University of Glasgow

LOFAR Family Meeting
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Observations and Simulations of the Shortest Solar Radio Bursts with LOFAR

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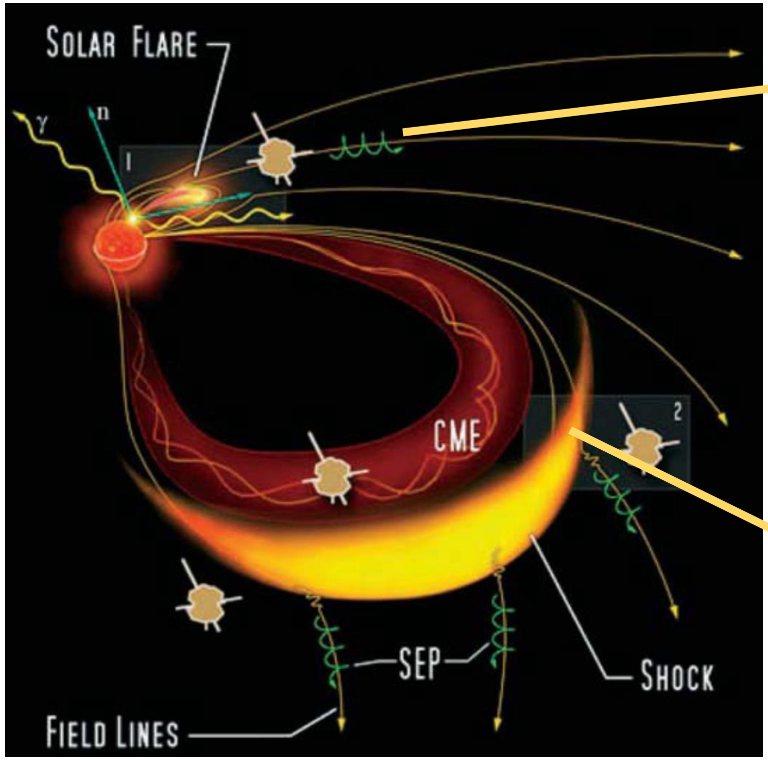
With thanks to:
Eduard Kontar, Nicole Vilmer, Mykola Gordovskyy, Xingyao Chen, and Nicolina Chrysaphi

Based on Clarkson et al. (2021, 2023)

Solar Radio Bursts

Release of magnetic energy in solar flares accelerates electron beams that propagate along field lines

- Plasma emission process leads to Langmuir wave growth and radio emission near plasma frequency and/or its harmonic.



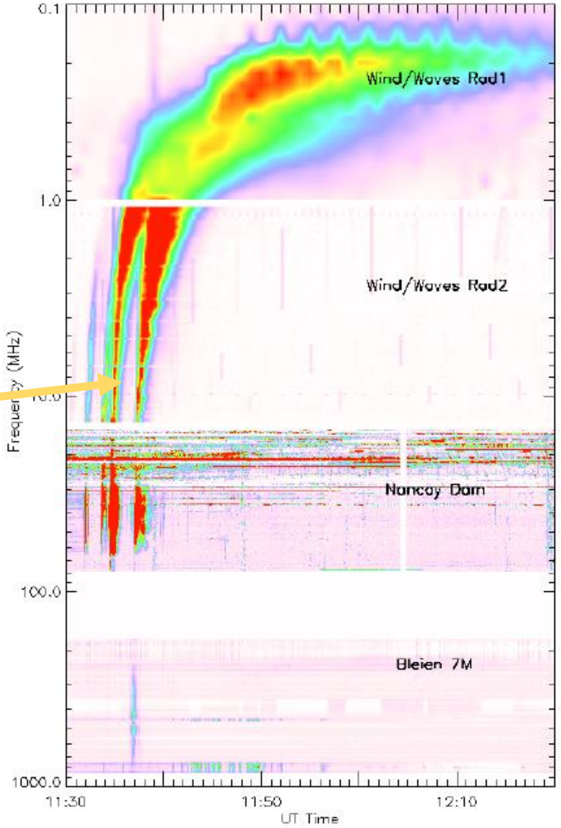
- Frequency relates to distance:

$f_{pe} \propto \sqrt{n_e(r)}$, where f_{pe} = plasma frequency

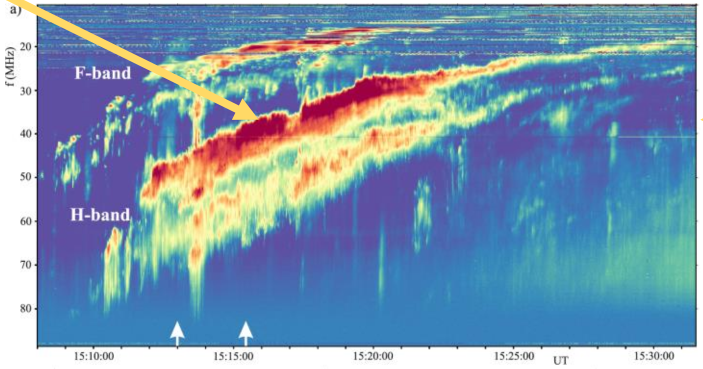
n_e = plasma density

r = radial distance

Reid+2014

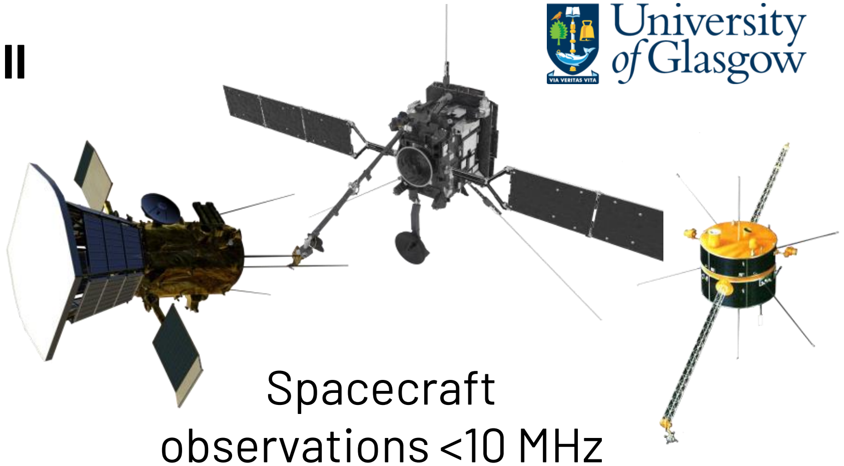


Type III



Type II

Magdalenić+2020



Spacecraft observations <10 MHz

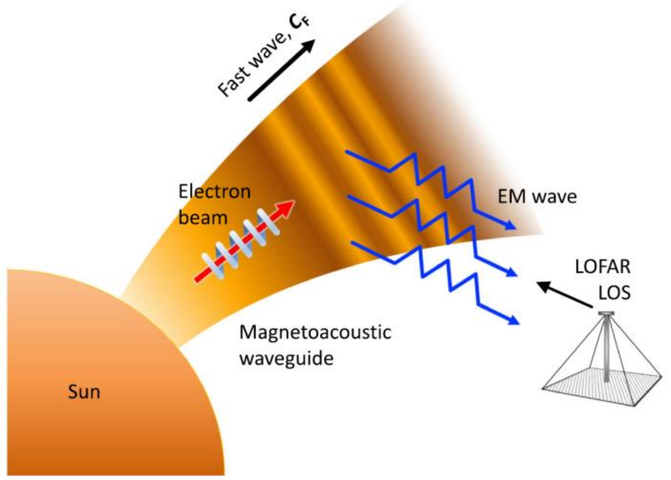
Spectroscopy & imaging

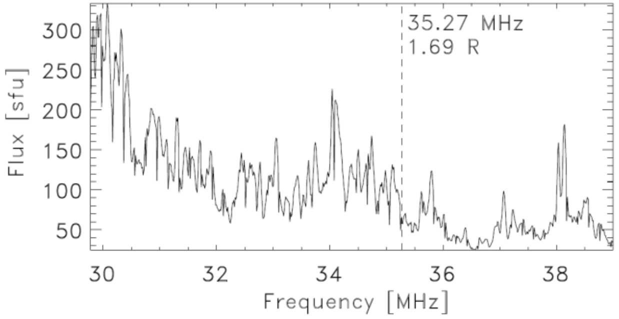
Ground based interferometers >20 MHz

Plasma Density Fluctuations & Radio Burst Fine Structures

Density fluctuations in the corona supress/promote the beam-plasma instability:

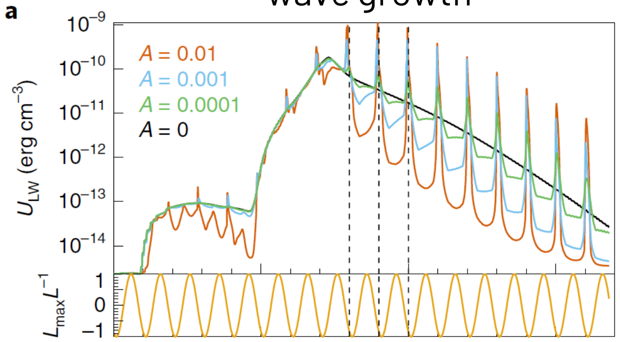
- ➢ Clumpy Langmuir wave growth
- ➢ Modulated radio emission (fine structures)





Kolotkov+2018

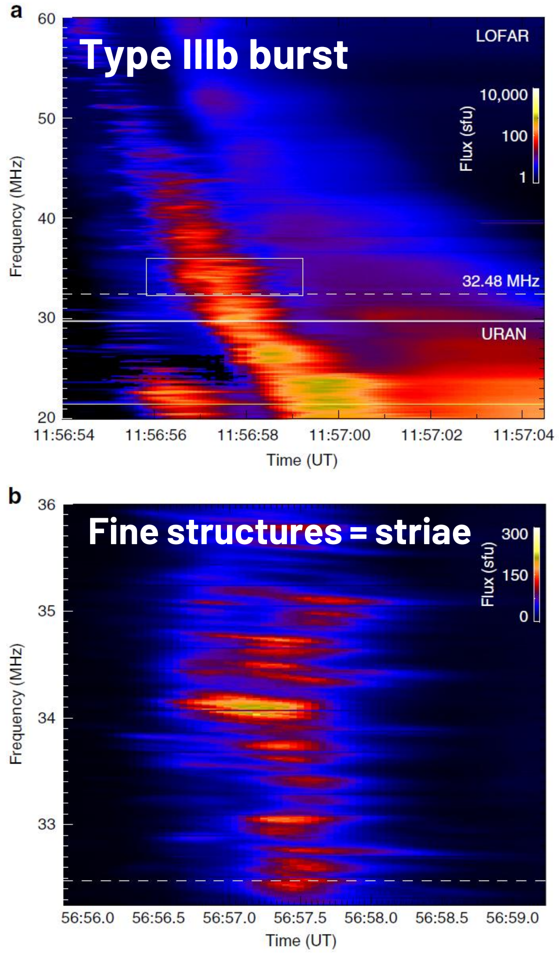
Clumpy Langmuir wave growth



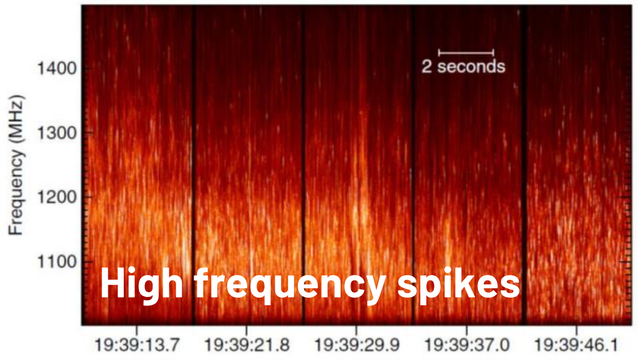
Oscillating density

Reid+2021

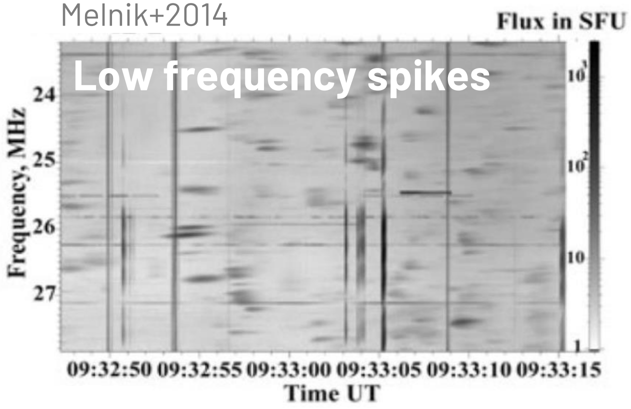
Kontar+2017



Cliver+2011



Melnik+2014



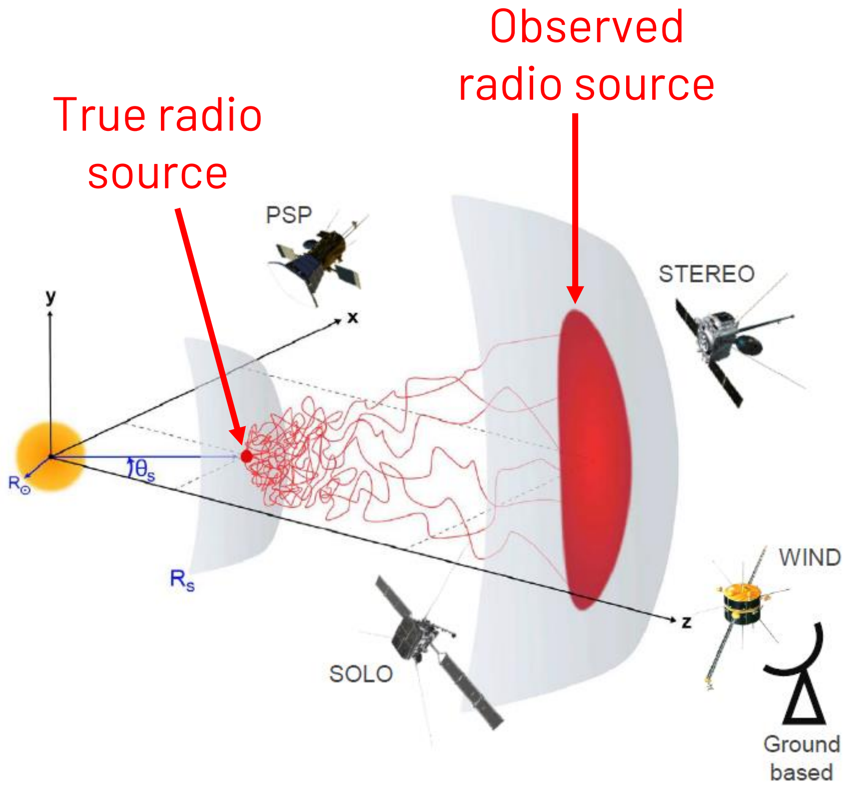
Radio Spikes:

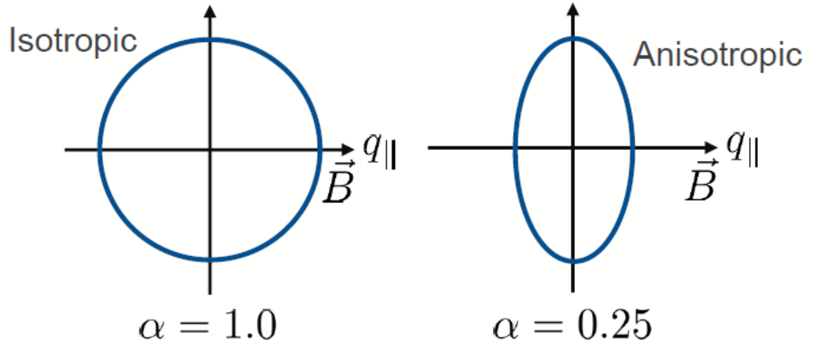
- ➢ Could be produced via **electron cyclotron maser emission** or **plasma emission**?
- ➢ Could be a signature of fragmented energy release?

Radio-wave Propagation Effects

Photons travelling through plasma experience small angle deflections $d\theta$ due to varying plasma density

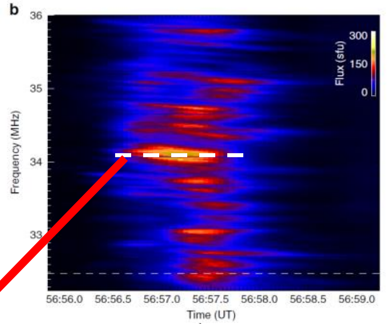
Refractive index varies as $n_{\mathrm{ref}} = \left(1 - \frac{\omega_{pe}^2}{\omega^2}\right)^{1/2}$ → strongest scattering near the emitting region



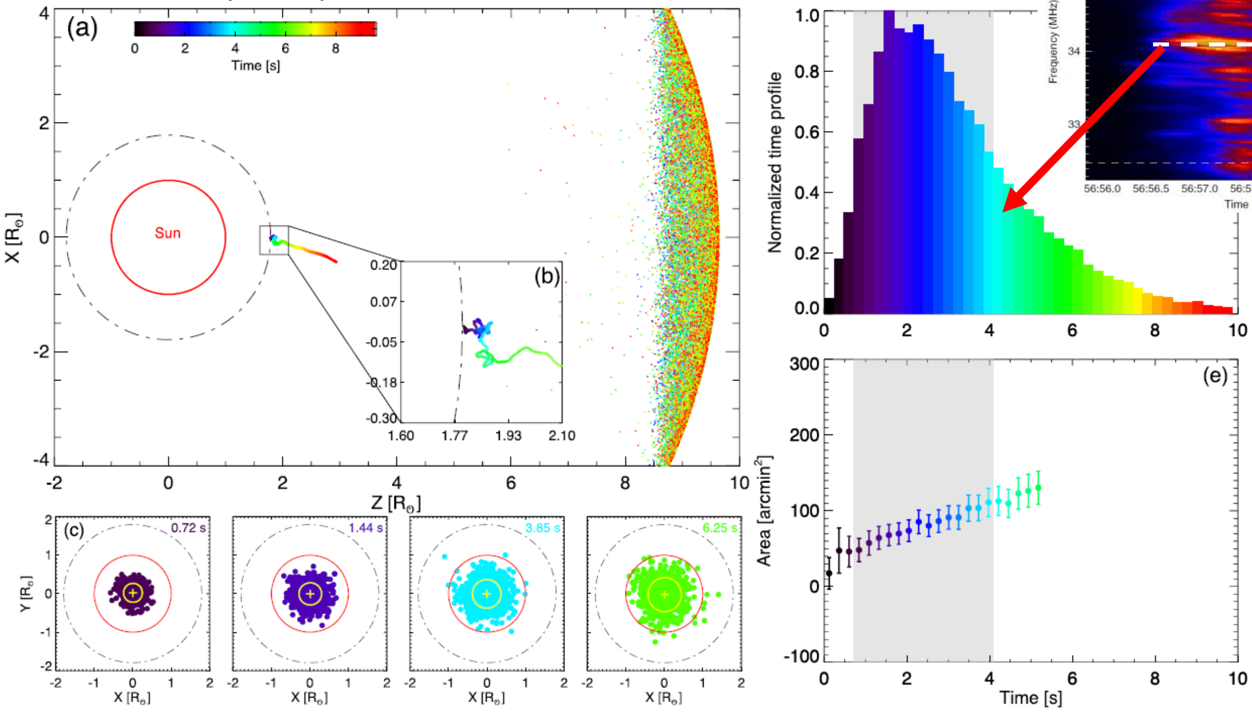


Field-aligned density fluctuations

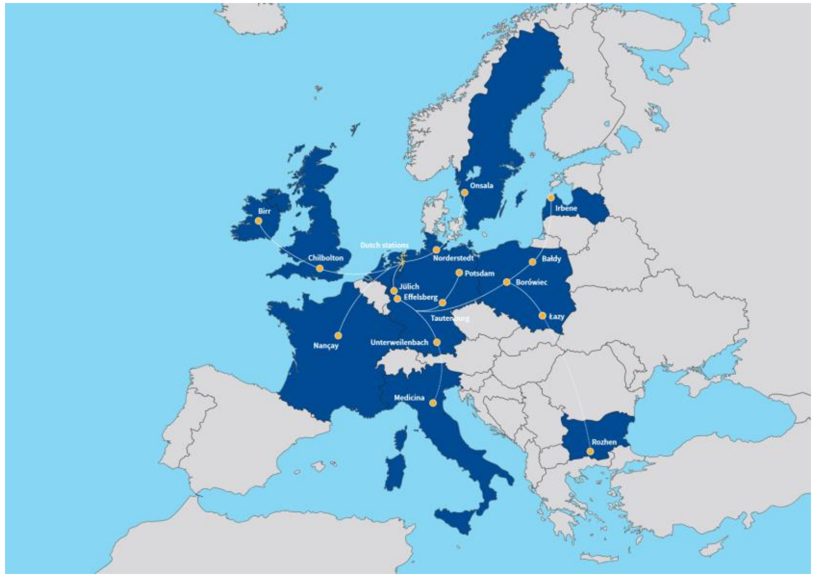
- elongated along magnetic field direction
- anisotropic scattering shifts the apparent position of the source in the direction of the local magnetic field *(Kontar+2017, 2019)*



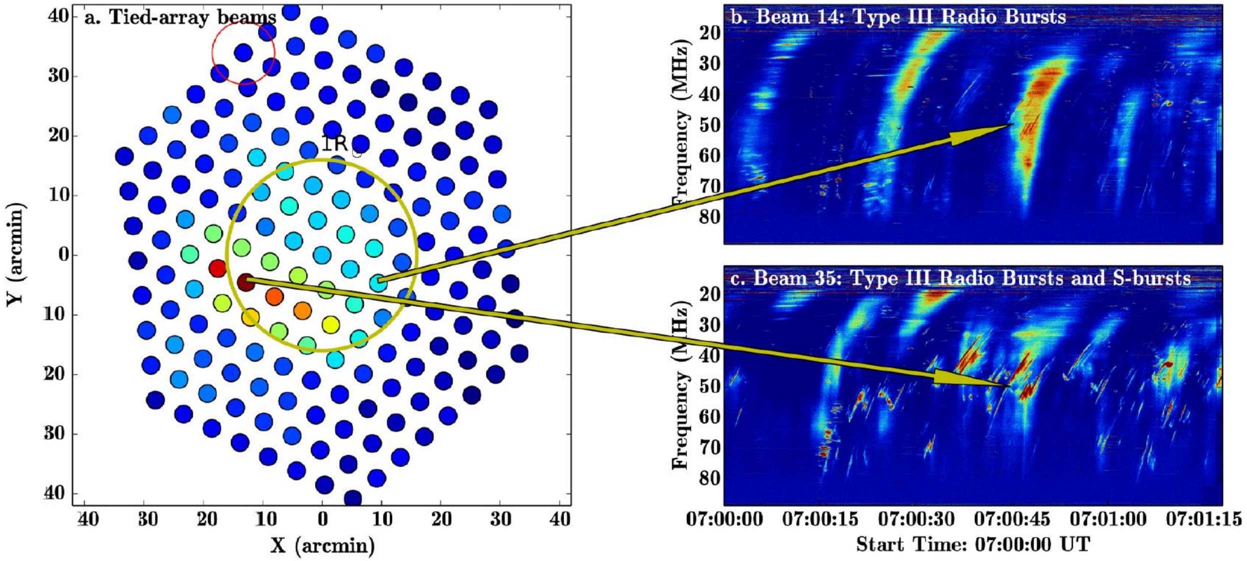
Chen et al. (2020)



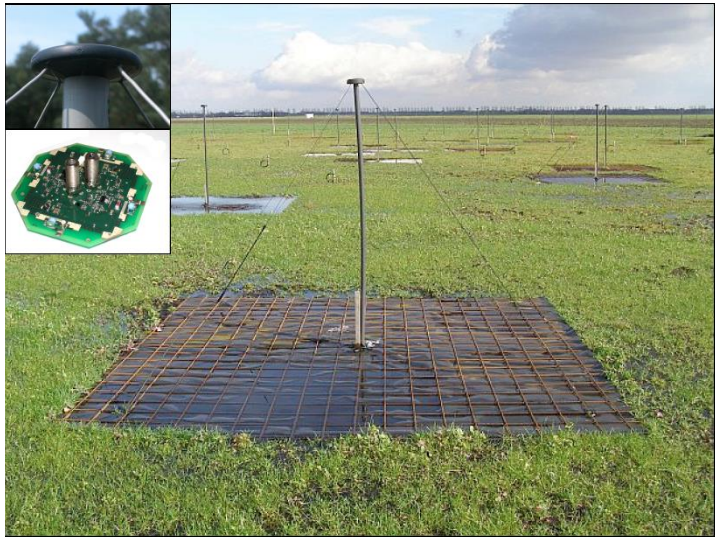
LOFAR



Morosan+2015



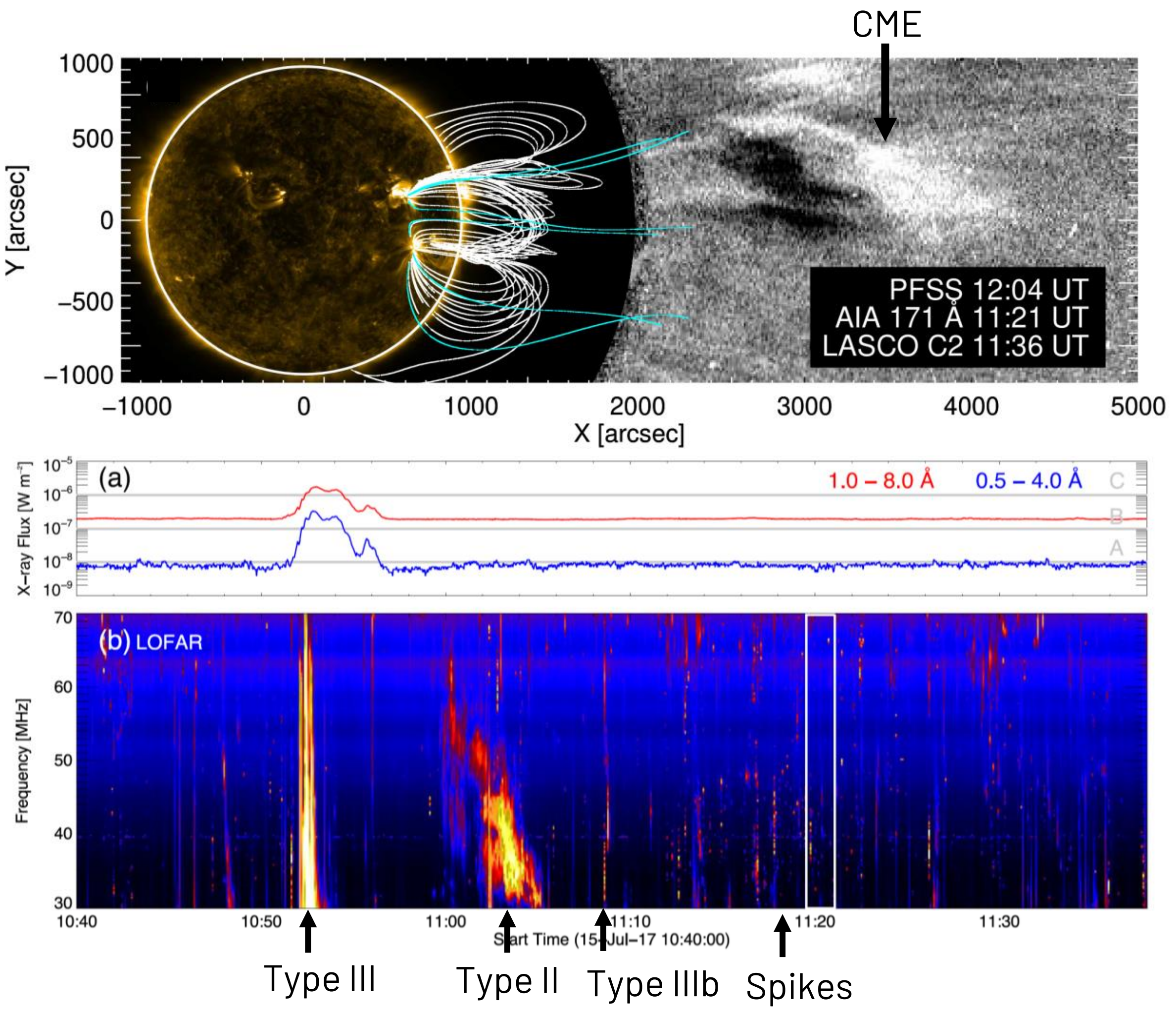
van Haarlem+2013

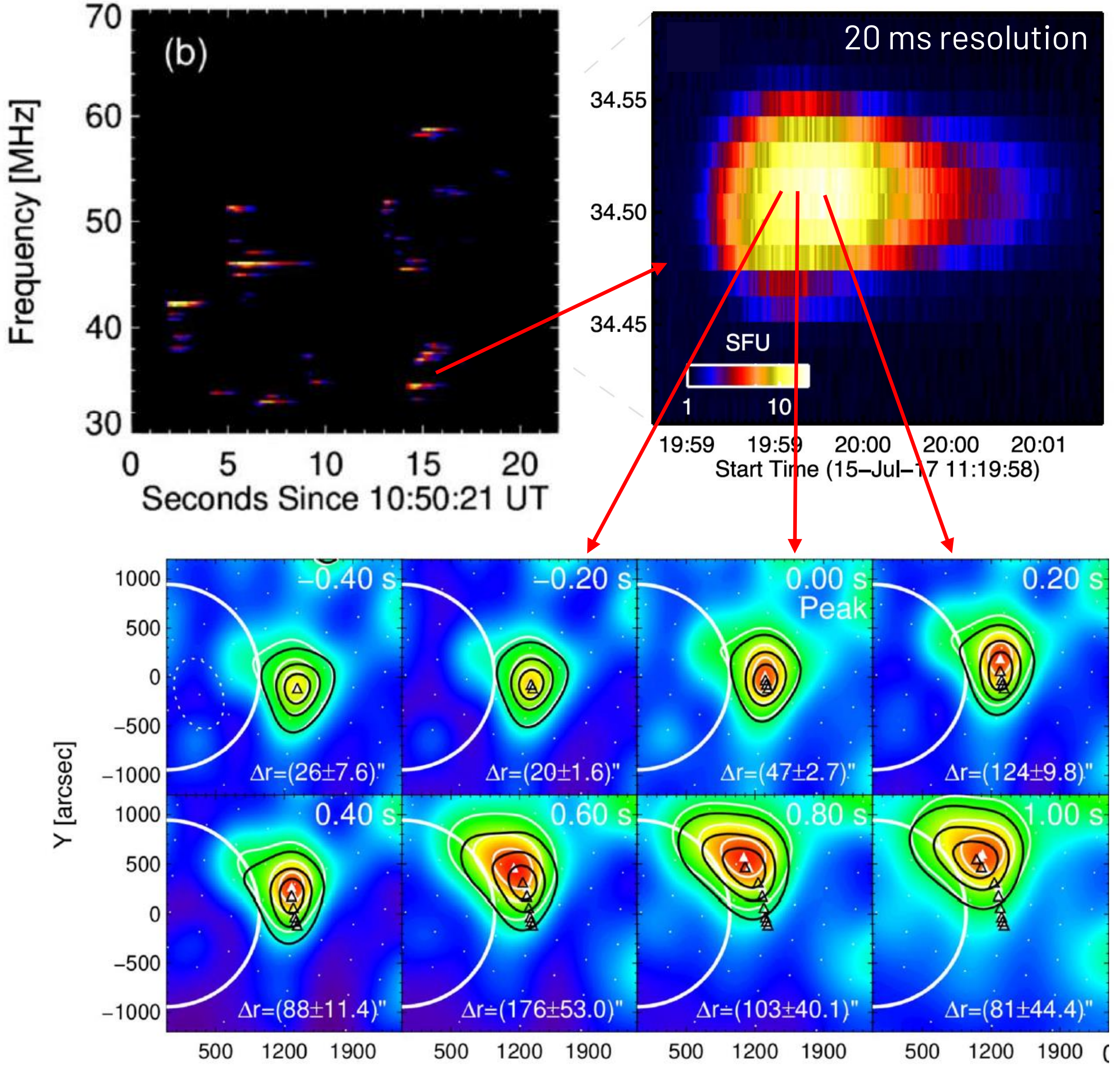


Low Band Antenna

- Baseline: 3.5 km
- Beam-formed mode
- Outer LBA configuration
- Time resolution: 10 ms
- Freq. resolution: 12.2 kHz
- Spatial Resolution: ~9′ at 30 MHz
- Frequency range: 10-80 MHz

Event Overview





Fixed Frequency Centroid Motion of Fine Structure Centroids

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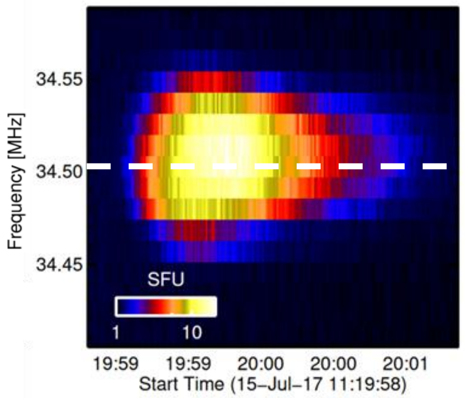
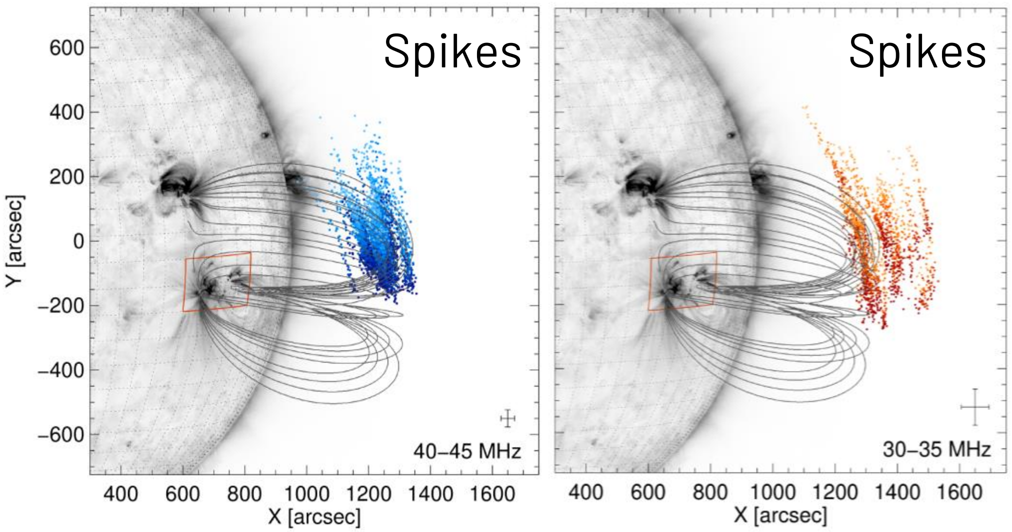
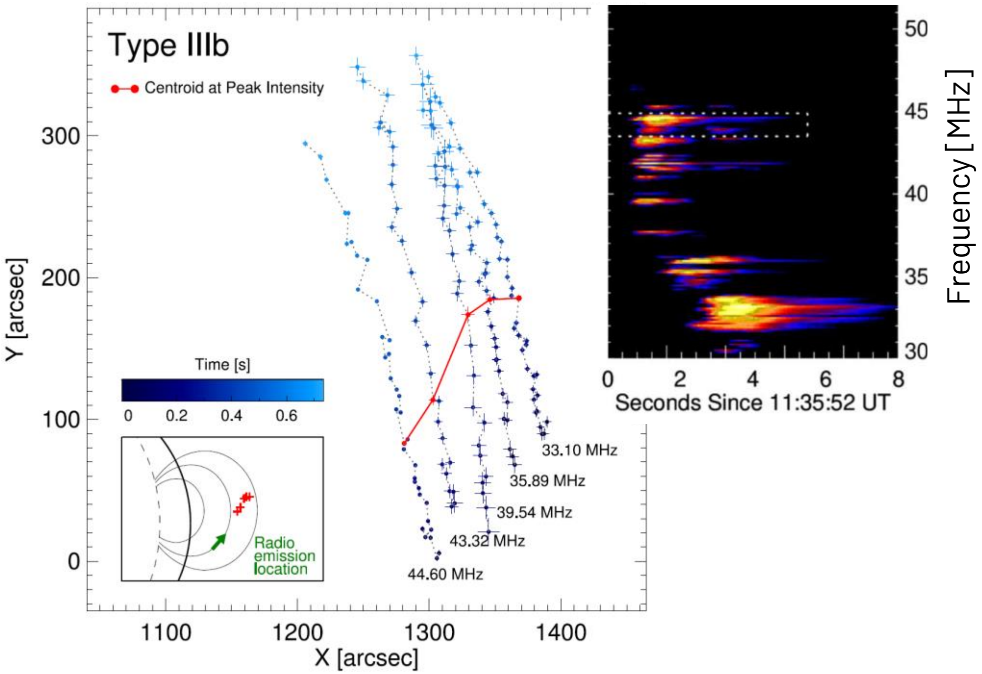
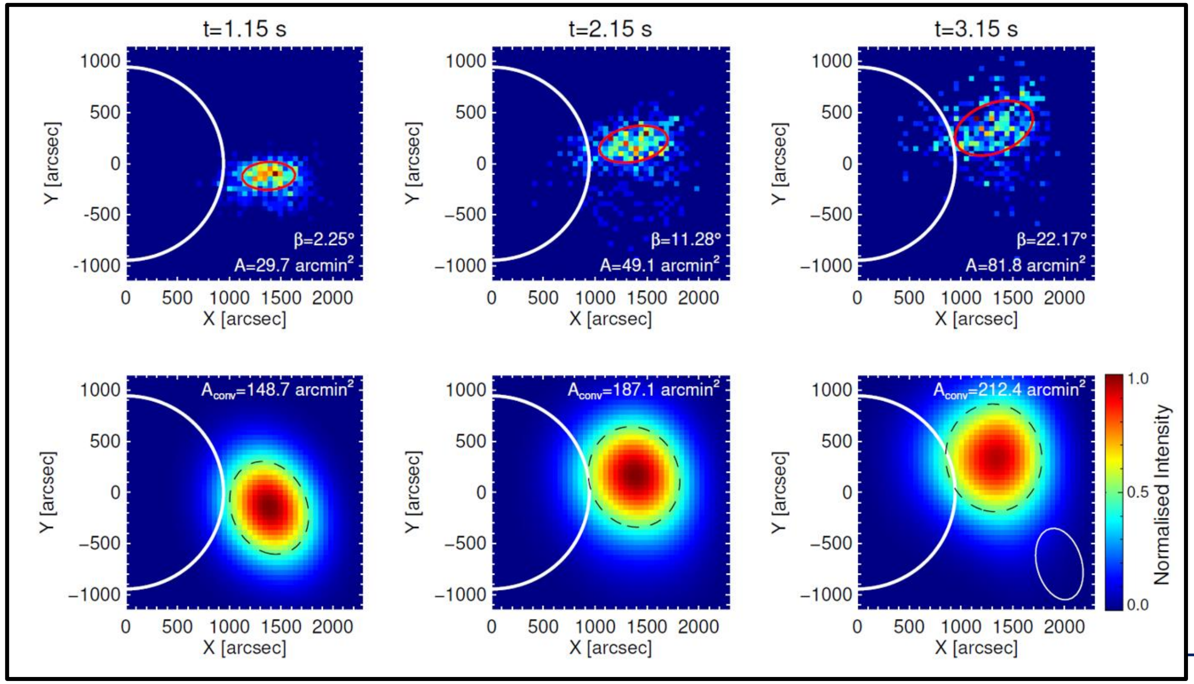






Simulations



Centroid locations show two components of motion:

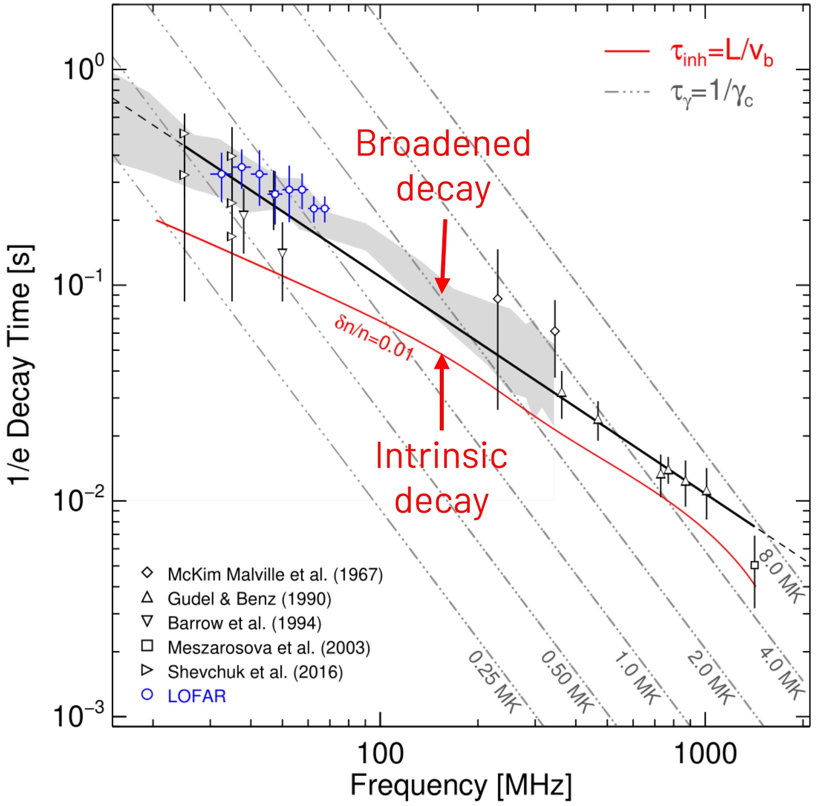
→ Frequency drift due to exciter location

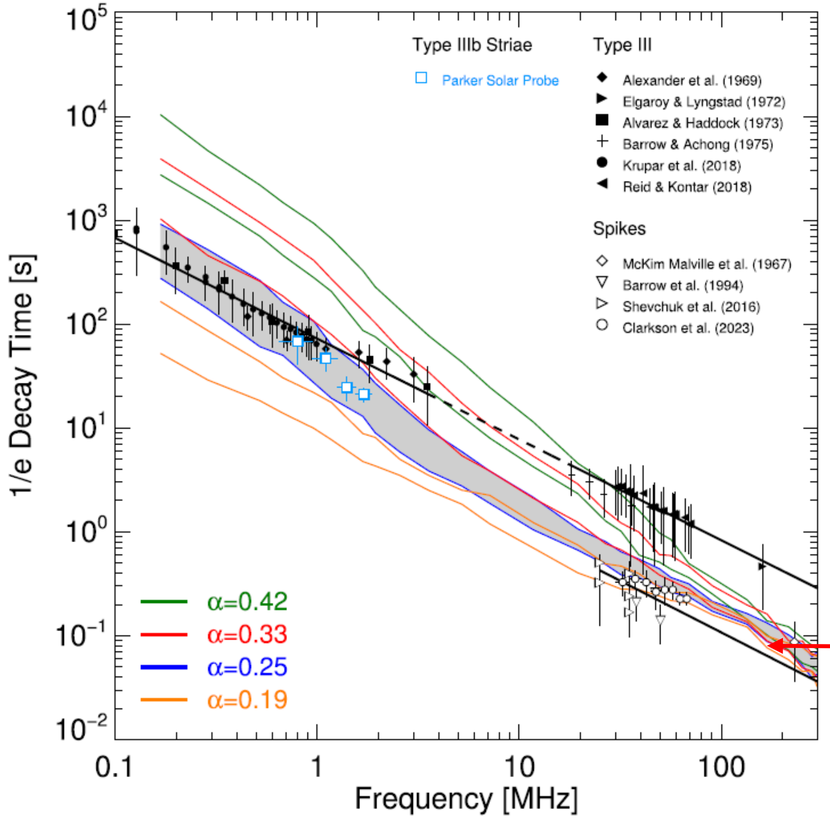
→ Shift in position at fixed frequencies over time

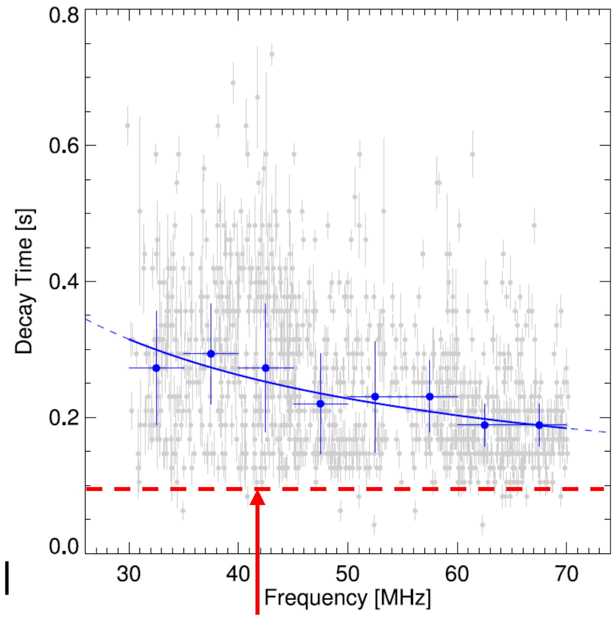
Fixed frequency centroid motion attributed to radio-wave scattering through **anisotropic** turbulence

Simulations of anisotropic scattering in a dipolar field can reproduce the observed non-radial centroid drift.

What Governs the Spike Decay Time?







Observed spike durations below ~1 GHz could be a combination of the time the electron beam takes to cross a particular inhomogeneity and broadening due to scattering

Observed spike time profile governed by radio-wave propagation effects, rather than particle collisions, and defines a minimum observable duration at a given frequency for particular turbulent conditions.

The emission timescale would be shorter and more intense than assumed without a scattering correction (tens of milliseconds at decametre wavelengths)

Conclusion

- Solar radio burst fine structures experience significant scattering effects, broadening their time profiles and source sizes, and shifting the apparent source.
- Directive centroid displacement parallel to the solar limb suggests strong anisotropy of the density fluctuation spectrum, indicating sources embedded in a large-scale coronal loop.
- Radio-wave scattering governs the time profile of the shortest duration radio bursts, defining a minimum observable duration at a given frequency.
- The non-radial motion of the spike sources can be replicated in anisotropic radio-wave scattering simulations using a dipolar magnetic field structure.
- Correcting the spike duration for scattering infers a shorter and more intense emission timescale than assumed from observations.