Sizes and shapes of spike sources observed by LOFAR

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Introduction

- Low density and magnetic field in the upper corona of the Sun mean that low-frequency radio-emission is the only source of information about energetic particles in this part of the solar atmosphere

- Spatial distribution of coherent radio emission is a unique diagnostic tool for
  - propagating energetic particles
  - plasma density structure
  - plasma turbulence

  in the upper corona

- Electron acceleration and beam kinematics – e.g. *Carley et al. 2016, Reid & Kontar 2017, Morosan et al. 2019*

  Scattering and turbulence – e.g. *Kontar et al. 2017, Chrysaphi et al. 2018, Kontar et al. 2019, Gordovskyy et al. 2019, Chen et al. 2020, Murphy et al. 2021, Clarkson et al. 2023, Chen et al. 2023 …*

Spikes

- Clarkson et al. 2021 ApJL 917 L32
- Clarkson et al. 2023 ApJ 946 33

First Frequency-time-resolved Imaging Spectroscopy Observations of Solar Radio Spikes

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Solar Radio Spikes and Type IIIb Striae Manifestations of Subsecond Electron Acceleration Triggered by a Coronal Mass Ejection

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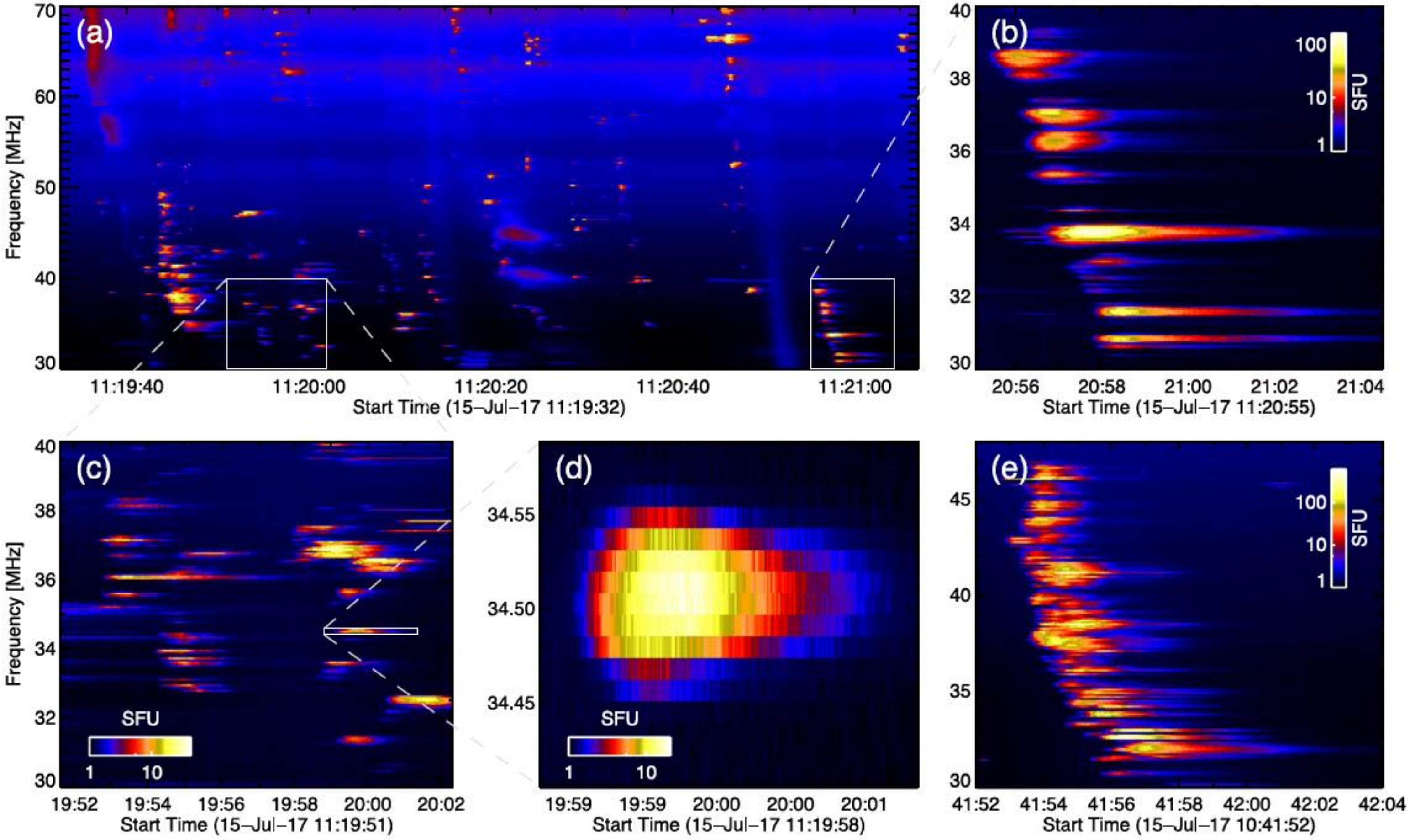
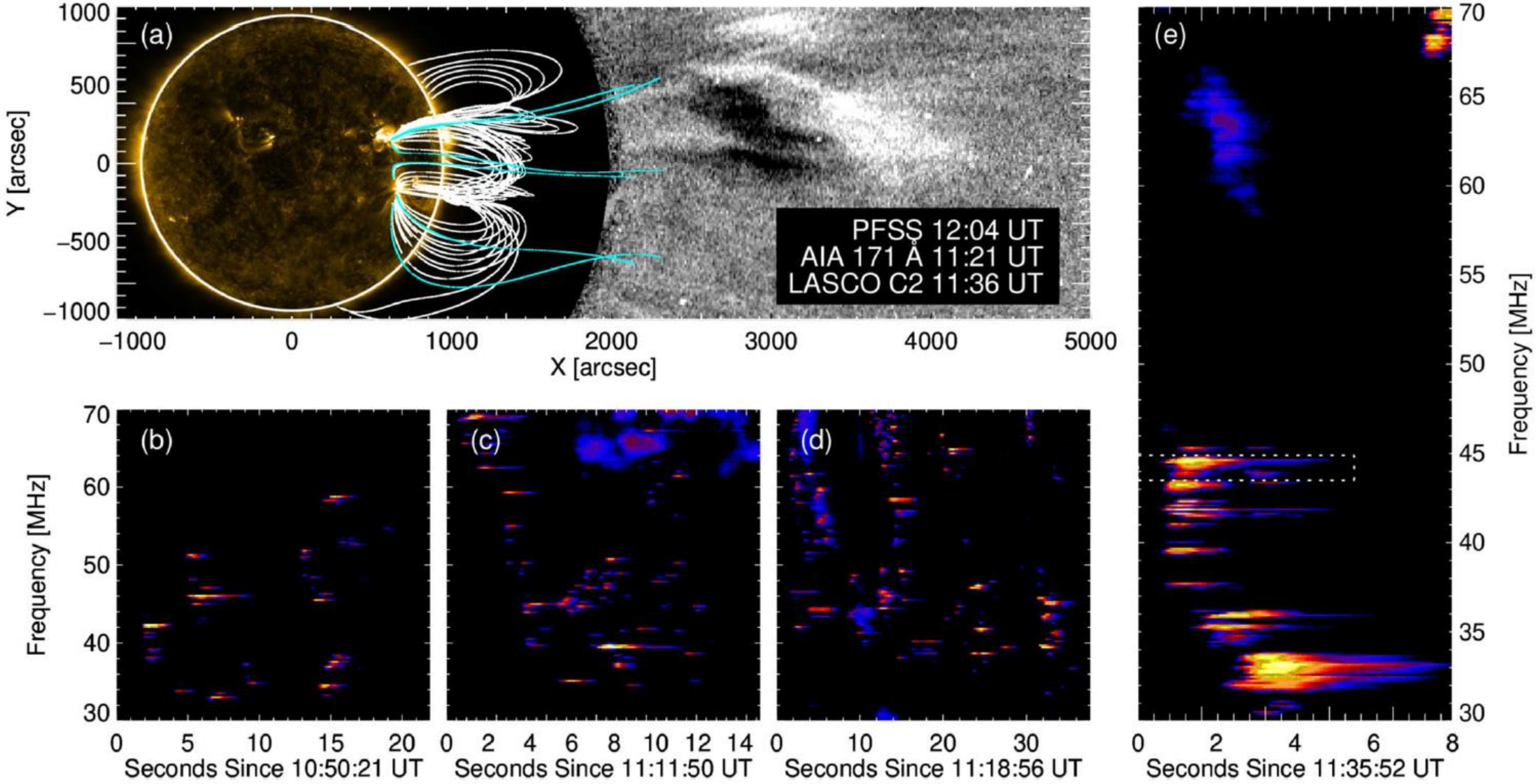
Spikes in DS



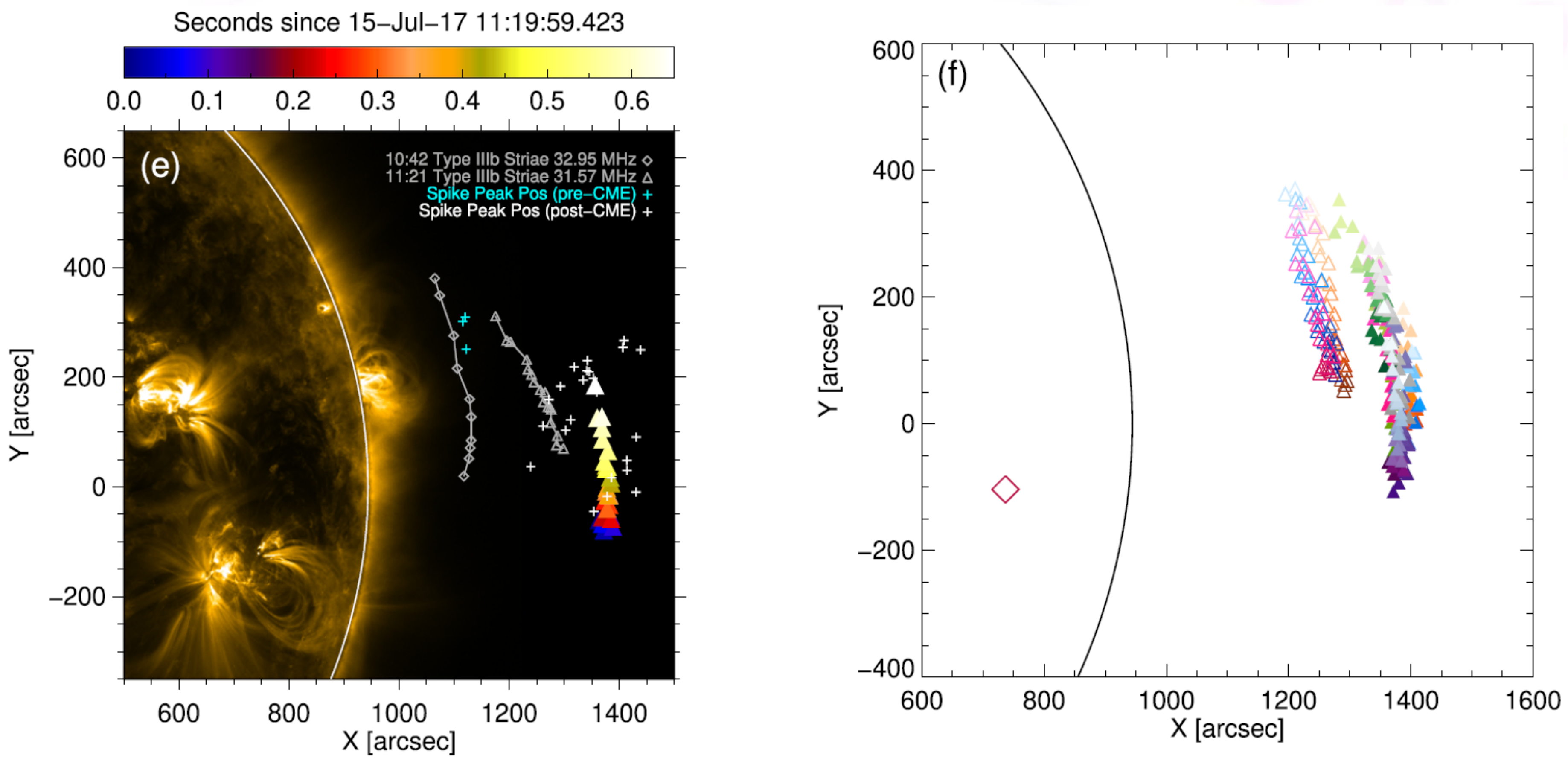
Clarkson et al. 2021 ApJL

Spikes in DS



Clarkson et al. 2023 ApJ

Spikes – apparent motion of apparent sources



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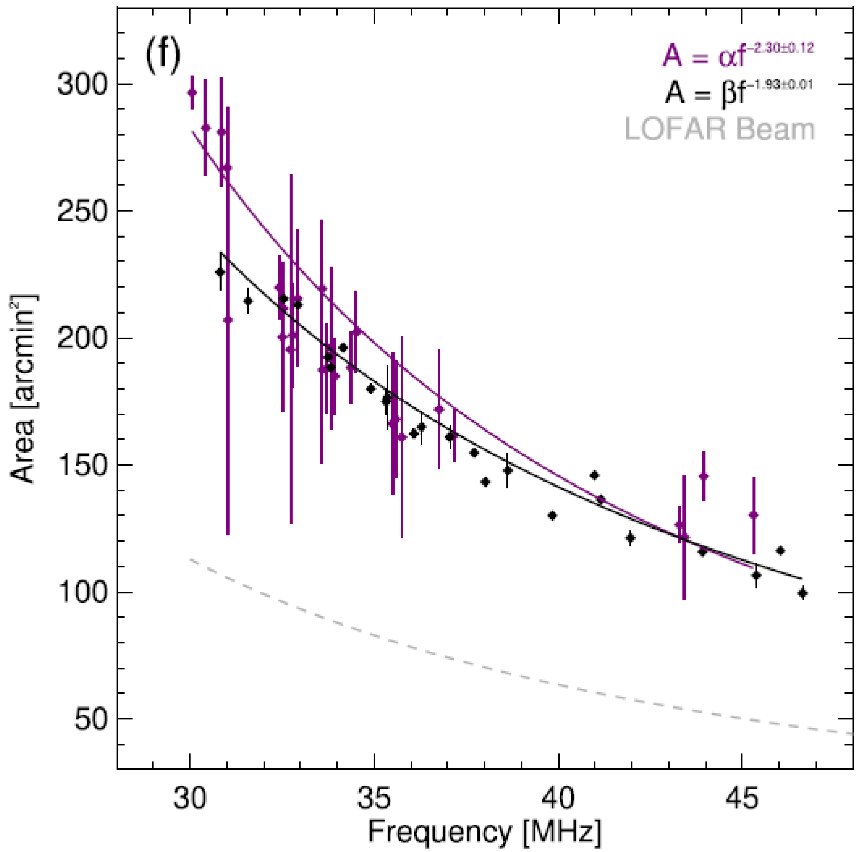
Spikes – apparent source sizes

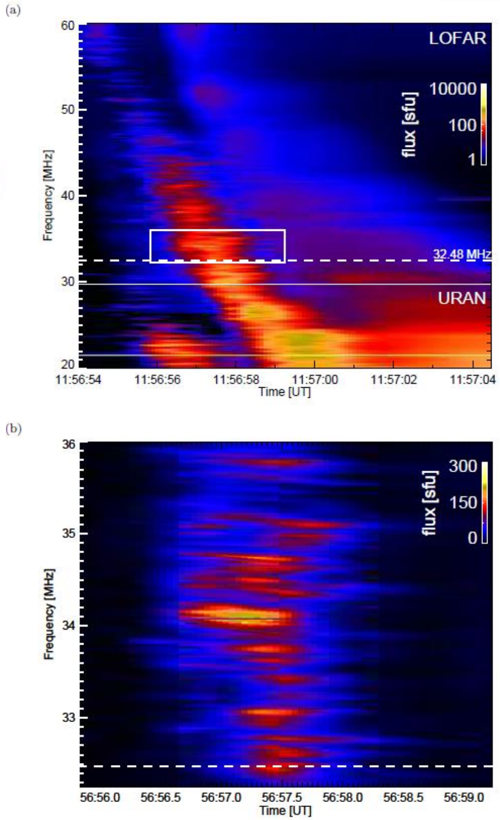


Clarkson et al. 2021 ApJL

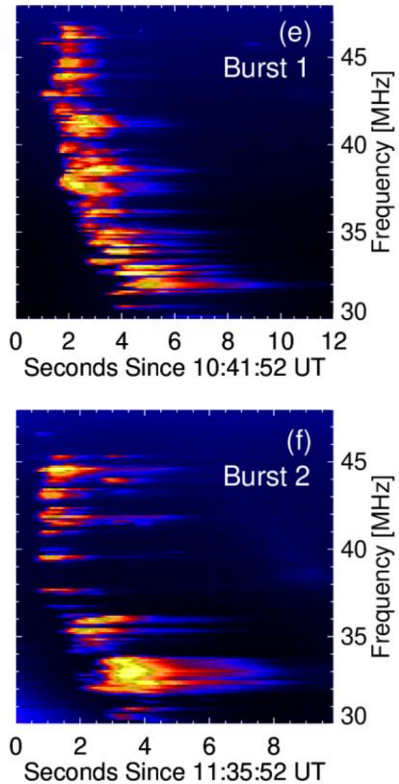
Spikes v "Normal" type III sources

- Spikes are very compact as DS features compared to the striae
- Nearly co-spatial
- (Apparent) spike sources show very fast, sometimes superluminal, (apparent) motion
- Spikes appear due to an interplay of several factors, including short impulses of electron acceleration and strong, non-uniform scattering
- Their DS properties are different, but what about their geometry, i.e. sizes and shapes?

Why not use the interferometric mode?



from Kontar t al. 2017 NatCo



from Clarkson et al. 2022 in prep.

Solar observations require high temporal and spectral resolution (0.1s and 0.1MHz or better) and spatial resolution

TBA mode

Image deconvolution

$$I_d(f, A, z) = I_0(f, A, z - \Delta z_{ir}(f)) \star \mathcal{F}(f, A, z, \Delta A, \Delta z)$$

Observed image

Real image

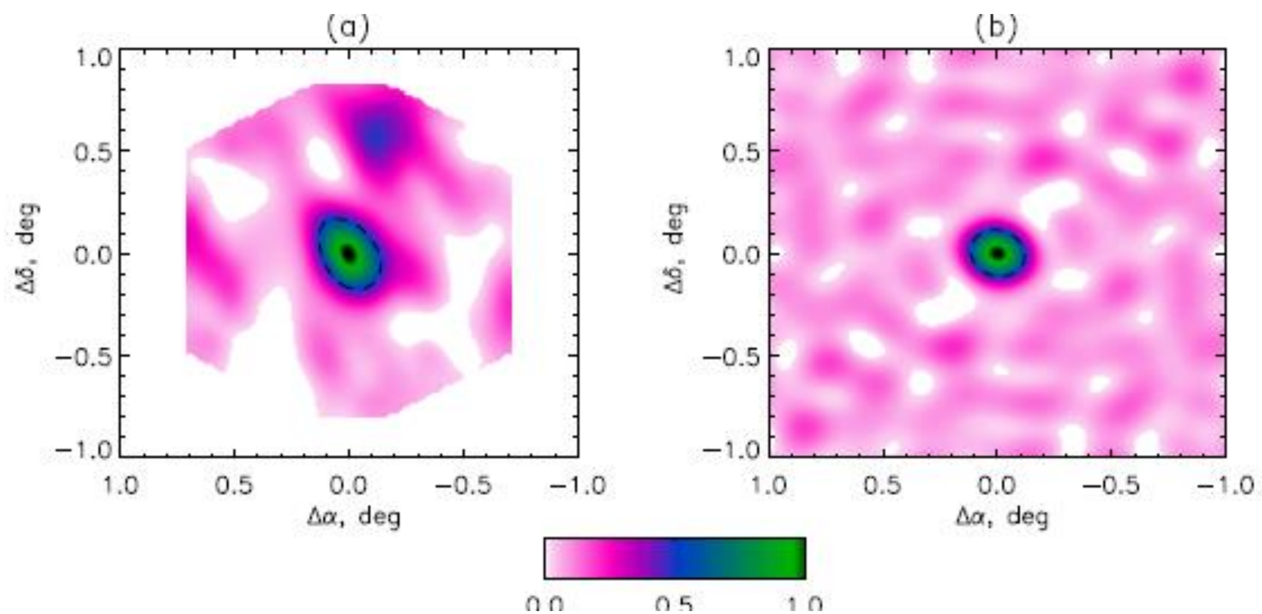
Ionospheric refraction

Point Spread Function PSF

Do we know the PSF?

Tau A

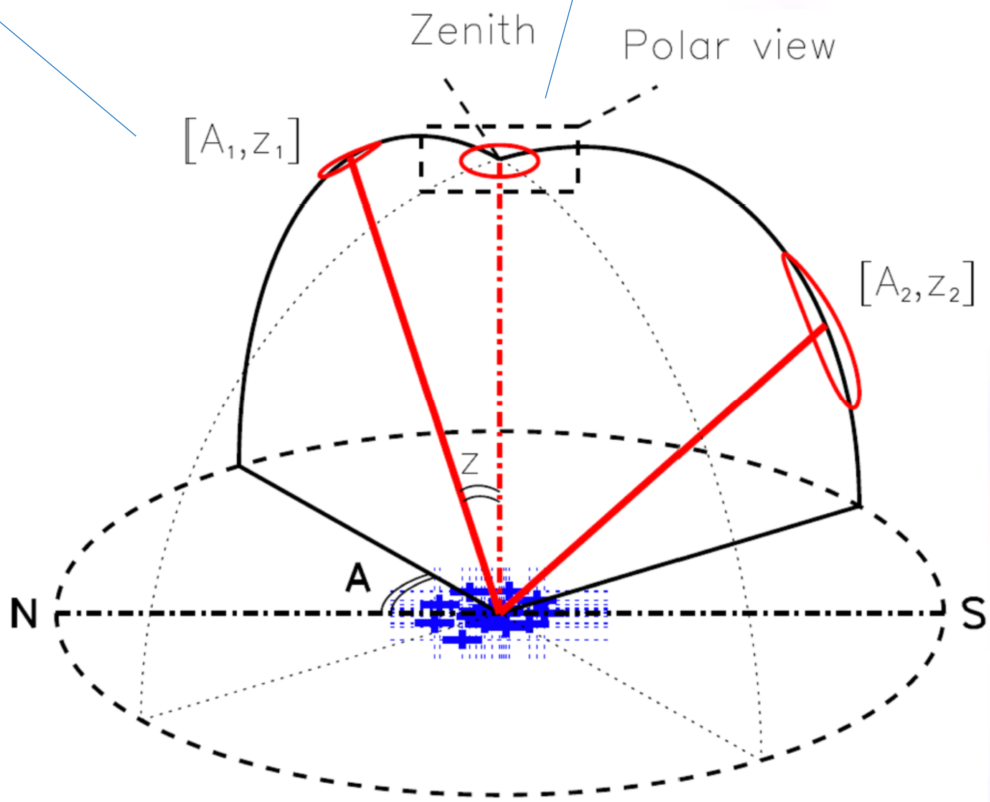
Synthetic PSF



PSF translation procedure

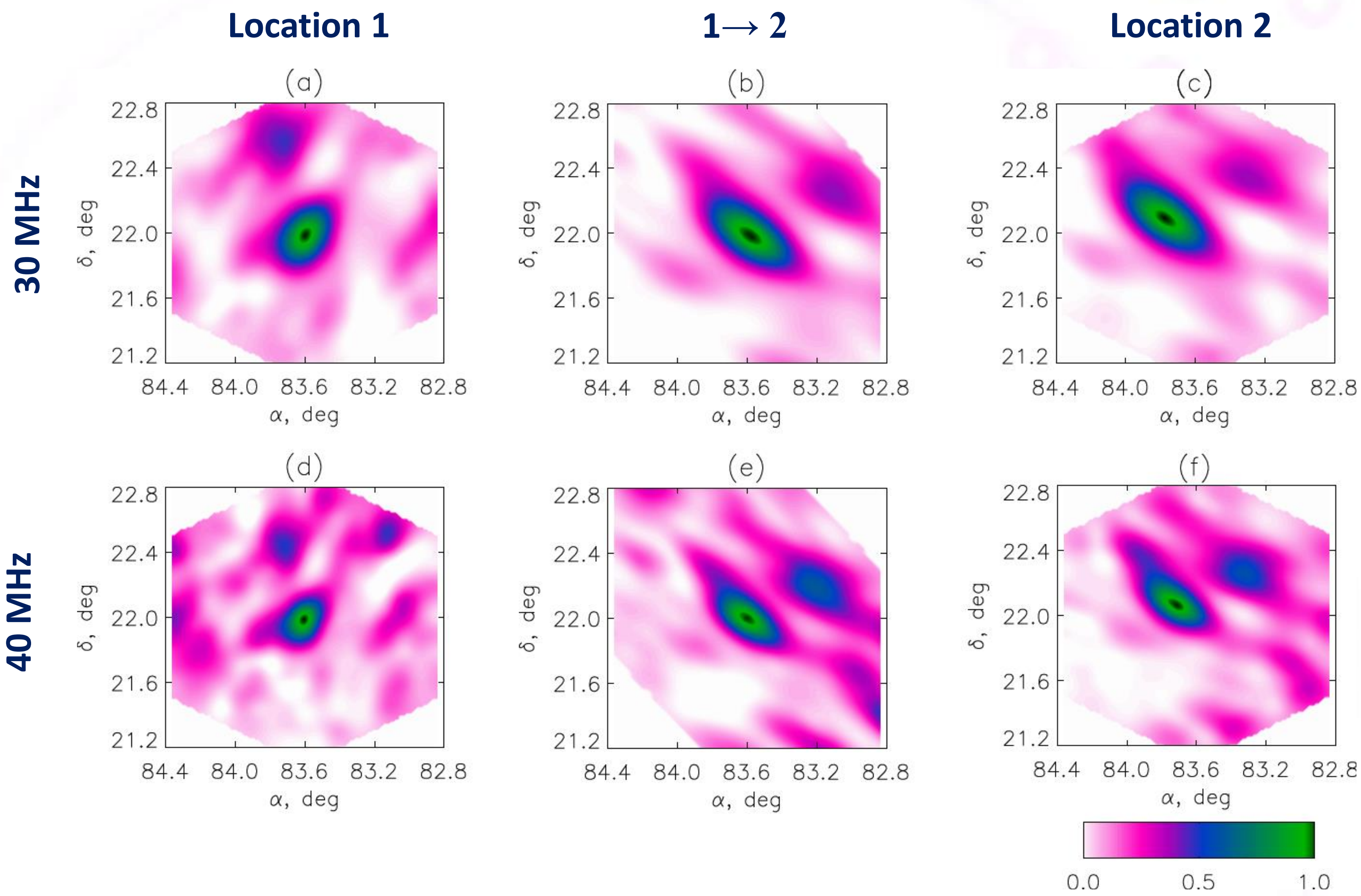
$P(A{=}A_1, z{=}0) = f(\Delta A, \Delta z)$

$P(A{=}A_1, z{=}z_1) = f(\Delta A, \Delta z/\cos(z_1))$
$A{=}A_1{+}\Delta A/\sin(z_1)$



PSF translation procedure

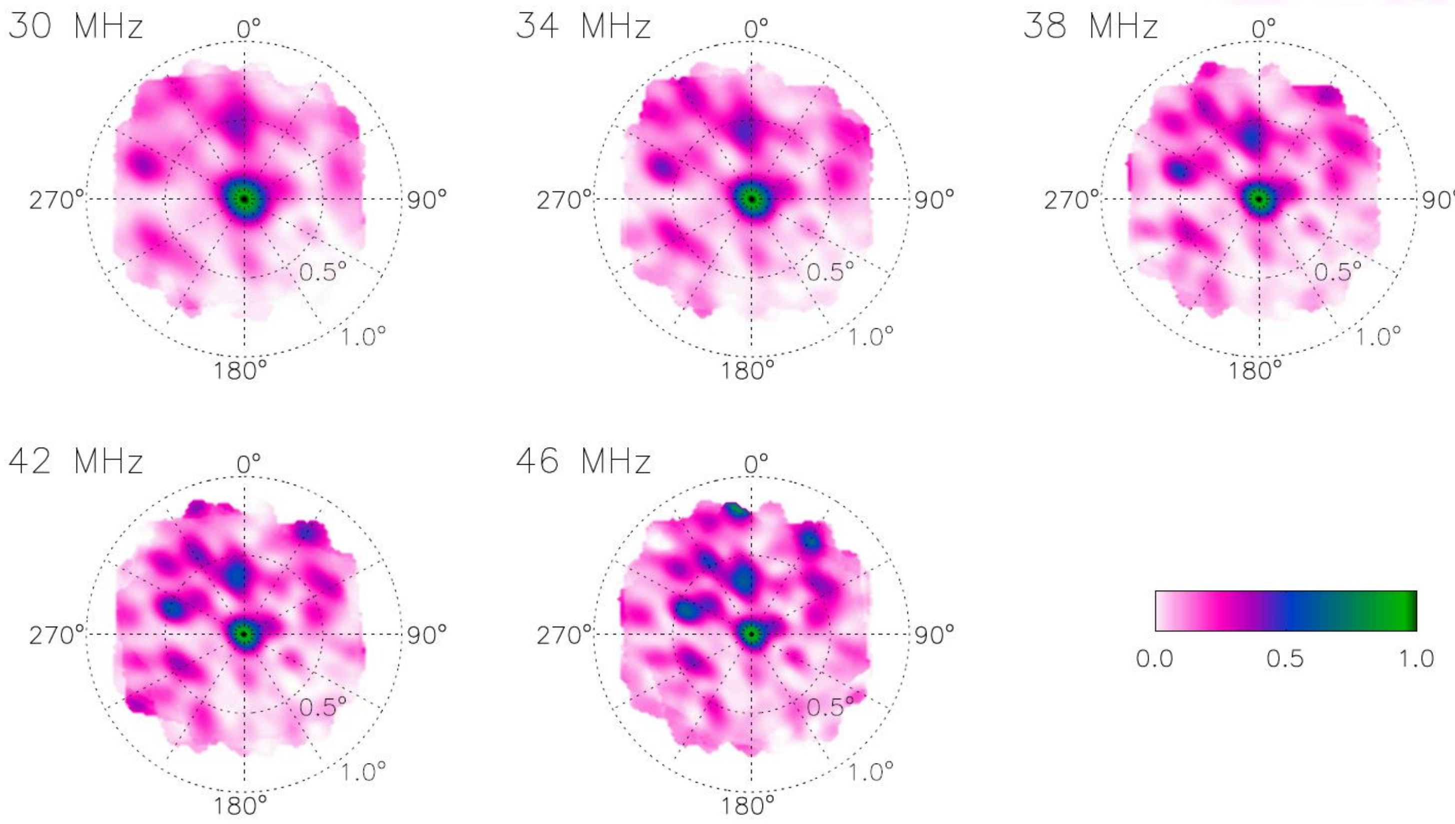
Tau A



LOFAR TBA PSF

- Around 30 individual observations of Tau A used
- Real Tau A shape is ‘deconvolved out’ of the observed intensity maps
- Intensity maps are ‘translated’ to zenith and combined

LOFAR TBA PSF at zenith

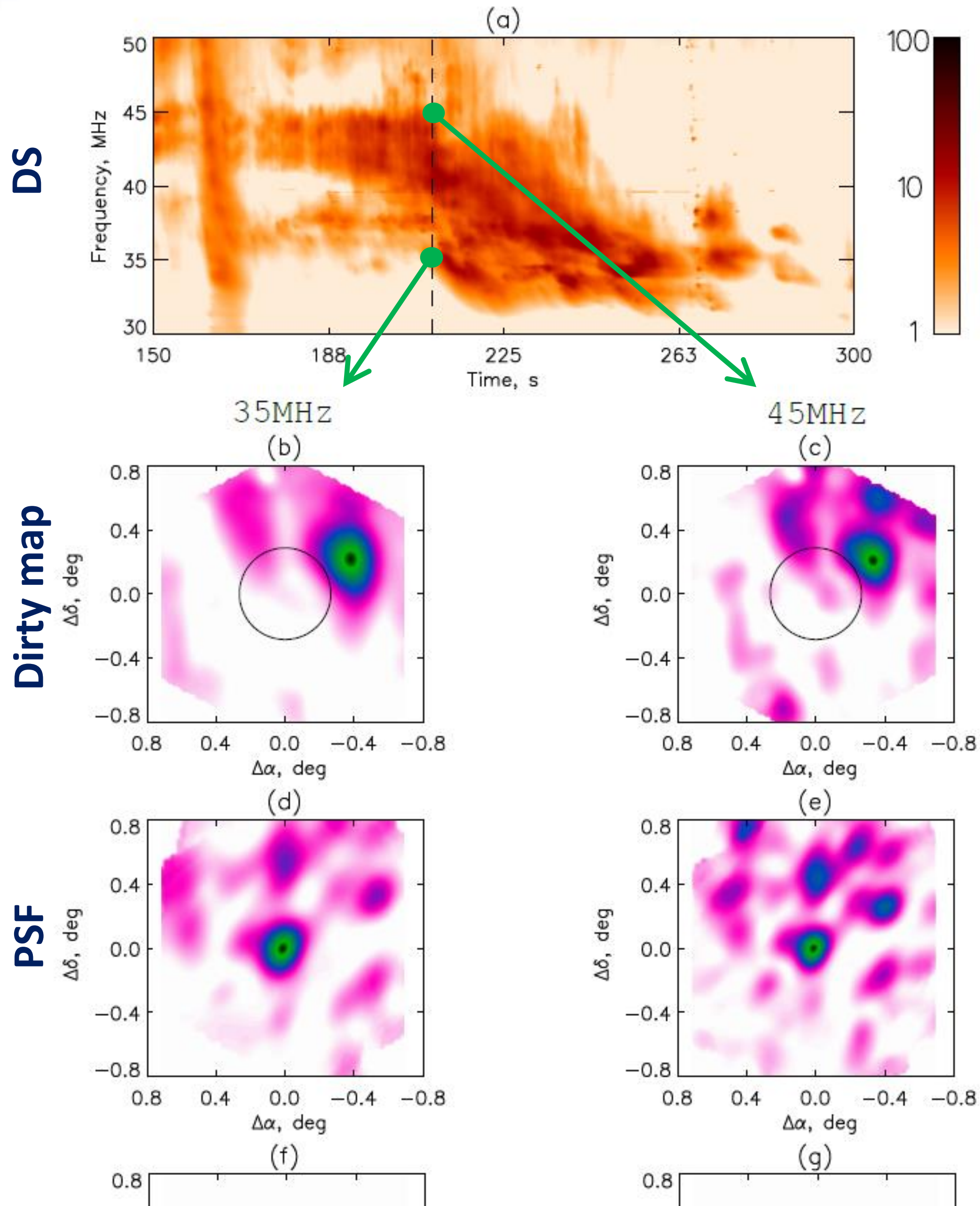


Deconvolving solar images

1) Create intensity maps for selected positions at the dynamic spectrum

2) Produce PSFs for required position of the Sun and frequency

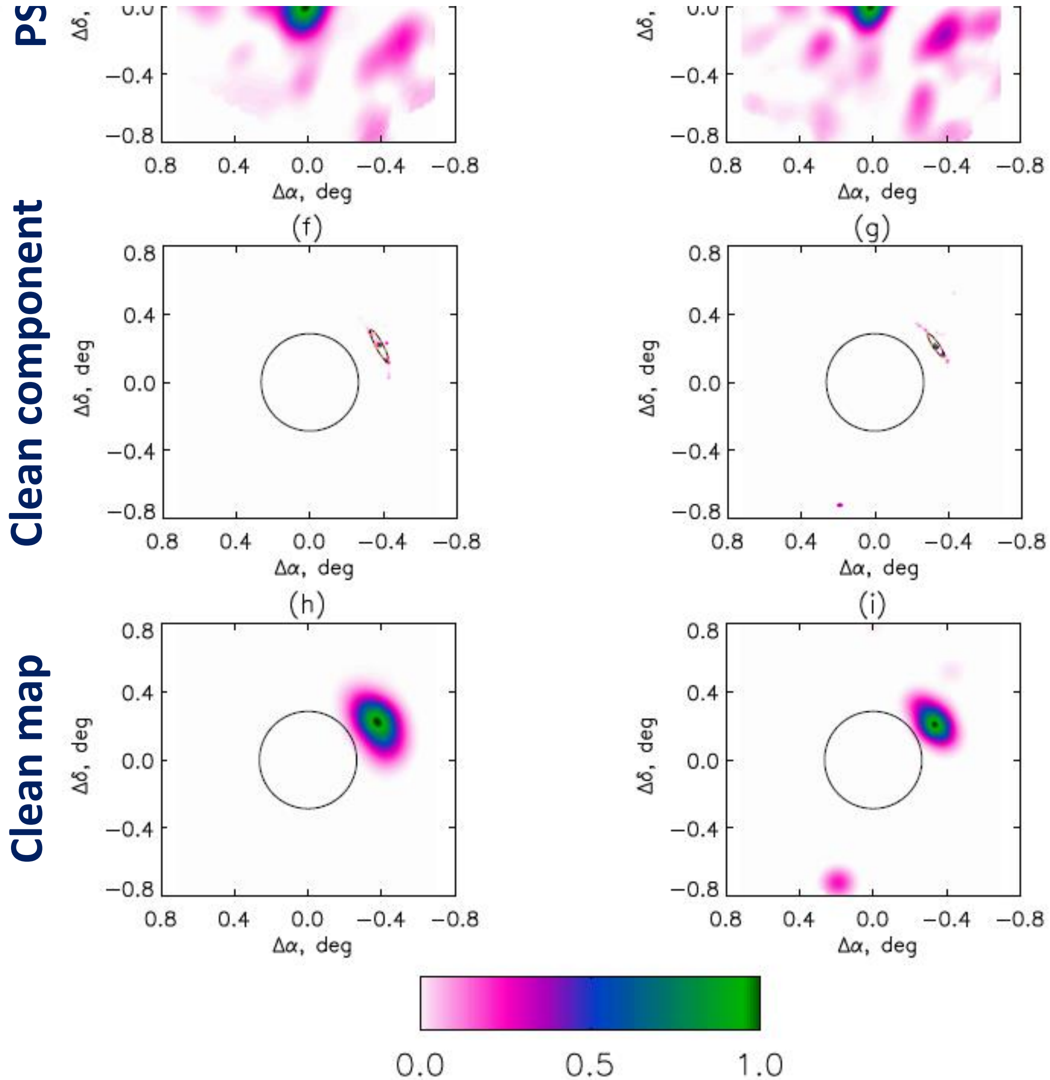
3) CLEAN



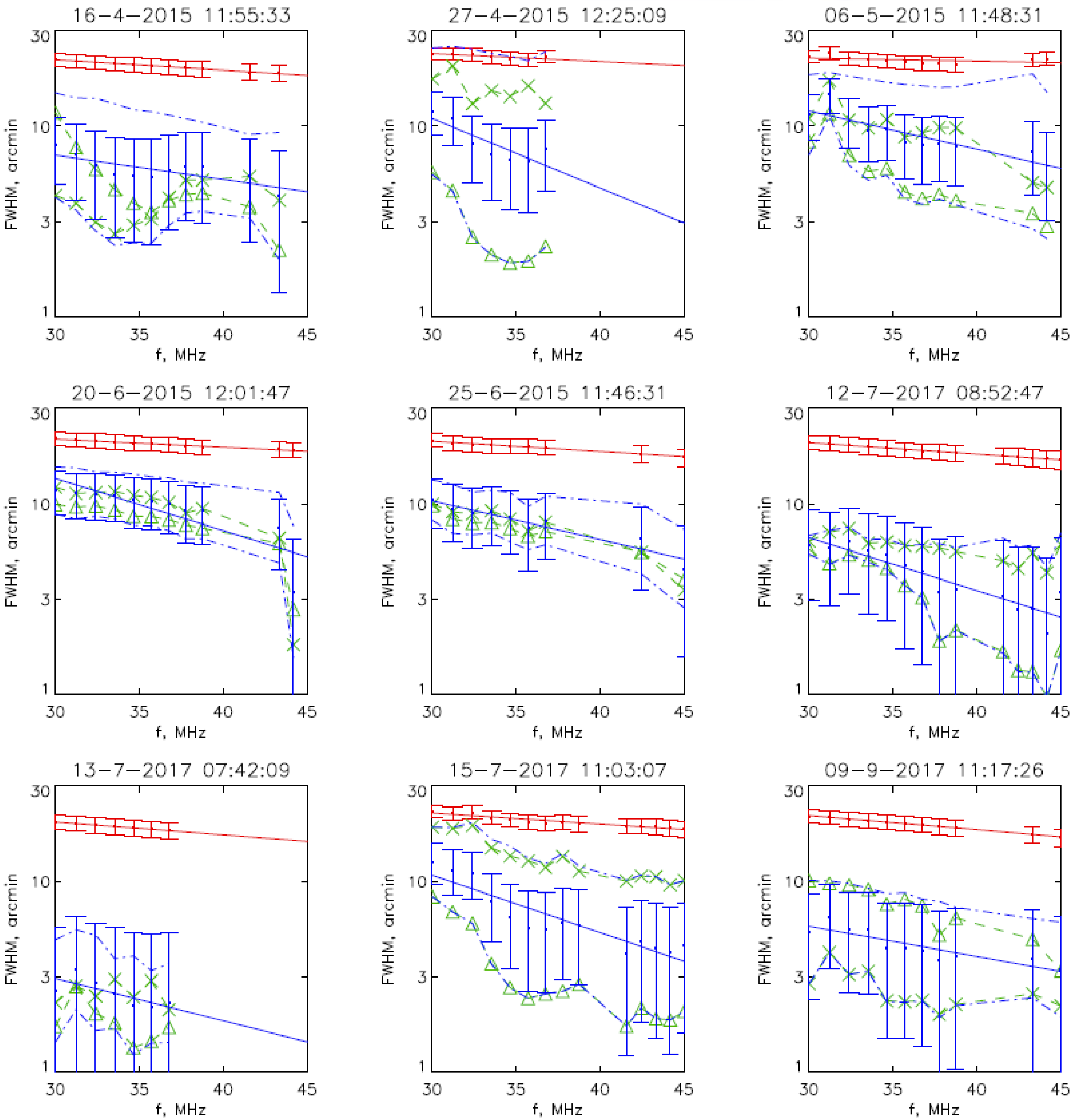
Deconvolving solar images

4) Derive clean component maps and clean maps

5) 2D Gaussians with elliptical cross-sections to clean component maps

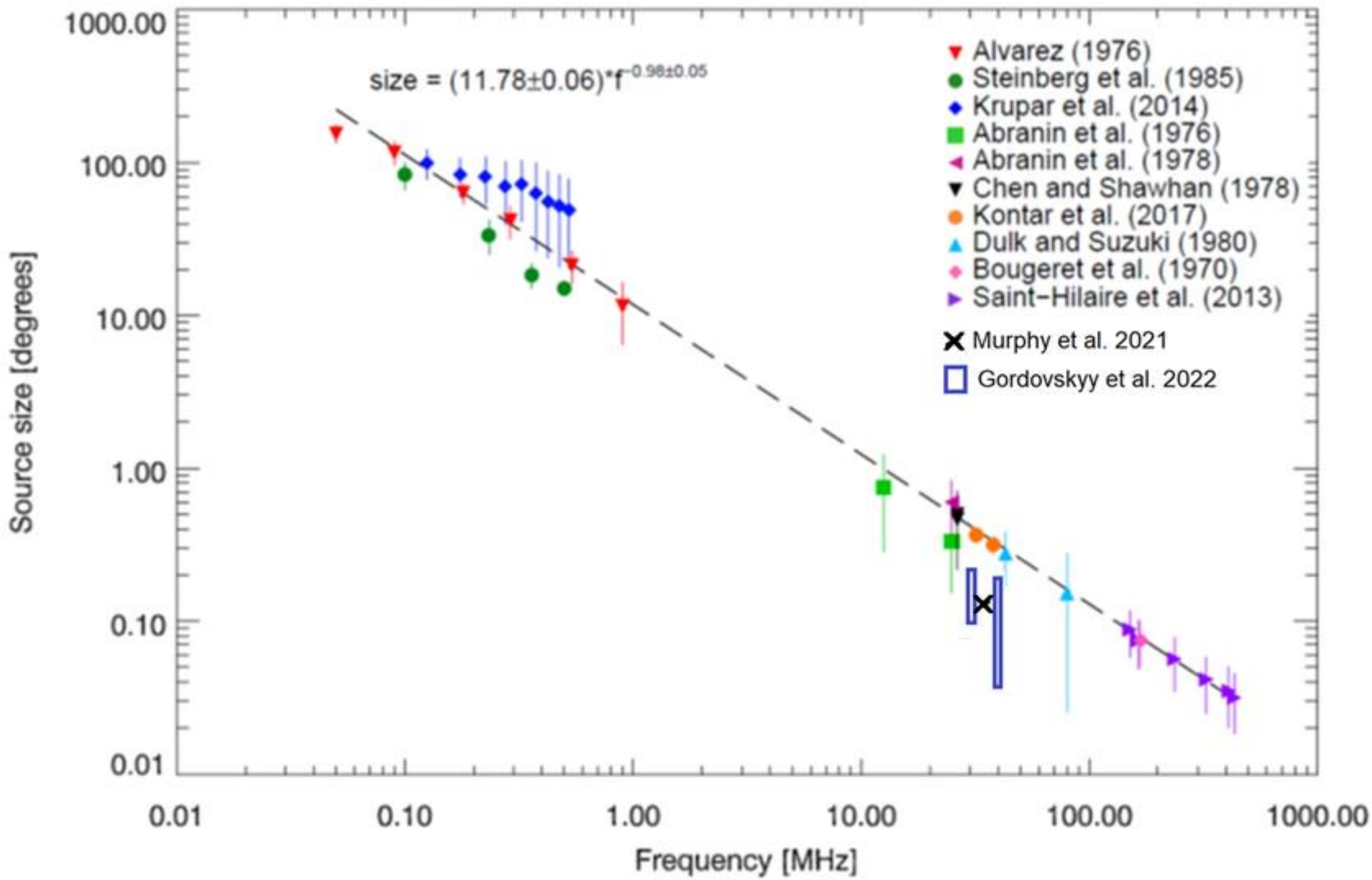


Sizes and shapes of ‘normal’ type II-IV sources



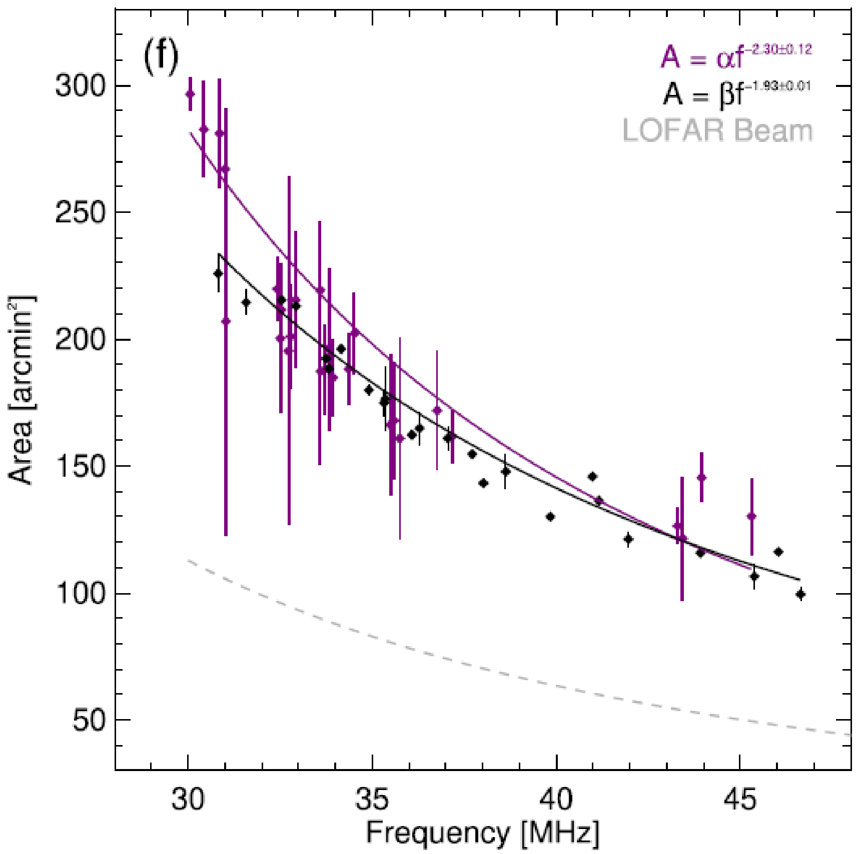
- Typical sizes are 5-10 arcmin at 30MHz
- $\sim f^{-1.8\pm0.5}$
- Small sample

Sizes and shapes of 'normal' type II-IV sources



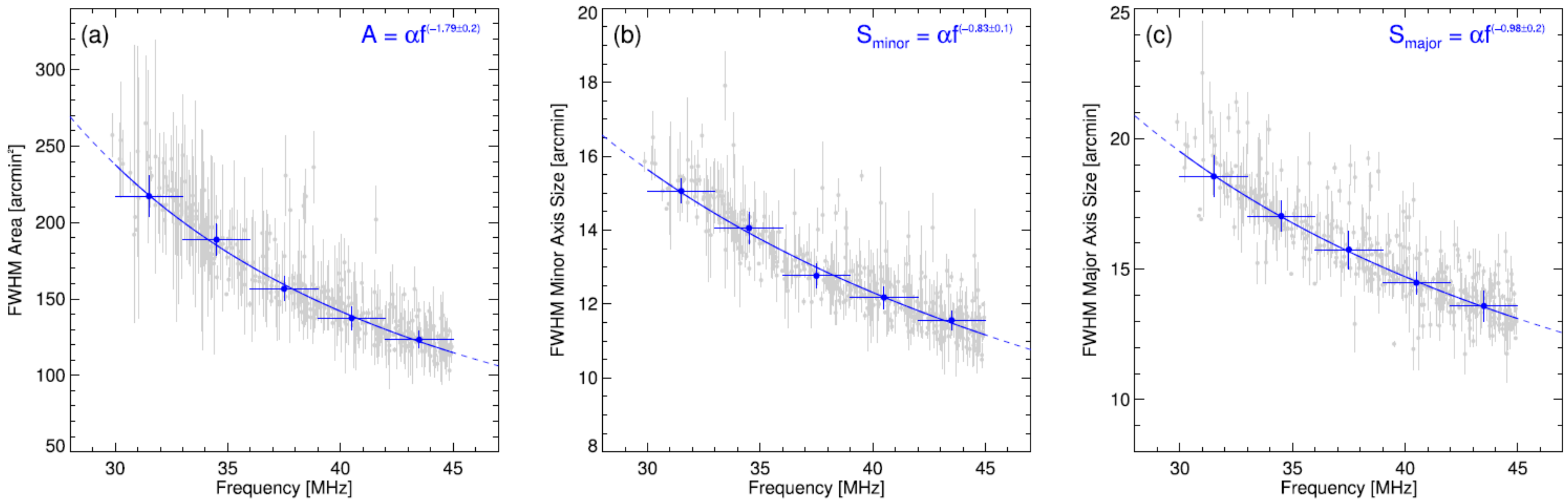
Background plot from Kontar et al. 2019

Sizes of spike sources



Clarkson et al. 2021 ApJL

Sizes of spike sources



Clarkson et al. 2023 ApJ

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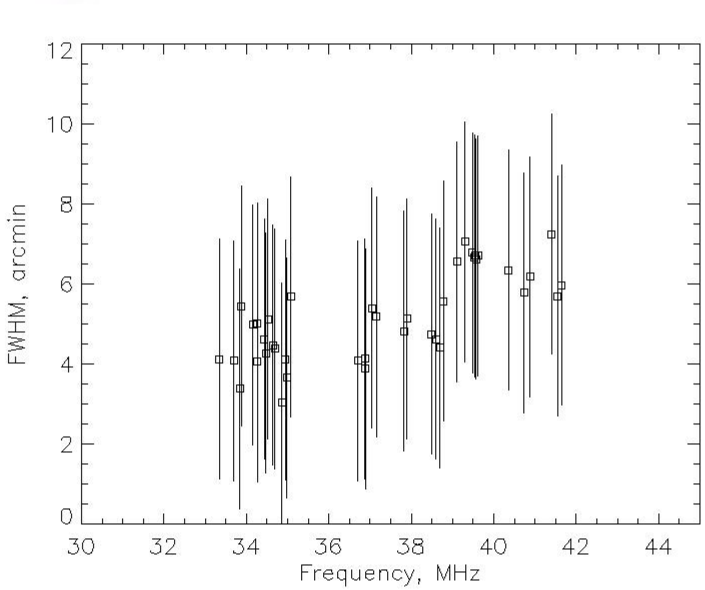

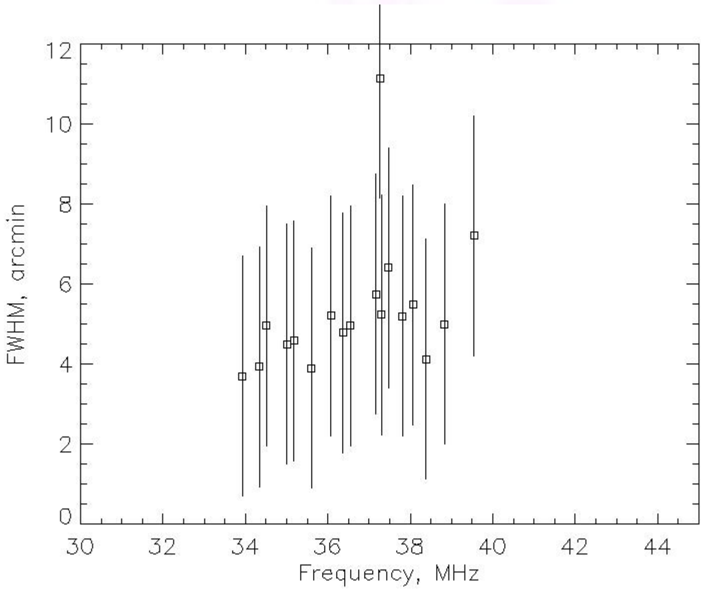

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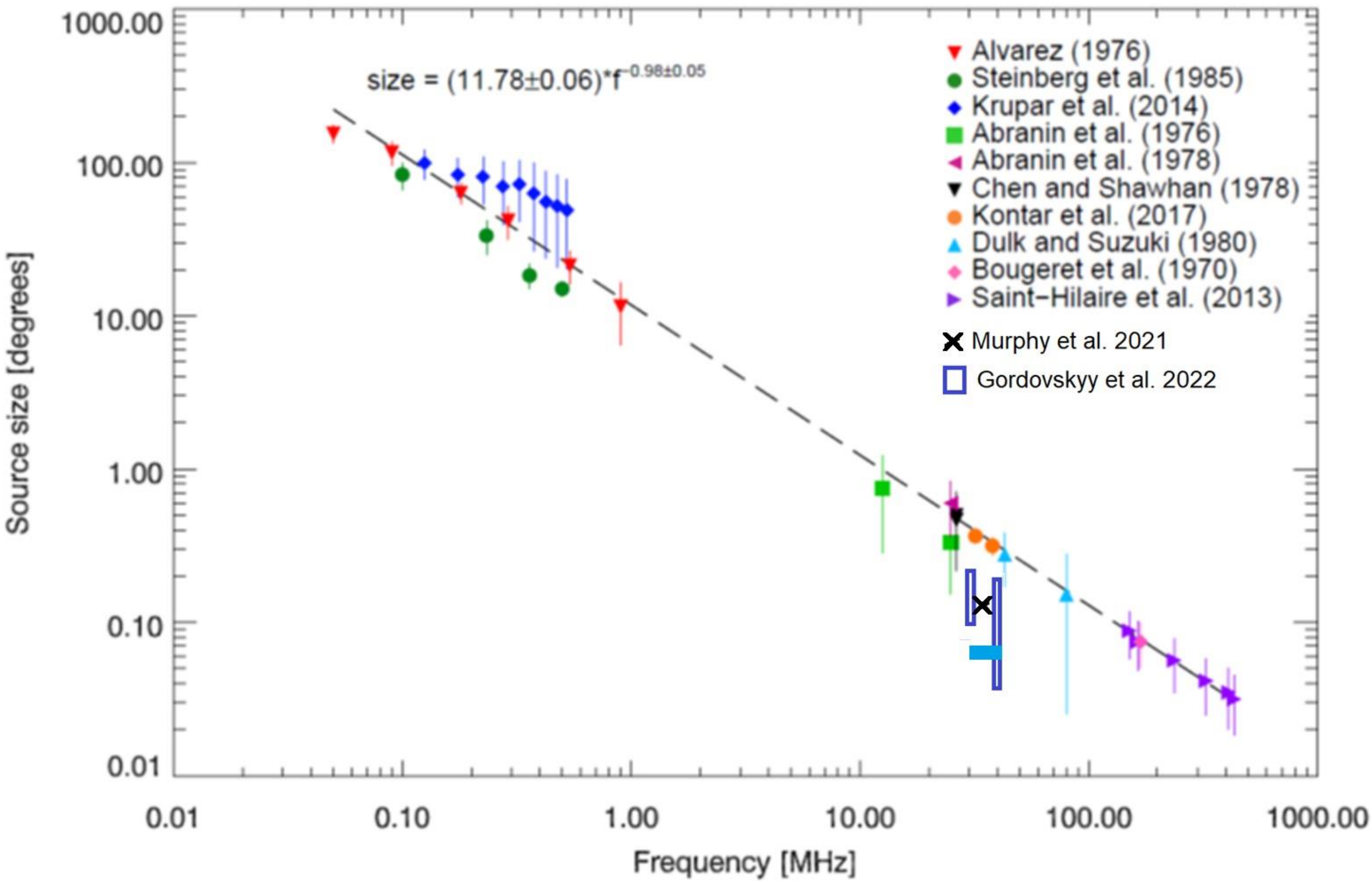

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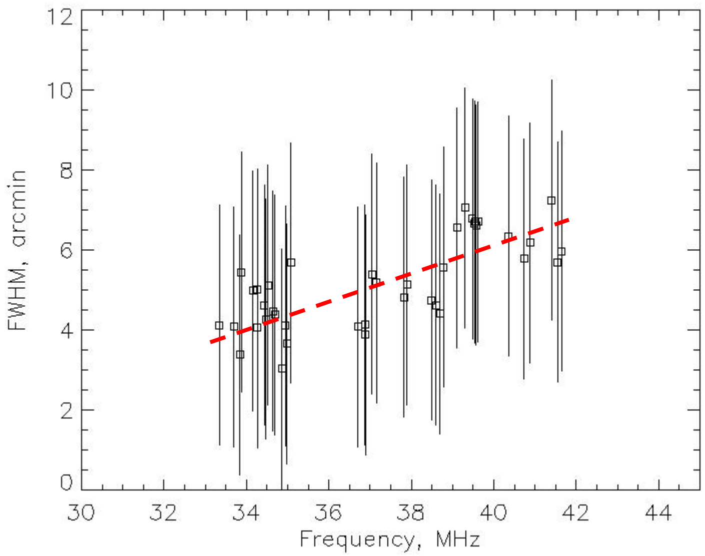
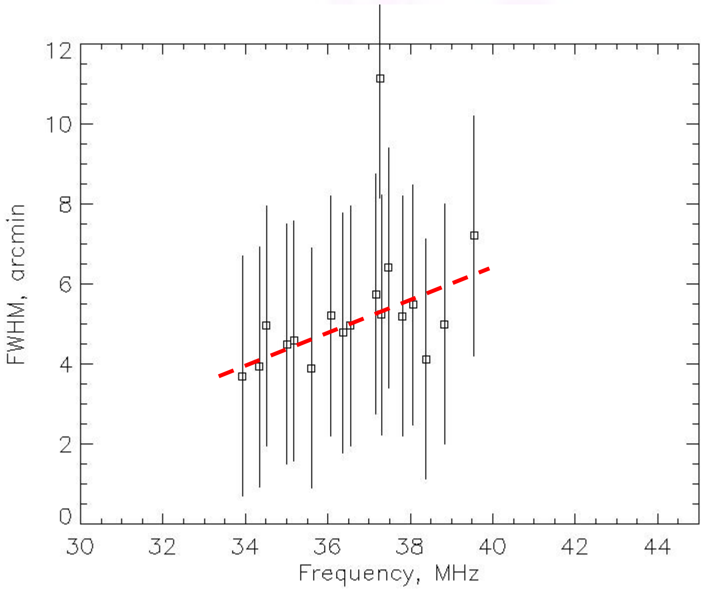
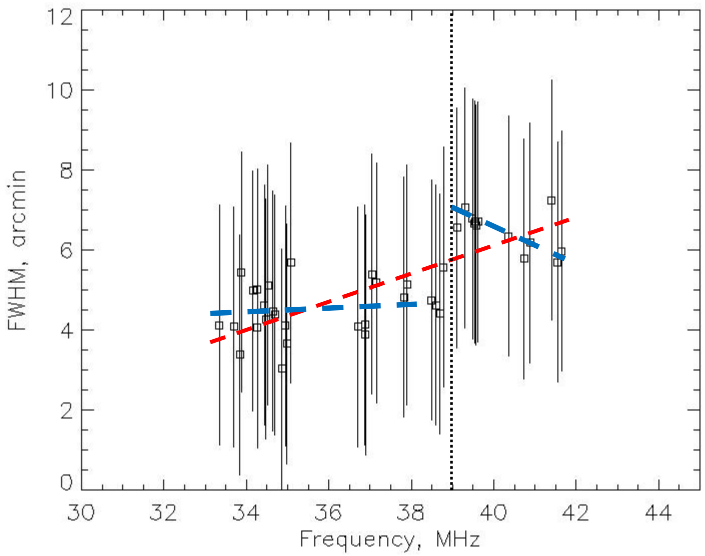


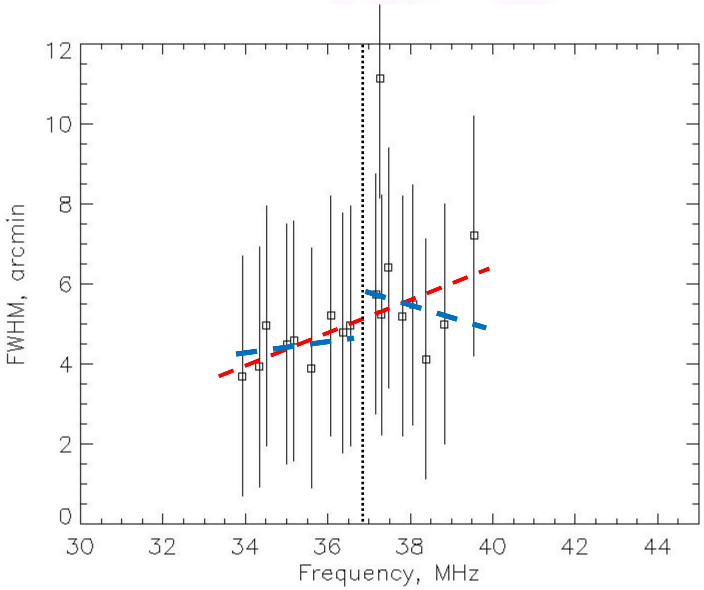
Power-law index 2.5



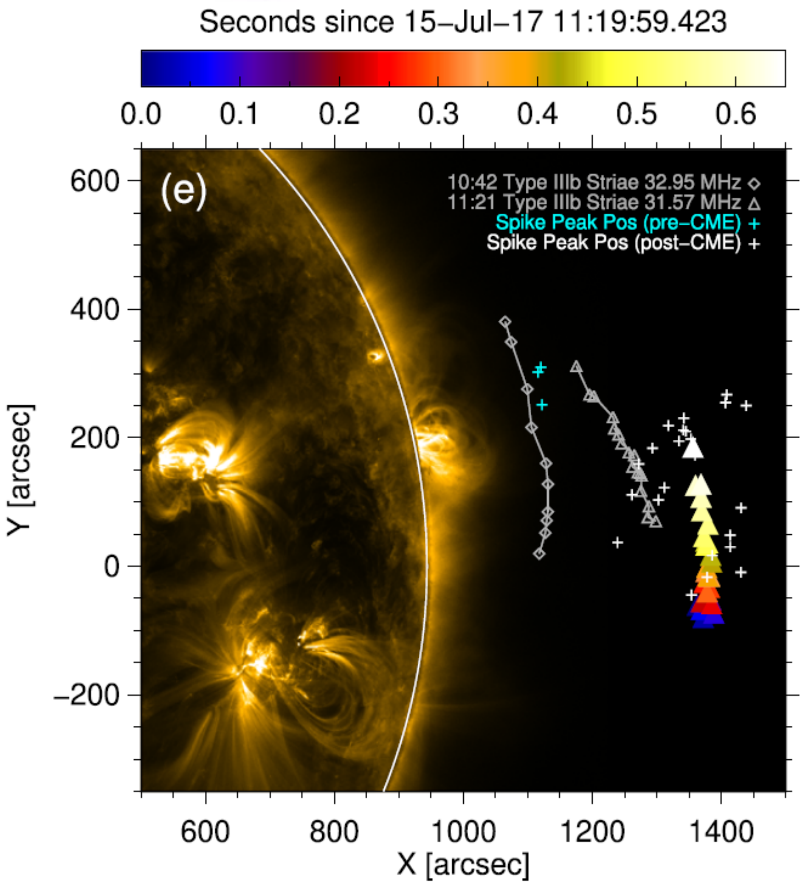
Power-law index 2.9

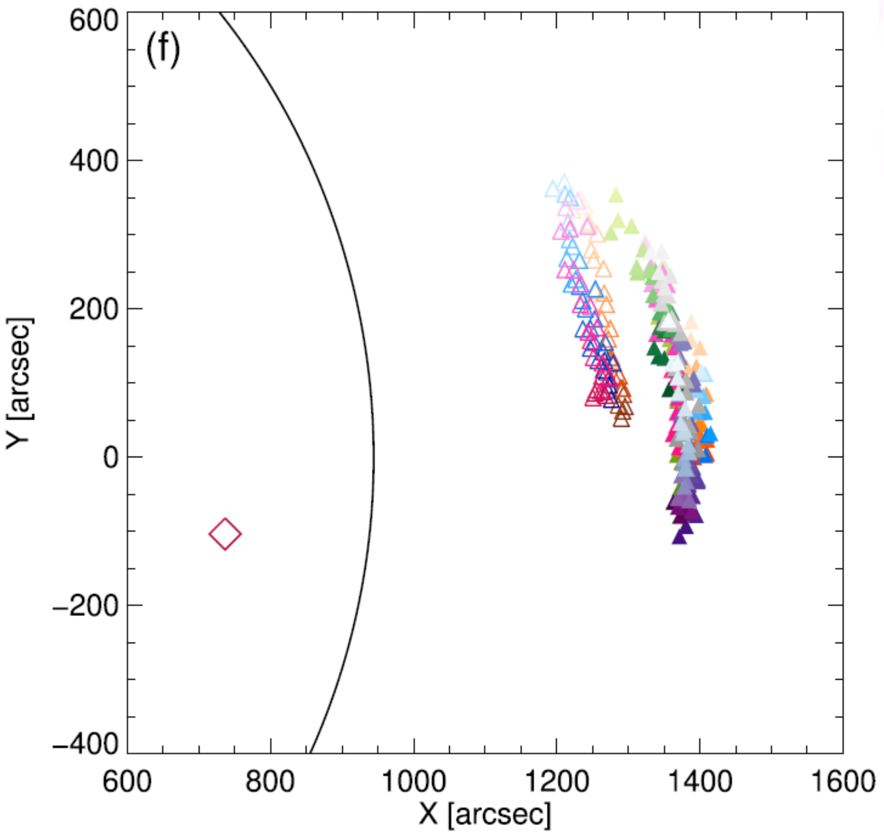
Sizes of spike sources





Shapes and trajectories of spike sources





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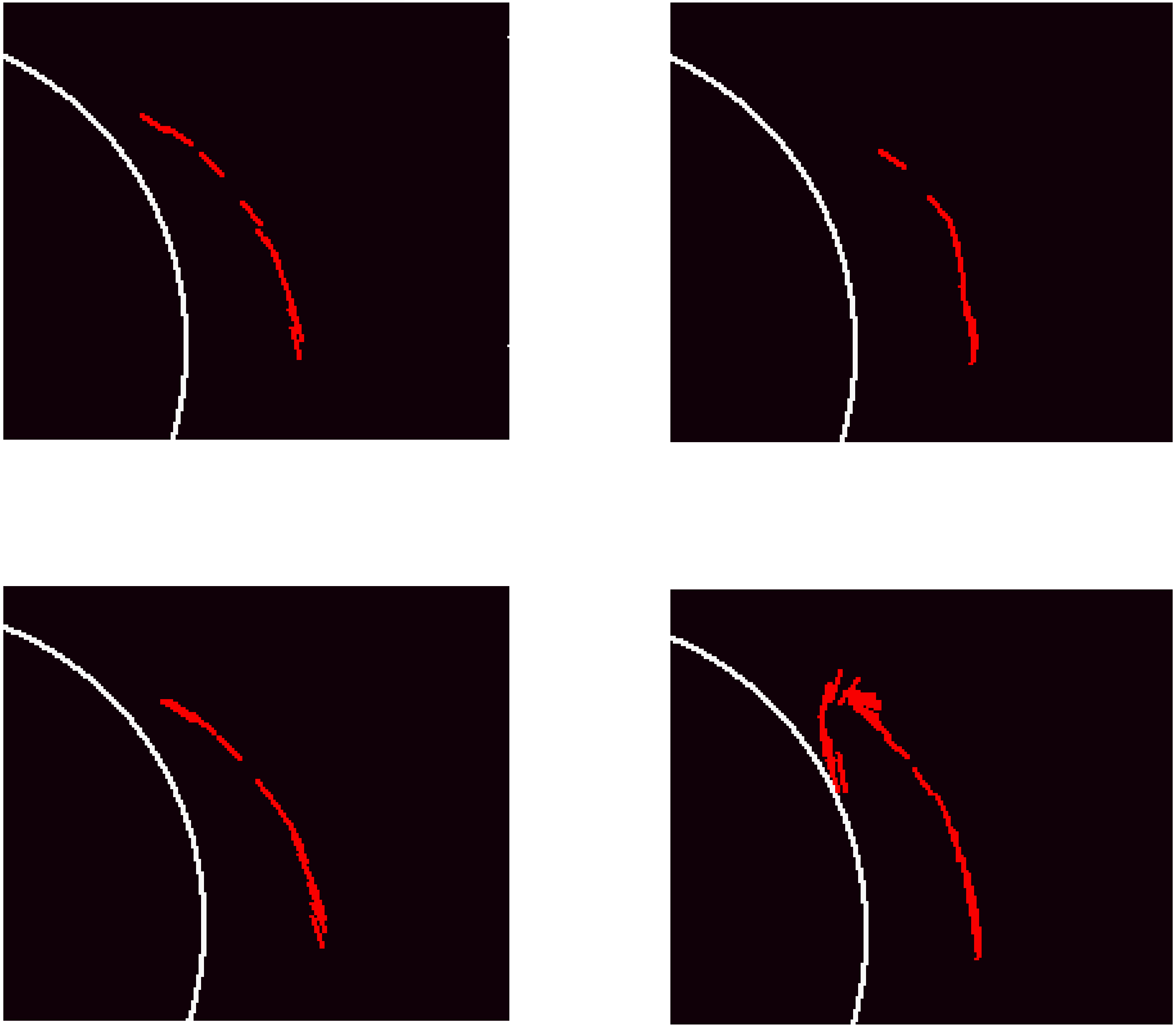

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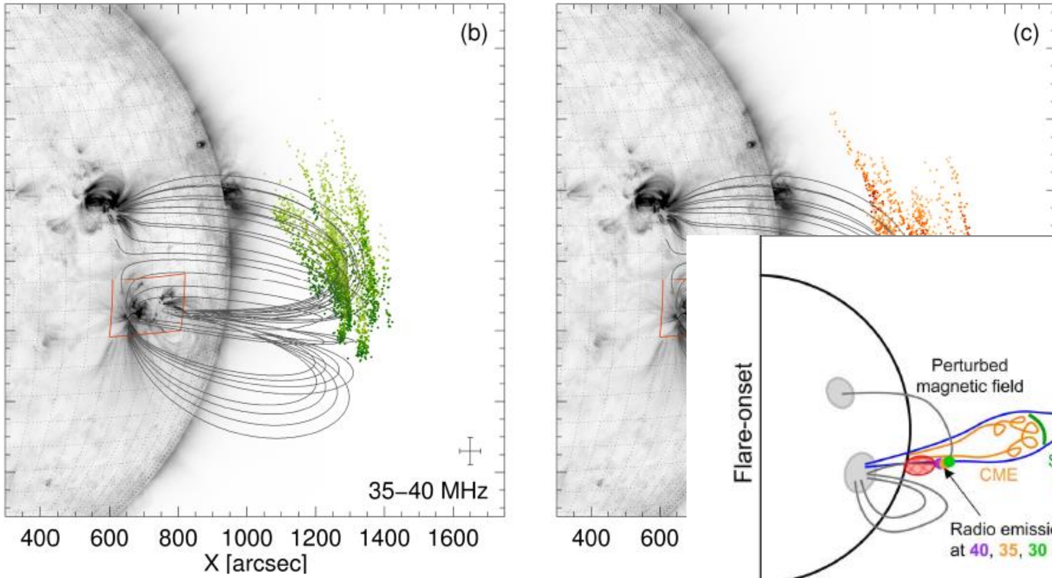
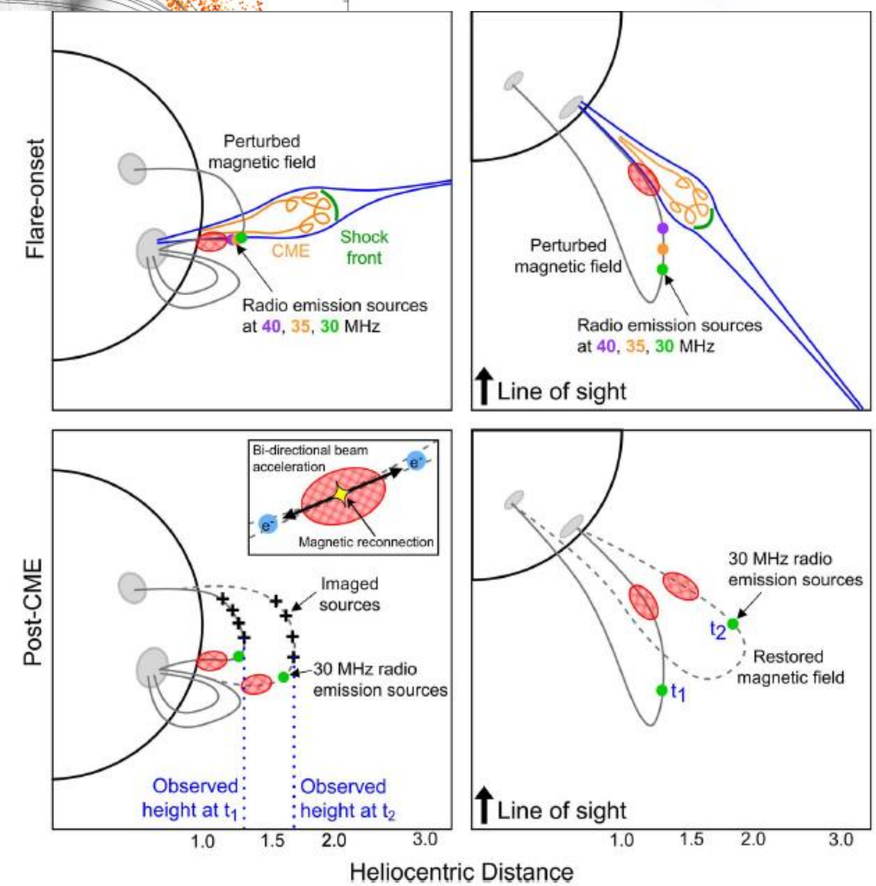




Summary

- We have derived empirical PSF of LOFAR in TBA mode for the 30-50MHz range. It is very different from synthetic PSF. We can CLEAN solar images in arbitrary locations

- Found that spikes

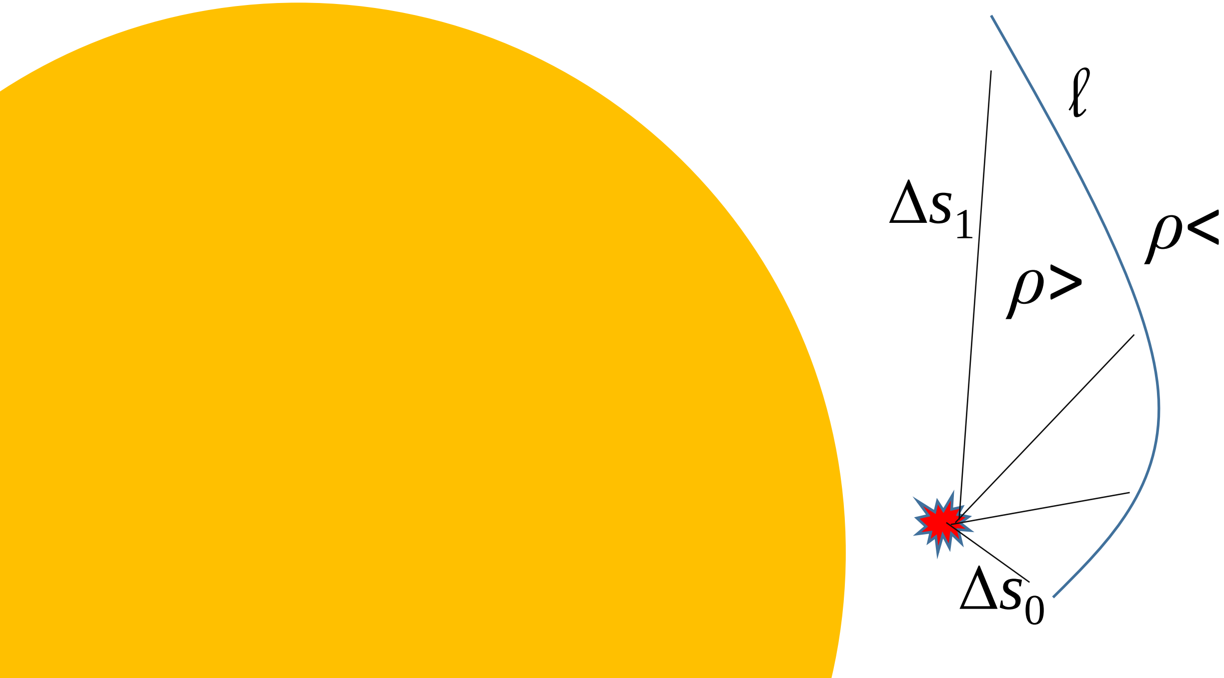
  - **are typically 2-3 times smaller than "normal" type III** sources

  - show apparent motion with ~c, **shape orientation correlates with the trajectory, and the trajectory is not r=const**

- Phenomenological interpretation? – Same as in Clarkson et al. 2021, 2023, but **we need a shock**

Why do we need a shock?

- It can help explain small sizes of spike sources
- Another possible explanation for the “trajectories” and superluminal velocities of apparent sources and



$$V_{\mathrm{app}} = c \, \frac{\ell}{\Delta s_1 - \Delta s_0}$$