En route to the SKA era:
MeerKAT's sharp new view on galaxy clusters

The *M*eerKAT *G*alaxy *C*luster *L*egacy *S*urvey II. Preparing for Big data with radio clusters

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Konstantinos Kolokythas

Postdoctoral Research Fellow, Rhodes University / SARAO

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Galaxy Clusters in numbers..

- Most massive bound objects in the Universe (10^{14} - 10^{15} $M_{\odot}$)

- Contain ~few thousand of galaxies out to ~2 - 10 Mpc

- Filled with 10 - 100 million degree hot gas (plasma)

- Intra-Cluster Medium (ICM) gas cools with X-ray emission via bremsstrahlung radiation

Credit:Composite X-ray (Chandra; NASA/CXC/MIT) / Optical (HST/NASA/STScI); 556 kpc on a side of cluster Abell 1689 at z = 0.18. Purple haze shows X-ray emission of the T ~ 10^8 K gas

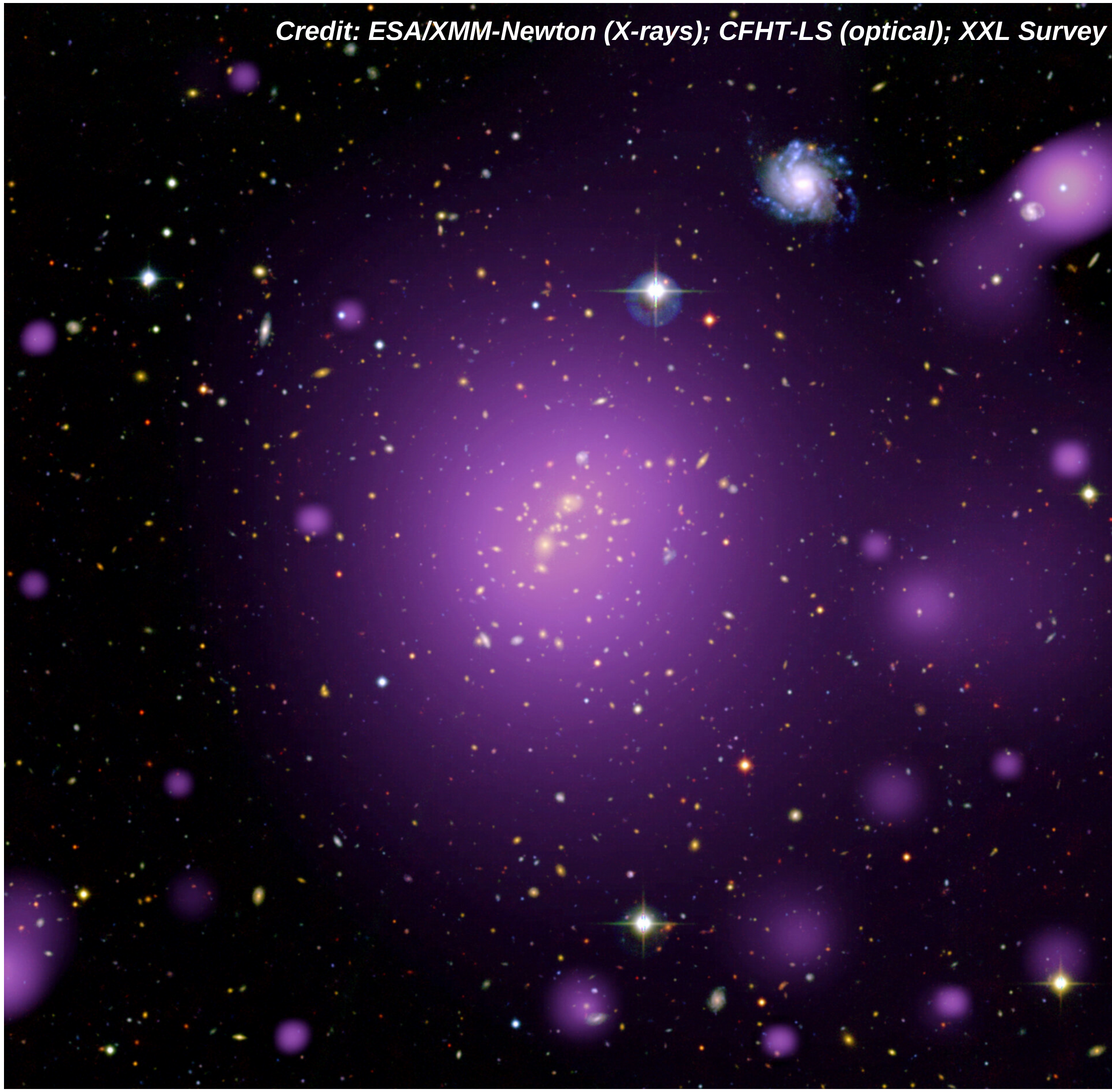
A (quick) recipe for Galaxy Clusters

3 main ingredients

- **Dark matter** accounts for **~80%** of the mass in a cluster, which holds everything else together

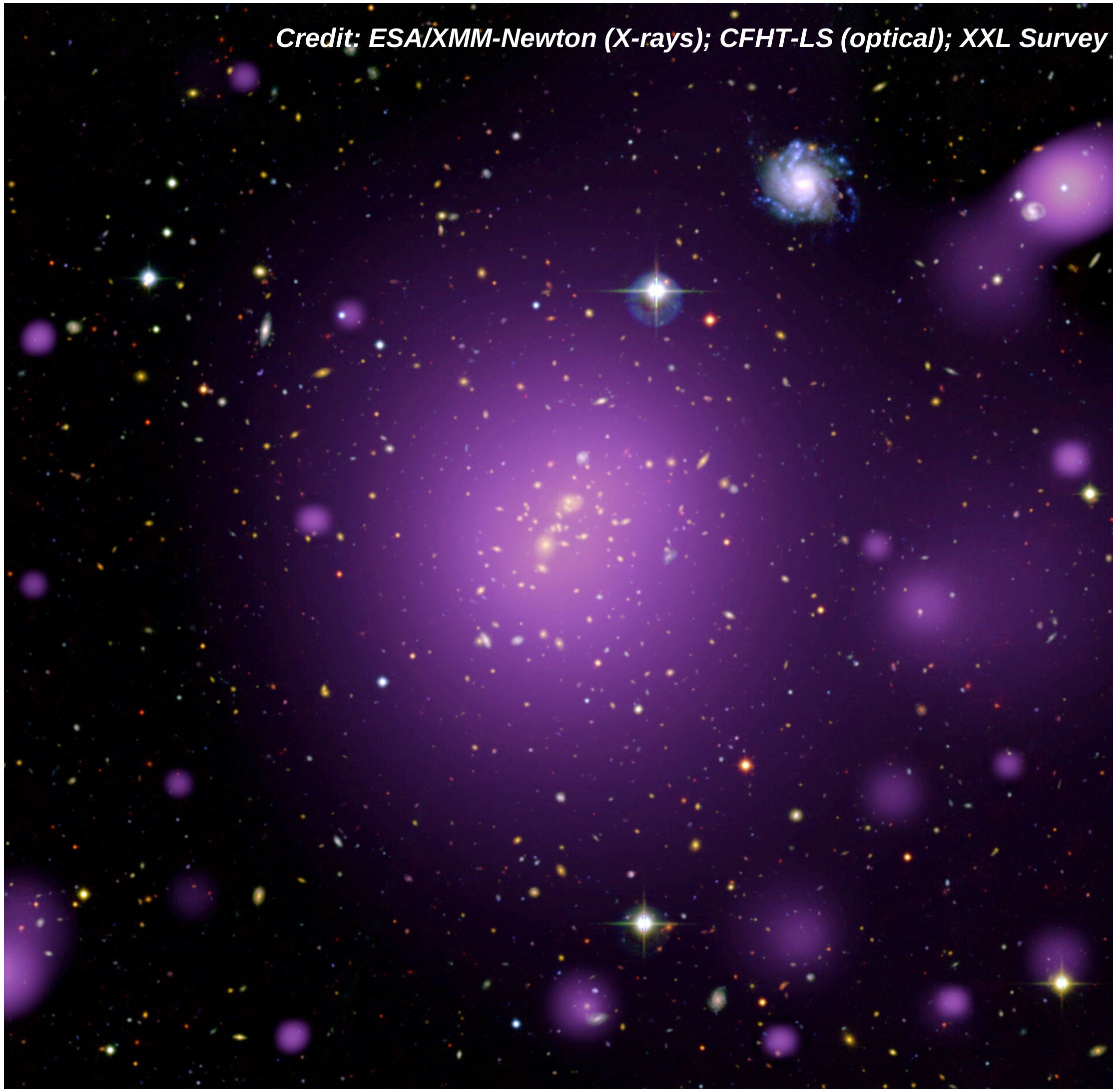
- **Hot gas** is 2nd most massive contribution to galaxy clusters in the form of hot plasma

- **~15%** of the total mass, which fills much of the space between the galaxies shinning brightly in X-ray light

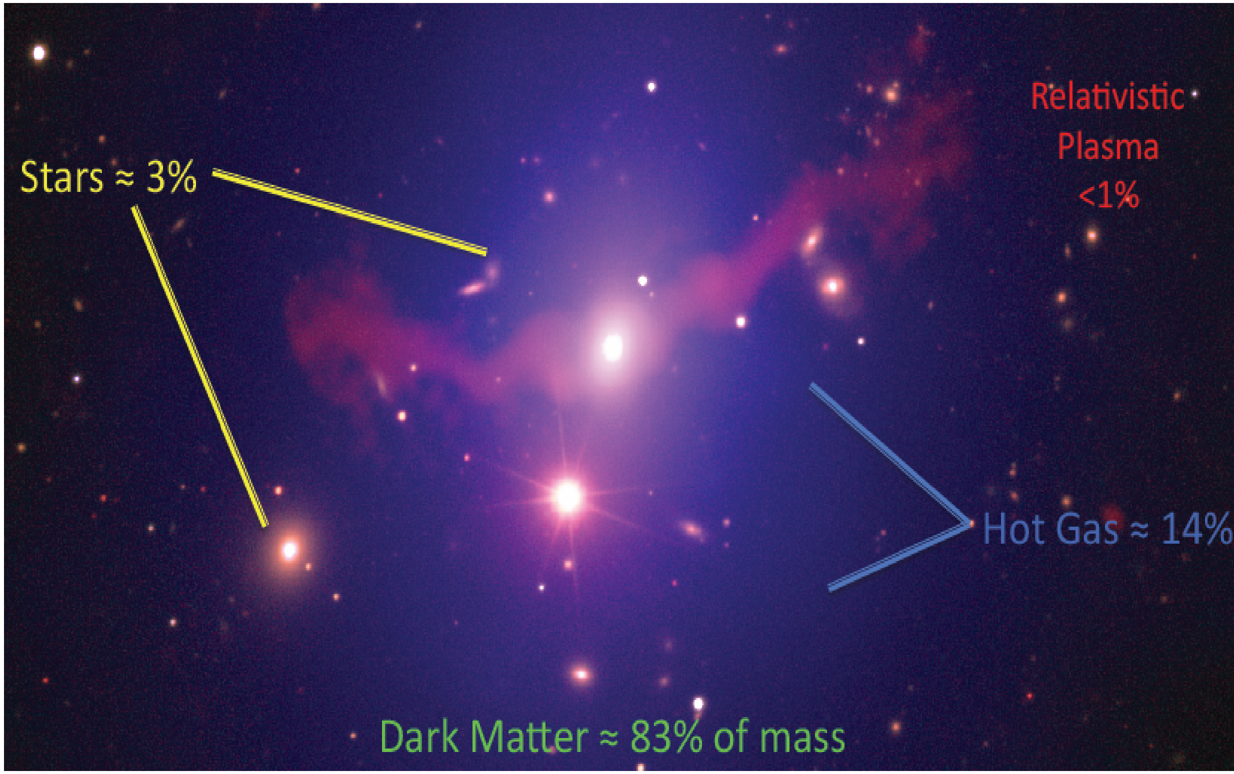


A (quick) recipe for Galaxy Clusters

- **Galaxies** are the smallest of the 3 ingredients making up a galaxy cluster
- The stars and gas in cluster galaxies only make up about **5%** of total mass
- Galaxies may weigh in the least, but are very important
- The largest galaxies in the universe live in clusters
- Galaxy cluster interactions are a laboratory understanding how these huge monsters form



A (quick) recipe for Galaxy Clusters



SKA precursor: MeerKAT

- 64–dish radio interferometer of 13.5 m-diameter each

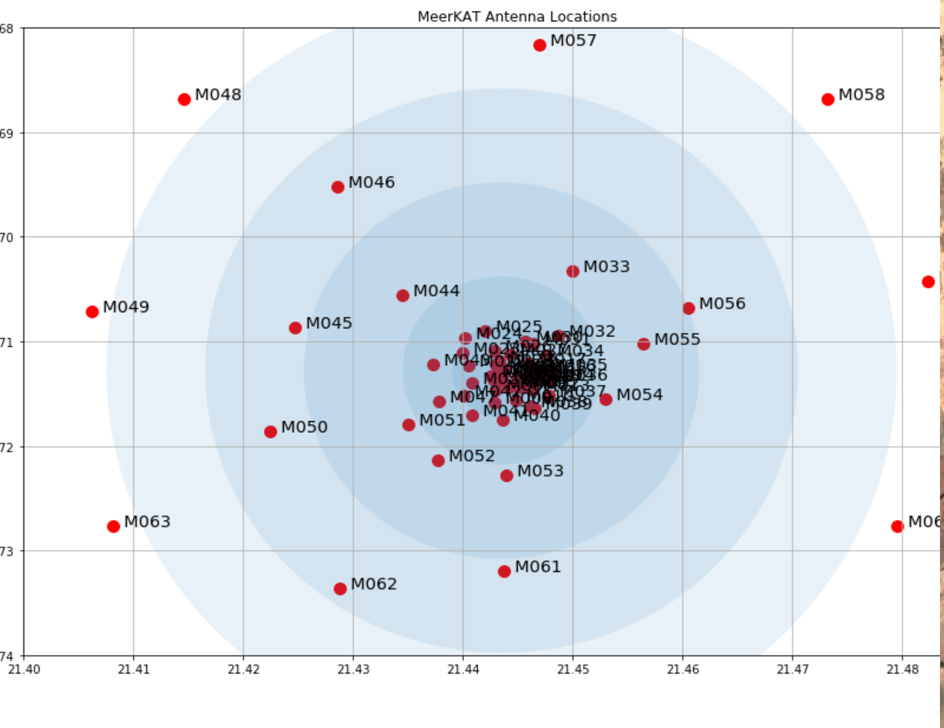
- Observes the sky below a DEC of **+15°**

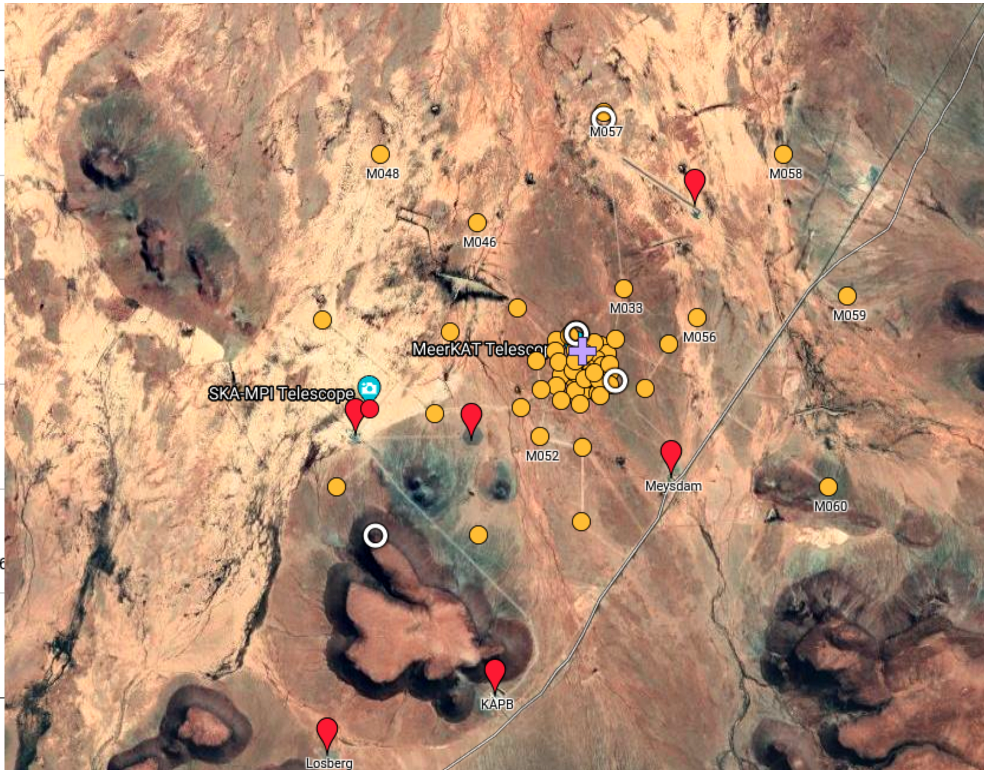
- Operational in L-(900–1670 MHz), S-(1750–3500 MHz), and UHF-bands (580–1015 MHz) see Jonas & MeerKAT Team (2016) and Camilo et al. (2018)

- 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





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
- Heterogeneous sample, with no mass or redshift selection criteria applied consisting of 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

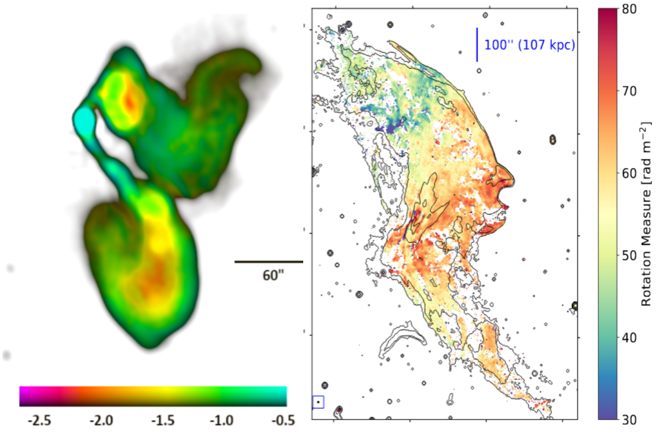
MGCLS: MeerKAT Galaxy Cluster Legacy Survey

- 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 datasets have a broad range of applications

- **Diffuse radio emission**
- In-band spectral indices / Polarization
- HI science, star formation
- Source catalogs
- Radio AGN



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 ($\alpha < -1.1$)

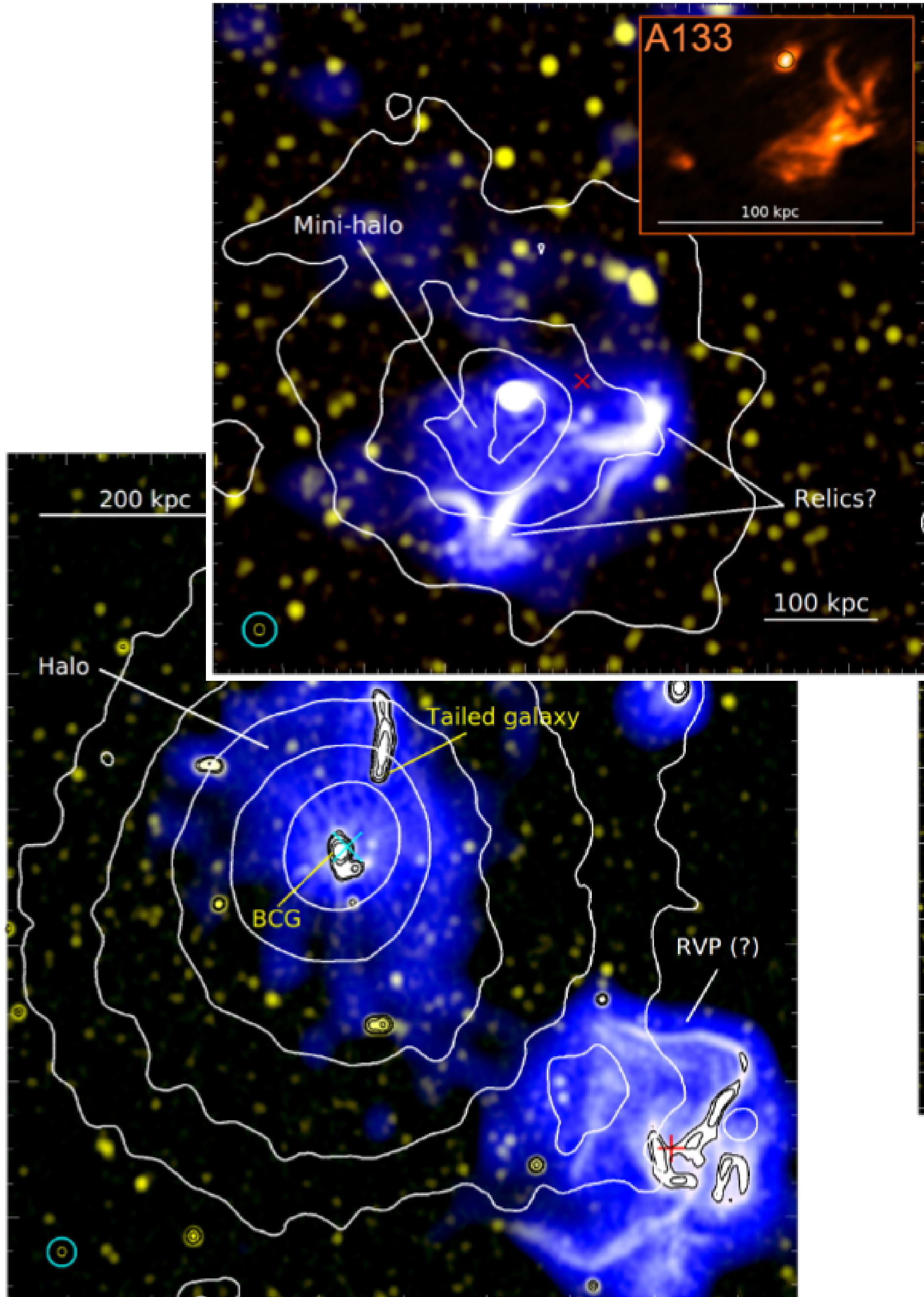
MGCLS: Cluster diffuse radio emission

- **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)

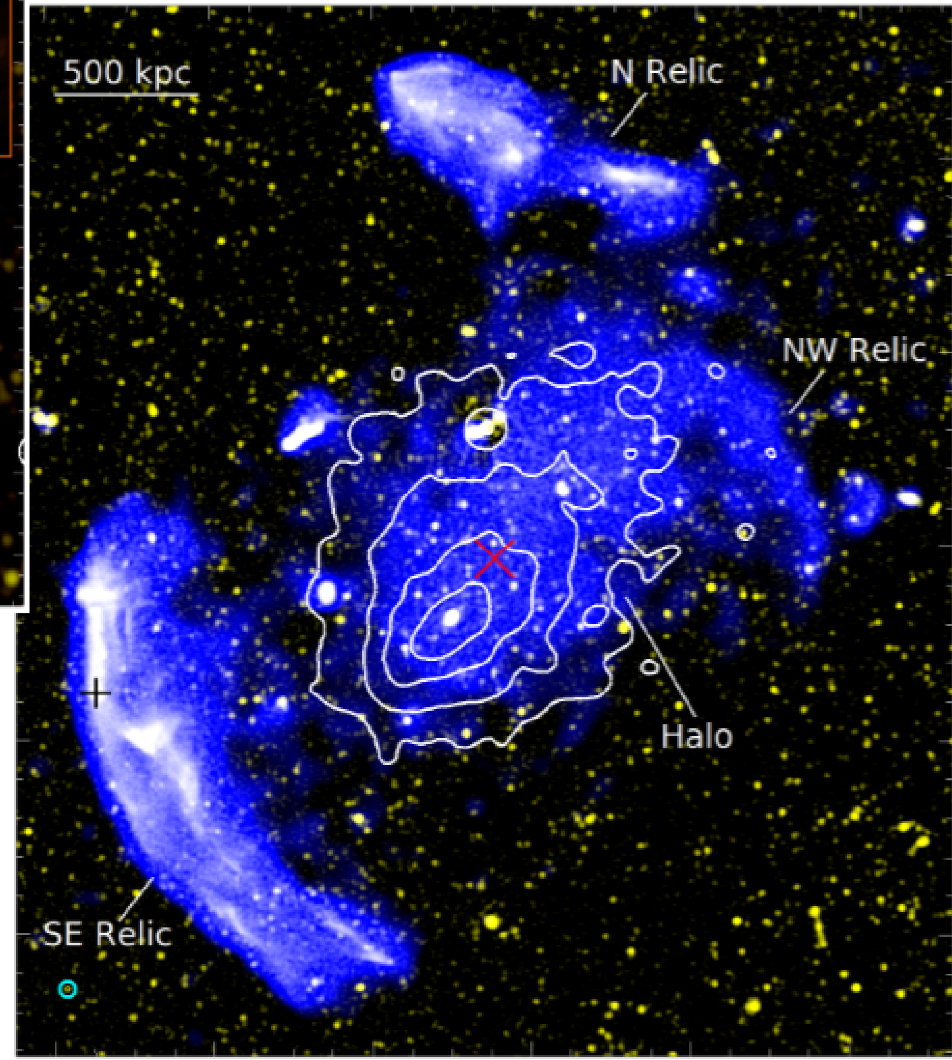
- **Radio mini-halos** found in central region of dynamically relaxed, cool-core clusters with projected sizes few tens to few hundreds of kpc; always a radio active BCG provides at least a fraction of the seed electrons that produce the diffuse emission (see Giacintucci et al. 2017)

- **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)

Randall+2010



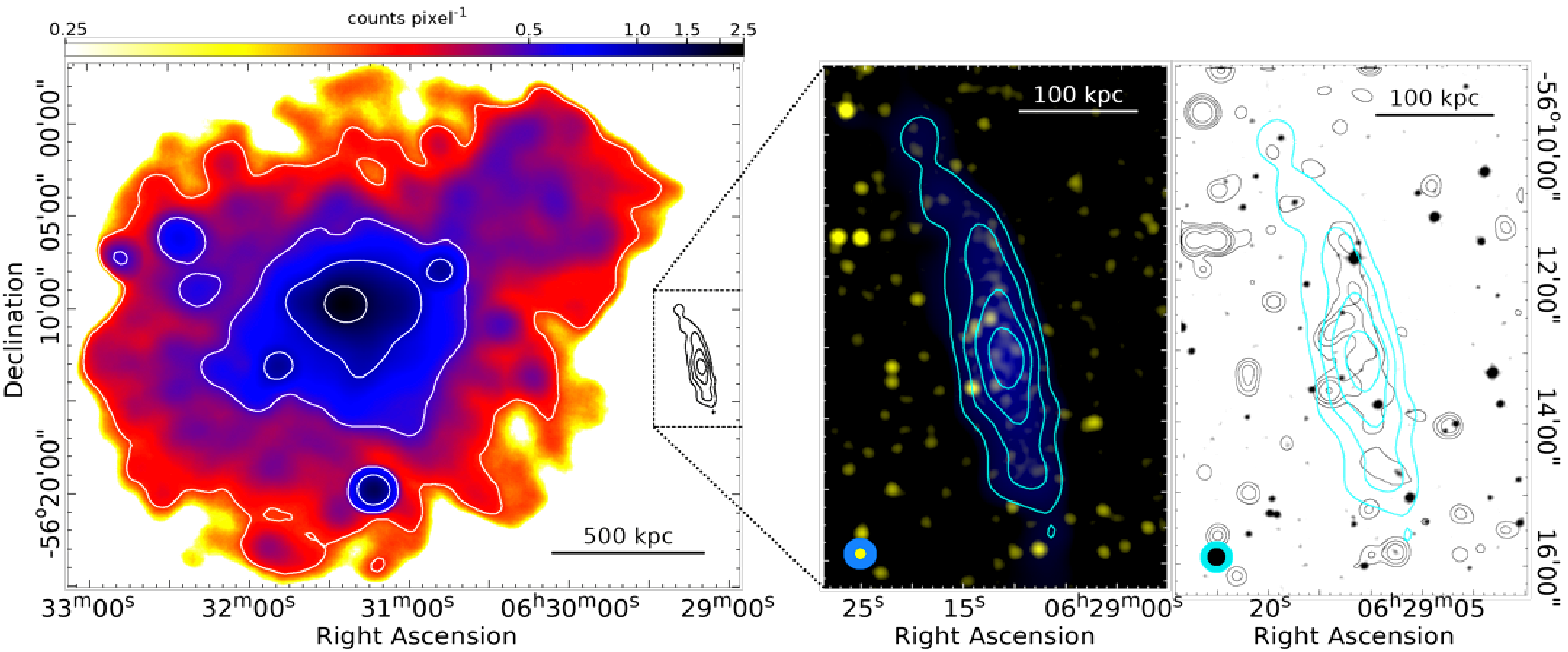
Discoveries +



New details for known sources

Slee et al (2001)

Discoveries +



Total 1.28 GHz flux density ~2.8 ± 0.2 mJy

At the cluster redshift of $z = 0.054$ corresponds to a k-corrected 1.4 GHz radio power of $(1.7 \pm 0.3) \times 10^{22}$ W Hz^{-1}

MGCLS II: The case of A521

Abell 521, rich galaxy cluster (z=0.248) with disturbed dynamic state; multiple merger clusters converging in centre
(Ferrari et al. 2003, 2006)

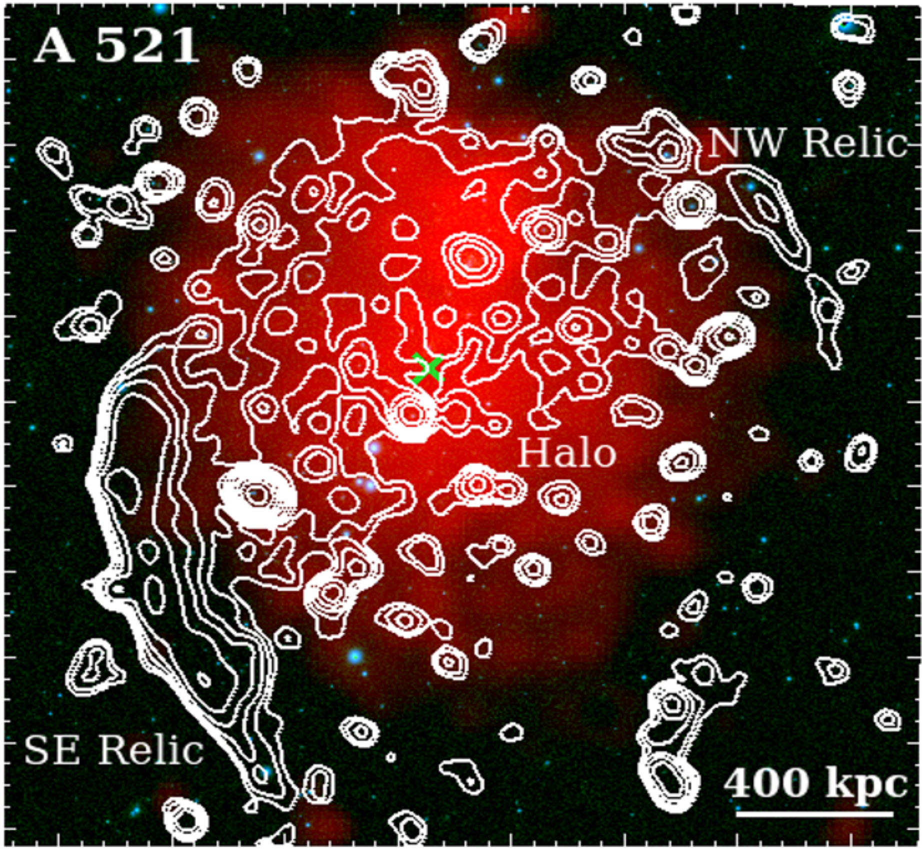
Prototype ultra-steep spectrum halos

SE arc-shaped radio-relic first detected at 610 MHz GMRT & 1.4 GHz VLA

(Giacintucci et al. 2006, 2008;Ferrari et al. 2006; Venturi et al. 2007)

MGCLS revealed new features (K22):
higher SE relic flux density over similar extent & a second NW counter-relic presenting complex sub-structures at opposite direction to the main SE relic

Radio halo extends all the way from SE relic to newly detected NW counter-relic



MeerKAT 1.28 GHz radio contours in white (1σ = 6 μJy beam^{-1}), overlaid on the adaptively smoothed 1.1–5.0 keV XMM-Newton image in red. Both radio contours and X-ray images are overlaid on the RGB composite PanSTARRS (z, i) optical image. The MeerKAT radio contours are spaced by a factor of two, starting from 3σ. Scale is 3.887 kpc arcsec^{-1}

MGCLS II: MeerKAT Galaxy Cluster Legacy Survey + DR2

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

Kolokythas et al., in prep (follows-up K22), we classify in detail all cluster-scale diffuse radio structures detected in MGCLS clusters, providing a complete catalogue of the properties of all radio sources & their respective clusters along with statistics on the sample presenting also the full-resolution & tapered images

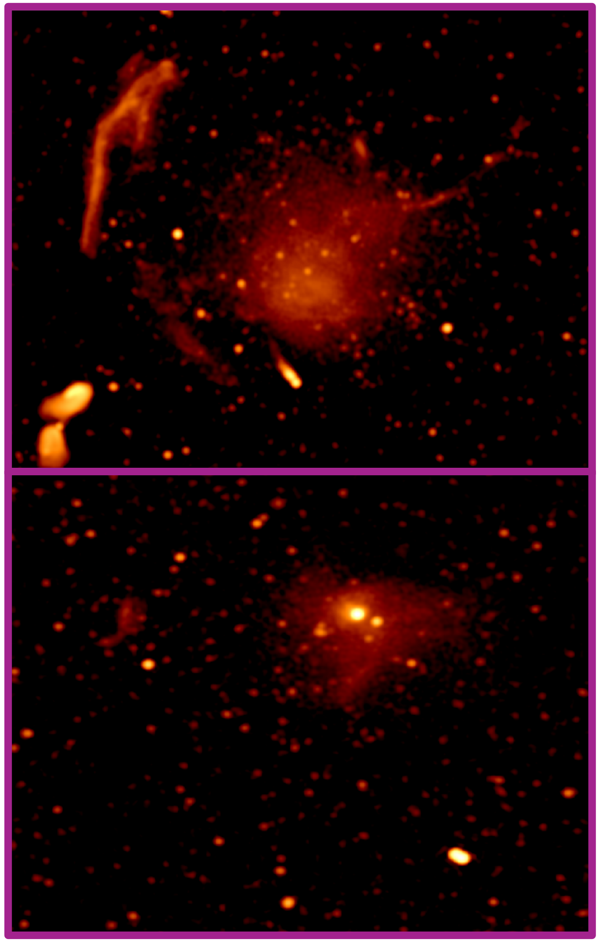
MGCLS DR2 is an underway project planning the release to the astronomical community of an extended database of more 'ready to use' data products such as MGCLS self-calibrated data & pol

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

MGCLS II: Diffuse Cluster radio emission Catalogue project

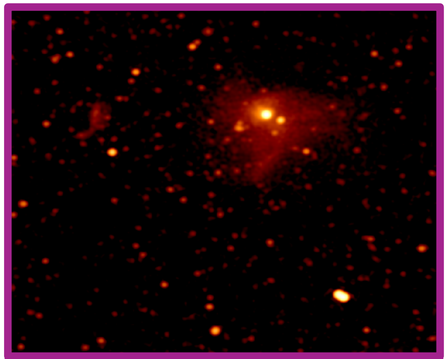
- A complete analysis of all diffuse cluster sources in 62 clusters, including flux densities, spixes, sizes, rms at low res, radio power measurements, presentation of radio images is shown in **Kolokythas et al., 2024, in prep.**

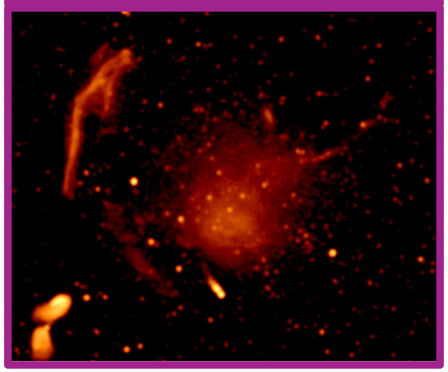
(1) Cluster Name	(2) RA (J2000)	(3) Dec. (J2000)	(4) z	(5) Morph	(6) rms_15″ (μJy)	(7) Flux Density (mJy)	(8) LLS (kpc × kpc)	(9) $P_{1.28GHz}$ (W Hz^{-1})
MACS J0257.6–2209[c]	02:57:40.3	–22:09:46.0	0.322	cHalo	6	**0.4**(faint)	430 × 500	1.3×10^{23}
	02:57:37.1	–22:09:59.7		SW cRelic	6	1.8	190 × 390	5.7×10^{23}
MACS J0417.5–1154	04:17:34.6	–11:54:32.0	0.443	Halo	7	16.1	840 × 1580	1.1×10^{25}
	04:17:27.0	–11:47:23.3		N cRelic	7	1.6	220 × 780	1.1×10^{24}
	04:17:13.8	–11:48:21.5		NW cRelic	7	1.0	210 × 490	6.6×10^{23}
RXC J0510.7–0801	05:10:44.3	–08:01:12.0	0.220	cHalo	8	5.8	430 × 1040	7.9×10^{23}
RXC J0520.7–1328[d]	05:20:47.2	–13:30:08.0	0.336					
	05:21:02.2	–13:35:26.5		SE cRelic	10	6.1	230 × 1100	2.1×10^{24}
	05:21:09.8	–13:29:07.7		E cRelic	10	2.5	280 × 910	9.3×10^{23}
	05:20:49.5	–13:31:57.0		S cRelic	10	4.9	470 × 1200	1.7×10^{24}
RXC J1314.4–2525	13:14:23.7	–25:15:21.0	0.244	Halo	12	20.6	840 × 1080	3.8×10^{24}
	13:14:46.0	–25:15:10.0		E Relic	12	12.7	230 × 620	2.2×10^{24}
	13:14:17.9	–25:15:50.6		W Relic	12	22.6	210 × 1080	4.0×10^{24}
RXC J2351.0–1954	23:51:04.9	–19:54:48.0	0.248	cHalo?	7	**N/A**	∼2600	-
	23:50:41.3	–19:56:27.1		W cRelic	7	0.6	100 × 1030	1.0×10^{23}
	23:51:29.9	–20:01:01.1		E cRelic	7	2.5	170 × 1340	4.3×10^{23}
J0027.3–5015	00:27:21.3	–50:15:04.0	0.145	cMHalo	6	0.3	170 × 210	1.6×10^{22}
J0145.0–5300	01:45:02.3	–53:00:50.0	0.117	Halo	4	2.5	320 × 620	8.5×10^{22}
J0145.2–6033	01:45:16.7	–60:33:54.0	0.181	cMHalo	4	0.9	220 × 320	8.2×10^{22}
J0216.3–4816	02:16:19.1	–48:16:23.0	0.163	cMHalo	6	3.3	220 × 240	2.3×10^{23}
J0217.2–5244	02:17:12.6	–52:44:49.0	0.343					
	02:17:04.0	–52:41:45.0		N cRelic	6	1.1	170 × 460	4.3×10^{23}
J0225.9–4154	02:25:54.6	–41:54:35.0	0.220	Halo	7	14.4	330 × 500	2.0×10^{24}
J0232.2–4420	02:32:16.8	–44:20:51.0	0.284	Halo	6	19.7	1120 × 1240	4.9×10^{24}
	02:32:17.9	–44:22:04.0		S cRelic	6	1.3	200 × 450	3.1×10^{23}
	02:32:42.2	–44:20:51.7		E cRelic	6	1.0	210 × 440	2.4×10^{23}
J0303.7–7752	03:03:46.4	–77:52:09.0	0.274	Halo	6	8.6	630 × 950	2.0×10^{24}
J0314.3–4525	03:14:19.8	–45:25:27.0	0.072	cMHalo	6	1.1	100 × 150	1.3×10^{22}
J0342.8–5338	03:42:53.9	–53:38:07.0	0.060	MHalo	6	5.6	280 × 340	4.4×10^{22}
J0351.1–8212	03:51:08.9	–82:13:00.0	0.061	cMHalo?	8	1.4	110 × 150	1.2×10^{22}
	03:51:52.4	–82:14:31.9		SE Relic	8	1.6	40 × 70	1.3×10^{22}
	03:51:37.0	–82:14:38.4		S Relic	8	2.8	40 × 90	2.3×10^{22}
	03:50:44.6	–82:13:55.8		W Relic	8	4.2	45 × 150	3.5×10^{22}
J0352.4–7401	03:52:29.5	–74:01:51.0	0.127	Halo	8	22.8	680 × 1460	9.2×10^{23}
	03:54:25.2	–74:05:06.5		SE Relic	8	71.7	420 × 2010	2.9×10^{24}
	03:50:29.0	–73:57:39.0		NW cRelic	8	-	-	-
	03:51:23.4	–73:50:35.4		NNW Relic	8	5.6	170 × 460	2.3×10^{23}



MGCLS II: Cluster diffuse radio emission Catalogue project

- ✗ 104 **distinct detections (61 are NEW)**
  - ✗ 3 mini-halos, 8 candidates (**all new**)
  - ✗ 26 radio halo detections, 8 candidates (**14 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)**

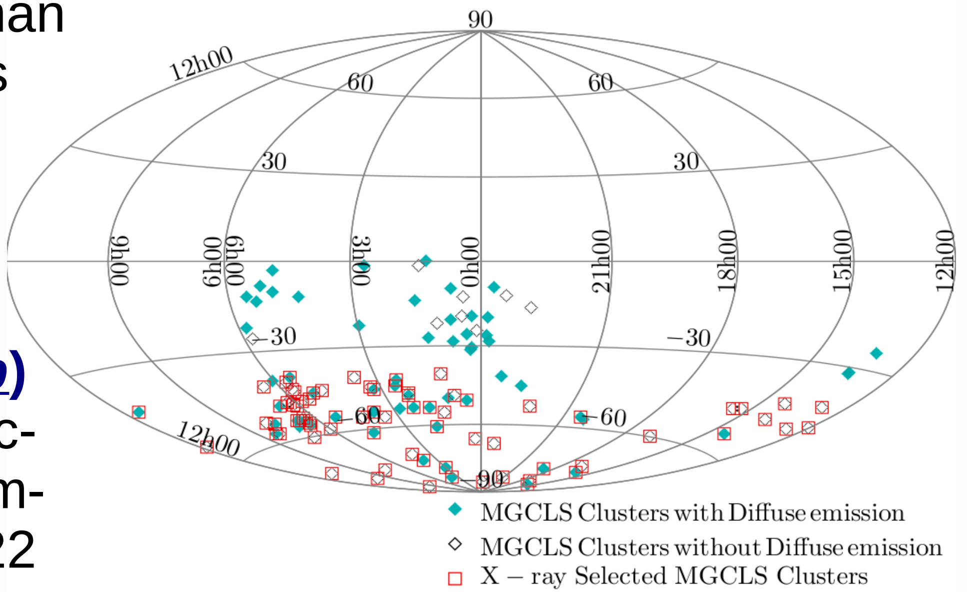
✗ **As candidate structures (c) are classed those presenting a marginal detection or an uncertain feature (in agreement with main properties of each class & optical location of radio emission)**

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

Kolokythas, Venturi, Knowles et al. 2024 in prep., MGCLS diffuse emission catalog Paper II

MGCLS II: Cluster diffuse radio emission Catalogue project

- Several MGCLS clusters host more than one radio or candidate radio structures
- 59% (61/104) of these detected radio structures reported as new in K22
- MGCLS II (*Kolokythas et al., in prep*) has expanded the detected radio structures (99 to 104) characterizing 8/9 ambiguous diffuse radio sources from K22



31% of the newly detected radio structures are discovered in the radio-selected sample (19/61) whereas the majority is found in the X-ray selected sample (69%; 42/61)

This suggests that existing X-ray-selected cluster samples are more likely to ‘reveal’ new radio structures in the southern sky due to the unique ability of MeerKAT to detect in a ‘blind’ search new radio structures

MGCLS II: Cluster diffuse radio emission Catalogue project

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

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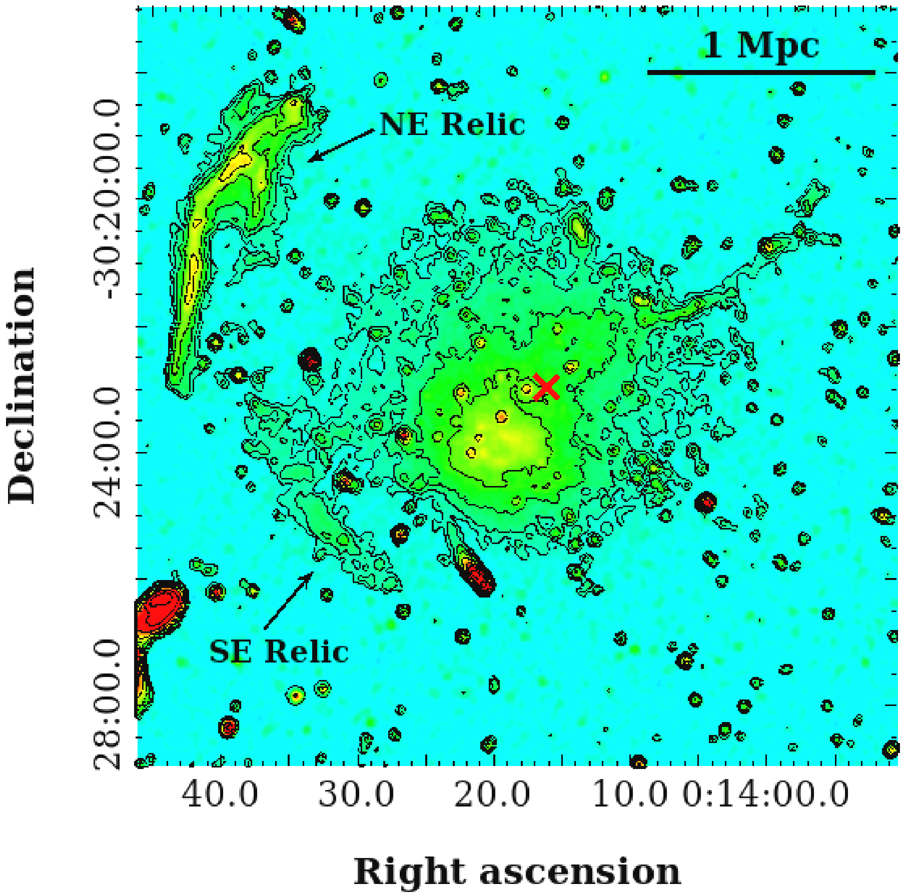
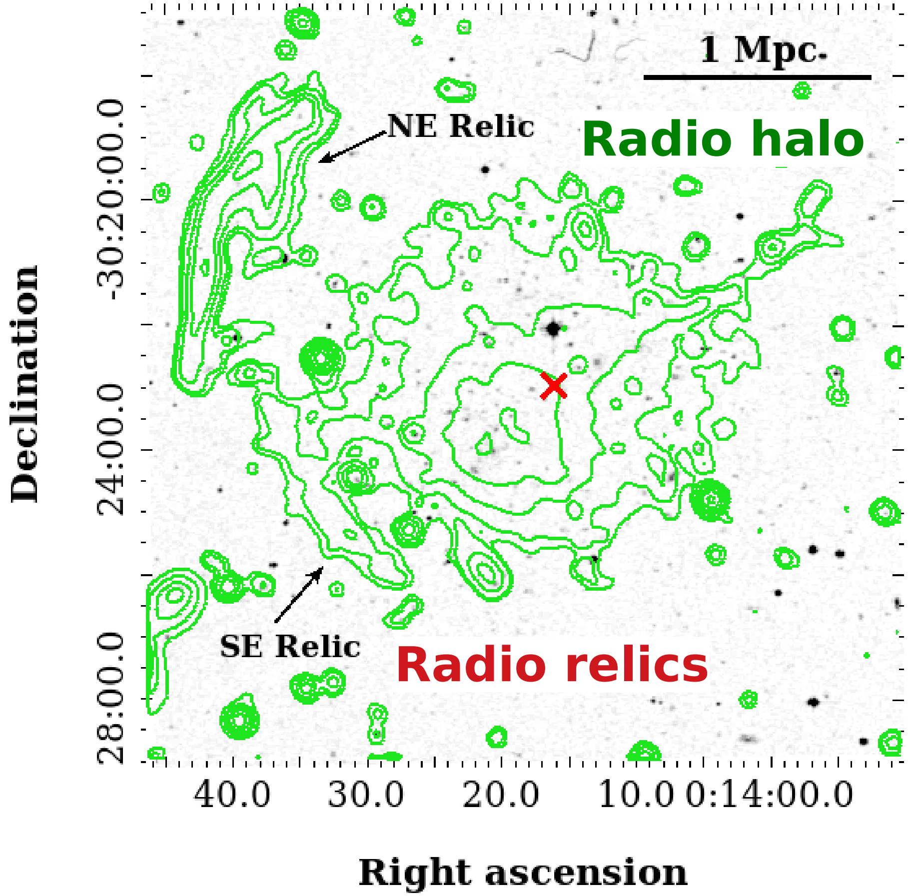
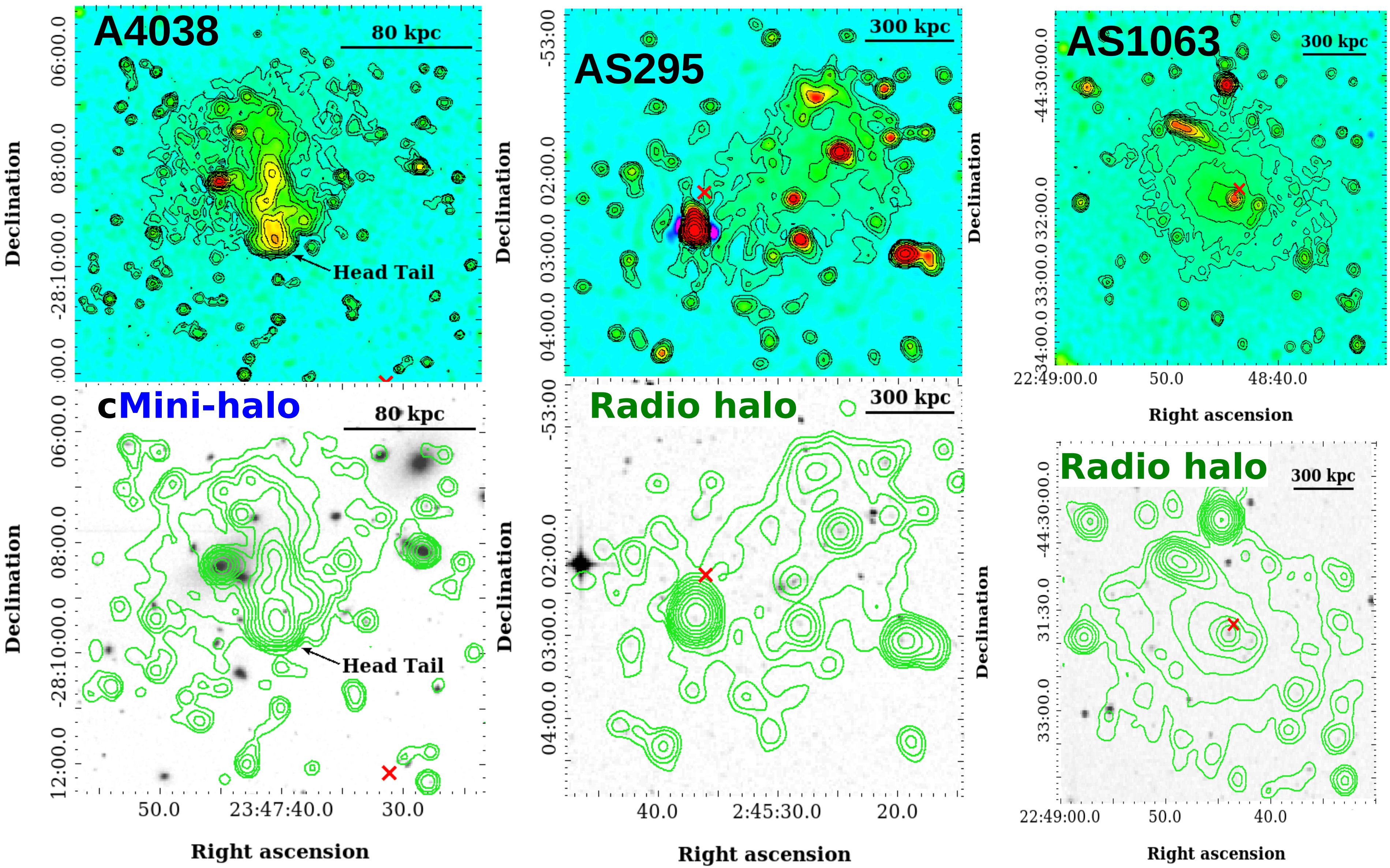
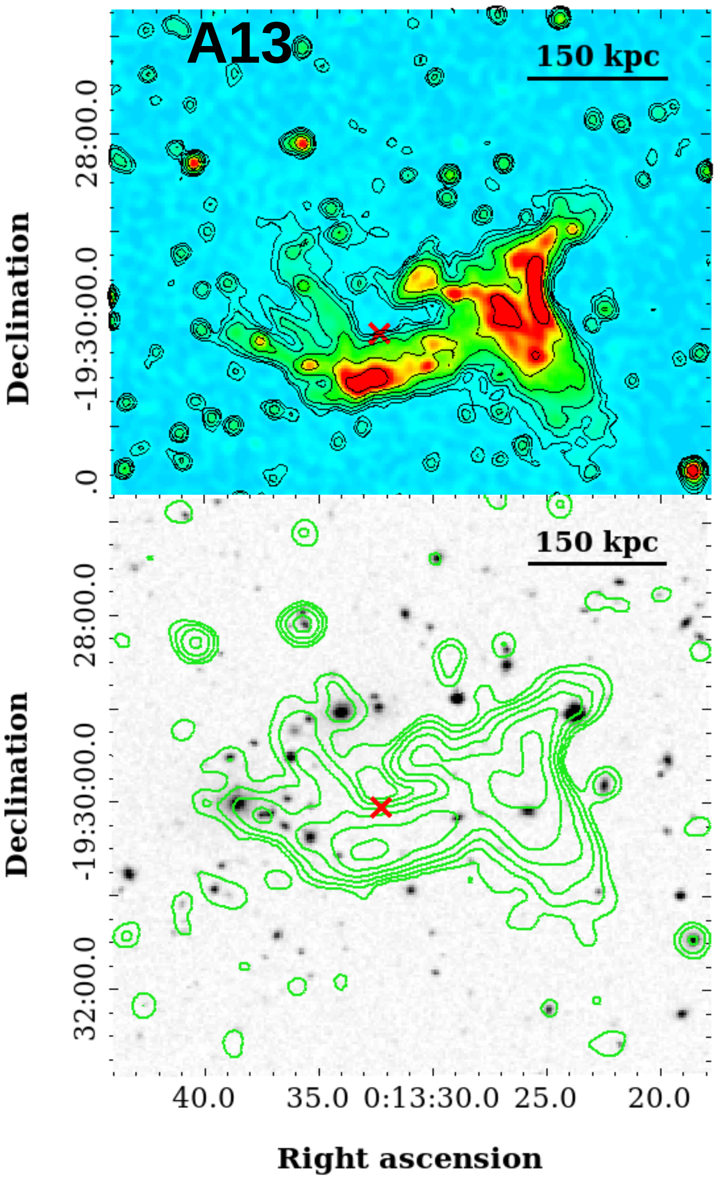


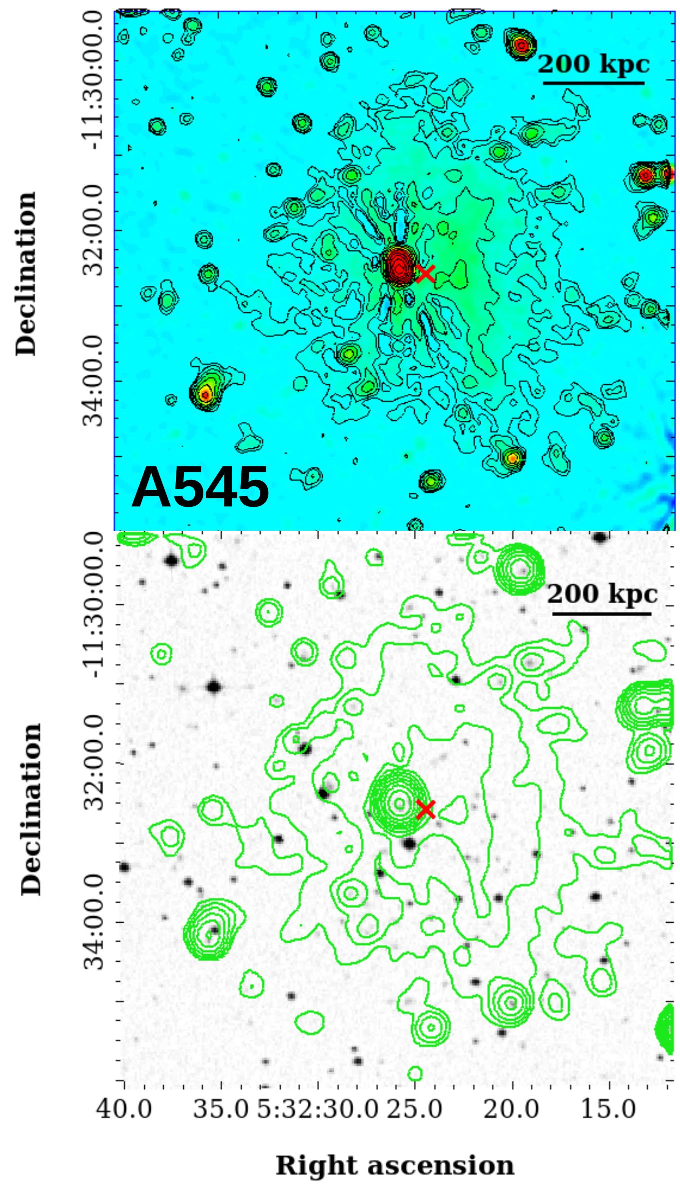


MGCLS II: Cluster diffuse radio emission Catalogue project



MGCLS II: Cluster diffuse radio emission Catalogue project





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% (34/115) 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

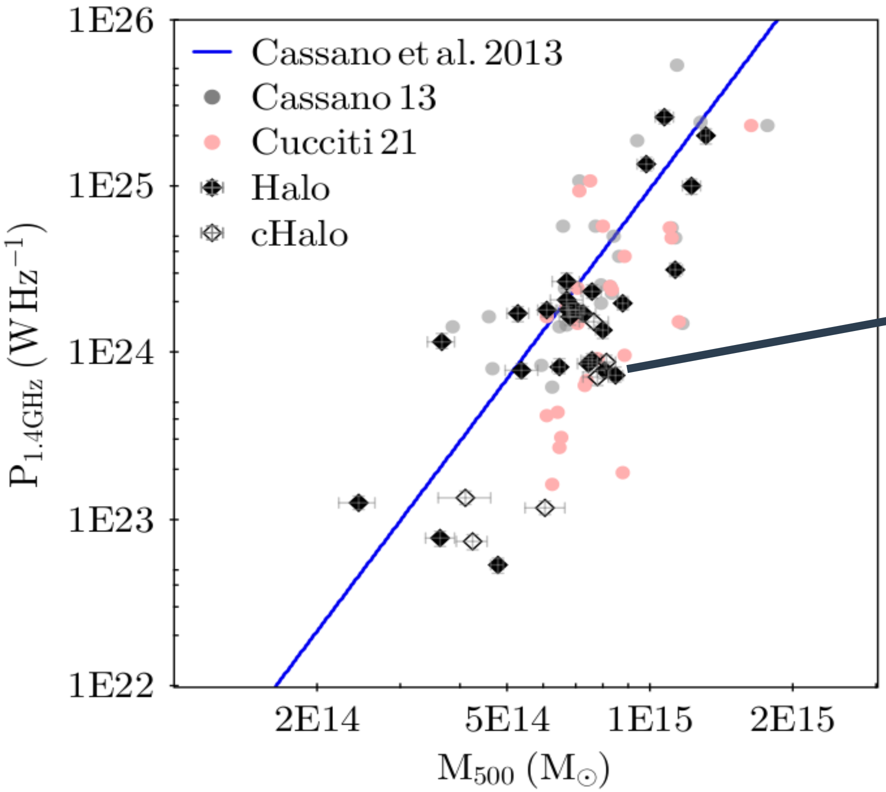
Detection fractions for the 104 radio structures

- Most commonly detected diffuse structures in MGCLS are radio relics at an occurrence rate of 53% (55/104)
- Radio halos follow at 33% (34/104) and mini-halos at 10% (11/104)
- Only 3% (3/104) are found to be Phoenixes with just 1% of the detected radio structures being listed as ambiguous/Unknown

MGCLS II: Kolokythas K., Venturi T., Knowles K. et al., 2024, in prep

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

Radio halos & respective candidates follow the known steep correlation 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

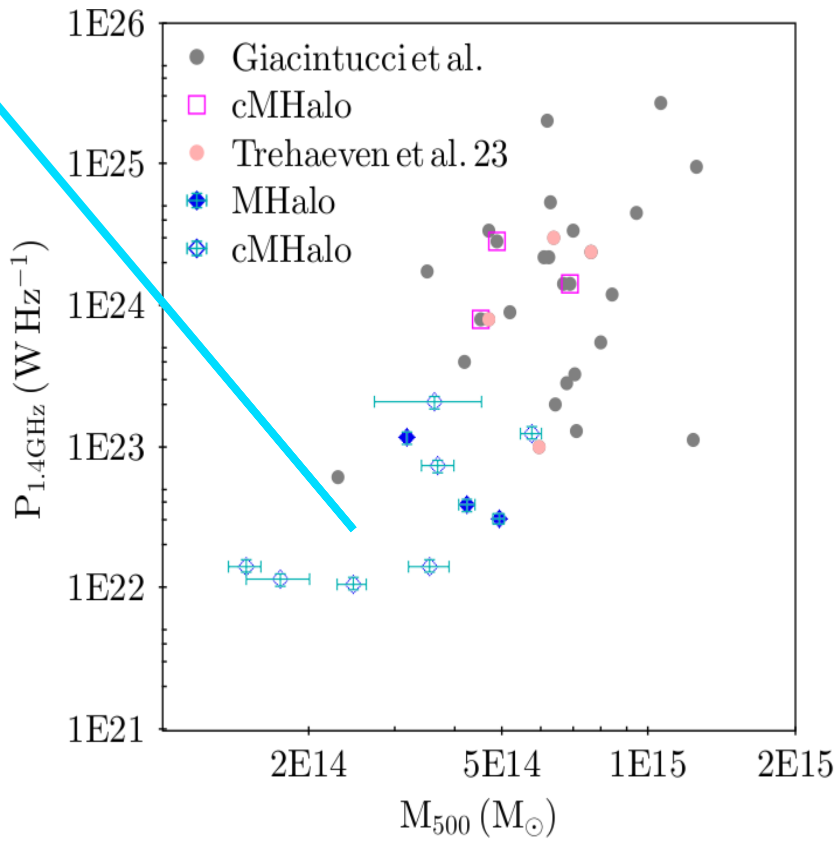
Scaling relation between cluster mass (M_{500}) and radio power ($P_{1.4GHz}$) for MGCLS systems that host RHs, cRHs and ***MHs, cMHs***

3 radio mini-halos & 7 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 for the first time



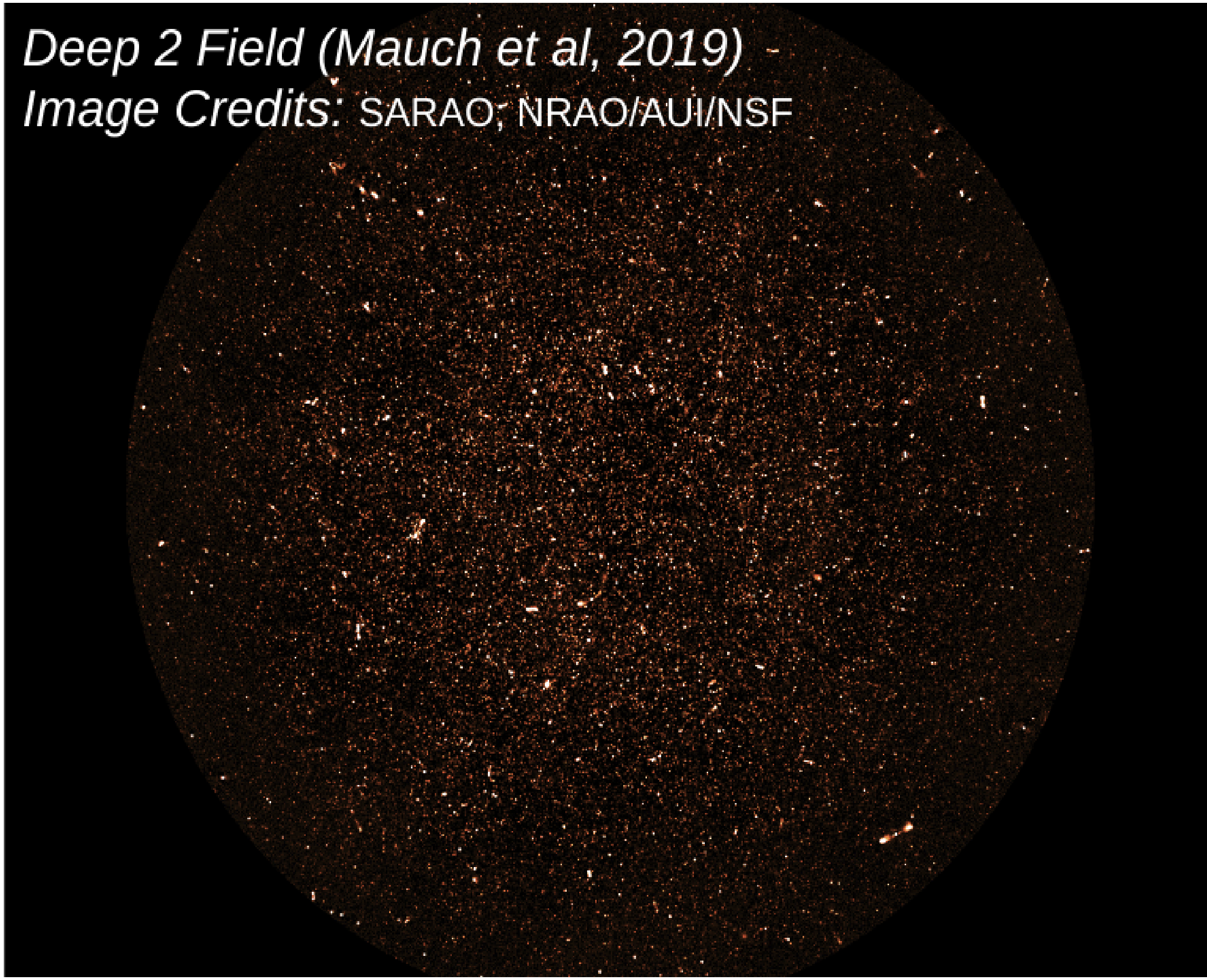
End-to-End Image Analysis in the era of Big Data

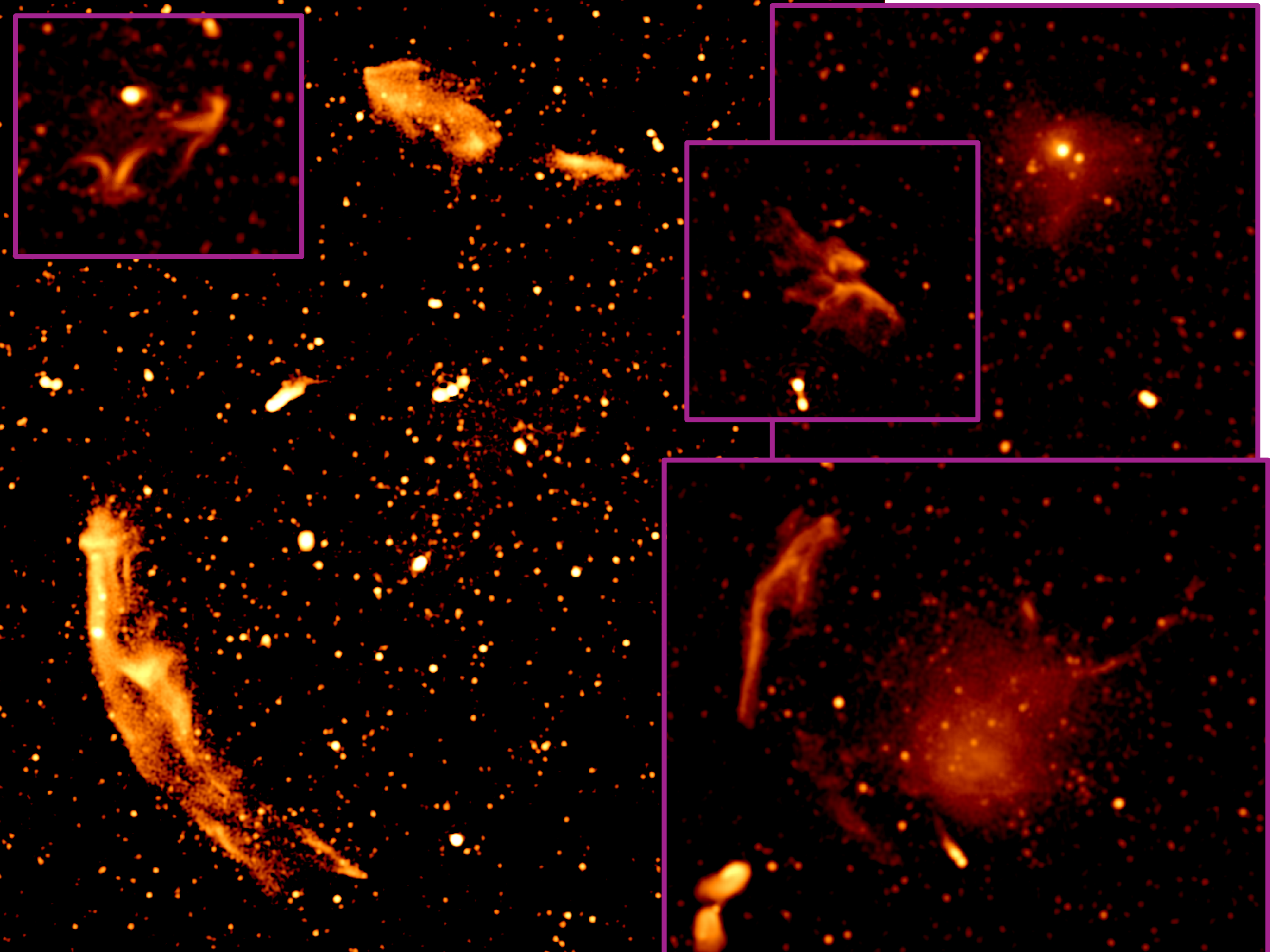
What's new about image analysis ?

The high spatial density of sources

Diffuse emission
(mixed with compact sources associated with distant AGNs and star-forming galaxies

Cross-matching with multi-wavelength data





MGCLS + Machine Learning

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

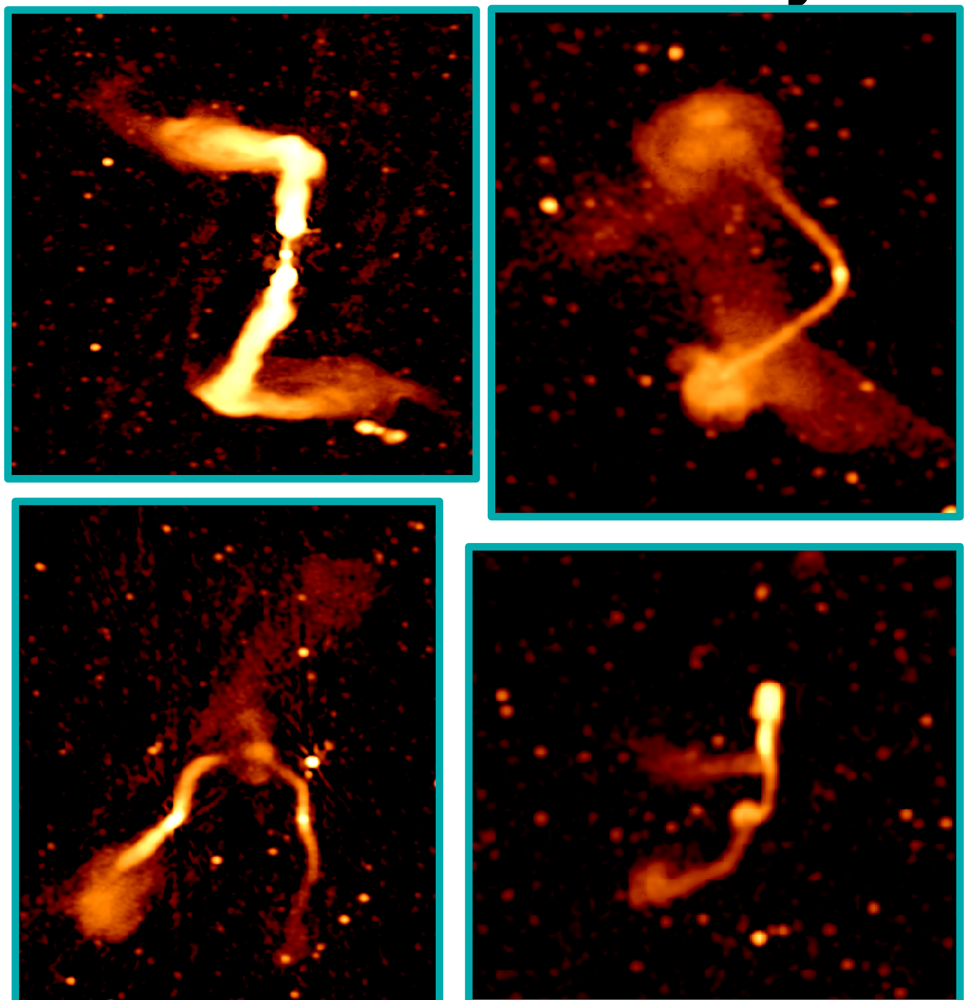
An automated way to detect and successfully classify the different cluster extended radio structures on a morphological basis using both supervised and unsupervised Machine Learning Techniques

Deep CNNs have been used for different applications in optical astronomy, such as star–galaxy classification (Kim & Brunner 2017) and redshift estimation (Hoyle 2016). A rotational invariant CNN was used for optical galaxy classification, which gave near-human accuracy (Dieleman et al. 2015)

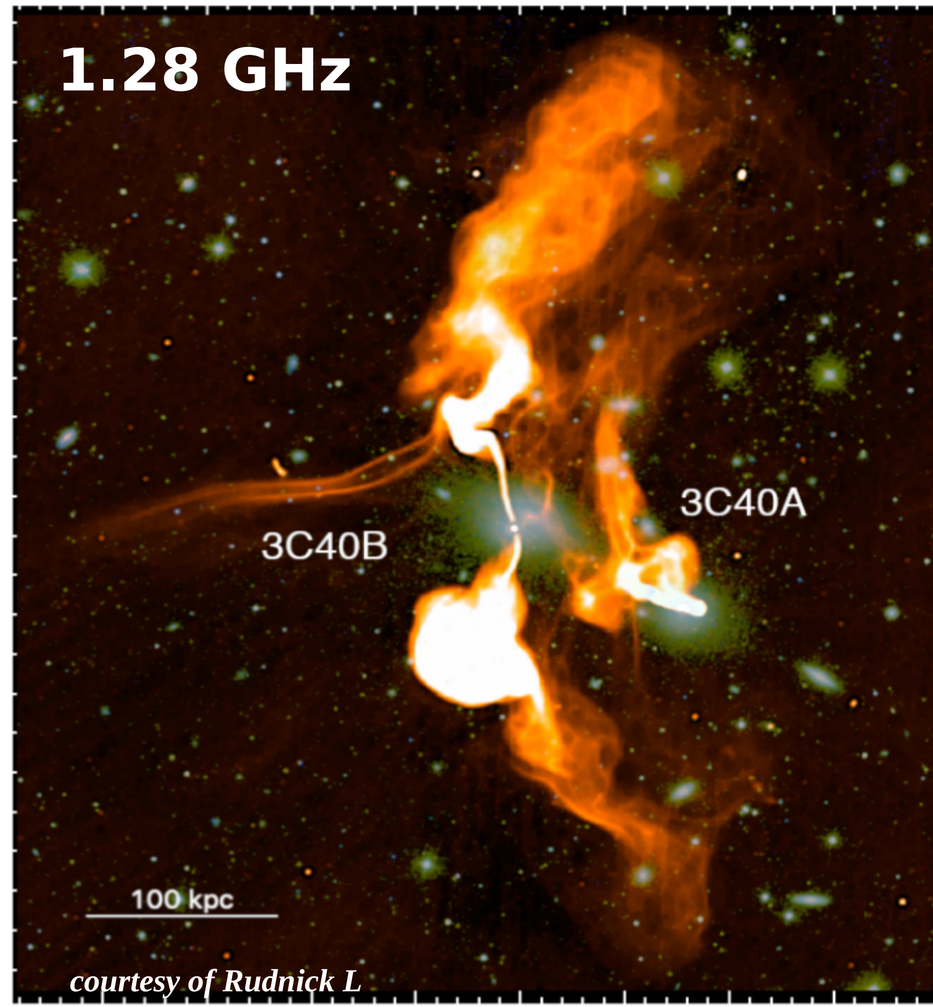
ML was also used as a tool for anomaly detection (Astronomaly; Lochner et al 2021), a general anomaly detection framework which can operate on most types of astronomical data, including images, light curves and spectra.

MGCLS + Machine Learning

Radio AGN variety



Complex AGN filaments

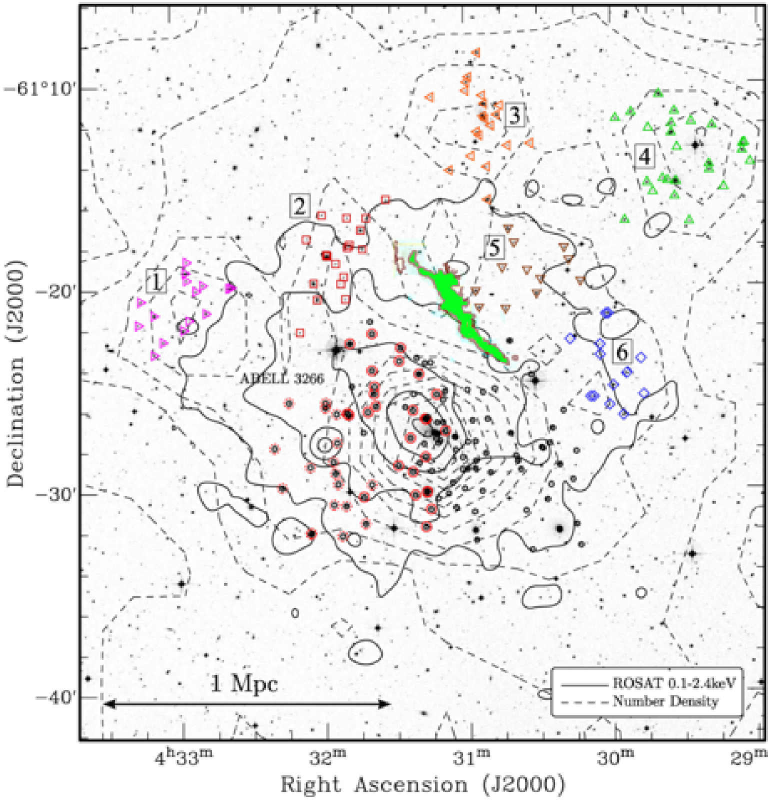


Newly revealed filamentary structures in Abell 194, cannot be explained with any current radio galaxy models as such very large-scale features are not seen in numerical simulations of radio galaxies, nor were predicted

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

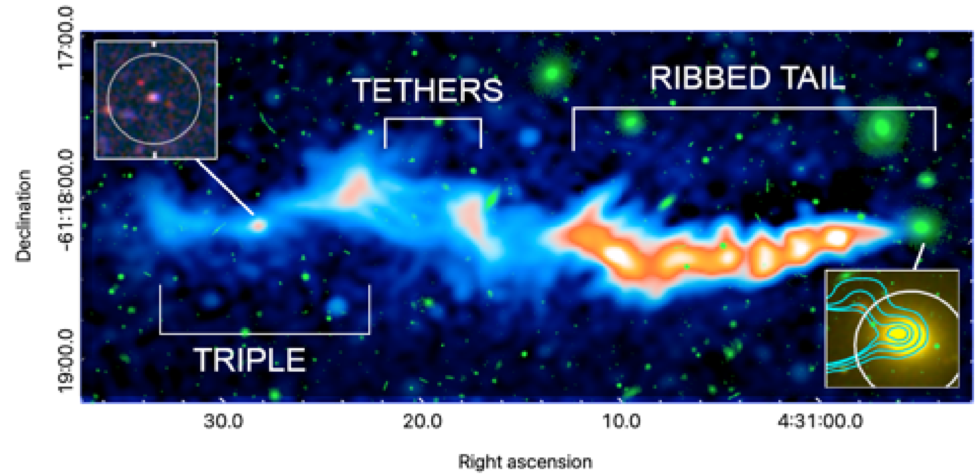
MGCLS: Case of a Mysterious radio galaxy tail in Abell 3266

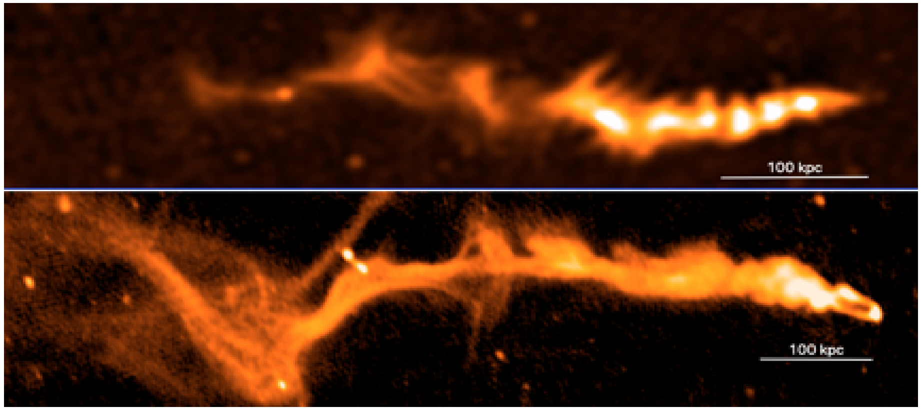
Ribs and tethers



Tethers and perhaps the ribs, likely belong to the newly emerging examples __of thin magnetized threads linking larger regions of relativistic plasma__ (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

MGCLS + Machine Learning

These results provide motivation for the application of such techniques to radio astronomy as well

ML techniques in handling large data sets by using DNNs were used to classify images of extended radio galaxies (FRI or FRII) using archival data from FIRST radio survey to train as well as test a CNN (Aniyan & Thorat 2017)

Challenges are there 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 II. Take away points

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

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 mild correlation between 1.4 GHz radio power & M500 cluster mass for the first time!

iii) Follow-up of MGCLS survey paper I (Knowles et al. 2022) is the catalog MGCLS diffuse emission paper II, (Kolokythas et al. in prep. 2024) that offers the basis to test and implement ML algorithms for extended radio sources classifications

iv) Collaboration between Rhodes University, SARAO and SWISS using the MGCLS products for co-supervision of Honours projects/students under the Radio Clusters project