NCRA • TIFR

MWA
MURCHISON
WIDEFIELD
ARRAY

Of Ripples and Roars : Progress and Promise in Low Frequency Radio Solar Physics

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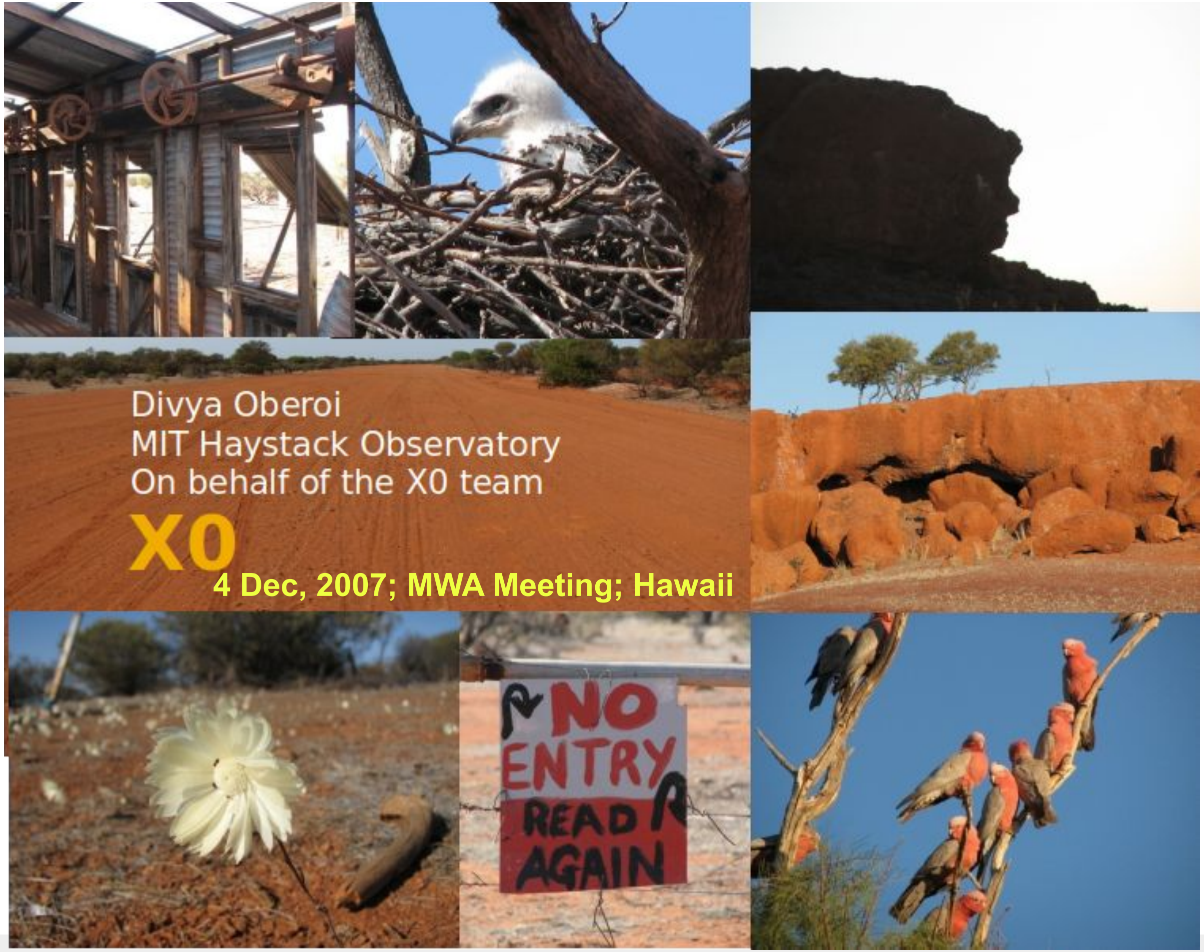
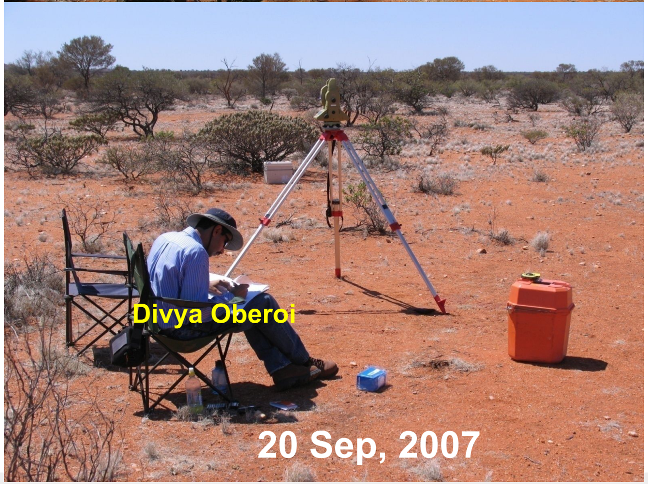
Iver Cairns, John Morgan, Colin Lonsdale,
Devojyoti Kansabanik, Surajit Mondal,
Rohit Sharma, Atul Mohan, Soham Dey, Puja Majee, Deepan Patra,
Akshay Suresh, Shilpi Bhunia, Eoin Carley,
Patrick McCauley, Mozibur Rahman

Radio Stars 2024; 18 Apr 2024

Early days…


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


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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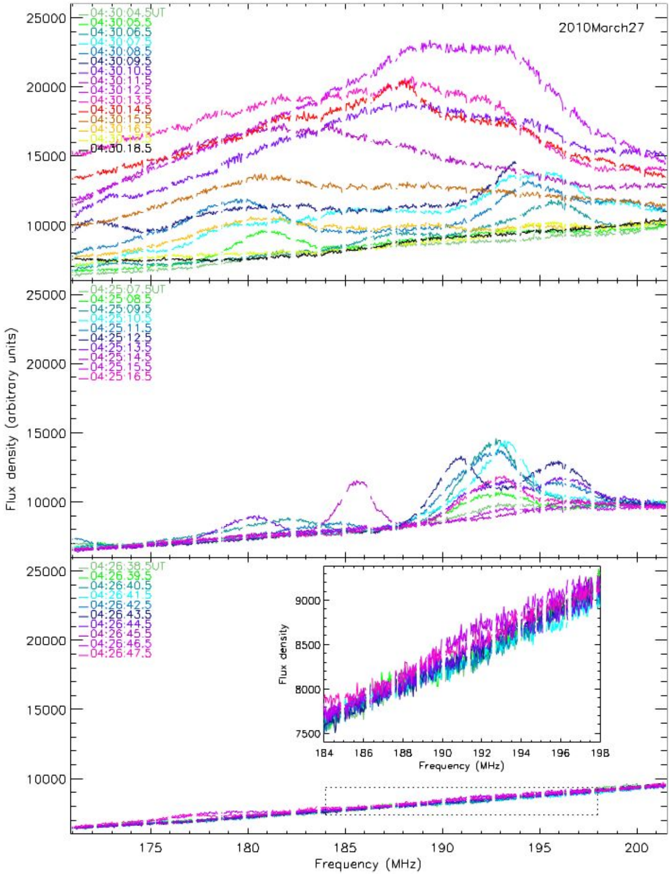
X13 - March 2010

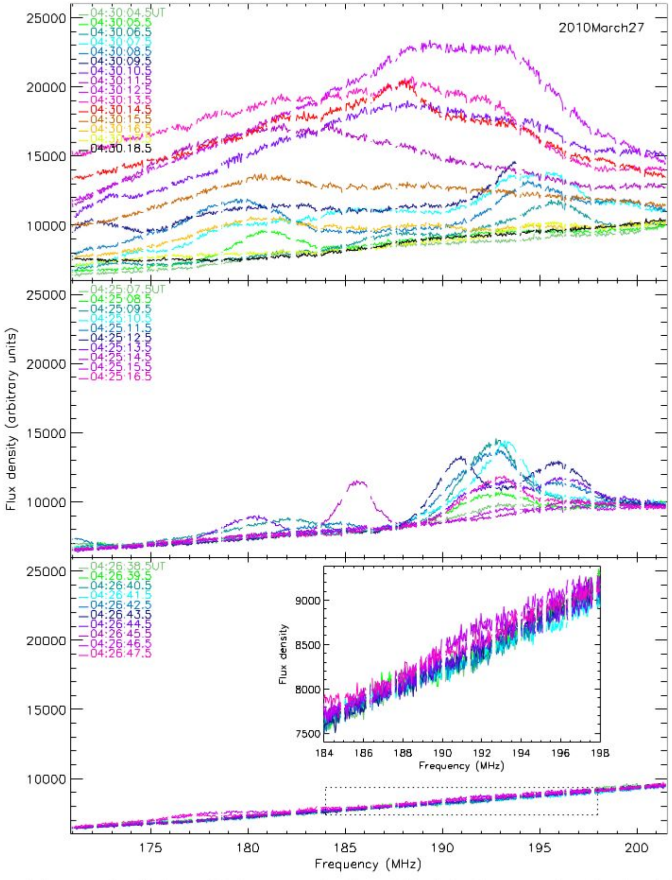
Dave Emrich (Curtin)
Chris Williams (MIT)
Prabu, Harish (RRI)

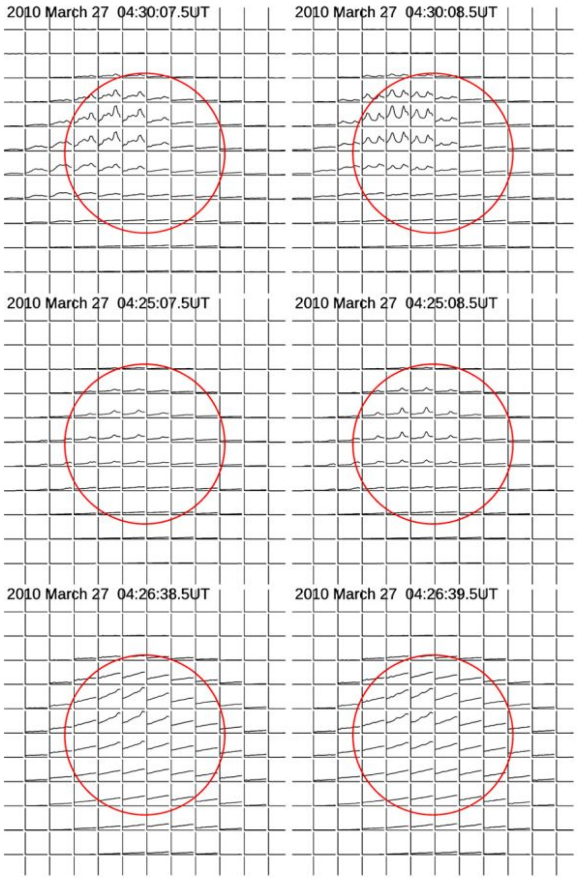
The First 32T Publication



Oberoi et al., 2011, ApJL

The First 32T Publication

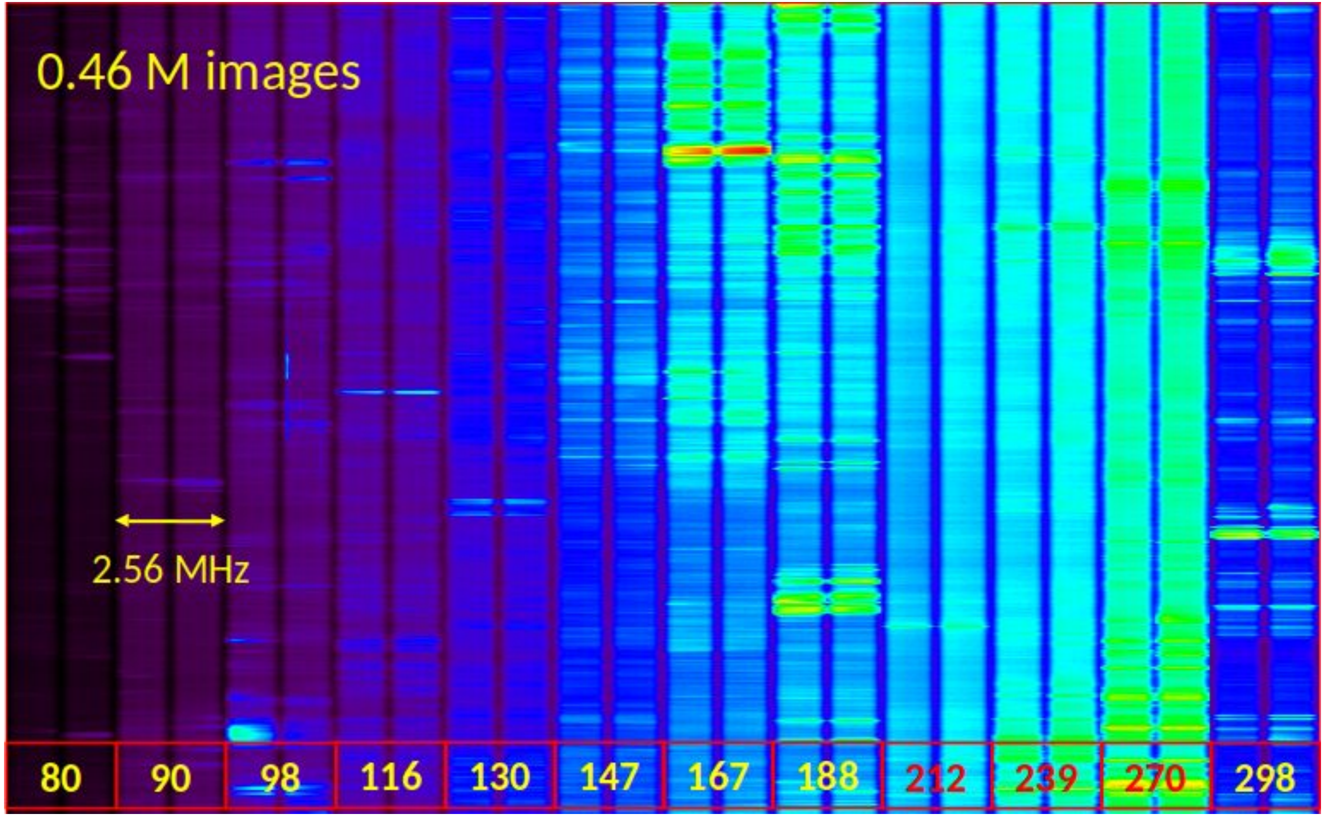




Oberoi et al., 2011, ApJL

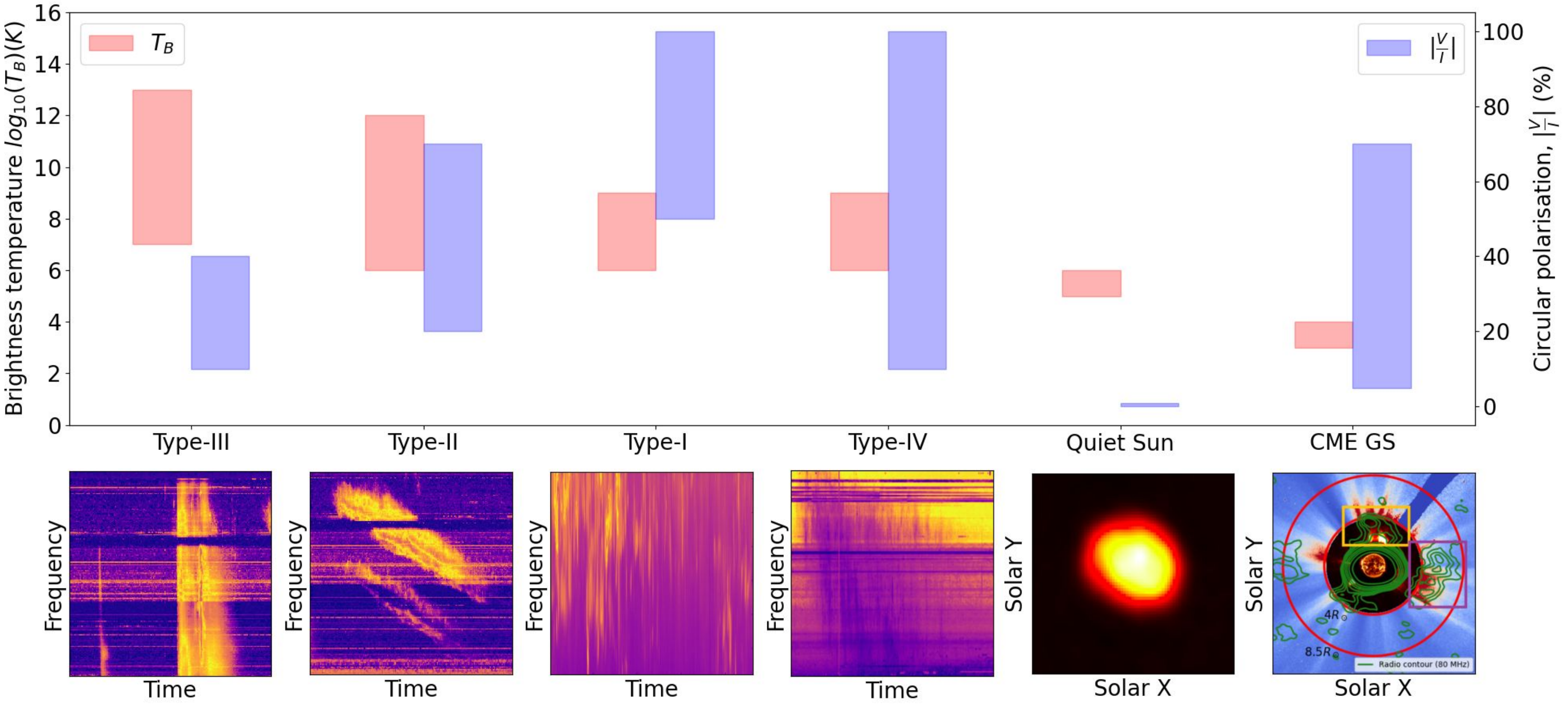
Observational Challenges of Solar Radio Imaging

Time
(0.5 s
5 min)



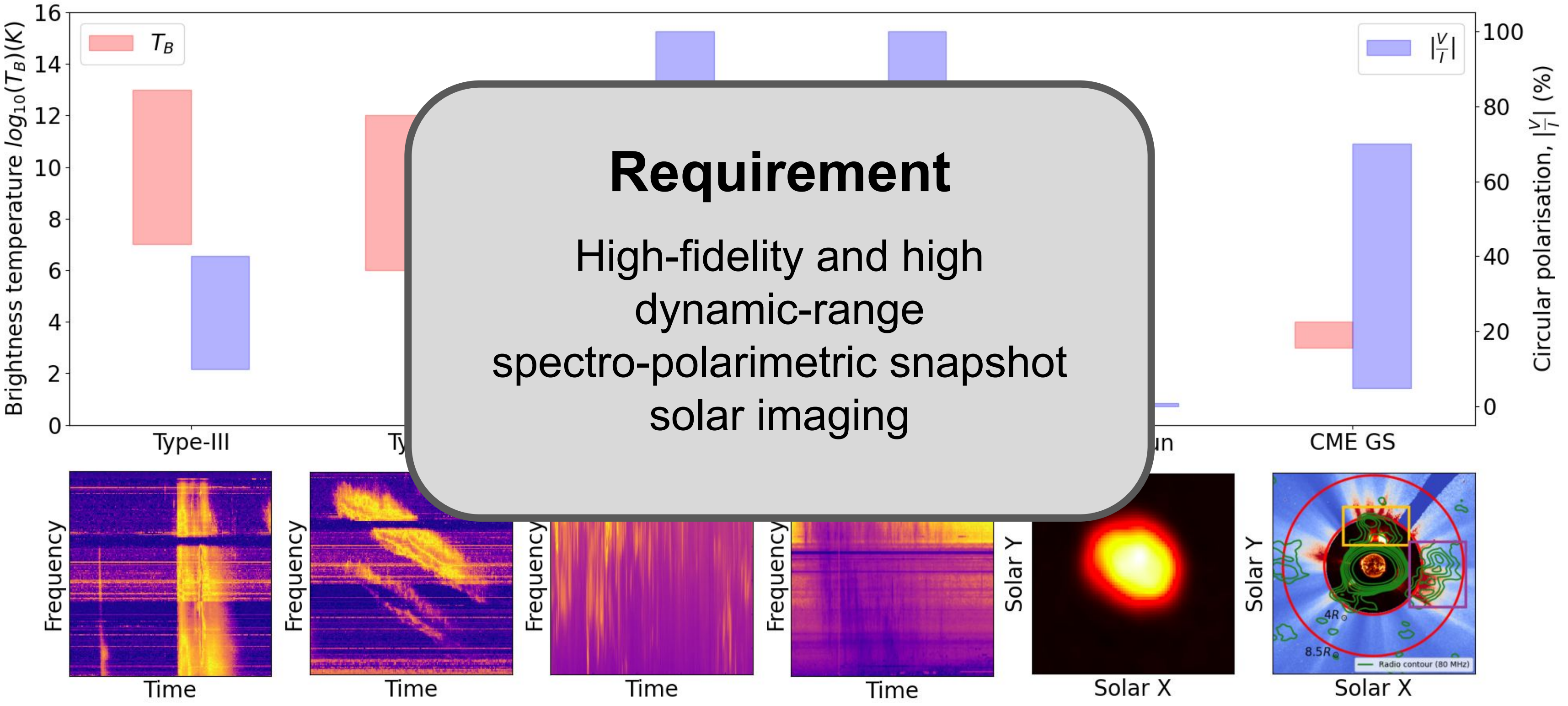
Frequency (MHz)
12 log spaced groups of 2.56 MHz each

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

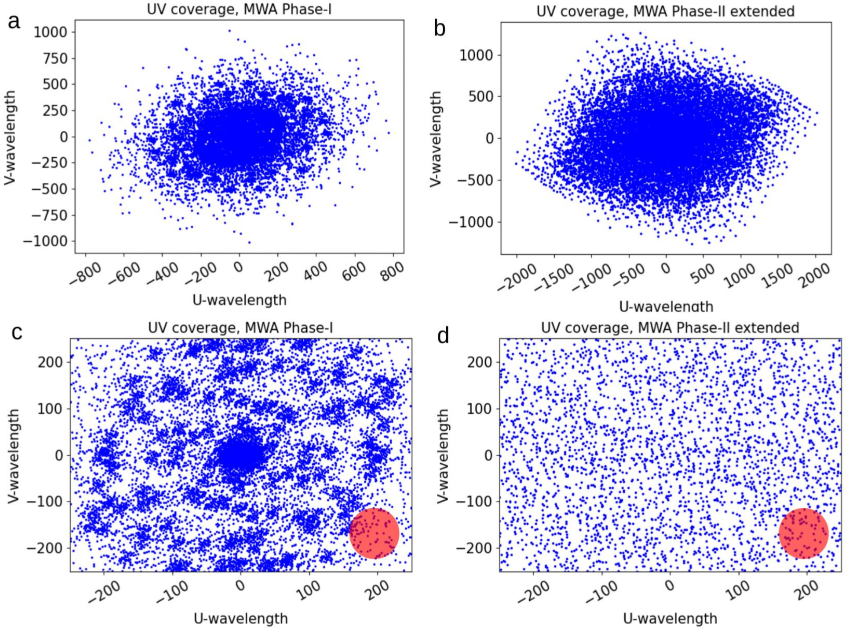
Kansabanik 2022, Solar Physics, 297, 122

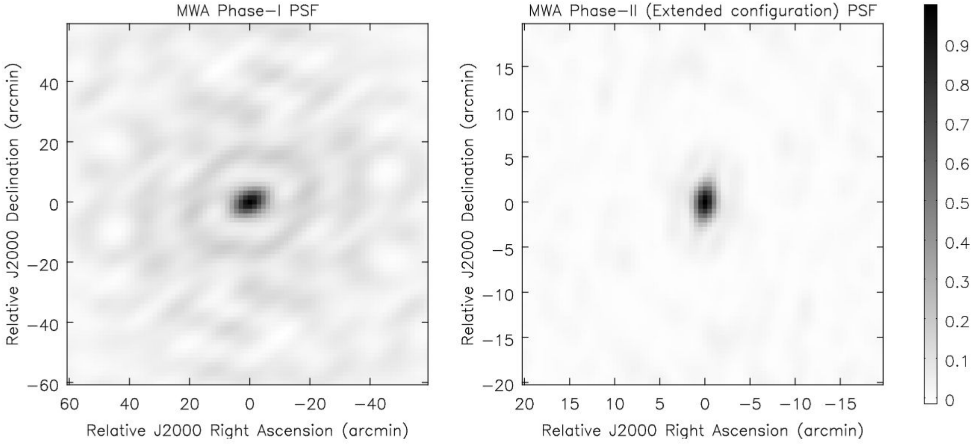
Solar Radio Studies: The Road Well Travelled …mostly…

- Most studies have relied on dynamic spectra (Sun-as-a-star)
- Few dedicated solar imaging instruments
  - Fewer have come close to meeting the needs of solar radio science
- Emphasis has largely been on:
  - Active emissions - bursts of all kinds
  - Big and bright bursts which can dominate the solar emission
  - Polarimetry has remained difficult to do… and hard to interpret…
- Coronal active radio emissions are hard to study in optical/ EUV/ X-rays
- Poor angular resolution and large difference in coronal height of radio and high energy sources, compounded by scattering ⇒ limited spatial correlations
- BUT, there have been exceptions…

What has changed? - Array design

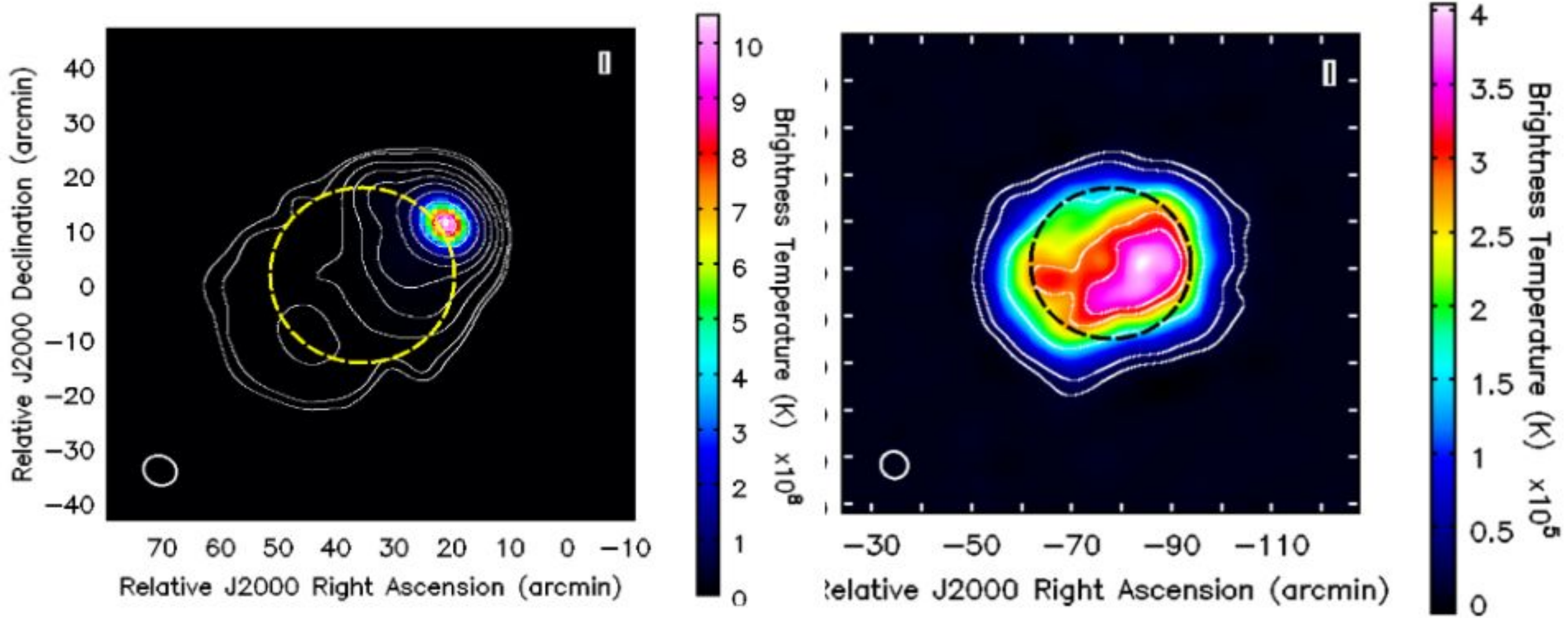
From synthesis imaging to snapshot imaging - Murchison Widefield Array (MWA)





Kansabanik 2022, Solar Physics, 297, 122

What has changed? - Imaging pipelines (AIRCARS)

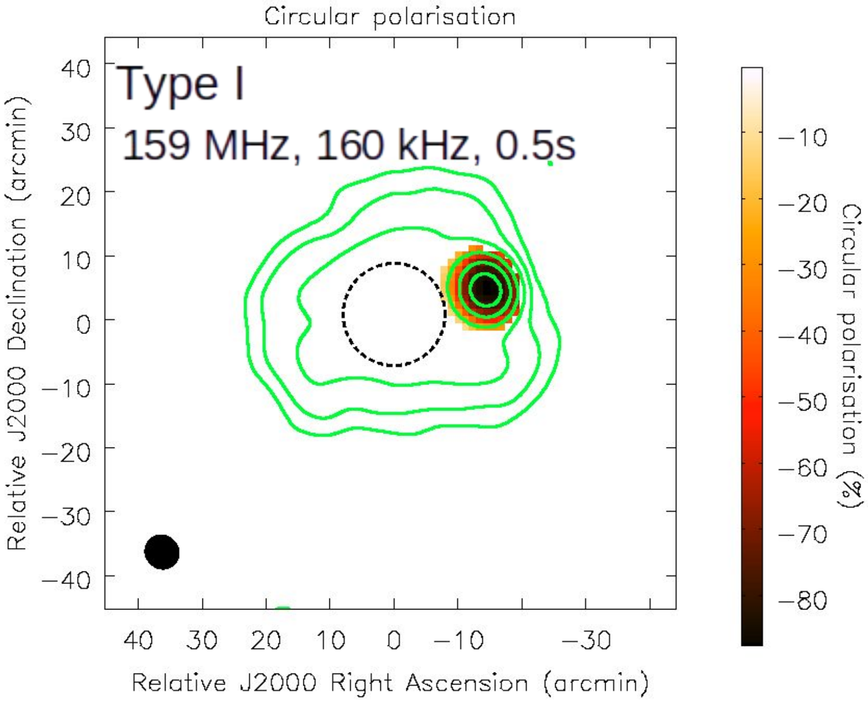


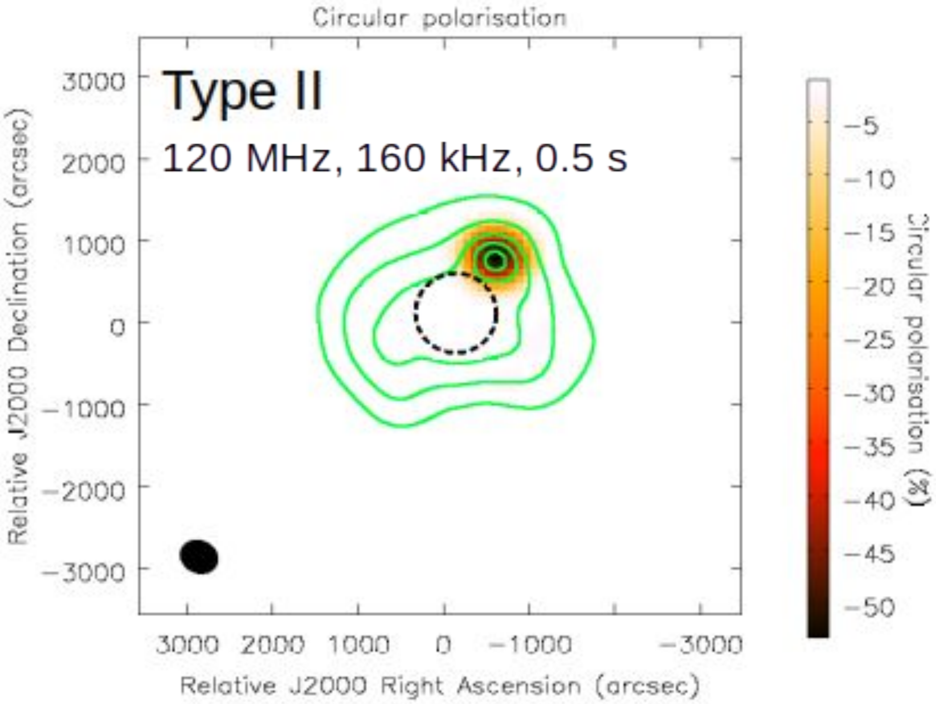
Contour levels: (0.0007, 0.002, 0.02, 0.2,0.4,0.8) X 10^9 K
144.32 MHz; 40 kHz; 0.5 s
Imaging dynamic range: >10^5

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

What has changed? - Imaging pipelines (P-AIRCARS)





Kansabanik et al., 2022,2023
Kansabanik, 2022

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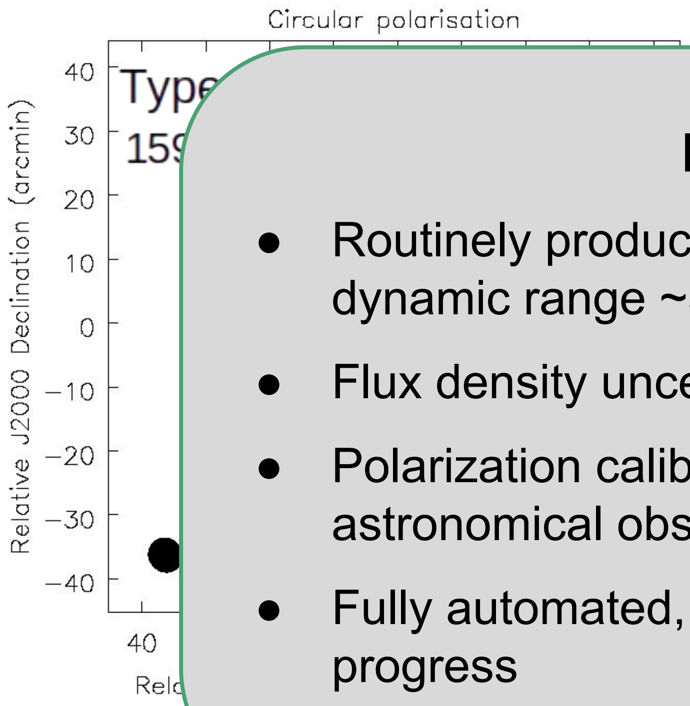
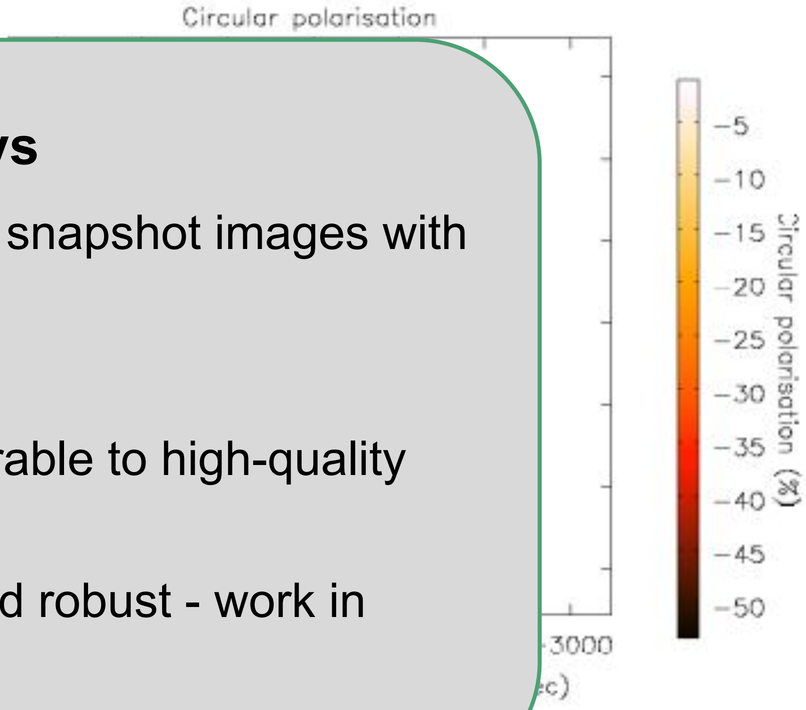


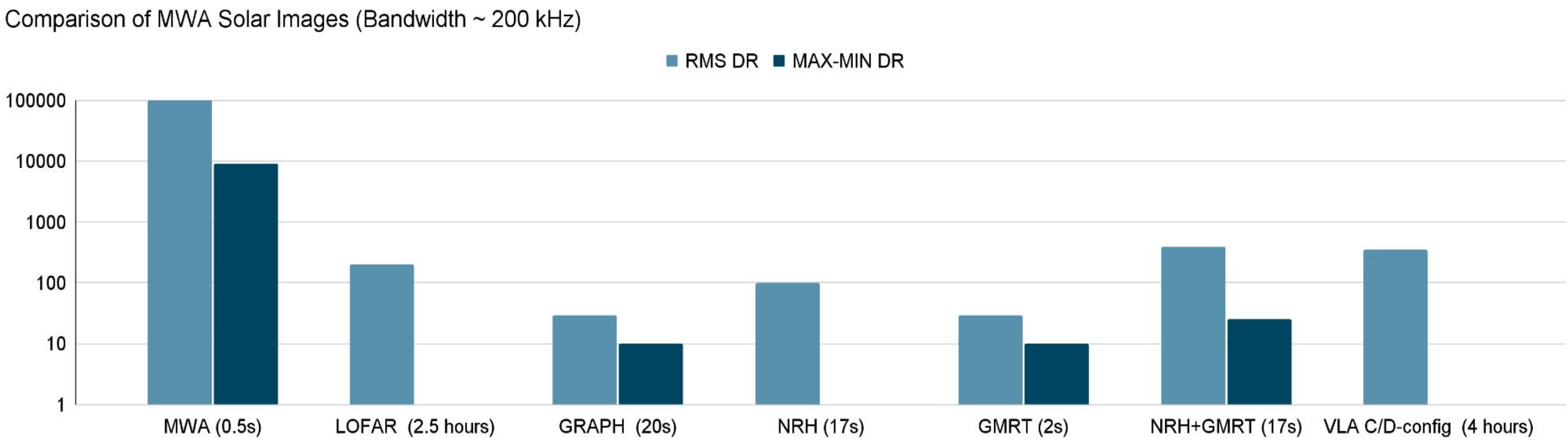
Key Takeaways

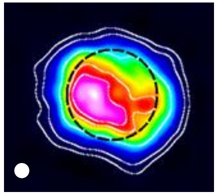
- Routinely produce spectroscopic snapshot images with dynamic range ~300 – 10^5
- Flux density uncertainty is ~10%
- Polarization calibration is comparable to high-quality astronomical observations
- Fully automated, user-friendly and robust - work in progress

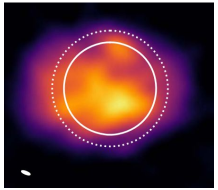


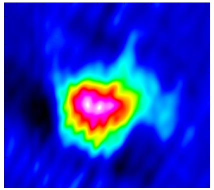
Kansabanik et al., 2022,2023
Kansabanik, 2022

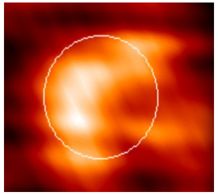
Where are we now? - Imaging dynamic range comparison

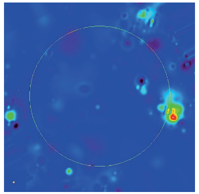


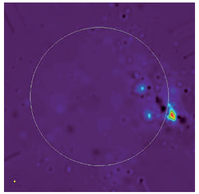

160 kHz


195 kHz


1 MHz


1 MHz


32 MHz


32 MHz

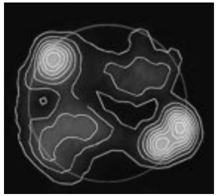

3.27 MHz

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 (Surajit Mondal’s talk later this session)
- Targeted studies of well known solar radio bursts
  - Types I, II, III
- Coronal holes
- Propagation effects
- Polarimetry (next talk by Devojyoti Kansabanik)

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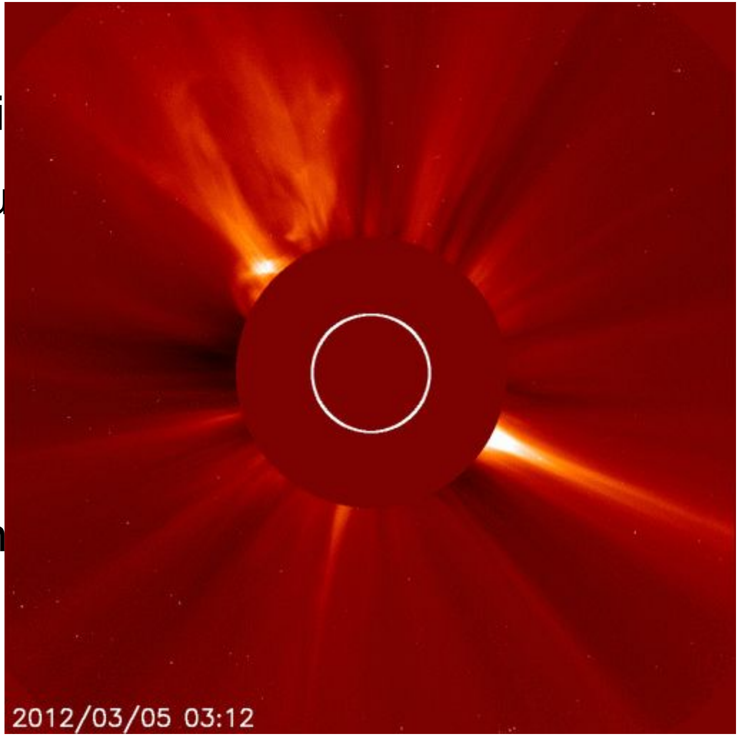

Image credit : SOHO LASCO C2 Coronagraph

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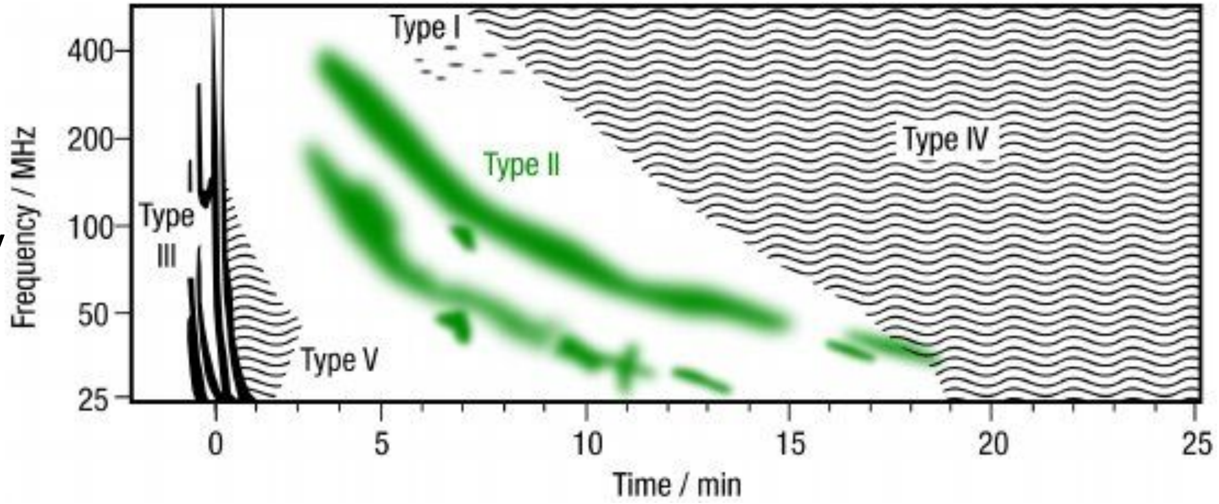
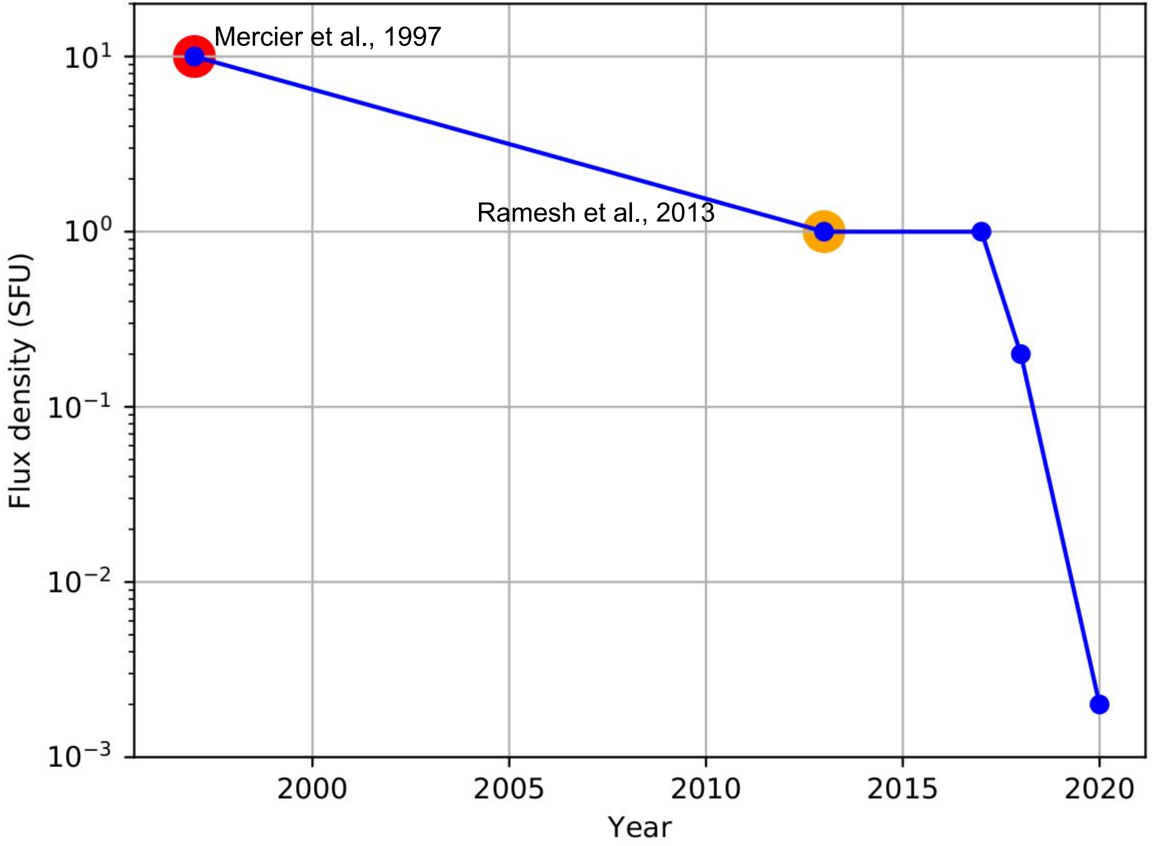


Progressively weaker non-thermal emissions



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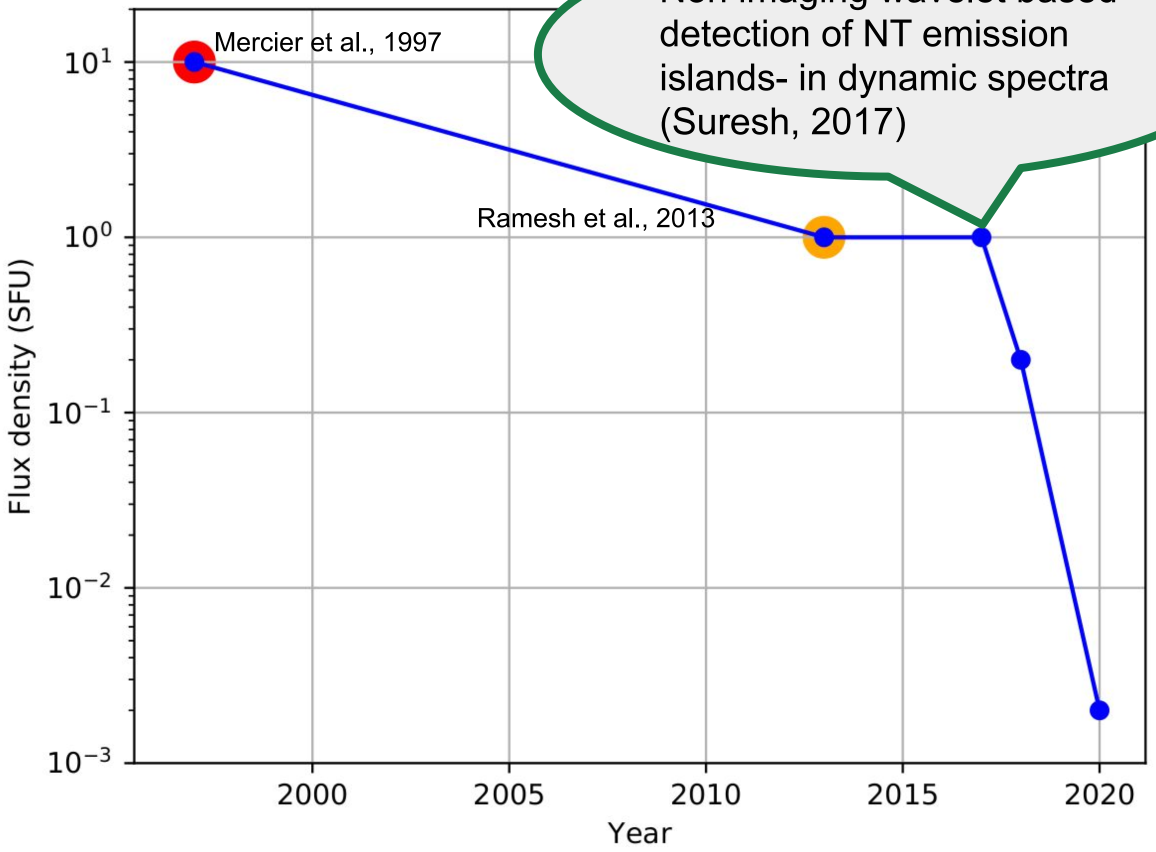
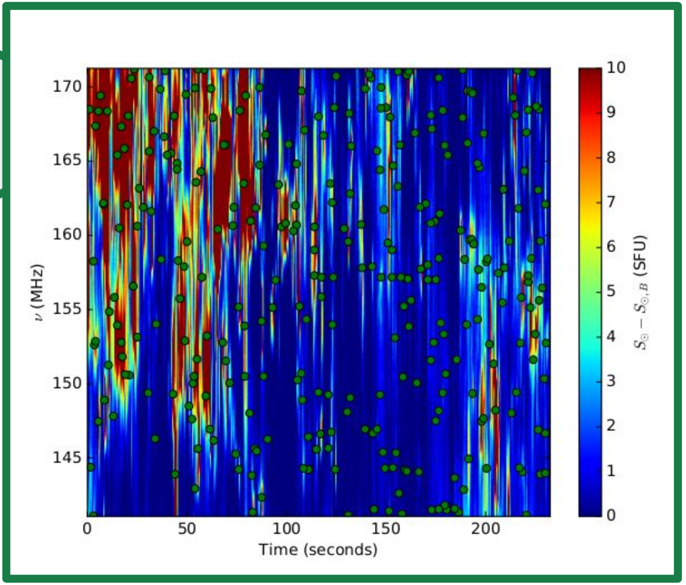
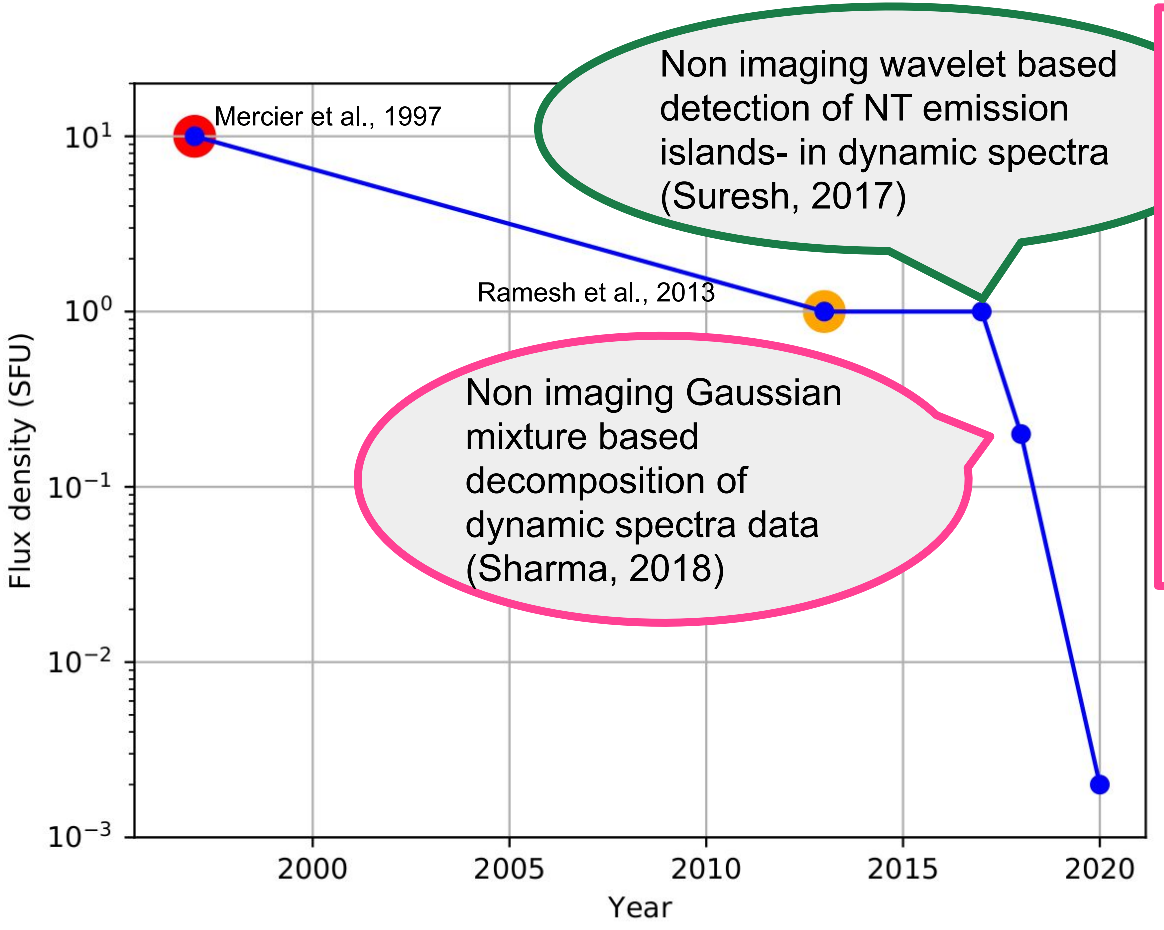
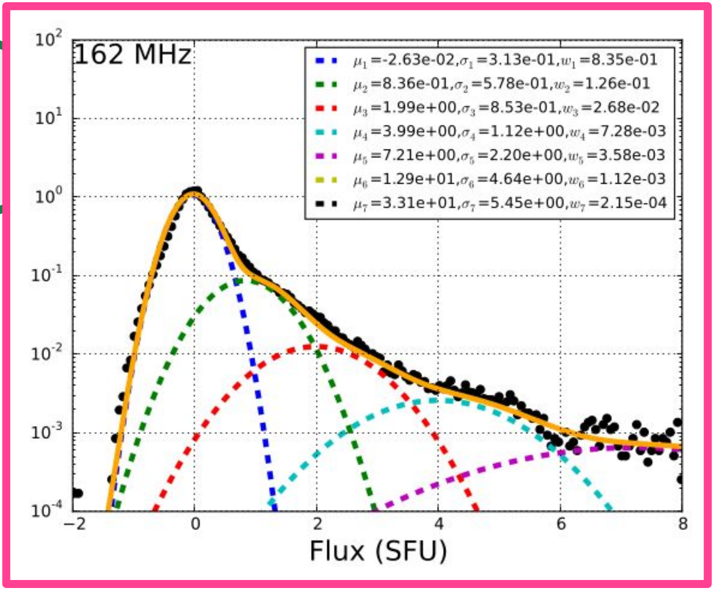


Non imaging wavelet based detection of NT emission islands- in dynamic spectra (Suresh, 2017)

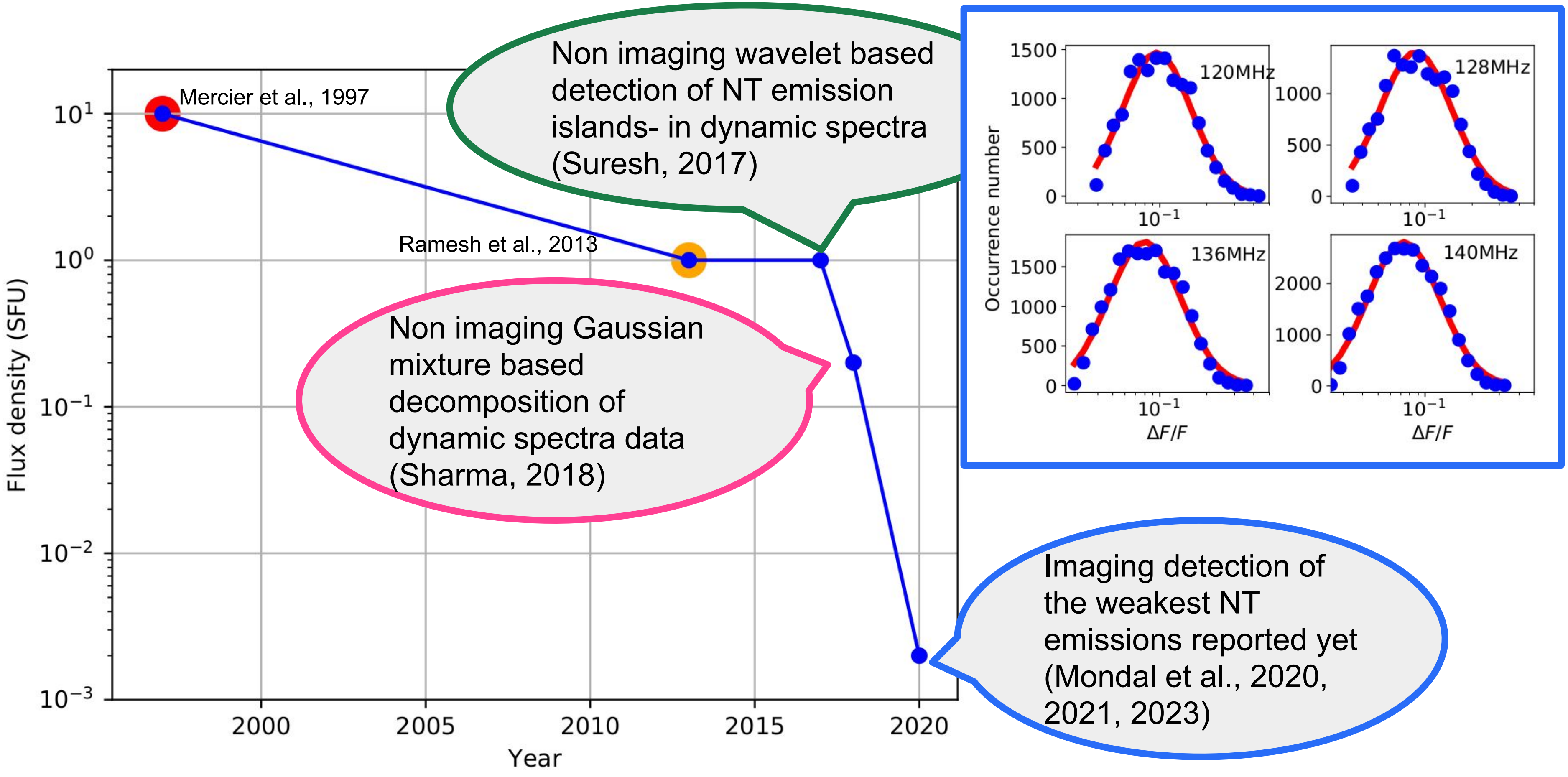


Progressively weaker non-thermal emissions

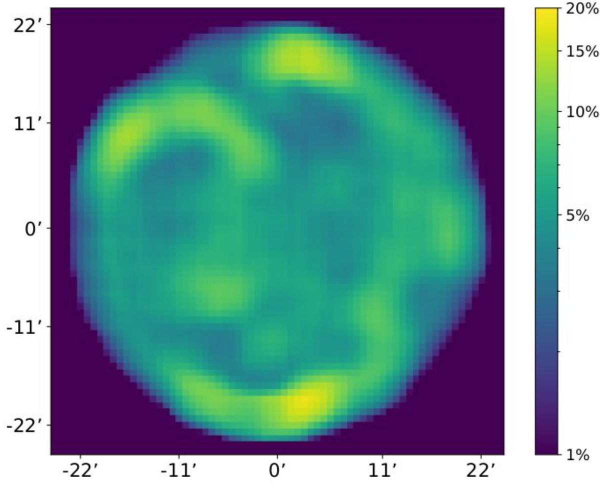


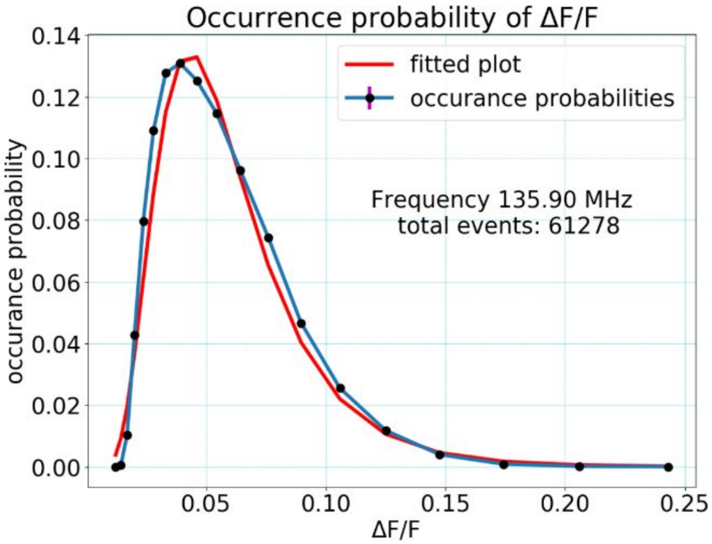


Progressively weaker non-thermal emissions



Weak Impulsive Narrowband Quiet Sun Emissions (WINQSEs)





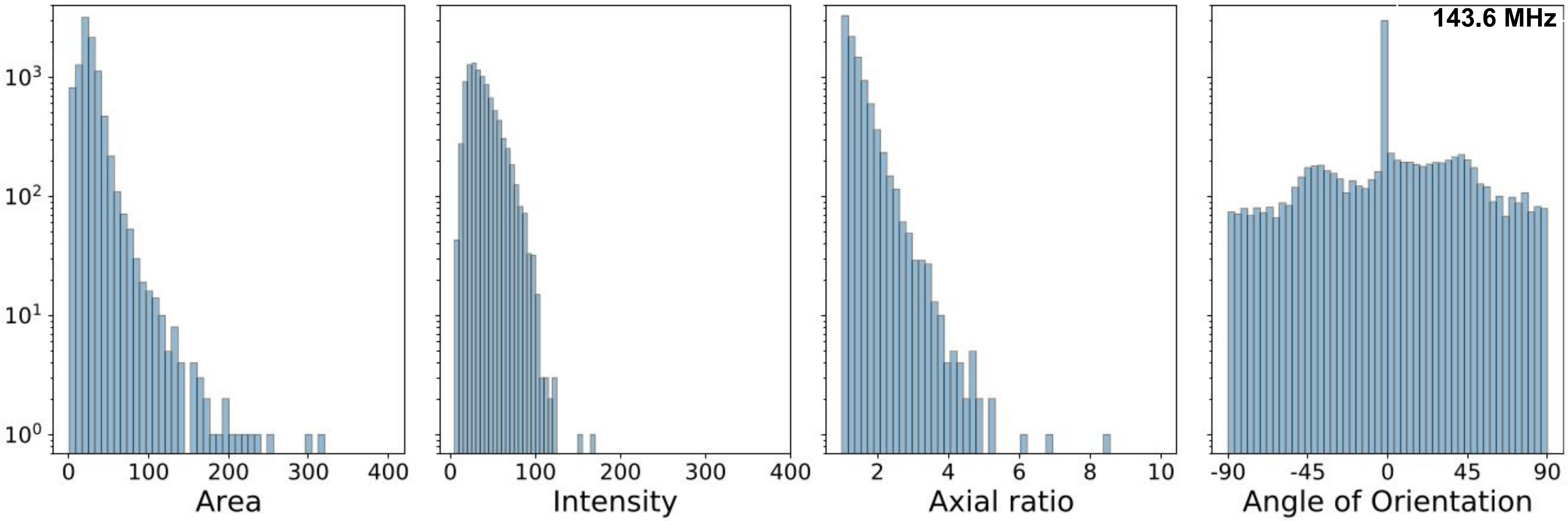
Radio counterparts of ‘nanoflares’, hypothesised to explain coronal heating

- 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

WINQSEs : Morphology



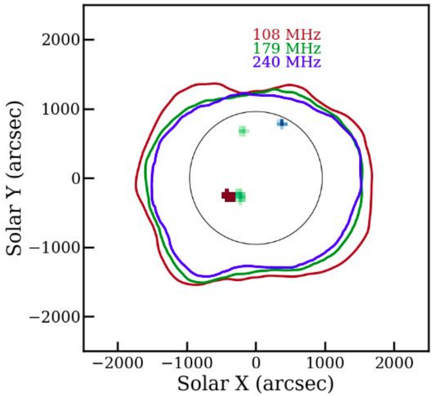
- Machine learning-based algorithm to detect WINQSEs, classify them based on their morphology, and model the isolated ones using 2D Gaussians.
- Improves upon the methodology used for detecting WINQSEs in earlier works

Bawaji et al., 2023

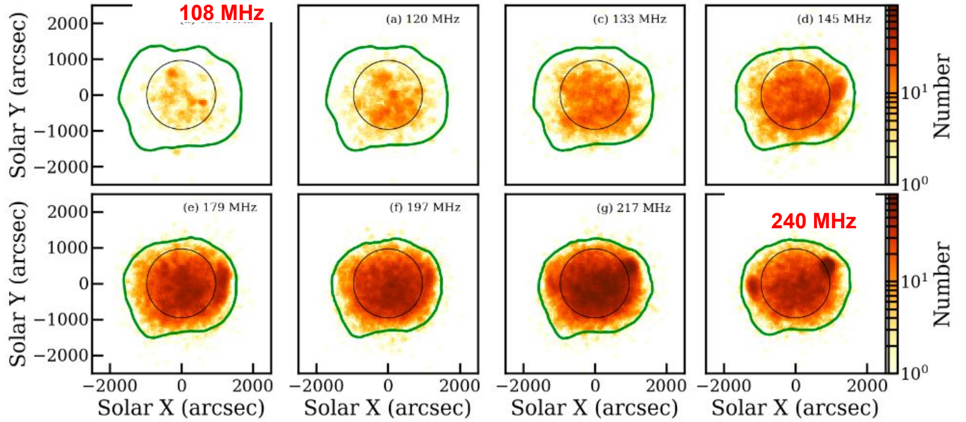
WINQSEs : An Alternative Detection Approach

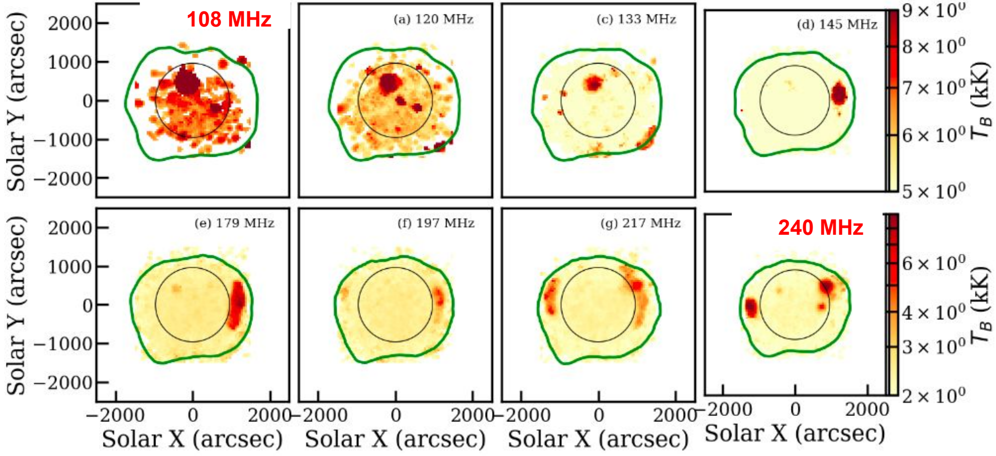
Using “residual visibilities” to image only the rapidly time varying part of solar emission.

Similar, in principle, to running difference images, only done in Fourier domain.



Sharma et al., 2022





(A) T_B of the detected bursts

WINQSEs : Current Status

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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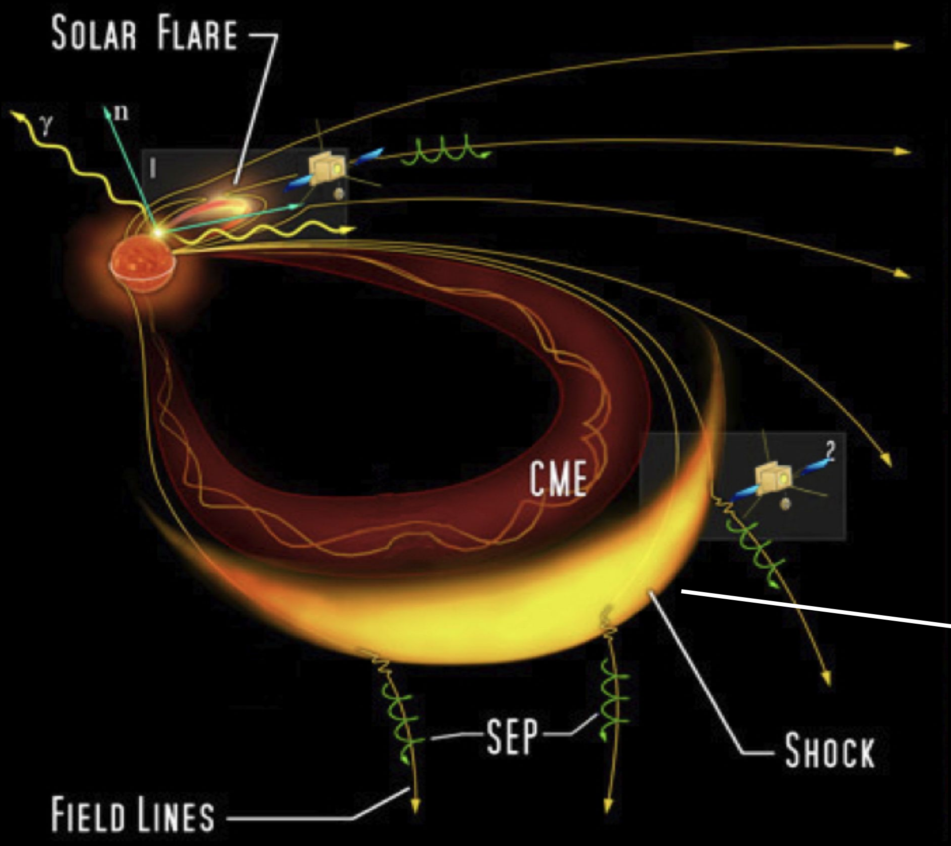
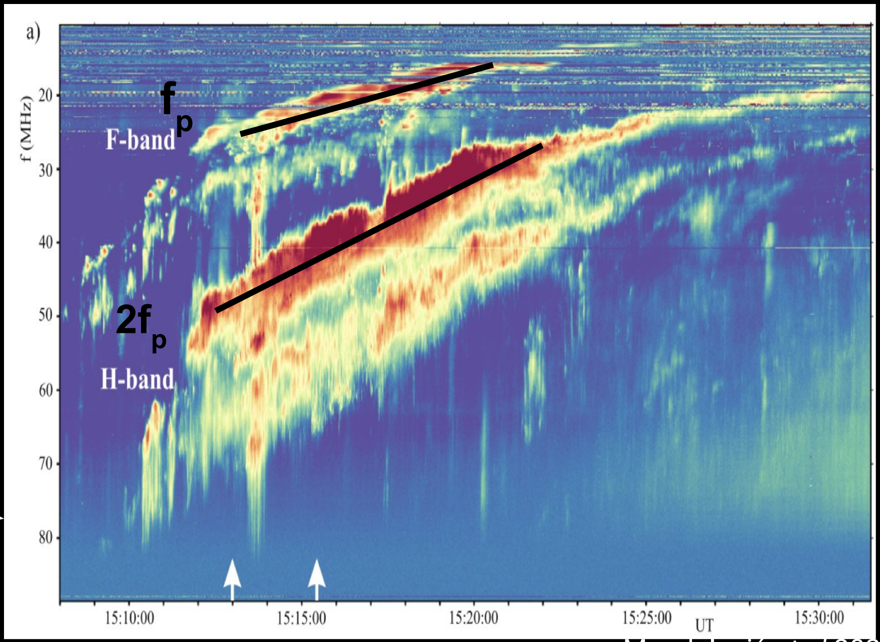
Type II solar radio bursts



Type II burst

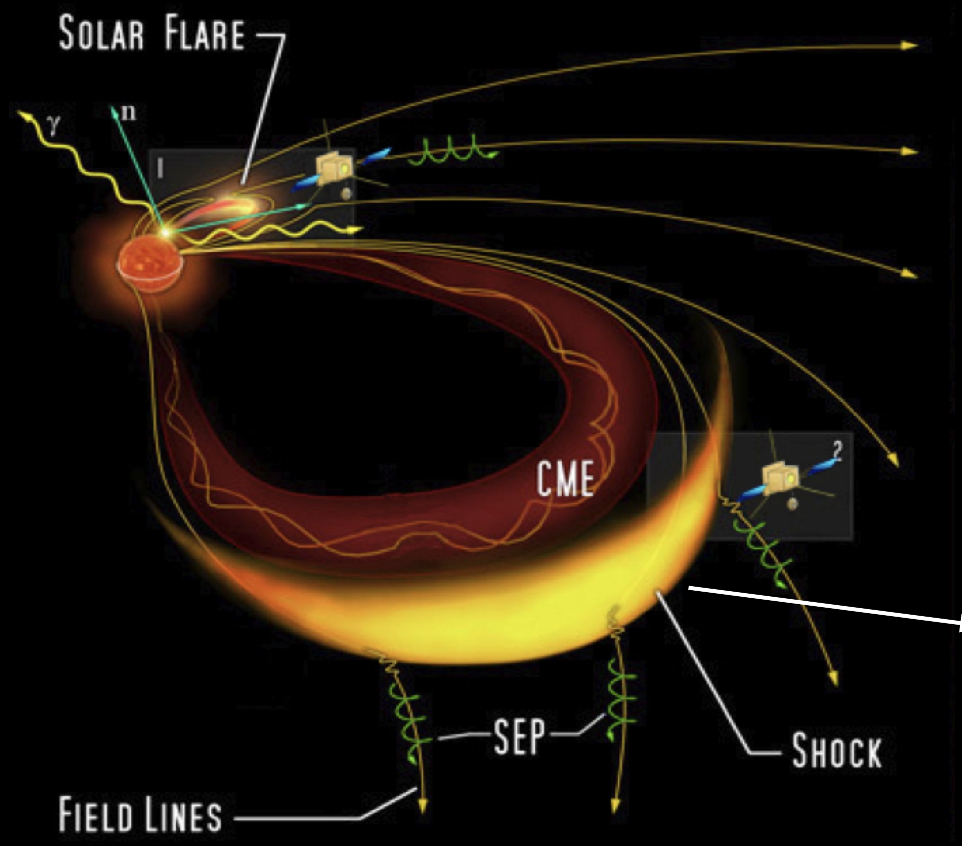


Magdalenić *et al* 2020

$V_{CME} > V_{Alfven}$

Plasma frequency (f_p) = $\sqrt{\frac{n_e e^2}{m_e \pi}}$ → h

Type II solar radio bursts



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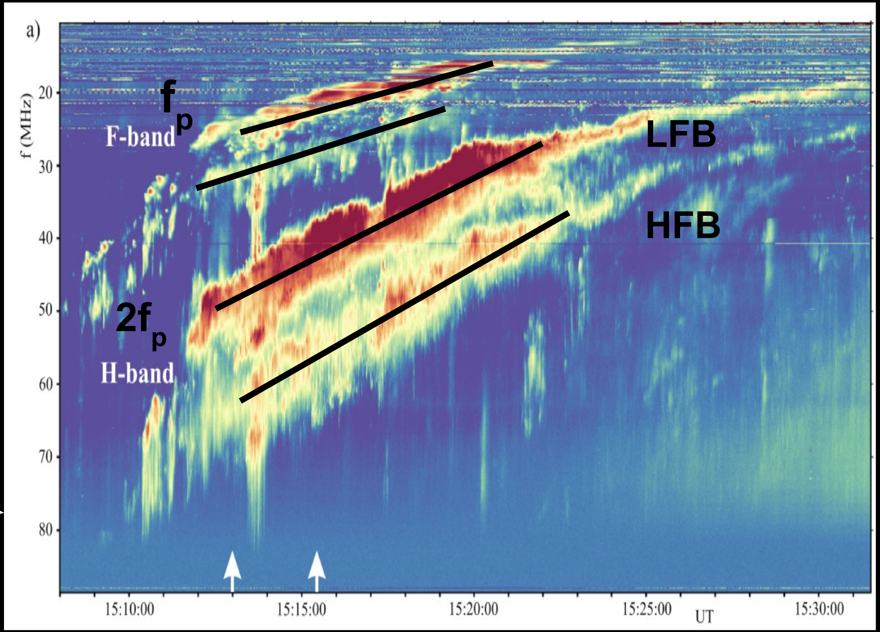


Magdalenić *et al* 2020

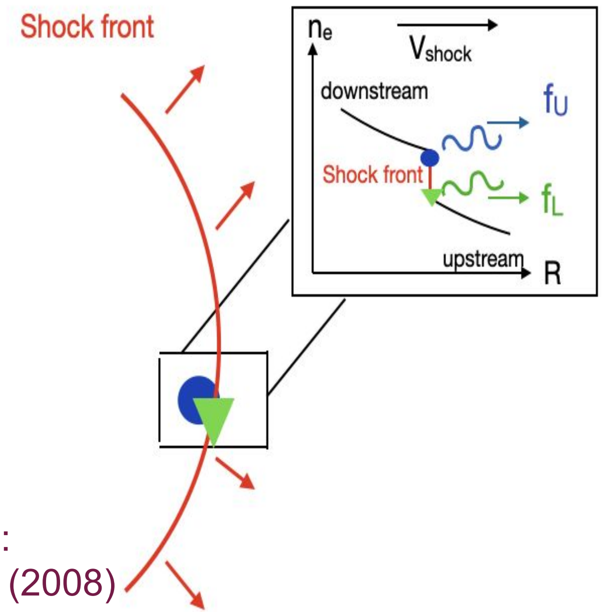
$V_{CME} > V_{Alfven}$

Plasma frequency (f_p) = $\sqrt{\frac{n_e e^2}{m_e \pi}}$ → h

bhunias@tcd.ie

What causes band-splitting in shock radio bursts?

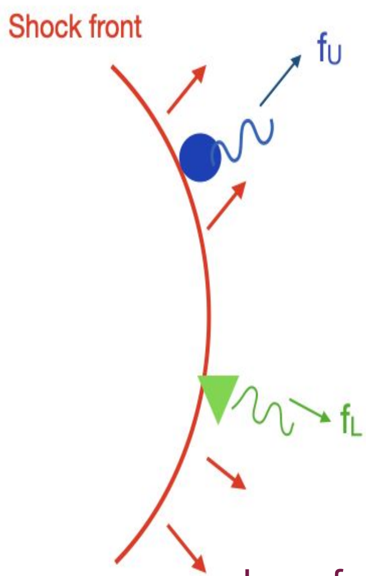
Upstream/Downstream



More conventional:

- Vrsnak et al. (2008)
- Zimovets et al. (2012)
- Chrysaphi et al. (2018)

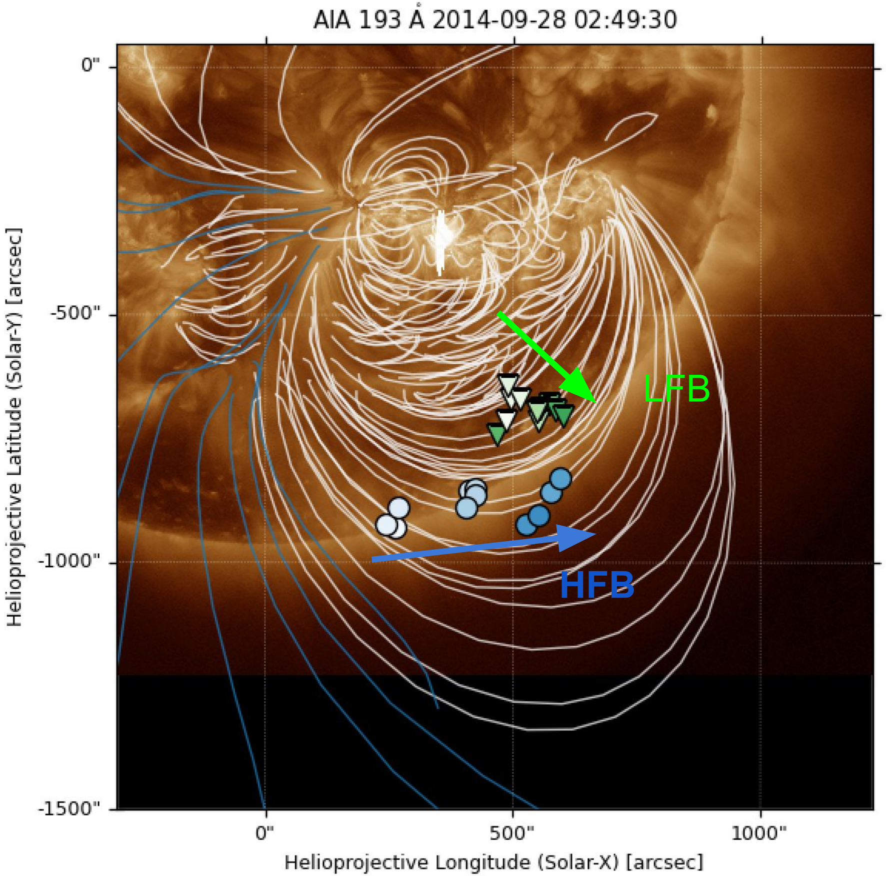
Independent emission sites



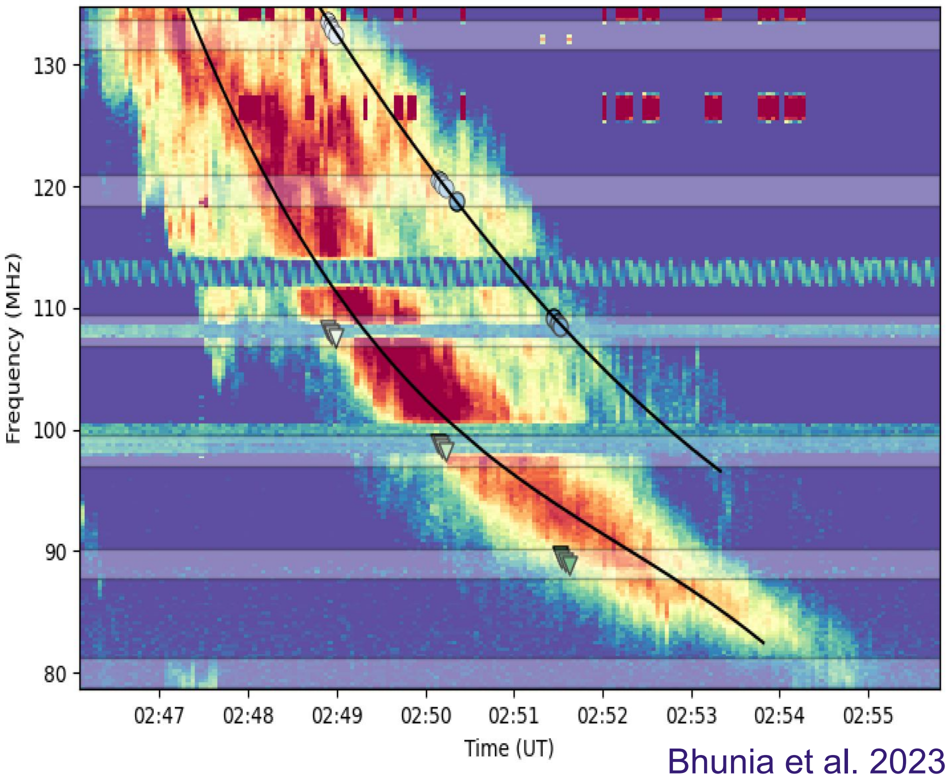
Less favoured

- McLean et al.(1967)

Motion of HFB and LFB sources



Rare but convincing evidence in favour of independent emission sites



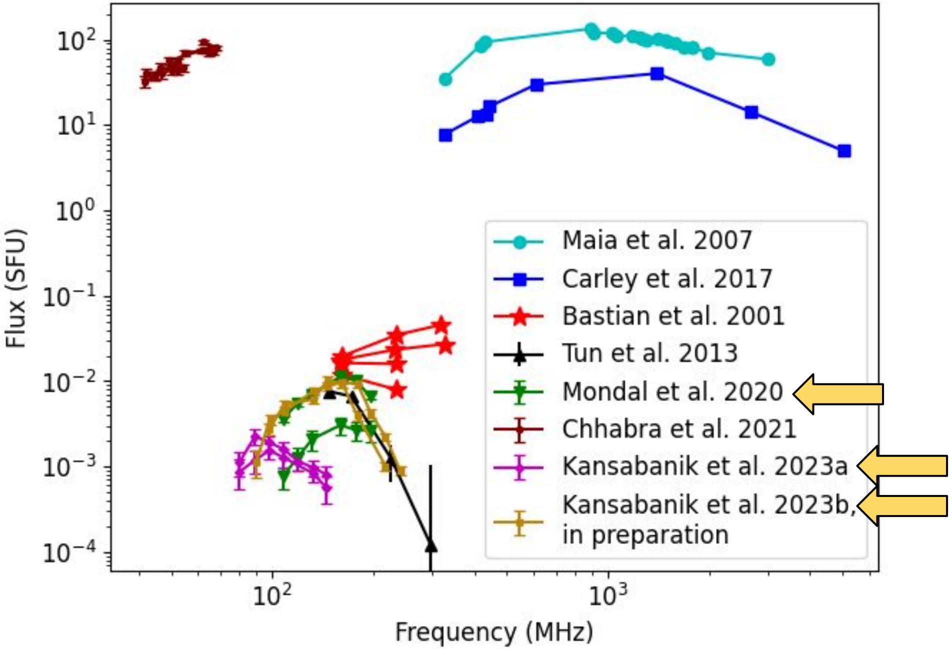
Bhunia et al. 2023

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 the Nançay Radioheliograph.

- Limited number of detections due to observational challenges.
- Associated with fast CMEs.
- Spectral coverage is not always sufficient.
- Includes non-imaging studies, so no spatial information



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- Most of ther
  the fast CM
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  good.
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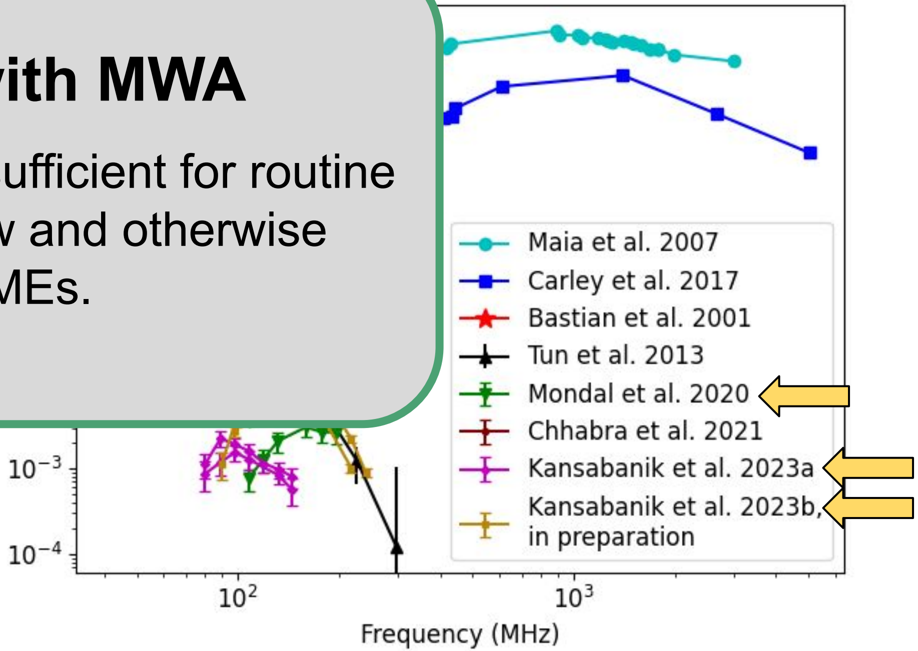
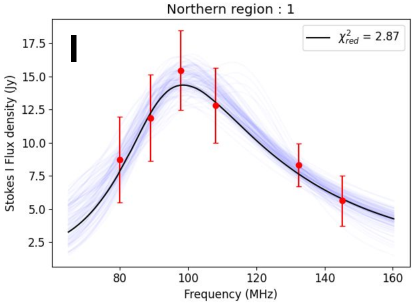
CME GS with MWA

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



The Challenge of Constraining CME GS Models

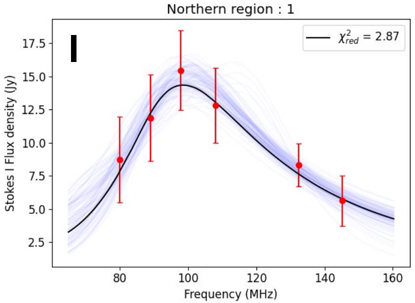
Stokes I only modeling :

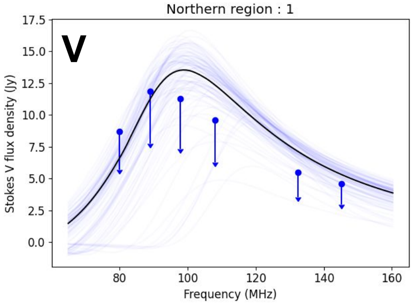


Kansabanik et al. 2024

Advantages of Using Stokes V Spectra

Stokes I only modeling :





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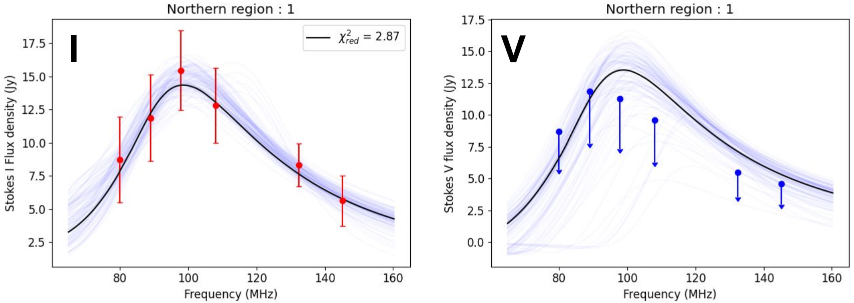
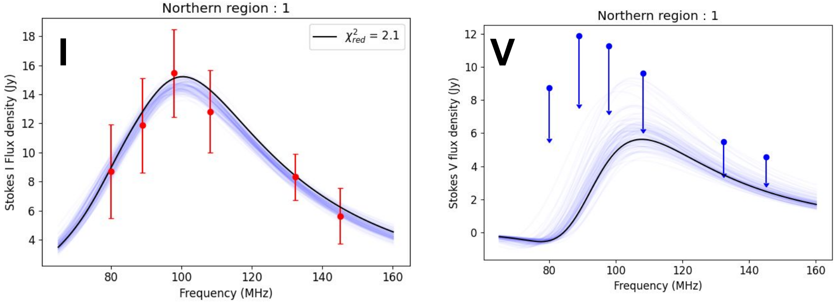
Advantages of Using Stokes V Spectra

Stokes I only modeling :



Stokes I and V joint modeling :



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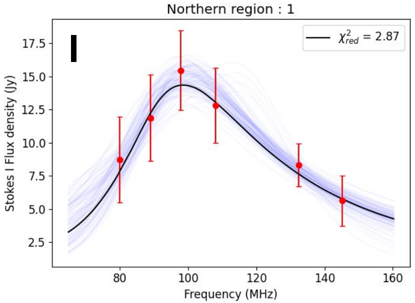
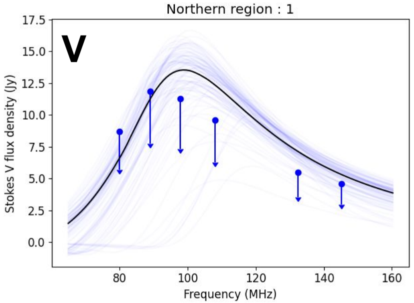
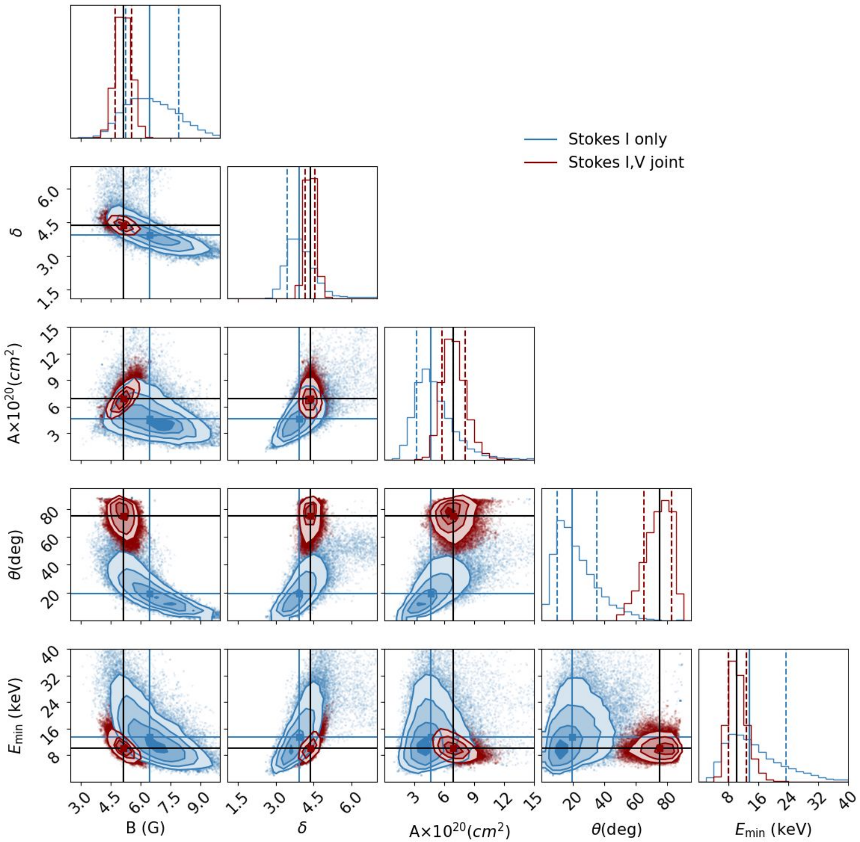
Advantages of Using Stokes V Spectra

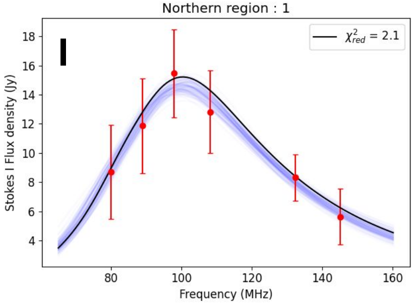
Stokes I only modeling :

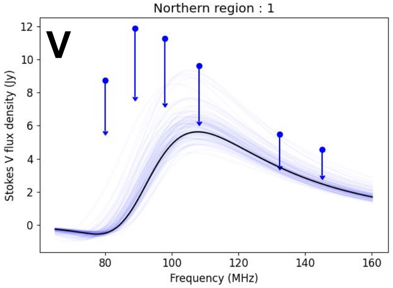






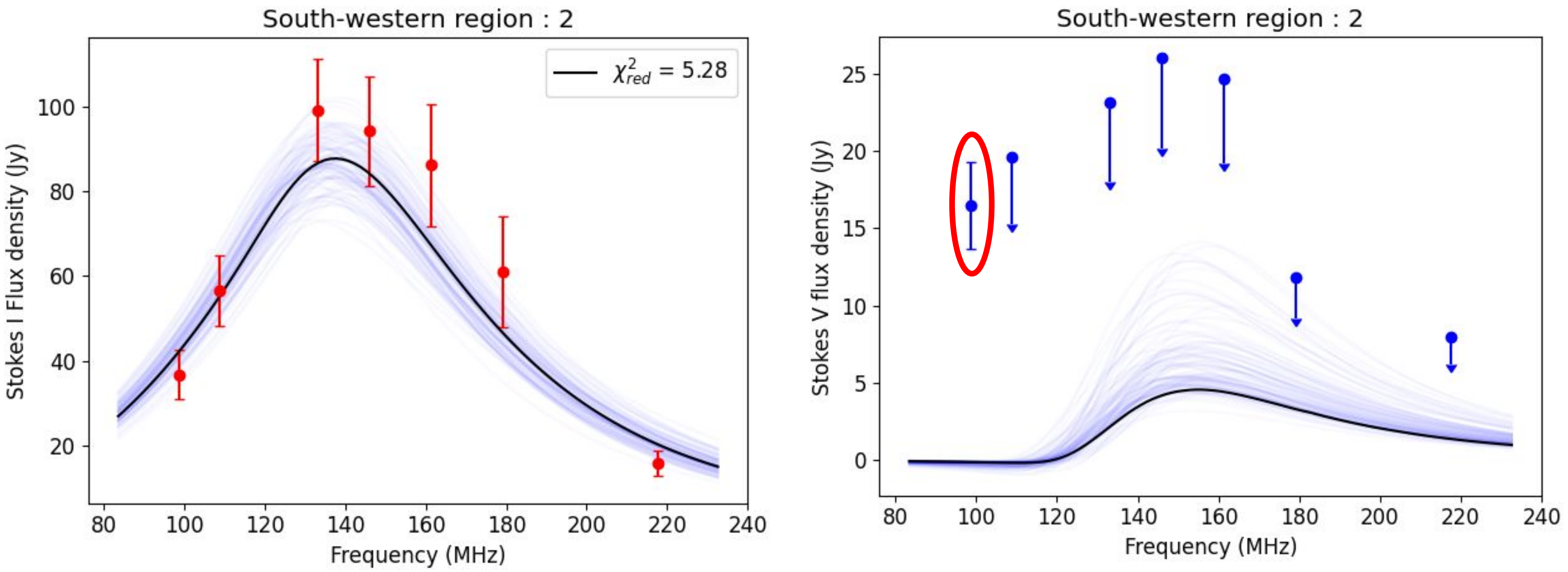
Stokes I and V joint modeling :





Kansabanik et al. 2023a

First detection of CME GS Stokes V



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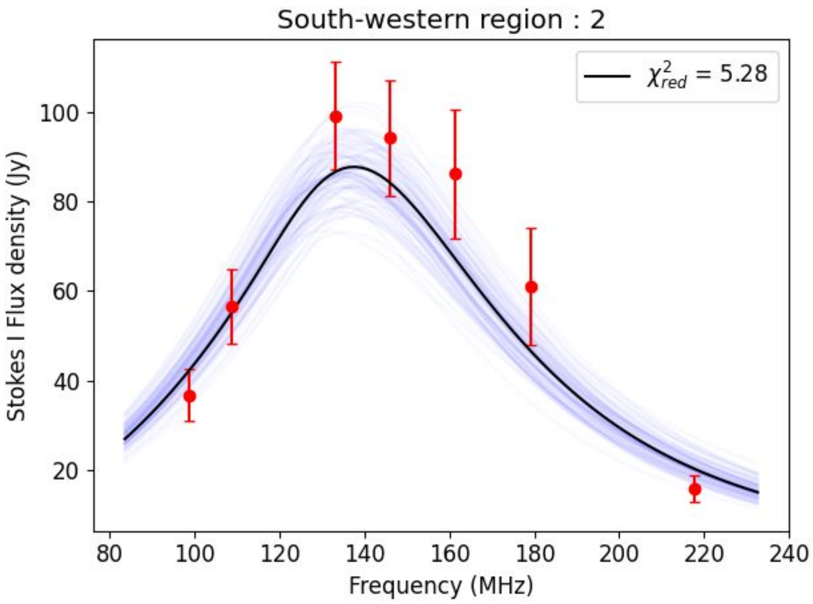
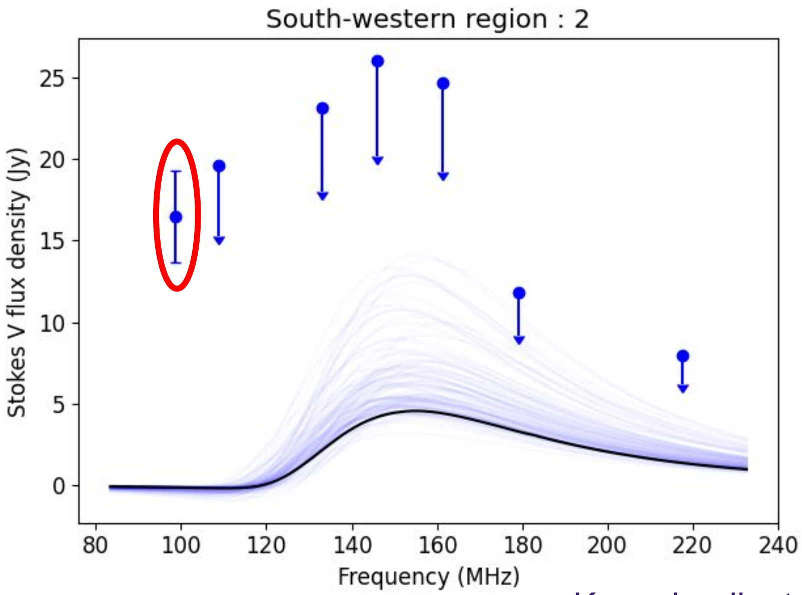
First detection of CME GS Stokes V

Prompting us to question model assumptions

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

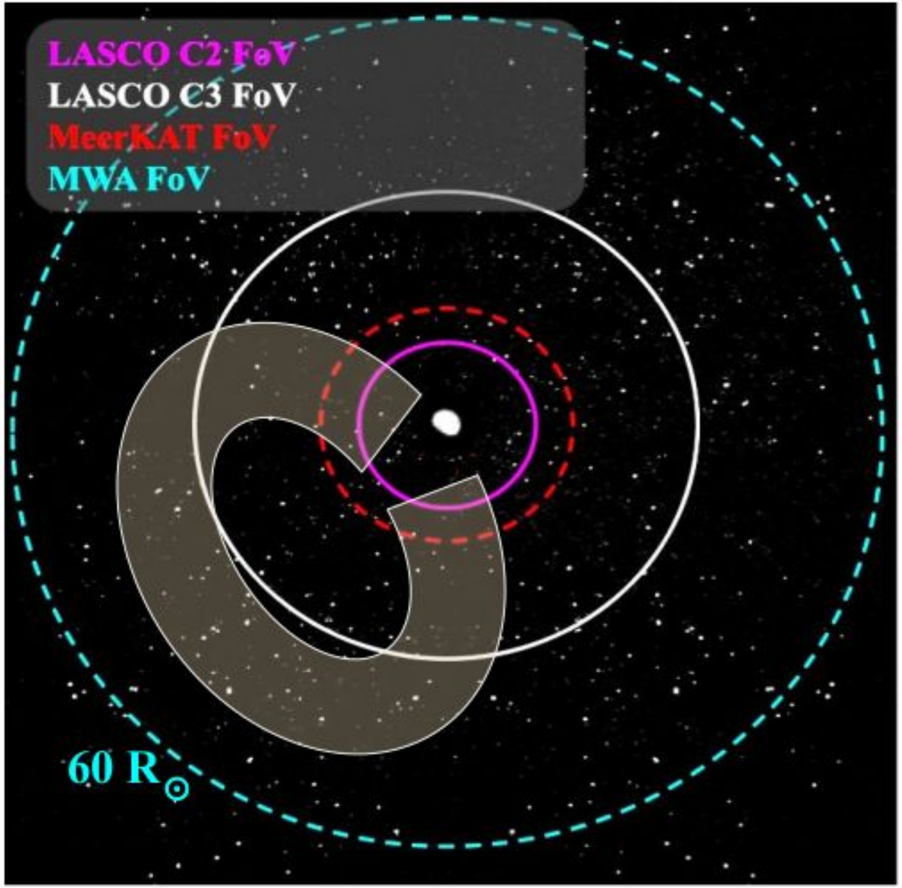




Kansabanik et al. 2024

Space Weather – CME Vector Magnetic Field

- Simultaneous Faraday rotation of linearly pol emission from a large number of background radio sources.
- Use them to constrain the best available CME models (Magnetic Flux Rope ~10 parameters)
- Low frequency and large FoV ⇒ ability to track CMEs to larger distances
- Source density 0.05 sources/ deg^2 for MWA; 2-5 sources/deg^2 at GHz frequencies (MeerKAT, ASKAP)



Quantifying propagation effects

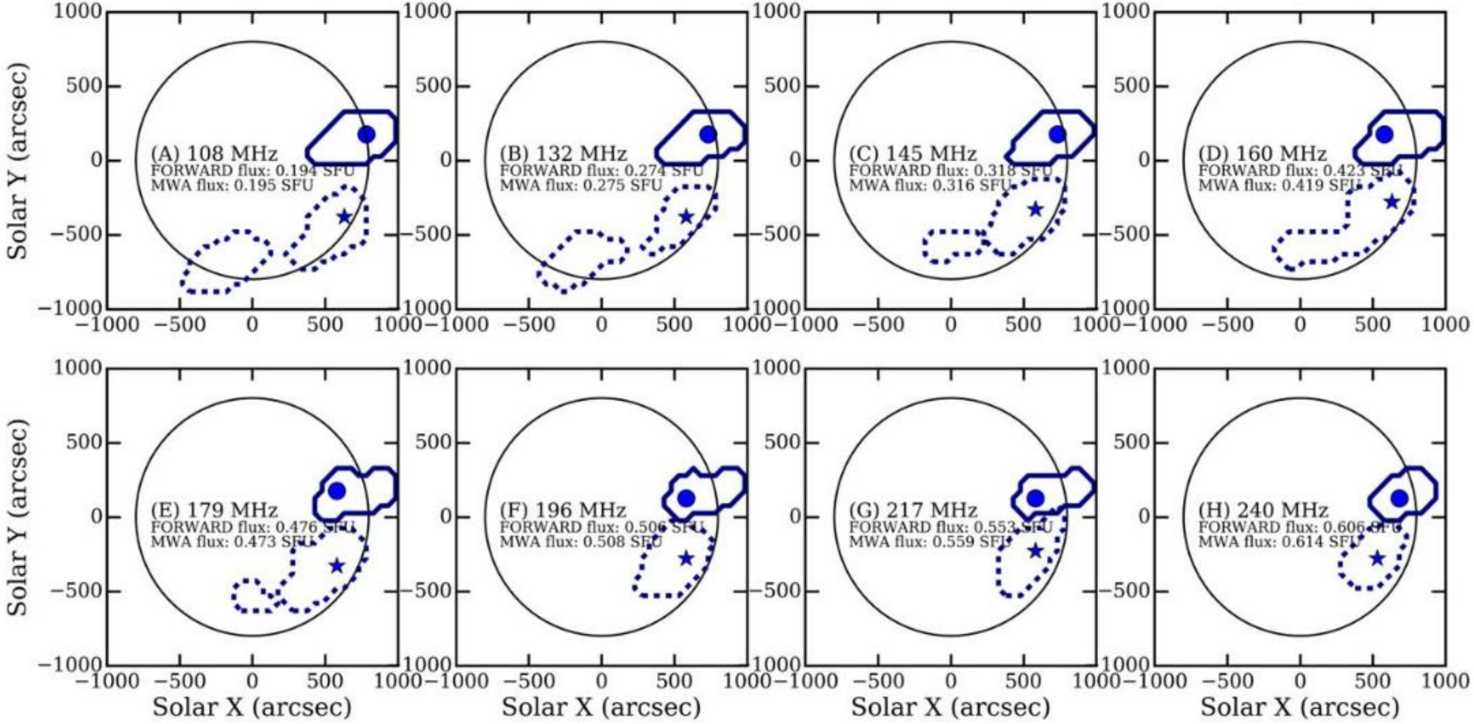
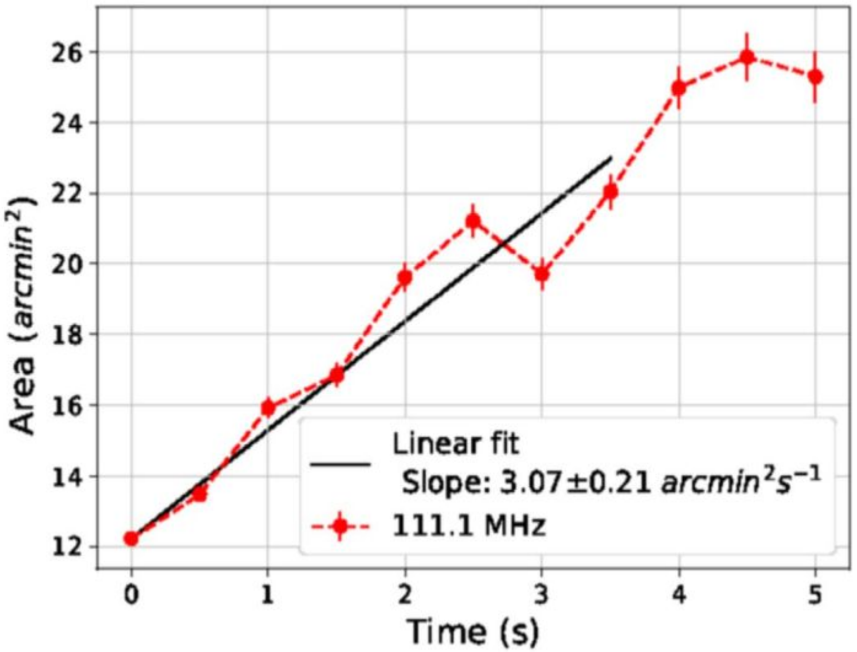


Figure 7. MWA and FORWARD contour maps for different frequencies. FORWARD contours are drawn at $T_B = 1.5$ MK and shown by a solid line. The MWA contours, shown by dashed lines, have been drawn to enclose the same flux density as is enclosed in the FORWARD contour. The filled circle and the star mark the locations of the flux density peak in the FORWARD and MWA maps, respectively.

Sharma and Oberoi, 2022

Quantifying propagation effects



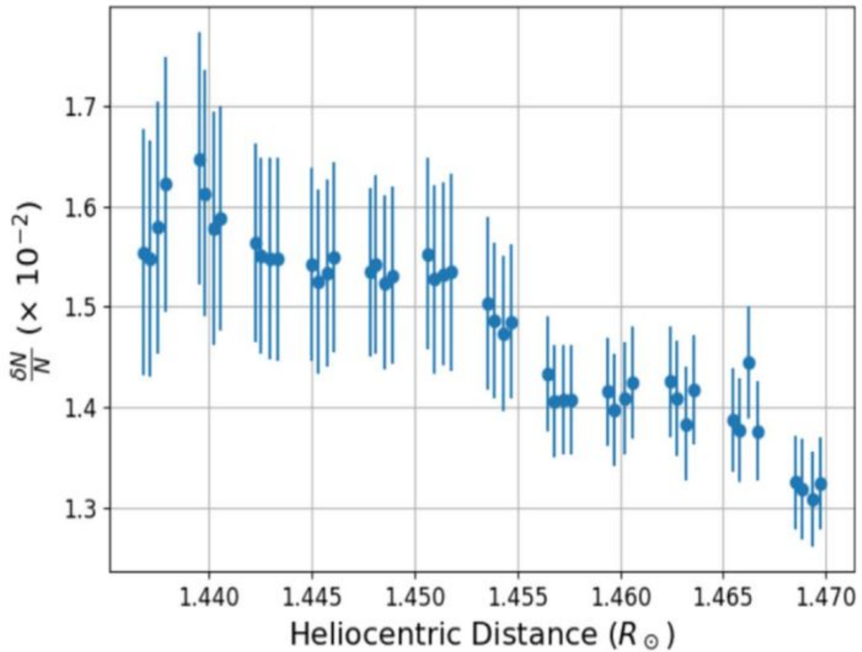
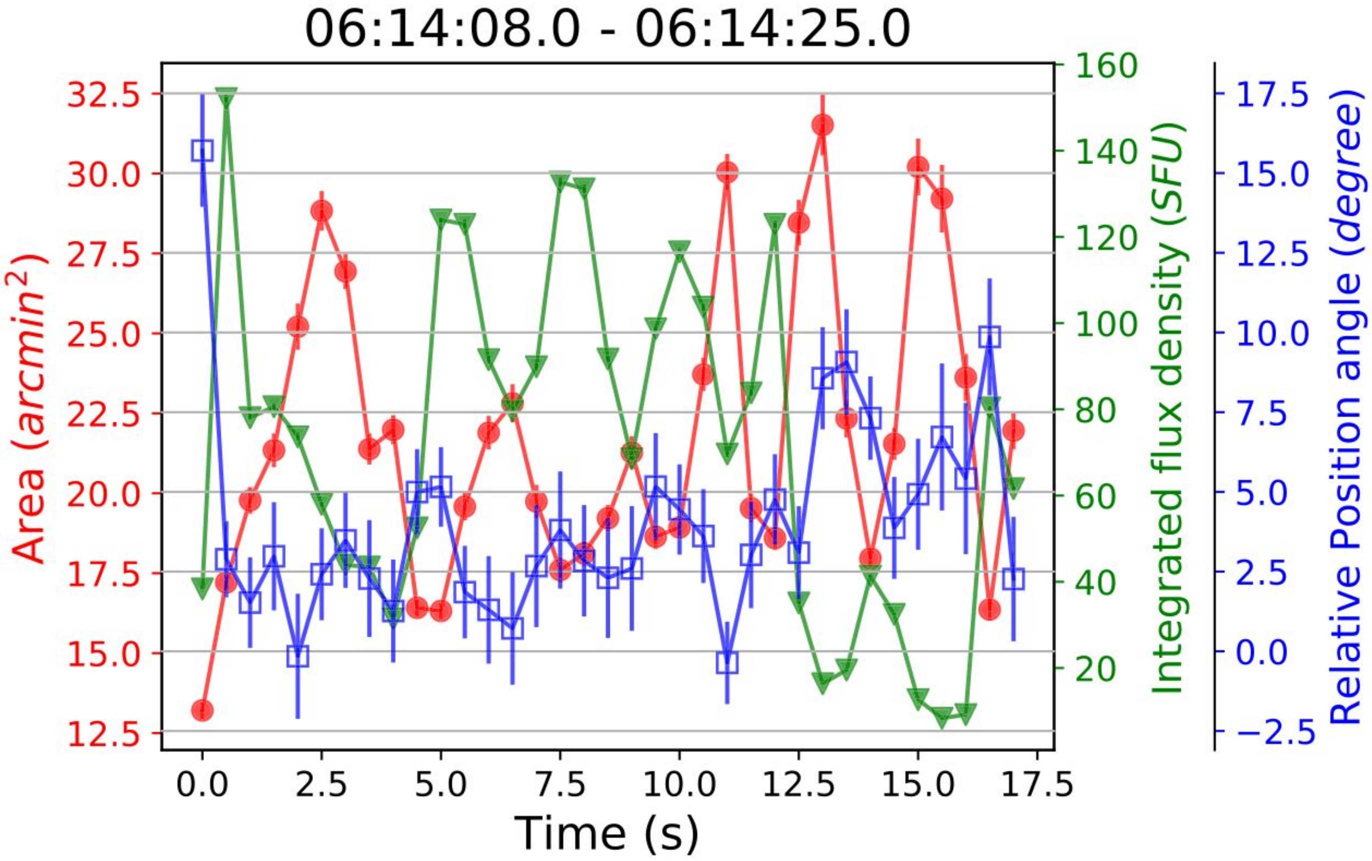


Figure 11. Left: diffusive growth period of the source area at 111.1 MHz for the first group of bursts. A linear fit is done to estimate the diffusion rate. Right: $\delta N/N$ as a function of heliocentric distance calculated using the area diffusion coefficients derived across frequencies. These values are nearly four times larger than the theoretical estimate for $\delta N/N_{\rm sat}$. Refer to the text for details.

Mohan et al., 2019

Quasi Period Pulsations (QPPs)



Mohan et al., 2019

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

Divya Oberoi[1](div@ncra.tifr.res.in), Atul Mohan[2] and Surajit Mondal[1]

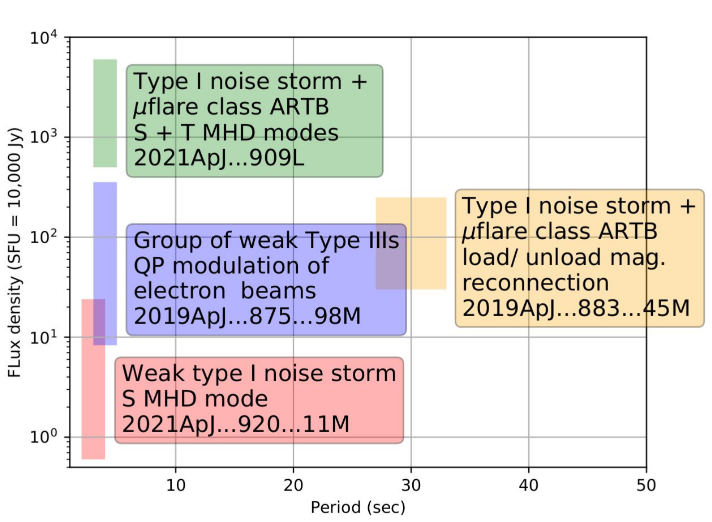
1 National Centre for Radio Astrophysics, Tata Institute of Fundamental Research, Pune, India

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

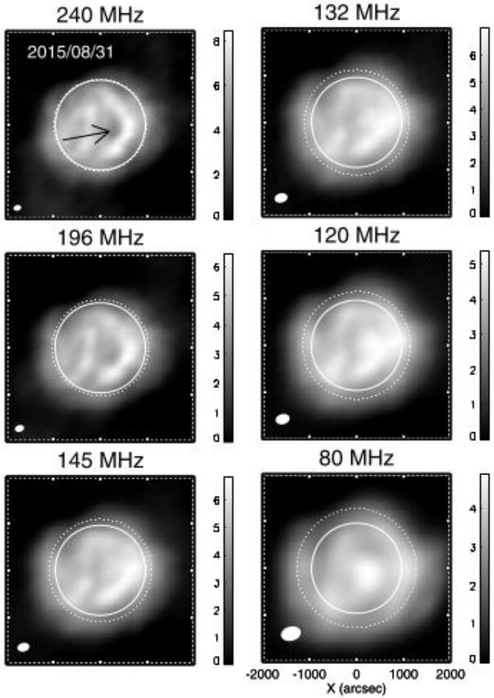


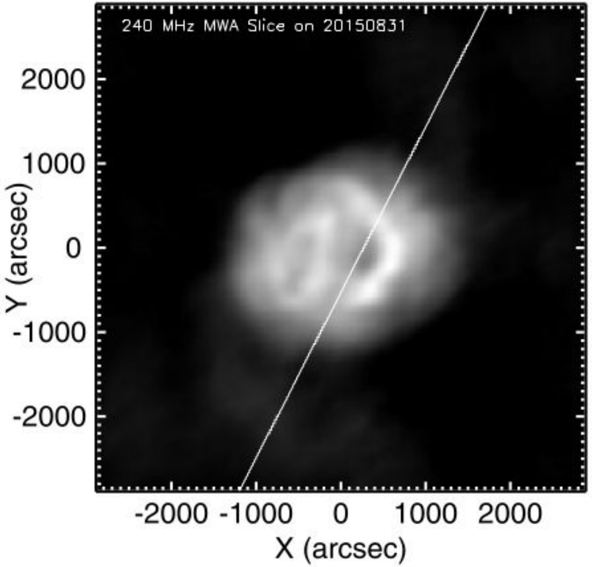
Phase space covered by observations in the period-flux density plane
S/ T – Sausage/ Torsional MHD modes

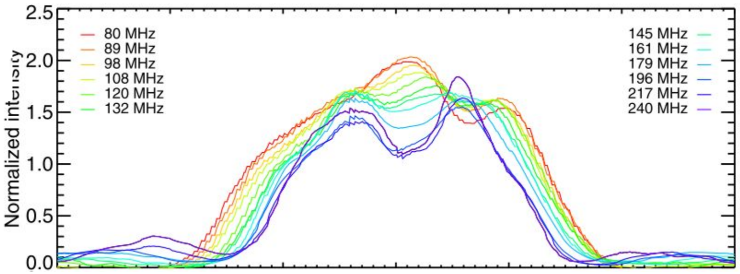
Conclusion

- 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

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

Approach

Realizing that:

- Solar radio science is limited by *'extrinsic'* reasons
  - lack of suitable instruments ⇔ small community, analysis issues, …
- Despite its challenging requirements, dedicated solar radio instrumentation will remain a poor cousin of the best-in-class instrumentation

We are trying to:

- Enable solar science with the best-of-class instrumentation
  - SKAO precursors... and eventually the SKAO
  - Enable triggered observations (initiated for the MWA)
- Make solar radio imaging analysis more accessible
  - Build and share a good imaging pipeline for use by a reasonably well informed user
- Build a larger community of solar radio scientists
- Deliver novel and interesting science, with potentially significant societal impact

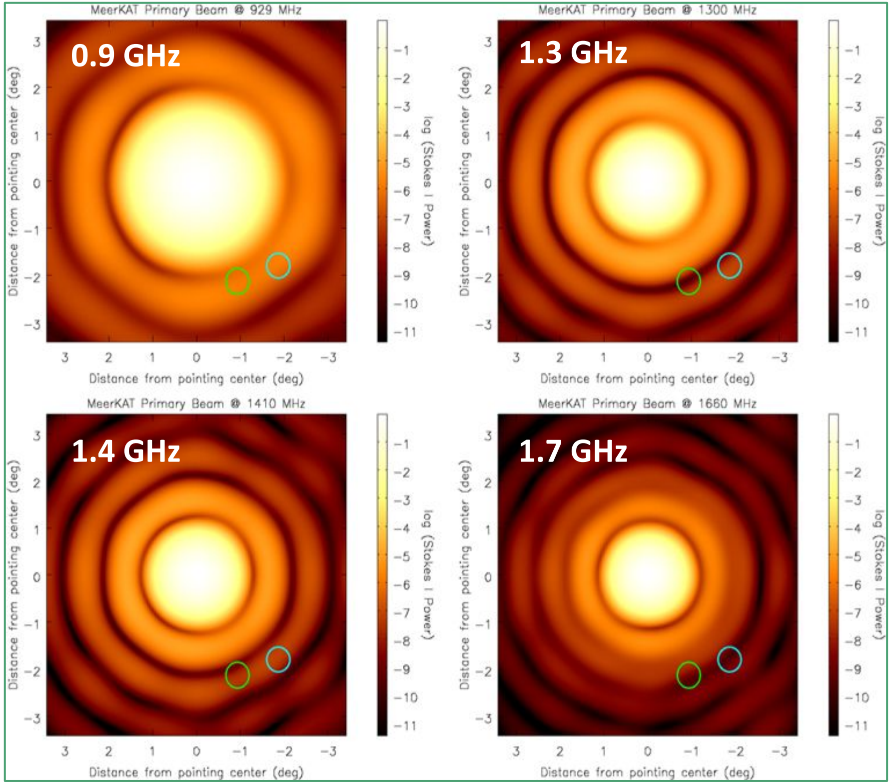
Future plans

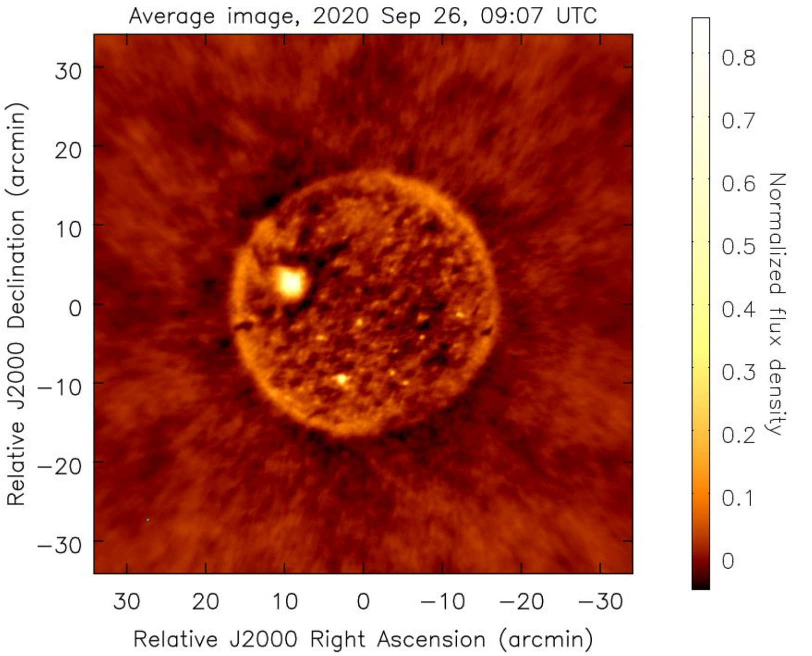
- Specific science targets
  - CME magnetic fields and Space Weather
    - Gyrosynchroton studies close to the Sun
    - Faraday rotation of background sources at larger elongations
  - High fidelity polarimetric studies of the Sun
    - Polarimetric properties of active and quiescent solar emissions
    - Investigate the reality of linearly polarized solar emission
  - Modeling slowly varying emission from the Sun
    - Minutes to hours and days (coronal holes, streamers)
  - Modeling and understanding propagation effects

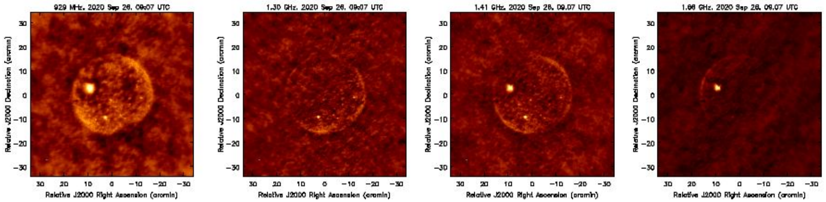
Summary

- Solar radio observable offer unique and/ or complementary information to what can be gained from other means
- They have however remained an underutilized tool, despite their intrinsic merits… for good reasons
- The current generation of radio instrumentation (SKAO precursors) allow us to explore very interesting phase space
- We are
  - delivering on the promise of solar radio science
  - trying to overcome some of the barriers holding us back
- The future is bright and sunny :-)

Enabling solar observations with MeerKAT

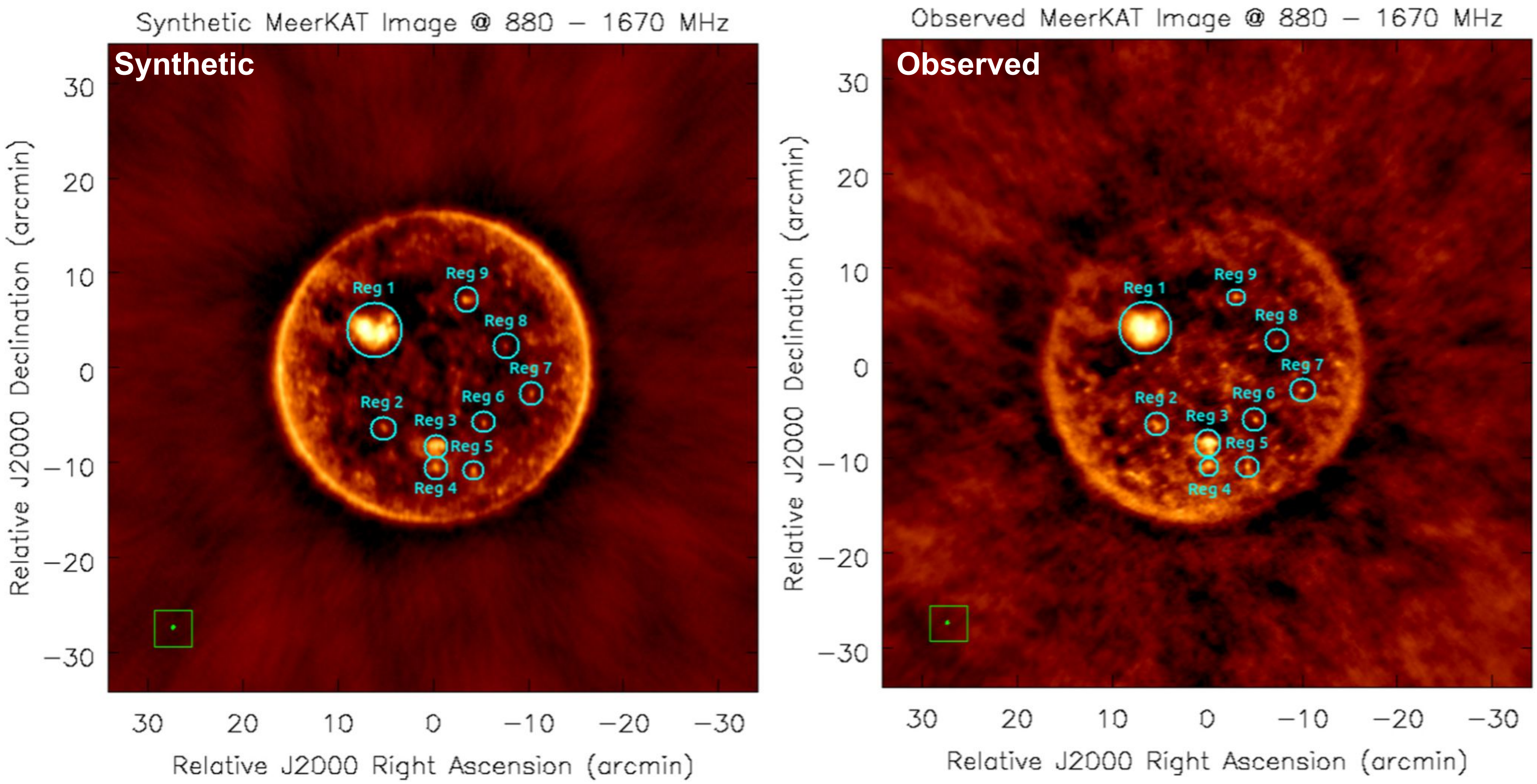






Kansabanik et al., 2024, ApJ 961 96

Enabling solar observations with MeerKAT



Kansabanik et al., 2024, ApJ 961 96