Radio observations of electron acceleration from shock waves during eruptions and flares in the solar corona

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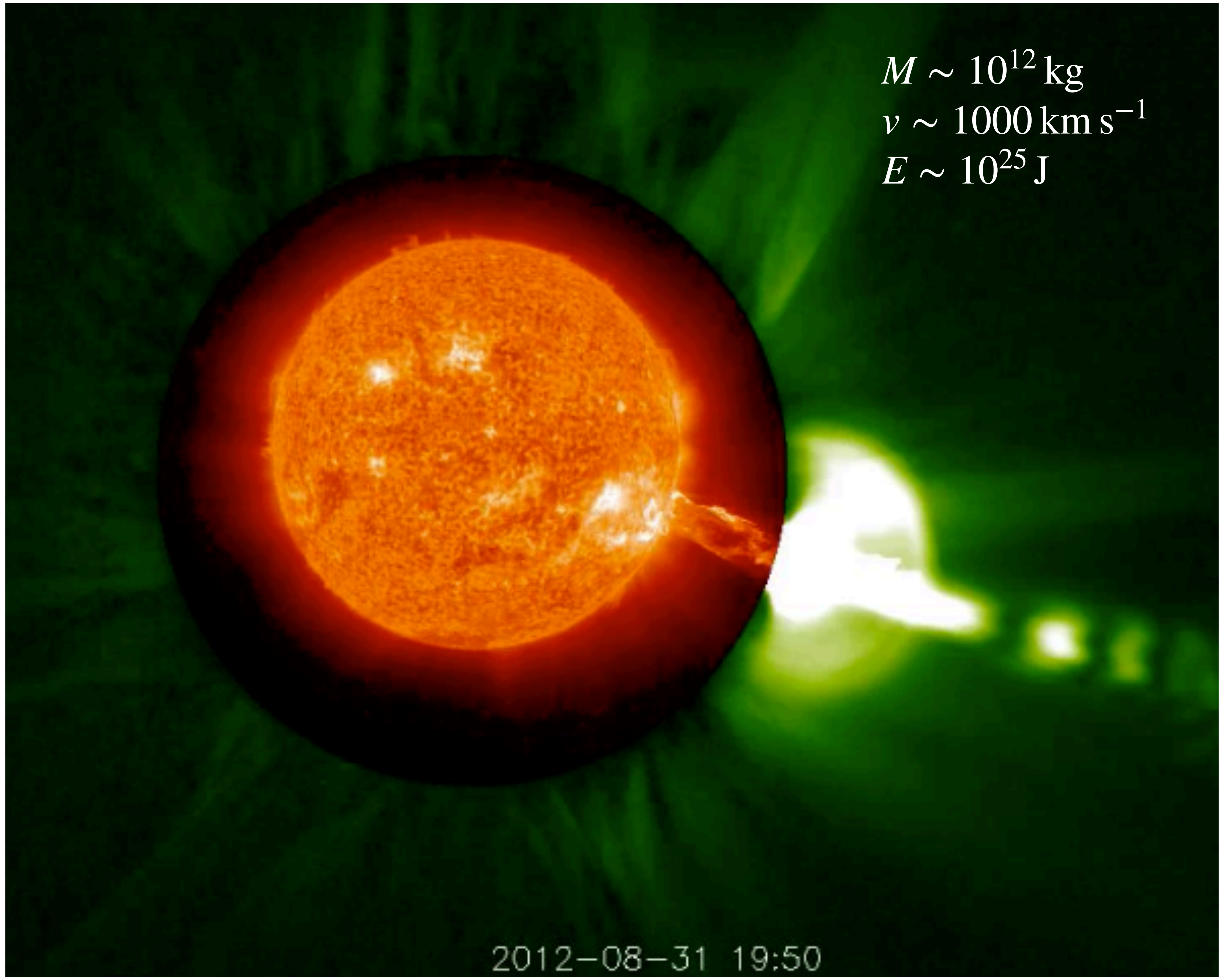
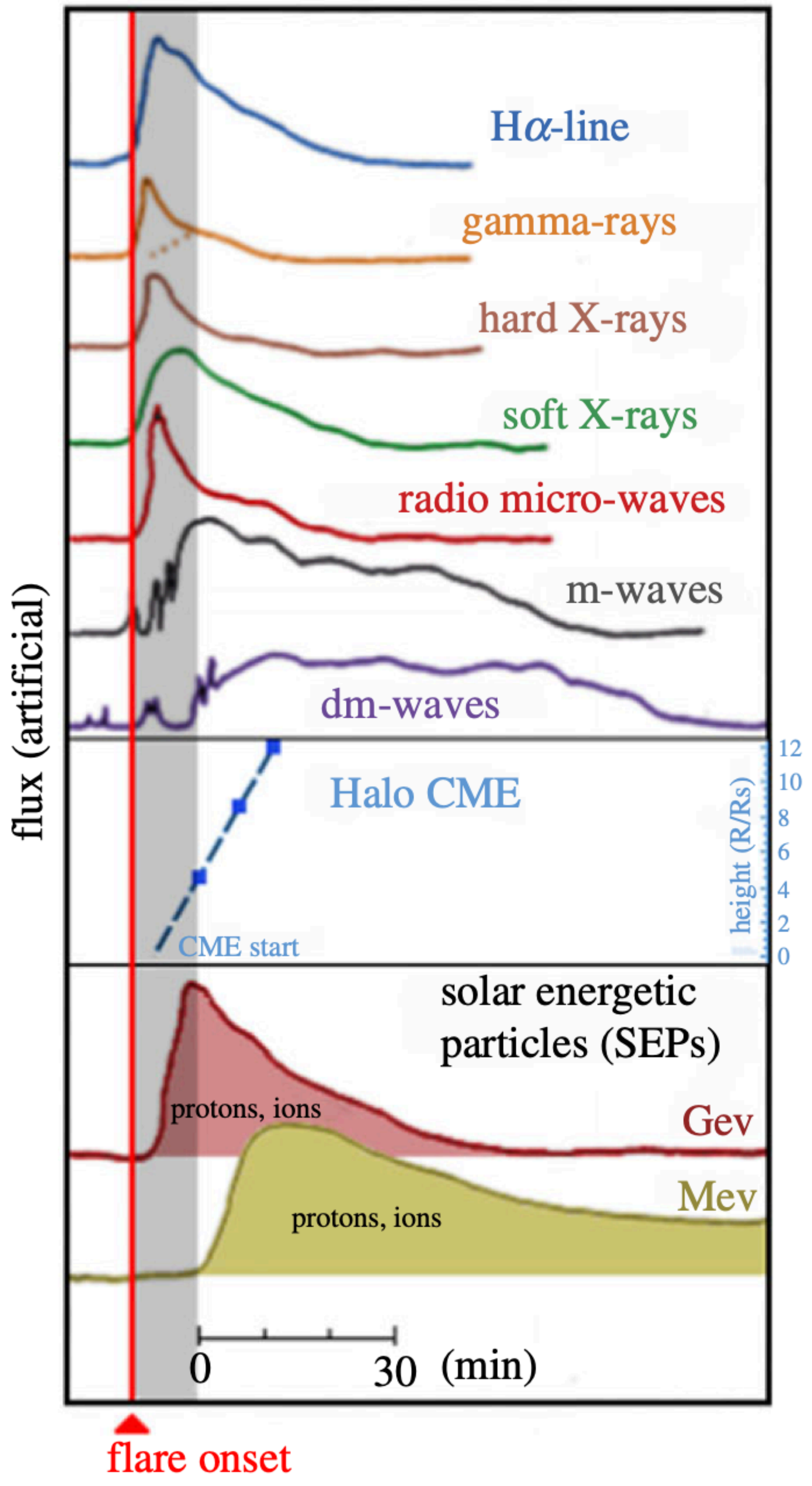
I-LOFAR

Coronal mass ejections, flares and energetic particles

STEREO-B COR1 and EUVI



Anastasiadas et al. (2019)



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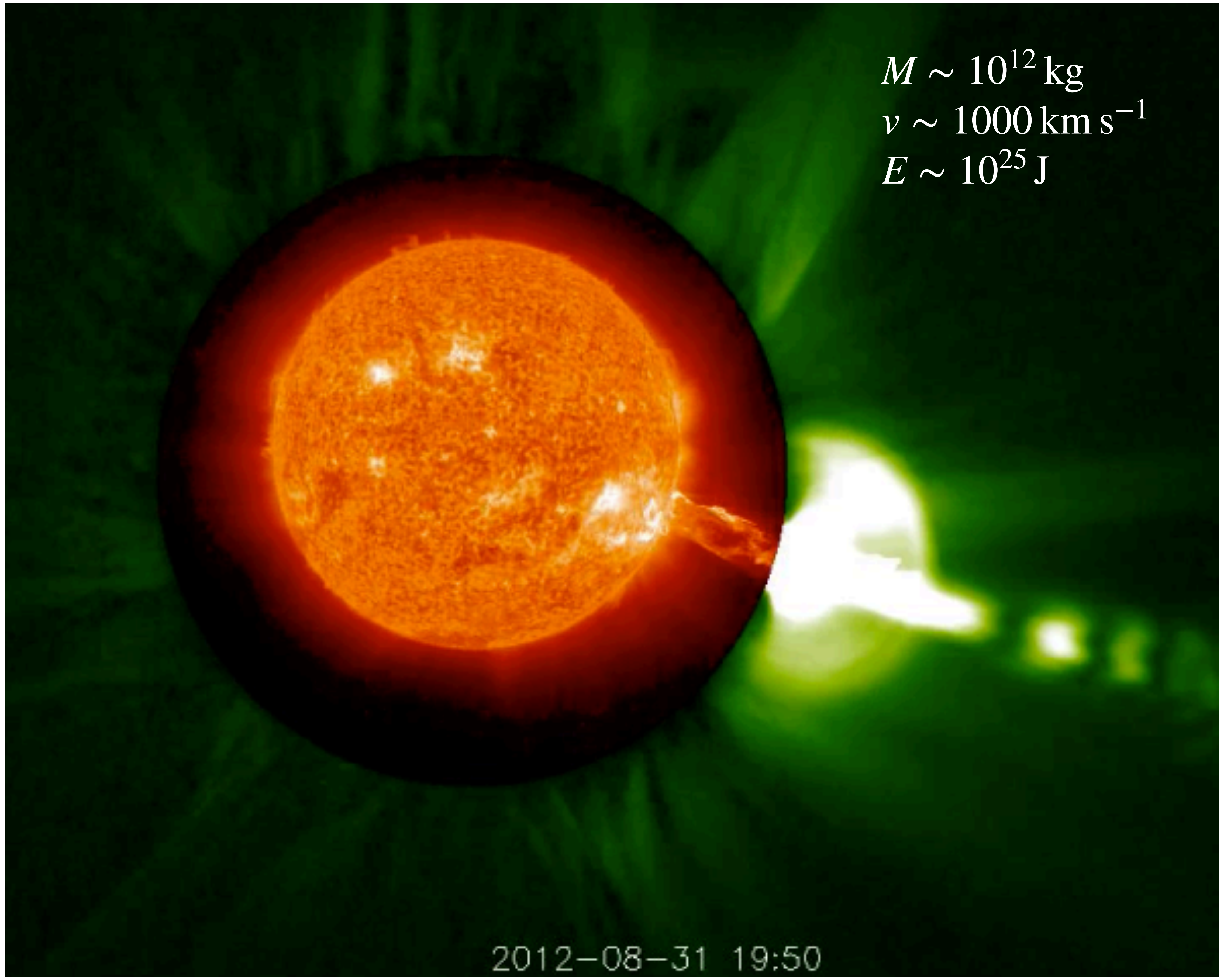

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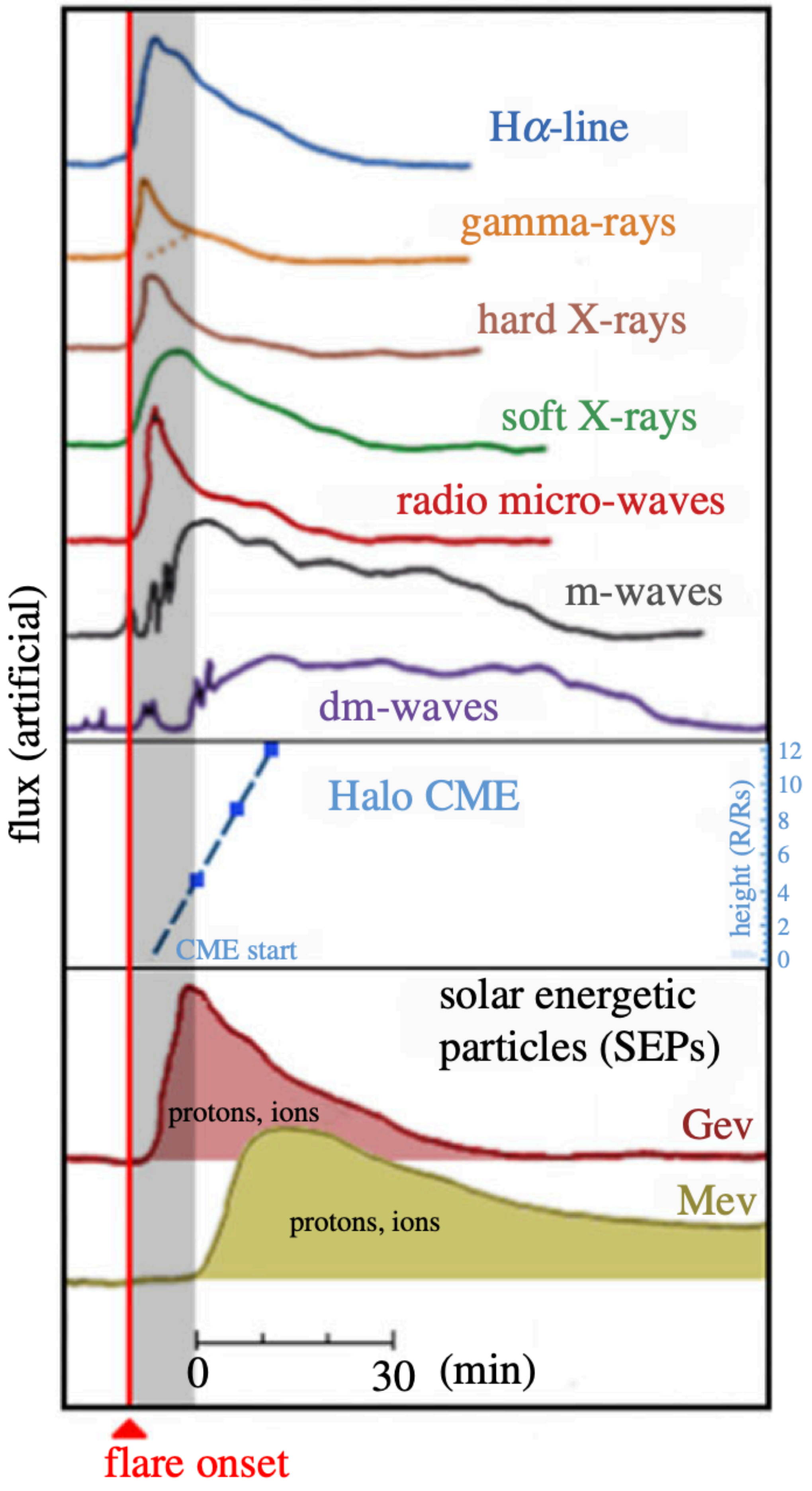
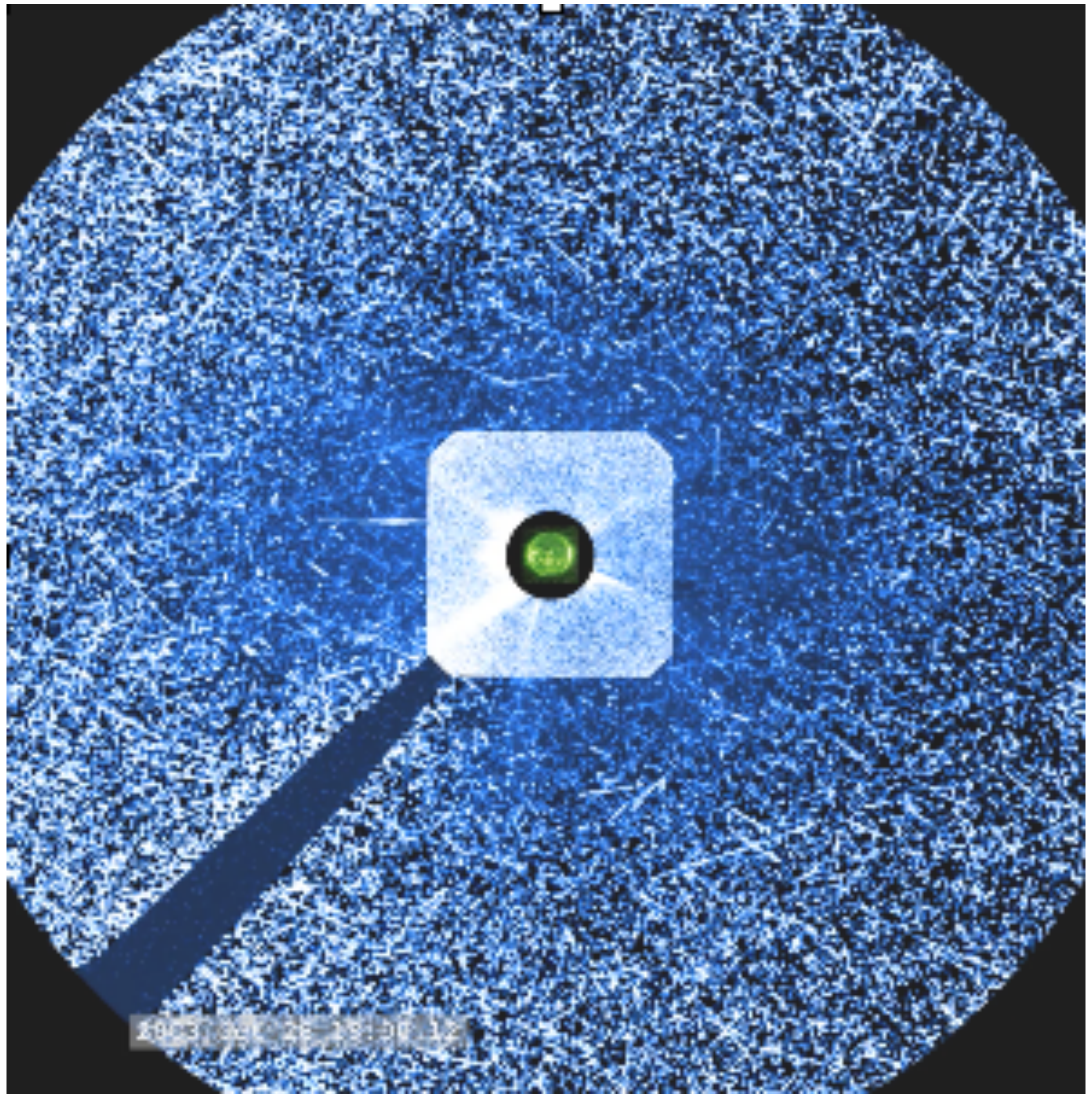
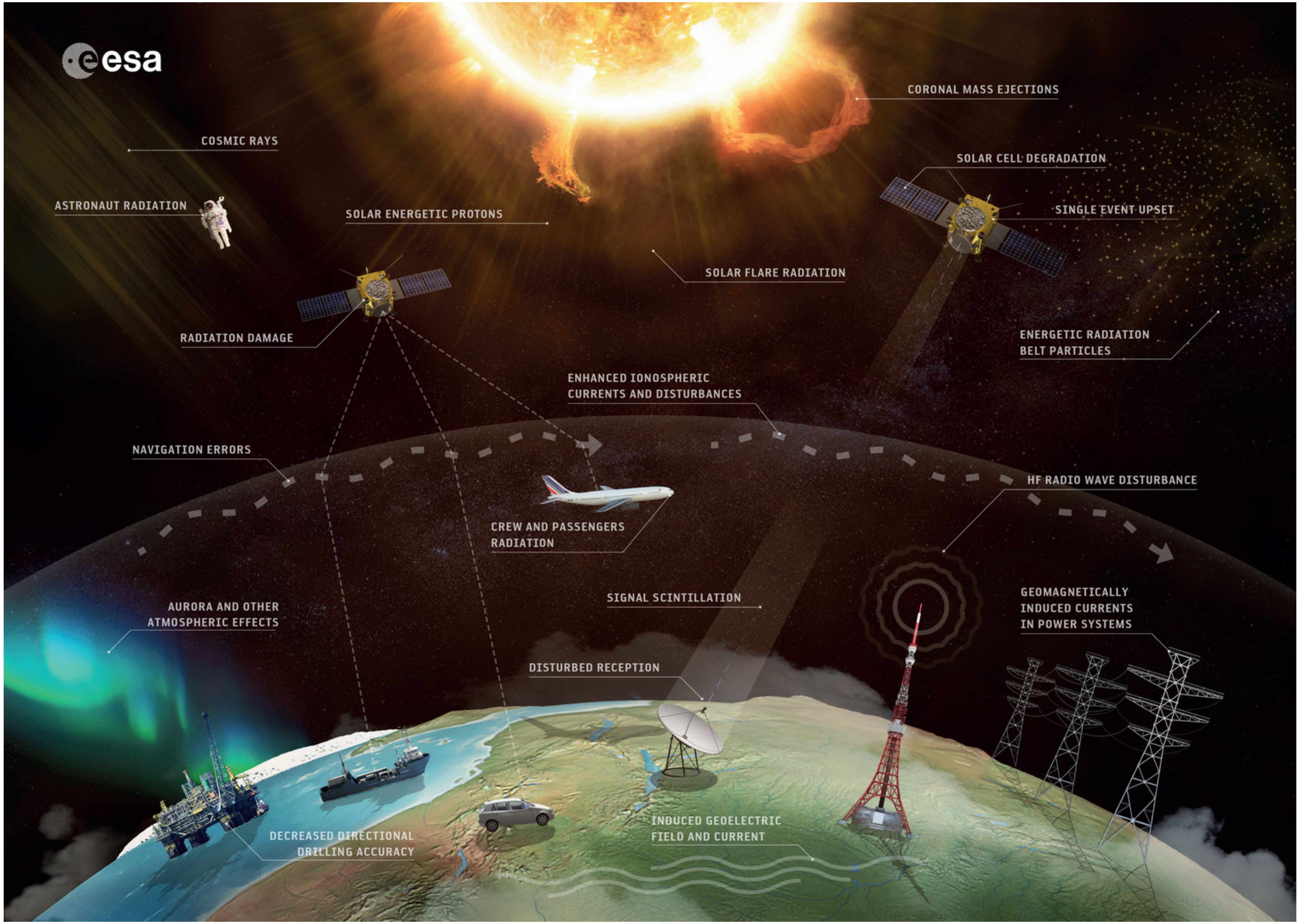


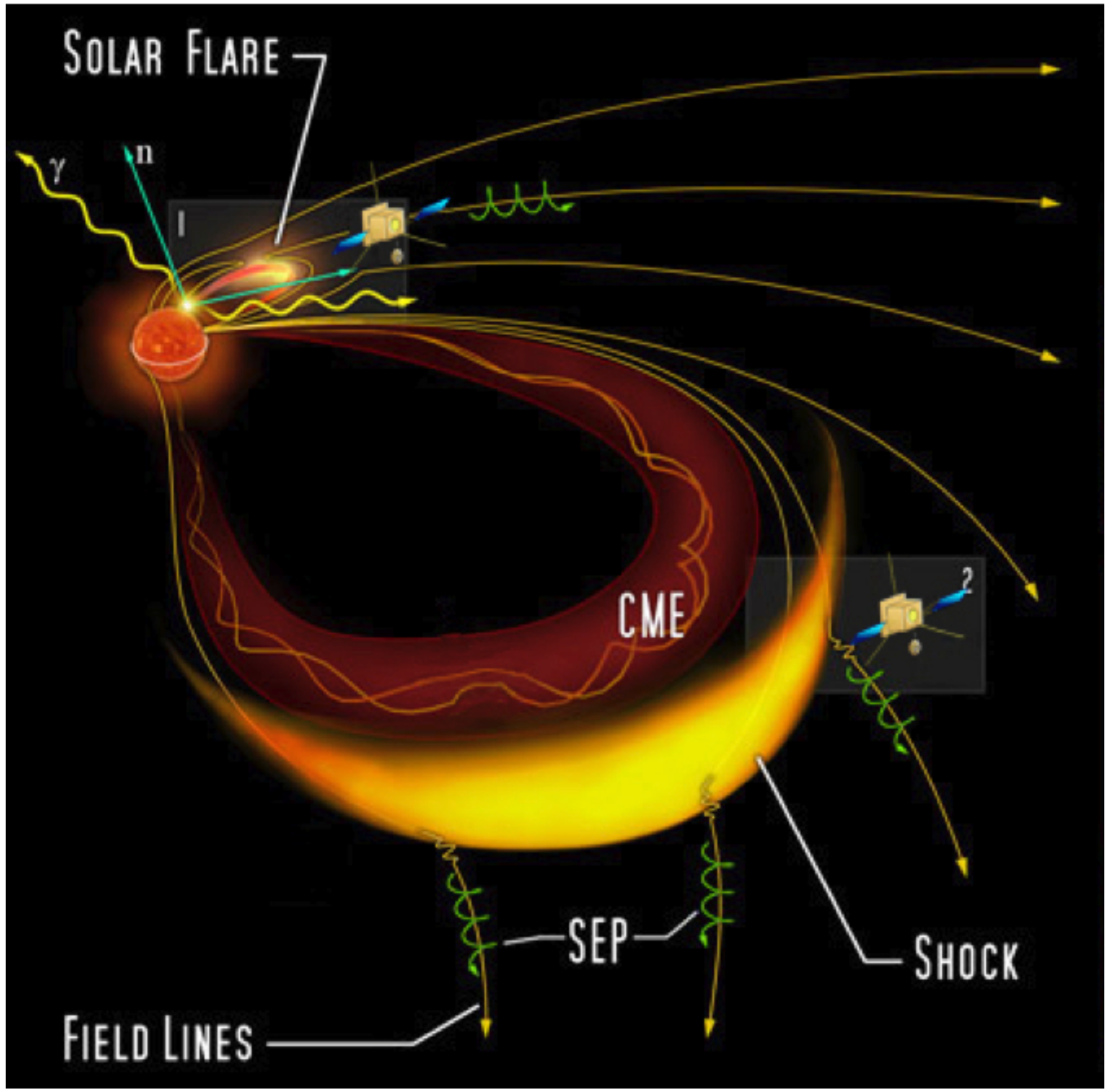
Particle impact on LASCO C2/C3 CCD



Space weather hazards

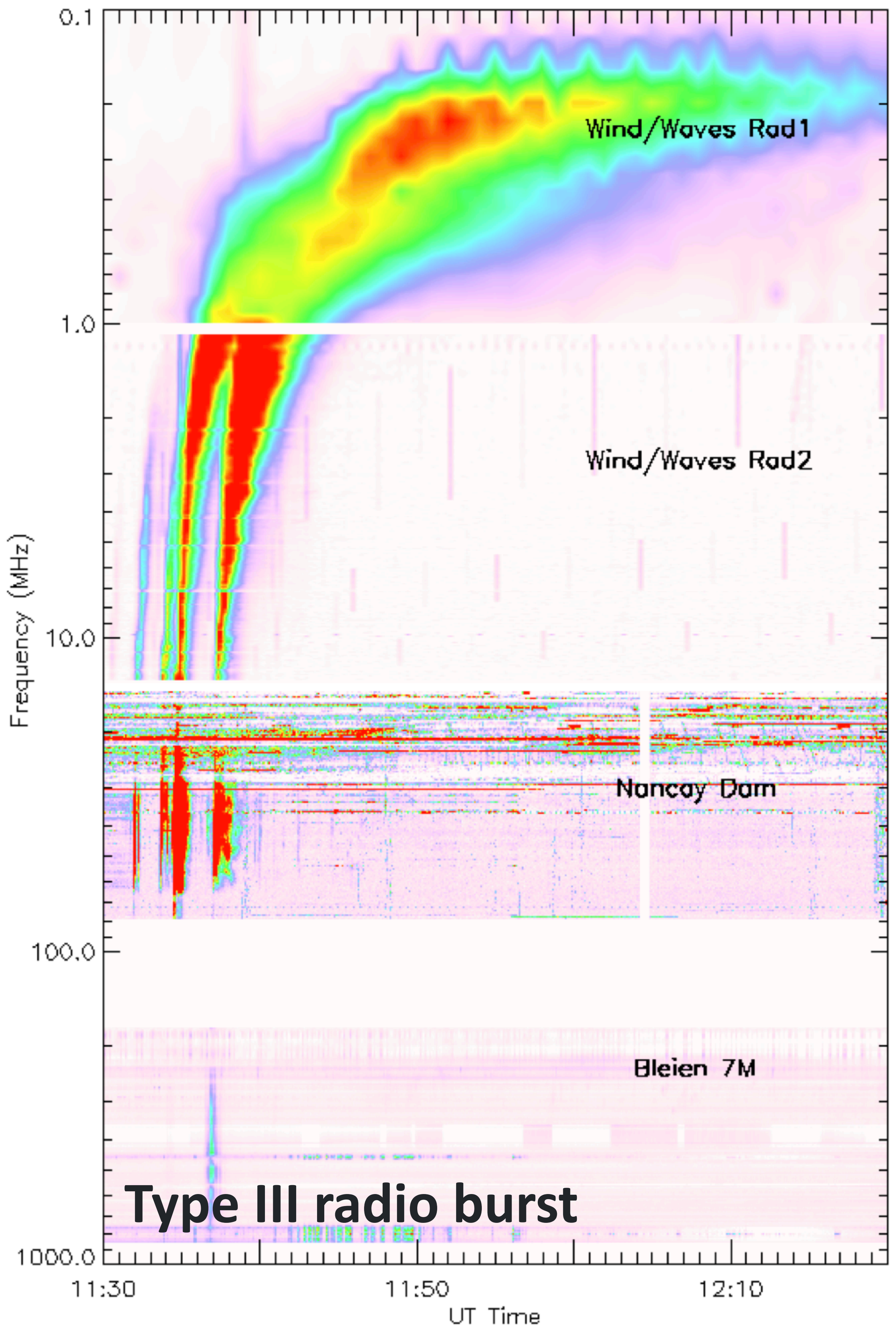


Coronal mass ejections and type II radio bursts

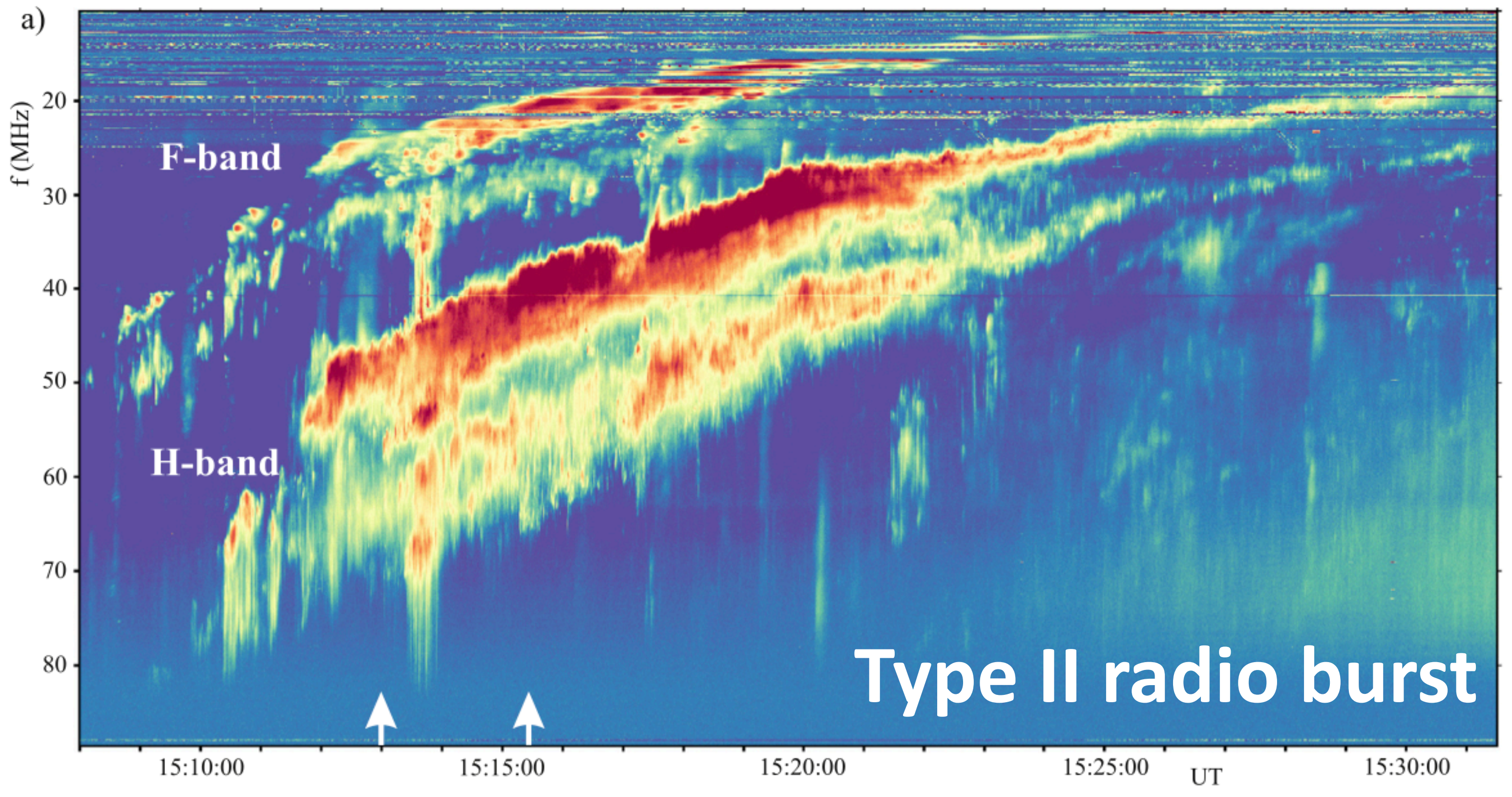


Credit: NASA Solar Sentinals

Reid & Ratcliffe (2014)



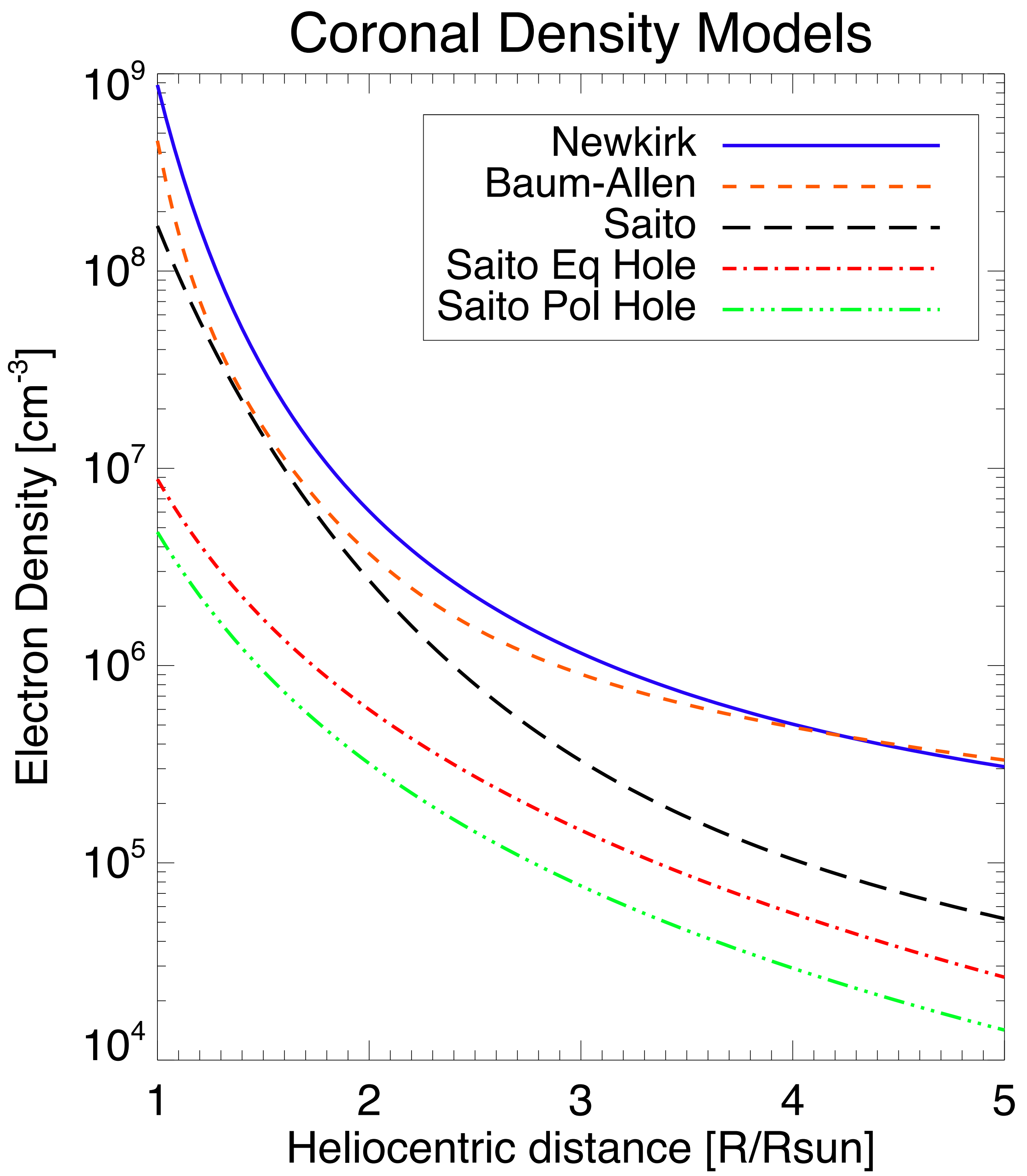
Magdalenic et al. (2020)



- Solar radio bursts are an excellent tracer of shocks and particle escape into the heliosphere.
- High-intensity plasma emission from energetic electrons during eruptive activity

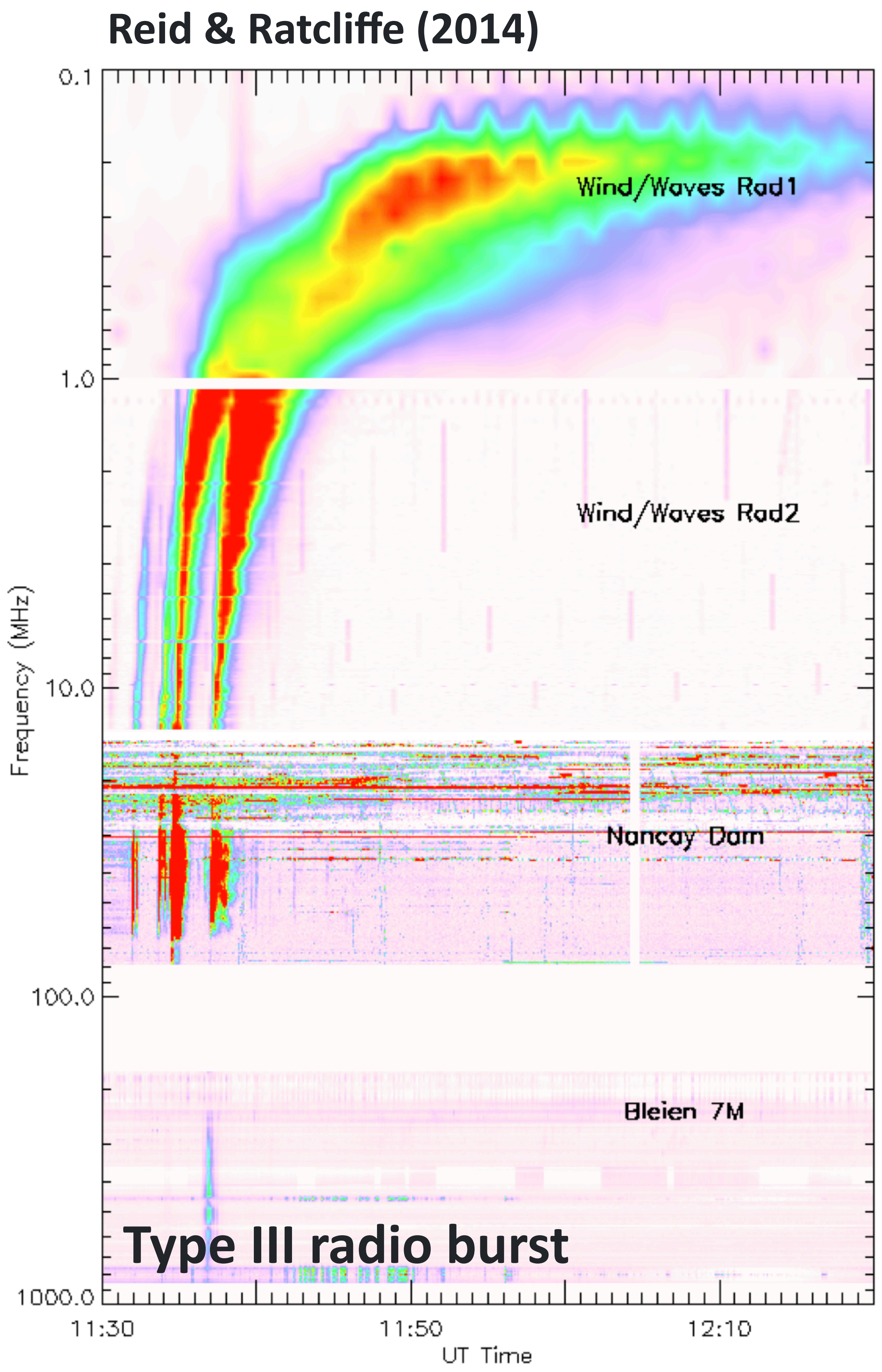
$$f_{plasma} = \left(\frac{e^2 n_e}{\pi m_e} \right)^{1/2}$$

Coronal mass ejections and type II radio bursts



$$n = n_0 \exp\left(\frac{1}{H}\left\{\frac{1}{r} - 1\right\}\right)$$

Reid & Ratcliffe (2014)



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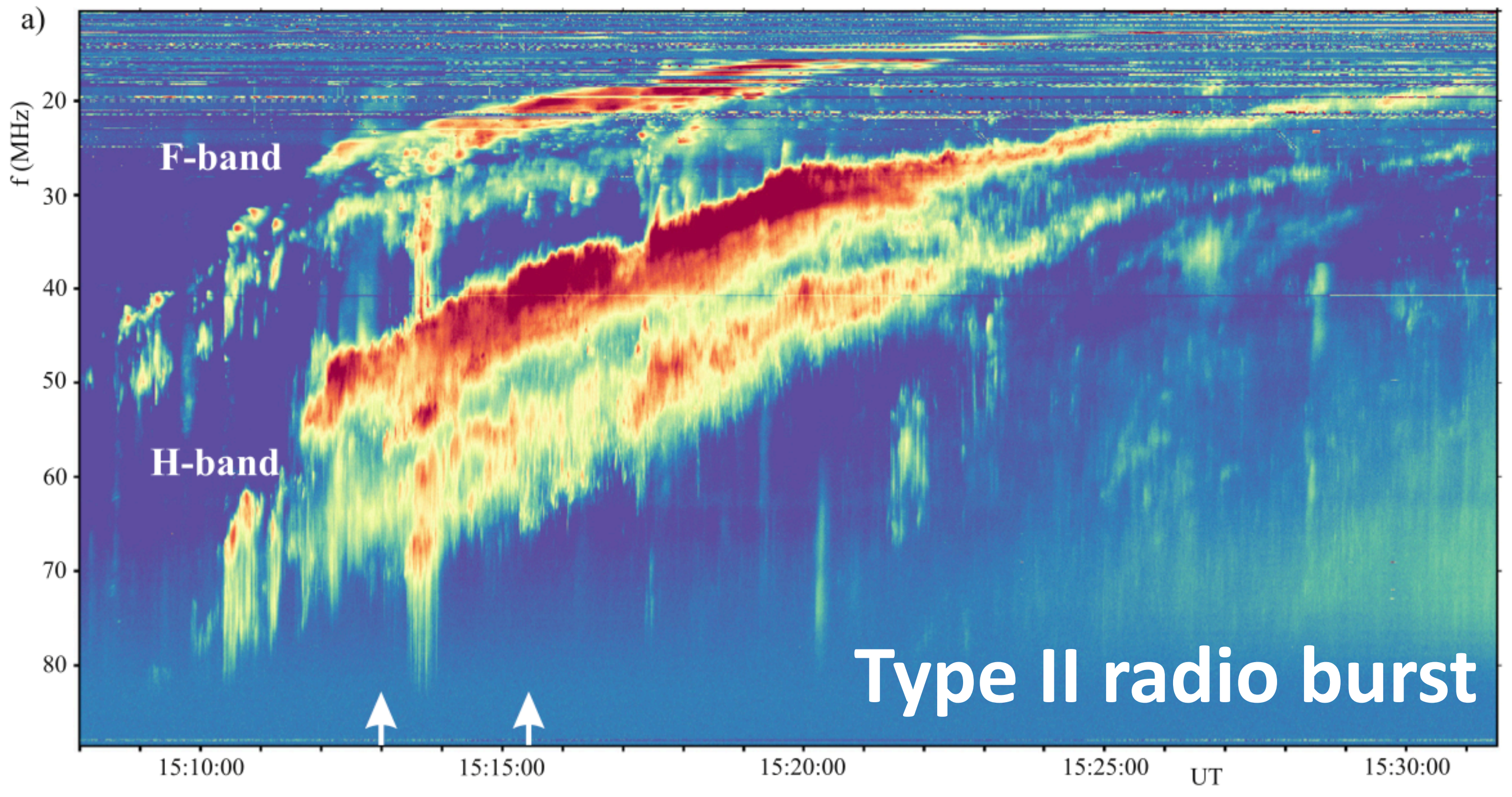

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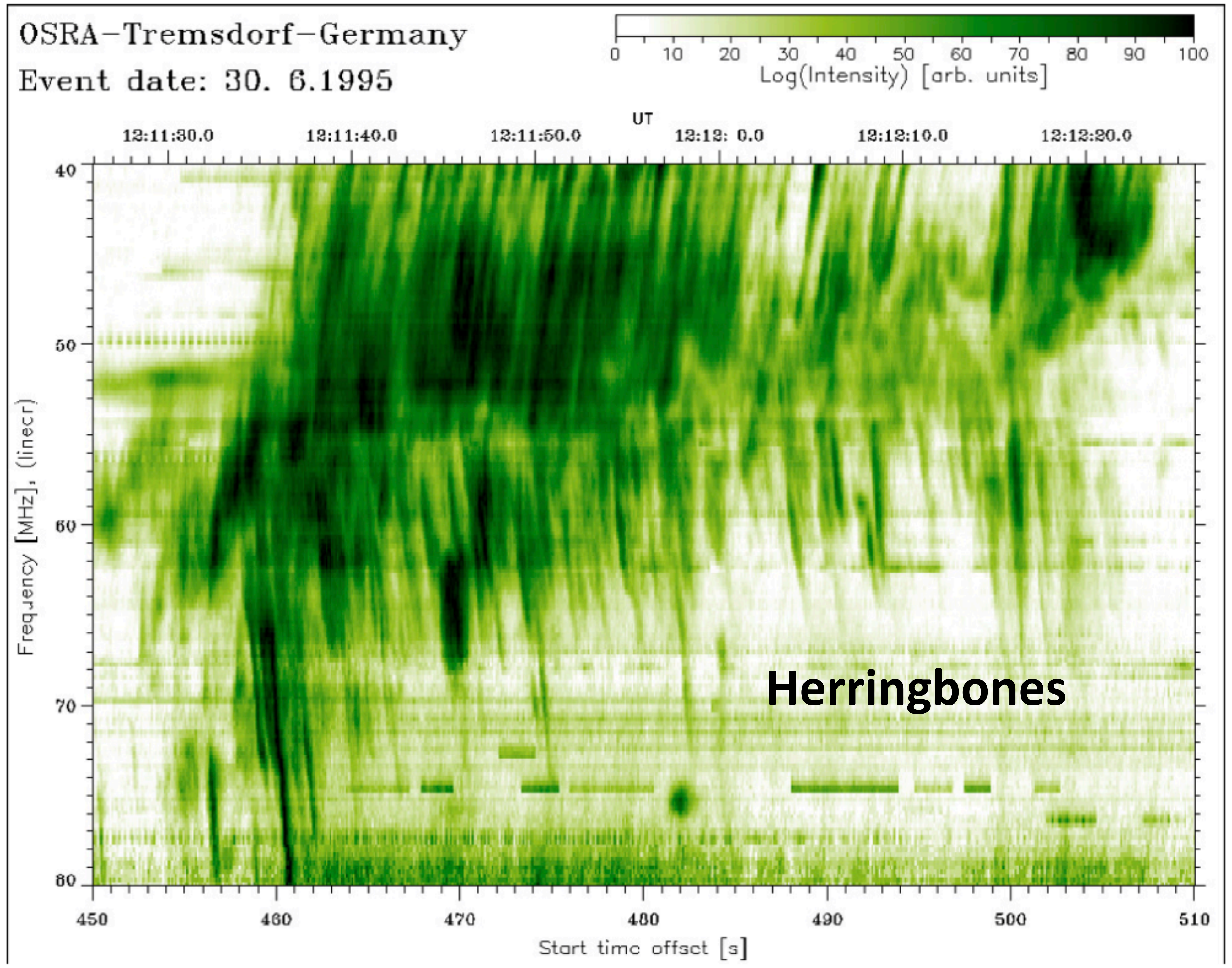
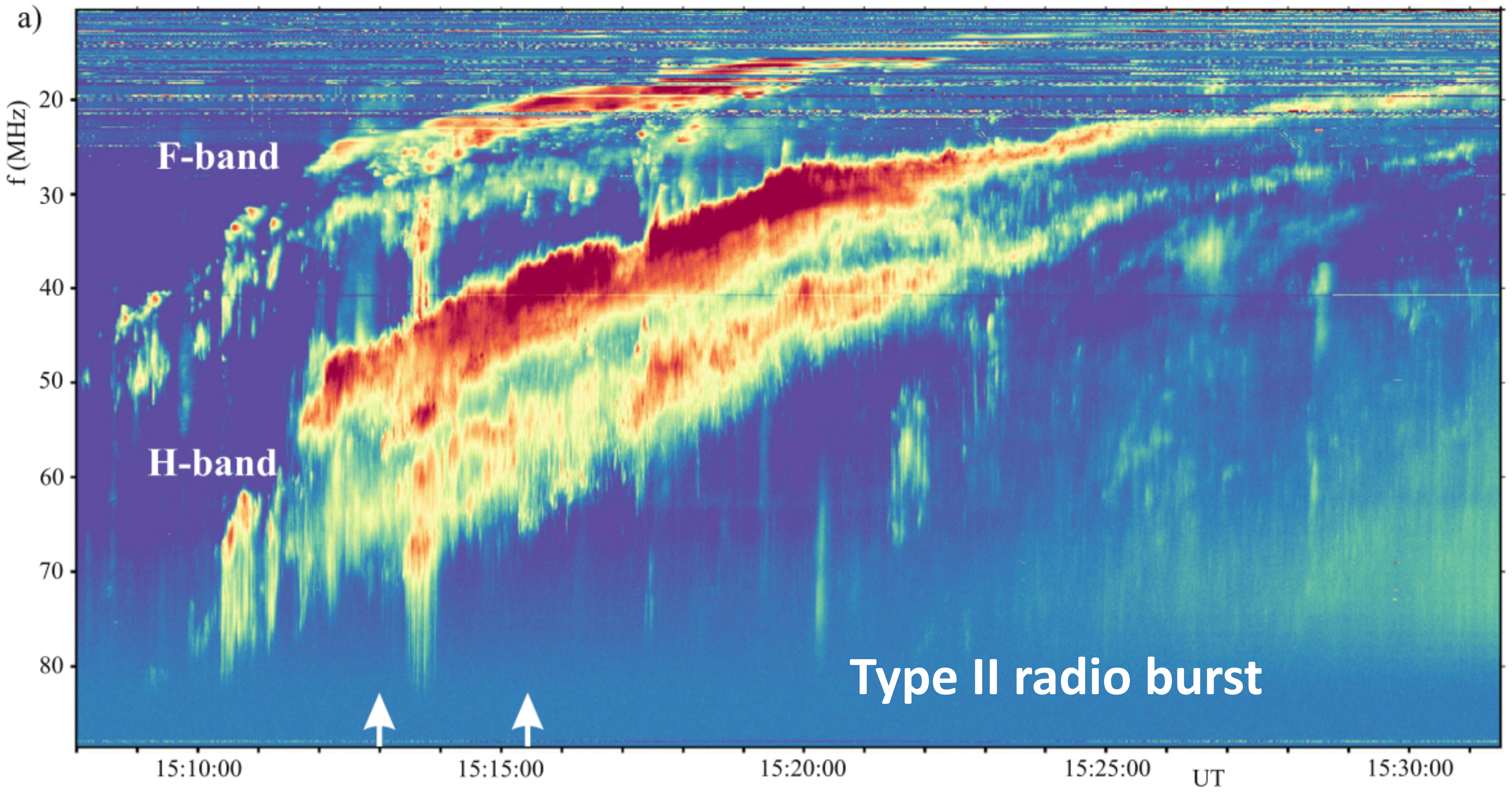
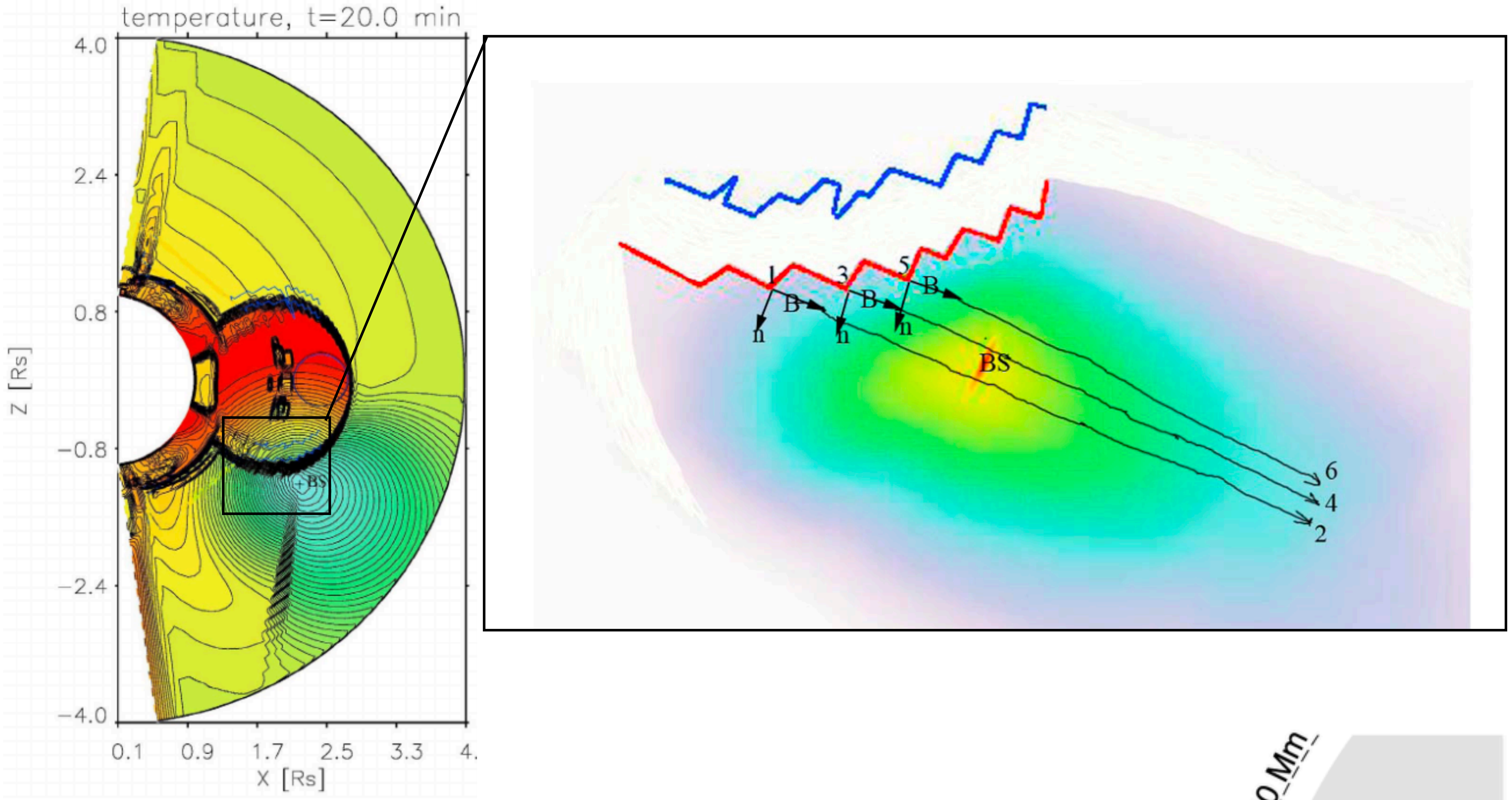
Type II bursts and Herringbones





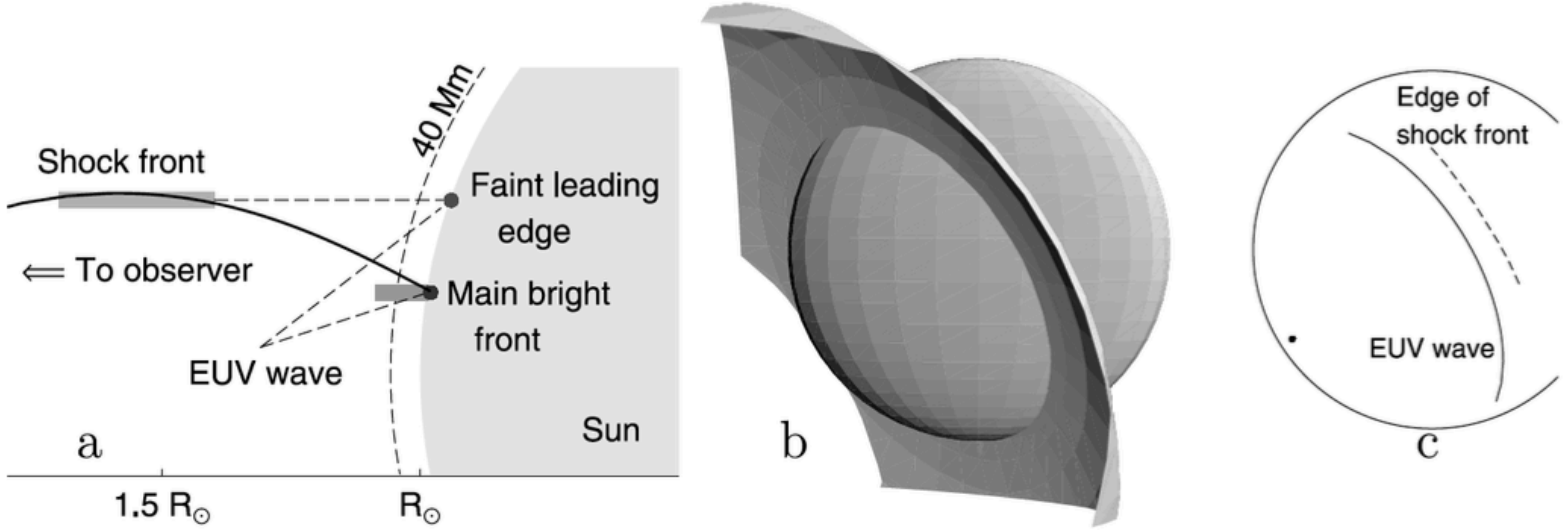
- A fine structure of bursty, forward and reverse drift bursts.
- A direct signature of electron beam acceleration at the shock
- Occur in about 20% of type II bursts

Herringbones: Origins and associations



- Some shock simulations show particle beam escape at a shock on the flank of a CME. (Schmidt & Cairns 2012)
- Some suggestions that turbulence and a rippled shock front cause the herringbones (Zlobec et al. 1993, Guo & Giacalone 2020, Vandas & Karlicky 2011)

- Flank shock potential association with EUV waves (Grechnev et al. 2011)



Open questions

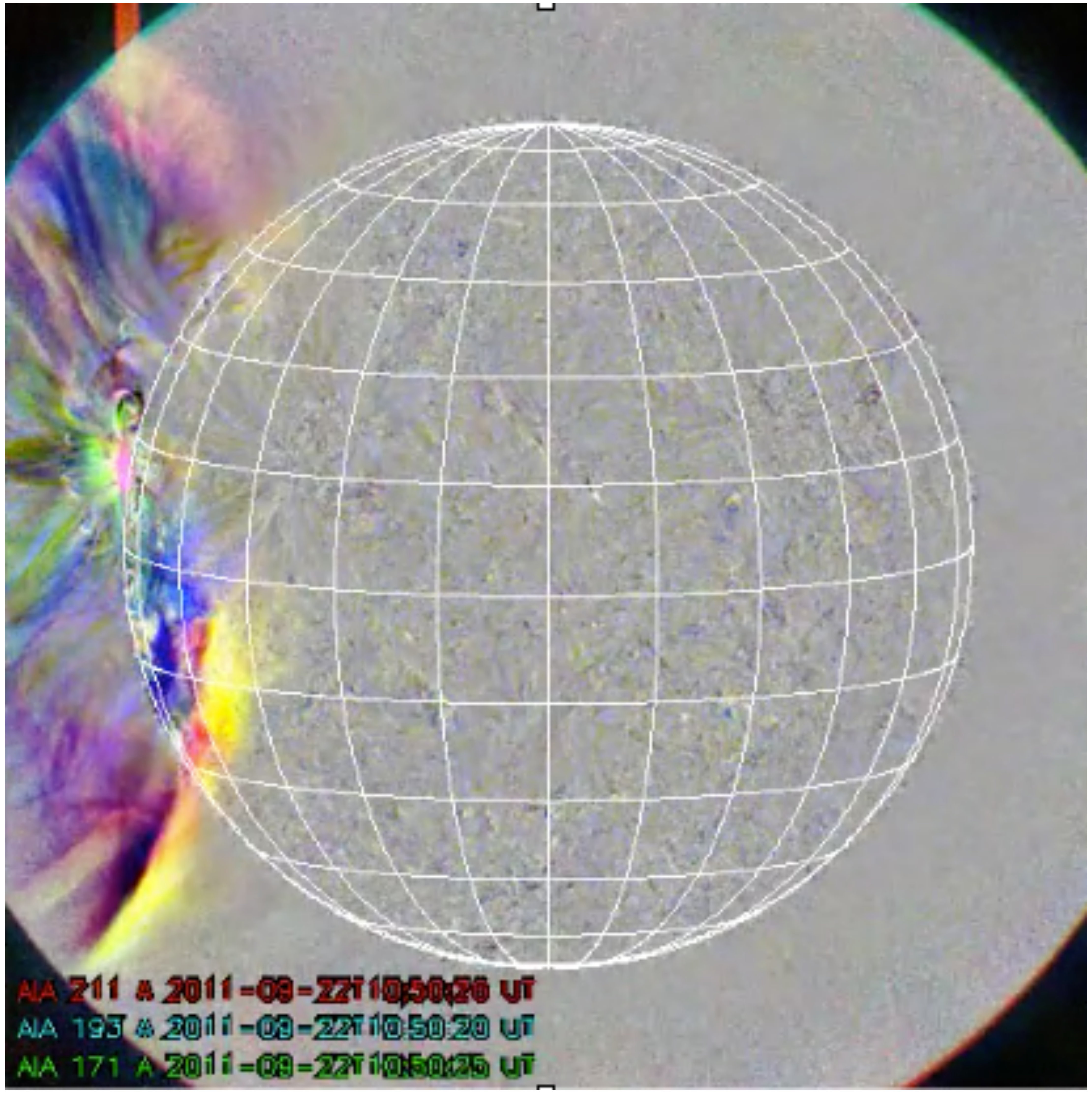
1. Where are shock electrons accelerated?

2. What is their relationship with the flare/CME/EUV wave?

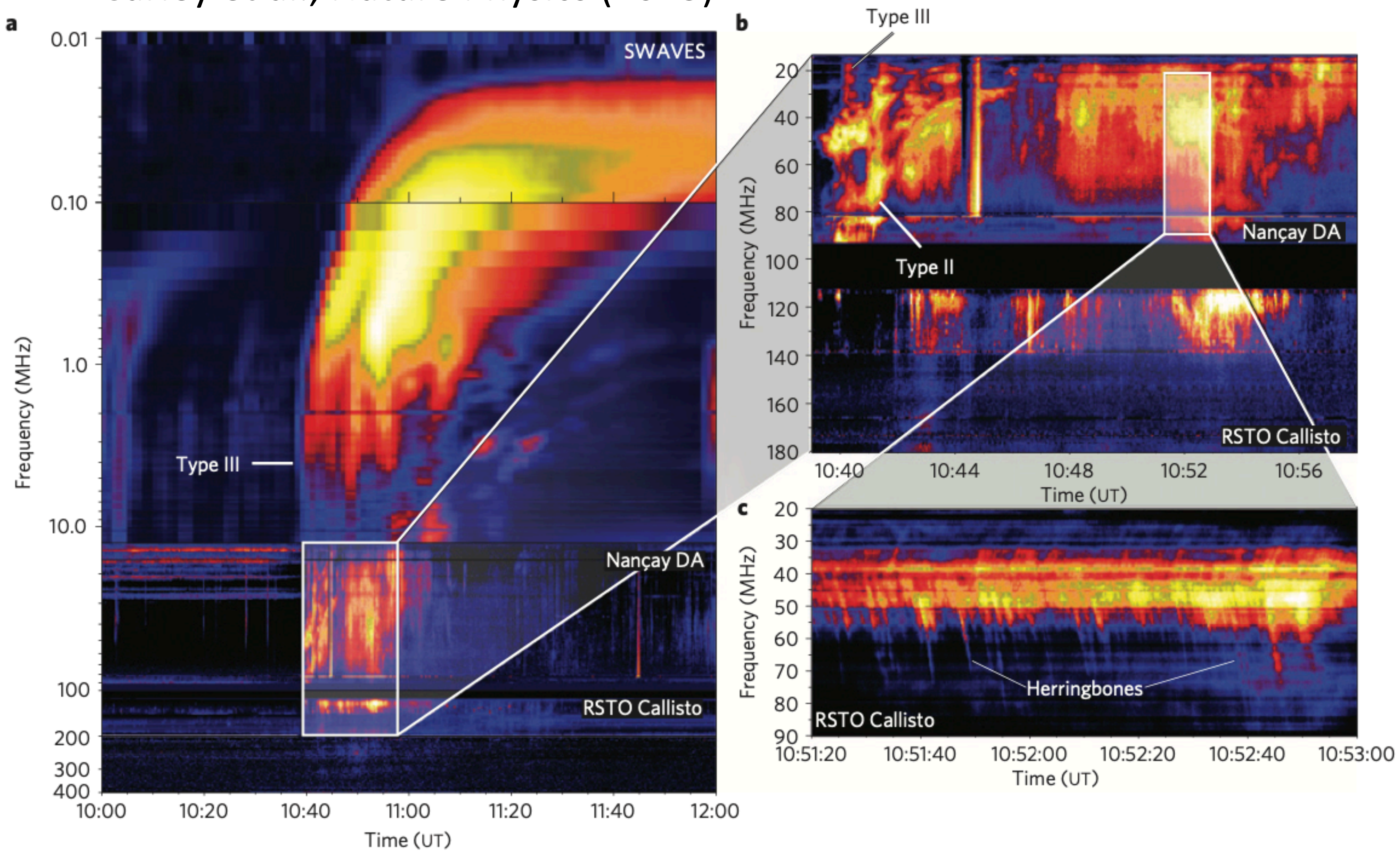
3. Can we tell anything about the shock-acceleration mechanism, and does turbulence play a role?

Combining radio and EUV imaging

EUV wave on 2011-09-22



Carley et al., Nature Physics (2013)



Radio spectra:

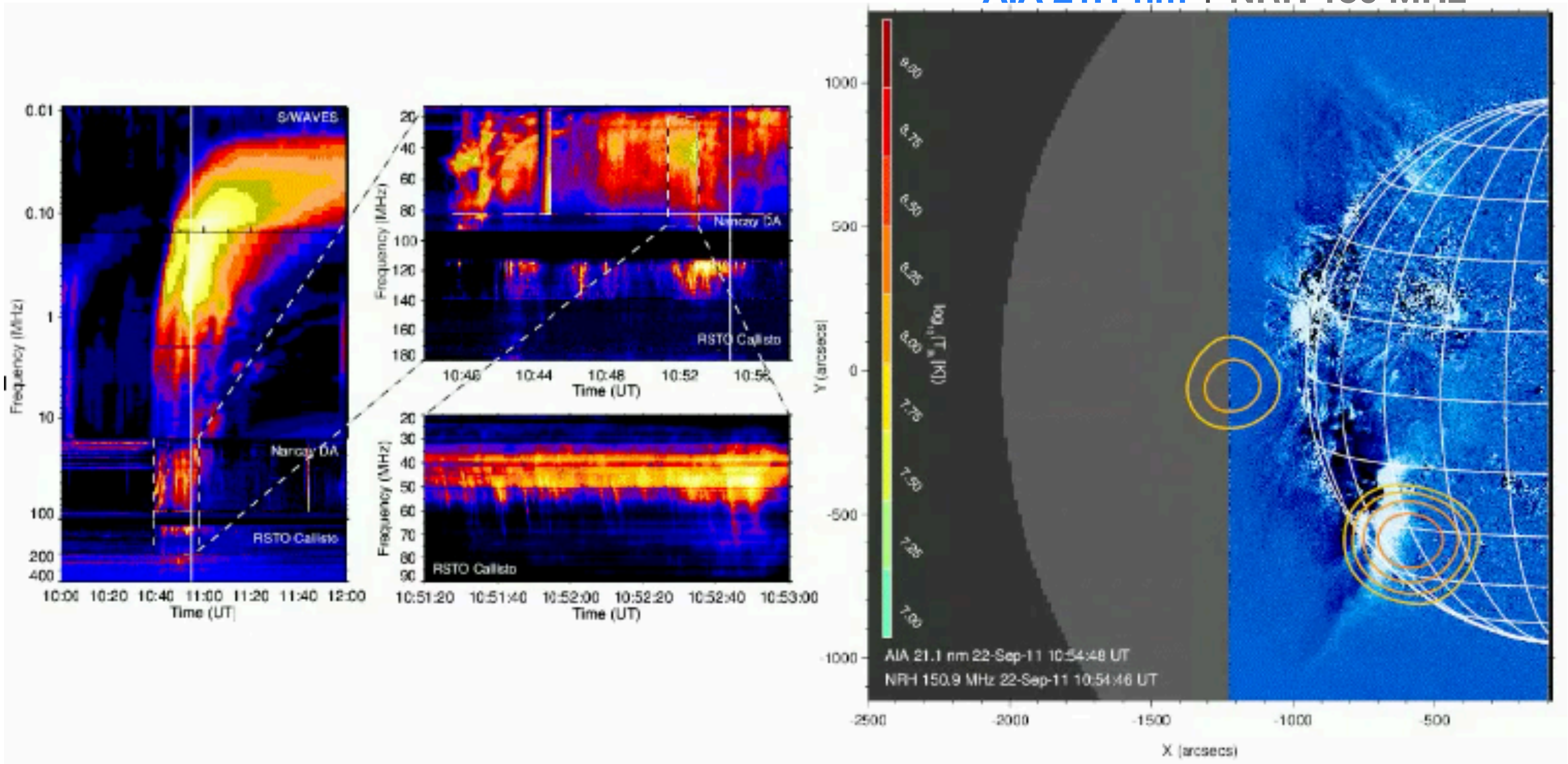
- Quasiperiodic shock electron acceleration
- Particle escape into heliosphere

EUV imaging:

- 'EUV wave': a large-scale MHD disturbance

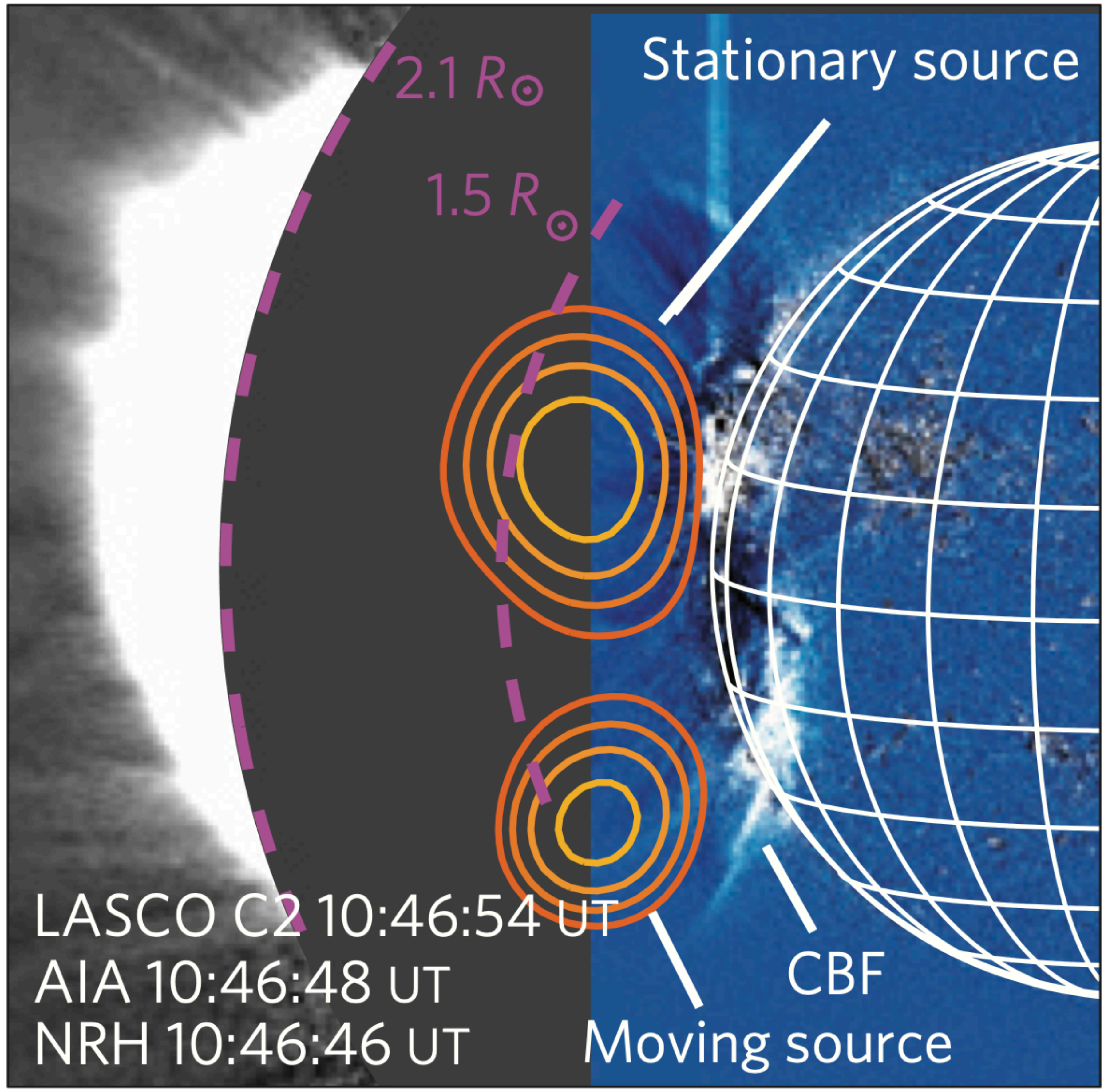
Nançay Radioheliograph (NRH): EUV wave - radio source

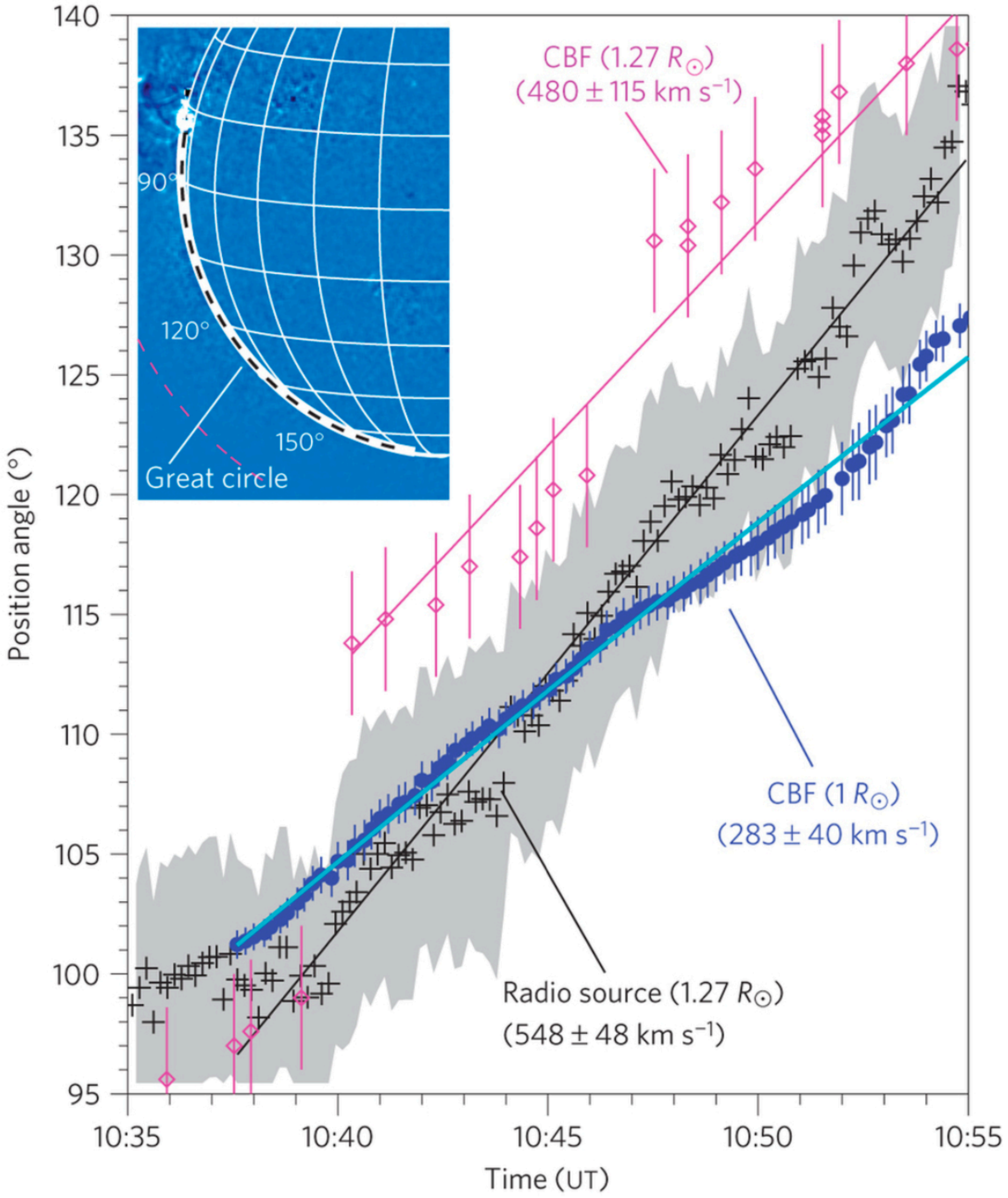
AIA 21.1 nm + NRH 150 MHz



EUV wave - radio source: Kinematics

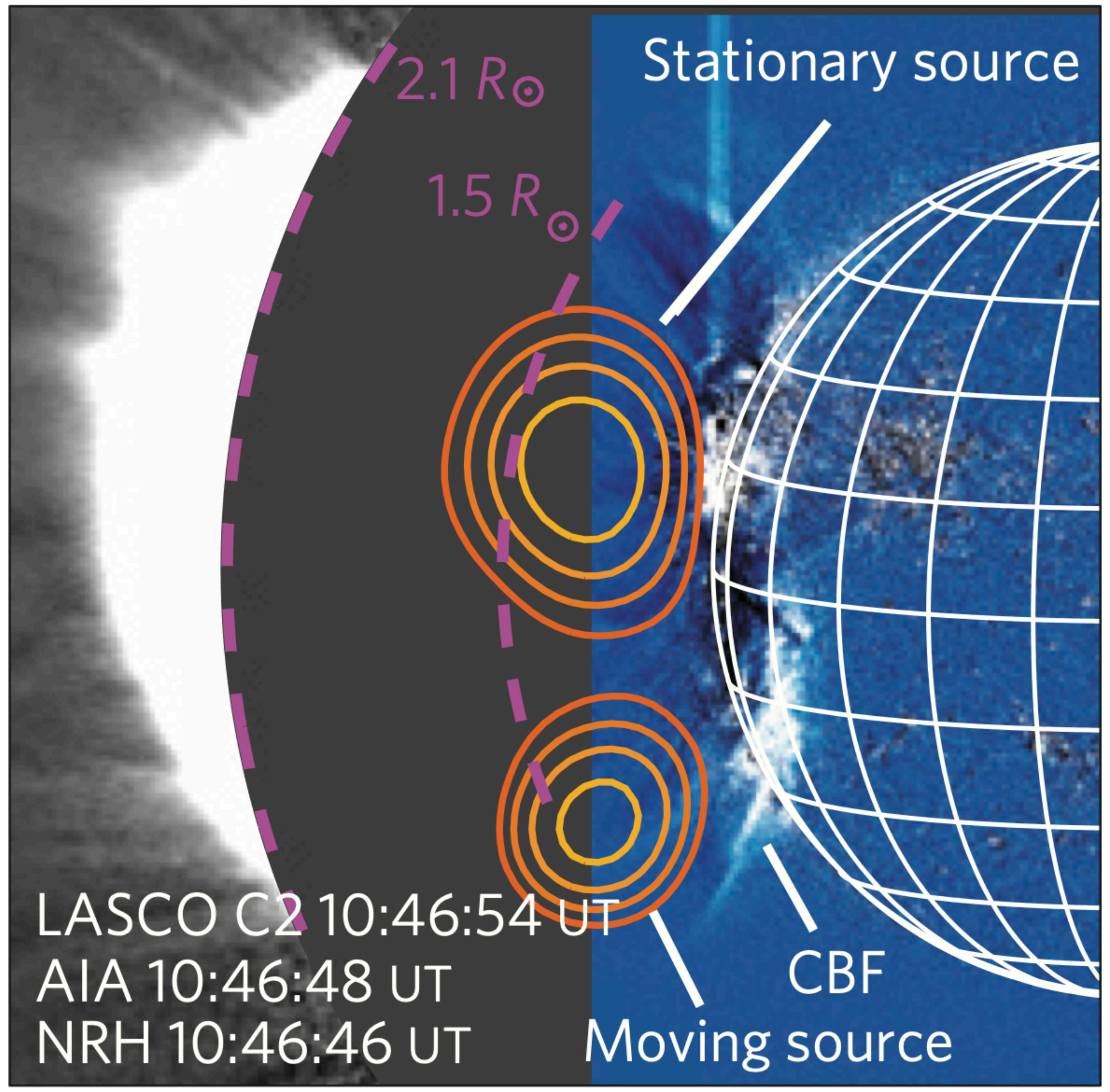
Carley et al. (2013)



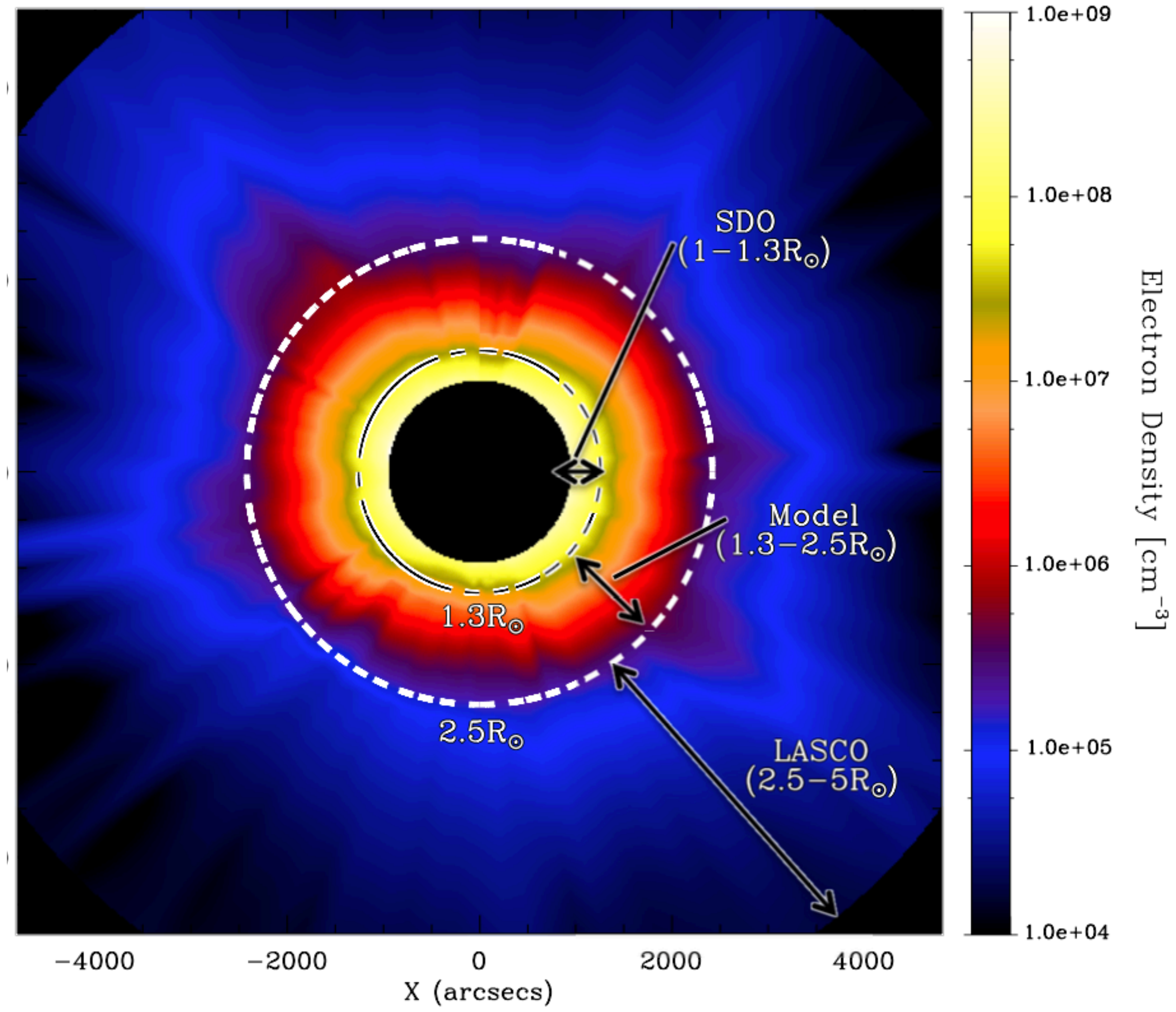


- EUV wave and radio source kinematically associated.
- Lateral propagation at 280 - 400 km/s
- Was there a shock at this location?

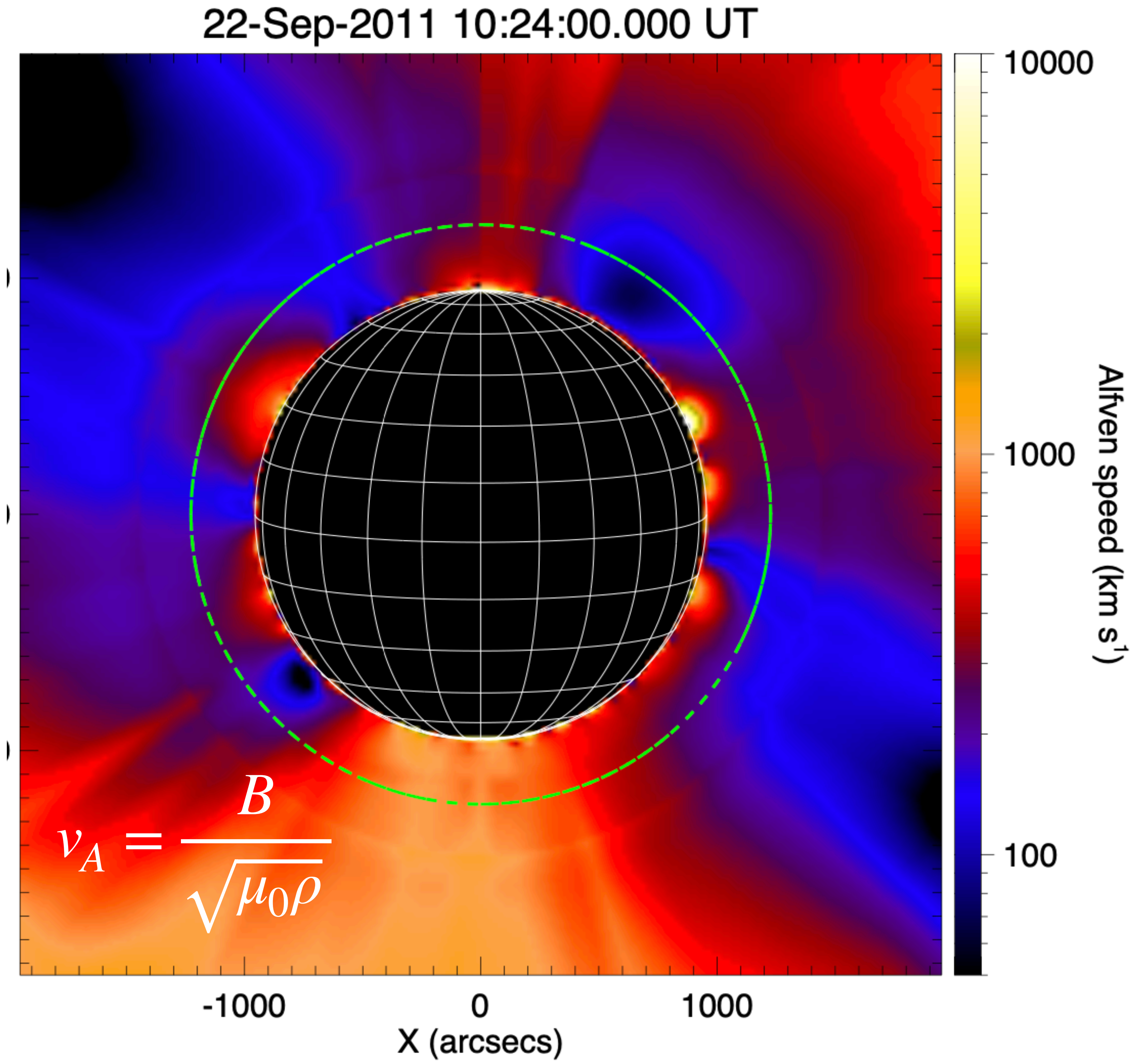
Density and Alfvén speed maps



Carley et al. (2013)
Zucca et al. (2014)

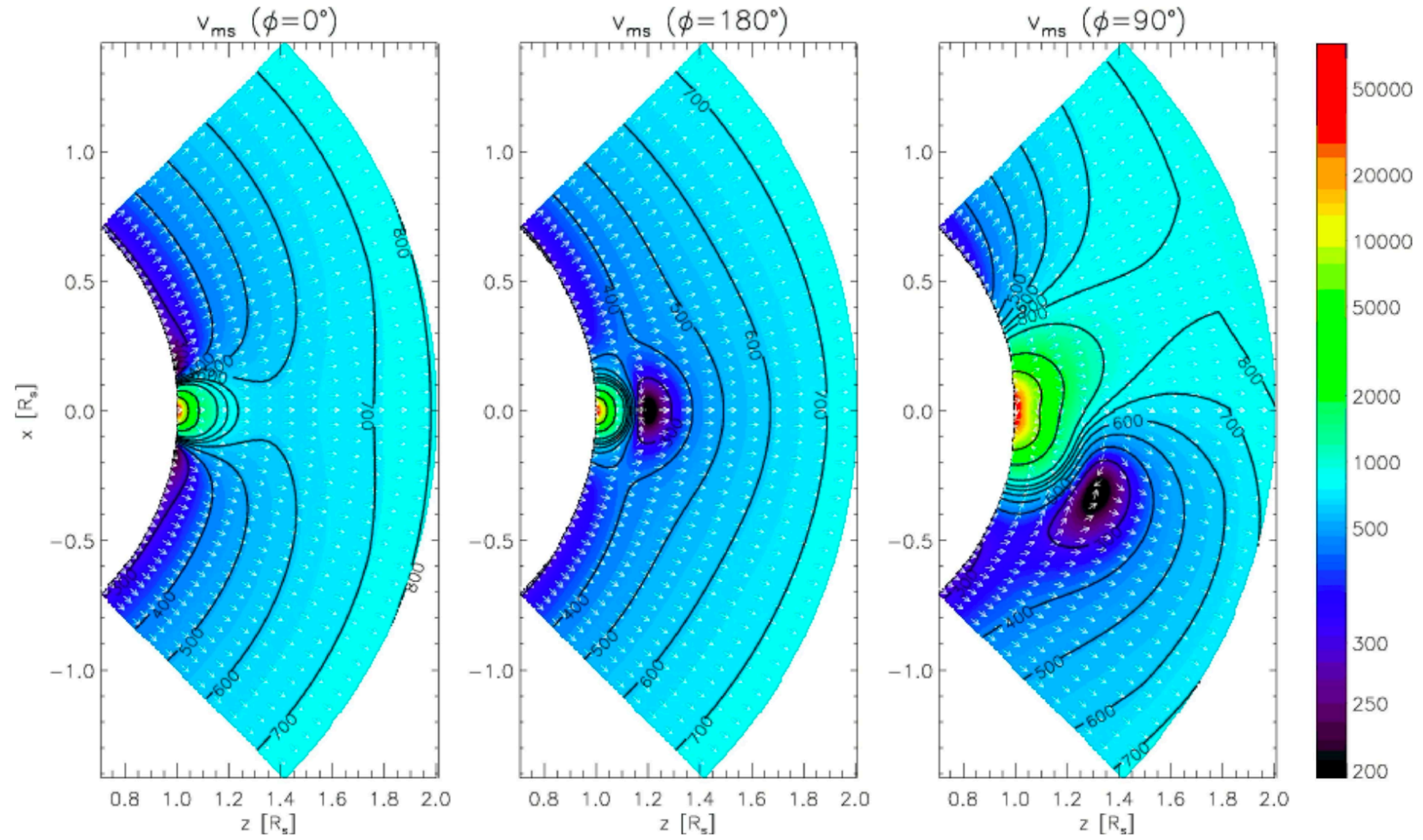


- 2D electron density map:
  - AIA Differential emission measure (DEM)
  - LASCO C2 polarised brightness measurements.

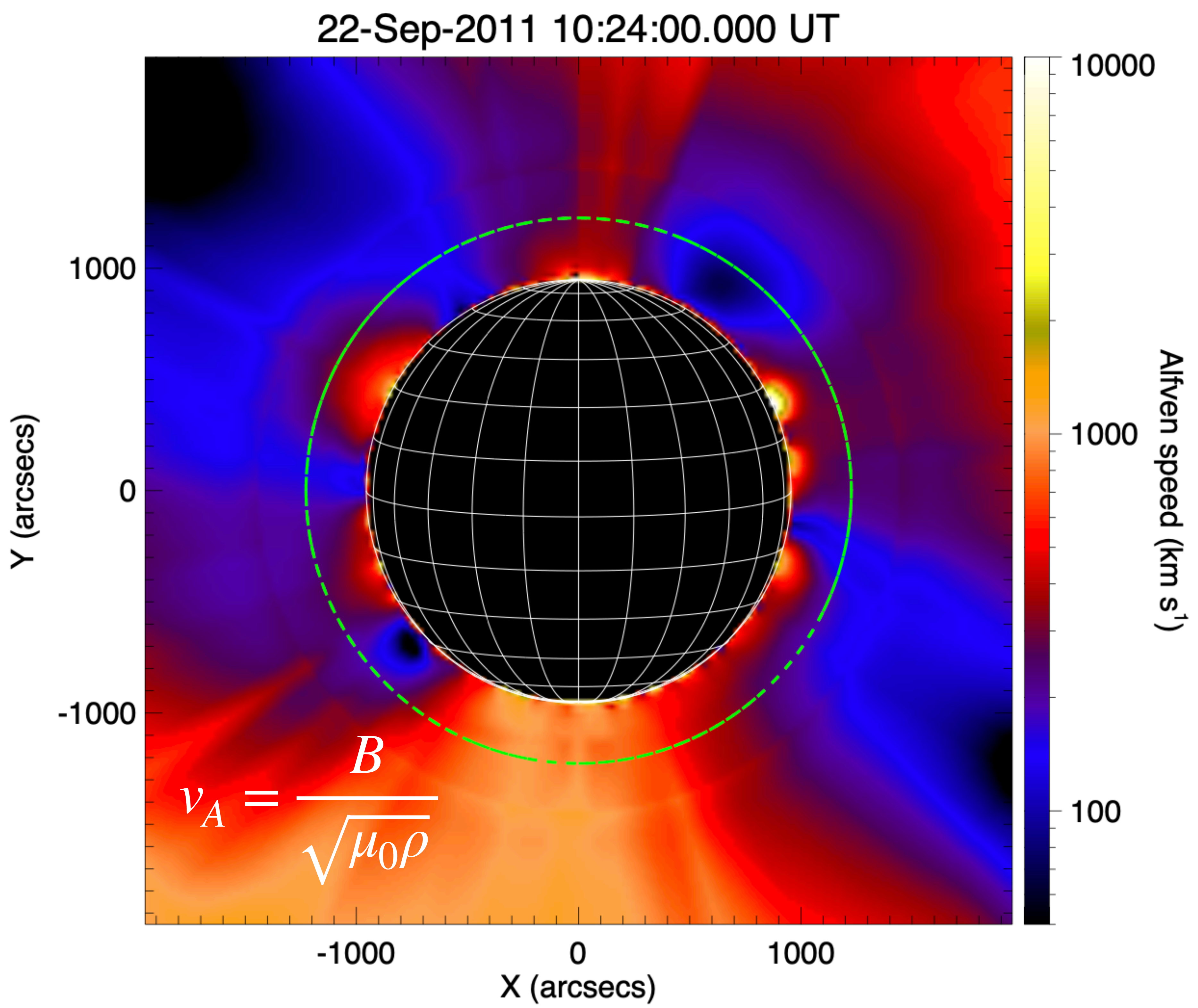


- 2D density map + the magnetic field from a PFSS.
- We see strong minima in the Alfvén speed.

Density and Alfvén speed maps



Alfvén speed modelling also shows these minima
Warmuth & Mann (2005)



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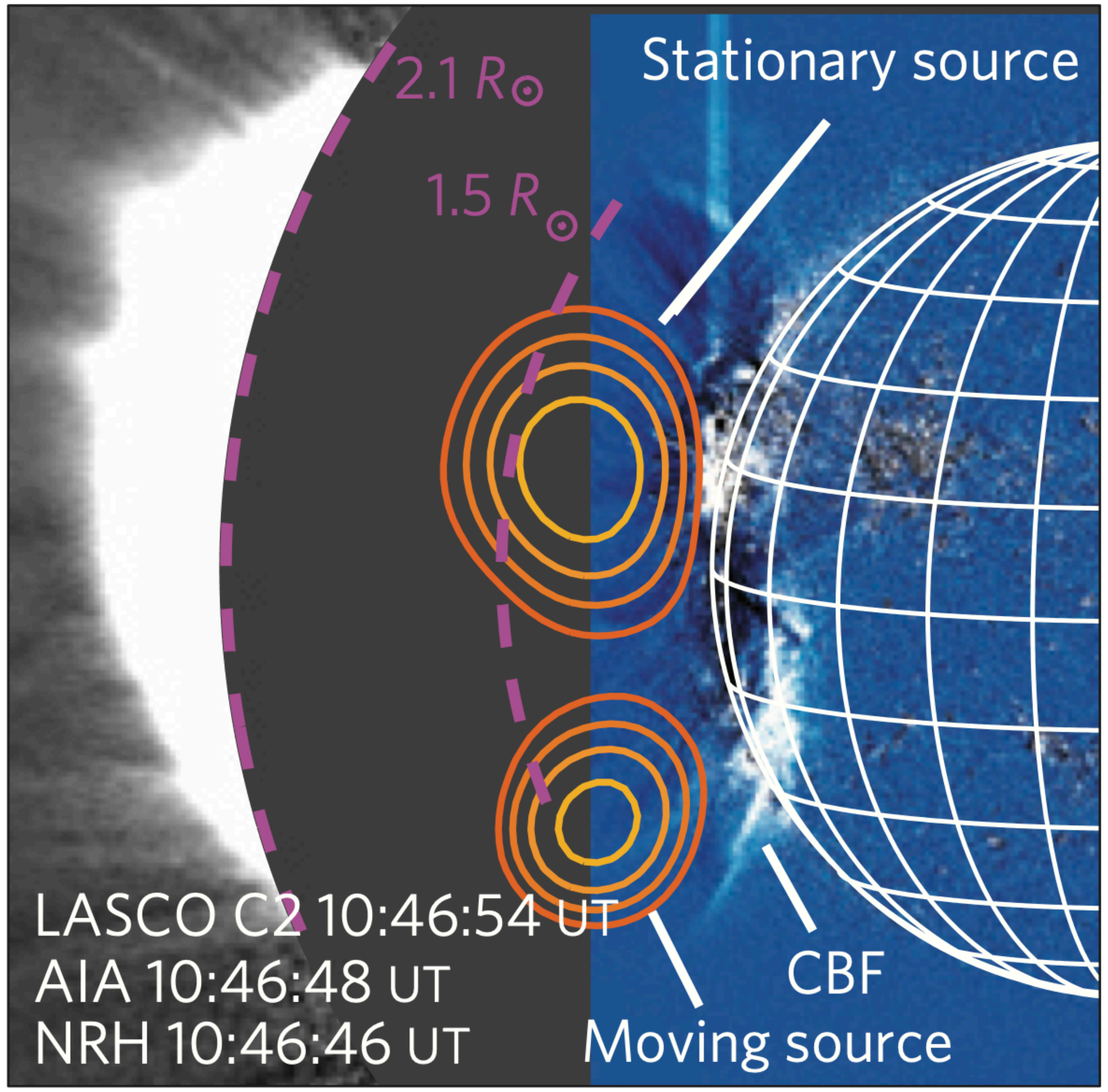
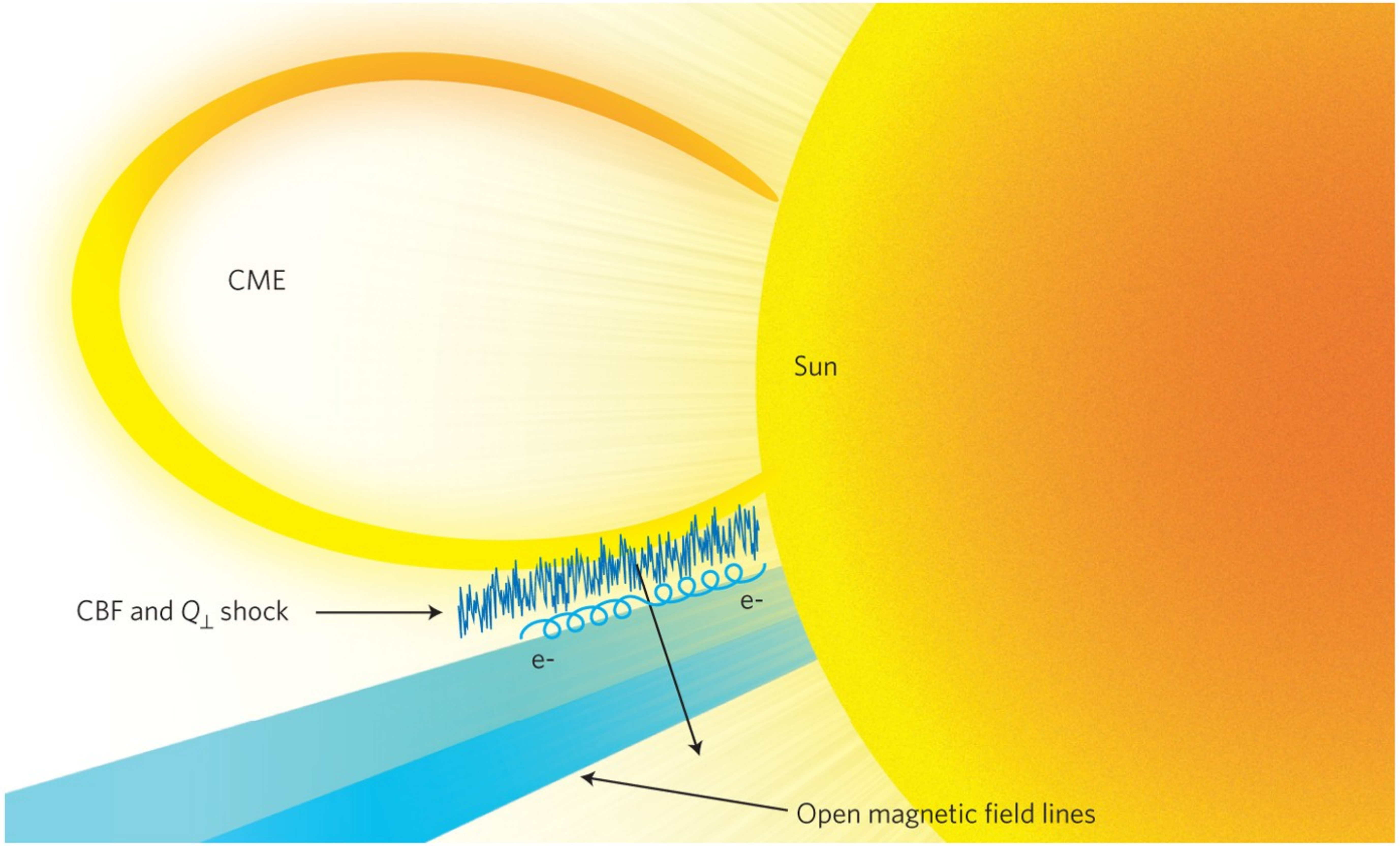
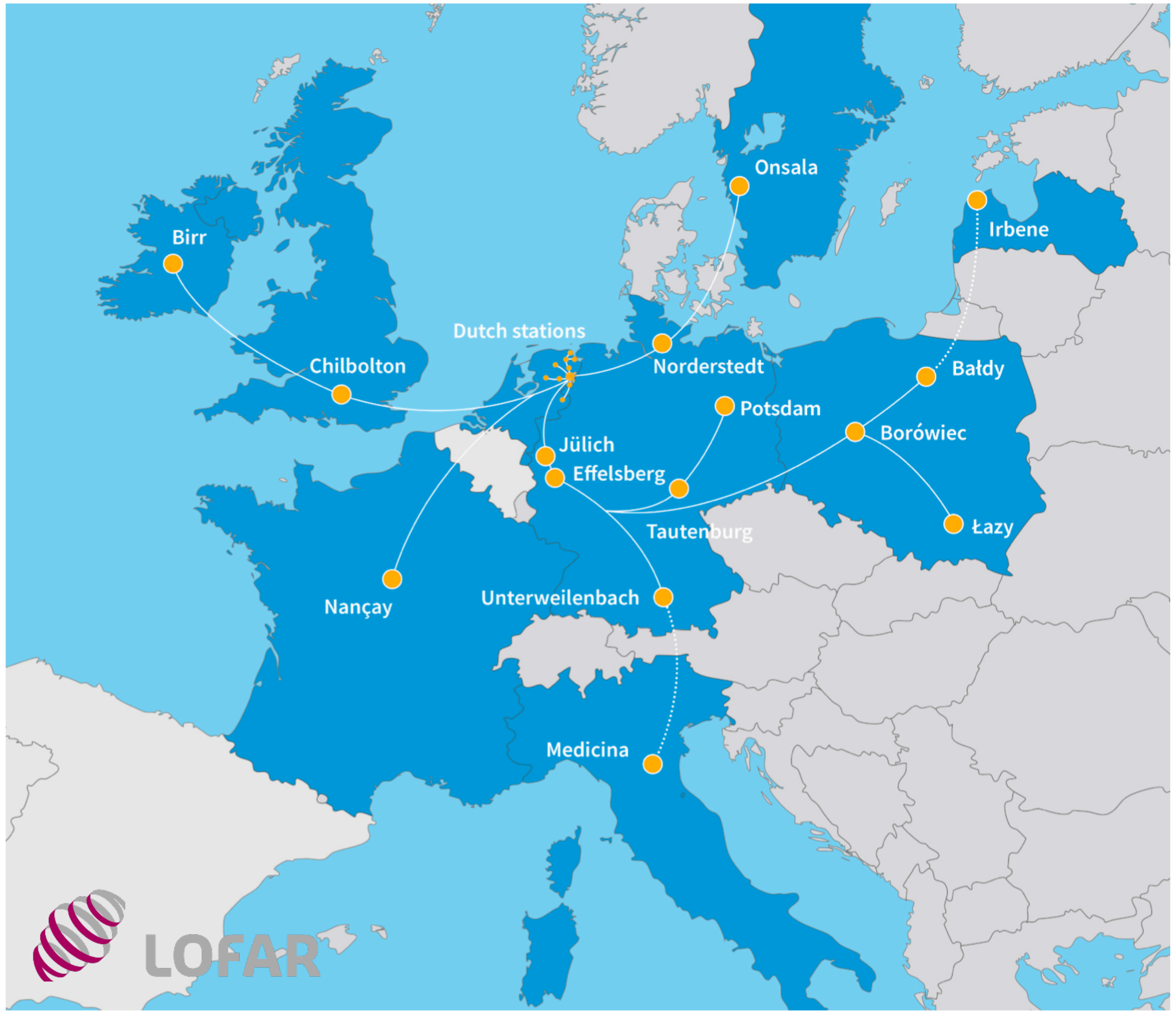
Electron acceleration on a CME flank?





- Interpretation:
  - Bursty electron acceleration on a CME flank
  - Acceleration is bi-directional
  - Unfortunately, only a couple of discrete NRH frequencies captured this activity

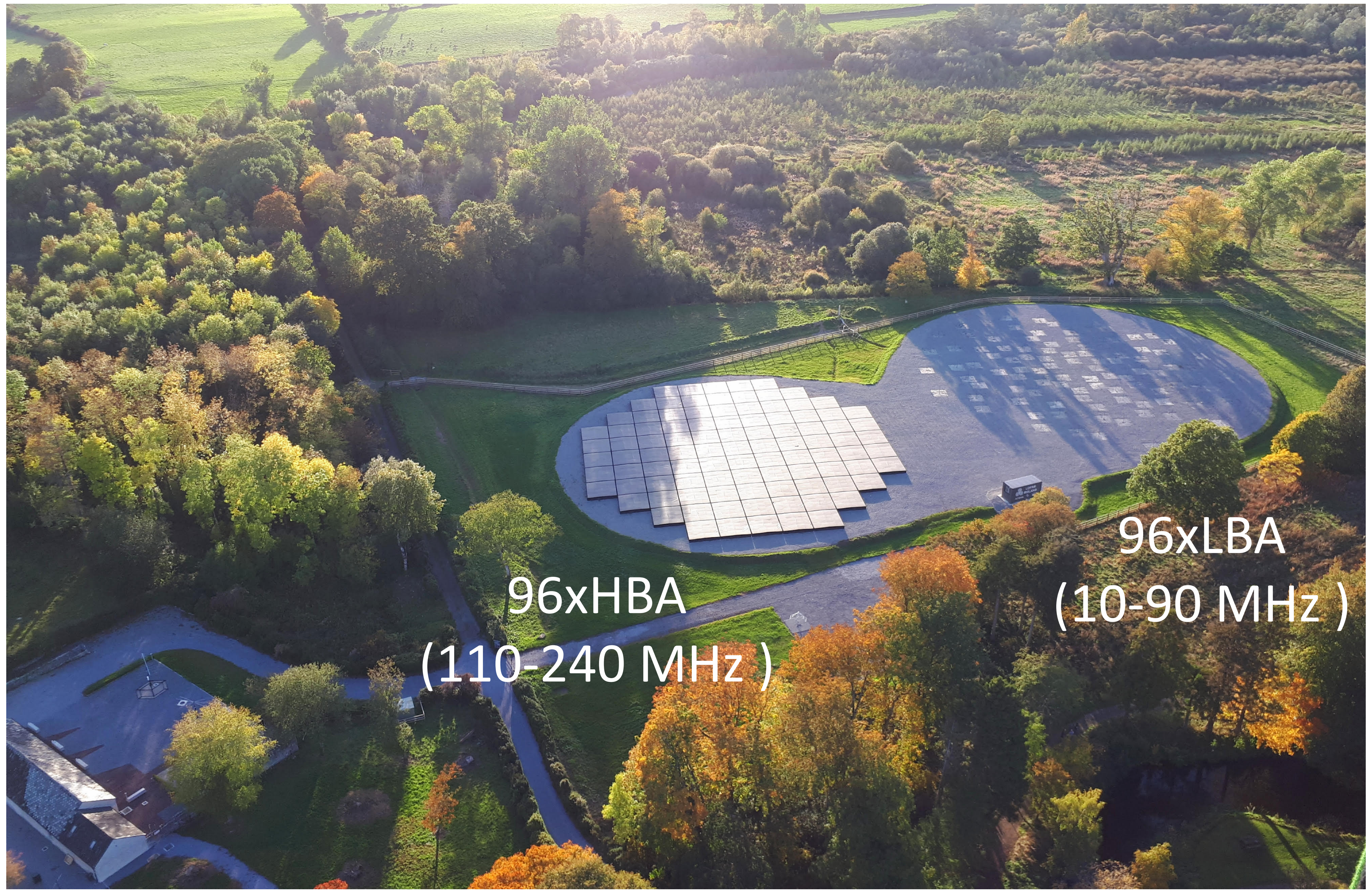
Low Frequency Array (LOFAR)

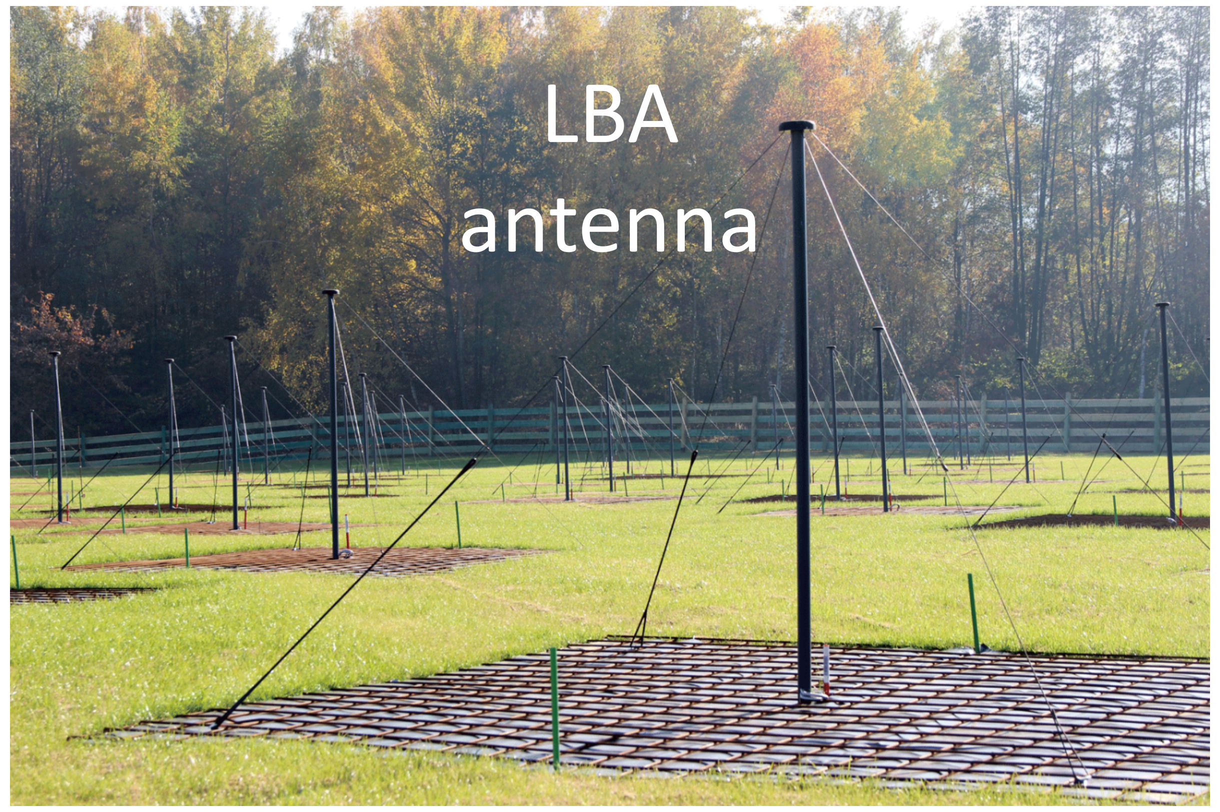


van Haarlem et al. (2013)

- International LOFAR telescope (ILT)
- Interferometer: 10 - 240 MHz
- 50 stations, 9 countries.
- Max baseline: ~2000 km
- Each station: 3 Gb/s
- 7 PB per year.
- Many Key Science Projects (KSP)
  - EoR, LoTSS, Pulsar and Transients, AGN….
- Solar and Space Weather KSP:
  - Pietro Zucca (Chair), Eoin Carley (Co-Chair)

I-LOFAR Consortium





DCU

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ARMAGH OBSERVATORY

AIT

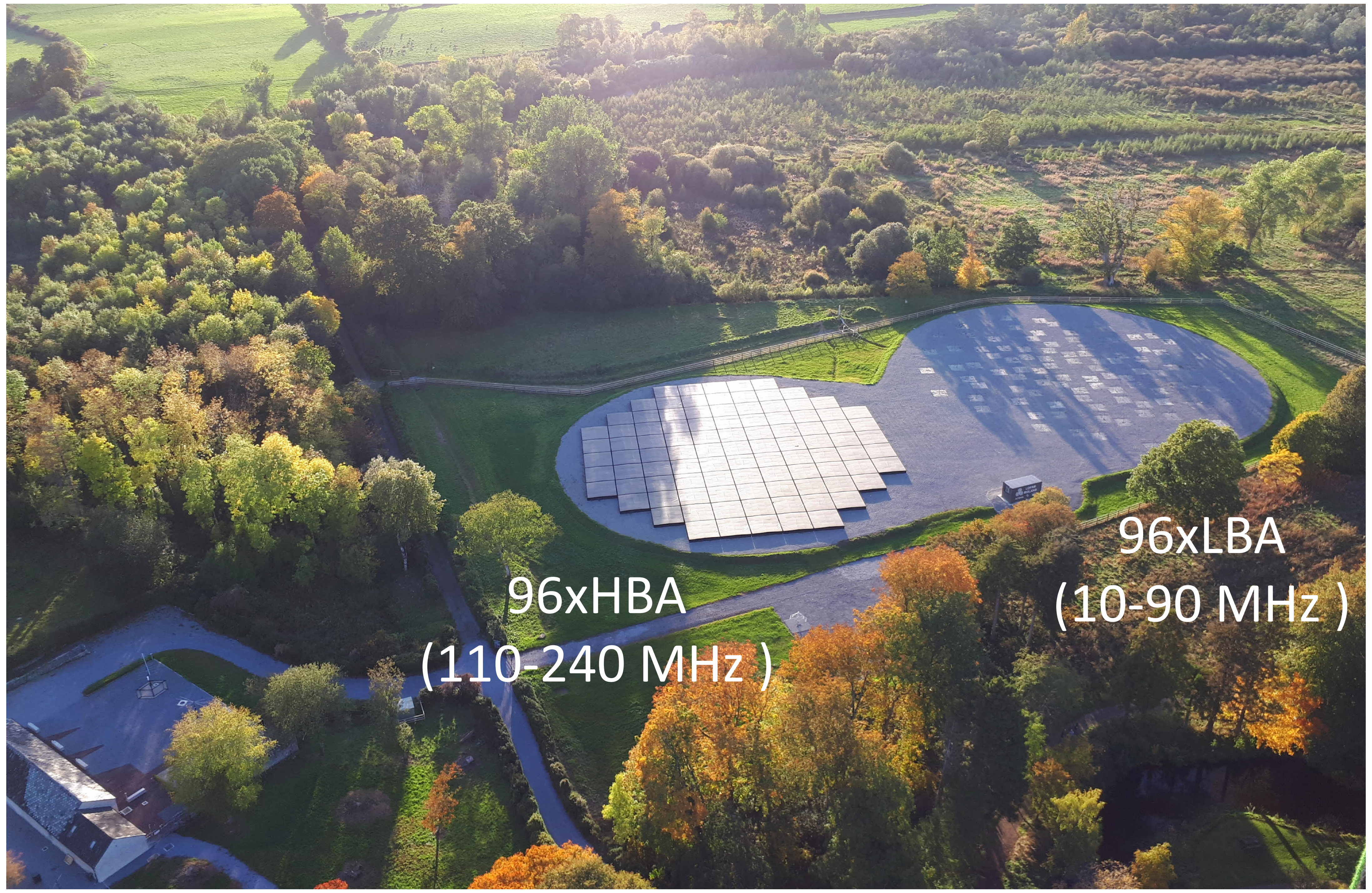
NUI Galway
OÉ Gaillimh

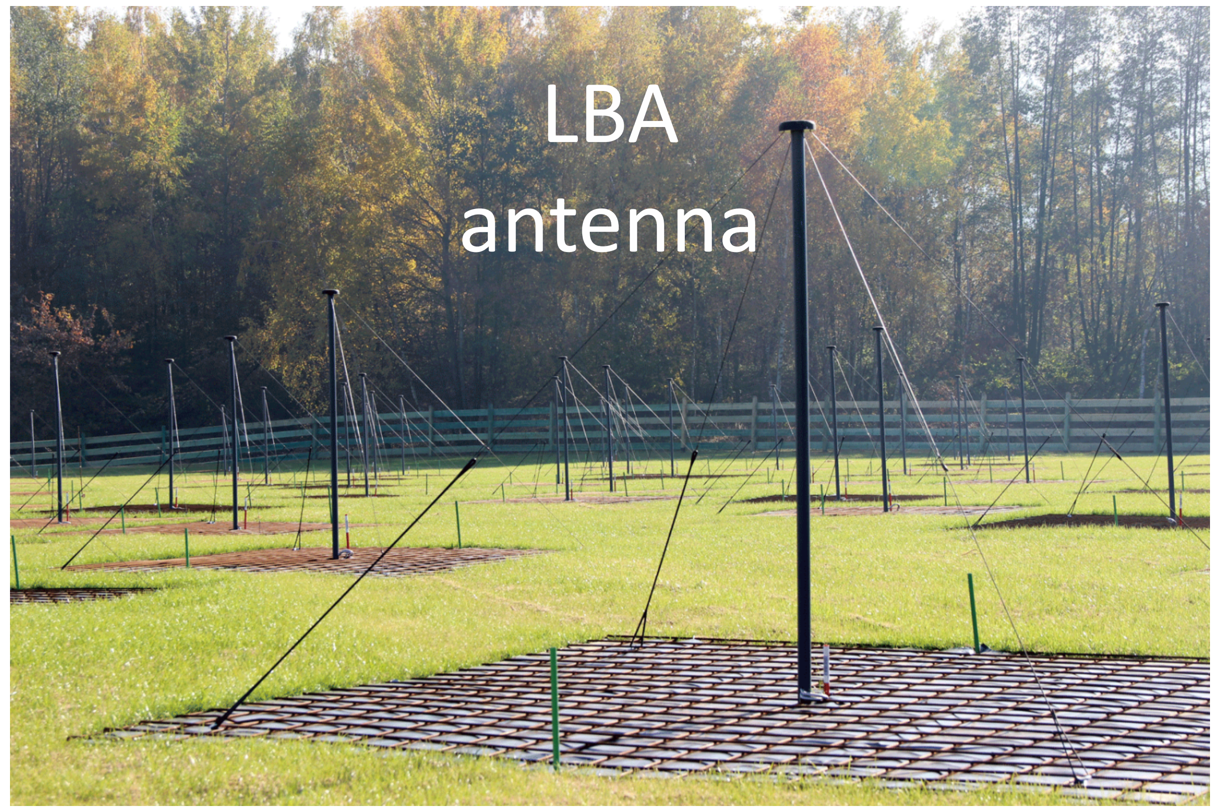
UCD DUBLIN

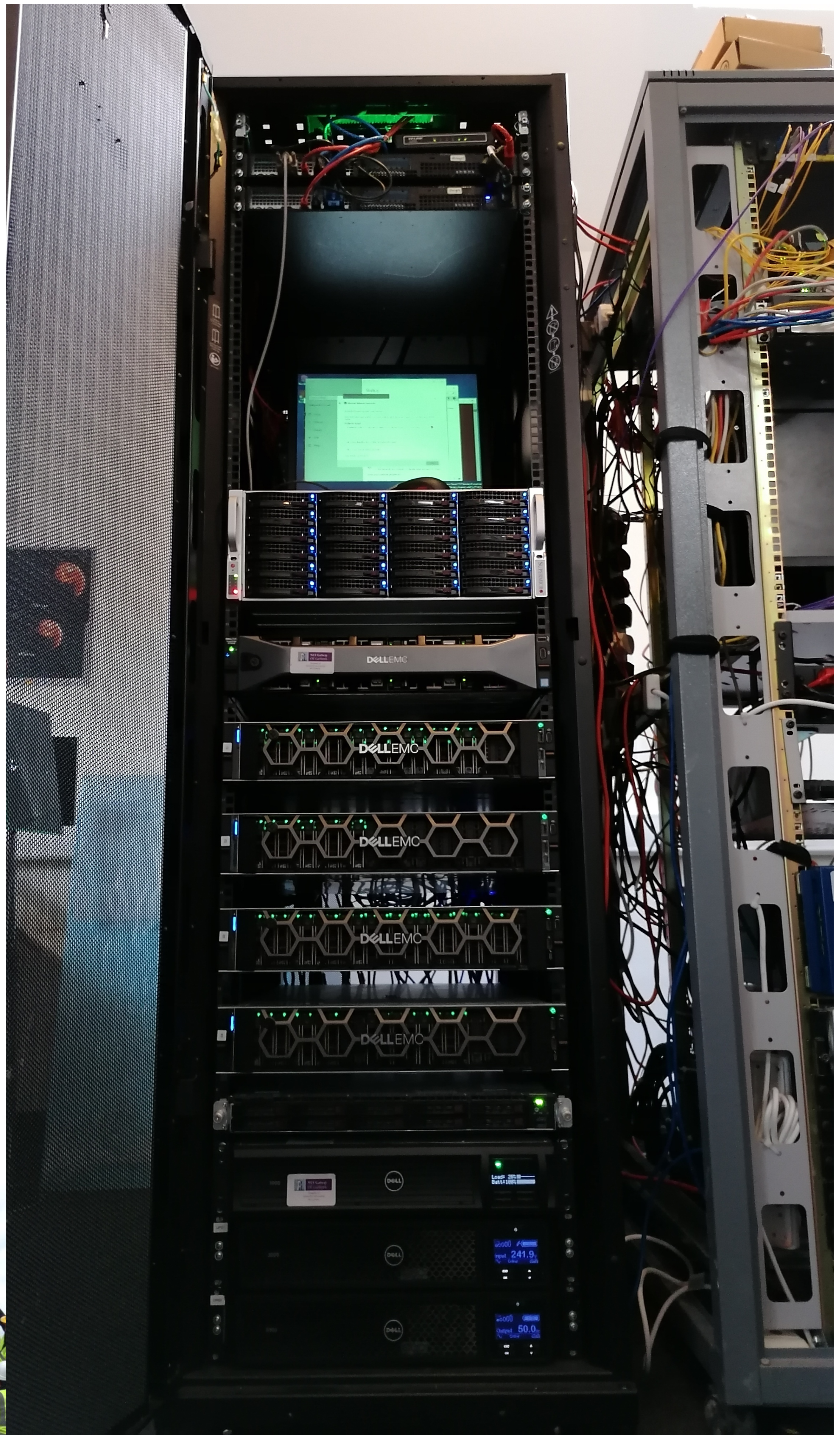
UCC
Coláiste na hOllscoile Corcaigh, Éire
University College Cork, Ireland

Trinity College Dublin
The University of Dublin

I-LOFAR Consortium







- Real-time Transient Acquisition (REALTA) cluster:
- Used for high time resolution data capture:
    - 5 μs sampling across the bandwidth.
    - 4 TB hr^{-1}
- Solar radio burst fine structure
- Pulsar and transients
- SETI research (Breakthrough Listen)
- Platform for deep-learning detection of transients.

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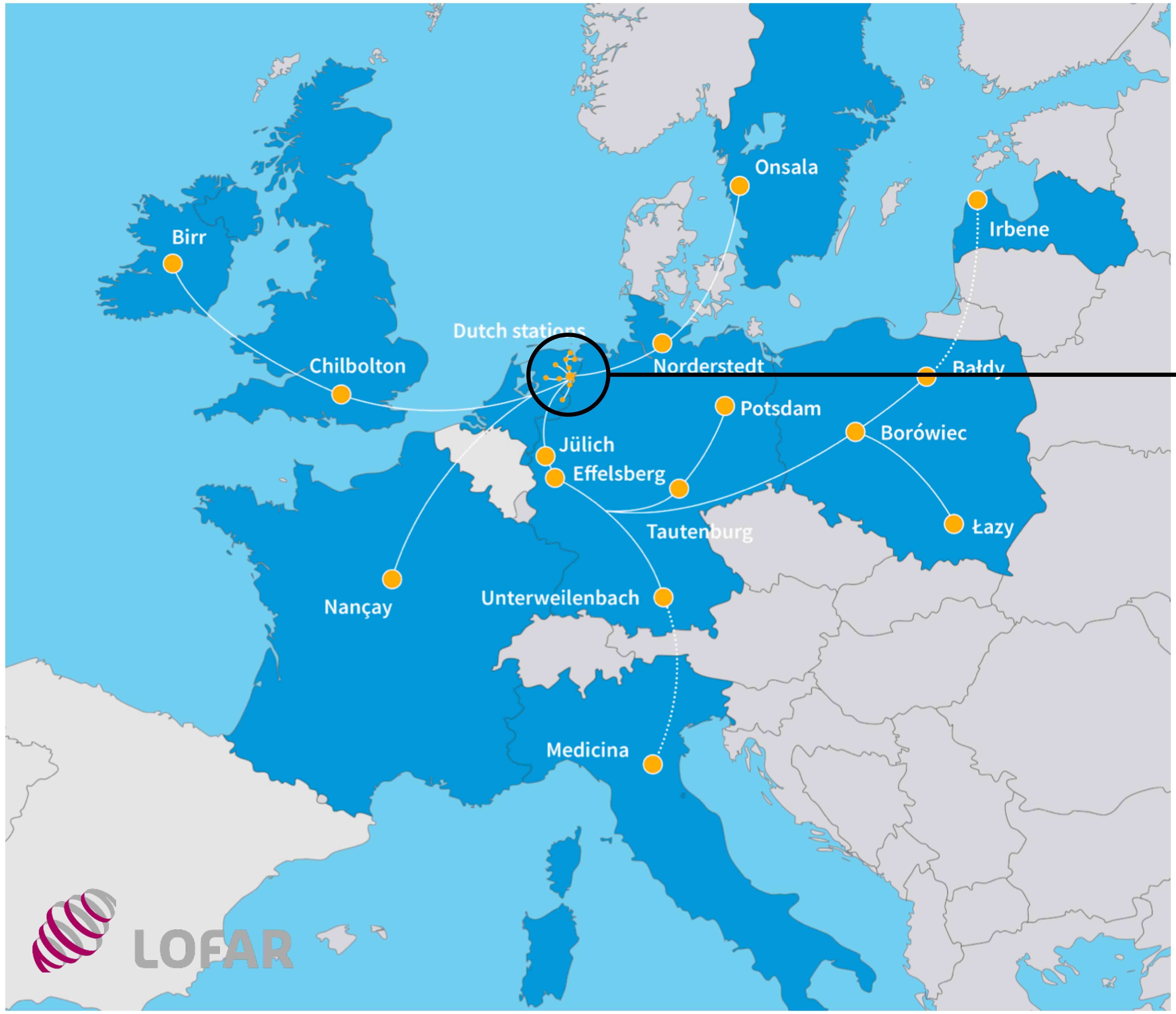
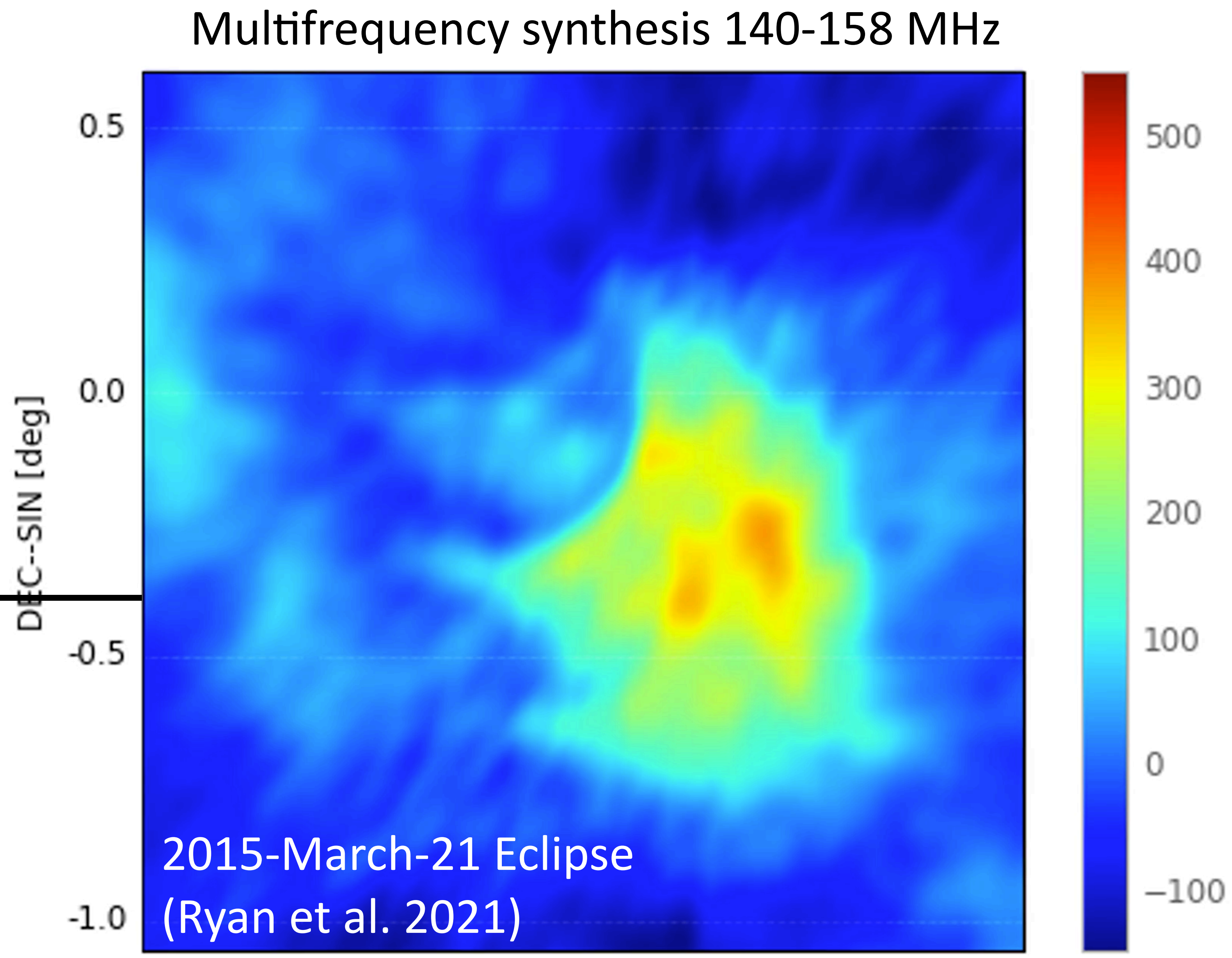
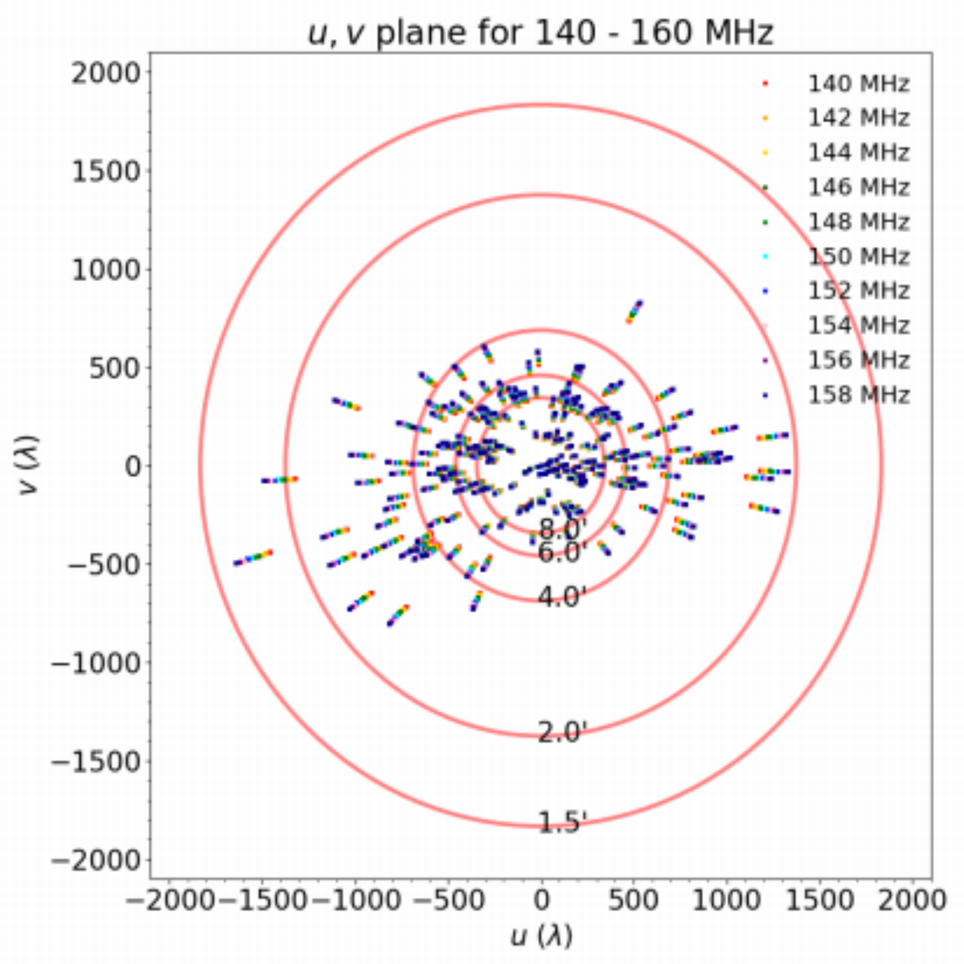
LOFAR and Solar Imaging



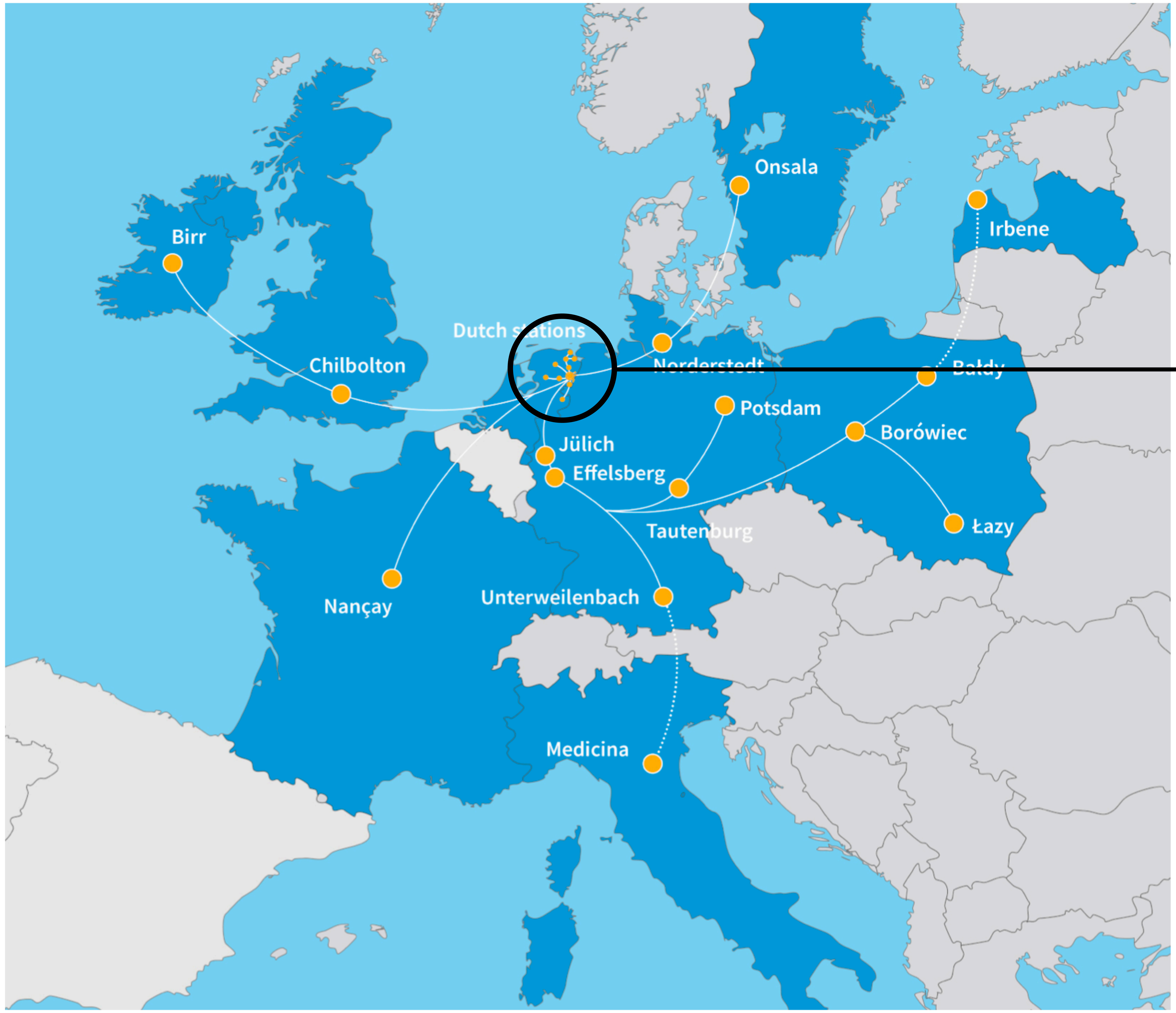
van Haarlem et al. (2013)

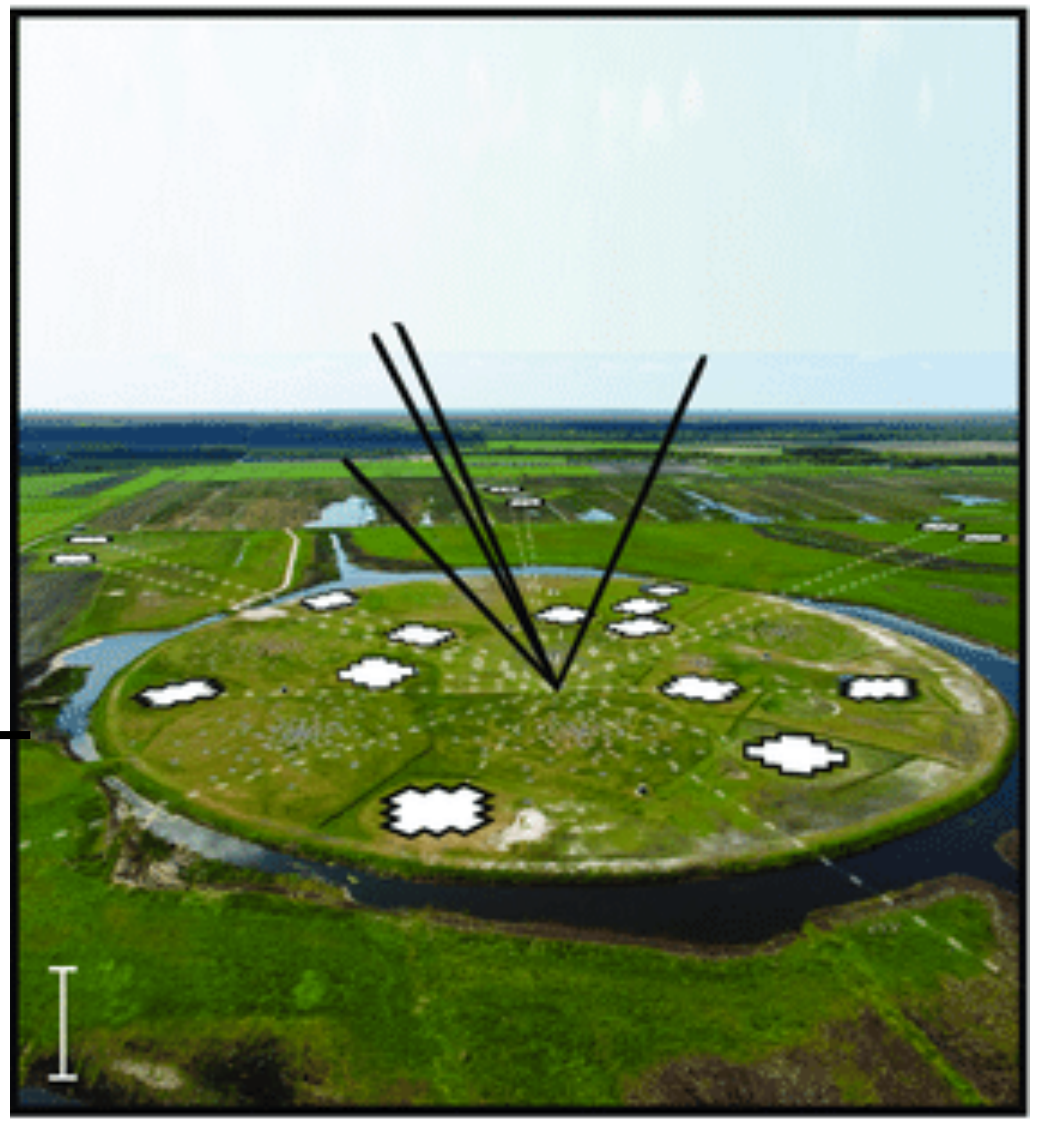


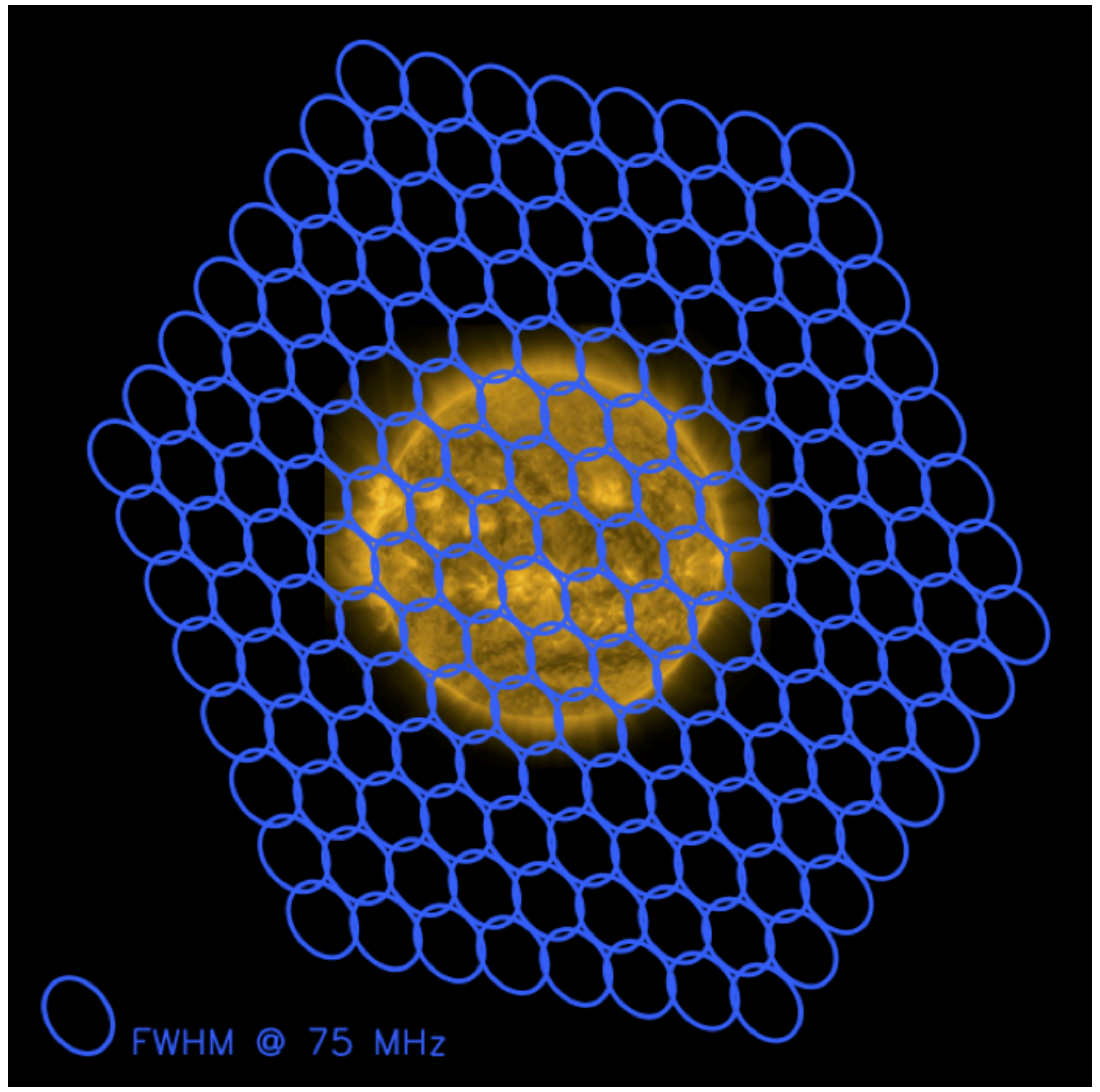


- Interferometric imaging
  - Full imaging spectroscopy 10-90 MHz
  - Time res.: 0.167 seconds.
- For solar imaging:
  - 36 Core + remote stations

LOFAR - Tied Array Beam (TAB) imaging

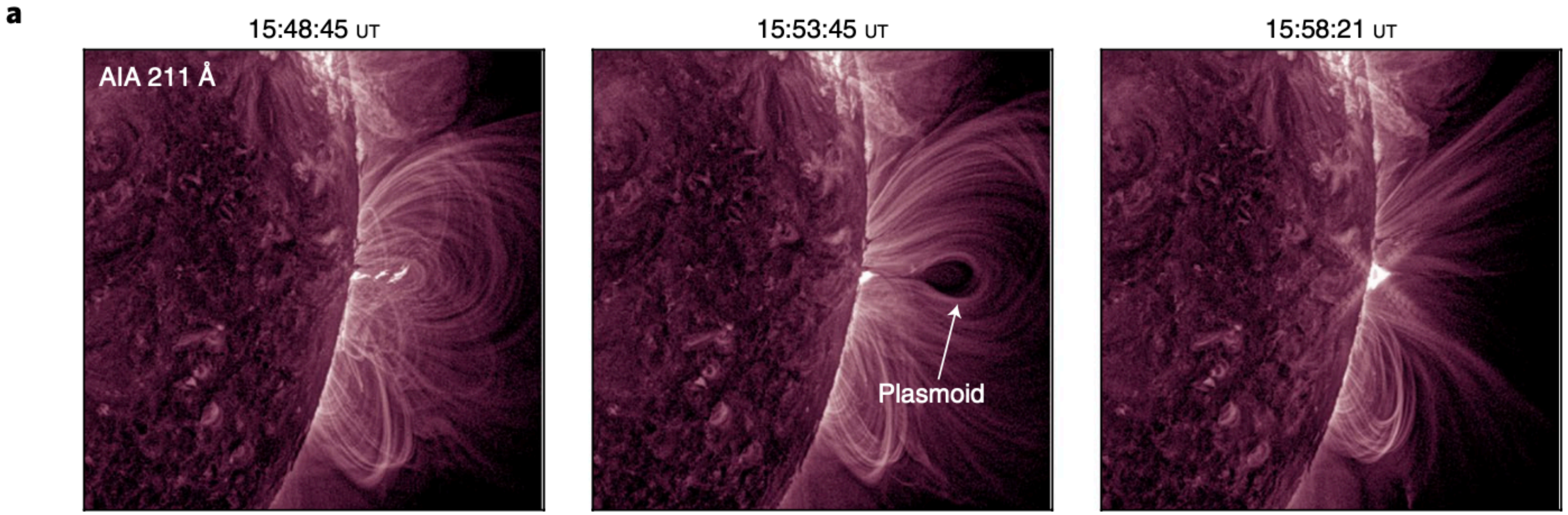


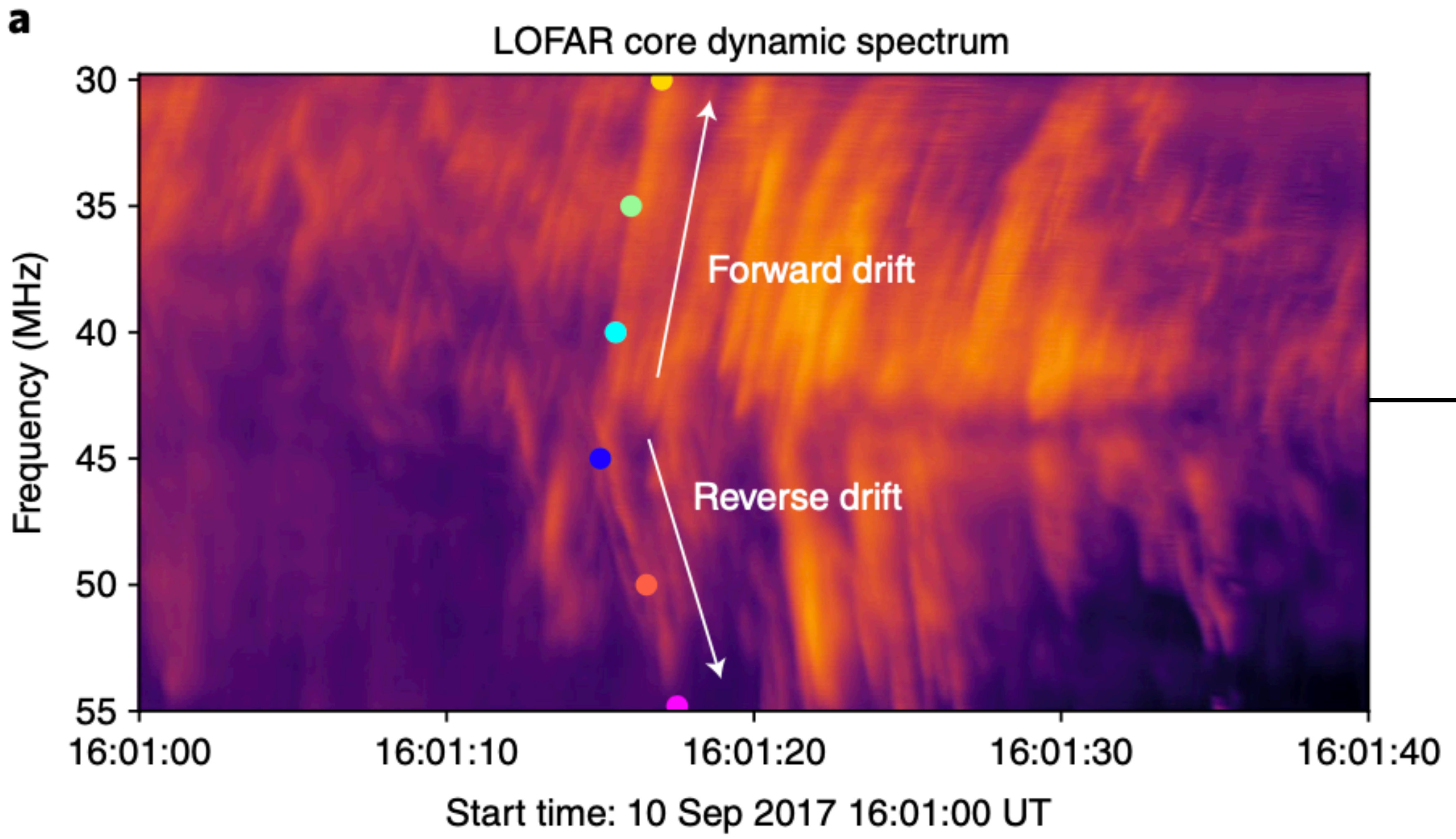




- 200+ beams arranged in a honeycomb pattern
- $\Delta t \geq 5\,\mu s$, depending frequency resolution
- Usual observations: $\Delta t = 5\,\mathrm{ms}$ and $\Delta f = 12.5\,\mathrm{kHz}$
- 6500 frequency channels across 10-90 MHz

Shock observations in the solar corona





12 million images

Morosan et al. (2019)

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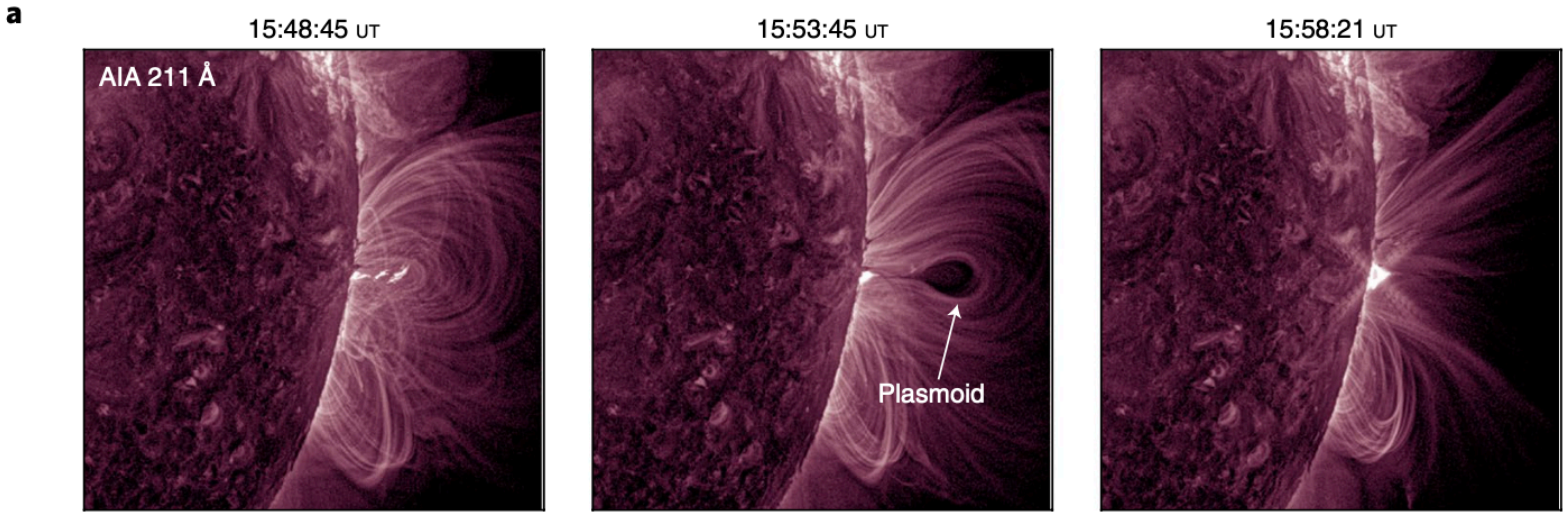

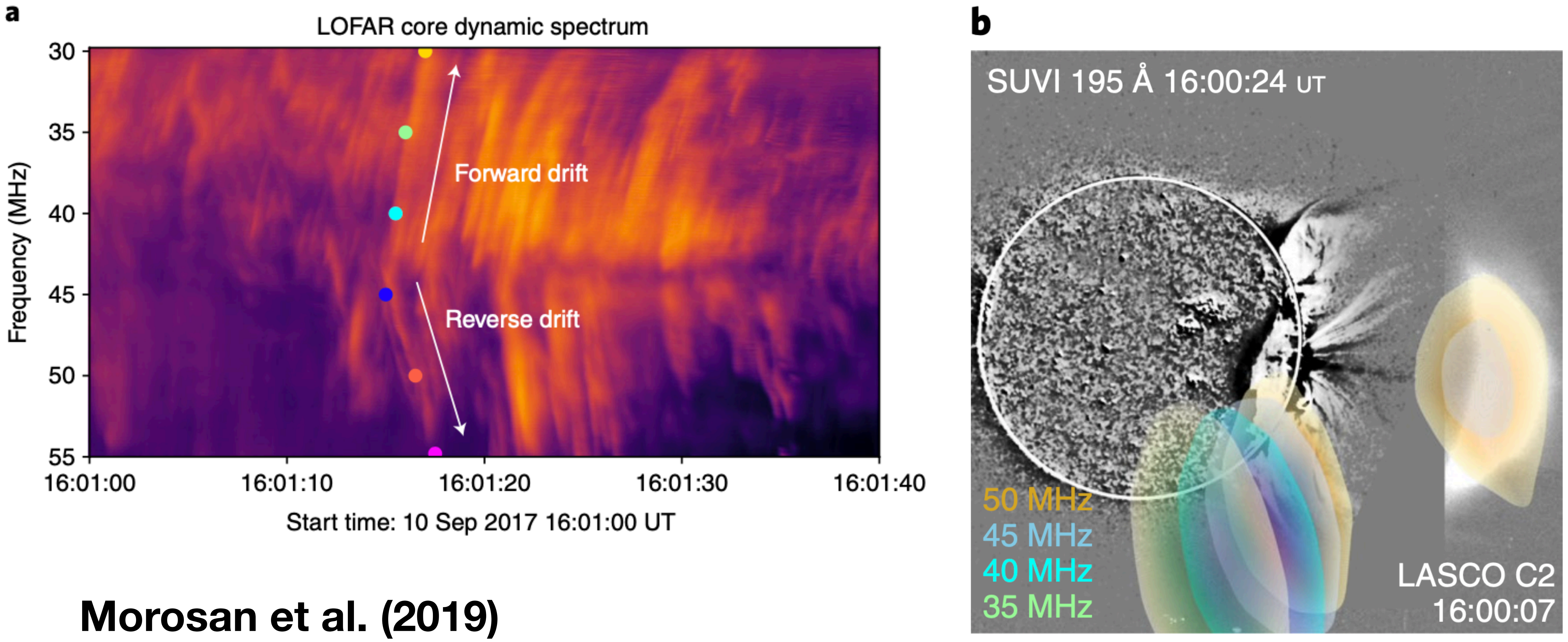

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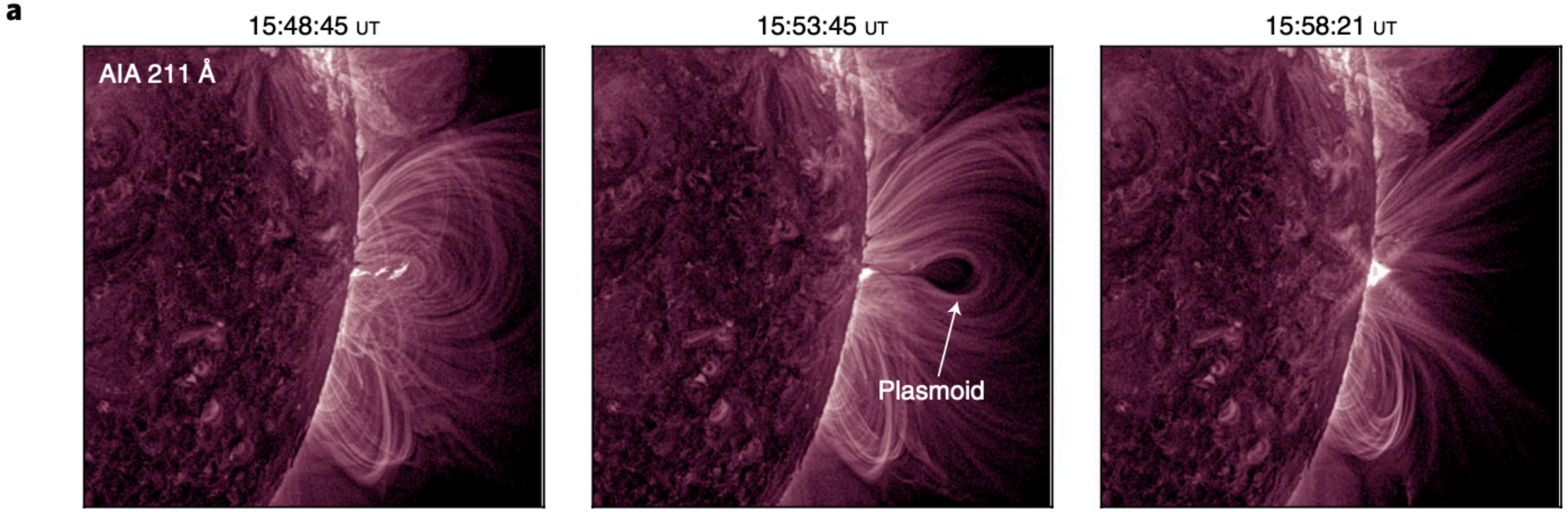

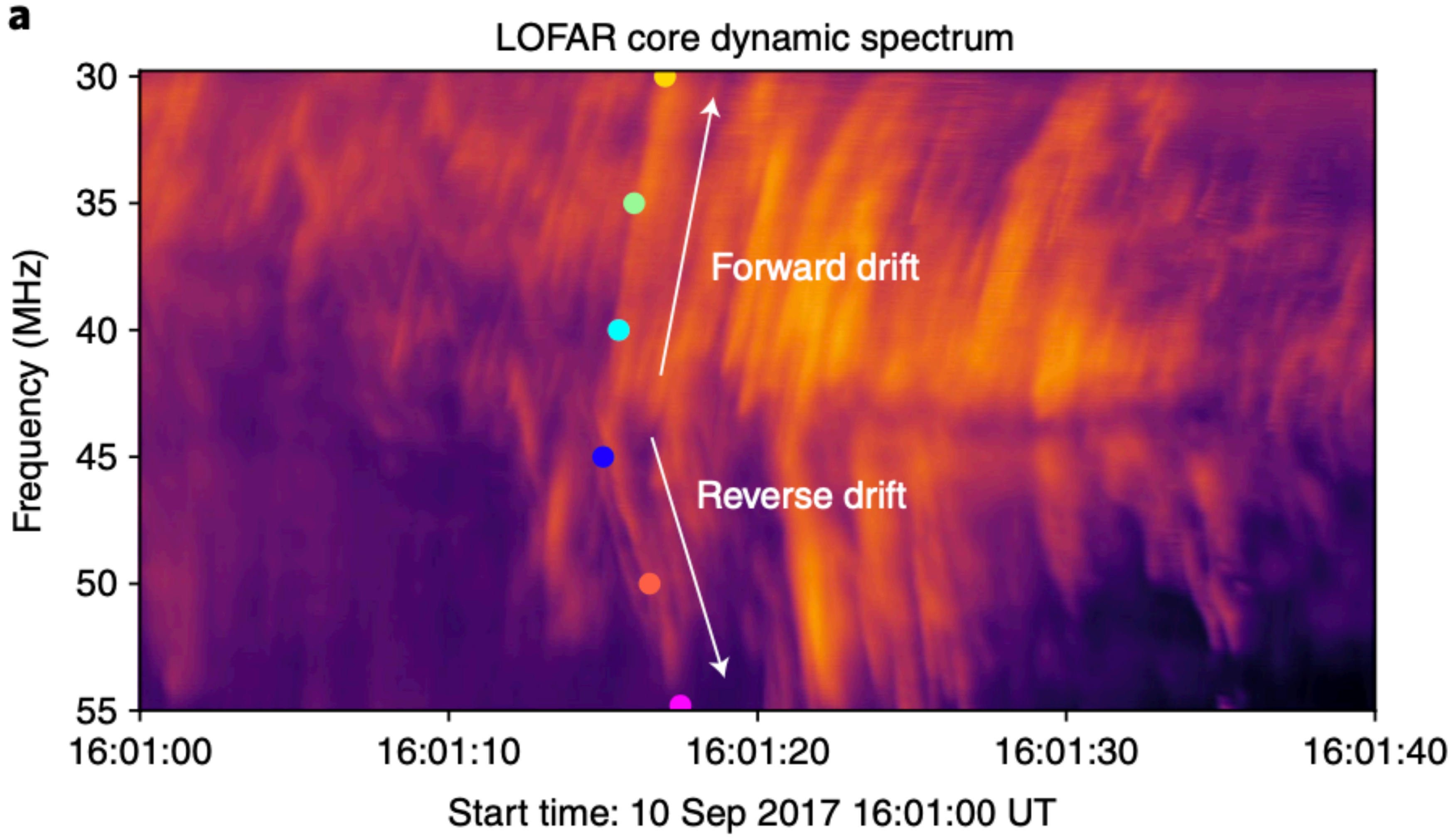

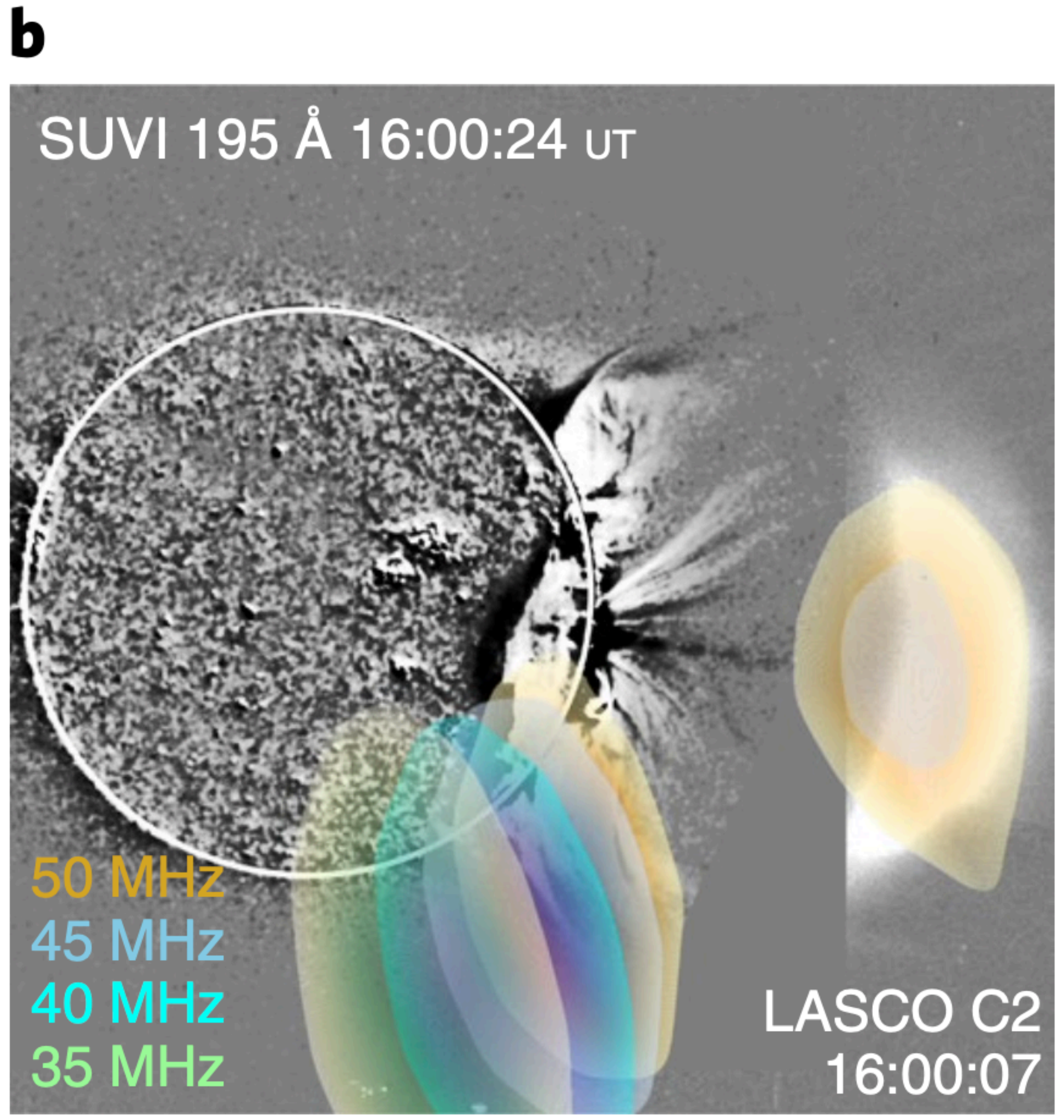

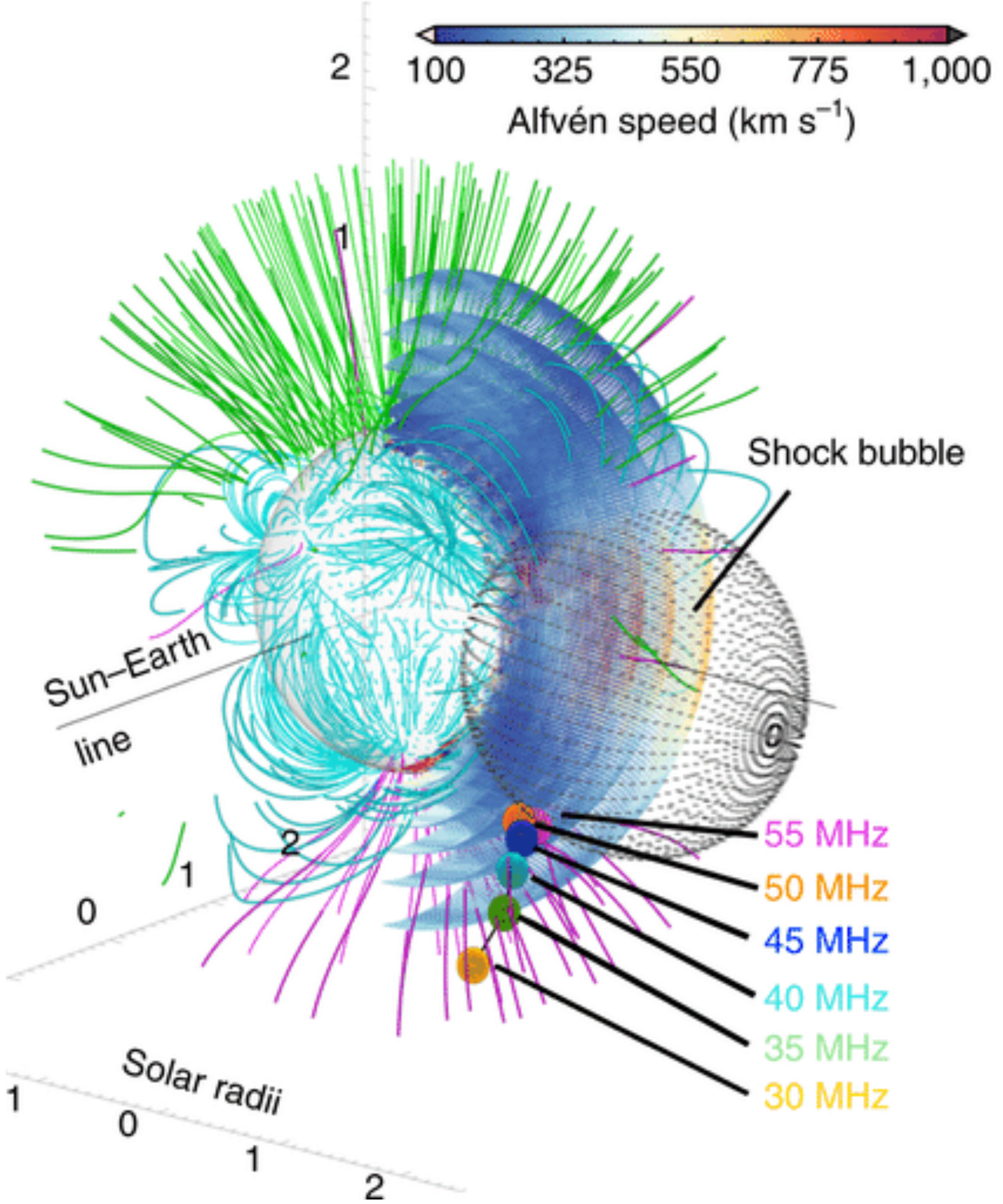

Morosan et al. (2019)

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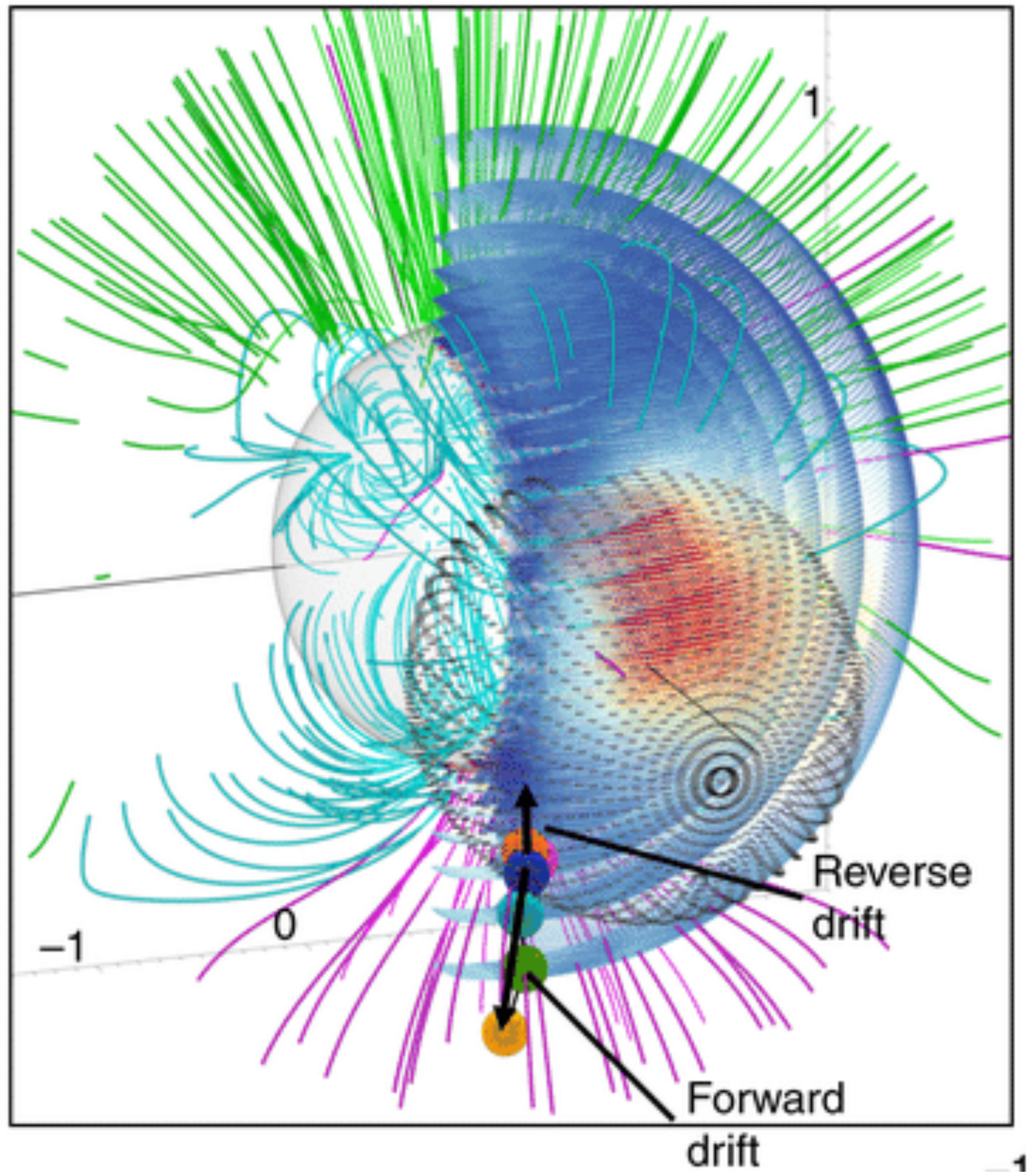
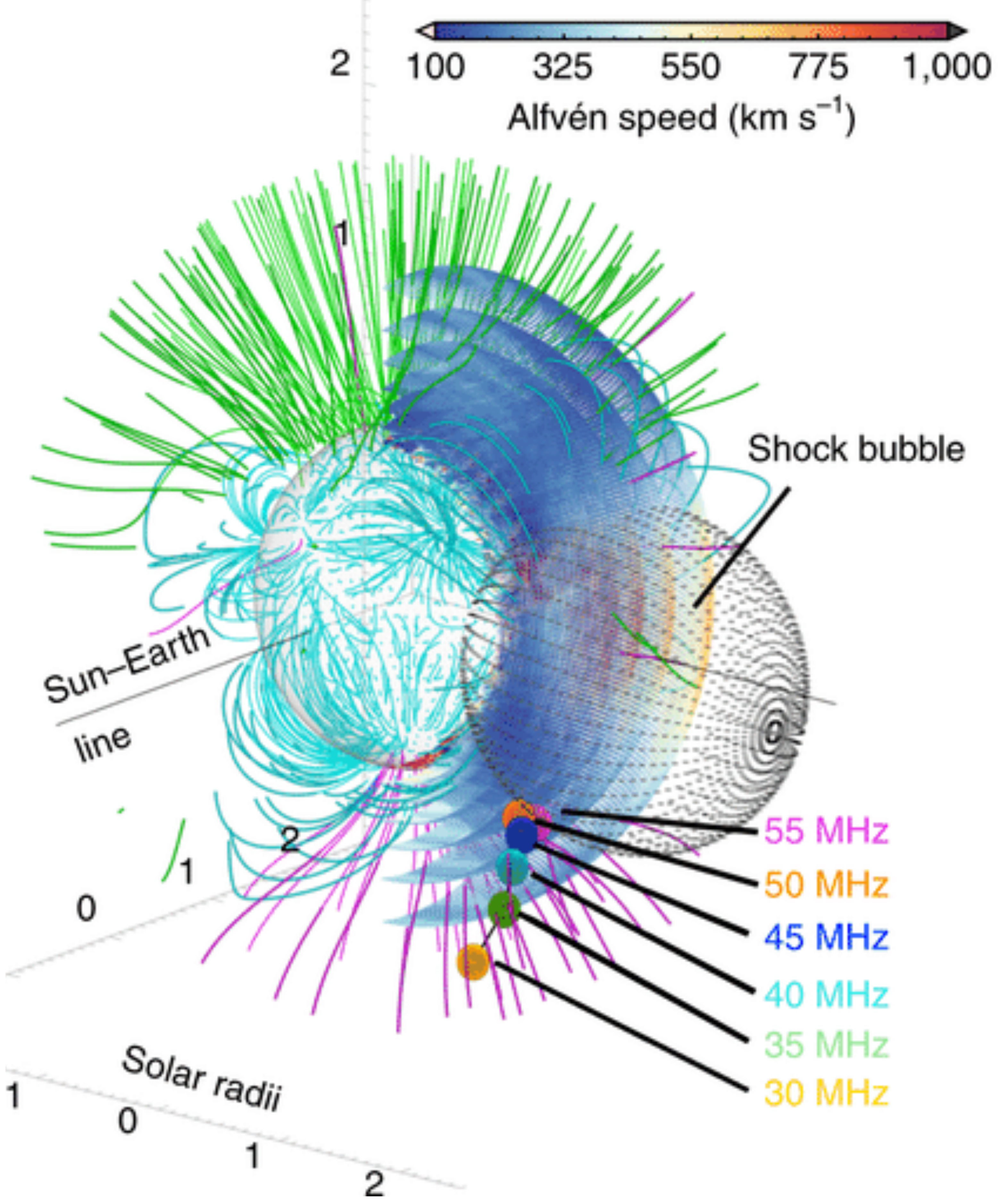




Bursty electron acceleration:

Beam speeds of 34 keV

Low Alfvén speed environment:

Shock of Alfvén-Mach 2.5

Quasi-perp geometry:

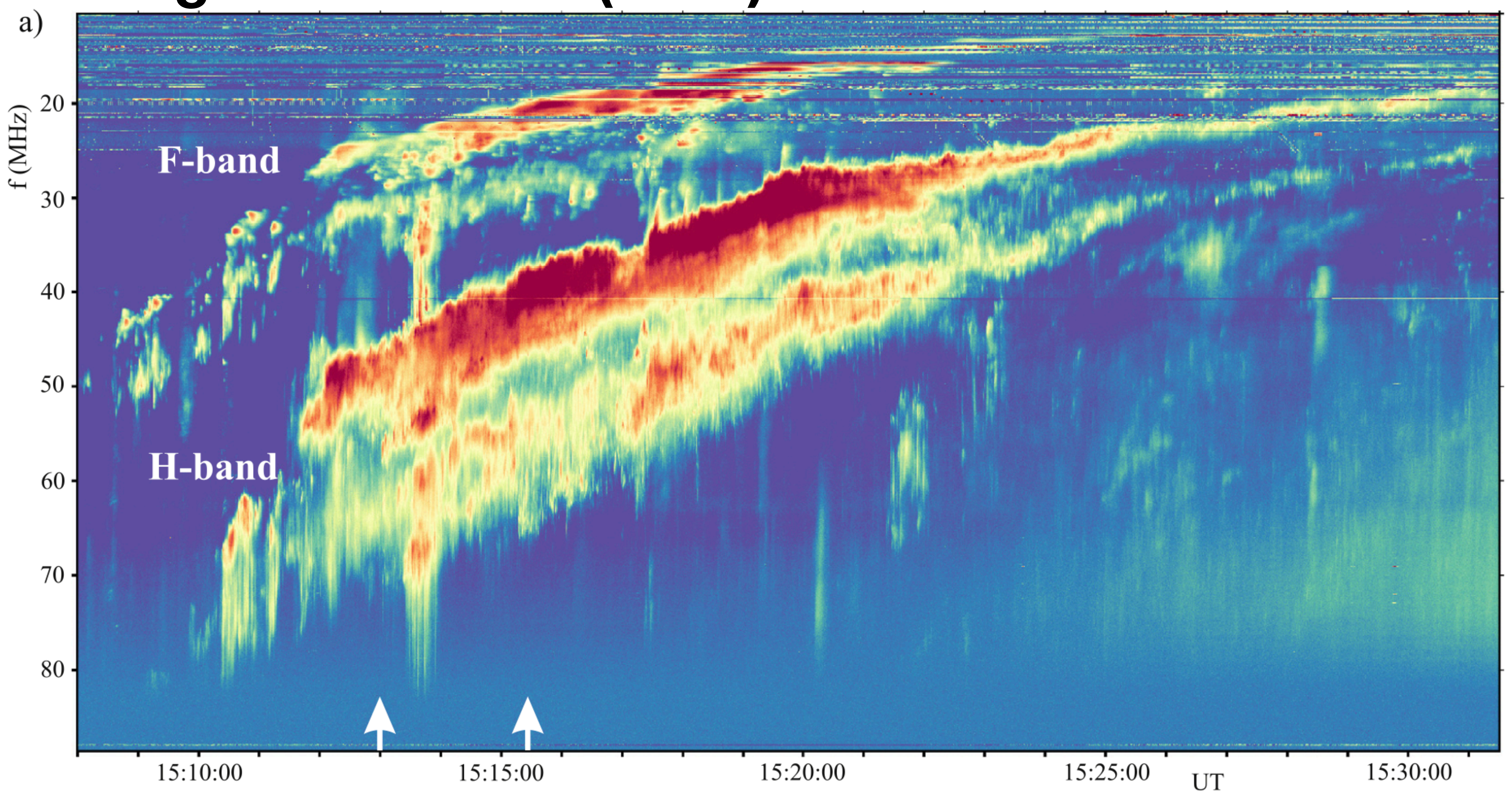
Shock-drift acceleration

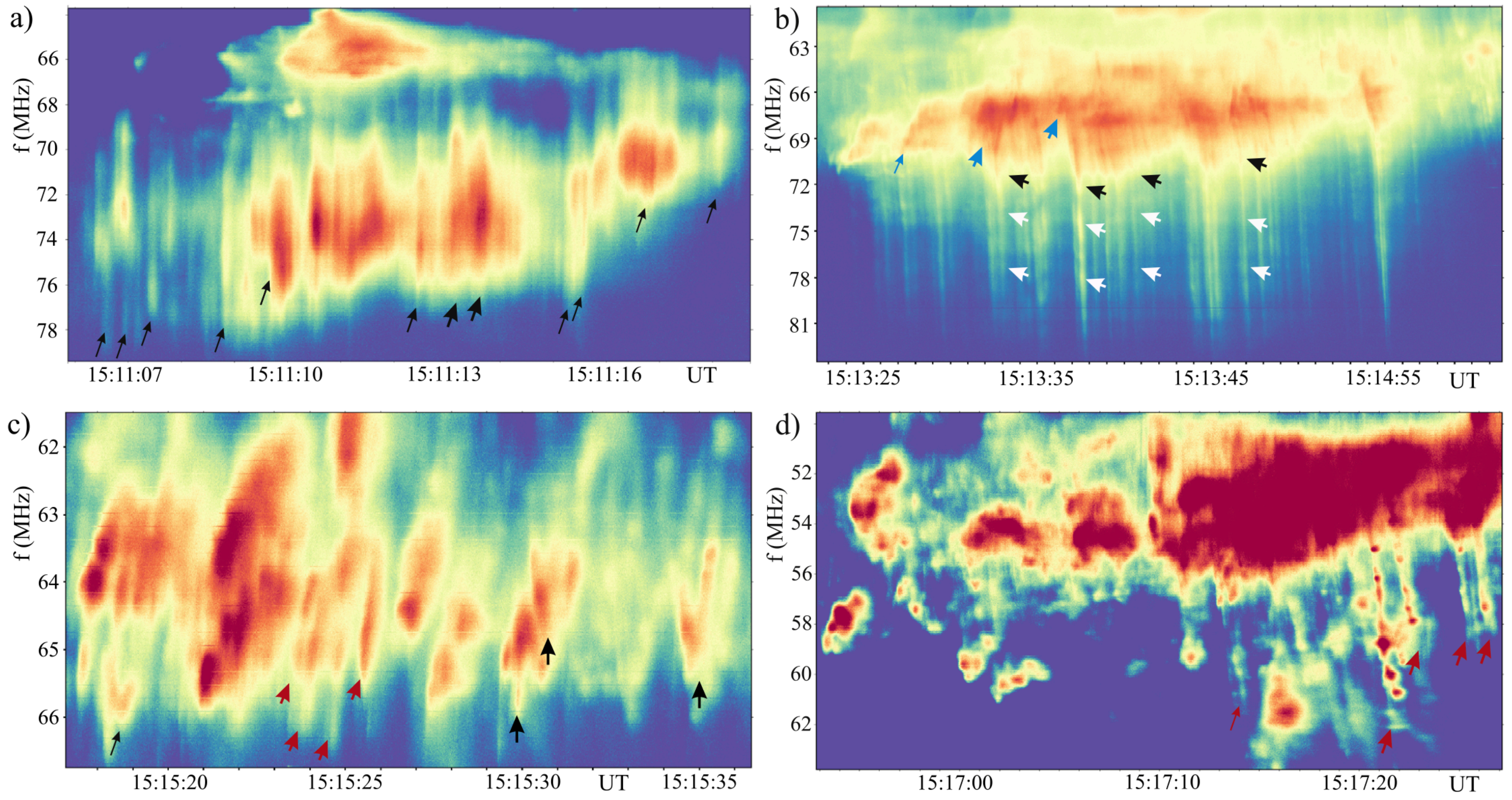
Can we tell anything more?

Morosan et al. (2019)

Motivation: what causes type II fine structure?

Magdalenić et al. (2020)





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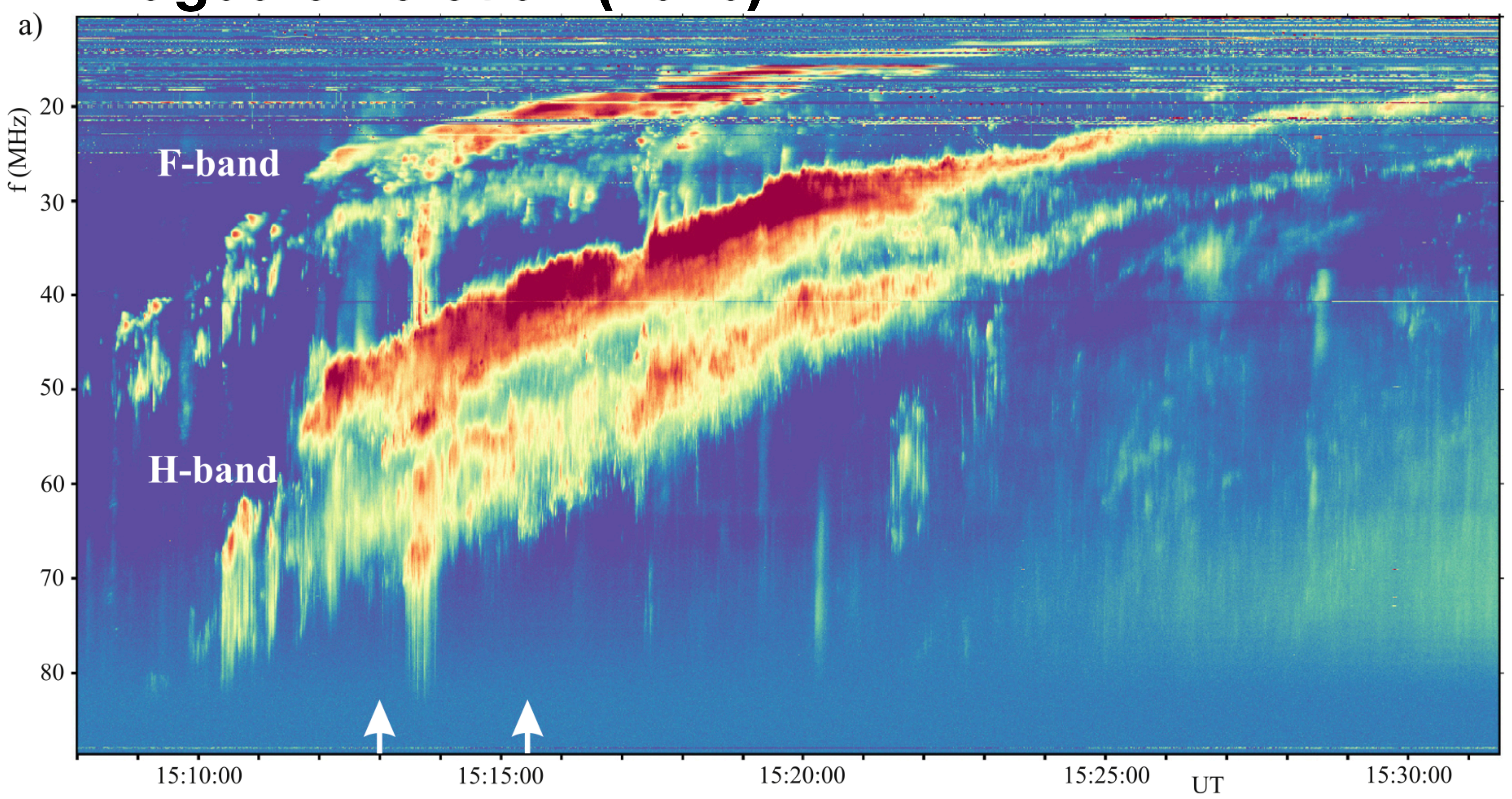
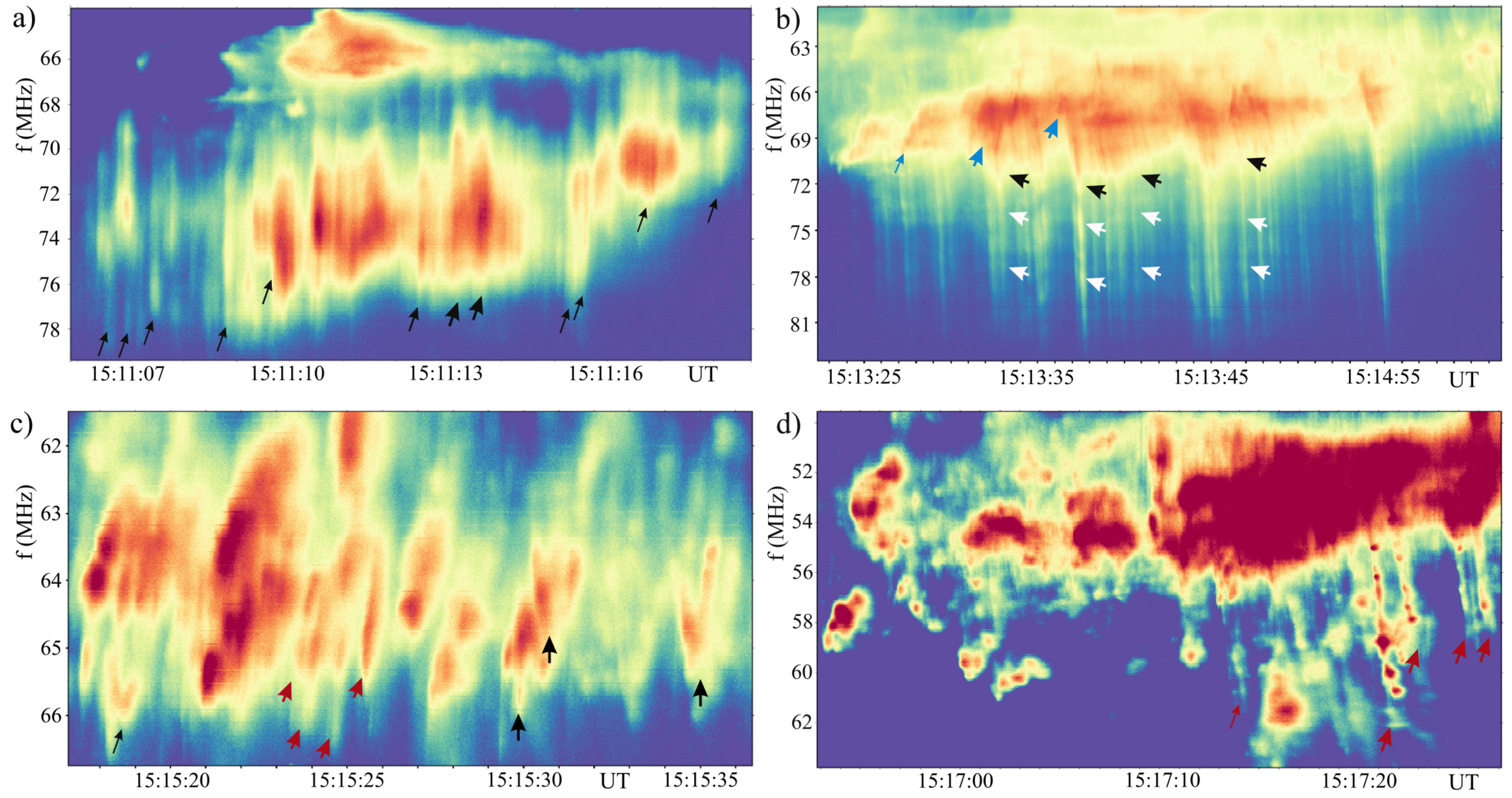
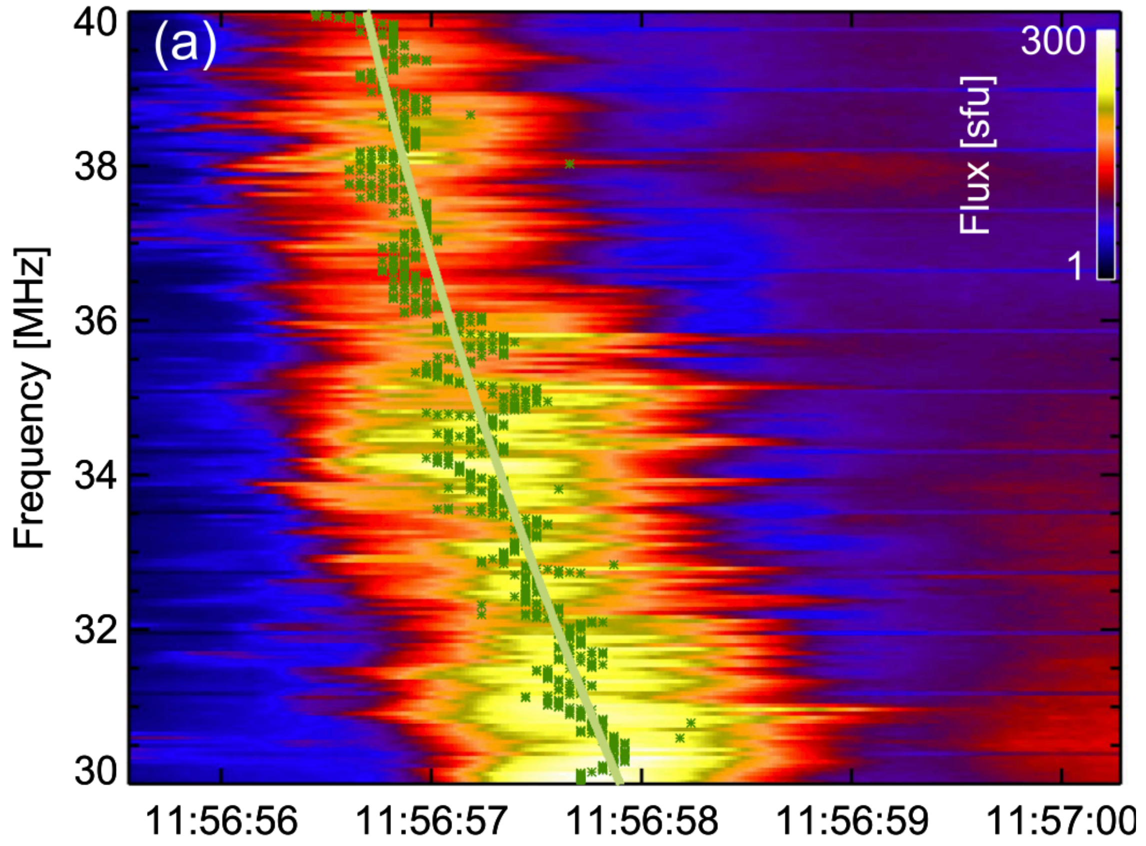
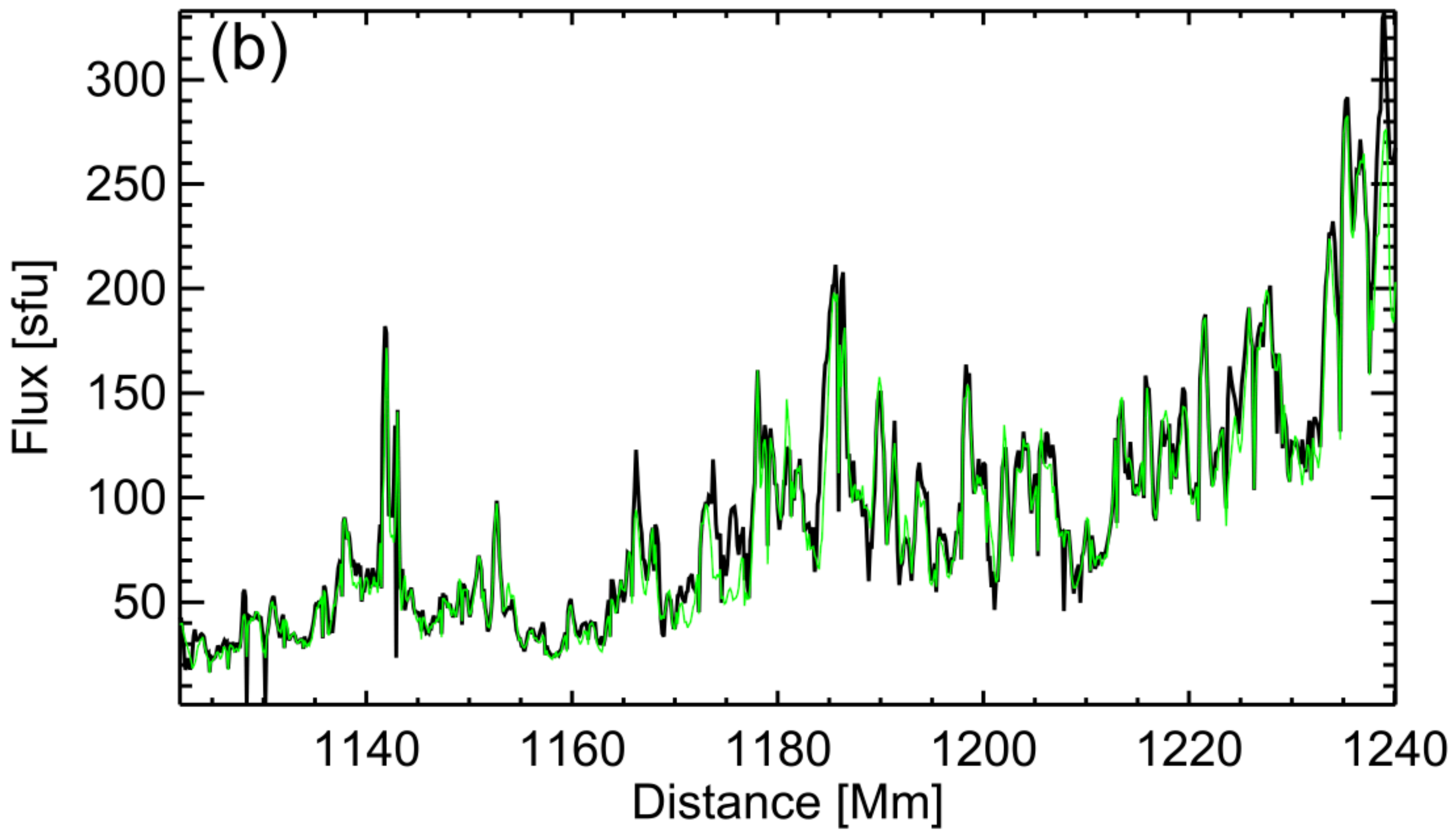
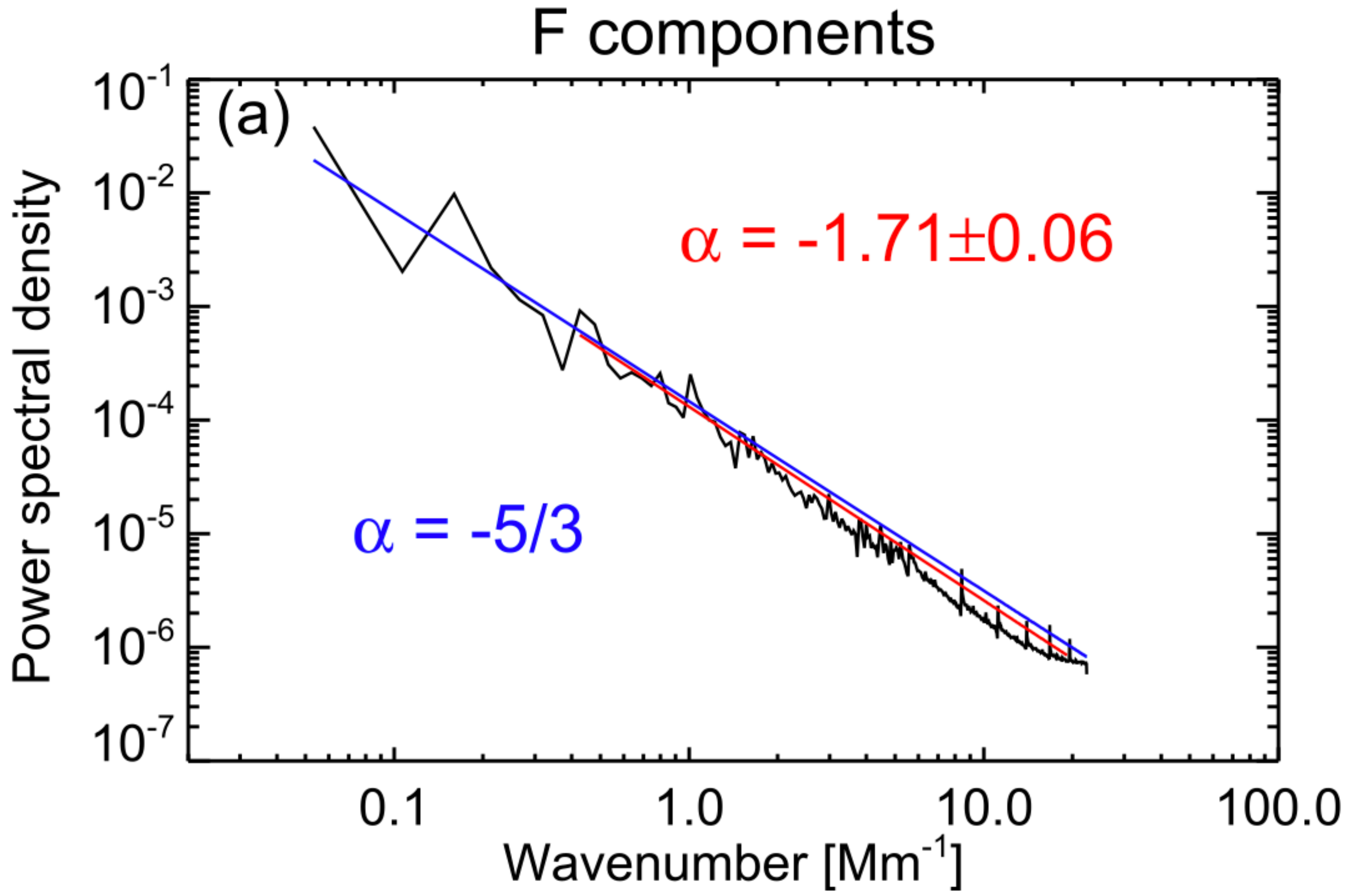




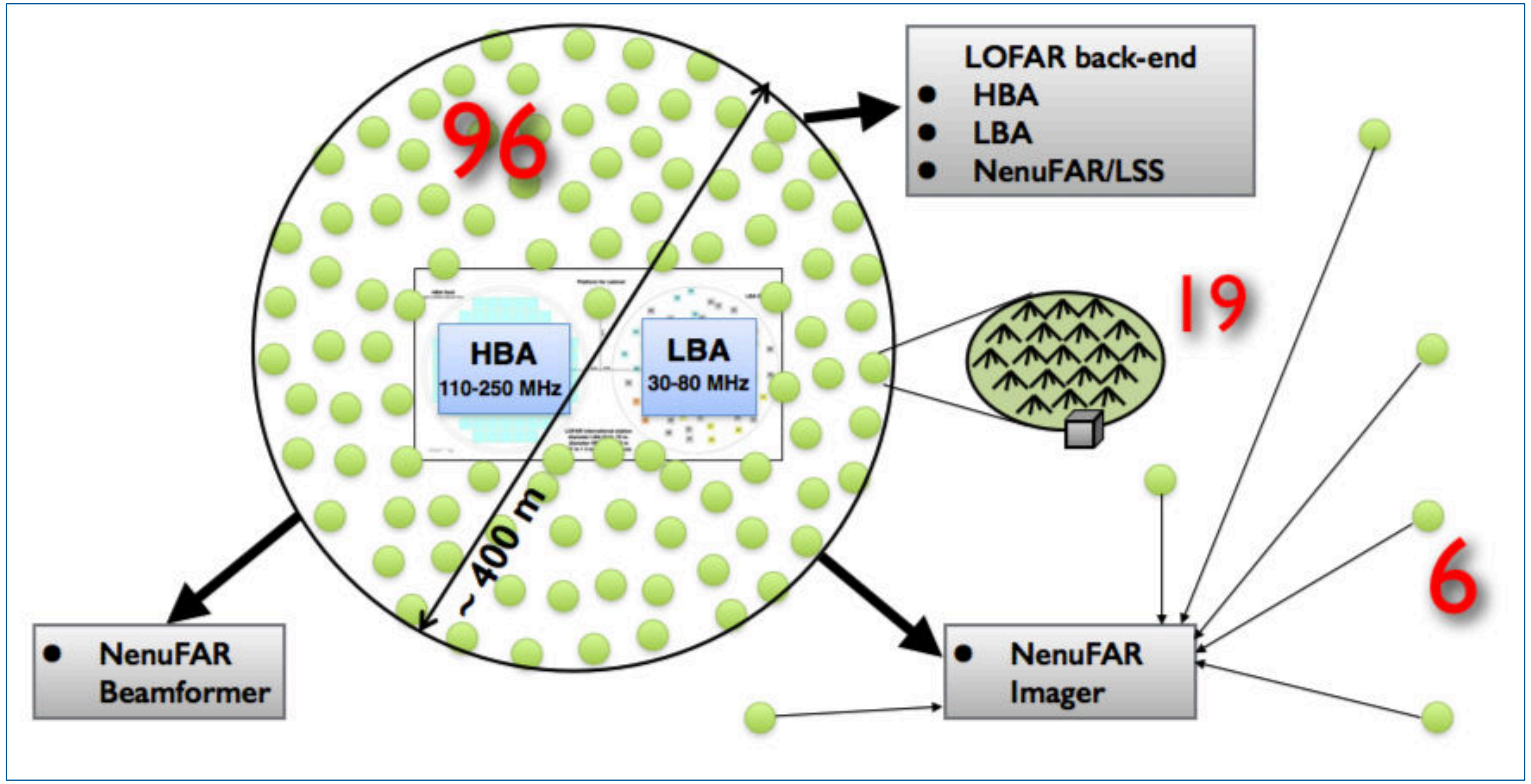
Chen et al. (2018)







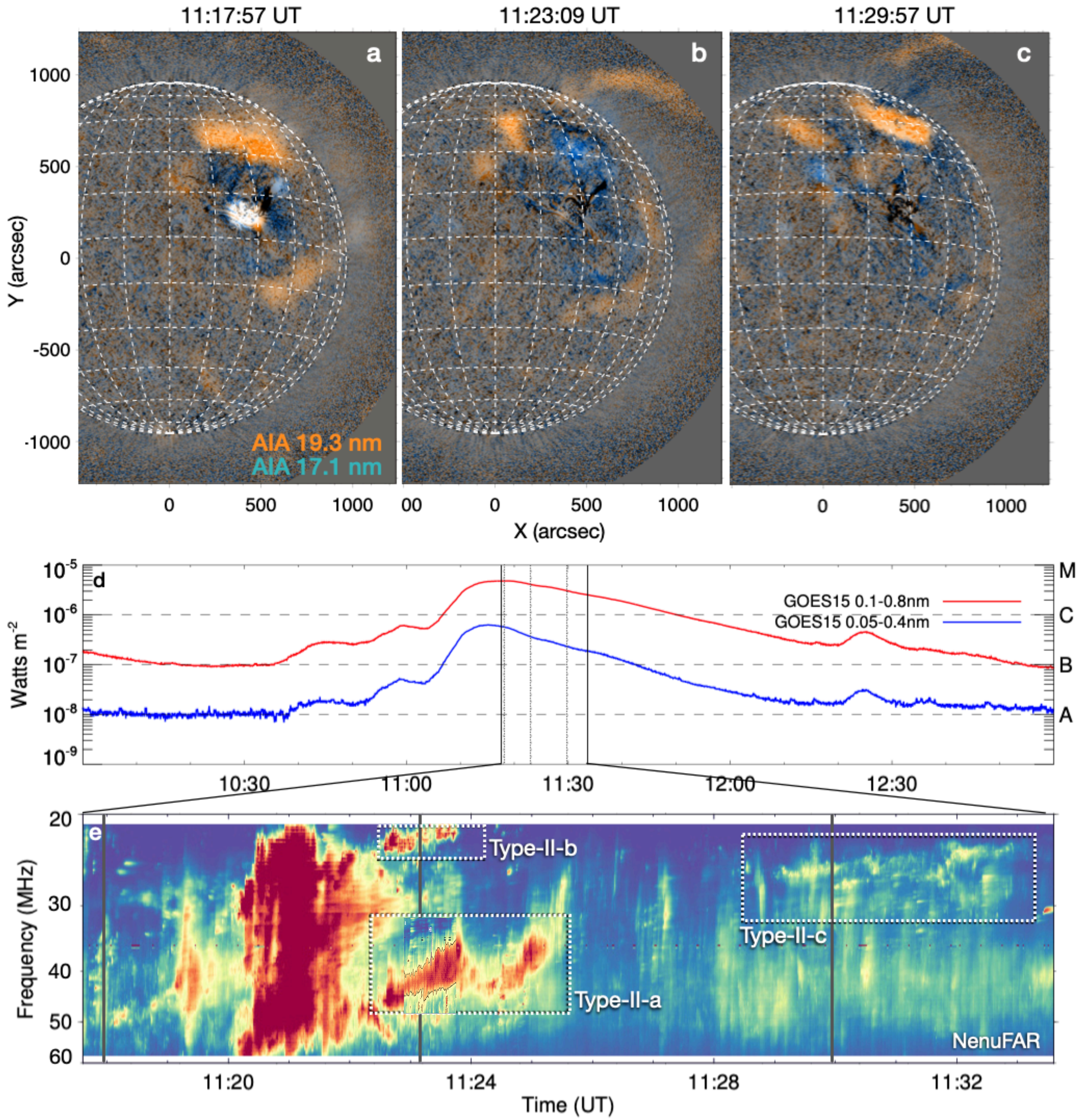
New Extension in Nançay Upgrading LOFAR (NenuFAR)



http://nenufar.obs-nancay.fr

- Radio interferometer operating between 10-85 MHz.
- Composed of 'mini-arrays' of 19 LWAs each.
- NenuFAR is still in its 'Early Science Phase'.
- 15 key programmes, e.g: Cosmic Dawn, Exoplanets & Stars, Pulsars, Transients, FRBs, Solar
- The 'Solar Key Project' of NenuFAR aims to observe quiet and active solar phenomena.

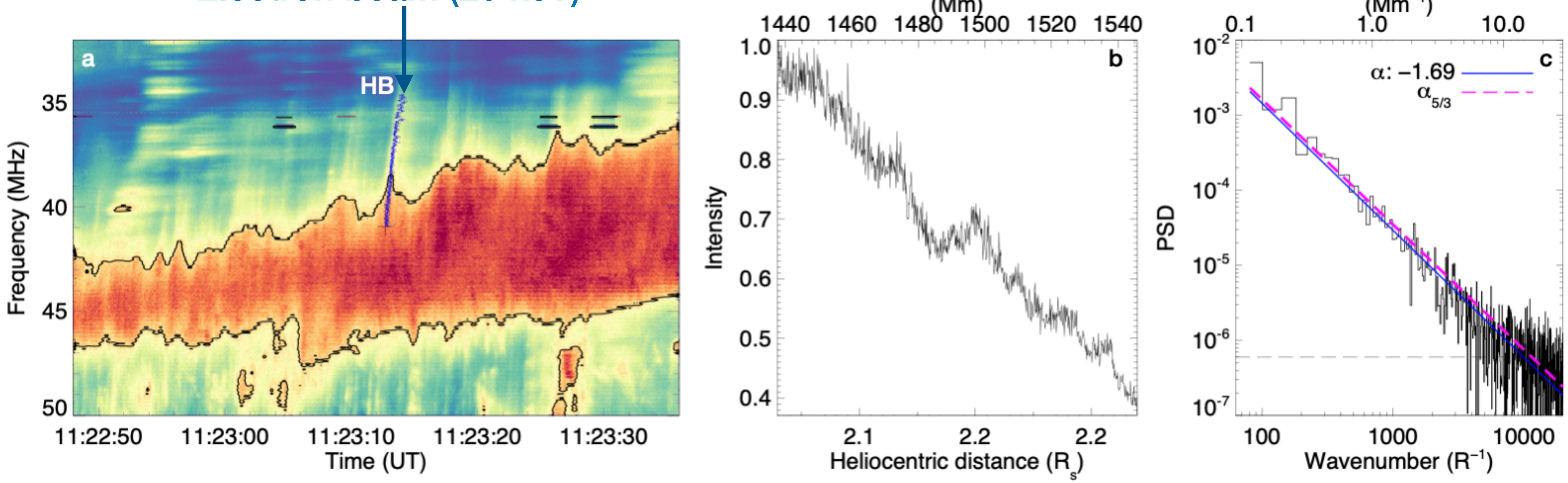
Solar eruptive event — 2019-March-20



- On 2019-March-20 an eruptive event was observed AIA
- Associated C4.8 flare
- NenuFAR observed a fragmented type II radio bursts
- The frequency and time resolution of 6 kHz and 5 ms, respectively:
  - Allows us to study type II burst fine structure.

Herringbones and turbulence

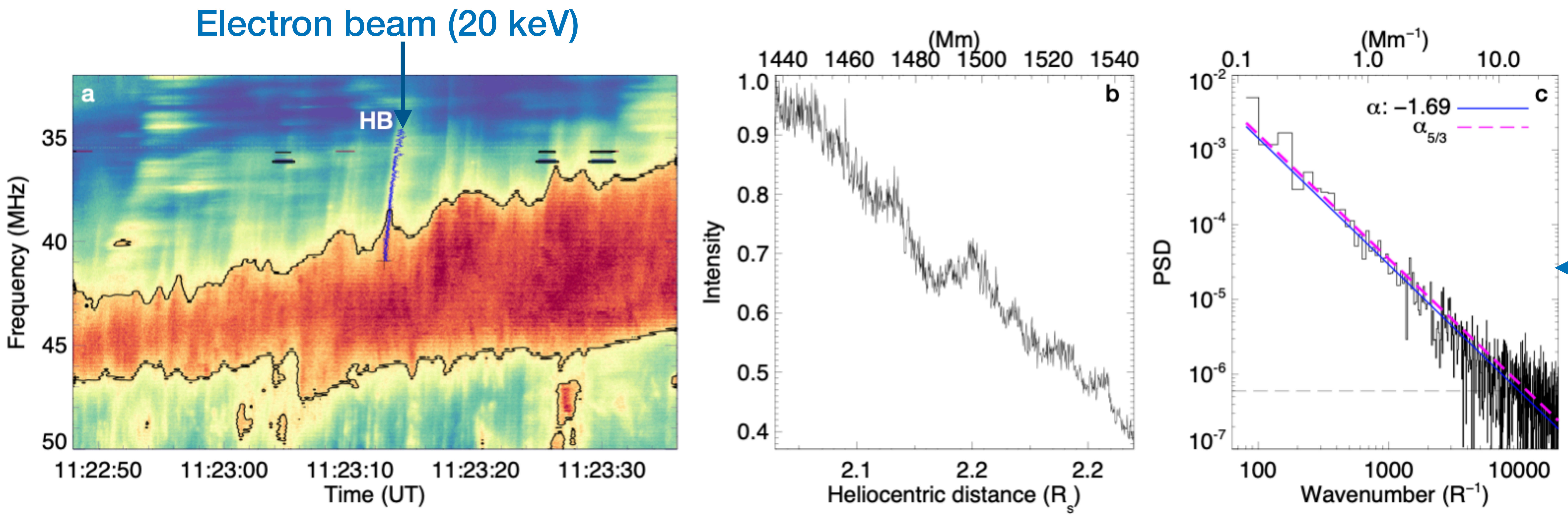
Electron beam (20 keV)



Shock radio burst

- v_{shock} = 1100 km/s,
- h_{shock} ~ 2 R_{sun}

Herringbones and turbulence



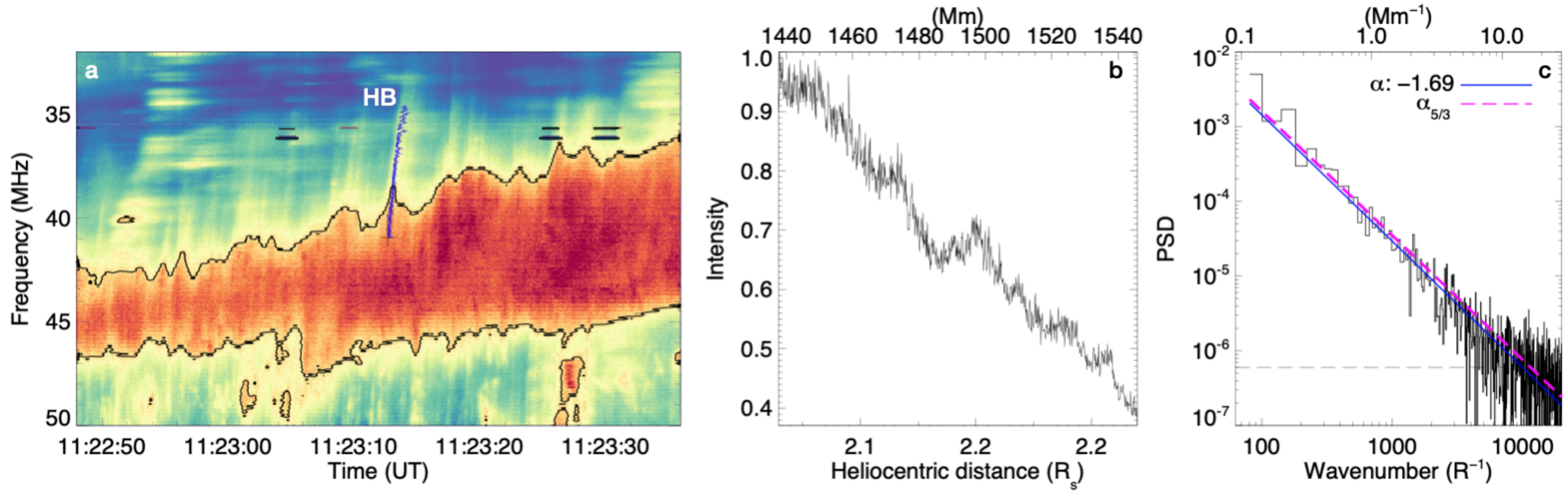
Density turbulence:

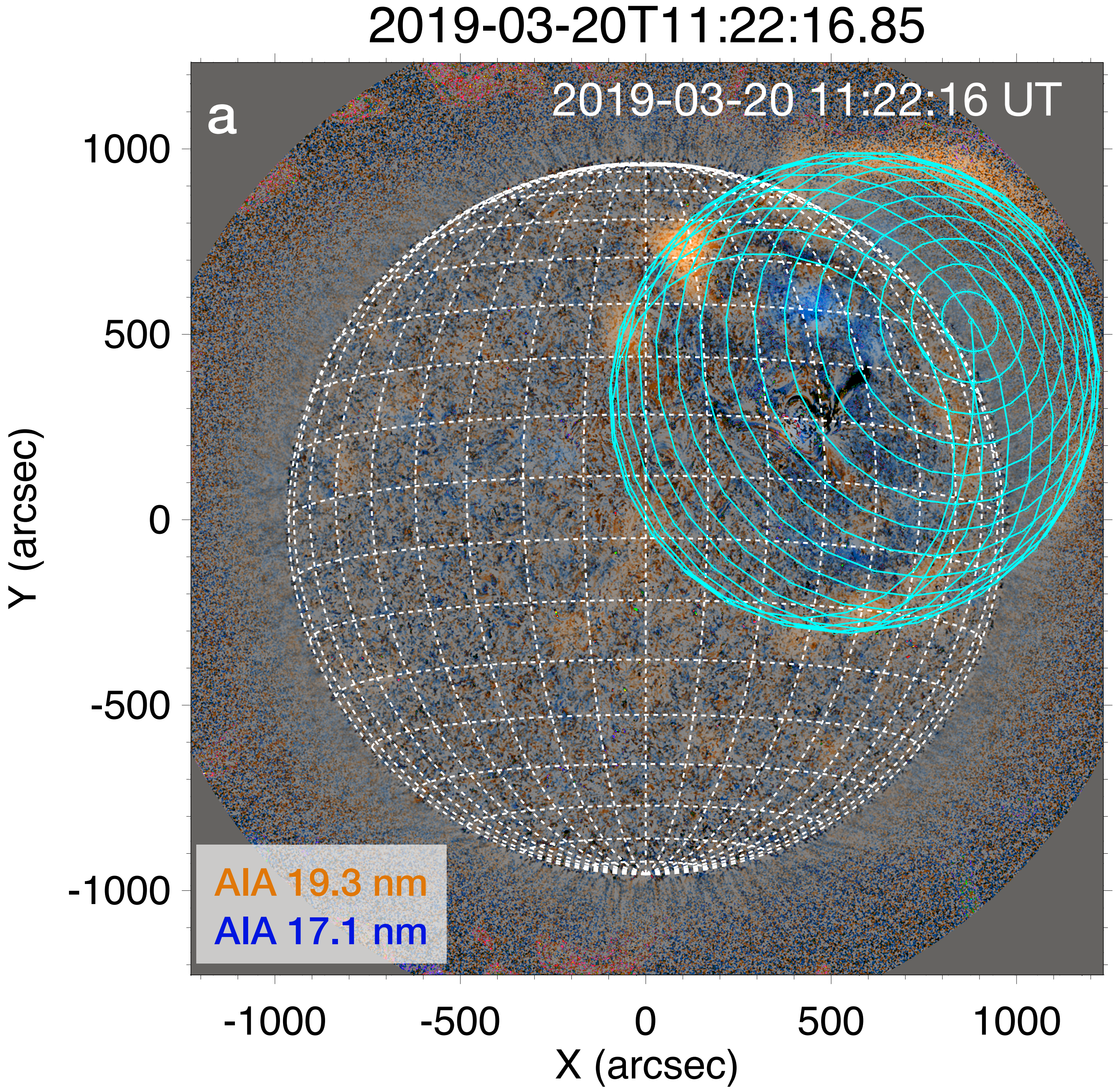
- $P \sim k^{-5/3}$
- $\Delta n/n \sim 0.8 \times 10^{-3}$

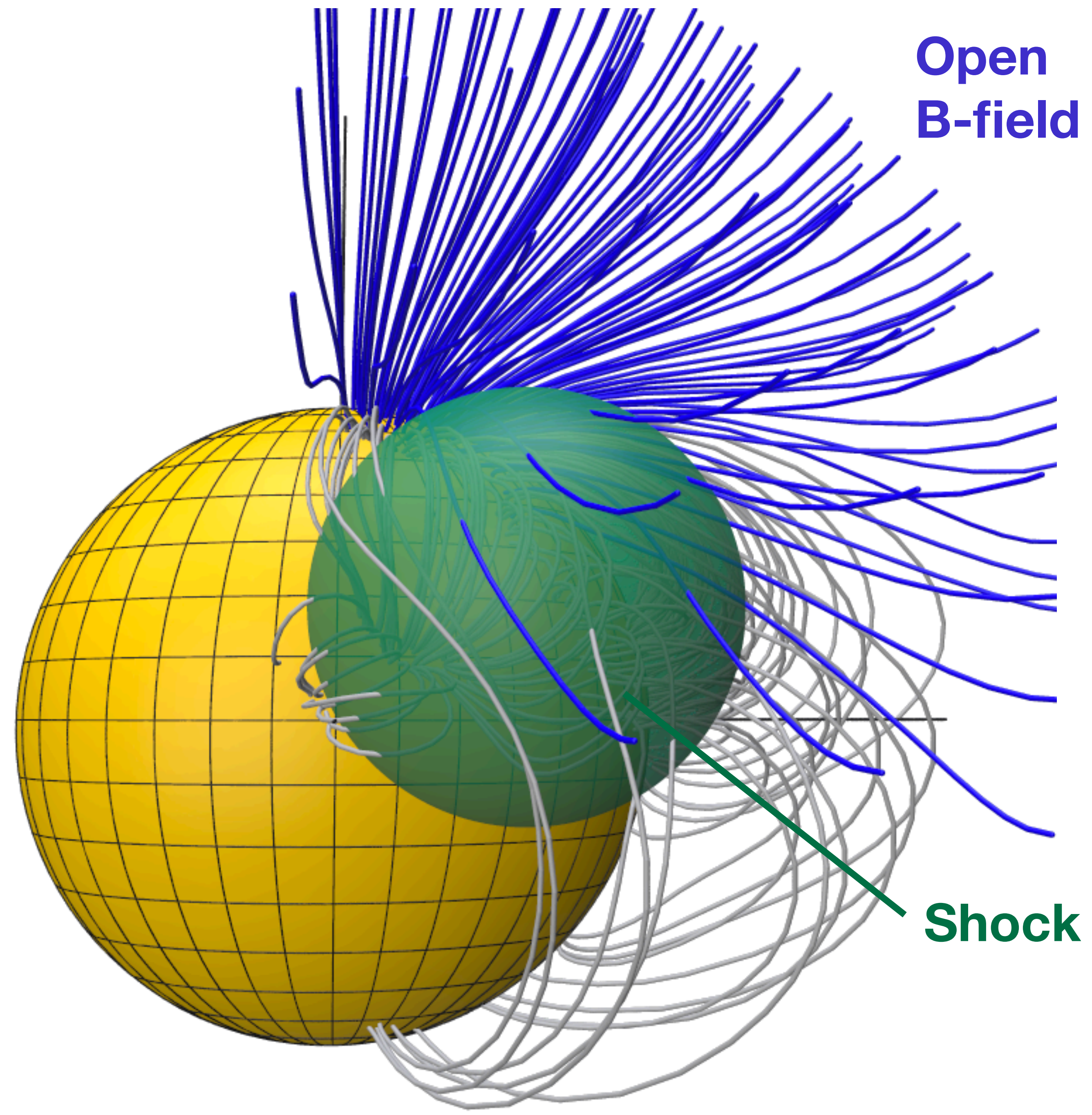
Shock radio burst

- v_{shock} = 1100 km/s,
- h_{shock} ~ 2 R_{sun}

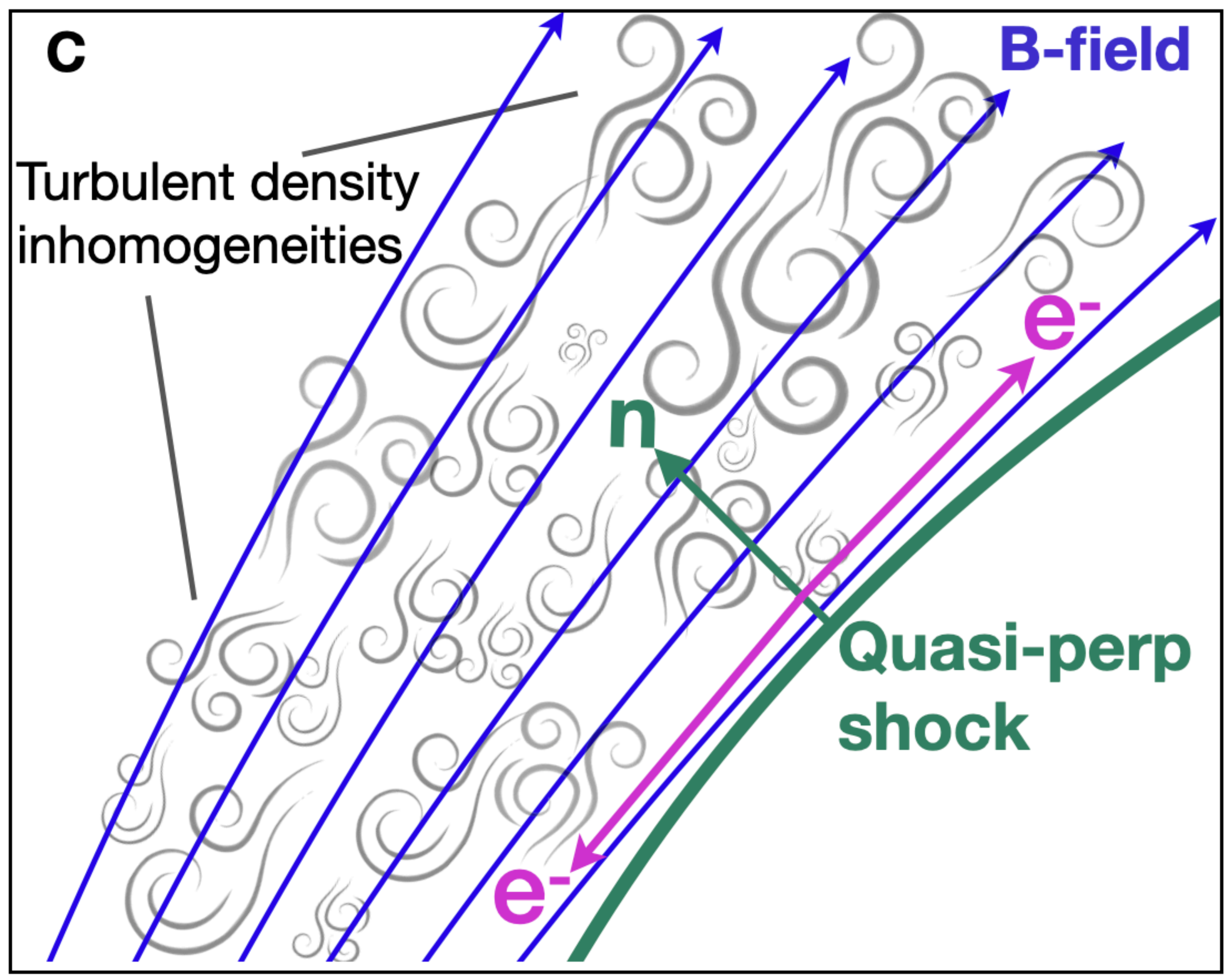
Herringbones and turbulence

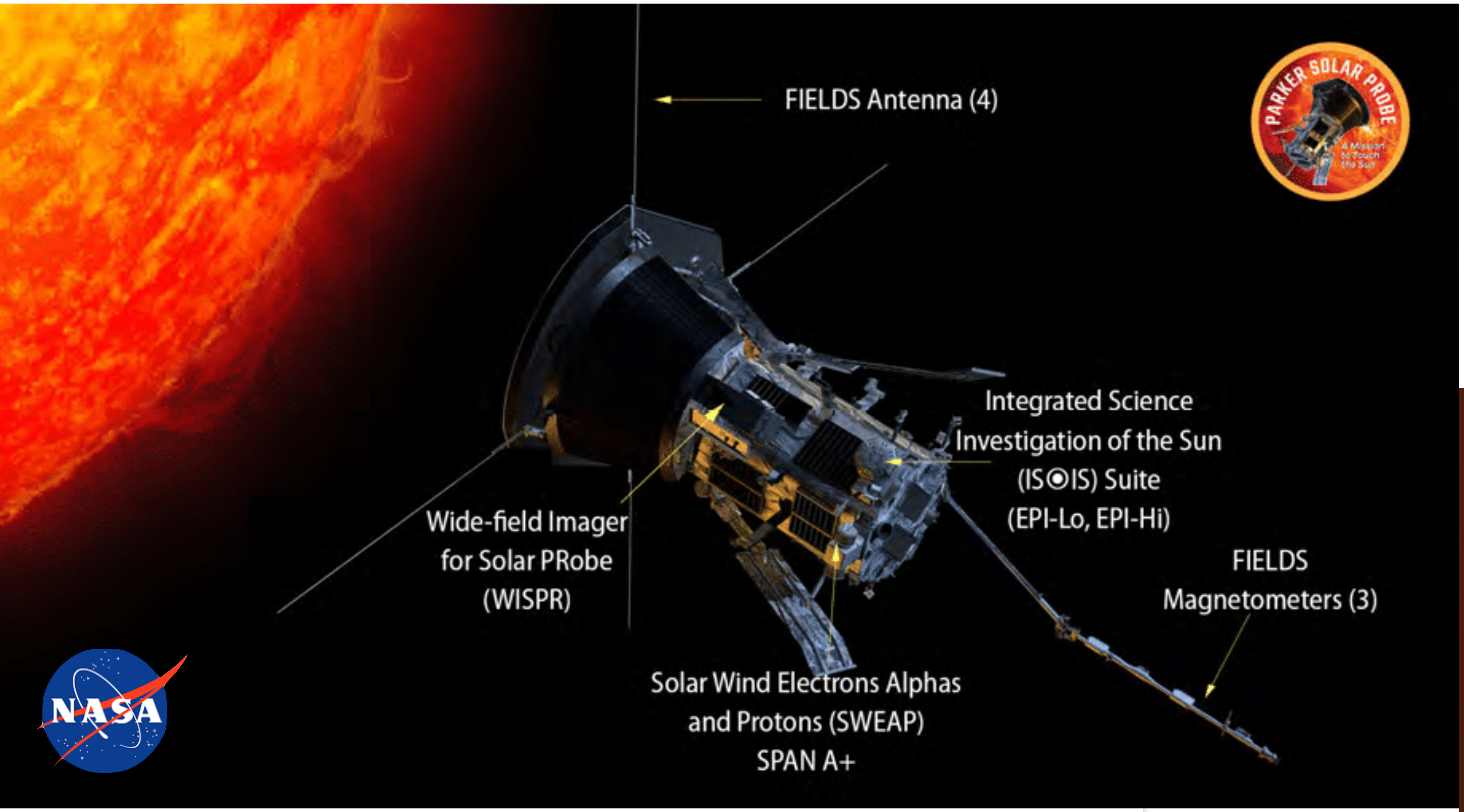






Carley et al., ApJ (in review)



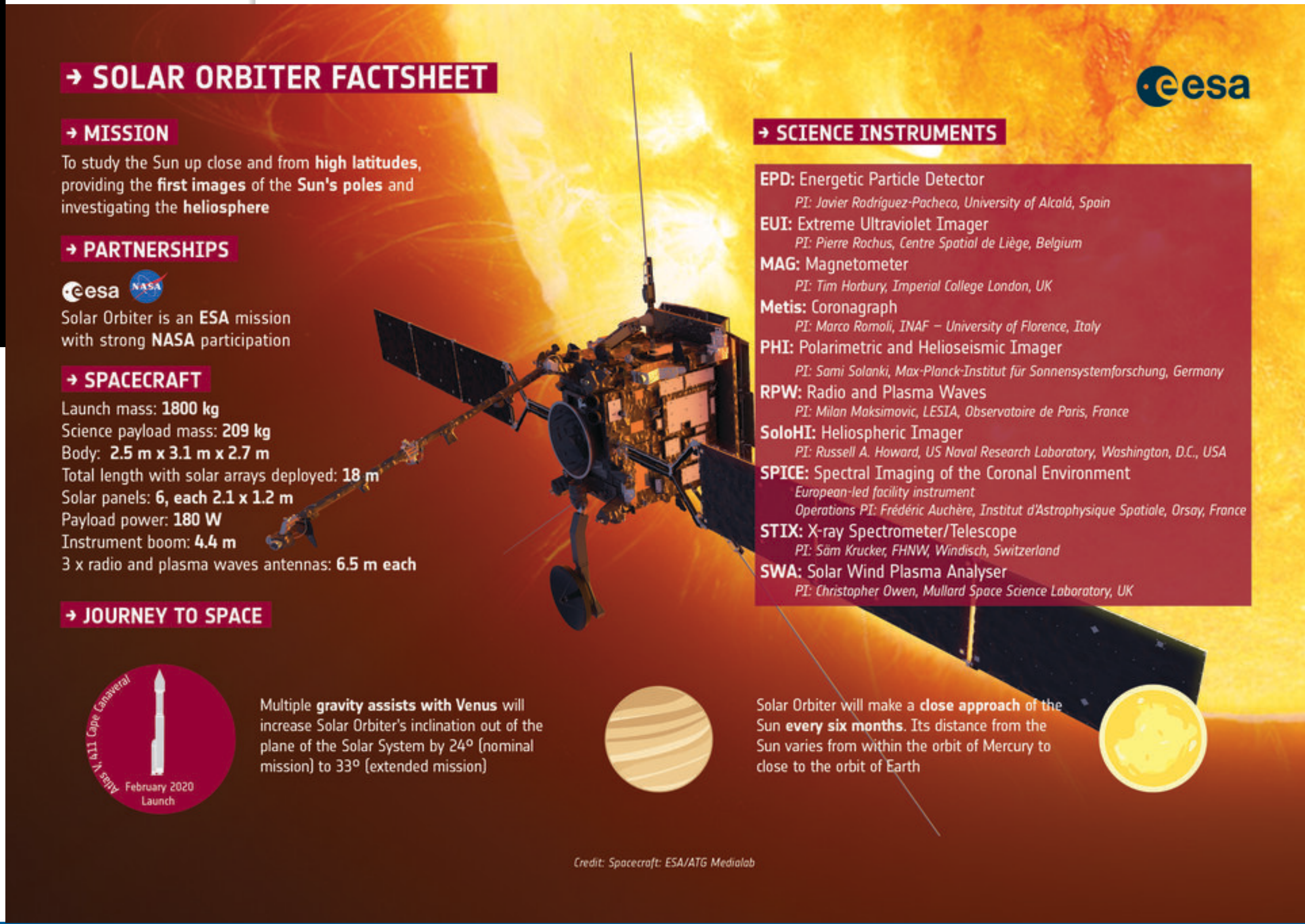


Parker Solar Probe

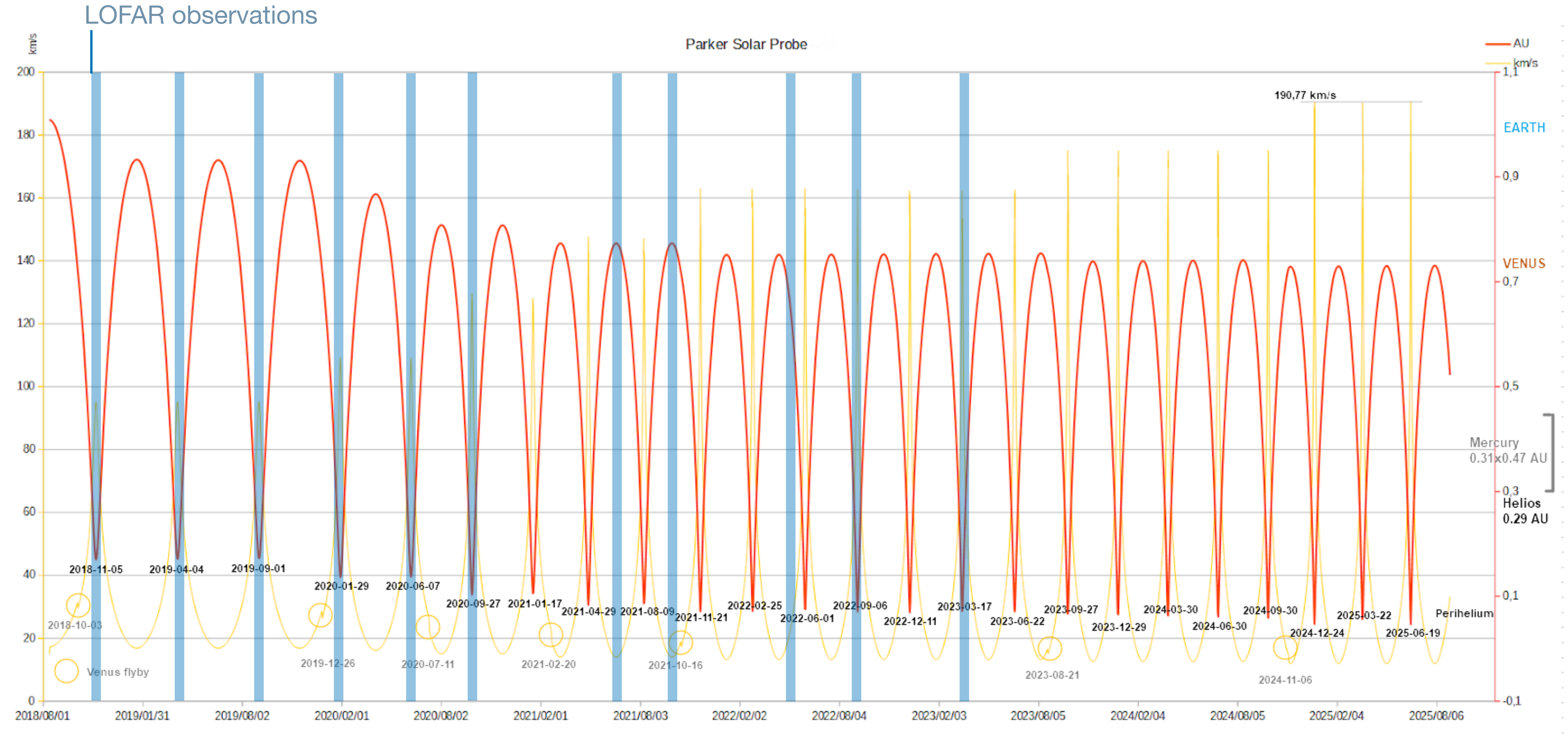
- Launched 2018-Aug-12
- Expected mission duration: ~7 years (nominal)
- 24 Orbits of the Sun.
- 5 instruments (remote-sensing and in-situ
- Closest approach: 9.9 R_{sun}

Solar Orbiter

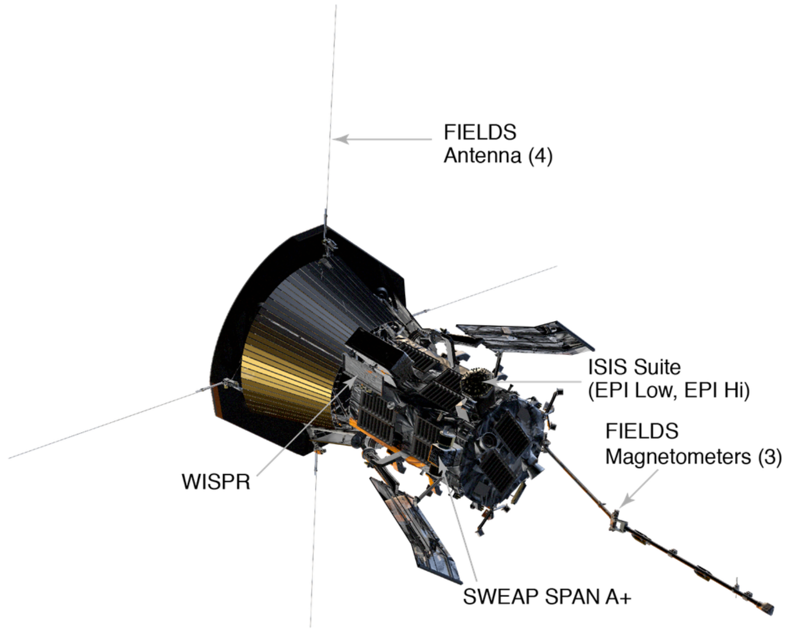
- Launched 2020-Feb-10
- Expected mission duration: ~7 years (nominal)
- 10 instruments on board (remote sensing and in-situ)
- Closest approach: 0.28 AU.

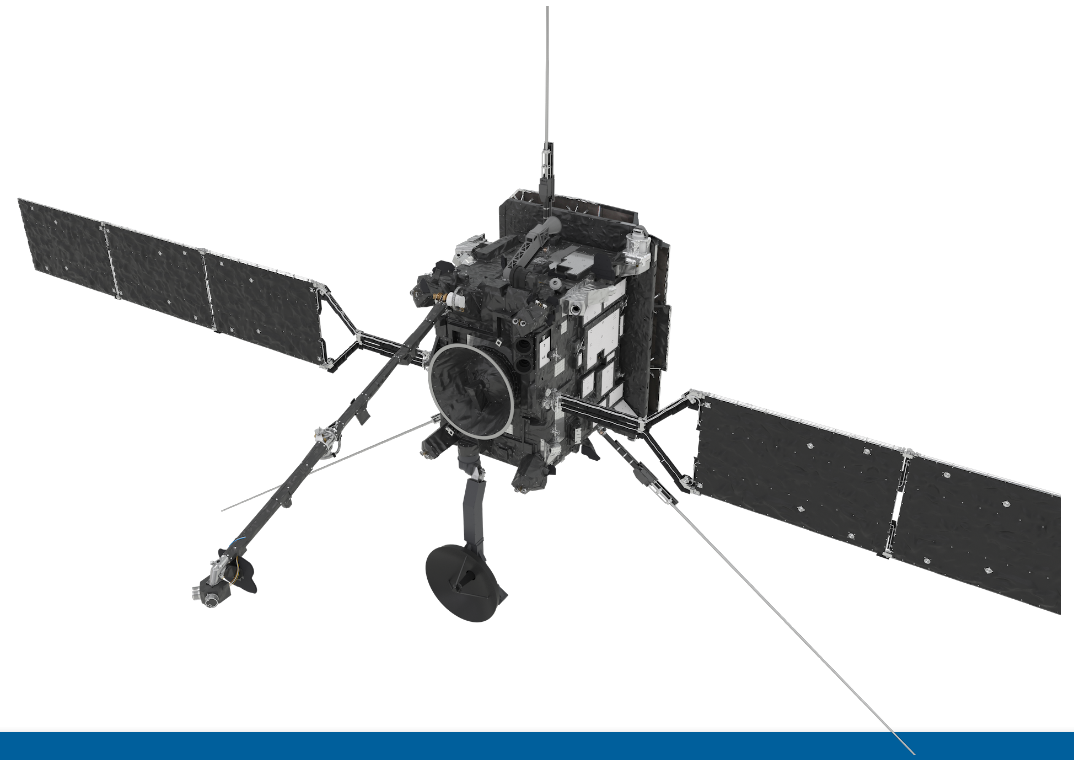


LOFAR, PSP and SoLO

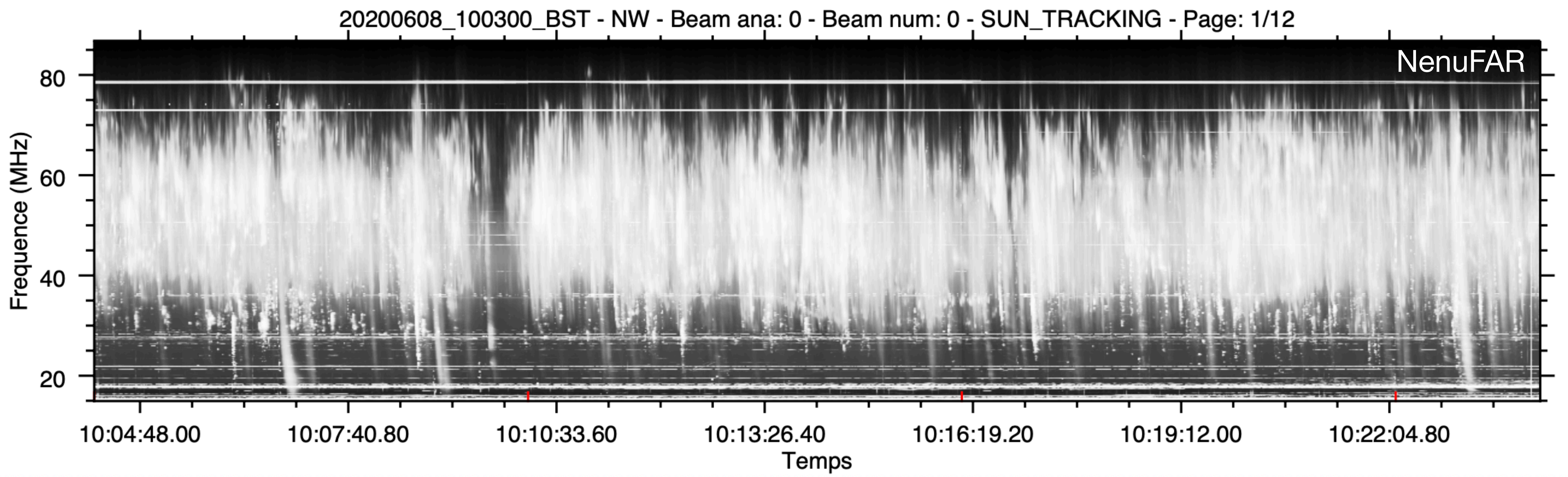


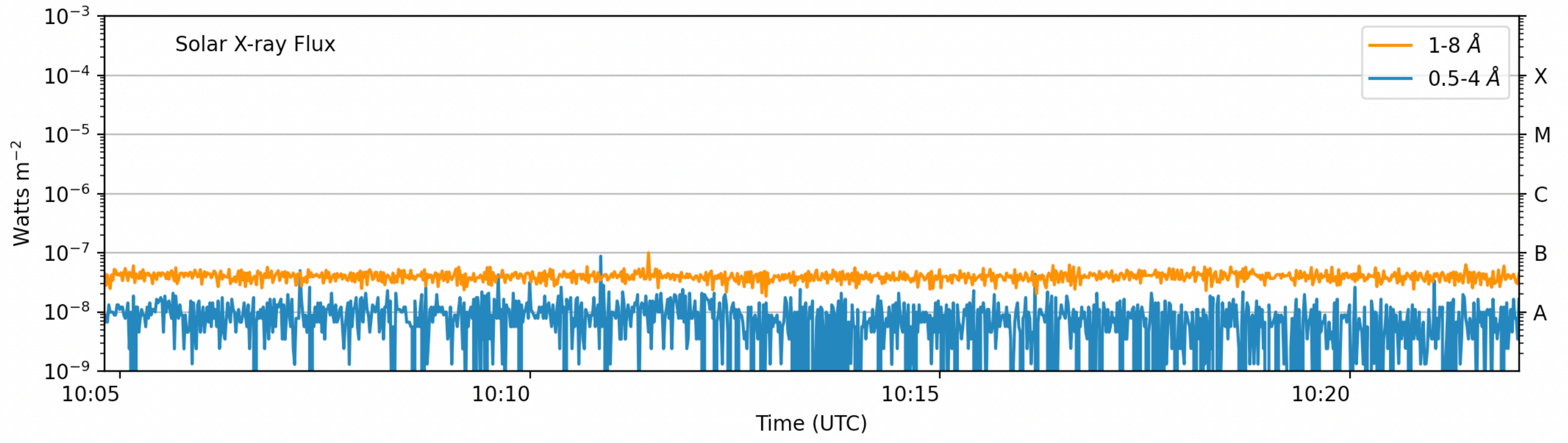
- LOFAR observations during PSP and SoLO perihelia:
  - TAB Imaging
  - Interferometric imaging
  - Interplanetary Scintillations Studies
  - Faraday Rotations Studies
  - Ionospheric scintillation
  - Full core, remote and international stations

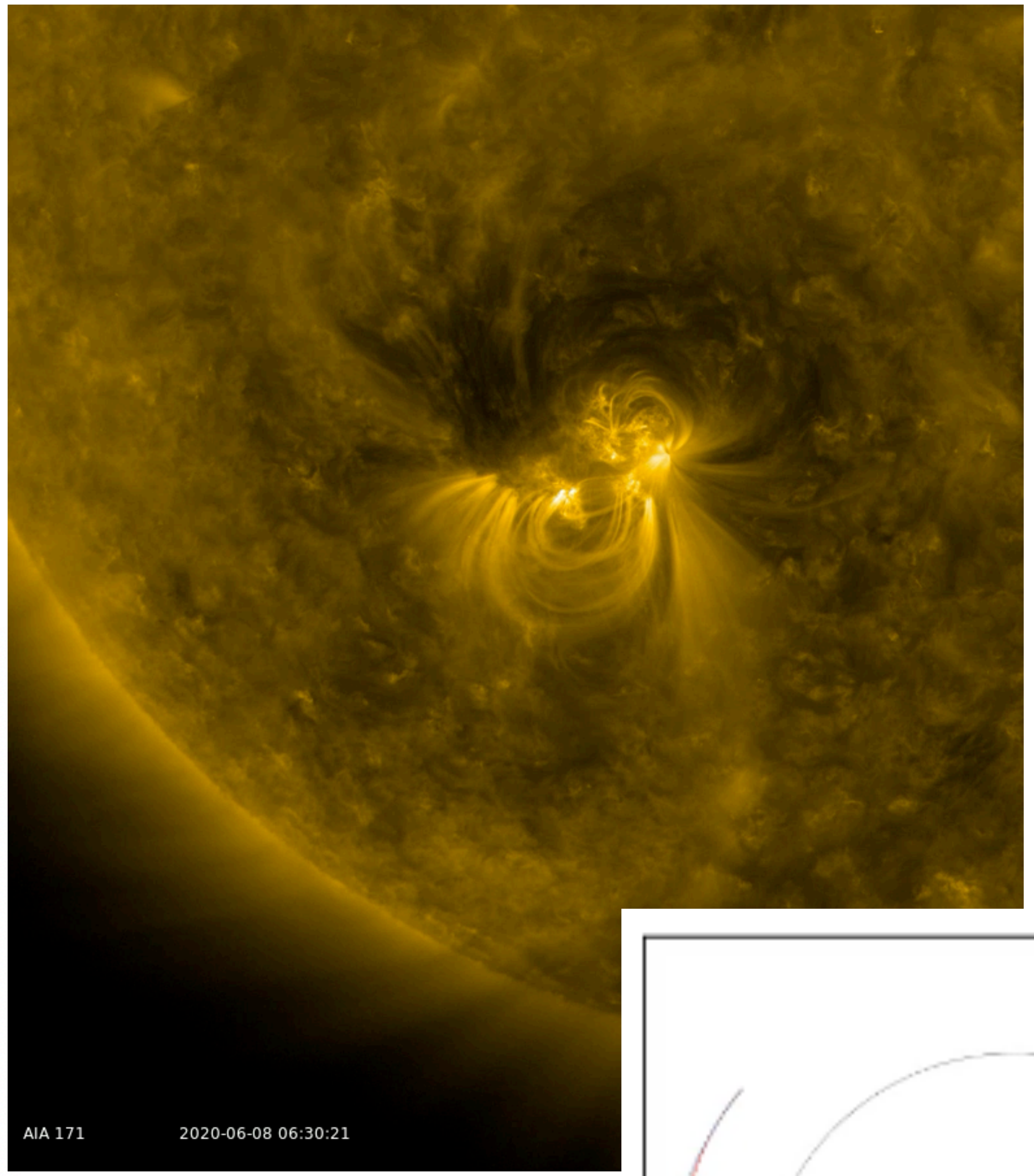


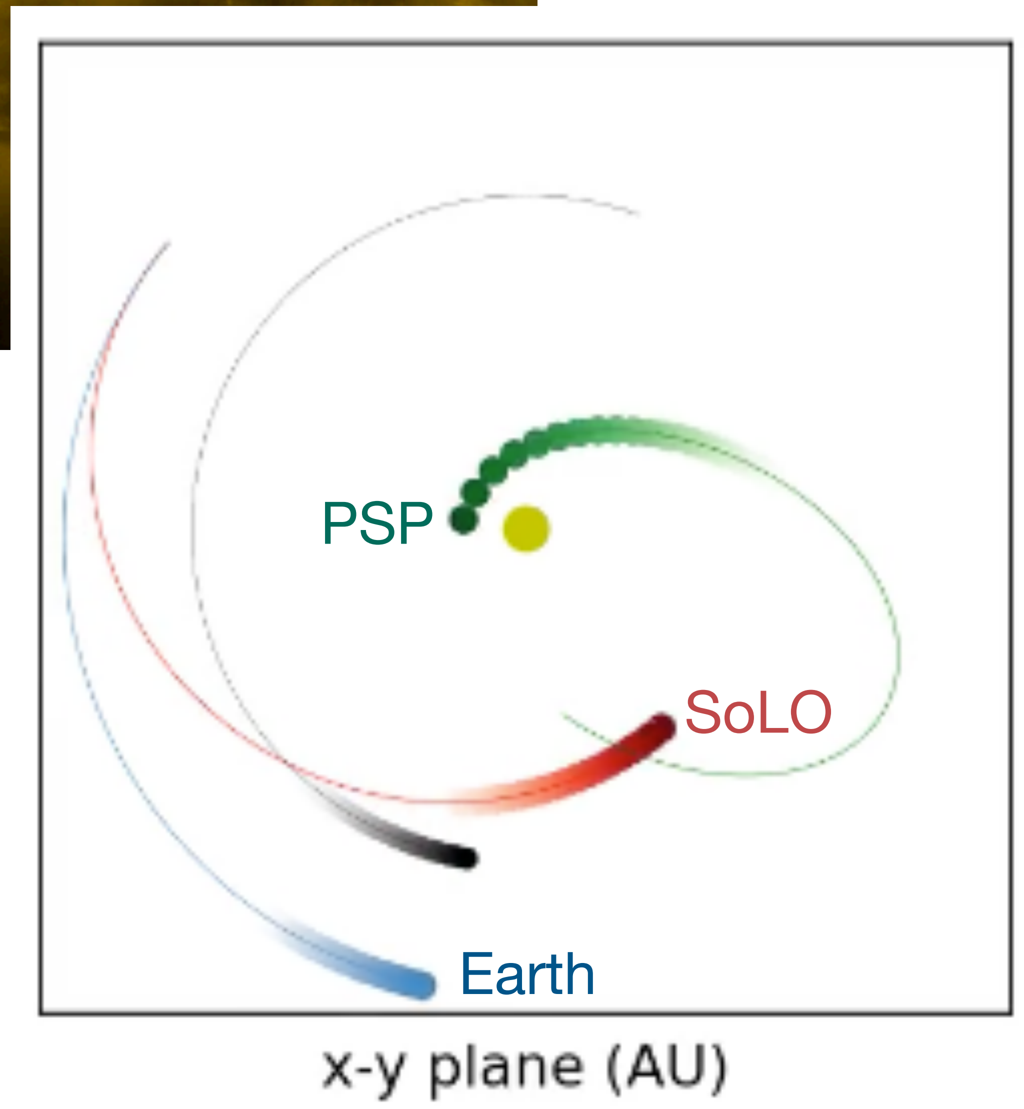


LOFAR, NenuFAR, PSP and SoLO



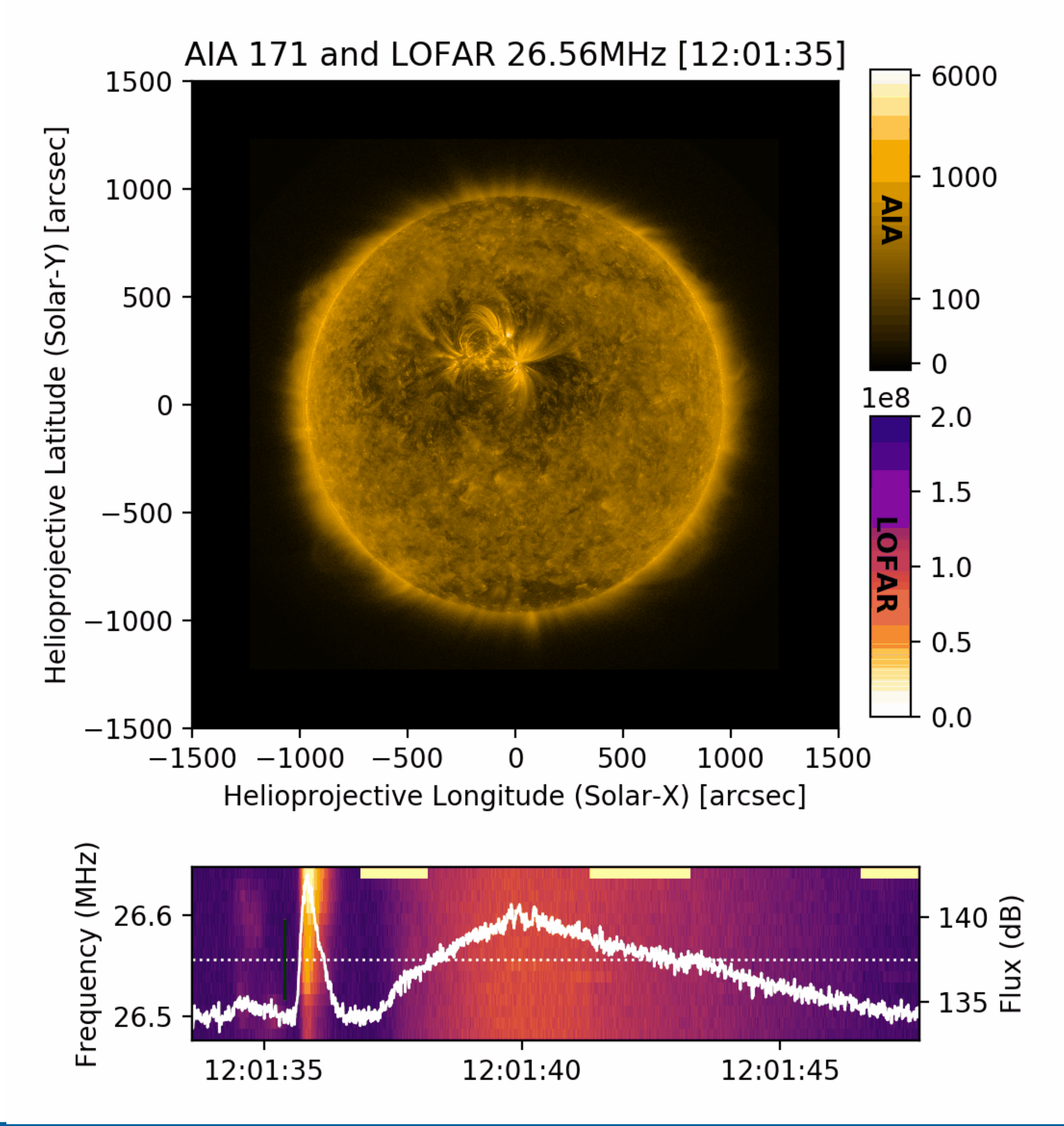




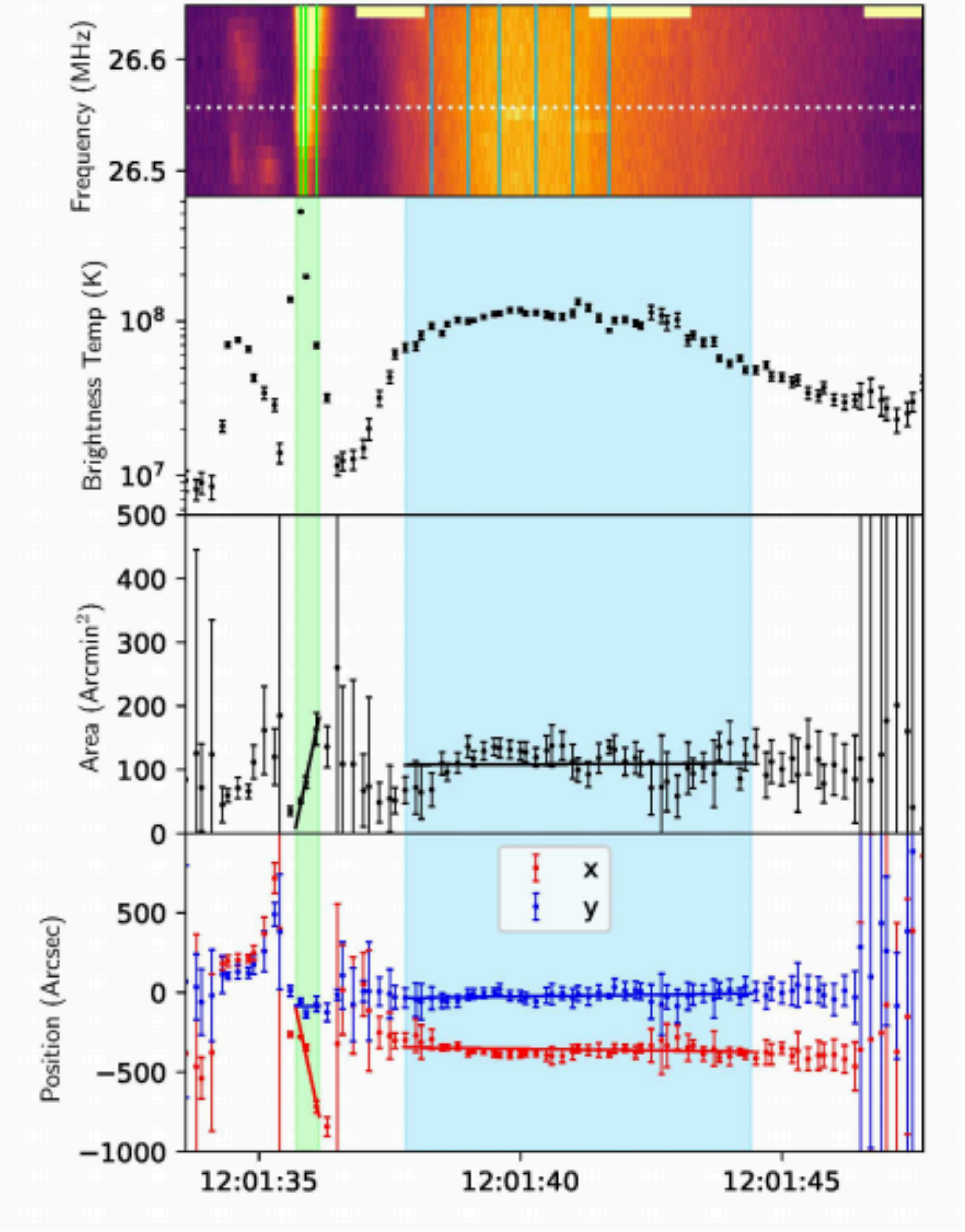


- No flaring (or very small) observed in X-ray or active region
- Thousands of type III radio bursts observed for hours.
    - What causes this continuous particle acceleration?

LOFAR, NenuFAR, PSP and SoLO

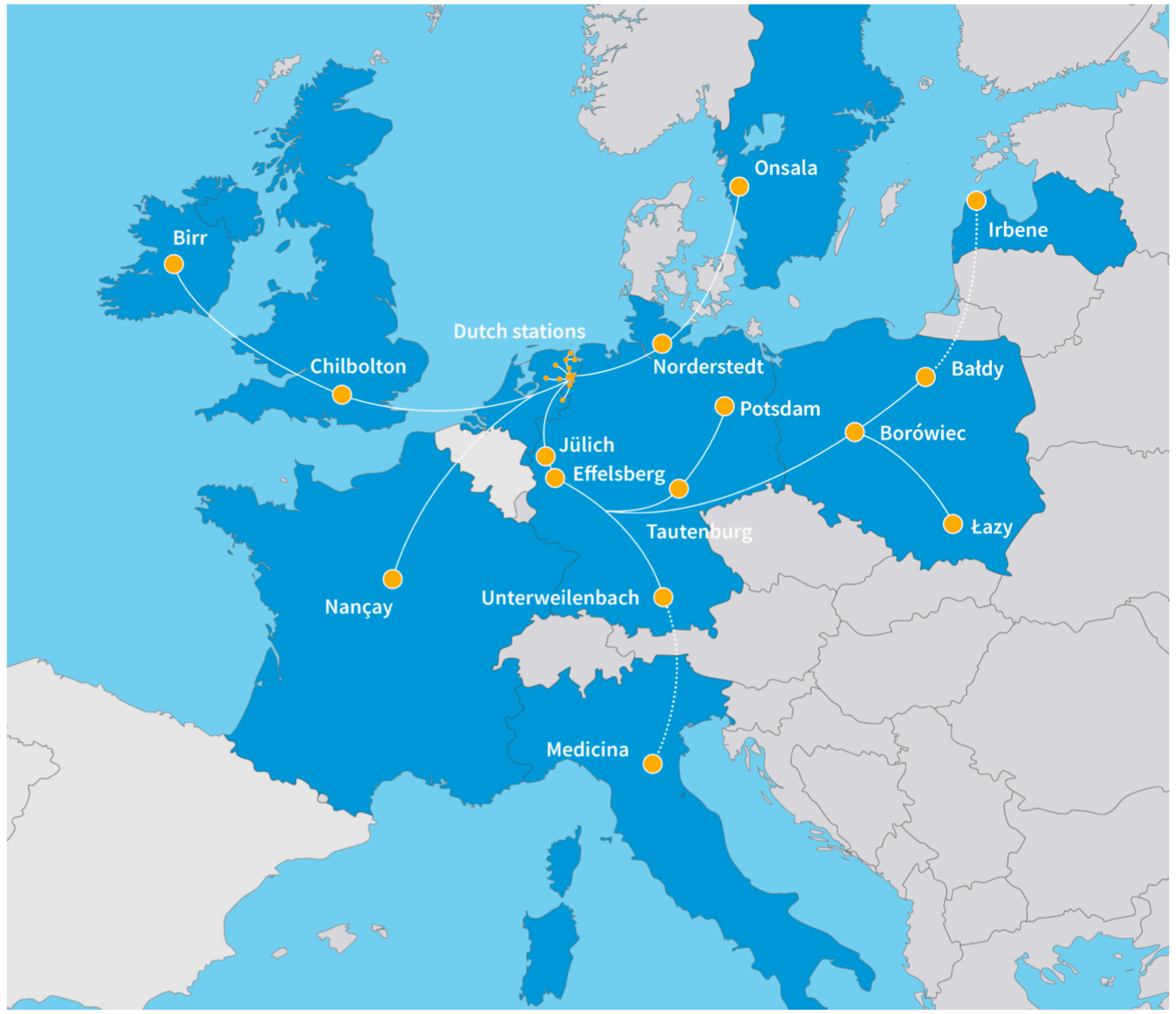


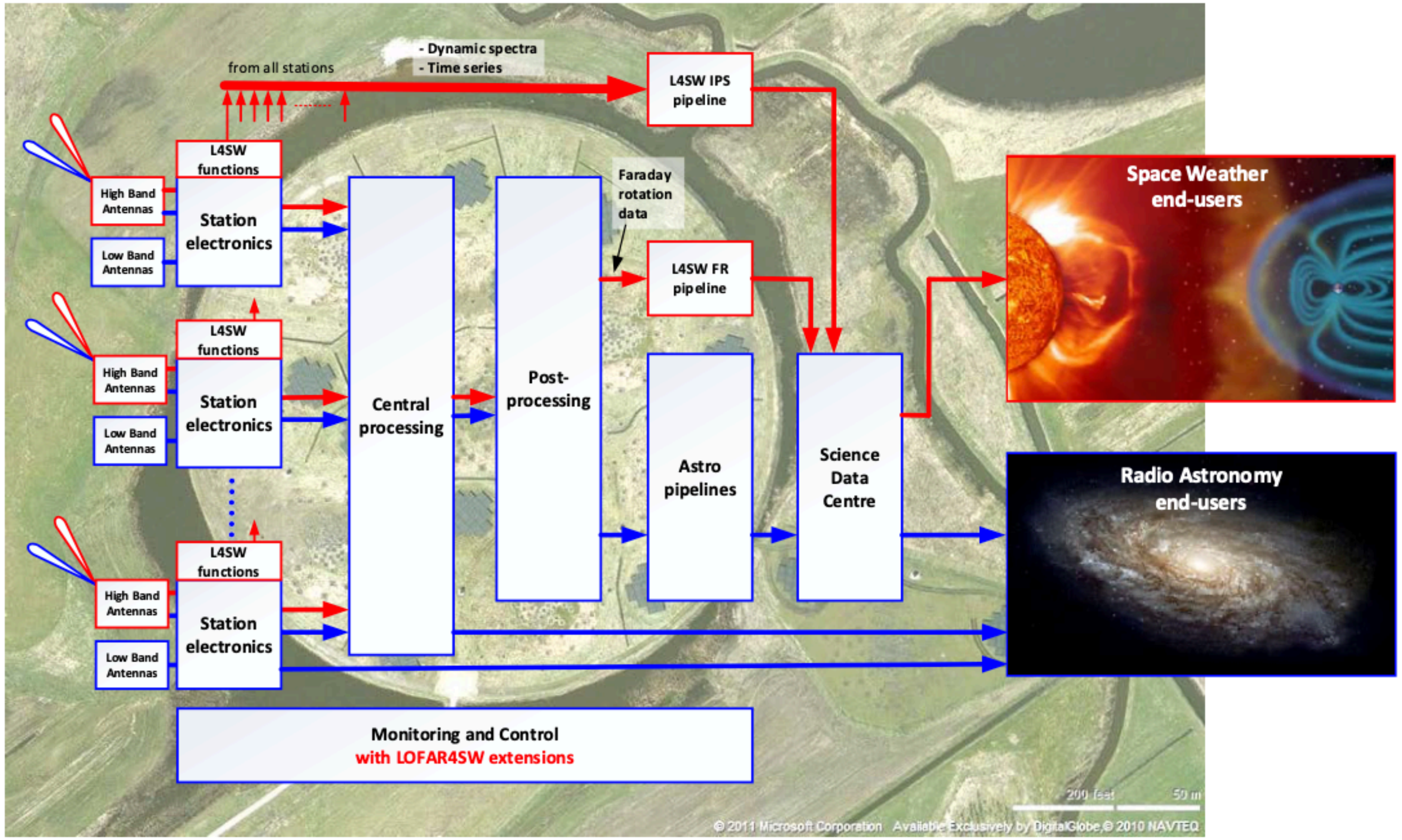
Zhang et al., A&A (2020)



LOFAR for Space Weather (LOFAR4SW)

- European Commission H2020 design study consisting of 8 European partners
- Aim to design an upgrade to allow LOFAR to *routinely* observe space weather phenomena



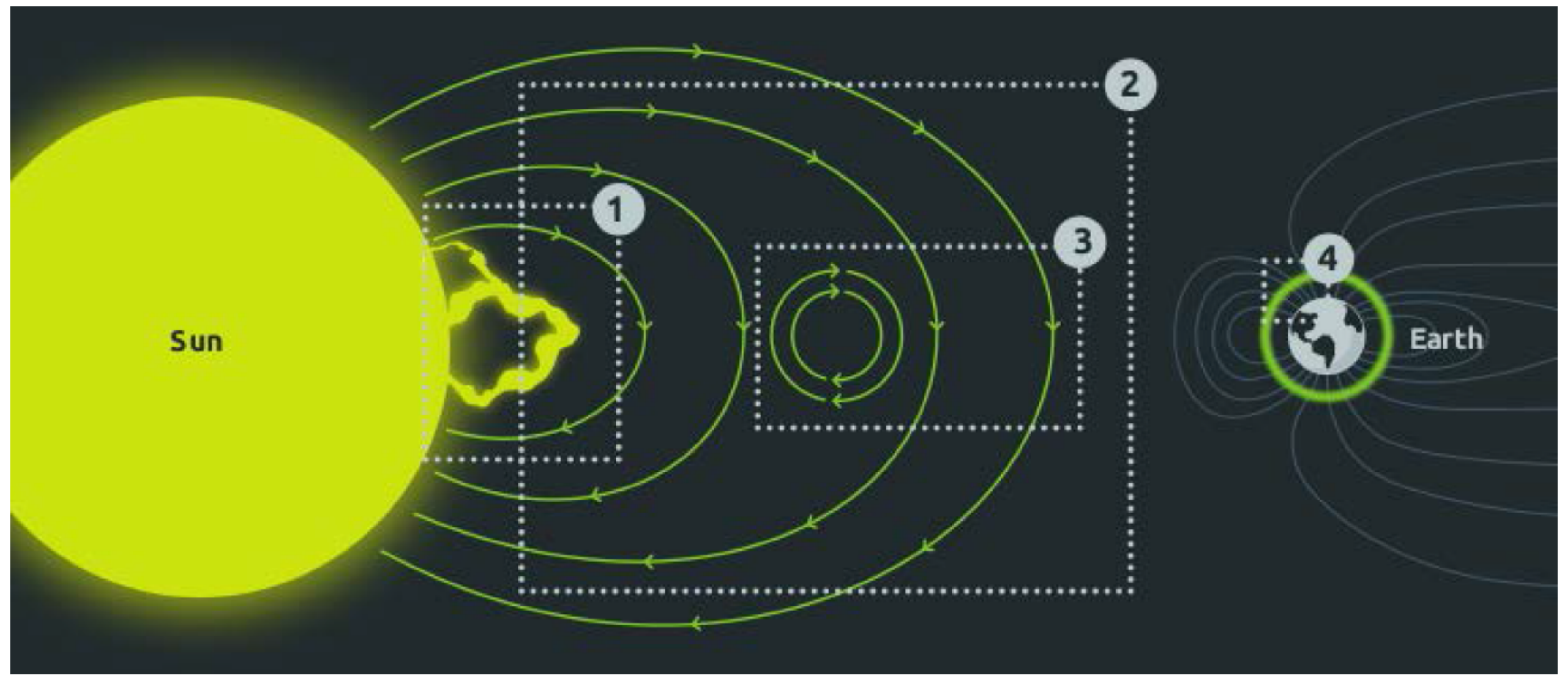


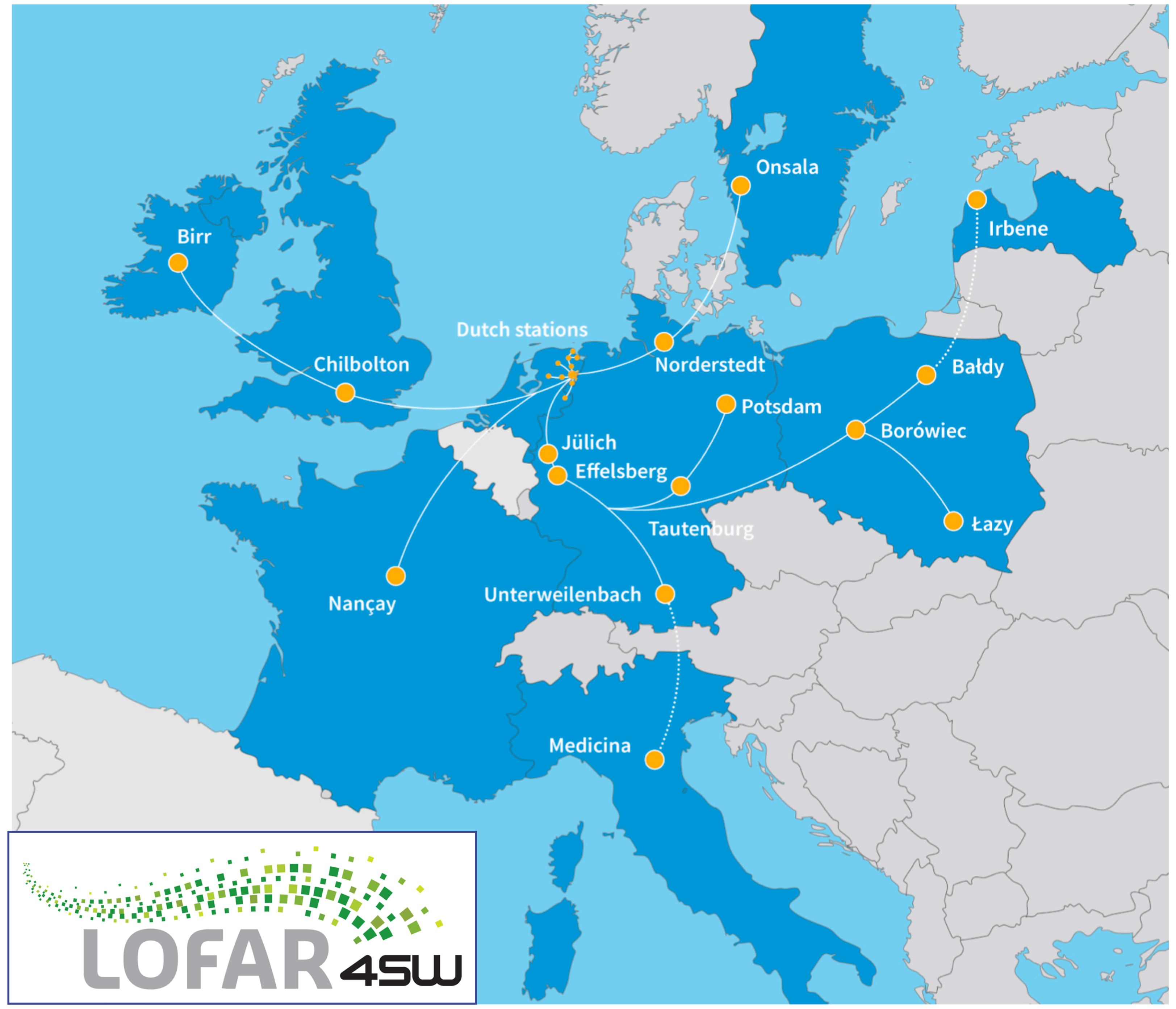
European Commission

LOFAR4SW

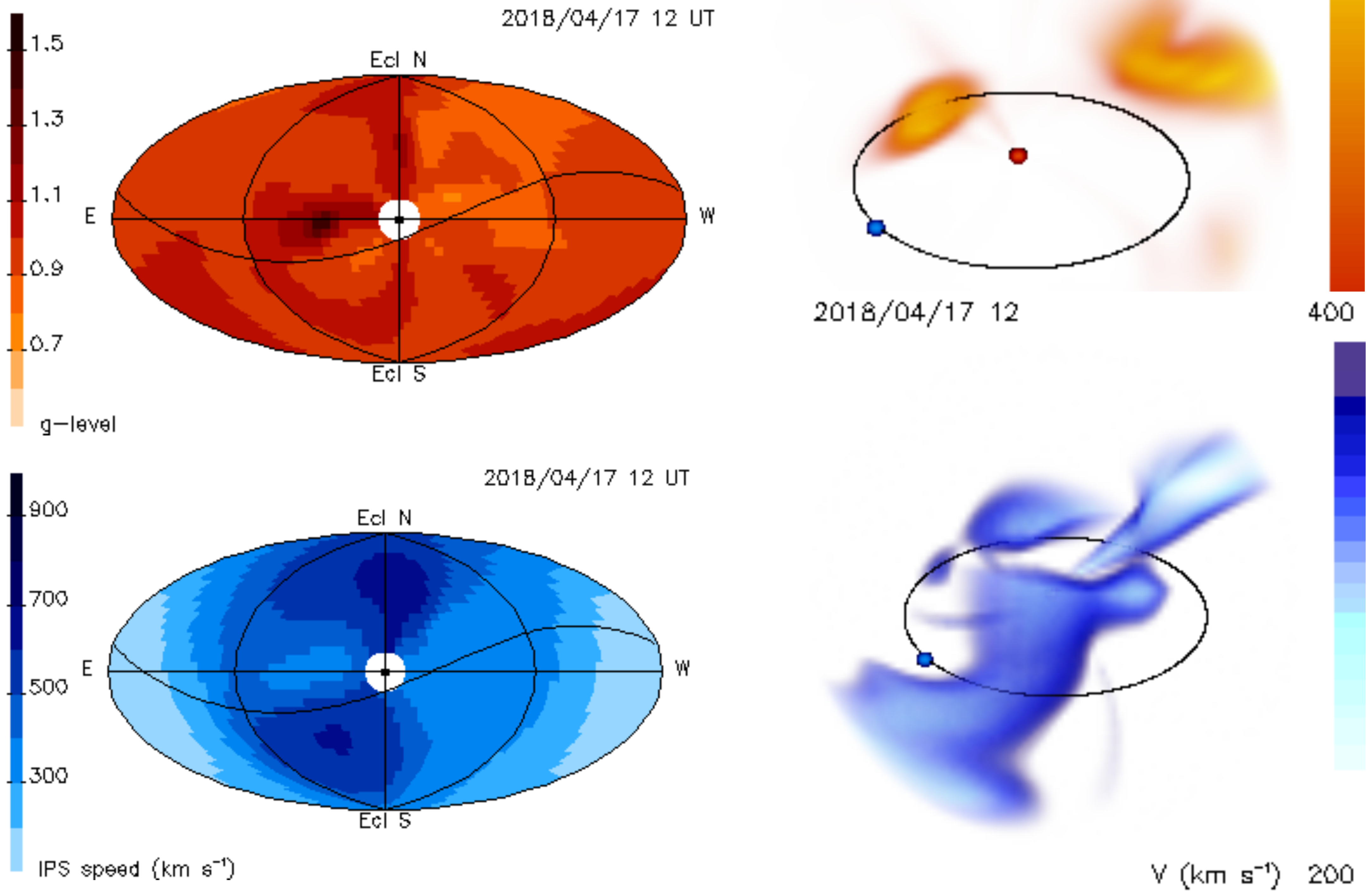
www.lofar4sw.eu

LOFAR for Space Weather (LOFAR4SW)

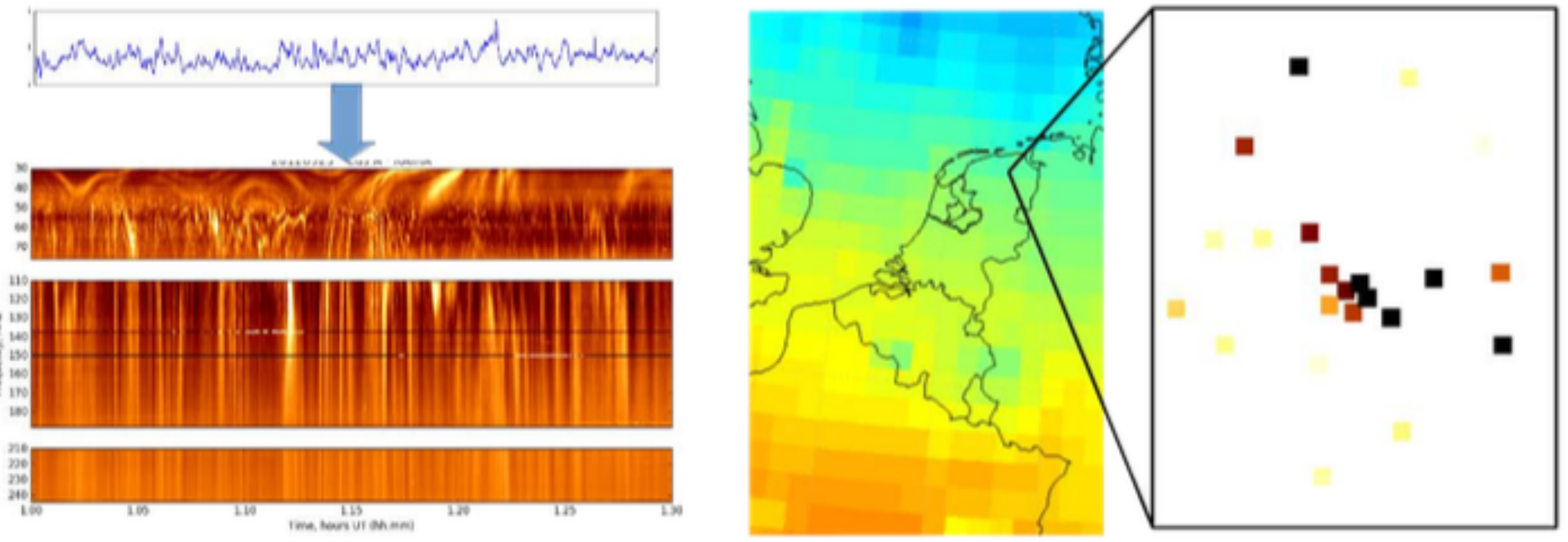




IPS and tomography of the solar wind

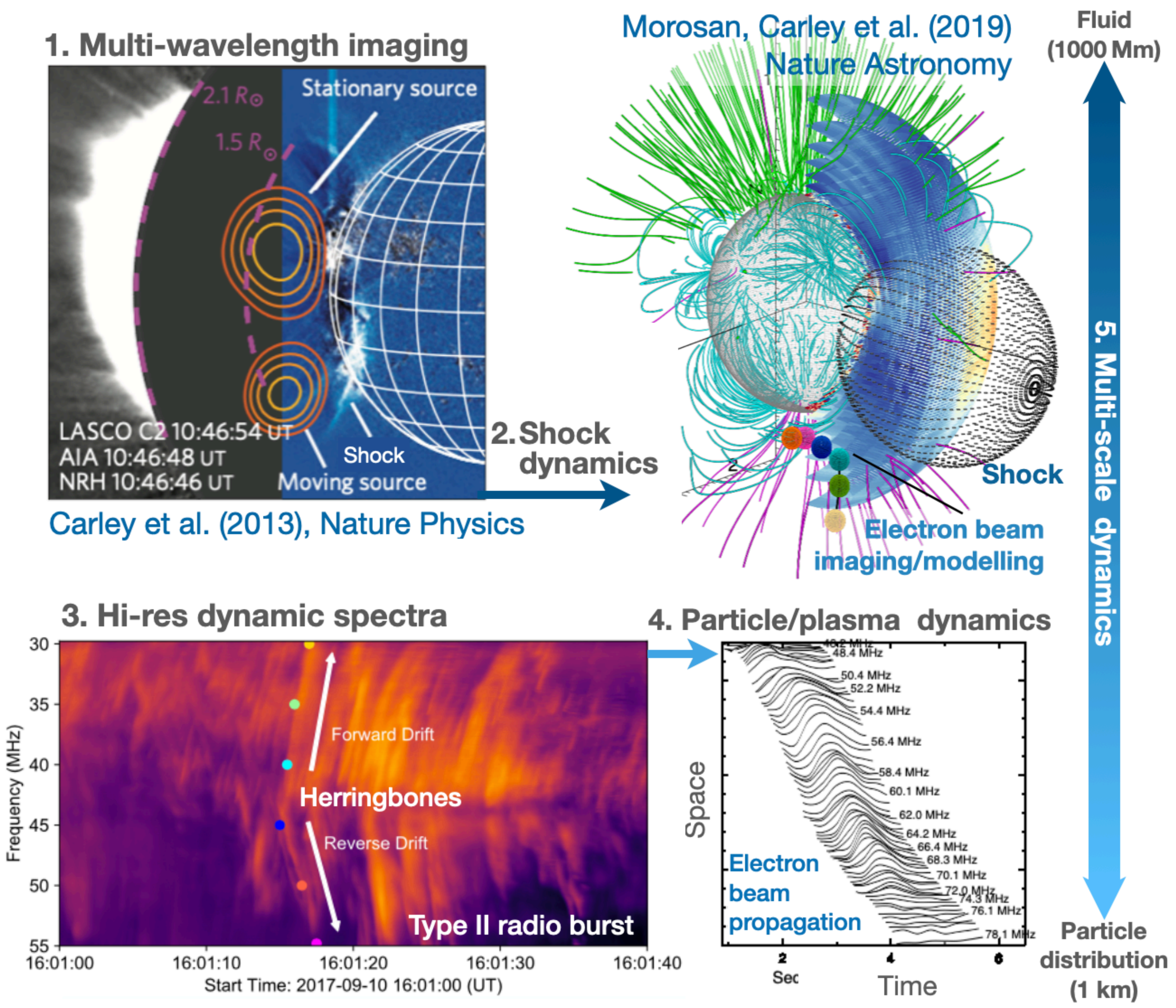


Ionospheric scintillation

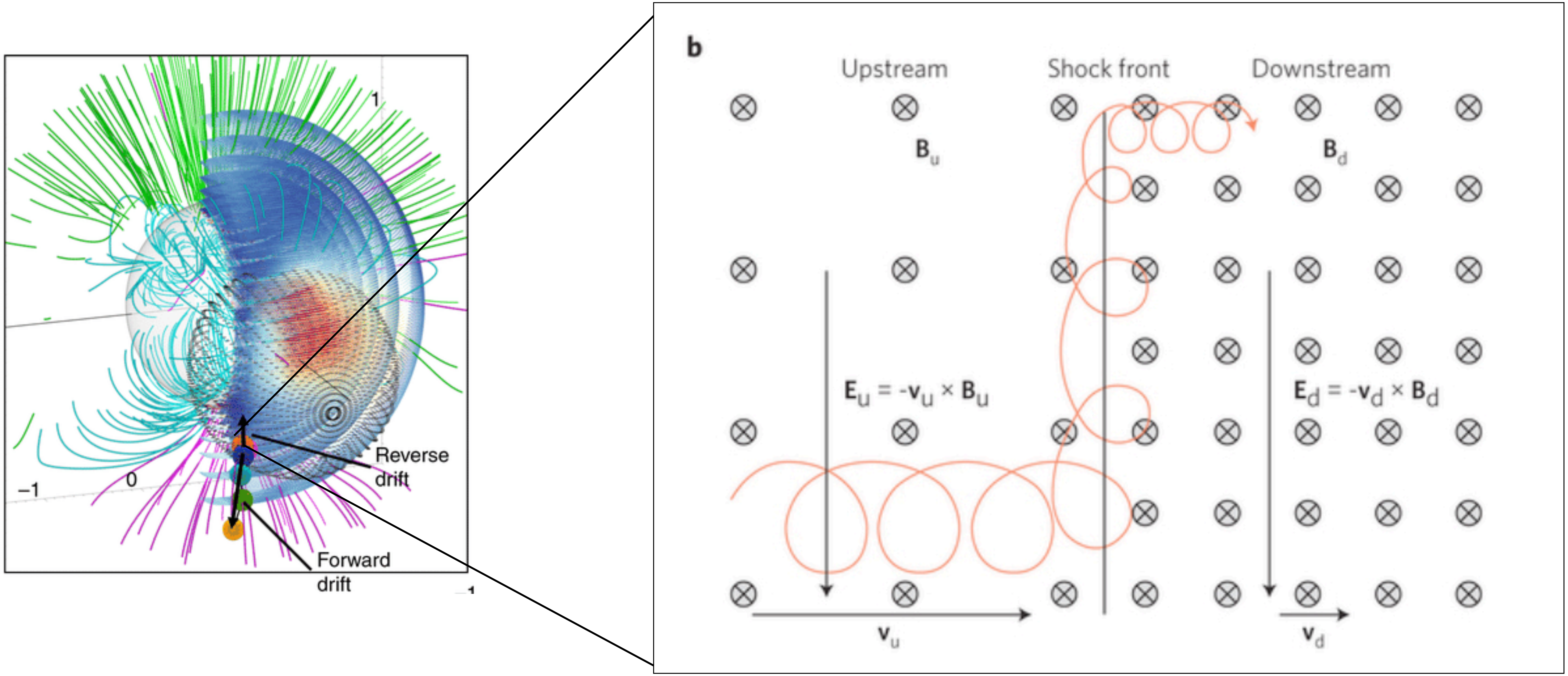


Summary

- Low frequency radio tells us a lot about coronal shocks:
  - Shock kinematics
  - Electron beam kinematics
  - Measures of turbulence
  - Why is the shock acceleration bursty/periodic?
- LOFAR and NenuFAR a providing excellent imaging spectroscopy of type IIs, type IIIs, many more different types:
- We are continuing our observational support of PSP and SoLO perihelia



Backup slides: Shock drift acceleration….

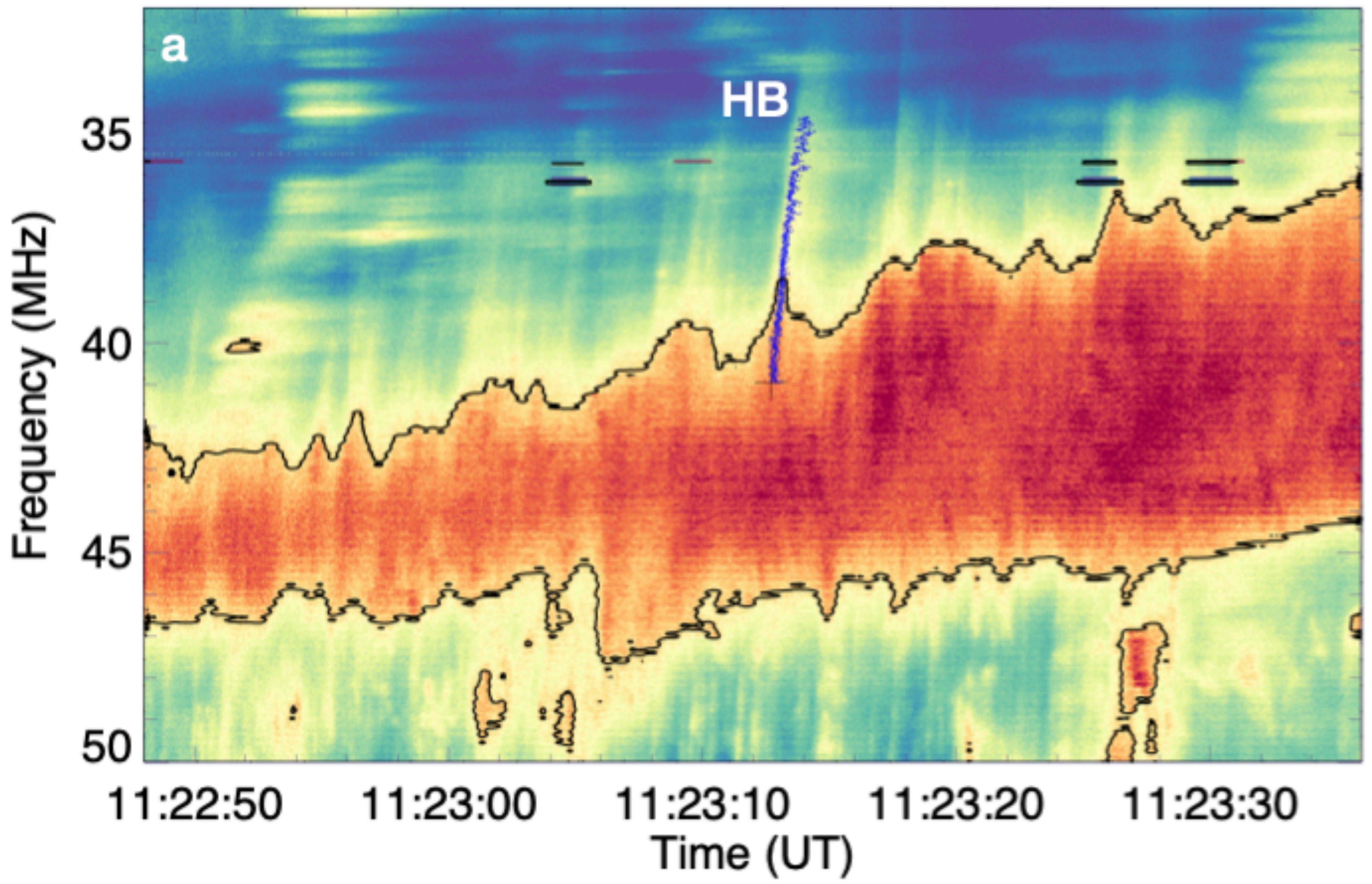


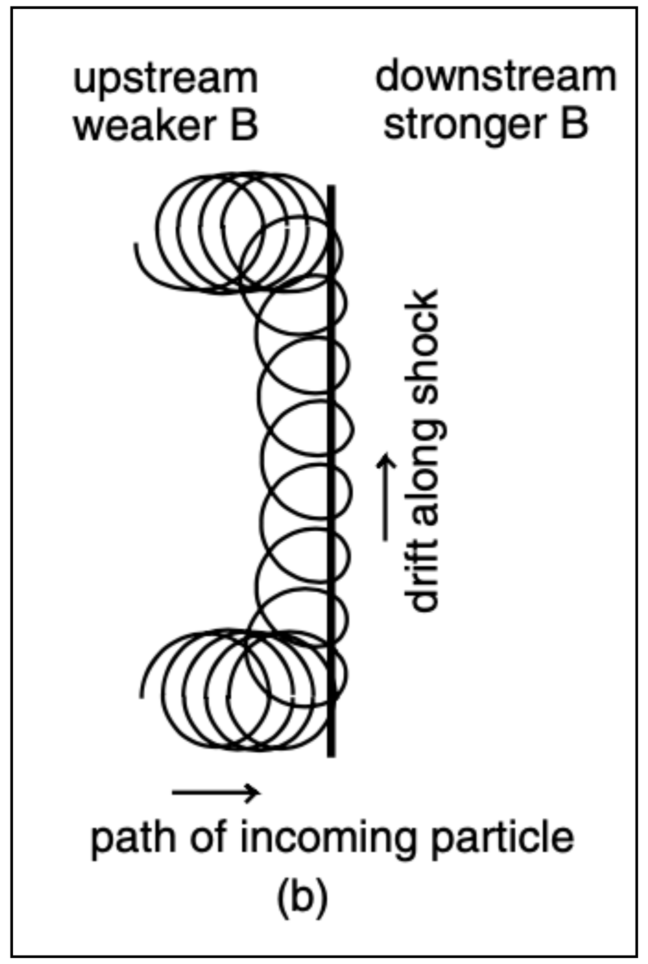
$$\frac{E_r}{E_i} = \frac{1+\sqrt{1-B_1/B_2}}{1+\sqrt{1-B_1/B_2}} \Rightarrow \frac{E_r}{E_i} < 13.93$$

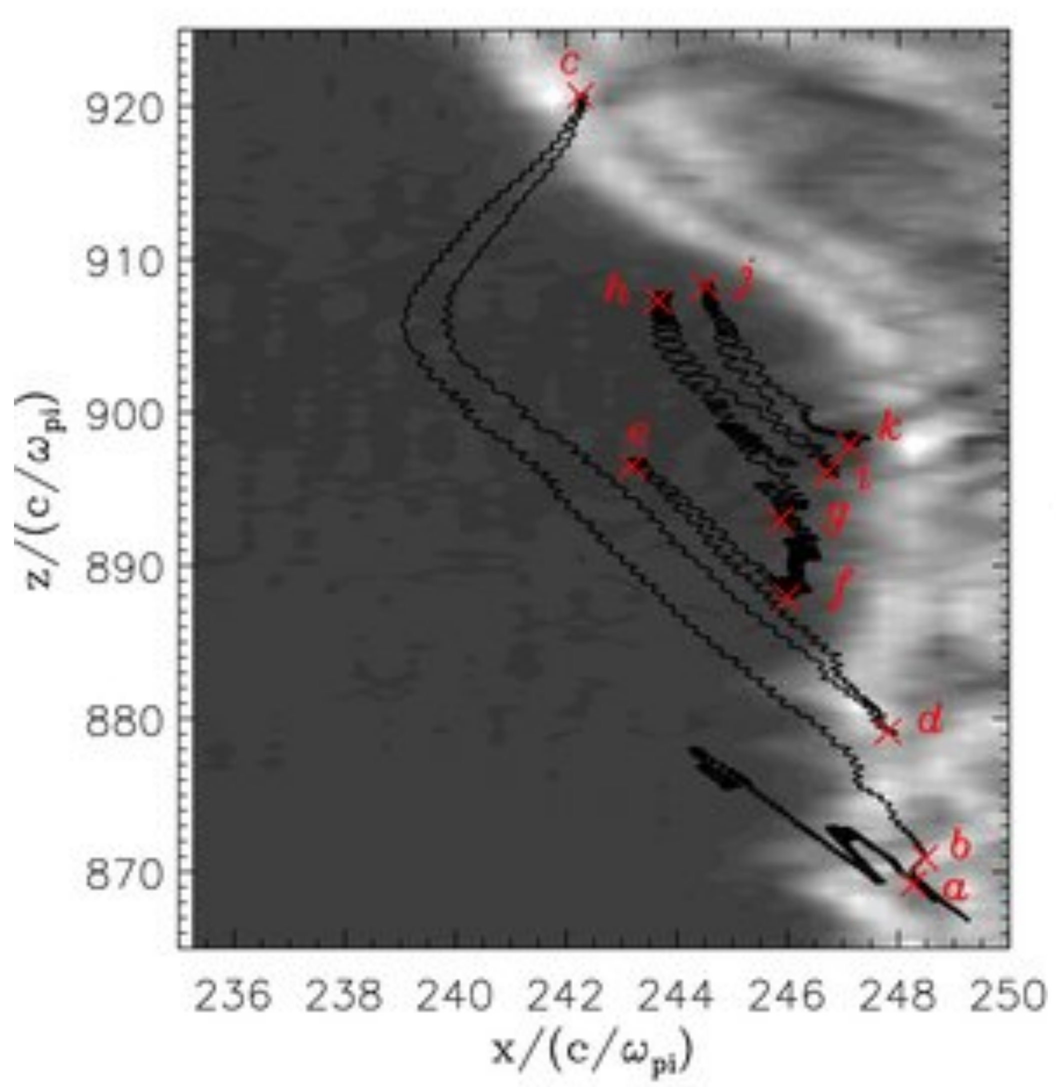
Ball & Melrose (2001)

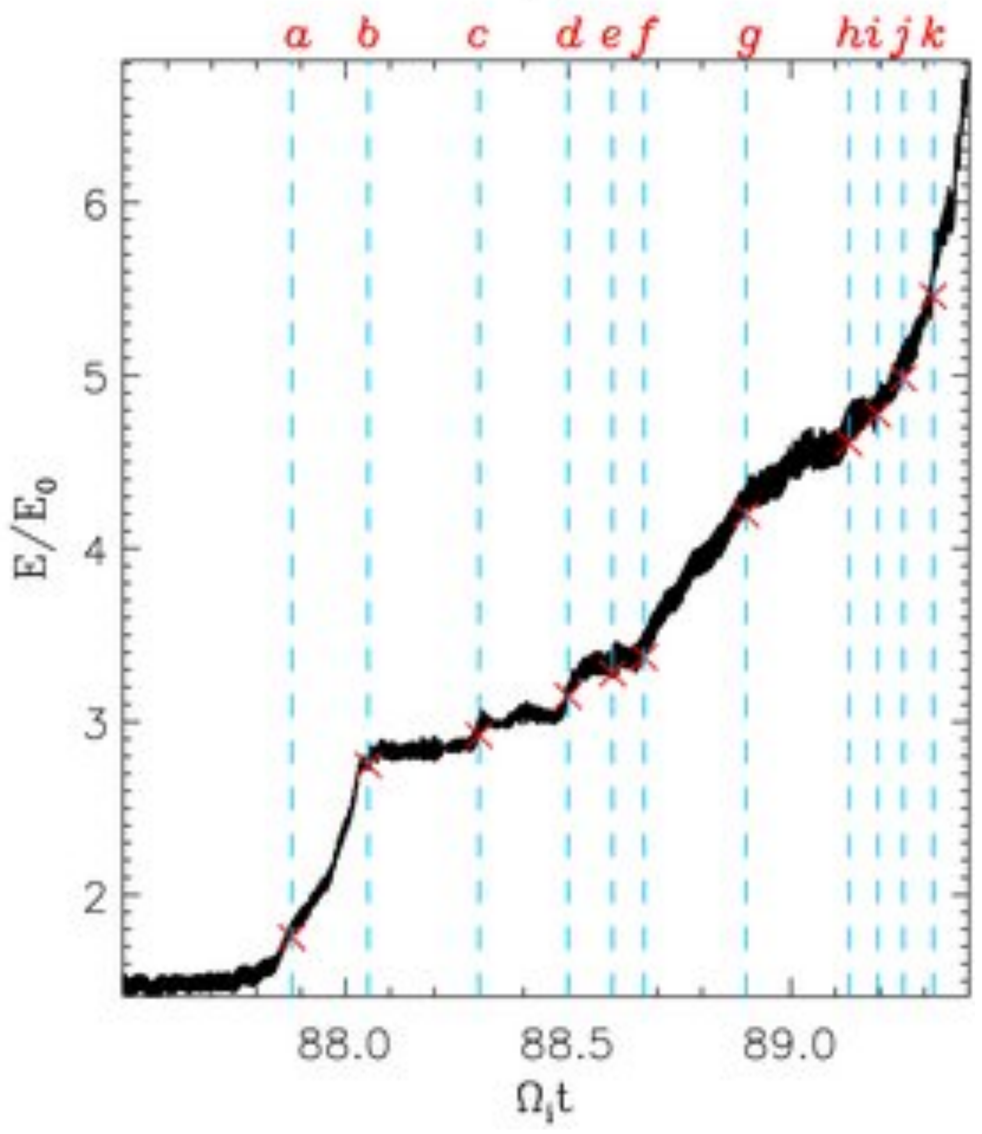
Shock drift acceleration + turbulence

- Electron energies up to 41 keV









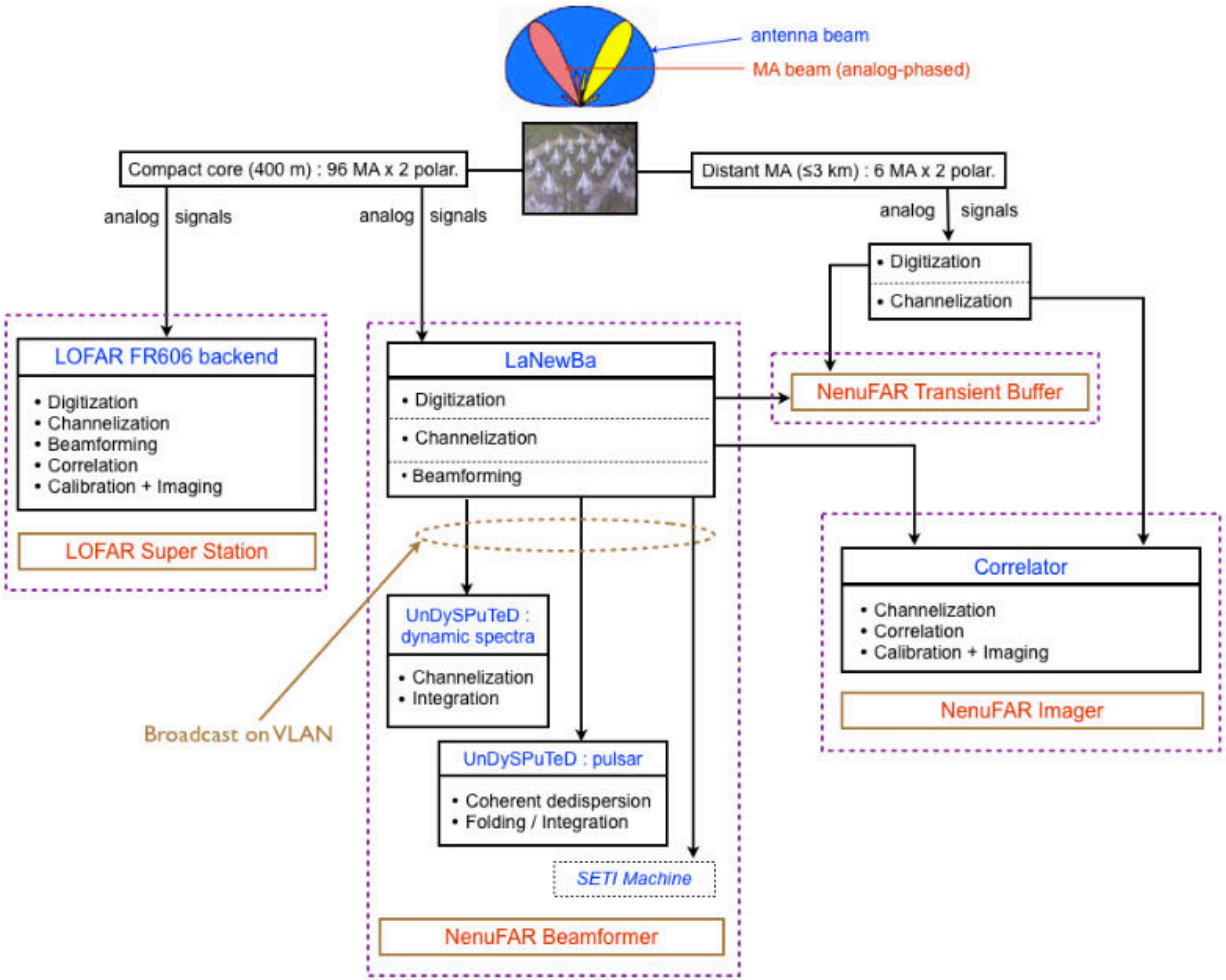
Guo & Giacalone (2010)

- SDA (Ball & Melrose 2001)

$$\frac{E_r}{E_i} = \frac{1+\sqrt{1-B_1/B_2}}{1+\sqrt{1-B_1/B_2}} \lesssim 14$$

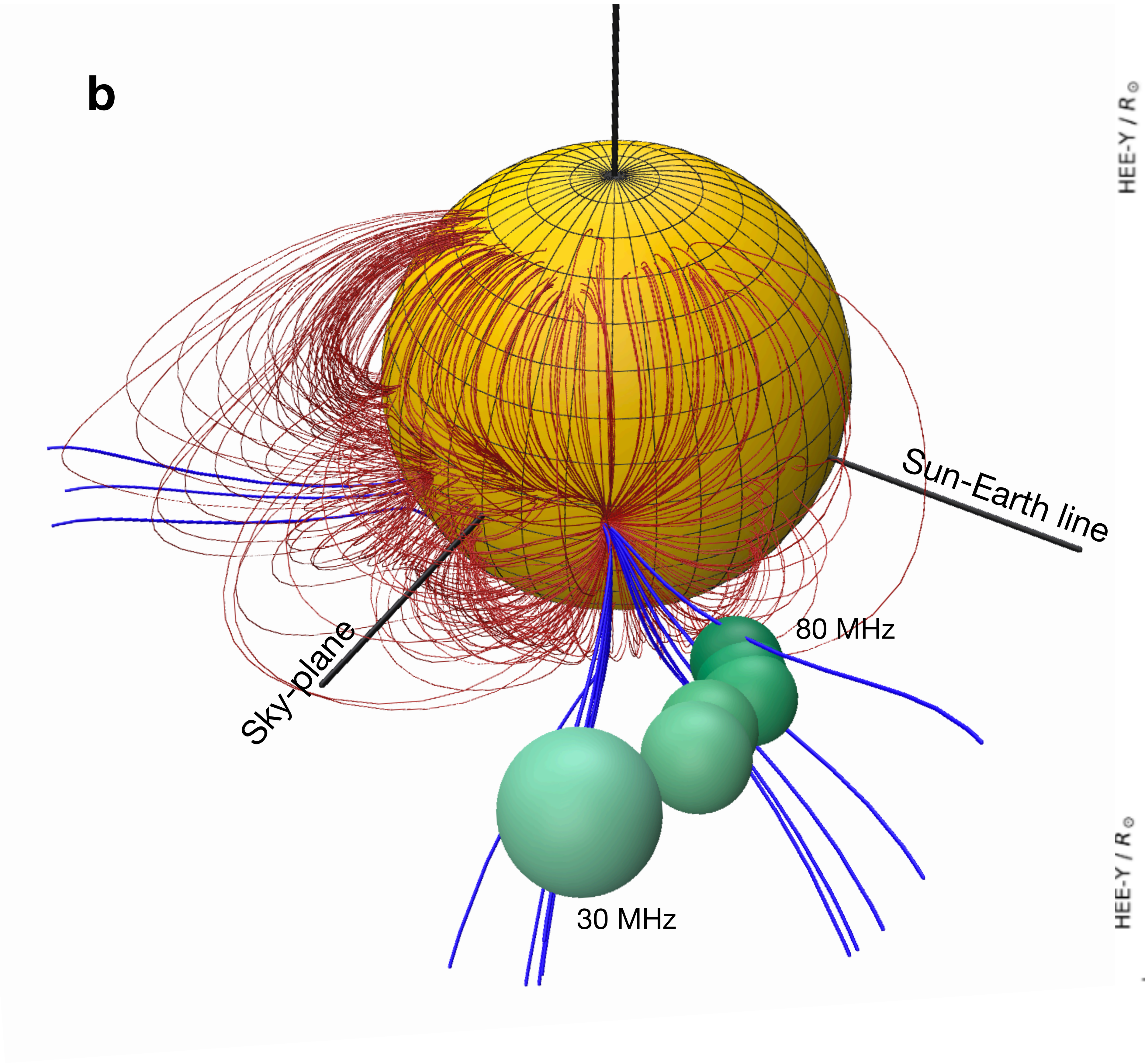
- Given $E_i < 1$ keV (thermal energy at 1 MK)
  - $E_{rmax} < 14$ keV (single reflection)
- SDA:
  - **Turbulence causes 'ripples' and many shock reflections**
  - **Boosts energy gain (Burgees 2006, Guo & Giacalone 2010)**

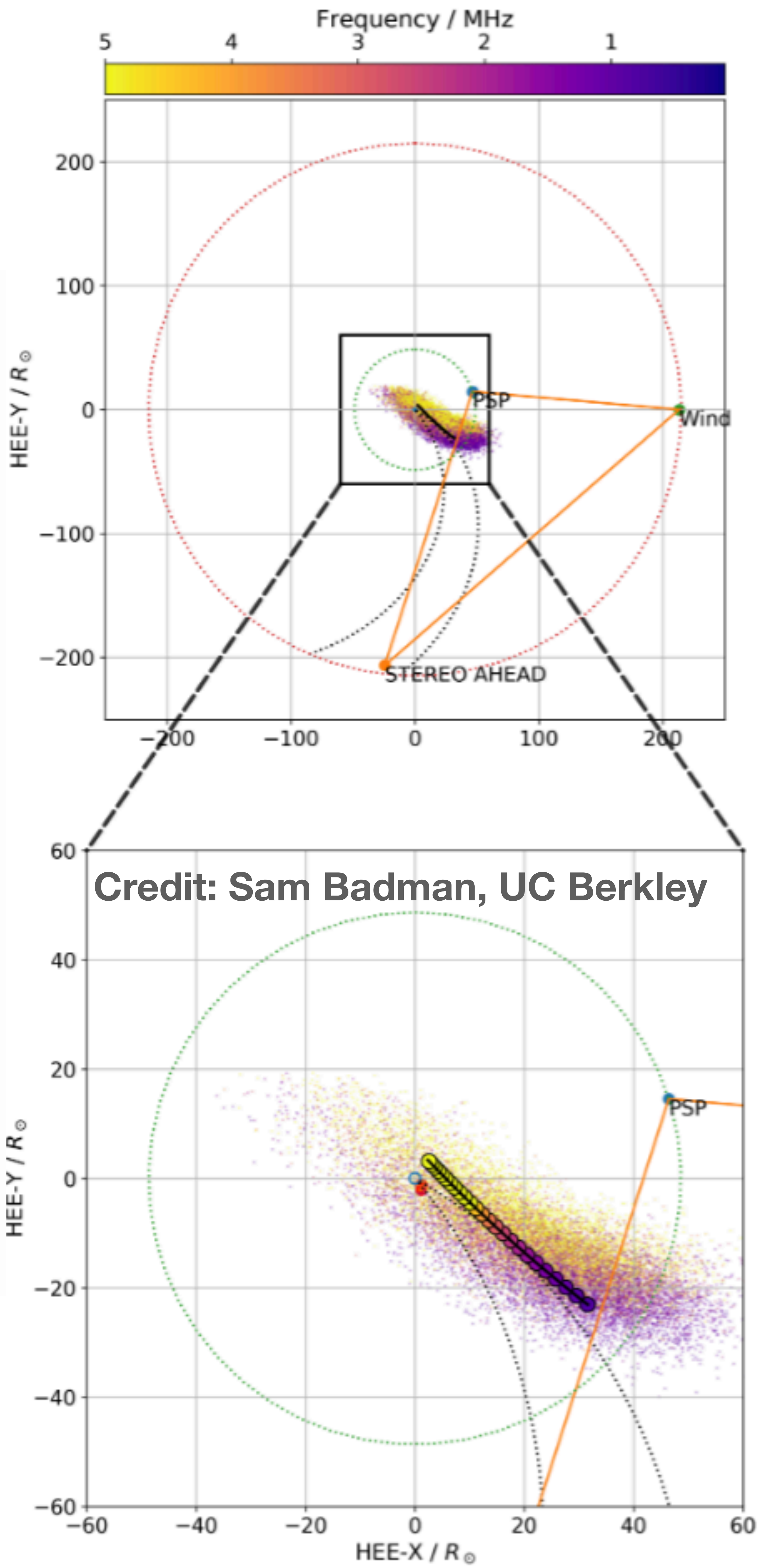
Extra

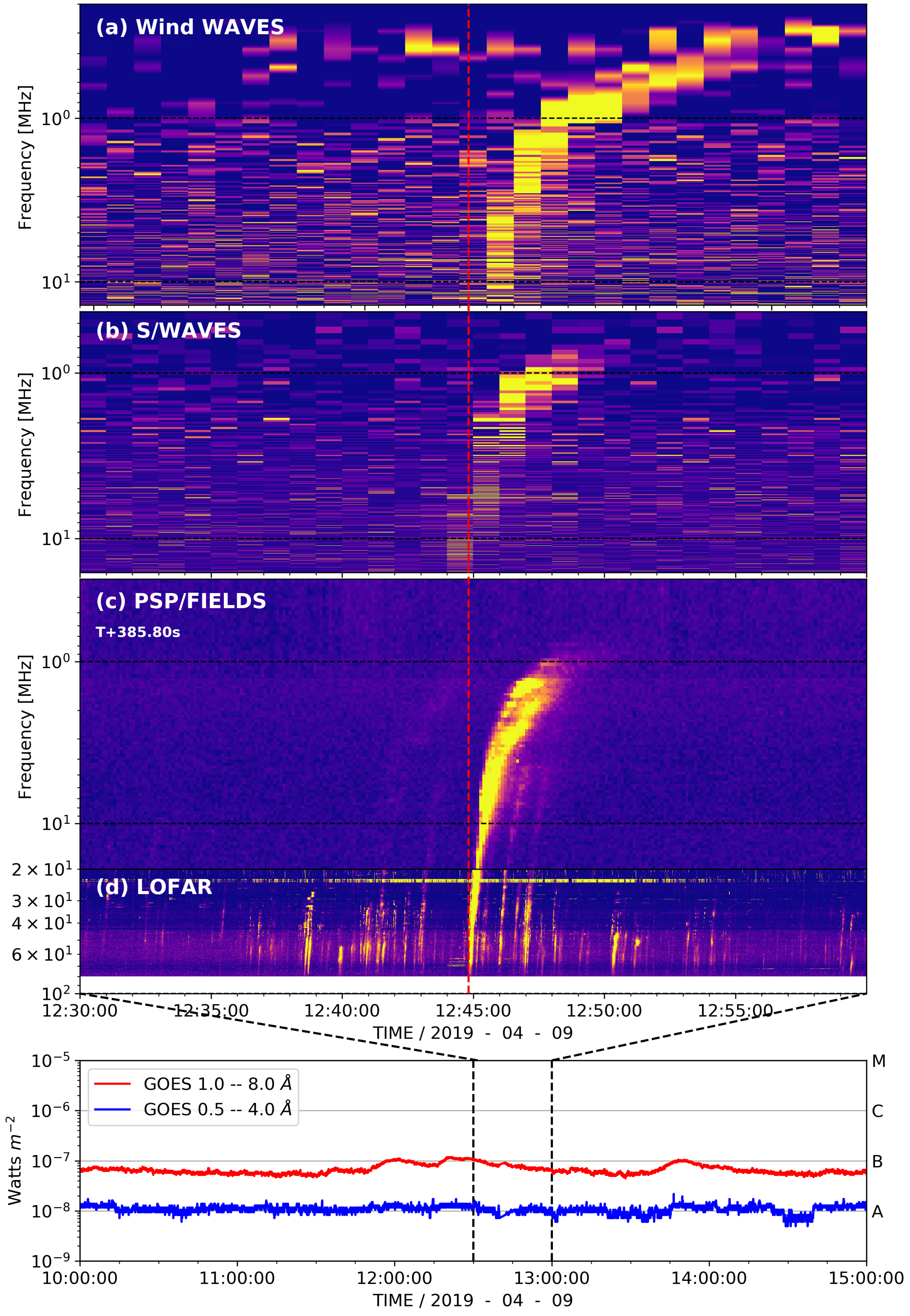


antenna beam
MA beam (analog-phased)
Compact core (400 m) : 96 MA x 2 polar.
Distant MA (≤3 km) : 6 MA x 2 polar.
analog signals
analog signals
analog signals
• Digitization
• Channelization
LOFAR FR606 backend
• Digitization
• Channelization
• Beamforming
• Correlation
• Calibration + Imaging
LOFAR Super Station
LaNewBa
• Digitization
• Channelization
• Beamforming
NenuFAR Transient Buffer
Correlator
• Channelization
• Correlation
• Calibration + Imaging
NenuFAR Imager
UnDySPuTeD : dynamic spectra
• Channelization
• Integration
Broadcast on VLAN
UnDySPuTeD : pulsar
• Coherent dedispersion
• Folding / Integration
SETI Machine
NenuFAR Beamformer

Type III radio burst; PSP, STA, WAVES

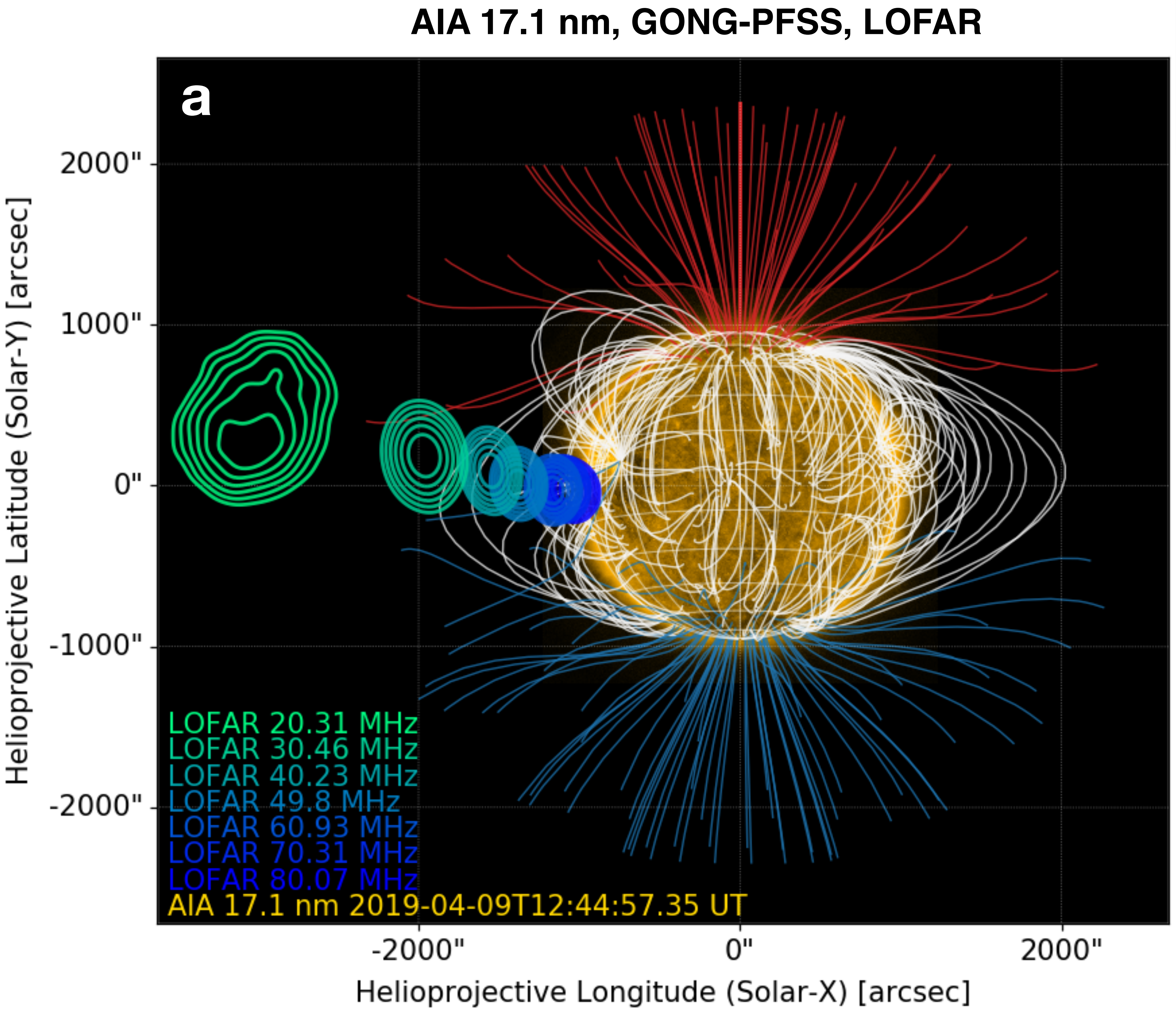


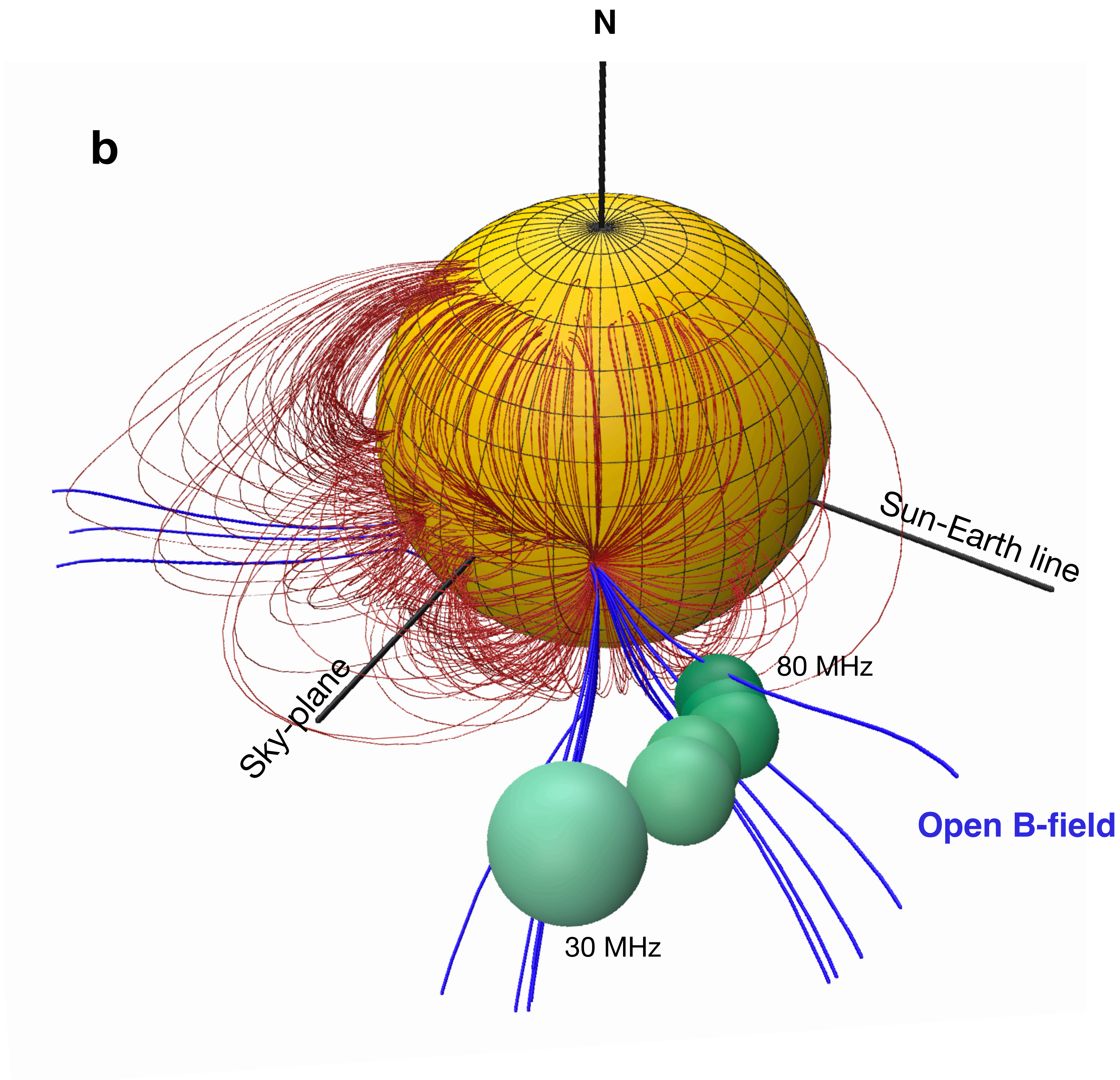




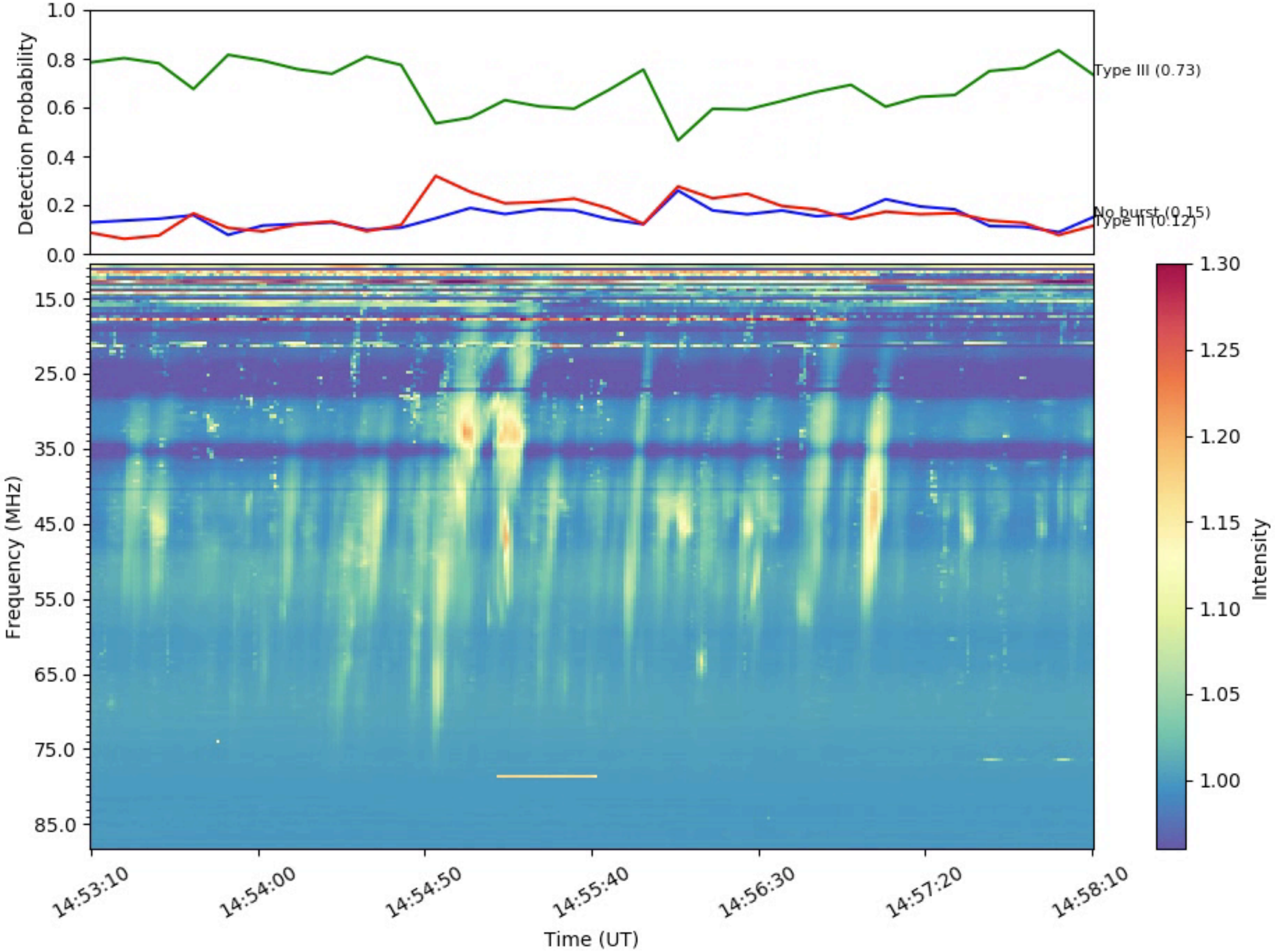
eoin.carley@dias.ie

Type III radio burst; LOFAR imaging





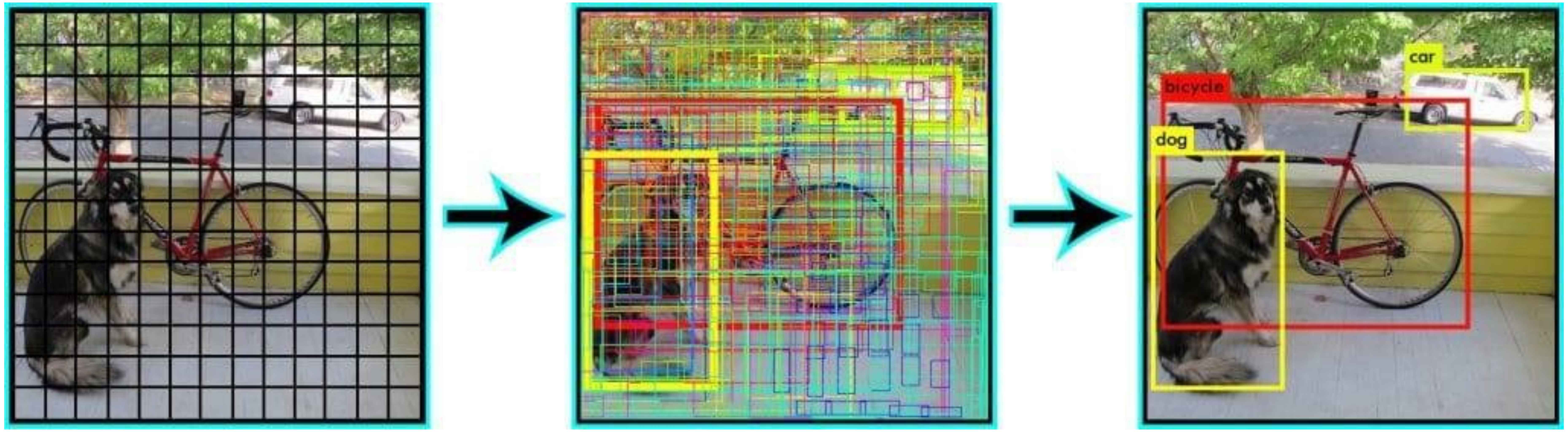
Radio burst classification - Inception CNN



- Trained on RSTN
- Applied to I-LOFAR
- Can recognise:
  - Type III bursts
  - Type II bursts
  - No bursts (true negatives)

- Does this only for the entire frame.
  - Can we located the bursts?

Radio burst classification - You Only Look Once (YOLO) v3



Loss function=

$$\lambda_{\text{coord}} \sum_{i=0}^{S^2} \sum_{j=0}^{B} \mathbb{1}_{ij}^{\text{obj}} (x_i - \hat{x}_i)^2 + (y_i - \hat{y}_i)^2$$

Box position

$$+ \lambda_{\text{coord}} \sum_{i=0}^{S^2} \sum_{j=0}^{B} \mathbb{1}_{ij}^{\text{obj}} \left(\sqrt{w_i} - \sqrt{\hat{w}_i}\right)^2 + \left(\sqrt{h_i} - \sqrt{\hat{h}_i}\right)^2$$

Box width/height

$$+ \sum_{i=0}^{S^2} \sum_{j=0}^{B} \mathbb{1}_{ij}^{\text{obj}} \left(C_i - \hat{C}_i\right)^2$$

$$+ \lambda_{\text{noobj}} \sum_{i=0}^{S^2} \sum_{j=0}^{B} \mathbb{1}_{ij}^{\text{noobj}} \left(C_i - \hat{C}_i\right)^2$$

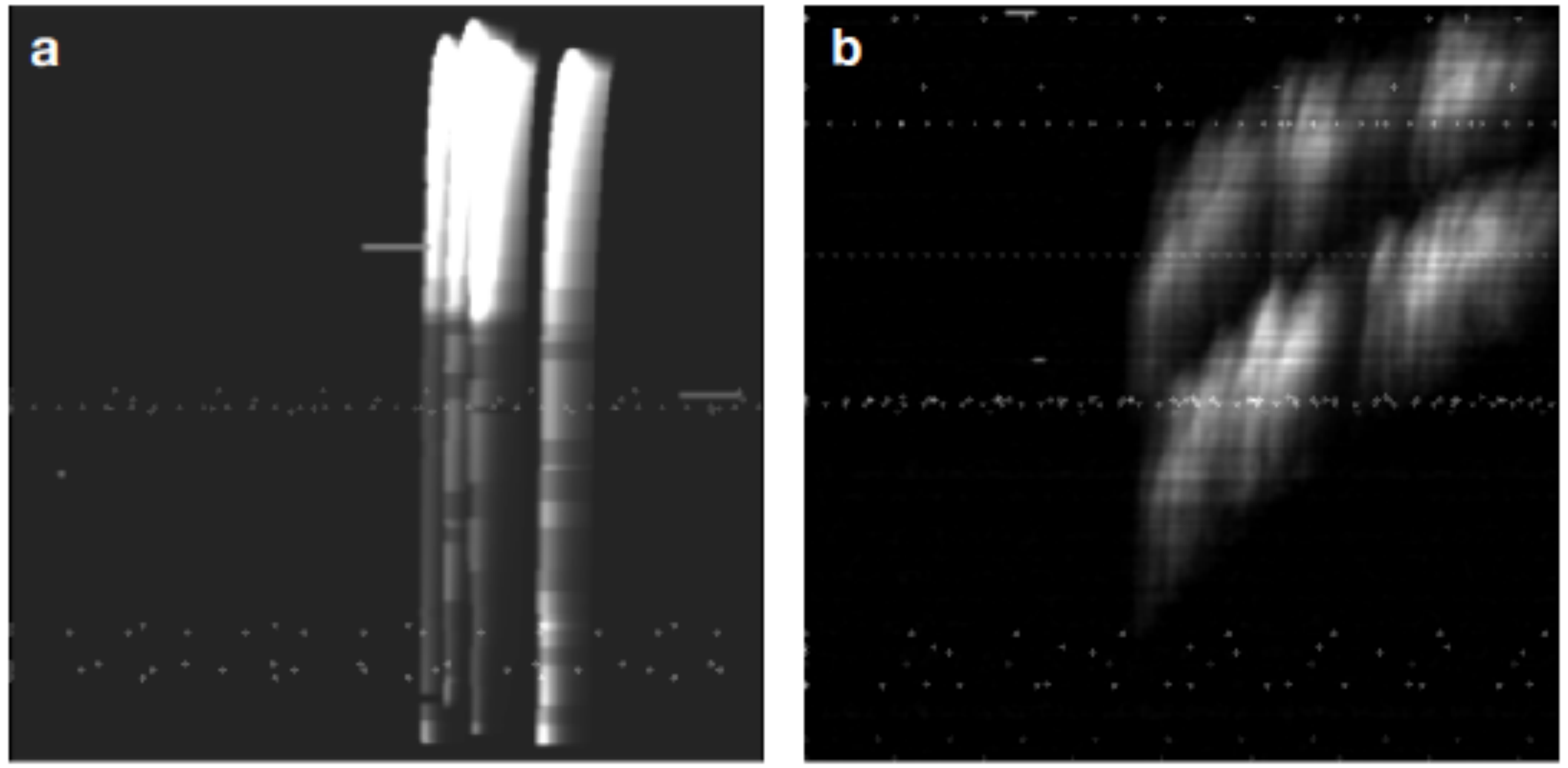
‘Objectness’ scores

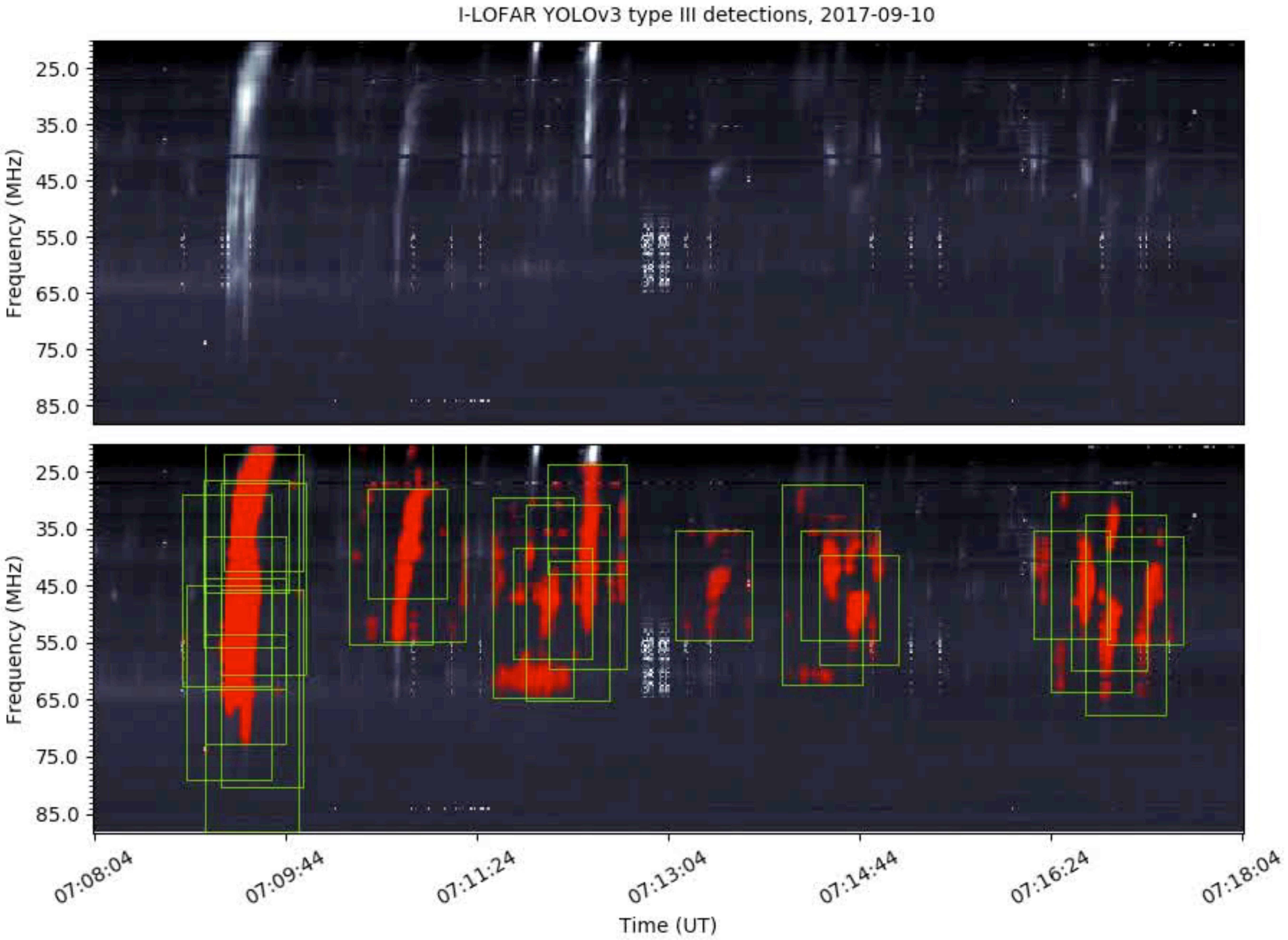
$$+ \sum_{i=0}^{S^2} \mathbb{1}_{i}^{\text{obj}} \sum_{c \in \text{classes}} (p_i(c) - \hat{p}_i(c))^2 \quad (3)$$

Classification probability

- One of fastest object detection and classification algorithms (Redmon et al. 2016).
- Loss function includes:
  - Usual classification probability
  - Parameters of correct box position, size
  - Object confidence scores

Backups: Radio burst classification - You Only Look Once (YOLO) v3

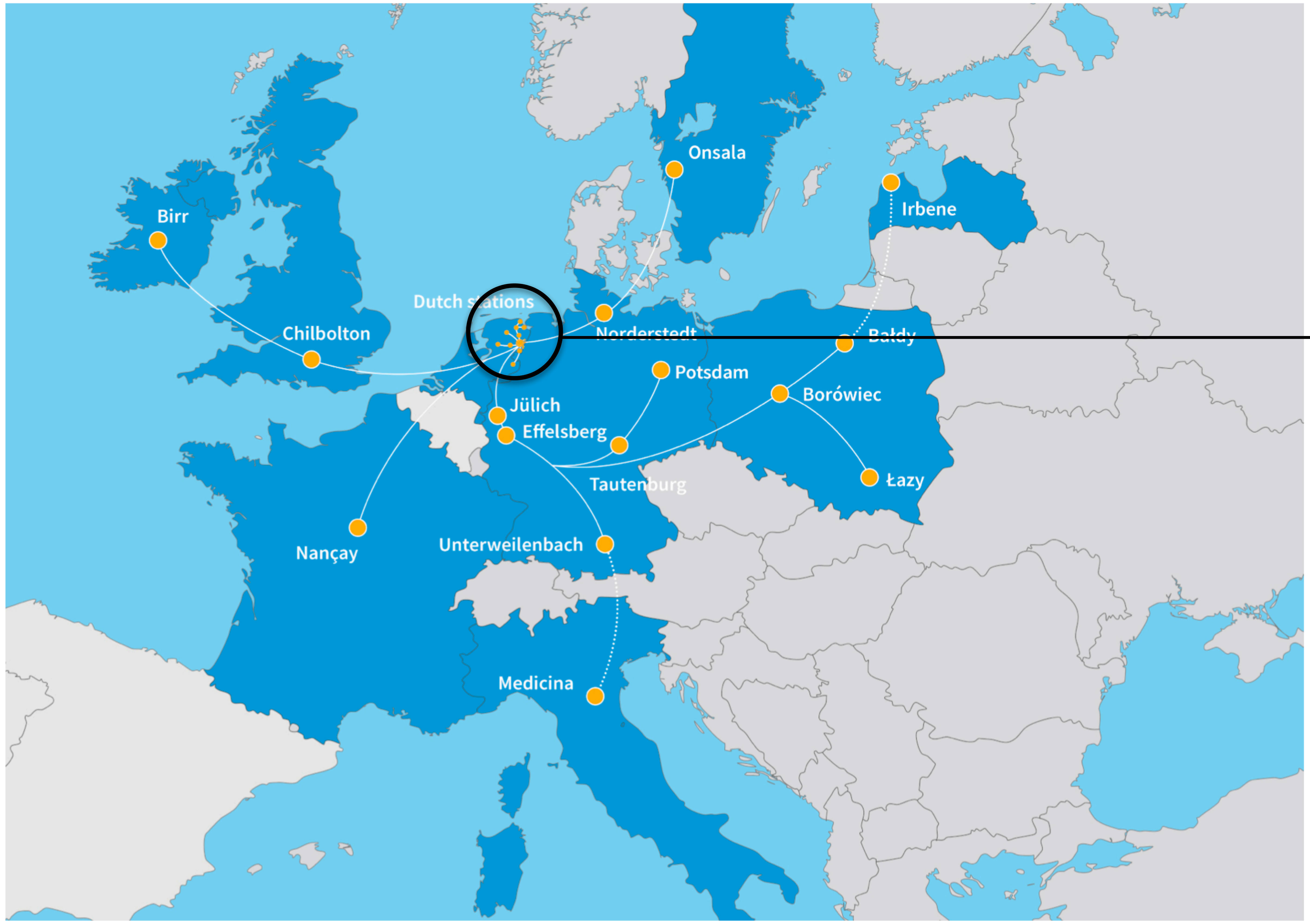


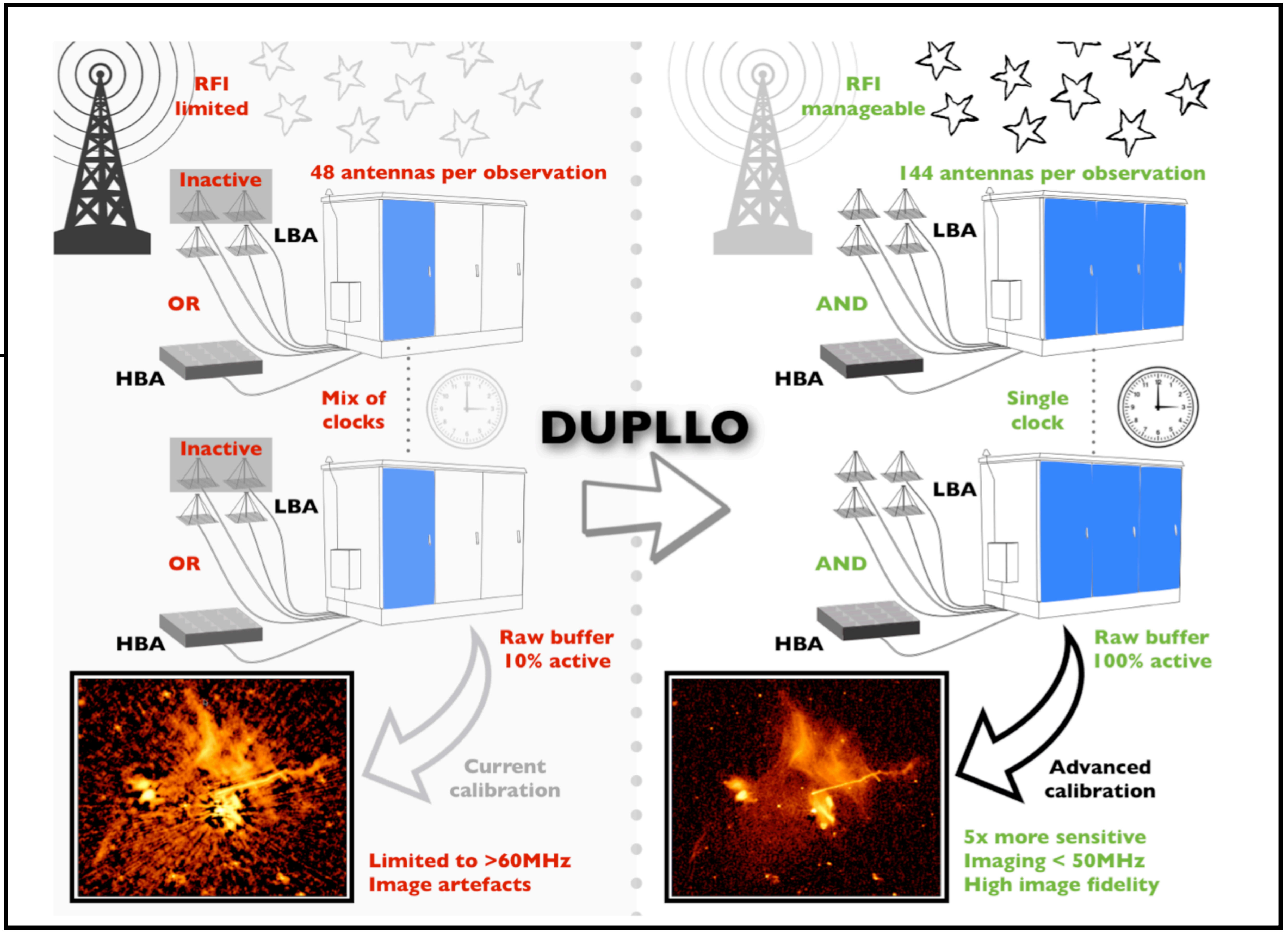


- ~50,000 simulated examples of each class
- Trained on NVIDIA Tesla K80
- ~1 hour for 1 epoch of training
- Initial results promising
- Problem with heavily saturated radio bursts

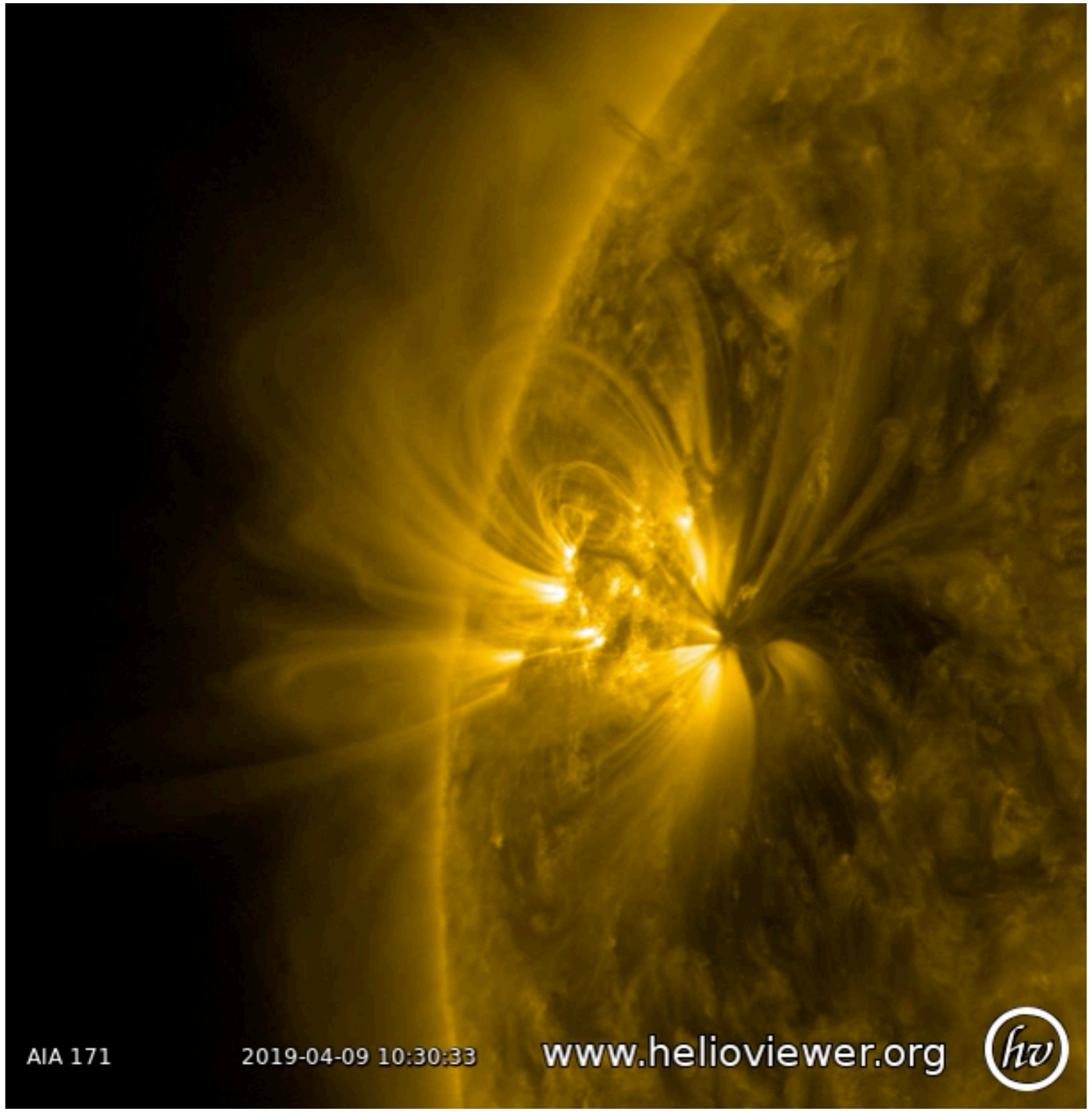
LOFAR2.0

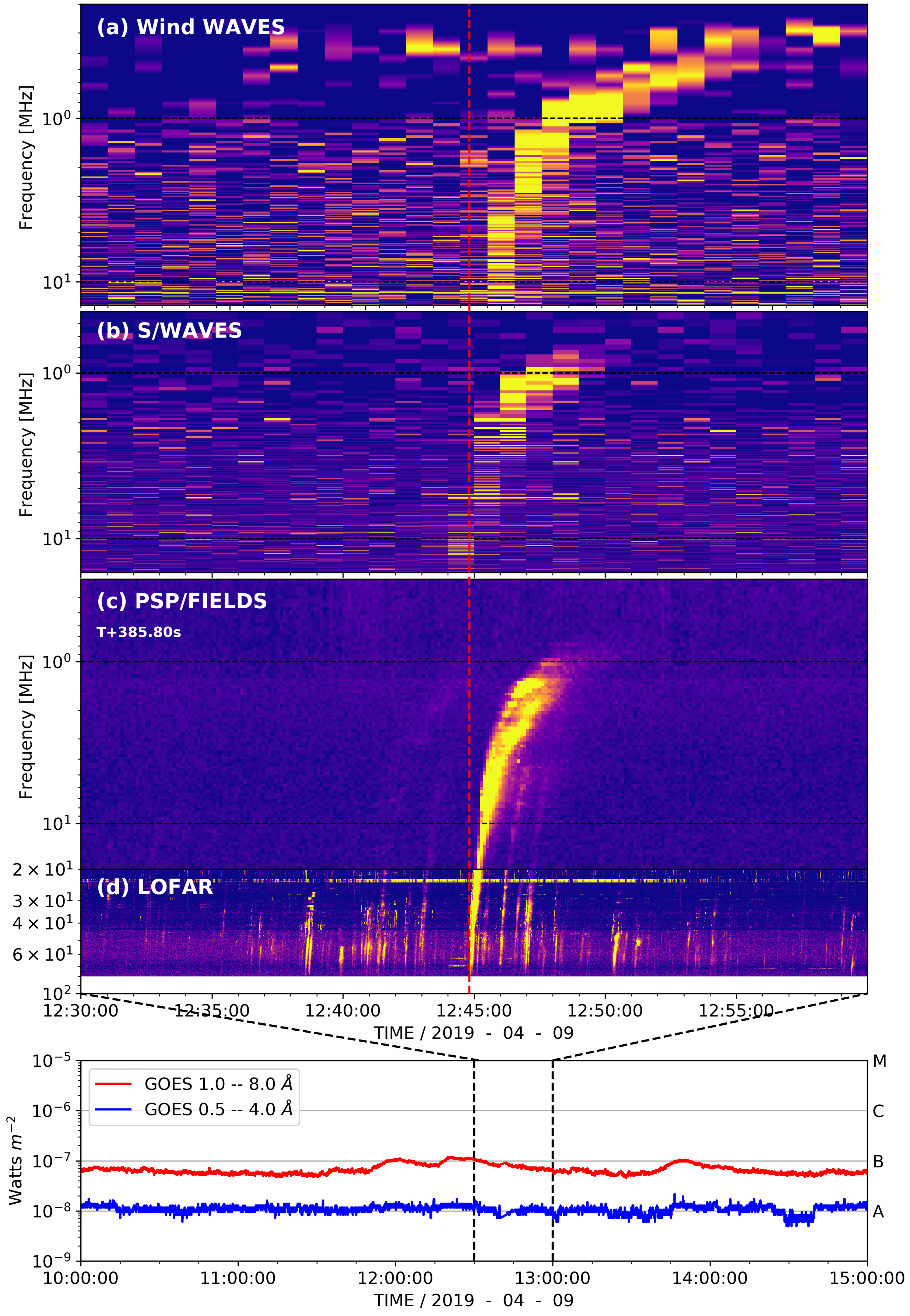
- LOFAR2.0 all Dutch stations on single timing distribution



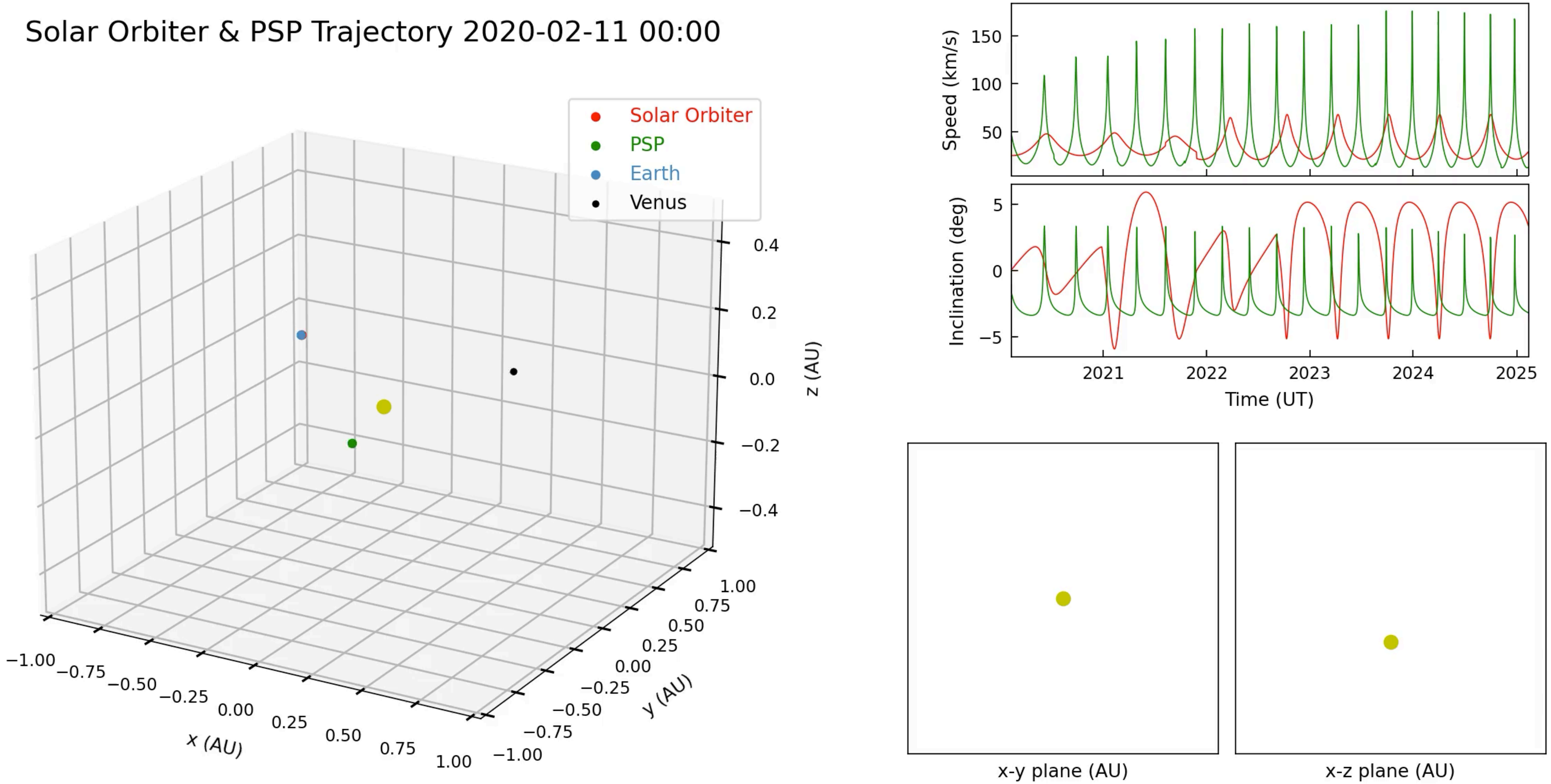


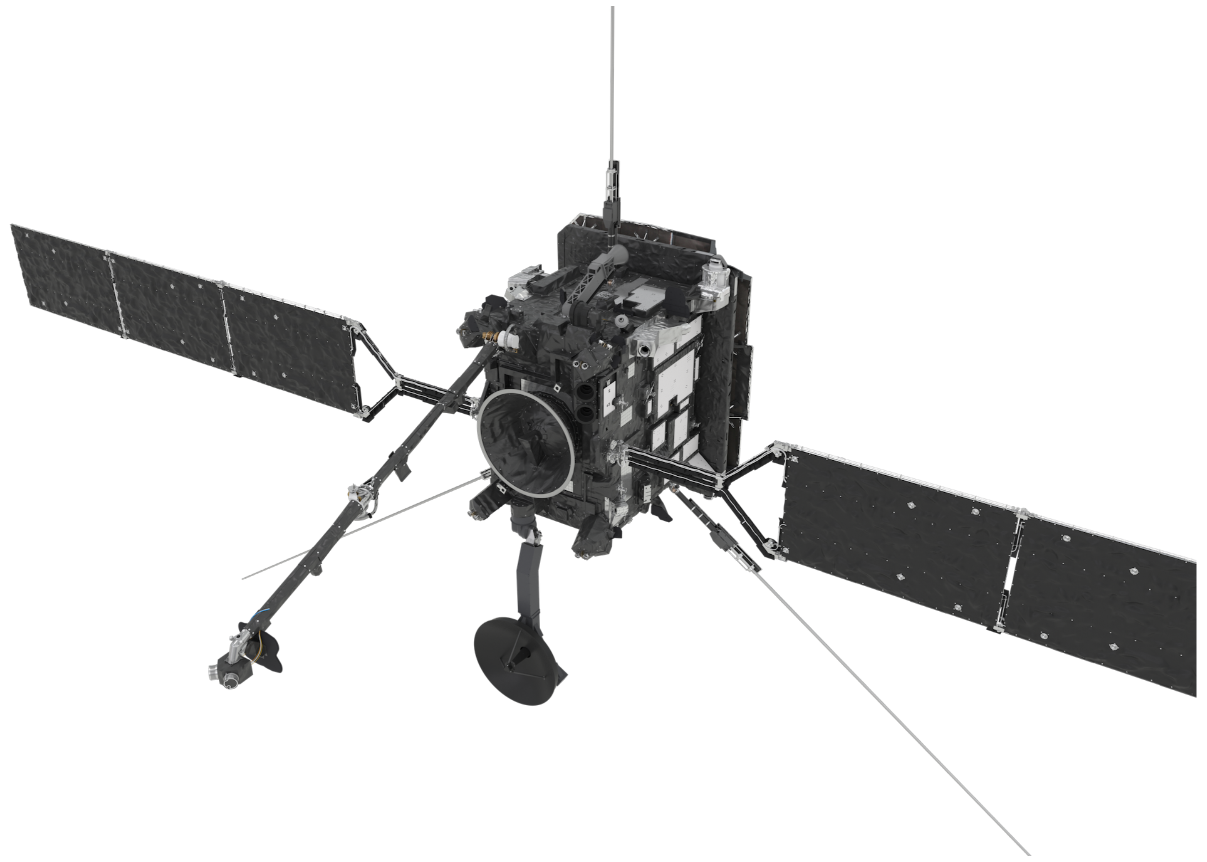
Parker Solar Probe - Encounter 2

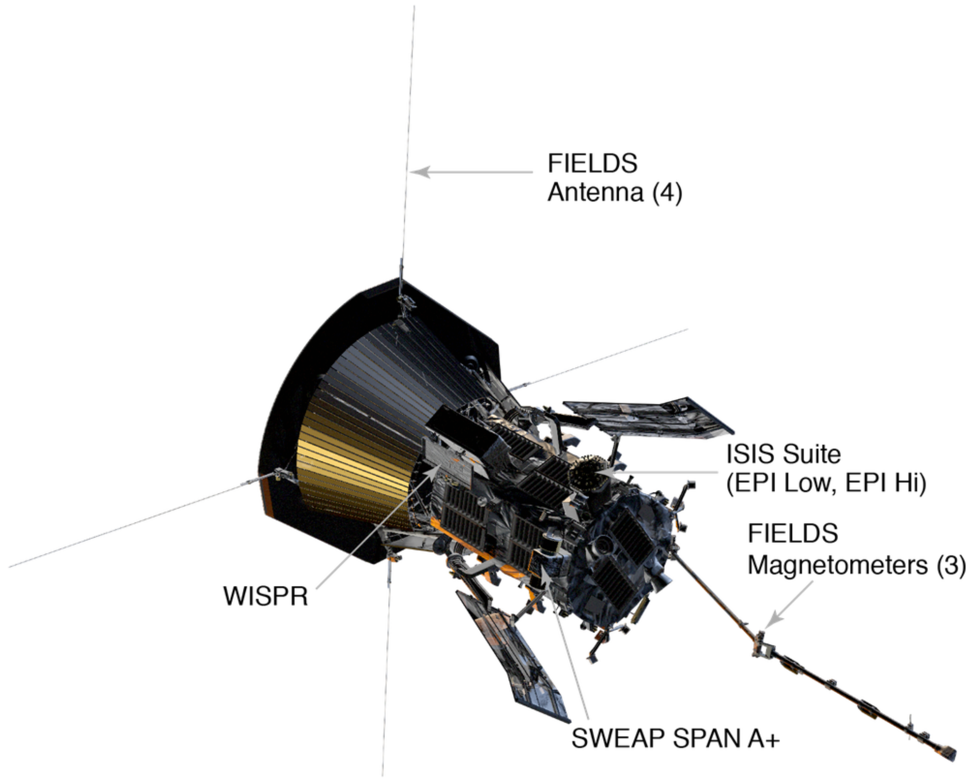




LOFAR, PSP and SoLO

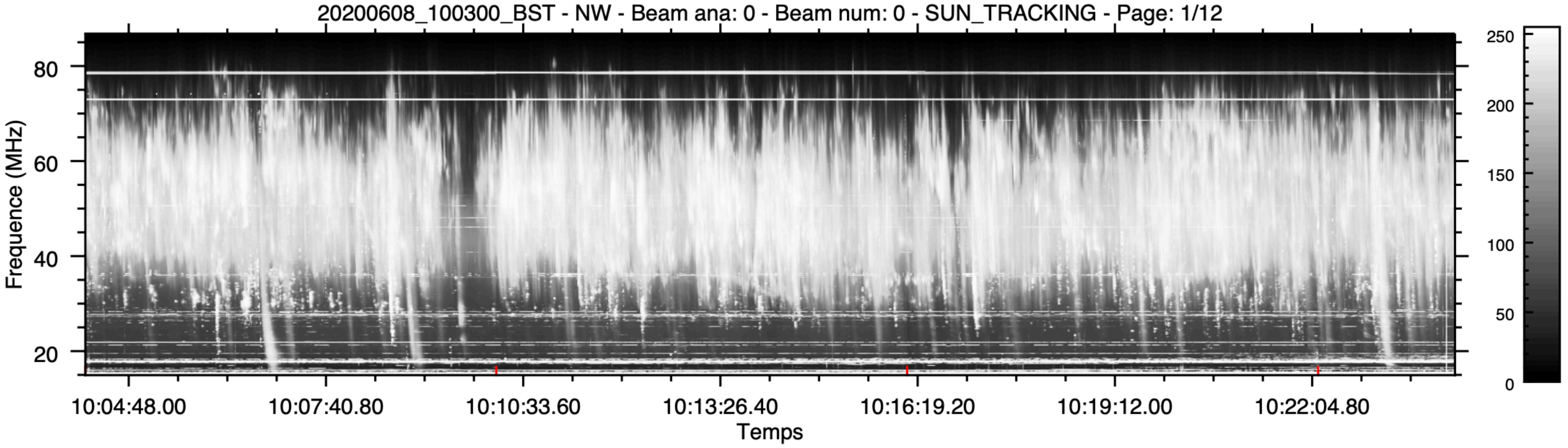






Movie Credit: Laura Hayes, DIAS

LOFAR, NenuFAR, PSP and SoLO



- Previous PSP encounters:
  - **Encounter 5:** 2020-June (type III bursts, noise storm)
  - **Encounter 6:** 2020-Sept
  - **Encounter 7:** 2021-Jan
  - **Encounter 8:** 2021-Apr (type III bursts, noise storm)
- Future support of PSP + SoLO observations
  - 2021-Sept (+LOFAR ILT)