III international SKA workshop
4 - 8 Oct. 2021

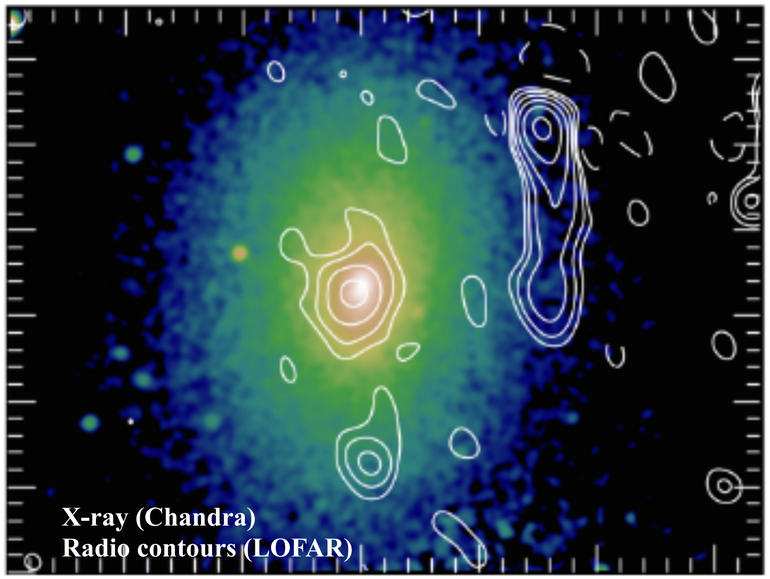
New LOFAR detection in the galaxy cluster A1413

Connection between non-thermal and thermal emission

Collaboration with **CHEX-MATE** and **LoTSS**

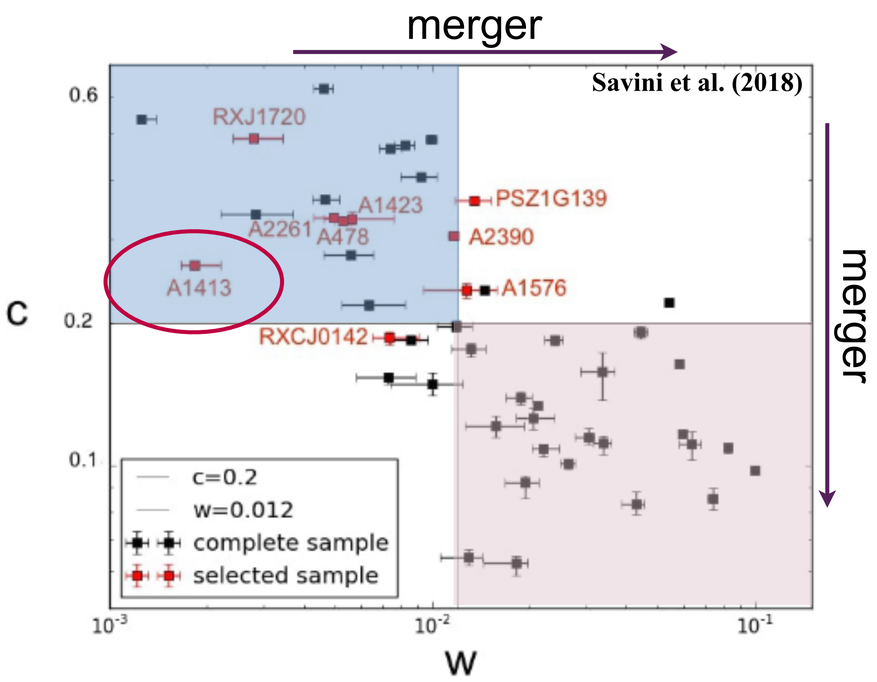
Giulia Lusetti

The galaxy cluster Abell 1413: a multi-wavelnghts analysis

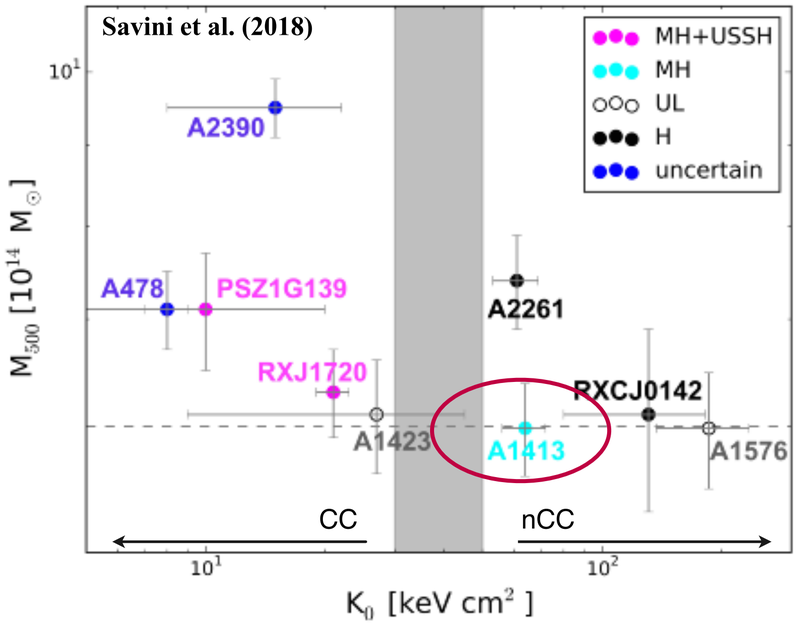


Savini et al. (2018)

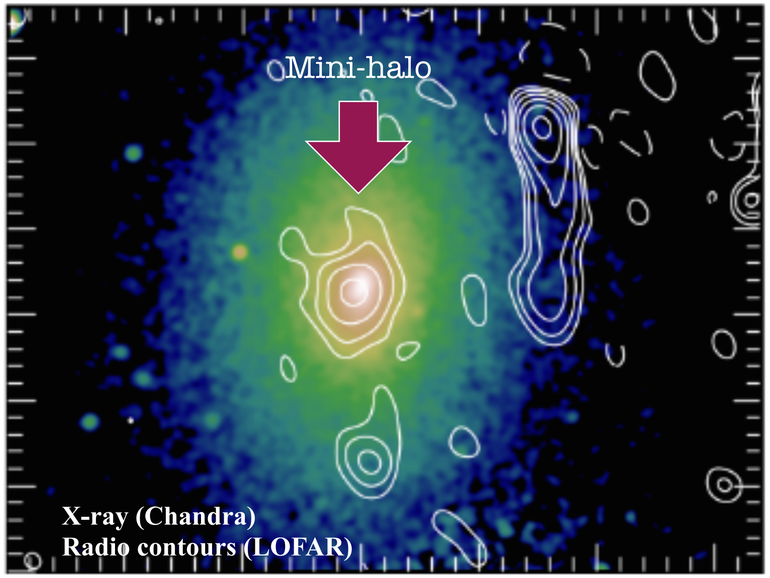
Merging vs non merging



CoolCore vs non CoolCore



The galaxy cluster Abell 1413: a multi-wavelnghts analysis



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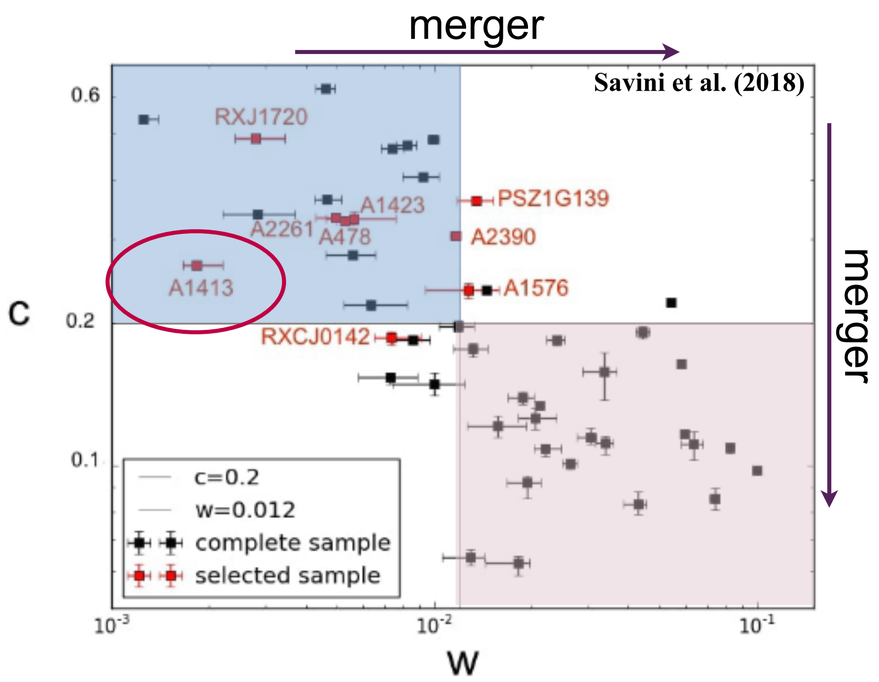

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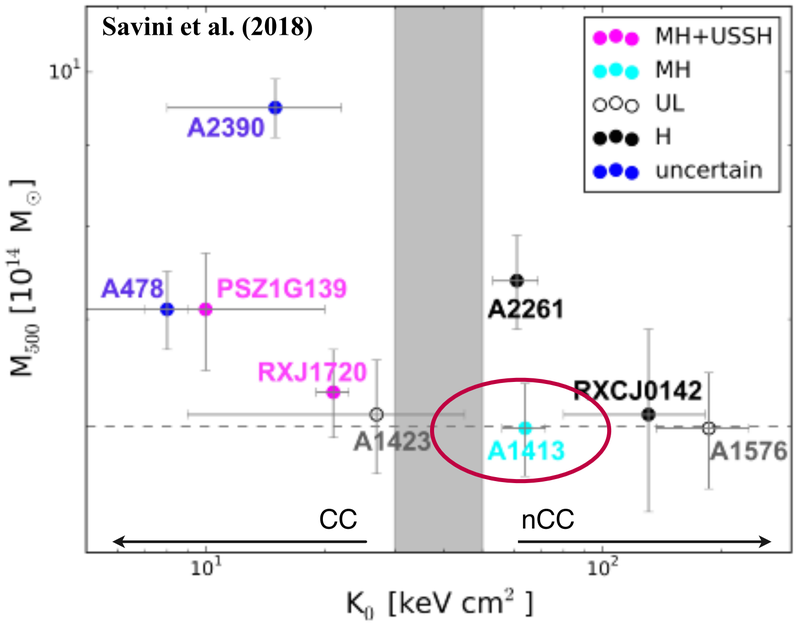
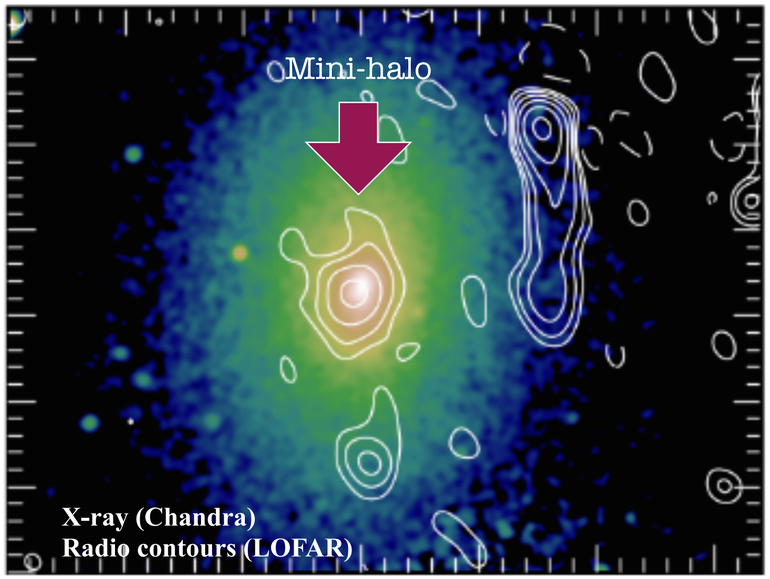


The galaxy cluster Abell 1413: a multi-wavelnghts analysis



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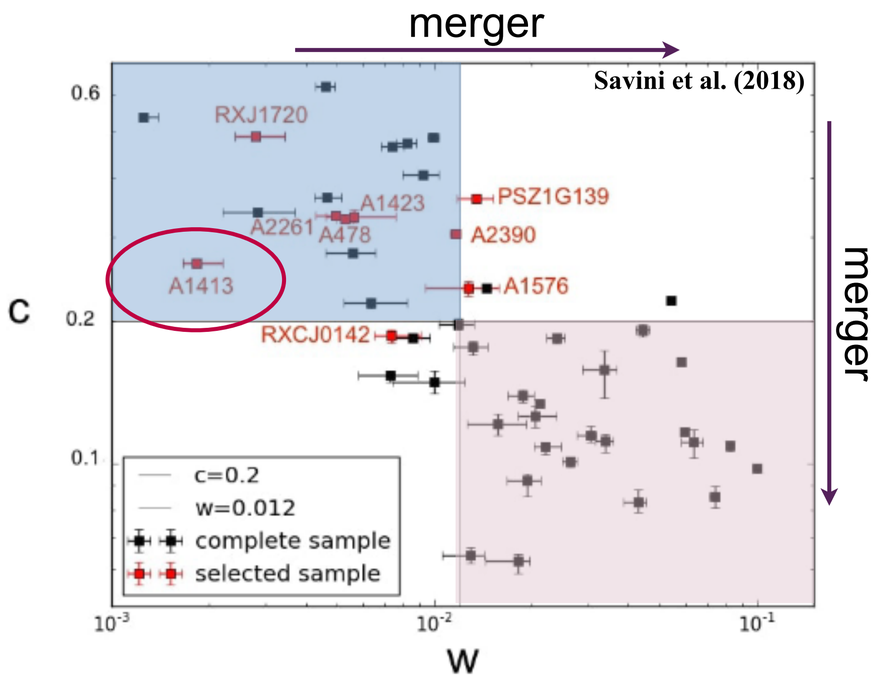

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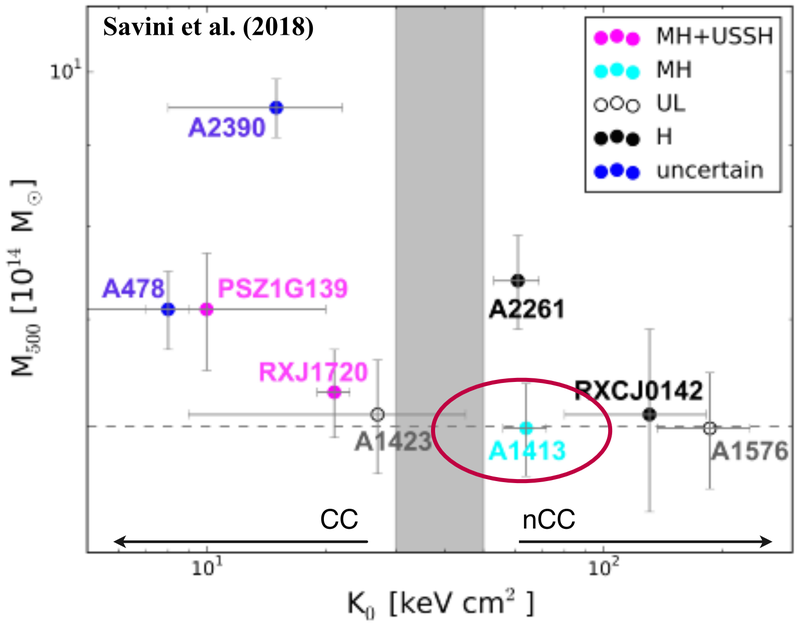
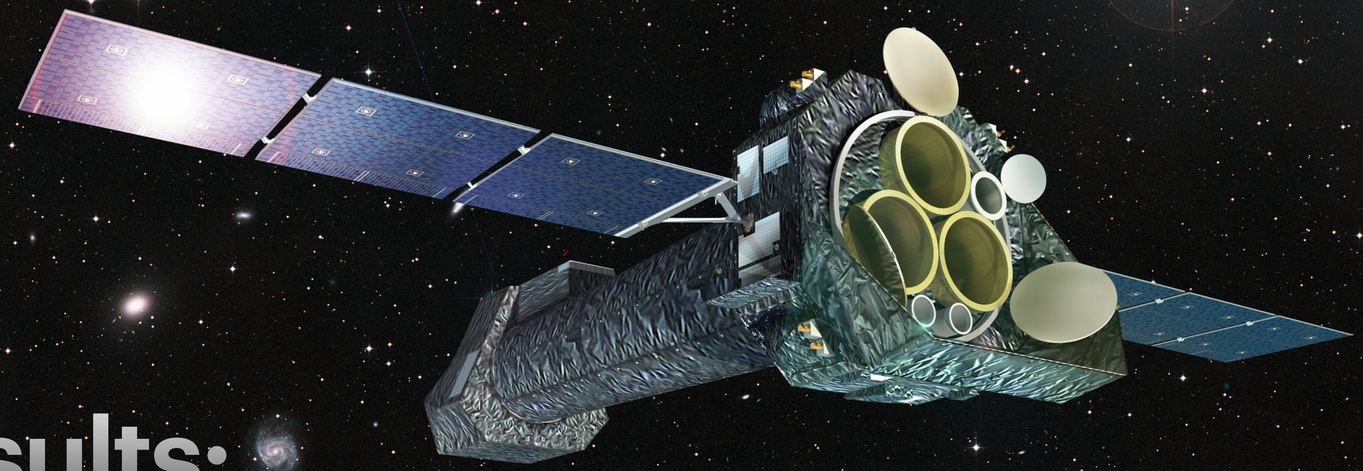


New updated multi-wavelenghts analysis of A1413, by

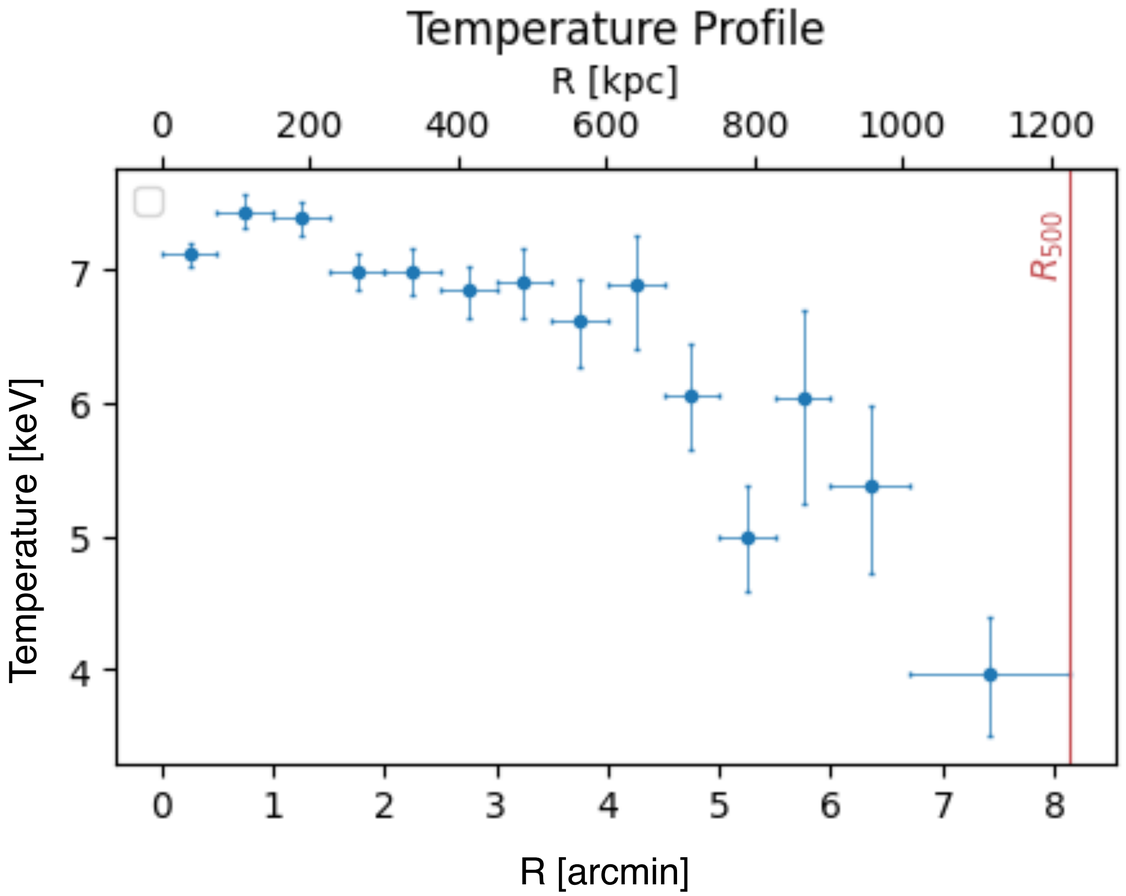
- characterizing the ***dynamical state***, throughout the study of ICM properties
- determining the properties of the ***diffuse radio emission*** hosted by the cluster.

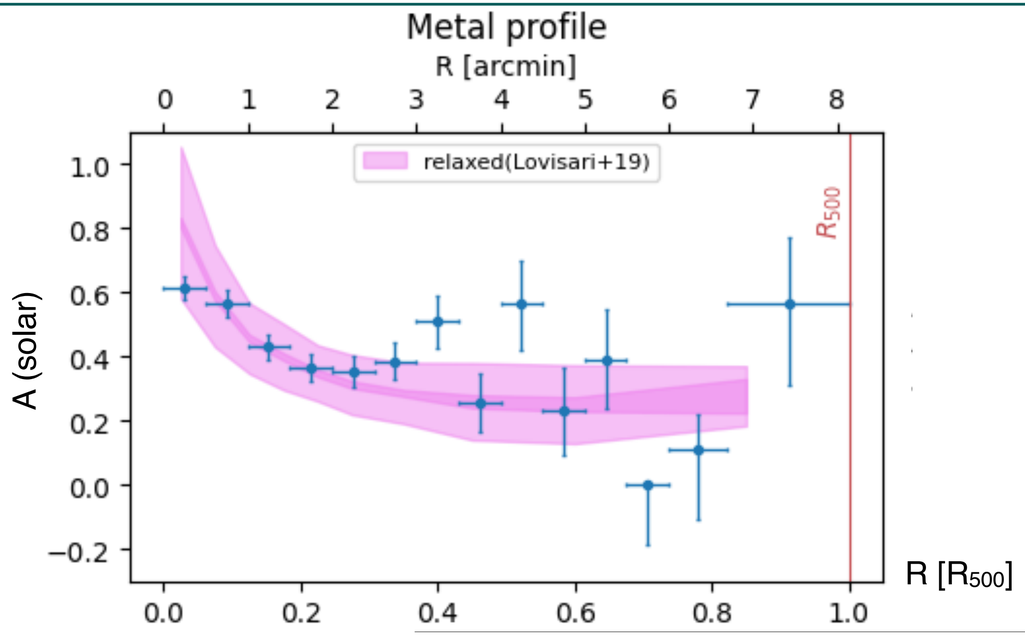


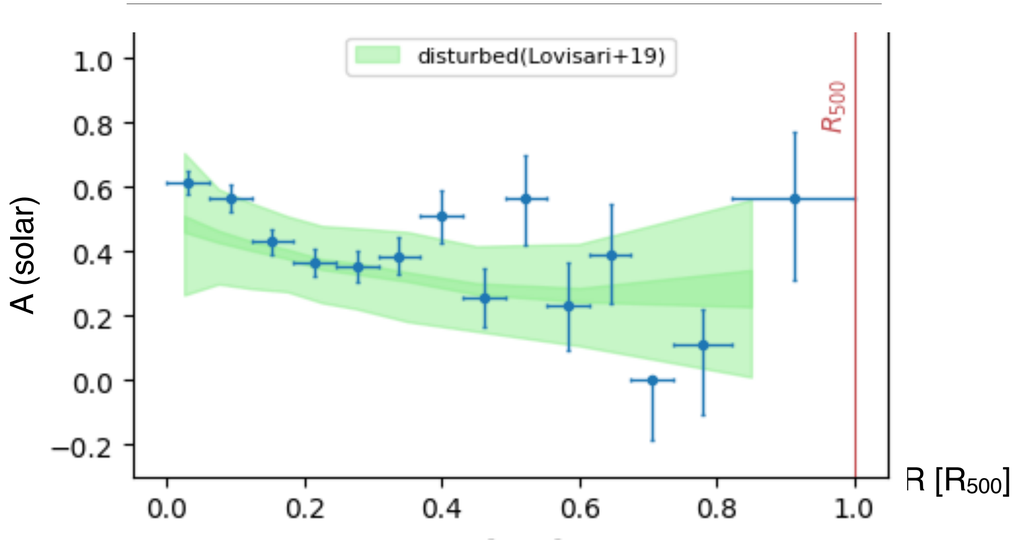
X-ray results:

Newly processed
XMM-Newton archive data of A1413
(~80 ks observation)

Spectral profiles



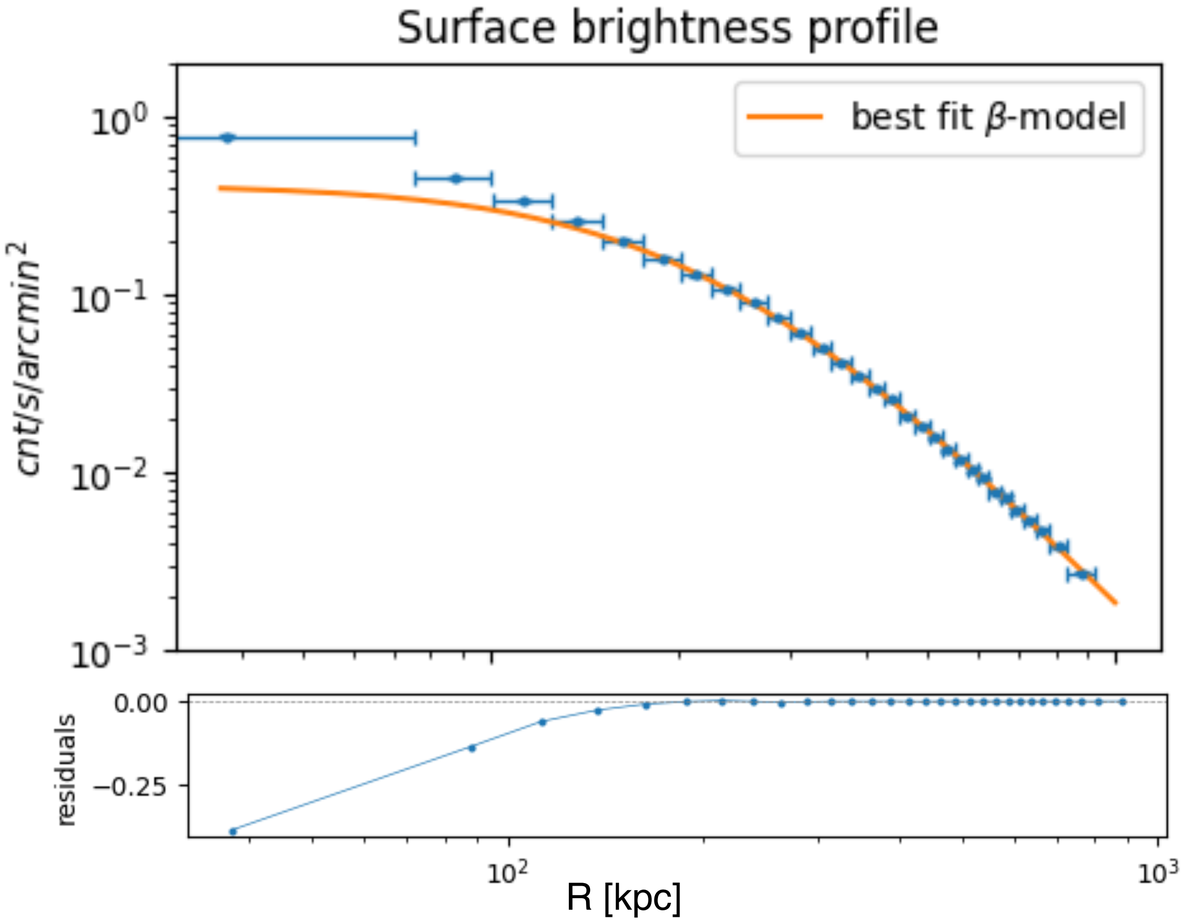


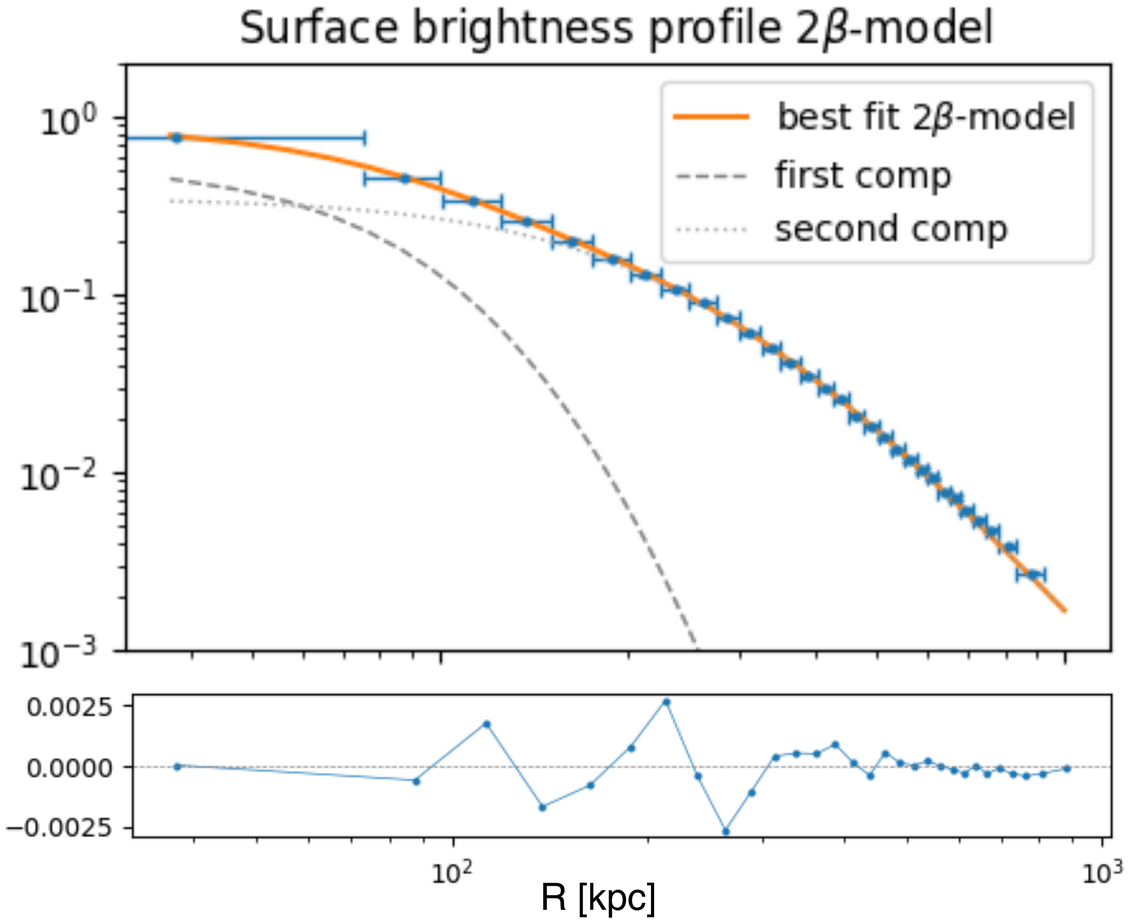


Surface brightness profile

$$S(r) = S_0 \left[1 + \left(\frac{r}{r_c}\right)\right]^{-3\beta+0.5}$$

$$S(r) = S_{0,1}\left[1 + \left(\frac{r}{r_{c,1}}\right)\right]^{-3\beta_1+0.5} + S_{0,2}\left[1 + \left(\frac{r}{r_{c,2}}\right)\right]^{-3\beta_2+0.5}$$





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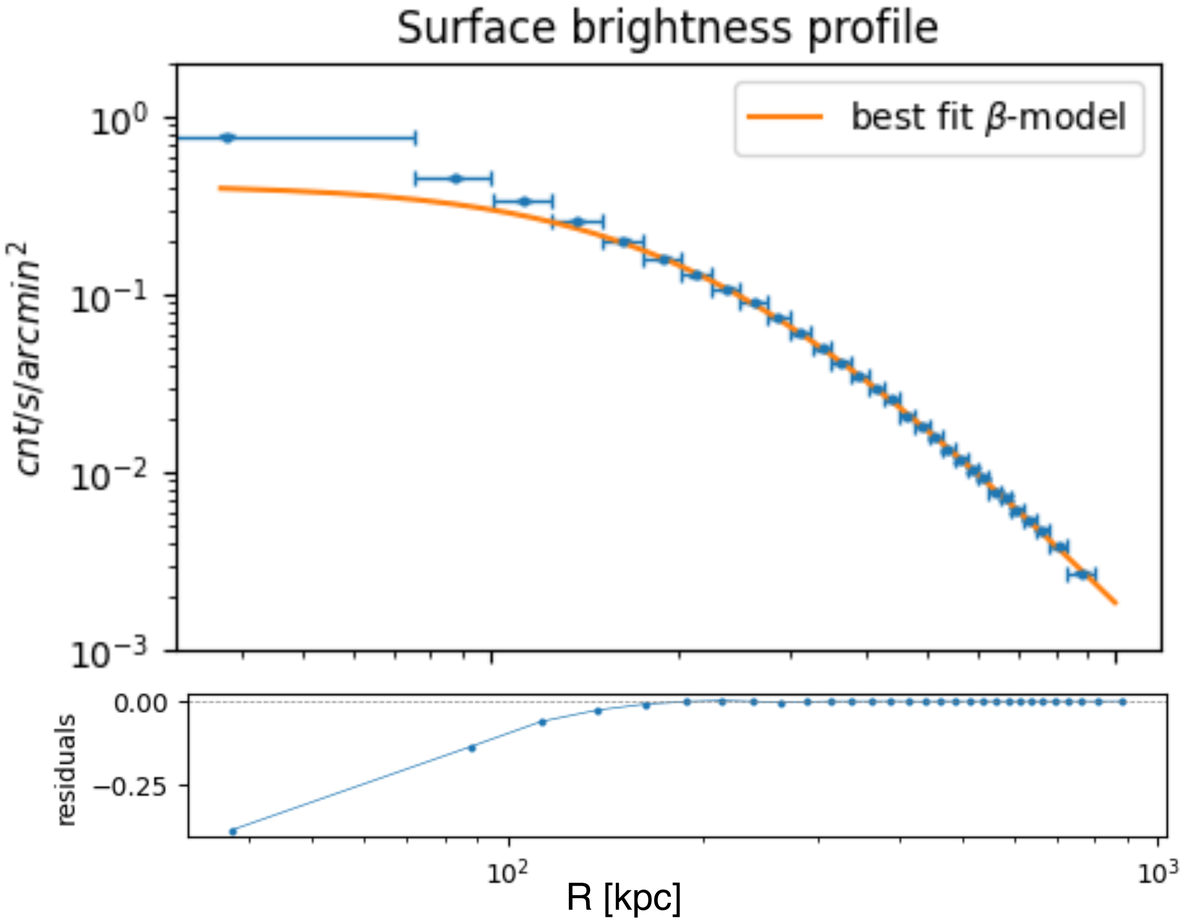
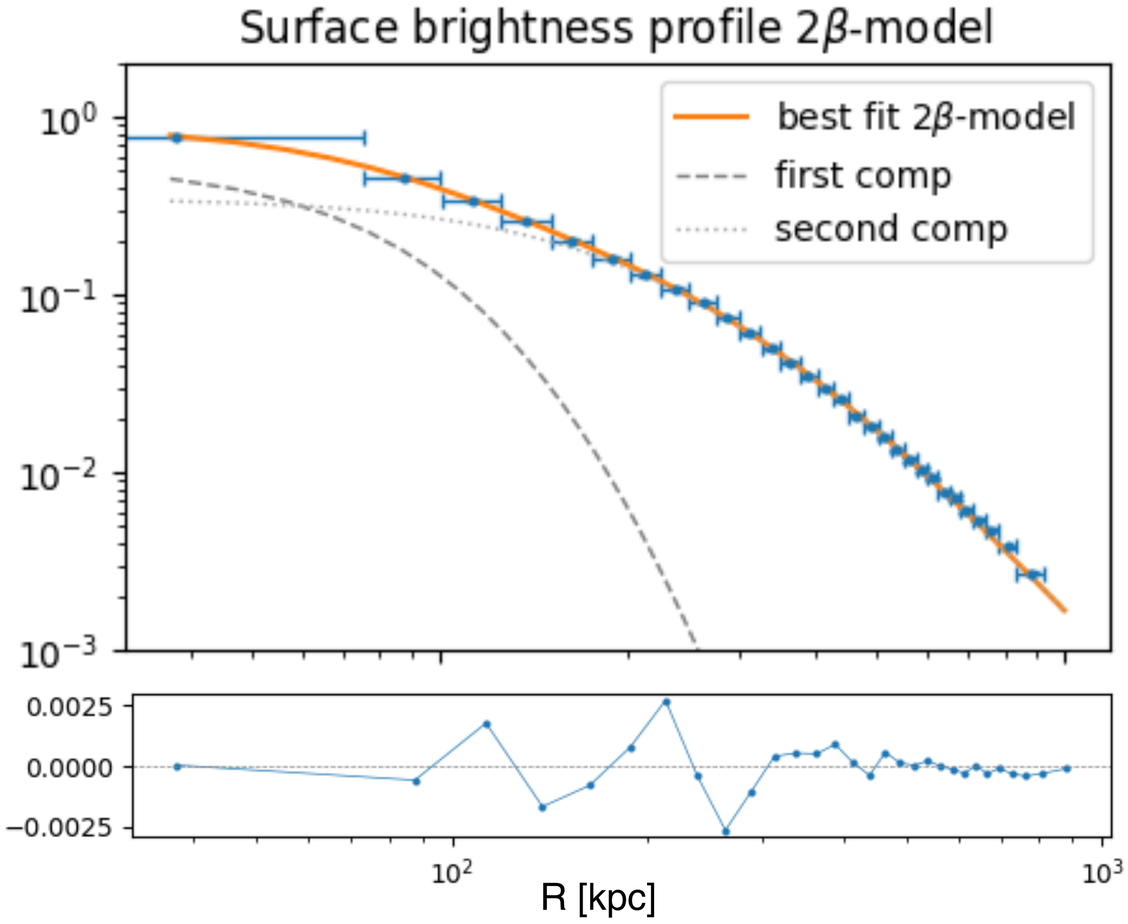
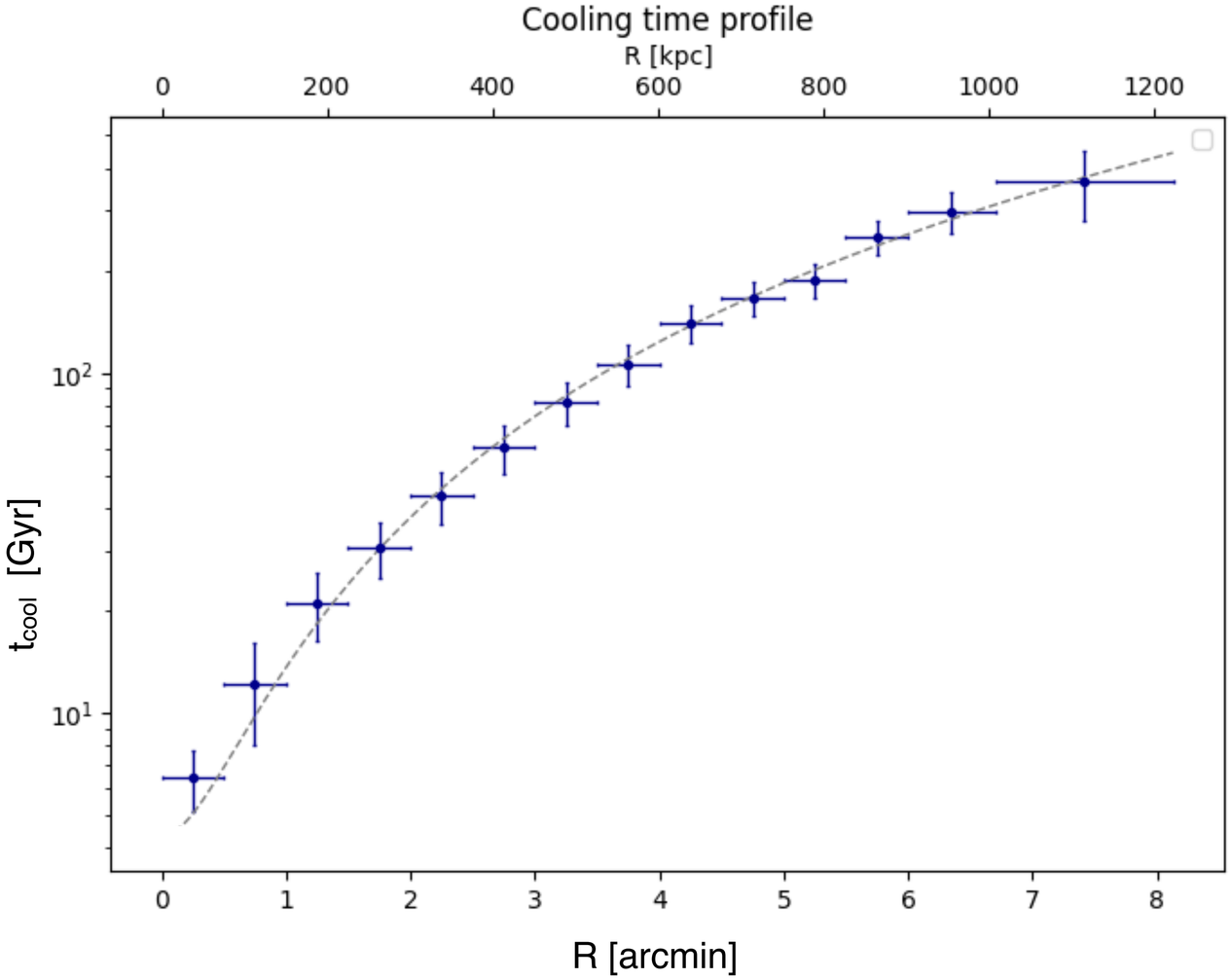


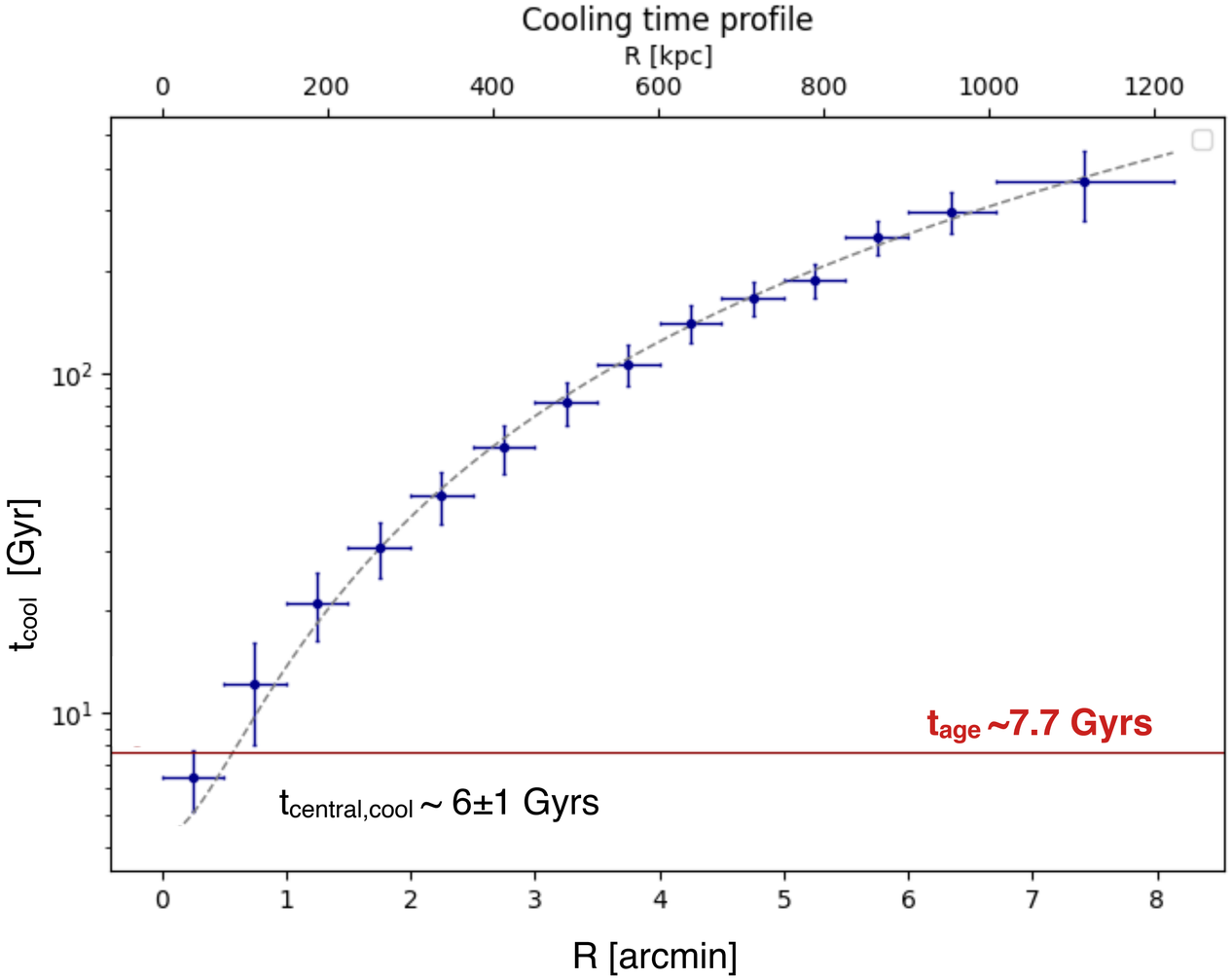


Cooling time profile



$$t_{cool} = \frac{H}{\Lambda(T) n_e n_p} = \frac{\gamma}{\gamma - 1} \frac{kT(r)}{\mu X n_e(r) \Lambda(T)}$$

Cooling time profile



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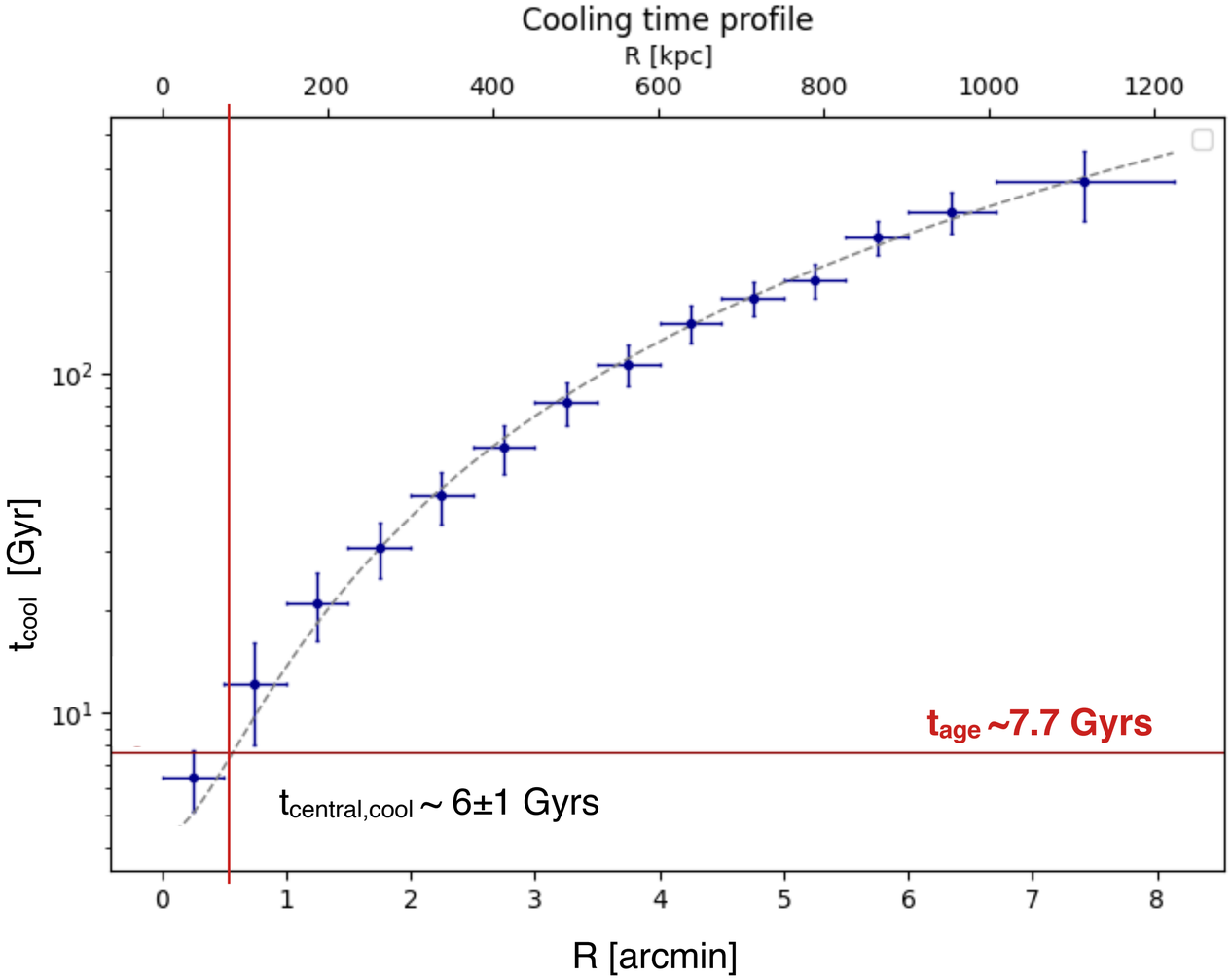
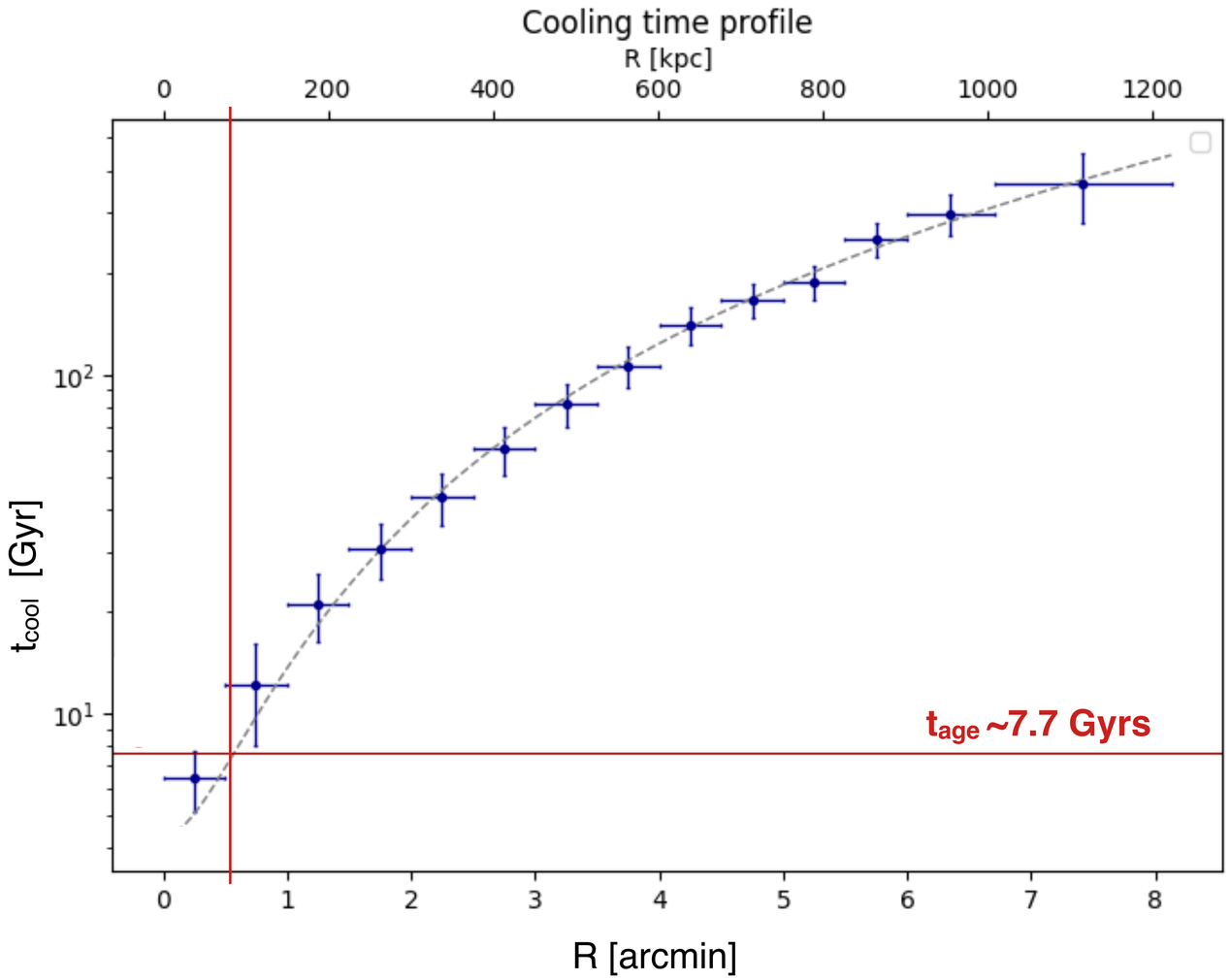


r_{cool} ~ 90 kpc

$$t_{cool} = \frac{H}{\Lambda(T) n_e n_p} = \frac{\gamma}{\gamma - 1} \frac{kT(r)}{\mu X n_e(r) \Lambda(T)}$$

Cooling time profile



$$t_{cool} = \frac{H}{\Lambda(T) n_e n_p} = \frac{\gamma}{\gamma - 1} \frac{kT(r)}{\mu X n_e(r) \Lambda(T)}$$

$t_{central,cool}$ ~ 6±1 Gyrs
r_{cool} ~ 90 kpc

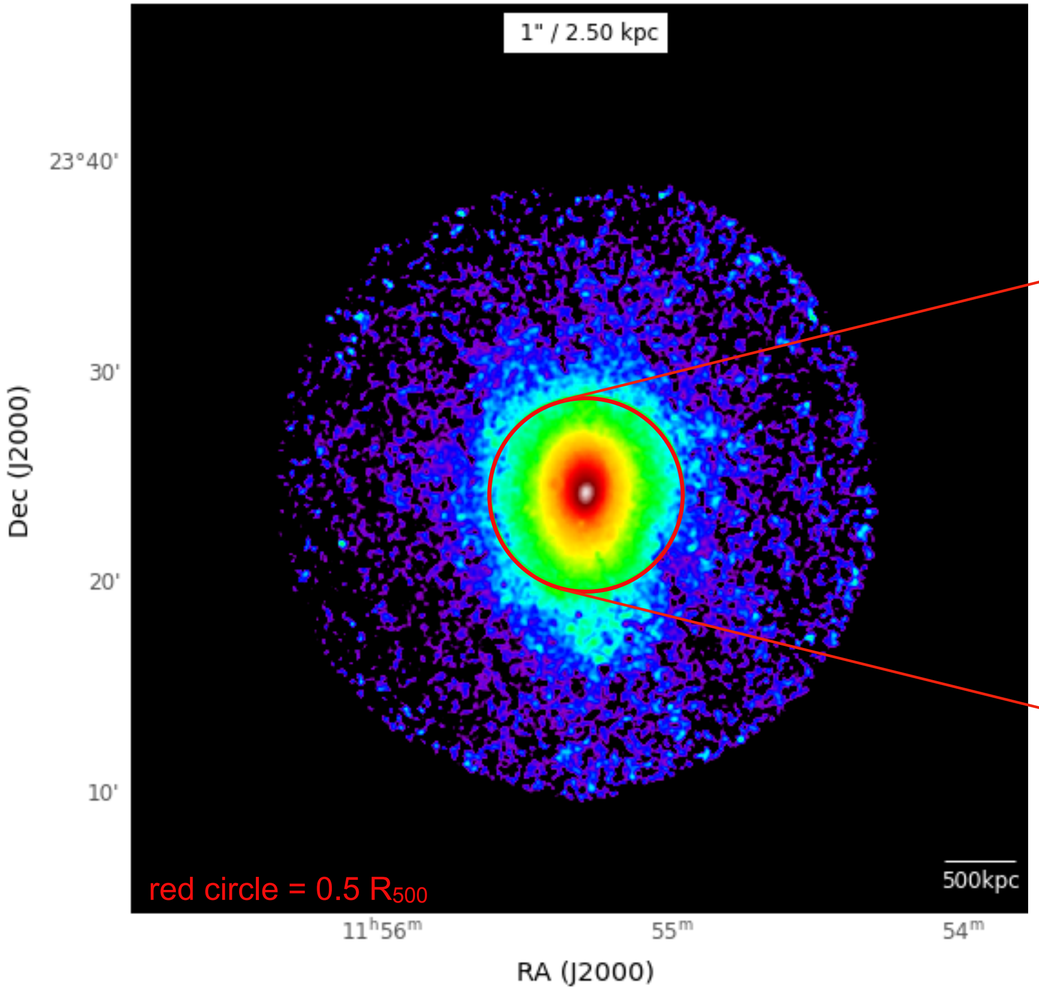
weak-cool-core system

1 Gyr < $t_{central,cool}$ < 7.7 Gyr ~ t_{age}

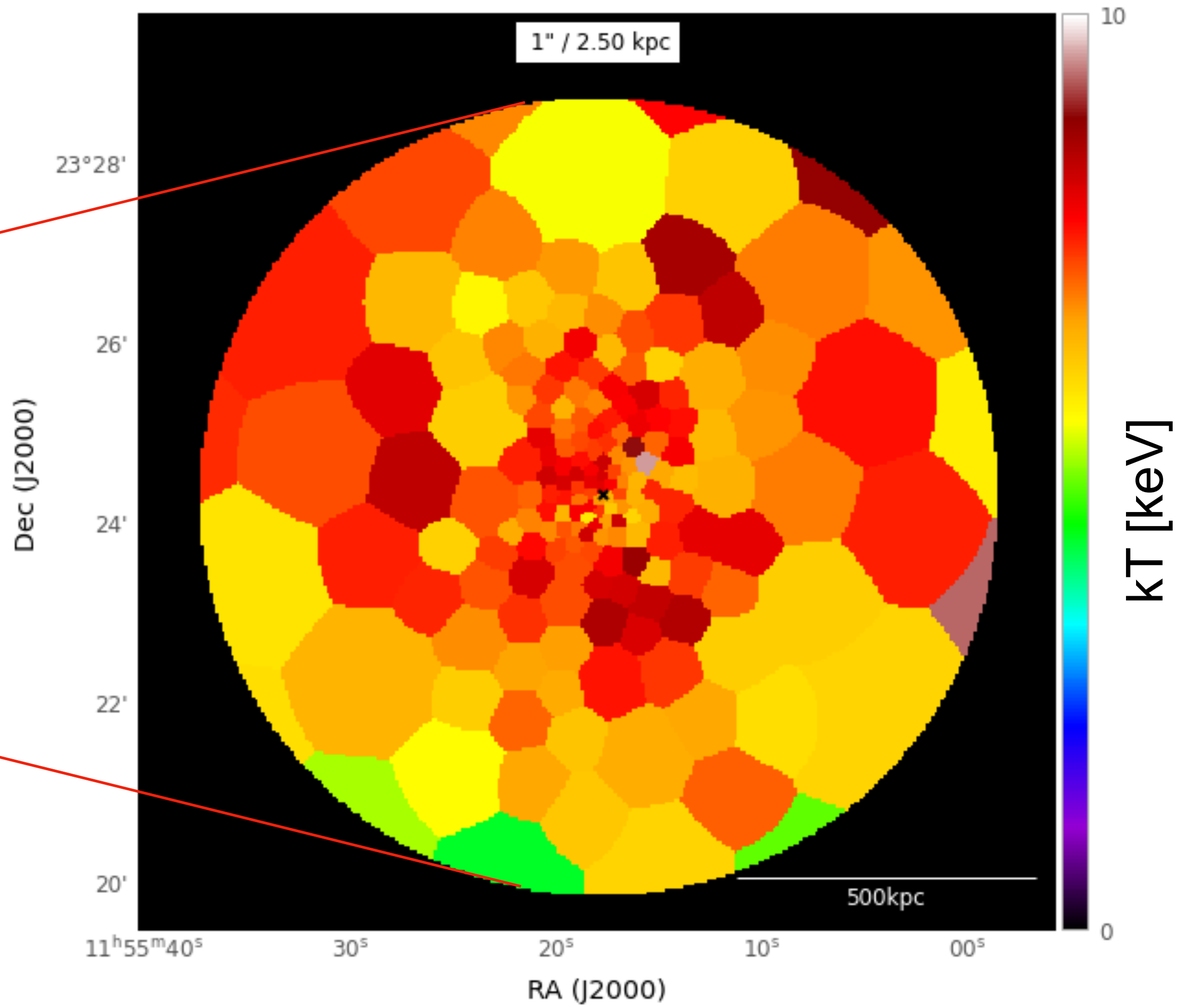
VS

strong cool-core clusters
$t_{central,cool}$ < 1 Gyr

2D temperature map



Background-subtracted and exposure-corrected image of A1413 in [0.3,7] keV



Temperature map *within 0.5 R_{500}*

X-ray summary

- Peculiar dynamical status of A1413

- A1413 has no disrupted morphology, but the elliptical shape of the surface brightness, the kT & Z azimuthal profiles, the cooling time and the variation of the 2D temperature map, suggest that it could have experienced a past of (minor) merger events → **not fully relaxed systems**

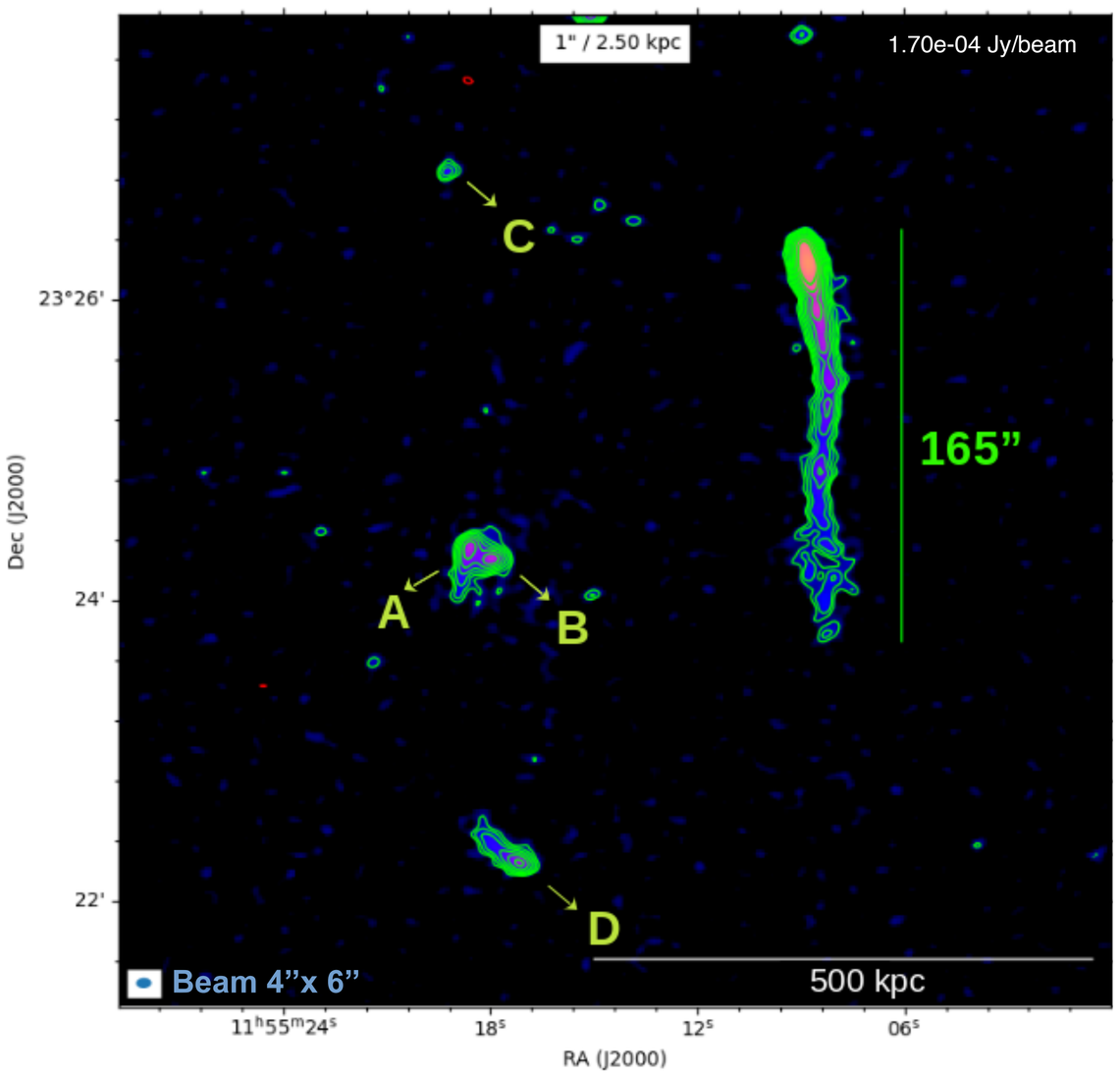
- A1413 has $t_{central,cool} \sim 6$ Gyr < 7.7 Gyr $\sim t_{age}$ → **weak-cool-core systems**

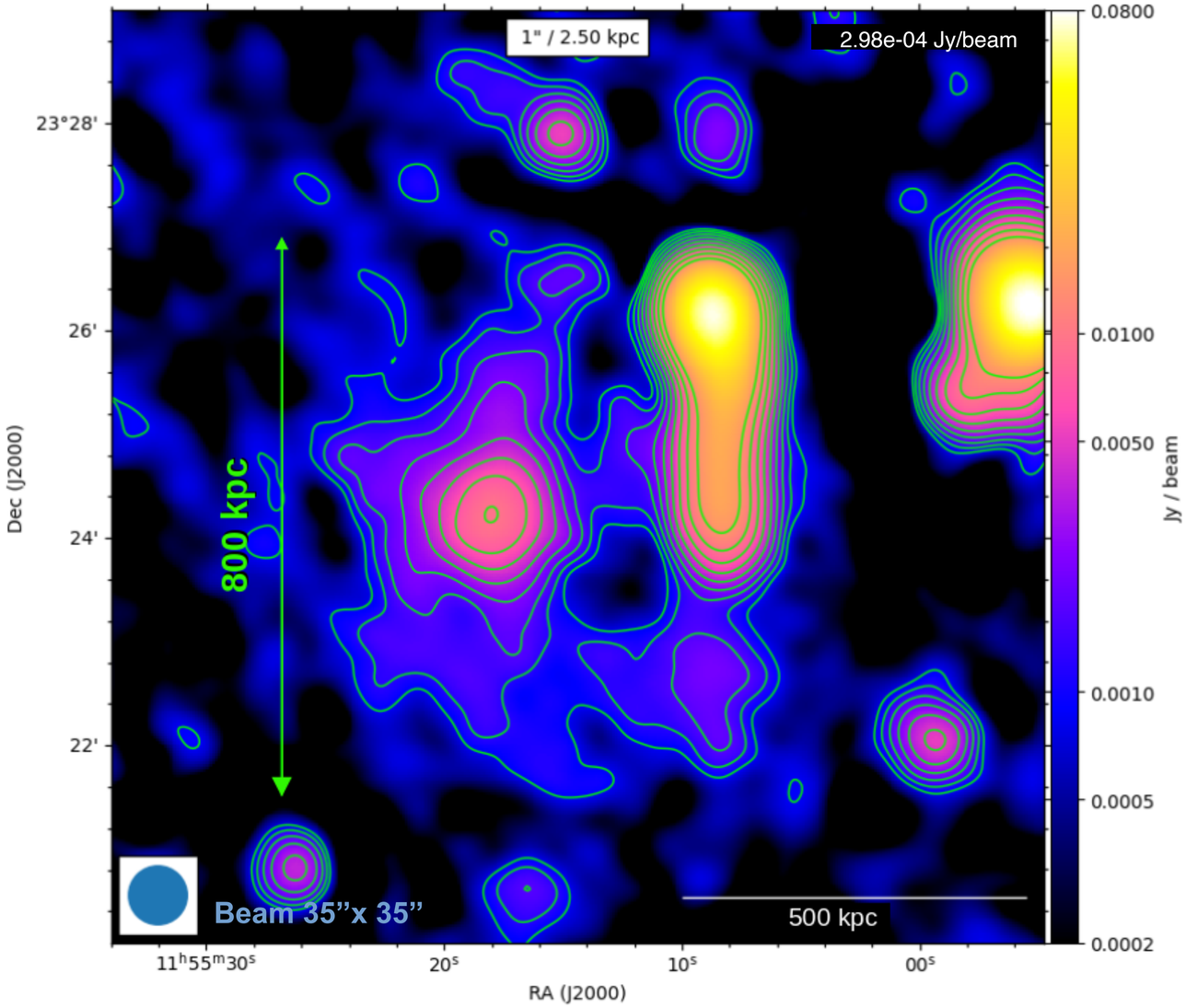
Radio results:

Imaging of new **LOFAR** observation from the LoTTS survey @144 MHz

LOFAR core stations of the Superterp

Imaging at low and high resolution





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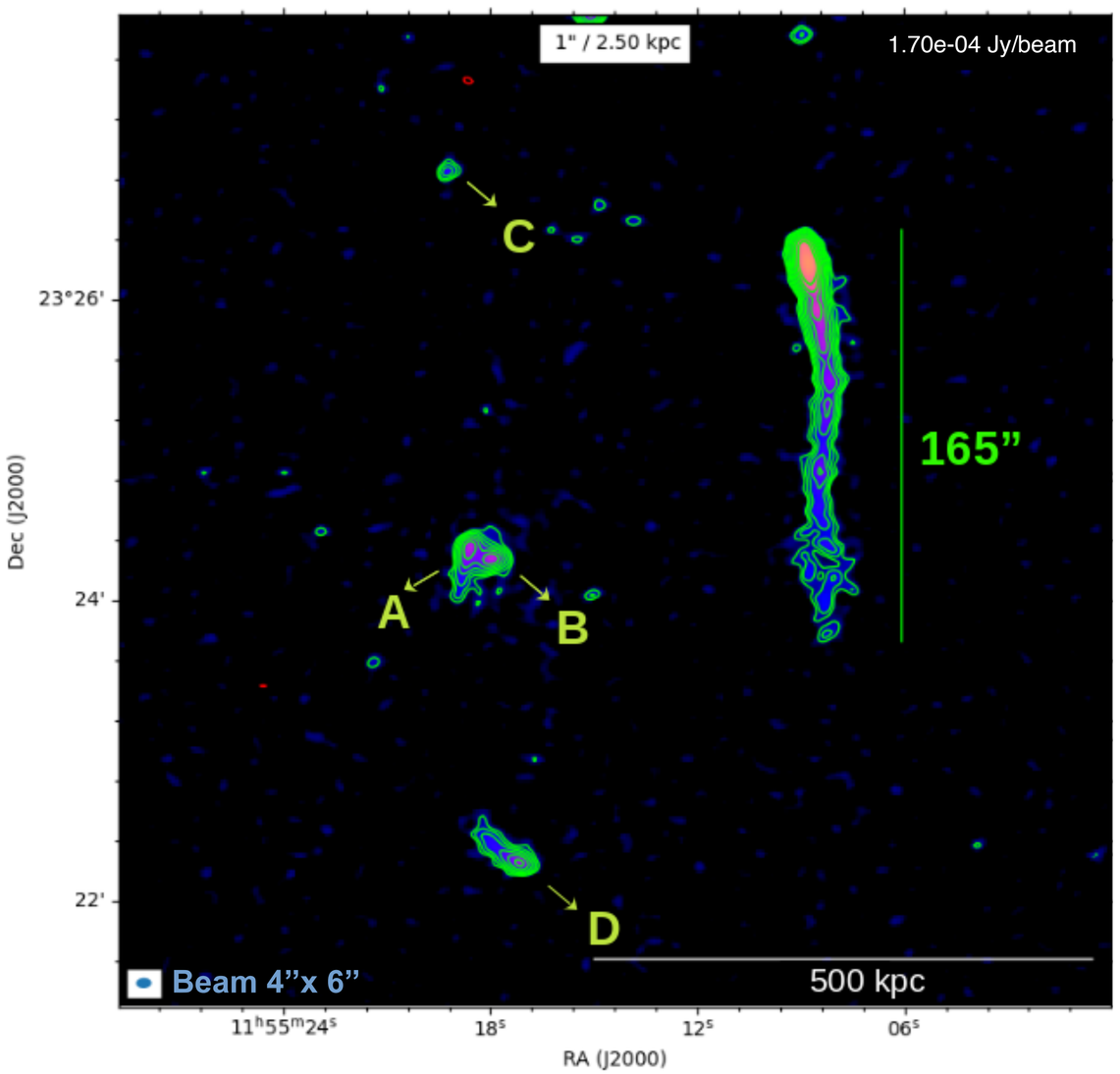
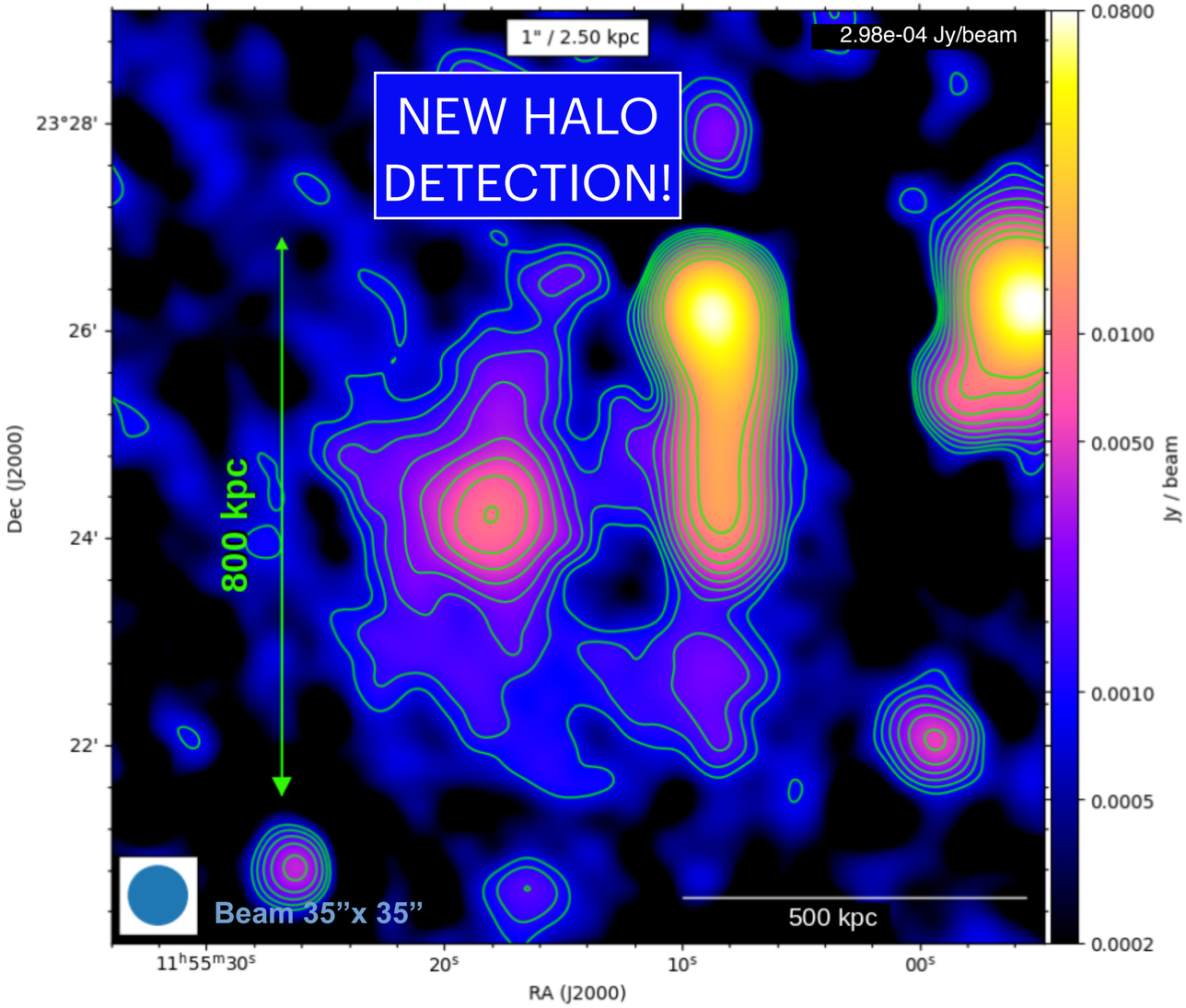
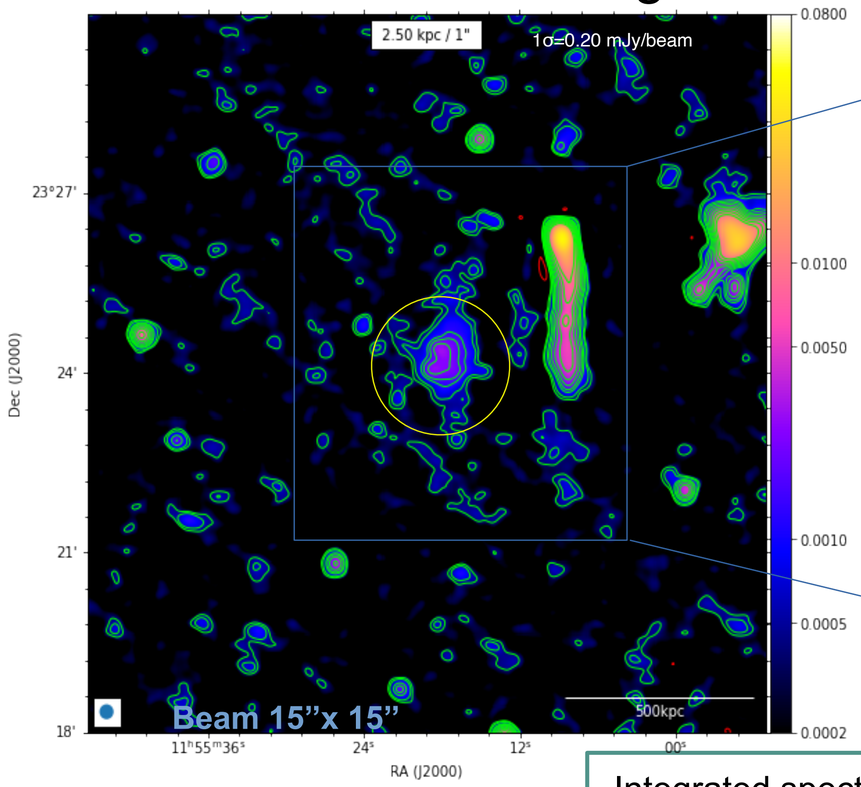


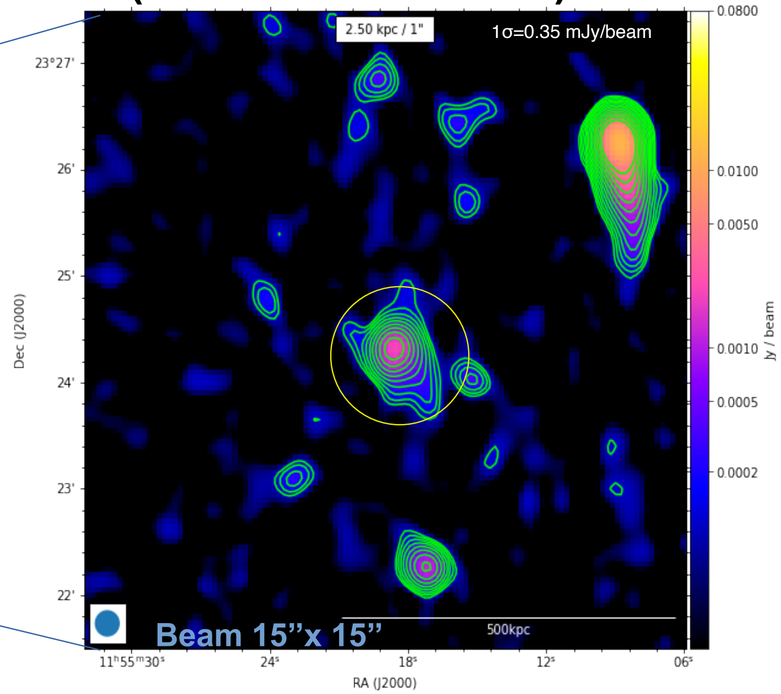


Comparison with high frequency data

LOFAR 114MHz image



VLA 1.4GHz image
(Govoni et al. 2009)



Integrated spectral index of central region

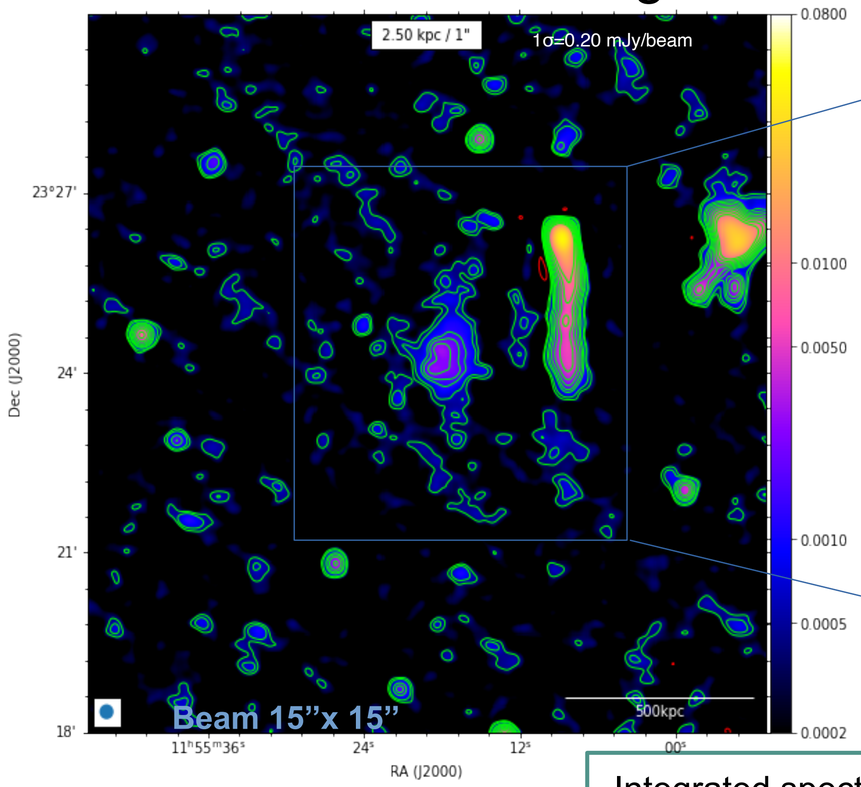
$S_\nu \sim \nu^{-\alpha}$

$\alpha =$ **1.1 ±0.2**

→ typical of mini-halo

Comparison with high frequency data

LOFAR 114MHz image



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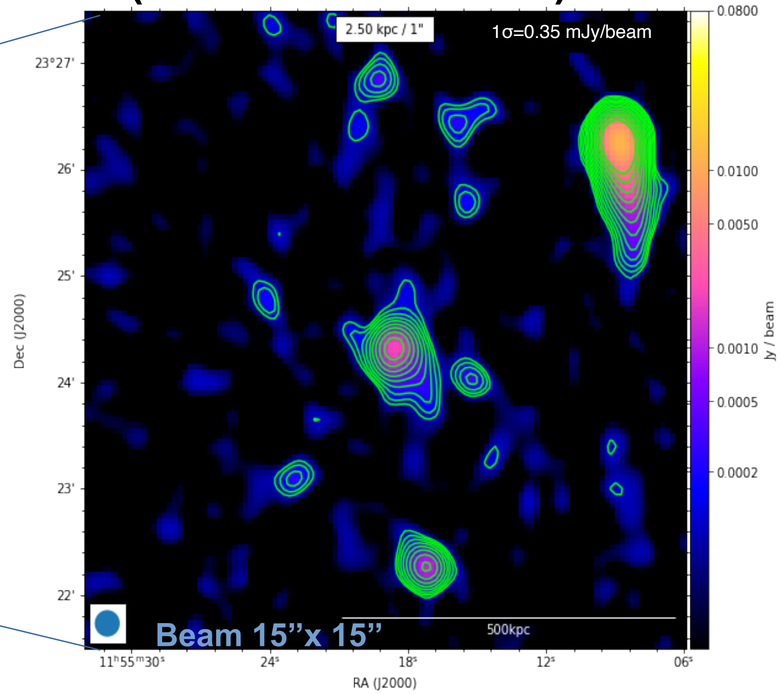


Integrated spectral index of central region

$S_\nu \sim \nu^{-\alpha}$

$\alpha =$ **1.1 ±0.2**

1σ limit for the **extended** emission

α > 1.6

→ typical of mini-halo

Halo emission analysis

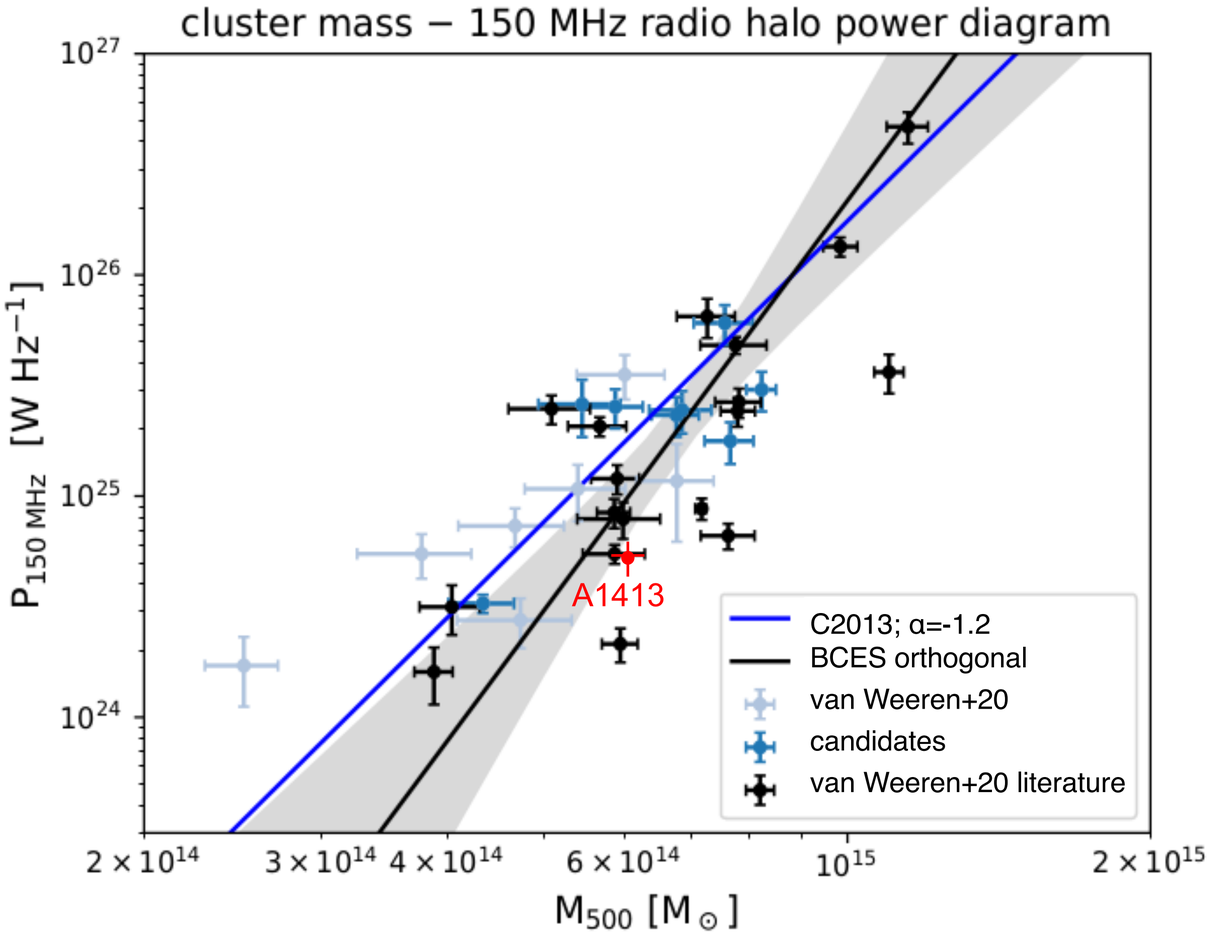
Radio Power – X-ray Luminosity relation

Radio Power – Mass relation

$P_{1.4GHz} \propto L_{X\text{-}ray}$ → $P_{144MHz} \propto M_{500}$

$\mathbf{P_{halo}}$=5.2±0.6 10^{24} W/Hz

$\mathbf{M_{500}}$=5.9±0.2 10^{14} M_{sun}



van Weeren et. al. 2020

Radio summary

- **New** halo **detection** in A1413 on ~800 kpc scale (N-S direction)
- A1413 hosts a **hybrid halo + mini-halo-like** radio source
- The 2 emissions have **different spectral index**

Point-to-point correlation

Point-to-point comparison between ***radio*** and ***X-ray*** *surface brightness*

$$\log(I_R) = A\ \log(I_X) + B$$

A<1
radio brightness declines
slower
than X-ray

A>1
radio brightness declines
faster
than X-ray

Point-to-point correlation

Point-to-point comparison between ***radio*** and ***X-ray*** *surface brightness*

$$\log(I_R) = A\ \log(I_X) + B$$

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radio brightness declines
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radio brightness declines
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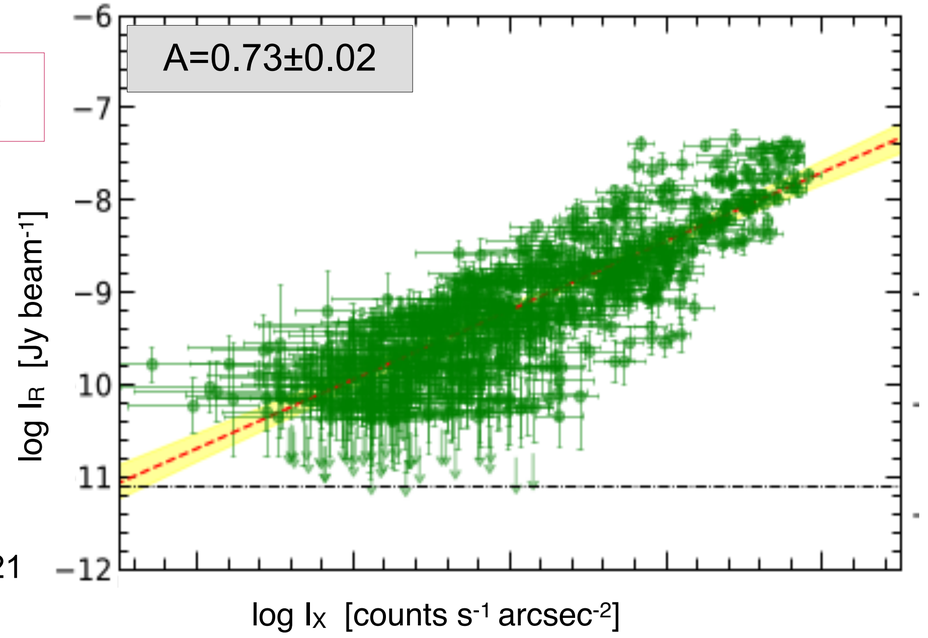
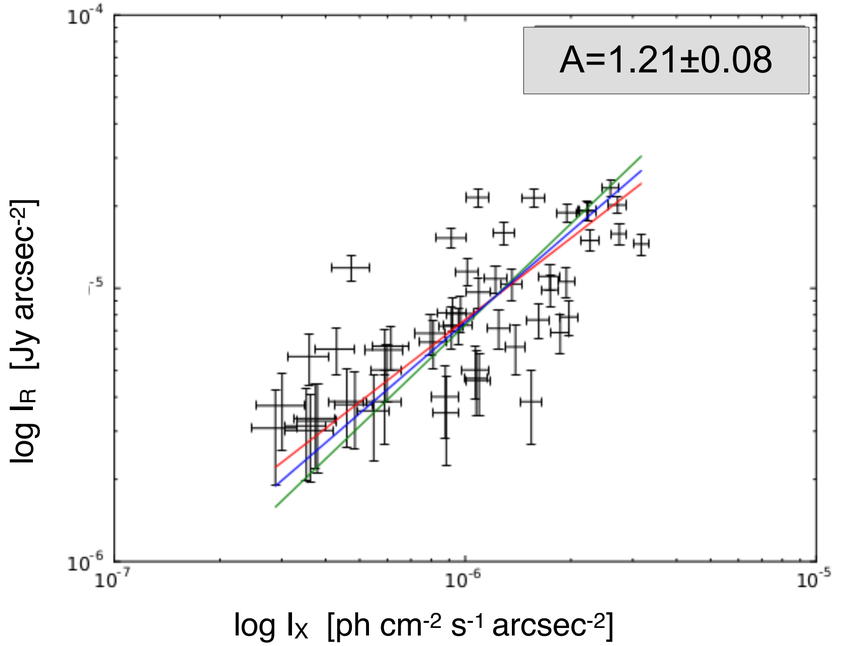
HALOS

Linear
or
Sub-linear
scaling



Rajpurohit et al. 2021

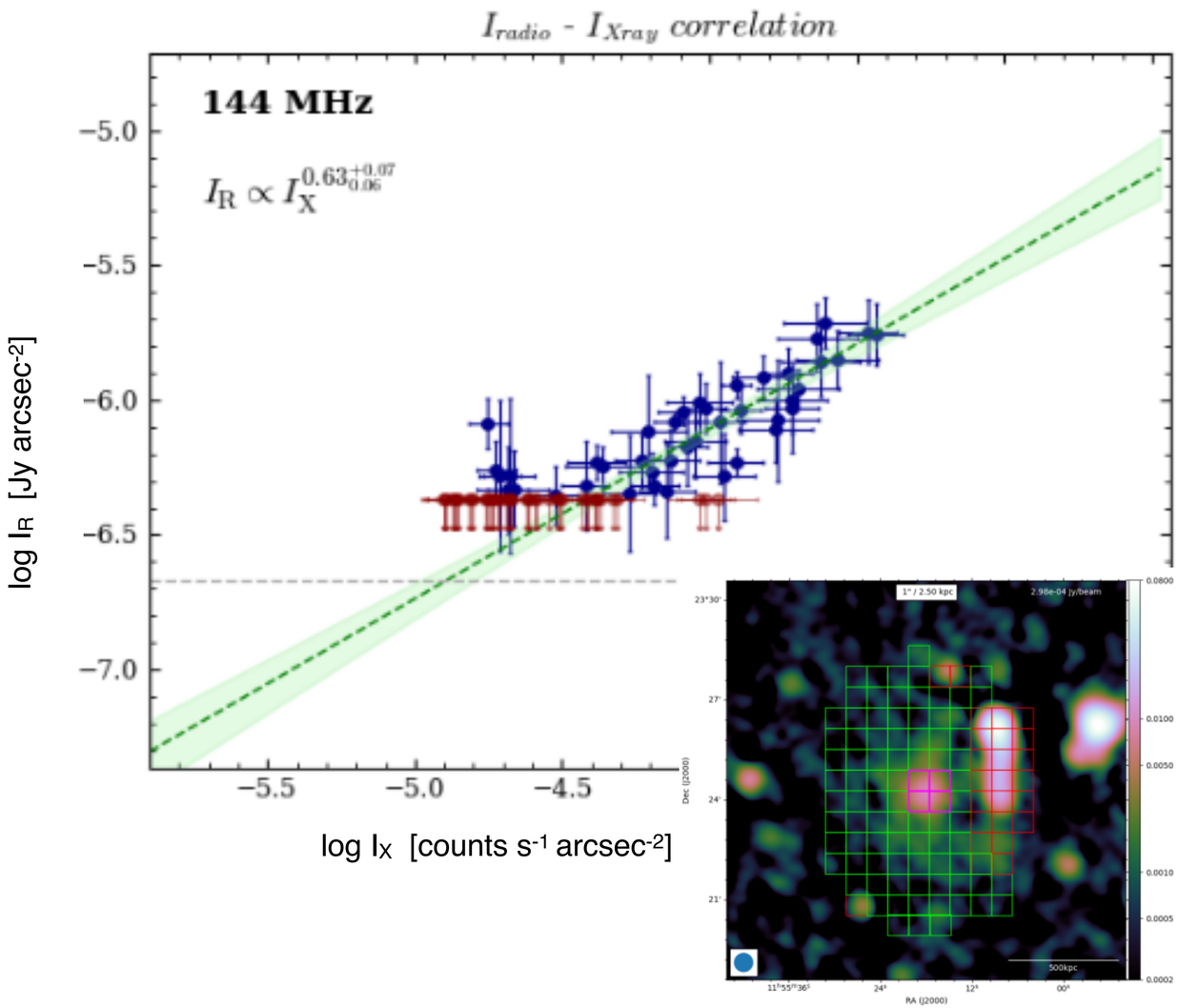


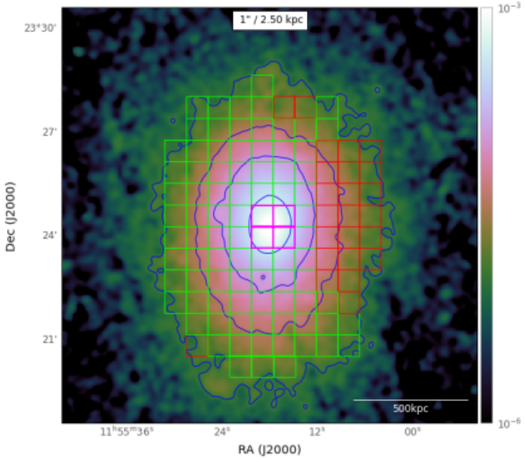
MINI-HALOS

Super-linear
scaling

Ignesti et al. 2020

Point-to-point correlation: *halo emission*





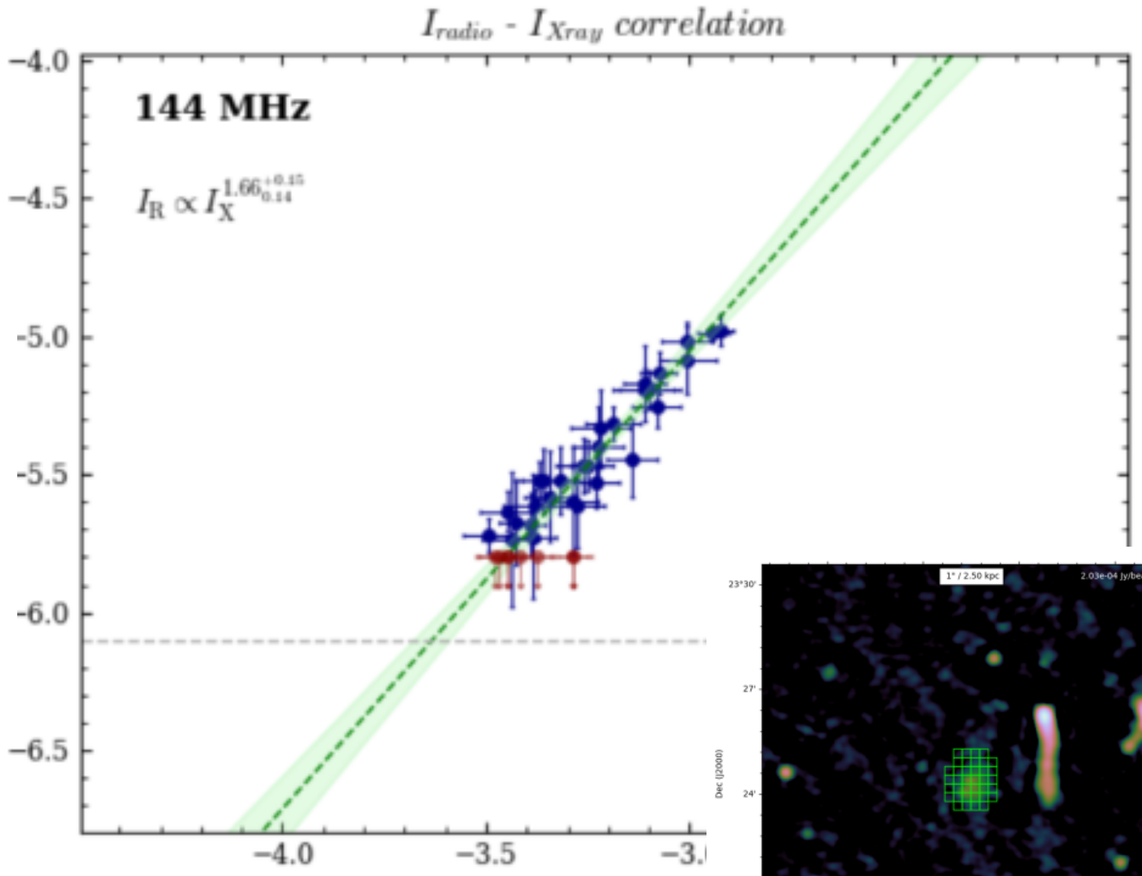
Halo	Grid	A	r_p
$I_R - I_X$	$35'' \times 35''$	$0.63^{0.07}_{0.06}$	0.82

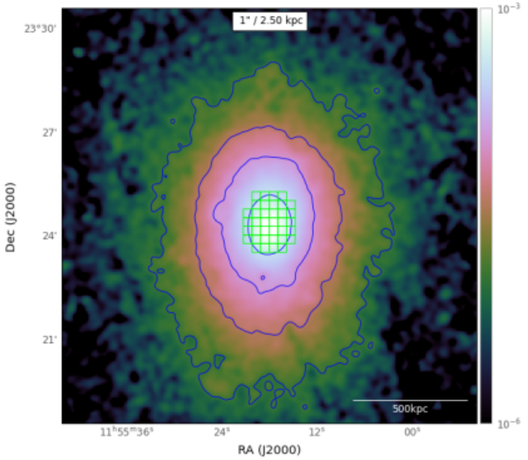
sub-linear

$I_{R,halo} \propto I_X^{0.63}$

(incompatible with hadronic models)

Point-to-point correlation: *mini-halo emission*





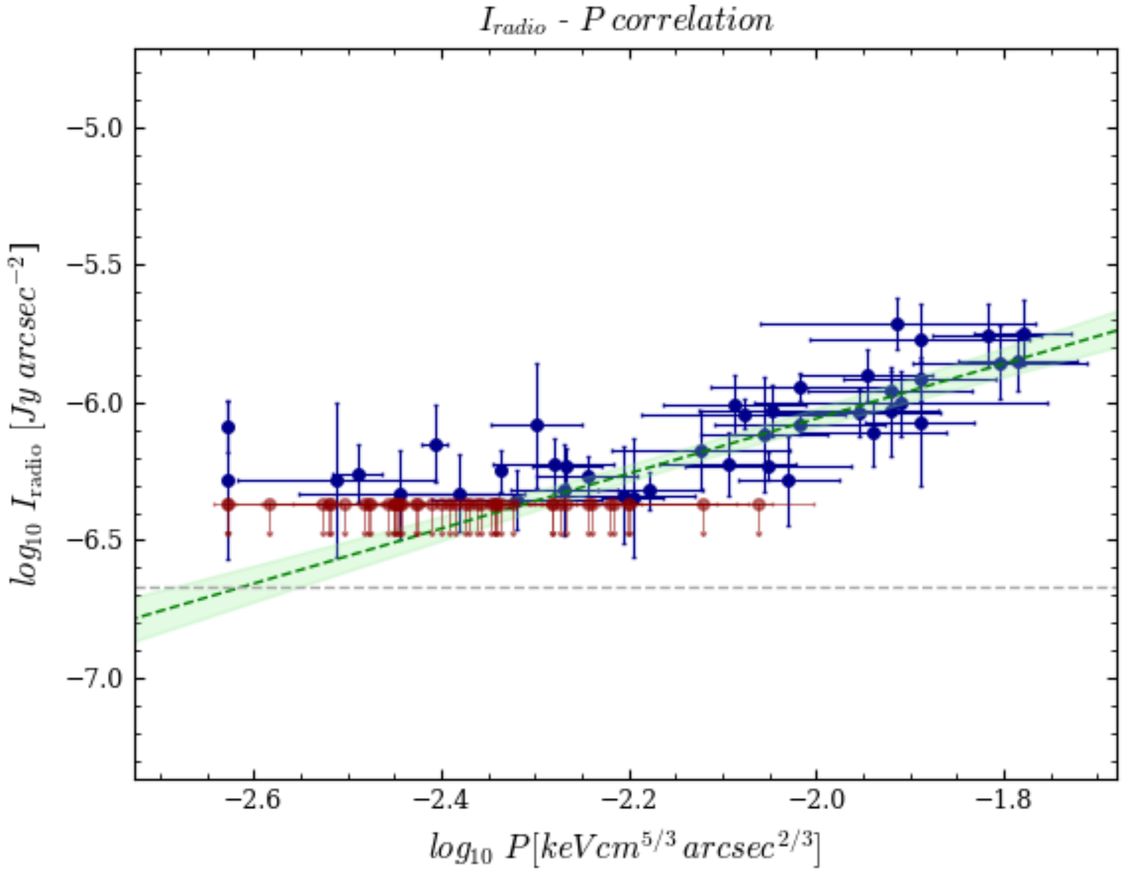
Mini-Halo	Grid	A	r_p
$I_R - I_X$	$15'' \times 15''$	$1.66^{0.16}_{0.13}$	0.93

super-linear

$I_{R,mini\text{-}halo} \propto I_X^{1.66}$

Further perspective:
connection with other thermodynamical quantities

Point-to-point comparison between ***radio*** surface brightness and ***pressure***



Halo	Grid	A	r_p
$I_R - P$	$35'' \times 35''$	$0.99^{0.13}_{0.12}$	0.78

$I_{R,halo} \propto P^{0.99}$

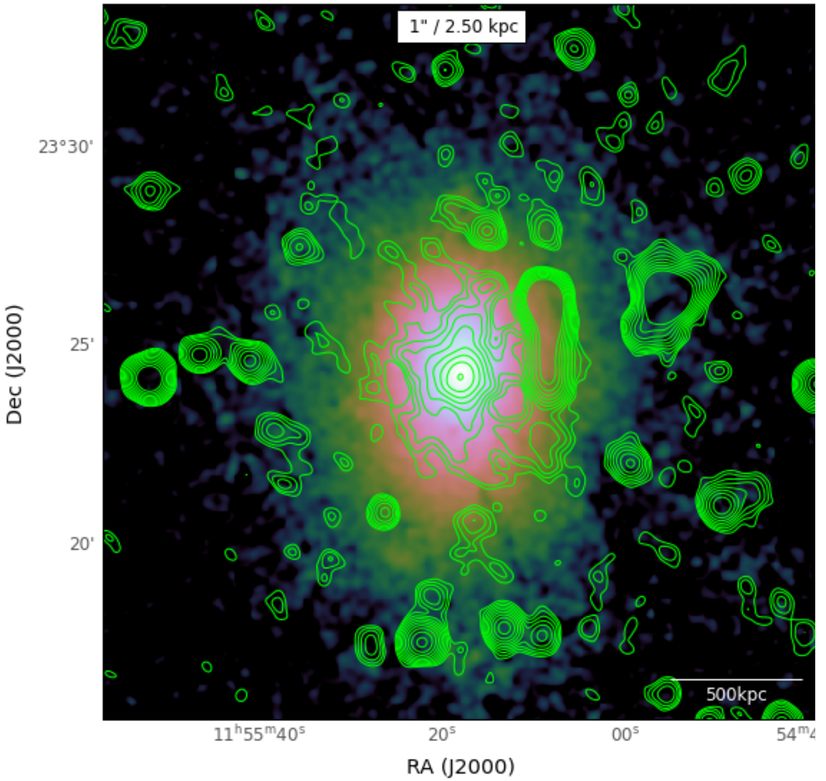
Summary:

- Multi-wavelenghts study
  - using archival **XMM-Newton** data newly processed
  - imaging of new recent **LOFAR** data at 144MHz from LoTTS

- A1413 is not undergoing mergers and does **not have a disturbed morphology**. There are indications that at later time the cluster experienced some minor merger event → **not fully relaxed cool-core**

- This turbulent event has created the extended radio halo emission wihtout destroying the cool core: cooling region < 90 kpc with
- $t_{central,cool} \sim 6$ Gyr < 7.7 Gyr $\sim t_{age}$ (**weak-cool-core cluster**)

- A1413 hosts an extended low brightness halo emission superimposed with a central mini-halo emission. The **coexistence** of two different kinds of radio emission is suggested by
  - Different spectral index: $\alpha_{mini\text{-}halo} = 1.1 \pm 0.2$ vs $\alpha_{halo} > 1.6$
  - Different X-ray and radio surface brightness correlations
  - $I_{R,halo} \propto I_X^{0.63}$ *sub-linear* *vs* $I_{R,mini\text{-}halo} \propto I_X^{1.66}$ *super-linear*




Thanks