

Recent results on galaxy cluster science with the Upgraded GMRT and realtime RFI mitigation

Ruta Kale

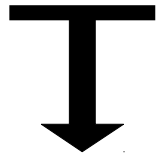
*National Centre for Radio Astrophysics,
Tata Institute of Fundamental Research,
Pune, India*

V. Parekh, K. S. Dwarkanath, T. Venturi, D. Dallacasa, S. Giacintucci, G. Brunetti, R. Cassano, J. Donnert, D. Eckert, K. Shende
Realtime RFI excision: K. D. Buch, S. Kudale, M. Muley, Ajith Kumar B. and Y. Gupta

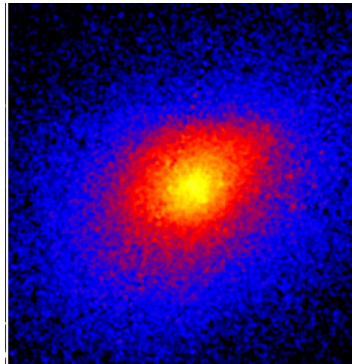


Galaxy clusters across the EM spectrum

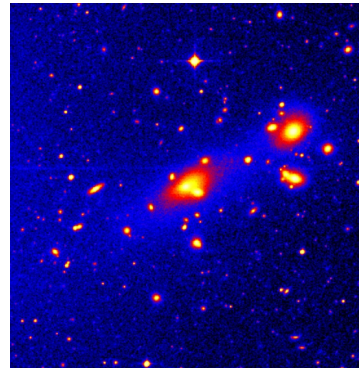
Gamma
rays



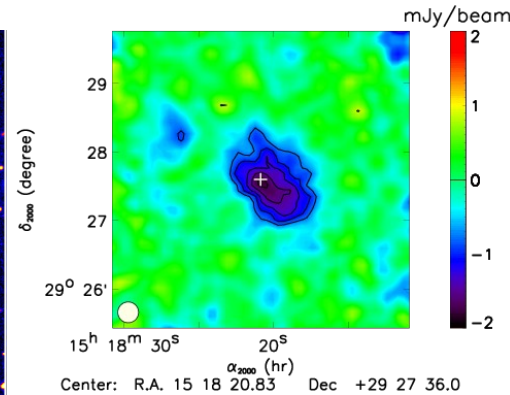
X-rays



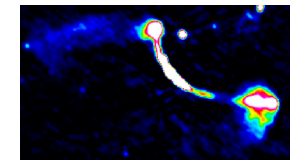
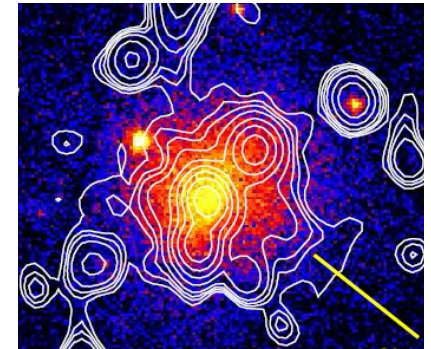
Optical



mm



RADIO



Hadronic
collisions

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

Stars

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

**GeV cosmic
ray electrons
and μ G
magnetic
fields**

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

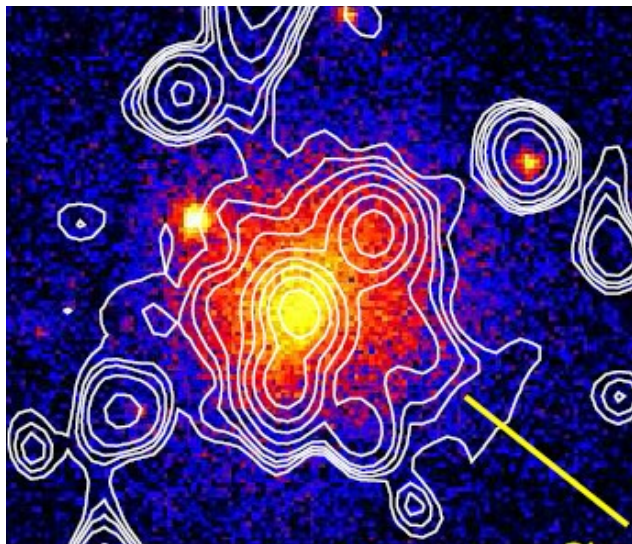
van Weeren et al 2019; Brunetti and Jones 2014; Huber et al 2013, Ackermann et al 2013; Rippin et al 2017; Sunyaev and Ze'ldovich 1979; Kale et al 2018; Giacintucci et al 2013

Cluster scale radio sources (~ 100 s kpc)

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

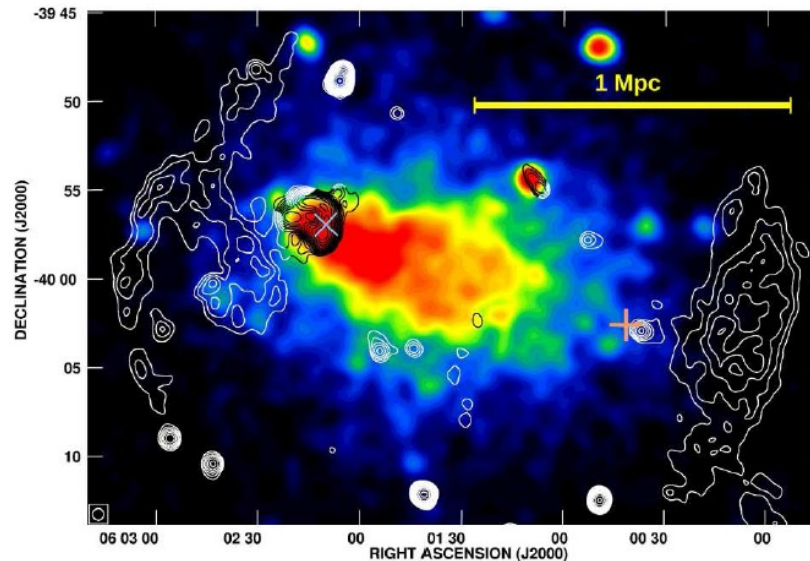
Extended
Faint

Radio halos



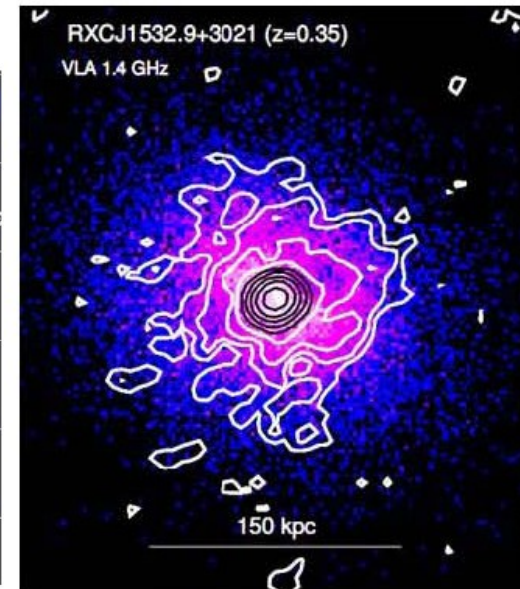
Giacintucci, Kale et al 2013

Radio relics



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

Mini-halos

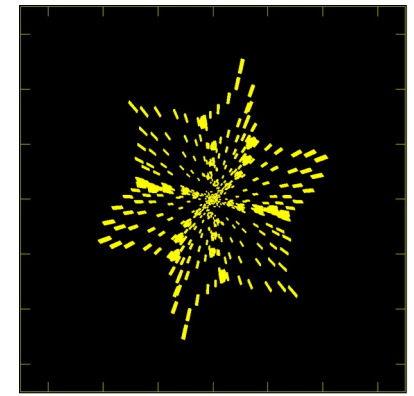


Hlavacek-Larrondo 2013; Kale et al 2013

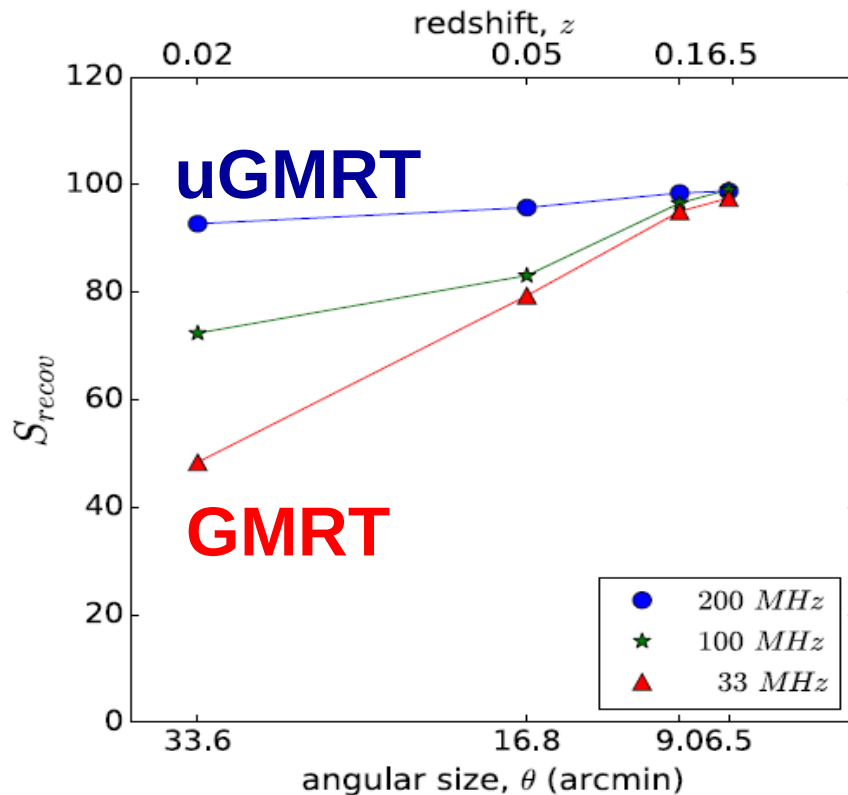
van Weeren et al 2019 review

Upgraded GMRT: a wideband instrument

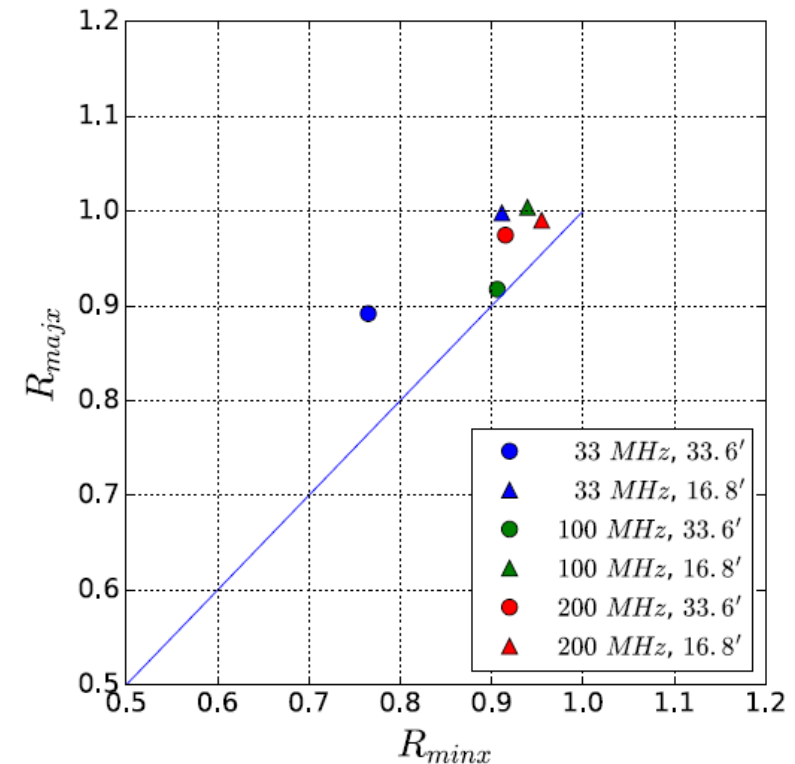
Gupta et al 2017



A factor of 2 better recovery of total flux density of diffuse sources



Reduced distortion in the recovery of source morphology.



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

Recent uGMRT studies of diffuse radio emission in galaxy clusters:

Abell 4038 – a cluster hosting a diffuse steep spectrum source: a remnant radio galaxy (revived): seeds for re-acceleration mechanisms like shocks and turbulence?

- What are the properties of the seed relativistic electrons in the ICM ?

Kale et al 2018, MNRAS, 480, 5352

Clusters near and far to constrain the CRe acceleration mechanism using clusters at different redshifts:

IC-CMB : strongly redshift dependent

Turbulent re-acceleration: expected to produce steepening in the spectrum at the frequency

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

Abell 521 : $z=0.247$

El Gordo : $z= 0.87$

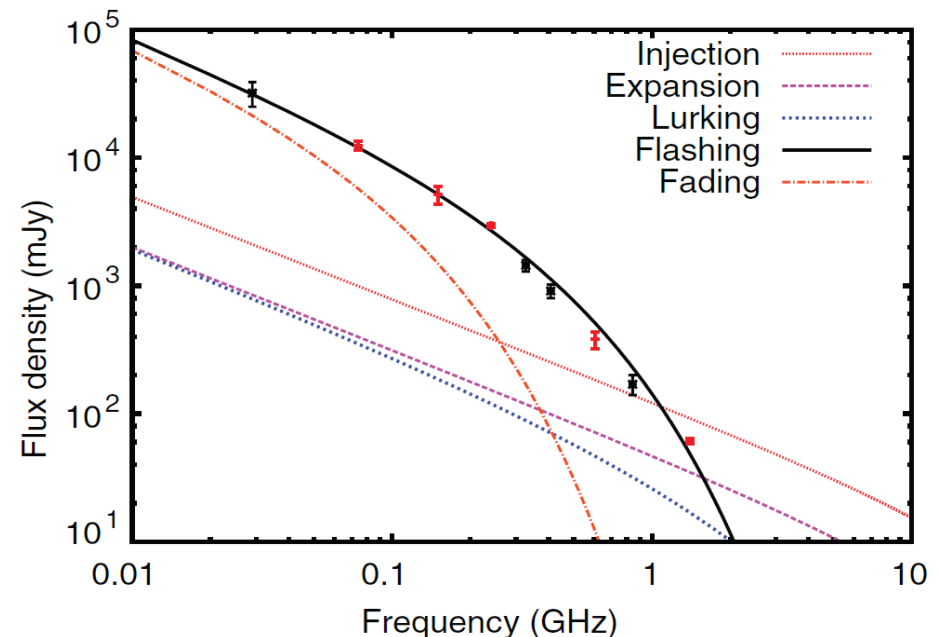
Abell 4038

- Cluster with a known steep spectrum remnant radio galaxy source
Slee et al 2001

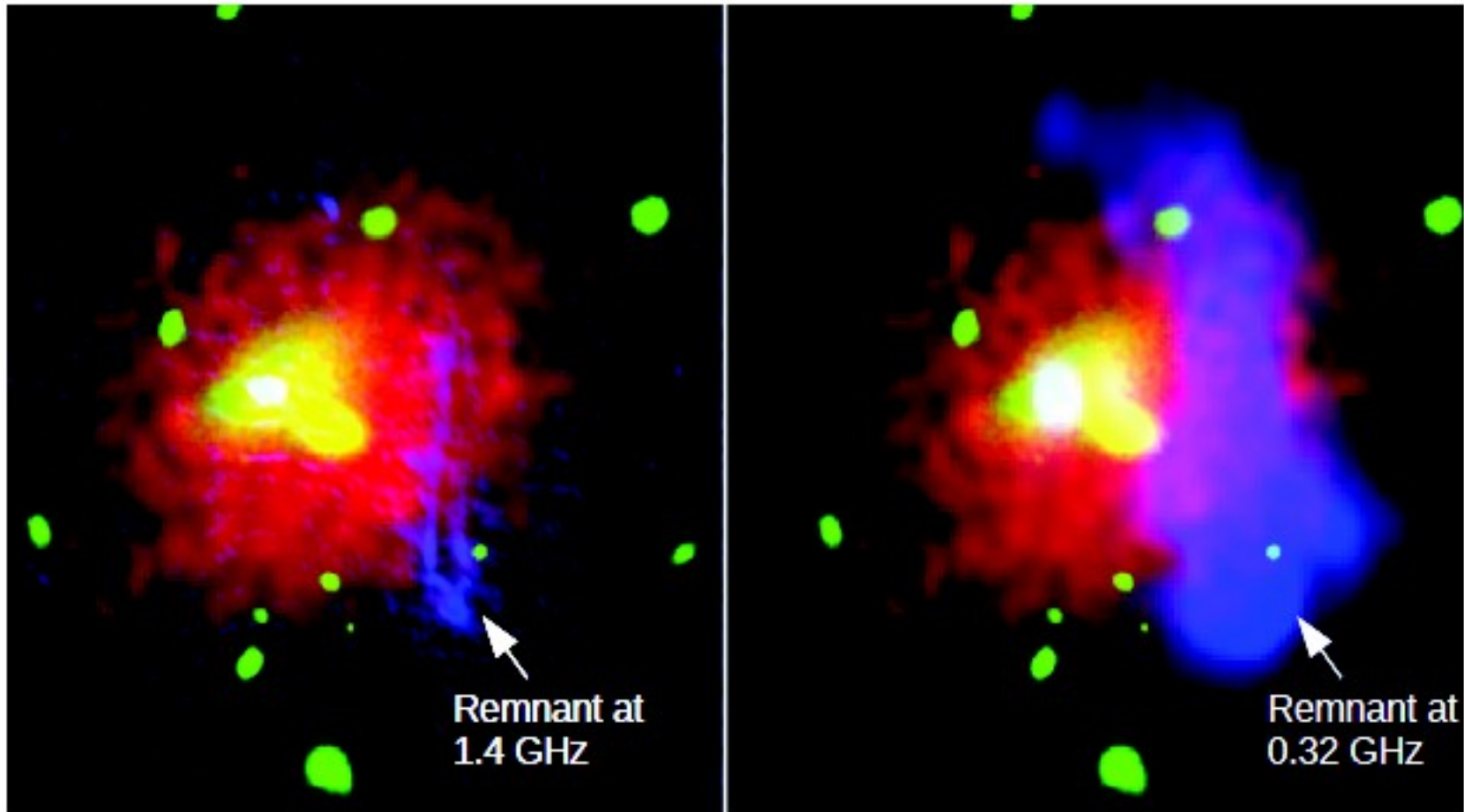
- Discovered larger extent
- Proposed to be adiabatically compressed remnant
Kale and Dwarkanath 2012

RA _{J2000}	23h47m43.2s
DEC _{J2000}	-28°08'29''
Redshift [†]	0.02819 ± 0.00055
kT [†]	2.69 ± 0.43 keV
$L_{[0.01-40]keV}$ ⁺⁺	$(1.900 \pm 0.025) \times 10^{44}$ erg s ⁻¹
M [‡]	$1.5 \pm 0.1 \times 10^{14}$ M _⊙

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



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



Abell 4038

- 8 hours each
- Band – 5 1050 – 1450 MHz
- Band – 3 300 – 500 MHz
- Feb. and March 2017. Band-4 was not available then.
- AOFlagger (Offringa et al 2012) and NRAO CASA used for data analysis.
- RMS at image centre:
Band-3 70 microJy/beam; 10"x5"
Band- 5 30 microJy/beam; 3.6"x1.7"



uGMRT spectral study of A4038

Due to RFI there were large gaps in the observed bands.

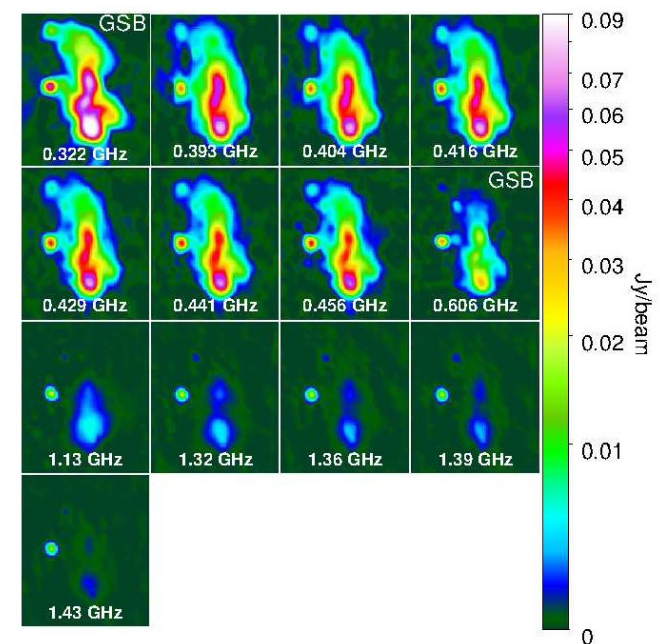
Sub-band imaging for uv-coverage matched spectral analysis:

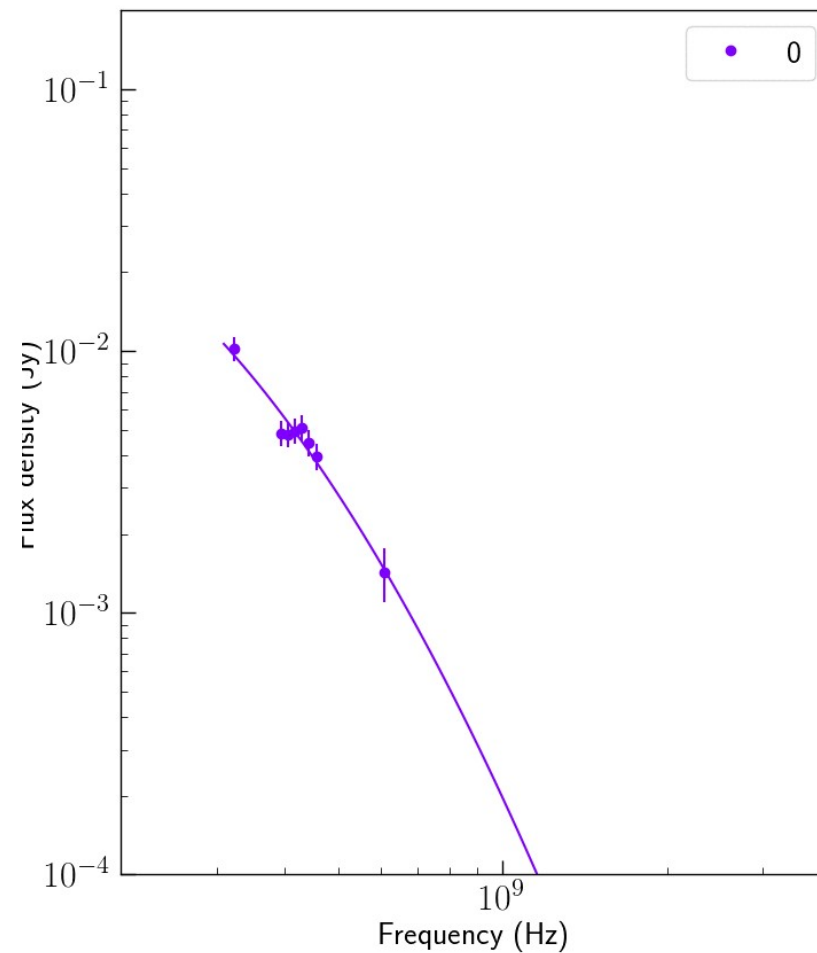
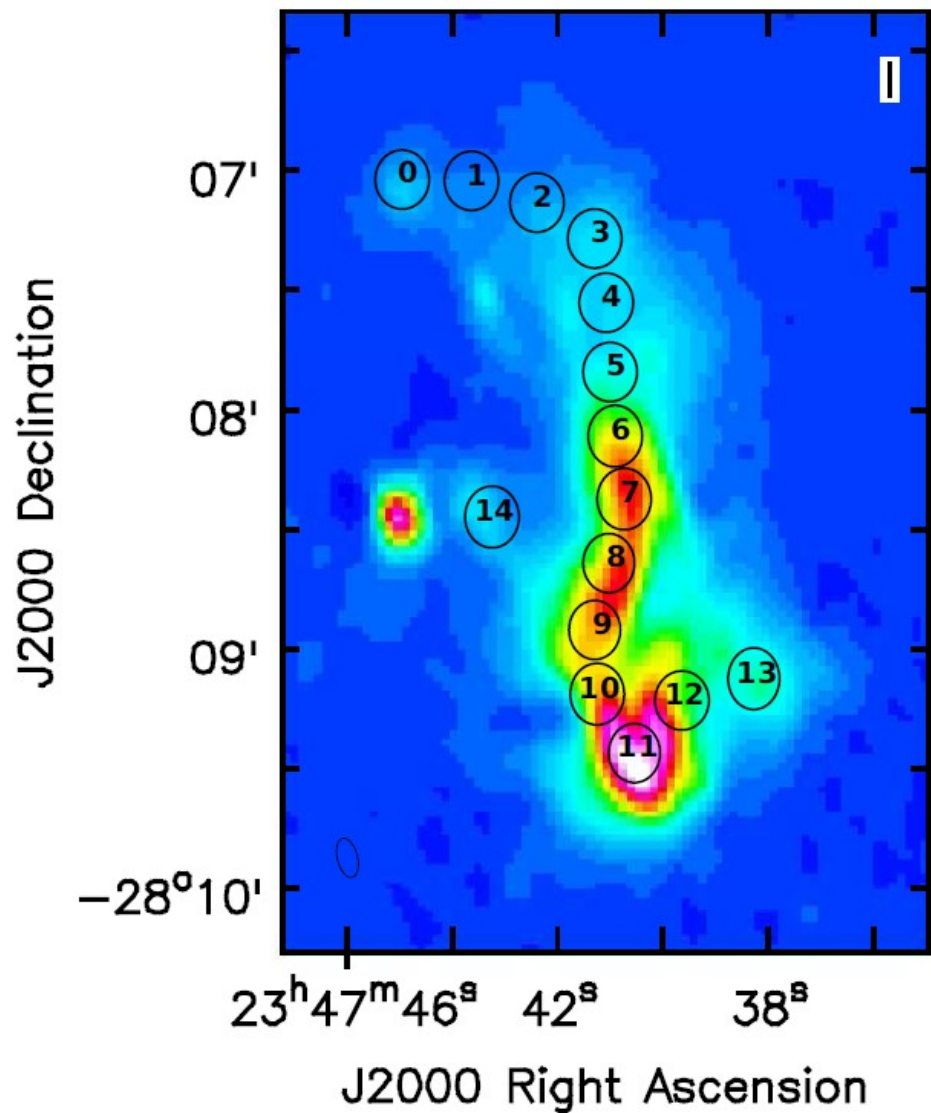
We made sub-band image in frequency range where RFI had less effect on the band.

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

This was achieved by keeping: $\Delta v/v = \text{constant}$

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



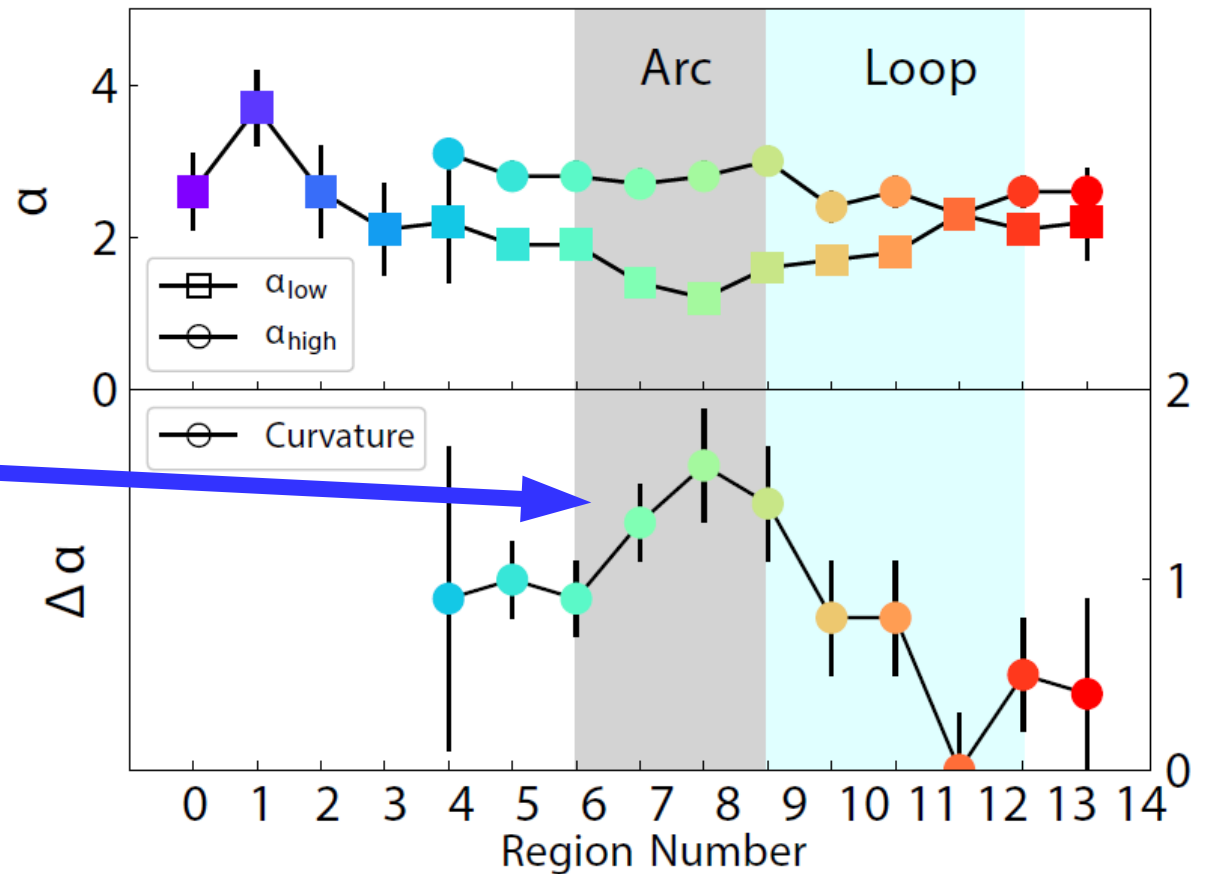
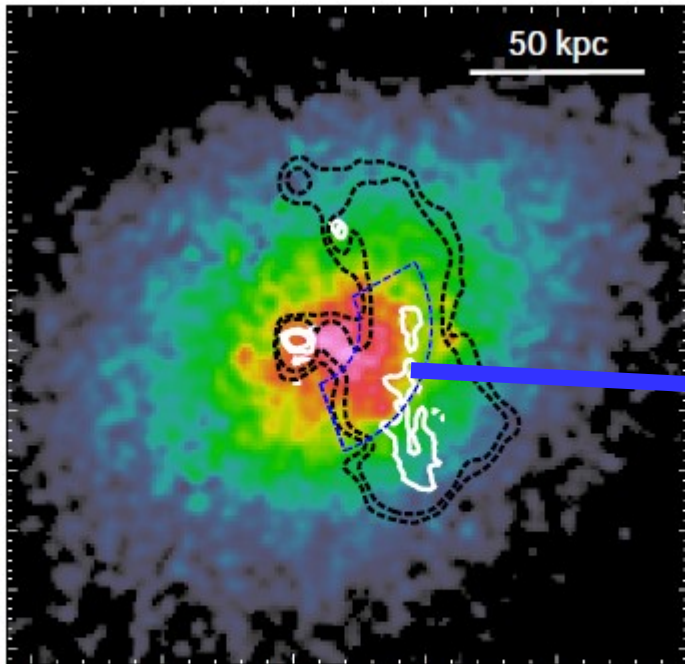


Variation in spectral shape across the relic

Curvature

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

X-ray



A CASA based pipeline for uGMRT data reduction

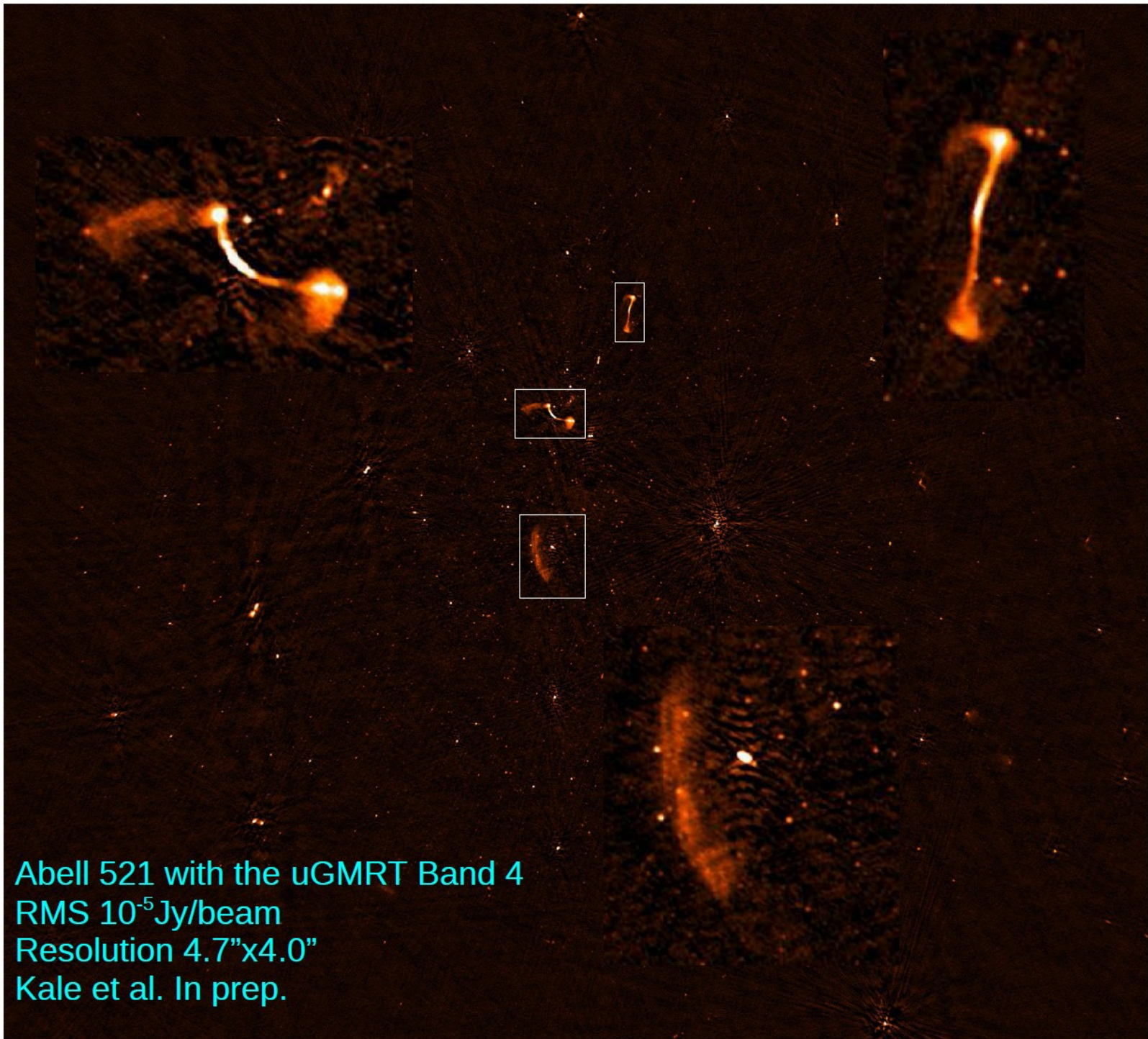
- Distinct flagging strategy for C-C baselines and other baselines
- Flags known narrow-band RFI at the GMRT
- Makes use of auto-multi-threshold masking implemented in CASA tclean

Further improvement plans:

- Correction of Direction dependent effects

Preliminary results towards Abell 521 and El Gordo

1
deg



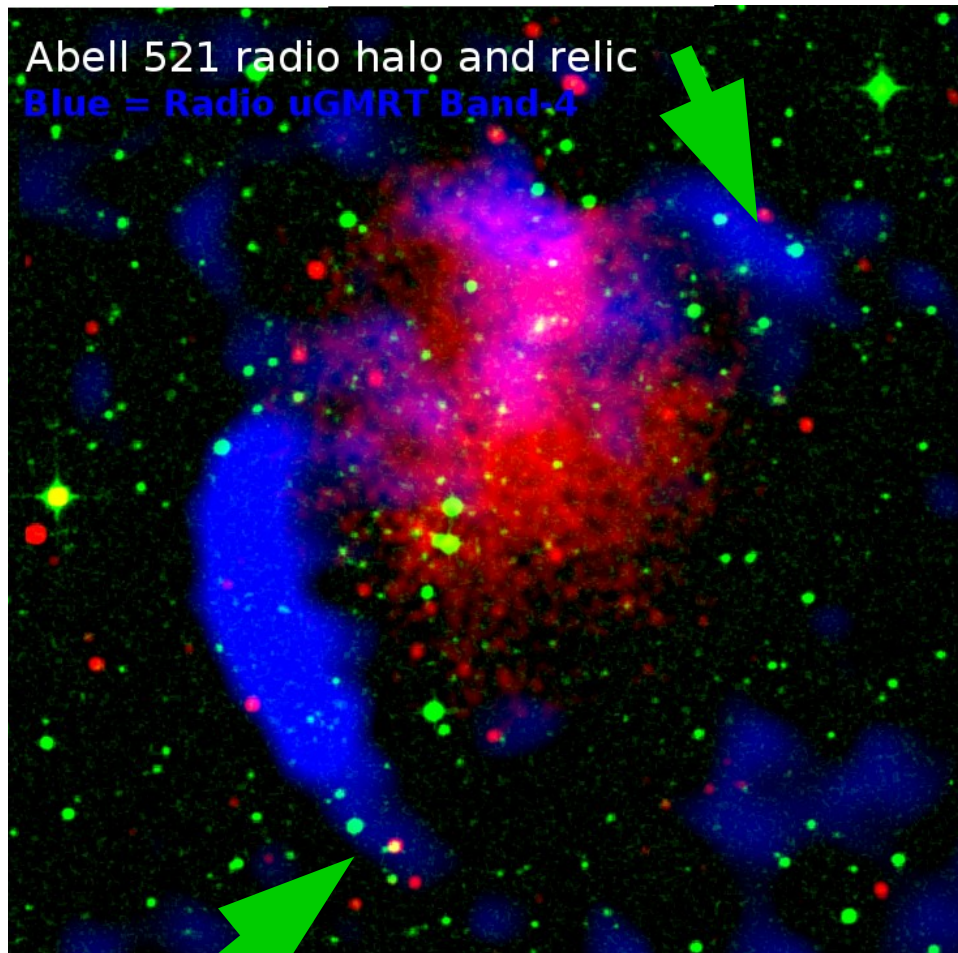
Abell 521 with the uGMRT Band 4
RMS 10^{-5} Jy/beam
Resolution 4.7"x4.0"
Kale et al. In prep.

1
deg

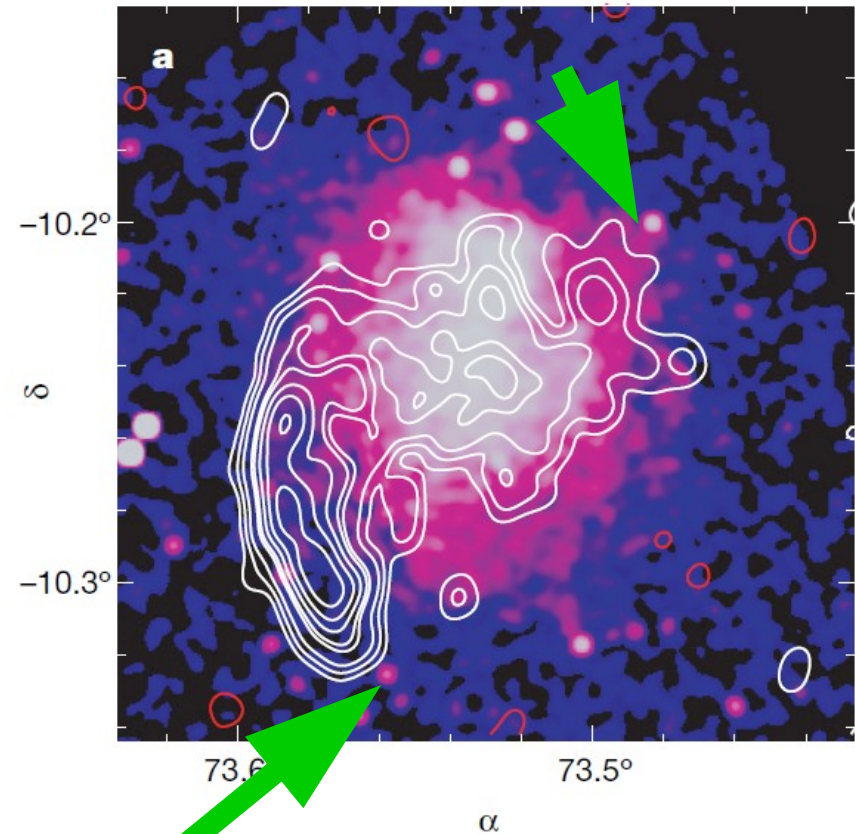
Abell 521 with the uGMRT Band 4
RMS 10^{-5} Jy/beam
Resolution 4.7"x4.0"
Kale et al. In prep.

nterms = 2;
Limited w-proj planes to 256
No multi-scale
Expect a further factor of 1.5
improvement

Low resolution image: discrete sources subtracted: additional emission ?



Red: Chandra X-ray image
Giacintucci et al 2008



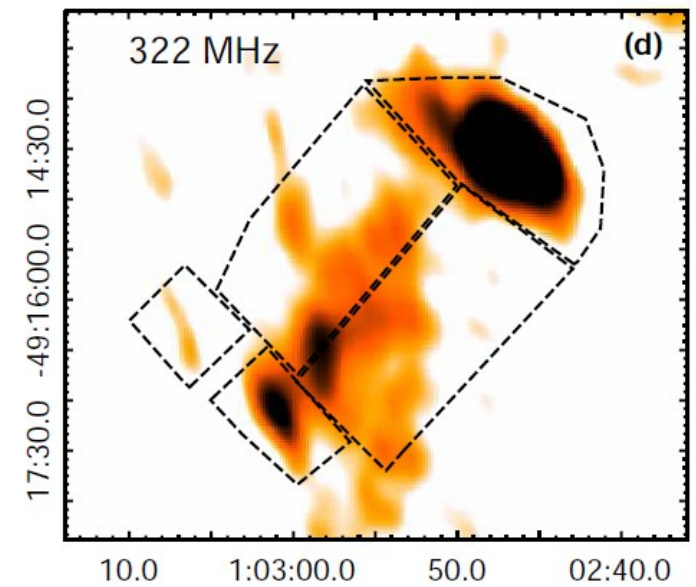
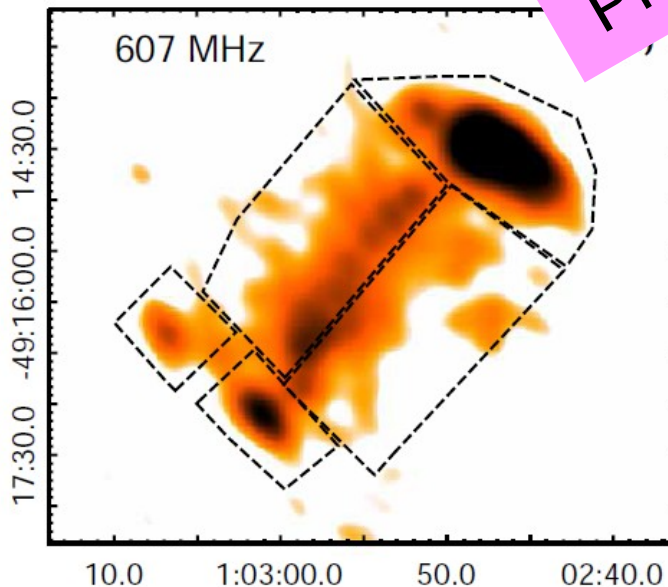
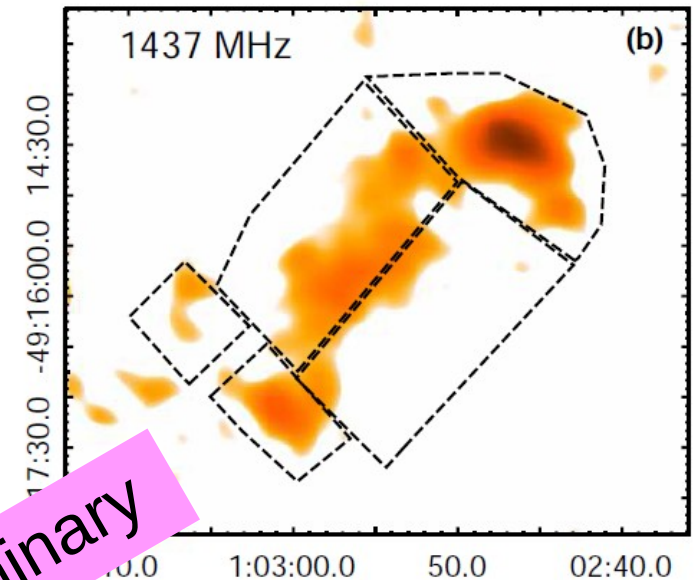
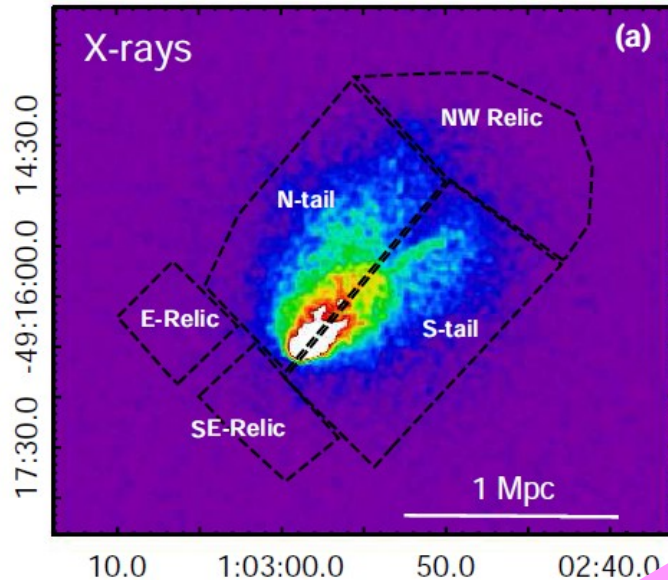
Analysis of the diffuse emission ongoing.

Kale, et al in prep.

El Gordo across Bands 3, 4 and 5

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

Spatial and spectral evolution of radio halo and the relic



Preliminary

Southern Cluster Scale Extended Source Survey (SUCCESS): *Exploring the SKA sky with pathfinders*

New radio halo

Kale et al 2019, MNRAS, accepted

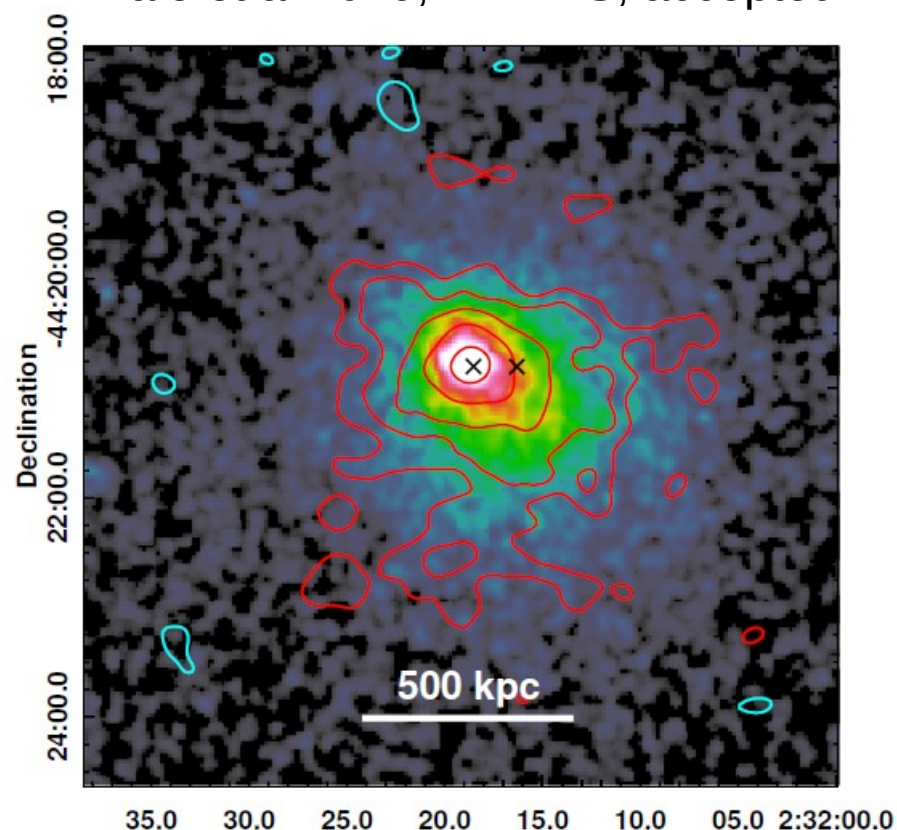
$z < 0.2$, $M > 5 \times 10^{14} M_{\odot}$

from Planck and SPT

Surveys.

9 clusters observed with the GMRT

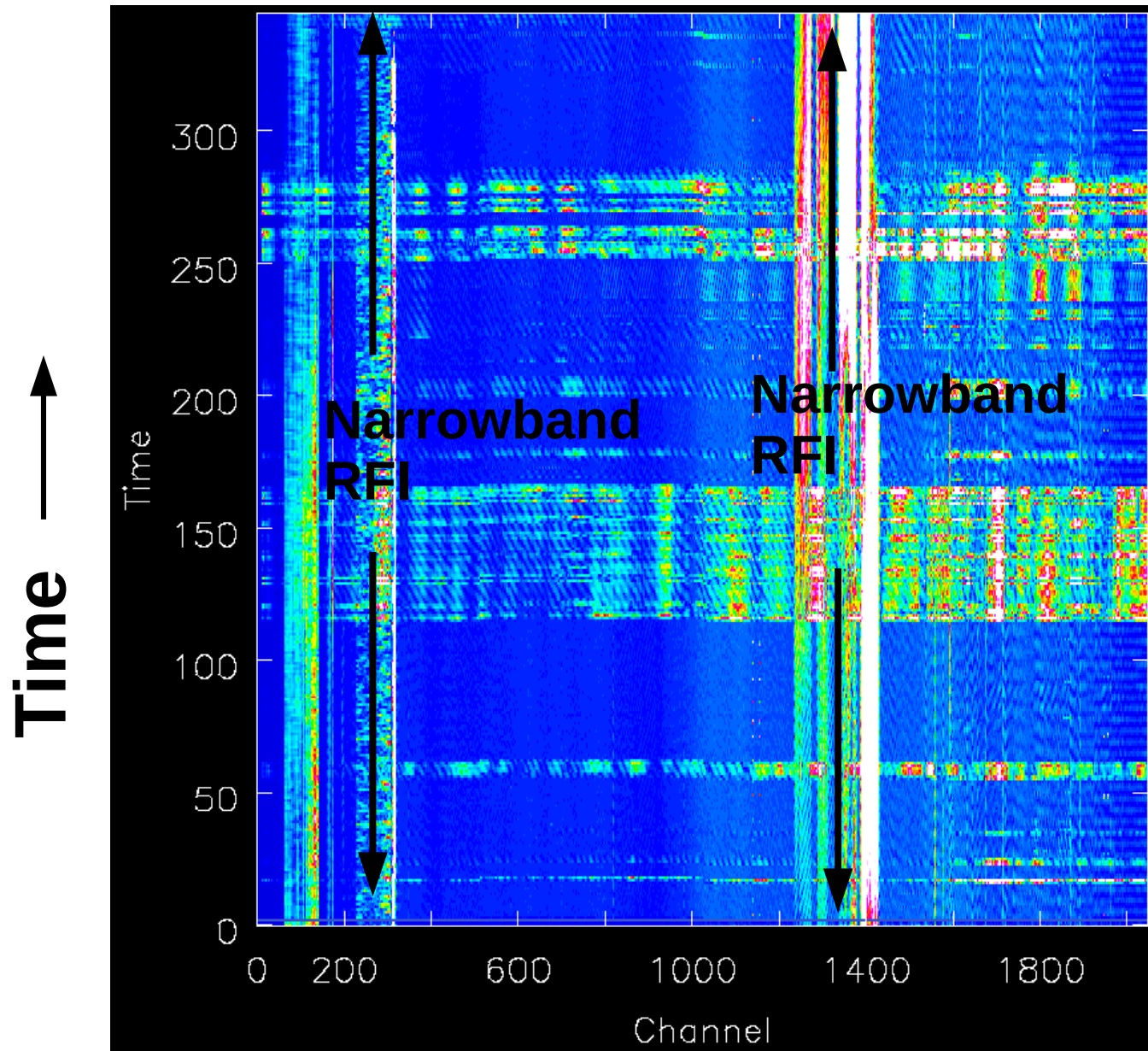
uGMRT observations scheduled.



RXCJ0232.2-4420

Radio Frequency Interference at the GMRT

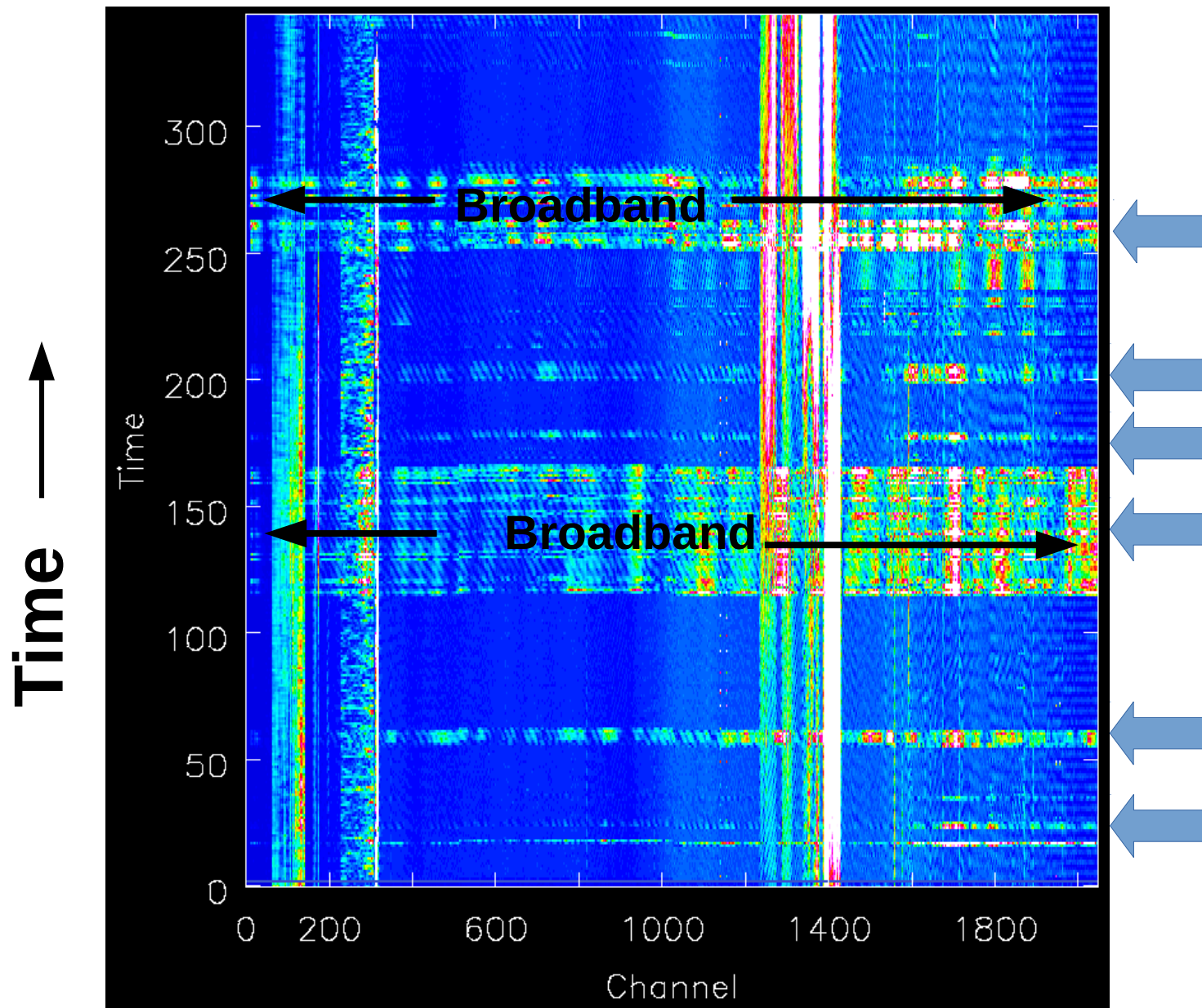
Time – frequency plane for a single baseline: an example



Frequency →

Ruta Kale, SPARCS-2019, Lisbon, 6th May 2019 (Remote talk)

Time – frequency plane for a single baseline: an example

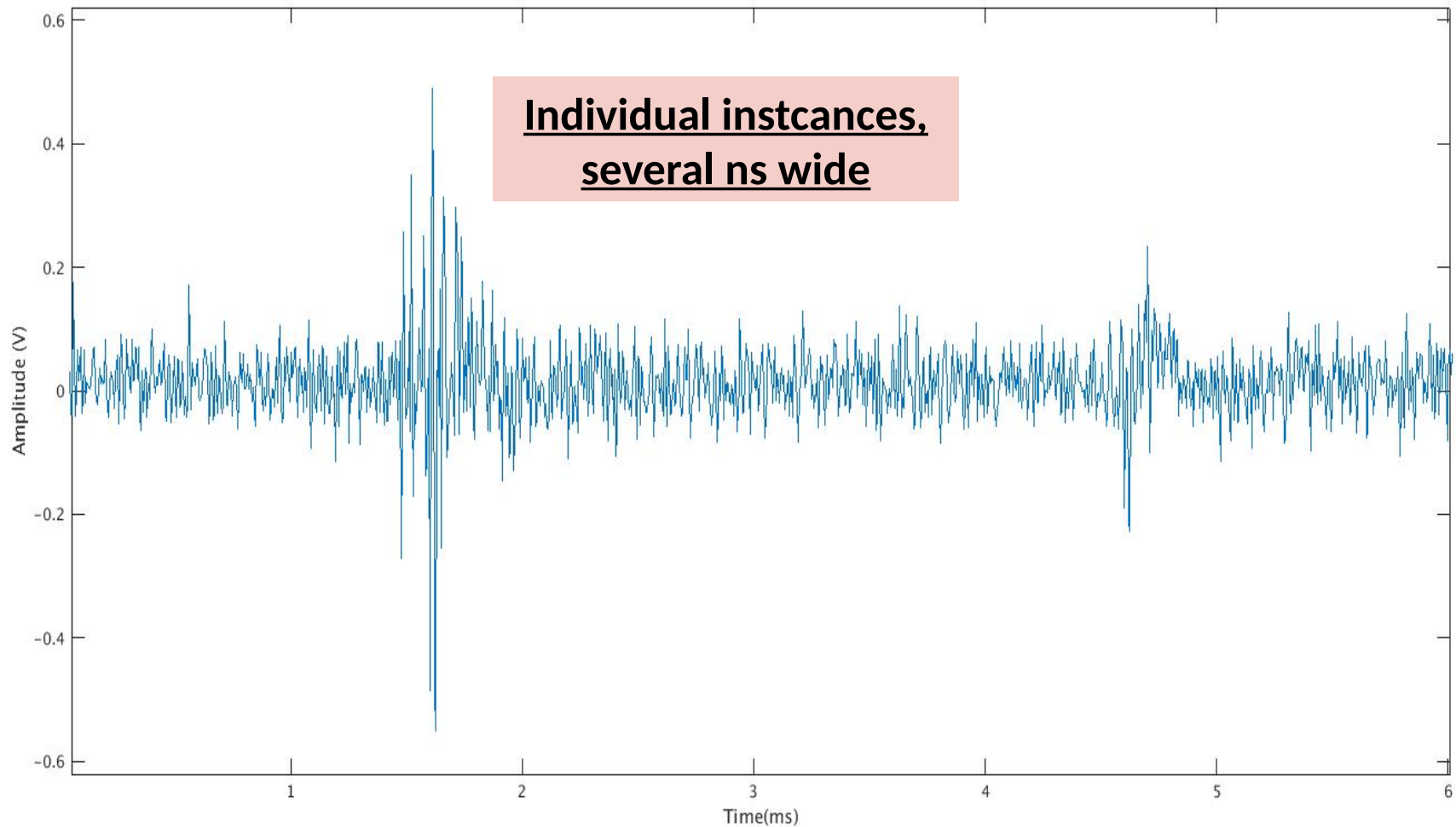


Frequency →

Ruta Kale, SPARCS-2019, Lisbon, 6th May 2019 (Remote talk)

Broadband RFI at the GMRT

Power-line RFI - impulsive



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

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

Robust threshold: $\text{median} \pm n^* \sigma_{\text{MAD}}$

- 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)

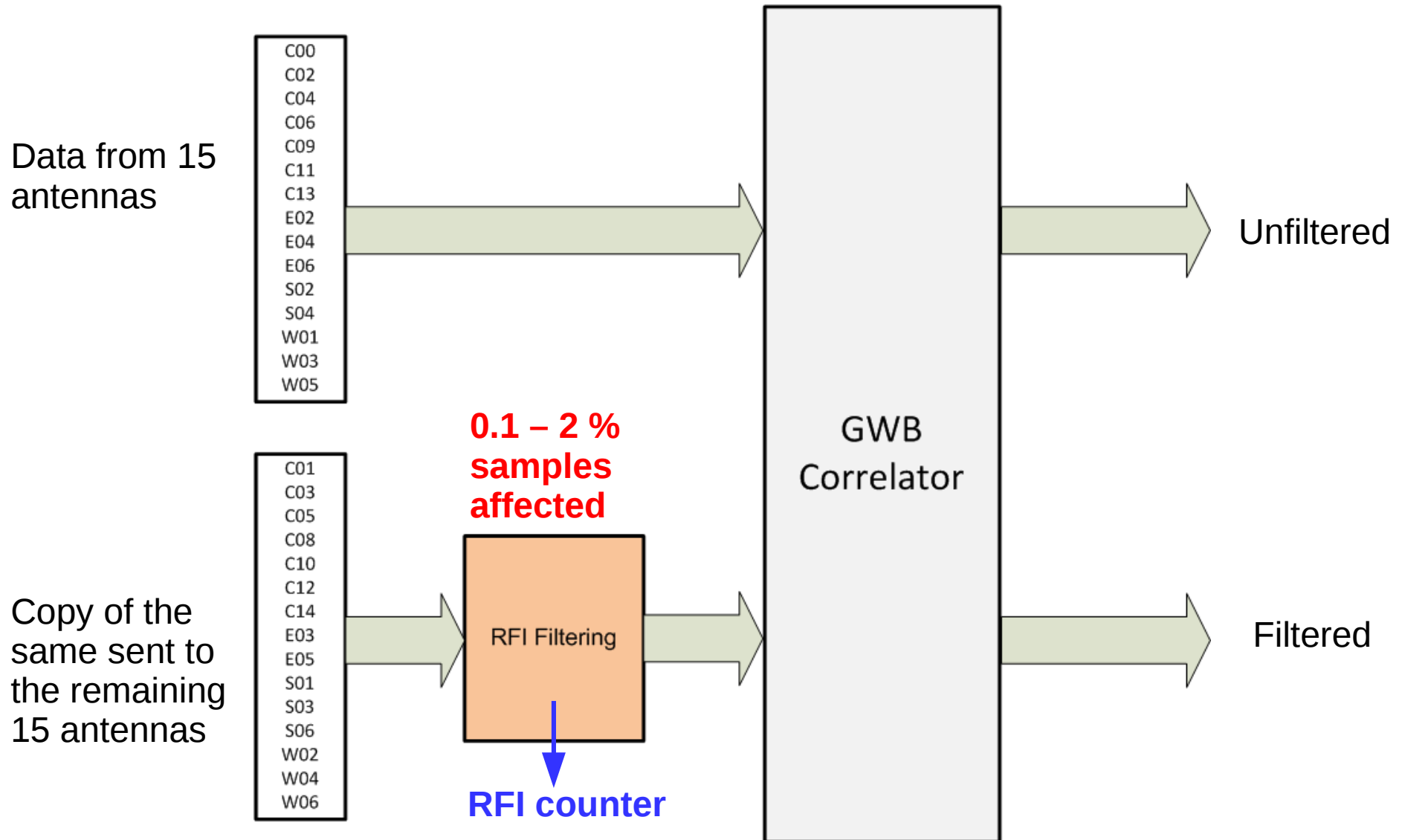
$$M_m = M(D_1, D_2, \dots, D_n)$$

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

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

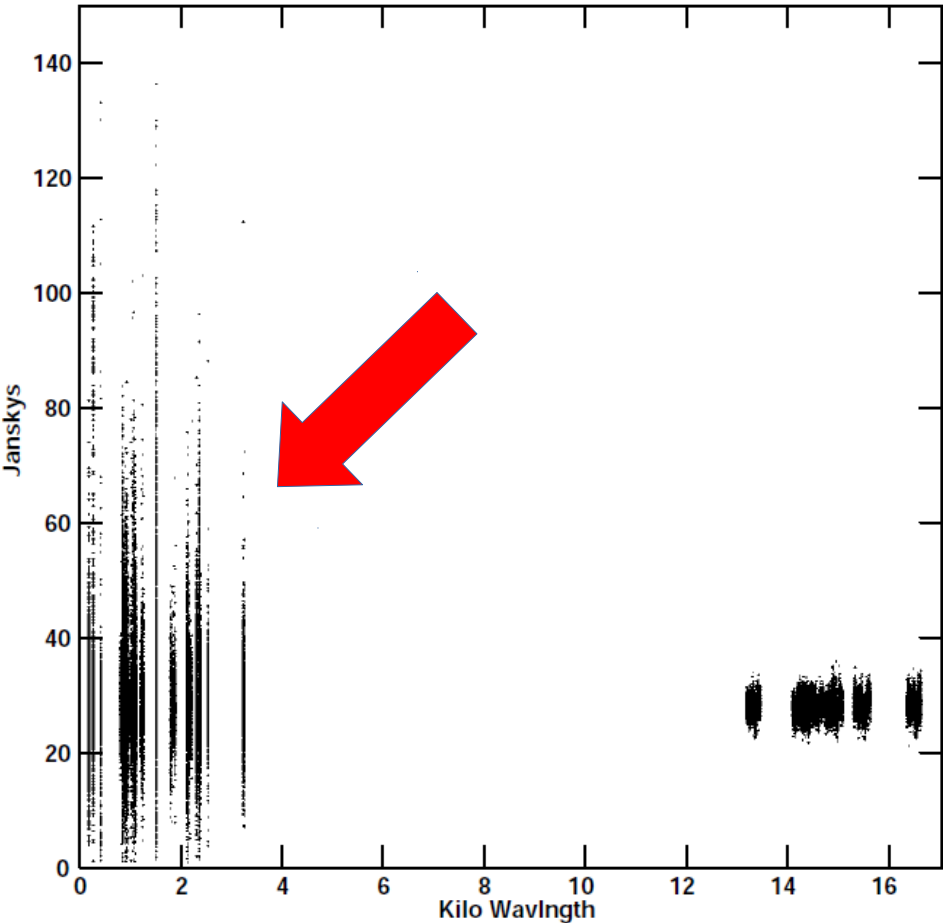
Buch et. al, “Real-time MAD-based RFI Excision on FPGA ”, JAI Special Issue on Interference Mitigation in Radio Astronomy, January 2019

Unfiltered and filtered data

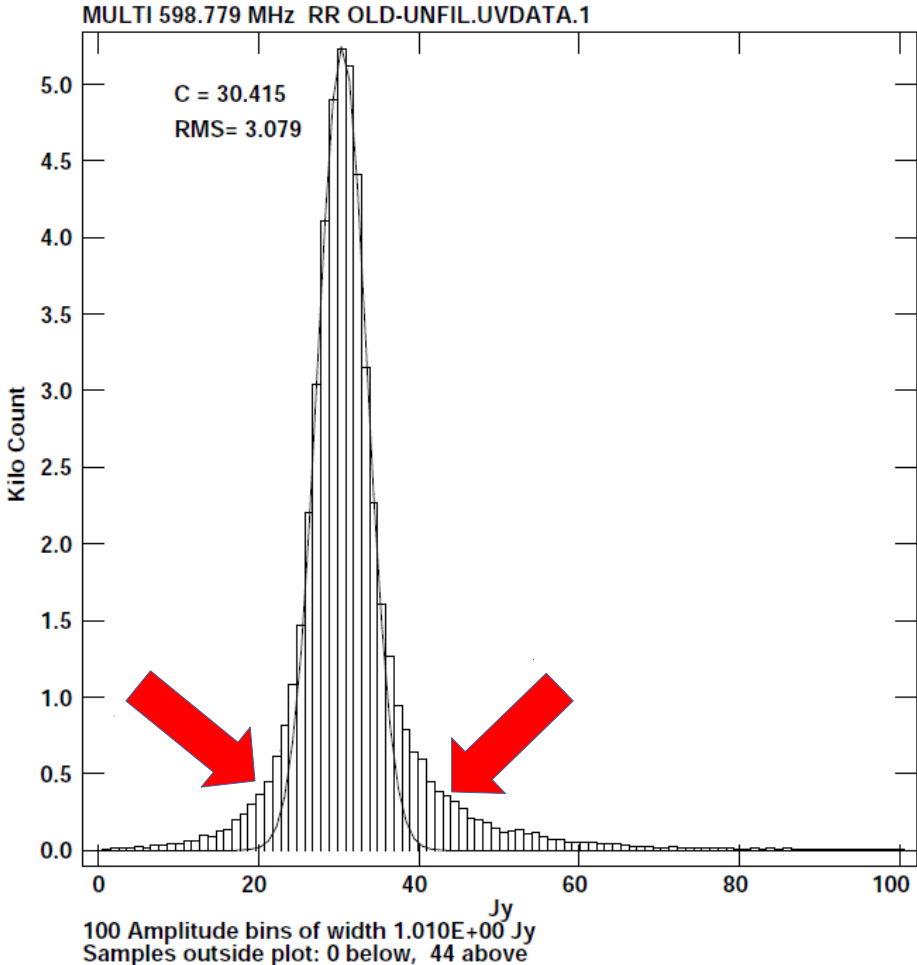


Single channel data plotted for a calibrator source.

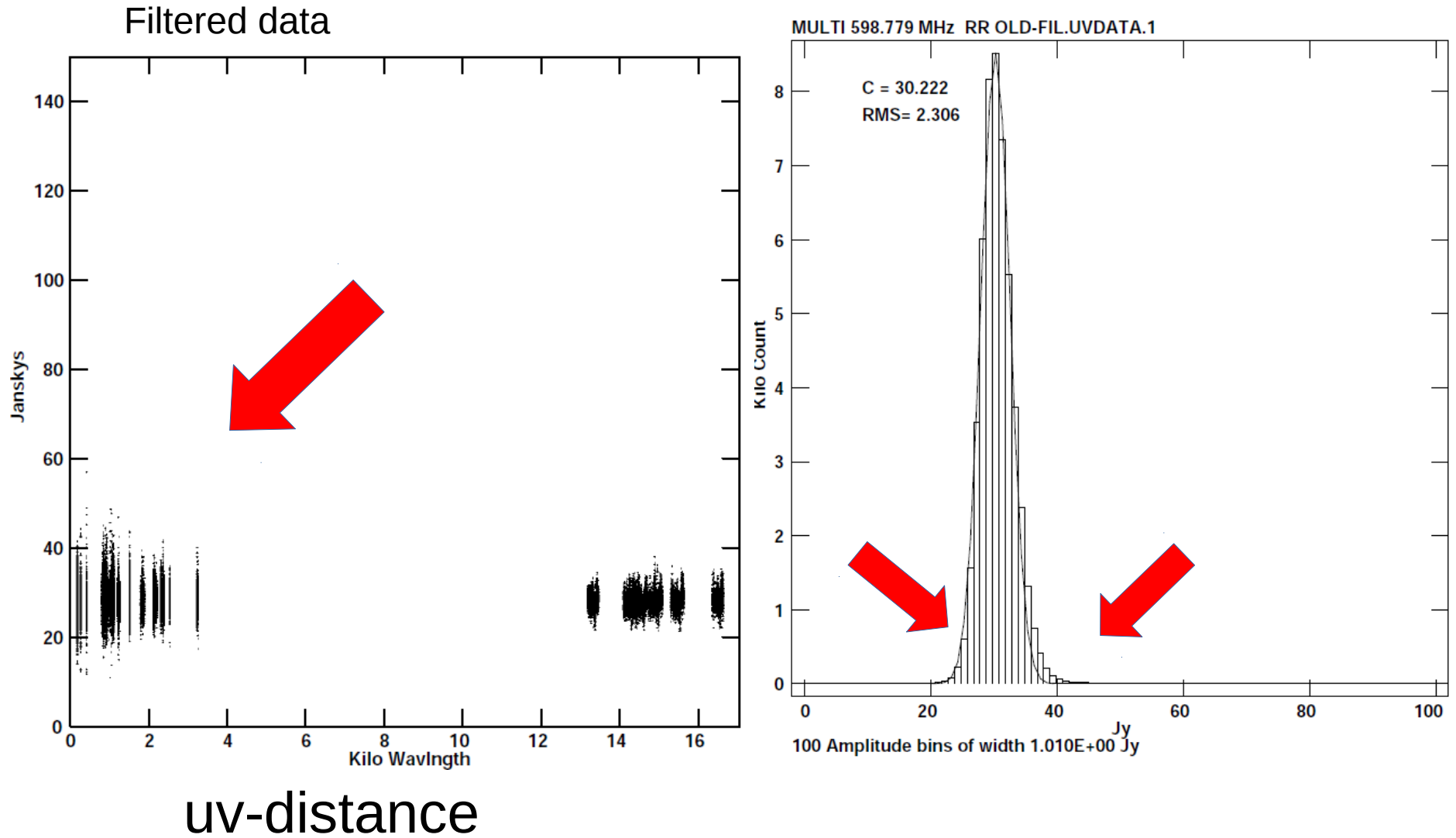
Unfiltered data



uv-distance

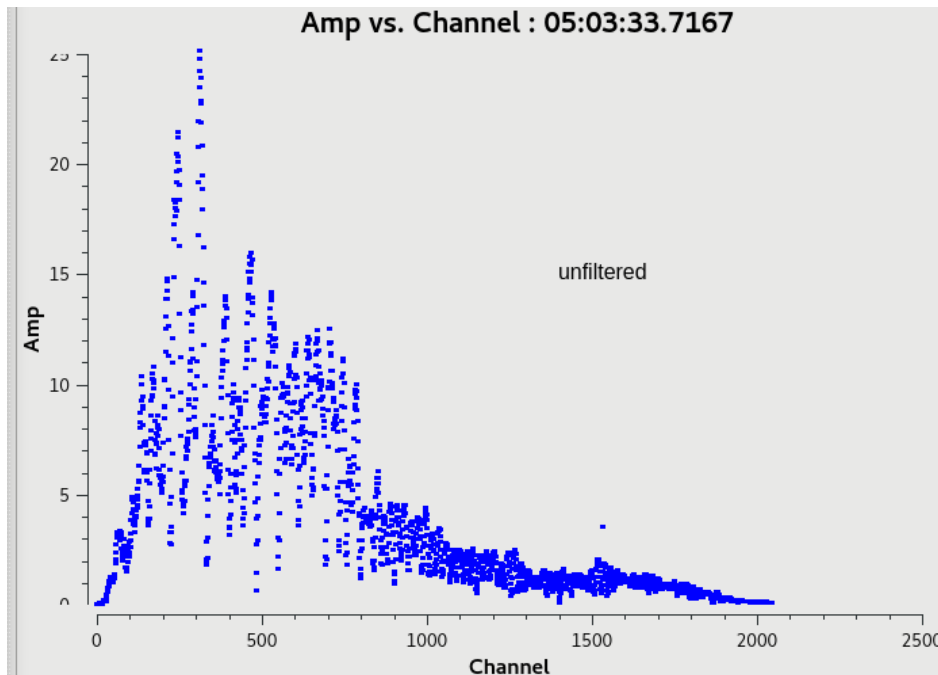


Single channel data plotted for a calibrator source.

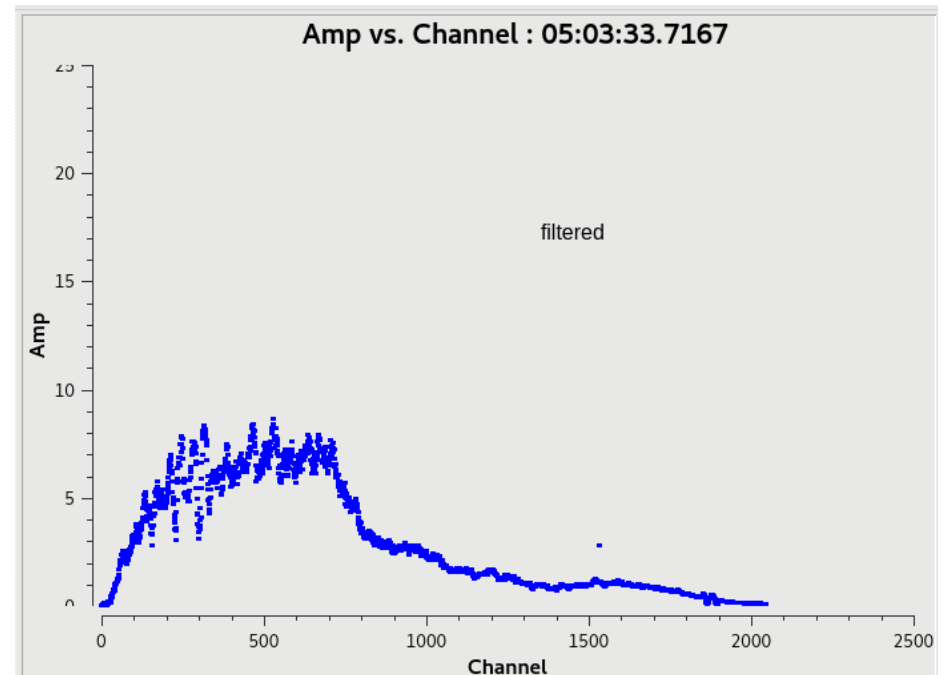


Reduction in overall scatter in the spectrum: an example

Unfiltered data



Filtered data



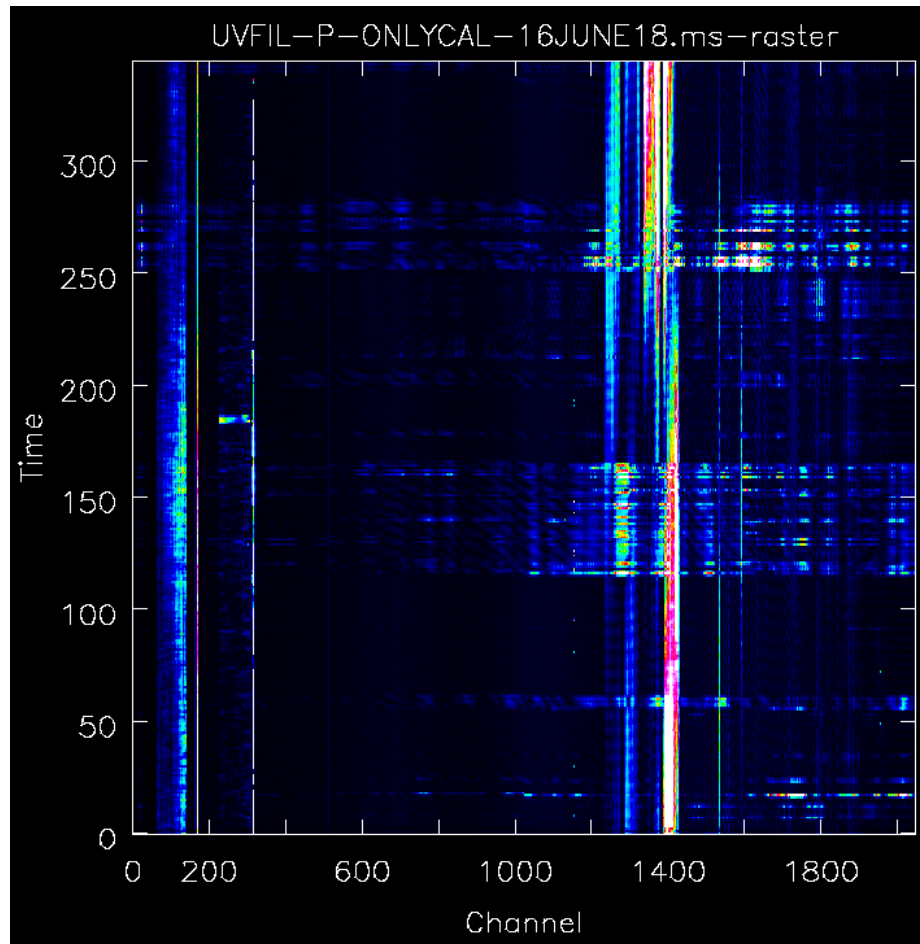
Spectrum at a particular time for a typical central square baseline is shown here.

Offline mitigation tools can result in flagging of the entire spectrum at such instances.

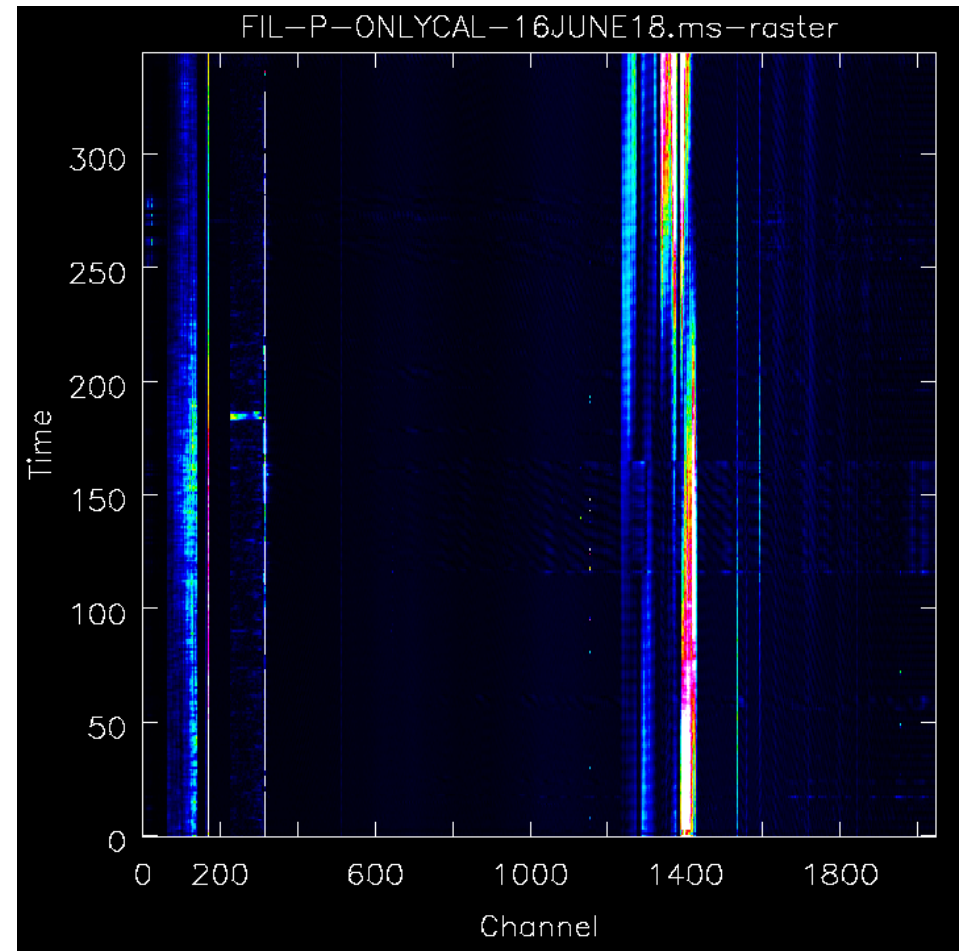
Comparison of time-frequency plane for a baseline

Band-3- 300 – 500 MHz data: 10 minutes scan on a calibrator for central square BL

Unfiltered data

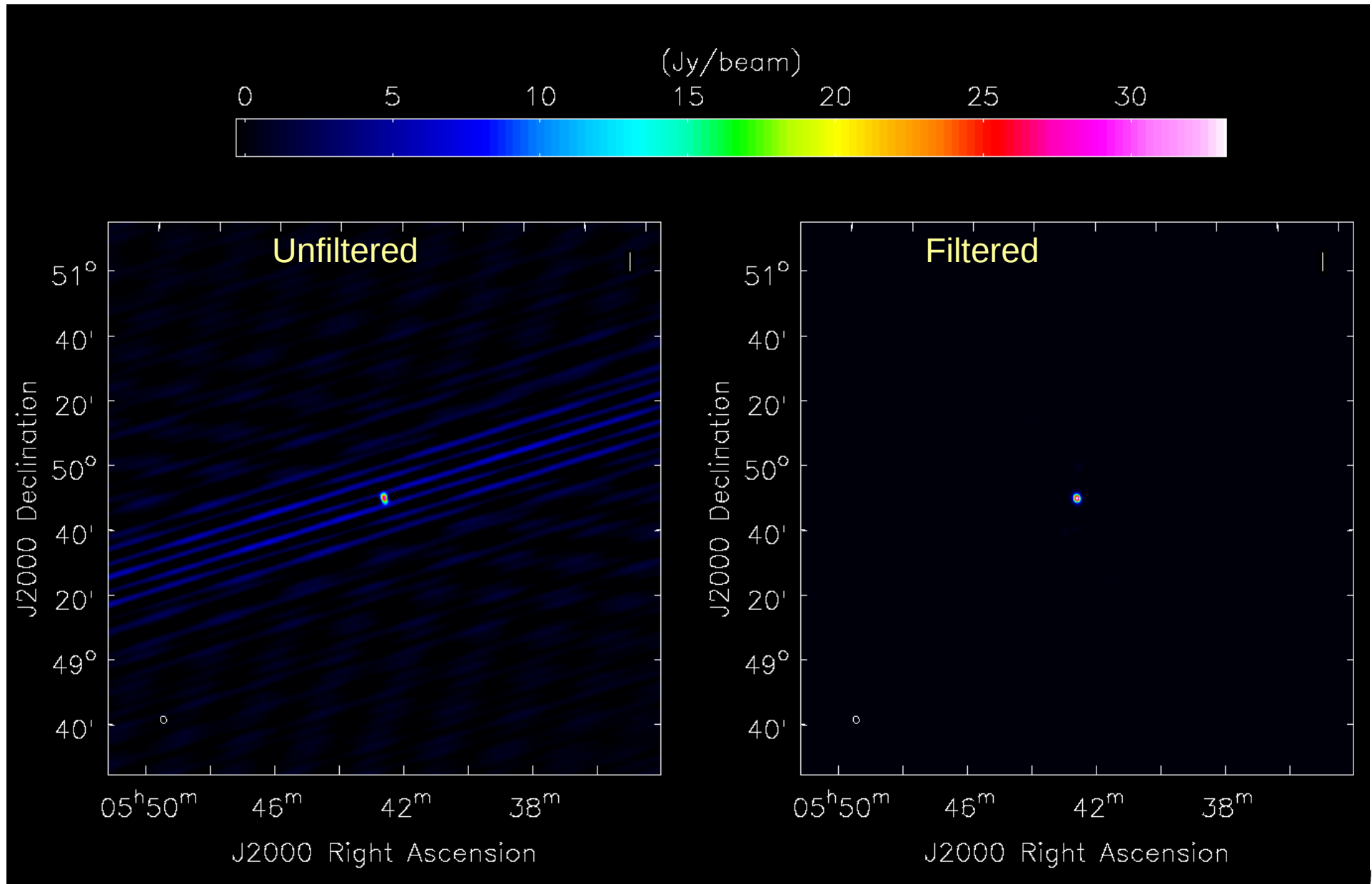


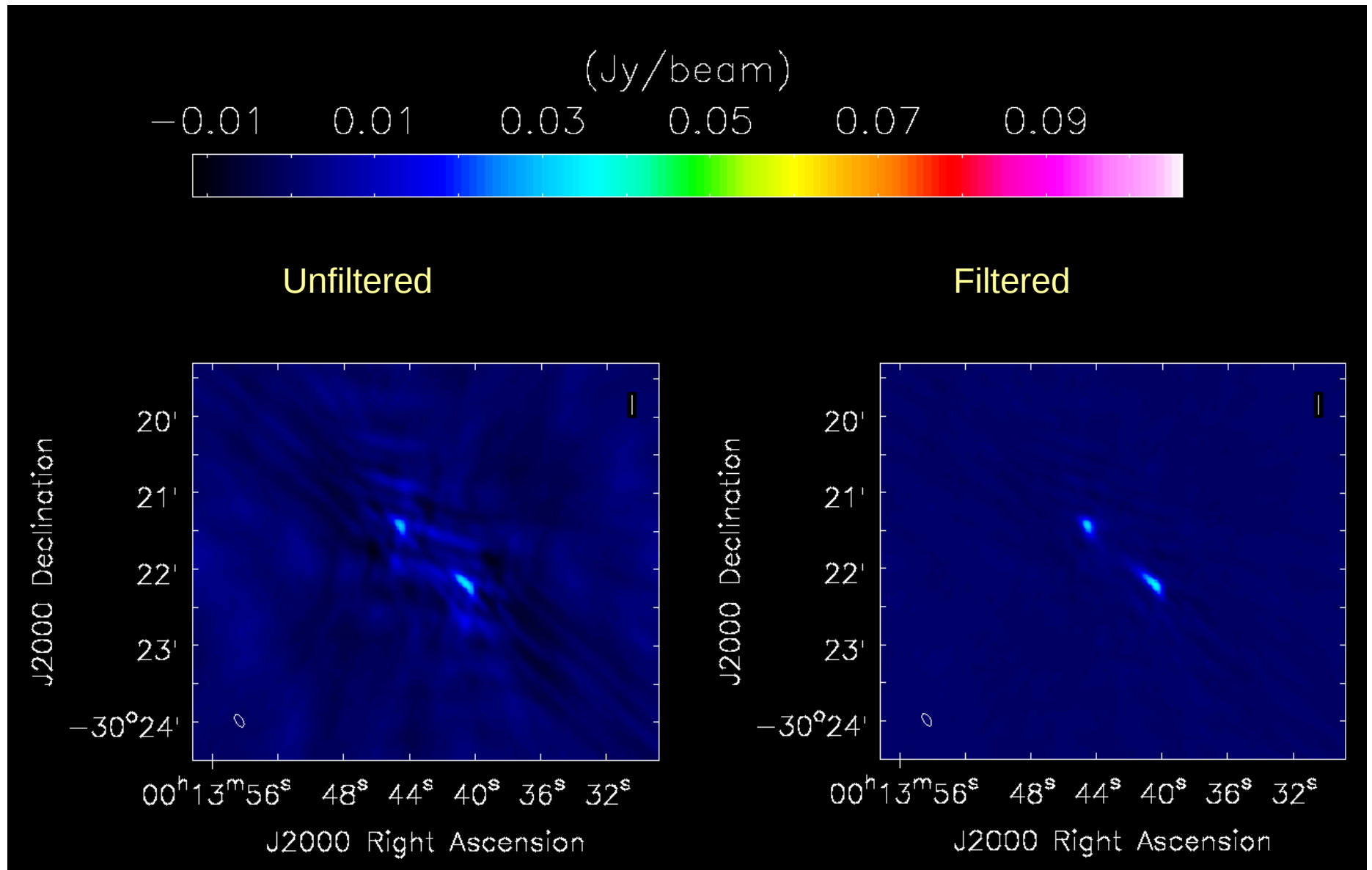
Filtered data



Broadband RFI reduced considerably- narrow band needs to be excised offline.

Images made only from baselines with length < 0.5 km





Summary

Cluster science with the uGMRT

Abell 4038: spectral curvature measurement of the remnant radio galaxy.

Abell 521 and El Gordo: Ongoing analysis of uGMRT data: A CASA based pipeline for uGMRT being tested and improved.

Possible new emission and spatial and spectral details of the diffuse sources: constraints on the theoretical models.

A realtime RFI excision system for the uGMRT is commissioned:

Shows upto factors of 3 improvement in rms at short baselines – crucial for cluster diffuse emission observations. First results in Kale et al in prep.

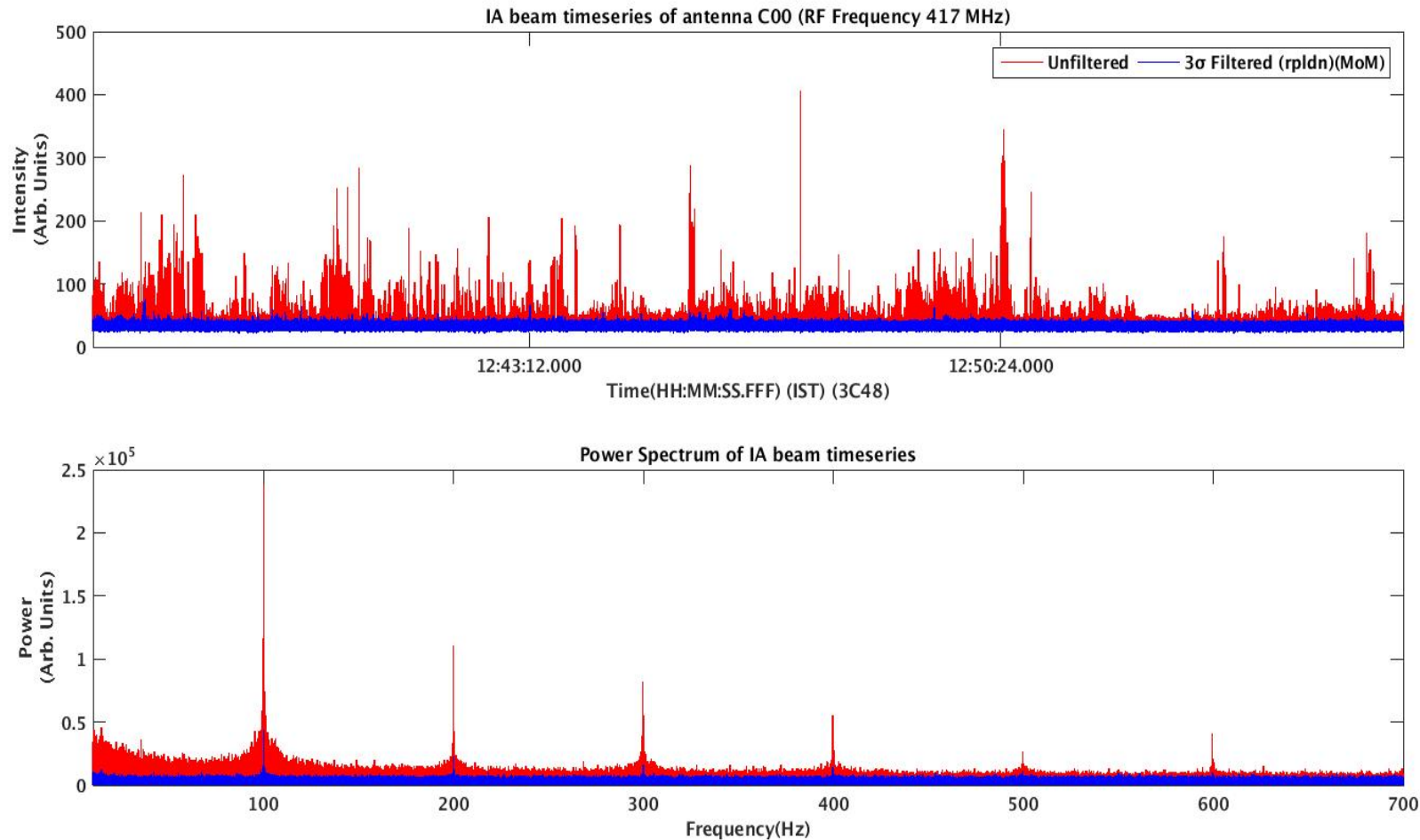
Contact me about a week before your observations if you would like to use the system: ruta@ncra.tifr.res.in

Future work for RFI:

An RFI mitigation plan for the uGMRT: online and offline combination.



Signals from single antenna single polarization



100 Hz power-line RFI signature and its harmonics –
removed after filtering