A closer look at particle acceleration in galaxy clusters using the Upgraded GMRT

Ruta Kale

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GMRT antennas image credit ASTROProject and S. Meshram

Outline

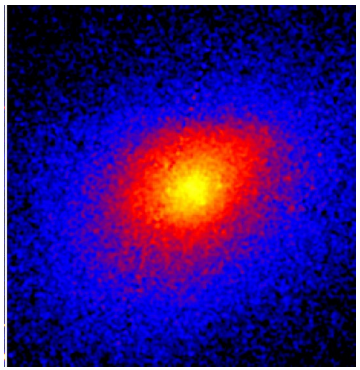
- Galaxy clusters in radio: why ?
- Recent results using the GMRT
- Upgraded GMRT: Characterising spectra of seeds; towards finding the relation between turbulence and radio halo emission
- Real-time broadband RFI excision system at the GMRT

Galaxy clusters across the EM spectrum

Gamma rays

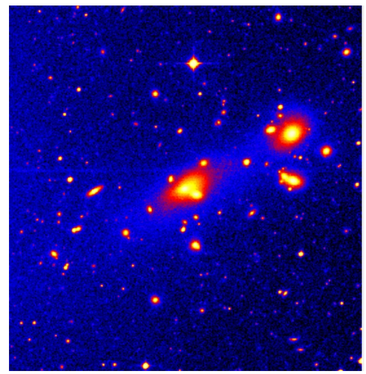
Hadronic collisions

X-rays



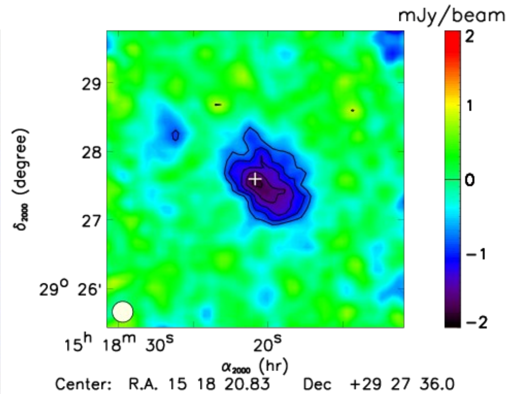
Thermal Bremsstrahlung
$10^7 – 10^8$ K plasma

Optical



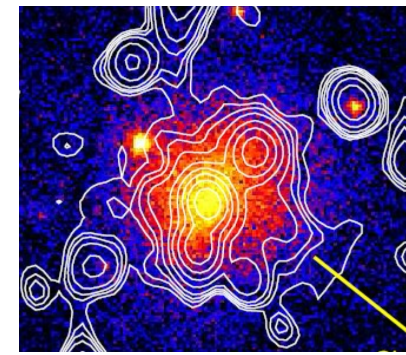
Stars

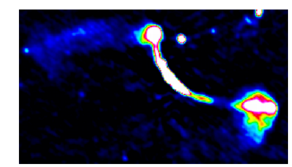
mm



Sunyaev-Zel'dovich effect: inverse Compton scattering of CMB by the ICM

RADIO





GeV cosmic ray electrons and μG magnetic fields

ICM is a high $\beta \sim 10\text{-}10^3$ plasma

Brunetti and Jones 2014; van Weeren et al 2019; Huber et al 2013, Ackermann et al 2013; Rippin et al 2017; Sunyaev and Ze'ldovich 1979; Kale et al 2018; Giacintucci et al 2013

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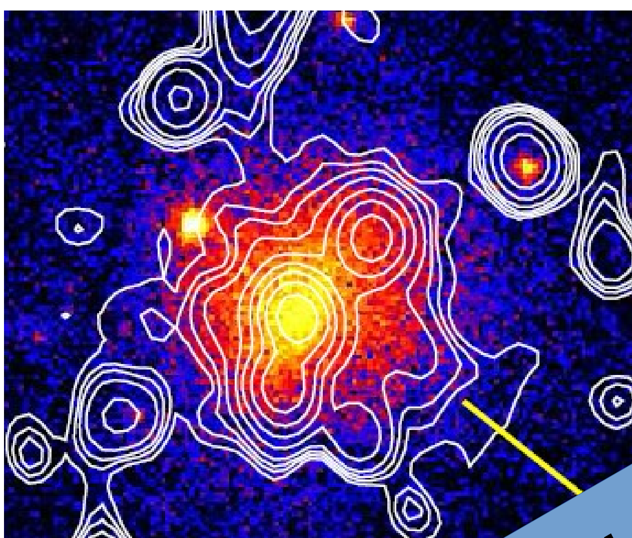
Cluster scale radio sources (~ 100s kpc)

Radio power at 1.4 GHz ~ $10^{24\text{-}26}$ W/Hz
Mpc Extents ~ a few to several tens of arcminutes
Surface brightness < 1 μJy arcsec^{-2}

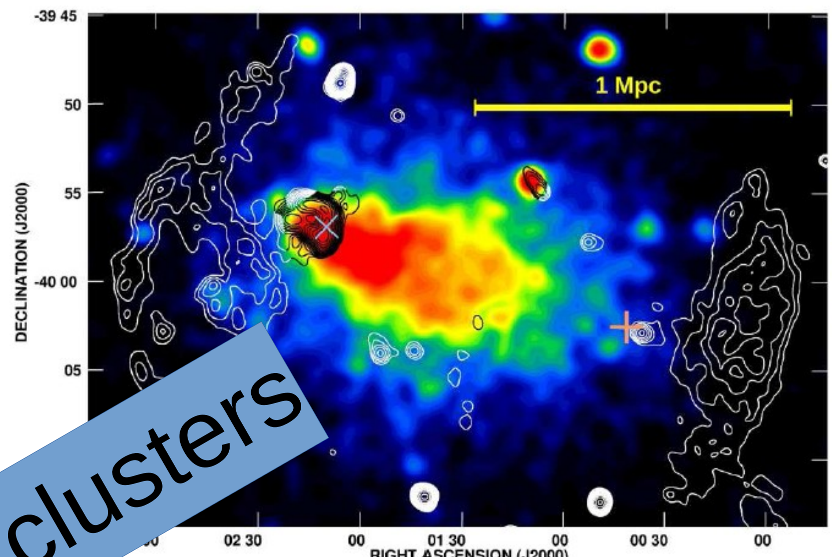
Classification rapidly evolving !

Radio halos



Giacintucci, K... ...013

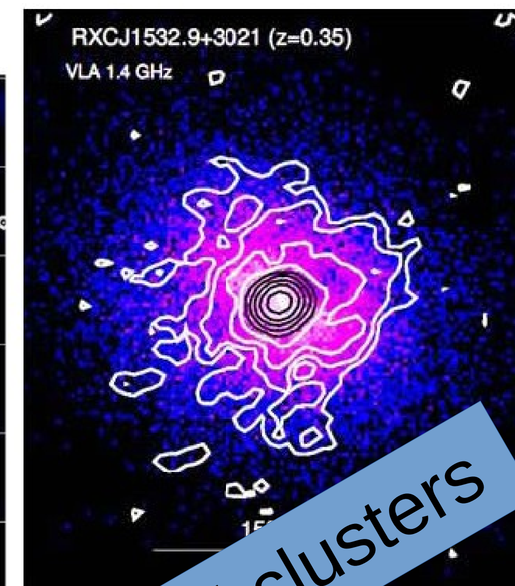
Radio relics



Abell 3376, Kale et al. 2012, Bagchi et al 2006

Merging clusters

Mini-halos



Hl... ...arrondo 2013; ... al 2013

Relaxed clusters

Origin of relativistic electrons in the ICM

Hadronic collisions

Galaxies, AGN, Radio galaxies

Re-acceleration mechanisms Shocks and turbulence

Cannot produce sufficient CRe- to power radio halos (also shock relics and mini-halos in some cases)

Inefficient processes to re-accelerate e- from thermal pool

Require mildly relativistic electrons as "seeds"

Radiative lifetime short as compared to diffusion time-scale

Seeds with modified spectra.

Processes to keep them energised:
Adiabatic compression
Gentle re-energisation

Dennison 1980; Blasi & Colafrancesco 1999; Dolag & Ensslin 2000; Miniati 2001; Pfrommer et al 2008; Keshet & Loeb 2010; Ensslin et al 2011; Brunetti et al 2001; Petrosian 2001; Donnert et al 2013; Donnert & Brunetti 2014; Pinzke et al 2013, 2017; Zuhone et al 2014; Ensslin & Gopal-Krishna 2001; Ensslin & Bruggen 2002; de Gasperin et al 2017; van Weeren et al 2017; Donnert et al 2019.

e. g. Review van Weeren et al 2019

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$$\nu_s/\mathrm{GHz} \sim (\tau_{\mathrm{acc}}/400\mathrm{Myr})^{-2}(1+\mathrm{z})^{-1}$$

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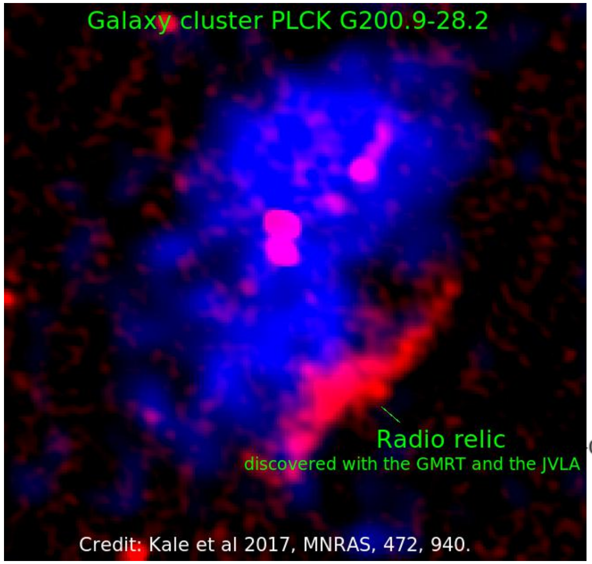
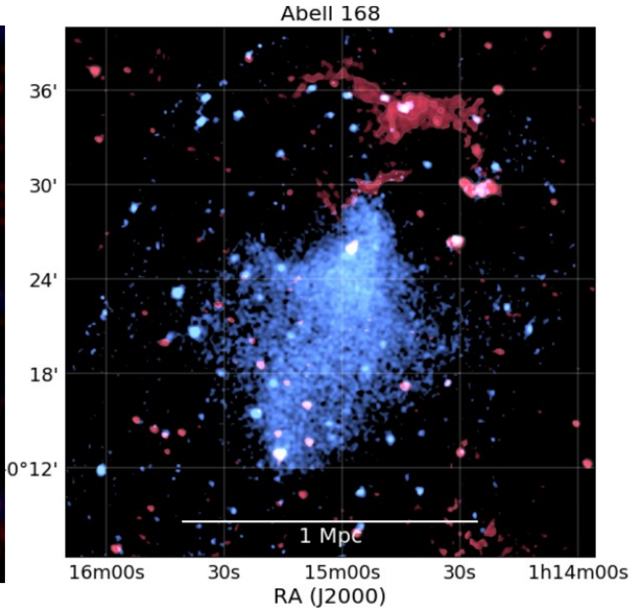
GMRT: Diffuse emission discoveries



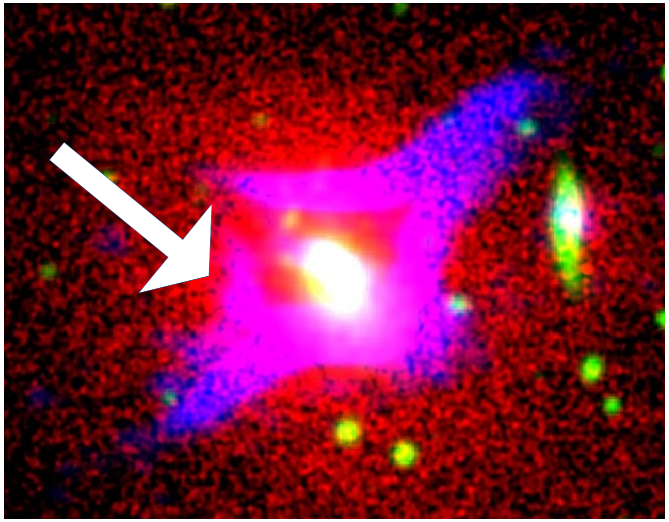
Kale et al 2017



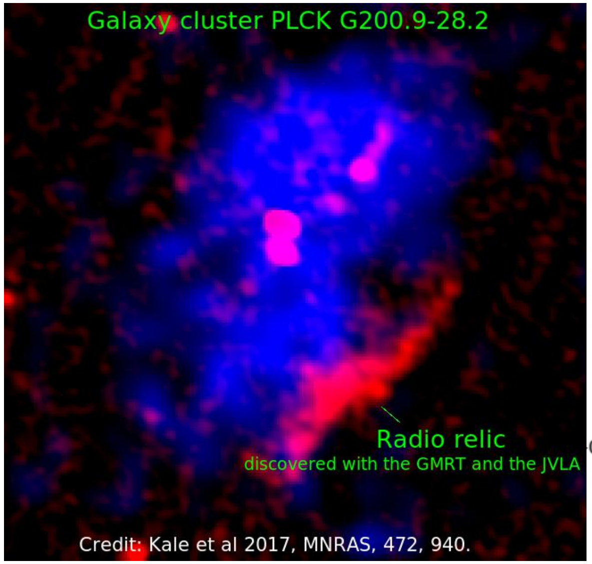
Dwarakanath, Parekh and Kale 2018
MWA+GMRT

GMRT: Diffuse emission discoveries

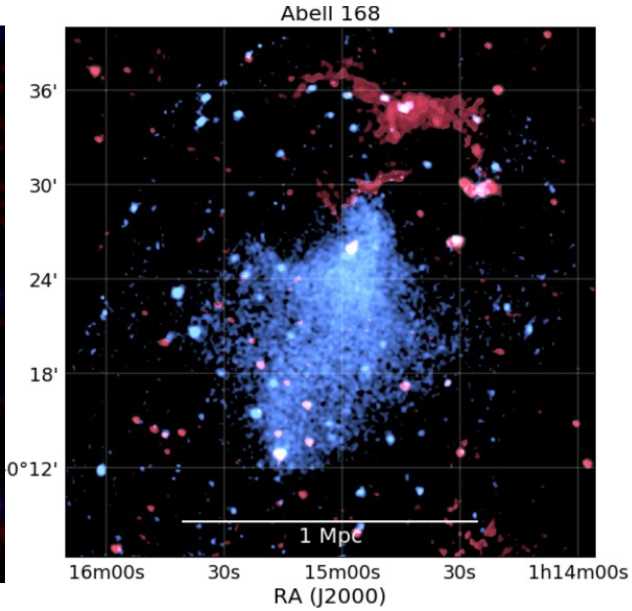
The fourth arc in
Abell 2626



Kale and Gitti 2017



Kale et al 2017

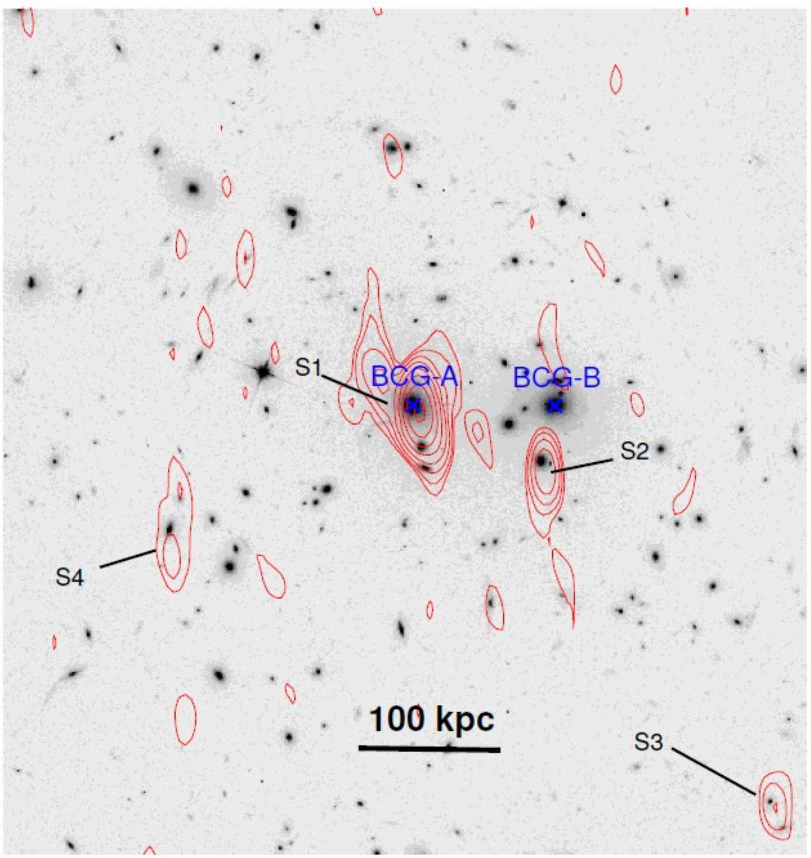


Dwarakanath, Parekh
and Kale 2018
MWA+GMRT

New radio halo: A “giant” mini-halo ?

RXCJ0232.2-4420

Poster by Krishna Shende



RA(J2000)(h m s)	02 32 18.7
DEC(J2000) (° ′ ″)	-44 20 41
Redshift (z)	0.2836[†]
$L_{X[0.1-2.4\mathrm{keV}]}$ (erg s^{-1})	13.3×10^{44}
$M_{500}(10^{14}\ M_{\odot})$	12.01 ± 1.80[†]
kT(keV)	8 ± 1.4[*]
Giant Mini-Halo	
Size	550×800 kpc^2
$S_{606\mathrm{MHz}}$	52 ± 5 mJy
$P_{1.4\mathrm{GHz}}$	4.5×10^{24} W Hz^{-1}

Kale et al 2019, MNRAS, submitted

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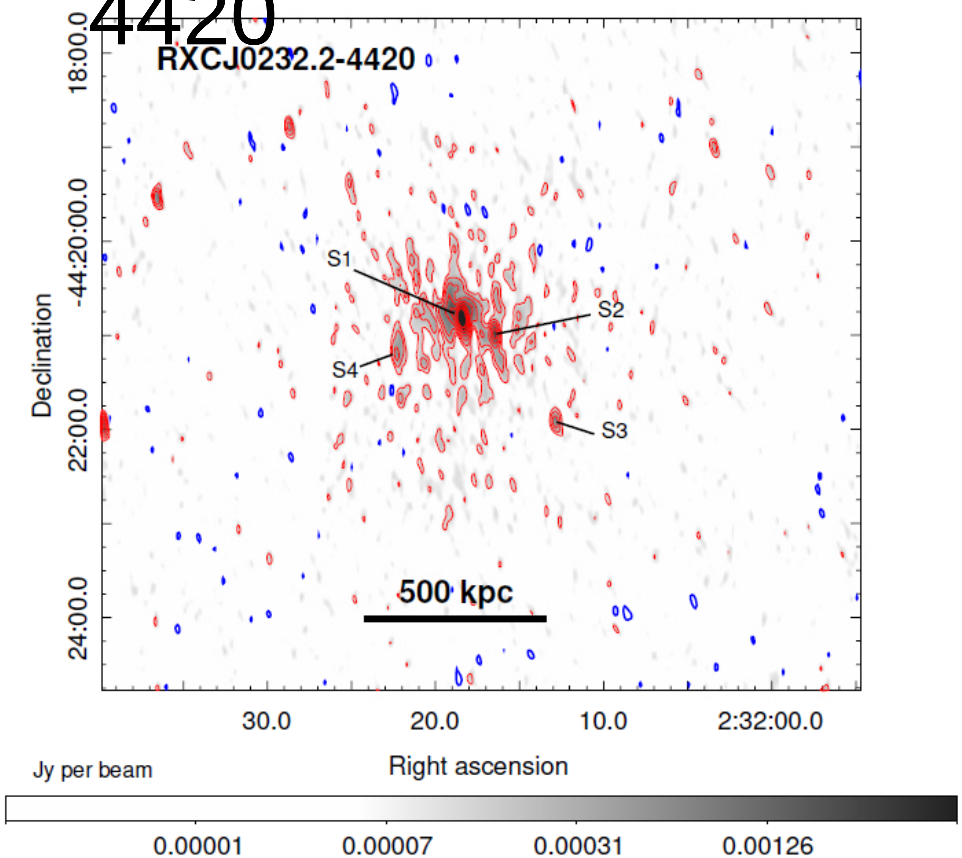

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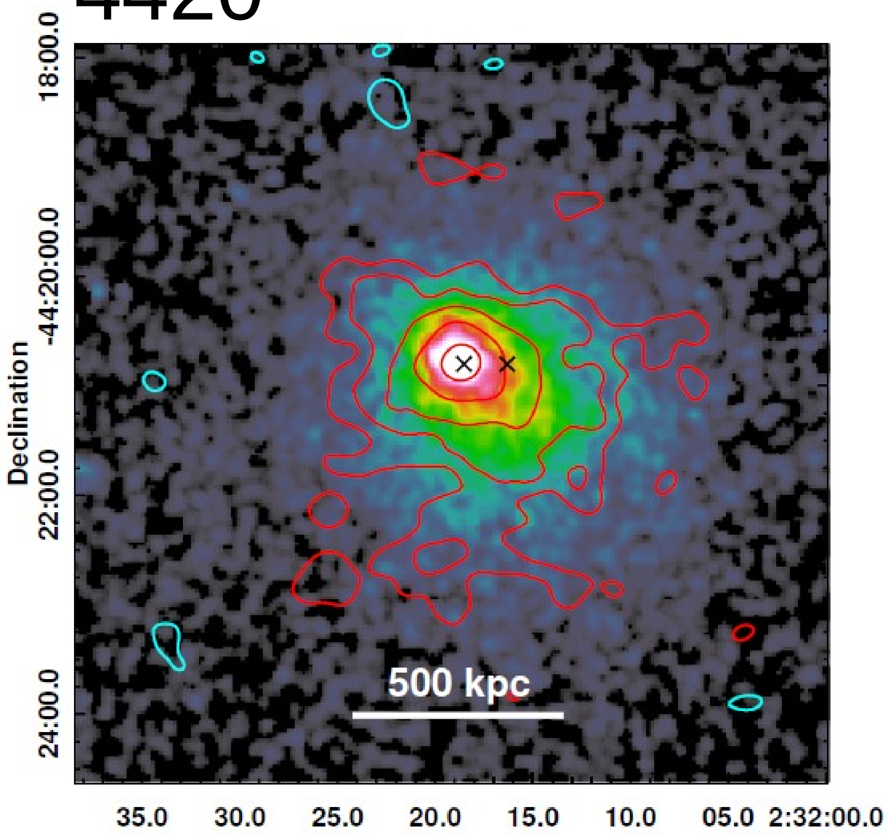
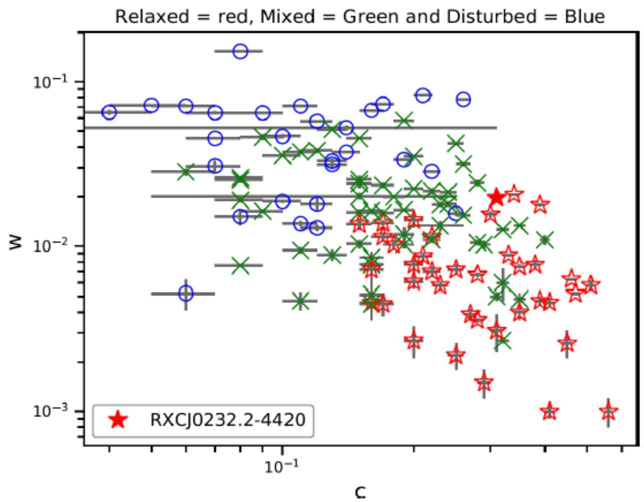
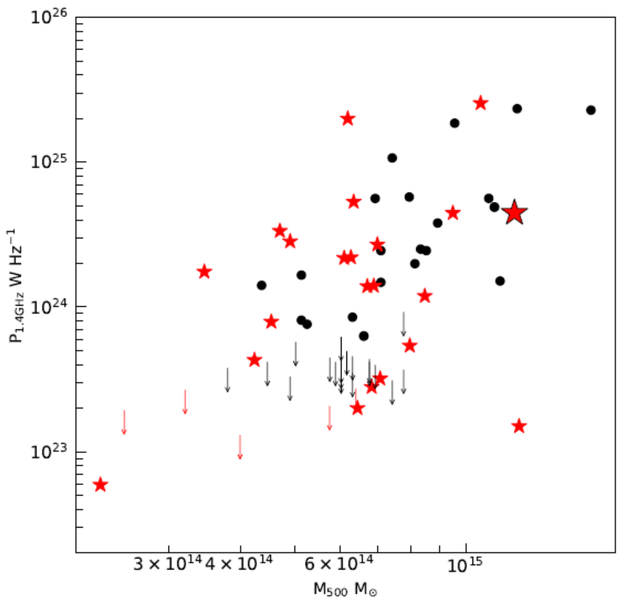






Kale et al 2019, MNRAS, submitted

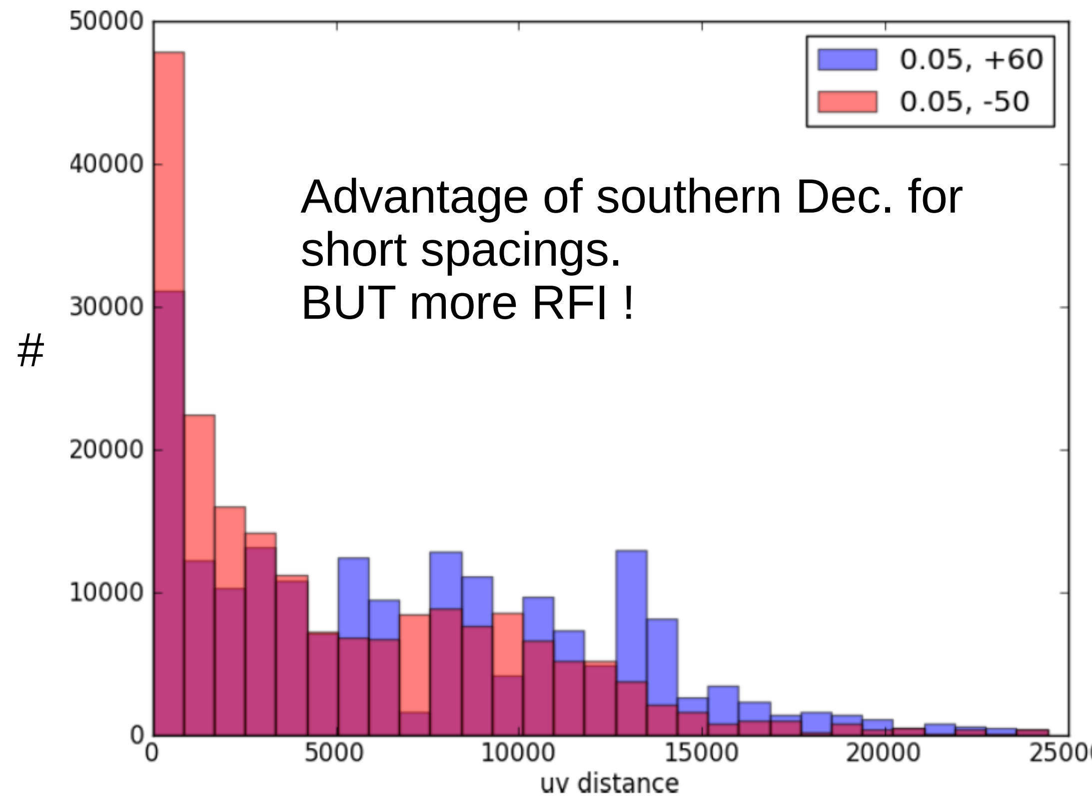
Southern Cluster Scale Extended Source Survey (SUCCESS)

$z < 0.2$, $M > 5 \times 10^{14}$ $M_{\odot}$ clusters

from Planck and SPT

Surveys.

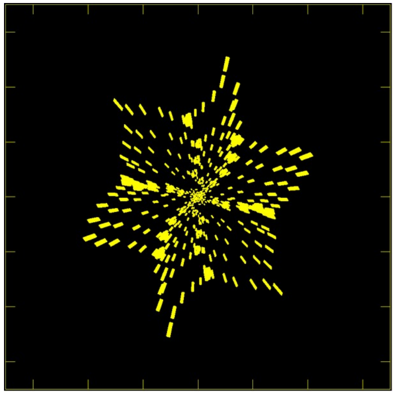
9 clusters observed with the GMRT

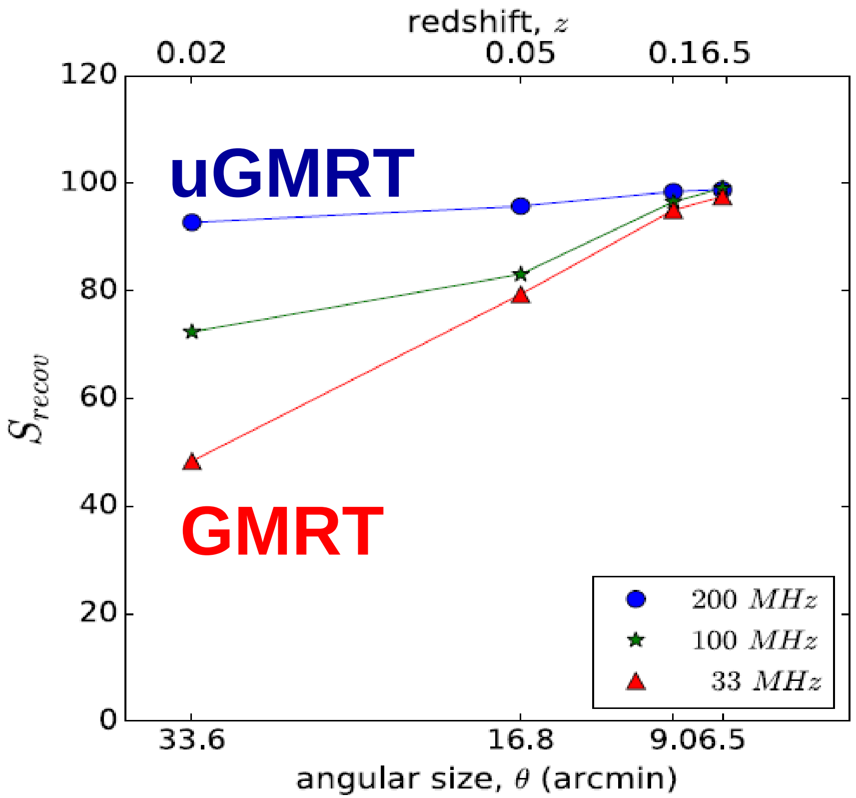


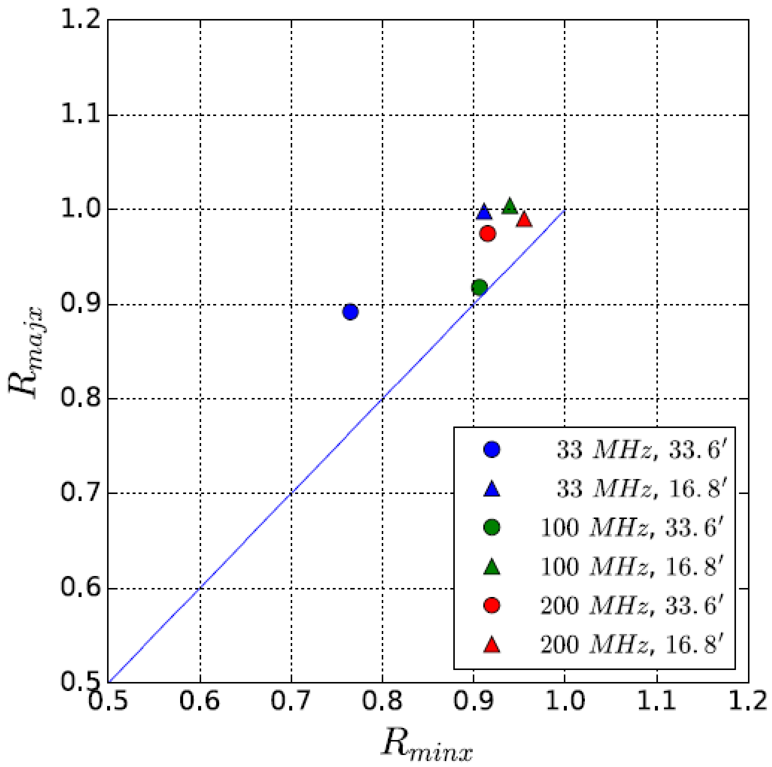
Being processed with a new pipeline that was developed for the uGMRT

Deo & Kale 2017, Experimental Astronomy

Upgraded GMRT: a wideband instrument
Gupta et al 2017







Factor of 2 better recovery of total flux density and reduced distortion in recovery of source morphology.

Deo and Kale 2017, Exp. Astron. 44,165

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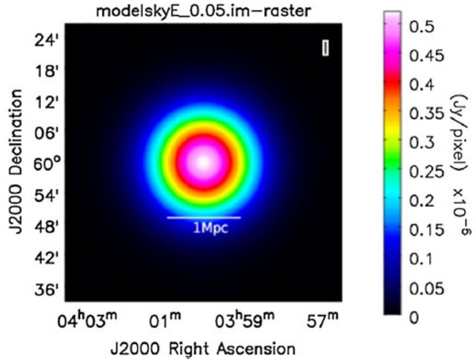
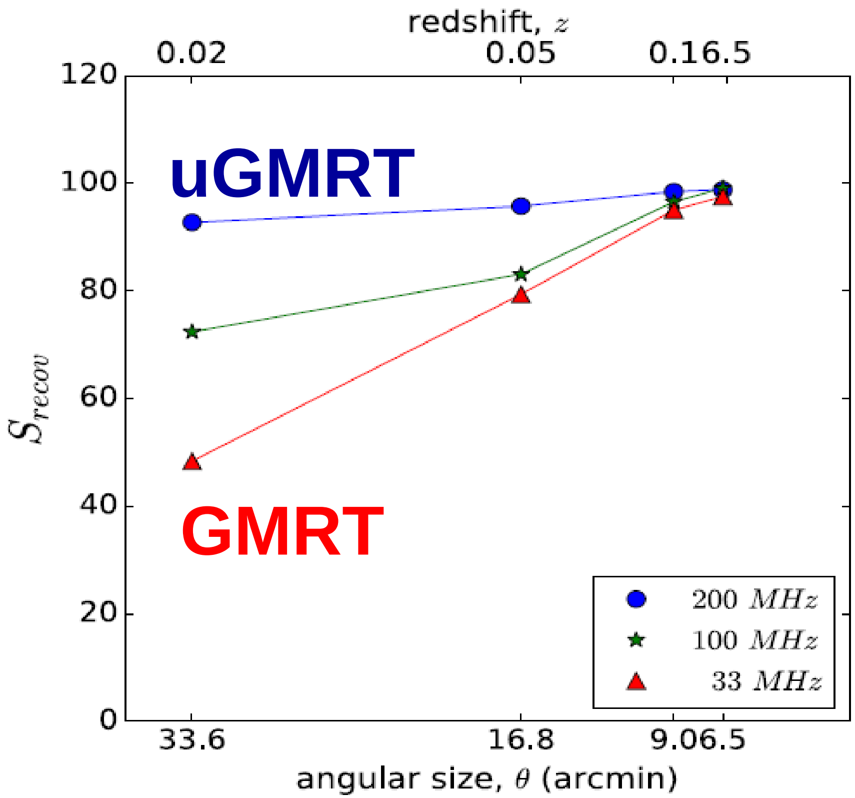
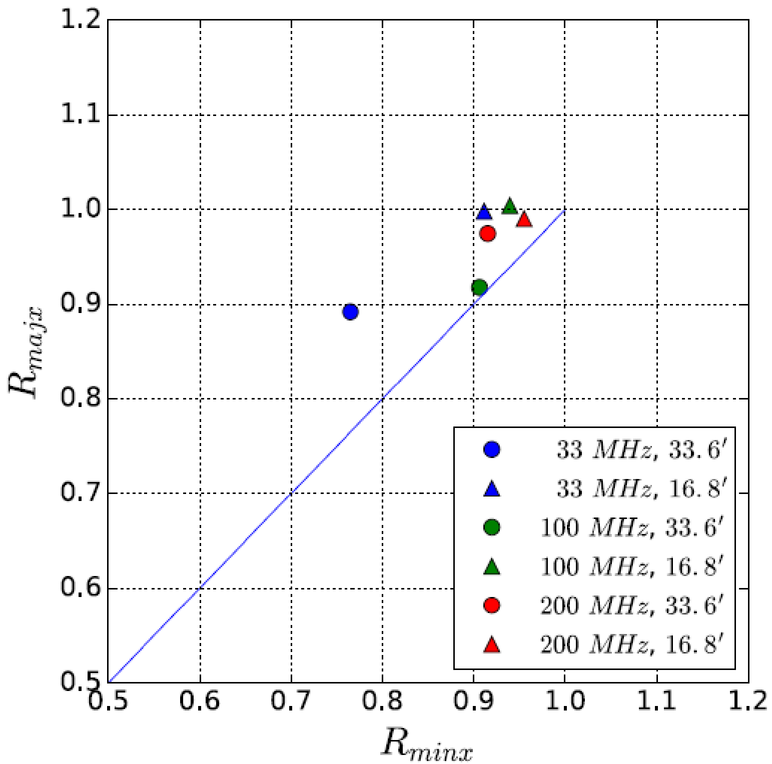
Upgraded GMRT: a wideband instrument

Gupta et al 2017







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Abell 4038: first target for uGMRT

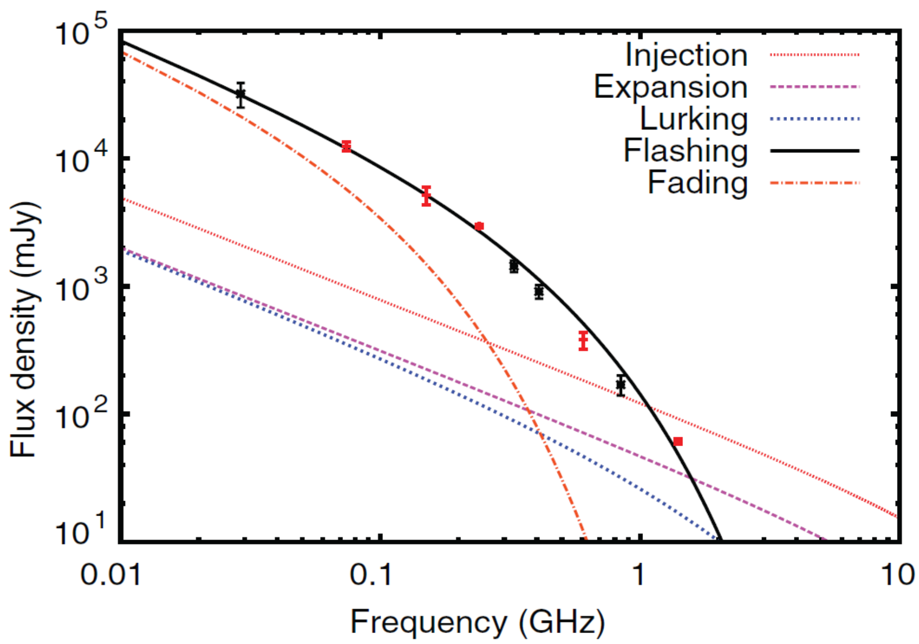
- Cluster with a known steep spectrum remnant radio galaxy source

Slee et al 2001

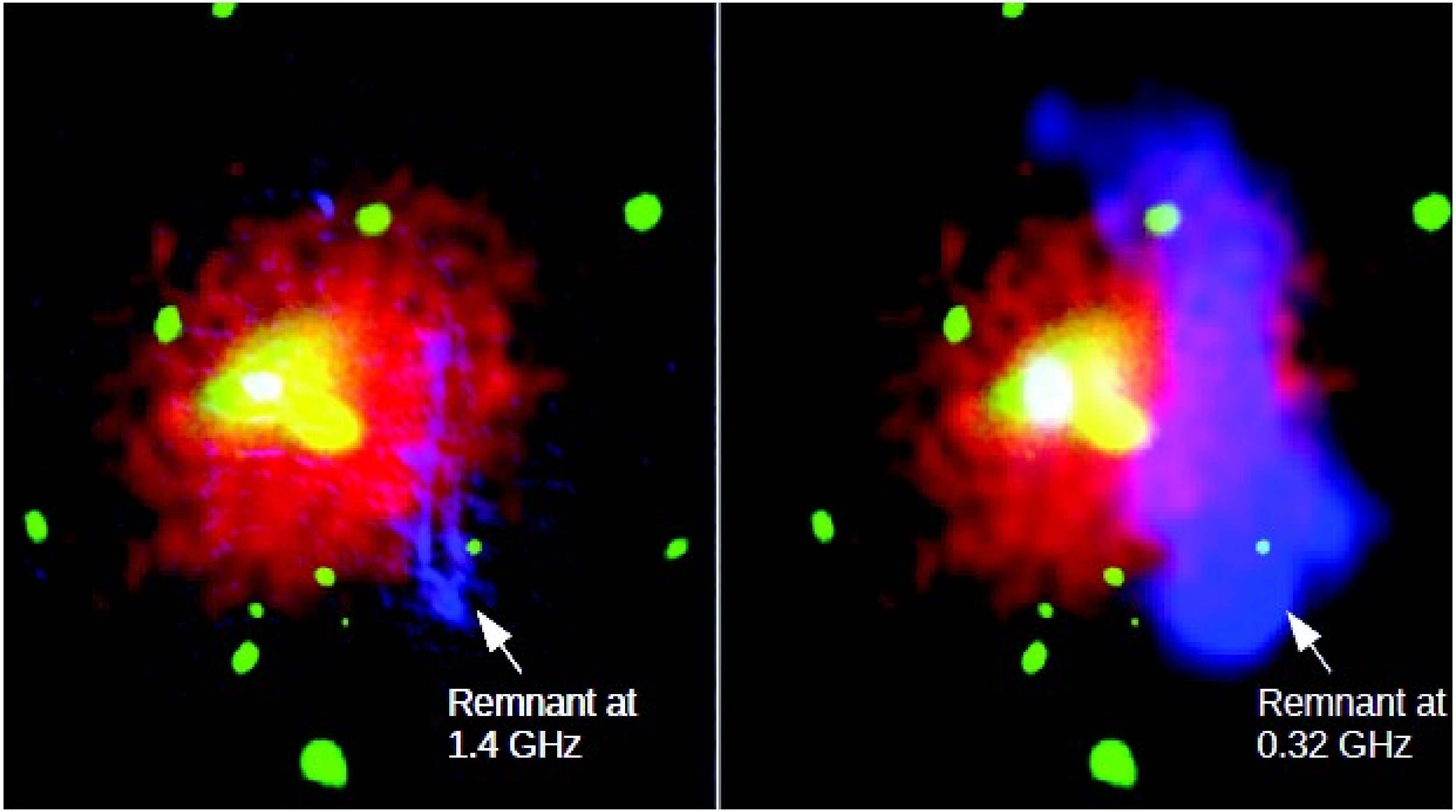
RA_{J2000}	23h47m43.2s
DEC_{J2000}	-28°08′29″
Redshift†	0.02819 ± 0.00055
$kT^{\dagger}$	2.69 ± 0.43 keV
$L_{[0.01-40]keV}$ ++	$(1.900 \pm 0.025) \times 10^{44}$ erg s^{-1}
$M^{\ddagger}$	$1.5 \pm 0.1 \times 10^{14}$ $M_{\odot}$

- Discovered larger extent
- Proposed to be adiabatically compressed remnant

Kale and Dwarakanath 2012



Red: Chandra X-ray image
Green: DSS R-band optical
Blue: Radio 1.4 GHz (left), 325 MHz (right)



Abell 4038: first target for uGMRT

- 8 hours each at Band – 5 and Band – 3
- Feb. and March 2017. Band-4 was not available then.

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$kT^{\dagger}$	2.69 ± 0.43 keV
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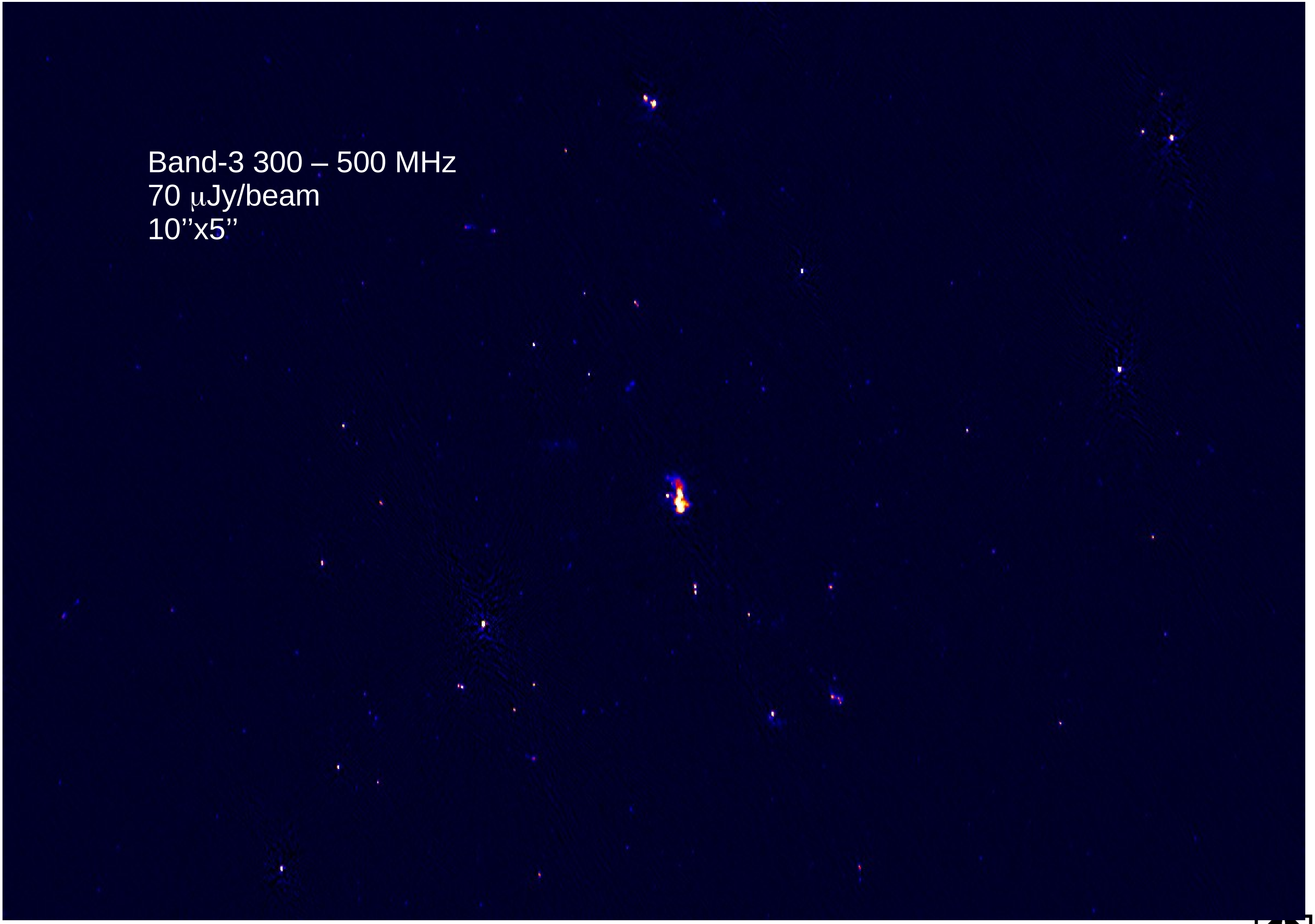
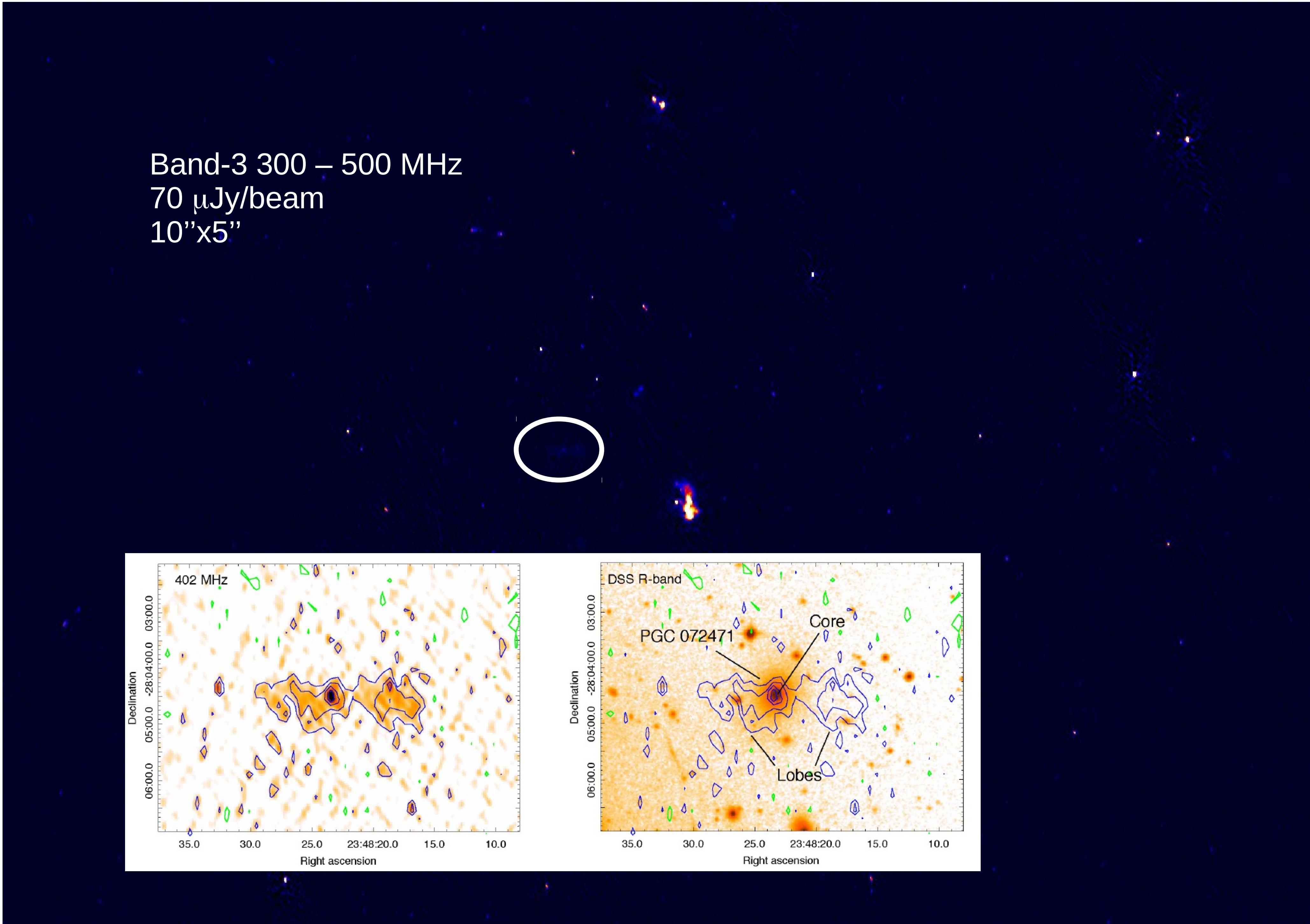
M‡	$1.5 \pm 0.1 \times 10^{14}$ $M_{\odot}$

† Sanders et al. (2011) ++ Mittal et al. (2011) ‡ Planck Collaboration et al. (2016)

- AOFlagger (Offringa et al 2012) and NRAO CASA used.

- RMS at image centre:
Band-3   70 microJy/beam; 10''x5''
Band- 5 30 microJy/beam; 3.6''x1.7''


Band-3 300 – 500 MHz
70 μJy/beam
10''x5''


Band-3 300 – 500 MHz
70 μJy/beam
10''x5''
402 MHz
Declination
03:00.0
-28:04:00.0
05:00.0
06:00.0
35.0
30.0
25.0
23:48:20.0
15.0
10.0
Right ascension
DSS R-band
PGC 072471
Core
Lobes

uGMRT spectral study of A4038

Due to RFI there were large gaps in the observed bands: affect the spectral index mapping of extended sources; could not get reliable maps with CASA clean.

Sub-band imaging for uv-coverage matched spectral analysis:

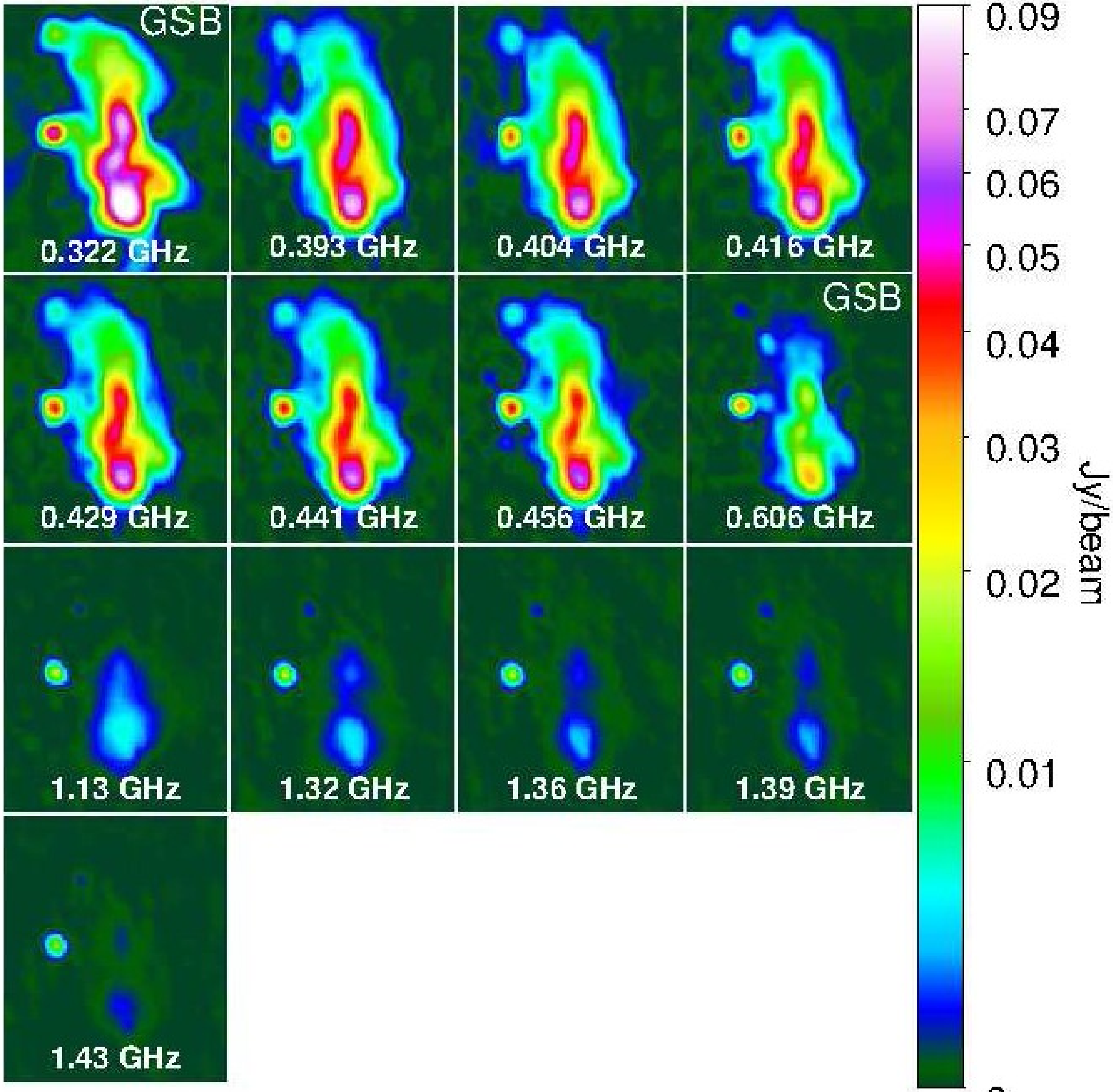
We made sub-band image in frequency range where RFI had less effect on the band.

But the sub-bands were chosen such that the uv-coverage would be closely matched.

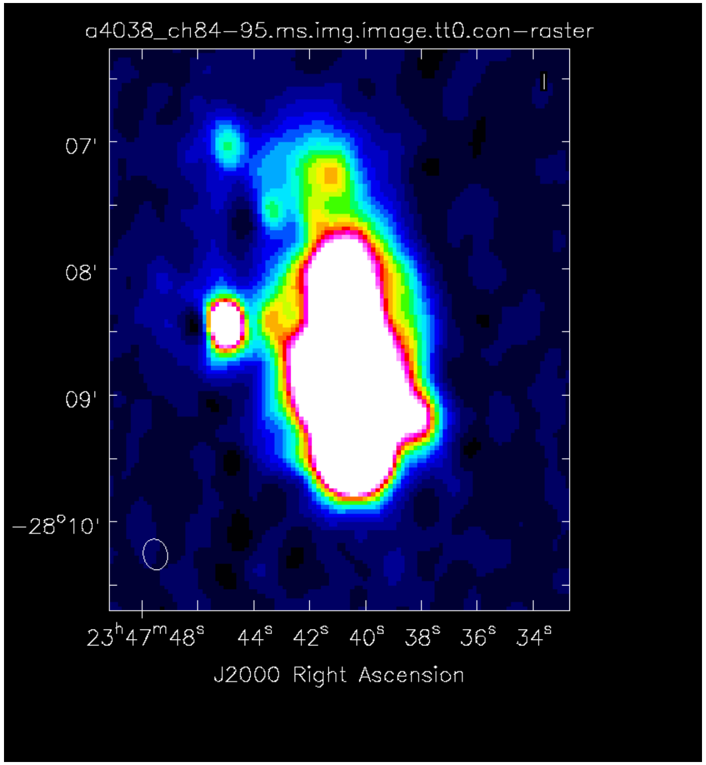
This was achieved by keeping: $\Delta\nu/\nu$ = constant

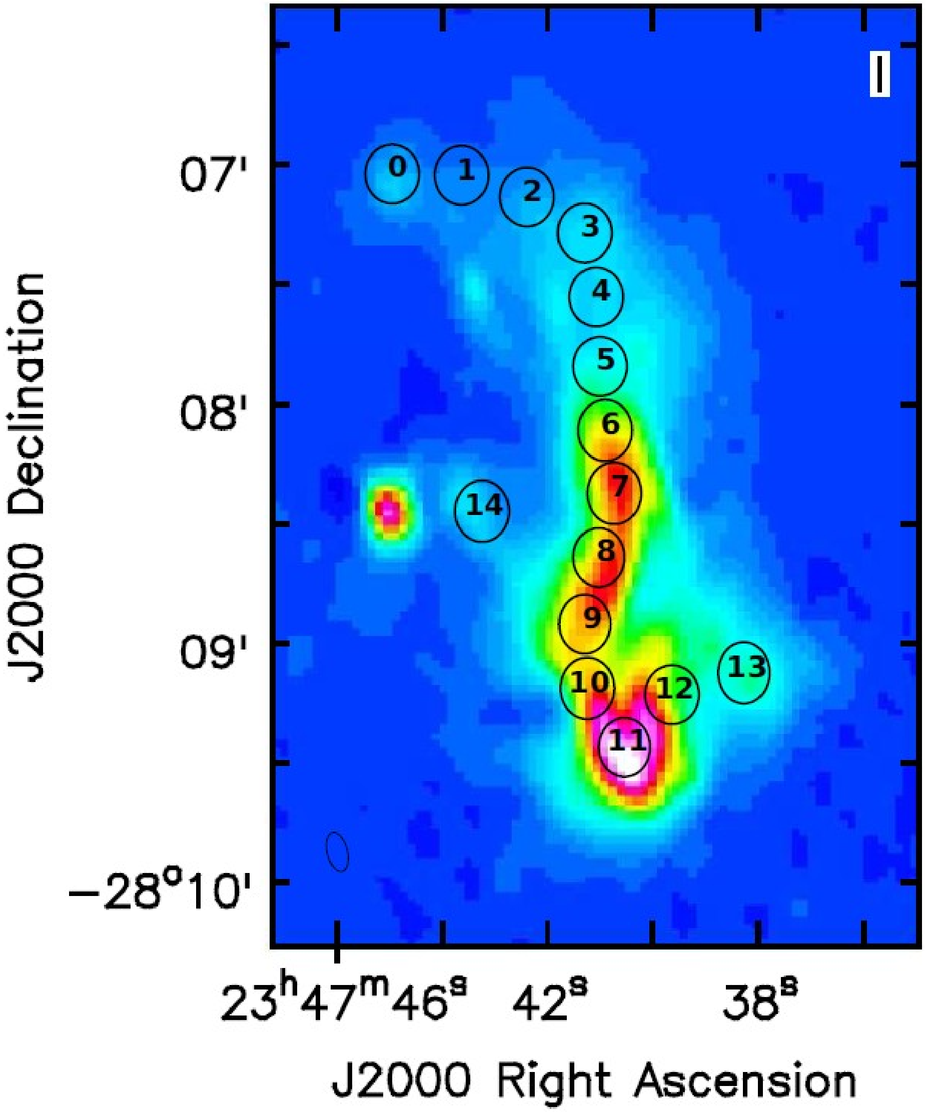
The constant used was 0.028. This resulted in sub-band bandwidths of 11 MHz to 40 MHz across 320 – 1400 MHz.

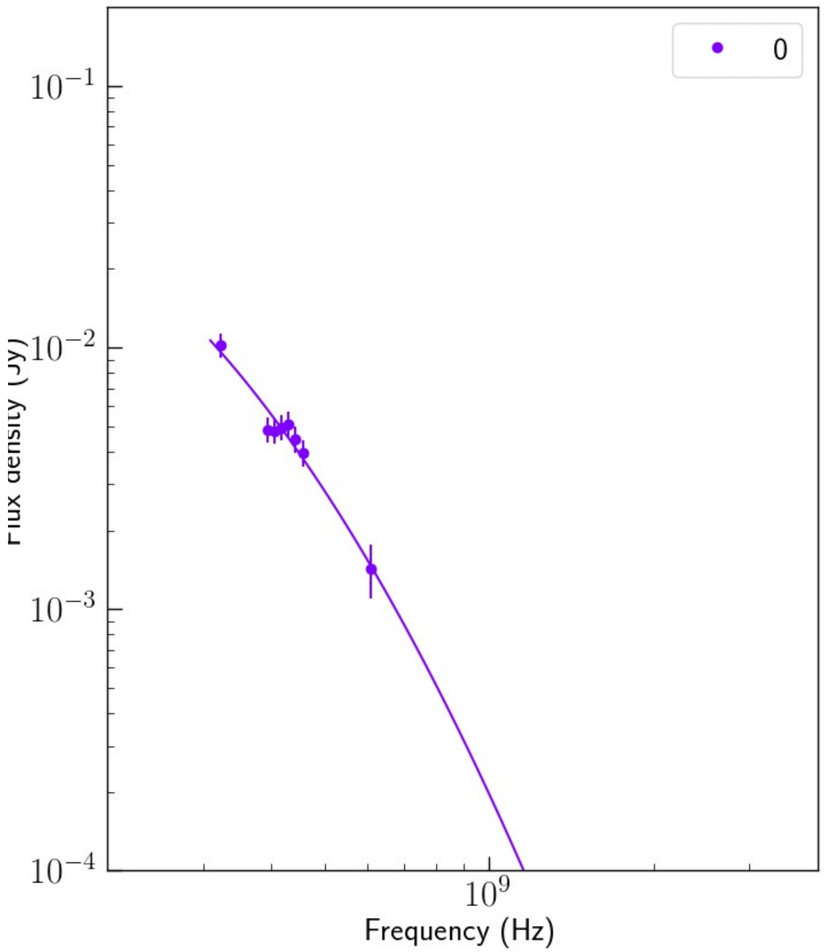
Sub-band- images



Remnant radio galaxy across 320 – 1400 MHz



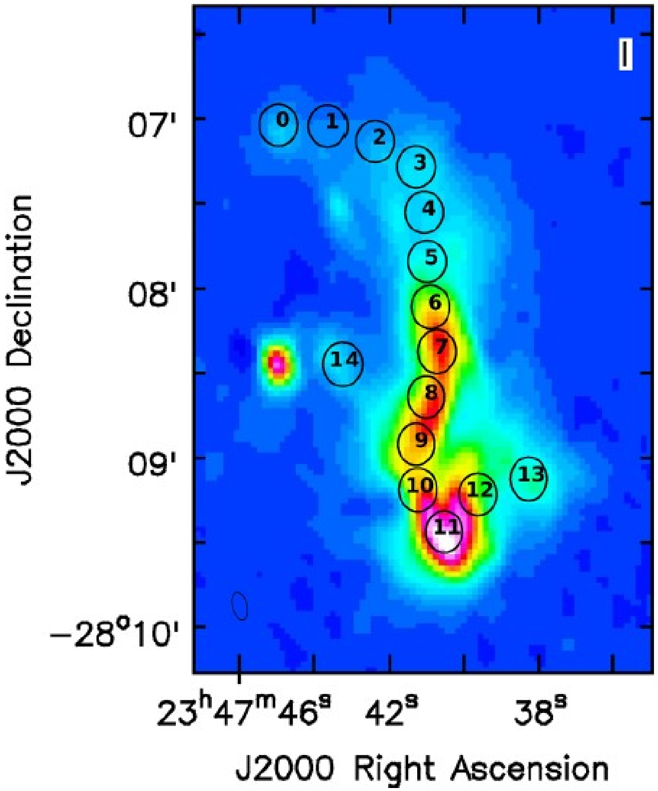


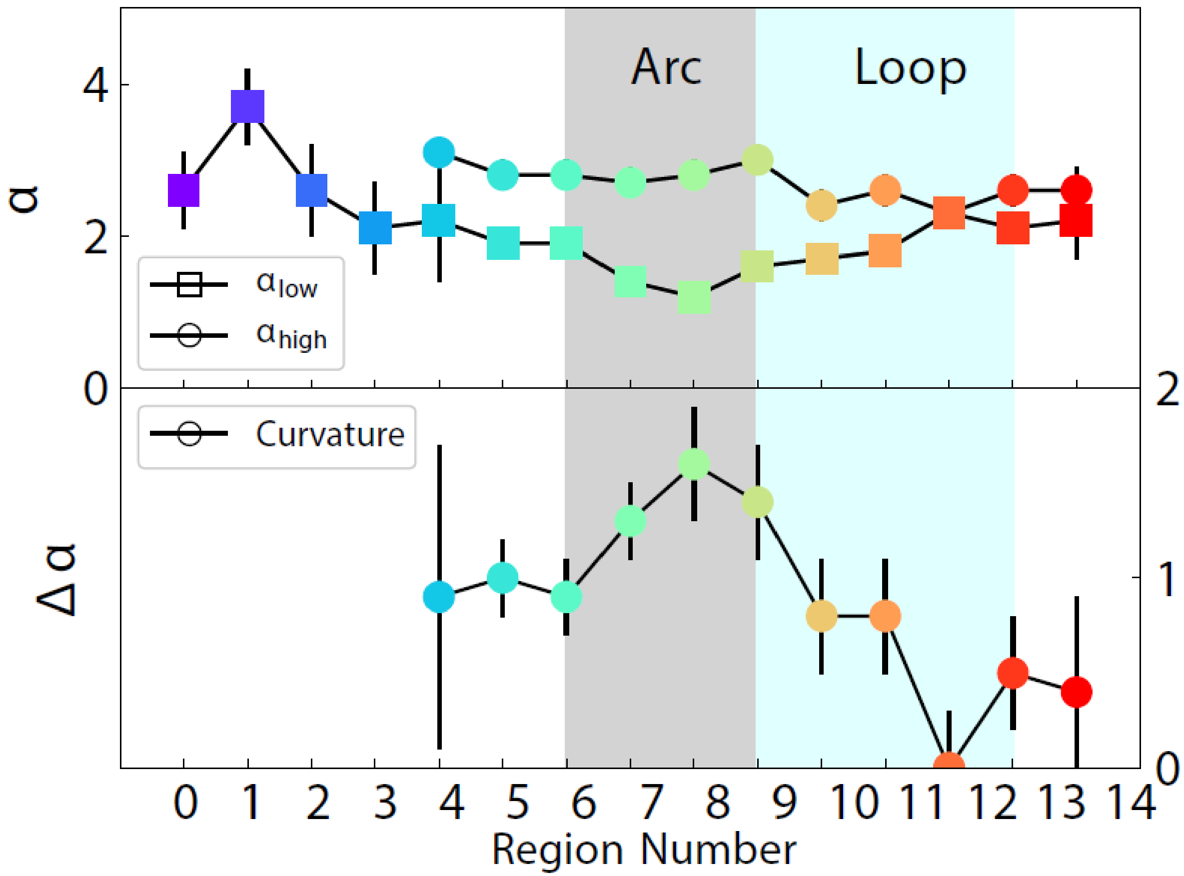


Variation in spectral shape across the relic

Curvature

$$\Delta\alpha = \alpha_{\rm high} - \alpha_{\rm low}$$





- Variation in curvature: relation to X-ray morphology
- Seed electron spectra can be curved and need to be considered in simulations before re-acceleration

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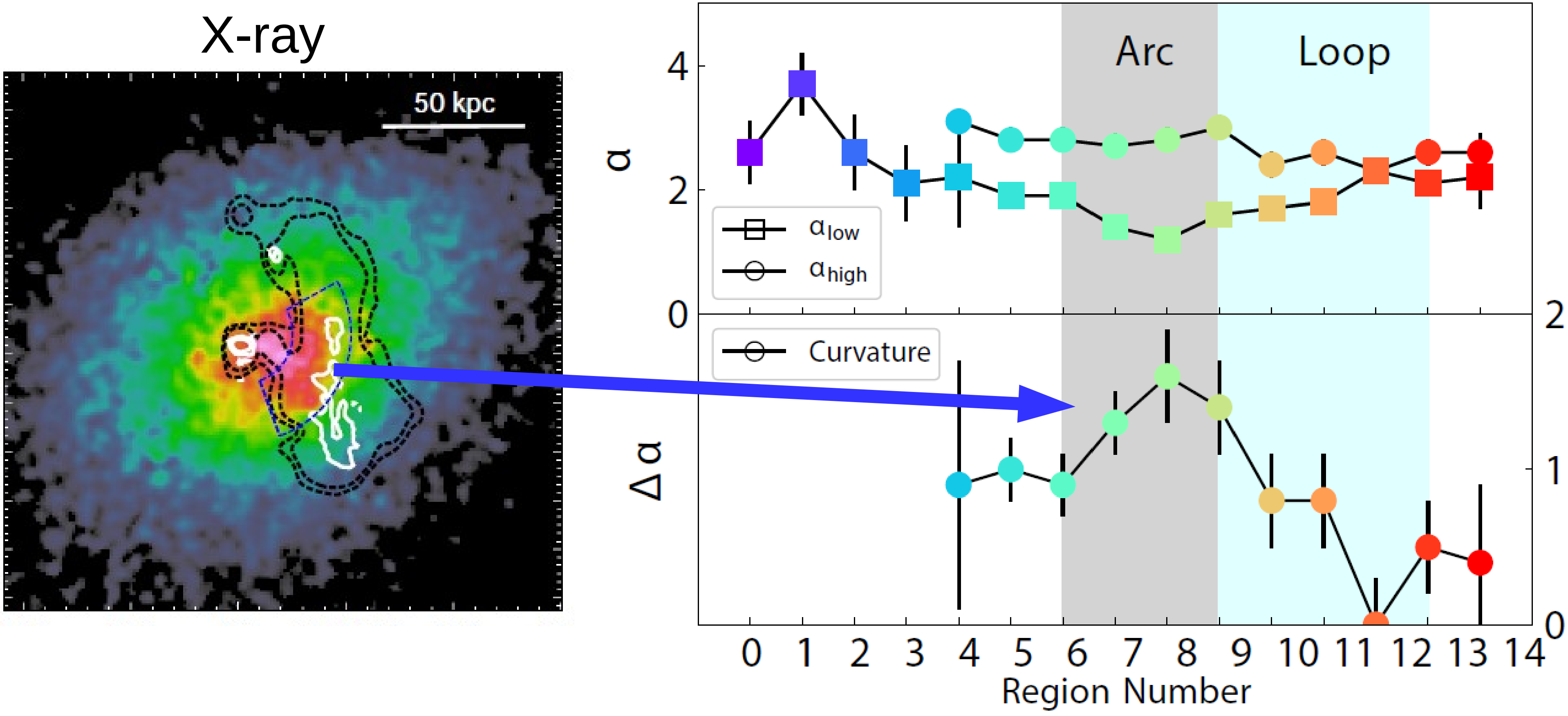
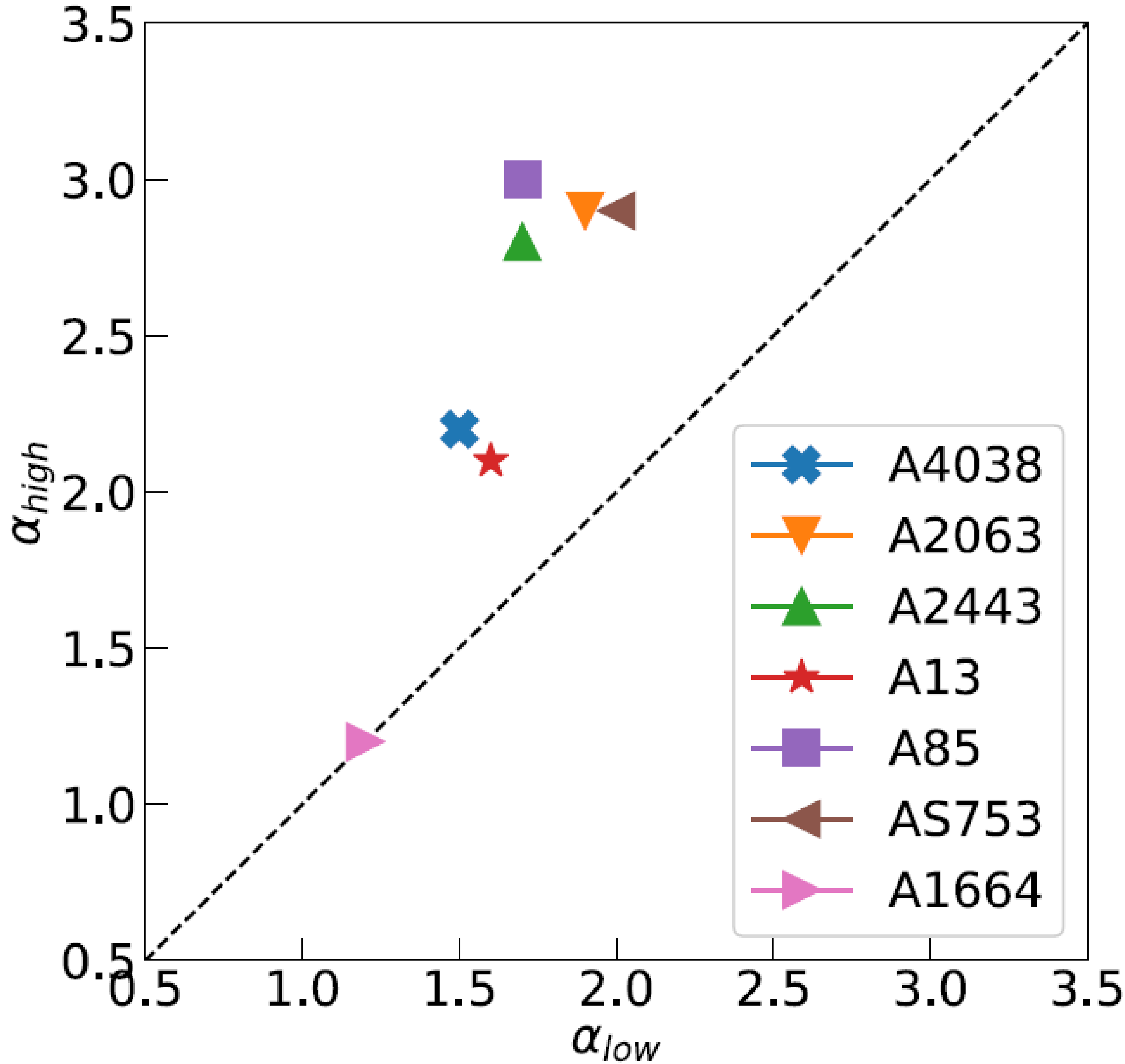
Curvature

$$\Delta\alpha = \alpha_{\text{high}} - \alpha_{\text{low}}$$



A4038 and other remnant radio galaxies in literature.



$\Delta\alpha$ Curvature
0.7
1.0
1.1
0.5
1.3
0.9
0.0

A CASA based pipeline for uGMRT data reduction

- Distinct flagging strategy for C-C baselines and other baselines
- Flags known narrow-band RFI at the GMRT
- Makes use of auto-multi-threshold masking implemented in CASA tclean

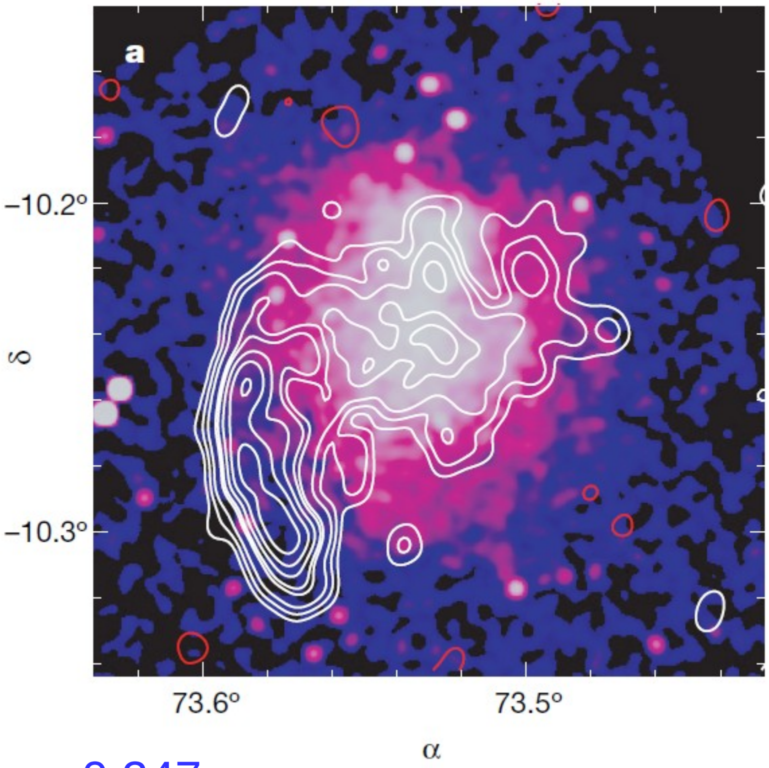
Further improvement plans:

- Implementation of peeling
- Use of LOFAR tools

Abell 521 and El Gordo

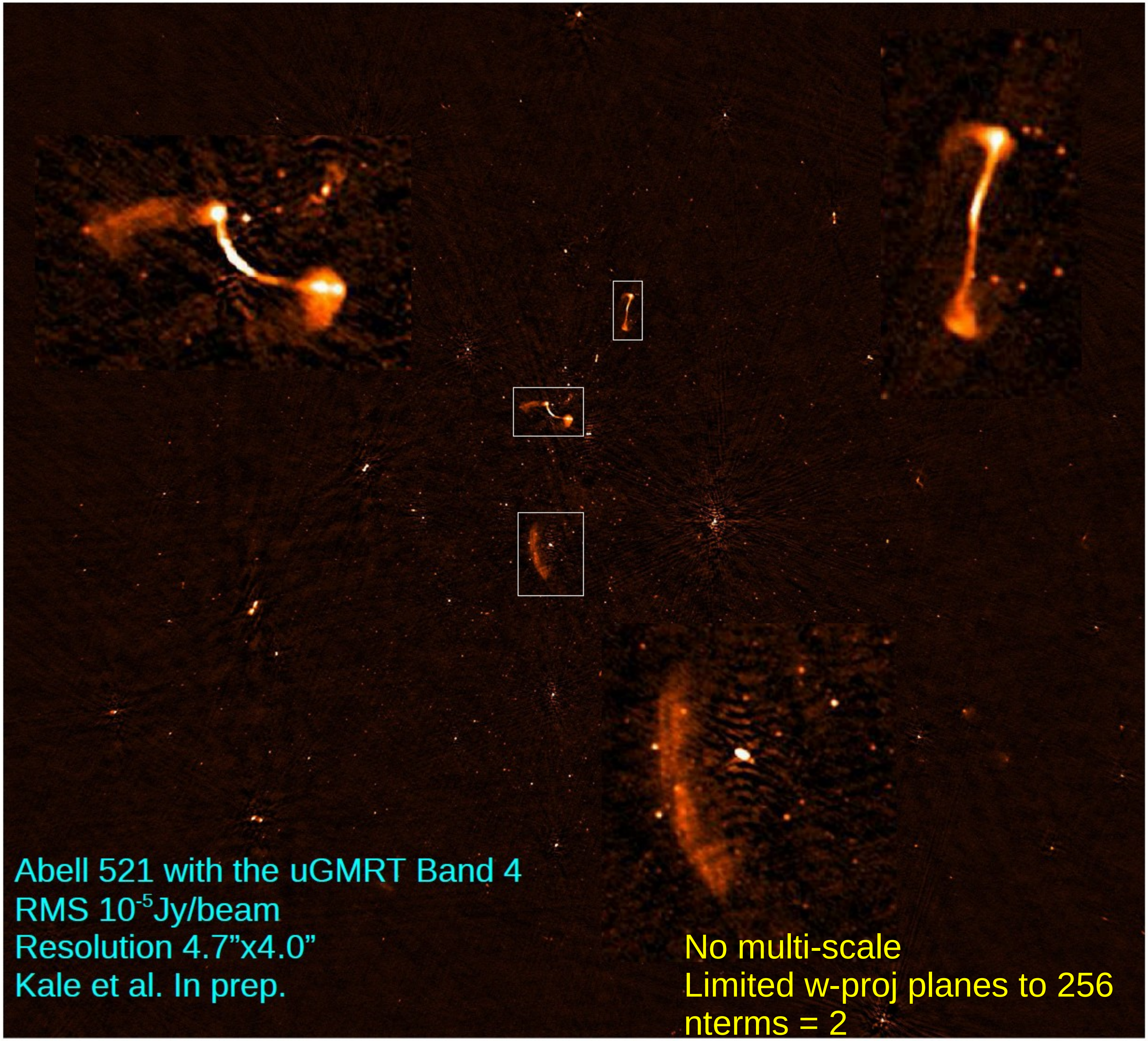
Ultra-steep spectrum radio halo

Brunetti et al 2008

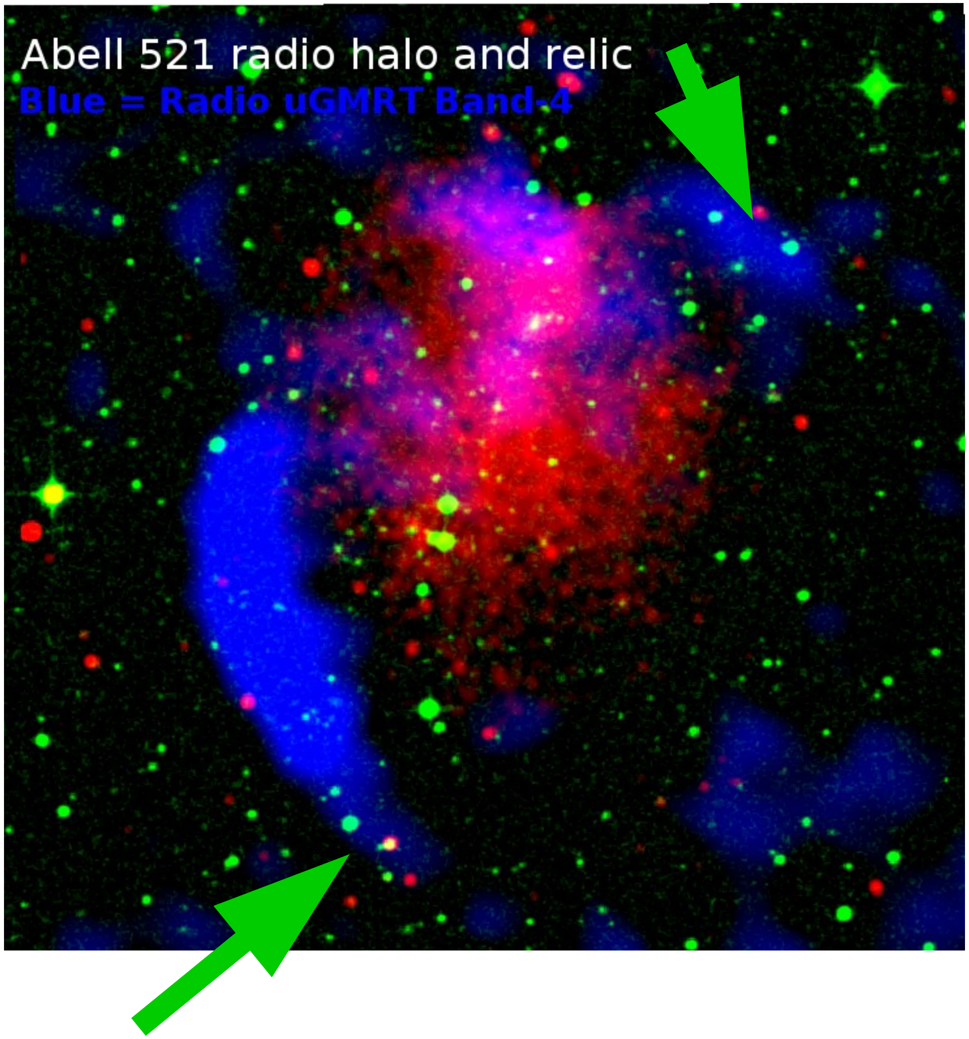


z = 0.247

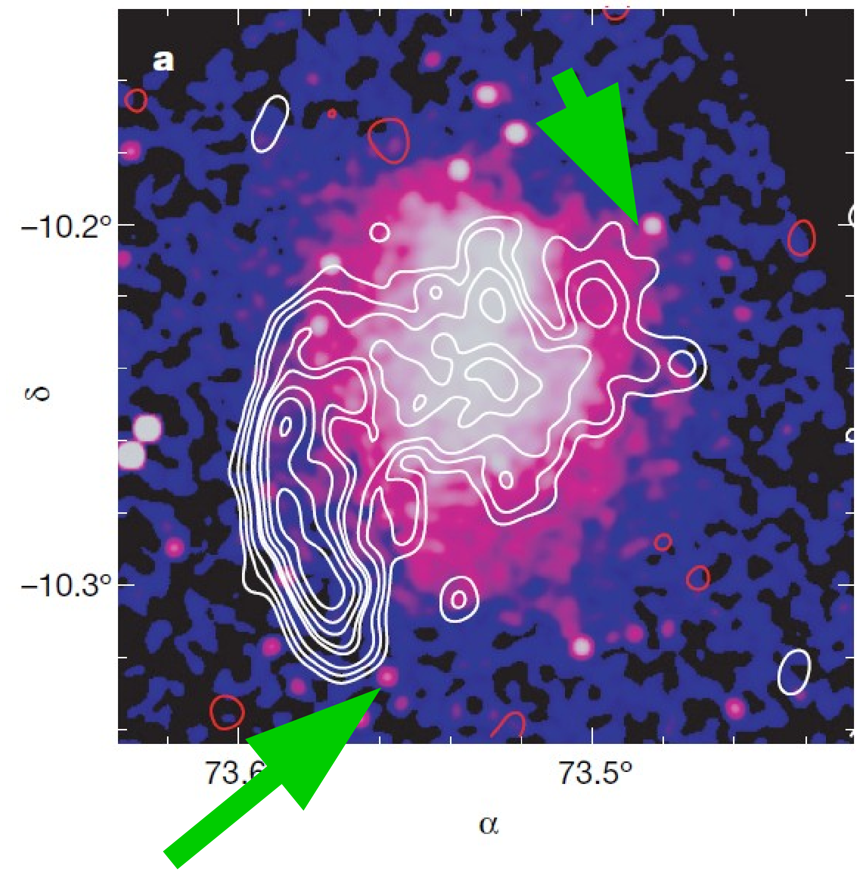
Giacintucci et al 2008;
Dallacasa et al 2009


Abell 521 with the uGMRT Band 4
RMS 10-5Jy/beam
Resolution 4.7”x4.0”
Kale et al. In prep.
No multi-scale
Limited w-proj planes to 256
nterms = 2

Low resolution image: discrete sources subtracted: additional emission ?



Preliminary results



Red: Chandra X-ray image
Giacintucci et al 2008

Kale, et al in prep.

Abell 521 and El Gordo

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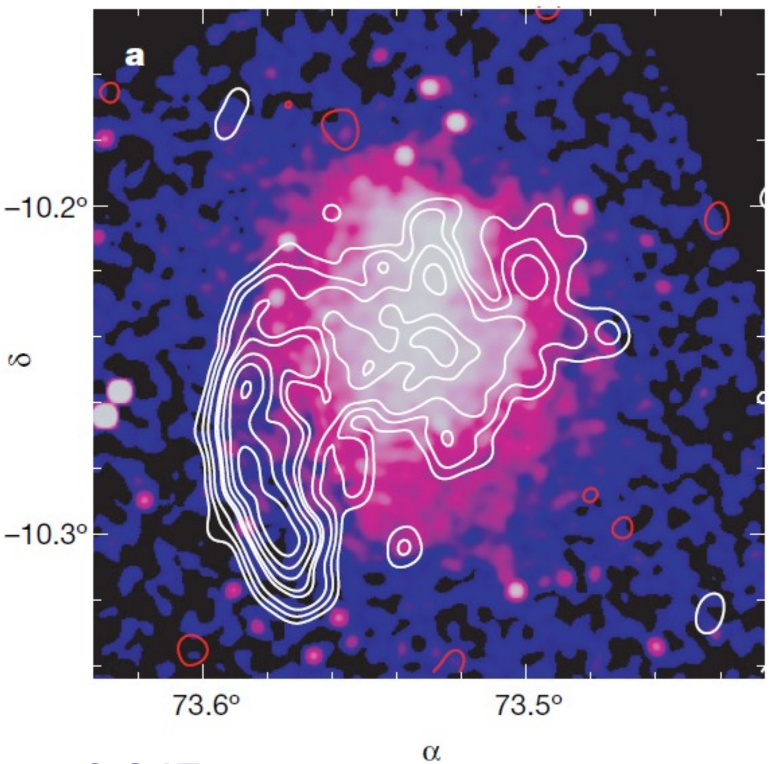

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Giacintucci et al 2008;
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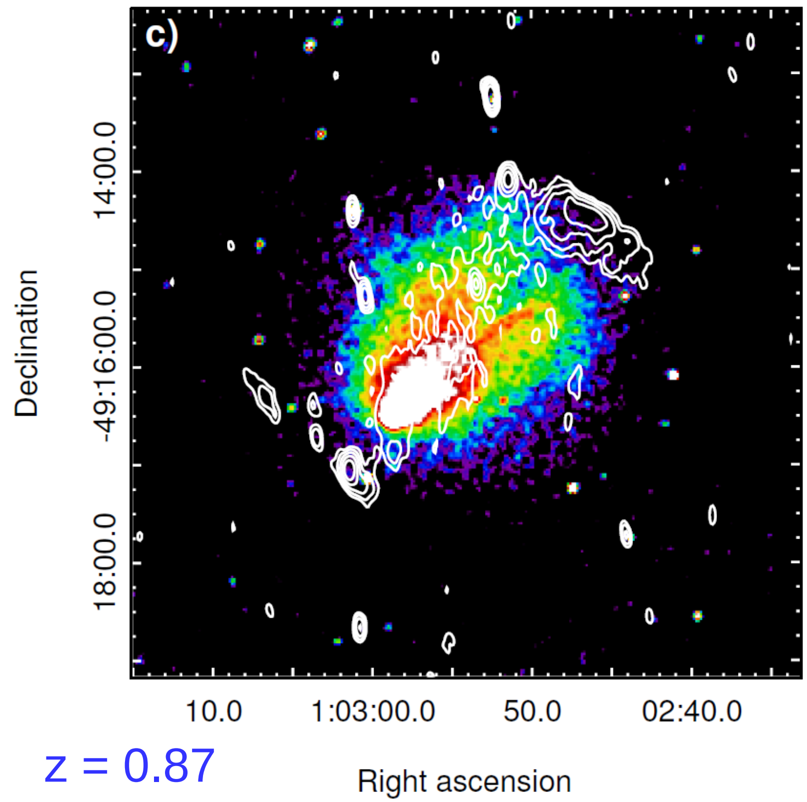
Highest redshift radio halo-relic system- (Lindner et al 2014)

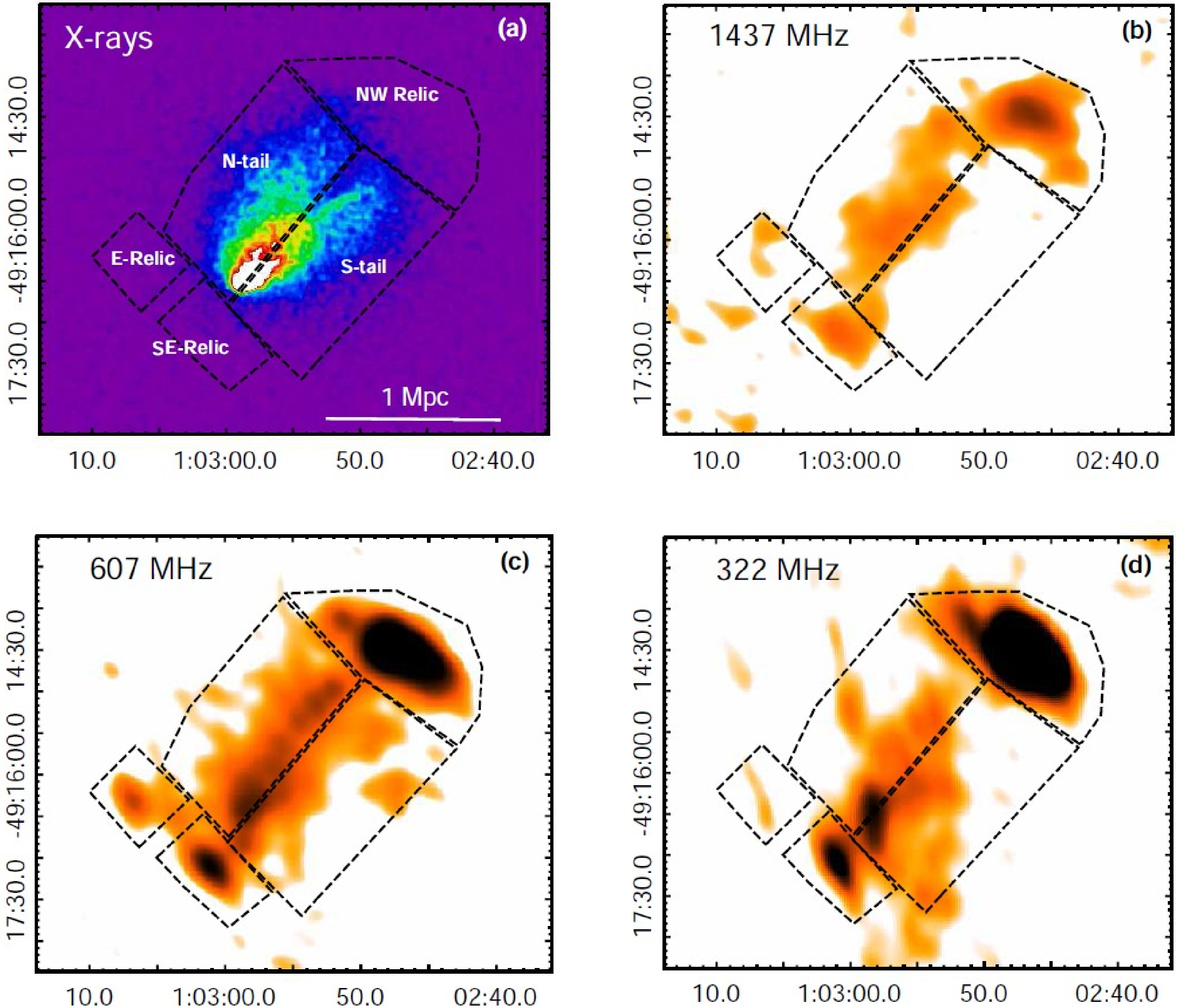


z = 0.87

Botteon, Gastadello, Brunetti and Kale 2017

El Gordo across Bands 3, 4 and 5 (Preliminary result)

Analysis of uGMRT data recorded in Nov- Dec 2017 from 300 – 1450 MHz



Kale, et al in prep.

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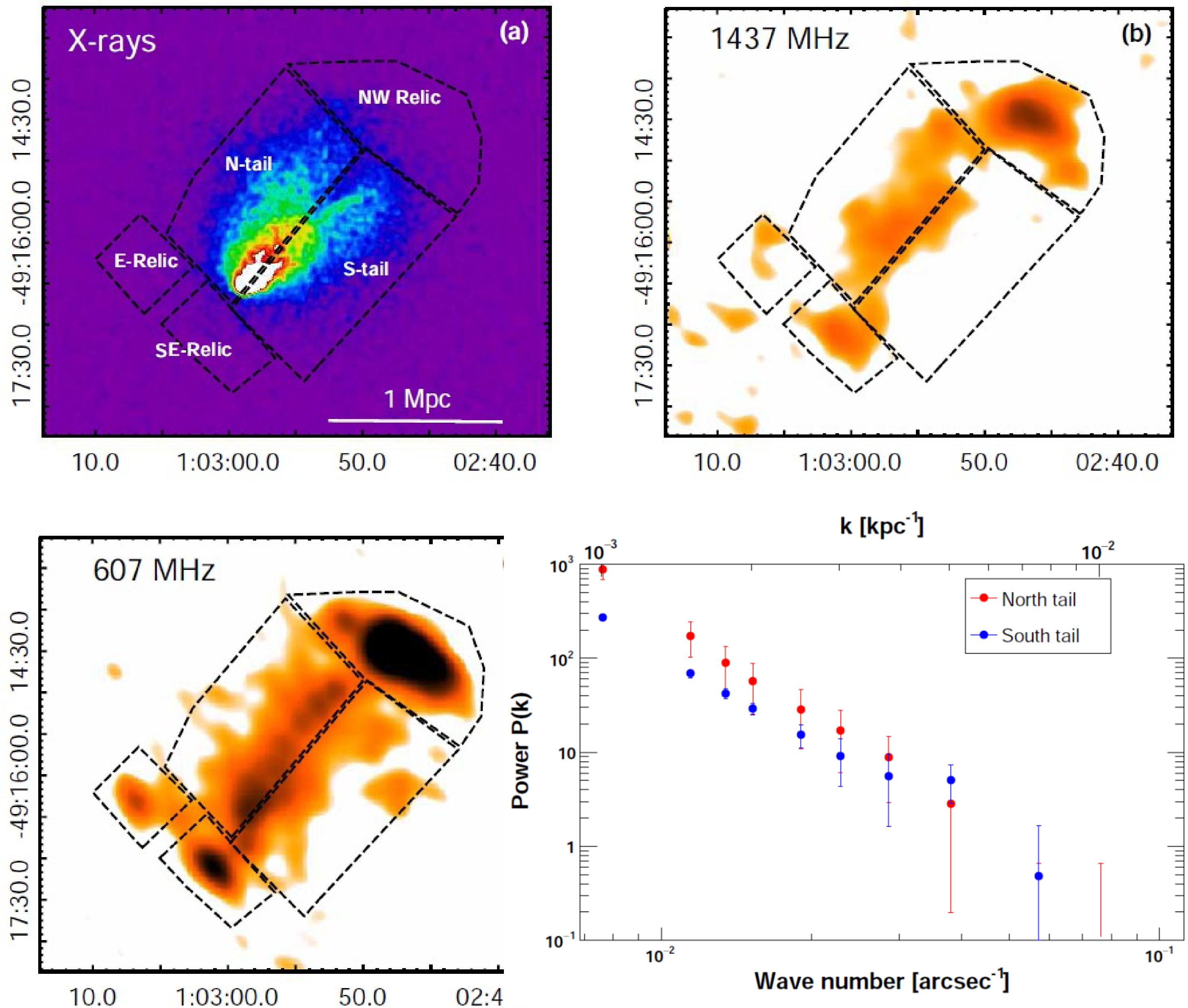

Kale, et al in prep.

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Broadband RFI at the GMRT

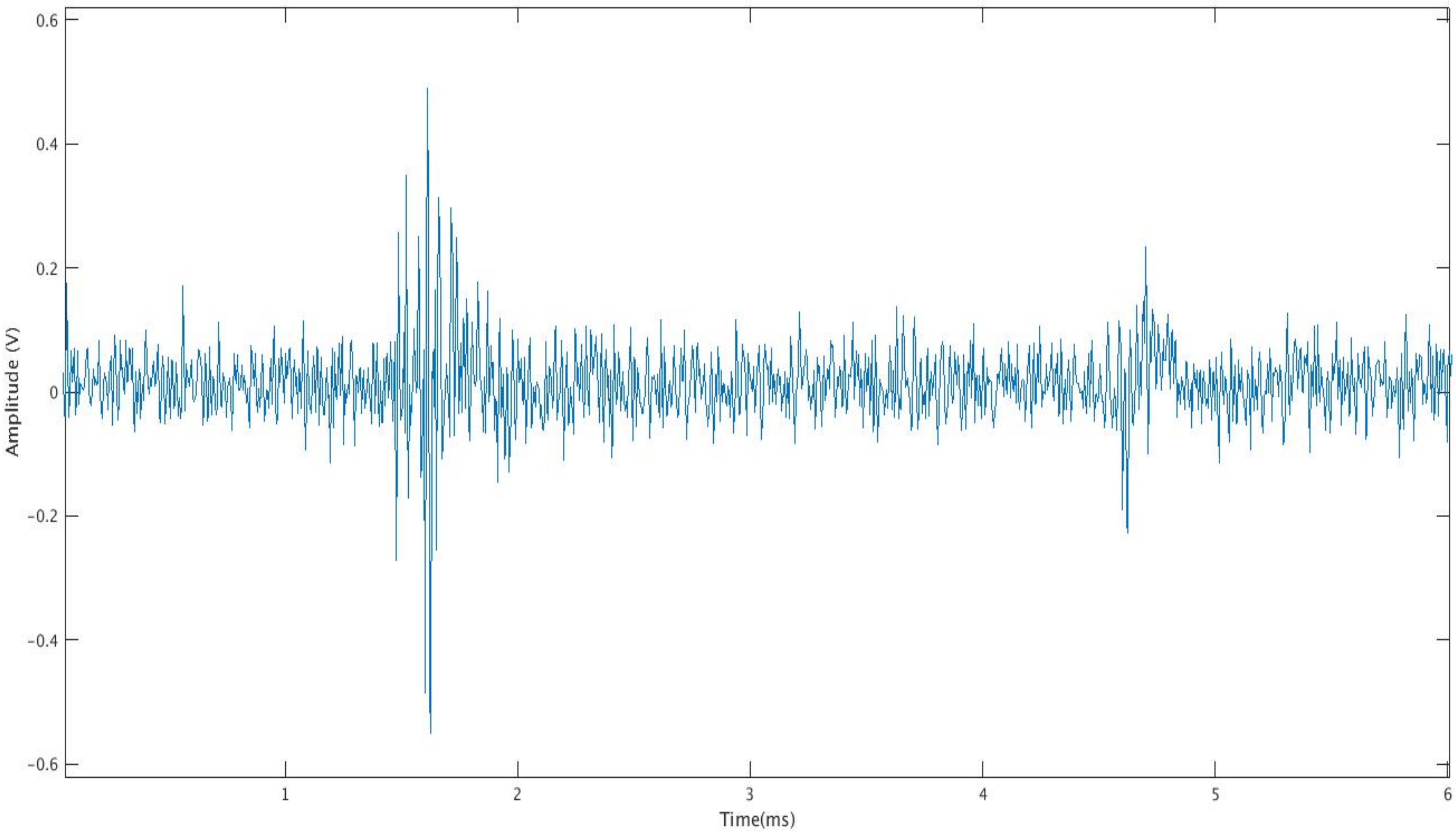
Power-line Radio Frequency Interference at the GMRT
NCRA Technical Report 223
G. Swarup

Real-time broadband RFI excision system at the GMRT

Poster by K. D. Buch

Team: K. D. Buch, S. Kudale, M. Muley, Ajith Kumar B. and Y. Gupta

Power-line RFI – impulsive



Individual instances, several ns wide

Power-line RFI – impulsive

Temporally impulsive RFI: Energy spreads post-FFT hence *excision is needed before FFT.*

- Power-line RFI: Low duty cycle but high spectral occupancy
- **RFI is correlated** in closely spaced antennas: adversely affects short baseline data critical for imaging extended sources

Excision at the best possible time resolution: reduction in loss of astronomical data due to flagging (tradeoff)

Real time RFI excision scheme implemented at the GMRT

Robust threshold using Median Absolute Deviation for RFI detection

$$\sigma_{MAD} = 1.4826(med(|x(i) - med(x)|))$$

Excision (filtering) by replacing the RFI samples by constant value or noise or threshold

Robust threshold: median ± n*σ_{MAD}

- Long-lasting RFI: Hold MAD values from consecutive windows in a memory buffer and compute the median (M) i.e. median of MAD (MoM) values (M_m)

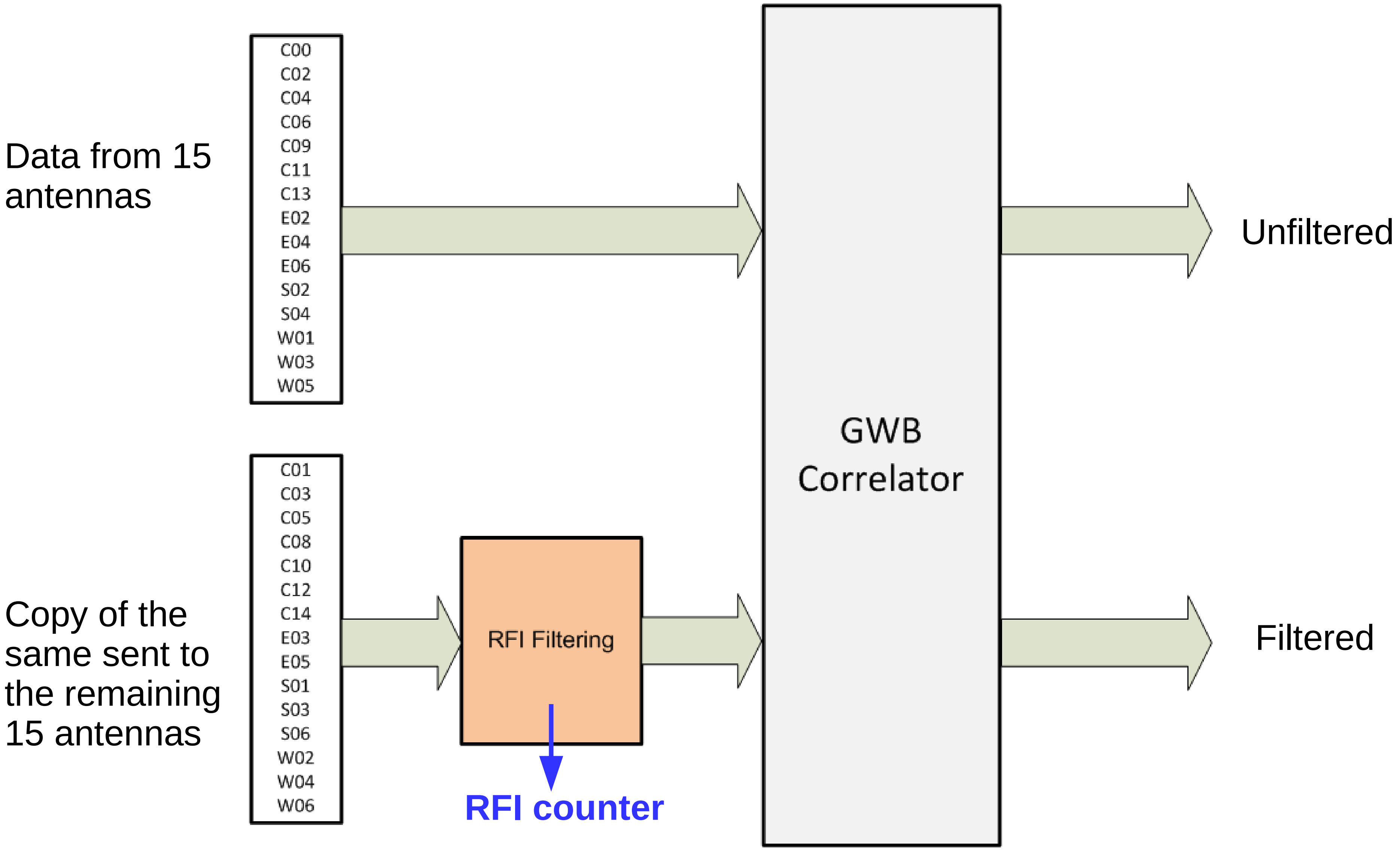
$$M_m = M(D_1, D_2, \ldots, D_n)$$

- Current design uses 16k MoM – i.e. median of 16k MAD values

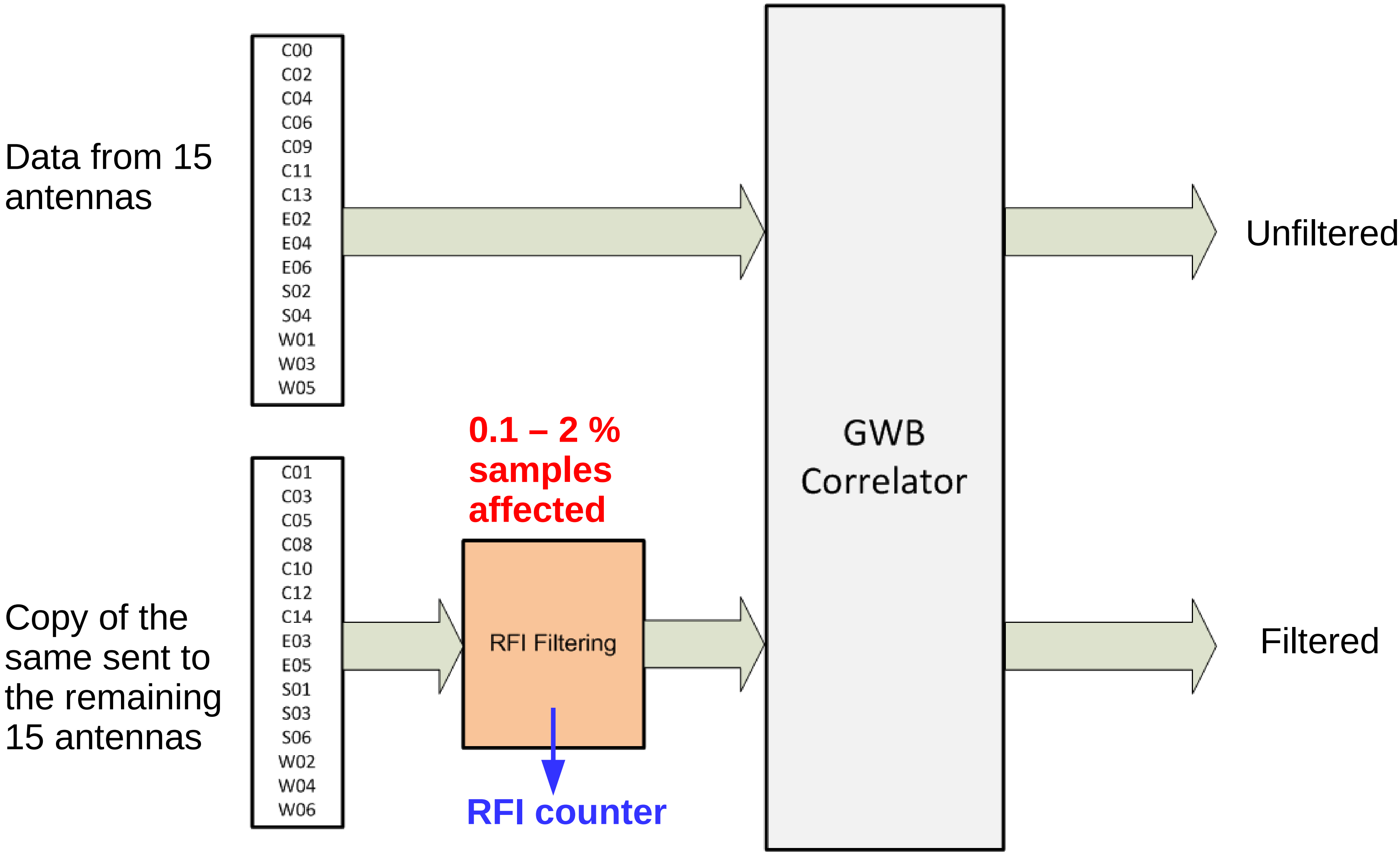
About 2 seconds of data used for statistics in real time.

Buch et. al, "Real-time MAD-based RFI Excision on FPGA ", JAI Special Issue on Interference Mitigation in Radio Astronomy, January 2019

Unfiltered and filtered data

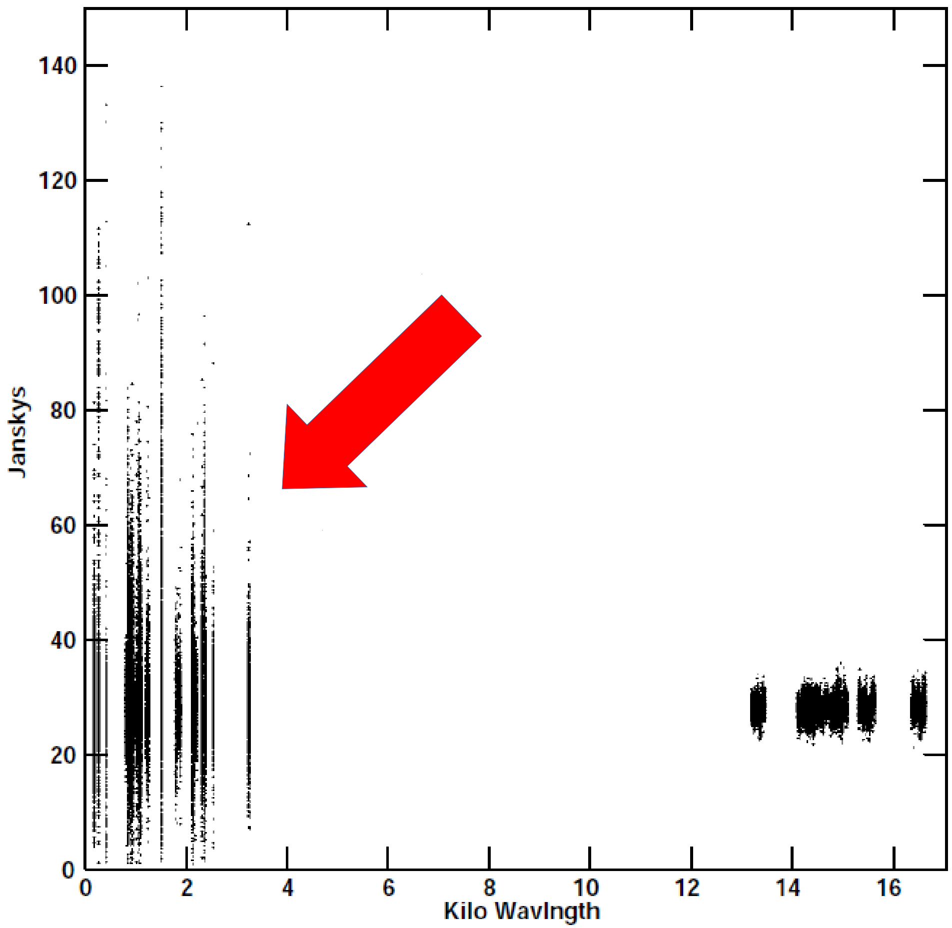


Unfiltered and filtered data

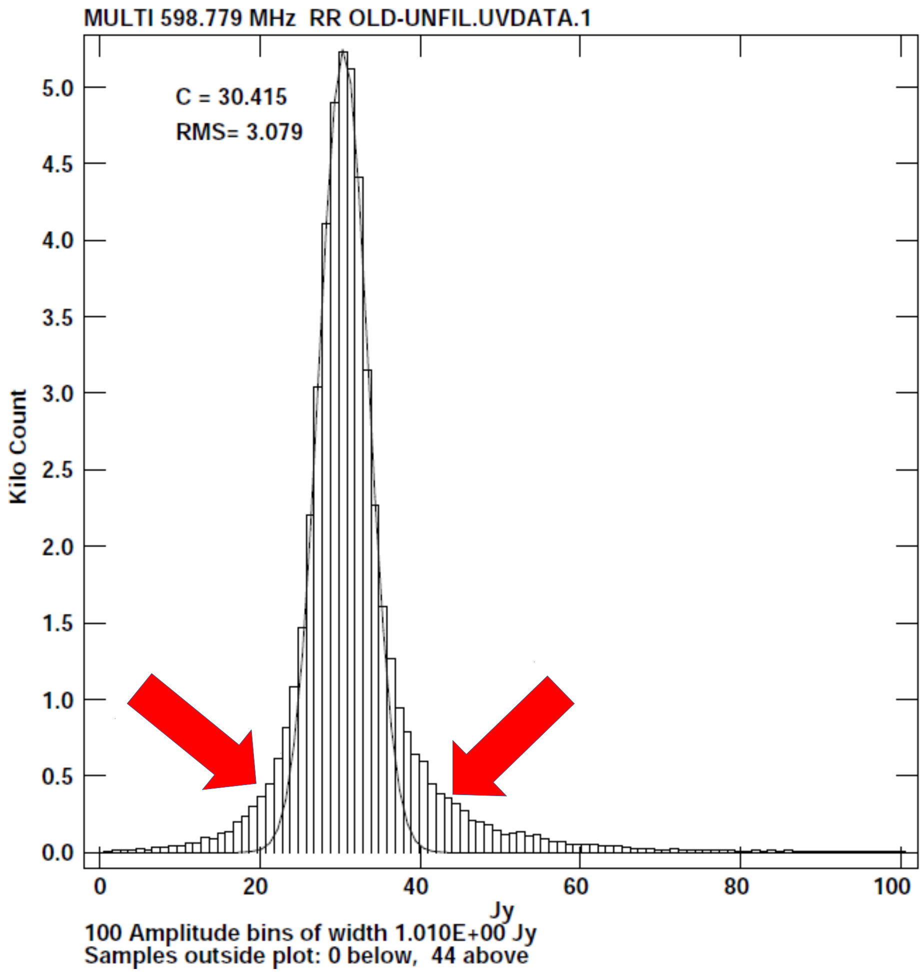


Single channel data plotted for a calibrator source.

Unfiltered data

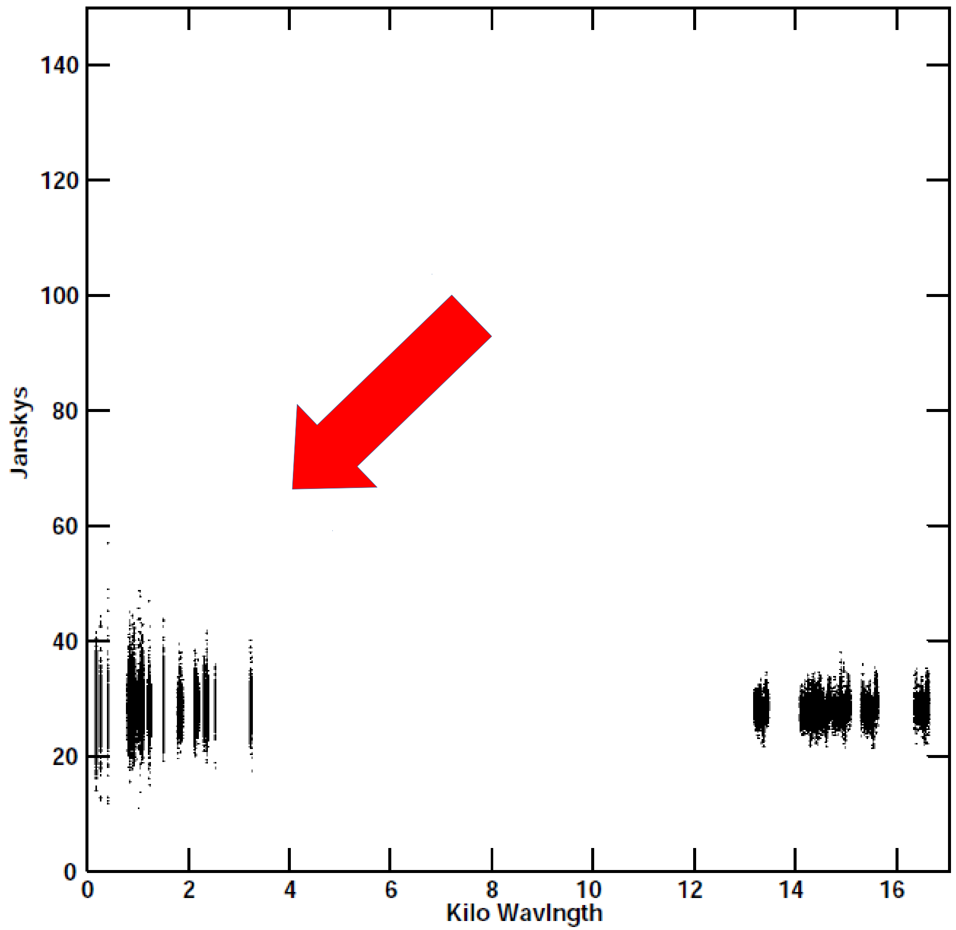


uv-distance

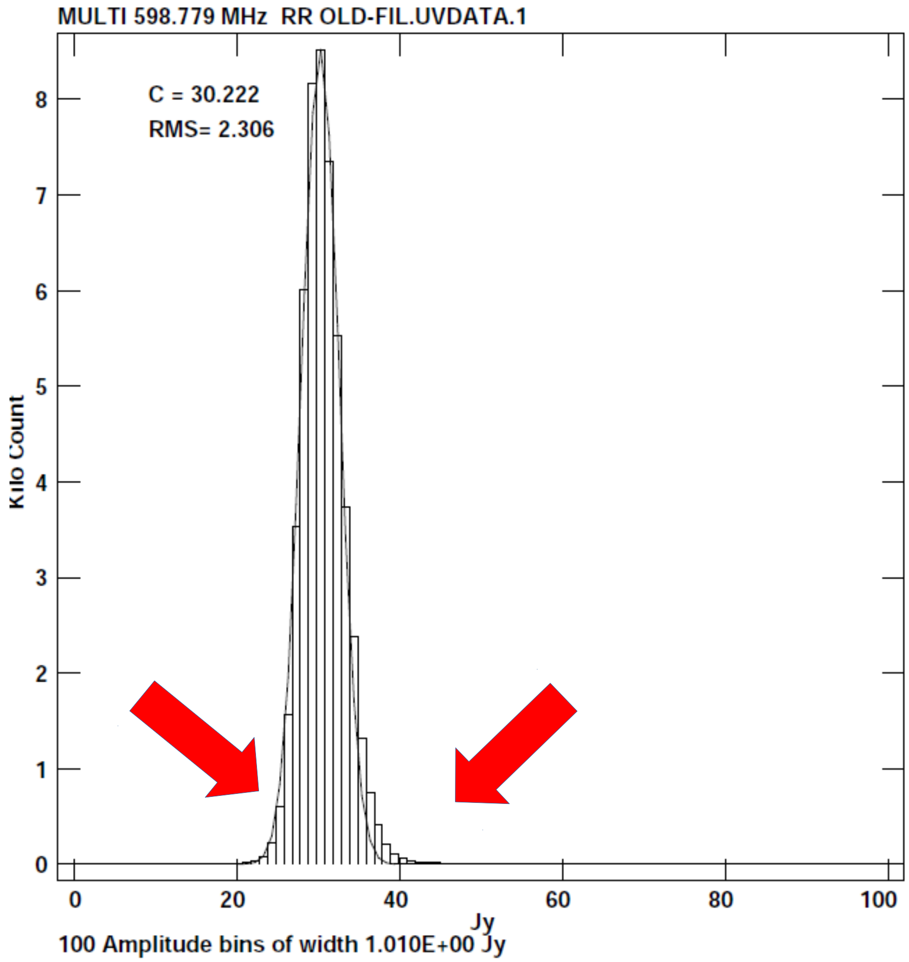


Single channel data plotted for a calibrator source.

Filtered data

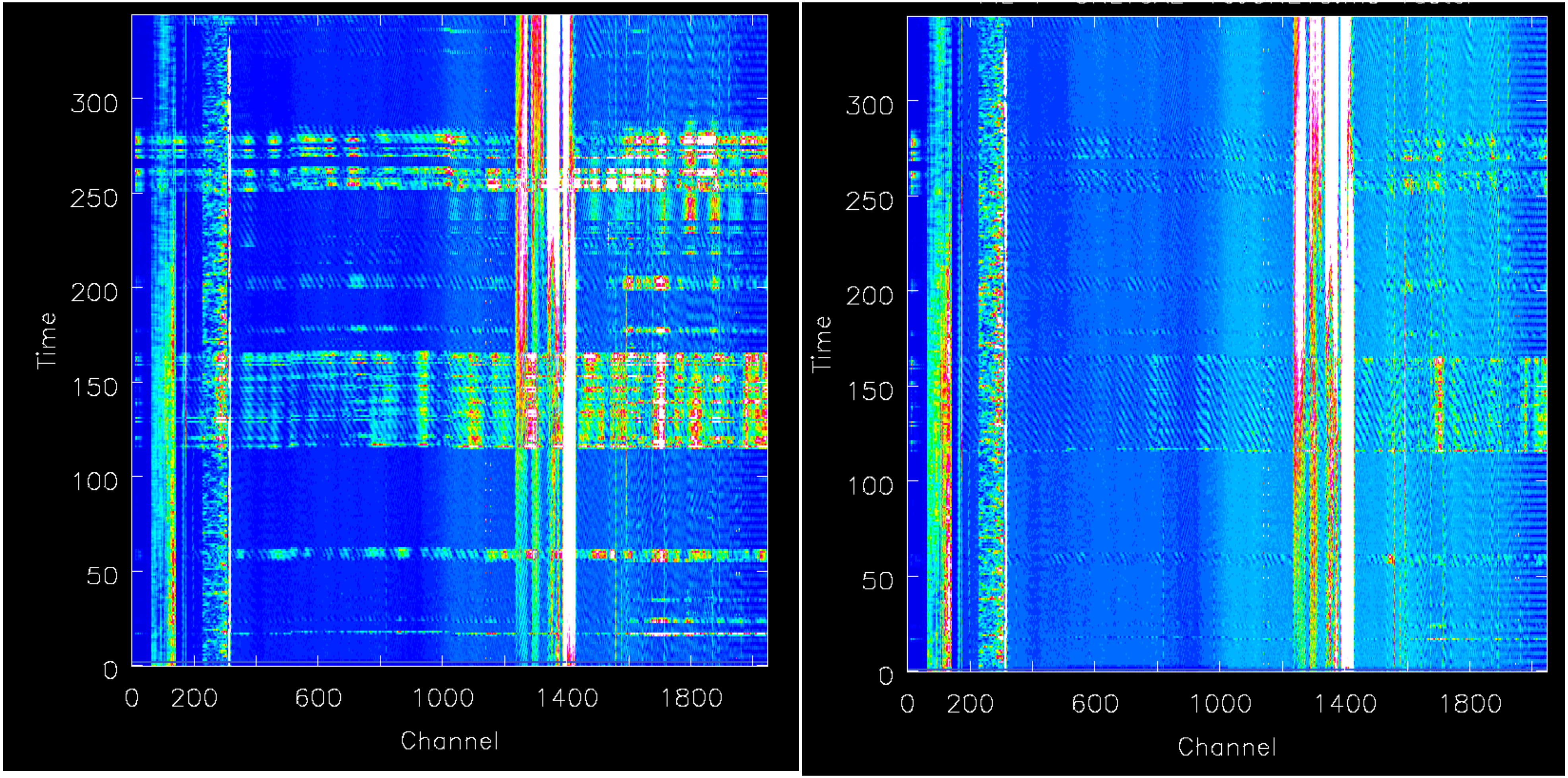


uv-distance



Comparison of time-frequency plane for a baseline

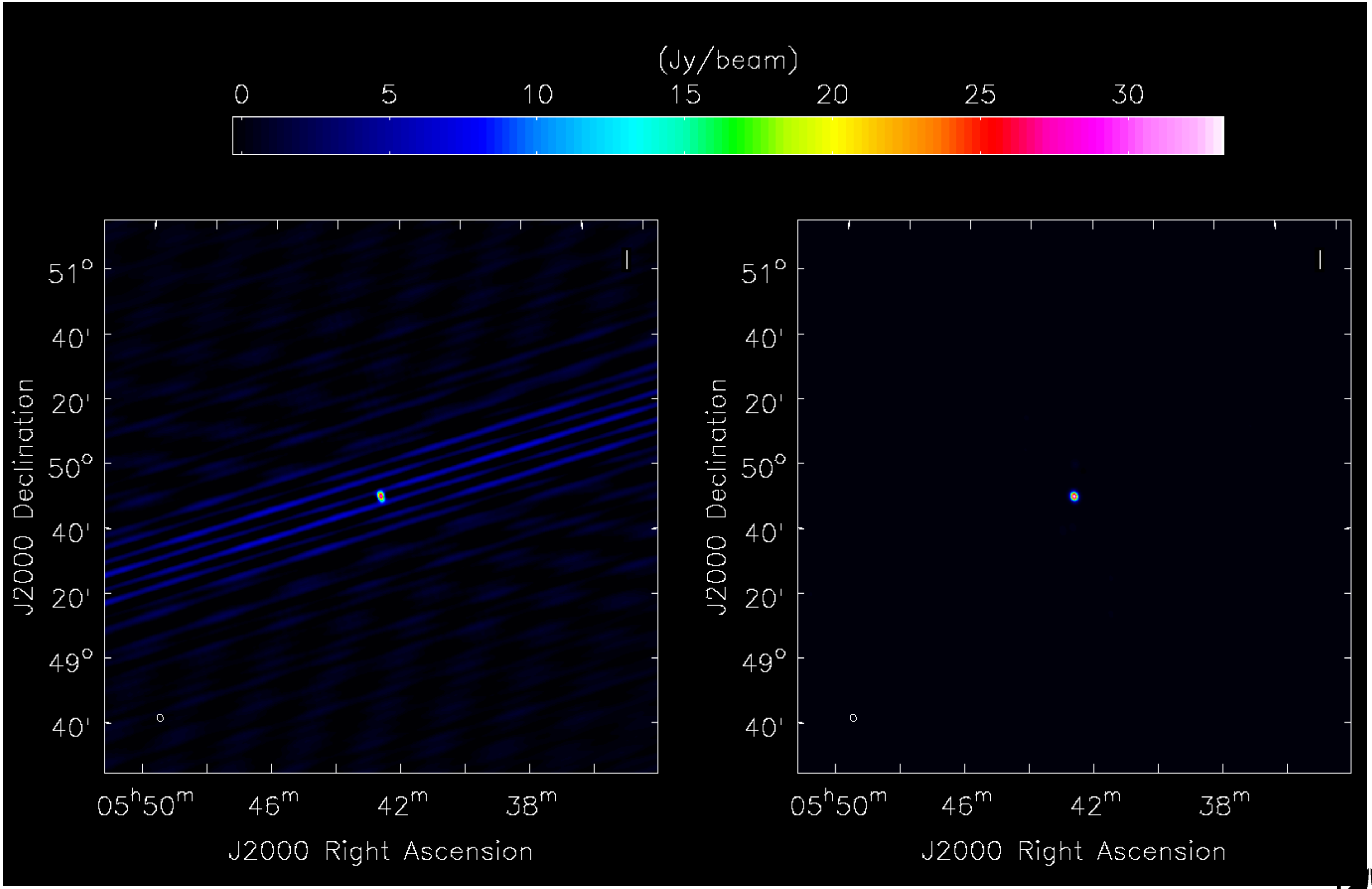
Unfiltered data | Filtered data

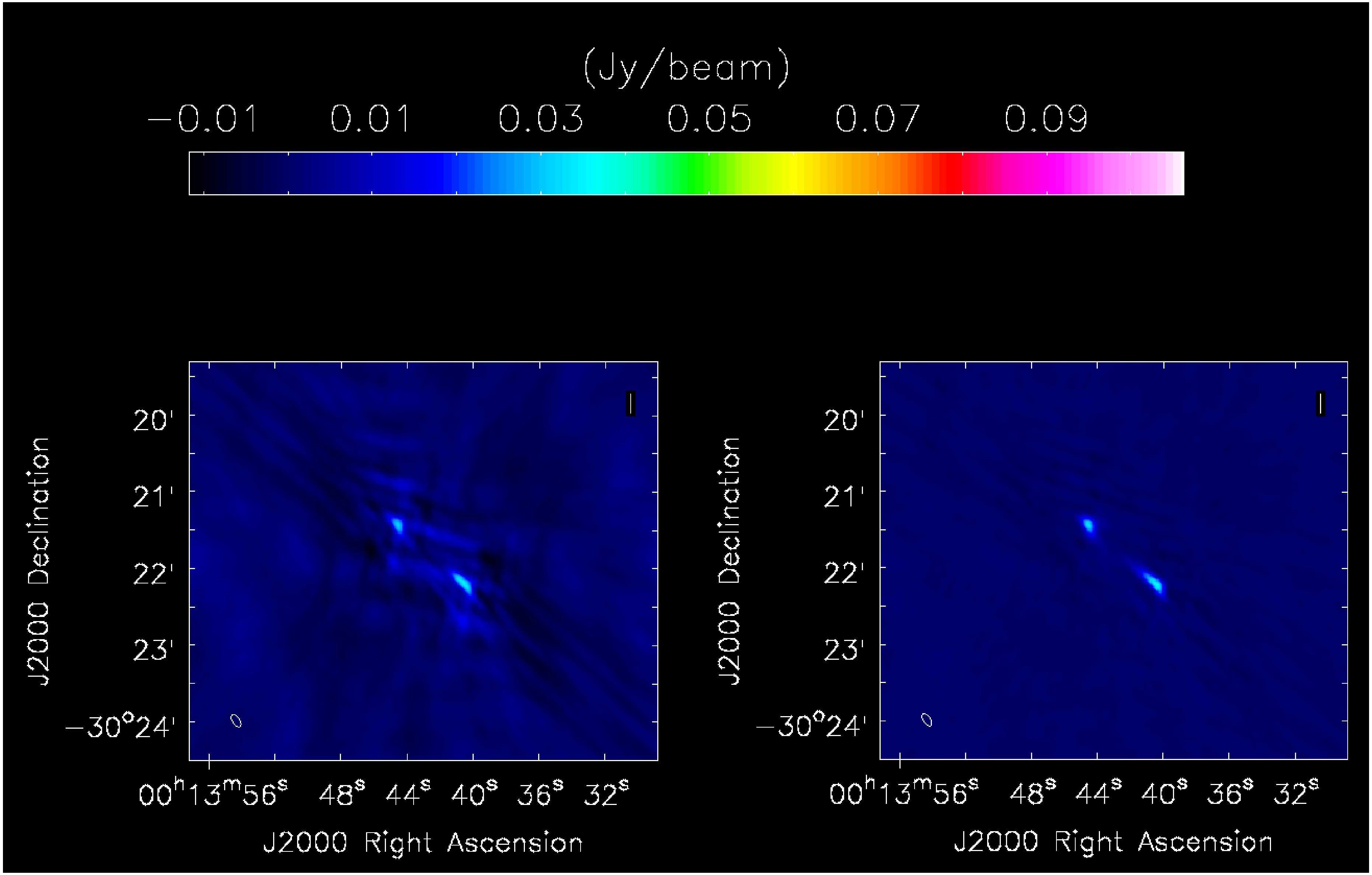


Band-3 data: 10 minutes scan on a calibrator is shown.

- Data analysis done with strategy to isolate the effects of the RFI excision alone.

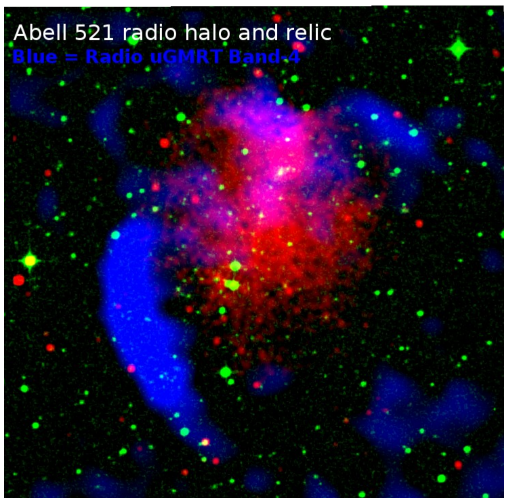
Images made only from baselines with length < 0.5 km

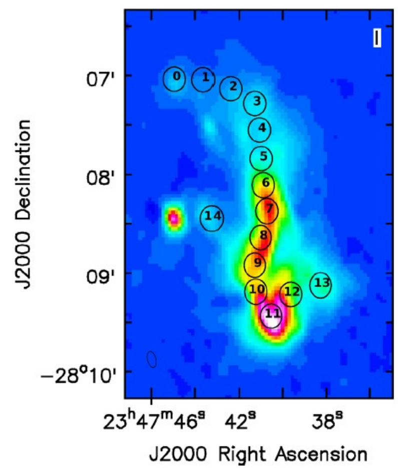


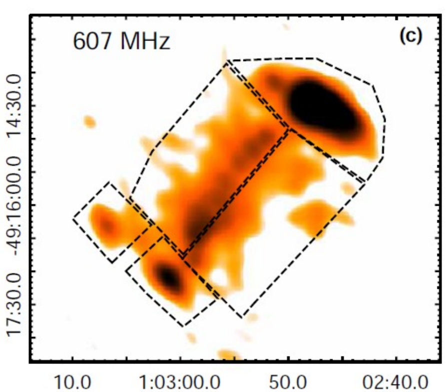

(Jy/beam)
−0.01 0.01 0.03 0.05 0.07 0.09
I
20'
21'
22'
23'
−30°24'
J2000 Declination
00h13m56s 48s 44s 40s 36s 32s
J2000 Right Ascension
I
20'
21'
22'
23'
−30°24'
J2000 Declination
00h13m56s 48s 44s 40s 36s 32s
J2000 Right Ascension

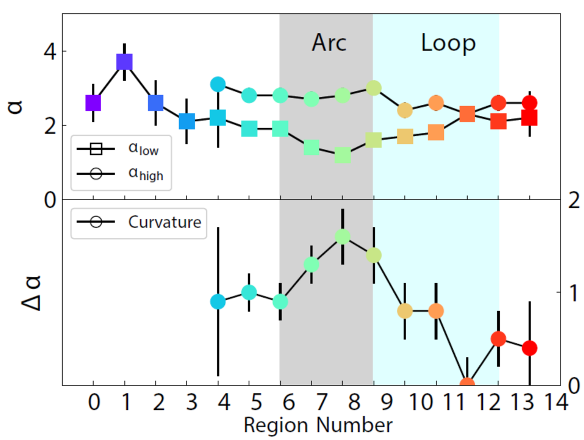
Summary

uGMRT: an instrument for cluster science









Real-time RFI excision

Implemented and tested. Presents a promising strategy to deal with broadband interference.