Introduction to LOFAR solar observations

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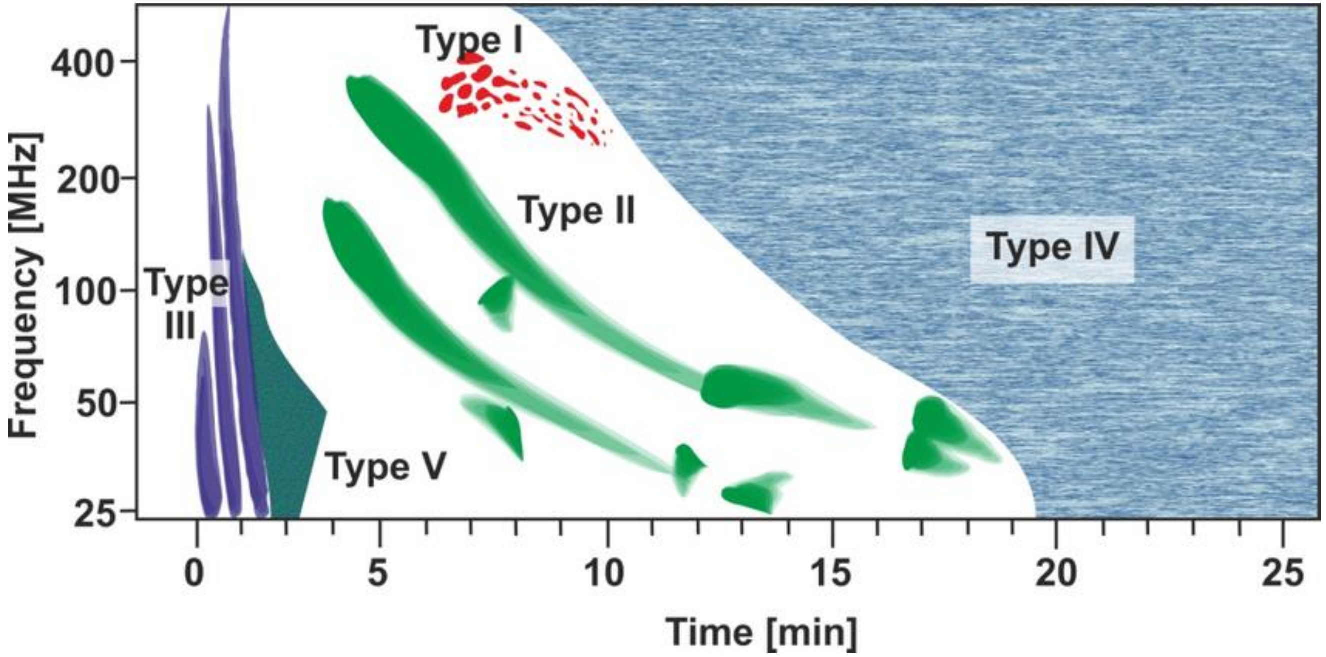
Solar Radio Emissions

Solar Radio Bursts:

- Often envisioned as continuous structures
- But when the temporal and spectral resolutions (and sensitivity) allow it:
  - Can distinguish many fine structures within or around the broader emissions
  - Also of solar origin

5 classical radio burst types:



Dabrowski et al. 2016, Acta Geophys., 64, 825

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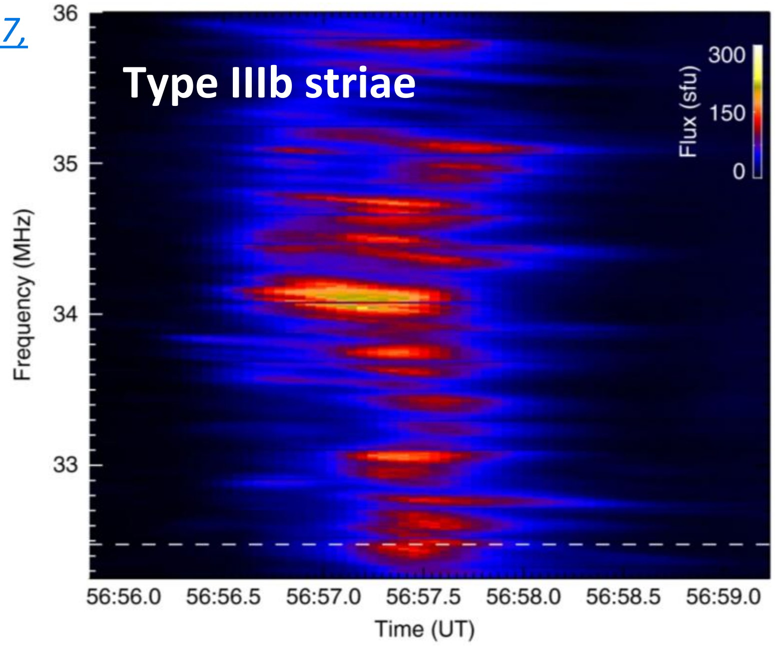
Fine Radio Burst Structures

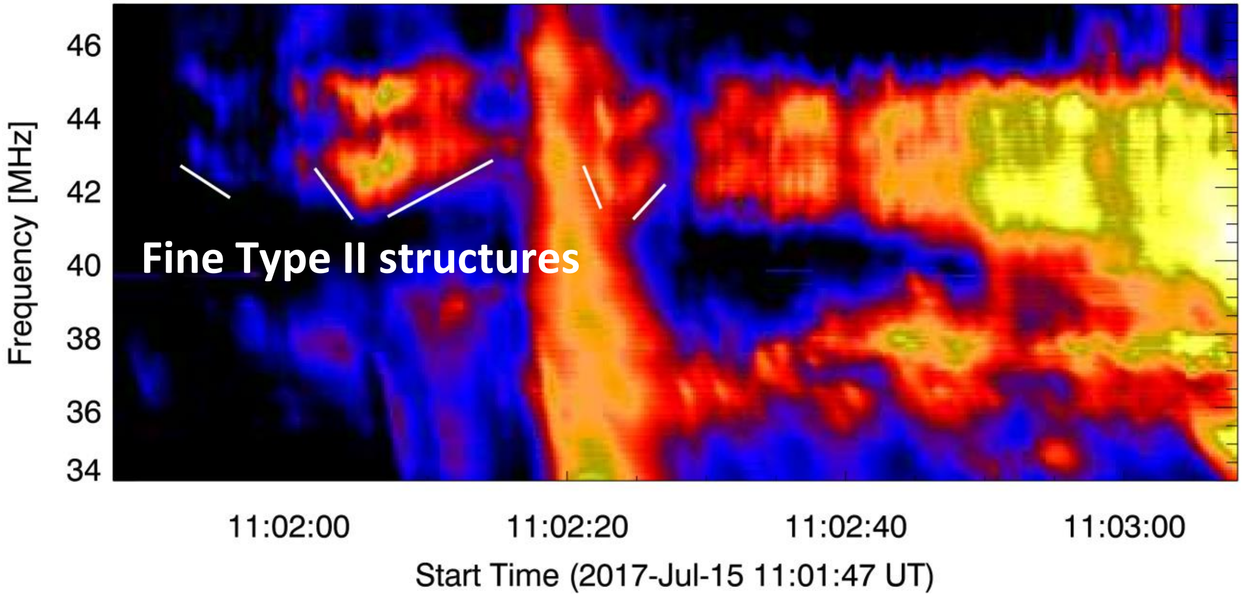
Fine structures:

- Can be "**sub-bursts**" observed within a broader emission OR **stand-alone** fine-structure bursts
- Short duration (a few seconds, or sub-seconds)
- Short bandwidth (a few MHz, or kHz)
- Excitation mechanism not always understood – may differ from that of broader, continuous structure

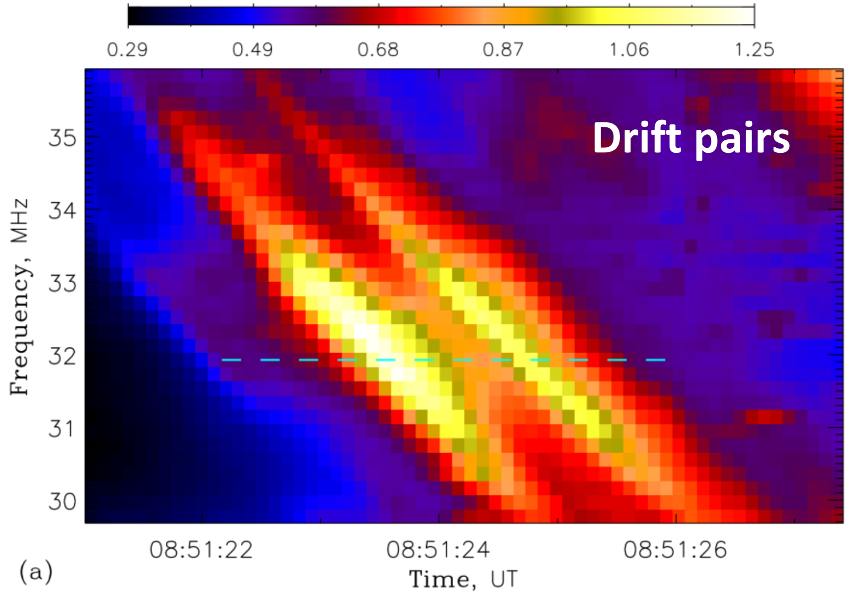
Kontar et al. 2017, NatCo, 8, 1515



Chrysaphi et al. 2020, ApJ, 893, 115



Kuznetsov et al. 2020, ApJ, 898, 94



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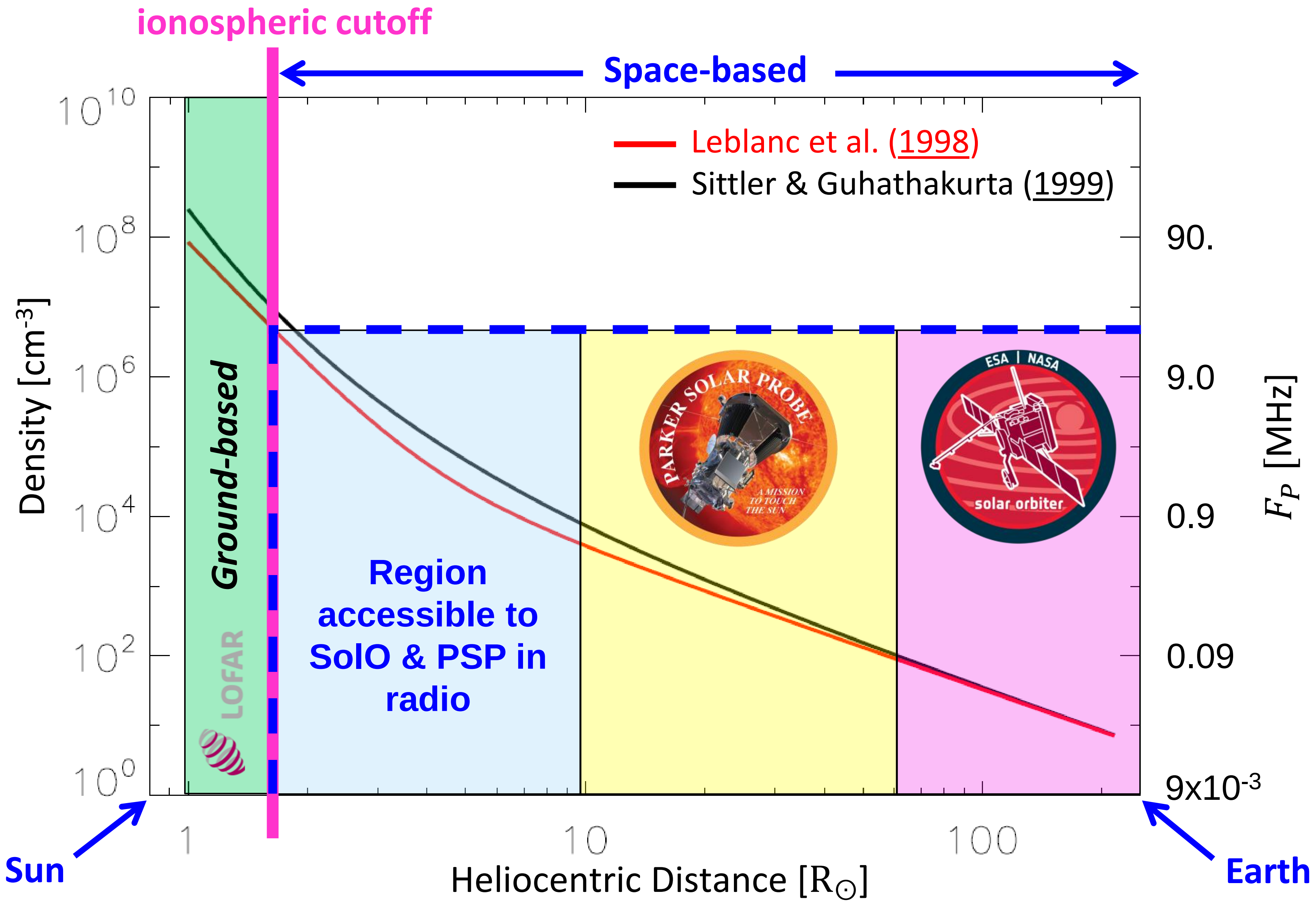
Ground- vs Space-based observations



- Ionospheric cut-off at ~10 MHz
- **Advantage of ground-based instruments:** longer baselines ⟹ higher spatial resolution

Figure based on data from M. Maksimovic.

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LOFAR: LOw-Frequency ARray

- Radio interferometer
- Innovative phased-array design
- Operating since late 2010
- Stations spread across Europe

- Array configuration:
  - Core stations
  - Remote stations
  - International stations (currently 14)
- Still expanding…

- Frequency range:
  - 10–240 MHz
  - Gap between 90–110 MHz due to FM radio (UN GE84)

- Very versatile
- Capabilities limited by computing power

Figure courtesy of ASTRON.

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LOFAR antennas

LOFAR antennas:

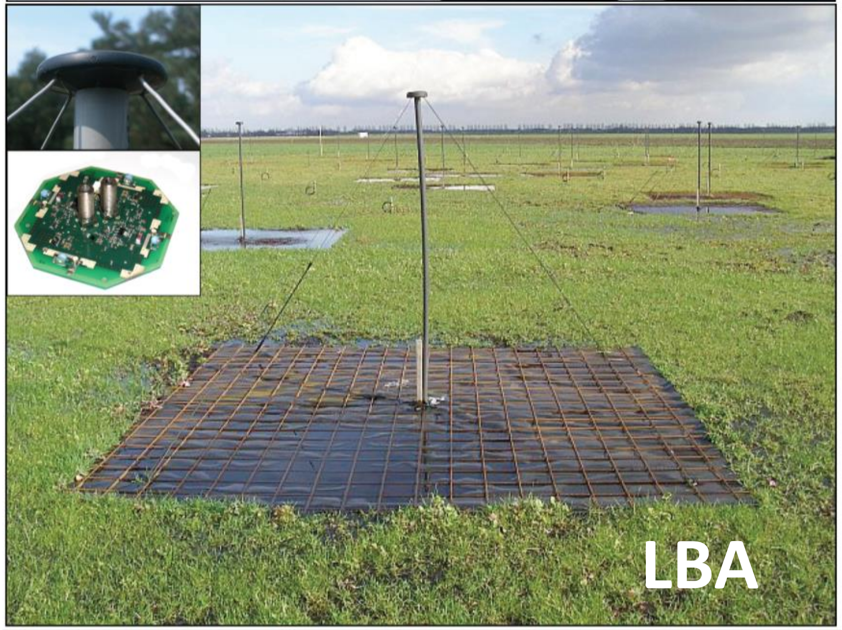
- No moving parts ⟹ low cost
- Digital beam pointing (using phase delays)

High-Band Antenna (HBA):

- Composed of tiles (16 dipoles each)
- Covers 110–240 MHz

Low-Band Antenna (LBA):

- Composed of dipoles
- Covers 10–90 MHz
- *Focus on LBA frequencies*



van Haarlem et al. 2013, A&A, 556, A2

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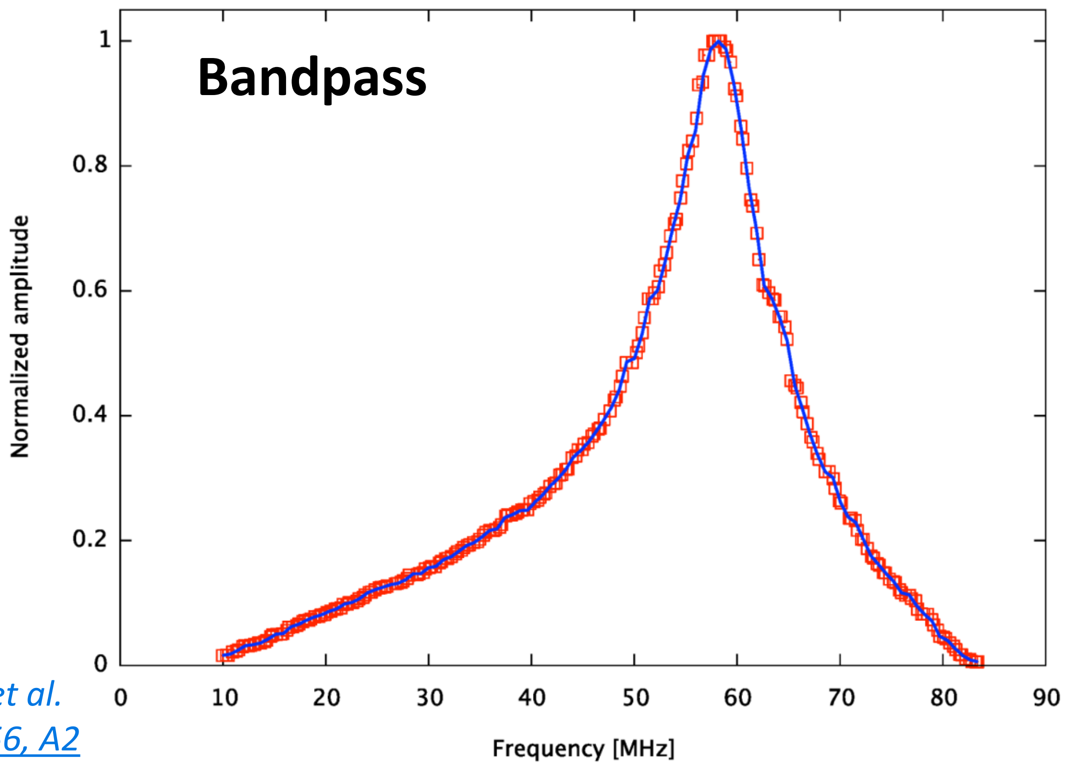
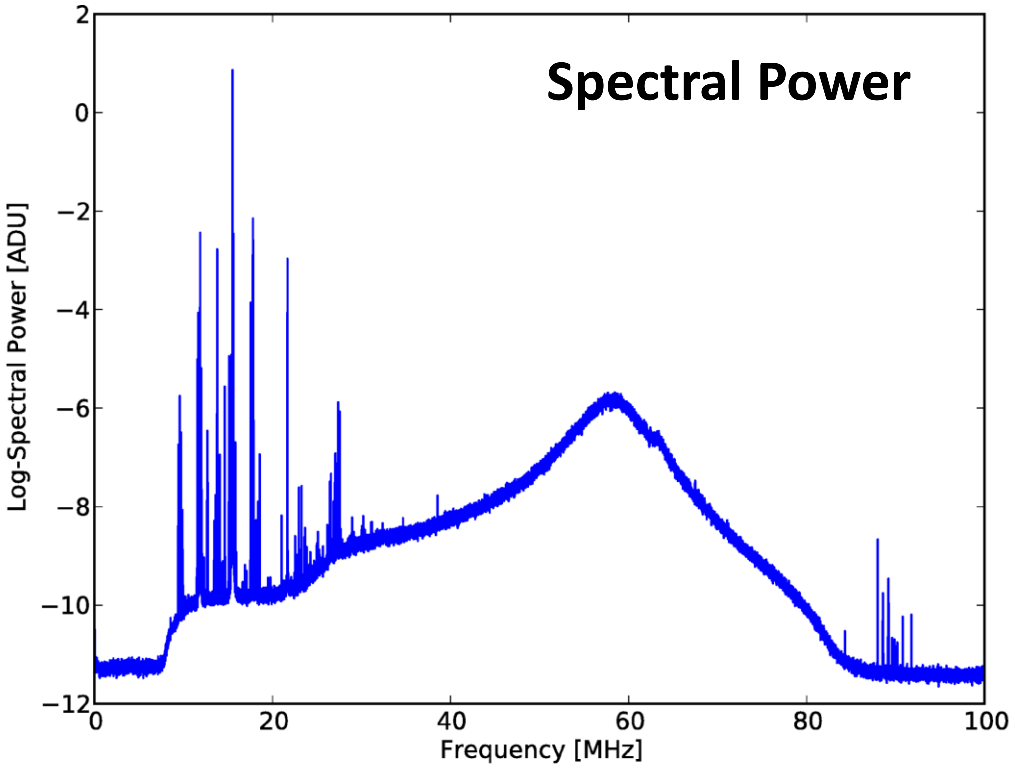
LBA: Low-Band Antenna

- Each LOFAR station has 96 LBA antennas
- LBA **most sensitive at ∼58 MHz** (in dry conditions) ⟹ calibration is essential

- Frequency range:
  - Design: 10–90 MHz
  - In practise: 30–80 MHz (due to strong RFI)
- Frequencies below 30 MHz can be suppressed





van Haarlem et al. 2013, A&A, 556, A2

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Digital Interferometry

- Can observe using individual antennas, stations, or combine many antennas/stations

Combining antennas/stations:

- Decreases FoV (i.e. increases spatial resolution)
- Increases sensitivity

Stappers et al. 2011, A&A, 530, A80

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Tied-array beam mode

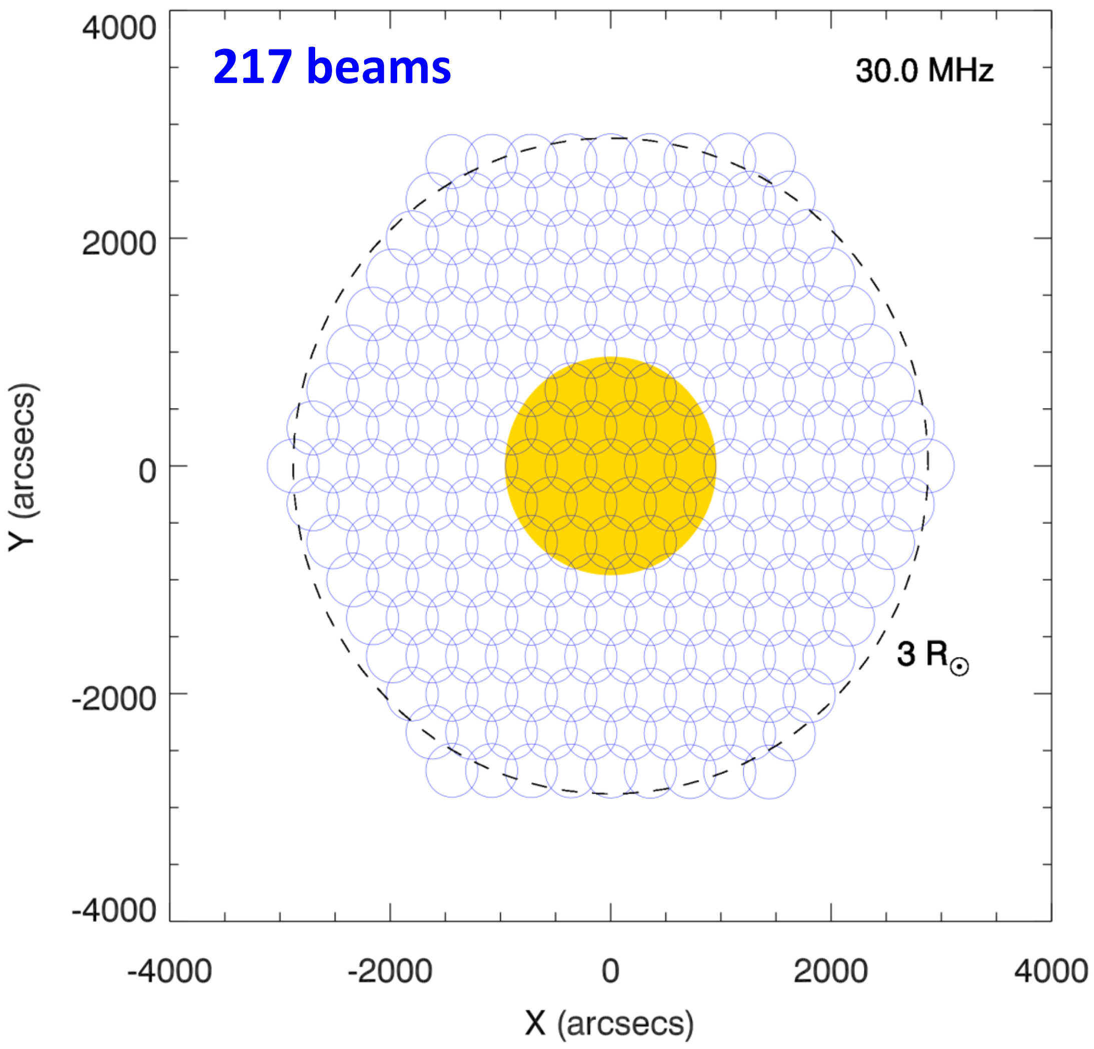

Figure from Chrysaphi PhD thesis (2021).

Tied-array beam:

- Coherent Stokes beam-formed mode
  ⟹ Coherent summation of beams (signals aligned before summation)

- Collection of individual beams define the FoV
  ⟹ a hexagonal mosaic

- Sensitivity equal to that of total collecting area
- Stations on same clock
  ⟹ required for real-time phase alignment

- **Aims:**
  - enough beams to produce a sufficiently large FoV
  - sufficient spatial resolution
  - partial beam overlapping (at lower frequencies)
    ⟹ compact tied-array (smaller side-lobes)

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LOFAR core stations

- Only core stations are on the **same clock signal**
- Total of 24 core stations (96 LBA antennas per station)
- Different LBA station configurations available
- Used **outer LBA configuration** for tied-array beam observations :
  - 48 (out 96) outermost antennas
  - maximum baseline of **~3.5 km**

van Haarlem et al. [2013, A&A, 556, A2]

The heart of the core stations, known as "Superterp".

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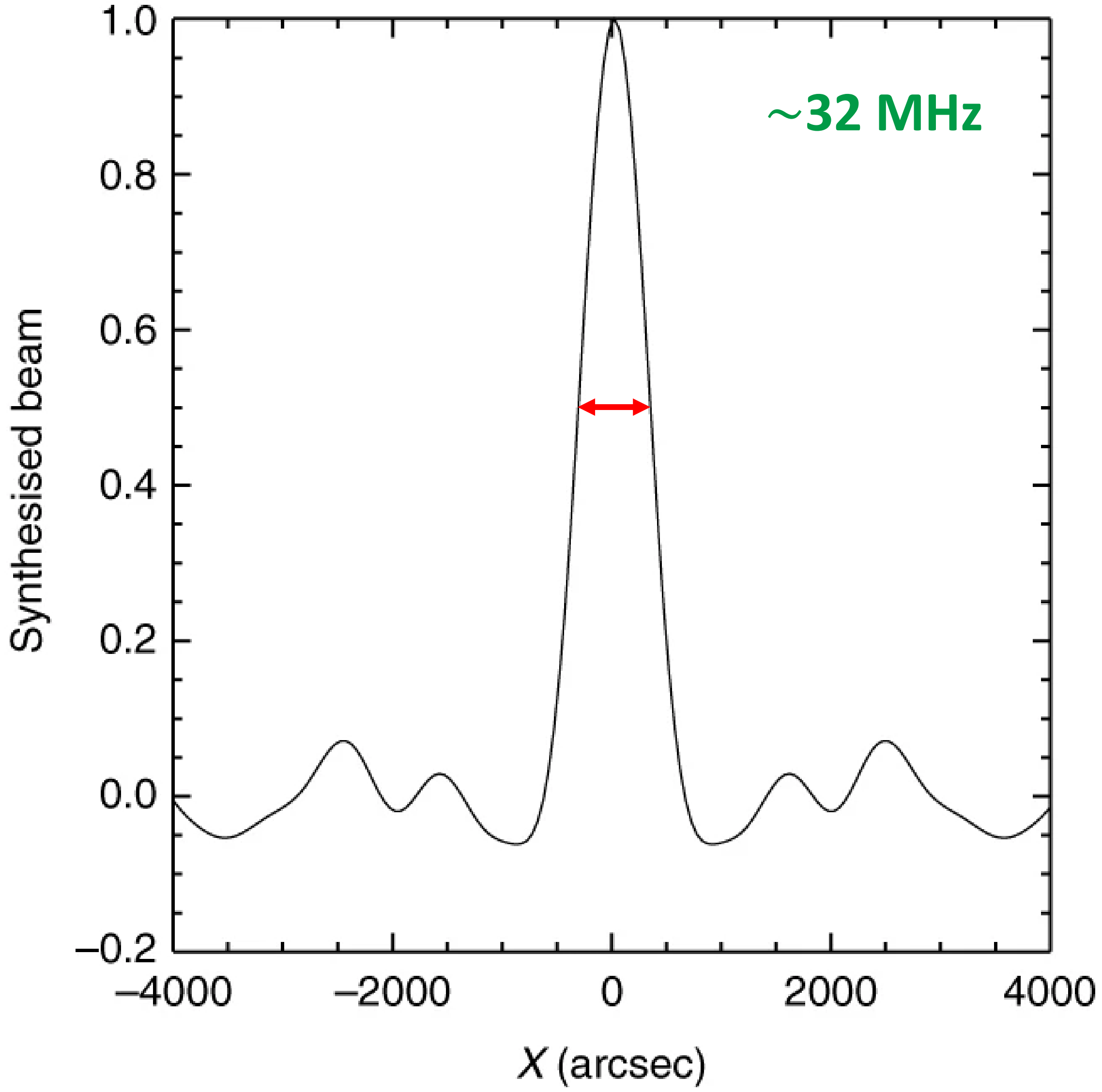
Obtained resolutions



Kontar et al. 2017, NatCo, 8, 1515

High resolution imaging spectroscopy – Defined parameters:

- Temporal resolution ~0.01 s
- Spectral resolution ~12.2 kHz
- Sensitivity $\lesssim$ 0.03 sfu per beam
- Centre-to-centre beam separations ~6 arcmin at 30 MHz (i.e. compact tied-array)
- Spatial resolution ~10 arcmin at 30 MHz (larger frequencies correspond to higher spatial resolutions)

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Imaging Spectroscopy

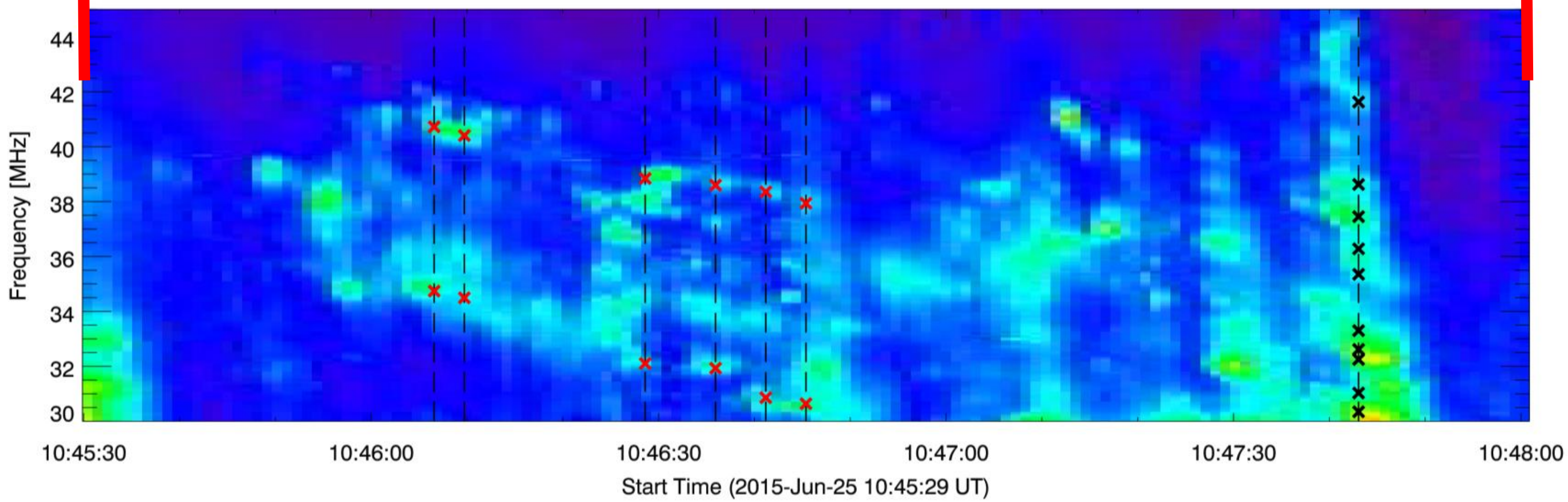
- Obtain both dynamic spectra and images with **equal resolution**

Stokes parameters:

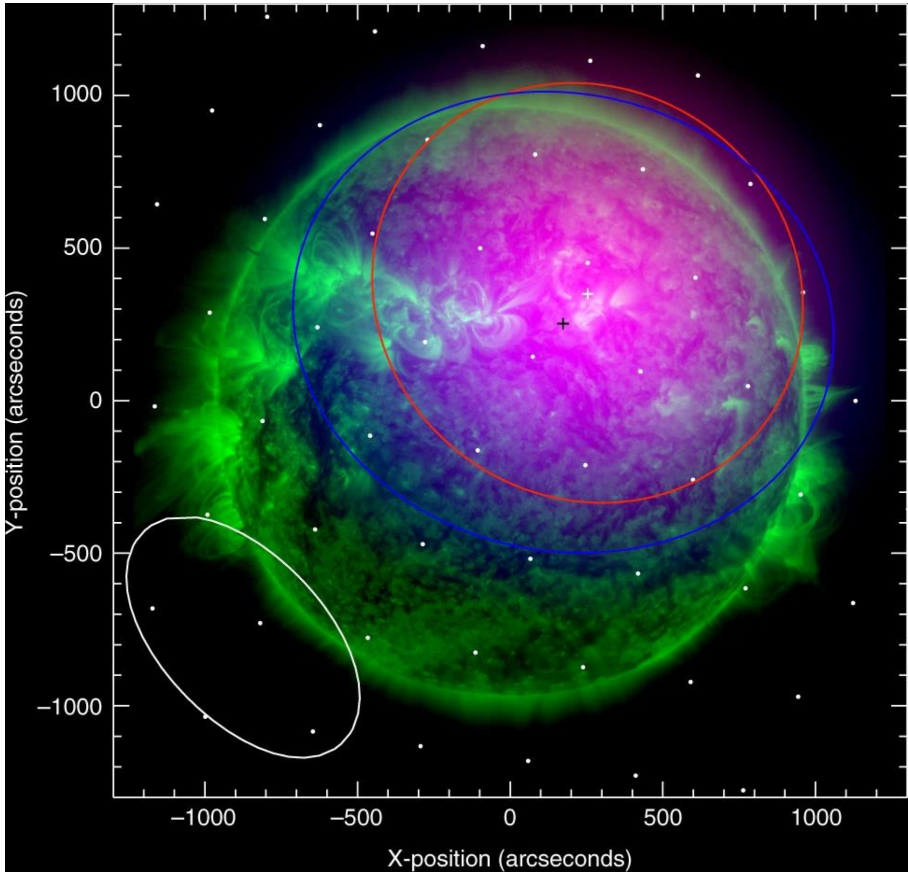
- Stokes I, Q, U, and V can be recorded (but demand more computing power)
- Chose **only Stokes I** (intensity) ⟹ allows a higher resolution

Chrysaphi et al. *2018, ApJ, 868, 79*

~ 18.5 million images!



Kontar et al. *2017, NatCo, 8, 1515*



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Spatial resolution

- **Nominal** FWHM spatial resolution:

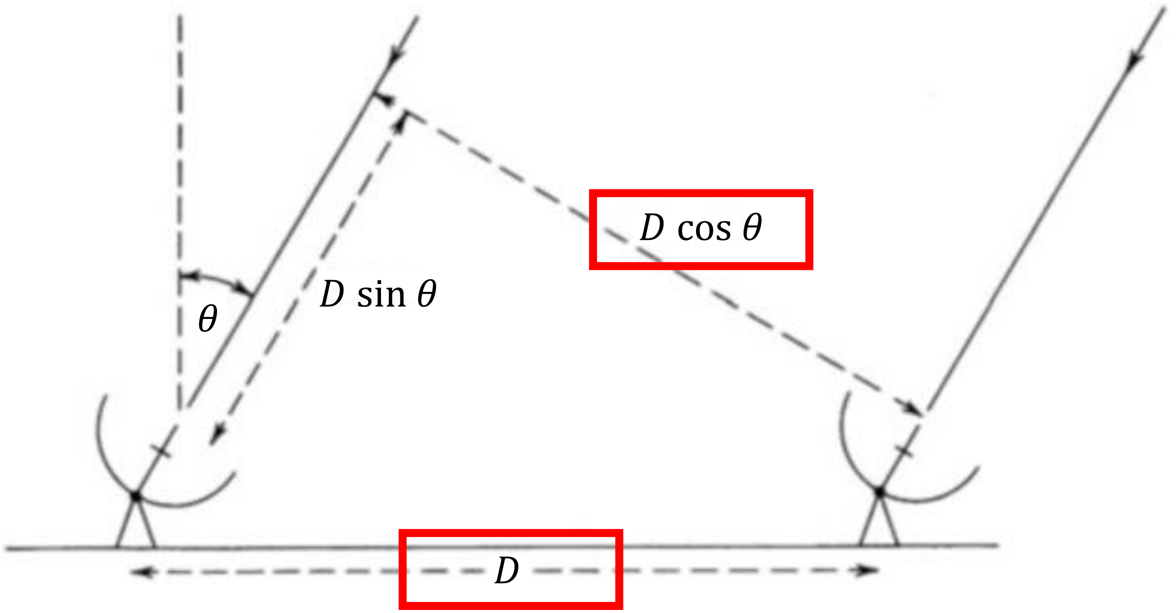
$$\theta_{res} \approx \frac{\lambda}{D}$$

where: λ = wavelength
D = baseline length

- **Nominal** FWHM beam area:

$$A_{beam} = \pi \left(\frac{\theta_{res}}{2}\right)^2$$

- **But in practise…**
  - D is a function of the source's elevation
  - Beam is elliptical (depends on source elevation)



Thompson et al. 2017, DOI: 10.1007/978-3-319-44431-4

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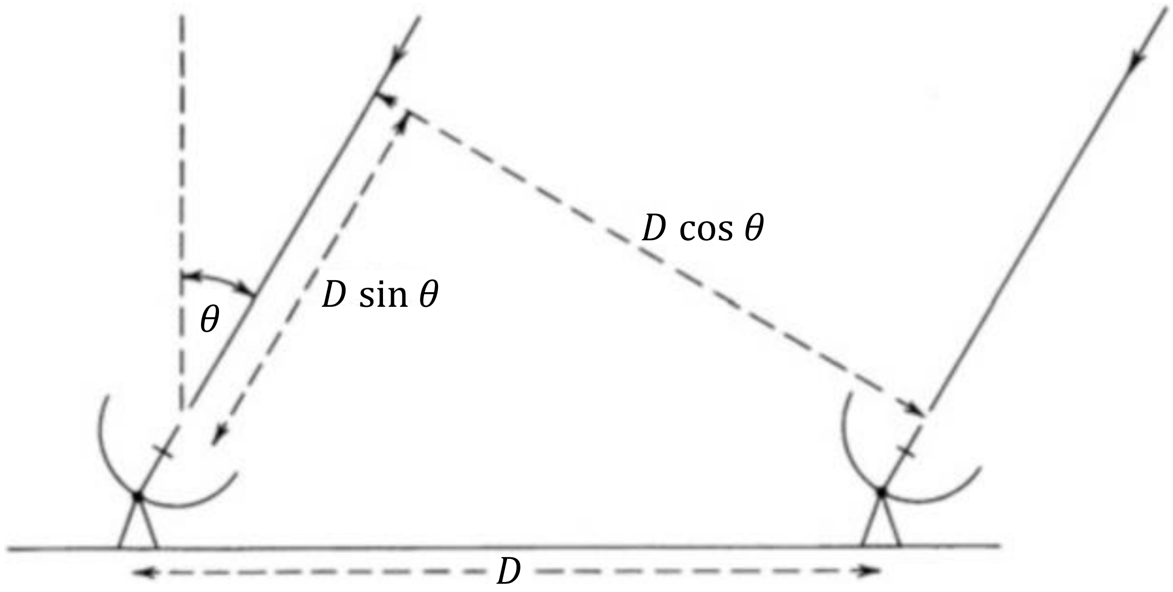
Source elevation

- Best observations when **source is at maximum elevation** above horizon, i.e. for solar observations:
  - near local noon (12:00)
  - near the summer solstice (i.e. around June for LOFAR)

- Higher source elevations ⟹ less atmospheric attenuation (e.g. scattering and absorption by Earth's atmosphere)



Thompson et al. 2017, DOI: 10.1007/978-3-319-44431-4

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Flux calibration

Flux calibration for solar tied-array beam observations:

- Use a point-like source and "empty sky"
- **Point-like source selection criteria:**
  - Well-defined, (relatively) non-variable, bright radio source
  - Isolated from other (bright) radio sources and sufficiently far from the Sun
- Chosen point-like source is **Tau A** (Crab Nebula)

- Two ways of conducting calibrator observations:

  Method 1:
  - Allocate 1 beam to the point source and 1 beam to the "empty sky"
  - Observe during the solar observation

  Method 2:
  - Use the full tied-array mosaic
  - Observe before and after the solar observation

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Contacts

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Zoom chat

Slack workspace: solarlofarschool2021.slack.com

Slack channels:

- General
- IDL-Help
- Slack-Help
- Random
- Direct (private) messages to lectures/tutors

- For fully-processed LOFAR data OR collaboration requests, contact (at least) Eduard Kontar.