Diffuse radio emission in the galaxy cluster RX J1347.5—1145:

Discovery of large-scale radio emission enveloping the mini-halo

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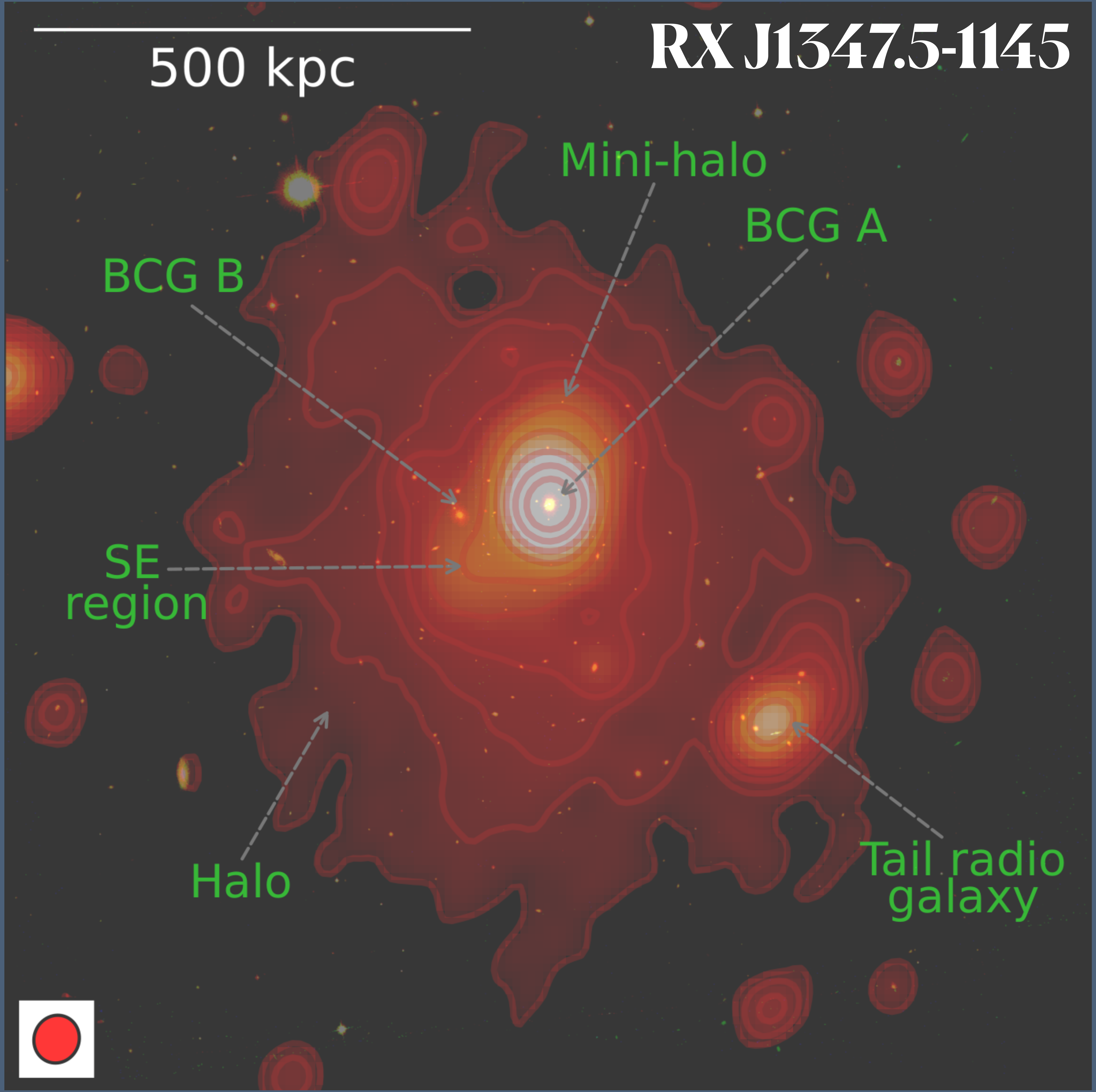

RX J1347.5-1145
500 kpc
Mini-halo
BCG A
BCG B
SE region
Halo
Tail radio galaxy

Galaxy clusters

★ Large-scale structure of the Universe:

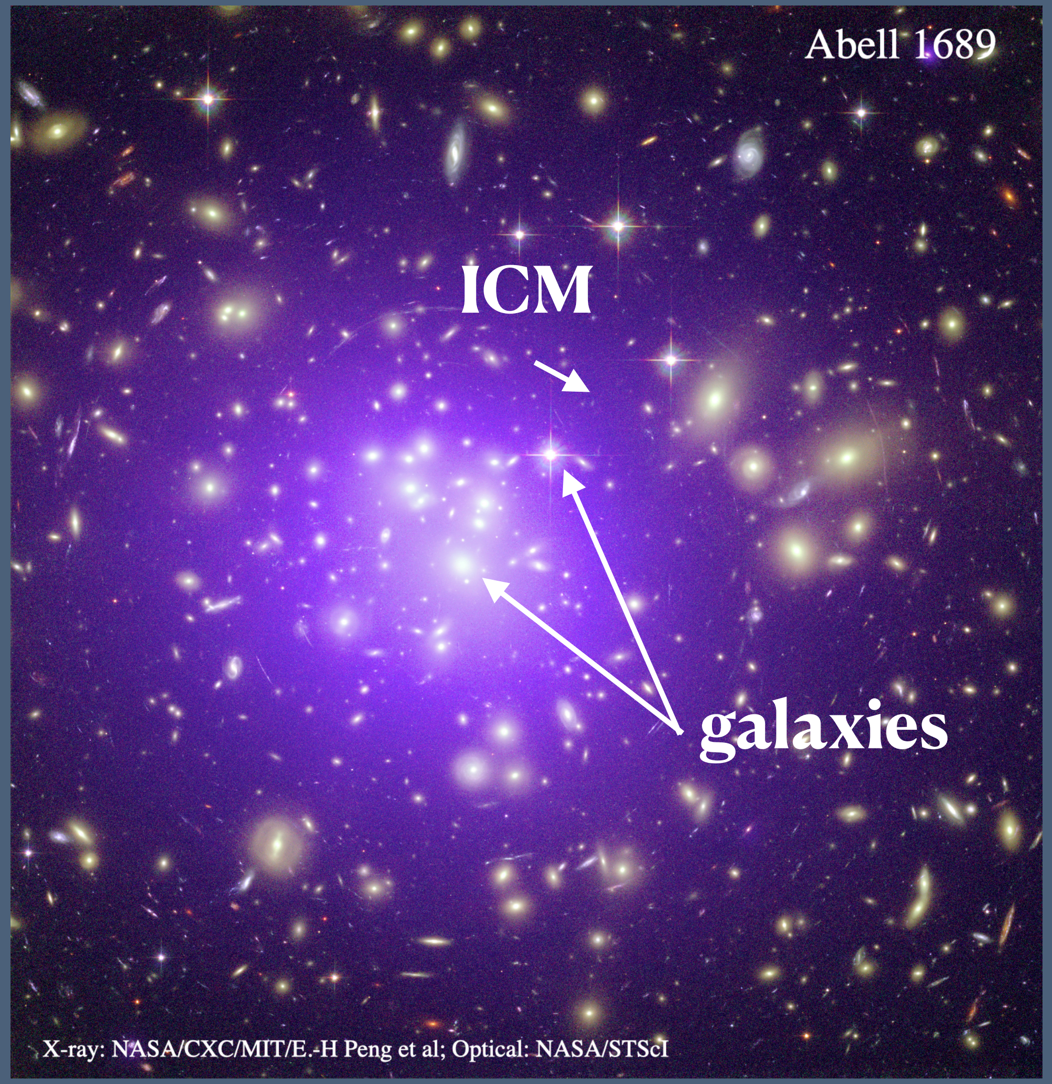
- filaments, nodes & voids

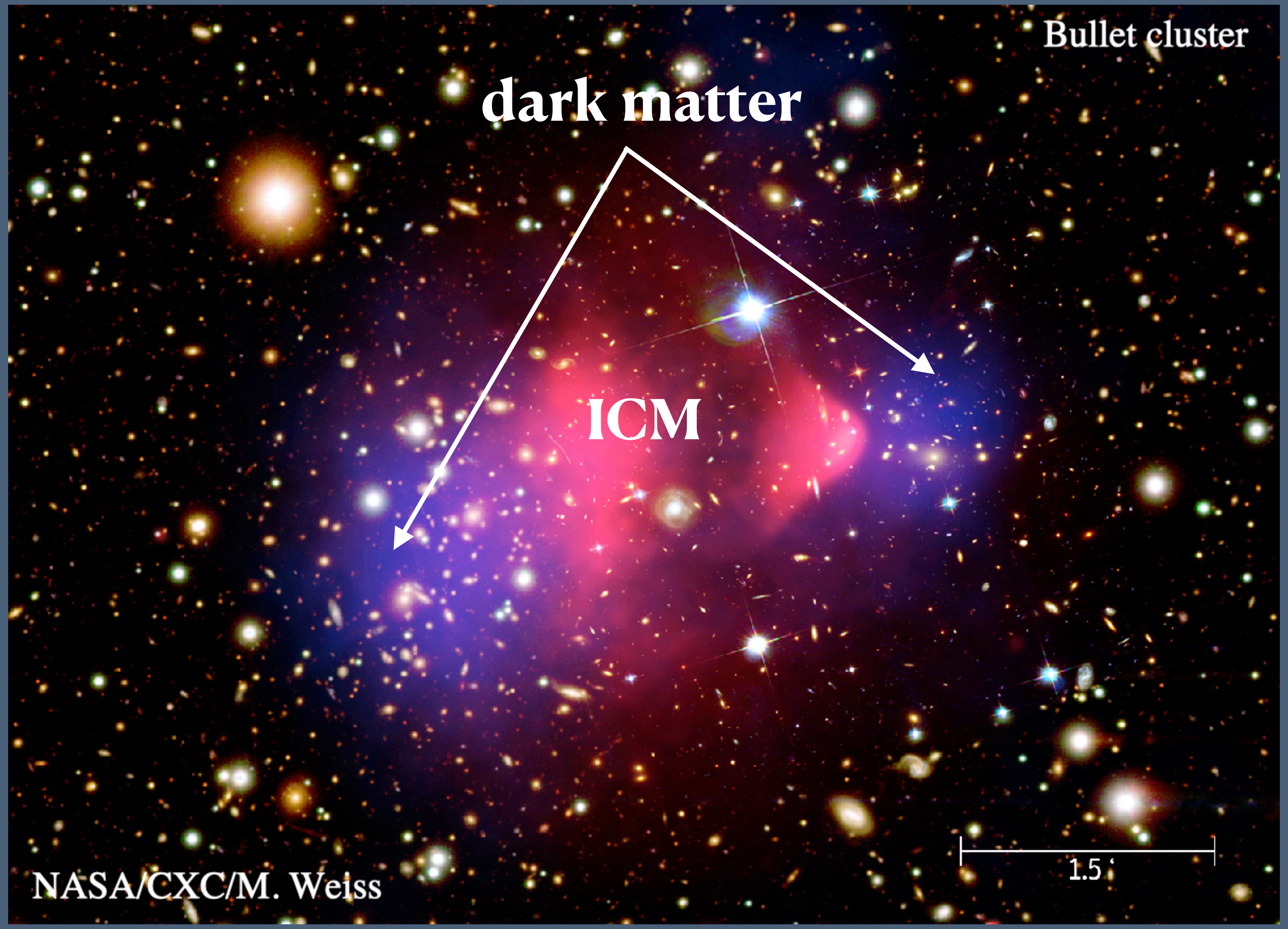
★ Galaxy clusters:

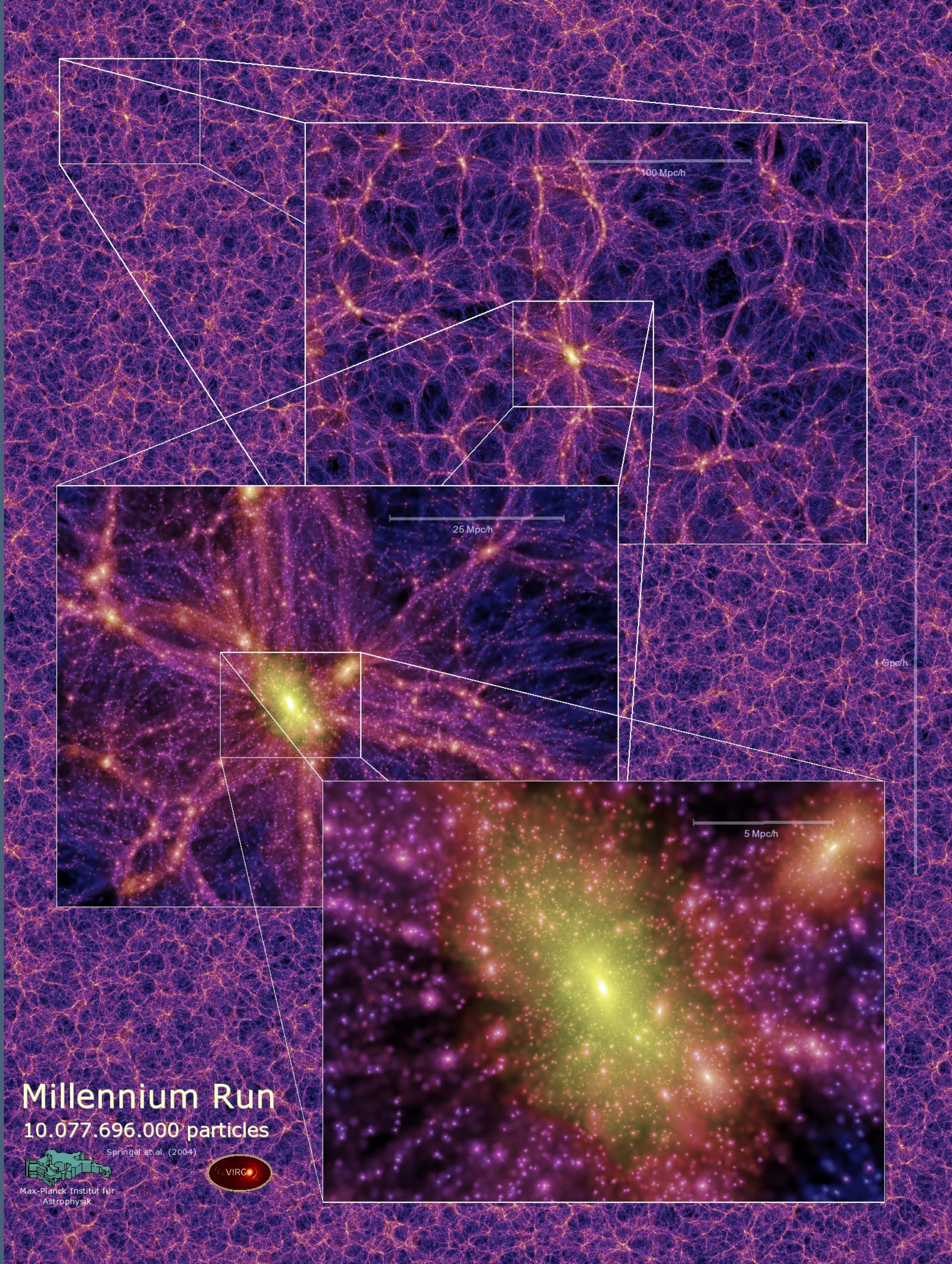
- consist of 100s to 1000s galaxies gravitationally bounded
- located at the nodes of the cosmic web

★ Total mass (~$10^{13} - 10^{15}$ solar mass):

- galaxies (5 %)
- intra-cluster medium (ICM, 15 %)
- dark matter (80 %)







Intra-cluster medium

★ Thermal particles

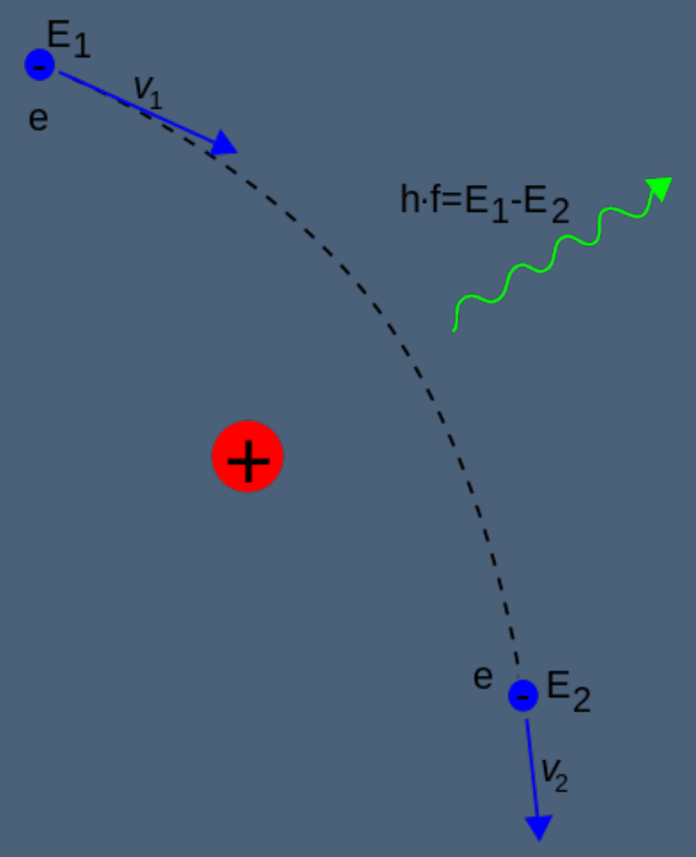
- electrons, protons, helium…
- low particle density: ~ 1000 particles/m3
- high temperature: $\sim (10 - 100) \times 10^6$ K

—> emitting X-rays via free-free (bremsstrahlung) mechanism

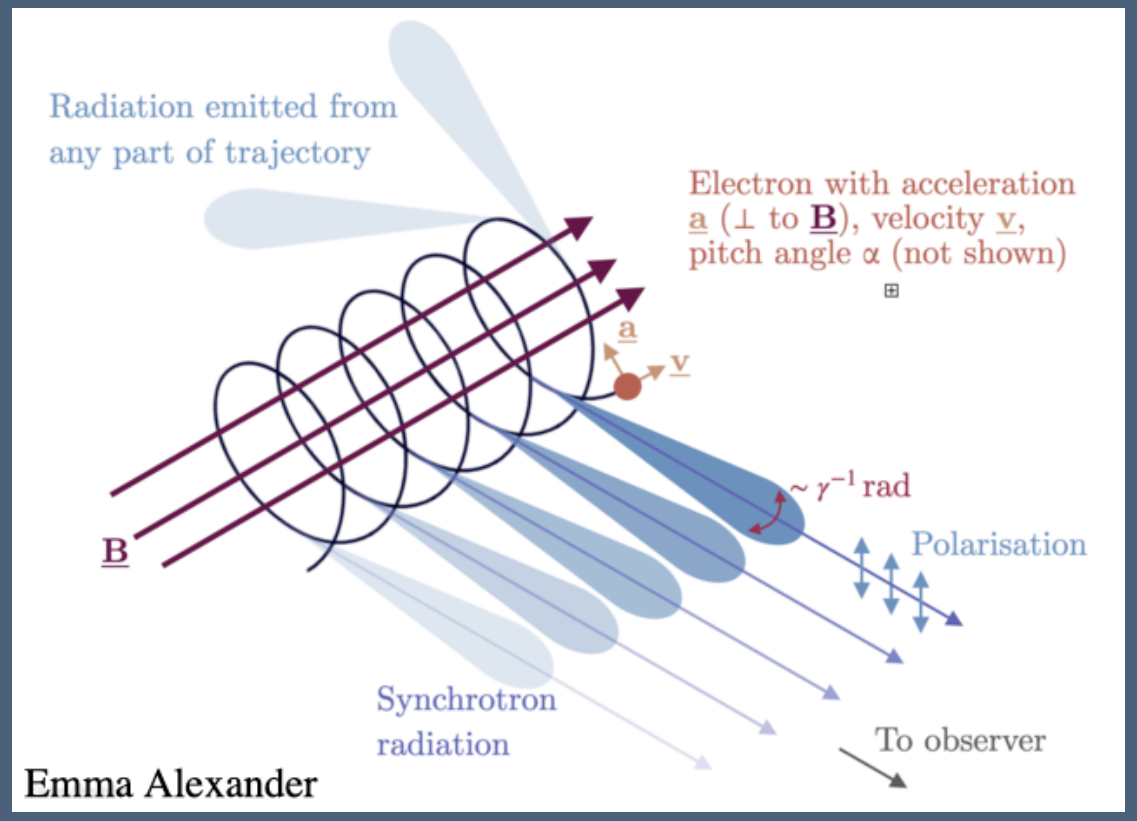
★ Non-thermal components

- cosmic ray electrons ($\gamma > 1000 - 5000$), protons.
- magnetic fields ($B = \sim \mu Gauss$)

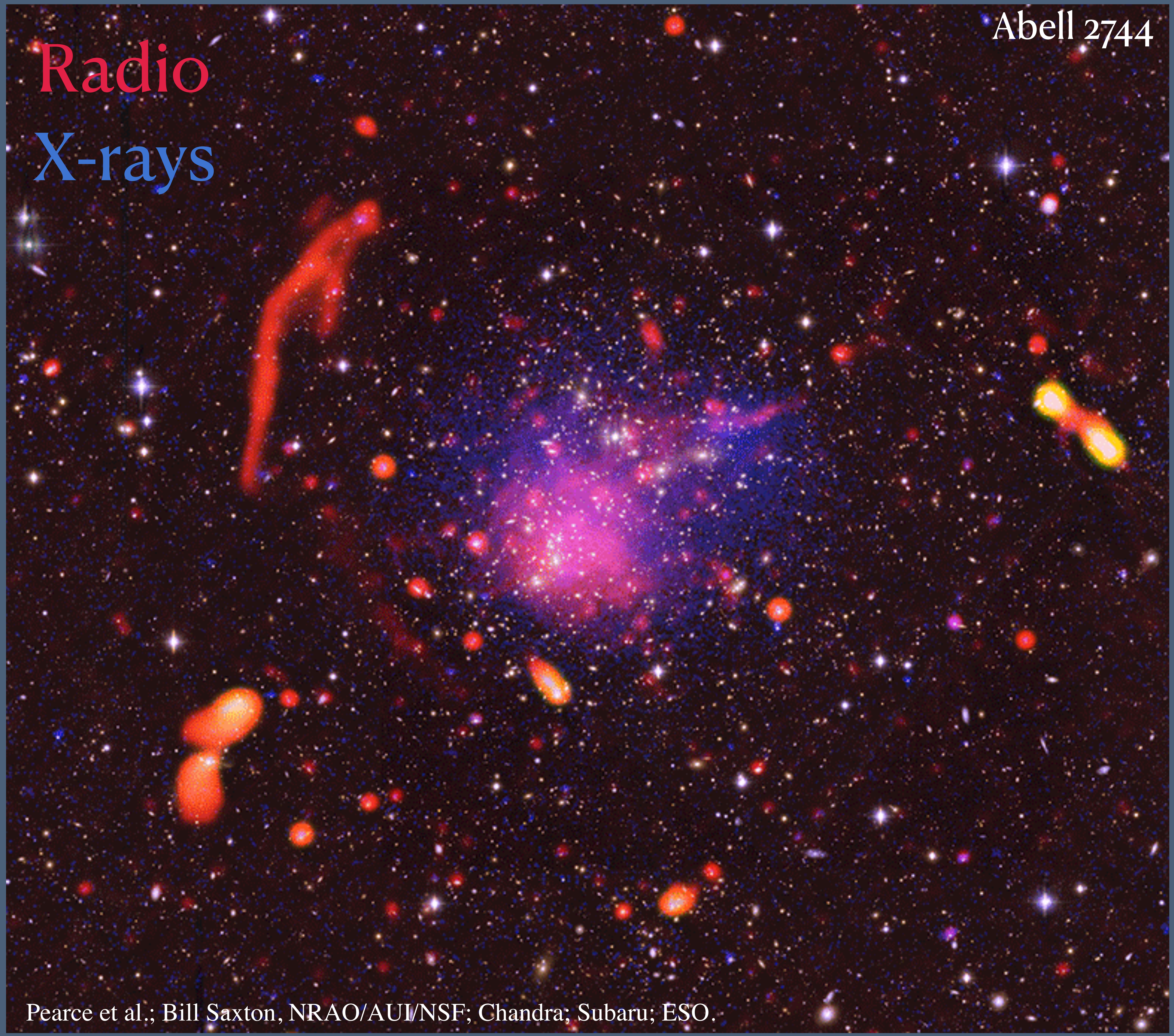
—> emitting radio emission via synchrotron mechanism



Free-free (bremsstrahlung) emission
(distribution of thermal particles)

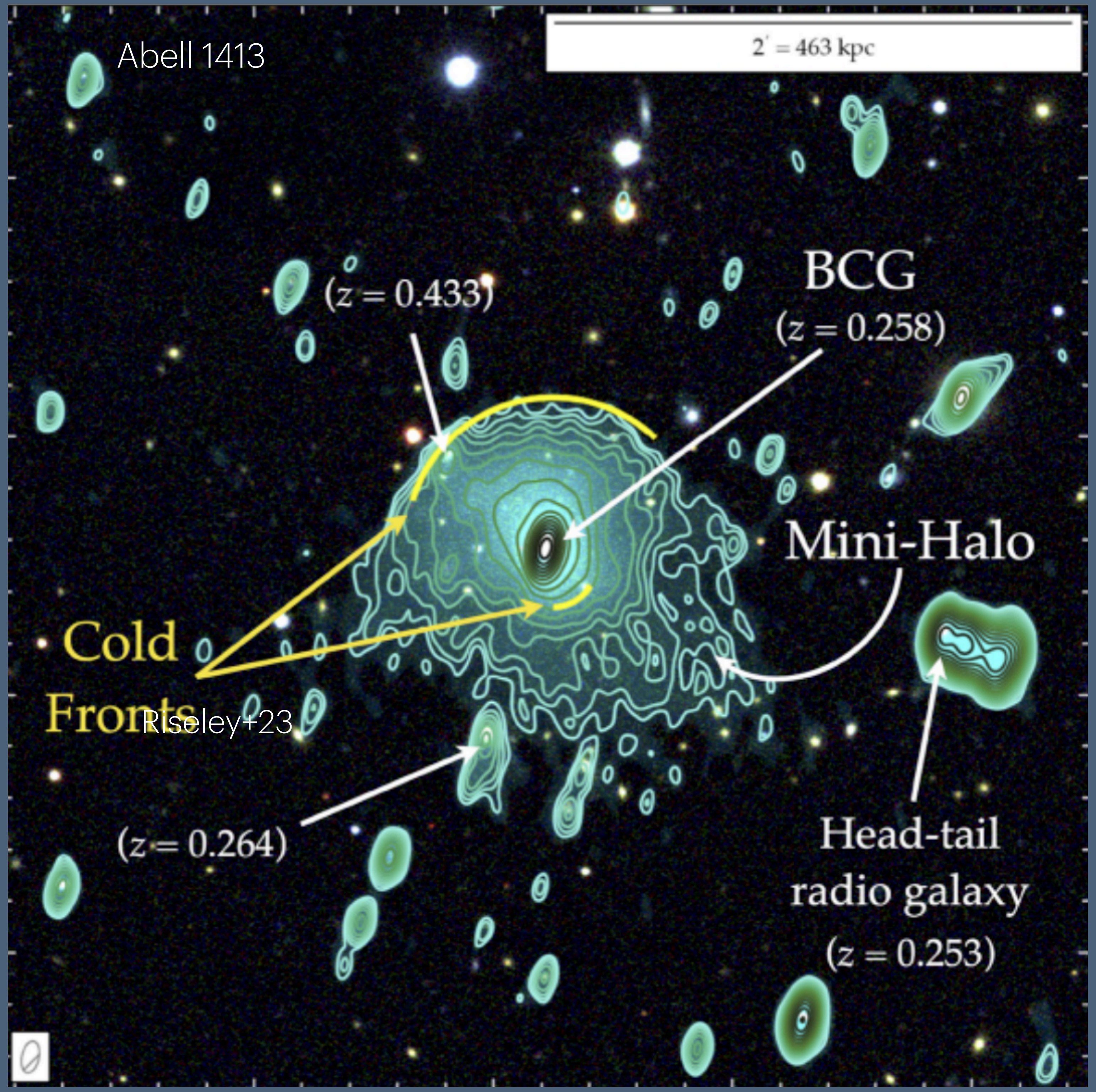


Synchrotron emission
(distribution of B and CRe)



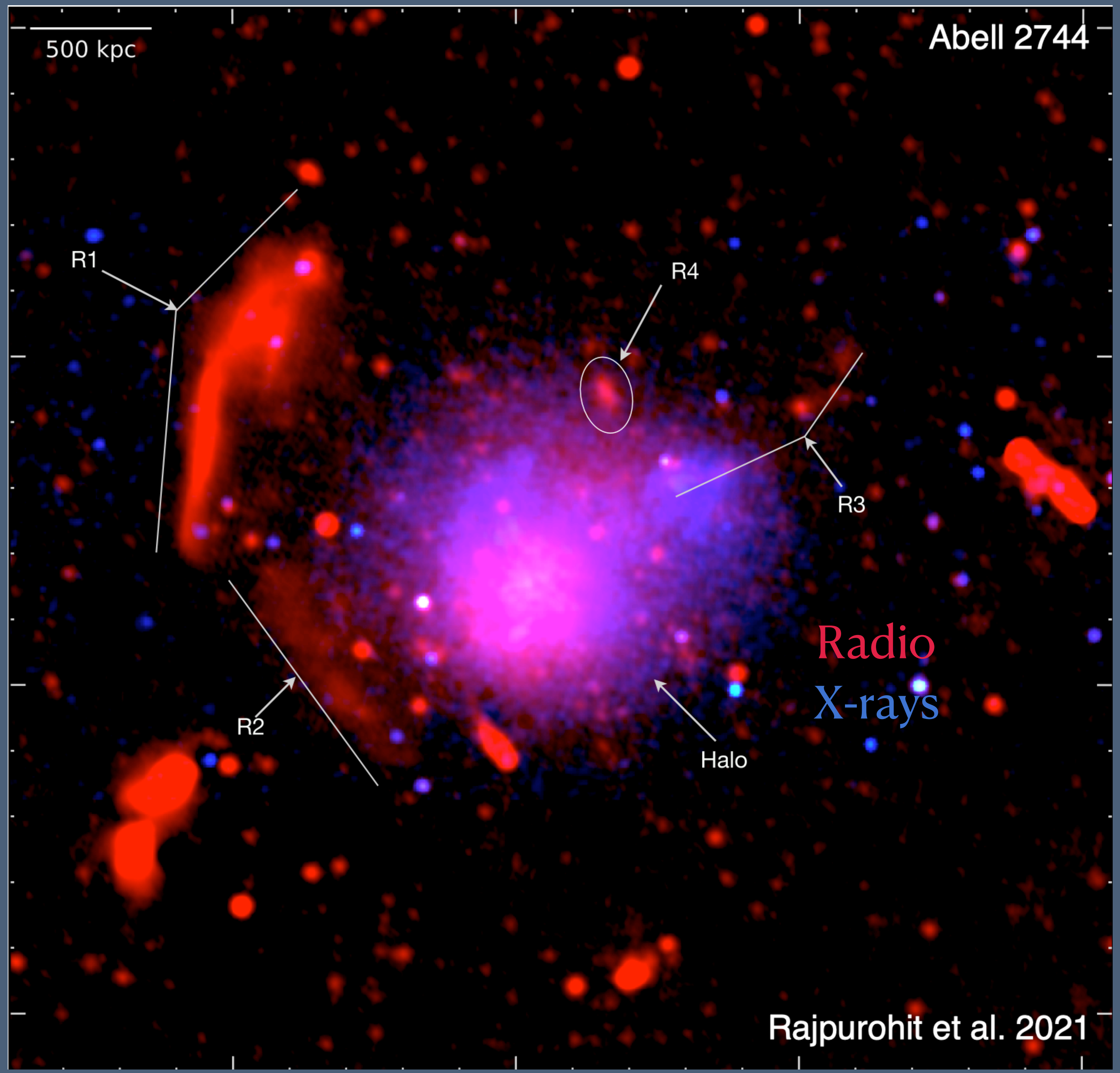
Central diffuse radio emission

Mini-halo



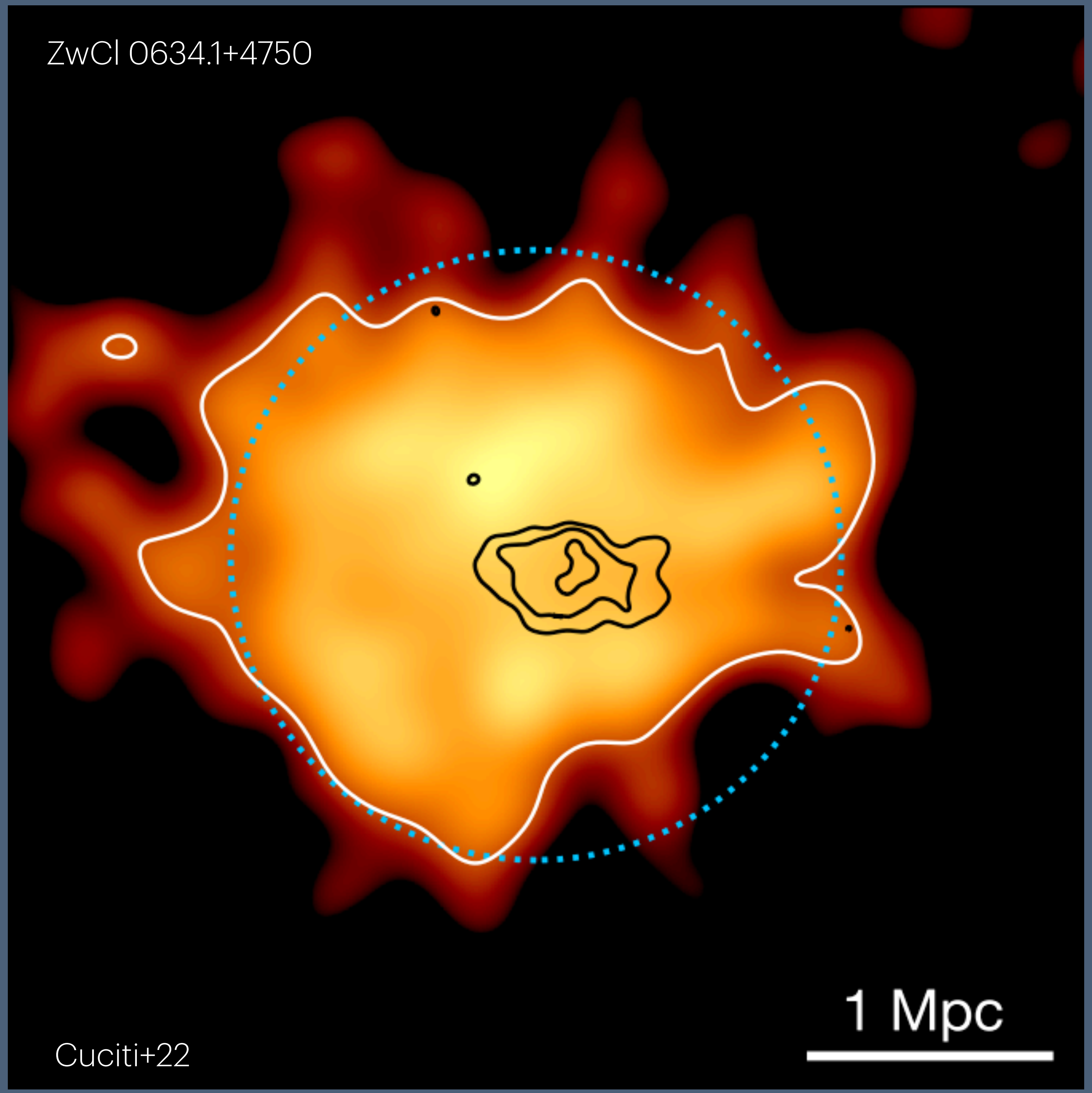
- Size of ~500 kpc
- Typically observed in relax, cool-core clusters
- Unpolarised radio emission
- Steep spectrum ($\alpha \lesssim -1$)

Halo



- Size of ~Mpc
- Typically observed in merging galaxy clusters
- Unpolarised radio emission
- Steep spectrum ($\alpha \lesssim -1$)

Mega-halo



- Size of >2 Mpc
- Found together with halo hosted galaxy clusters
- Unknown polarisation
- More steep spectrum ($\alpha \lesssim -1.3$)

Central diffuse radio emission vs. cluster dynamical states

- Radio halos are often found in disturbed clusters of galaxies.
- Mini-halos are typically observed in relaxed galaxy clusters.

Morphological parameters:

- c: concentration
- w: centroid shift
- P_3/P_0: Power ratio

Radial surface brightness profile

- Radial SB of mini-halo and halos known to follow a single-component exponential function:

$$I(r) = I_0 \exp(-r/r_e)$$

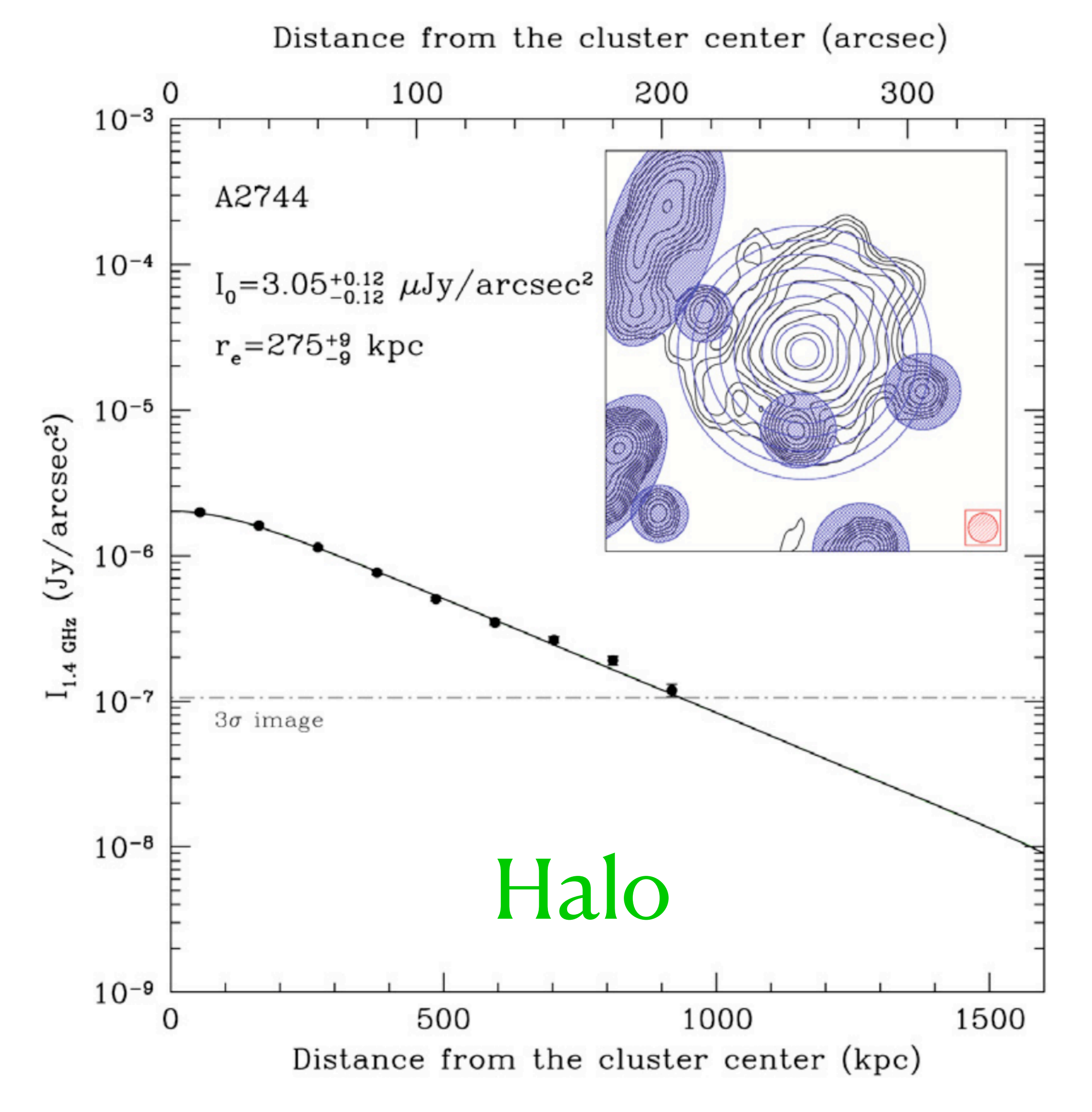
- Peak brightness: $I_0^{MH} >> I_0^{H}$ (up to 2 orders of magnitude)

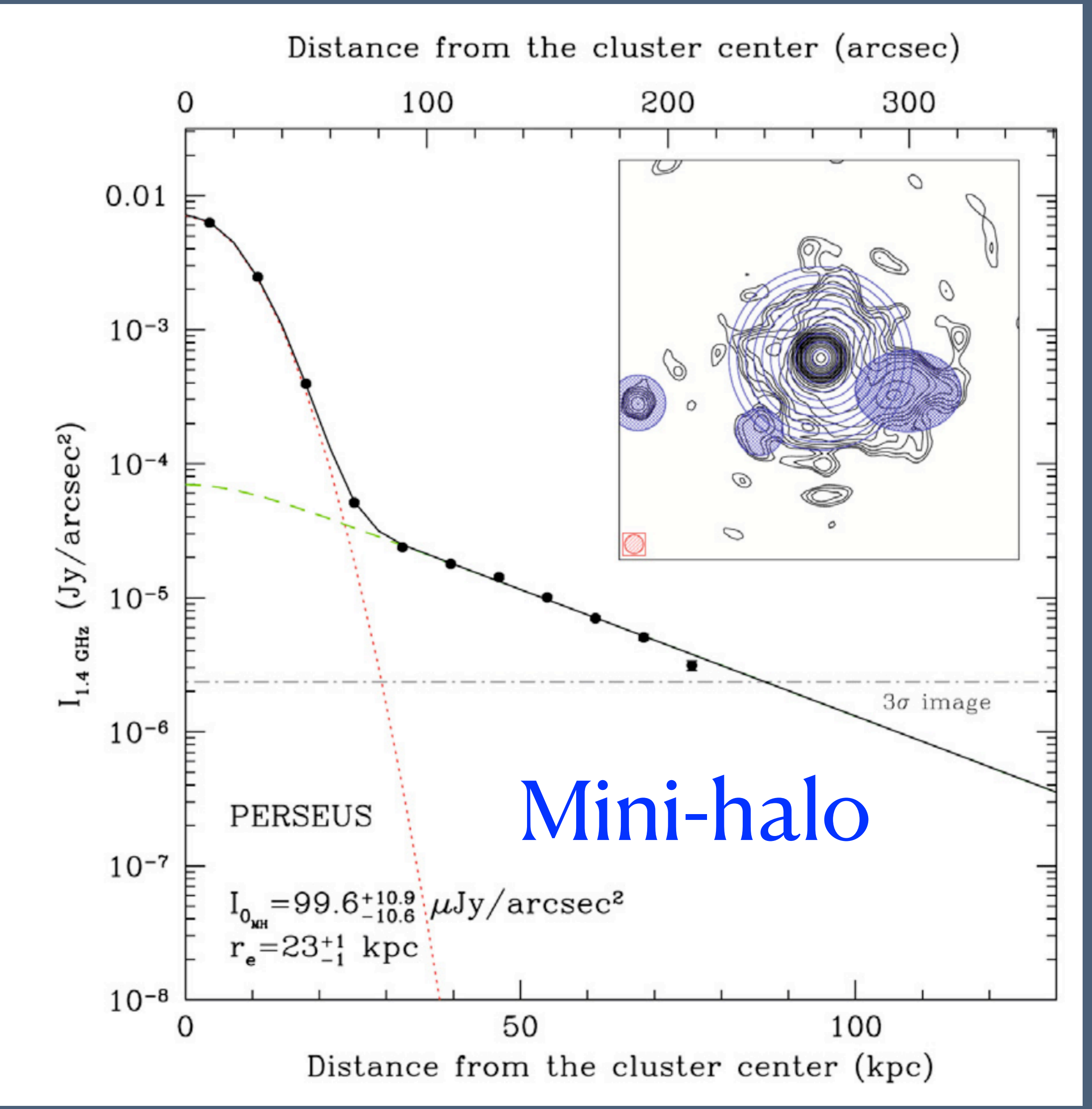
- Emissivity: $\langle J_{MH} \rangle >> \langle J_{MH} \rangle$ (up to 3 orders of magnitude)

Table 3. Radio information of halos and mini halos taken from the literature and reanalyzed in this work with the exponential model fit.

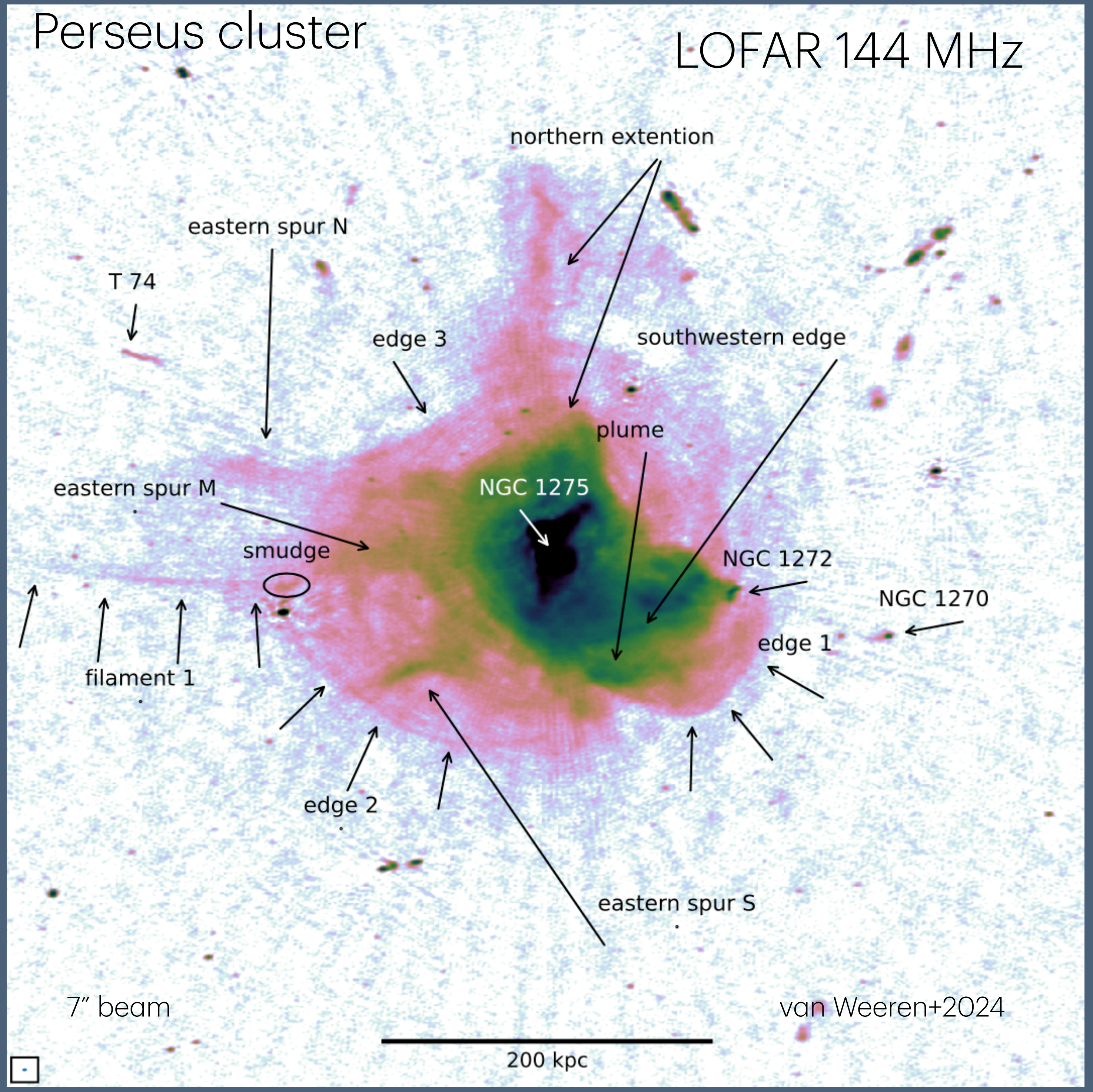
Cluster	Type	Reference	z	kpc/″	*FWHM* arcsec	I_0 μJy/arcsec^2	r_e arcsec	r_e kpc	$\langle J \rangle$ erg s^{-1} Hz^{-1} cm^{-3}	χ^2_{RED}
A2744	H	Govoni et al. (2001a)	0.3080	4.50	50	$3.05^{+0.12}_{-0.12}$	61^{+2}_{-2}	275^{+9}_{-9}	$2.5^{+0.17}_{-0.16} \times 10^{-42}$	1.5
A665	H	Giovannini Feretti (2000)	0.1819	3.03	53	$1.09^{+0.08}_{-0.08}$	78^{+6}_{-5}	236^{+18}_{-15}	$7.0^{+1.0}_{-1.0} \times 10^{-43}$	0.9
A2219	H	Bacchi et al. (2003)	0.2256	3.59	53	$1.10^{+0.08}_{-0.08}$	100^{+5}_{-4}	359^{+18}_{-14}	$5.4^{+0.6}_{-0.6} \times 10^{-43}$	3.7
A2255	H	Govoni et al. (2005)	0.0806	1.50	25	$0.65^{+0.02}_{-0.02}$	135^{+4}_{-4}	203^{+6}_{-6}	$3.4^{+0.20}_{-0.19} \times 10^{-43}$	4.8
A773	H	Govoni et al. (2001a)	0.2170	3.48	30	$0.75^{+0.07}_{-0.07}$	32^{+3}_{-3}	111^{+10}_{-10}	$1.1^{+0.24}_{-0.2} \times 10^{-42}$	0.7
A545	H	Bacchi et al. (2003)	0.1540	2.64	45	$1.31^{+0.15}_{-0.13}$	57^{+4}_{-4}	150^{+11}_{-11}	$1.2^{+0.22}_{-0.19} \times 10^{-42}$	0.6
A2319	H	Feretti et al. (1997)	0.0557	1.07	30	$1.11^{+0.04}_{-0.04}$	185^{+7}_{-6}	198^{+7}_{-6}	$5.4^{+0.35}_{-0.36} \times 10^{-43}$	2.4
A2218	H	Giovannini Feretti (2000)	0.1756	2.94	35	$1.06^{+0.34}_{-0.27}$	26^{+9}_{-6}	76^{+26}_{-18}	$2.0^{+1.4}_{-0.9} \times 10^{-42}$	1.0
A2163	H	Feretti et al. (2001)	0.2030	3.31	62	$2.23^{+0.07}_{-0.07}$	119^{+2}_{-2}	394^{+7}_{-7}	$9.2^{+0.4}_{-0.4} \times 10^{-43}$	2.1
A401	H	Bacchi et al. (2003)	0.0737	1.38	45	$0.44^{+0.06}_{-0.05}$	79^{+15}_{-11}	109^{+21}_{-15}	$4.1^{+1.3}_{-1.0} \times 10^{-43}$	0.7
A2254	H	Govoni et al. (2001a)	0.1780	2.98	45	$1.56^{+0.22}_{-0.20}$	80^{+19}_{-13}	238^{+57}_{-39}	$9.7^{+3.4}_{-2.8} \times 10^{-43}$	1.1
RXJ1314	H	Feretti et al. (2005)	0.2439	3.81	45	$1.05^{+0.31}_{-0.25}$	42^{+16}_{-10}	160^{+61}_{-38}	$1.2^{+0.8}_{-0.5} \times 10^{-42}$	0.1
RXJ1347	MH	Gitti et al. (2007)	0.4510	5.74	18	$26.0^{+40.7}_{-15.4}$	9^{+3}_{-2}	52^{+17}_{-11}	$1.8^{+0.7}_{-0.5} \times 10^{-40}$	0.2
A2390	MH	Bacchi et al. (2003)	0.2280	3.62	20	$60.8^{+27.0}_{-21.1}$	10^{+1}_{-1}	36^{+4}_{-4}	$3.1^{+1.0}_{-0.8} \times 10^{-40}$	1.2
Perseus	MH	Pedlar et al. (1990)	0.0179	0.36	45	$99.6^{+10.9}_{-10.6}$	64^{+4}_{-3}	23^{+1}_{-1}	$3.6^{+0.5}_{-0.5} \times 10^{-40}$	2.4

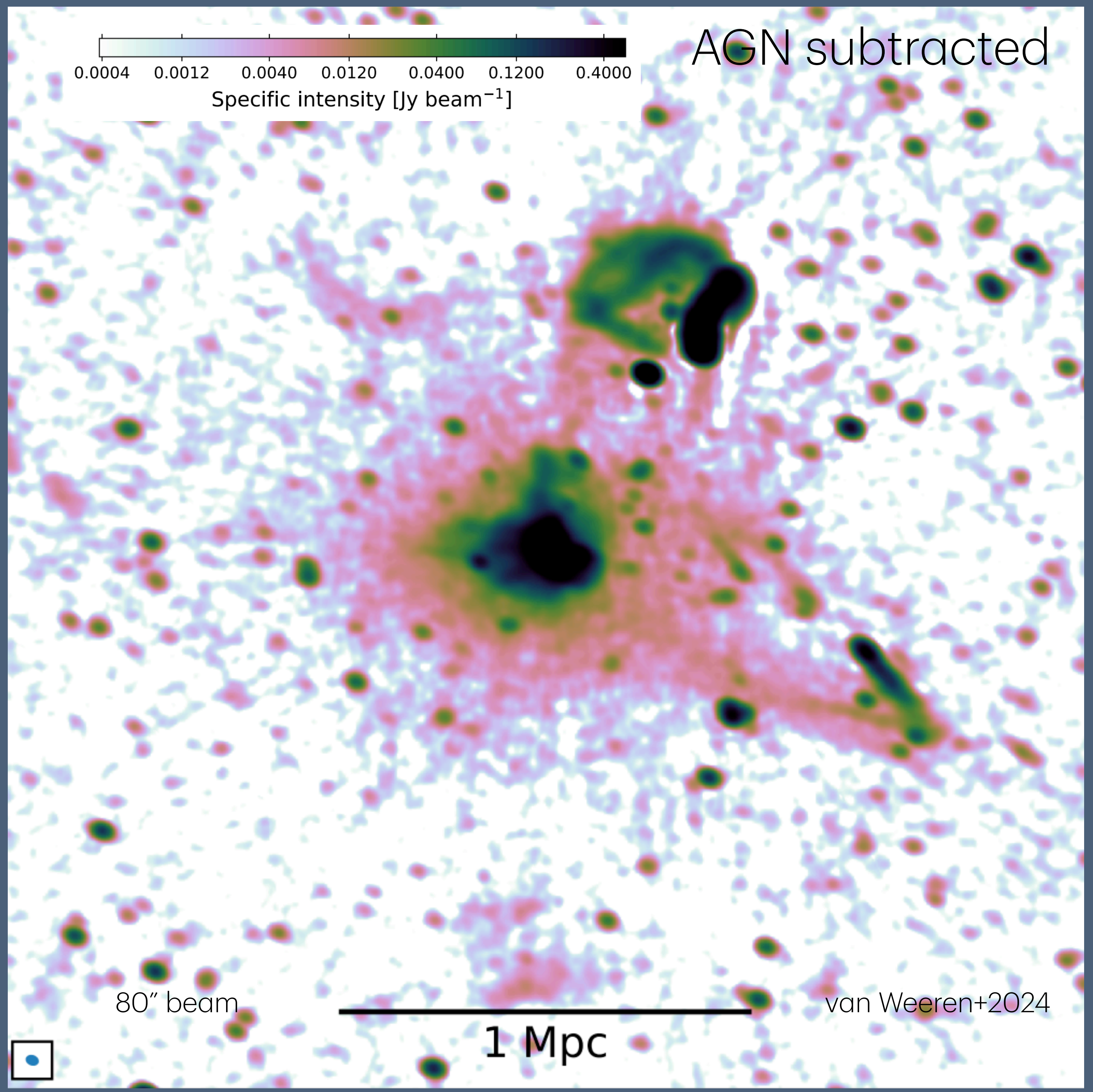
Column 2: type of diffuse emission contained (H = halo, MH = mini halo); Col. 6: *FWHM* of the circular Gaussian beam; Col. 10: average radio emissivity over the volume of a sphere of radius $3r_e$, k-corrected with $\alpha = 1$.

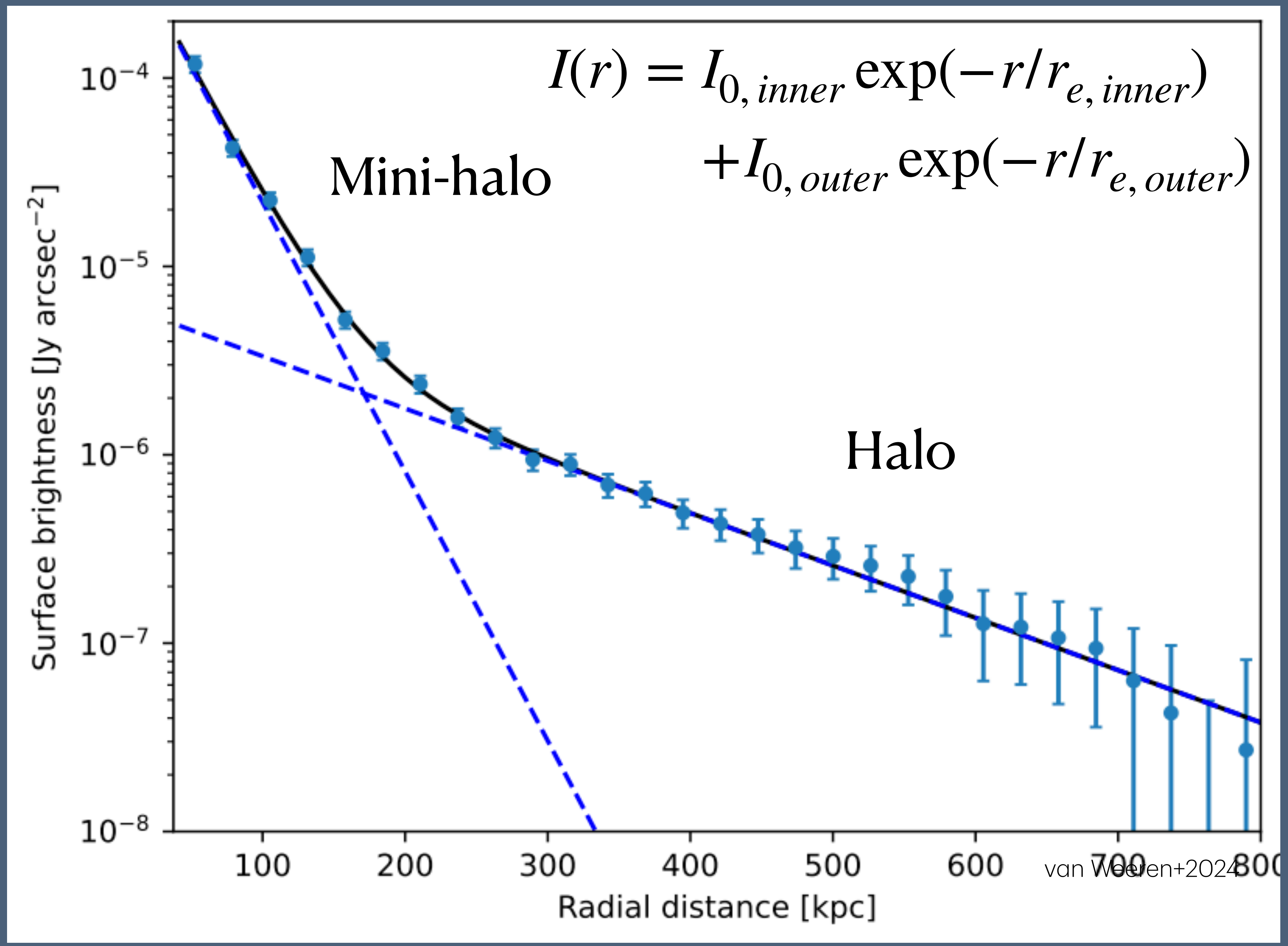




Double-component diffuse emission: Halo + Mini-halo

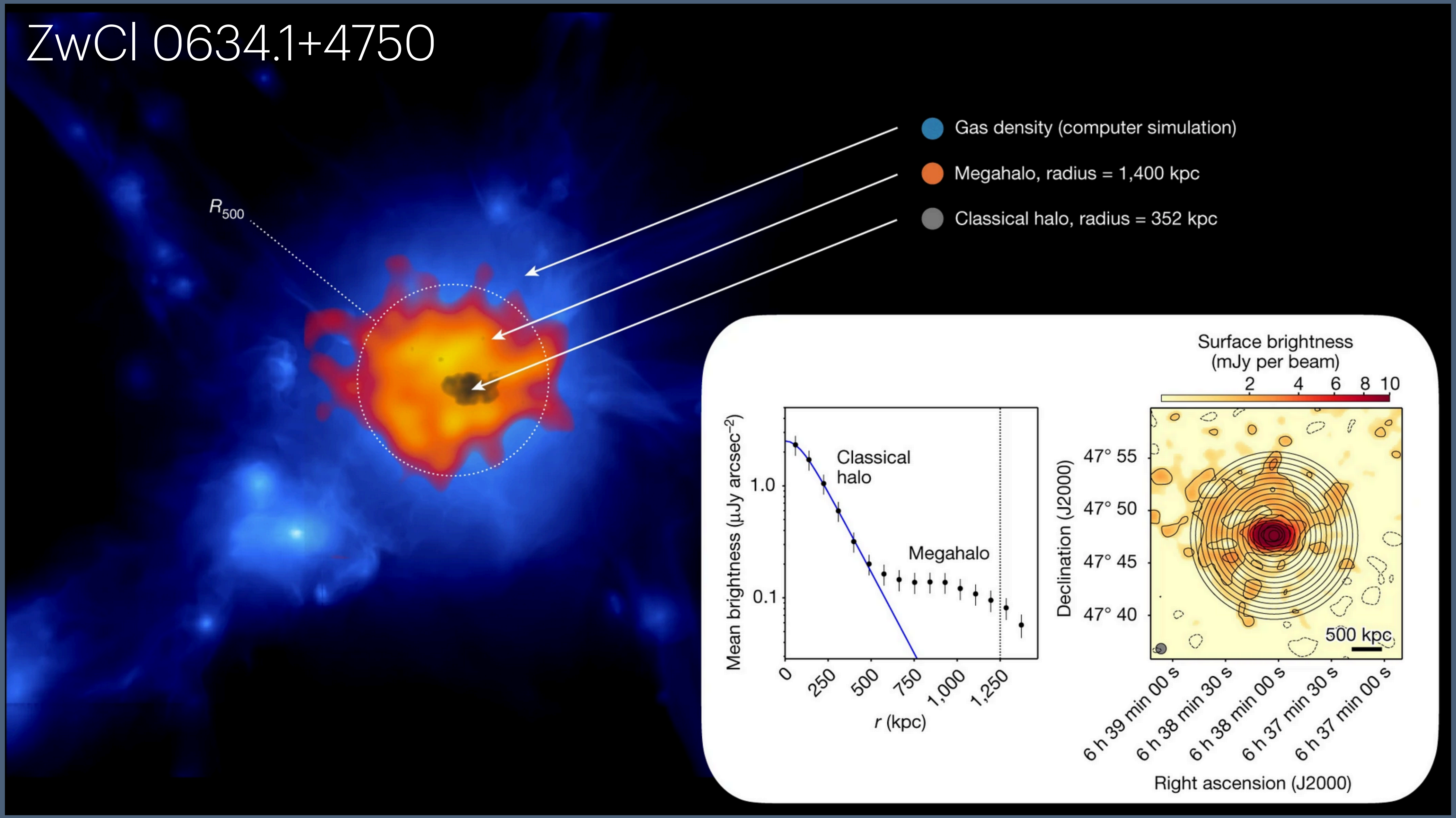






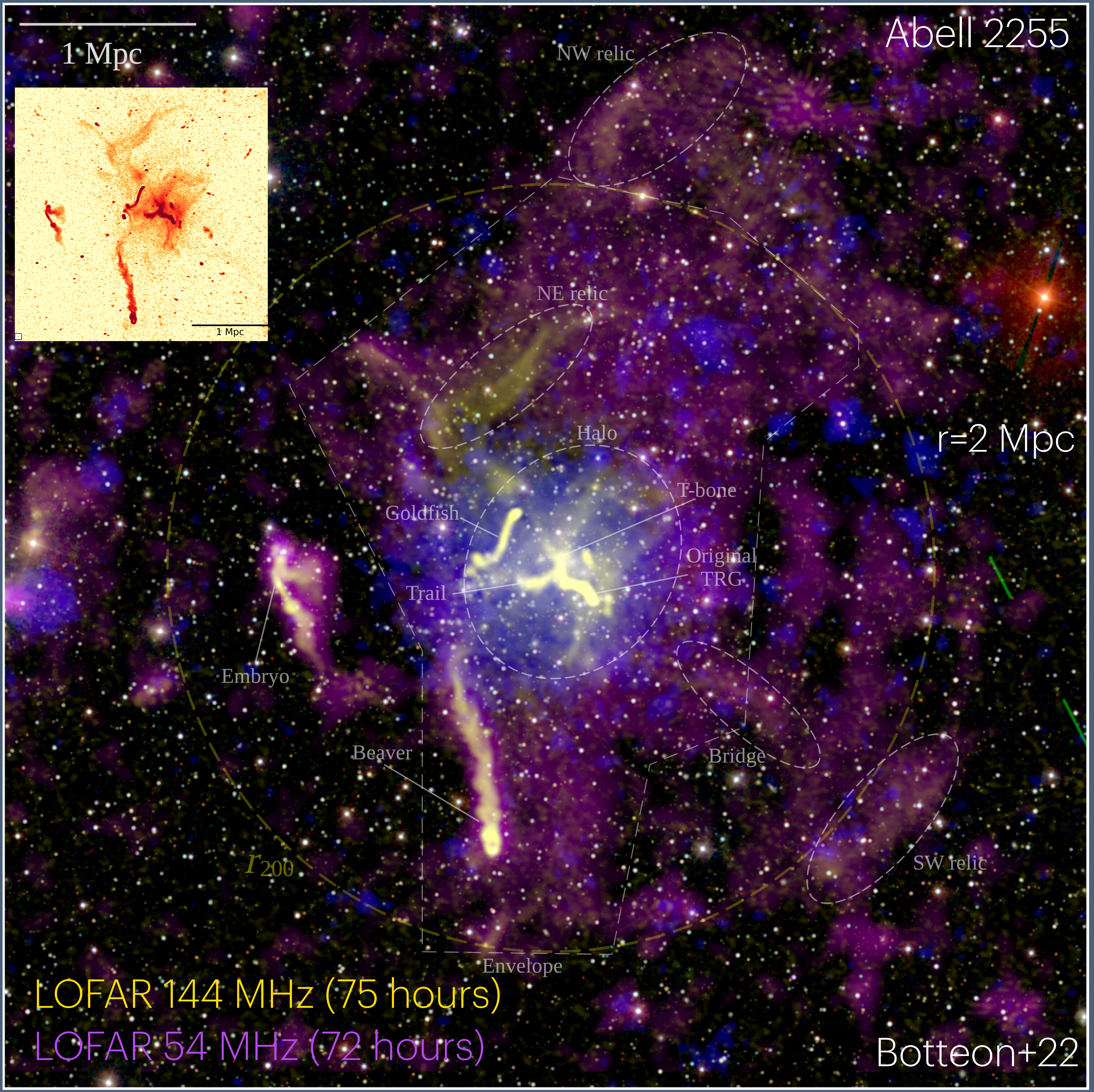
- LOFAR observations of the Perseus cluster indicate double-component (mini-halo + halo) diffuse radio emission (van Weeren+24).
- Also a few other cases reported in Savini+19, Lusetti+23, Biava+24.

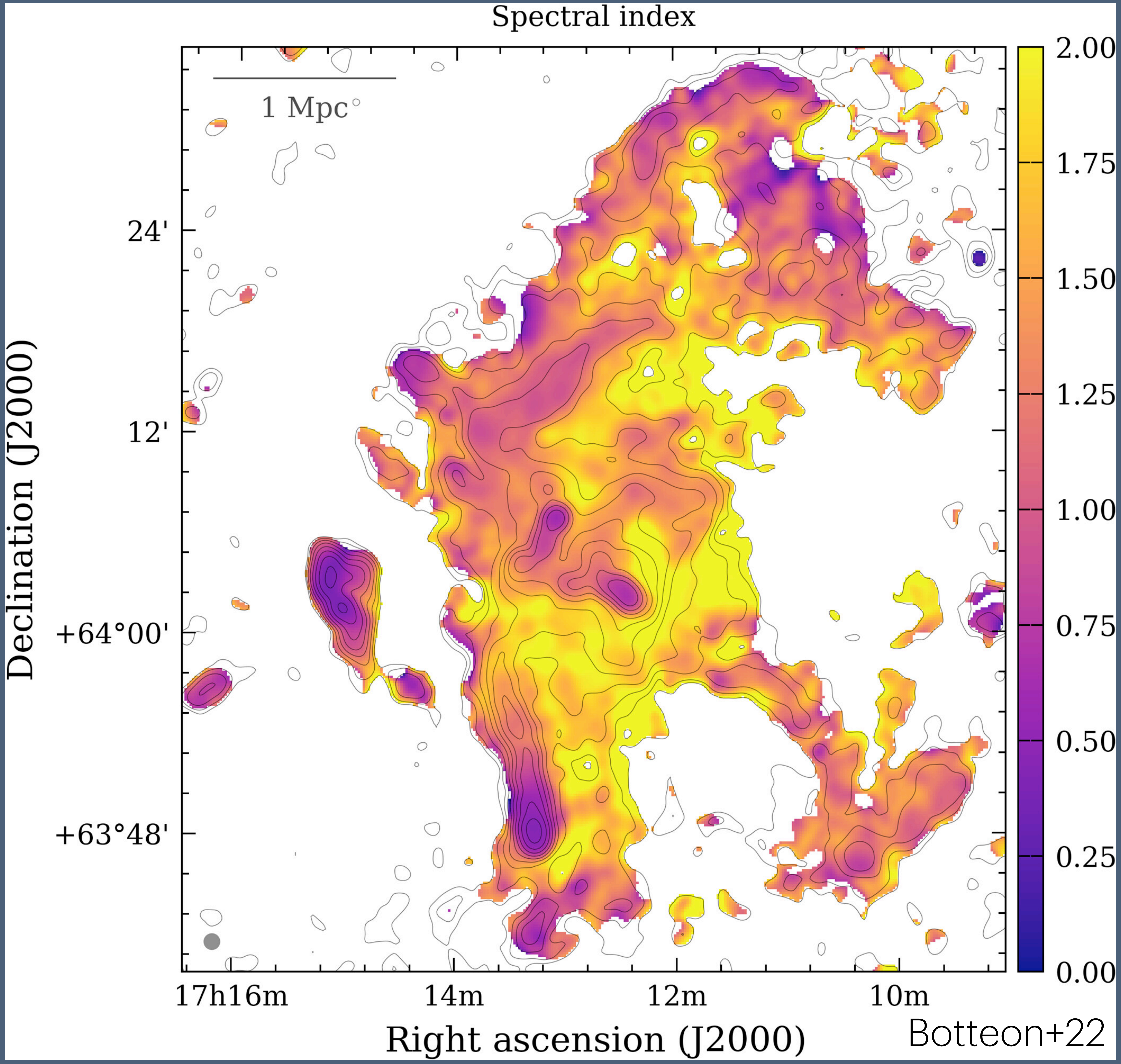
Double-component diffuse emission: Halo + Mega-halo



- 4 mega-halos in galaxy clusters known to host regular radio halos (Cuciti+22).
- Filling volume: ~30 times larger (than halos)
- Emissivity: ~20 times dimmer
- Steep spectrum in the mega-halos: $\alpha \lesssim -1.3$ (low stat.)

Double-component diffuse emission: Halo + Mega-halo (cont.)

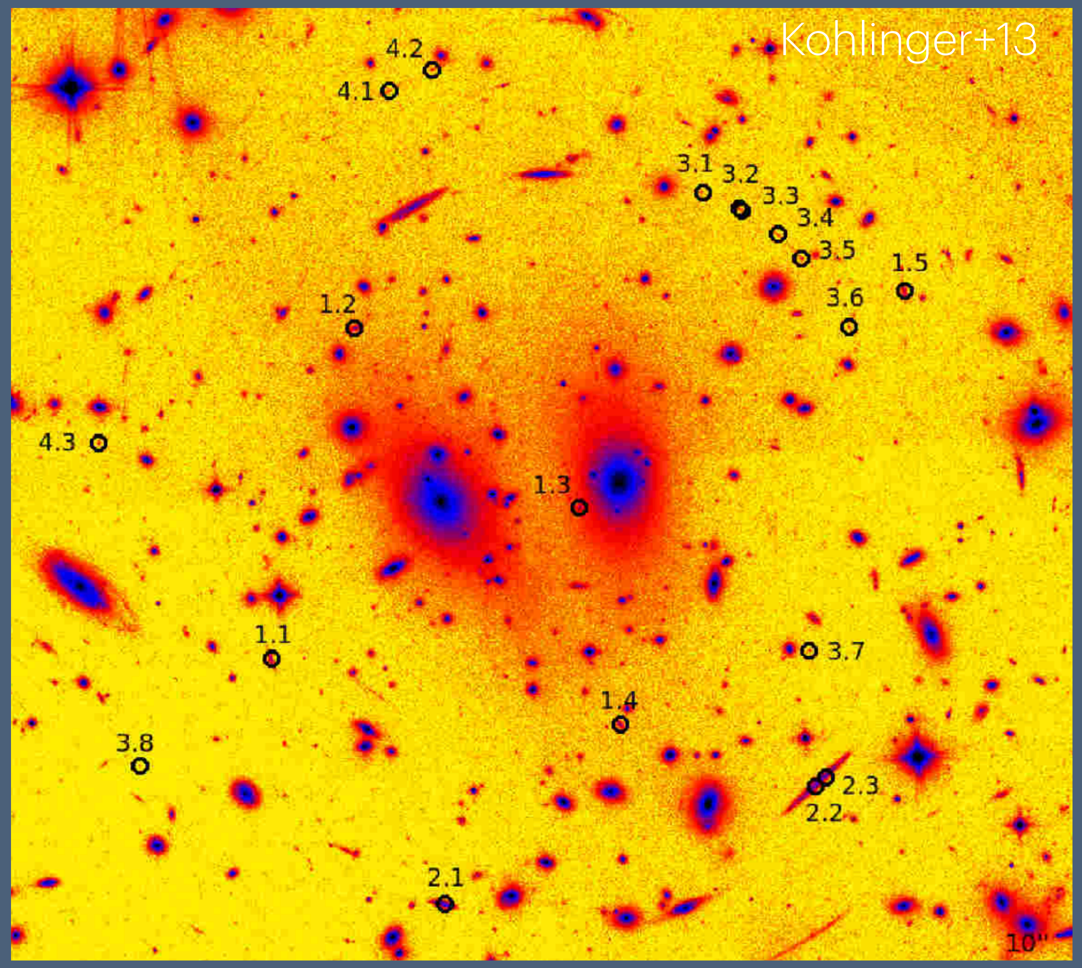




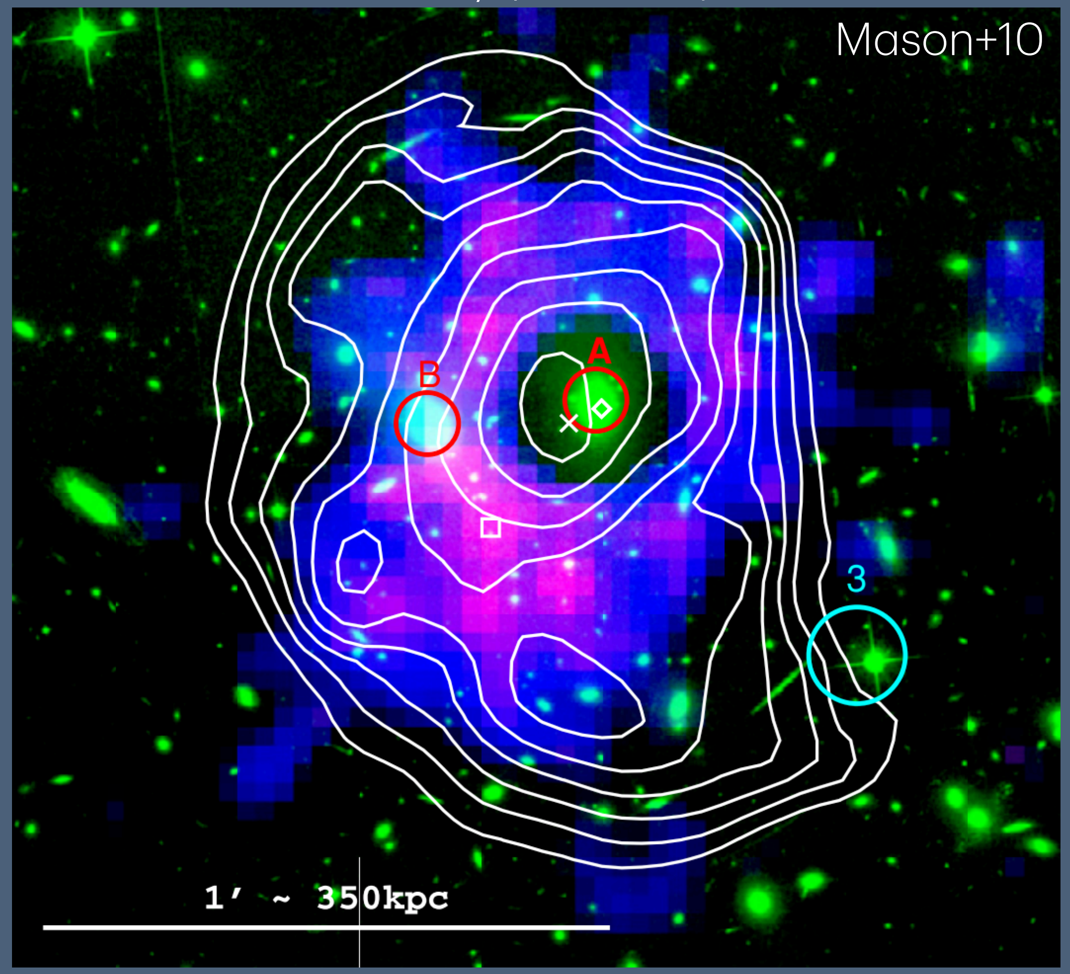
The target: RX J1347.51145

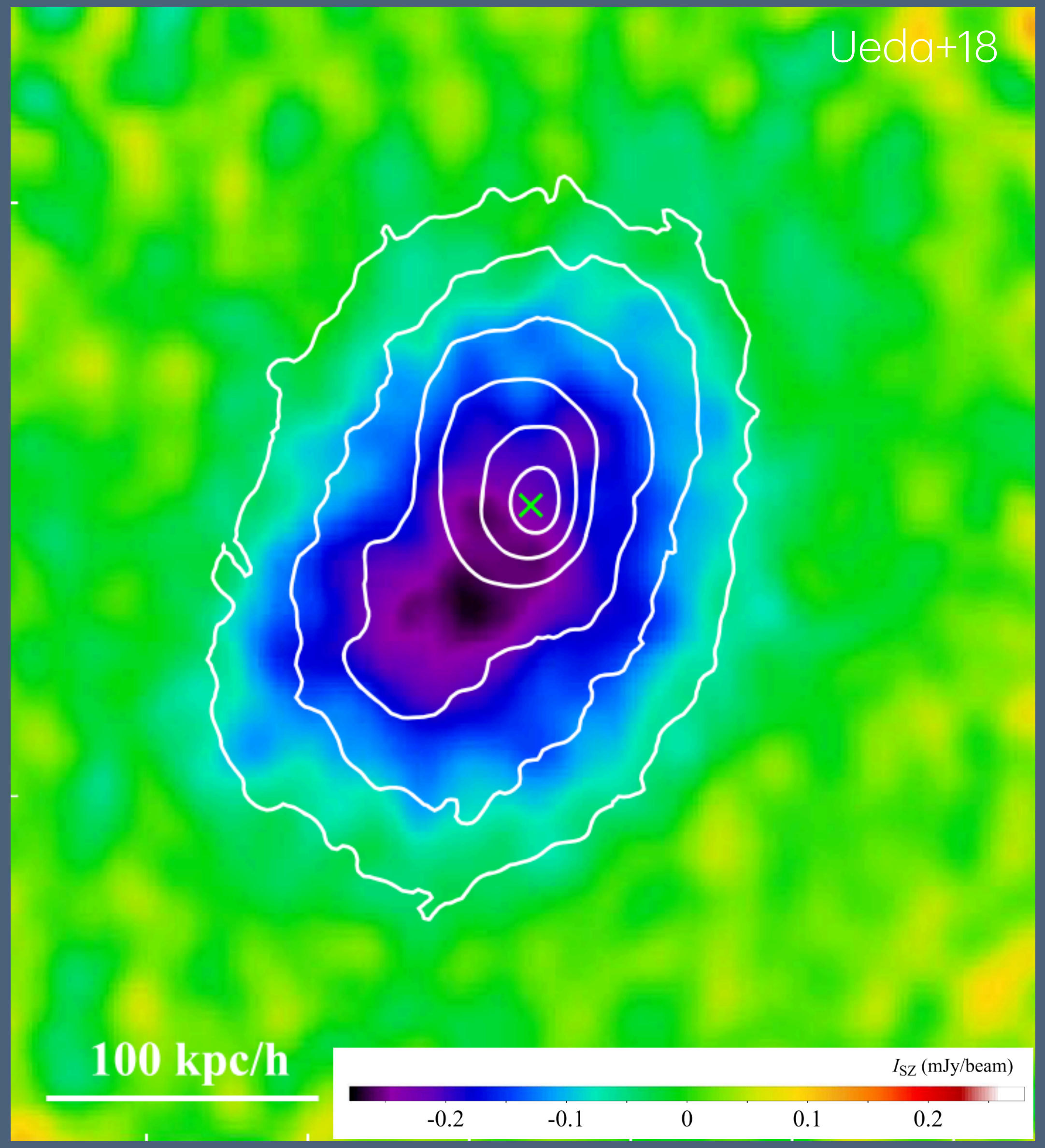
- The most luminous X-ray galaxy cluster:
  $L_X = (6.2 \pm 0.6) \times 10^{45}$erg s^{-1} (Schindler+95)
- Redshift $z = 0.45$
- Massive galaxy cluster: $10^{15} M_{\mathrm{sun}}$ (Ueda+18)
- ICM temperature: 10 keV (Allen+02, Gitti+04)
  SE region: 20 keV (Kitayama+04, Ota+08, Ueda+18)
- Cool-core in the cluster centre

Optical HST

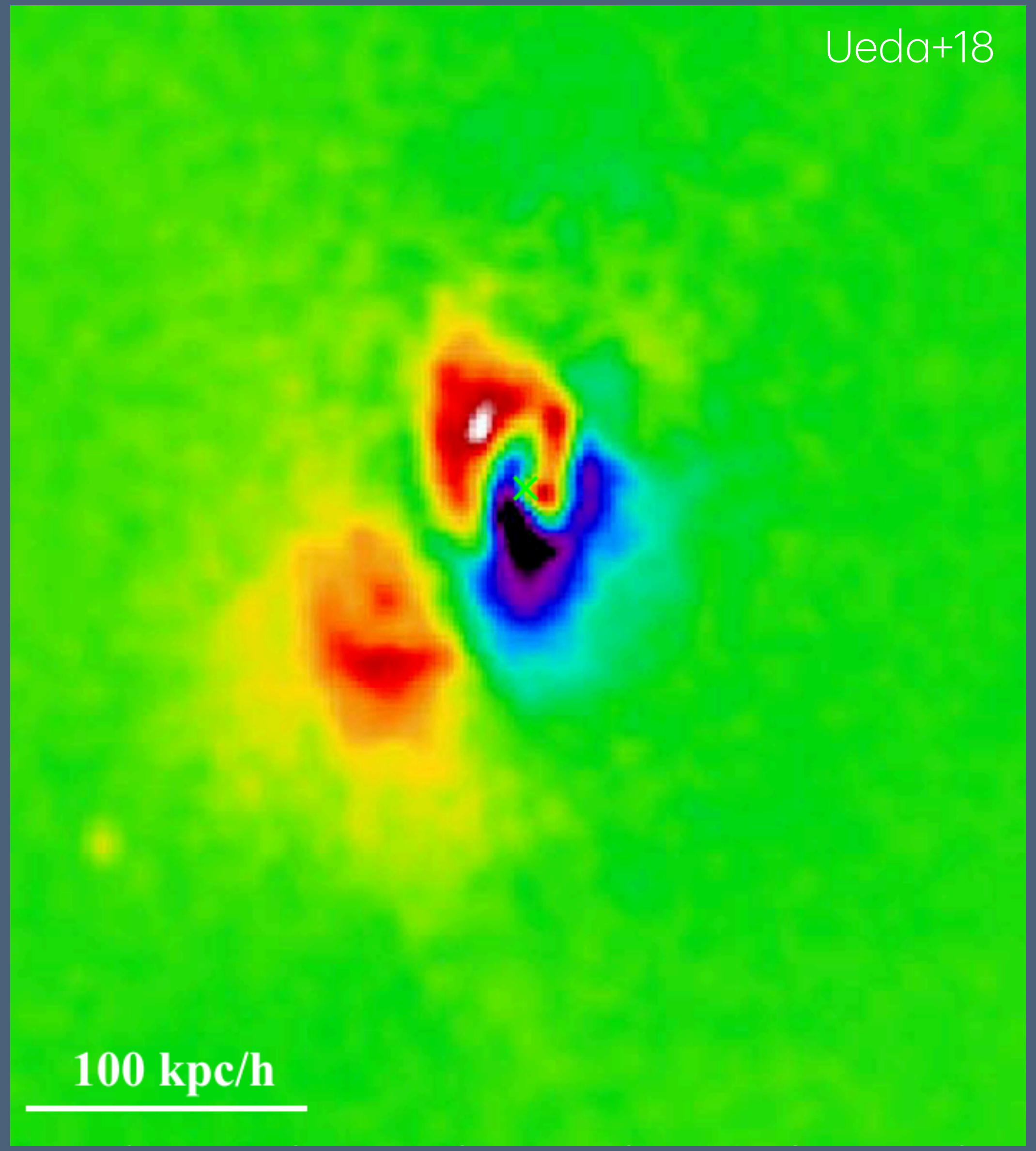


MUSTANG SZ (green+red)
Mass density (contours)



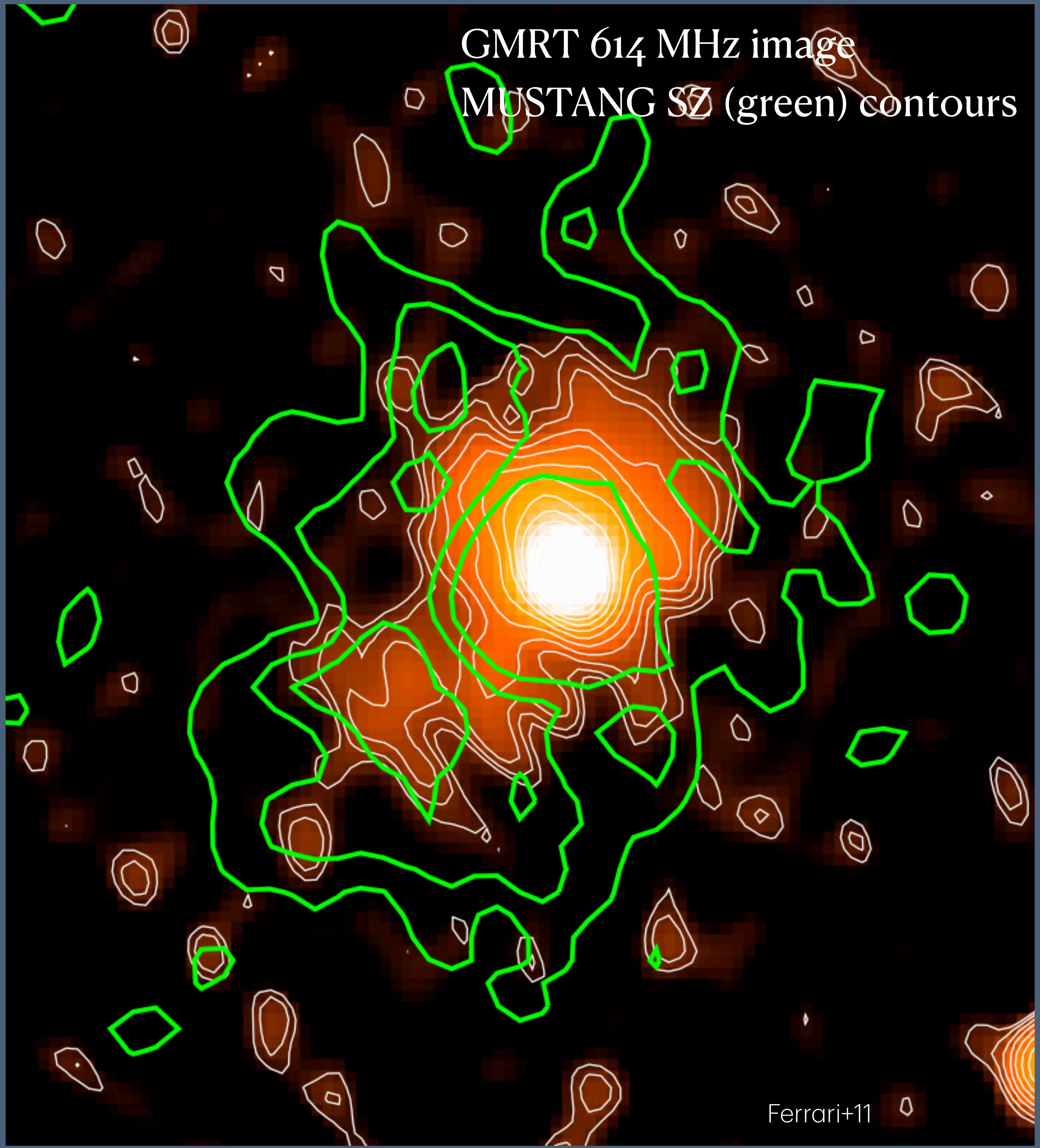


ALMA SZ 92 GHz image
Chandra X-ray contours



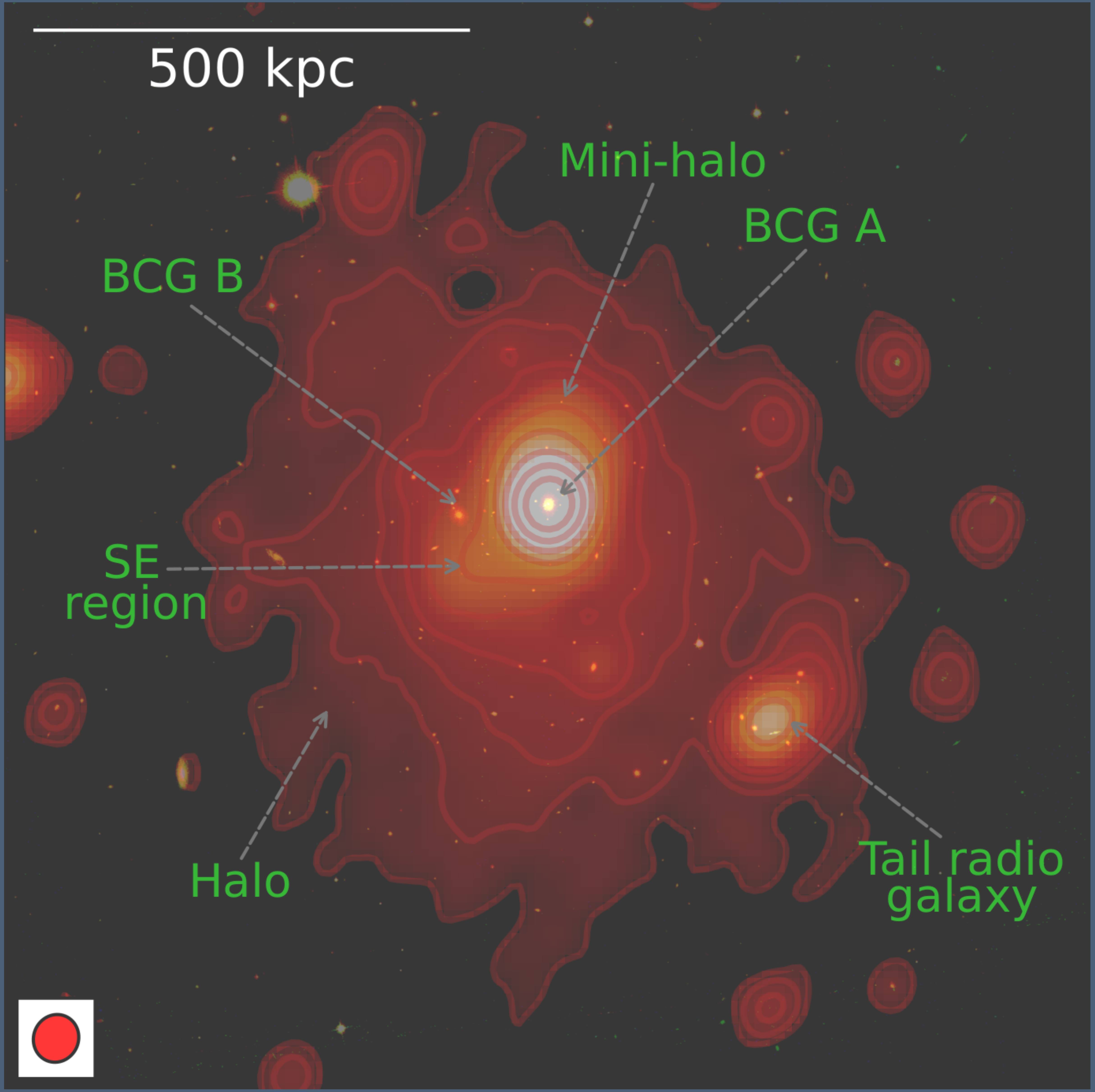
X-ray residual image

The target: RX J1347.51145 (cont.)



- Mini-halo in the cluster centre (LLS 640 kpc)
- Spectral index: $\alpha_{237\,\mathrm{MHz}}^{614\,\mathrm{MHz}} = -0.98 \pm 0.05$

MeerKAT L-band observations



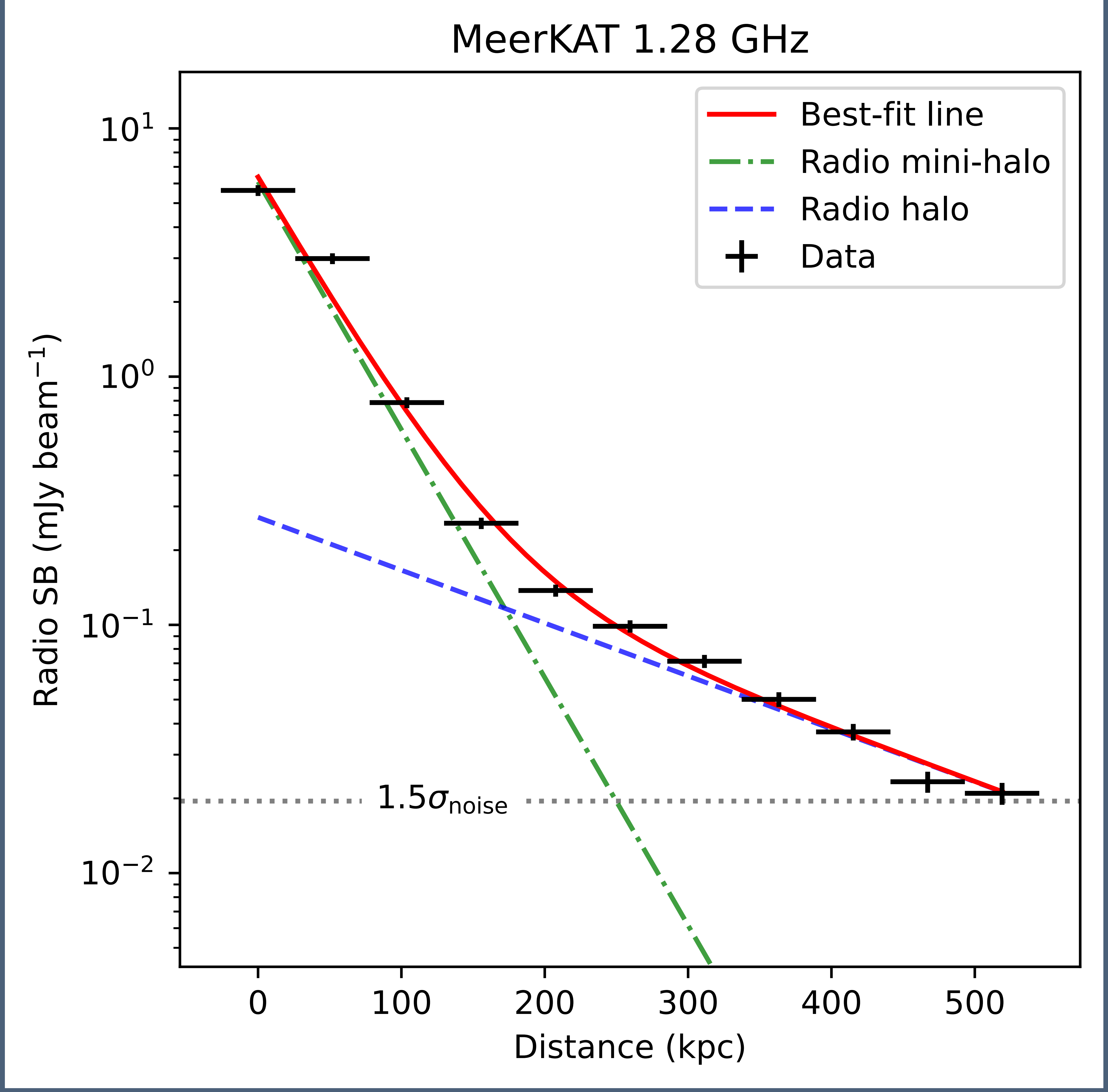
- MeerKAT 890 — 1668 MHz
- Duration: 8.3 hours
- Noise: 10 μJy/beam
- Detection:
  - ✓ Central diffuse emission with LLS of 840 kpc
  - ✓ Excess radio emission in the SE region
  - ✓ Extended emission to all directions, not just along the merger axis SW — NE

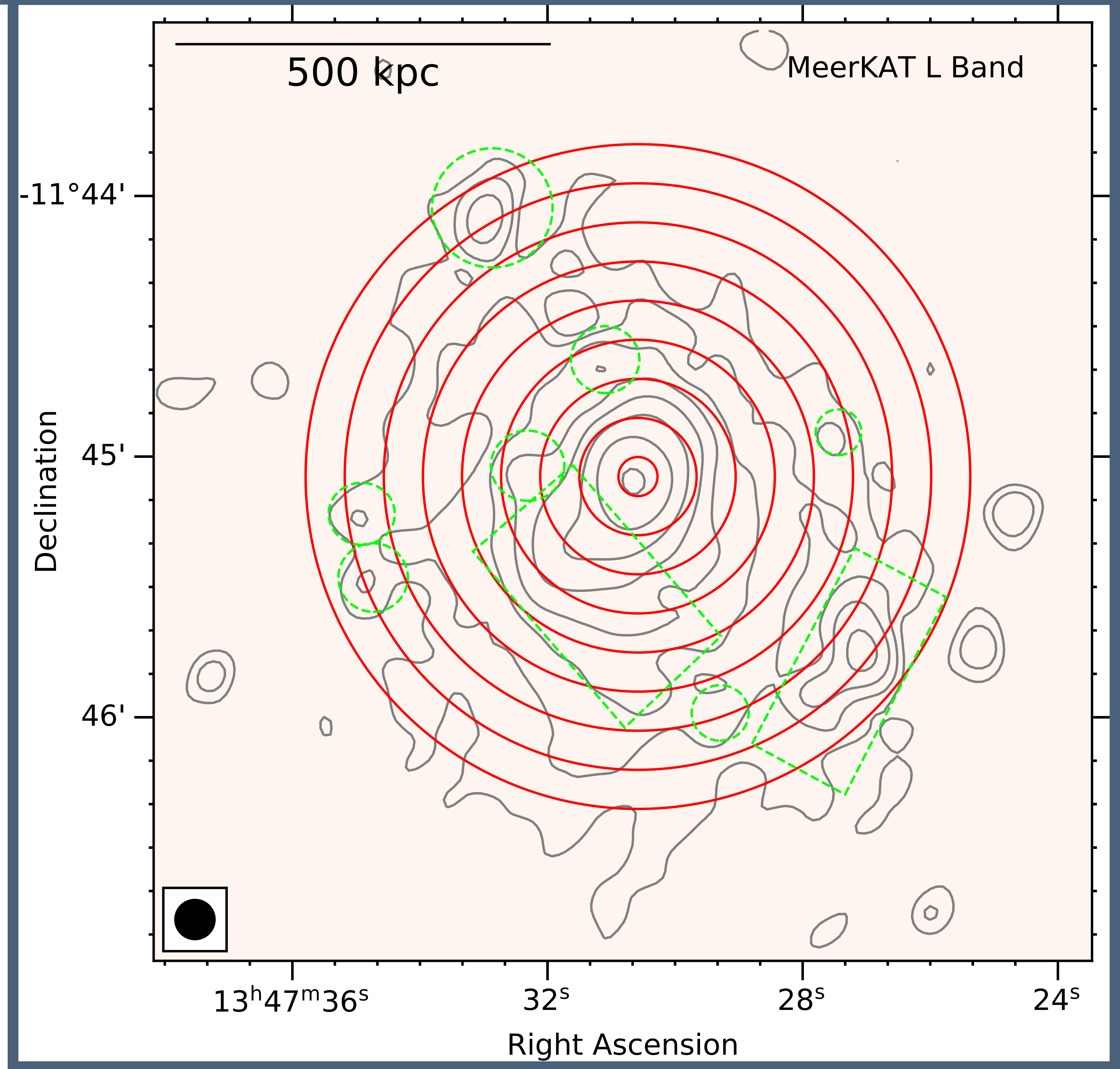
Radial surface brightness profile

- Fitting radial surface brightness profile to double-exponential function:

$$I(r) = I_{0,\,inner}\exp(-r/r_{e,\,inner}) + I_{0,\,outer}\exp(-r/r_{e,\,outer})$$

- Peak brightness: $I_0^{MH} \approx 20 \times I_0^{H}$
- LLS of mini-halo: ~500 kpc
- LLS of halo: ~1 Mpc



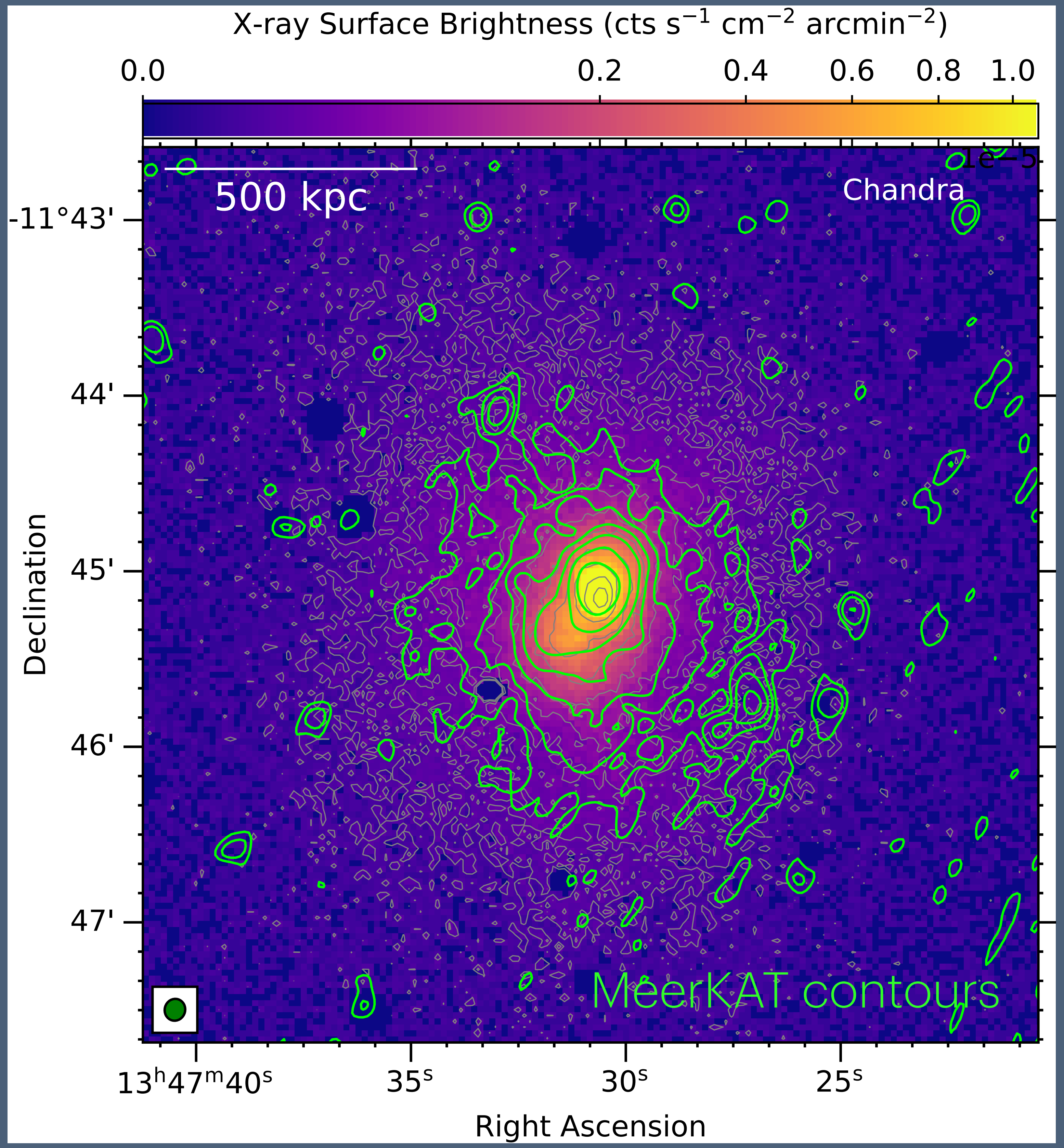


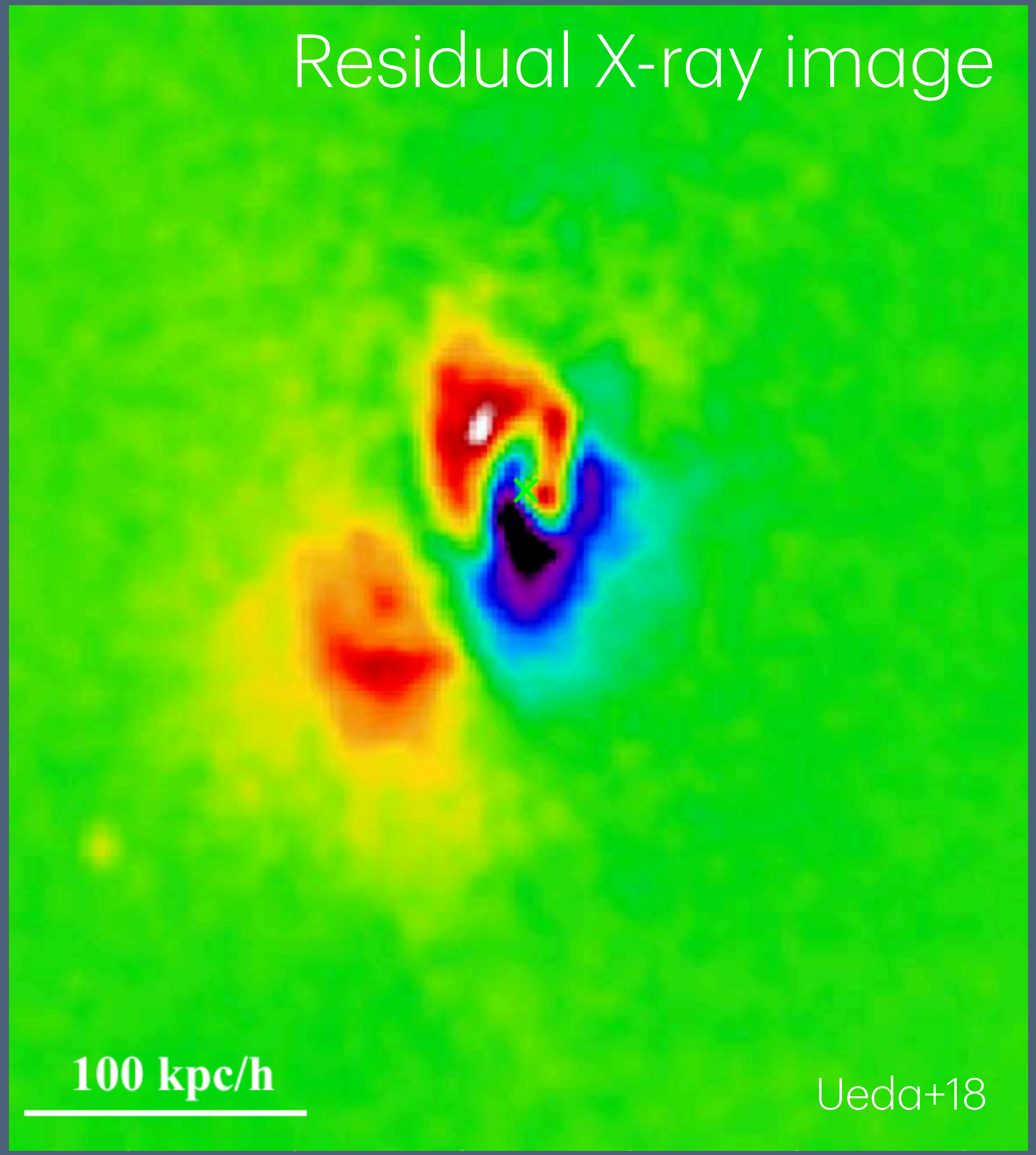
MeerKAT 1.28 GHz	
$I_{0,MH}$ (mJy beam^{-1})	6.2 ± 0.8
$r_{e,MH}$ (kpc)	43 ± 5
$I_{0,H}$ (mJy beam^{-1})	0.3 ± 0.2
$r_{e,H}$ (kpc)	204 ± 58
χ^2	0.5

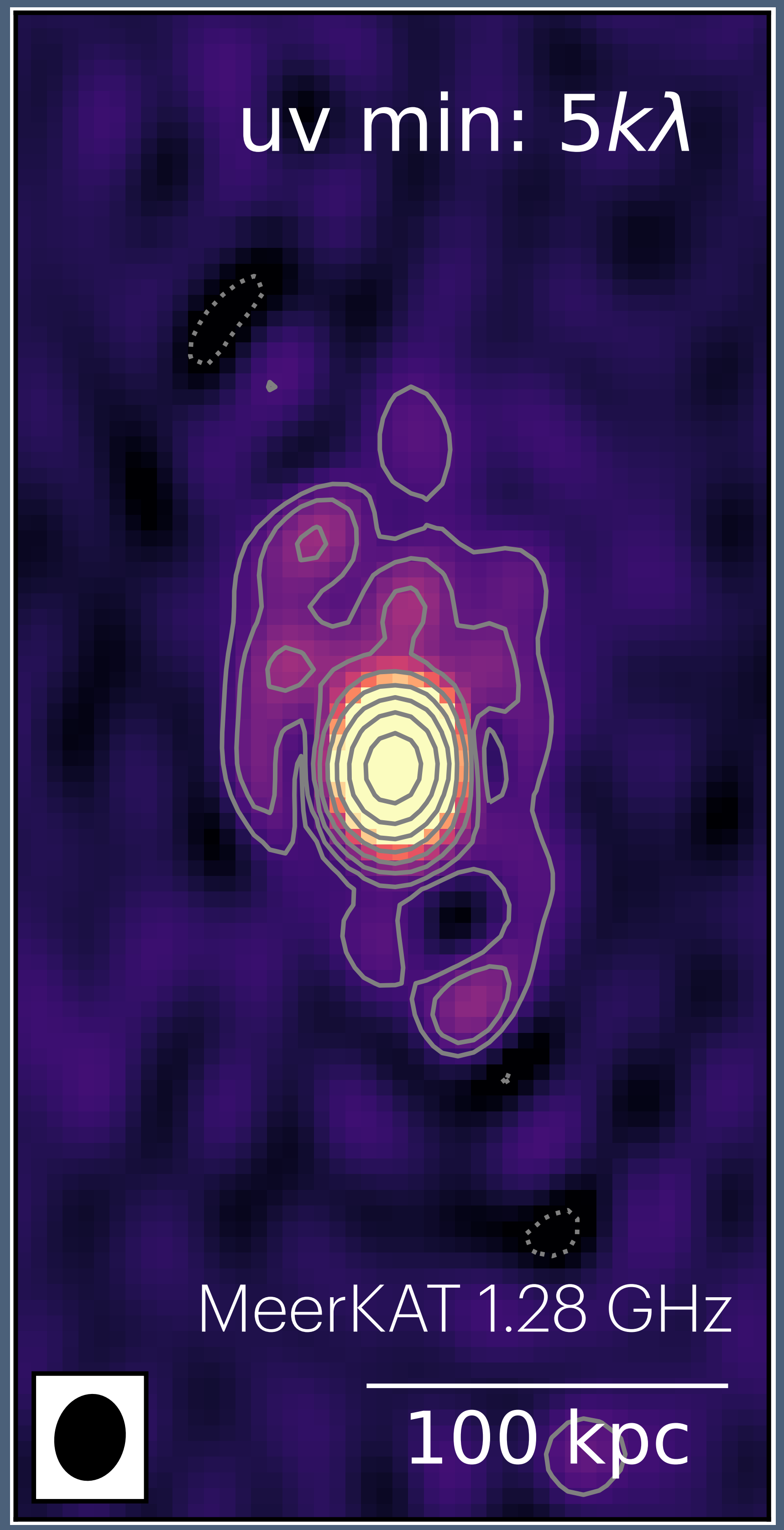
Radio - X-ray correlation

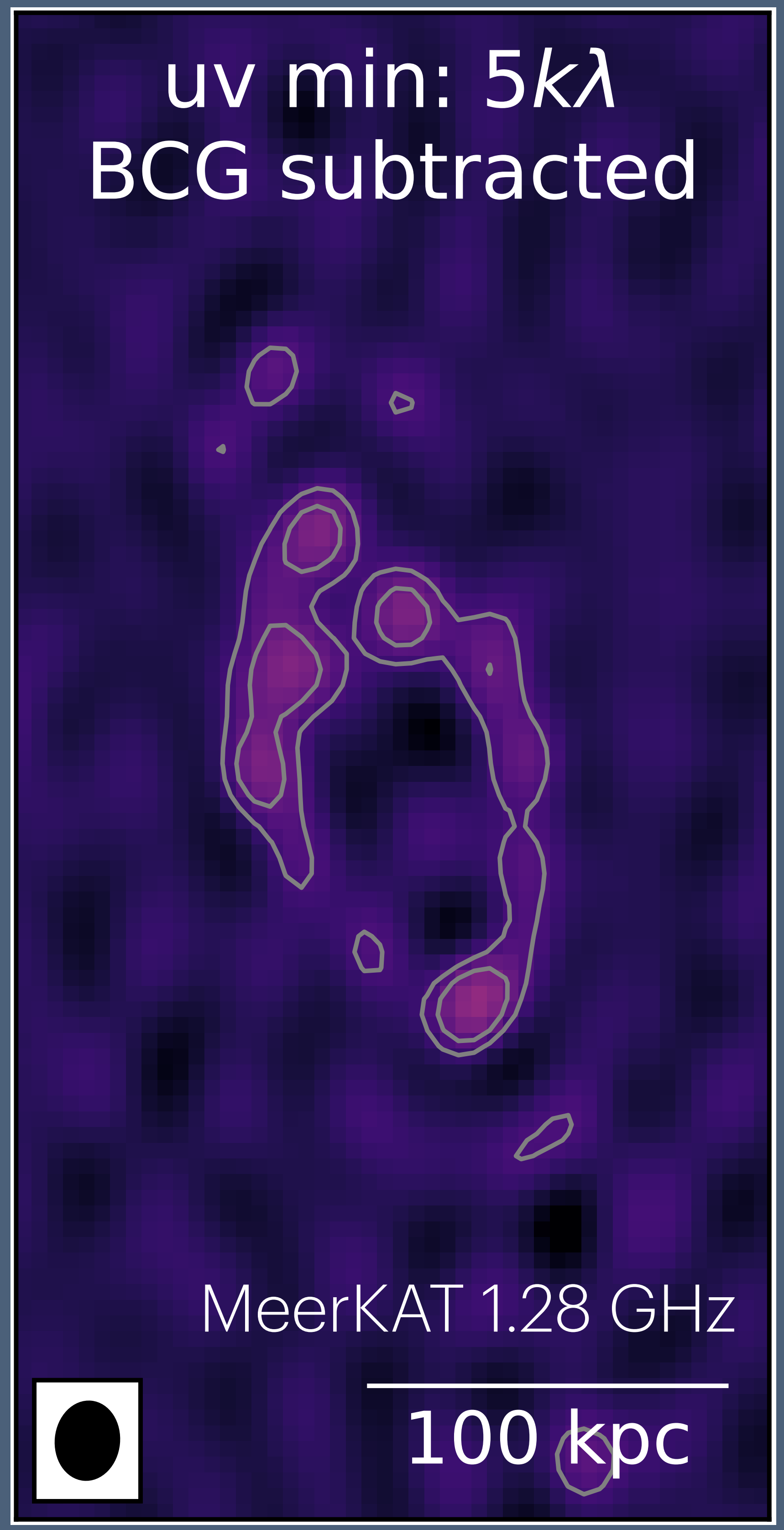
- Different spectral index trends in the core (mini-halo) and the outer (halo) regions.
- The powering mechanisms are different for these regions.
  the core is energised by the gas sloshing. The outer region is consistent with turbulent re-acceleration.

Radio - X-ray SB correlation (core)









- Dipolar pattern in the residual X-ray image —> Gas sloshing in the core
- Similar radio emission in the radio images with uv-minimum cutoff —> connection between mini-halo emission and gas sloshing

Summary

- Multi-wavelength observations of RXJ1347 with MeerKAT + uGMRT
- Multi-components diffuse radio emission: mini-halo + halo
- Different particle acceleration mechanisms in the core and outer regions of the cluster
- Deep observations with sensitive telescopes (LOFAR, MeerKAT, SKAP, SKA) detect many more multi-component systems —> the properties of their host clusters