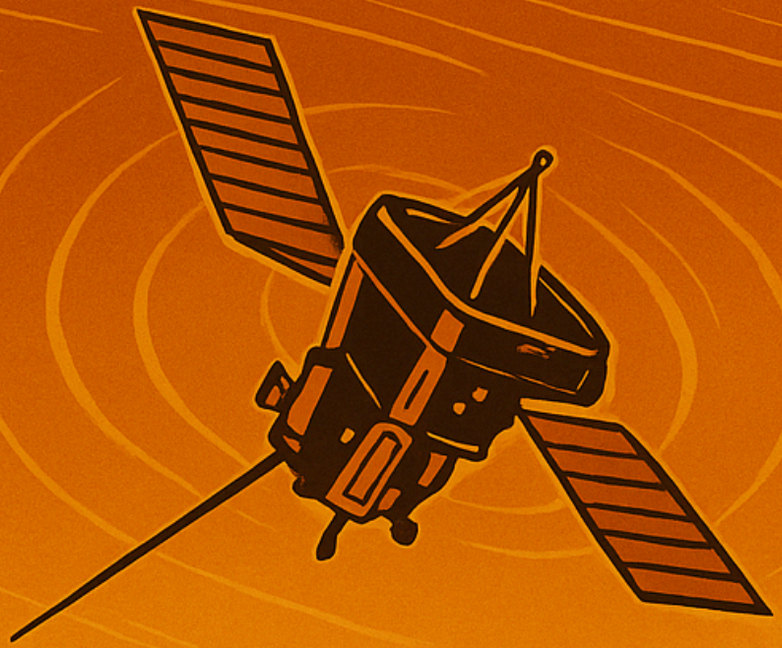
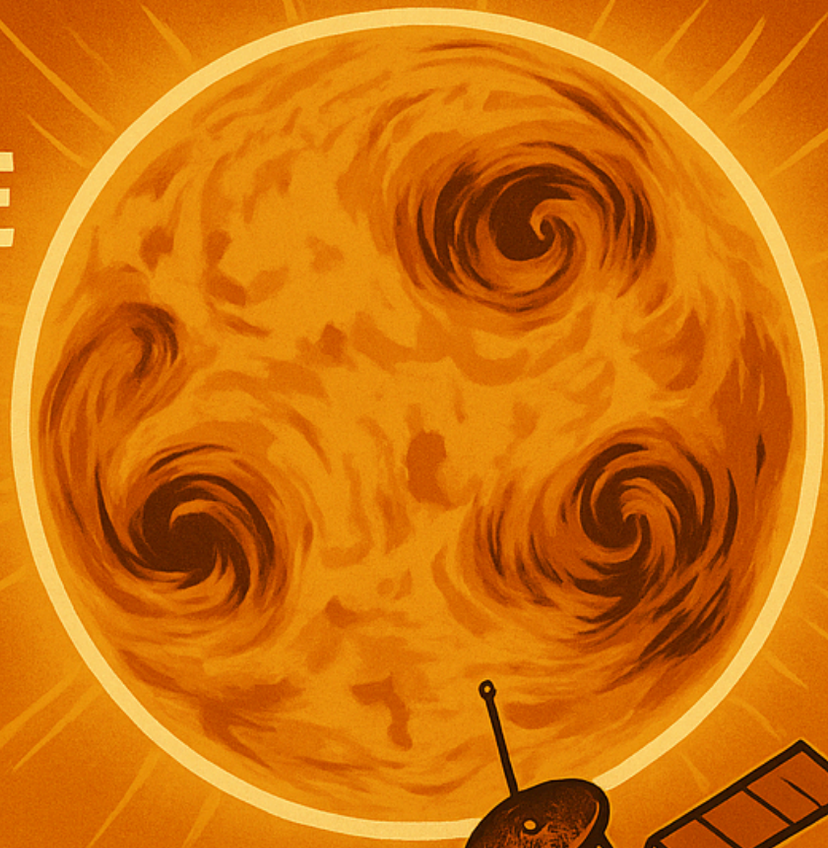
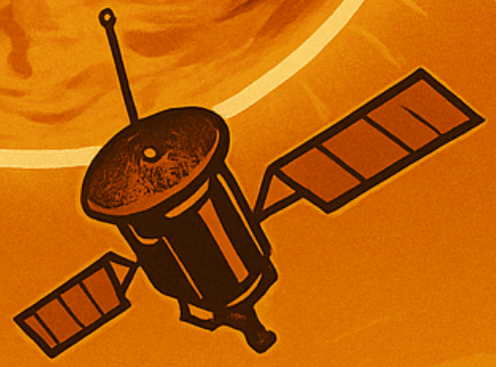
A GOLDEN AGE FOR SOLAR RADIO SCIENCE BELOW THE CUTOFF







Immanuel C. Jebaraj

V. Krasnoselskikh, M. Pulupa, A. Voshchepynets

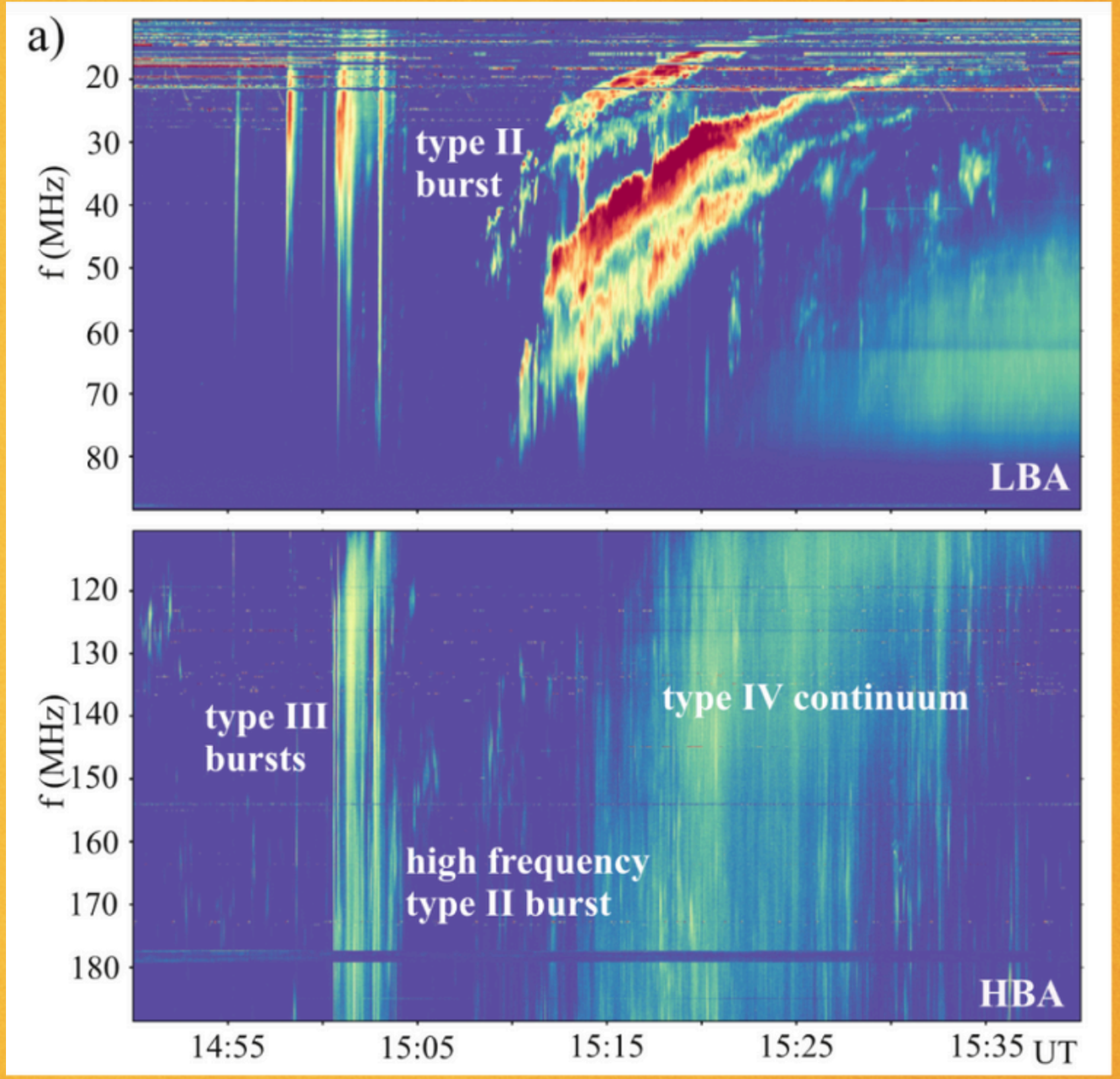
O. Agapitov T. D. De Wit S. Bale

Solar Radio Bursts

Associated with different transient events on the Sun.

Coherent and Incoherent emissions

Observational probe into a rich domain of plasma physics

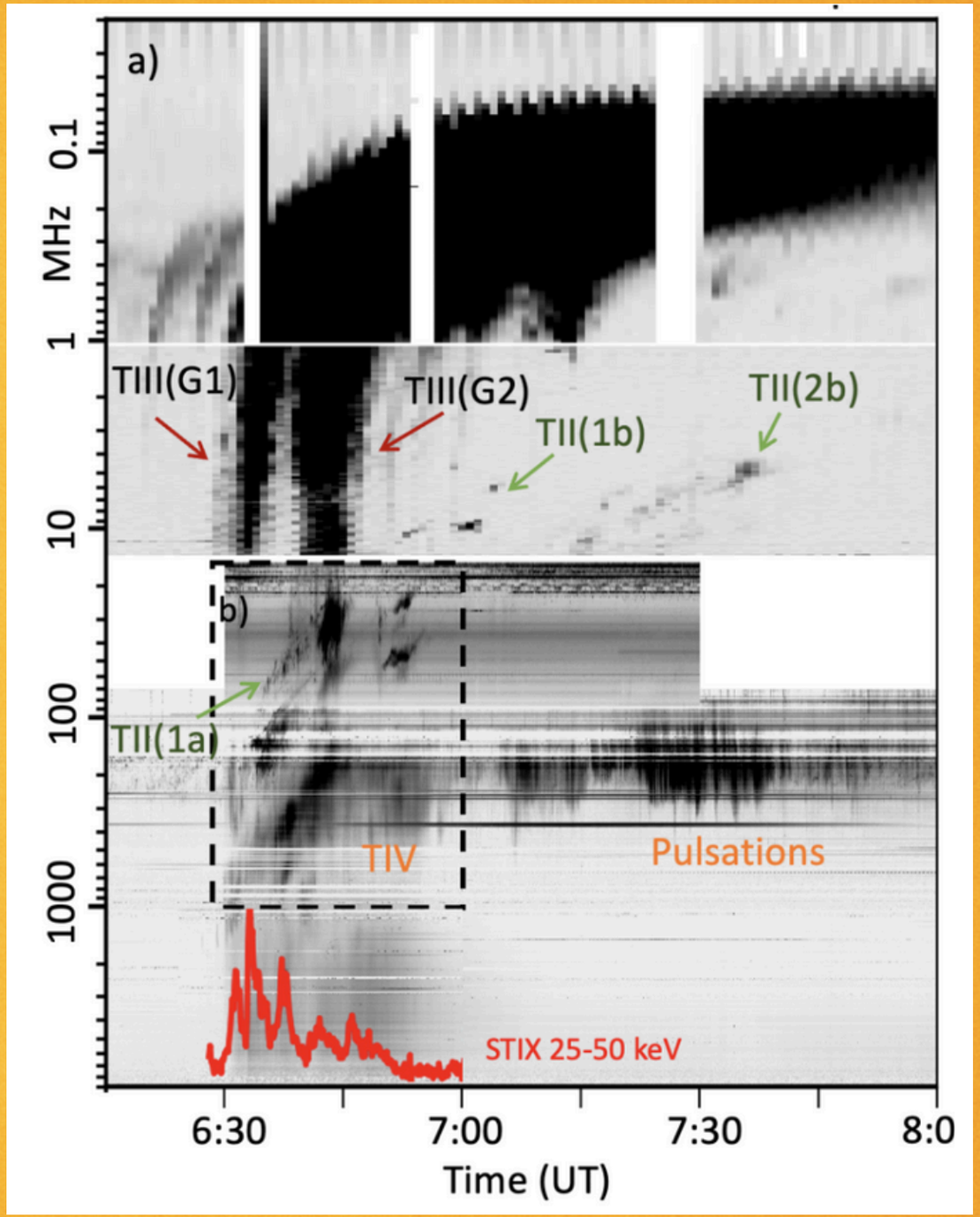


Magdalenic et al. 2020 ApJL

But what happens away from a few solar radii from the Sun?

Not possible to probe the vast interplanetary domain from ground.

When combined, provides the only true Sun-Earth connection.



Jebaraj et al. 2023b A&A

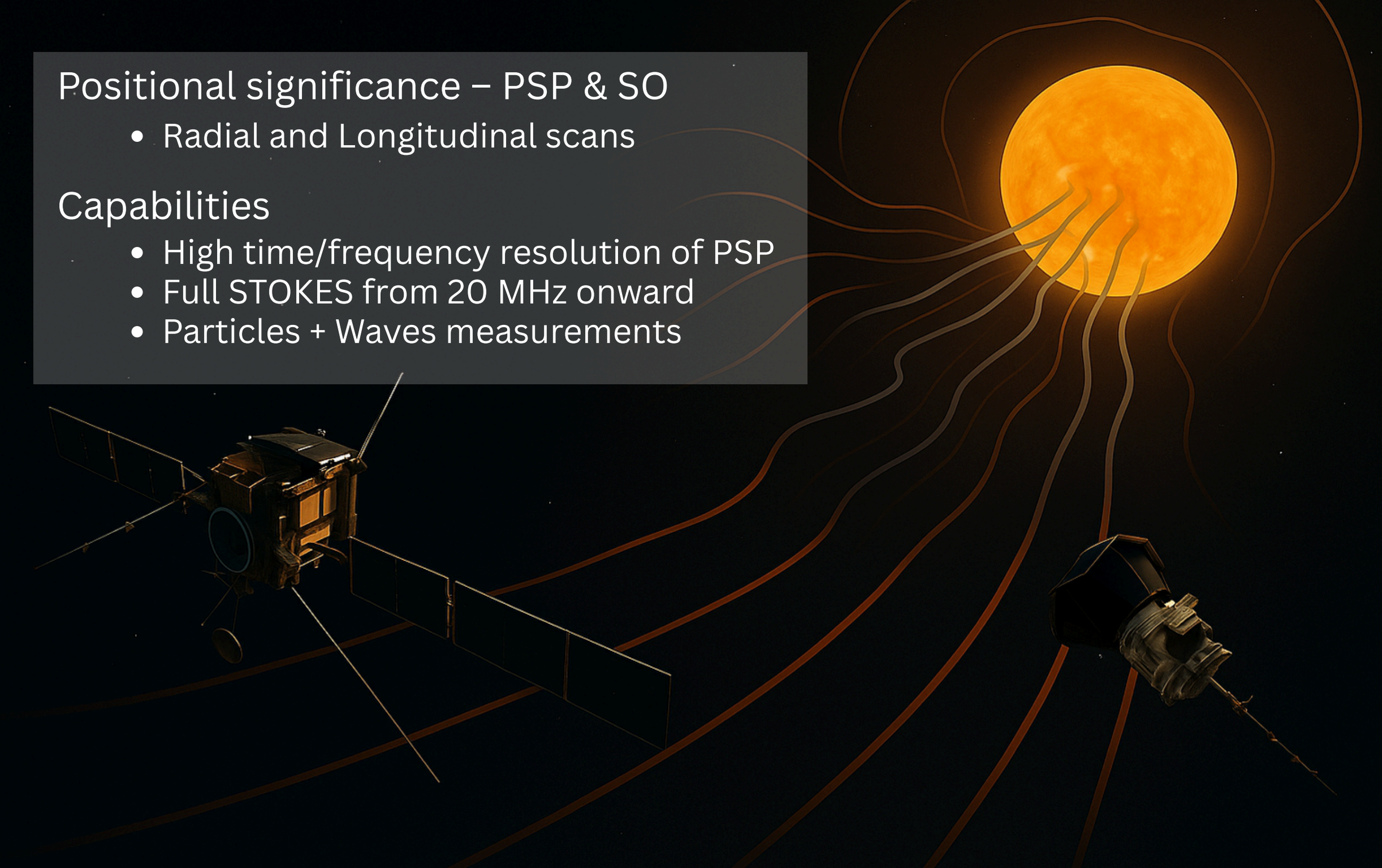
HELIOSPHYSICS MISSIONS

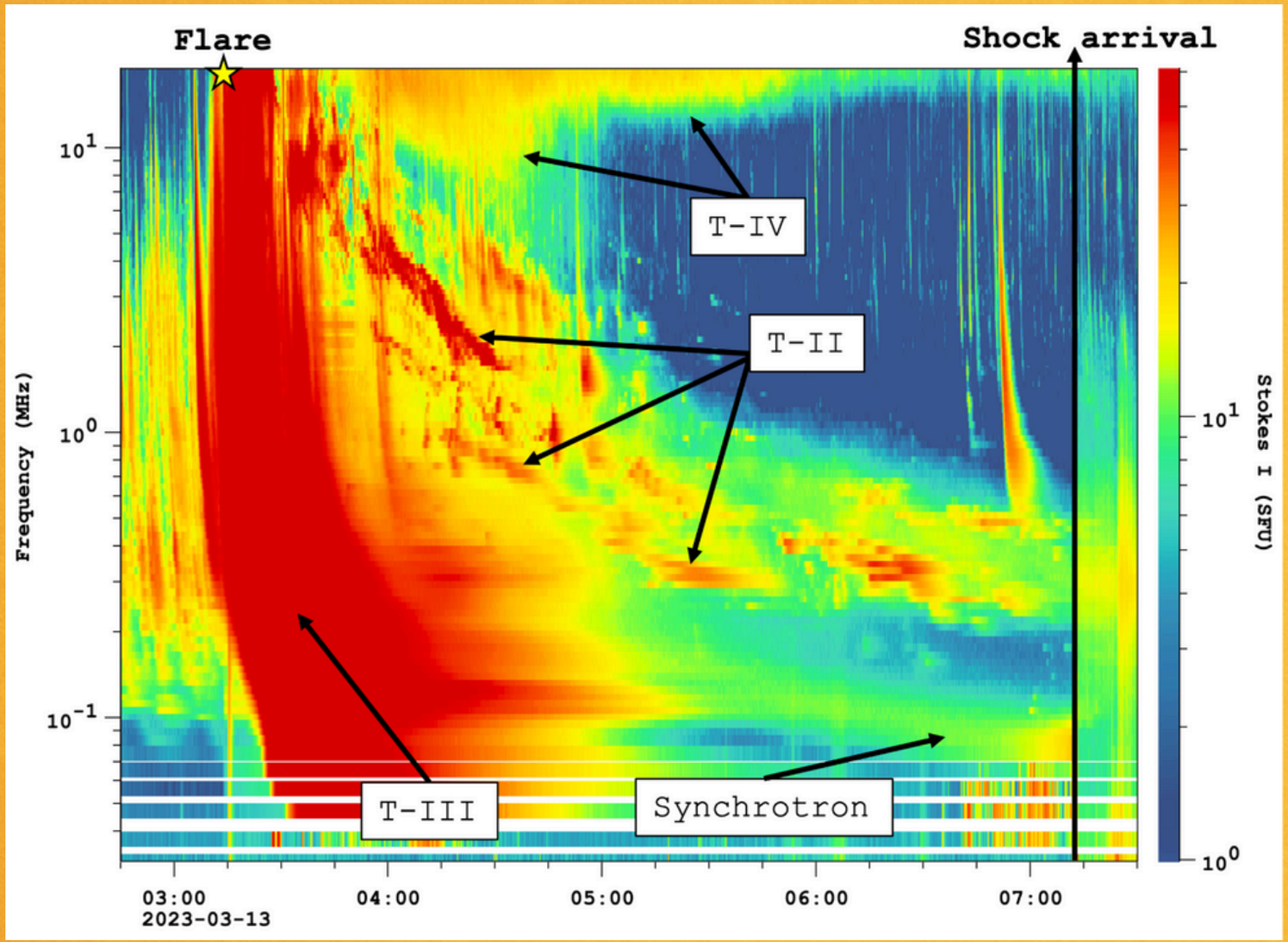
Positional significance – PSP & SO

- Radial and Longitudinal scans

Capabilities

- High time/frequency resolution of PSP
- Full STOKES from 20 MHz onward
- Particles + Waves measurements





Palmerio et al. in prep

This is what you can see with sufficient resolution and when you get close to the source!

How are radio waves generated?

Can we distinguish fundamental emission from higher harmonics?

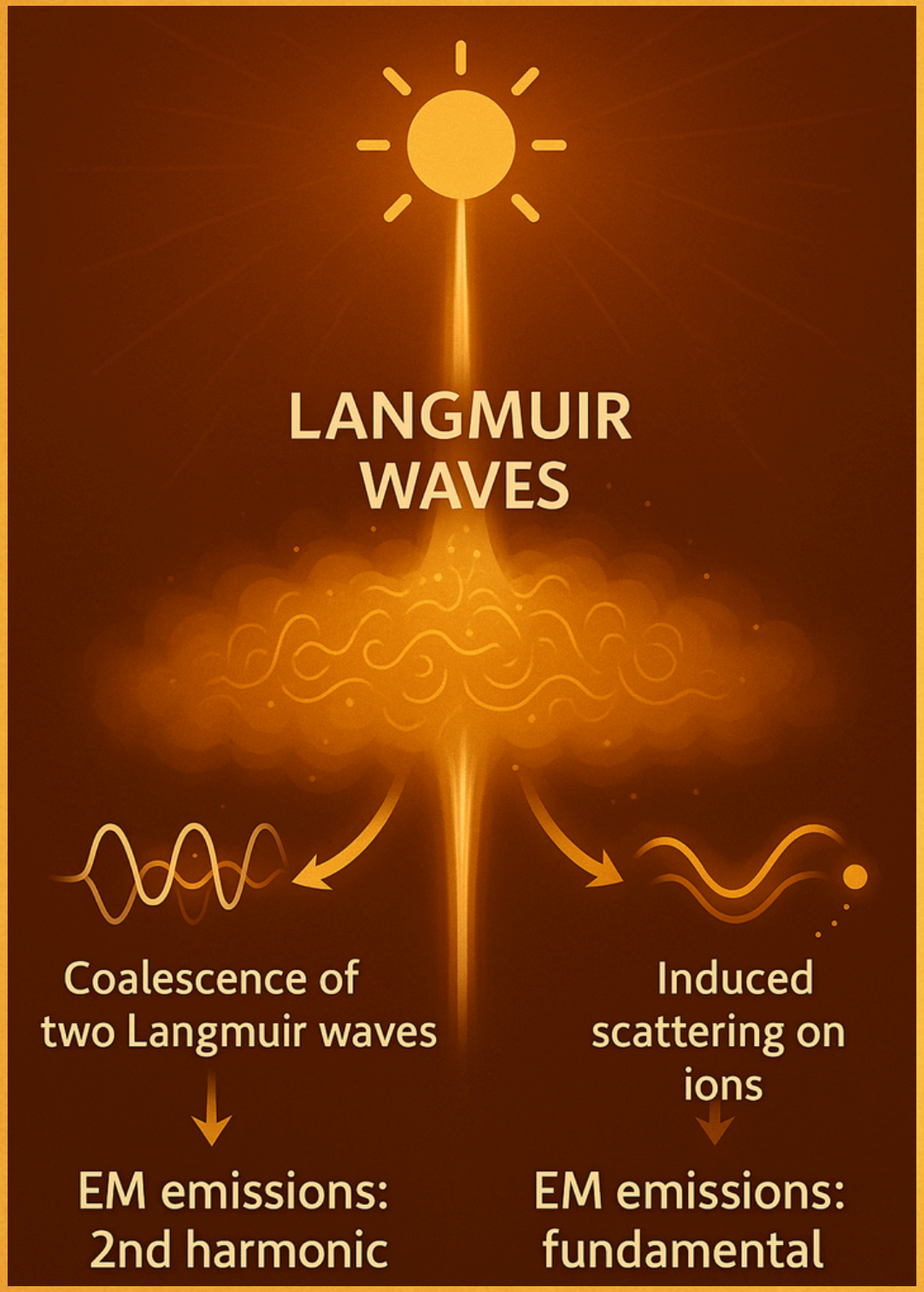
What about structures?

THEORY IS LIMITED BY REMOTE OBSERVATIONS

Do we observe more incoherent radio emissions?

What about fine structures?

How do wave properties evolve with respect to the source?



The Ginzburg-Zheleznyakov model

Predicts emission at Fundamental (***F***) and Harmonic (***H***)

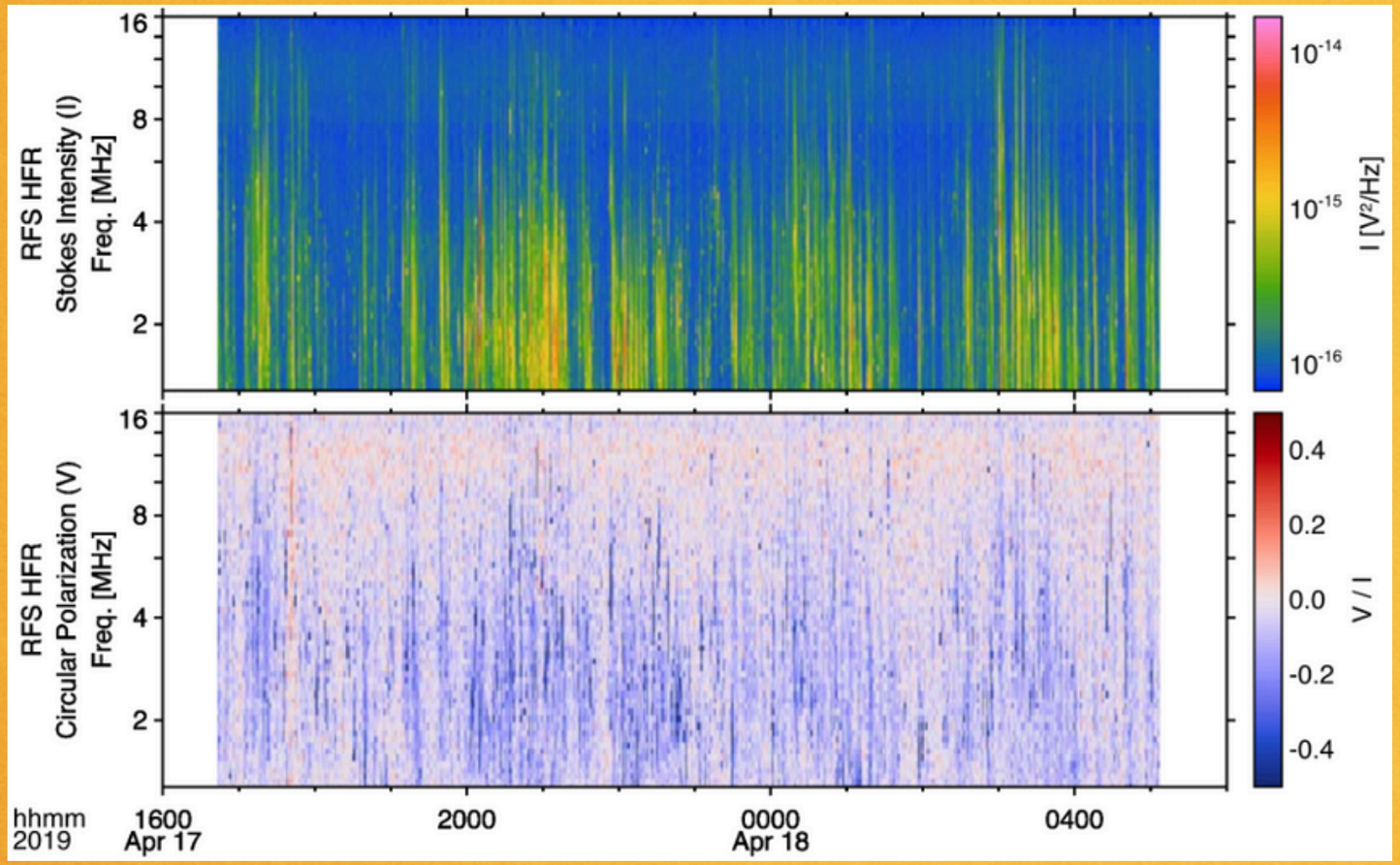
Theory is non-linear for both ***F*** and ***H***
(E.g. Melrose 1980)

Applicable to type III (non-stationary), and type II (stationary limit).

Considering random density inhomogeneities leads to direct (linear) transformation for ***F.***

E.g. Voshchepynets et al. 2015, Krasnoselskikh et al. 2019

Type III Storms

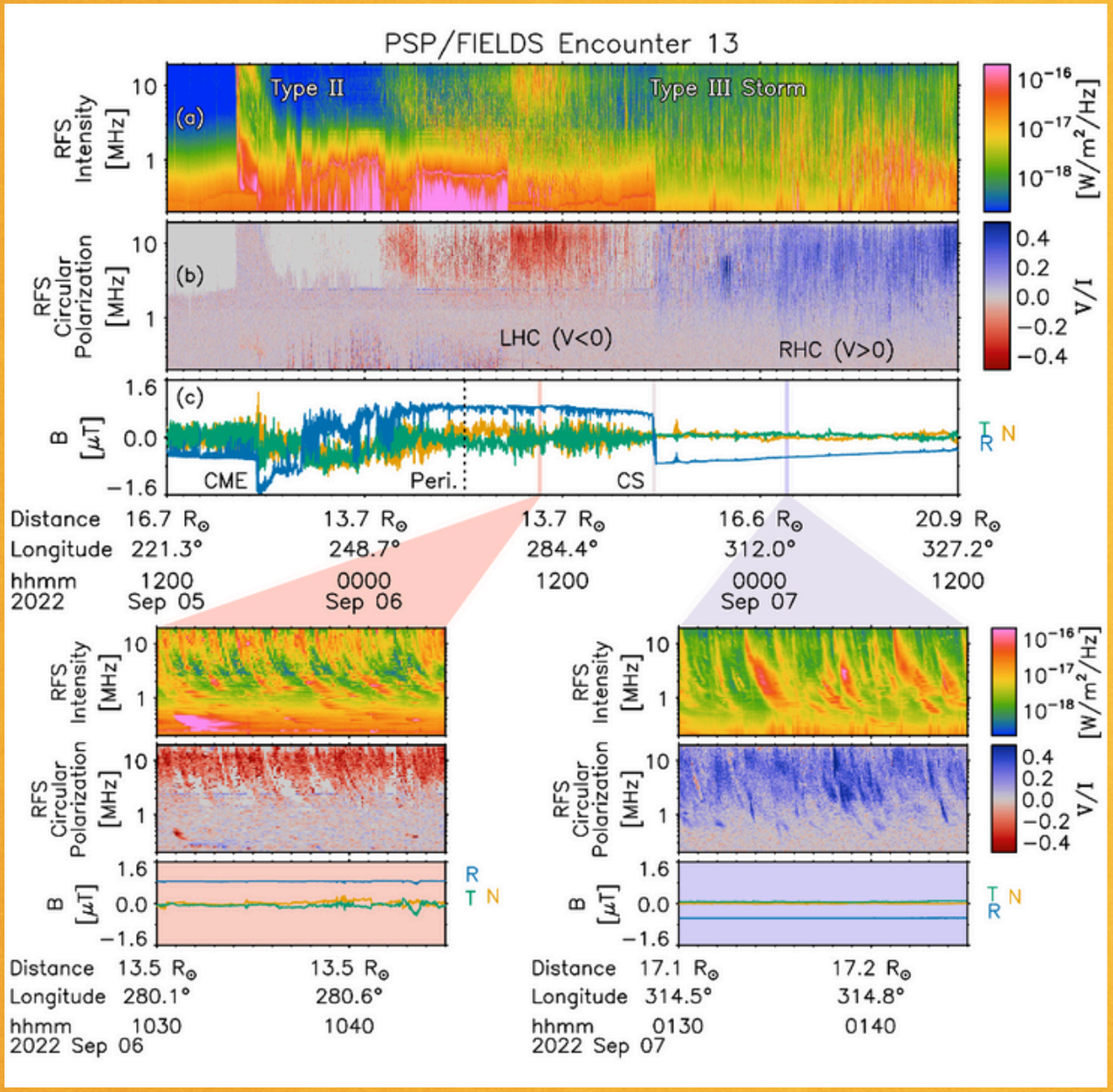


Pulupa et al. 2020 ApJS

Almost every PSP close encounter has type III storms.

These bursts are weak generated by weak electron fluxes - much of which not seen from 1 au.

High degree of circular polarization!

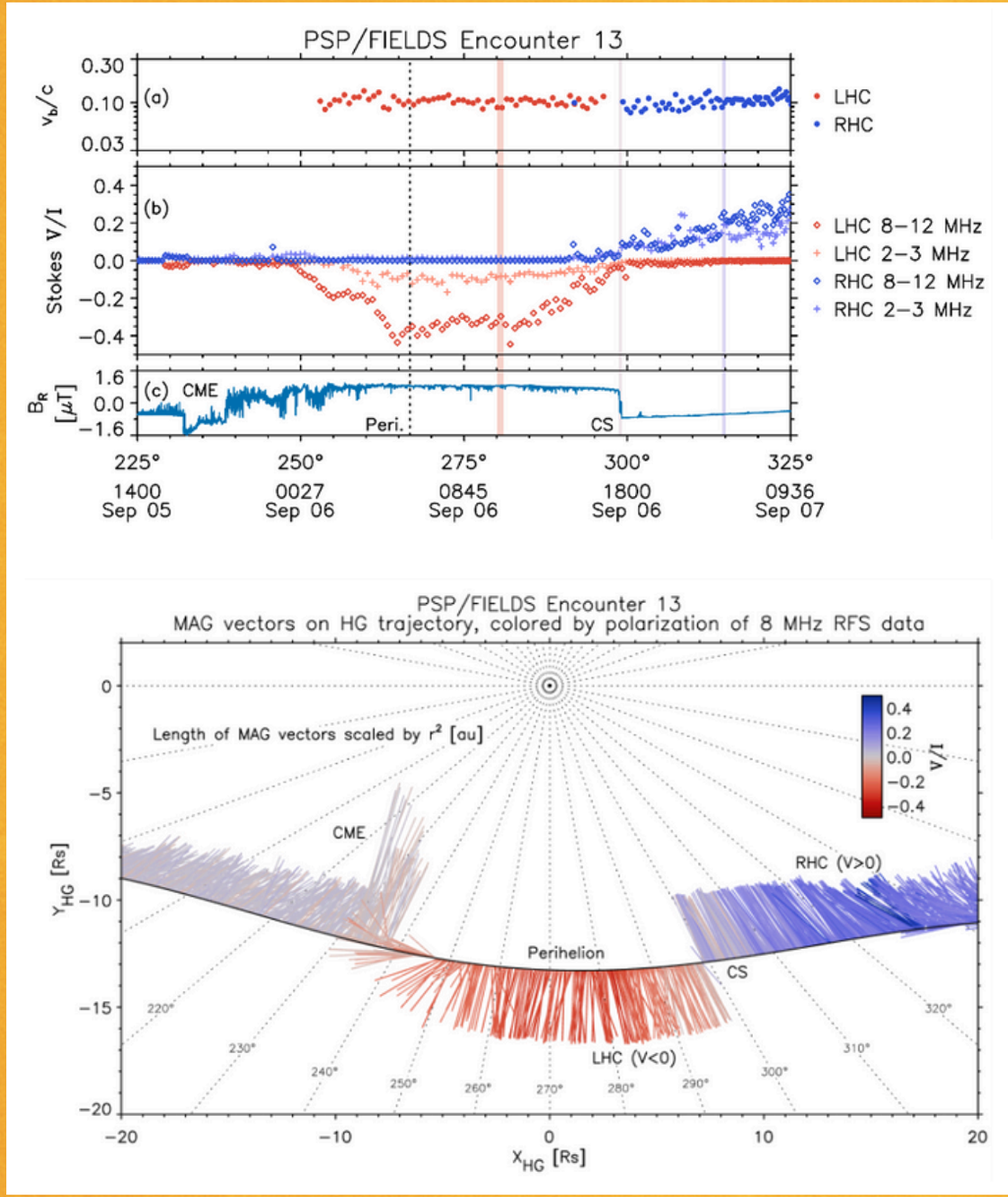


Pulupa et al. 2025 ApJL

Storm polarization

Perfect *O*-mode polarization during the full storm period.

Polarization exceeds 50% for most and peaks at nearly 100%.



Pulupa et al. 2025 ApJL

Storm polarization

Perfect *O*-mode polarization during the full storm period.

Polarization exceeds 50% for most and peaks at nearly 100%.

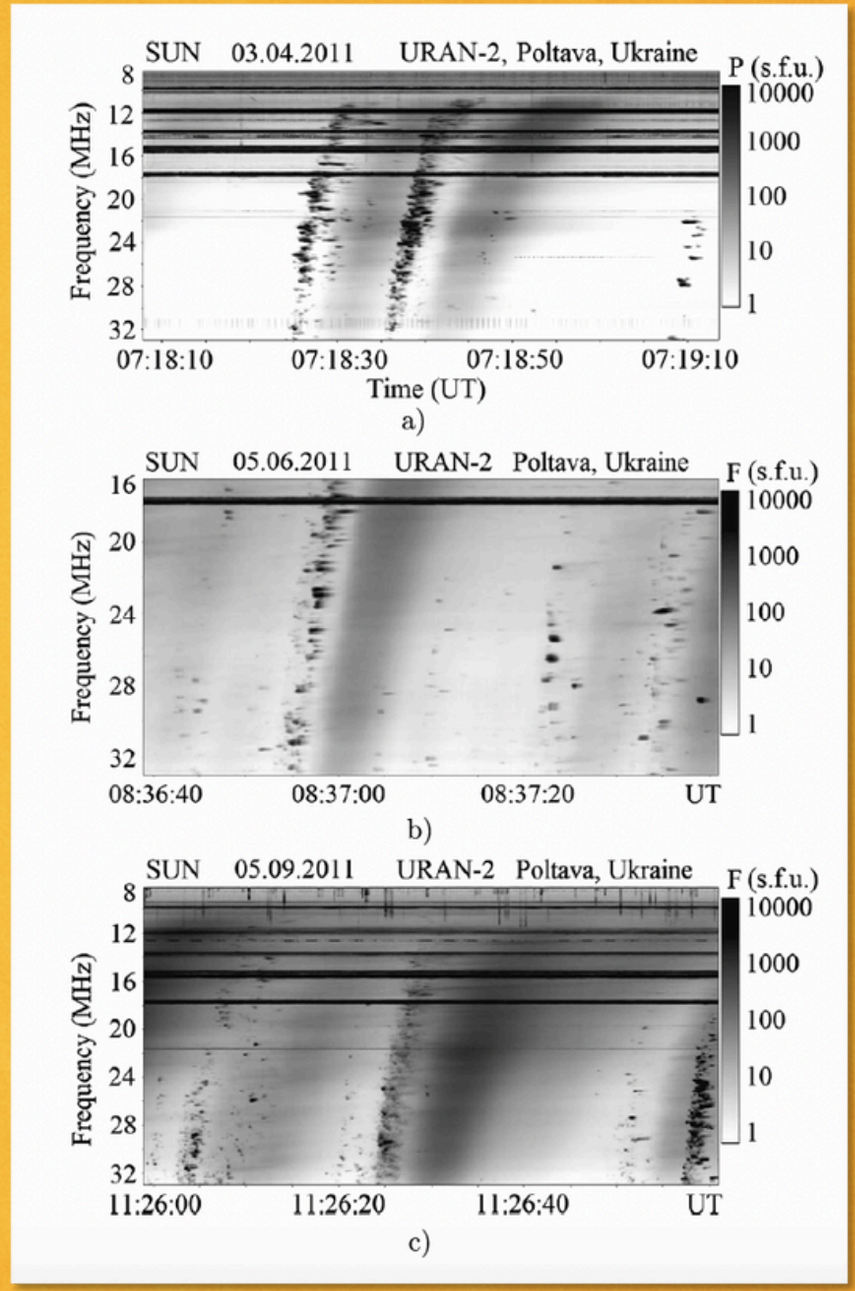
Fundamental-Harmonic pairs

Plasma emission mechanism predicts the generation of harmonics.

Occasionally observed for type II radio bursts – but easier to distinguish.

Difficult to distinguish for type III radio bursts – rare! (even in metric-decametric)

Never been observed in deca-hecto-kilometric! (PSP's observational range)

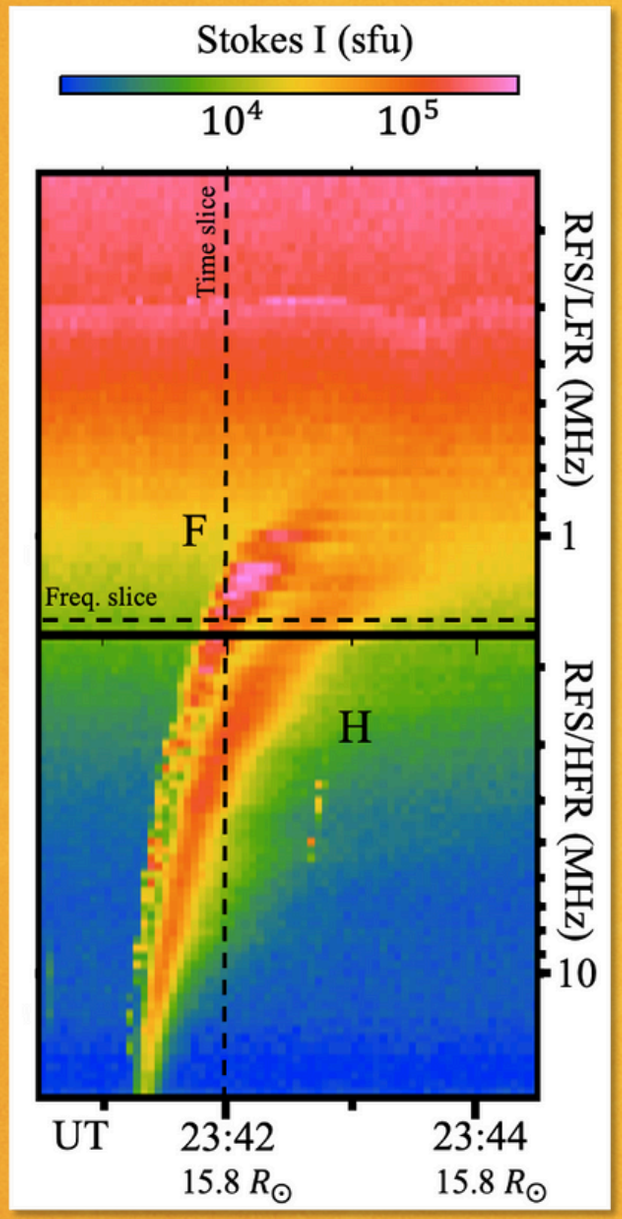


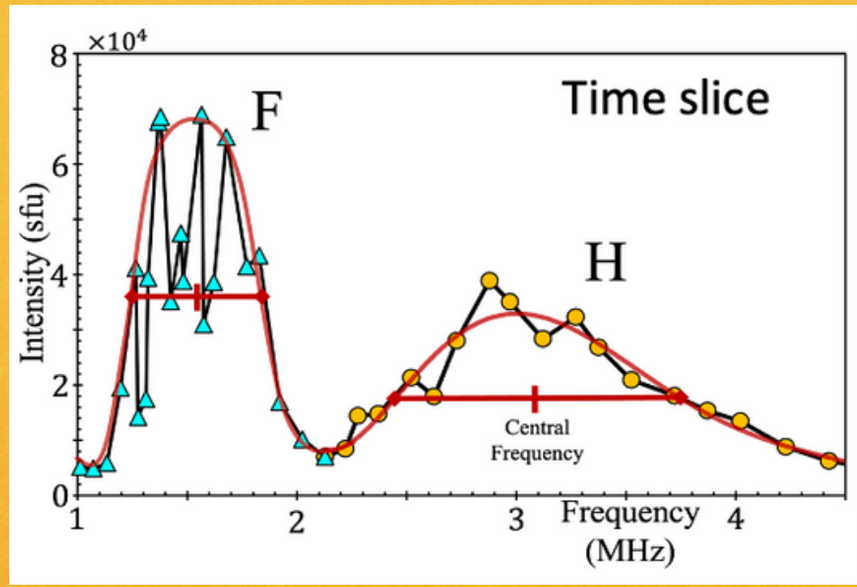
Melnik et al. 2019 Sol.Phys

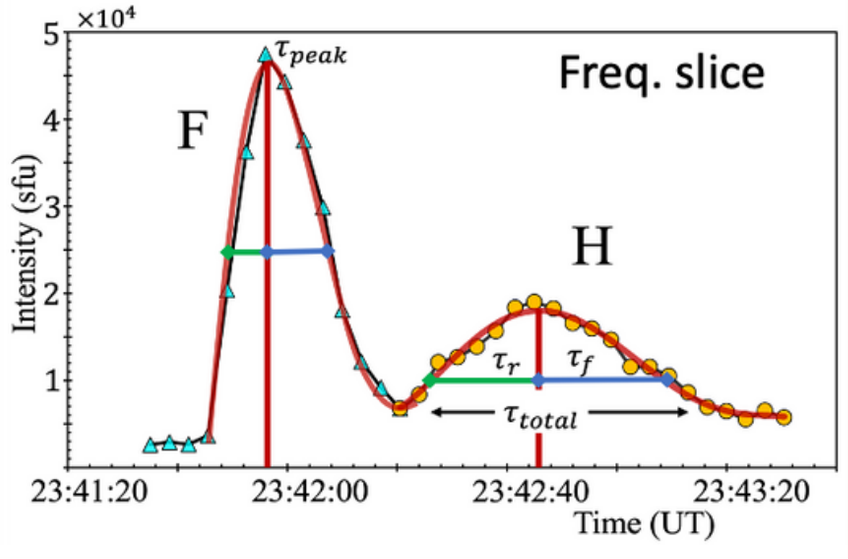
Majority of PSP bursts are *F - H* pairs

Proximity to the source

PSP's sensitivity and improved time-resolution



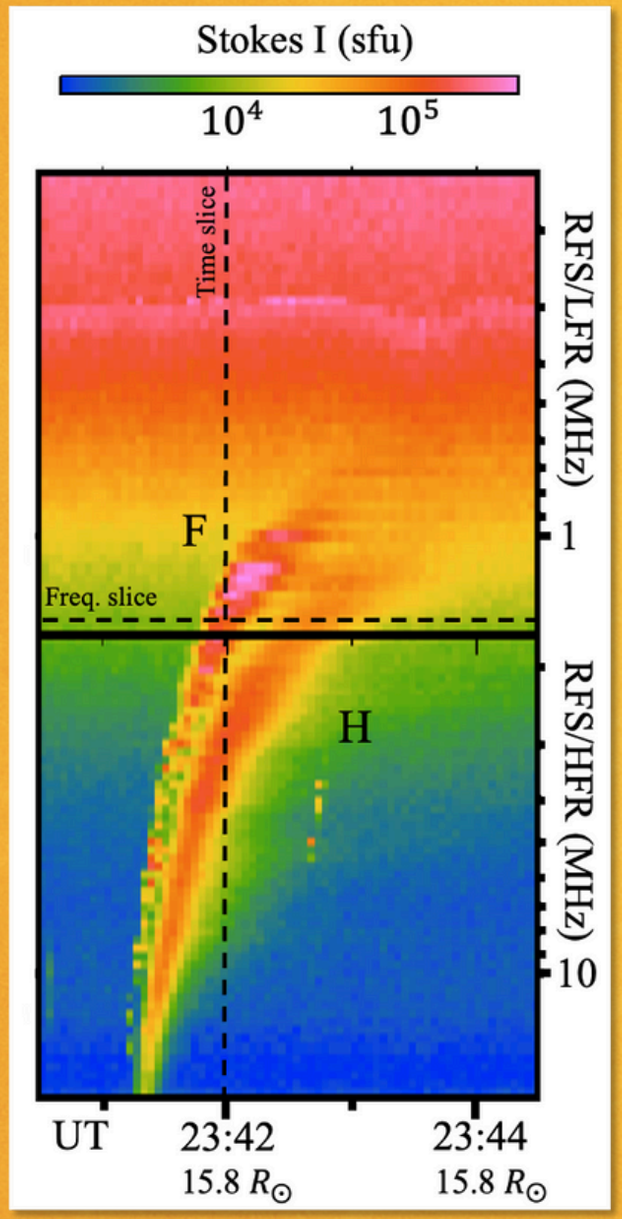


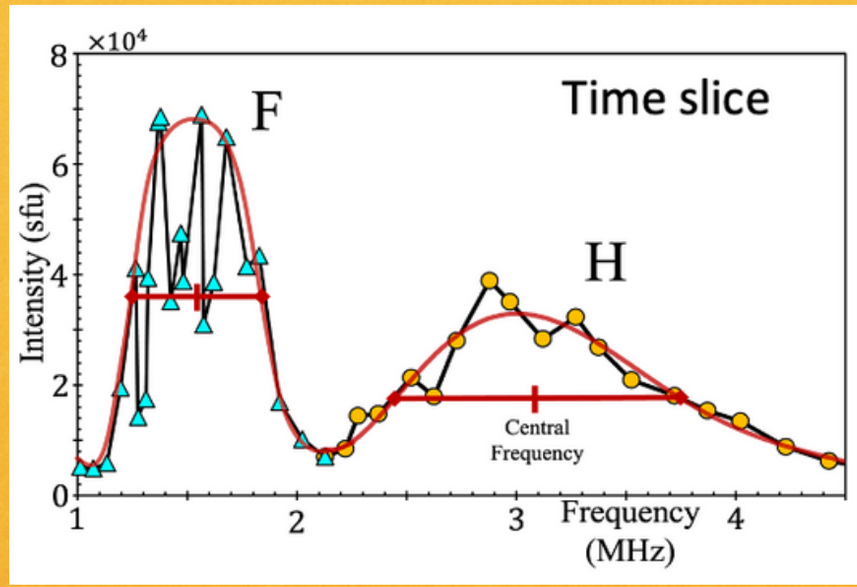


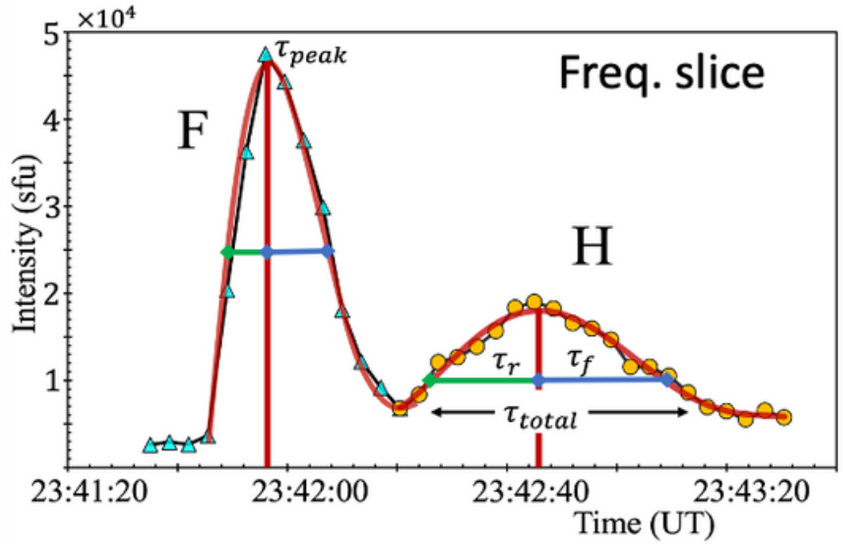
Jebaraj et al. 2023 ApJL

Majority of PSP bursts are *F - H* pairs

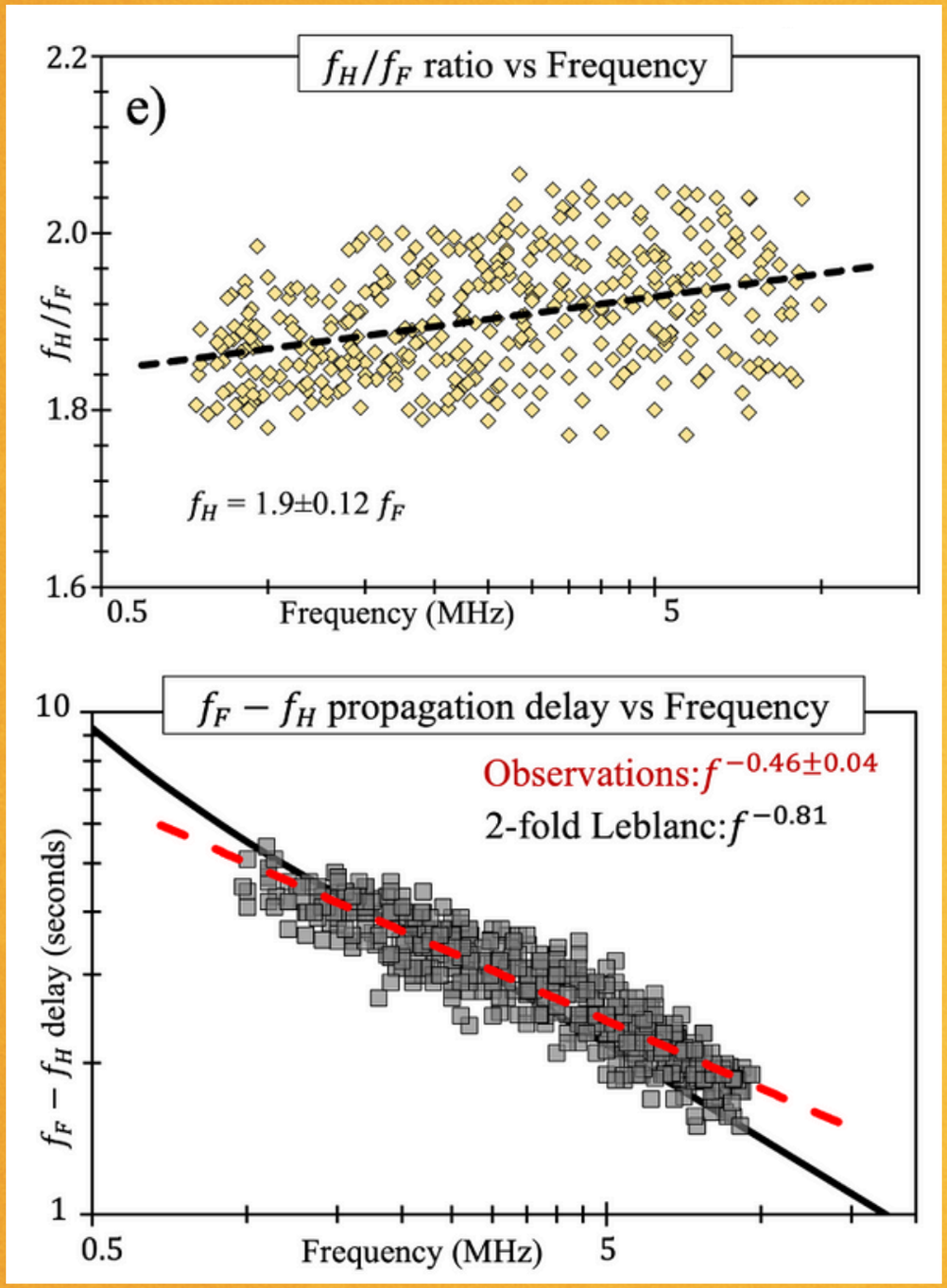
F is strongly structured, ***H*** is smooth/diffuse and only shows weak structuring.







Jebaraj et al. 2023 ApJL



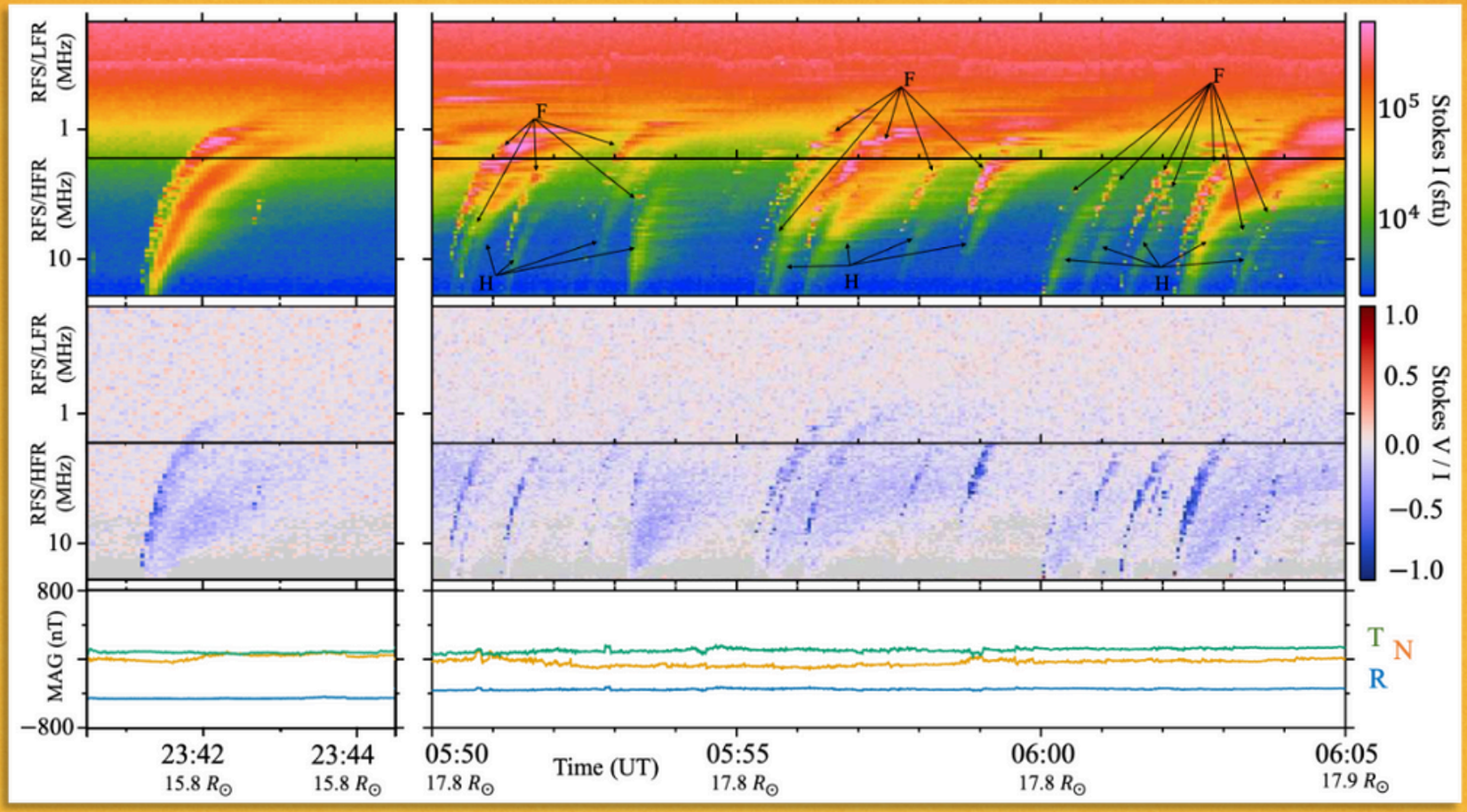
Jebaraj et al. 2023 ApJL

Propagation delay

F and ***H*** propagate with different group speeds.

Predicts an offset in the arrival of ***F*** and ***H*** causing observations to deviate from ***H*** = 2***F***

Surprisingly, predicted group delay aligns well with the observed delay in data even with a simple Leblanc density model.



Jebaraj et al. 2023 ApJL

F is polarized to a greater degree (>60%) than ***H*** (~15-20%).

F is sharp and structured while ***H*** is diffuse and smooth

F emitted via linear processes and ***H*** via non-linear process
→ leads to ***F*** being pure *O*-mode, while ***H*** is both *X*- and *O*-mode

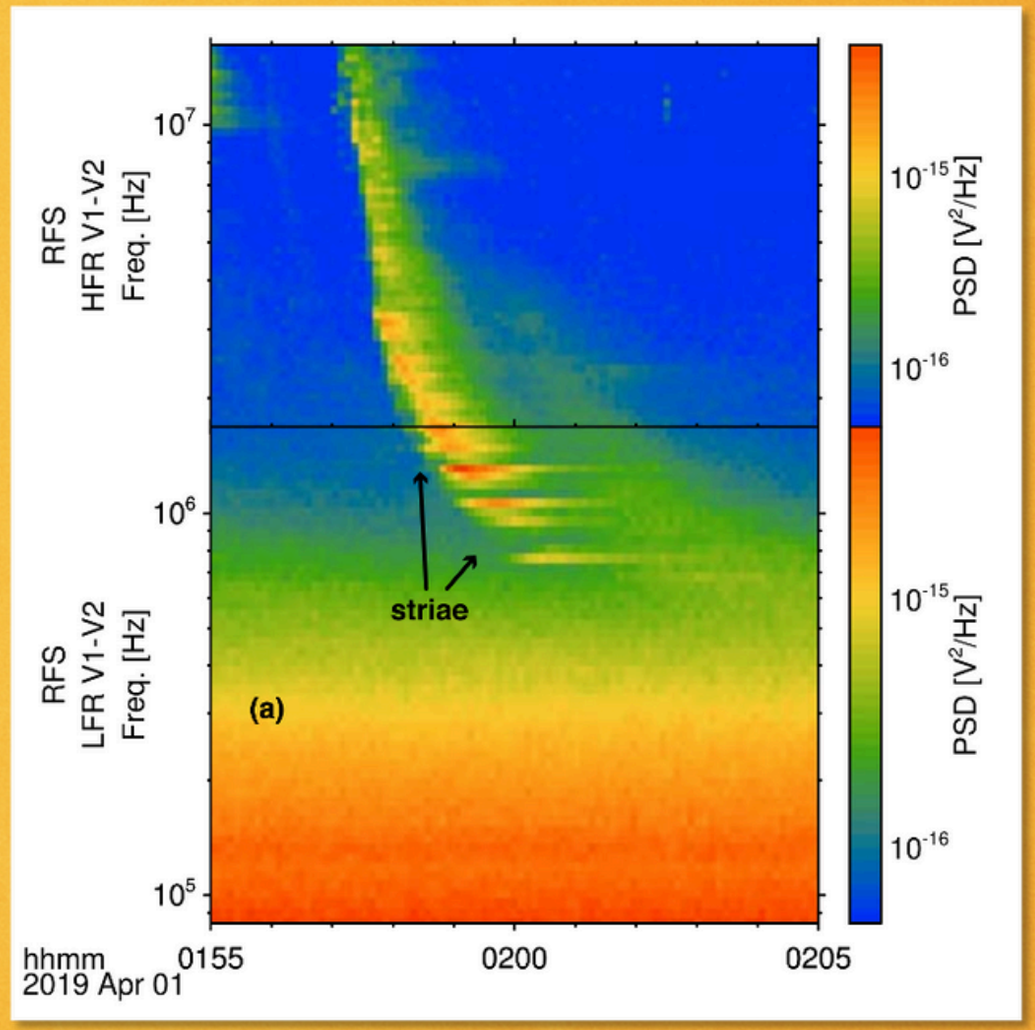
Fine structures

F is highly structured

Rare sightings in STEREO/WAVES and Wind/WAVES observations (Jebaraj et al. 2023)

Morphological similarities to metric-decametric fine structures

Seen at small bandwidths if resolution allows as found by Krupar et al. 2025 (ApJL).



Pulupa et al. 2020 ApJS

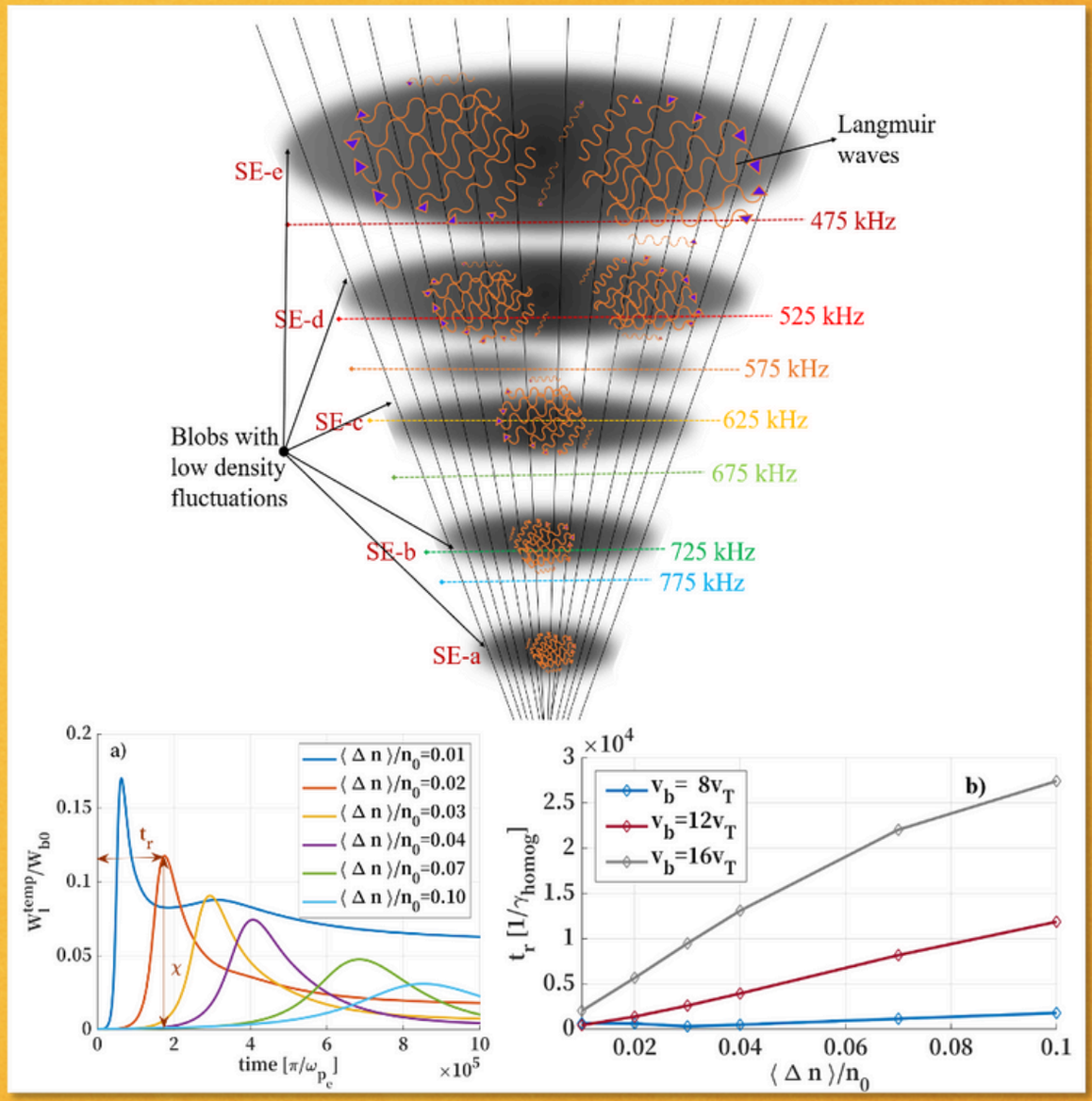
Fine structures

Natural consequences of beam evolution in inhomogeneous plasma

Low inhomogeneity → Striae elements
High inhomogeneity → No emission

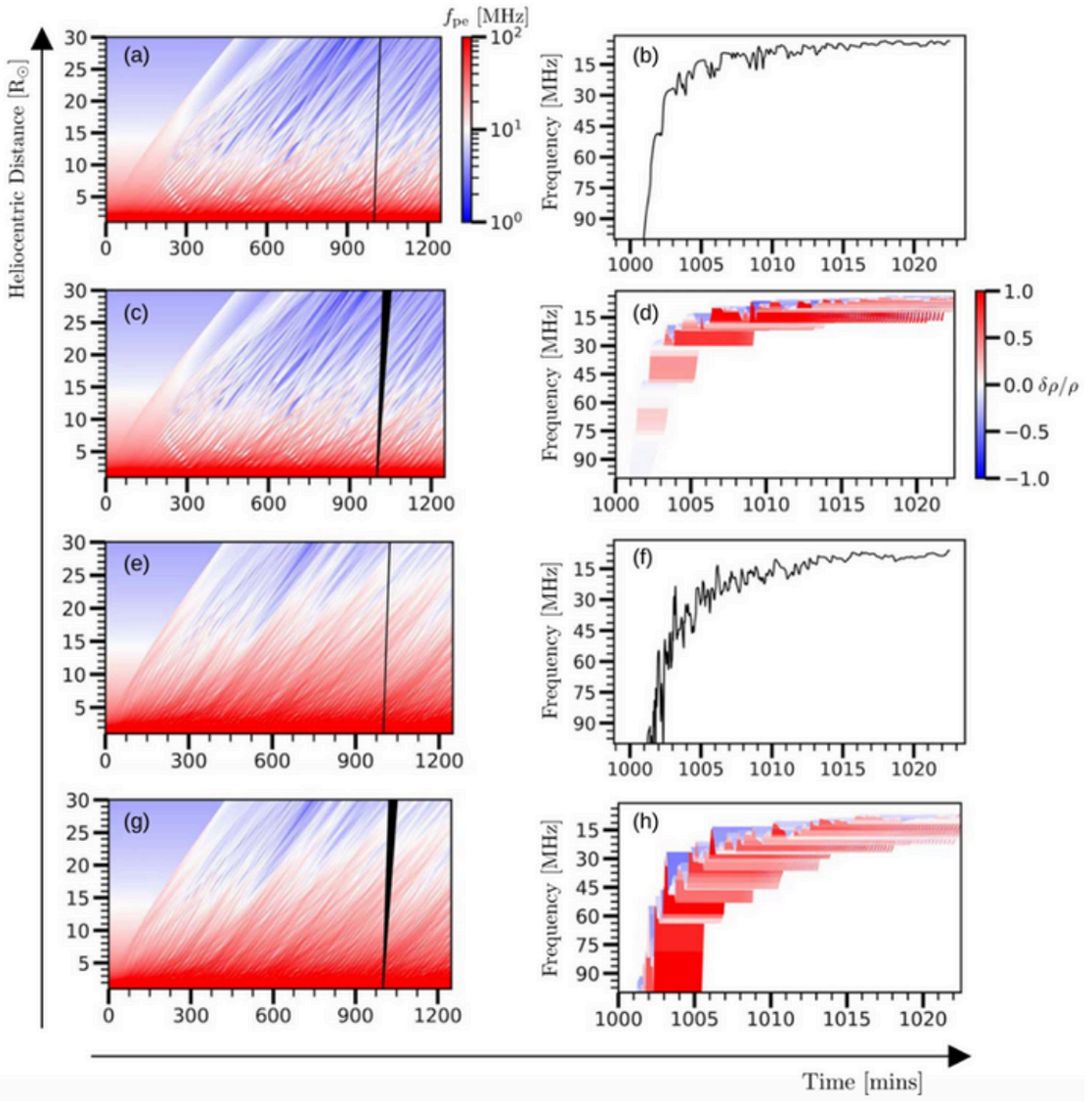
Probabilistic model: Voshchepynets et al. 2015 (ApJ), Krasnoselskikh et al. 2019 (ApJ), Jebaraj et al. 2023a (A&A)

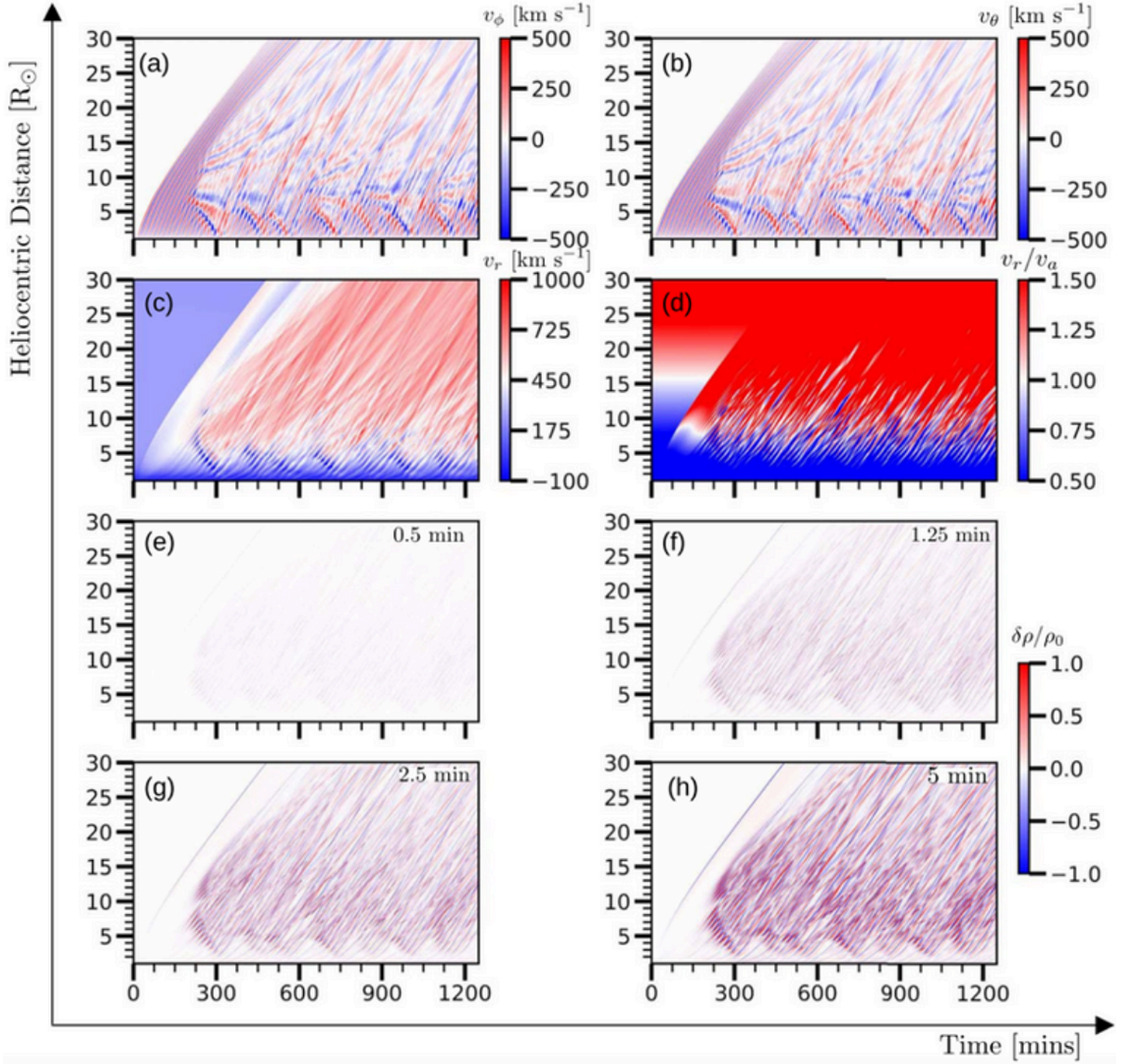
Similar results using simulation by Krafft et al. 2013 (ApJ), 2015 (ApJ)



Jebaraj et al. 2023 A&A

Why so many striae?





Sishtla et al. 2024 ApJL

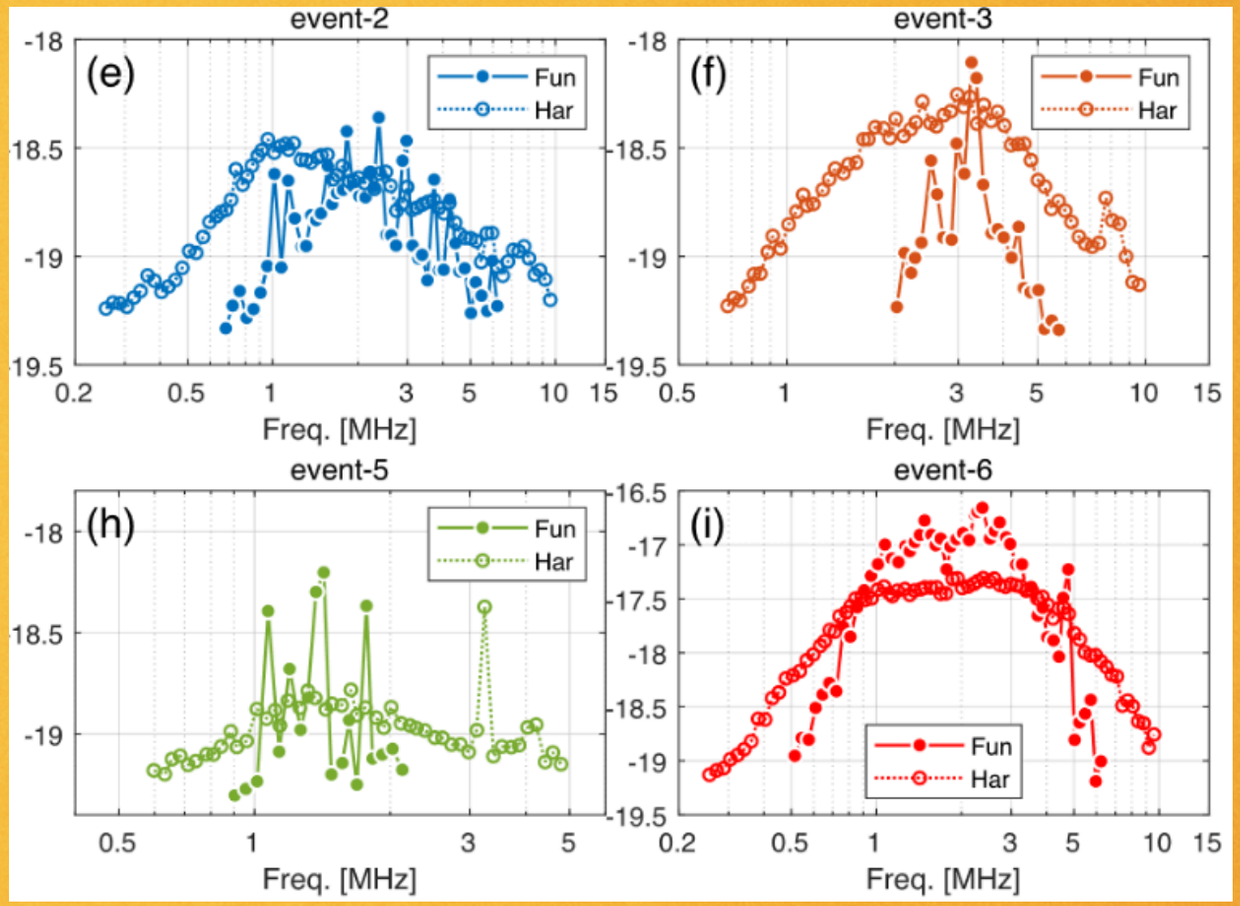
Weak bursts

Most bursts are weak!

F is weaker than ***H*** mostly.

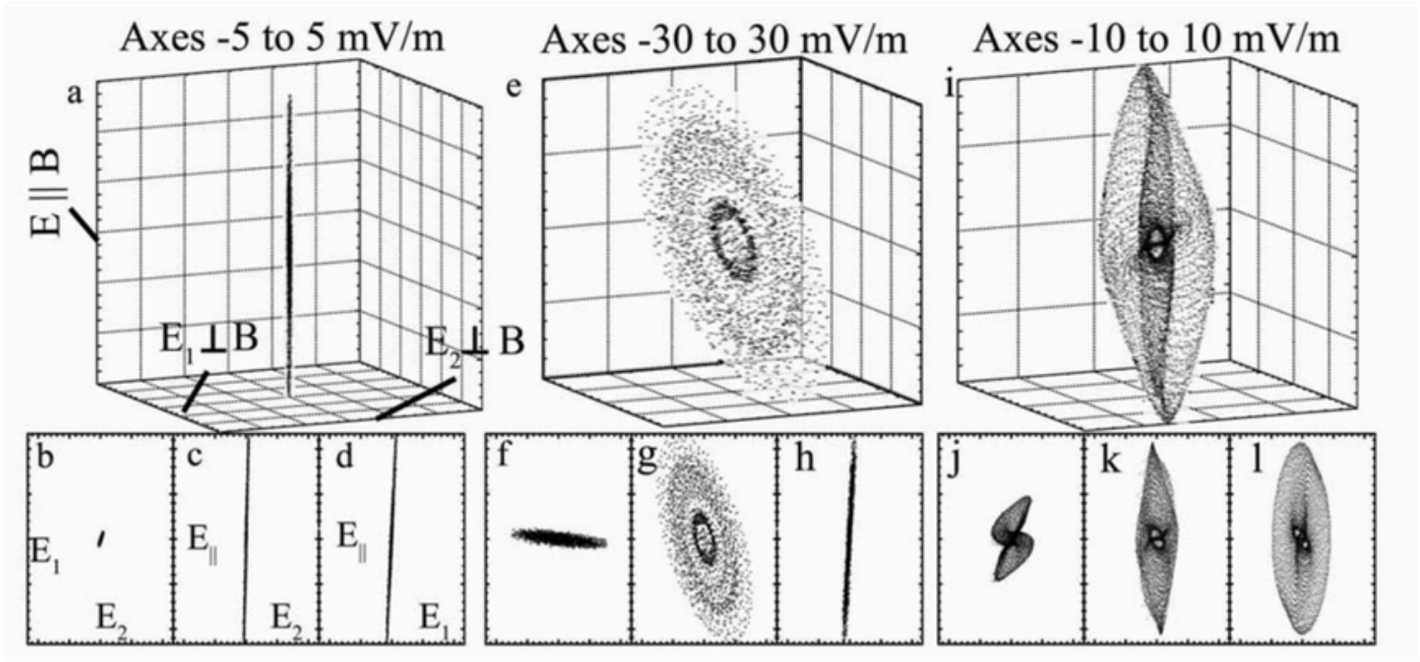
Fine structures are brighter than ***H***

This finding is in line with what the original study by Jebaraj et al. 2023 (ApJL) found statistically.

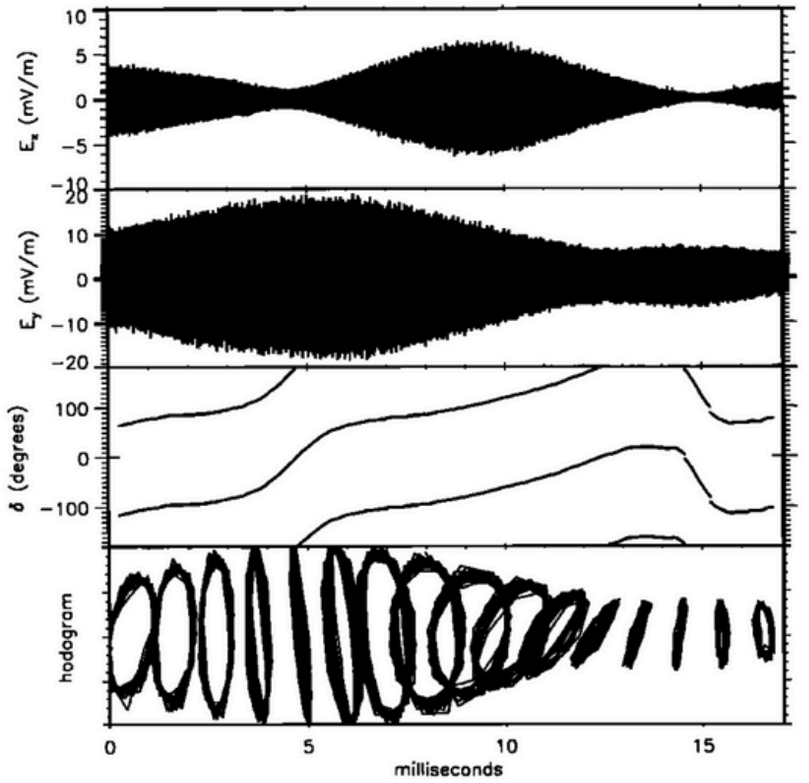


Chen et al. 2024 ApJL

Z-mode waves



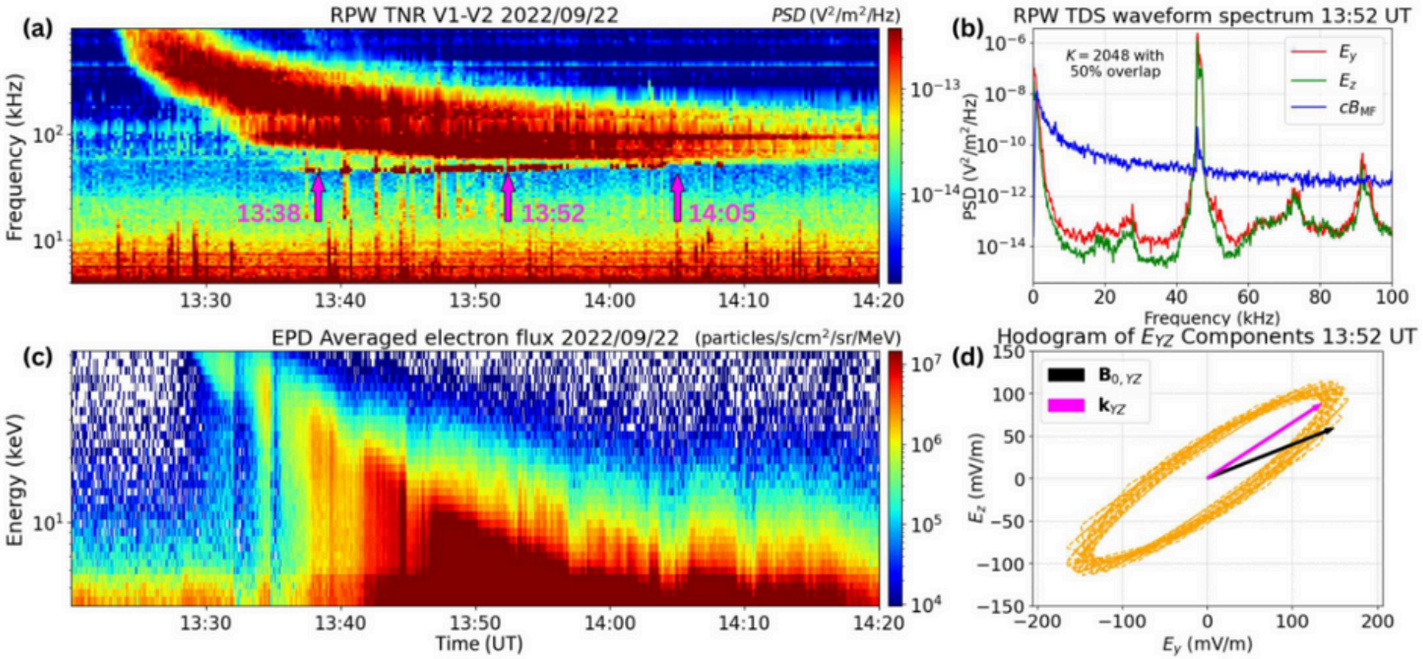
Malaspina & Ergun 2008 JGR



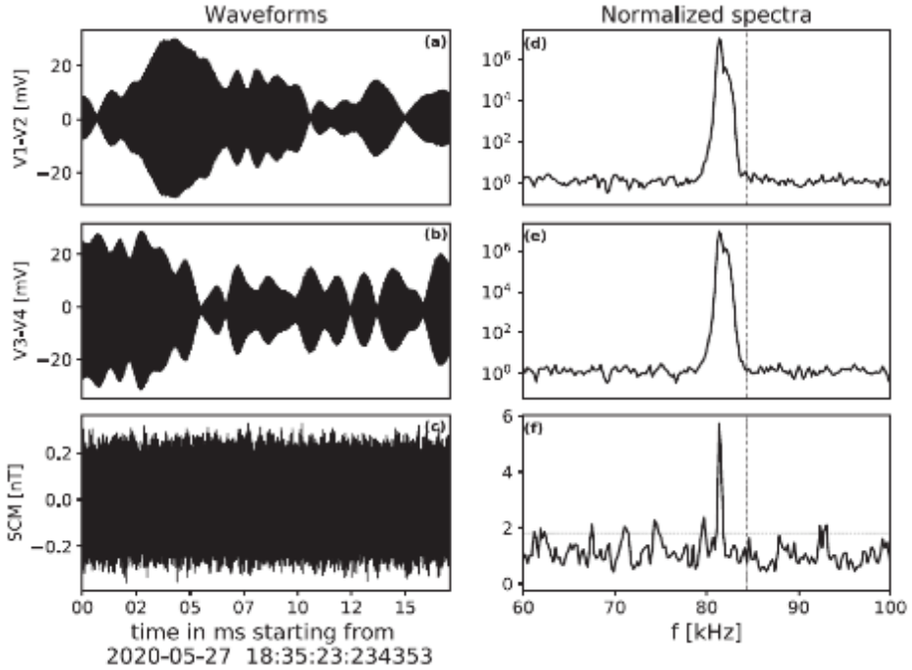
Bale et al. 1998 GRL

Langmuir waves in **inhomogeneous plasma** are not purely electrostatic.
They gain a magnetic component in density depletions.
Tunneling leads to direct transformation into *O*-mode radiation.

PSP/SolO Observations



Formanek et al. 2025 ApJL



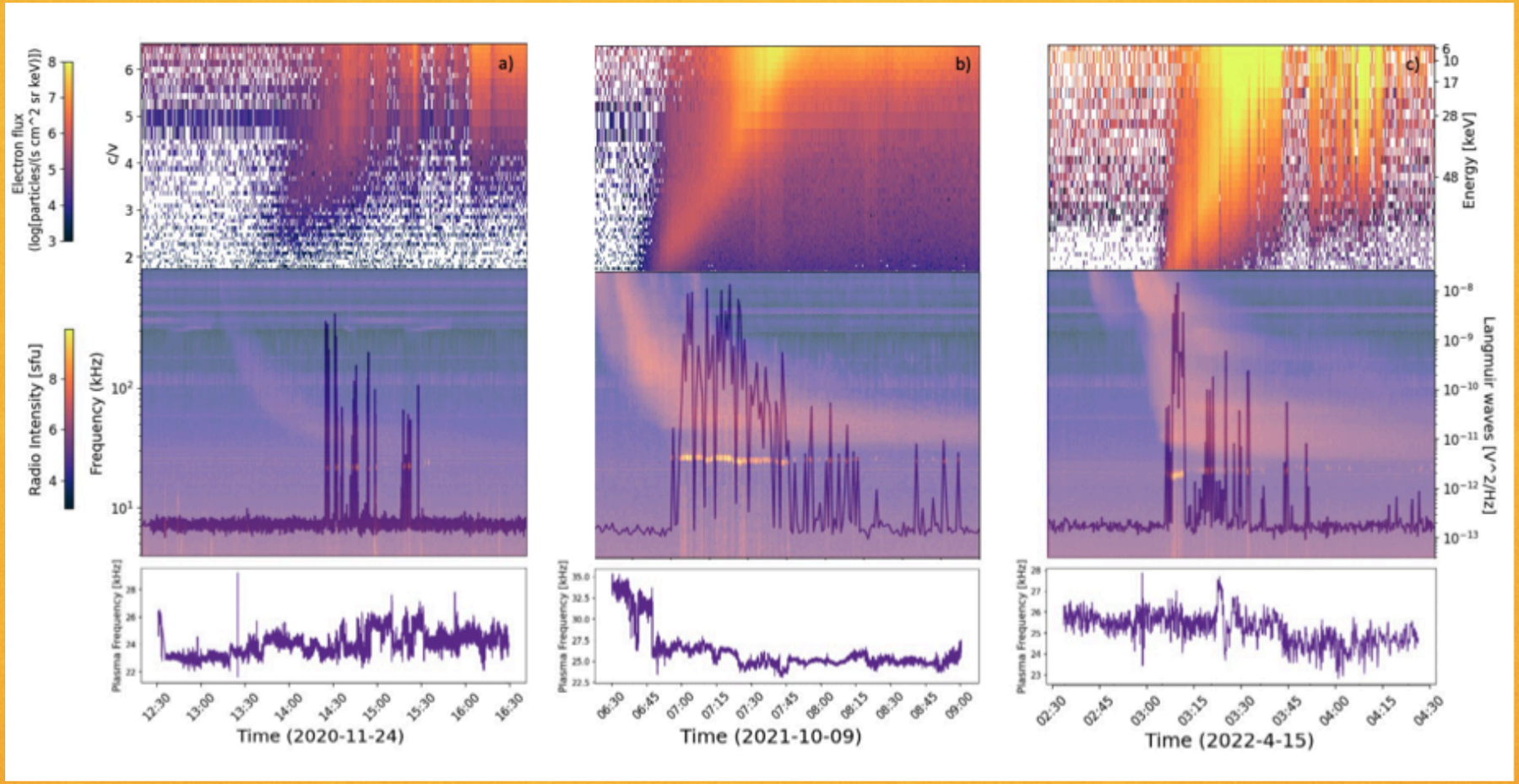
Larosa et al. 2022 ApJ

First measurements of the magnetic component of generated waves (Larosa et al. 2022 ApJ)

Z-mode waves are now being found and studied together with the electron flux generating them (Formanek et al. 2025 ApJL).

Evolution of source and waves

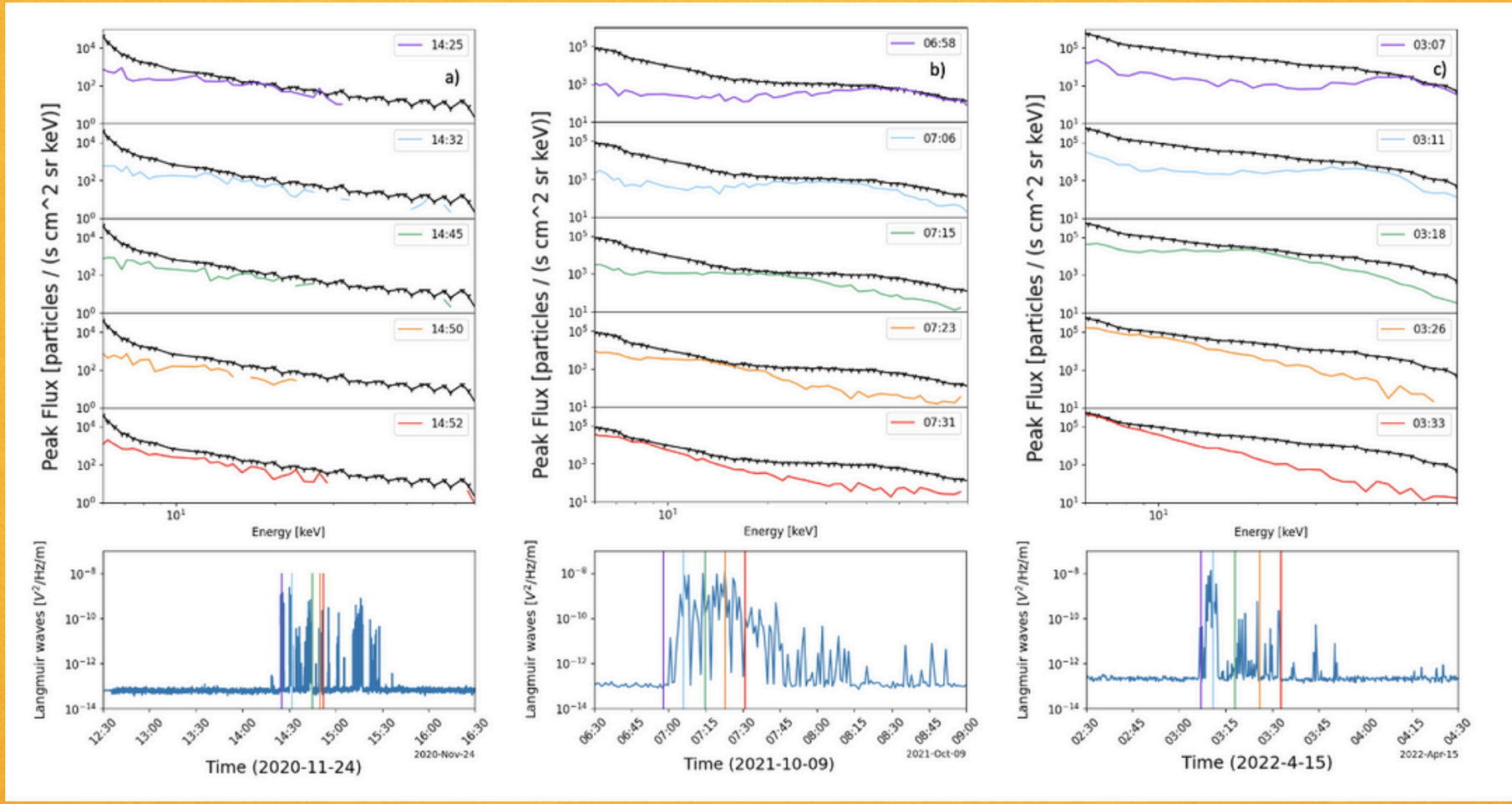
Solar Orbiter can measure electron distributions and wave characteristics consequently at high cadence.



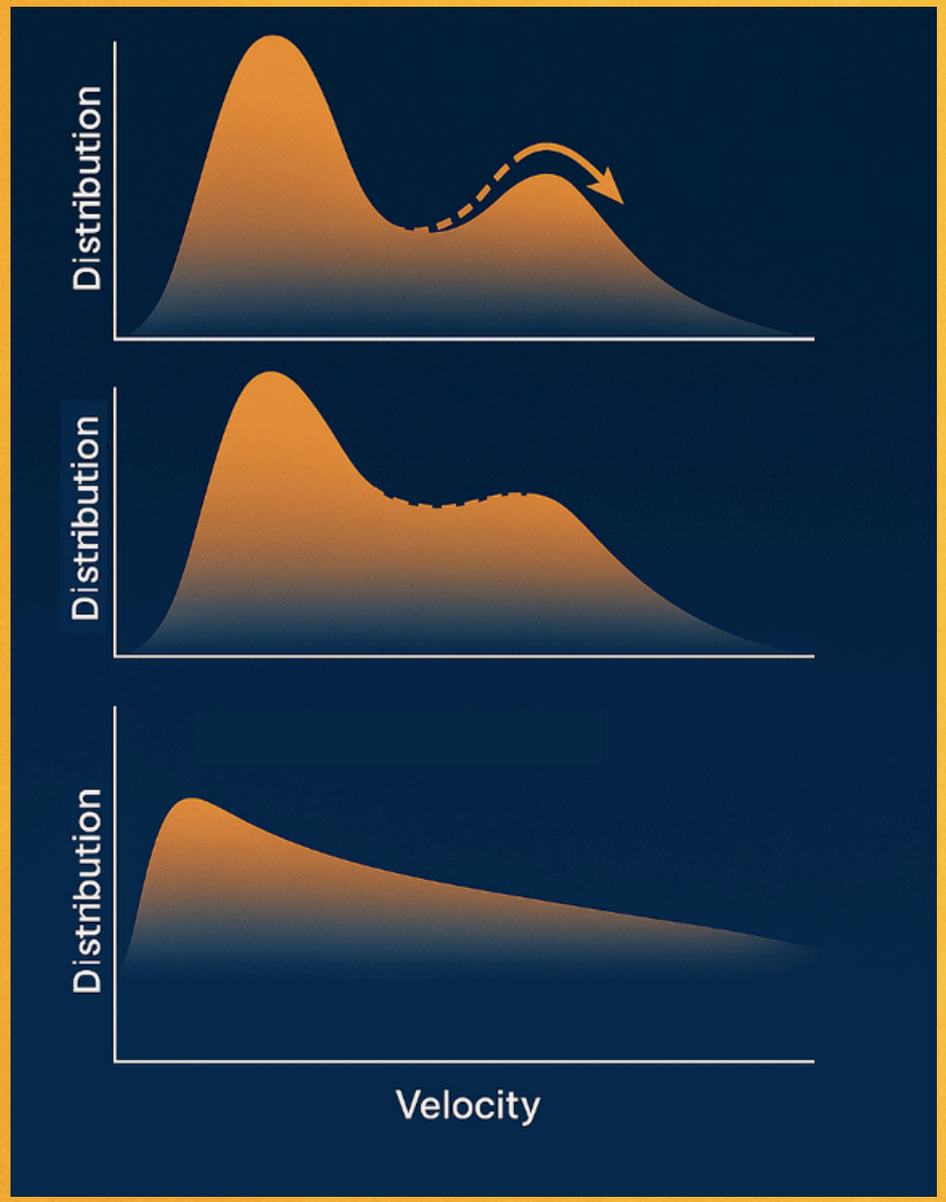
Lorfing et al. 2023 ApJ

Evolution of source and waves

We can study the radial evolution of the energetic beam and the characteristics of the waves



Lorfing et al. 2023 ApJ



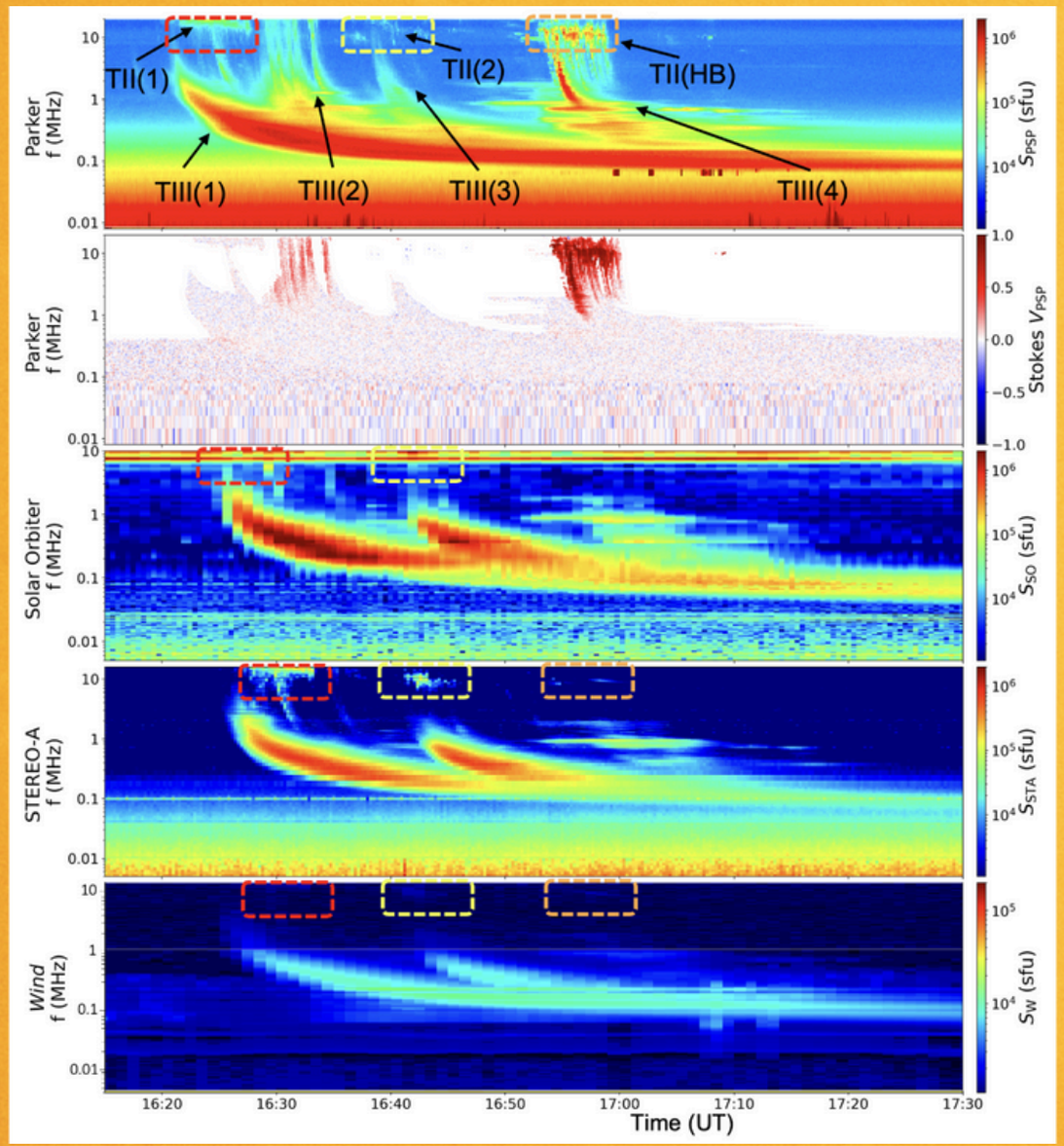
Beam relaxation

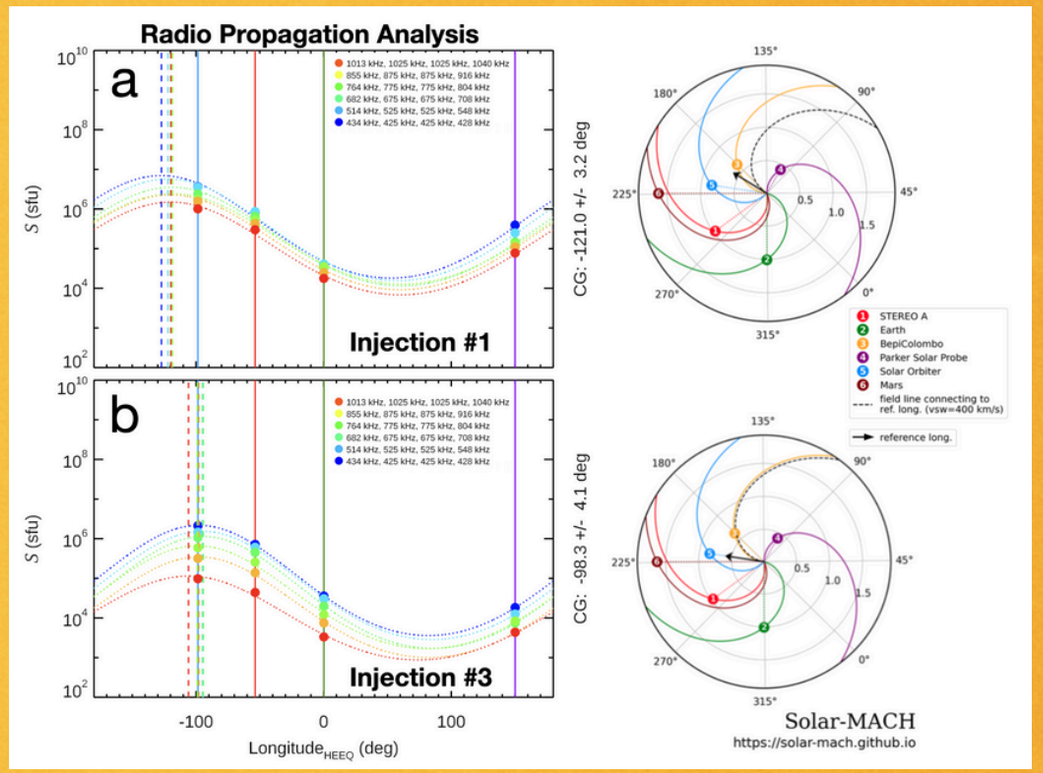
A lack of a bump is predicted in theory (Voshchepynets et al. 2015a,b)

A plateau or negative slope suggests beam is quasi-relaxed

This circumvents the Sturrock paradox and allows the beam to propagate far.

Multi-messenger Science



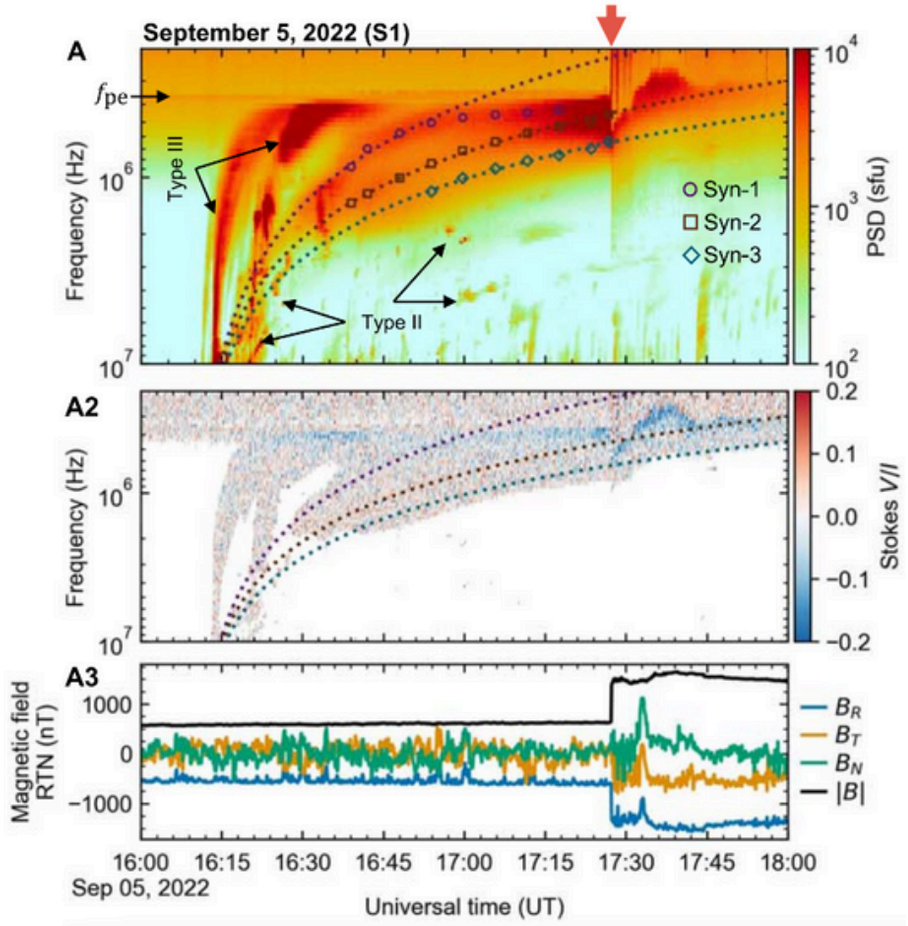


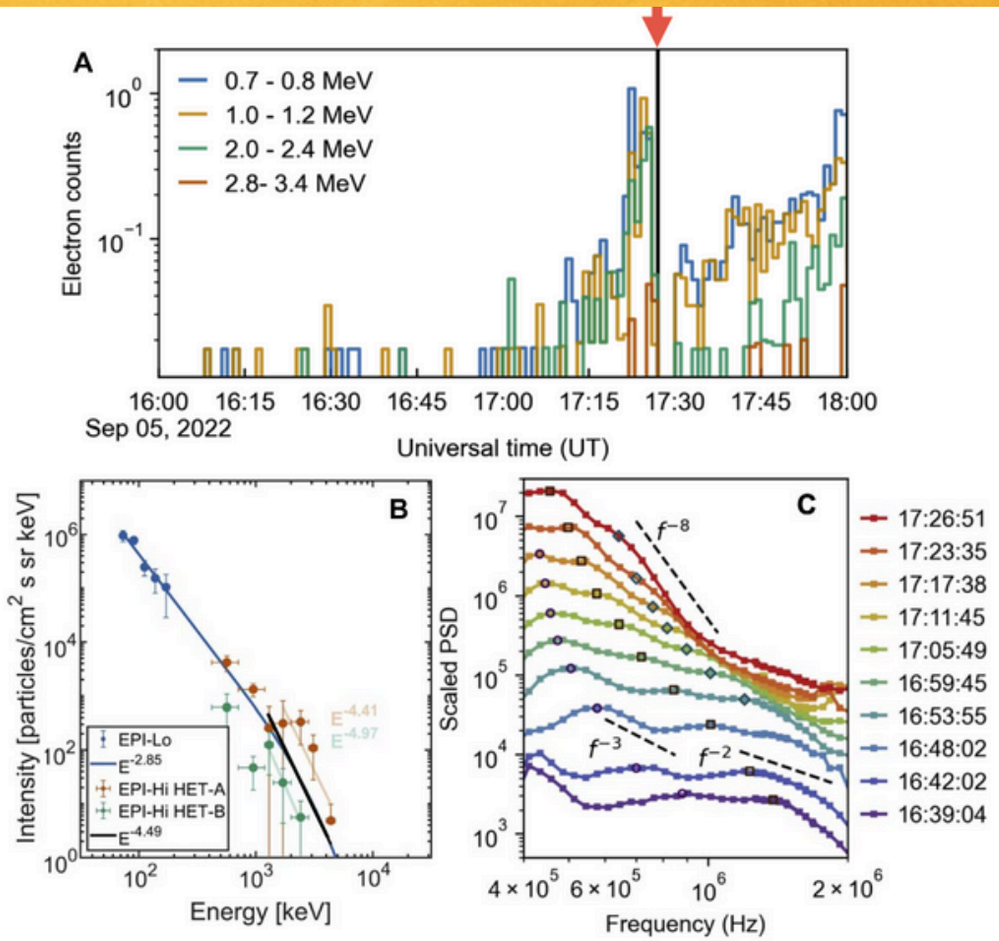
Dresing et al. 2023 A&A

Widespread event on April 17, 2021. Complex electron event with unclear injection profile.

Radio observations provided a unique insight through which we identified the source.

Synchrotron emission





Jebaraj et al. 2024b ApJL

PSP observes coronal transient events up-close (large solid angle)

For the first time, we can measure synchrotron emission + the emitting electrons + the shock that is accelerating them!

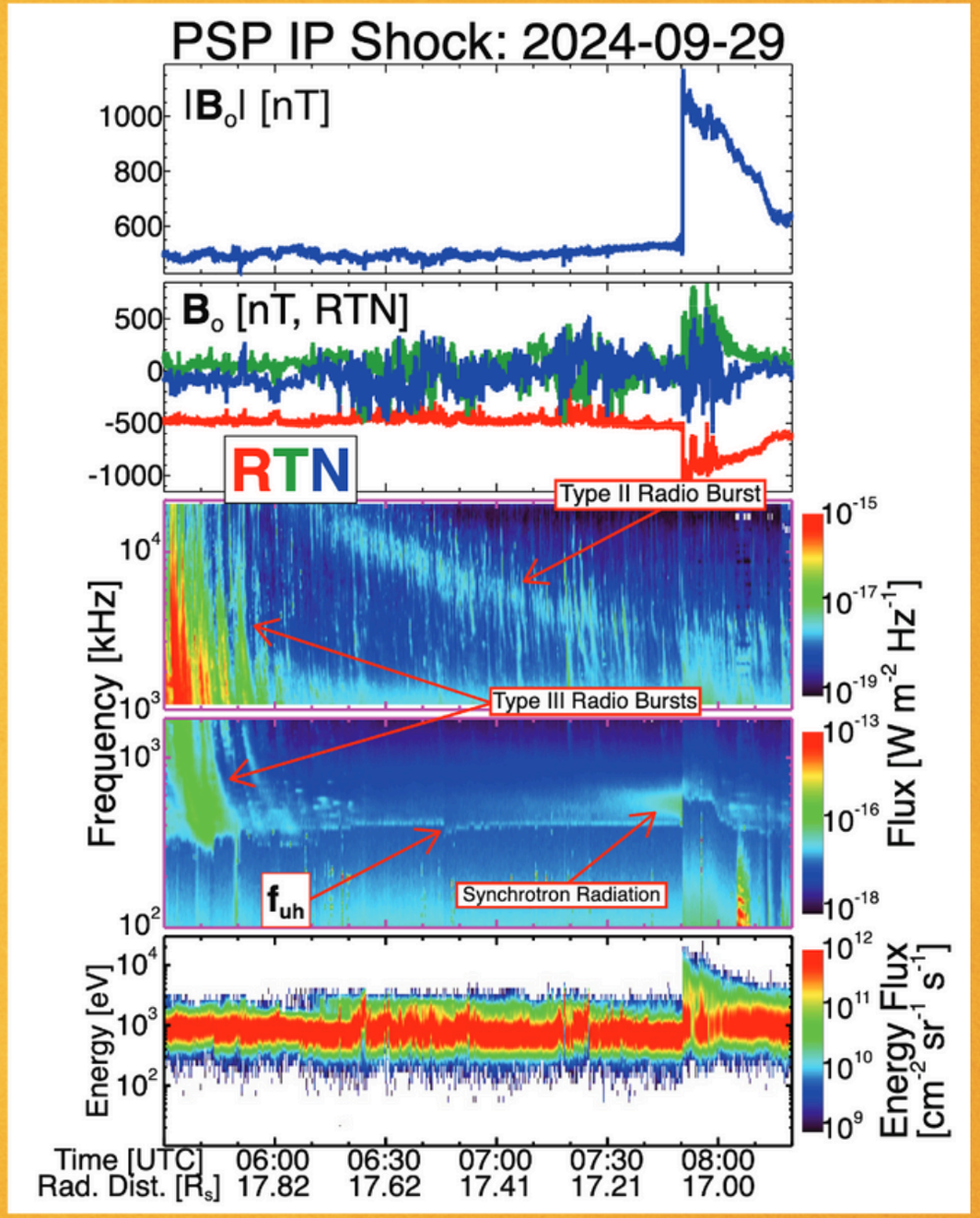
Even weak shocks!

Synchrotron emission is observed even in the weakest shocks close to the Sun!

Evidence of electron acceleration (a long standing problem).

Close to the source → Increased solid angle → More light is received!

Relativistic electrons are not that rare after all.



Wilson III et al. 2025 ApJ

Summary

Modern space-based observations have provided means for testing and improving theory of radio emission generation and propagation.

Multi-messenger radio capabilities provide an unparalleled understanding of energetic particle acceleration and their transport.

They have also opened new avenues for remotely tracking the evolution of radio sources from its origin to 1 AU.

Polarization measurements at low-frequency have allowed us to get a new perspective of the emission source.

We are routinely measuring (gyro)synchrotron emission close to the Sun

There is so much data to analyze!

INTERNATIONAL SPACE SCIENCE INSTITUTE

UNIVERSITY OF TURKU

Thank you