NCRA • TIFR

MWA
MURCHISON
WIDEFIELD
ARRAY

Ten years of Solar Science with the Murchison Widefield Array

Divya Oberoi
National Centre for Radio Astrophysics, TIFR
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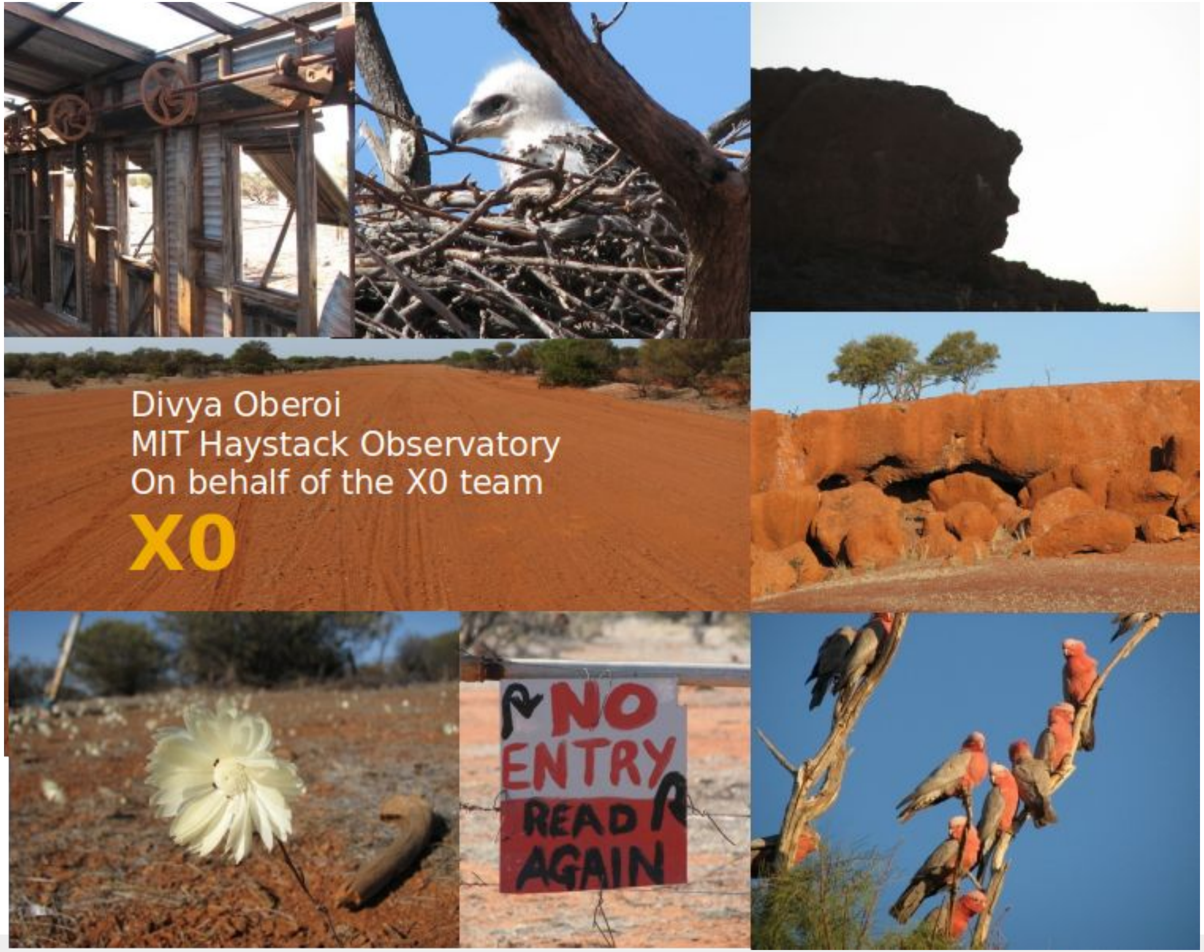
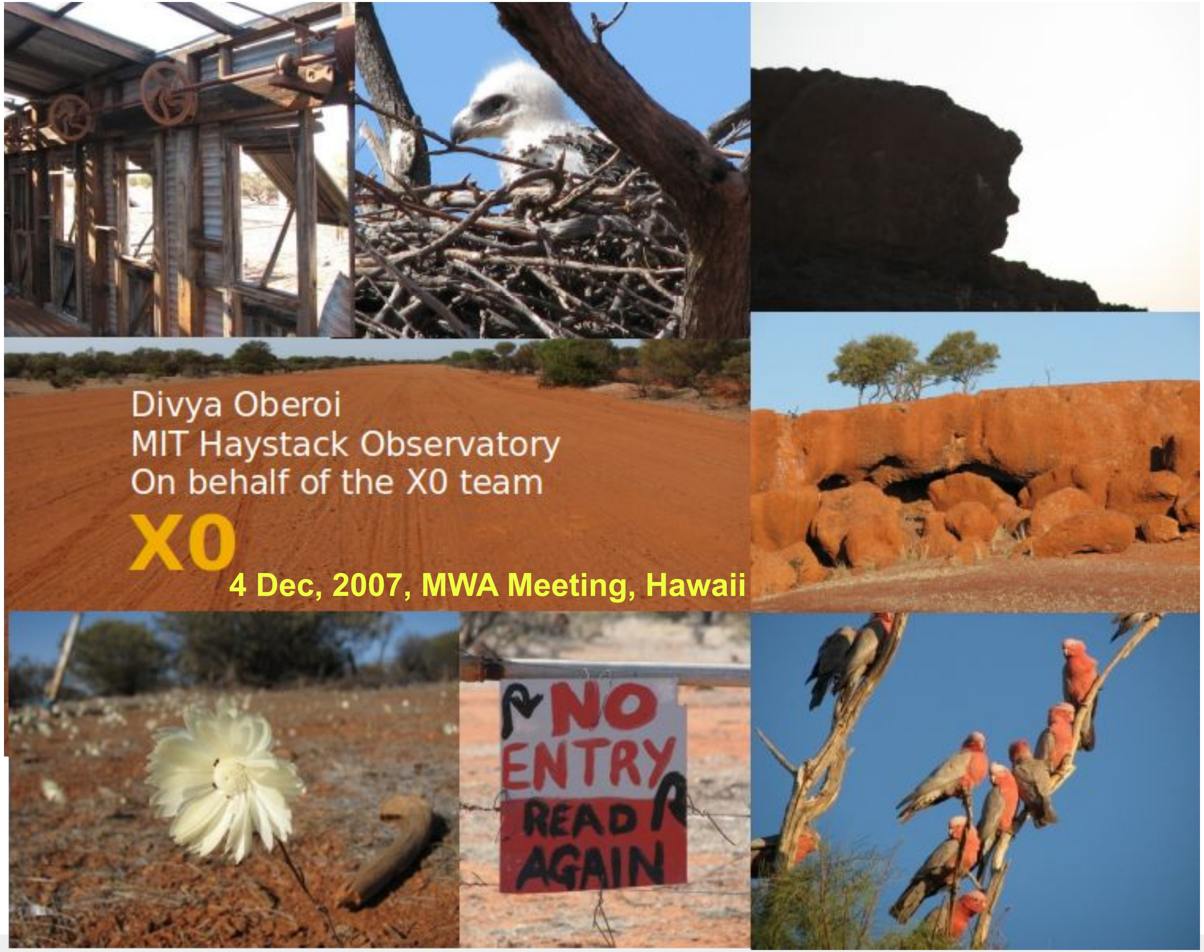
Colin Lonsdale, Iver Cairns, John Morgan
Devojyoti Kansabanik, Surajit Mondal,
Rohit Sharma, Atul Mohan, Soham Dey, Puja Majee,
Shilpi Bhunia, Eoin Carley
Patrick McCauley, Mozibur Rahman

MWA@10; 26 July, 2023



Divya Oberoi
MIT Haystack Observatory
On behalf of the X0 team
X0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On behalf of the X0 team
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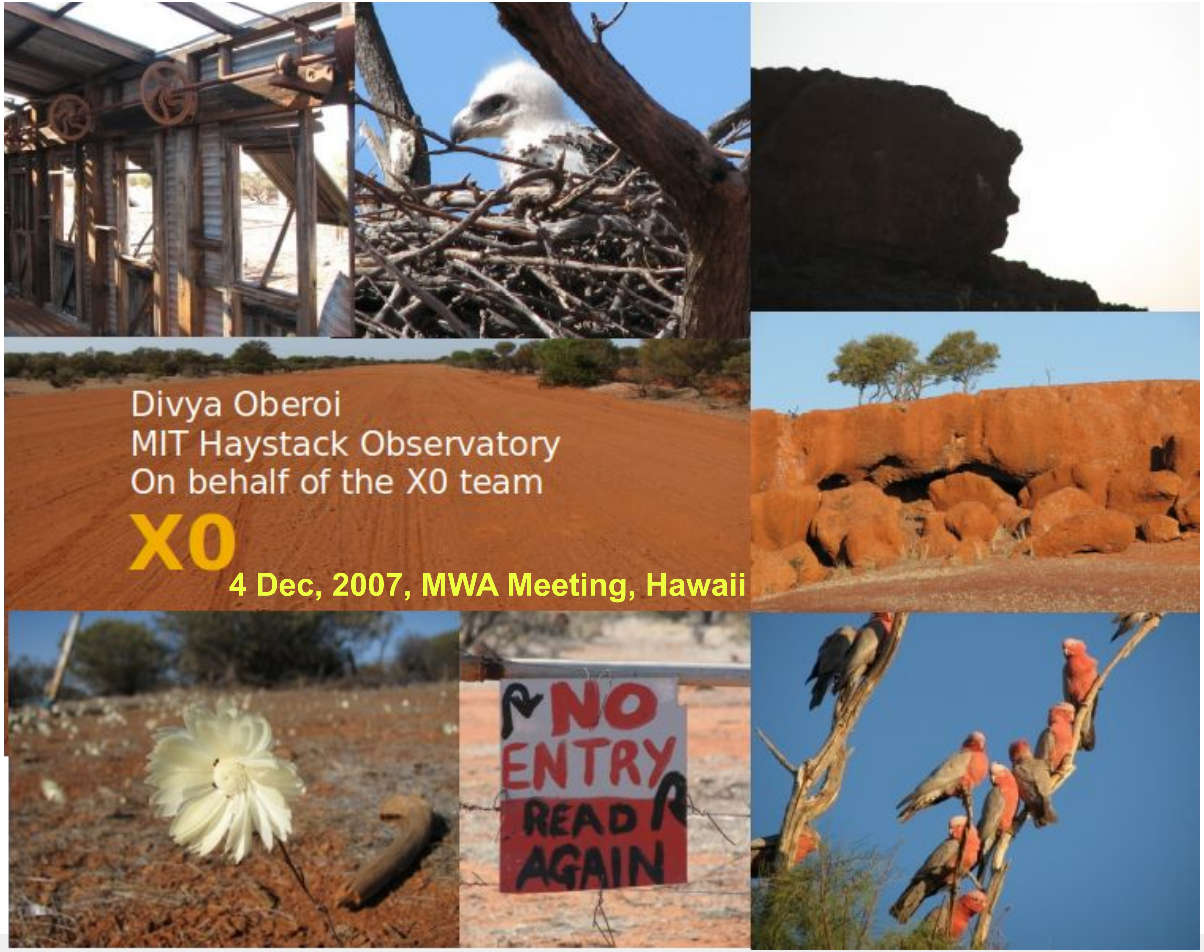
4 Dec, 2007, MWA Meeting, Hawaii
NO
ENTRY
READ
AGAIN

Early days…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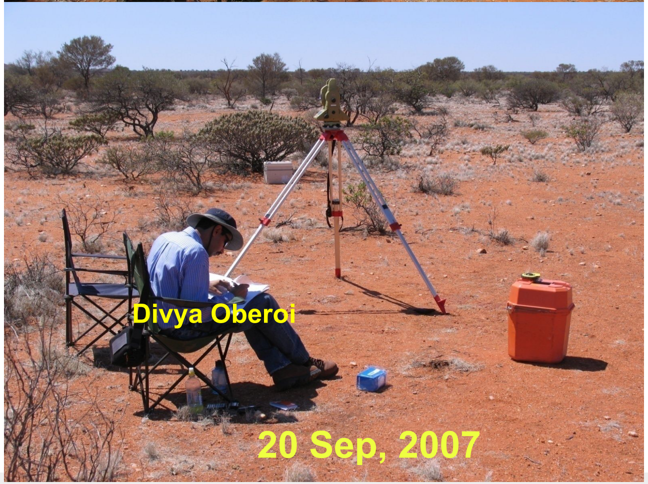
Merv Lynch
David Herne
Tony Sweetnam


Divya Oberoi
20 Sep, 2007

The First 32T Publication

The Astrophysical Journal Letters, 728:L27 (7pp), 2011 February 20 doi:10.1088/2041-8205/728/2/L27

FIRST SPECTROSCOPIC IMAGING OBSERVATIONS OF THE SUN AT LOW RADIO FREQUENCIES WITH THE MURCHISON WIDEFIELD ARRAY PROTOTYPE

Divya Oberoi[1], Lynn D. Matthews[1], Iver H. Cairns[2], David Emrich[3], Vasili Lobzin[2], Colin J. Lonsdale[1], Edward H. Morgan[4], T. Prabu[5], Harish Vedantham[5], Randall B. Wayth[3], Andrew Williams[6], Christopher Williams[4], Stephen M. White[7], G. Allen[8], Wayne Arcus[3], David Barnes[9], Leonid Benkevitch[1], Gianni Bernardi[10], Judd D. Bowman[11], Frank H. Briggs[12], John D. Bunton[8], Steve Burns[13], Roger C. Cappallo[1], M. A. Clark[14], Brian E. Corey[1], M. Dawson[12], David DeBoer[8,15], A. De Gans[12], Ludi deSouza[8], Mark Derome[1], R. G. Edgar[14,16], T. Elton[8], Robert Goeke[4], M. R. Gopalakrishna[5], Lincoln J. Greenhill[10], Bryna Hazelton[17], David Herne[3], Jacqueline N. Hewitt[4], P. A. Kamini[5], David L. Kaplan[18], Justin C. Kasper[10], Rachel Kennedy[1,15], Barton B. Kincaid[1], Jonathan Kocz[12], R. Koeing[8], Errol Kowald[12], Mervyn J. Lynch[3], S. Madhavi[5], Stephen R. McWhirter[1], Daniel A. Mitchell[10], Miguel F. Morales[17], A. Ng[8], Stephen M. Ord[10], Joseph Pathikulangara[8], Alan E. E. Rogers[1], Anish Roshi[5,19], Joseph E. Salah[1], Robert J. Sault[20], Antony Schinckel[8], N. Udaya Shankar[5], K. S. Srivani[5], Jamie Stevens[8], Ravi Subrahmanyan[5], D. Thakkar[2], Steven J. Tingay[3], J. Tuthill[8], Annino Vaccarella[12], Mark Waterson[3,12], Rachel L. Webster[20], and Alan R. Whitney[1]

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[6] Perth Observatory, The University of Western Australia, Perth, Australia
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[14] Faculty of Arts and Sciences, Harvard University, Cambridge, MA, USA
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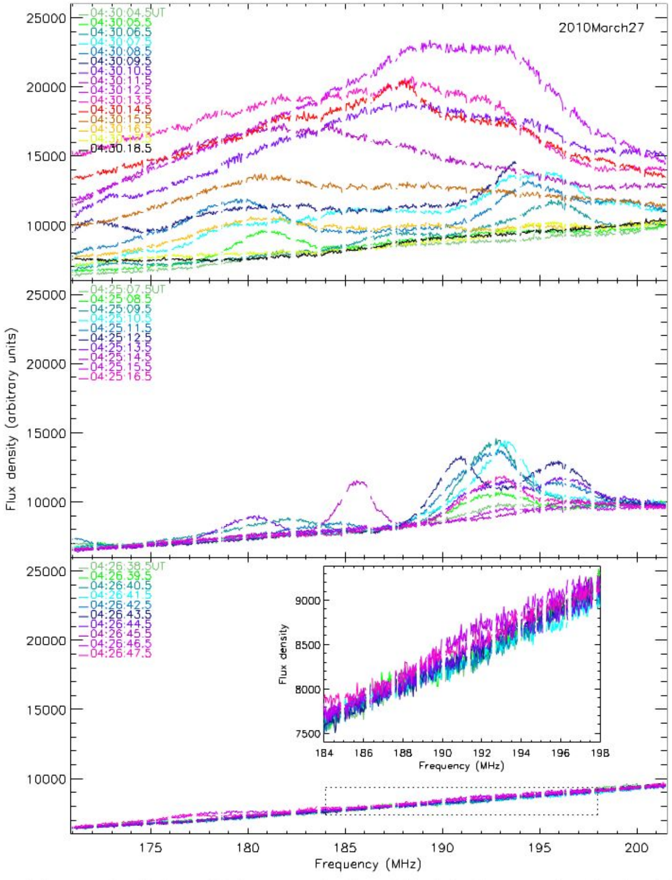
X13 - March 2010

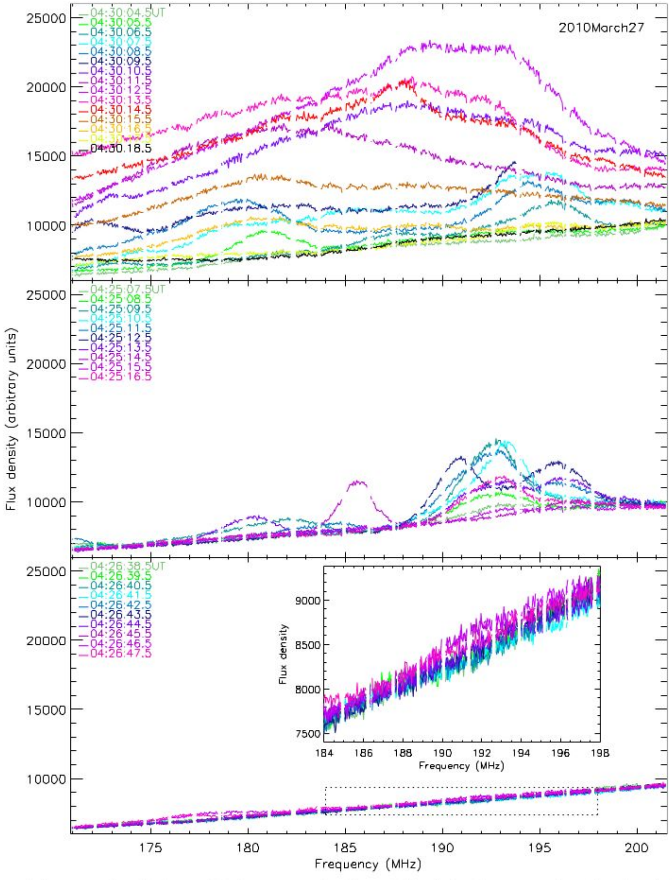
Dave Emrich
Chris Williams (MIT)
Prabu, Harish (RRI)

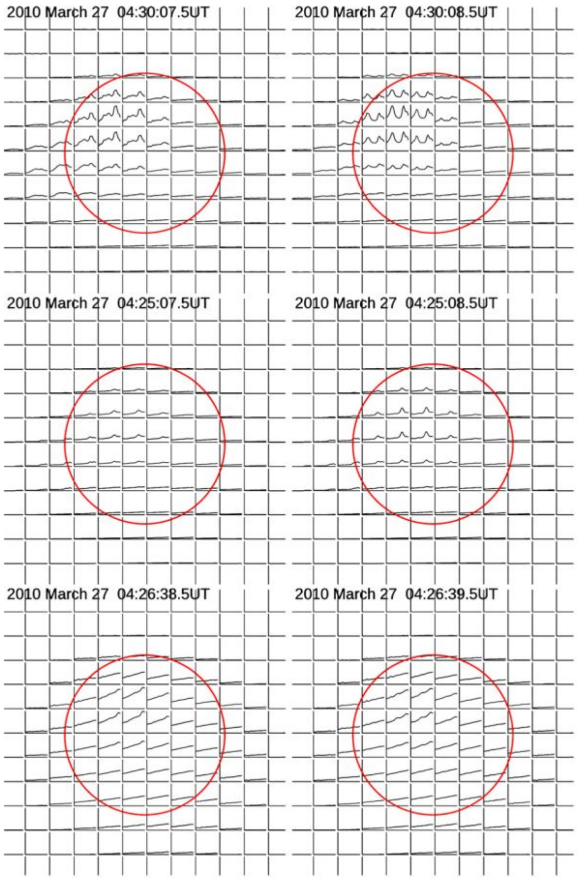
The First 32T Publication



Oberoi et al., 2011, ApJL

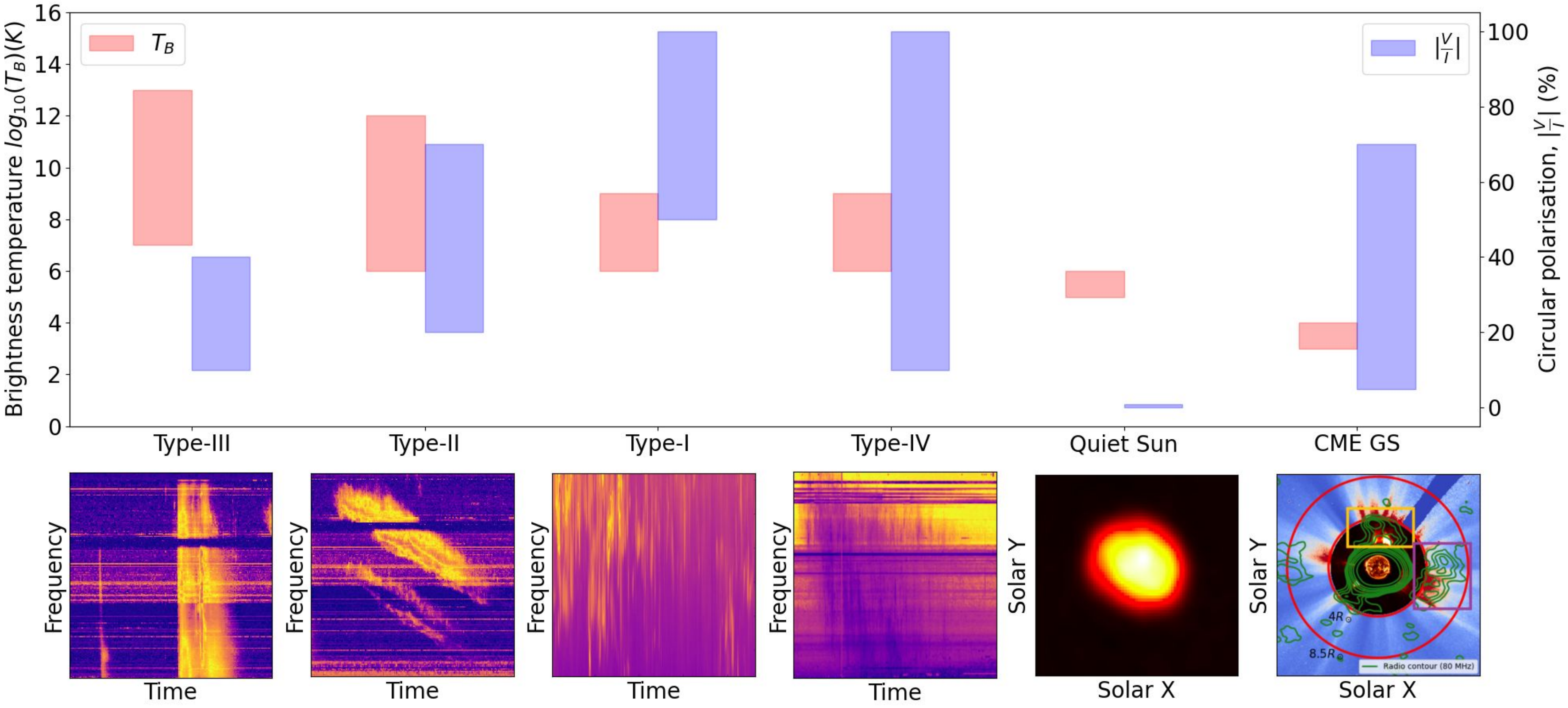
The First 32T Publication





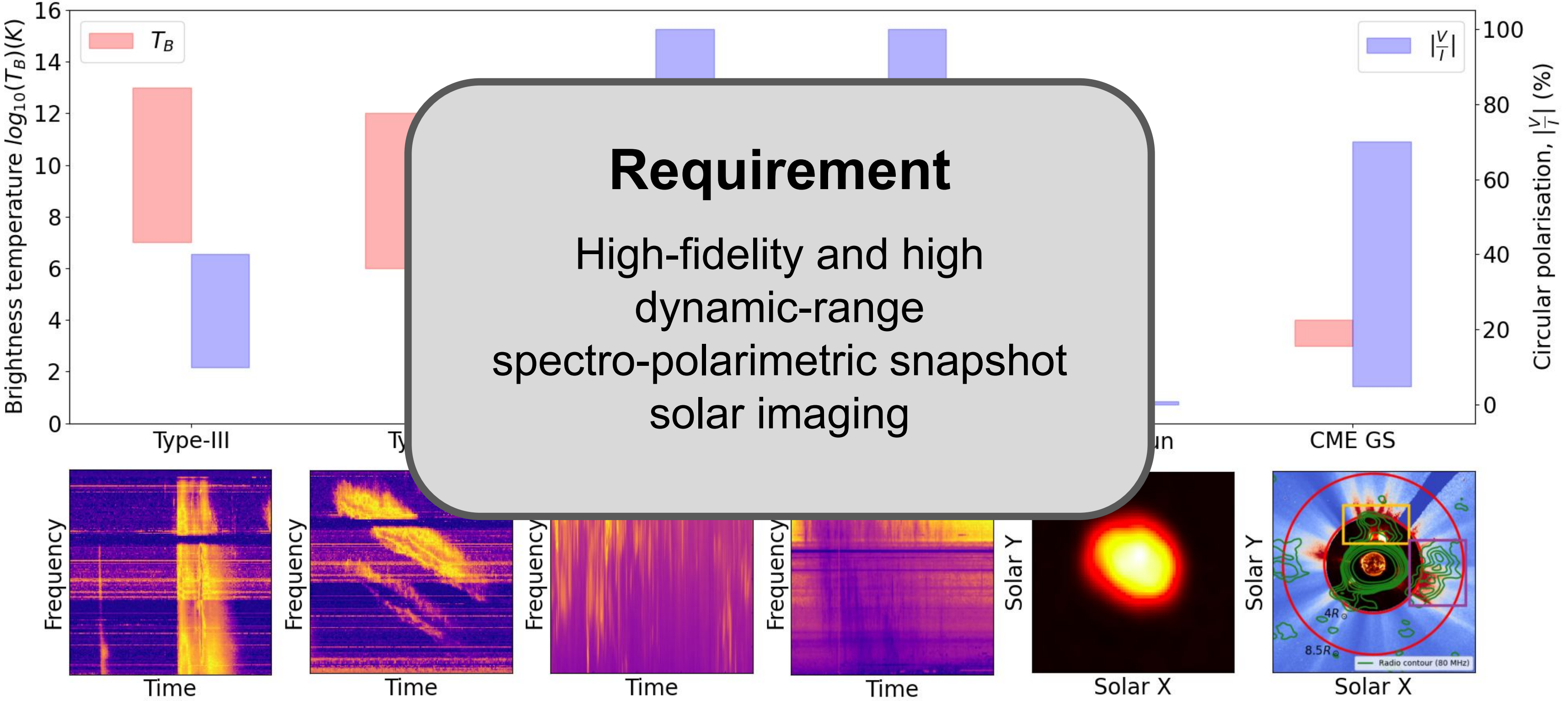
Oberoi et al., 2011, ApJL

Observational Challenges of Solar Radio Imaging



Kansabanik 2022, Solar Physics, 297, 122

Observational Challenges of Solar Radio Imaging

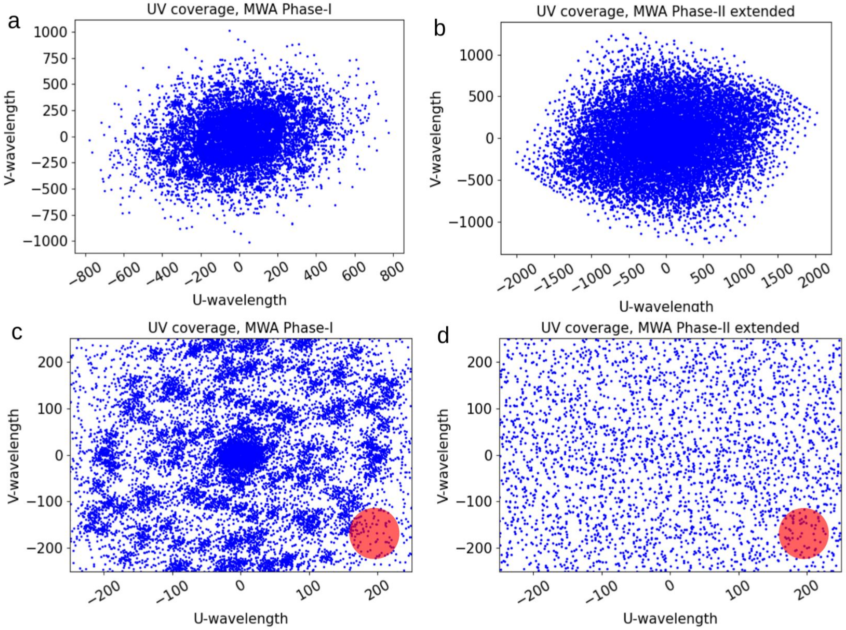


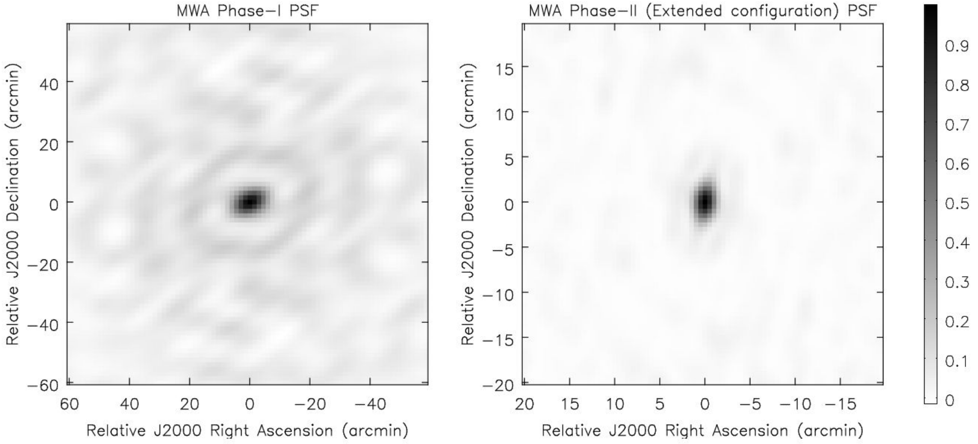
Requirement

High-fidelity and high dynamic-range spectro-polarimetric snapshot solar imaging

Kansabanik 2022, Solar Physics, 297, 122

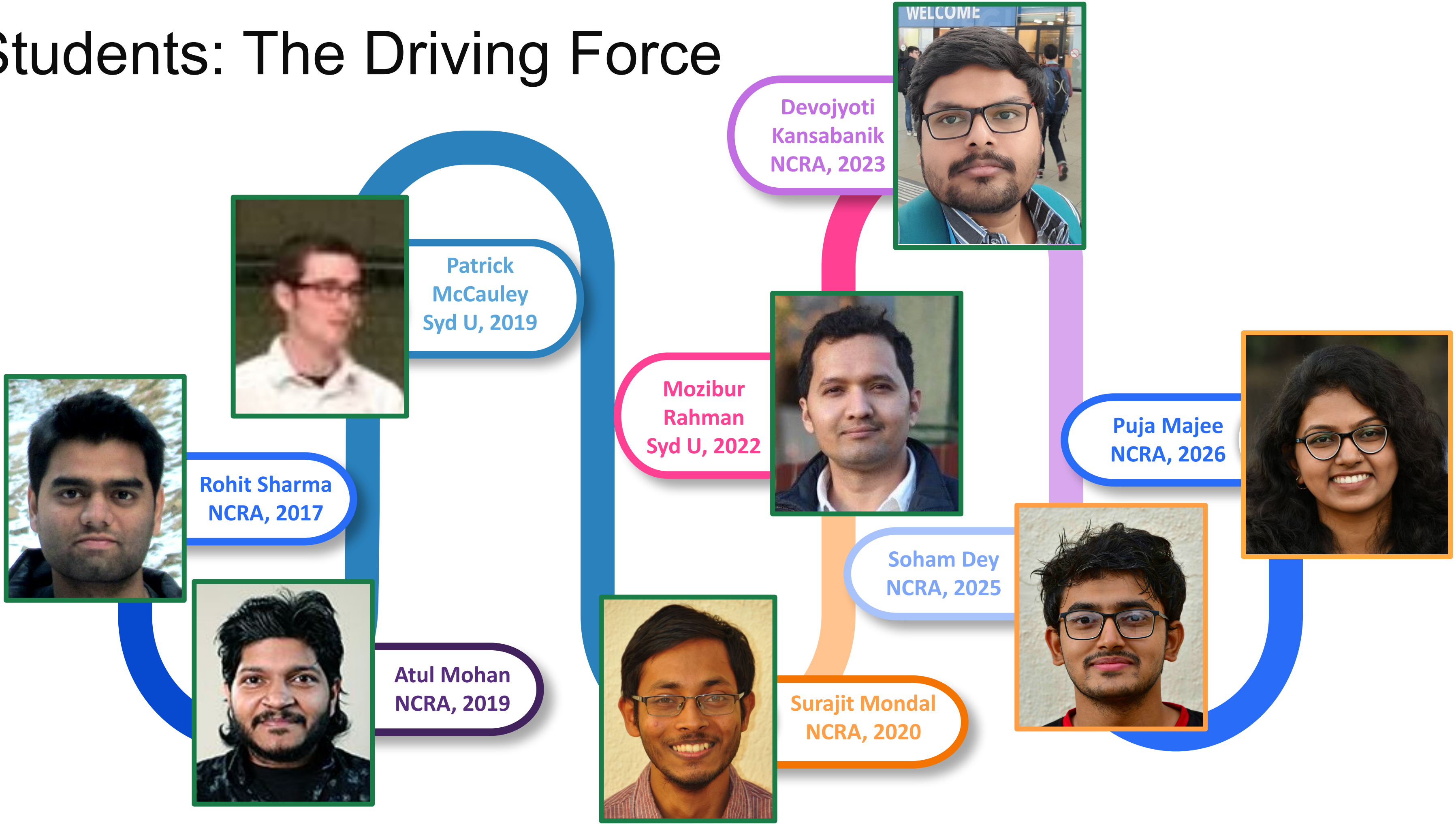
Murchison Widefield Array





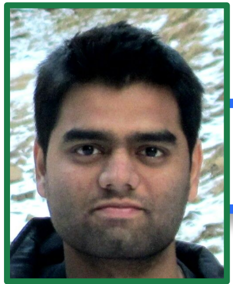
Kansabanik 2022, Solar Physics, 297, 122

Students: The Driving Force



Students: The Driving Force

MS students
Akshay Suresh (2017)
Shilpi Bhunia (2020)
and many many short term students



Rohit Sharma
NCRA, 2017

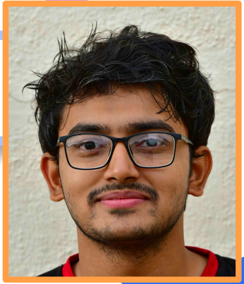
Patrick McCauley
Syd U, 2019

Atul Mohan
NCRA, 2019

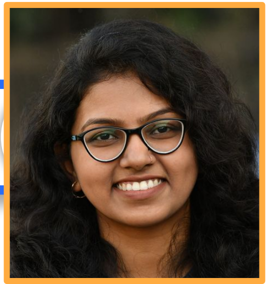
Surajit Mondal
NCRA, 2020

Mozibur Rahman
Syd U, 2022

Devojyoti Kansabanik
NCRA, 2023

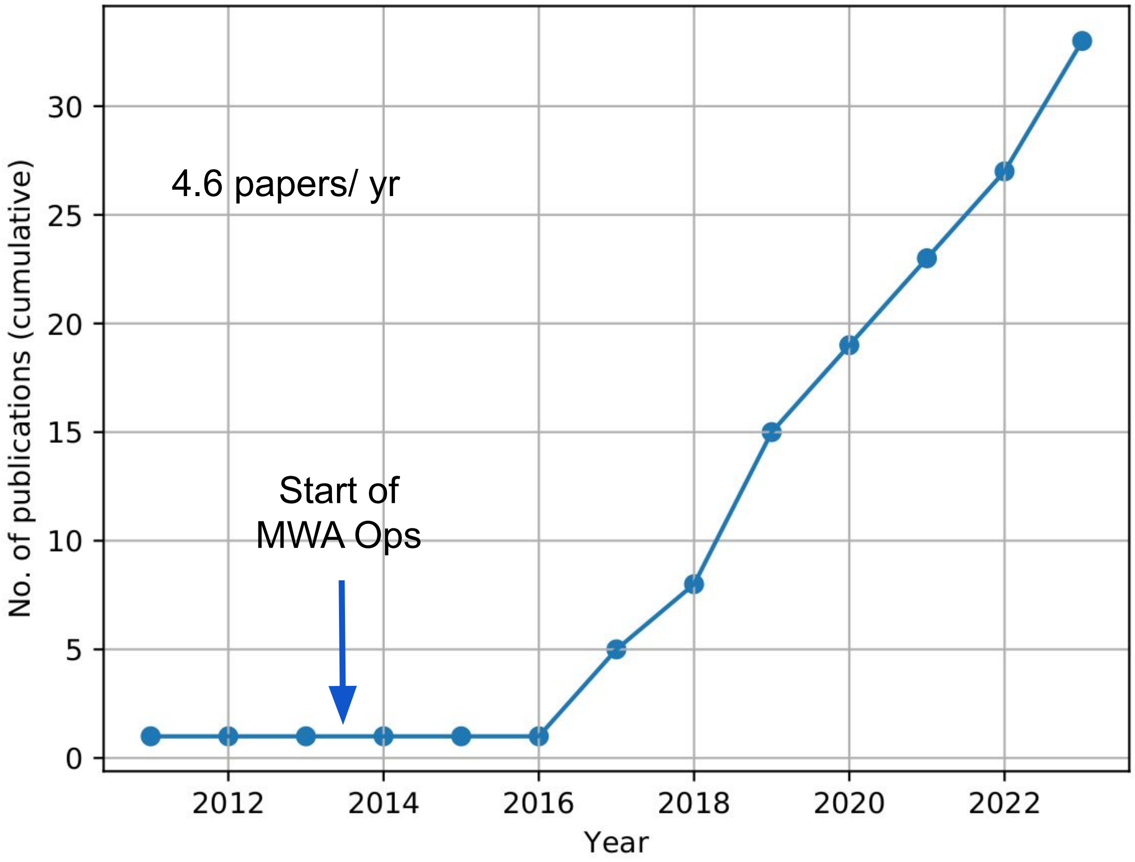


Soham Dey
NCRA, 2025



Puja Majee
NCRA, 2026

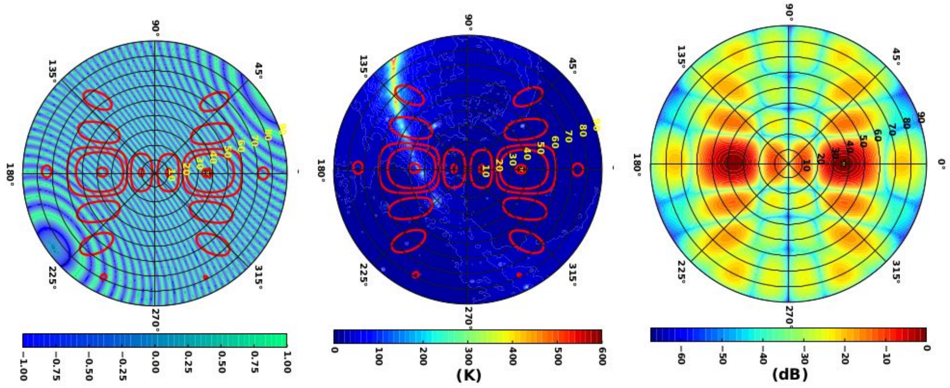
Publication Record (only solar)



Absolute Flux Density Calibration

Used the well characterised Galactic background and the MWA beams and receivers to determine solar flux density (Oberoi et al., 2017)

- Relied on availability of baselines short enough to not resolve the Sun



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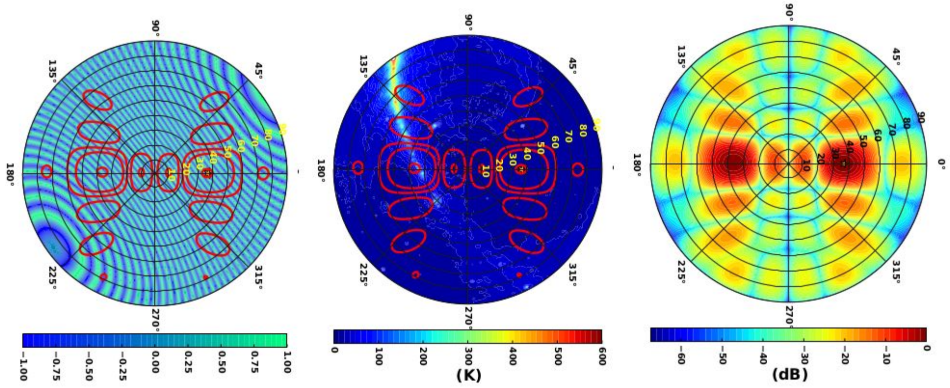
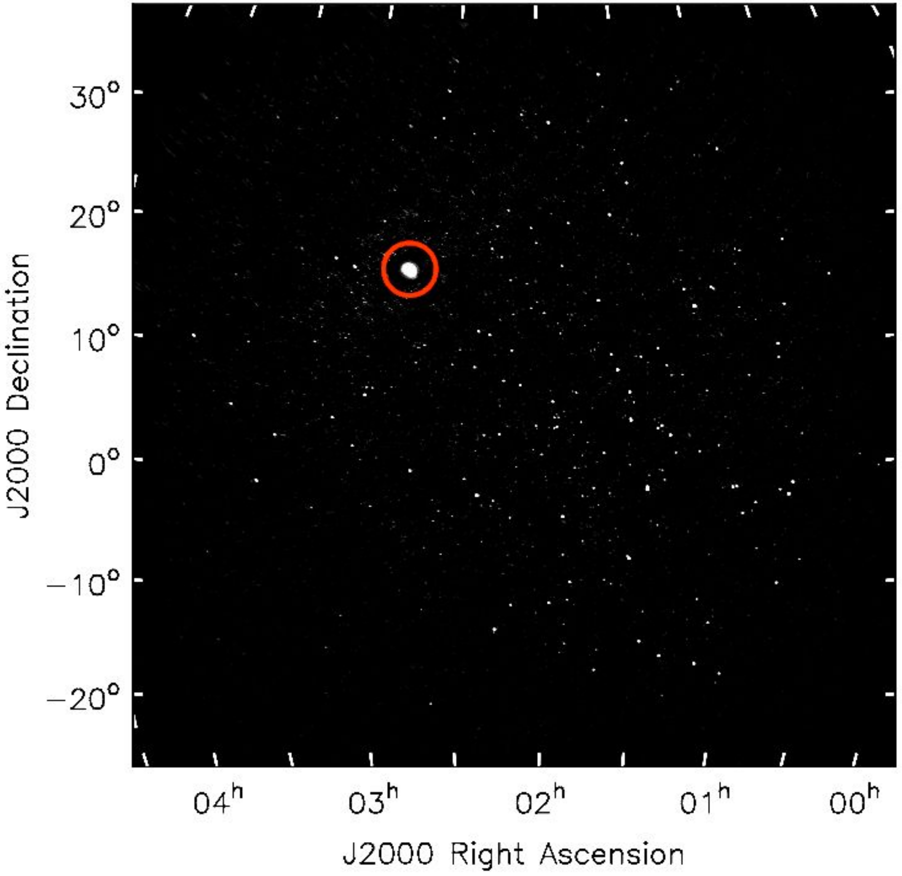
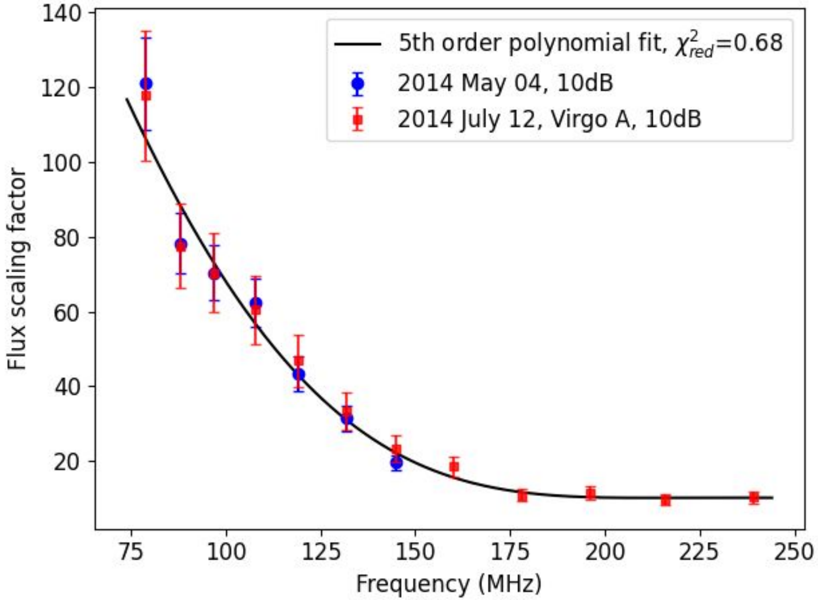


Multipronged approach to flux density calibration (Kansabanik et al., 2022)

- Presence of bright sources in the FoV (Crab, VirgoA)
- High dynamic-range imaging - detect numerous background radio sources and use GLEAM catalogue flux densities
- Observations of strong calibrators with and without solar attenuation
- Use the database of calibration solutions by Sokolowski et al. (2020)

Absolute Flux Density Calibration



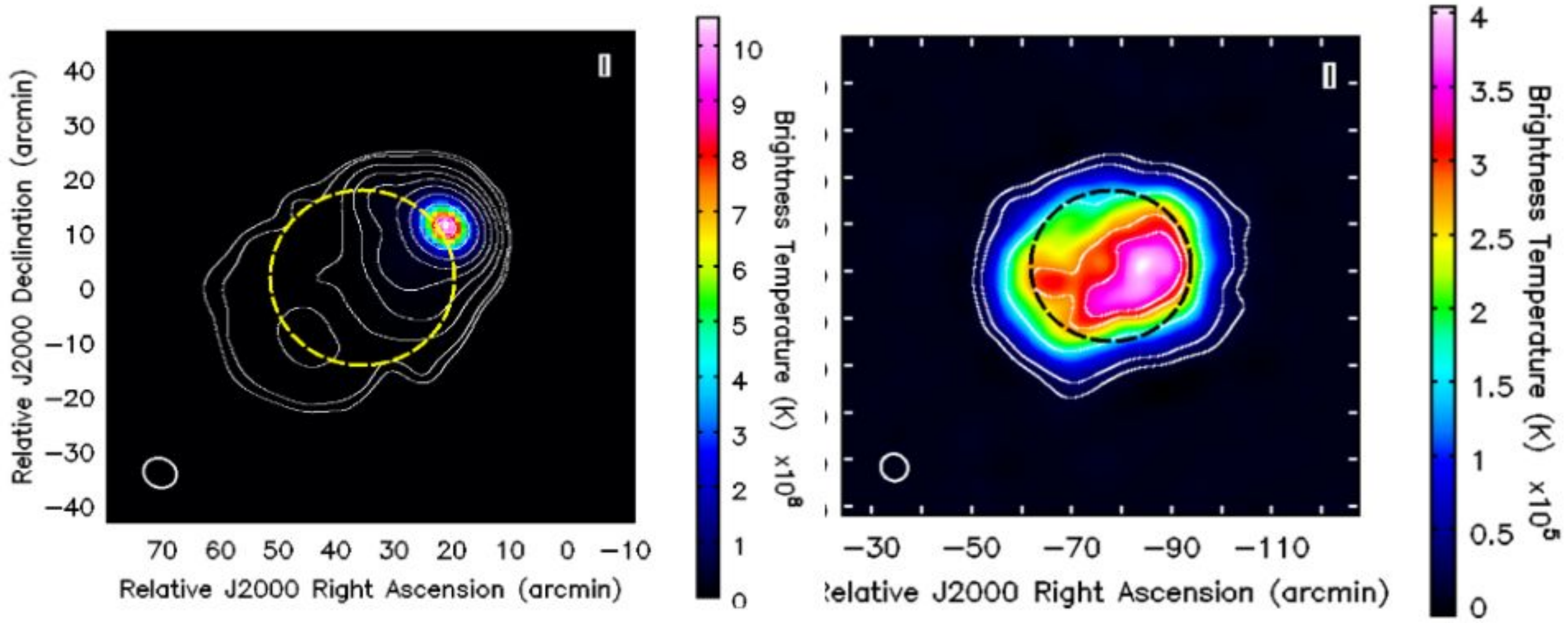


Detect sources down to 4 Jy flux-density in the presence of $>10^4$ Jy Sun.

Uncertainty ~10%

Kansabanik et al., 2022a, ApJ 927 17

Imaging pipelines (AIRCARS)

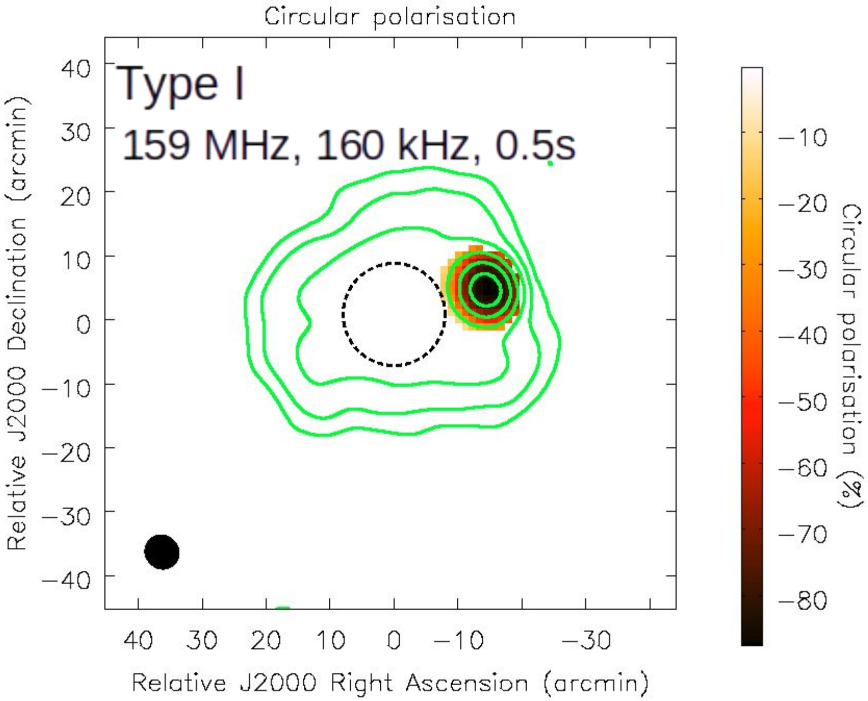


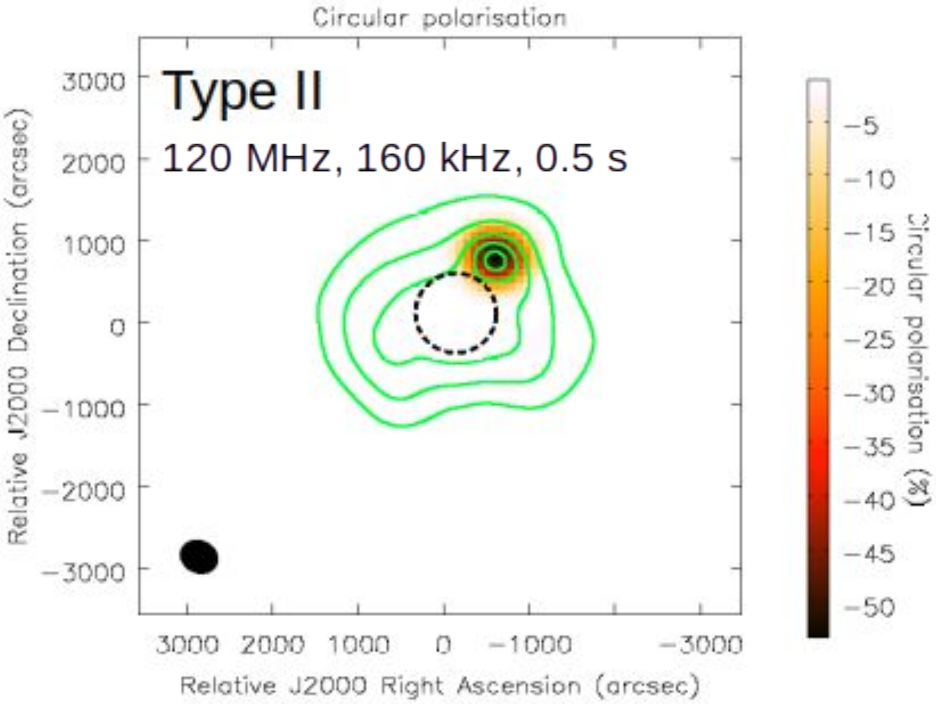
Contour levels: (0.0007, 0.002, 0.02, 0.2,0.4,0.8) X 10^9 K
144.32 MHz; 40 kHz; 0.5 s
Imaging dynamic range: $>10^5$

Contour levels: (0.03, 0.09, 0.4, 0.7, 0.8) x 4x10^5 K
239.10 MHz; 160 kHz; 0.5 s
Imaging dynamic range: ~1000

Mondal et al., 2019, ApJ

Imaging pipelines (P-AIRCARS)





Kansabanik et al., 2022,2023
Kansabanik, 2022

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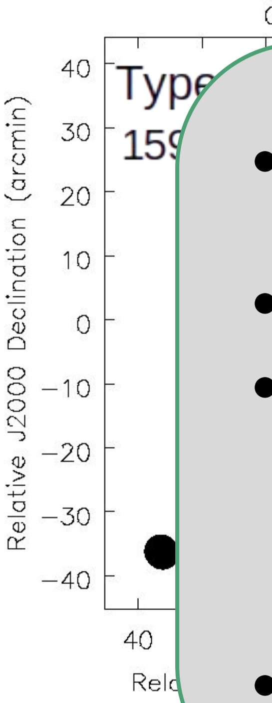
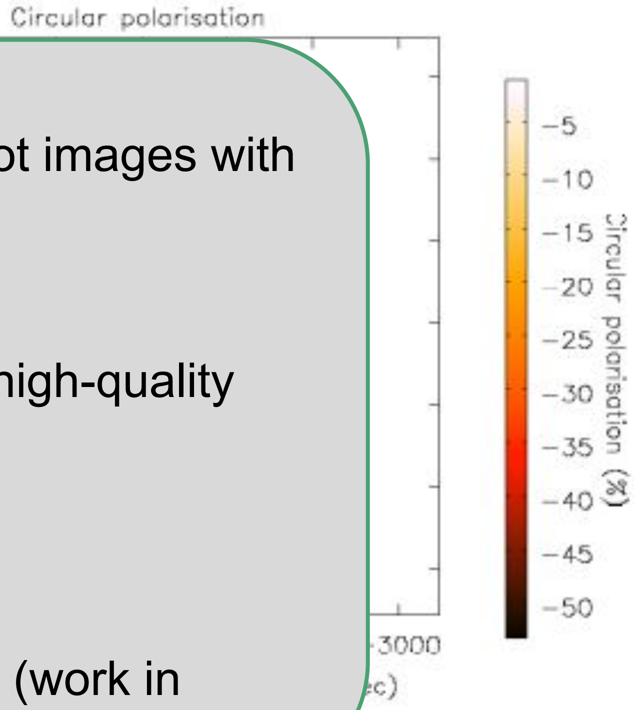


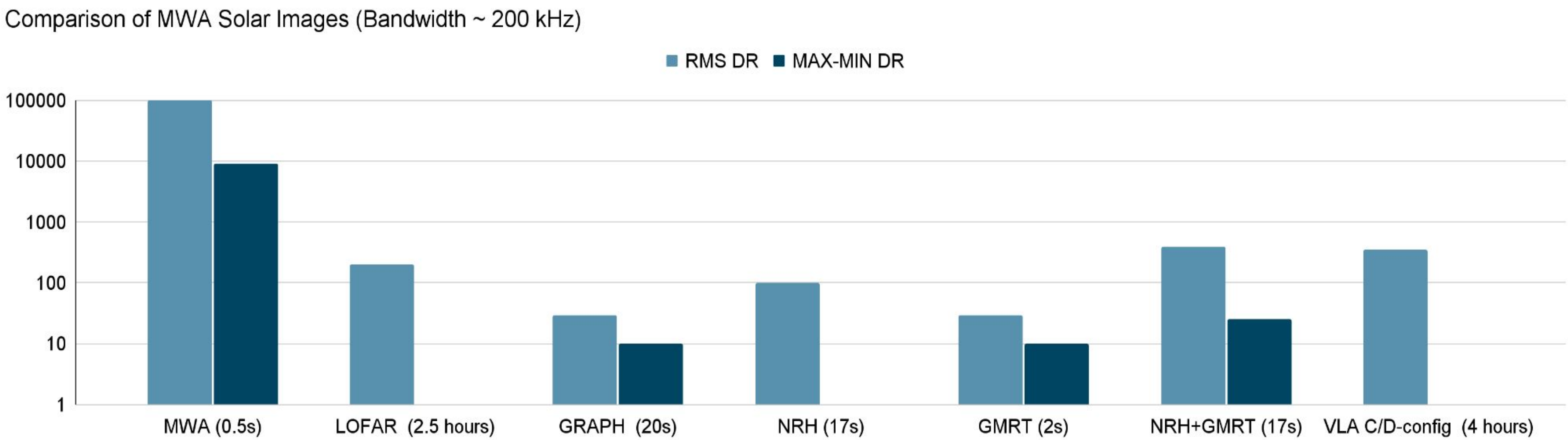
Key Takeaways

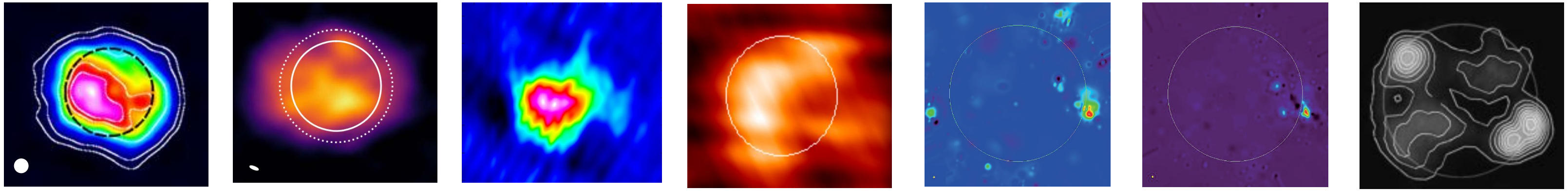
- Routinely produce spectroscopic snapshot images with dynamic range ~300 – 10^5
- Flux density uncertainty is ~10%
- Polarization calibration is comparable to high-quality astronomical observations
  - Residual Stokes I ↔ Q is ~1%
  - Residual Stokes I ↔ U, V is ~0.1%
- Fully automated, user-friendly and robust (work in progress)



Kansabanik et al., 2022,2023
Kansabanik, 2022

Imaging dynamic range comparison





160 kHz 195 kHz 1 MHz 1 MHz 32 MHz 32 MHz 3.27 MHz

Image credits: Mondal et al. 2019, Zhang et al. 2022, Mercier et al. 2015, Willson 2000

Science targets - chosen to maximize the MWA advantage

- Studies of weak(er) non-thermal emissions
- CME Gyrosynchroton (GS) emissions
- Targeted studies of well known solar radio bursts
  - Types I, II, III
- Coronal holes
- Polarimetry
- Propagation effects

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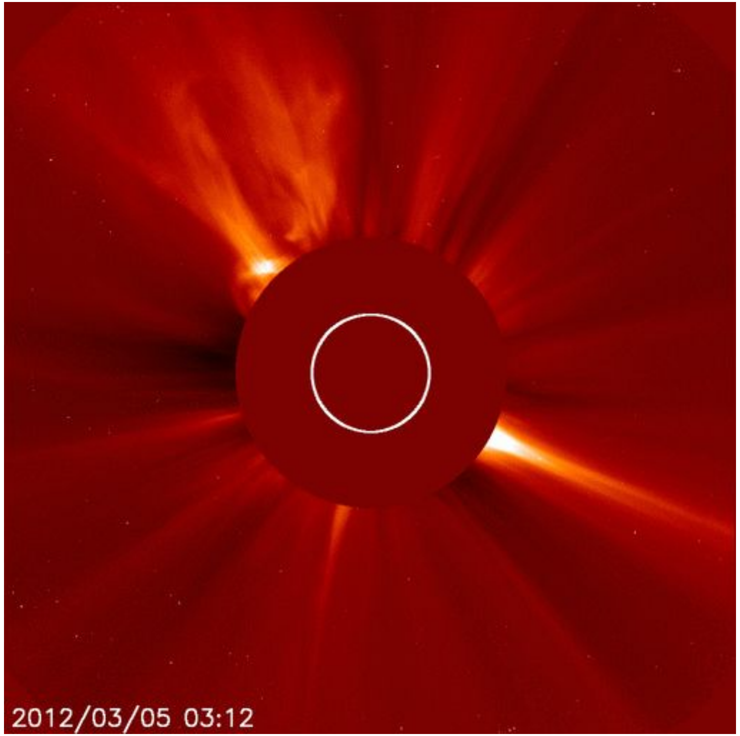

Image credit : SOHO LASCO C2 Coronagraph

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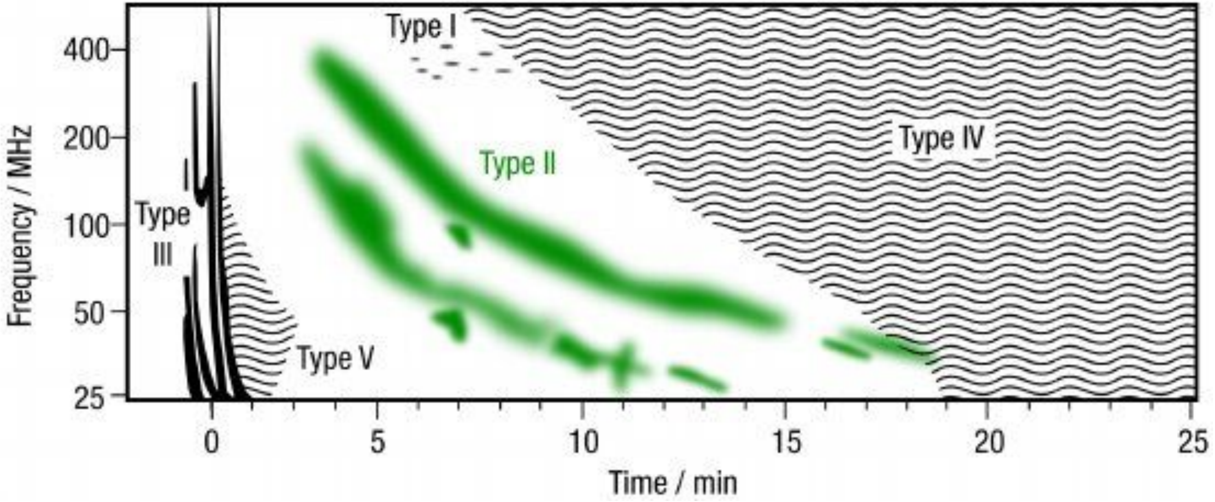
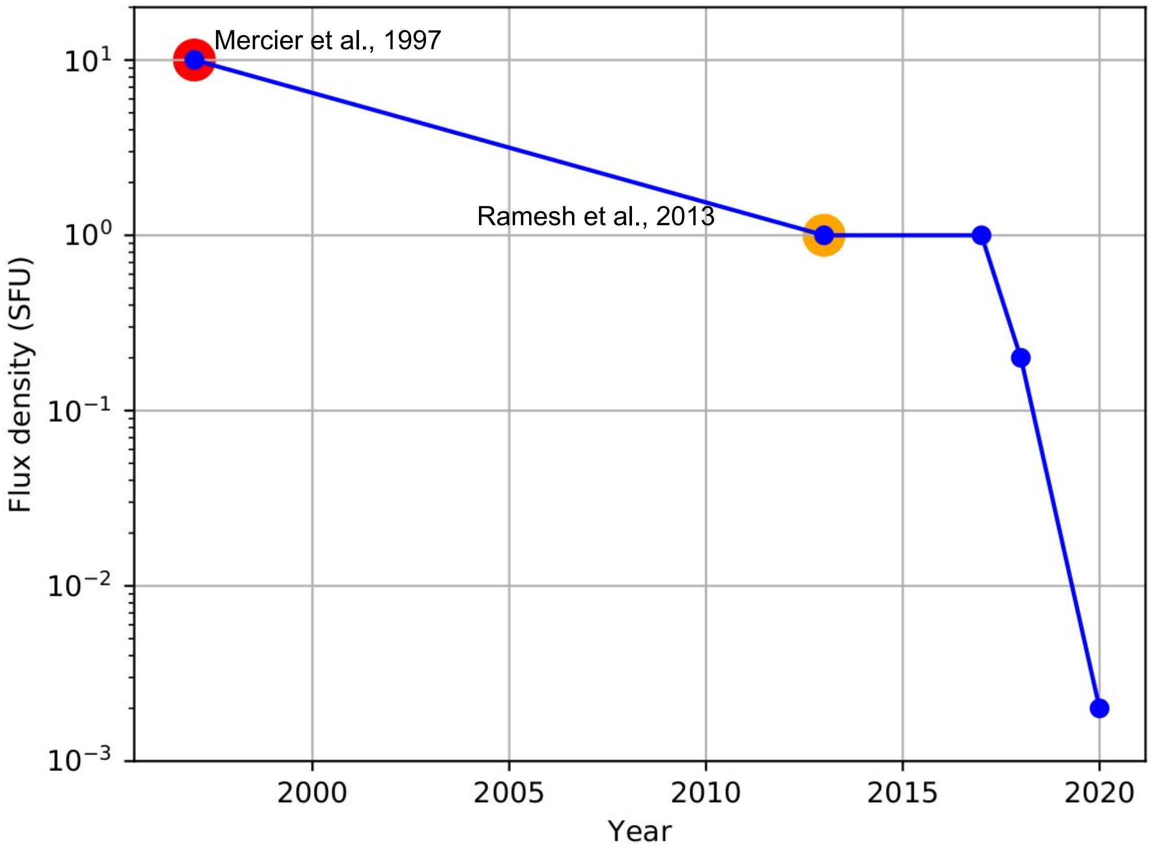


Progressively weaker non-thermal emissions



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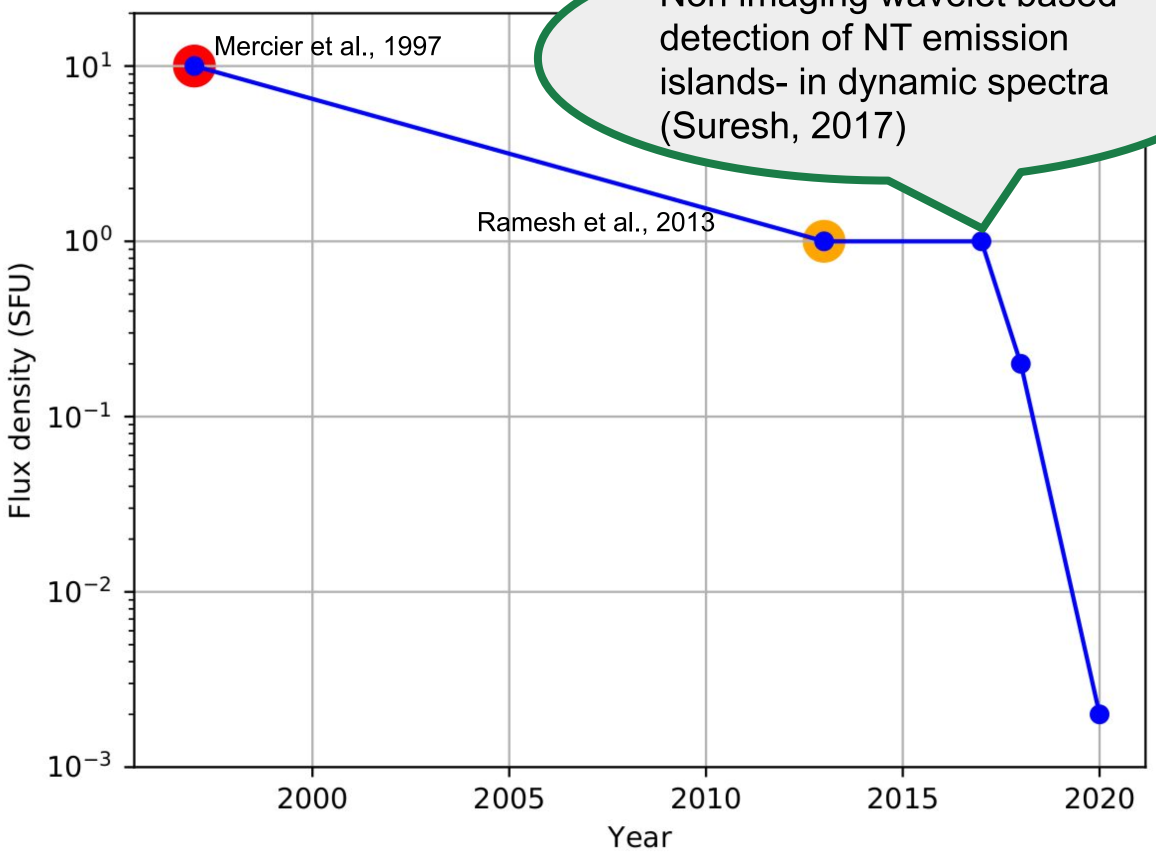
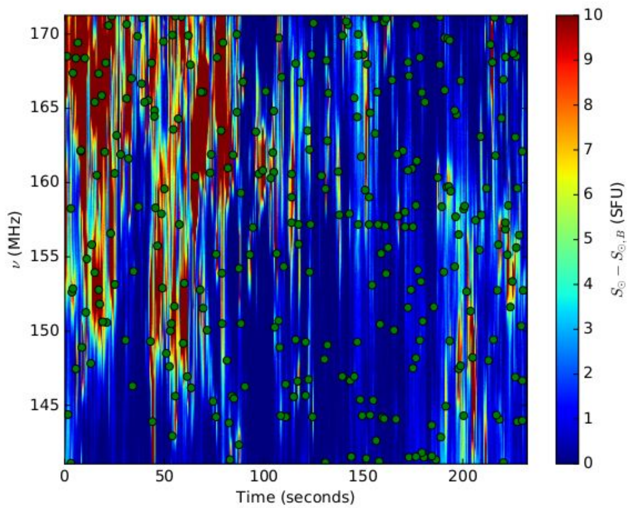
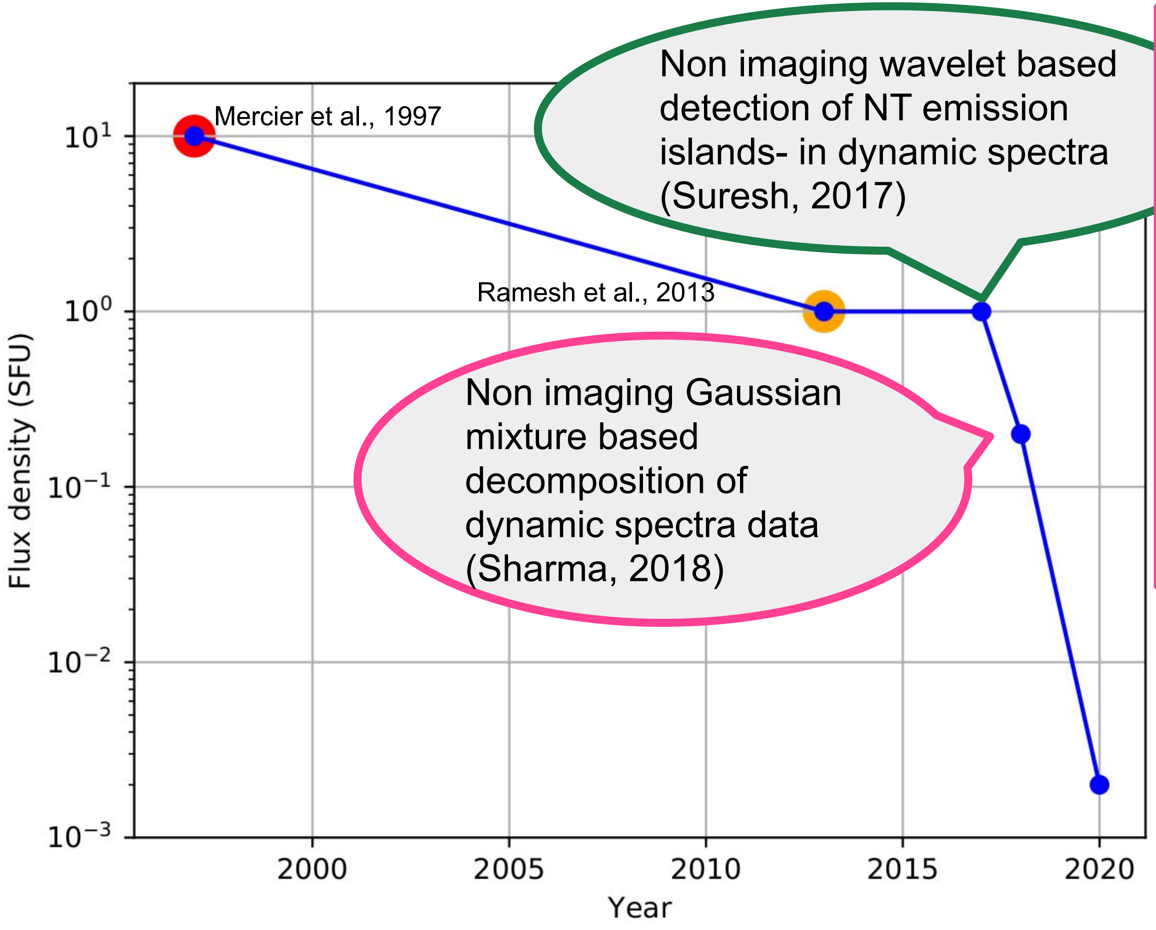
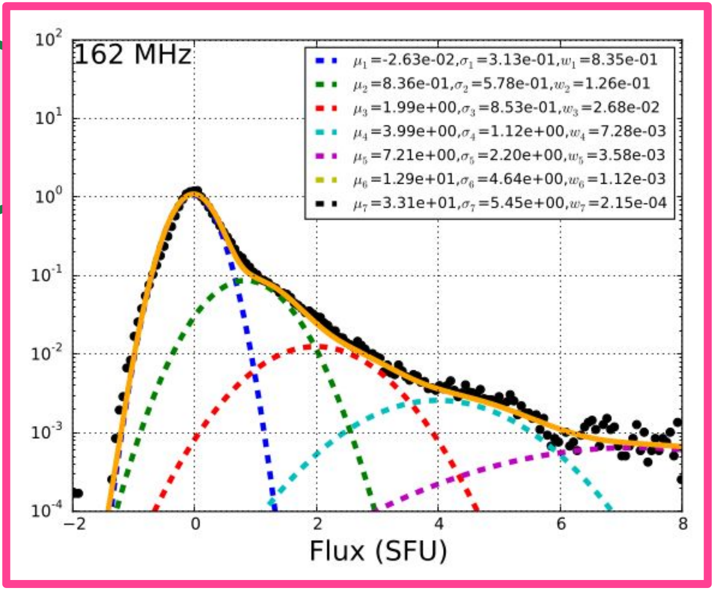


Non imaging wavelet based detection of NT emission islands- in dynamic spectra (Suresh, 2017)



Progressively weaker non-thermal emissions





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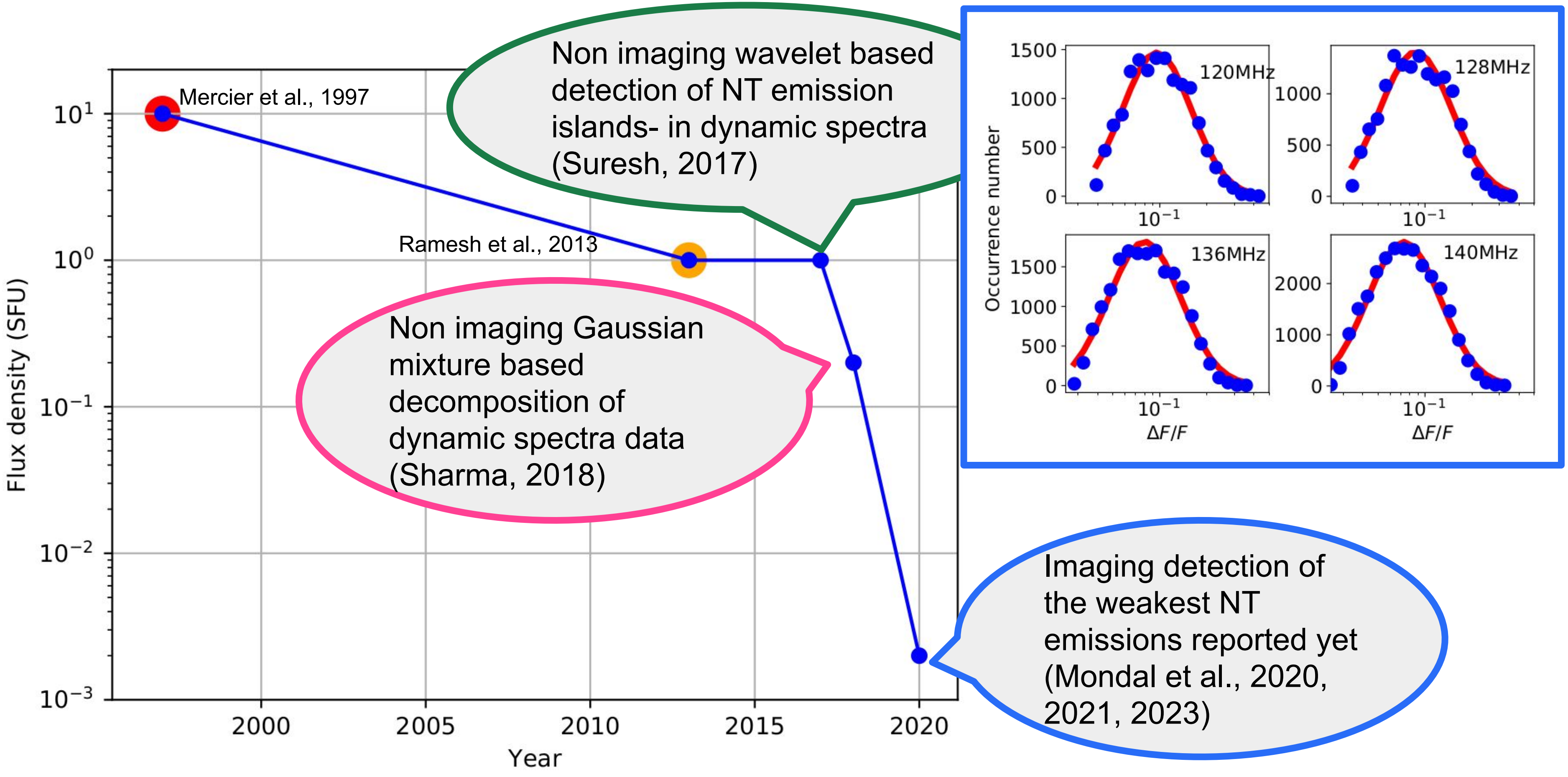
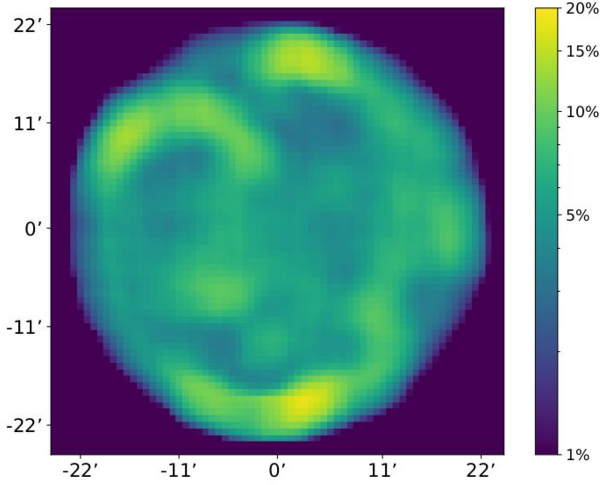
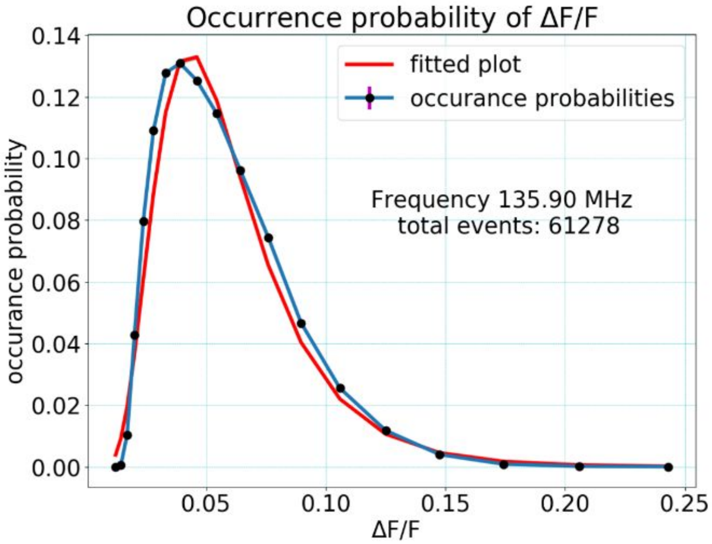


Weak Impulsive Narrowband Quiet Sun Emissions (WINQSEs)





Radio counterparts of ‘nanoflares’, hypothesised to explain coronal heating

- Meet all of the expectations
- Enable us to probe much weaker energies than possible at EVU and X-rays

Distribution well described by a log-normal function
Similar result was obtained by Pauluhn and Solanki (2007) for EUV data

Mondal et al., 2020, 2021, 2023; Bawaji et al. 2023

Solar WINQSEs

Investigations so far

- Ubiquitous on the Sun even during the quietest of solar conditions (Mondal et al., 2022)
- Found EUV counterparts of a group of co-located WINQSEs (Mondal, 2021)
    - Energy deposited in the corona ~10^25 ergs (DEM analysis)
- Tried to estimate their bandwidth/ spectral shape (Mondal et al., 2023)
    - ~100 kHz
- Examined morphology of WINQSEs (Bawaji et al., 2023)
    - Usually compact morphology
- Detection of WINQSEs using an independent technique (Sharma et al., 2022)

Radio counterparts of ‘nanoflares’, hypothesised to explain coronal heating

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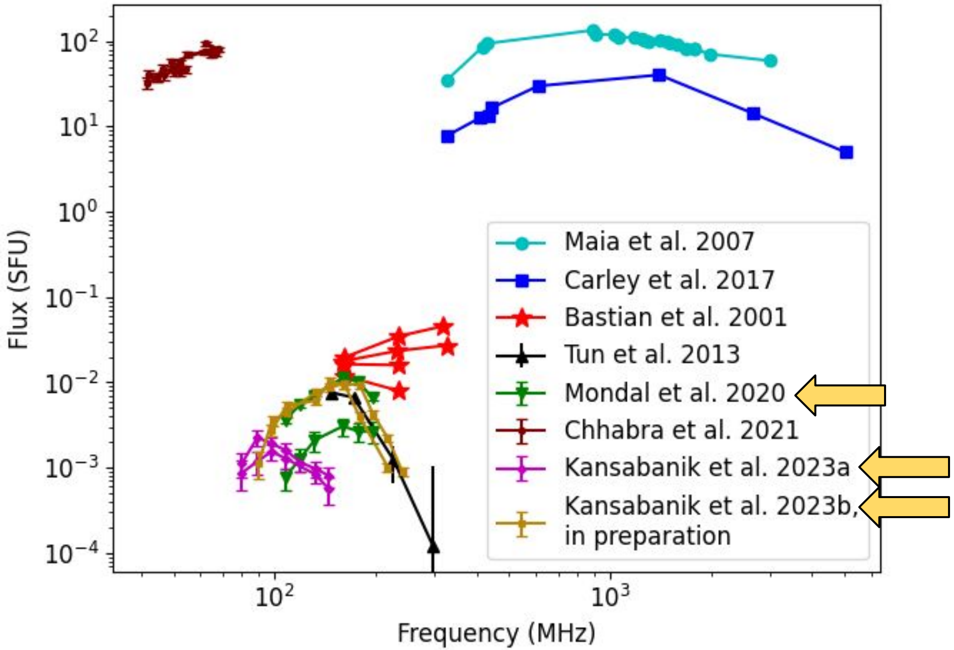
Gyrosynchrotron (GS) emission from CMEs

One of the few remote sensing techniques for estimating CME magnetic fields

First detection in 2001 (Bastian et al.) from Nançay Radioheliograph.

- Limited number of detections due to observational challenges.
- Most of them are associated with the fast CMEs.
- Spectral coverage is not always good.
- Many of them are non-imaging studies, hence cannot provide any spatial information.



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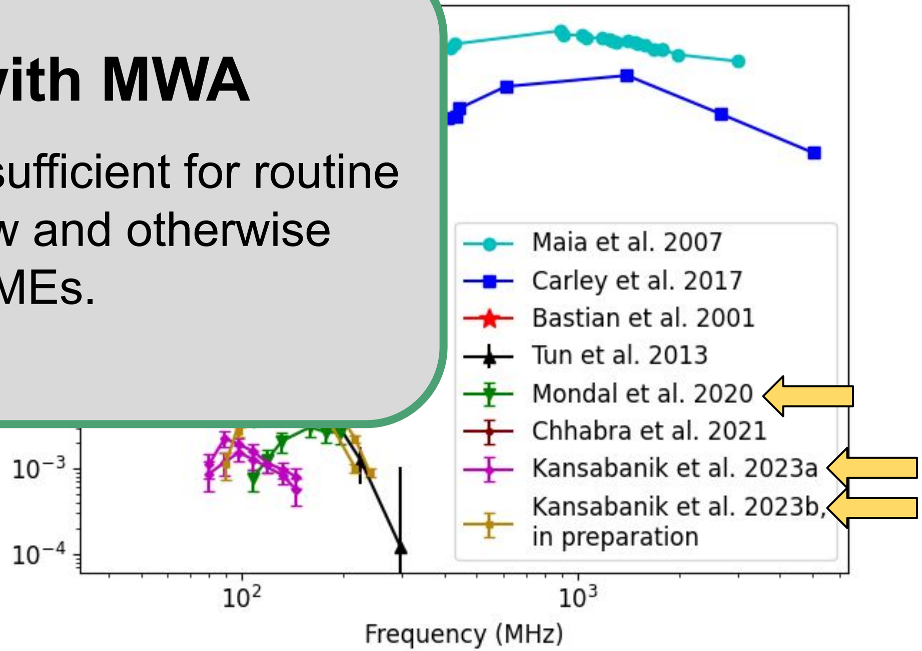
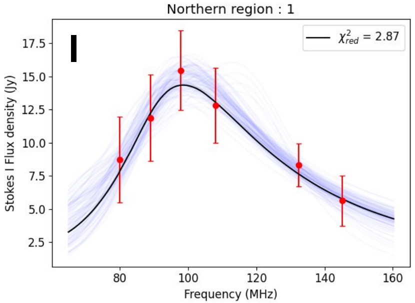
CME GS with MWA

Imaging quality sufficient for routine detection for slow and otherwise unremarkable CMEs.



Advantages of Using Stokes V Spectra

Stokes I only modeling :



Kansabanik et al. 2023a

Advantages of Using Stokes V Spectra

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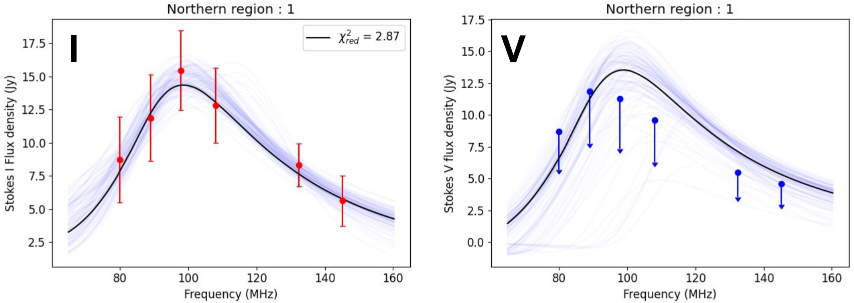

Kansabanik et al. 2023a

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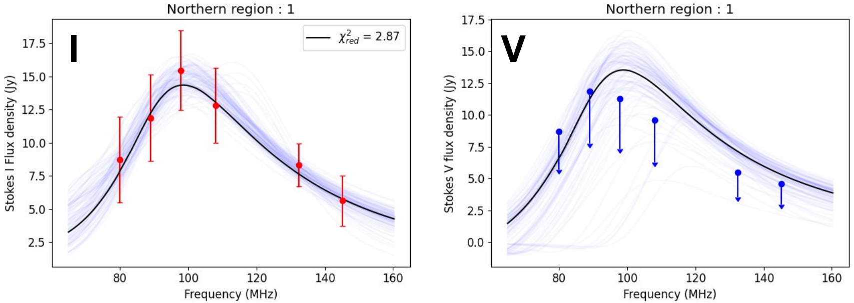
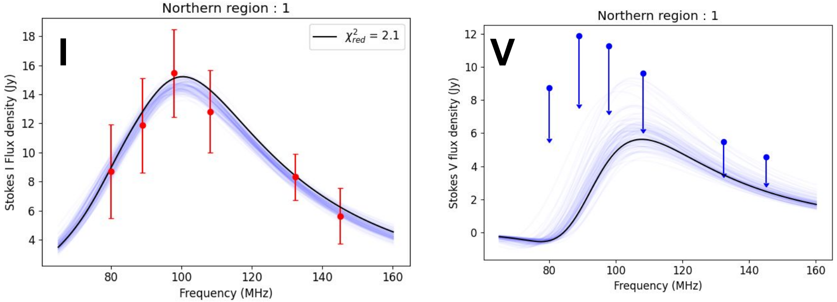


Stokes I and V joint modeling :



Kansabanik et al. 2023a

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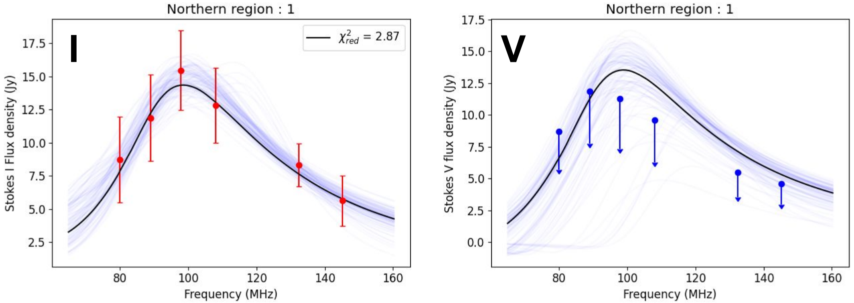

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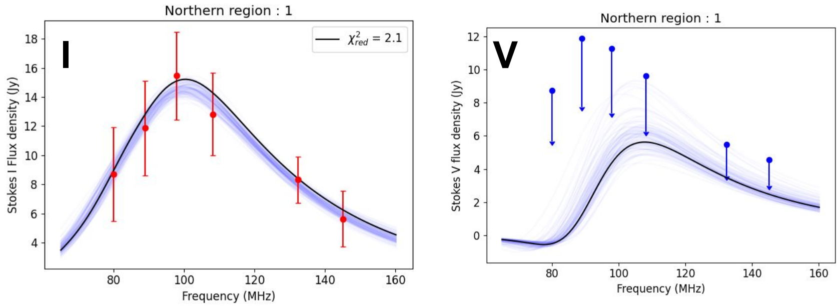
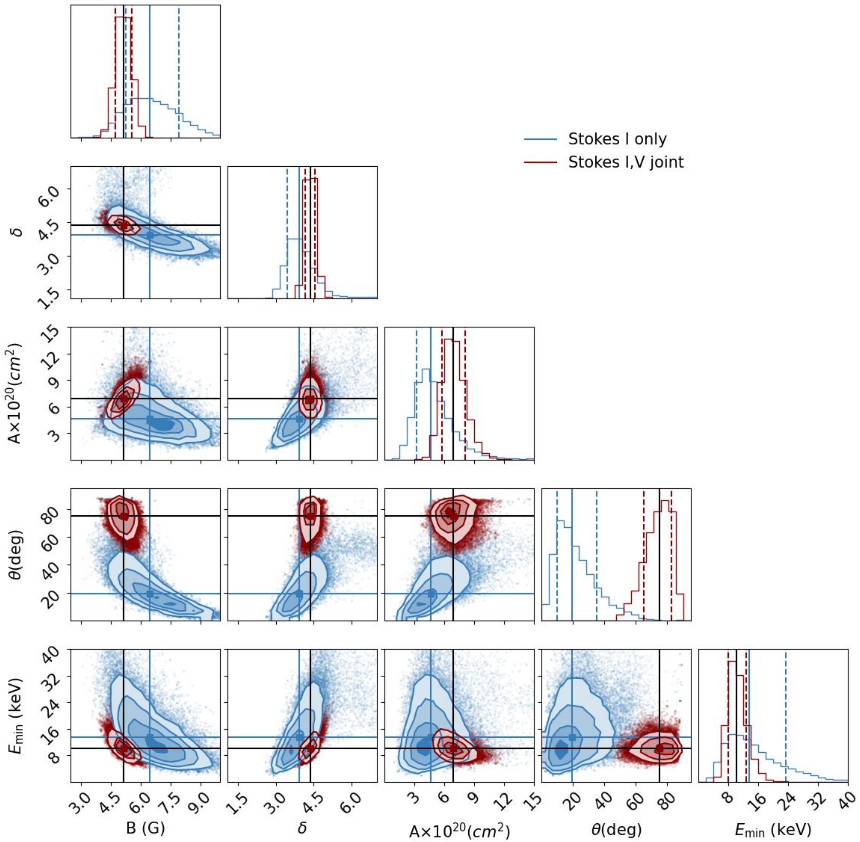
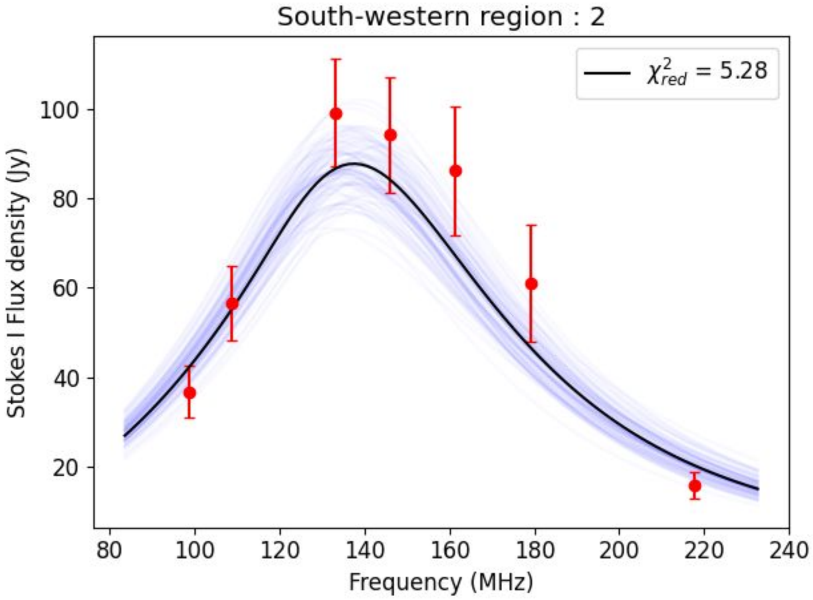
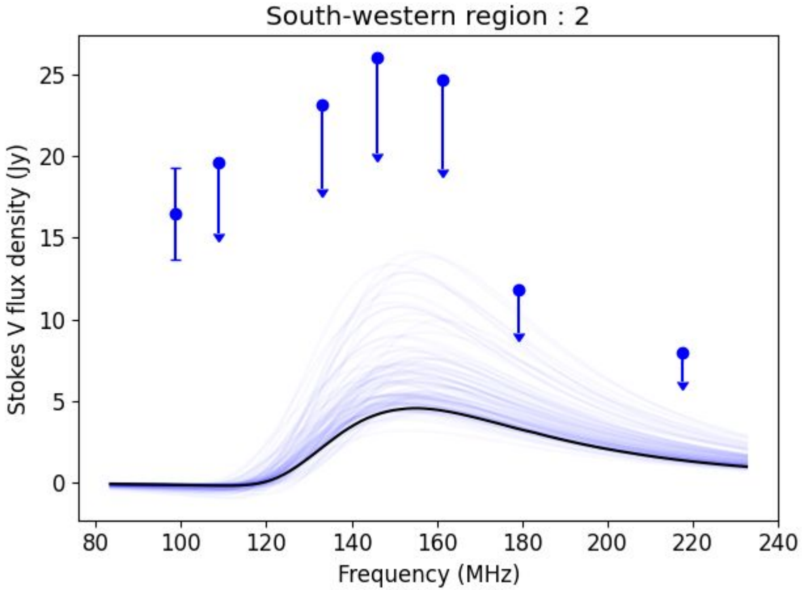




Kansabanik et al. 2023a

First detection of CME GS Stokes V



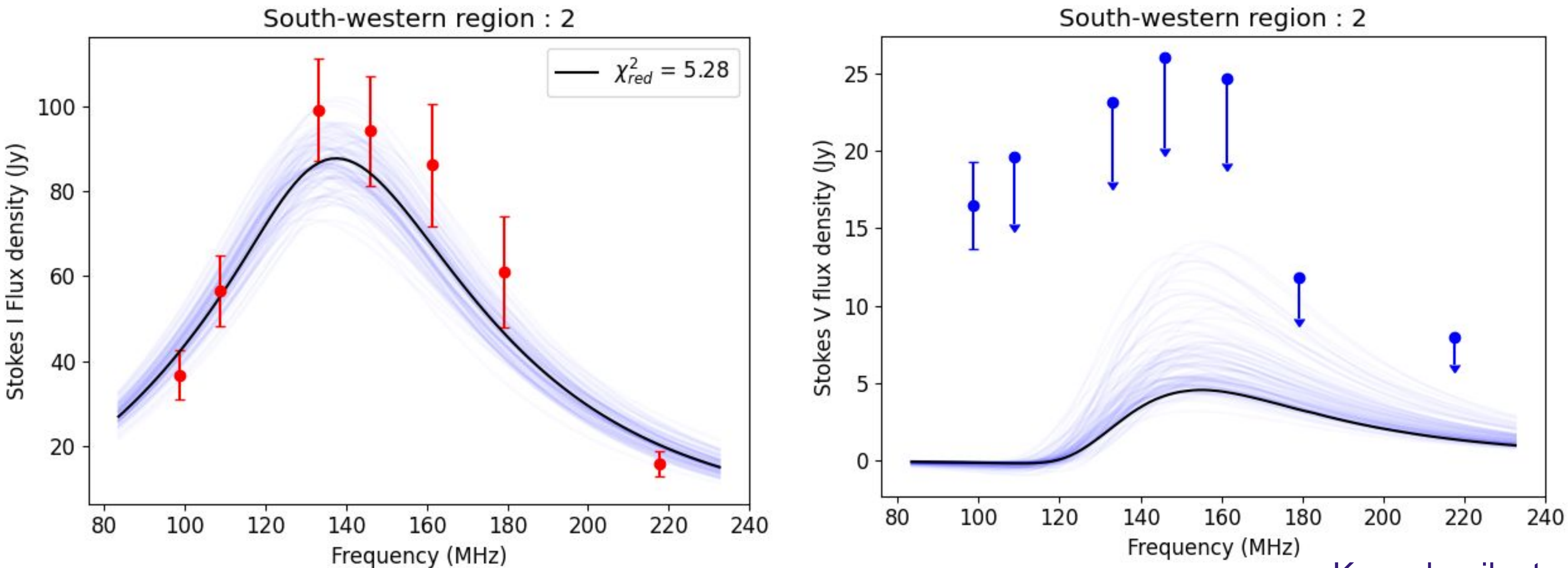


Kansabanik et al. 2023b

First detection of CME GS Stokes V

Prompting us to question model assumptions

- Homogeneous distribution along the LoS
- Isotropic pitch-angle distribution of electrons



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Waves and Quasi-Periodic-Pulsations in Weak Active Solar Emissions

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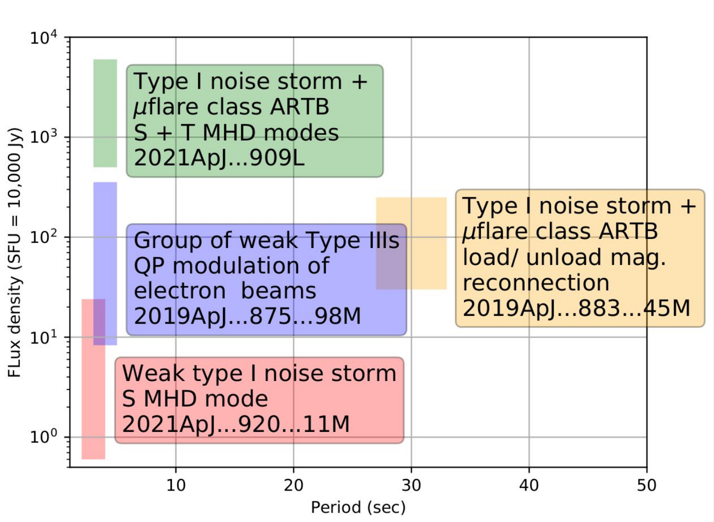
2 Rosseland Centre for Solar Physics, University of Oslo, Norway

Motivation

- Quasi Periodic Pulsations (QPPs) - common feature of flaring energy release; Observed primarily at X-rays, EUV and high radio freq.
- Spatially resolved observations – numerous at higher frequencies, rare at radio wavelengths
- New generation instruments like the Murchison Widefield Array (MWA) now make it possible
- Present a few examples illustrating the new insights obtained about the nature of coronal magnetic features at large coronal heights

Radio QPPs

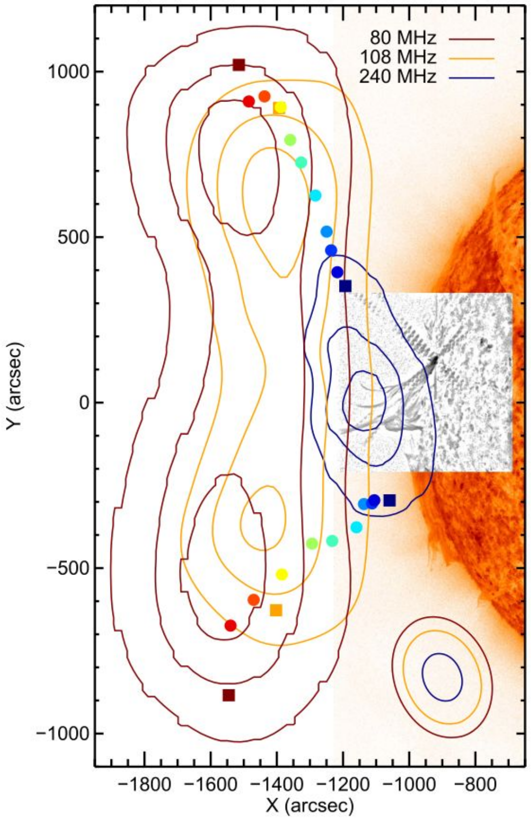


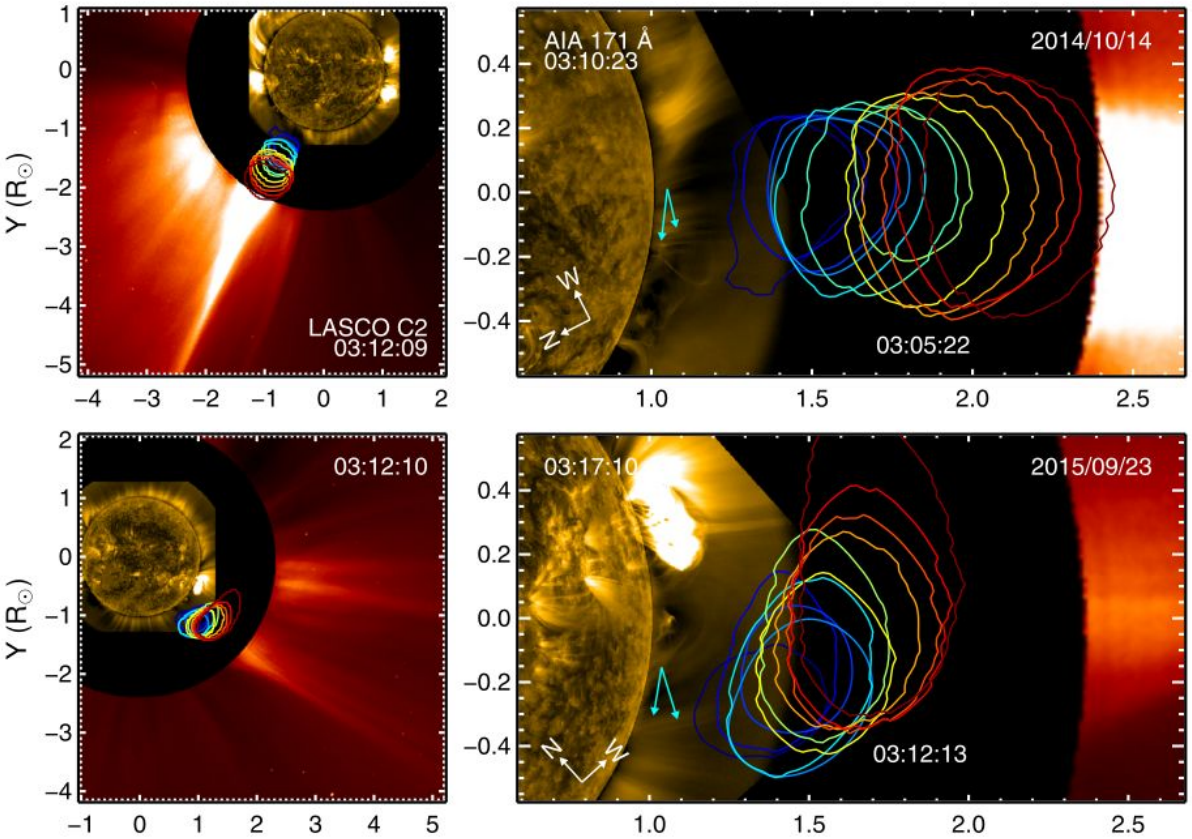
Phase space covered by observations in the period-flux density plane
S/ T – Sausage/ Torsional MHD modes

Conclusion

- Spectroscopic snapshot imaging capability - new tool for probing QPPs in the radio regime.
- Widespread presence across wide range of flux densities
- Energetically weak - “test particles”, probe of the features of the system without altering its properties
- Robust detection of sausage and torsional MHD modes + much more

Type IIIs - splitting & estimating coronal densities

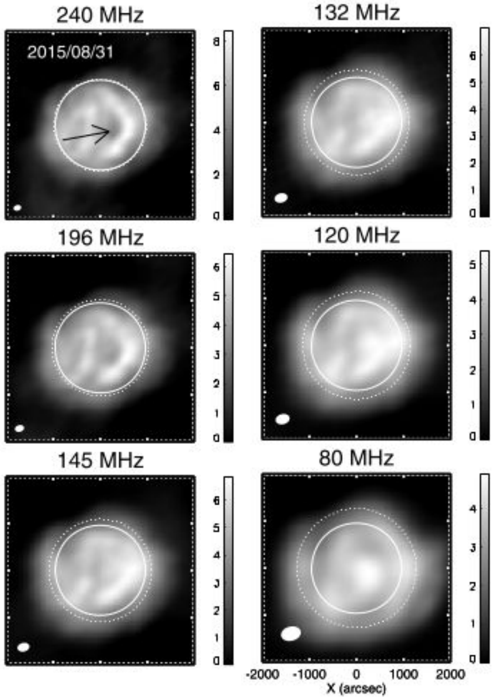


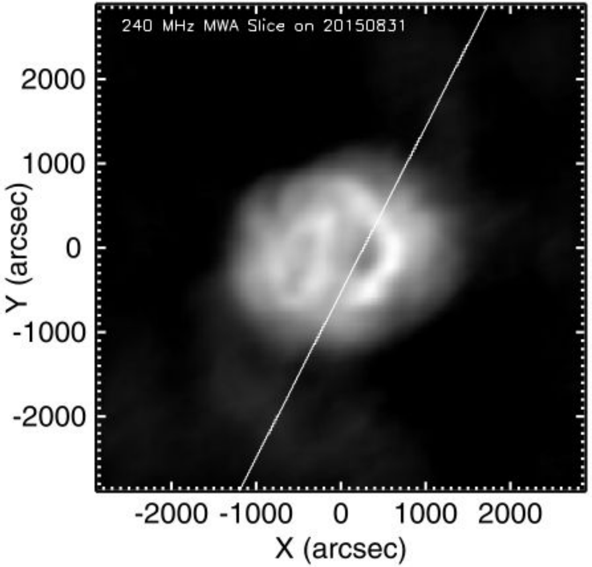


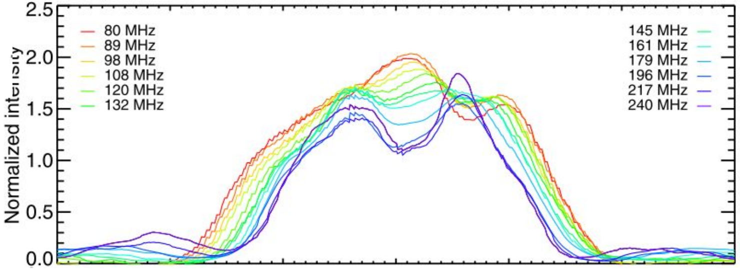
McCauley et al. 2017

McCauley et al. 2018

Coronal Holes (CH)





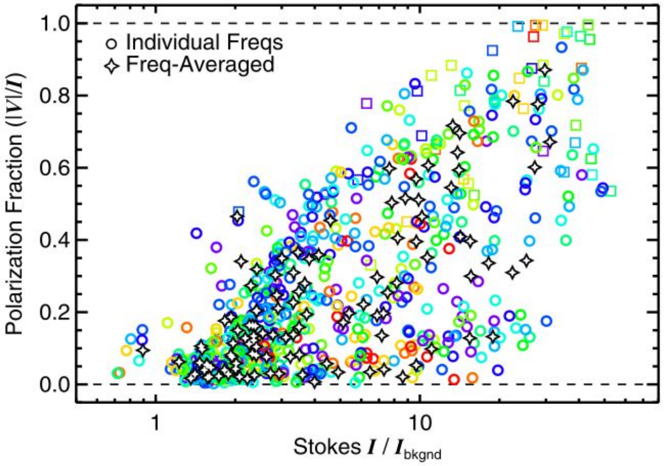


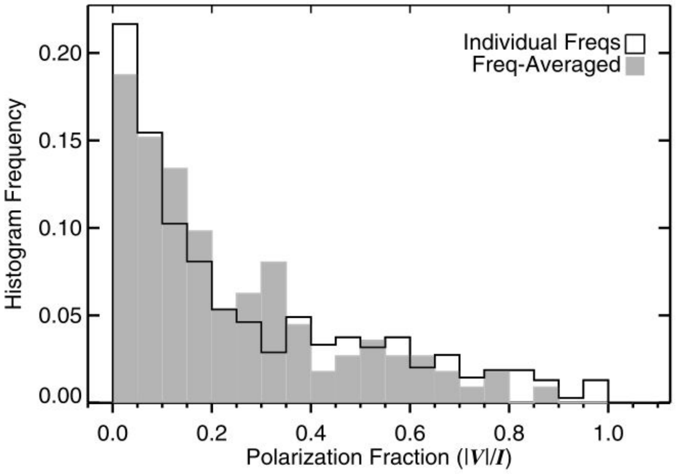
CH - Regions of low density wrt ambient medium

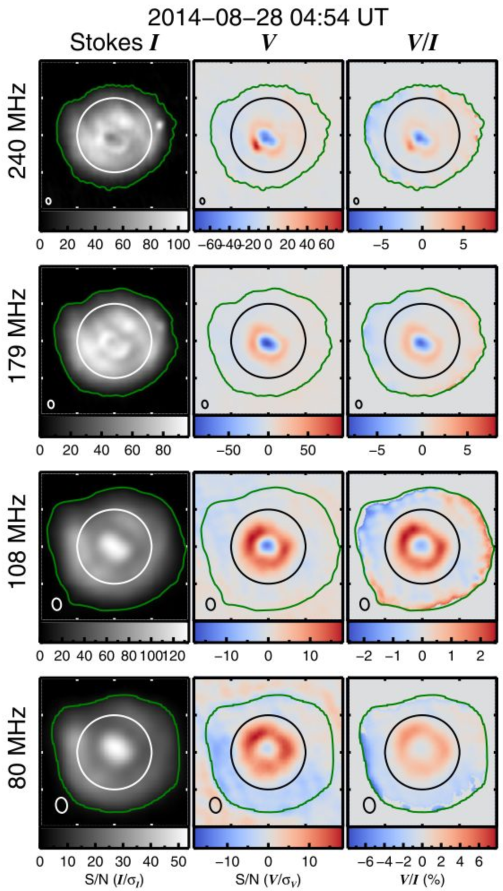
- Sometimes transition from being darker at high frequencies (low heights) to being brighter at lower frequencies
- Explained in terms of refraction of radio waves from neighbouring regions into in the CH regions

Mozibur et al. 2019

The first polarimetric study - survey of Stokes V







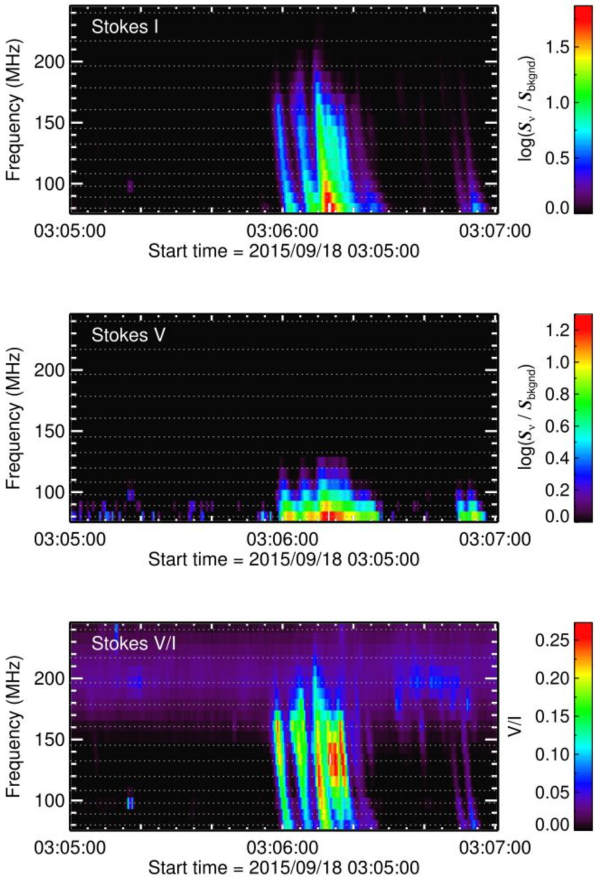
Found ~700 compact Stokes V sources in ~100 observing runs near solar maximum, but during quiet periods

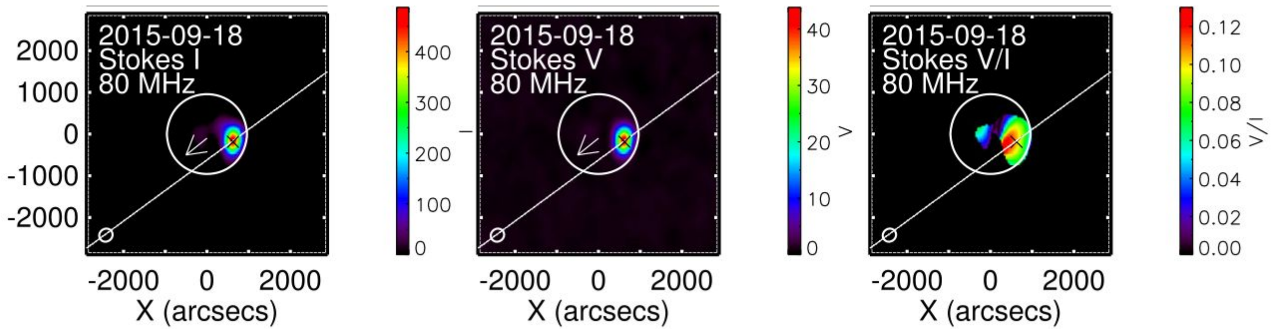
Plasma emission from active regions (noise storms - continuum of type I bursts)

Bulls-eye structure in Stokes V in low-latitude coronal holes

McCauley et al. 2019

Polarimetric imaging of type IIIs





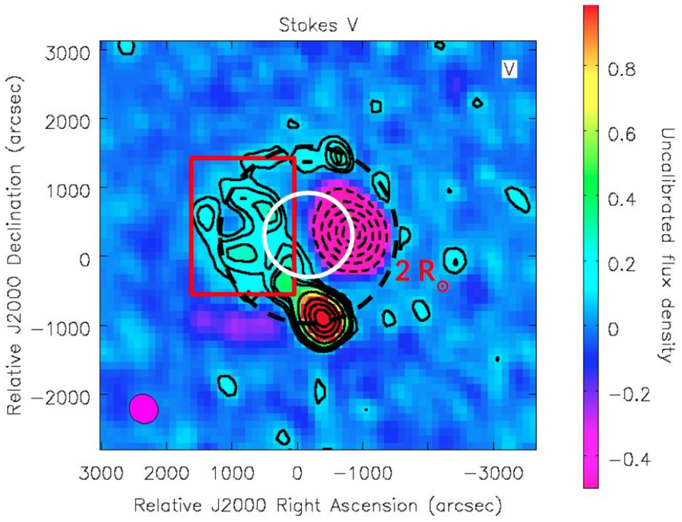
Detailed study examining many different aspects of type IIIs

- Polarisation fraction as a function of bursts position (higher pol close to centre and lower close to the limb)
- Correlation between source motion and degree of polarisation
- Variations in fractional polarisation as a function of time
- …

Mozibur et al. 2020

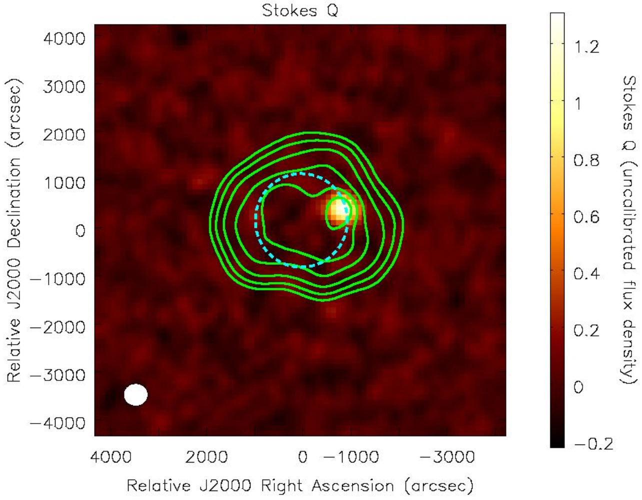
Recent Discoveries and Results from polarimetric imaging

First detection of low-level (<1%) circular polarization from quiet Sun thermal emission



- Average Stokes V is 0.5% (residual leakage < 0.07%).
- Can provide B_{LoS} at mid and higher coronal heights, $\langle B_{LOS} \rangle \approx 100$ mG

First ever robust imaging detection of linearly polarized emission in a variety of active solar radio emissions (types I, II and III)



- Expected no linear polarization from meter-wavelength coronal radio emission.
- Recent simultaneous MWA and GMRT observation confirm this (work in progress)

MWA solar imaging status

To our credit:

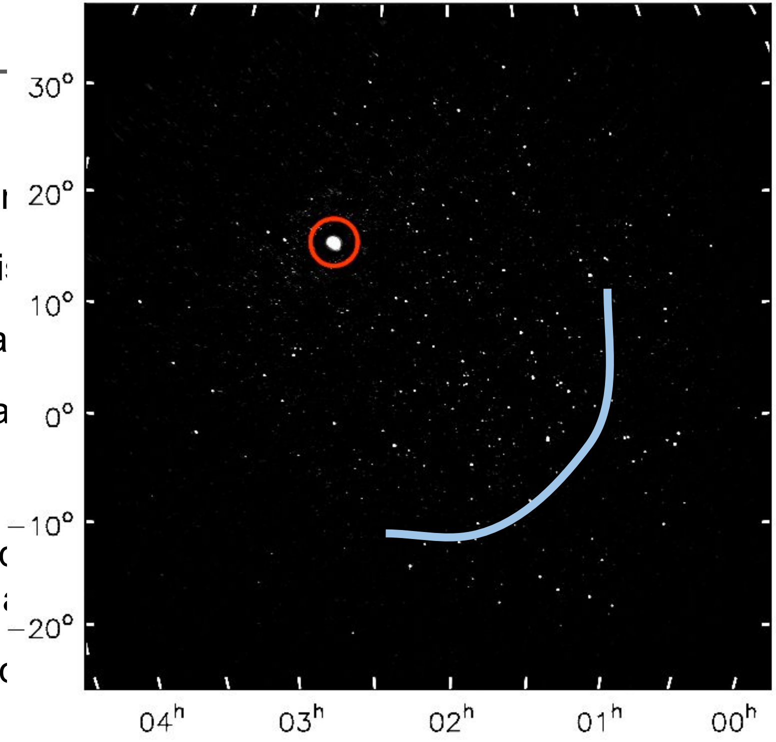
- The highest imaging dynamic range at metrewaves
- The highest polarimetric purity
- Perhaps the best flux density calibration

- Discovery of the weakest (mSFU level) nonthermal emissions yet
  - Weak Impulsive Narrowband Quiet Sun emissions (WINQSEs)
- CME GS emissions
  - Detection at the largest heliographic heights
  - First detection of Stokes V from CME GS emission
- First detection of Stokes V from the Quiet Sun
- Robust imaging detection of linearly polarised emission in many active solar emissions

Future plans

- ~1% solar data imaged yet. Obtain resources for imaging an order of magnitude larger fraction
  - Access to the proto Proto-SKA-Regional-Centre is being set up at NCRA (240 cores, 1 PB)
  - 3 different proposals in 2 countries currently in varying stages of evaluation/ submission
    - ~20-30% of the carefully selected parts of archived data
- Making solar radio imaging mainstream
  - Dramatically reduce the potential barrier by providing an easy to drive and robust pipeline for producing state-of-the-art spectro-polarimetric snapshot images
- 2 thesis + a smaller term project currently underway (polarimetry, larger scale explorations of archival data)
- Space weather - detecting and modeling the FR due to CME plasma to arrive vector B of the CME
- Plenty of good stuff to look forward to both in the short and the longer term…

Future plans



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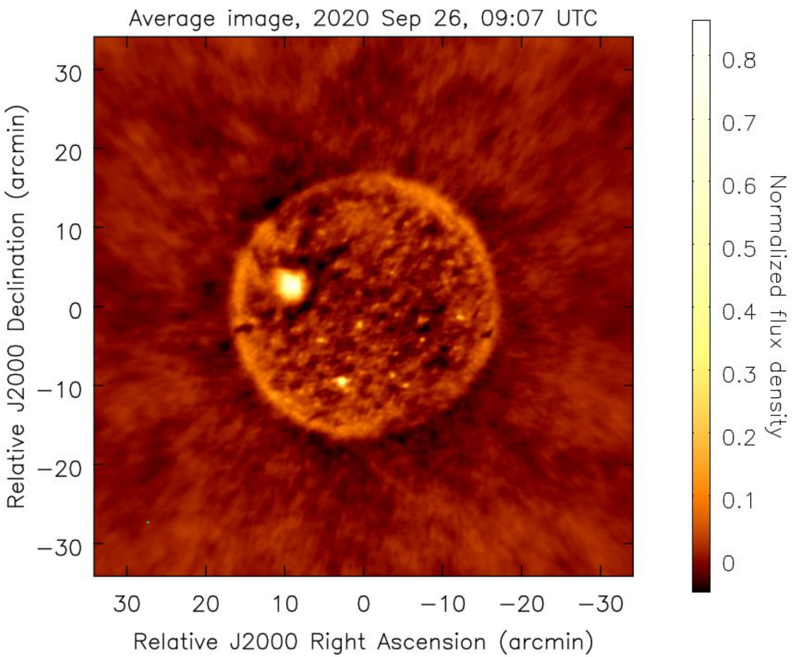
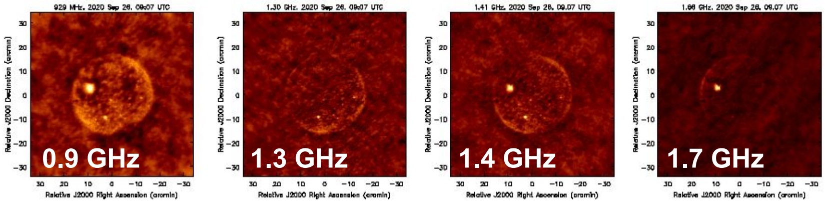
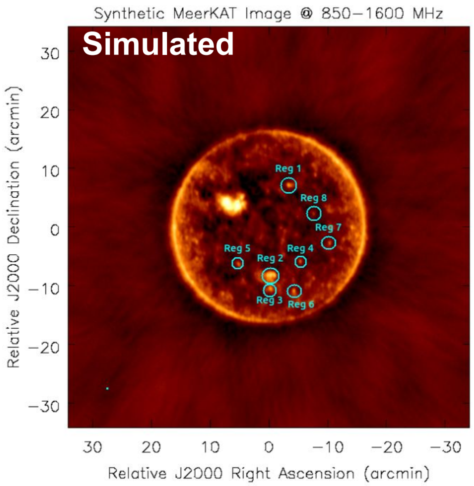
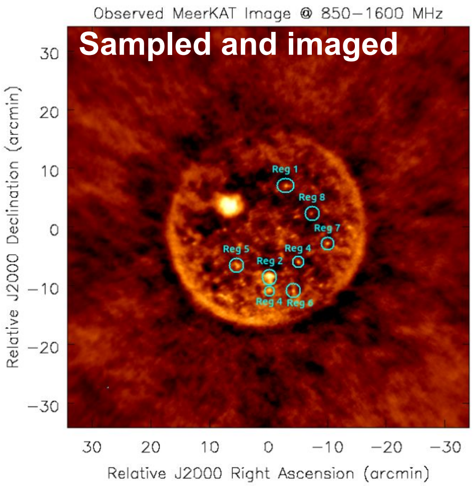
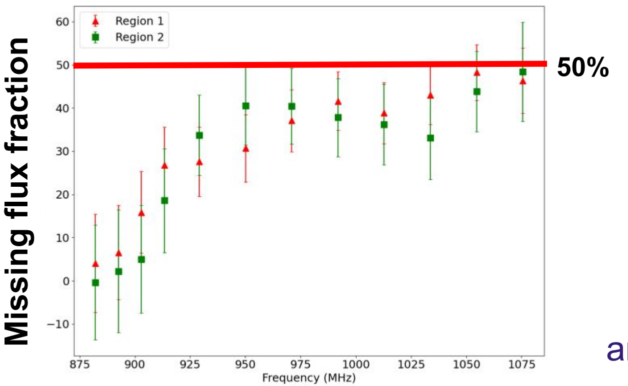
Explore higher frequencies - MeerKAT











Kansabanik et al. 2023,
arXiv:2307.01895, in prep

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