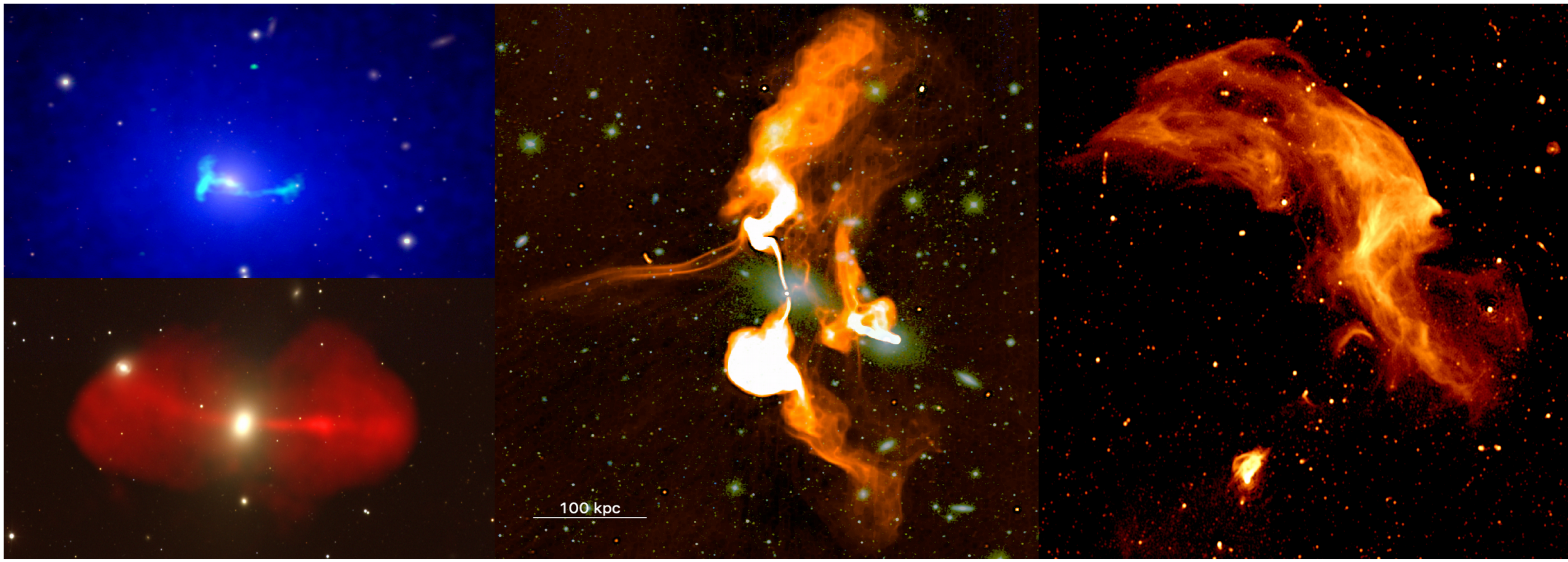
From Group Dynamics to Cluster Halos: A Multi-Band view of Galaxy Evolution in Groups and the Diffuse Skies in Clusters



INAF IASF-Milano, *Seminar Talk*
Milan | Italy, 11th March 2026

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Postdoctoral Research Fellow, Rhodes University / SARAO

Special thanks to: O'Sulllivan E. (Harvard CfA), Venturi T. (INAF Bologna), Knowles Kenda (Rhodes Univ/SARAO), Intema H. (Leiden Univ), Giacintucci S. (NRAO), Cathy Horellou (Chalmers Univ of T), Smirnov Oleg (Rhodes Univ/SARAO)

Overview

- ✓ **Introduction on galaxy clusters and groups**

Part 1: Galaxy Groups

- CLoGS Radio & X-ray
- CO gas in BGEs
- AGN feedback and SFR in BGEs
- Deep dive in NGC 1550
- Deep dive in NGC 5044

Part 2: Galaxy Clusters

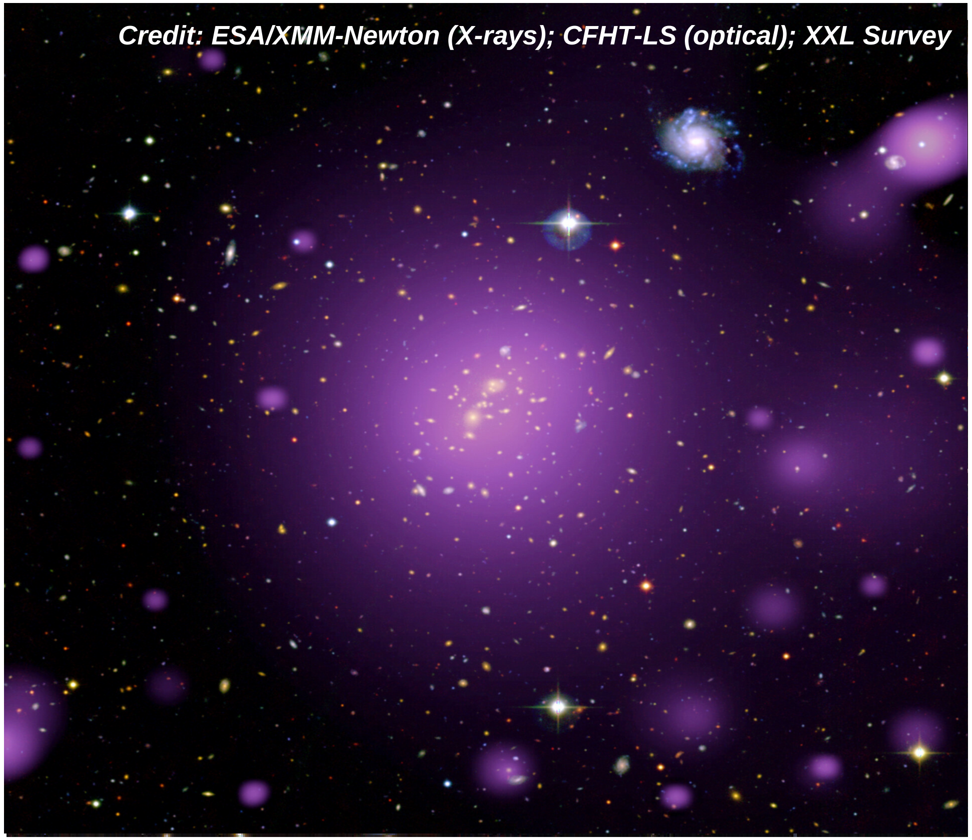
- MeerKAT Galaxy Clusters Legacy Survey (MGCLS)
- MGCLS II DE catalogue challenges and results + DR2
- 3GC radio image analysis
- Era of Big Data / Machine Learning

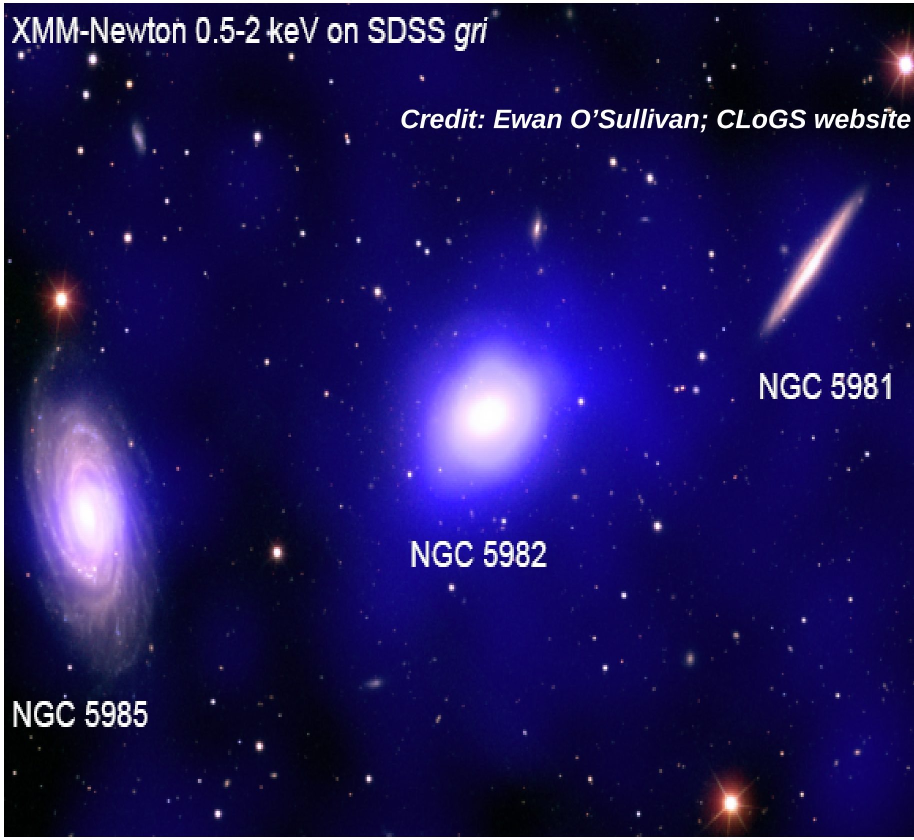
Galaxy Environments

Galaxy clusters *contain ~2% of all galaxies. Members are thousands of galaxies in a size of several Mpc with a mass of* $>10^{14}\ M_\odot$ *→ Filled with 10 - 100 million degree hot gas (plasma) and X-ray emission*

Galaxy groups *contain typically less than ~50 members (up to 100) in a size less than a few Mpc with a mass range of* $10^{12.5}$ *-* $10^{14}\ M_\odot$ *The spread of velocities for the individual galaxies is smaller than in clusters (~150 – 400 km/s)*

Galaxy Environments





Galaxy clusters *contain ~2% of all galaxies. Members are thousands of galaxies in a size of several Mpc with a mass of $>10^{14}\ M_\odot$ → Filled with 10 - 100 million degree hot gas (plasma) and X-ray emission*

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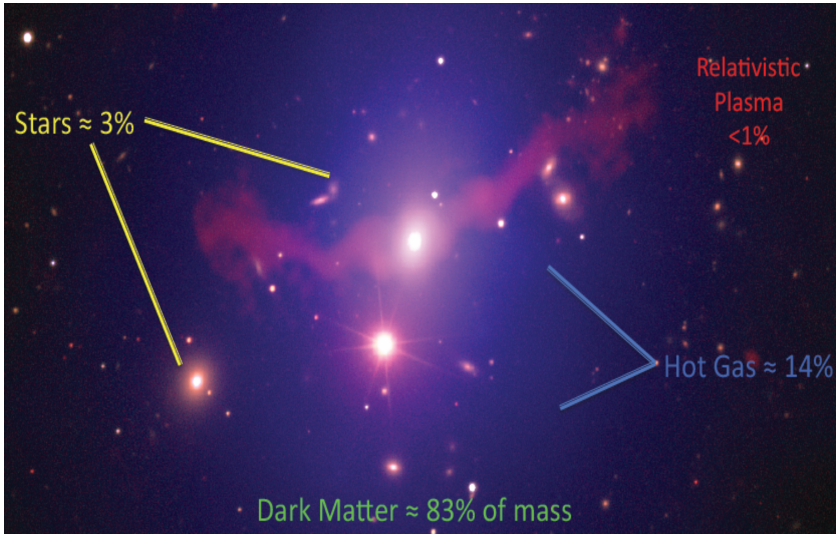
Galaxy Groups vs Clusters

- ➢ Groups are often simplistically considered scaled down versions of clusters

However, groups and clusters have notable differences:

- ✓ In clusters → dominance of the ICM over the galactic component (Giodini et al. 2009)
- ✓ Groups have a smaller baryon fraction than clusters
- ✓ Main cooling mechanism in groups is line emission / in clusters is thermal bremsstrahlung



Why Groups of Galaxies

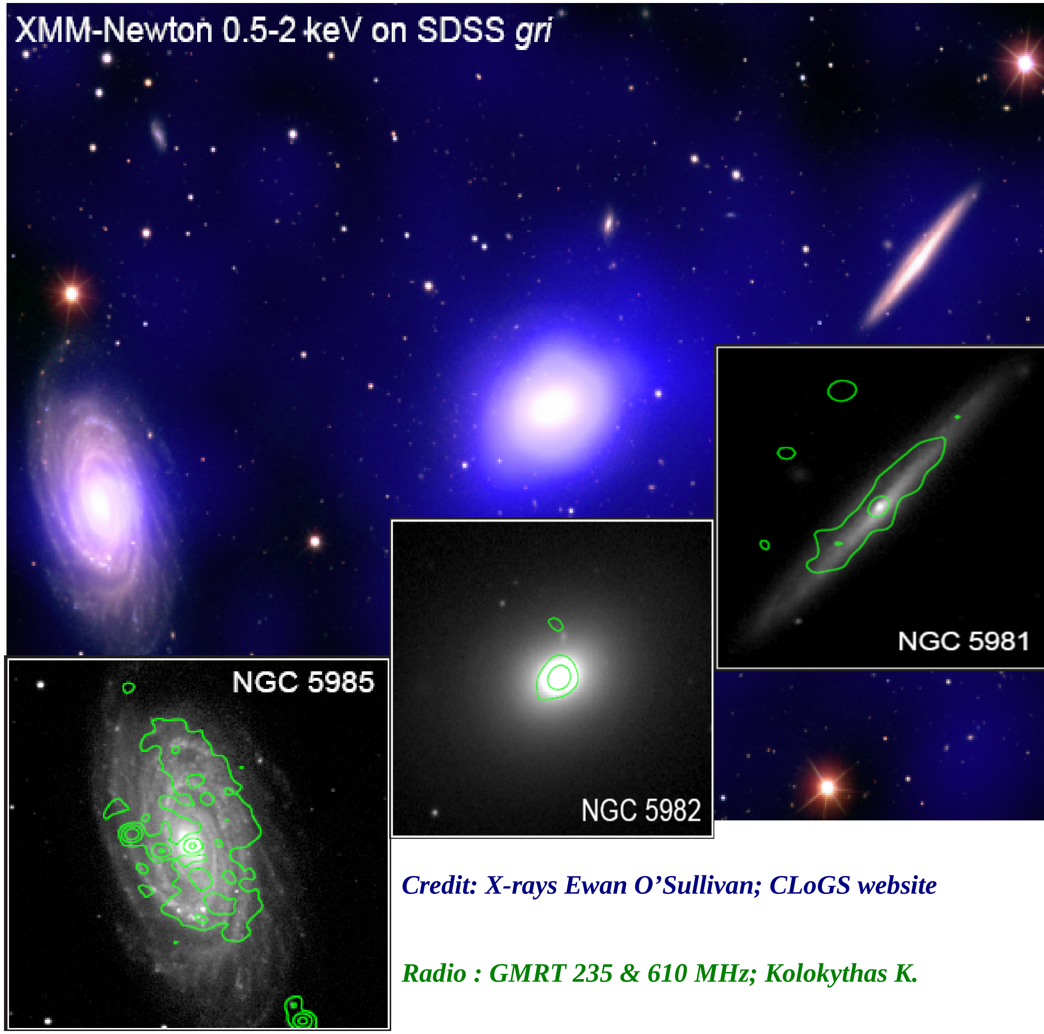
- >50% of Local Universe galaxies resides in Groups (Eke et al. 2006)

- Most of galaxy evolution takes place in the group environment:

  - close proximity, low relative velocities
  - promoting tidal interactions, mergers

- Extensive halos of hot gas; short CCT, fuel star form & active nuclei

- Shallower gravitational potential thus AGN heating has stronger imprints



Credit: X-rays Ewan O'Sullivan; CLoGS website

Radio : GMRT 235 & 610 MHz; Kolokythas K.

Obstacle:Lack of statistically complete radio/X-ray nearby groups sample

Complete Local-Volume Groups Sample

- Optically selected, statistically complete sample of 53 nearby groups (<80 Mpc; **O'Sullivan et al. 2017**)

- CLoGS project has been the first statistically volume-limited complete survey of galaxy groups observed in the
  - X-ray – hot gas (*Chandra* and *XMM-Newton* Ewan O'Sullivan)
  - Optical - galaxies
  - Radio – AGN activity (GMRT 235 and 610 MHz)

- Several publication products on sample study and individual systems:

  (Radio CLoGS I,II: **Kolokythas et al. 2018, 2019;** NGC 4261: **Kolokythas et al. 2015;** NGC 5903: **O'Sullivan et al. 2018a;** NGC 1550: **Kolokythas et al. 2020;** NGC 5044: **Rajpurohit et al. 2025)**

- Expanded studies in CO (**O'Sullivan et al. 2015, 2018b**), MUSE (**Olivares et al. 2022**), MUSE stellar kinematics (**Loubser et al. 2022**), MUSE ionization mechanisms (**Lagos et al. 2022**) and the use of archival FUV, Near-IR and Mid-IR data (**Kolokythas et al. 2022)**

CLoGS project

Sample selection

Begin with Lyon Galaxy Groups (Garcia 1993)

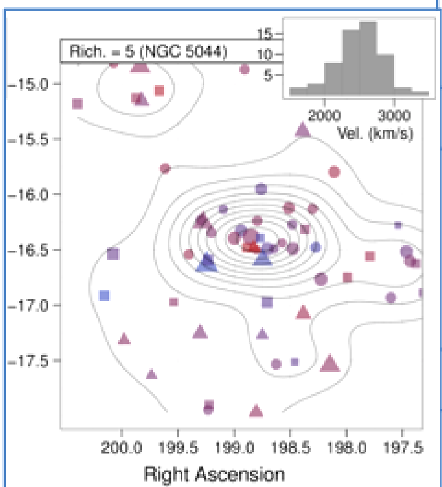
- *All-sky, optically-selected*, cz<5500 km s^{-1} (D<80Mpc)

485 groups

Select from LGG list: systems with

- ≥4 members
- ≥1 early-type member with $L_B \geq 3\times10^{10} L_\odot$
- Declination >-30° (visible from GMRT and VLA)

67 groups



Expand and refine membership

- Update membership from HyperLEDA
- Use isodensity maps to reject problem cases

Filter on *richness* (*R* = N_{gal} with $L_B \geq 1.6\times10^{10} L_\odot$)

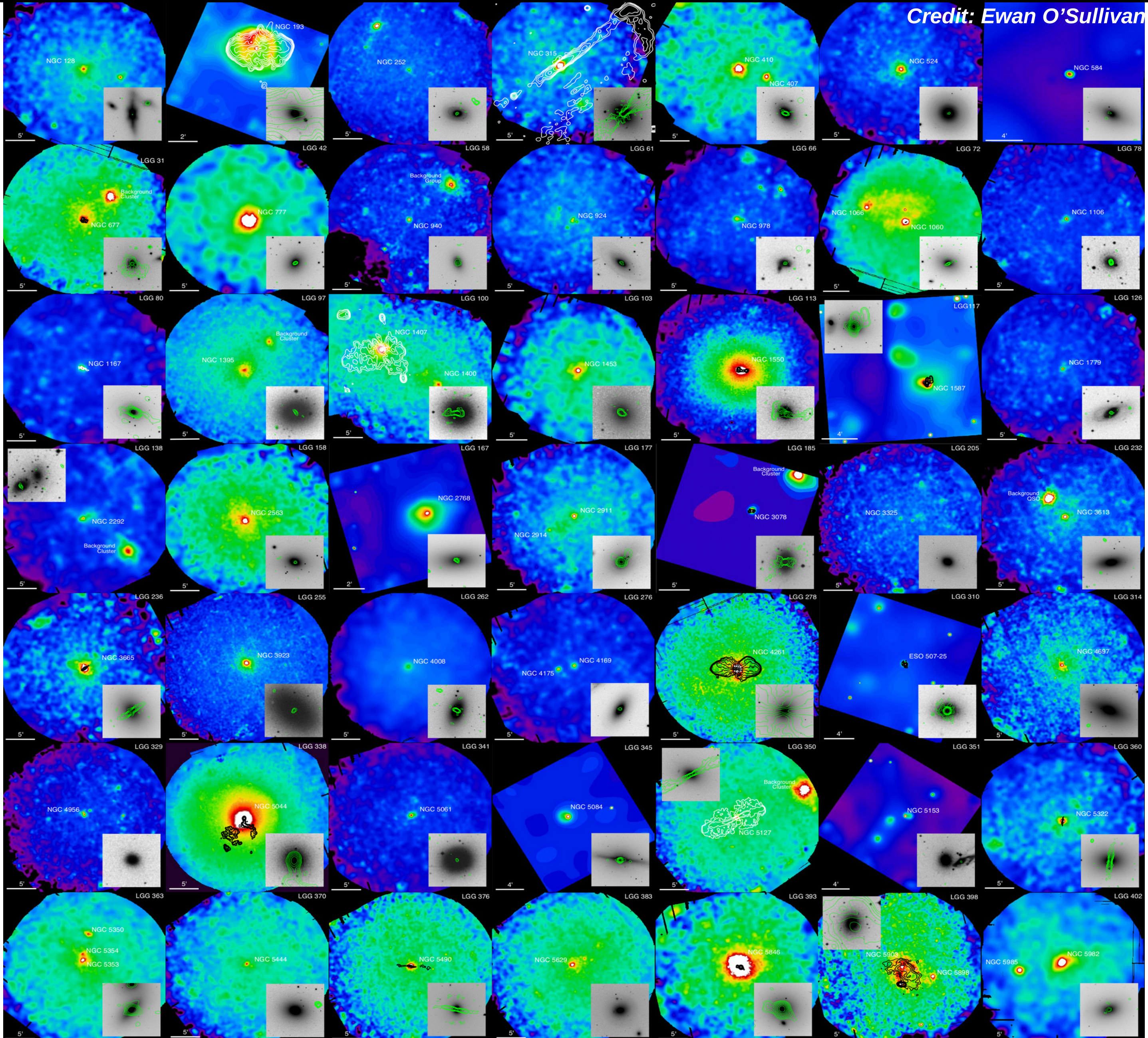
- Exclude known clusters: R≥10
- Exclude groups too small to characterize: R=1

53 groups

26 groups
High-richness subsample (R=4-8)

27 groups
Low-richness subsample (R=2-3)

Complete Local-Volume Groups Sample

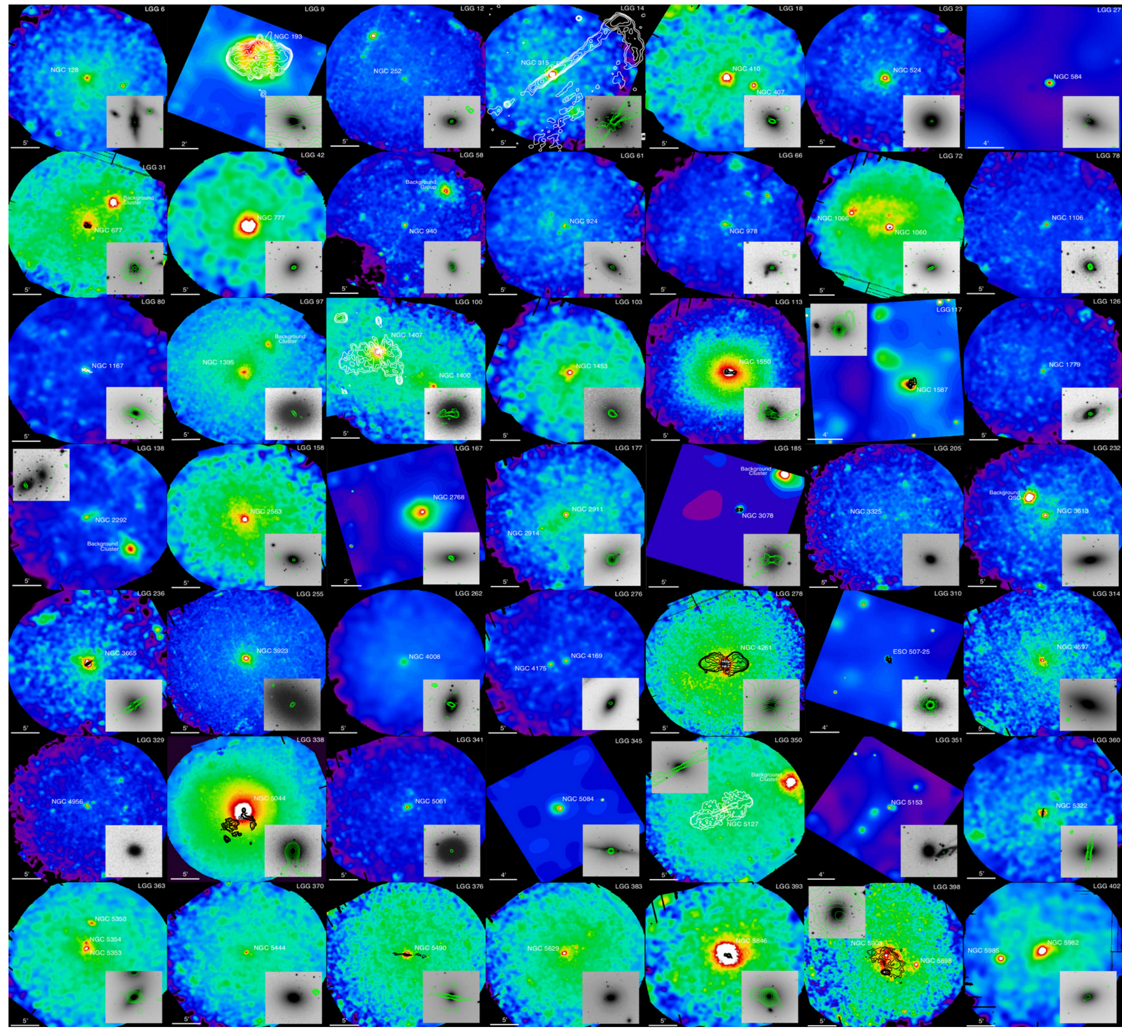


CLoGS: Radio properties of BGEs

- **46/53 group (87%)** central BGEs are **detected** at any radio frequency using **GMRT** & **NVSS/FIRST**

- **53%** present **point-like** radio emission, **19%** having **jets** with **non-detections** at **13%**

- BGEs present wide ranges of radio power ($P_{235\ MHz}$) at 235 MHz **(10^{21} - 10^{25} W Hz^{-1})** **projected sizes (~3 kpc to 2 Mpc)**



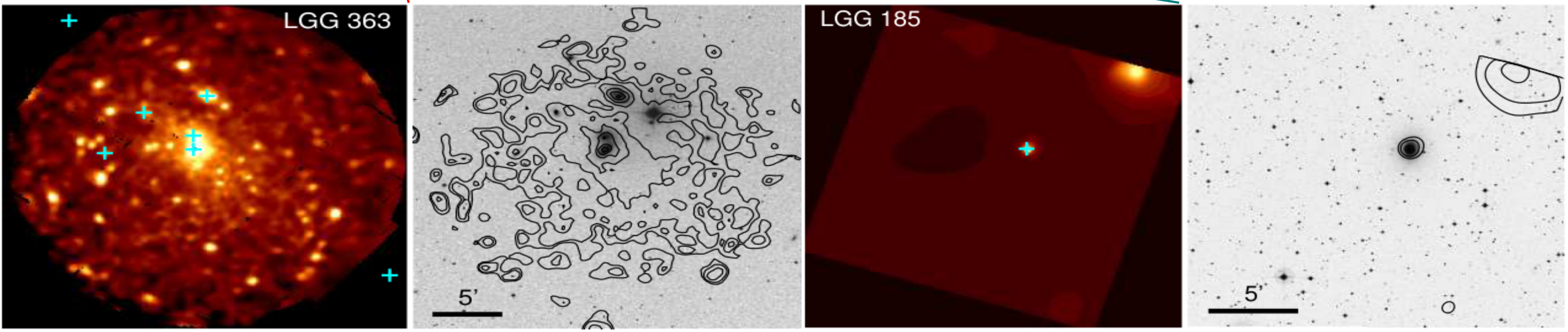
Radio CloGS II: **Kolokythas K.,** O' Sullivan et al., 2019, MNRAS, 489, 2488 (Paper III)

Results: X-rays

- Groups categorized in 2 Classes according to their X-ray properties:

➢ *Class I includes groups with X-ray emission detected at >65 kpc from their cores (X-ray bright)*

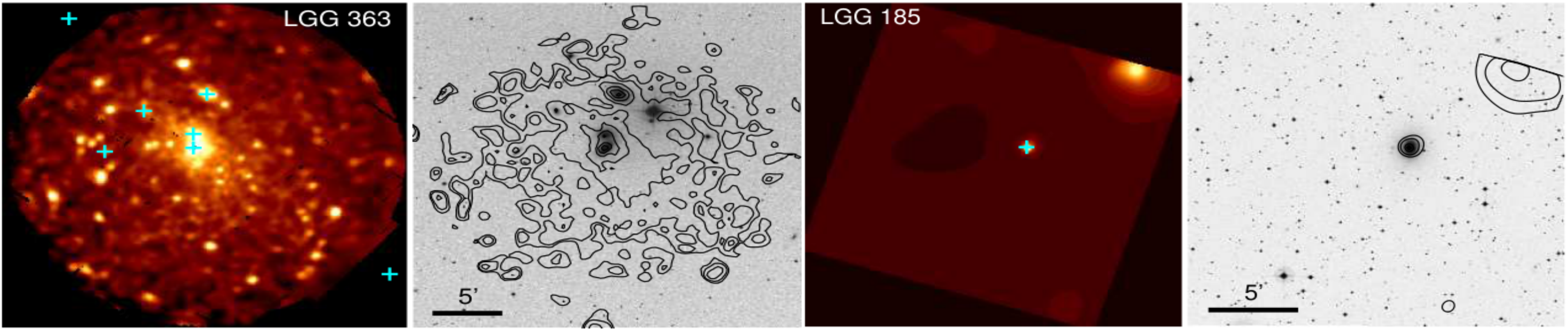
➢ *Class II, includes the remaining galaxies that present galaxy scale or point X-ray emission, which are X-ray faint (<65 kpc)*



Xray CLoGS: O' Sullivan, Ponman, **Kolokythas K.** et al., 2017, MNRAS, 472, 1482 (Paper I)
Radio CLoGS: **Kolokythas K.,** O' Sullivan et al., 2018, MNRAS, 481, 1550 (Follow up Paper II)
Radio CloGS II: **Kolokythas K.,** O' Sullivan et al., 2019, MNRAS, 489, 2488 (Paper III)

CLoGS: Results in X-rays

- ~**49%** of the groups (26/53) have a full-scale IGrM
- 11/26 (~42%) of *X-ray bright* groups host radio jet systems (small + large scale)
- Implying an AGN duty cycle for CLoGS groups >1/3
- All 5 jet systems in *X-ray bright* groups are found in cool core systems
- All radio non-detection found in *X-ray faint* groups



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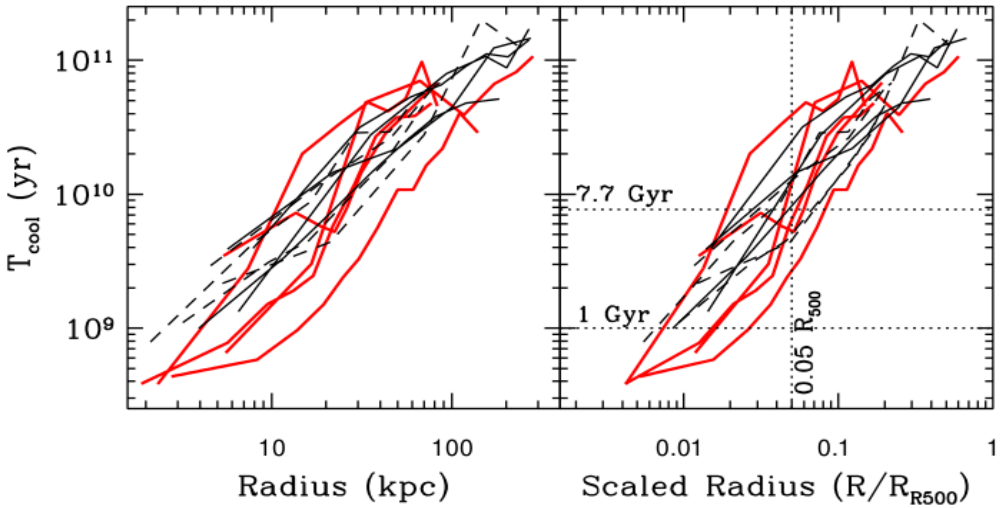
CLoGS: Radio / X-ray comparison

- Jet systems while injecting energy in the IGM they <u>have not dramatically increased the entropy</u> in their immediate surroundings (except NGC 193)

- **Jet activity correlated to short CCTs rather than low central entropies** (Central entropies not enhanced in jet systems except NGC 193)

- All jet sources in ***X-ray bright*** groups have short tcool (<7.7 Gyr) **-** All groups are **cool cores** by cluster definition!

Entropy or tcool at fixed radius is poor predictor of jet activity



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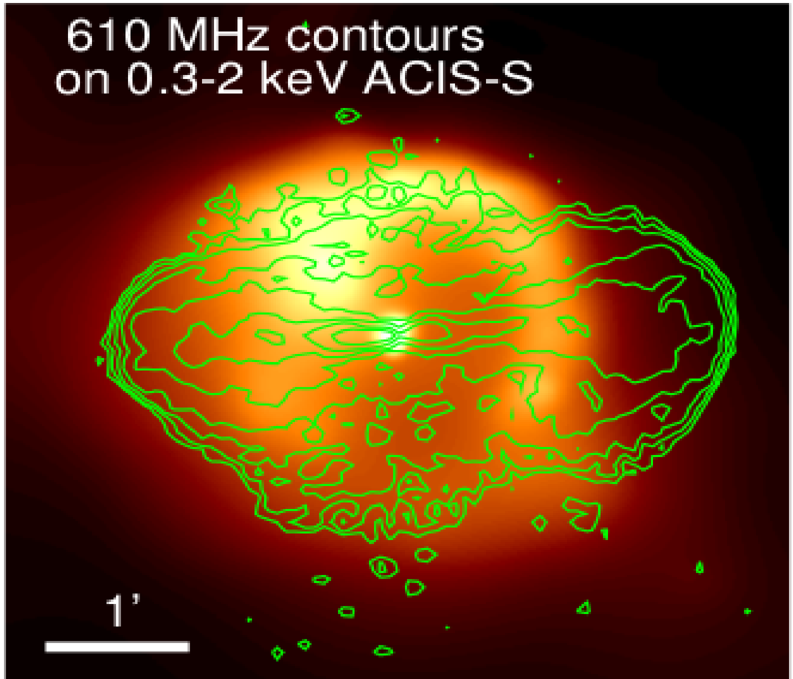

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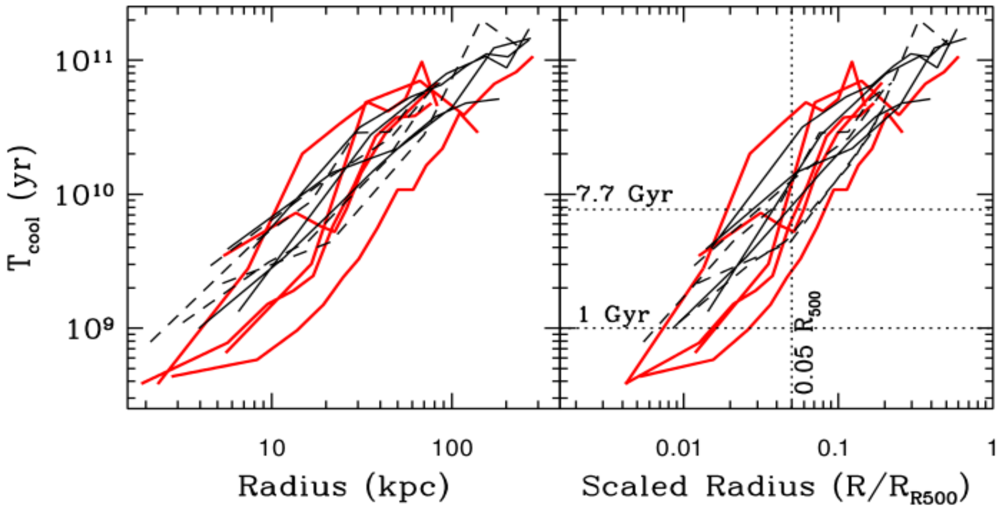
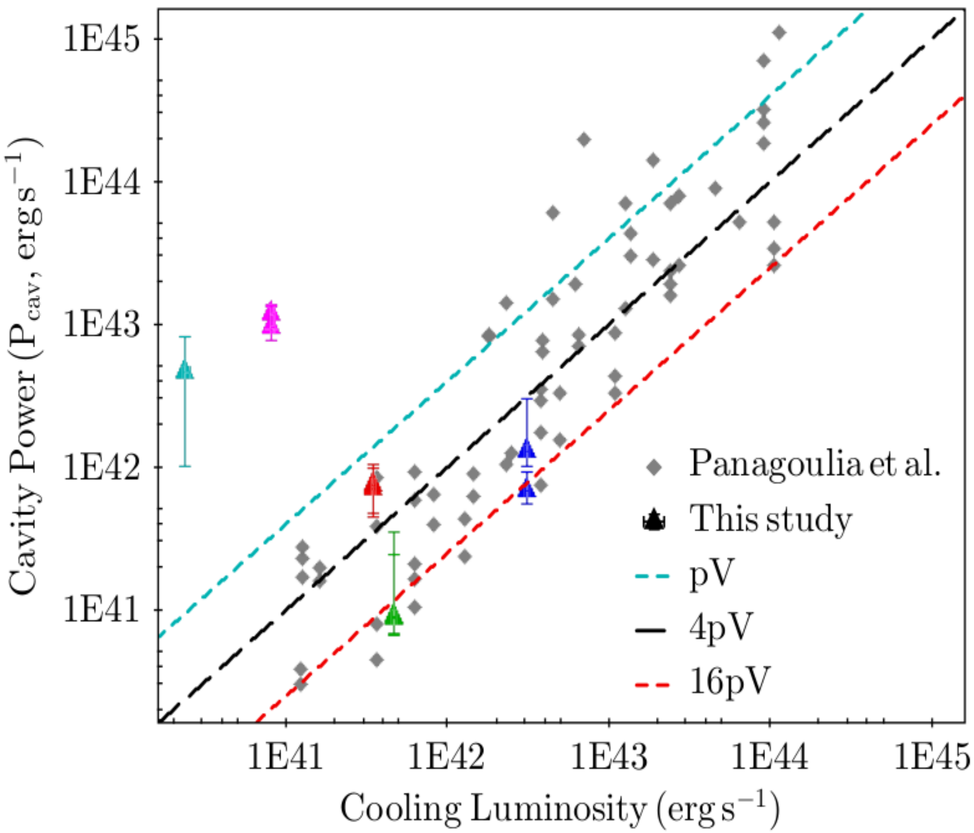


Energetics: Heating vs Cooling

- Small scale and remnant jets lie within the scatter, indicating approx thermal balance

- NGC 193 & NGC 4261 significantly over-powered exceeding over 100x their environment's L_{cool}



AGN feedback in groups can manifest as relatively gentle near-continuous thermal regulation, but also as extreme outbursts, which could potentially shut down cooling for long periods of time!

Xray CLoGS: O' Sullivan, Ponman, **Kolokythas K.** et al., 2017, MNRAS, 472, 1482 (Paper I)
Radio CLoGS: **Kolokythas K.,** O' Sullivan et al., 2018, MNRAS, 481, 1550 (Follow up Paper II)

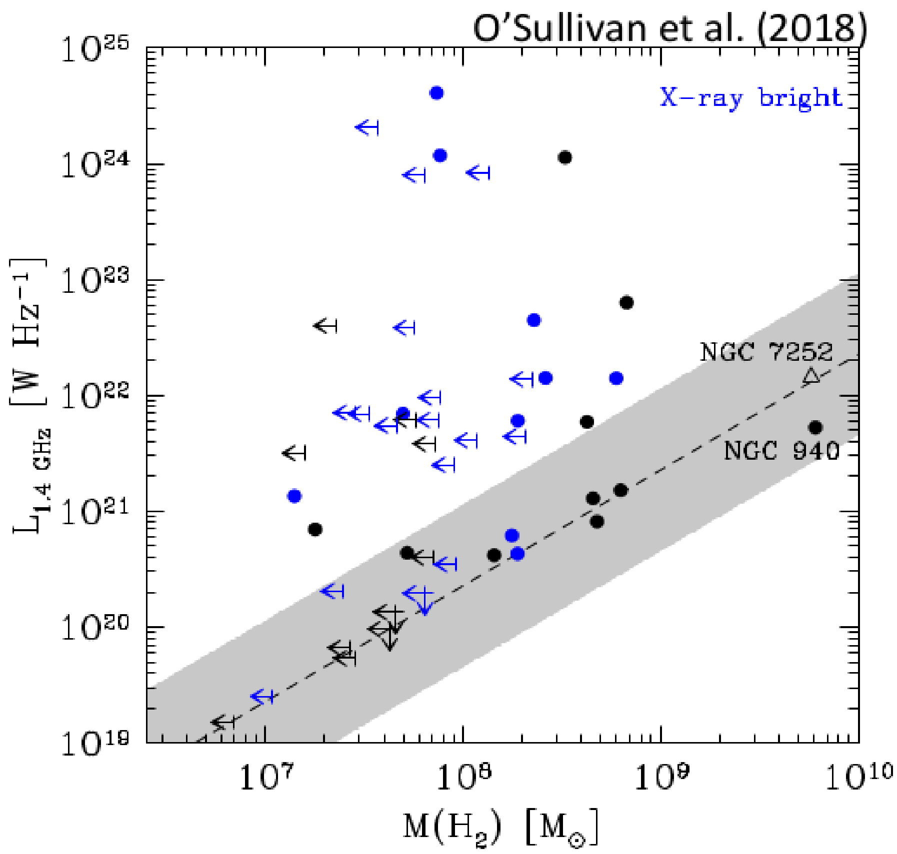
Molecular gas in CLoGS BGEs

All 53 BGEs surveyed in CO using the IRAM 30m and APEX telescopes

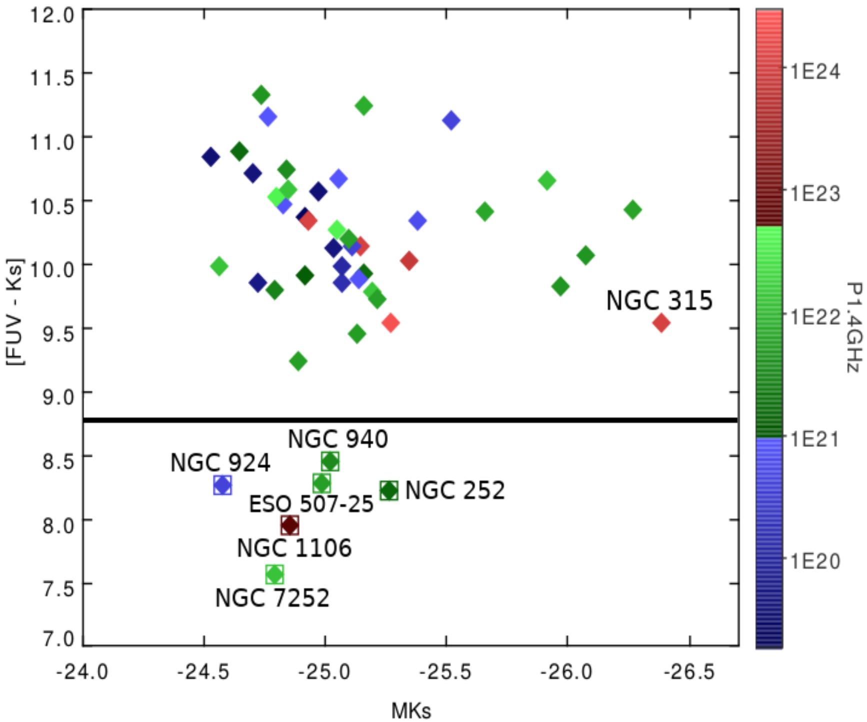
- CO detection rate in group-dominant galaxies: ~40%
- More than **50%** of CO detected systems have HI emission
- CO detection is found in both ***X-ray bright*** and ***X-ray faint*** groups

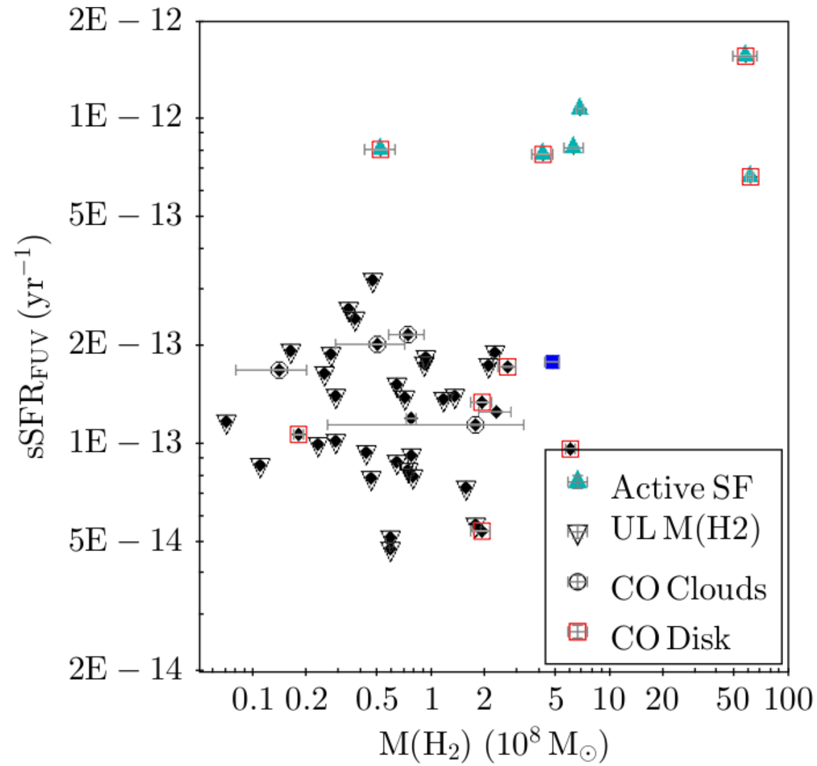
Implies both cooling and merger origins

- BGEs present low SFR (<1 $M_\odot$ yr^{-1}) and short depletion time (<10^8 yr)
- Large CO mass isn't required to trigger an AGN outburst



sSFR and cold gas in BGEs





- SF is not driven merely by the presence of cold gas, but its dynamical state -> disks provide stable environment in which gas has time to collapse & form stars

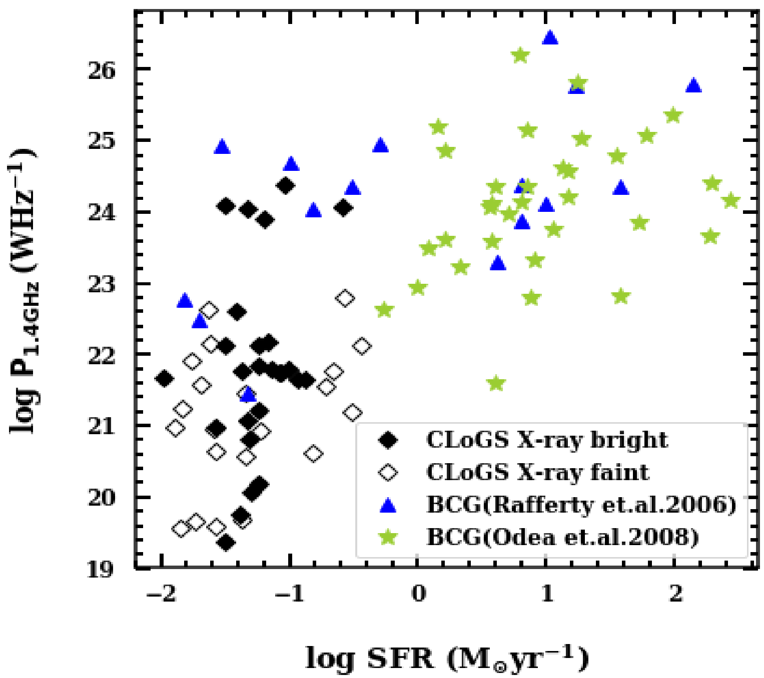
- Since all ASF occupy X-ray faint systems -> cold gas is unlikely to be the product of cooling from a hot IGrM, more likely acquired through gas-rich mergers / tidal interactions

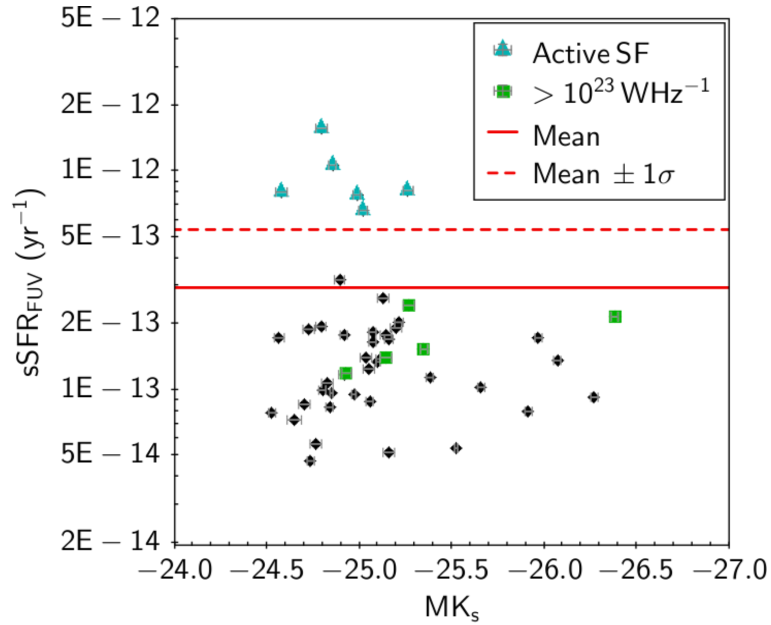
Kolokythas K., Vaddi S., O'Sullivan E., et al., 2022, MNRAS, 510, 4191

sSFR and cold gas in BGEs

- By contrast, most radio powerful BGEs occupy X-ray bright groups, demonstrating the linkage between IGrM cooling & jet-mode feedback

- No evidence that presence of radio jets affects SF in BGEs, even most powerful & long-lived radio galaxies





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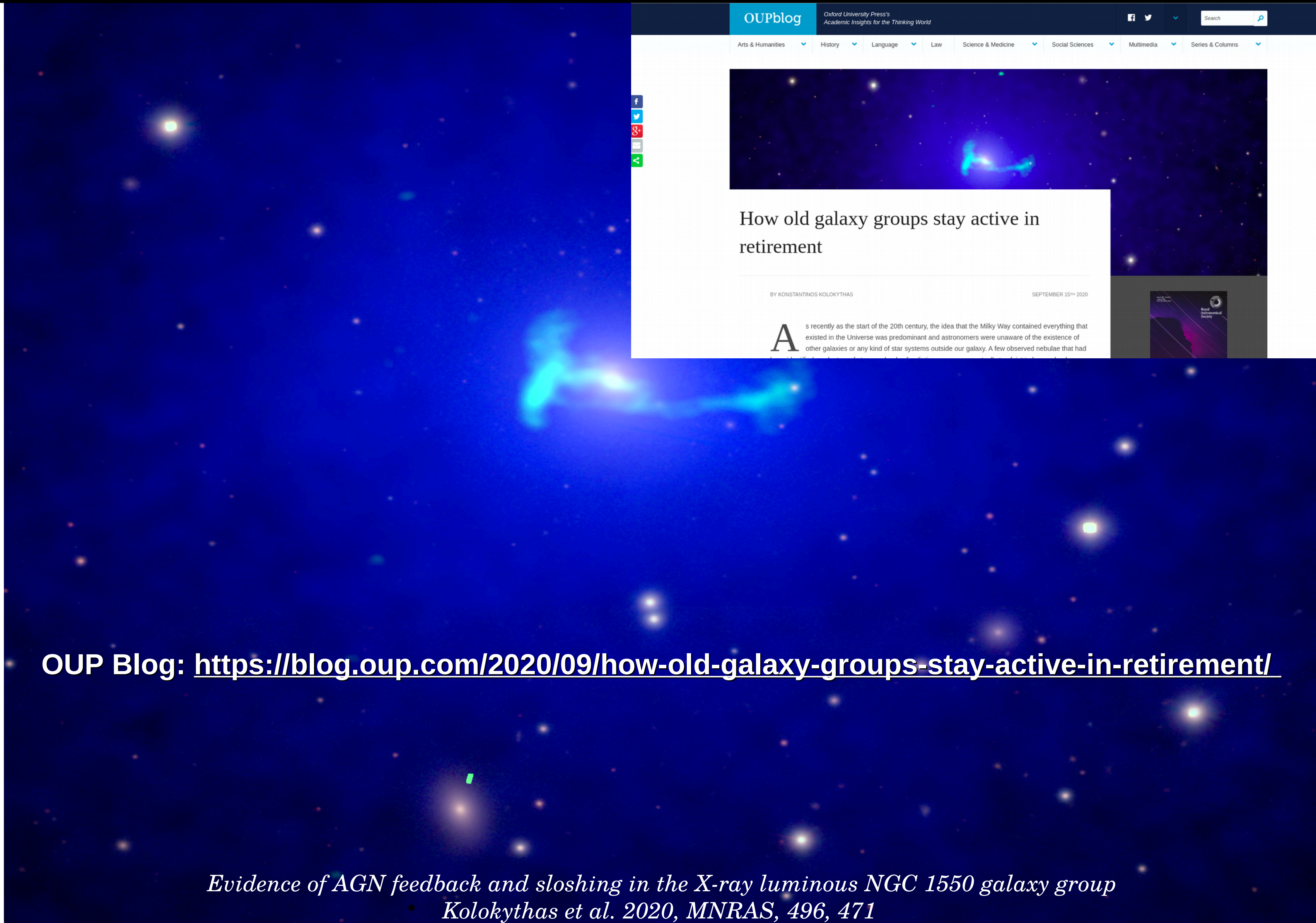
How old galaxy groups stay active in retirement: The case of NGC 1550



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How old galaxy groups stay active in retirement

BY KONSTANTINOS KOLOKYTHAS

SEPTEMBER 15TH 2020

As recently as the start of the 20th century, the idea that the Milky Way contained everything that existed in the Universe was predominant and astronomers were unaware of the existence of other galaxies or any kind of star systems outside our galaxy. A few observed nebulae that had

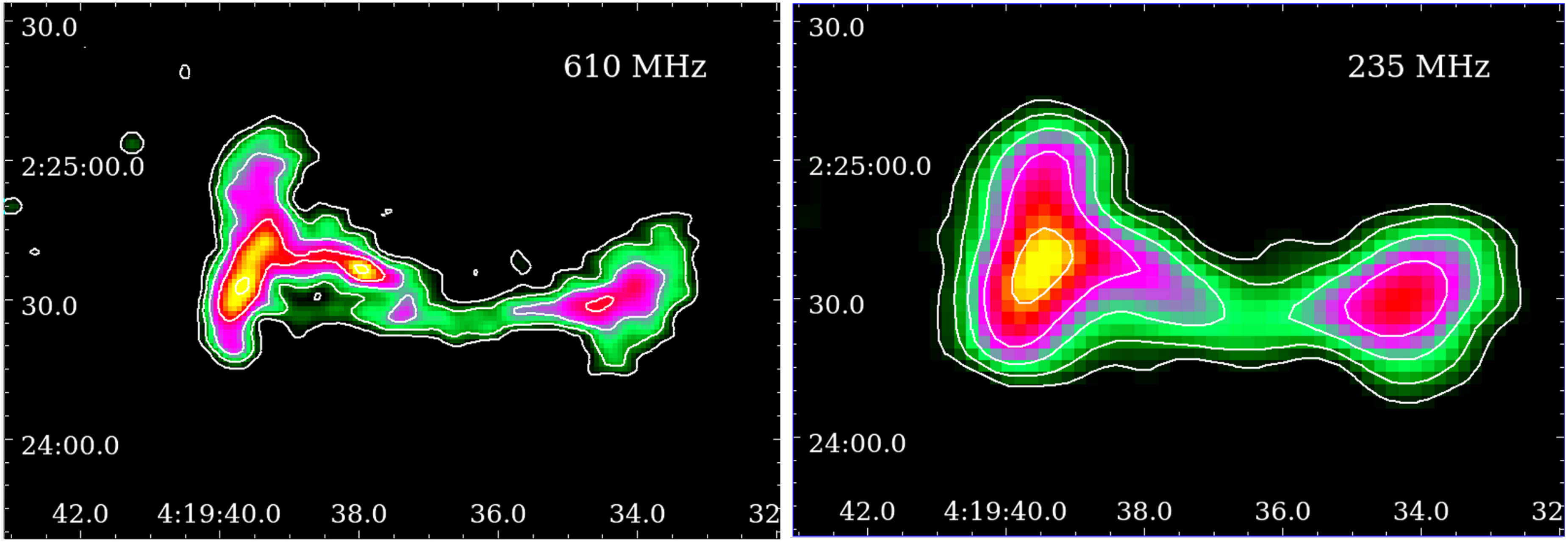
OUP Blog: https://blog.oup.com/2020/09/how-old-galaxy-groups-stay-active-in-retirement/

Evidence of AGN feedback and sloshing in the X-ray luminous NGC 1550 galaxy group
Kolokythas et al. 2020, MNRAS, 496, 471

The case of NGC 1550

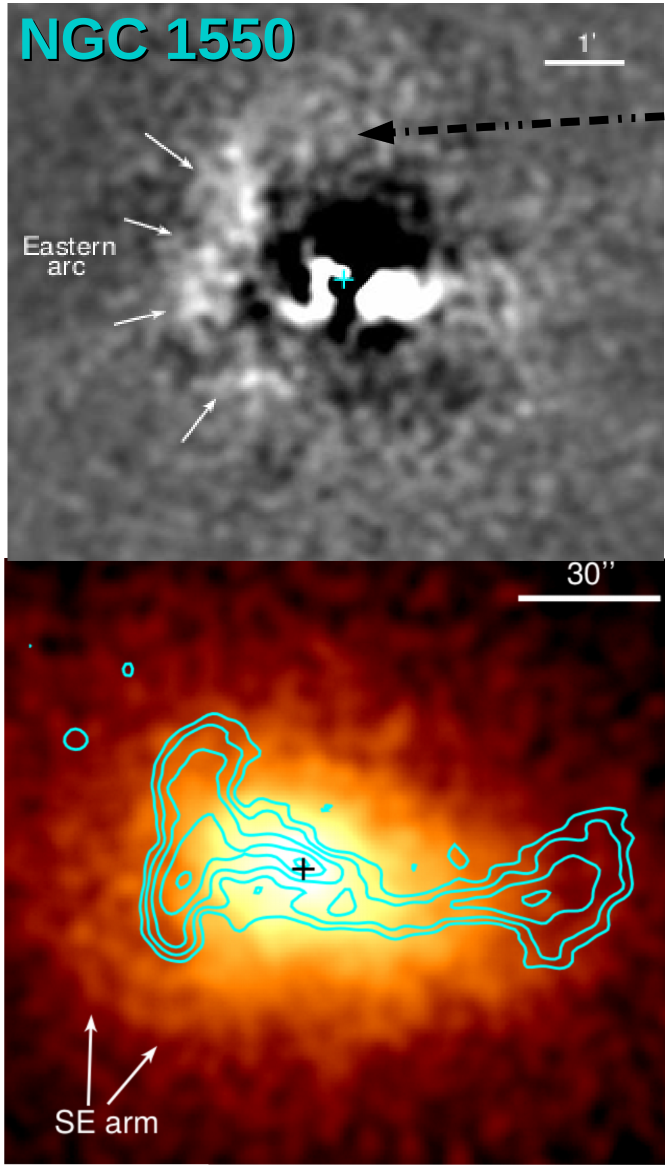
- Discovered previously unknown lobes in NVSS J041937+022435 radio source associated with NGC 1550

- Radio source is asymmetric, W jet extends twice as far from nucleus as E jet, and W jet has a bend or kink in it.



Kolokythas K., O'Sullivan E., Giacintucci S., Intema H. et al., 2020, MNRAS, 496, 1471

The case of NGC 1550



- Indications of **sloshing** from the observed **arc-shaped** structure in the X-ray residual map

- Trad≈**35 Myr** agreement with dynamical X-ray timescale (35−40Myr) & shortest timescale estimate for sloshing motions (40−80Myr)

The observed radio/X-ray structure is a combination of sloshing motions with effects of buoyant forces from jet/lobe growth in the IGM

Although NGC 1550 has been considered relaxed hosting a decaying radio source, we find evidence that has undergone a recent minor merger

OUP Blog: https://blog.oup.com/2020/09/how-old-galaxy-groups-stay-active-in-retirement/

Kolokythas K., O'Sullivan E., Giacintucci S., Intema H. et al., 2020, MNRAS, 496, 1471

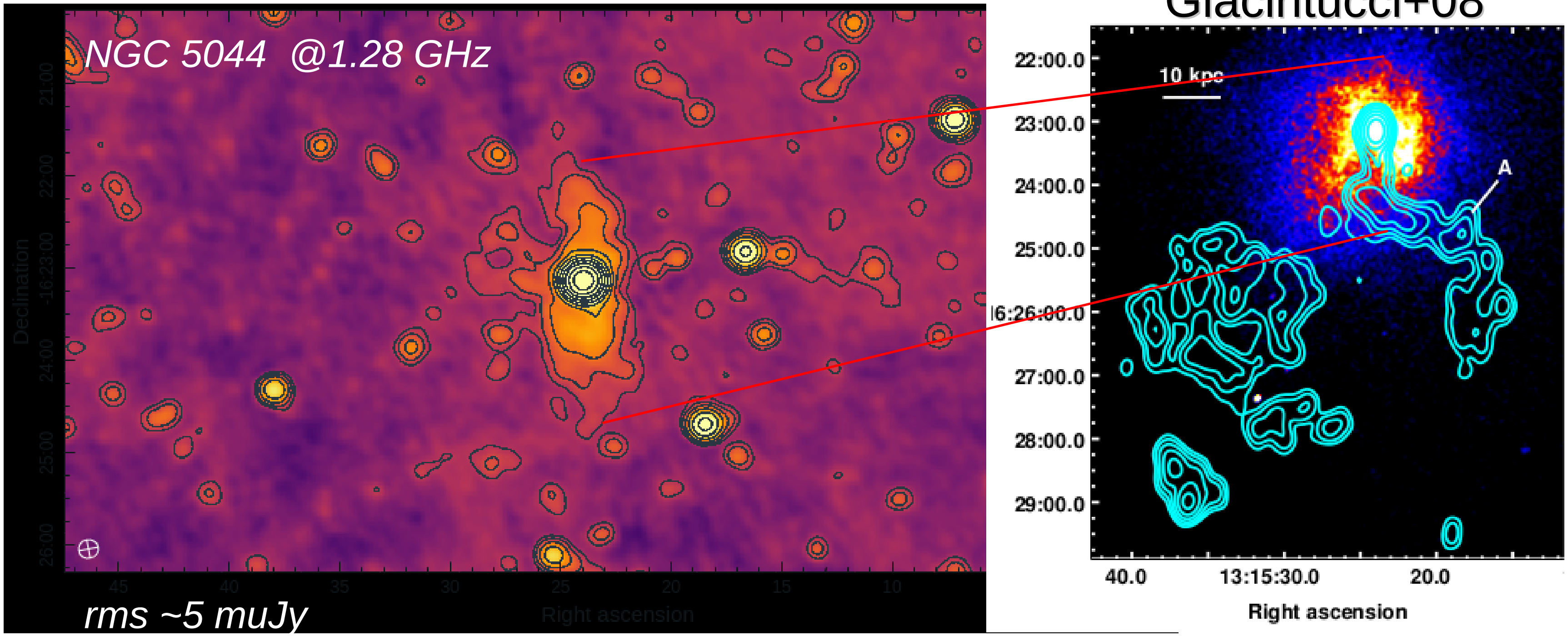
Radio continuum and HI emission: The case of NGC 5044

(PI Kolokythas) for 10 CLoGS groups (MeerKAT continuum plus HI)

- X-ray brightest group in the sky and best-studied cooling flow group

- X-ray, GMRT & VLBA observations reveal 4 cycles of AGN outbursts, including steep spectrum emission from an old jet and lobe bent

Giacintucci+08

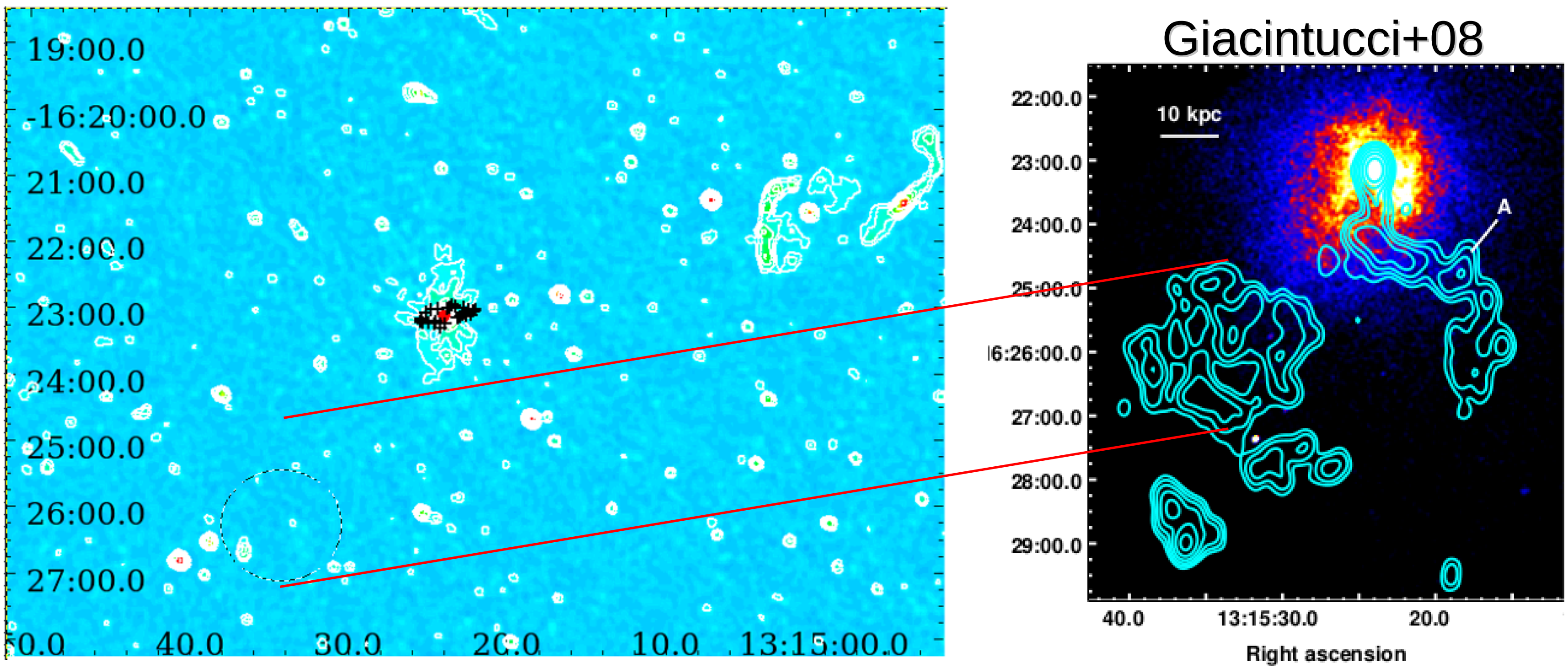


Rajpurohit K., Deb T., **Kolokythas K.,** et al., 2025, ApJ, 984, 120

Revisiting the Group-Dominant Elliptical NGC 5044 in the Radio Band: Continuum Emission and Detection of HI Absorption

Radio continuum and HI emission: The case of NGC 5044

➢ Rapid IGM cooling in the group core traced by Hα filaments, H2 and [C II] line emission, while molecular clouds from ALMA and ACA are also mapped (David et al. 2014, 2017, Schellenberger et al. 2020).



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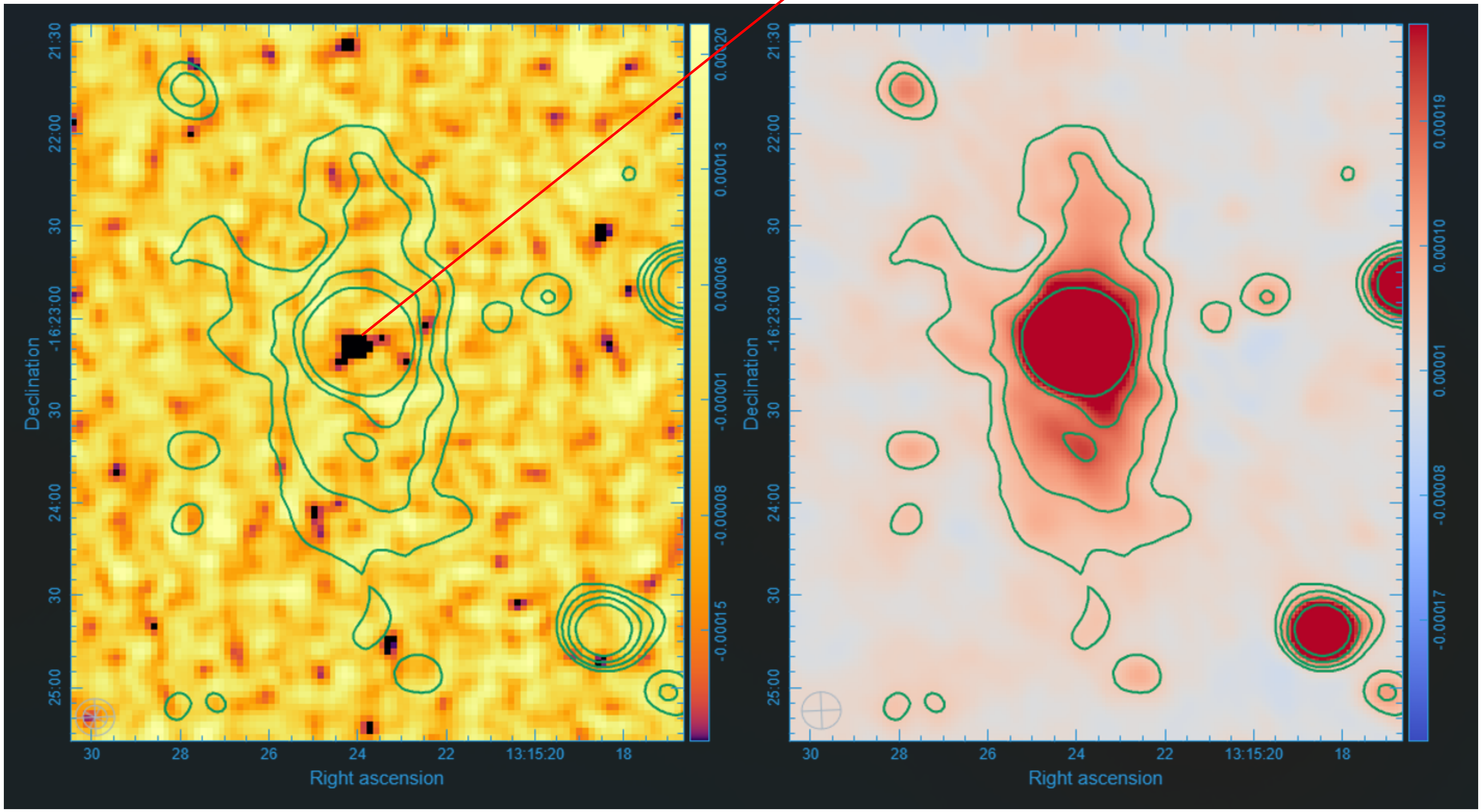
Radio continuum and HI emission: The case of NGC 5044

- We find the first direct evidence of neutral atomic gas in NGC 5044, in the form of a 3.8σ significant two-component HI absorption signal near the core line seen against the emission of the active nucleus



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Revisiting the Group-Dominant Elliptical NGC 5044 in the Radio Band: Continuum Emission and Detection of HI Absorption

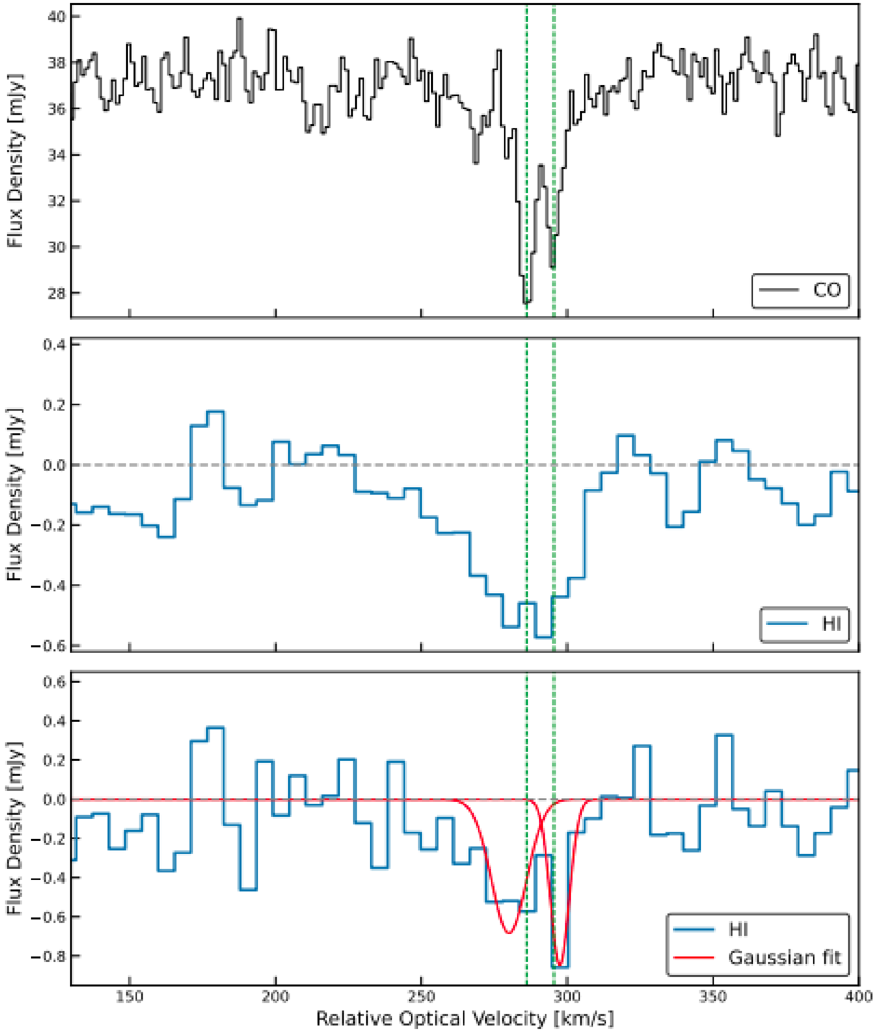
Radio continuum and HI emission: The case of NGC 5044

- No HI emission detected, Upper Limit $M_{HI} < 5.4\times10^7\ M_\odot$ in the central 15″ (2.2 kpc) of the galaxy

- Significantly less than the estimated molecular gas content

- With these gas phases forming through cooling from the hot IGM

<u>Also constrained the spin temperature to Tspin ≤ 950 K, indicating that the detected H I is in the cold neutral phase</u>



Rajpurohit K., Deb T., **Kolokythas K.,** et al., 2025 accepted in ApJ

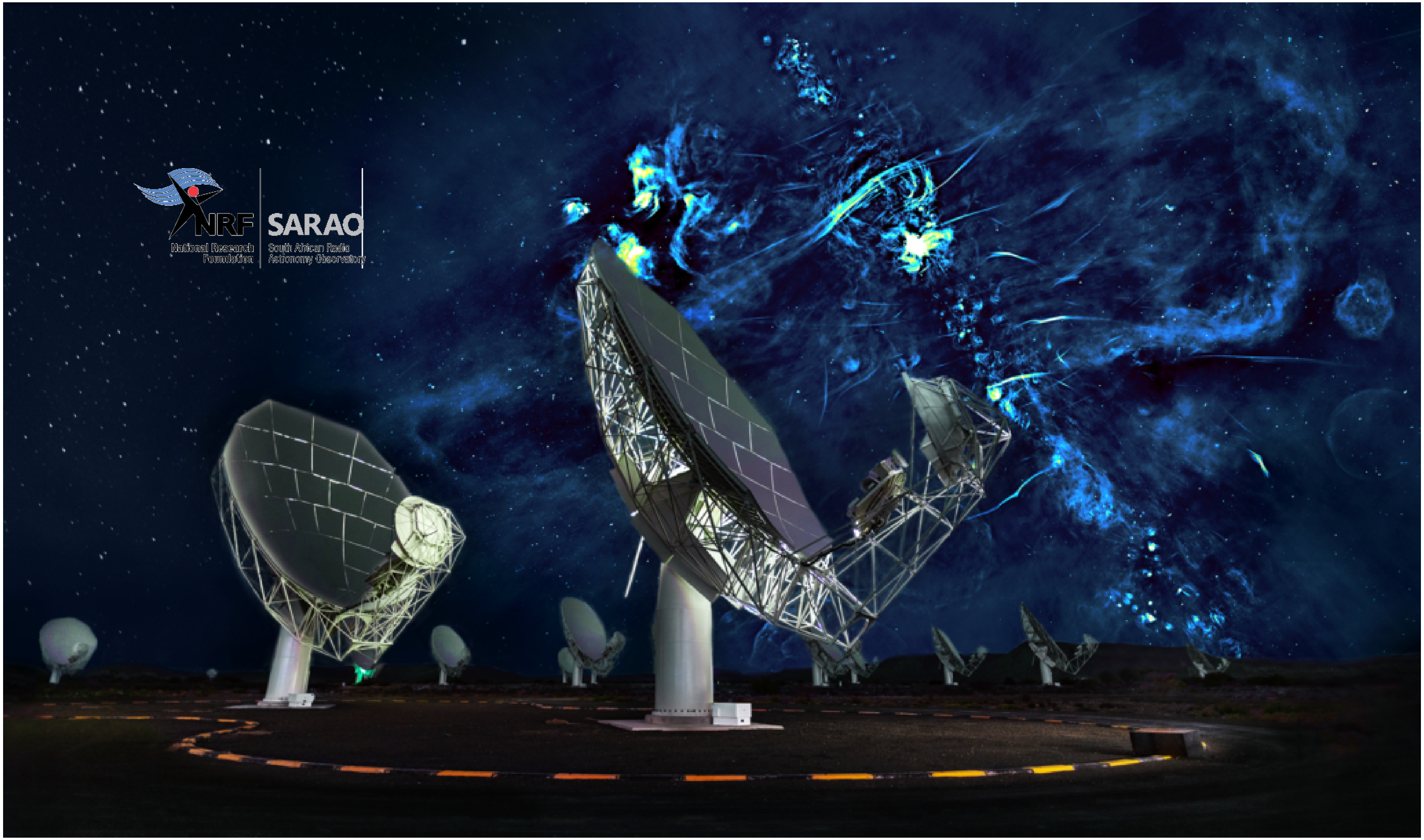
End of Part 1: Take home points on Galaxy Groups

Extreme outbursts are also occurring in the group environment rather than only low-power weak AGN

CLoGS sample BGEs constitute a mosaic of systems, whose evolution is affected by a combination of secular processes & mergers/interactions, regulated by environment they reside

The presence of a large cold gas reservoir in the form of a rotating disk, seems to promote active SF, & originate from gas rich mergers/interactions, while the presence of an X-ray bright IGrM increases the chances of AGN jet activity with the origin of cold gas in this case is cooling from the IGrM

Part 2 :
Diffuse Skies in Clusters with MeerKAT

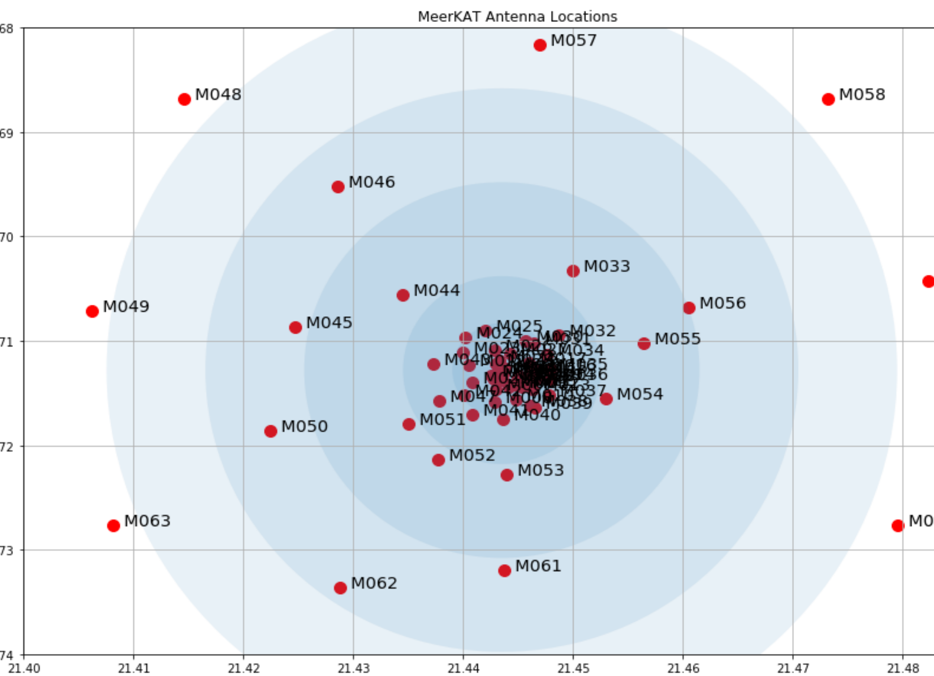


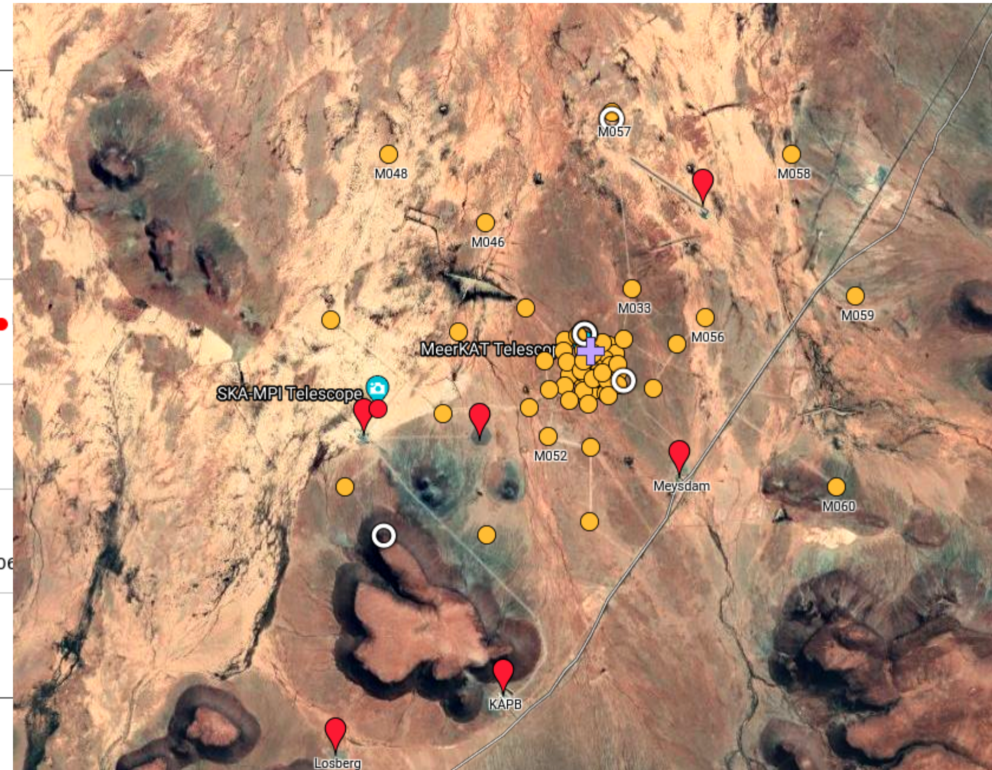
SKA precursor: MeerKAT

- 64–dish radio interferometer of 13.5 m-diameter each
- Observes the sky below a DEC of **+15°**
- Operational in L-(900–1670 MHz), S-(1750–3500 MHz), and UHF-bands (580–1015 MHz) see Jonas & MeerKAT Team (2016) and Camilo et al. (2018)
- MeerKAT's L-band, primary beam full-width half-maximum (FWHM) of **1.2°** at 1.28 GHz, was first to be commissioned in 2018

SKA precursor: MeerKAT

- MeerKAT's min baseline is **29 m** and max baseline **7700 m**
- A dense inner component contains 70% of the dishes
- An outer component contains 30% of the dishes





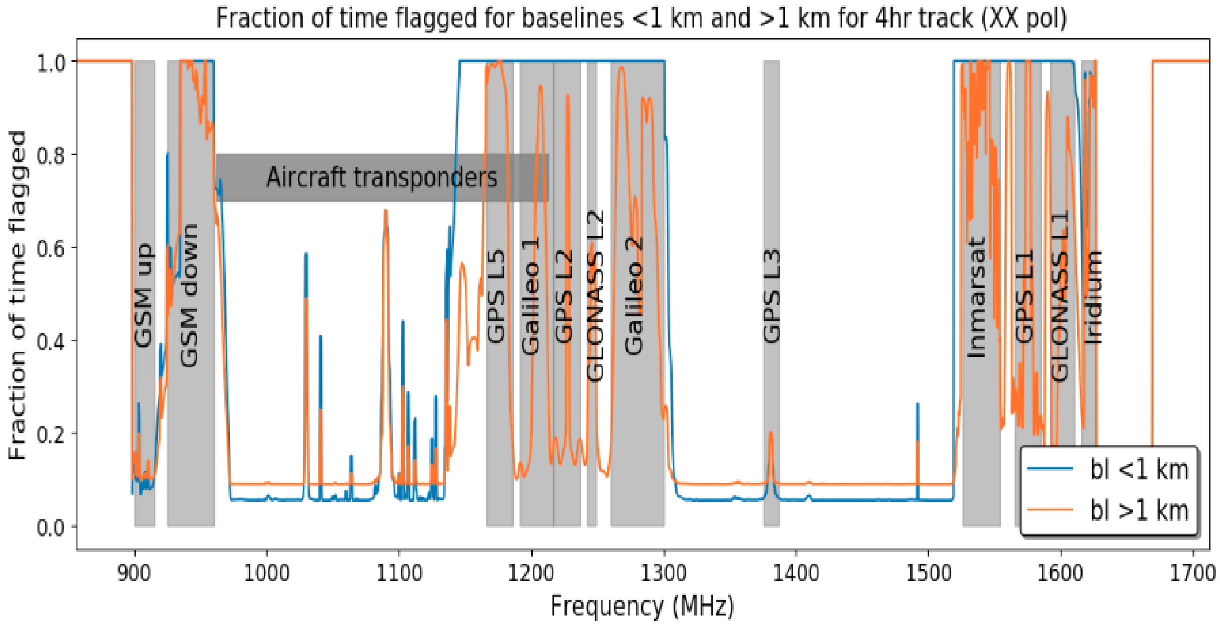
SKA precursor: MeerKAT

- With up to 2016 baselines & 4 pol products per baseline, MeerKAT data volumes are not insignificant

- Recorded data rates for 4K channel mode & 8s integration period is **~0.14 TB/hr**, up to **~1.1 TB/hr** for 32K channel mode

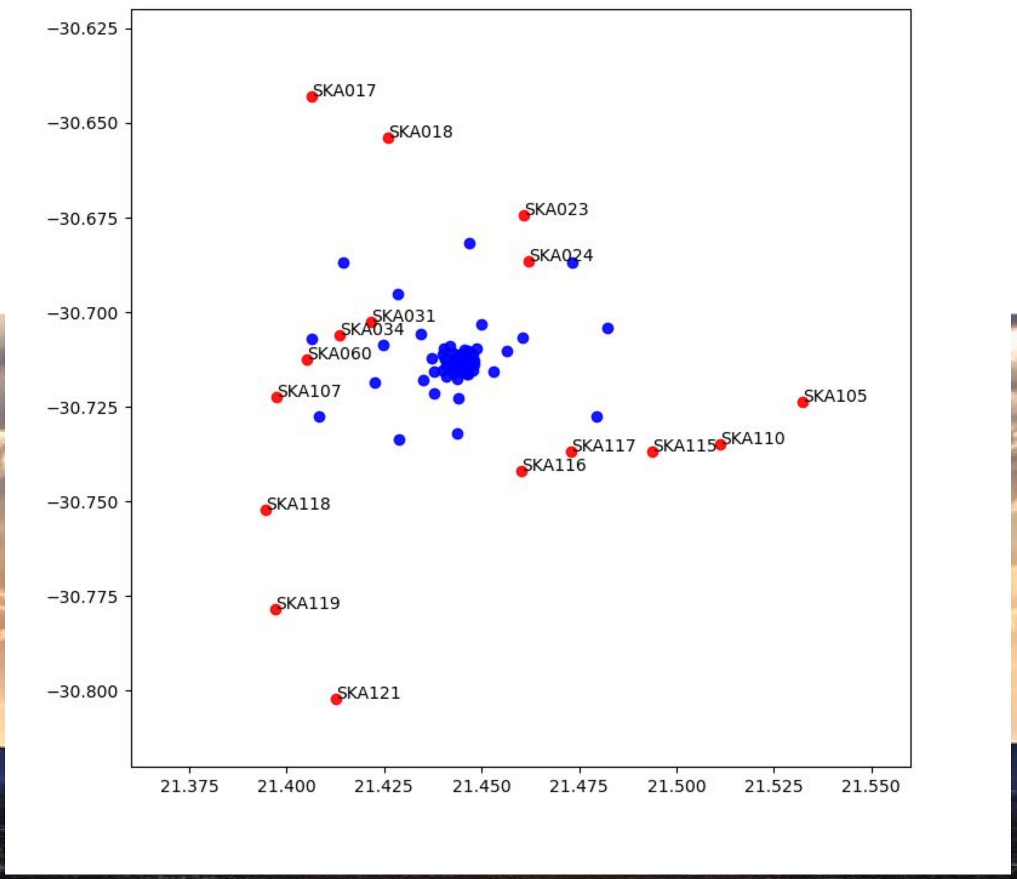
RFI is also a challenge at wide-band even at 1.28 GHz

RFI source	Frequency range (MHz)
GSM (Mobile phones)	900 - 915 uplink 925 - 960 downlink
Aircraft transponders	Multiple <1 MHz bandwidth intermittent signals
GPS	L1: 1565 - 1585 L2: 1217 - 1237 L3: 1375 - 1387 L5: 1166 - 1186
GLONASS	L1: 1592 - 1610 L2: 1242 - 1249
Galileo	1191 - 1217, 1260 - 1300
Iridium	1616 - 1626
Inmarsat	1526 - 1554



MeerKAT Extension (MK+) Updates

- 16 new antennas, of ‘SKA design’ (~1.35x more sensitive than MeerKAT’s)
  - Maximum baselines ~17 km (~twice as much as MeerKAT)
    - Populated with L- and S-band receivers (not UHF)



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- 'L' are SKA Band-2 receivers (0.95–1.76 GHz, compared to 0.9–1.67 GHz for MeerKAT L)
  - Only half of the S band (1.75–3.5 GHz) processed at once
  - Backend to process all 80 antennas simultaneously

MGCLS: MeerKAT Galaxy Cluster Legacy Survey

- **115 targets** observed between June 2018 and June 2019
- ~1000 hours with ~60 dishes *(minimum 59)*
- L-band (900-1670 MHz) FULL POL mode
- 8 – 12 hours observation/cluster with ~ 5.5 – 9 hours on source

Knowles et al. 2022, MGCLS survey Paper I, A&A, 657, A56

MGCLS: MeerKAT Galaxy Cluster Legacy Survey

- Heterogeneous sample, with no mass / *z* selection criteria, in two groups:

Radio- (41 from earlier diffuse radio emission studies)

X-ray-selected (74 selected from the MCXC catalog; Piffaretti et al. 2011)

- **–80º** to **+15º** declination
- median **z ~ 0.14** **(only 4 clusters at z > 0.4)**

Knowles et al. 2022, MGCLS survey Paper I, A&A, 657, A56

MGCLS: MeerKAT Galaxy Cluster Legacy Survey

- Raw visibilities (More info at : https://doi.org/10.48479/7epd-w356)

- Image Products (~3 – 5 uJy/beam RMS)
  - Basic: 16-plane cube (total intensity, spix, 14 freq)
  - Enhanced (~7’’ and 15’’ resolution):
    - PB-corrected total intensity + spix cube (5pln)
    - PB-corrected frequency cube (12 planes)

MGCLS
MeerKAT Galaxy Cluster Legacy Survey

Broad range of applications

- **Diffuse radio emission**
- Source catalogs
- Radio AGN

62/115 MGCLS clusters (~54%) present some kind of diffuse emission

Some hosting more than one (any type) diffuse cluster radio source

Knowles et al. 2022, MGCLS survey Paper I, A&A, 657, A56

MGCLS: Cluster diffuse radio emission

Key aspect of radio observations of galaxy clusters is the detection of diffuse cluster-scale synchrotron emission

Carries information about the cluster formation history

There are several different classifications of diffuse cluster radio emission, historically separated into three main classes:

radio halos, mini-halos, and radio relics

All classes are characterised by low surface brightness and steep radio spectra ($\alpha < -1.1$)

MGCLS: Cluster diffuse radio emission

- **Radio halos** are diffuse sources which cover scales >500 kpc, with many spanning Mpc-scales typically seen to have morphologies closely linked to those of the X-ray emitting ICM; Main mechanism is particle re-acceleration from cluster mergers (see van Weeren et al 2019)

- **Radio mini-halos** found in central region of dynamically relaxed, cool-core clusters with projected sizes few tens to few hundreds of kpc; always a radio active BCG provides at least a fraction of the seed electrons that produce the diffuse emission (see Giacintucci et al. 2017)

- **Radio relics** are elongated Mpc-scale structures located at the periphery of merging galaxy clusters with their origin related to the presence of merger-induced shocks in the ICM (high polarisation)

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **543**, 1638–1704 (2025) https://doi.org/10.1093/mnras/staf1499
Advance Access publication 2025 September 9

The MeerKAT Galaxy Cluster Legacy Survey – II. Catalogue of the diffuse radio emission in MeerKAT-GCLS clusters

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MGCLS
MeerKAT Galaxy Cluster Legacy Survey

Welcome to the web-home of the MGCLS

Astronomers are continuously striving to image the sky with increasing sensitivity and resolution. The new era of radio astronomy is here, with powerful telescopes like MeerKAT able to image the sky deeper and with better sensitivity to fine-scale structure and diffuse large-scale emission than ever before.

The MeerKAT Galaxy Clusters Legacy Survey (MGCLS) is a programme of long-track MeerKAT L-band (900–1670 MHz) observations of 115 galaxy clusters, observed between June 2018 and June 2019, with target clusters observed for ~ 6-10 hours each. The MGCLS can be used for a wide range of science, including galaxy star formation and AGN activity, cluster dynamics and magnetism, and studying neutral hydrogen in the nearby Universe. A series of Legacy Data Products are made available for use by the astronomical community.

Details of the survey and its science capabilities are presented in the survey overview paper.

http://mgcls.sarao.ac.za/

NRF National Research Foundation | SARAO South African Radio Astronomy Observatory

Contact details for MGCLS queries:
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Email: kendaknowles.astro(AT)gmail(DOT)com

MGCLS II: Kolokythas, Venturi, Knowles et al., 2025, MNRAS, 543, 1704

MGCLS II: Diffuse Cluster radio emission Catalogue

➢ **Kolokythas et al. 2025**, focuses on 62 MGCLS clusters where diffuse radio emission reported K22 providing a detailed description & complete analysis of its properties presenting also the full-resolution & tapered images

➢ The features reported are the sizes and 1.28 GHz flux densities visible in the 15'' resolution images along with radio powers, rms on low res, spixes

*****NO DDE calibration*** was performed (Obit package 2; Cotton 2008)*
***Separating the diffuse emission by filtering or source subtraction, followed by convolution, might lead to larger values in some cases.*

➢ Expanded & updated classification of 8/9 clusters that were characterized as unknown or uncertain in K22, with updates in a few more systems

MGCLS II: Kolokythas et al., 2025, MNRAS, 543, 1704

https://www.ru.ac.za/latestnews/mgclsii.html

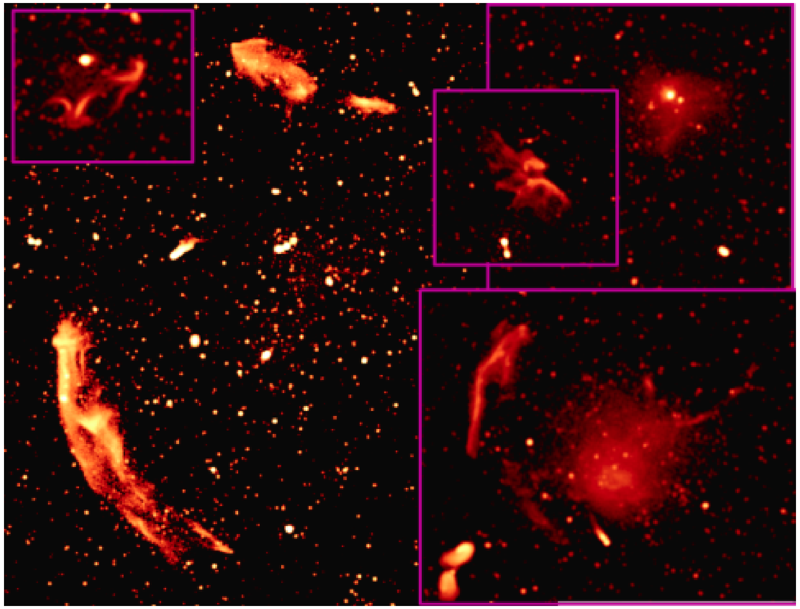
26 NOV

The MGCLS II catalogue: listening to the quiet signals that shape our Universe

The Universe is not silent, and apart from what we observe with our eyes, much of what it says arrives as faint radio whispers that we are able to listen to if we tune into the right frequency. South Africa's MeerKAT telescope has become one of the world's finest listeners, revealing structures in deep space that were simply invisible to previous instruments. At the centre of this effort is the MeerKAT Galaxy Clusters Legacy Survey (MGCLS), a programme led by the South African Radio Astronomy Observatory (SARAO).

These clusters contain hundreds or thousands of galaxies, all immersed in a vast atmosphere of hot electrified gas. When clusters collide or merge, they leave behind an imprint of faint diffuse radio structures – large, faint clouds of emission produced by extremely fast-moving charged particles interacting with magnetic fields. These features act as tracers of cosmic upheaval. They show where shock waves have passed, where turbulence is stirred, and how magnetic fields thread through systems millions of light years wide.

The new MGCLS II catalogue, published at Monthly Notices of the Royal Astronomical Society, led by Rhodes University and SARAO researcher Dr Konstantinos Kolokythas, marks a significant advance. Following up on the MGCLS overview paper), it charts in detail the diffuse radio emission in 115 galaxy clusters, detecting these faint radio structures in more than half of them and expanding the known population to 103 structures; 60 of which had never been seen before.



Diffuse radio emissions revealed in galaxy clusters

This catalogue demonstrates what occurs when South African engineering is combined with South African scientific leadership," Dr Kolokythas states. "MeerKAT has uncovered structures that were previously beyond the reach of earlier telescopes, and each one teaches us something more about how galaxy clusters grow, collide, and evolve."

This work's value goes well beyond astrophysics. It highlights a research environment in South Africa that contributes directly to global knowledge, strengthens the country's scientific standing, and trains researchers who will lead future projects with the Square Kilometre Array (SKA). It also demonstrates the tangible

MGCLS II: Kolokythas, Venturi, Knowles et al., 2025, MNRAS, 543, 1704

nature africa

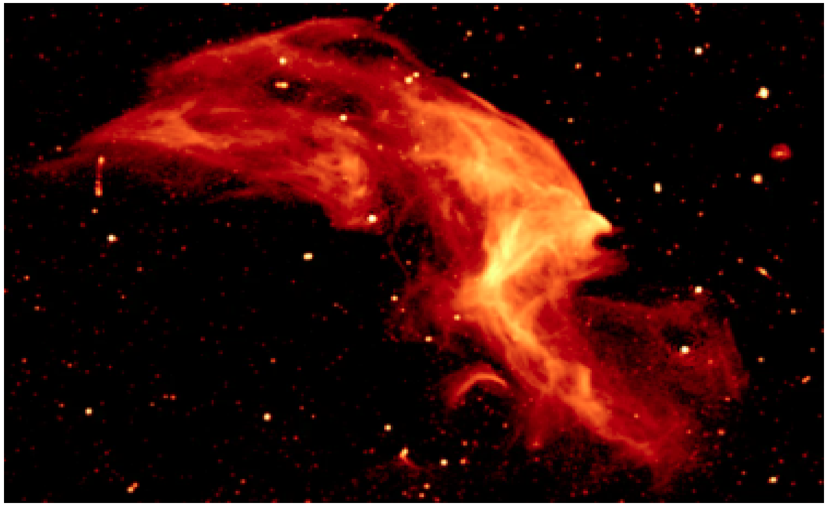
NEWS | 27 February 2026

MeerKAT observations push back the timeline of cosmic disorder

Cosmic turbulence and magnetic fields were established far earlier than expected.

By Akashni Ashok Latchanna

https://www.nature.com/articles/d44148-026-00042-x



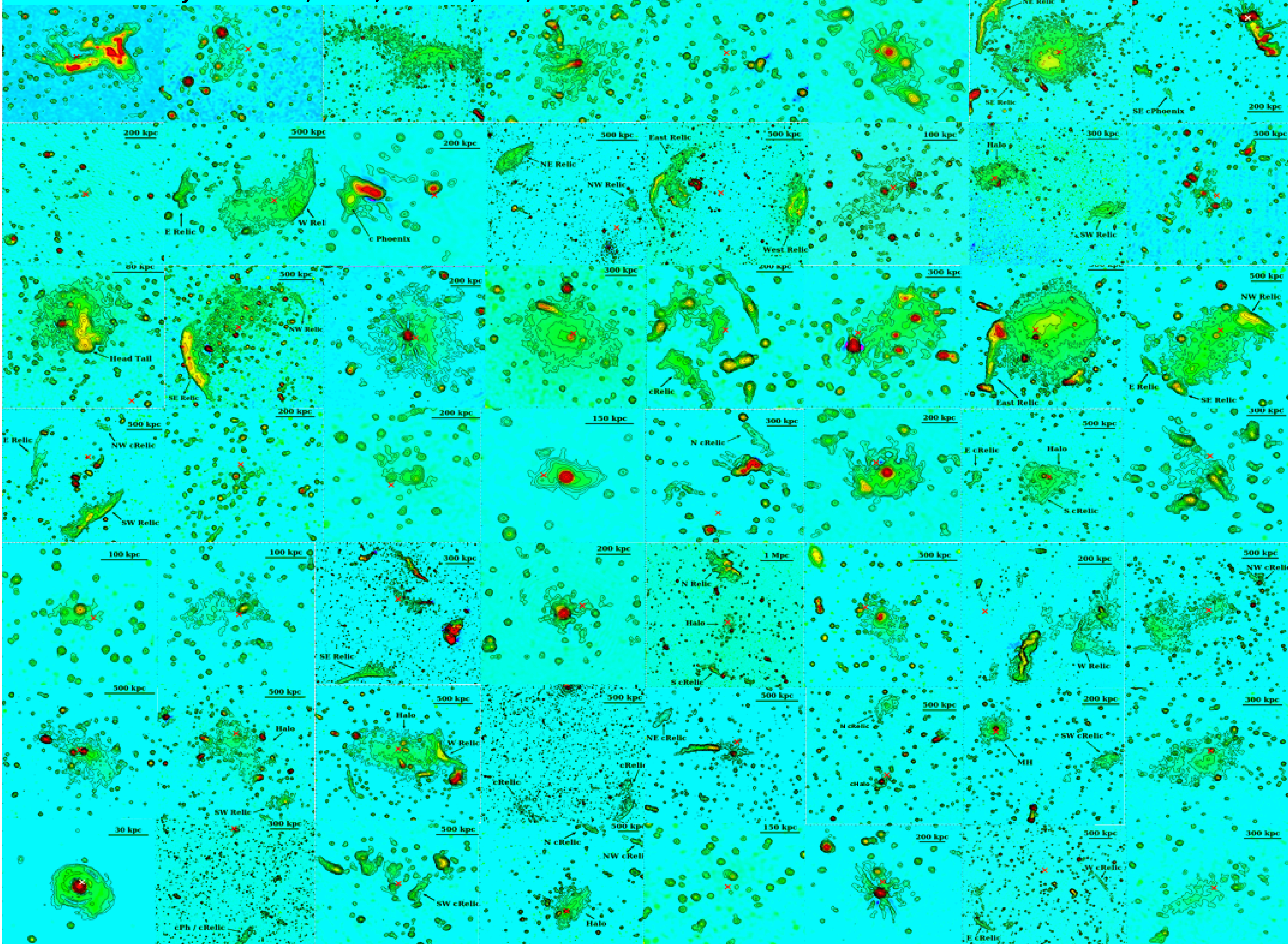
Cluster Diffuse radio emission using MeerKAT at 1.28 GHZ (MGCLS II). Credit: Konstantinos Kolokythas

Lire en français

Galaxy clusters in the early universe were thought to be relatively orderly systems, with turbulence, shocks and magnetic fields emerging gradually as they grew and merged. Observations from South Africa's MeerKAT radio telescope now reveal that clusters were already turbulent and magnetised more than seven billion years ago.

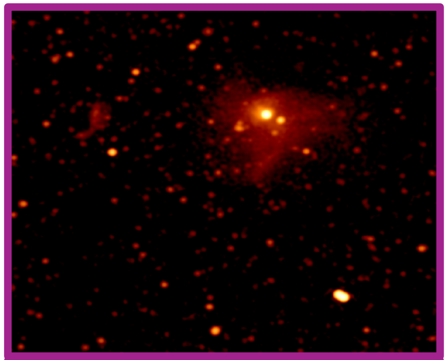
In 2025, two major MeerKAT-based studies detected vast, faint clouds of radio emission, known as radio halos, both in extremely distant galaxy clusters and across a large population of nearer systems. Together, the results suggest that non-thermal activity driven by turbulence and magnetic fields formed much earlier and is far more common than existing models predicted.

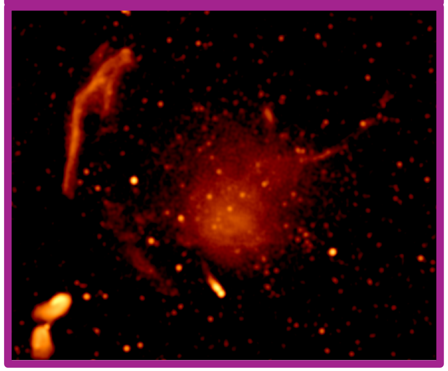
MGCLS II: Kolokythas et al., 2025, MNRAS, 543, 1704



MGCLS II: Cluster diffuse radio emission Catalogue

- ✗ 103 **distinct detections (60 are NEW)**
  - ✗ 3 mini-halos, 8 candidates (**all new**)
  - ✗ 26 radio halo detections, 7 candidates (**13 new**)
  - ✗ 31 radio relics detected, 24 candidates (**33new**)
  - ✗ 1 radio phoenix, 2 phoenices candidates, **(all new)**
  - ✗ 1 ambiguous / unknown (**new**)





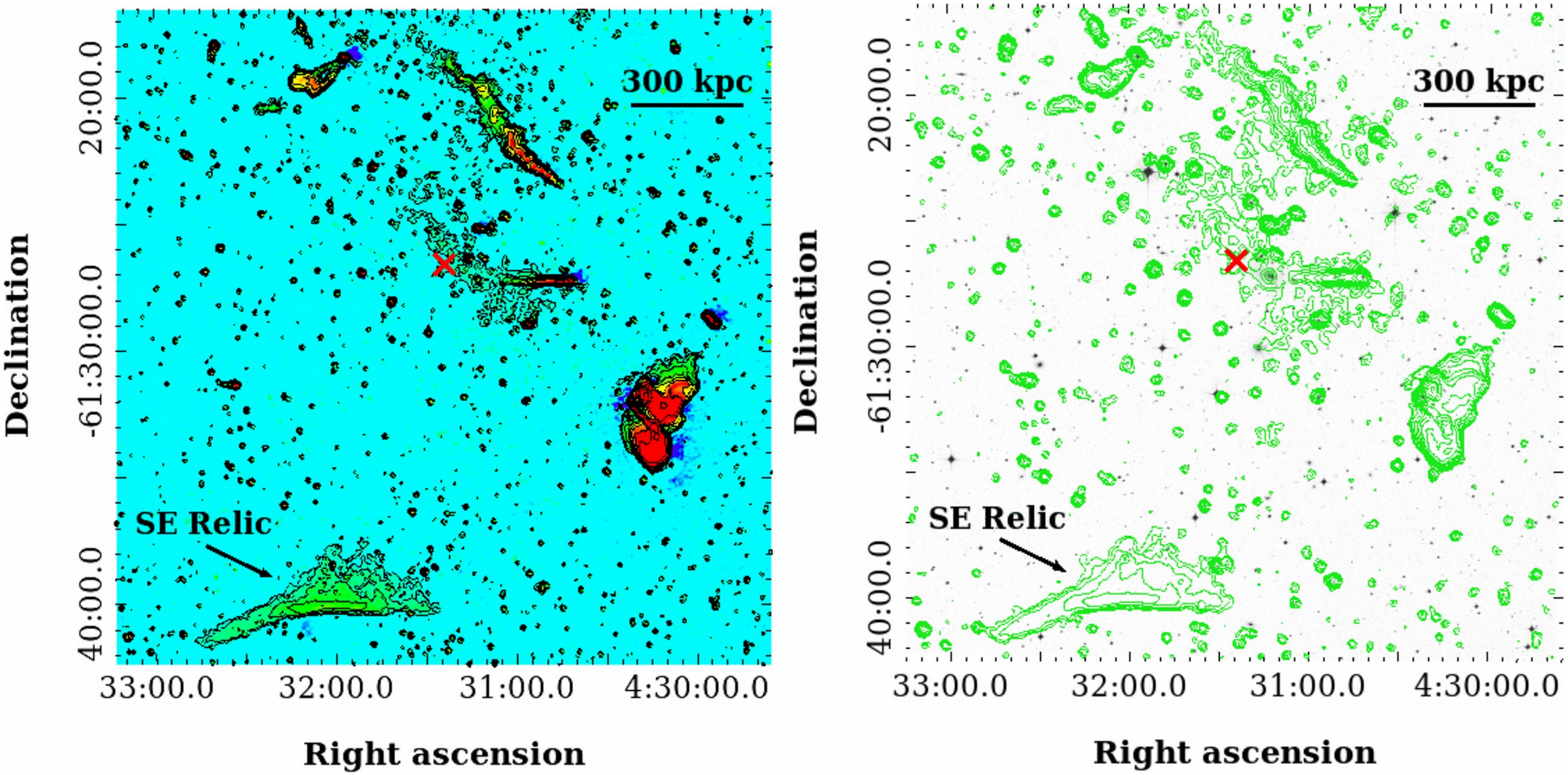
✗ **Systems with no consistent diffuse emission with any of the radio halos, mini-halos, & radio relics, classes are classed as Unknown (U)**

✗ **As candidate structures (c) are classed those presenting a marginal detection or an uncertain feature (in agreement with main properties of each class & optical location of radio emission)**

MGCLS radio data products were inspected while overlaid with optical & X-ray data, where available, to better understand the nature of a diffuse source.

MGCLS II: Classification Challenges of Cluster diffuse radio emission

➢ MGCLS products at hand carefully classify the radio sources based on their morphology, available X-ray & optical data, and relative location → 41 candidates & 1 source (J0431 or A3266; Riseley+ 22) marked as unknown



MGCLS II: Kolokythas et al., 2025, MNRAS, 543, 1704

MGCLS II: Classification Challenges of Cluster diffuse radio emission

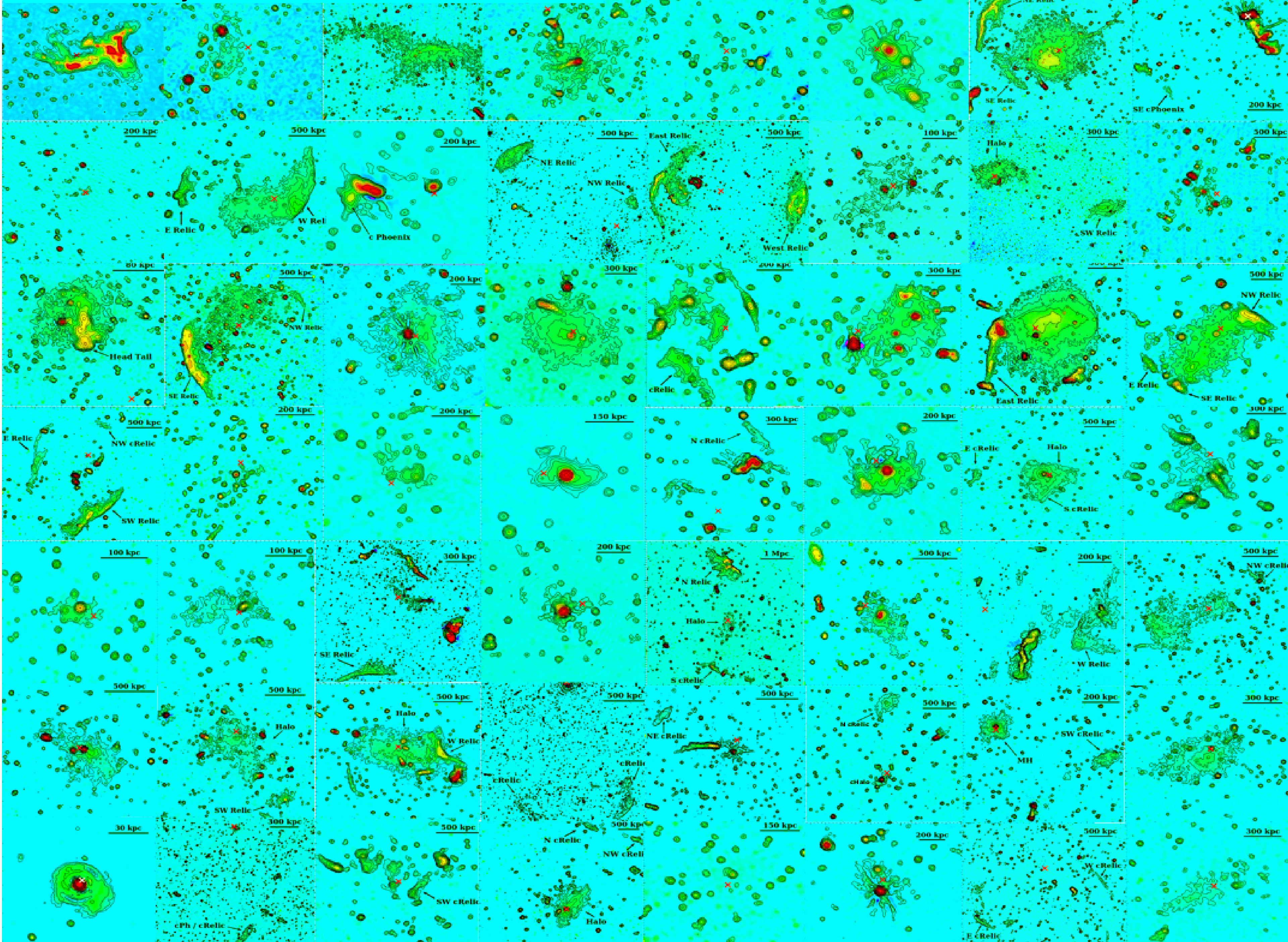
- **Reason 1:** Limitation that comes from radio data itself, the sensitivity of which in some cases is affected by the presence at the cluster core of a bright, compact radio source, creating residuals in analysis due to imperfect calibration, disallowing a clear classification of faint radio sources

- **Reason 2:** Dense blending and emission contamination of compact radio sources in confined space areas → blending of only one but extended radio source can also be challenging for a secure classification, as cluster radio shocks co-exist and blend with old AGN radio plasma (A4038)

- **Reason 3:** Classification may also be hampered by projection effects, i.e. a chance superposition of an AGN-origin fossil plasma may resemble a cluster radio shock if observed at the cluster periphery

MGCLS II: Kolokythas et al., 2025, MNRAS, 543, 1704

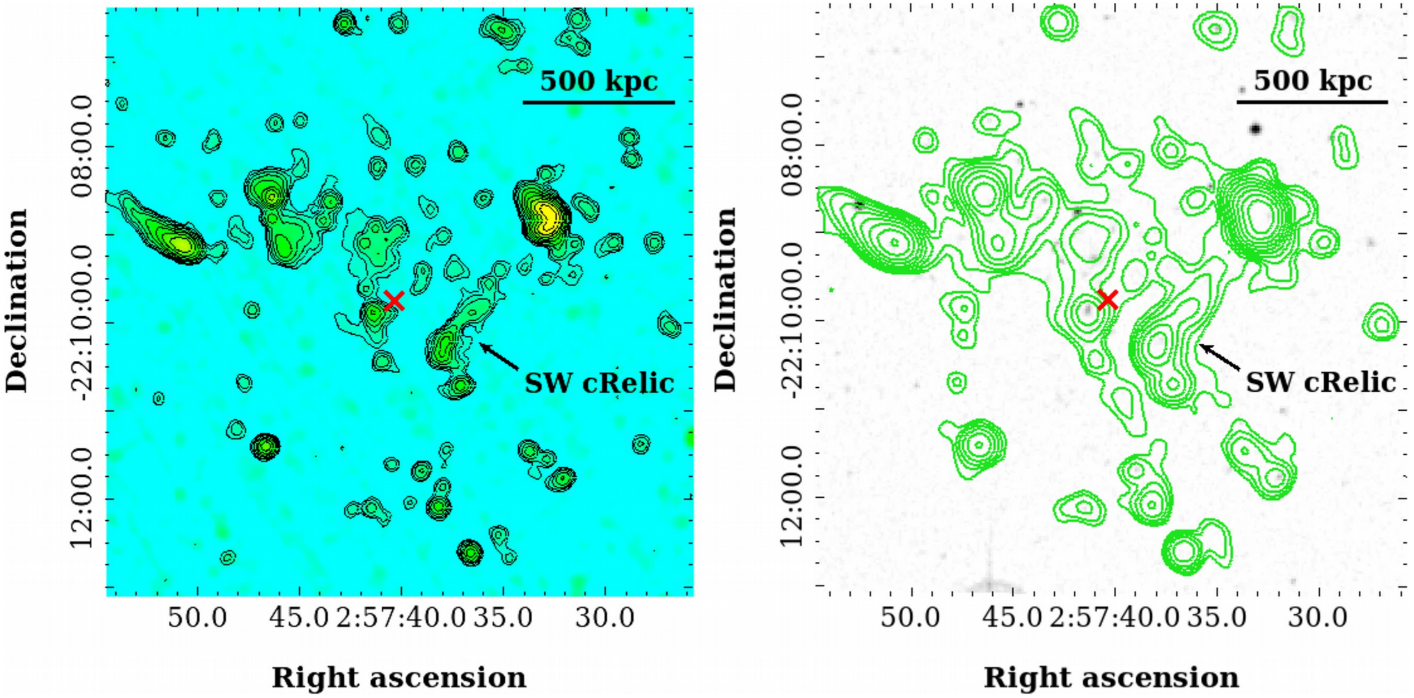
MGCLS II: Kolokythas et al., 2025, MNRAS, 543, 1704



MGCLS II: Classification Challenges of Cluster diffuse radio emission

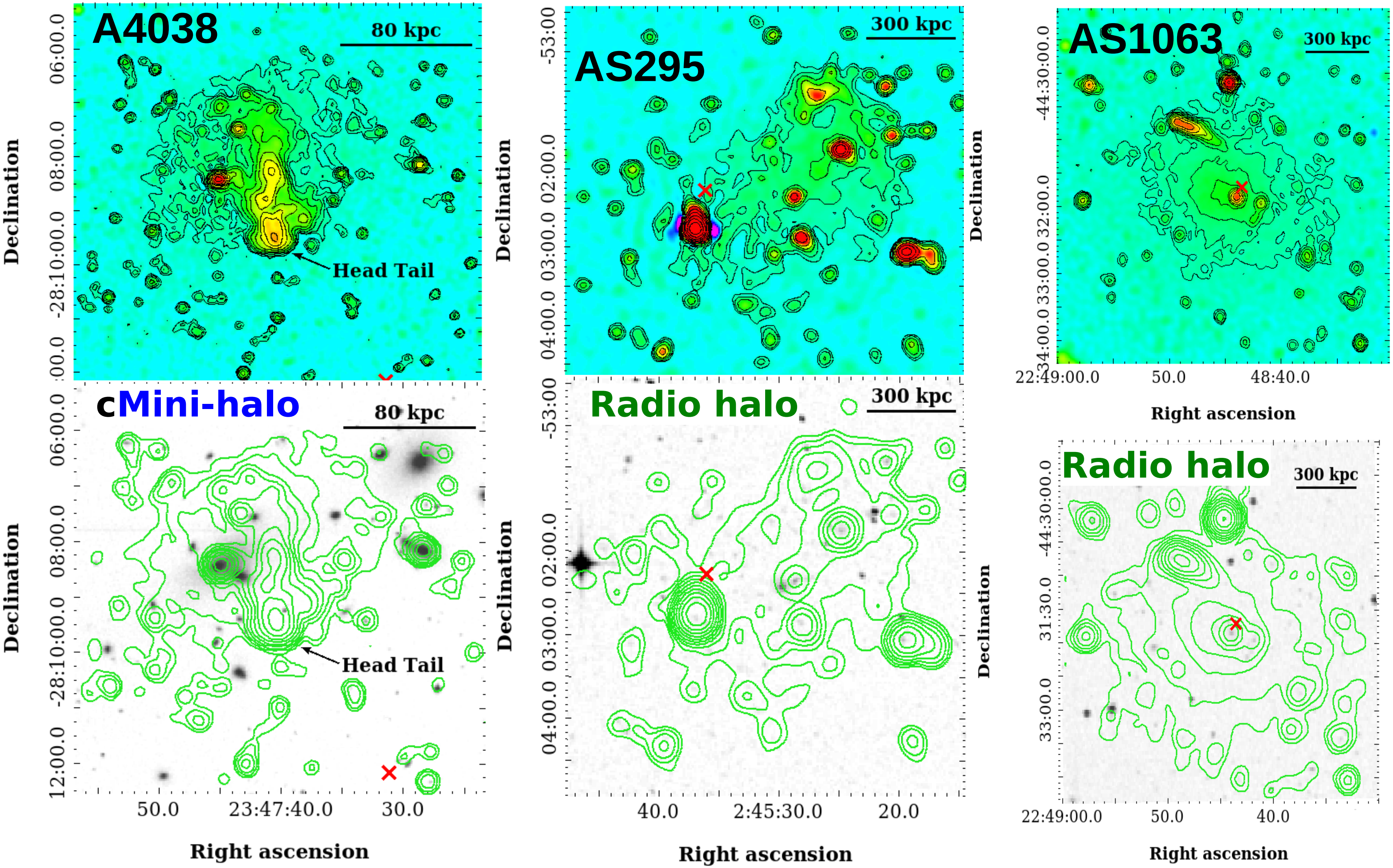
➢ **Reason 2:** Dense blending and emission contamination of compact radio sources in confined space areas → blending of only one but extended radio source can also be challenging for a secure classification, as cluster radio shocks co-exist and blend with old AGN radio plasma (A4038)

MACS J0257.6–2209



MGCLS II: Kolokythas et al., 2025, MNRAS, 543, 1704

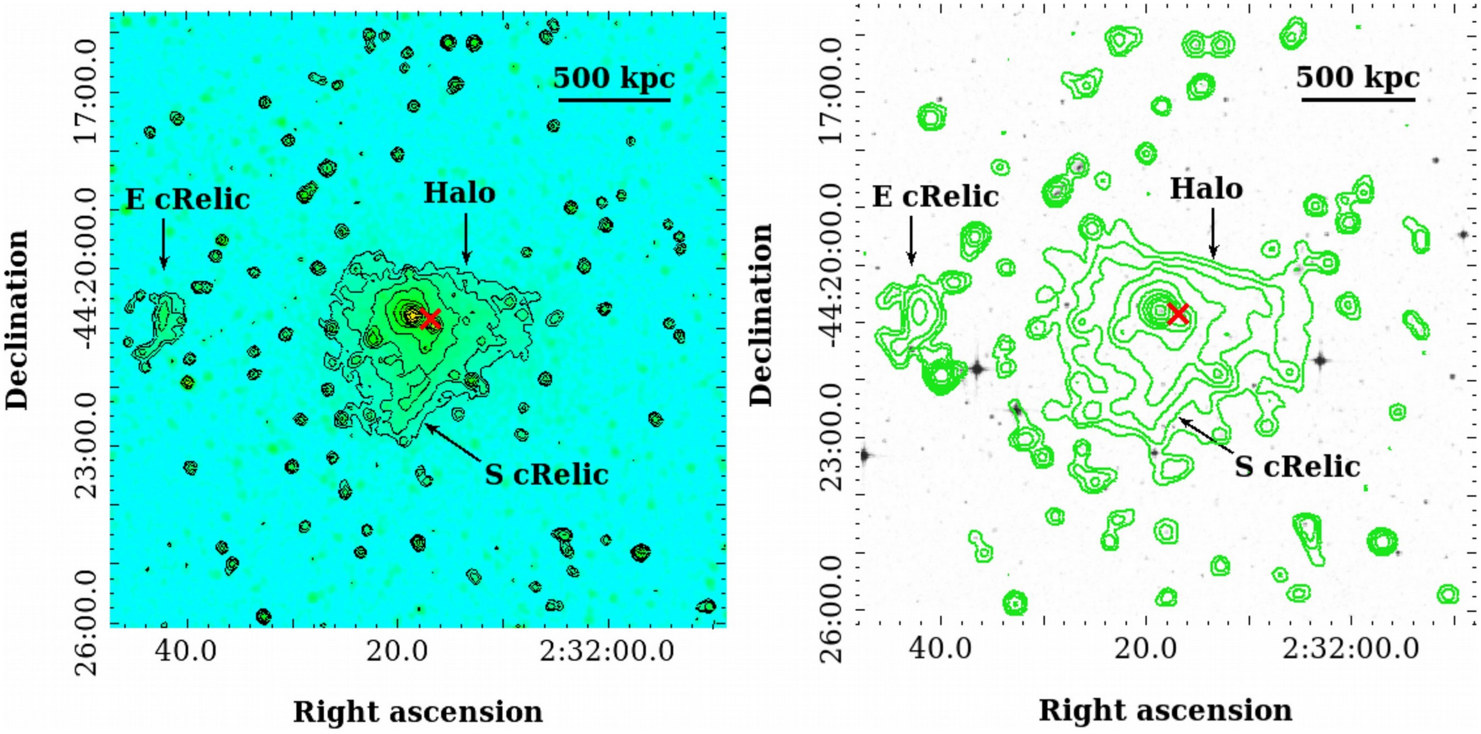
MGCLS II: Classification Challenges of Cluster diffuse radio emission



MGCLS II: Classification Challenges of Cluster diffuse radio emission

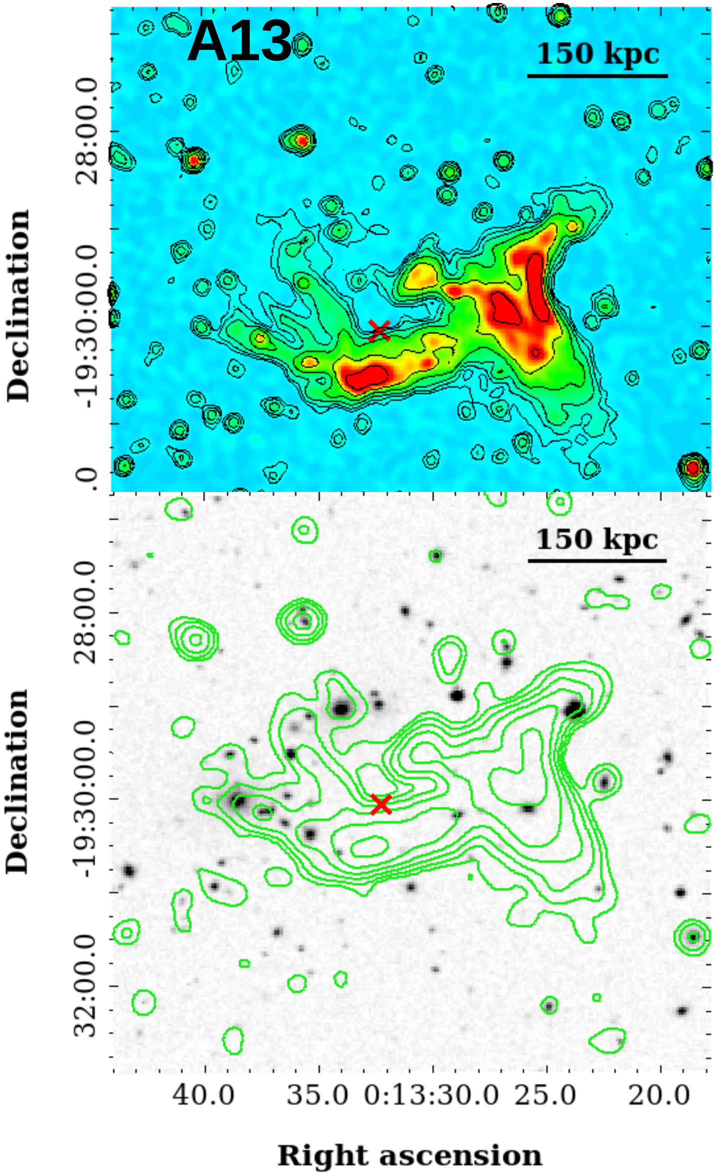
➢ **Reason 3:** Classification may also be hampered by projection effects, i.e. a chance superposition of an AGN-origin fossil plasma may resemble a cluster radio shock if observed at the cluster periphery

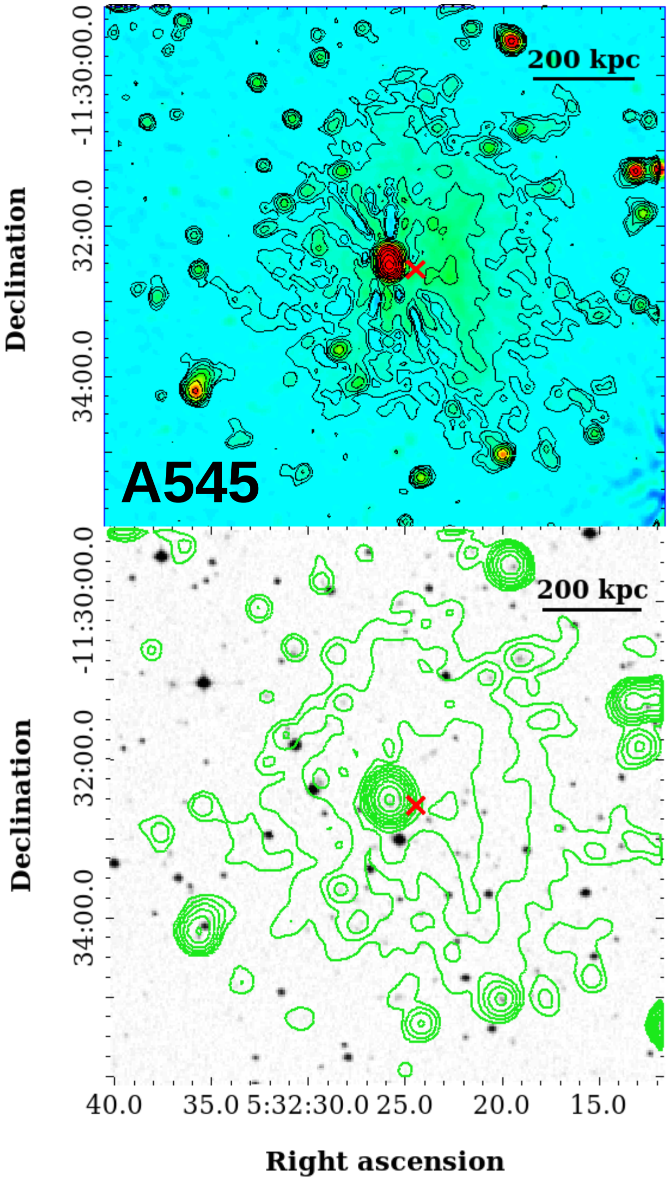
J0232.2–4420



MGCLS II: Kolokythas et al., 2025, MNRAS, 543, 1704

MGCLS II: Classification Challenges of Cluster diffuse radio emission

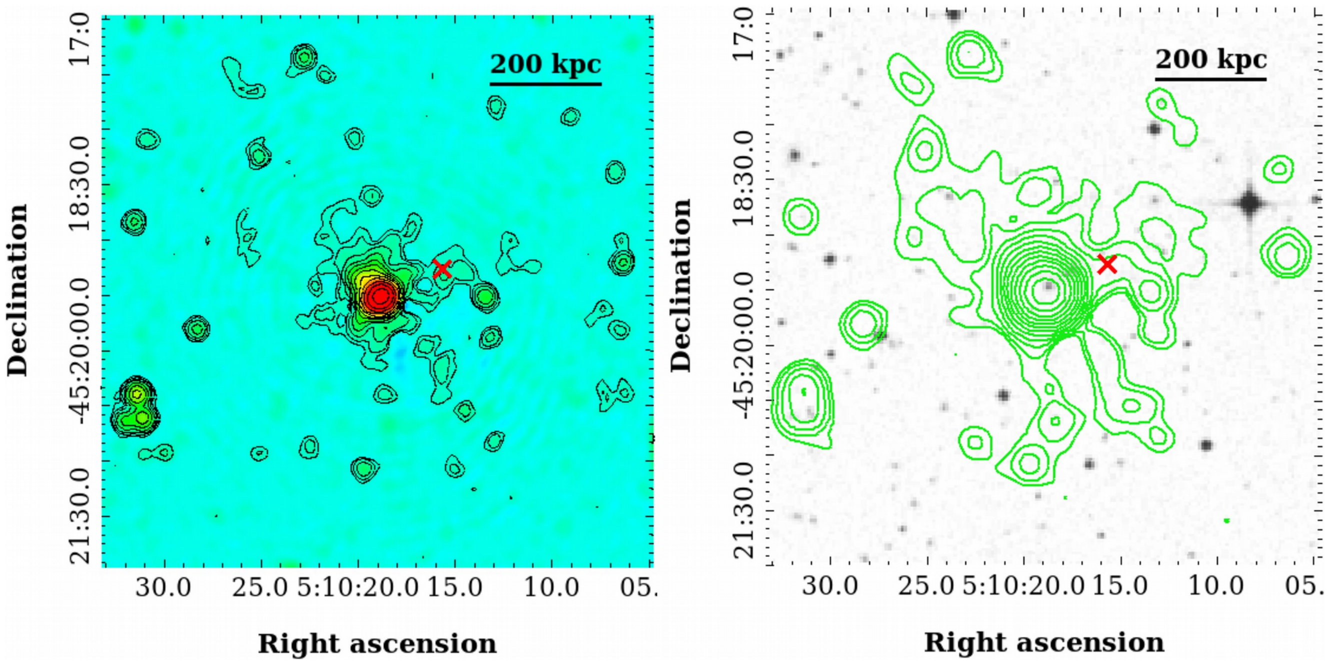




MGCLS II: Classification Challenges of Cluster diffuse radio emission

- **Reason 4:** Requirement for complementary data to determine the nature of the diffuse radio emission. For the systems that are classified as candidate relics and mini-haloes, majority of X-ray data come from low-resolution, shallow X-ray observations by ROSAT & Chandra telescopes

J0510.2–4519



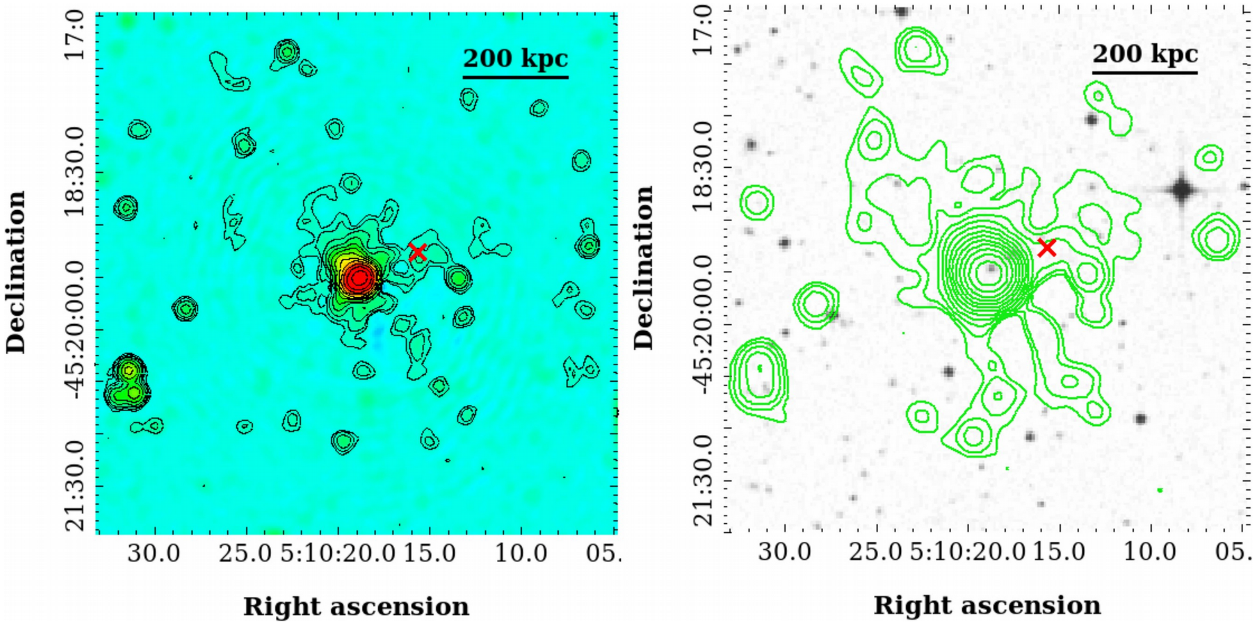
MGCLS II: Kolokythas et al., 2025, MNRAS, 543, 1704

MGCLS II: Classification Challenges of Cluster diffuse radio emission

➢ High-resolution images are also essential to distinguish between AGN lobes and mini-haloes. Due to these observational limitations, the detection and classification of mini-haloes were bound to an observational selection bias dependent on the current radio telescopes’ detection limit

****We note that several fainter radio mini-haloes are being detected by MGCLS because of MeerKAT’s sensitivity**

J0510.2–4519



MGCLS II: Kolokythas et al., 2025, MNRAS, 543, 1704

MGCLS II: Cluster diffuse radio emission Catalogue project

Detection fractions for the 115 MGCLS clusters

~10% (11/115) of MGCLS clusters (including cands) present mini-halos
~30% (33/115) of MGCLS clusters present radio halos
~16% (18/115) exhibit only a radio halo without the presence of a relic
~29% (33/115) of MGCLS clusters present at least one radio relic

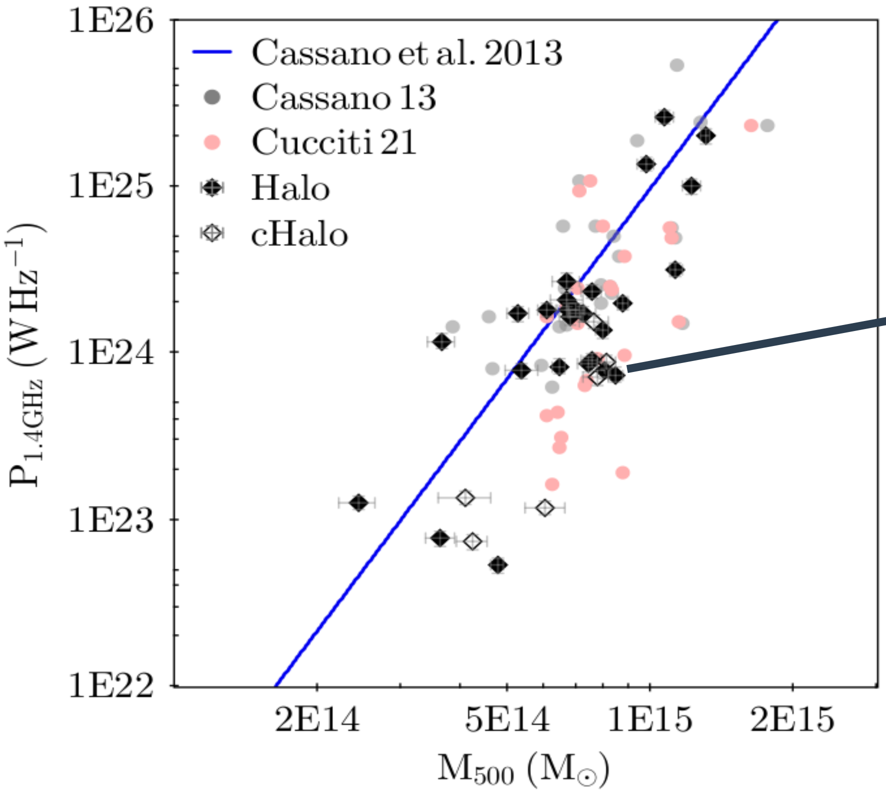
Detection fractions for the 103 radio structures

- Most commonly detected diffuse structures in MGCLS are radio relics at an occurrence rate of 53% (55/103)
- Radio halos follow at 33% (33/103) and mini-halos at 10% (11/103)
- Only 3% (3/103) are found to be Phoenixes with just 1% of the detected radio structures being listed as ambiguous/Unknown

MGCLS II: Kolokythas et al., 2025, MNRAS, 543, 1704

MGCLS II: 1.4 GHz radio power - M_{500} scaling relation

*Scaling relation between cluster mass (M_{500}) and radio power ($P_{1.4GHz}$) for MGCLS systems that host **RHs, cRHs** and MHs, cMHs*



M_{500} for MGCLS clusters were extracted by PSZ2 catalogue (Planck Collaboration et al. 2016; SZ-based)

26 radio halos, & 7 candidate radio halos

<u>Radio halos & respective candidates follow the known steep correlation</u> for the M_{500} – $P_{1.4\,GHz}$ relation with radio powers showing a scatter around the correlation that extends for over three orders of magnitude

MGCLS II: 1.4 GHz radio power - M_{500} scaling relation

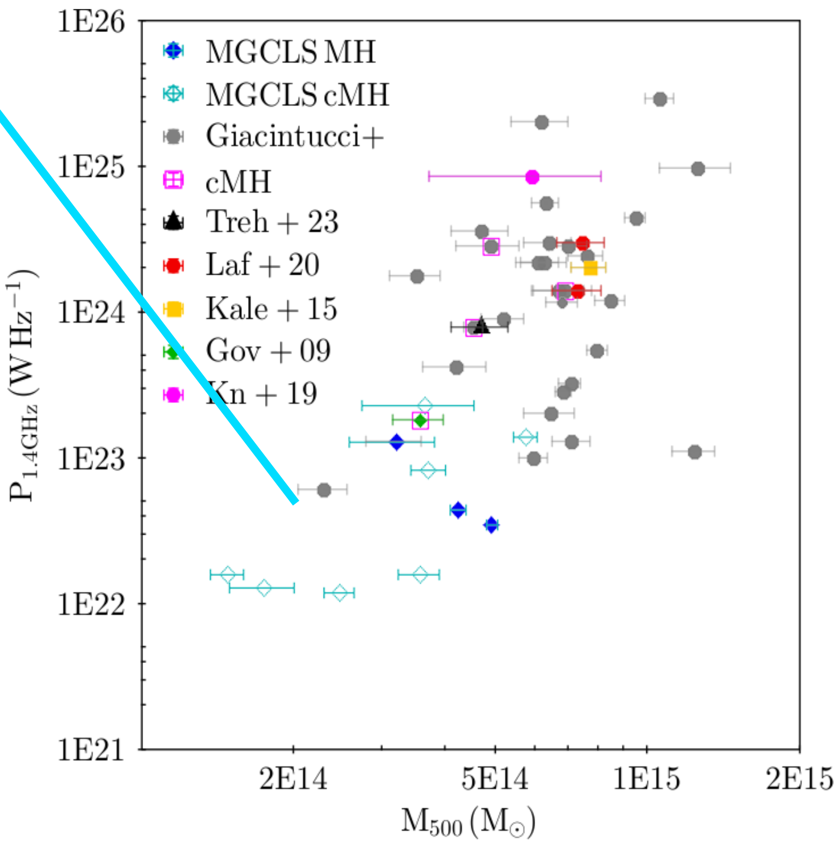
Scaling relation between cluster mass (M_{500}) and radio power ($P_{1.4GHz}$) for MGCLS systems that host RHs, cRHs and ***MHs, cMHs***

3 radio mini-halos & 8 c radio mini-halos

Majority of detected MGCLS mini-halos & c mini-halos occupy the lower mass region ($M_{500} < 5\times10^{14}\ M_{\odot}$) & lower radio power region $P_{1.4\ GHz} < 10^{23}$ W Hz^{-1}

The low-powered c mini-halo systems provide a new view of an unexplored mini-halo region thanks to MGCLS's high sensitivity & ability to detect mini-halo & associate candidate systems at low-powers

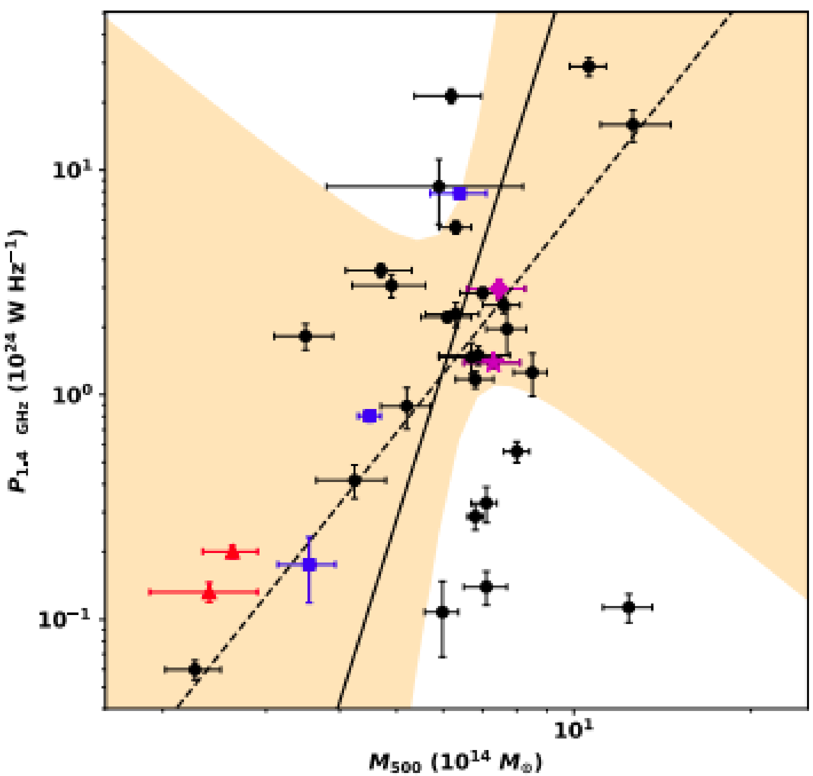
Suggest for radio mini-halos a mild correlation between 1.4 GHz radio power & the M500 cluster mass

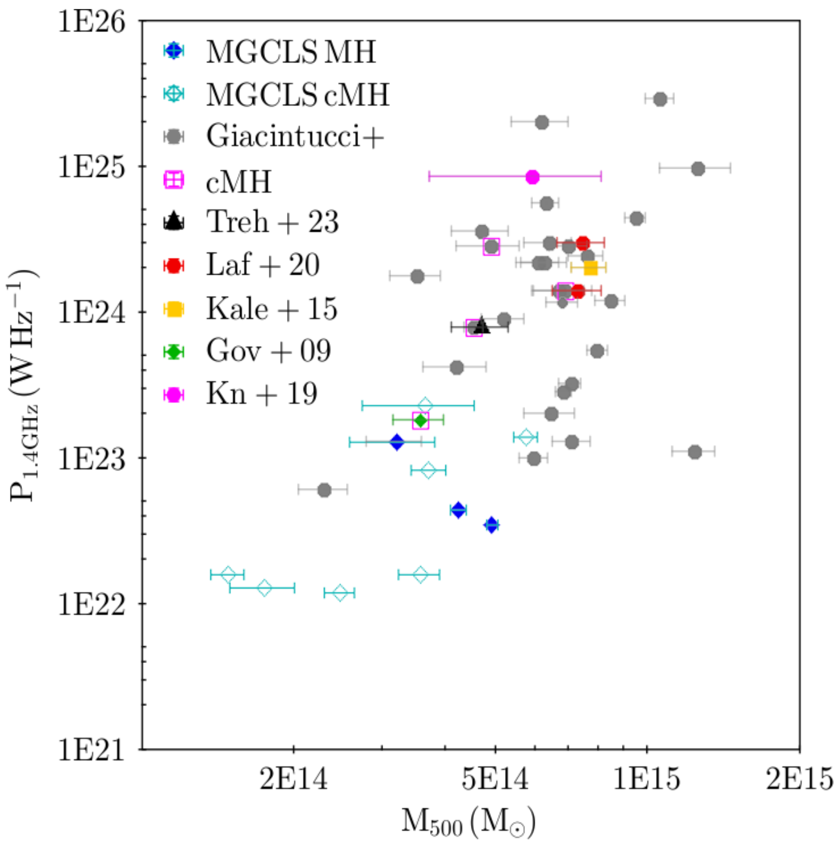


MGCLS II: 1.4 GHz radio power - M_{500} scaling relation

Scaling relation between cluster mass (M_{500}) and radio power ($P_{1.4GHz}$) for MGCLS systems that host RHs, cRHs and ***MHs, cMHs***

Laferrière et al. 2020





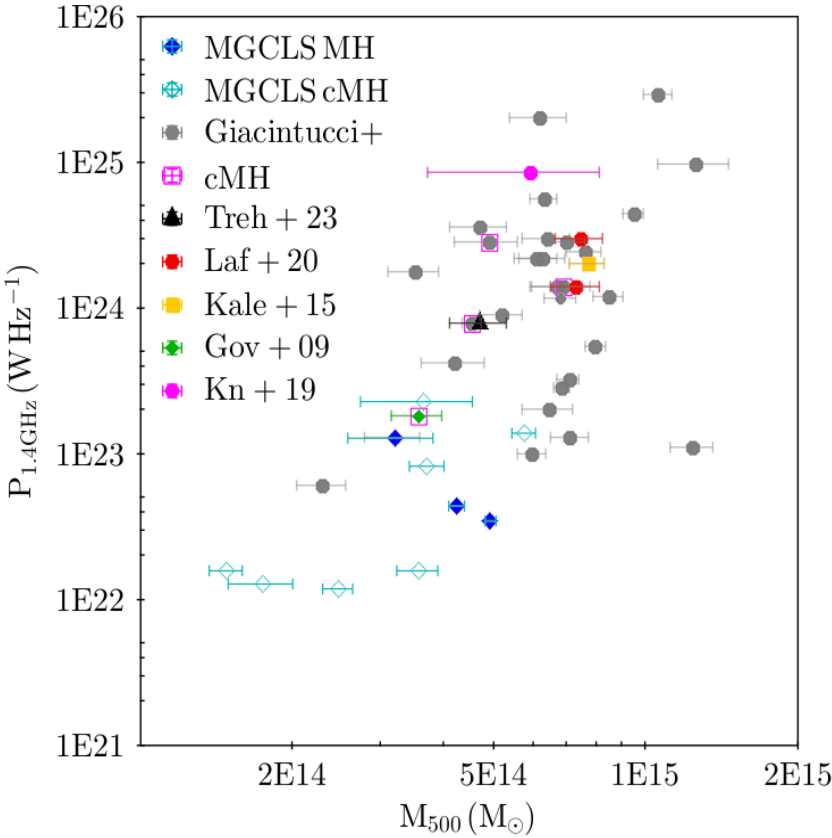
MGCLS II: MHalo 1.4 GHz radio power - M_{500} scaling relation

Surpising mild trend, as mini-halo radio powers are not related to global cluster mass at 1st order, but there may have been room for a mild trend only at 2nd order

- MH isn't a direct product of the cluster's total gravitational potential, but rather a locally driven phenomenon (Giacintucci+17,19; Laferriere+20)
- This "second-order" logic holds considering in many MH systems, exists a strong link between the BCG and the surrounding diffuse emission

Hence the correlation chain is:

Cluster Mass --> BCG Mass/Luminosity --> AGN Power --> Seed Electrons --> Mini-Halo Power



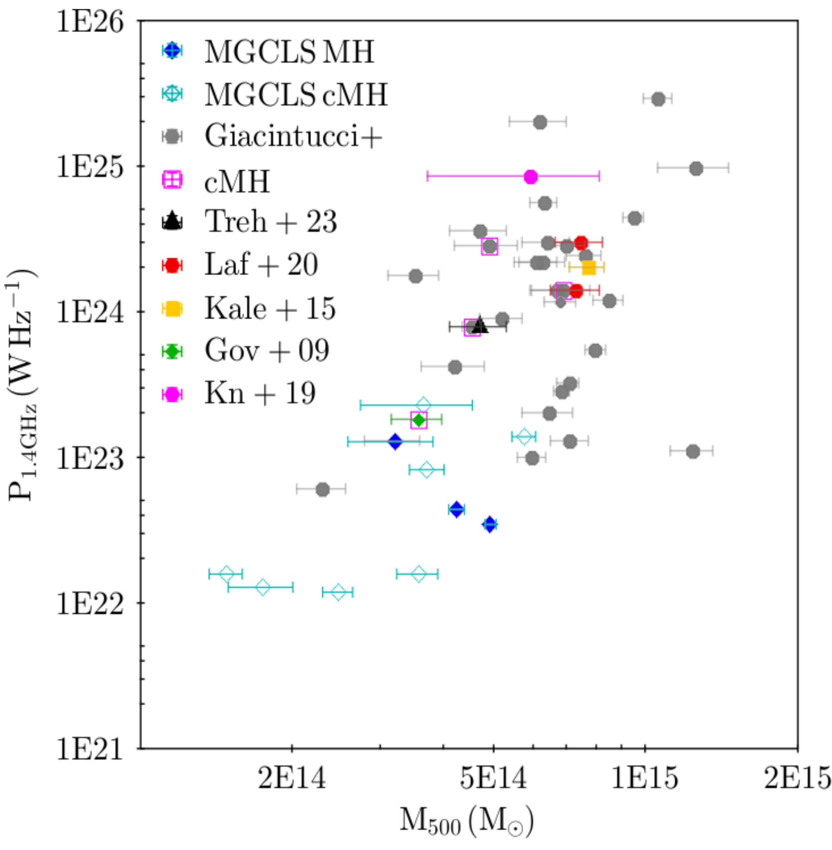
MGCLS II: MHalo 1.4 GHz radio power - M_{500} scaling relation

<u>Each step in this chain has its own efficiency and duty cycle (the AGN isn't always "on")</u>

→ <u>final correlation between the first and last steps (Mass to MH) is "washed out" or weak</u>

Turbulence for MHs is local, not global;

MHs are powered by a localised hydrodynamic disturbance in the cool core (gas sloshing), often triggered by a minor sub-cluster passage



MGCLS: MeerKAT Galaxy Cluster Legacy Survey DR2

….more to come

IN PROGRESS

MGCLS DR2 is an underway project planning the release to the astronomical community of an extended database of more ‘ready to use’ data products such as MGCLS self-calibrated data for all 115 clusters including DDE calibration and where possible polarization data

MGCLS DR2: Kolokythas K., Knowles K., R. van Weeren et al., in prep.

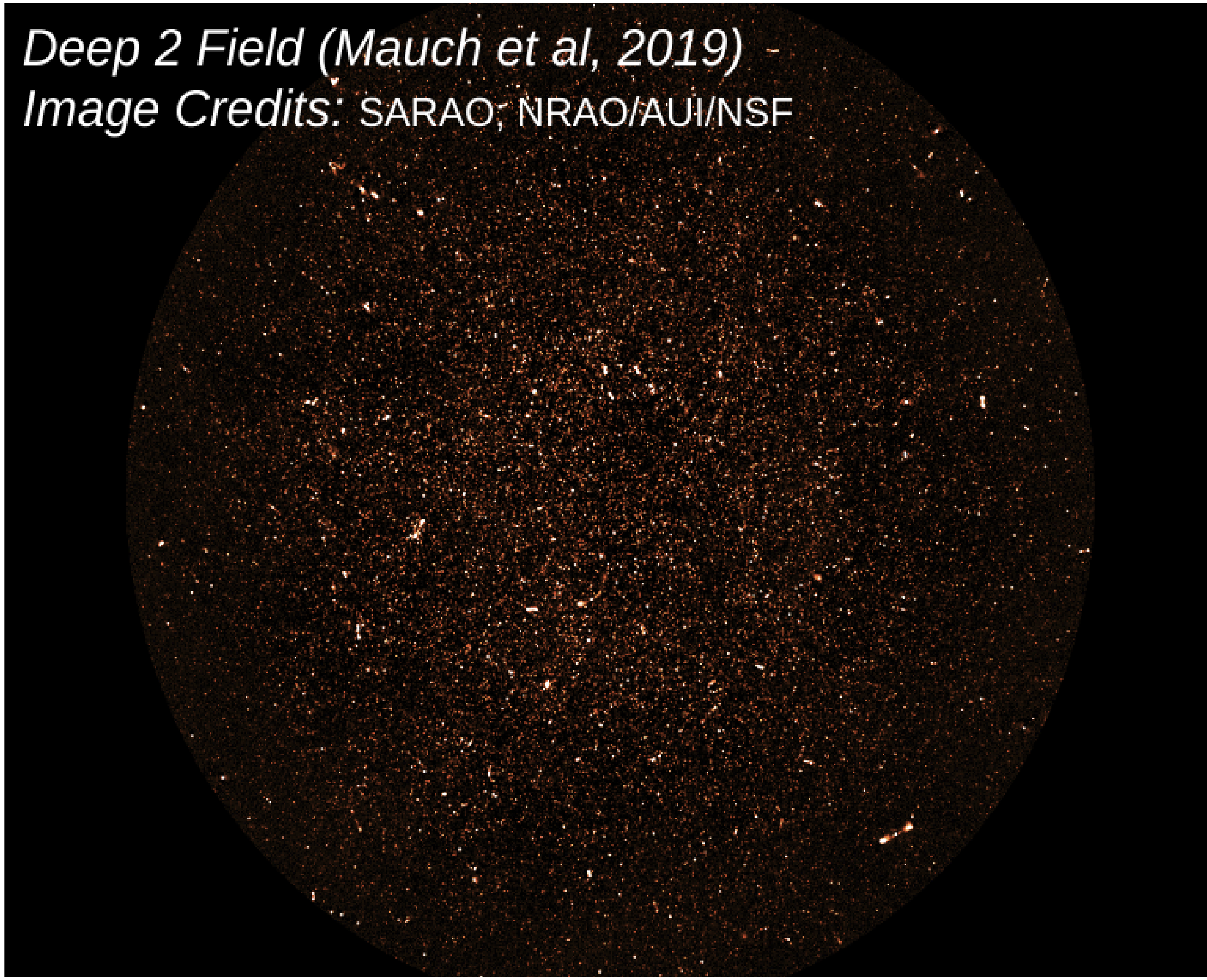
End-to-End Image Analysis in the era of Big Data

What's new about image analysis ?

<u>The high spatial density of sources</u>

<u>Diffuse emission</u>
(mixed with compact sources associated with distant AGNs and star-forming galaxies

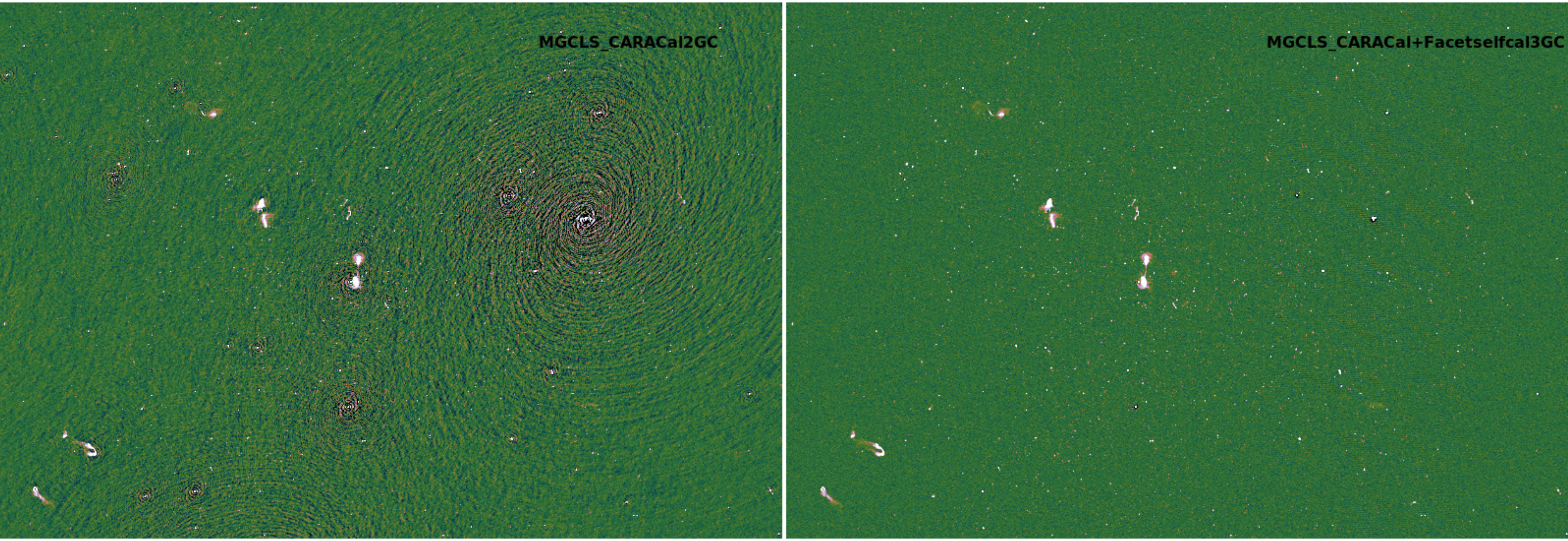
<u>Cross-matching with multi-wavelength data</u>



MGCLS: MeerKAT Galaxy Cluster Legacy Survey DR2

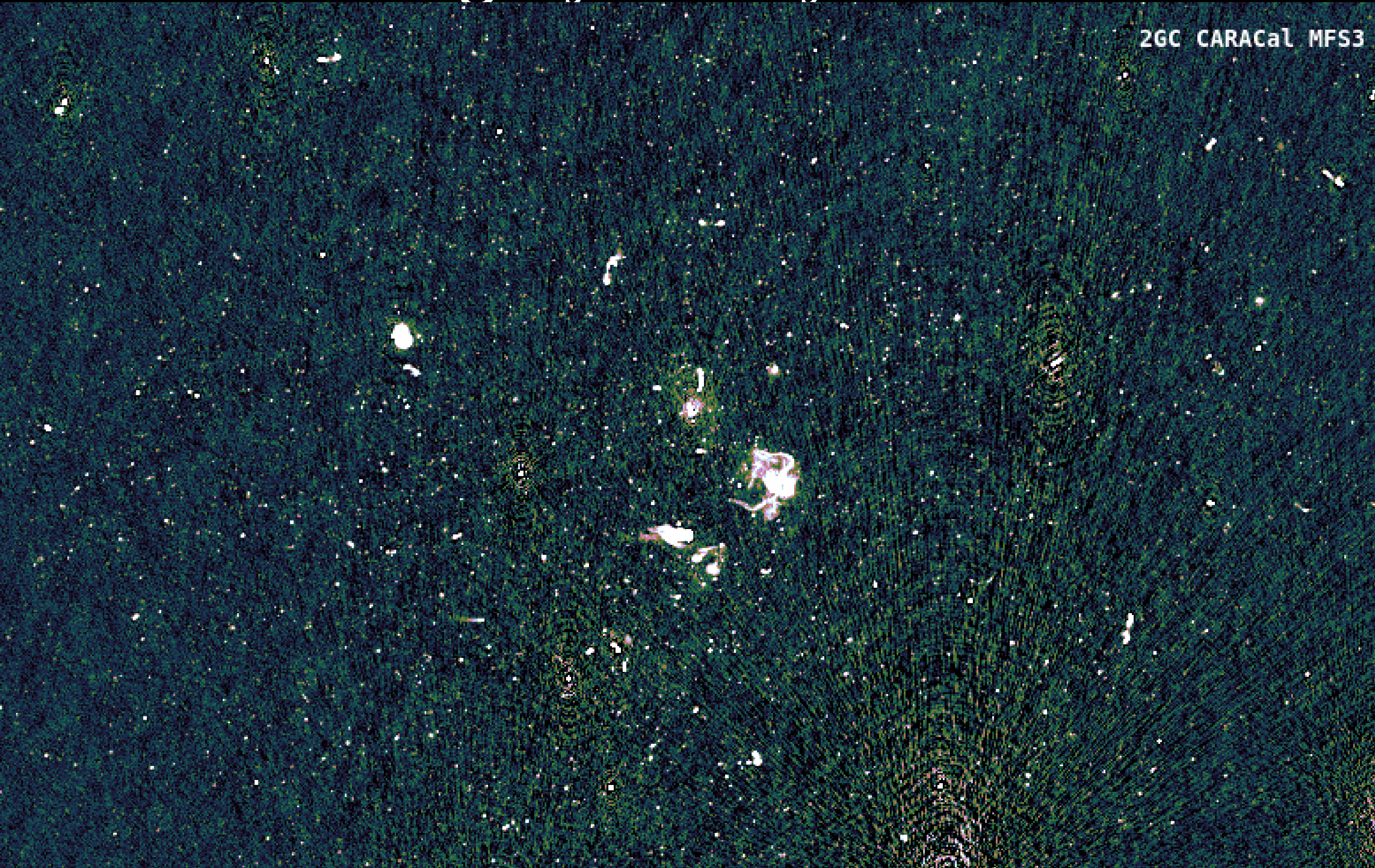
- Using facetselfcal pipeline (van Weeren et al. (2021, A&A, 651, 115) General direction-independent and direction-dependent self-calibration

- Performs refinement self-calibration for individual 'extracted' datasets full field of view self-calibration and extraction of regions of interest

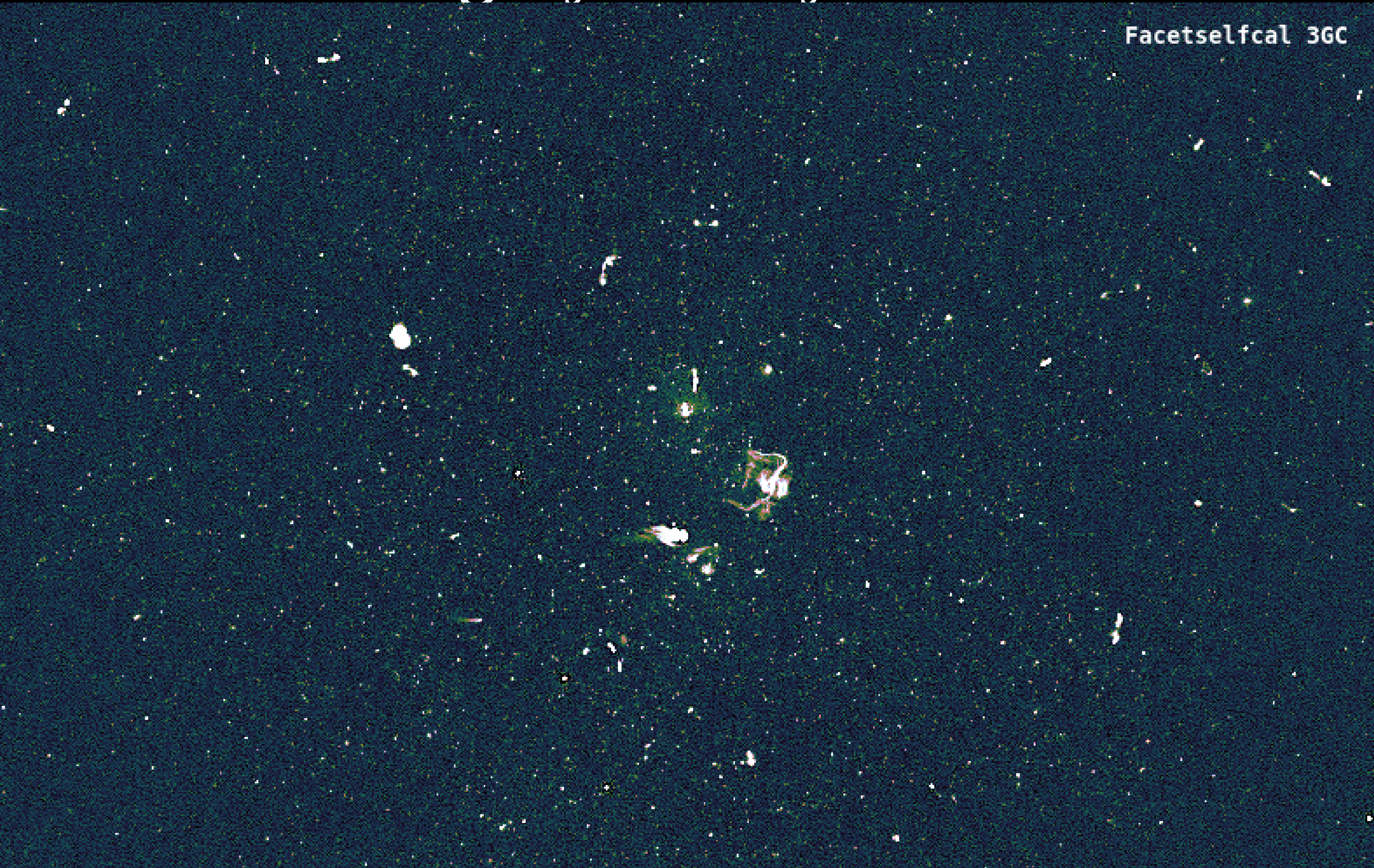


MGCLS DR2: Kolokythas K., Knowles K. et al., in prep.

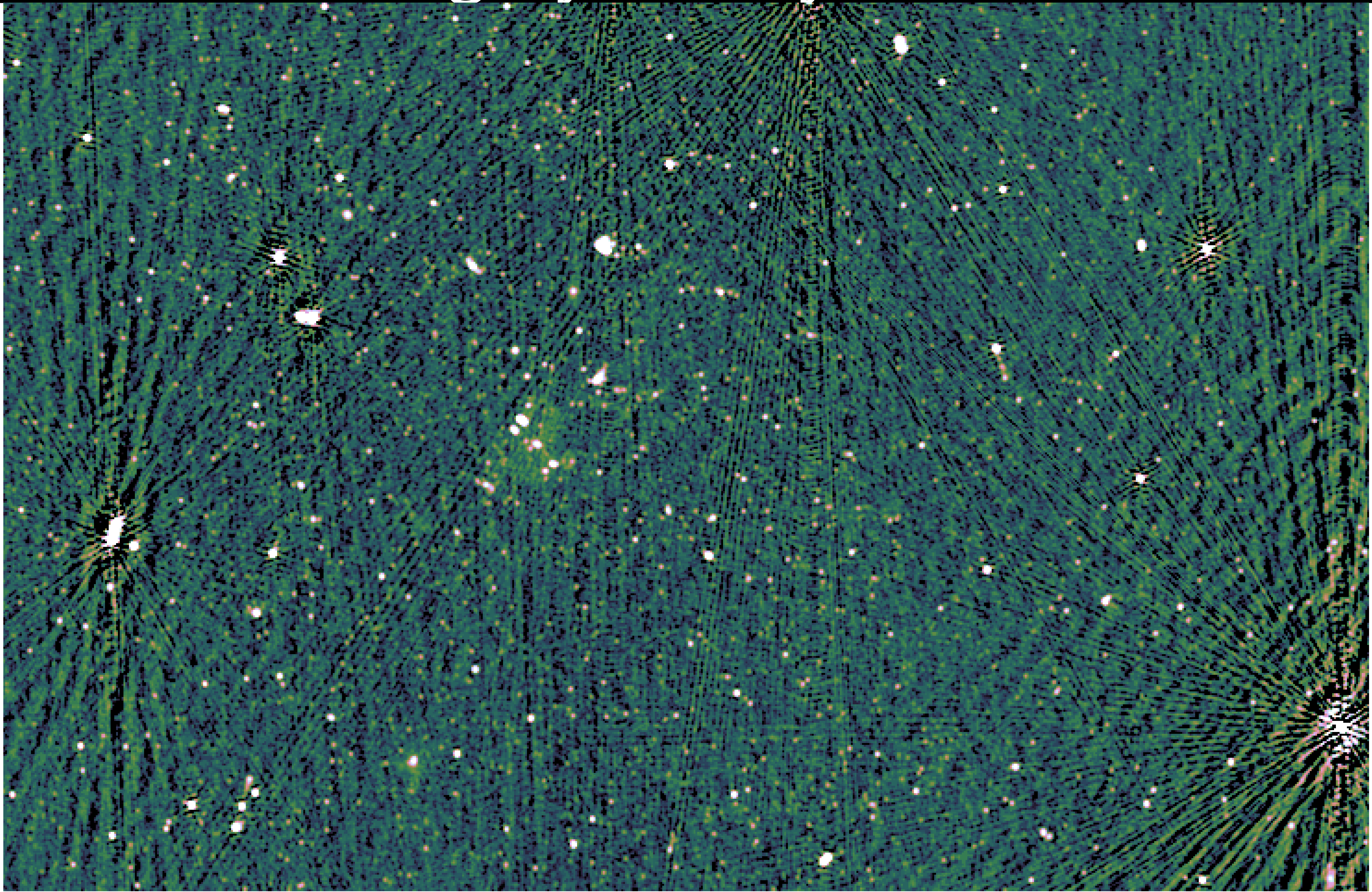
MGCLS: MeerKAT Galaxy Cluster Legacy Survey DR2



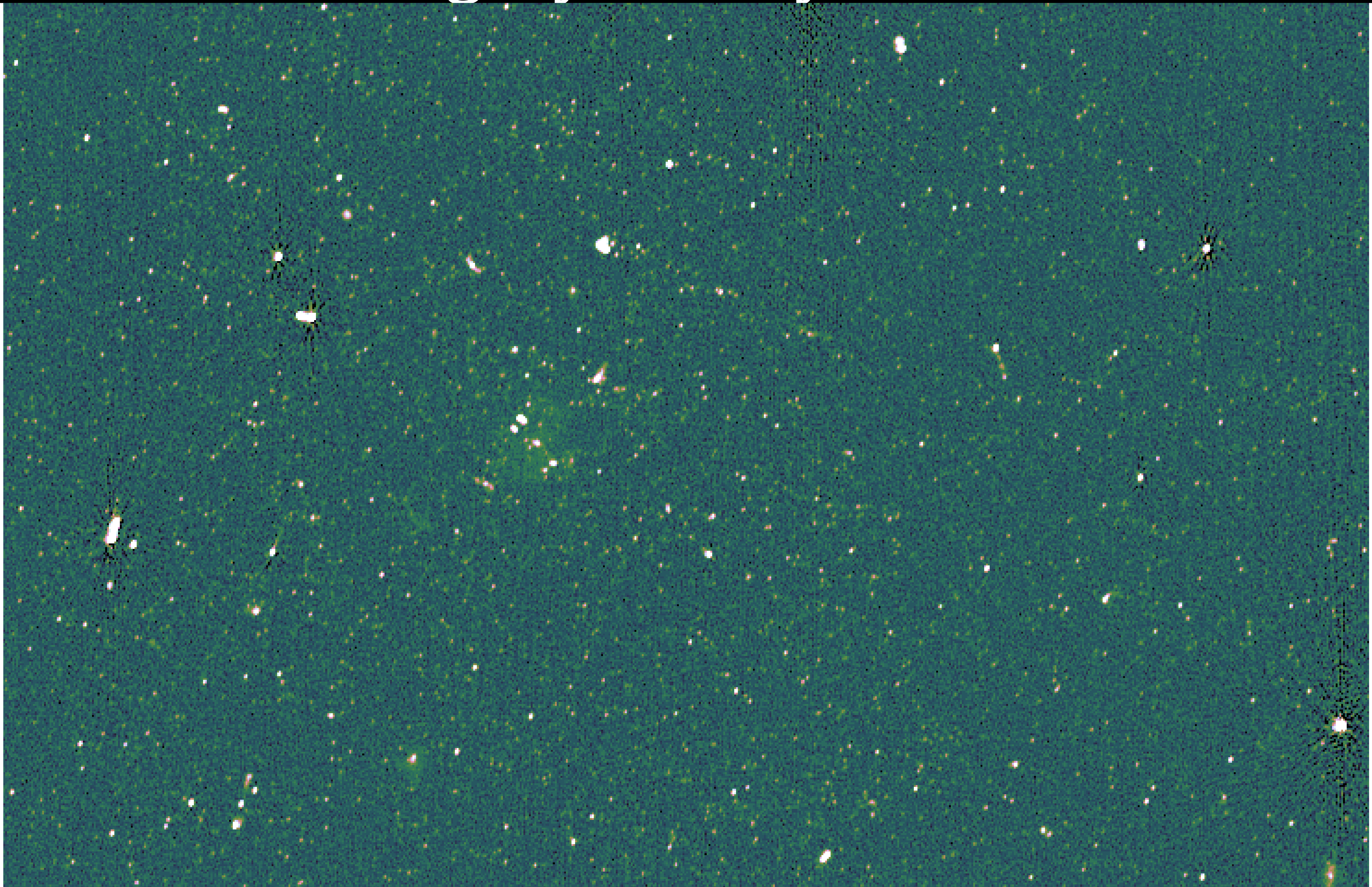
MGCLS: MeerKAT Galaxy Cluster Legacy Survey DR2



MGCLS: MeerKAT Galaxy Cluster Legacy Survey DR2



MGCLS: MeerKAT Galaxy Cluster Legacy Survey DR2



Preparing for Big data with MGCLS radio clusters

and lots of work to be done with the legacy products using Machine Learning (ML)

MGCLS products offer a fertile basis to test and implement ML algorithms
(Etsebeth V., Lochner M., ***Kolokythas K.*** *et al. 2026 in press.)*

An automated way to detect and successfully classify the different cluster extended radio structures on a morphological basis using both supervised and unsupervised Machine Learning Techniques
(In collab with EPFL, UWC RadioClusters project E. Tolley, K. Knowles, M. Lochner)

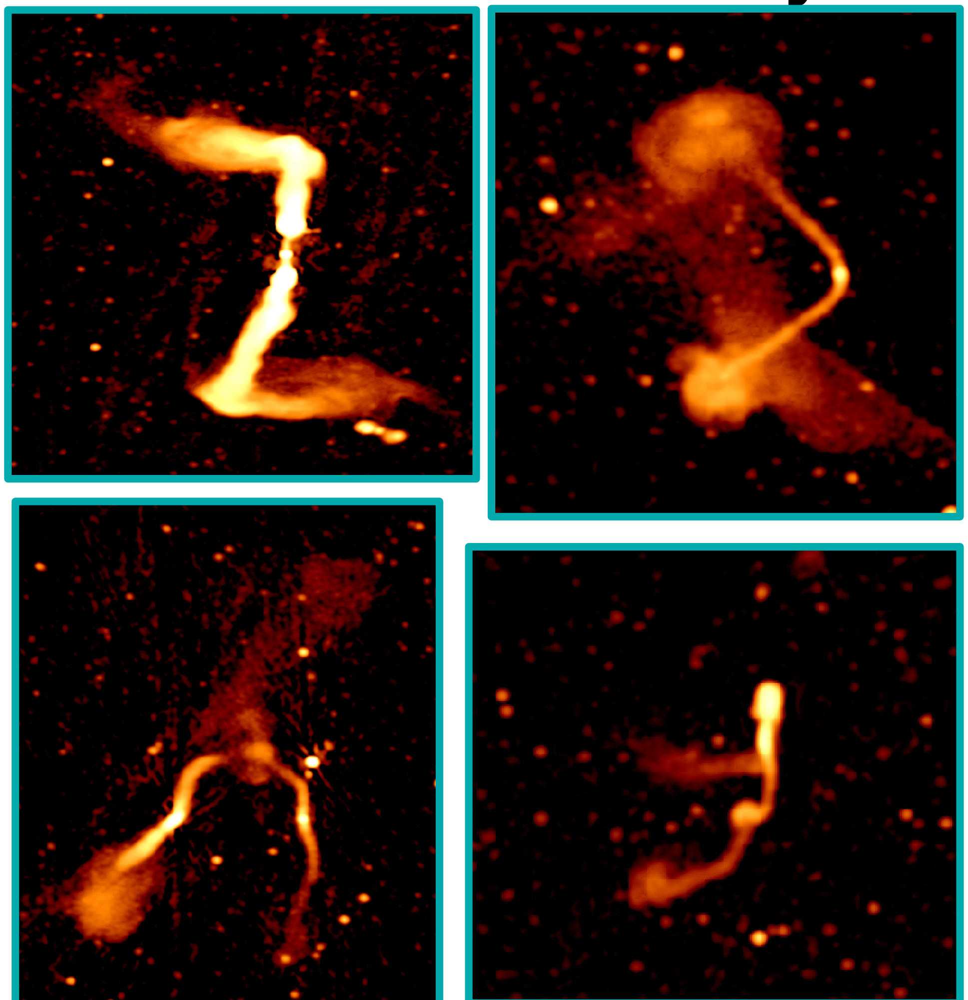
Challenges such as instrumental artefacts, background noise, astronomical source confusion (similar morph → different origin mechanism)

Will require:

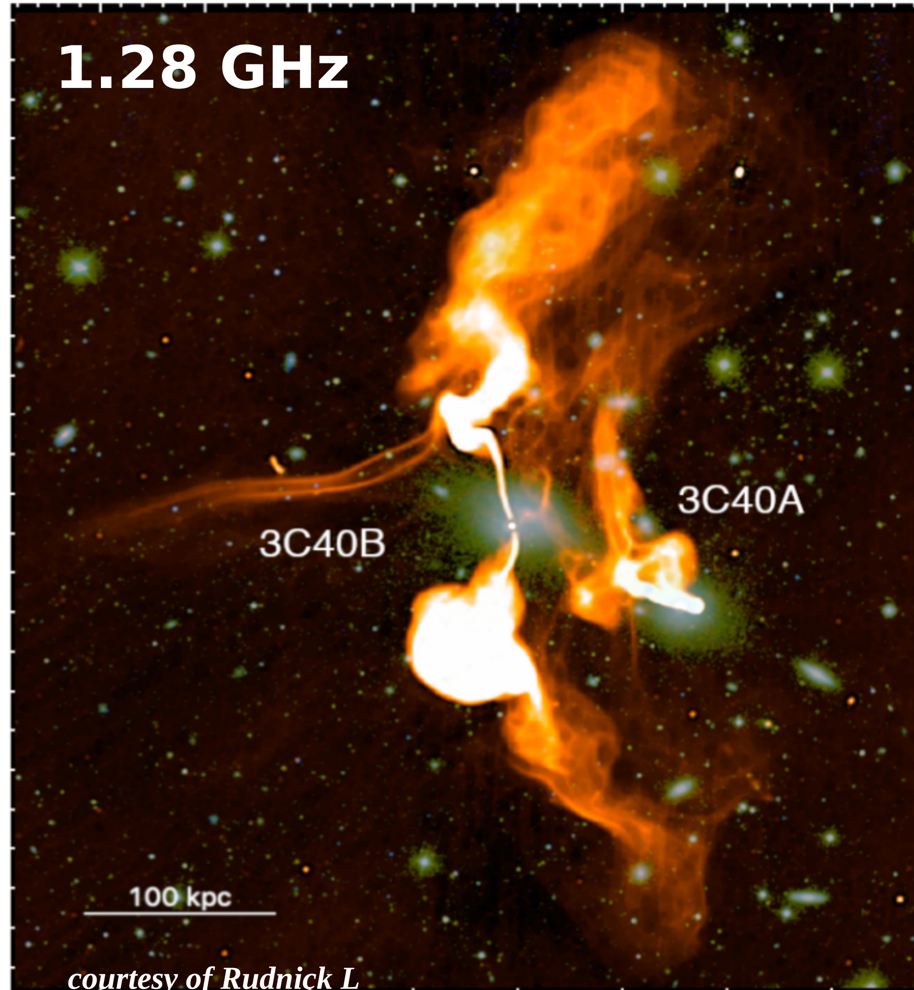
i) Choice of specific neural network model
ii) A pre-processing for the sample source images
iii) A training process
iv) Classification model

MGCLS + Machine Learning

Radio AGN variety



Complex AGN filaments

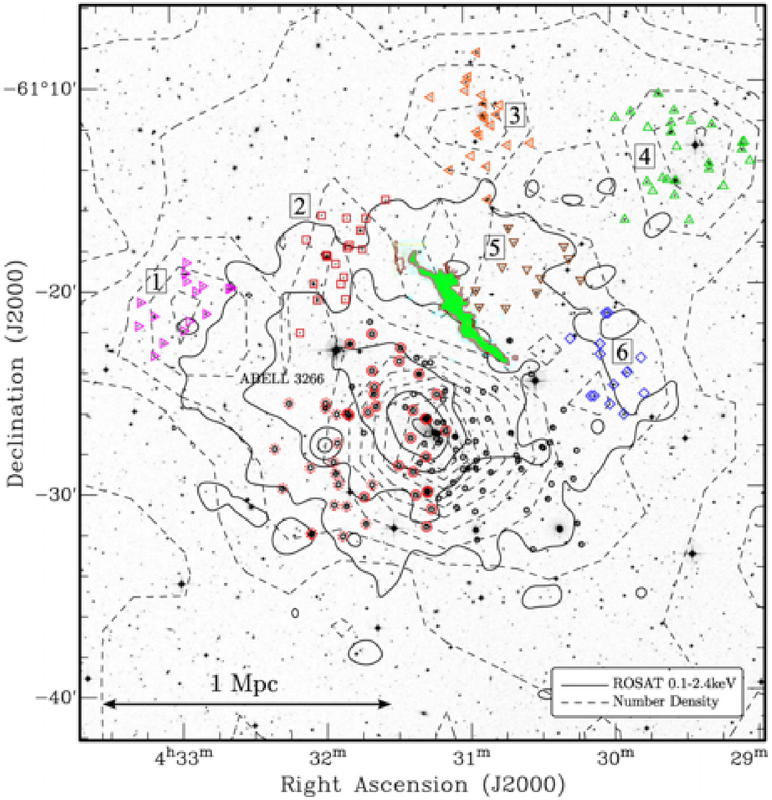


Newly revealed filamentary structures in Abell 194, cannot be explained with any current radio galaxy models as such very large-scale features are not seen in numerical simulations of radio galaxies, nor were predicted

Data from newer telescopes is fundamentally different from previous surveys in terms of complexity and detail !

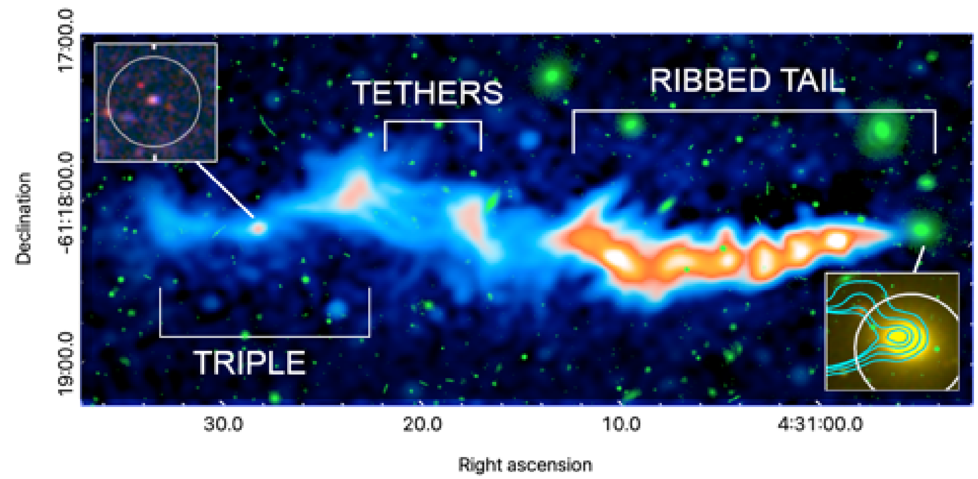
MGCLS: Case of a Mysterious radio galaxy tail in Abell 3266

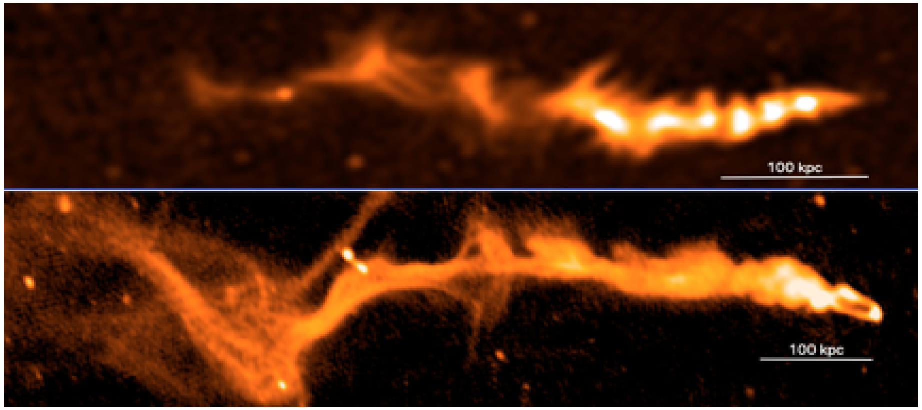
Ribs and tethers



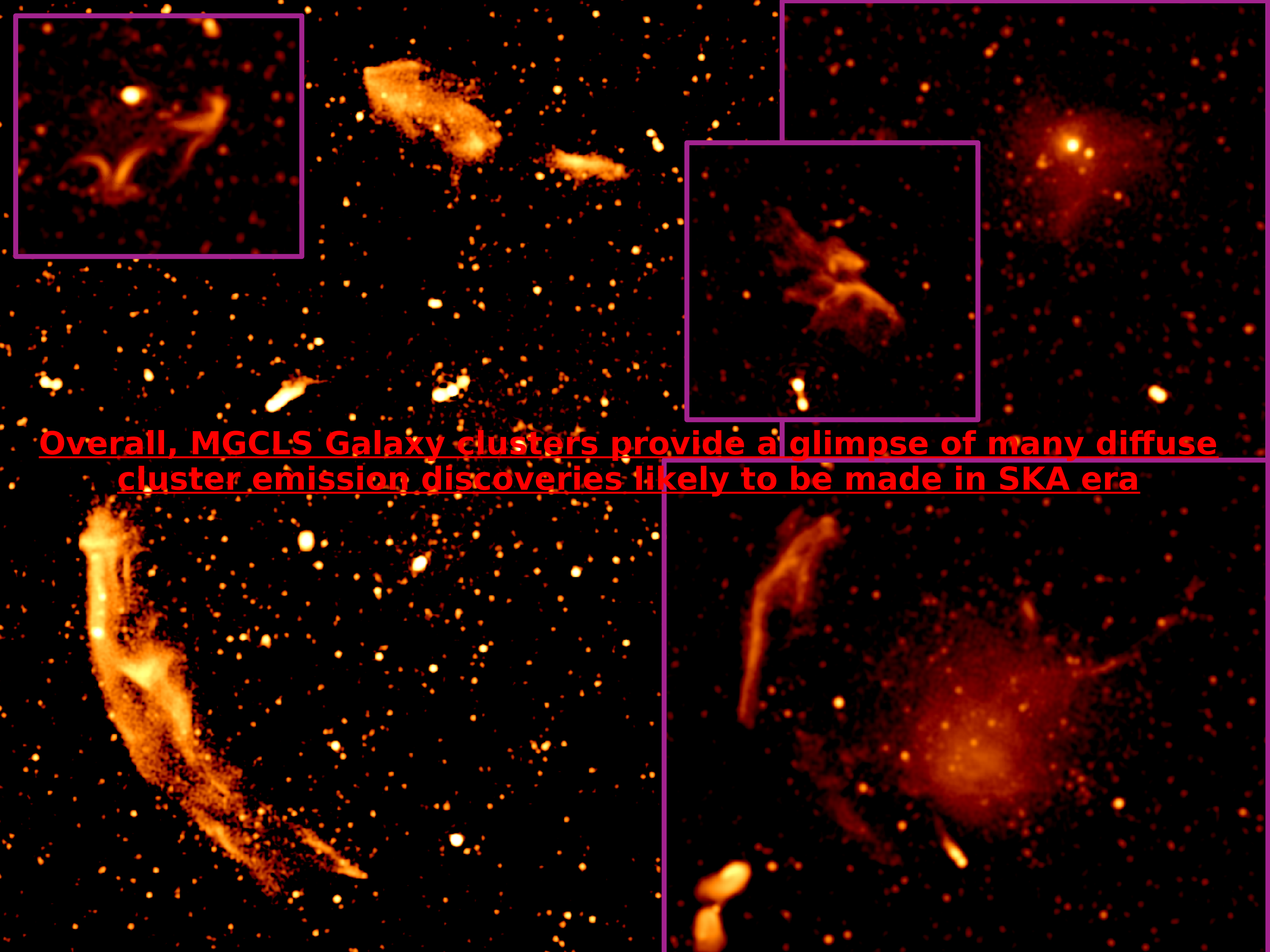
Tethers and perhaps the ribs, likely belong to the newly emerging examples <u>of thin magnetized threads linking larger regions of relativistic plasma</u>
(seen also before in Ramatsoku et al. 2020)

Rudnick, Cotton, Knowles & Kolokythas, 2021, Galax, 9, 81R





MeerKAT observations of MysTail / image produced using LOFAR observations of IC711, (courtesy of van Weeren et al. 2021), on similar scales, showing the emergence of unusual features associated with tailed radio galaxies


Overall, MGCLS Galaxy clusters provide a glimpse of many diffuse cluster emission discoveries likely to be made in SKA era

MGCLS II. Take away points

i) **Structures in several clusters do not fall into typical classes revealing need for new dynamical or particle/field amplification processes in ICM**

ii) **Thanks to MGCLS's high sensitivity & ability to detect mini-halo & associate candidate systems at low-powers we suggest for radio mini-halos a possible mild correlation between 1.4 GHz radio power & M500 cluster mass**

iii) **MGCLS II, (Kolokythas et al. 2025) provides a complete catalogue with radio properties for 62 MGCLS clusters with diffuse emission and also offers the basis to test and implement ML algorithms for extended radio sources classifications**

iv) **Challenges for the diffuse emission classification can be minimized by DDE (3GC) calibration and Cross-matching with multi-wavelength data**

The end!

Based on the phrase of Plato, a mnemonic for pi (π = 3.1415926..) was derived:

Ἀεὶ	ὁ	θεὸς	ὁ	μέγας	γεωμετρεῖ	τὸ	σύμπαν
3 letters .	1 letter	4 letters	1 letter	5 letters	9 letters	2 letters	6 letters

'Aeì ho theòs ho mégas geōmetreî tò sýmpan'

Translation: **Always the great god applies geometry to the Universe**