Methods and results for detecting low-frequency exoplanetary radio emissions with the NenuFAR radiotelescope

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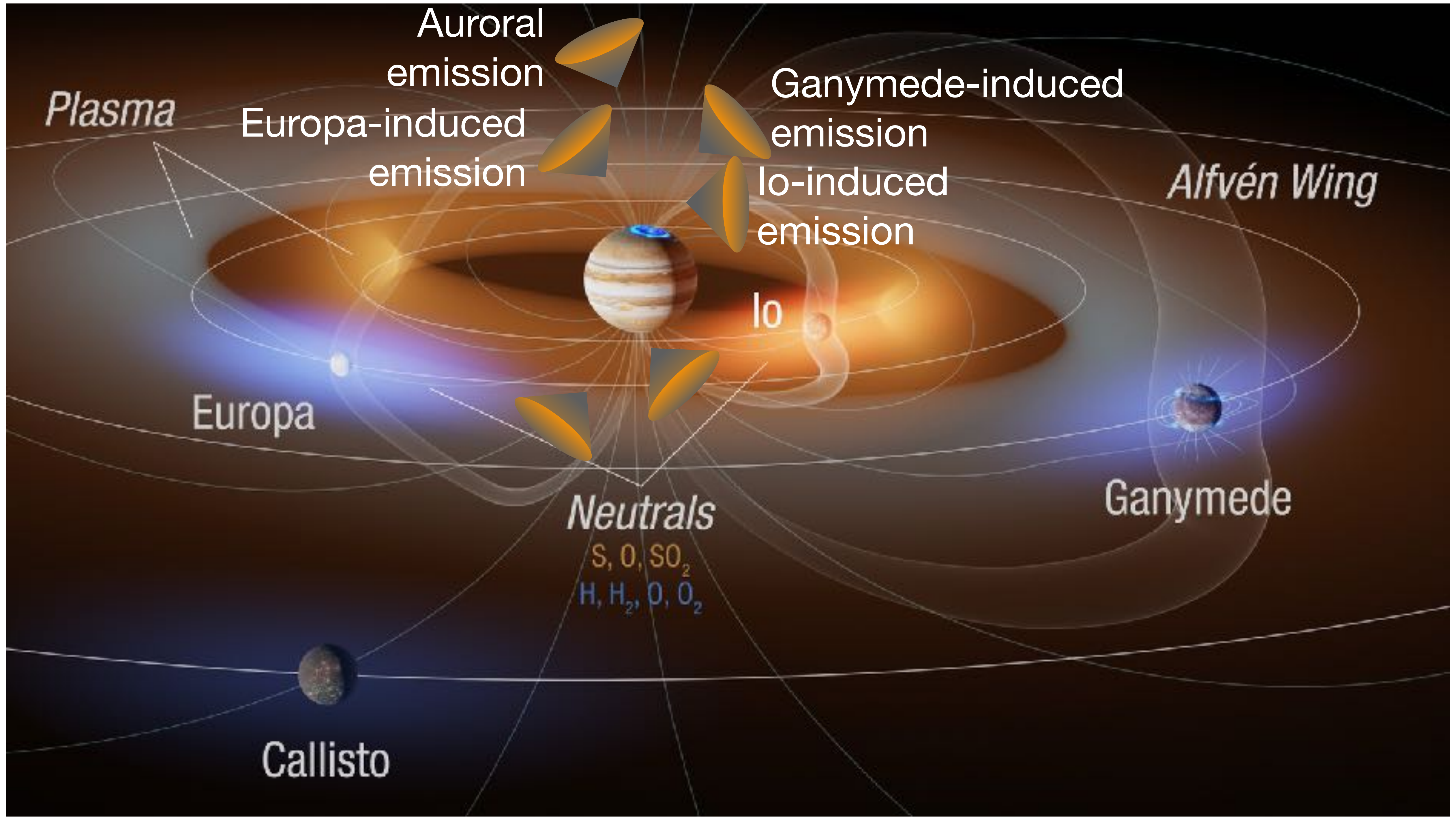
J.-M. Grießmeier, B. Cecconi, Q. Nénon, S. Corbel

LIRA Observatoire de Paris | PSL

Context
Planetary Auroral Radio Emissions



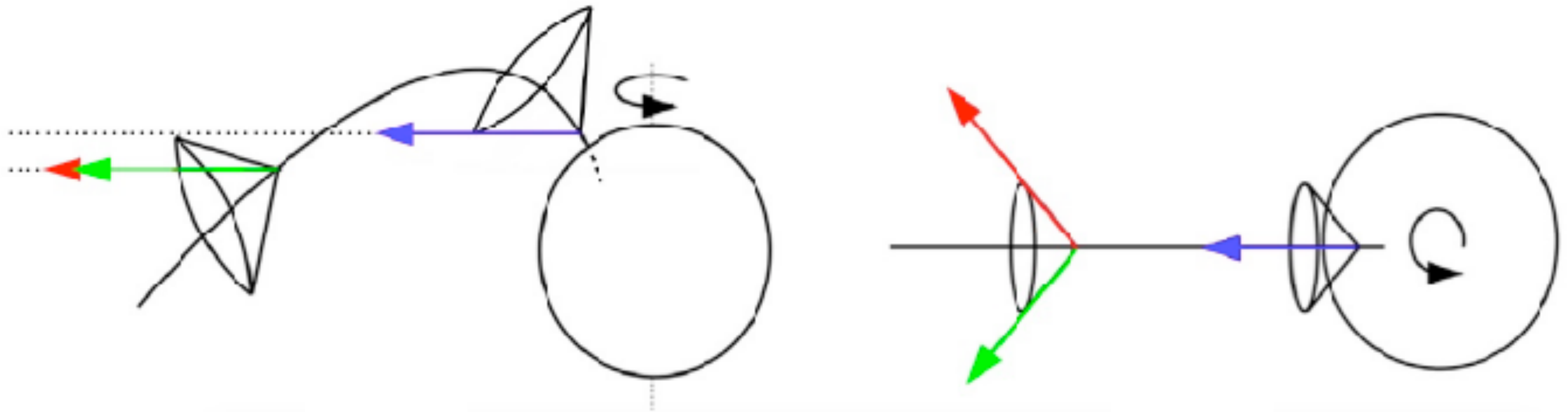
[Adapted from Szalay et al. 2022]

Auroral or Satellite-Planet Interaction Emissions :

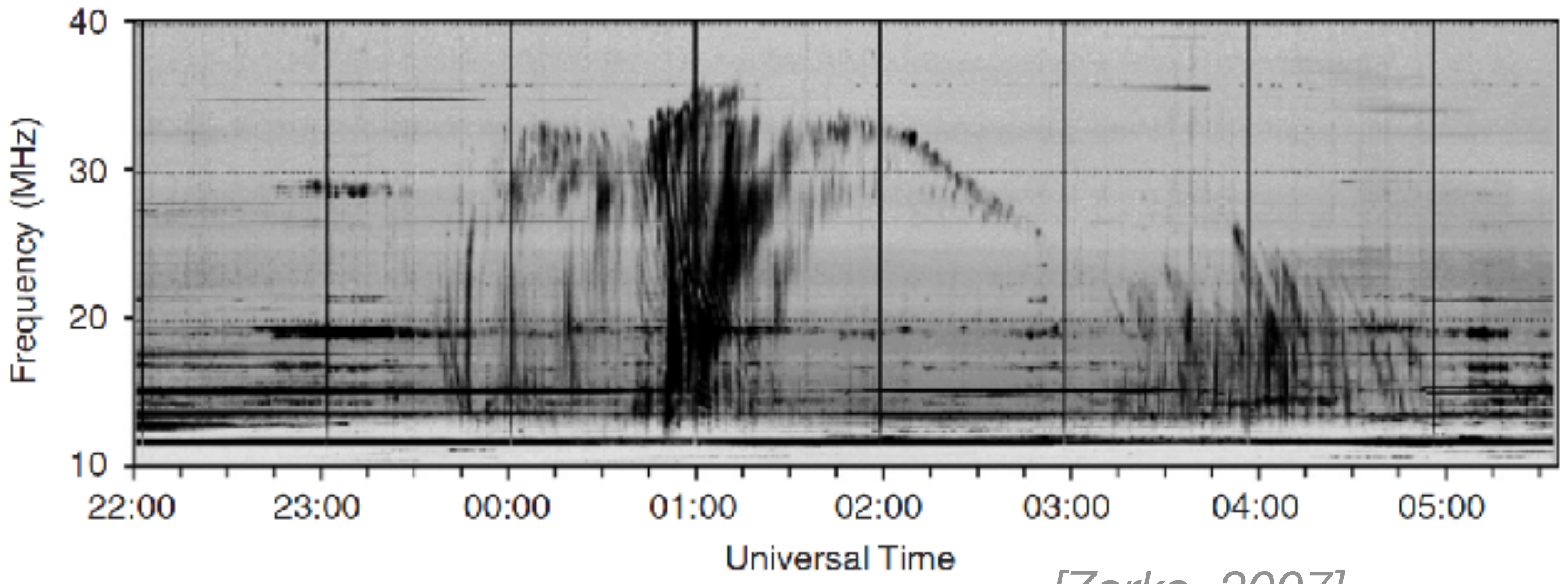
- Cyclotron Maser Instability (CMI) :

$$f_{\mathrm{CMI}} = f_{\mathrm{ce}}/\Gamma + \frac{k_{||}v_{||}}{2\pi}$$

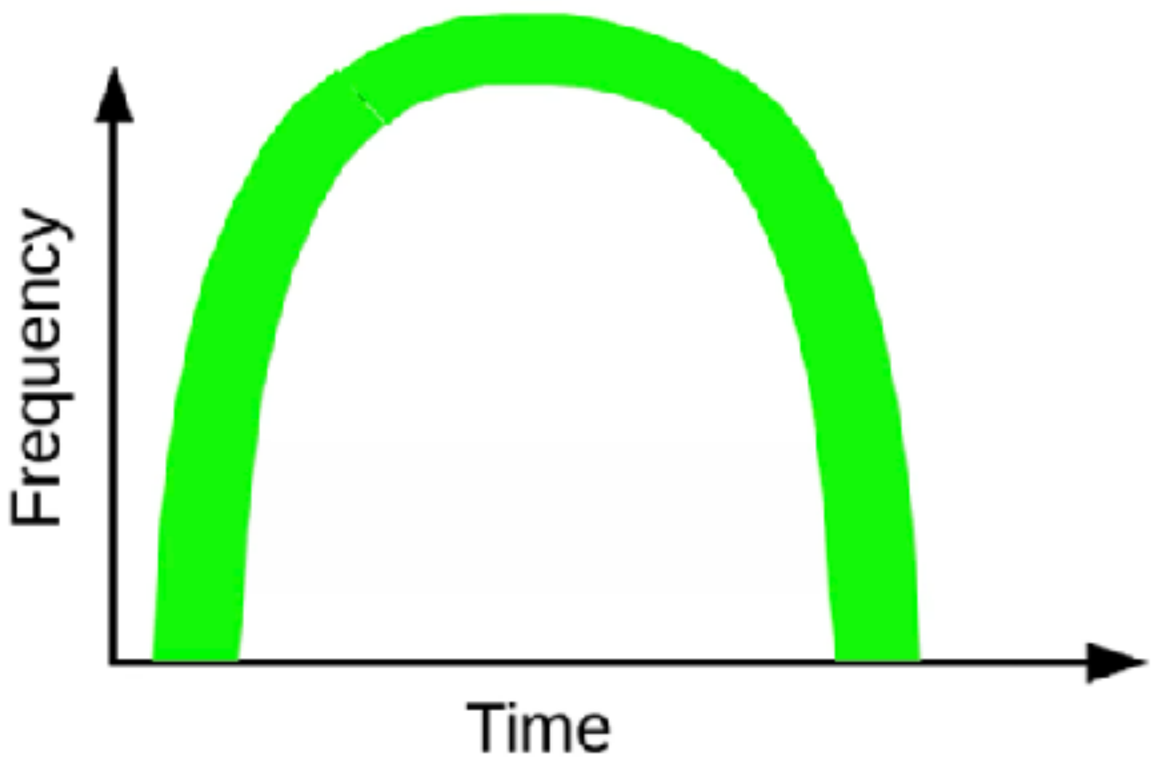
$$f_{\mathrm{CMI}} \simeq f_{\mathrm{ce}} \propto B \quad \rightarrow \quad \text{direct evidence of magnetic field!}$$



Time-Frequency Spectrogram



[Zarka, 2007]



Tasse, … Louis et al. (submitted)

Context
Planetary Auroral Radio Emissions

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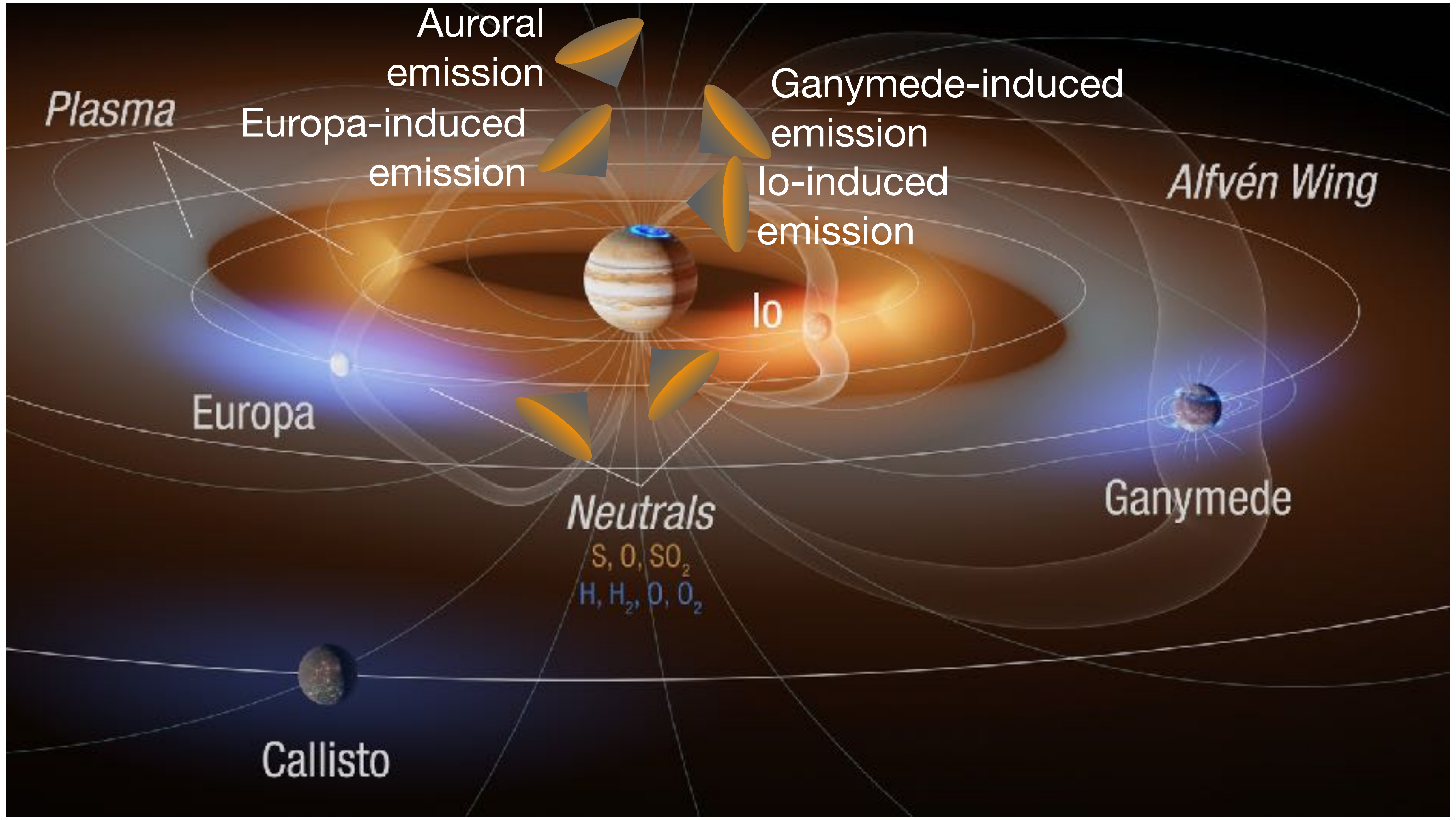

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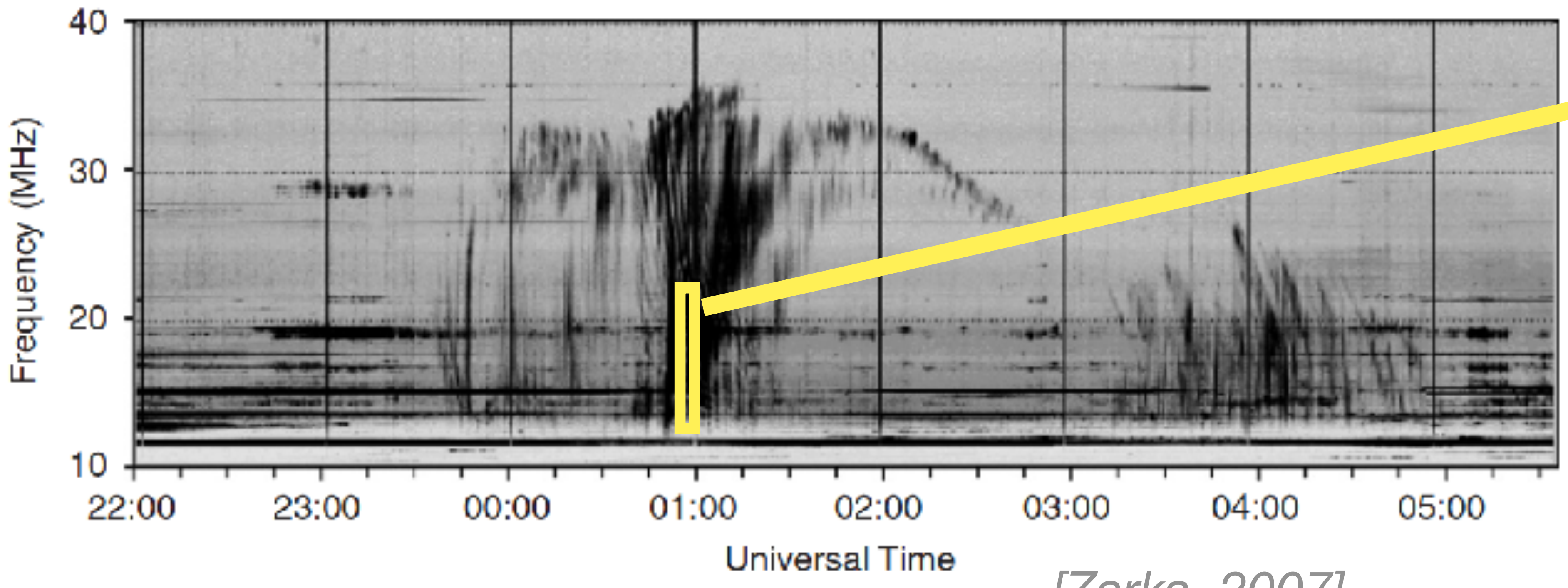
➡ millisecond bursts: direct measurement of electrons velocity

Time-Frequency Spectrogram



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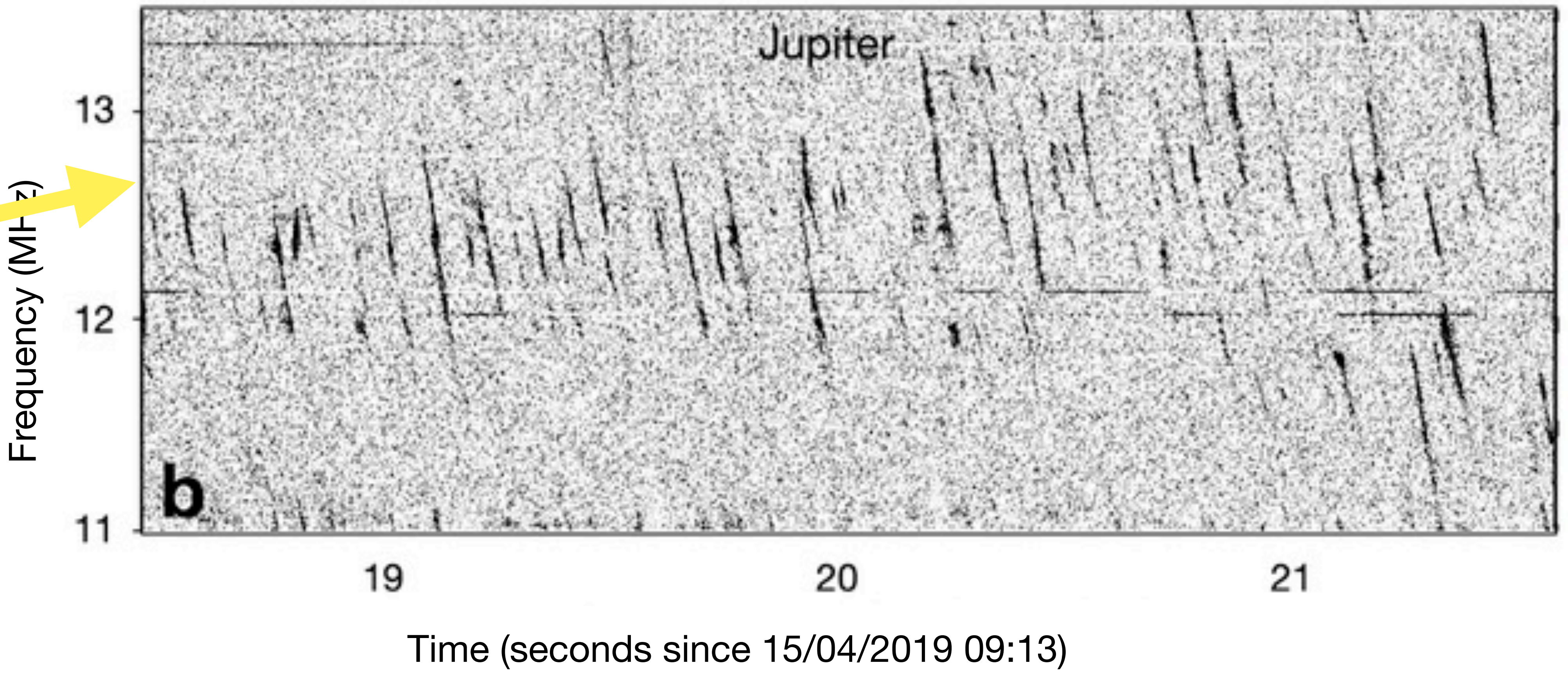

[Mauduit et al., 2023]

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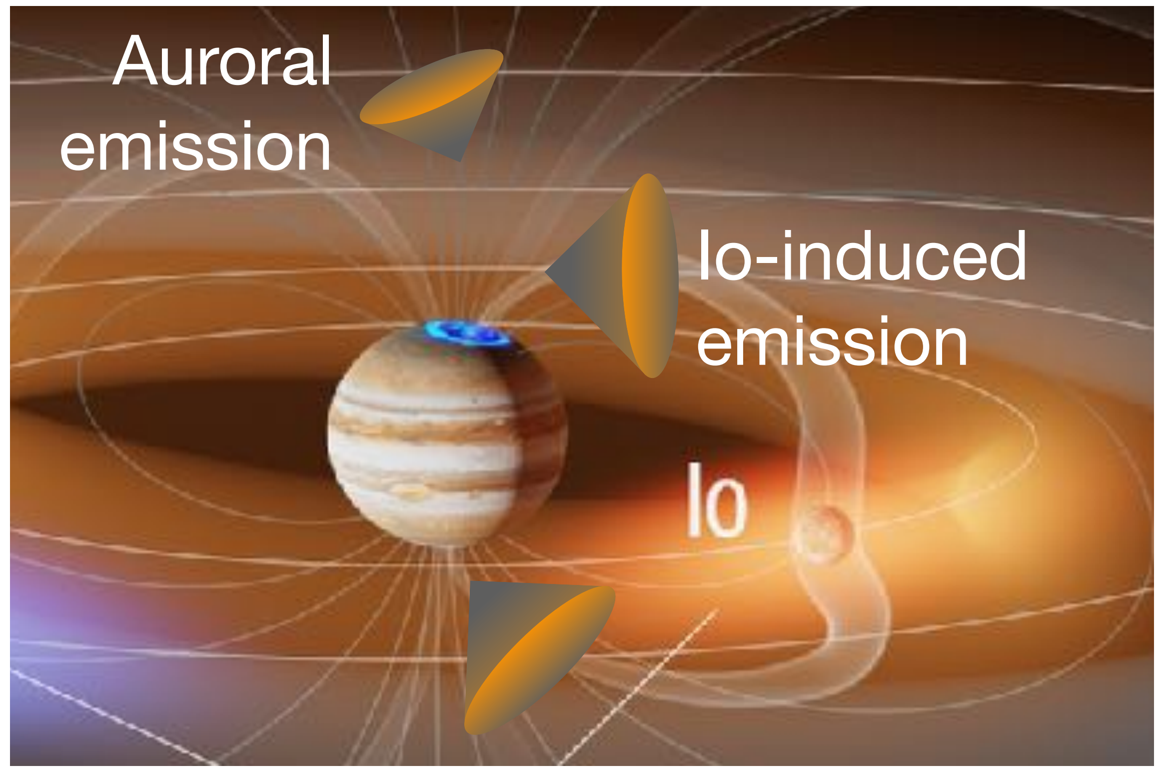
CMI Radio Emissions



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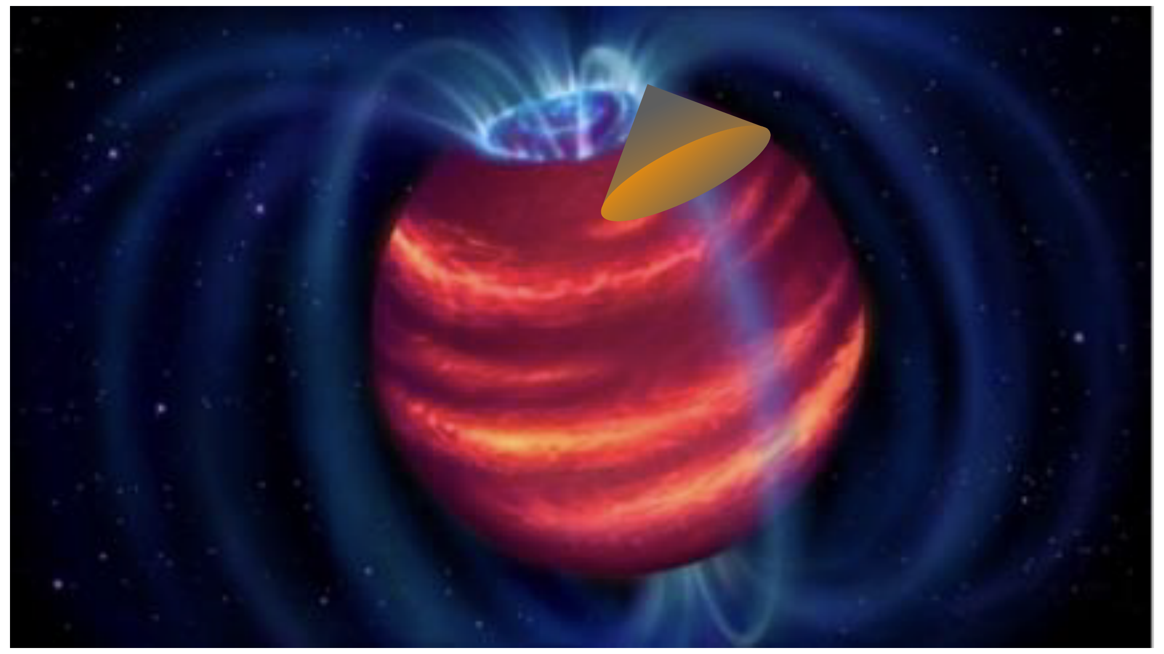
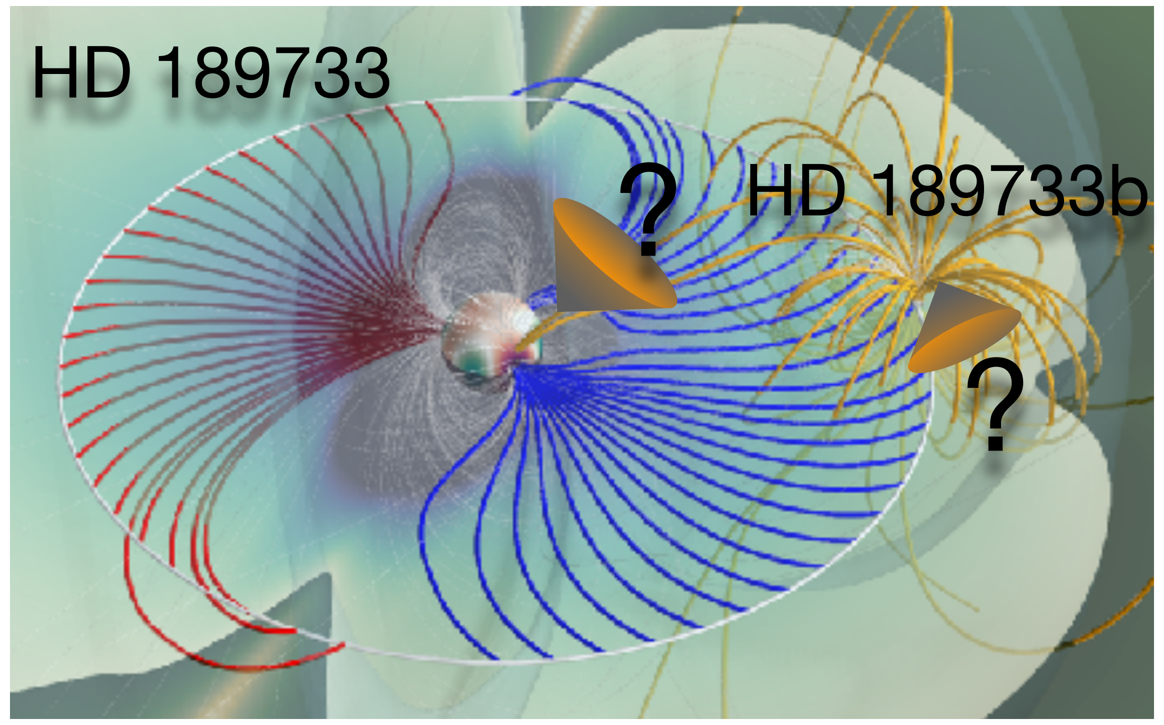


[Credits: ASTRON, Vedantham et al. 2020]



[A. Strugarek, personal communication]

Jupiter

- 1950s : First observation of Jovian radio emission (Burke & Franklin, 1955)
- 1960s : First observation of Io-induced radio emission (Bigg, 1964)
- < 1973 : not-accessible *in situ*
  - Unresolved image → One pixel in an image
  - Physical Informations → in the time-frequency spectrograms

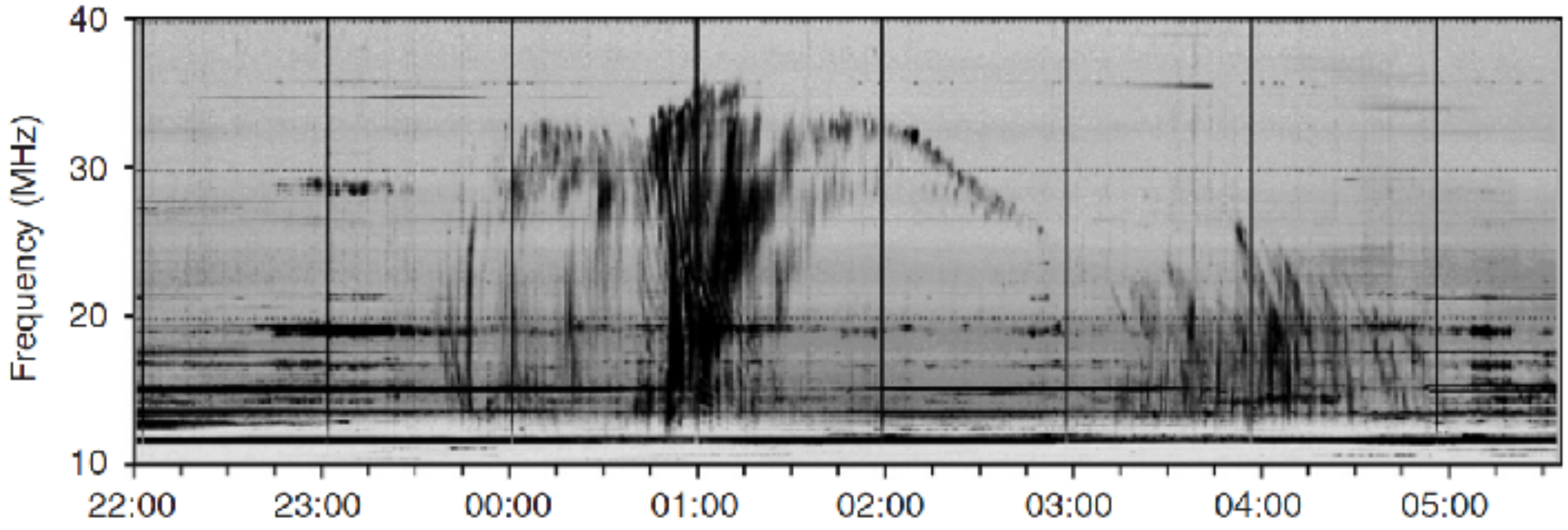
Exoplanets and Stars

Emerging field:
1st detections or radio bursts with LOFAR, NenuFAR or FAST

- From Stars
  (**J. Zhang, …, Louis et al. 2024, 2025, Zarka, Louis et al., 2025**)
- From Star-Planet Interactions?
  (Turner et al., 2021, 2023, Pérez-Torres et al., 2021, **X. Zhang , …, Louis et al., submitted**)

Expertises

- Plasma physics (SPI interaction)
- Stellar and (Exo)Planetary Radio emissions simulation
- Processing and analyse of "time-frequency spectrogram" dataset



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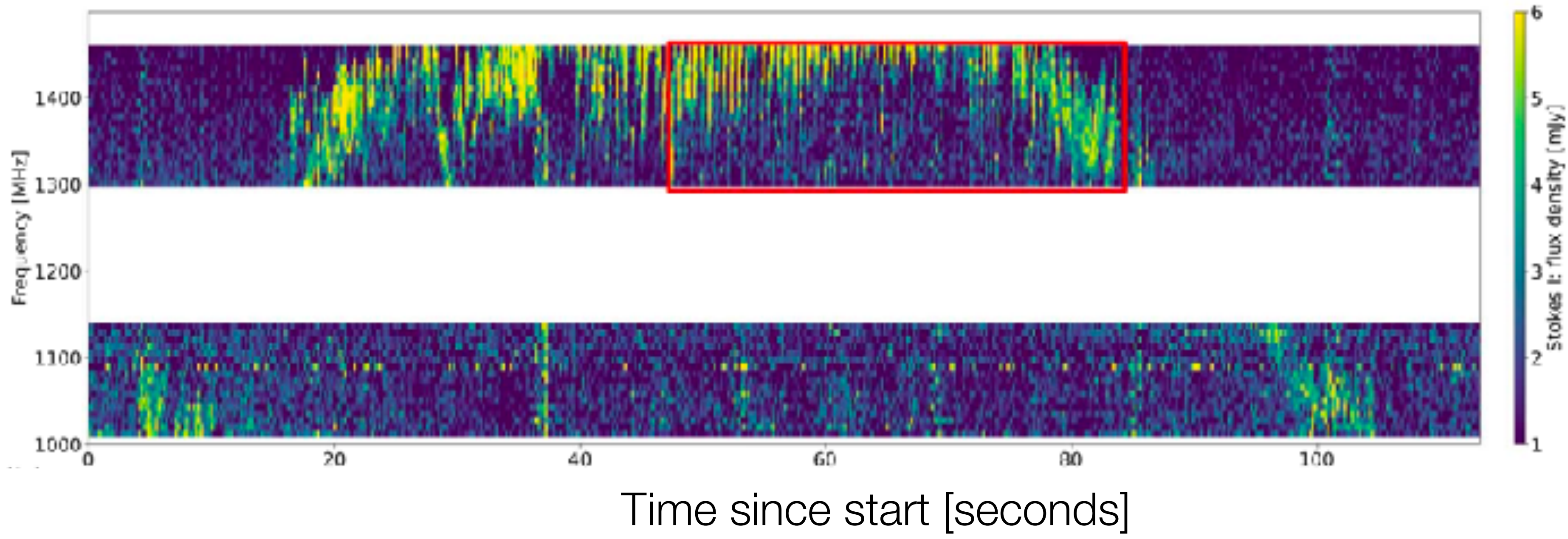
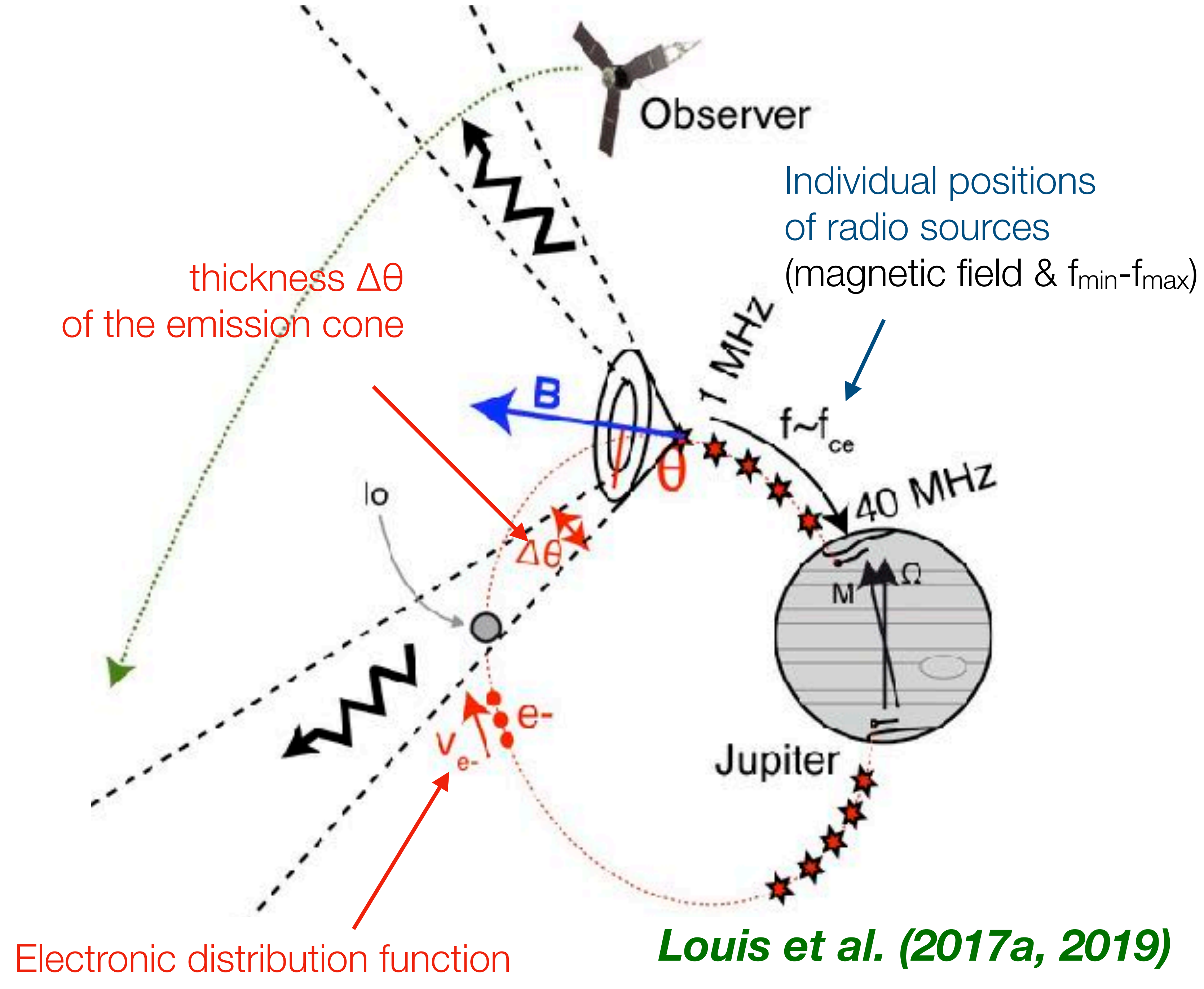


[Zarka, Louis et al., 2025]

[Tasse, …, Louis et al., submitted]

1) Simulation of Radio Emissions

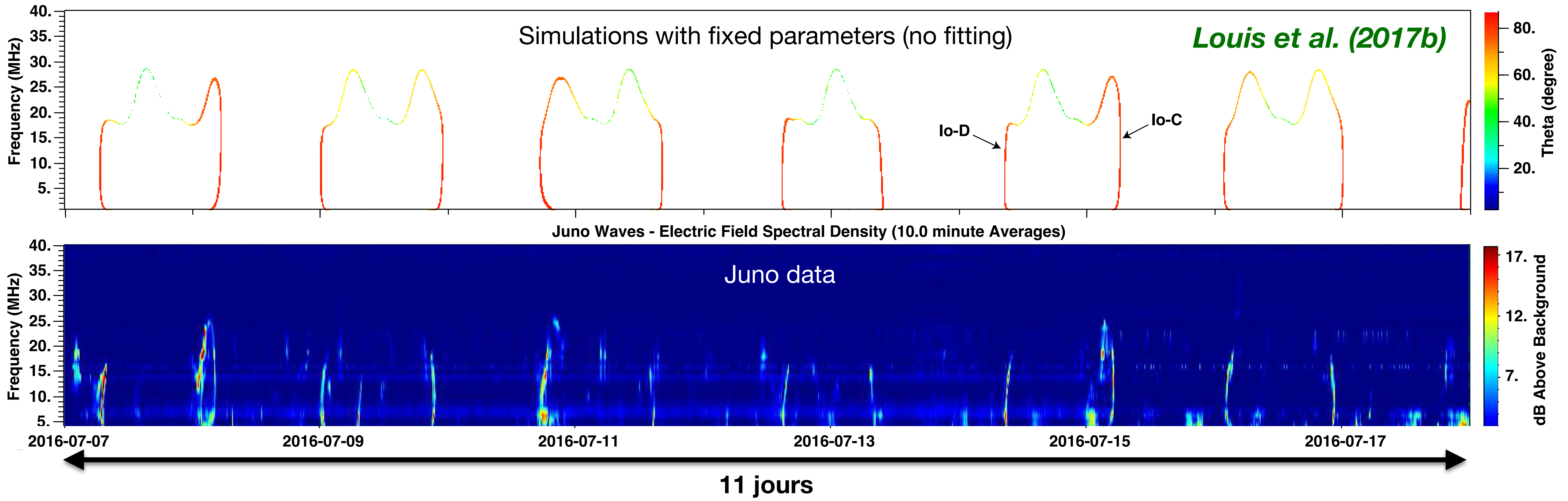


Main results

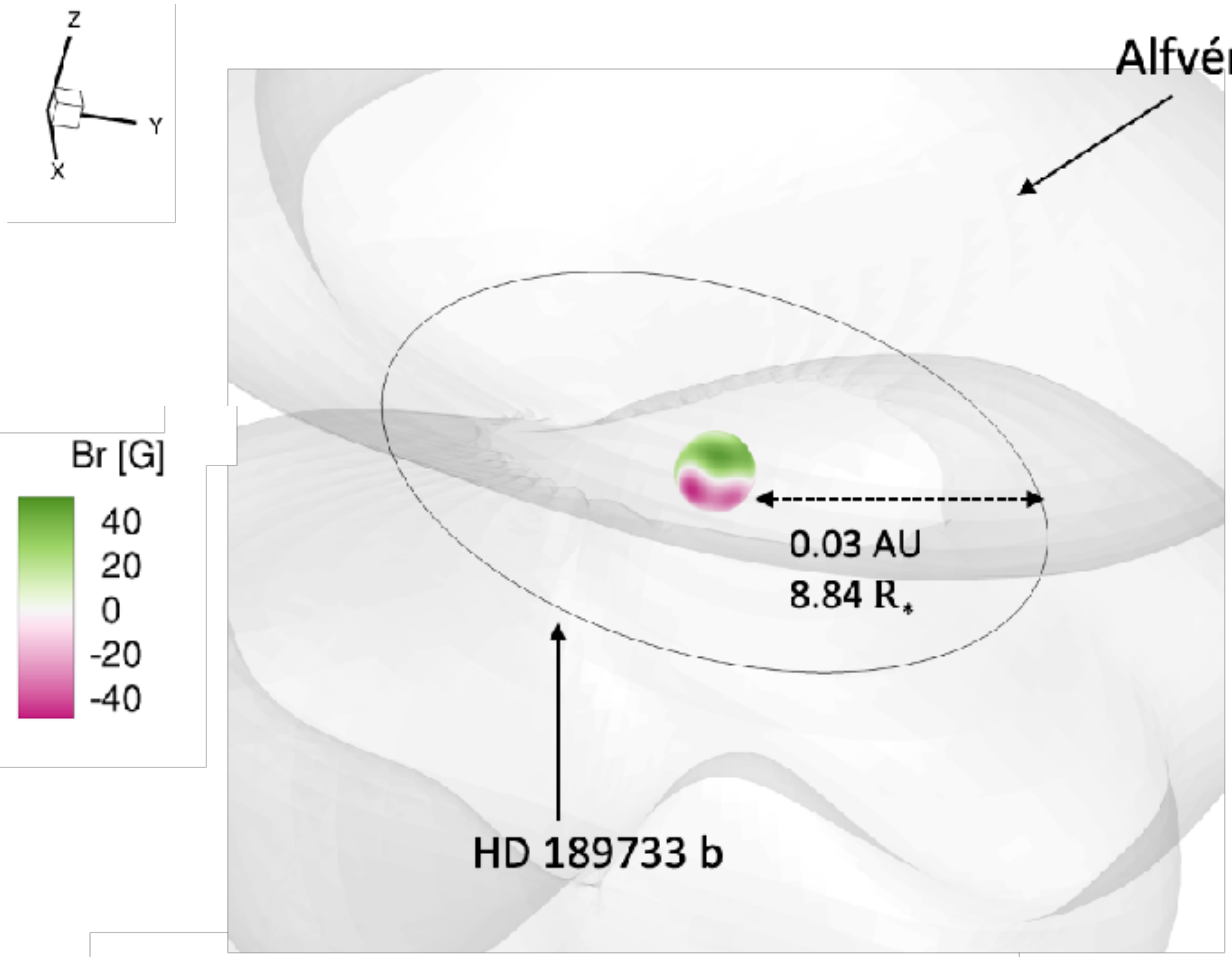
(i) Simulations:

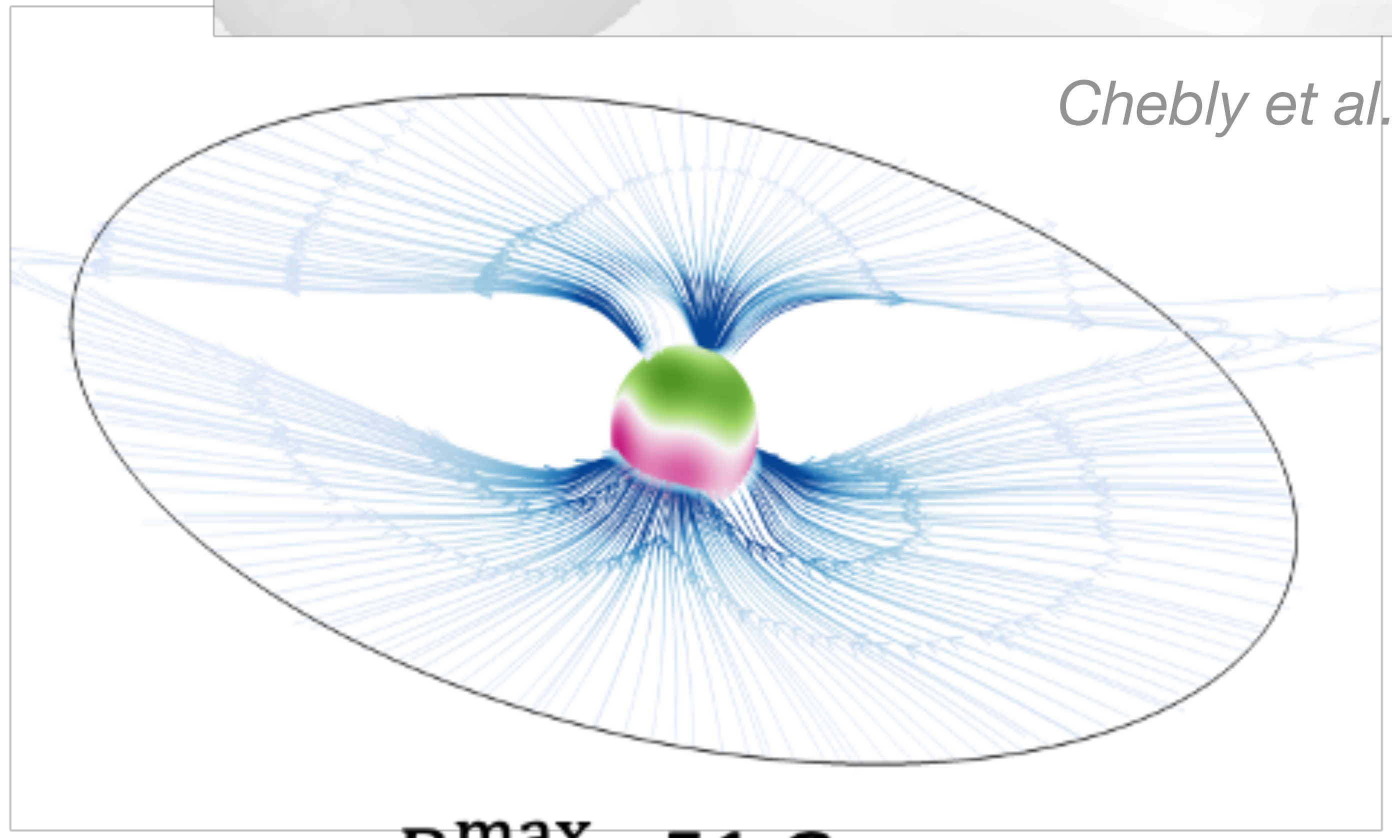
- Accurate reproduction of emissions
- Constraints on emissions characteristics:
  - source position
  - electron energy
  - beaming pattern
- Prediction of (new) emissions

Louis et al., (2017c)
Zarka, ..., Louis et al. (2018)
Jacome, ... Louis et al. (2022)



Radio emissions Simulations of HD189733



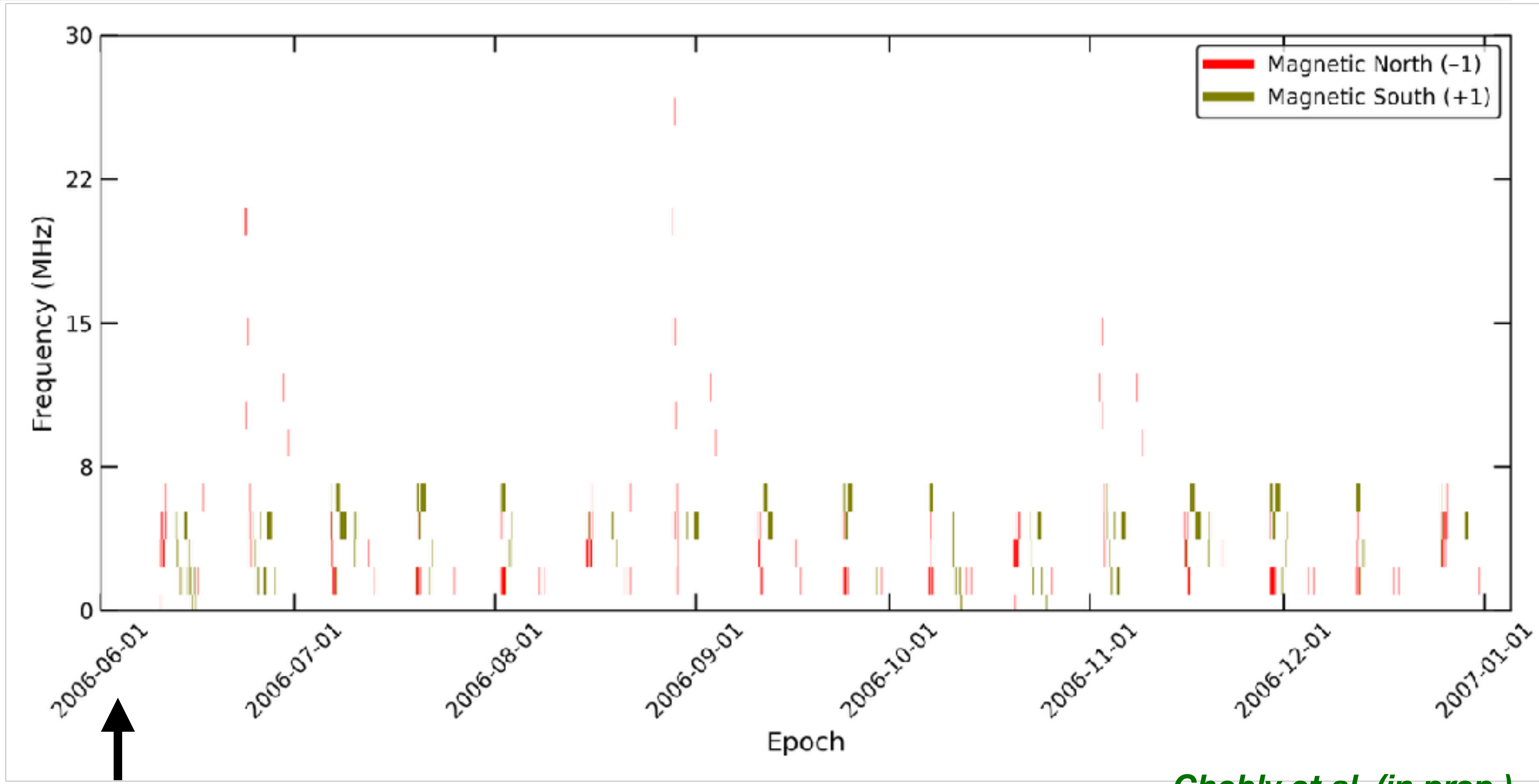


Chebly et al. (2023)

B_r^{max}= 51 G

↓

$f_c^{max} = 2.8 \times B_r^{max} = 142.8$ MHz



Epoch of ZDI observations

Chebly et al. (in prep.)

Star properties

Rotation period (days): 12.5
Distance (pc): 19.7

Planet properties

Planet mass (R_J) : 1.11
Orbital period (days) : 2.2
Rotation period (days) : 2.2

What do we learn?

For that epoch, radio emissions visible < 8 MHz with some emissions visible up to 25 MHz

Next steps

Use ZDI measurements at ≠ epochs
Run new simulations

2) Search for periodicity in “slowly varying signals”

Search for Periodic Signals
Use Lomb-Scargle Methodology

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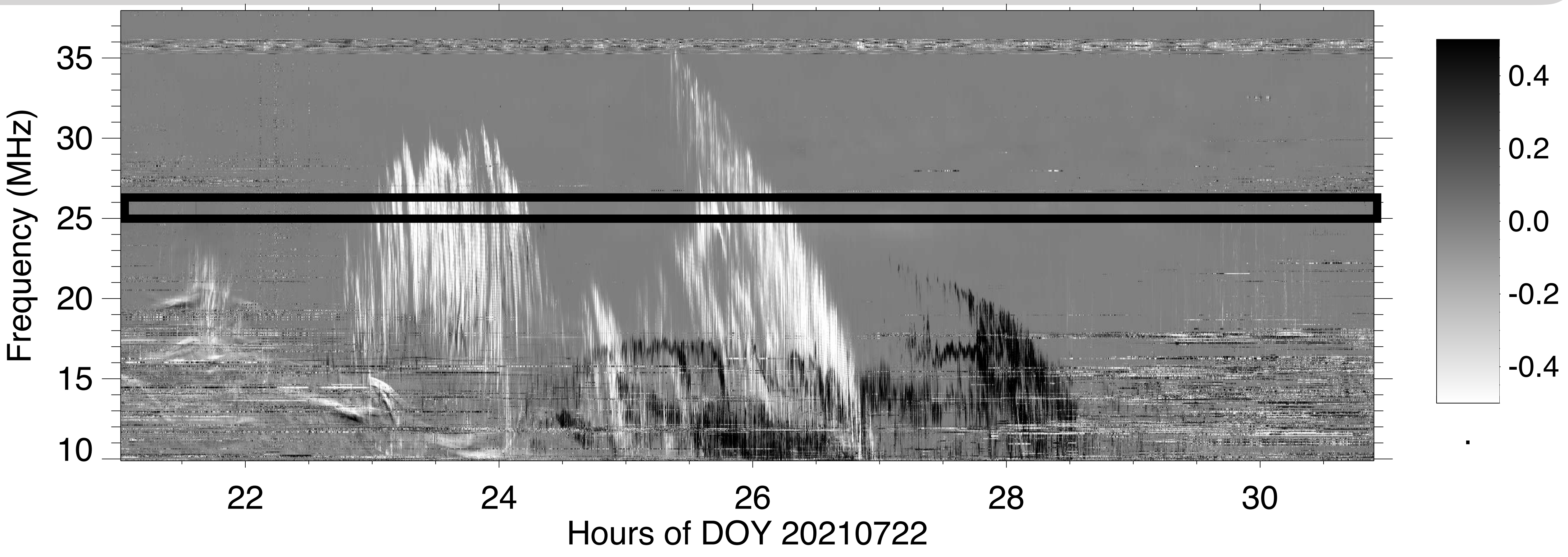
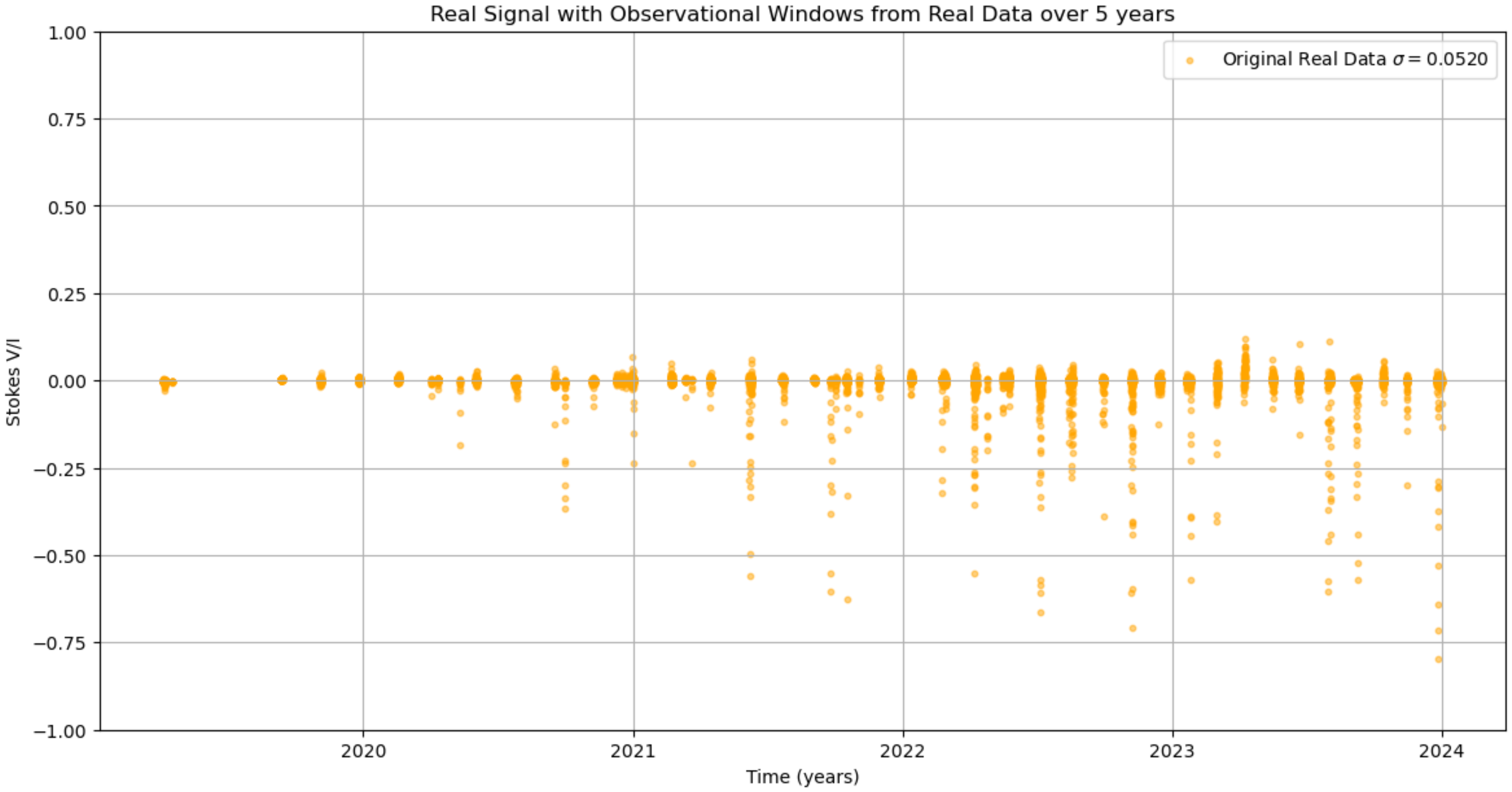
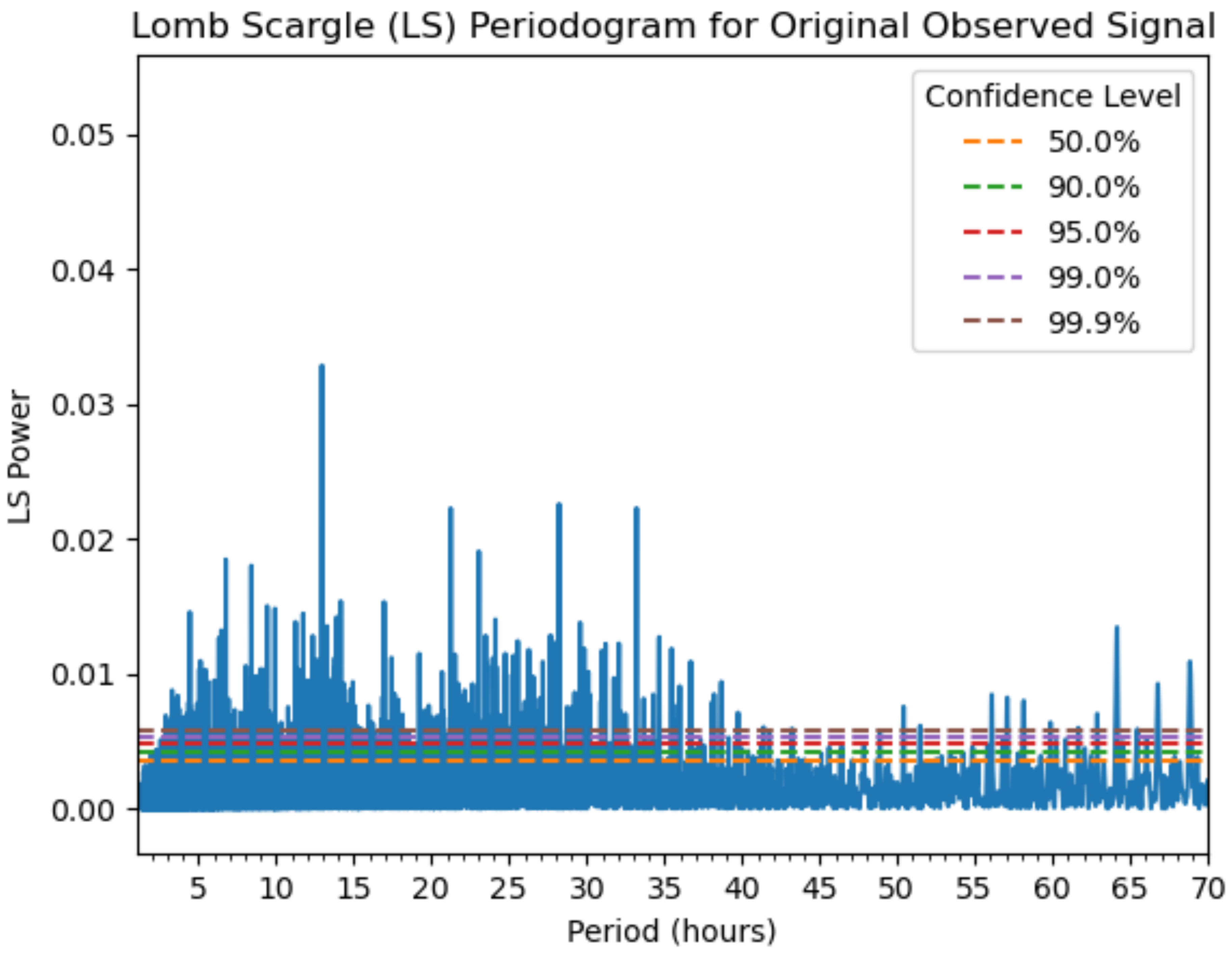
- NenuFAR Observation of Jupiter
- 1100 hours in 125 intervals of $|T_{obs}|$ = 8.2 hours spaced by T_{gap} = N × 24.061 hours (N = 1, 2, 3, 4,…)
- Over 5 years







Louis et al. (2025, in revision)

Search for Periodic Signals
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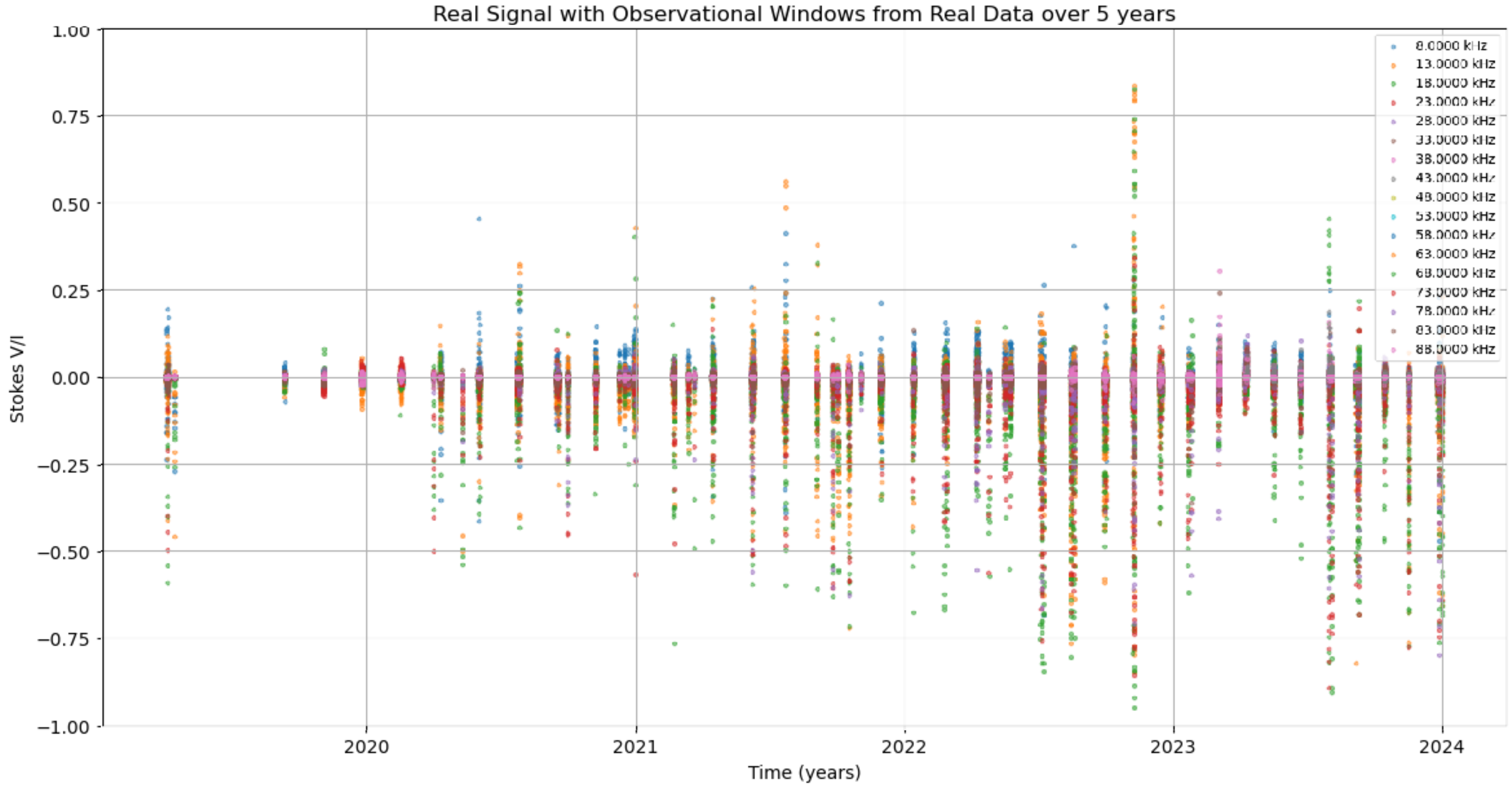

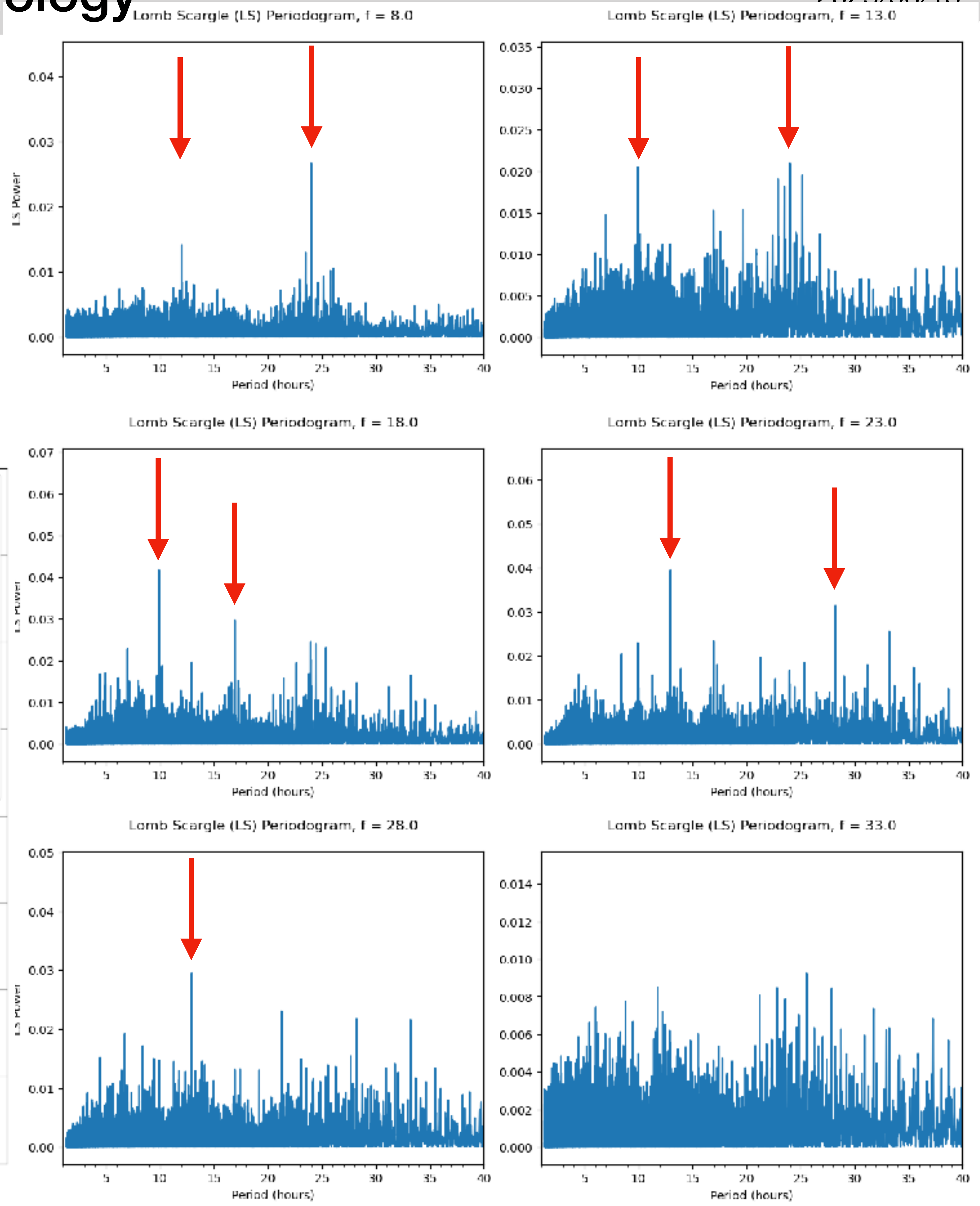

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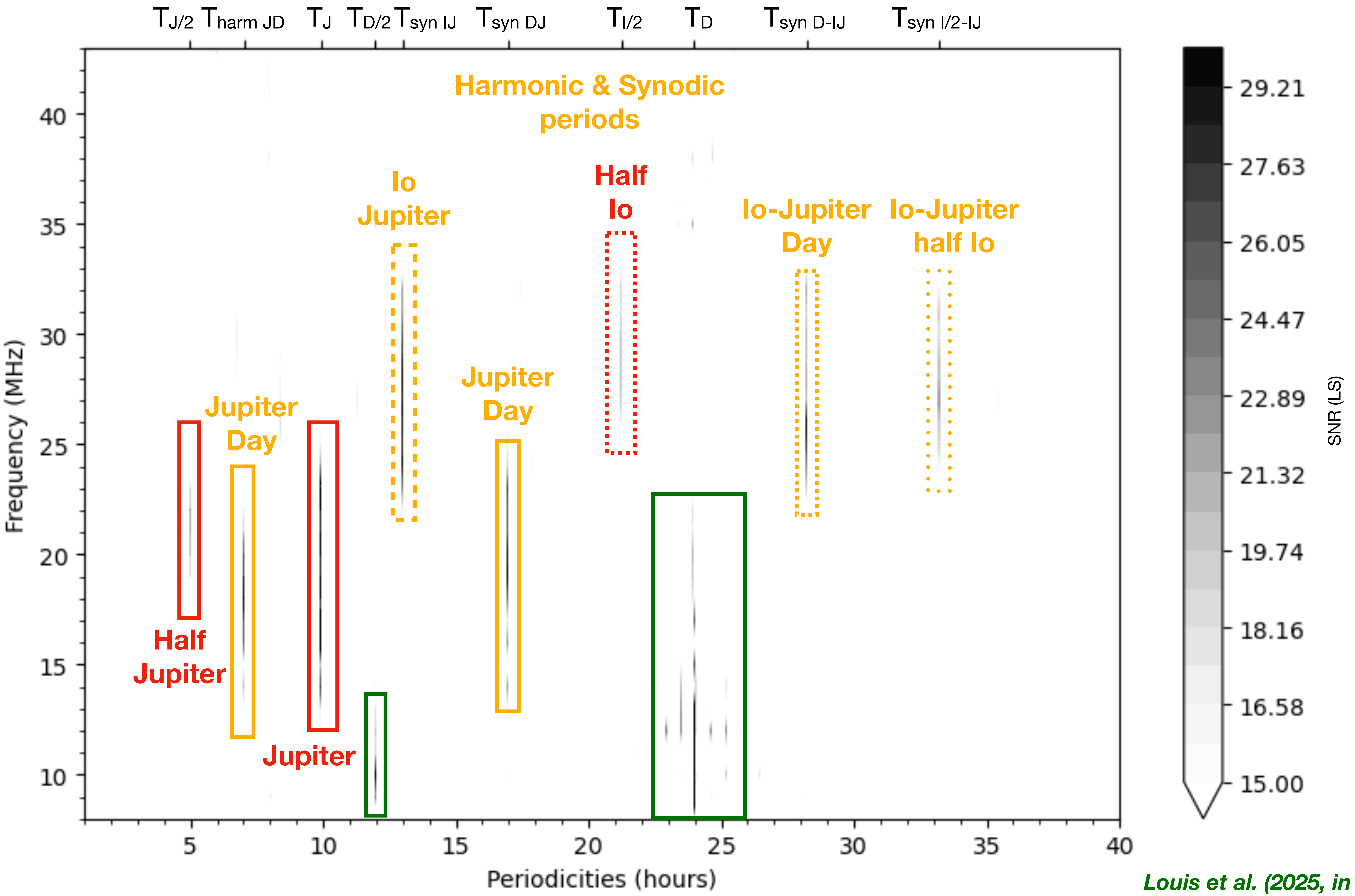

Louis et al. (2025, in revision)

Lomb-Scargle window sliding in time

Louis et al. (2025, in revision)

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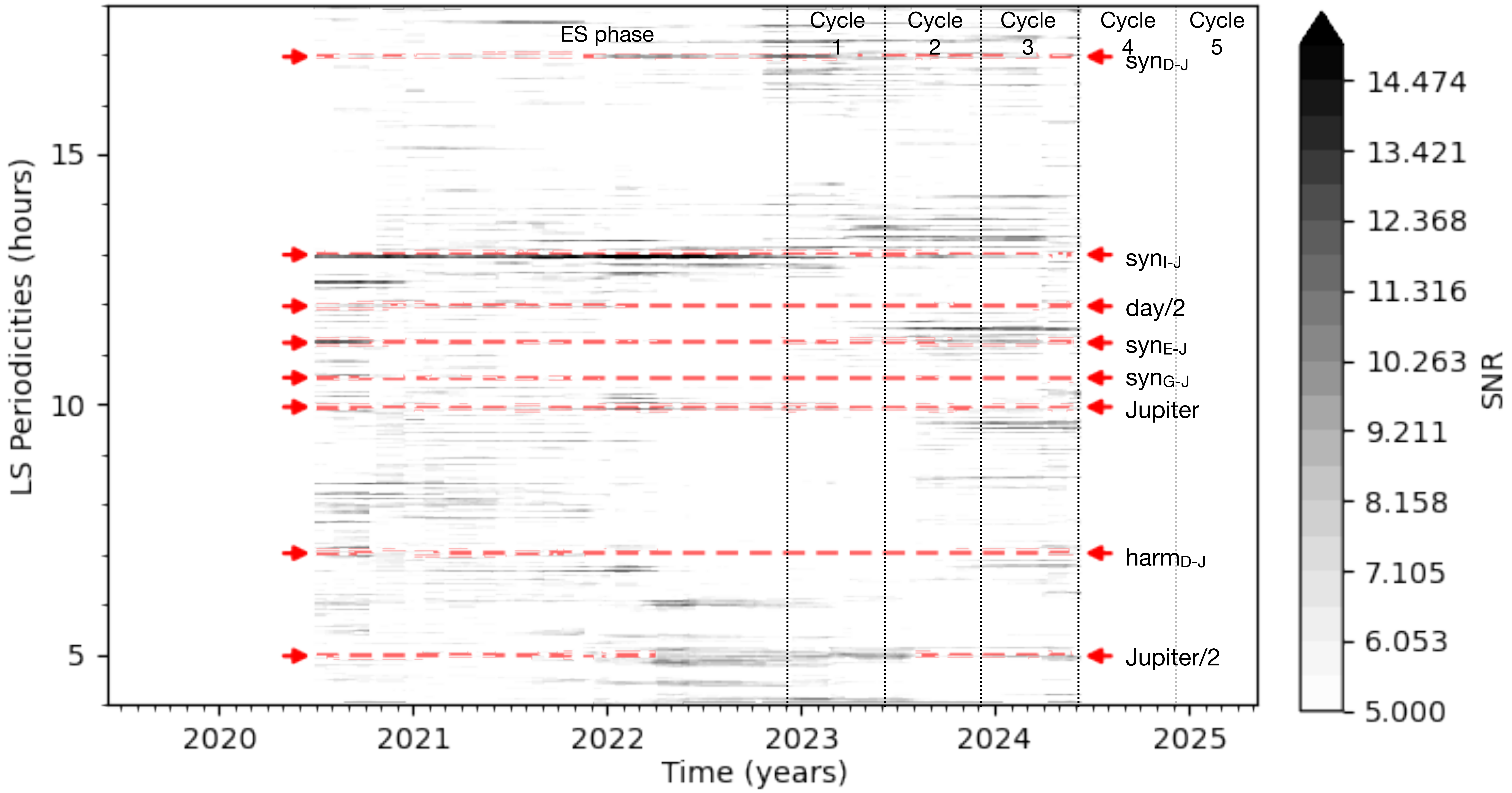

Louis et al. (2025, in revision)

3) Automatic detection of milliseconds bursts

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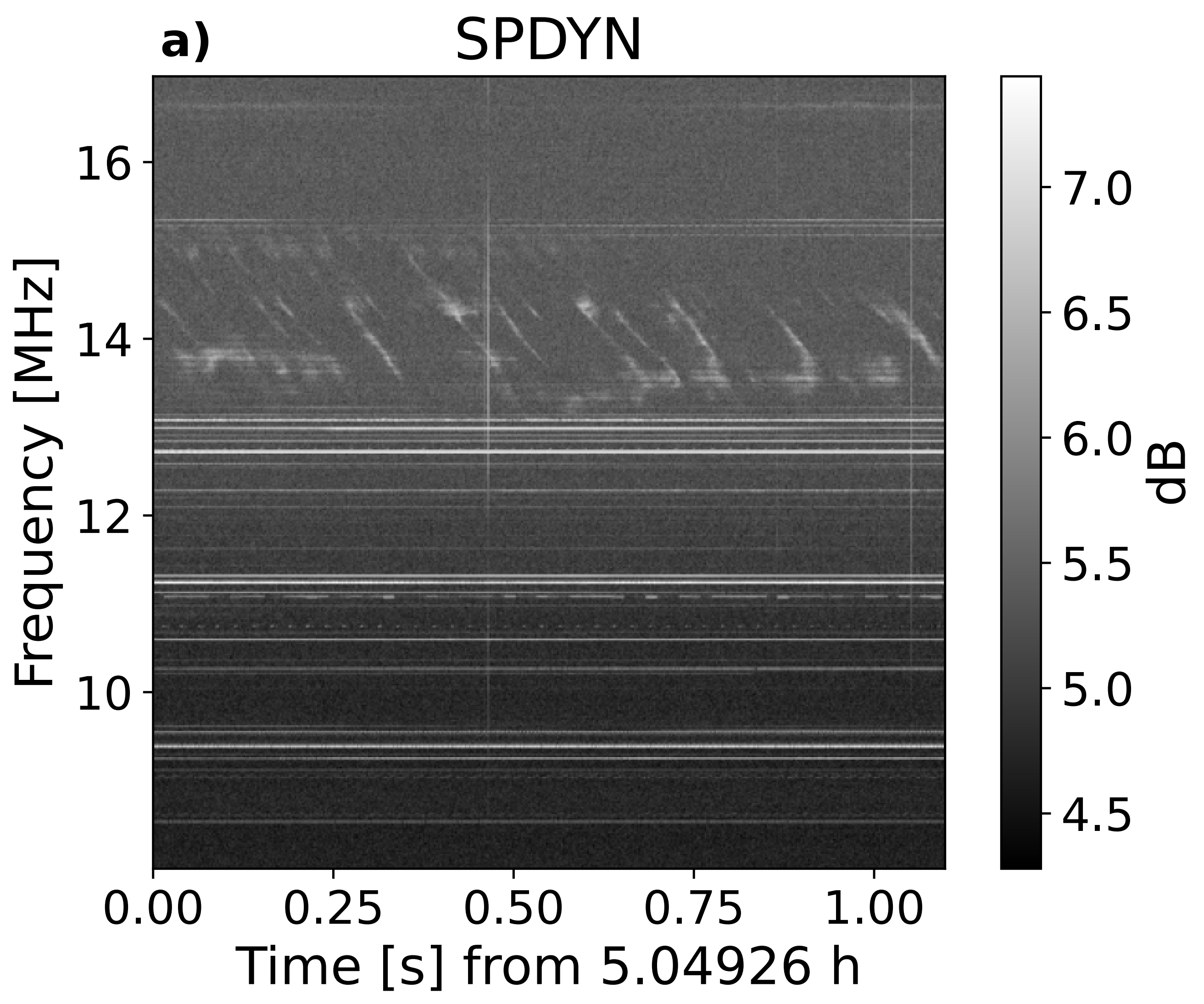
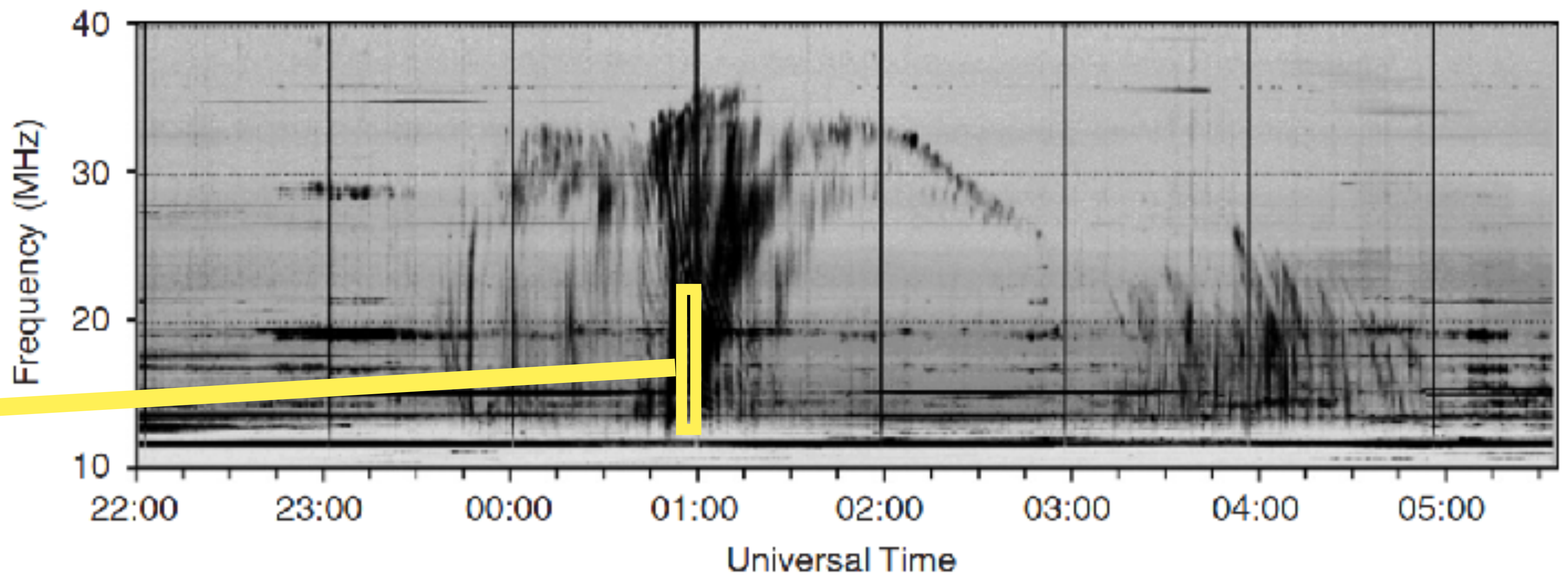
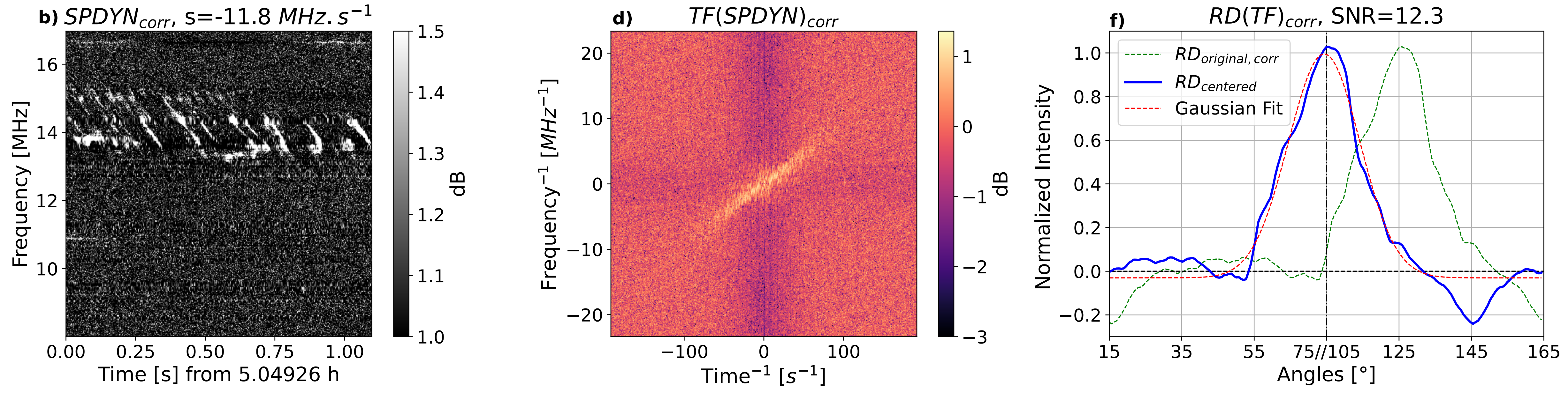
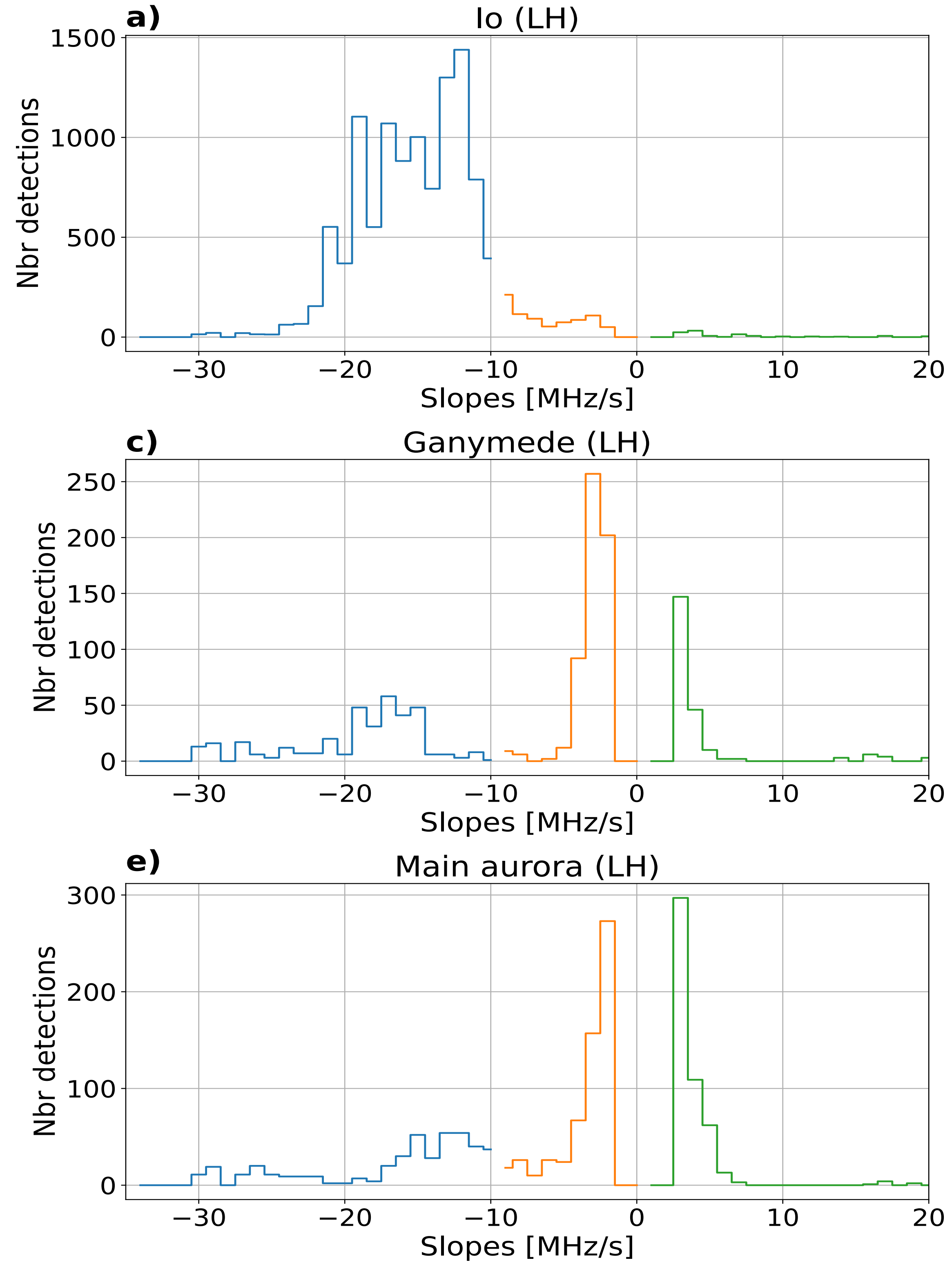
2025/06/13

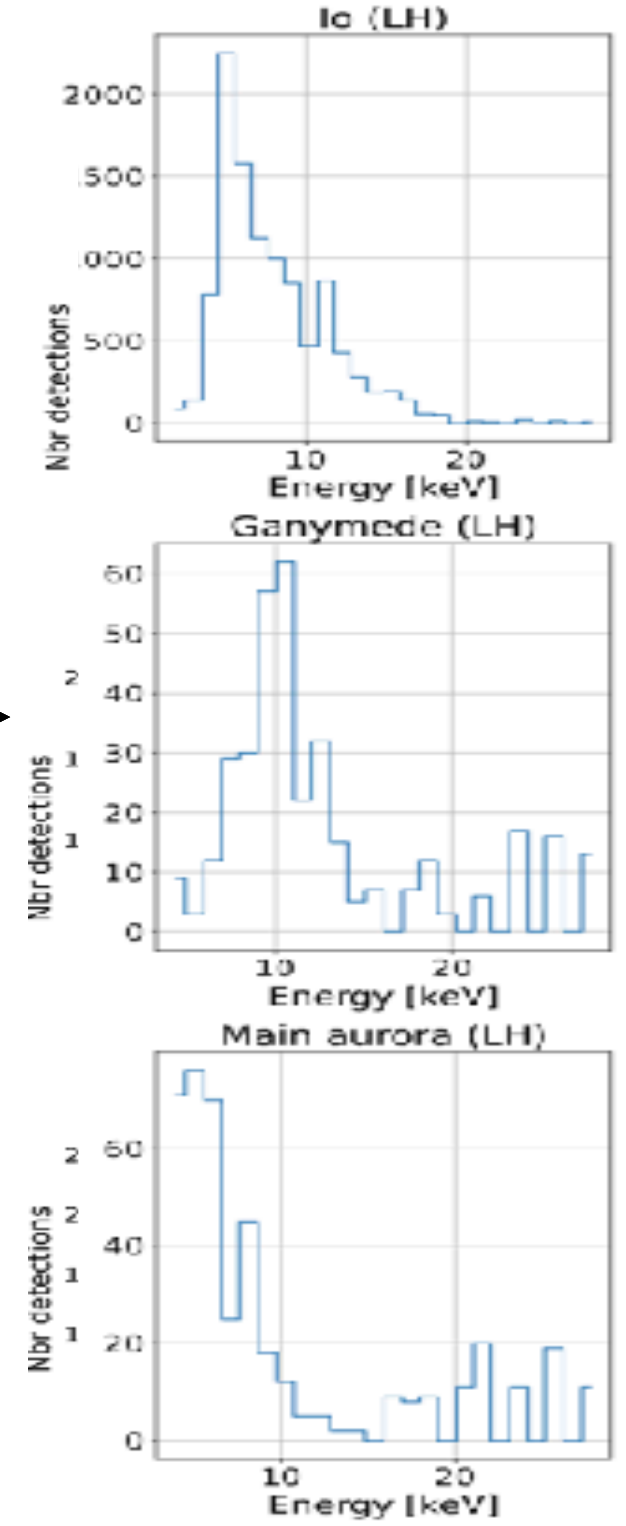
- Method :





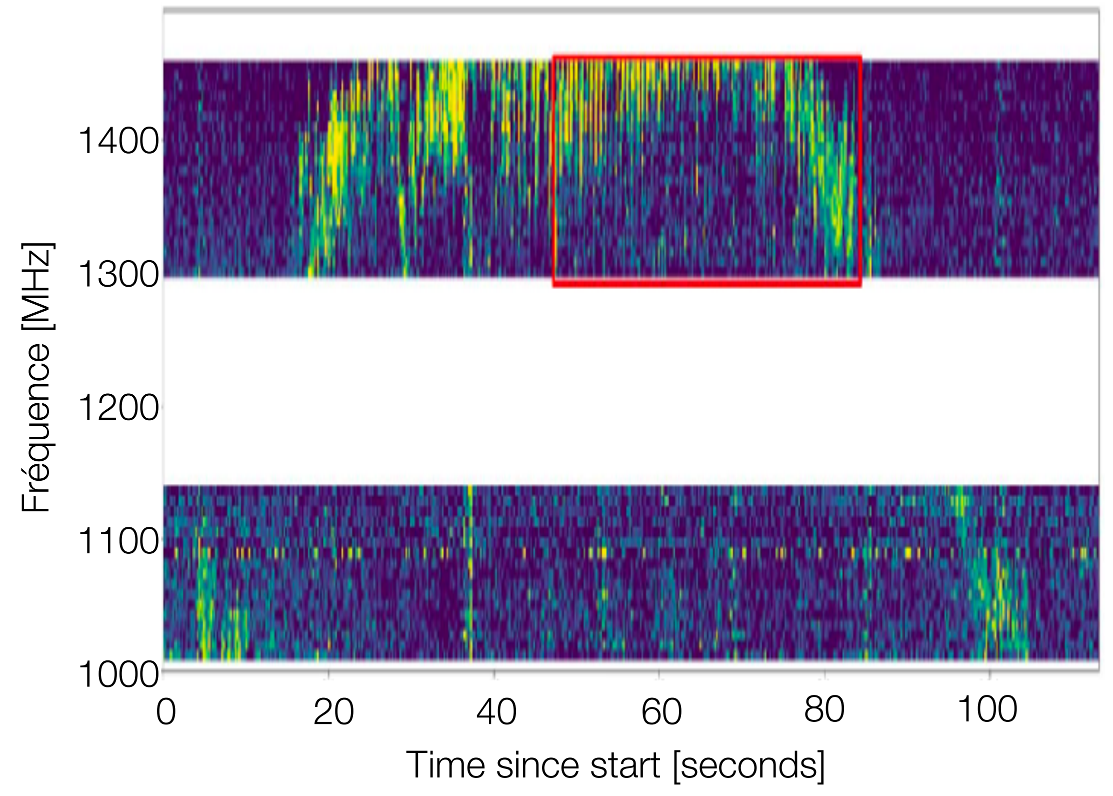


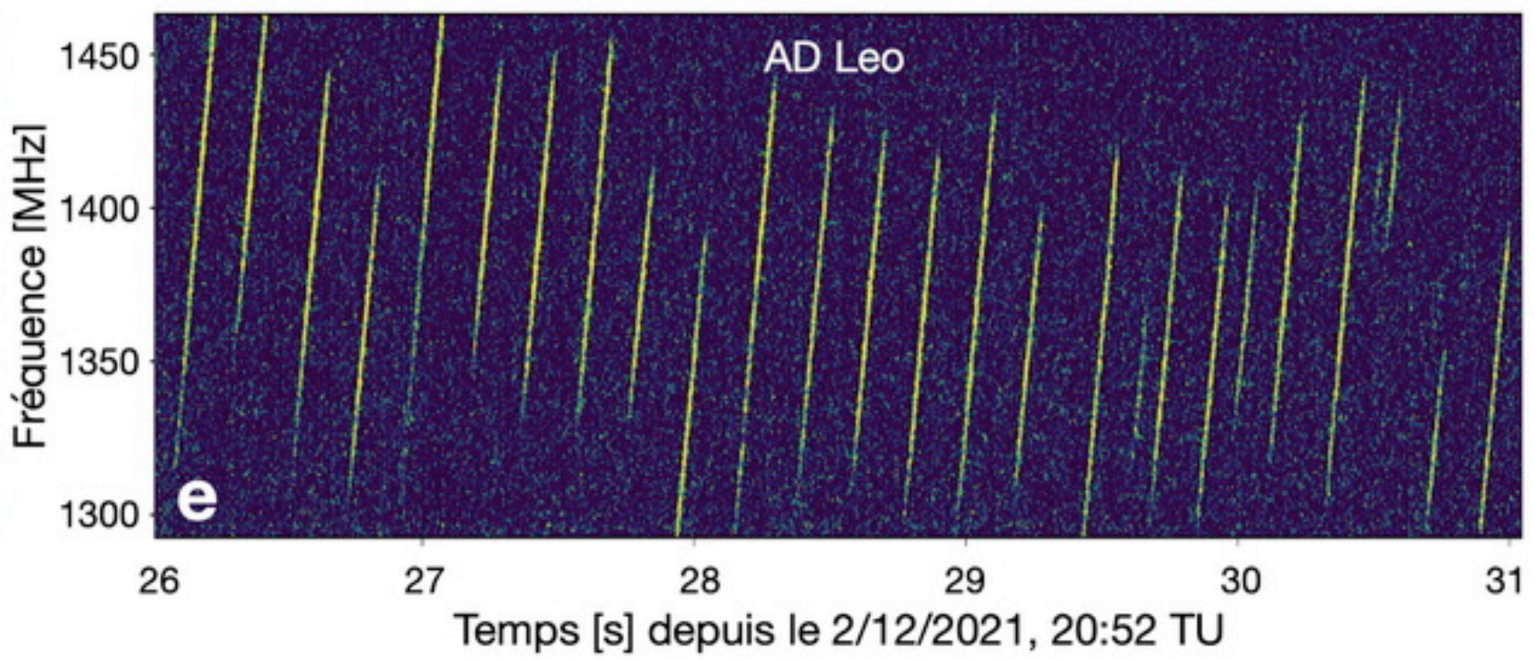




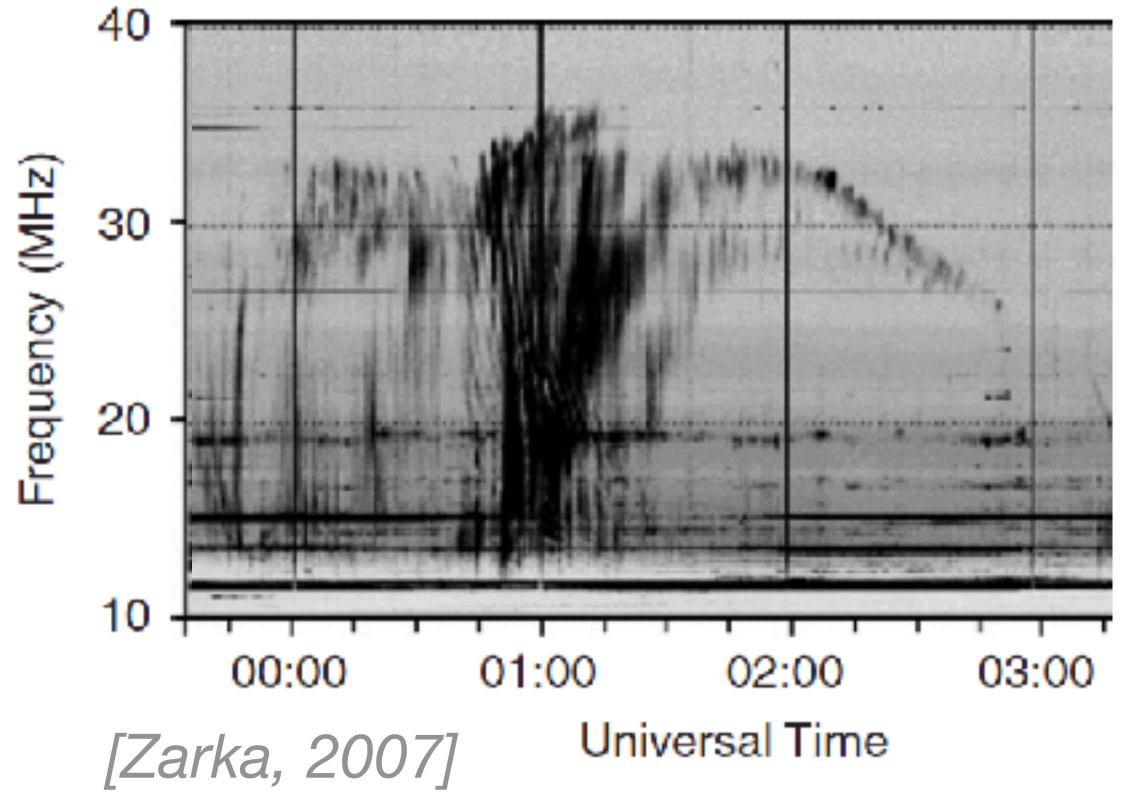
4) Application to “Exoplanet & Star” Targets

Detection of Stellar Radio from AD Leonis: "In situ" characterization

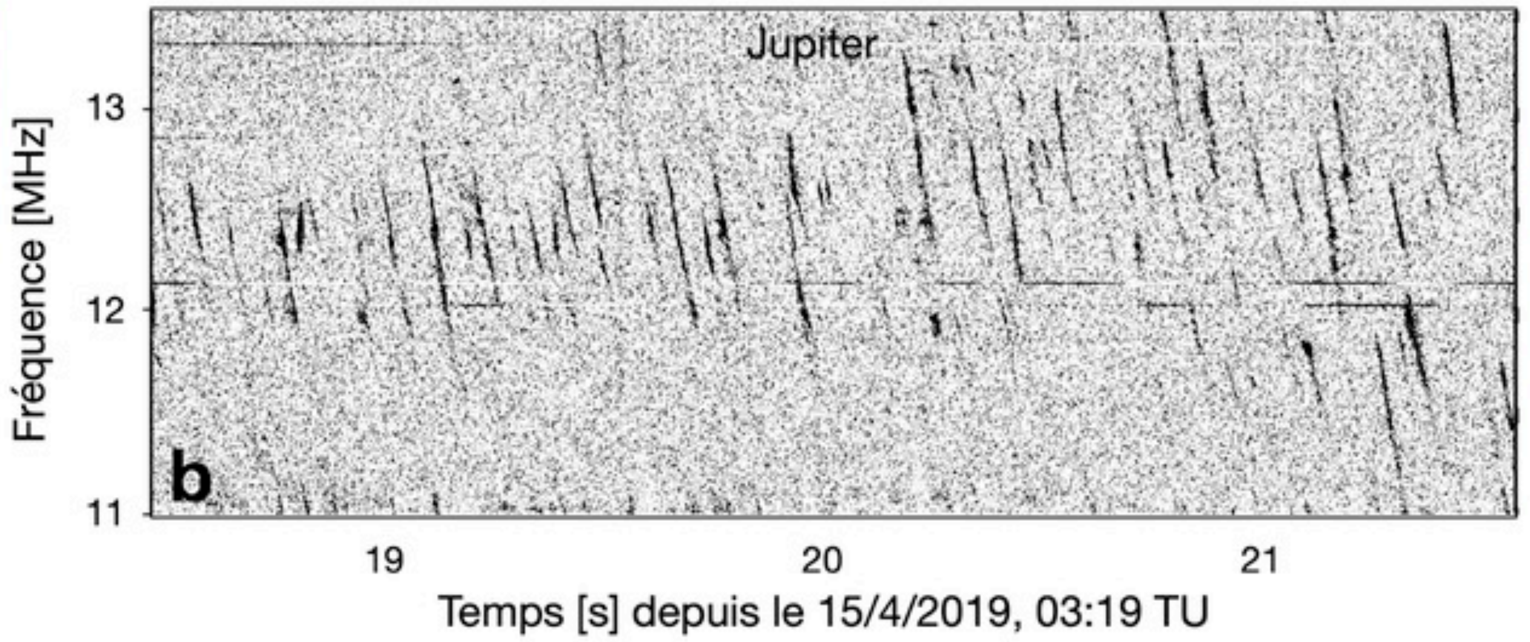




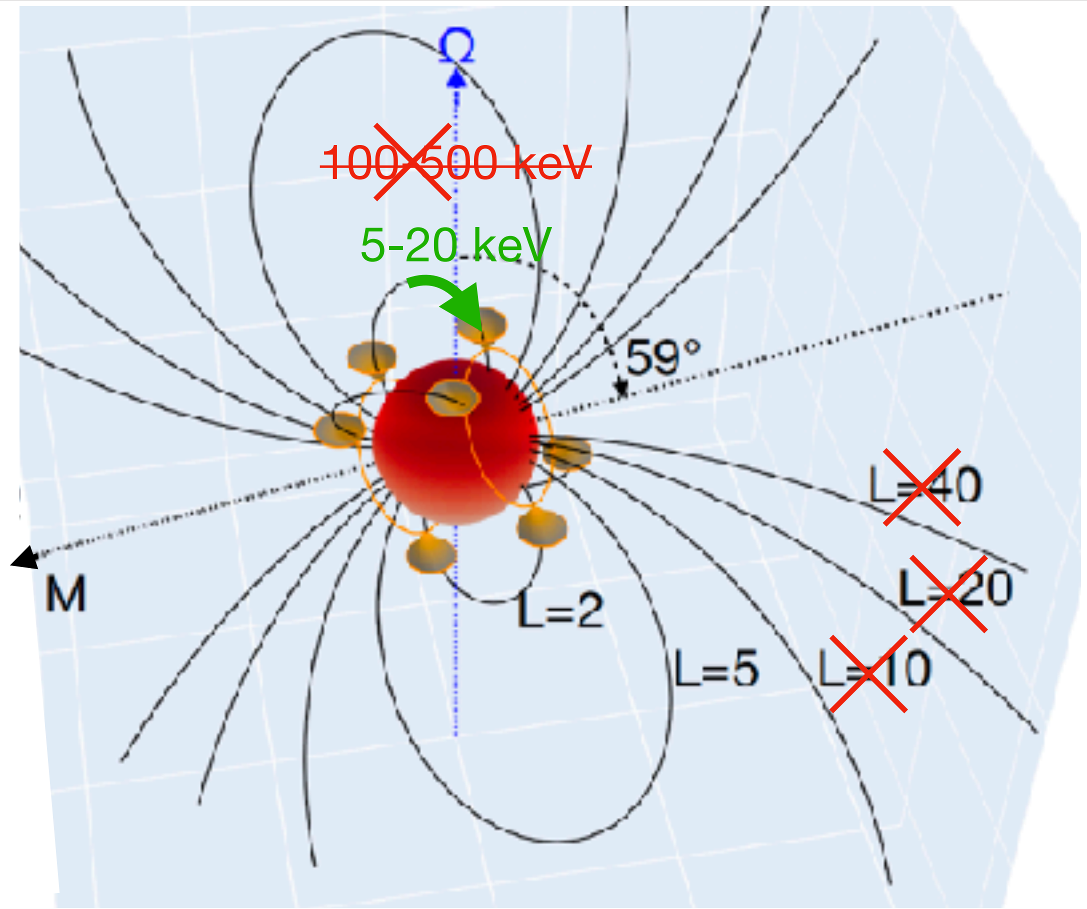
Zarka, Louis et al. (2025)
J. Zhang, …, Louis et al. (2024, 2025 in review)

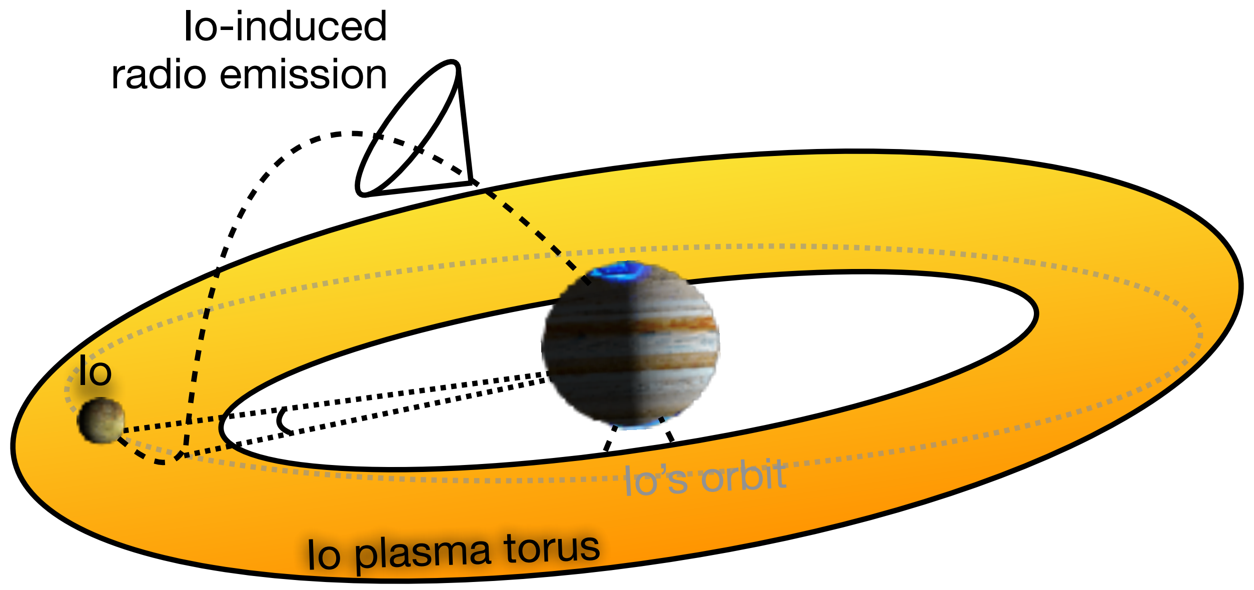


[Zarka, 2007]



[Mauduit et al., 2023]





Majors Results

- Through Simulation & theoretical calculations:
  - Source Location : L shell = 2-5 ~~(10-40)~~
  - Electron Energies : Ee- = 5-20 keV ~~(100-500 keV)~~

- 3 observations: No periodicity → Stellar hotspots
- 1st series of articles demonstrating what science can be done

CONCLUSIONS

- Lomb-Scargle method: very efficient to find periodic signal
- Even (very) weak and sporadic signal such as Europa-induced radio emissions

  FIY: Io-induced signal: discovered by Bigg., 1964
  Europa-induced signal: definitive proof of existence by Louis et al. (2017), Jacome et al. (2022)

- Use synodic (or beat) periods and harmonic resonances to confirm detections

- Use Lomb-Scargle window sliding in time to determine **when** the detected emissions have been observed

- Mauduit et al. (2023) technic (FFT + Radon Transform) very powerful
  to detect milliseconds bursts
  and
  infer the electrons energy

PERSPECTIVES

- Apply these technics to Star and Star-Planet Interaction targets.
- Limitations:
  - Good spread in time over the years — e.g., Jupiter: 1100 hours over 5 years
  - Enough observations for the statistic
  - (A ~~bit~~ lot of luck to have the sources active during the observations)…

Stay tuned….