Low-frequency radio emissions from stellar and exoplanetary systems

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Jake Turner[6], Laurent Lamy[1,7], Julien Girard[1,2], Alan Loh[1,2],
Quentin Duchêne[1], & Benjamin Poux-Bouret[1,3]

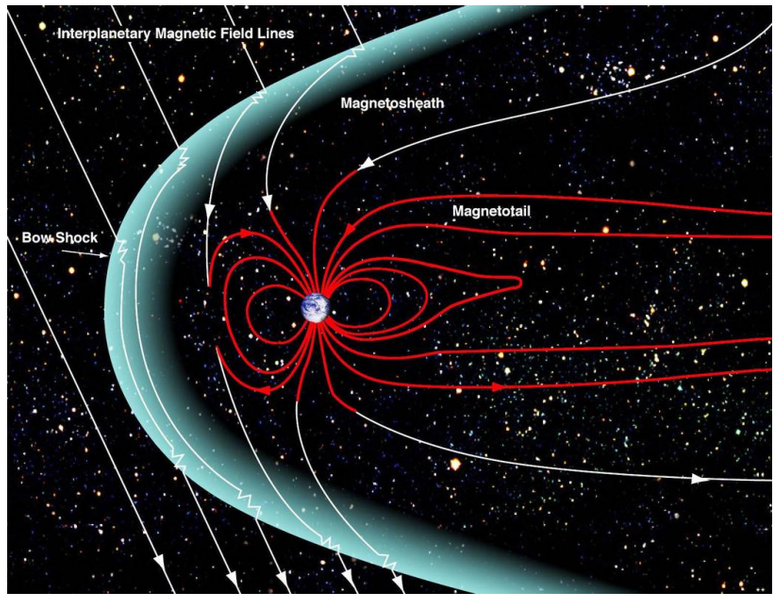
[1]LIRA, [2]ORN, [3]LUX, [4]SKAO, [5]LPC2E, [6]Cornell, [7]LAM

+ thanks to H. Vedantham, J. Callingham, T. Shimwell, M. Hardcastle ...

European Research Council

What ?

- Radio emissions from all Solar system magnetized planets



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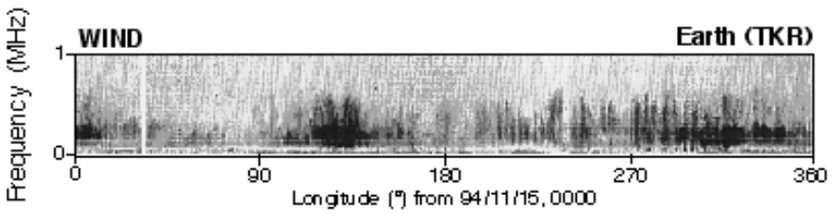

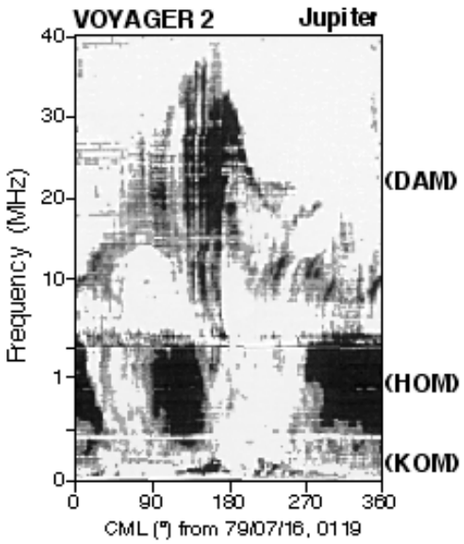

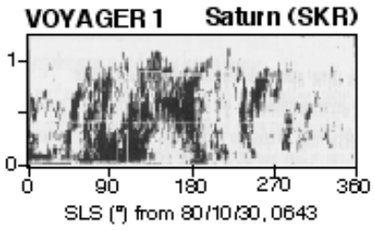

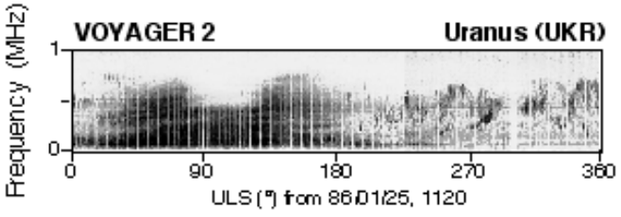

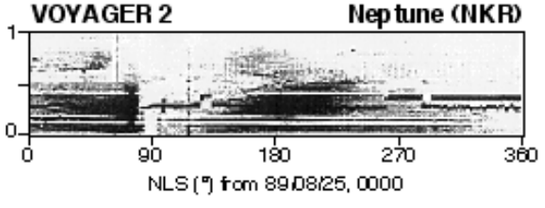

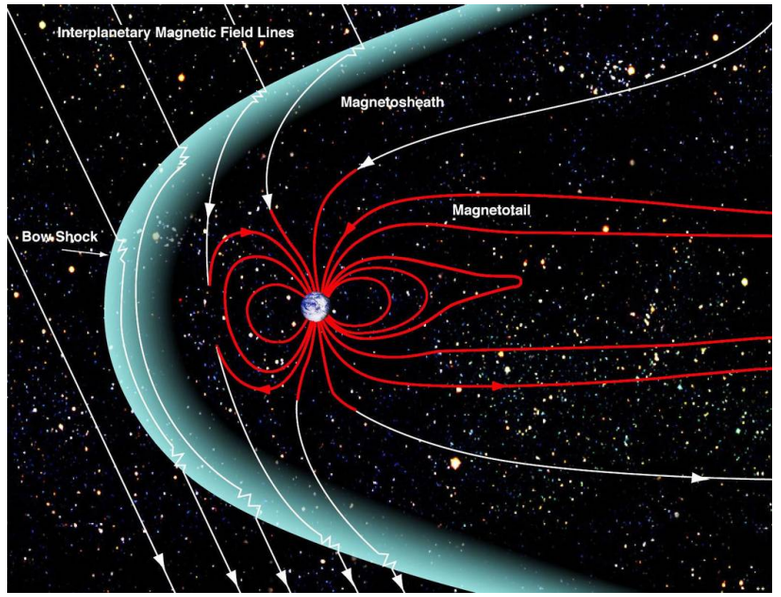

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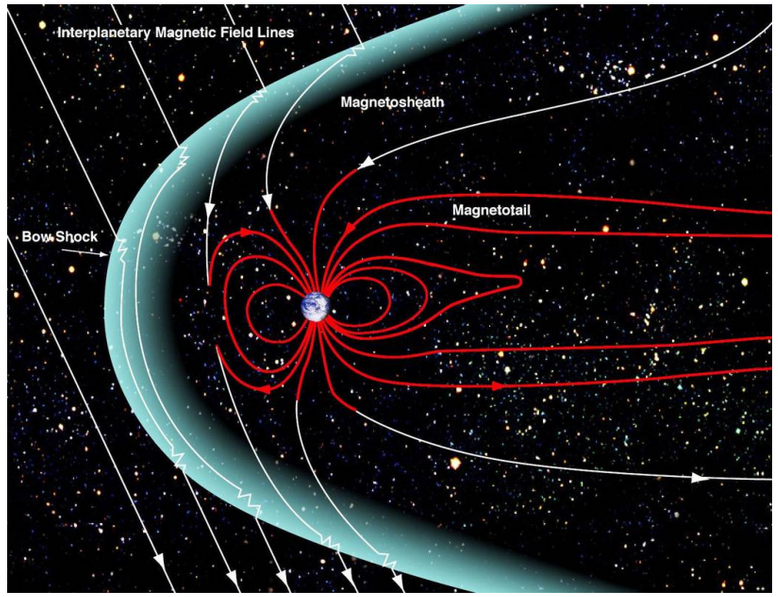
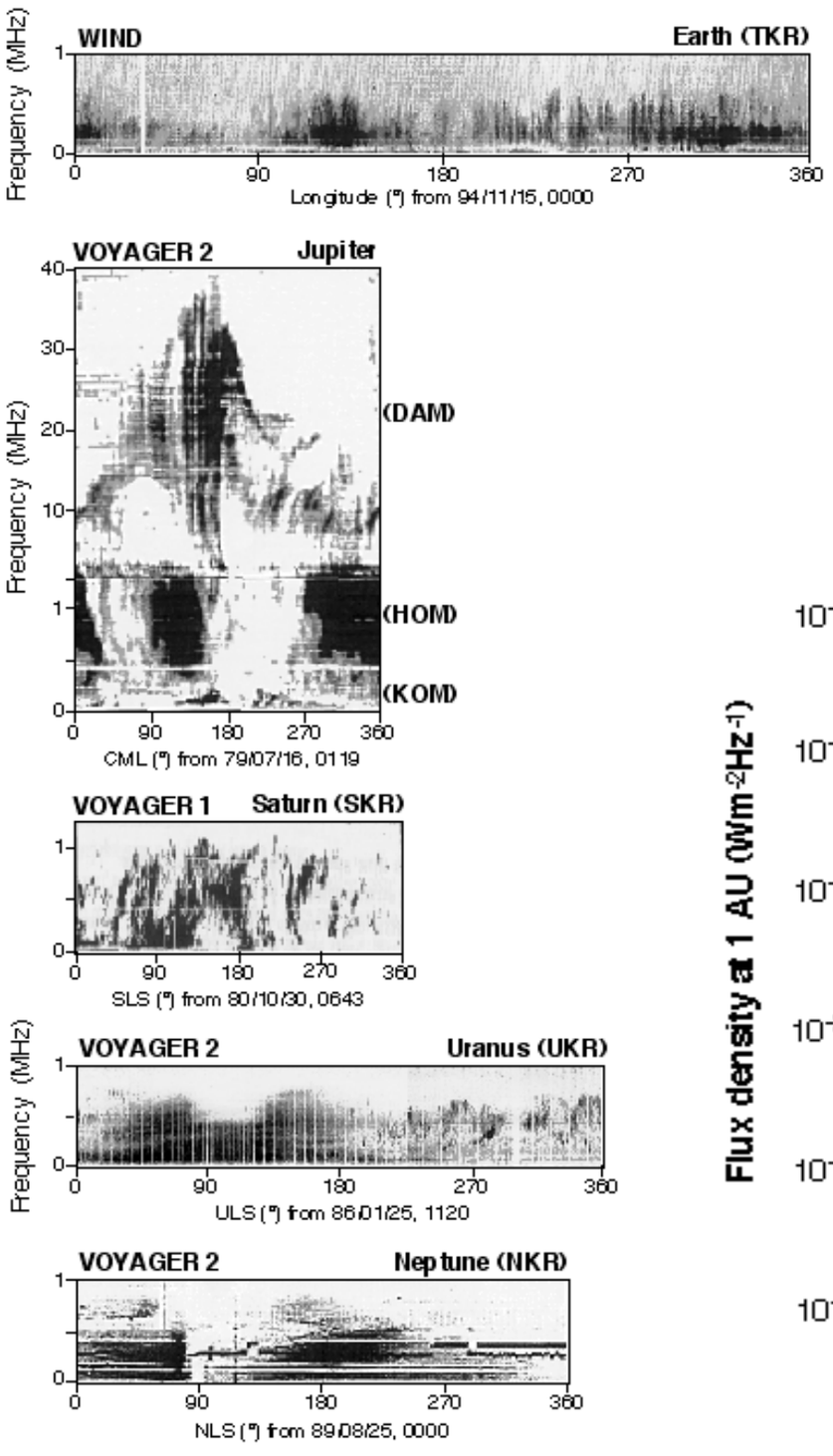
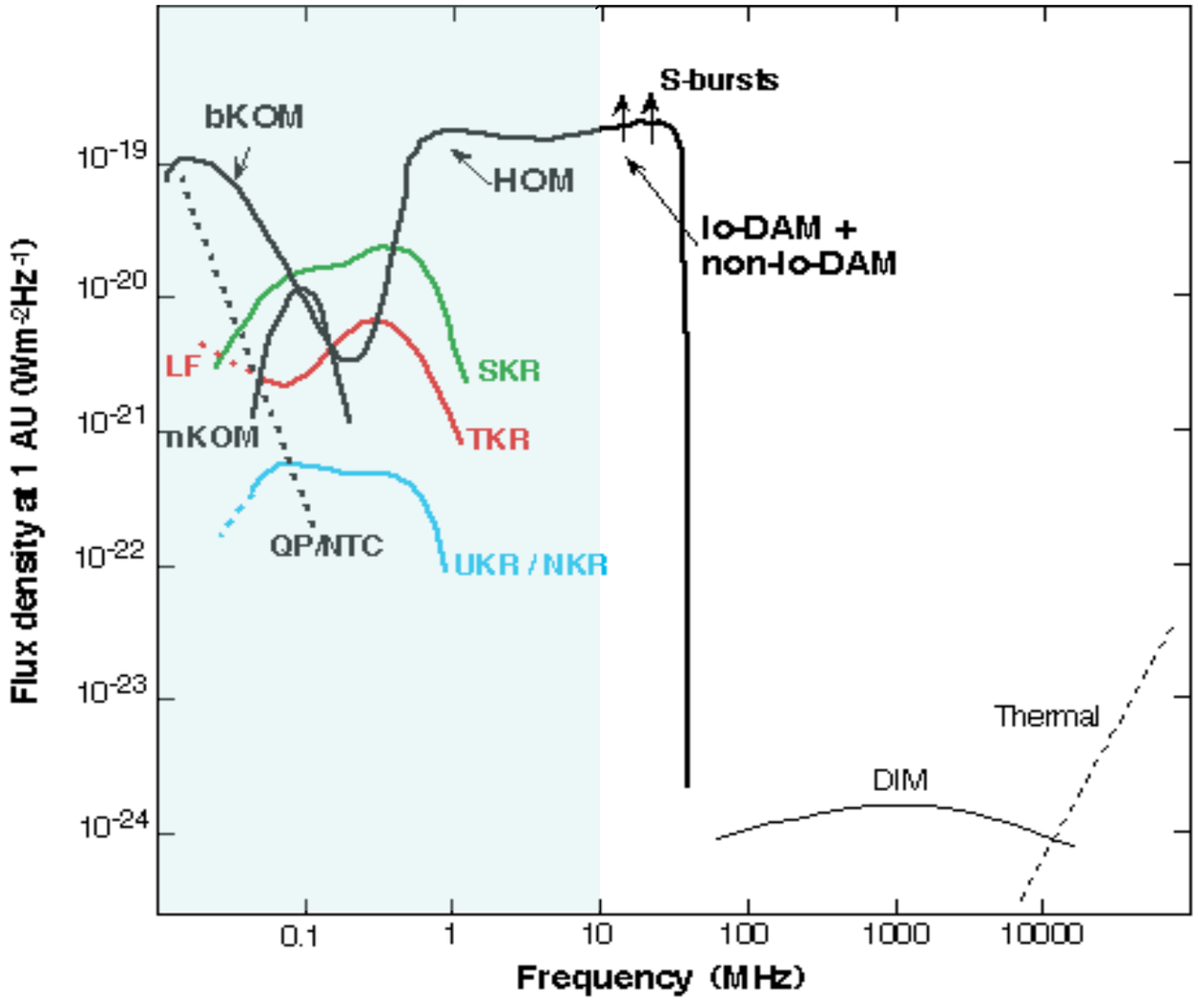


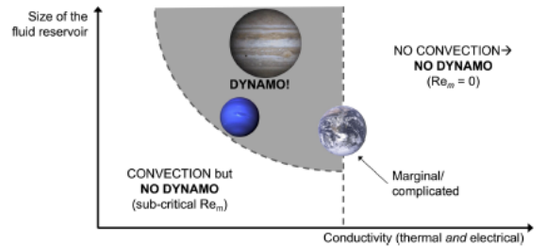




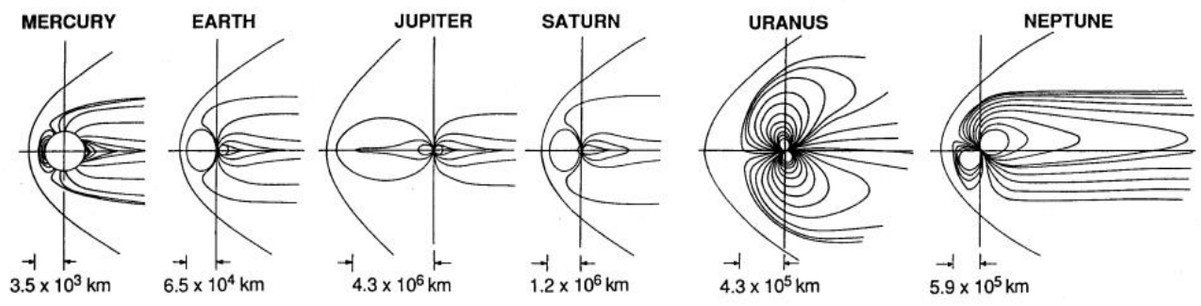
[Zarka 1998, 2000]

Why ?

- **|B| & tilt → dynamo → internal structure**
- Planetary rotation → spin-orbit locking ?
- Orbit inclination
- **Magnetosphere diversity**
  → populations studies



[Brain+ 2024]



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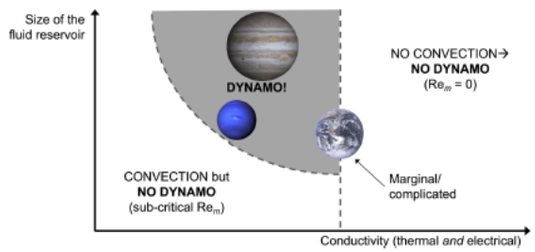

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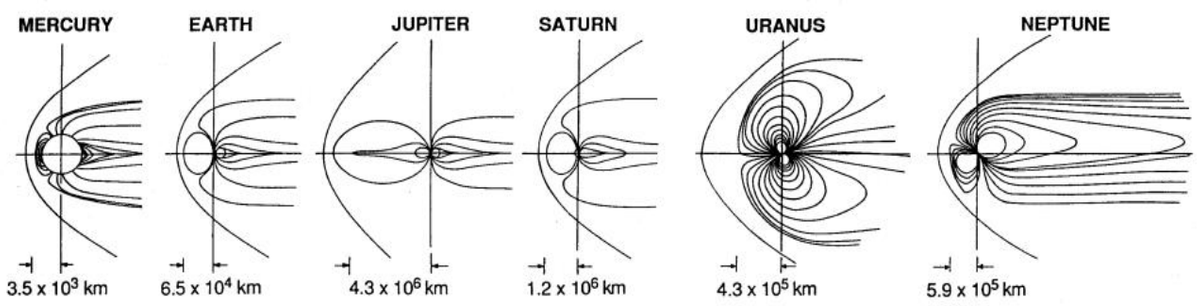
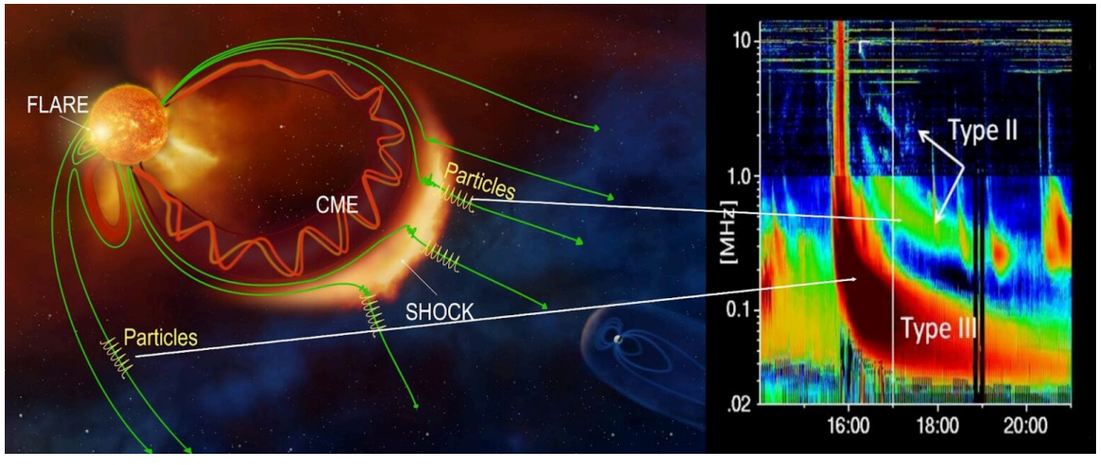
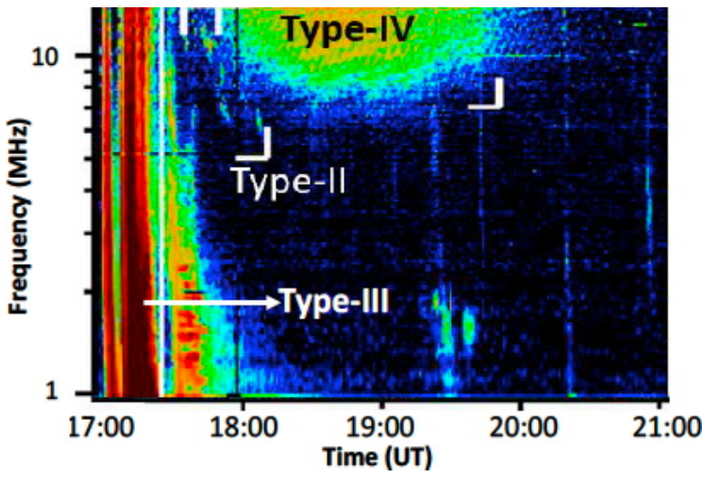


- Energetics of Star-Planet plasma Interactions (SPI)
- **Exo-space weather signatures in star-planet systems (type II, III, IV),** extreme environments (strongly magnetized dwarfs or active stars)





[Carley+ 2019, Mohan+ 2024]

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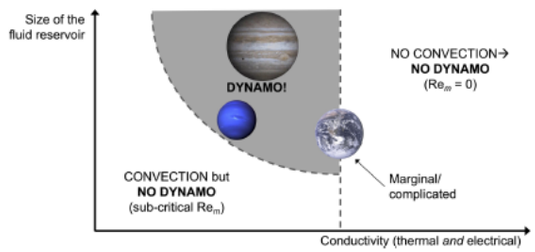

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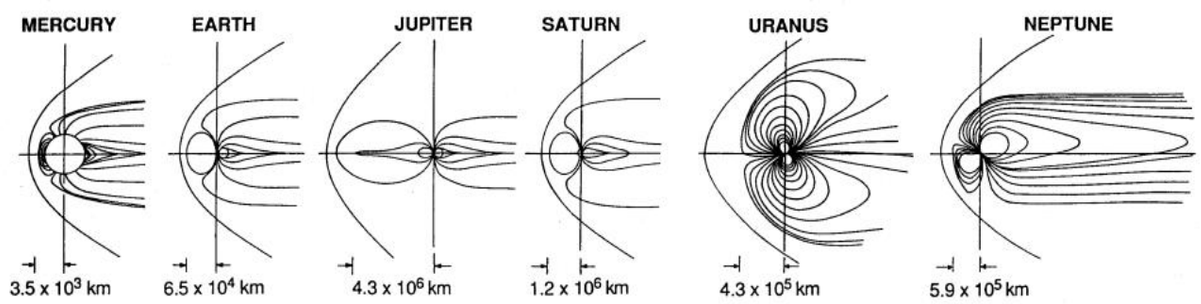

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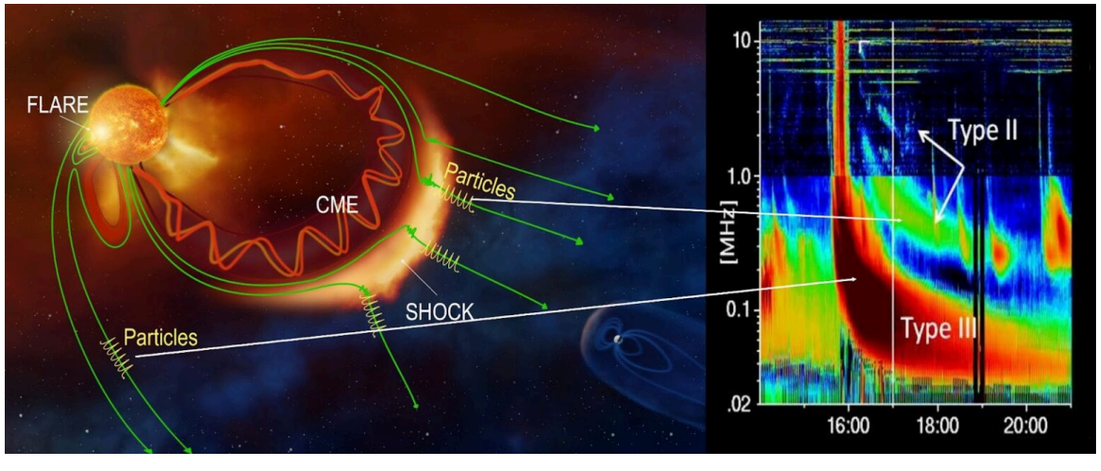
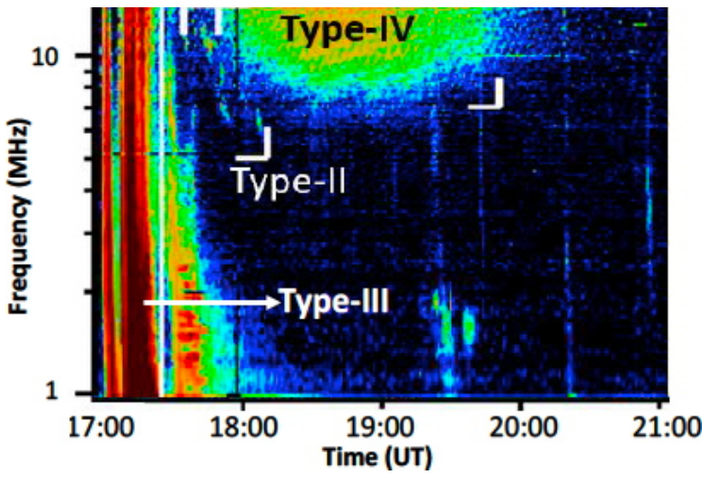


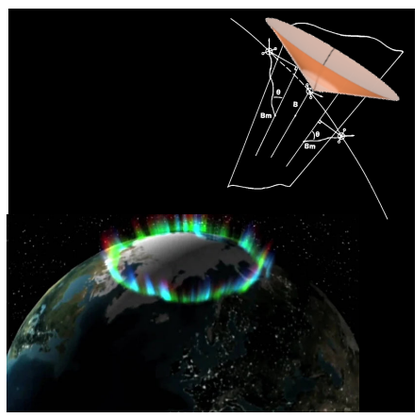


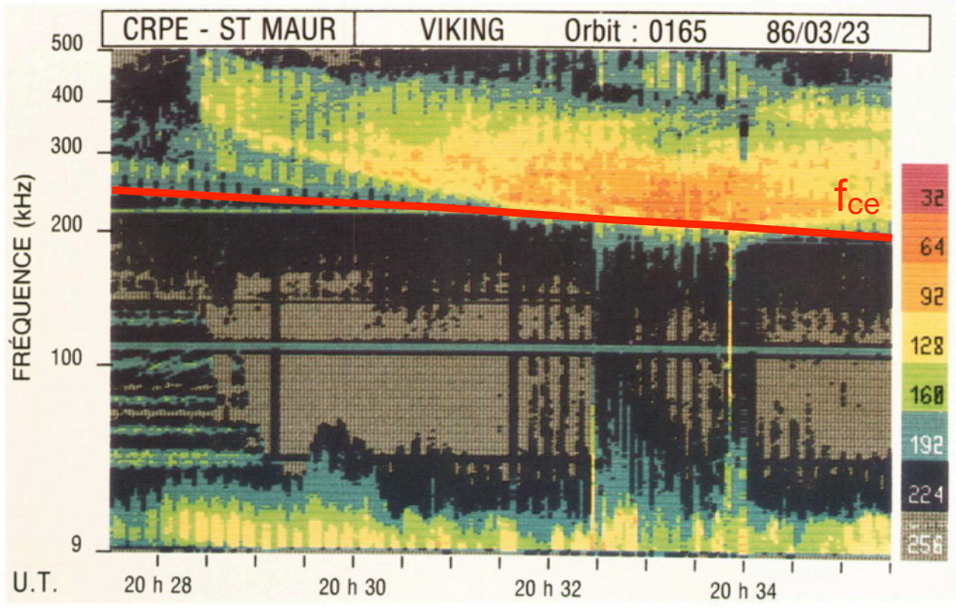
[Carley+ 2019, Mohan+ 2024]

- Implications for atmosphere evolution (escape / erosion, CR bombardment / O3 destruction, CME…) & habitability
- Discovery tool (e.g. around M dwarfs) ?

How ?

- Physics of generation well understood :
  → microphysics studied in-situ : ECMI
  → simulations: ExPRES code





[Roux+ 1993]

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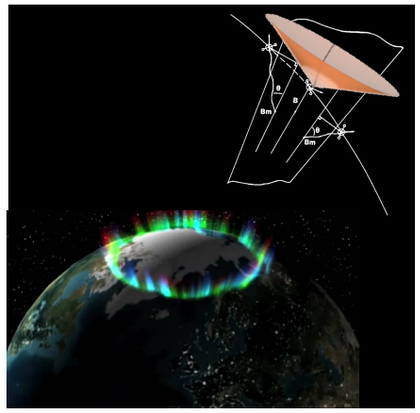
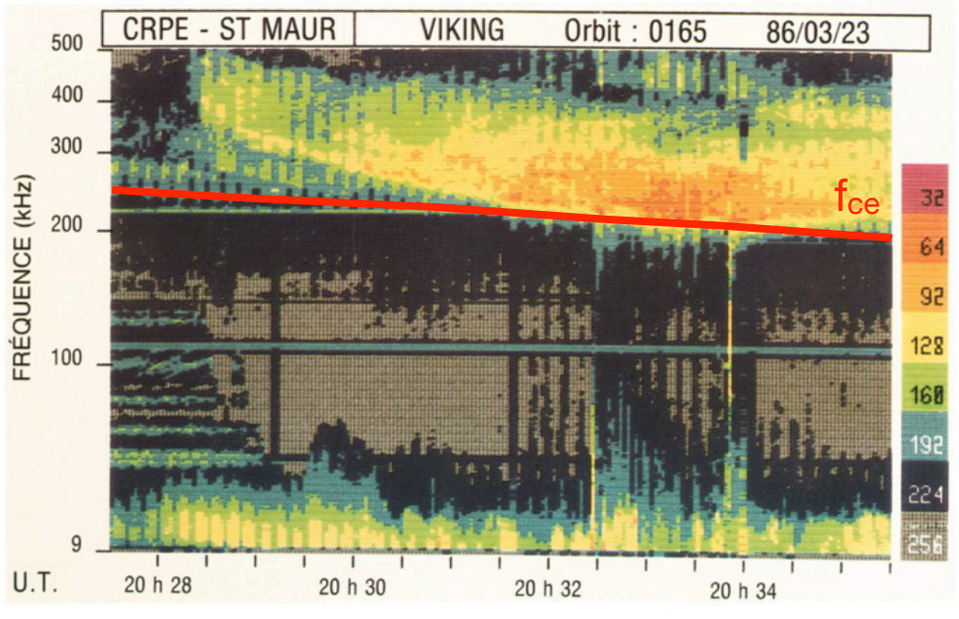
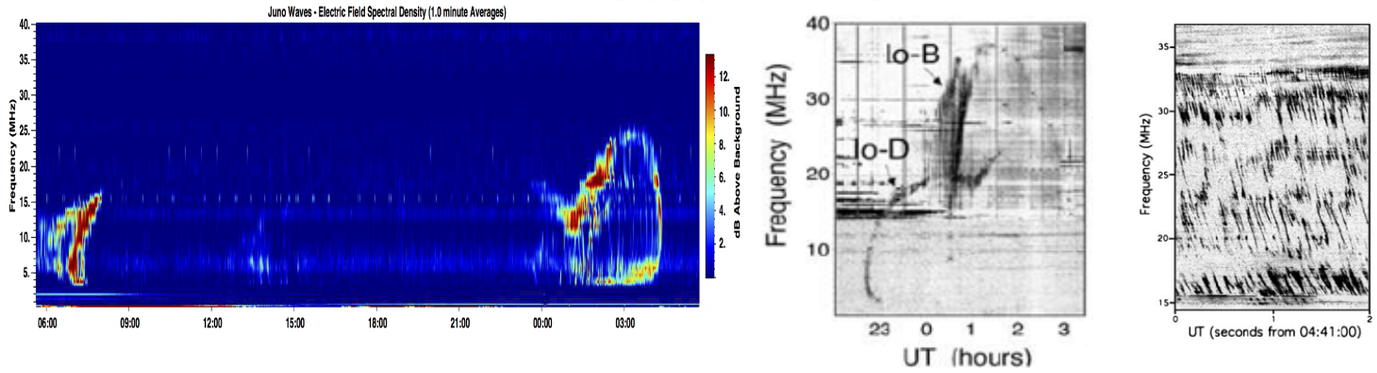


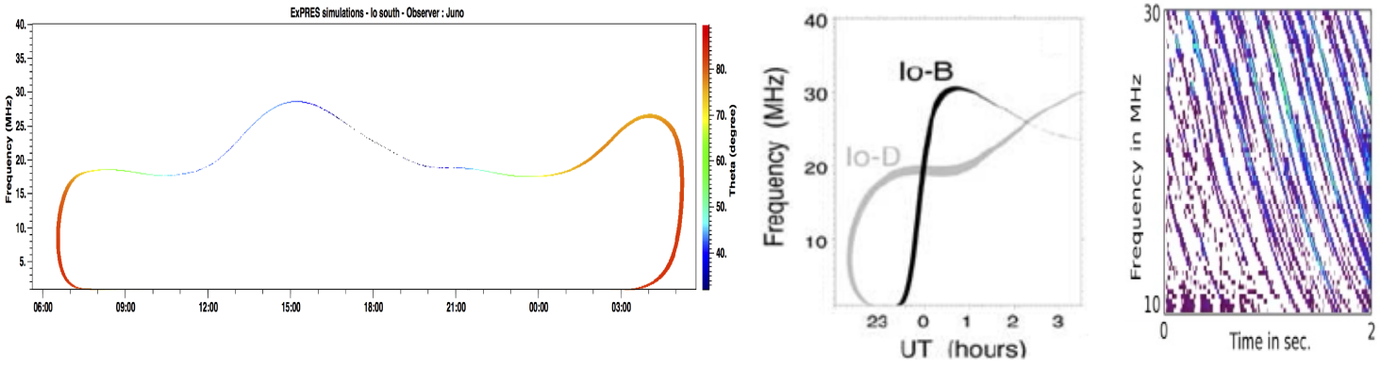


[Roux+ 1993]

Observations



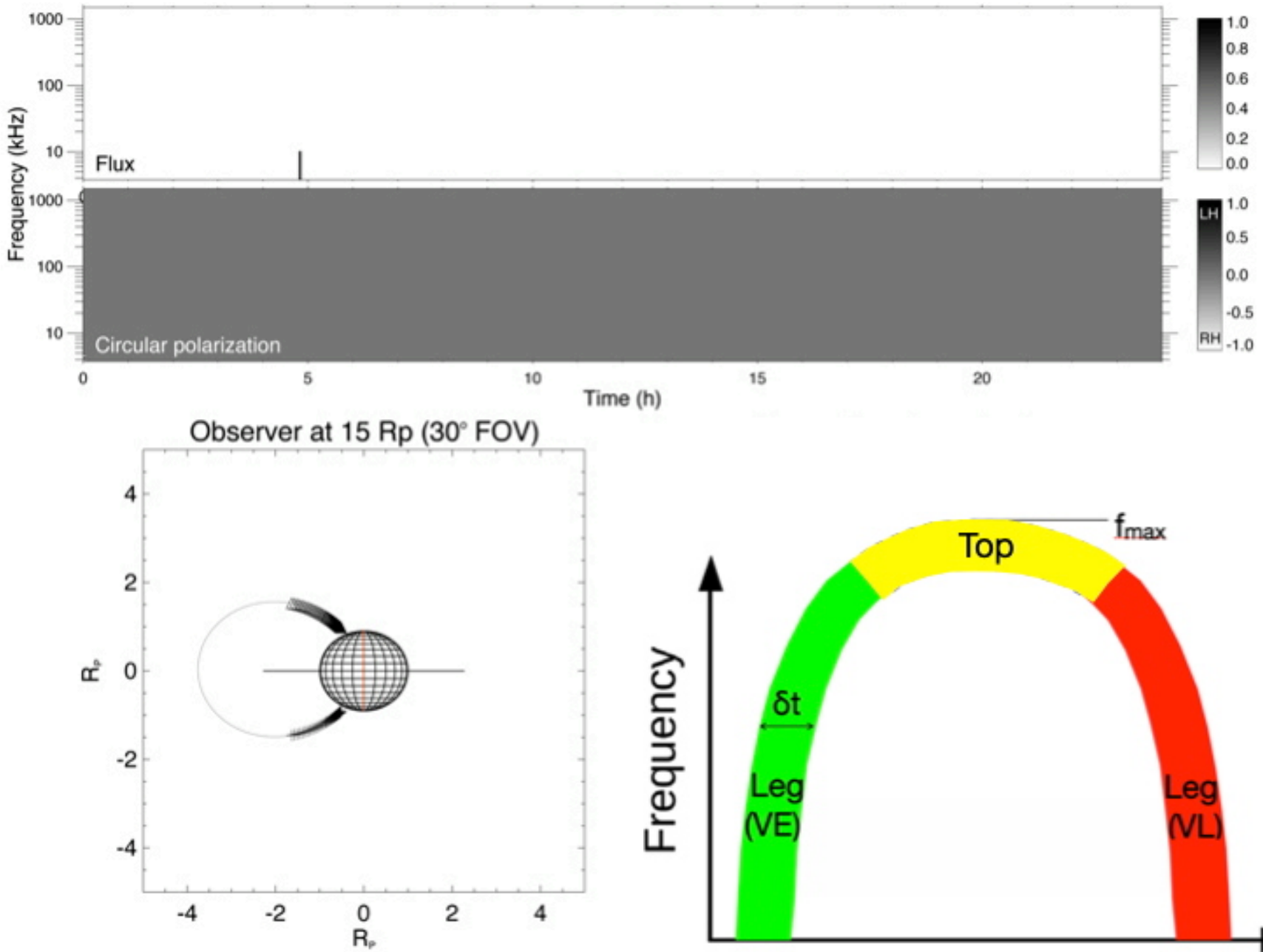
Theory / Simulations



[Zarka 2004, Hess+ 2008, 2009, Louis+ 2017, 2019]

How ?

- Ubiquitous arch-like signals



[courtesy L. Lamy]

[Hess+ 2014, Tasse+ 2026]

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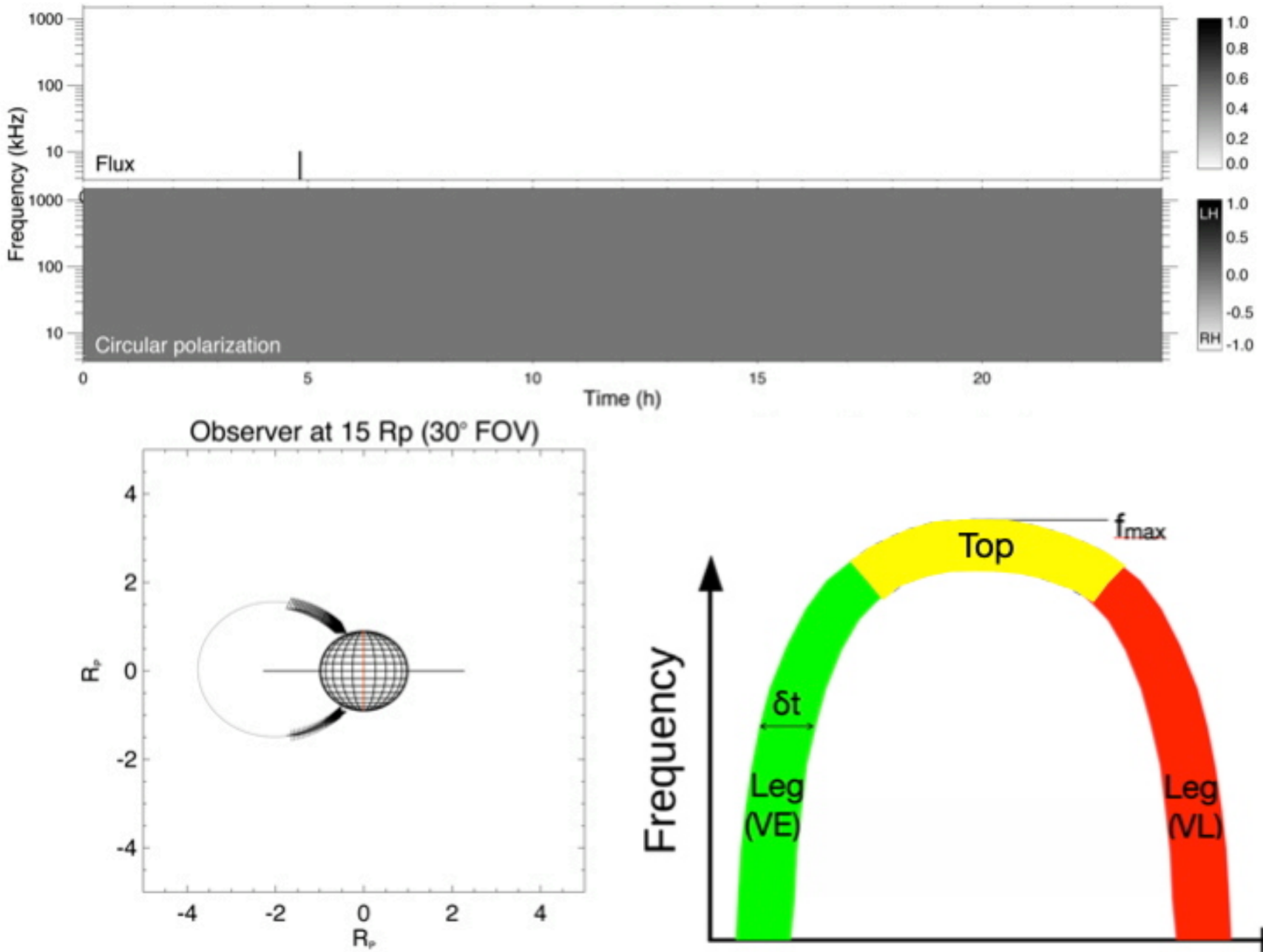

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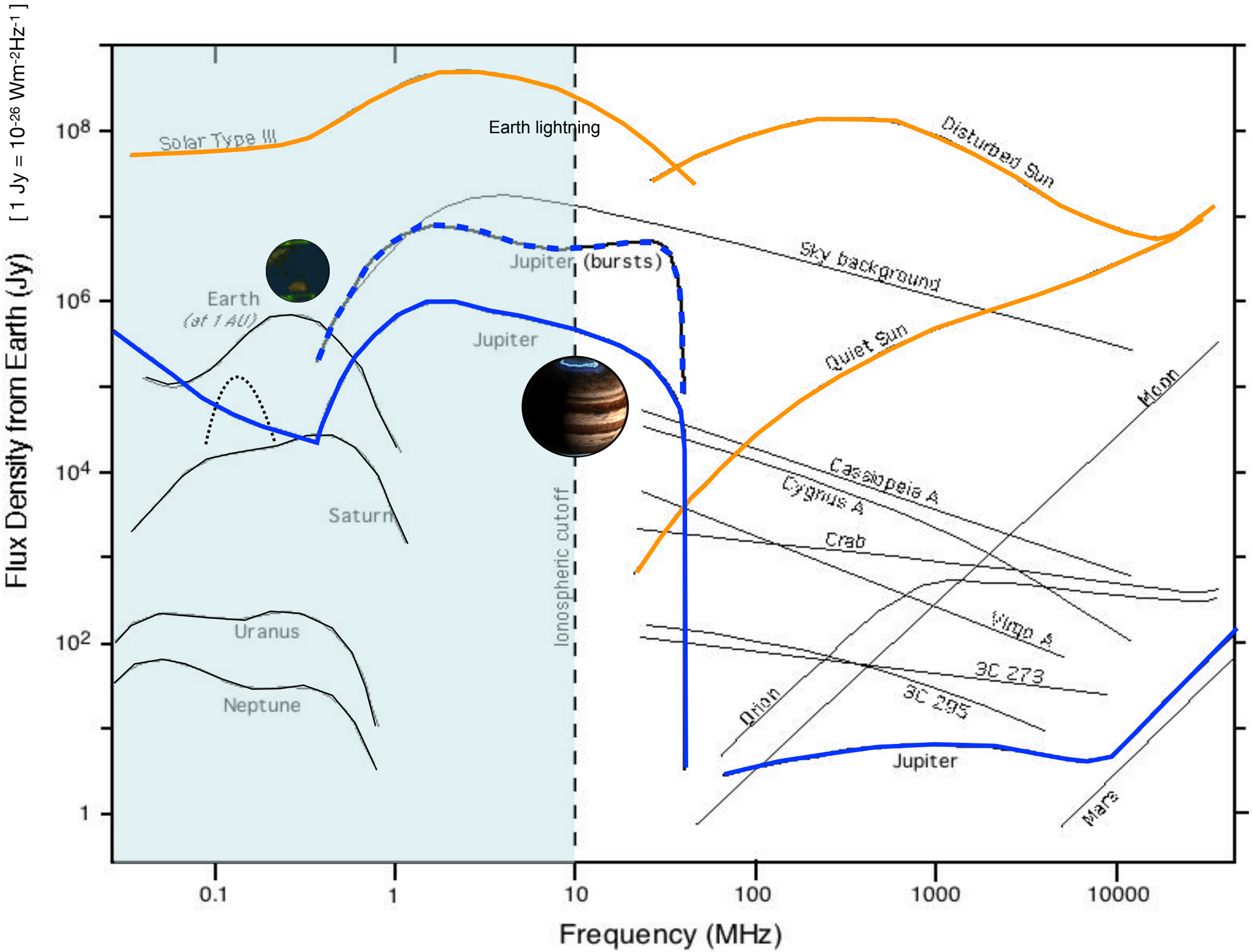
- Solar system radio emisions intense compared to Sun's ...



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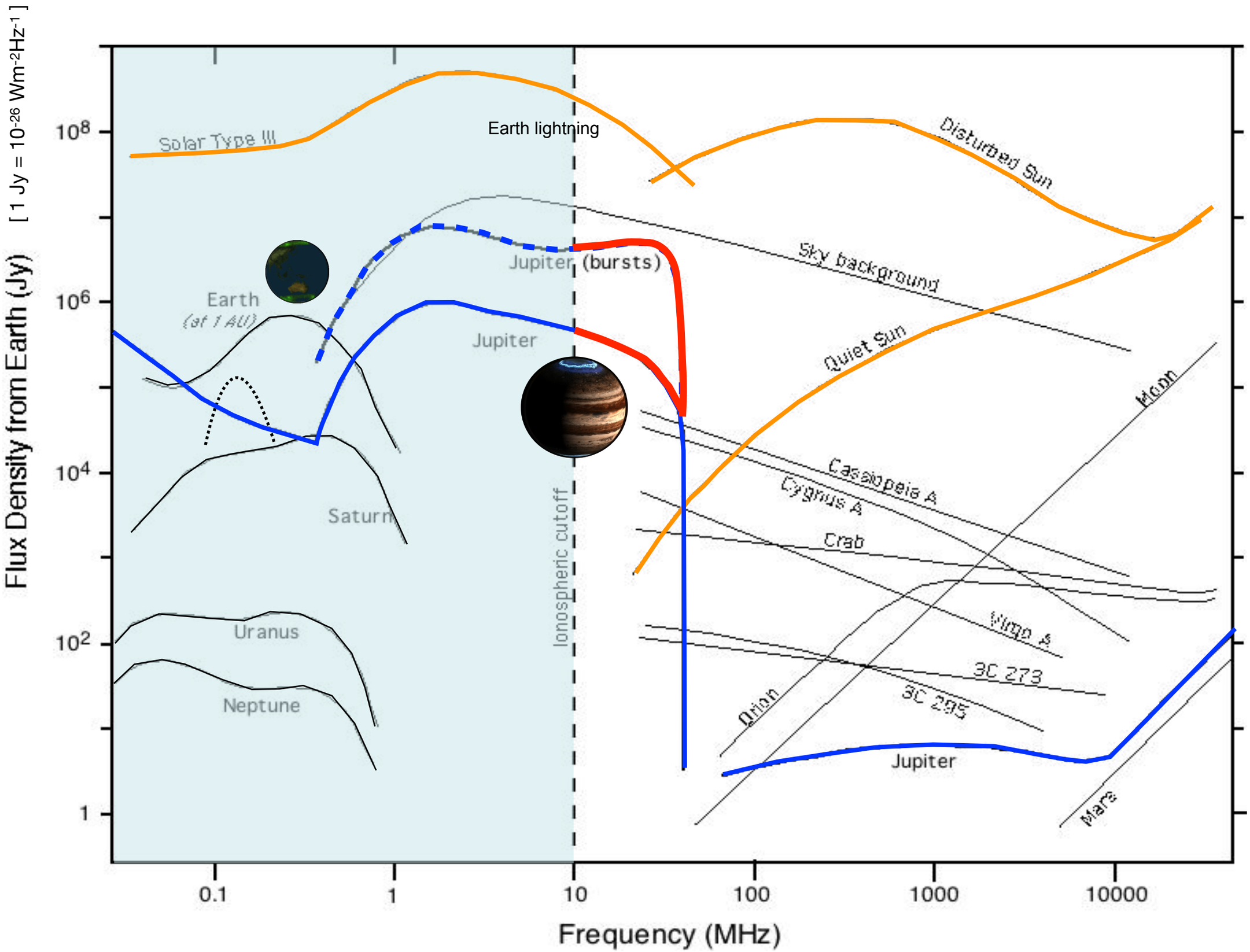
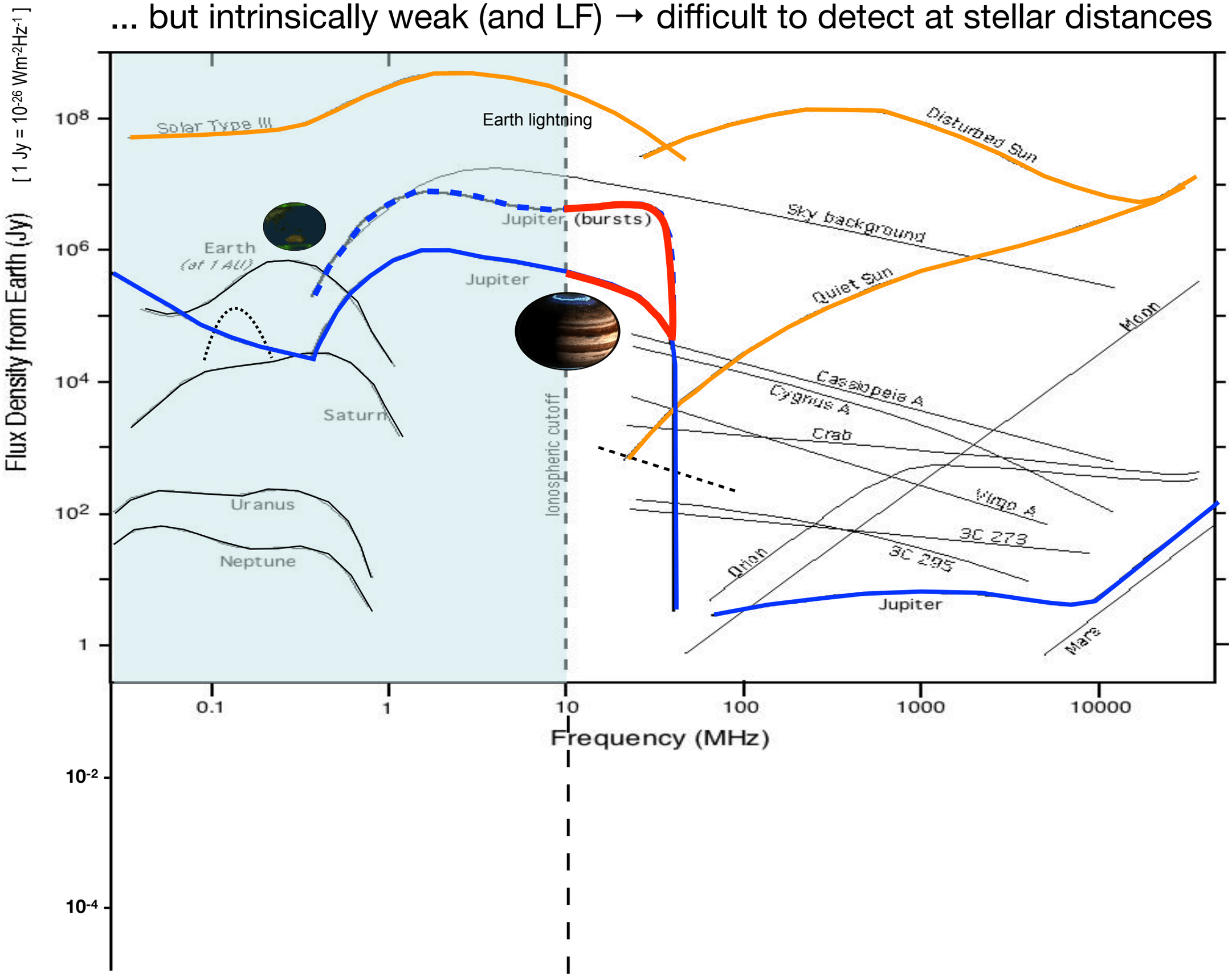


Detection ?

... but intrinsically weak (and LF) → difficult to detect at stellar distances



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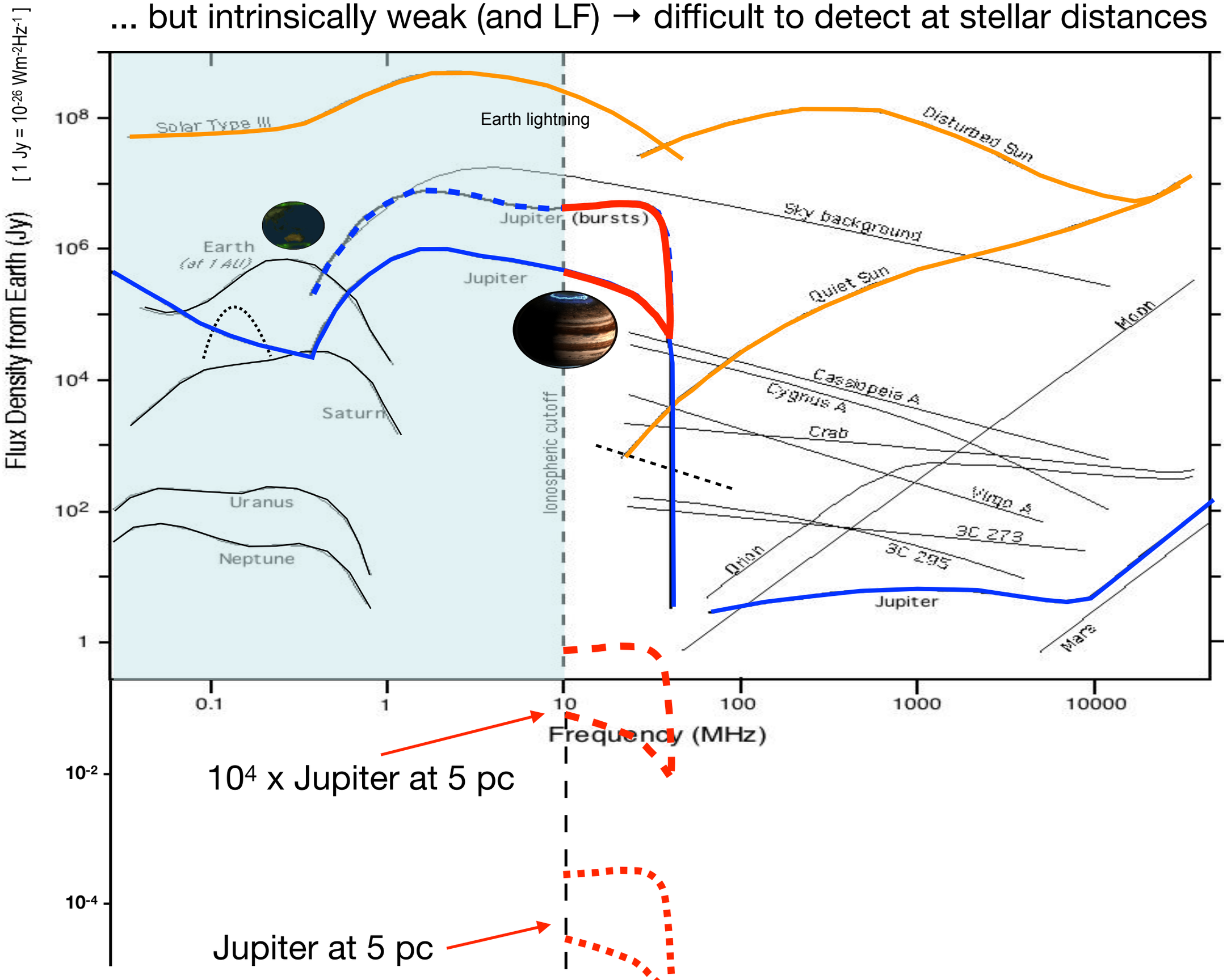

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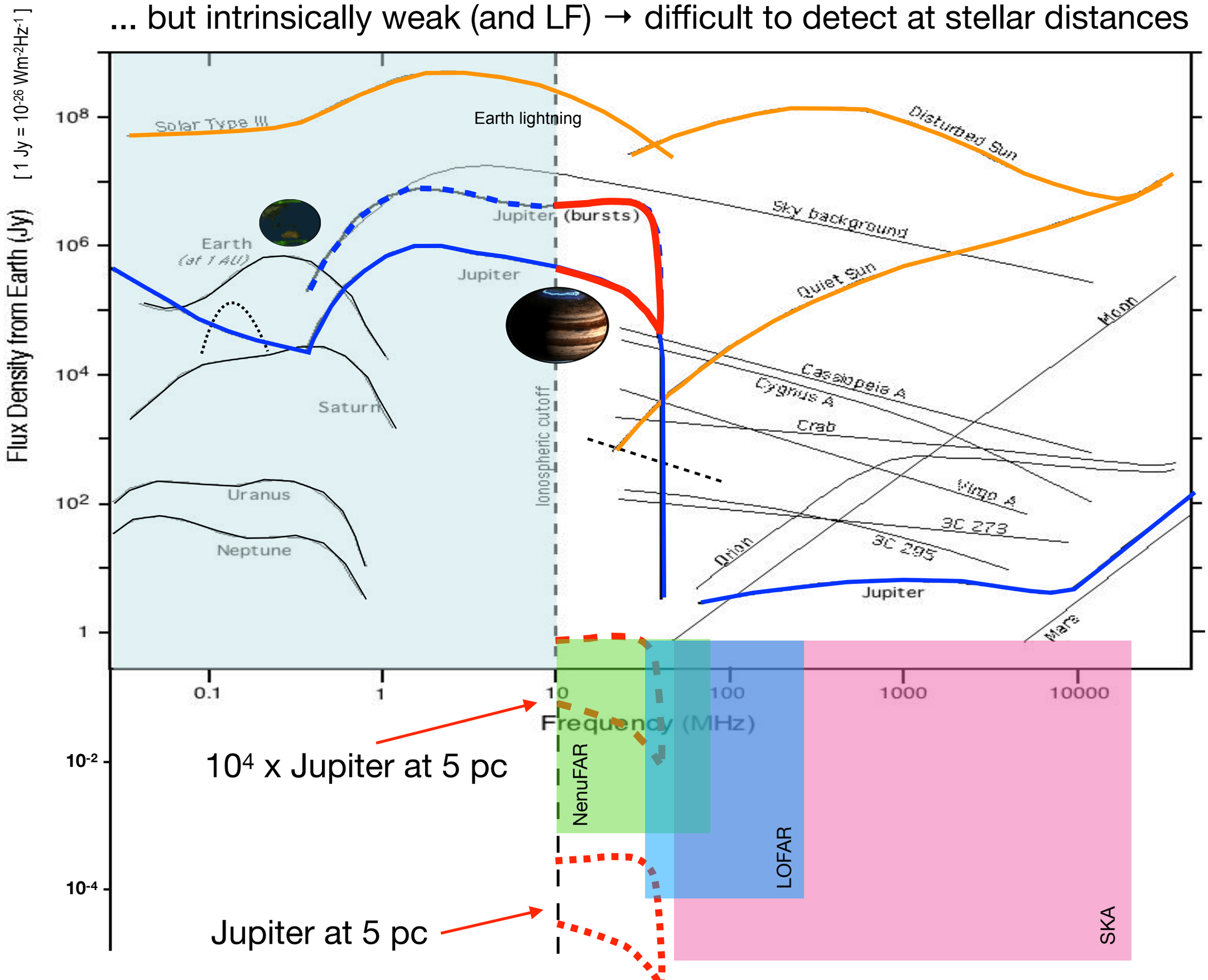


Theory ?

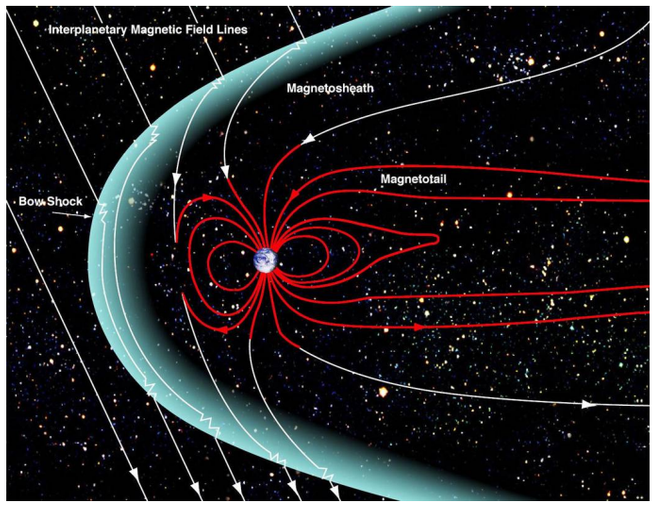
- 3 drivers:

  1) Solar Wind - Magnetosphere interaction (e.g. Earth)

  2) Magnetosphere - Ionosphere interaction (corotation breakdown, e.g. Jupiter)

  3) Satellite - Magnetosphere interaction (e.g. Io-Jupiter, Ganymede-Jupiter)

[Dungey 1961]



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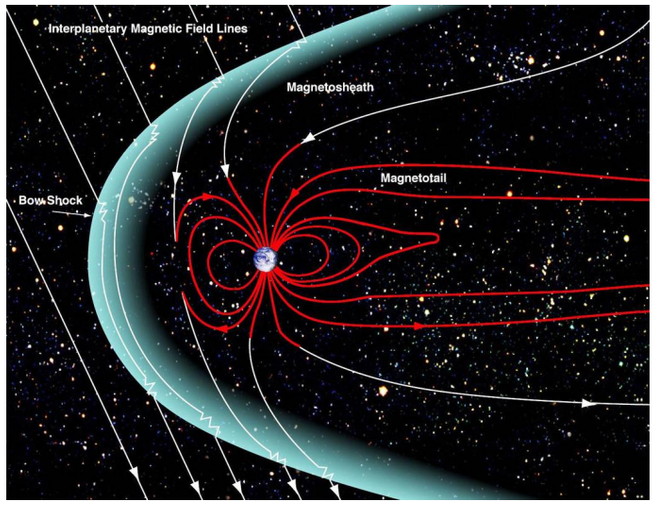

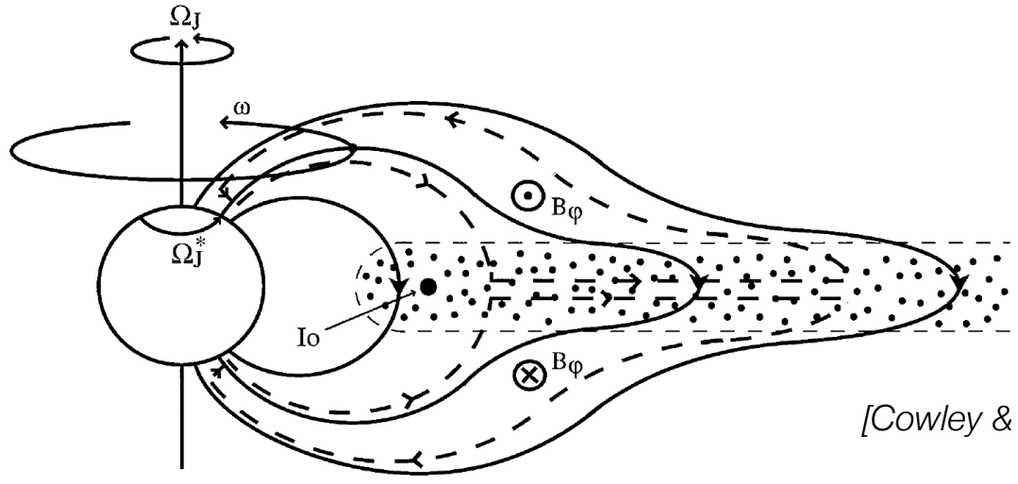

[Cowley & Bunce 2001]

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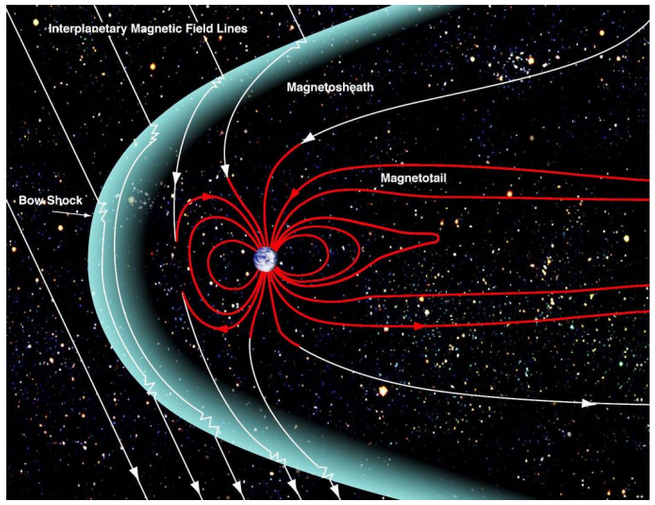

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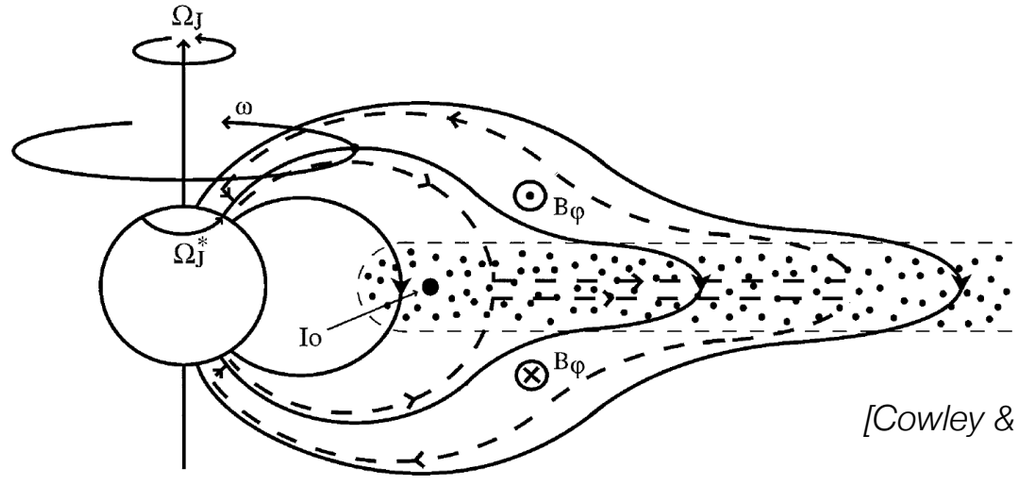

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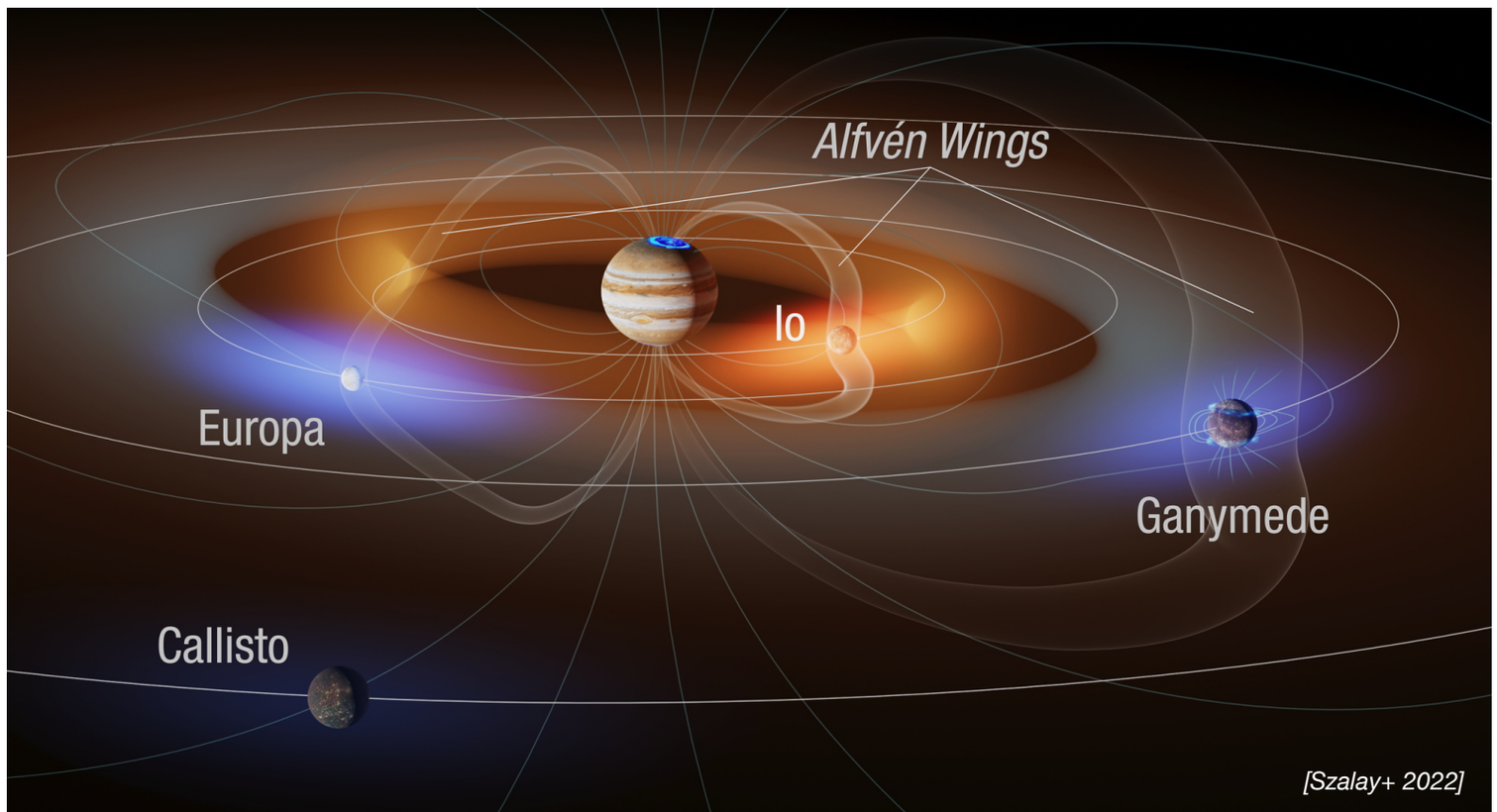
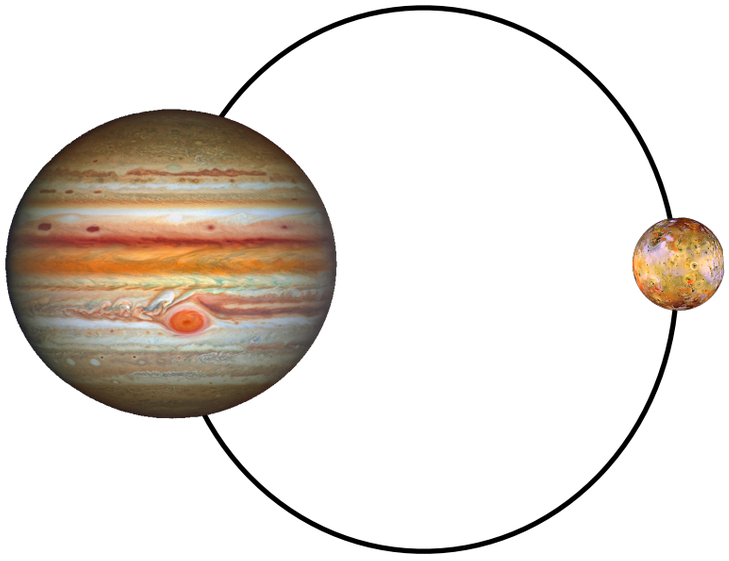


[Bigg 1964, Louis+ 2017, Zarka+ 2018, Jacome+ 2022]

Theory ?

- Solar system based scaling law suggests that 1) and 3) can be largely upscaled



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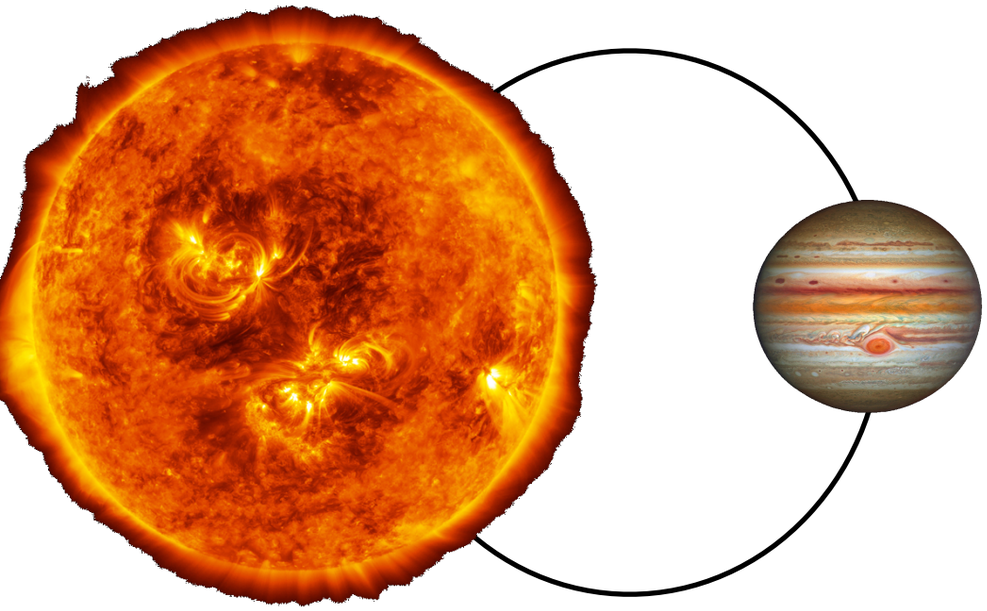

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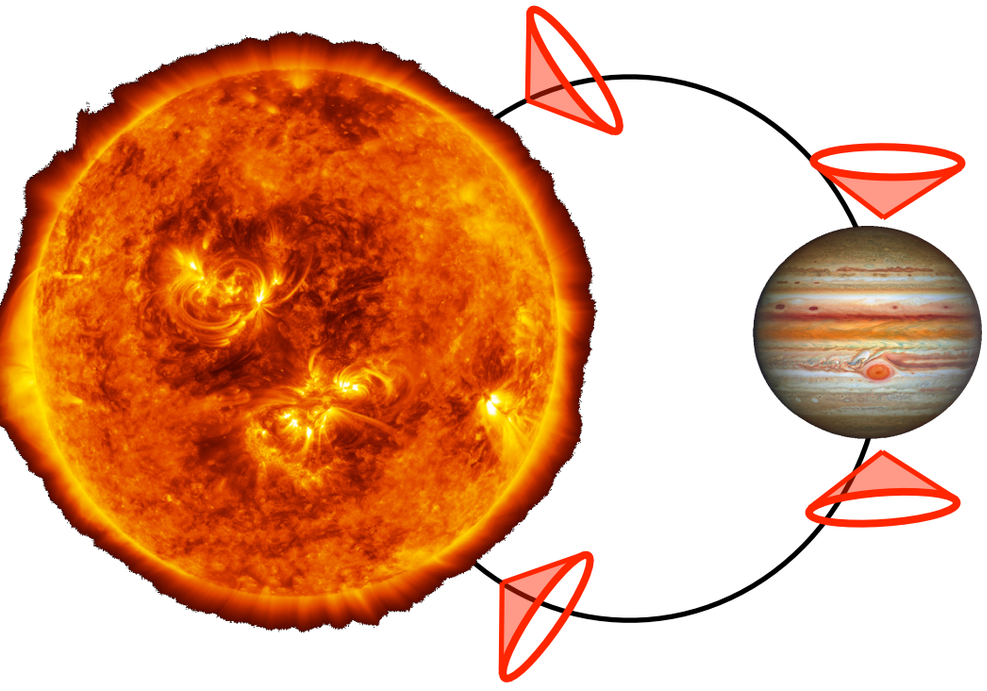

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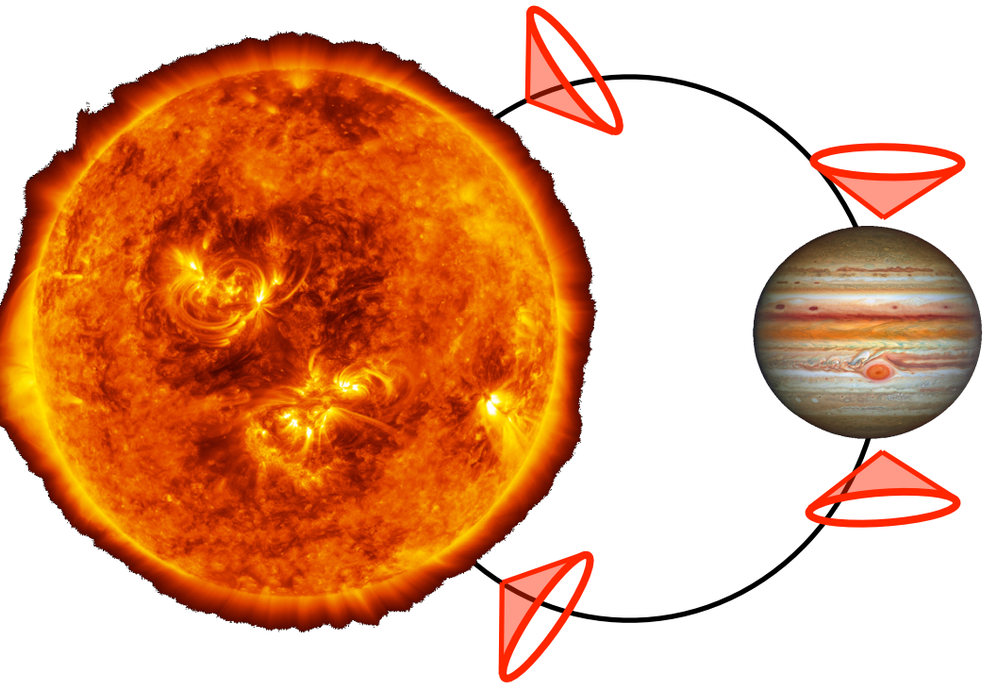

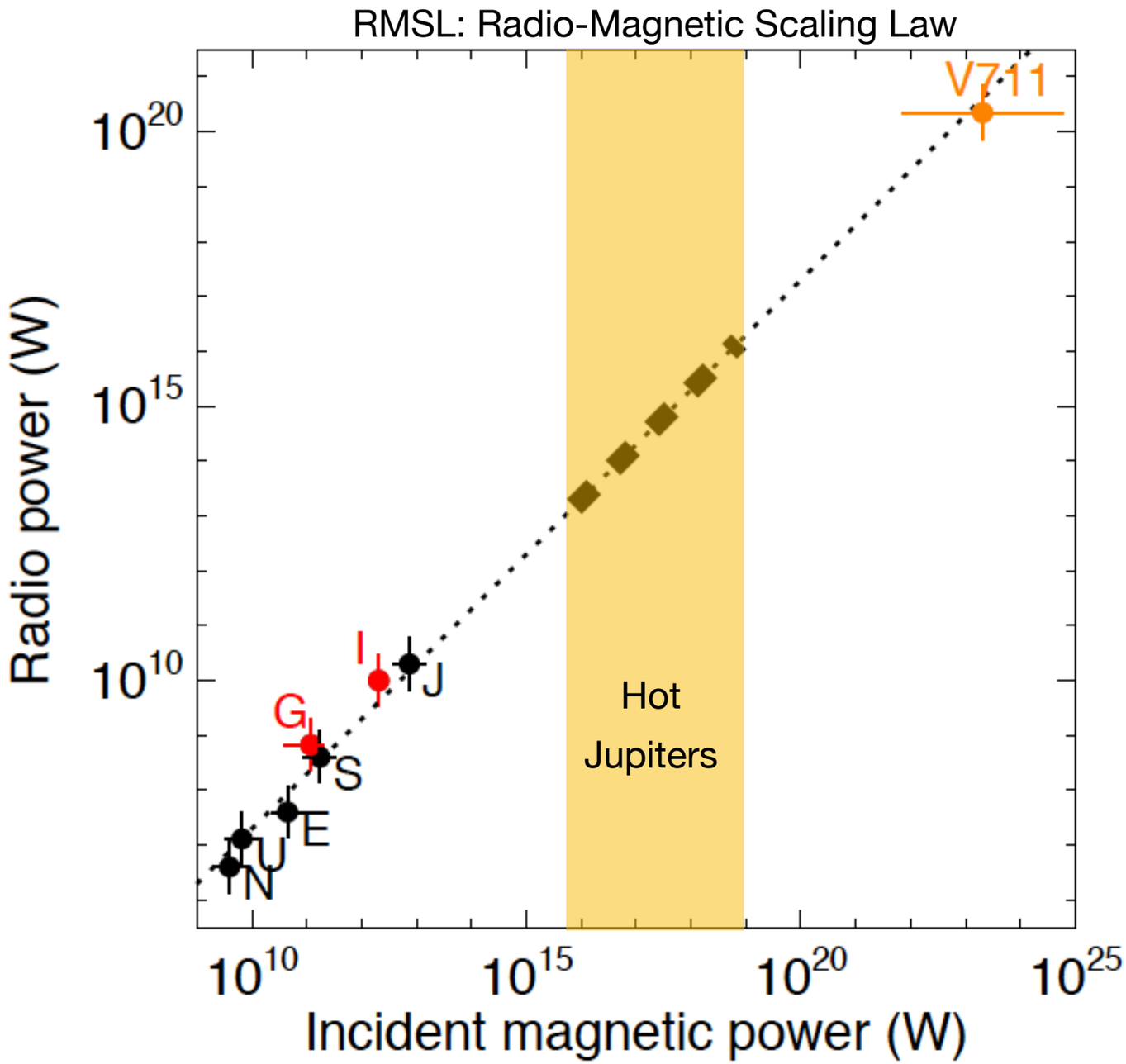

[Zarka+ 2001, 2018, Zarka 2007]

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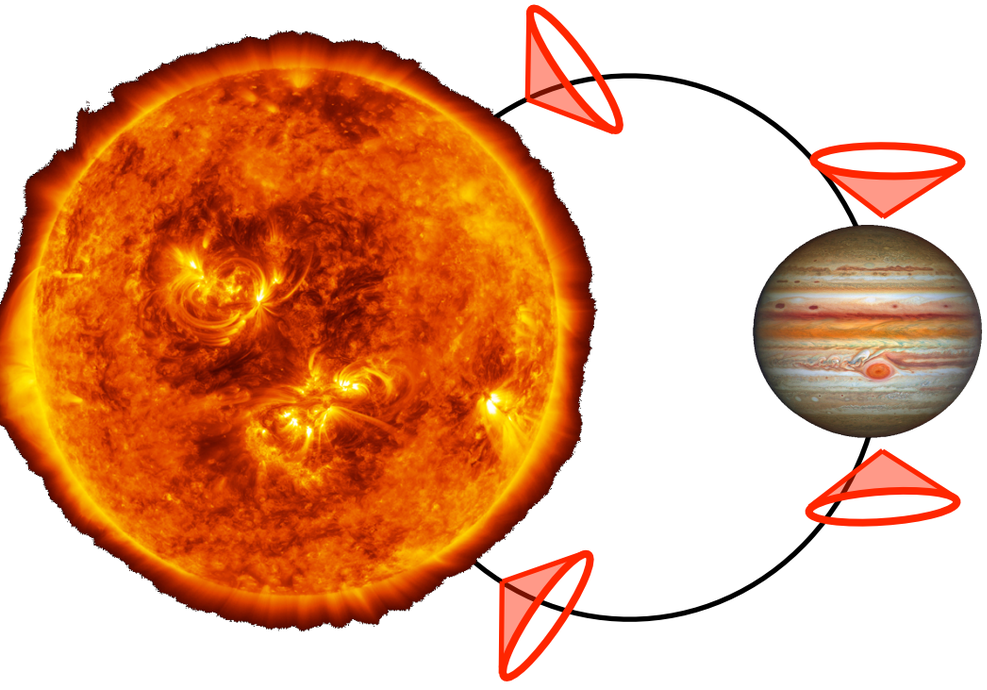
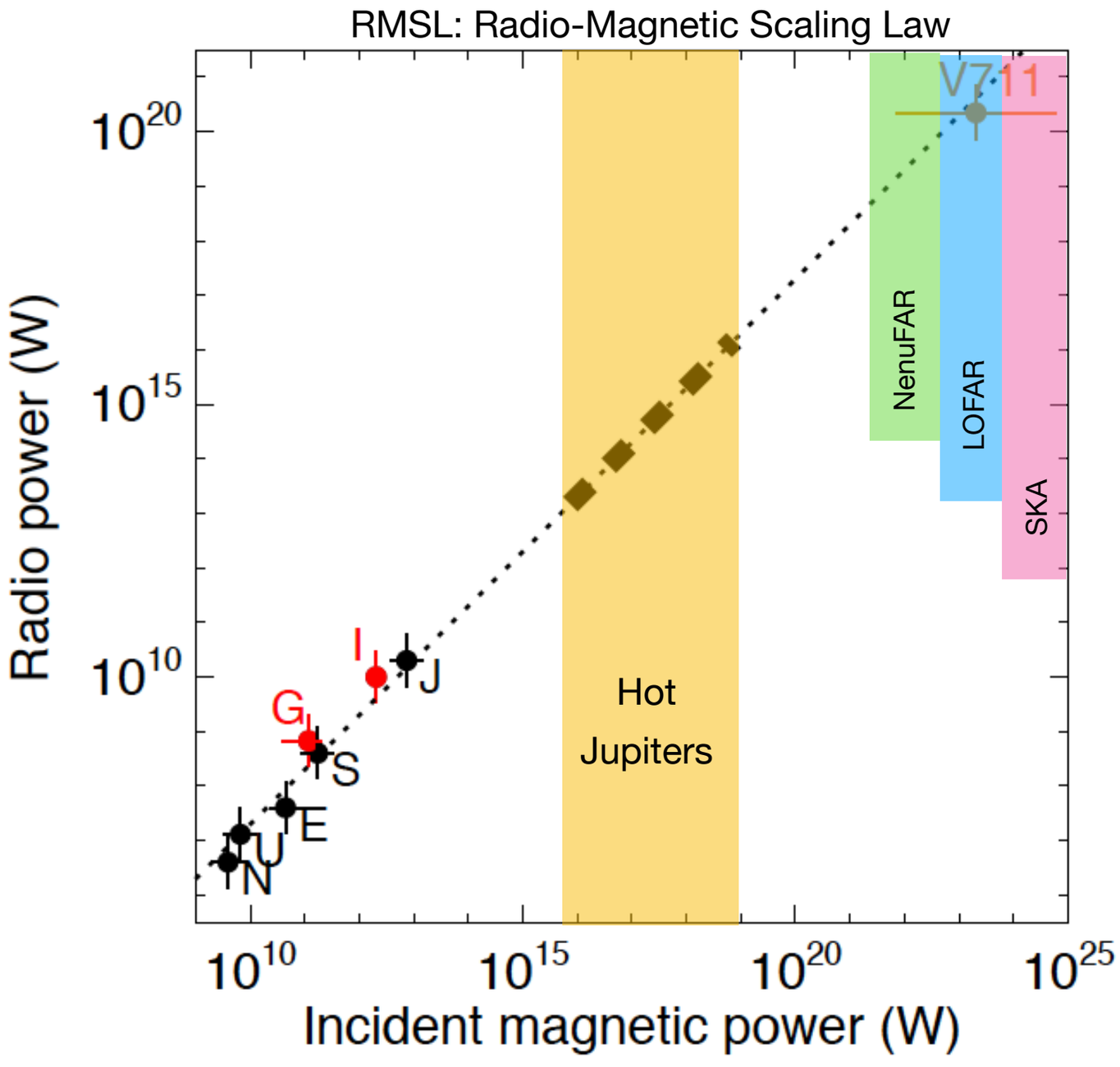
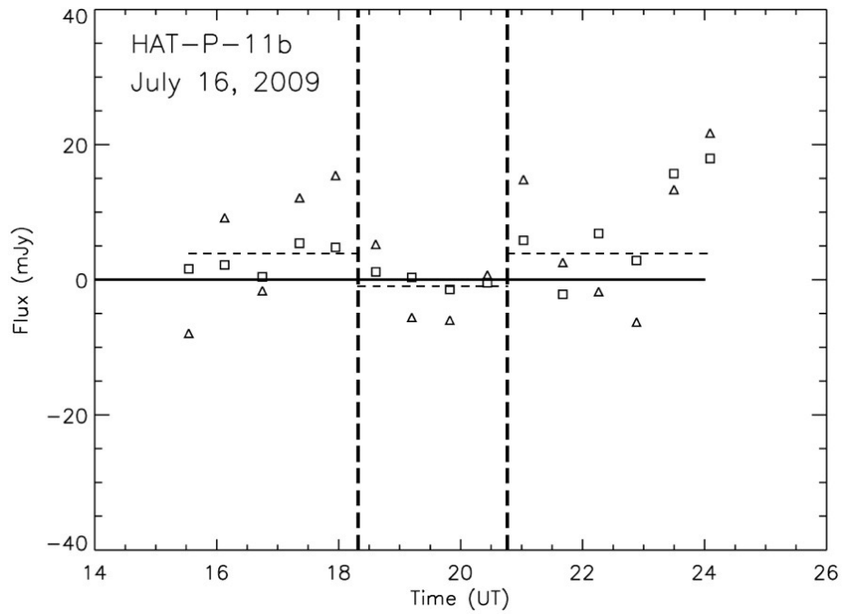




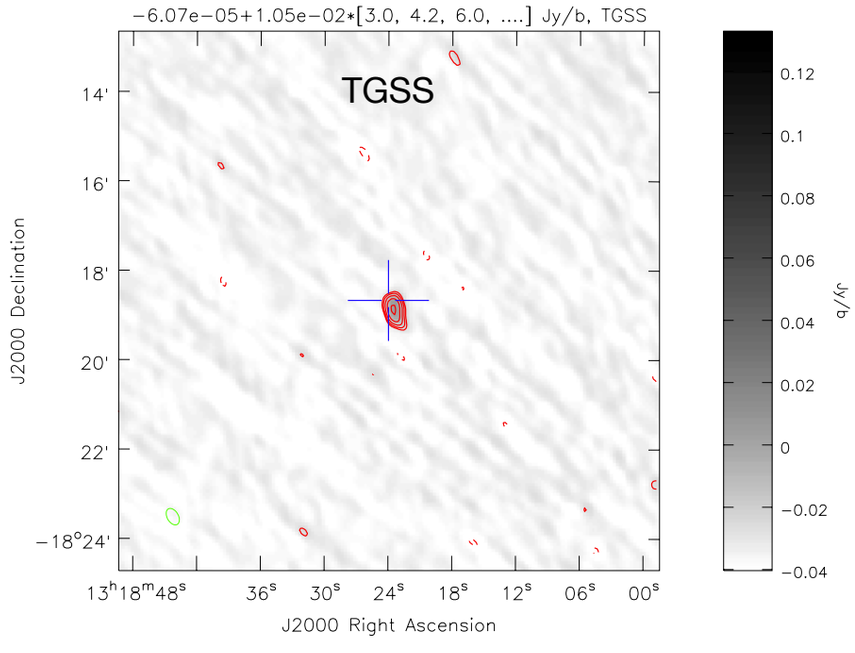
[Zarka+ 2001, 2018, Zarka 2007]

Observations

- 1994 - ~2010 : non-detections
- 2013-18 : unconfirmed detections with GMRT, upper limits with MWA



[Lecavelier+ 2013]



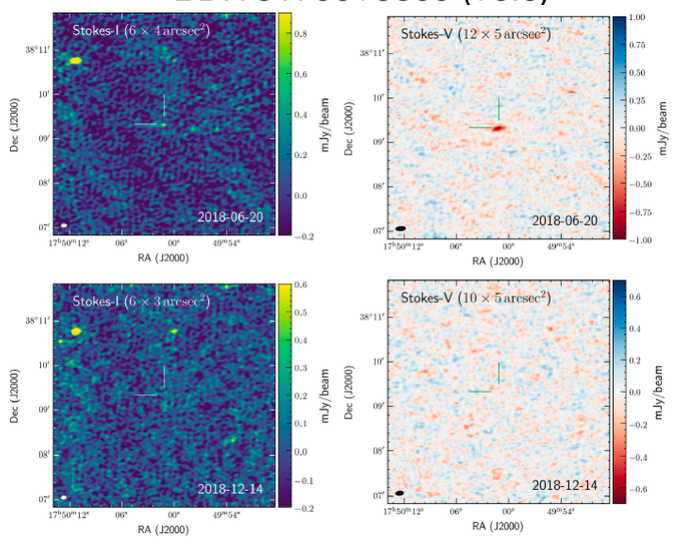
[Sirothia+ 2014]

Observations

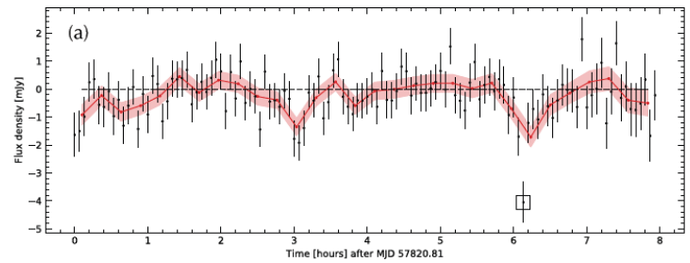
Steep progress since ~2019:

- 2020-23 : detections with LOFAR / VLA / ATCA in imaging mode of many stellar LF radio emissions, including discovery of a brown dwarf and a pulsating T dwarf

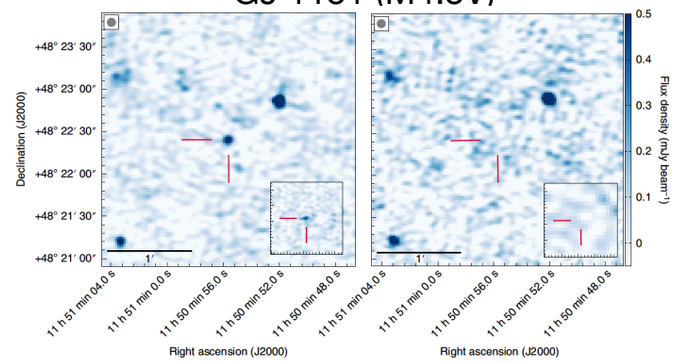
BDR J1750+3809 (T6.5)



WISEP J101905.63+652954.2 (T5.5 / T7)



GJ 1151 (M4.5V)



[Vedantham+ 2020a,b, Callingham+ 2021a, 2023]

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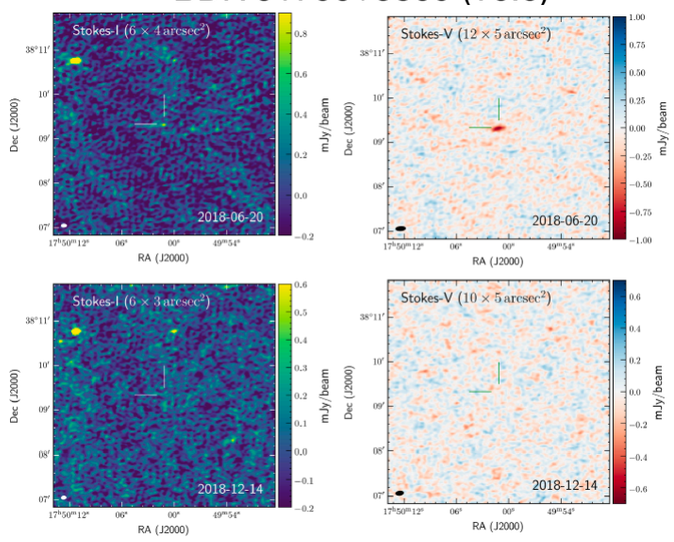
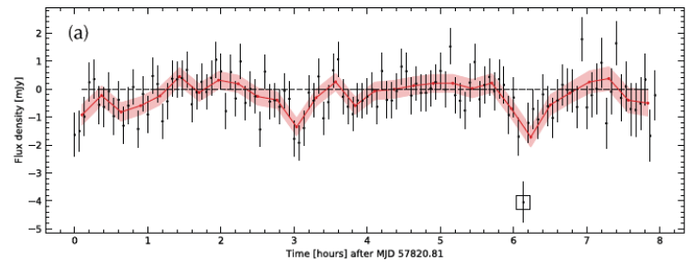
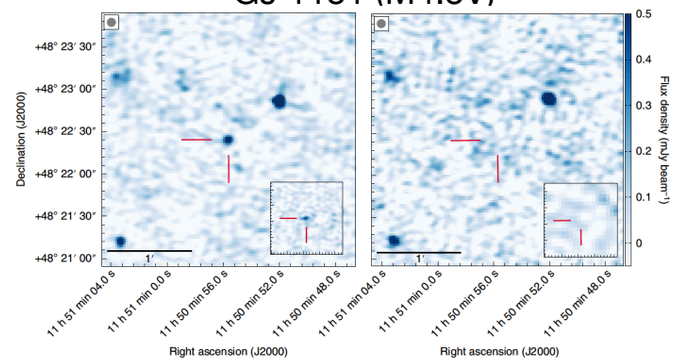


WISEP J101905.63+652954.2 (T5.5 / T7)



GJ 1151 (M4.5V)



[Vedantham+ 2020a,b, Callingham+ 2021a, 2023]

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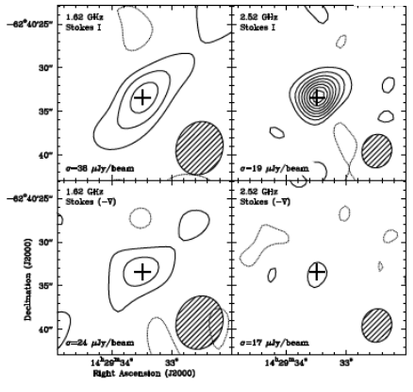

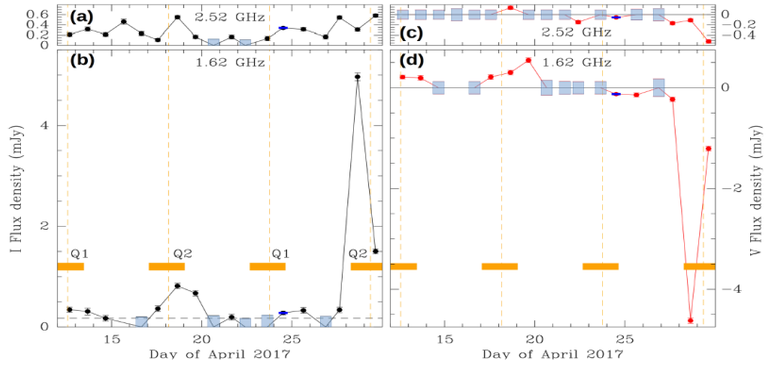

[Perez-Torres+ 2021]

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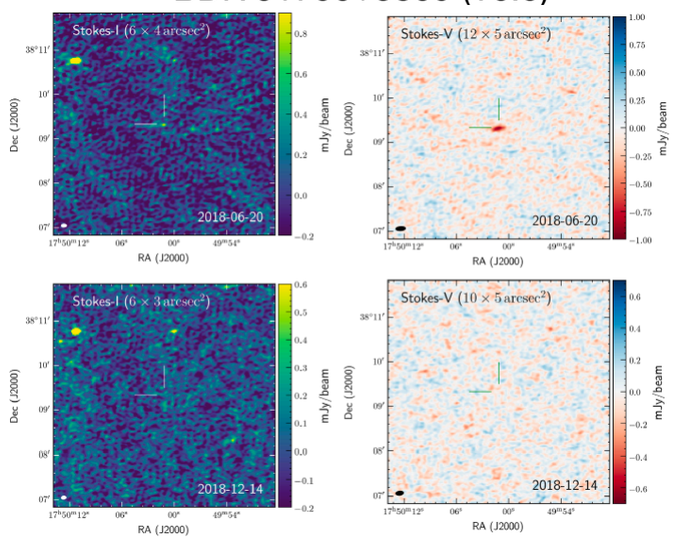

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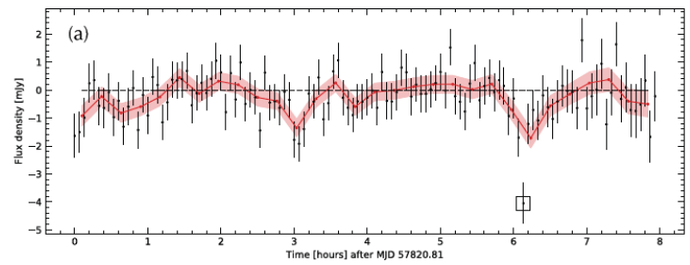

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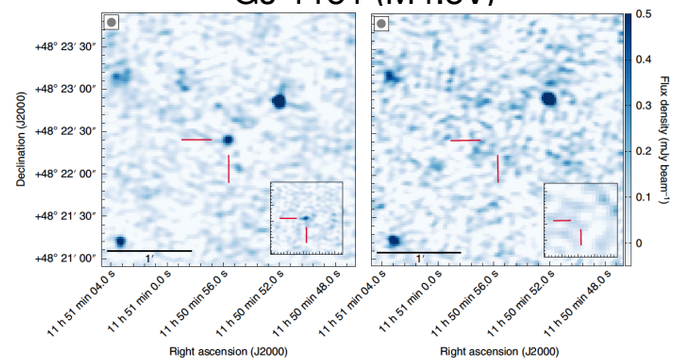

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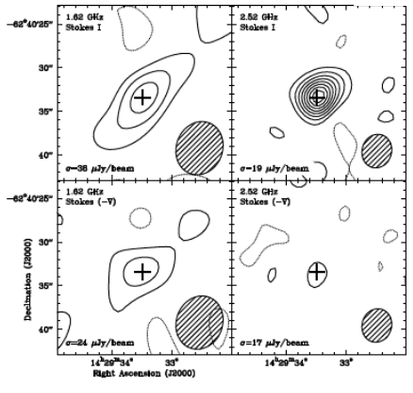

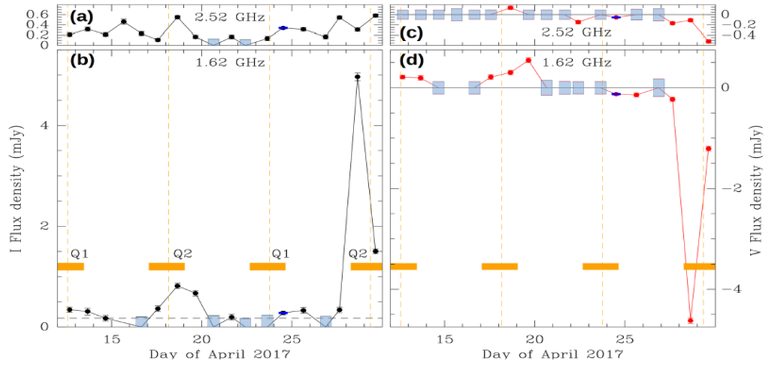

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- Limitations of imaging : → limited sensitivity to transients
  → low information on unresolved sources

Observations

- 2019-24 : detections with LOFAR / VLA / ASKAP / GMRT of radio bursts in the time-frequency (t-f) plane, via dynamic spectra synthesized by Σ interferometric visibilities at the phase center

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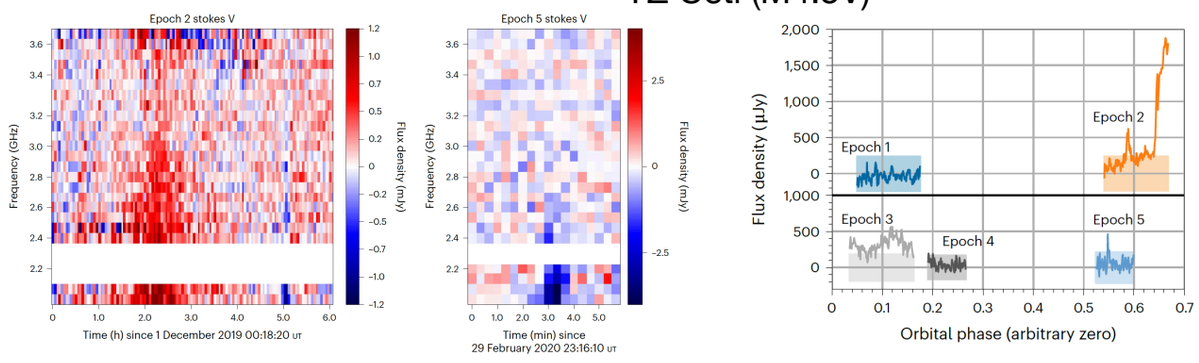

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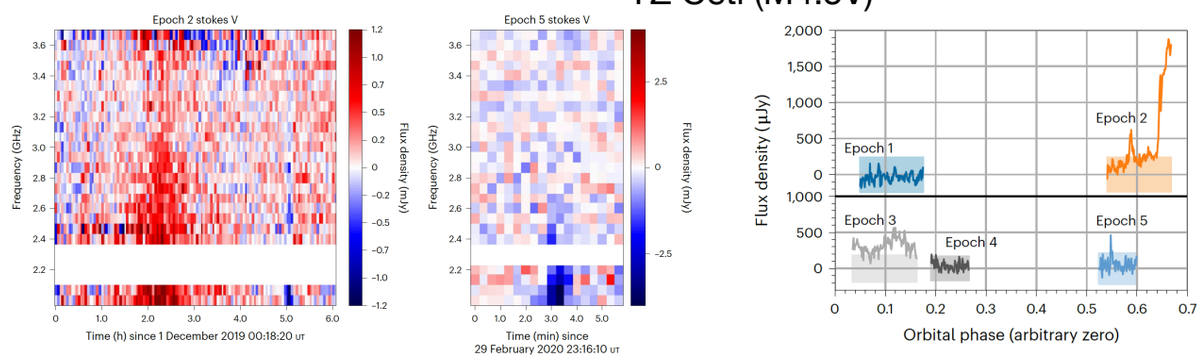

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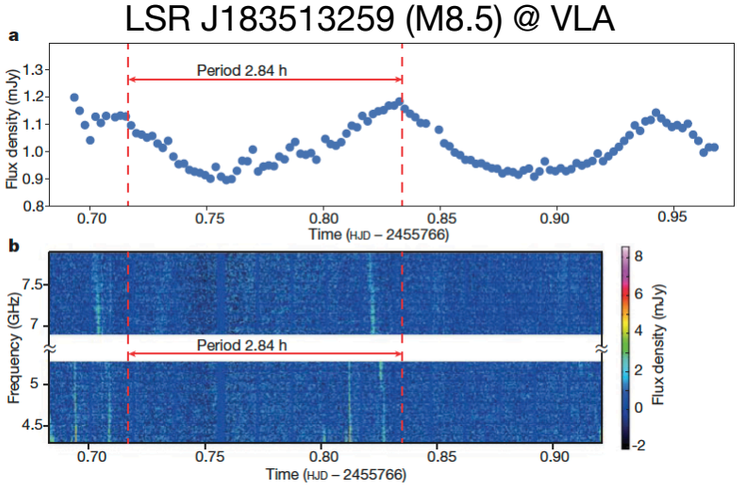

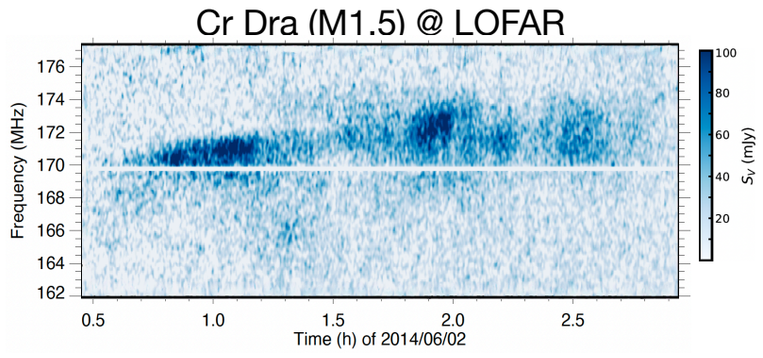

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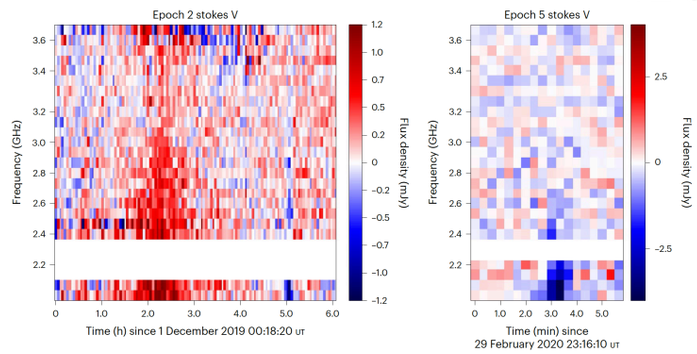

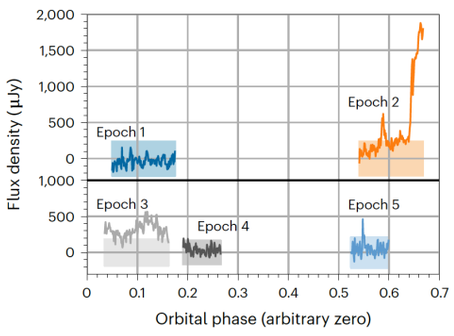

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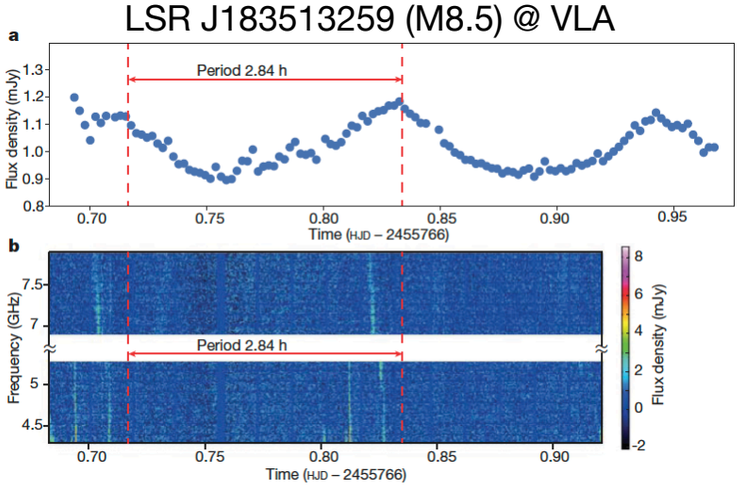

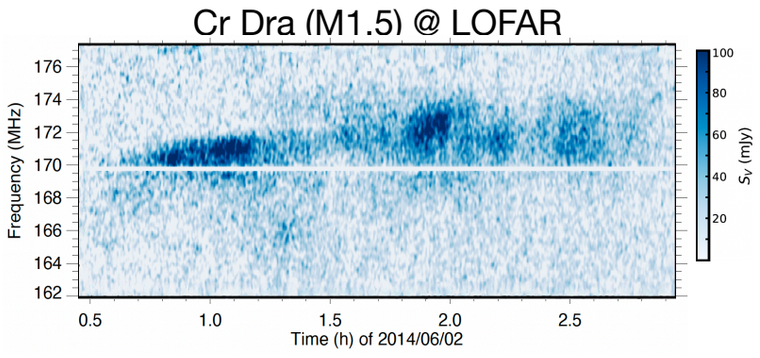

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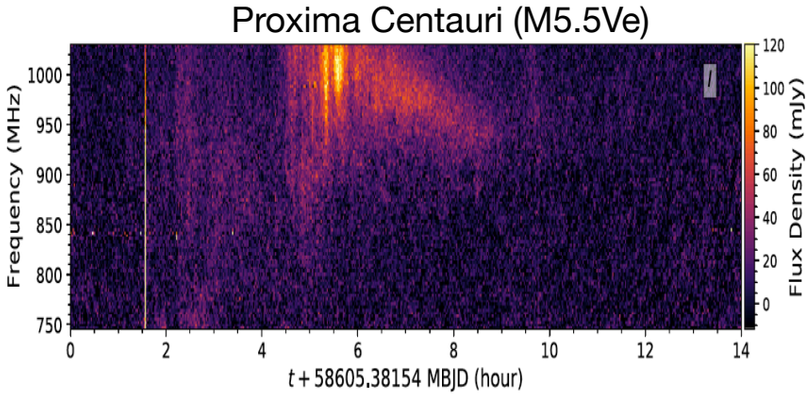

→ first stellar Type IV bursts

[Zic+ 2020, Mohan+ 2024]

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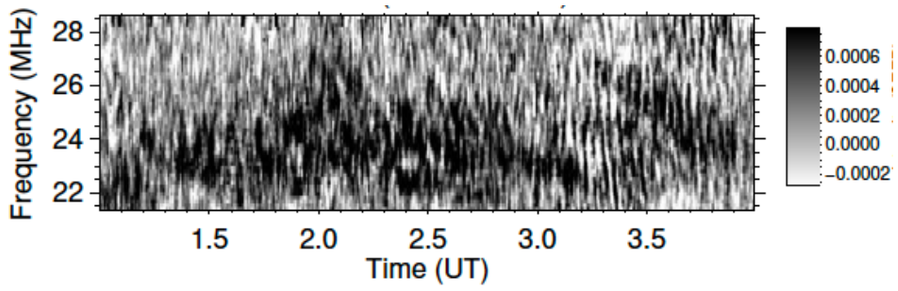

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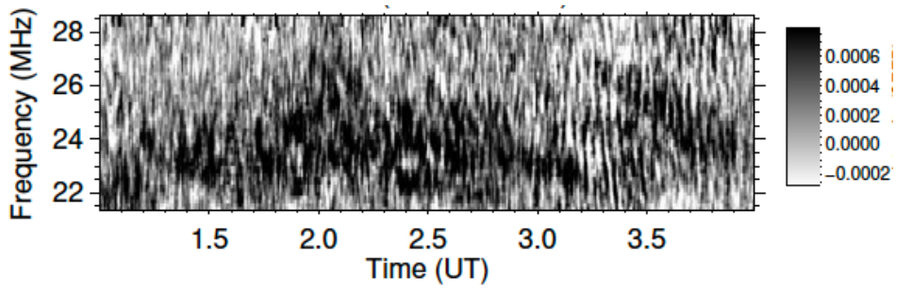

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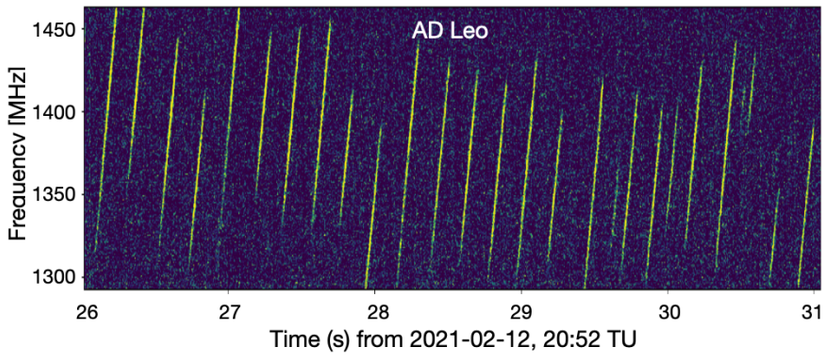

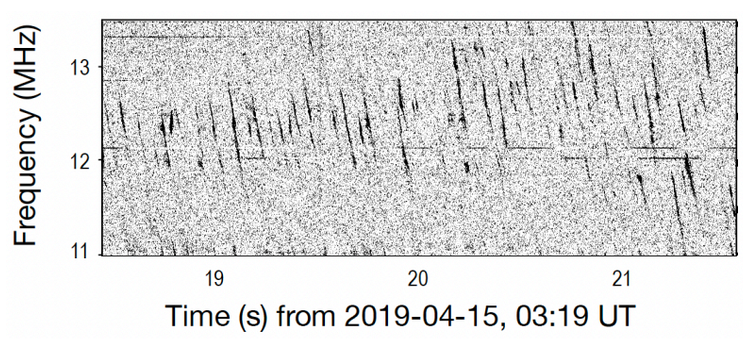

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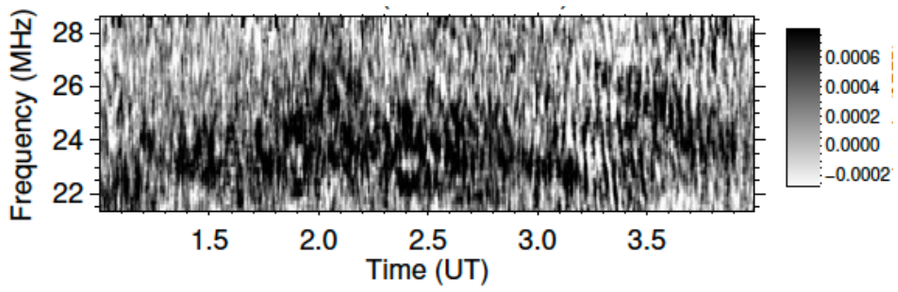

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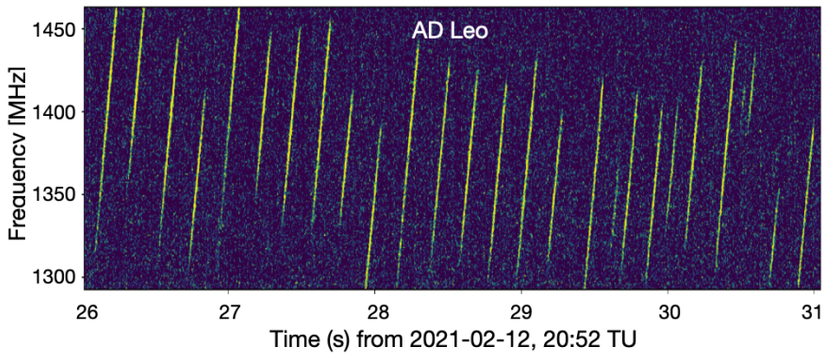

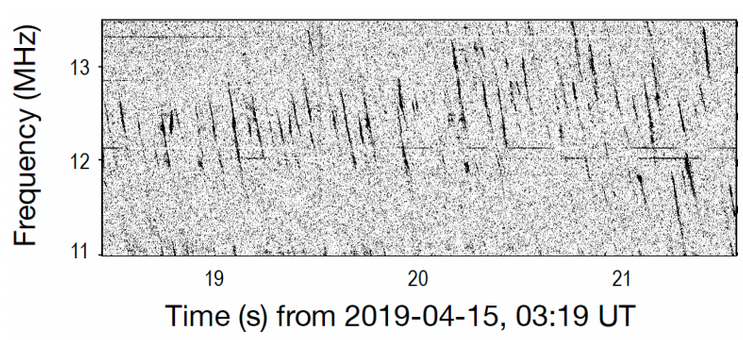

[Zhang+ 2023, Zarka+ 2025]

- Limitations of t-f studies : → limited sensitivity of beamformed mode
  → low efficiency of dynamic spectra at phase center

Recent Observations

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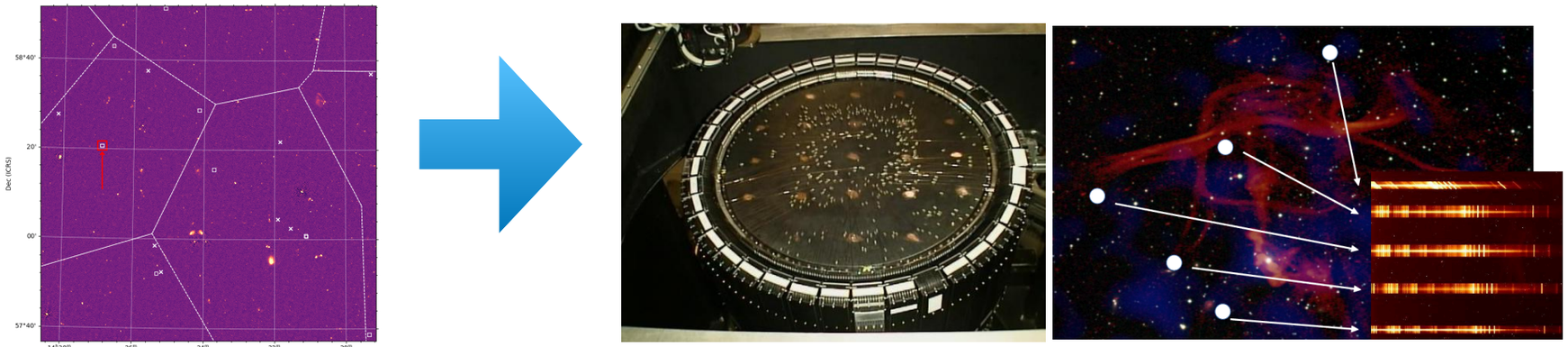

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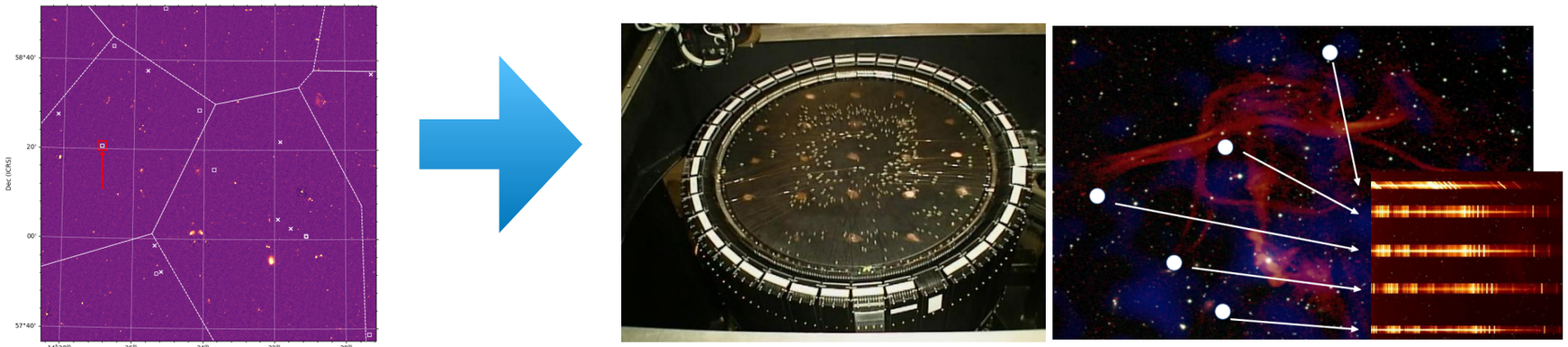
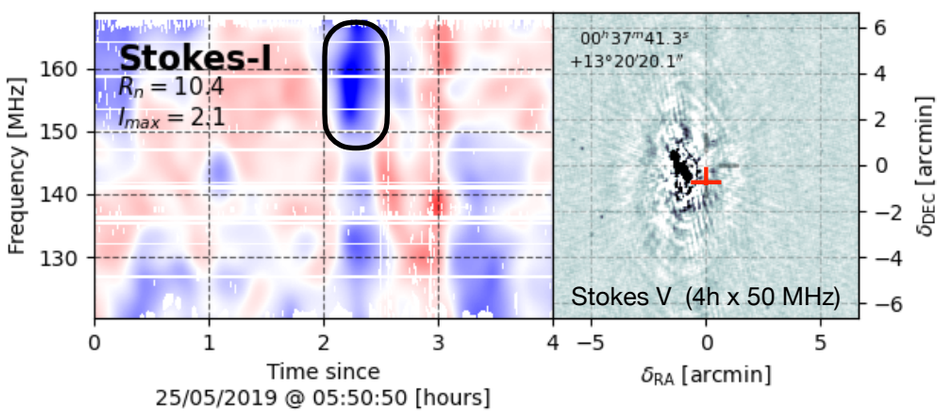
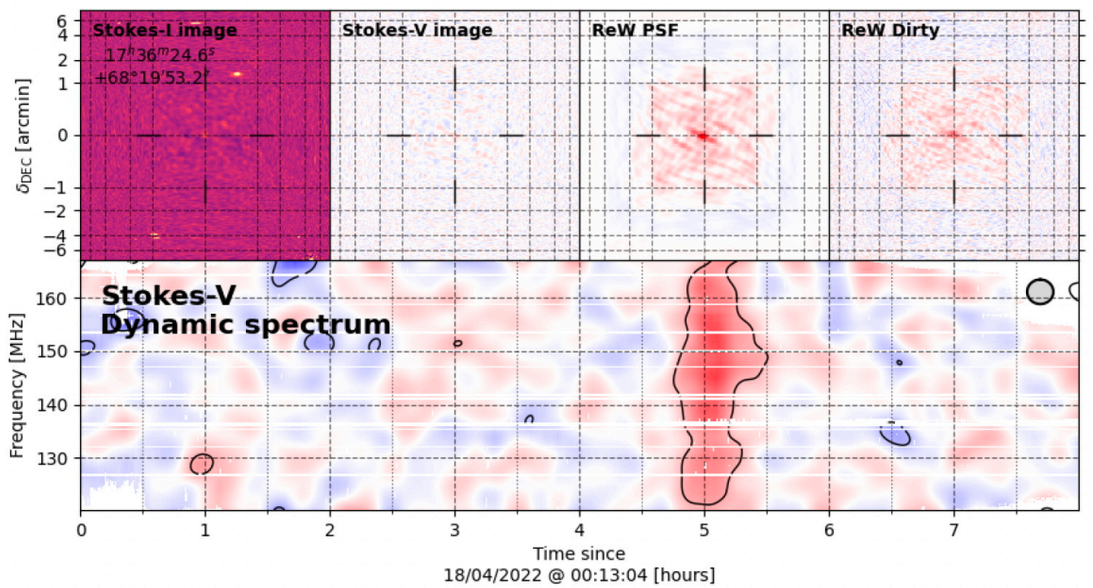


- Input catalog of exoplanets, stars, dwarf, active, Gaia (~a few 10^5 objects)
- Confirmation via re-imaging of residual visibilities restricted to the t-f of the burst



⇒ spurious



[Tasse+ 2026]

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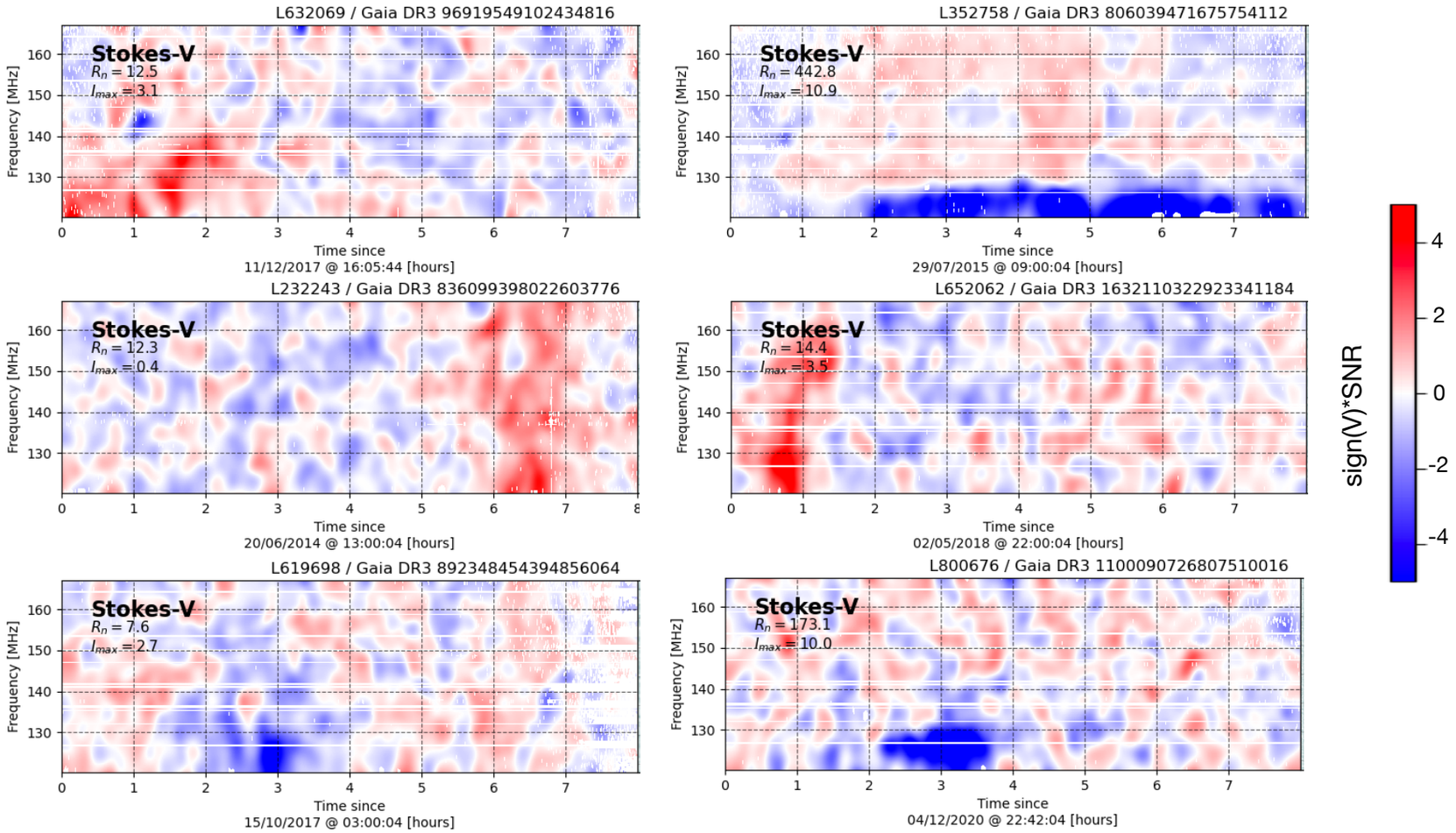
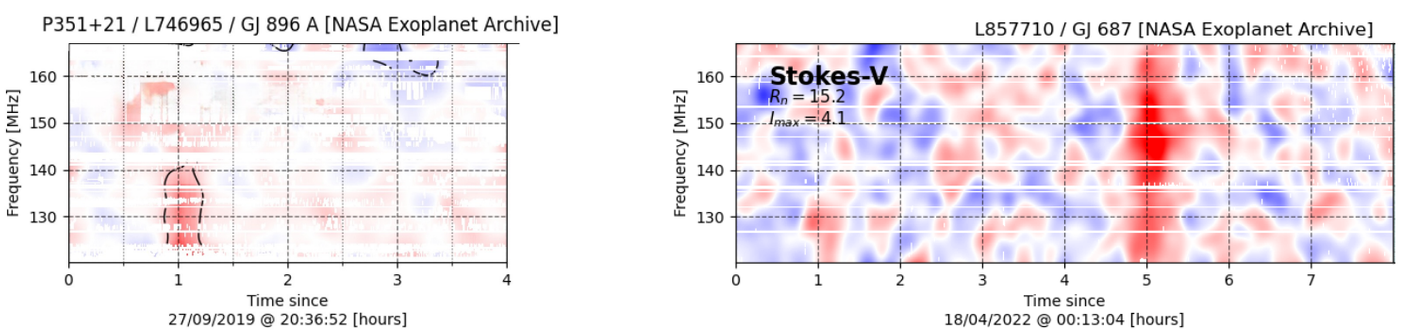
RIMS @ LOFAR

- Detection of 27 stellar LF radio bursts in LoTSS/DR2 including 2 from exoplanet hosting systemsmany arch-like, SPI or exoplanetary ?

Stars



Star-Exoplanet systems



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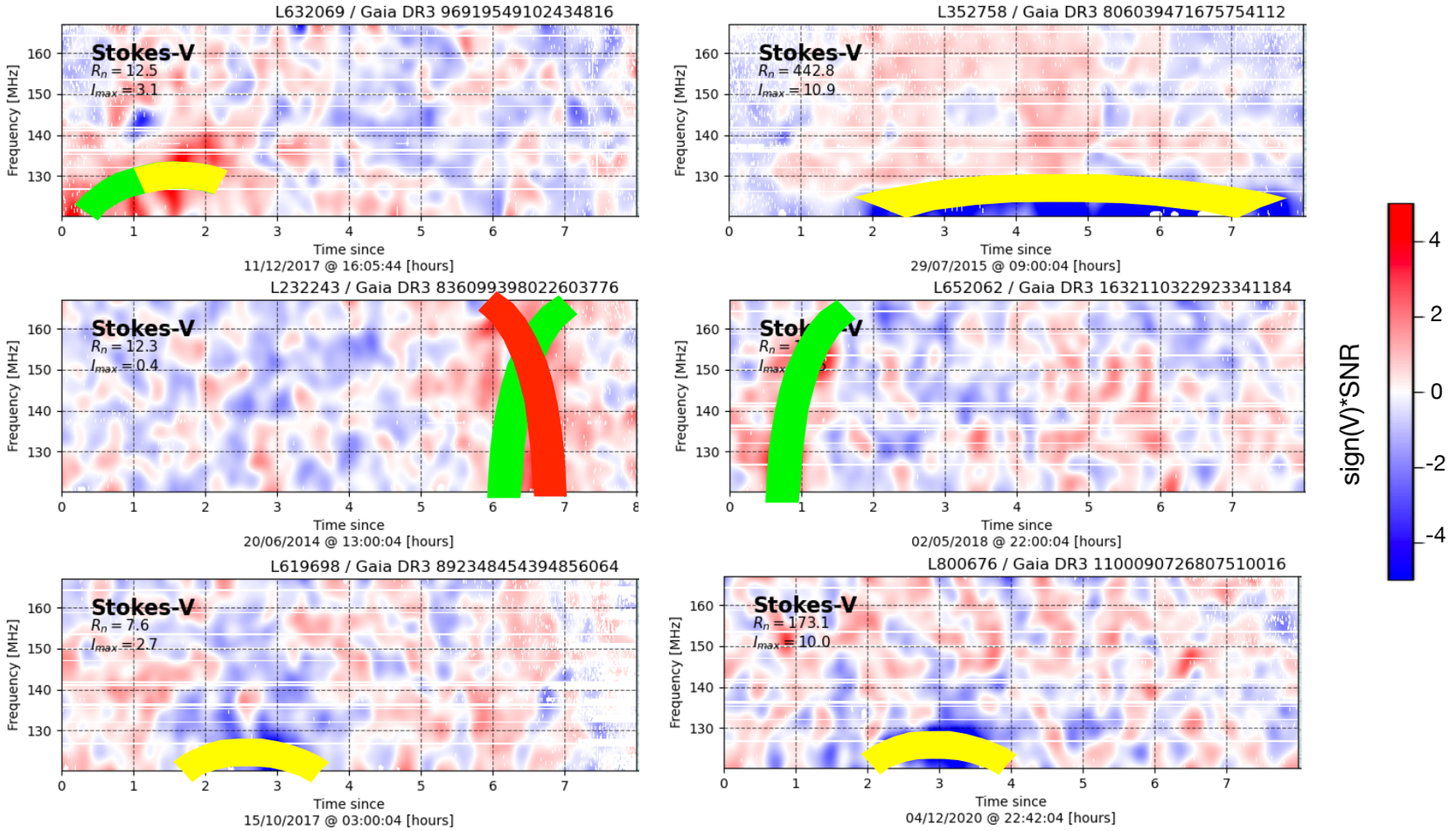

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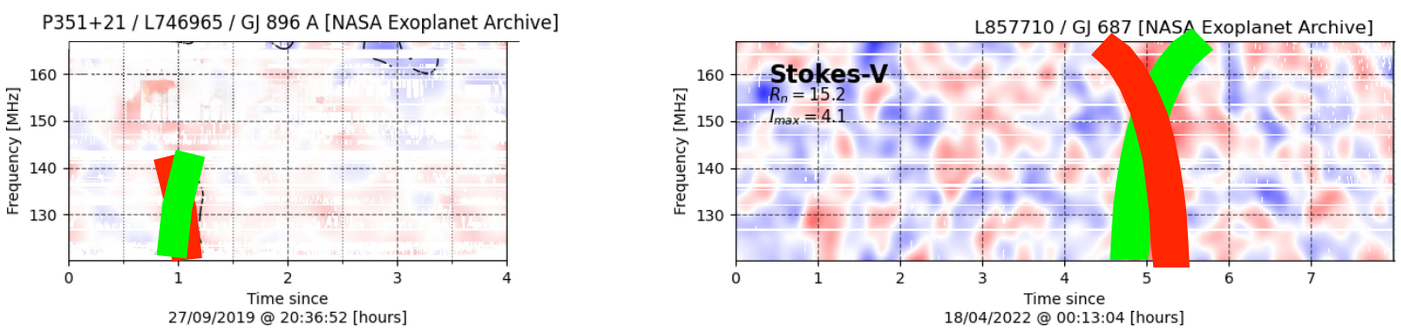

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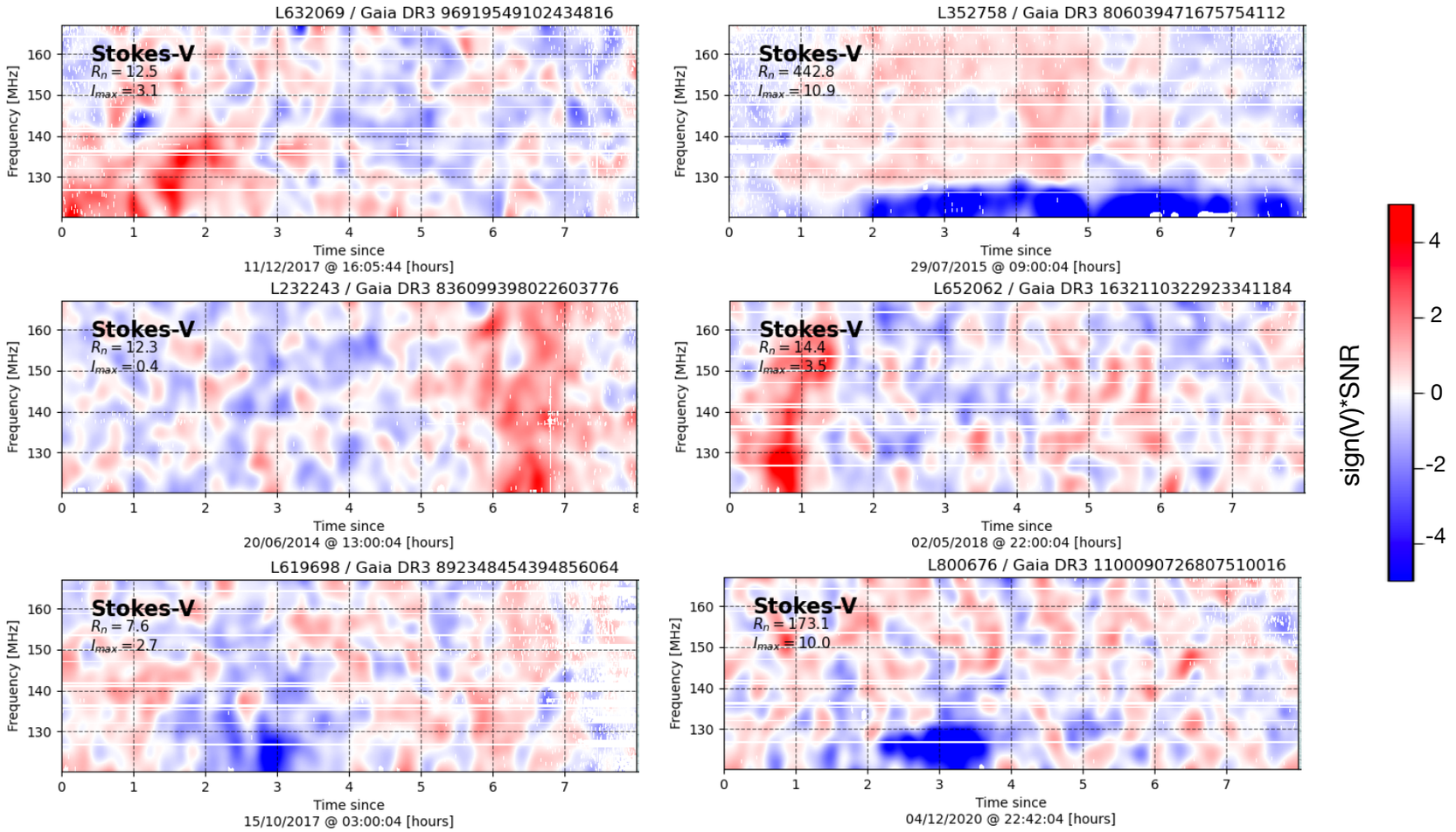

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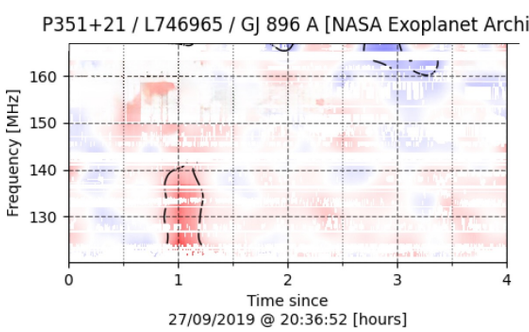
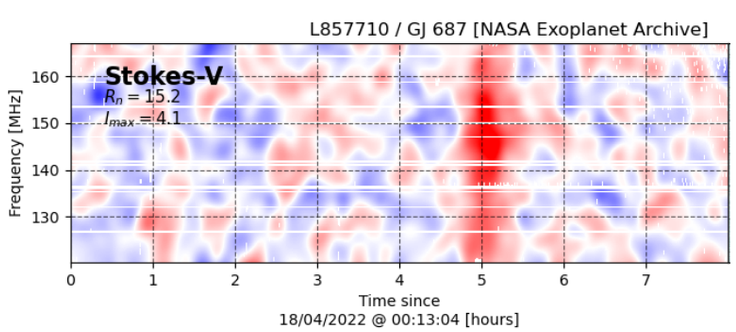
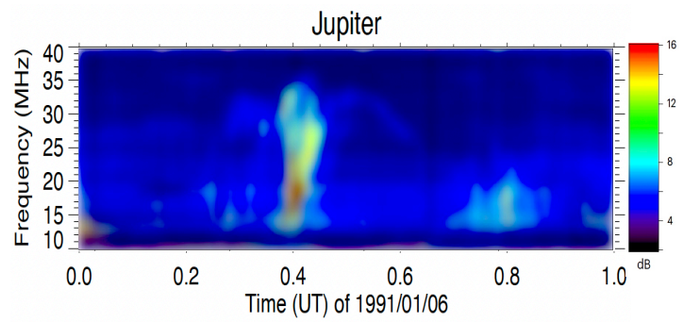
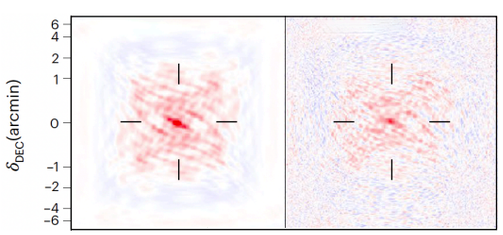




[Tasse+ 2026]

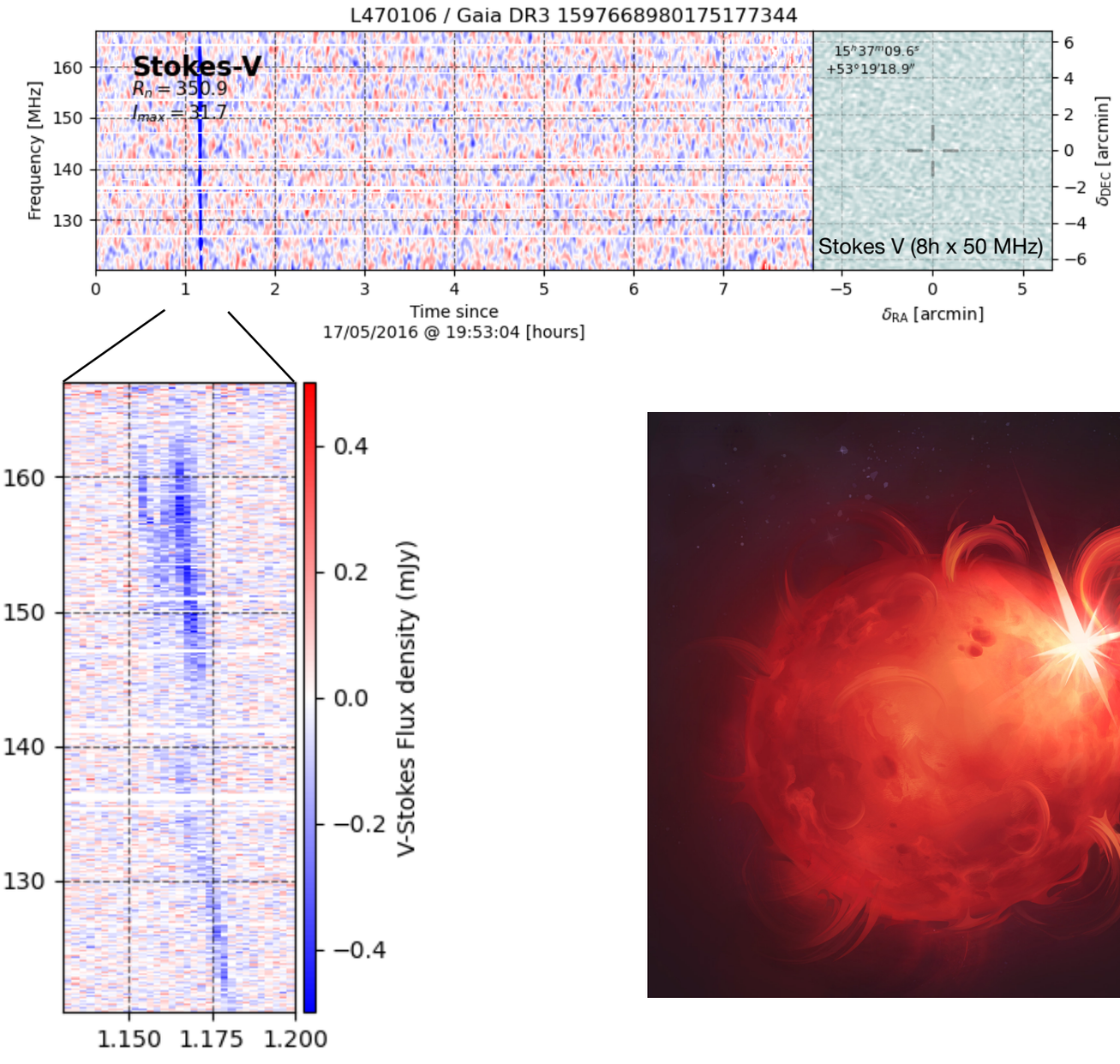
- SPI with hot Neptune ?
- First exoplanetary magnetospheric emission ?





RIMS @ LOFAR

- Detection of the first stellar (superstrong) Type II burst
  → potentially harmful to an exoplanet's atmosphere



- + detection of the first stellar Type III burst

[Callingham+ 2025, Konijn+ in prep.]

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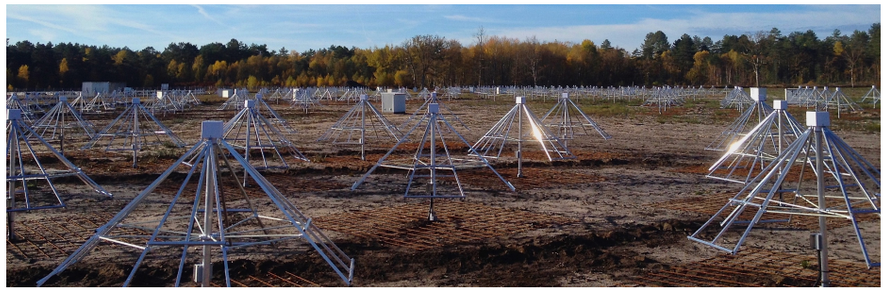
- Detection of 14 many LF bursts from star-planet systems, including one with Jupiter-like t-f structure



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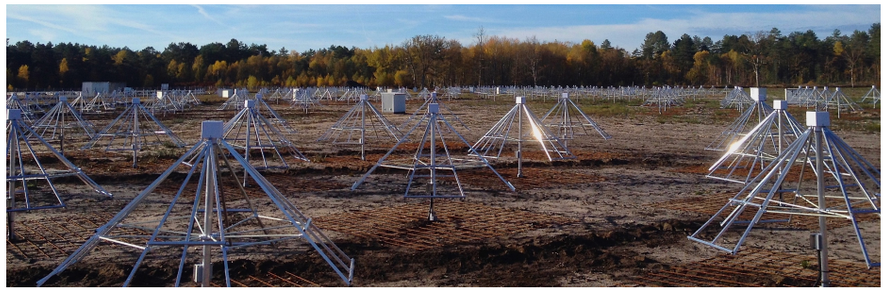

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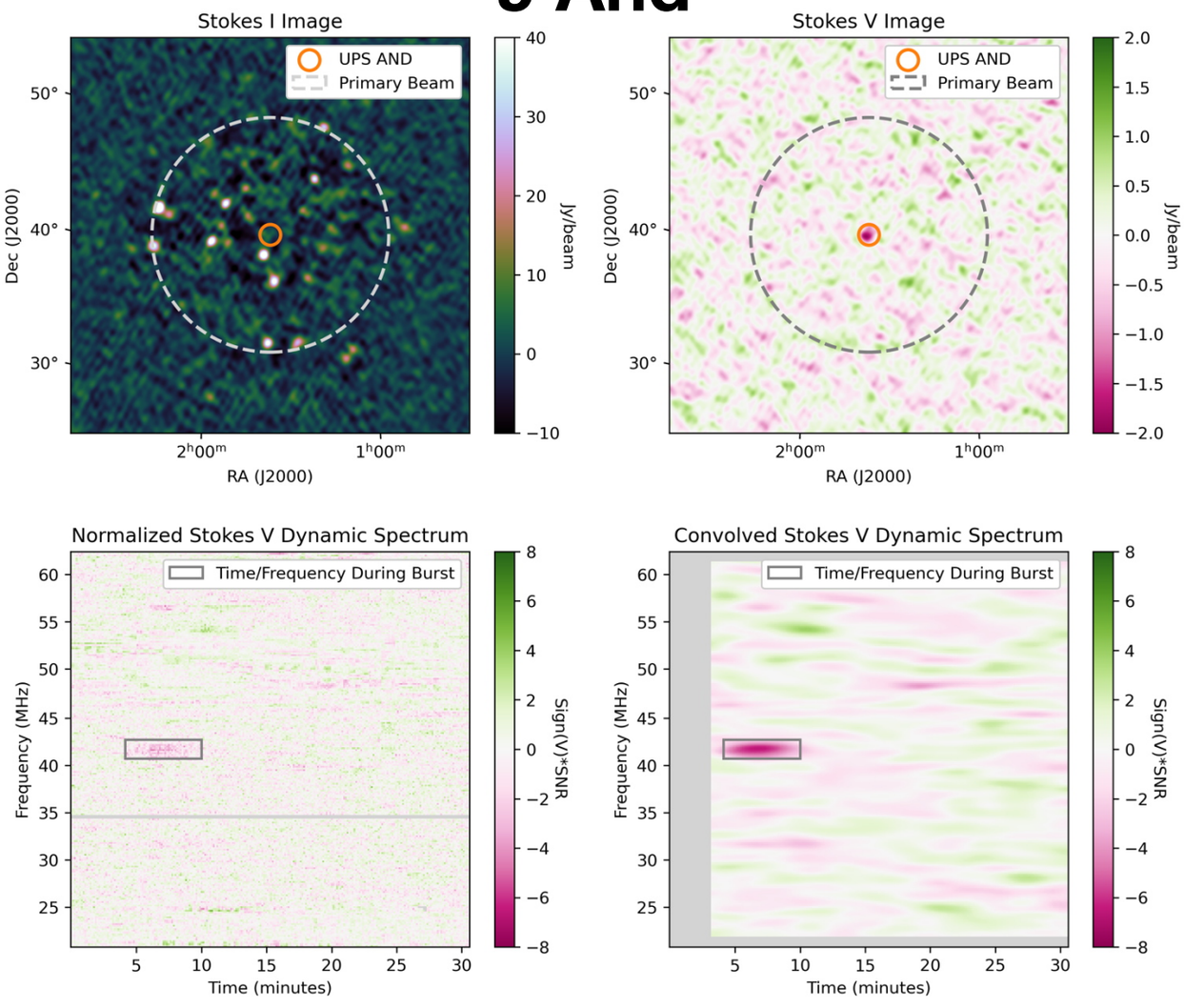

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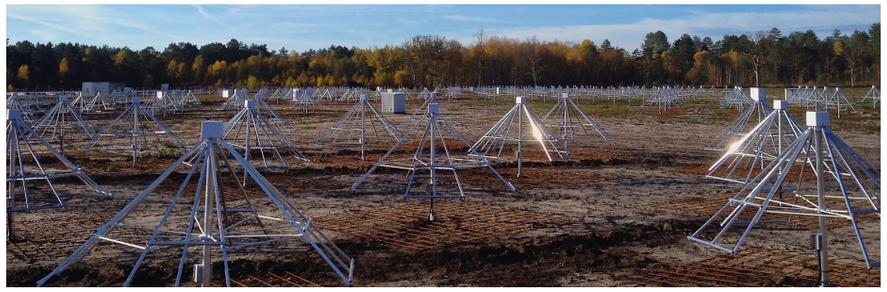

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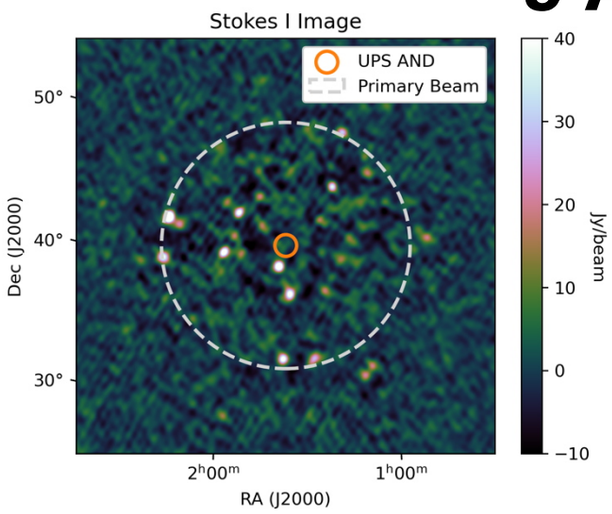
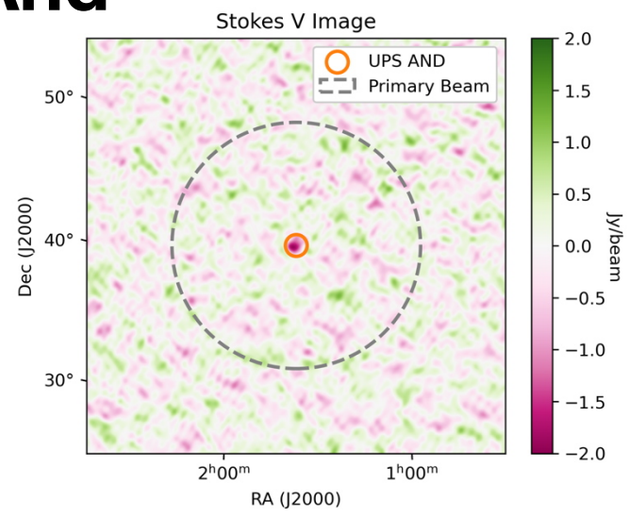
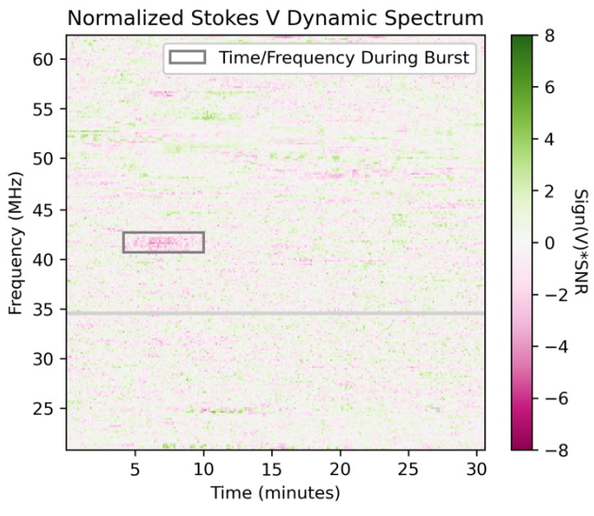
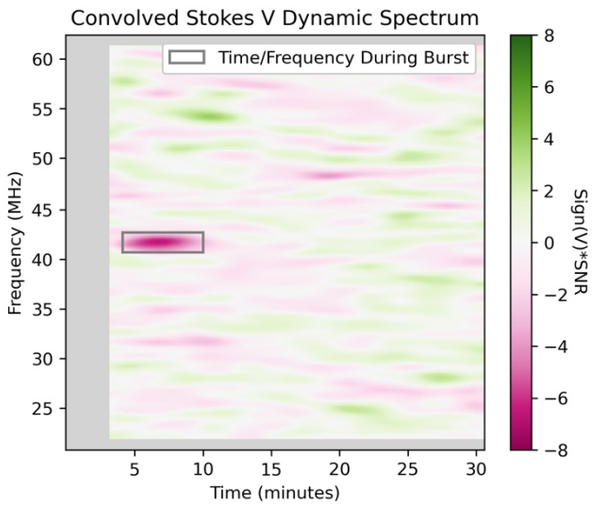
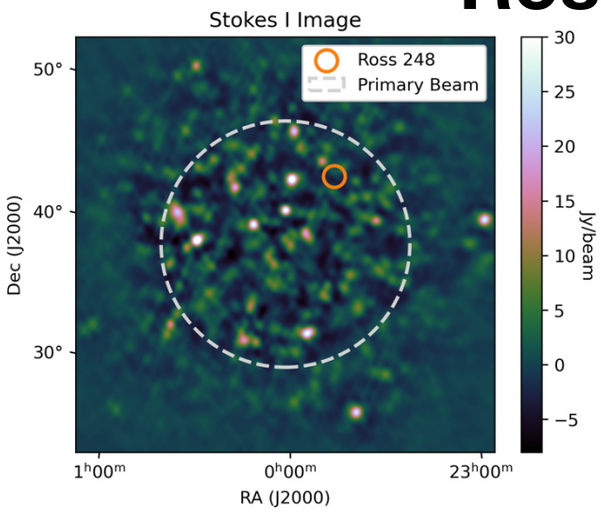


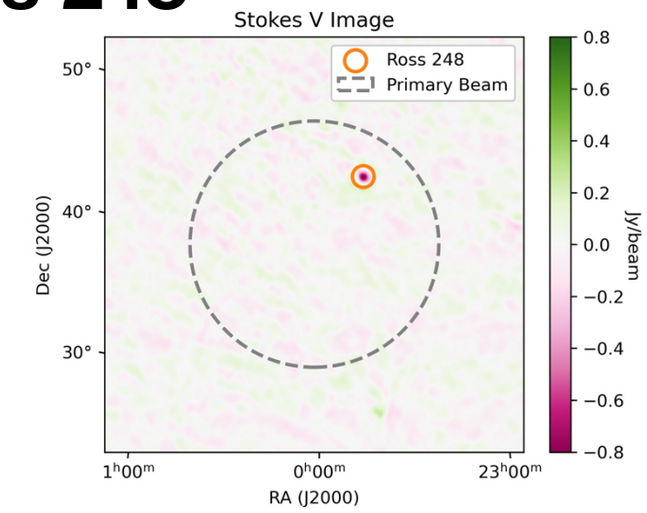


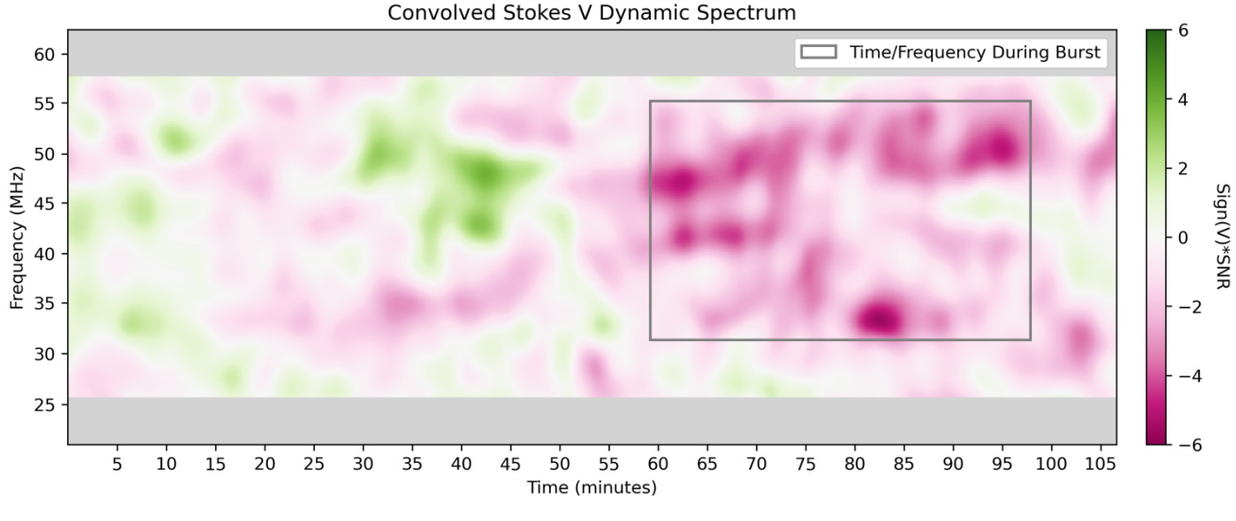




Ross 248



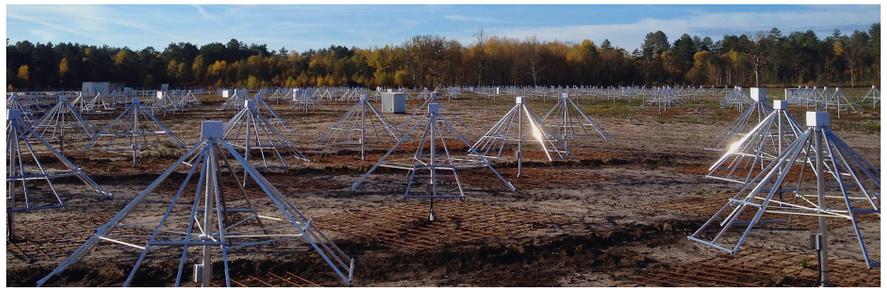




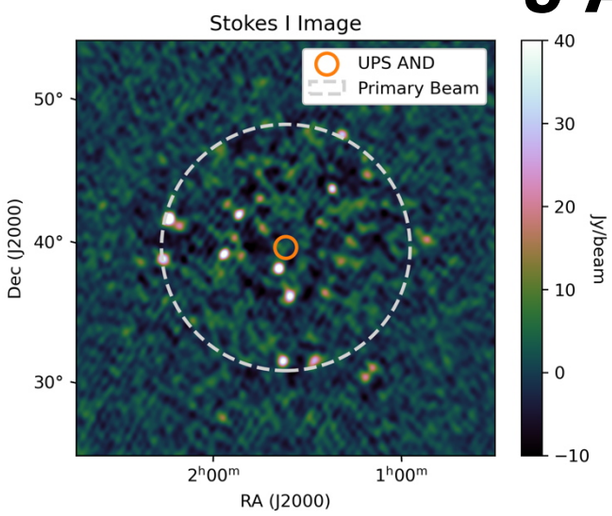
[Zhang+ 2025 ; Zhang+ in prep.]

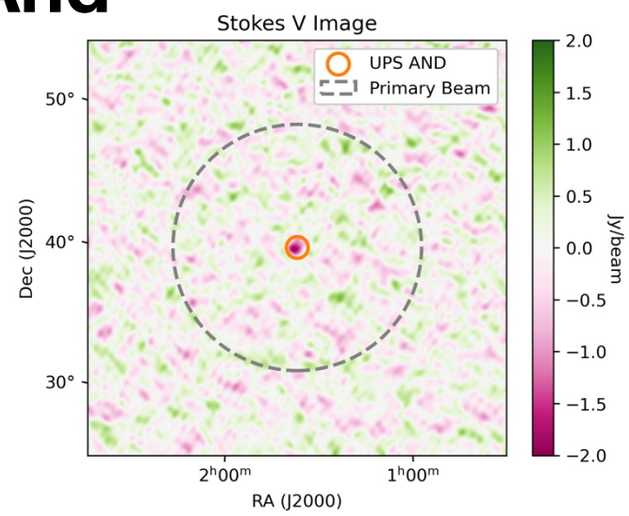
RIMS @ NenuFAR

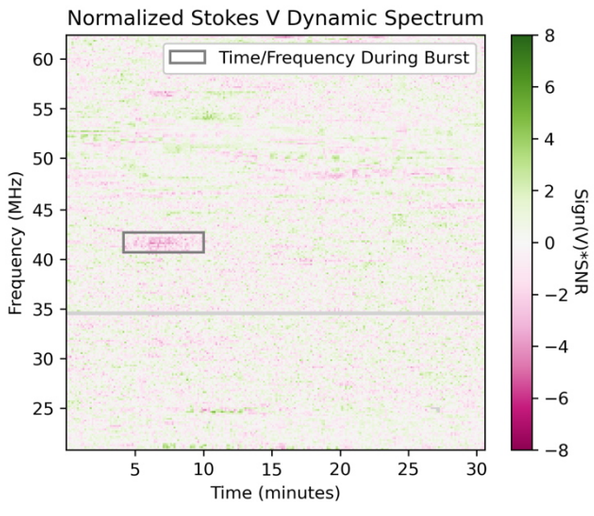
- Detection of 14 many LF bursts from star-planet systems, including one with Jupiter-like t-f structure

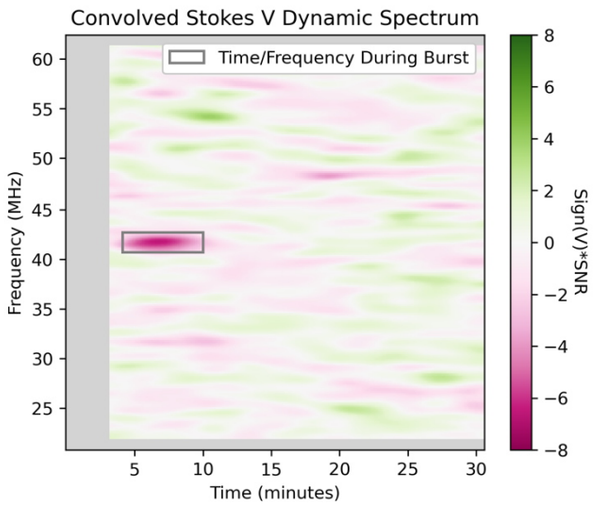


υ And

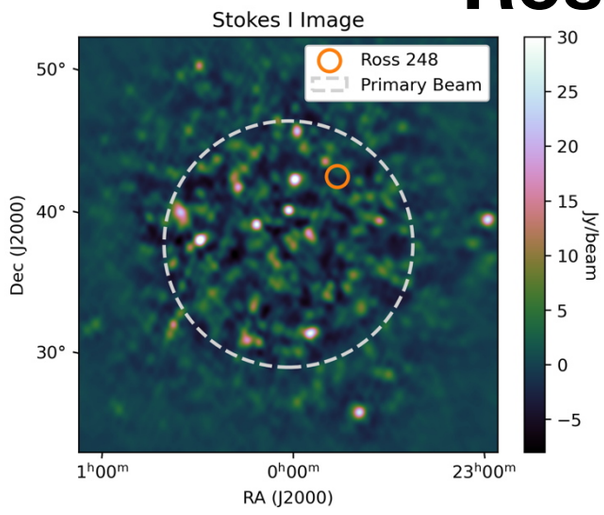


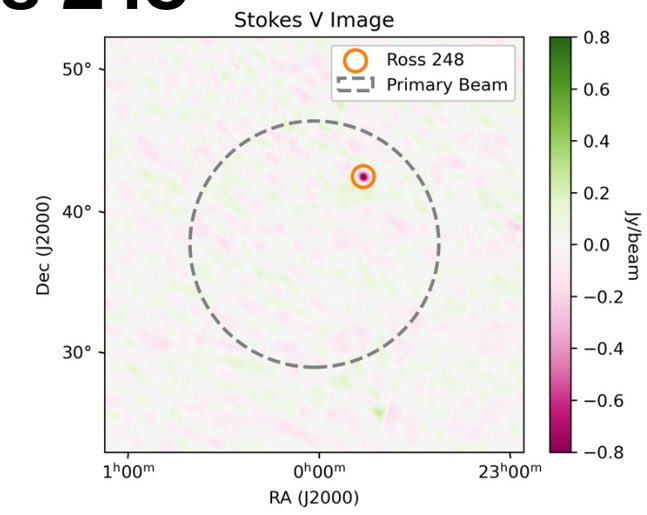


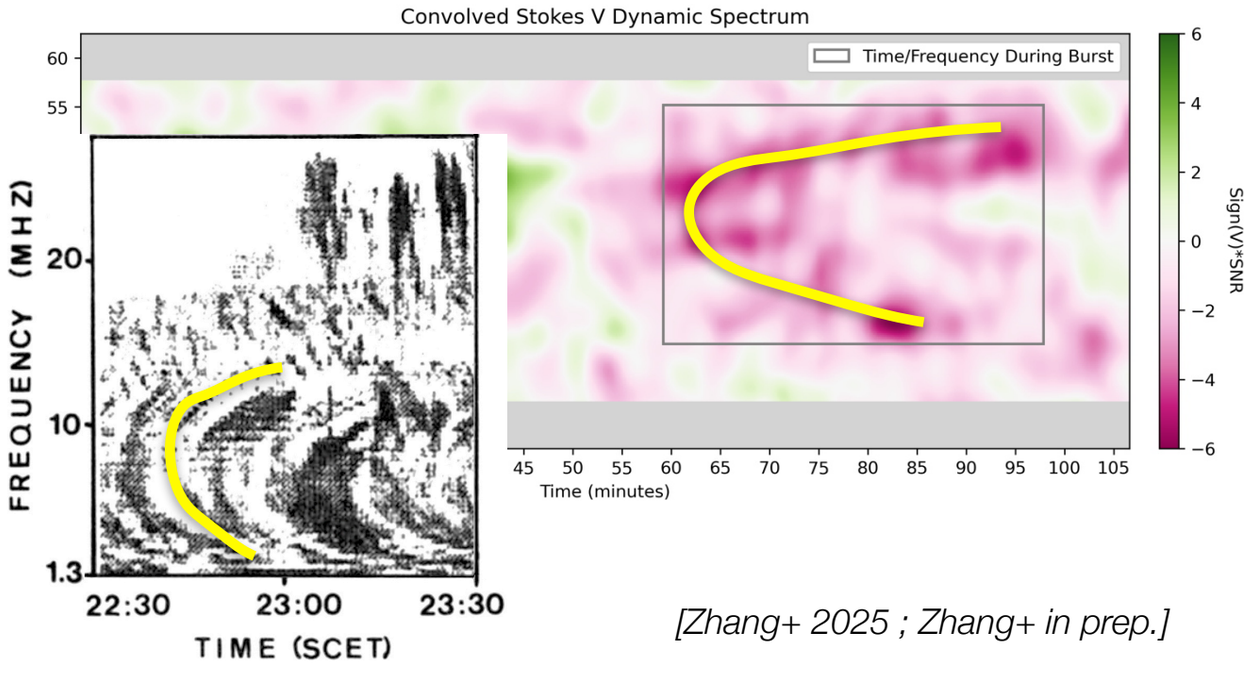




Ross 248

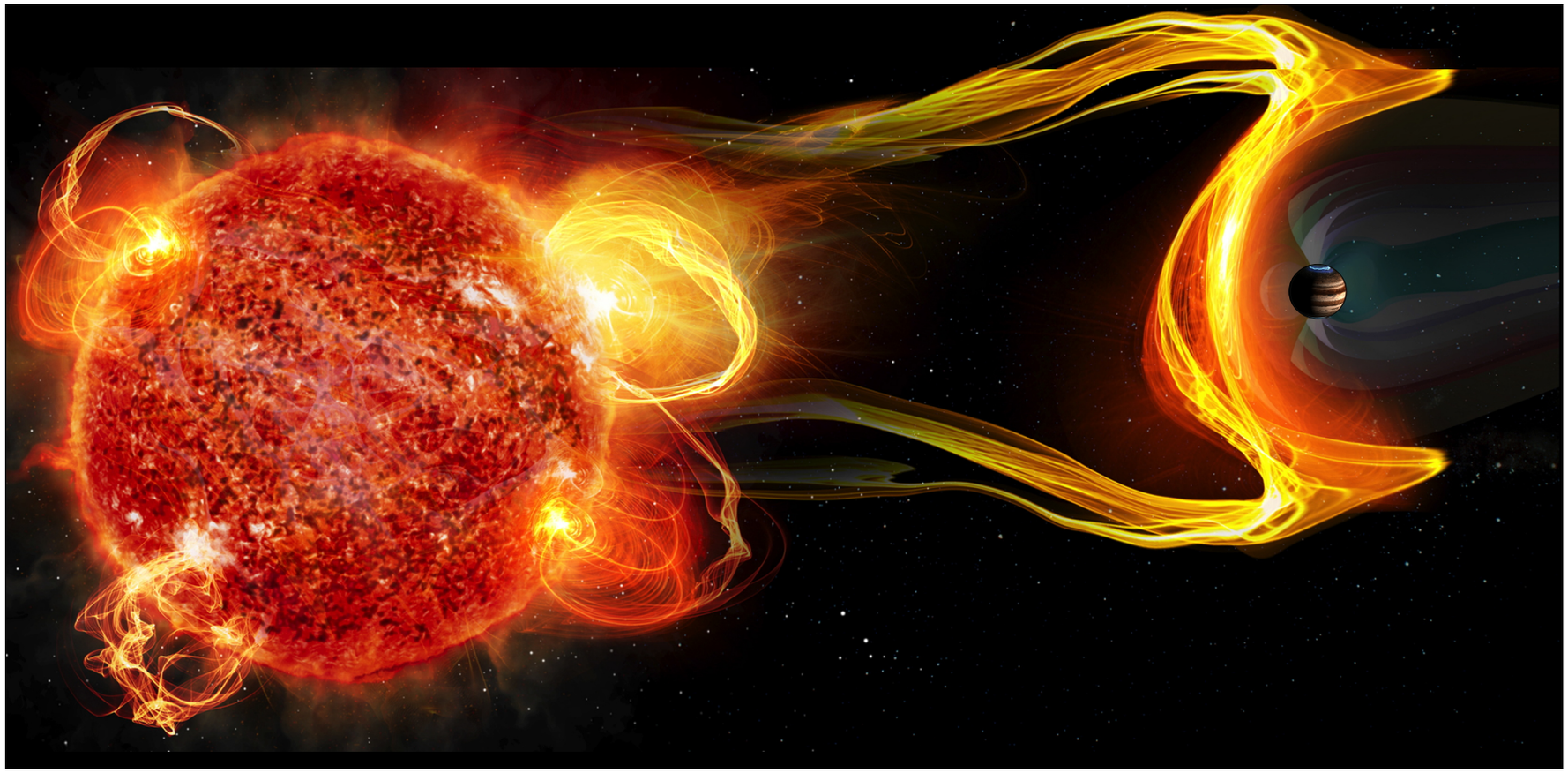






[Zhang+ 2025 ; Zhang+ in prep.]

Origin of the signals (star / SPI / exoplanet)



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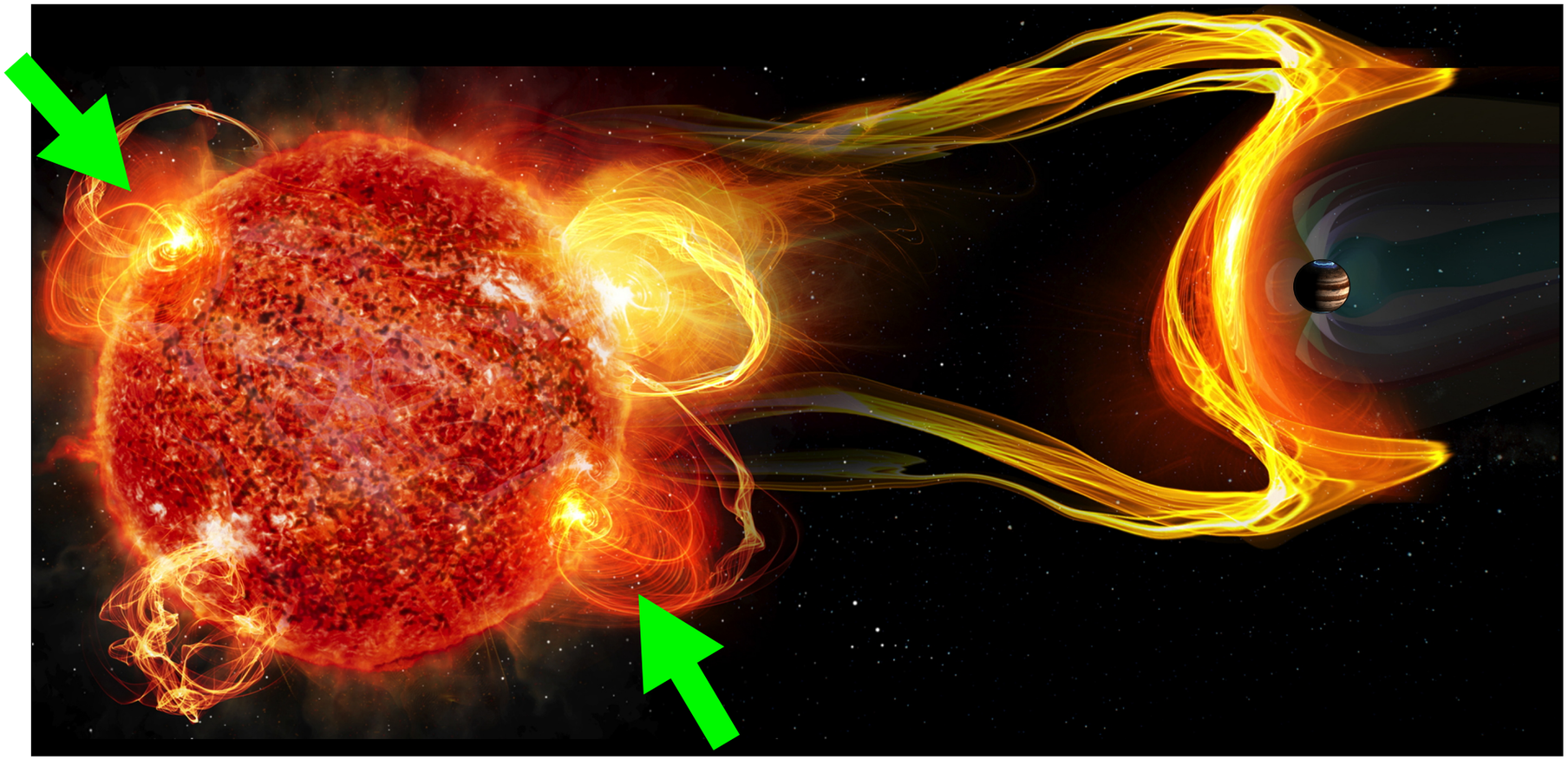

Origin of the signals (star / SPI / exoplanet)

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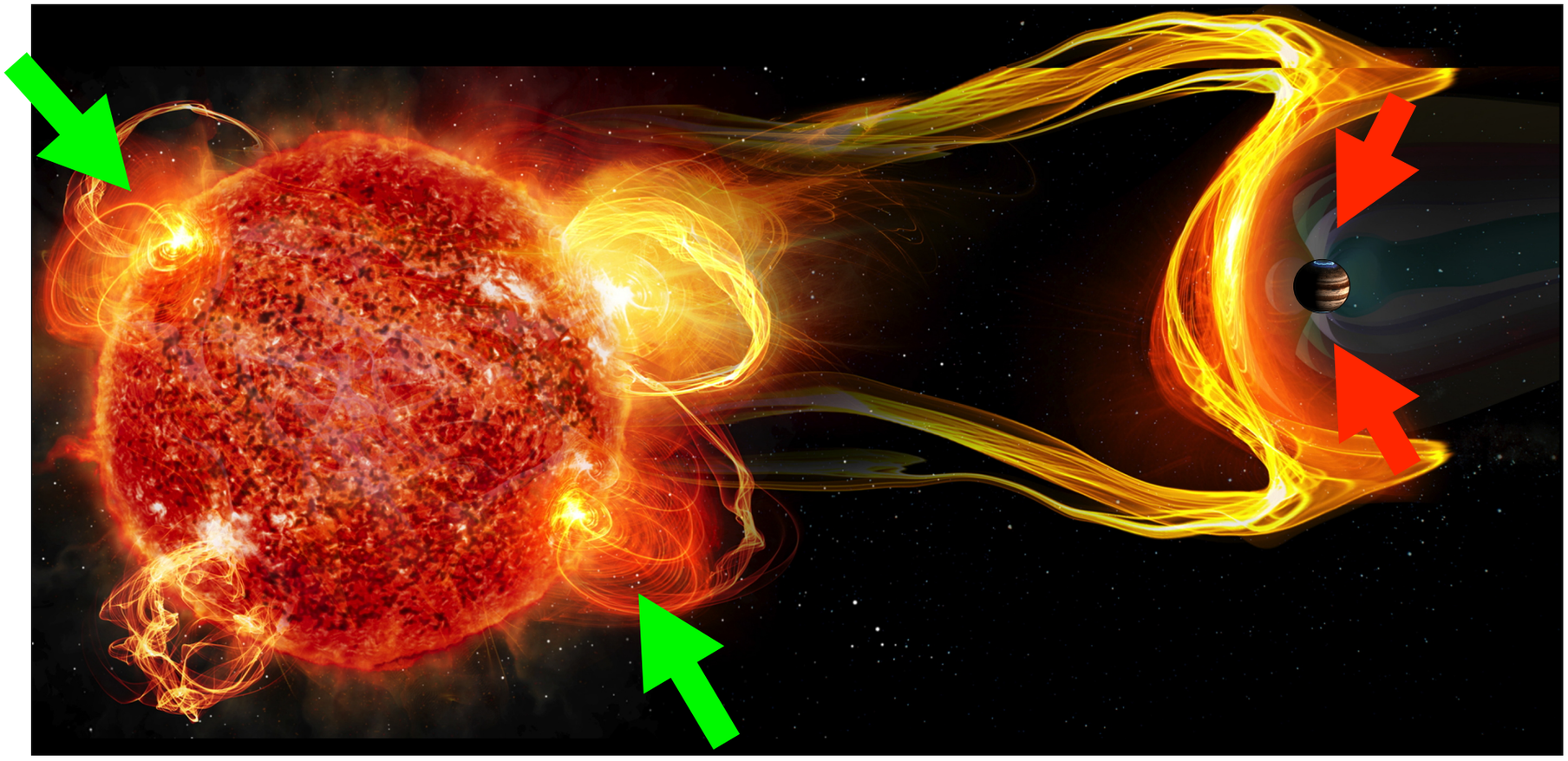

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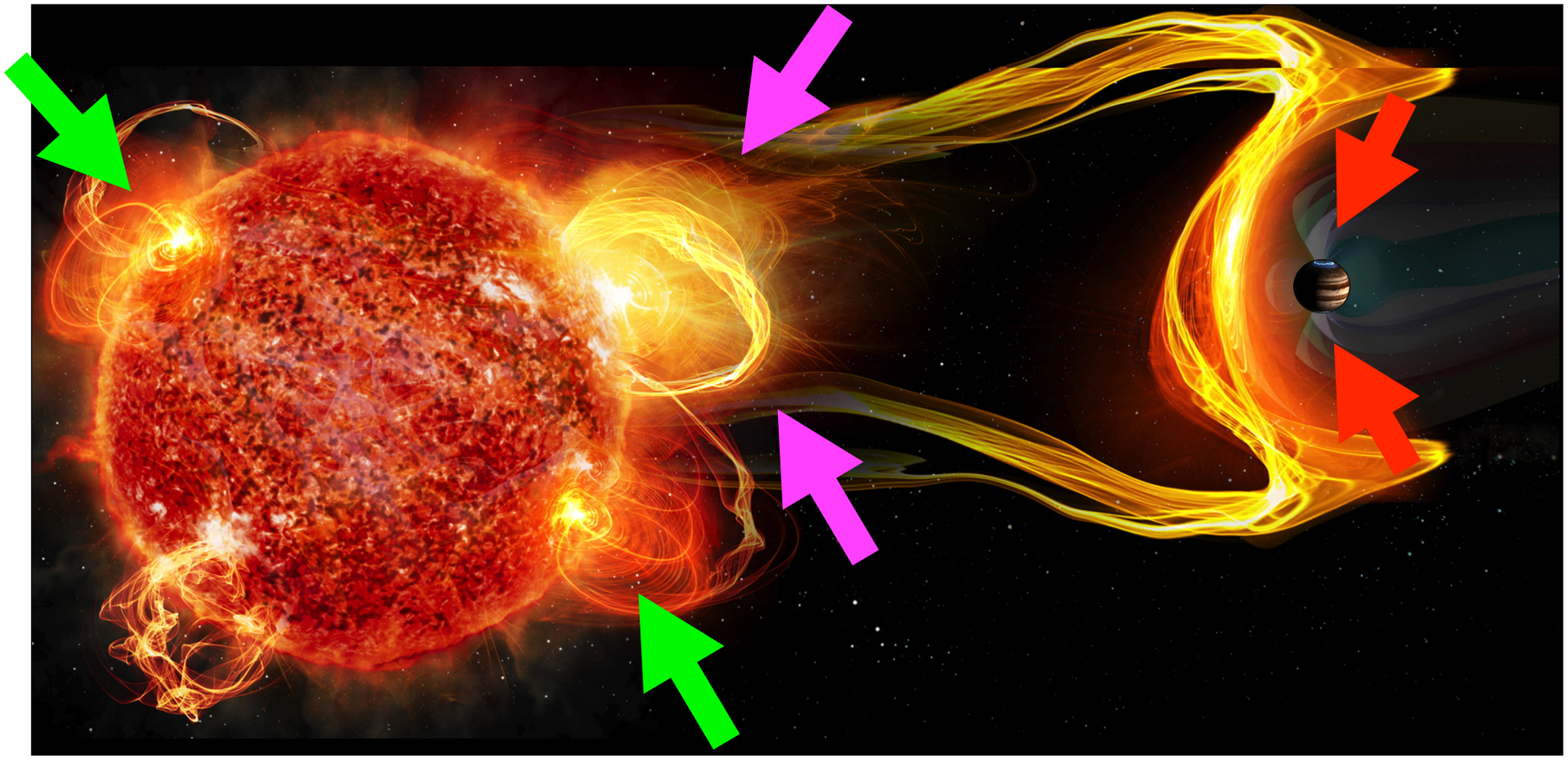

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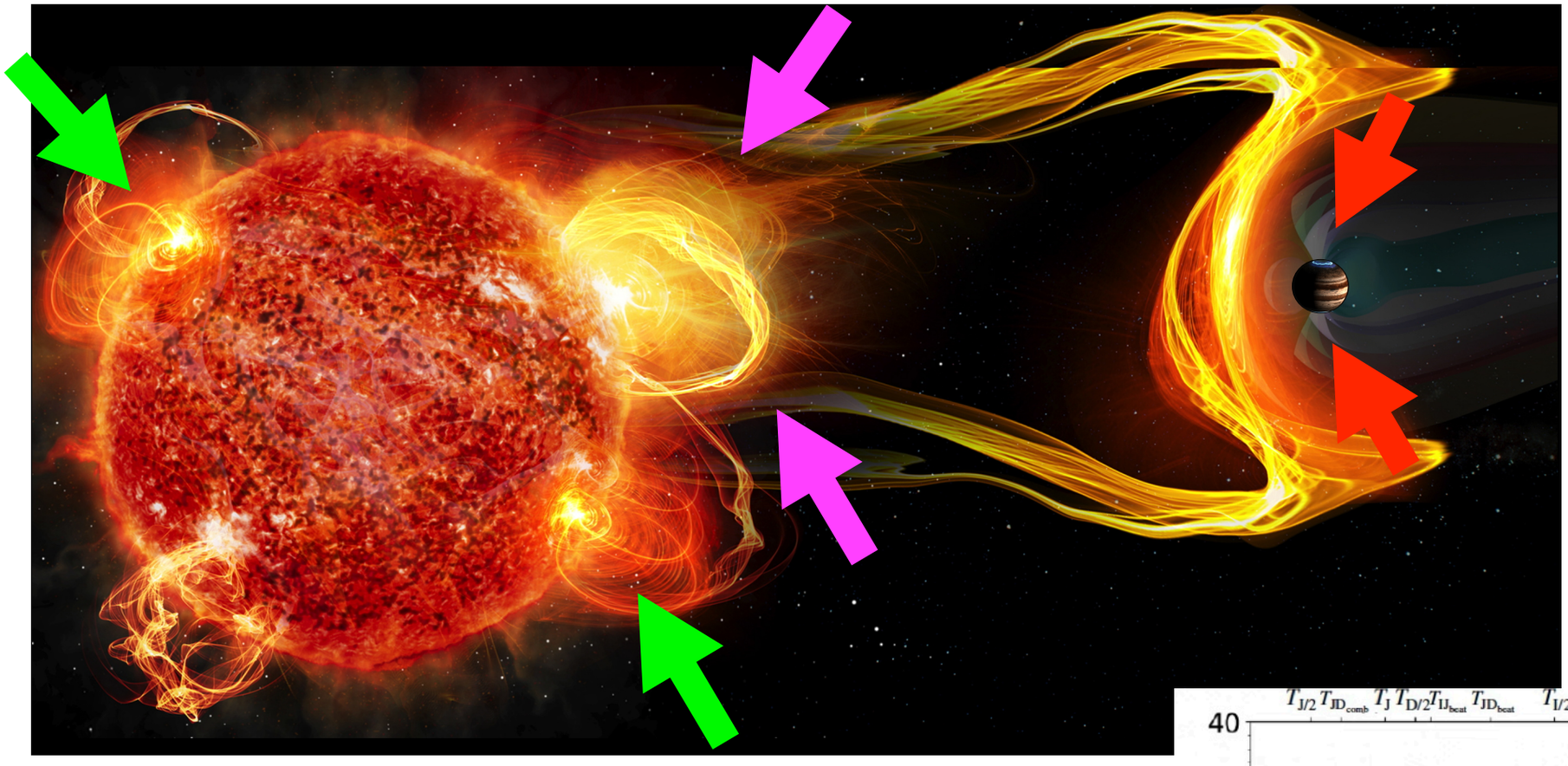
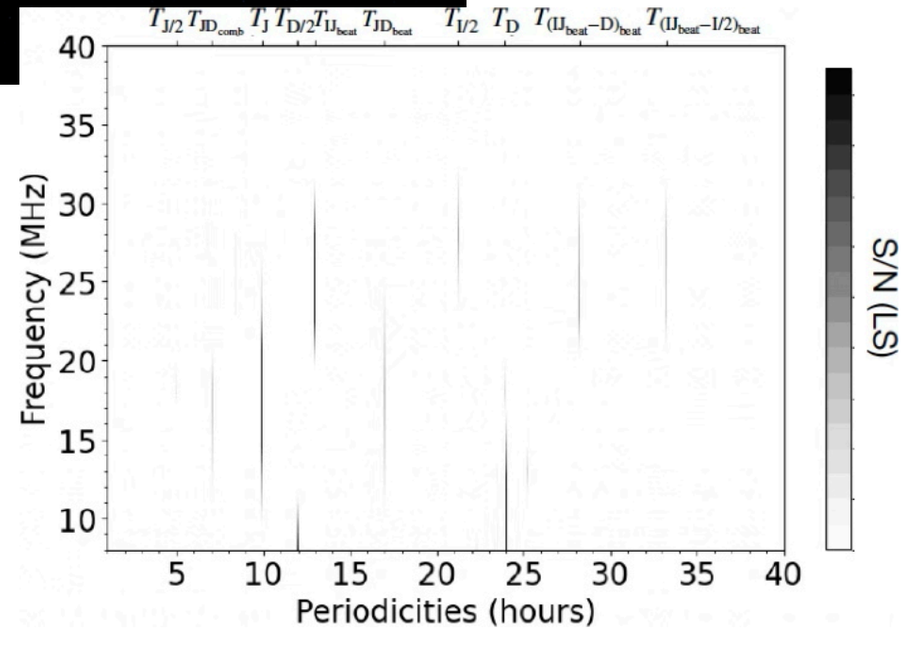


- Need for long time series of radio measurements
- Search for signal periodicities
  (planetary orbit, star's rotation, synodic)

[Louis+ 2026]



Predictions / Interpretations

- MHD + Express simulations *[Chebly+ 2026]*
- Stellar magnetic field database & RMSL-based population predictions

[Duchêne+ 2026, Mauduit+ 2023, 2026]

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[Duchêne+ 2026, Mauduit+ 2023, 2026]

Future Observations

- RIMS = key to massive detections, especially with

LoTSS/DR3 (120-168 MHz)

LOFAR 2.0 (30-200 MHz)

NenuFAR (10-85 MHz)

SKA (50-15000 MHz)

Lunar radio interferometer (0.1-100 MHz ?) ...