

AGN jet feedback & life cycle

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IRA-INAFA, Bologna, Italy

INAFA PhD School “Francesco Lucchin”, Bertinoro, October 2026

AGN (jet) feedback

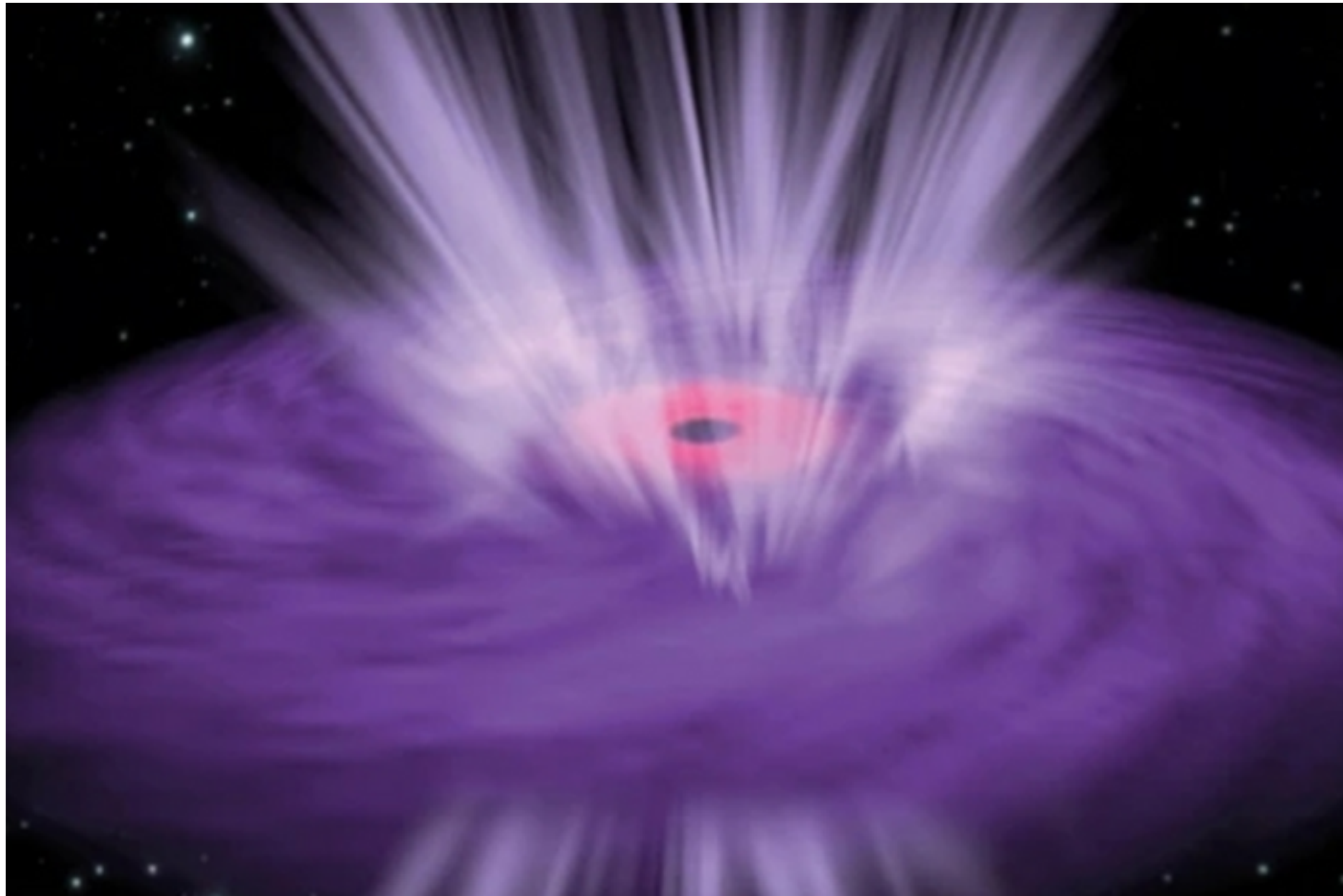
i.e. impact of energy release on external medium

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

- ◆ Explain correlation between 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

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

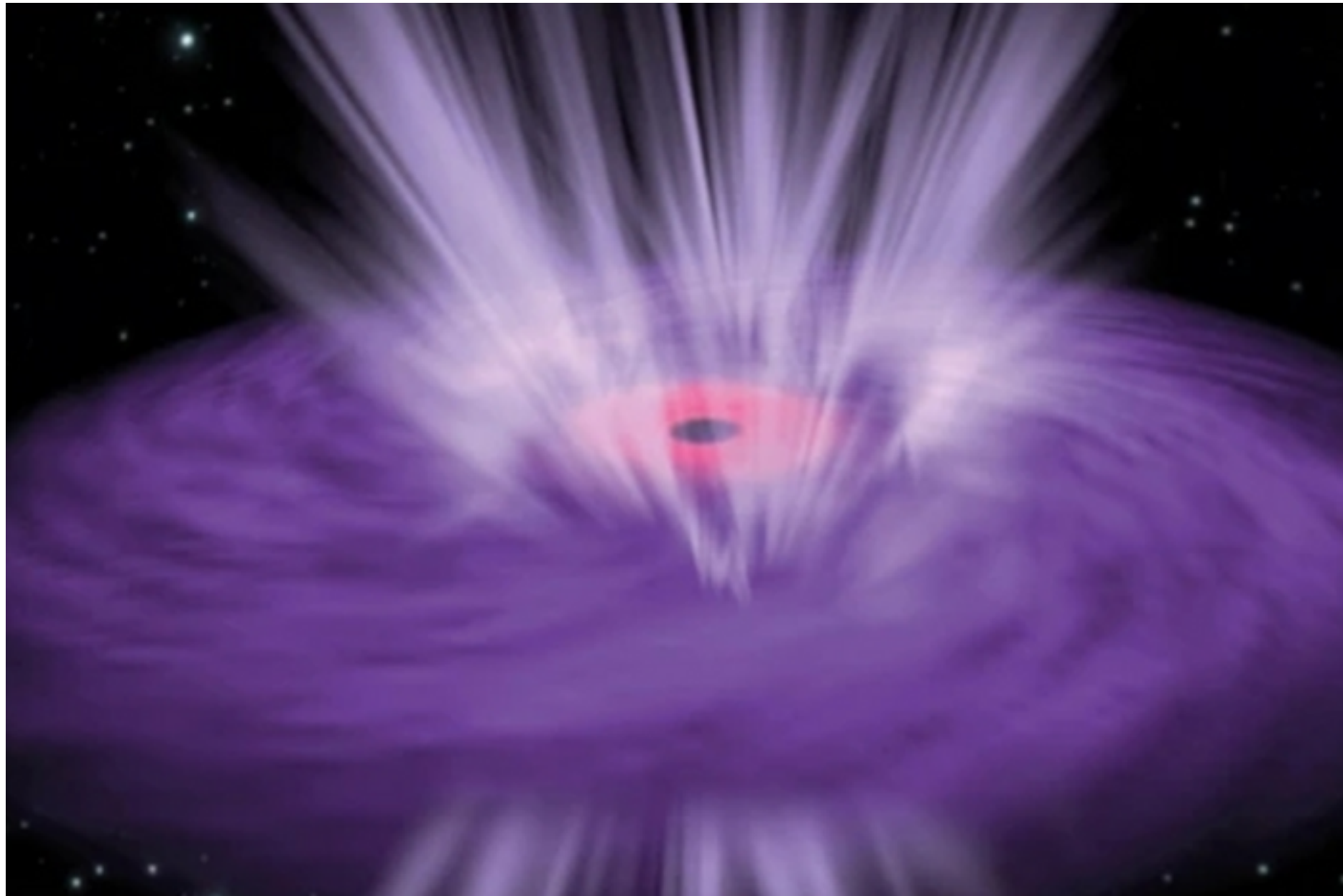


Jets of relativistic particles

(Mostly) Low accretion rate AGN

AGN (jet) feedback

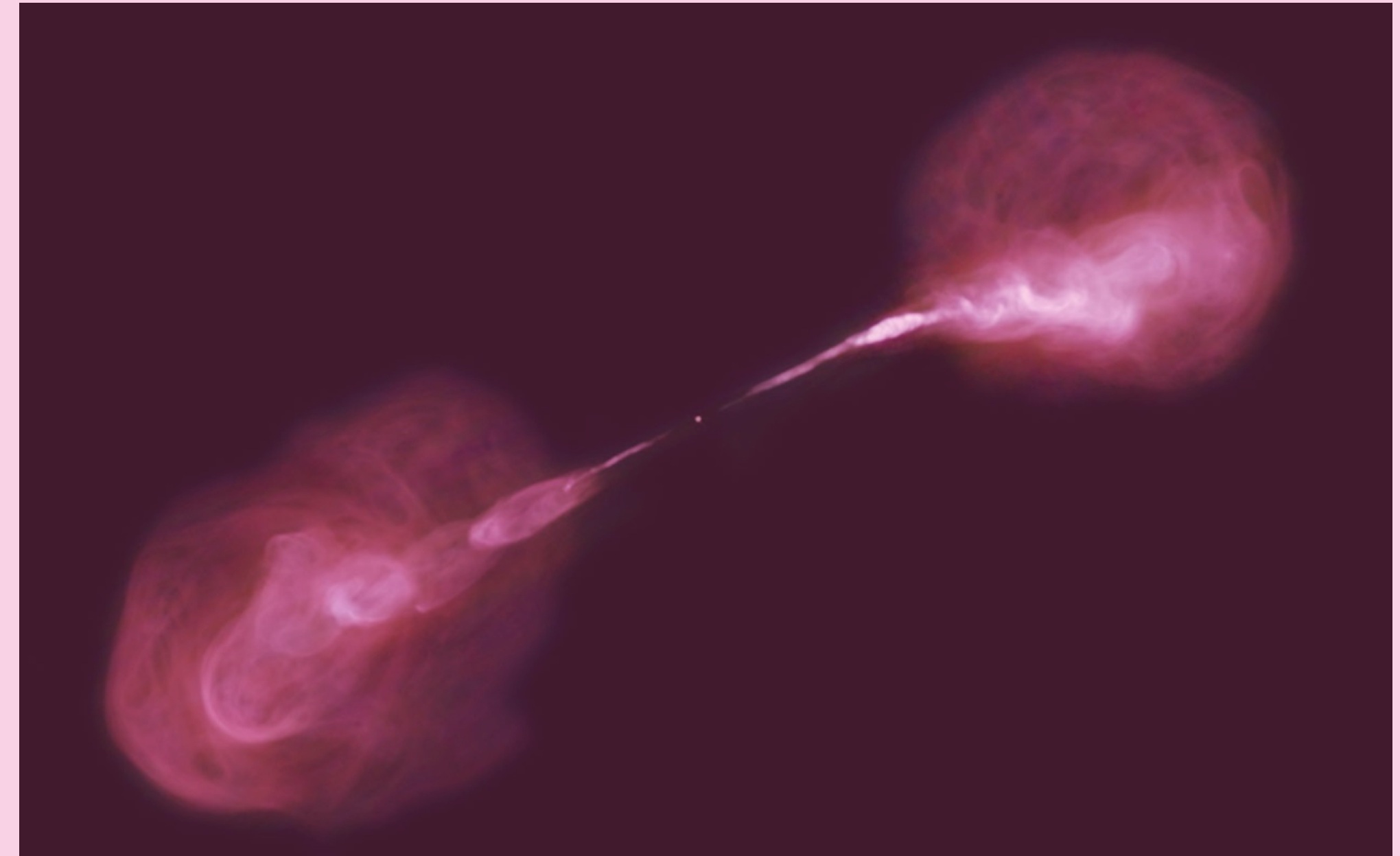
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High accretion rate AGN

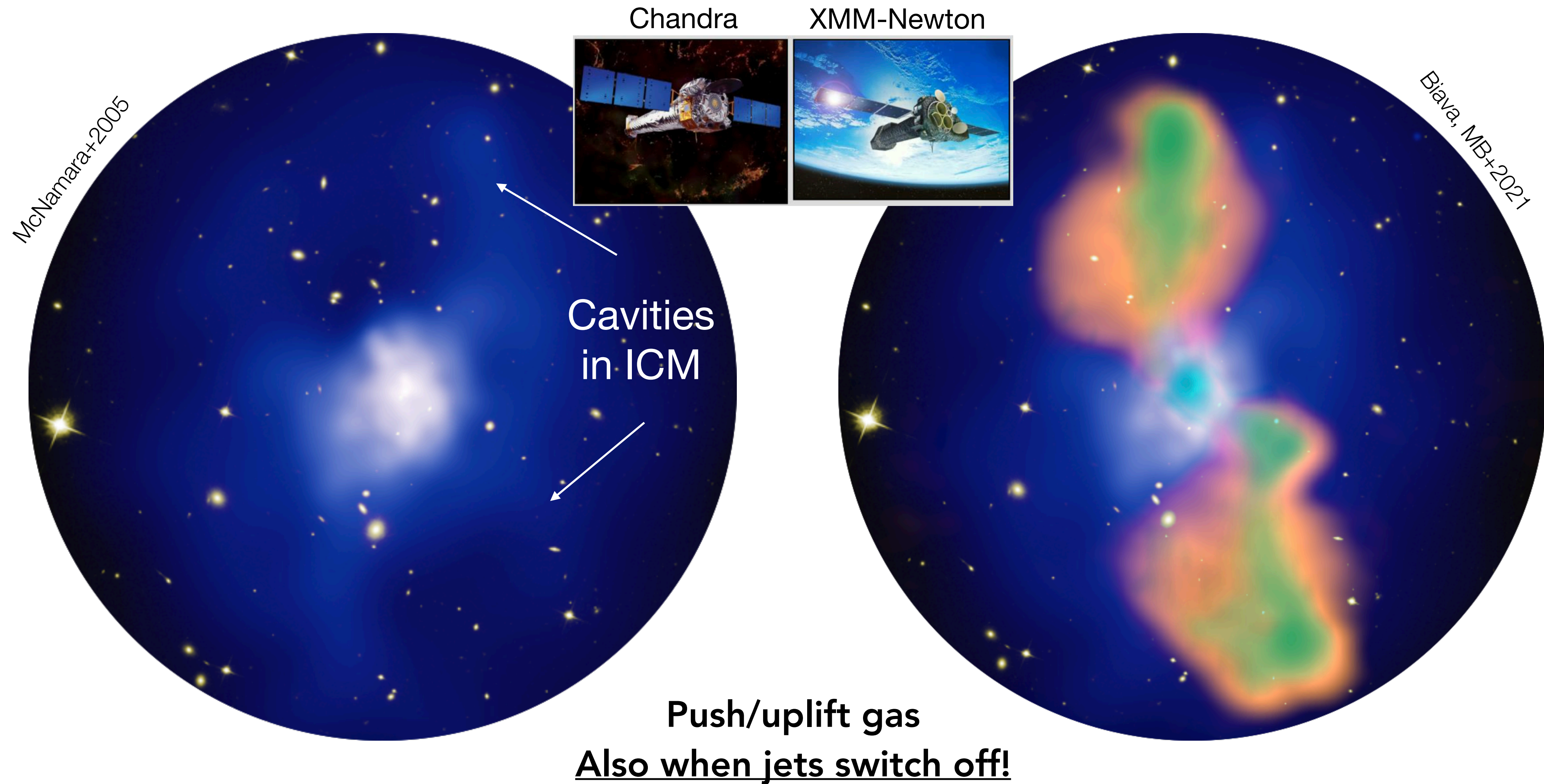
Winds vs jets



Jets of relativistic particles

(Mostly) Low accretion rate AGN

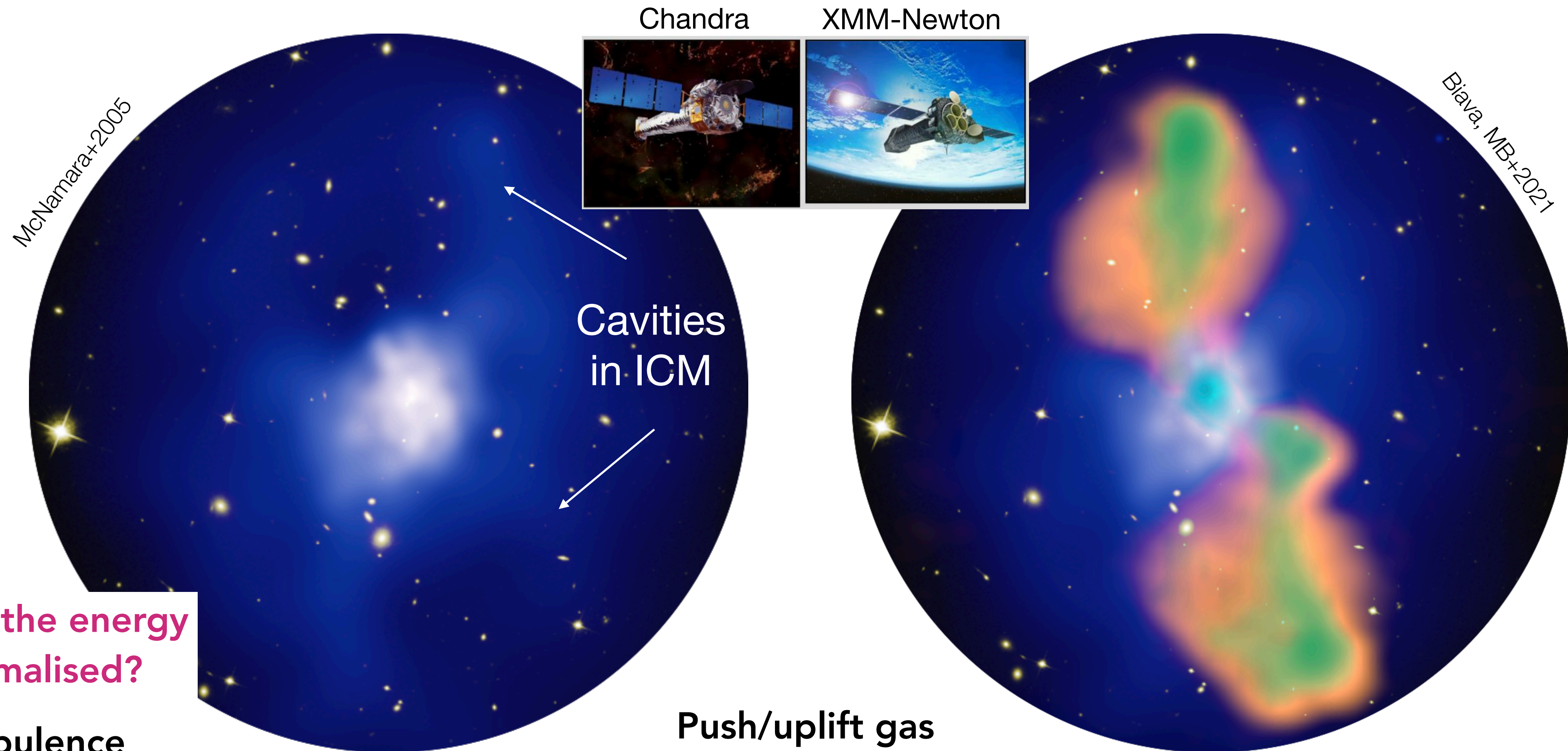
AGN jet feedback in galaxy groups and clusters



Mechanical power can be inferred...

see next lecture! Spoiler...Power= 10^{40} - 10^{46} erg/s

AGN jet feedback in galaxy groups and clusters



How is the energy
thermalised?

Turbulence
Shocks/soundwaves
Mixing

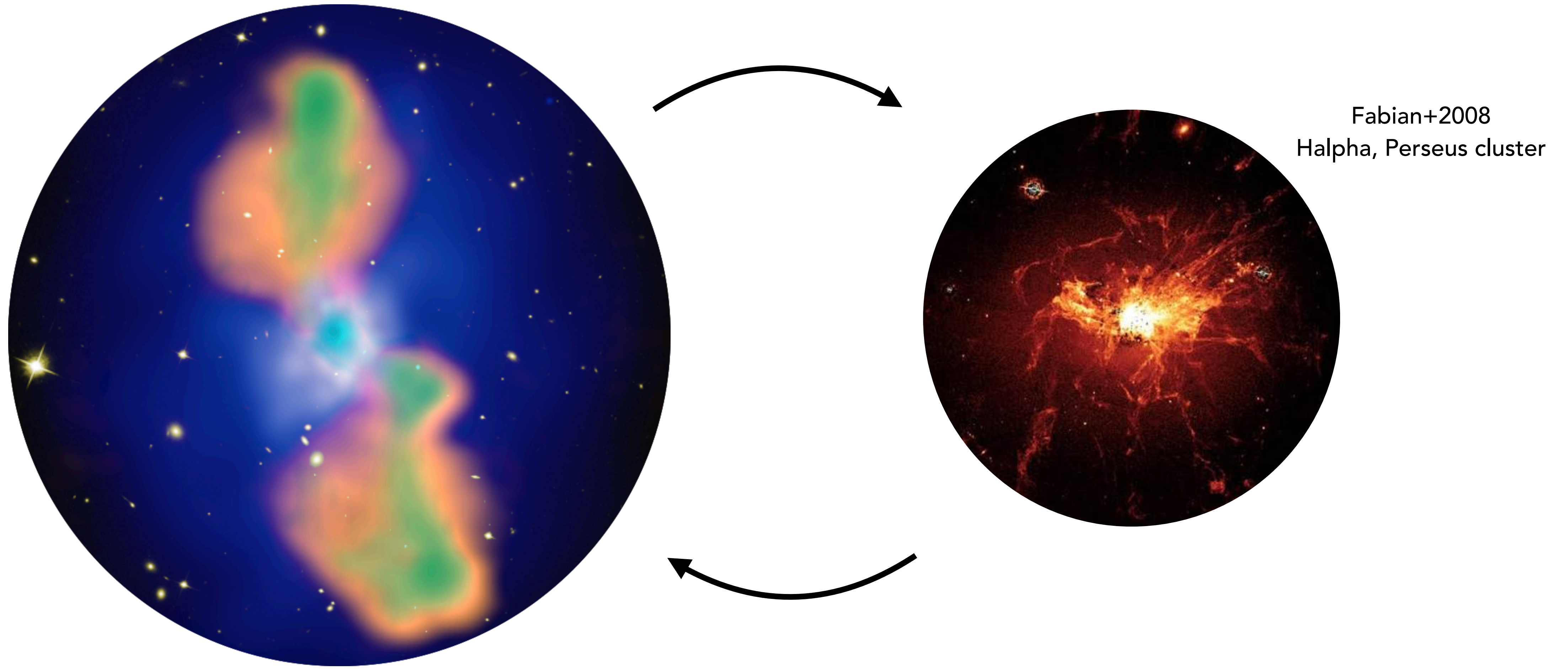
Push/uplift gas
Also when jets switch off!

Mechanical power can be inferred...

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

AGN jet feedback in galaxy groups and clusters

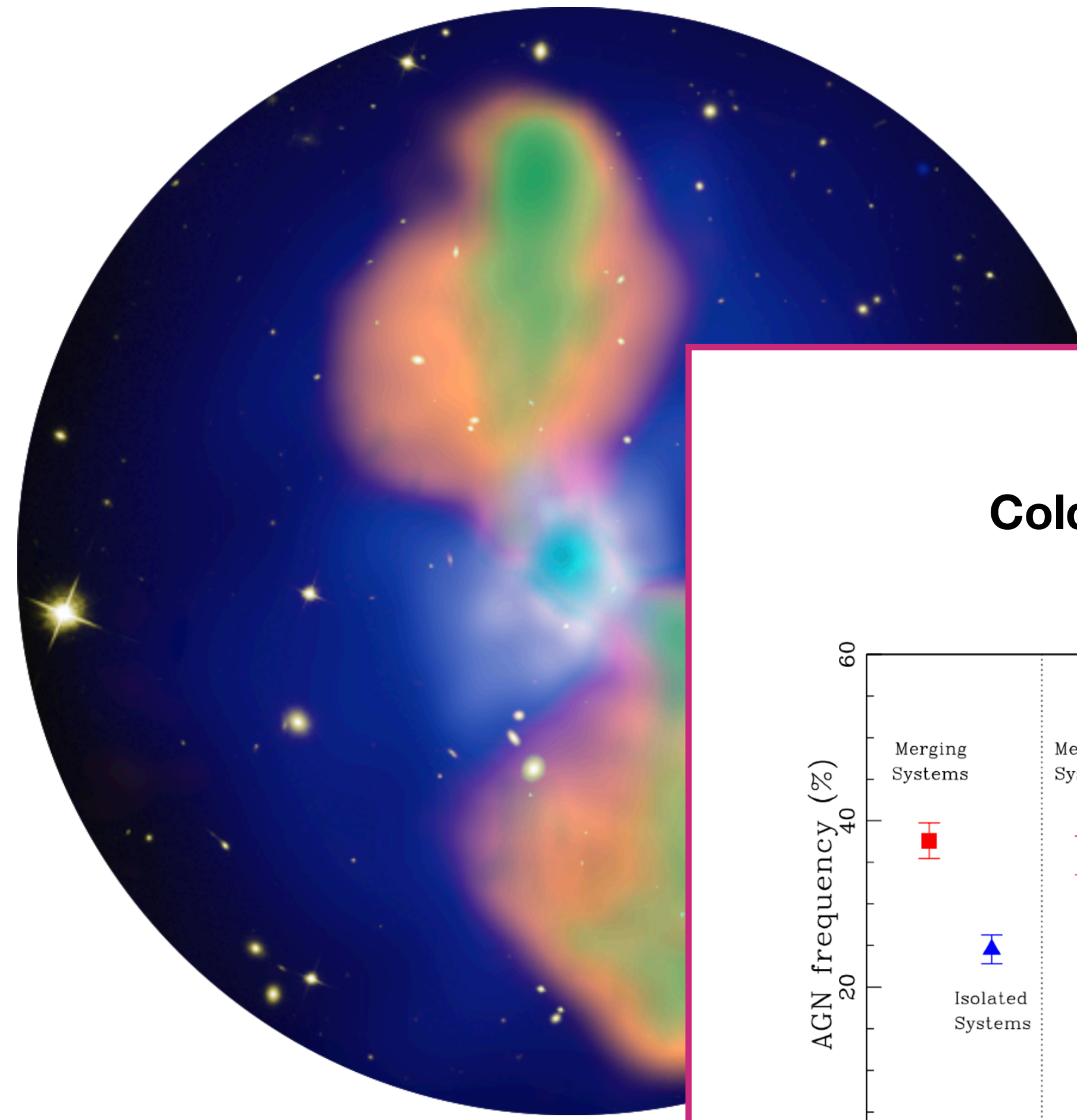
Autoregulated Feeding - Feedback loop



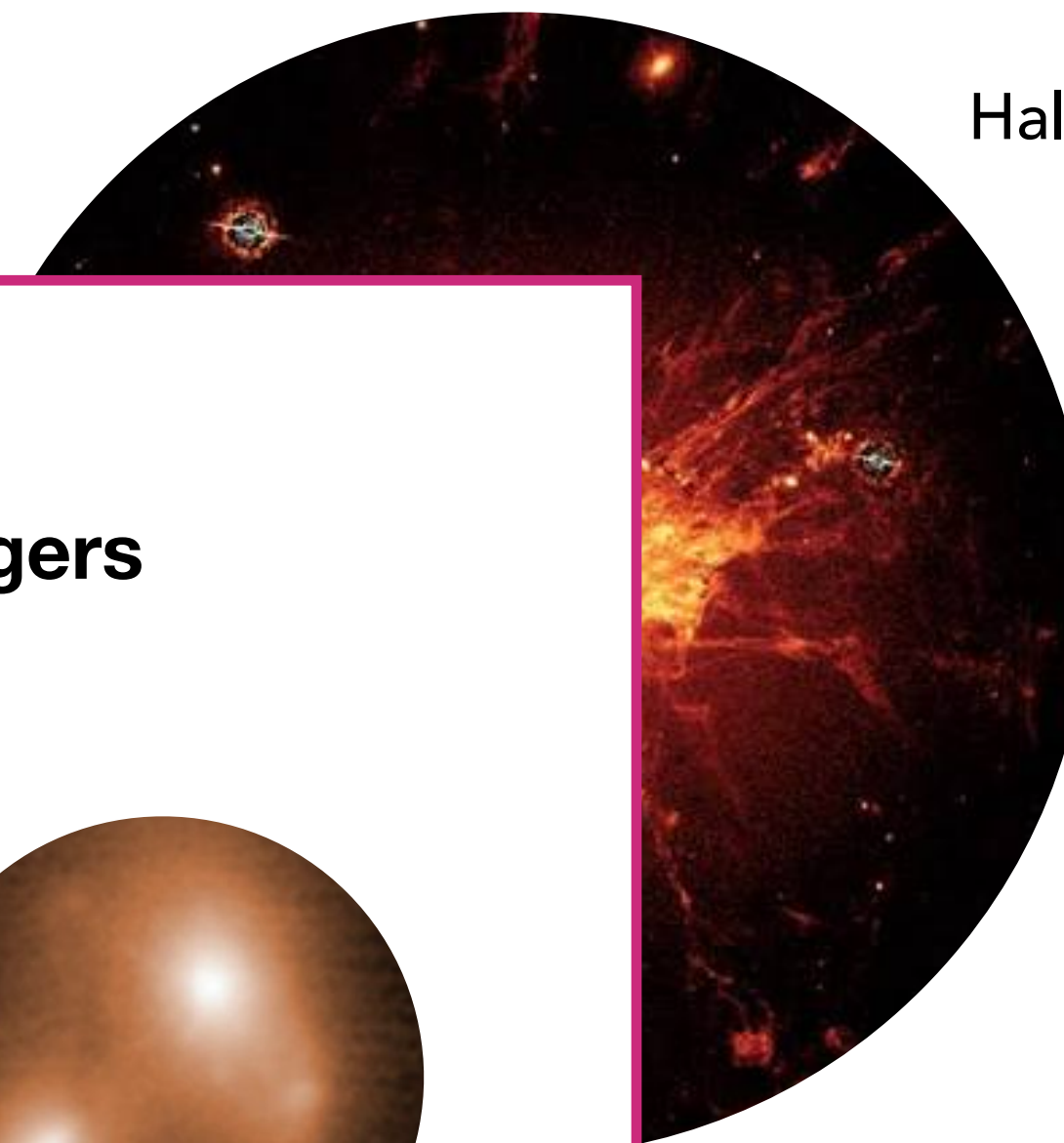
SMBH accretes gas from hot halo forming jets until heating stops cooling,
jets switches off $\rightarrow$ cooling can restart

AGN jet feedback in galaxy groups and clusters

Autoregulated Feeding - Feedback loop



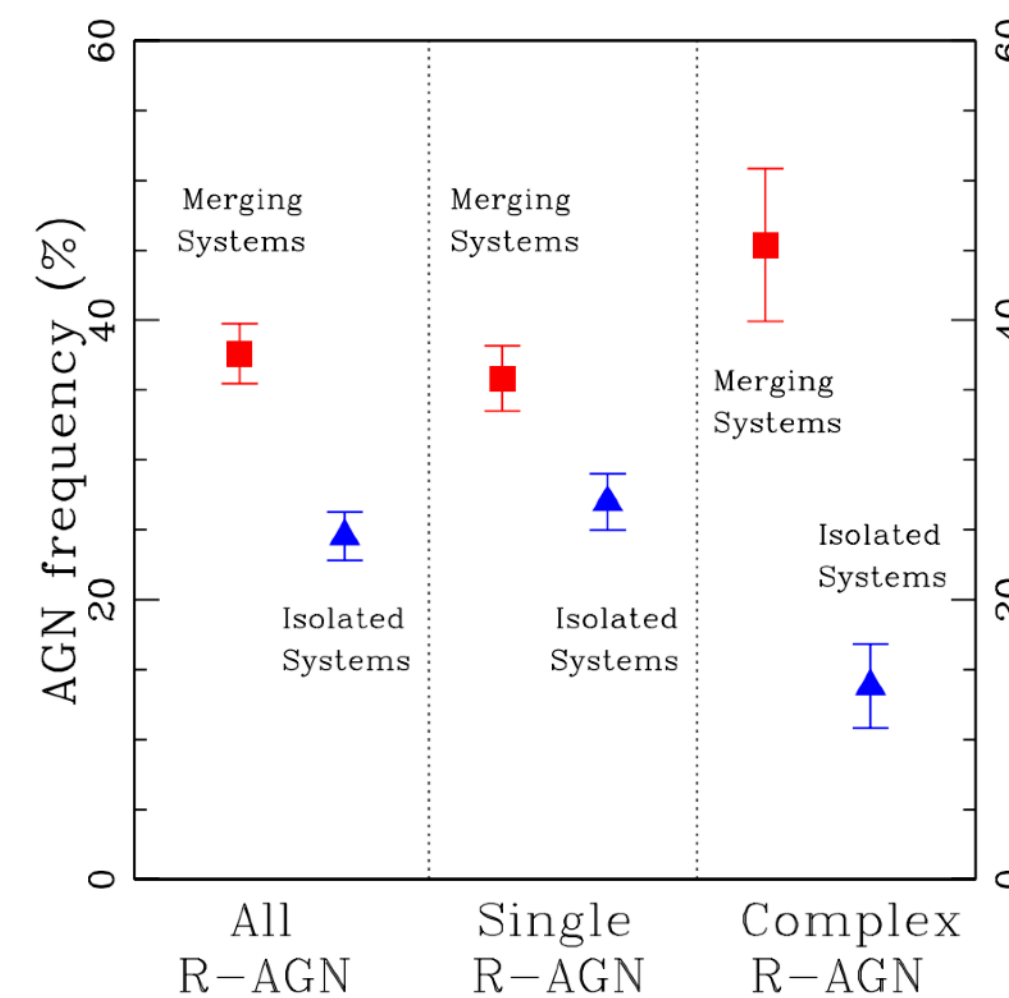
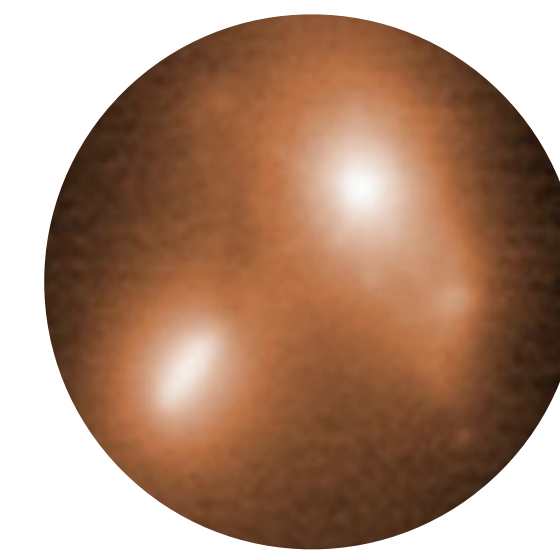
SMBH accre



Fabian+2008
H α , Perseus cluster

Vs

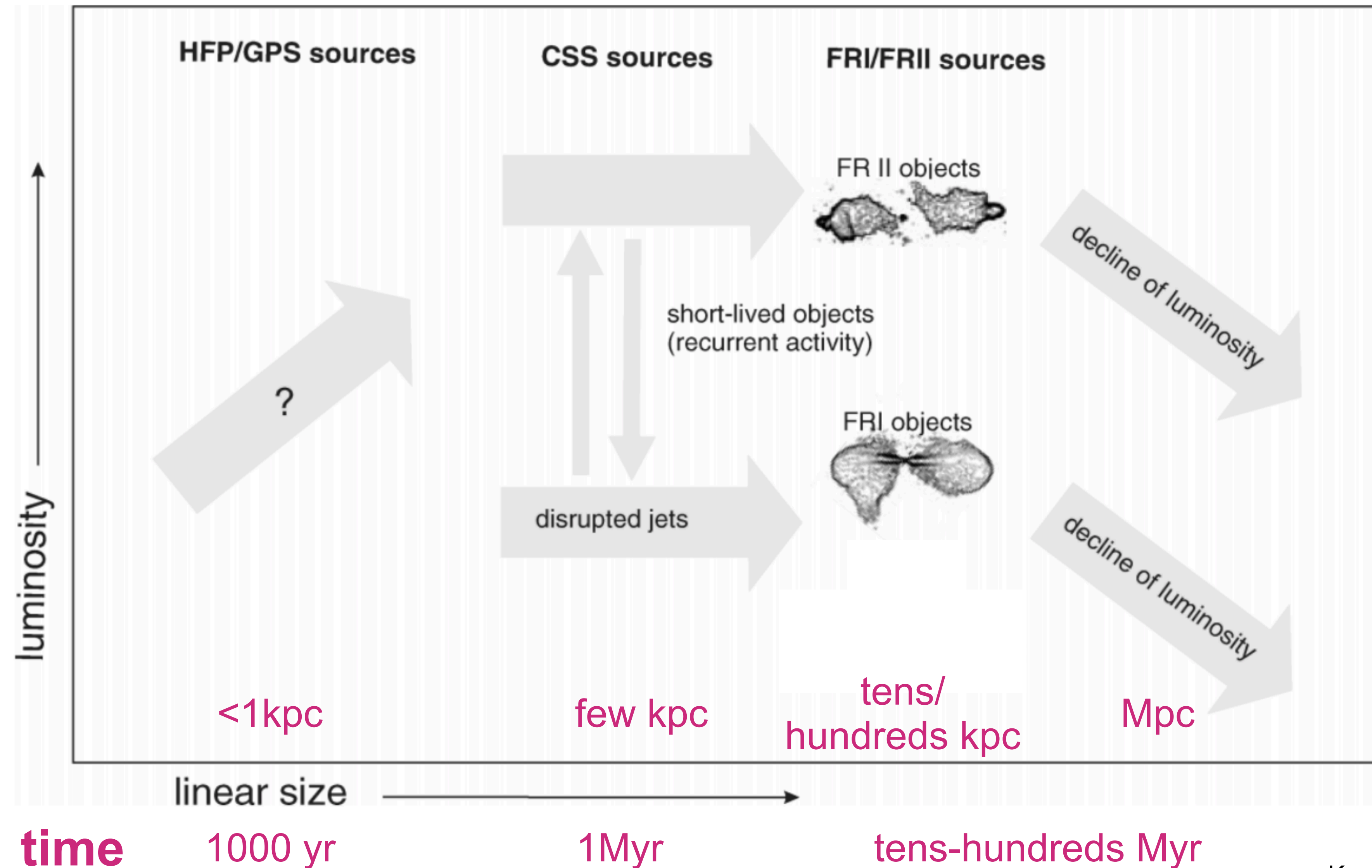
Cold gas from galaxy mergers



e.g. Magliocchetti+2026
LOFAR+Euclid

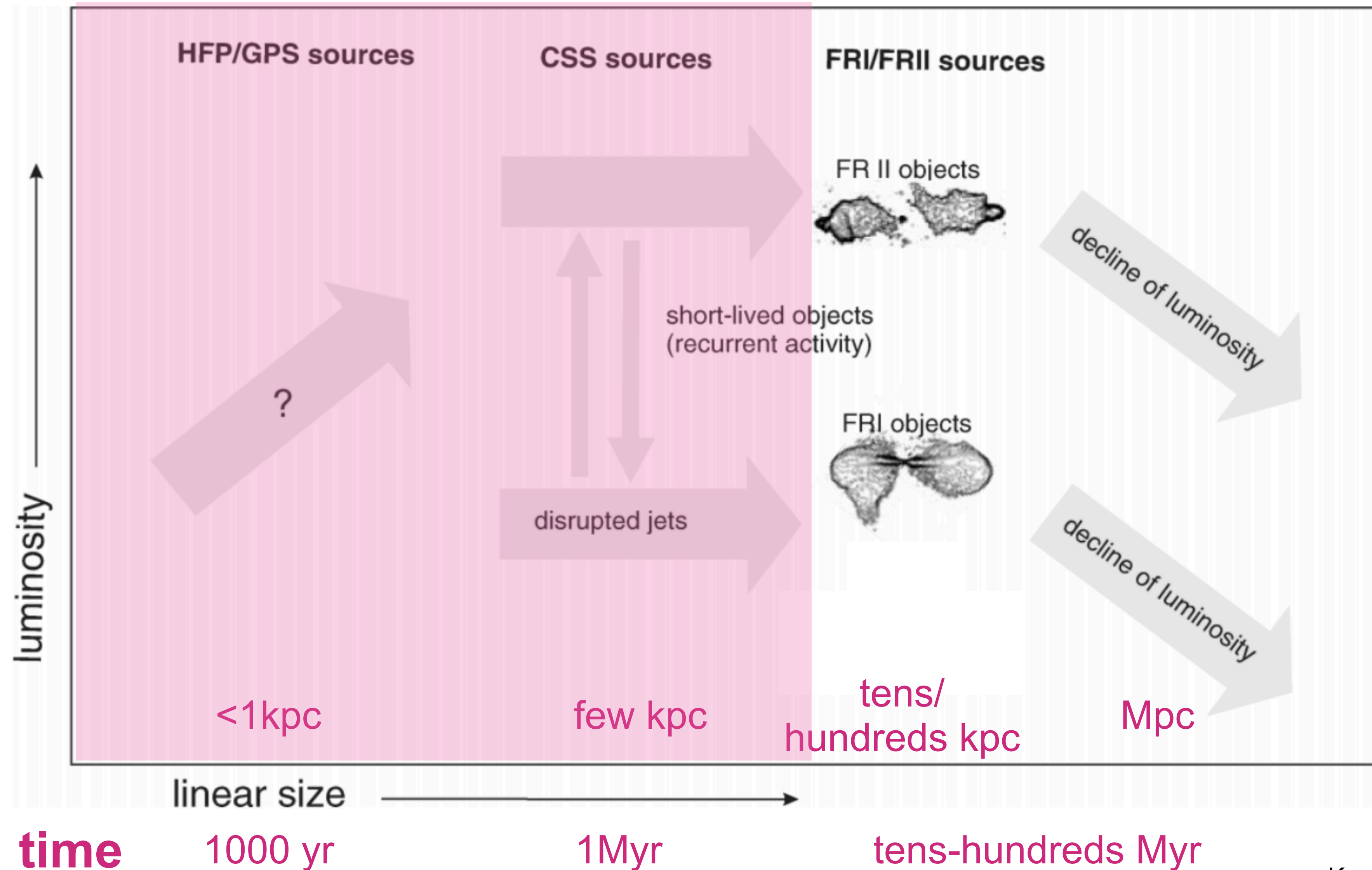
ing stops cooling,

AGN jet release energy on galaxy scale (kpc)



AGN jet release energy on galaxy scale (kpc)

Most jets in the Universe!



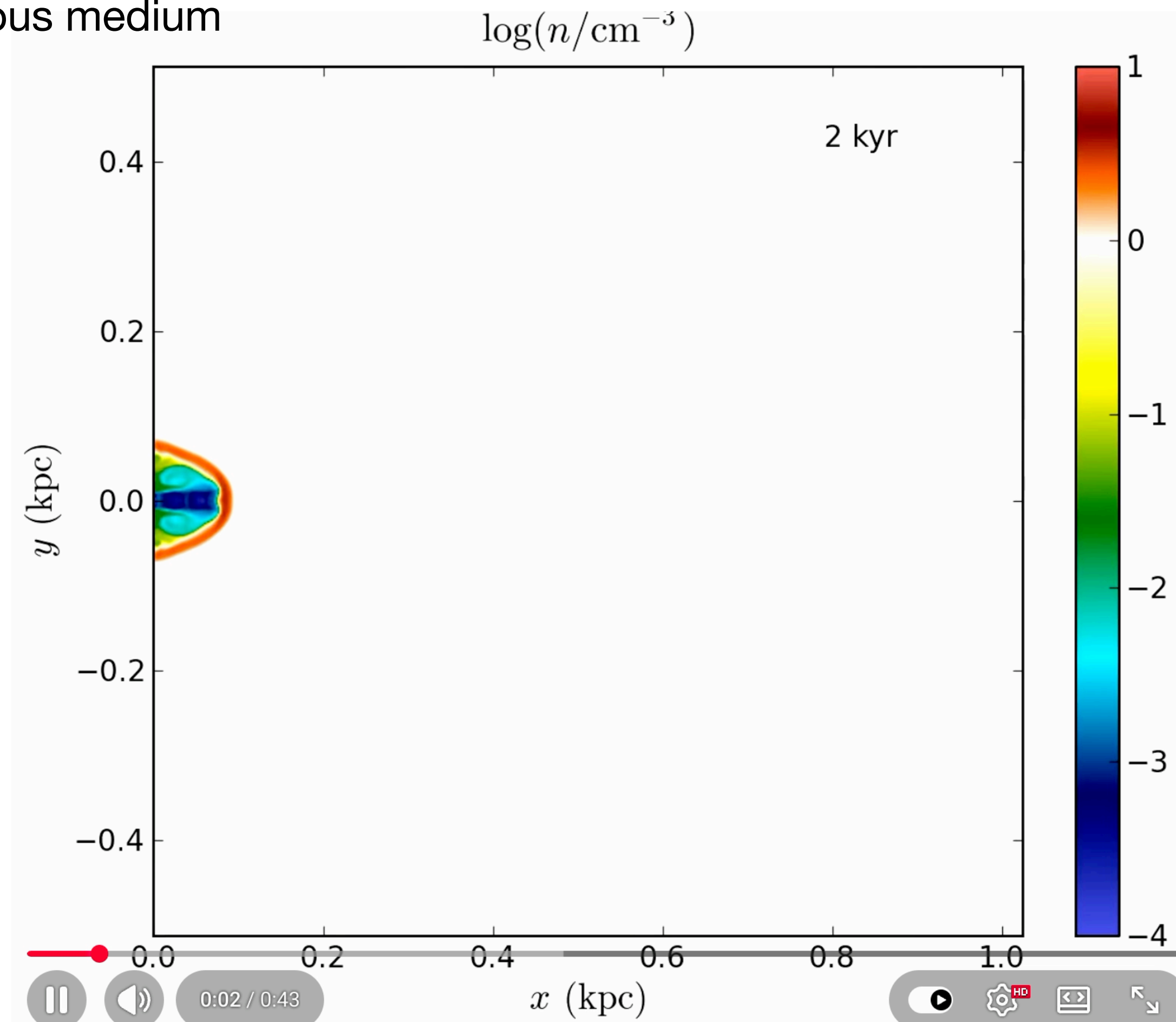
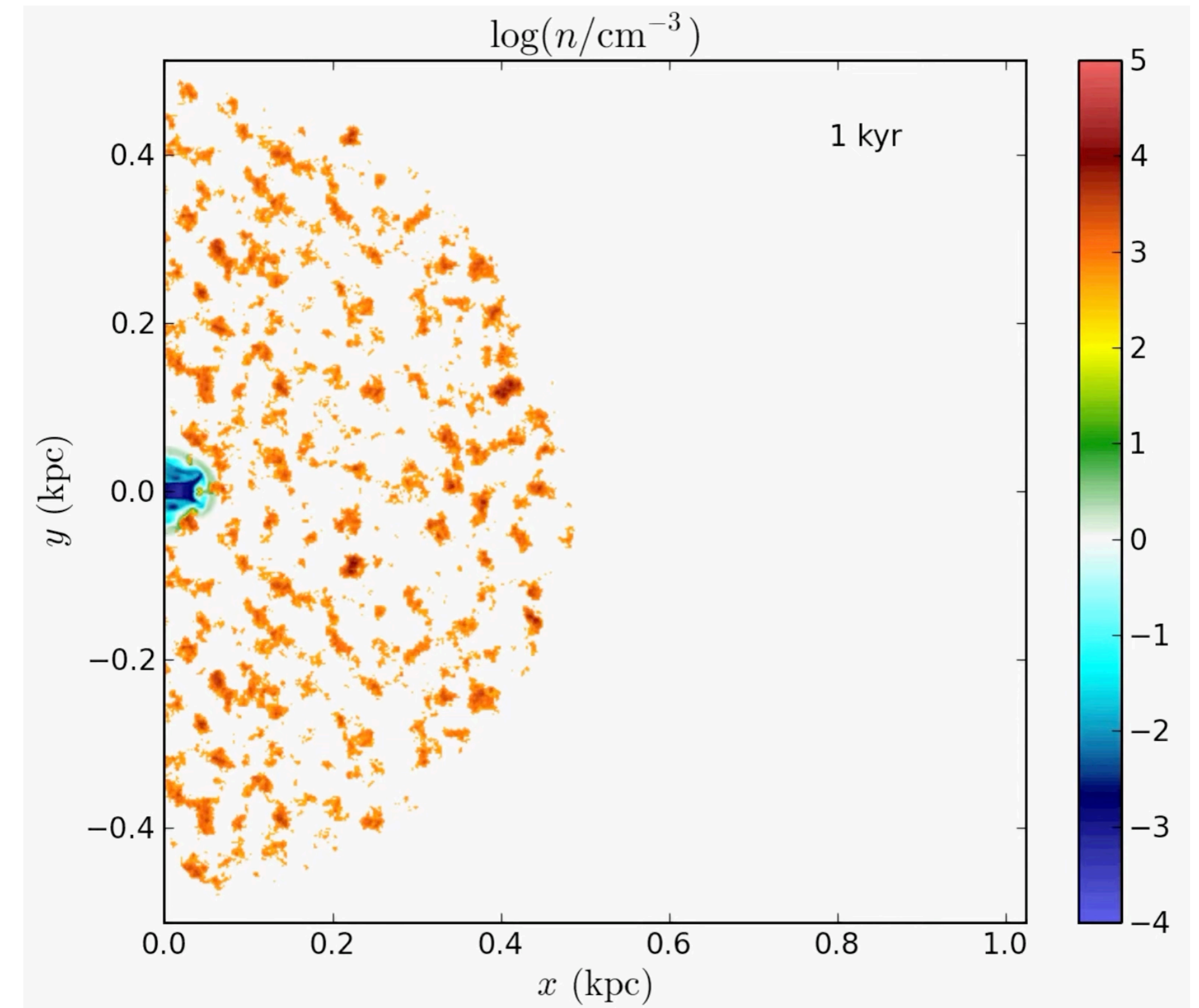
AGN jet release energy on galaxy scale (kpc)

Jet power = $1e45$ erg/s

Clumpy medium

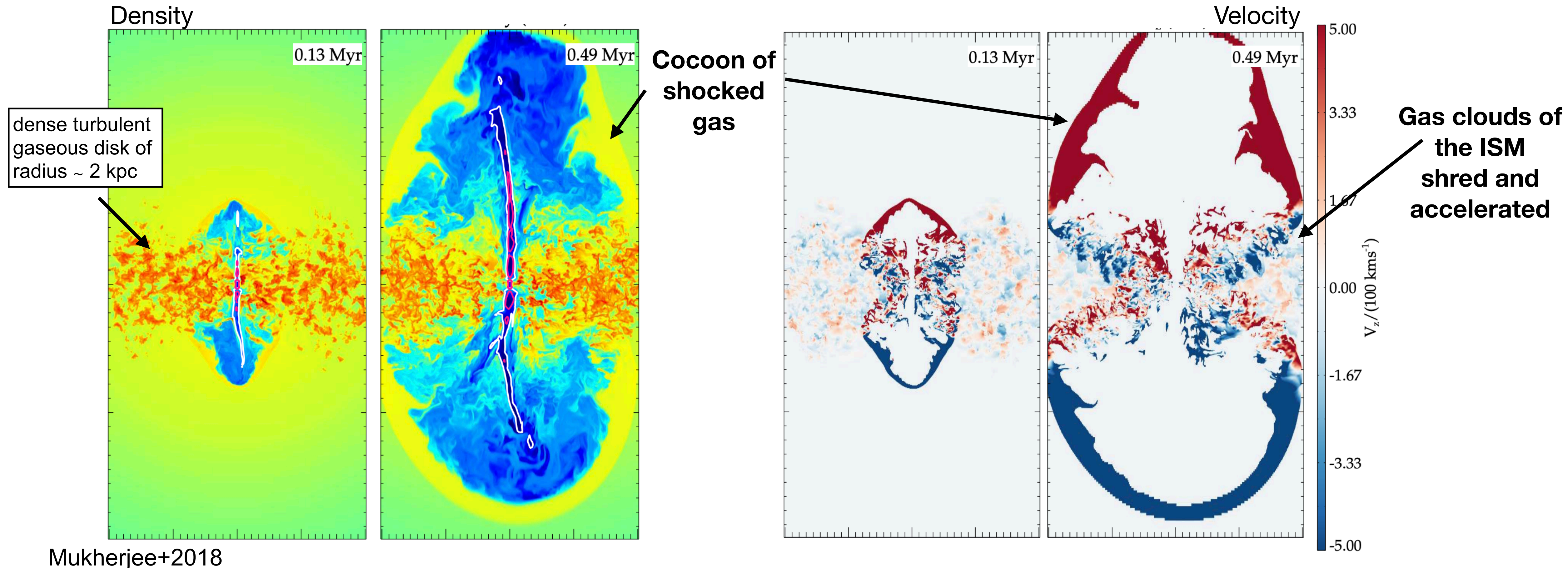
Hot halo $1e7$ K + clouds $1e4$ K

Homogeneous medium



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

AGN jet release energy on galaxy scale (kpc)



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 $M_{\odot}/\text{yr}$

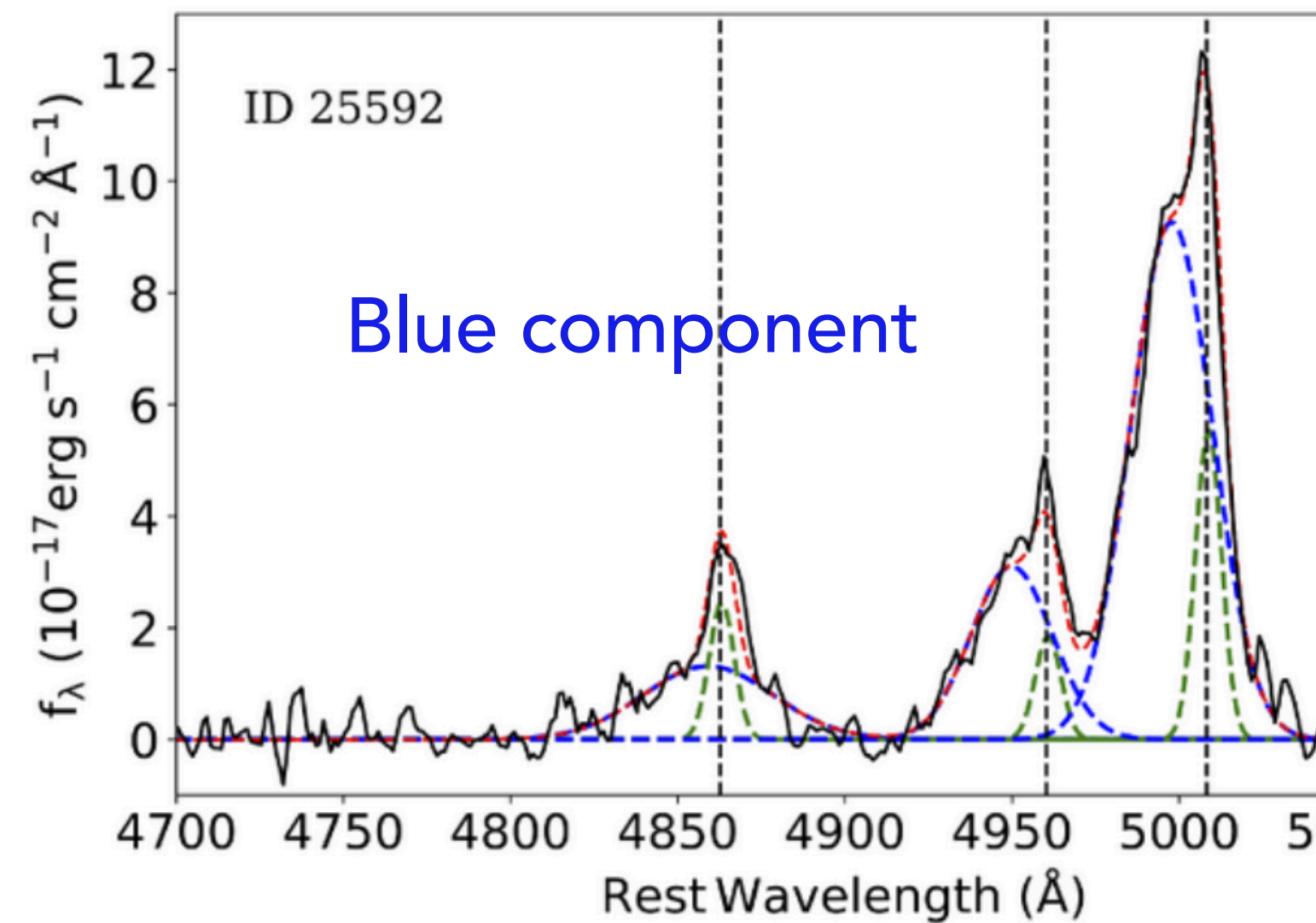
$v_{\text{out}} \sim 500 - 2000 \text{ km/s}$

Outflows

Wings with respect
to systemic velocity

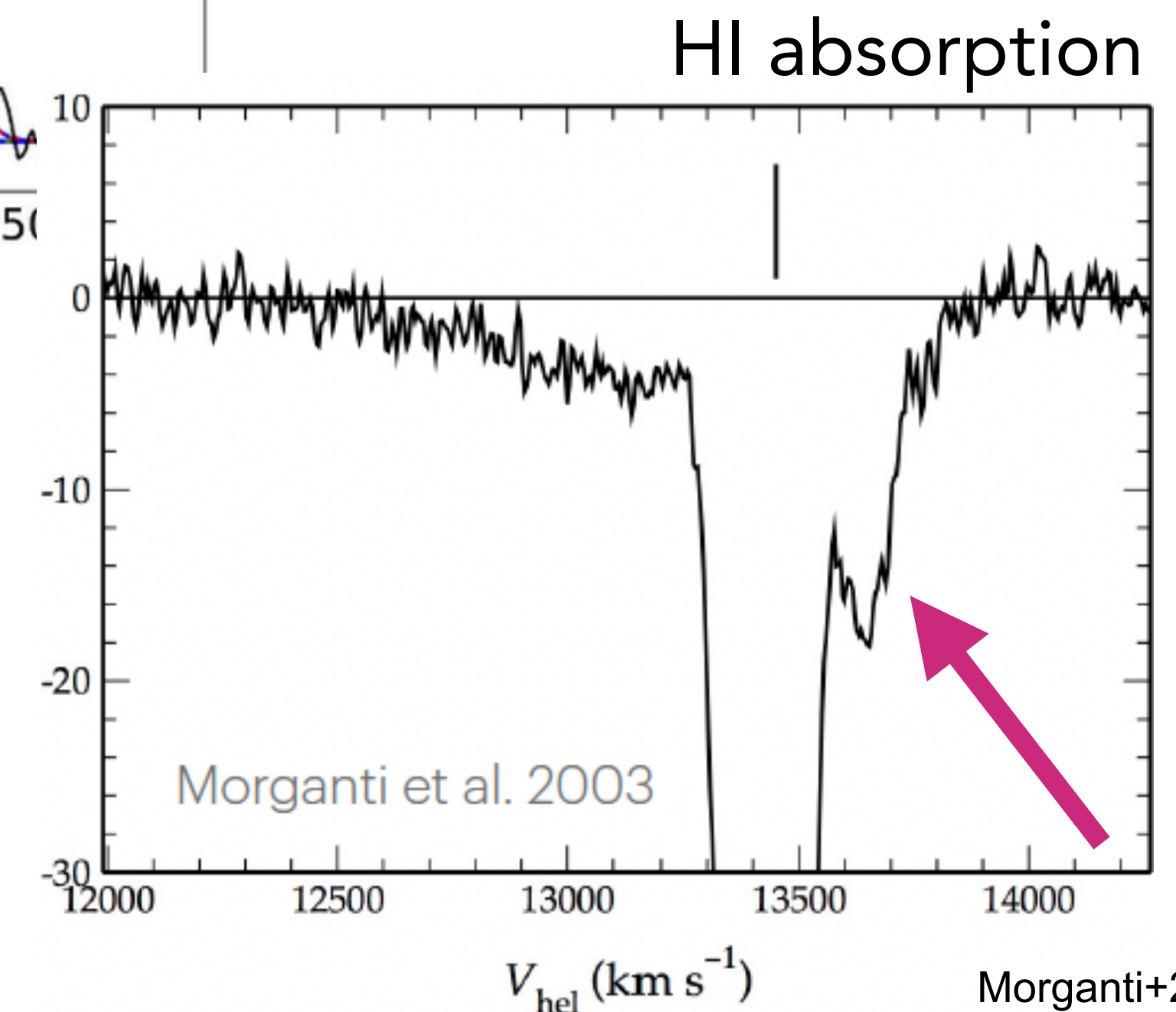
Turbulence

Large velocity dispersions



OIII emission

Musiimenta et al. 2023



HI absorption

Morganti+2005

AGN jet release energy on galaxy scale (kpc)

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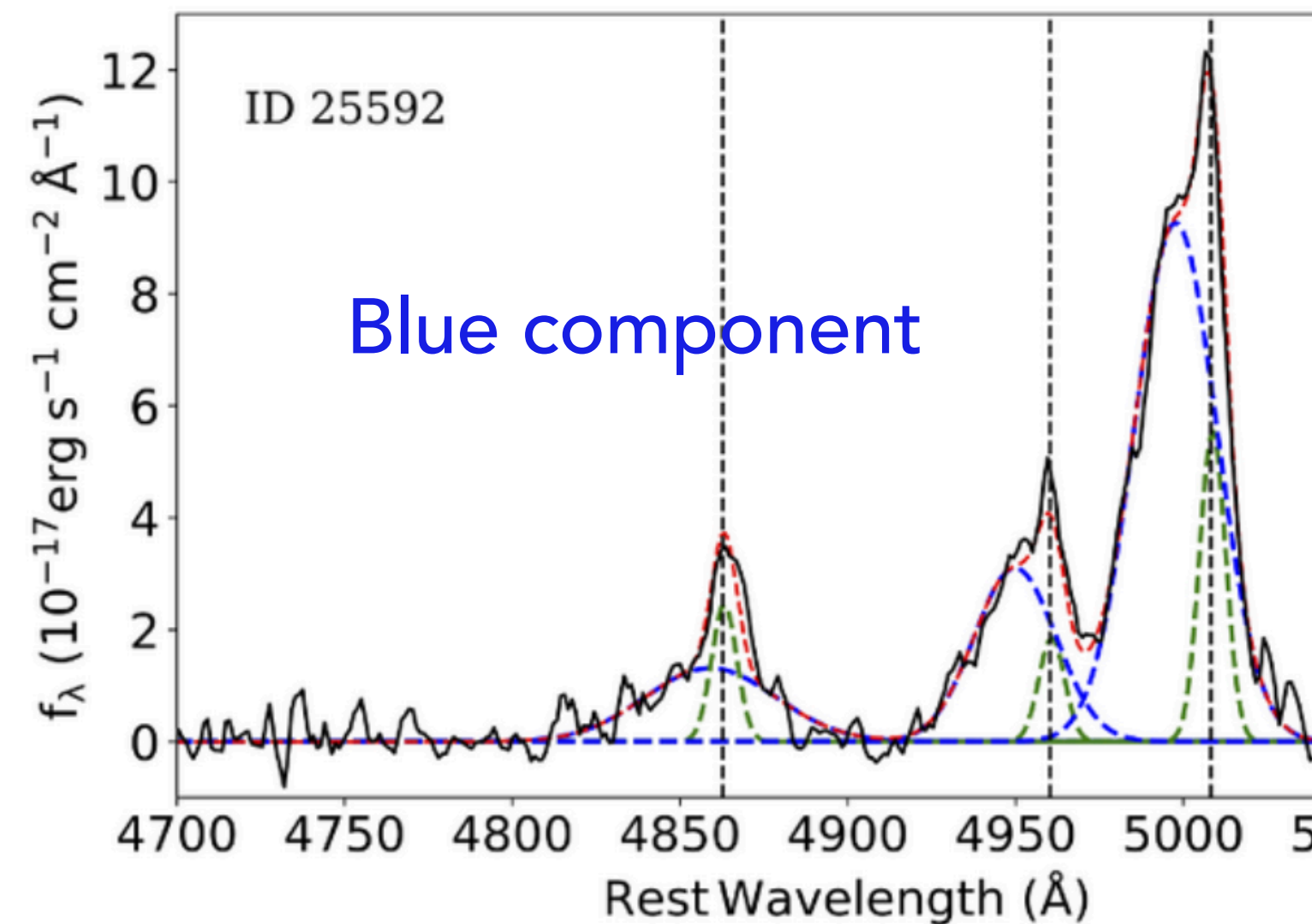
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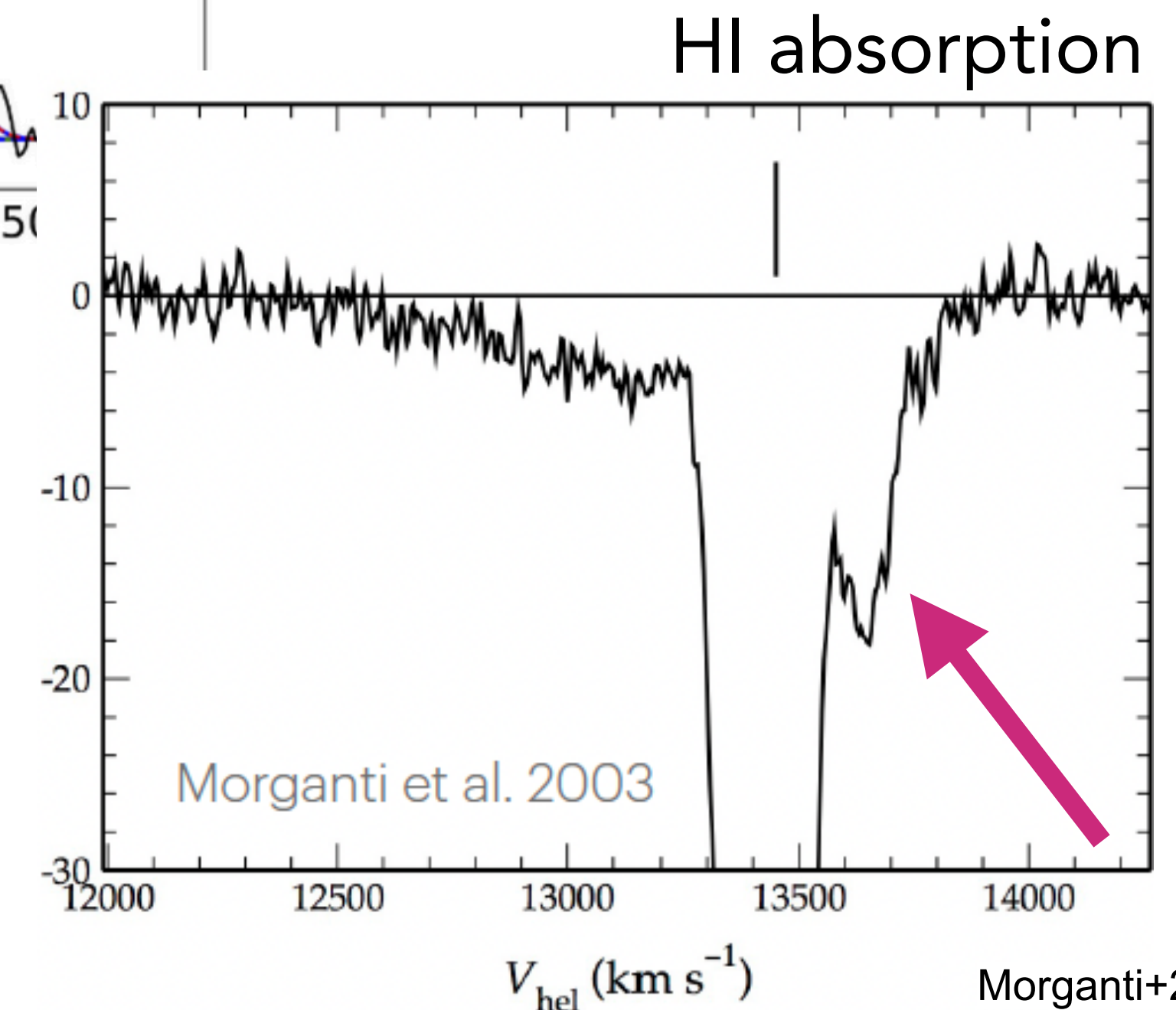
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Musiimenta et al. 2023

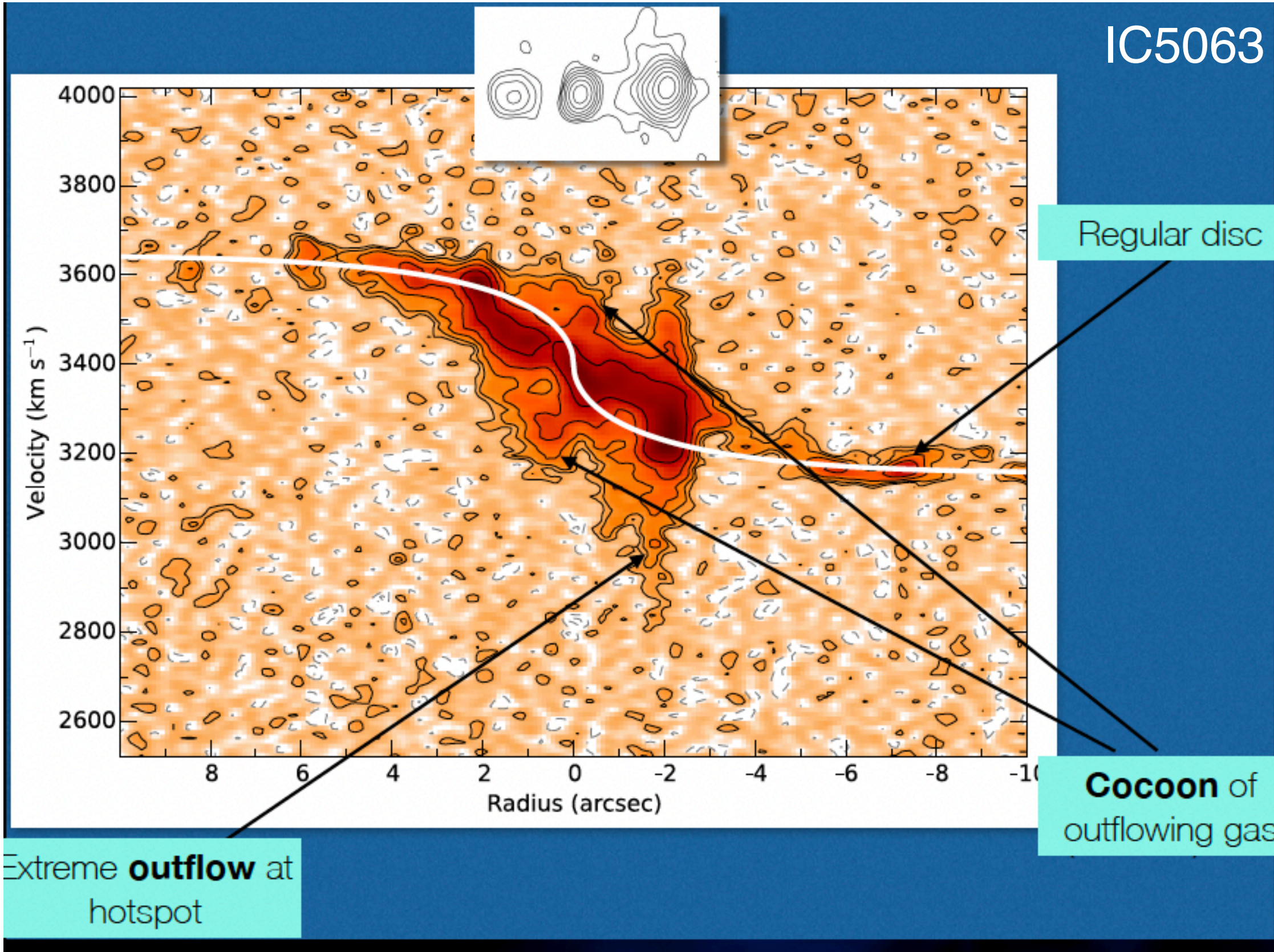


Morganti+2005

An ocean of literature!
What is driving these galaxy scale
outflows?

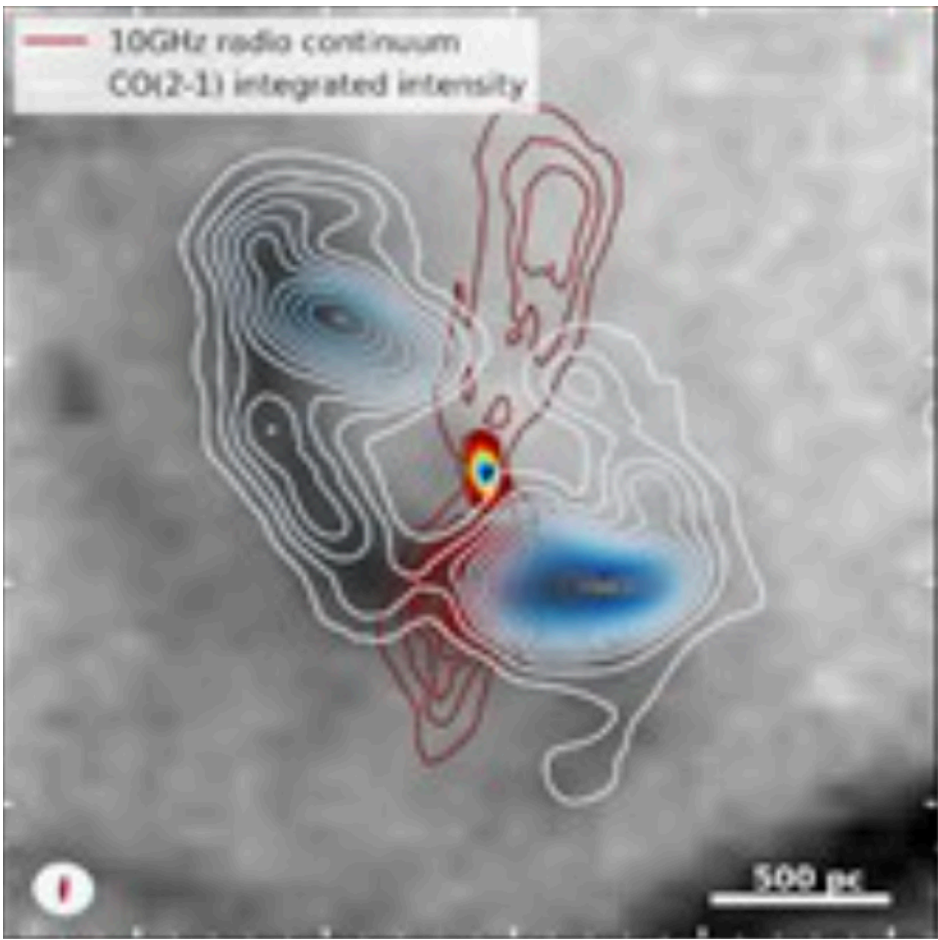
AGN jet release energy on galaxy scale (kpc)

Outflows + turbulence

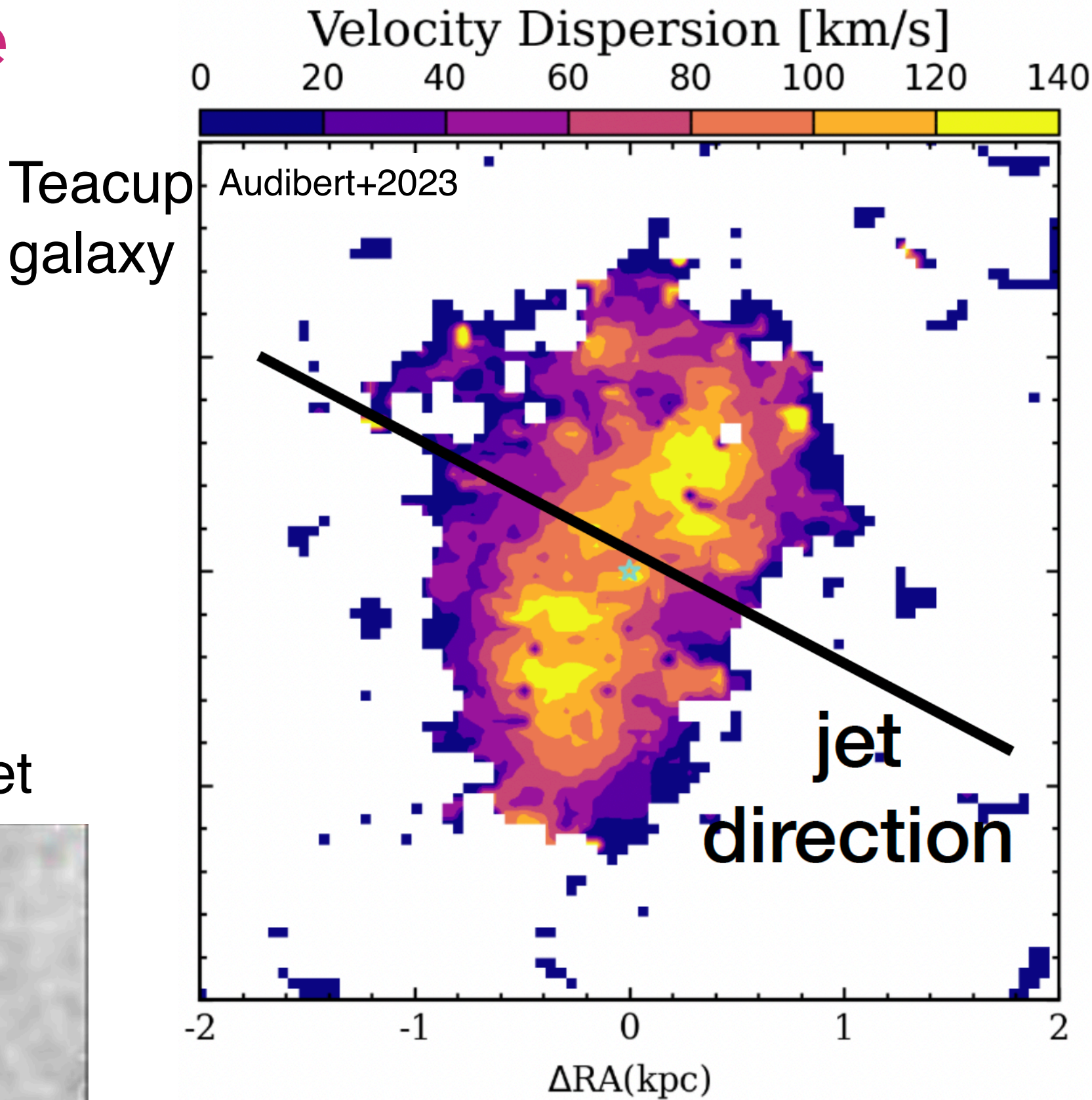


CO

White = CO, red = jet



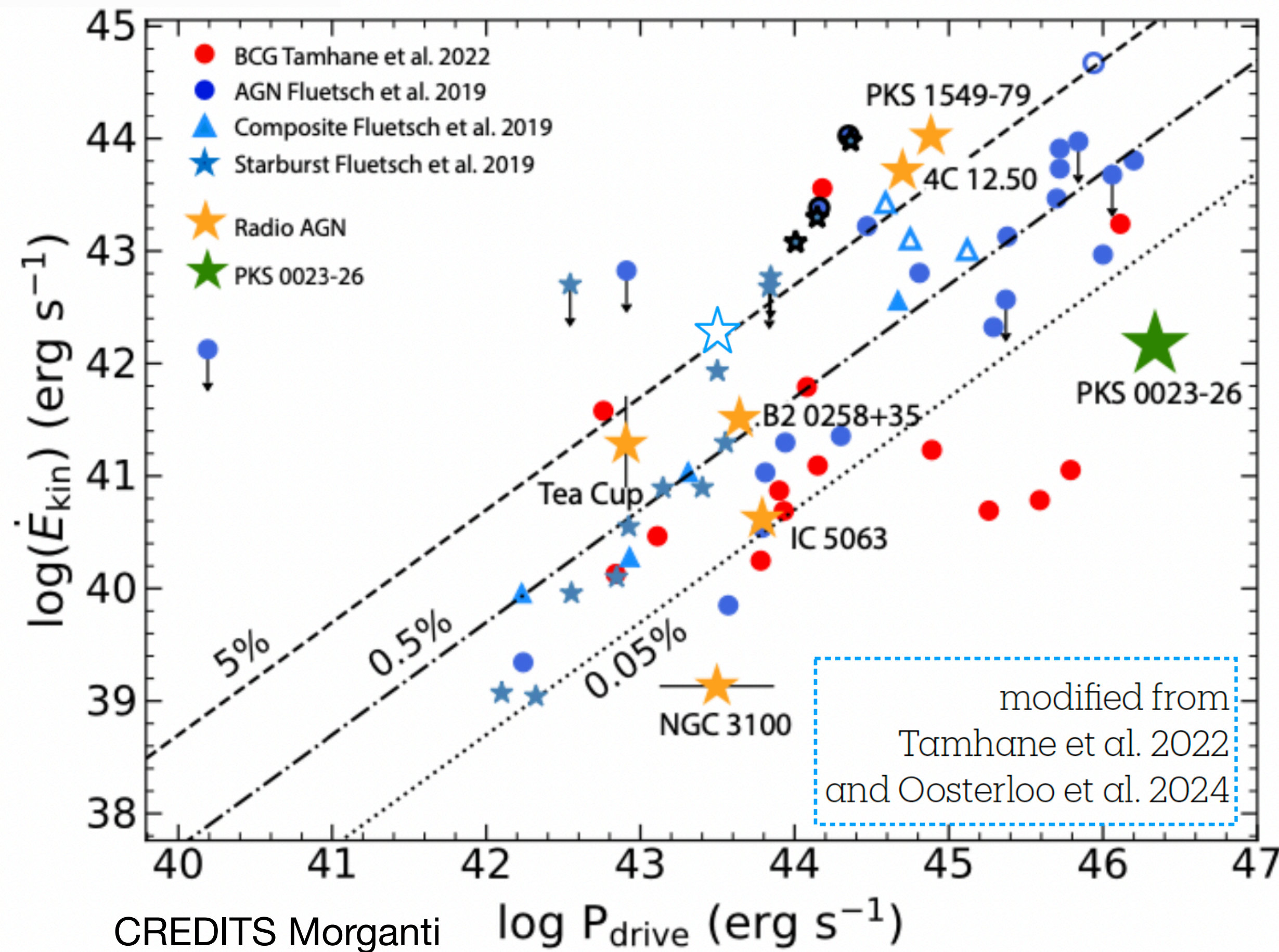
Ruffa+2022



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

AGN jet release energy on galaxy scale (kpc)

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



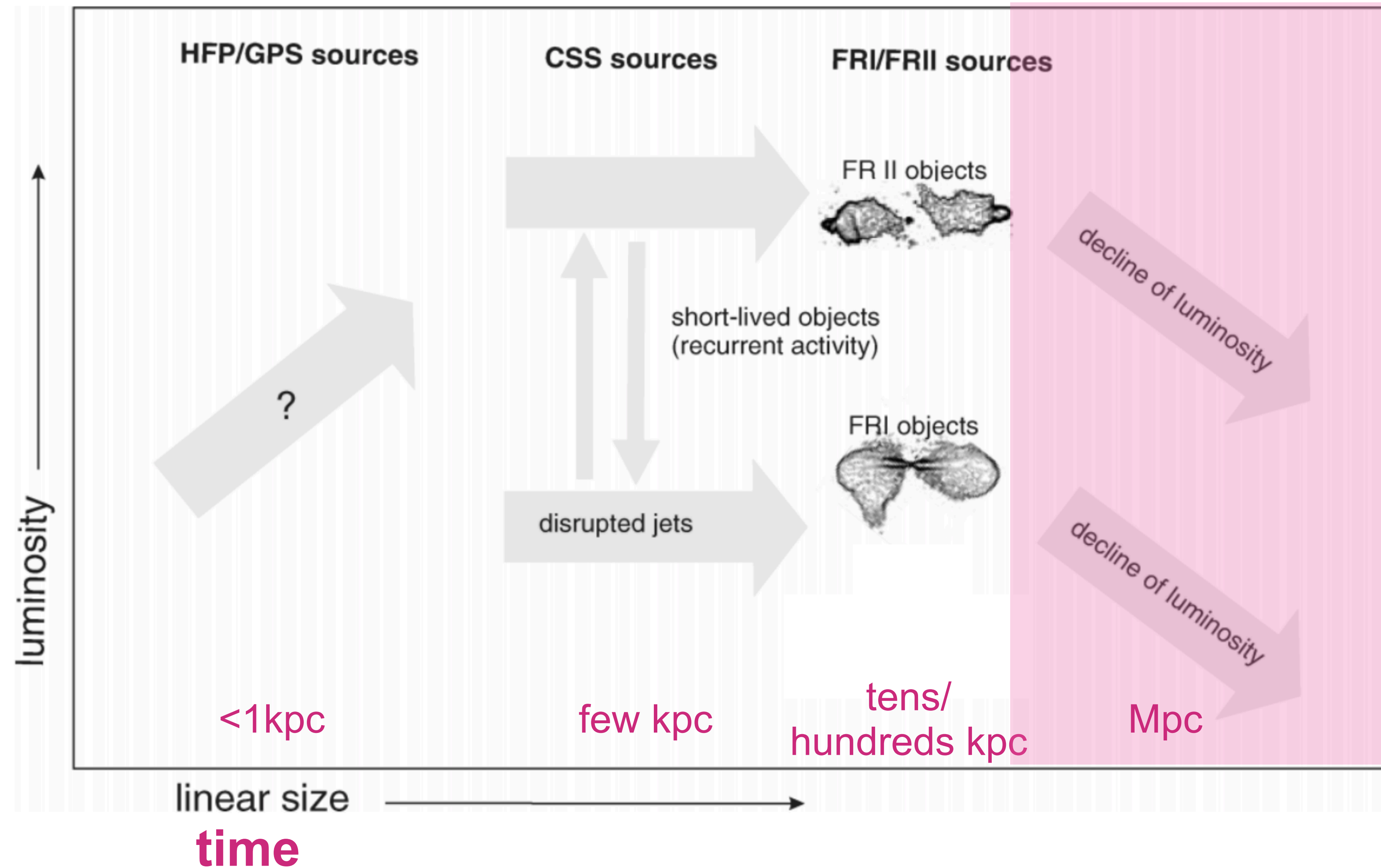
$\dot{E}_{\text{kin}}/P_{\text{jet}}$ between ~5% and <0.5% = a small fraction of the jet power goes into accelerating the gas BUT rest is dissipated as heat or contributes to turbulent motions within the ISM (prevents gas from cooling)

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 $P_{\text{drive}} = P_{\text{mech}}$ for jets

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



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 population through machine learning and Bayesian inference

R. I. J. Mostert^{1,2,*}, M. ...

A&A 650, A51 (2021)
<https://doi.org/10.1051/0004-6361/202140528>
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A new distant **giant** radio galaxy in the Boötes field serendipitously detected by Chandra

Alberto M...

Monthly Notices
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ROYAL ASTRONOMICAL SOCIETY

MNRAS **501**, 3833–3845 (2021)
Advance Access publication 2020 December 14

MIGHTEE: are **giant** radio galaxies more

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. Simonte¹, H. Andernach^{2,3}, M. Brüggen¹, G. K. Miley⁴, and P. Barthel⁵

Astronomy
&
Astrophysics

Monthly Notices
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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. Panessa¹, L. Bassani⁴, D. Dallacasa^{2,3}, T. Venturi³, R. D. Baldi^{3,5},
Botteon⁶, A. Drabent⁷, A. Malizia⁴, F. Massaro^{8,9,10,11}, H. J. A. Röttgering⁶, P. Ubertini¹, F. Ursini¹²

A&A 635, A5 (2020)
<https://doi.org/10.1051/0004-6361/201935589>
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Giant radio galaxies in the LOFAR Two-metre Sky Survey

Astronomy
&
Astrophysics

Environmental properties[★]

Shimwell^{1,3}, M. J. Hardcastle⁴, S. Sankhyayan⁵, R. Morganti^{3,6},
Kulevski⁸, and K. J. Duncan¹

doi:10.1093/mnras/staa3837

A&A, 699, A257 (2025)
<https://doi.org/10.1051/0004-6361/202452961>
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Properties of **giant** radio galaxies larger than 3 Mpc

H. Andernach^{1,2,*} and M. Brüggen³

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

A&A, 691, A185 (2024)
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Constraining the giant radio galaxy population
learning and Re

R. I. J. Mostert^{1,2,*}, M. Simonte¹, H. Andernach^{2,3}, M. Brüggen¹, G. K. Miley⁴, and P. Barthel⁵

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A new distant giant radio galaxy

Alberto M.

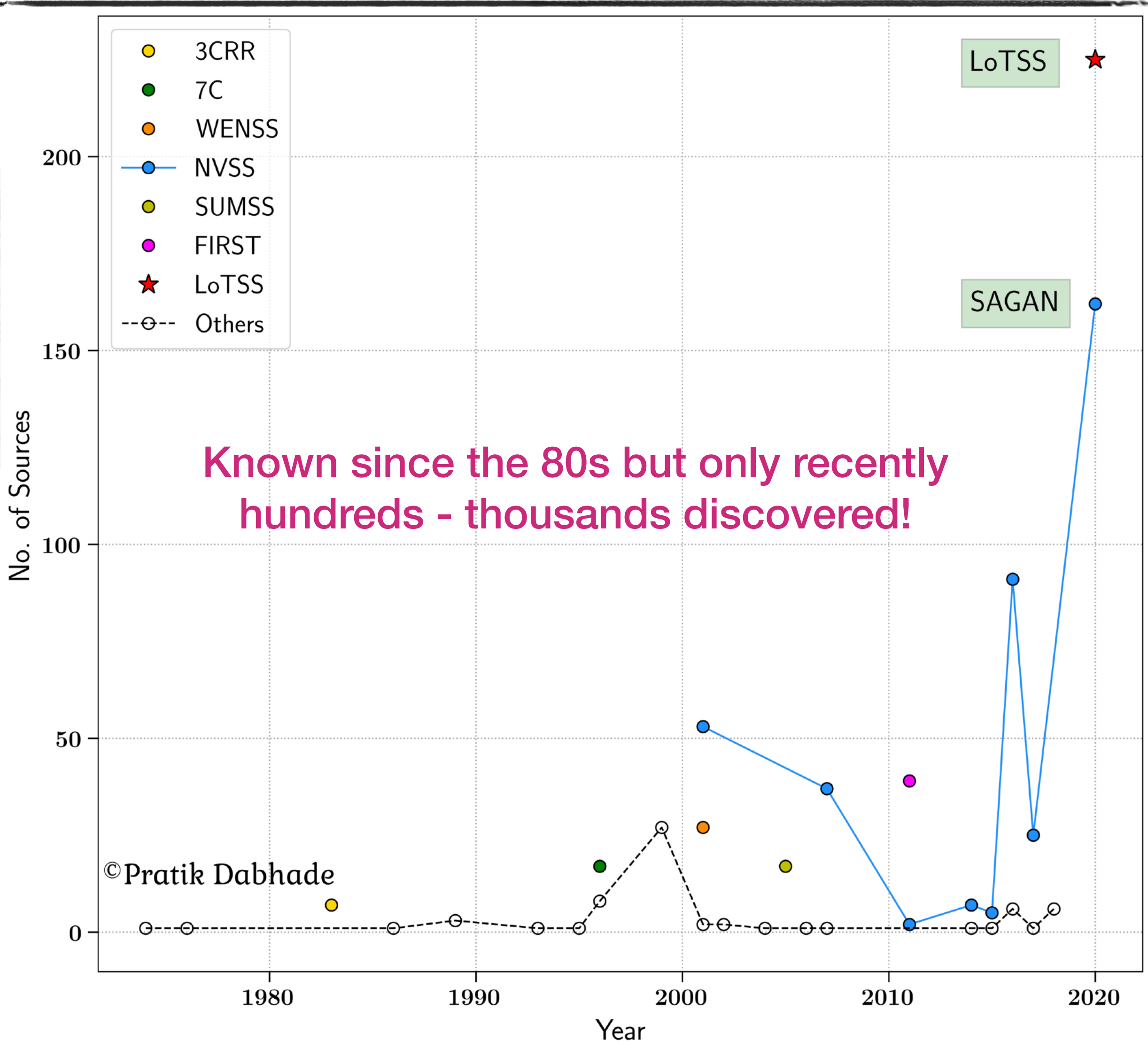
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MNRAS **501**, 3833–3838
Advance Access published 2021

MIGHTY

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Astrophysics

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Astronomy
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Astrophysics

Galaxies larger than 3 Mpc
and M. Brüggen³

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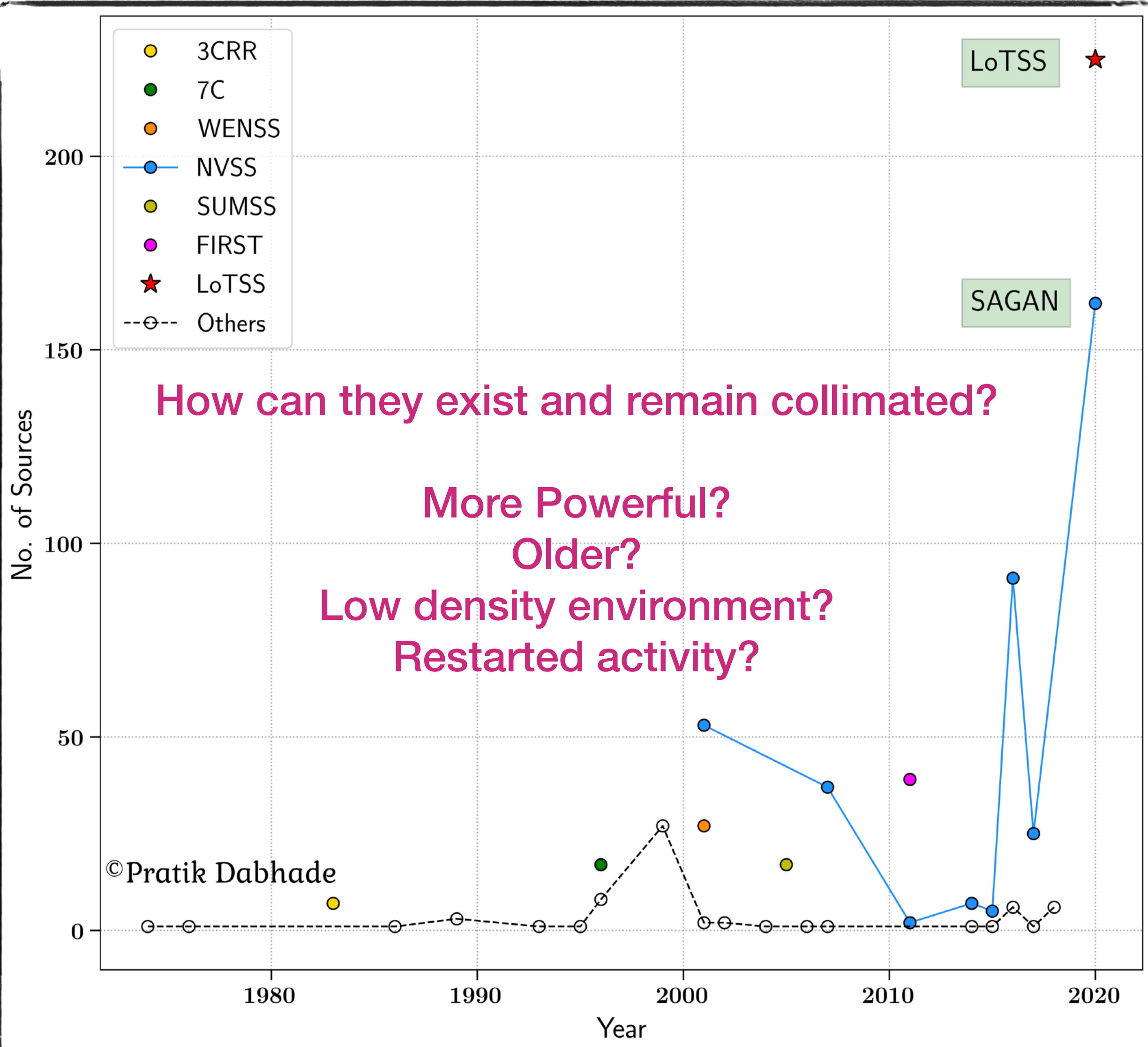
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Environmental properties

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Galaxies larger than 3 Mpc

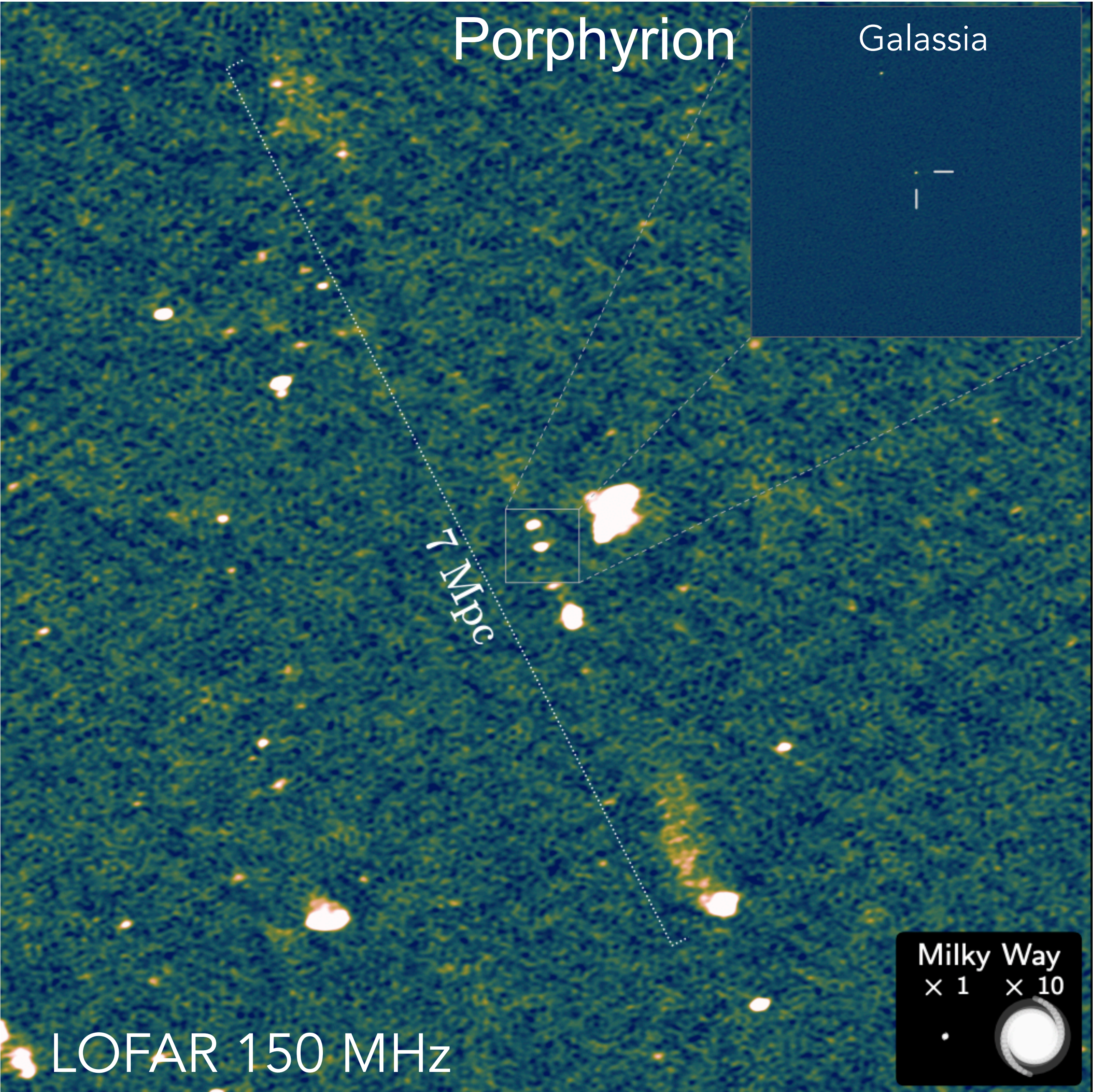
and M. Brüggen³

Black hole jets on the scale of the cosmic web

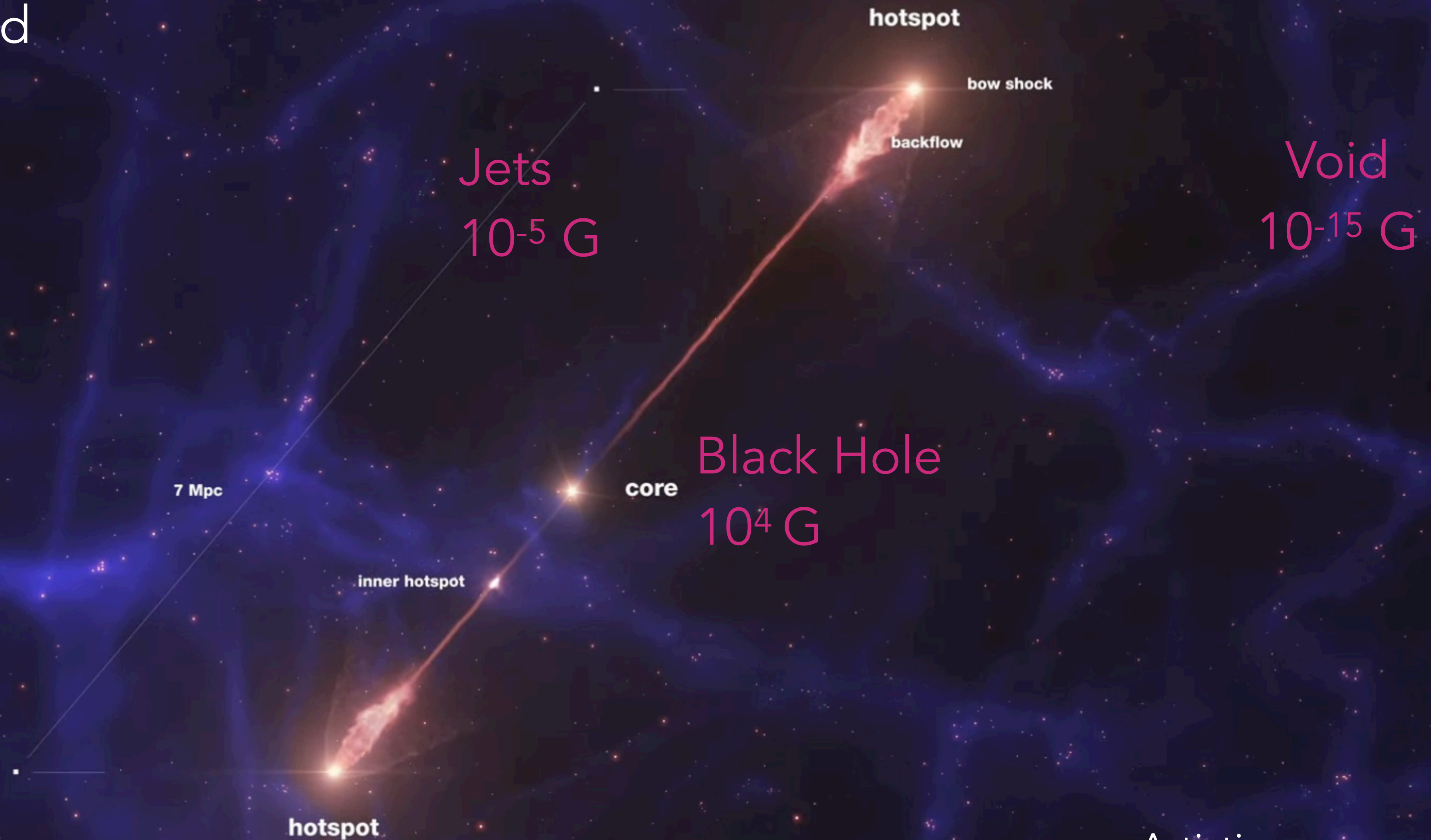
[Martijn S. S. L. Oei](#) , [Martin J. Hardcastle](#), [Roland Timmerman](#), [Aivin R. D. J. G. I. B. Gast](#), [Andrea Botteon](#), [Antonio C. Rodriguez](#), [Daniel Stern](#), [Gabriela Calistro Rivera](#), [Reinout J. van Weeren](#), [Huub J. A. Röttgering](#), [Huib T. Intema](#), [Francesco de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

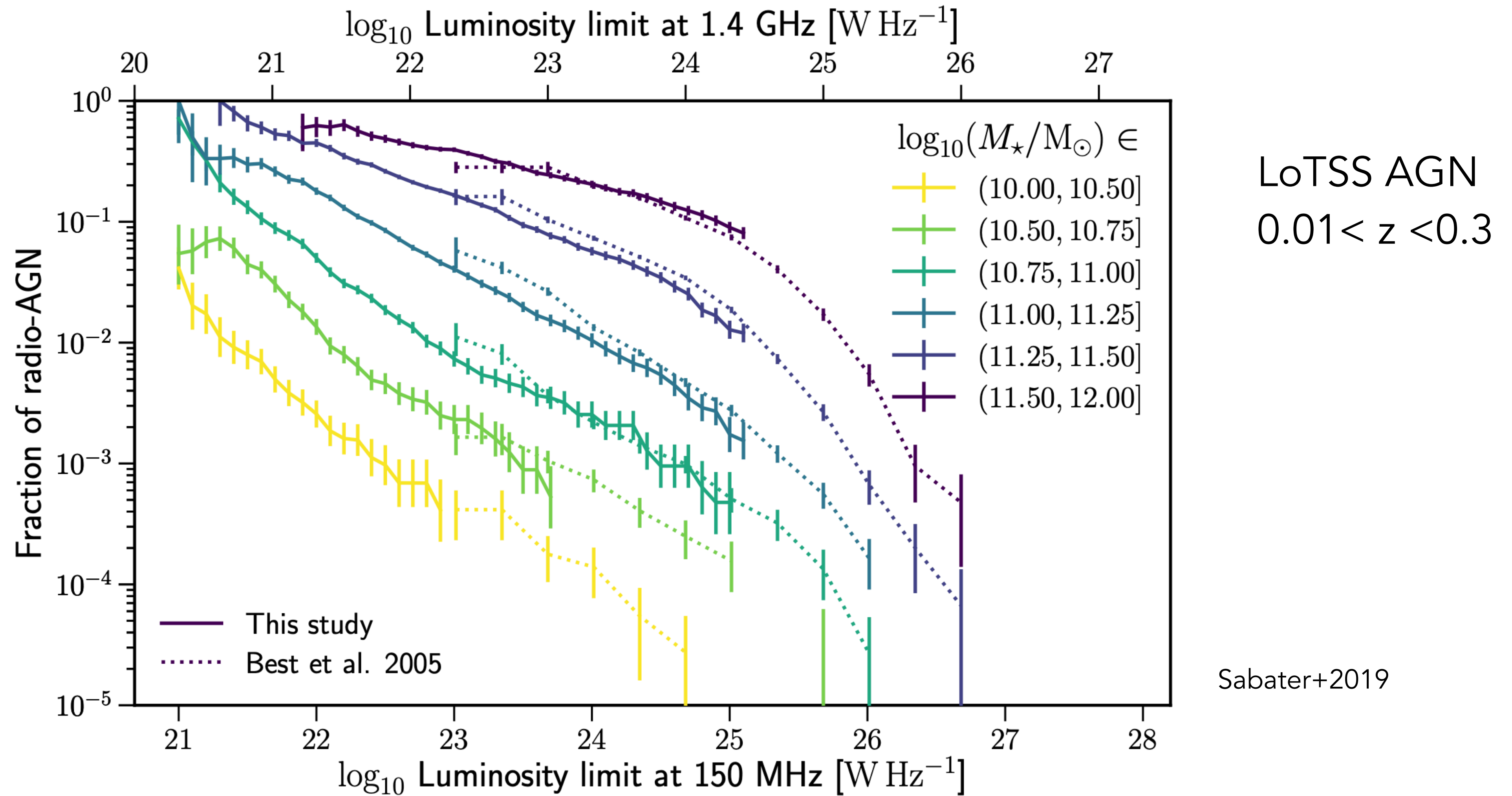


Only a small fraction of jet magnetic field able to overwrite the field from primordial magnetogenesis

Artistic representation
CREDITS: Martijn Oei

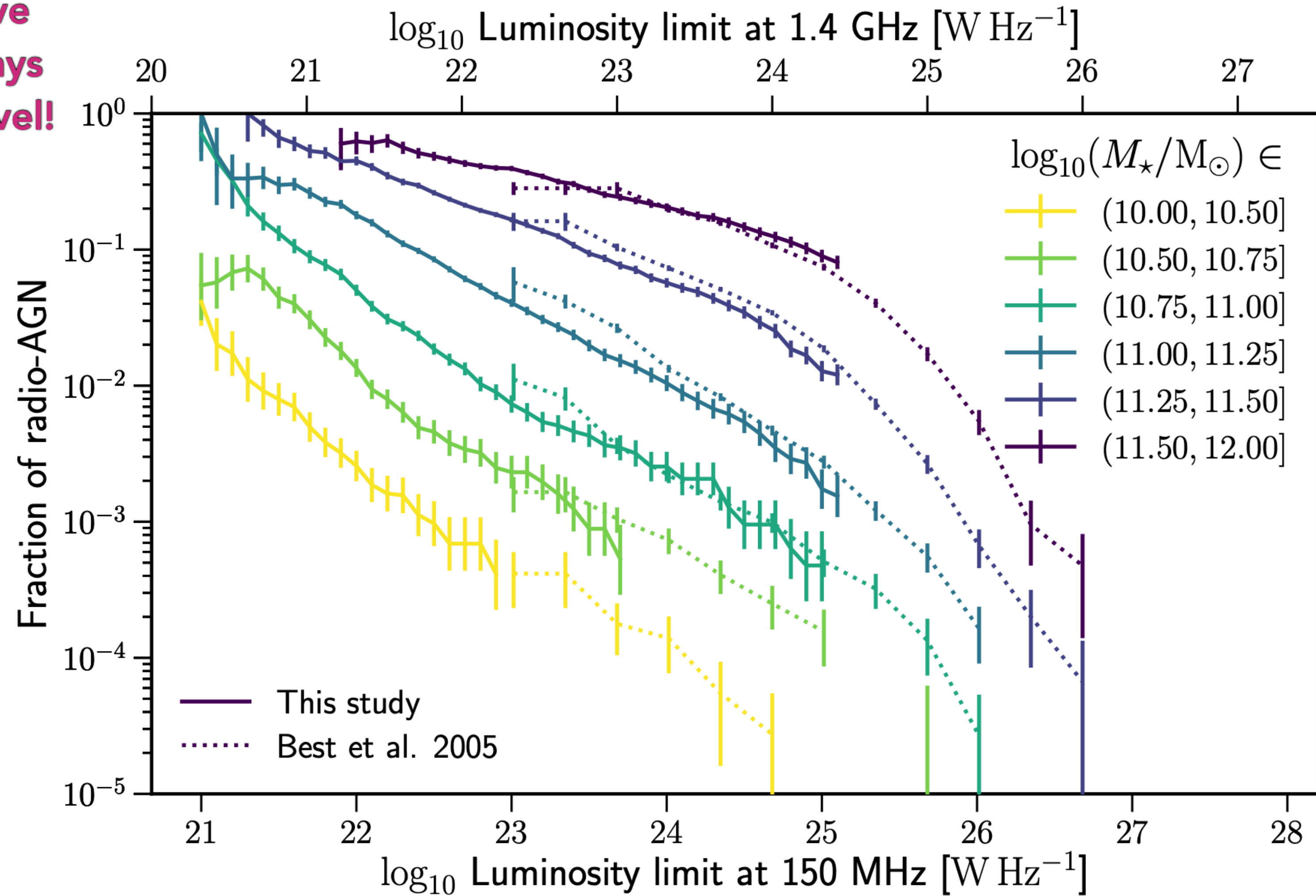
Caltech

Cumulative jet feedback: a statistical approach



Cumulative jet feedback: a statistical approach

The most massive galaxies are always active at some level!

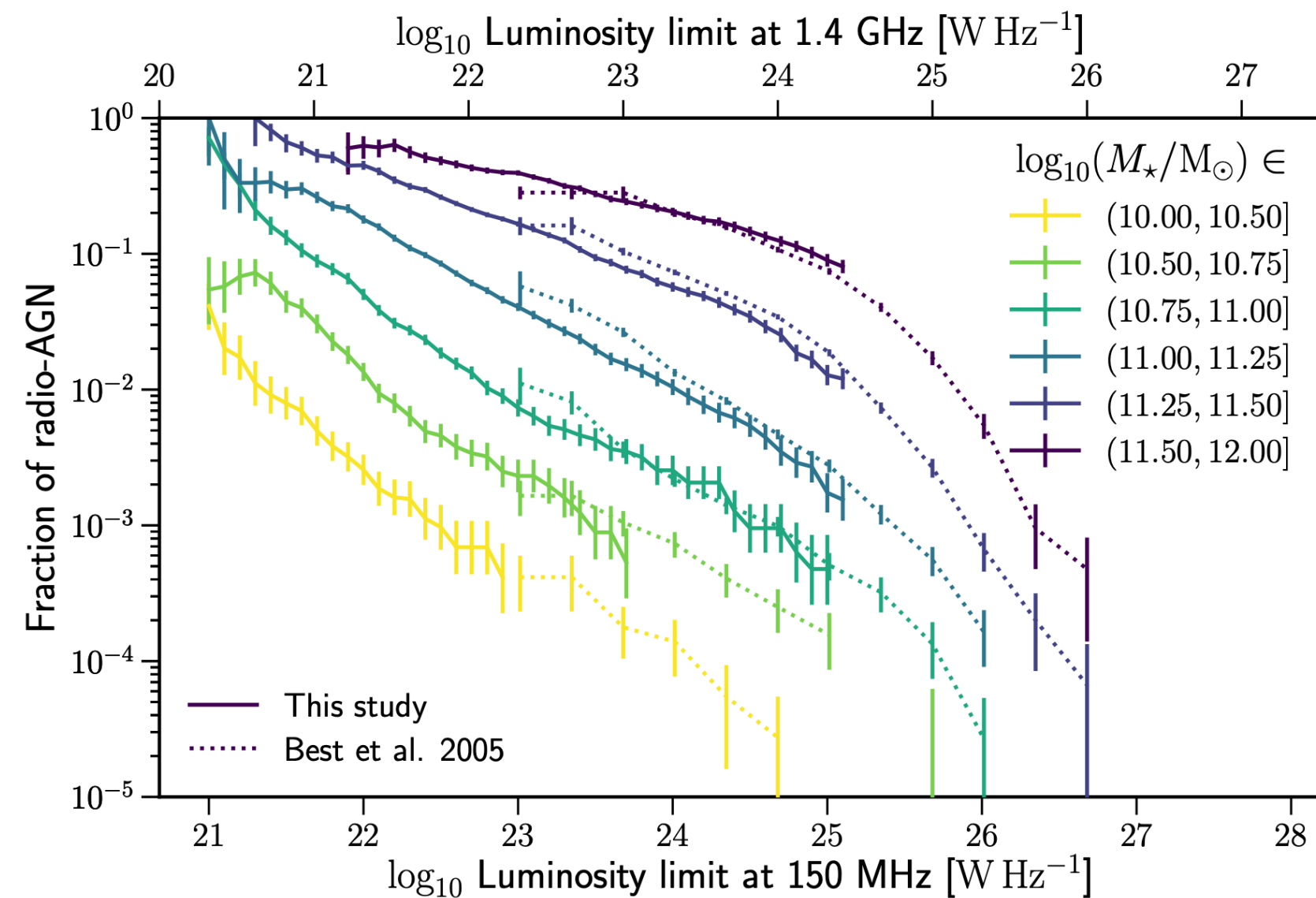


LoTSS AGN
 $0.01 < z < 0.3$

Sabater+2019

Cumulative jet feedback: a statistical approach

Sabater+2019

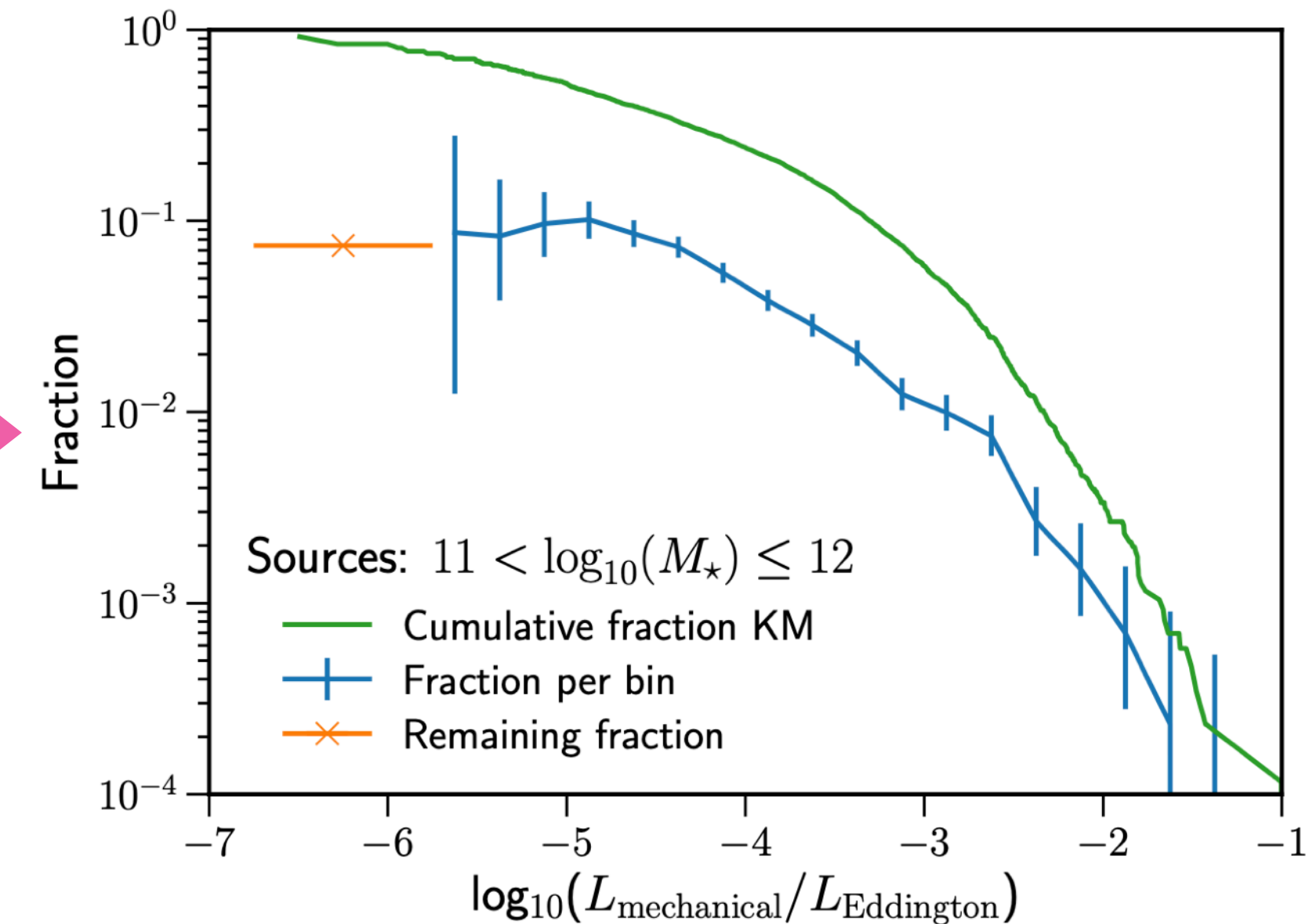


Convert radio luminosity into
jet mechanical power
calibrated from X-ray cavities.

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

Heckman & Best (2014)

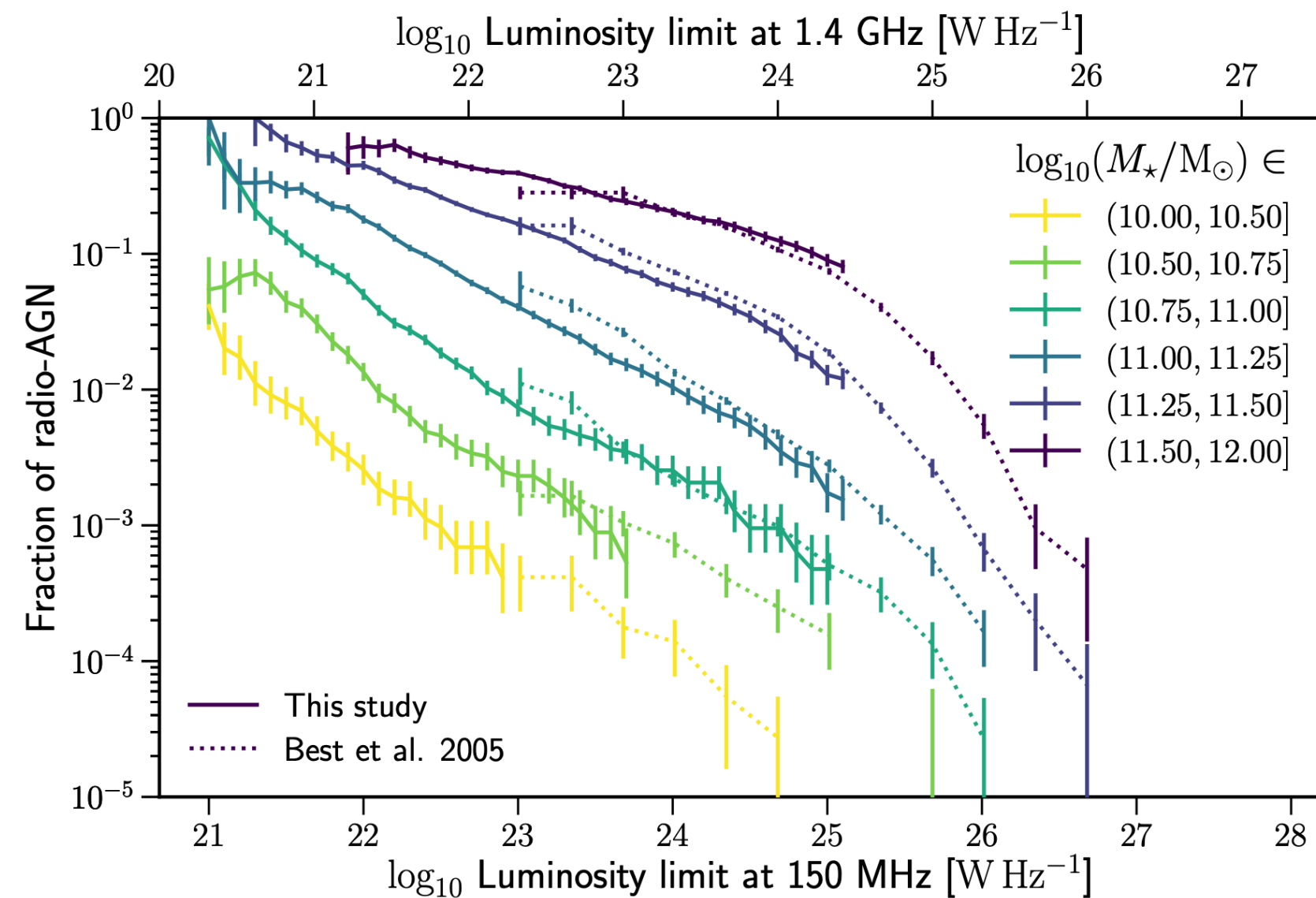
Normalise by $L_{\text{Eddington}}$ so that you
can consider all galaxies belonging
to the same population and the
relative fractions can be directly
linked to the time spent by the AGN
at each accretion rate (duty cycle).



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

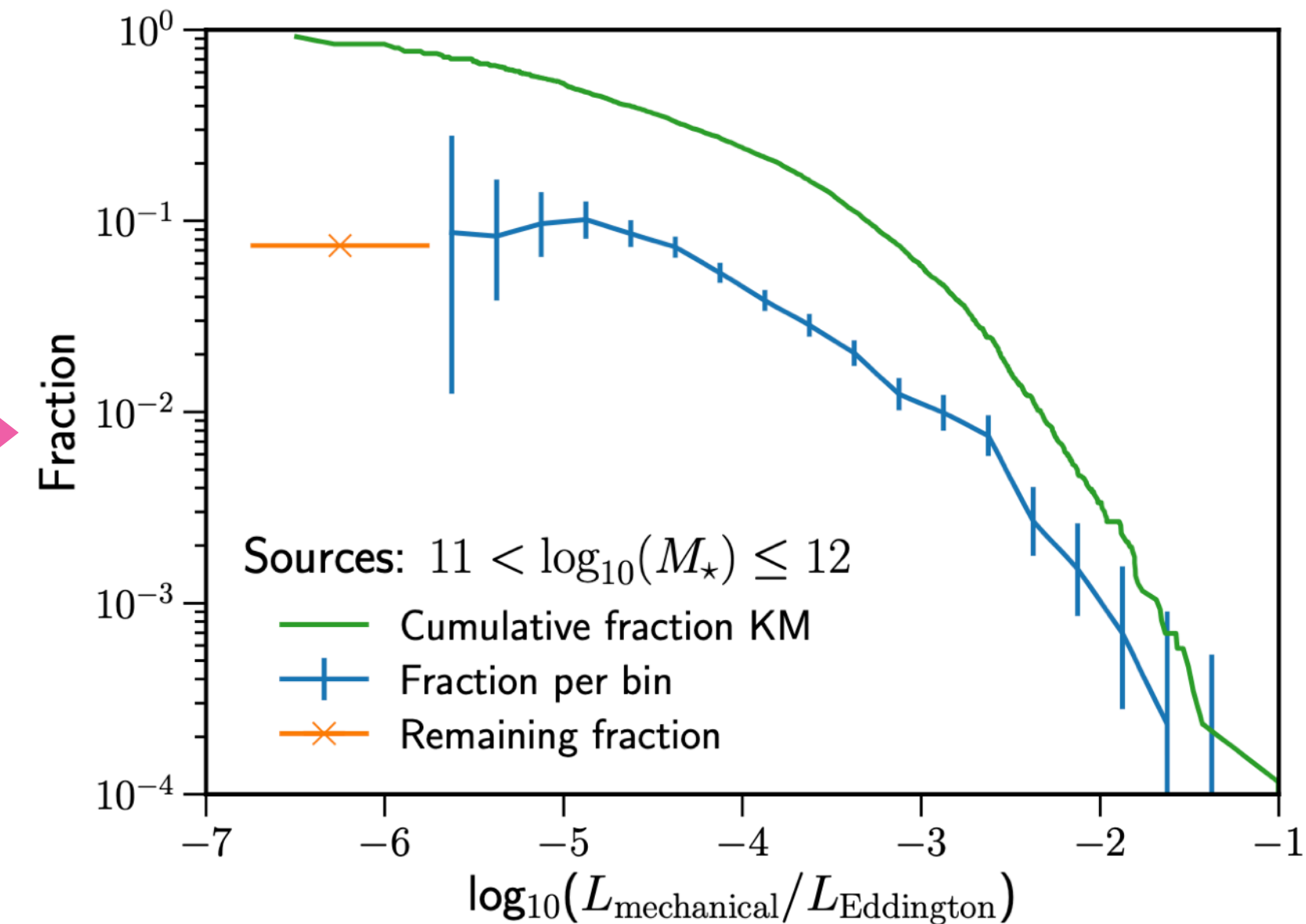


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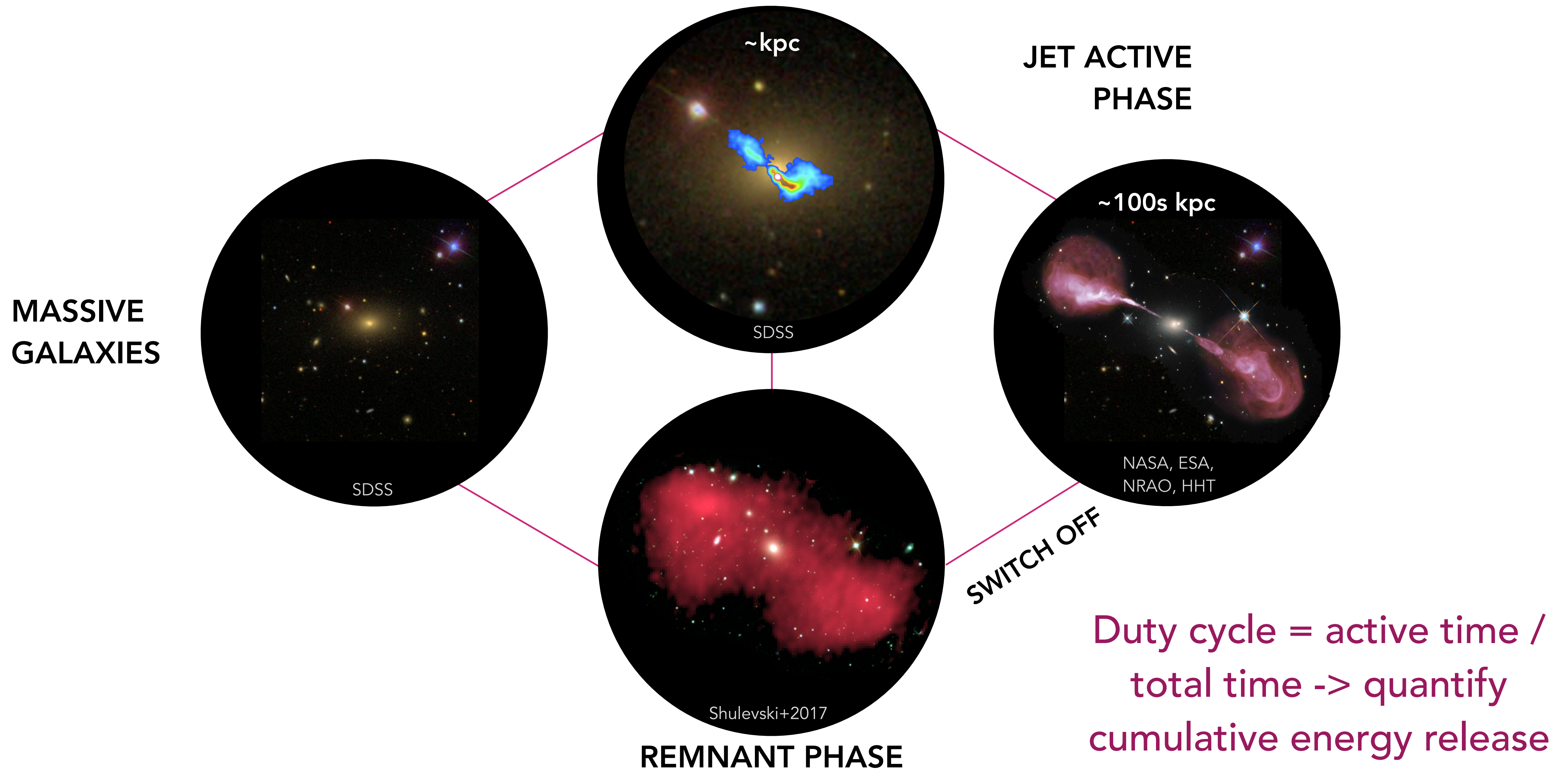


This is why knowing JET POWER matters!

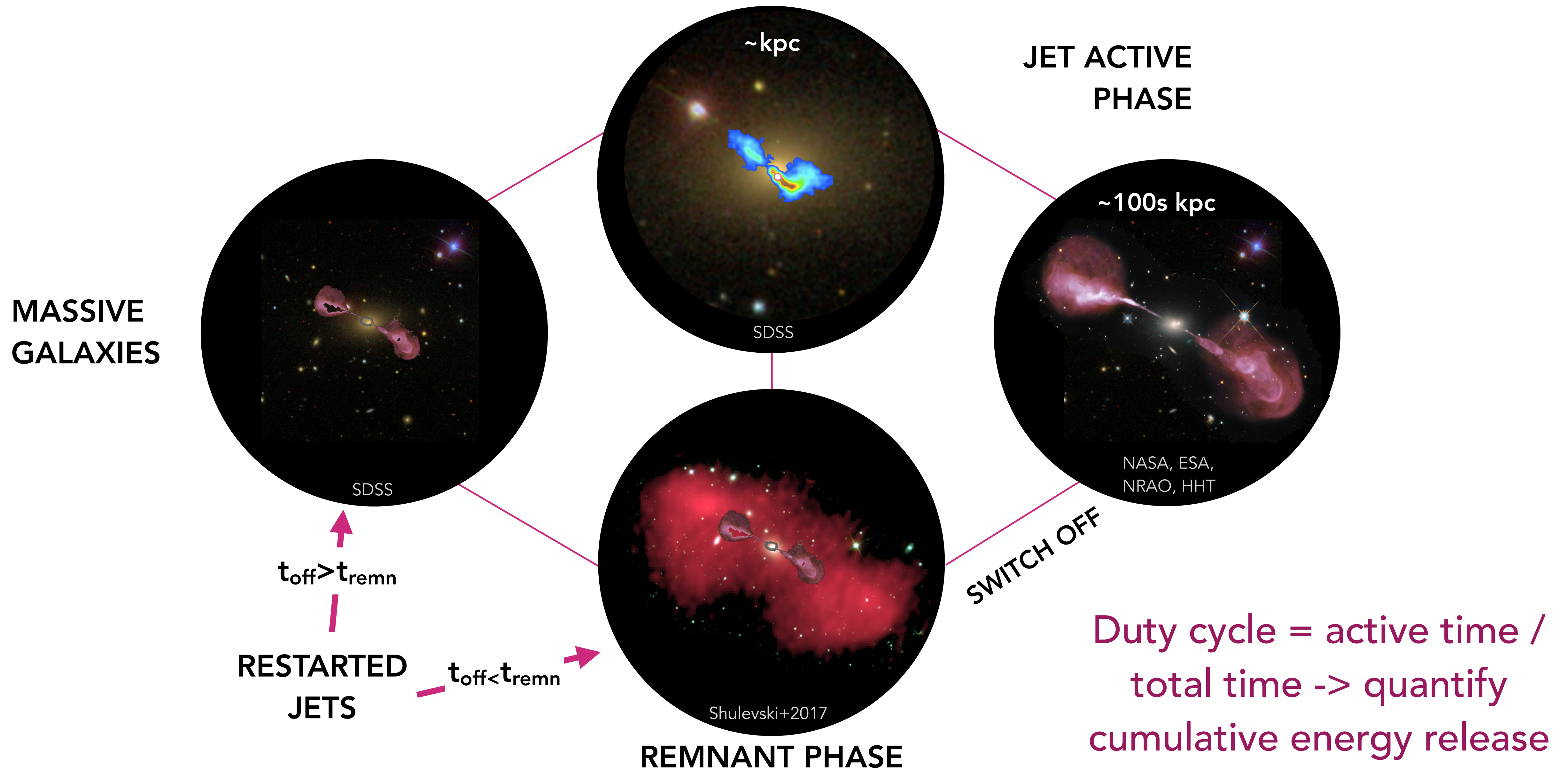
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The life cycle (and duty cycle) of jets

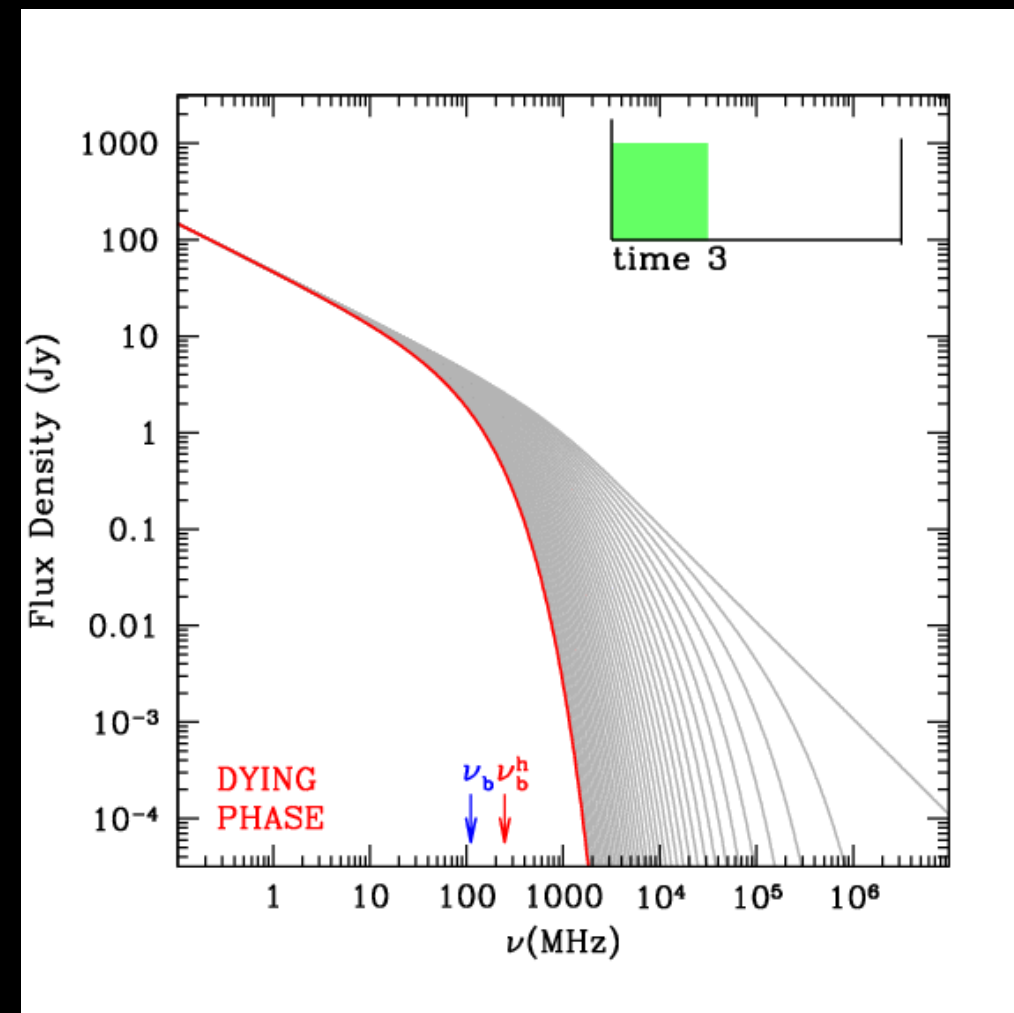
The life-cycle of AGN jets



The life-cycle of AGN jets



Remnant plasma evolution

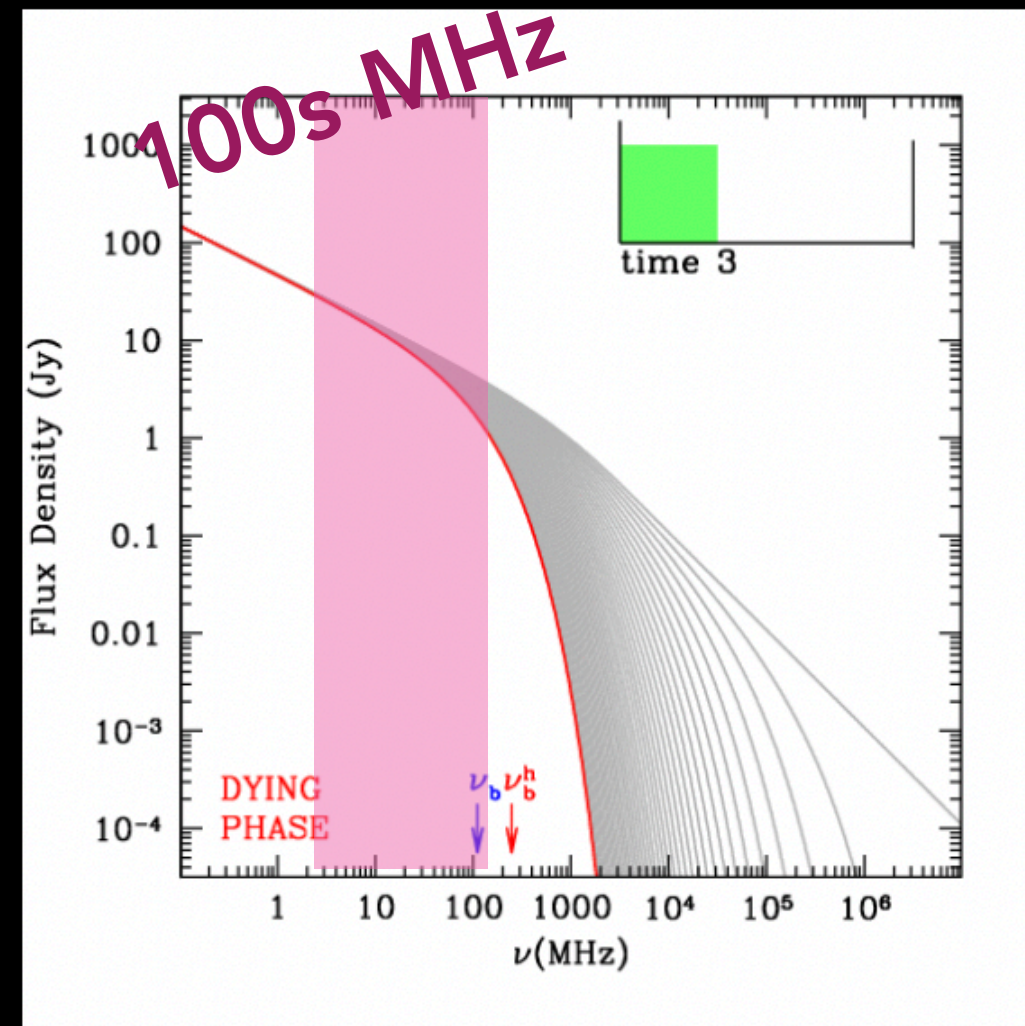


Courtesy of M. Murgia

Radiative losses

(depend on magnetic field, redshift)

Remnant plasma evolution



Courtesy of M. Murgia

Radiative losses

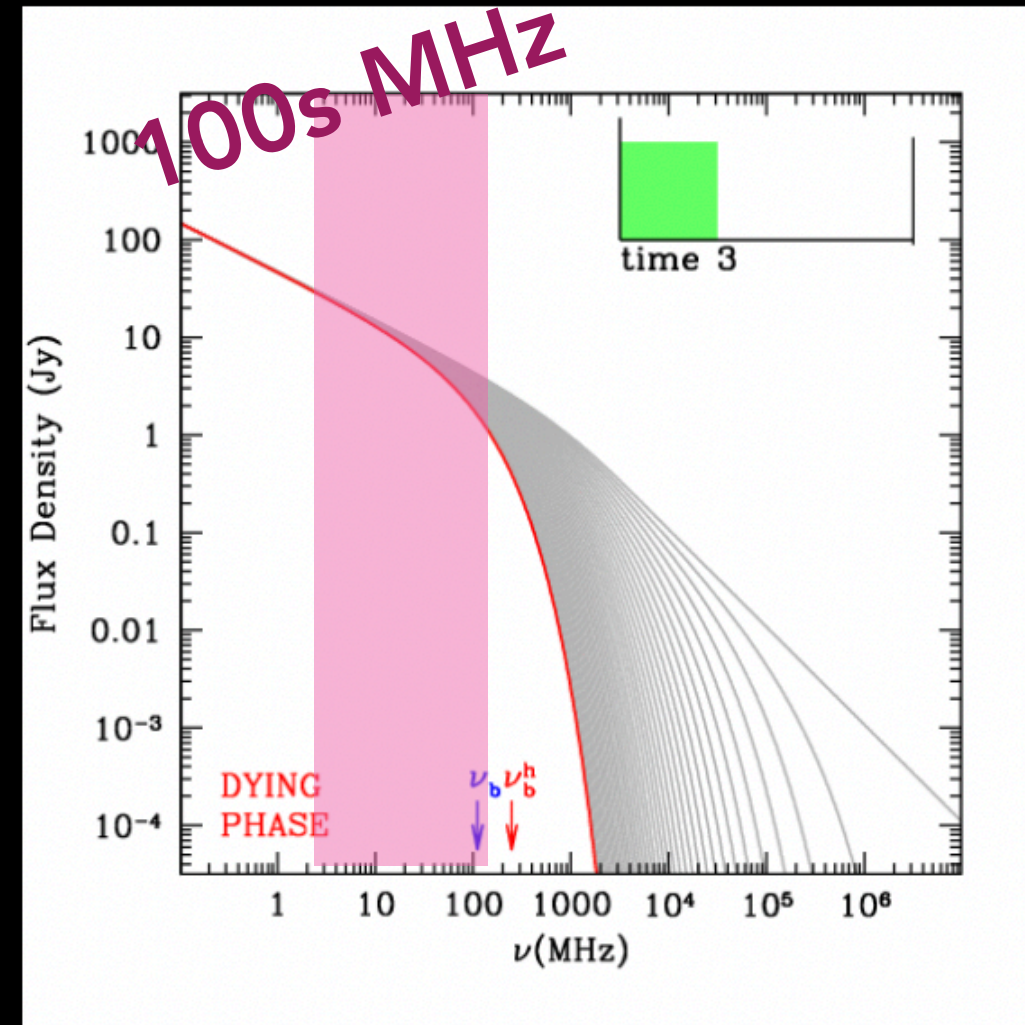
(depend on magnetic field, redshift)



Expansion losses

(depend on jet power,
external gas density)

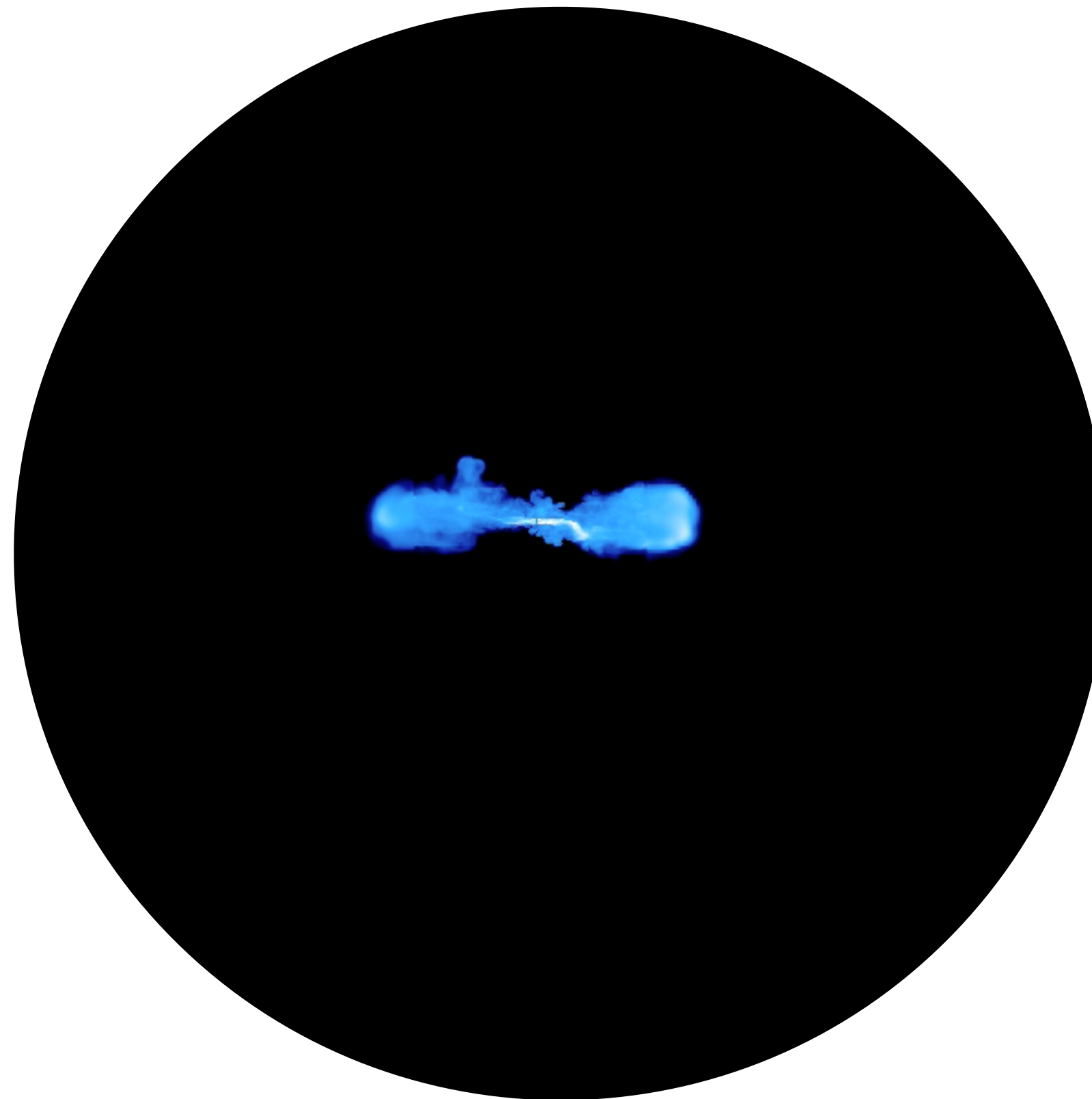
Remnant plasma evolution



Courtesy of M. Murgia

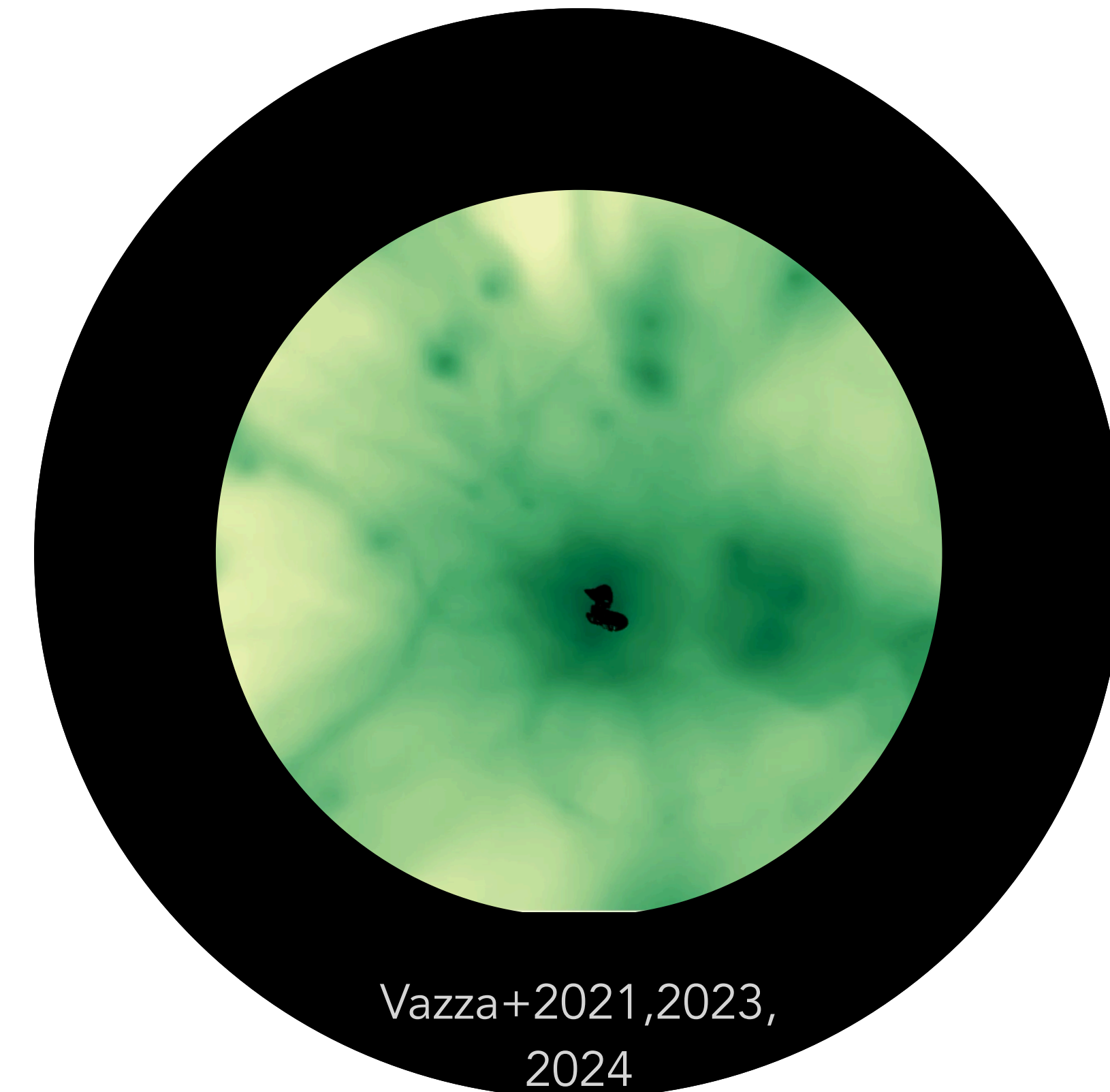
Radiative losses

(depend on magnetic field, redshift)



Expansion losses

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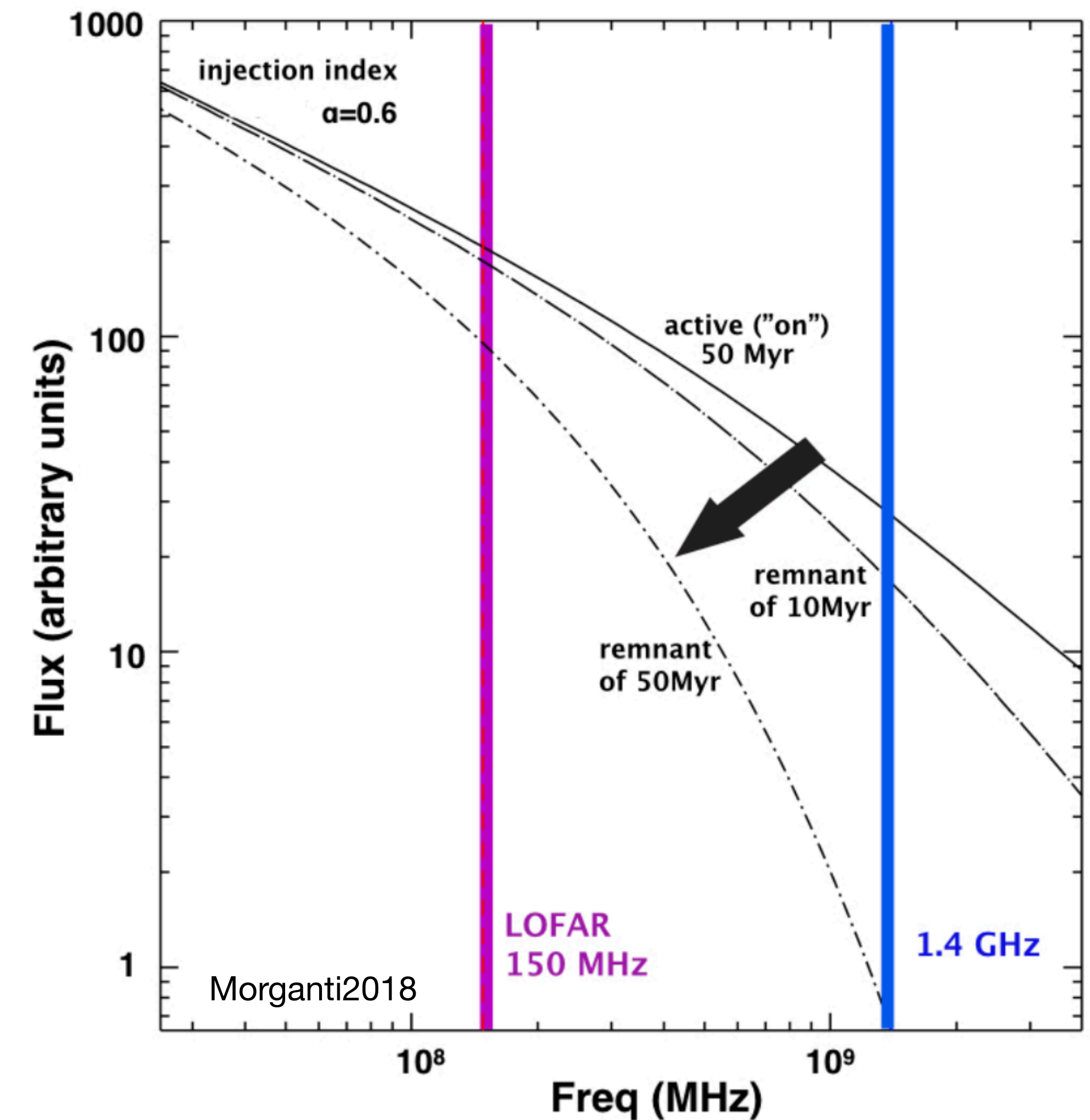


Vazza+2021,2023,
2024

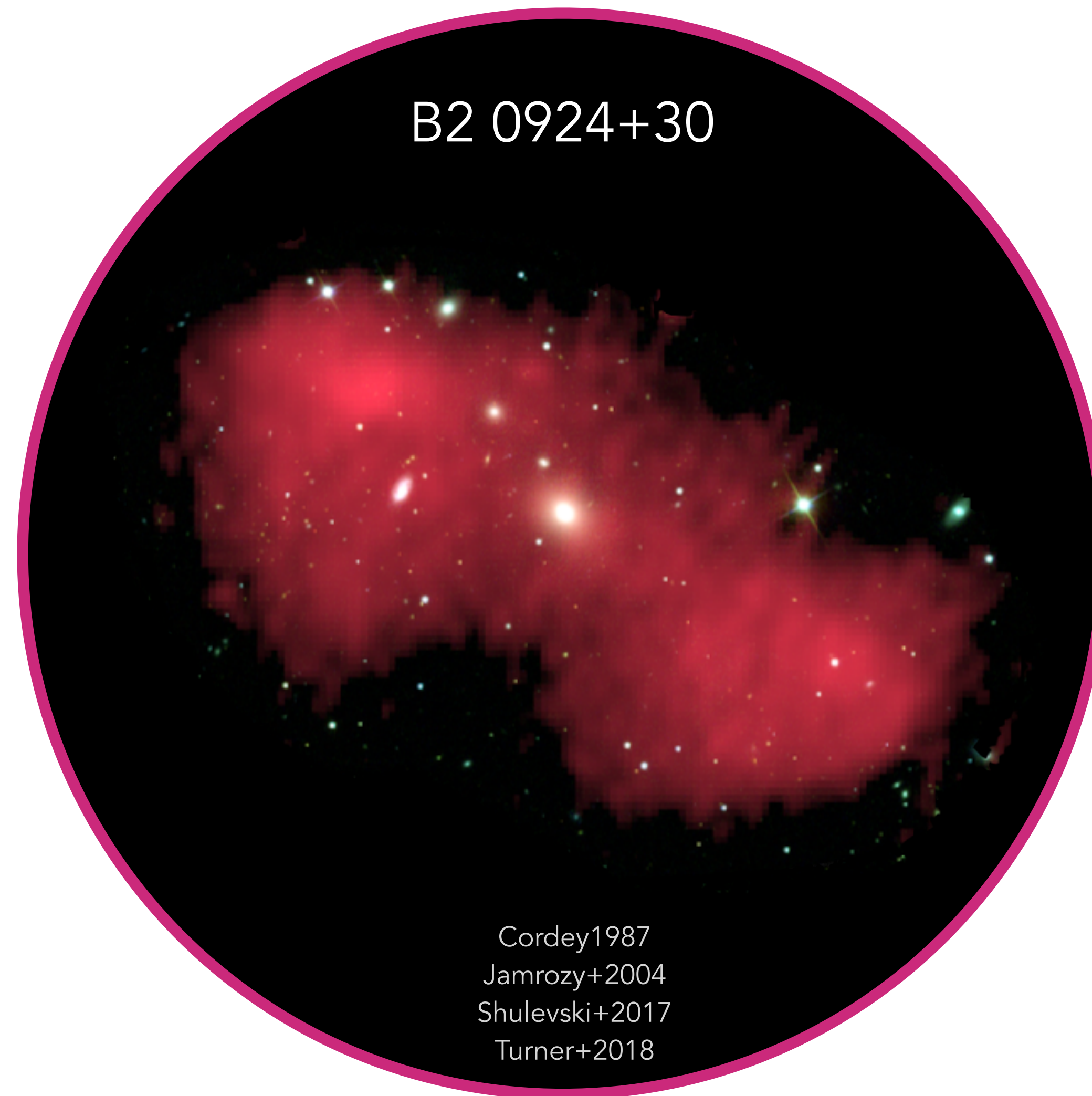
Disruption by dynamics of large scale environment

Advances with SKA precursors/pathfinders

Low radio frequencies ($< \sim 1$ GHz)
sensitive to extended optically thin lobes,
especially the oldest emitting particles



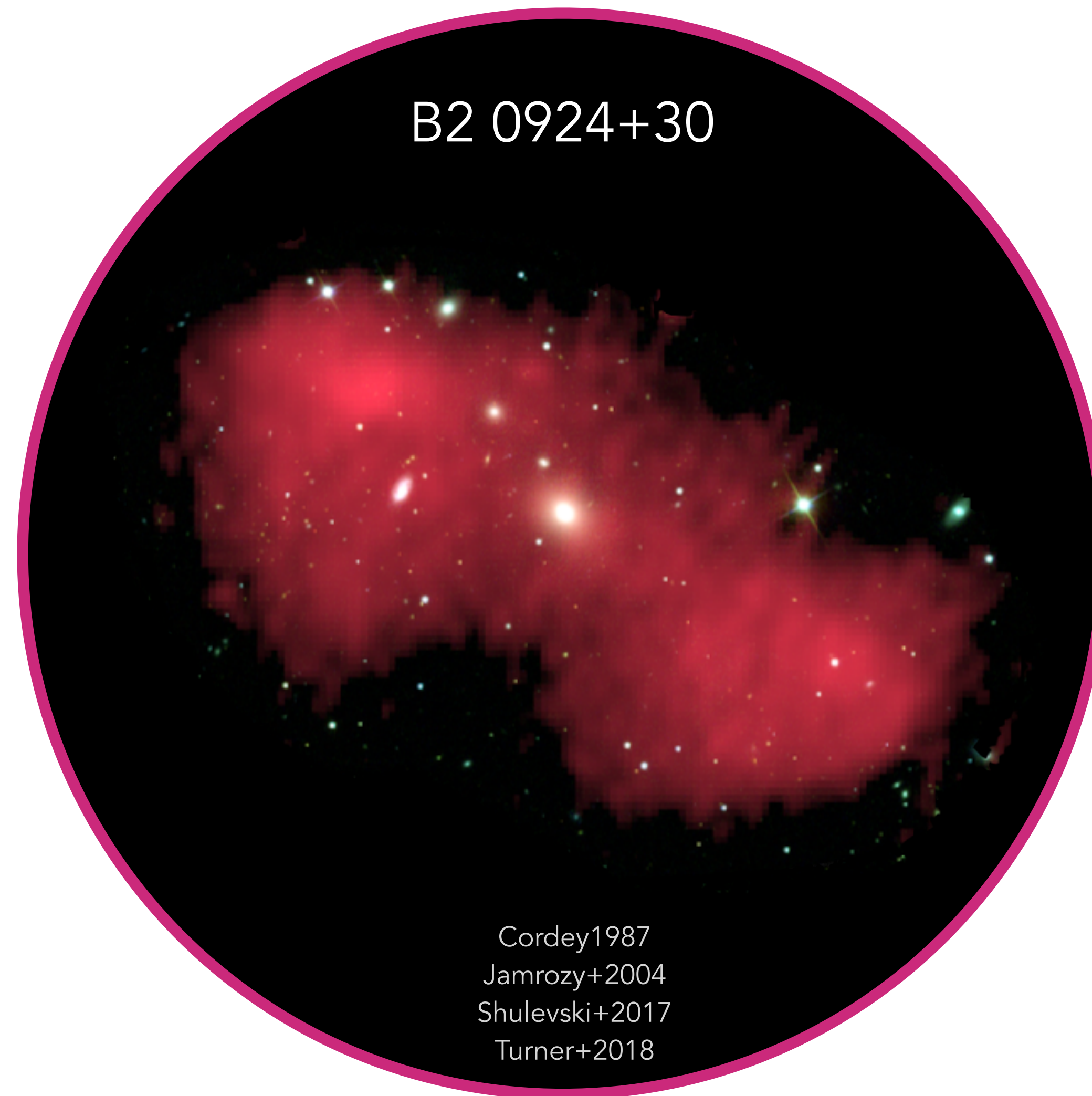
Remnant radio galaxies



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



Classically:

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- Relaxed morphology
- Low surface brightness
- Ultra steep spectra
(USS, $\alpha > 1.2$)
- Curved spectrum
(SPC, $\alpha > 0.5$)

but ... depends on frequency and resolution

The challenge of selecting AGN remnants

Selection criteria:

- **Ultra steep spectrum (USS, $\alpha > 1.2$)**
- Spectral curvature ($\alpha_{\text{high}} - \alpha_{\text{low}} > 0.5$)
- Core prominence
- Morphology

The challenge of selecting AGN remnants

Selection criteria:

- **Ultra steep spectrum (USS, $\alpha > 1.2$)**
- Spectral curvature ($\alpha_{\text{high}} - \alpha_{\text{low}} > 0.5$)
- Core prominence
- Morphology

1

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

LOFAR LoTSS 150 MHz noise $\sim 100 \mu\text{Jy/b}$ @ 6"



$\alpha > 1.2$



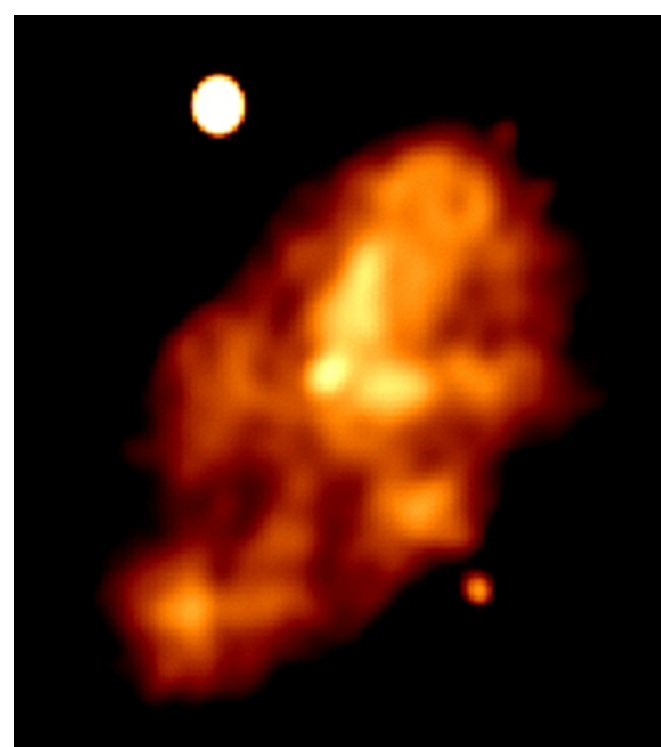
1.4 GHz noise $< 20 \mu\text{Jy/b}$

2

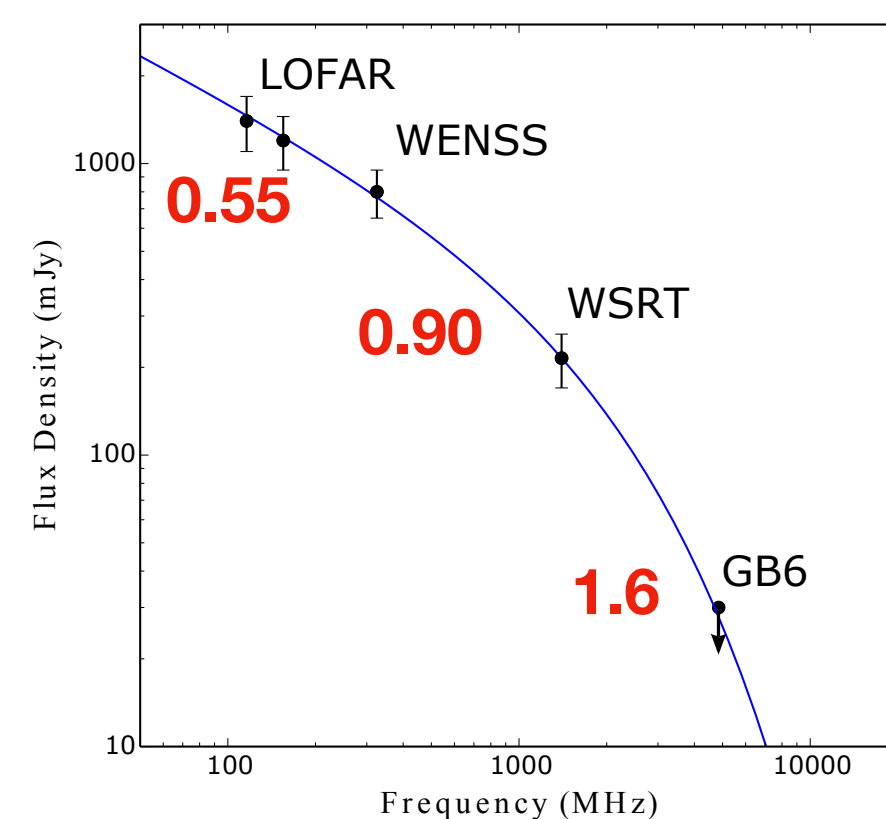
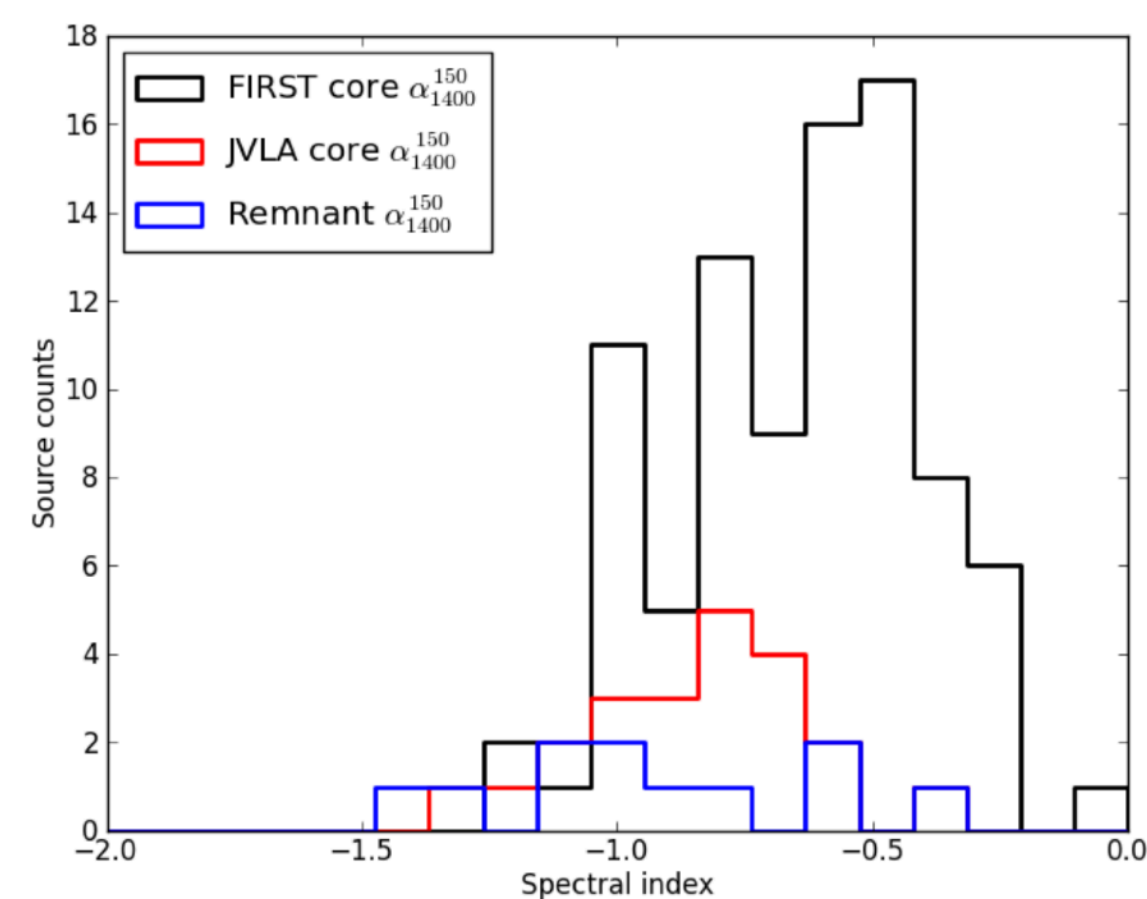
The challenge of selecting AGN remnants

Not always ultra-steep >1.2

OBSERVATIONS



Brienza+2016



Mahatma+2018

But also.. e.g.

Hurley-Walker+2015, Duchesne&Jhonston-Hollit+2019, Quici+2021

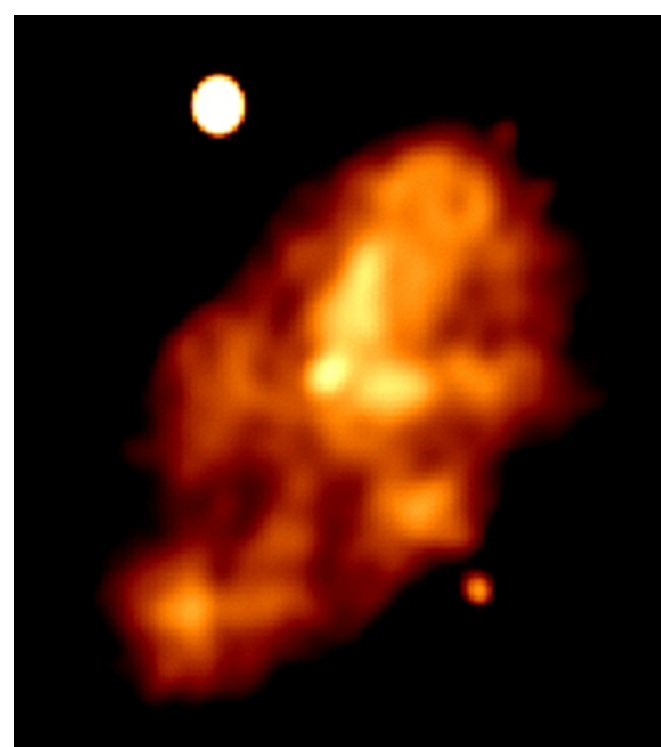
Randriamanakoto+2020, Lal+2021, Tamhane+2015, Jurlin+2021, Dutta+2023

2

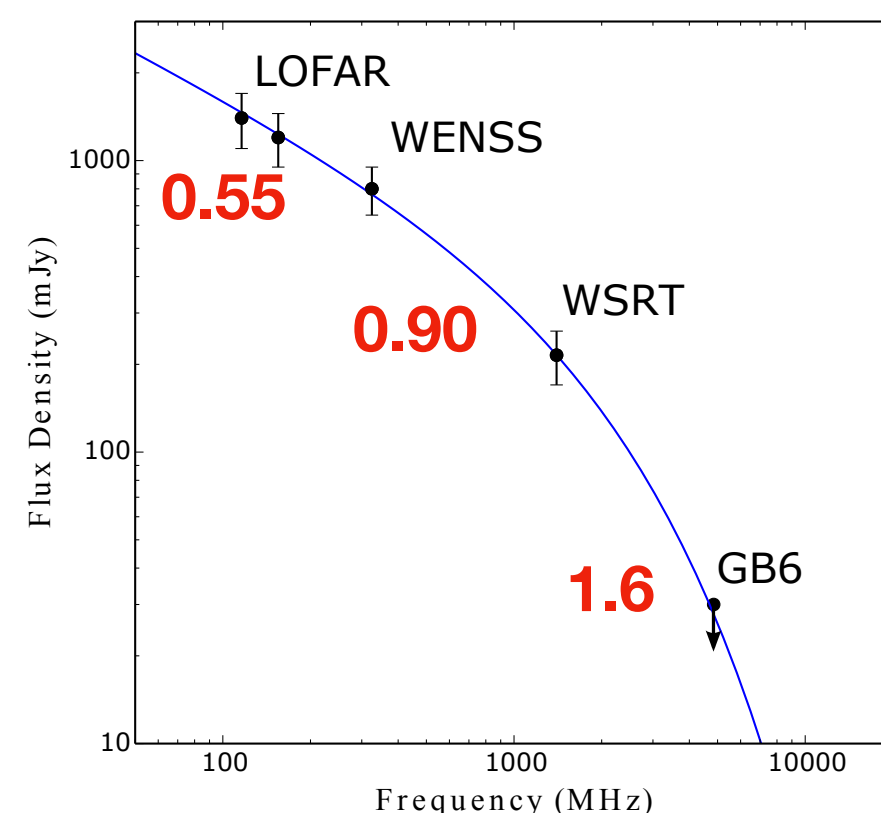
The challenge of selecting AGN remnants

Not always ultra-steep >1.2

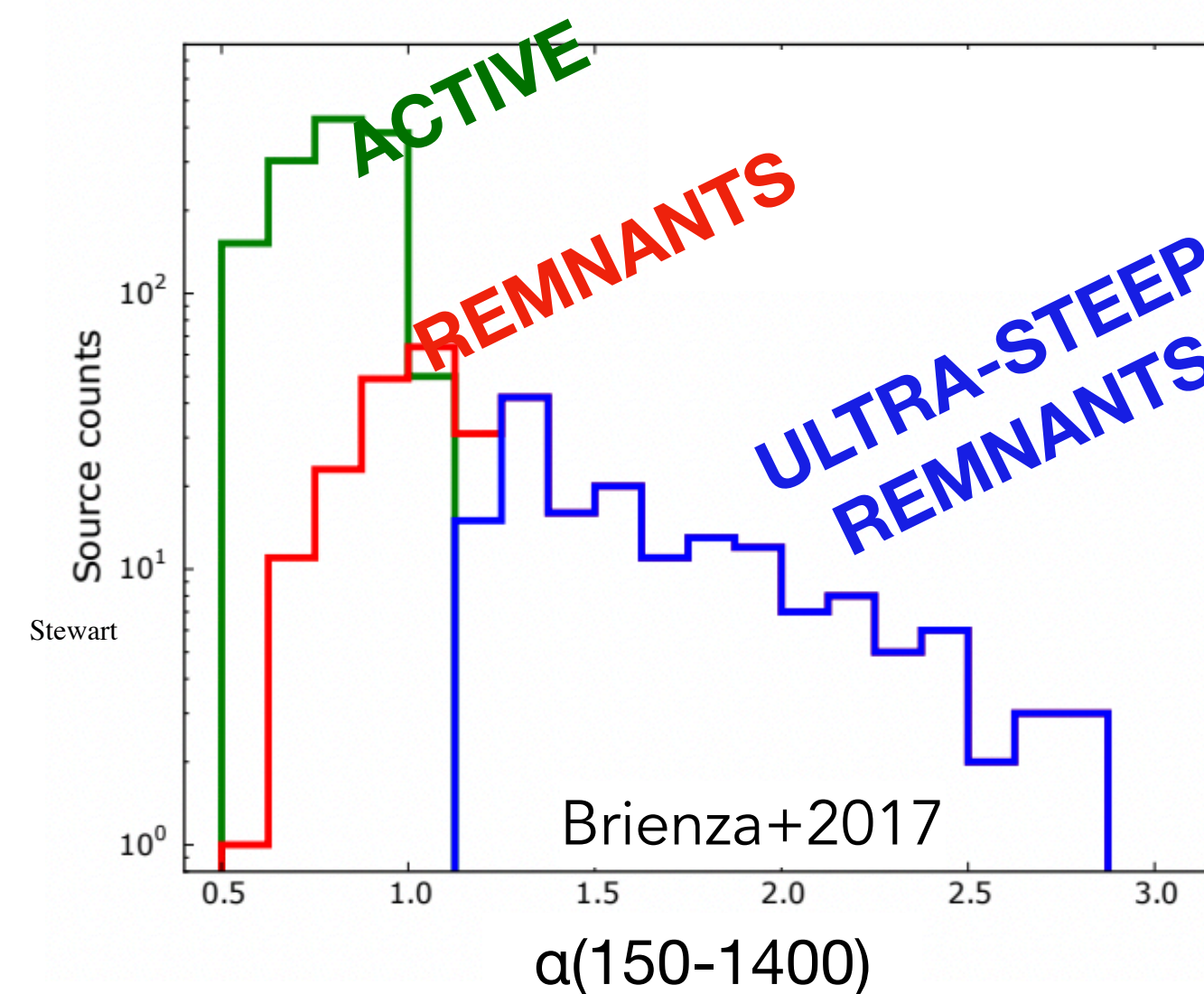
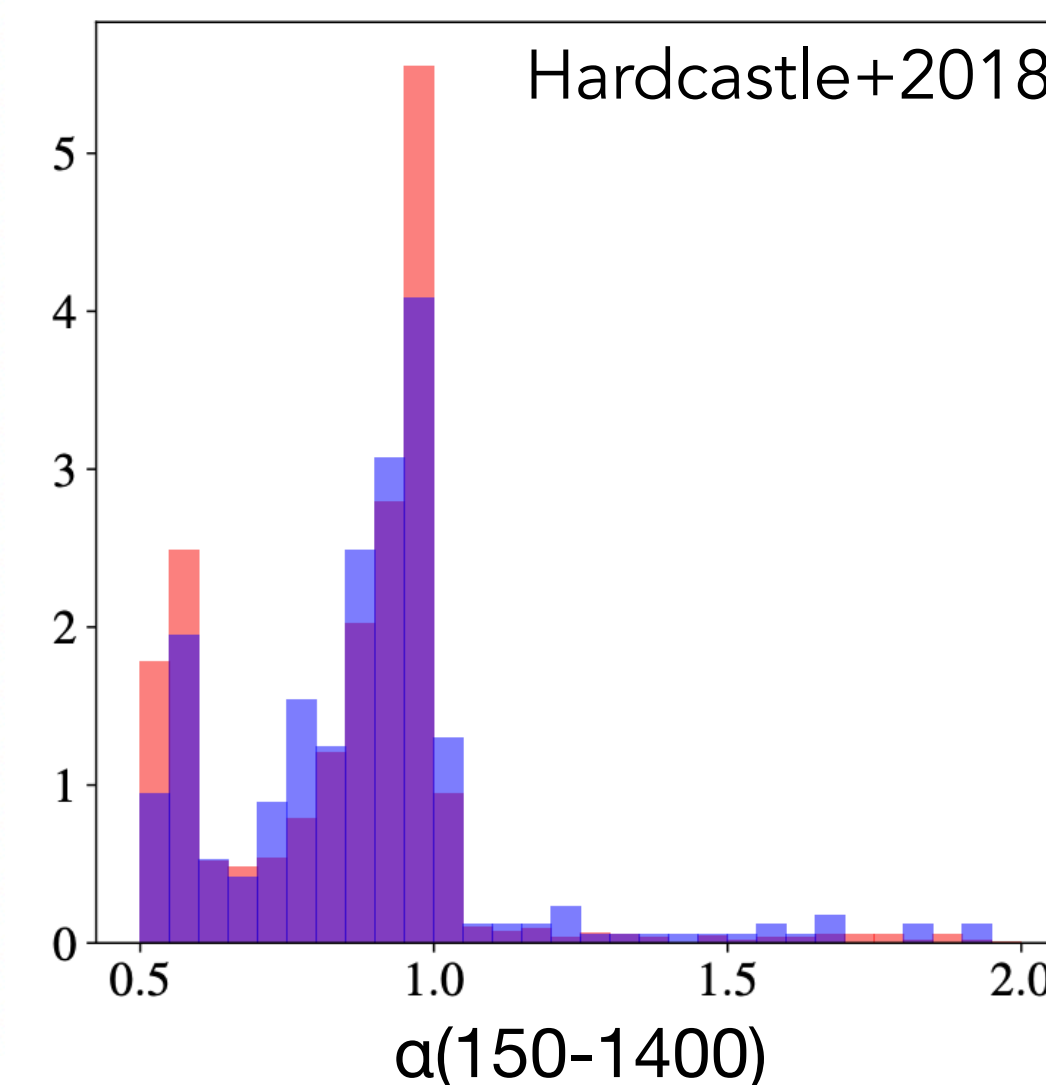
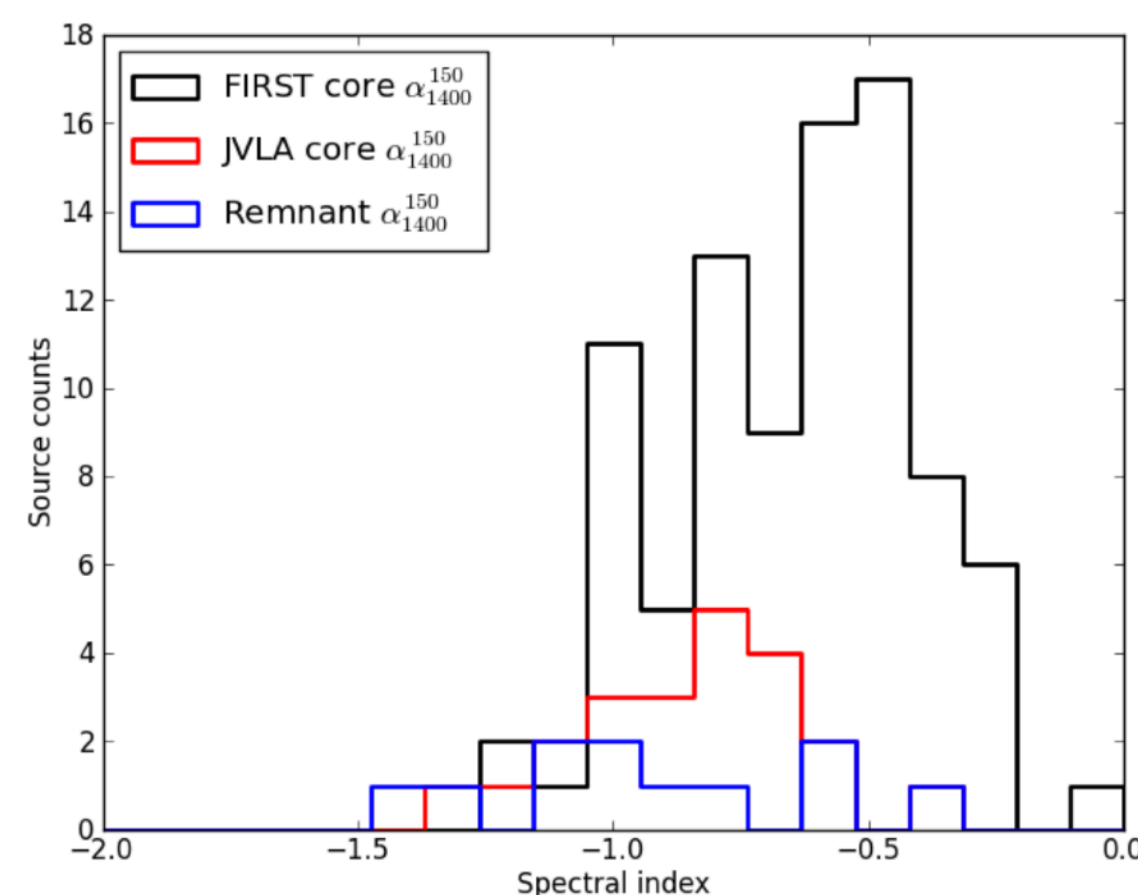
OBSERVATIONS



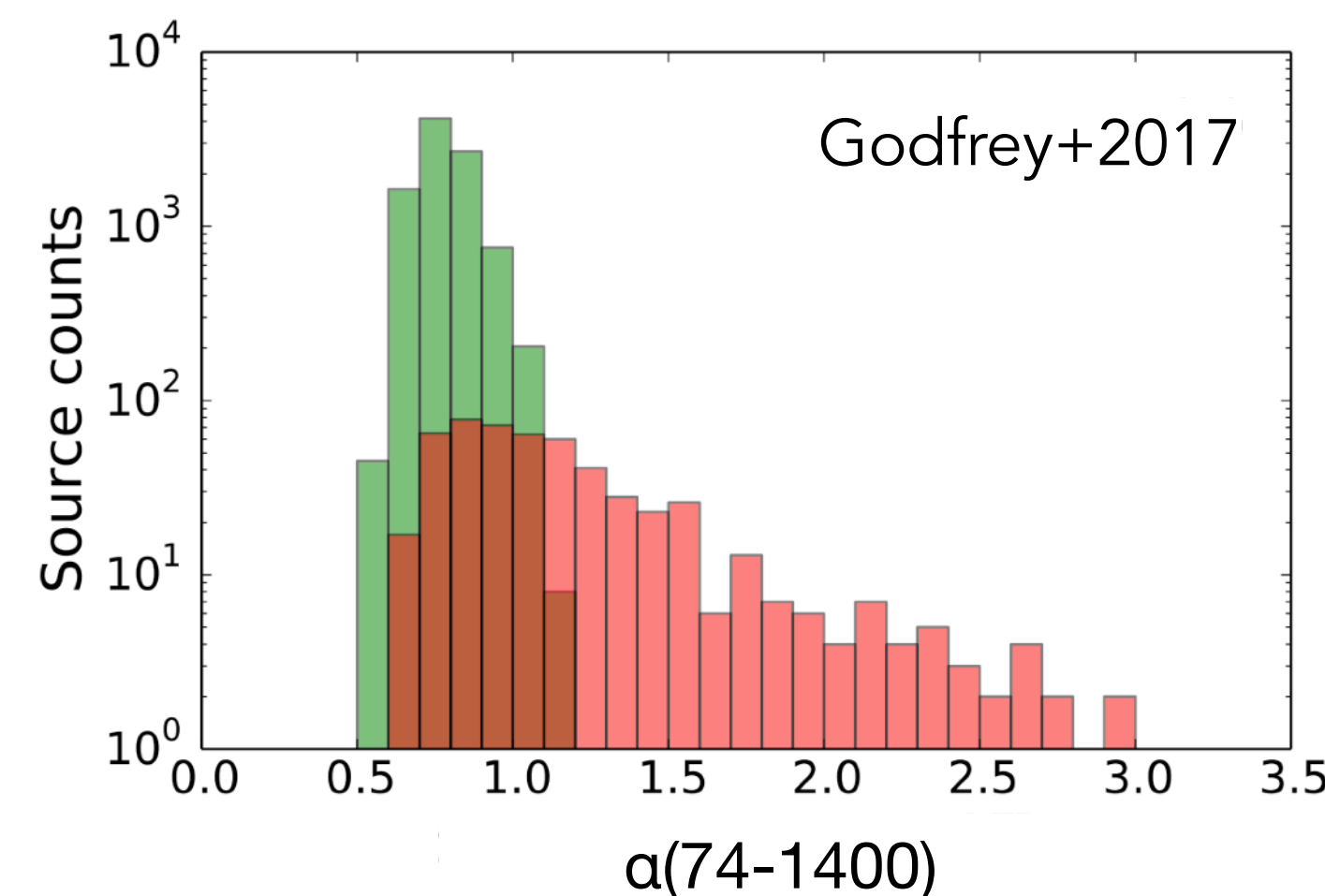
Brienza+2016



SIMULATIONS



Mahatma+2018



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

But also.. e.g.

Hurley-Walker+2015, Duchesne&Jhonston-Hollit+2019, Quici+2021

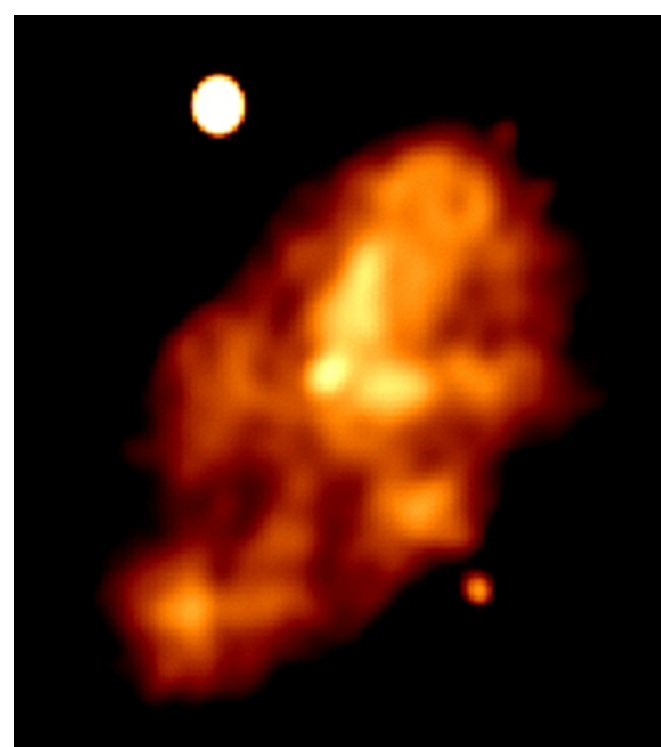
Randriamanakoto+2020, Lal+2021, Tamhane+2015, Jurlin+2021, Dutta+2023

2

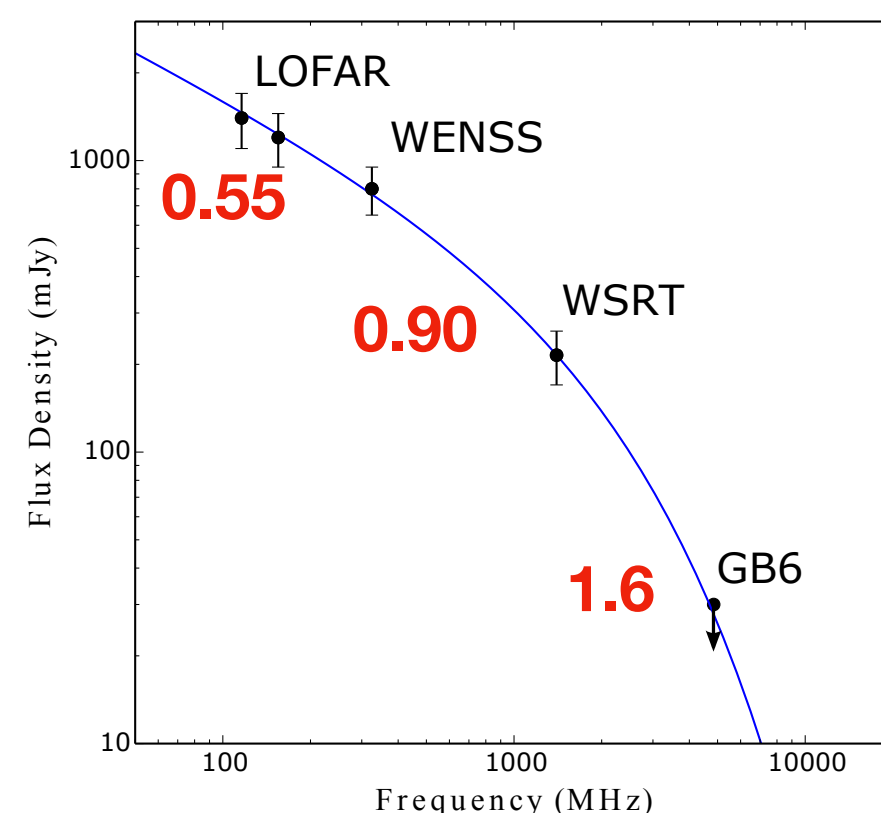
The challenge of selecting AGN remnants

Not always ultra-steep >1.2

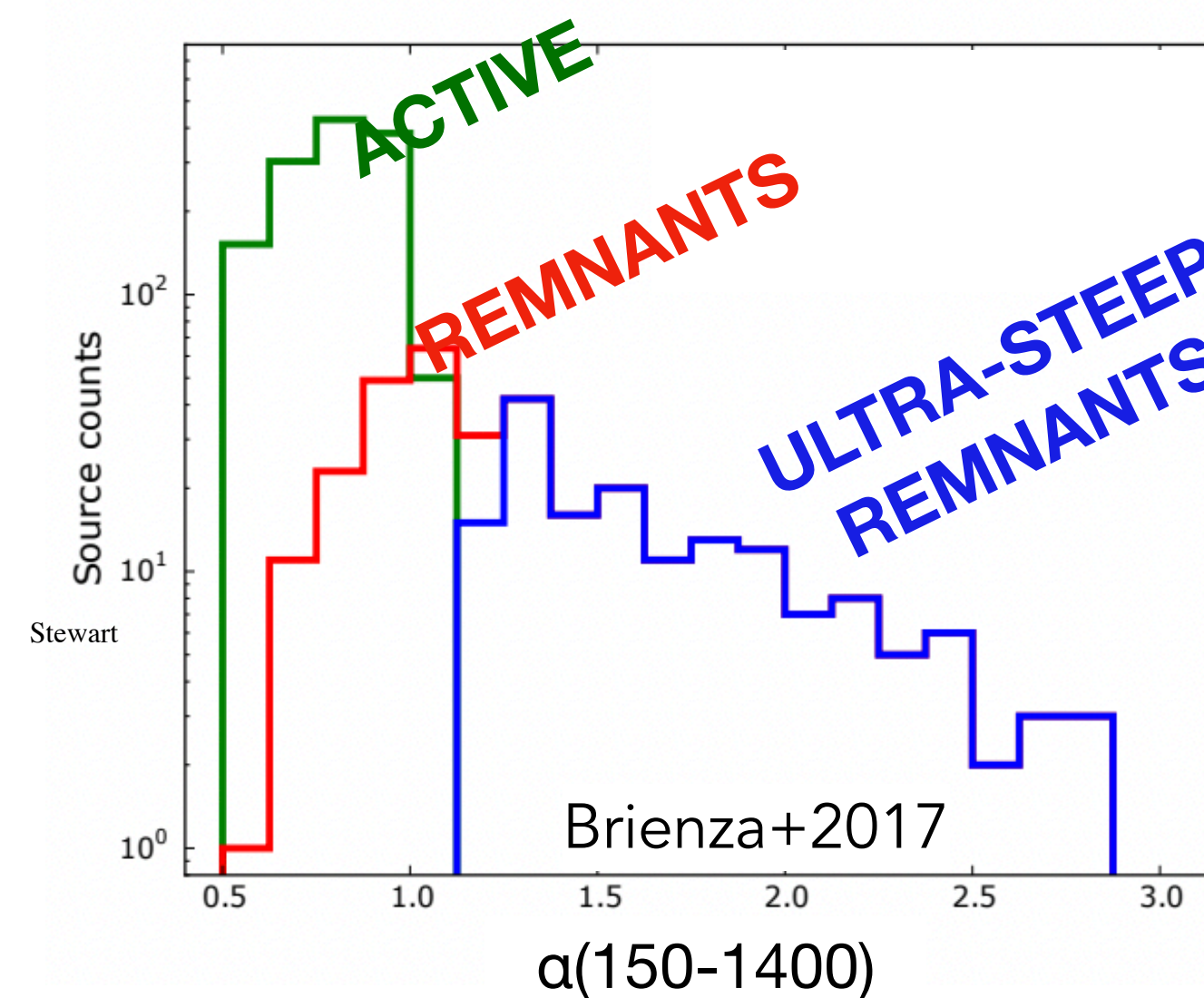
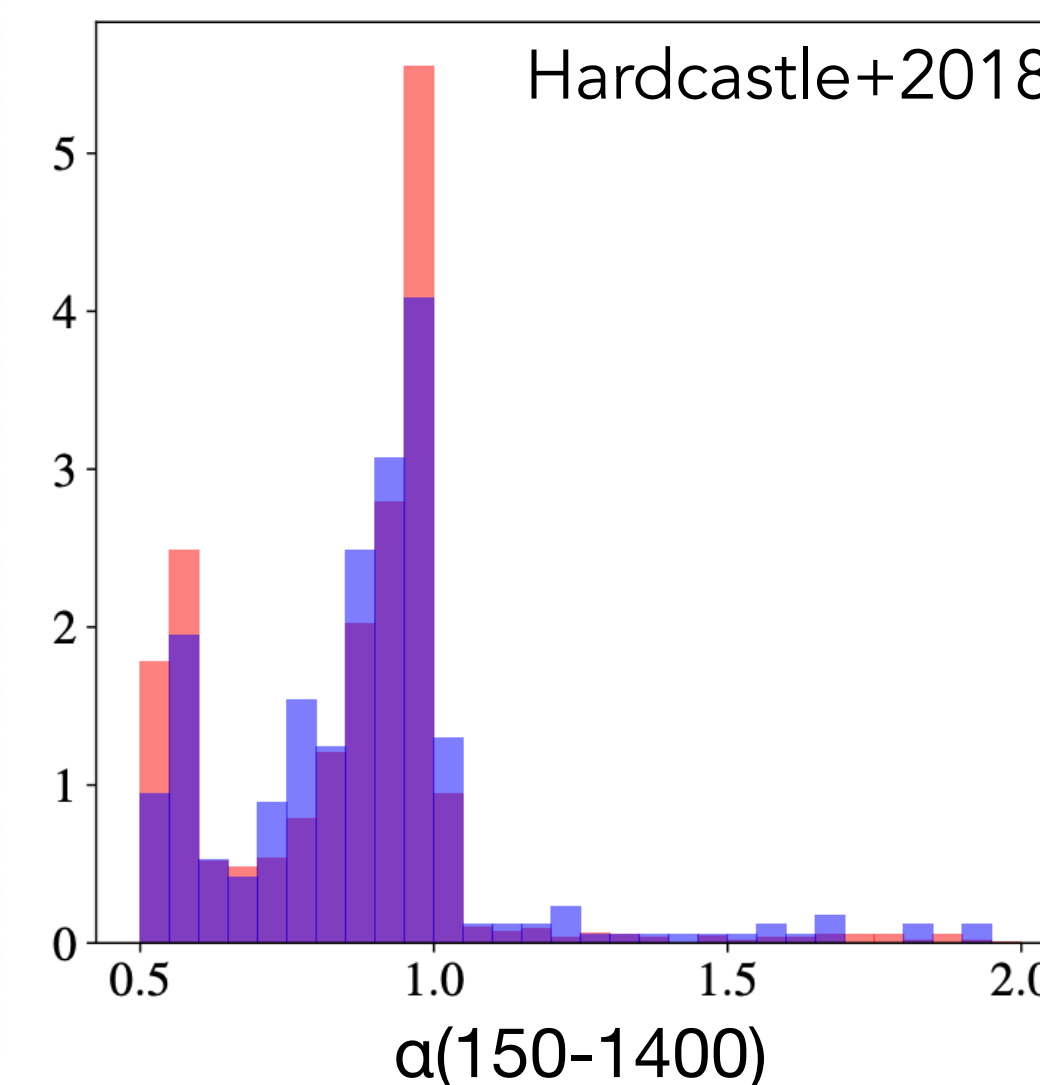
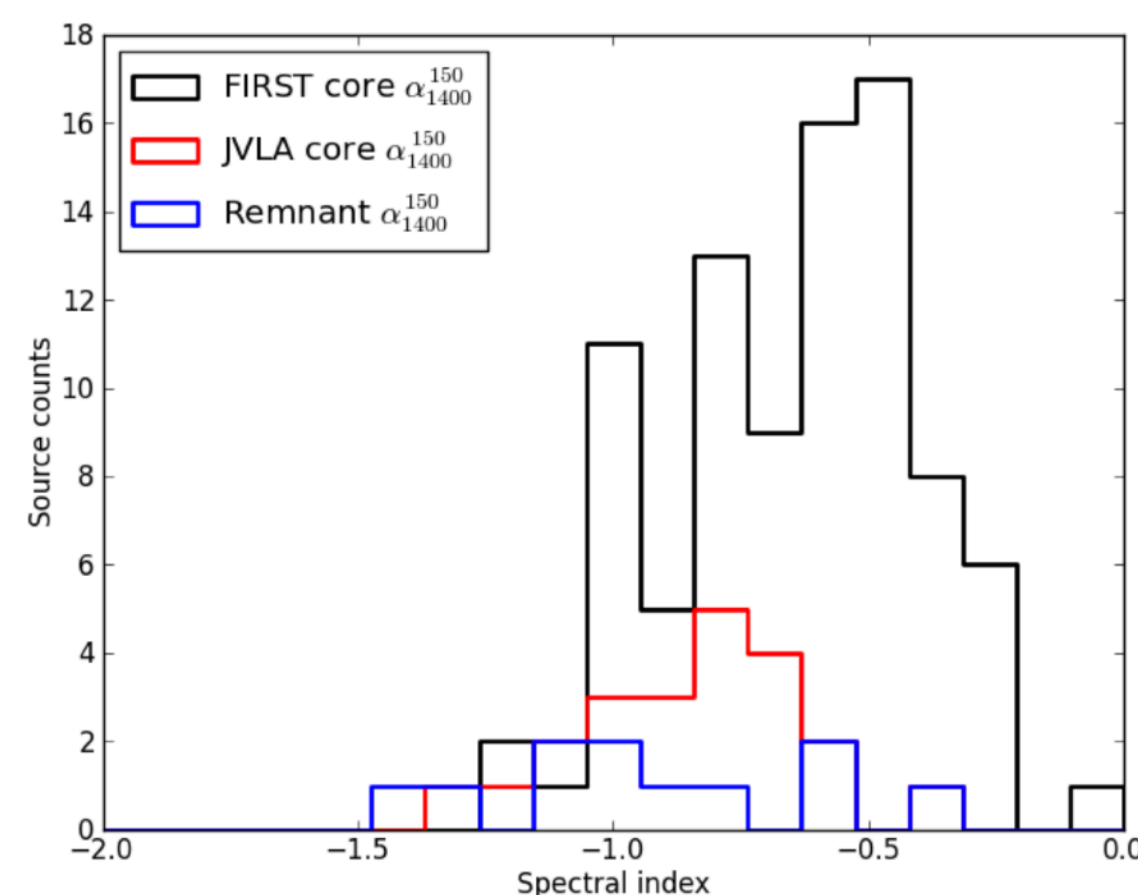
OBSERVATIONS



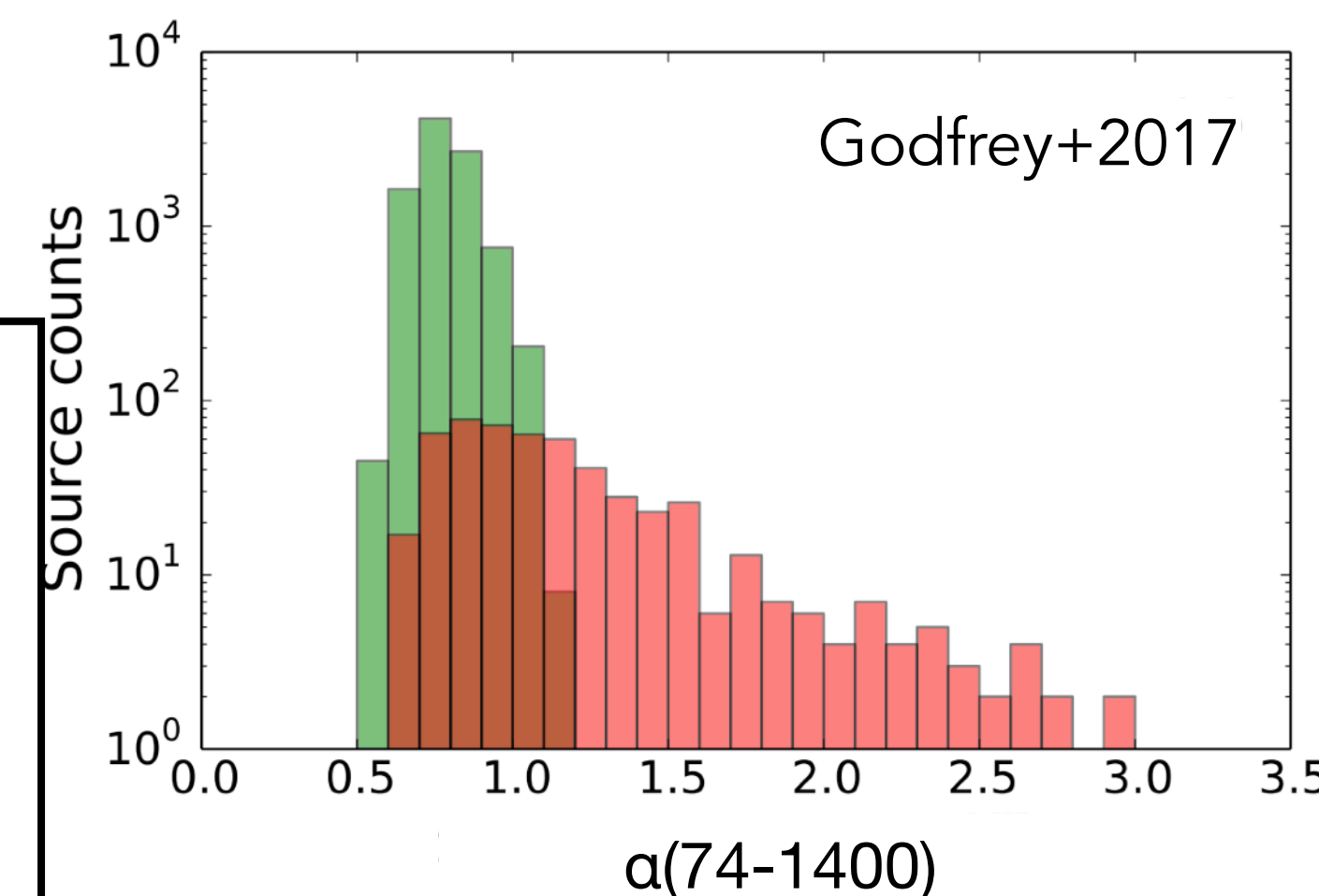
Brienza+2016



SIMULATIONS



Mahatma+2018



Need to combine
spectral and
morphological
criteria!

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

But also.. e.g.

Hurley-Walker+2015, Duchesne&Jhonston-Hollit+2015

Randriamanakoto+2020, Lal+2021, Tamhane+2015, Ju

The challenge of selecting AGN remnants

Murgia+2011

Parma+2007

Saripalli+2012



5 remnants



6 remnants



~30 remnants/restarted

Ultra steep α + SPC

The challenge of selecting AGN remnants

Murgia+2011

Parma+2007

Saripalli+2012

....

e.g.

Godfrey+2017

Brienza+2017, Jurlin+2022

Mahatma+2018

Quici+2025

Quici+2020

Dutta+2023

Jurlin+2021

Nair+2024

Morganti+2021

Mostert+2023

Capetti+2022, Capetti&Brienza2023

And many more single object studies

→ 5 remnants
→ 6 remnants
→ ~30 remnants/restarted

→ ~60 remnants
→ 13 remnants
→ 11 remnants
→ 79 remnants
→ 10 remnants
→ 21 remnants
→ 22 restarted
→ 69 restarted core
→ 15 remnants + restarted

Ultra steep α + SPC

Core prominence

Morphology

Resolved spectra

Machine learning

The challenge of selecting AGN remnants

Murgia+2011

Parma+2007

Saripalli+2012

....

e.g.

Godfrey+2017

Brienza+2017, Jurlin+2022

Mahatma+2018

Quici+2025

Quici+2020

Dutta+2023

Jurlin+2021

Nair+2024

Morganti+2021

Mostert+2023

Capetti+2022, Capetti&Brienza2023

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Ultra steep α + SPC

Core prominence

Morphology

Resolved spectra

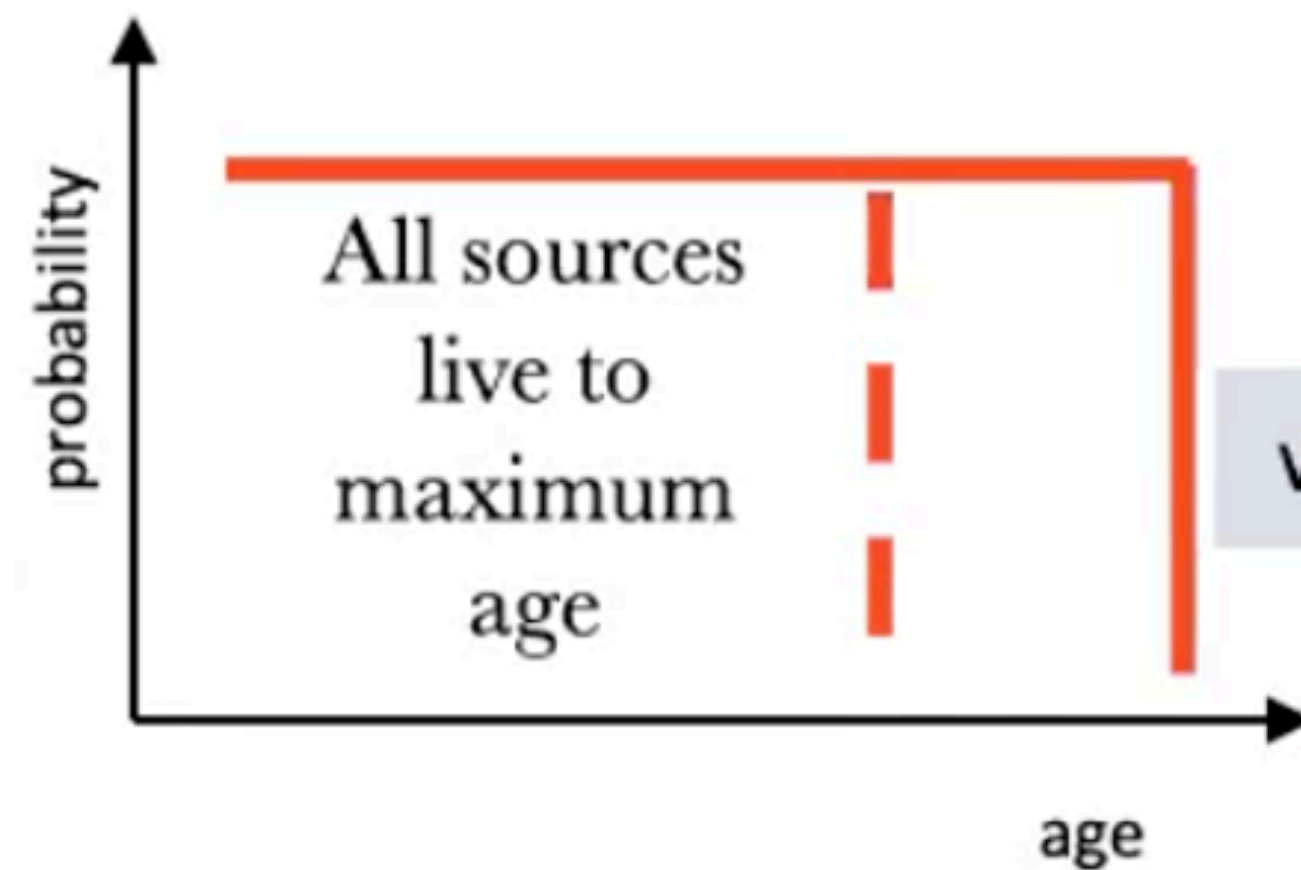
Machine learning

From few up to ~20% of radio sources.
Complete samples remain challenging!

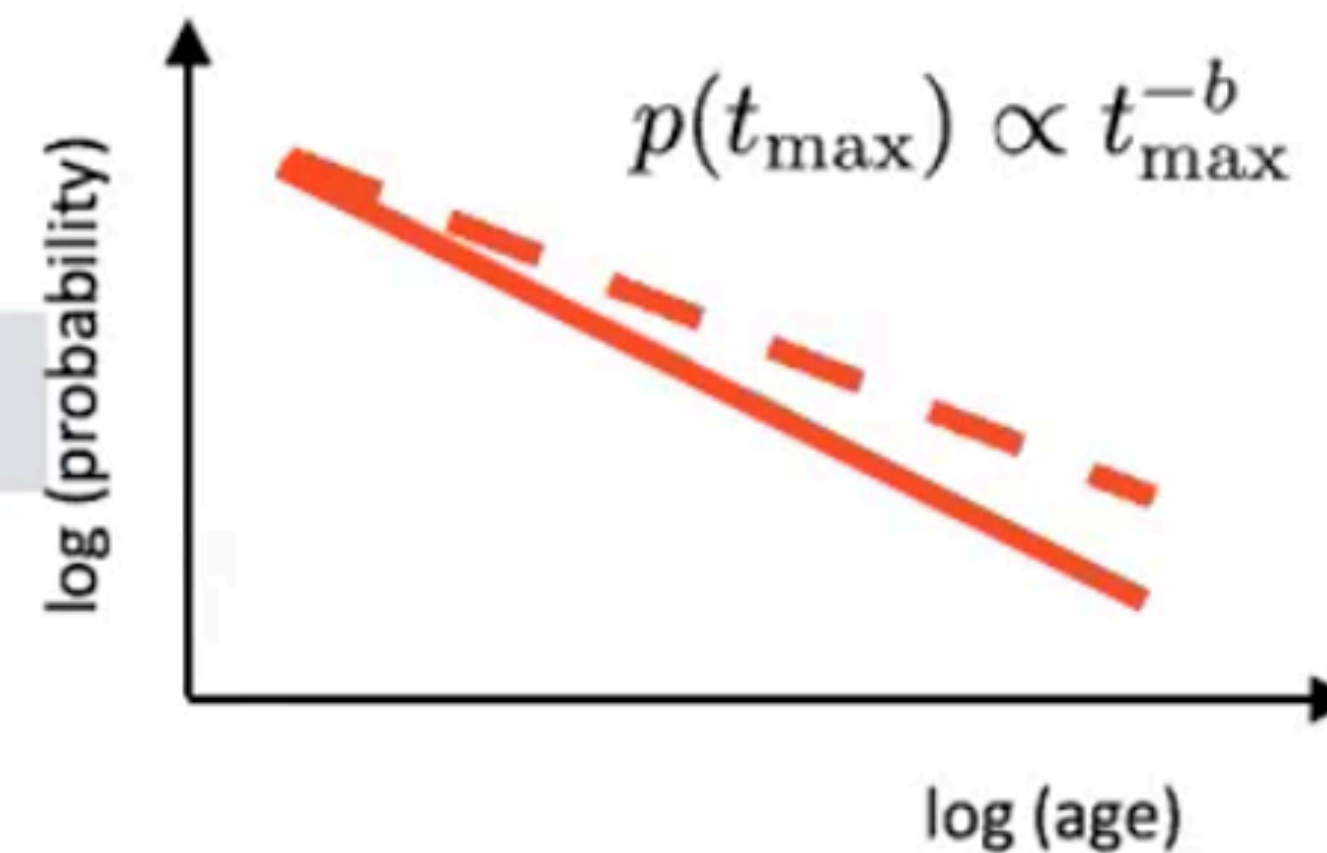
WHY searches and samples of remnants and restarted

Constrain models (e.g. jet duration)

Shabala+2020



vs



Constraints: distributions in
angular size
flux density
redshift

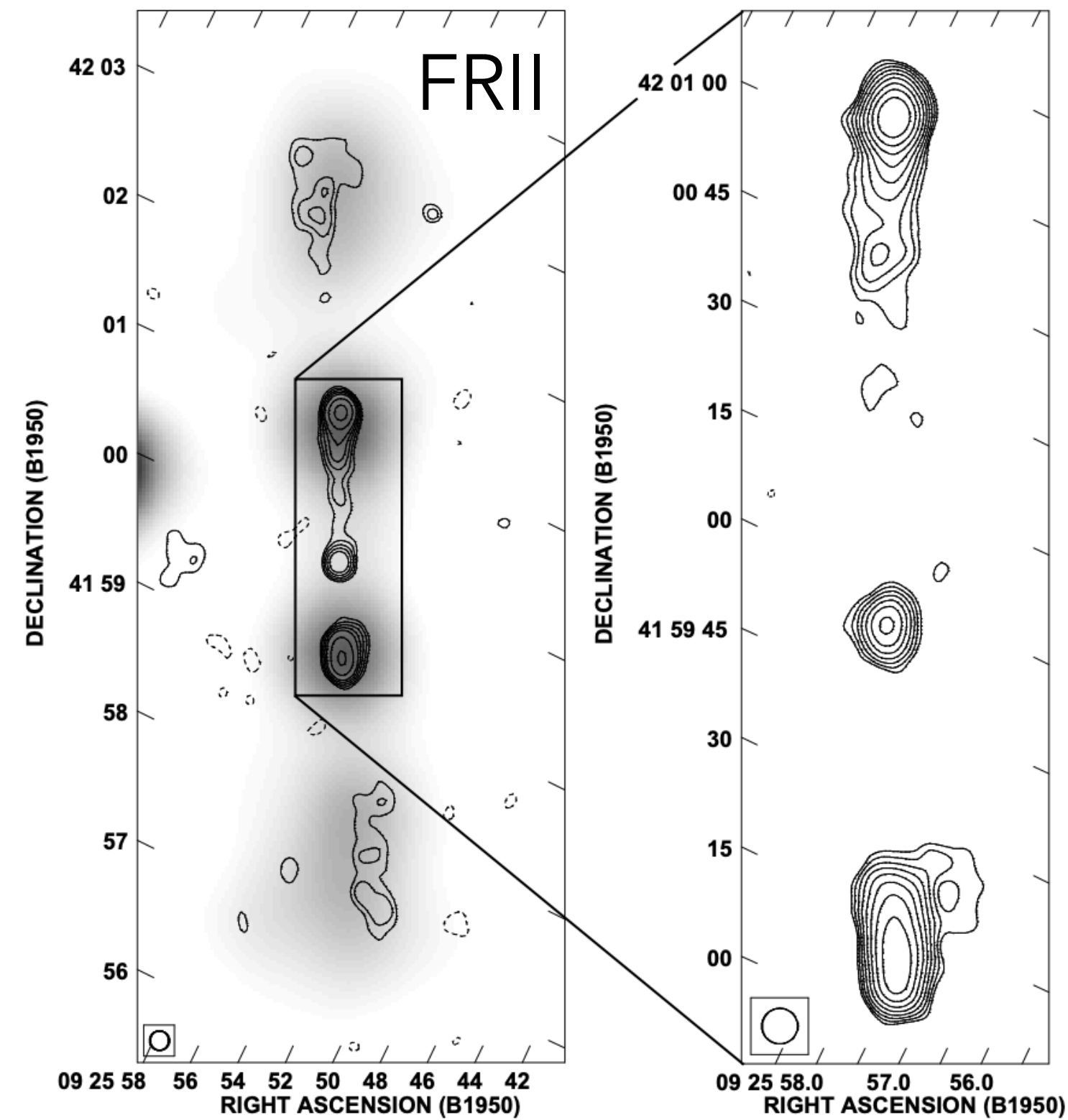
<5% remnants

>10% remnants

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

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

Double Double

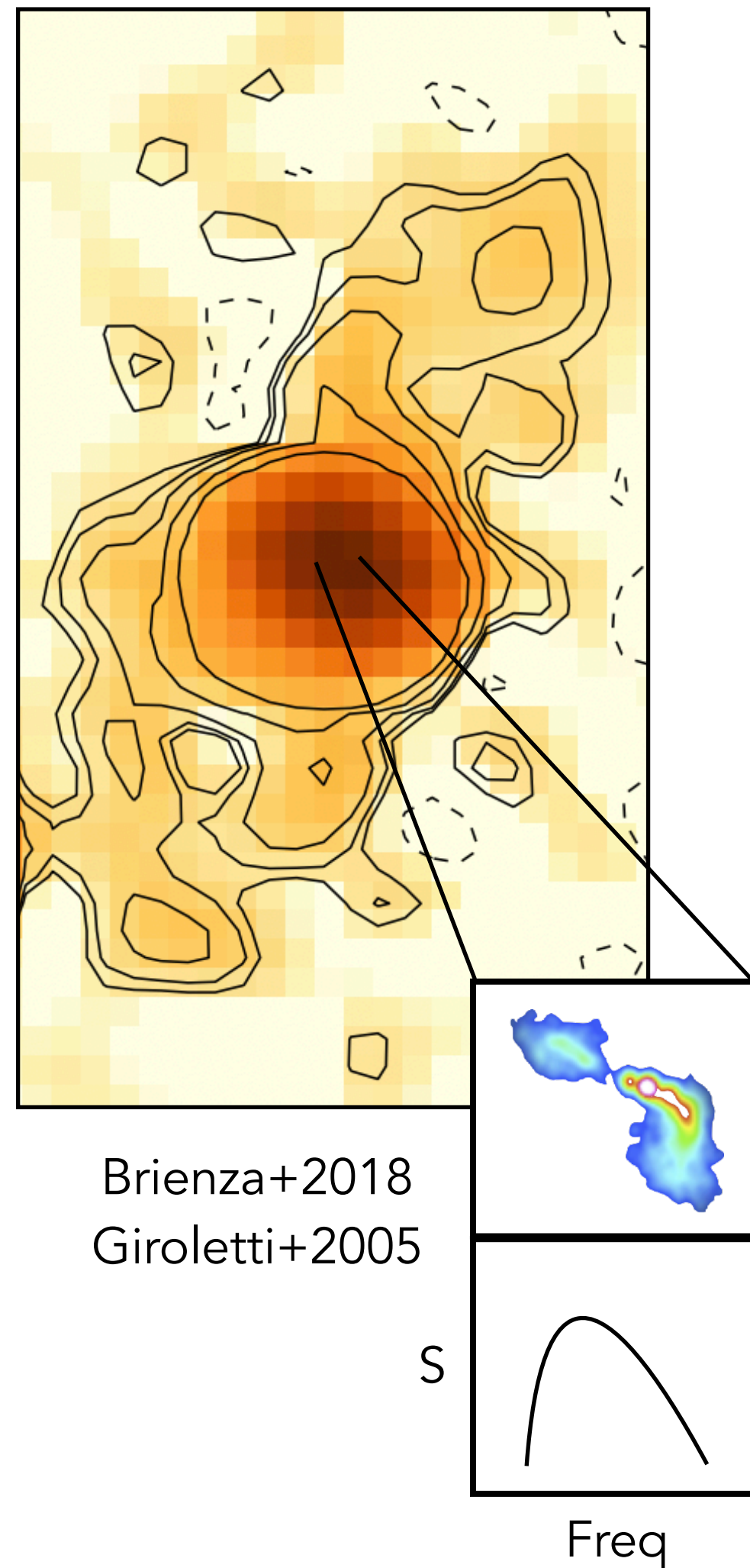
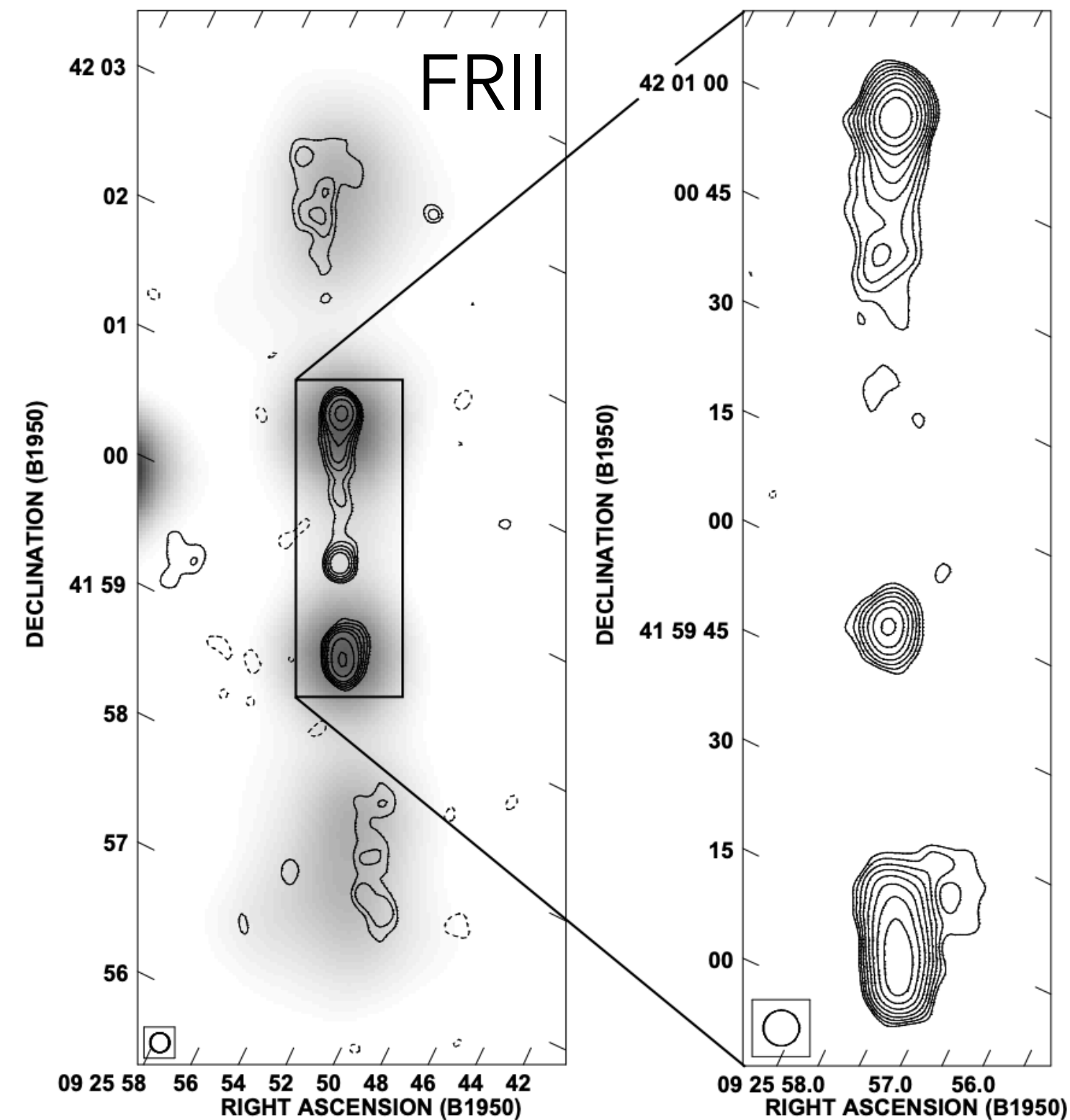


Schoenmakers+2000

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

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

Double Double

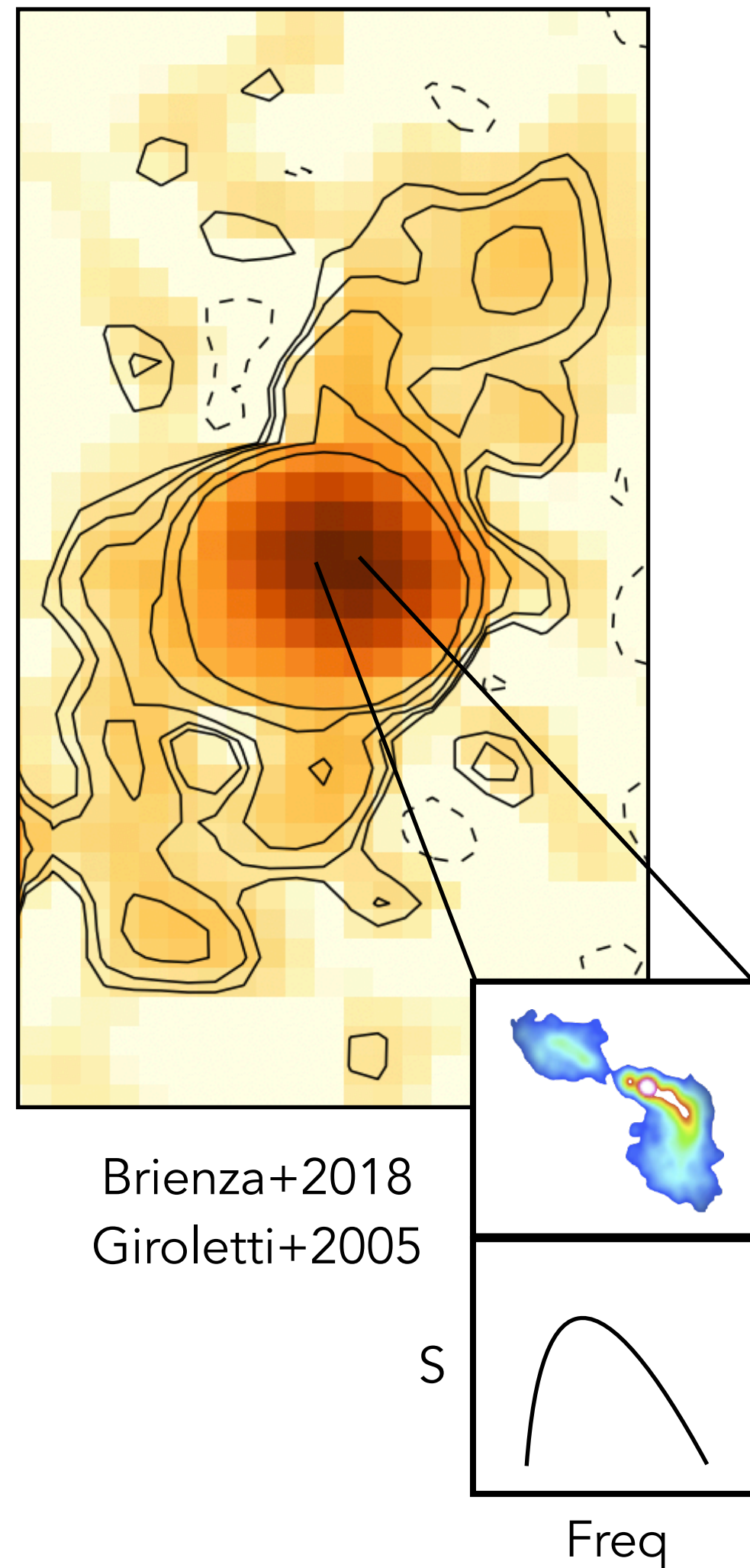
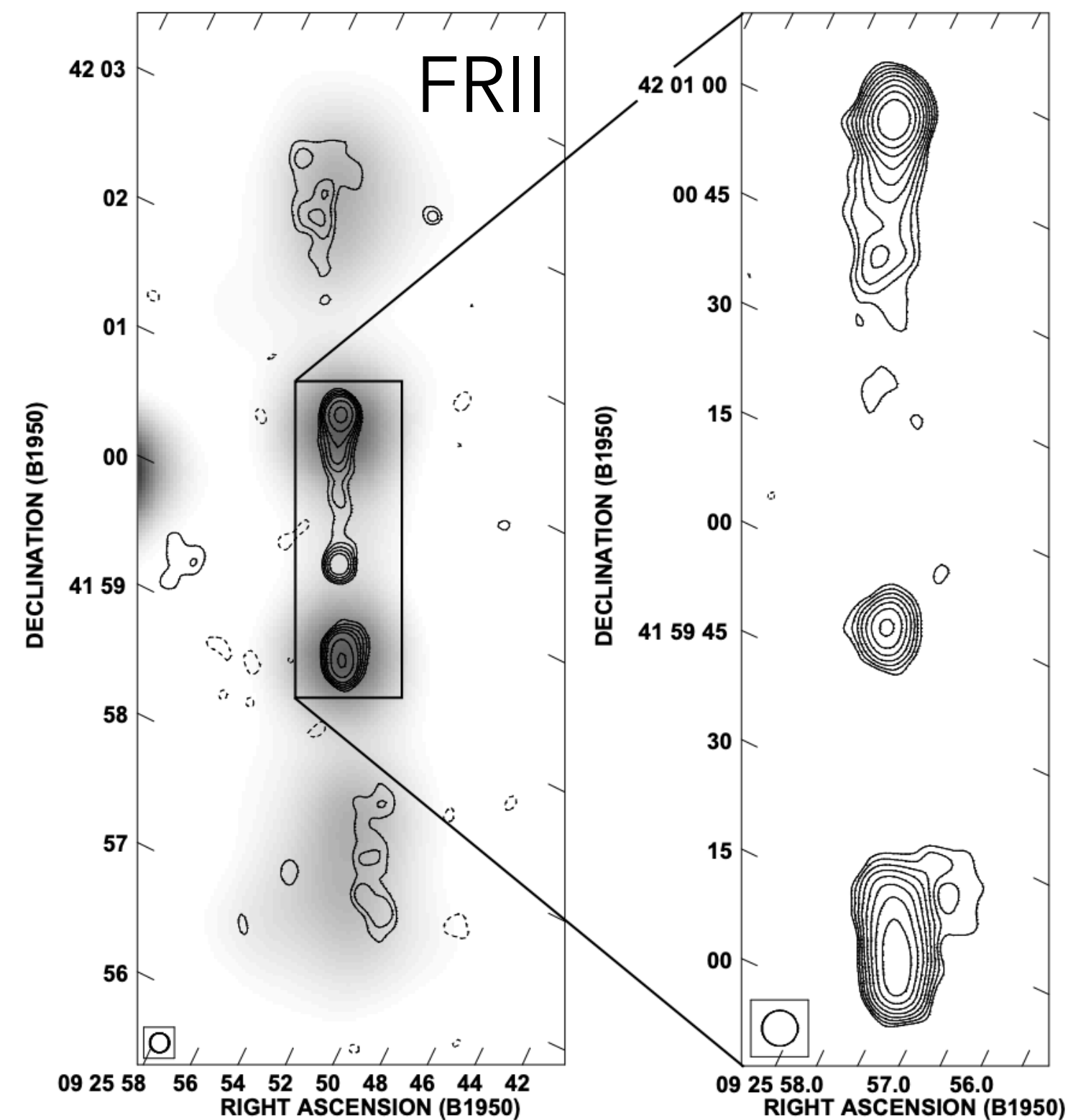


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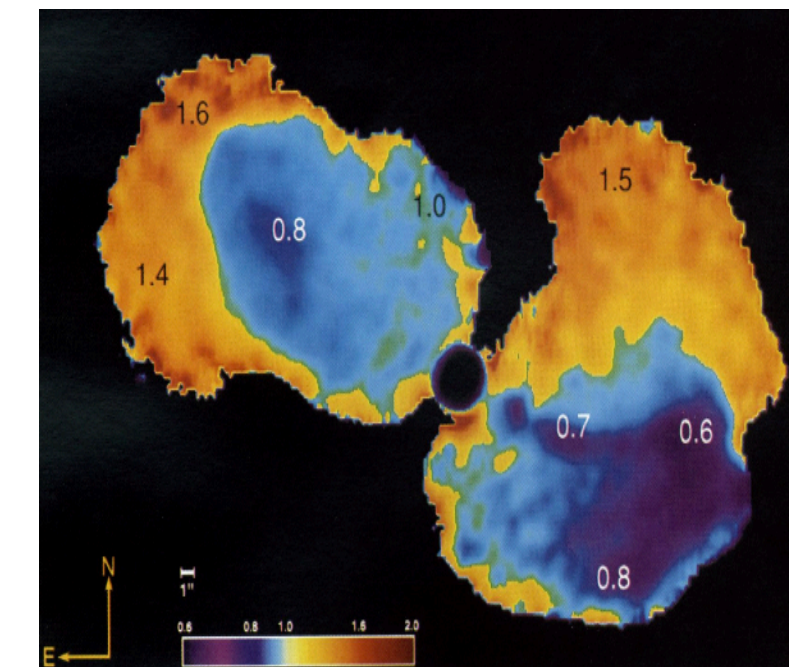
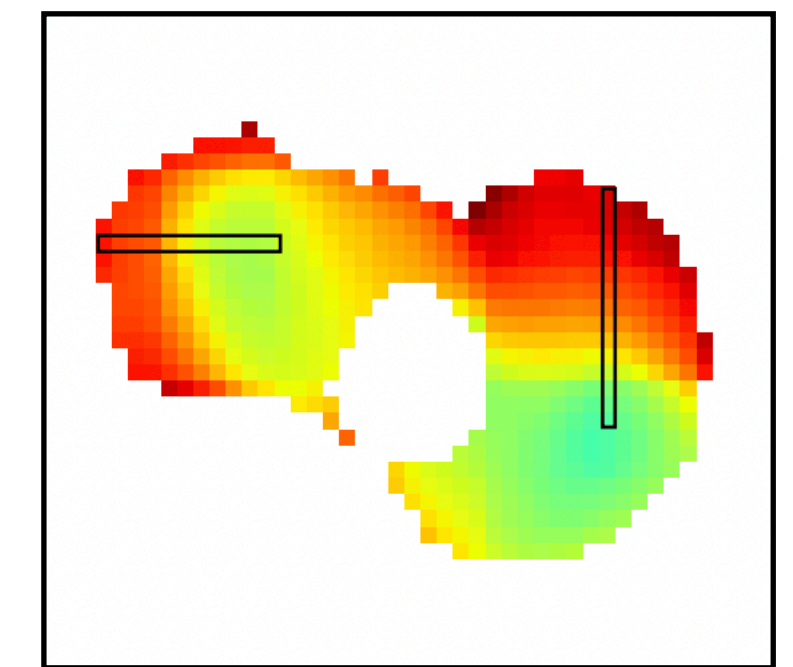
Restarted radio galaxies ($t_{\text{off}} < t_{\text{remnant}}$): the zoo

Double Double

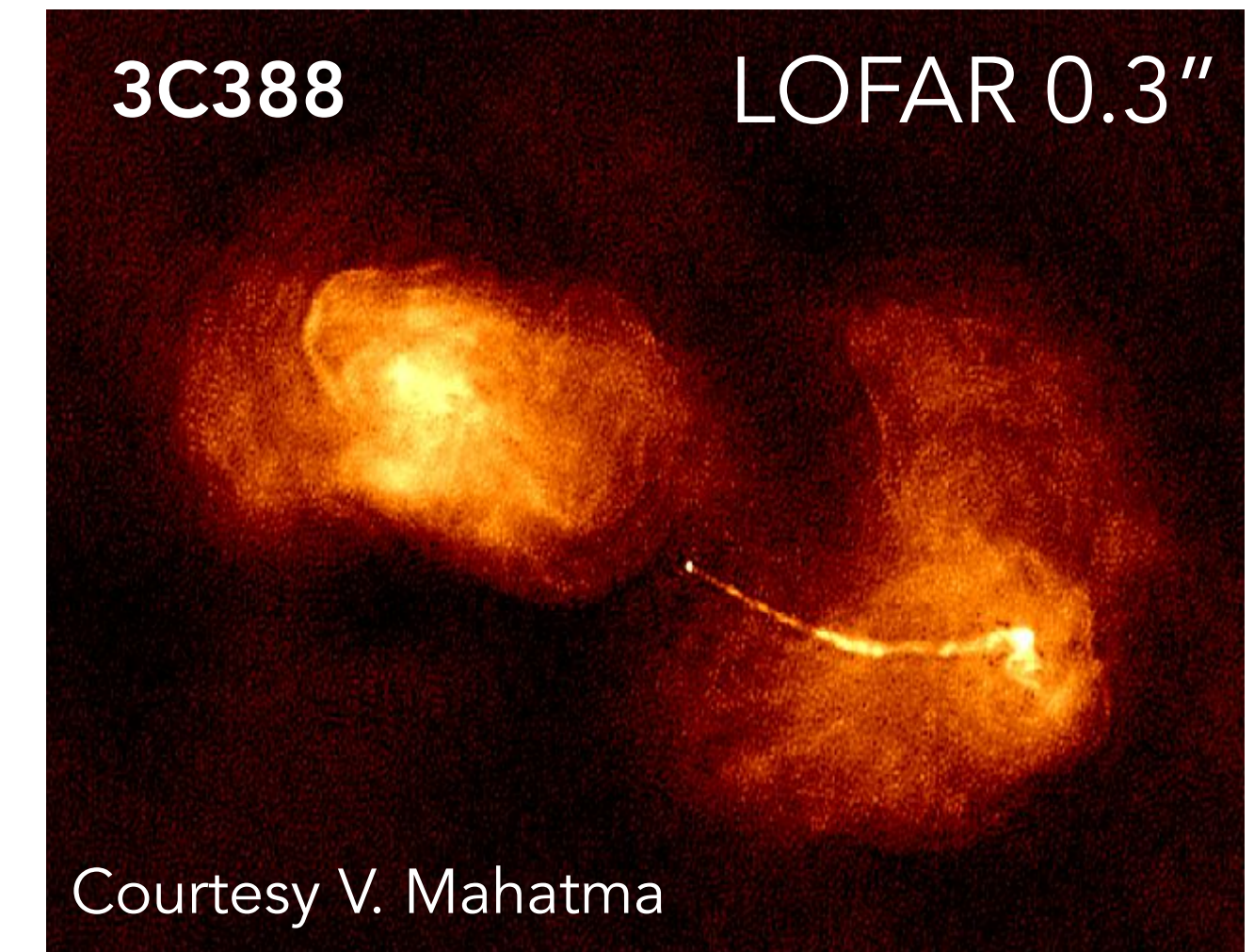


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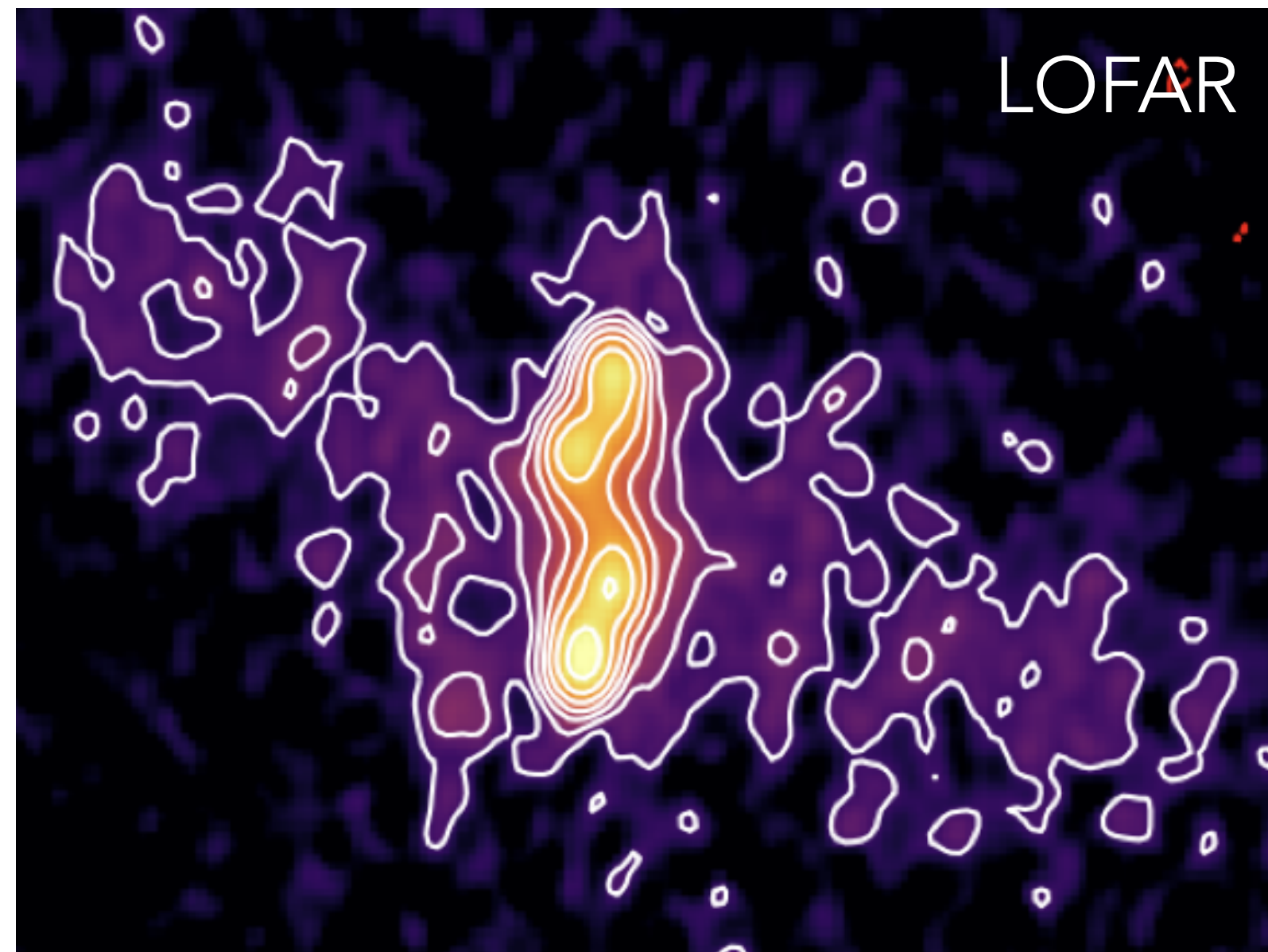


Brienza+2020,
Roettiger+1994

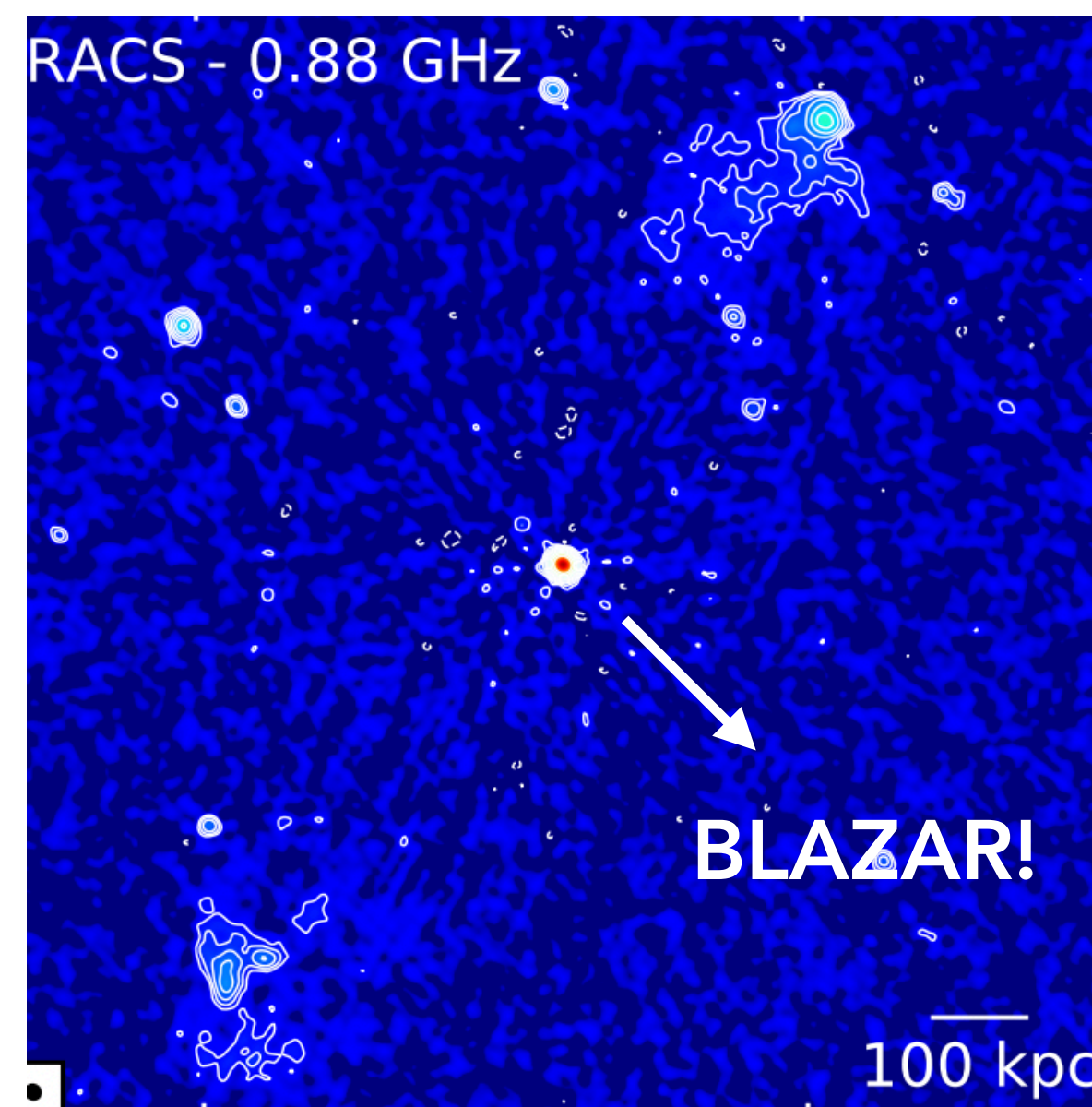


Restarted radio galaxies ($t_{\text{off}} < t_{\text{remnant}}$): the zoo

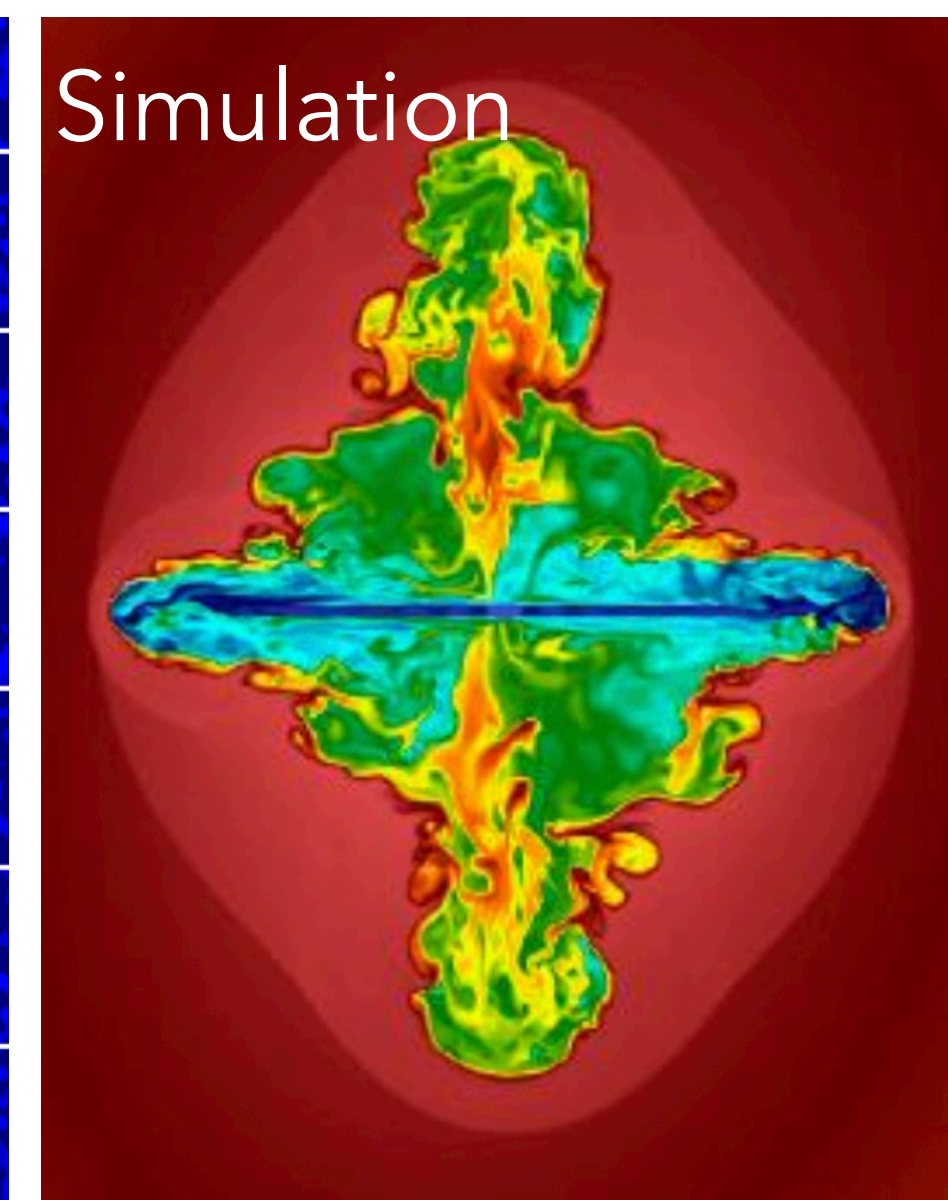
Re-orientation



Ubertosi+2024



Hernández-García+2023



Giri+2024

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

1.4 GHz (OLD VLA)

Murgia et al. 2011

NGC 507
(B2 0120+33)

X

50 kpc

NGC 6086
(B2 1610+29)

X

100 kpc

Two remnant radio galaxies
(at the center of galaxy
groups)... which became
restarted radio galaxies!

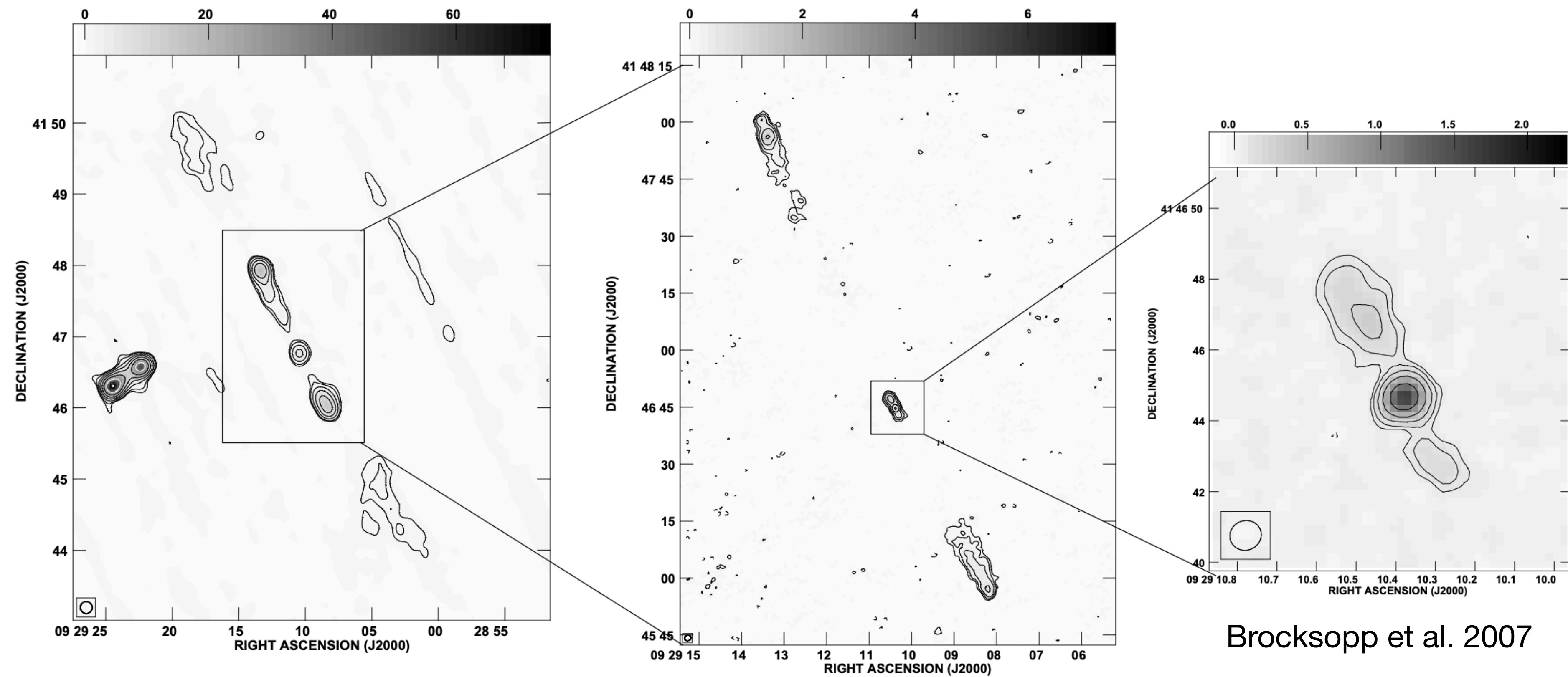
144 MHz (LOFAR)

Brienza, Lovisari+2022

Candini, Brienza+2023

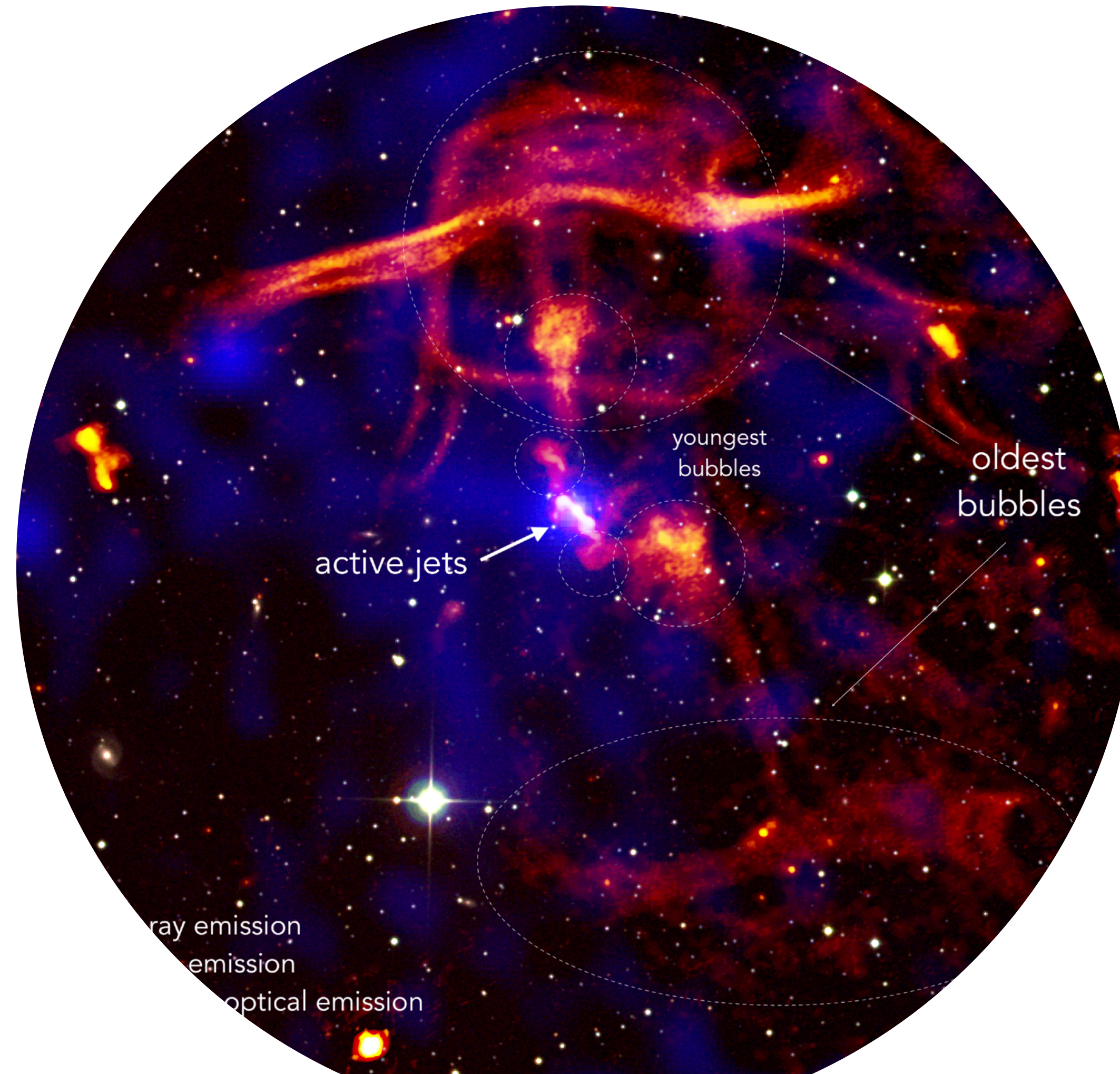
Restarted radio galaxies ($t_{\text{off}} < t_{\text{remnant}}$): the zoo

Triple Double



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

Restarted radio galaxies ($t_{\text{off}} < t_{\text{remnant}}$): 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

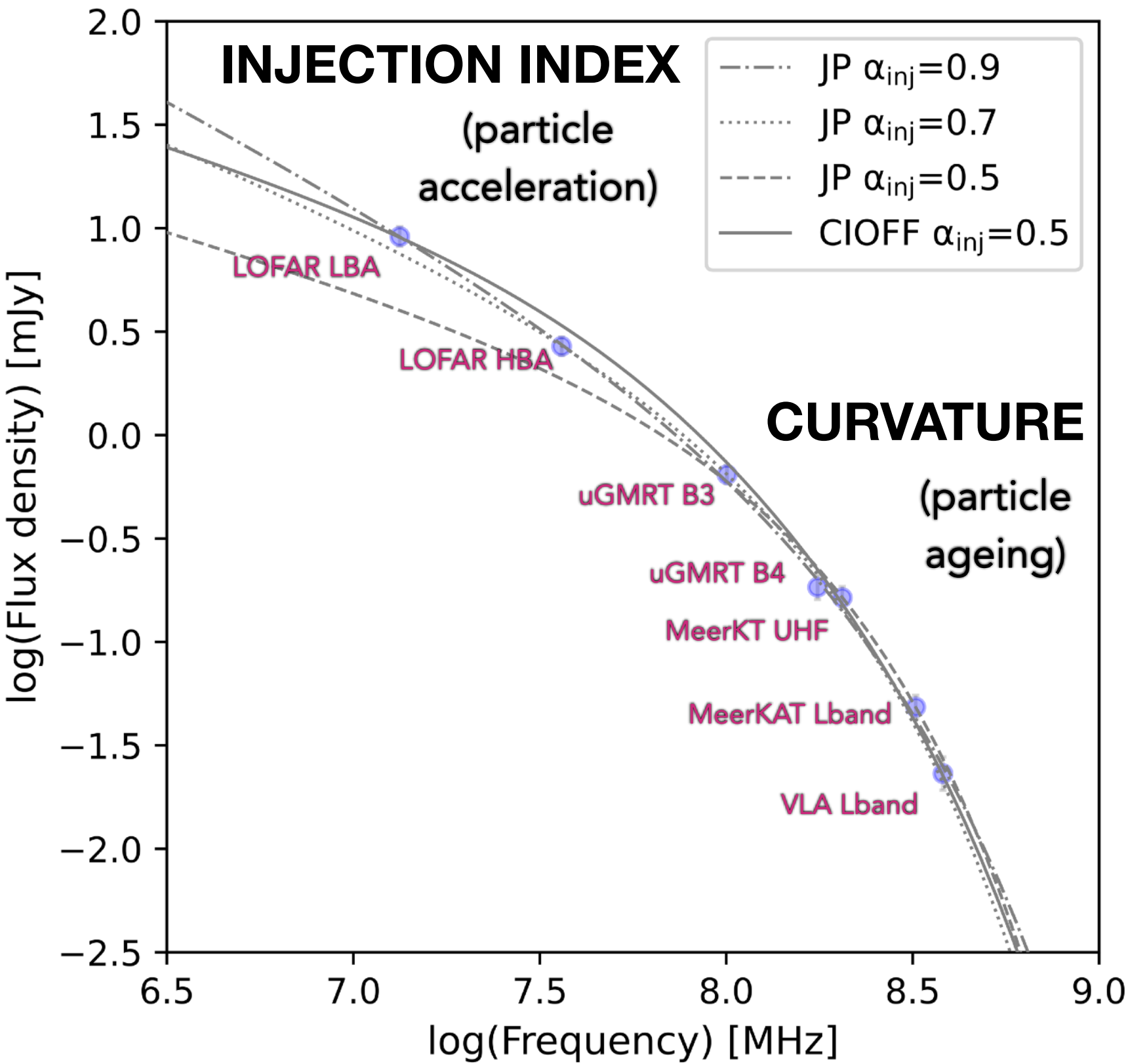
Analytic
equation

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

Vs

Numerical
models

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



Timescales from spectral ageing

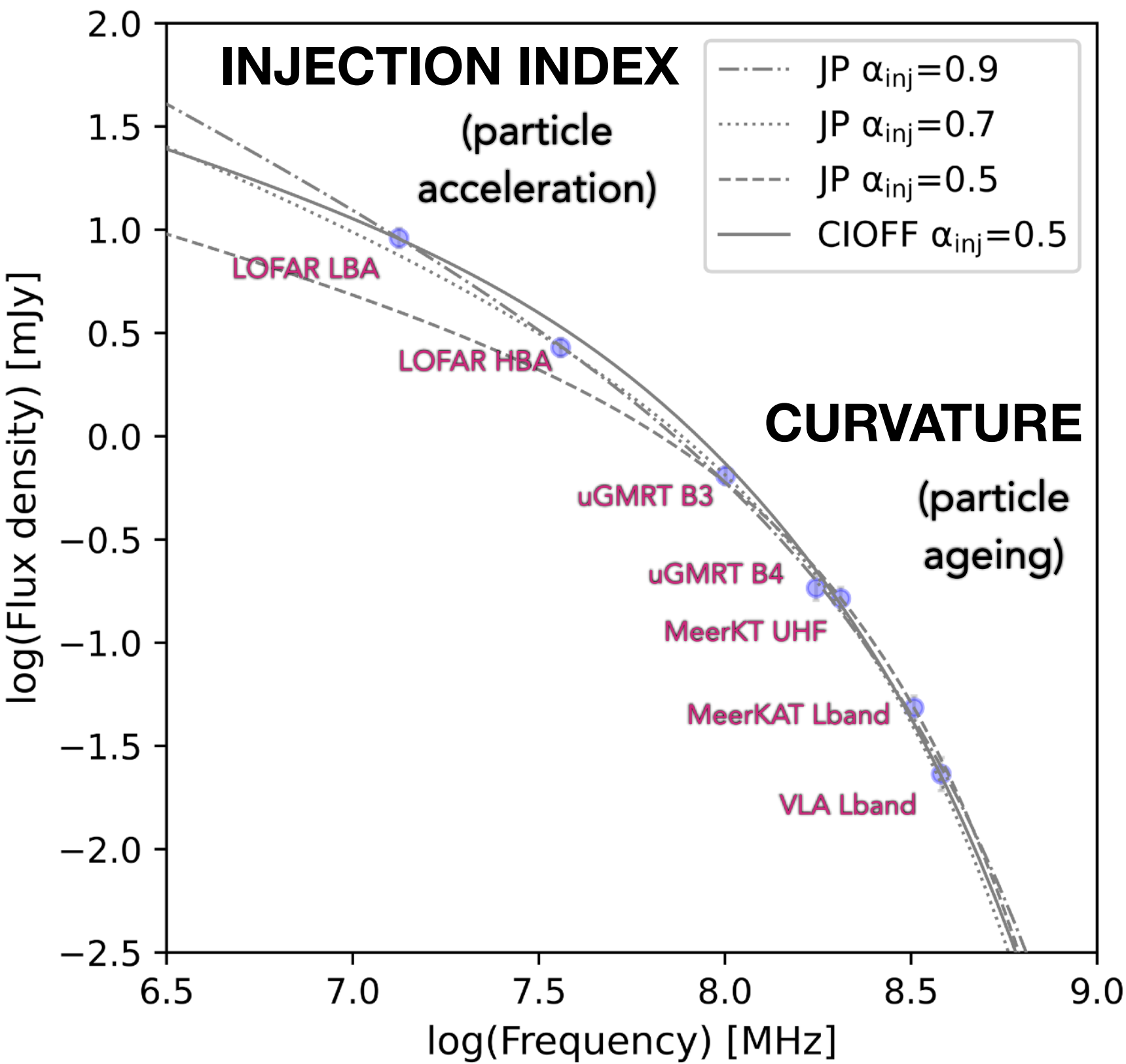
Analytic
equation

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

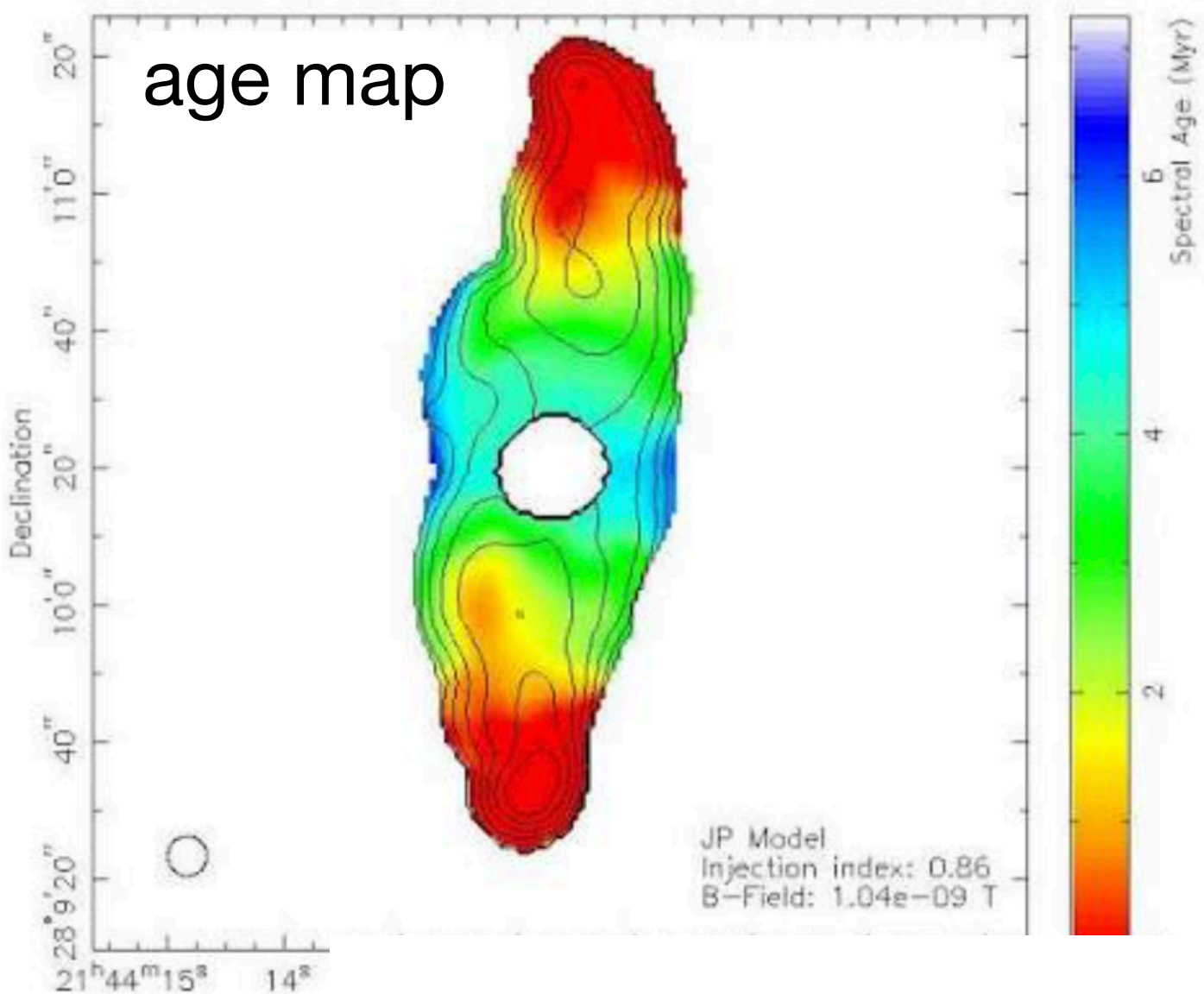
Vs

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

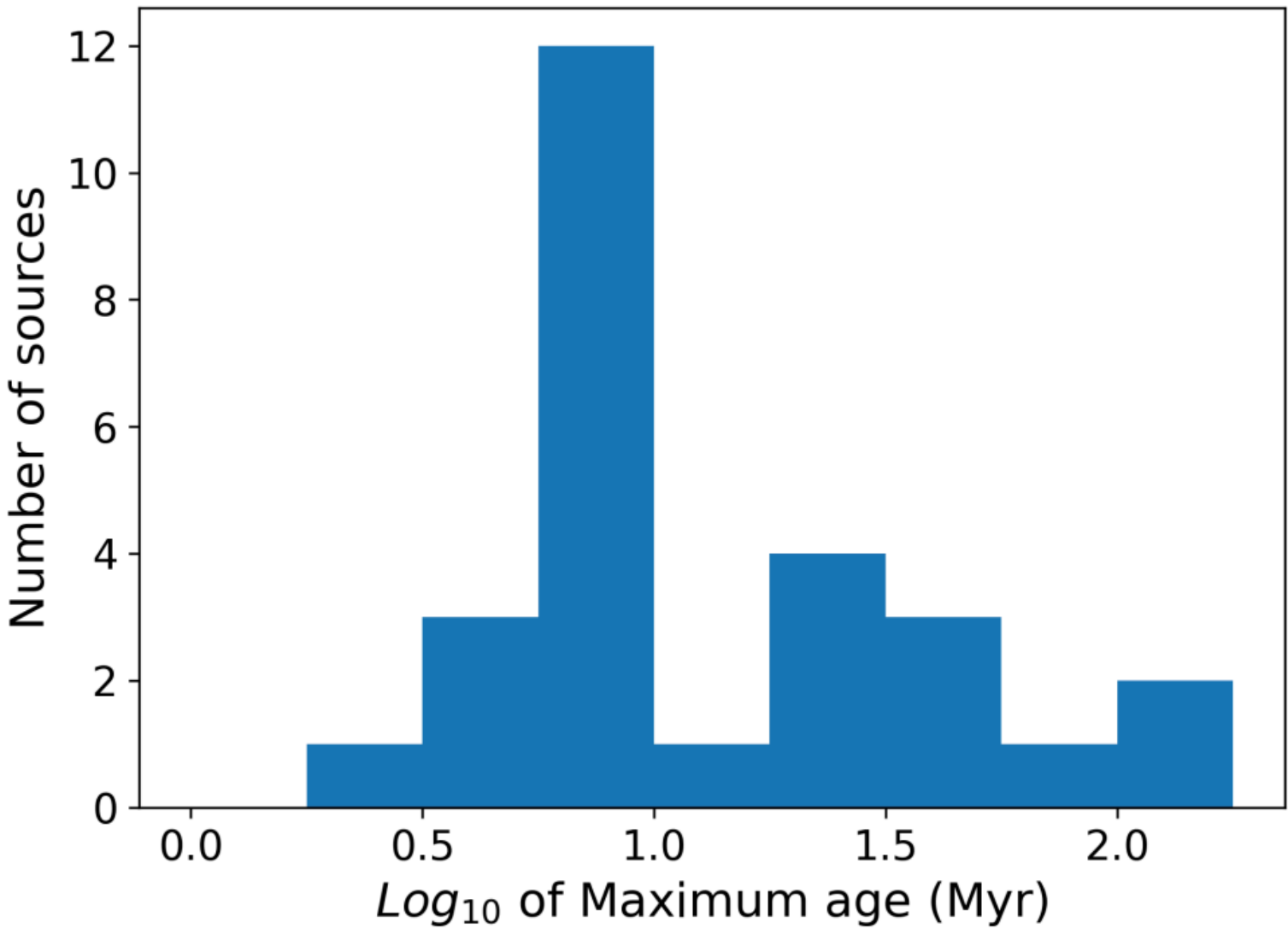


Brienza+2025



Harwood+

Siddhant+23



Timescales from spectral ageing

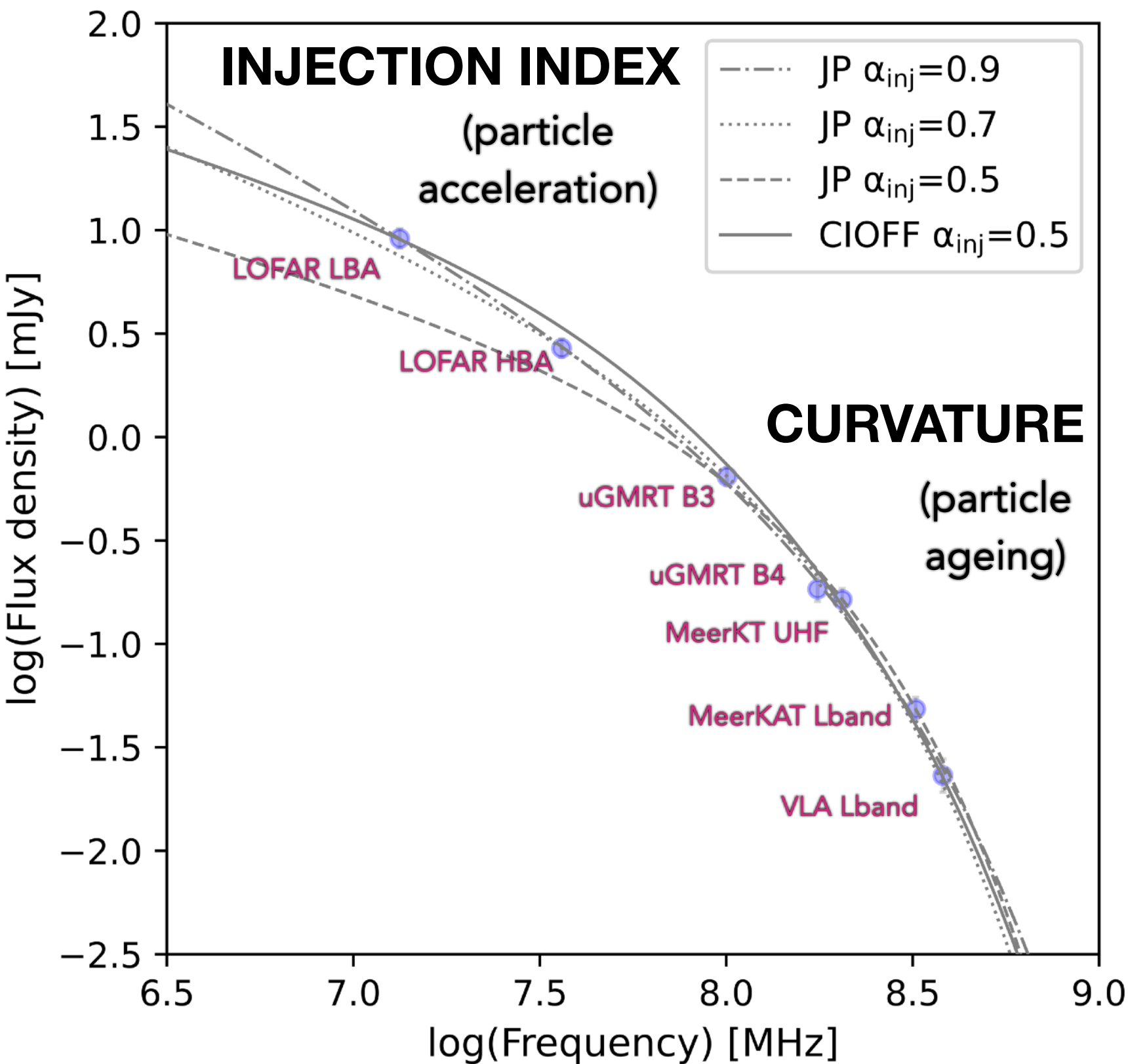
Analytic
equation

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

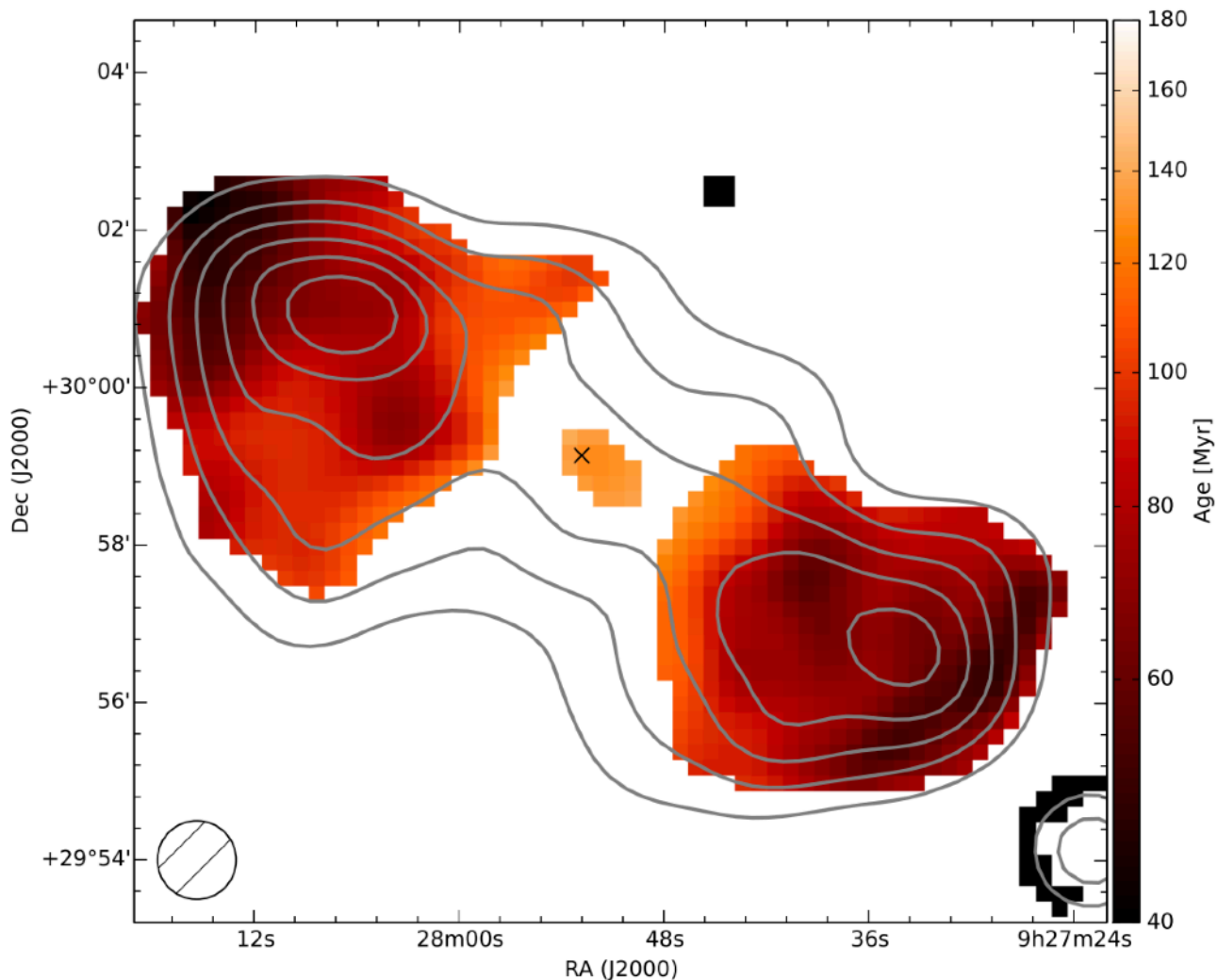
Vs

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

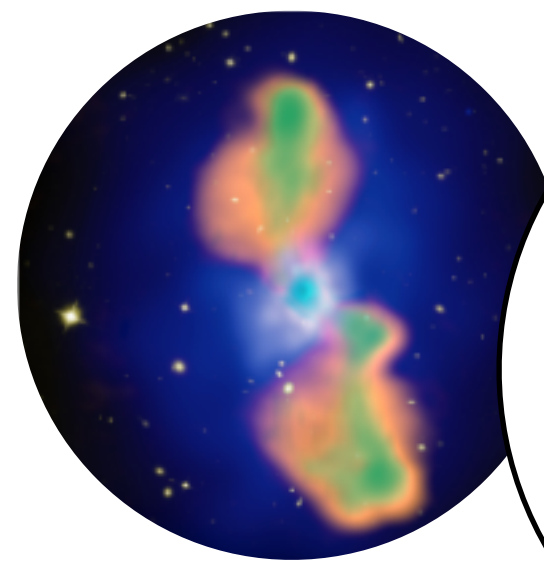
10 Myr on +
50 Myr off

Shulevski+2017

Observationally
expensive but possible!

Duty cycle from spectral ageing...some examples

Biava+2021



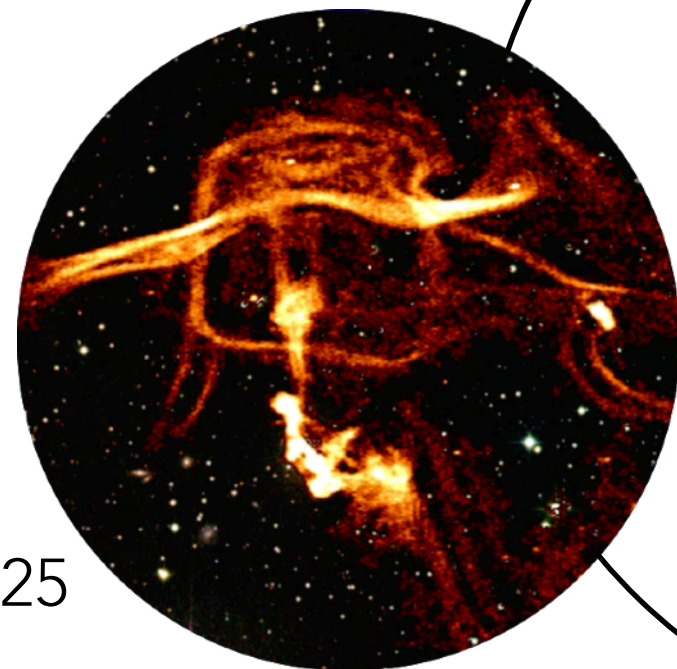
DUTY CYCLE

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

DUTY CYCLE

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

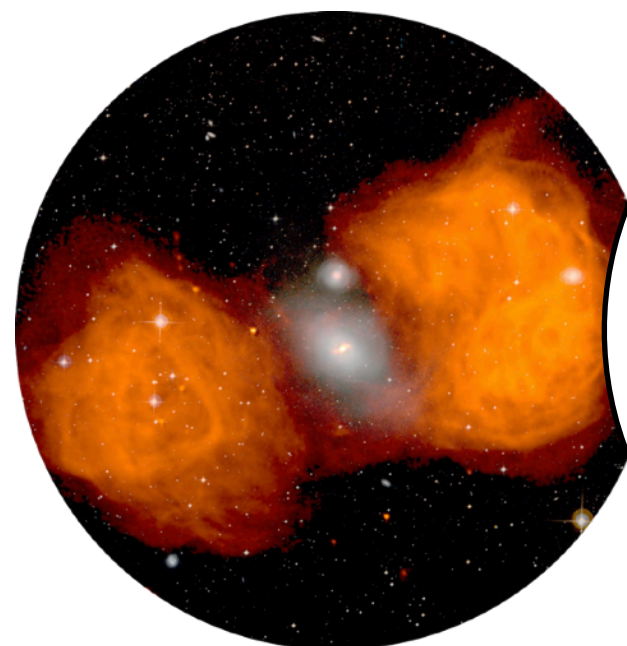
Brienza+2025



DUTY CYCLE

13 Myr ON
12 Myr OFF
1 Myr ON
2 Myr OFF

Maccagni+2020

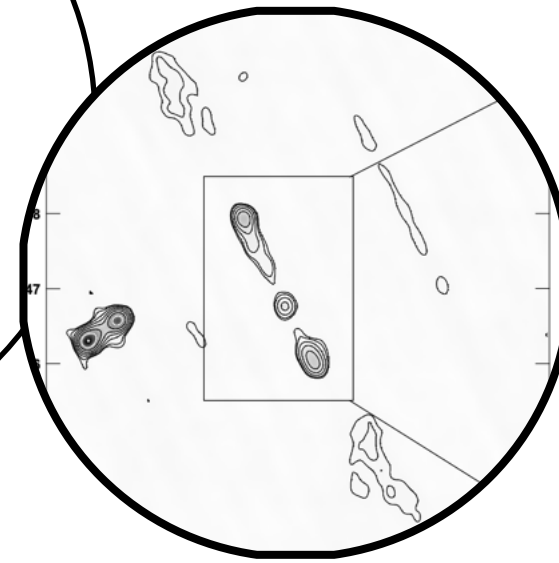


DDRGs

DUTY CYCLE

~20-100 ON
1-100 Myr OFF

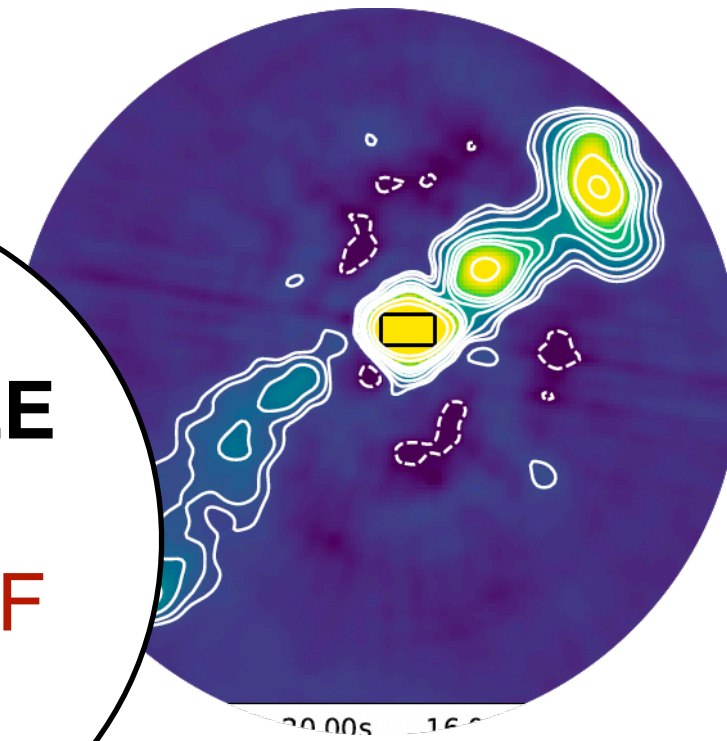
Konar+2012,2013
Rarivoarinoro+2026



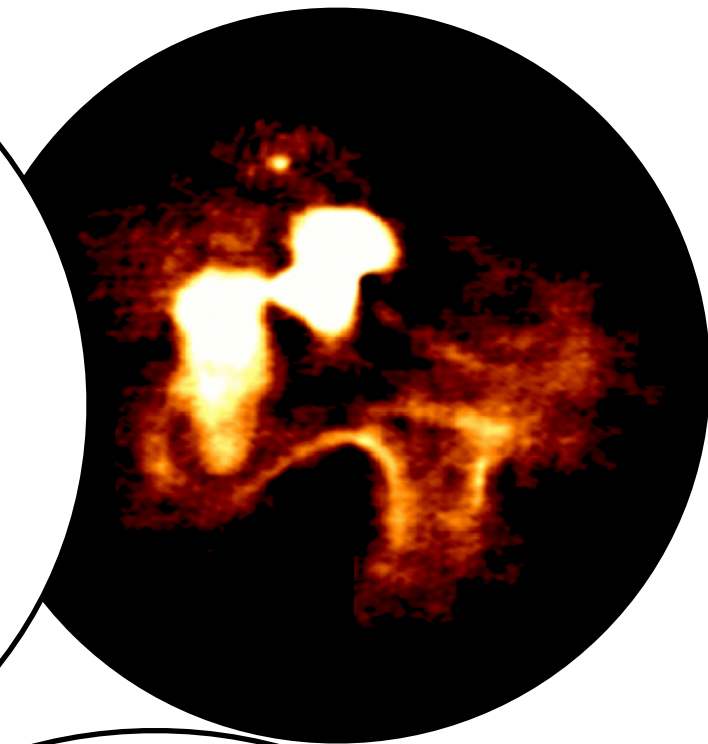
DUTY CYCLE

~20 ON
Few Myr OFF
<0.3 Myr

Kukreti+2021

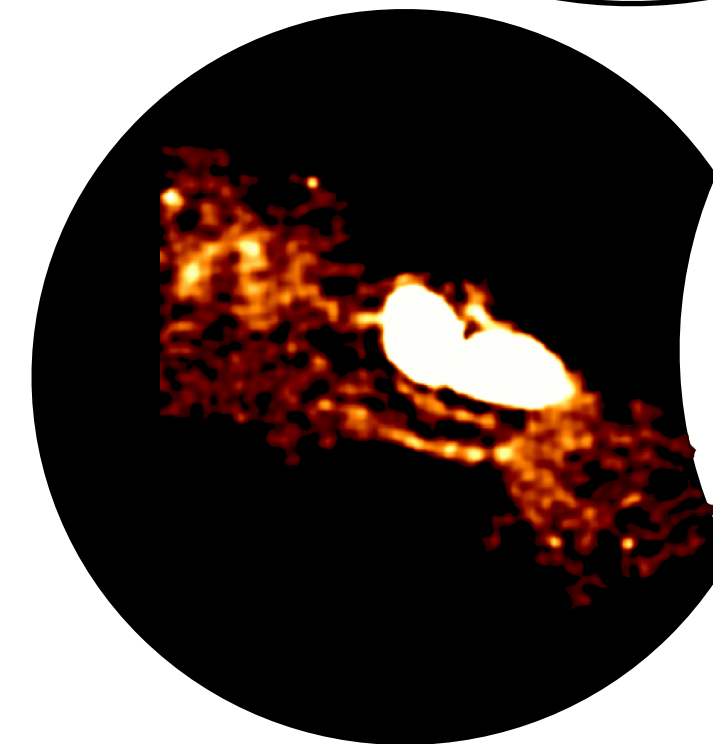


Brienza+2022



DUTY CYCLE

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



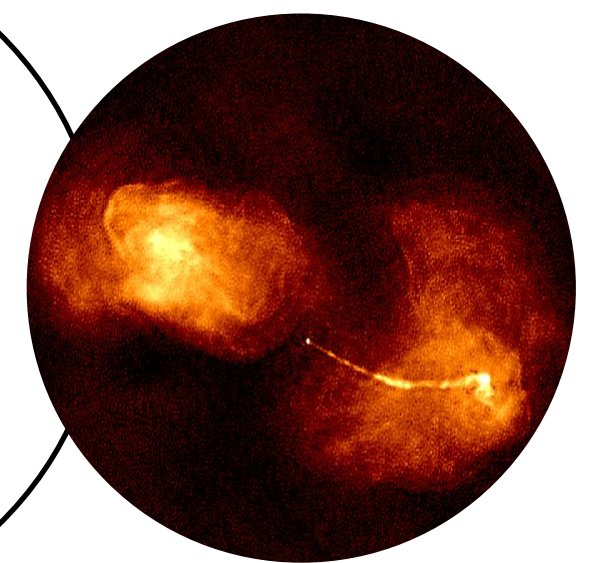
Candini+2023

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)

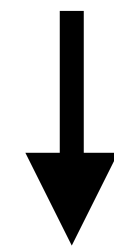
Timescales from spectral ageing



- 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 $B \sim 0.3-0.5 B_{eq}$ for FRIs $\rightarrow$ 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) = $t_{spec} < t_{dyn}$

e.g. Mahatma+2019, Jerrim+2025

A note on small jets

The majority of radio loud AGN are low power (10^{23-25}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

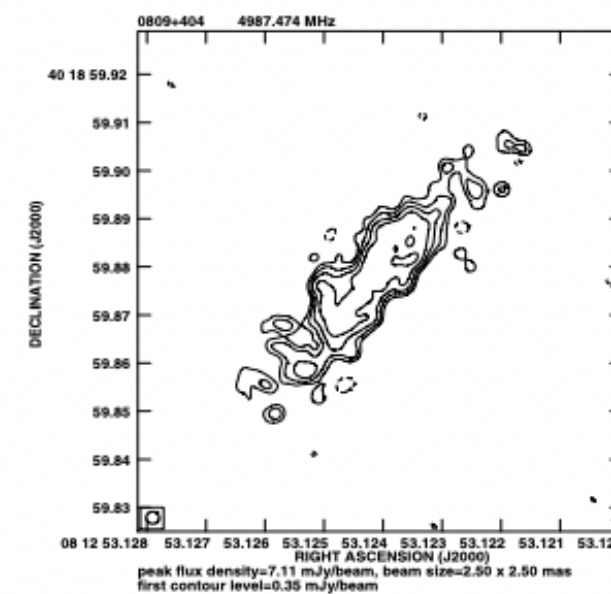
The majority of radio loud AGN are low power (10^{23-25} W/Hz @1.4 GHz) with sizes within the galaxy!

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!

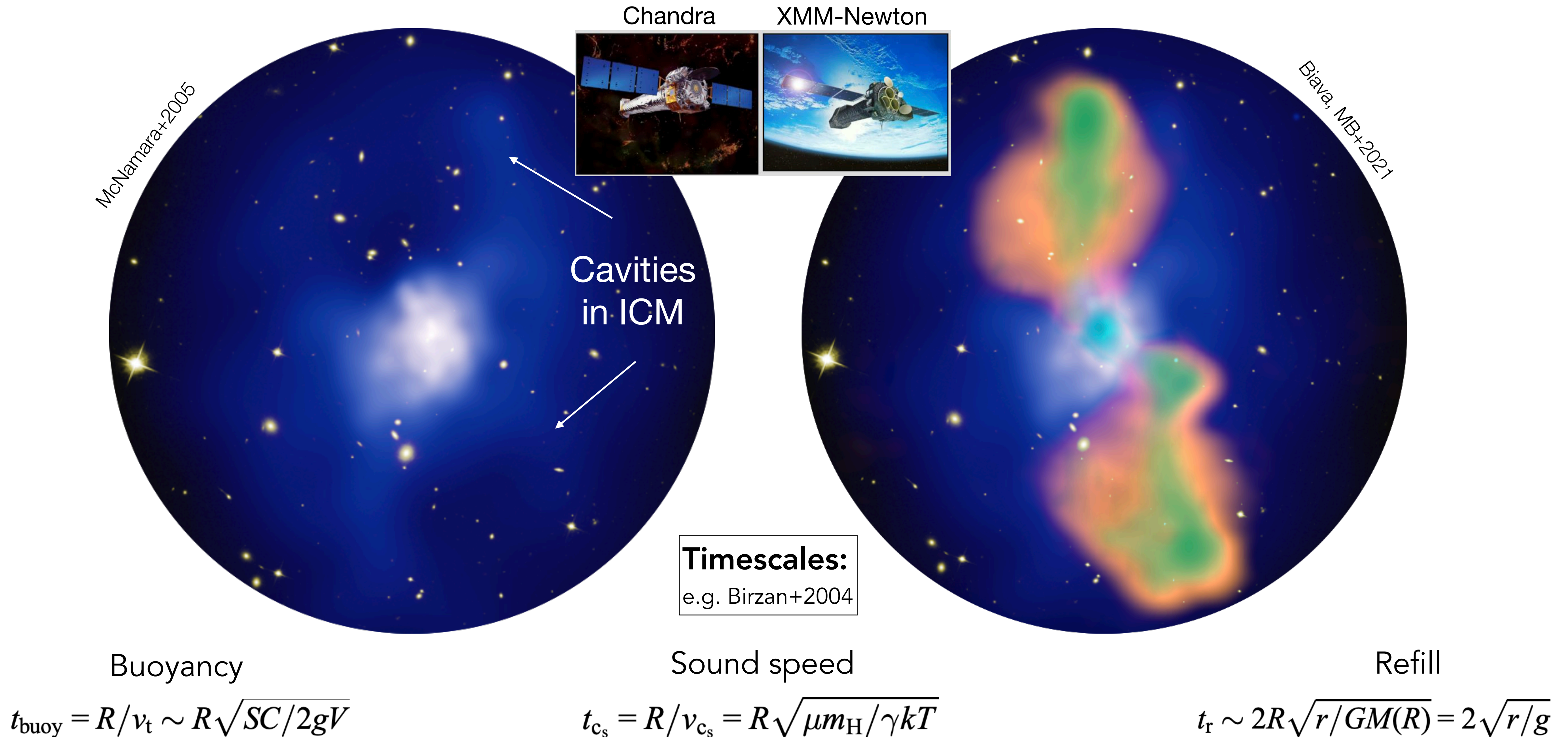


Kunert-Bajraszewska+2006

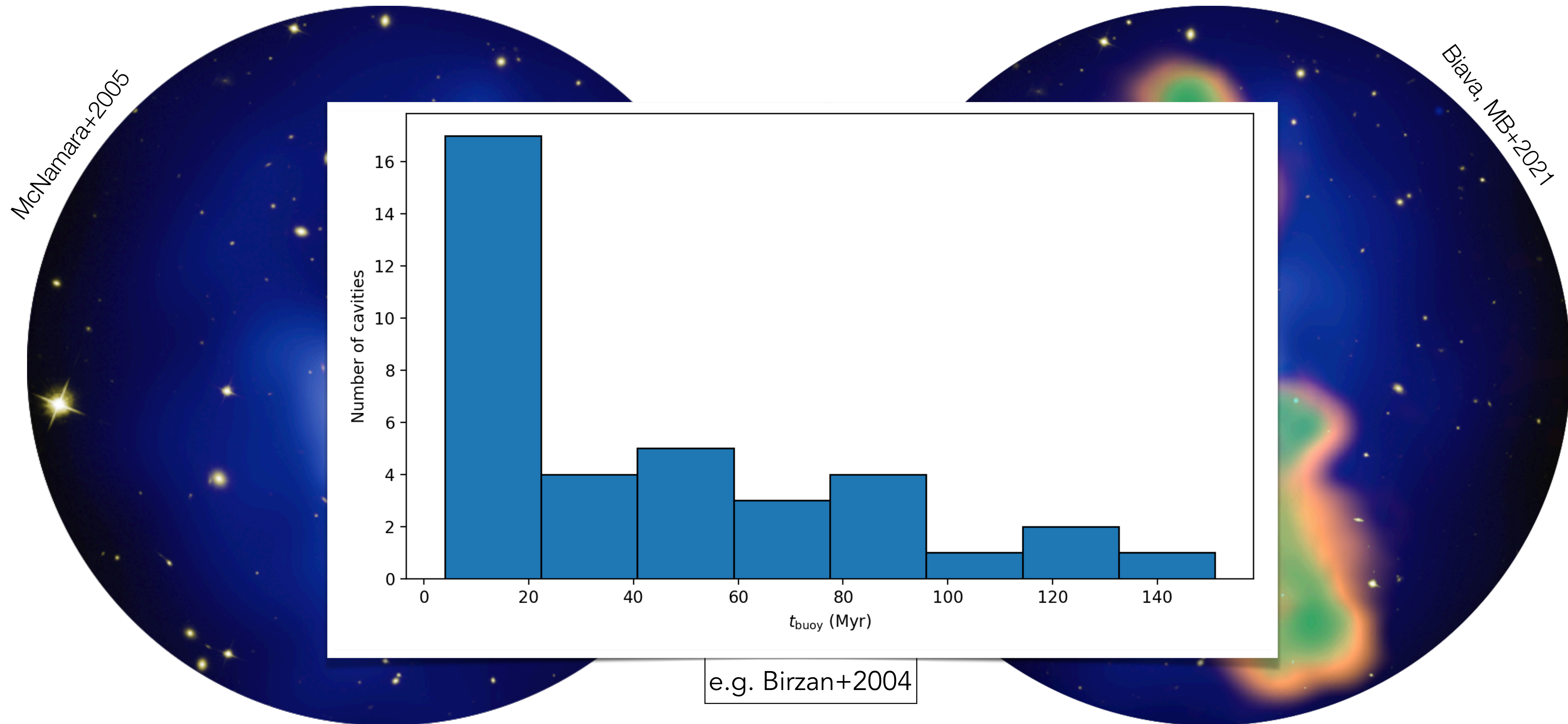
BUT also e.g...
Callingham+2015, Orienti+2010, 2021
Webster+2021, Giroletti+2003
Kunert-Bajraszewska+2005, Zeng+2026

LOFAR VLBI can be a key!

Timescales from AGN jet cavities in galaxy groups and clusters



Timescales from AGN jet cavities in galaxy groups and clusters



Buoyancy

$$t_{\text{buoy}} = R/v_t \sim R\sqrt{SC/2gV}$$

Sound speed

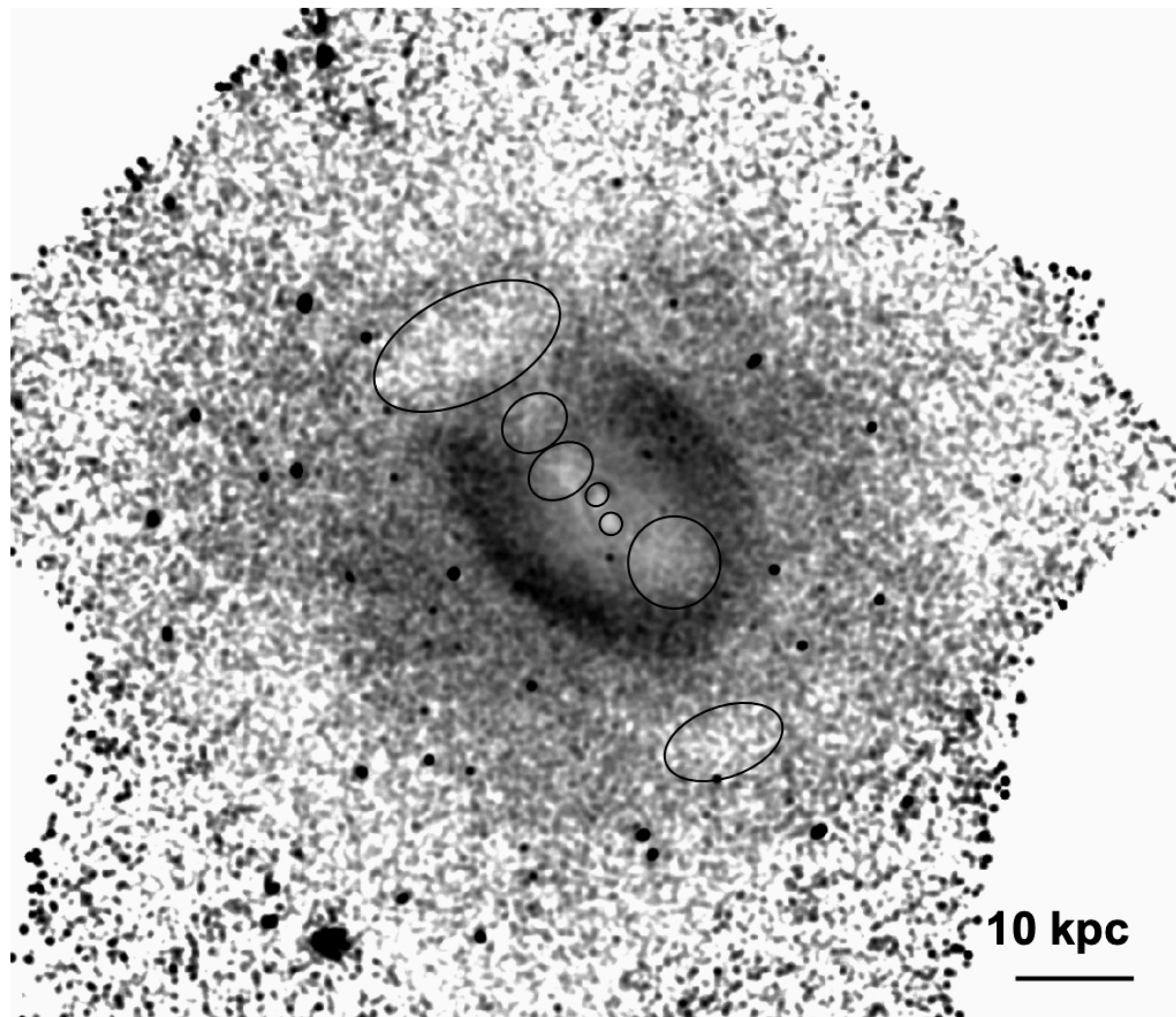
$$t_{\text{cs}} = R/v_{\text{cs}} = R\sqrt{\mu m_{\text{H}}/\gamma kT}$$

Refill

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

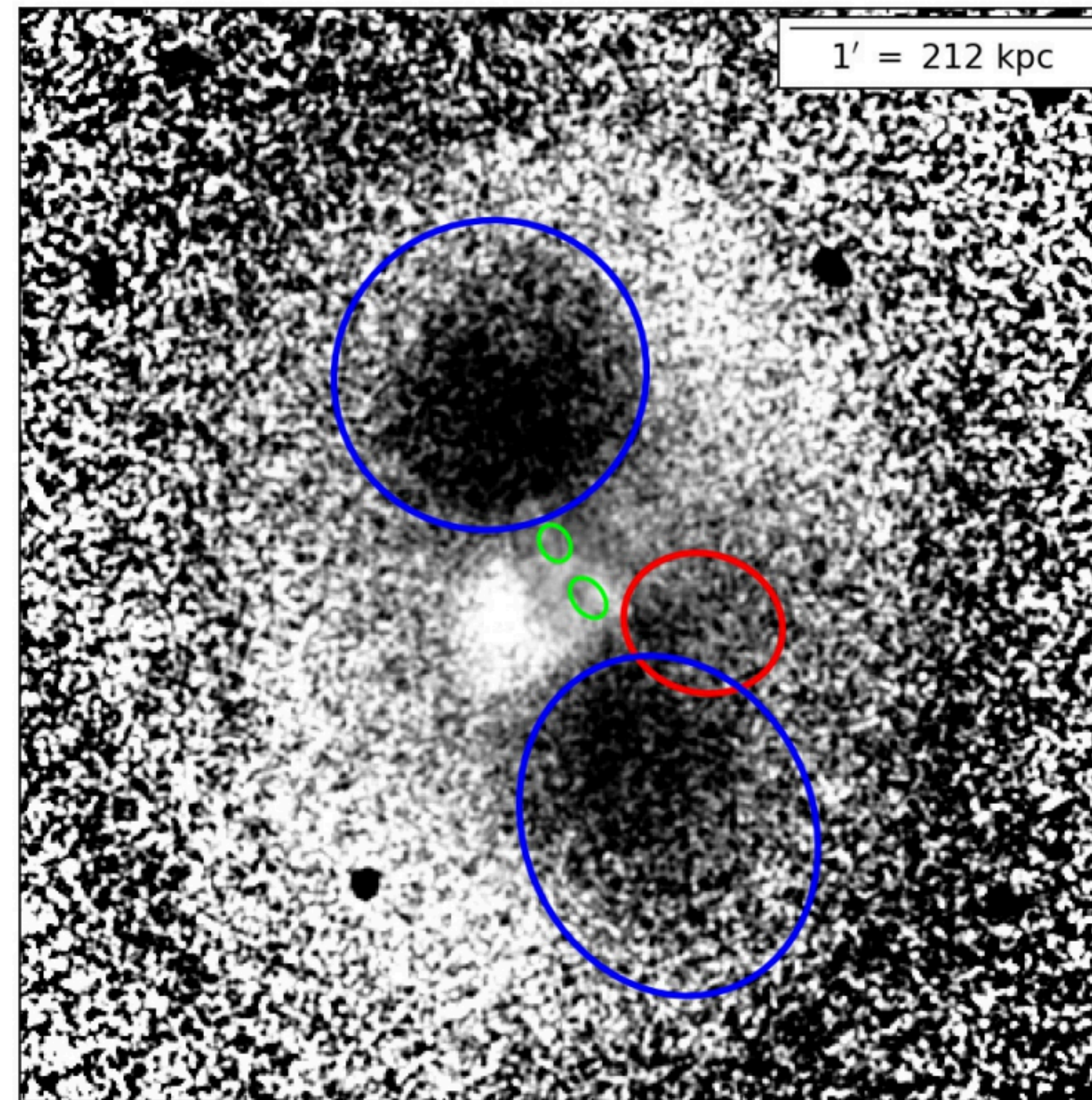
Multiple AGN jet cavities in galaxy groups and clusters

Randall+2011,2015



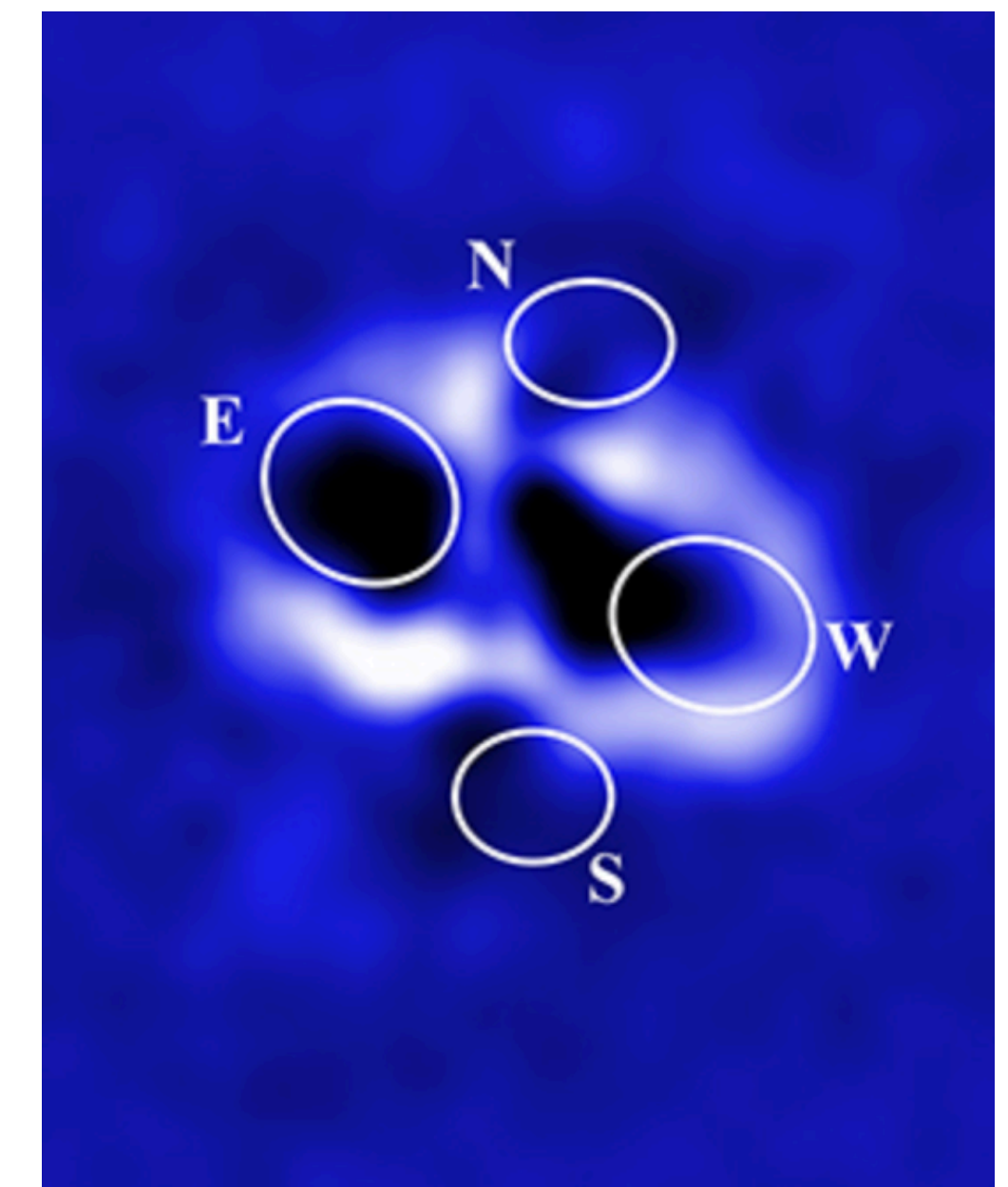
Galaxy group NGC5813

Biava, MB+2021



Galaxy cluster MS 0735.6+7421

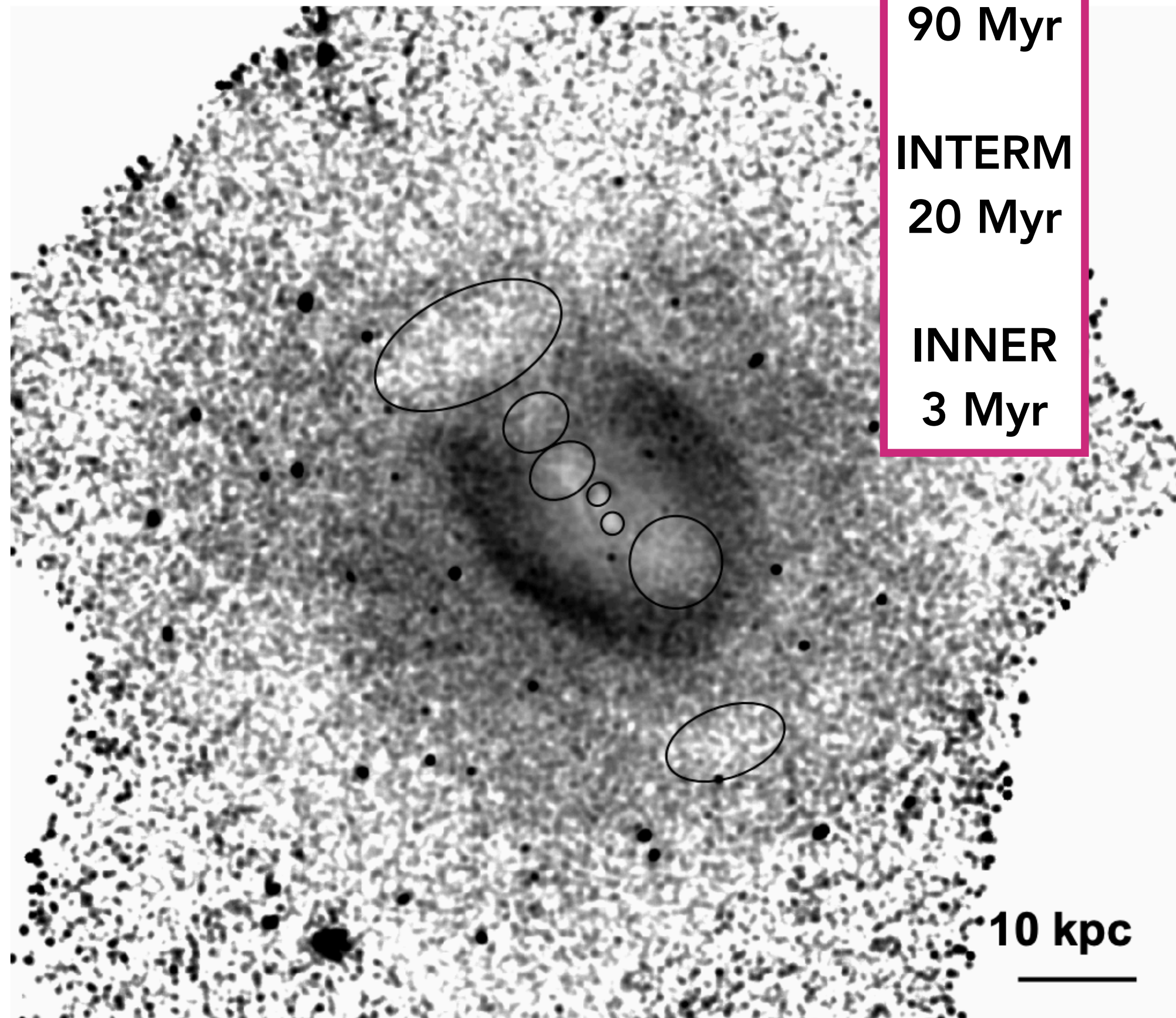
Ubertosi+2021



Galaxy cluster RBS797

Multiple AGN jet cavities in galaxy groups and clusters

Randall+2011,2015



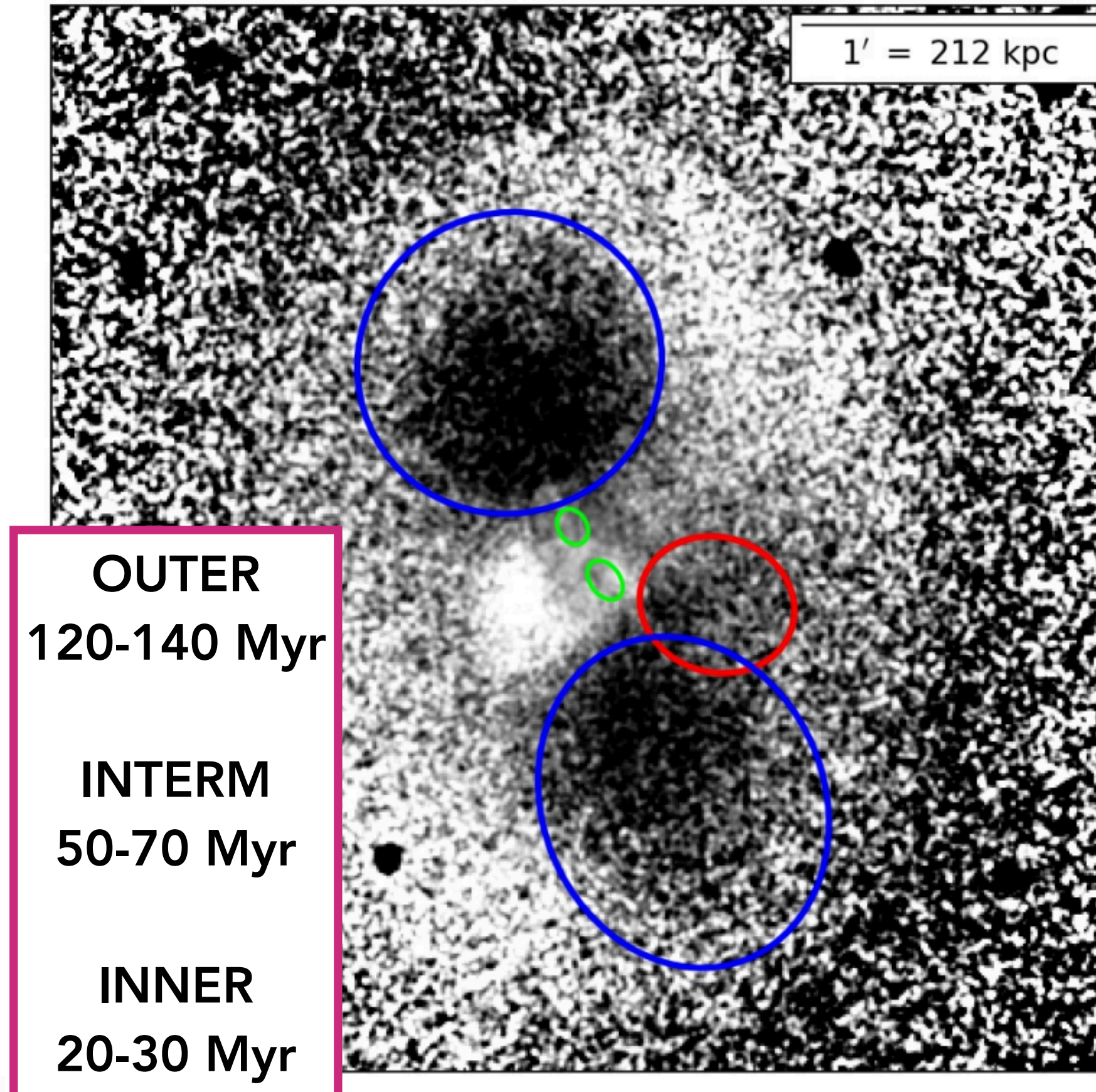
OUTER
90 Myr

INTERM
20 Myr

INNER
3 Myr

Galaxy group NGC5813

Biava, MB+2021



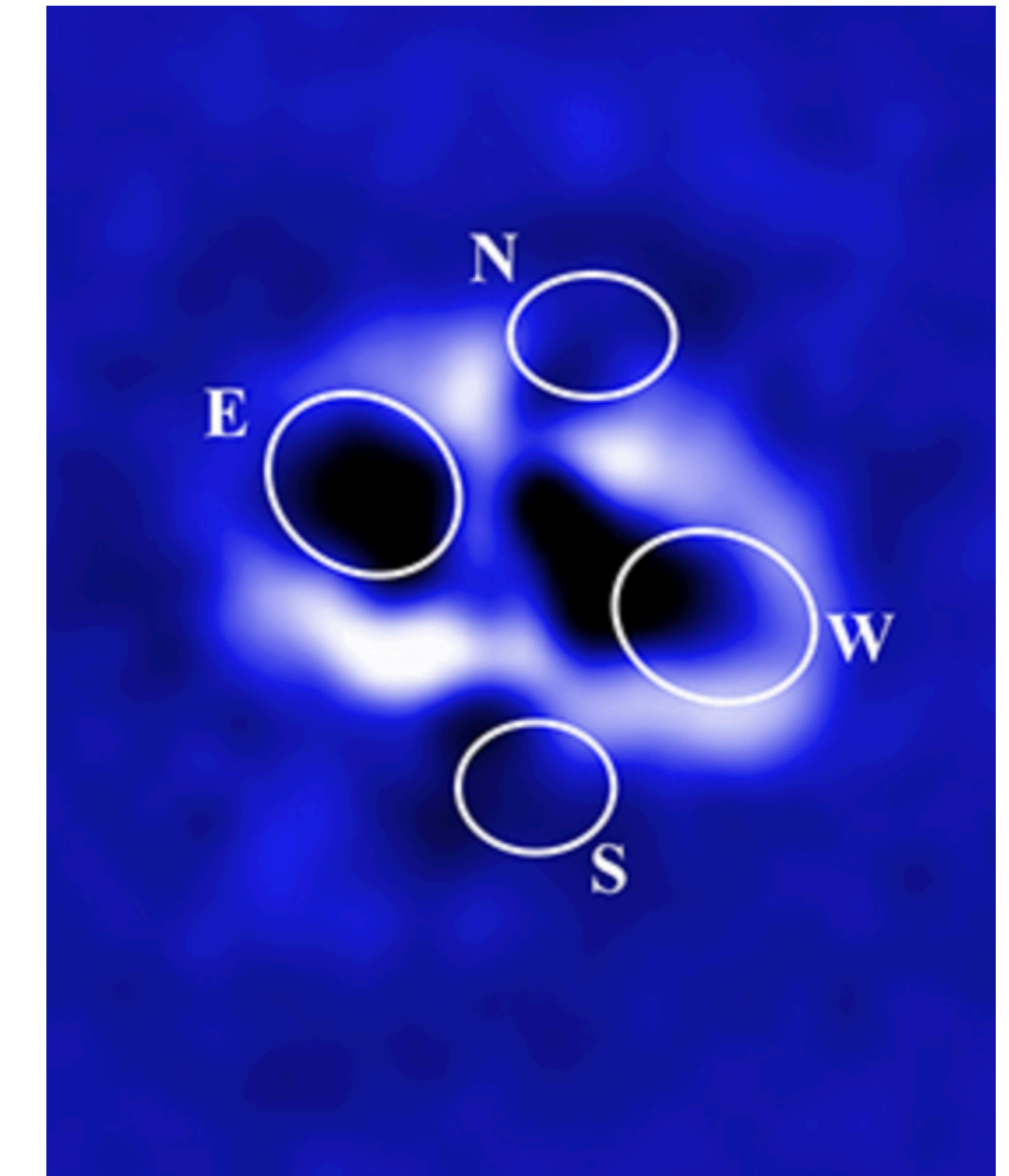
OUTER
120-140 Myr

INTERM
50-70 Myr

INNER
20-30 Myr

Galaxy cluster MS 0735.6+7421

Ubertosi+2021



20-30 Myr
Both pairs

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)

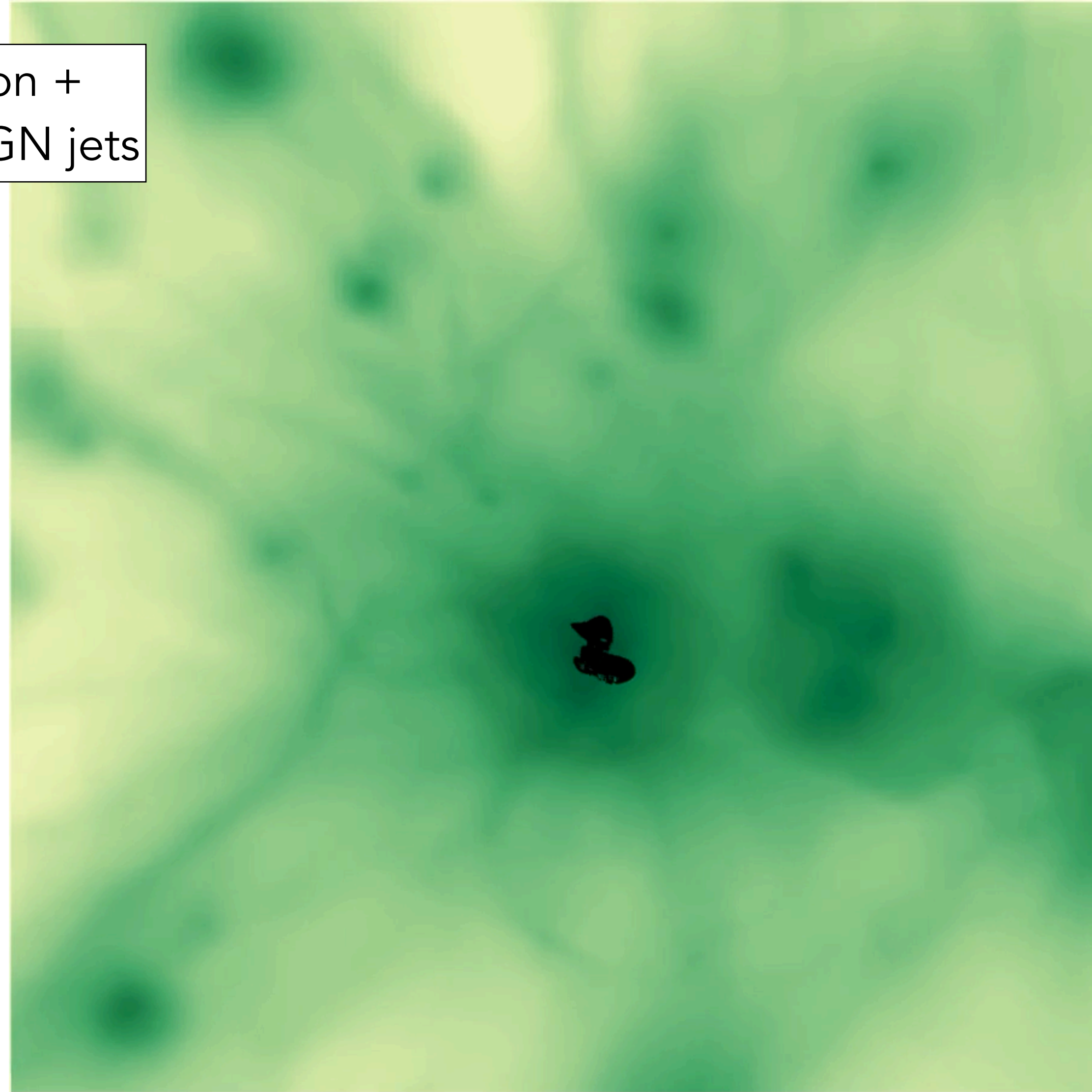


- Need long exposures and high resolution -> especially in systems outskirts
and low mass systems (no adequate telescopes)
- Detectability influenced by position, orientation, and angular extent of the cavities
(e.g. Enßlin & Heinz 2002; Diehl et al. 2008; Brüggen et al. 2009)
- Weak assumptions: e.g. neglects bubble expansion during jet active time, projection etc..

Interplay between AGN remnant plasma and the surrounding medium

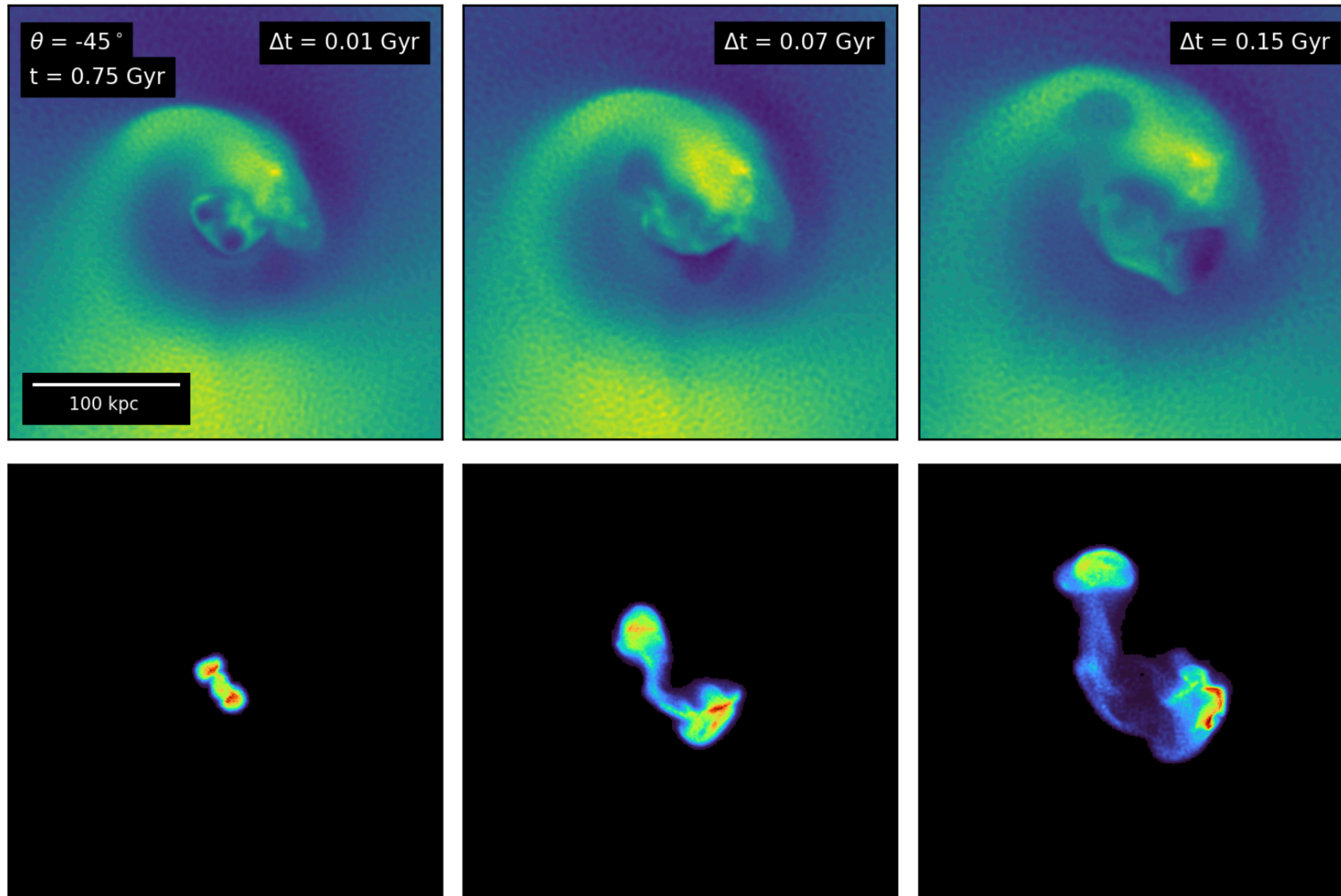
Moving/shredding old AGN bubbles in the ICM/IGrM

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



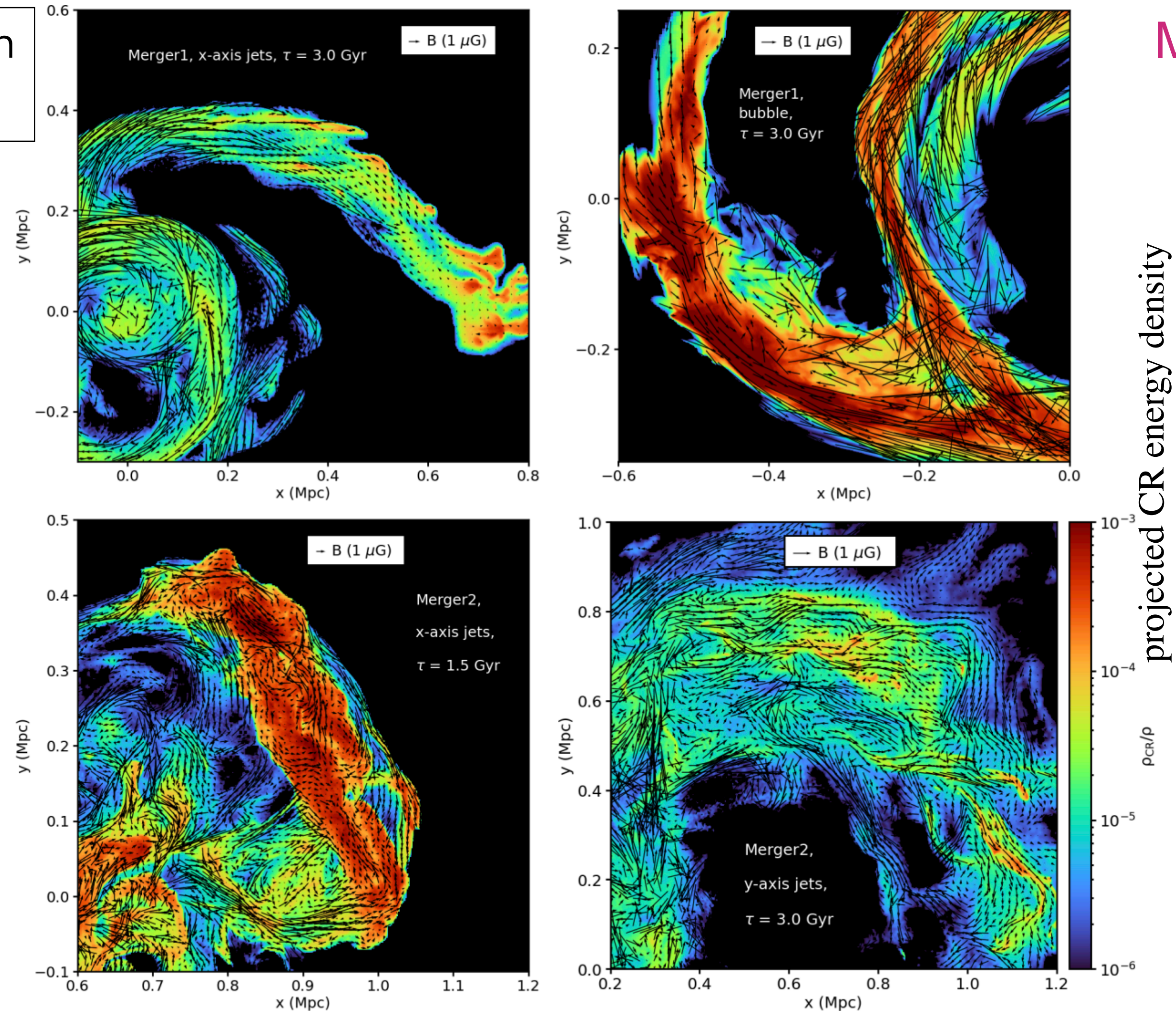
Moving/shredding old AGN bubbles in the ICM/IGrM

Sloshing
motion



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

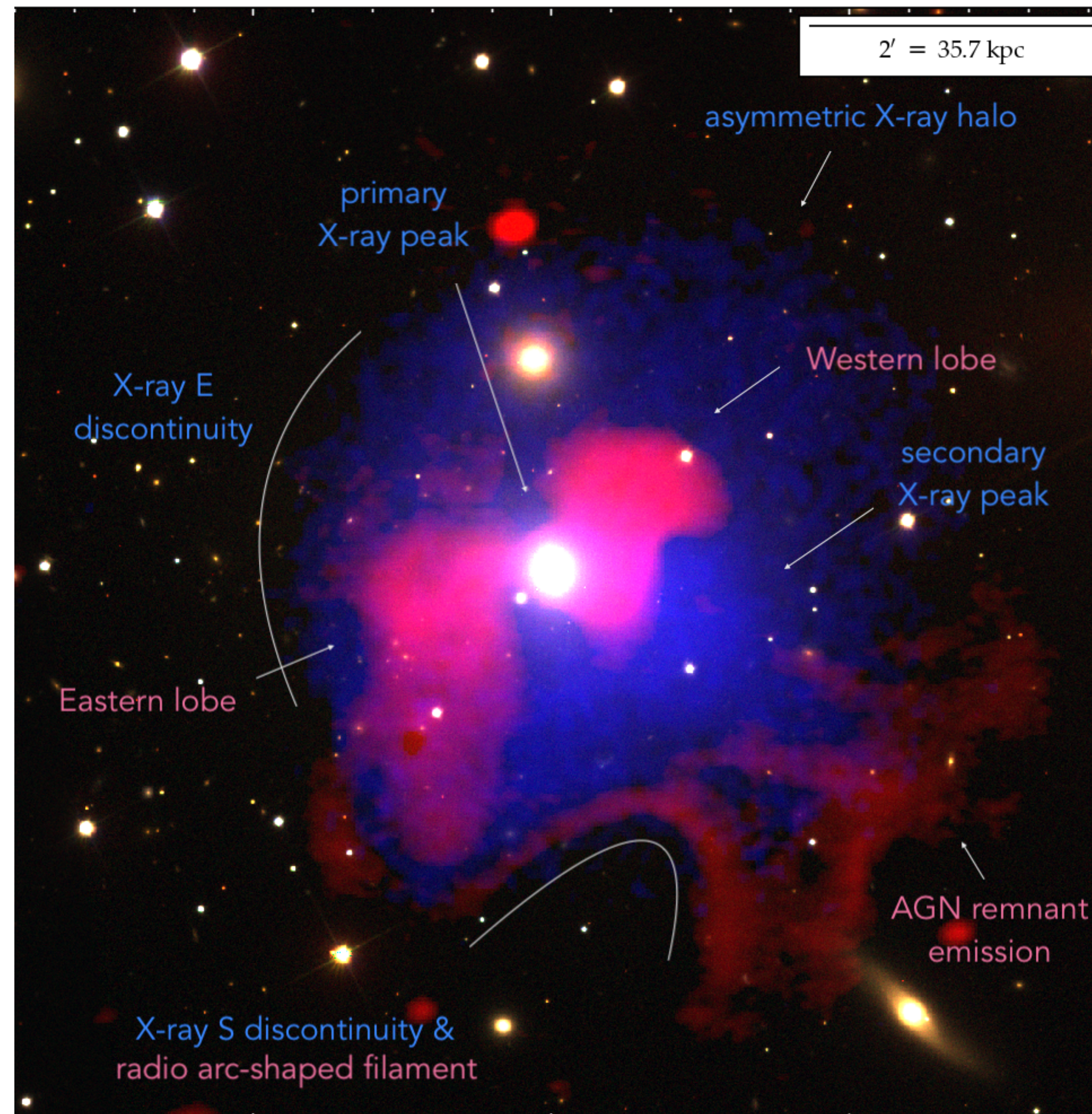
Moving/shredding old AGN bubbles in the ICM/IGrM

SDSS

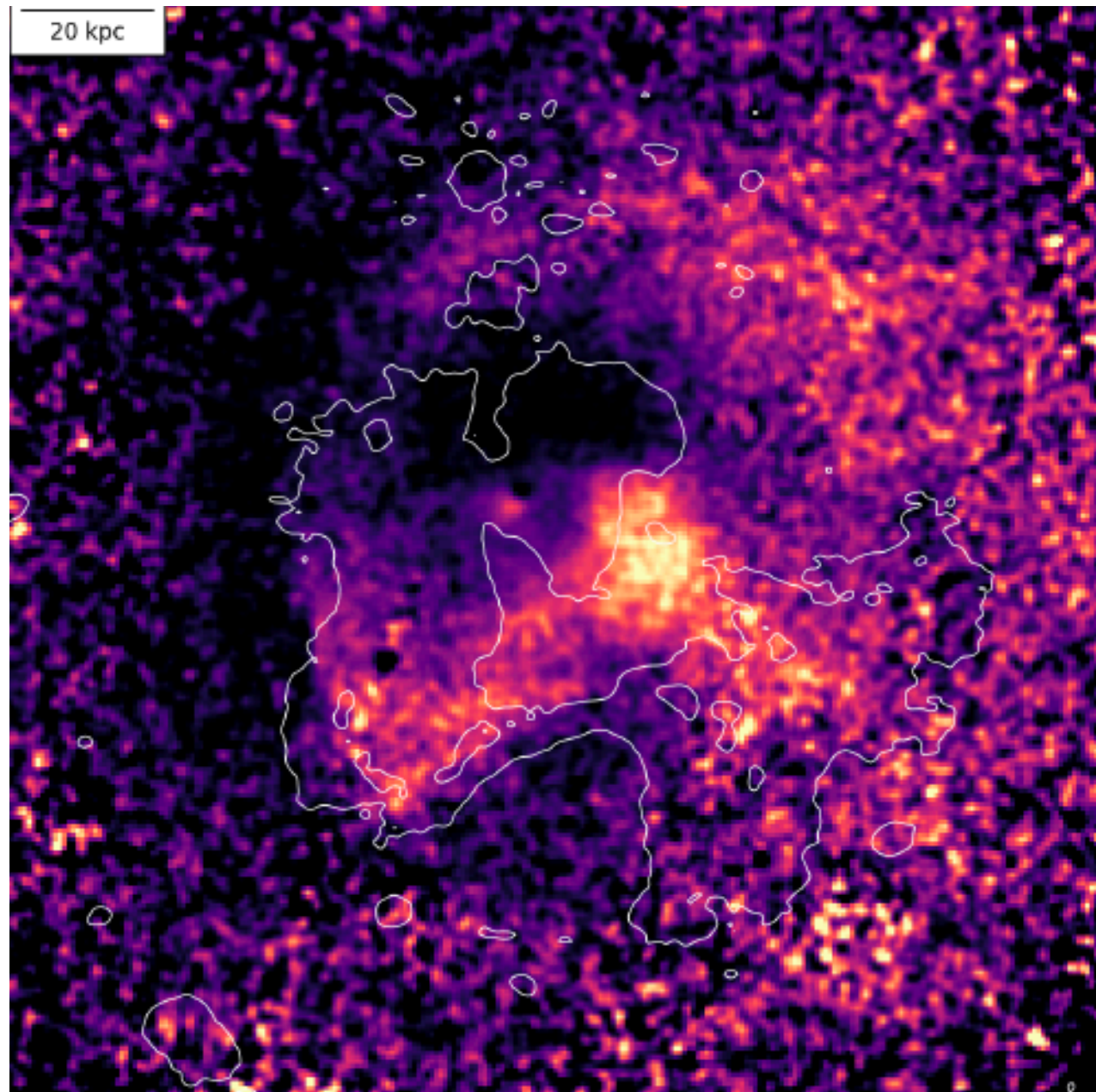
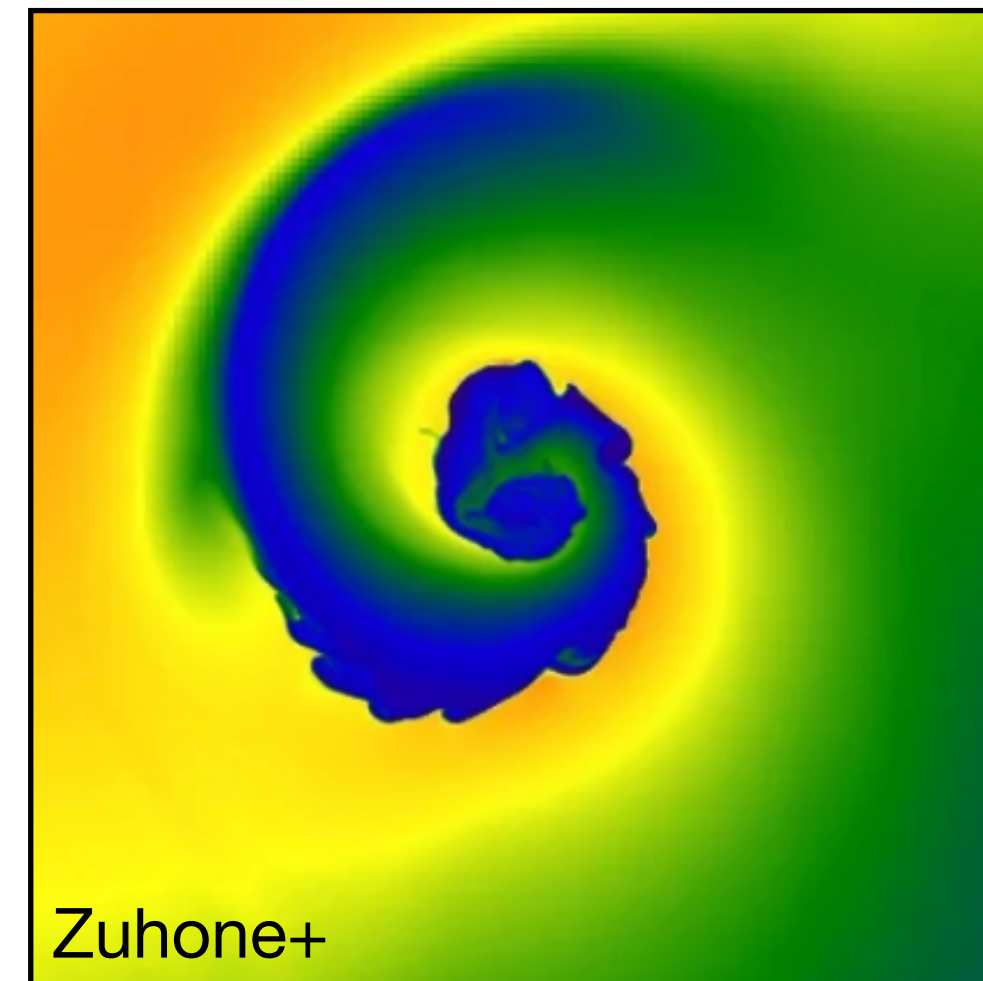
LOFAR 144 MHz - 6''

XMM 0.7-2 keV

NGC 507
Galaxy group

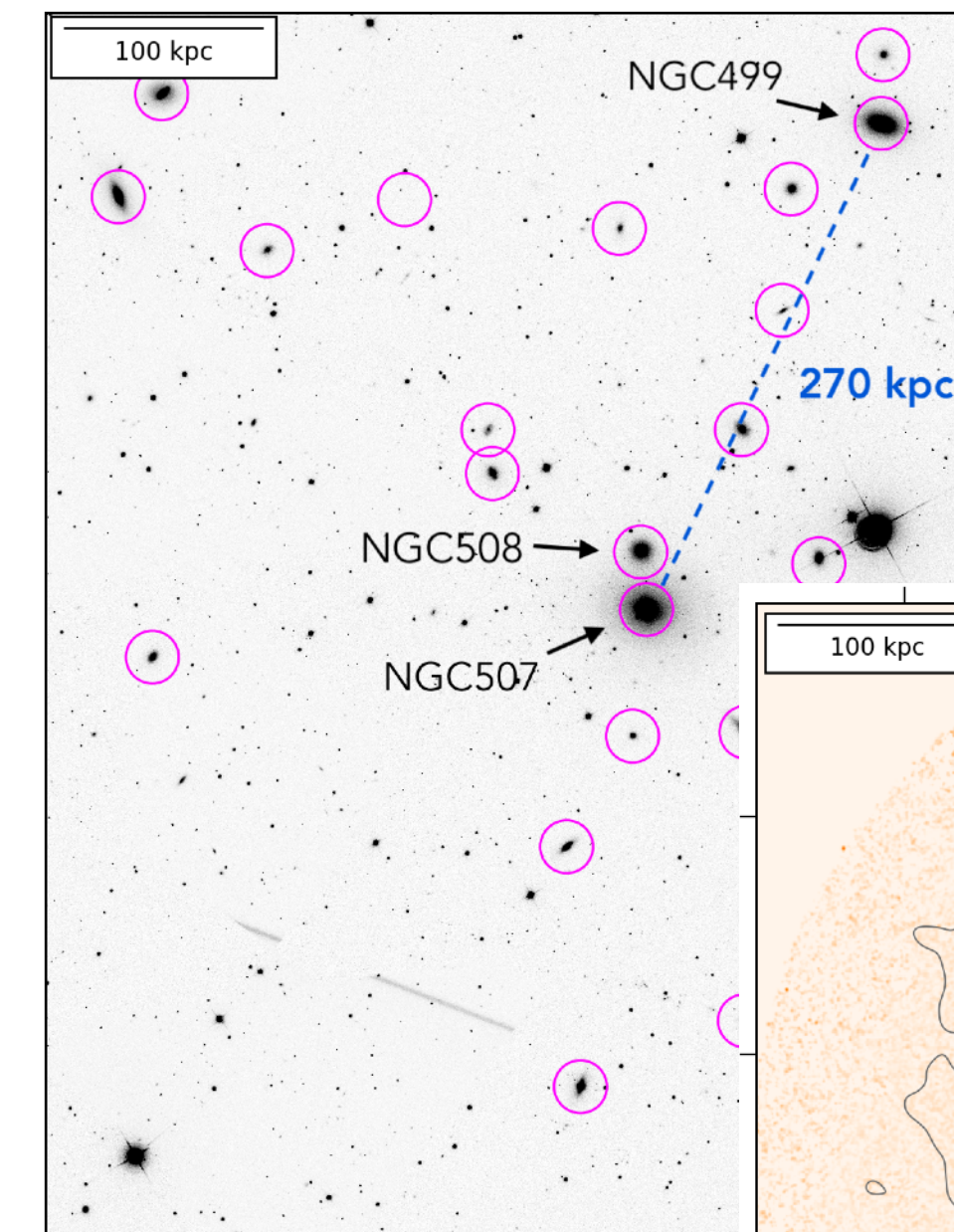


Moving/shredding old AGN bubbles in the ICM/IGrM

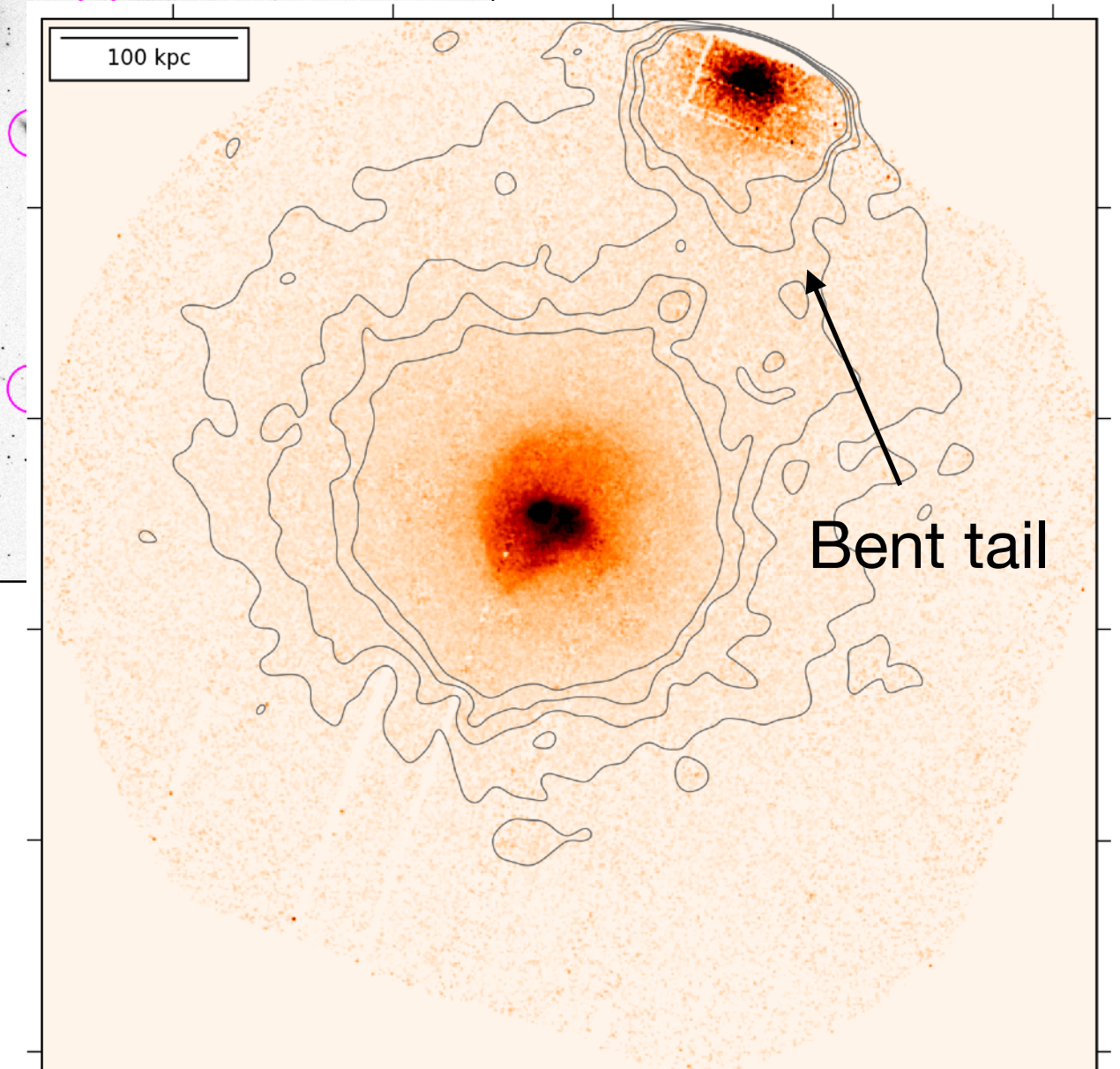


Remnant AGN plasma transported by **SLOSHING** motions during its buoyant rise in the group atmosphere, still not mixed with the IGrM (with perturber in the plane of the sky e.g. Roediger et al. 2011)

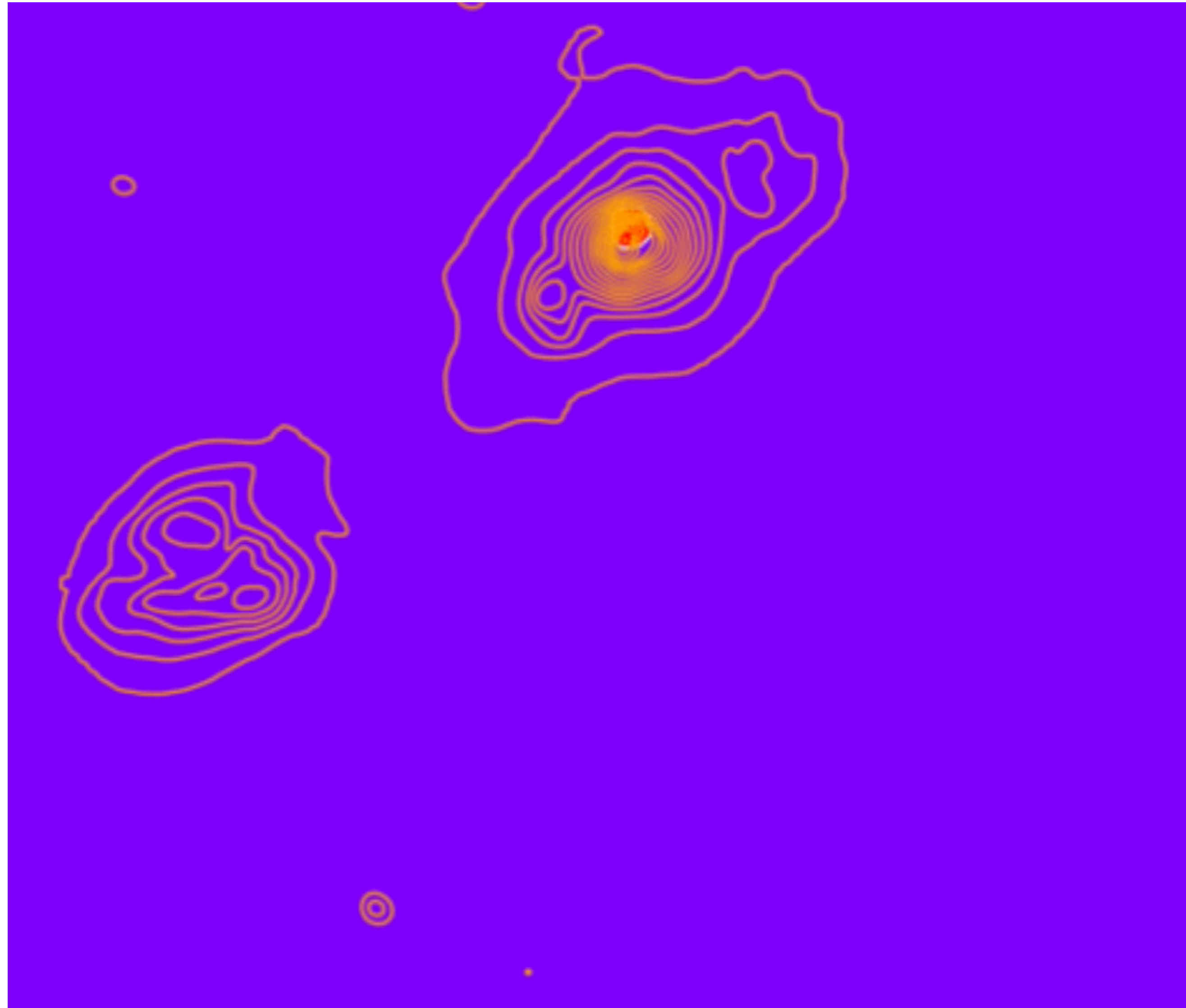
Timescales
Sloshing ~145 Myr
vs
Remnant plasma ~300 Myr



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



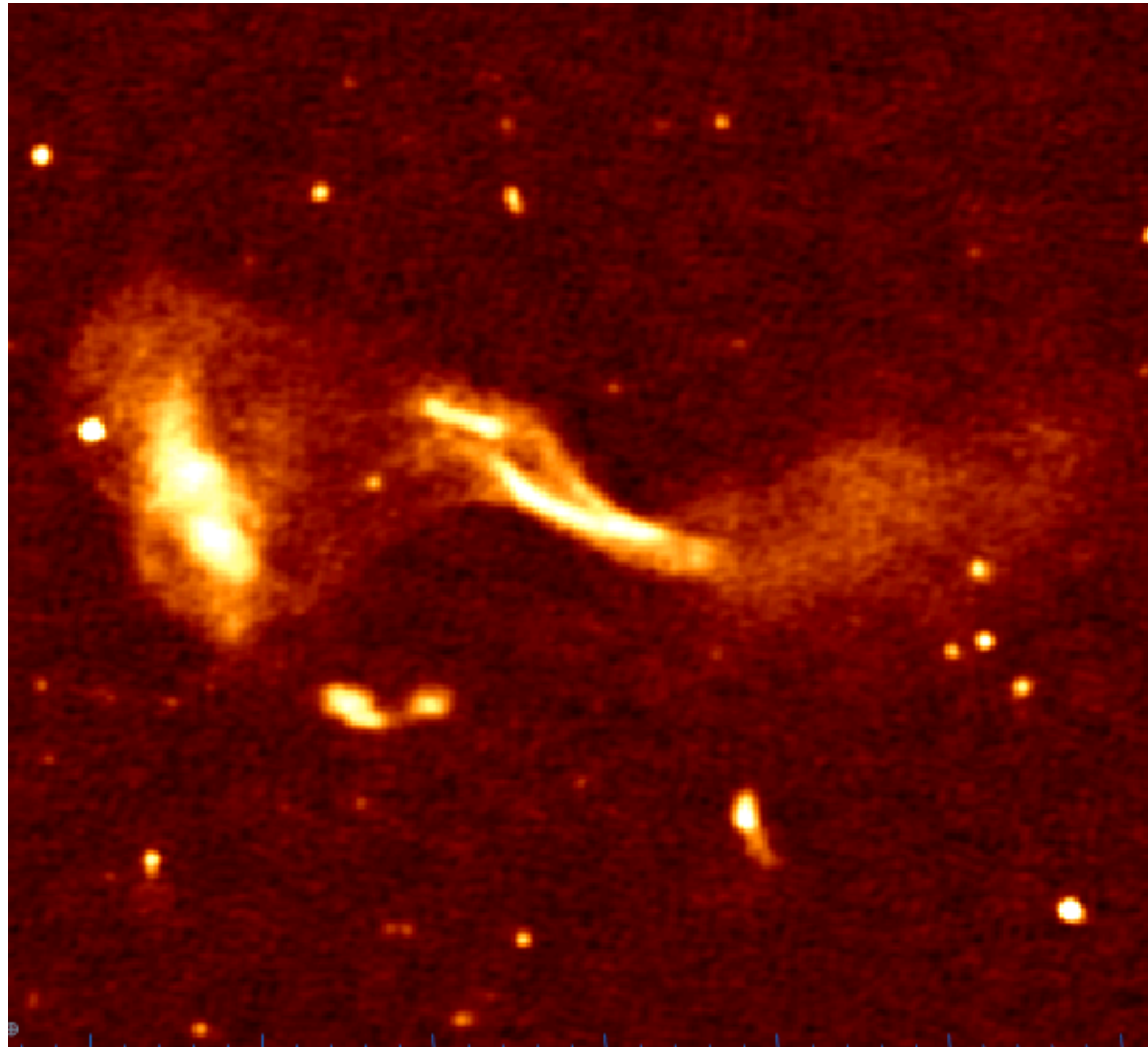
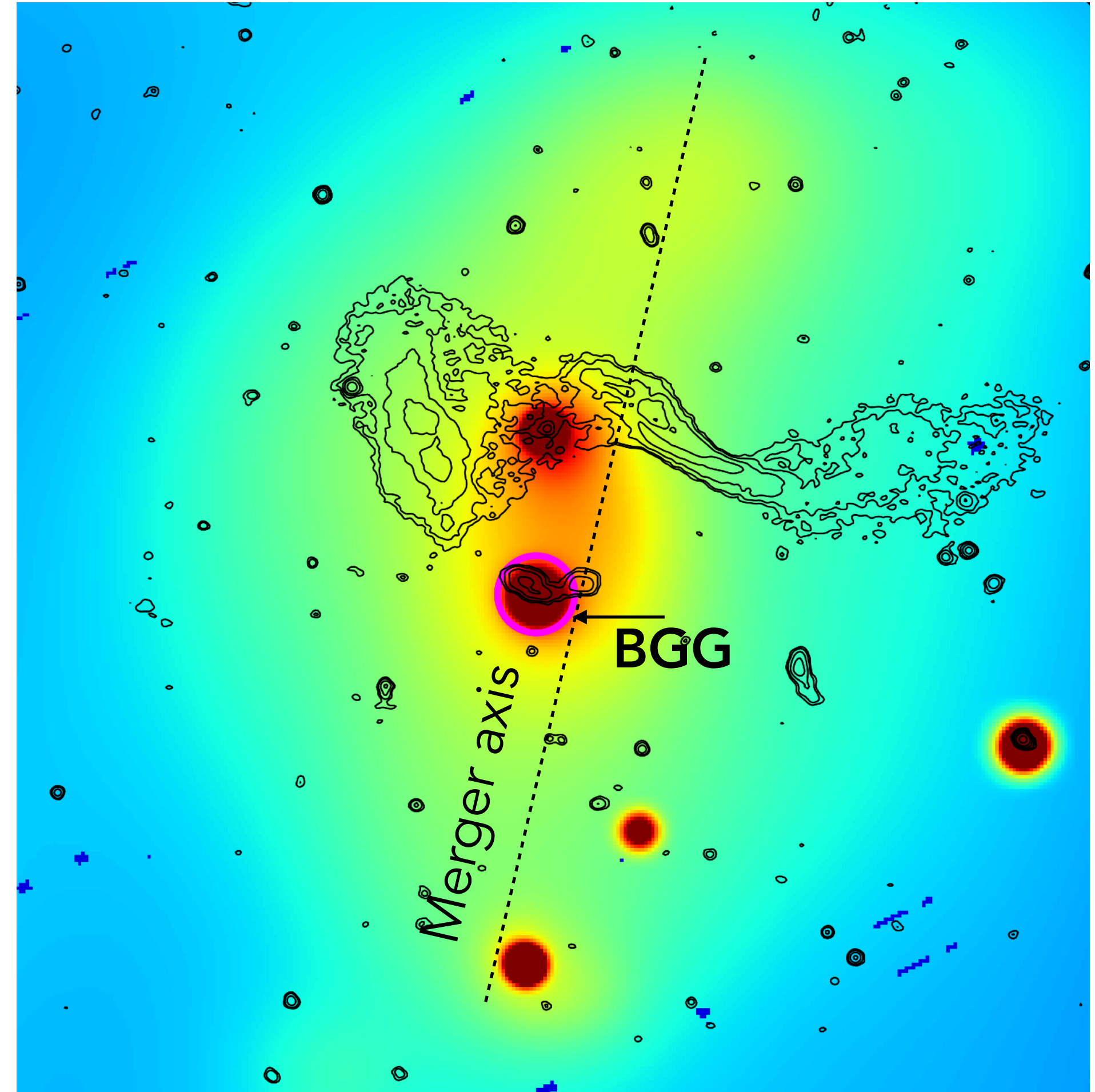
Moving/shredding old AGN bubbles in the ICM/IGrM



Moving/shredding old AGN bubbles in the ICM/IGrM

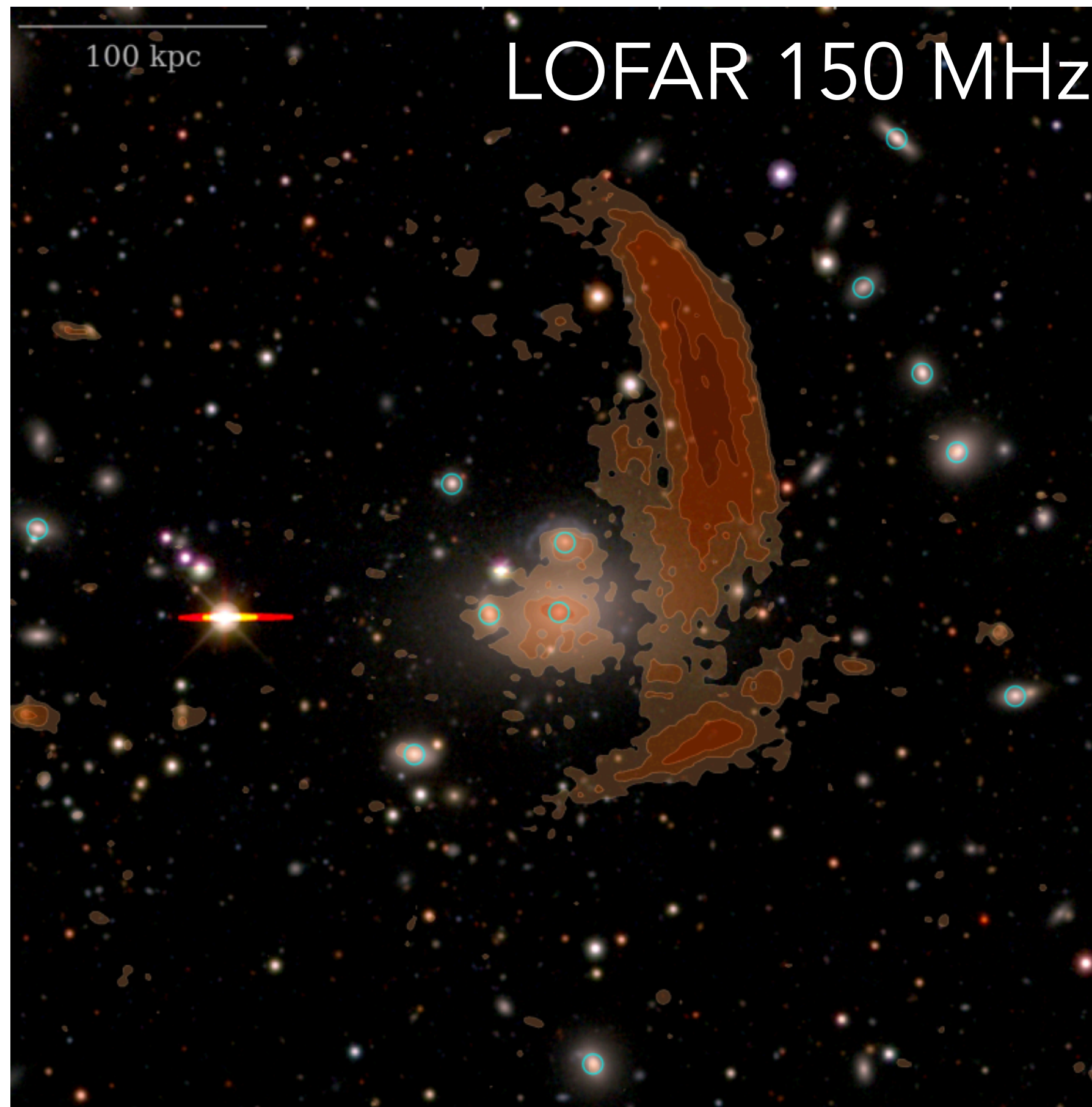
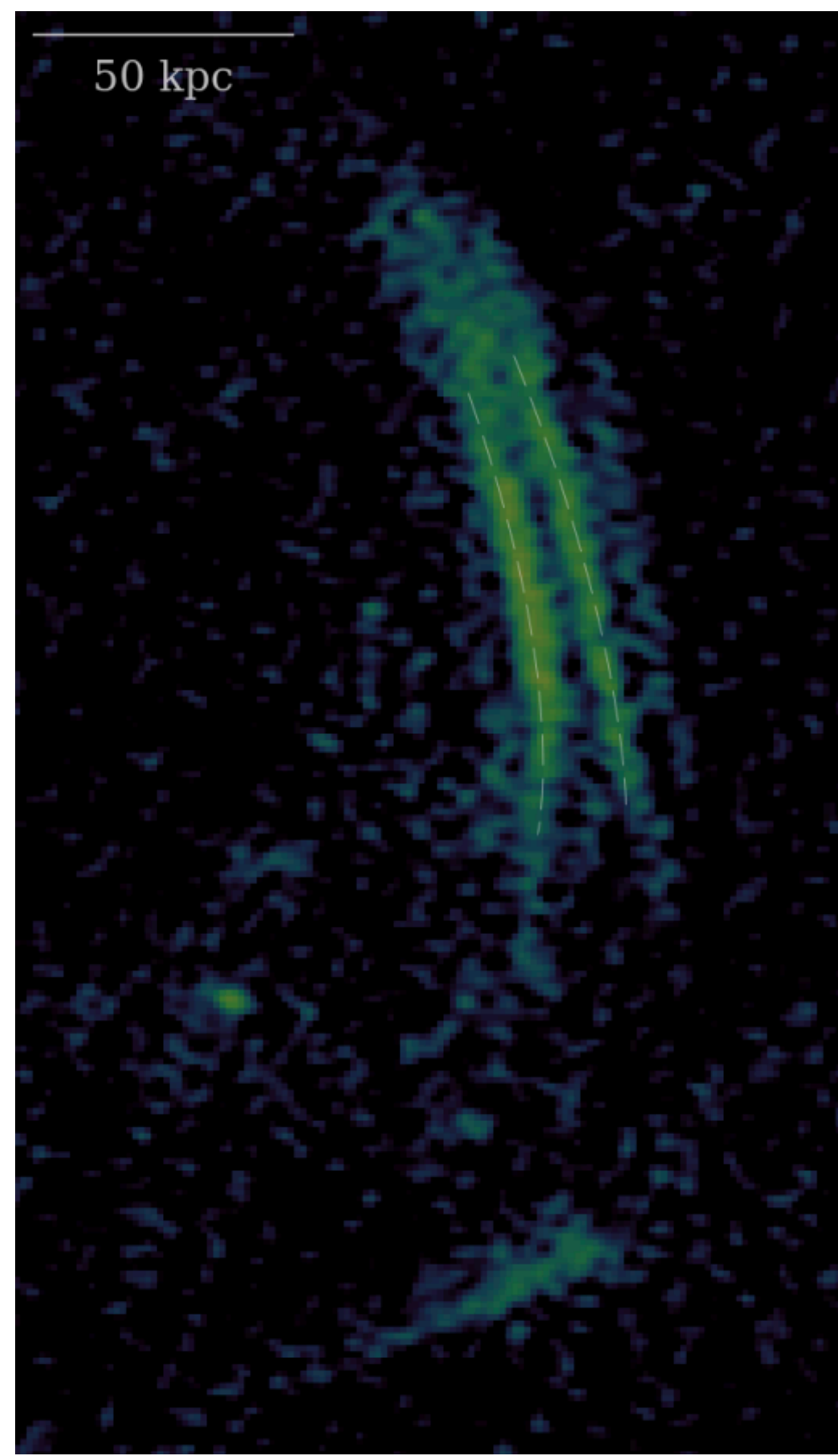
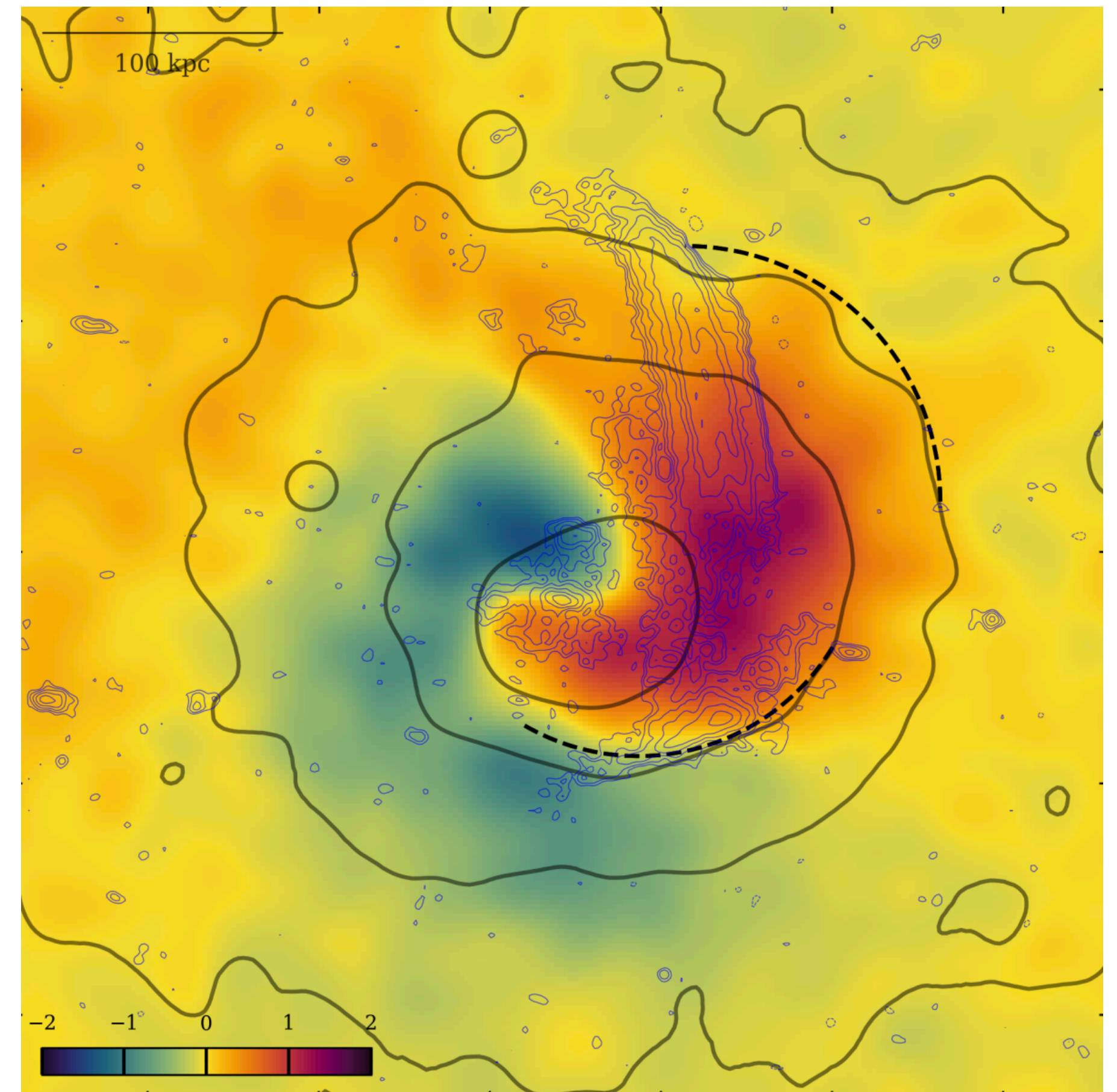
A1318 galaxy group

250 Myr plasma from radio spectra

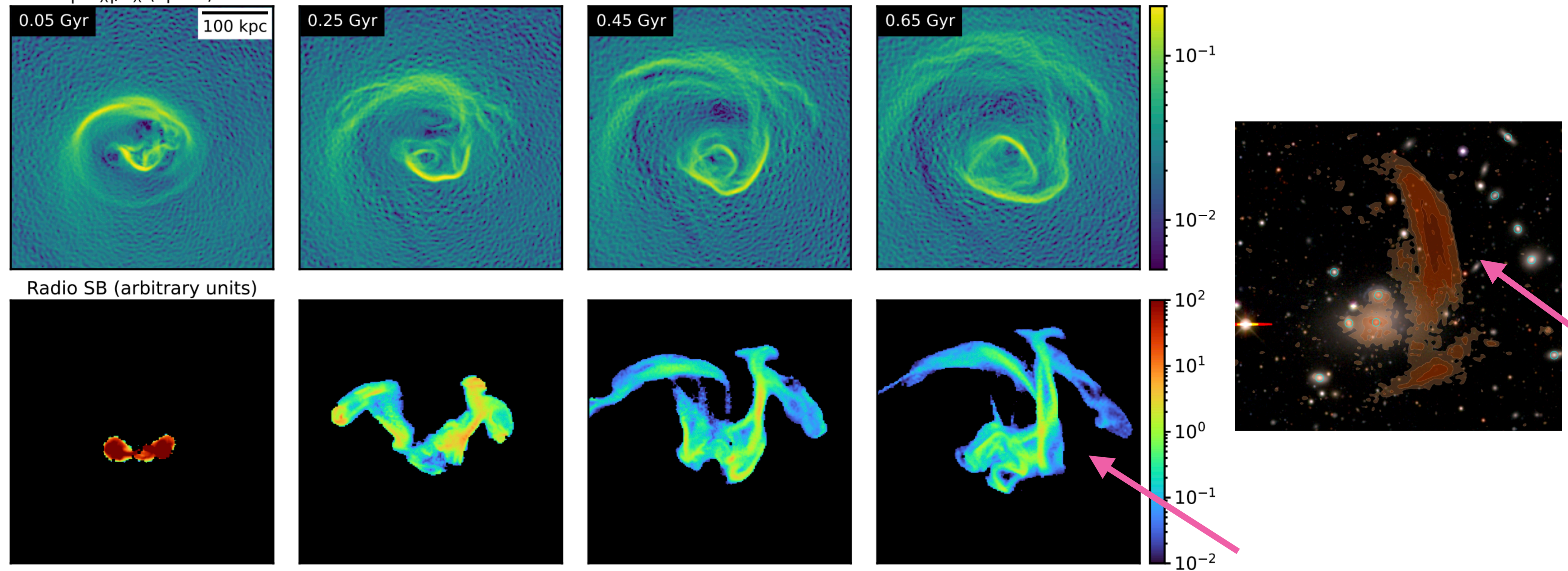


Moving/shredding old AGN bubbles in the ICM/IGrM

Abell2657



Moving/shredding old AGN bubbles in the ICM/IGrM

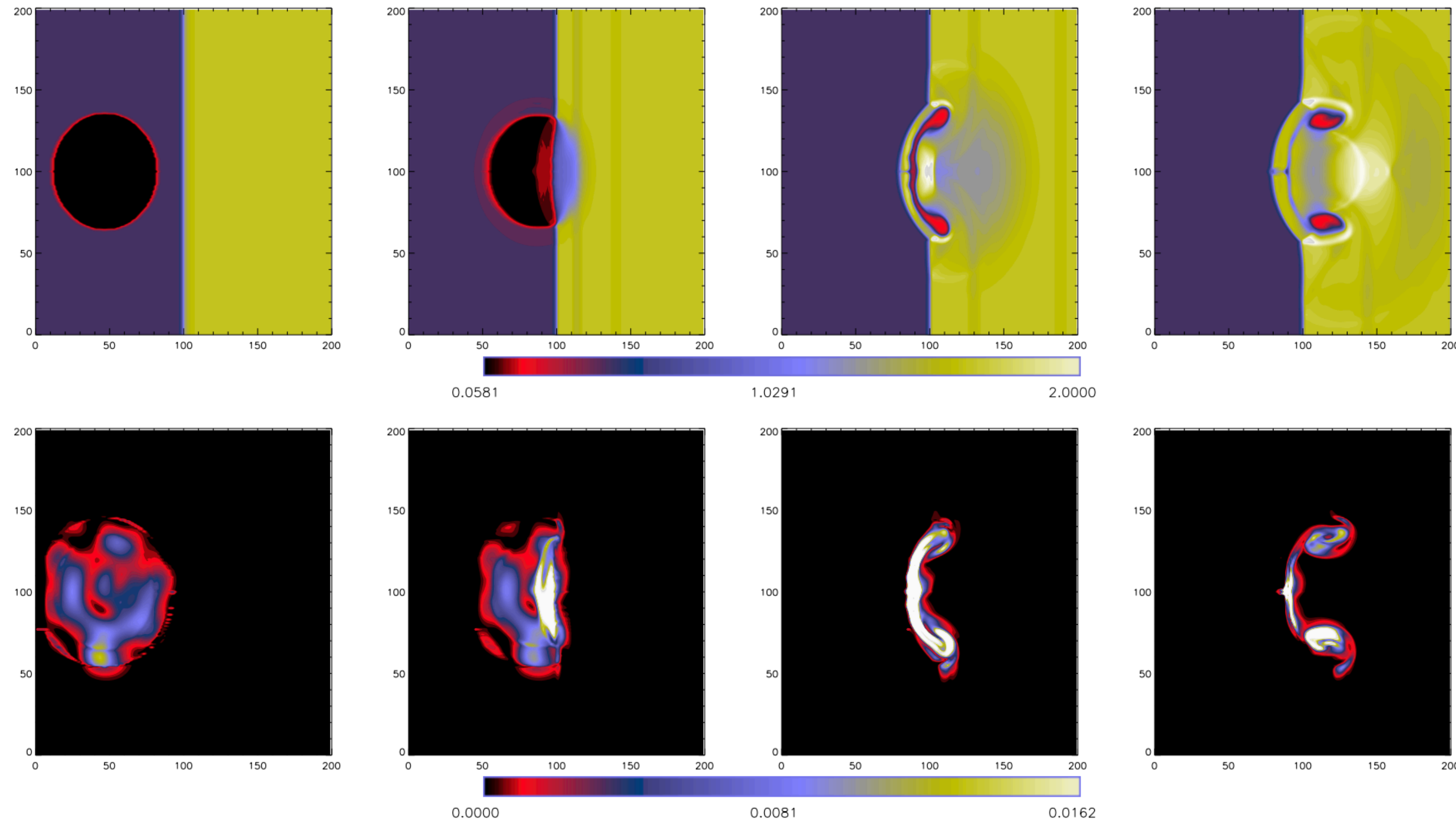


Revived old AGN plasma/bubbles... radio phoenixes

Old AGN
bubble
crossed by a
shock

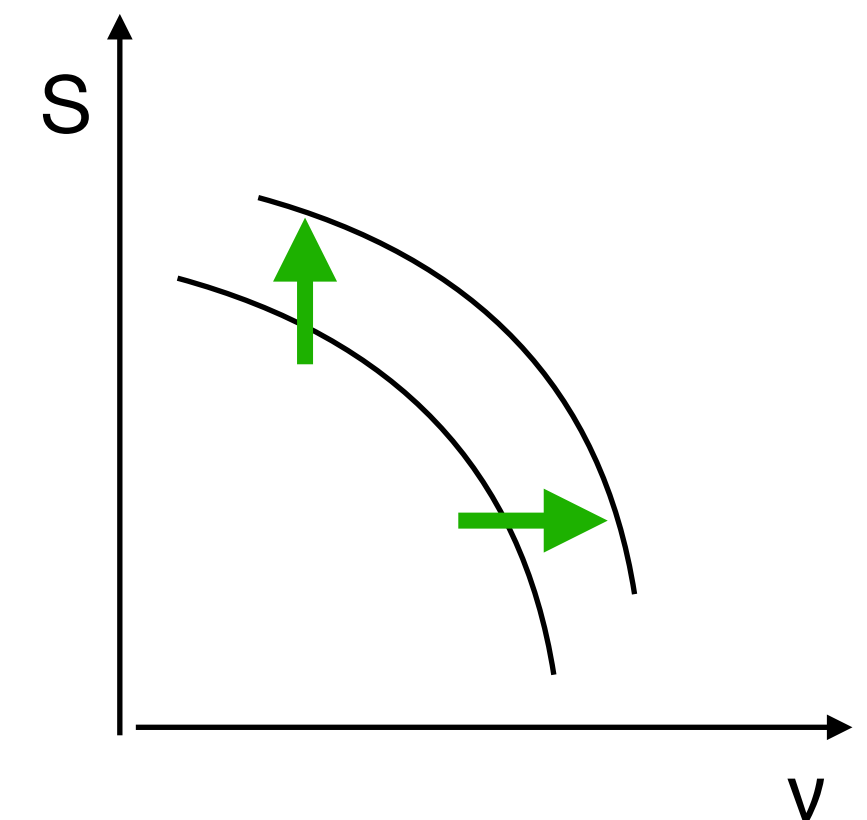
First
compressed
then torn into
filamentary
structures

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!



Time

Revived old AGN plasma/bubbles... radio phoenixes

Magnetic field parallel to filaments

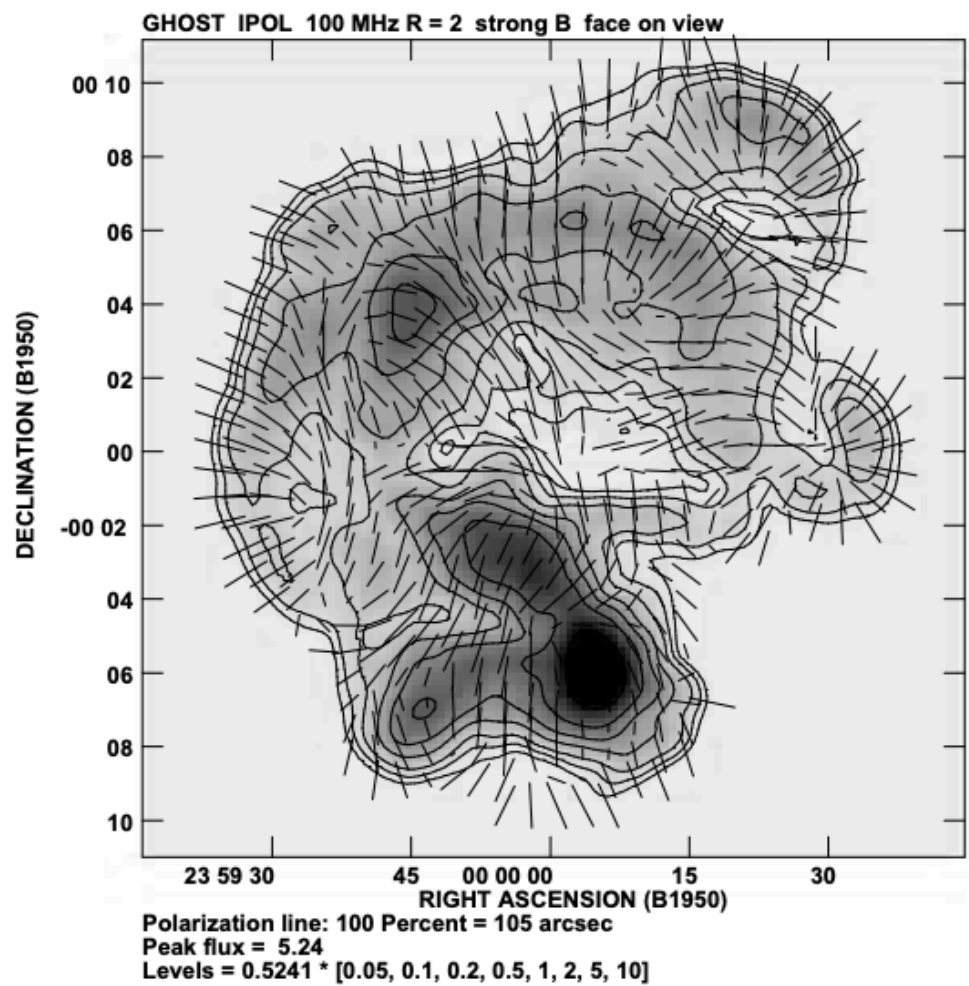


Figure 7. Face-on view of the late stage of the shock passage in the model *wSsB*. For details see Fig. 5.

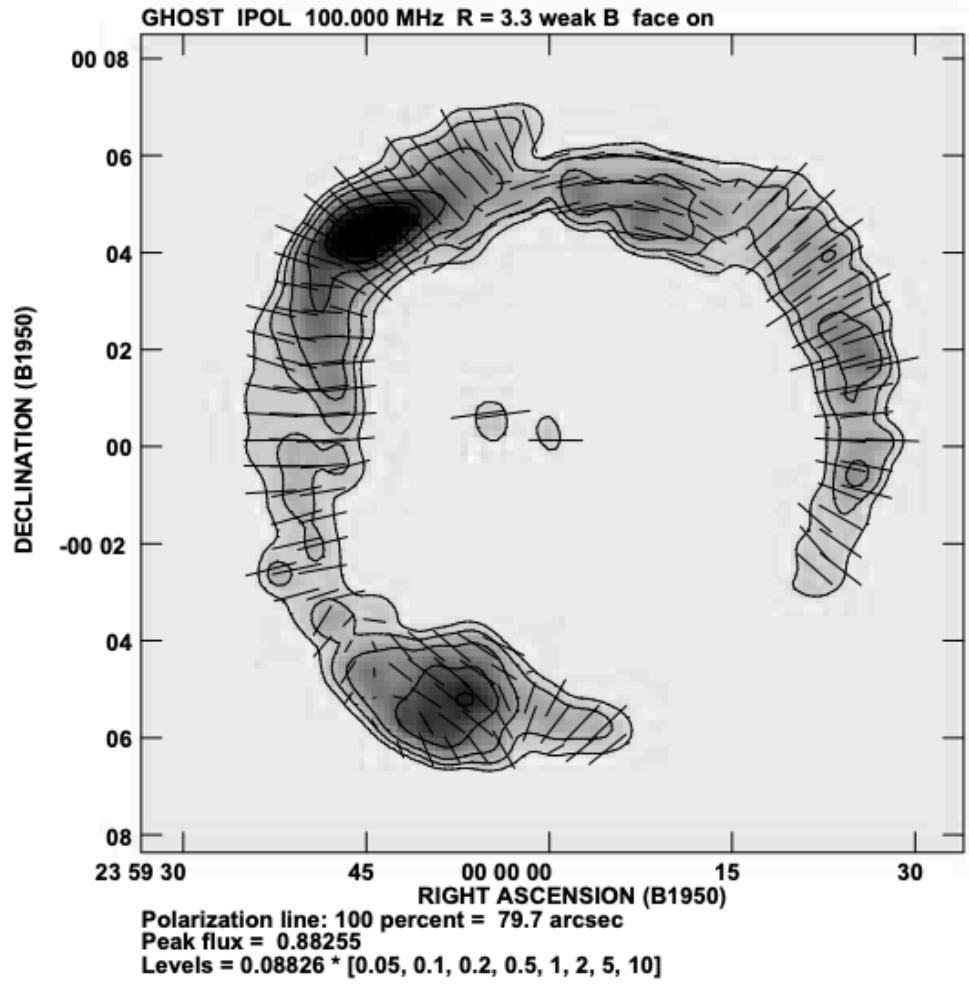
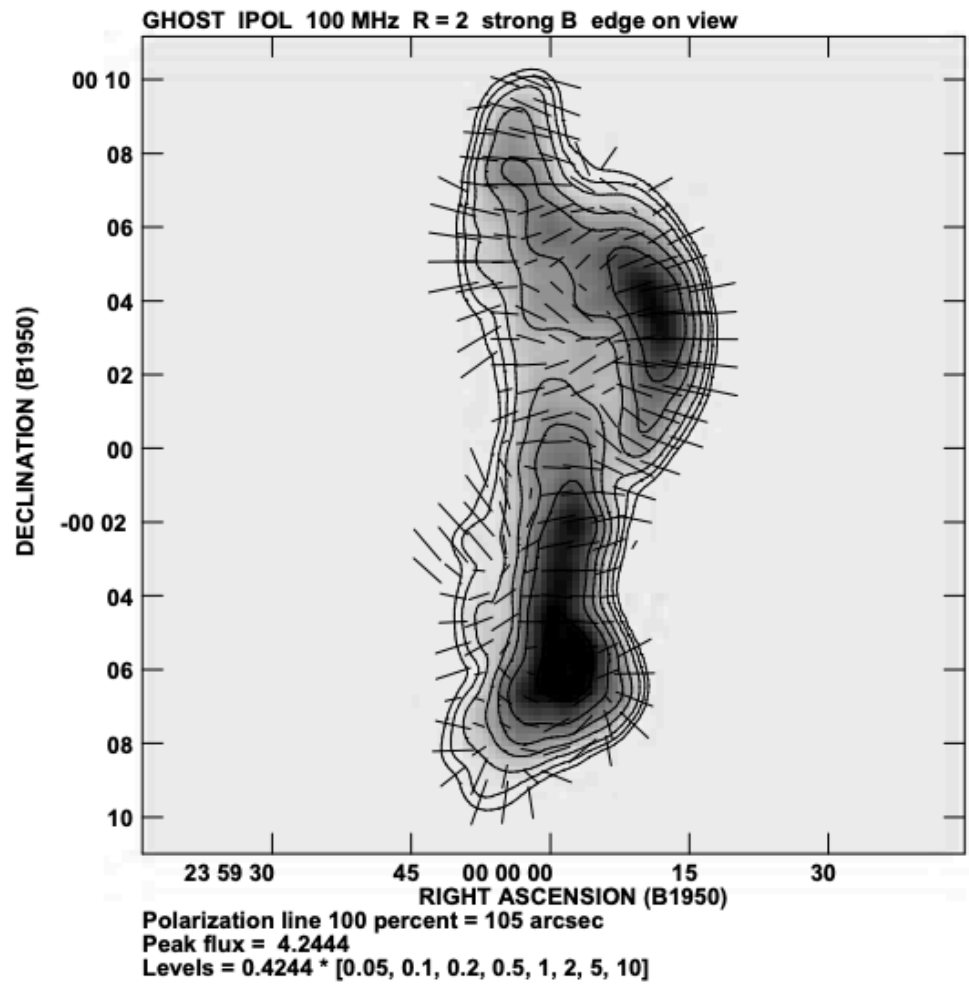
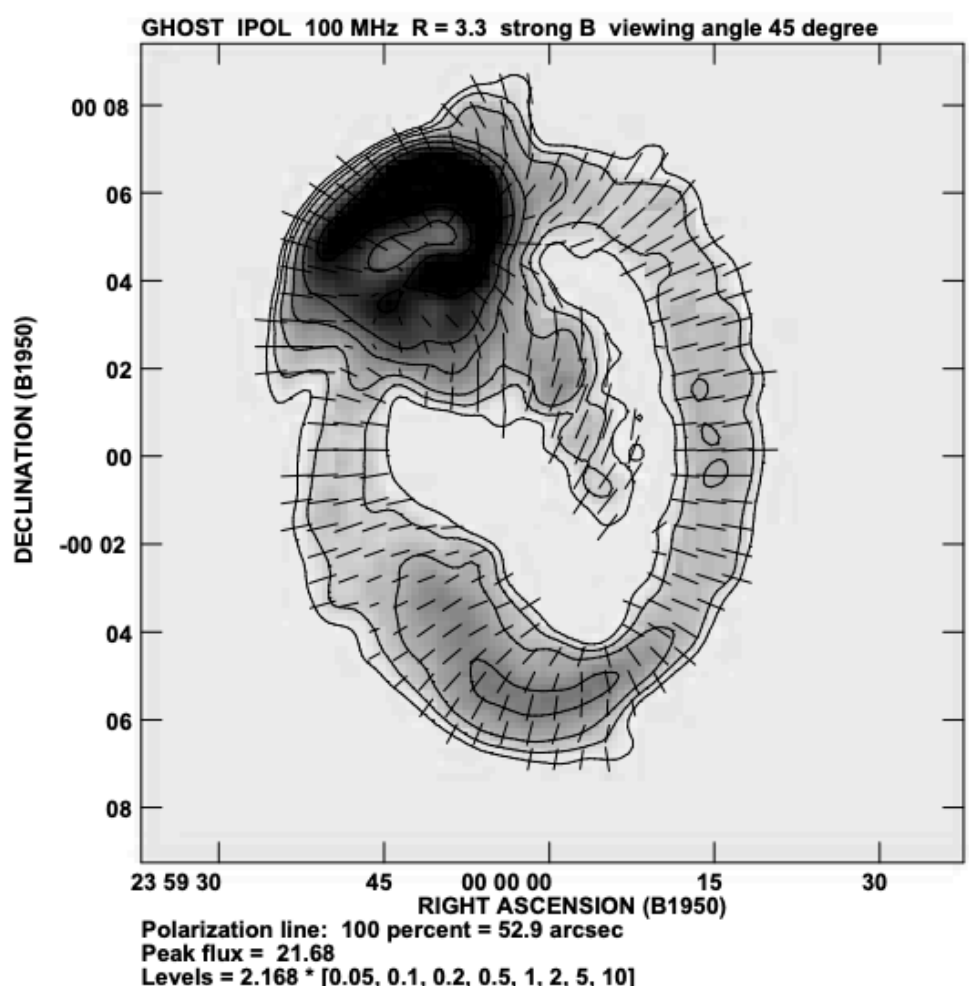


Figure 9. Face-on view of the late stage of the shock passage in the model *sSwB*. For details see Fig. 5.



Revived old AGN plasma/bubbles... radio phoenixes

Compression factor

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

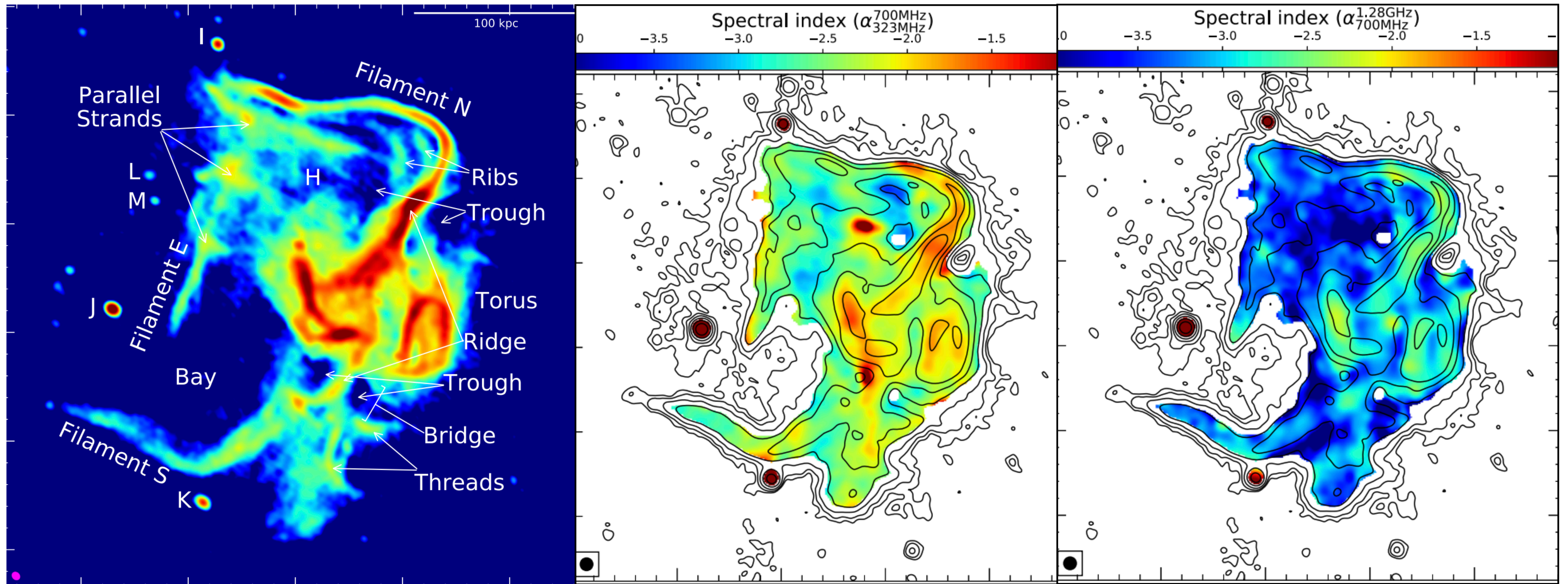
Pressure ratio (before and after the shock passage)

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

Mach number

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

Revived old AGN plasma/bubbles... radio phoenixes

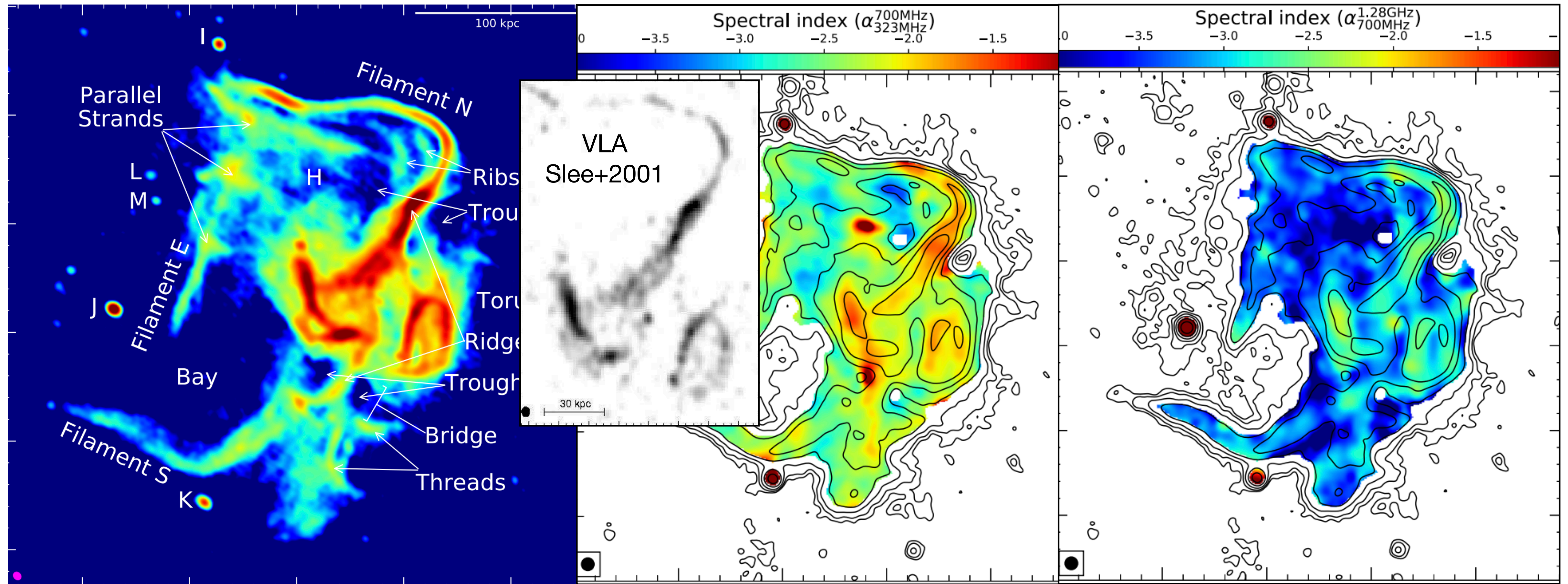


Raja+2024

Remember: steeper = older!

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

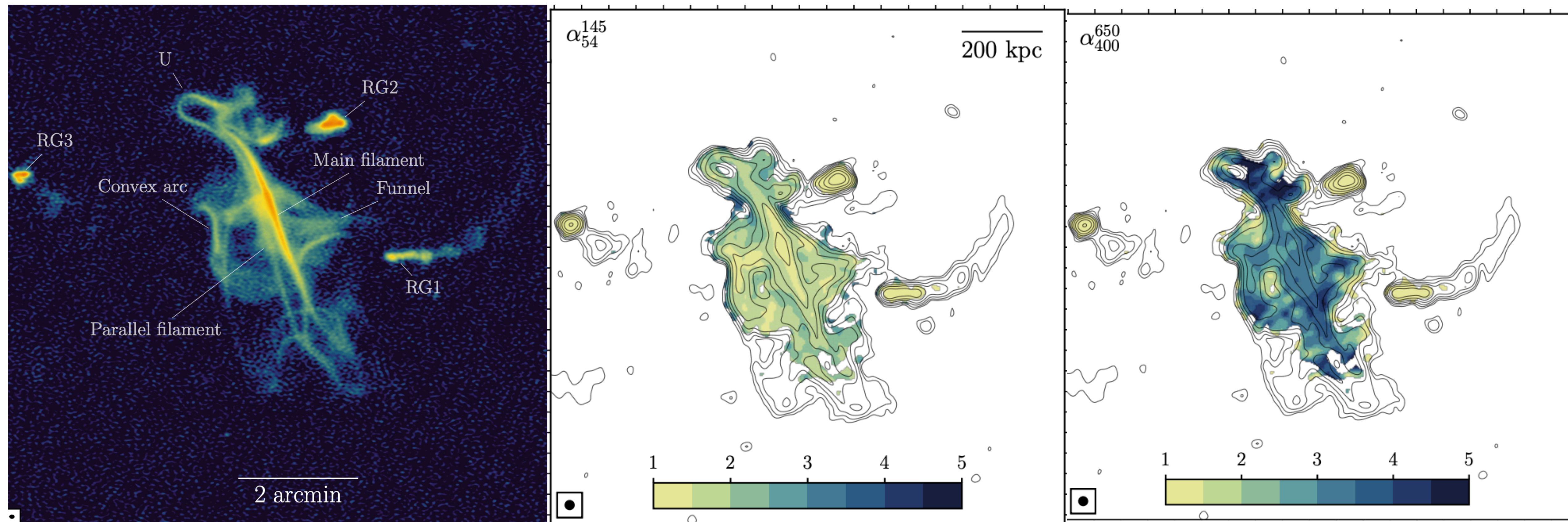
Revived old AGN plasma/bubbles... radio phoenixes



Raja+2024

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

Revived old AGN plasma/bubbles... radio phoenixes



VLSSJ0318.9+5755

Botteon+2026

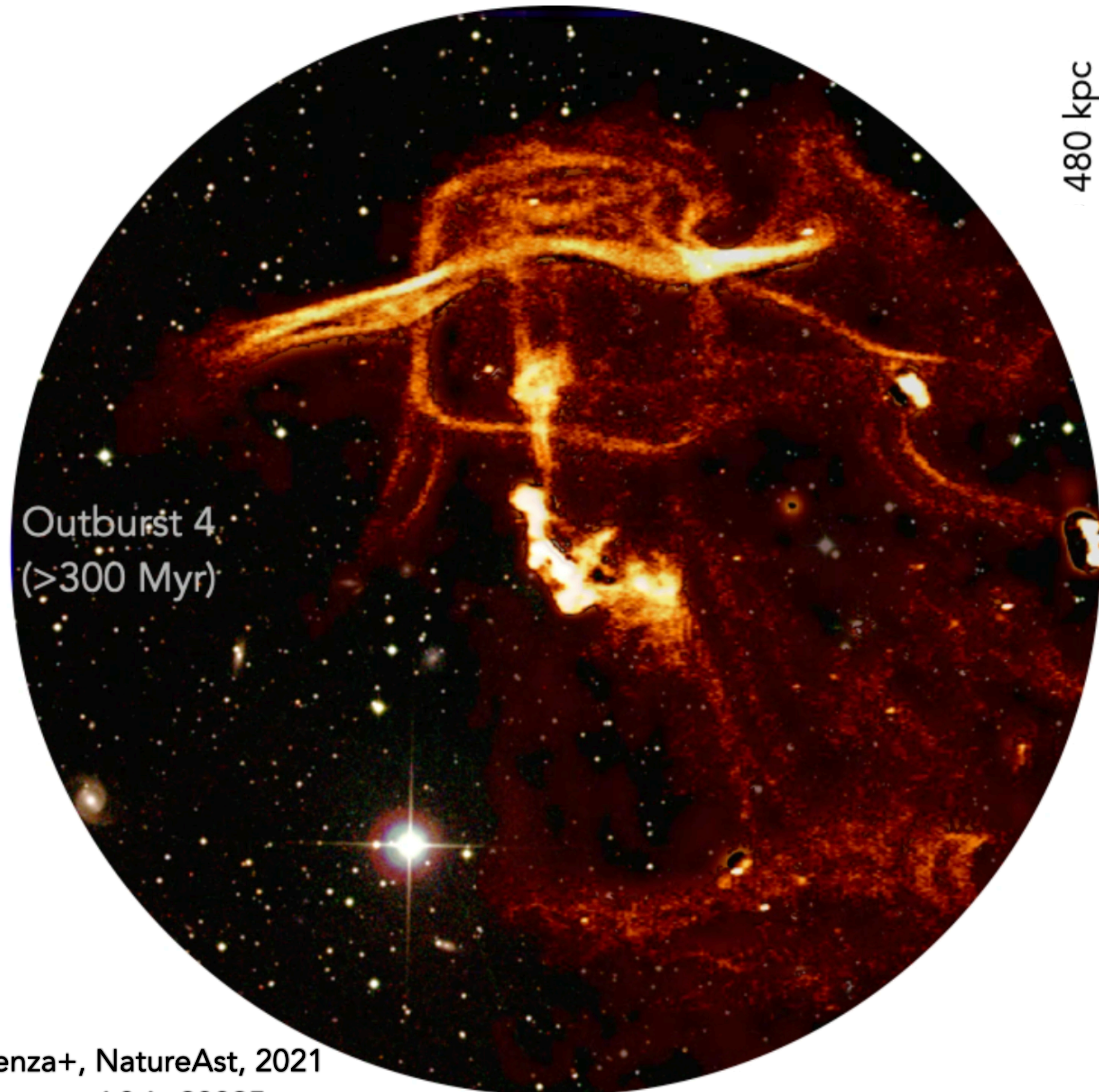
But also e.g. slee2001, ensslin2002, kempner2004, vanweeren2009, degasperin2015, Giovannini+1999; Kale & Dwarakanath 2012

Nest200047

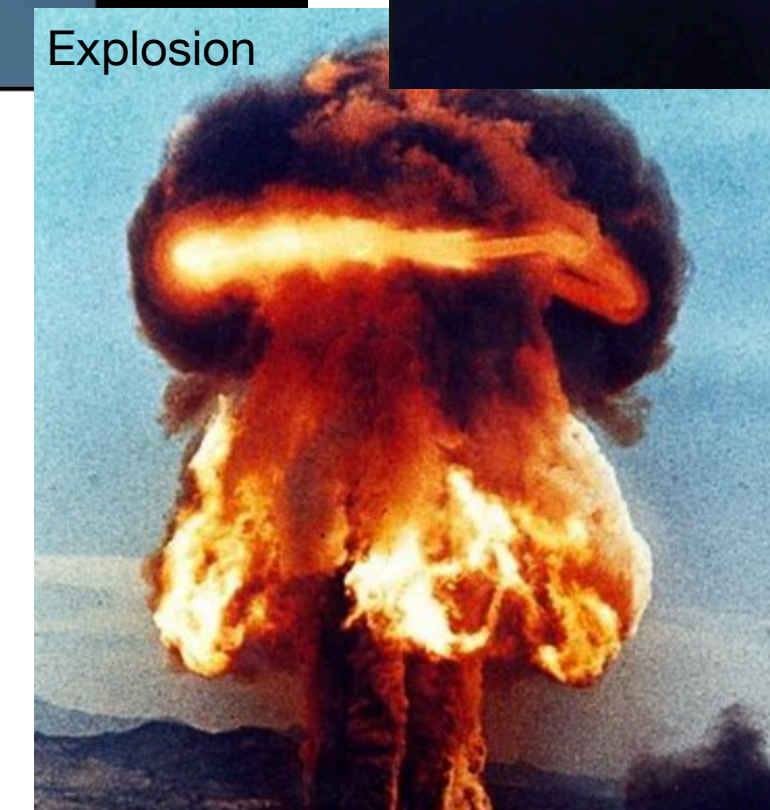


- Galaxy group $\sim 6e13$ Msun, $z=0.018$, $\log M_{\text{gal}}=11.56$
- **Multiple generations** of AGN bubbles (not aligned!)
Oldest ~ 400 Myr

Nest200047

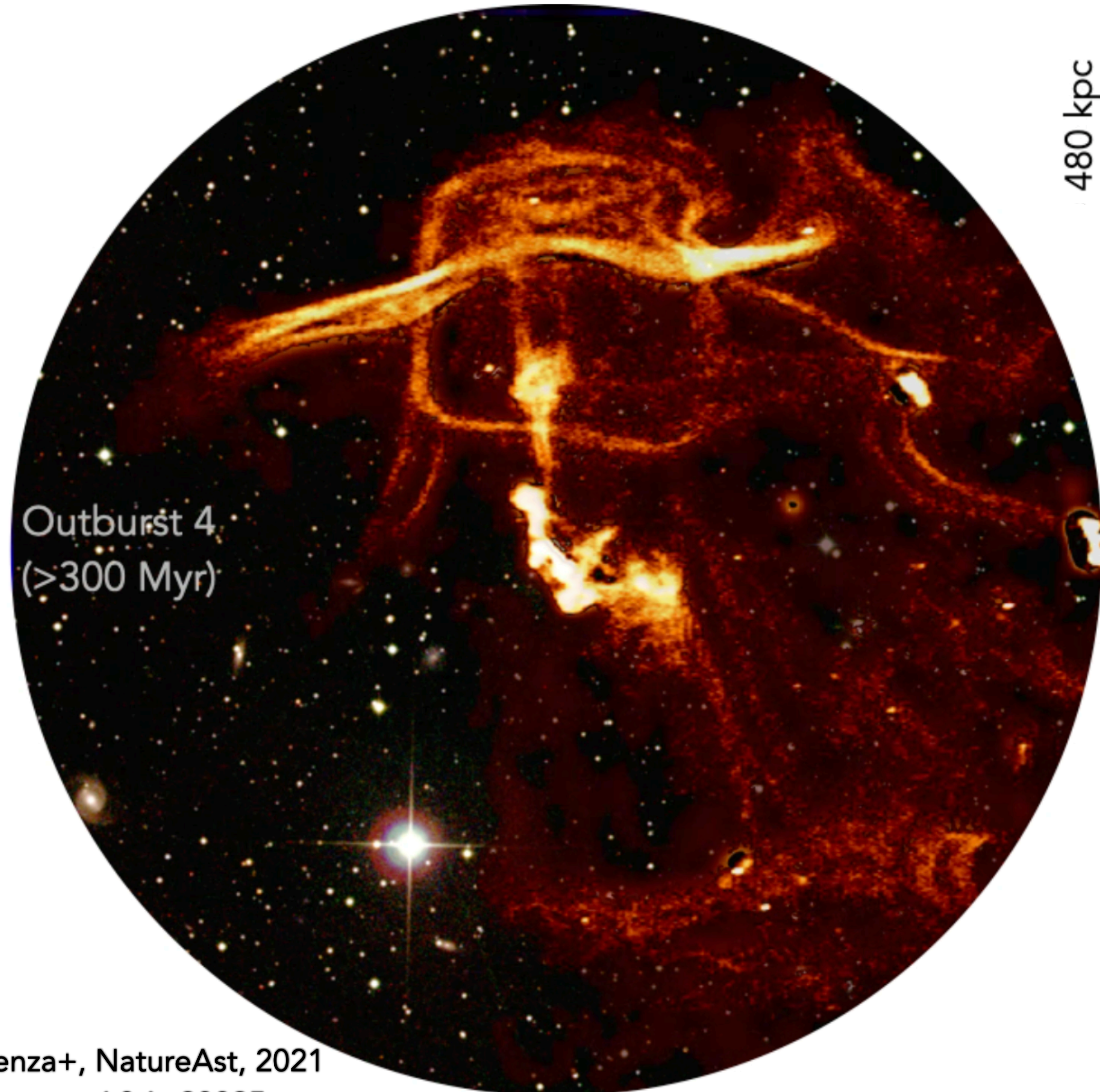


- Galaxy group $\sim 6e13$ Msun, $z=0.018$, $\log M_{\text{gal}}=11.56$
- **Multiple generations** of AGN bubbles (not aligned!)
Oldest ~ 400 Myr



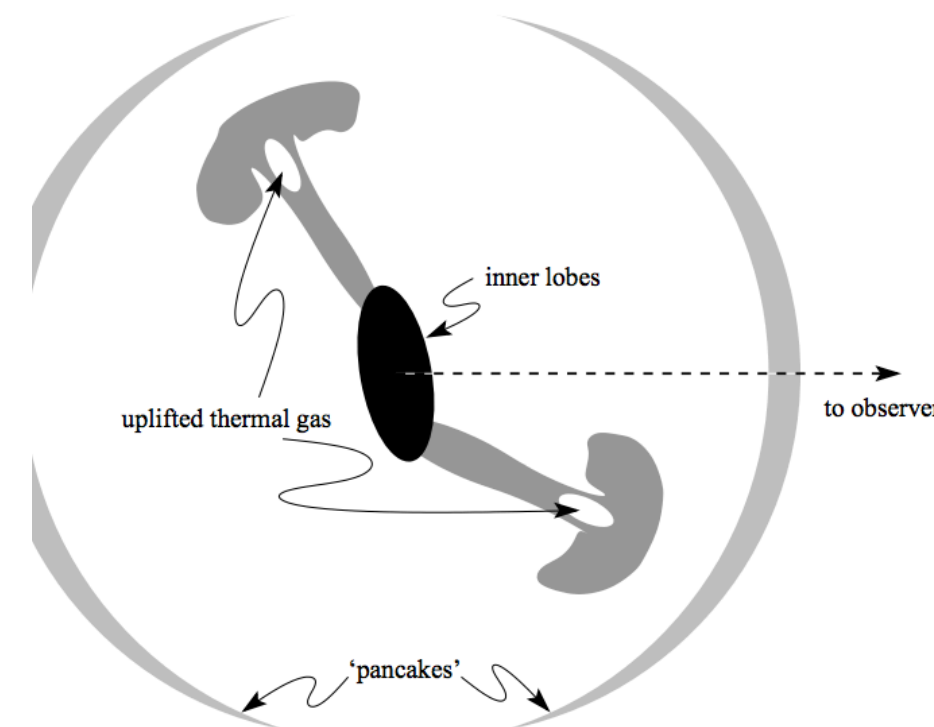
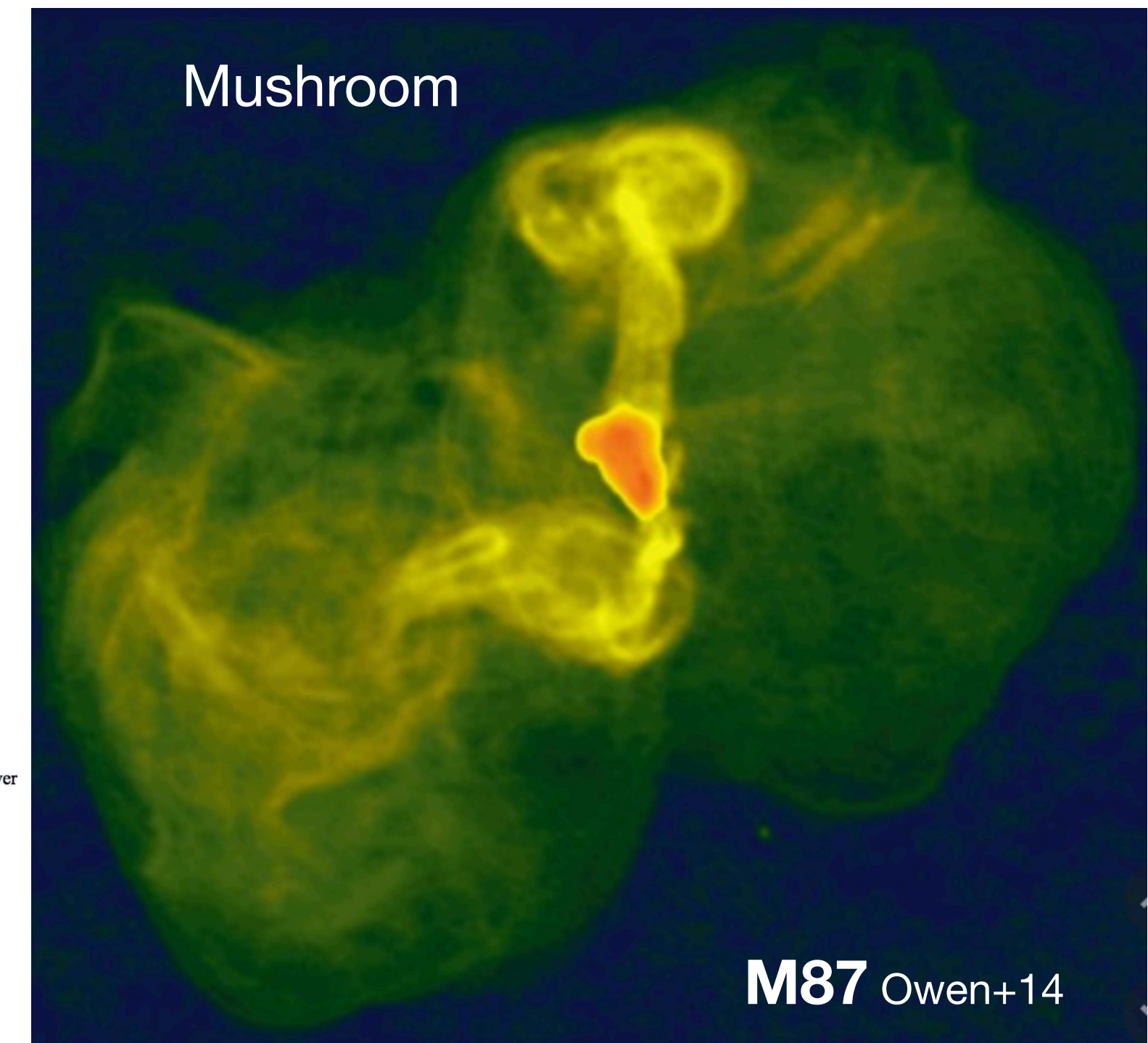
Pressure gradient present
around the bubble transforms
a roughly spherical bubble into
a torus (vortex ring)

Nest200047

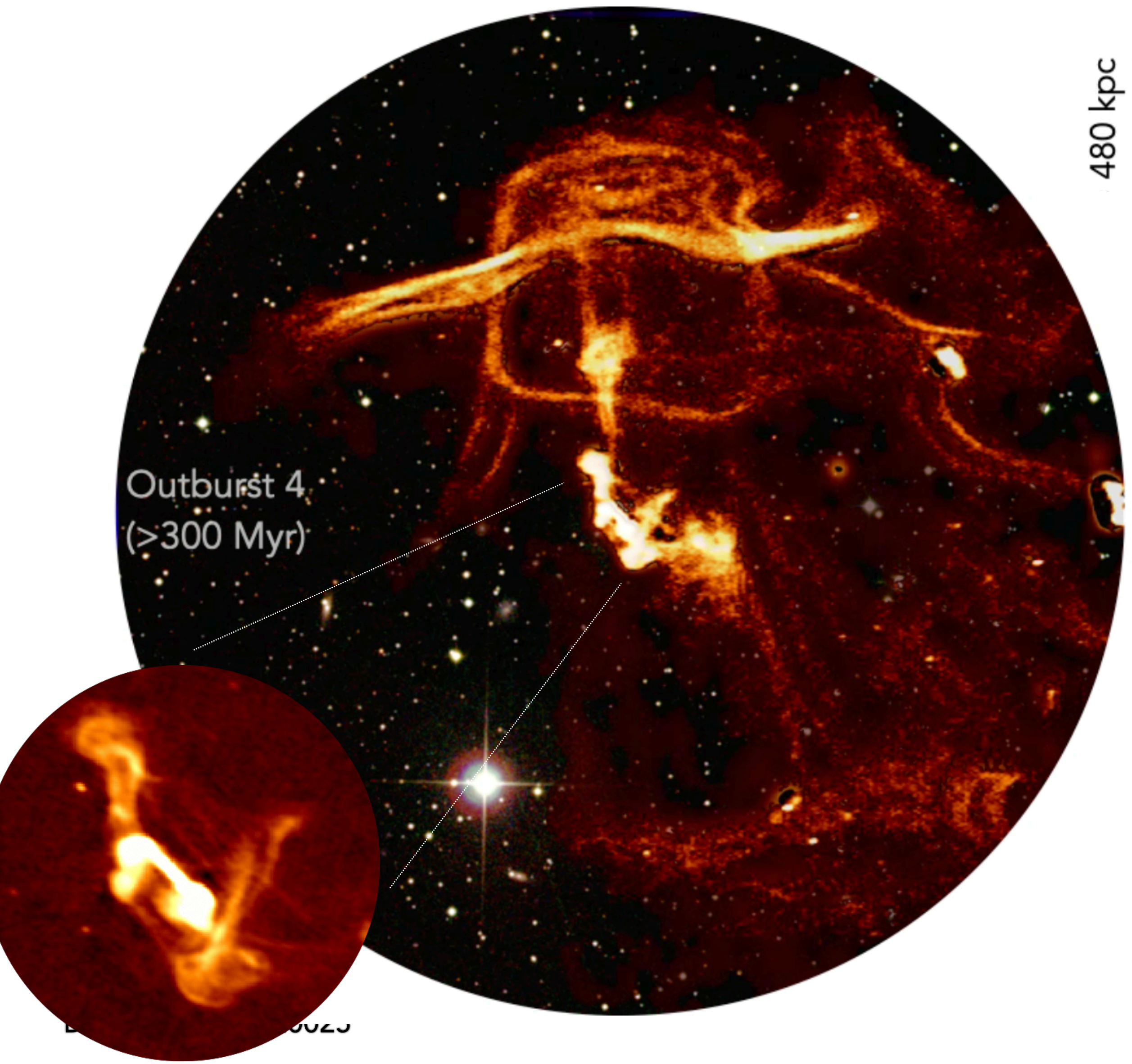


- Galaxy group $\sim 6e13$ Msun, $z=0.018$, $\log M_{\text{gal}}=11.56$
- **Multiple generations** of AGN bubbles (not aligned!)
Oldest ~ 400 Myr

Churazov+2001



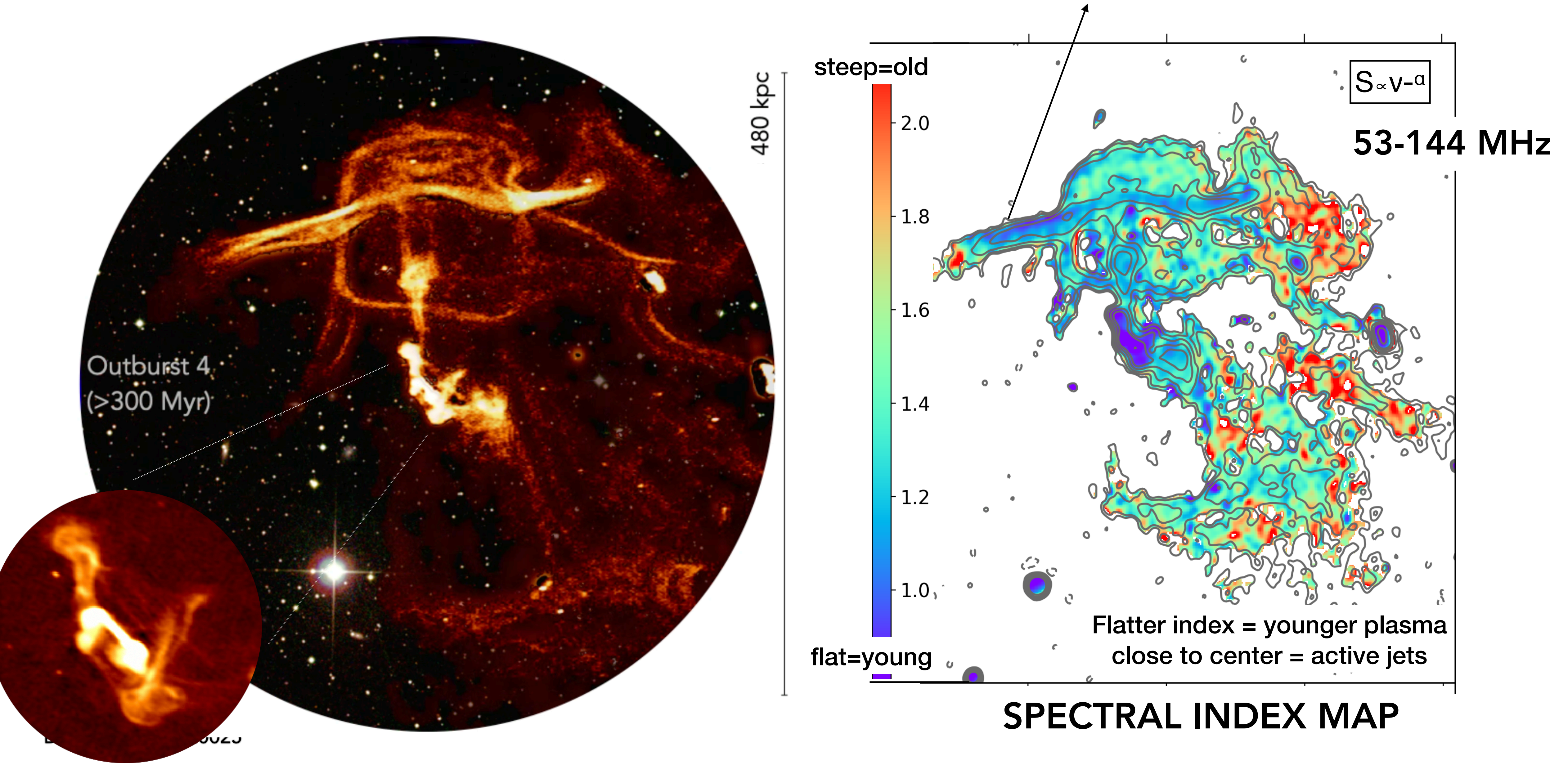
Nest200047



- Galaxy group $\sim 6e13$ Msun, $z=0.018$, $\log M_{\text{gal}}=11.56$
- **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!

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

Nest200047

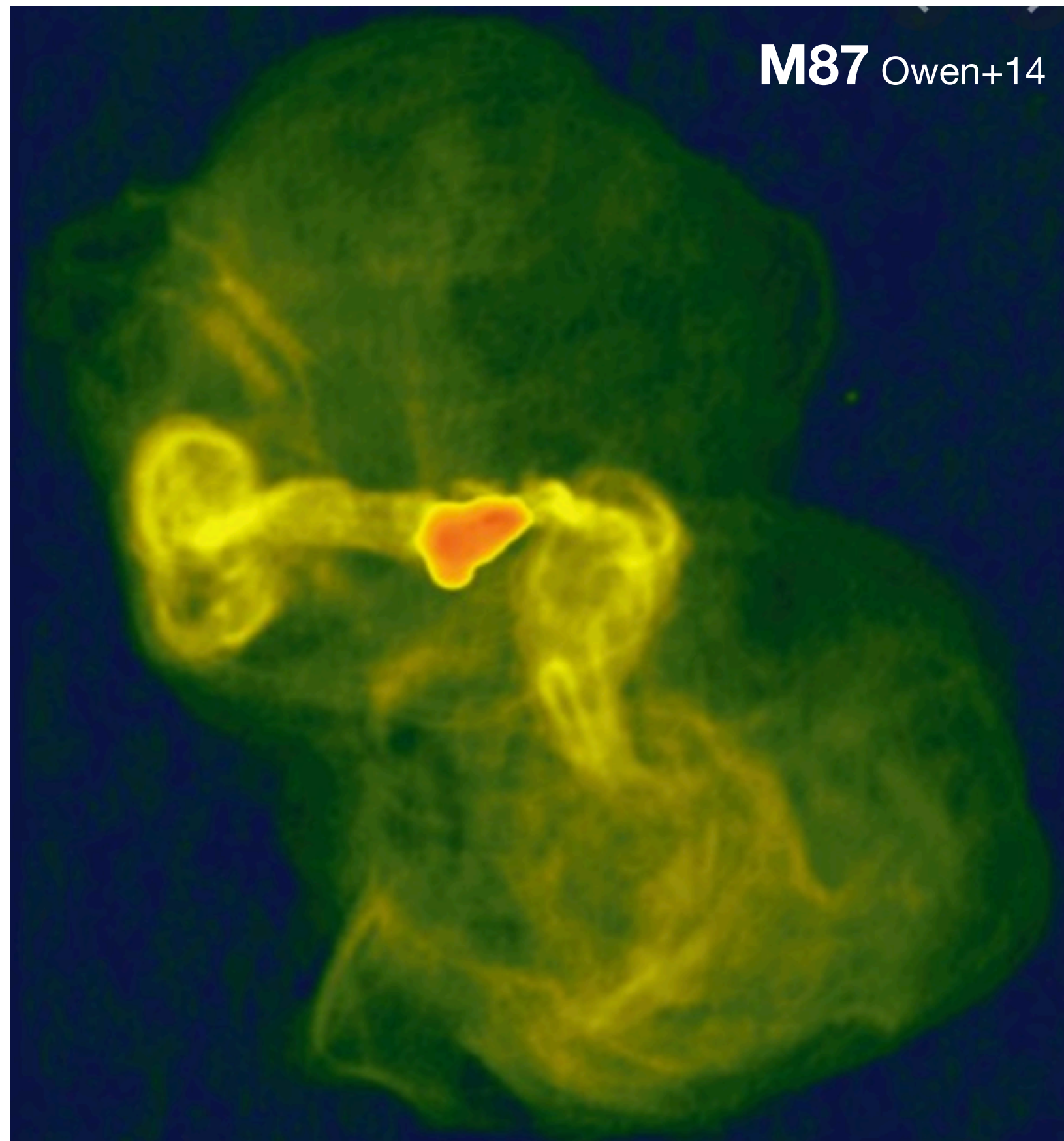
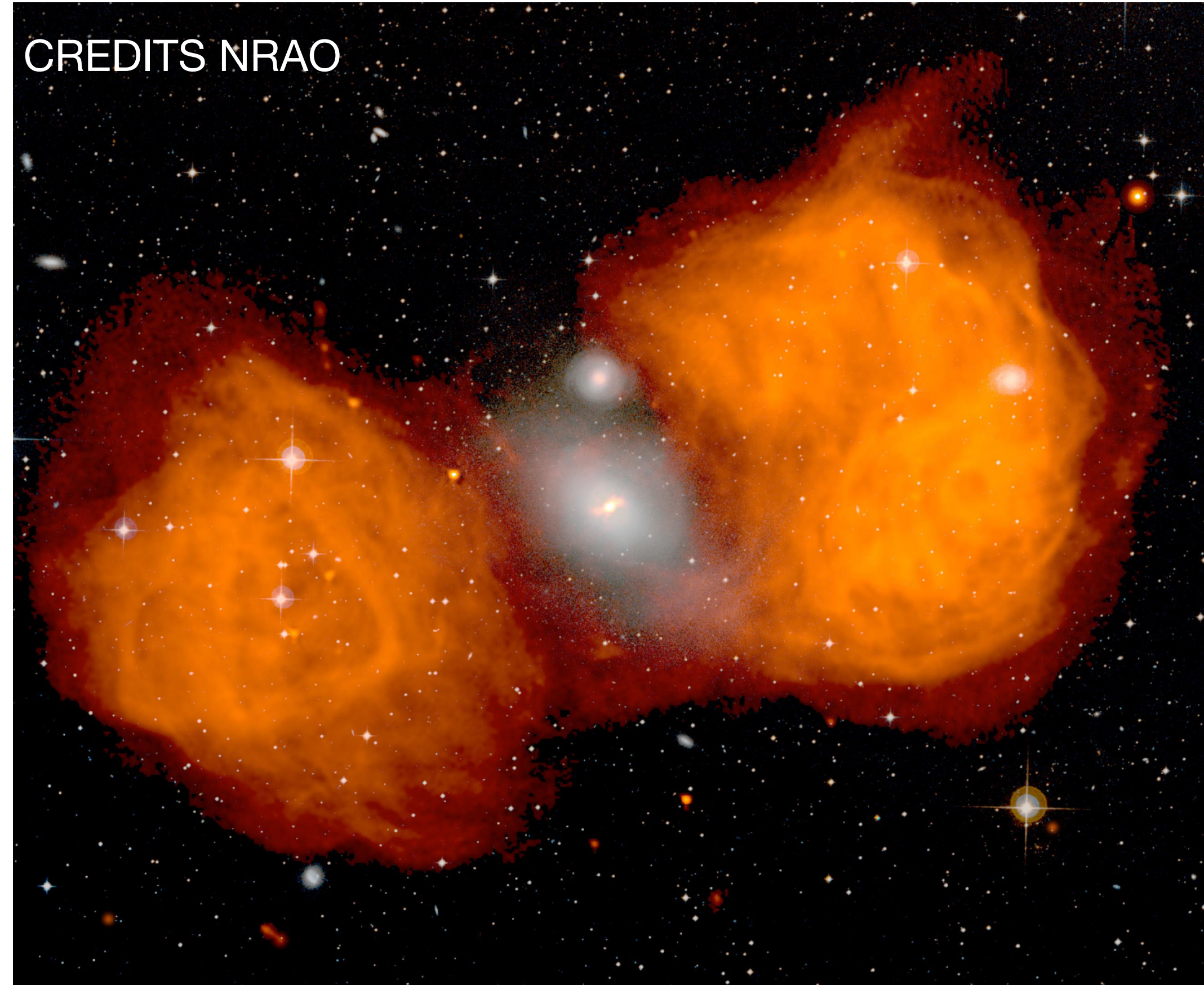


Filaments
are everywhere!

Filaments

are everywhere!

Within radio galaxy lobes...

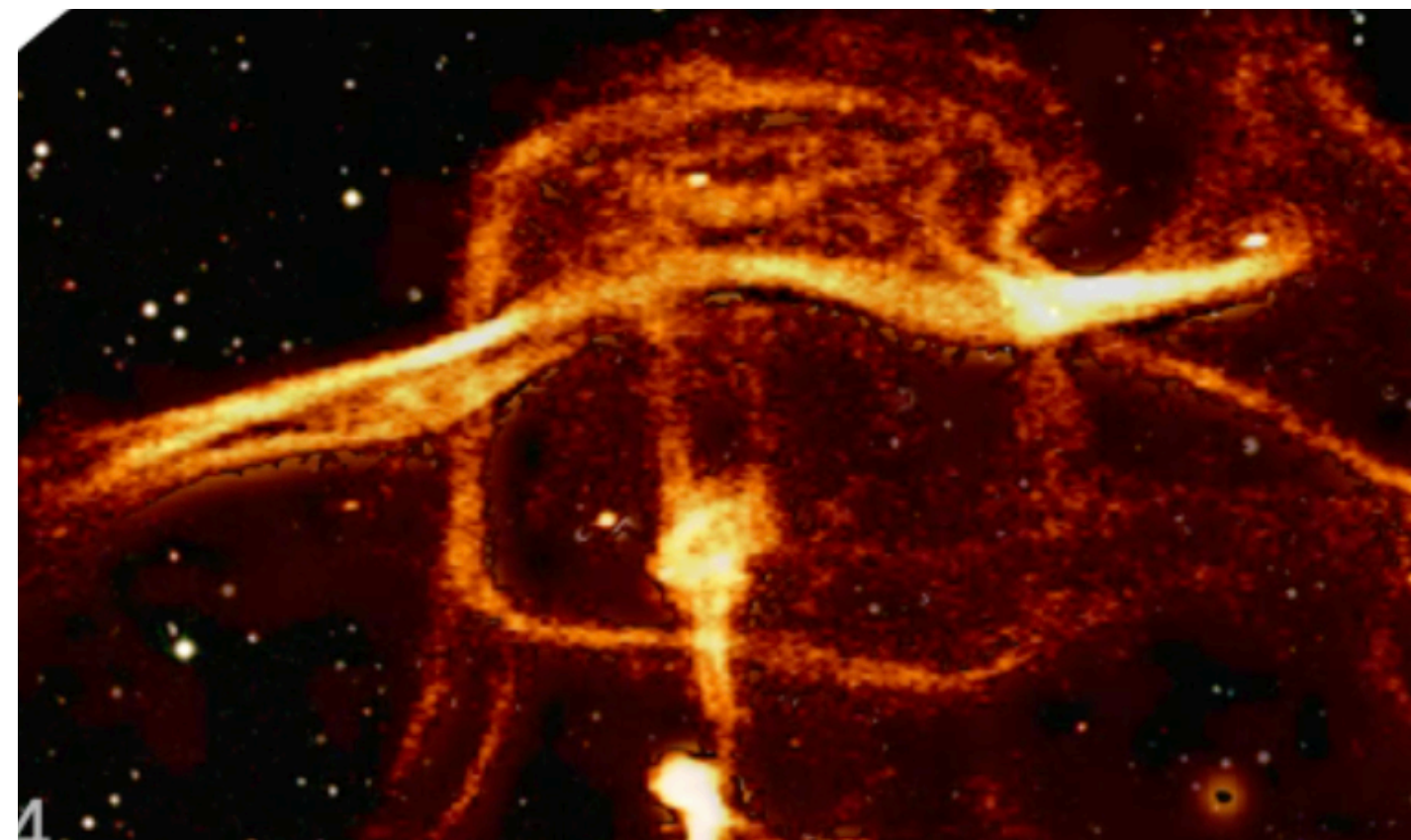


MHD simulations suggest that filaments trace enhancements in the magnetic field distribution (e.g. Huarte-Espinosa et al. 2011; Hardcastle 2013), which form as a consequence of the complex internal dynamics of the lobes

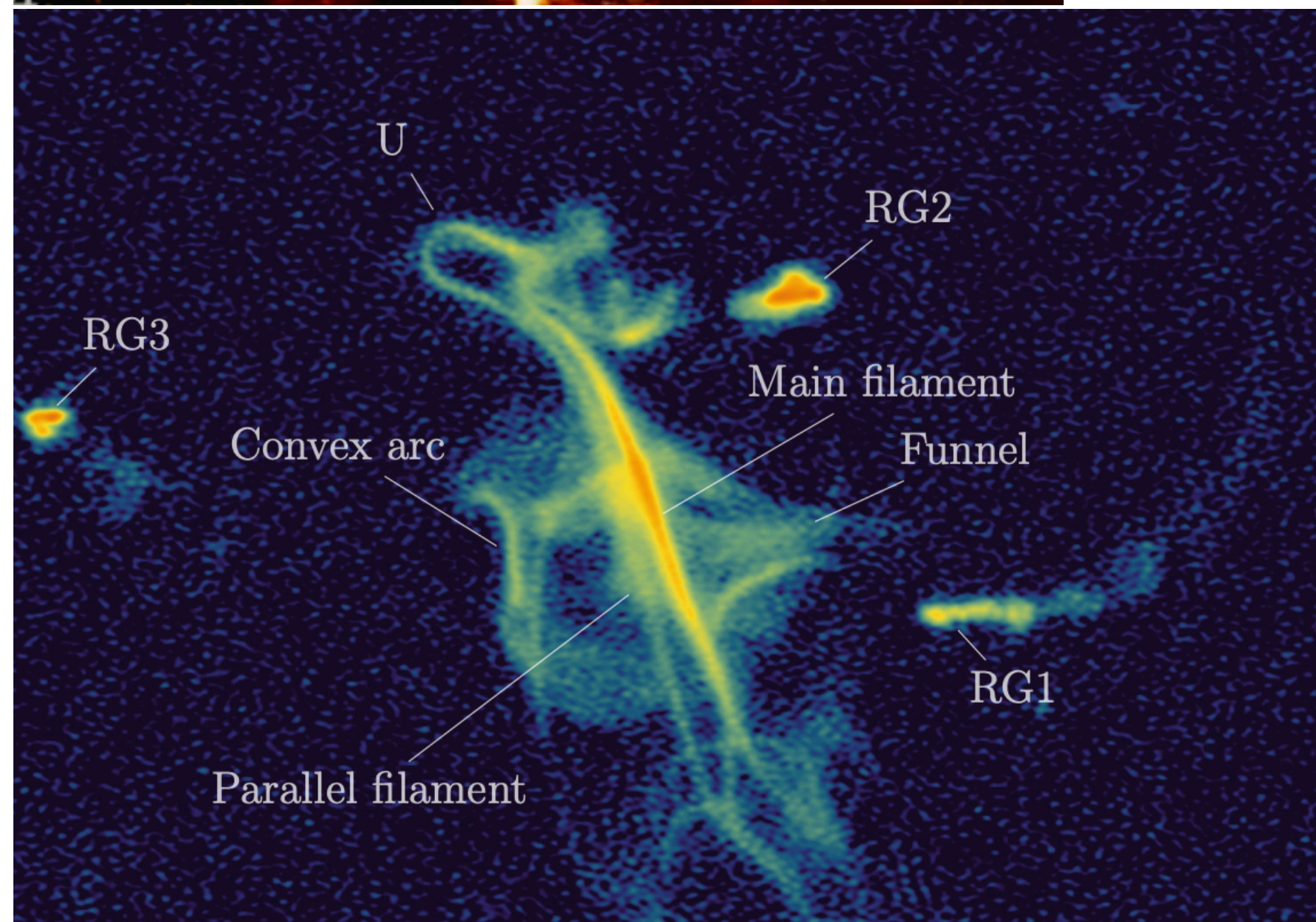
Filaments

are everywhere!

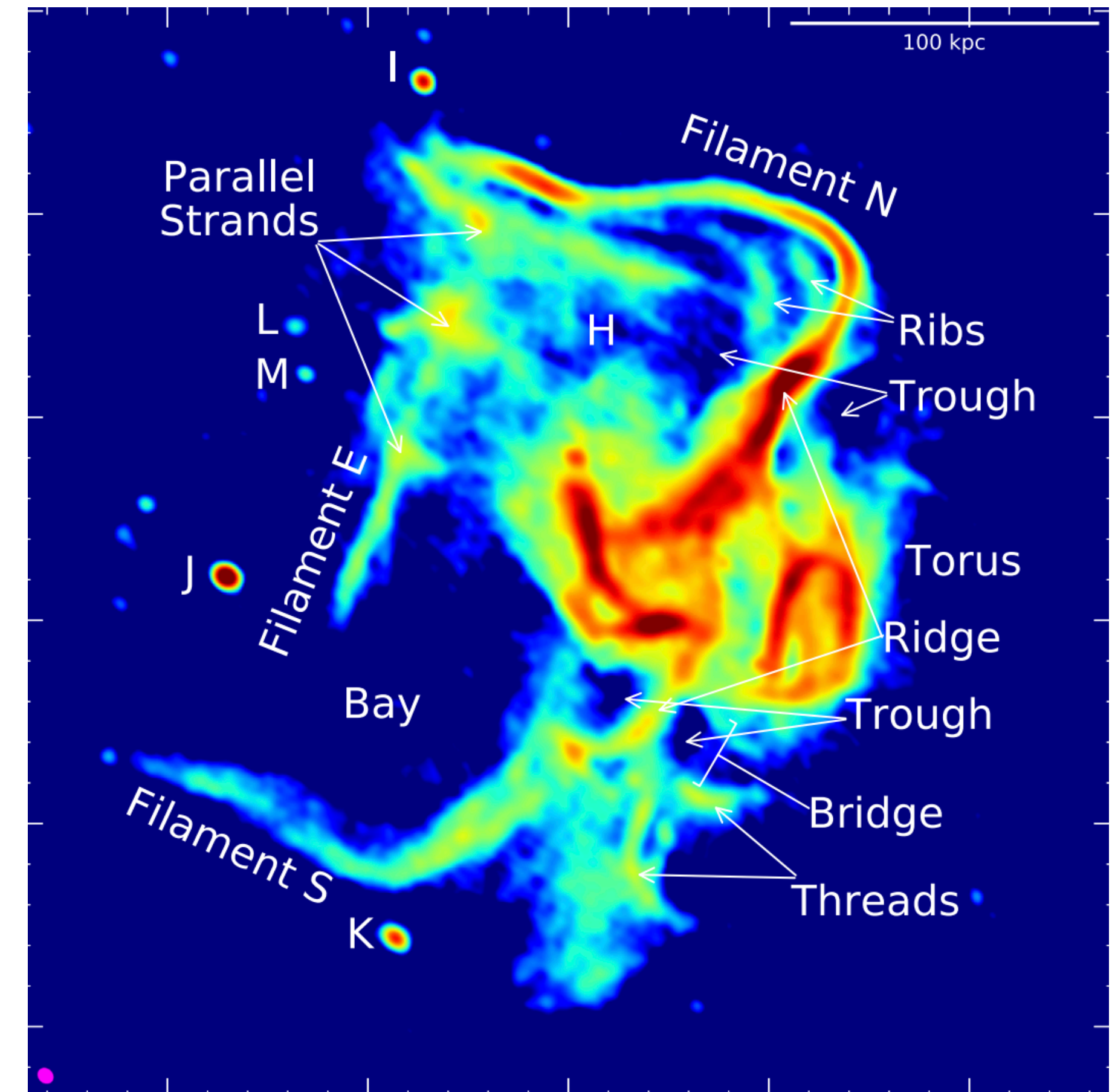
Within old AGN lobes...



Brienza+21, 25



Botteon+2026

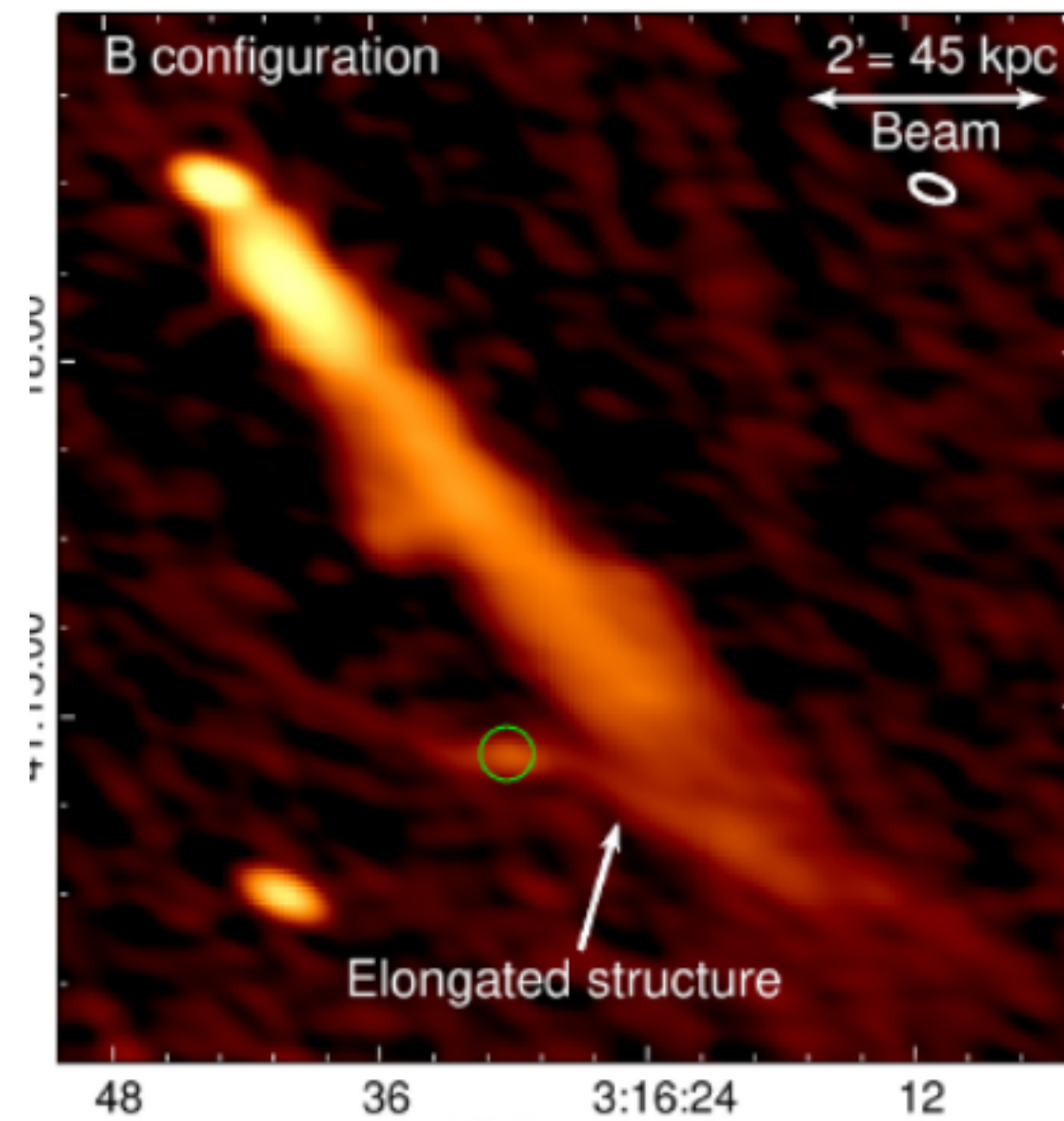


Raja+2024

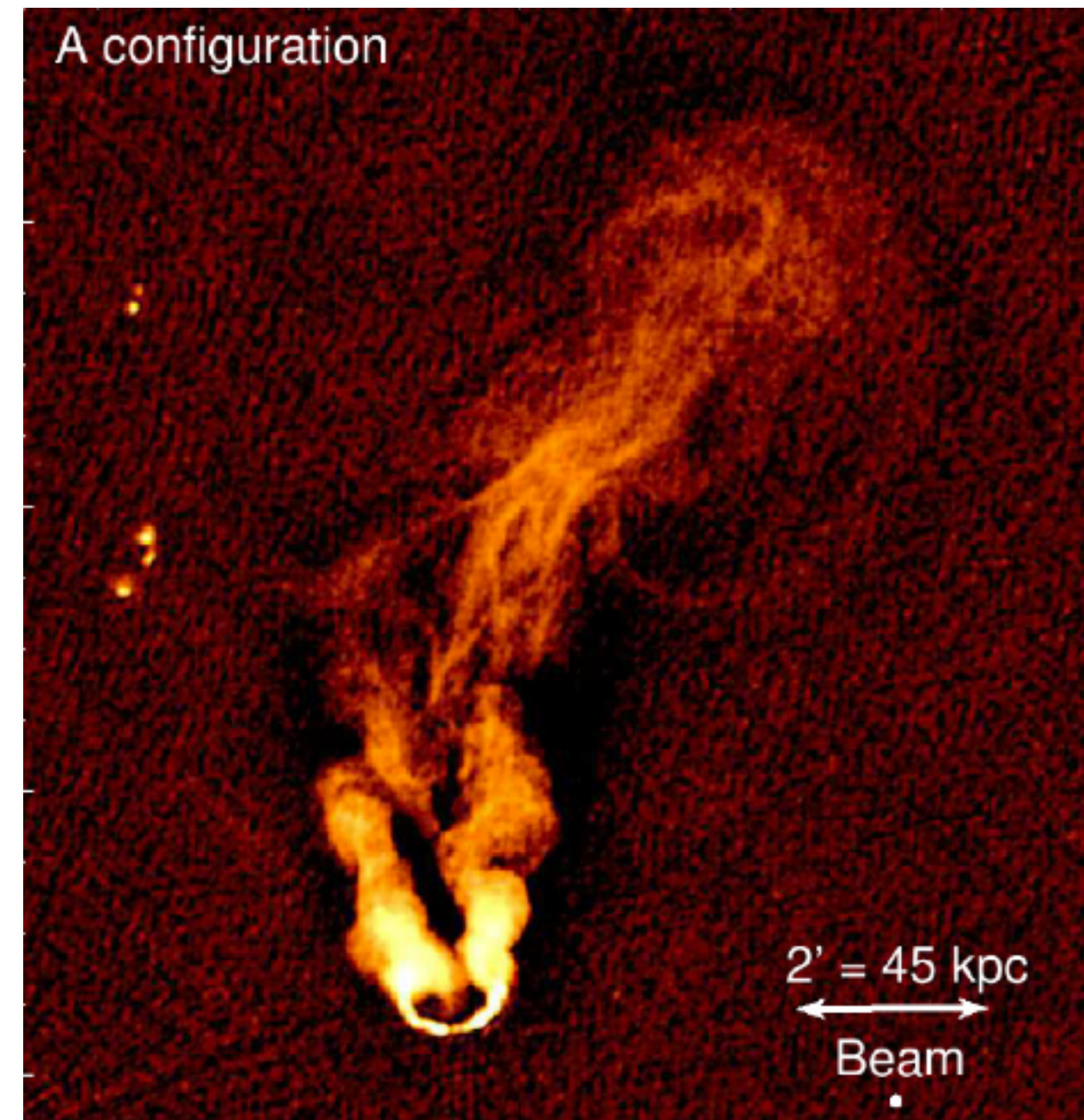
Filaments

are everywhere!

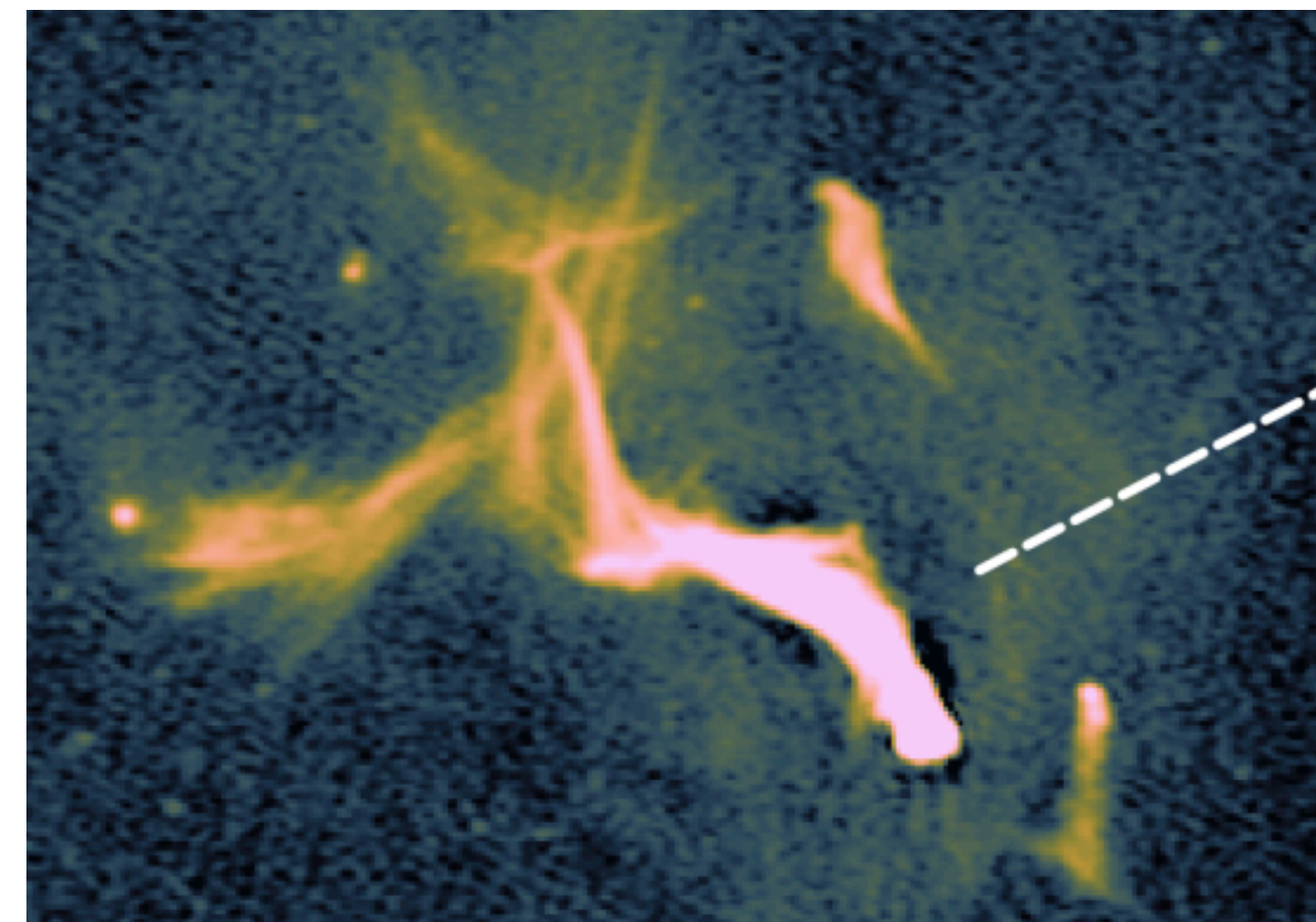
Within radio galaxy tails...



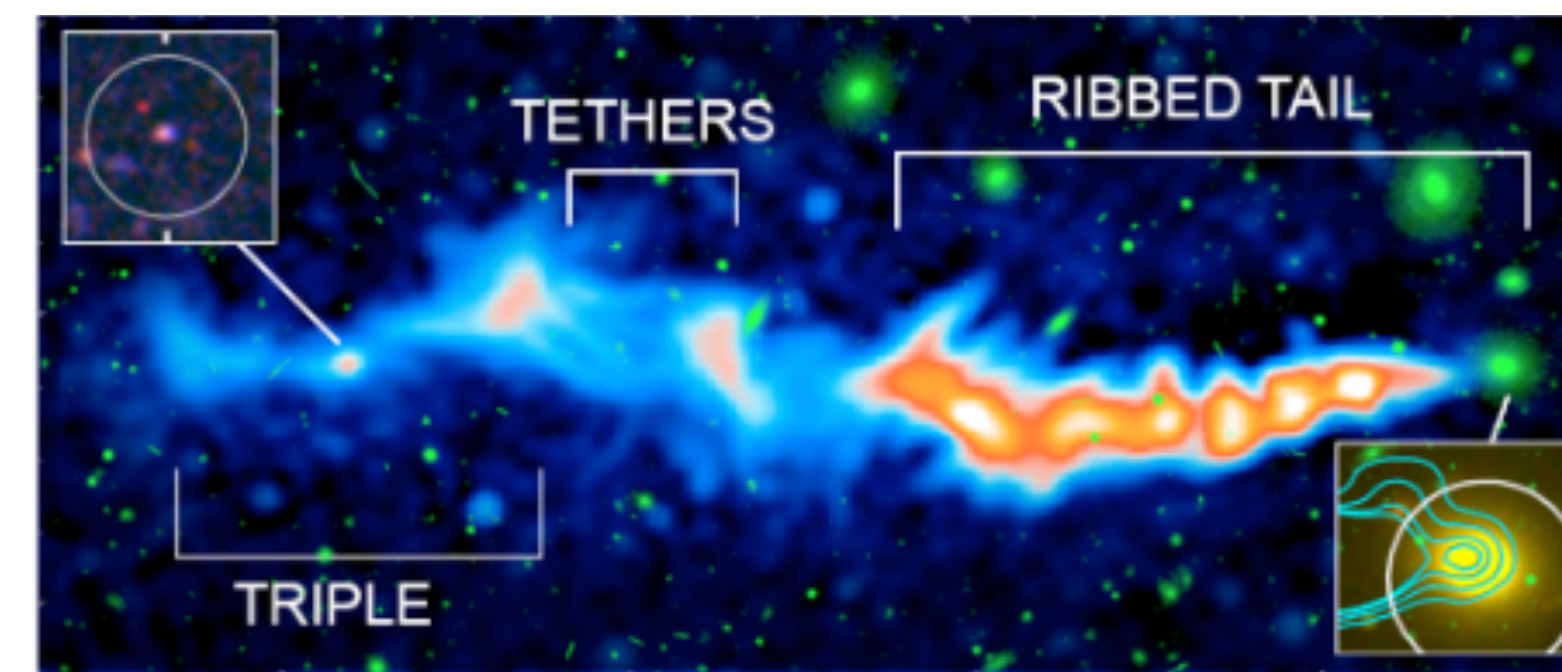
Rudnick+



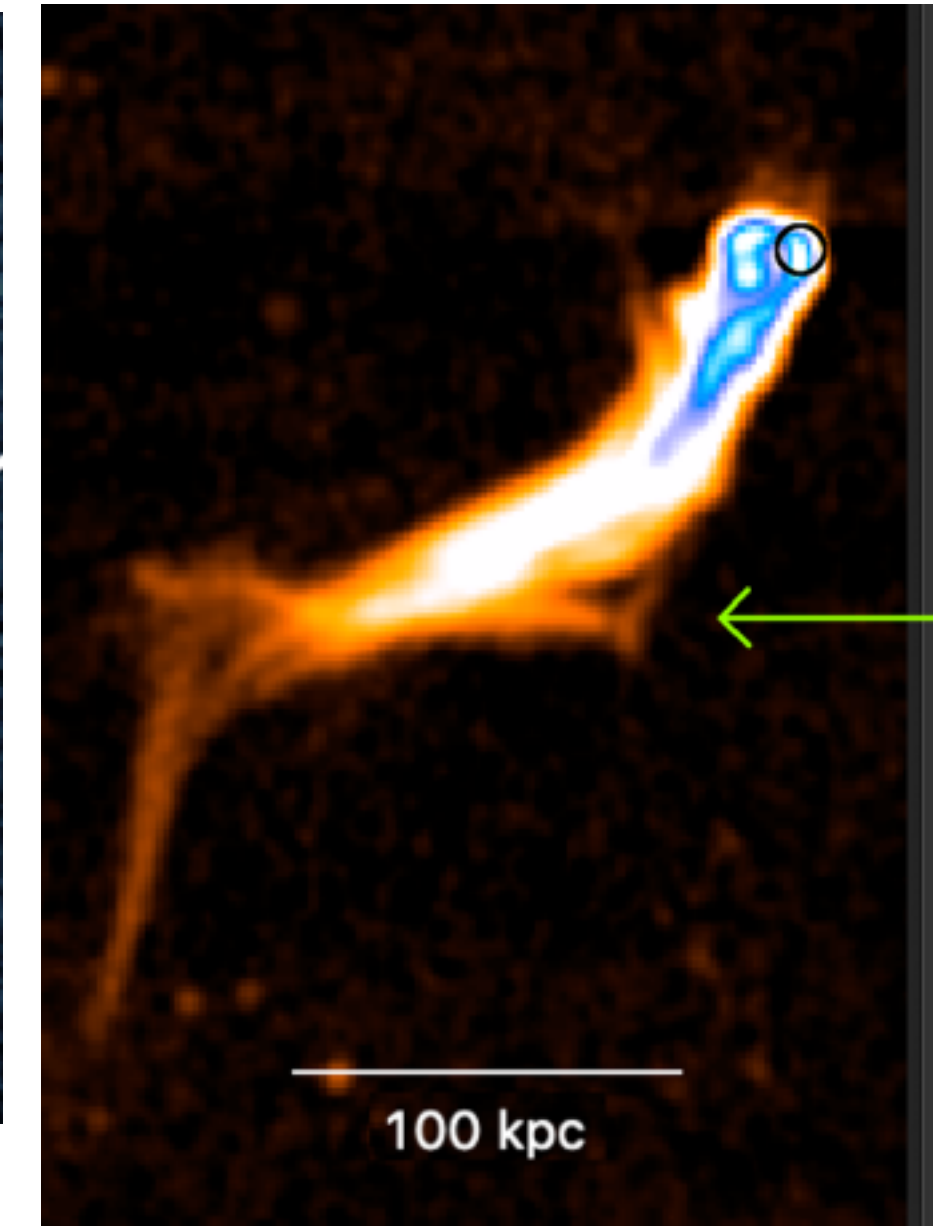
Gendron-Marsoais+



De Rubeis + 2025, 2026



Rudnick+

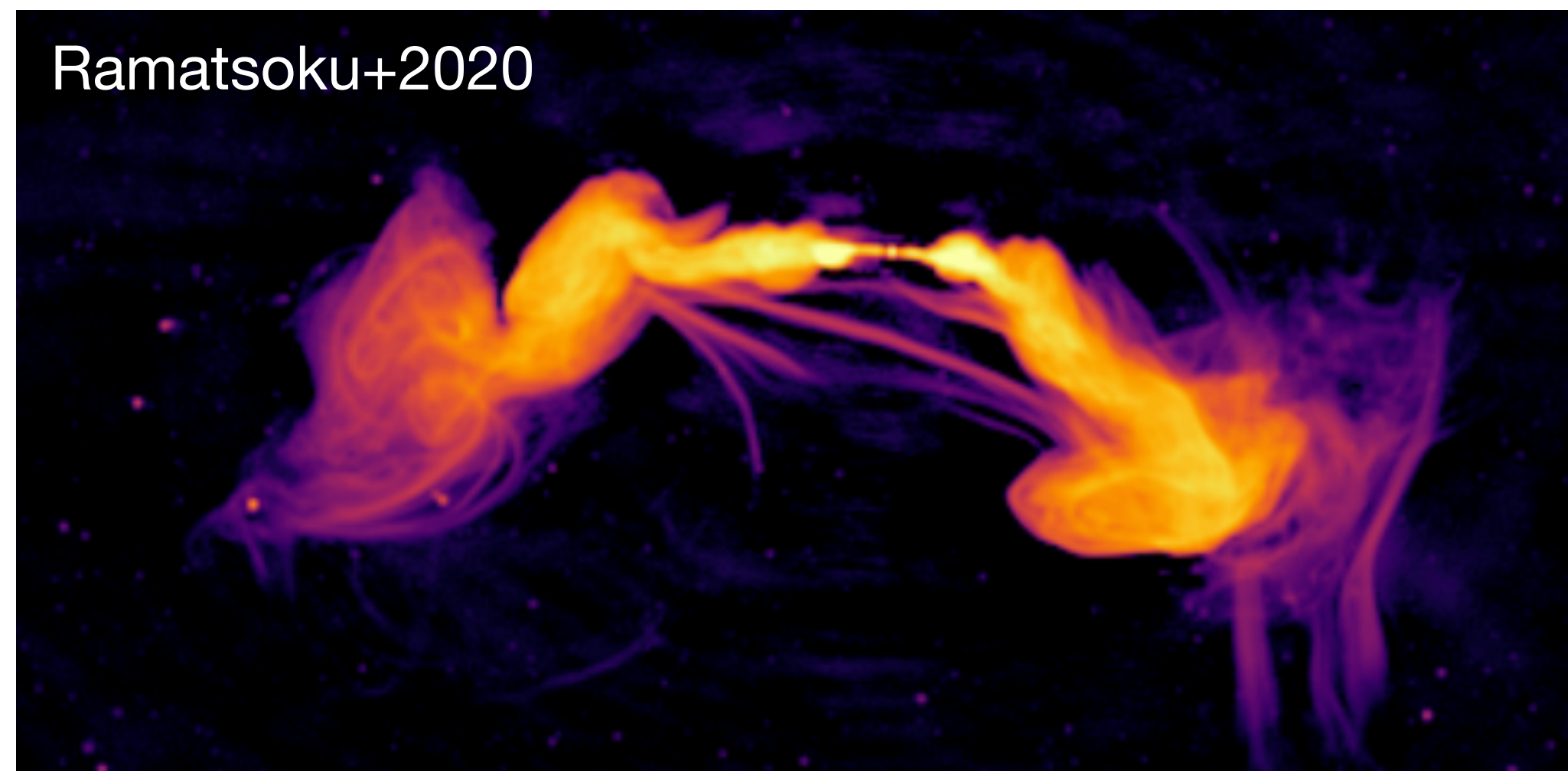
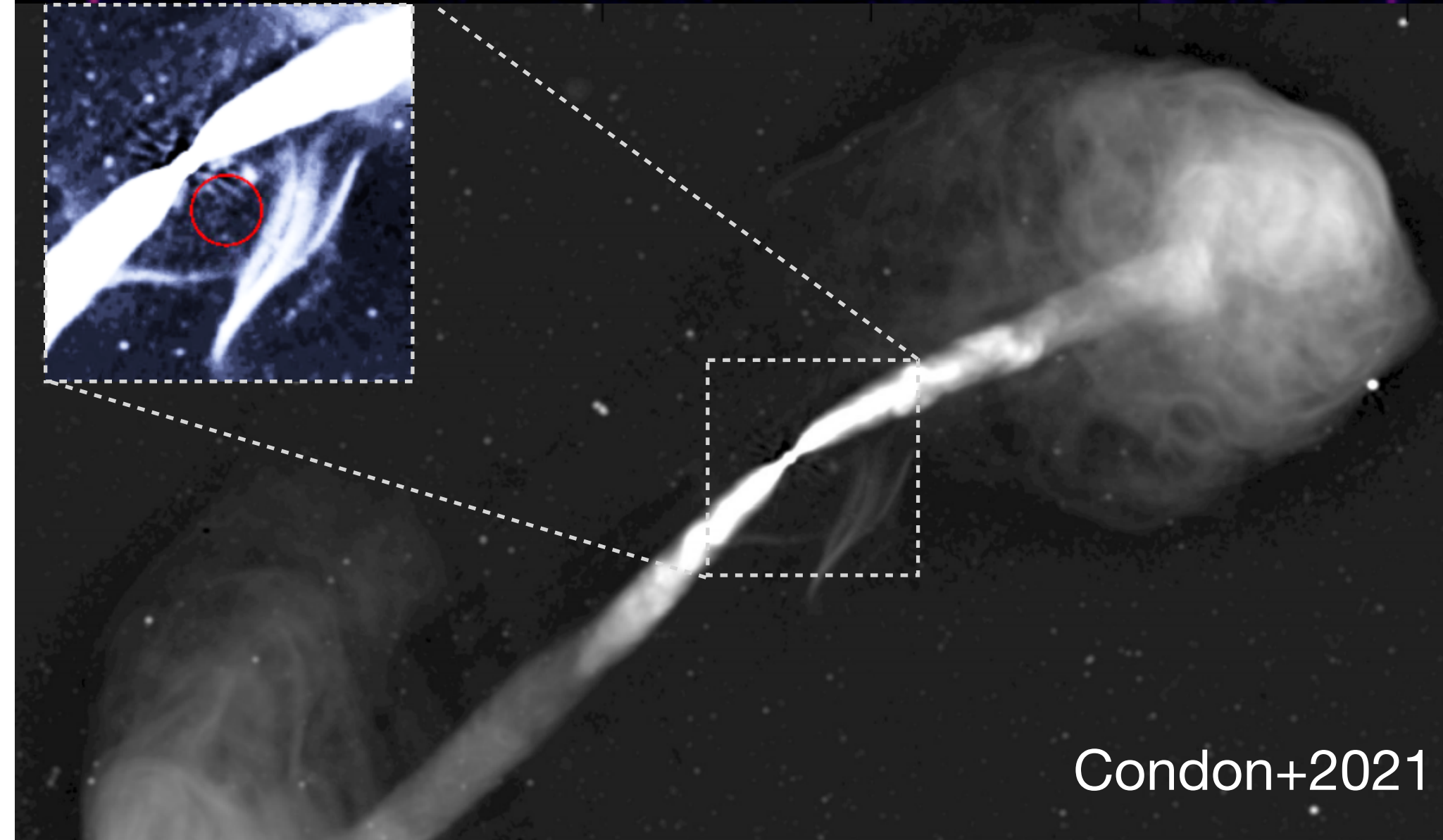


Clarke+

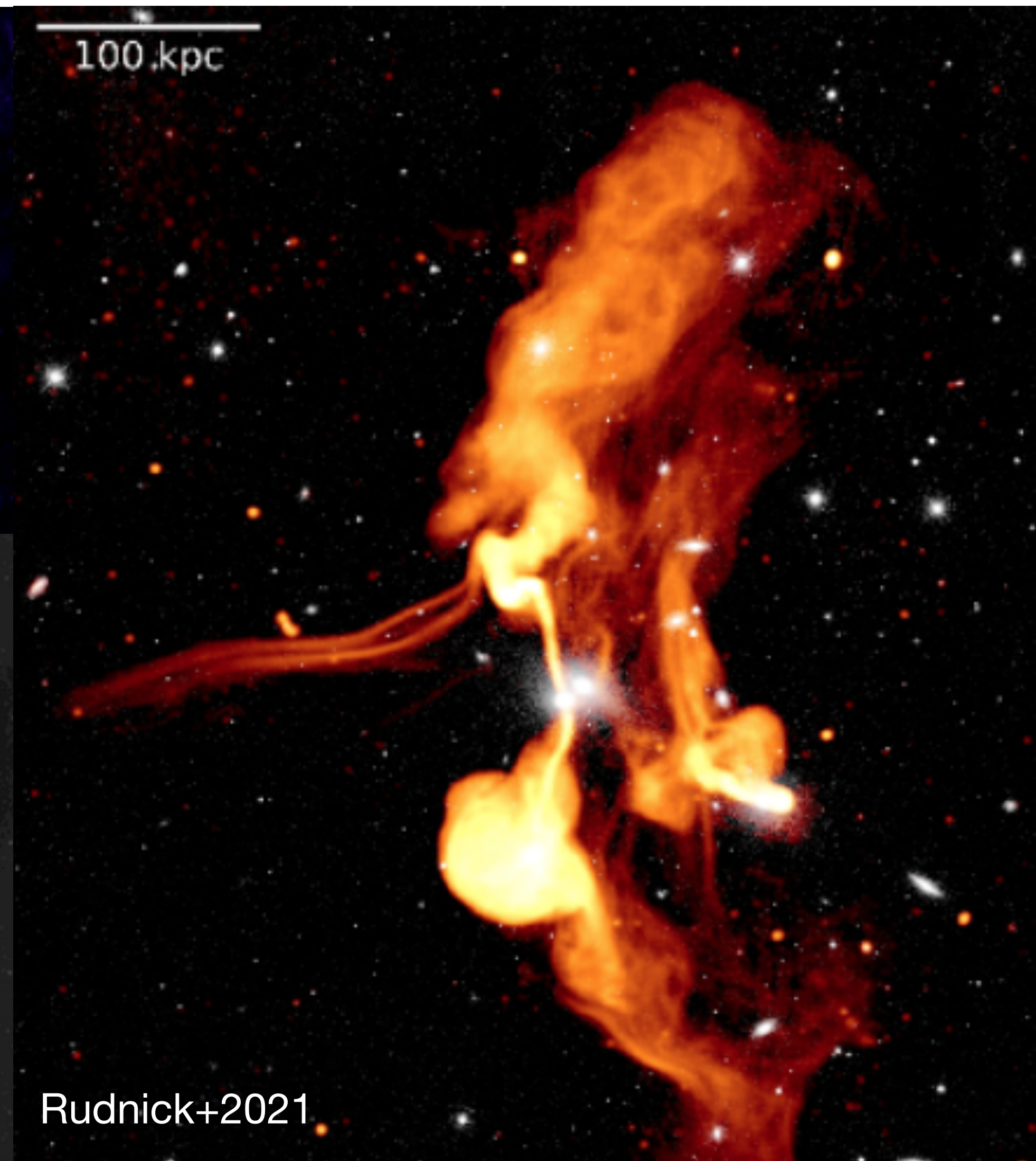
Filaments

Departing from / connecting lobes... *are everywhere!*

Often come in pairs or bundles!



Condon+2021



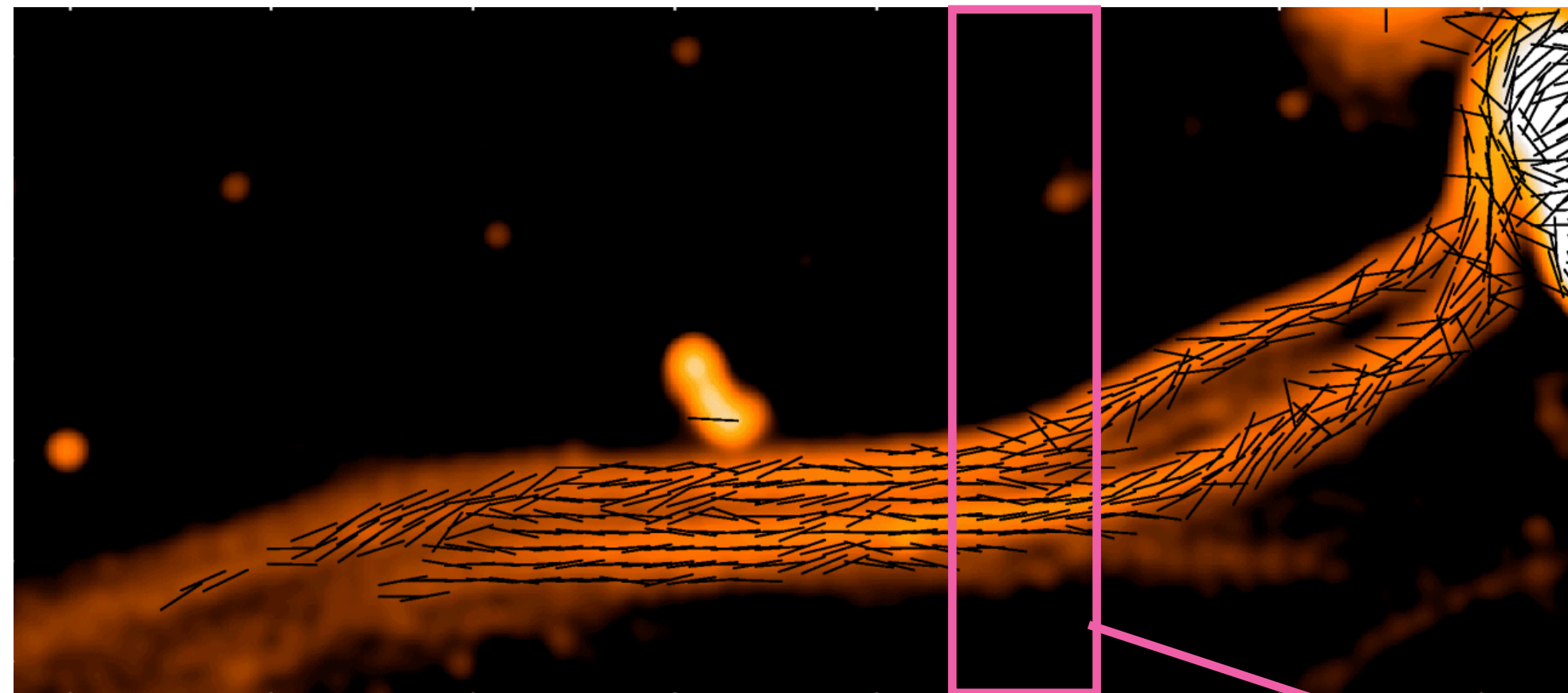
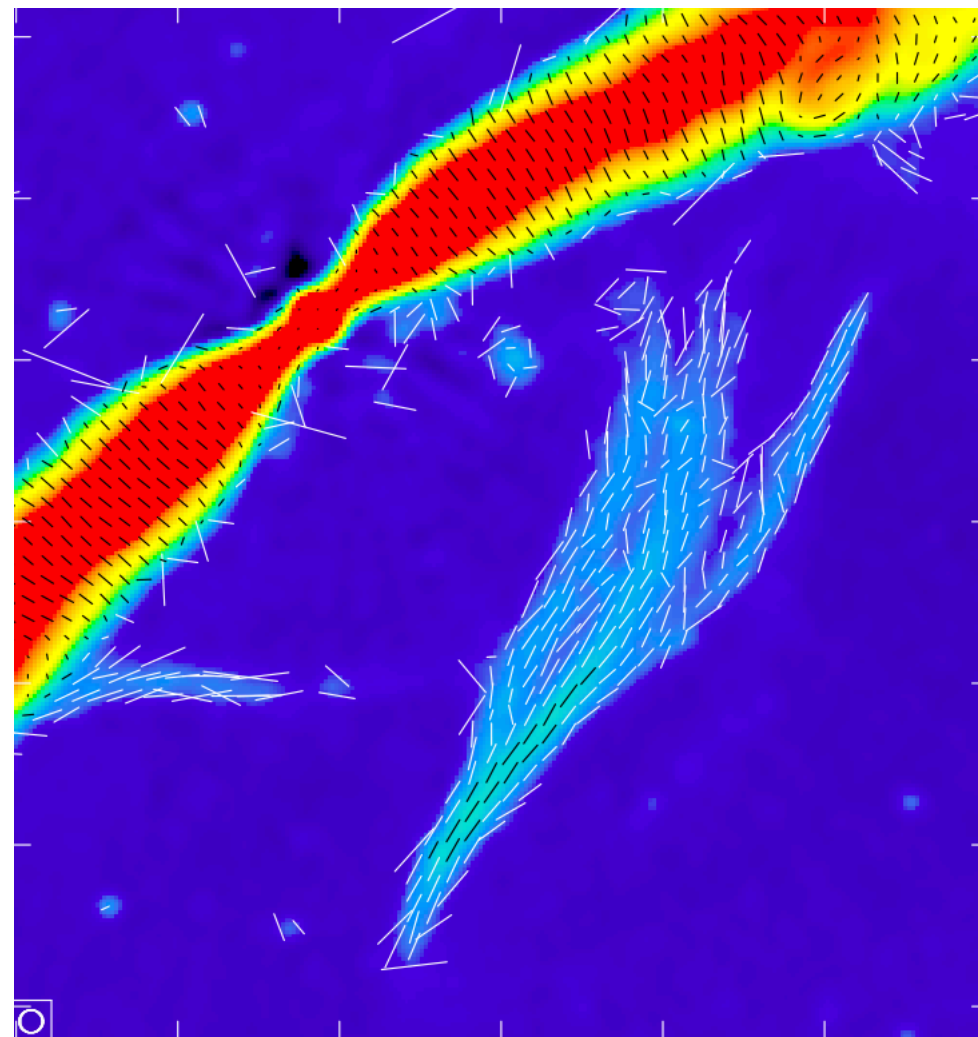
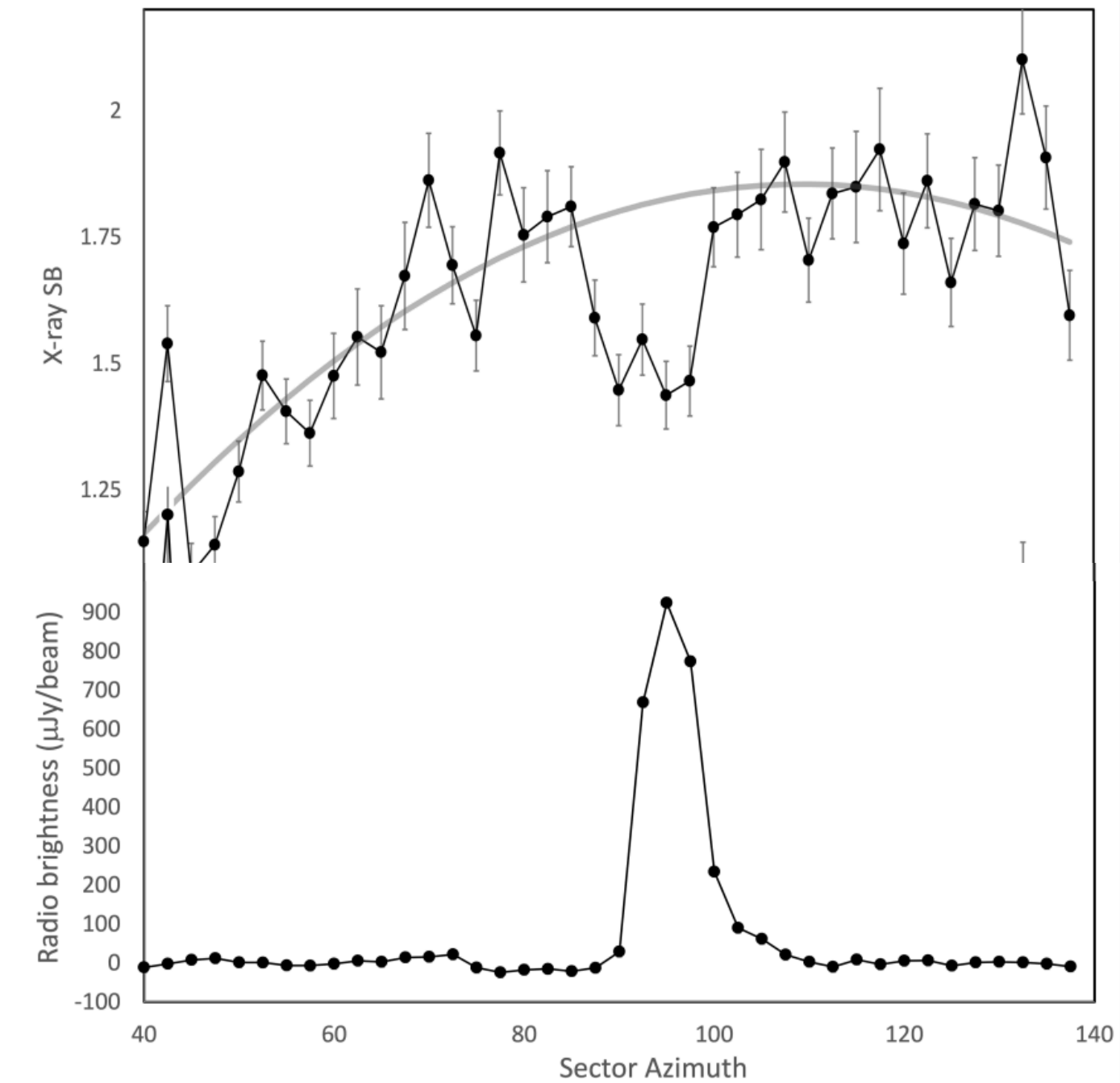
Rudnick+2021

Filament properties

Few kpc width and up to hundreds kpc long

Aligned B and high polarisation (40-70%)

X-ray depression = cavity



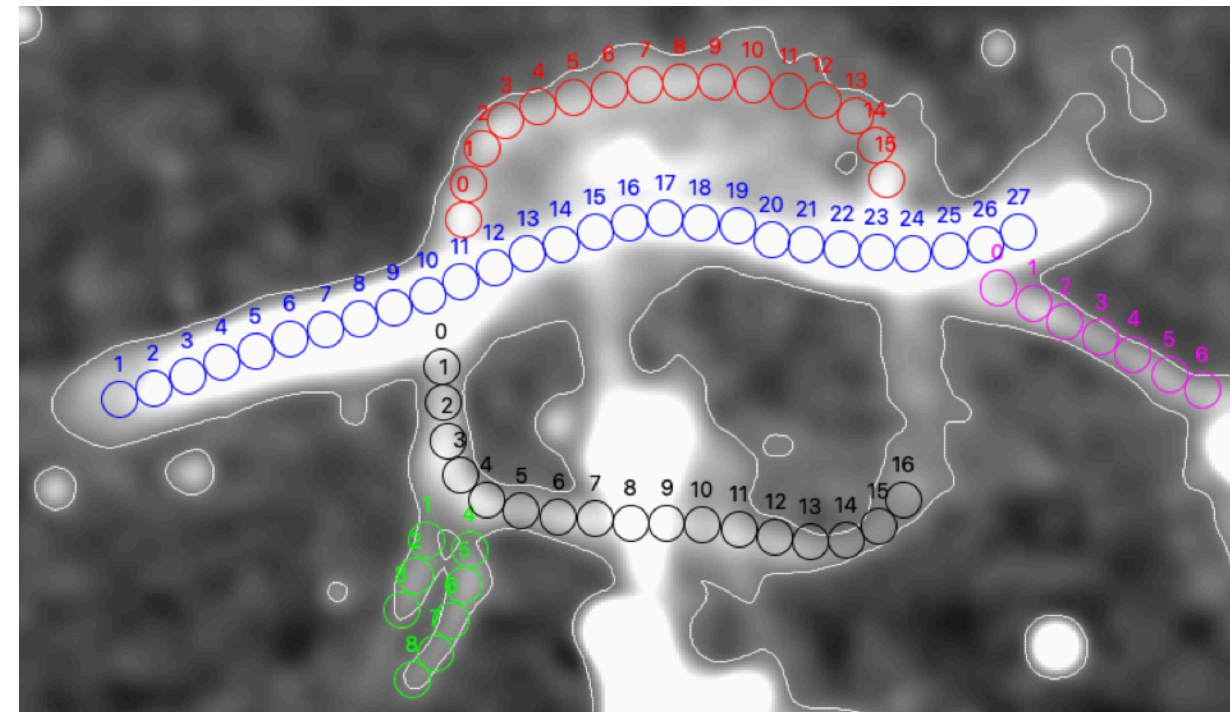
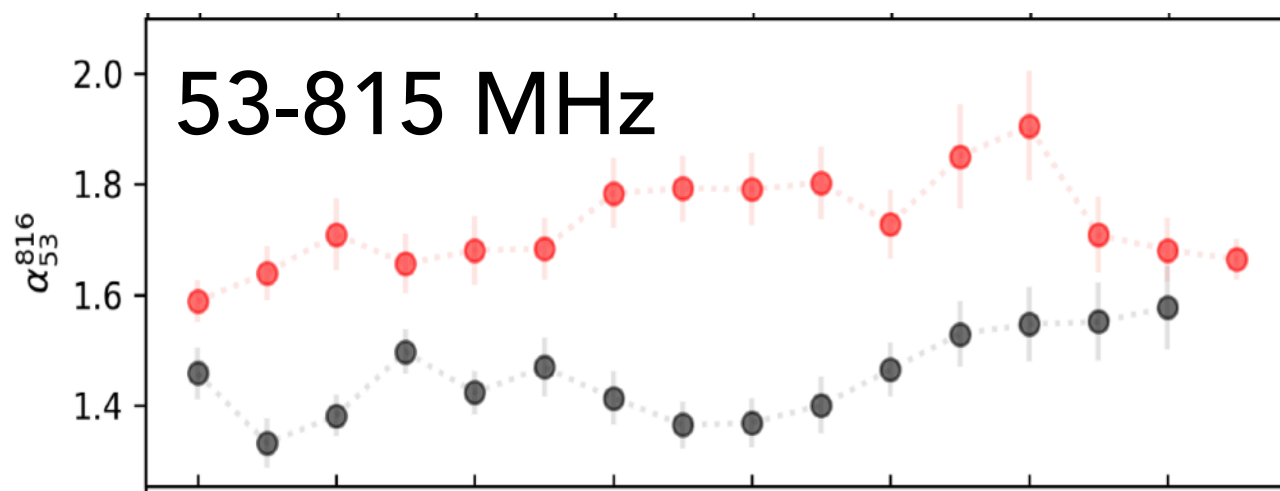
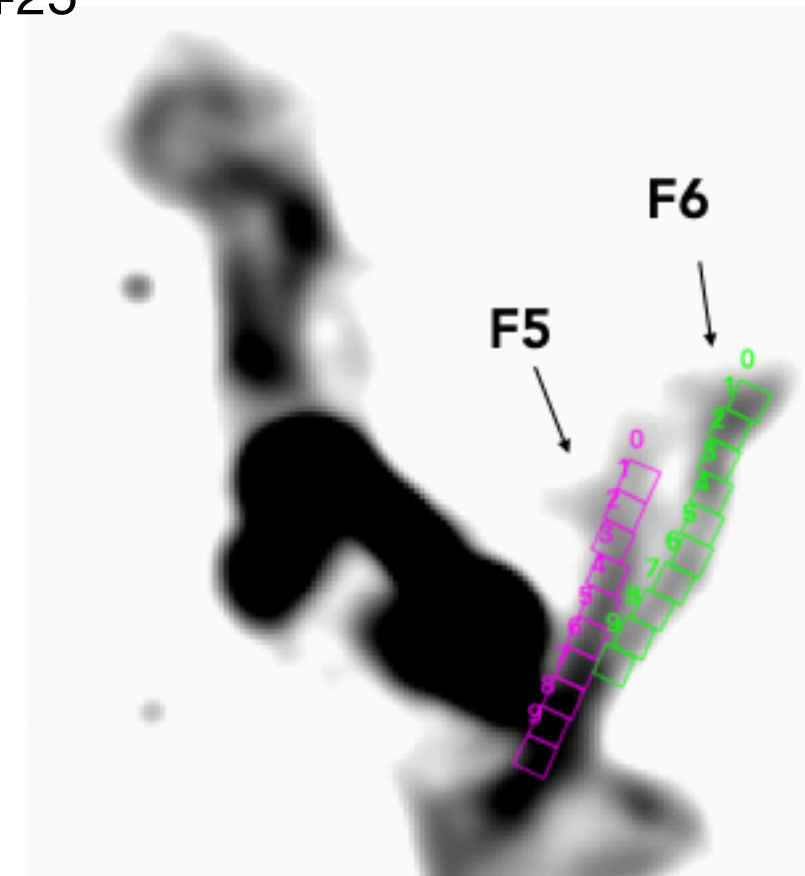
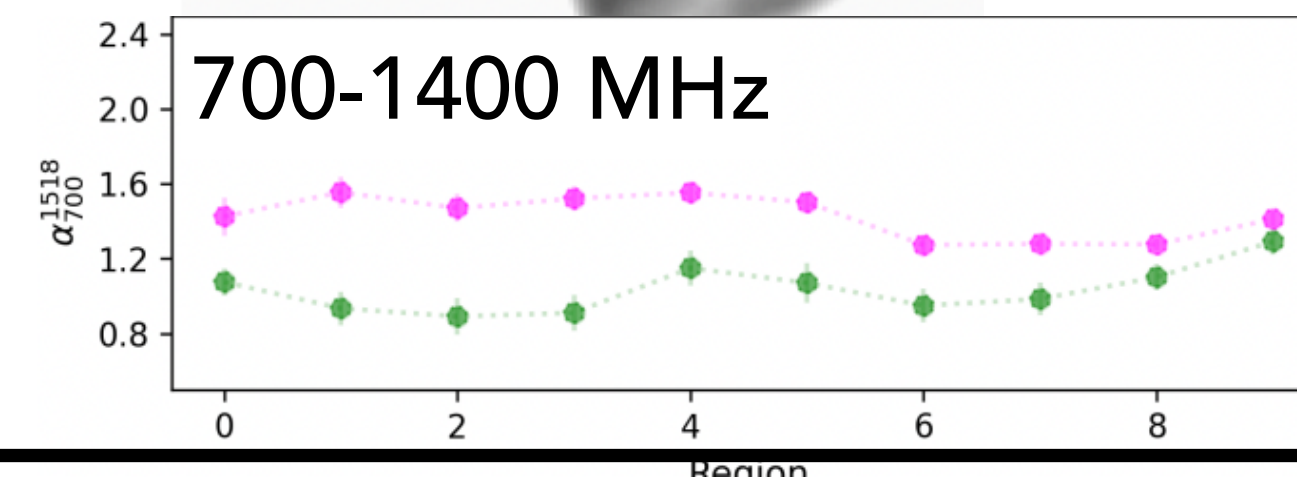
X-ray surface
brightness profile

Radio surface
brightness profile

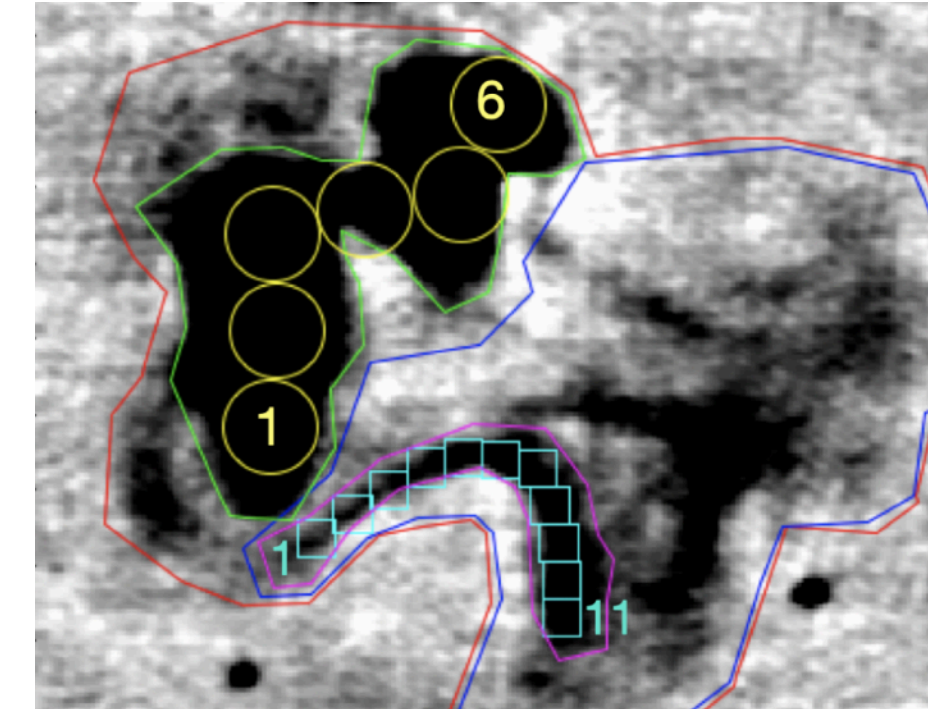
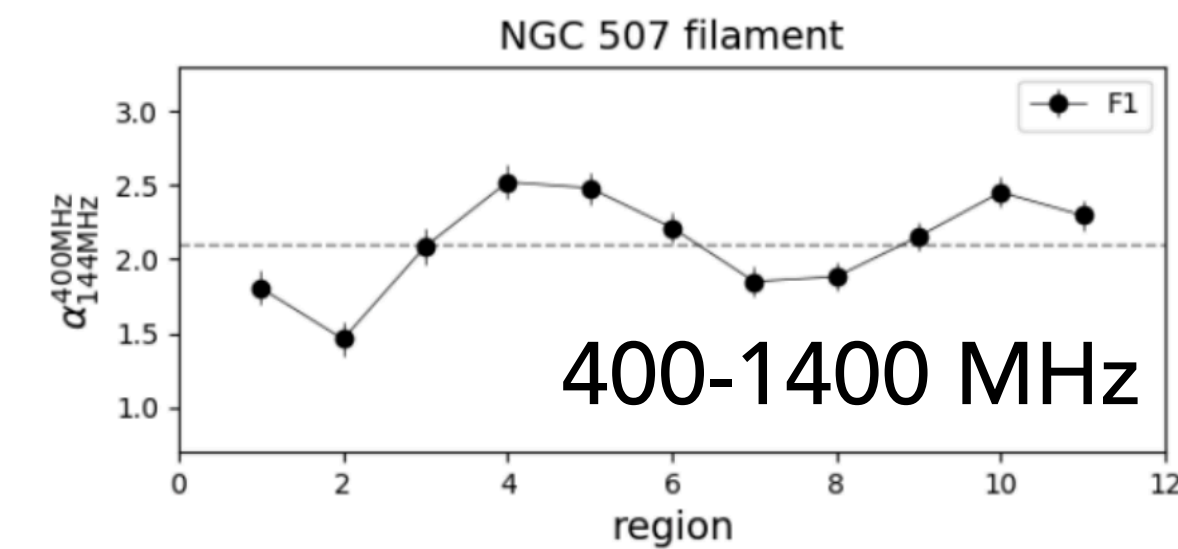
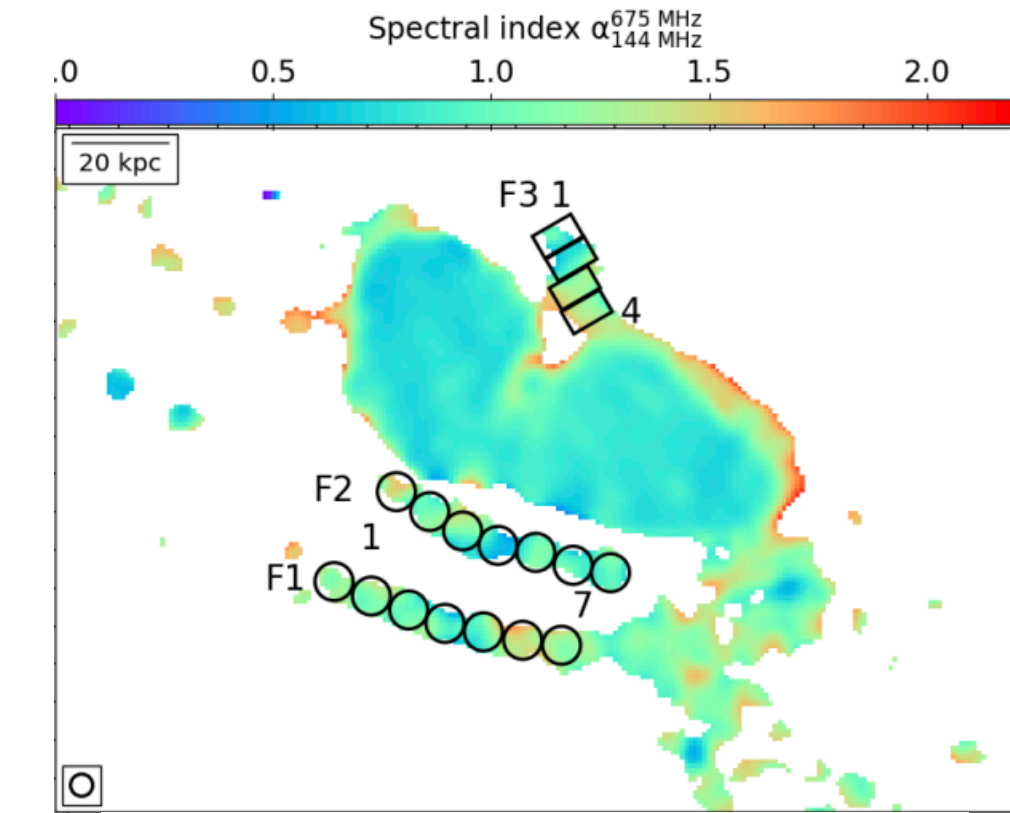
Filament properties

Constant spectral trend!

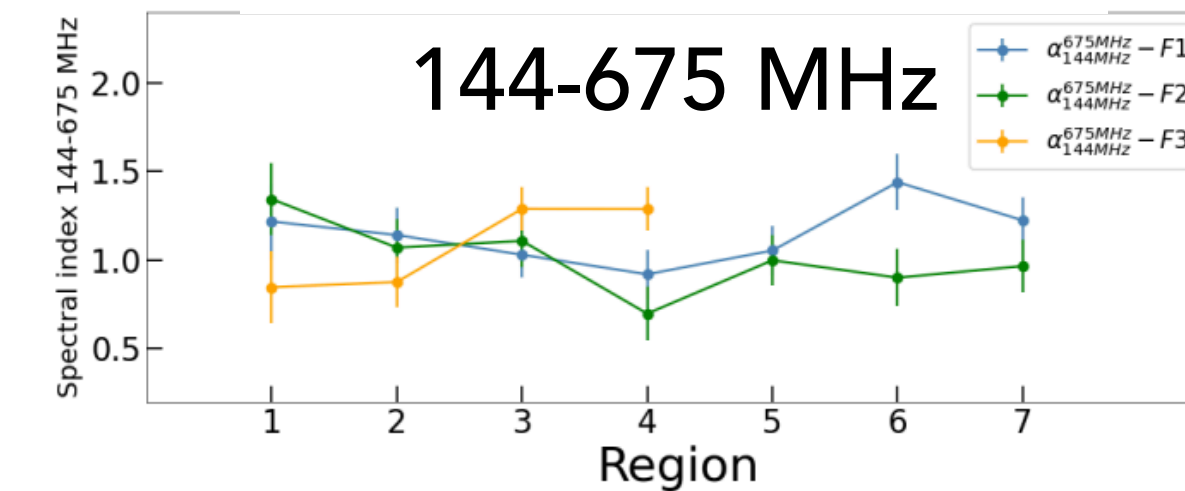
Brienza+25



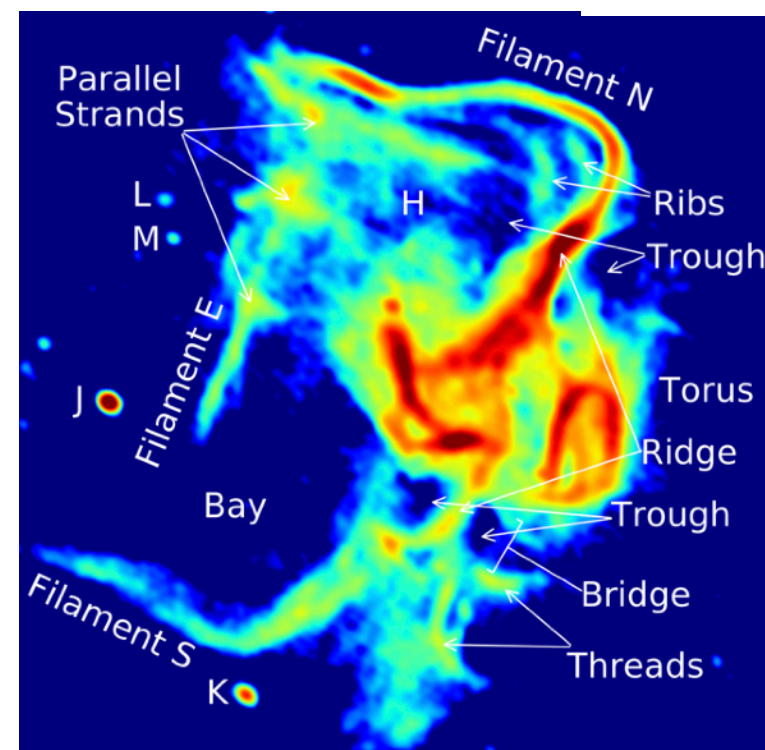
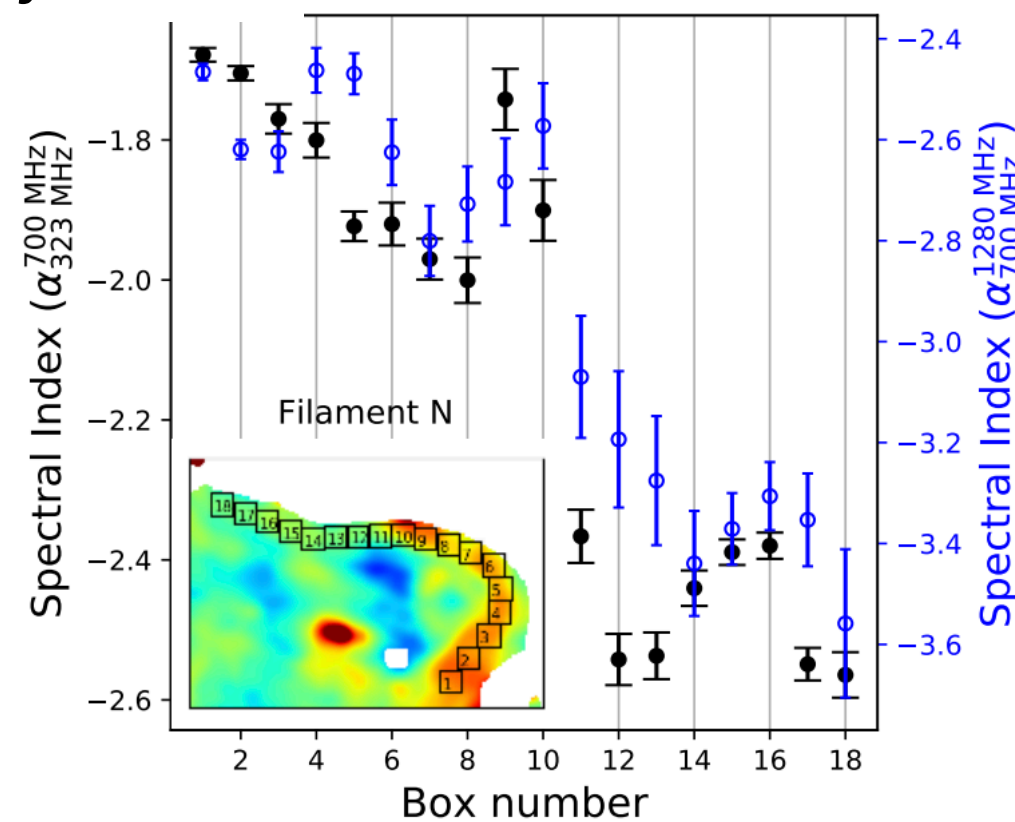
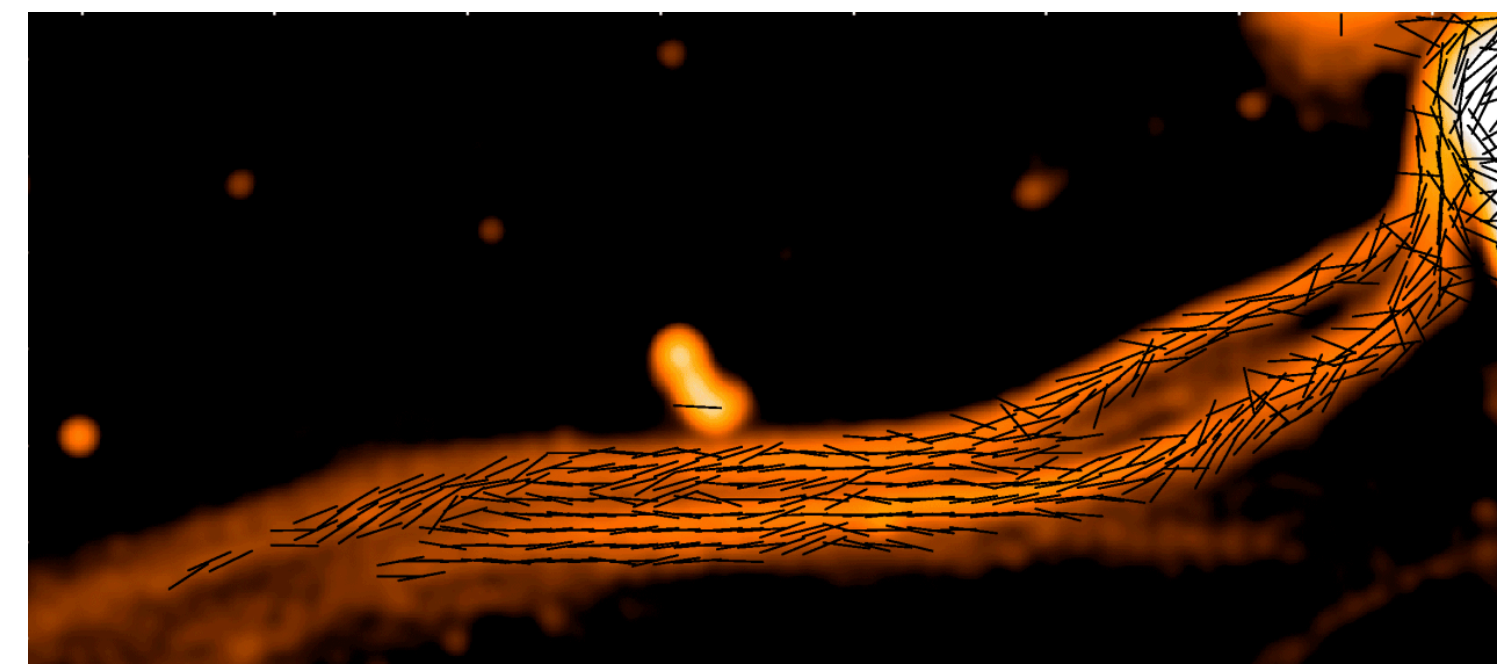
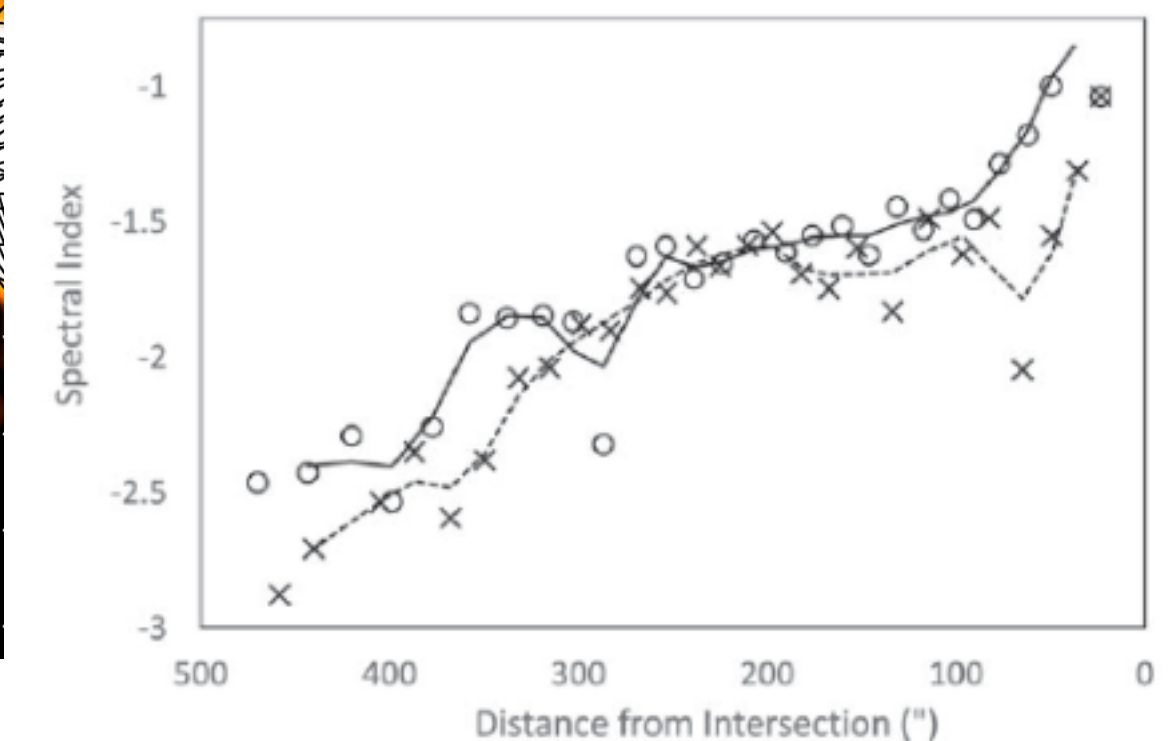
Brienza+2022



NGC6086, Candini+2023



A85, Raja+2025



Steepening along the filament!

Filament origin

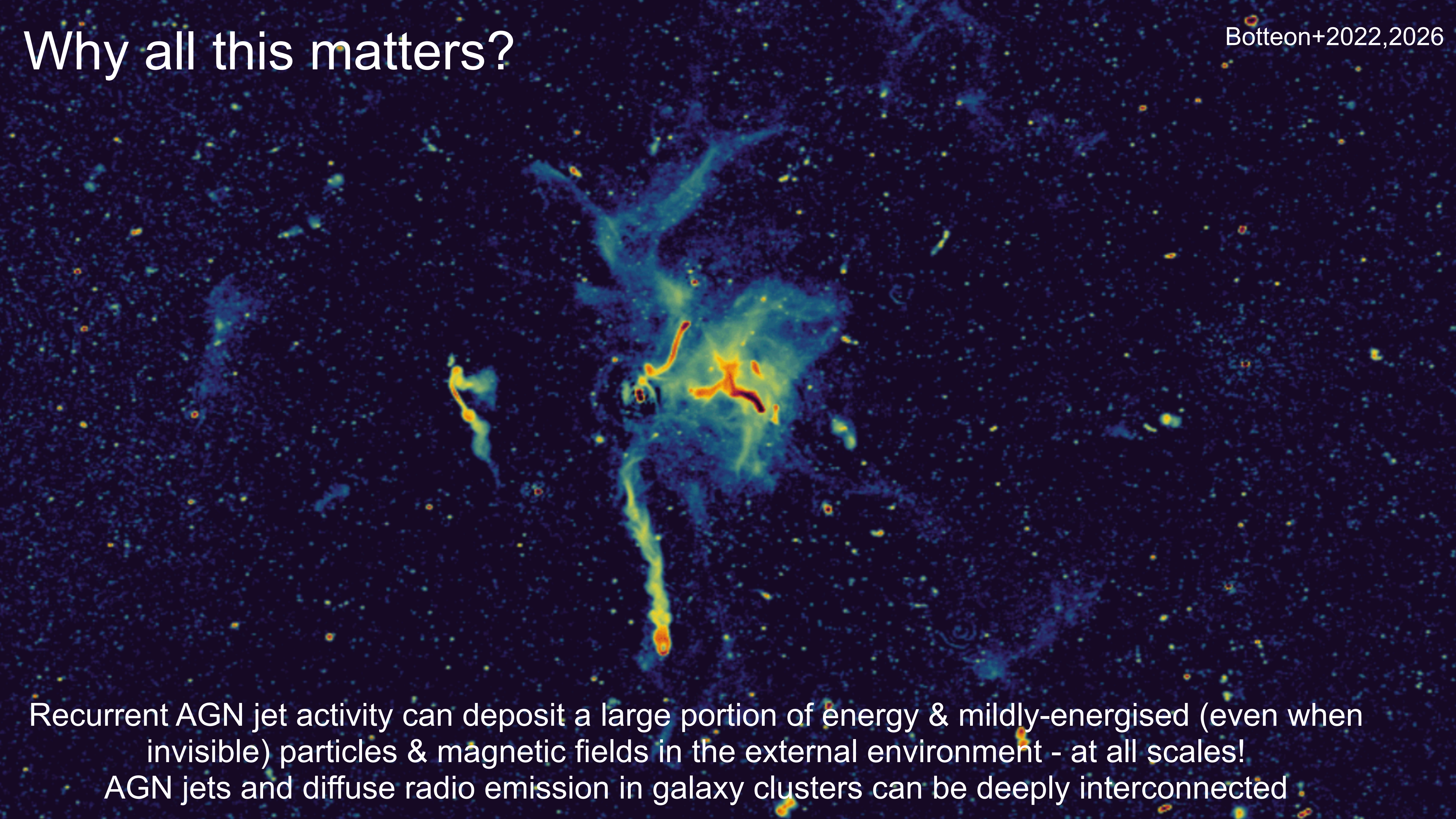
- ◆ Regions of compressed/stretched plasma?
- ◆ Magnetic field reconnection?
- ◆ Old AGN plasma enlighting underneath complex magnetic field structure?
- ◆ Imprint of fluctuation dynamo in turbulent ICM?
- ◆ Particle streaming in beta=1 filaments?

Churazov+2026

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

If ICM depleted ($\beta \ll 1$) -> B dominates and particle can travel at Alfvén speed

$$v_A = \frac{B}{\sqrt{4\pi\rho}}$$



Why all this matters?

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