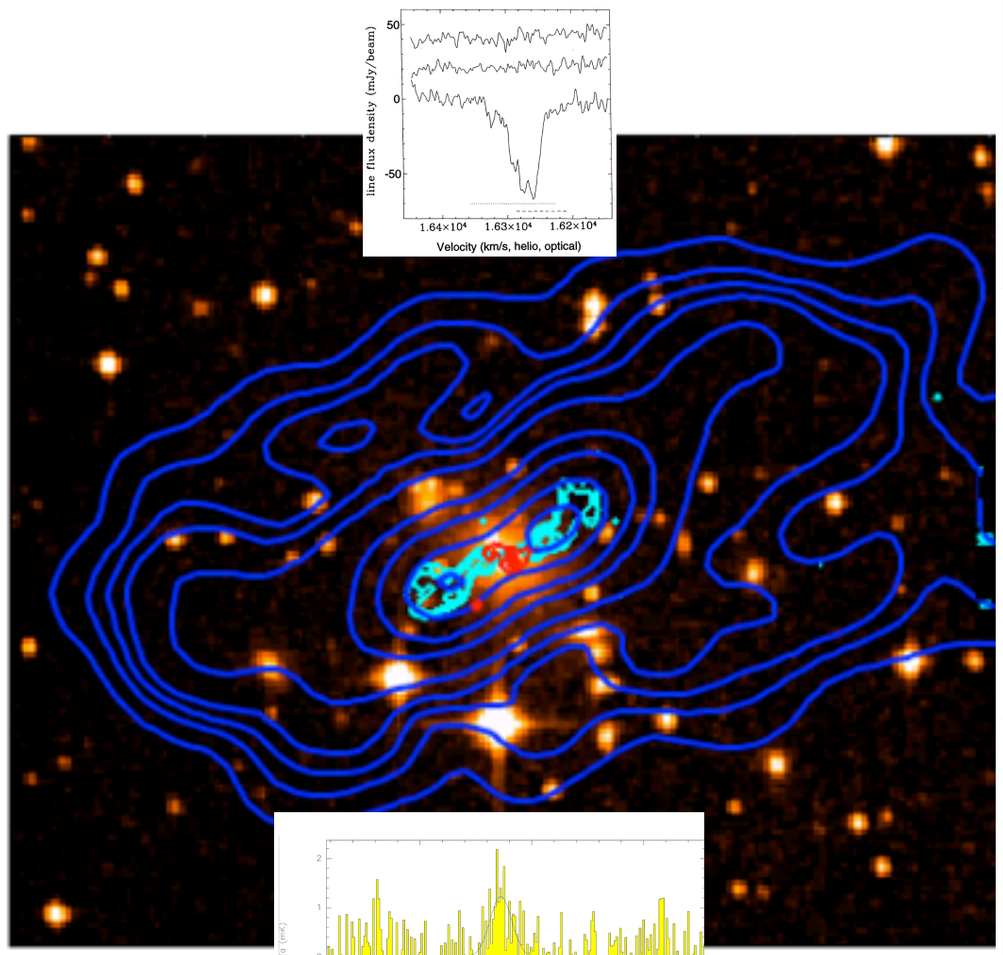
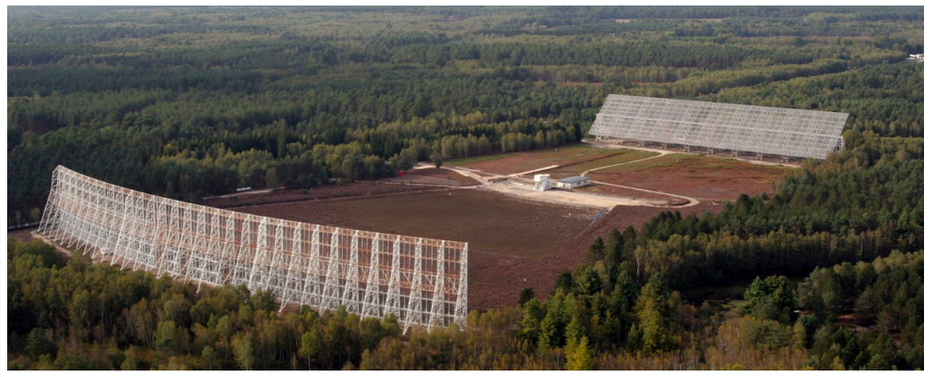
Probing the non-thermal emission and cold gas in Galaxy clusters





Mamta Pommier

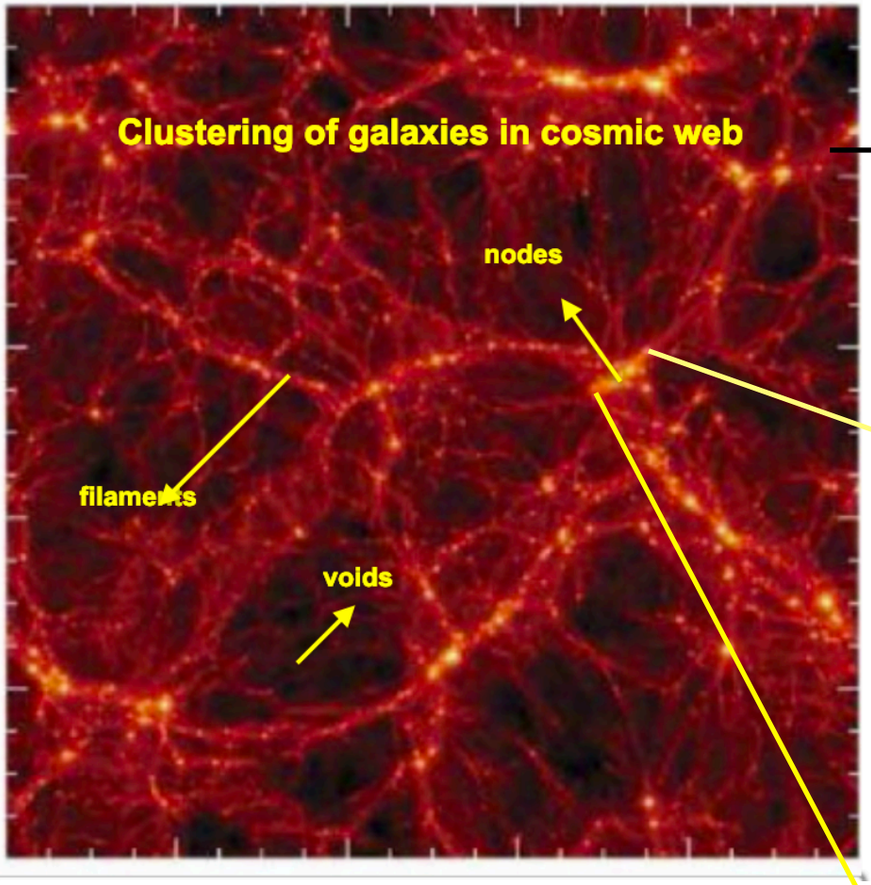
USN, Paris Observatory and CRAL- Lyon observatory, France

W. van Driel, A. Edge, F. Combes, B. Guiderdoni, H. Röttgering , M. Brüggen, J. M. Martin, P. Bonifacio + LOFAR/WEAVE consortium members

Plan of the talk

- **Galaxy clusters**
- **Non-thermal emission at low frequencies (GMRT, LOFAR, NenuFAR)**
- **Bright galaxies in the cluster environment**
- **Cold gas (Optical, CO)**
- **HI survey with the NRT**
- **Prospects with MeerKAT and Apertif**
- **SKA Science case**
- **Conclusion and future surveys**

Feretti et al.2012, Brüggen et al.2011, Brunetti & Jones 2014



80% (dark matter) +15% (diffuse hot gas) + 5% (baryonic matter in galaxies and intracluster medium (ICM)

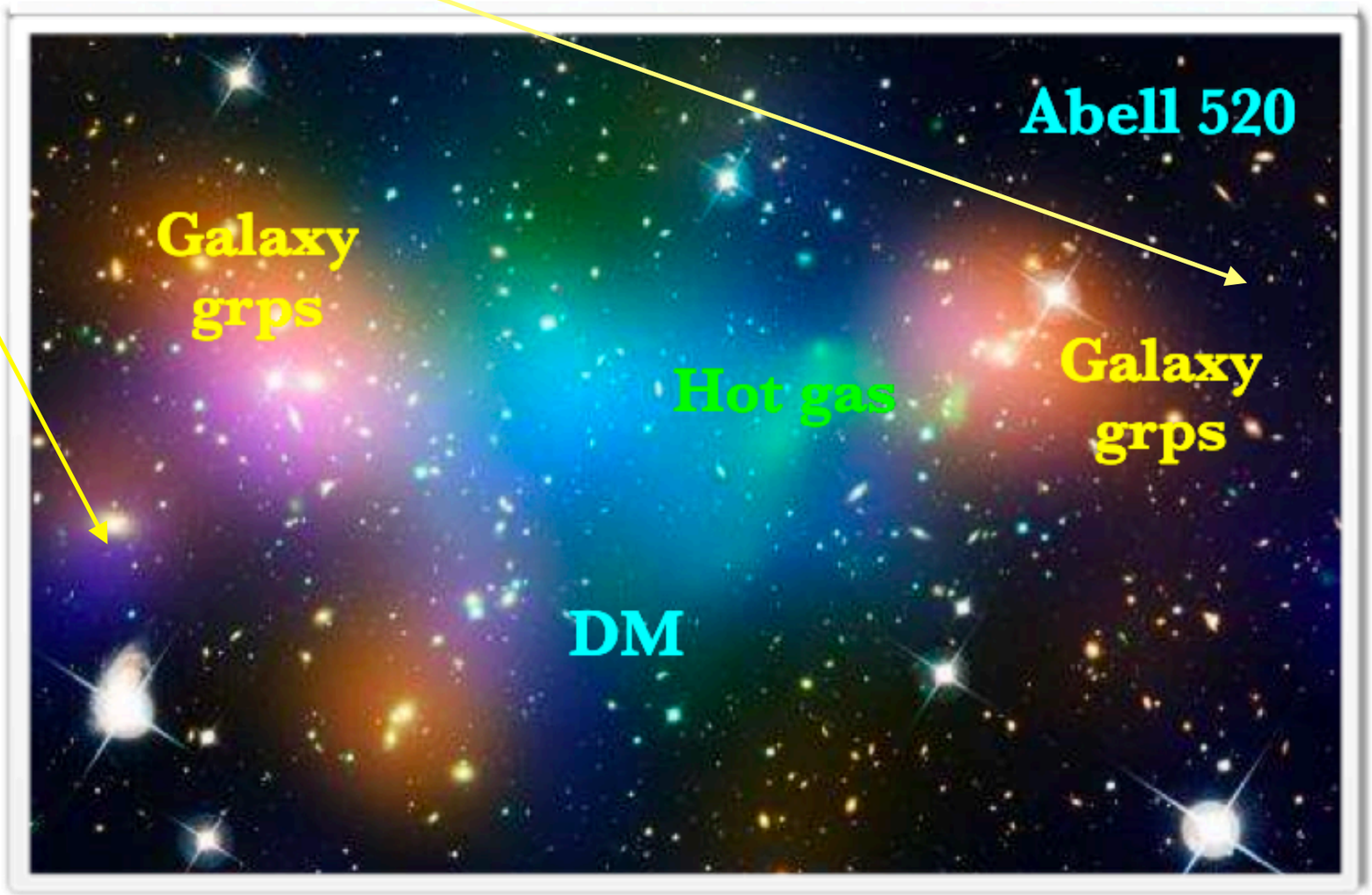


Fig. Galaxy Cluster classification

Galaxy clusters at low frequencies

Pandey-Pommier et al. 2013, 2014,2015,2016,2019

1. **Non-thermal emission in clusters pose fundamental question about their origin, impact on the thermal gas as well as the interaction between thermal and non-thermal gas components giving important insights on the cluster dynamical state and its evolution.**
2. **Radio emission measured in the ICM of ≥120 clusters (GMRT/LOFAR), however the detection rate still remains at the tip of the ice-bergs**
3. **Ultra steep spectrum radio haloes are new population yet be discovered with the SKA!**

Survey: **GMRT/LOFAR/VLA/NRT/IRAM/MUSE/HST survey on 28 cluster of galaxies from MACS catalog** (Ebeling et a. 2001)

*(**P.I M. Pommier**, F. Combes, B. Guiderdoni, J. Richard + M. Bruggen, H. Rottgering, G. Brunetti, T. Shimwell + LOFAR KSP members)*

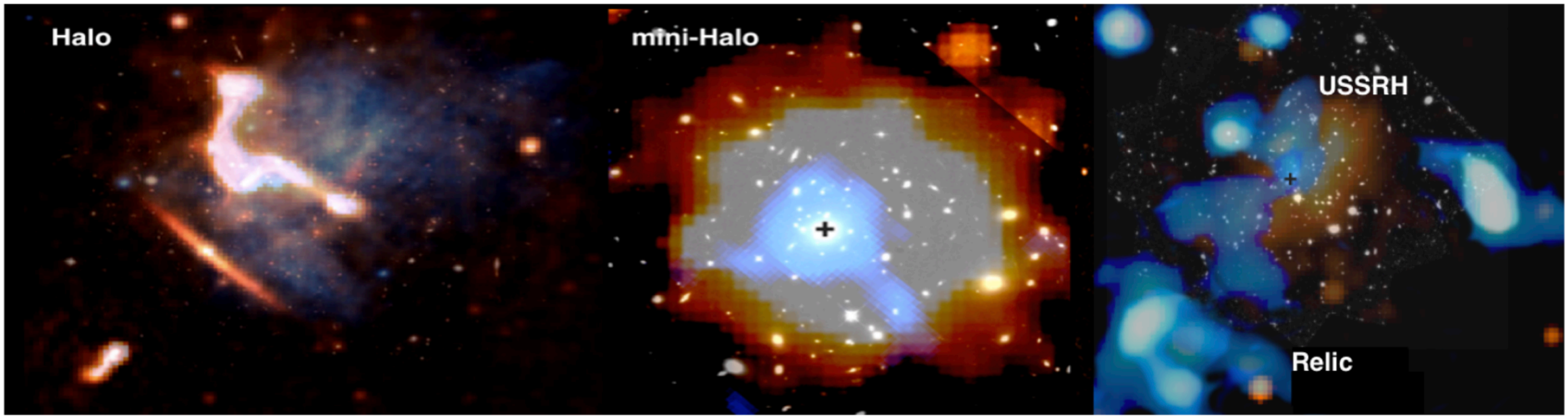


Fig. Non thermal emission in Galaxy clusters at low frequencies with the GMRT/LOFAR

Result- Cluster dynamical state and non-thermal emission

Pandey-Pommier et al. 2013, 2014,2015,2016,2019

5. **Diffuse radio emission from the ICM detected in 80% clusters of our sample.**

6. **84% of merging clusters (non cool core) host diffuse central Giant halo (> 1 Mpc), relic or phoenix emission. 75% cool-core clusters host radio mini-halo (size < 500 kpc), with an exception in 3 cases where halos of size > 500 kpc were detected.**

7. **3 clusters host Ultra steep (alpha<-1.5) spectrum radio halos.**

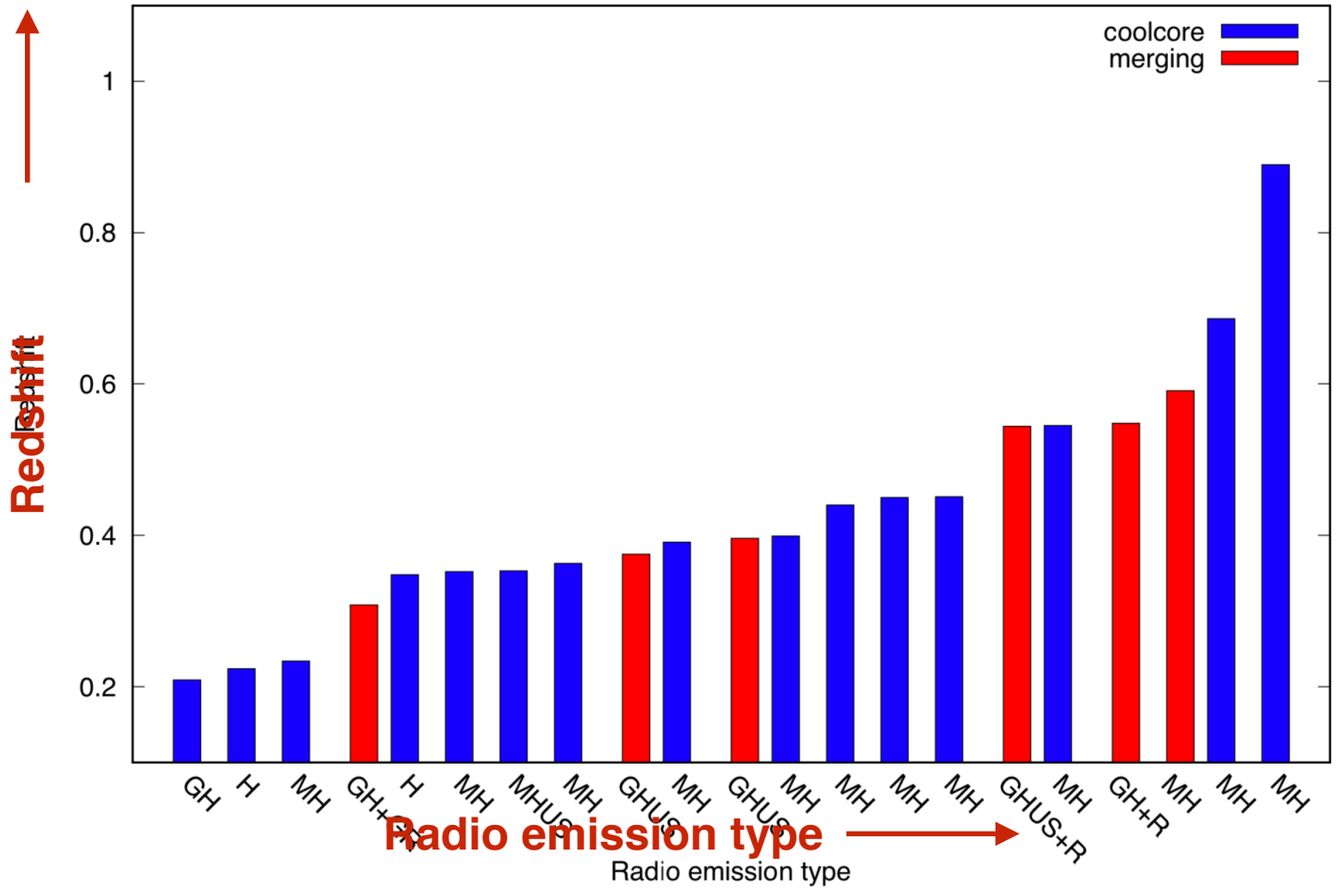


Fig. Radio emission detection in MACS cluster of galaxies showing Giant Halo (GH), Relic (R), Halo (H), Mini-Halo(MH), Ultra Steep spectrum (US) emission based upon their dynamical state

Pandey-Pommier et al. 2013, 2014,2015,2016,2019

8. Bimodility in (*$P_{1.4\ GHz}$- L_X plane*)-Brunetti et al. 2009, Cassano et al. 2010).

9. Cool core clusters host MHs.

10. USSRH are the best population to be detected by LOFAR and SKA

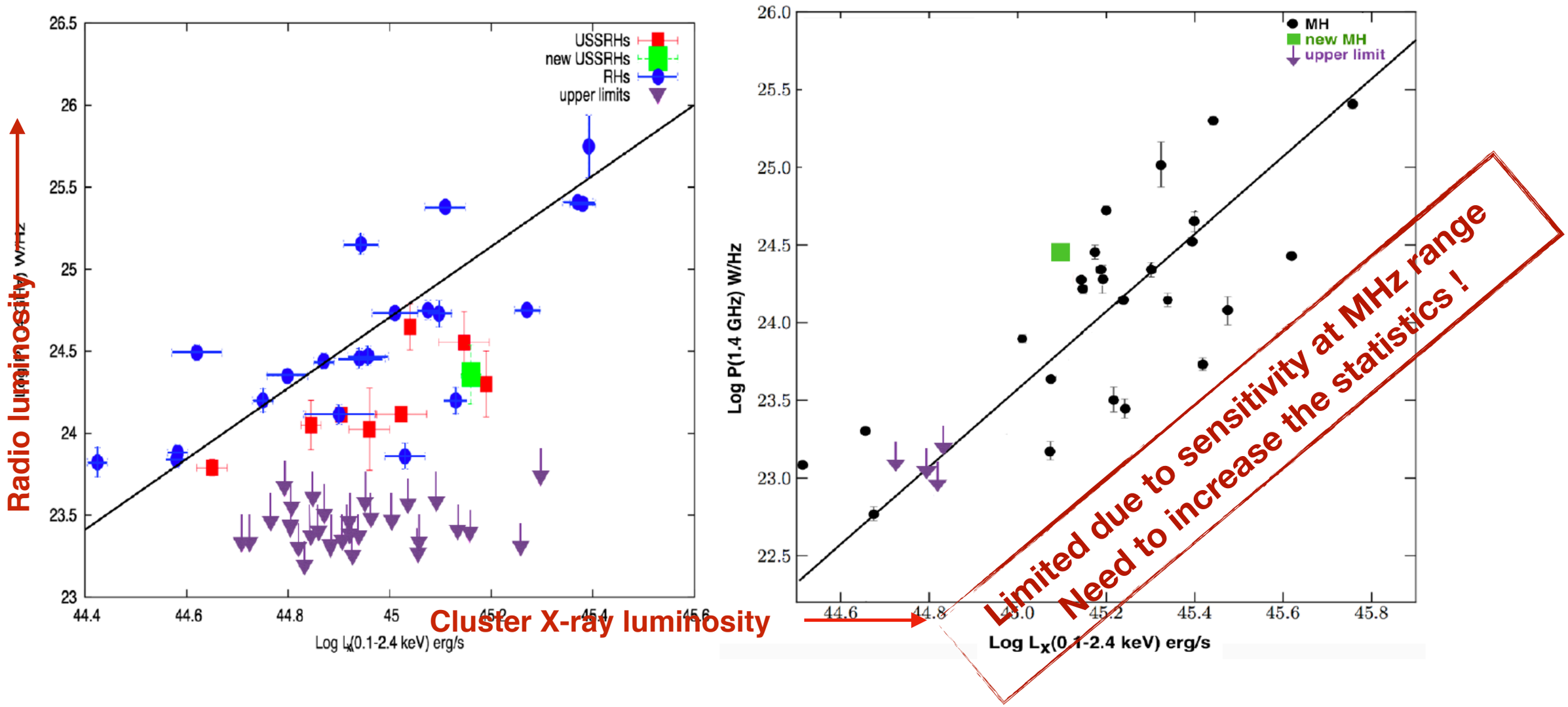


Fig. The $P_{1.4\ GHz}$- L_X correlation plot for RHs (Left Panel) and mini-halos (Right Panel) from literature with blue circles showing RHs, black circles showing MHs, red boxes showing USSRHs, violet arrows showing upper limits and green boxes showing recent new detections.

Galaxies within the cluster environment , Optical nebula and radio jet properties

Pandey-Pommier et al. 2019

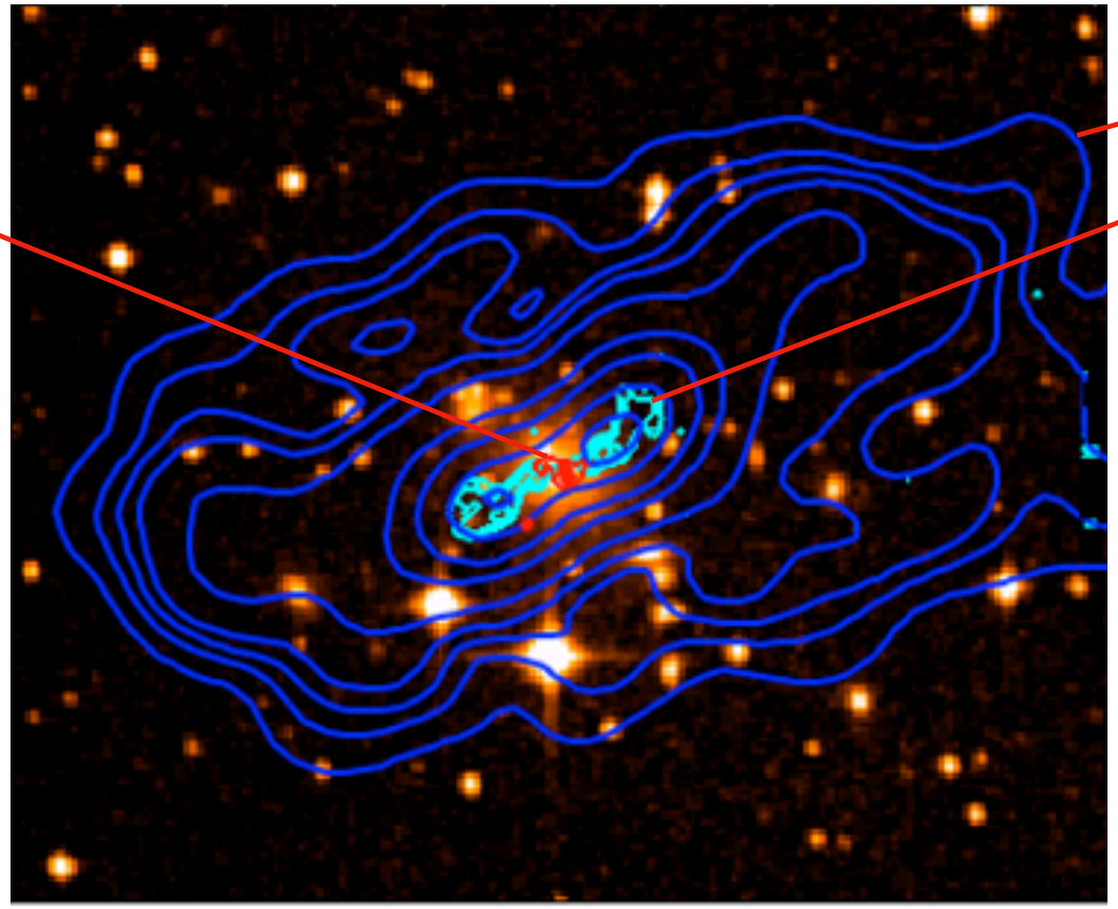
1. **Cooling flow problem"- AGN Feedback !**
2. **Radio jet emission of a few 10s-100 kpc is always present in bright central Galaxies (mostly Giant ellipticals)**
3. **Radio relics seen <150 MHz and are new population yet be discovered with the SKA!**

Survey: **Multi wavelength study carried out on 26 clusters** at a redshift range of 0.02< z< 0.24 to investigate feedback mechanism using Radio/X-ray/Optical correlation

*(**P.I M. Pommier**, A. Edge, F. Combes, S. Hamer et al.)*

Optical emission (H-alpha)
Hot ionized gas from disc region

Compact disc, ellipticals, disturbed disc structures



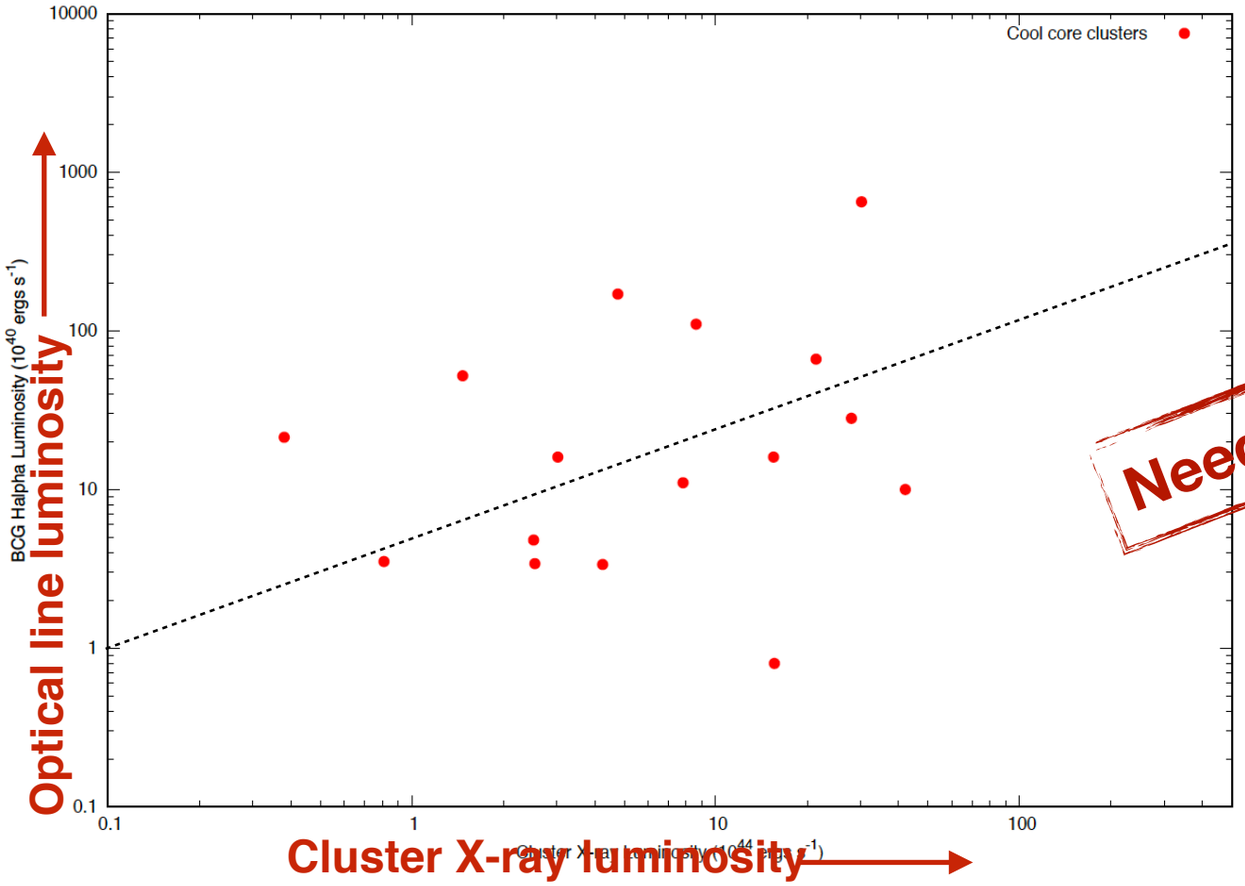
Radio emission (synch.)
Non thermal, jet region

Radio jets from few 10s to 100s Kpc scale, relics

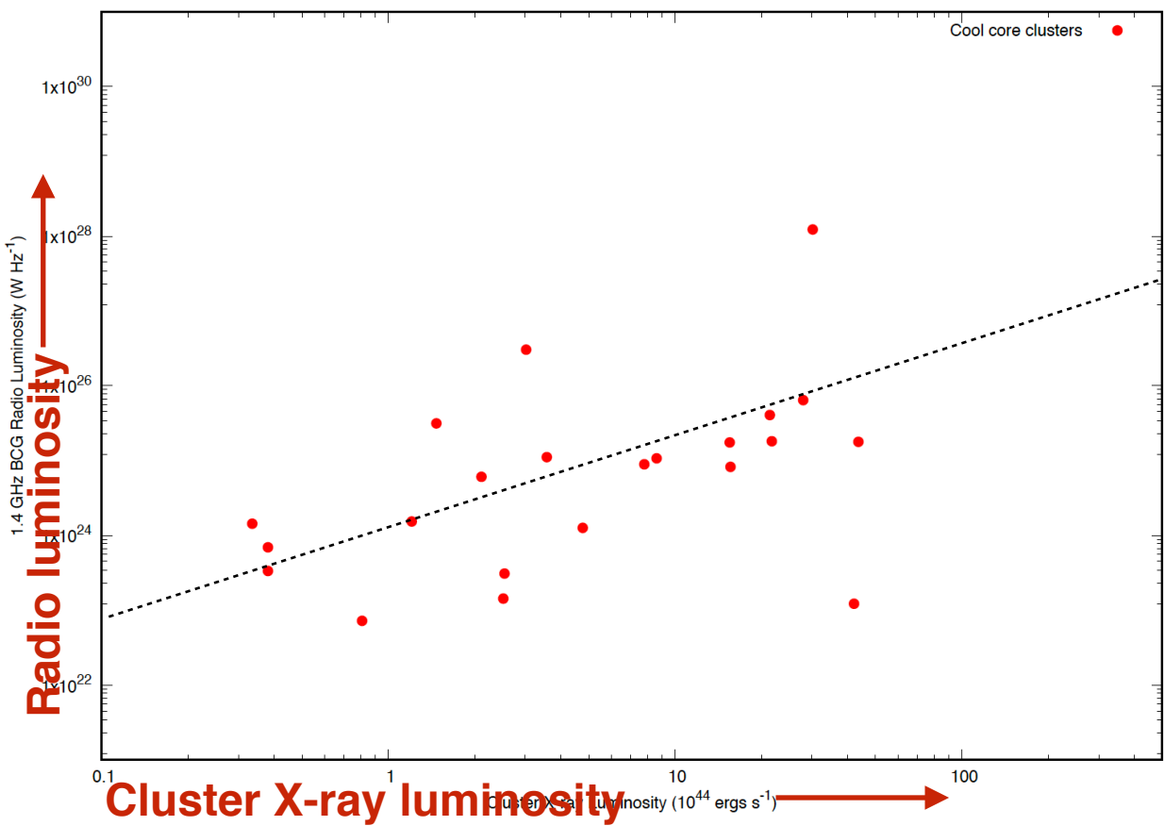
Results- Multi wavelength luminosity correlation

Pommier et al. 2019

LOFAR, SKA and its precursors (MeerKAT and ASKAP) in combination with optical imaging and spectroscopy data from survey instrument like WEAVE, MSE, EUCLID, LSST will immensely improve the statistics of this analysis and provide complete information on the feedback



Need to increase the statistics !



Salome et al. 2006, Combes et al.2015, 2018

ICM at the centers of cool clusters with dense cool gas reservoirs at pc scale

Hot gas generates large scale (kpc) Cooling Flow.

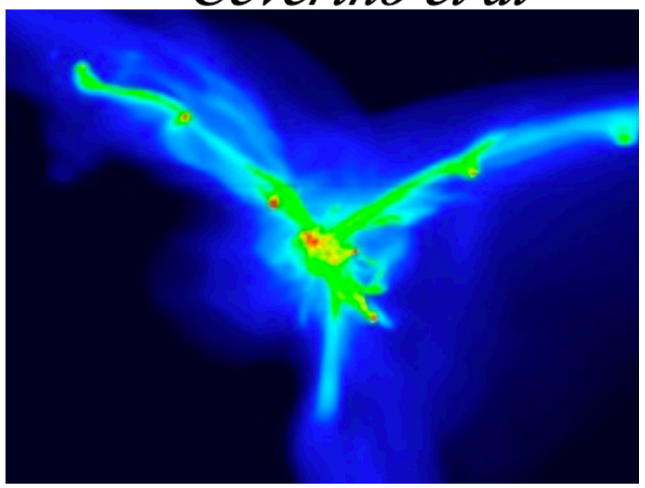
Outflows more visible than inflow

Outflows are **violent** events (~1Myr)
Inflow is a **slow** process (~1Gyr)

Cosmic filament size~50kpc
Larger than a galaxy, **diffuse gas**
Settles down in the disk in rotation

➔ Secular evolution. slow infall **in the disk**

Ceverino et al



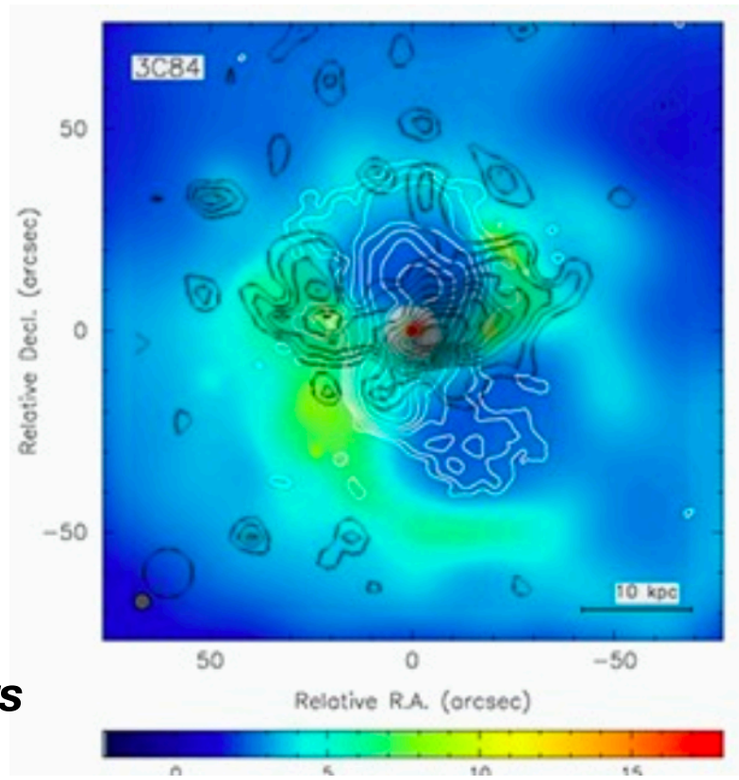


Fig. Molecular gas in cool core clusters

Gas outflows in central galaxy of clusters

Salome et al. 2003, Edge et al.2001, Pommier et al. 2019

IRAM observations on clusters detects CO emission suggesting the presence of a reservoir of cold gas in the disc regions of the central bright galaxy.

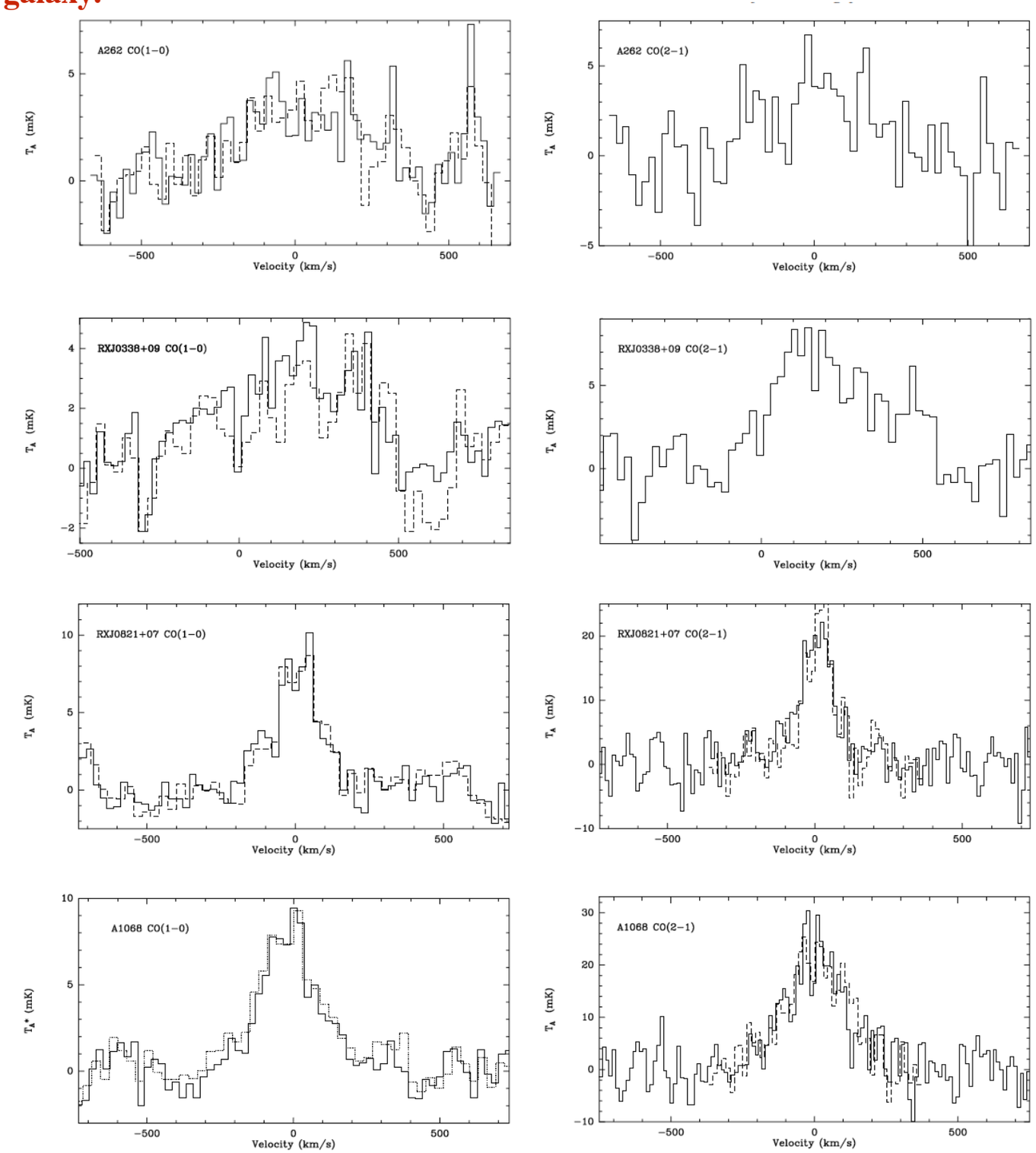
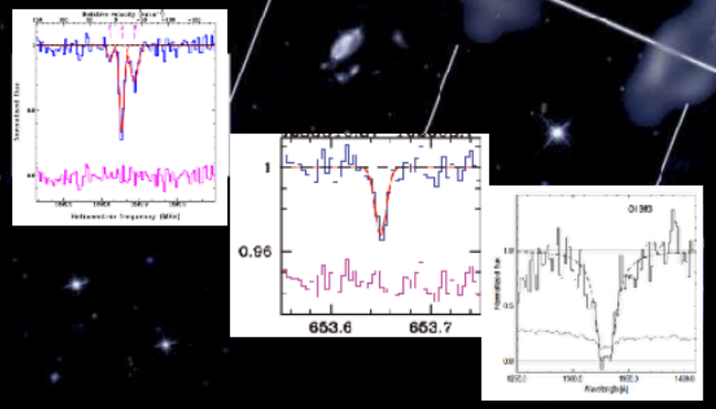


Fig. CO emission in cool core clusters with IRAM

Do we find such signatures of cooling also in HI !

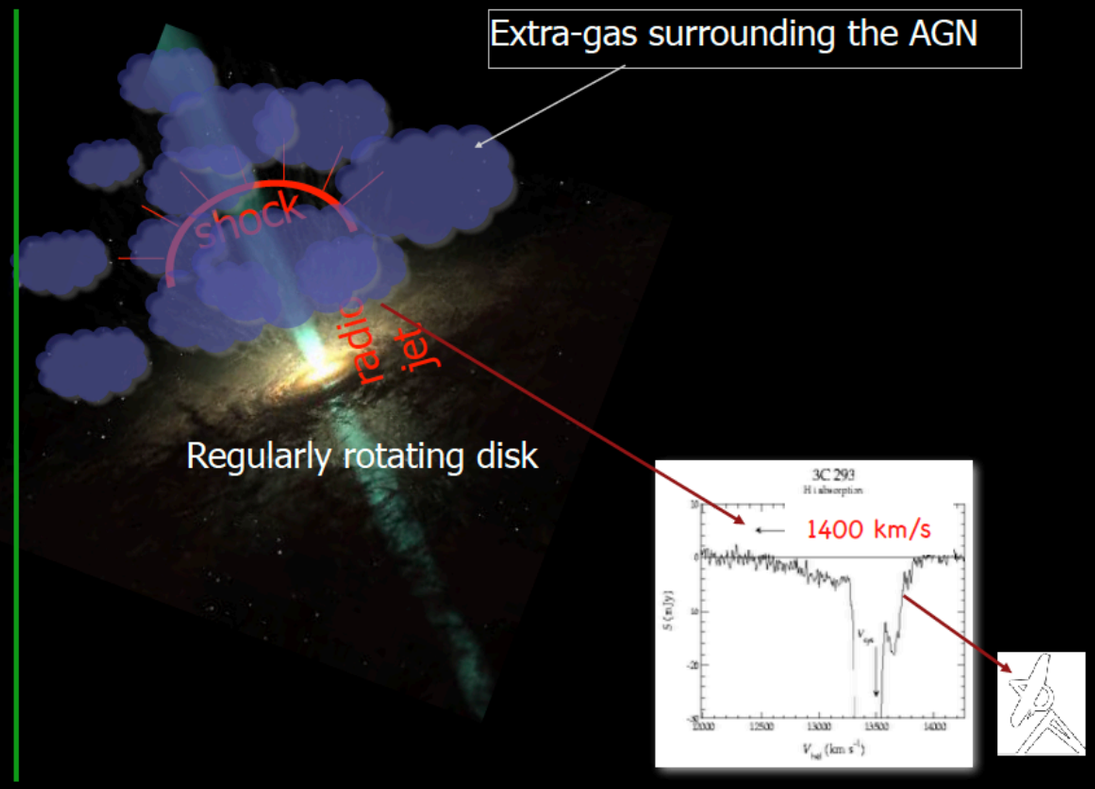
Mellema et al. 2002, Morganti et al. 2004

Tracing HI with absorption: intervening and associated



Tracer of *cold* neutral hydrogen in the distant universe, can detect and
probe gas within **normal** galaxies out to very high redshift:

- *Typical size and mass of galaxies as function of redshift ➜ test galaxy formation scenarios*
- *Evolution of neutral gas content with redshift ➜ explore relation HI content and SFR*



Tracer of the gas in the inner parts of the galaxy close to AGN

- *Tracer of circumnuclear disks*
- *Infalling gas ➜ feeding*
- *Outflowing gas ➜ feedback*

Neutral atomic HI gas in the disc of bright galaxies via HI absorption

HI absorption suggesting the presence of a reservoir of cold gas in the disc regions

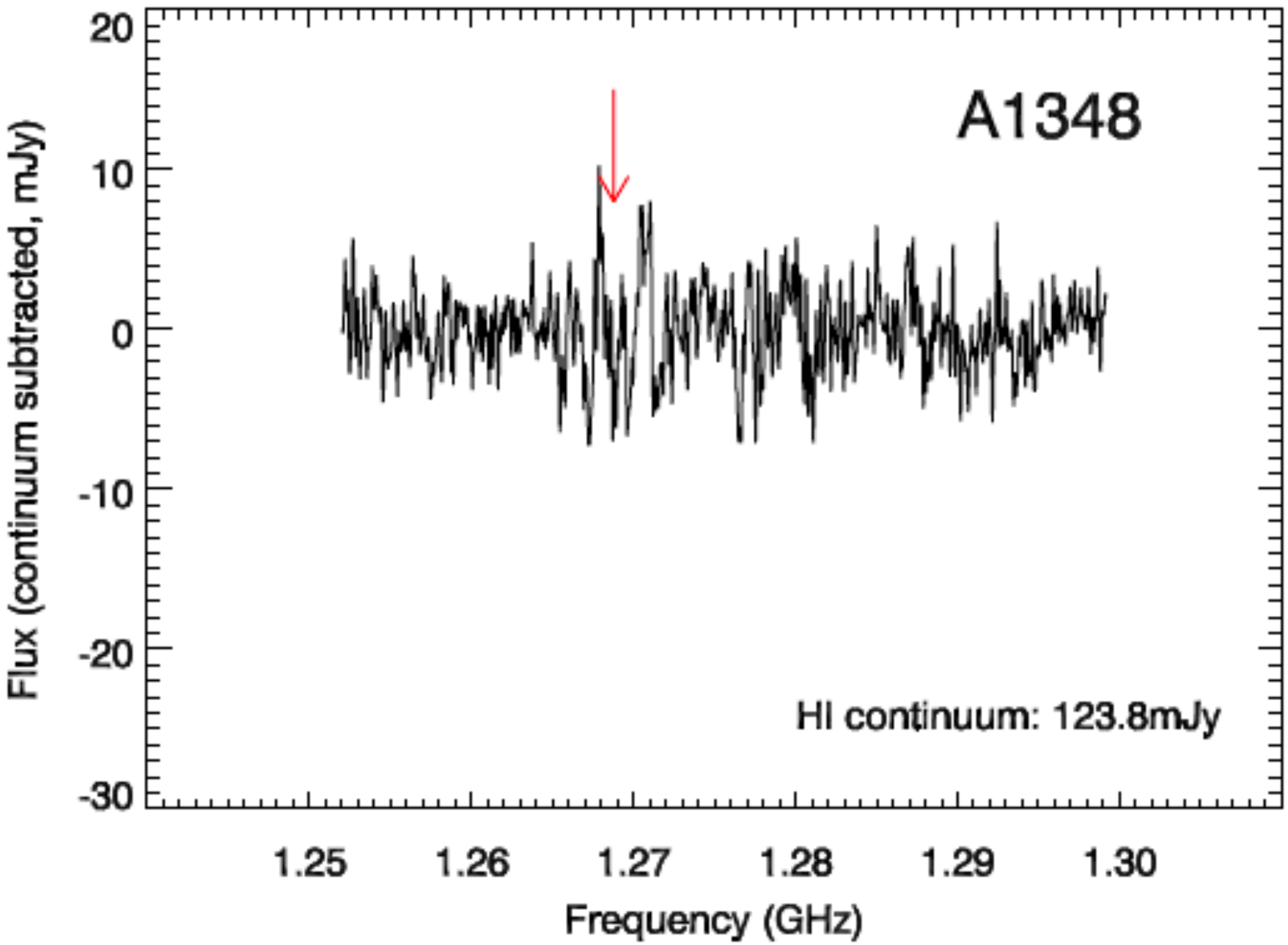


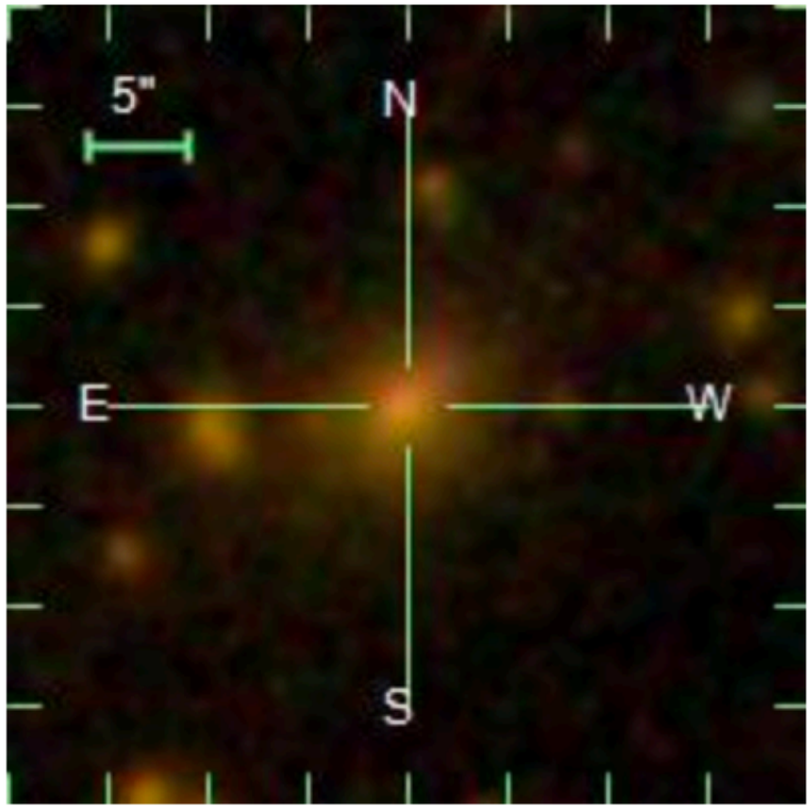
Fig. HI absorption with ATCA

Tracing gas outflows via neutral atomic HI observations

Pommier, van Driel et al. 2019

Survey: **NRT observations were carried out on 26 clusters** at a redshift range of 0.02< z< 0.24 to investigate presence of HI gas in disc regions

*(**P.I M. Pommier**, A. Edge, W. Van Driel, S. Hamer, J. M. Martin, F. Combes et al.)*



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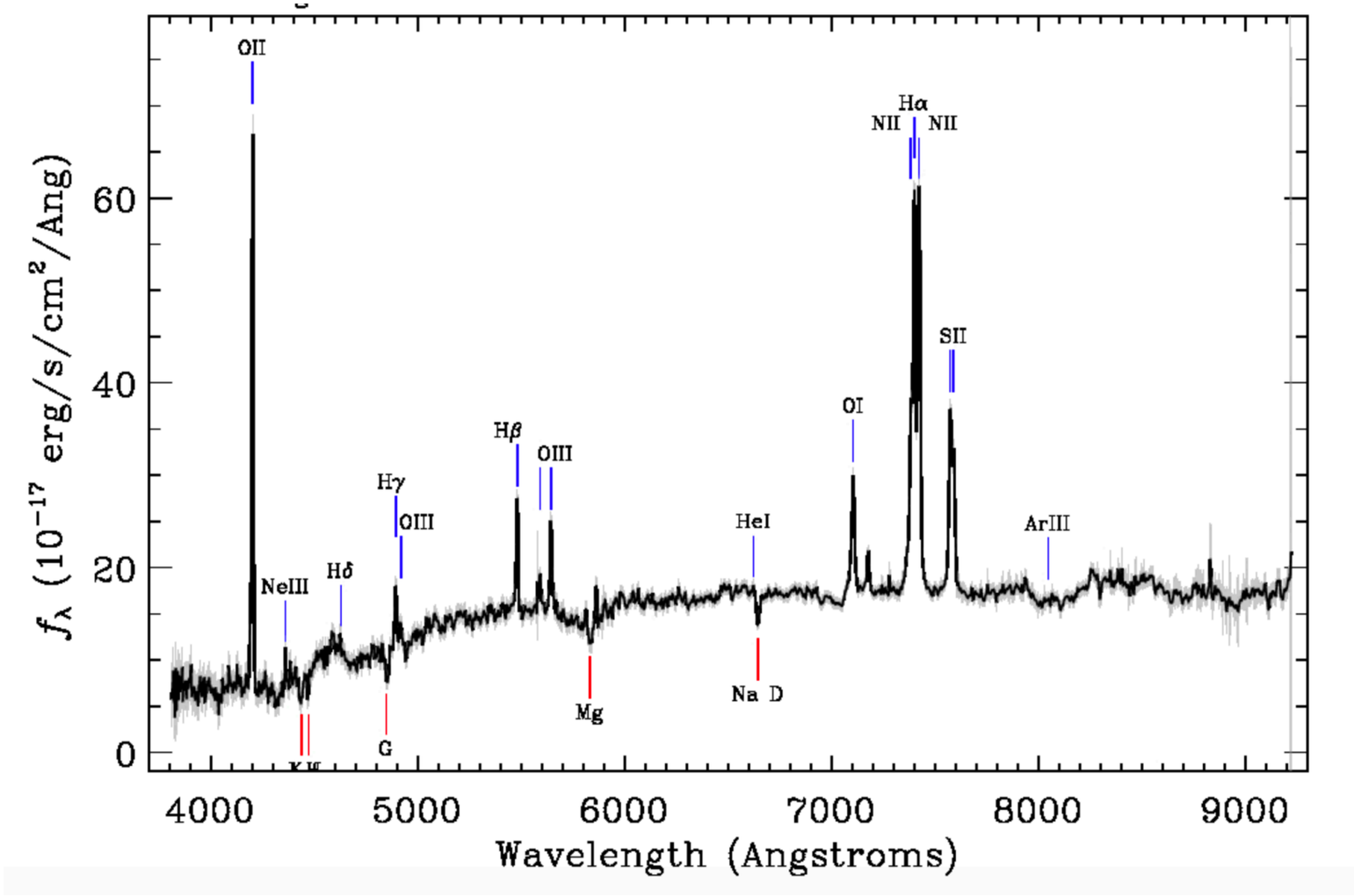


Fig. SDSS image and H-alpha emission in clusters

Investigation of neutral atomic HI gas in the disc of bright galaxies in clusters via NRT observations-

Pommier, van Driel et al. 2019

HI absorption signal was positively detected in 15% (4 cases) cool core clusters with 1 new detection and 3 confirmed from the literature, suggesting the presence of ionized hydrogen in the disc of bright galaxies and indicating strong cooling flows.

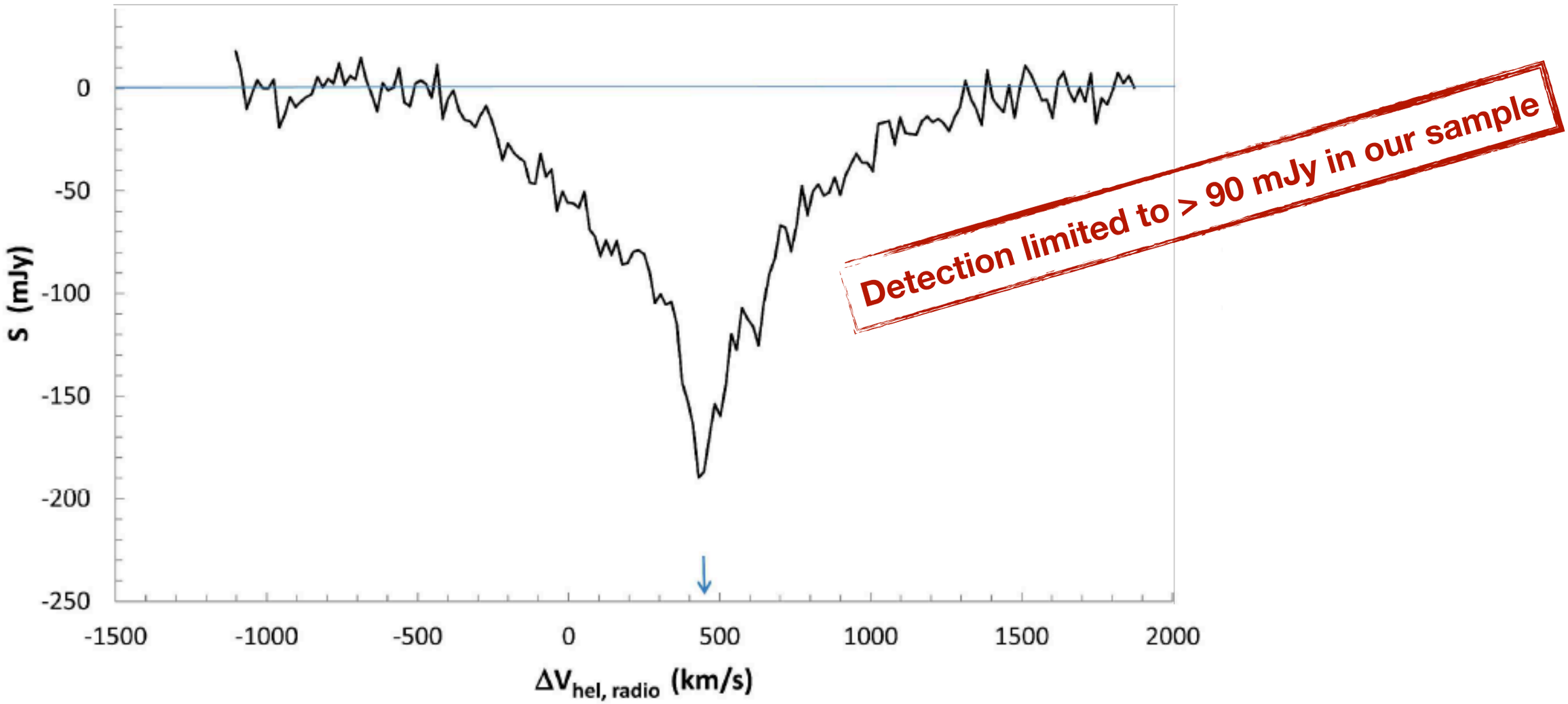
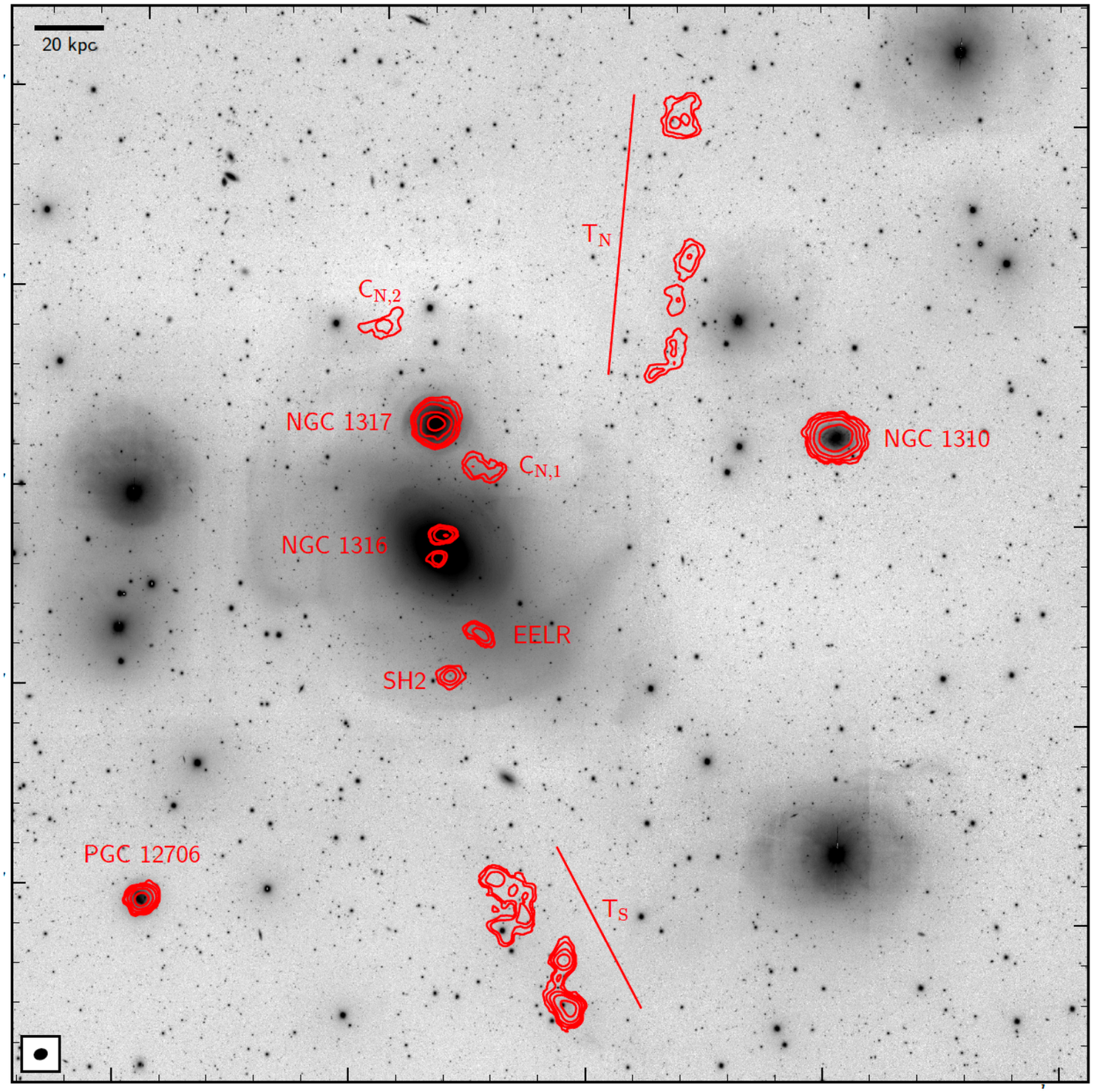


Fig. HI absorption in cool core clusters with NRT

Location of HI absorption and Cold gas in galaxy clusters via HI imaging with MeerKAT

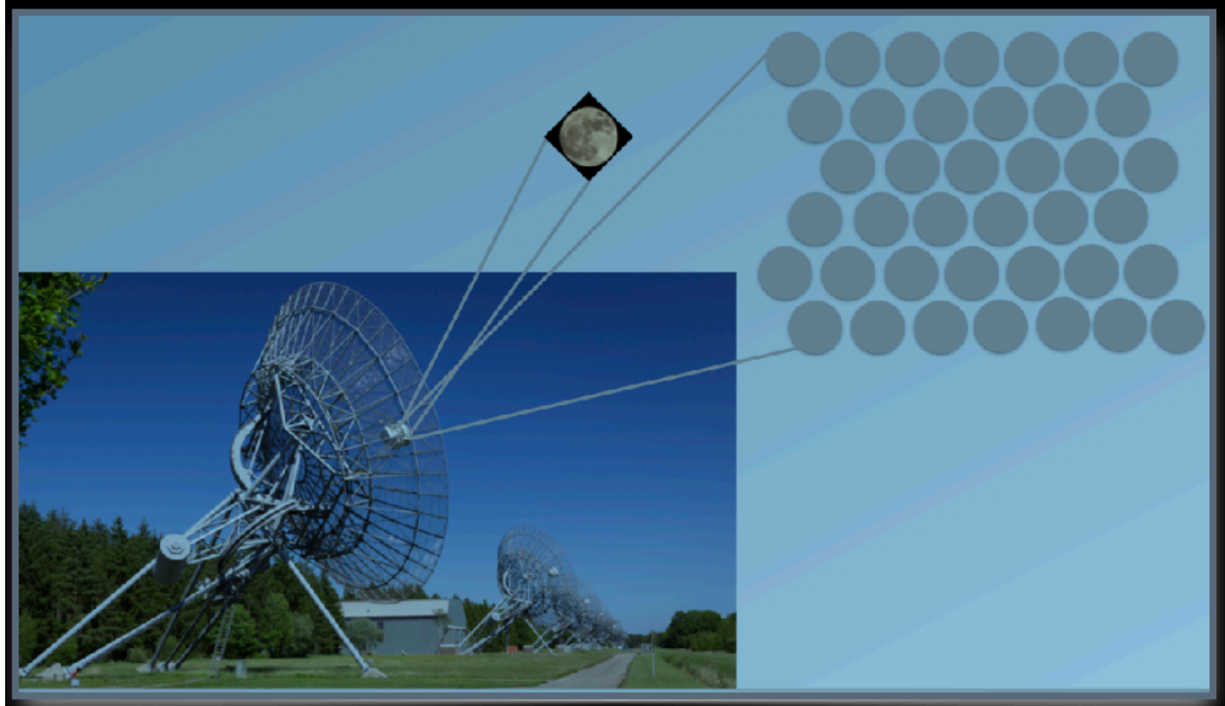
Serra et al. 2019

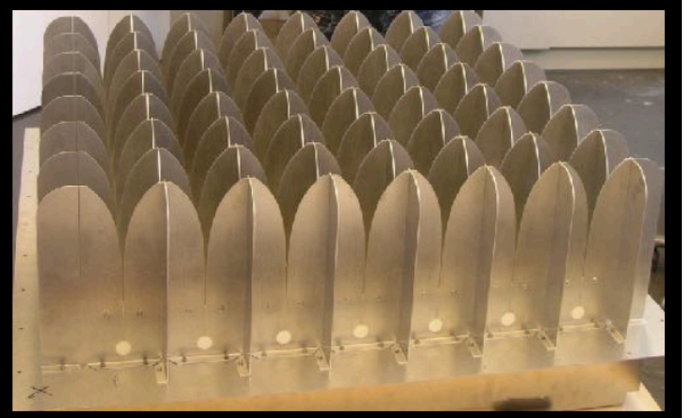
Recent results:



SHARP survey: Search for HI absorption with APERTIF

Can do in a day what before took a month
Synergy with LOFAR





121 receptors (60+61)
39 beams on the sky
FoV 6 deg^2
Range freq: 1130 – 1700 MHz
T_{sys} 70 K
Aperture efficiency 75%
Bandwidth 300 MHz
24576 channels - 4-5 km/s resolution
12 dishes

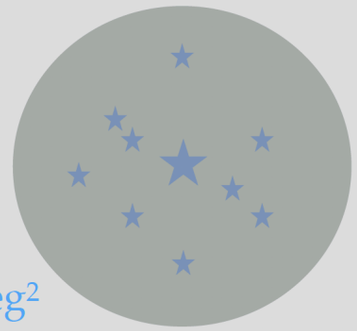
Gupta et al. 2018

The MeerKAT Absorption Line Survey (MALS)

Main science themes:

- Evolution of cold gas in galaxies and its relationship with SFR density **(~200 detections)**,
- Fuelling of AGN, AGN feedback and determining fraction of dust-obscured AGNs **(~500 detections)**,
- Variation of fundamental constants of physics: most stringent constraints (comparable to terrestrial atomic clocks).

Each pointing will be centered on a >400 mJy radio source.



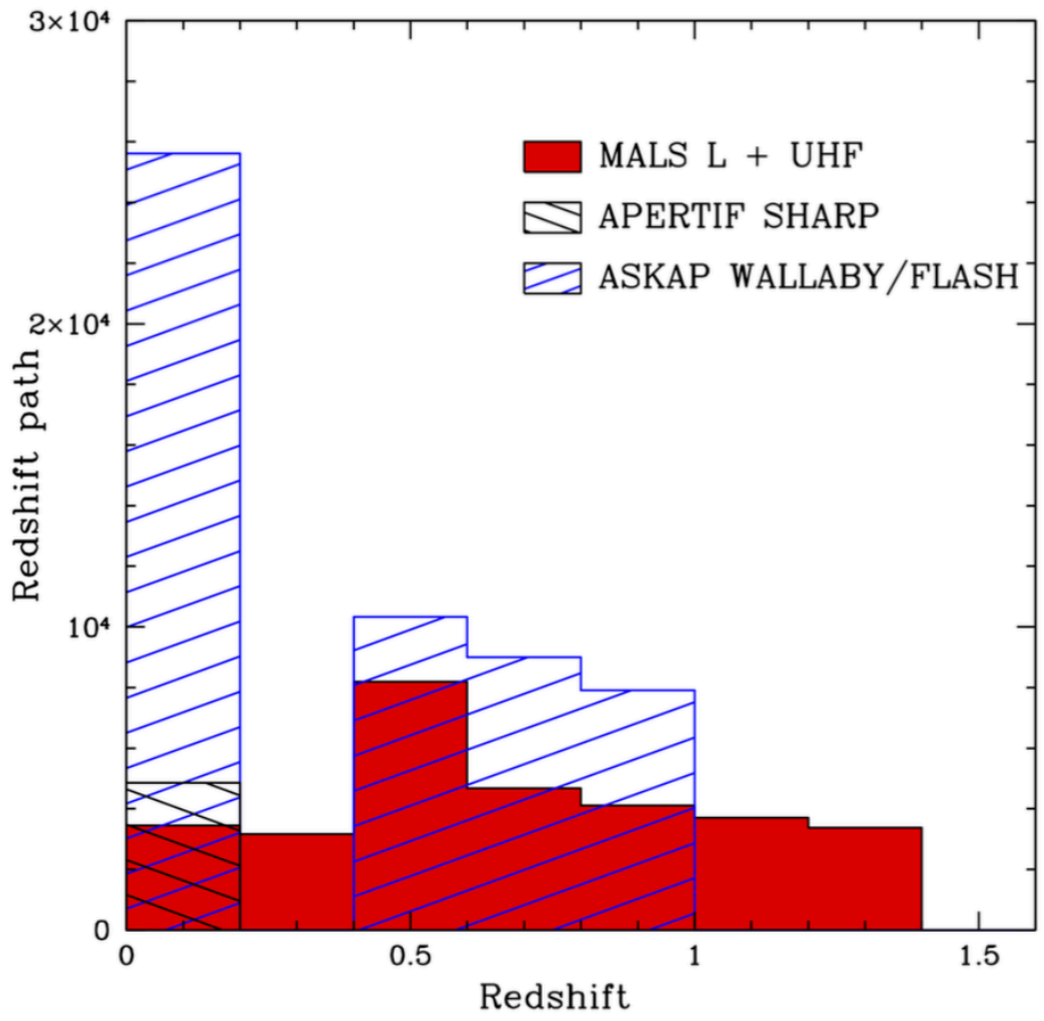
L-band: 1 deg^2

MALS phase	Number of pointings	Time per pointing (mins)	Spectral rms† (mJy beam^{-1})	Continuum rms (μJy beam^{-1})	Total on-source time (hrs)
L-band (900-1670 MHz)	740	56	0.5	3	691
UHF-band (580-1015 MHz)	370	121	0.6	3	746

† 900-1670 MHz; ‡ 580-1015 MHz.

Estimated at ~1200 MHz and ~800 MHz for the full band split into 32768 channels.

Comparison with other surveys



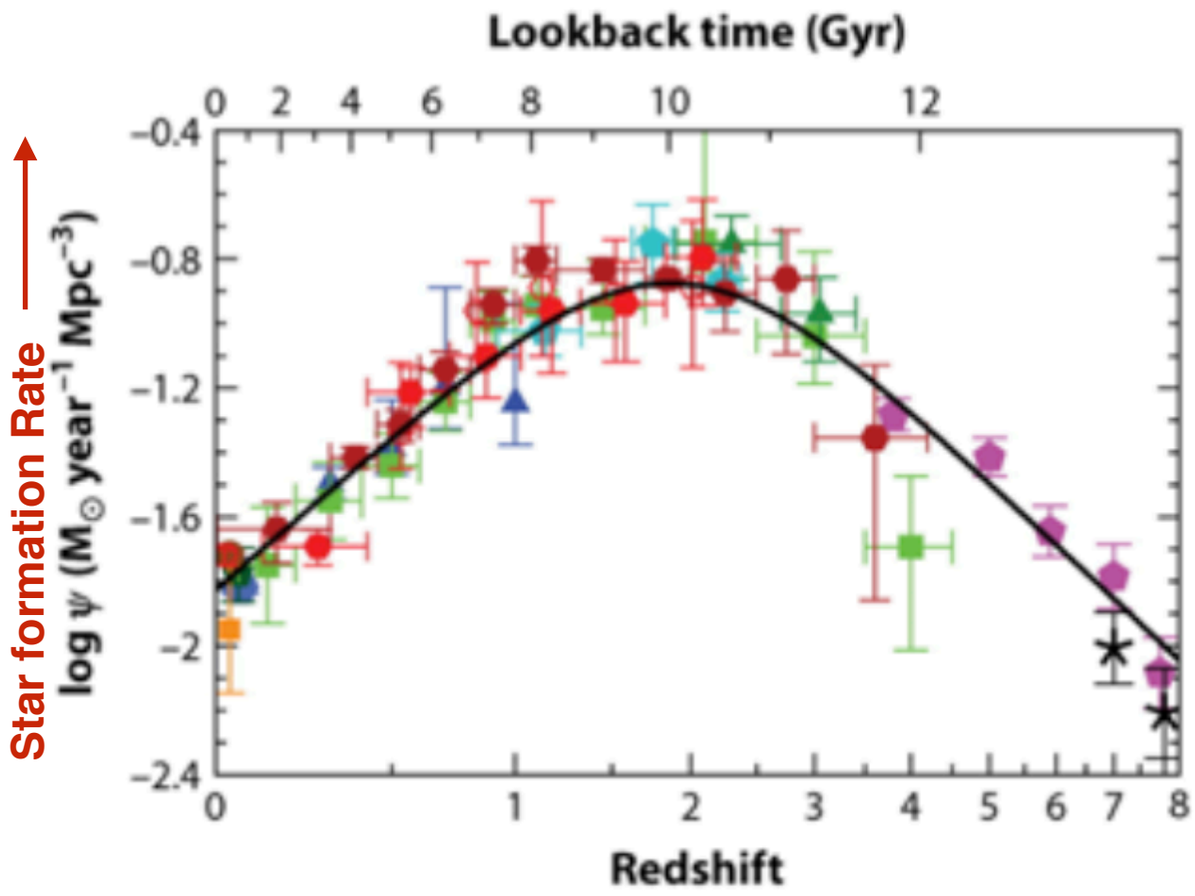
Uniform coverage over 0<z<1.5

+ HI emission, and deep continuum and polarisation images

Gupta et al. 2018

The MeerKAT Absorption Line Survey (MALS)

1655 hrs for the sensitive search of HI 21-cm and OH 18-cm absorption lines to map the evolution of cold atomic and molecular gas in galaxies at 0<z<2: the redshift range where most of the evolution in the star-formation rate density takes place.

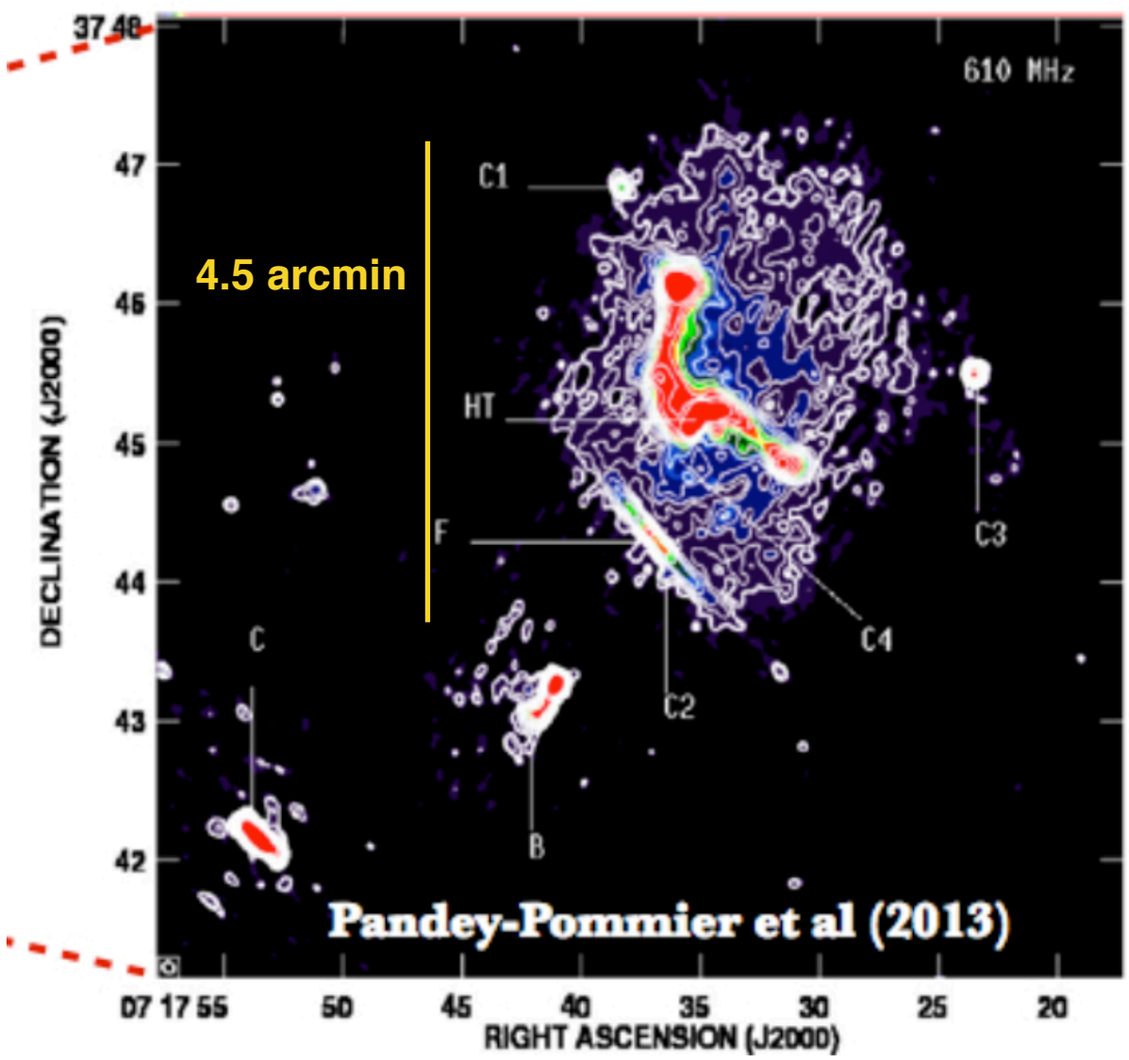


MALS

NenuFAR (Stand alone mode)- Clusters and AGNs NenuFAR Survey (CANS)

Pommier et al. 2013, A&A

Galaxy clusters host a variety of diffuse and extended (arcmin-scale) radio sources: tailed radio galaxies (Feretti & Venturi 2002); radio bubbles (de Gasperin et al. 2012); diffuse giant radio sources, "halos" and "relics" (Pommier et al. 2013,2014.2015).



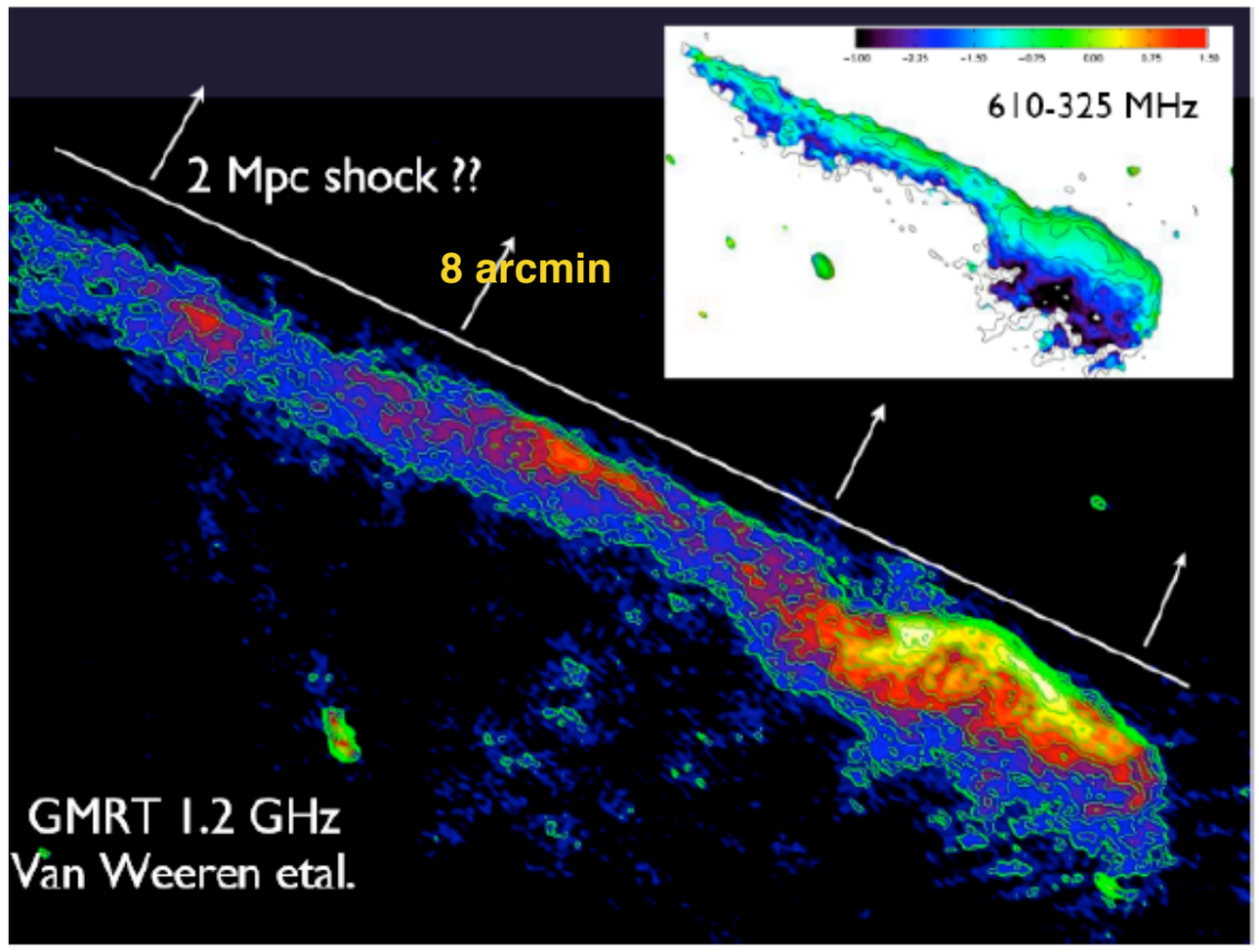


Figure 3- Observation on galaxy clusters show diffuse halo (left) and shocked relic (right) regions. Spectral index map shows aging plasma

NenuFAR (+LOFAR long baseline mode)- Galaxy clusters and AGNs Science case

Pommier et al. 2018 LOFAR LB busy week report

NenuFAR+LOFAR:

-NenuFAR data in combined mode help us to identify the source morphology and detect more diffuse emission due twice more sensitive at short baselines than the LOFAR core, but will also provide highly sensitive long baselines to detect faint objects.

Faint (mJy-level) source at 150 MHz with LOFAR long baselines using FR606

Long Baseline pipeline is compatible at LBA frequencies !

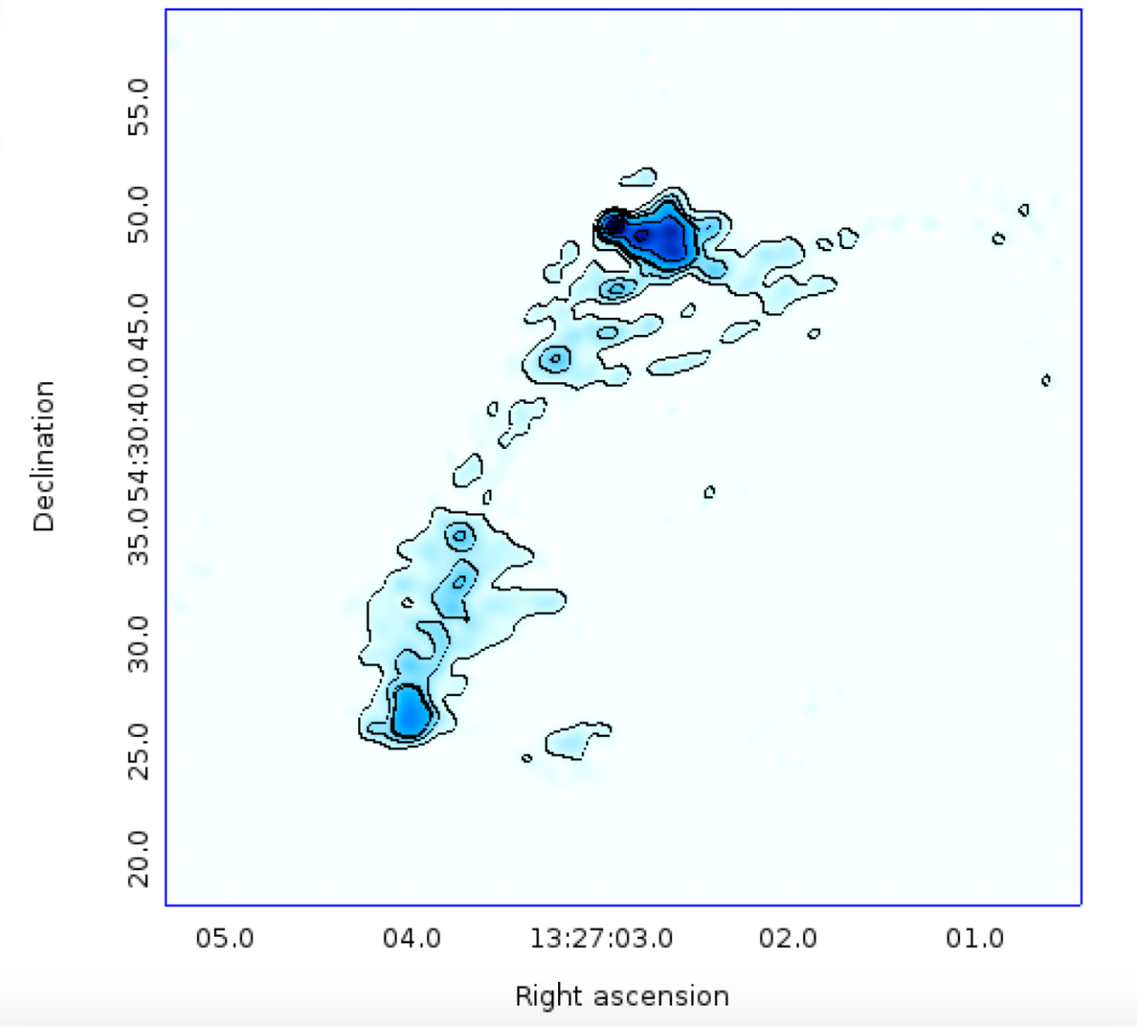


Figure *FRII Radio galaxy 1327+5430 of size 23 arcsec imaged with LOFAR long baseline (rms 100.5 microJy, resolution 0.3 arcsec) in at 150 MHz*

Conclusion and future surveys

- Non-thermal emission from the ICM in clusters is regularly detected with LOFAR with steep spectral index

- With the NenuFAR complete array in the imaging mode, at 80 MHz with 5 arcmin resolution and a noise level of a few 10s of mJy/beam, we will be able to resolve the structure of diffuse emission in AGNs and clusters of galaxies upto 5 arcmin- ***CANS*** survey (PI. M. Pommier). However, limited for bright source population only.

- NRT observations detected (0.047<z<0.23, > 90 mJy) HI in absorption in 15% of our sample! Ongoing work with the NRT (PI. M. Pommier, W. van Driel, J.M. Martin et al.).

- Correlation and evolution of HI and CO regions with redshift and evolution of star forming regions in the Universe.

- Synergies with multi wavelength facilities (IRAM, MUSE, WEAVE, MSE, EUCLID, LOFAR, MeerKAT, NRT, SKA)

- **ASKAP-Wallaby Pilot survey on HI (PI. M. Pommier)**
- **SKA Science case 'Radio mode feedback in cluster of galaxies' (PI. M. Pommier)**
- **SKA Science case 'Cluster of galaxies and the cosmic web with SKA' (Collaborator M. Pommier)**
- **SKA Science case 'From nearby low luminosity AGN to high redshift radio galaxies: science interests with SKA' (Collaborator M. Pommier)**
- **SKA-VLBI Science case 'Distant universe with Gravitational lensing - SKA and EUCLID' (Collaborator M. Pommier)**

- **Science case for LOFAR-WEAVE and MSE project (PI or CoI. M. Pommier)**