★

…Shimwell[1,3], M. J. Hardcastle[4], S. Sankhyayan[5], R. Morganti[3,6], …ulevski[8], and K. J. Duncan[1]

A&A, 686, A21 (2024)
https://doi.org/10.1051/0004-6361/202348904
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Giant radio galaxies in the LOFAR deep fields★

M. Simonte[1], H. Andernach[2,3], M. Brüggen[1], G. K. Miley[4], and P. Barthel[5]

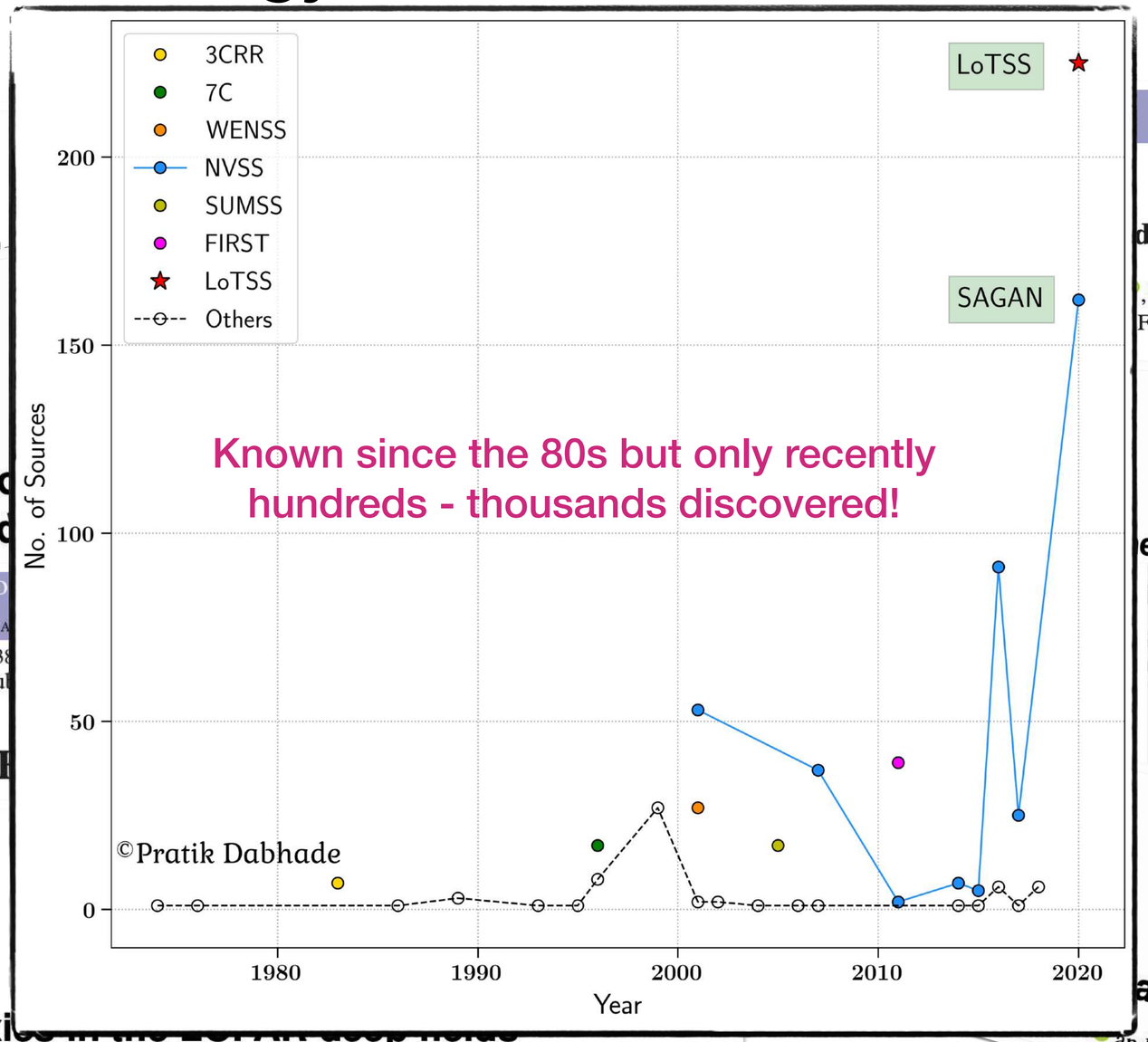
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Properties of giant radio galaxies larger than 3 Mpc

H. Andernach[1,2,★] and M. Brüggen[3]

Astronomy & Astrophysics

AGN jet release energy on the scale of the cosmic web (Mpc)



A&A, 691, A185 (2024)
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A new distant giant radio

Alberto Ma

Monthly No
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MNRAS **501,** 3833–38
Advance Access pub

MIGHTE

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Astronomy & Astrophysics

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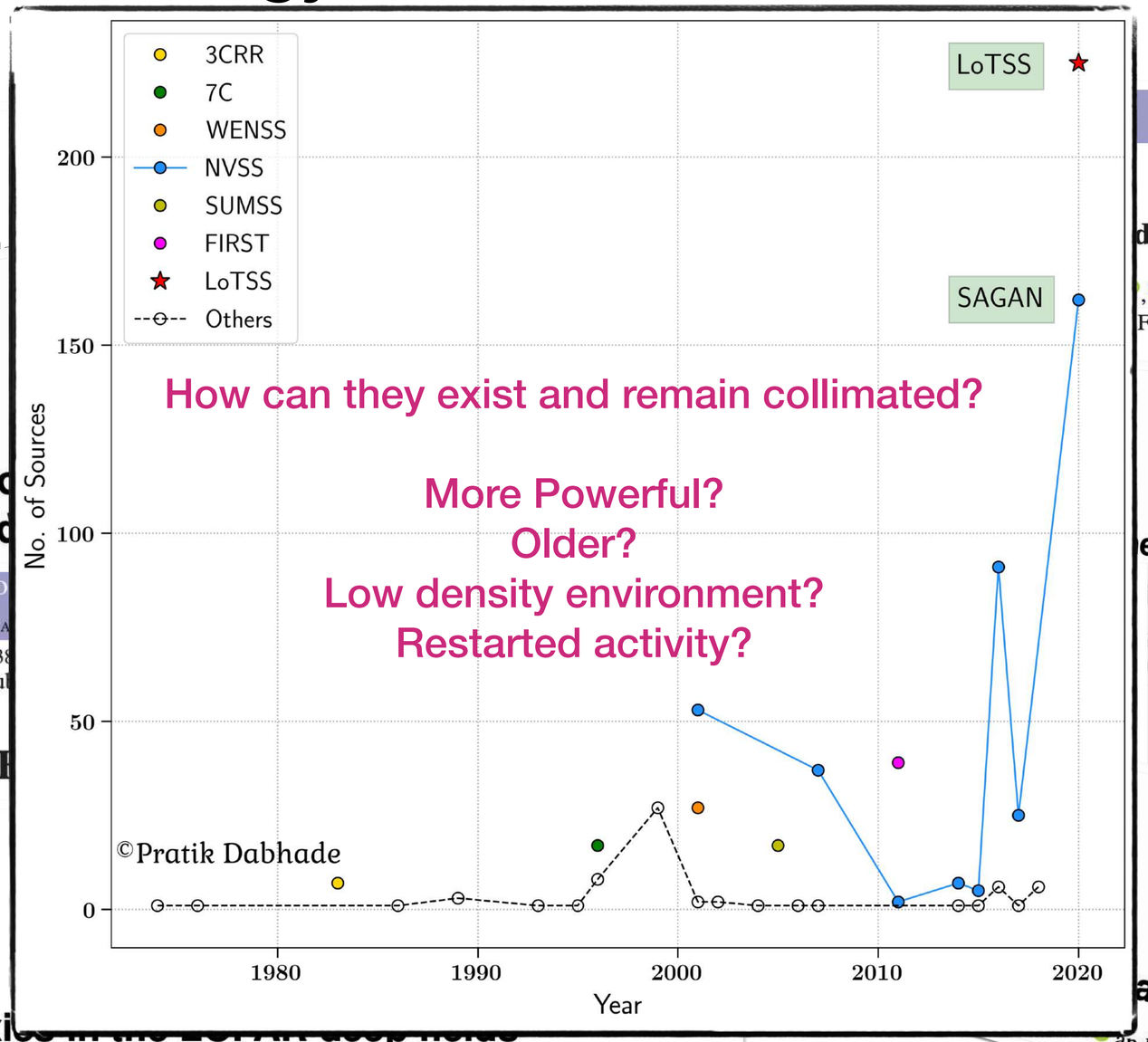
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and M. Brüggen[3]

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A new distant giant radio …

Alberto Ma…

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…alaxies larger than 3 Mpc

… and M. Brüggen[3]

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Black hole jets on the scale of the cosmic web

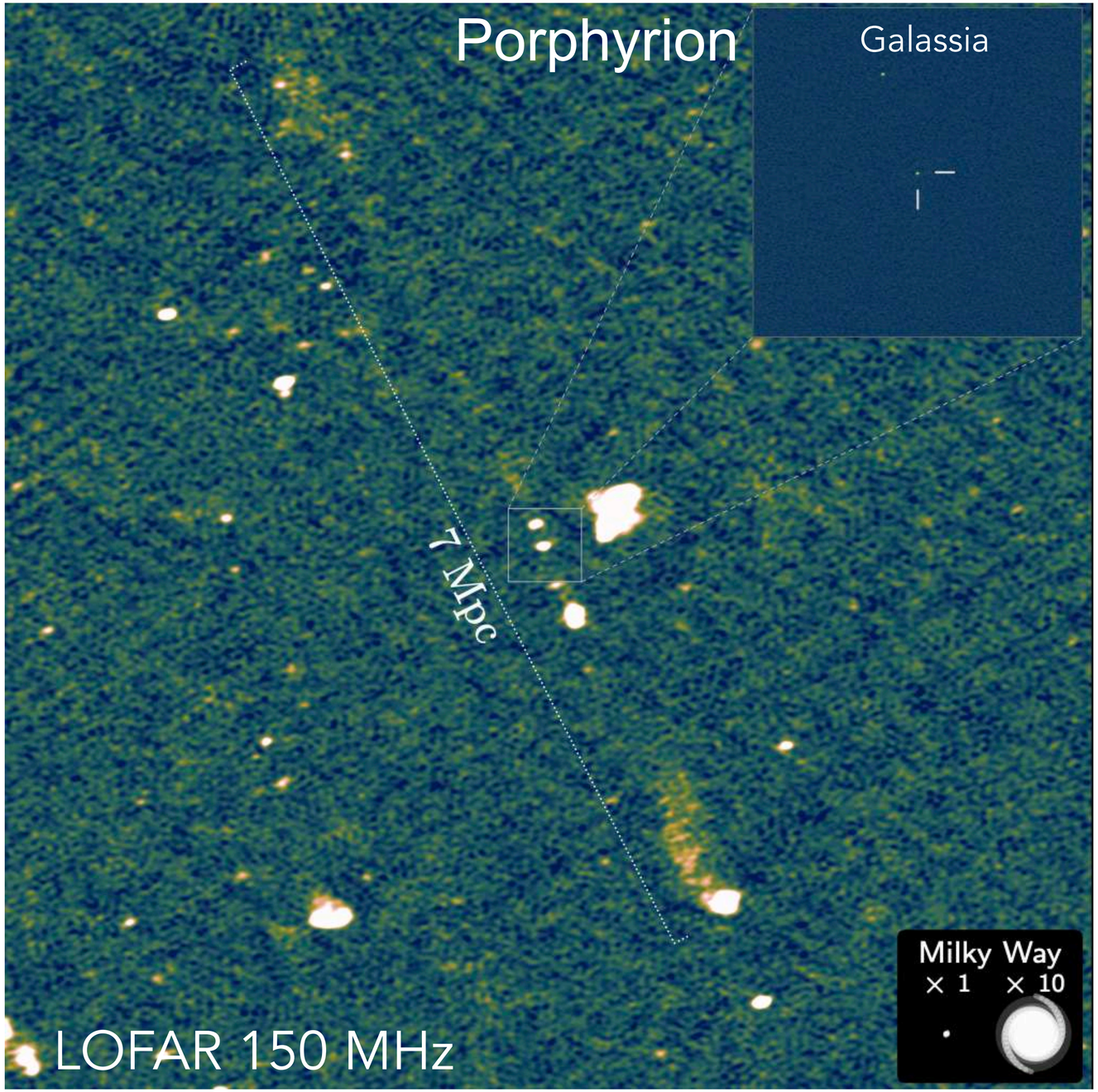
Martijn S. S. L. Oei ✉, Martin J. Hardcastle, Roland Timmerman, Aivin R. D. J. G. I. B. Gast, Andrea Botteon, Antonio C. Rodriguez, Daniel Stern, Gabriela Calistro Rivera, Reinout J. van Weeren, Huub J. A. Röttgering, Huib T. Intema, Francesco de Gasperin & S. G. Djorgovski

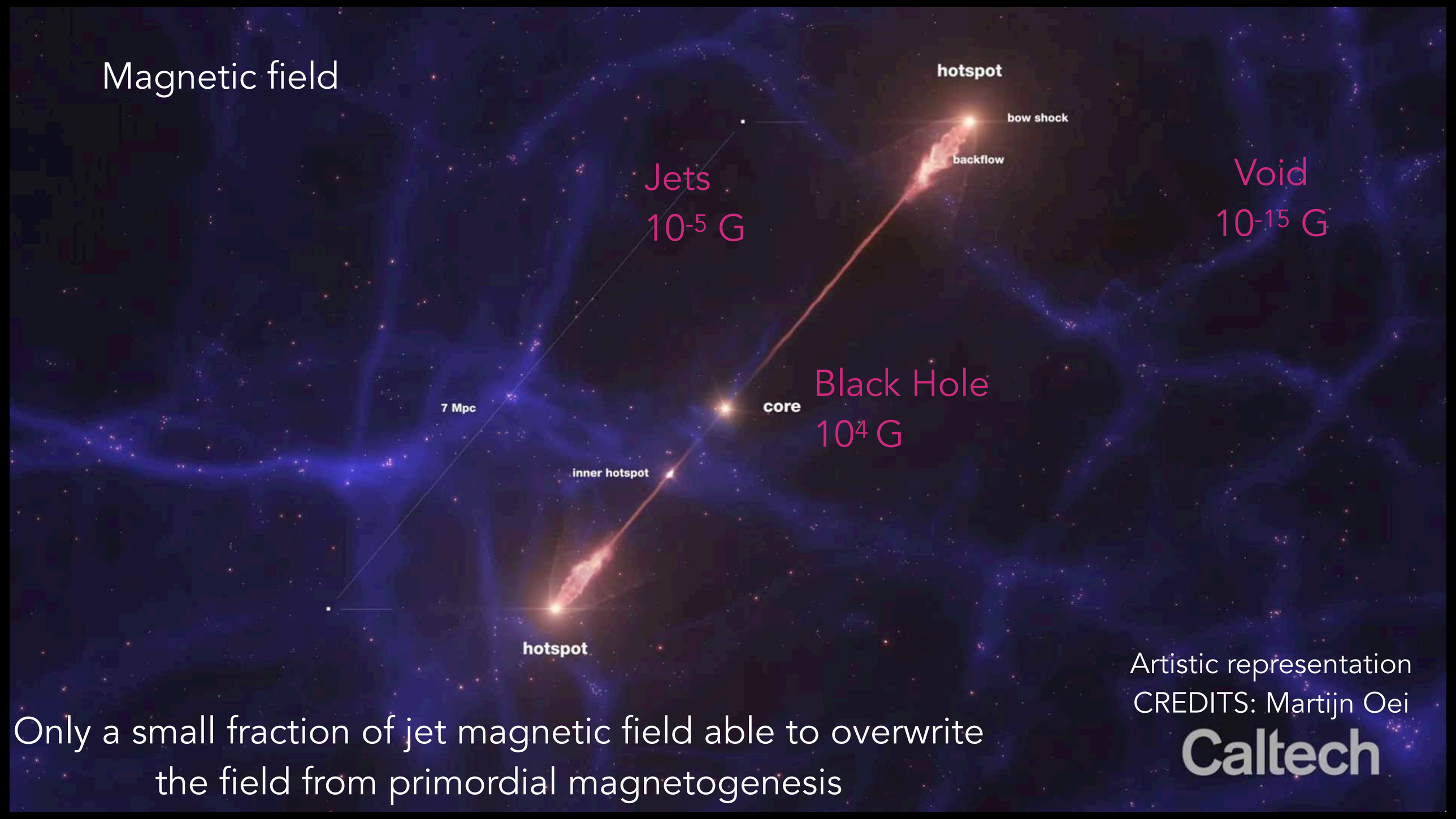
Nature **633**, 537–541 (2024) | Cite this article

- 13′~7 Mpc @ z = 0.896

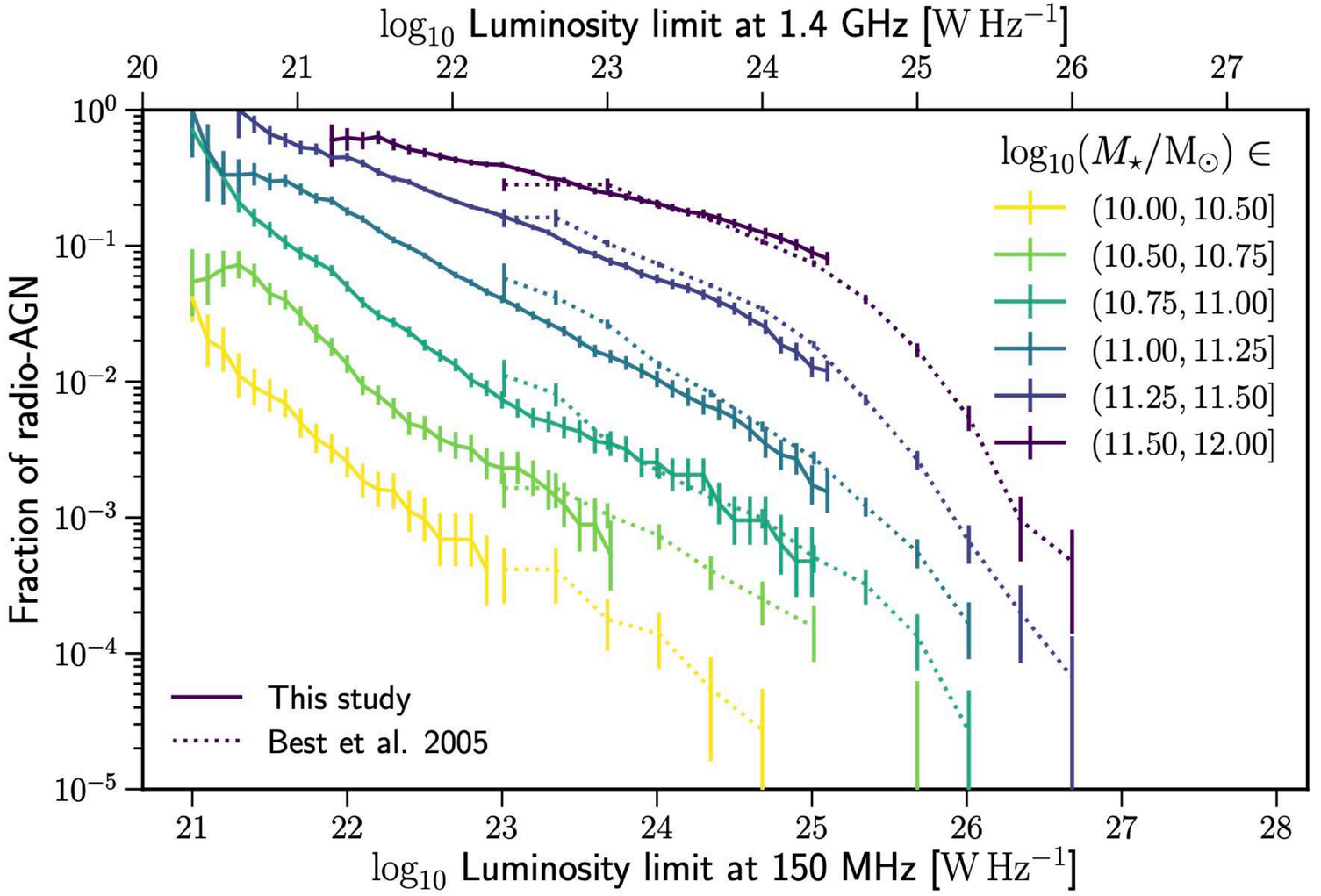
  6.3 Gyr after the Big Bang

- 95% chance jets encounter void of CW
- >60% of typical void dimension at that z




Magnetic field
hotspot
bow shock
backflow
Jets
10^{-5} G
Void
10^{-15} G
Black Hole
10^{4} G
7 Mpc
core
inner hotspot
hotspot
Artistic representation
CREDITS: Martijn Oei
Caltech
Only a small fraction of jet magnetic field able to overwrite
the field from primordial magnetogenesis

Cumulative jet feedback: a statistical approach



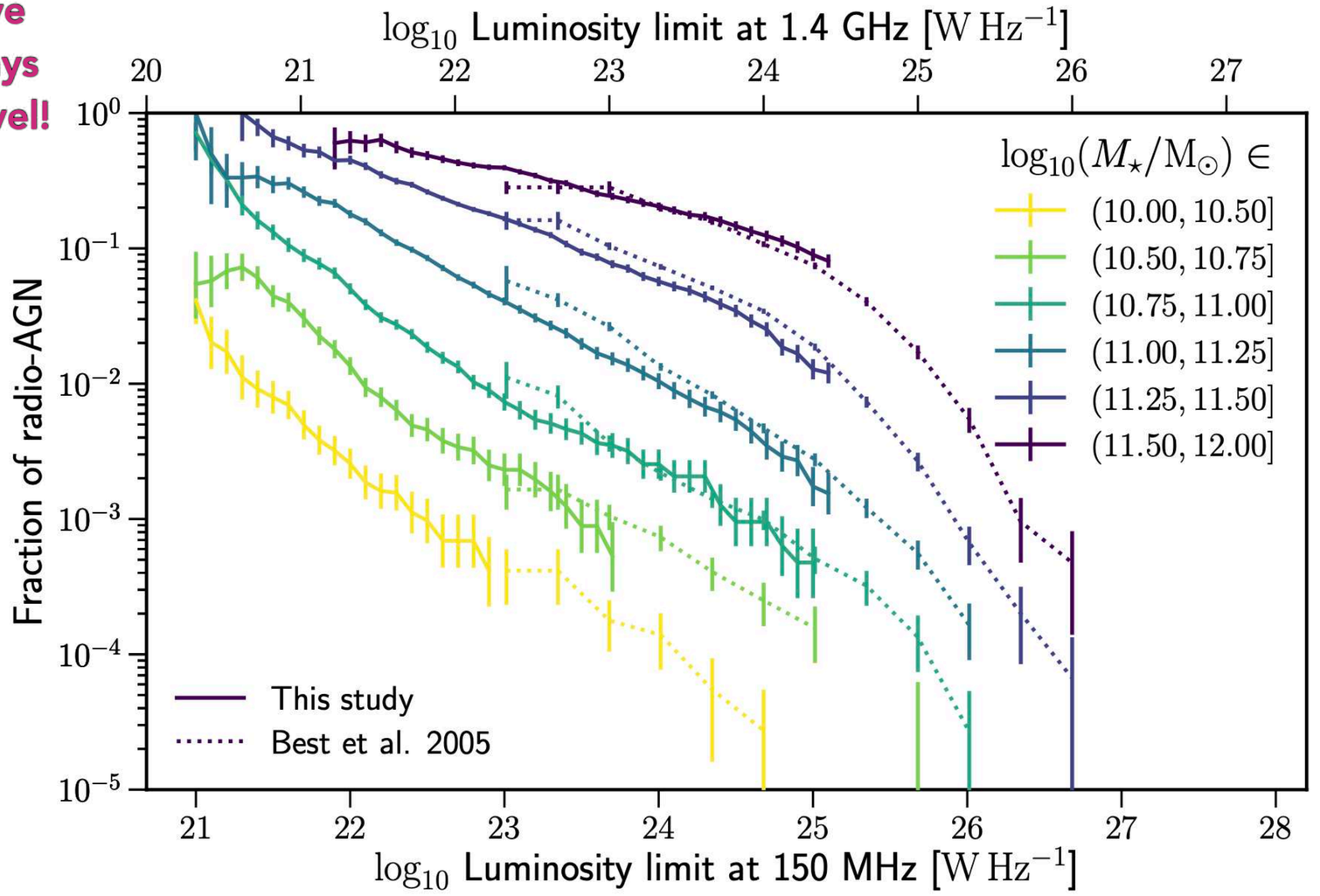
LoTSS AGN
0.01< z <0.3

Sabater+2019

See also e.g. Best+2005, Shabala+2008

Cumulative jet feedback: a statistical approach

The most massive galaxies are always active at some level!



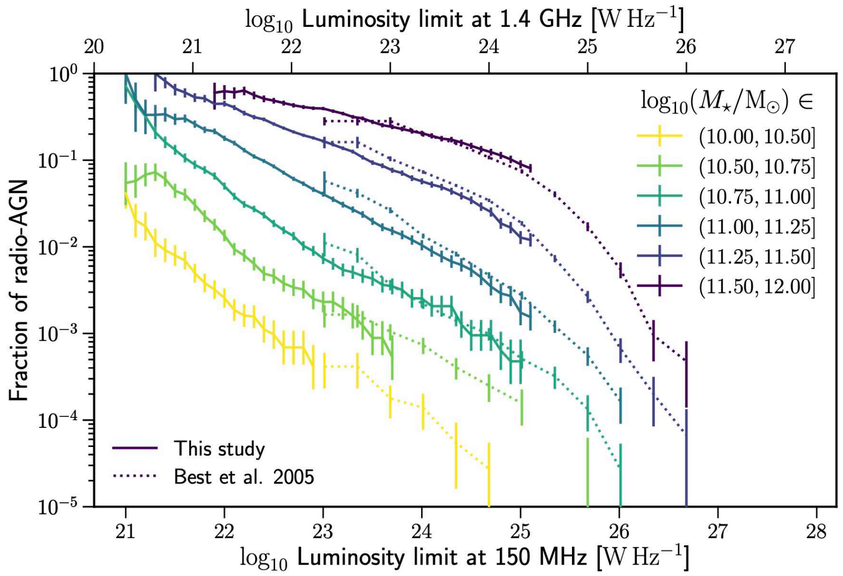
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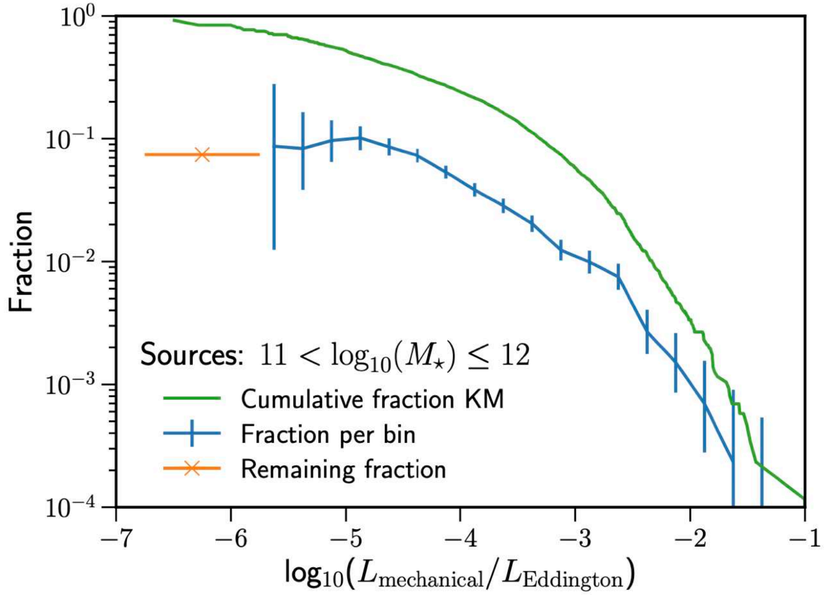


Convert radio luminosity into jet mechanical power calibrated from X-ray cavities.

$$P_{\rm mech,cav} = 2.8 \times 10^{37} \left(\frac{L_{1.4\,\rm GHz}}{10^{25}\,\rm W\,Hz^{-1}} \right)^{0.68} \rm W$$

Heckman & Best (2014)

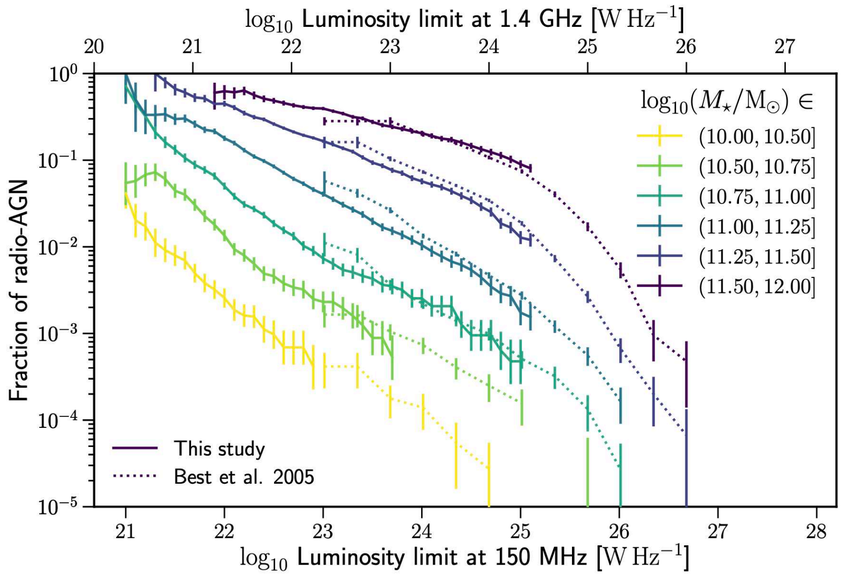
Normalise by $L_{Eddington}$ so that you can consider all galaxies belonging to the same population and the relative fractions can be directly linked to the time spent by the AGN at each accretion rate (duty cycle).



Galaxies spend most of their time at relatively low accretion rates but the bulk of the time-averaged energy output is produced during the relatively short times at higher Eddington-scaled accretion rates

Cumulative jet feedback: a statistical approach

Sabater+2019

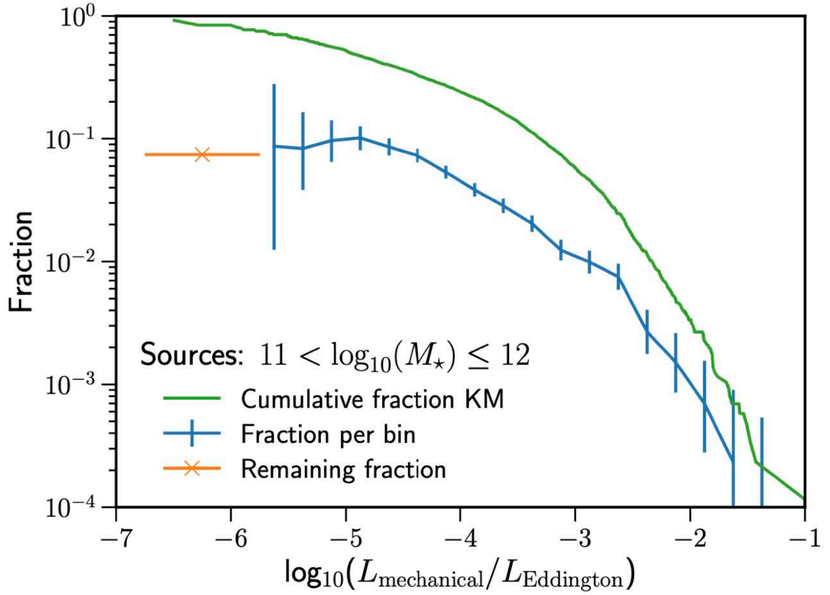


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Heckman & Best (2014)

Normalise by $L_{Eddington}$ so that you can consider all galaxies belonging to the same population and the relative fractions can be directly linked to the time spent by the AGN at each accretion rate (duty cycle).

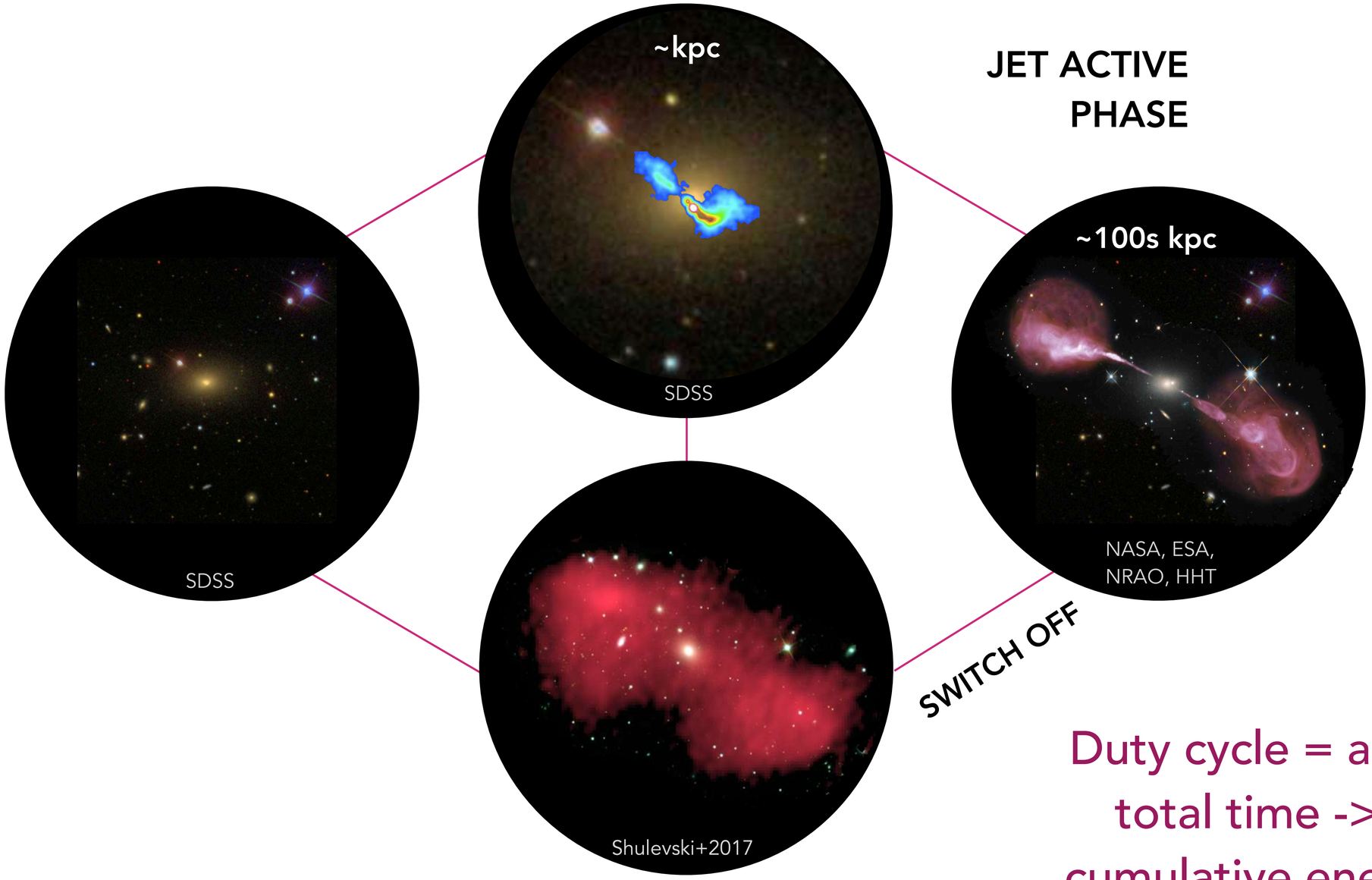


Galaxies spend most of their time at relatively low accretion rates but the bulk of the time-averaged energy output is produced during the relatively short times at higher Eddington-scaled accretion rates

This is why knowing JET POWER matters!

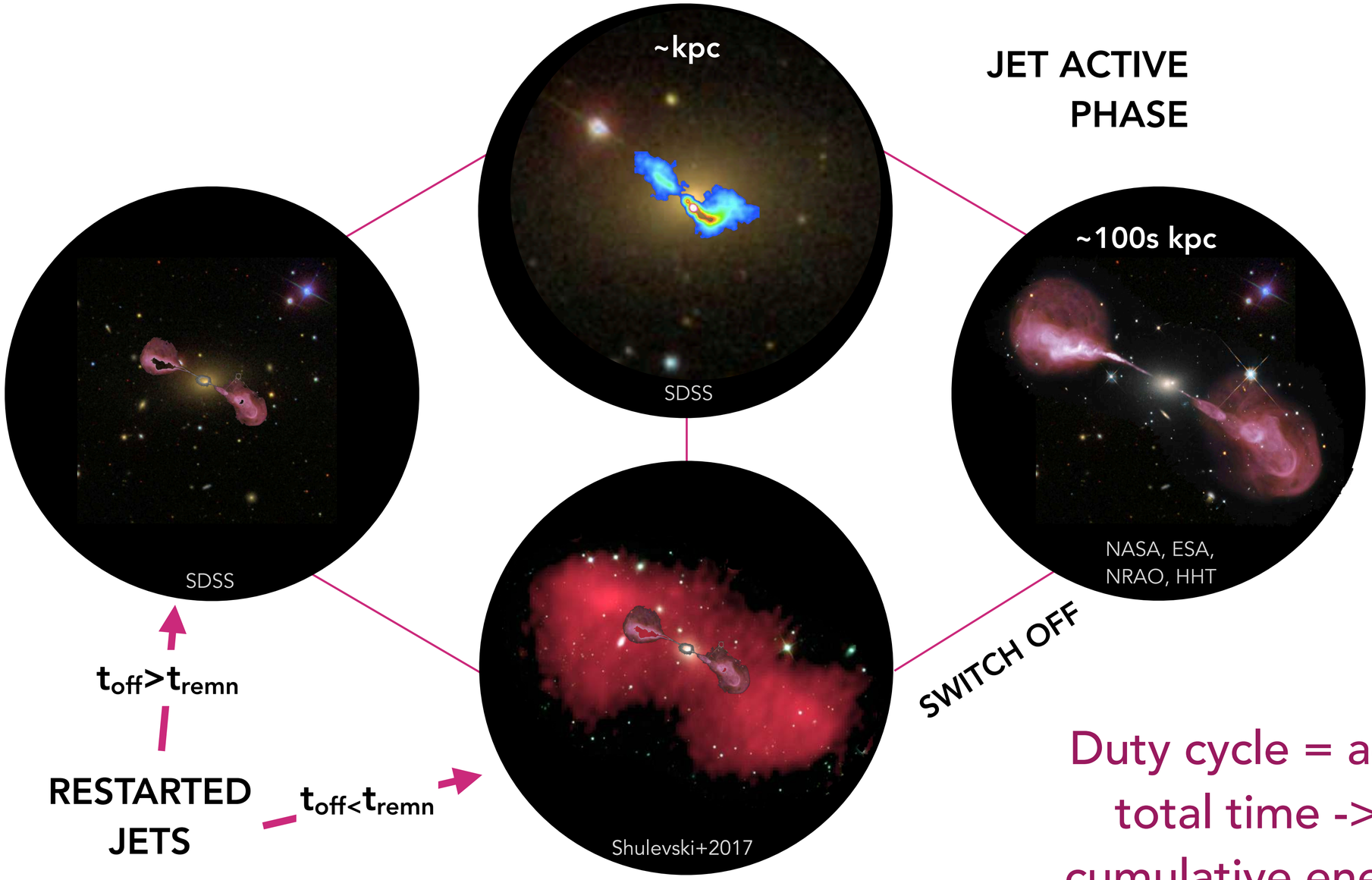
The life cycle (and duty cycle) of jets

The life-cycle of AGN jets



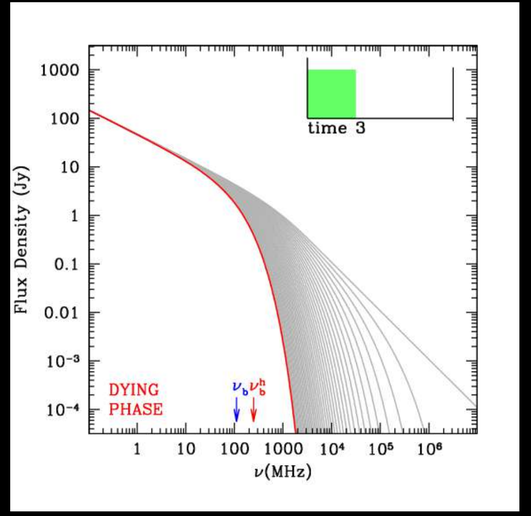
Duty cycle = active time / total time -> quantify cumulative energy release

The life-cycle of AGN jets



Duty cycle = active time / total time -> quantify cumulative energy release

Remnant plasma evolution

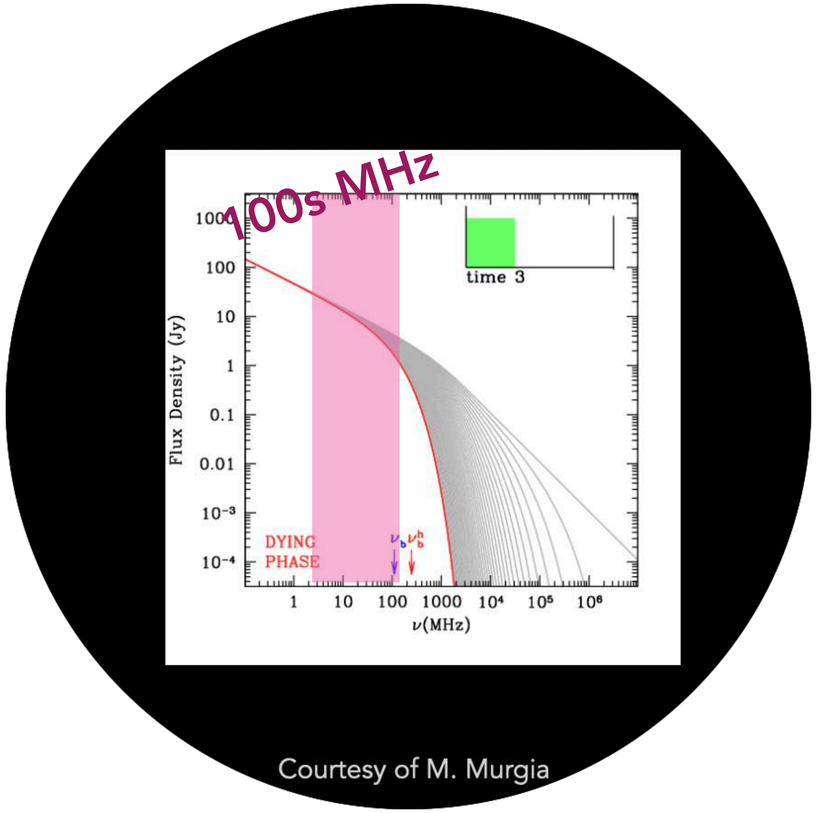


Courtesy of M. Murgia

Radiative losses

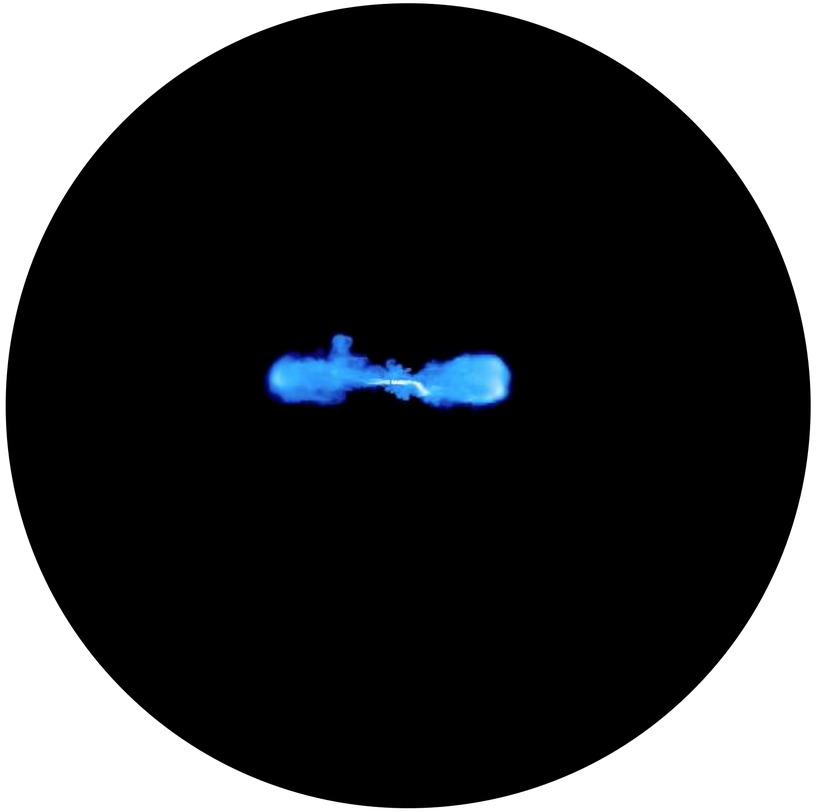
(depend on magnetic field, redshift)

Remnant plasma evolution



Radiative losses

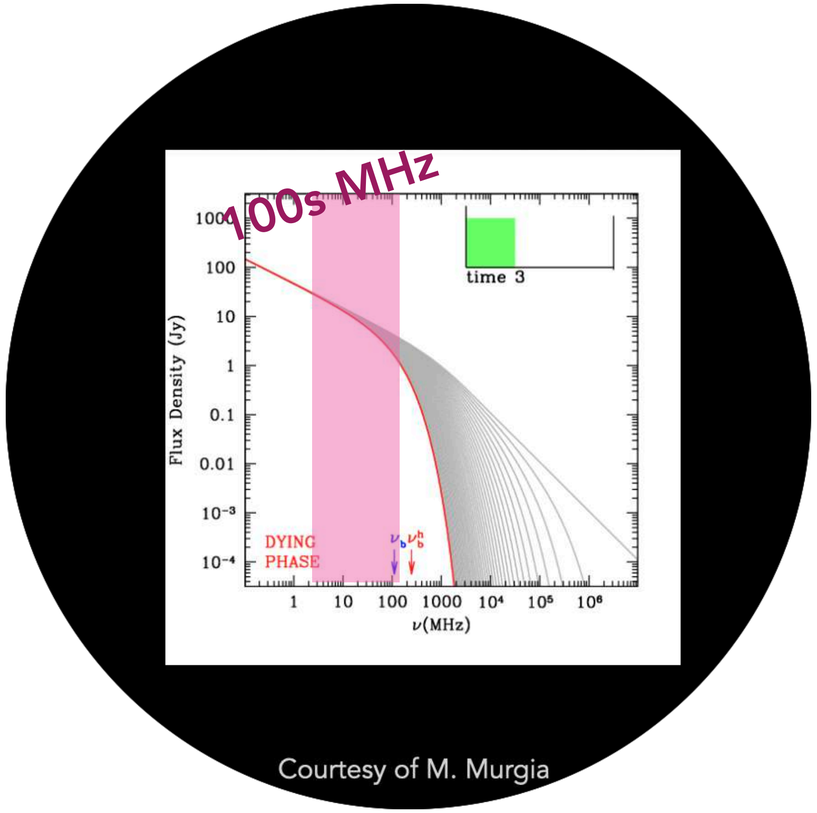
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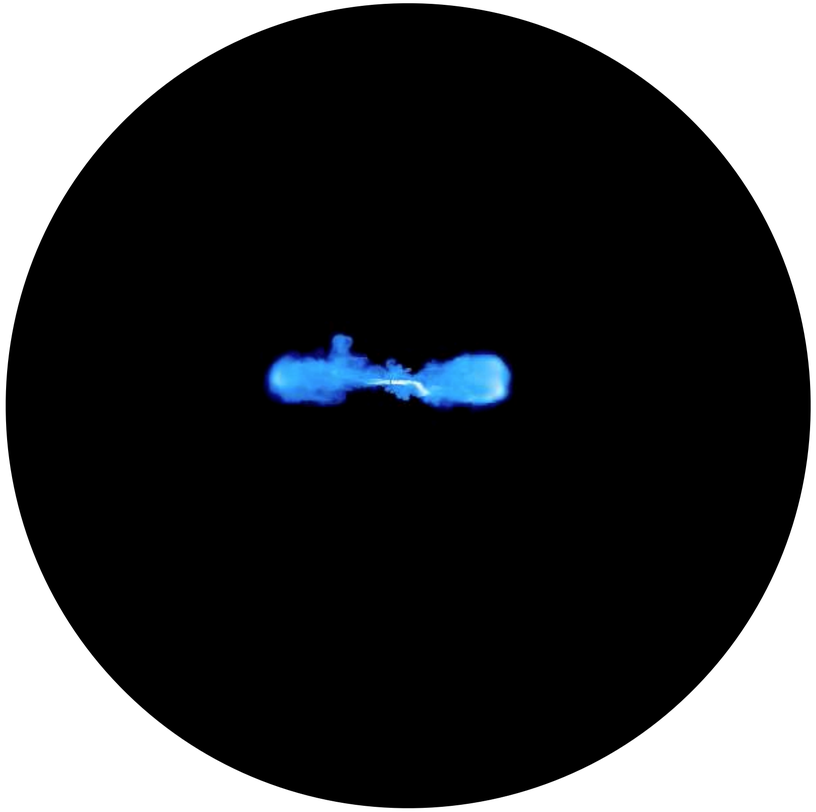
Expansion losses

(depend on jet power, external gas density)

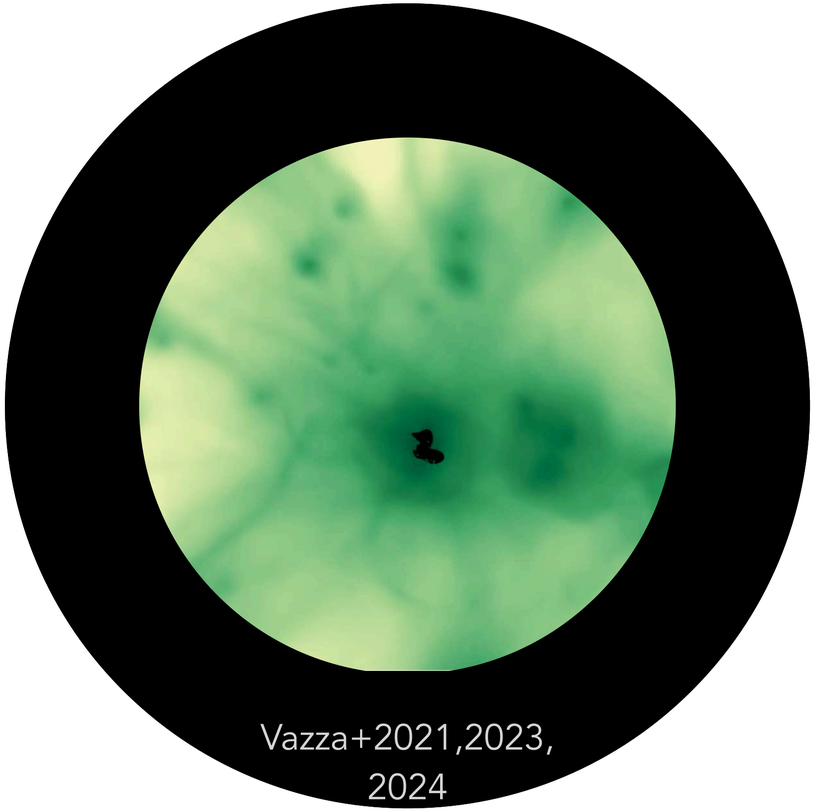
Remnant plasma evolution



Radiative losses
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(depend on jet power,
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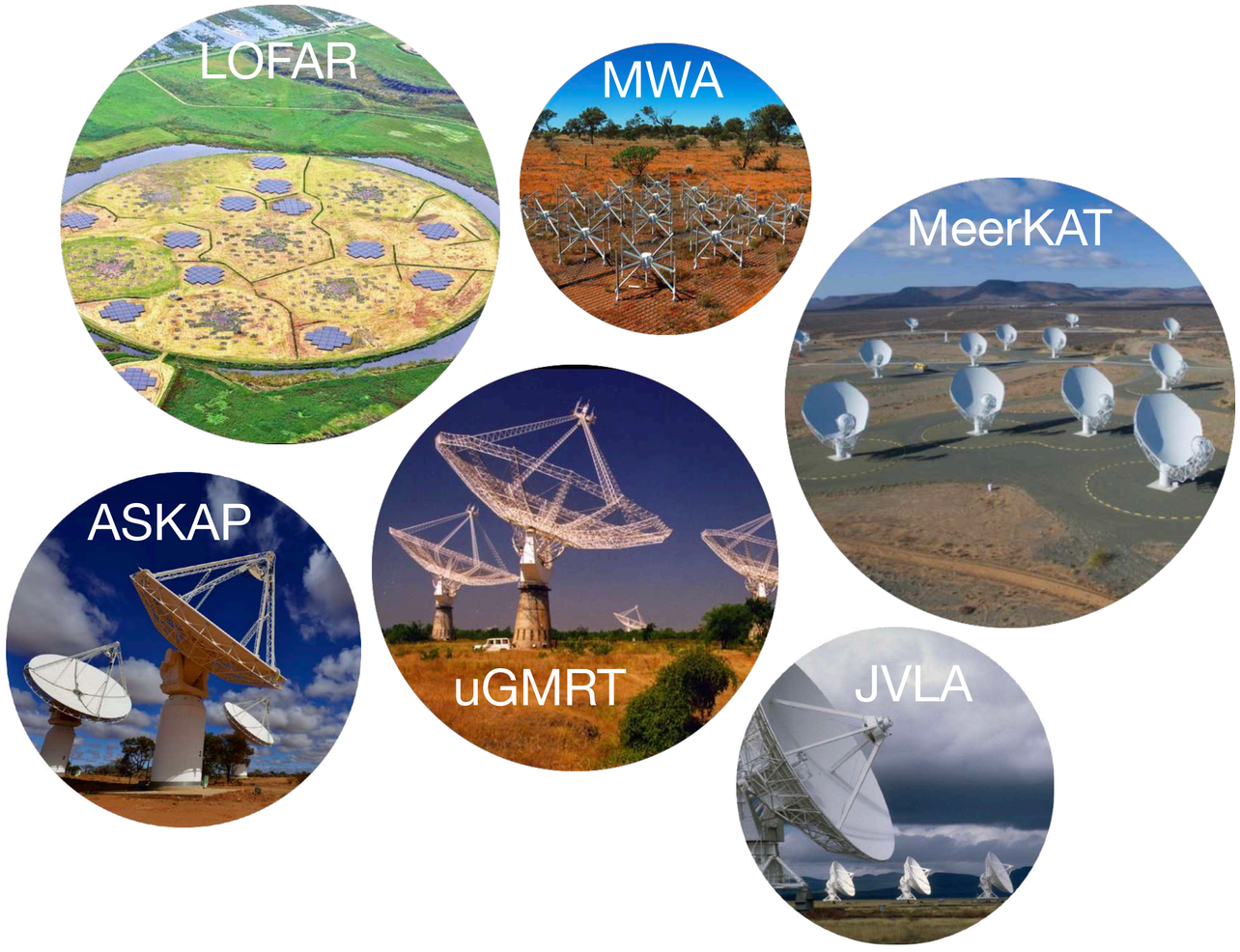


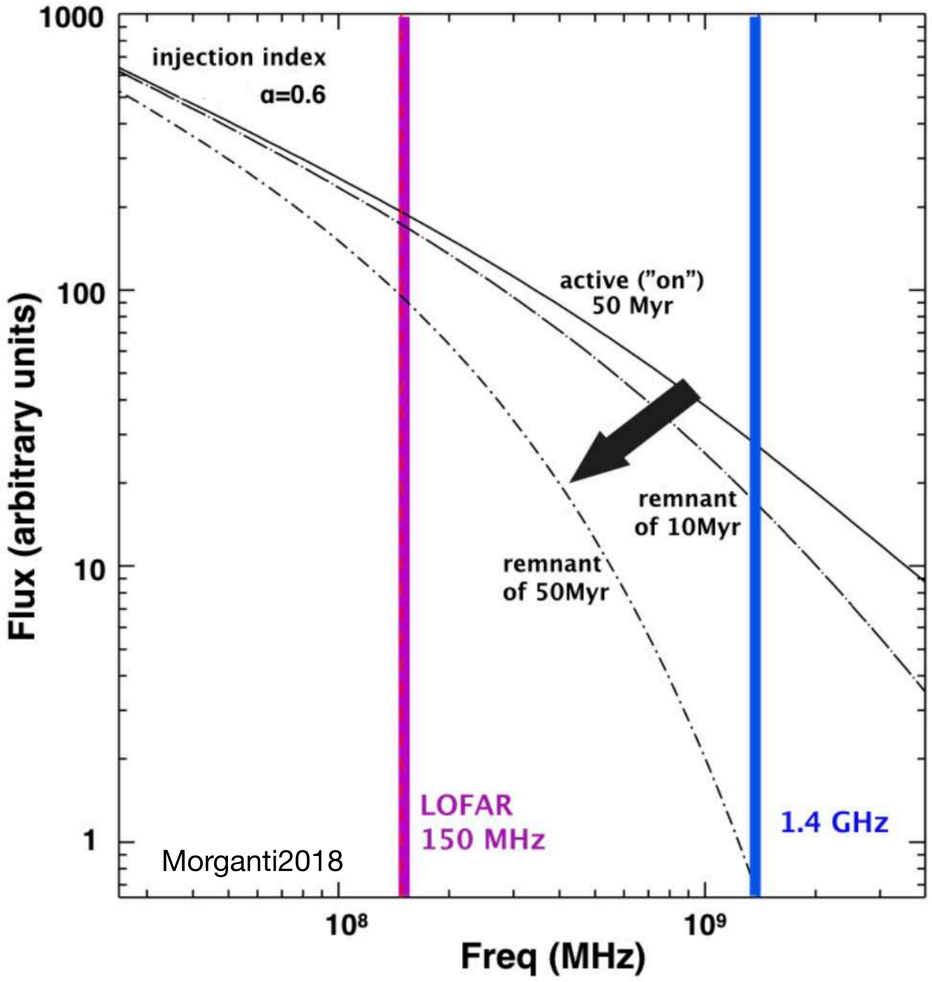
Disruption by dynamics of large scale environment

Advances with SKA precursors/pathfinders

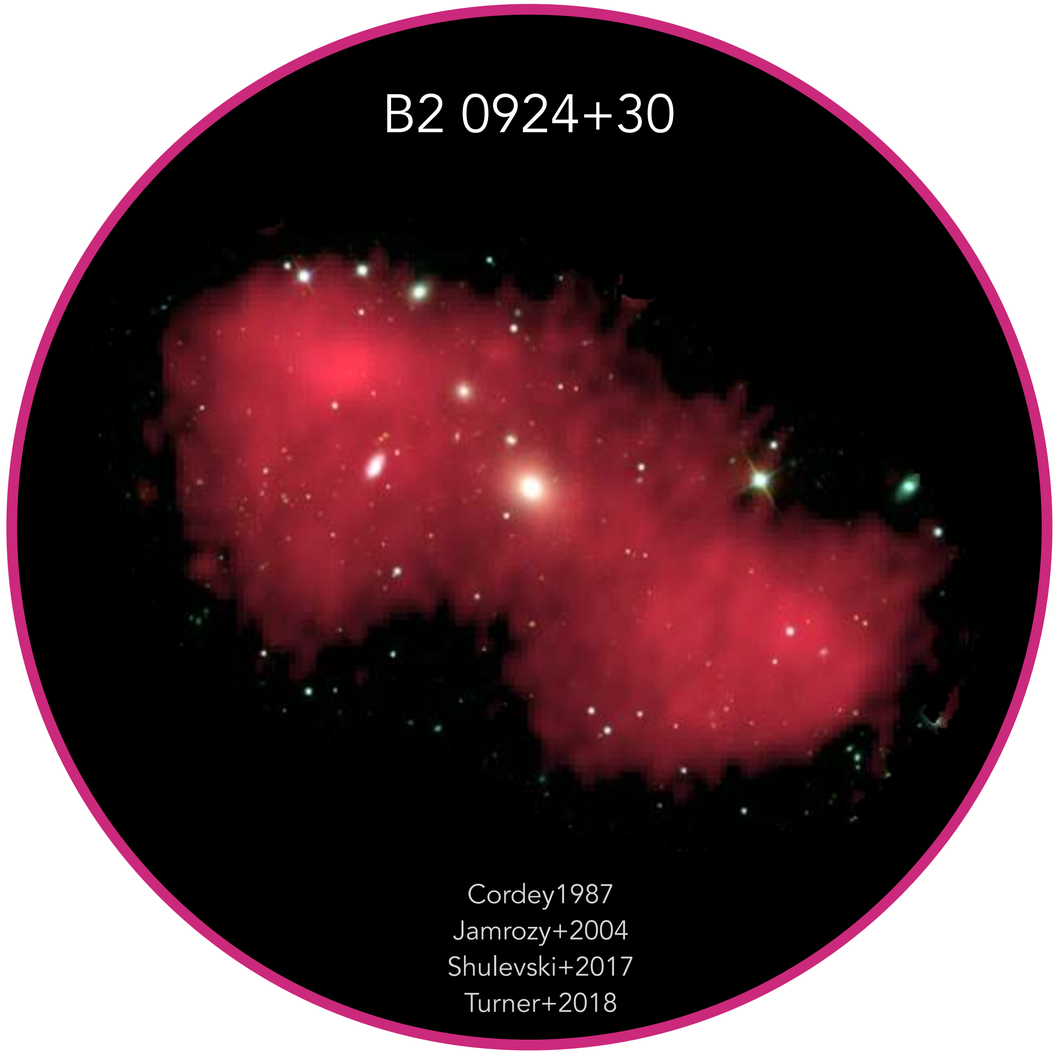
Low radio frequencies (<~1 GHz)

sensitive to extended optically thin lobes, especially the oldest emitting particles





Remnant radio galaxies

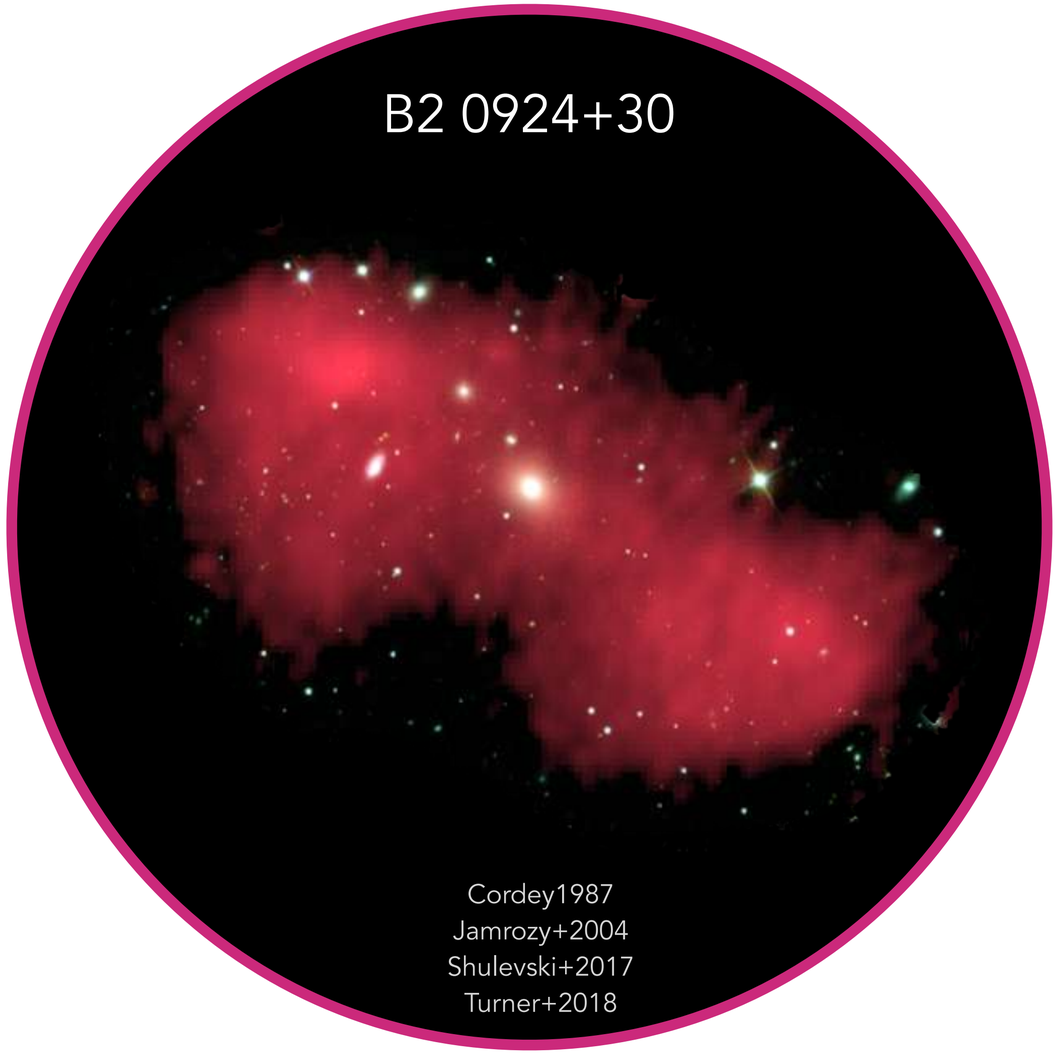


Classically:

- No compact components (Core, hotspots,jets)
- Relaxed morphology
- Low surface brightness

- Ultra steep spectra (USS, $\alpha>1.2$)
- Curved spectrum (SPC, $\alpha>0.5$)

Remnant radio galaxies



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- Curved spectrum (SPC, $\alpha>0.5$)

but … depends on frequency and resolution

The challenge of selecting AGN remnants

Selection criteria:

- **Ultra steep spectrum (USS, α>1.2)**
- Spectral curvature (α_{high}-α_{low}) > 0.5
- Core prominence
- Morphology

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1

Complementary wide-area survey
at **TWO FREQUENCIES**
with consistent uv-coverage & sensitivity

LOFAR LoTSS 150 MHz noise ~100 μJy/b @ 6″

↓ alpha>1.2

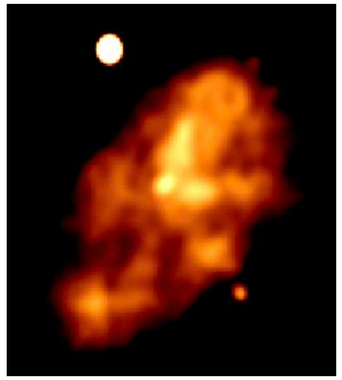
! 1.4 GHz noise <20 μJy/b

2

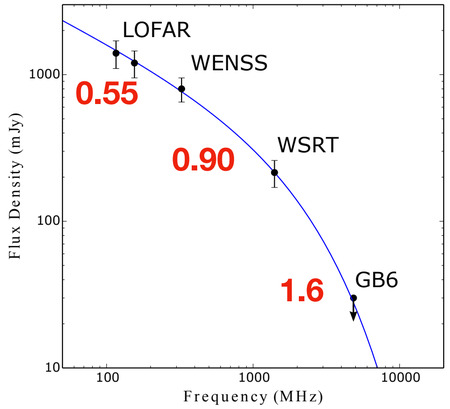
The challenge of selecting AGN remnants

Not always ultra-steep >1.2

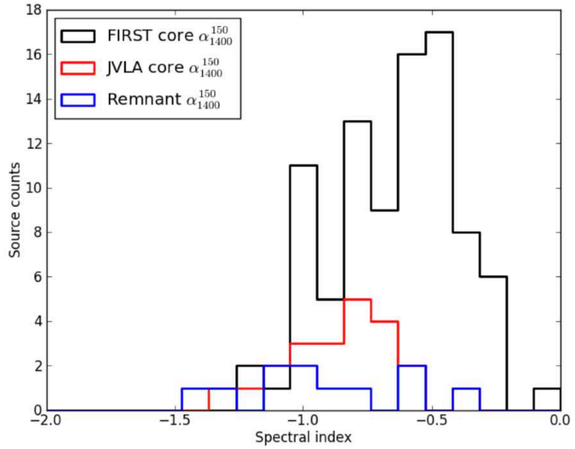
OBSERVATIONS



Brienza+2016



Mahatma+2018



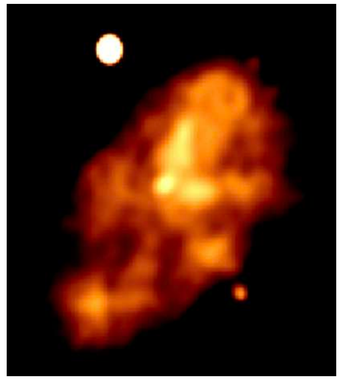
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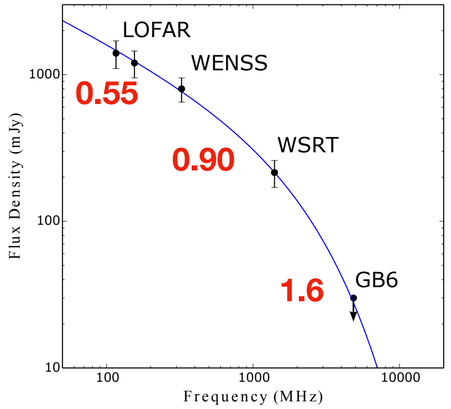
The challenge of selecting AGN remnants

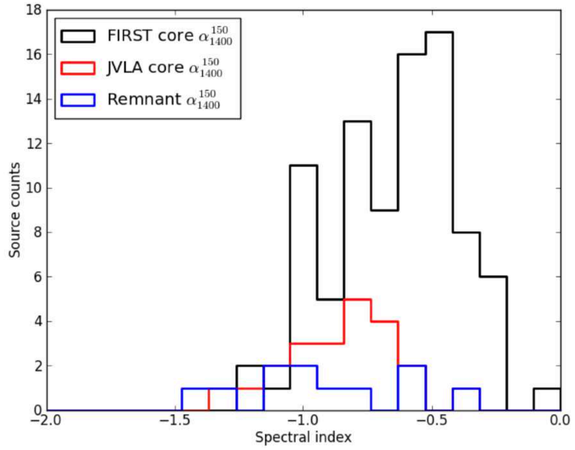
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OBSERVATIONS



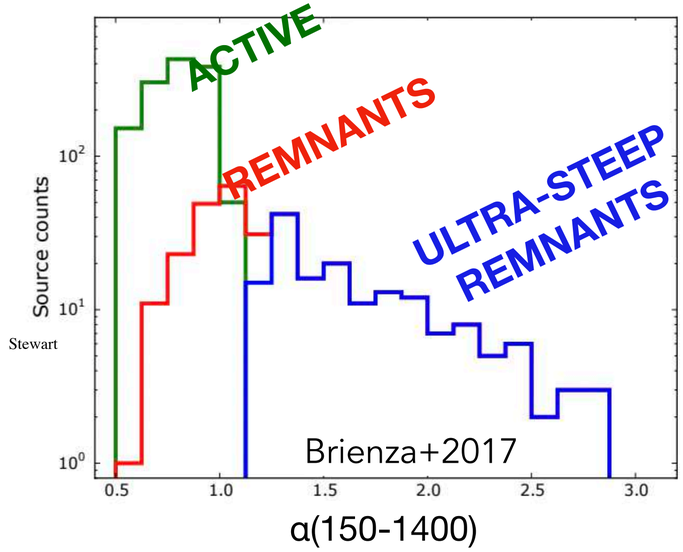
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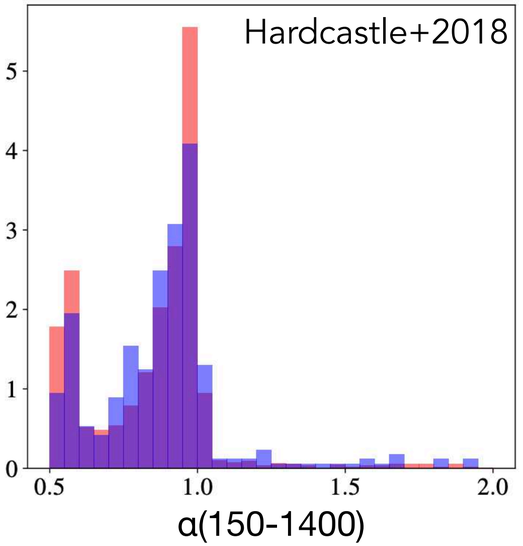


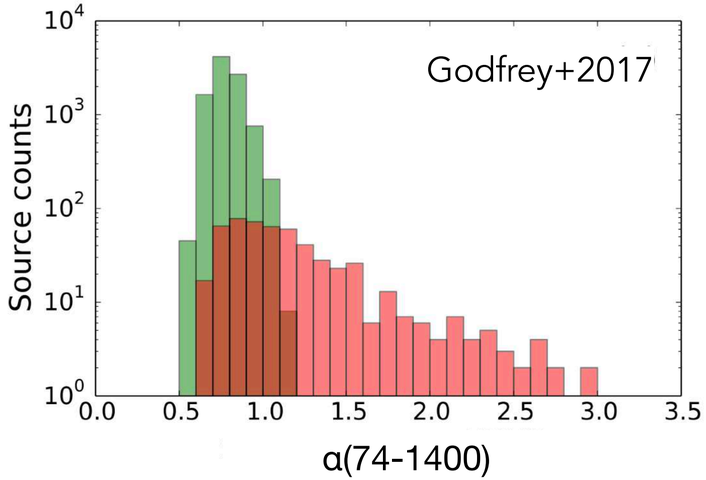


Mahatma+2018

SIMULATIONS







Need 5GHz to recover all remnants based on spectra.. challange!

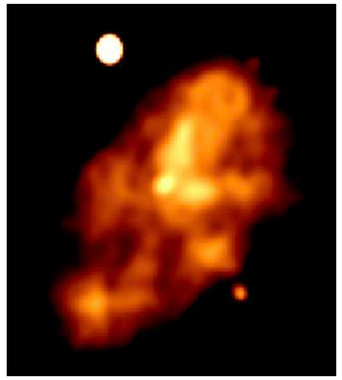
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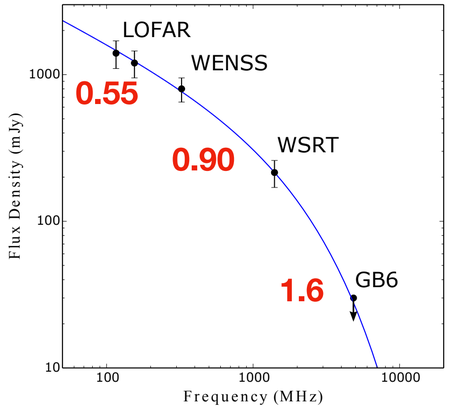
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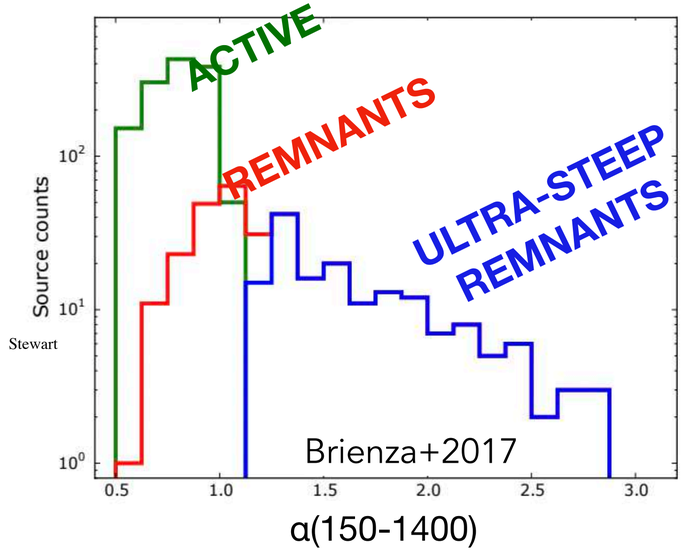
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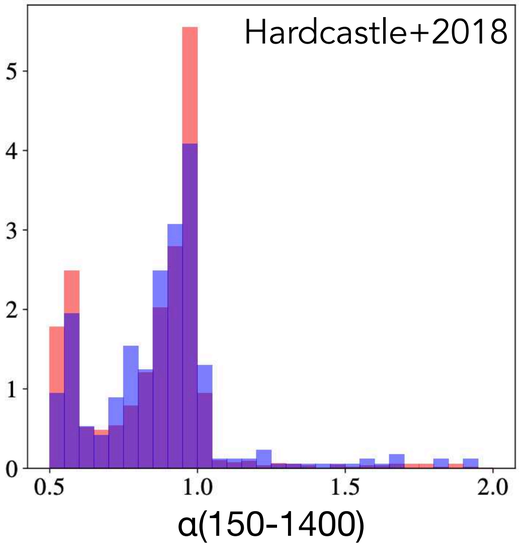


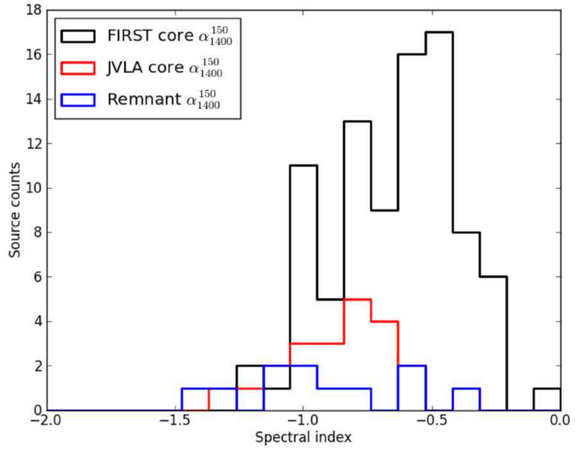
Brienza+2016



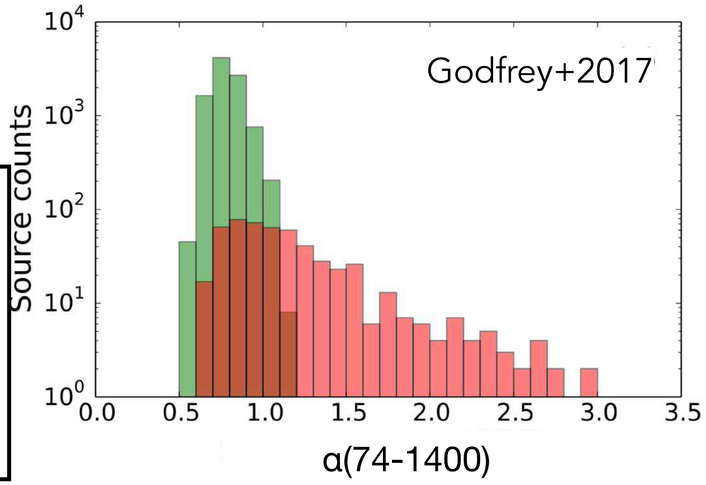
SIMULATIONS







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But also.. e.g.
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Need to combine spectral and morphological criteria!

Need 5GHz to recover all remnants based on spectra.. challange!

The challenge of selecting AGN remnants

Murgia+2011 → 5 remnants
Parma+2007 → 6 remnants
Saripalli+2012 → ~30 remnants/restarted

Ultra steep α + SPC

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….
e.g.
Godfrey+2017 → ~60 remnants
Brienza+2017, Jurlin+2022 → 13 remnants
Mahatma+2018 → 11 remnants
Quici+2025 → 79 remnants
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Dutta+2023 → 21 remnants
Jurlin+2021 → 22 restarted
Nair+2024 → 69 restarted core
Morganti+2021 → 15 remnants + restarted
Mostert+2023
Capetti+2022, Capetti&Brienza2023
And many more single object studies

Ultra steep α + SPC
Core prominence
Morphology
Resolved spectra
Machine learning

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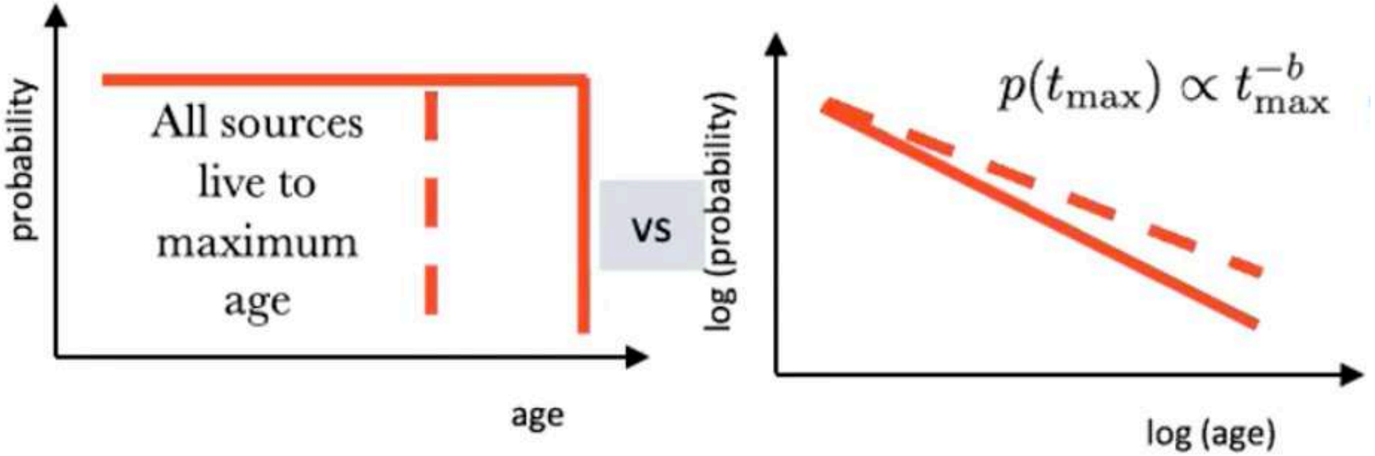
Ultra steep α + SPC
Core prominence
Morphology
Resolved spectra
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From few up to ~20% of radio sources.
Complete samples remain challenging!

WHY searches and samples of remnants and restarted

Contrain models (e.g. jet duration)

Shabala+2020



Constraints: distributions in
angular size
flux density
redshift

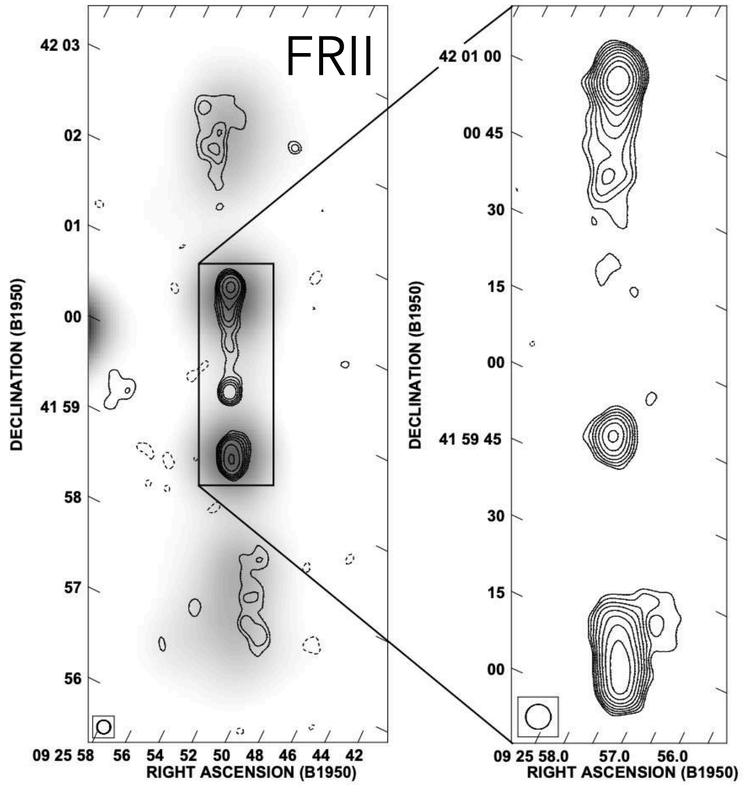
<5% remnants

>10% remnants

Observed fraction ~15% (Jurlin+2020) implies dominant population of **short-lived jets**

Restarted radio galaxies (t_{off}<$t_{remnant}$): the zoo

Double Double

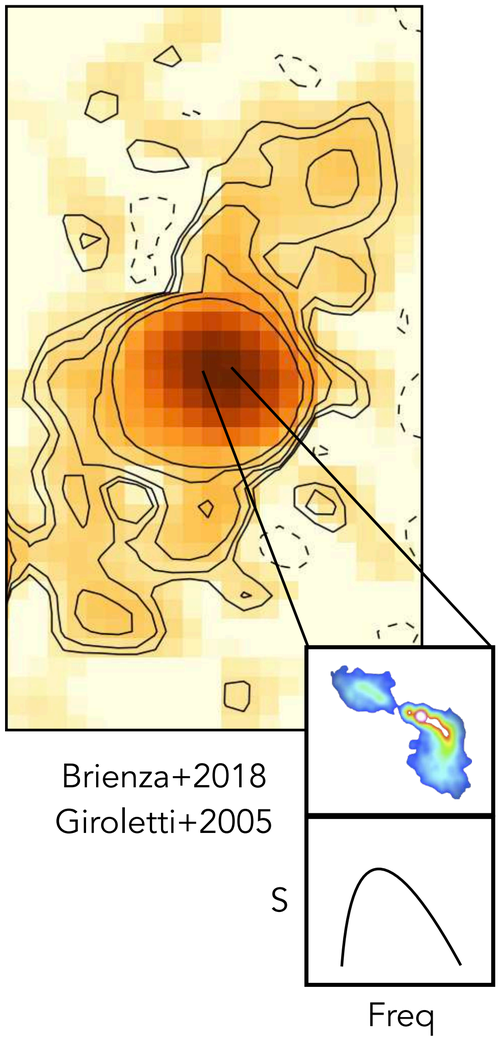


Schoenmakers+2000

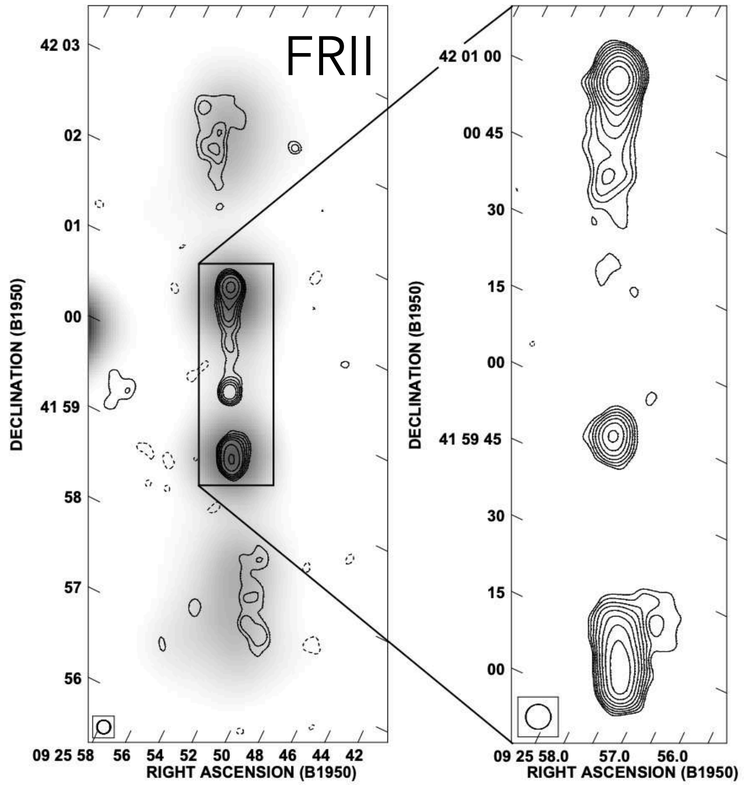
but also e.g. Mahatma+2019, Saripalli et al., 2003; Saikia et al., 2006; Safouris et al., 2008; Konar et al., 2013; Konar and Hardcastle, 2013; Nandi et al., 2019; Saikia and Jamrozy, 2009; Dabhade et al., 2025

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Double Double



Brienza+2018
Giroletti+2005

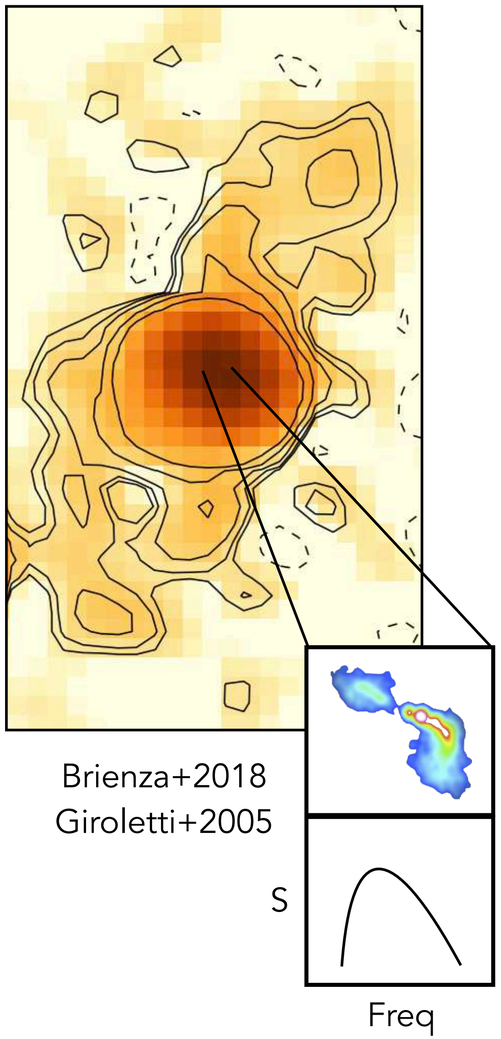


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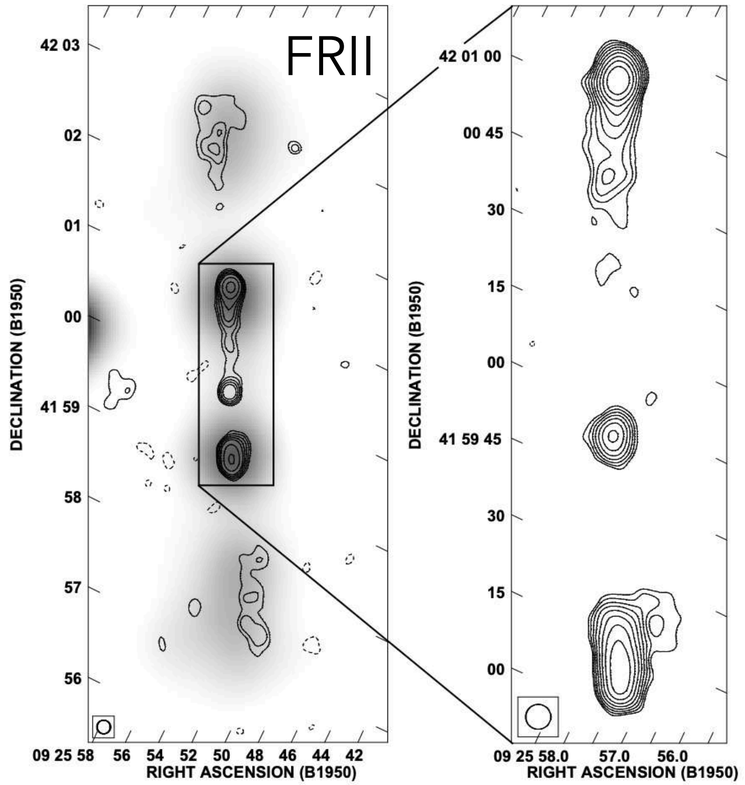
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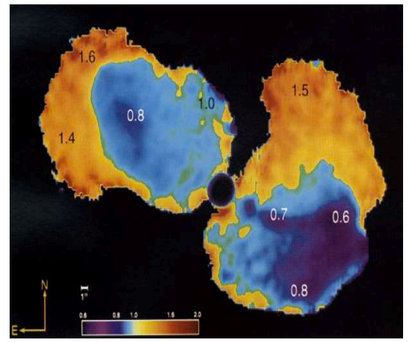


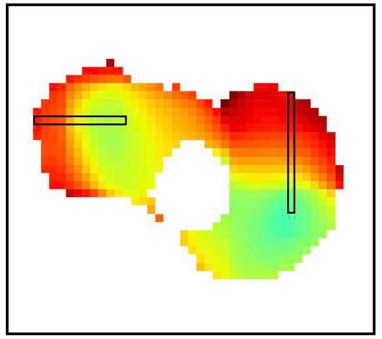
Brienza+2018
Giroletti+2005

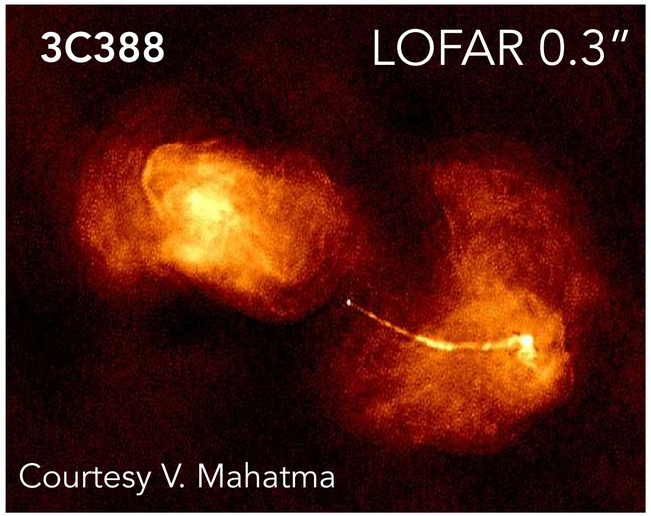


Schoenmakers+2000

Brienza+2020,
Roettiger+1994



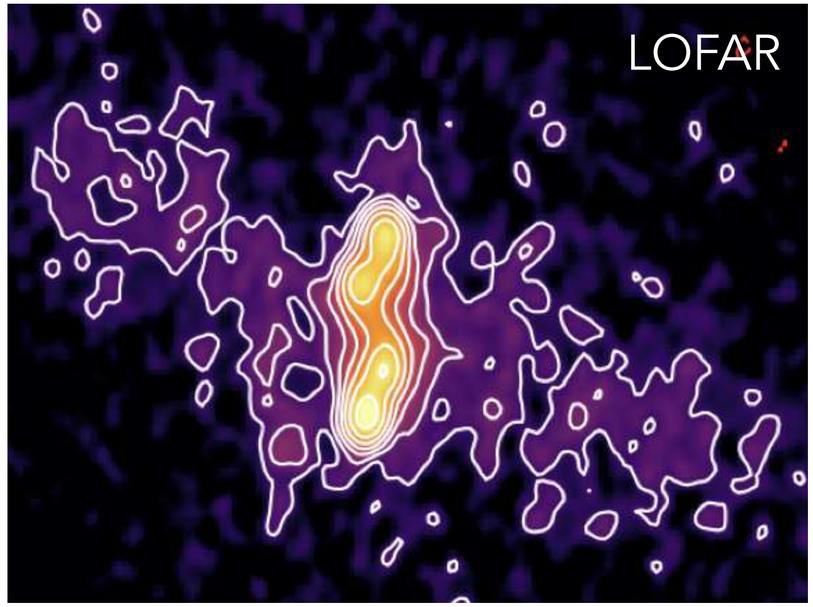




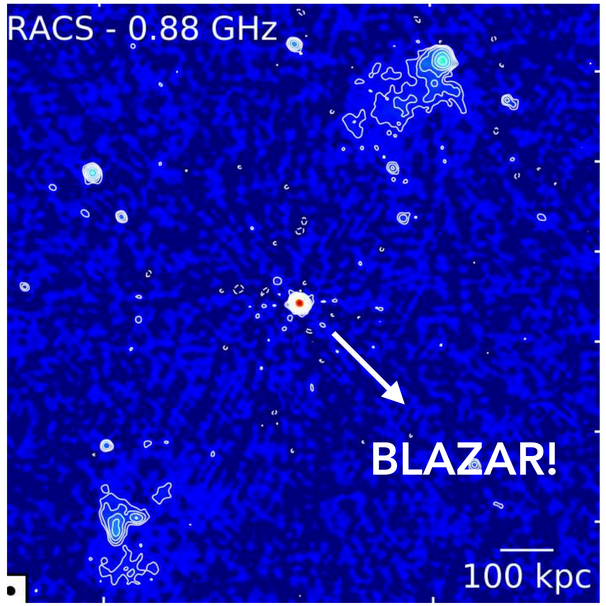
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Restarted radio galaxies ($t_{off}<t_{remnant}$): the zoo

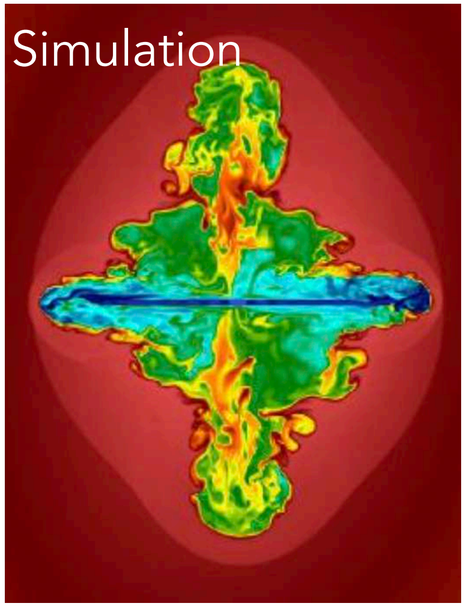
Re-orientation



Ubertosi+2024

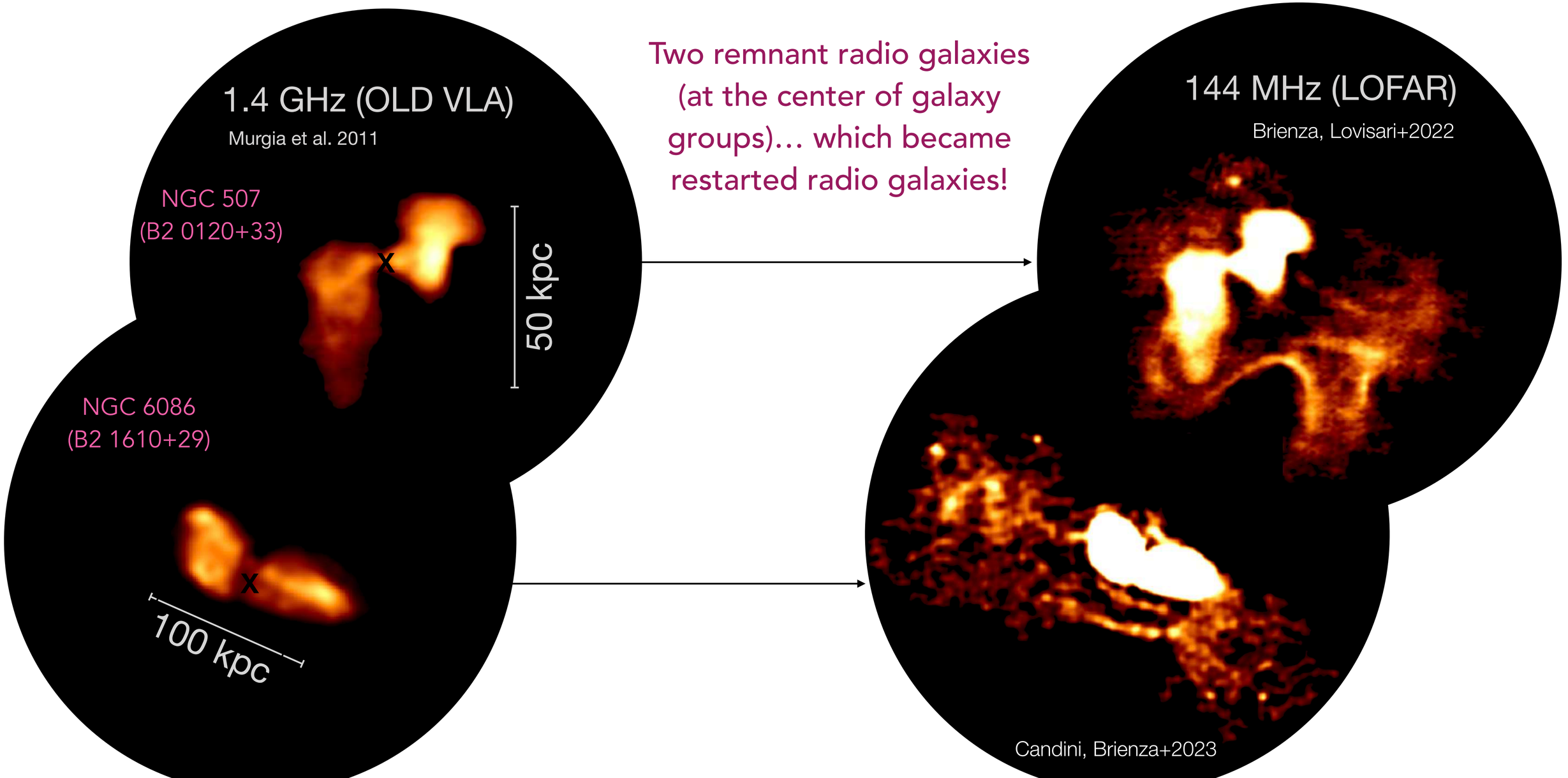


Hernández-García+2023



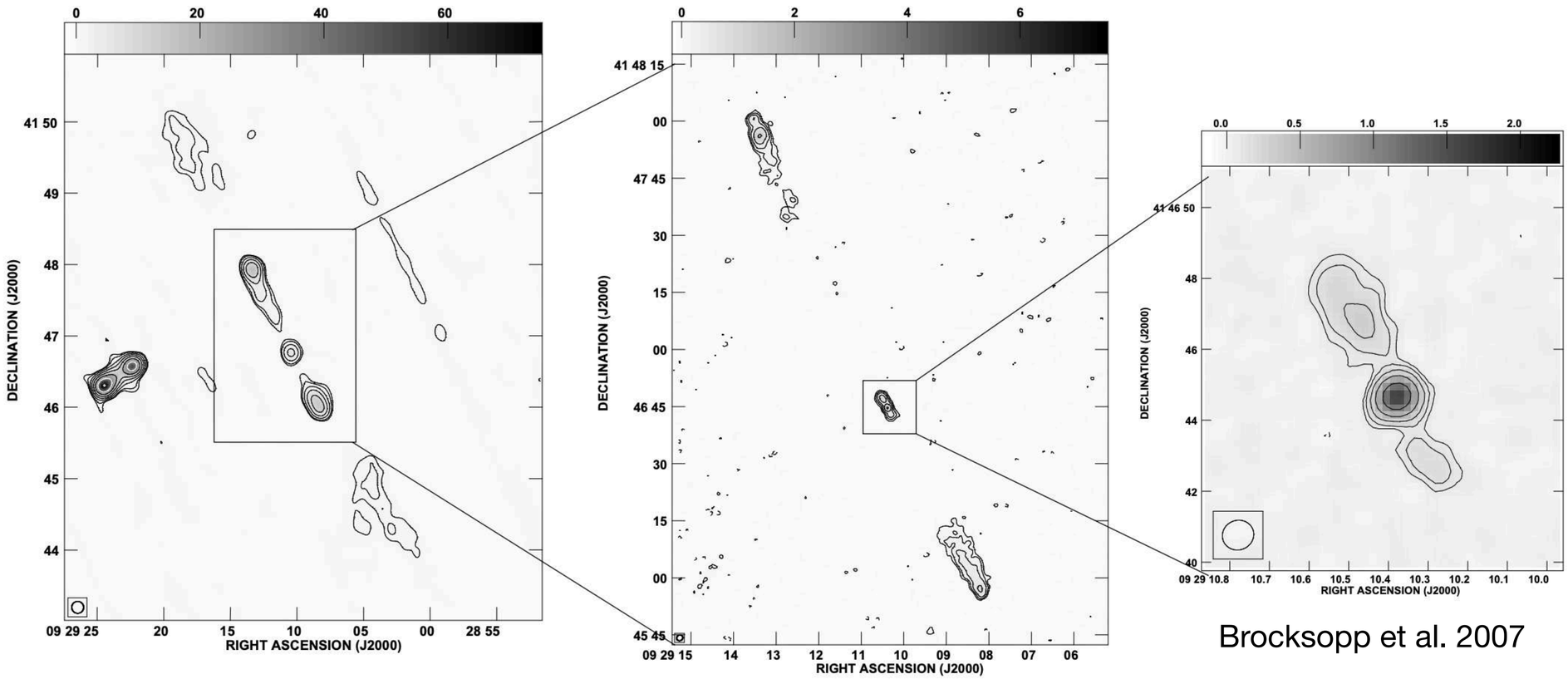
Giri+2024

Restarted radio galaxies (t_{off}<$t_{remnant}$): the zoo



Restarted radio galaxies (t_{off}<$t_{remnant}$): the zoo

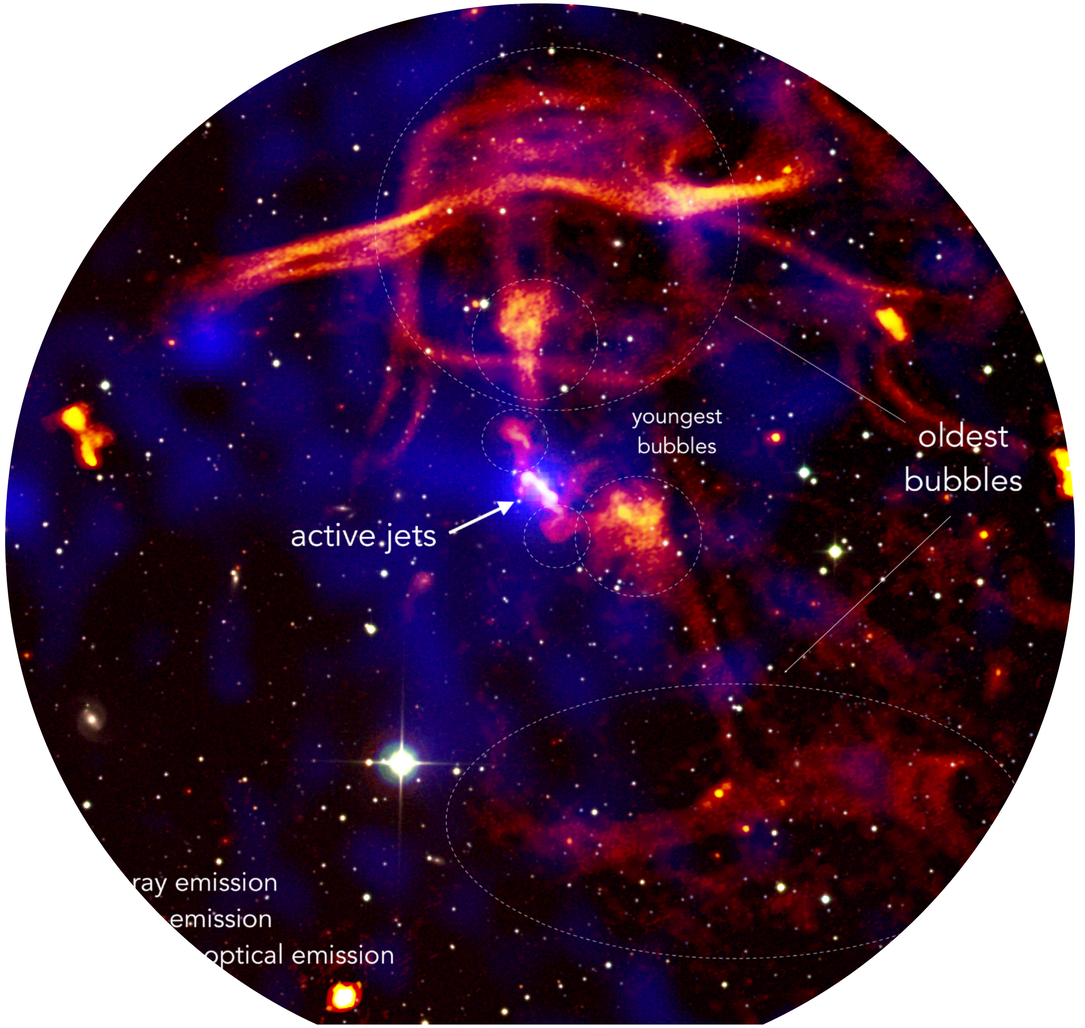
Triple Double



Brocksopp et al. 2007

but also e.g. Rarivoarinoro+2026, Wolnik+2025, Chavan et al. 2023

Restarted radio galaxies (t_{off}<$t_{remnant}$): the zoo



Nest200047
A galaxy group at z=0.018

4 different pairs of bubbles!

Brienza+, NatureAst, 2021
Brienza+, A&A, 20025

Timescales from spectral ageing

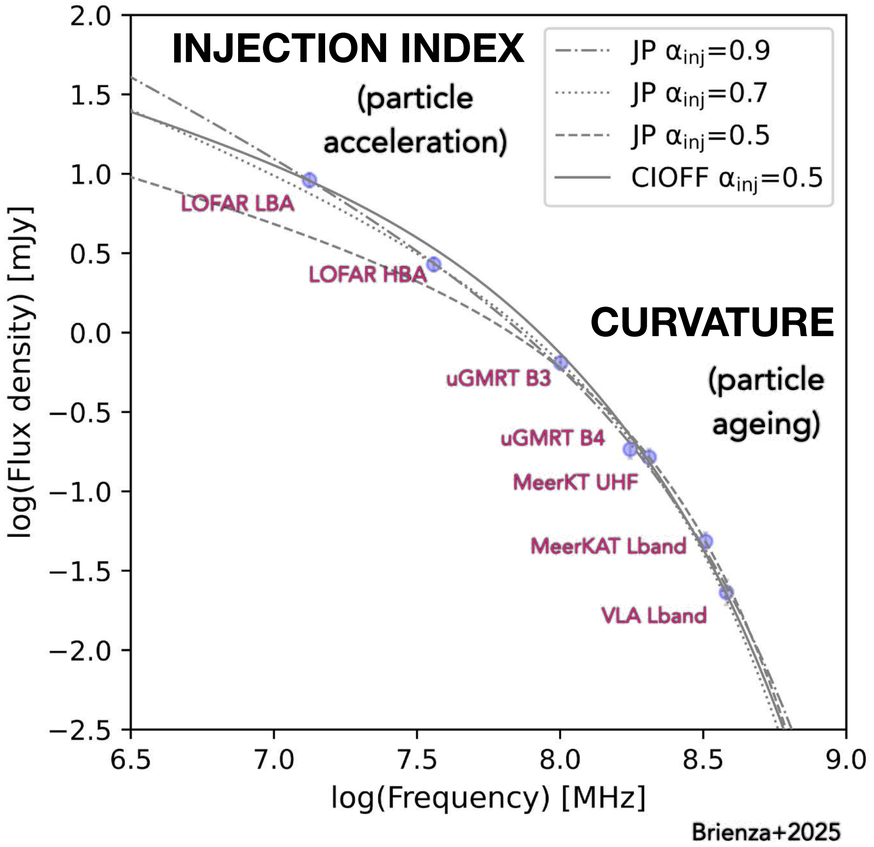
Analytic equation

$$t_s = 1590 \frac{B_{eq}^{0.5}}{(B_{eq}^2 + B_{CMB}^2)\sqrt{\nu_b(1+z)}},$$

Vs

Numerical models

Kardashev & Pacholczyk1970
Jaffe & Perola1973
Tribble 1991,1993
Komissarov & Gubanov1994



Brienza+2025

Timescales from spectral ageing

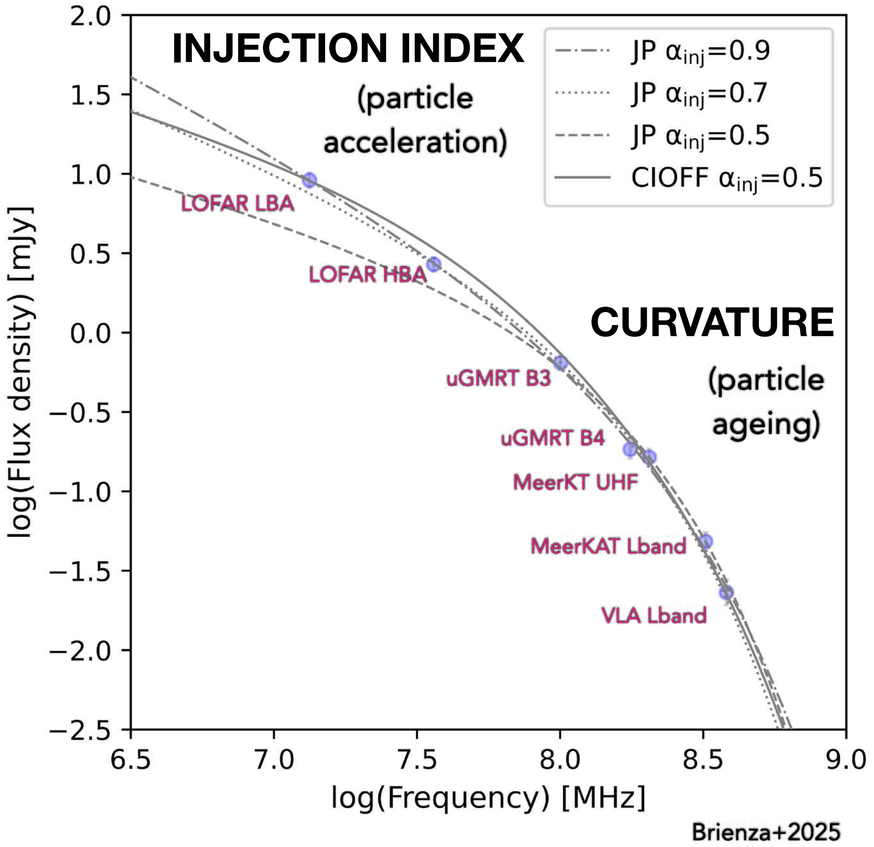
Analytic equation

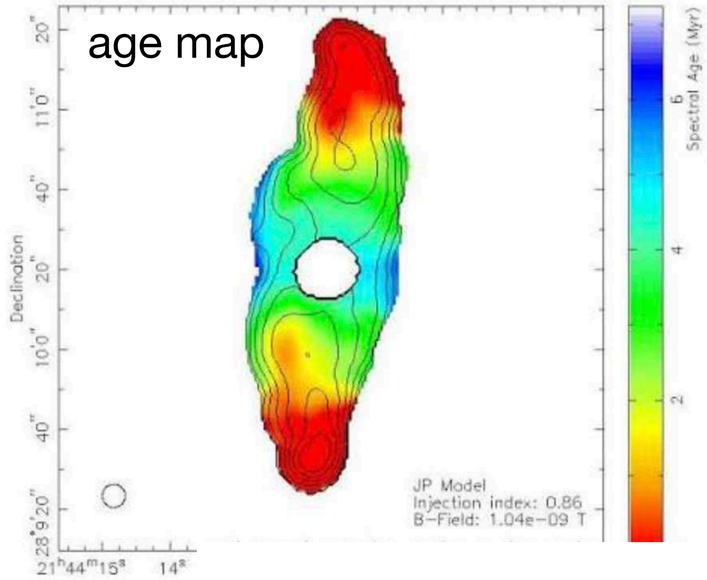
$$t_s = 1590 \frac{B_{eq}^{0.5}}{(B_{eq}^2 + B_{CMB}^2)\sqrt{\nu_b(1+z)}},$$

Vs

Numerical models

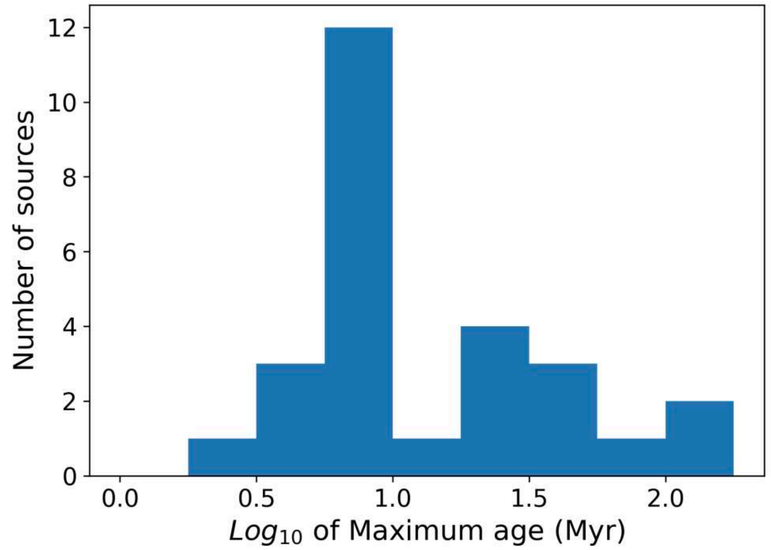
Kardashev & Pacholczyk1970
Jaffe & Perola1973
Tribble 1991,1993
Komissarov & Gubanov1994





Harwood+

Siddhant+23



Timescales from spectral ageing

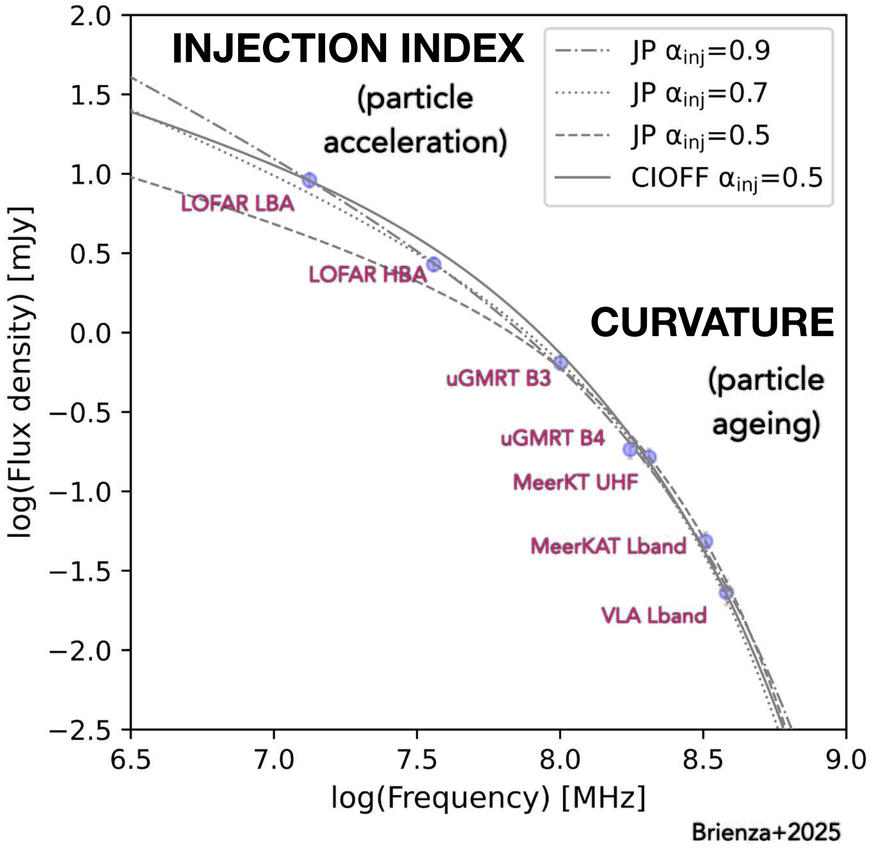
Analytic equation

$$t_s = 1590 \frac{B_{eq}^{0.5}}{(B_{eq}^2 + B_{CMB}^2)\sqrt{\nu_b(1+z)}},$$

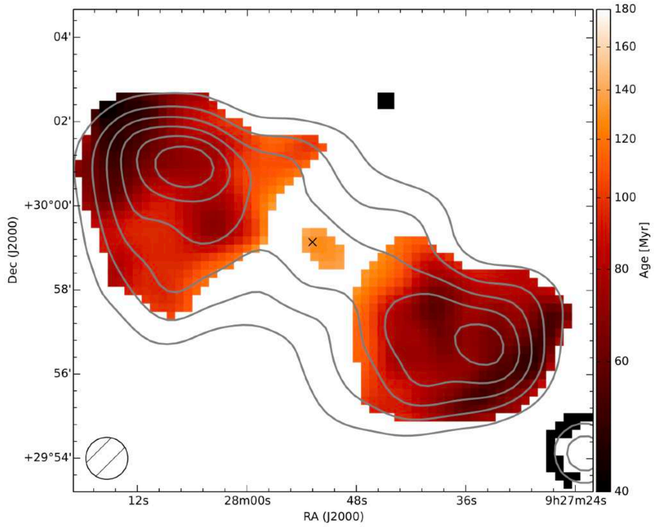
Vs

Numerical models

Kardashev & Pacholczyk1970
Jaffe & Perola1973
Tribble 1991,1993
Komissarov & Gubanov1994



Brienza+2025



Spectral age map

Pixel by pixel modelled spectrum

Duration jet activity= tmax-tmin

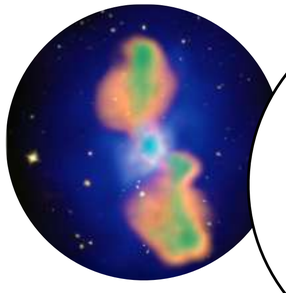
10 Myr on + 50 Myr off

Shulevski+2017

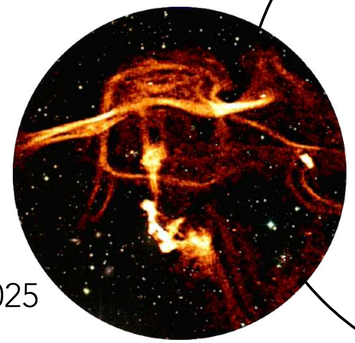
Observationally expensive but possible!

Duty cycle from spectral ageing…some examples

Biava+2021

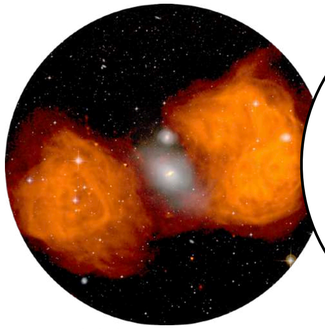


DUTY CYCLE
~40 Myr ON
~ few Myr OFF
<100 Myr ON
~few Myr OFF



Brienza+2025

DUTY CYCLE
~90 Myr ON
~few Myr OFF
~70 Myr ON
~few Myr OFF
~50 Myr ON
~few Myr OFF
Restarted
(compact jets)

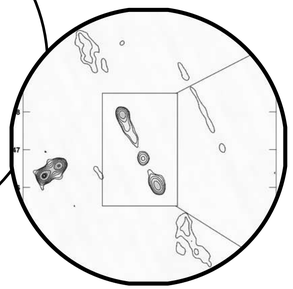


Maccagni+2020

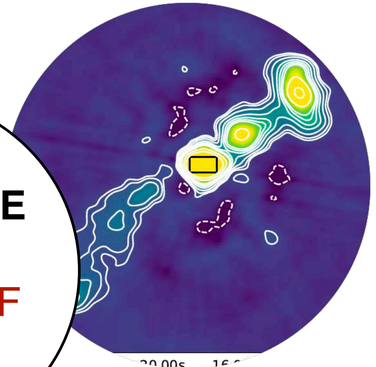
DUTY CYCLE
13 Myr ON
12 Myr OFF
1 Myr ON
2 Myr OFF

DDRGs

DUTY CYCLE
~20-100 ON
1-100 Myr OFF



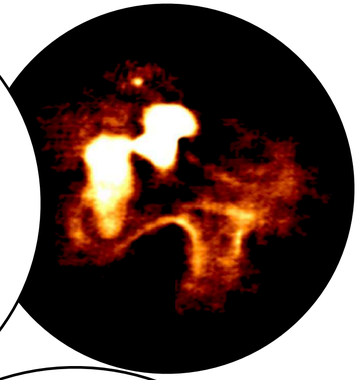
Konar+2012,2013
Rarivoarinoro+2026



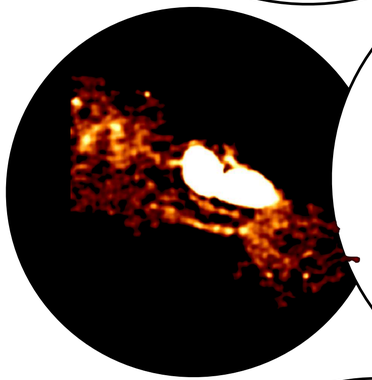
DUTY CYCLE
~20 ON
Few Myr OFF
<0.3 Myr

Kukreti+2021

Brienza+2022



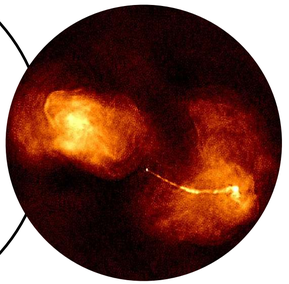
DUTY CYCLE
~60 Myr ON
~90 Myr OFF
~24 Myr ON
~45 Myr OFF
Restarted
(VLBI jet)



Candini+2023

DUTY CYCLE
~30 Myr ON
~150 Myr OFF
~100 Myr ON
>50 Myr OFF
Restarted?
(Nuclear emission)

DUTY CYCLE
>30 ON
<20 Myr OFF
>30 Myr



Brienza+2020

(Remember, biased by construction)

Timescales from spectral ageing



- Plenty of data available and upcoming at low frequency tracing the oldest visible electrons up to hundreds of Myr old (not more!)



- Assumptions on B (e.g. real B~0.3-0.5 B_{eq} for FRIIs -> Croston et al. 2005, Kataoka & Stawarz 2005, Migliori et al. 2007 and Ineson et al. 2017, Turner et al. 2018)
- Expansion + compression/acceleration + mixing (e.g. Turner+2017, Harwood+2017)



All possible origins for **discrepancy between spectral and dynamical age** obtained through radio galaxy evolution models (Qjet+environment)= $\mathbf{t_{spec} < t_{dyn}}$

e.g. Mahatma+2019, Jerrim+2025

A note on small jets

The majority of radio loud AGN are low power ($10^{23\text{-}25}$W/Hz @1.4 GHz) with sizes within the galaxy!

e.g. Best+2005, Baldi+2017

They cannot be all the young progenitors of extended radio galaxies -> TOO MANY!

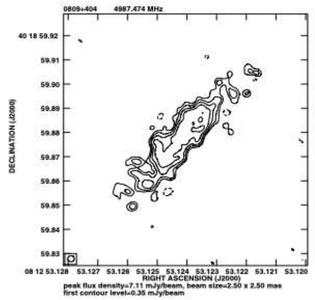
A note on small jets

The majority of radio loud AGN are low power ($10^{23\text{-}25}$W/Hz @1.4 GHz) with sizes within the galaxy! e.g. Best+2005, Baldi+2017

They cannot be all the young progenitors of extended radio galaxies -> TOO MANY!

◆ Are they short-lived? ◆ Are they active for long but too low power to be observed?

Small remnants and restarted must exist and do exist BUT difficult!

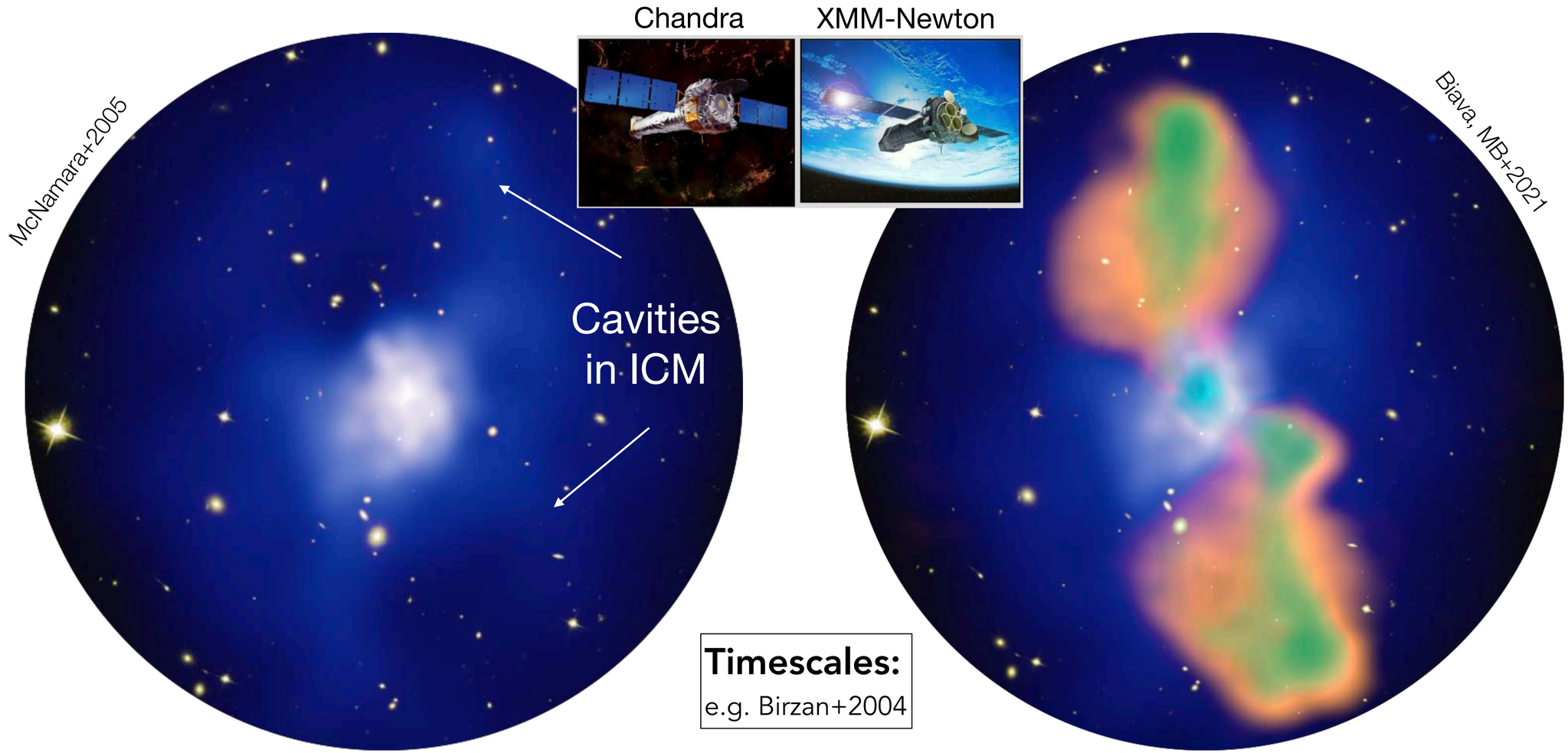


Kunert-Bajraszewska+2006

BUT also e.g…
Callingham+2015, Orienti+2010, 2021
Webster+2021, Giroletti+2003
Kunert-Bajraszewska+2005, Zeng+2026

LOFAR VLBI can be a key!

Timescales from AGN jet cavities in galaxy groups and clusters



Timescales:
e.g. Birzan+2004

Buoyancy

$$t_{\rm buoy} = R/v_{\rm t} \sim R\sqrt{SC/2gV}$$

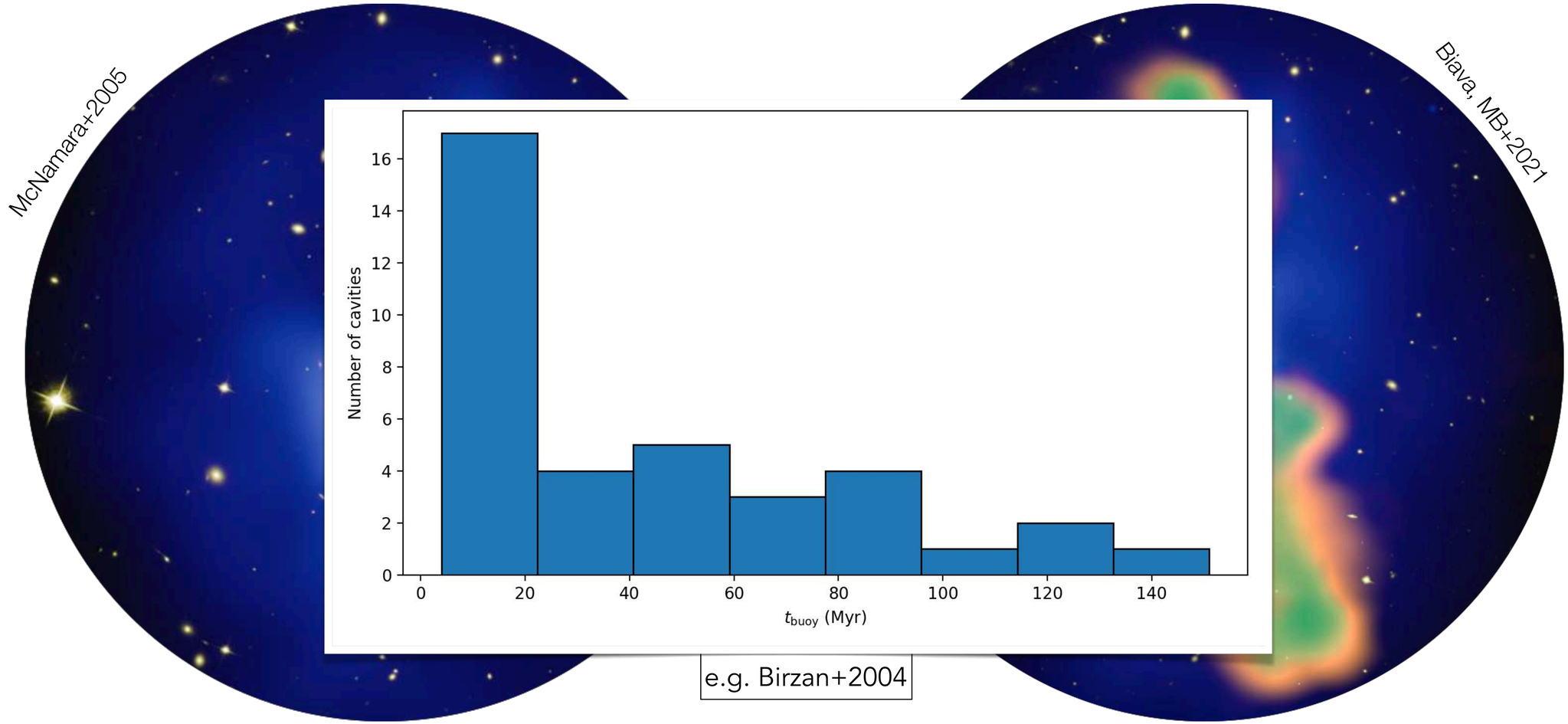
Sound speed

$$t_{\rm c_s} = R/v_{\rm c_s} = R\sqrt{\mu m_{\rm H}/\gamma kT}$$

Refill

$$t_{\rm r} \sim 2R\sqrt{r/GM(R)} = 2\sqrt{r/g}$$

Timescales from AGN jet cavities in galaxy groups and clusters



e.g. Birzan+2004

Buoyancy

$$t_{\rm buoy} = R/v_{\rm t} \sim R\sqrt{SC/2gV}$$

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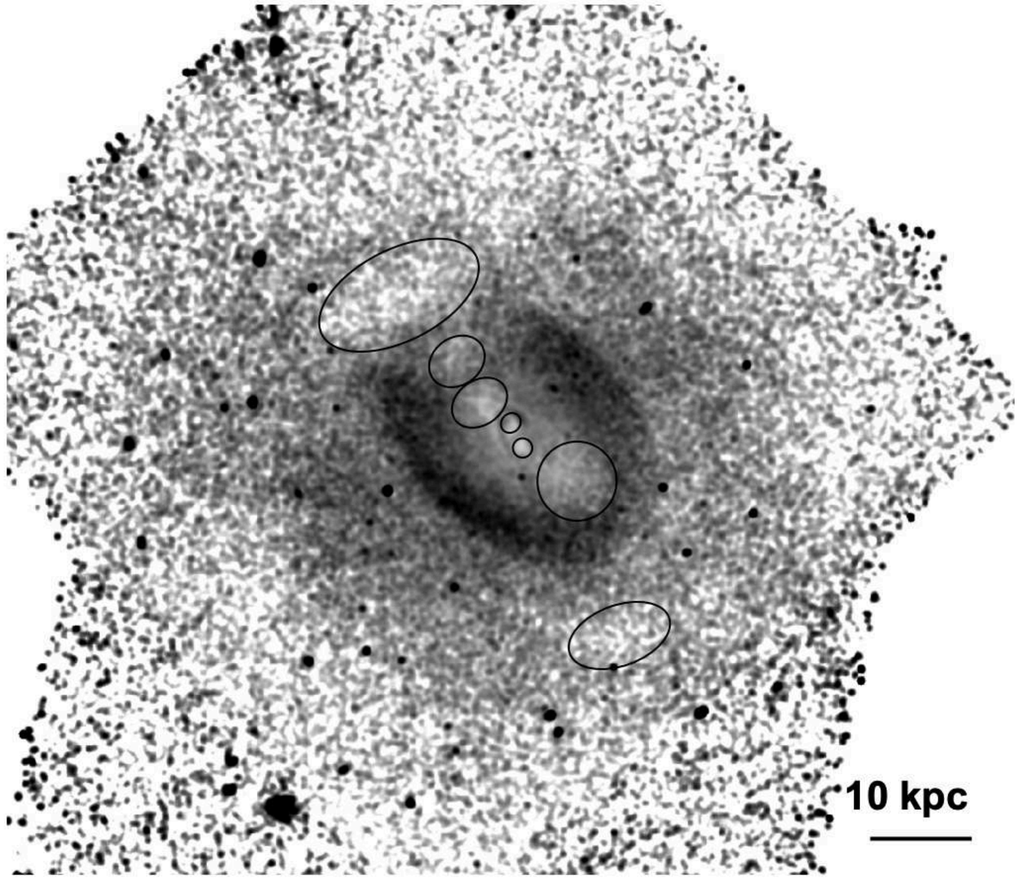
$$t_{\rm c_s} = R/v_{\rm c_s} = R\sqrt{\mu m_{\rm H}/\gamma kT}$$

Refill

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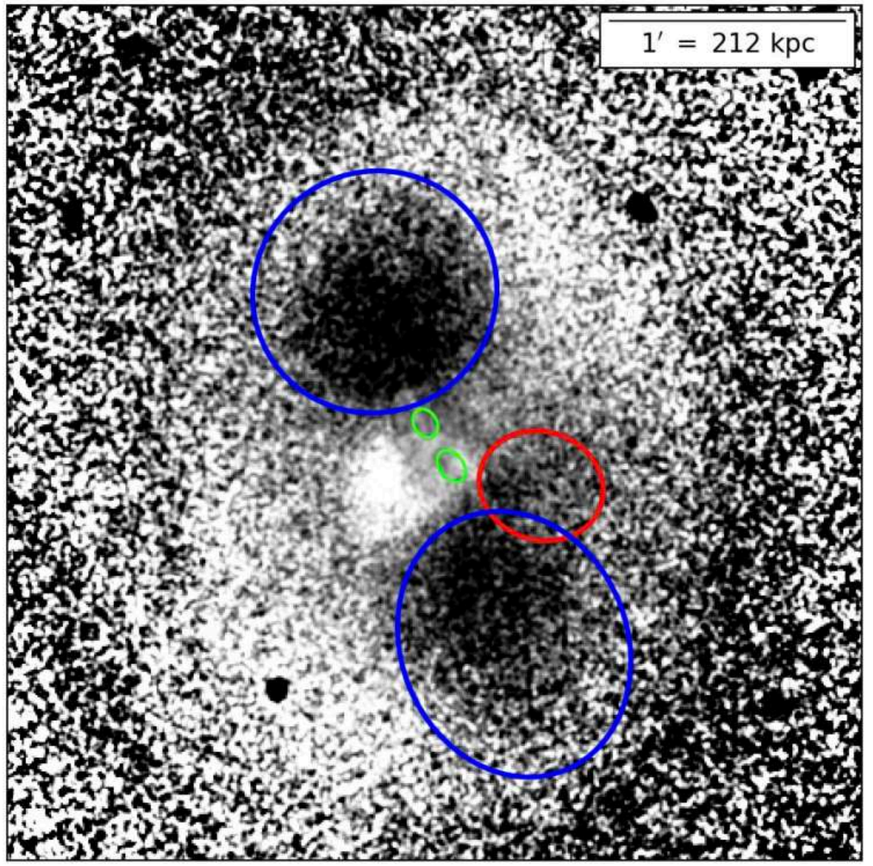
Multiple AGN jet cavities in galaxy groups and clusters

Randall+2011,2015



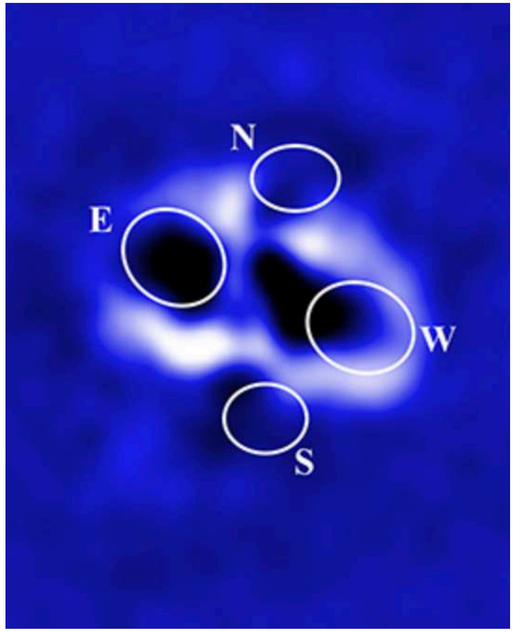
Galaxy group NGC5813

Biava, MB+2021



Galaxy cluster MS 0735.6+7421

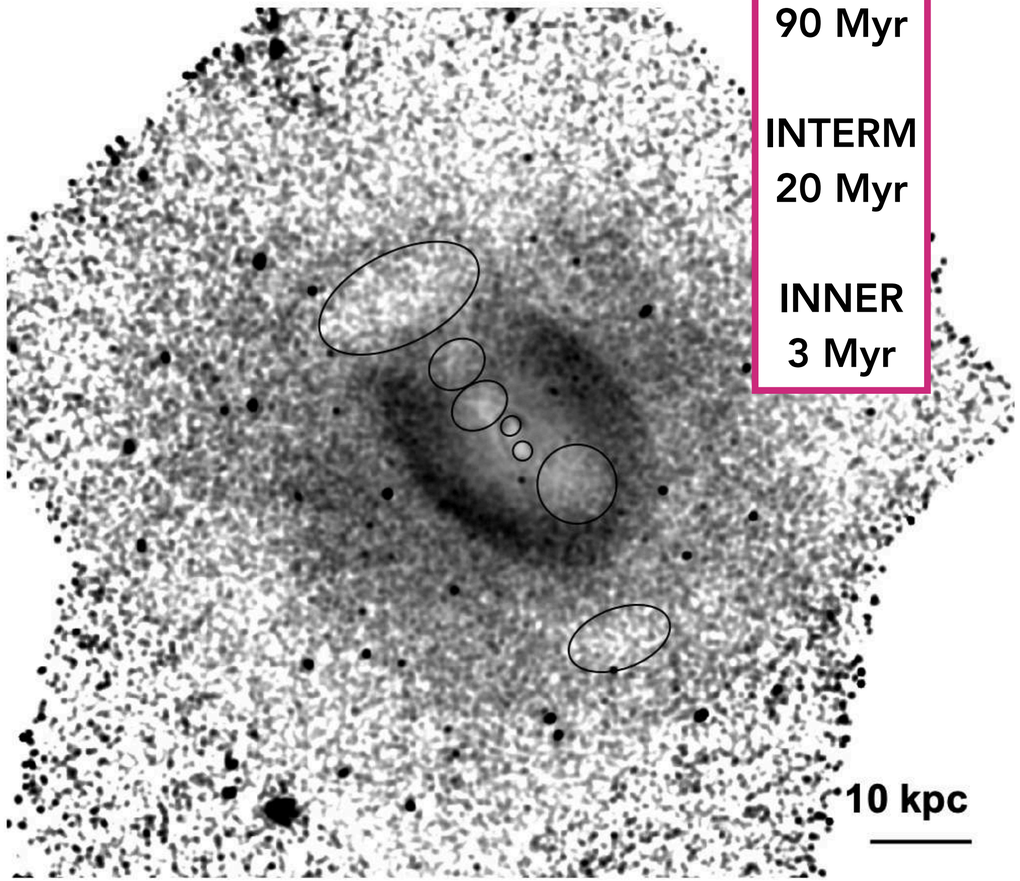
Ubertosi+2021



Galaxy cluster RBS797

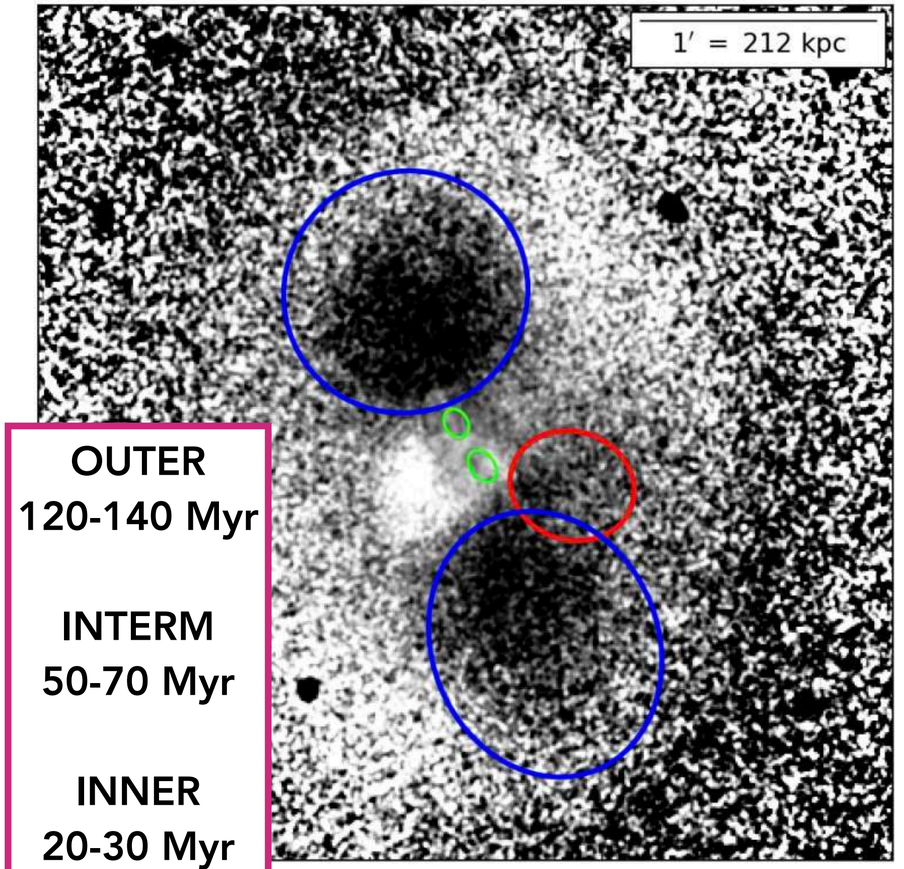
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Randall+2011,2015



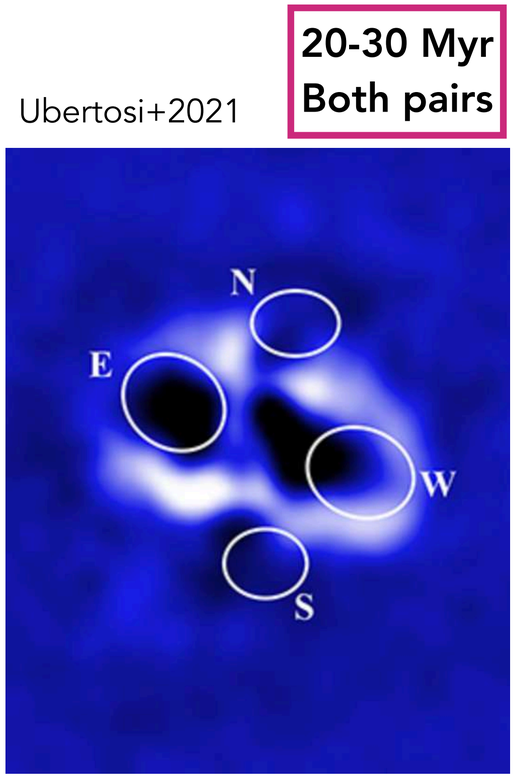
Galaxy group NGC5813

Biava, MB+2021



Galaxy cluster MS 0735.6+7421

Ubertosi+2021



Galaxy cluster RBS797

Timescales from AGN jet cavities



- Cavities remain visible for longer periods than radio

  -> Ghost cavities = X-ray depressions without radio

  (e.g. Fabian+2000, McNamara+2001, Birzan+2004, 2020)

- Need long exposures and high resolution -> especially in systems outskirts and low mass systems (no adequate telescopes)

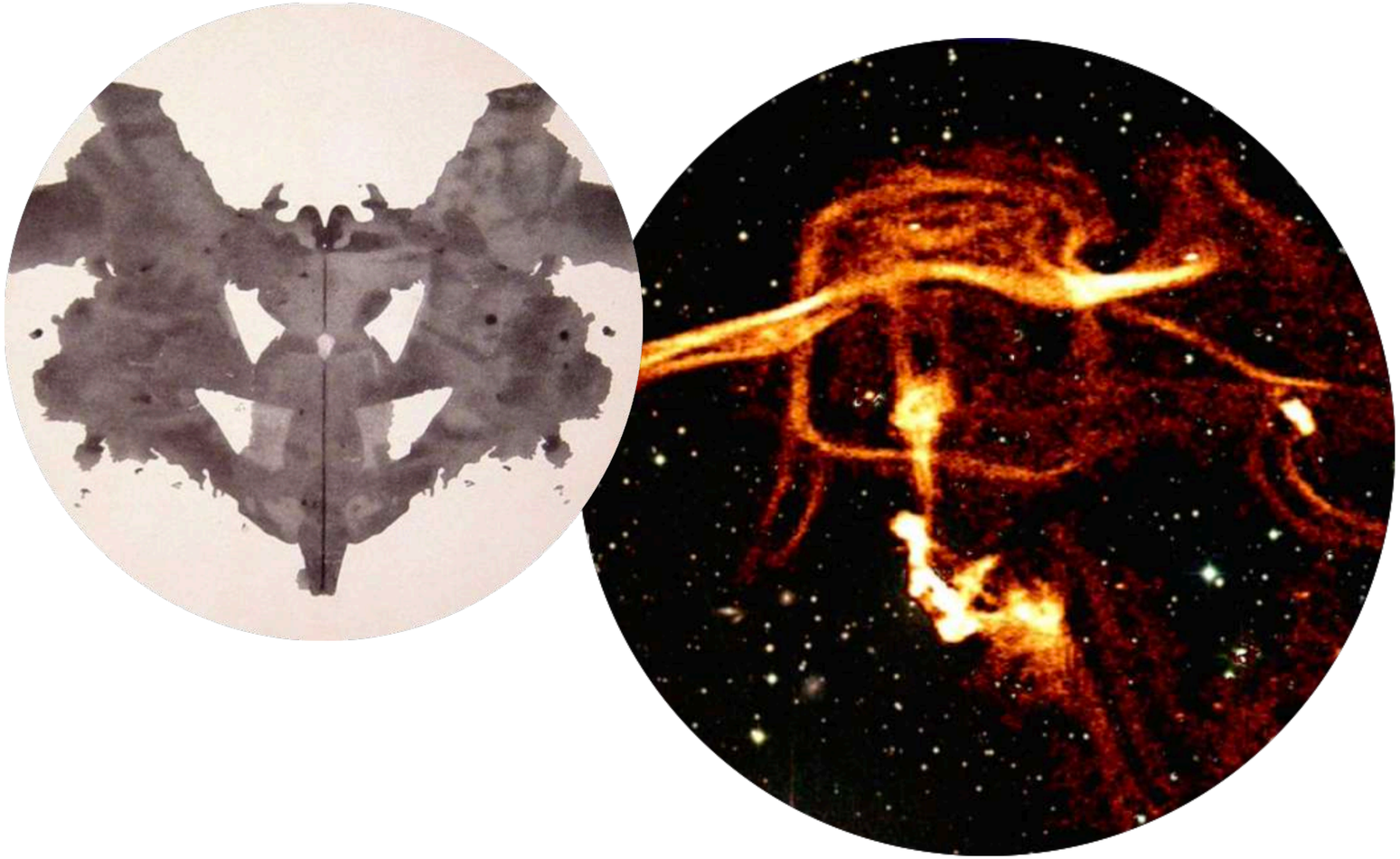


- Detectability influenced by position, orientation, and angular extent of the cavities

  (e.g. Enßlin & Heinz 2002; Diehl et al. 2008; Brüggen et al. 2009)

- Weak assumptions: e.g. neglets bubble expansion during jet active time, projection etc..

The astronomer’s test for personality of Rorschach!

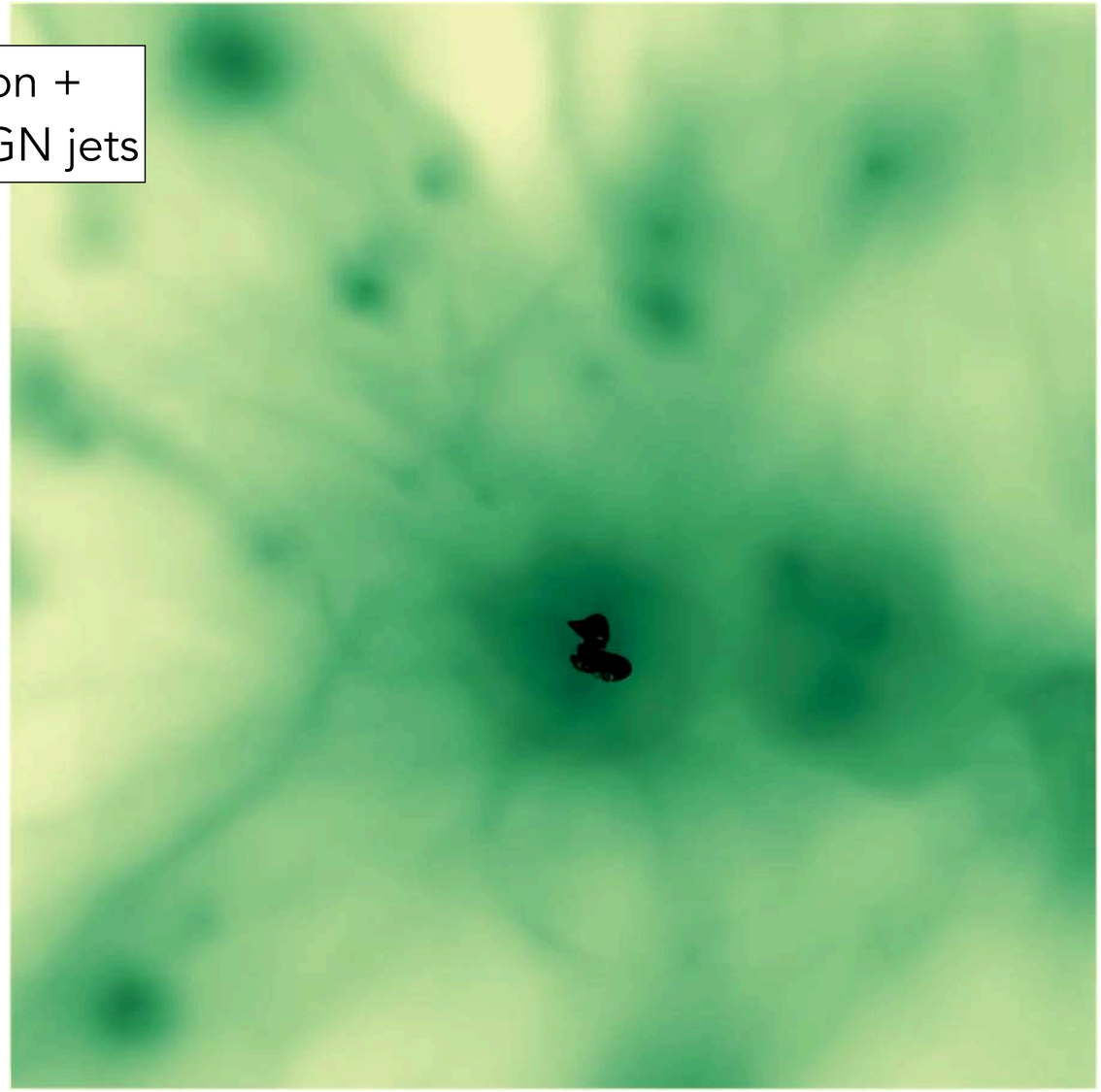


What do you see?

Interplay between AGN remnant plasma and the surrounding medium

Moving/shredding old AGN bubbles in the ICM/IGrM

Green = cosmological simulation +
Black = particle tracers from AGN jets

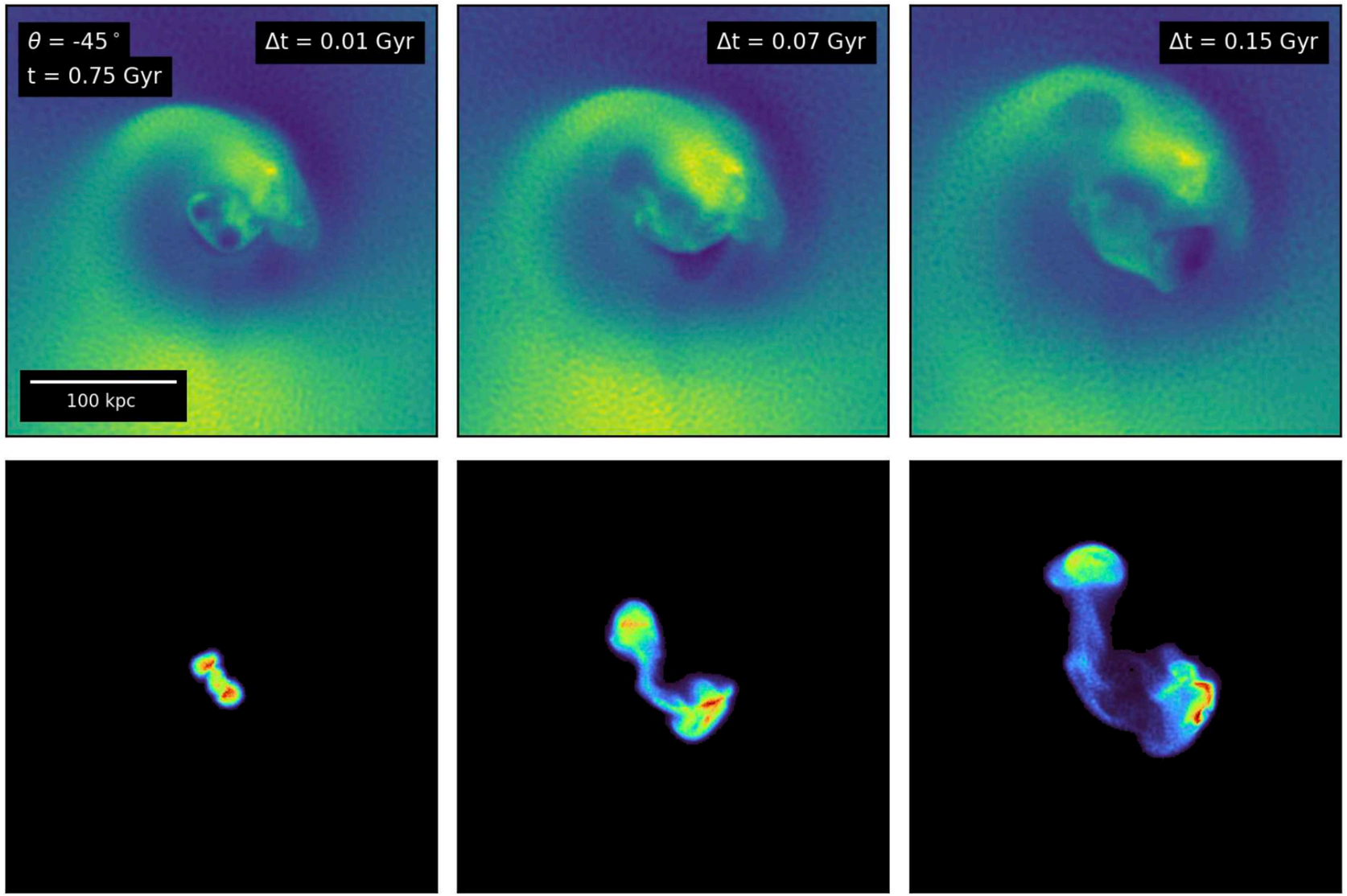


Vazza+2021,2023,2024

Moving/shredding old AGN bubbles in the ICM/IGrM

Sloshing motion

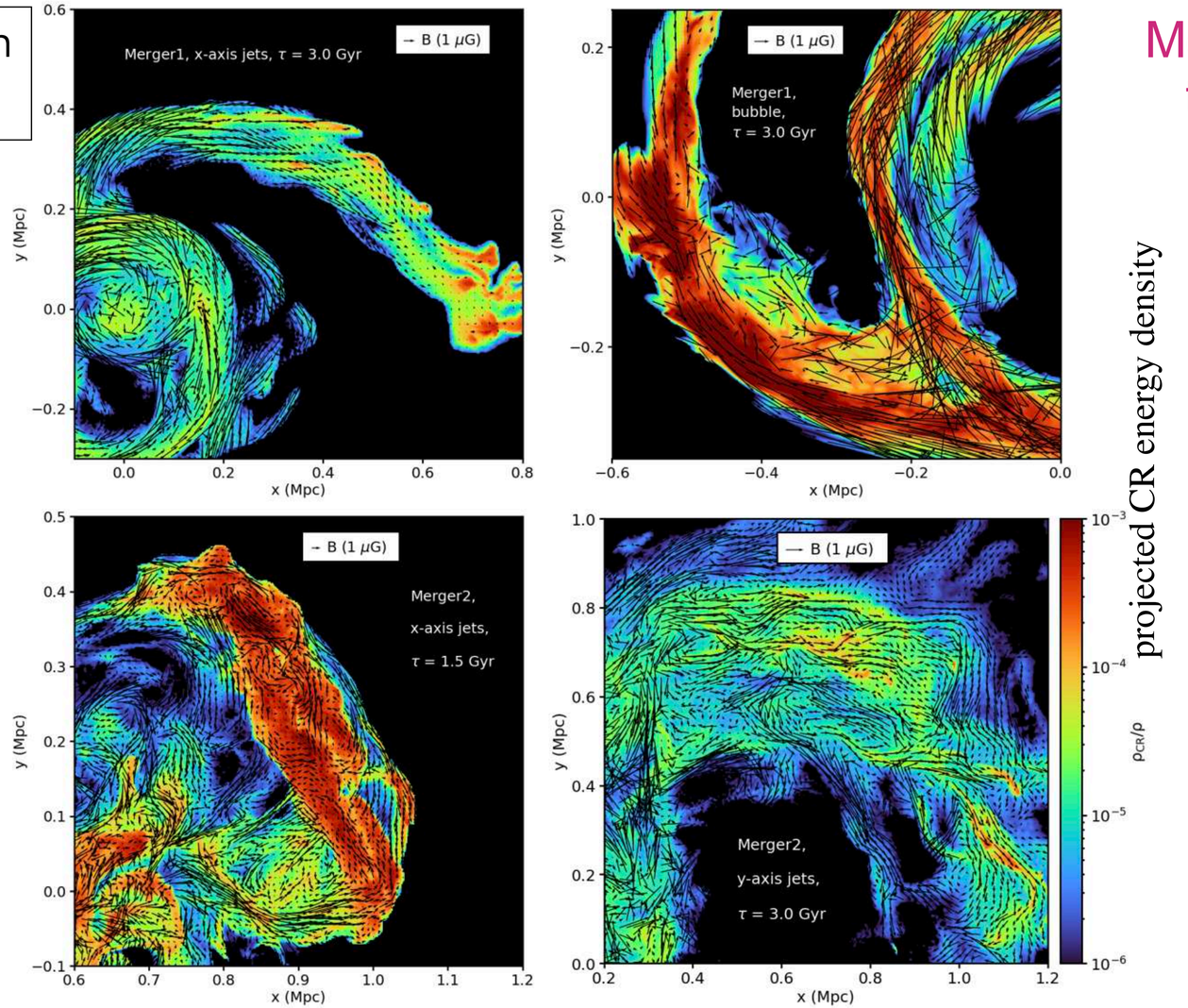




Fabian+2021

Moving/shredding old AGN bubbles in the ICM/IGrM

Magnetic field distribution in old shredded bubbles

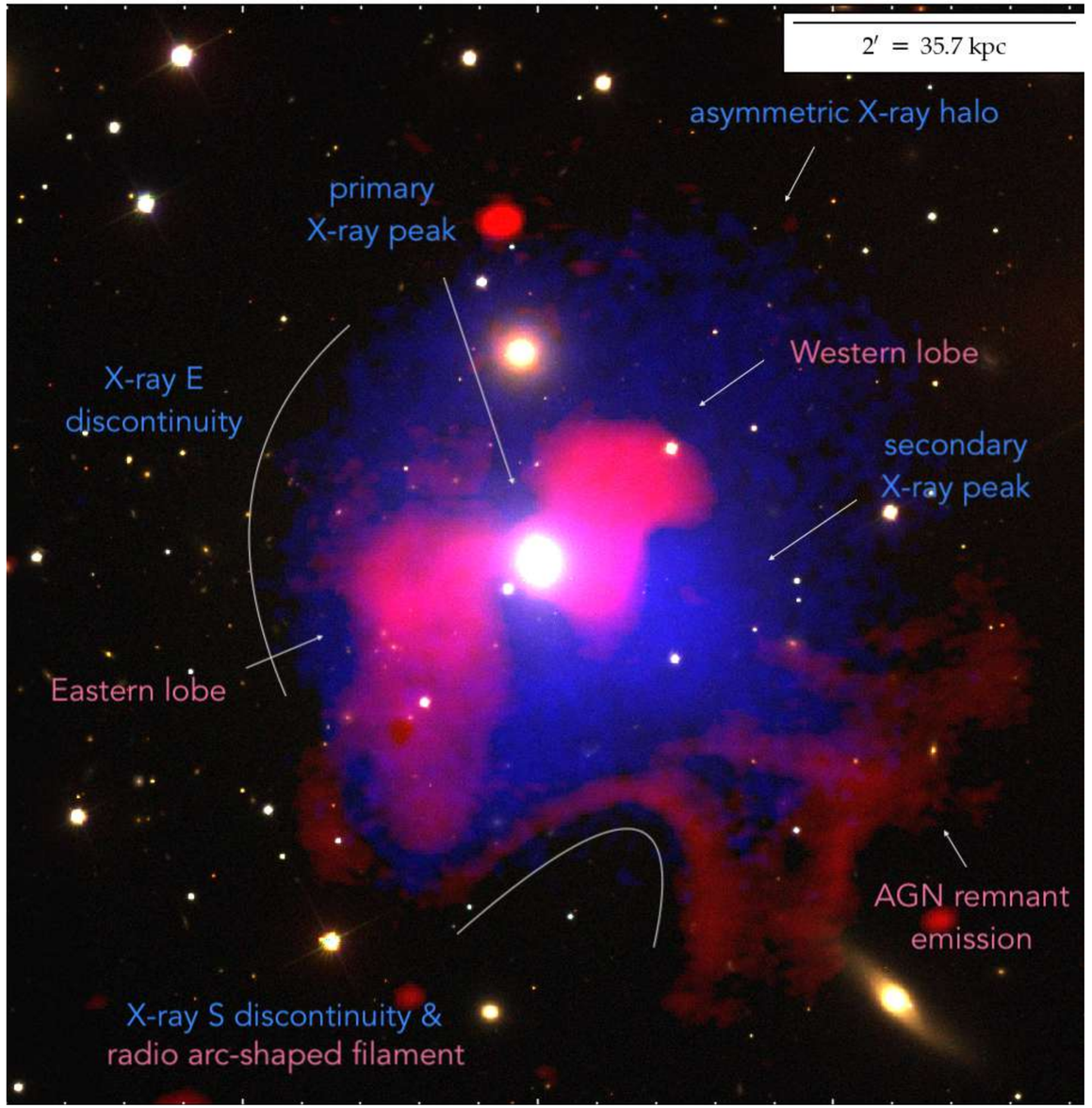


Motions stretch and amplify the magnetic field along the same direction

Zuhone+2021

Moving/shredding old AGN bubbles in the ICM/IGrM

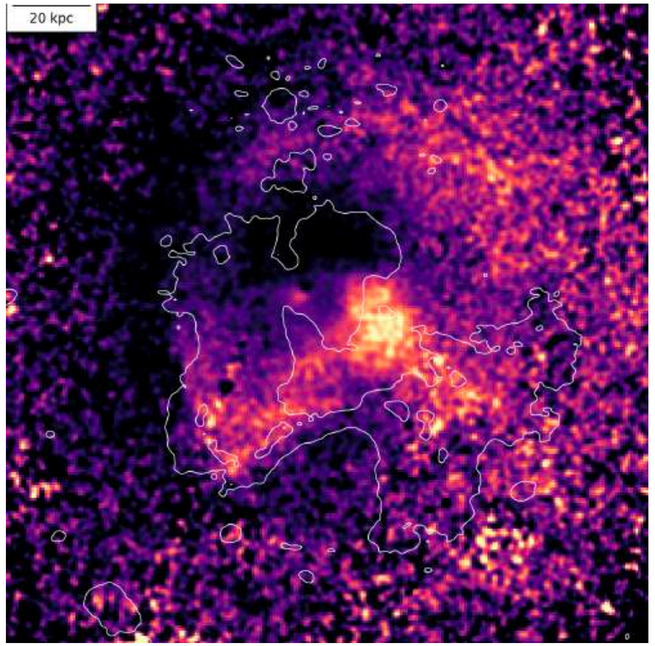
SDSS
LOFAR 144 MHz - 6”
XMM 0.7-2 keV

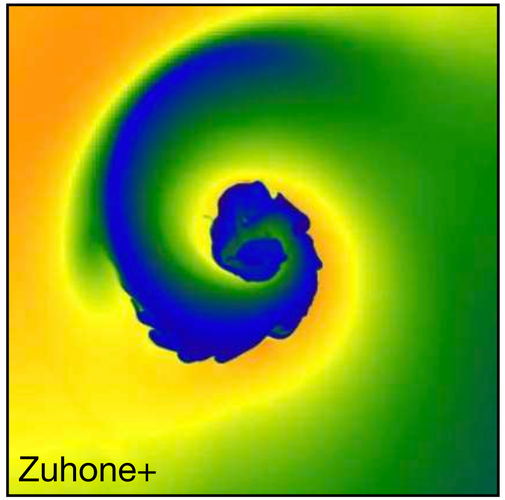


NGC 507
Galaxy group

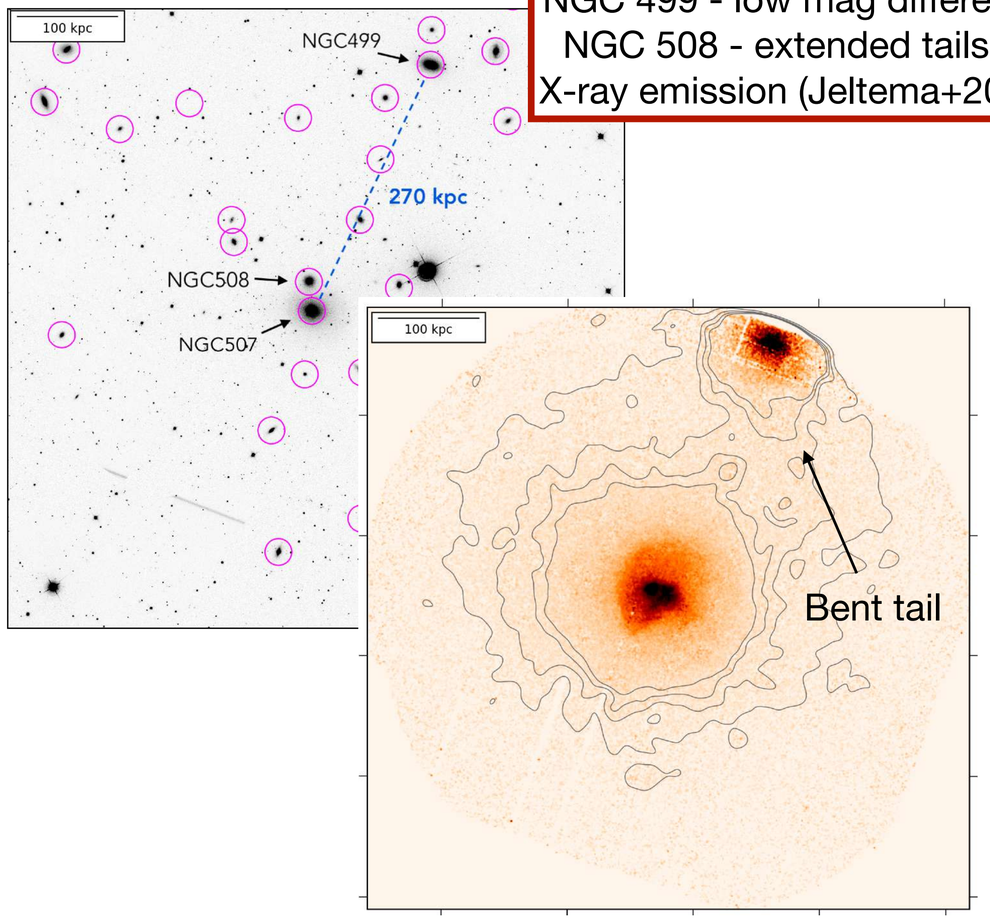
Brienza+2022

Moving/shredding old AGN bubbles in the ICM/IGrM





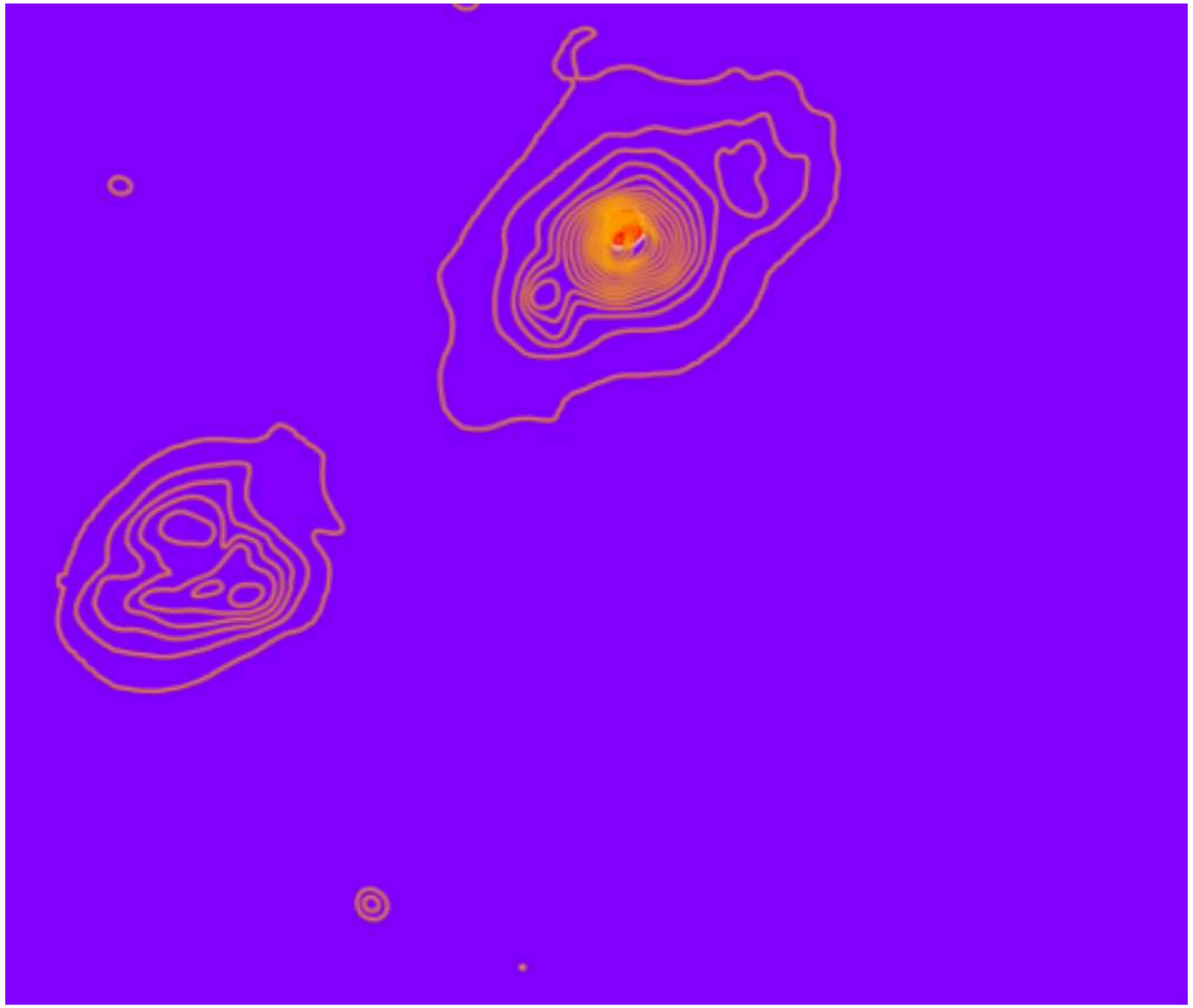
Sloshing perturber?
NGC 499 - low mag difference
NGC 508 - extended tails of X-ray emission (Jeltema+2008)



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

Moving/shredding old AGN bubbles in the ICM/IGrM

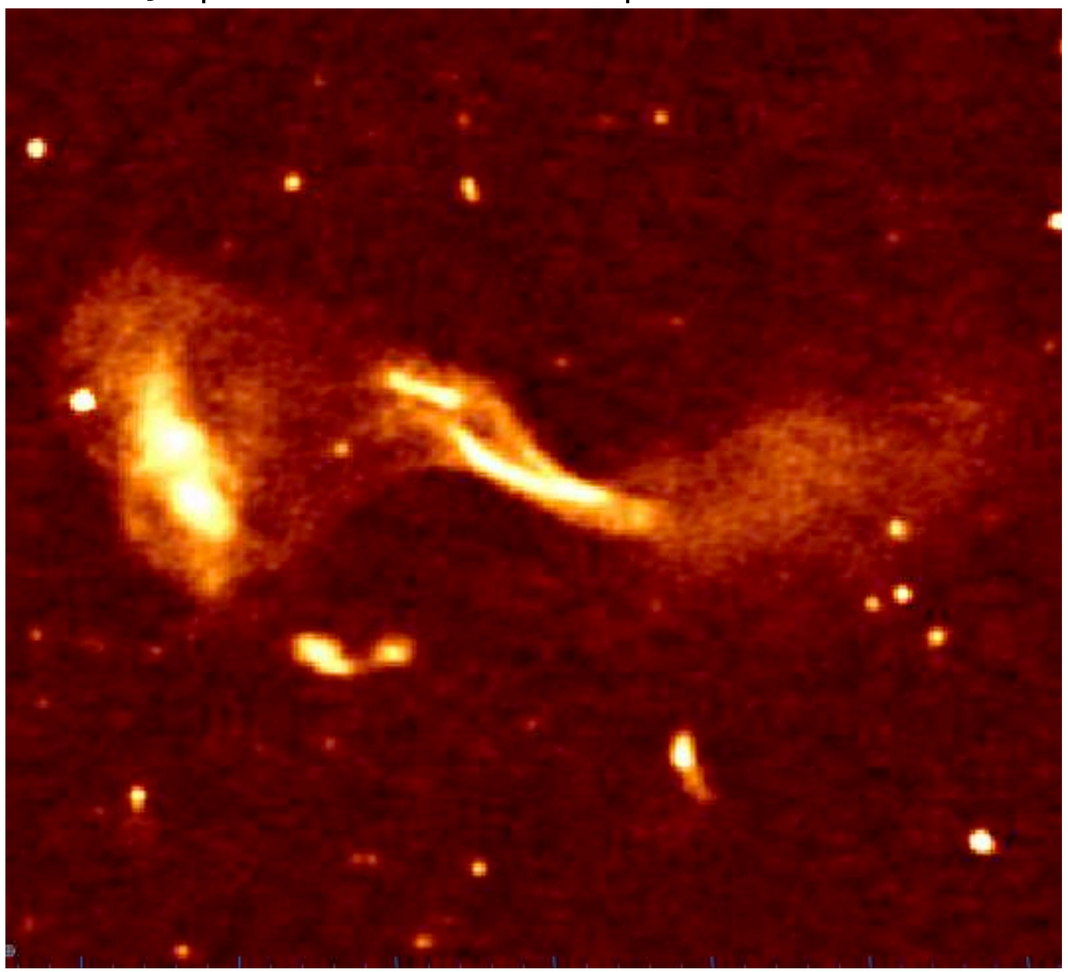


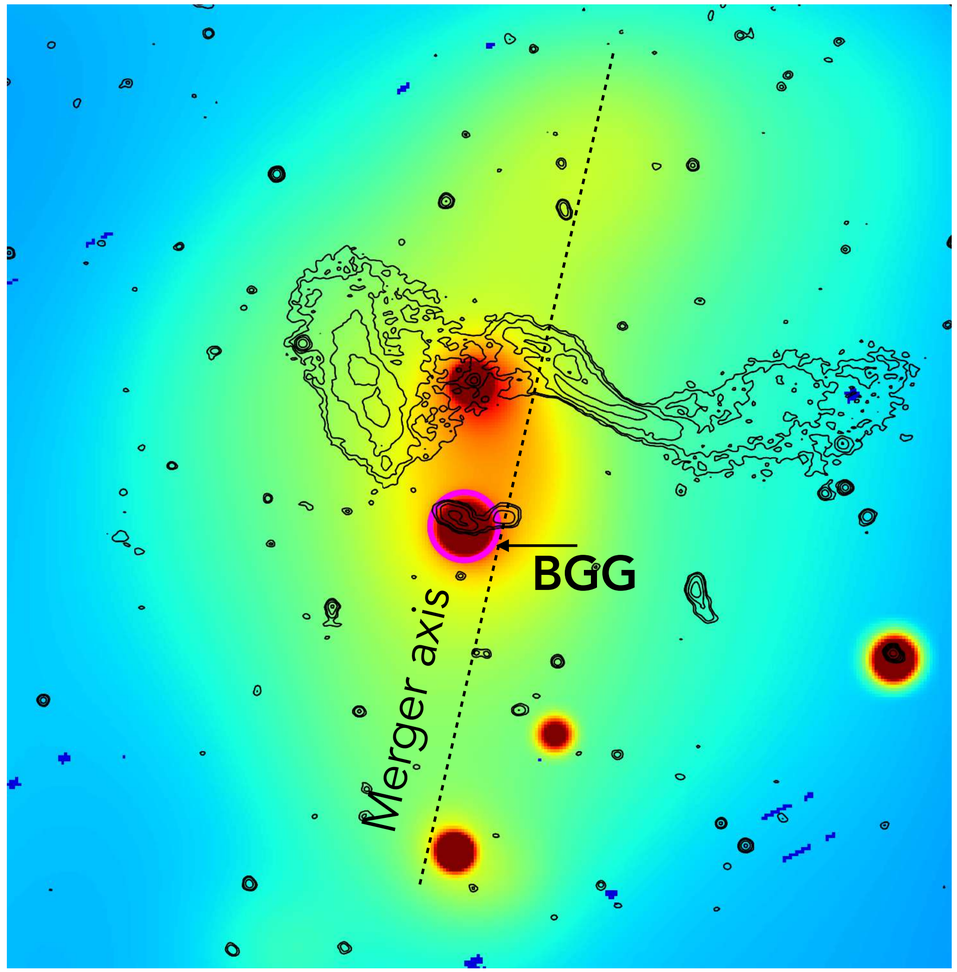
Vazza+

Moving/shredding old AGN bubbles in the ICM/IGrM

A1318 galaxy group

250 Myr plasma from radio spectra

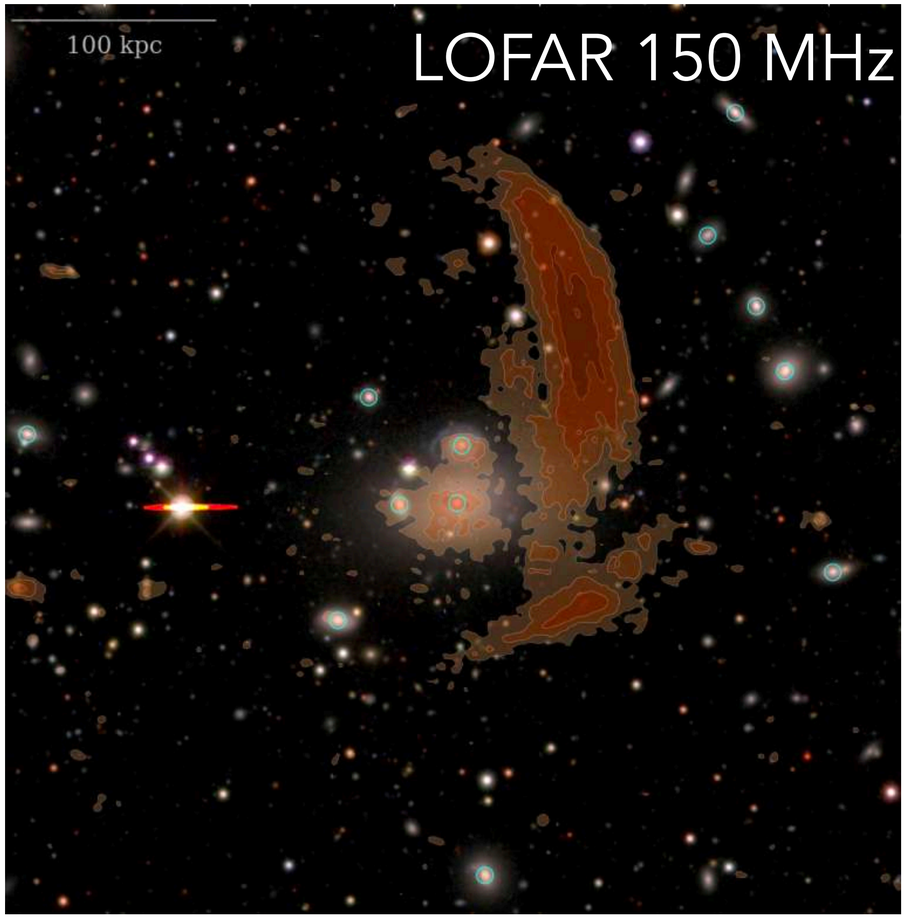


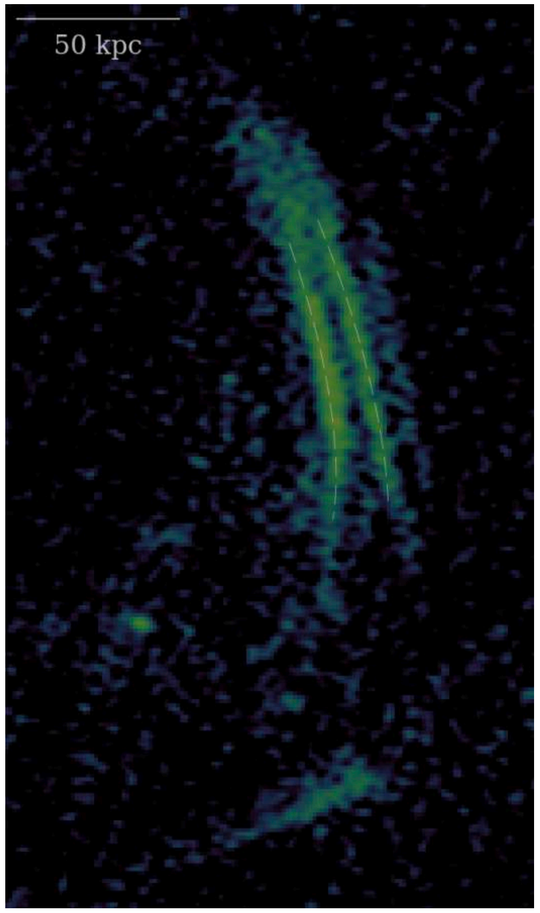


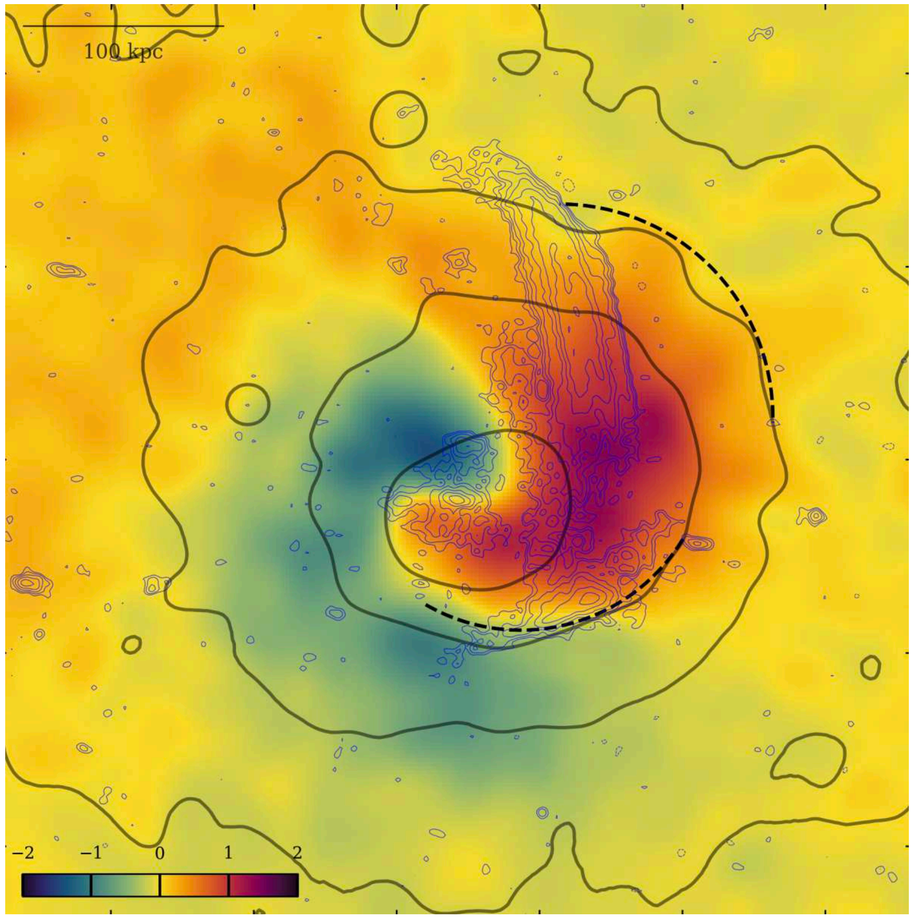
Shulevski+2024

Moving/shredding old AGN bubbles in the ICM/IGrM

Abell2657

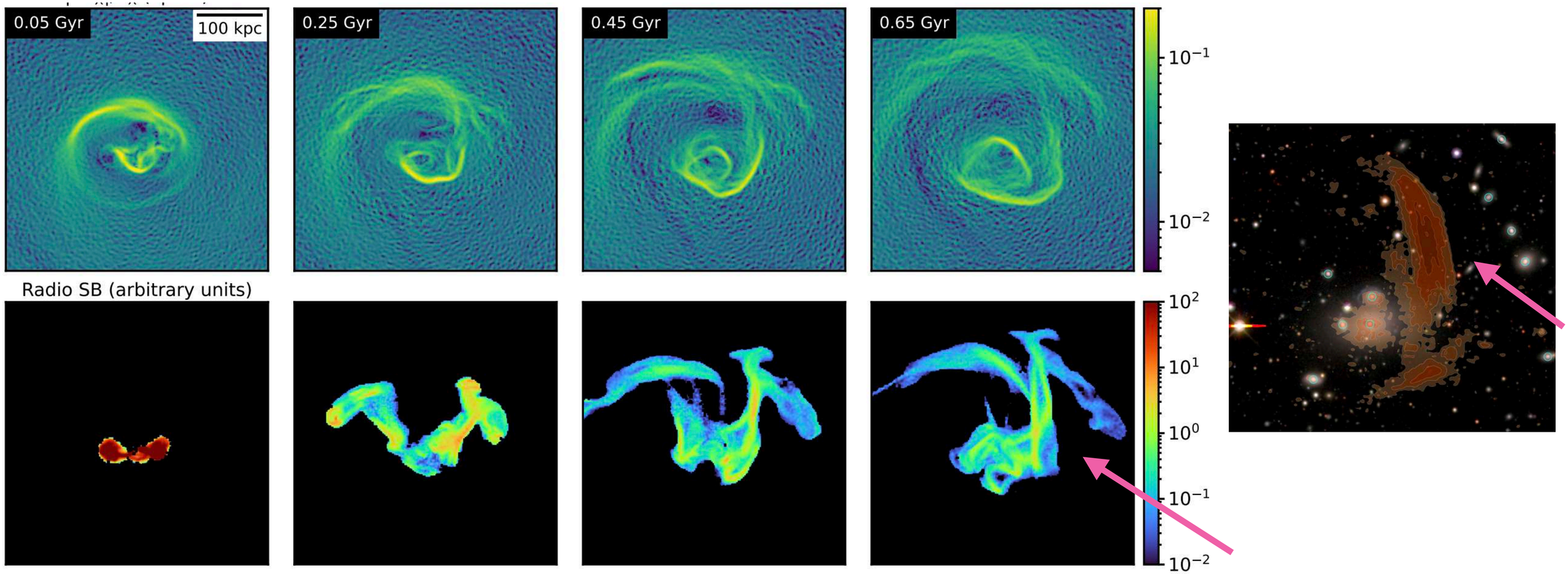






Botteon+2023

Moving/shredding old AGN bubbles in the ICM/IGrM



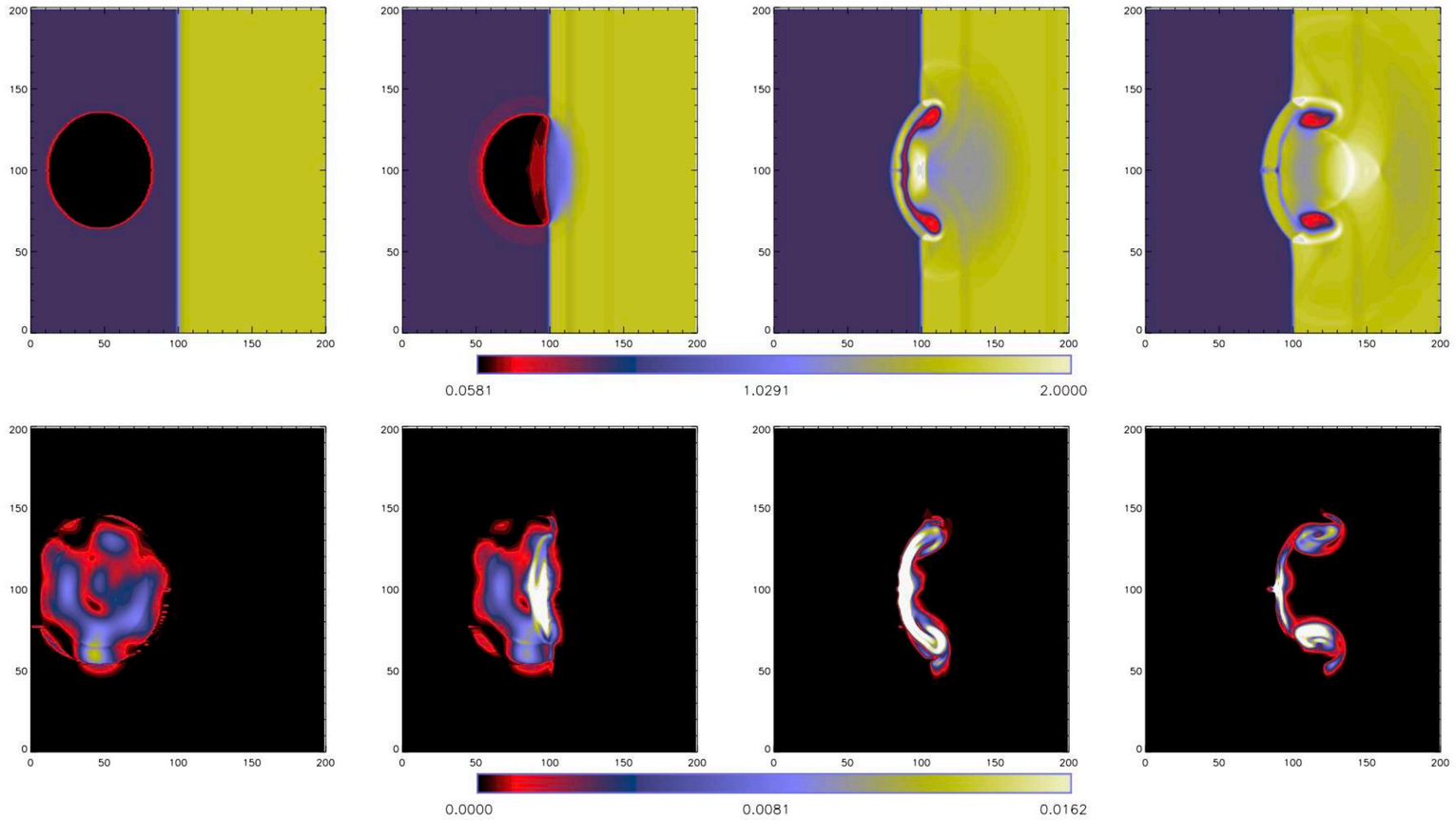
Simulations in support…

Revived old AGN plasma/bubbles… radio phoenices

Old AGN bubble crossed by a shock

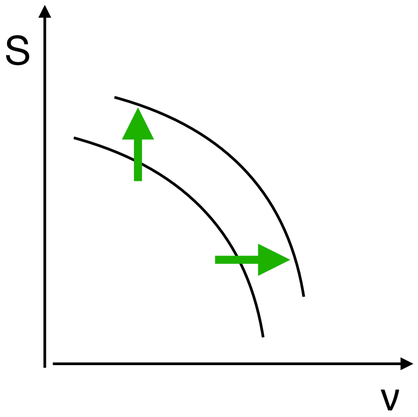
First compressed then torn into filamentary structures

Initially spherical bubble transformed into a torus because of pressure difference



Adiabatic compression: Electron energy increased and magnetic field increased/aligned= shift to higher frequency and emission boost

Visible again!



Ensslin&Bruggen2001,2002

Revived old AGN plasma/bubbles… radio phoenices

Magnetic field parallel to filaments

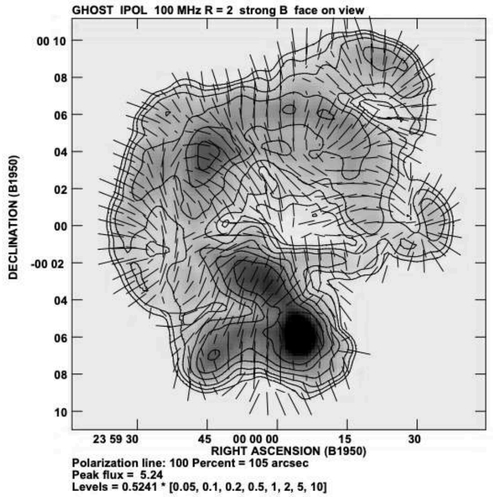


Figure 7. Face-on view of the late stage of the shock passage in the model *wSsB*. For details see Fig. 5.

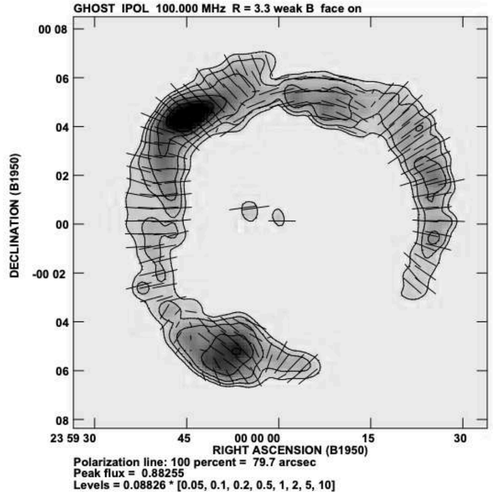
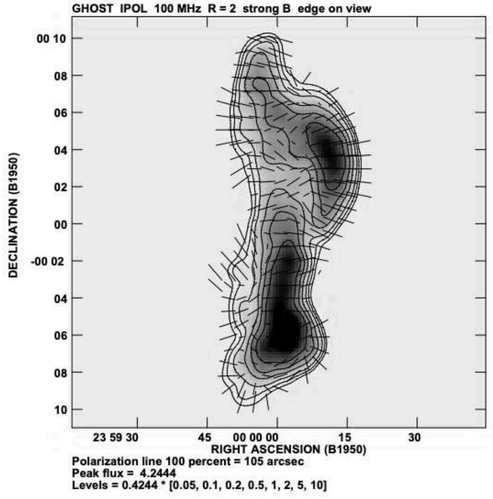
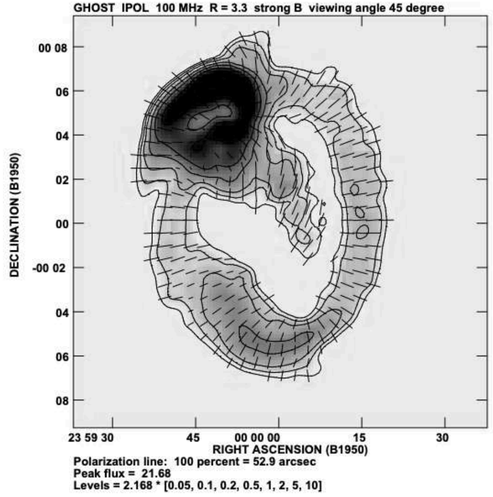


Figure 9. Face-on view of the late stage of the shock pass the model *sSwB*. For details see Fig. 5.





Ensslin&Bruggen2001,2002

Revived old AGN plasma/bubbles… radio phoenices

Compression factor

$$C = \frac{V_{\text{sphere}}}{V_{\text{torus}}} = \frac{4\pi R^3/3}{2\pi^2 R r^2} = \frac{2R^2}{3\pi r^2}$$

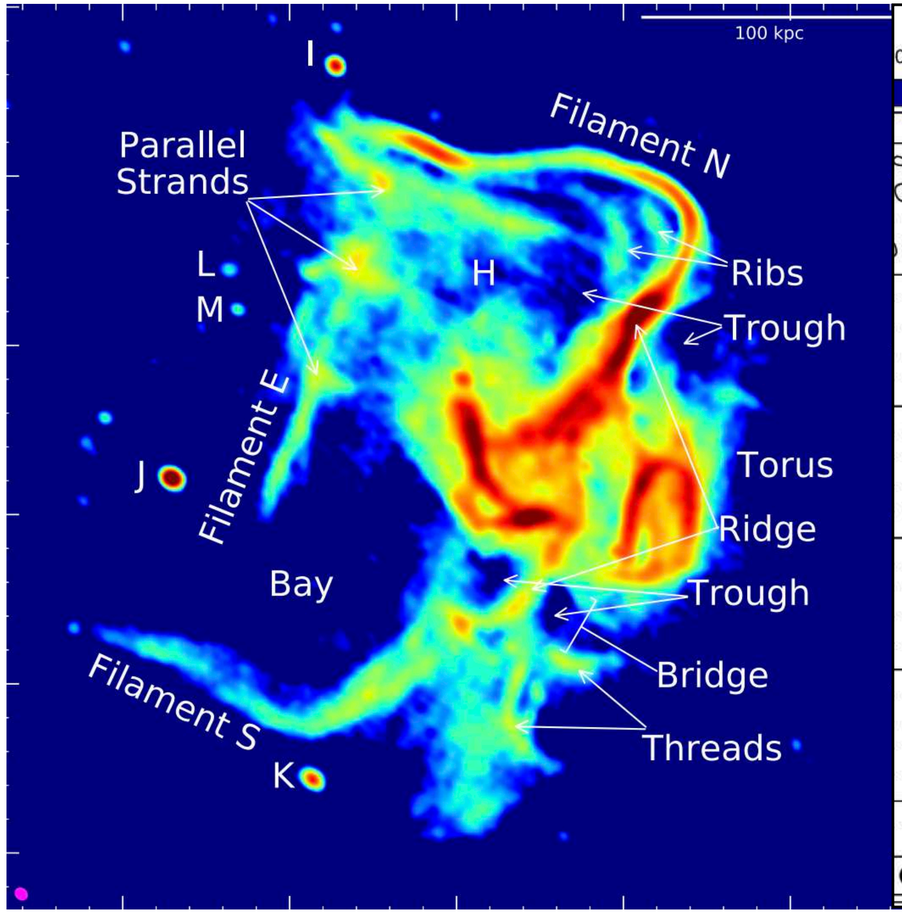
Pressure ratio (before and after the shock passage)

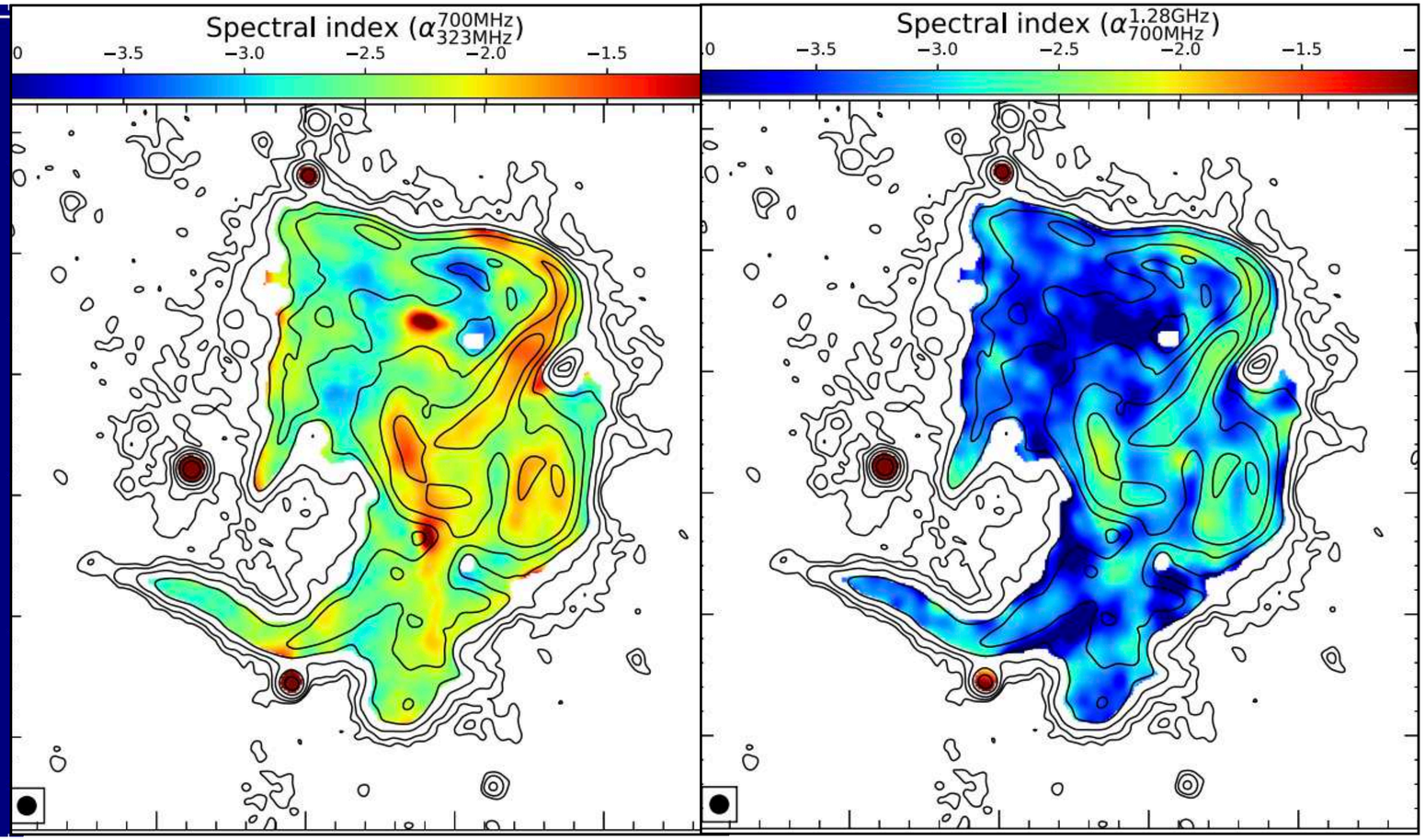
$$P_2/P_1 = C^{\gamma_{\text{rp}}}$$ γ = adiabatic index

Mach number

$$\frac{P_2}{P_1} = \frac{2\gamma M^2 - (\gamma - 1)}{\gamma + 1}$$

Revived old AGN plasma/bubbles… radio phoenices



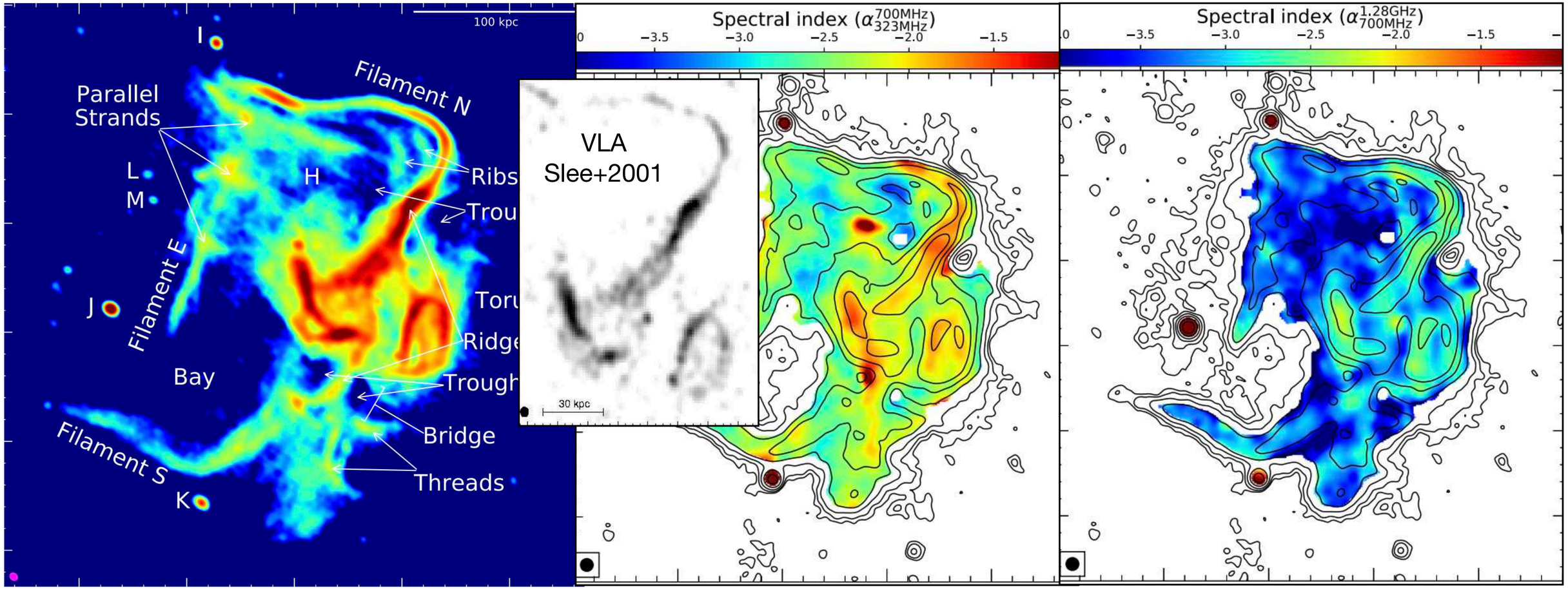


Raja+2024

Remember: steeper = older!

But also e.g. slee2001, ensslin2002, kempner2004, vanweeren2009, degasperin2015, Giovannini+1999; Kale & Dwarakanath 2012

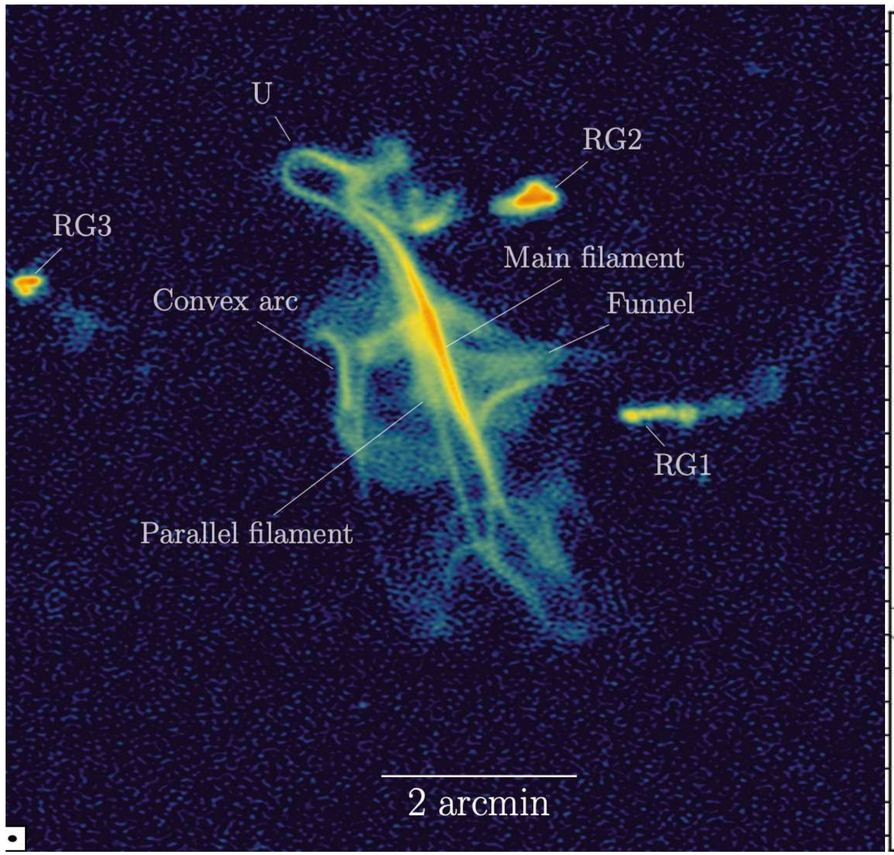
Revived old AGN plasma/bubbles… radio phoenices

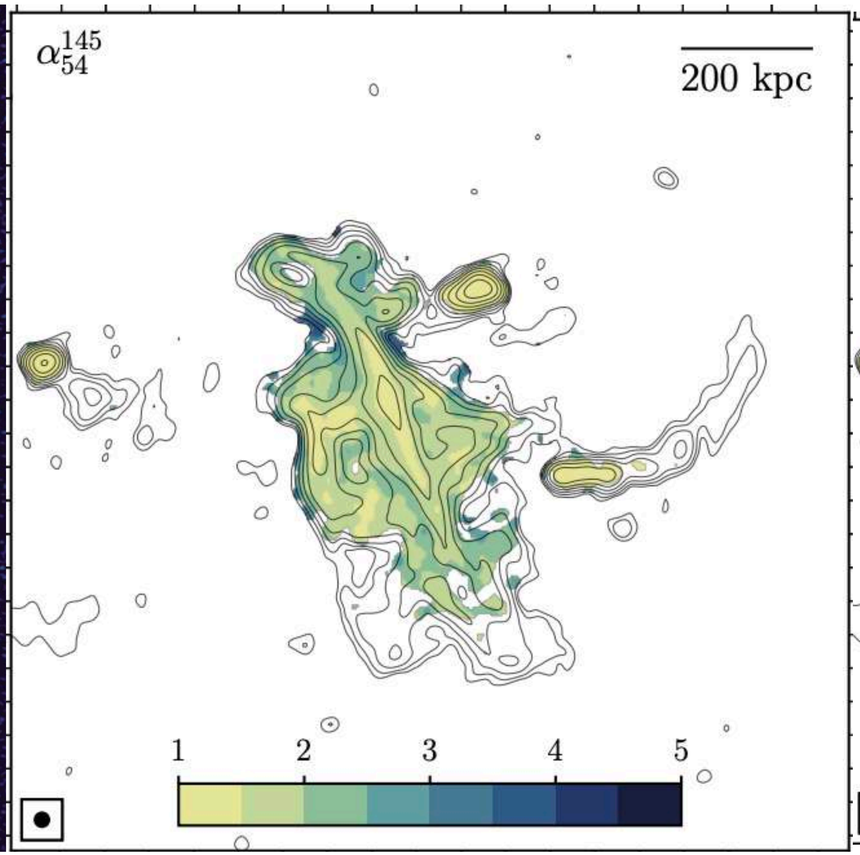


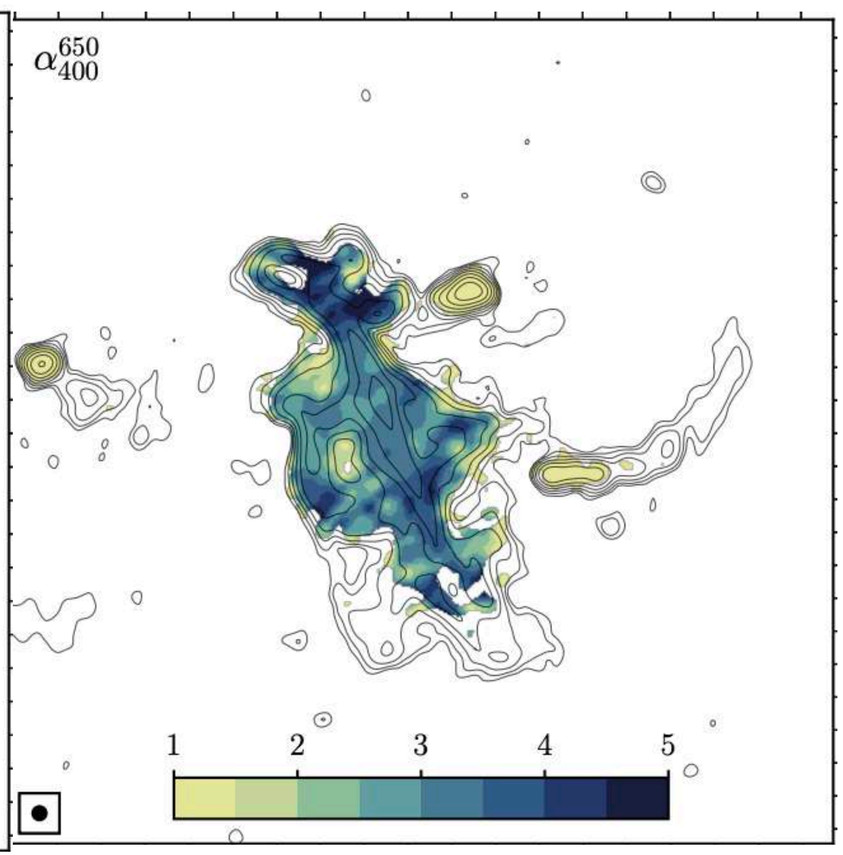
Raja+2024

But also e.g. slee2001, ensslin2002, kempner2004, vanweeren2009, degasperin2015, Giovannini+1999; Kale & Dwarakanath 2012

Revived old AGN plasma/bubbles… radio phoenices







VLSSJ0318.9+5755
Botteon+2026

But also e.g. slee2001, ensslin2002, kempner2004, vanweeren2009, degasperin2015, Giovannini+1999; Kale & Dwarakanath 2012

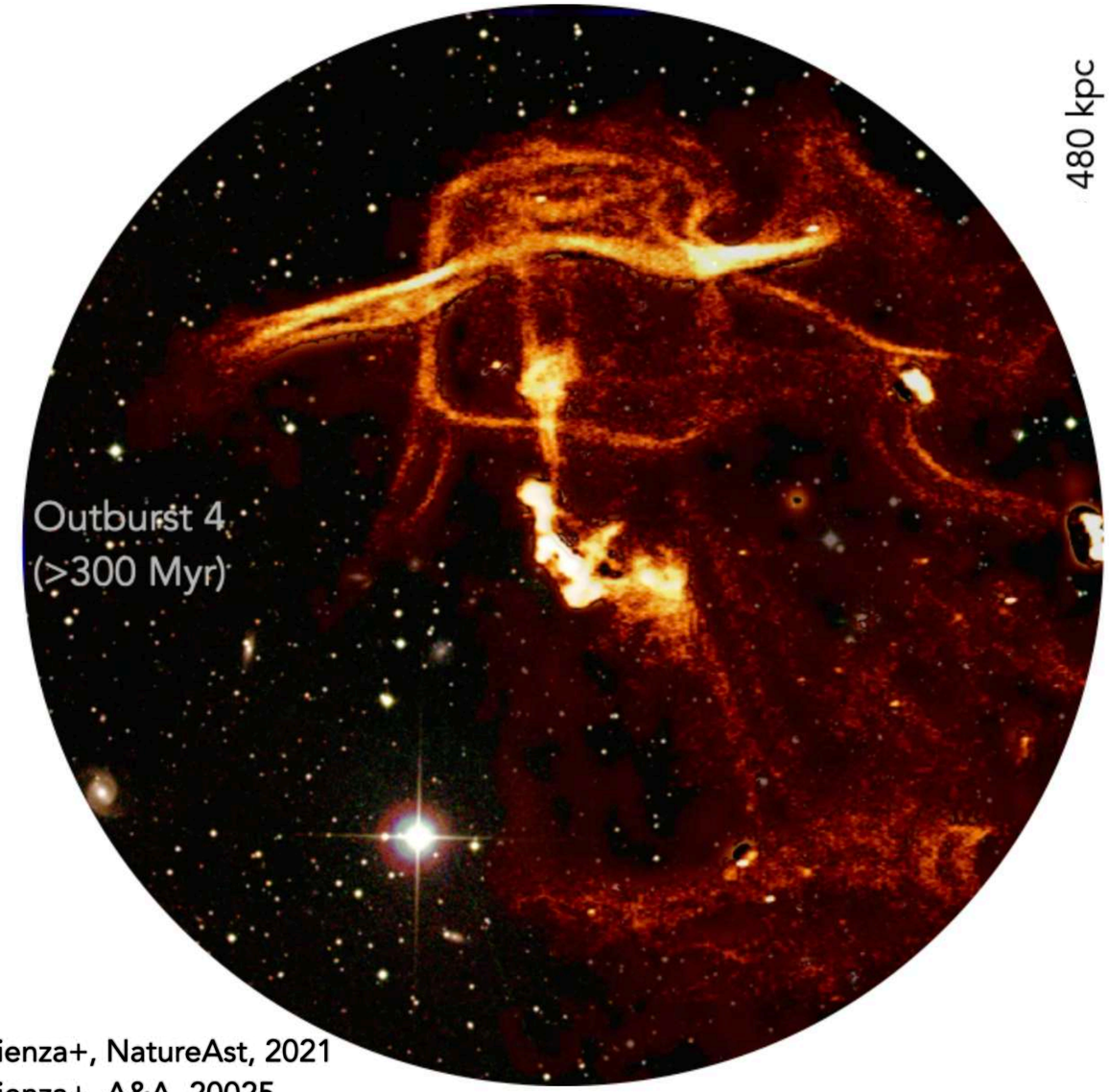
Nest200047



Brienza+, NatureAst, 2021

- Galaxy group ~6e13 Msun, z=0.018, $\log M_{gal}$=11.56
- **Multiple generations** of AGN bubbles (not aligned!)
  Oldest ~400 Myr

Nest200047



Brienza+, NatureAst, 2021
Brienza+, A&A, 20025

- Galaxy group ~6e13 Msun, z=0.018, $\log M_{gal}$=11.56
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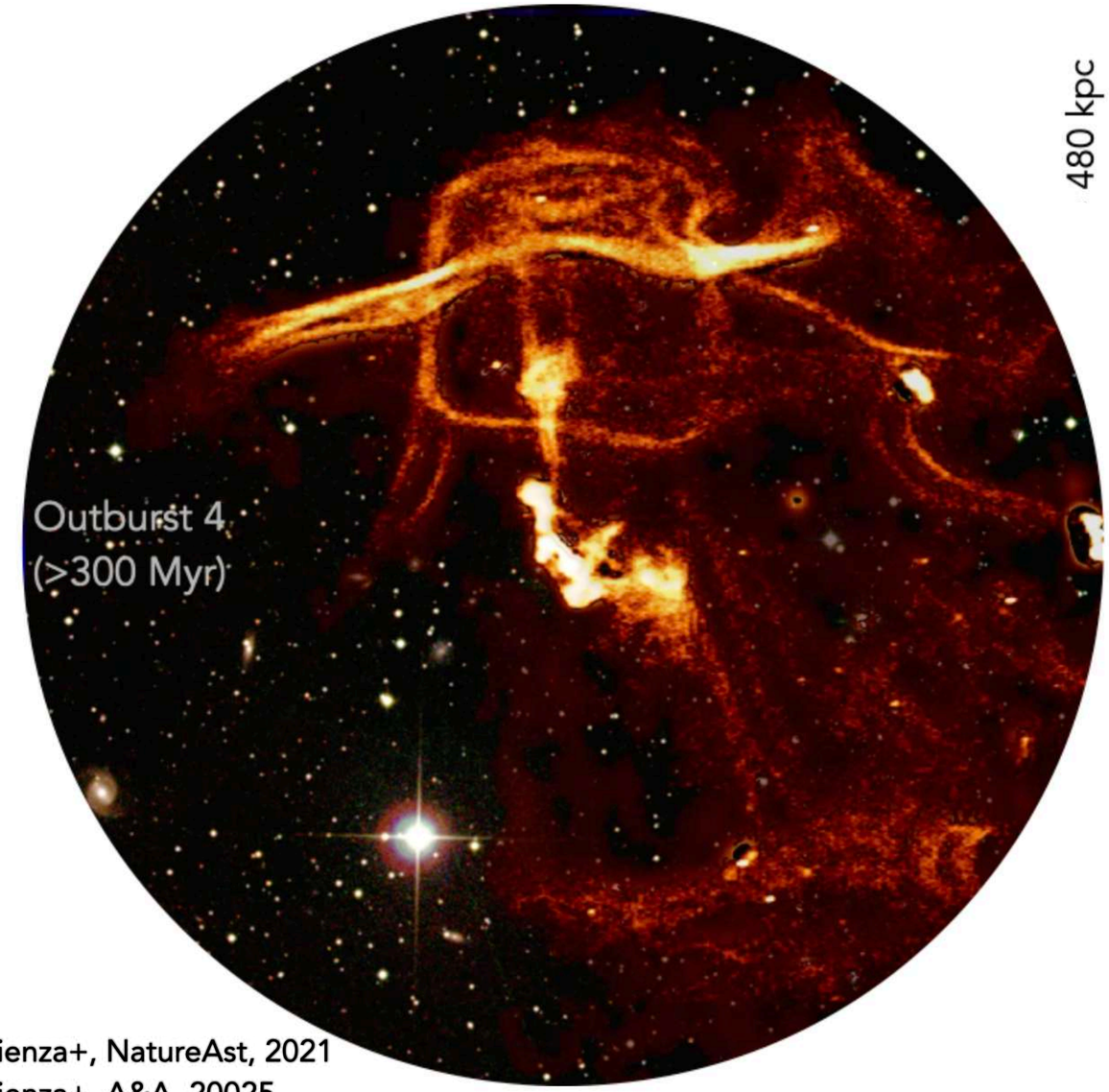






Pressure gradient present around the bubble transforms a roughly spherical bubble into a torus (vortex ring)

Nest200047

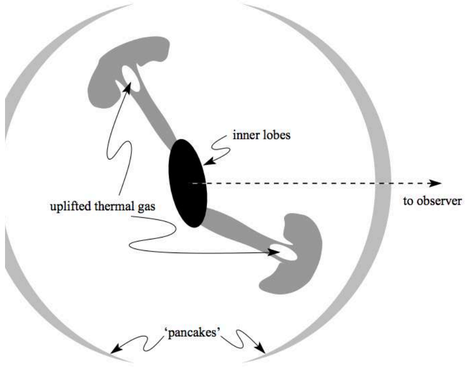


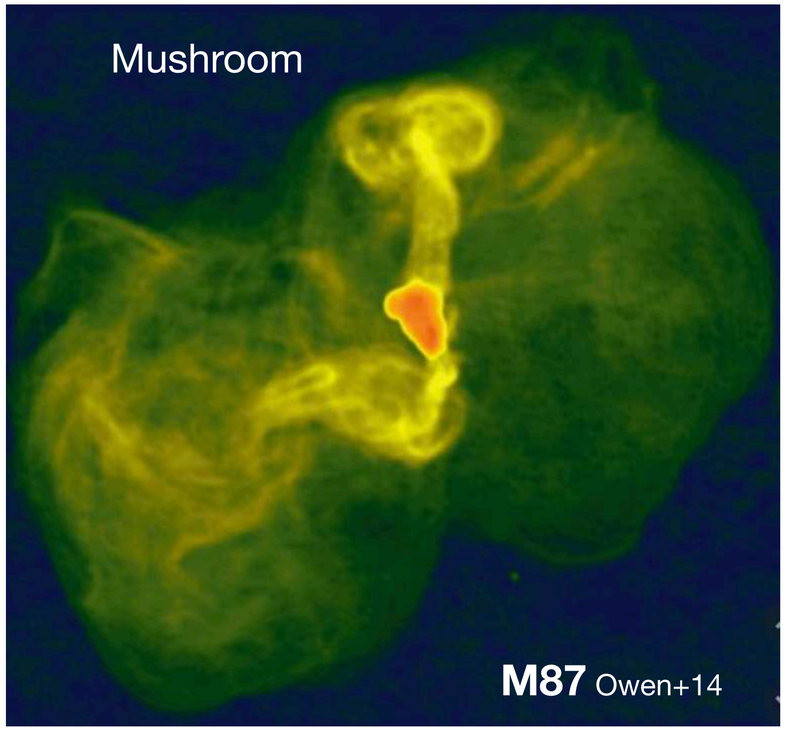
480 kpc

Brienza+, NatureAst, 2021
Brienza+, A&A, 20025

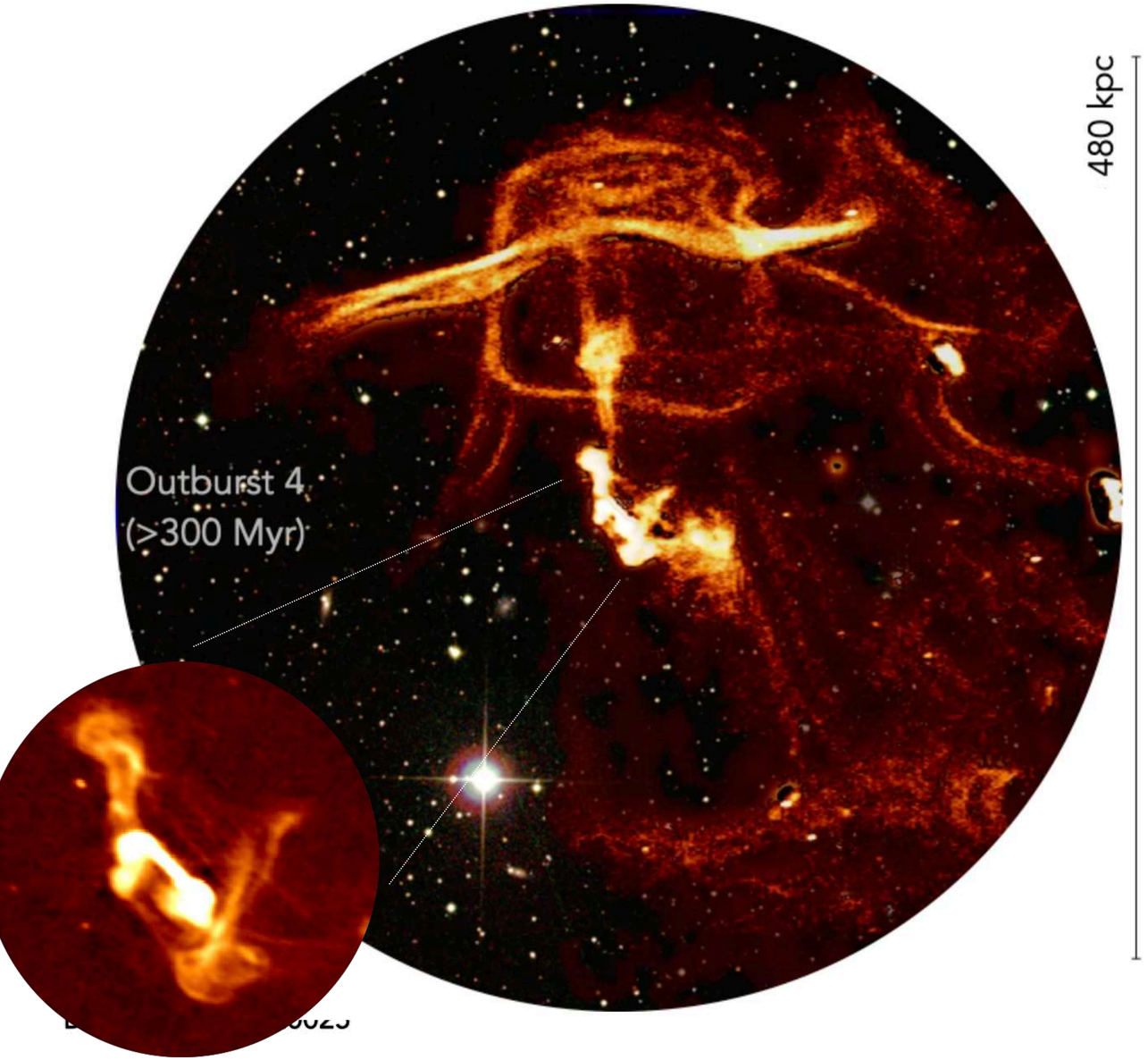
- Galaxy group ~6e13 Msun, z=0.018, $\log M_{gal}$=11.56
- **Multiple generations** of AGN bubbles (not aligned!)
  Oldest ~400 Myr

Churazov+2001





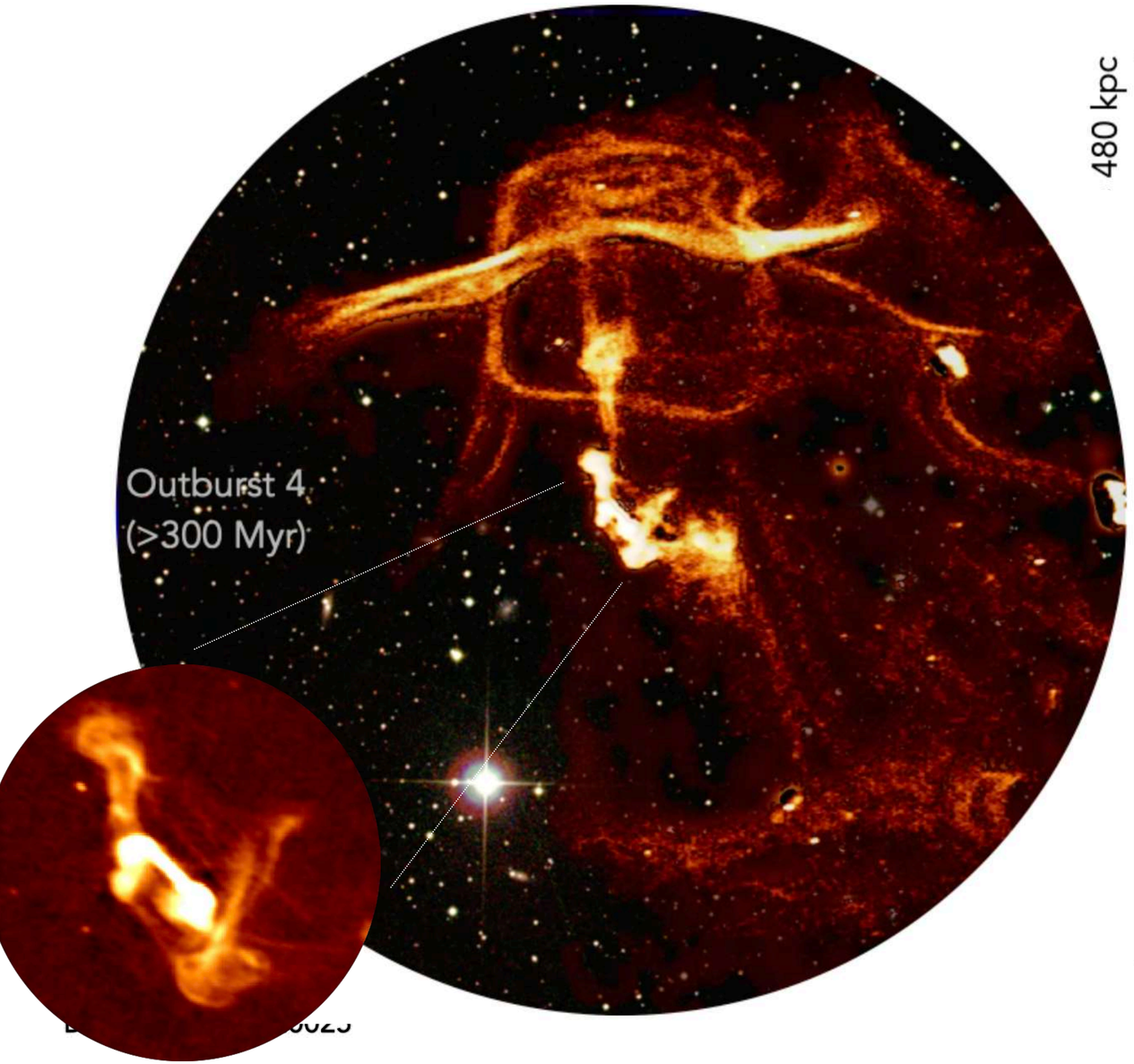
Nest200047

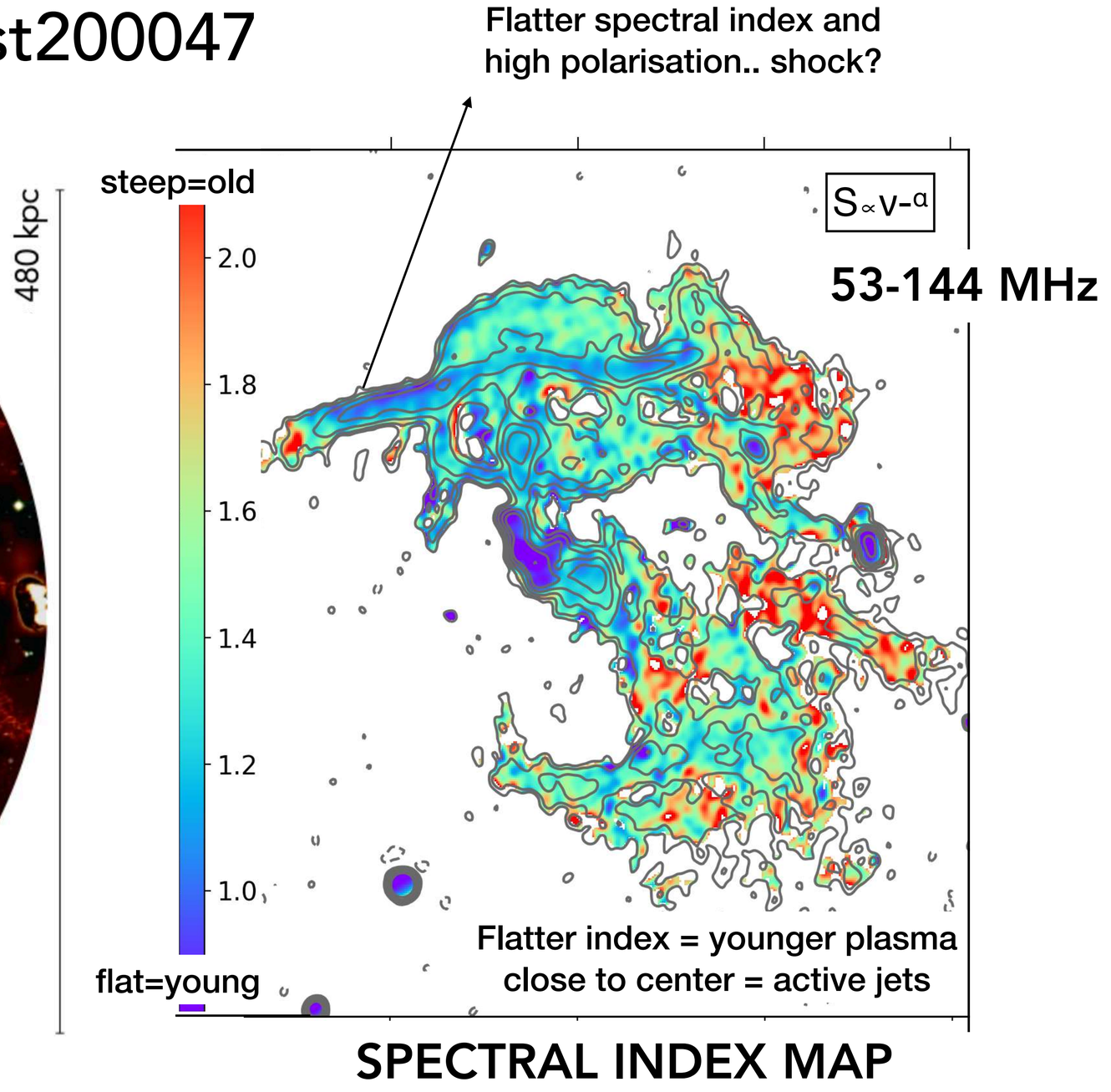


- Galaxy group ~6e13 Msun, z=0.018, $\log M_{gal}$=11.56
- **Multiple generations** of AGN bubbles (not aligned!)
  Oldest ~400 Myr
- Old plasma clearly **large portion**
of the **group volume**
- Plasma broken into **FILAMENTS**
likely **supported by magnetic fields**
Alfven scale = few kpc = filaments width!

$$l_A = 2\ \mathrm{kpc} \times (t/350\ \mathrm{Myr})^3 \times (L/100\ \mathrm{kpc})^{-2} \times (\beta_{pl}/100)^{-3/2}$$

Nest200047





SPECTRAL INDEX MAP

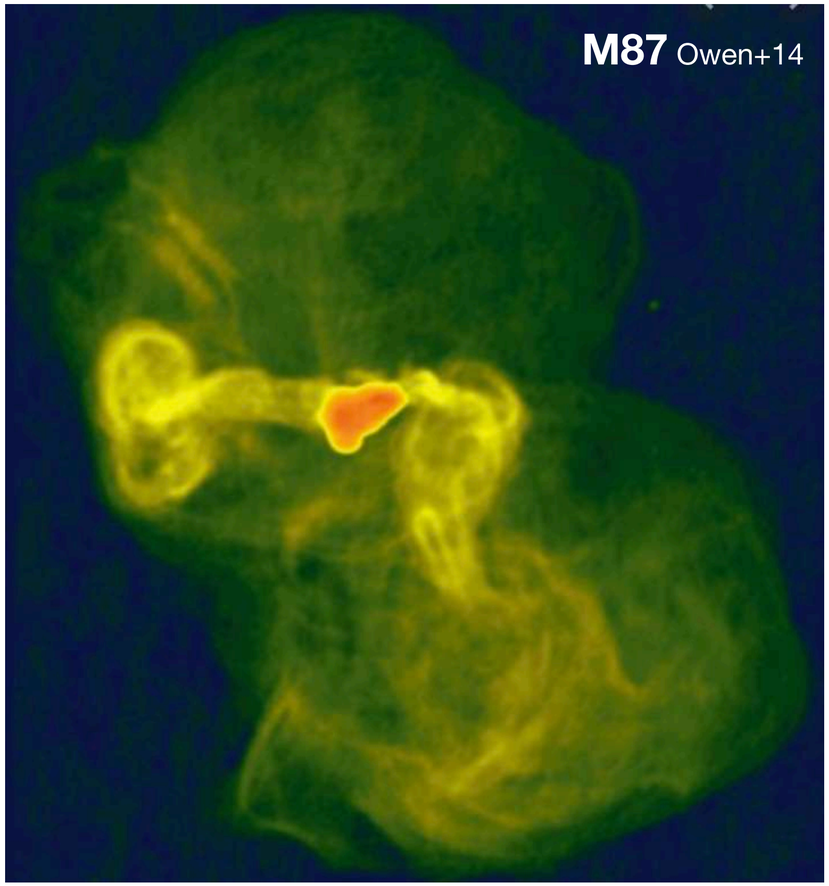
Filaments

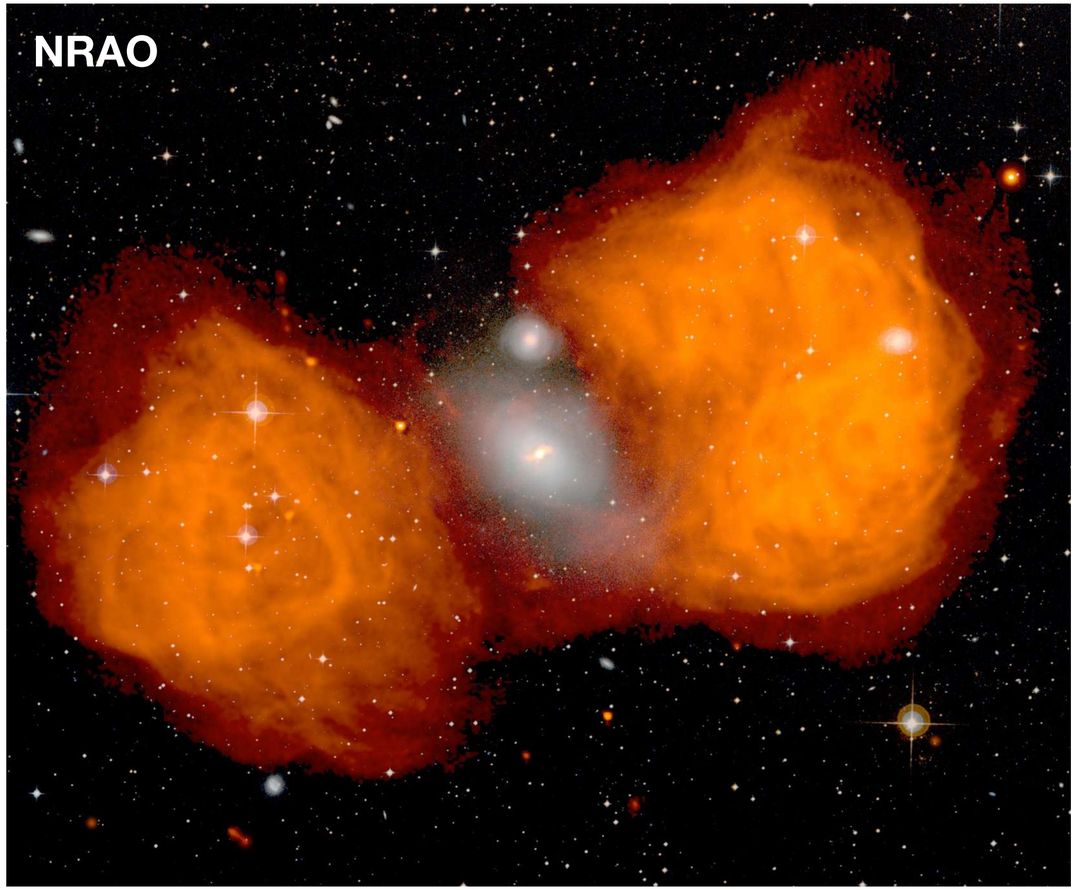
are everywhere!

Filaments

are everywhere!

Within radio galaxy lobes…





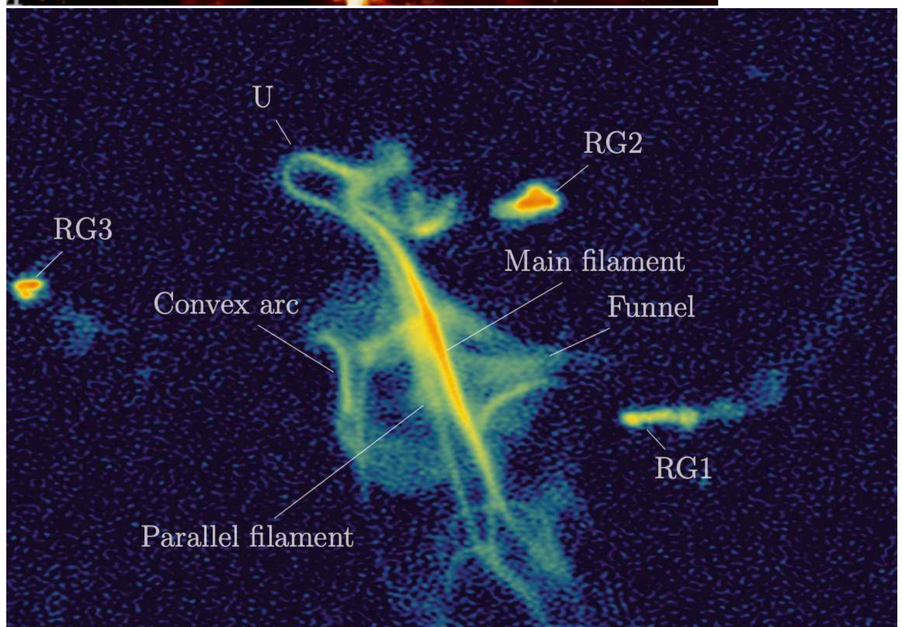
MHD simulations suggest that filaments trace enhancements in the magnetic field distribution (e.g. Huarte-Espinosa et al. 2011; Hardcastle 2013), which form as a consequence of the complex internal dynamics of the lobes

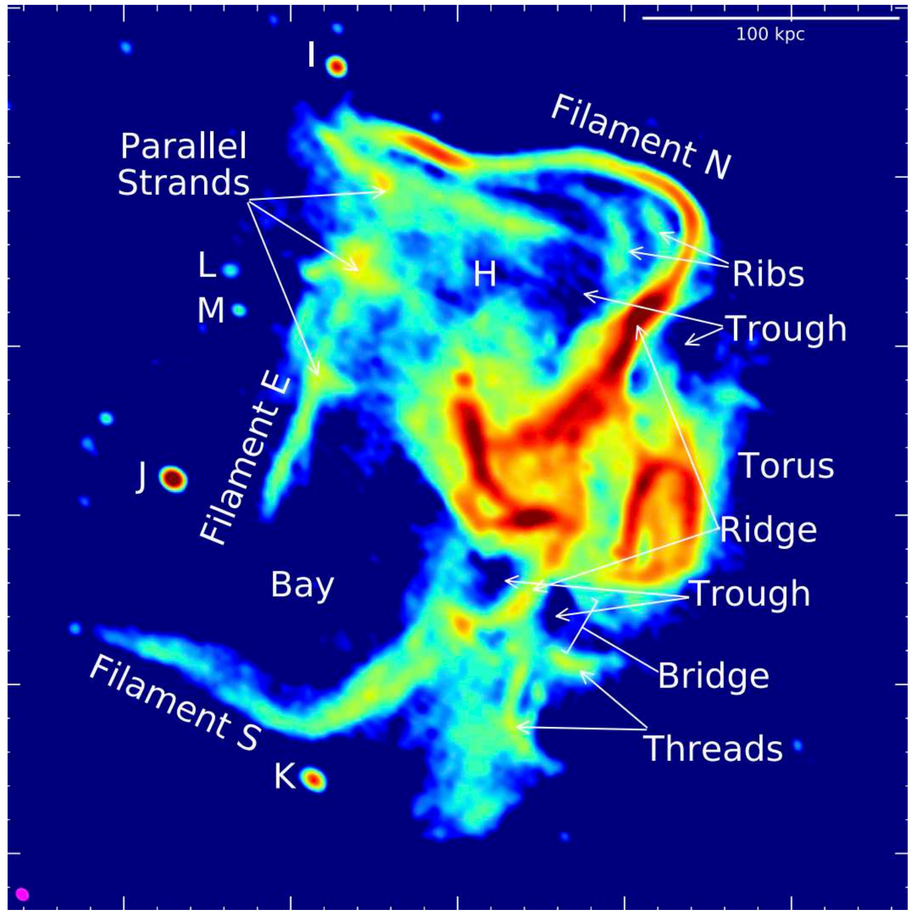
Filaments

are everywhere!

Within old AGN lobes…



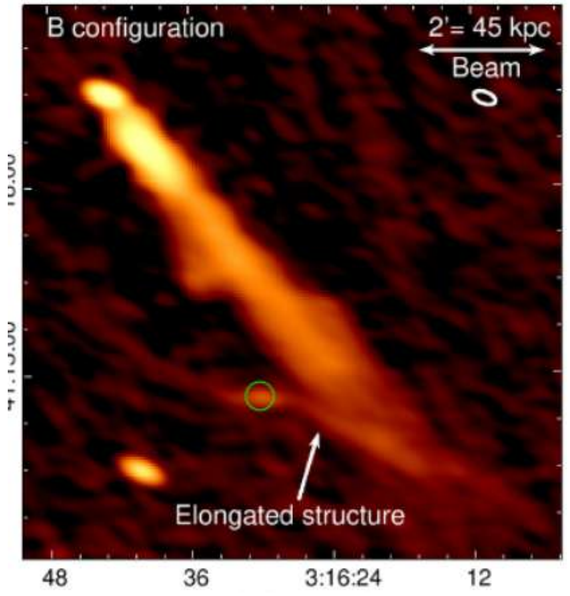


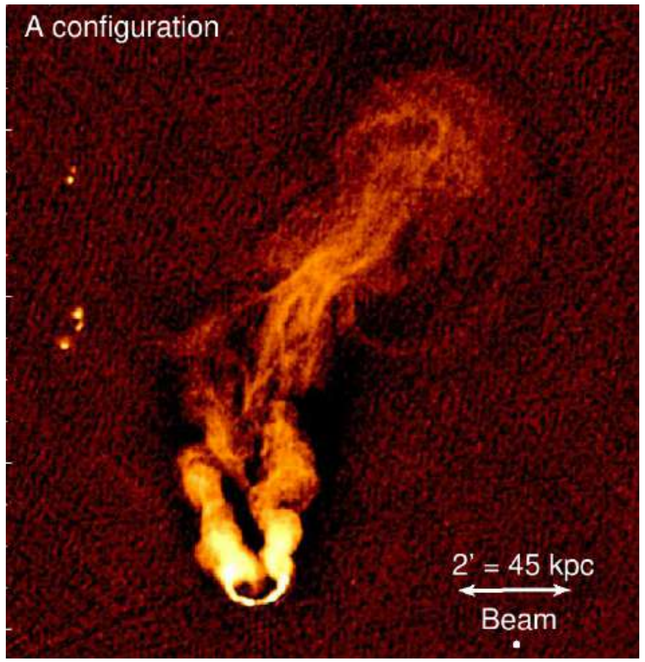


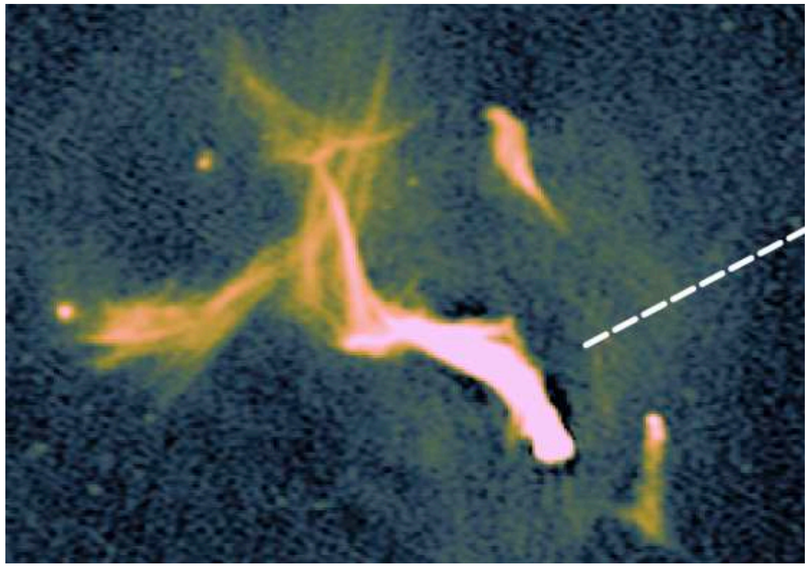
Filaments

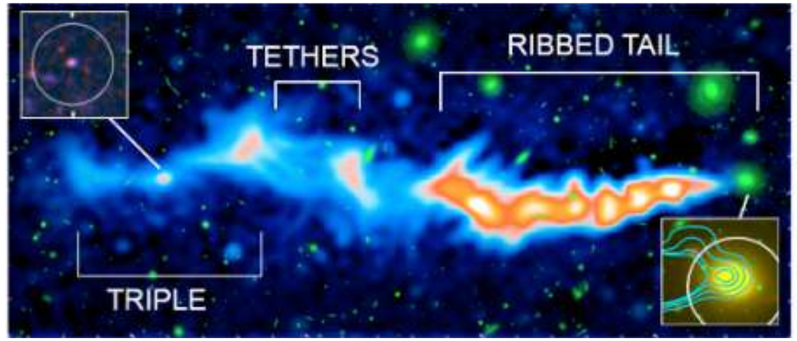
are everywhere!

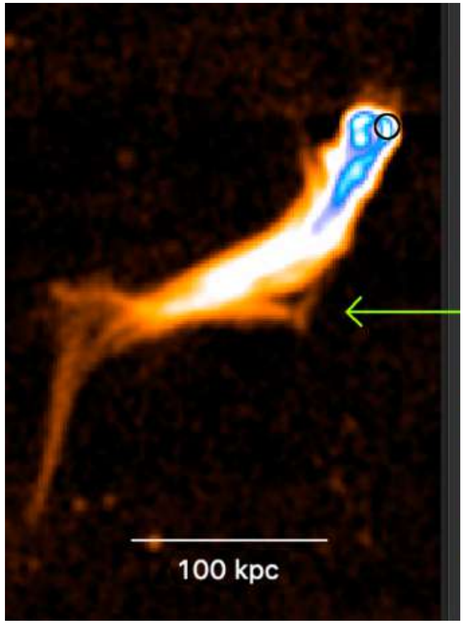
Within radio galaxy tails…









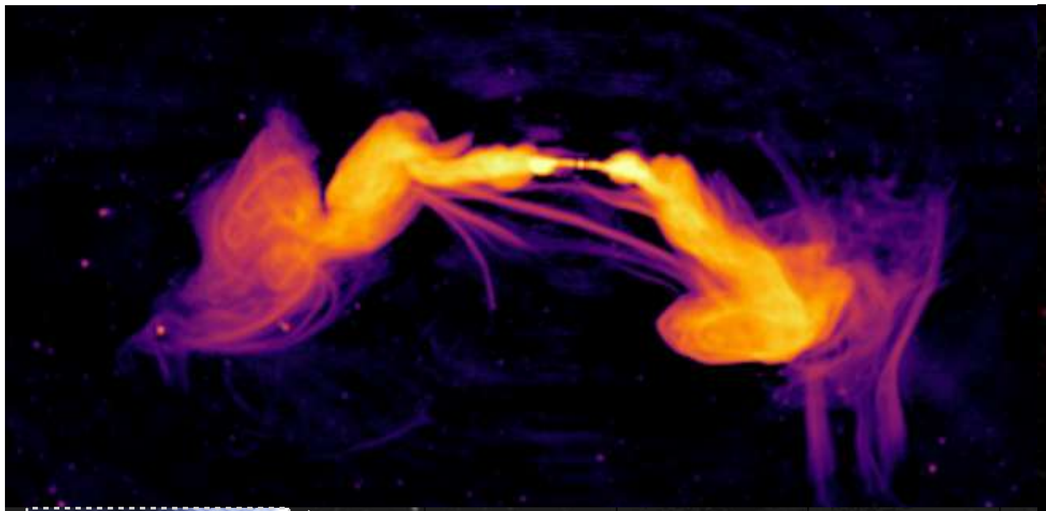


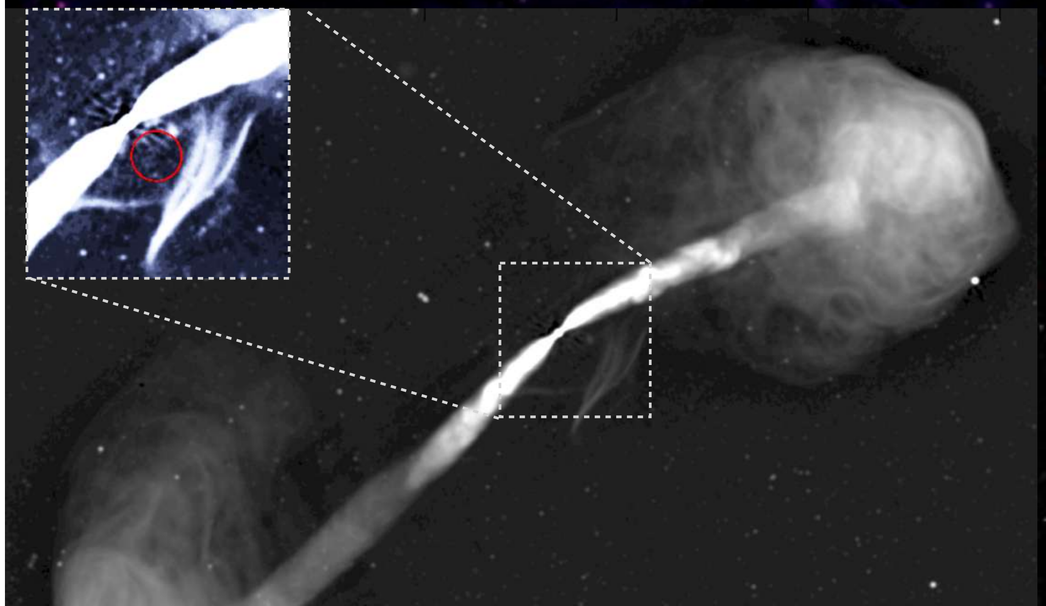
Filaments

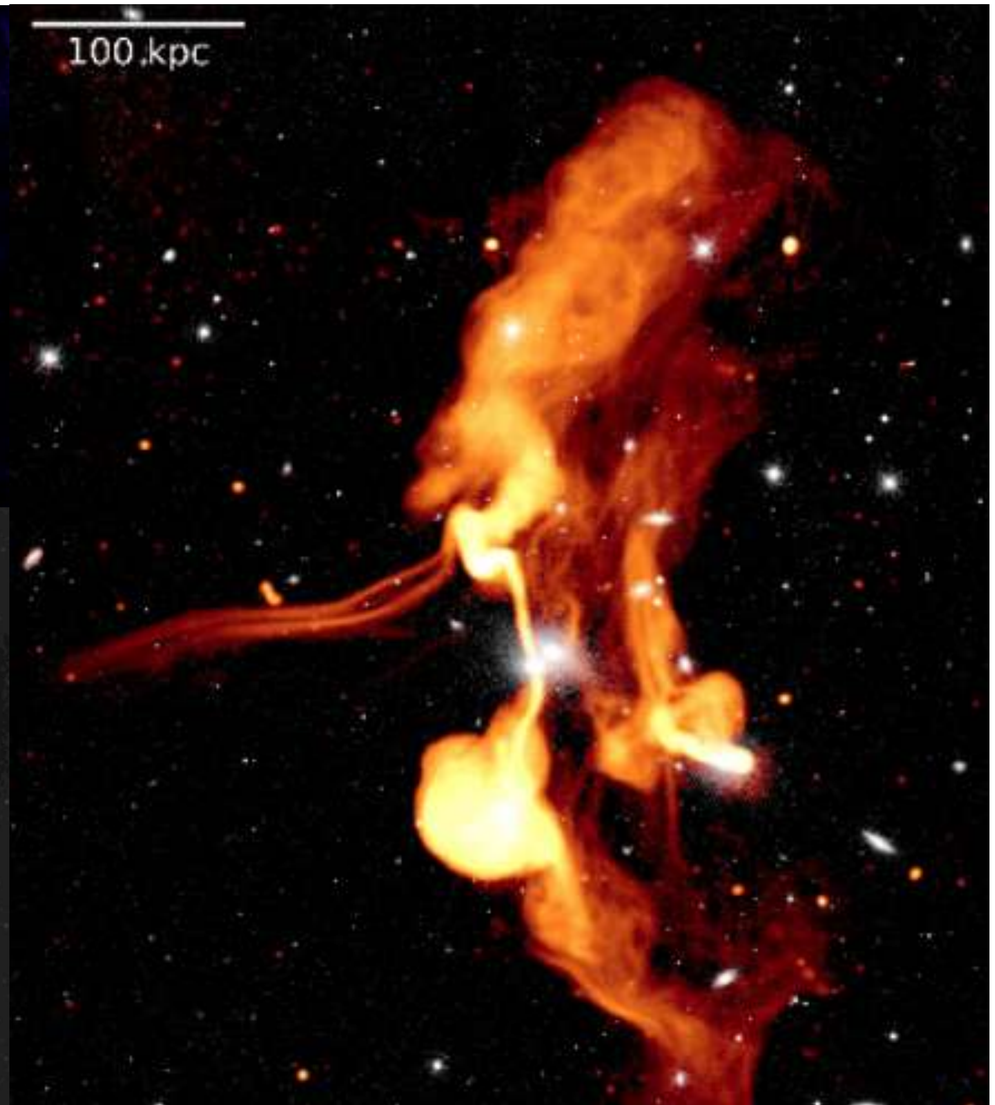
are everywhere!

Departing from / connecting lobes…

Often come in pairs or bundles!



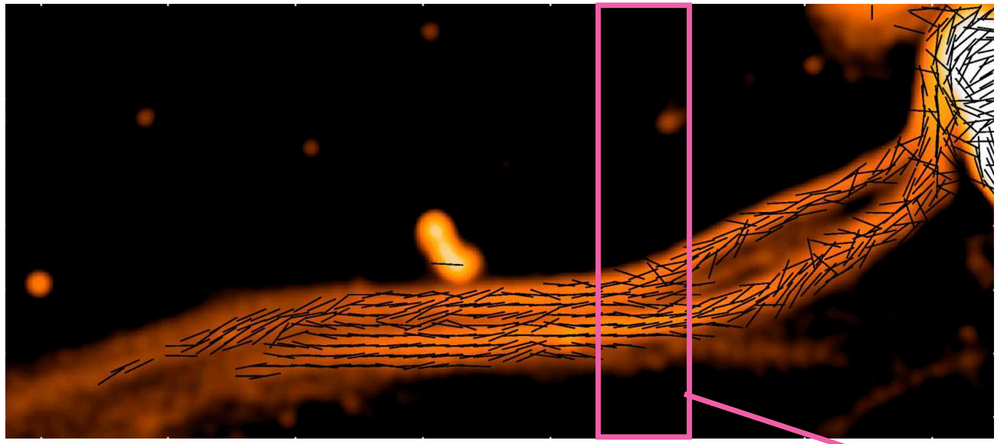


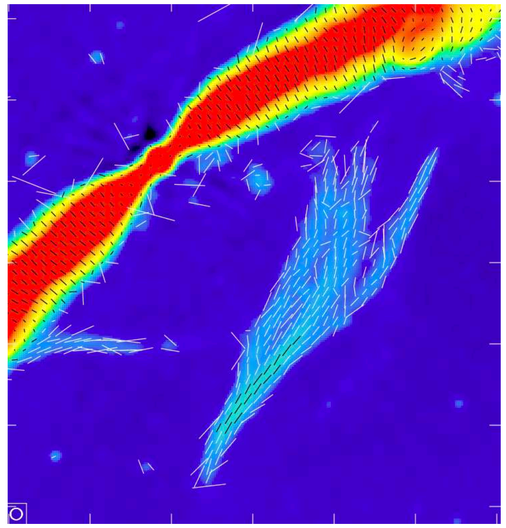


Filament properties

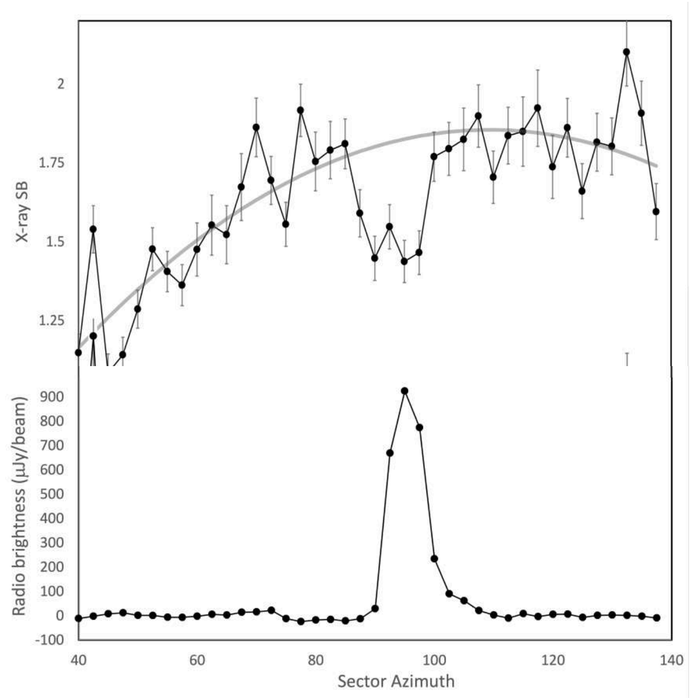
Few kpc width and up to hundreds kpc long

Aligned B and high polarisation (40-70%)





X-ray depression = cavity

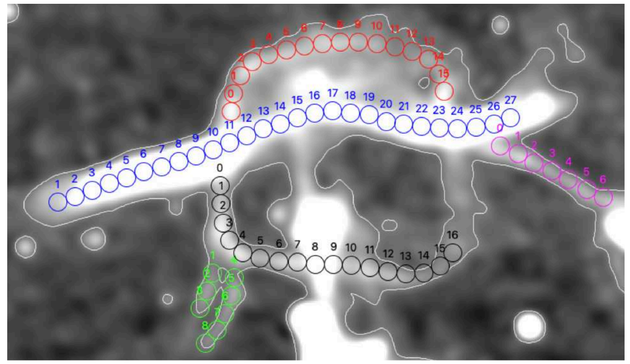


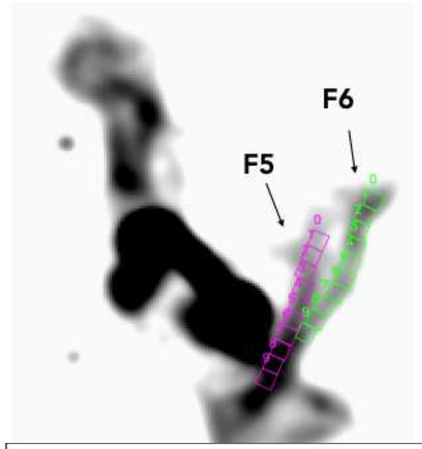
X-ray surface brightness profile

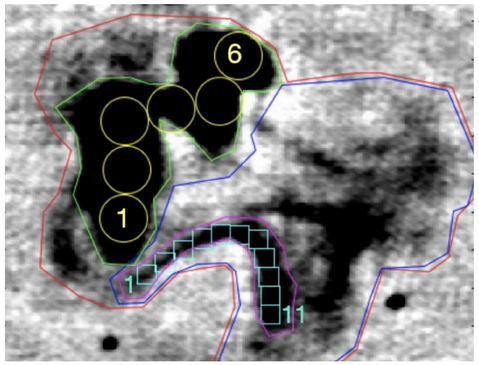
Radio surface brightness profile

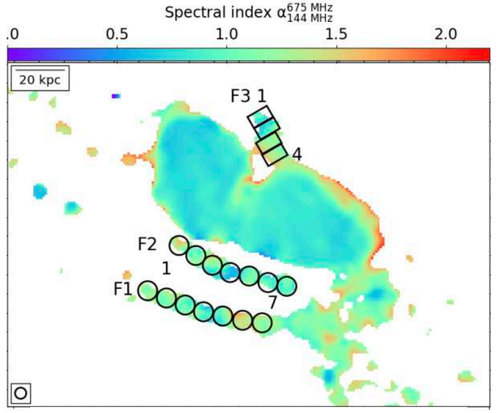
Filament properties

Constant spectral trend!

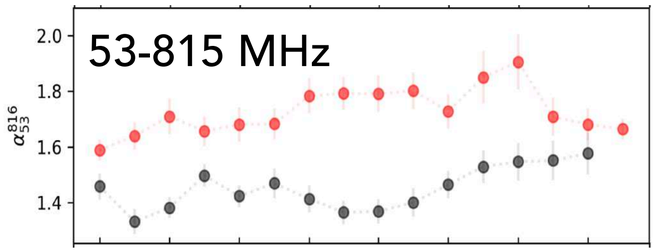


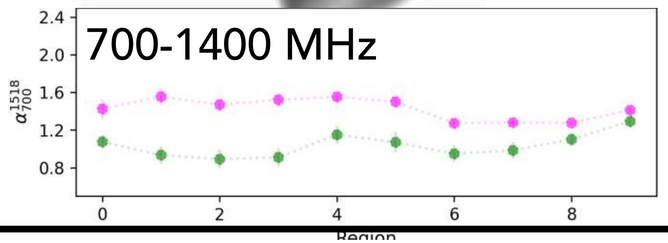


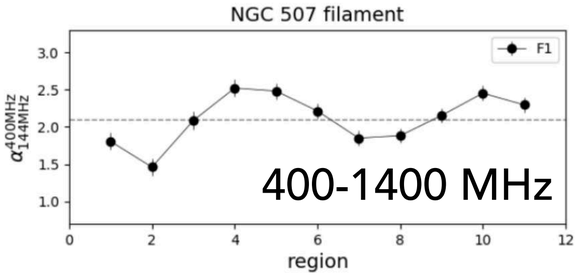


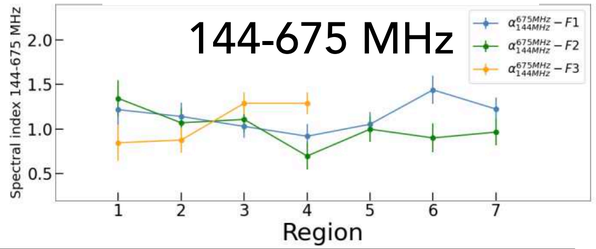


NGC6086, Candini+2023

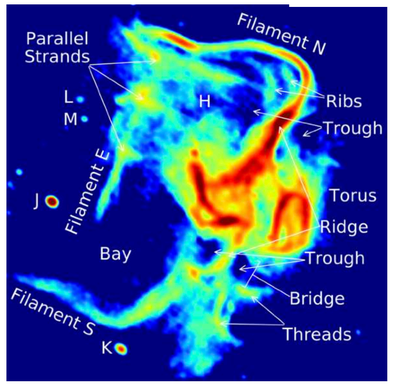


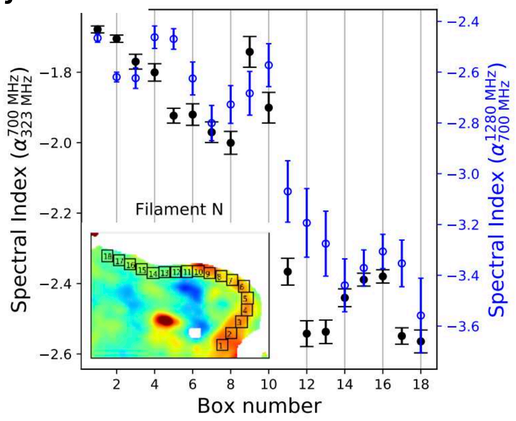


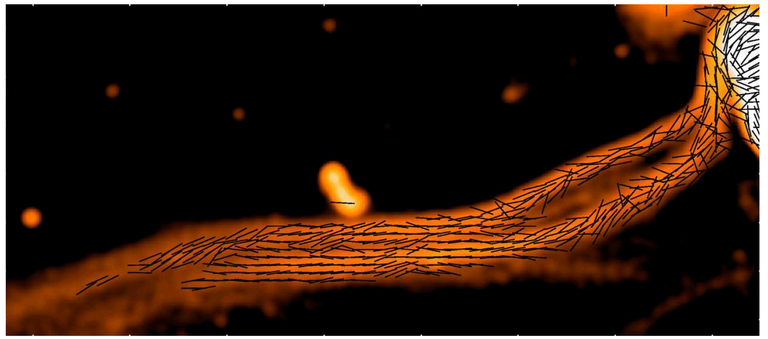


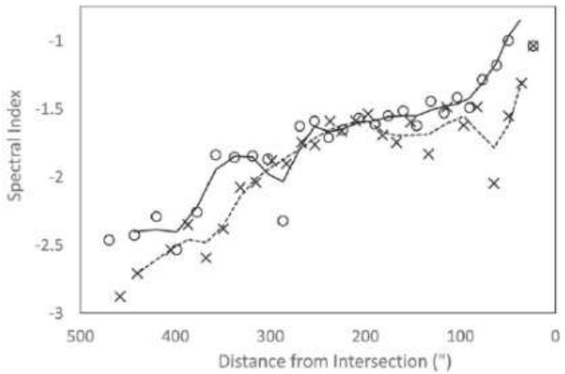


A85, Raja+2025









Steepening along the filament!

Filament origin

- Regions of compressed/stretched plasma?
- Magnetic field reconnection?
- Old AGN plasma enlighting underneath complex magnetic field structure?
- Imprint of fluctuation dynamo in turbulent ICM?
- Particle streaming in beta=1 filaments?

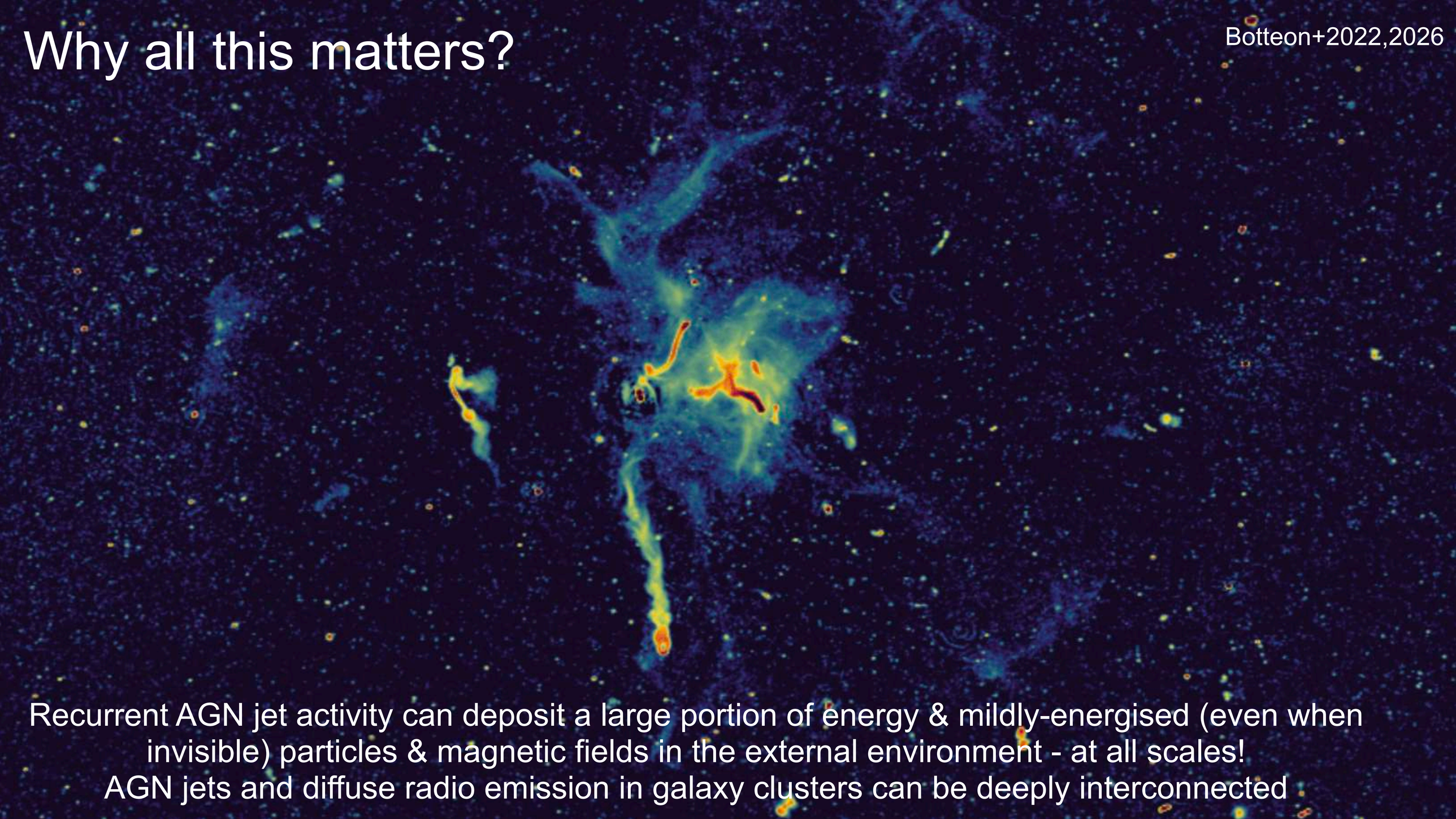
Churazov+2026

$$\beta = \frac{P_{\rm th}}{P_B} = \frac{8\pi P_{\rm th}}{B^2}$$

If ICM depleted (**ρ** <<) -> B dominates and particle can travel at Alfvén speed $v_A = \frac{B}{\sqrt{4\pi\rho}}$

Why all this matters?

Botteon+2022,2026



Recurrent AGN jet activity can deposit a large portion of energy & mildly-energised (even when invisible) particles & magnetic fields in the external environment - at all scales!
AGN jets and diffuse radio emission in galaxy clusters can be deeply interconnected