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Frequency-time-resolved Imaging Spectroscopy of Fine Structures in a Solar Radio Noise Storm

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Based on:
Clarkson & Kontar (2026), *ApJ* (Accepted)



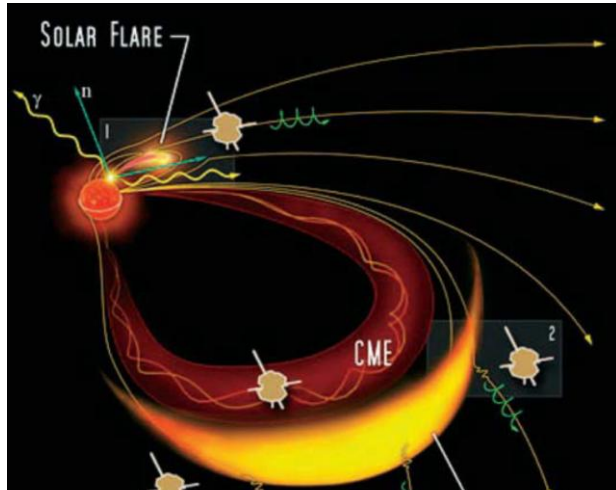
ApJ

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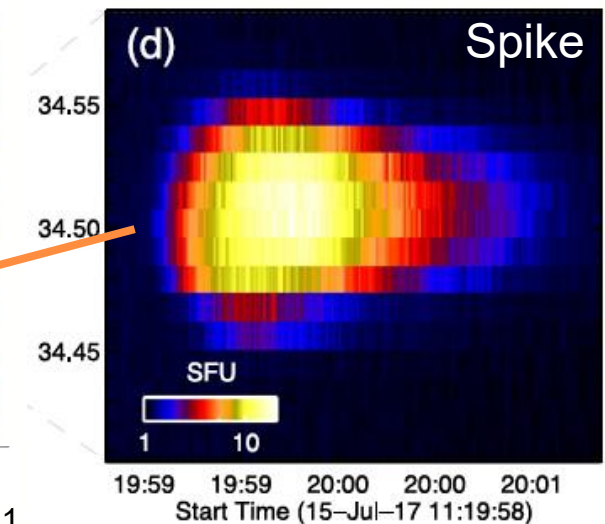
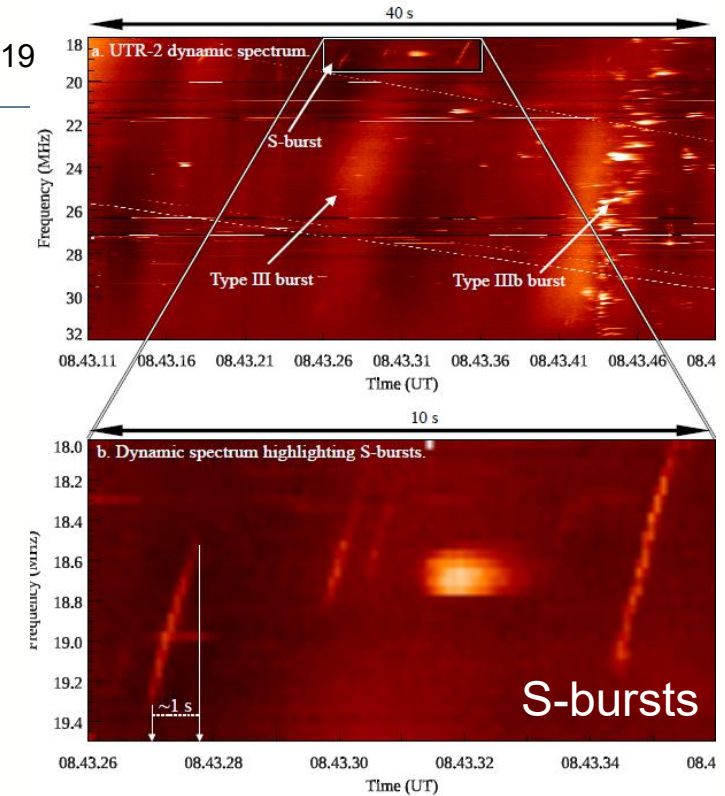
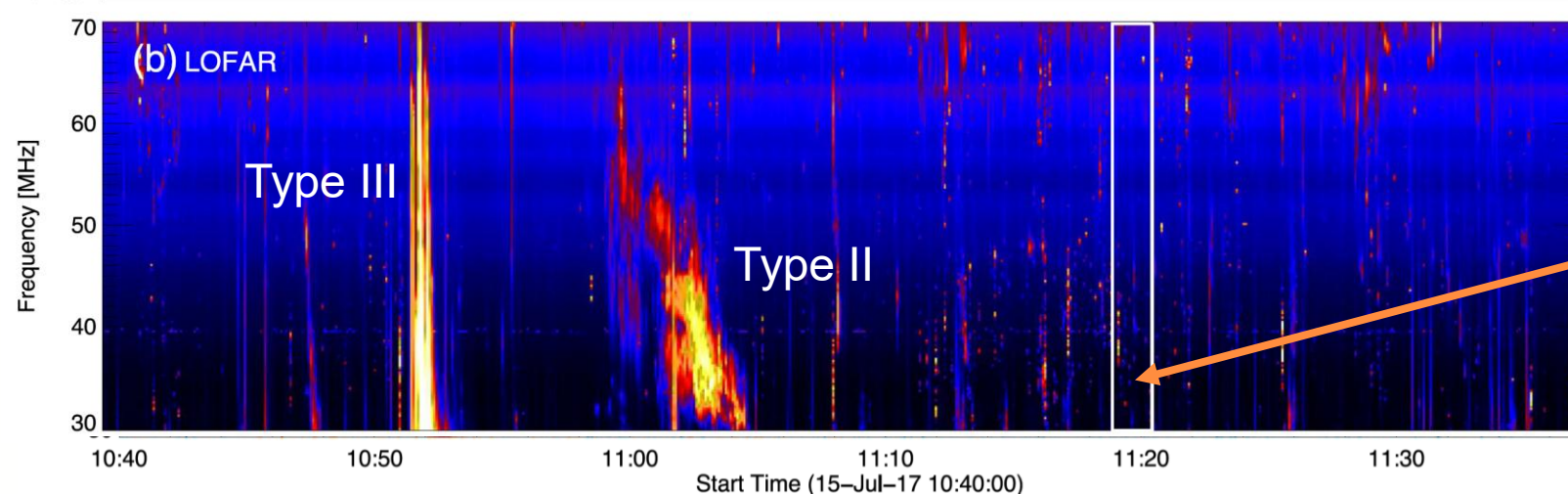
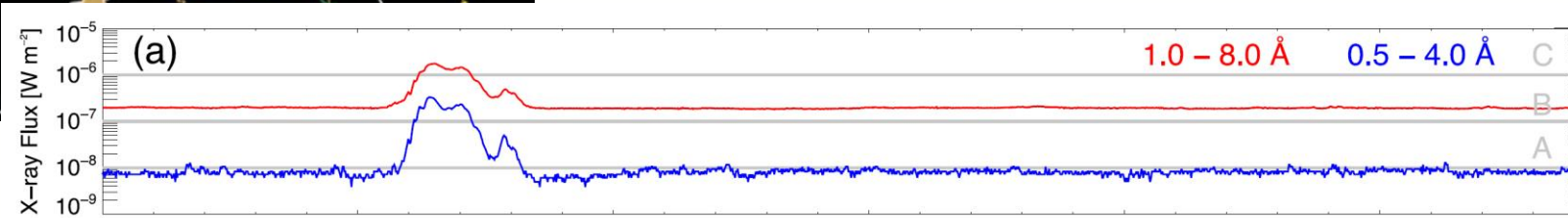


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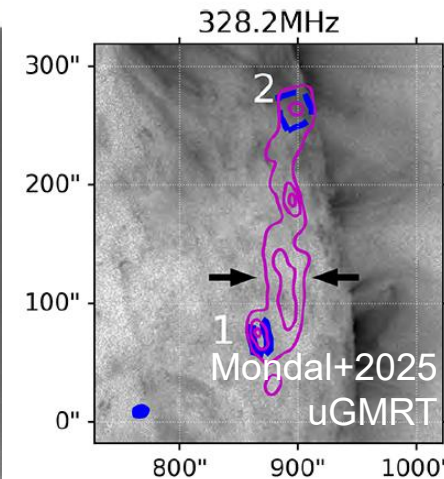
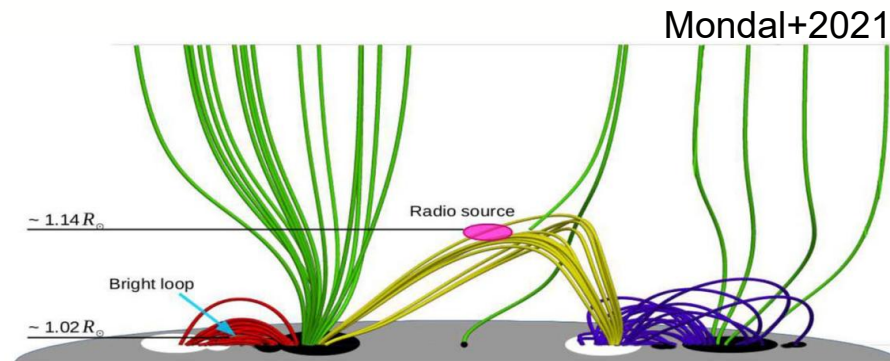
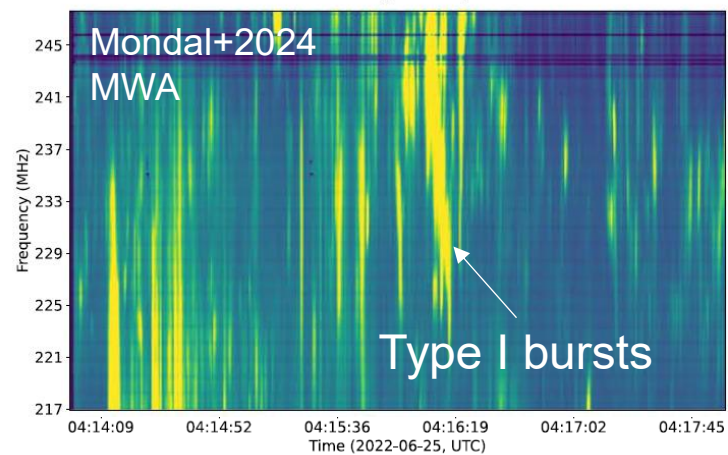
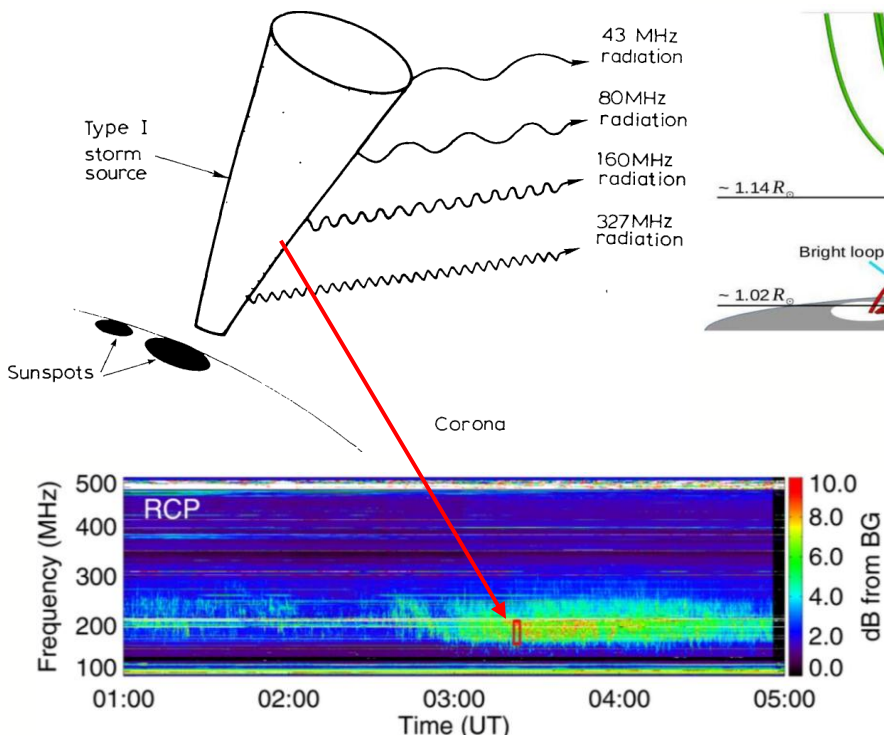




- Magnetic energy release from solar flares accelerates electrons to non-thermal energies
- Electron beams stream along magnetic field lines, generating radio waves near the local plasma frequency via the plasma emission mechanism
- Fine structures are associated with density turbulence modulating the emission process

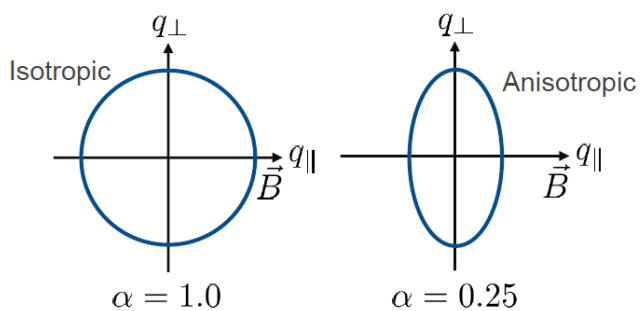
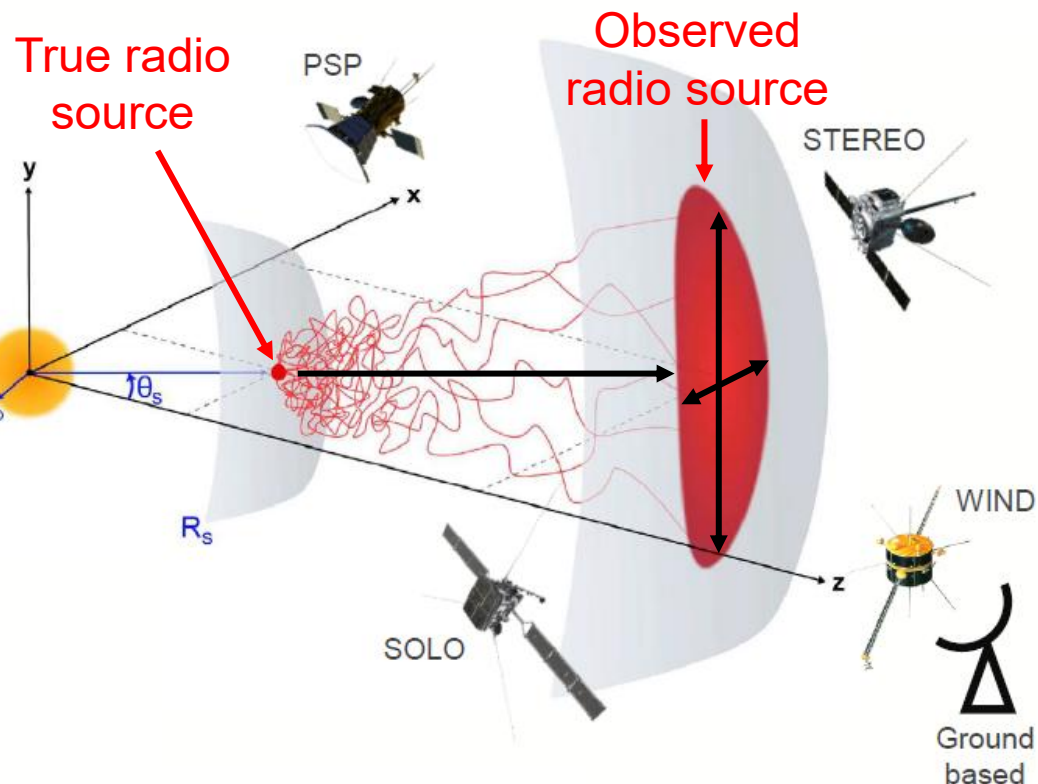


Type I Noise Storms



- Last hours to days, associated with complex sunspot groups, with the storm source (trapped electron populations) in loop structures
- Consist of many sub-second "Type I" bursts superimposed on continuum emission – distinct from other fine structures such as spikes, S-bursts
- High T_B and strong polarisation suggests fundamental plasma emission (coalescence of Langmuir waves with ion-sound waves)
- Imaging analysis indicates type I noise storm sizes are **smaller than type III** sizes
 - Puzzling, since radio-waves scattering dominates source sizes!
 - Small minor sizes have been used to suggest that the level of radio-wave scattering is overestimated (e.g. Mercier+2015)

Radio-wave Propagation



$$\alpha = \frac{q_{\parallel}}{q_{\perp}} = 0.1 - 0.4$$

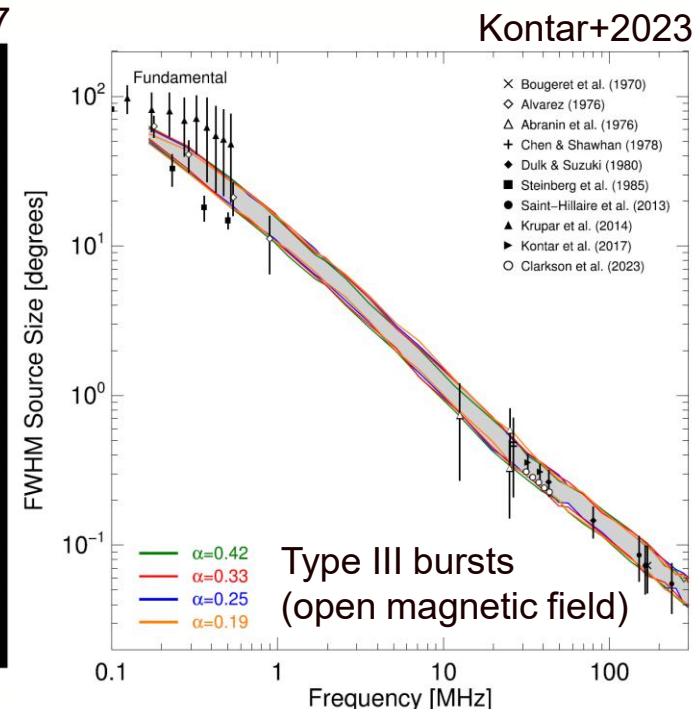
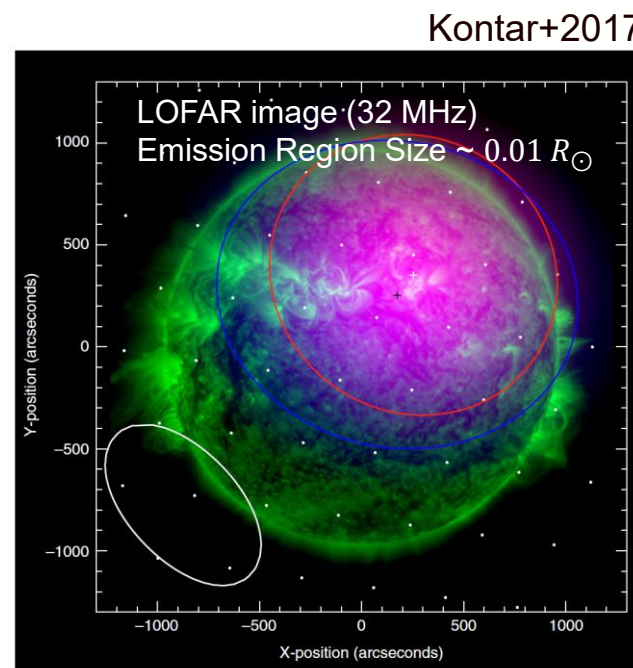
Field-aligned density fluctuations

- Elongated along magnetic field direction
- Anisotropic scattering shifts the apparent position of the source in the direction of the local magnetic field (*Kontar+2017, 2019*)
- ...and broadens the emission predominately perpendicular to the magnetic field

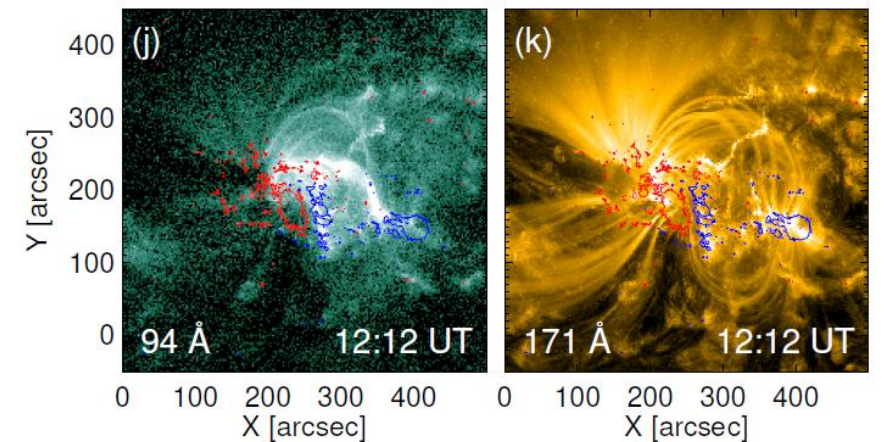
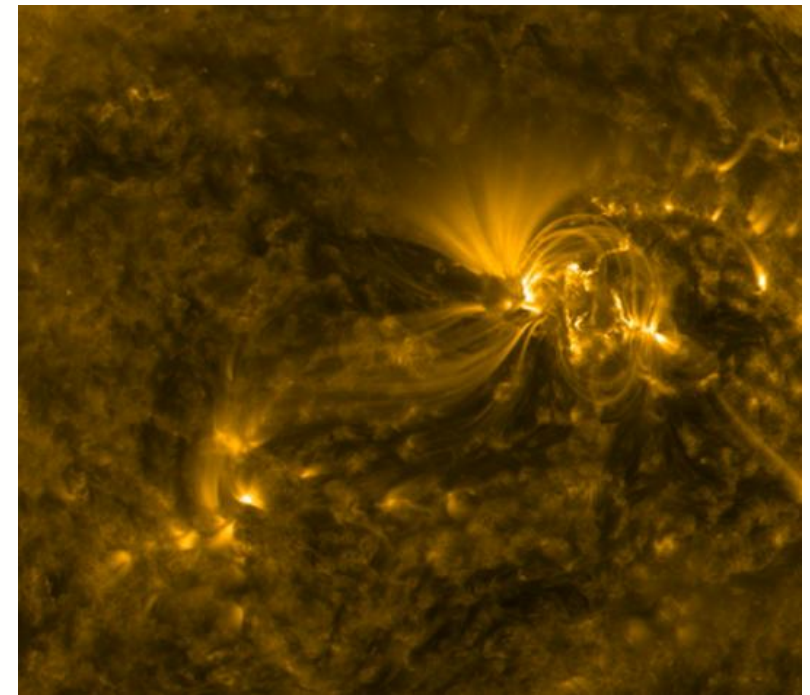
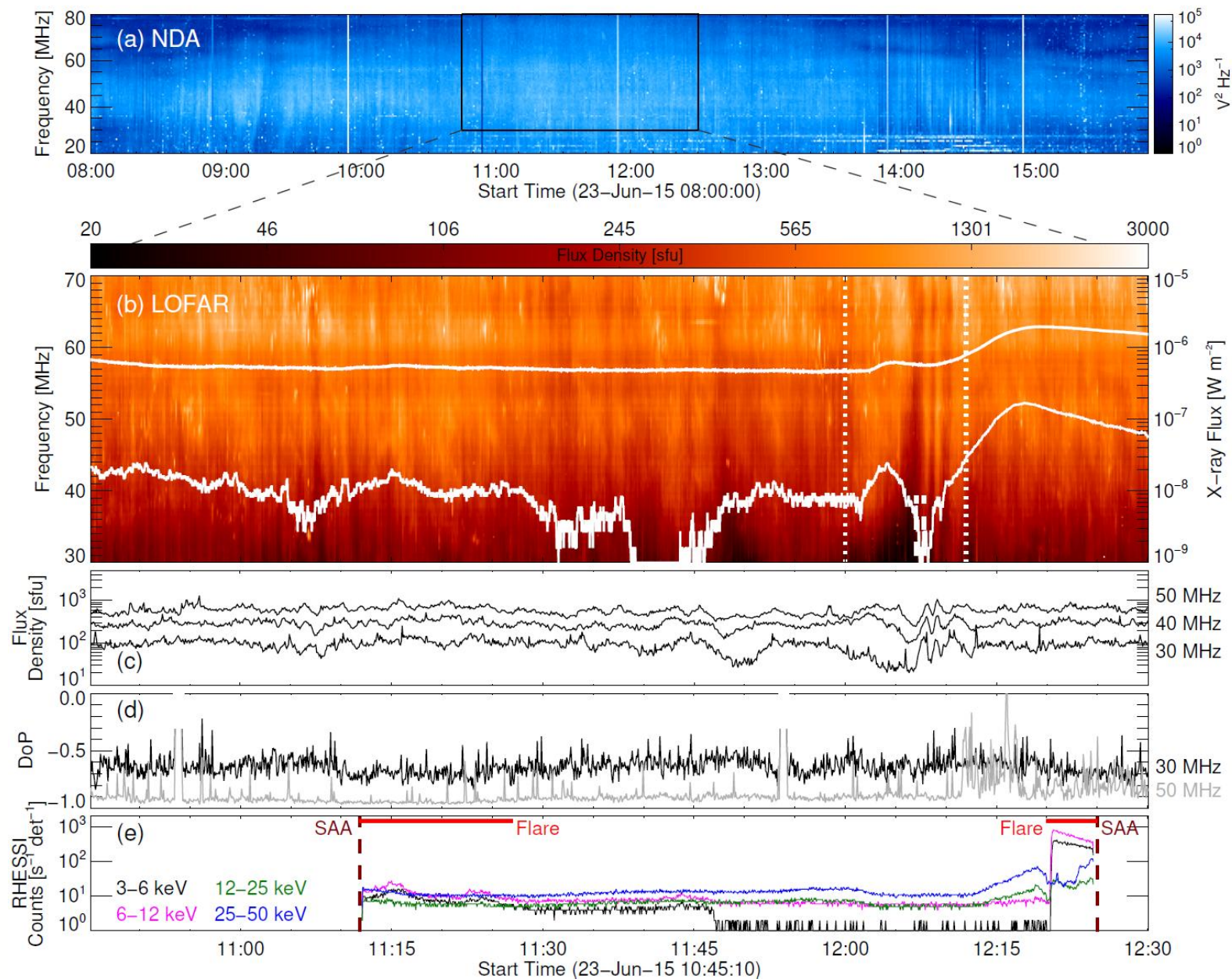
Radio-wave propagation affects:

- Position of the source
- **Size** of the source
- Shape of the source
- Directivity
- Time-profile
- Polarisation

Disentangling these effects is challenging...



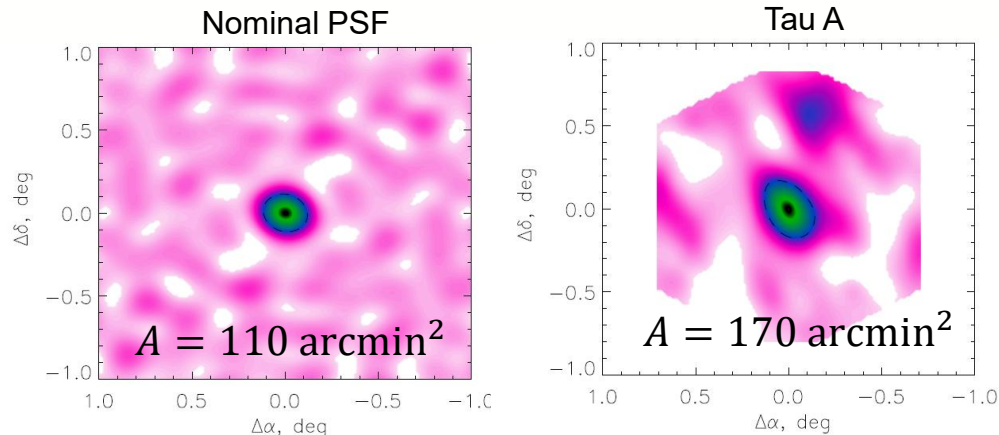
Type I Noise Storm Observed with LOFAR



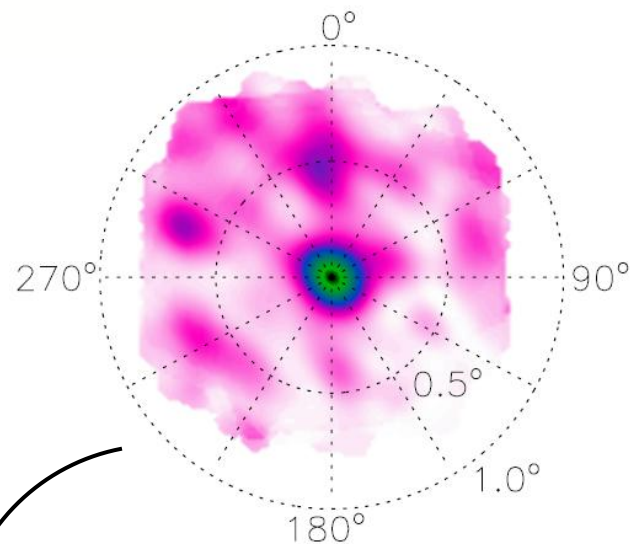
Type I Noise Storm Imaging

Gordovskyy+2022

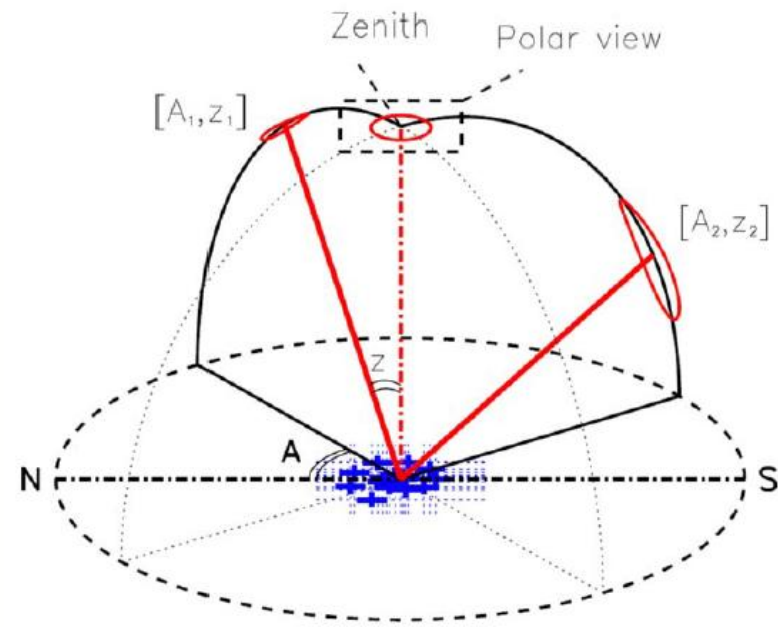
Tau A observed by LOFAR at **30 MHz**, compared to the nominal PSF at the same time & sky coordinates



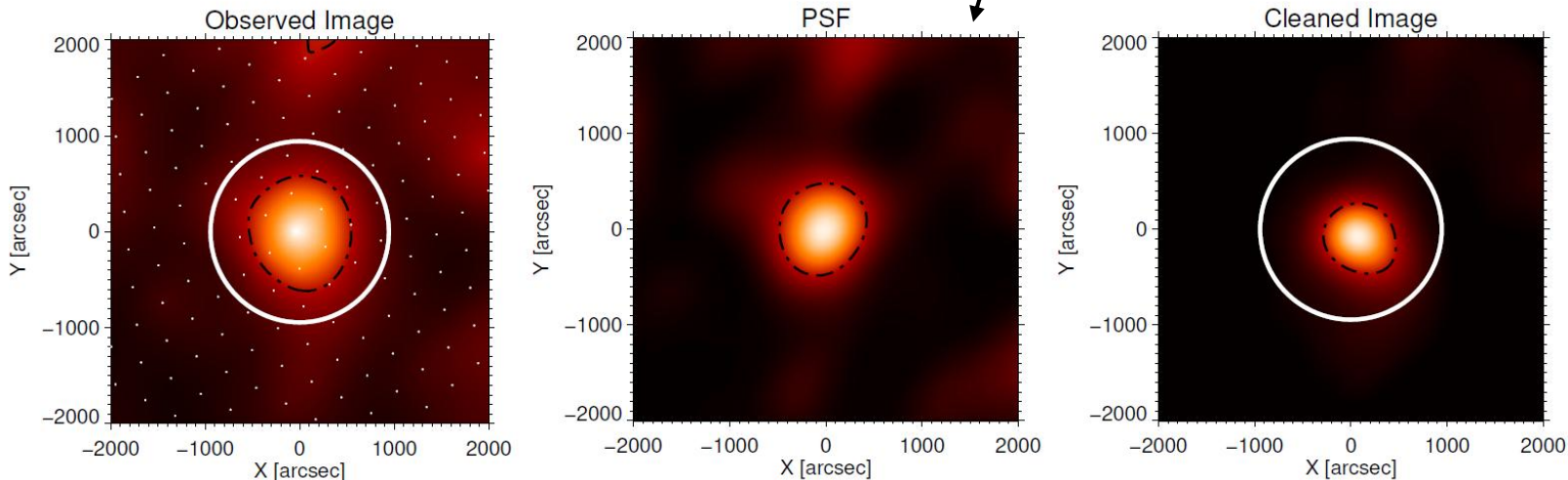
22 Tau A observations projected to zenith & averaged



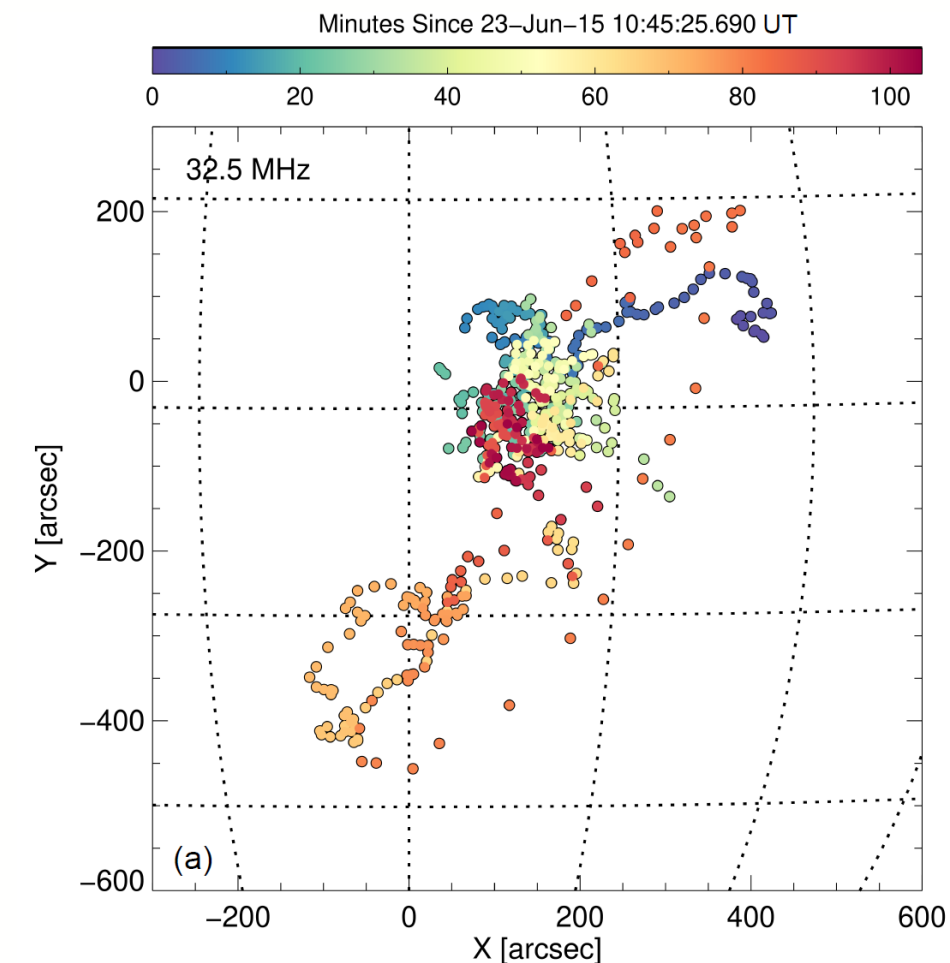
Rotated to solar position on date & time of observation



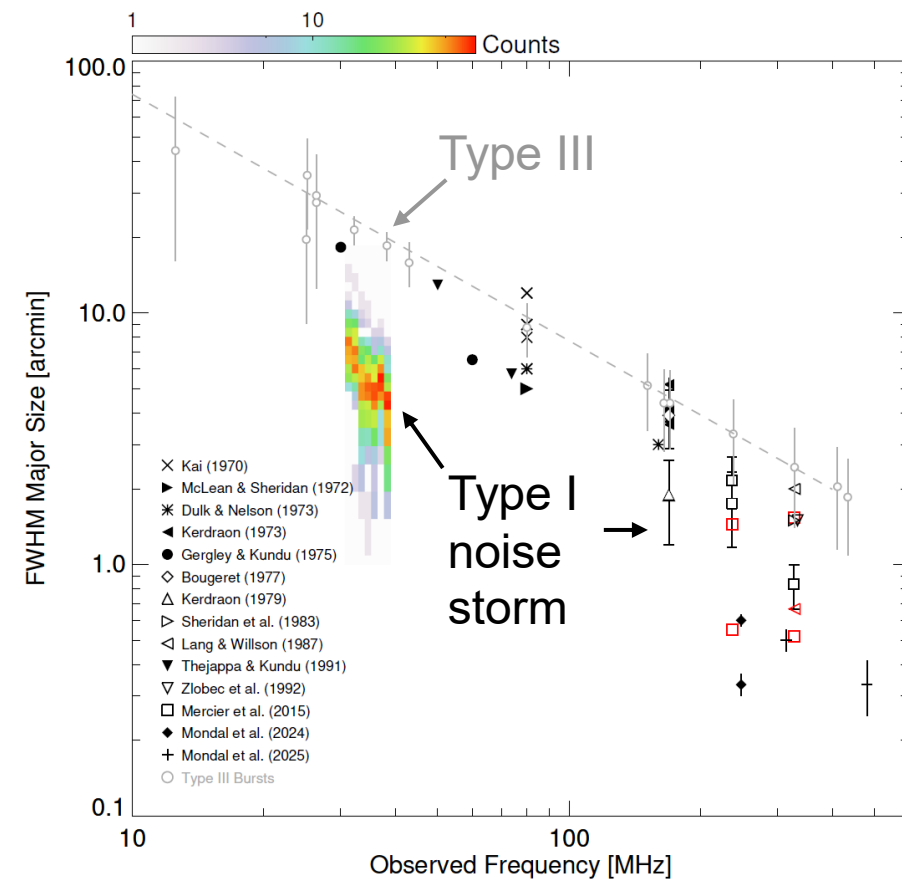
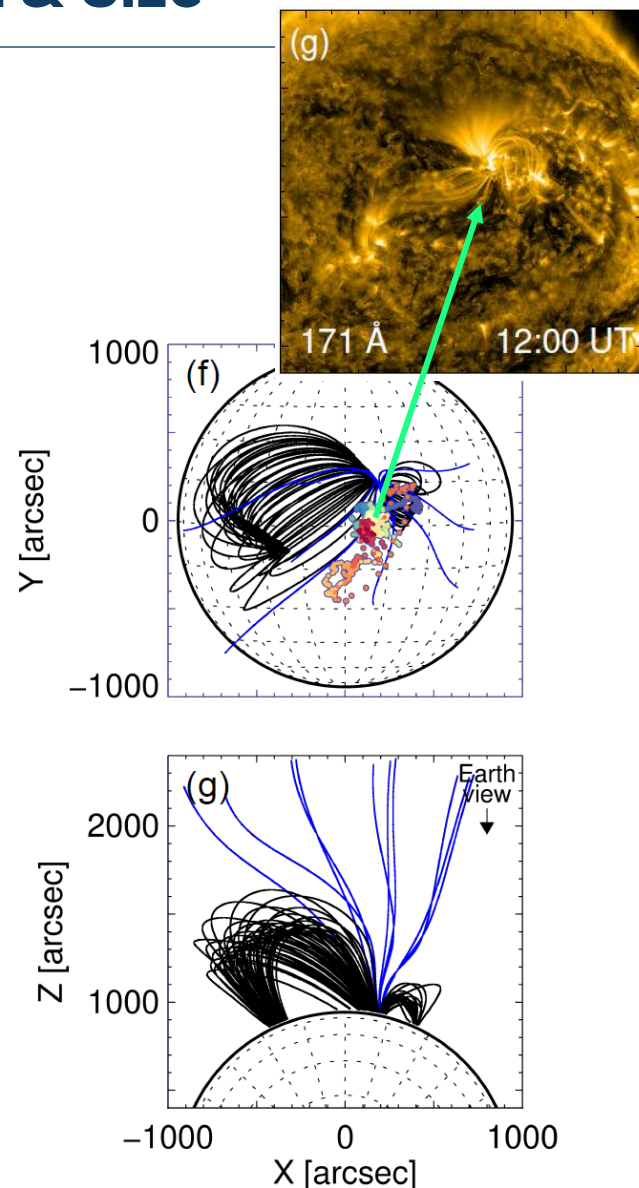
- LOFAR observations performed in tied-array beam forming mode
- 24 LBA stations in the outer configuration
- 10 ms temporal and 12.2 kHz spectral resolution
- 169 beams pointing across the solar disk and corona



Type I Noise Storm Position & Size



Noise storm source is moving along the field lines bridging two active regions approximately near the Alfvén speed



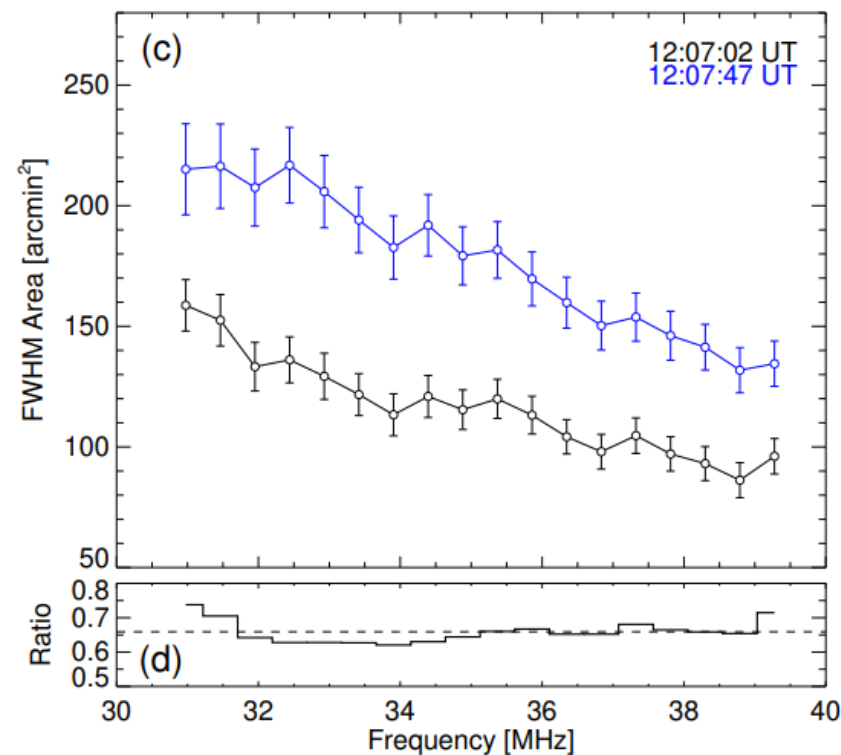
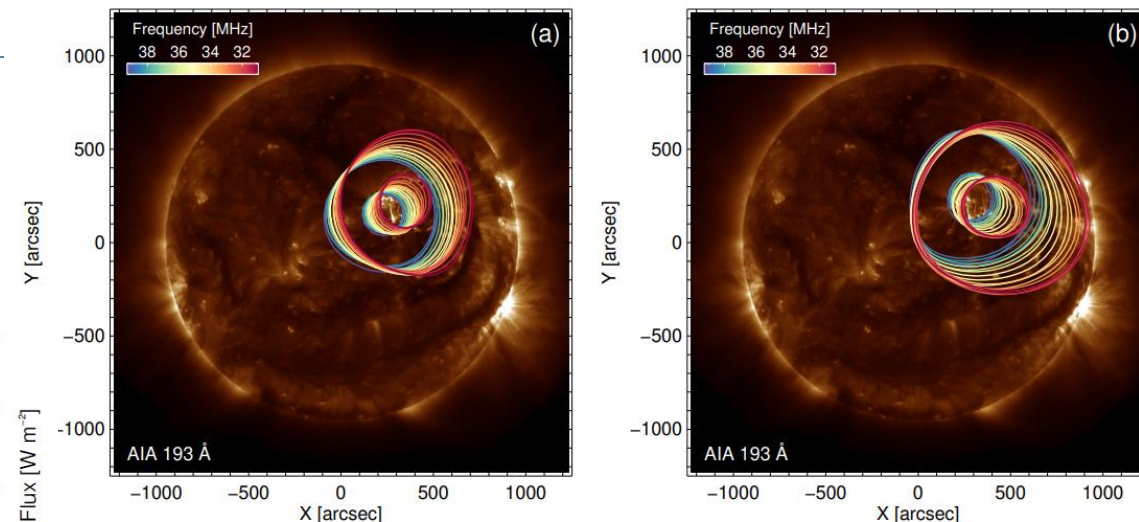
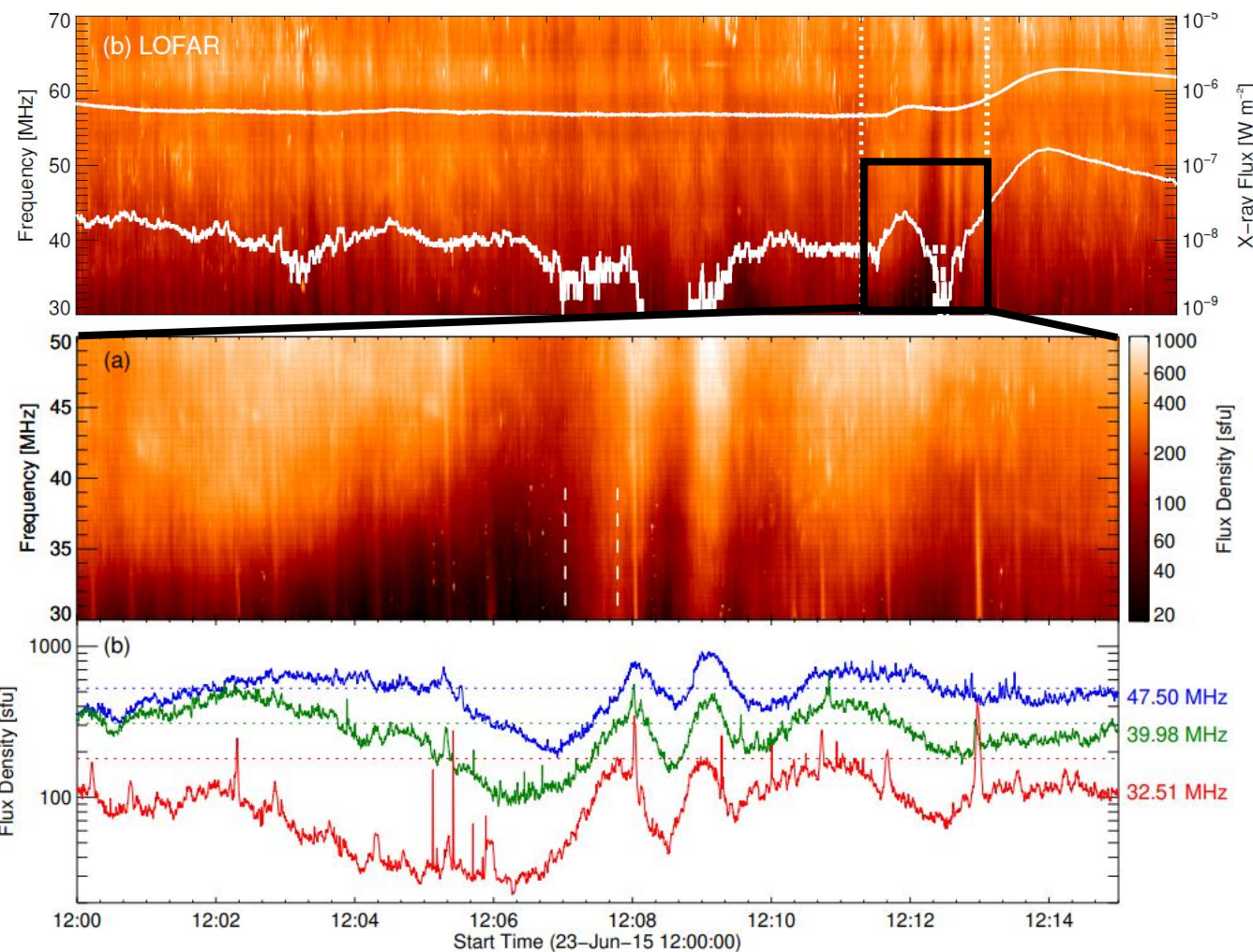
Sizes determined using 2D Gaussian fits to cleaned images and beam-corrected

Noise storm sizes >2x smaller than type III
→ **needs explaining within same scattering model!**

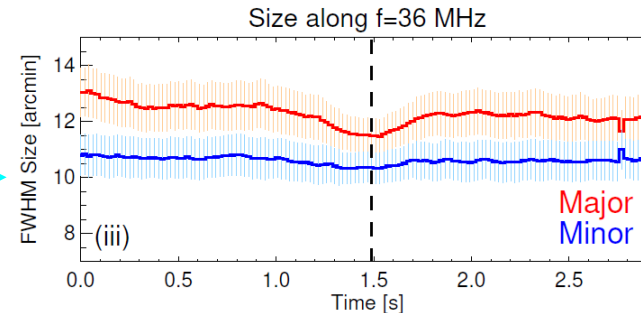
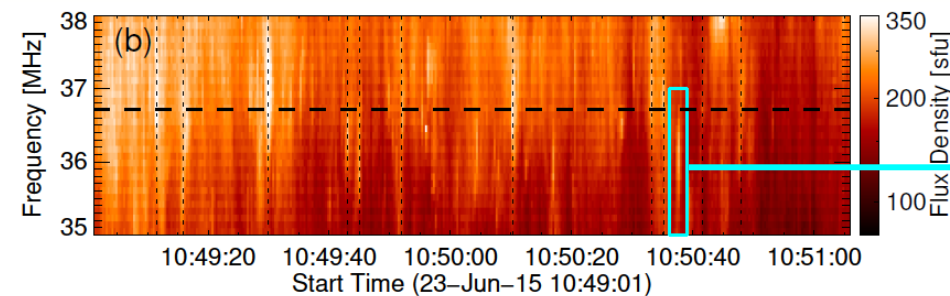
Noise Storm Size

Continuum size larger after the flaring episode, possibly related to:

- a change in the magnetic field topology?
- a change in the density, turbulence, anisotropy?

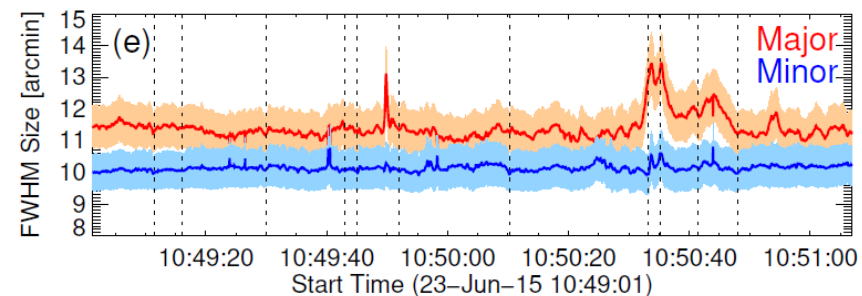
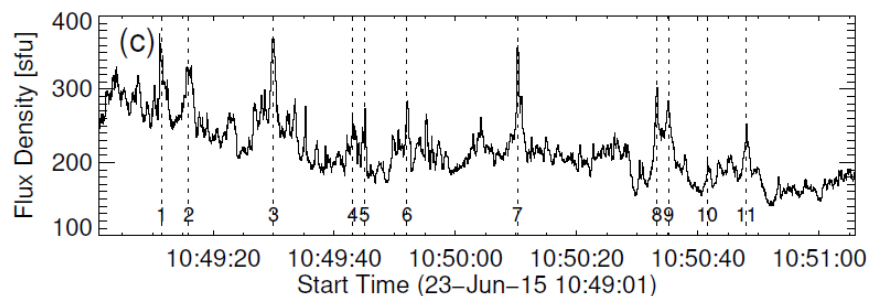


Size Over Minute and Sub-second Scales

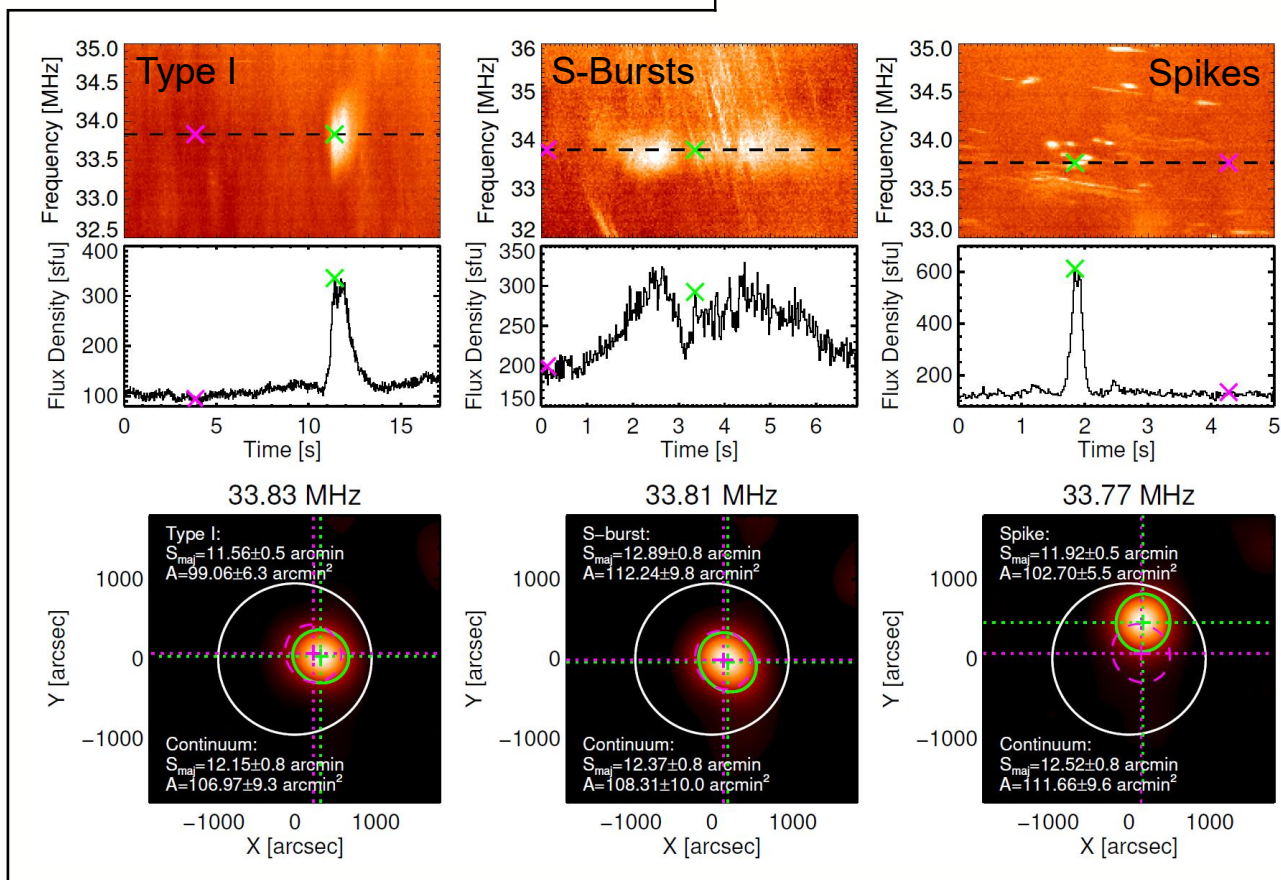
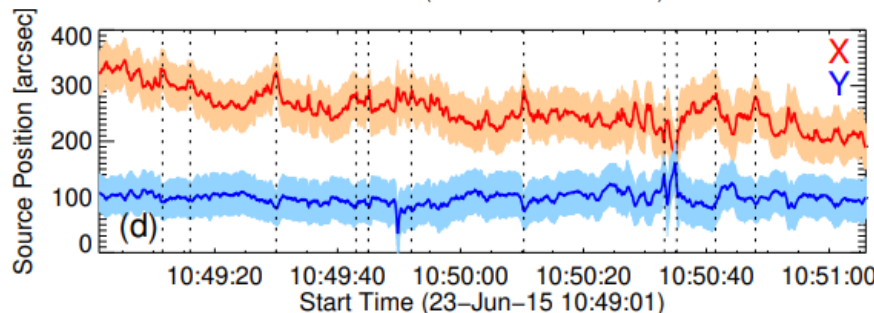


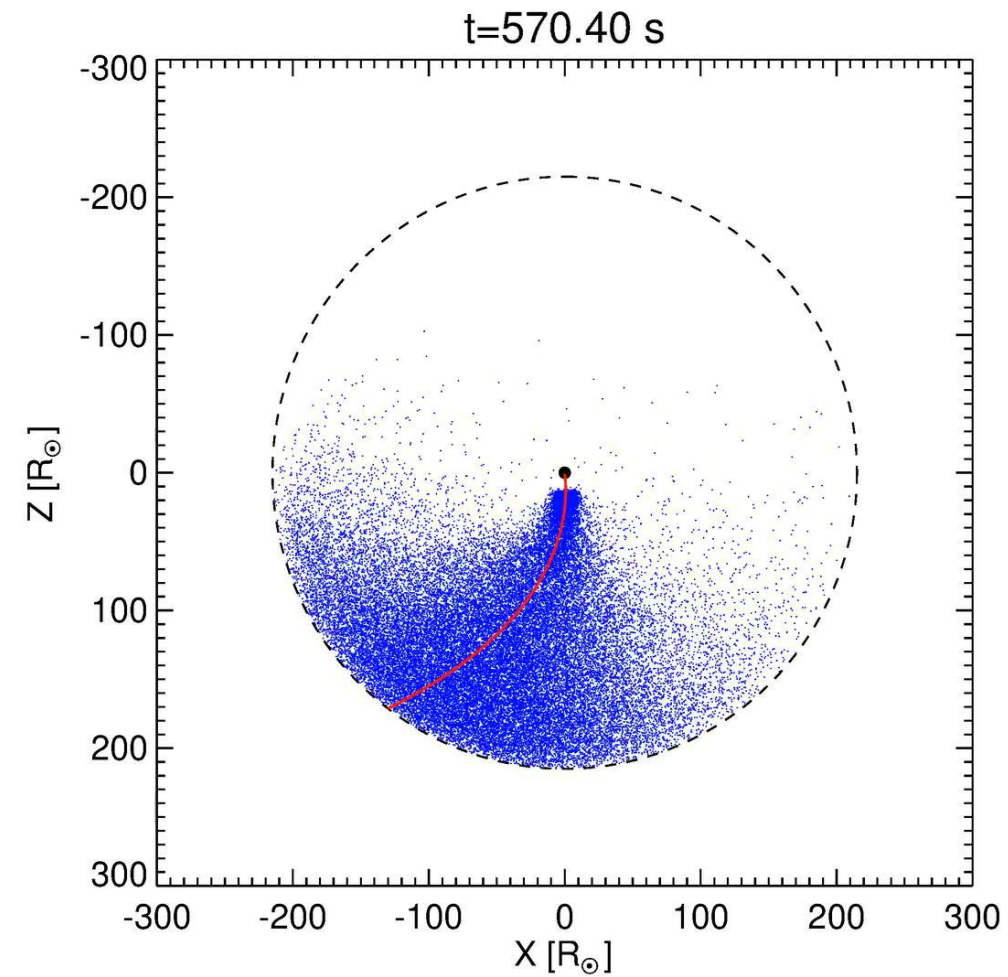
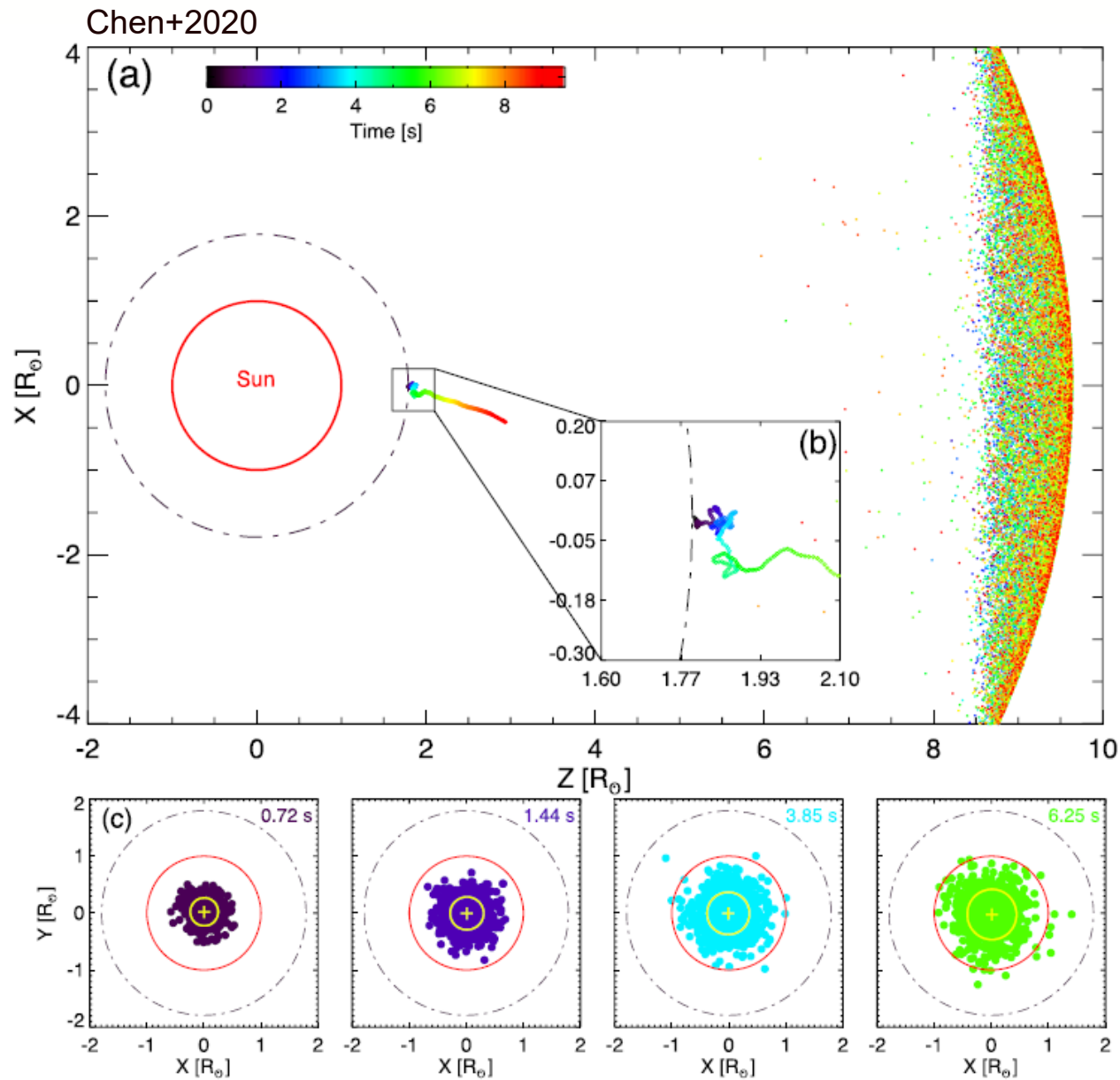
Type I bursts, spikes, S-bursts, and continuum present identical sizes within the uncertainties

- Require a common size-determining mechanism that should also apply to type III!

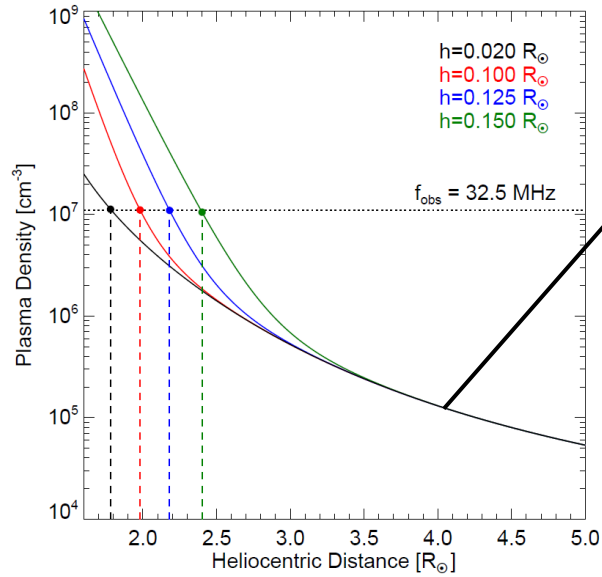


No change in size between the continuum and type I bursts





Apparent Source Size in Open & Closed Magnetic Fields



$$n_p(r) = 4.8 \times 10^9 \left(\frac{r}{R_\odot} \right)^{-14} + 3 \times 10^8 \left(\frac{r}{R_\odot} \right)^{-6} + 1.4 \times 10^6 \left(\frac{r}{R_\odot} \right)^{-2.3}$$

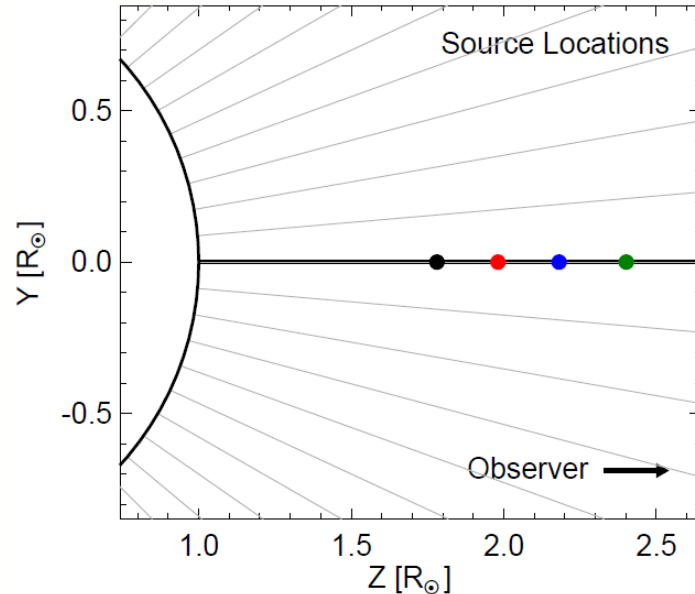
$$n_l(r) = 10^{11} \exp\left(-\frac{r-1}{h}\right)$$

$$n(r) = n_p(r) + n_l(r)$$

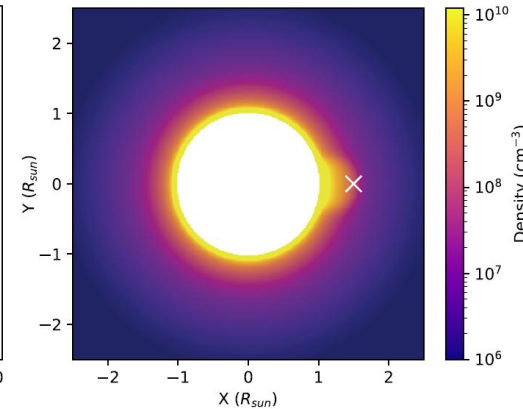
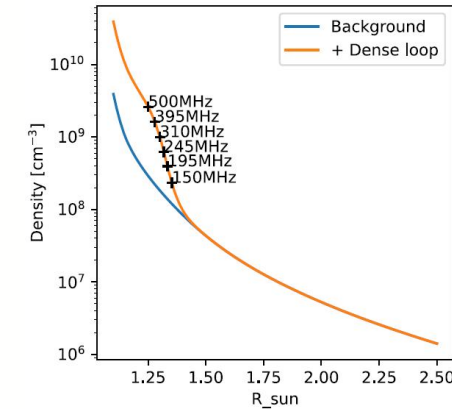
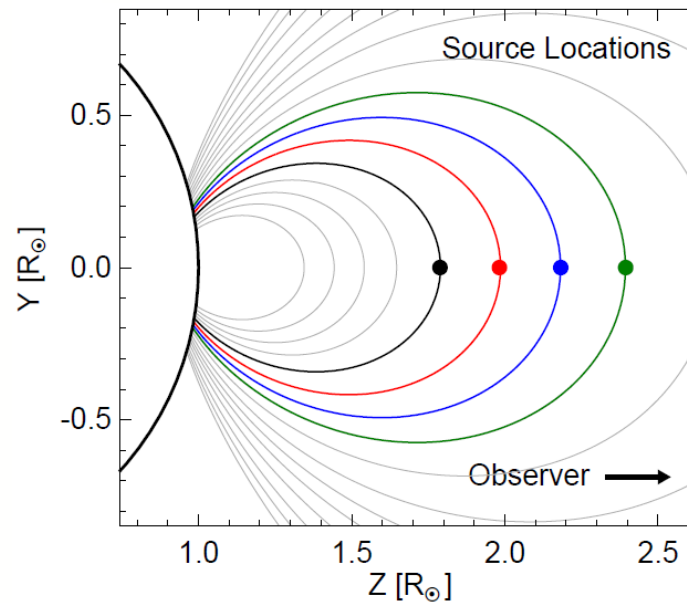
$$\mathbf{B}(\mathbf{r}', \phi') = \frac{B_0}{(r')^3} (2 \cos(\phi') \hat{\mathbf{r}}' + \sin(\phi') \hat{\boldsymbol{\phi}}')$$

- We simulate over-dense structures, and open/closed magnetic fields
- Steeper density gradient causes “shell” of strong scattering to be narrower
 - Radio-waves propagate away from the plasma frequency surface faster
- Simulated over-dense regions in scattering simulations performed by Mondal+2025
 - Resulted in smaller sizes compared to background density levels, but fell short of reproducing the observed compact sizes

Open Field

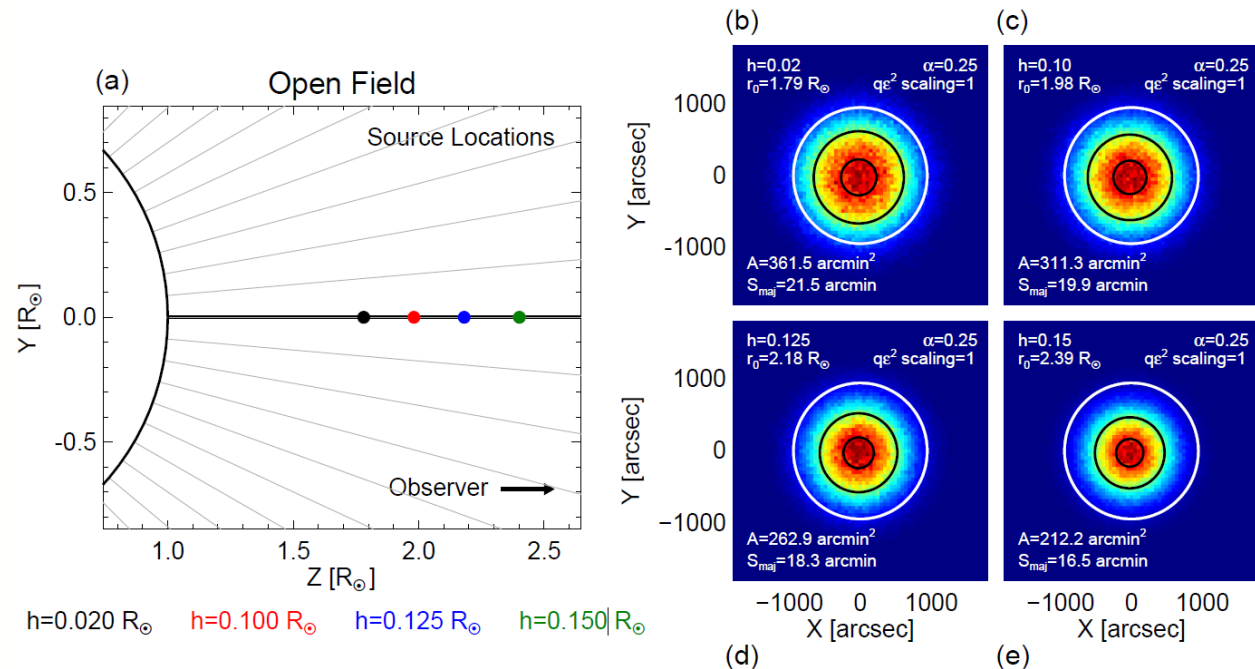


Closed Field



Mondal+2025

Apparent Source Size in Open Magnetic Fields (32 MHz)



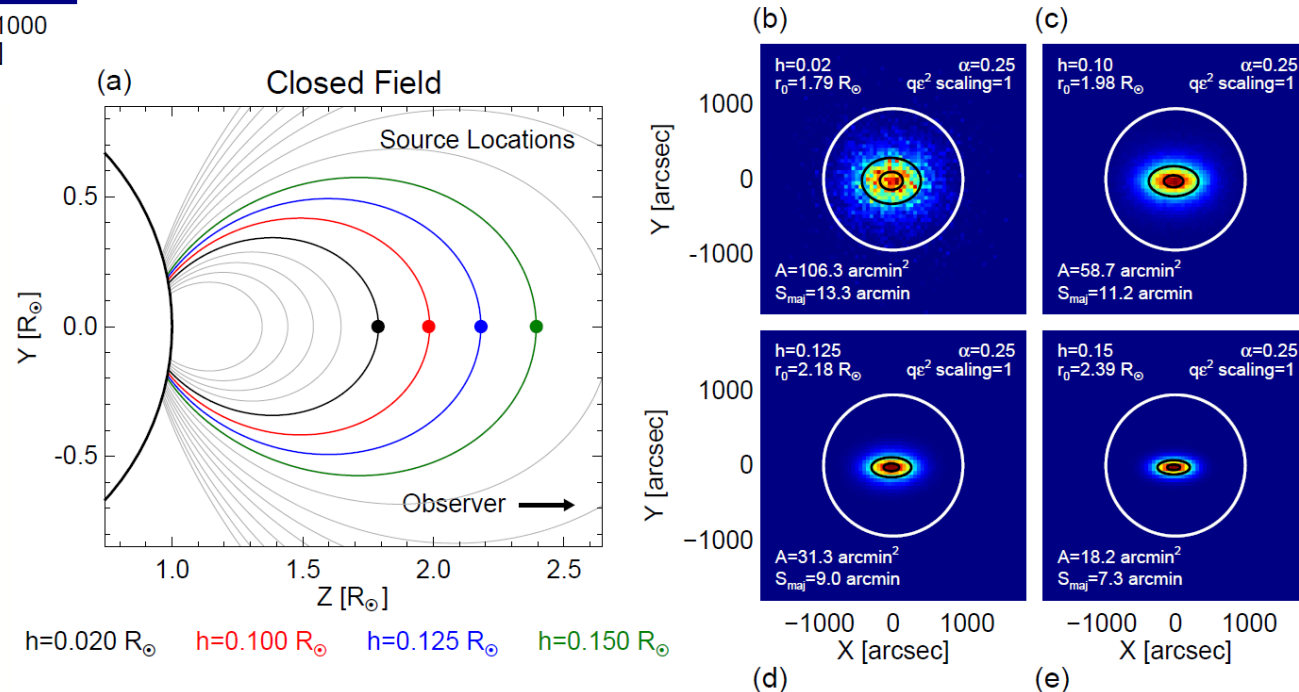
Open field:

- Steeper density gradient reduces the source size between $\sim 1 - 5$ arcmin. Still approx. double the observed sizes

Closed Field:

- Introducing a dipolar field reduces source size by 8 arcmin compared to the radial case $\rightarrow$ photons are preferentially scattered away from the observer
- Stronger anisotropy reduces source size by 4 arcmin
- Halving scattering rate reduces source size by 20% (same as the radial case)

- Compact sizes of type I noise storms is achieved mainly using a closed magnetic field structure
- Apparent size of solar radio sources are governed by the large-scale coronal environment rather than the intrinsic emission processes
- Provides a unified explanation for compact sizes of diverse fine structures within noise storms **using the same scattering model** that reproduces type III burst properties



- Noise storm continuum source drifts across the solar disk over tens of minutes along closed magnetic field structure bridging two active regions
- Between 30-40 MHz, measured major axis is between 4.3 arcmin (38 MHz) to 8.0 arcmin (31 MHz), more than twice as small as type III bursts
- Different burst types in the same noise storm exhibit varied morphology yet identical compact sizes, suggests a common size-determining mechanism
- Radio-wave propagation simulations show that compact source sizes arise naturally for emission embedded within closed magnetic structures – same turbulence model also explains larger type III sizes (open fields)
 - Secondary influences: enhanced densities and steeper gradients, reduced turbulence, stronger fluctuation anisotropy
- Magnetic topology & anisotropic scattering plays a crucial role in determining the observed source size, and should be considered when interpreting solar radio bursts



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