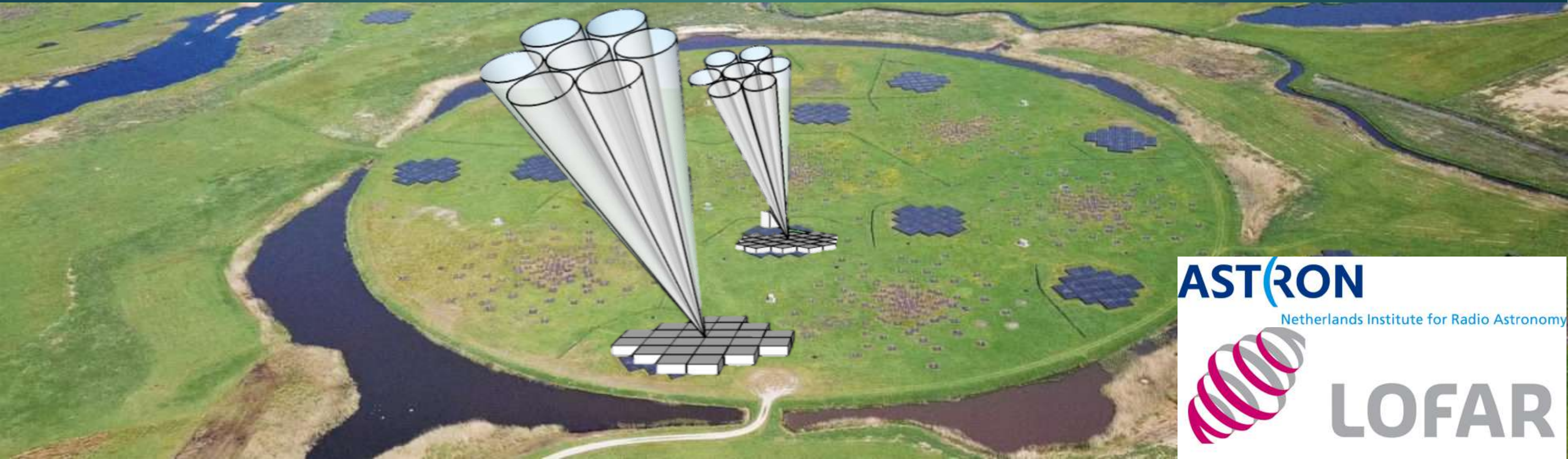
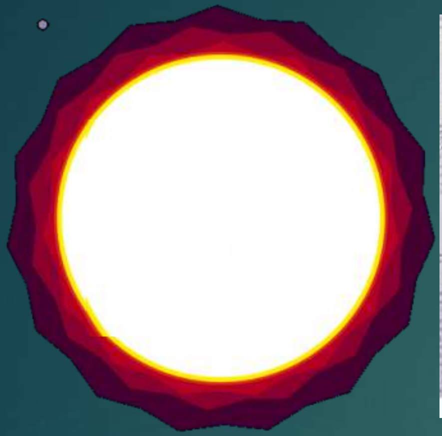
Observing the Sun with **LOFAR**:

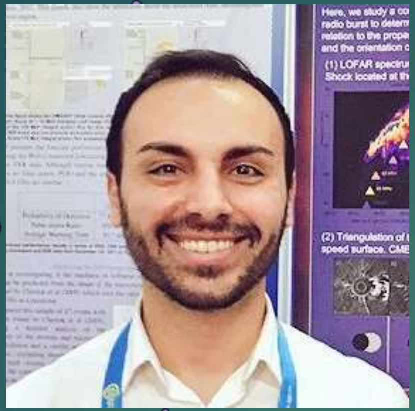
a summary of the current results and observing modes.

Pietro Zucca and the solar KSP

ASTRON Netherlands Institute for Radio Astronomy

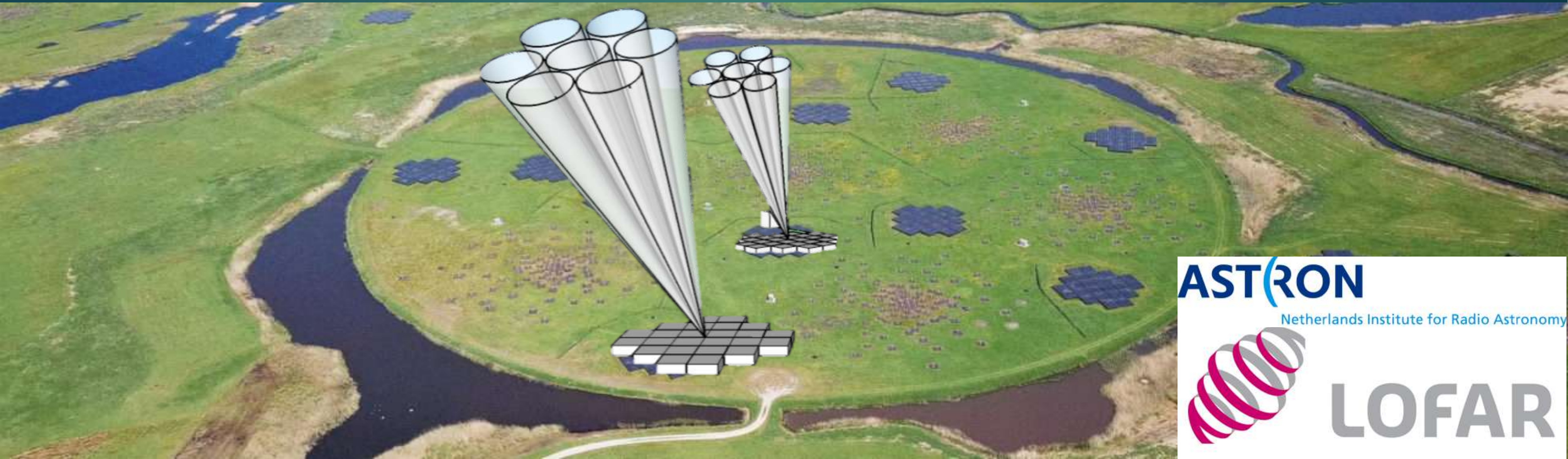






Pietro Zucca
LOFAR Telescope Astronomer
Solar Physics and Space Weather

ASTRON Netherlands Institute for Radio Astronomy



ASTRON
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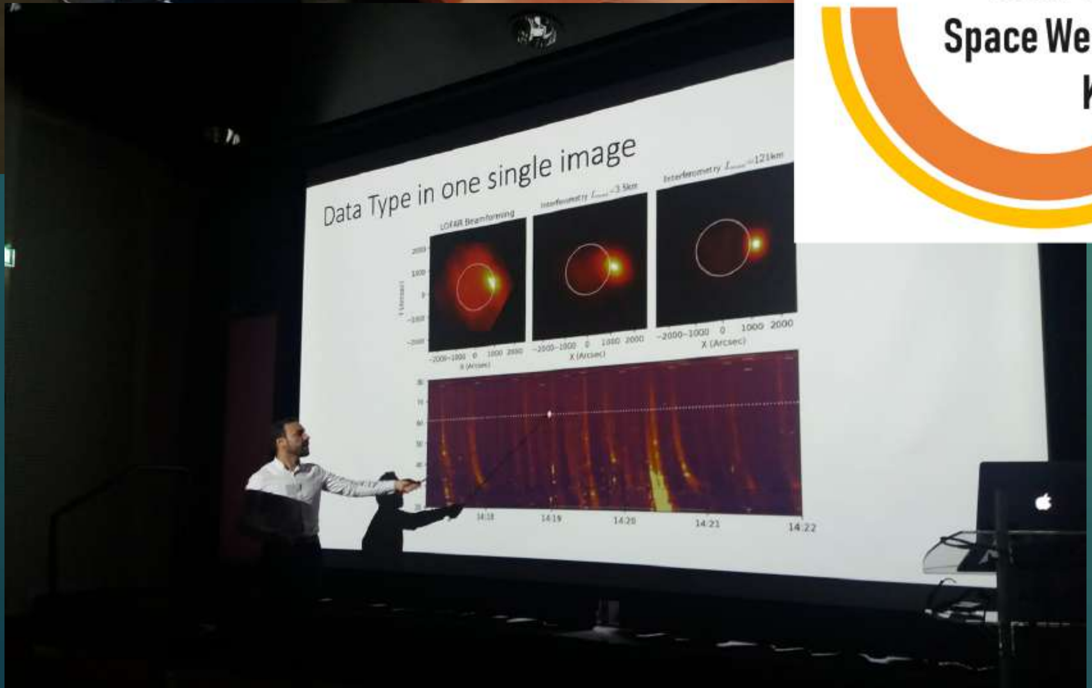
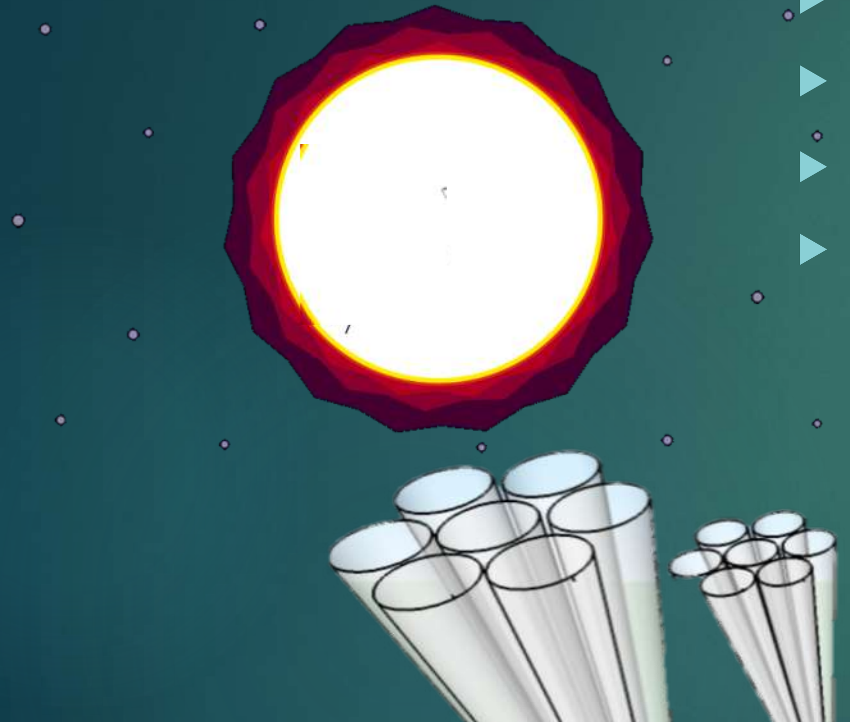
LOFAR

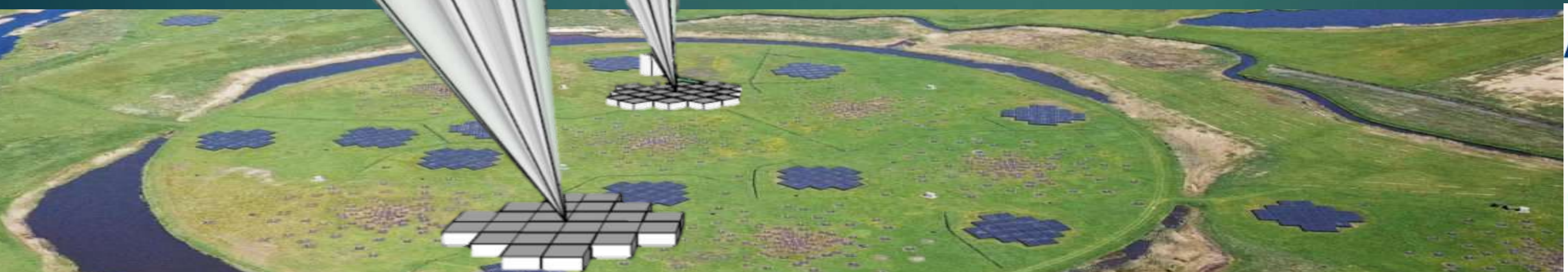
LOFAR
Solar and
Space Weather
KSP



Overview

- Introduction to LOFAR
- LOFAR Observing modes and KSP campaigns
- Solar Observations (Tied array beam and Interferometric)
- Observing scintillation from compact objects and pulsars around the Sun extracting DM and RM of the solar wind and transients





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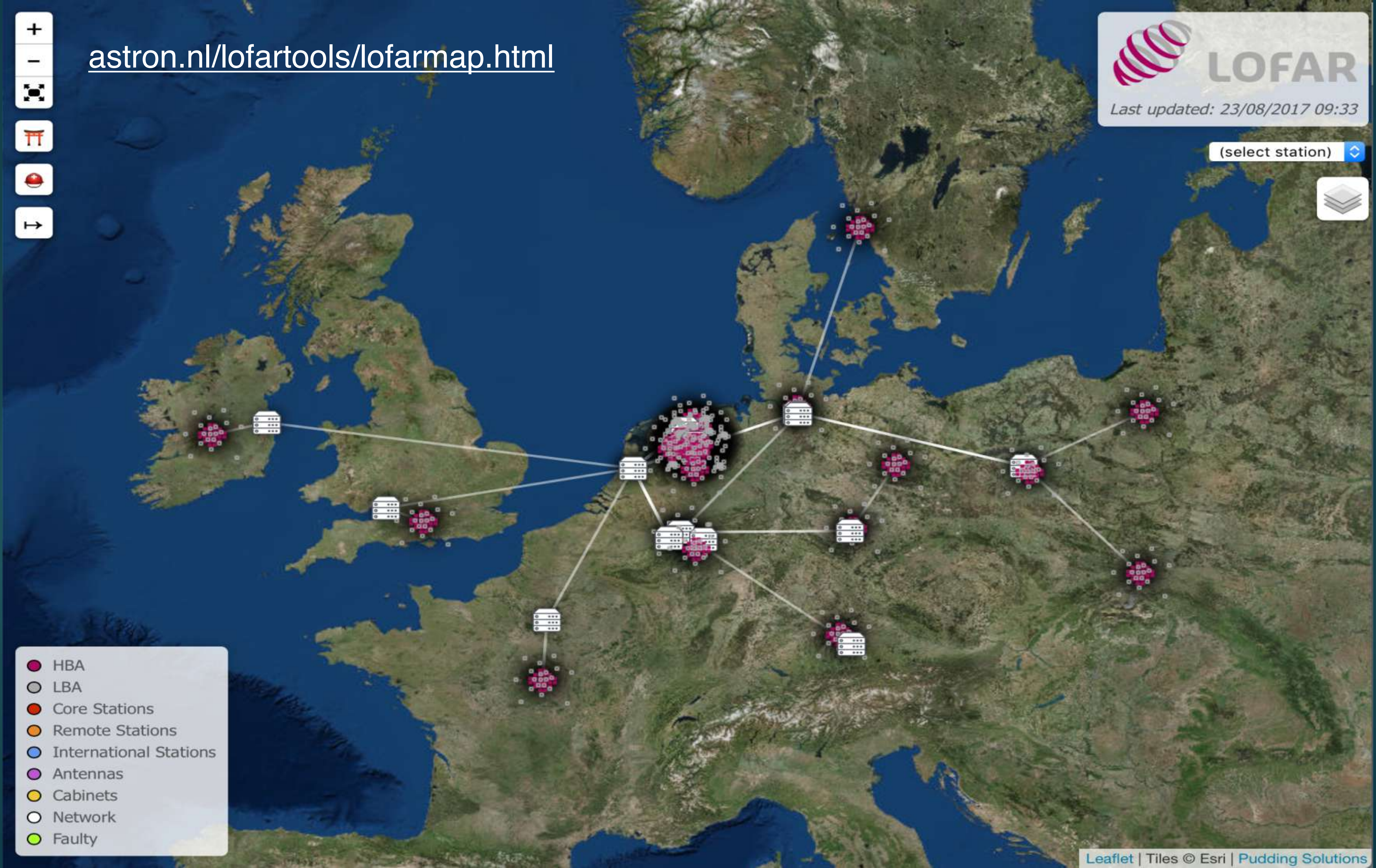
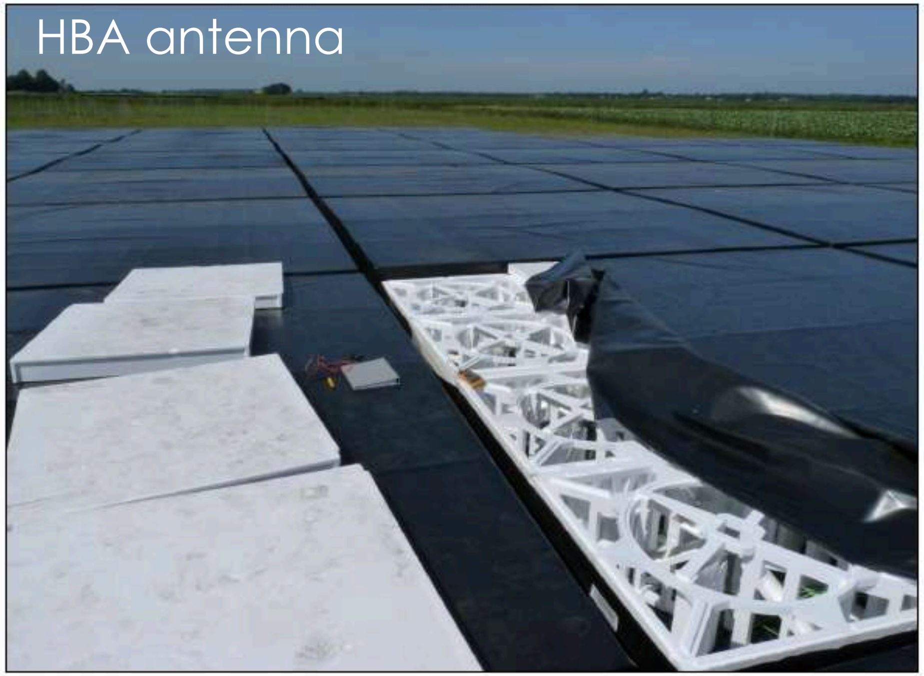
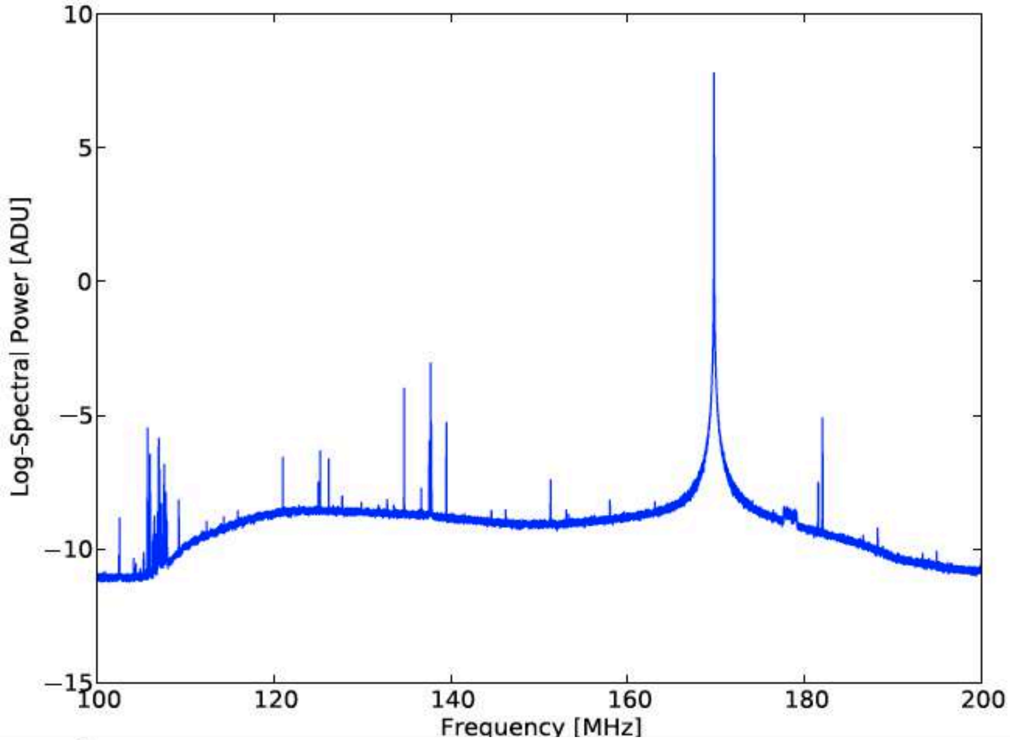
LOFAR

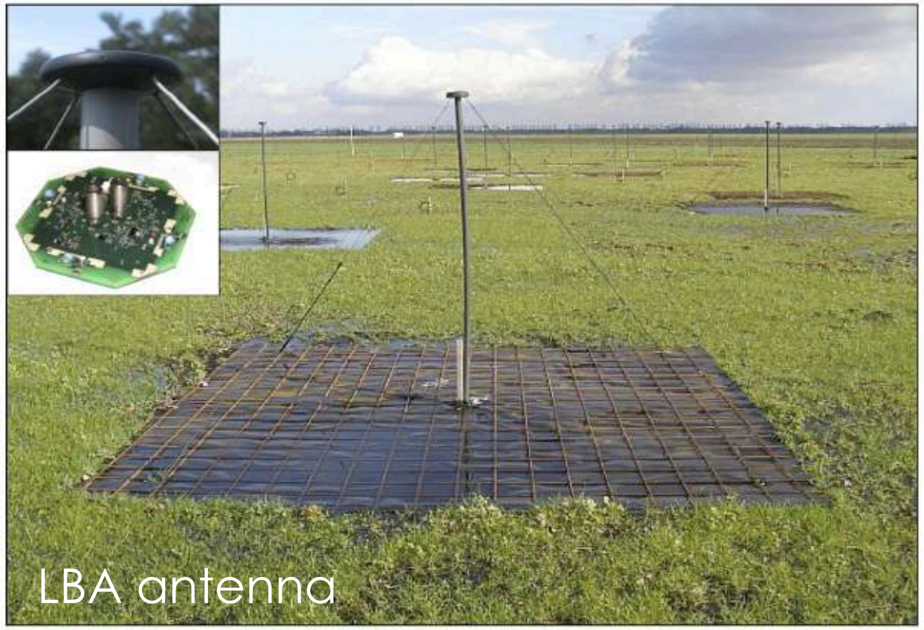

Low Frequency Array (LOFAR) superterp
Exloo, Netherlands

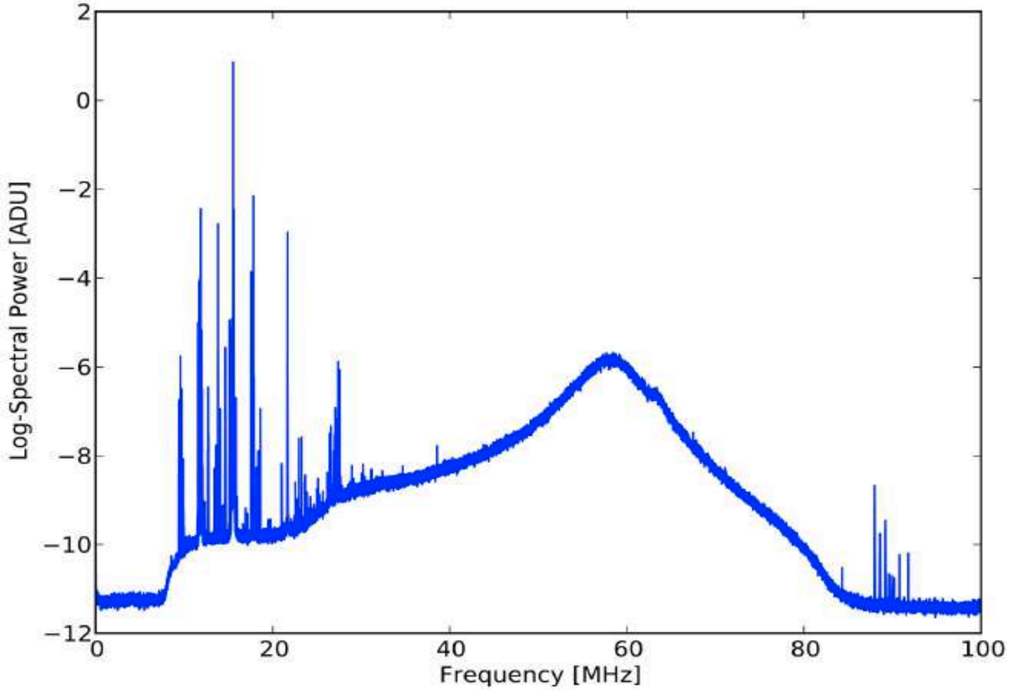
astron.nl/lofartools/lofarmap.html



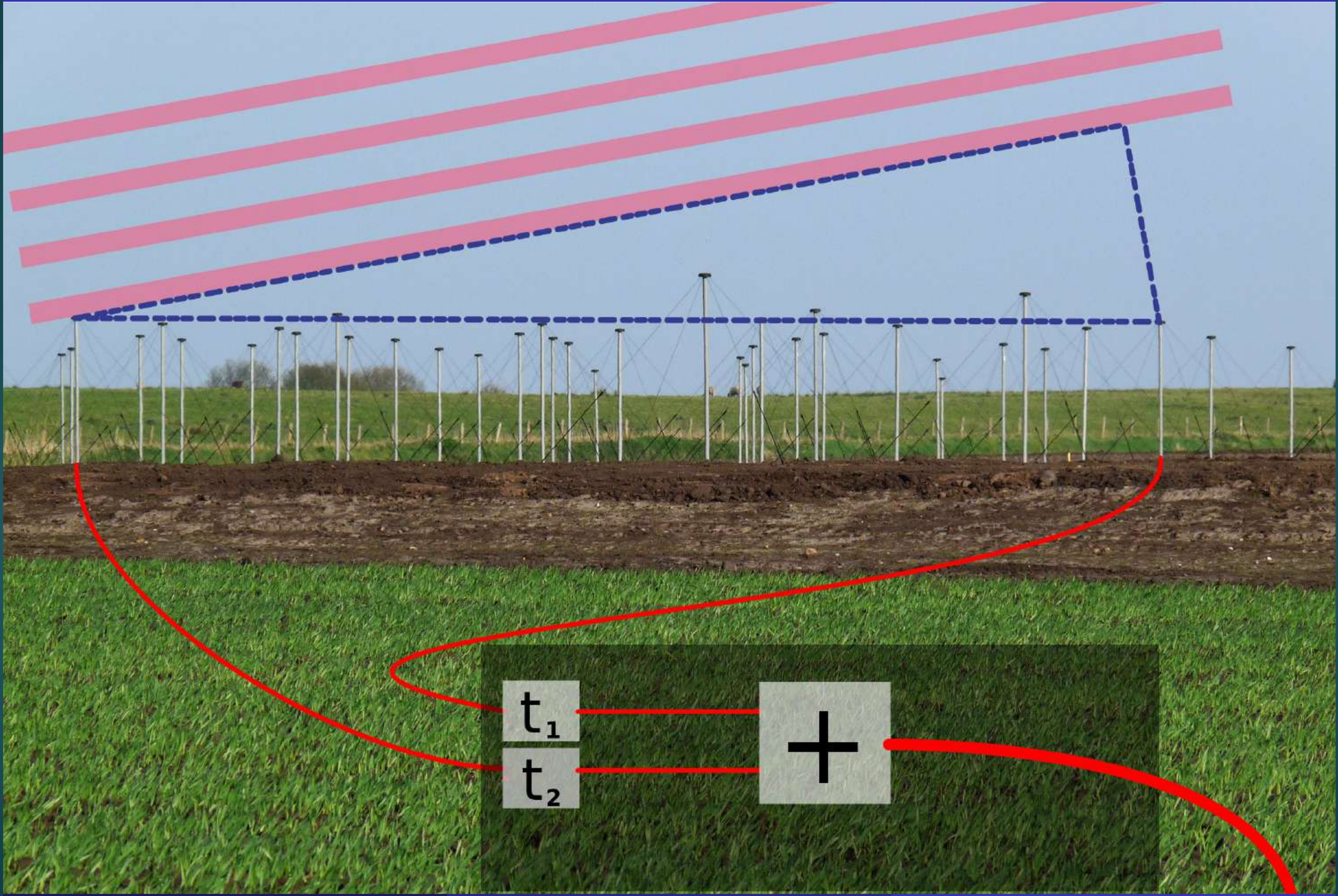

HBA antenna

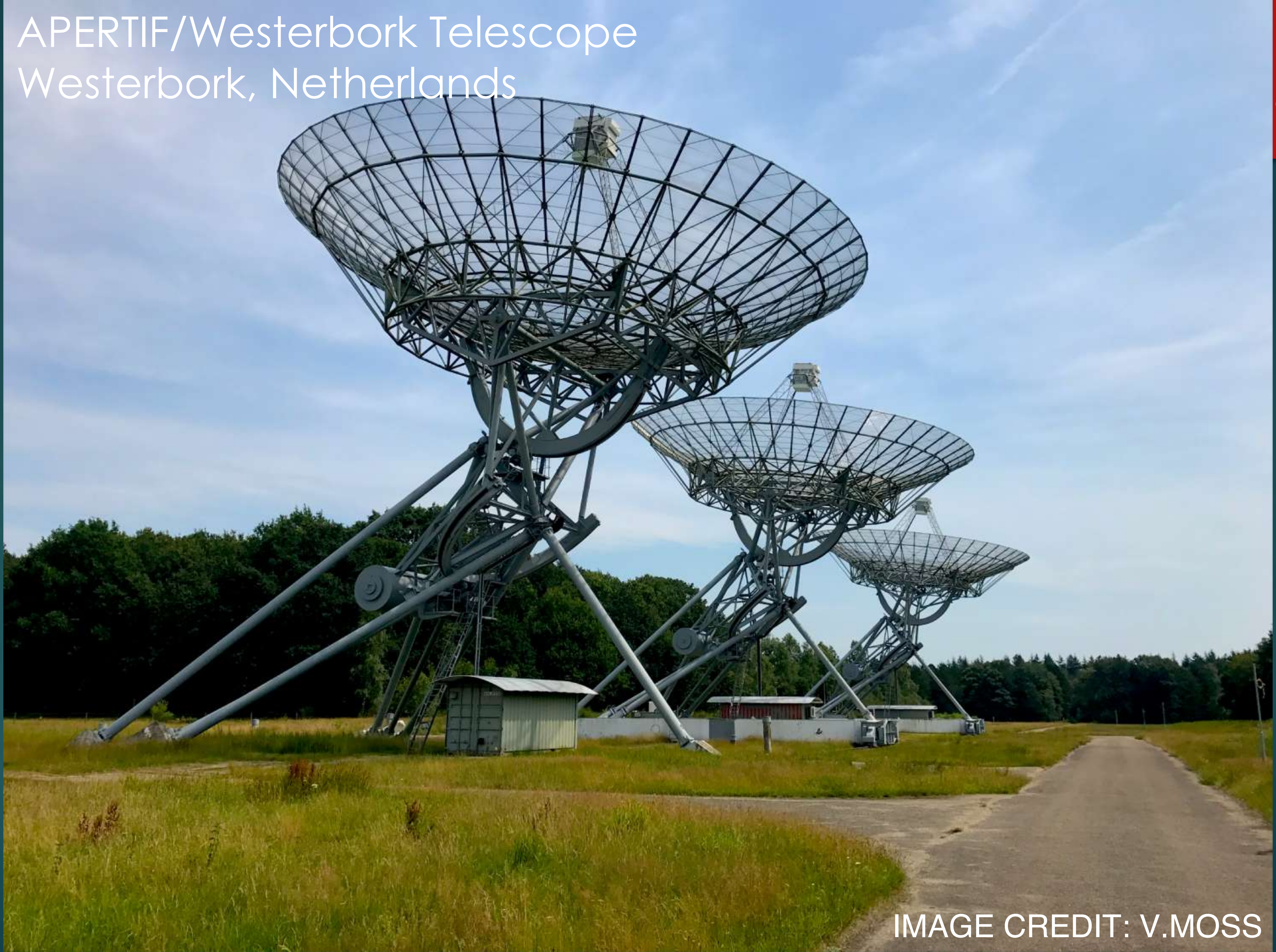

Log-Spectral Power [ADU]
Frequency [MHz]
10
5
0
−5
−10
−15
100
120
140
160
180
200


LBA antenna


Log-Spectral Power [ADU]
Frequency [MHz]
2
0
−2
−4
−6
−8
−10
−12
0
20
40
60
80
100

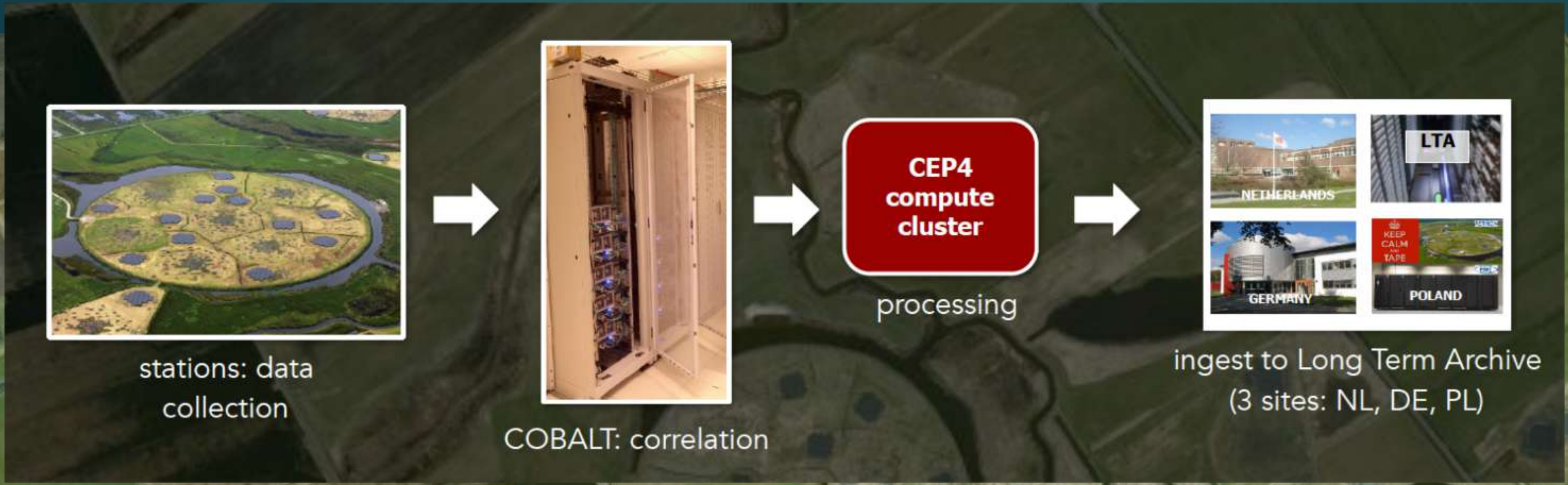
Beam forming



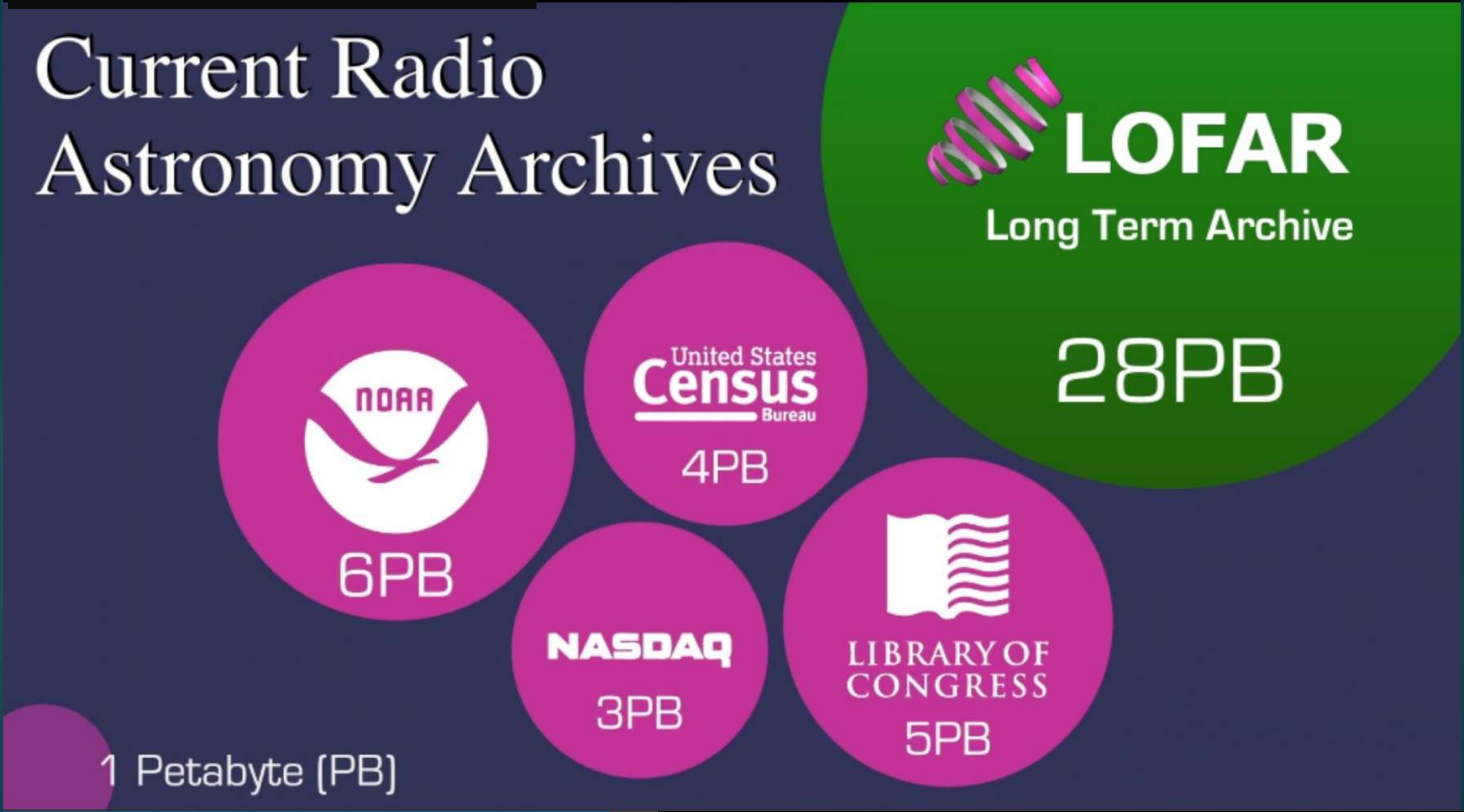

APERTIF/Westerbork Telescope
Westerbork, Netherlands
IMAGE CREDIT: V.MOSS

Beamforming

THE LOFAR SYSTEM: DATA FLOW



- ➢Transport, processing and storage of large amounts of data :
  - Data flow from all antennas combined: 1.7 TB/s
  - To COBALT from station after beamforming: 28 GB/s
  - Correlator output to disk: between 2-10 GB/s
  - Data storage challenges: ~ 80 TB/h
- ➢LOFAR: important technological pathfinder for SKA

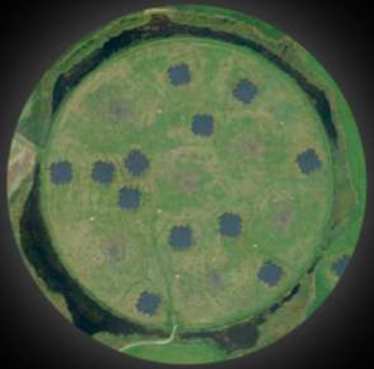

Current Radio
Astronomy Archives
LOFAR
Long Term Archive
28PB
United States
Census
Bureau
4PB
NOAA
6PB
NASDAQ
3PB
LIBRARY OF
CONGRESS
5PB
1 Petabyte (PB)

THE DATA CHALLENGE

HOW BIG IS BIG?

Australia Telescope Compact Array
12 GB/hr

Australian SKA Pathfinder
36 TB/hr



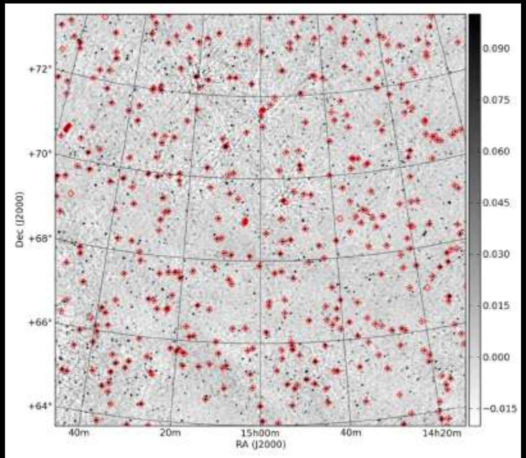
Low Frequency Array (LOFAR)
7 PB/hr*

The Square Kilometre Array
360 PB/hr*

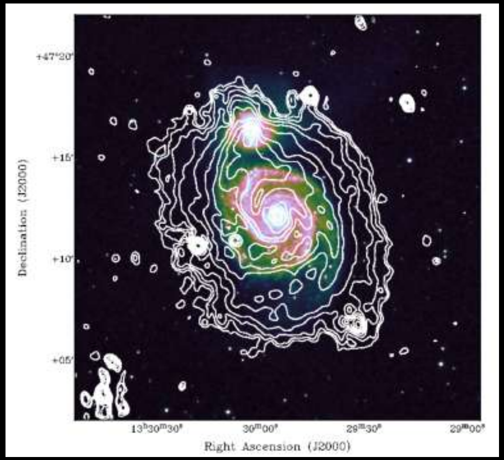
STACKING CDS TO REPRESENT DATA RATES: V. MOSS

LOFAR KEY SCIENCE PROJECTS

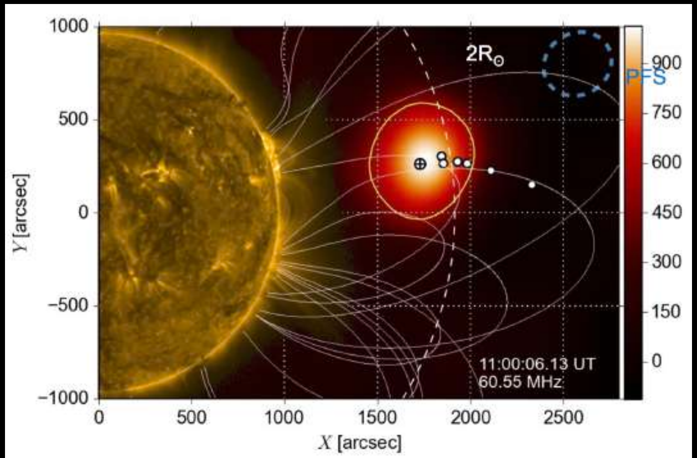
Surveys



Cosmic magnetism

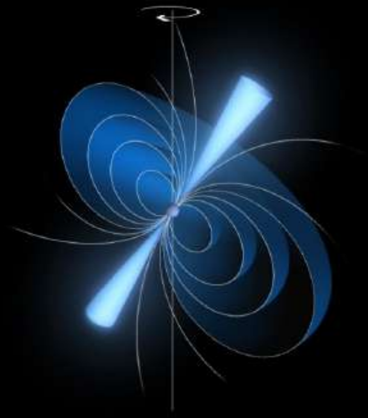


Solar physics & Space weather

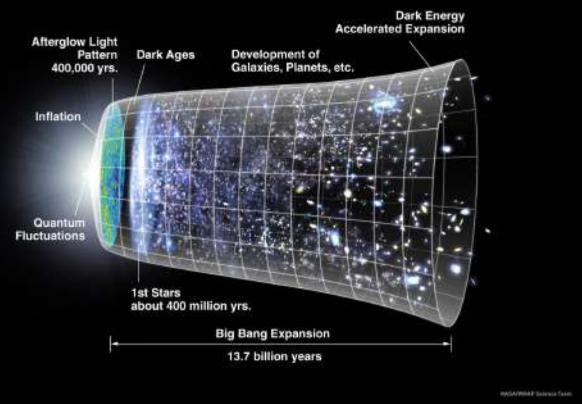


Cosmic rays

Pulsars & Transient sky

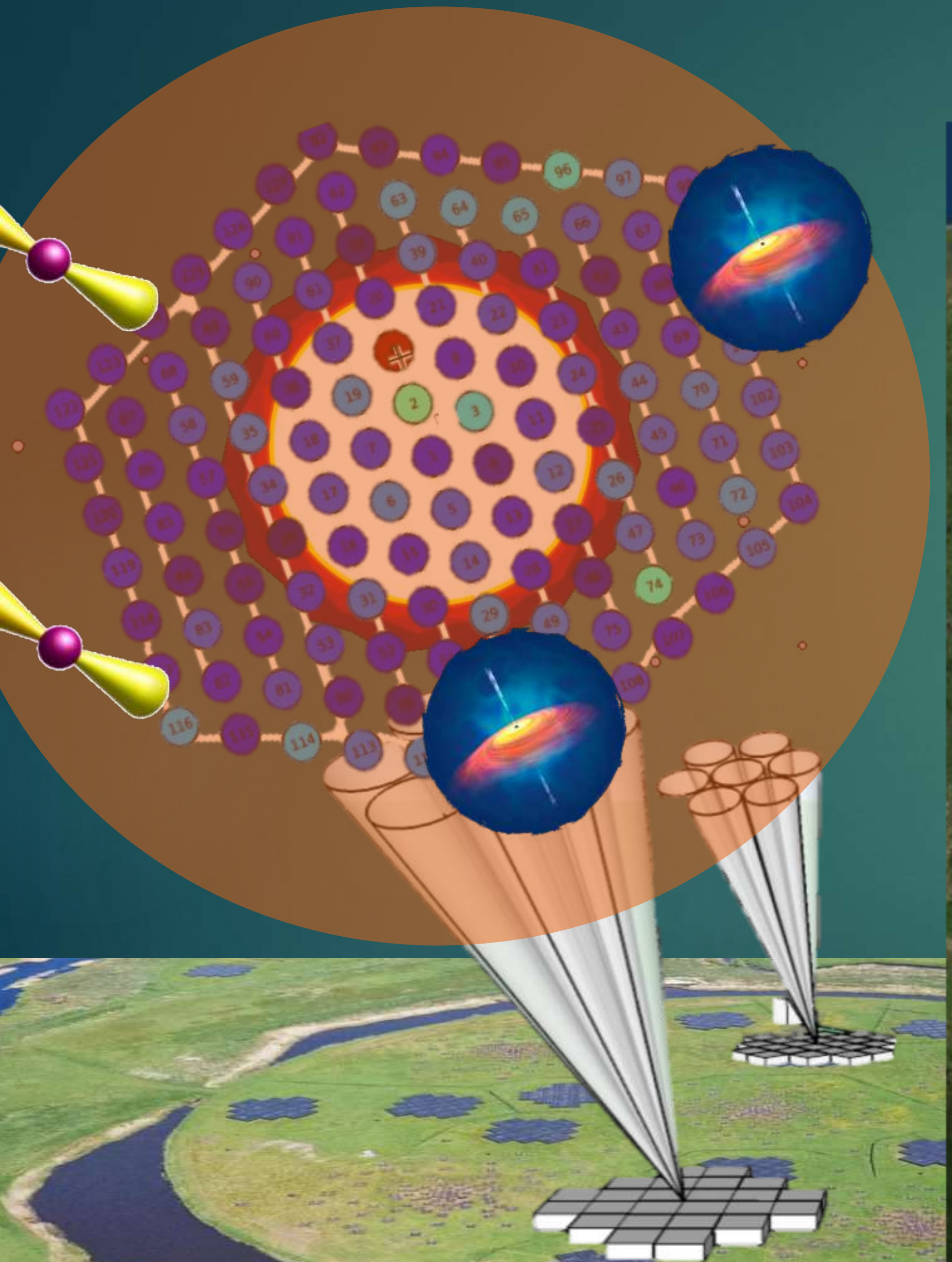


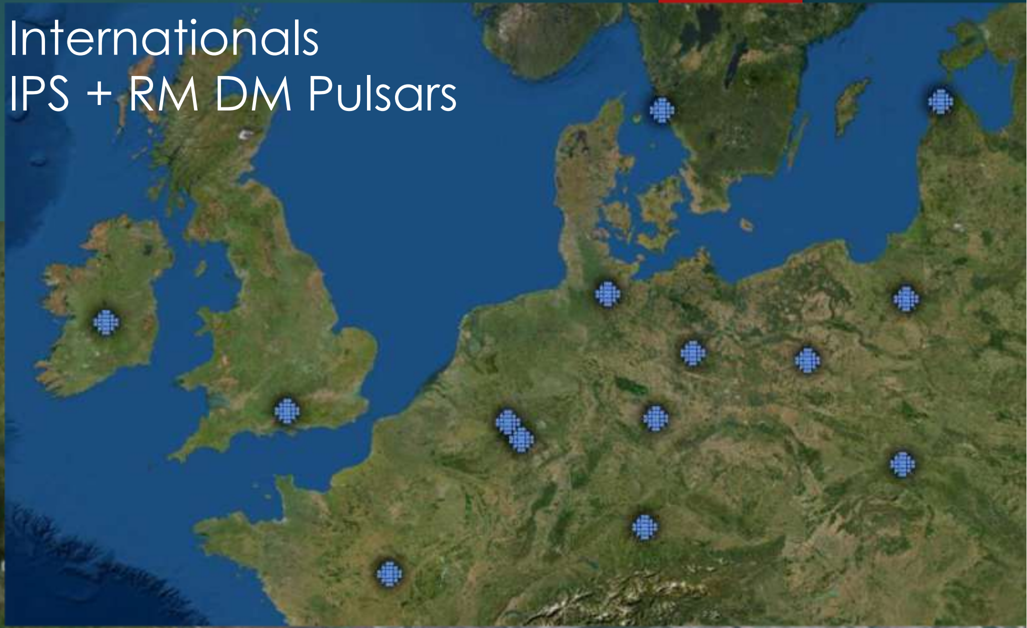
Epoch of Reionization

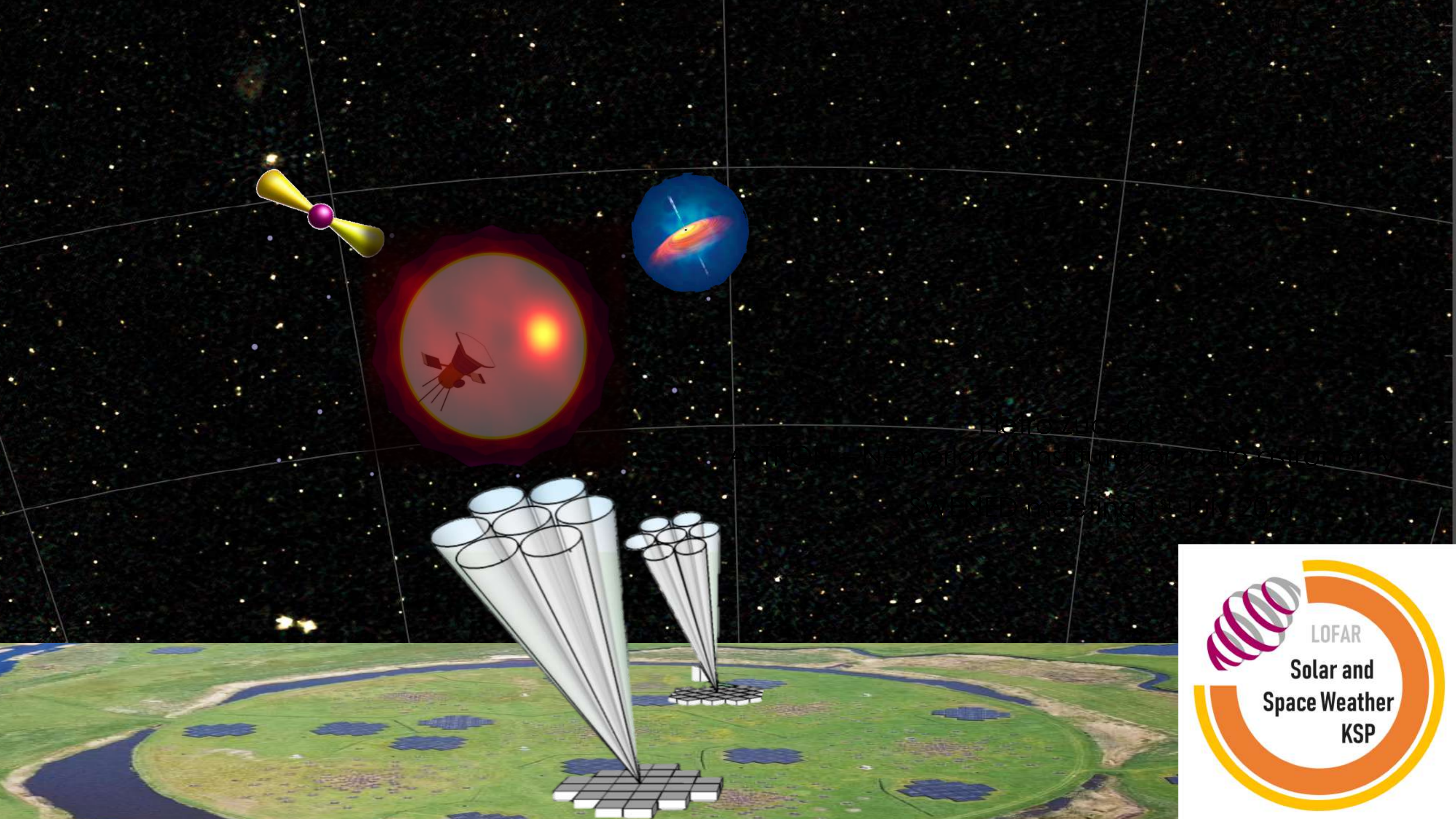


LOFAR
Solar and
Space Weather
KSP

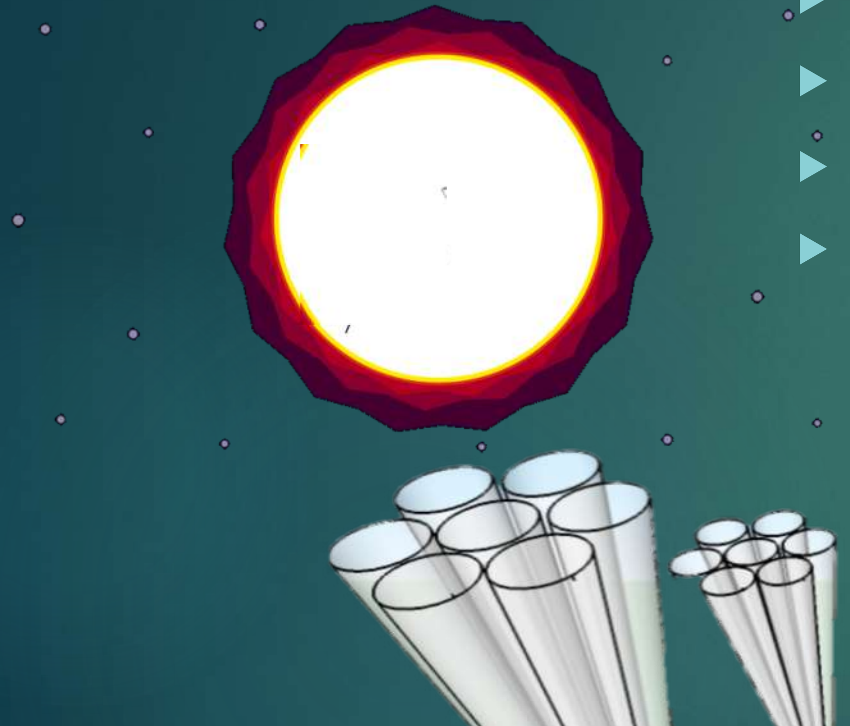
LOFAR KSP Observing mode






Pietro Zucca
ASTRON – Netherlands Institute for radio astronomy
SWENED meeting
LOFAR
Solar and
Space Weather
KSP

Overview



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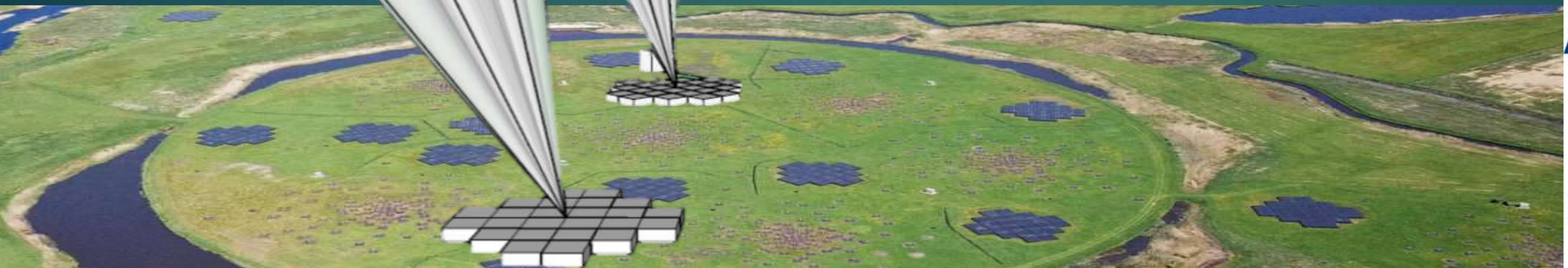


Interferometric

- Spatial resolution and quality of the imaging
- Complex sources with multiple peaks

Tied-Array

- Limited spatial resolution (beam spacing and size)
- Localization of the radio source without clear shape of the source

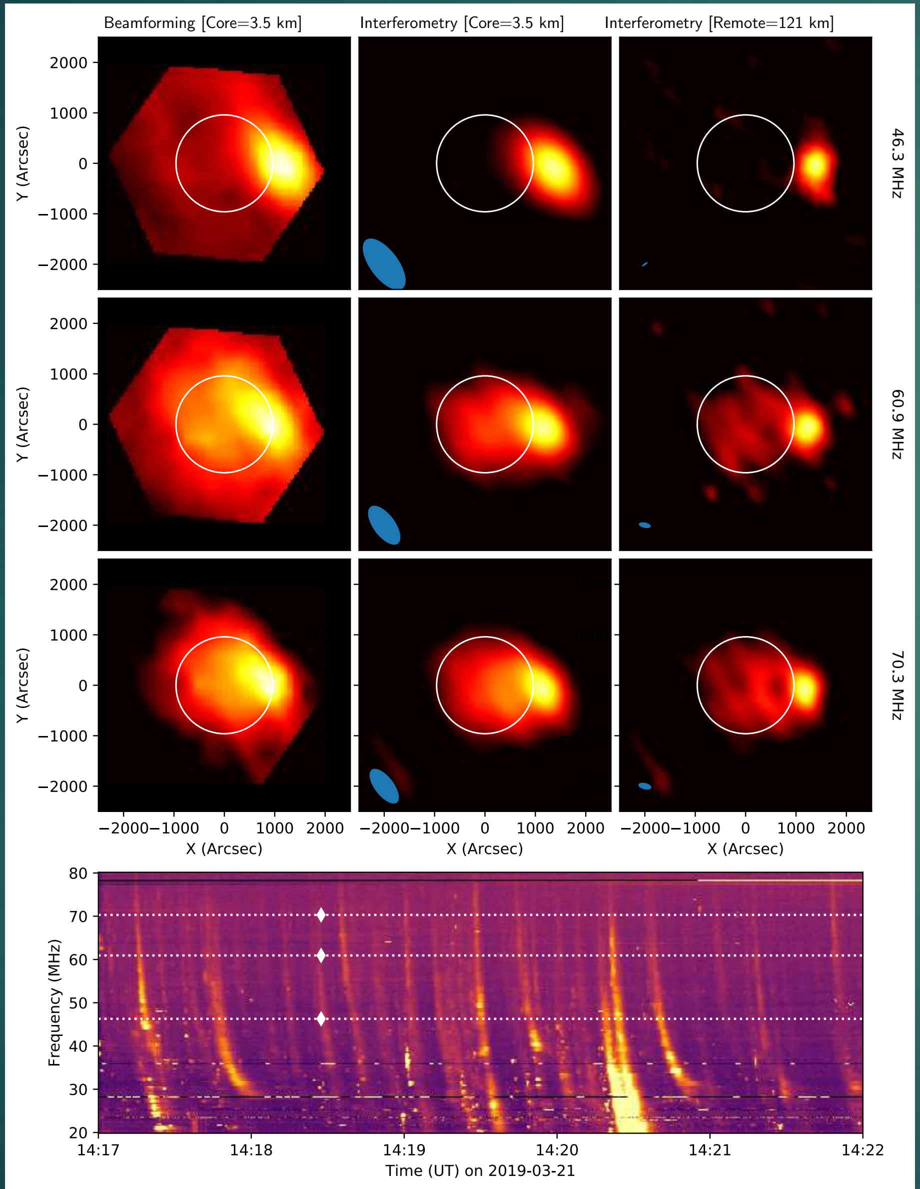
Tied-Array

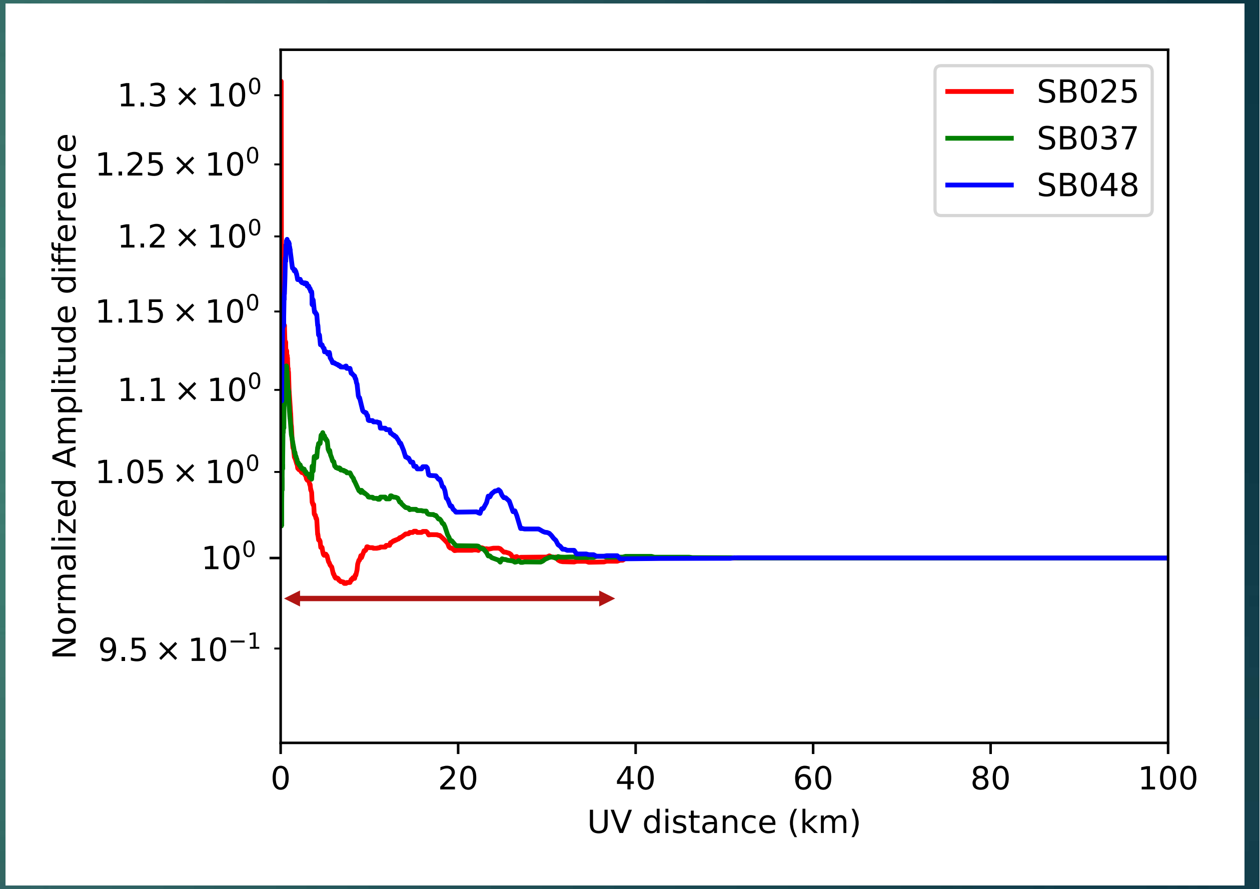
- Time resolution (milliseconds)
- Advantage for quasi-relativistic beam propagation

Interferometric

- Limited time resolution (0.16 seconds)
- Not ideal for quasi-relativistic beam propagation

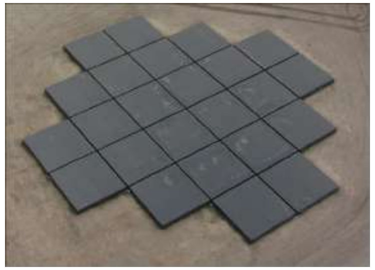
Tied Array Beam and Interferometric mode

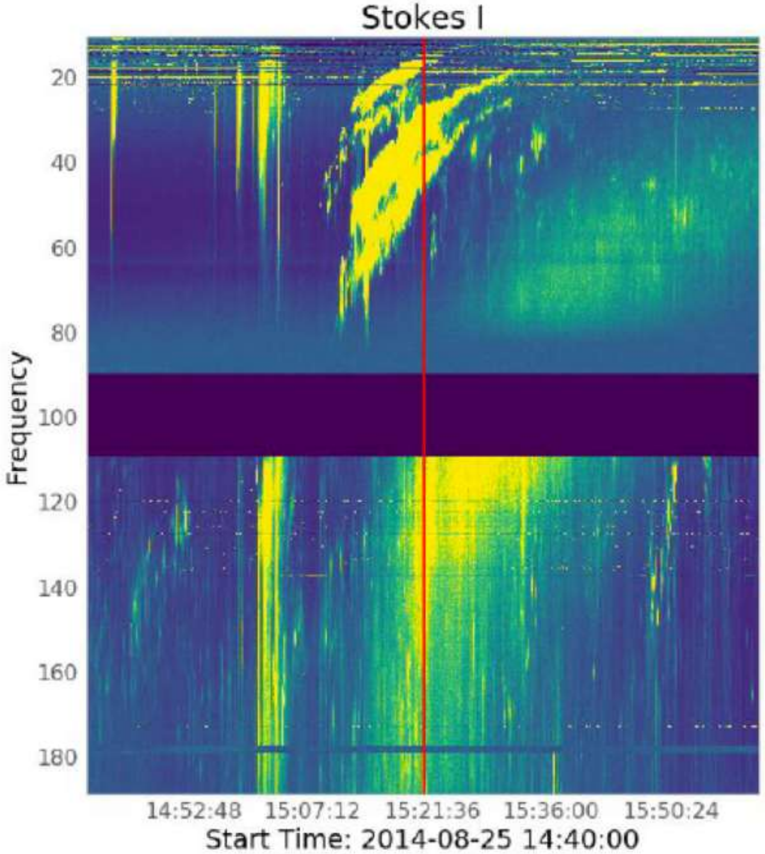


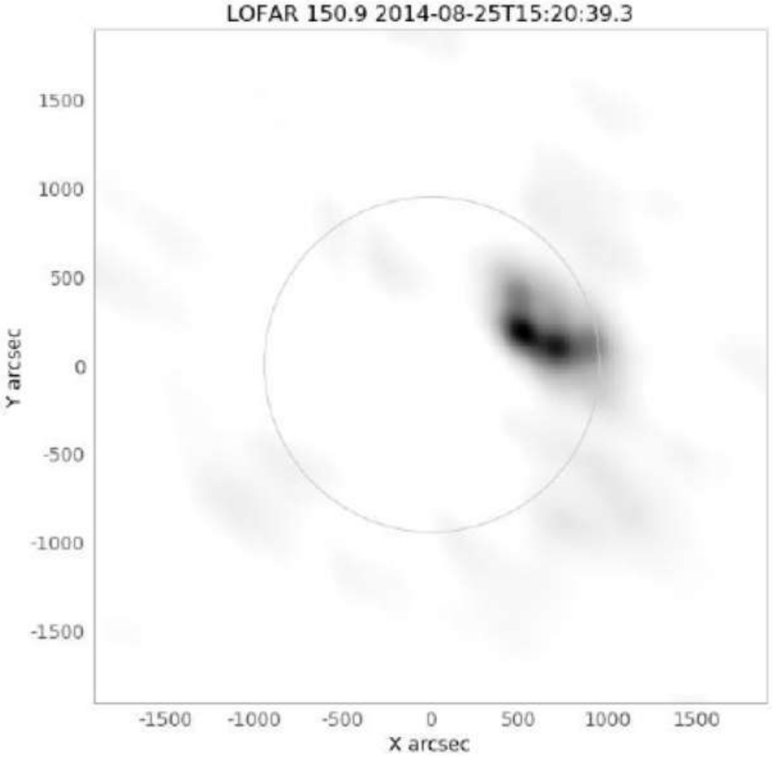


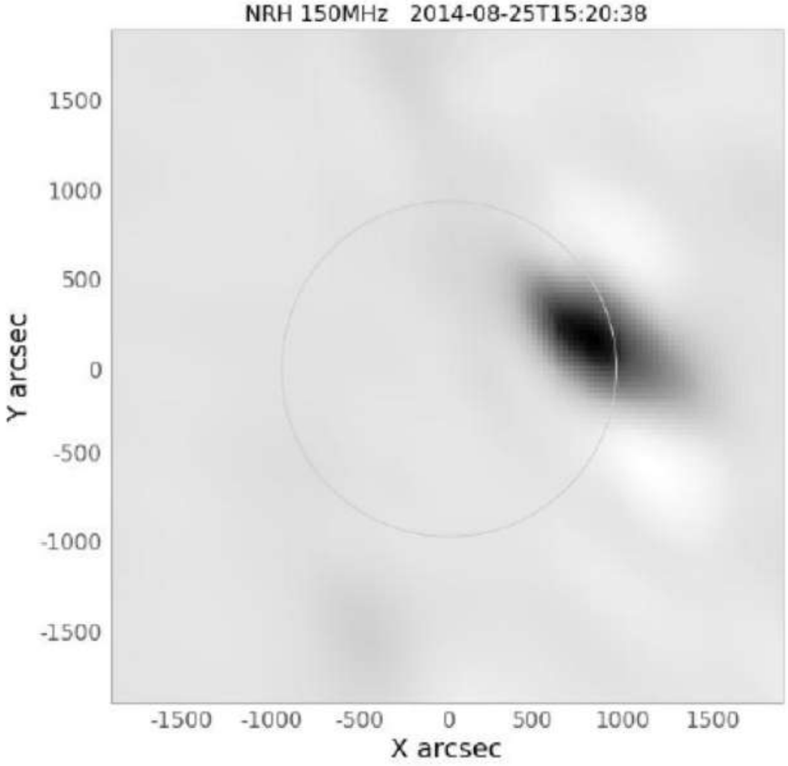
Zucca, Zhang, Morosan Reid et al. A&A in prep.

Comparison of LOFAR imaging with NRH



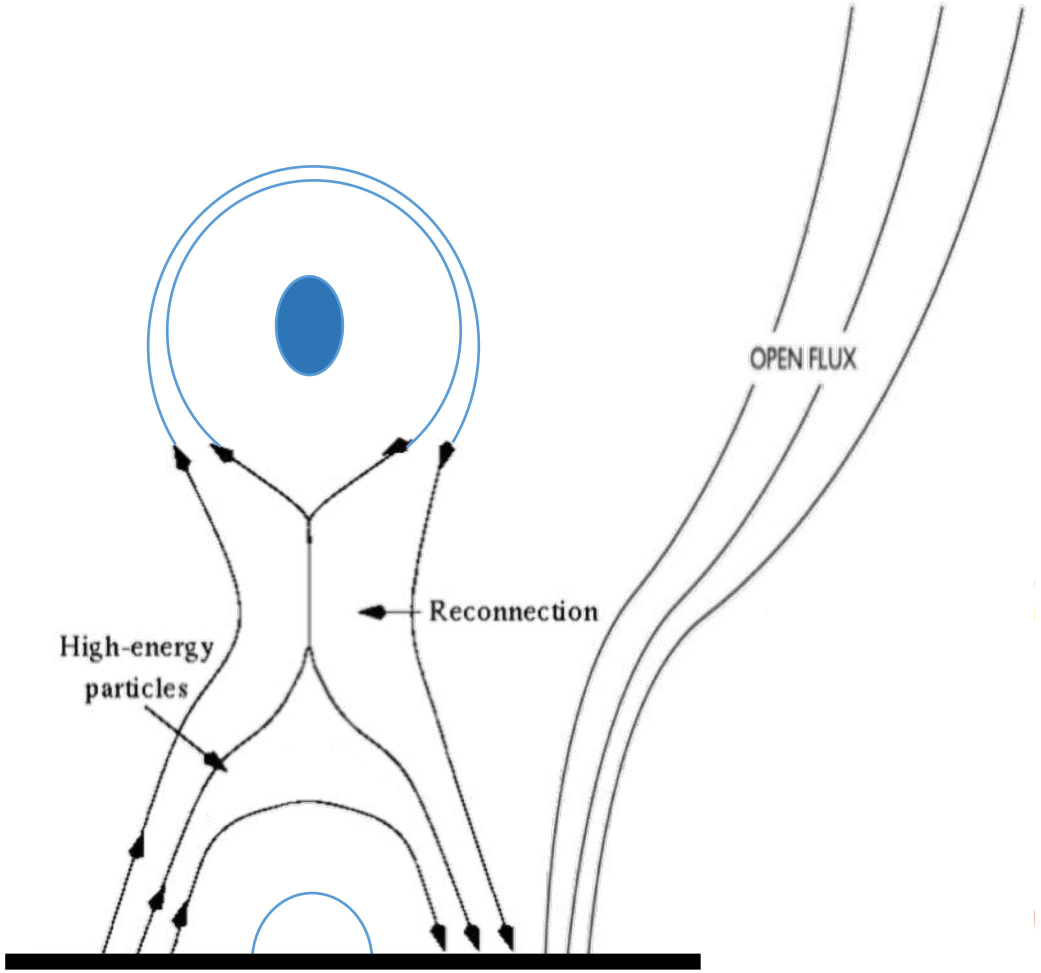






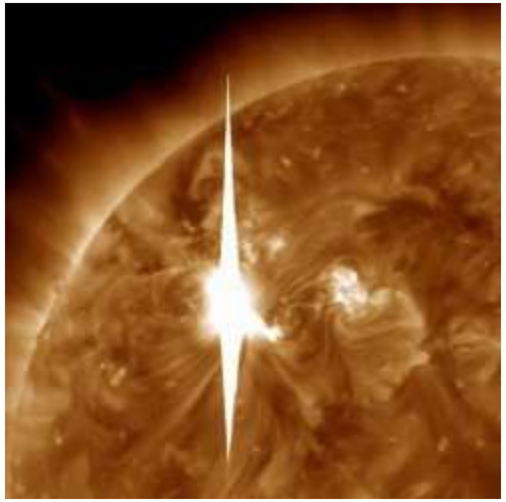
H. Liu et al. submitted

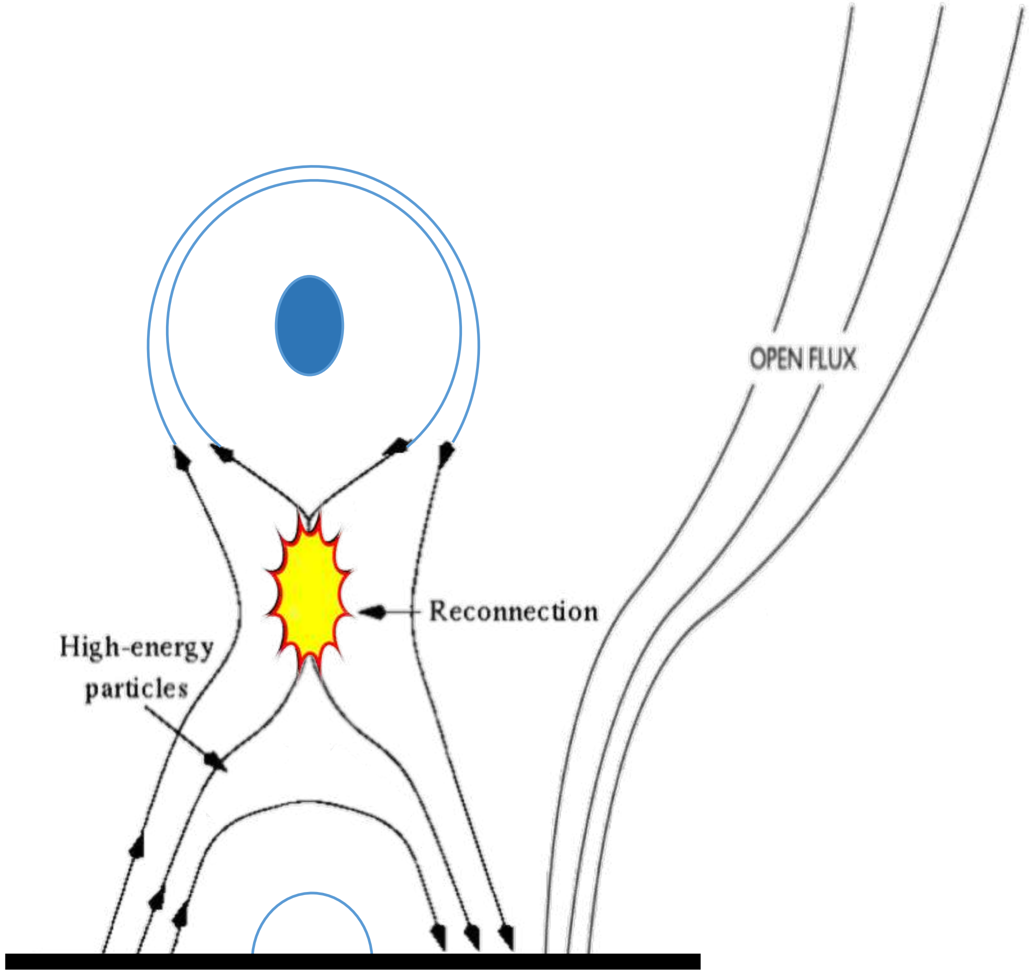
Solar and Heliospheric Radio Emission



Solar and Heliospheric Radio Emission

Solar Flares





Solar and Heliospheric Radio Emission

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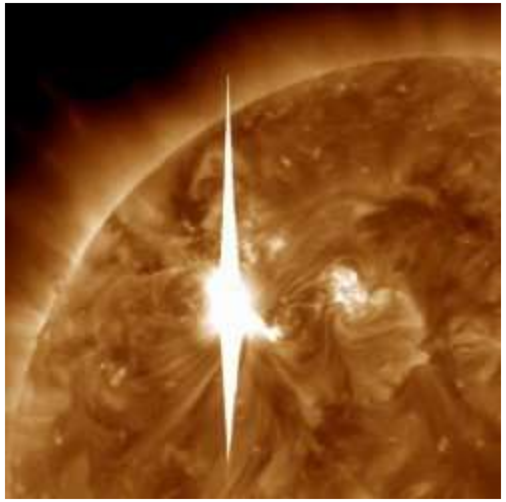
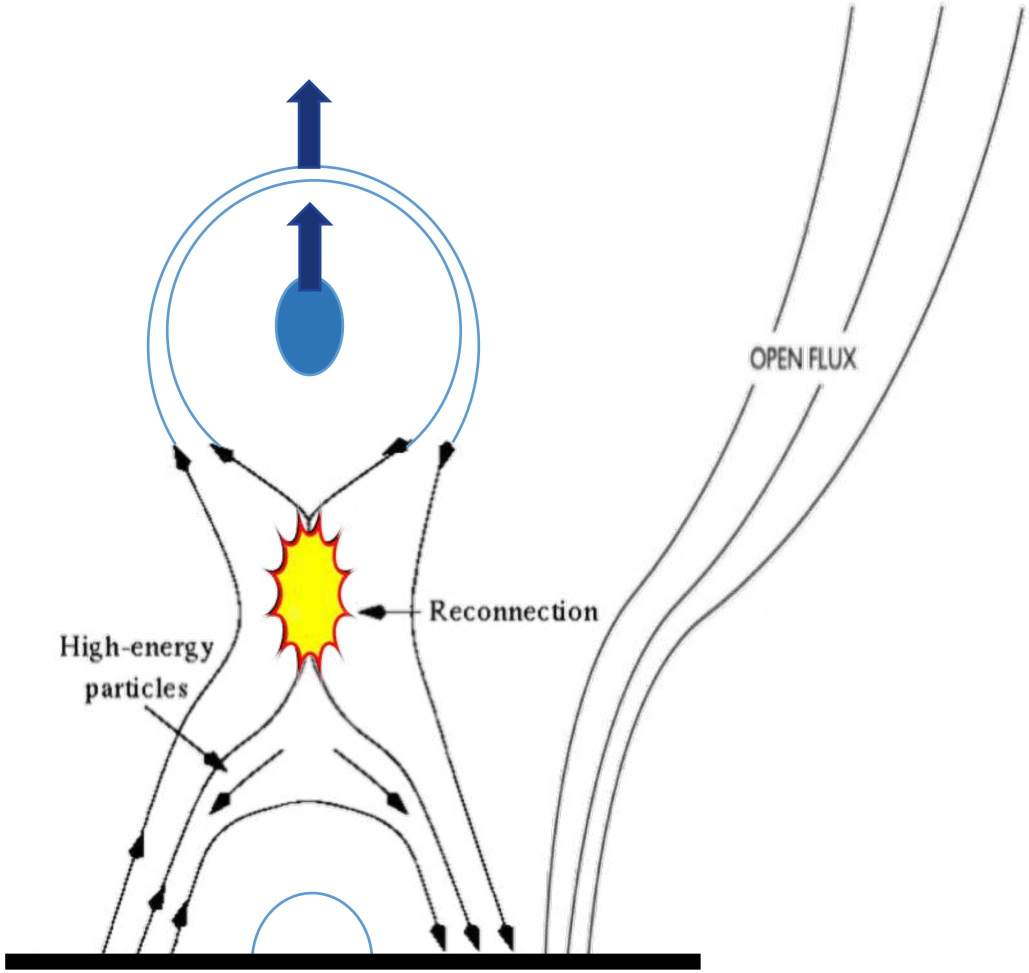
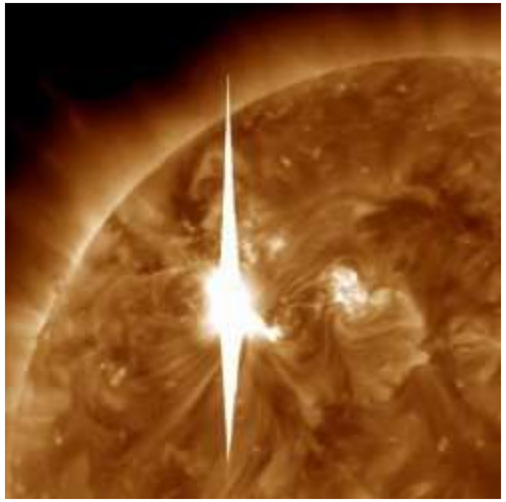




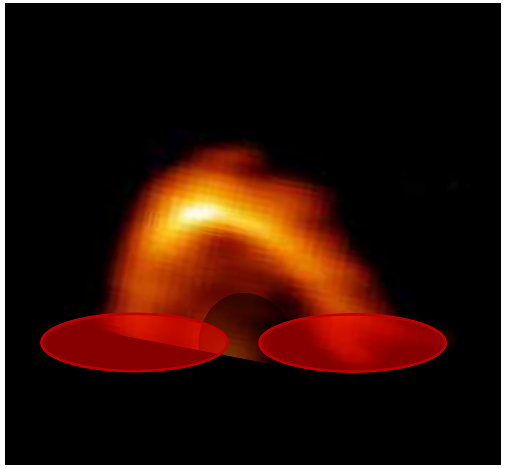
Solar and Heliospheric Radio Emission

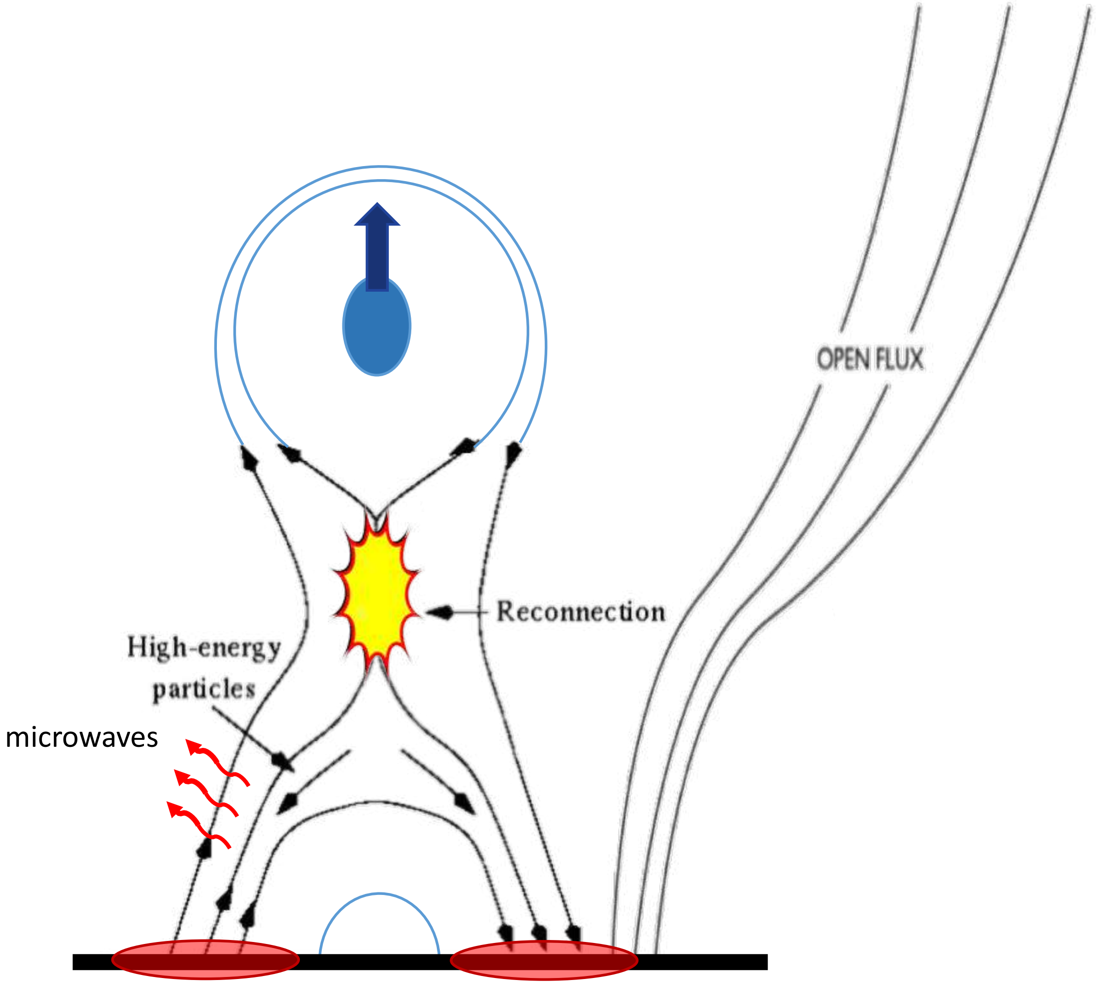
Solar Flares

SDO EUV



Nobeyama 17 GHz





Solar and Heliospheric Radio Emission

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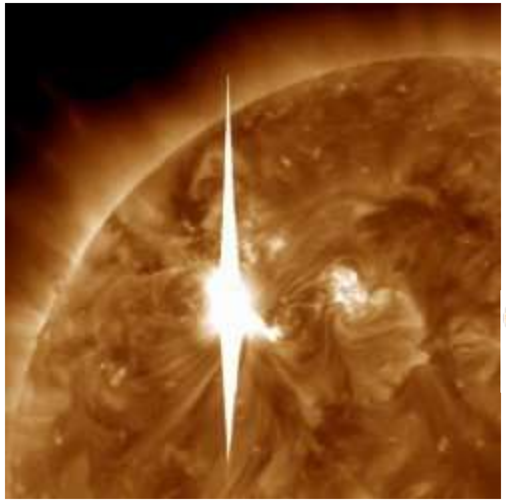
SDO EUV



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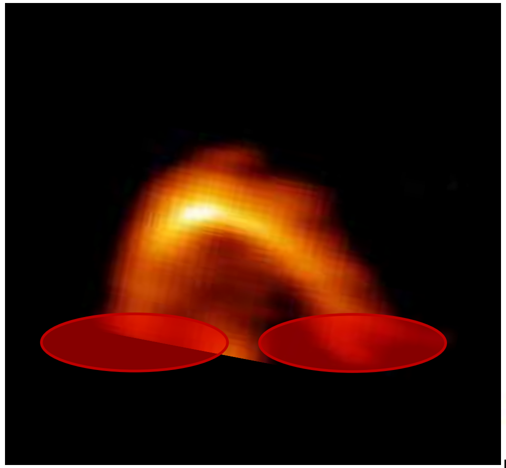
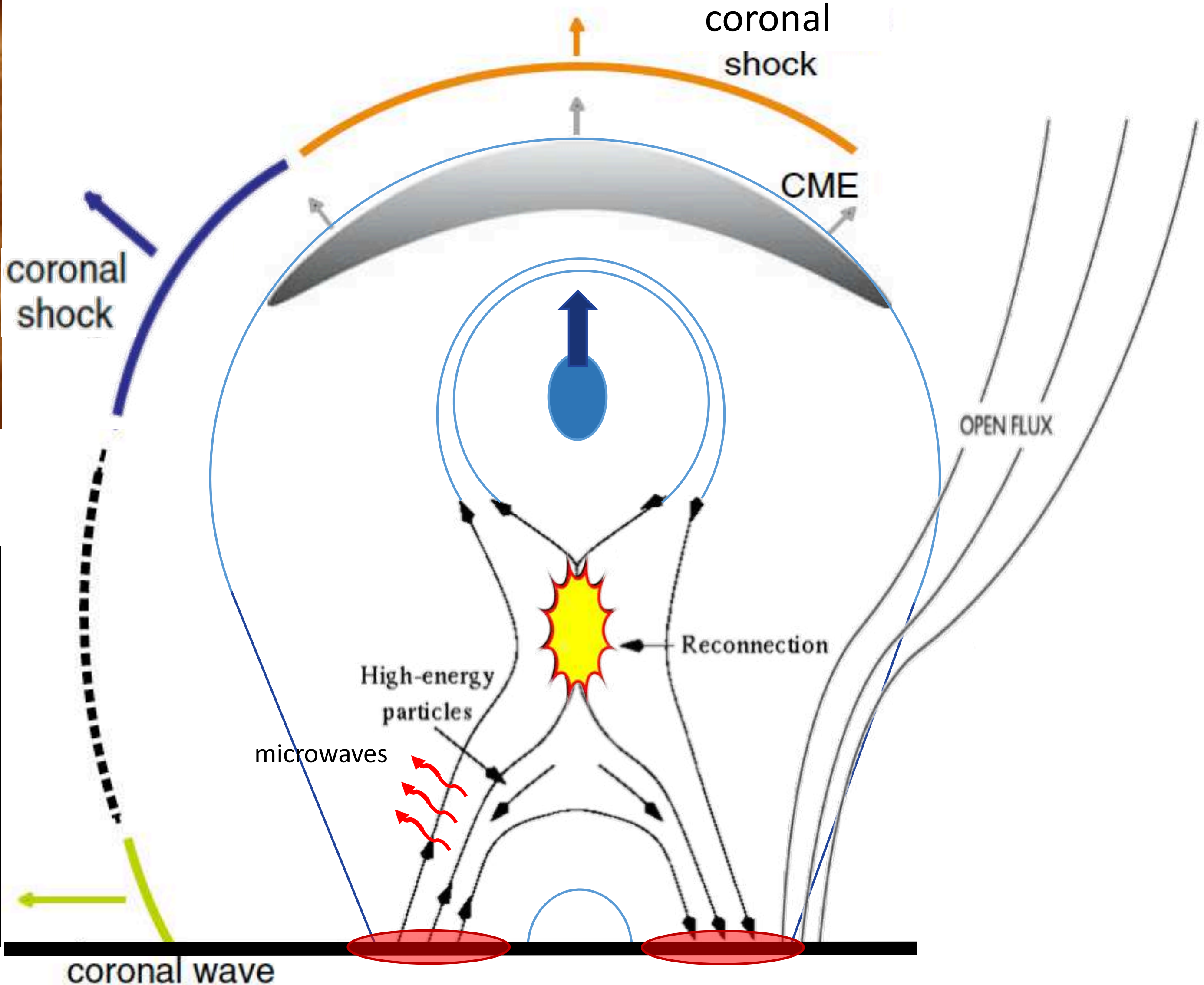
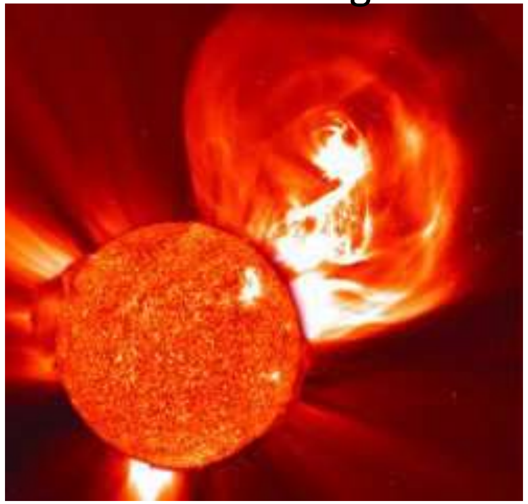




Coronal Mass Ejections

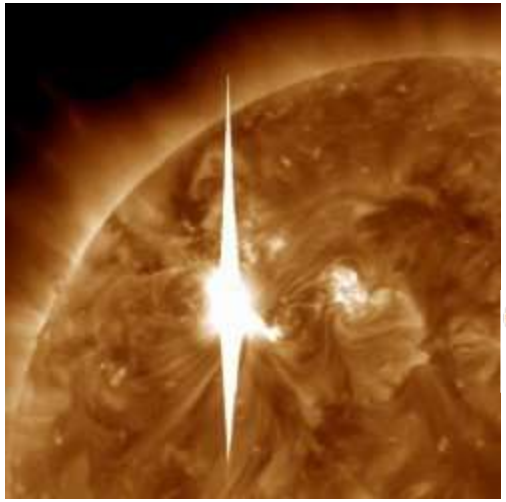
SOHO white light



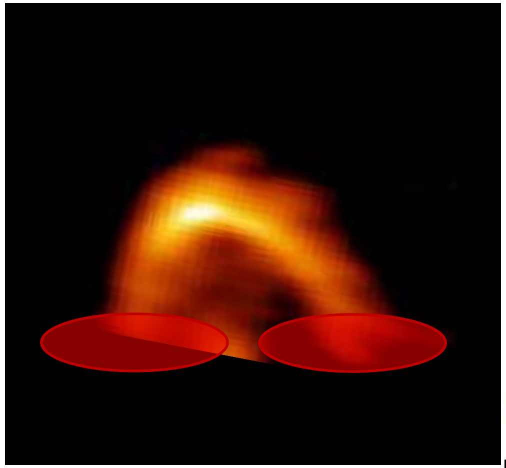
Solar and Heliospheric Radio Emission

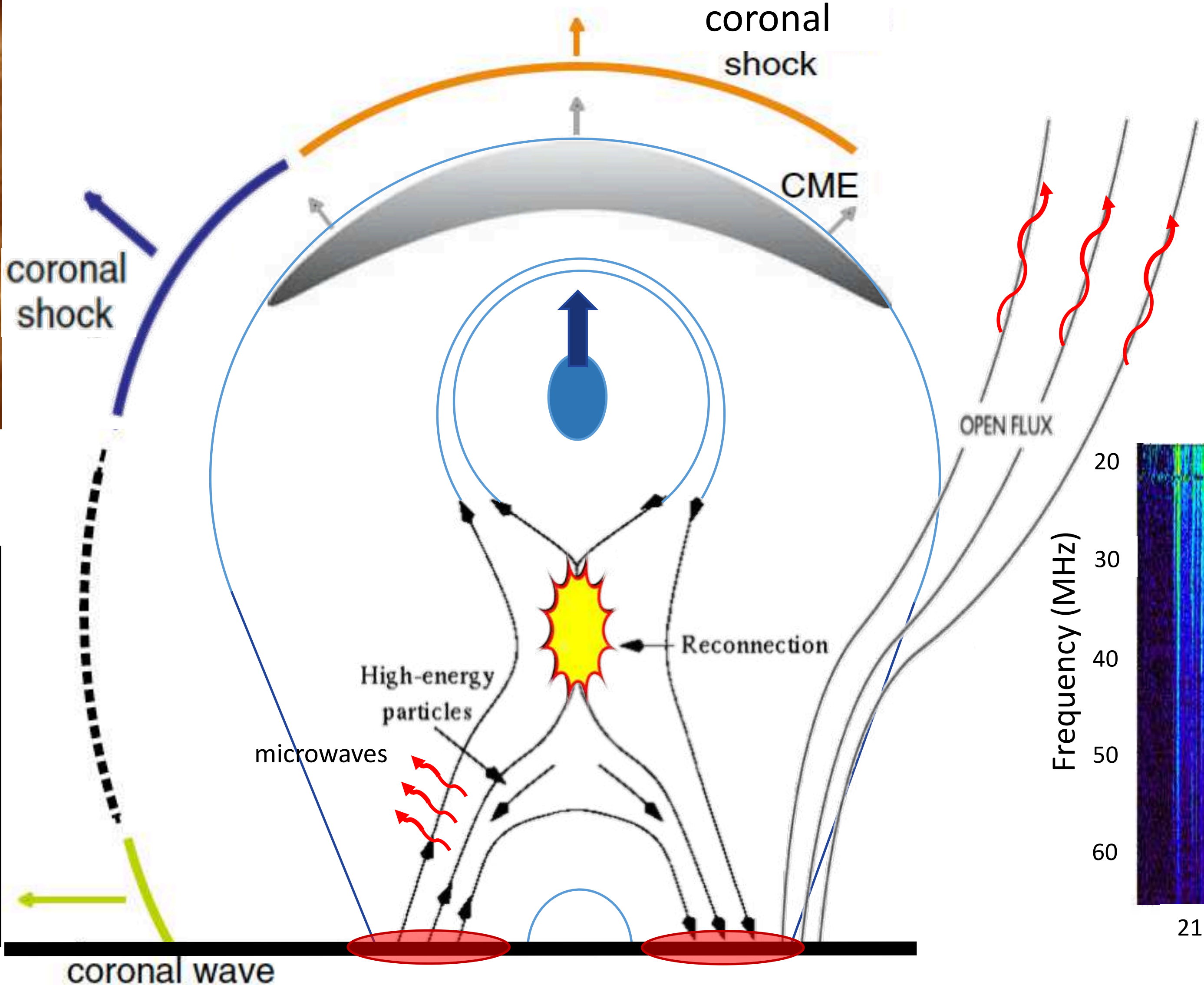
Solar Flares

SDO EUV



Nobeyama 17 GHz





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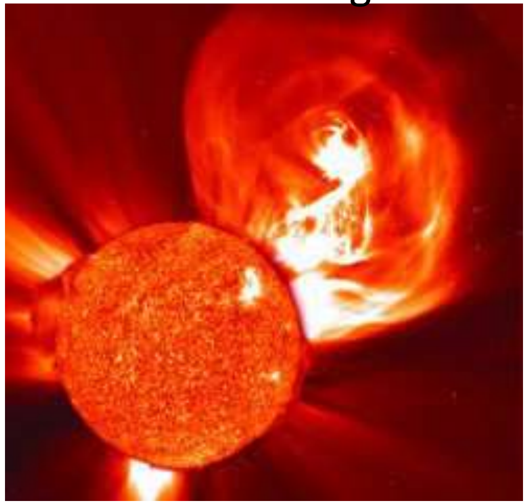

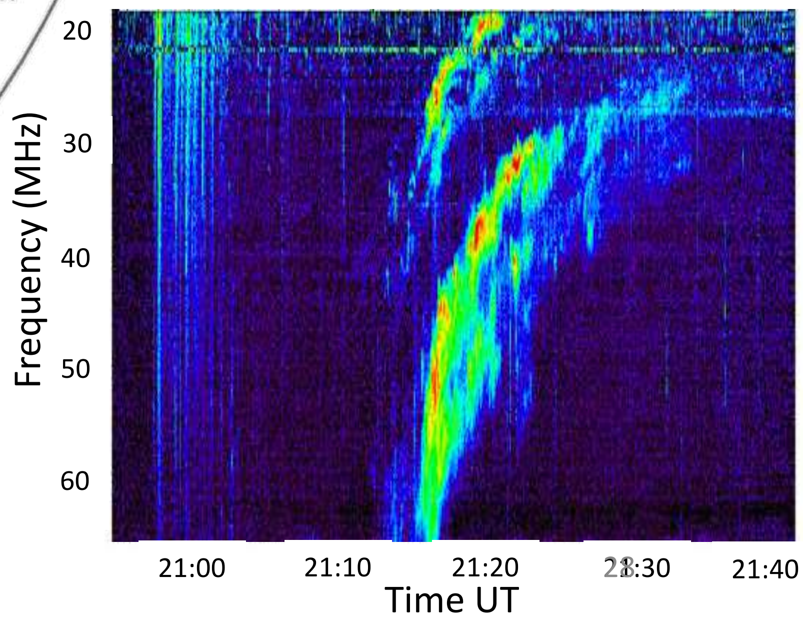

Solar and Heliospheric Radio Emission

Solar Flares

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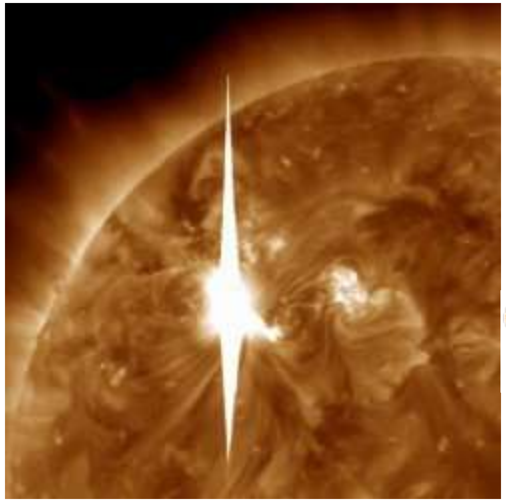
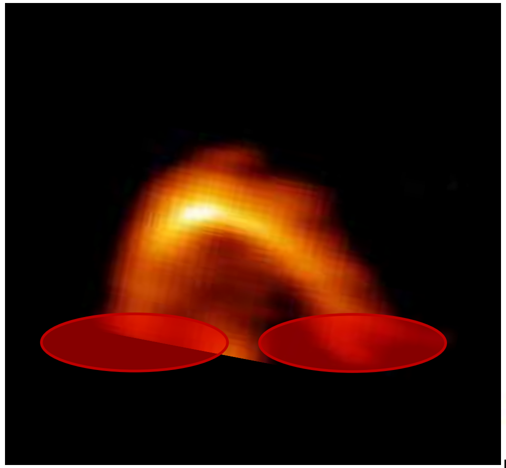
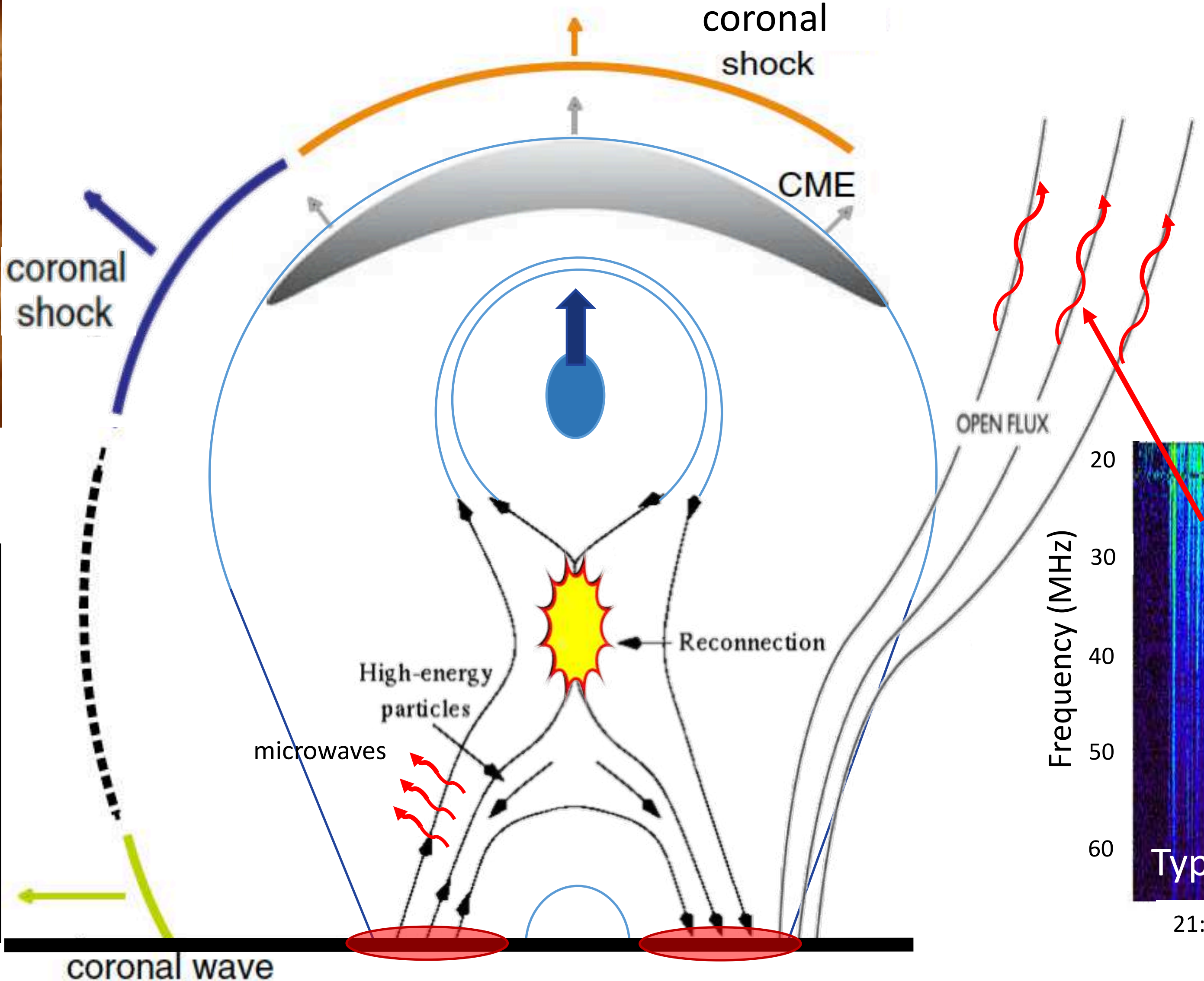


Nobeyama 17 GHz





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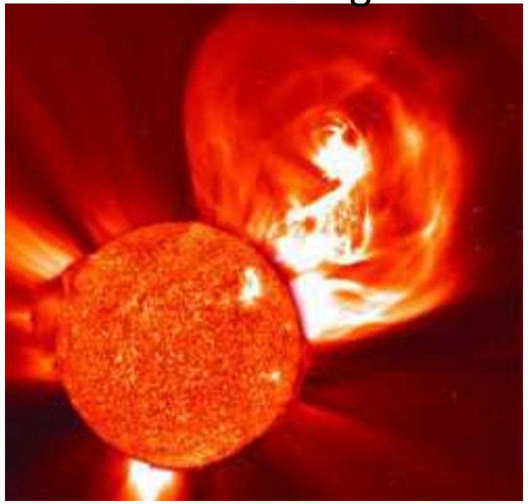

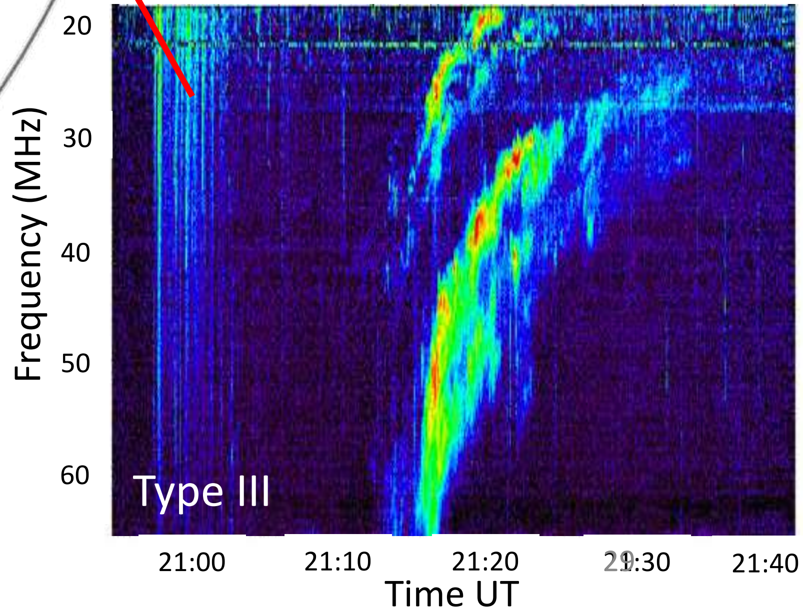

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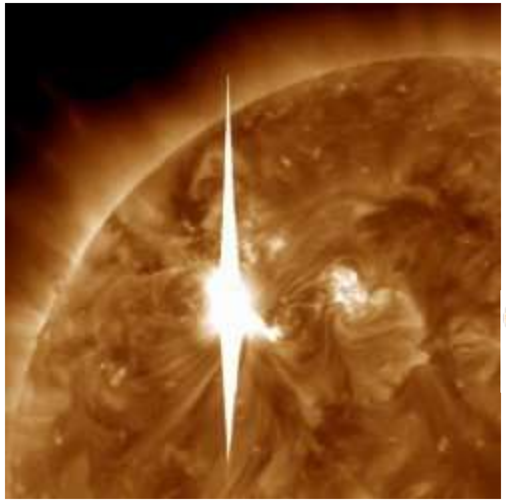

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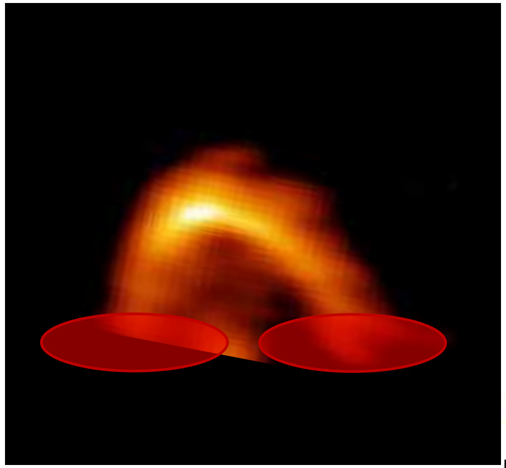

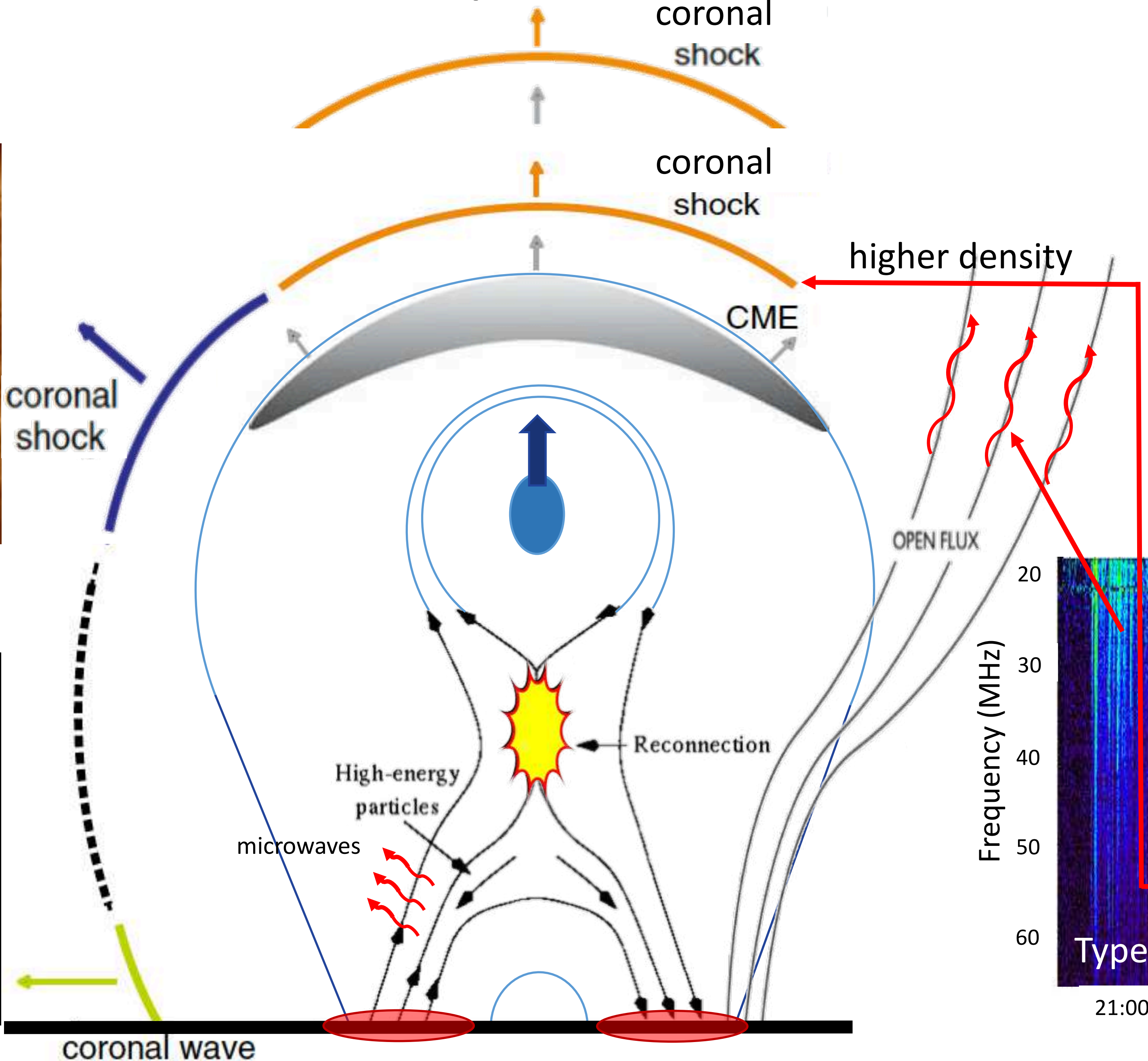

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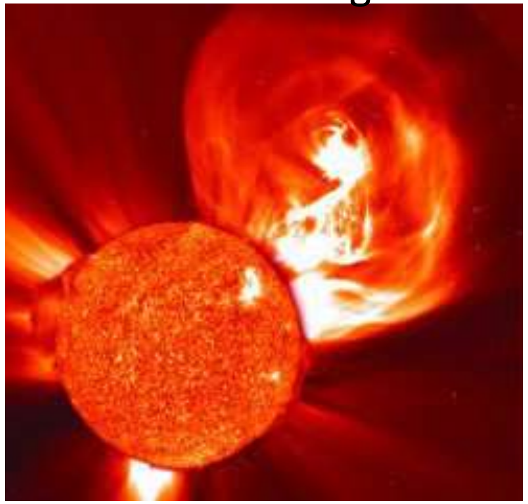

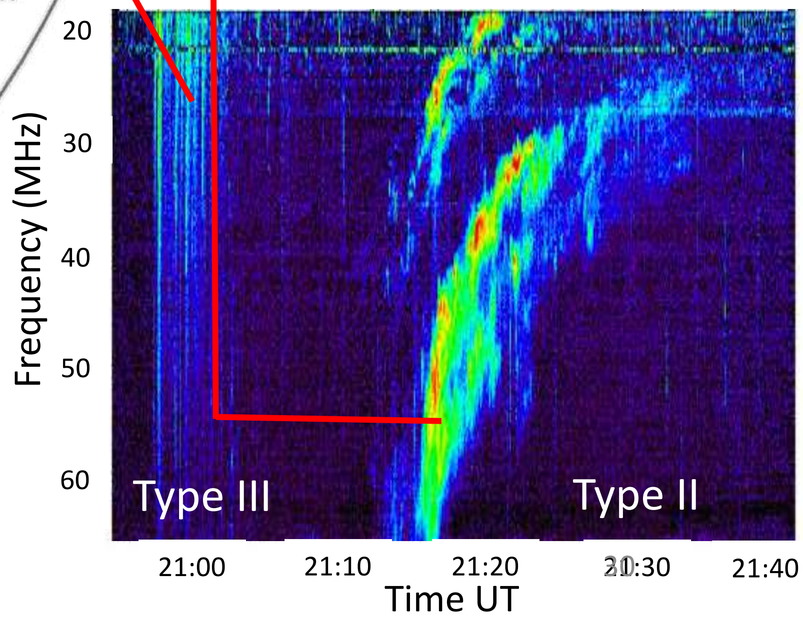

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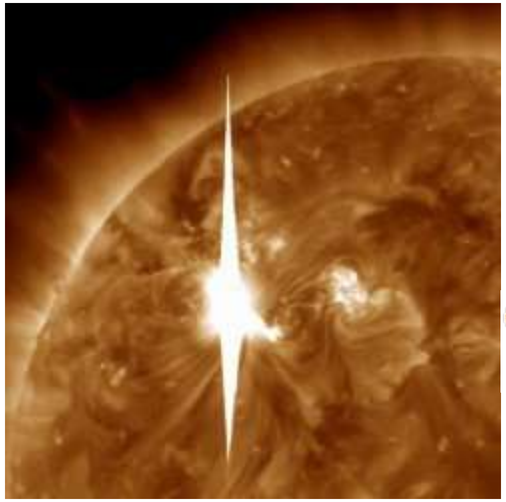

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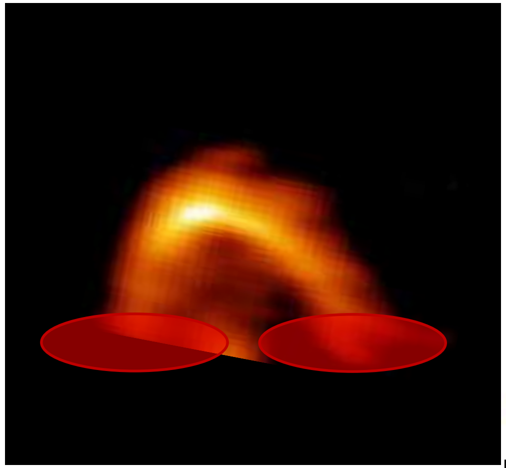

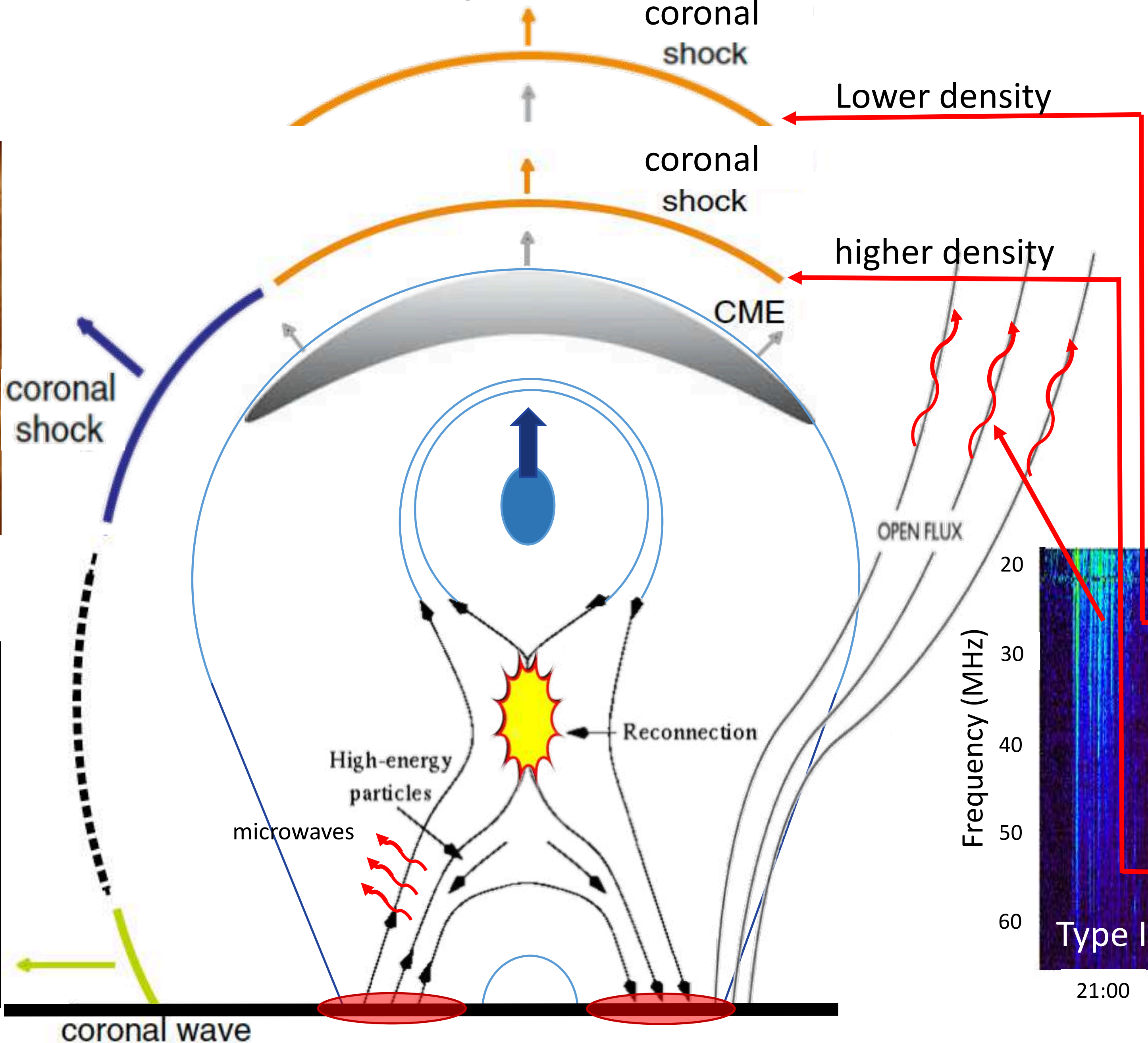

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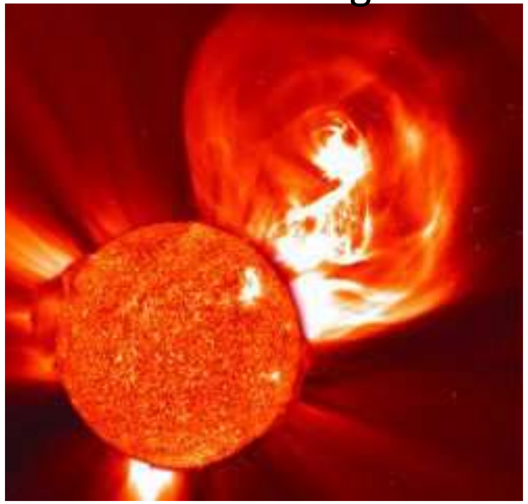
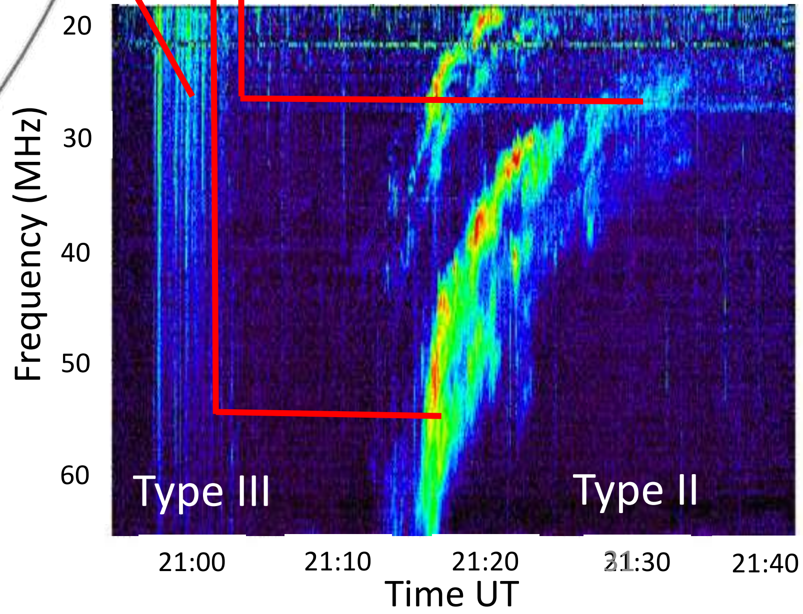
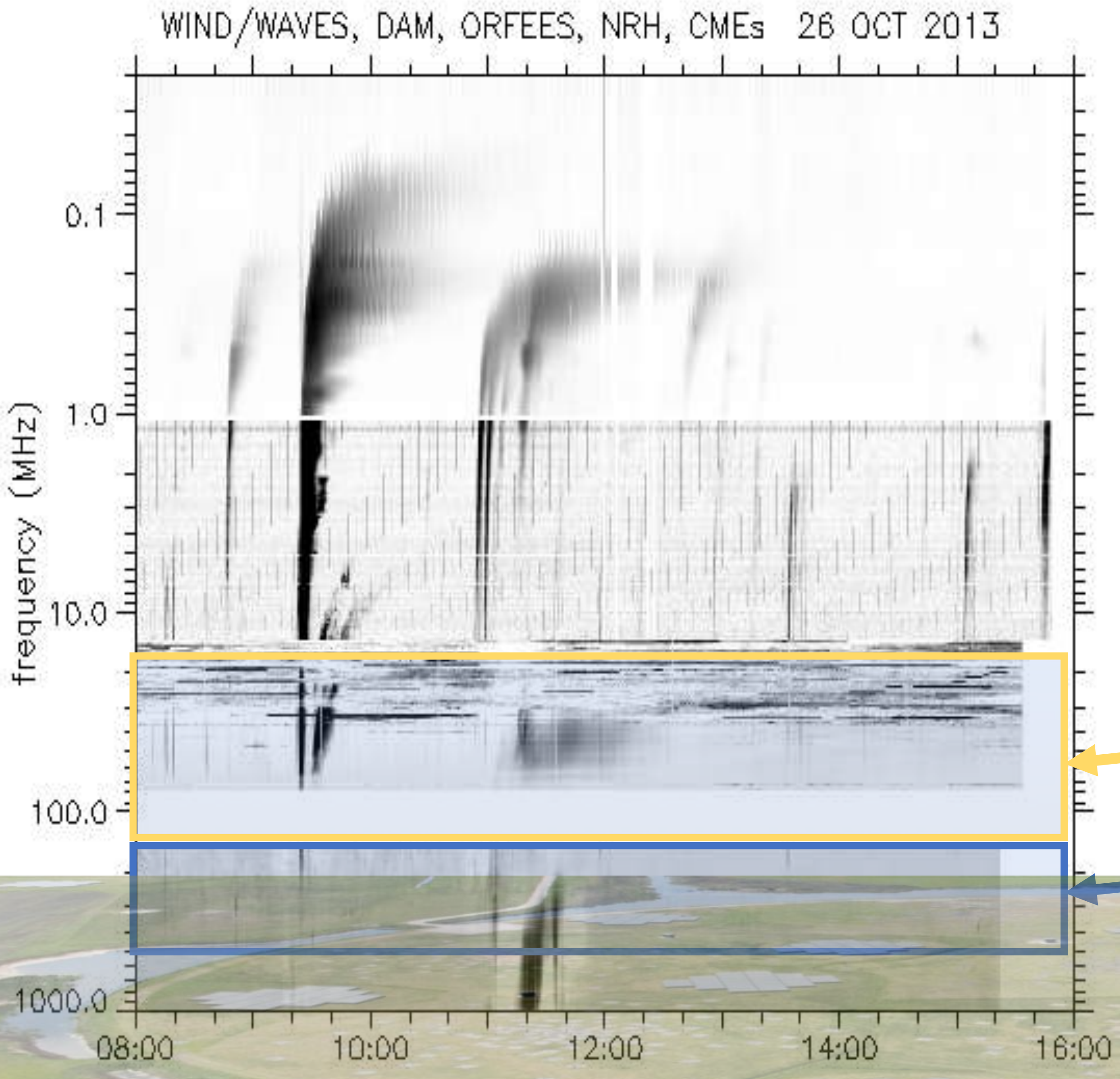
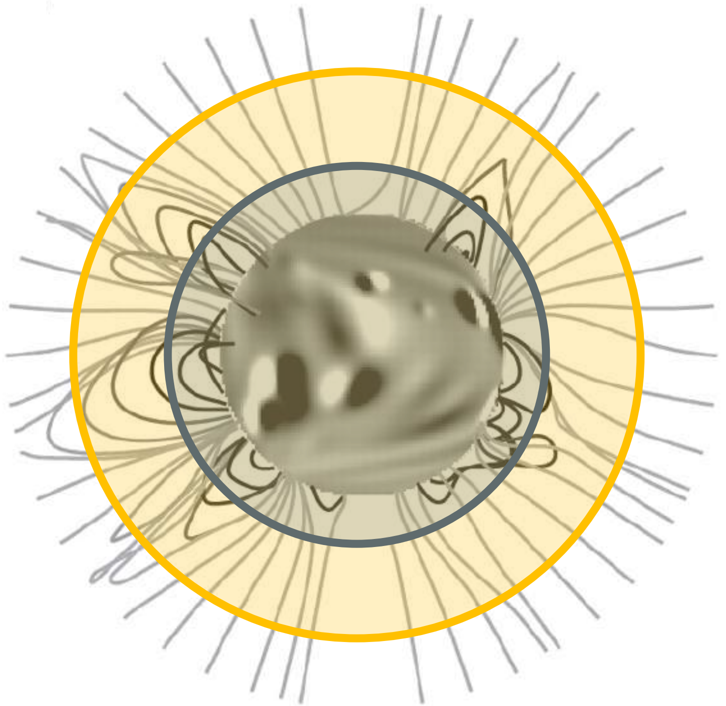


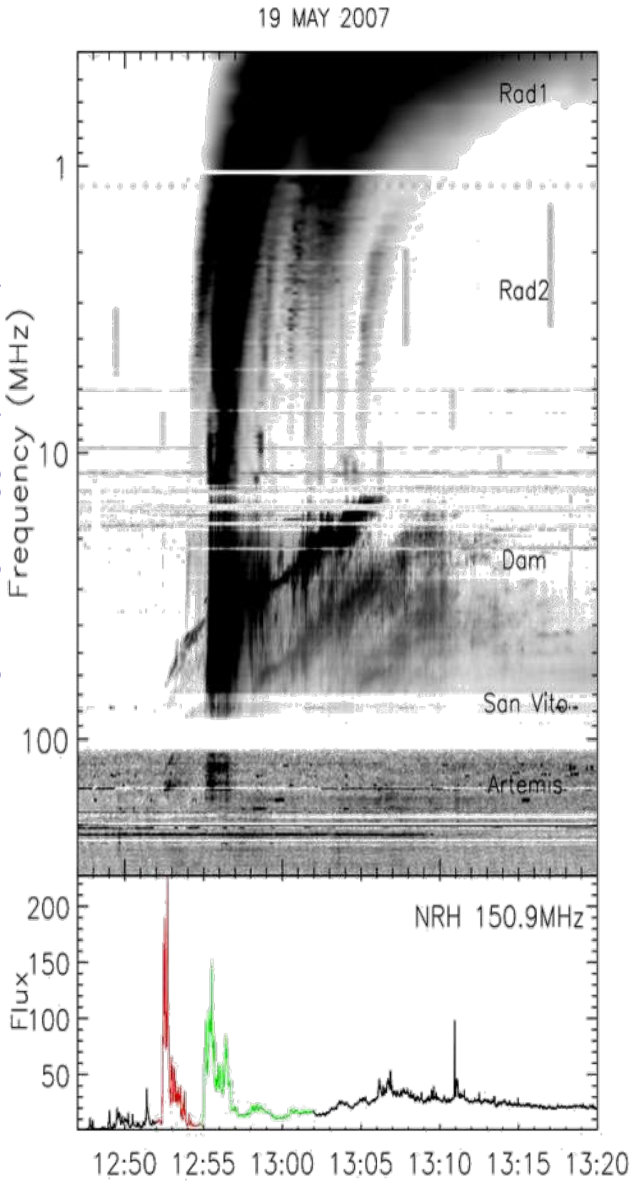


LOFAR imaging of the solar corona



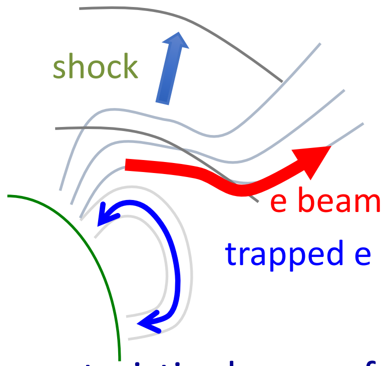


The Radio Sun

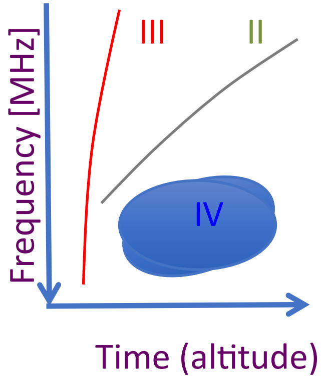


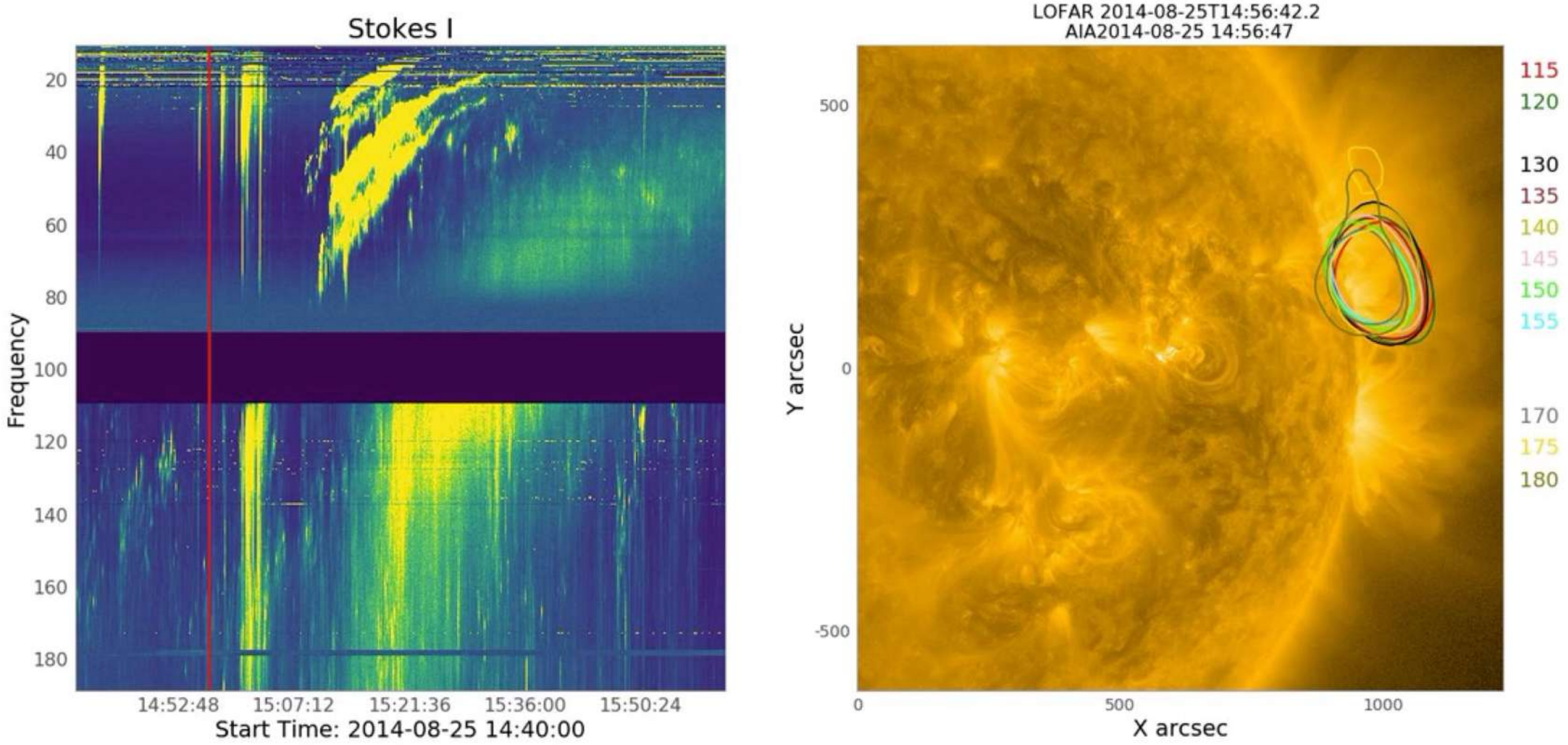
Kerdraon, Pick, Hoang, Wang, Haggerty 2010 ApJ 715, 468

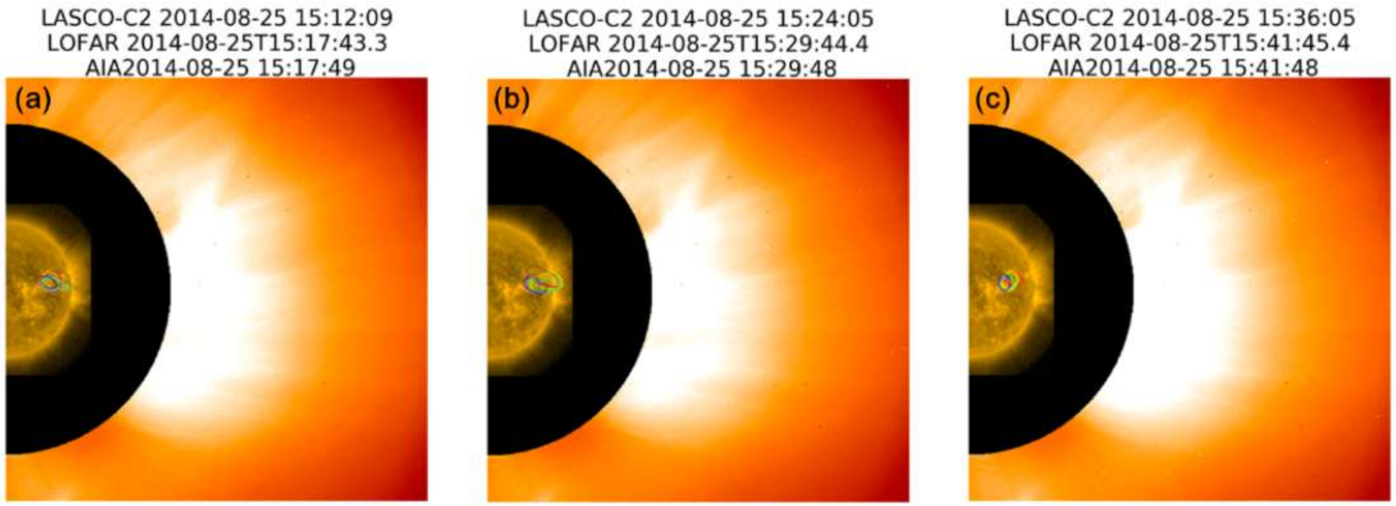
- Propagating exciter in a quasi-static atmosphere or expanding loops (CME):

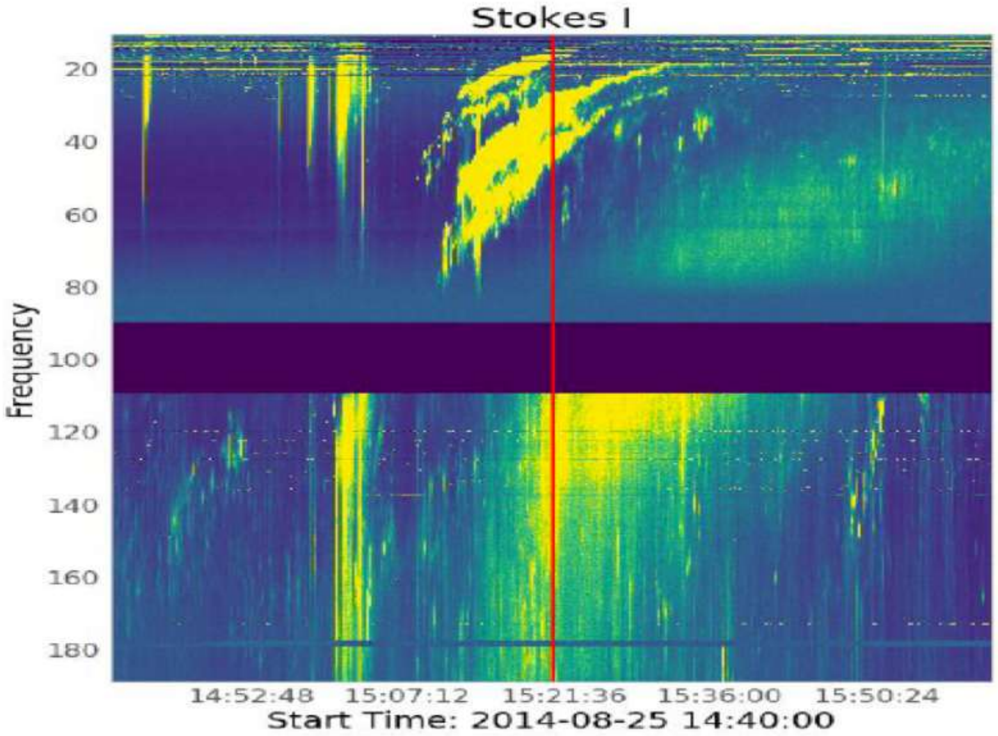


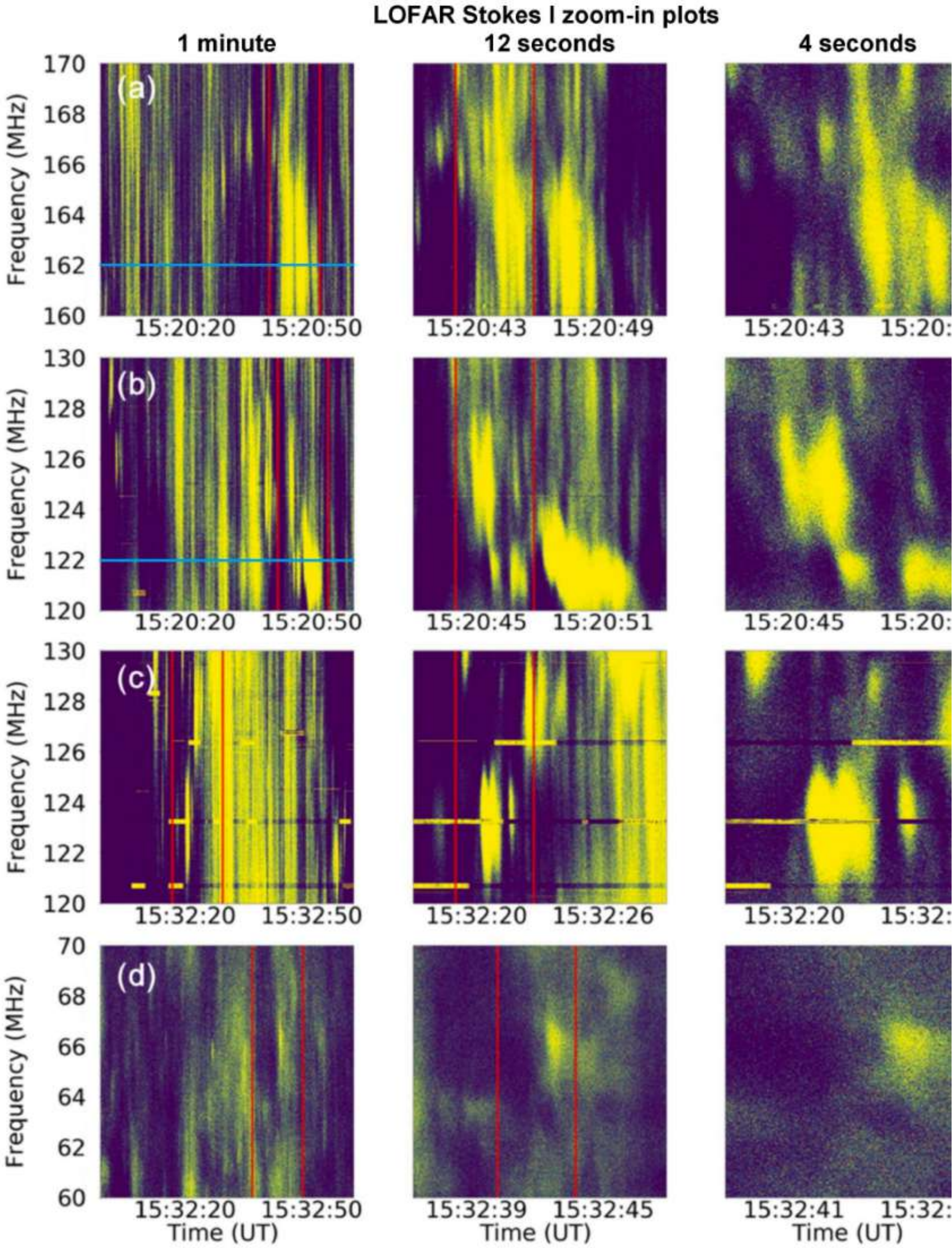
- Characteristic shapes of the radio burst spectra:




Stokes I
Frequency
20
40
60
80
100
120
140
160
180
14:52:48
15:07:12
15:21:36
15:36:00
15:50:24
Start Time: 2014-08-25 14:40:00
LOFAR 2014-08-25T14:56:42.2
AIA2014-08-25 14:56:47
Y arcsec
500
0
-500
X arcsec
0
500
1000
115
120
130
135
140
145
150
155
170
175
180



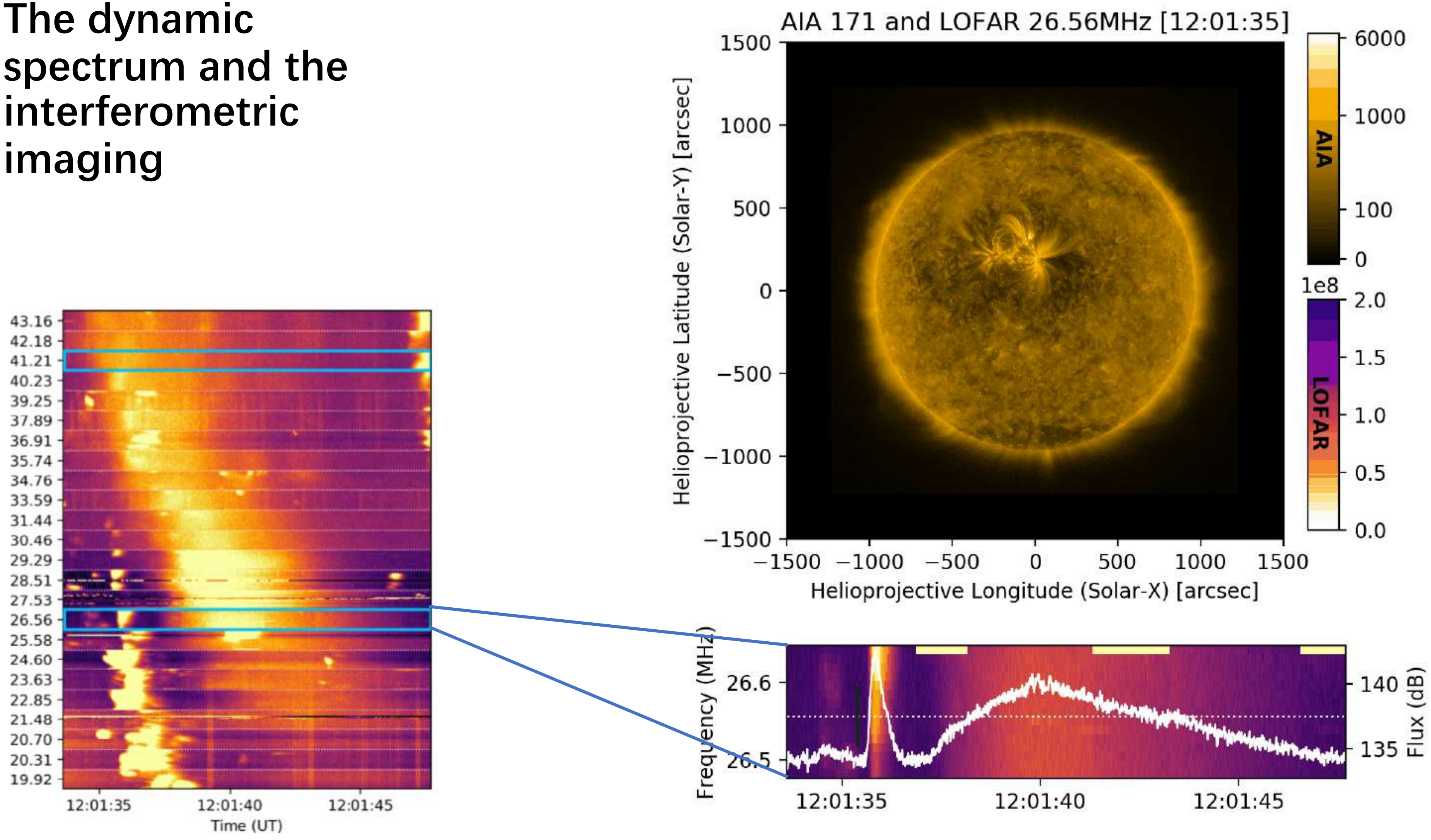




H. Liu et al. in prep

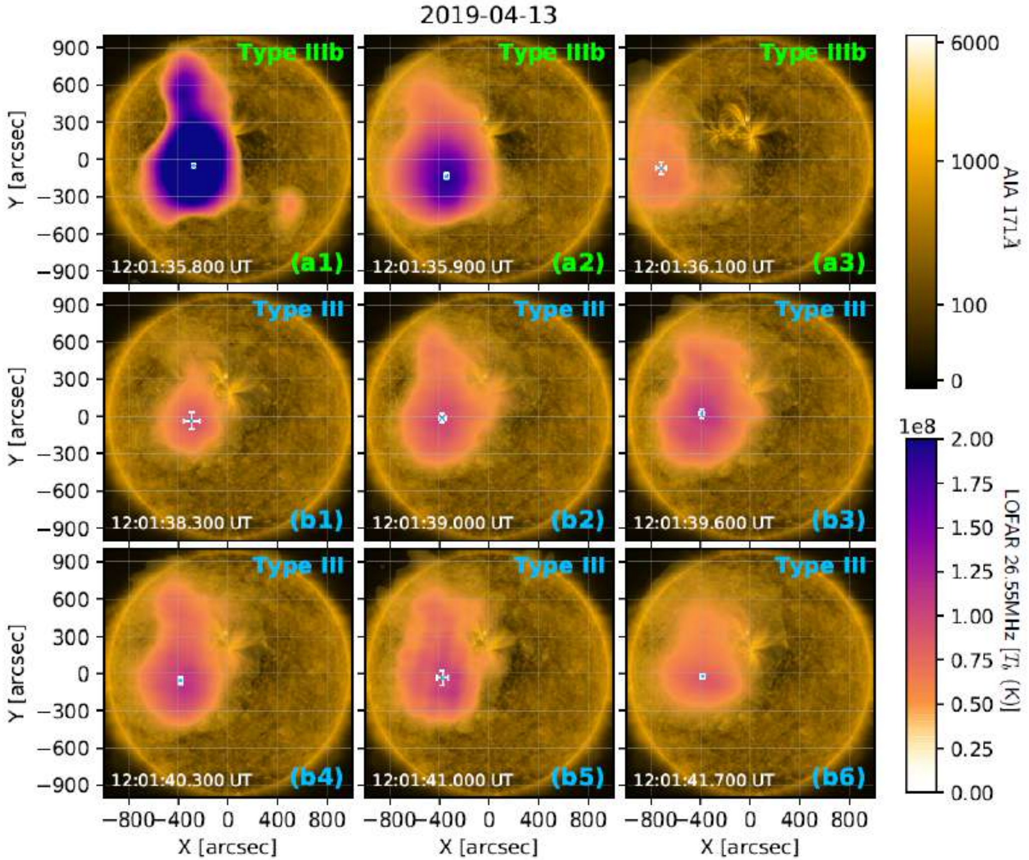
Type IIIb pair

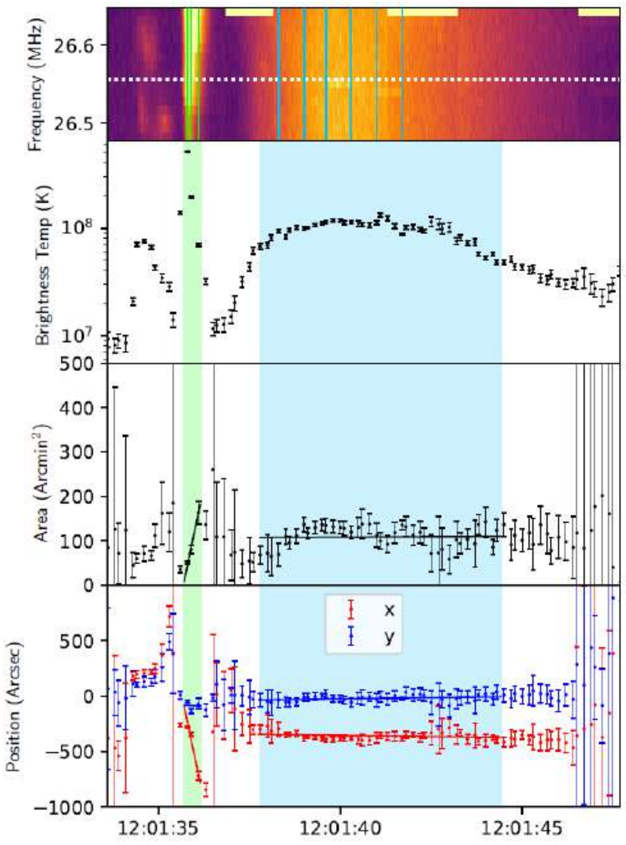
- **The dynamic spectrum and the interferometric imaging**

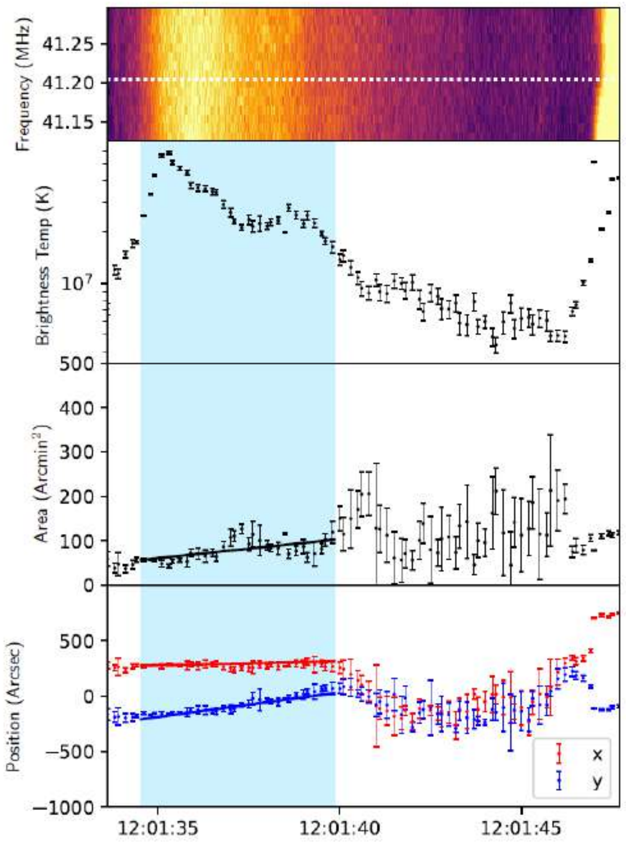


Zhang, Zucca, Sridhar, Wang and al. A&A 2020

Size and Source Position

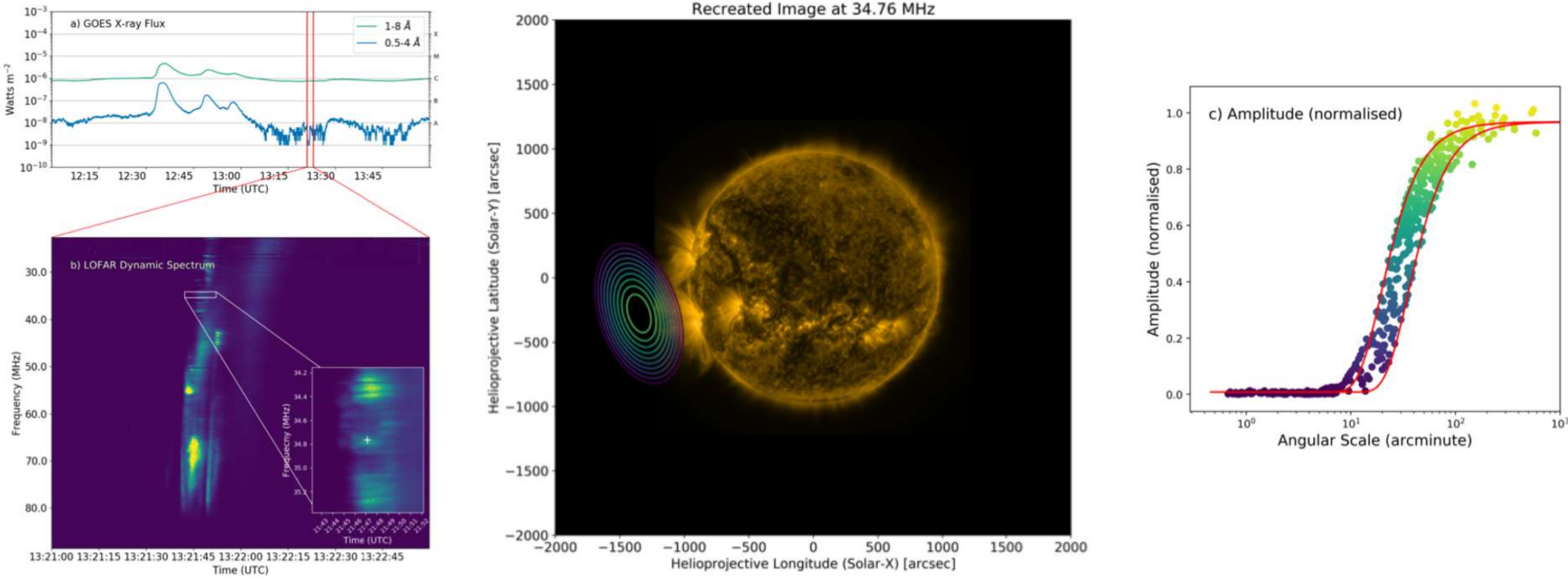






Zhang, Zucca, Sridhar, Wang and al. A&A 2020

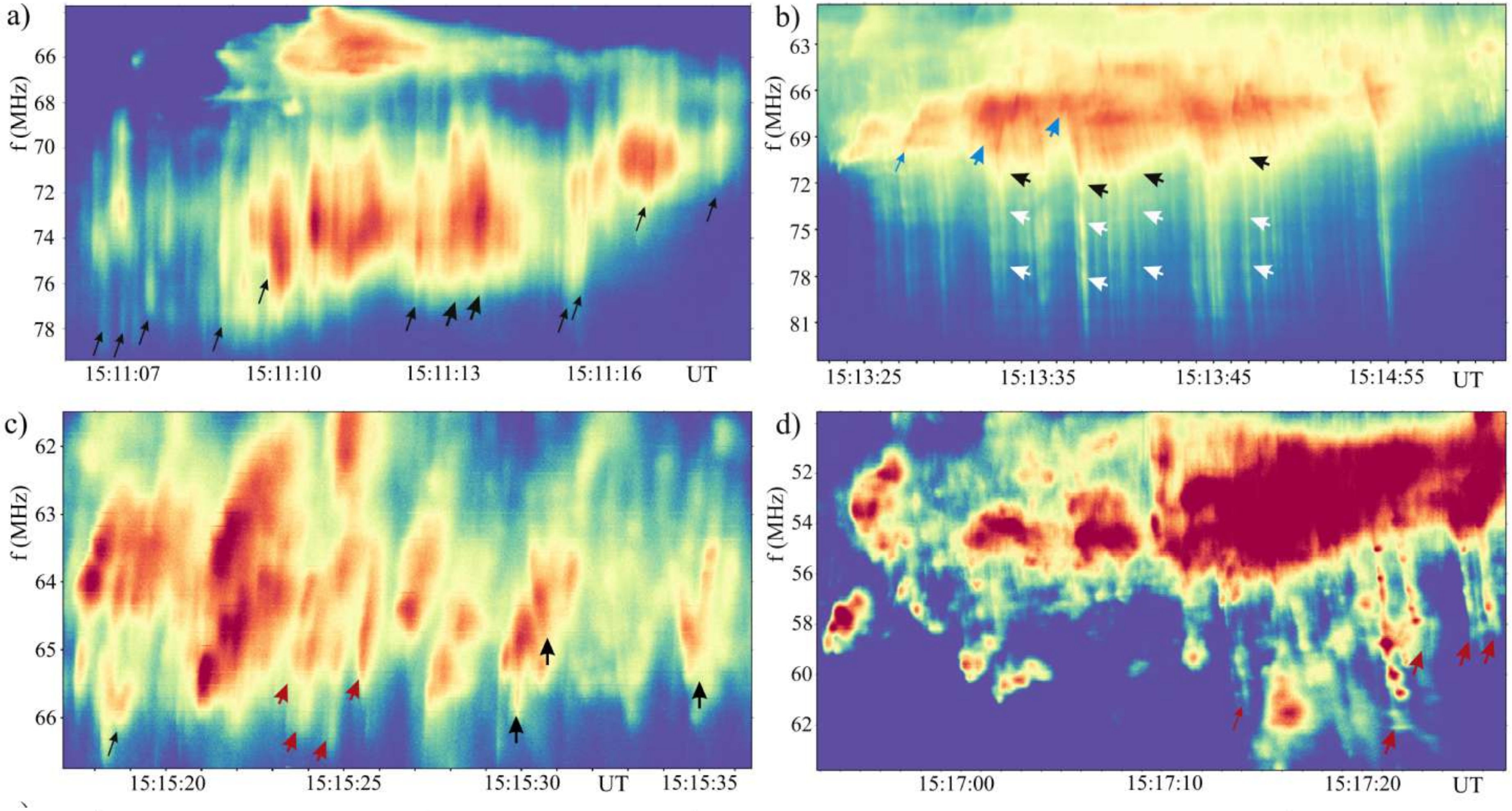
Fitting the source size in the UV plane



Murphy, Carley, Ryan, Zucca, Gallagher A&A 2020

The band- width of an individual striation at 34.76MHz suggests an FWHM source size of 3.18''.
Directly fitting visibilities reveals FWHM source sizes of 18.8′ to 10.2′

Fine Structures

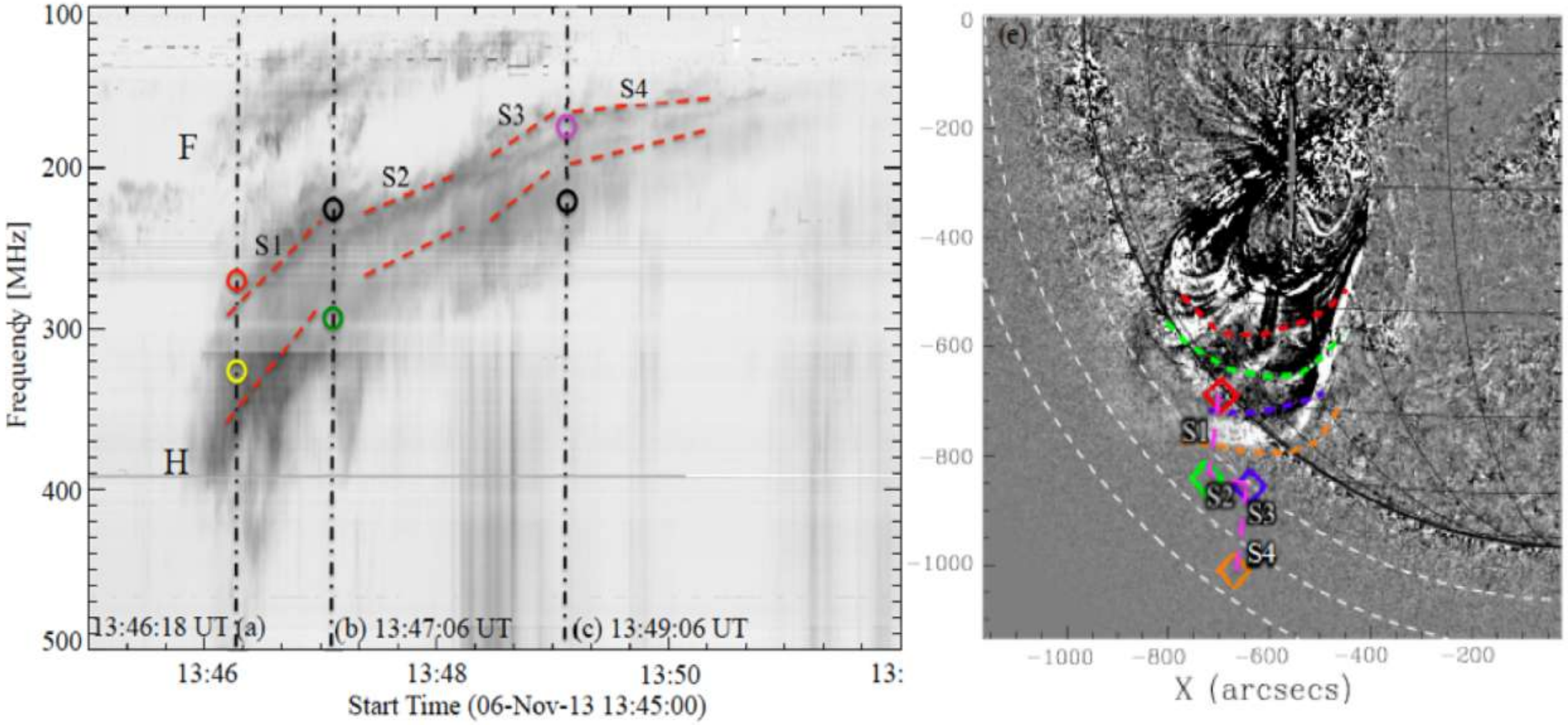


Magdalenic et al. 2020

Imaging and spectroscopy of CME-driven shocks

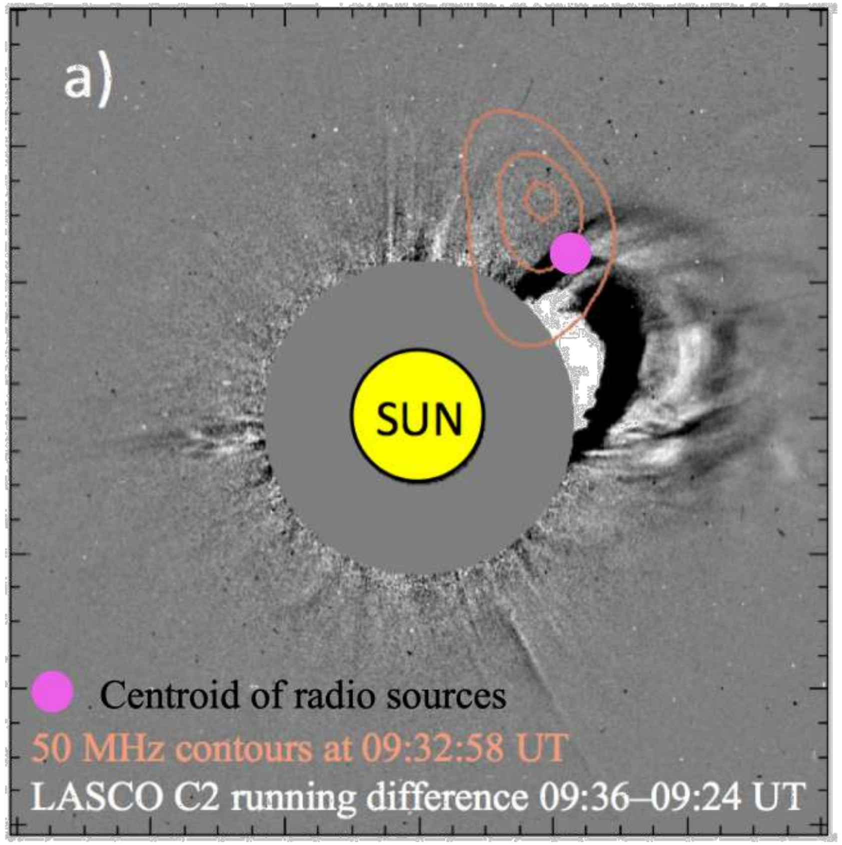
NRH, ORFEES and DAM

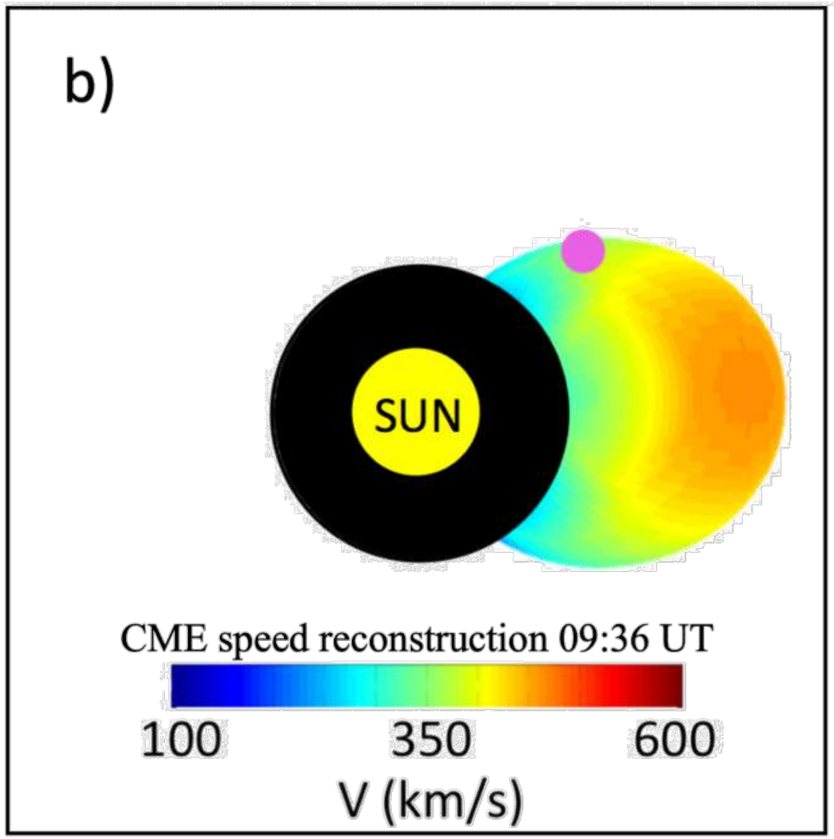
Zucca et al. **ApJ** (2014b)



CME speed and radio emission

- Expansion of the flank slower than the apex

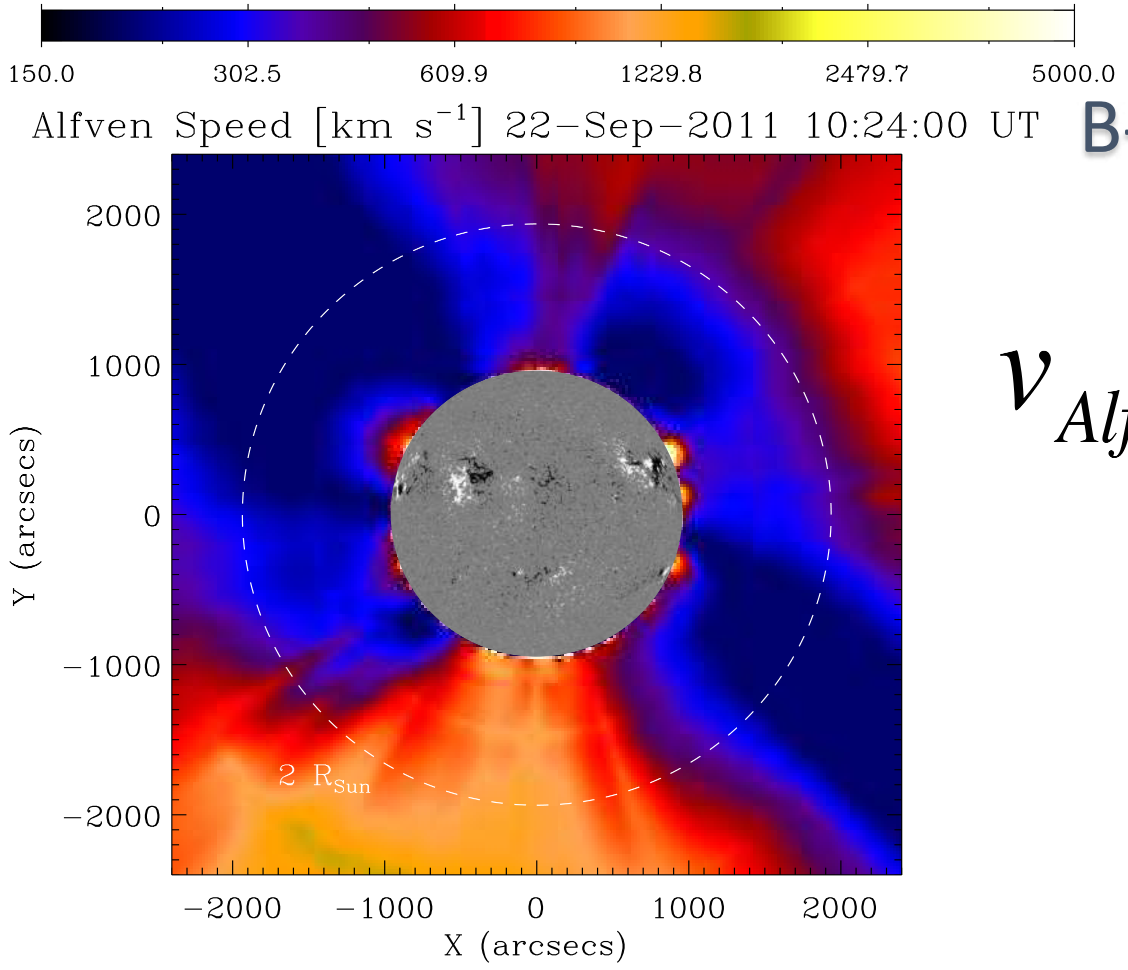




Triangulation of CME using
Rouillard et al. ApJ (2016) method

Zucca et al. 2018

Estimating the Mach number



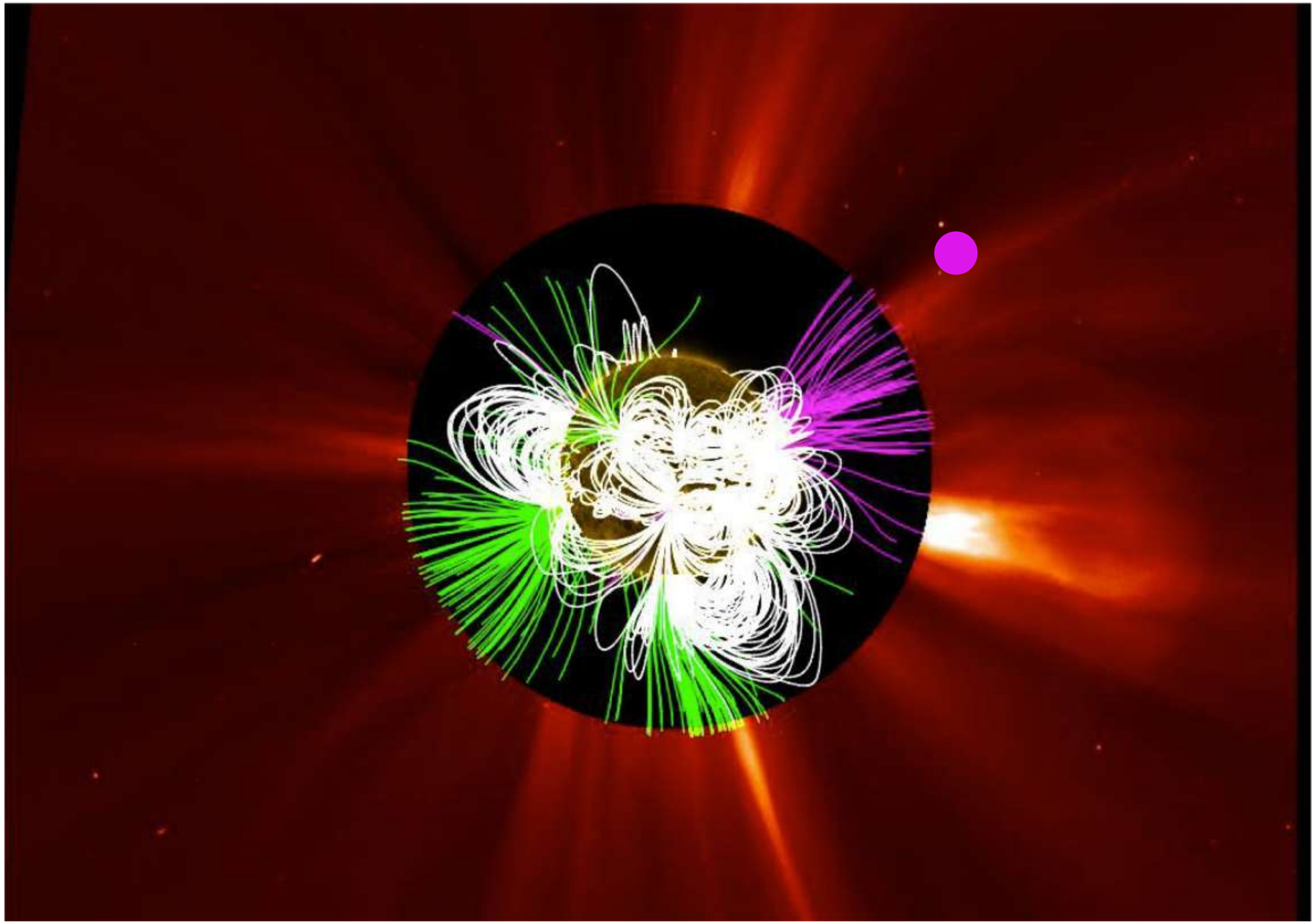
Zucca et al. 2014a

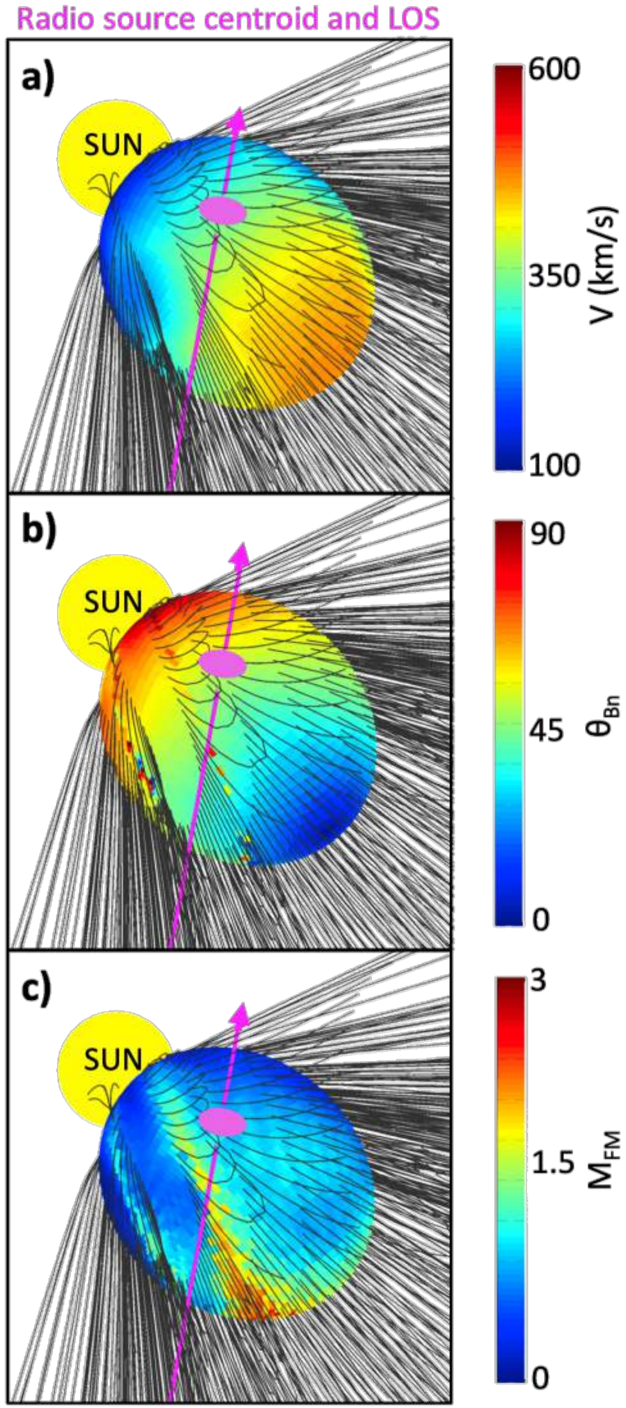
B-Field with PSFF

$$v_{Alfven}(x,y) = \frac{B(x,y)}{\sqrt{\mu m_p n_e(x,y)}}$$

Density Map with SDO/AIA and SOHO/LASCO

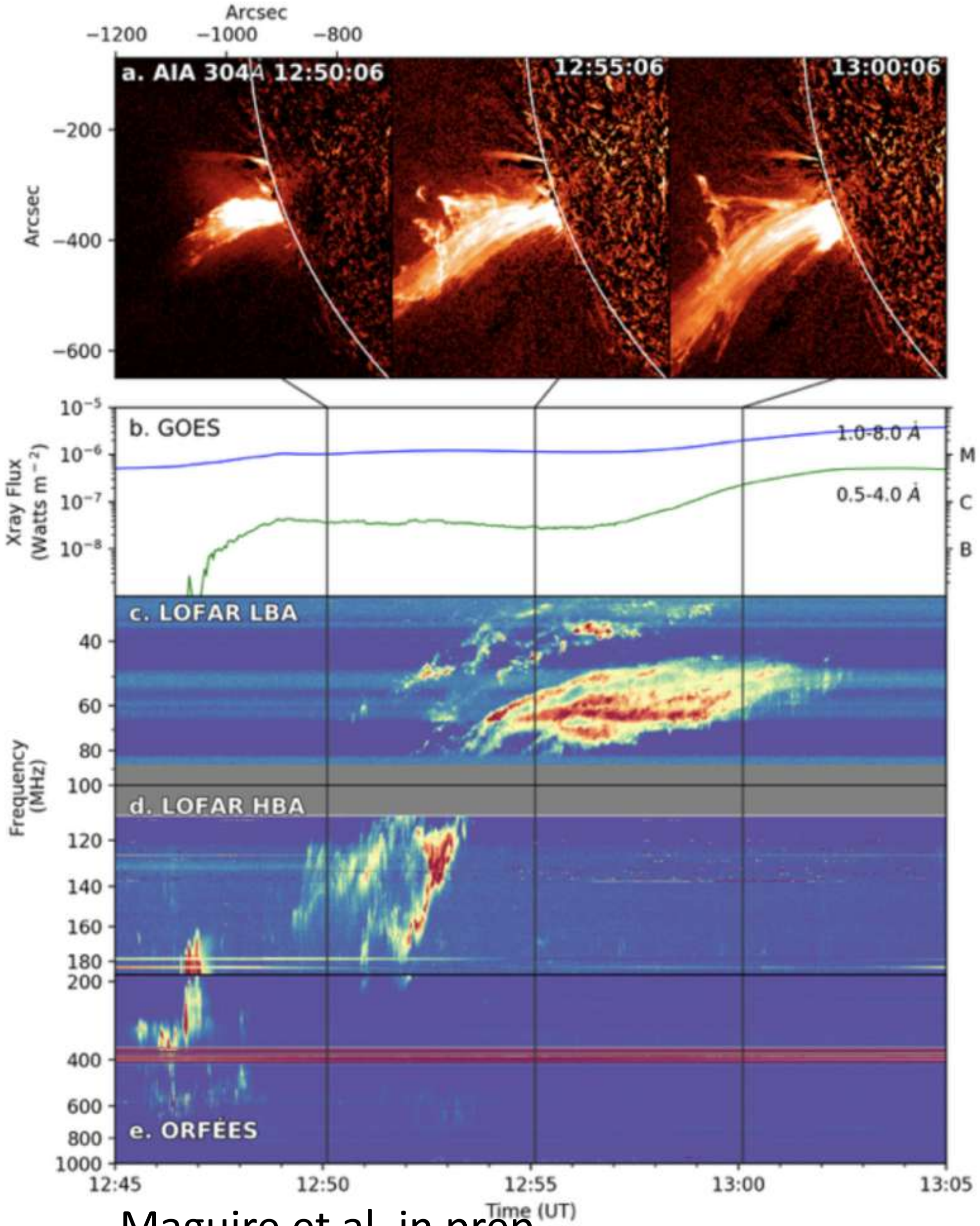
Mach Number and B-field Geometry



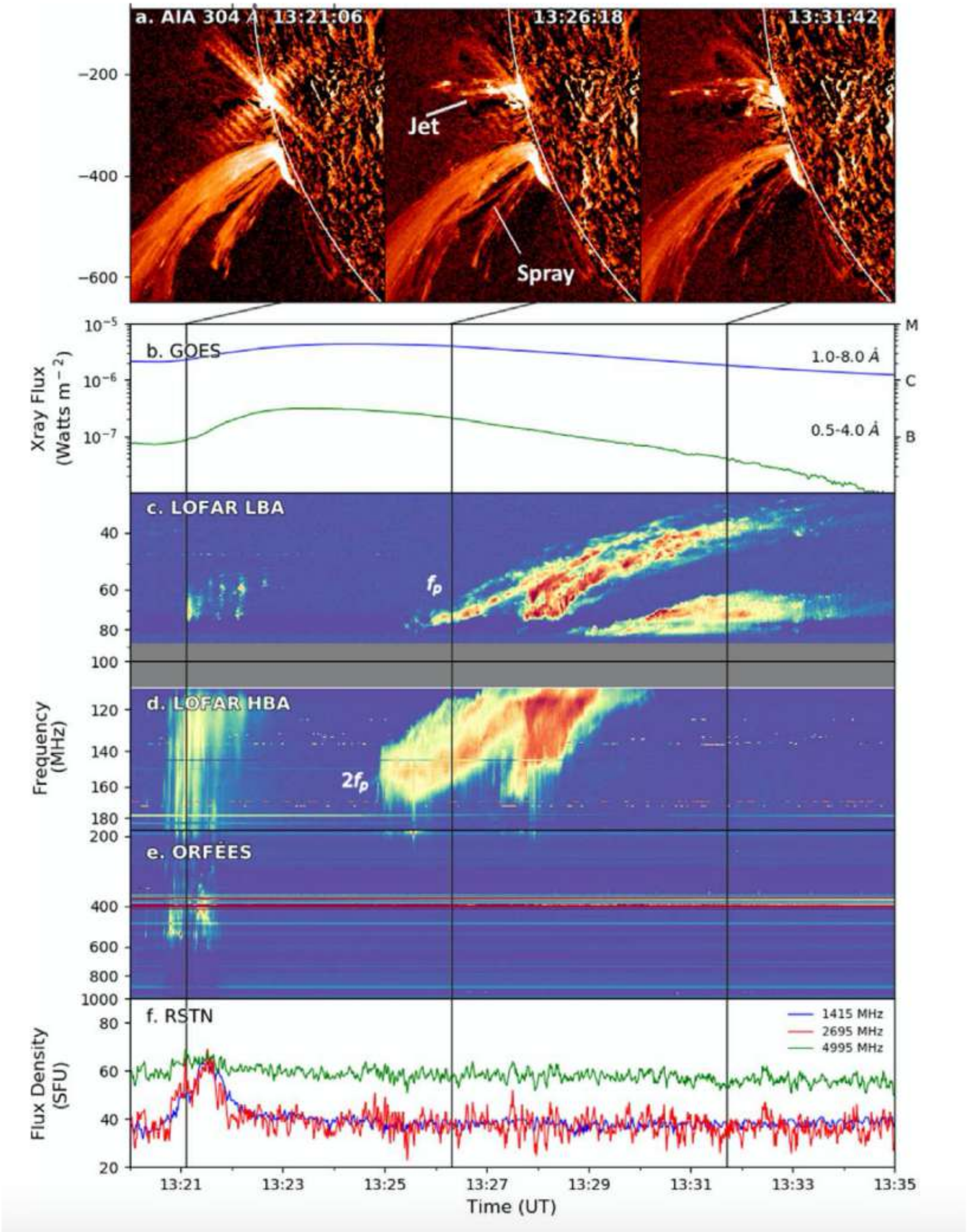


Zucca et al. 2018

Type II Radio Bursts

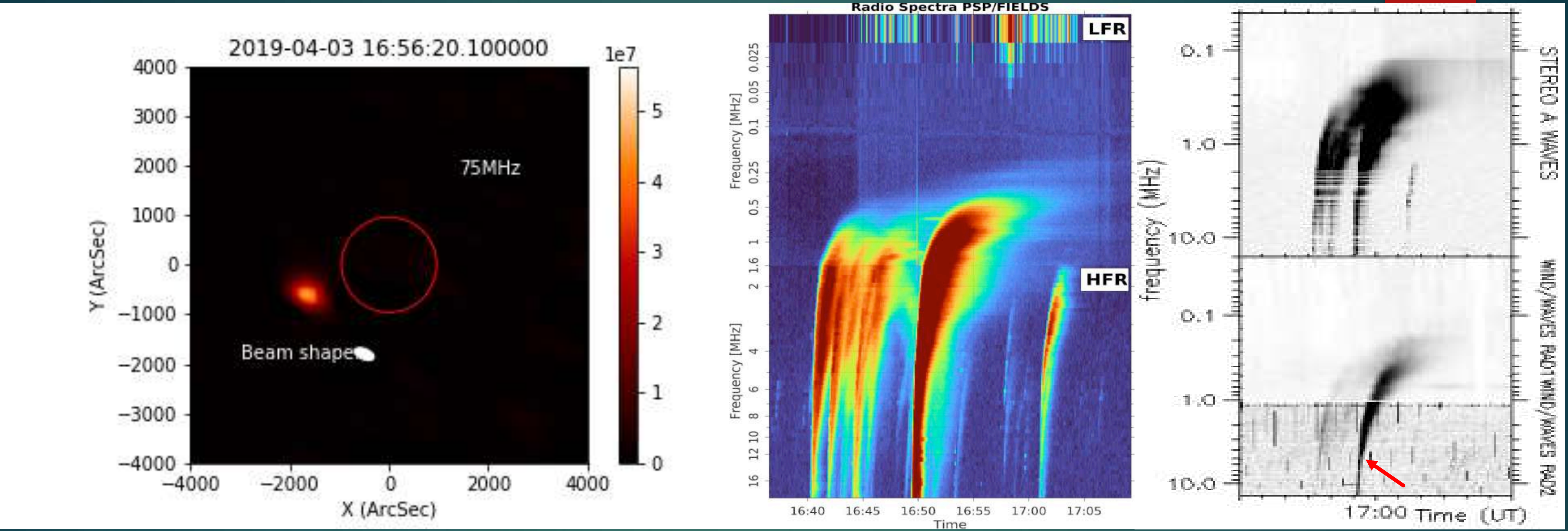


Maguire et al. in prep



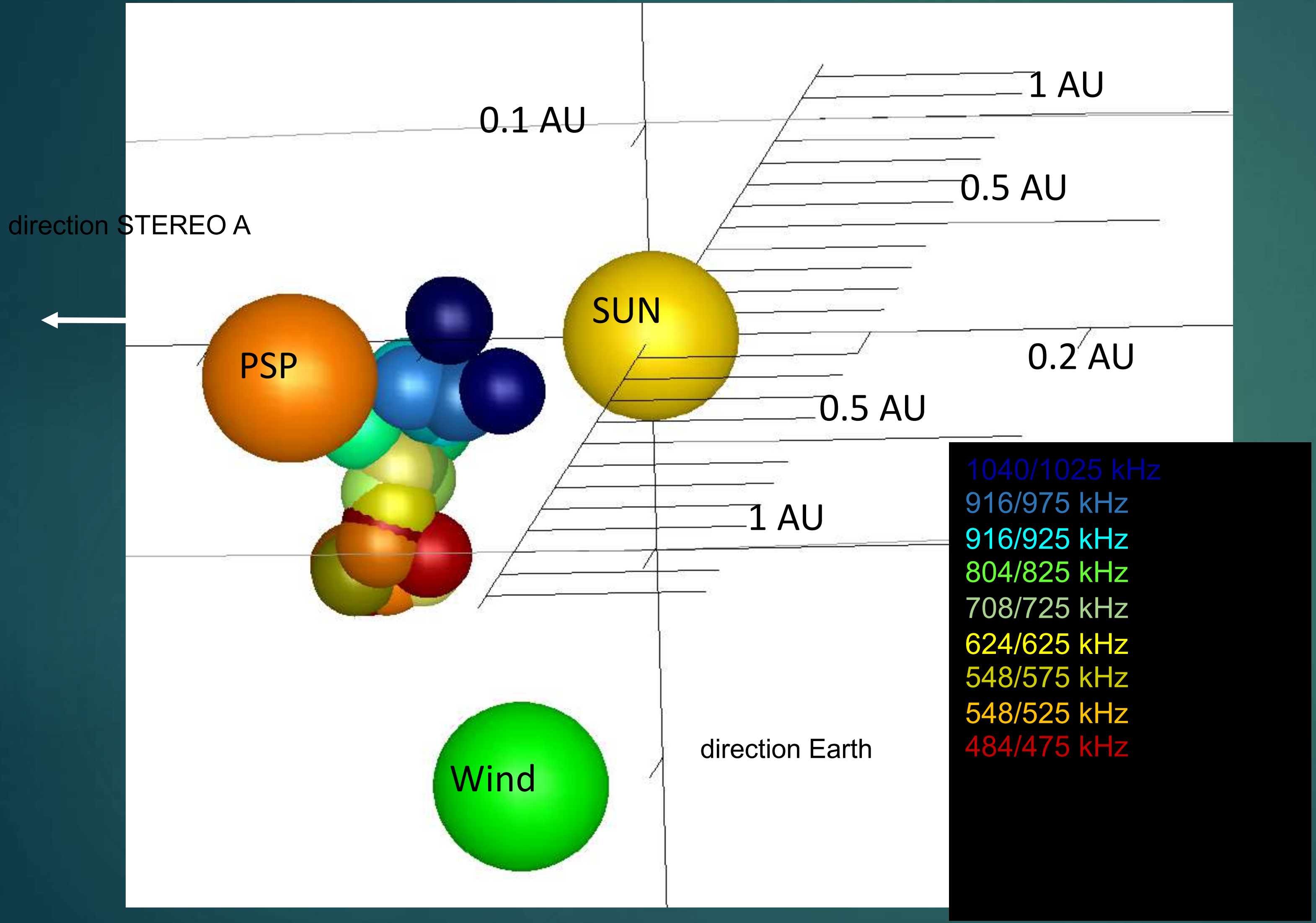
Maguire et al. 2021

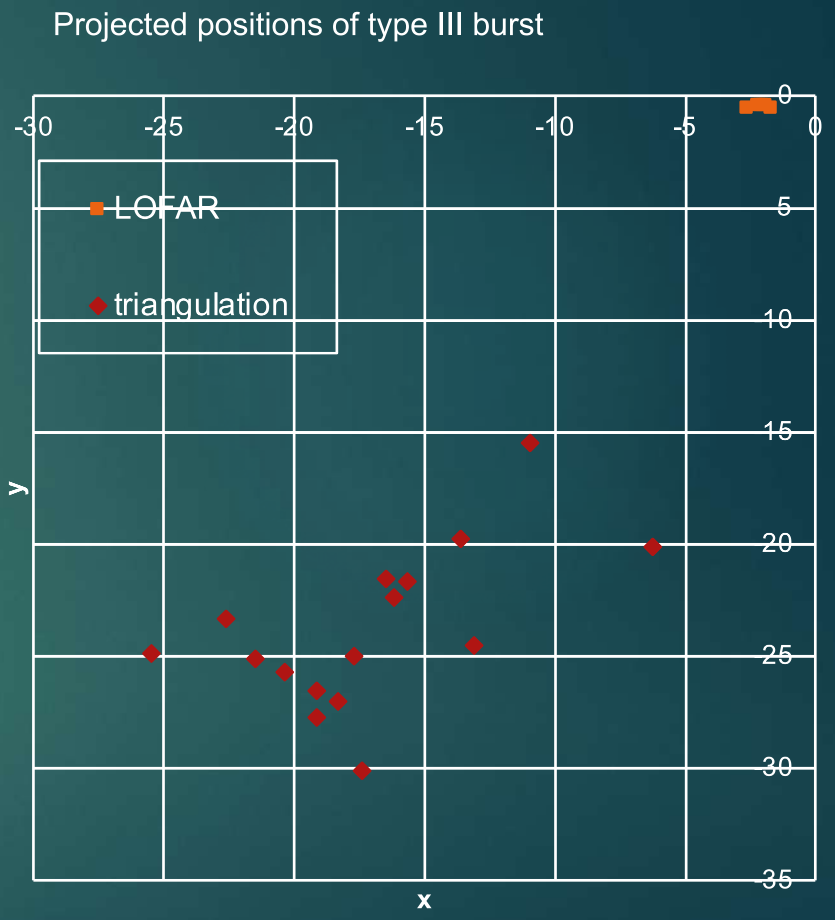
Type III radio bust on 03 April 2019



Magdalenic, J; Jebaraj, I; Zucca, P.; Kouloumvakos, A.; Krupar, V.; Poedts, S., in preparation

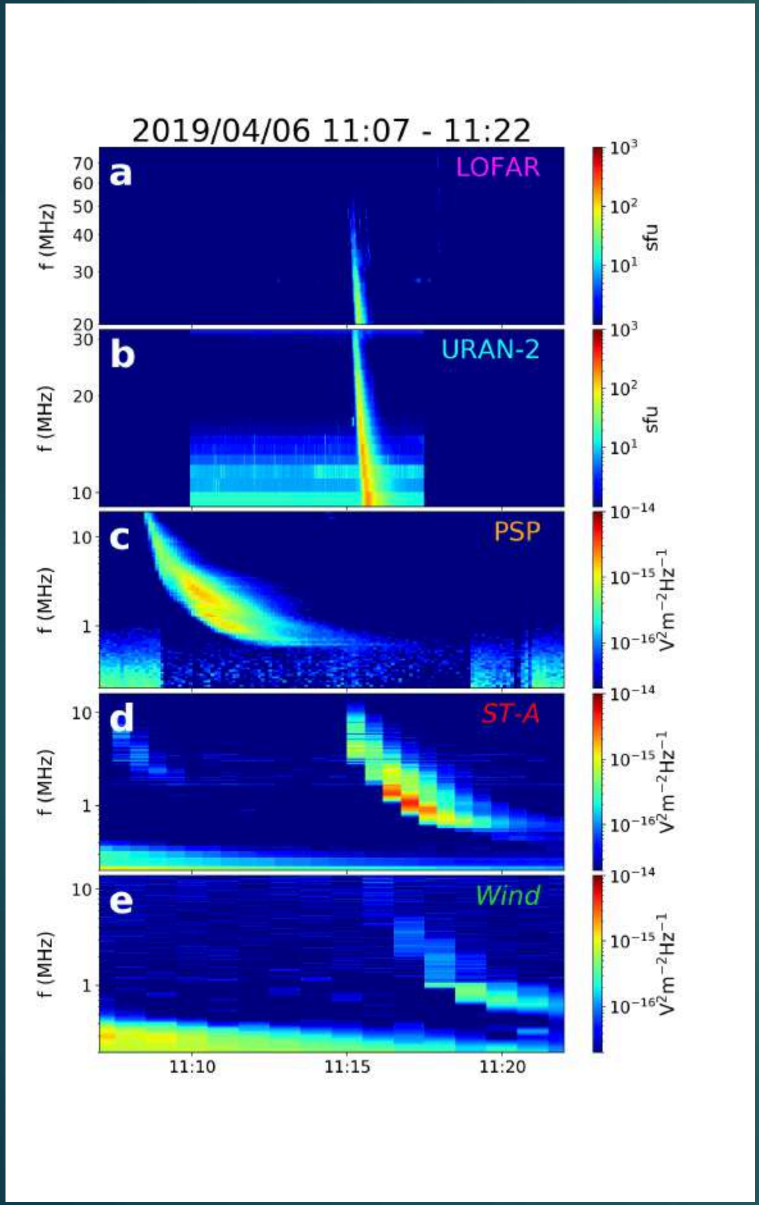
Type III radio bust on 03 April 2019

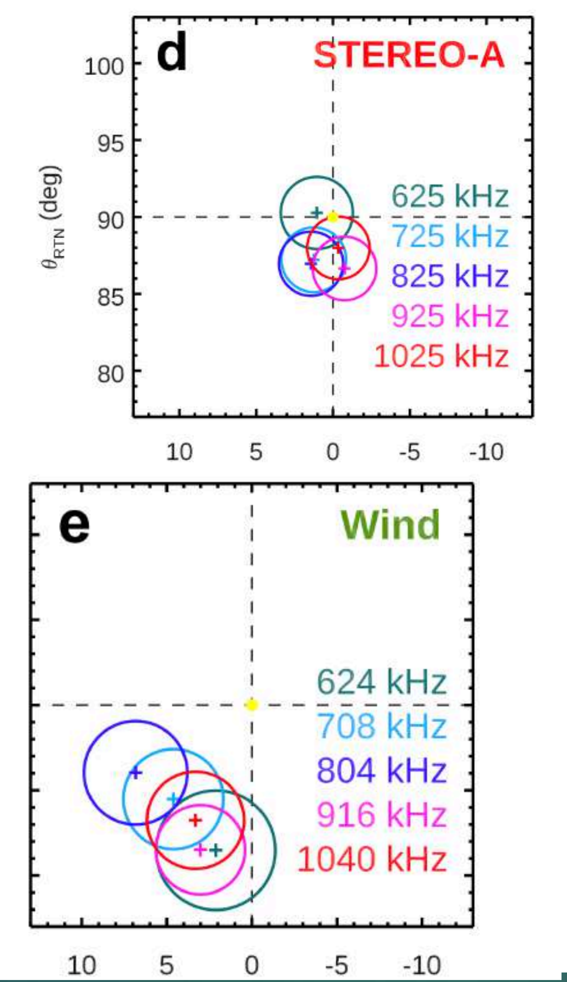


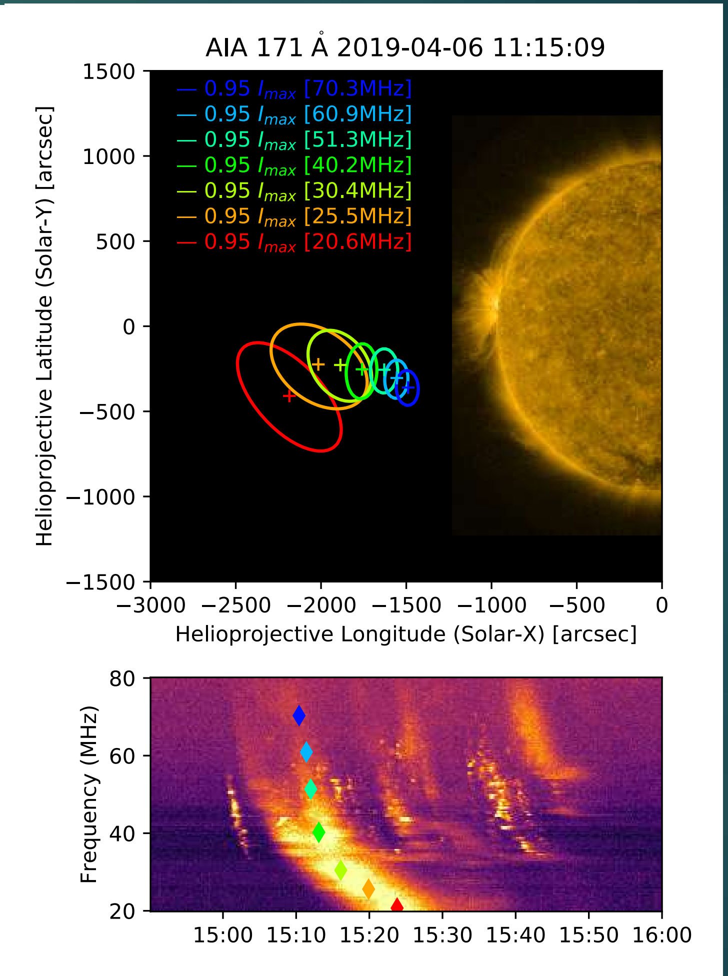


Magdalenic, J; Jebaraj, I; Zucca, P.; Kouloumvakos, A.; Krupar, V.; Poedts, S., in preparation

Type III radio bust on 06 April 2019

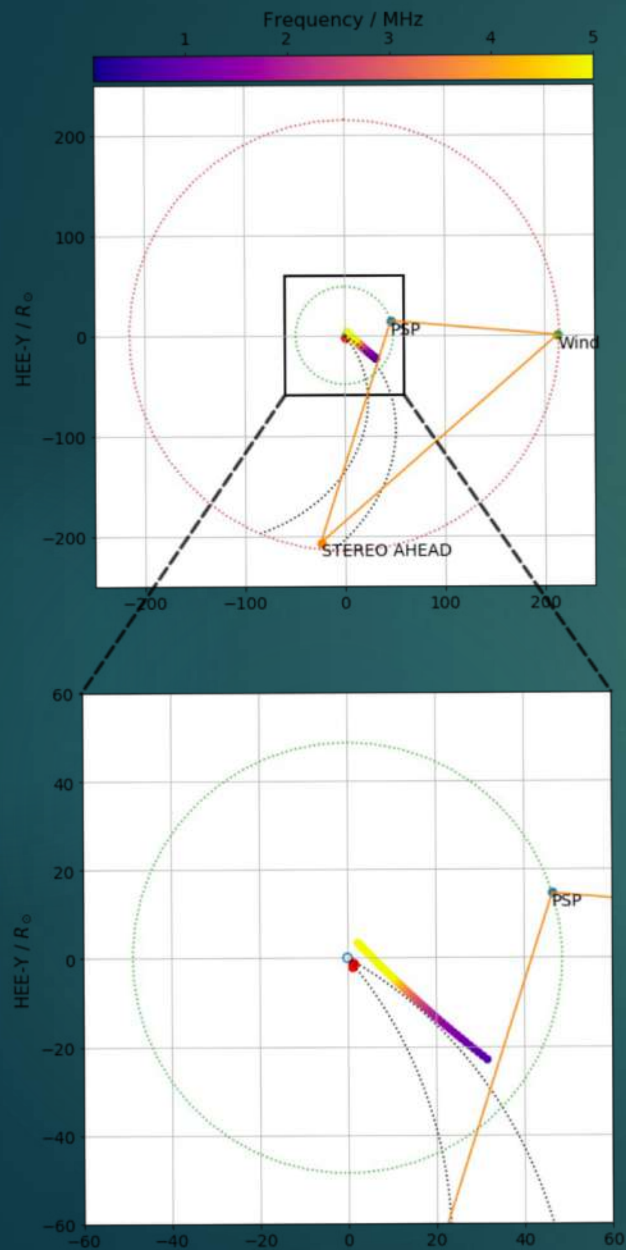


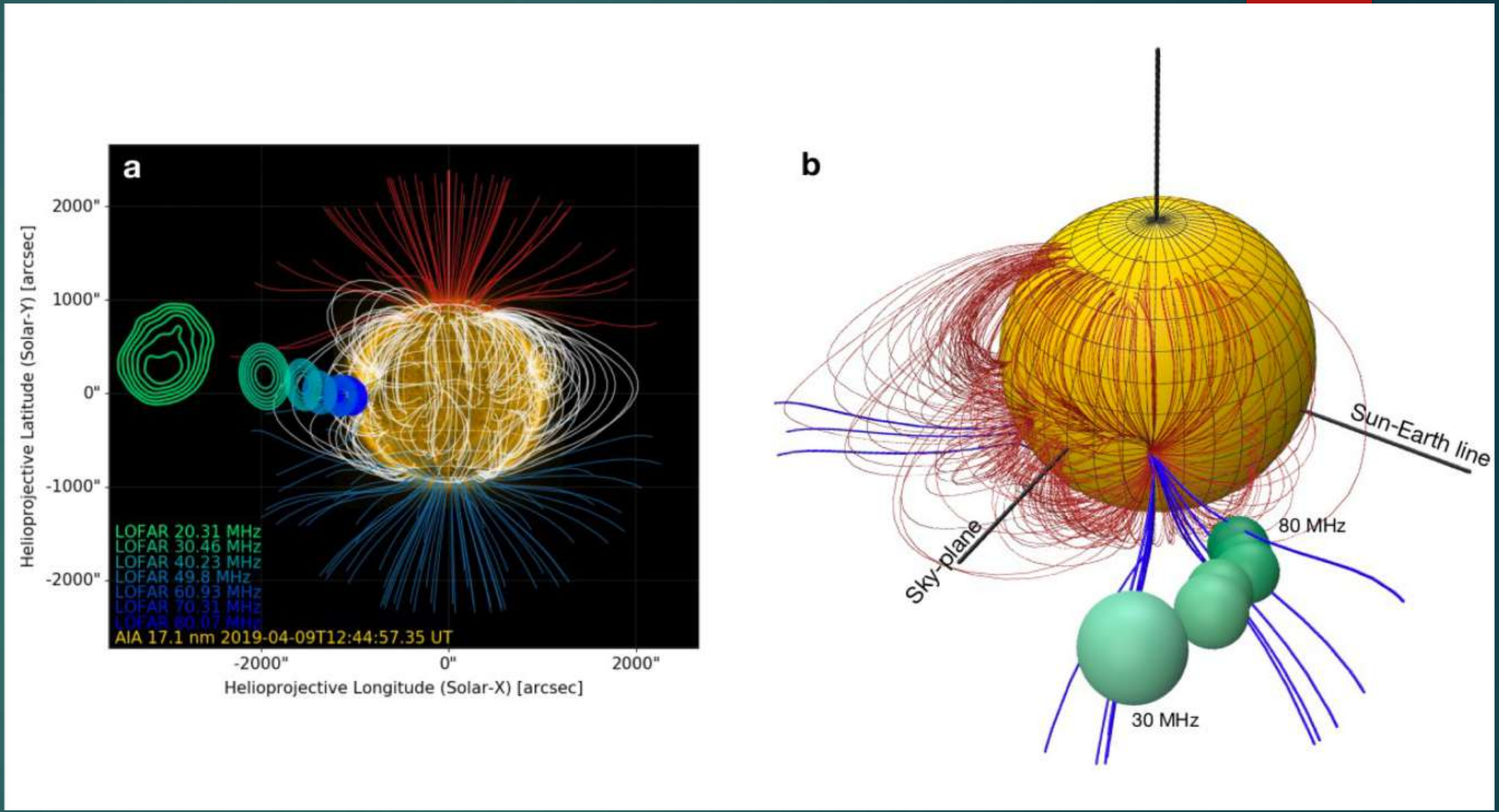




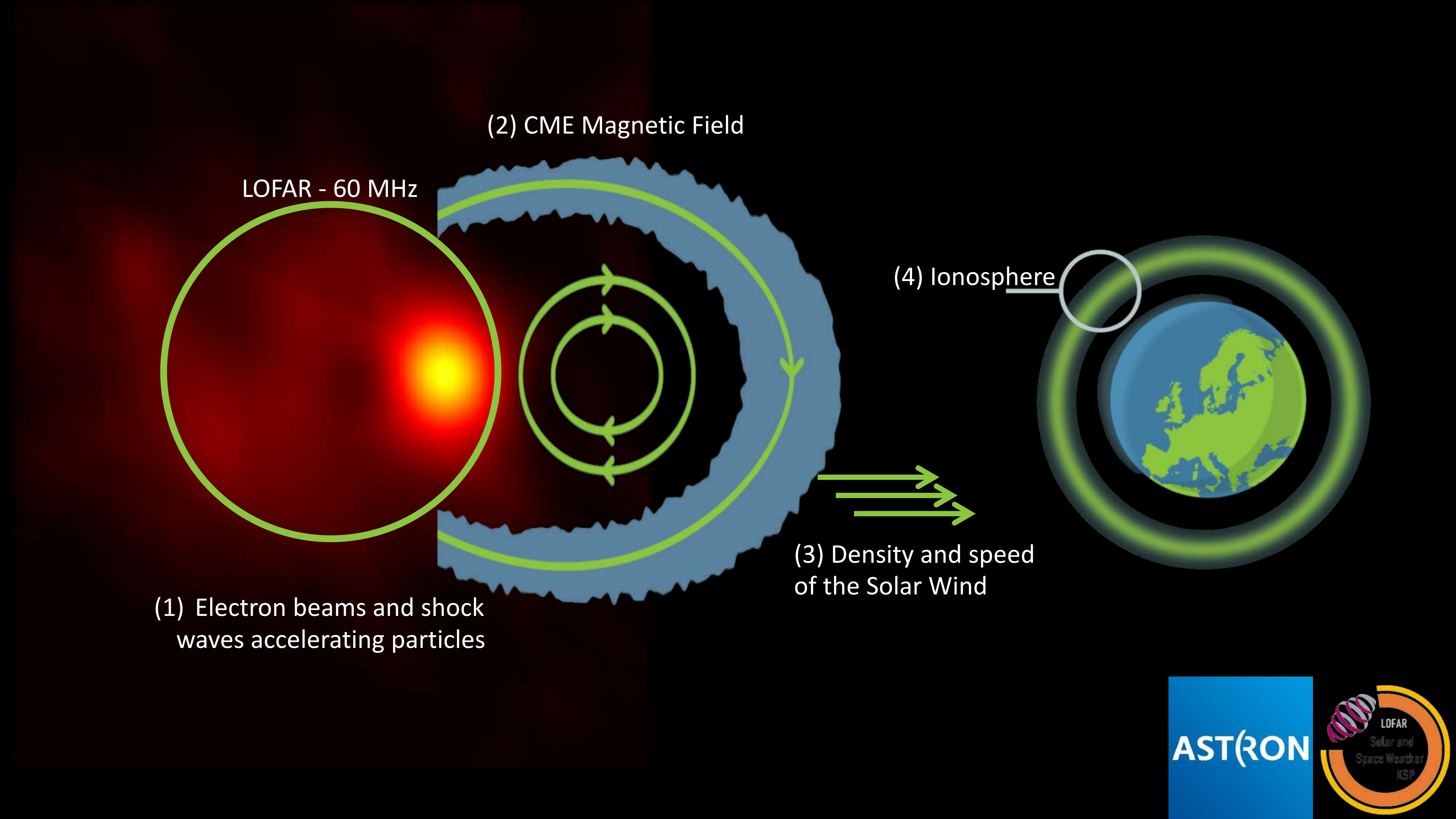
V. Krupar, S. D. Bale, L. Balmaceda, A. I. Brazhenko, A. V. Frantsuzenko, A. A. Konovalenko, E. P. Kontar, O. Kruparova, M. Maksimovic, J. C. Martinez Oliveros, V. N. Melnik, F. Nemec, M. Pulupa, H. A. S. Reid, A. Szabo, P. Zhang and P. Zucca in preparation

Type III radio Burst on 09 April 2019

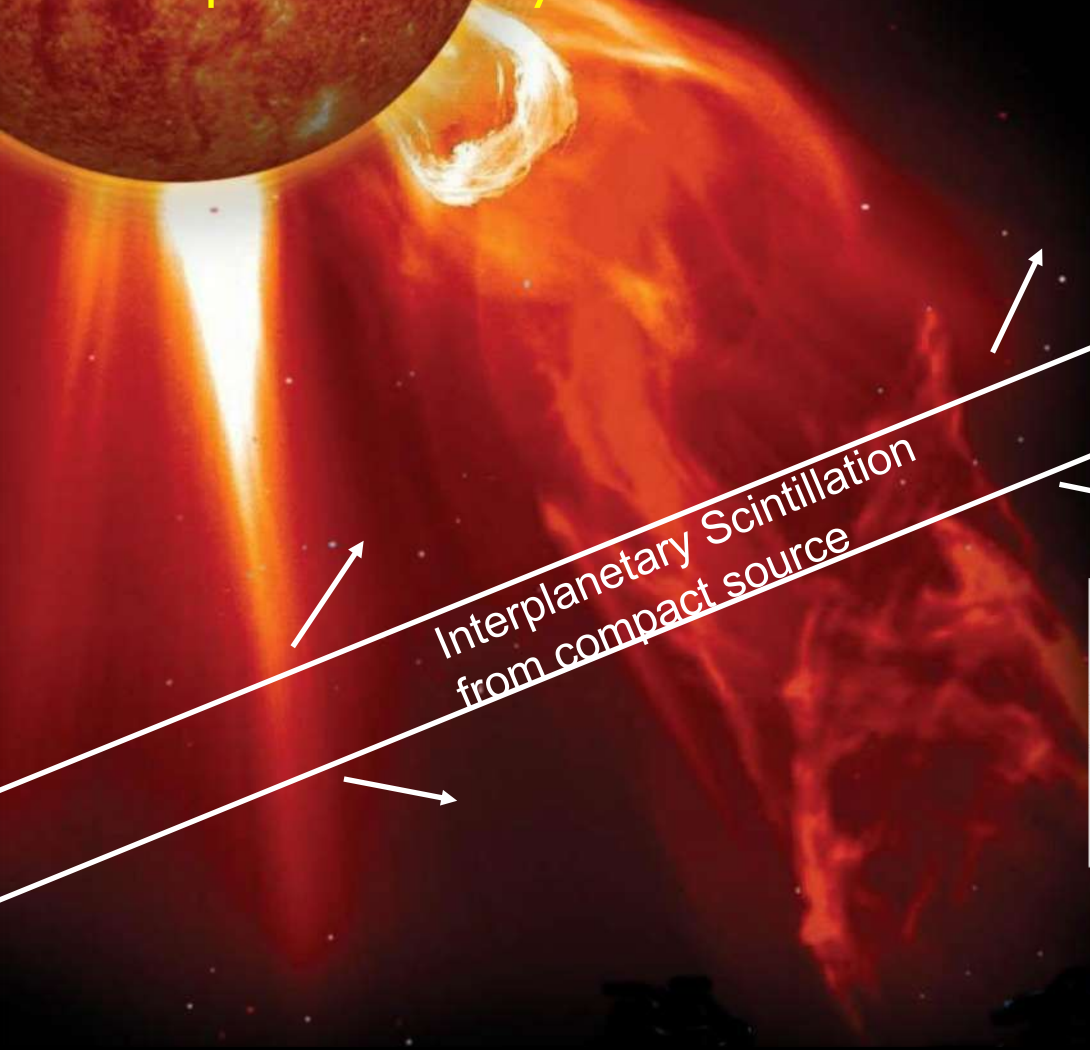


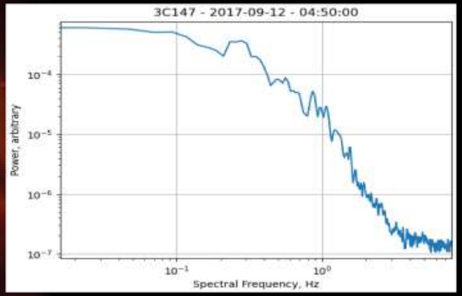


Sam Badman, Eoin Carley, Luis Alberto Cañizares, Nina Dresing, Lan Jian, David Lario, Marc Pulupa, Stuart Bale in preparation


(2) CME Magnetic Field
LOFAR - 60 MHz
(4) Ionosphere
(3) Density and speed
of the Solar Wind
(1) Electron beams and shock
waves accelerating particles

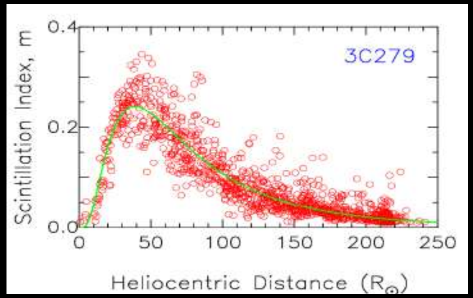
Interplanetary Scintillation - IPS





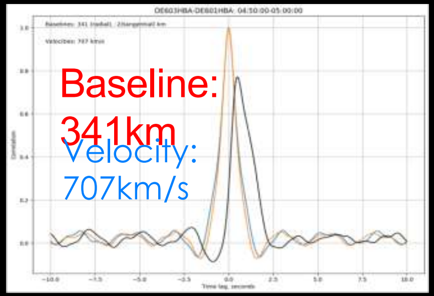
Model single-station power spectrum:

Velocity



Variation in scintillation level, normalised for the decrease with distance:

Related to density.

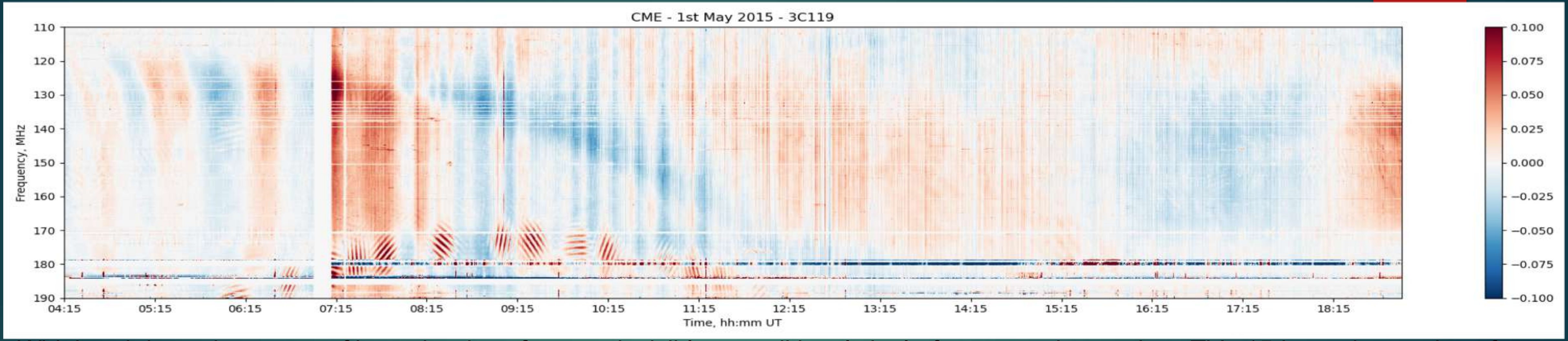


Cross-correlations of intensity time series from each station:

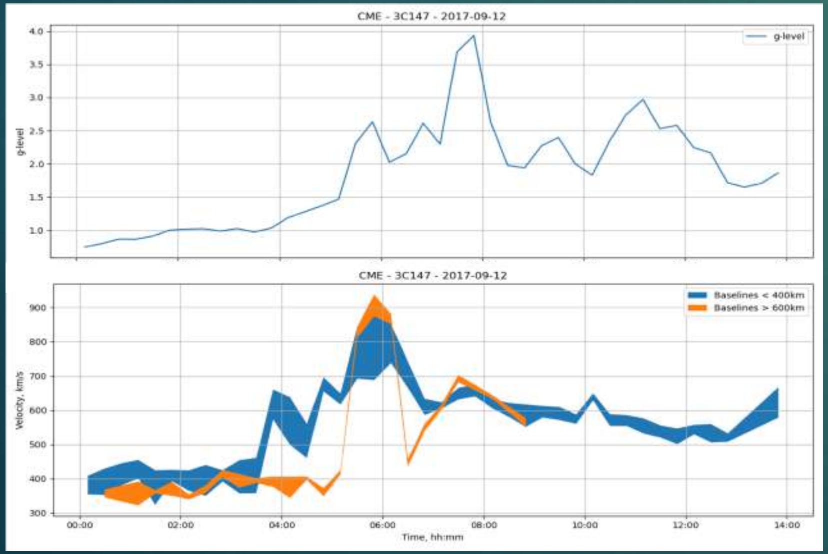
Fit baselines vs time-lags = velocity(s)

Slide Courtesy of R. Fallows

CME Observations - Demonstrating IPS Techniques

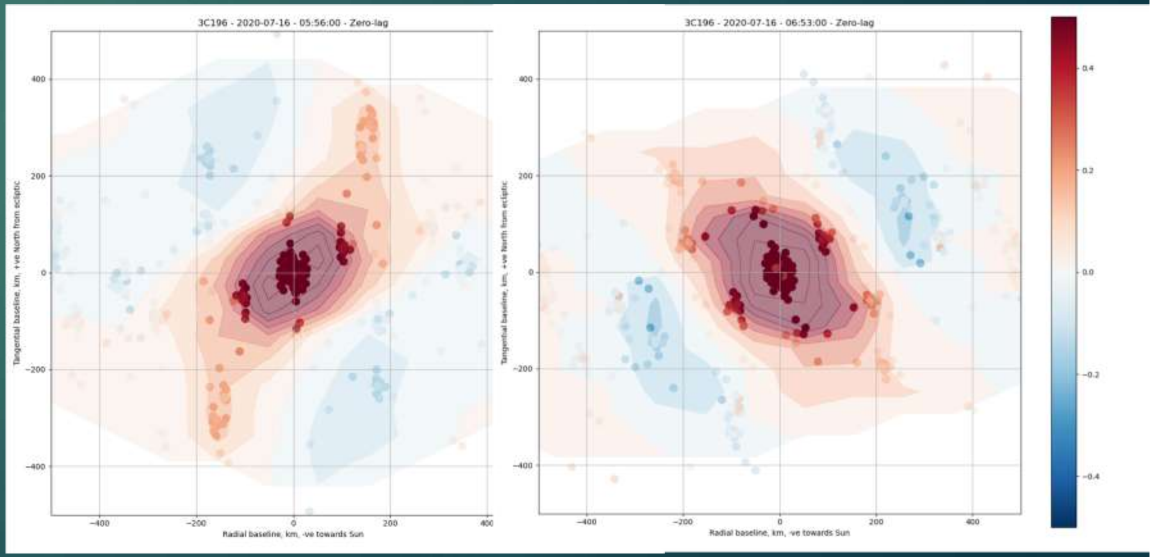


Wideband dynamic spectra of intensity show features invisible to traditional single-frequency time series. This 15-hour observation of a CME (above) shows structure on a ~30-minute time-scale for the first few hours, probably related to large-scale structure in the CME.



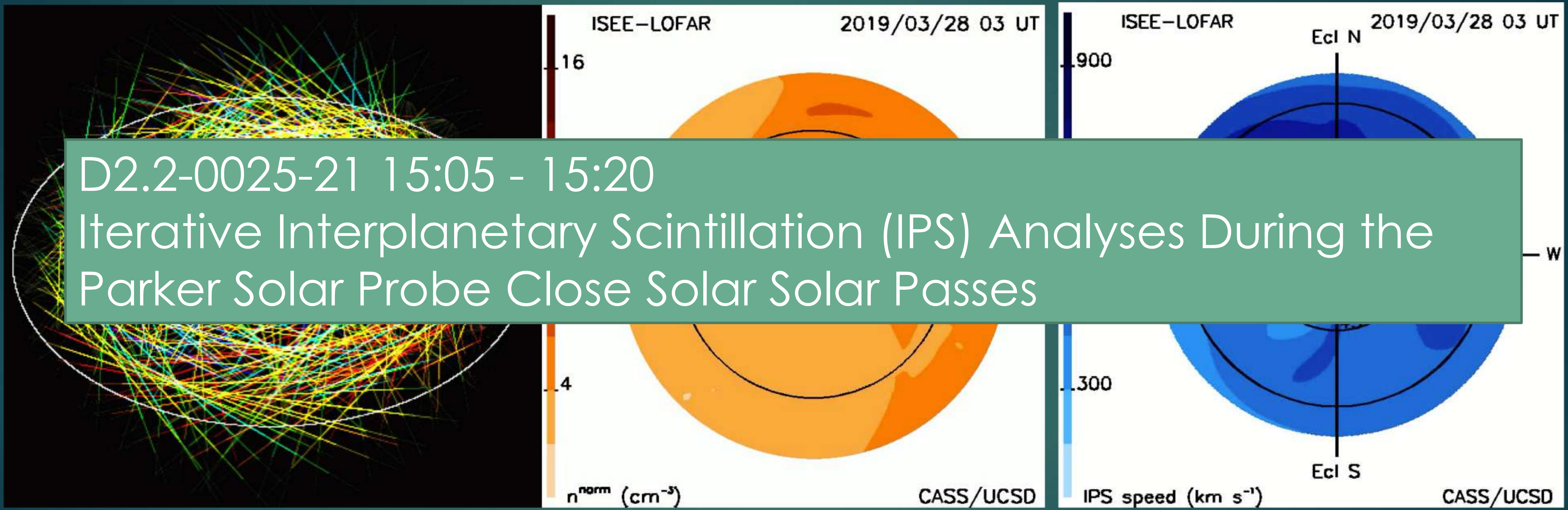
Left: g-level (related to density - top) and velocity from an ultra-fast CME in September 2017.

Right: two spatial correlation functions (a reflection of the small-scale density structure) show rotation related to the interplanetary magnetic field.



Slide Courtesy of R. Fallows

IPS and Tomography

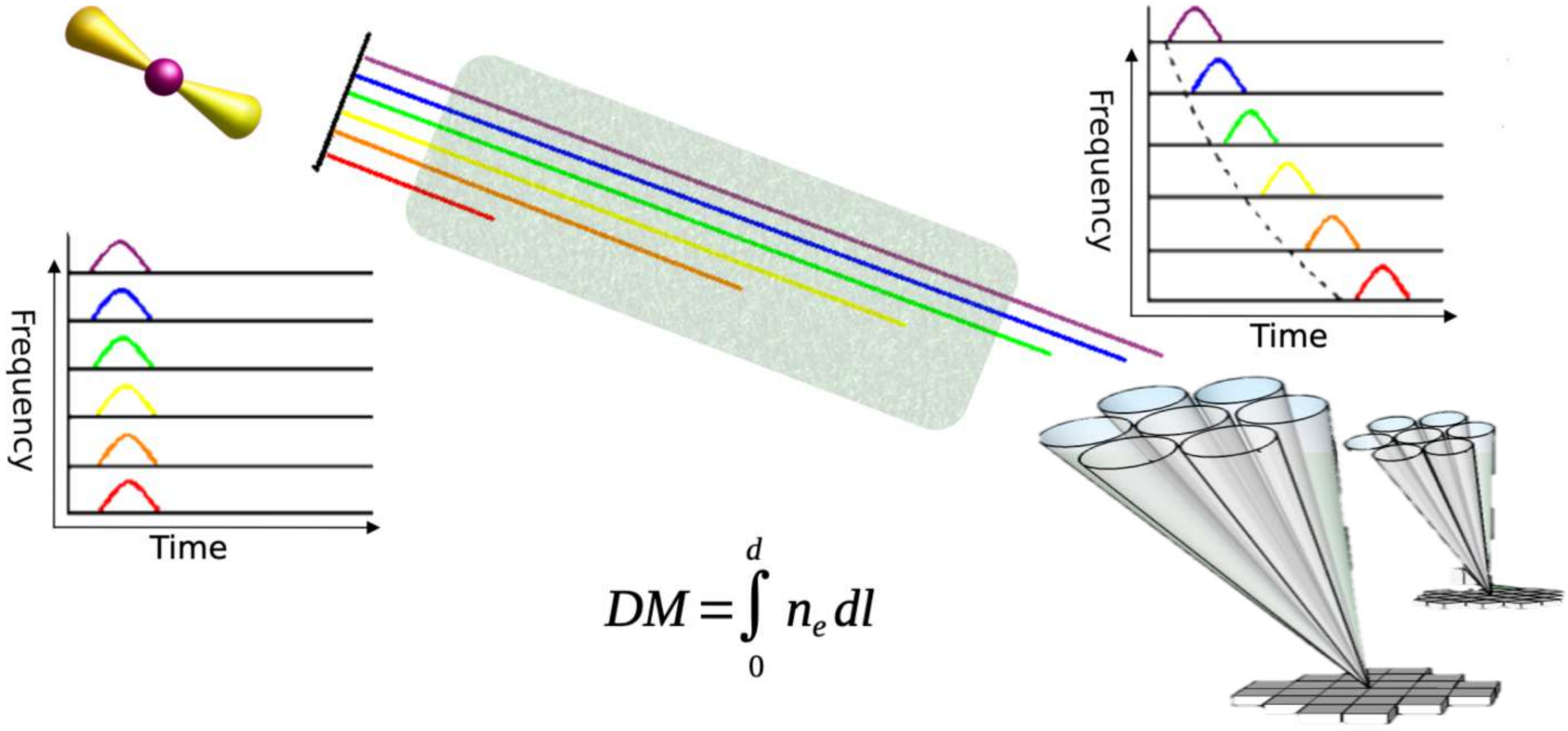


D2.2-0025-21 15:05 - 15:20

Iterative Interplanetary Scintillation (IPS) Analyses During the Parker Solar Probe Close Solar Solar Passes

Bernard Jackson, Richard Fallows, Mario Bisi and the ISEE LOFAR working group

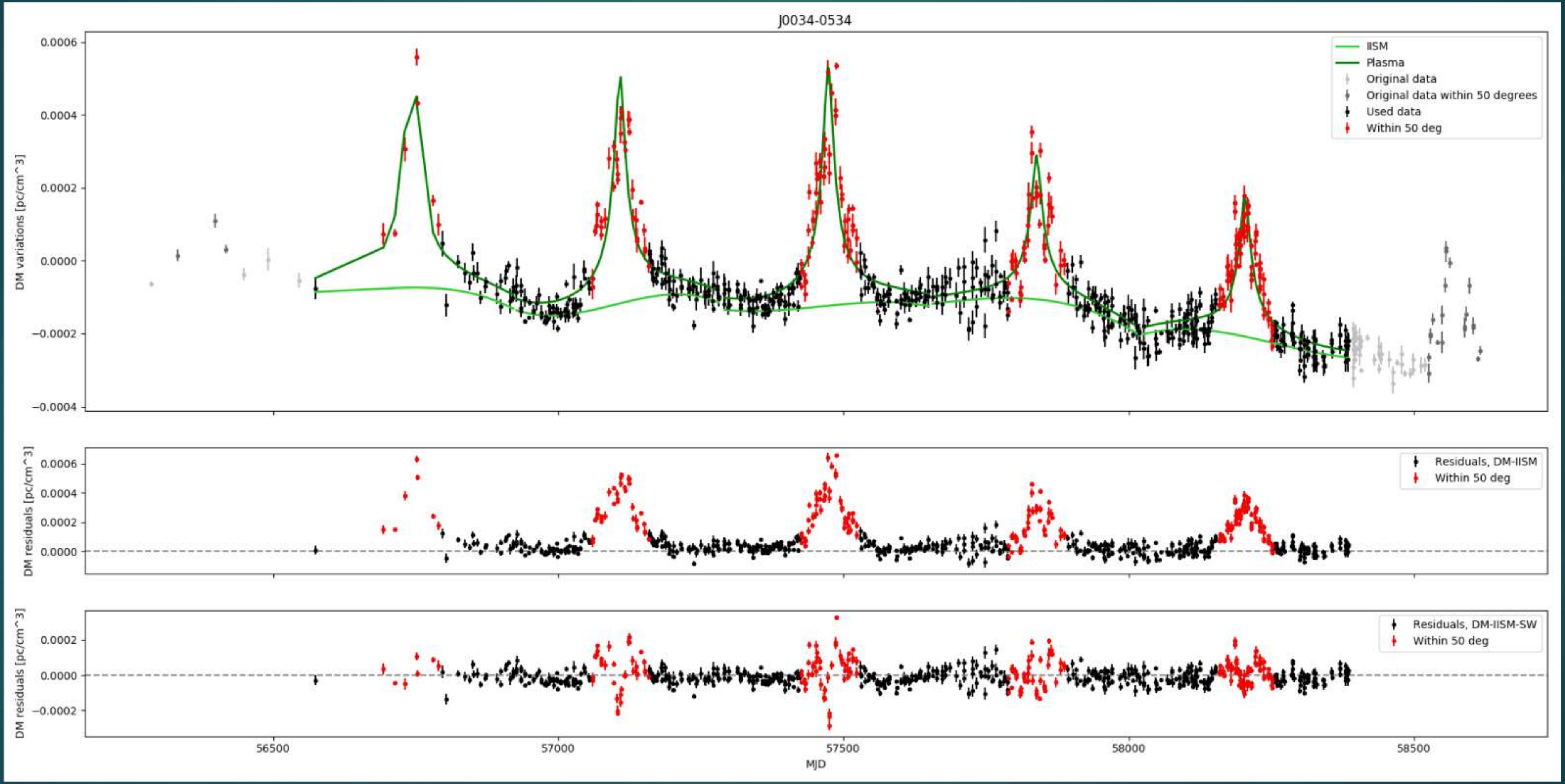
Using Pulsars



$$DM = \int_0^d n_e \, dl$$

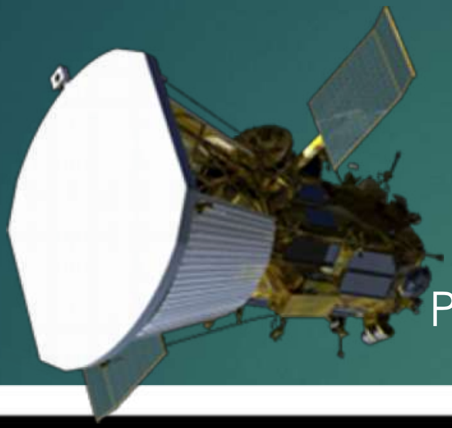
Slide Courtesy of Caterina Tiburzi

Solar Wind Variability



Tiburzi et al. 2020

Model validation - EUHFORIA



PSP in-situ measurements

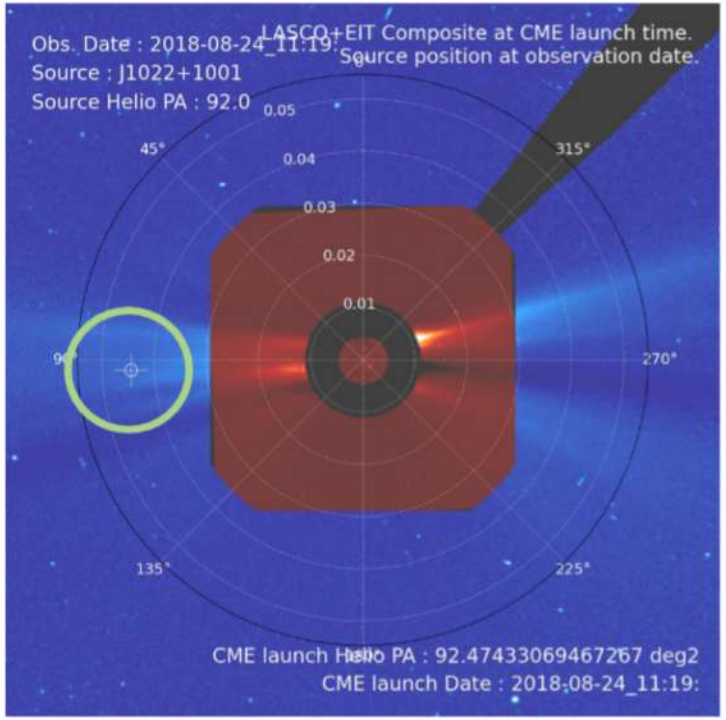
Tiburzi et al. in prep

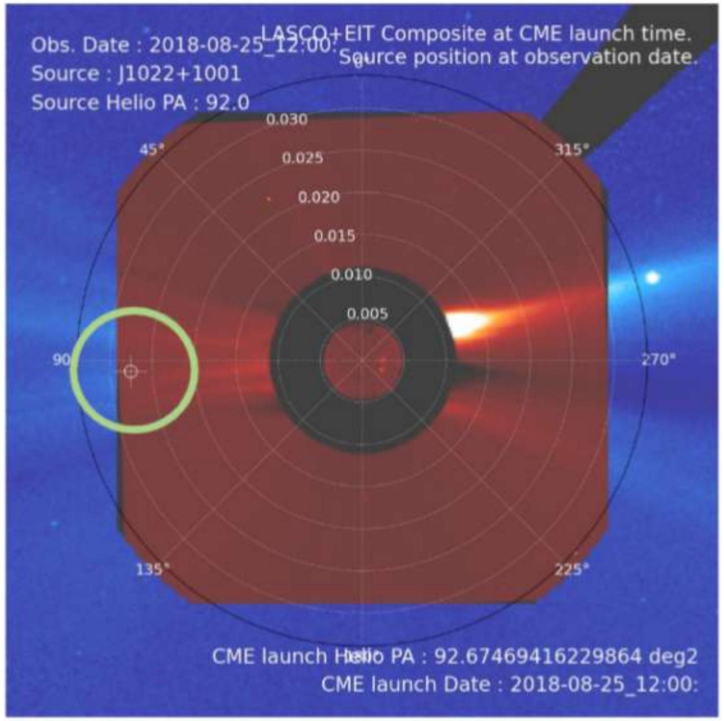
EUHFORIA RUNS from Jebaraj, Magdalenic, Samara

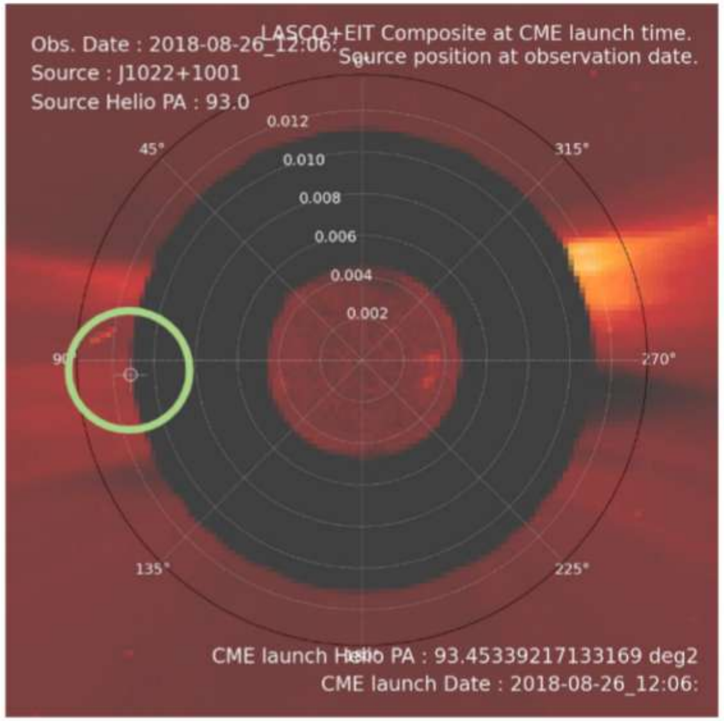
Streamers

Hunting streamers along pulsar's LoS

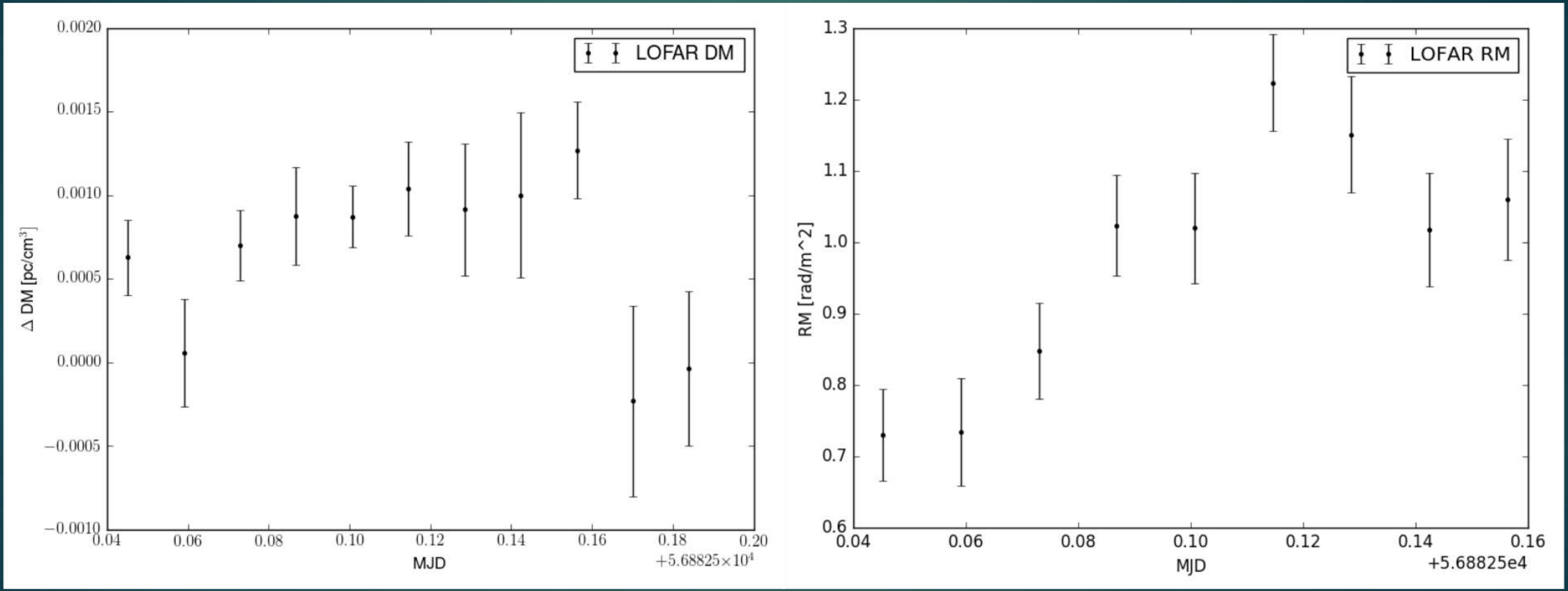
Tiburzi, Shaifullah, Guglielmino, Capuano, Zucca, Pellizzoni







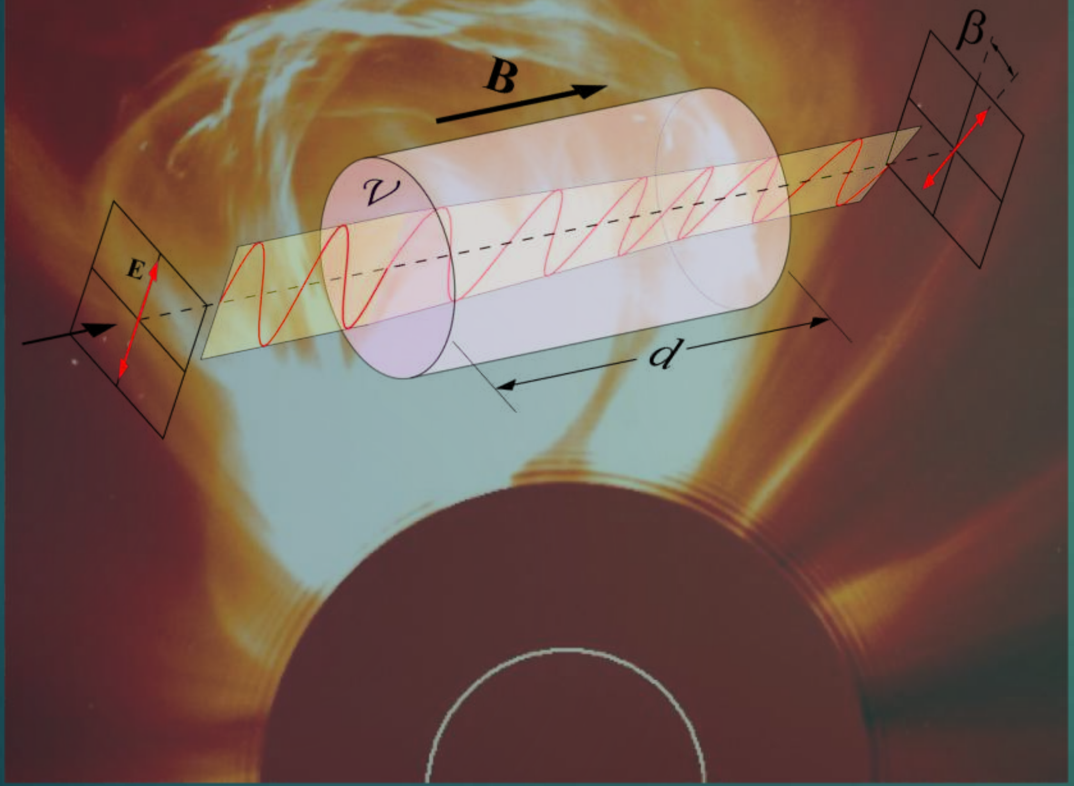
Promising RM result

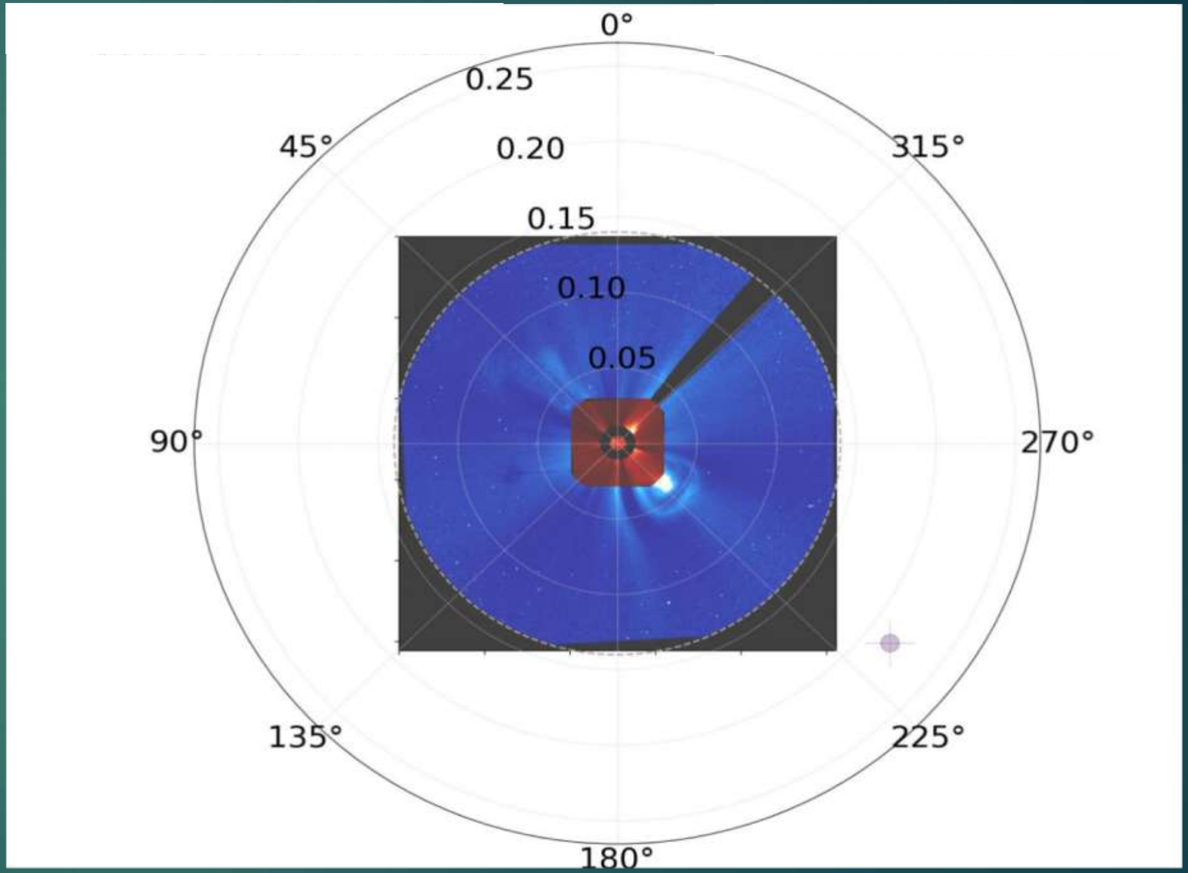


Work in progress from Bisi, Tiburzi, Fallows and KSP et al.

Pulsars to extract Density and B field

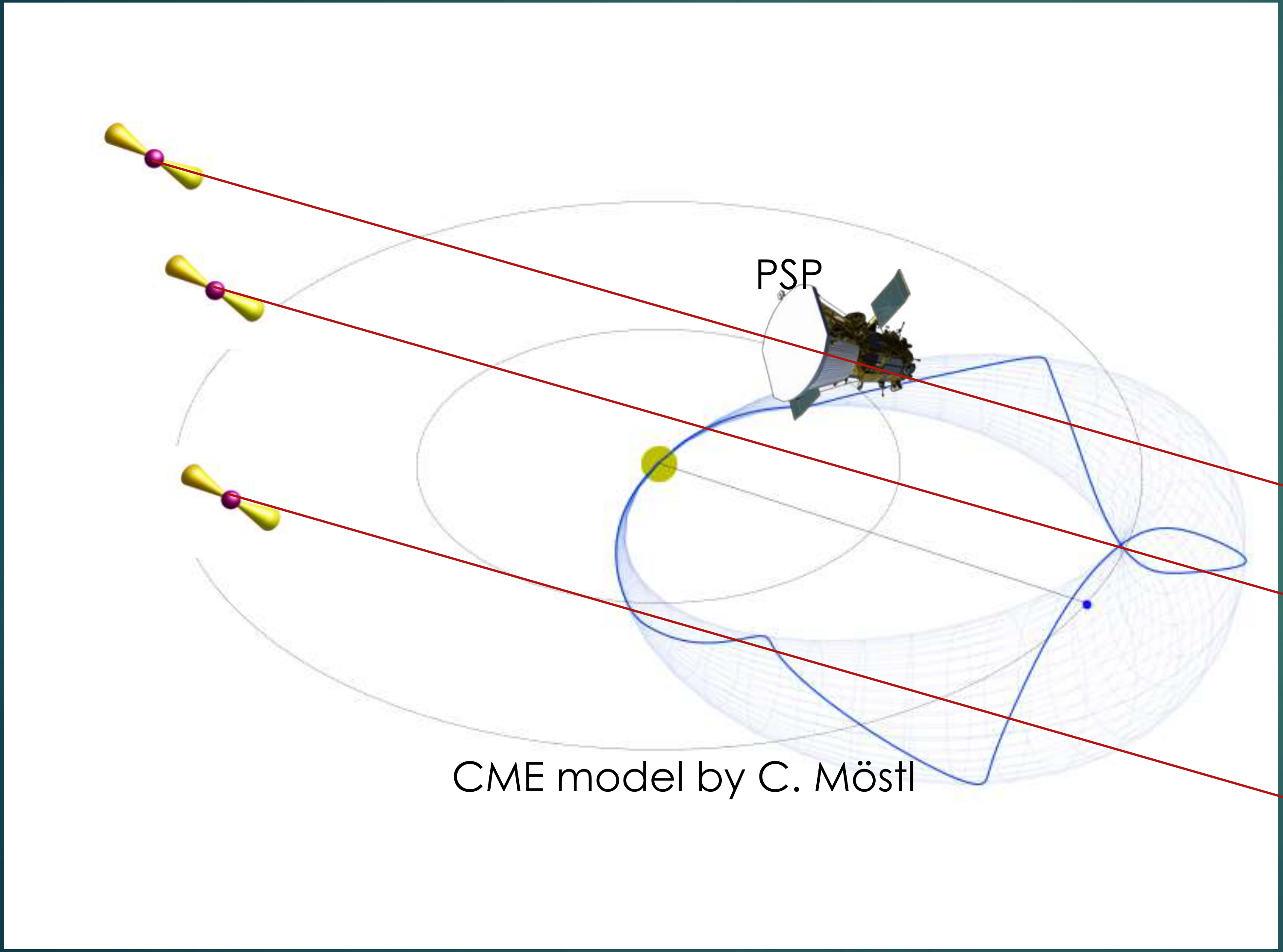
B field - Difficult because of the ionosphere

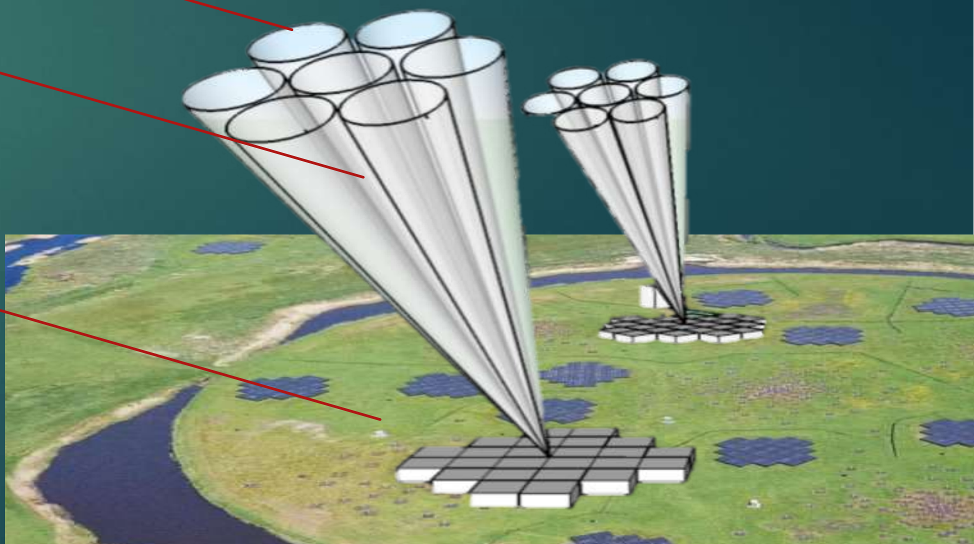




Caterina Tiburzi, Golam Shaifullah, Pietro Zucca and the LOFAR KSP team

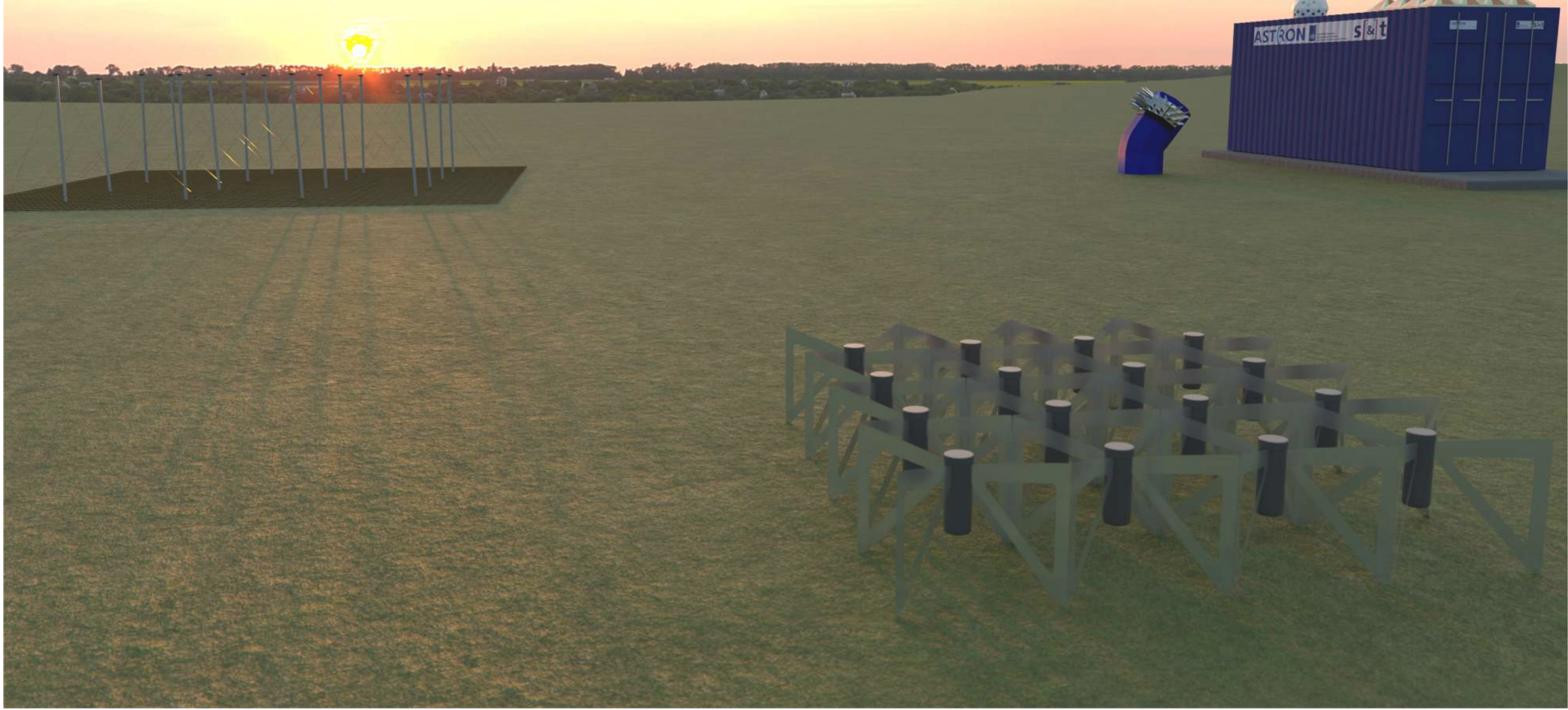
Models + in-situ PSP



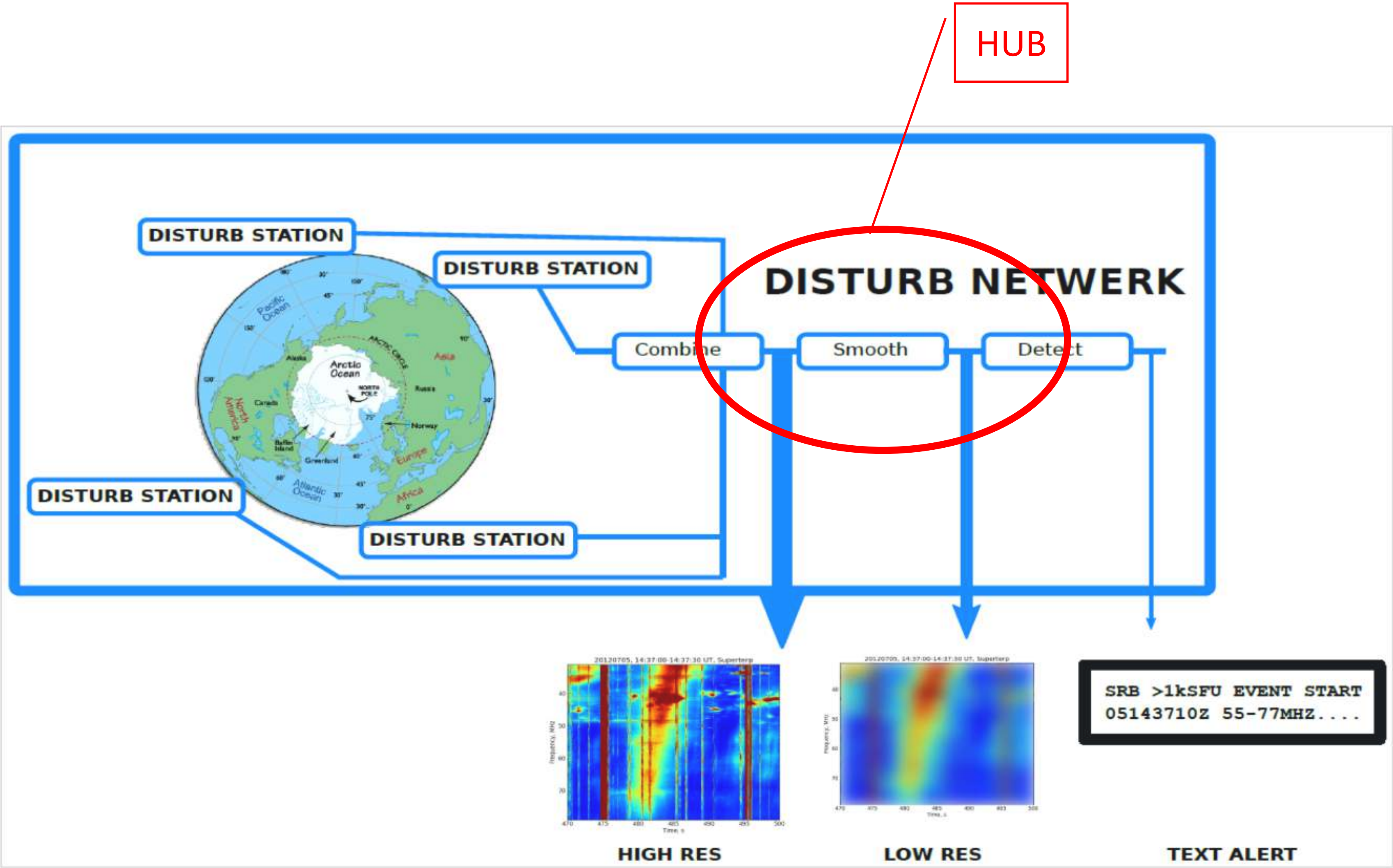


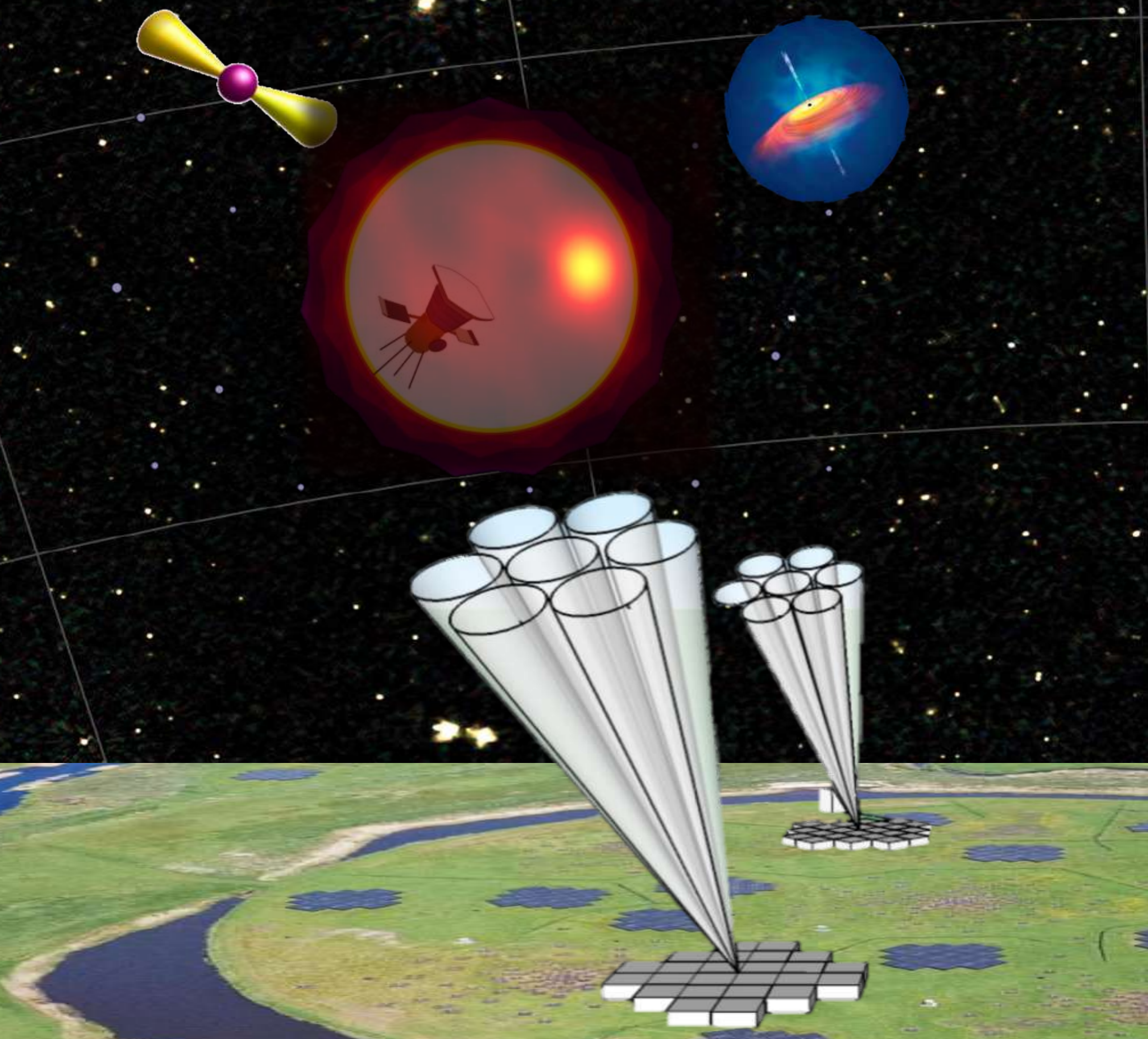
Tiburzi, Shaifullah, Zucca, Dumbovic, Mostl in prep.

DISTURB-1 design



DISTURB System design





Thanks for your attention!

LOFAR
Solar and
Space Weather
KSP

ASTRON