Unravelling the origin of extended X-ray emission surrounding FR II radio galaxies

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in collaboration with
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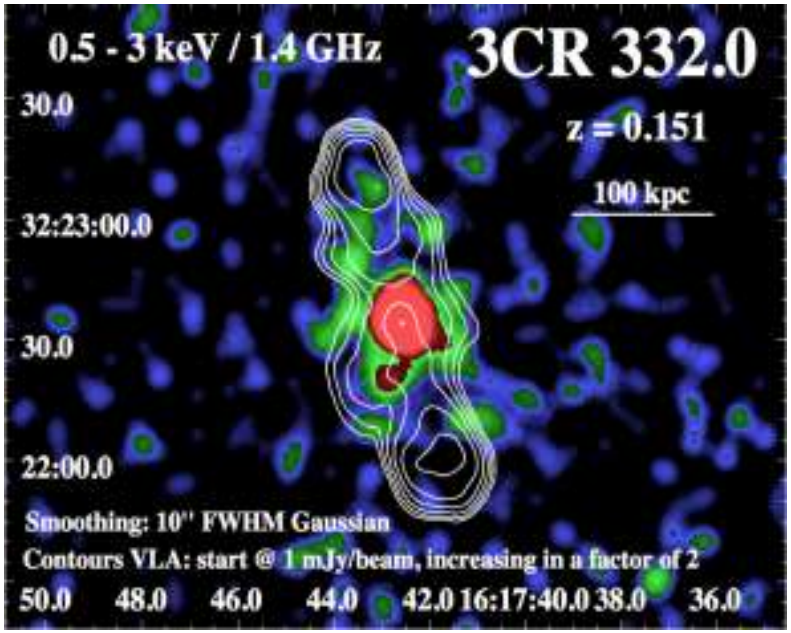
Outline

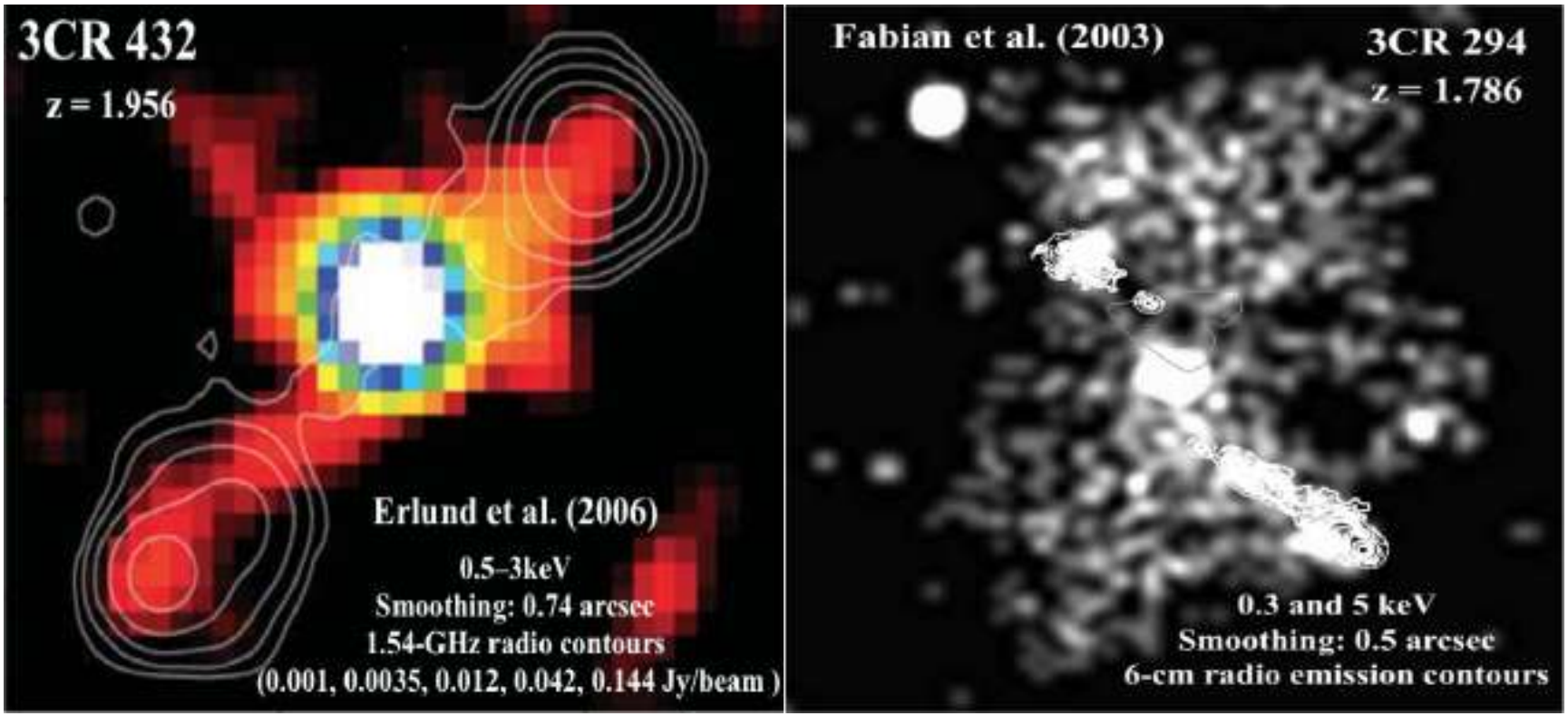
- Analysis of extended X-ray emission in FR II radio galaxies in the 3CR catalog.
  - Revealing lobes, hotspots and IGM from galaxy clusters.
  - Origin of extended X-ray emission.



- X-rays: 3CR *Chandra* Snapshot Survey
- Radio: NRAO VLA Sky Survey and MERLIN archival observations.
- Details of 3CR catalog and of 3CR *Chandra* Snapshot Survey presented in Alessandro Paggi's talk.

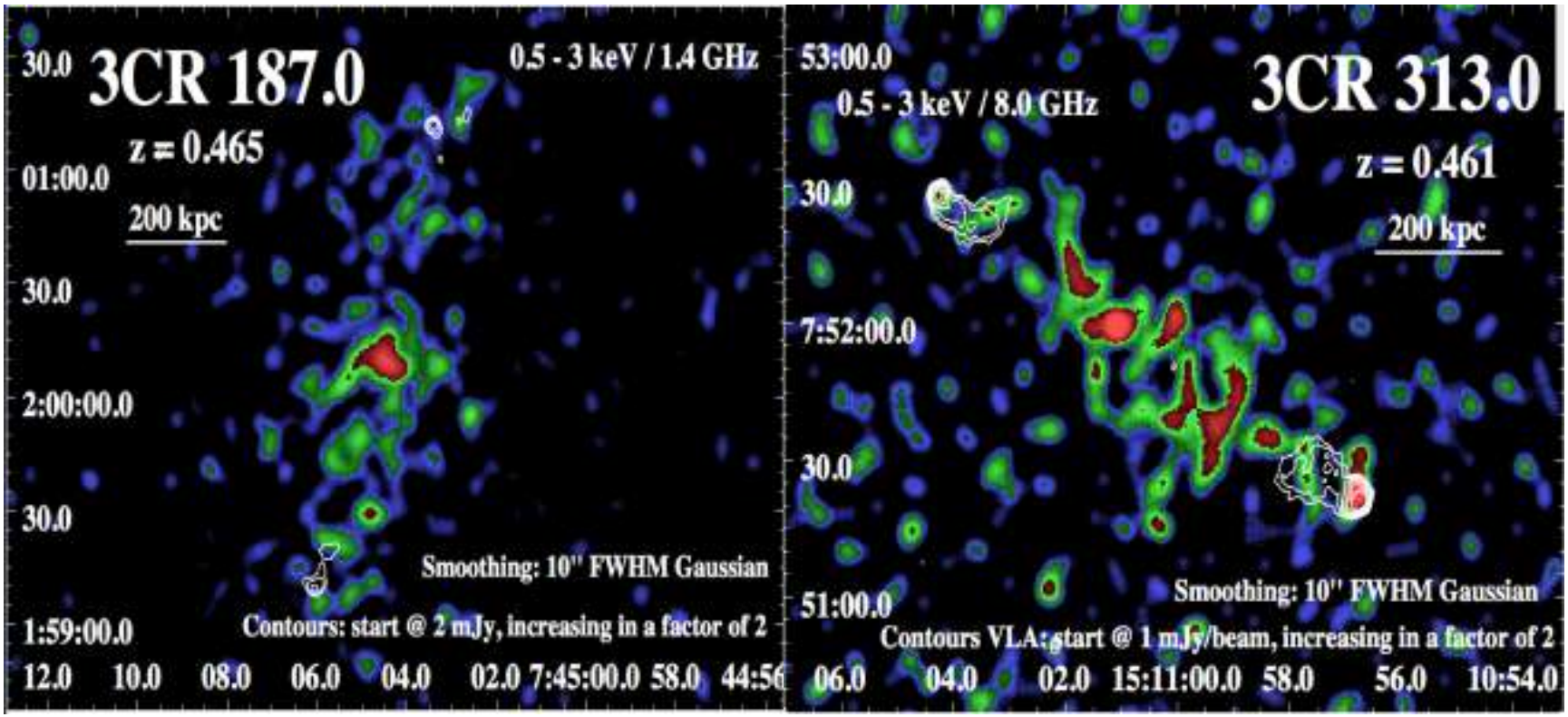
Extended X-ray emission along the radio axis

- Extended X-ray emission with no radio counterparts beyond the radio structure $\Rightarrow$ "X-ray halos".
- Fabian et al. (2003, 2009), Erlund et al. (2006), Smail et al. (2009, 2012).
- Traditionally found at $z \sim 2$.



Extended X-ray emission along the radio axis

- Extended X-ray emission along the radio axis also visible in the 3CR *Chandra* Snapshot Survey (< 20 ks and $z < 1$).



Origin of the extended X-ray emission

The nature of the extended X-ray emission with no radio counterparts can be:

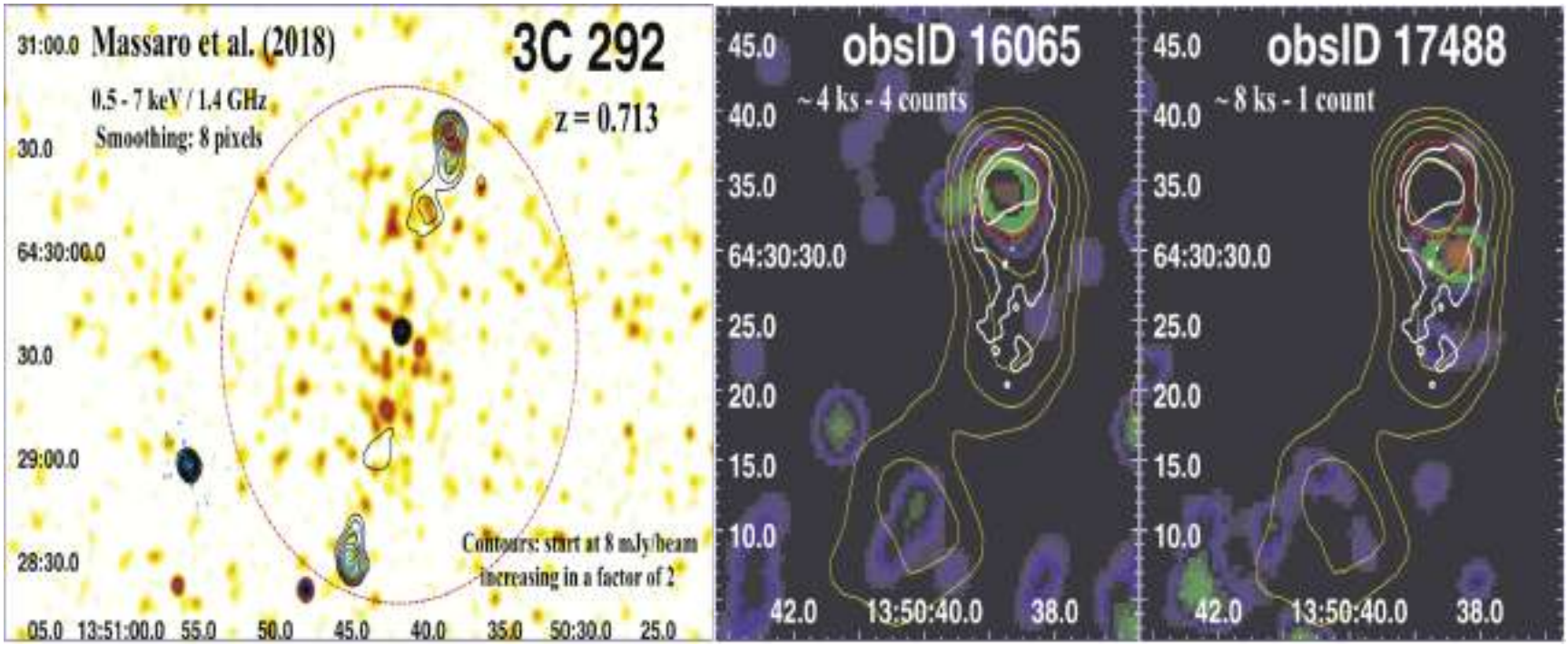
- Non-thermal: IC/CMB from lobes (Croston et al., 2005) not visible at GHz frequencies with VLA or MERLIN $\Rightarrow$ future LOFAR observations.
- Thermal: IGM from a galaxy cluster.
- A mixture of both.

To distinguish between these scenarios:

- X-ray morphology and extension of the emission $\Rightarrow$ X-ray surface brightness profiles:
  - Emission mostly concentrated along the radio axis suggests IC/CMB or both.
  - More symmetrical distribution suggests thermal emission from IGM.
- Large scale environments in optical/IR.

Hotspot detection

- Massaro et al. (2010, 2012, 2013, 2015, 2018) claimed detection of hotspots and lobes for sources in the 3CR *Chandra* Snapshot Survey.
- Sources with extended X-ray emission $\Rightarrow$ candidate hotspots could be fluctuations of "local background" (e.g., 3CR 292.0).



- Detection significance with respect to the "local background".

Sample selection

Sources spectroscopically identified as FRII radio galaxies from the sources in the 3CR *Chandra* Snapshot Survey observed before Cycle 20, excluding:

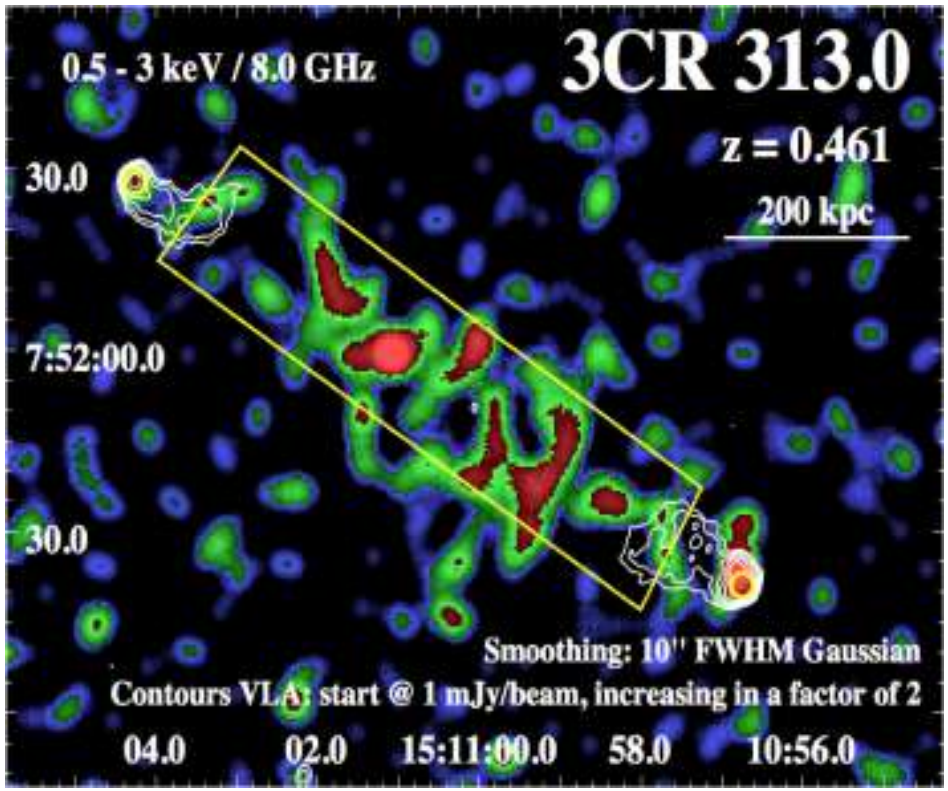
- 3CRR sources: work in progress (Wilkes et al., 2003; Nedzinskas et al., 2016)
- 3CR 187.0: Paggi et al. (in prep.)
- 3CR 196.1: Ricci et al. (2018)
- 3CR 320.0: Vagshette et al. (2019)
- Sources with angular sizes < 5 arcsec.

Total number: 37

Hotspot detection

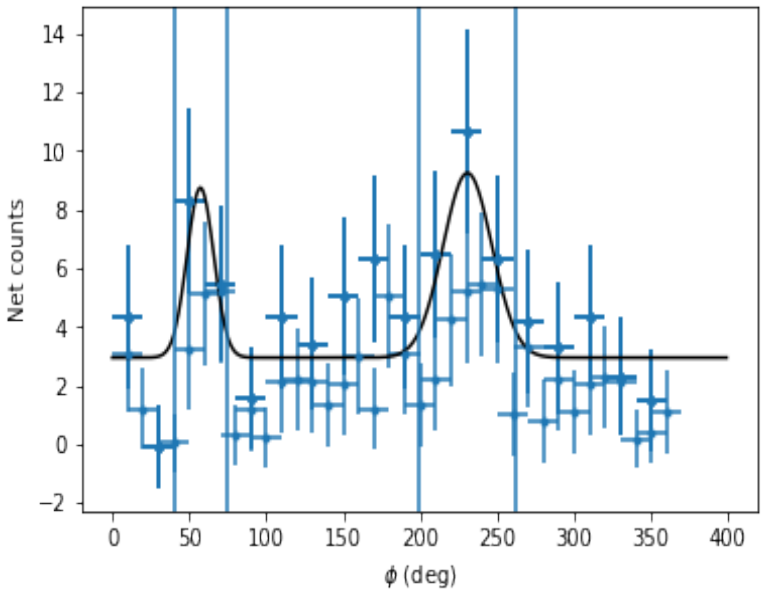
Using Poisson statistics: detection significance of hotspots with respect to background and to "local background", taking:

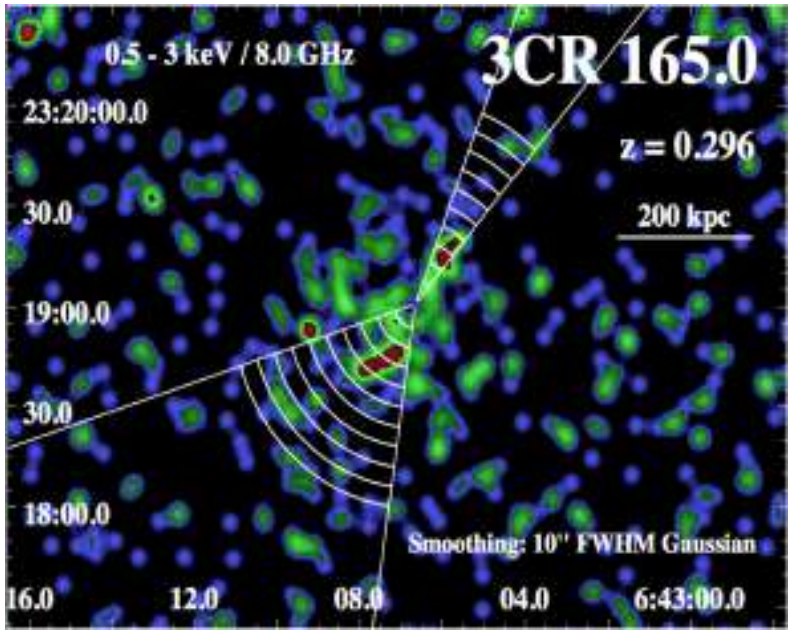
- Hotspots: a circular region of 2 arcsec of radius centered on the radio position of the hotspot.
- "Local" background: a polygonal region including the extended emission along the radio axis.



X-ray surface brightness profiles

- To choose cone and crosscone directions: angular bins of 10 - 20 degrees and fitted with a double Gaussian.
- Binning of 4, 6 or 8 arcsec for the extension of the radio source and changing to an adaptive binning based on the SNR further away.



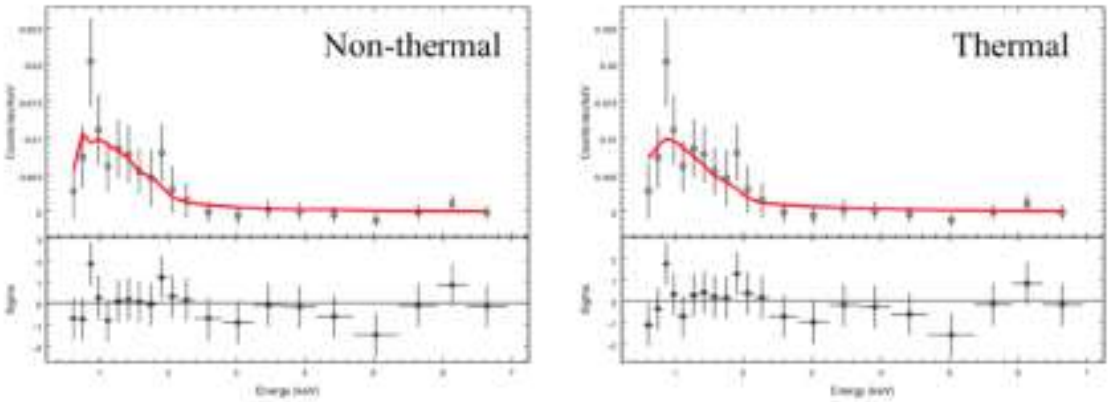


- Detection of hotspots as “enhancements” in the SB profiles.
- Fitting the SB profiles using a standard β model (Cavaliere & Fusco-Femiano 1976, 1978) $\Rightarrow$ presence of a galaxy cluster and the extension of the X-ray emission.

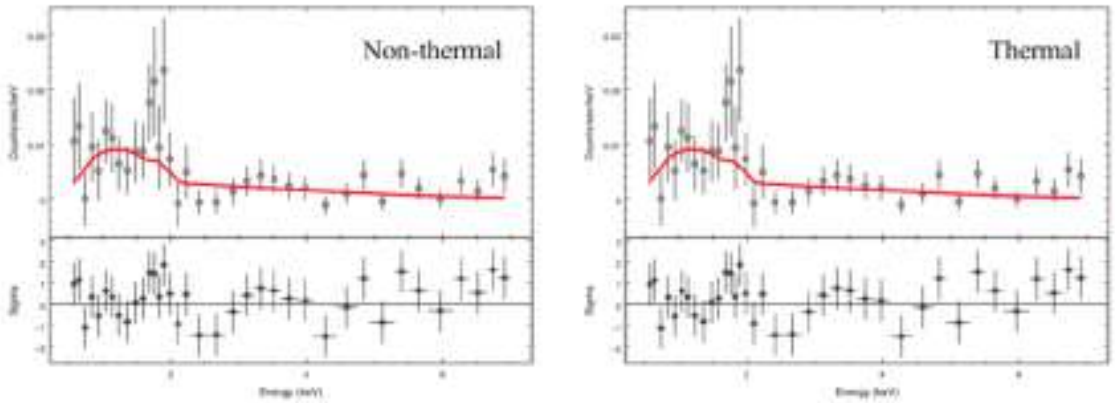
Spectral analysis

Spectral analysis for the north (139 counts) and south (278 counts) cones of 3CR 187.0:

North cone



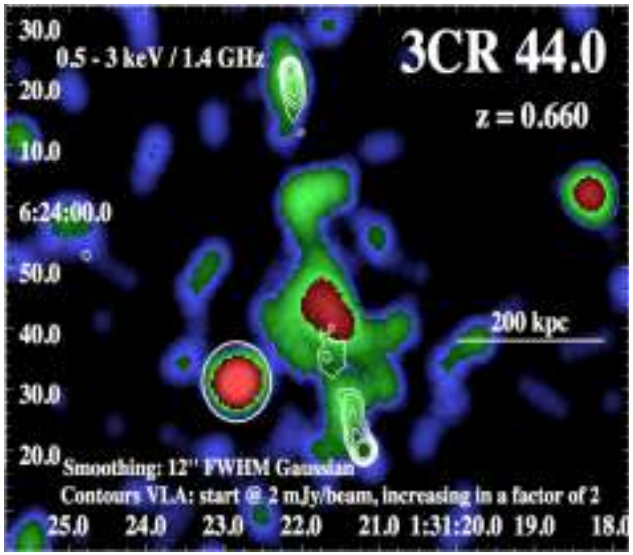
South cone

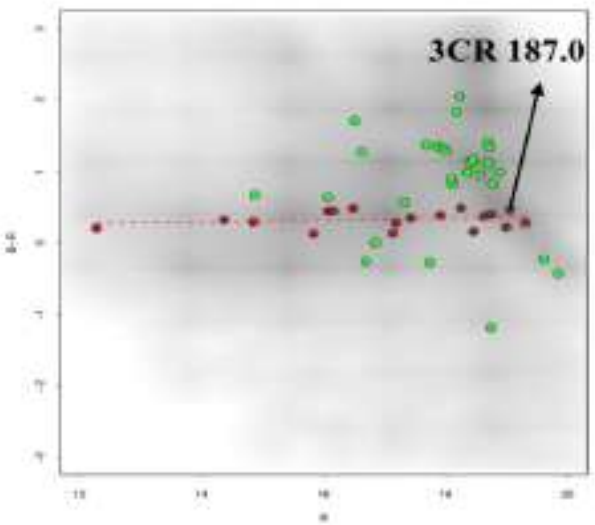


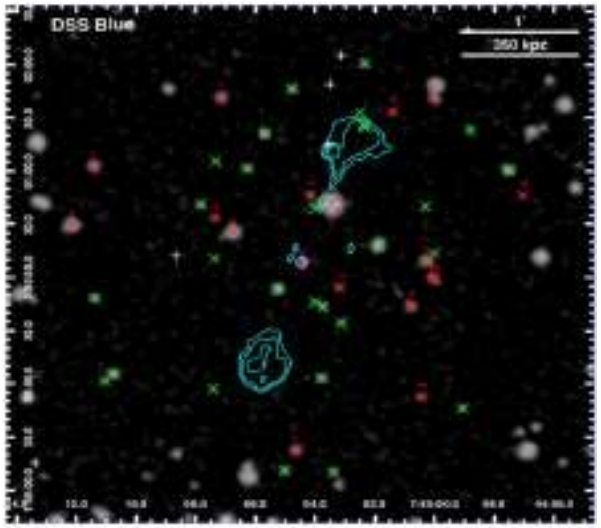
Discriminating between thermal and non-thermal emission just from the spectral analysis is not feasible.

Perspectives

- Detection of point sources with CIAO task **wavelet** not sufficient ⇒ Manual subtraction comparing with WISE.
- Additional check: red sequence using PANSTARRS.



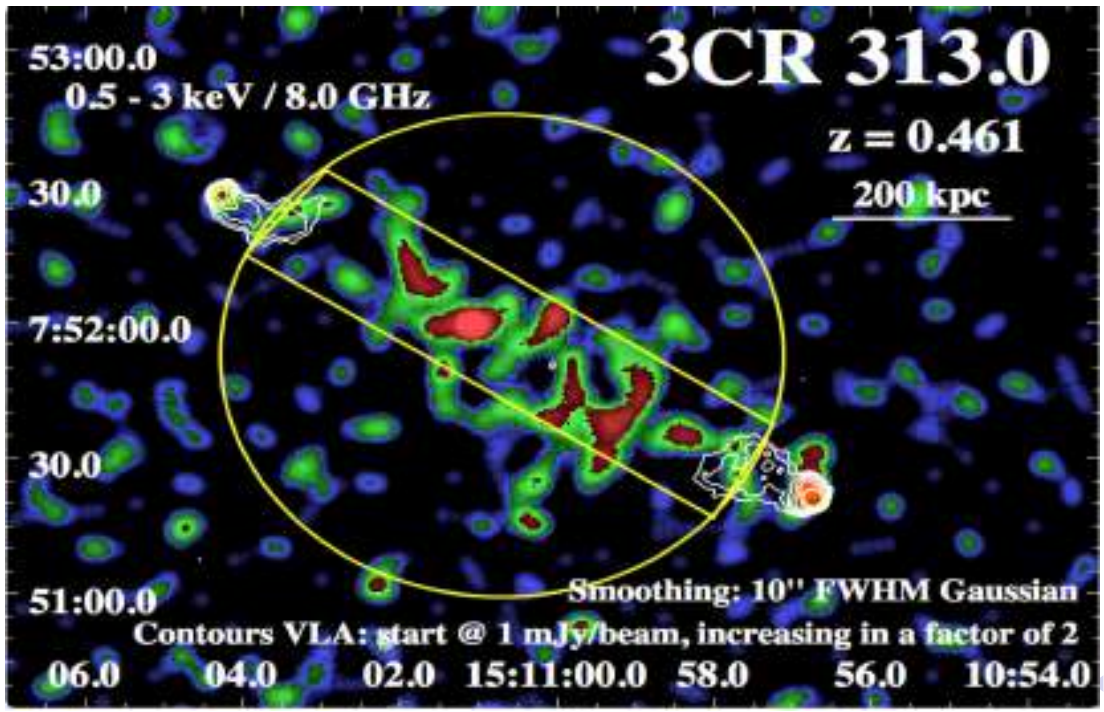




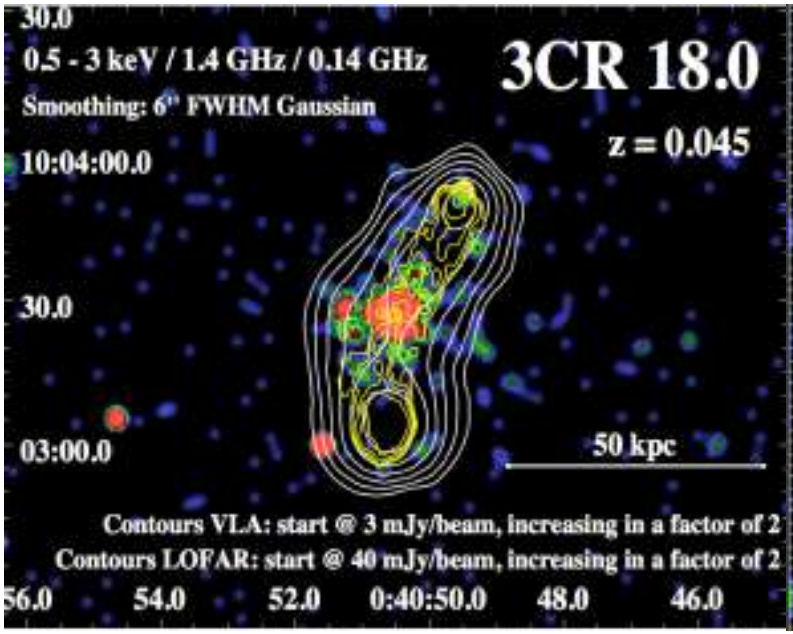
Detection of hotspots

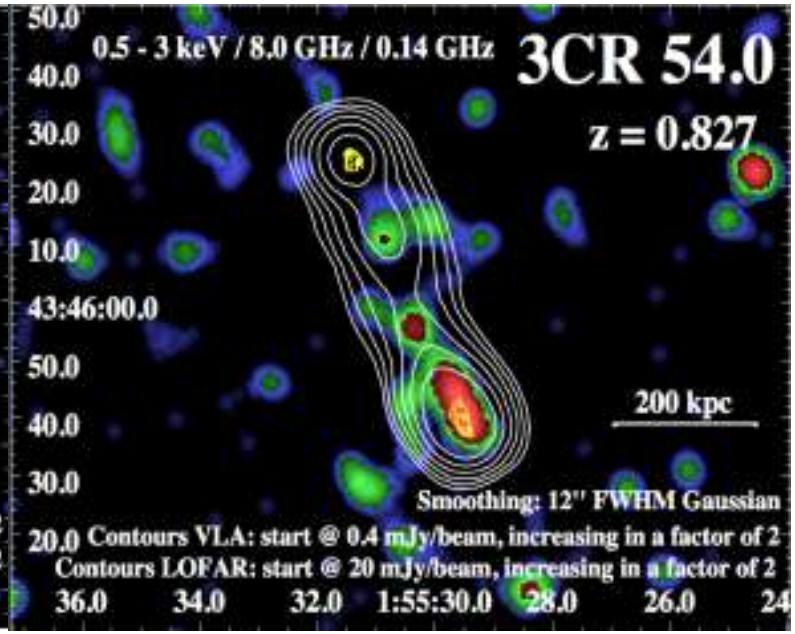
Comparing with Massaro et al. (2010, 2012, 2013, 2015, 2018) for the 37 RGs in our sample:

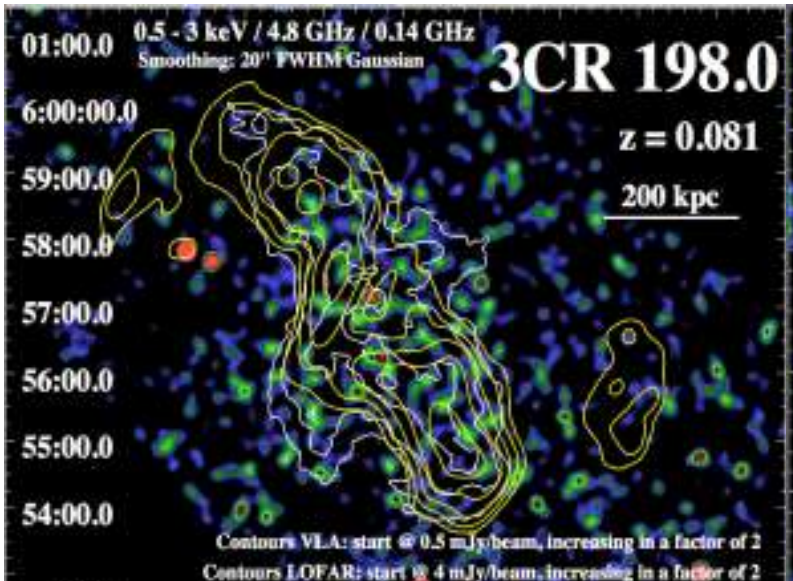
- Cone emission: 33 sources with significant ($\geq 3\sigma$) cone emission, 25 above 5σ, only 3 previously claimed.
- Crosscone emission: 20 sources, 13 above 5σ, no IGM detection claimed in the literature.
- Hotspots: 19, 5 above 5σ, only 7, 4 above 5σ, considering the "local background". In the literature, 6 were claimed.

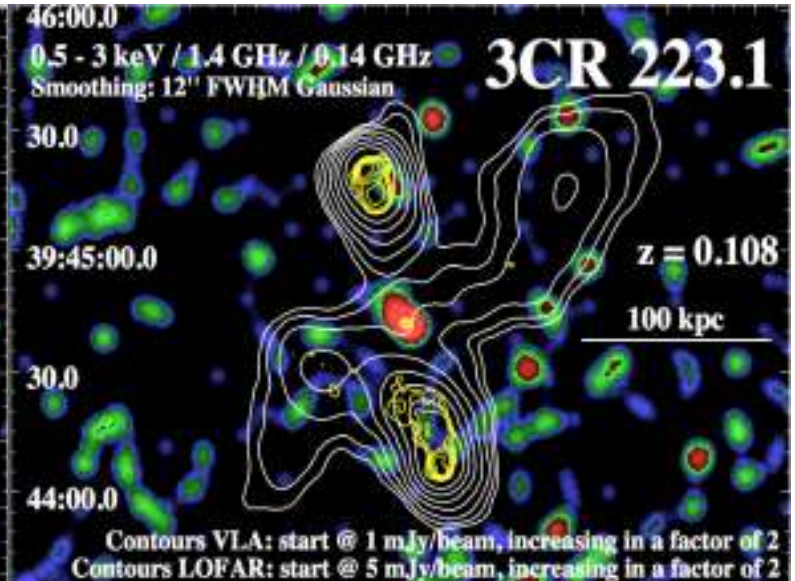


LOFAR observations

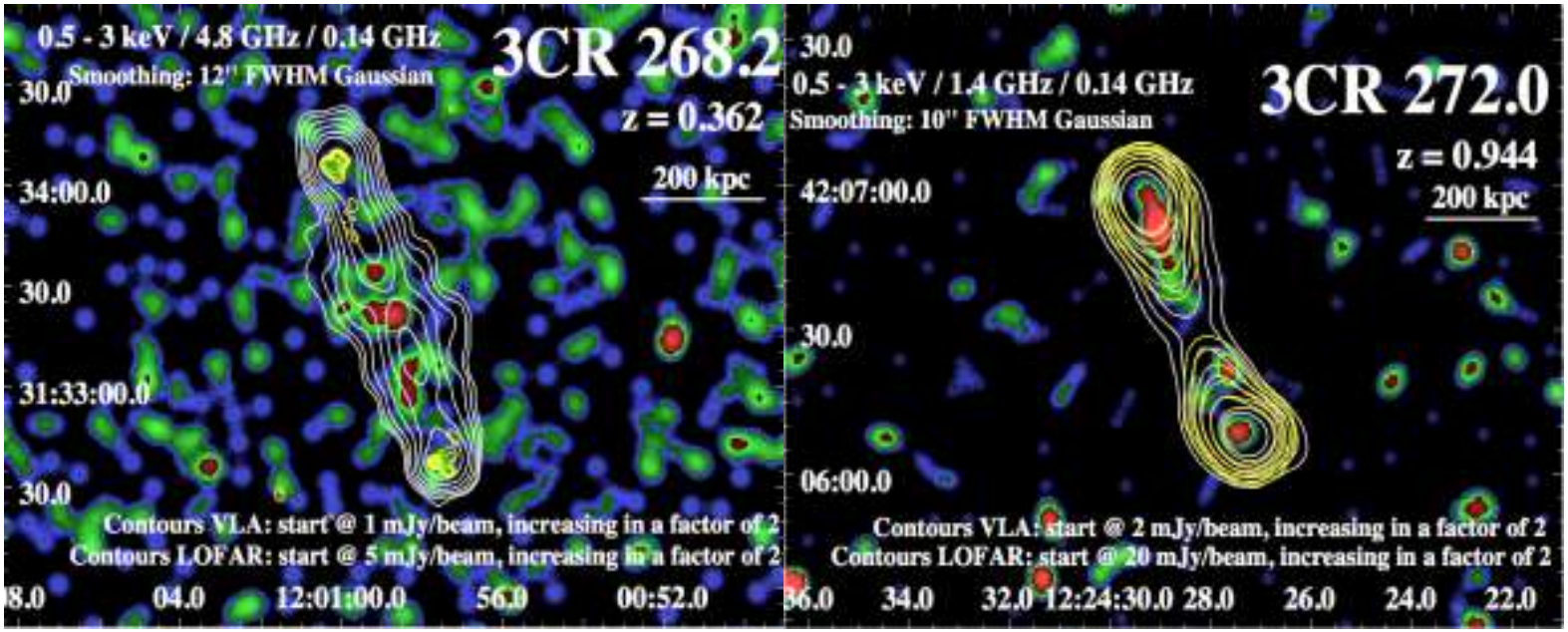








LOFAR observations

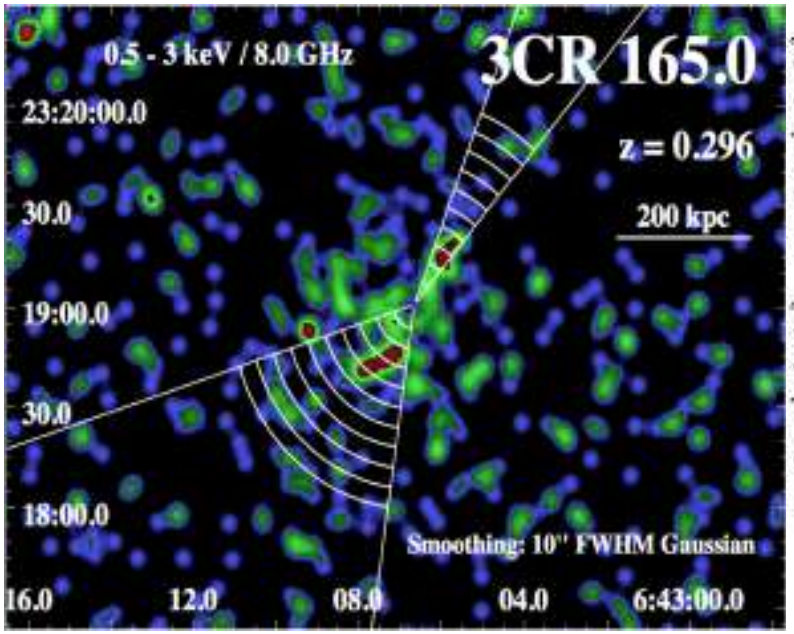


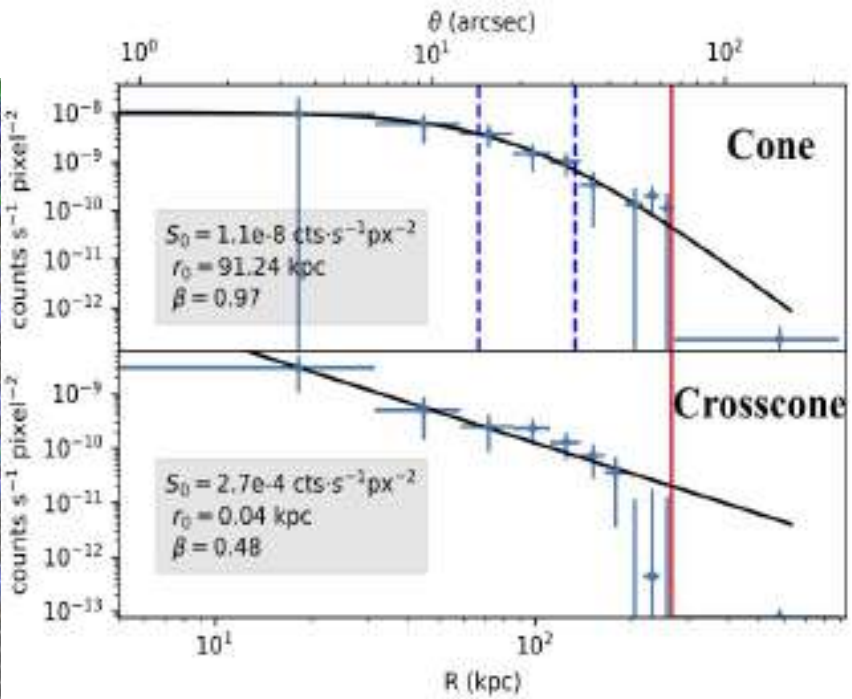
X-ray surface brightness profiles

Aims:

- Typical SB profiles for cone and crosscone of FR IIs.
- Presence of IGM to verify if FR IIs are isolated.

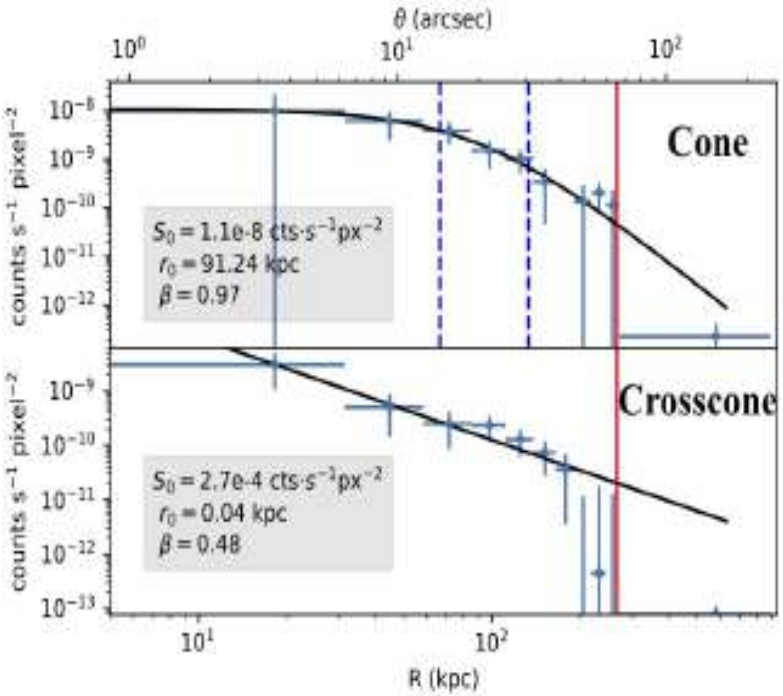
$$S_b(r) = S_0 \left[1 + \left(\frac{r}{r_0}\right)^2\right]^{1/2-3\beta} \quad (1)$$

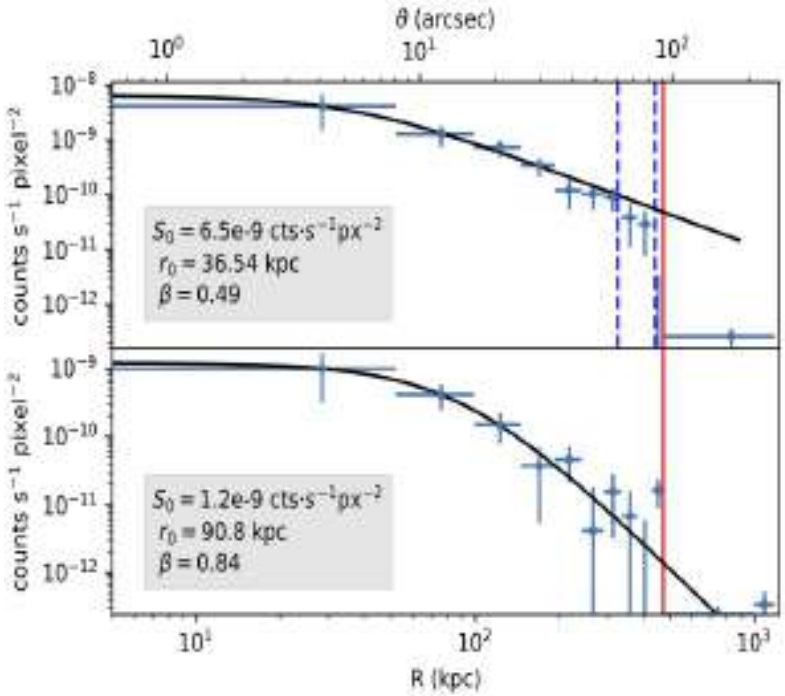




X-ray surface brightness profiles

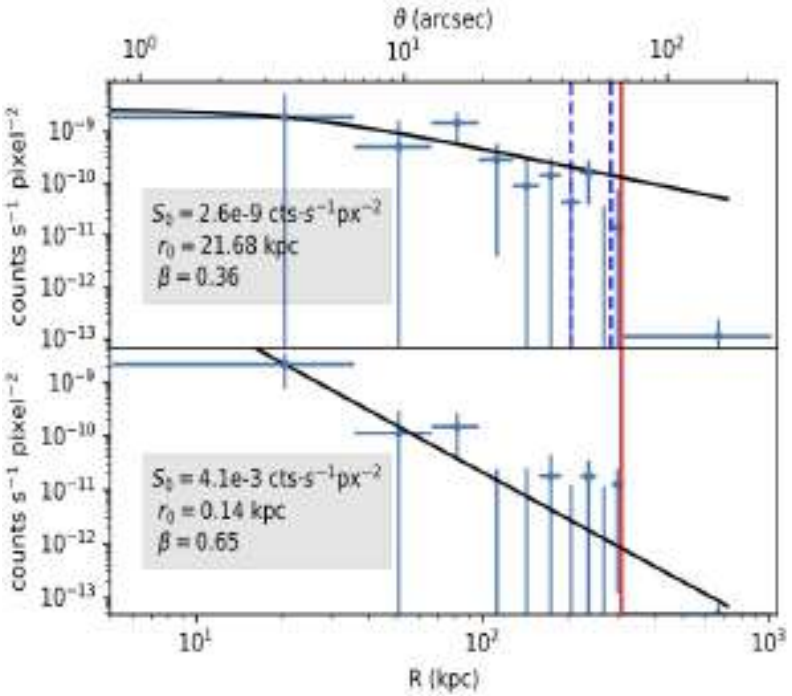
3CR 165.0 and 3CR 313: extended X-ray emission along the radio axis for all the extension of the radio emission, but less extended along the crosscone direction (emission from cone and crosscone detected for both).

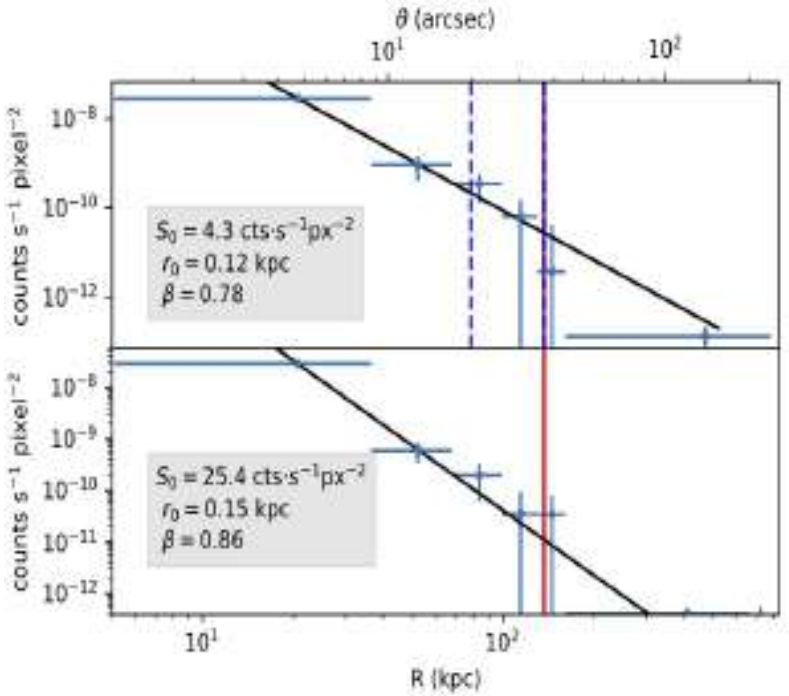




X-ray surface brightness profiles

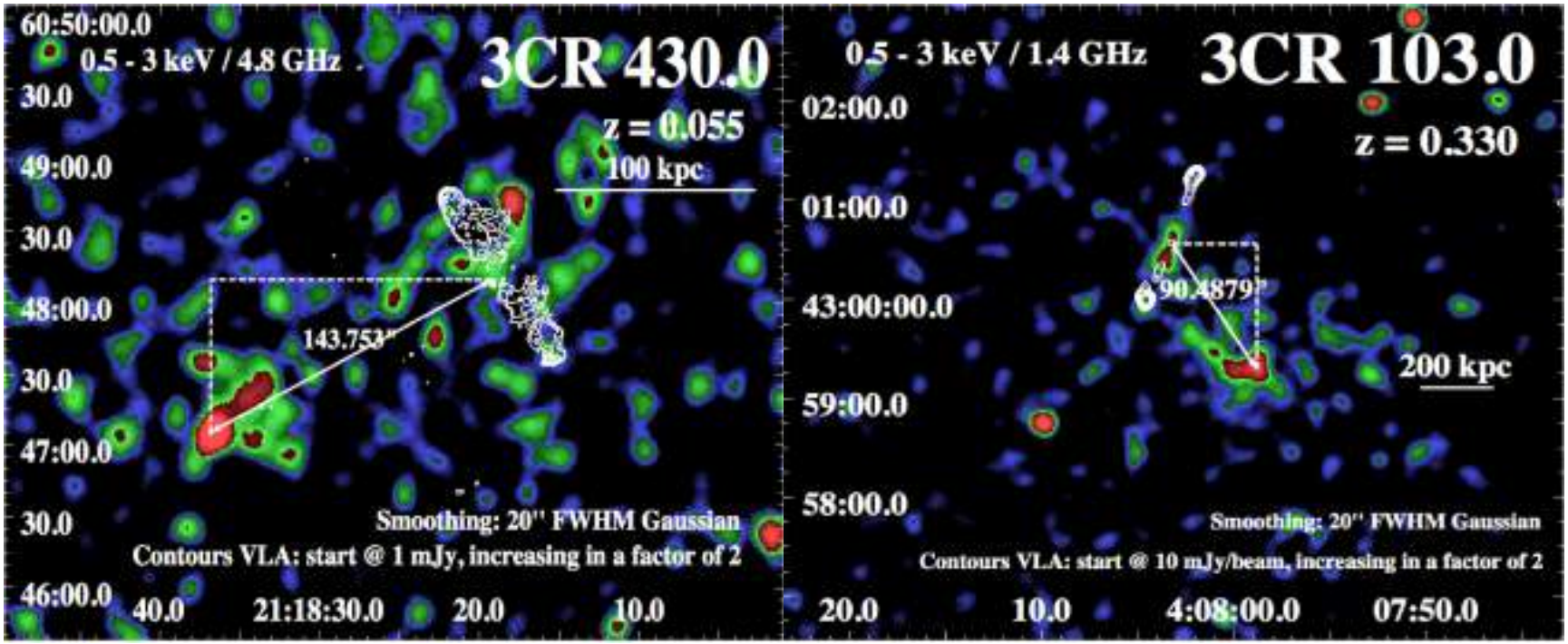
3CR 268.2: Cone more extended than crosscone (which was not detected).
3CR 410.0: Similar SB profiles for cone and crosscone (both detected).





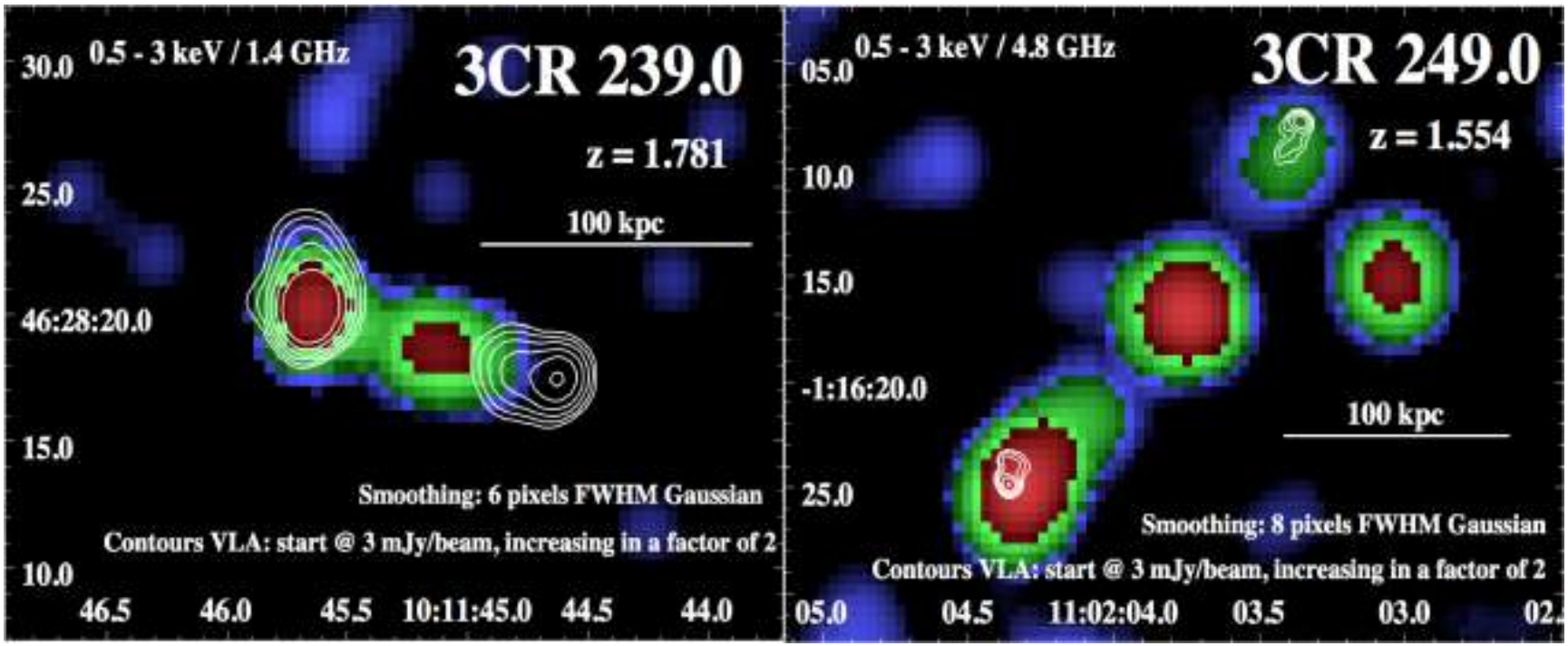
Galaxy clusters

Additionally, we discovered, with only a few ks, galaxy clusters that were not previously reported ⇒ Follow-up X-ray observations planned!



AO 20

- AO20 at $z > 1 \Rightarrow$ we expect more IC/CMB from lobes, $u_{CMB} \propto (1+z)^4$.
- Out of the 7 already observed $\Rightarrow$ 4 of them seem to have also extended X-ray emission along the radio axis.



Conclusions

- Out of the 37 FRII radio galaxies in our sample:
  - 33 of them have significant ($\geq 3\sigma$) emission along the radio axis, 25 of them above 5σ.
  - 20 of them also present extended emission in the crosscone direction, 13 above 5σ $\Rightarrow$ maybe thermal emission from IGM in galaxy clusters or a combination of both.
  - For those with no extended emission along the crosscone $\Rightarrow$ maybe IC/CMB from lobes $\Rightarrow$ LOFAR observations could confirm the presence of lobes.
  - We detect 7 hotspots over the cone background, 4 of them above 5σ.
- Perspectives: optical/IR analysis to confirm presence of galaxy clusters.
- Follow-up observations planned.
- Paper in preparation.