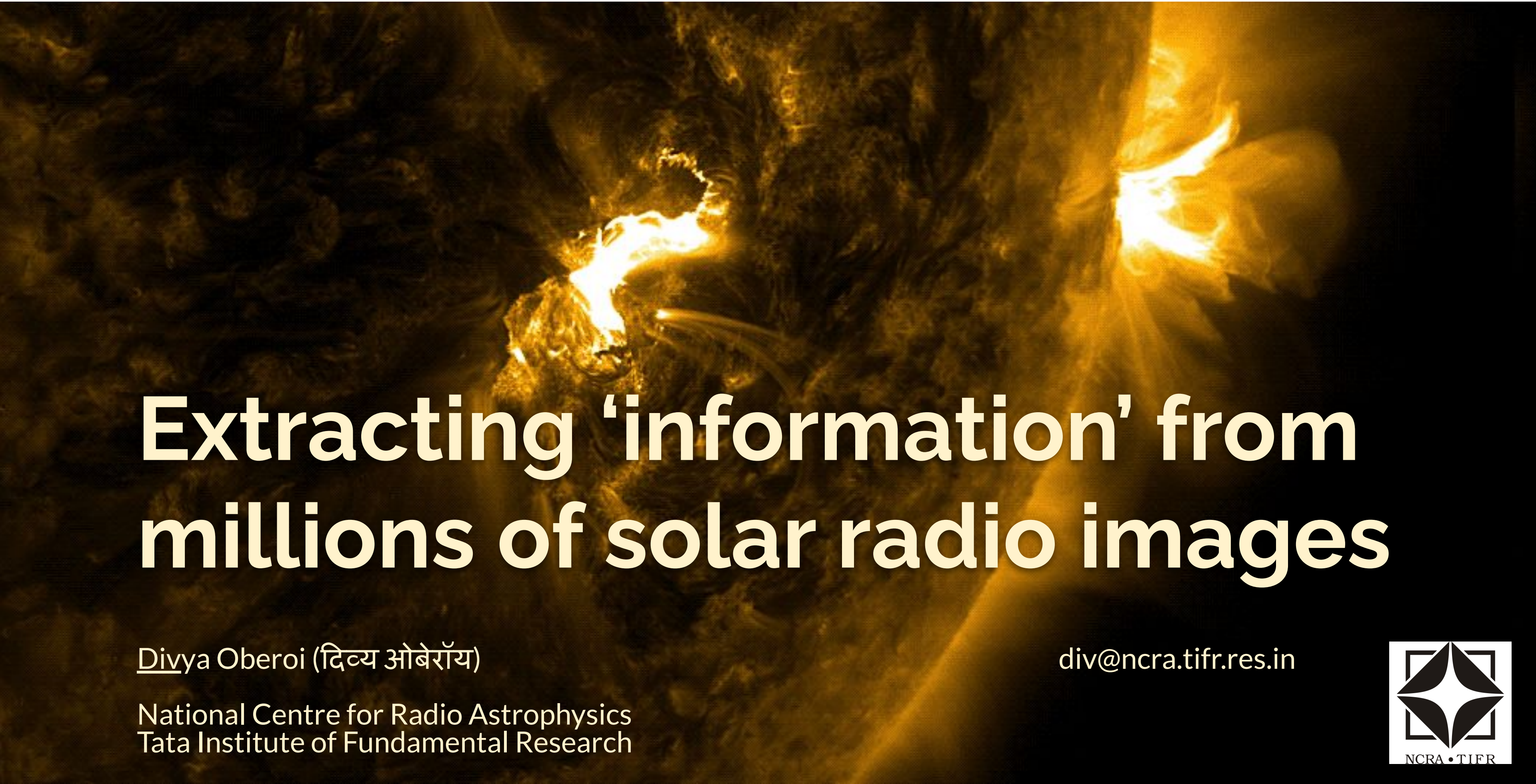

Extracting ‘information’ from millions of solar radio images

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National Centre for Radio Astrophysics
Tata Institute of Fundamental Research

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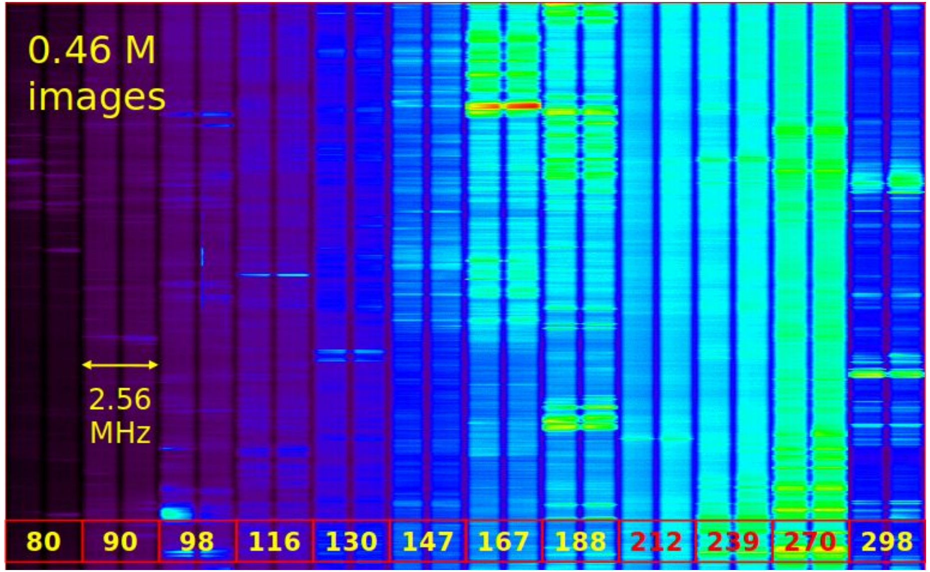
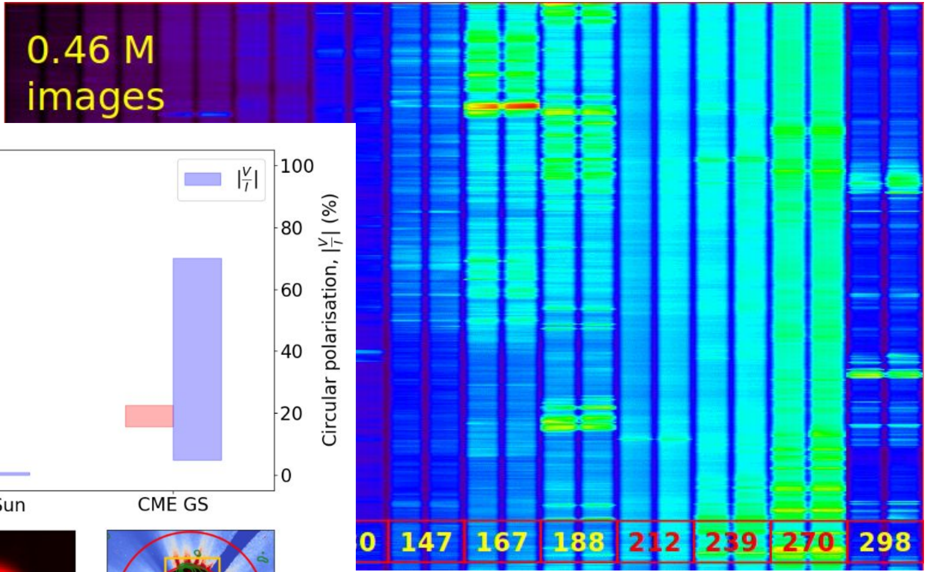
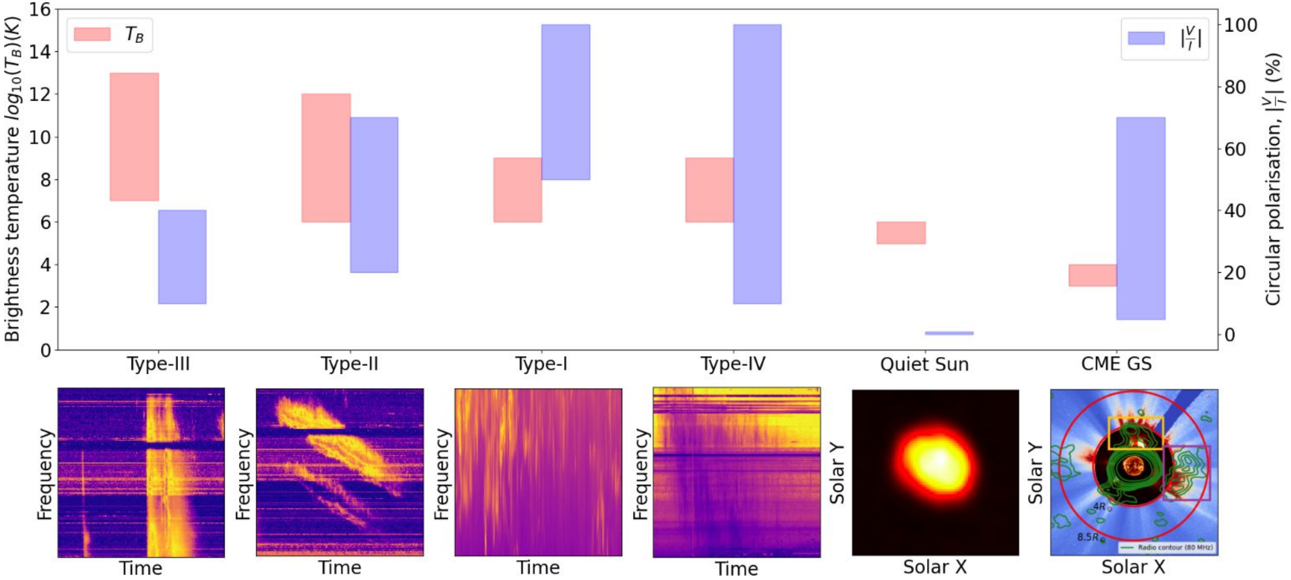
Nature of low-frequency radio solar emission



Nature of solar radio emission





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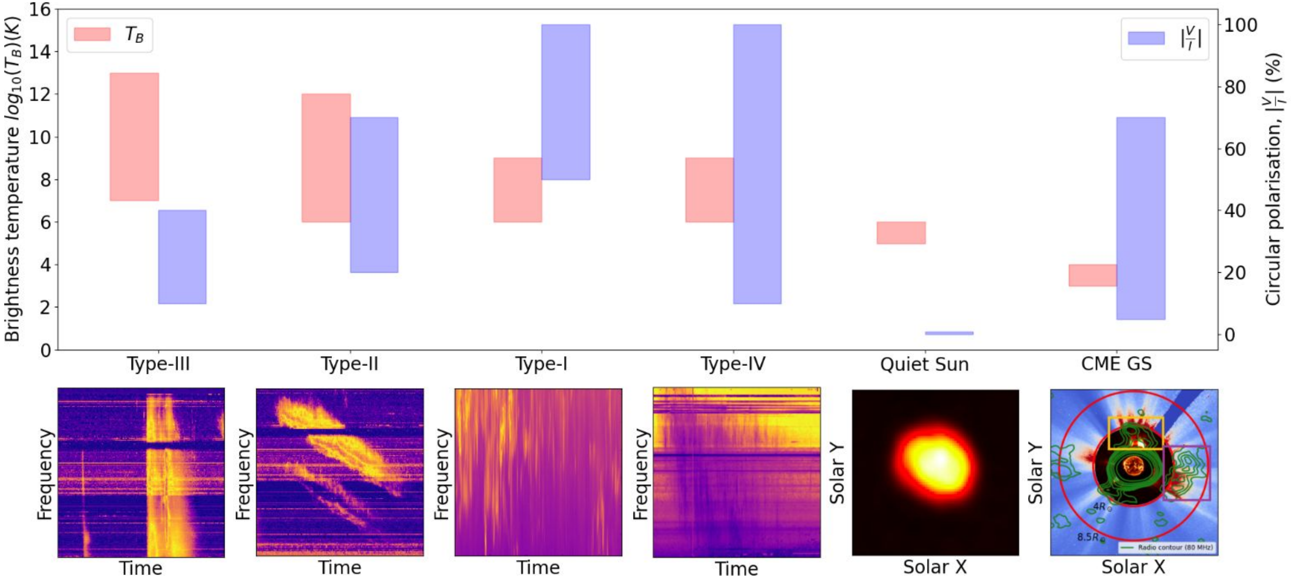
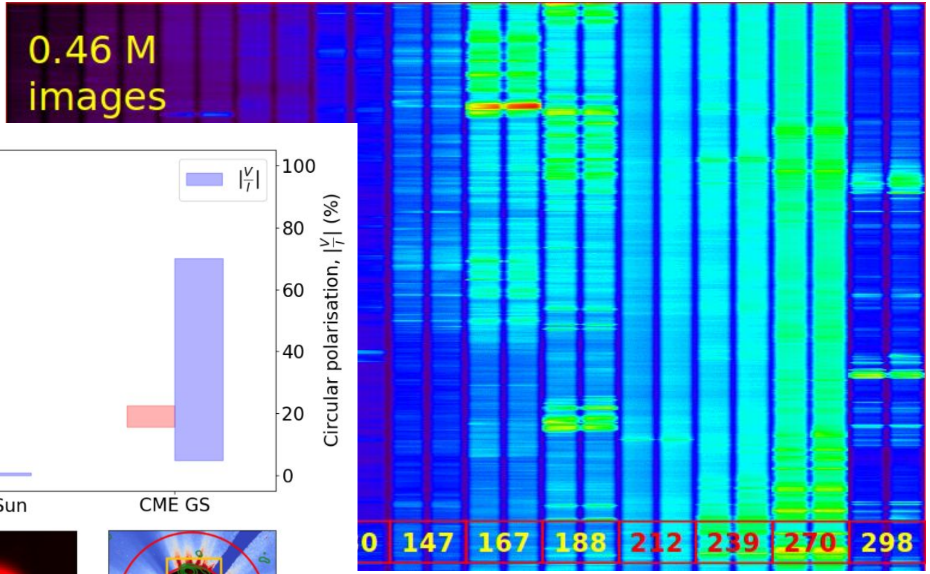
Nature of solar radio emission





Structured over small temporal and spectral scales; Rapid changes in morphology
Spans 9+ orders of magnitude in intensity and 2+ orders in fractional polarisation

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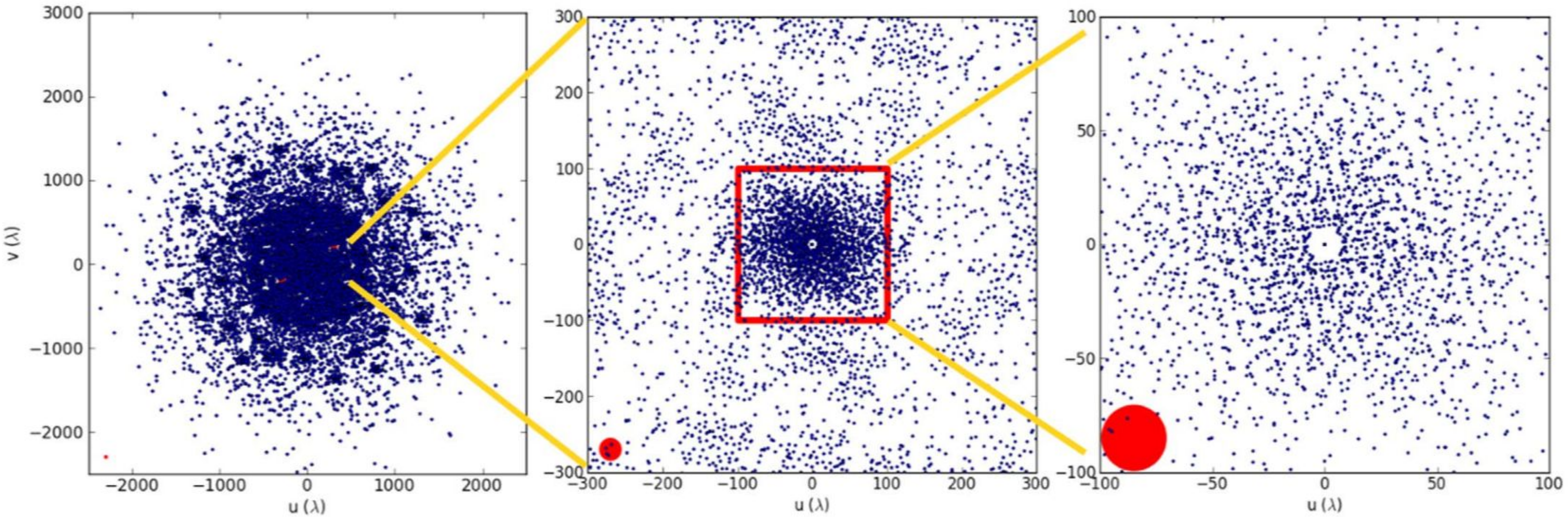
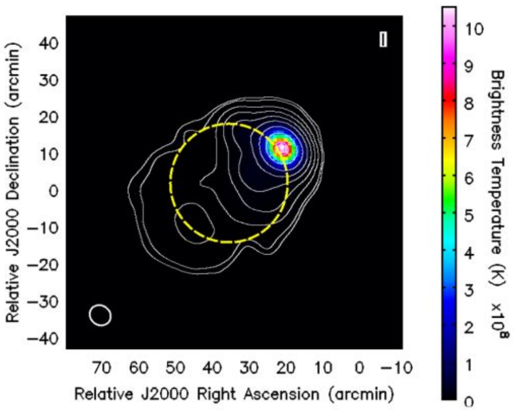
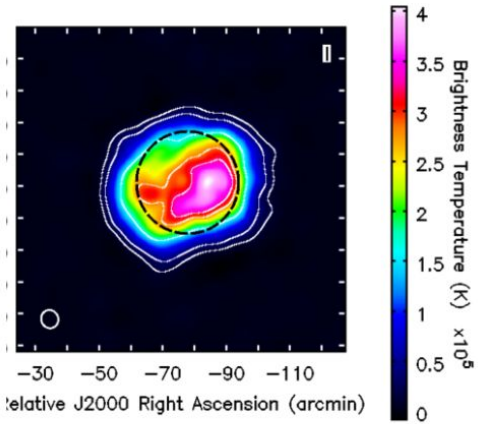
Interferometry primer

- Fourier imaging technique - each baseline measures one Fourier component of the radio sky
- Must gather all of the information needed over short time duration and spectral span (full polar snapshot spectroscopic imaging).
- Has become possible only recently with new technology instrumentation.



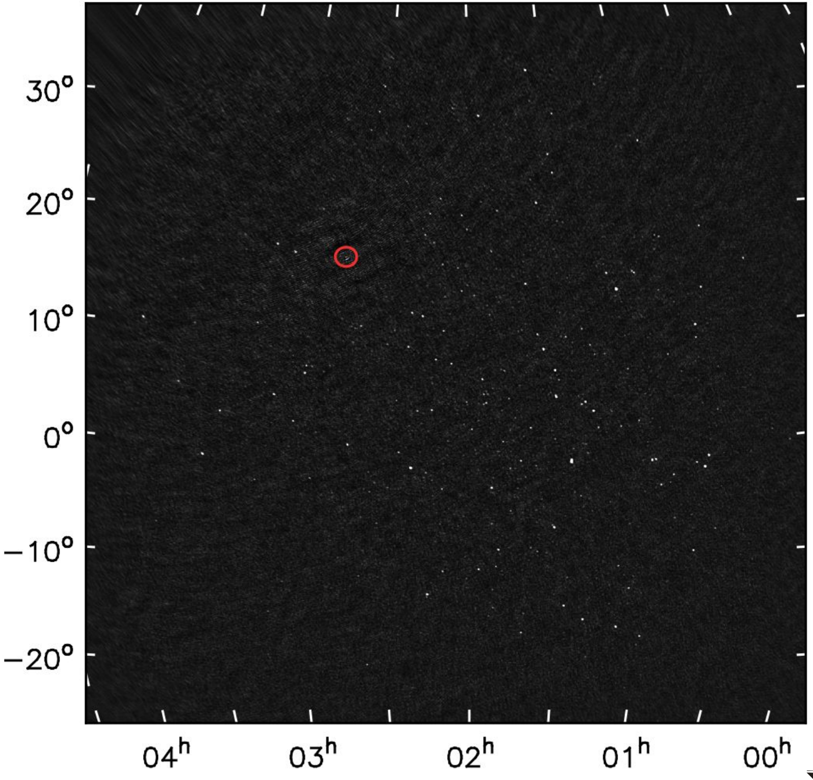
Making state-of-the-art solar radio images





Dynamic range = 10^5

10^3



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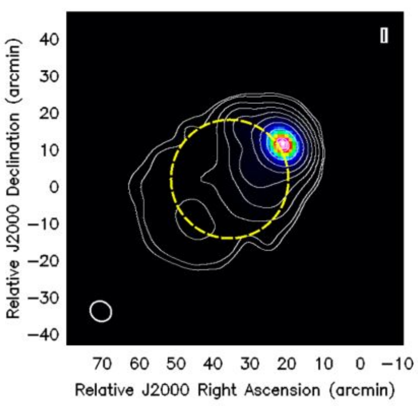

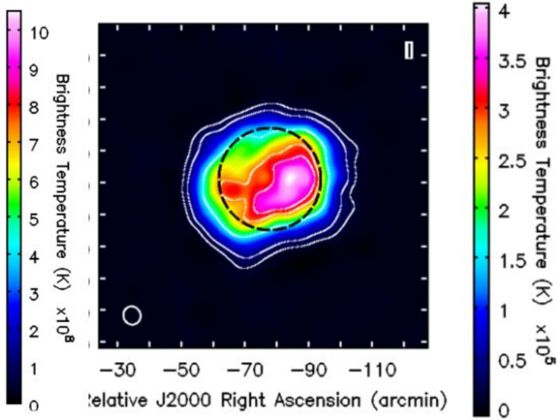

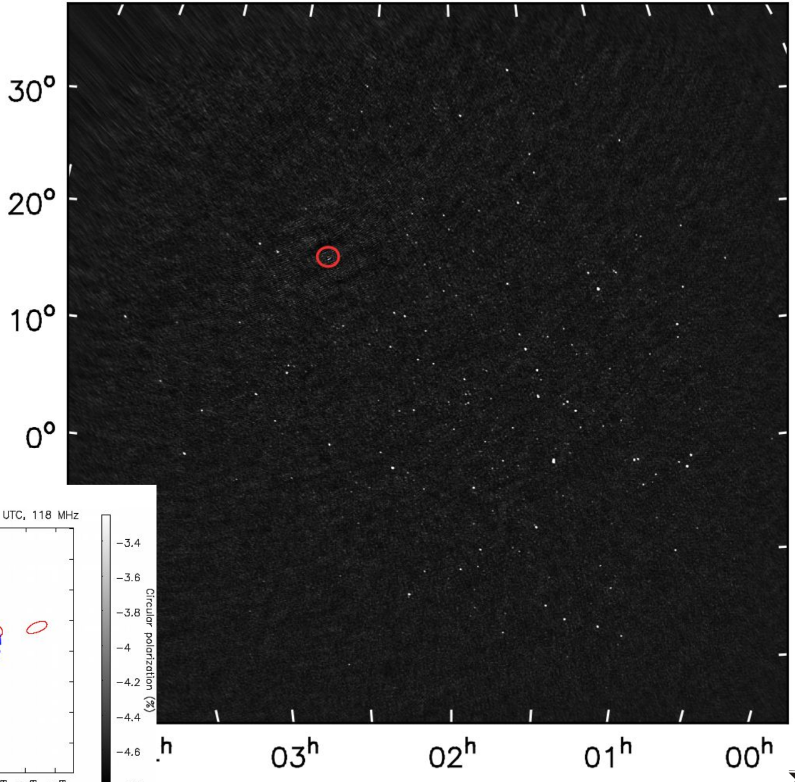

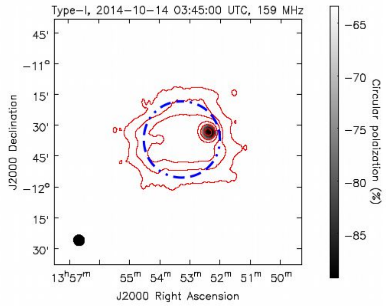

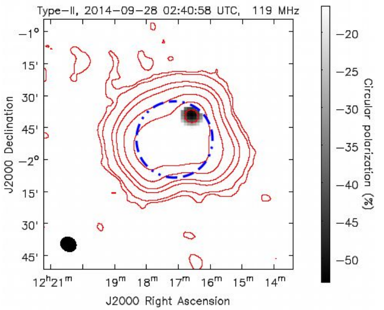

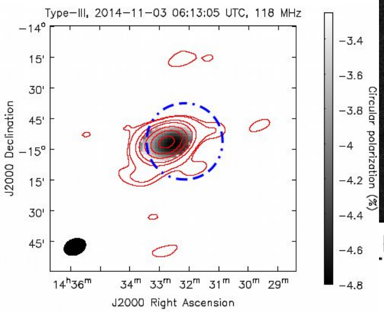

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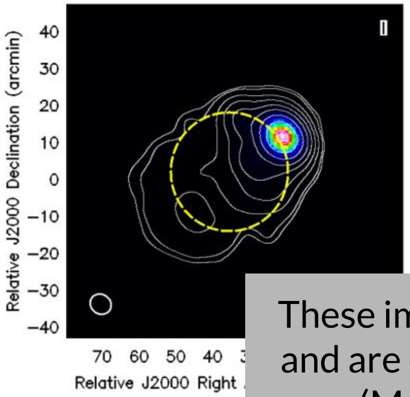
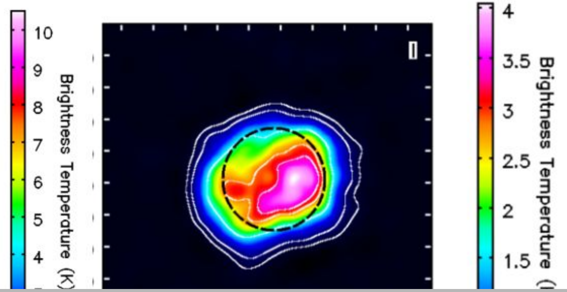
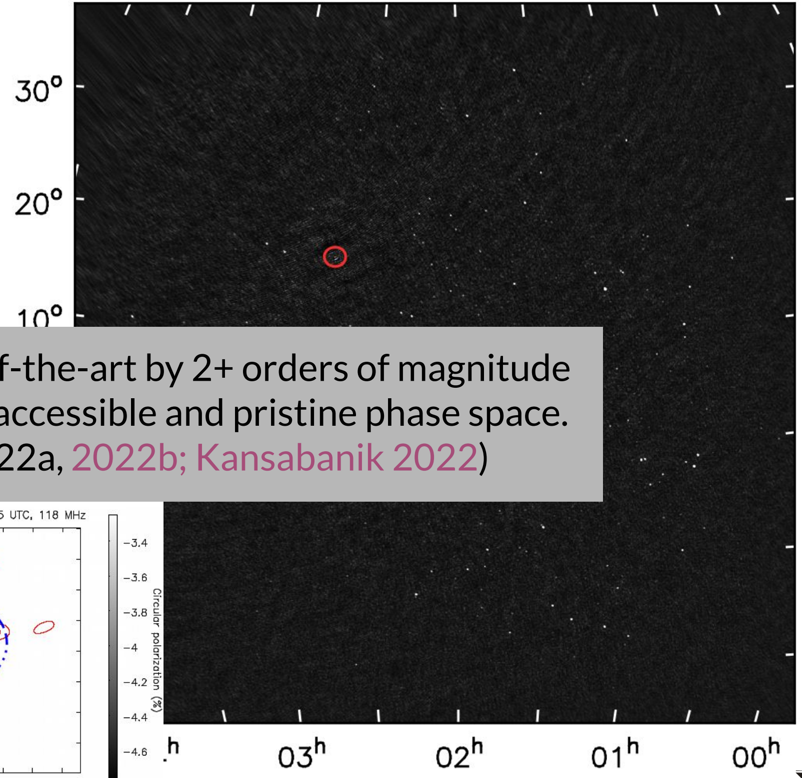
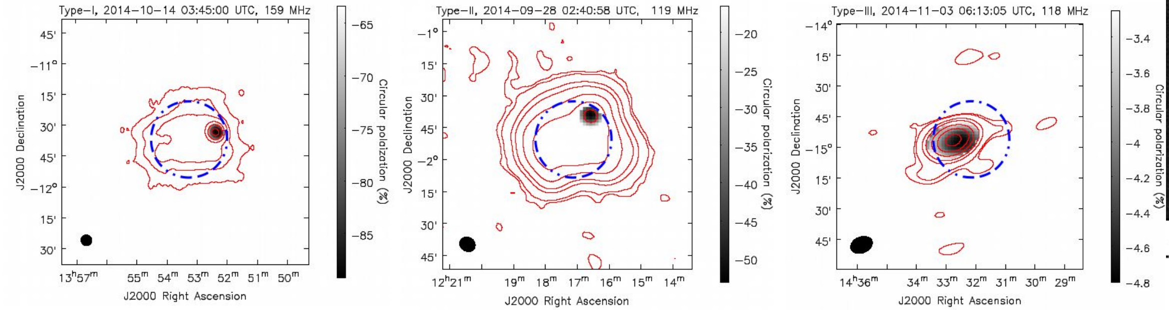
Making state-of-the-art solar radio images







These images exceed the DR of earlier state-of-the-art by 2+ orders of magnitude and are enabling explorations of previously inaccessible and pristine phase space.
(Mondal et al. 2019; Kansabanik et al. 2022a, 2022b; Kansabanik 2022)



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Discoveries (*)/ Realisations from our work

1. Weak nonthermal emissions are much more common than previously realised (*Suresh et al. 2018; Sharma et al. 2018, 2022*)
2. Gyrosynchrotron emission from CMEs is much more common than previously thought (*Mondal et al. 2020a; Kansabanik et al., 2022c*)
3. * WINQSEs - Weak Impulsive Narrowband Quiet Sun Emissions - Strongest observations evidence for nanoflares from the Quiet Sun (*Mondal et al., 2020b, Mondal 2021; Bawaji et al. 2022; Mondal et al. 2022*)
4. * Quasi Periodic Pulsations in a range of active solar radio emissions - evidence for ubiquitous presence of MHD waves in the quiescent corona (*Mohan et al. 2019a, 2019b; Mohan 2021a, 2021b; Mondal & Oberoi, 2021*)
5. * Detection of linearly polarised emission from active solar emissions (*Dey et al., 2022*)
6. * Detection of circularly polarised emission from quiet Sun (*Kansabanik et al., 2022d*)

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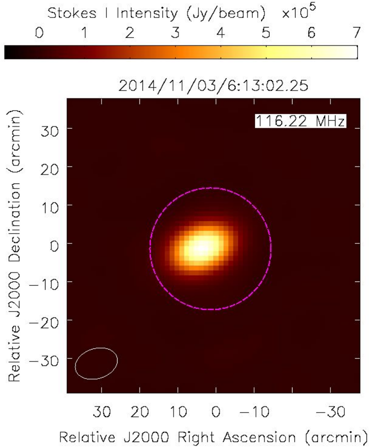
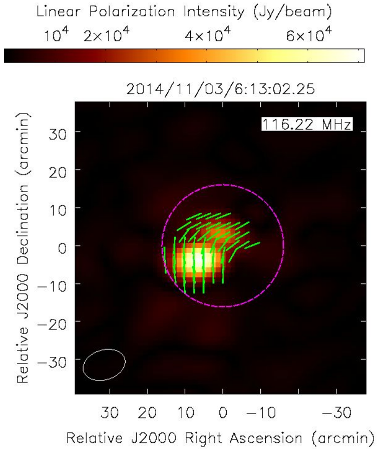




Challenge: from data to images

4D data stack per Stokes parameter $S(\theta, \phi, t, \nu)$

Stokes parameters are a 4 vector $S = [I, Q, U, V]$

Need to examine a 4x4 dimensional phase space

Time resolution = 0.25s (0.5s till recently)

Frequency resolution = 40 kHz

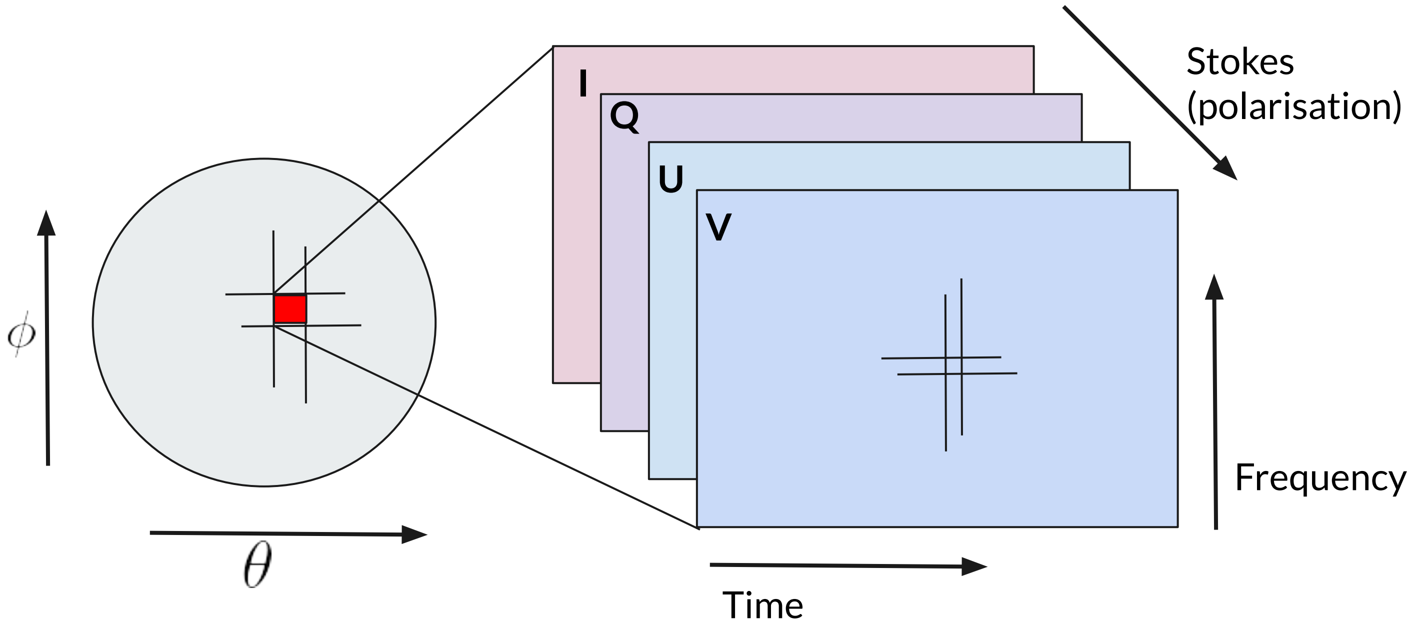
# of images per hour = 11 million

Data in the archive > 3000 hours (> 3PB)

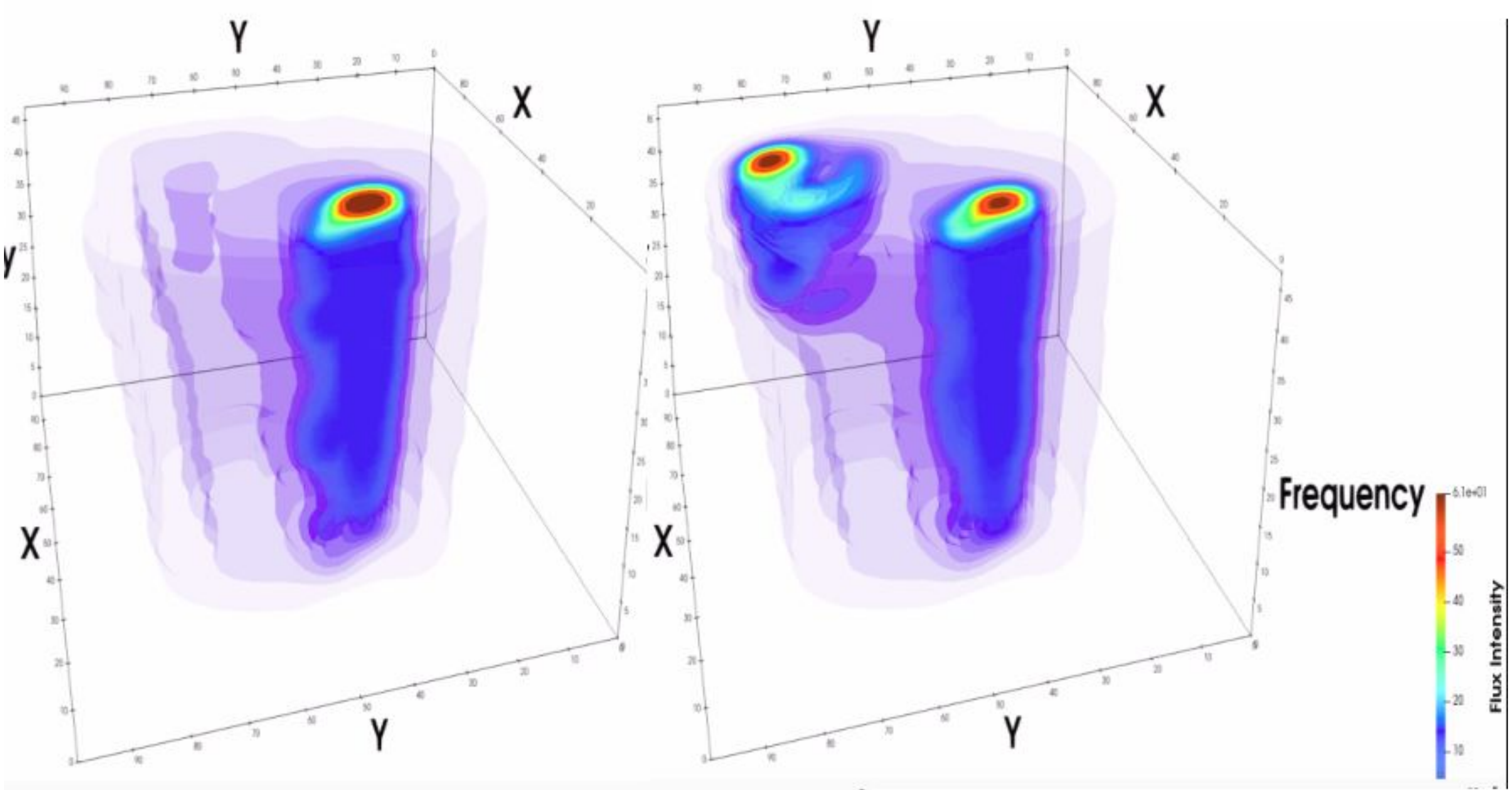
The challenge of imaging:

- Algorithmic complexity
  - Mostly under control
- Computational capacity
  - Efforts underway to enhance compute capacity
  - Not the limiting factor currently

Structure of data



A stack of spectral slices (Stokes I)



Challenge: from images to science

Extracting information from these image hypercubes (5D space) $(\theta, \phi, t, \nu, S)$

All sorts of creatures live in this zoo:

- Wide variety in time and frequency structures (<0.5s to tens of minutes)
- Large spans in intrinsic brightness and polarisation properties
- Motion in the image plane, changes in morphology
- Variations in parameters (e.g. linear growth; quasi periodicities in intensity, area and orientation)
- Relationships between different parameters (e.g. anti-correlation between area and intensity)
- Relationships with observations at other bands (X-ray, Extreme-UV, UV)

We will find only (some of) what we look for, and we will (mostly) look only for what we expect/imagine.

Risk missing discoveries...

Problem ill-suited for the human brain...

More capable telescopes on the way (Square Kilometer Array), will provide even more detailed information...

Rich ground for AI/ML approaches

Well suited for AI/ML application

- Looking for structures, patterns, relationships in a large multi-dimensional dataset
- Part of it might be posed as a ‘classification problem’
- Other parts might be ‘unguided discovery’

- Taking baby steps
  - Identifying and characterising weak emission features in frequency-time plane (no imaging, Stokes I only; Suresh et al., 2018)
  - Locating WINQSEs and characterising their morphology one image at a time - conditioning noisy data + heuristics for fitting weak (~1%) 2D Gaussians (Bawaji et al, 2022);
  - In collaboration with e4r ThoughtWorks

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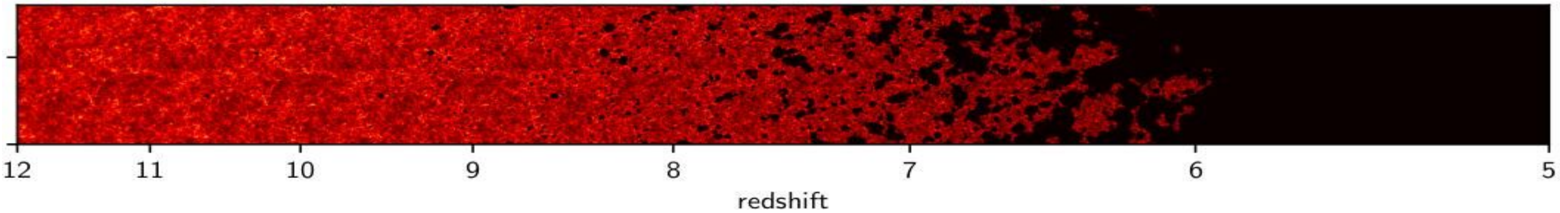
Reionization simulations (Tirthankar Roy Choudhury, NCRA)



Epoch of reionization: the cosmic phase when hydrogen was ionized by the first stars.

Studied using observations in different wave bands, from 21 cm (radio) to CMB (microwave) to quasar absorption spectra (NIR/optical/UV).

Interpretation of the data requires theoretical modelling via simulations, often expensive (~hours-days to run). Uncertain physics leads to unknown parameters in the models.

Bottleneck: exploring the parameter space demands running these simulations multiple (few thousand) times, practically impossible with current resources.

Solution: use AI-based emulators (train + predict). Possible techniques: GPR, ANN, SVM.

Challenge: optimizing the algorithm for a particular simulation technique. Work in progress.

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