Émissions radio basses fréquences provenant de systèmes stellaires et exoplanétaires

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

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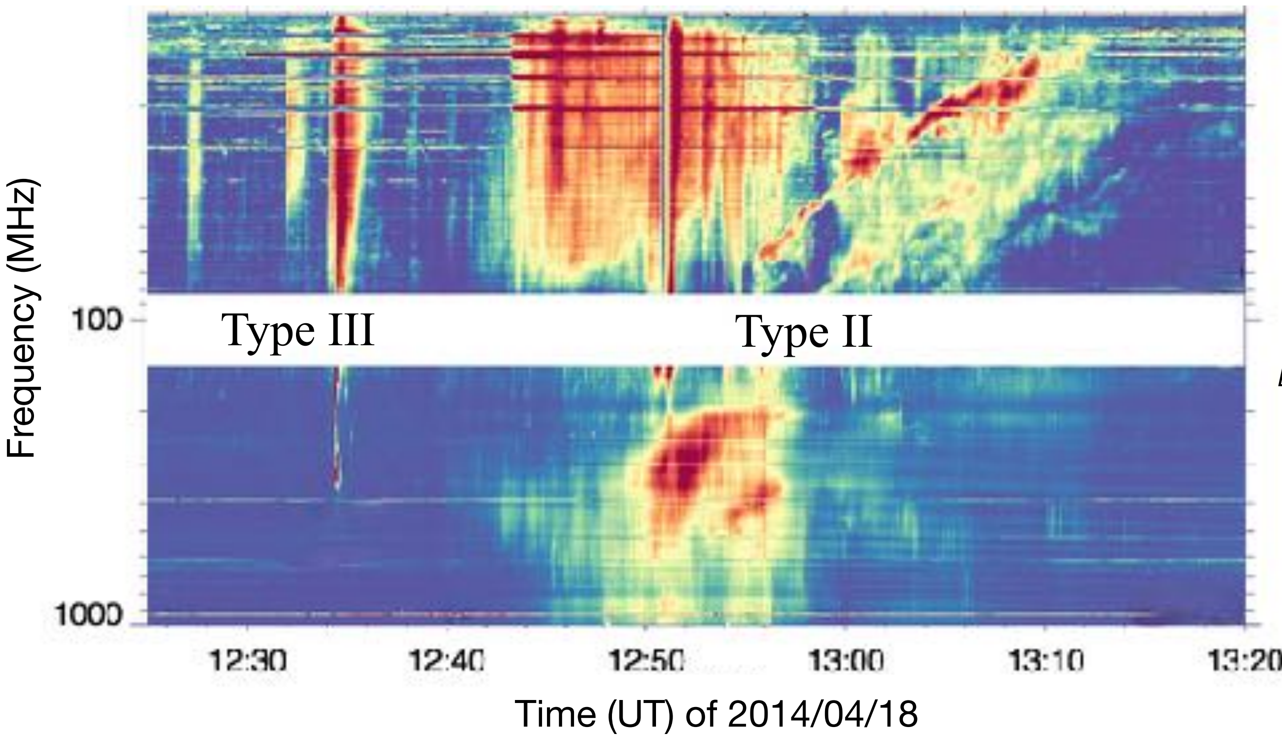
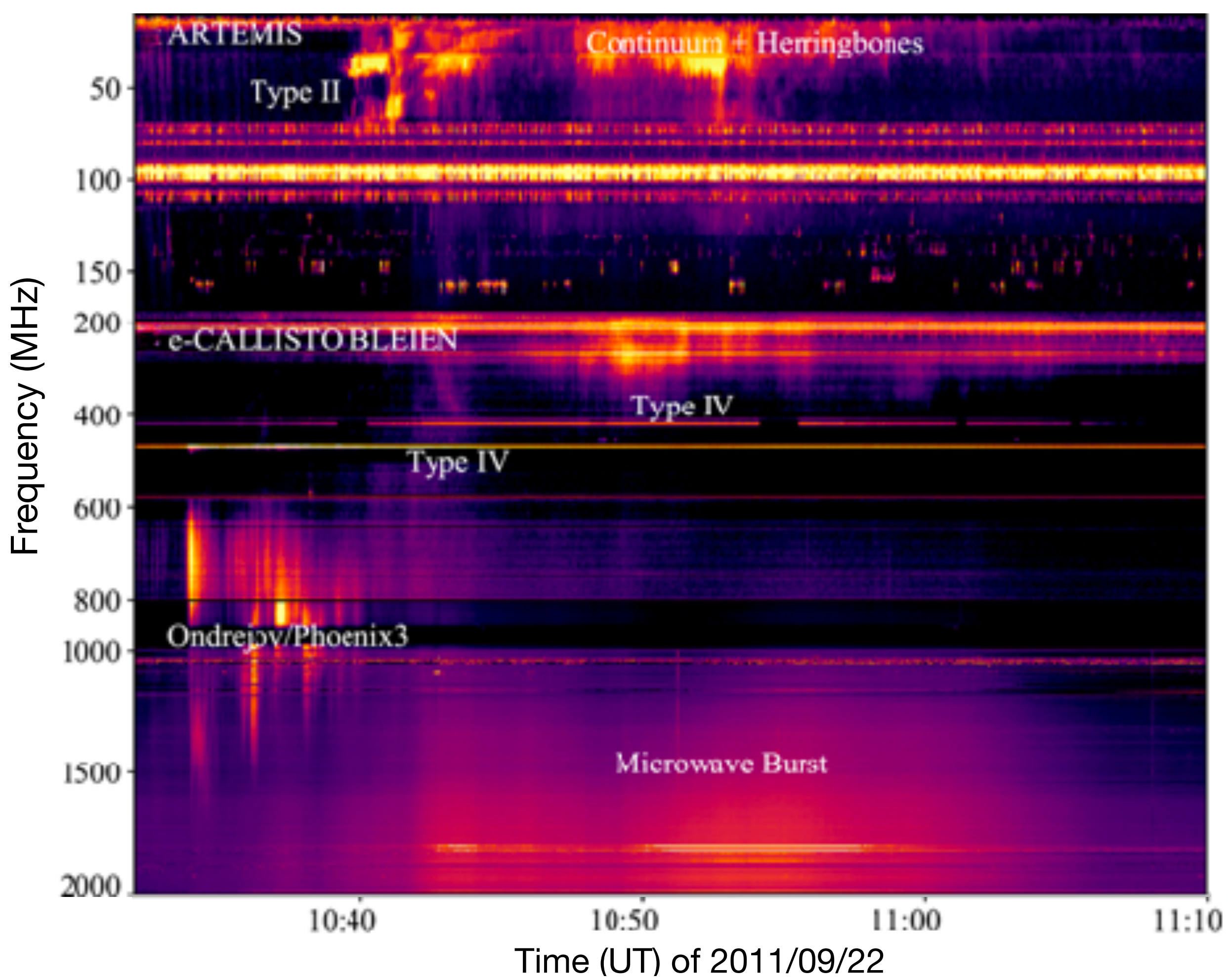
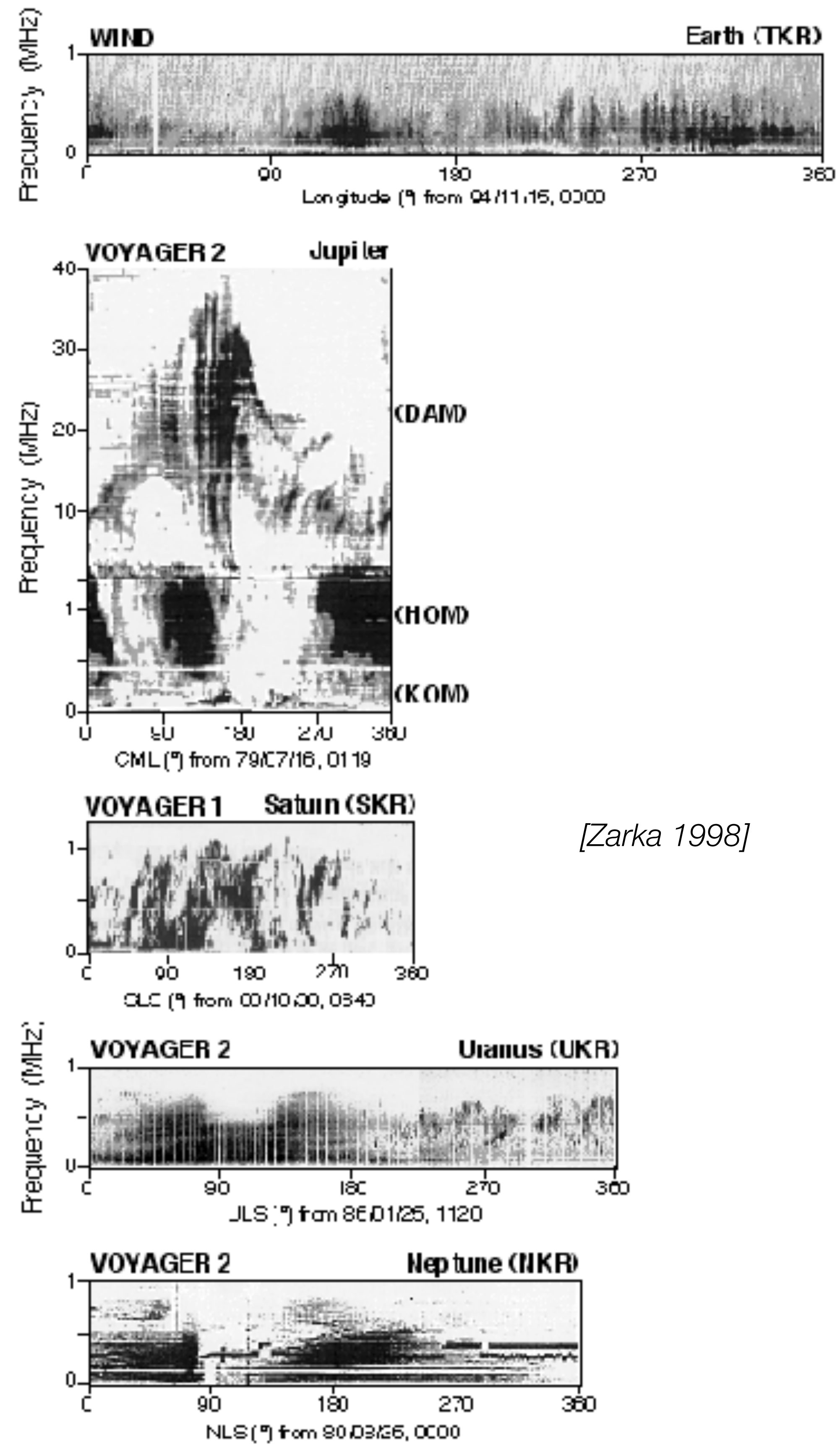
Solar & Planetary Radio Emissions



[Carley+2019]



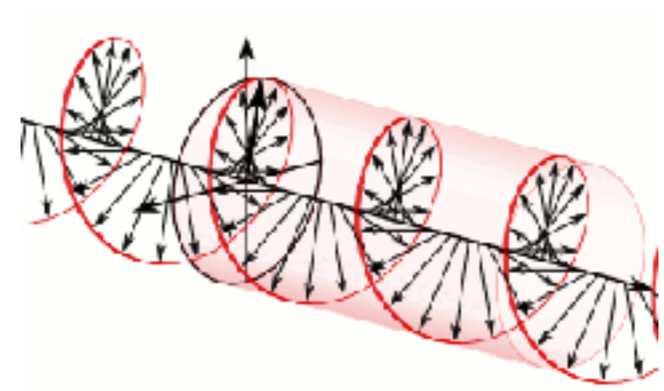
[Morosan+ 2019]

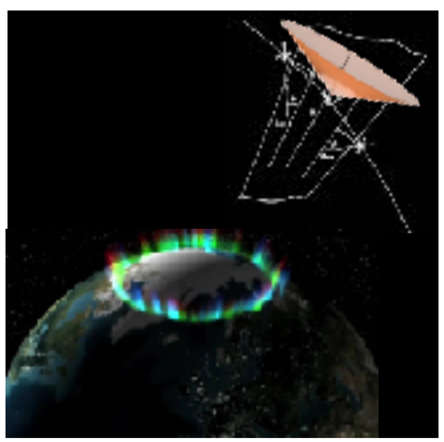


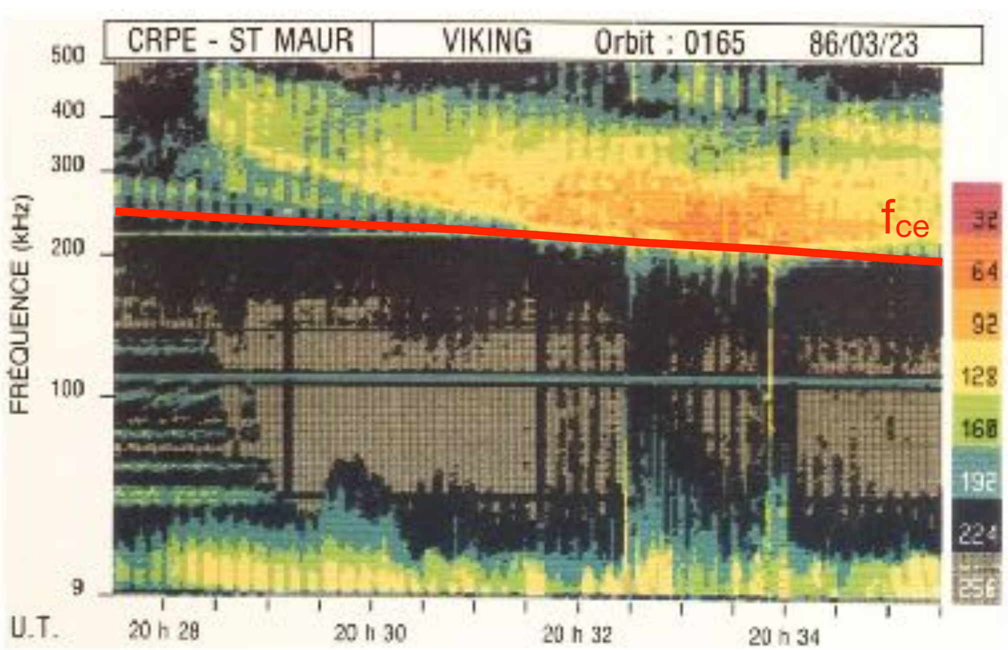
[Zarka 1998]

Planetary radio emissions : emission mechanism

- Physics of generation well understood :
  - → microphysics studied in-situ : ECMI (Electron Cyclotron Maser Instability)
  - → simulations: ExPRES code
  - → circular polarisation ubiquitous

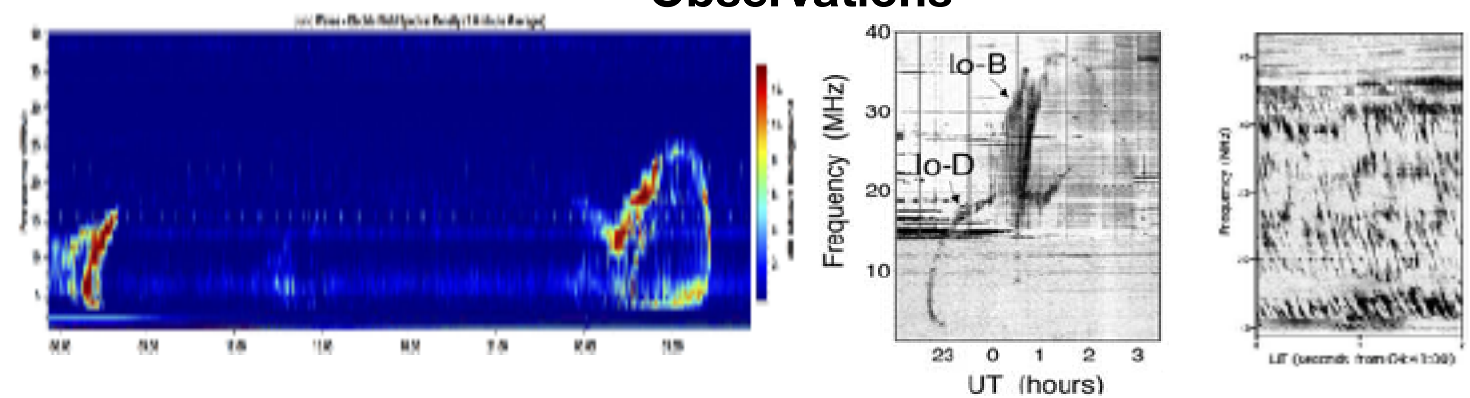




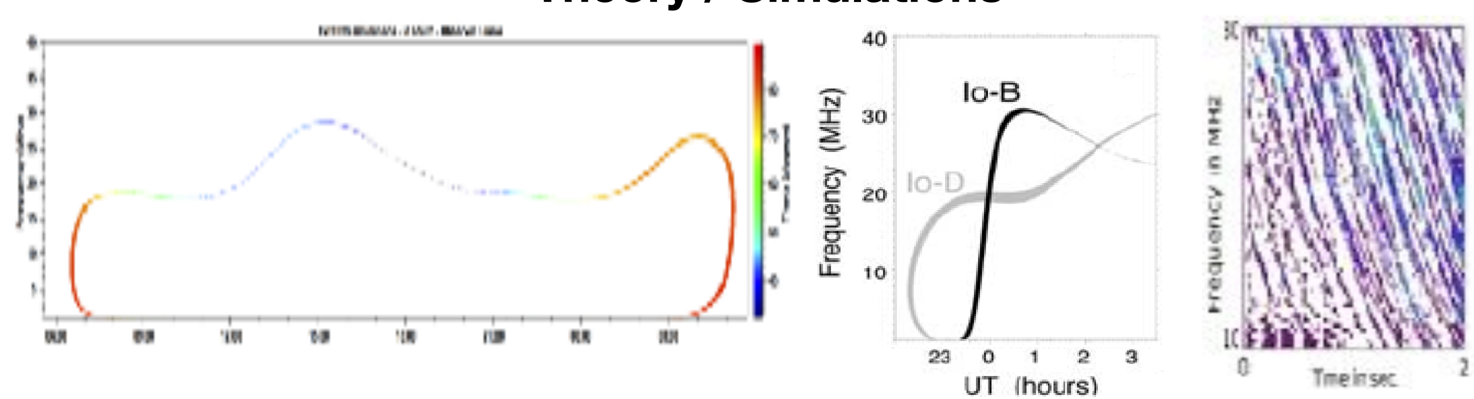


[Roux+ 1993]

Observations



Theory / Simulations

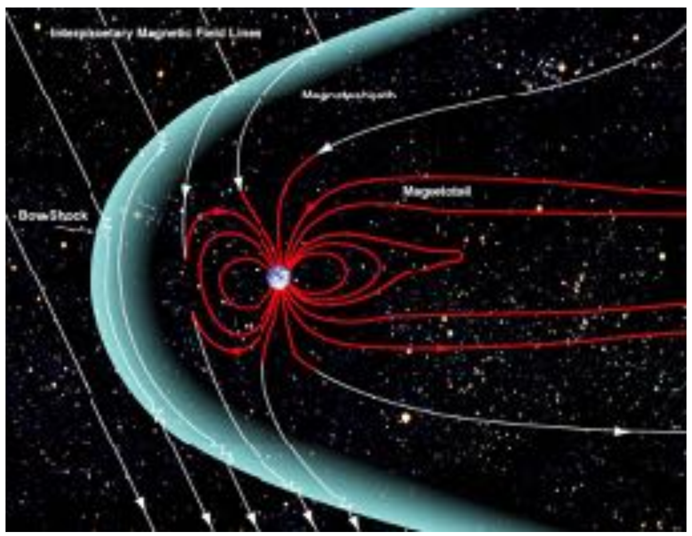


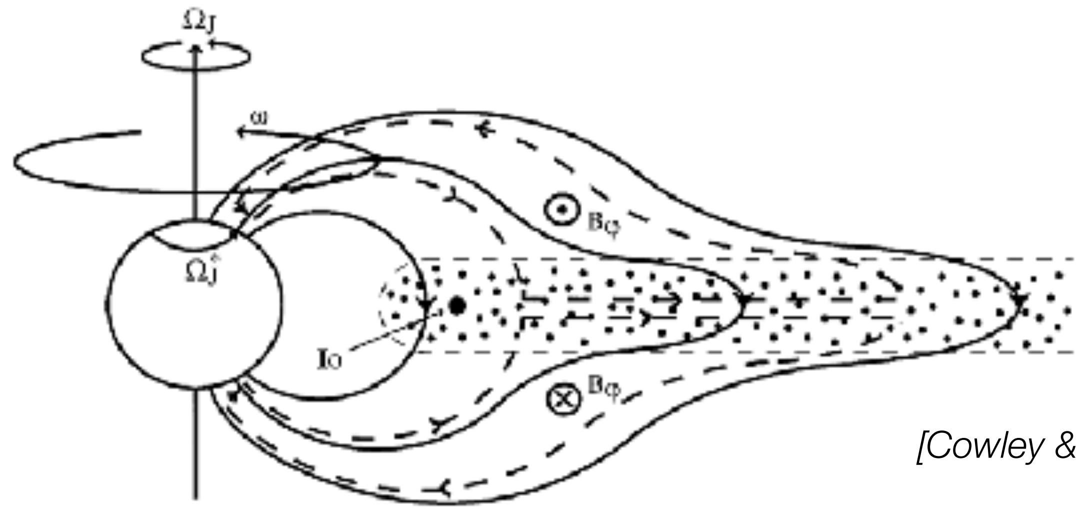
[Zarka 2004, Hess+ 2008, 2009, Louis+ 2017, 2019]

Planetary radio emissions : emission scenario

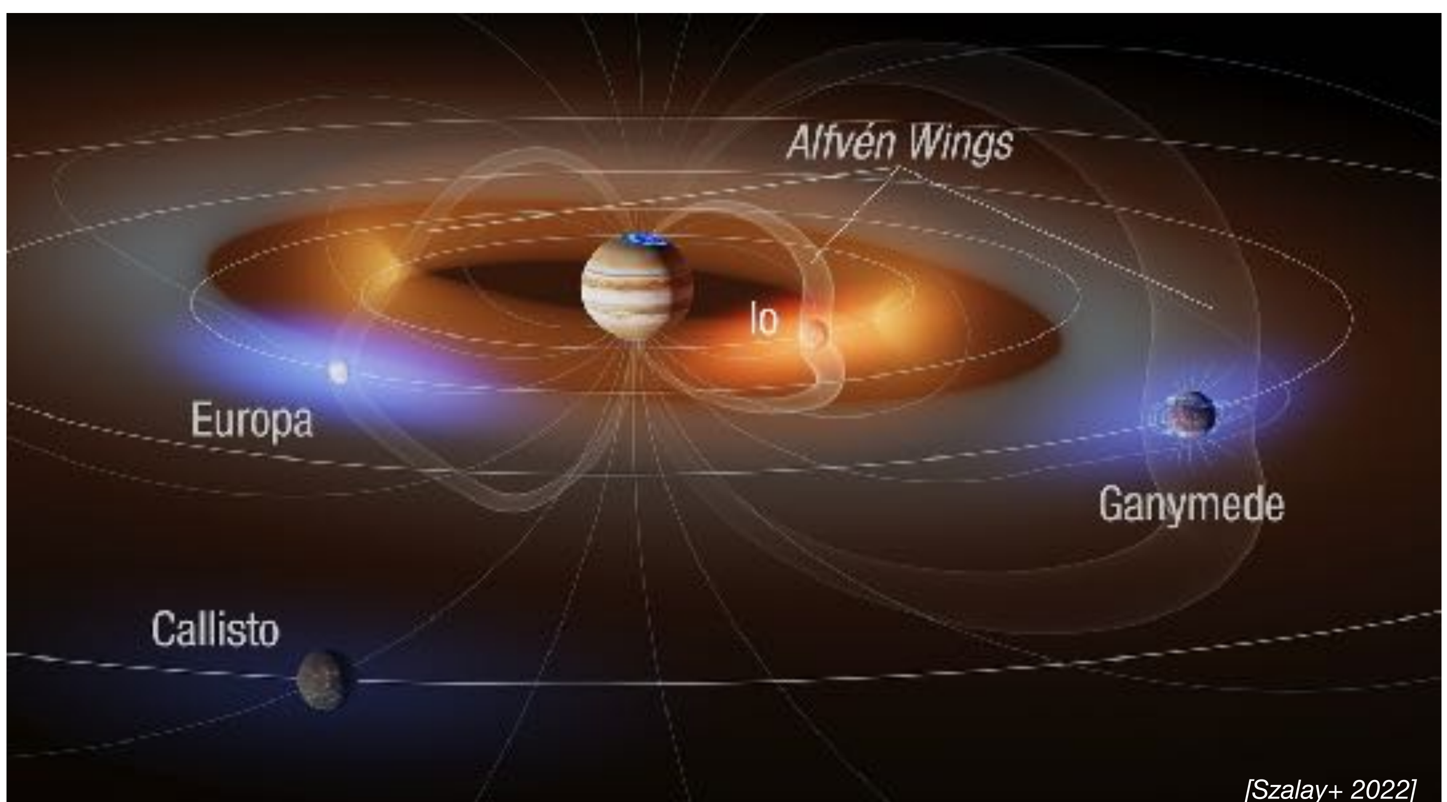
- Three drivers identified:
  → Solar Wind - Magnetosphere interaction (e.g. Earth)
  → Magnetosphere - Ionosphere interaction (corotation breakdown, e.g. Jupiter)
  → Satellite - Magnetosphere interaction (e.g. Io-Jupiter, Ganymede-Jupiter)

[Dungey 1961]





[Cowley & Bunce 2001]



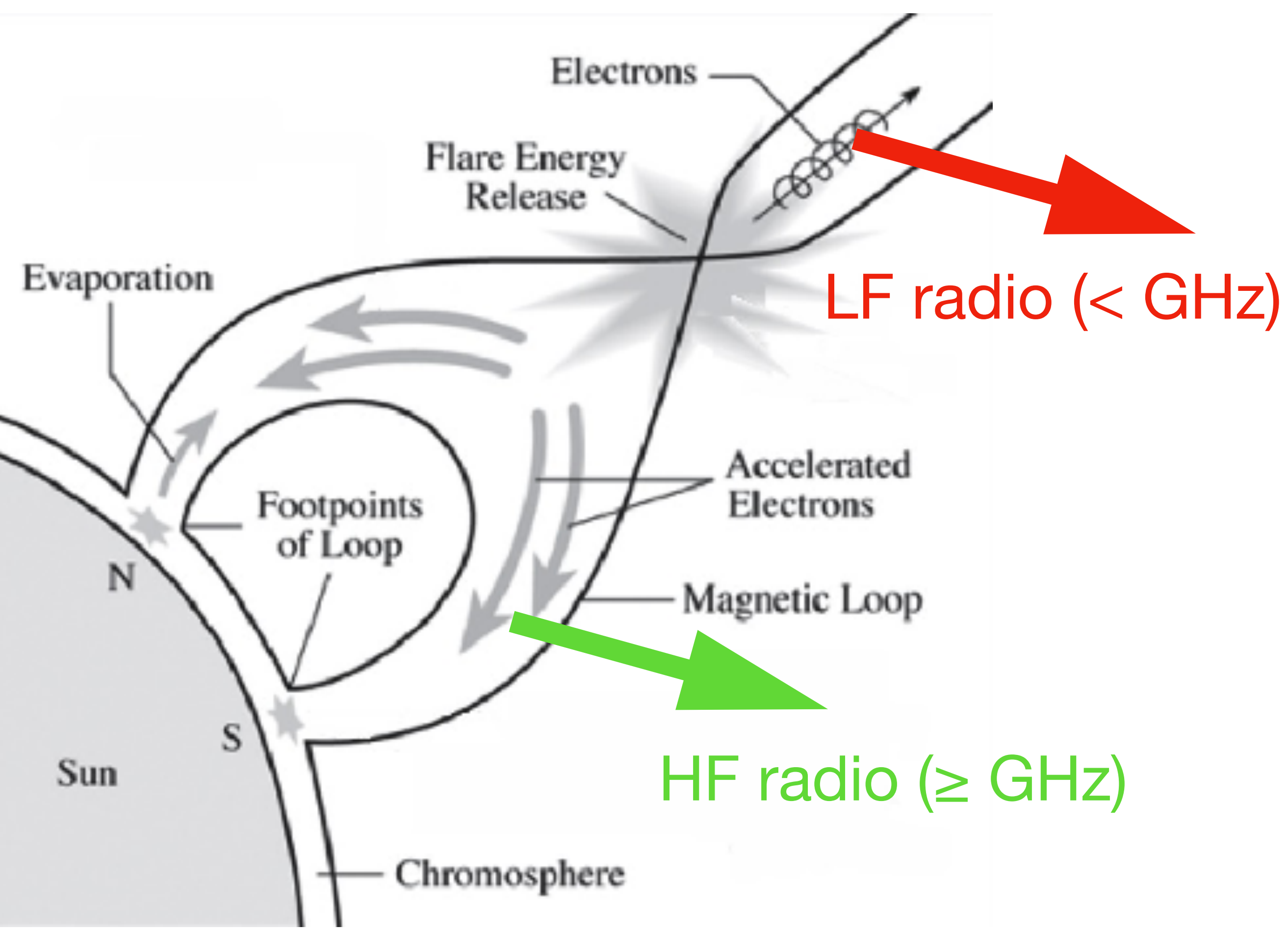
[Bigg 1964, Louis+ 2017, Zarka+ 2018, Jacome+ 2022]

Solar radio emissions: emission mechanism & scenario

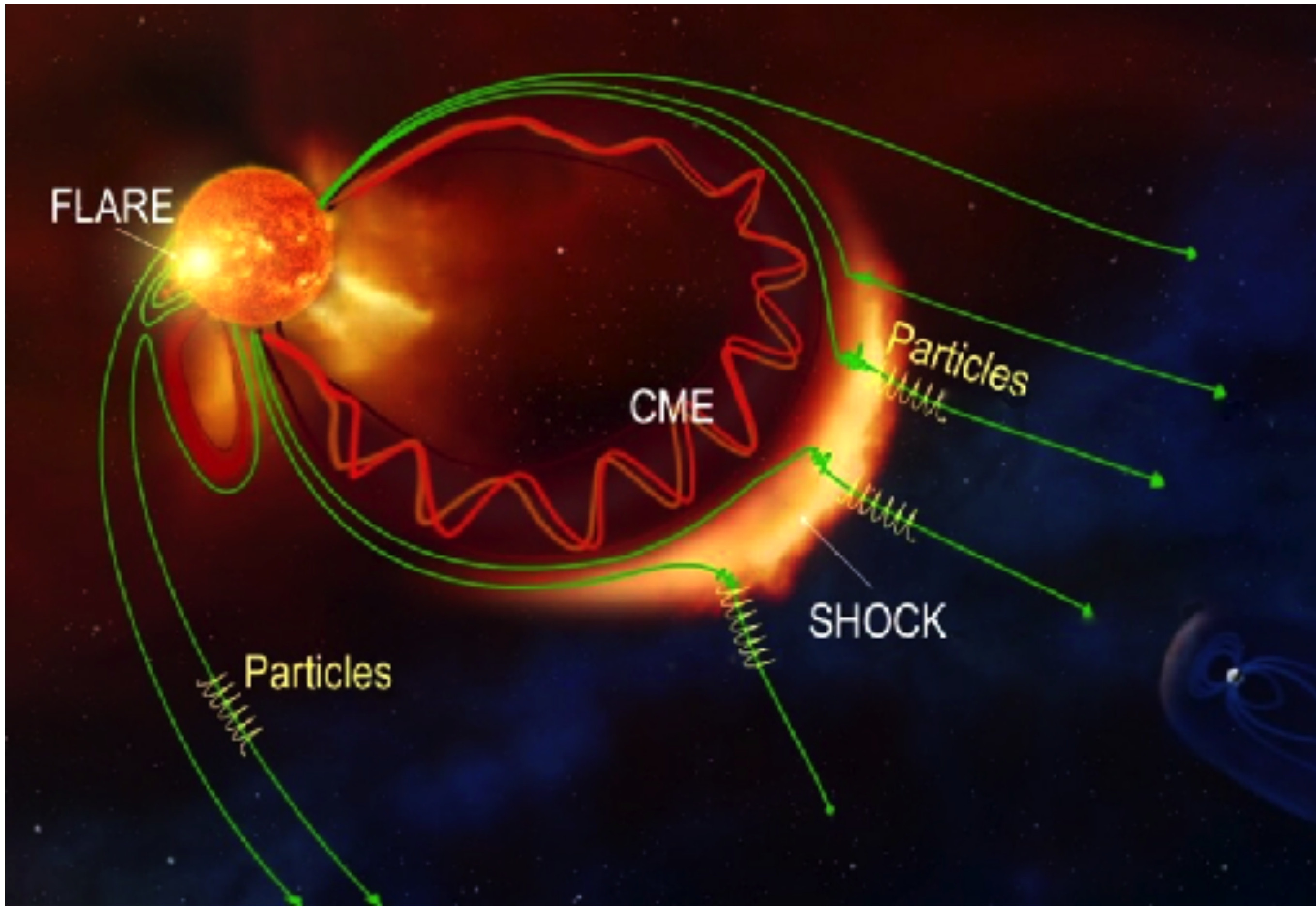
- Mechanism(s) :
  → plasma emission at f_{pe} & 2 x f_{pe} (type II & III)
  → gyrosynchrotron, ECMI ? (type IV, HF emission/spikes)

[Dulk 1985]

- Scenarios :
  → Type II from electrons accelerated by shocks & CMEs
  → Type III from relativistic electron beams
  → Type IV from broadband continuum emissions often associated with CMEs
  → HF emission/spikes from electrons accelerated by flares/reconnection in loops

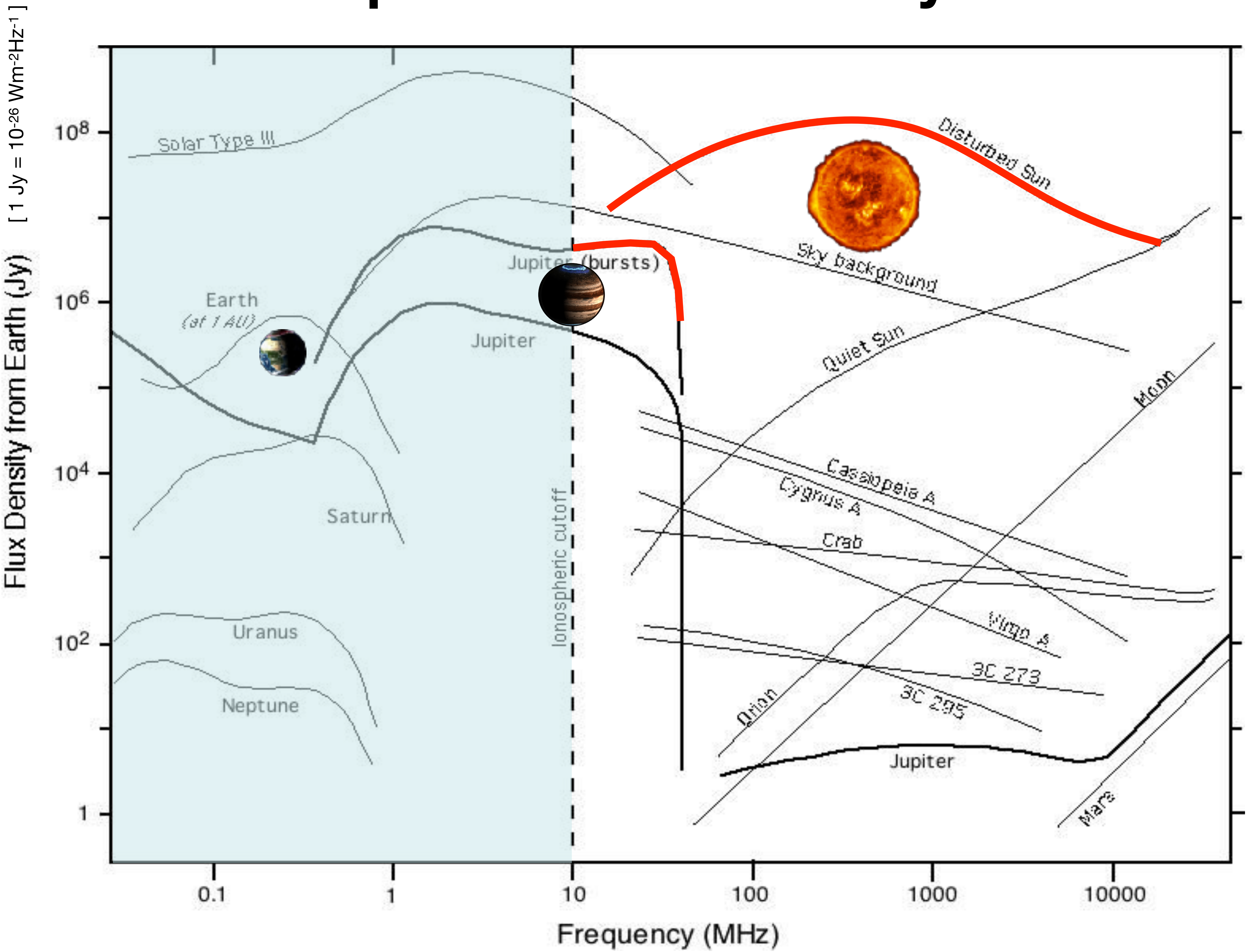


[Lang 2006]

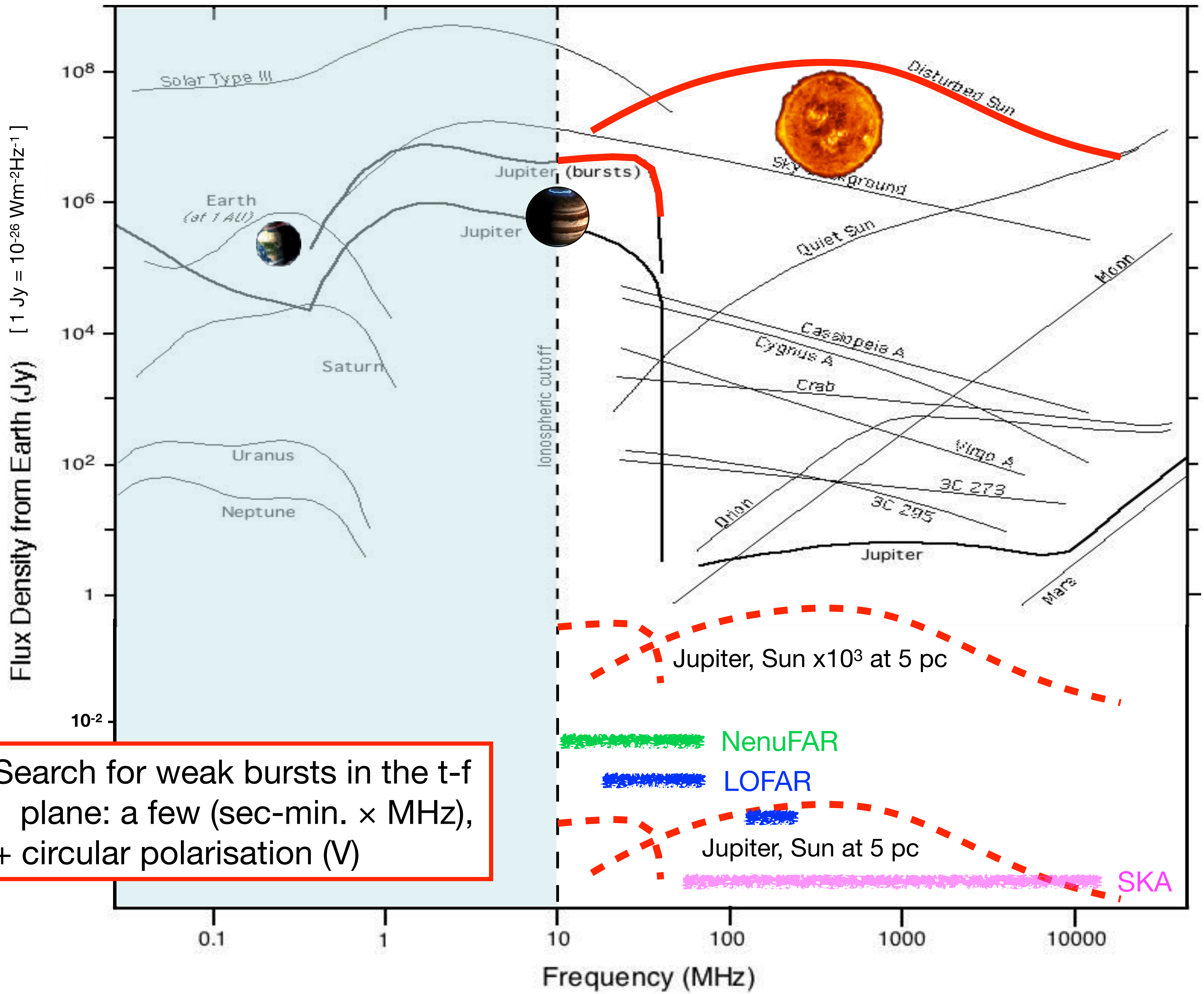


[Weigt+ 2023]

Spectrum & sensitivity



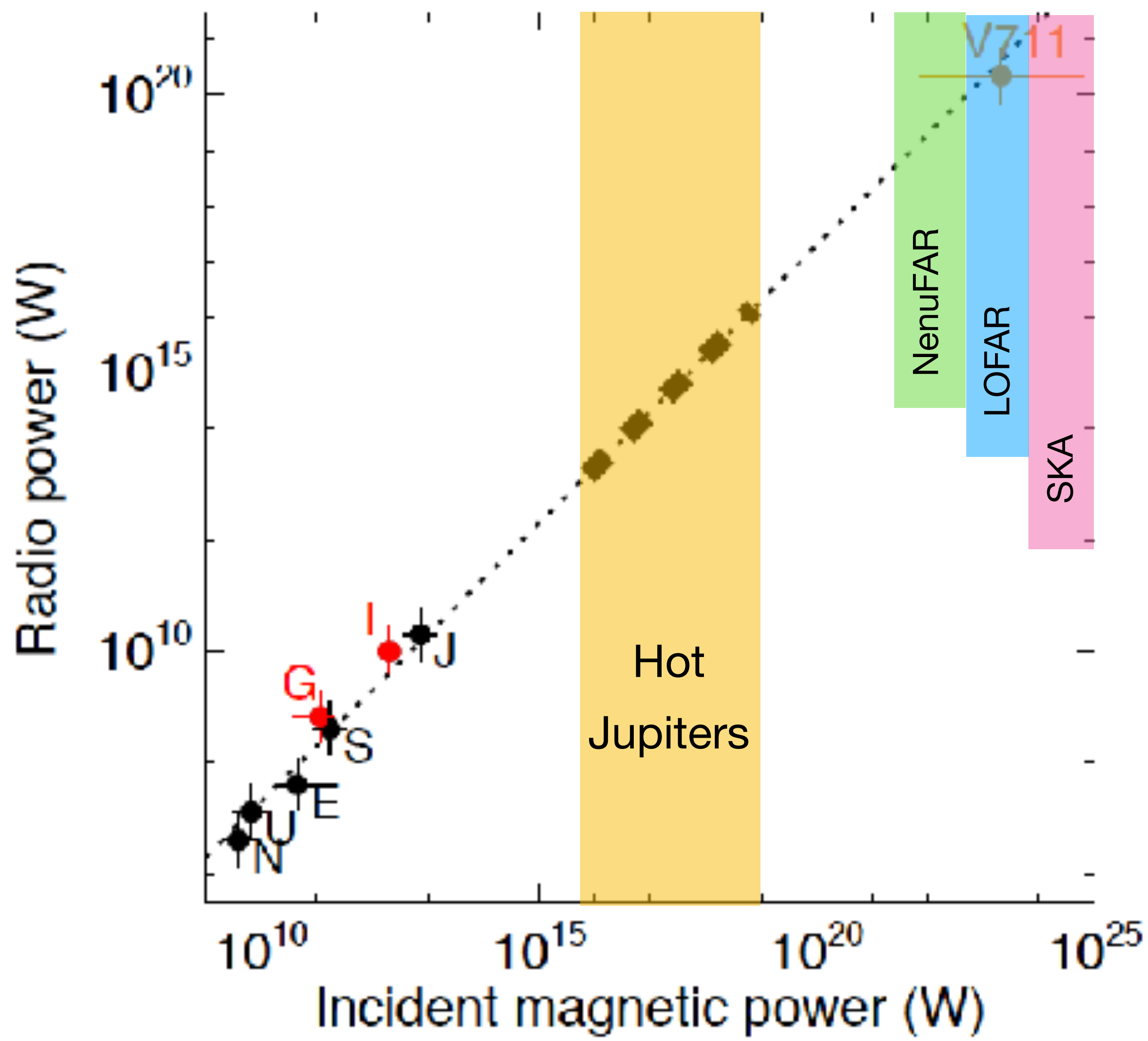
Spectrum & sensitivity



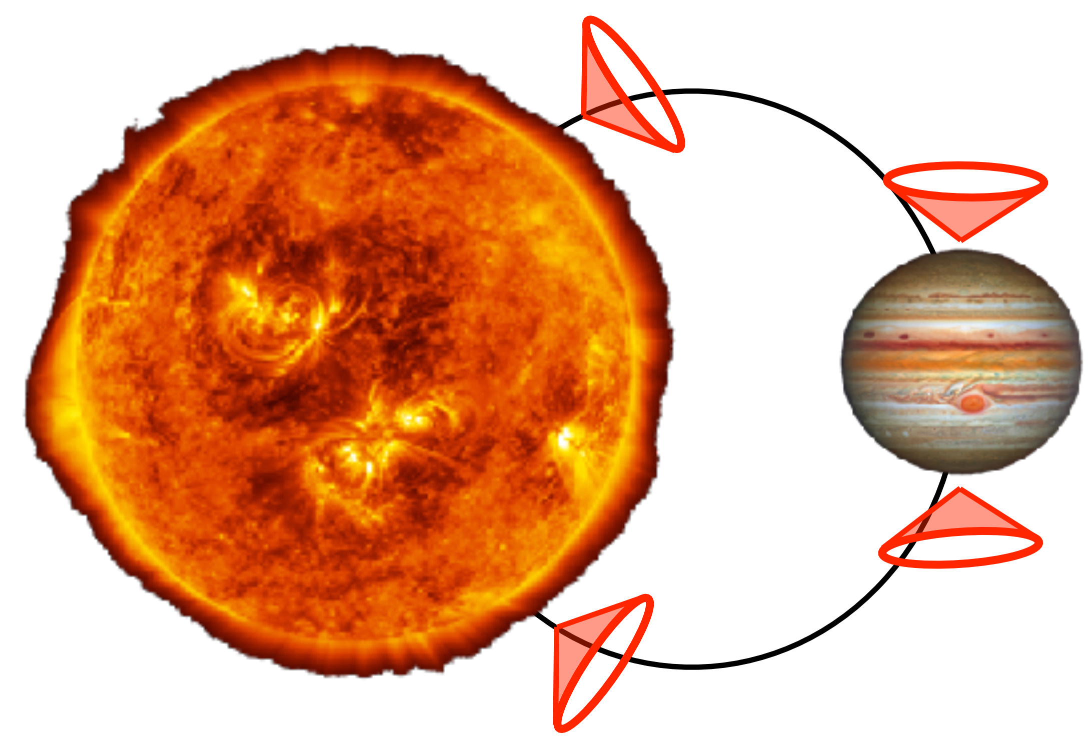
Search for weak bursts in the t-f plane: a few (sec-min. × MHz), + circular polarisation (V)

Stronger radio bursts ?

- Solar-system based scaling law suggests possible upscaled SW-MS & MS-satellite emissions (especially star-planet interactions (SPI))



[Zarka+ 2001, 2007, 2018]

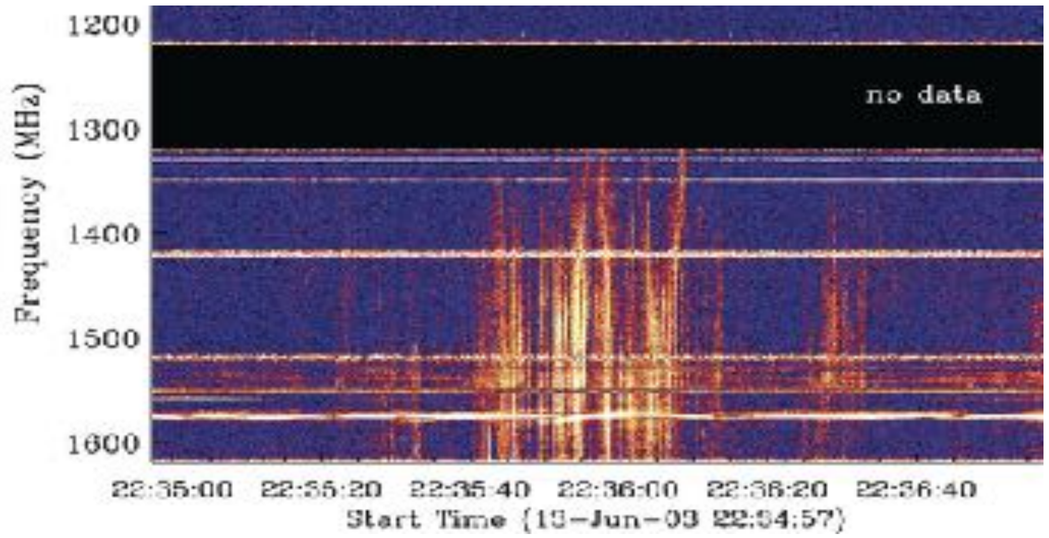


- Stellar flares up to 10^{4-5} x solar

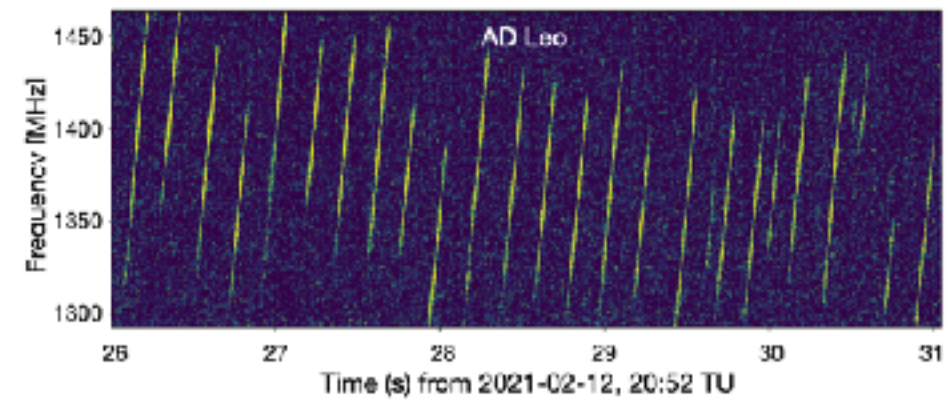
Single-dish & Beamformed observations

- Beamformed = Σ antenna signals → dynamic spectrum in selected direction

- Arecibo, FAST : AD Leo (M3, 5 pc, P_{rot}=2.23 d) at 1.4 GHz → stellar spikes, HF

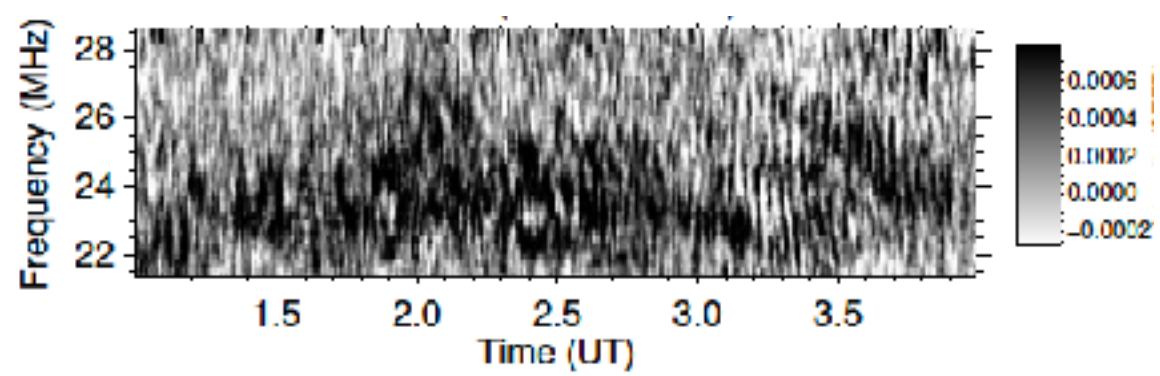


[Abada-Simon+ 1994, Osten+ 2006]



[Zhang+ 2023, Zarka+ 2025]

- LOFAR : τ Boo Ab (F6 star at 15.6 pc, P_{orb}=3.31 d) at 20-30 MHz
  → tentative detection of radio bursts from the hot Jupiter τ Boo Ab ?



[Turner+ 2021]

- Limitations : → limited sensitivity of beamformed mode, high noise, confusion
  → low efficiency (single target at a time)

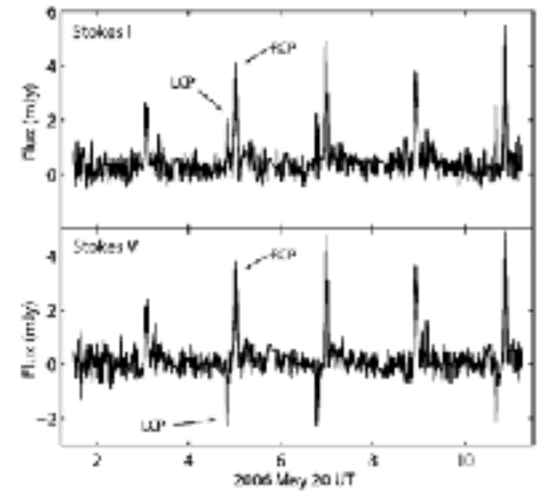
Interferometric imaging

- **FT** (gridded visibilities = correlations between pairs of antennas)

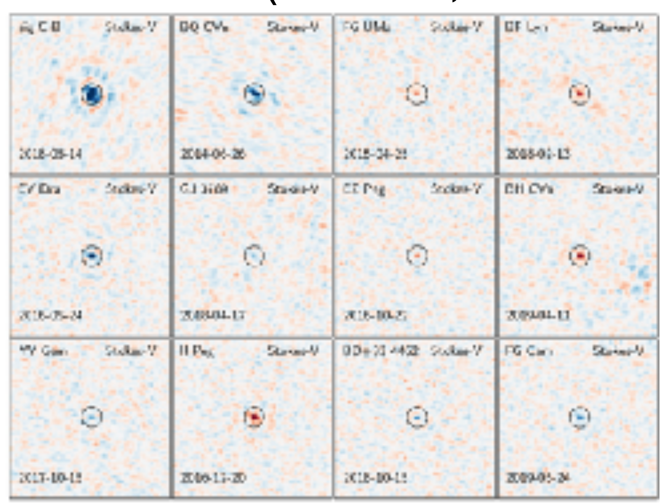
- VLA : TVLM 513 (M9, 10 pc, P_{rot}=1.96h) at 8.44 GHz

→ ECMI ?

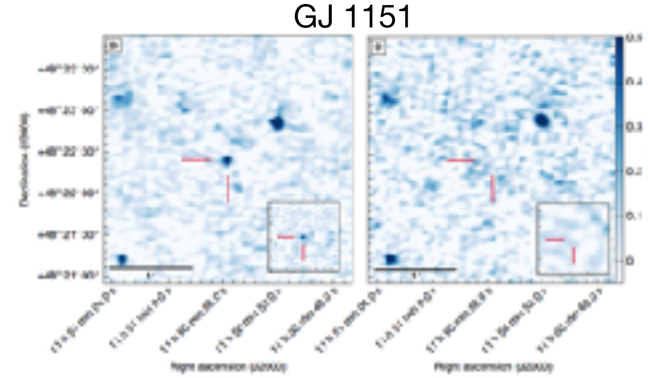
[Hallinan+ 2007]



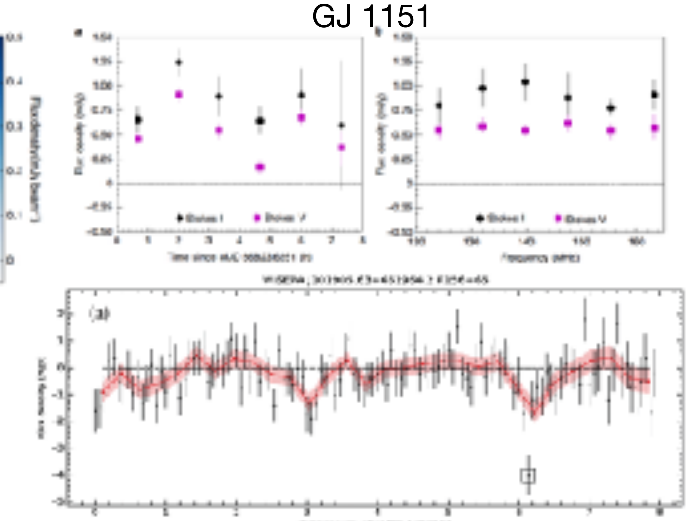
- LOFAR : radio stars at 150 MHz (RSCVn, red/brown/pulsating dwarfs...)



GJ 1151

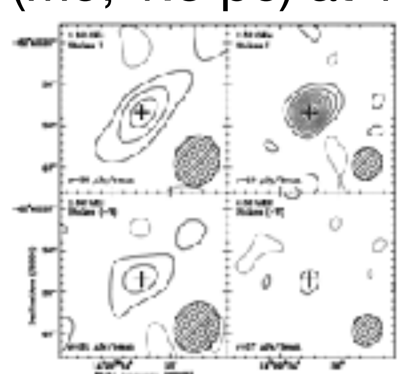


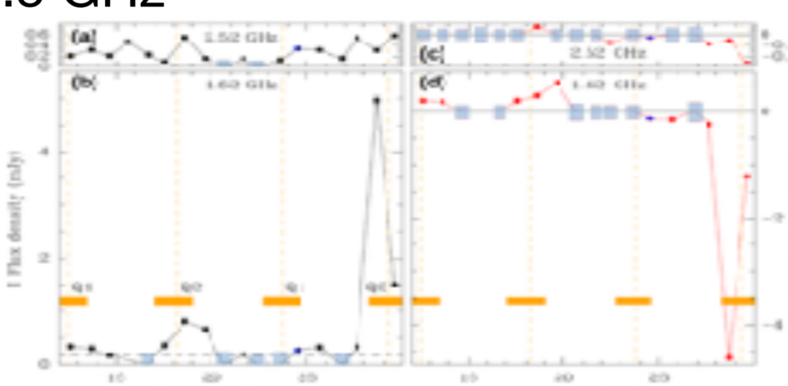
GJ 1151



[Vedantham+ 2020, Toet+ 2021, Vedantham+ 2023]

- ATCA : Proxima Centauri (M5, 1.3 pc) at 1.6-2.5 GHz





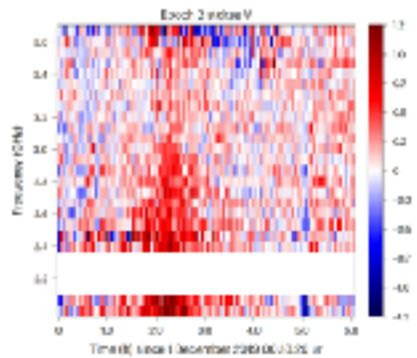
[Perez-Torres+ 2021]

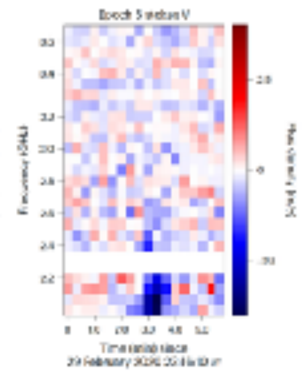
- Limitations : → unresolved sources, overall spectrum & limited time variations
  → low sensitivity to transients

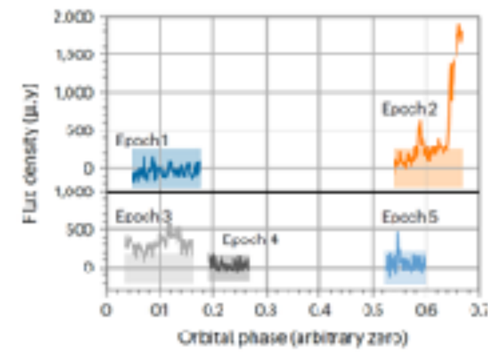
Dynamic spectrum at phase center

- Σ interferometric visibilities = dynamic spectrum at the phase center

- VLA : YZ Ceti (M4, 3.7 pc, P_{orb}=2.02 d) at 2-4 GHz → SPI ?





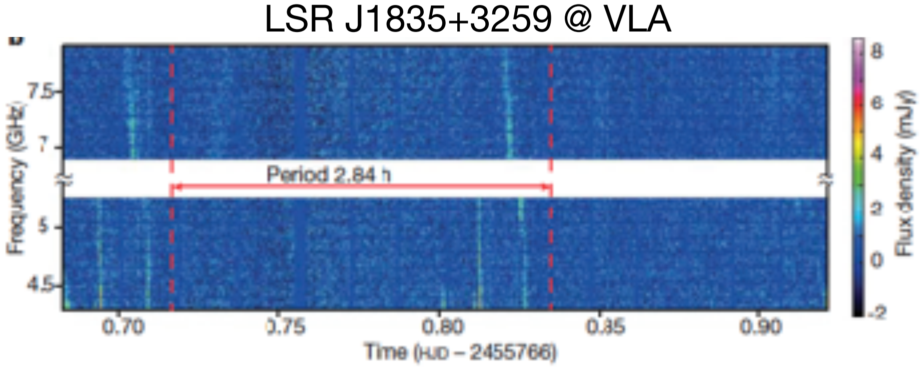


[Villadsen+ 2019, Pineda+ 2023]

- VLA : LSR J1835 (M8, 5.7 pc, P_{rot}=2.84 h) at 4-8 GHz
- LOFAR : CR Dra (M1, 20 pc, P_{rot}=1.984 d) at 170 MHz

→ corotation breakdown in star's environment ?

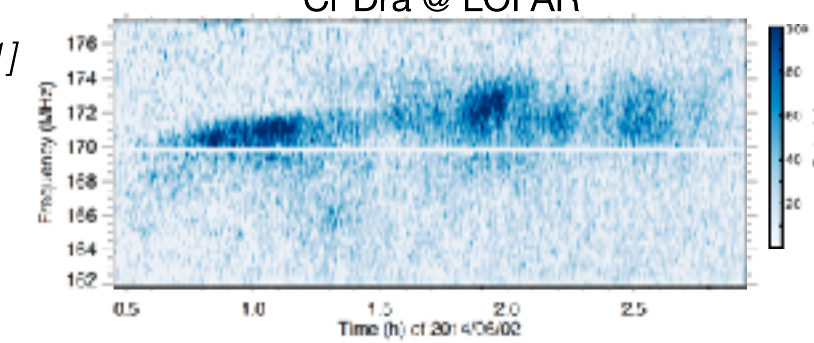
LSR J1835+3259 @ VLA



[Hallinan+ 2015]

[Callingham+ 2021]

Cr Dra @ LOFAR

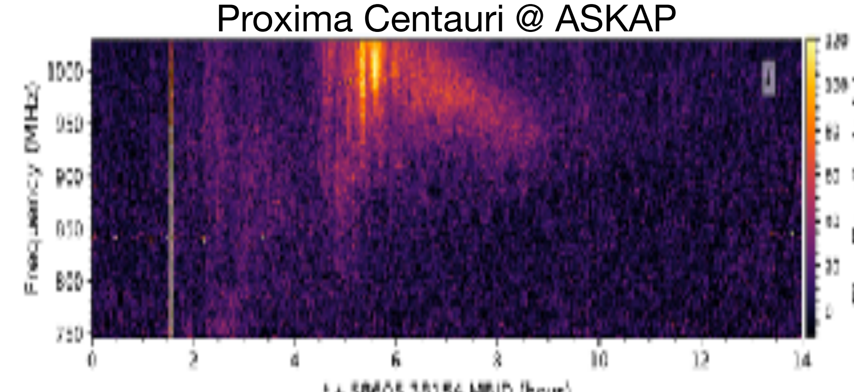


- ASKAP : Proxima Centauri (M5, 1.3 pc) at 0.7-1.1 GHz
- GMRT : AD Leo (M3, 5 pc, P_{rot}=2.23 d) at

→ first stellar Type IV bursts

[Zic+ 2020, Mohan+ 2024]

Proxima Centauri @ ASKAP



- Limitation : → low efficiency (single target at a time)

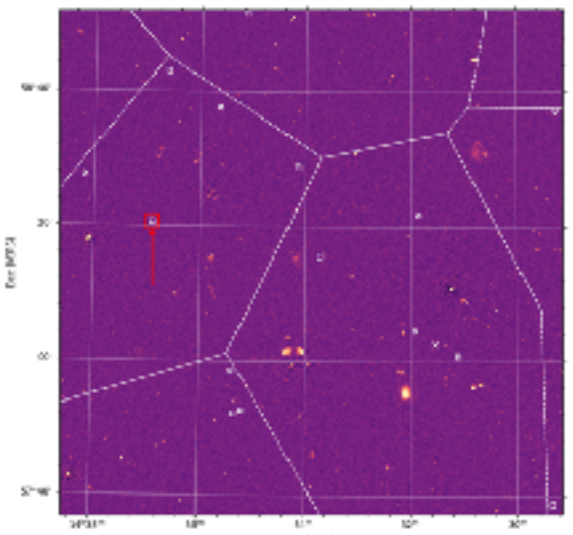
New method : t-f from interferometric imaging

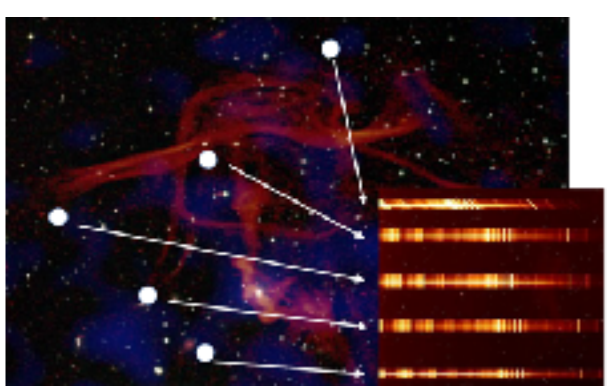
- 2025+ : development of the Radio Interferometric Multiplexed Spectroscopy (**RIMS**)

technique → Σ interferometric <u>residual</u> visibilities with phase terms exp(i**k.b**)

→ dynamic spectrum (t-f) toward any directions in the FoV, <u>simultaneously</u>

= **digital integral field dynamic spectroscopy**



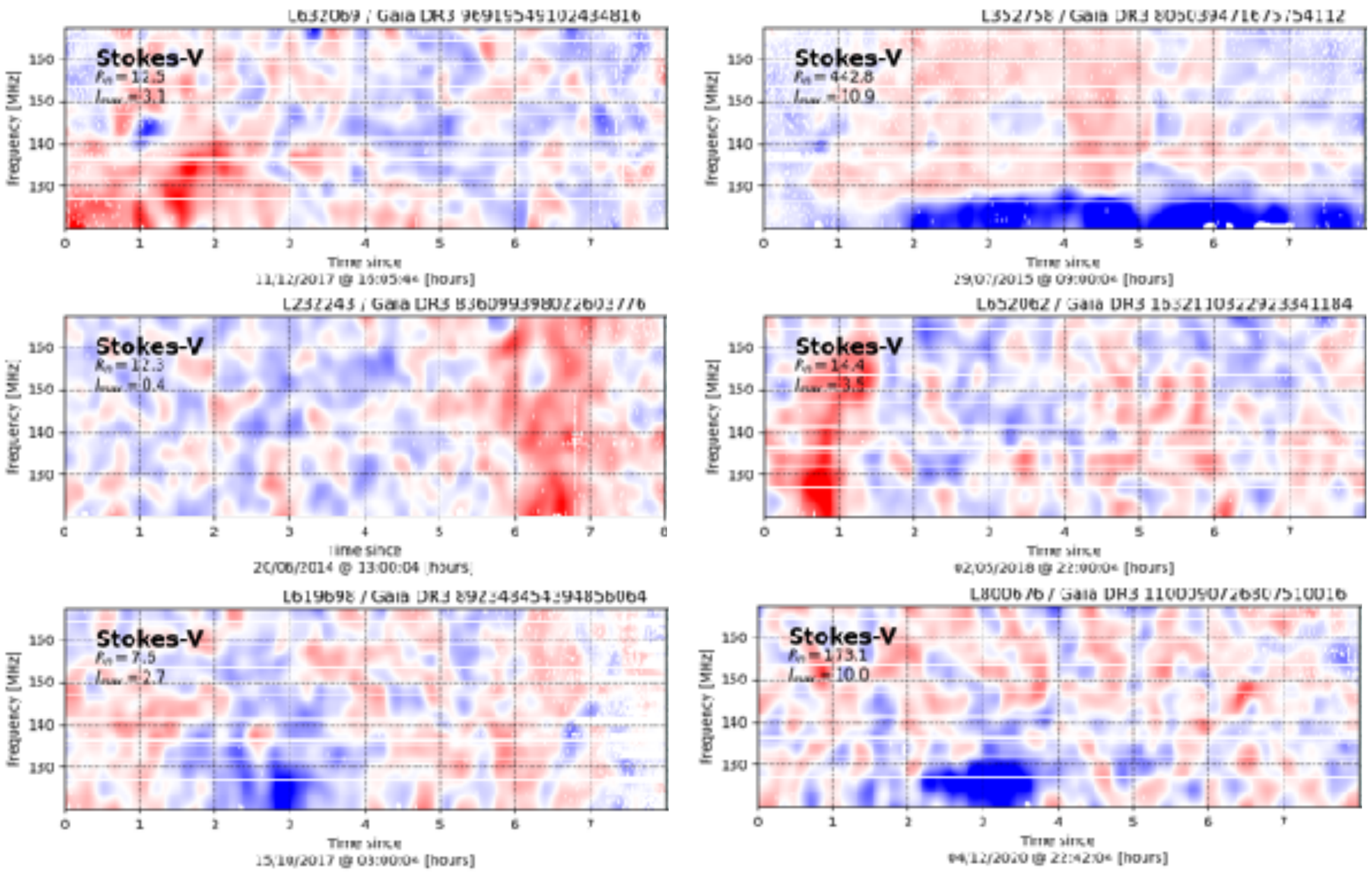


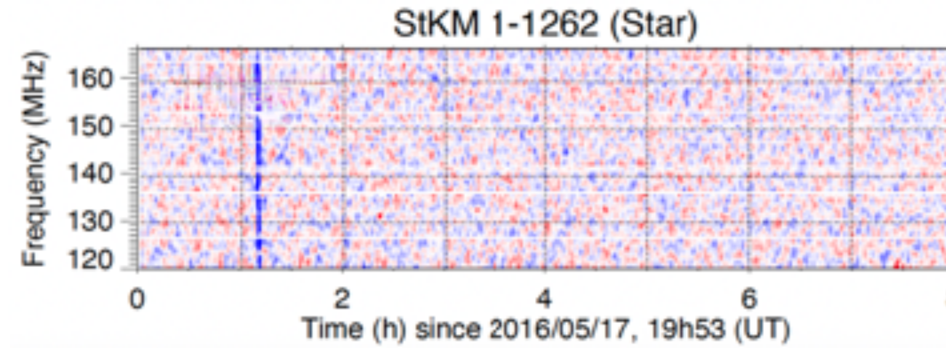
- Input catalog of exoplanets, stars, dwarf, active, Gaia (~a few 10^5 objects)

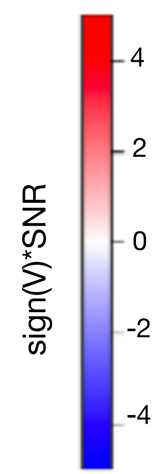
Polarized bursts in LoTSS

- 27 bursts including 2 from exoplanet hosting systems in LoTSS DR2 (~13000 h)

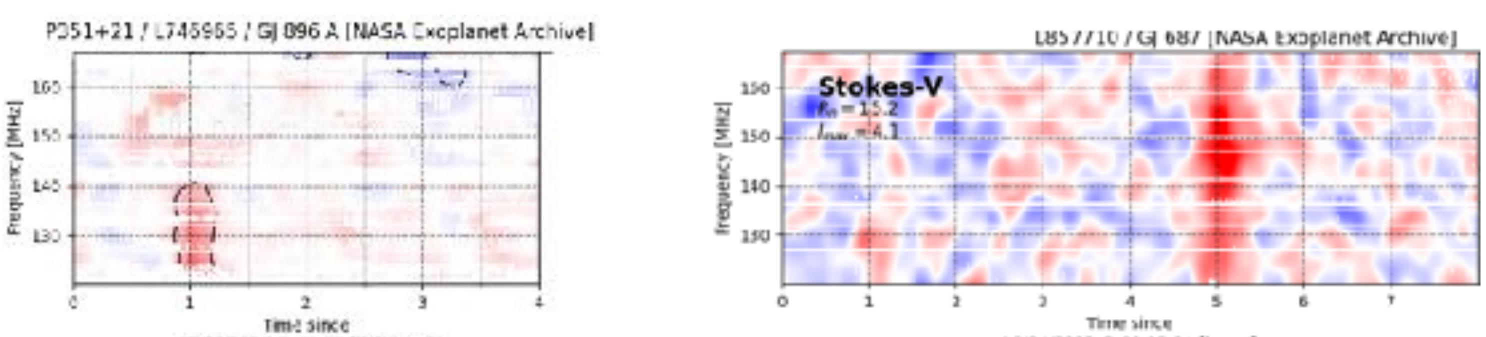
Stars

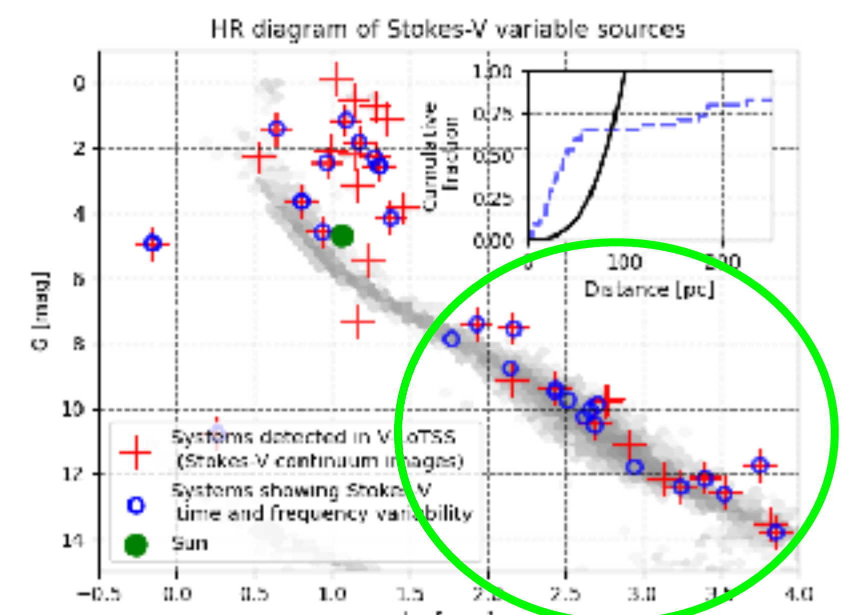






Star-Exoplanet systems

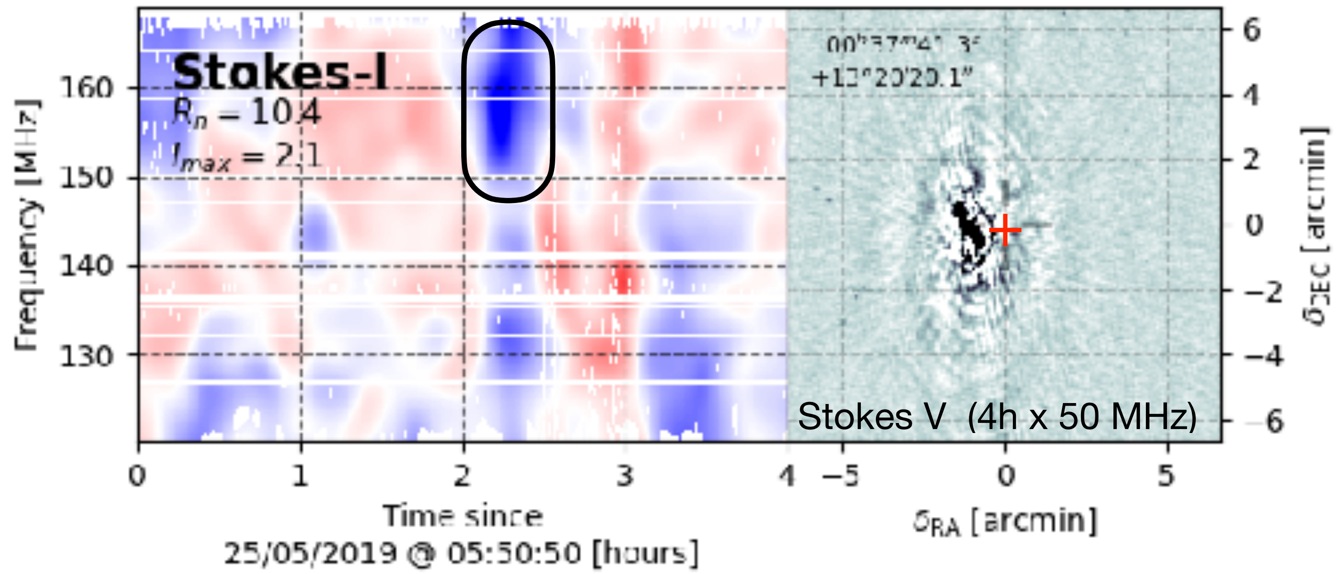




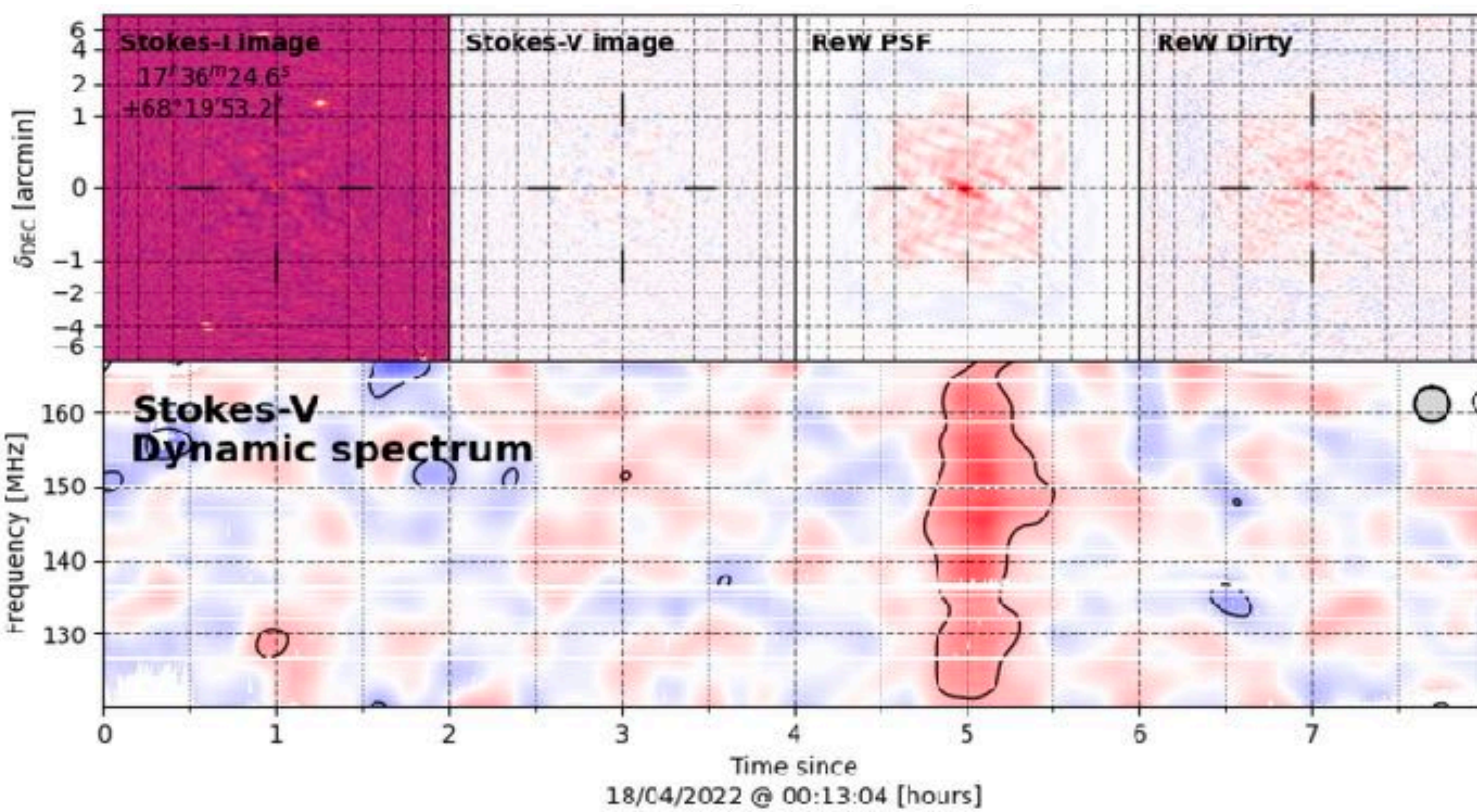
[Tasse+ 2026]

Confirmation of detections

- re-imaging of a subset of residual visibilities restricted to the t-f covered by the burst

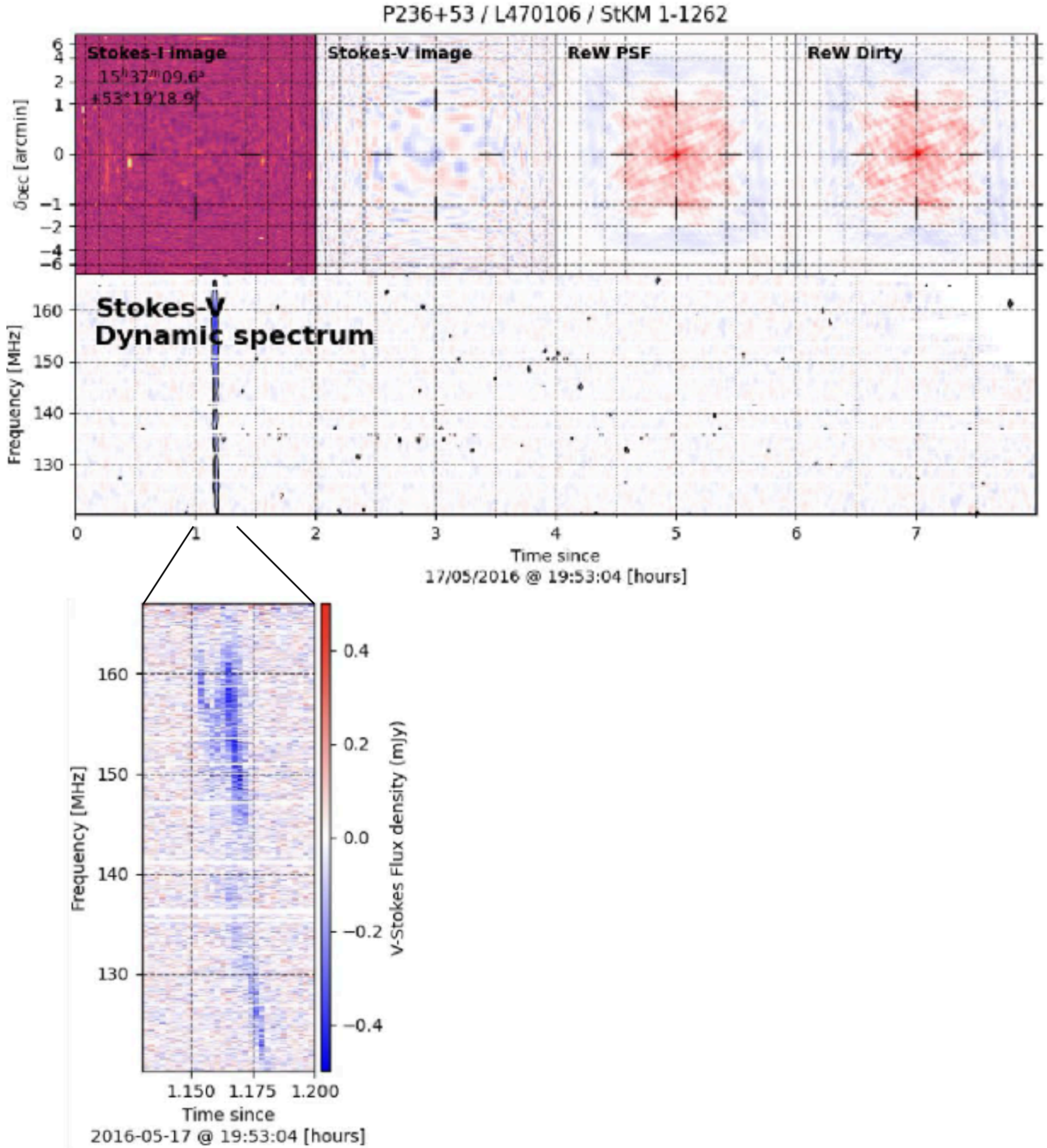


⇒ spurious



⇒ confirmed

Drifting polarized bursts in LoTSS



Drifting polarized bursts in LoTSS

- **StKM 1-1262** : main sequence M0V red dwarf

$M_* = 0.6\ M_\odot$, $R_* = 0.6\ R_\odot$, d = 40.8 pc, P=1.24 d, T~ 3900 K, B~300 G

- Corona ~ in hydrostatic equilibrium: $N_e = N_o \exp(-z/H)$

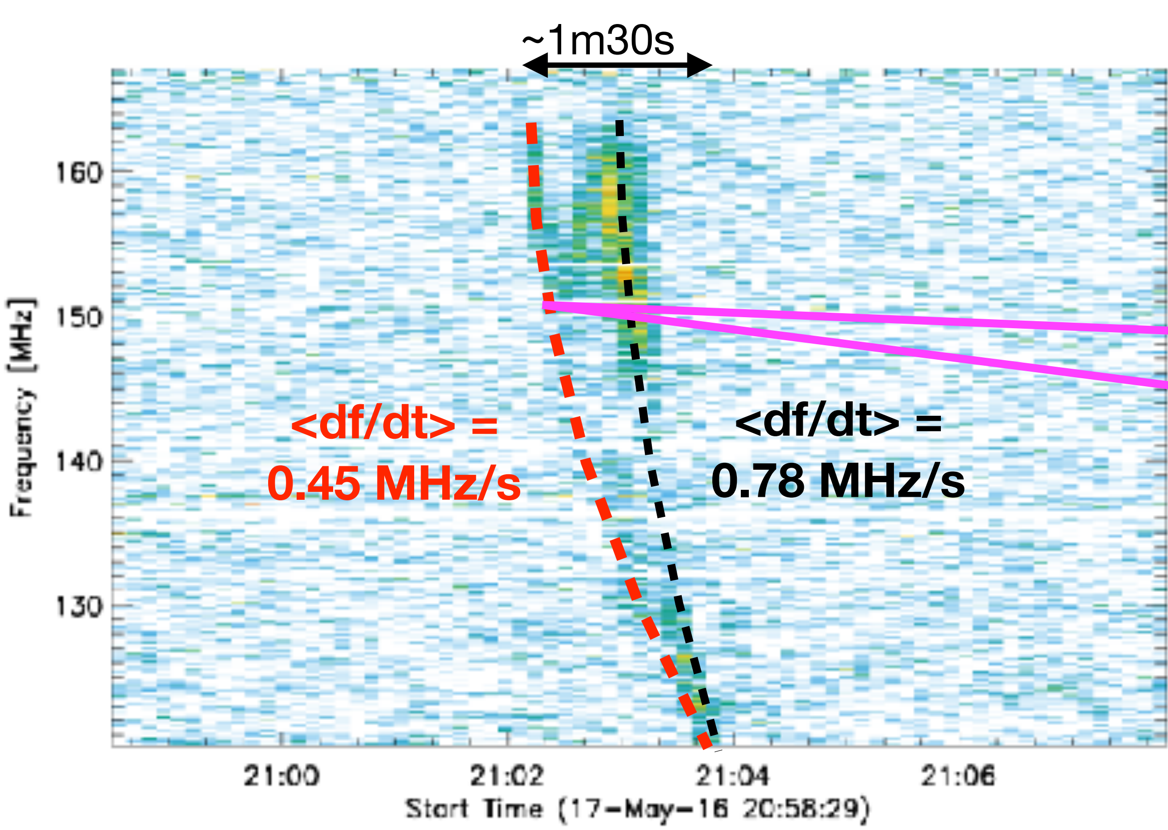
$N_o \sim 0.6\text{-}2.5\ 10^{10}\ cm^{-3}$ *[Villadsen & Hallinan, 2019]*

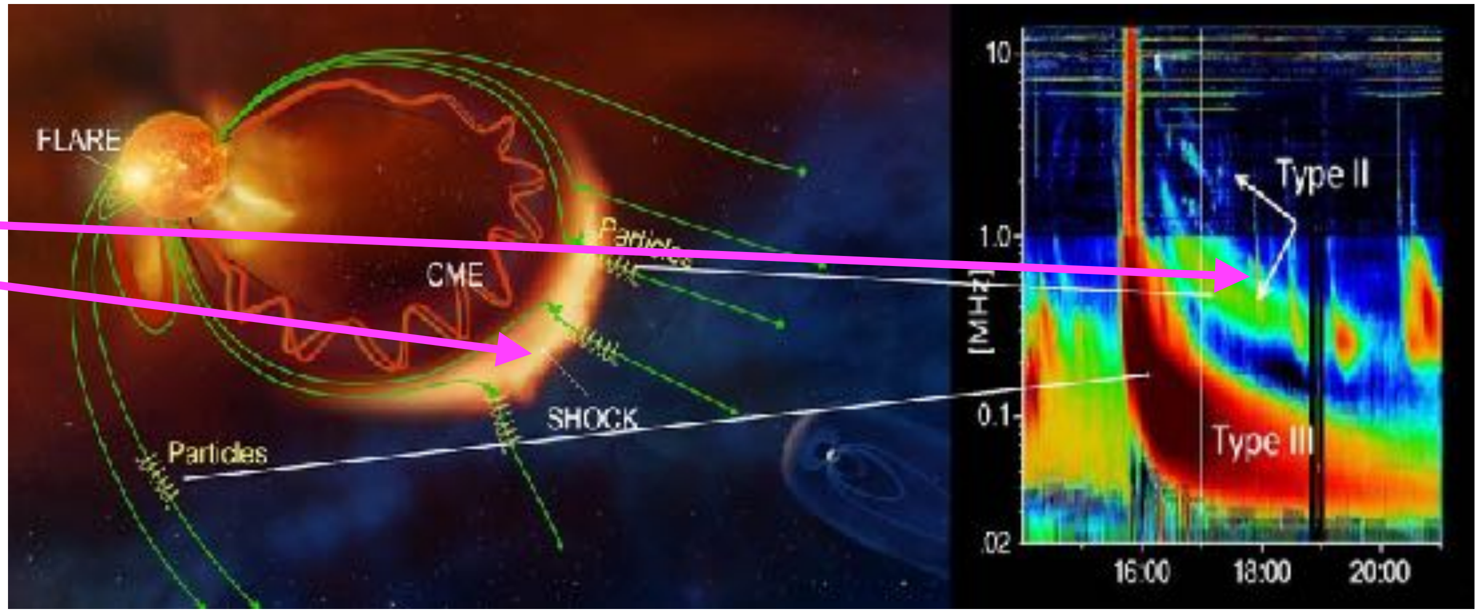
T_{corona}~7.8 MK (from X-ray measurements) → $H = kT/mg \sim 0.33\ R_*$

- V/I ~ 90% → $f \sim f_{pe}$ (fundamental plasma emission) ~ $N_e^{1/2}$

f ~ 150 MHz → N_e= 2.8 $10^8\ cm^{-3}$ → $z \sim H \log(N_o/N_e) \sim 1\text{-}1.5\ R_*$

Drift -rate $df/dt = -f\ V / 2H$ → $|V| = (2H/f)\ df/dt > 2400$ km/s → **first stellar type II burst**





[Callingham+ 2025]

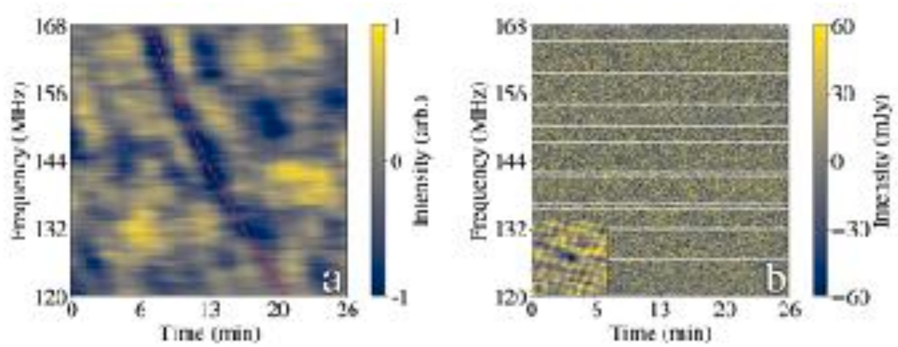
Drifting polarized bursts in LoTSS

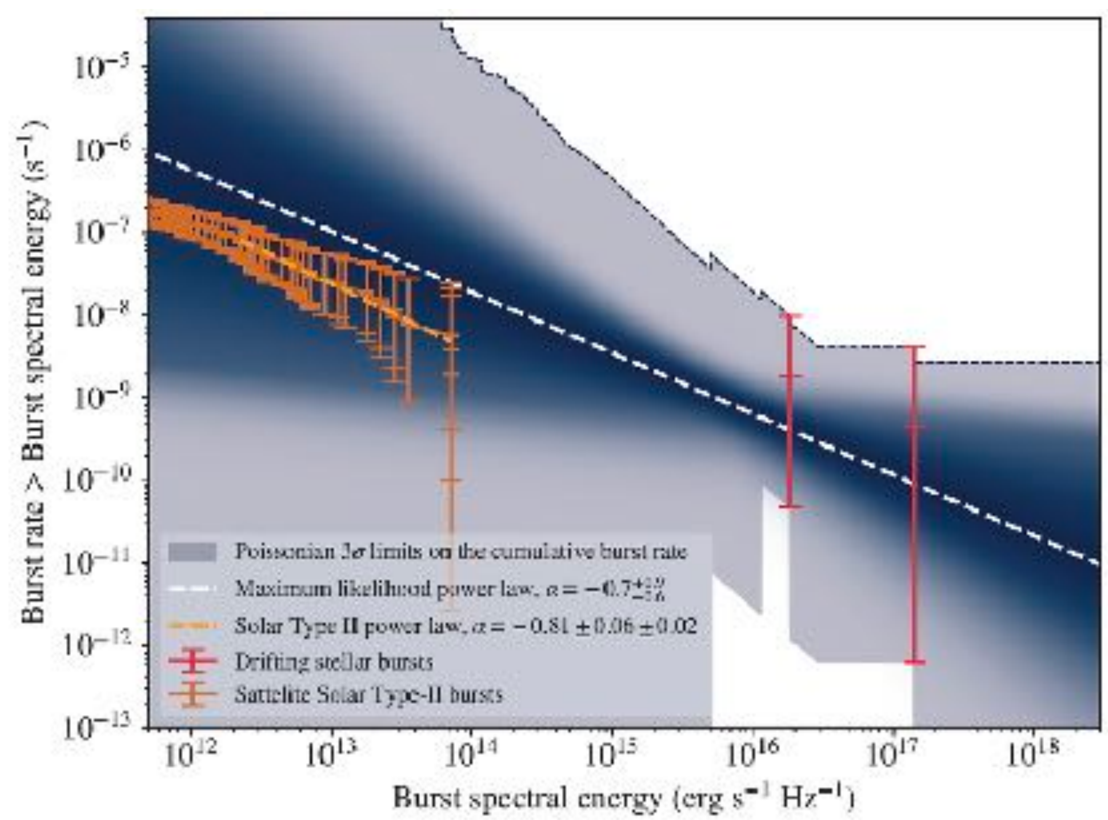
- S = 110-440 mJy → T_B ~ 4 10^{14} K → $10^{3\text{-}4}$ × the strongest type II
  → potentially harmful to an exoplanet's atmosphere ?

[Callingham+ 2025]

- Occurrence rate ~ 0.8 10^{-3} / d / star
  → comparable to the occurrence rate of Solar type II
  with V > 2400 km/s ~ 0.05% × 1.2 /d = 0.6 10^{-3} / d

- Detection of a second type II burst → occurrence statistics

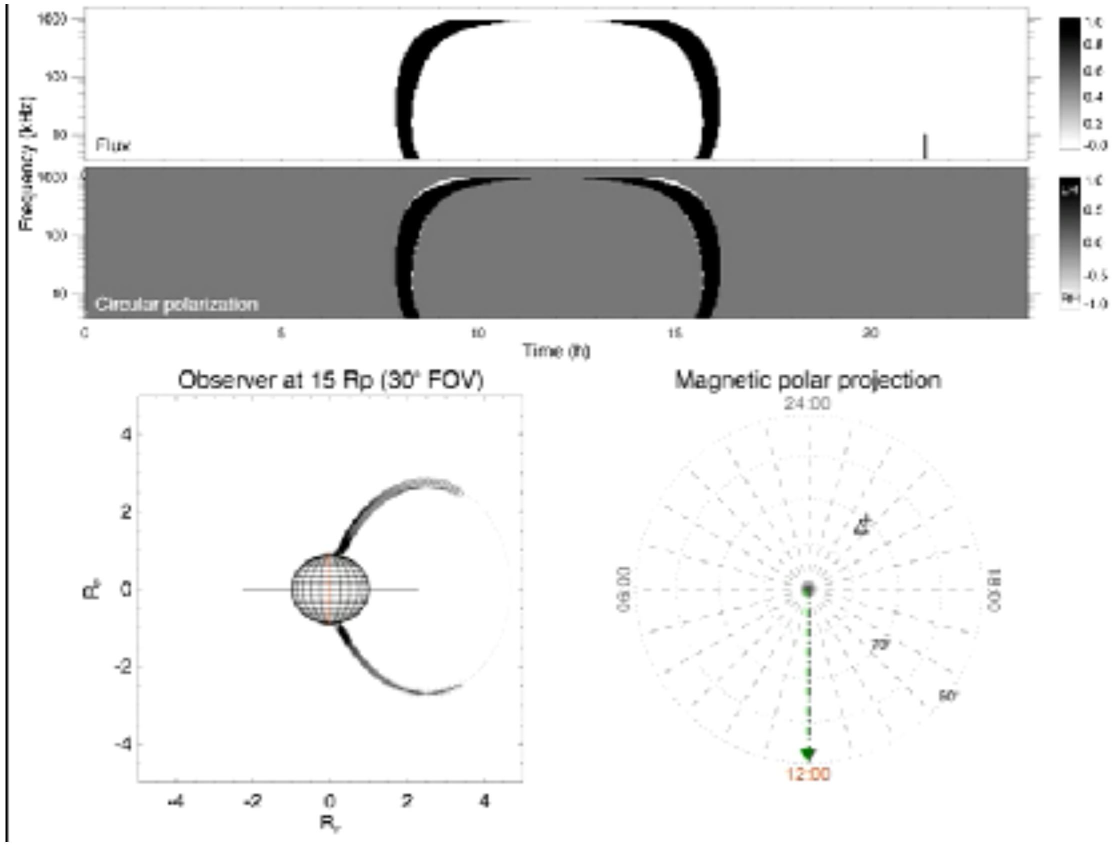


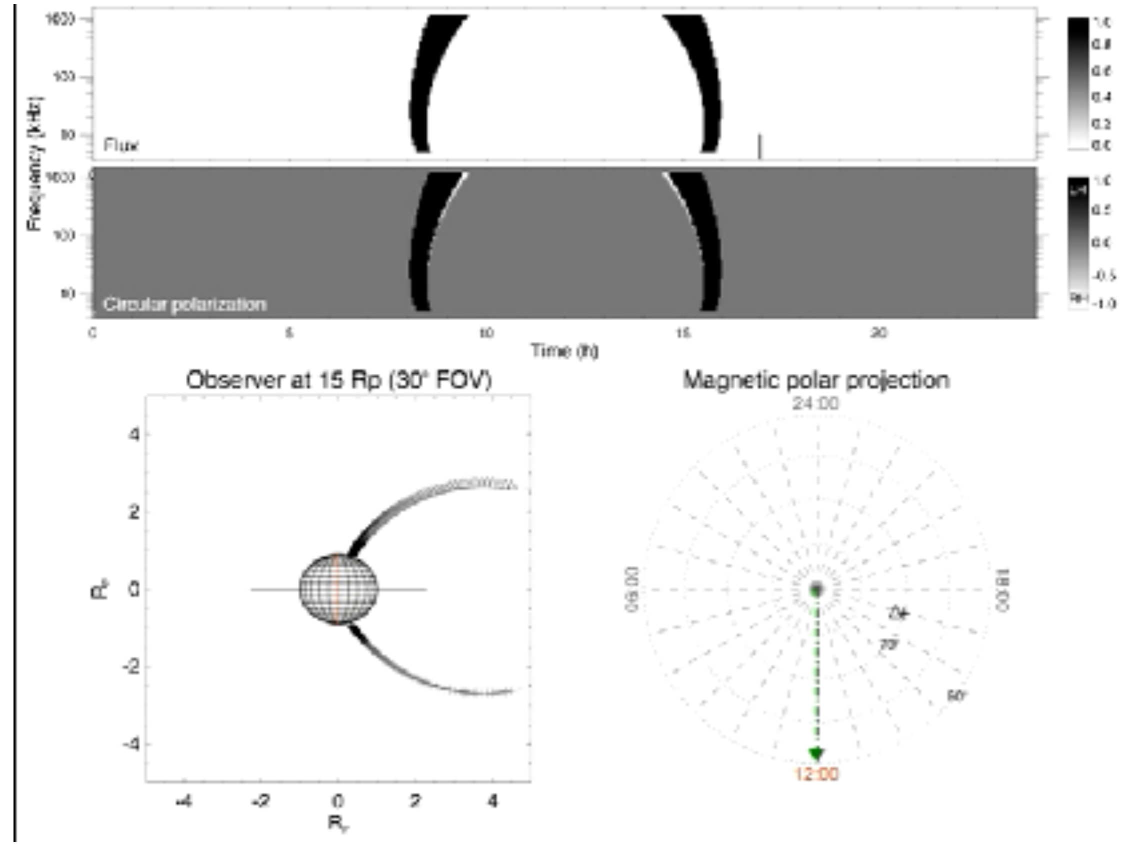


[Konijn+ 2025]

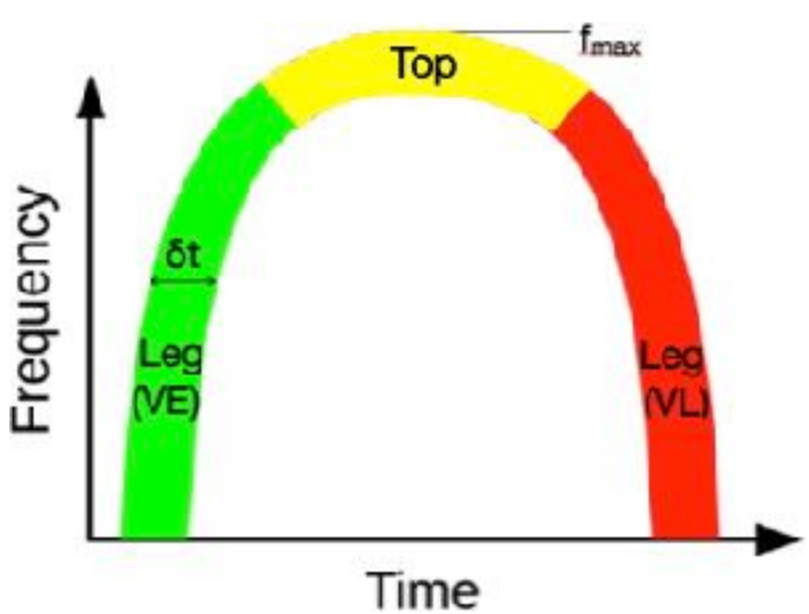
Non-drifting polarized bursts

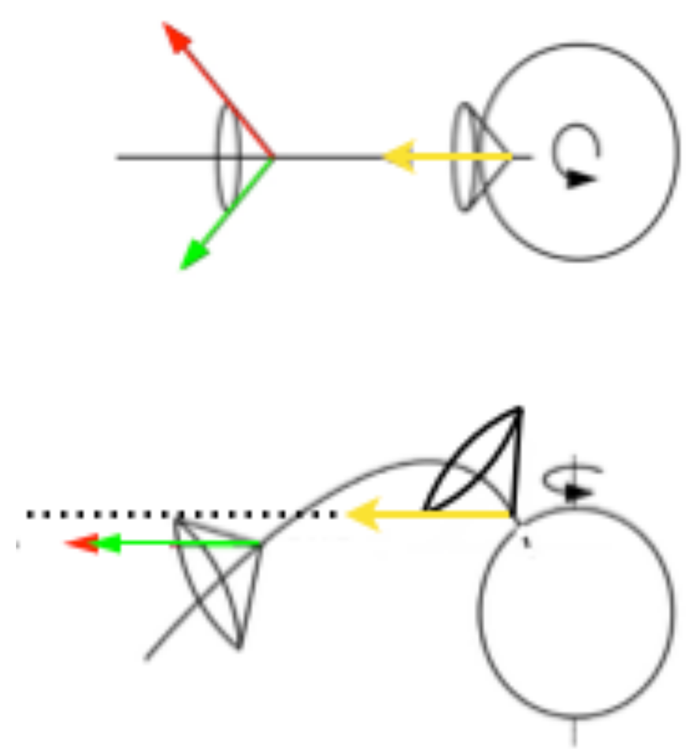
- ECMI produces ubiquitous arch-like signals (from an emitting magnetic flux tube)





[courtesy L. Lamy]

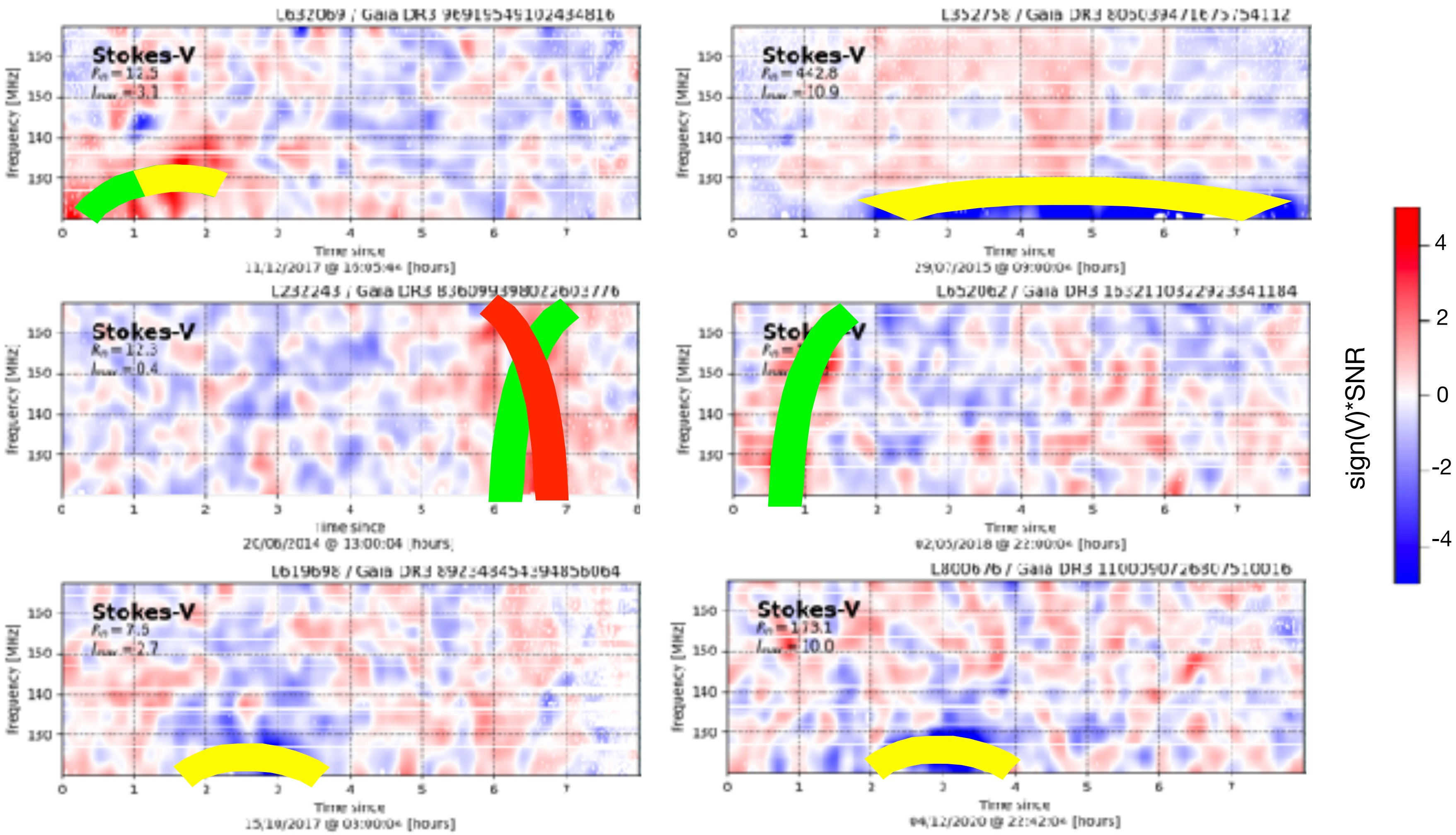


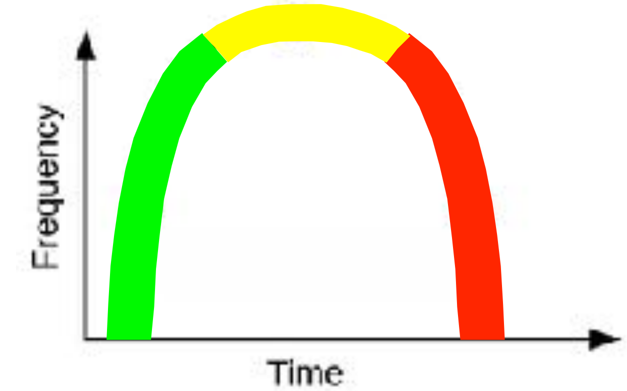


[Hess+ 2014]

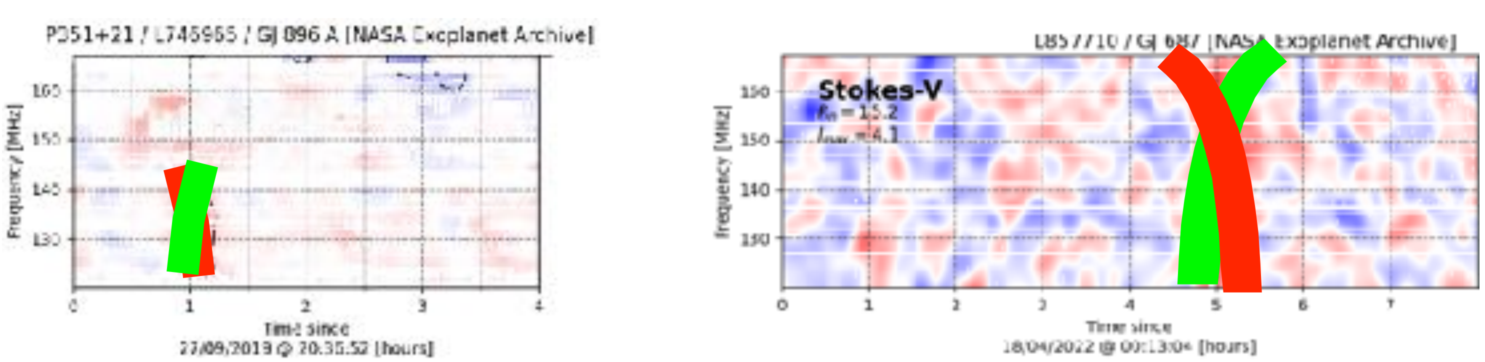
Non-drifting polarized bursts in LoTSS

Stars





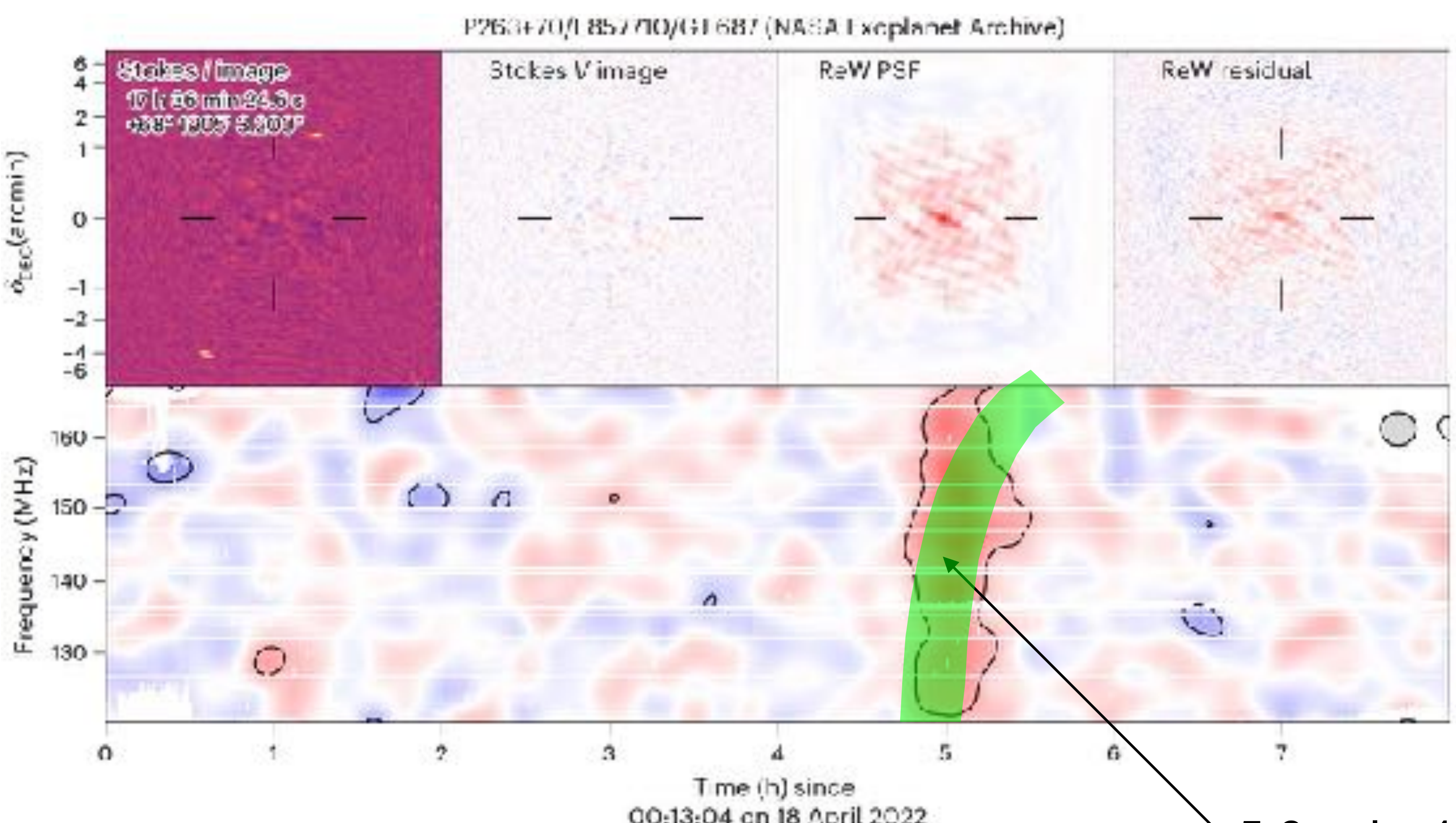
Star-Exoplanet systems



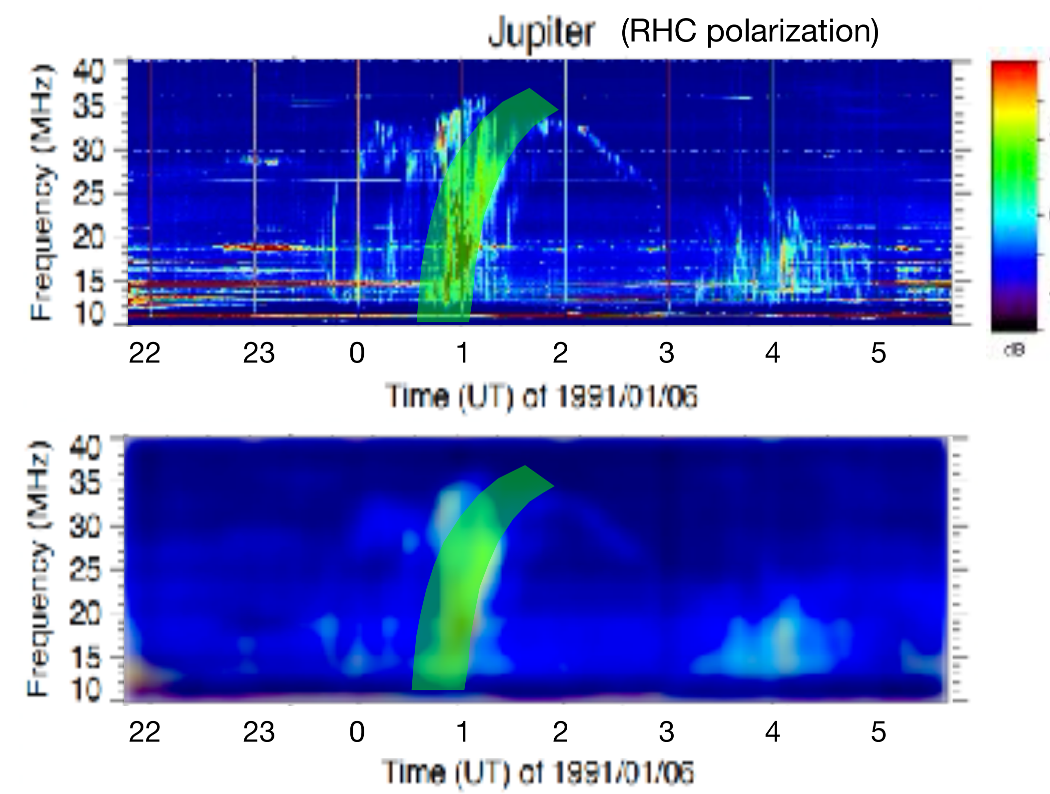
[Tasse+ 2026]

Case study of GJ 687

- Main sequence red dwarf (M3, 4.5 pc) with 2 orbiting planets (0.16 & 1.16 AU)

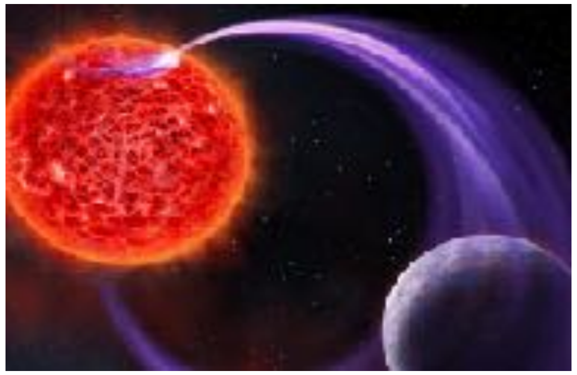


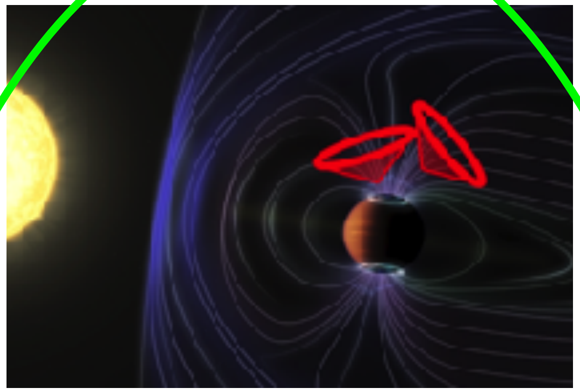
5.6 mJy, 45 min.



- **GJ 687** : $M_* = 0.4\ M_\odot$, $R_* = 0.4\ R_\odot$, P=61.8 d, T~ 3400 K, B~280 G ?
- Hot Neptune **GJ 687b** : a = 0.16 AU, e = 0.17 (P=38.1 days), Msin(i) = 0.054 M_J
- S ~ 5.6 mJy → $T_B = S\ \lambda^2\ d^2 / (k\ \pi\ R_P^2) \sim 10^{14}$ K , & V/I = 70-100% → ECMI

Case study of GJ 687





	SPI	Exoplanetary auroral emission
Emitted radio power (W)	2.6×10^{13}	2.6×10^{14}
RMSL power for an unmagnetized planet	$0.7 - 2.6 \times 10^{13}$	
RMSL power for an 1 G planet surface field ($R_{MP} = 3.2\text{-}4.1\ R_P$)	$0.9 - 2.3 \times 10^{14}$	
RMSL power for an 30 G planet surface field ($R_{MP} = 10.1\text{-}12.7\ R_P$)	$8.8 - 22 \times 10^{14}$	$8.8 - 22 \times 10^{14}$
ECMI cone thickness (°)	~ 0.3	≤ 0.3

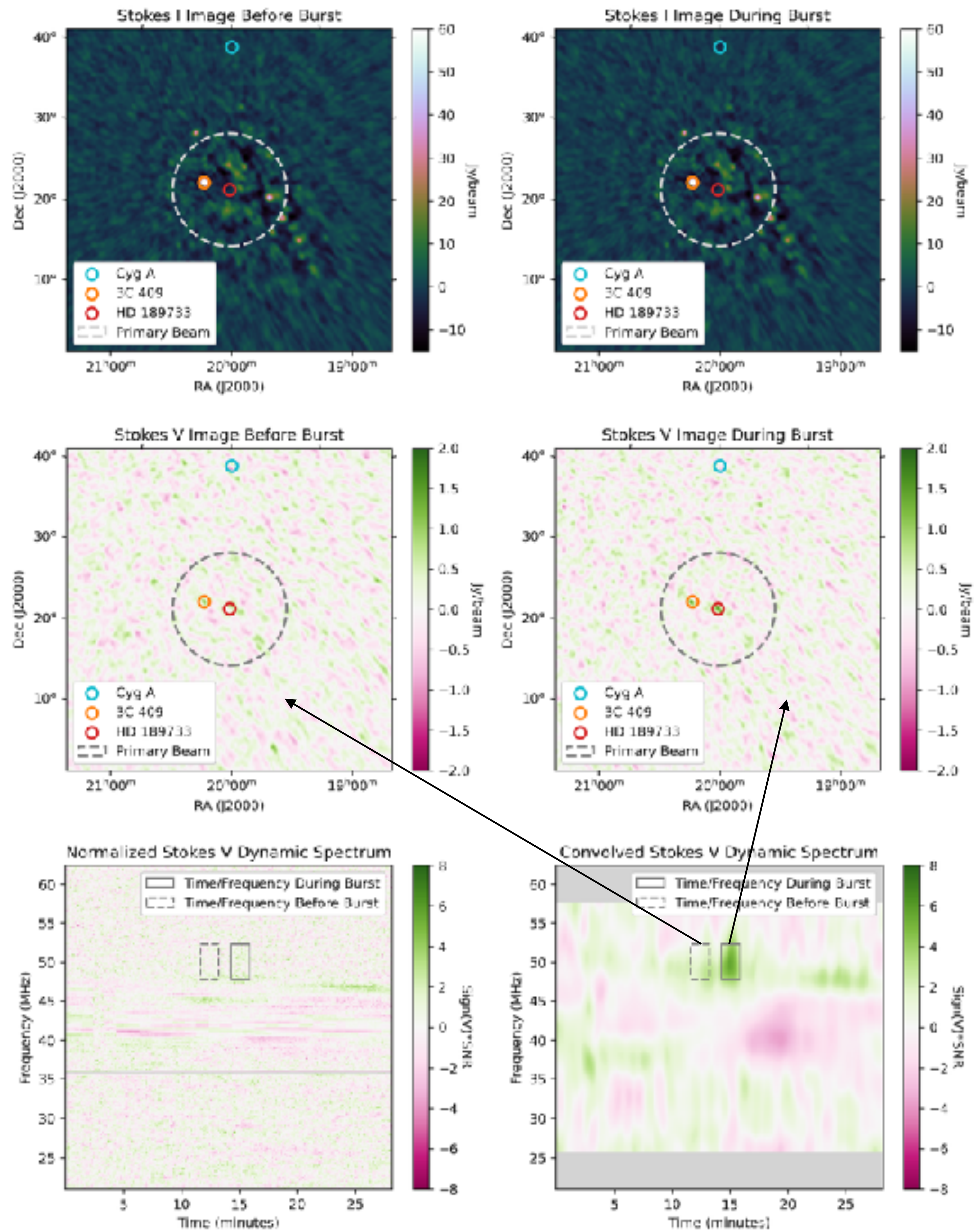
- Recent ZDI measurement of GJ 687 *[courtesy A. Strugarek]* : B* ~ 40 G → super-Alfvénic interaction

→ First exoplanetary magnetospheric radio emission ?

Polarized bursts with NenuFAR

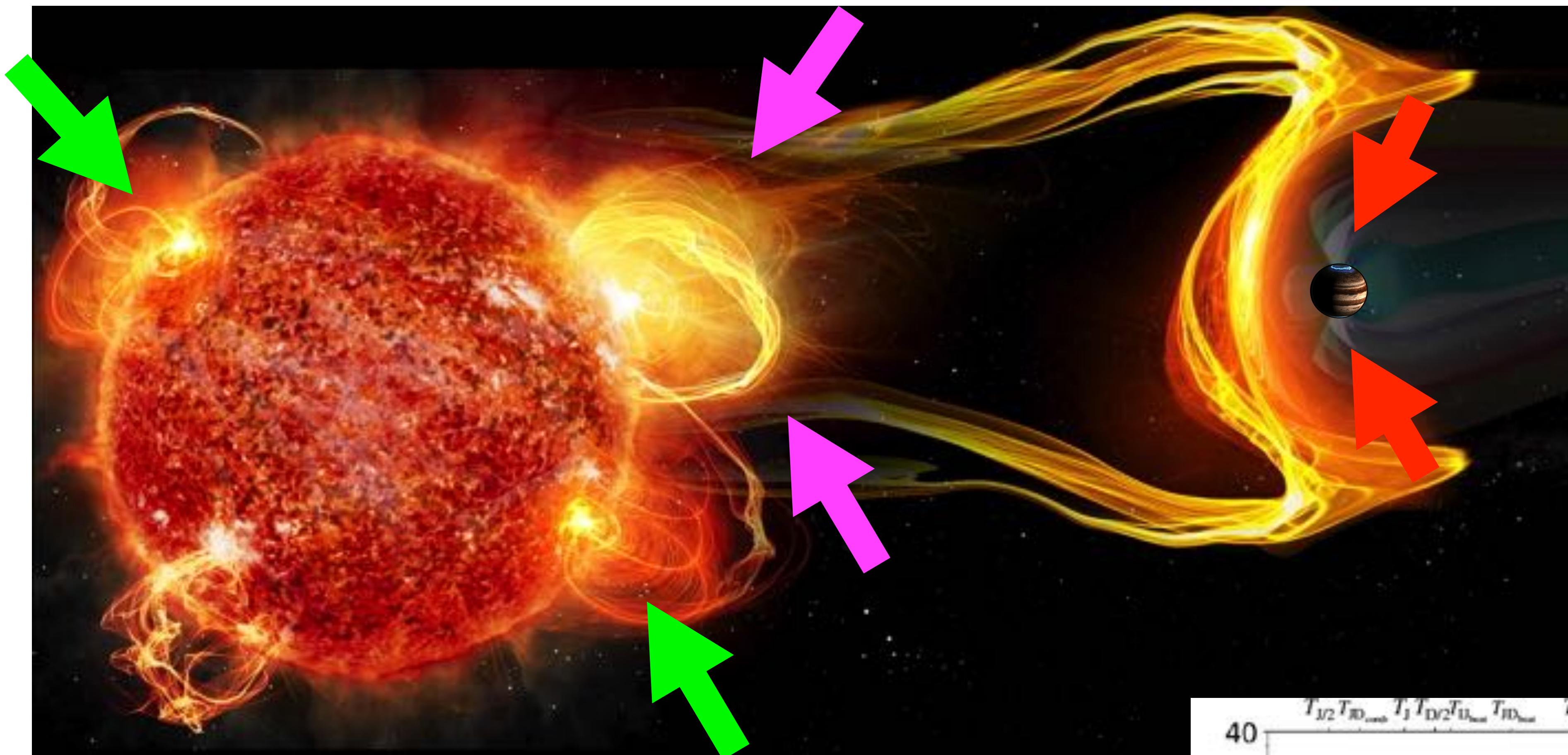
- Detection with RIMS of a LF burst from the star-planet system **HD 189733**
- ~100 h observation, covering all orbital phases
- 1 burst, 1.5 Jy, 6σ, 96 s × 4.5 MHz
- Fractional polar. >38%
- Burst at ~planet transit
- $T_B \geq 7\times10^{15}$ K, $P_R \geq 4\times10^{15}$ W → coherent emission, CMI ?

[Zhang+ 2025]

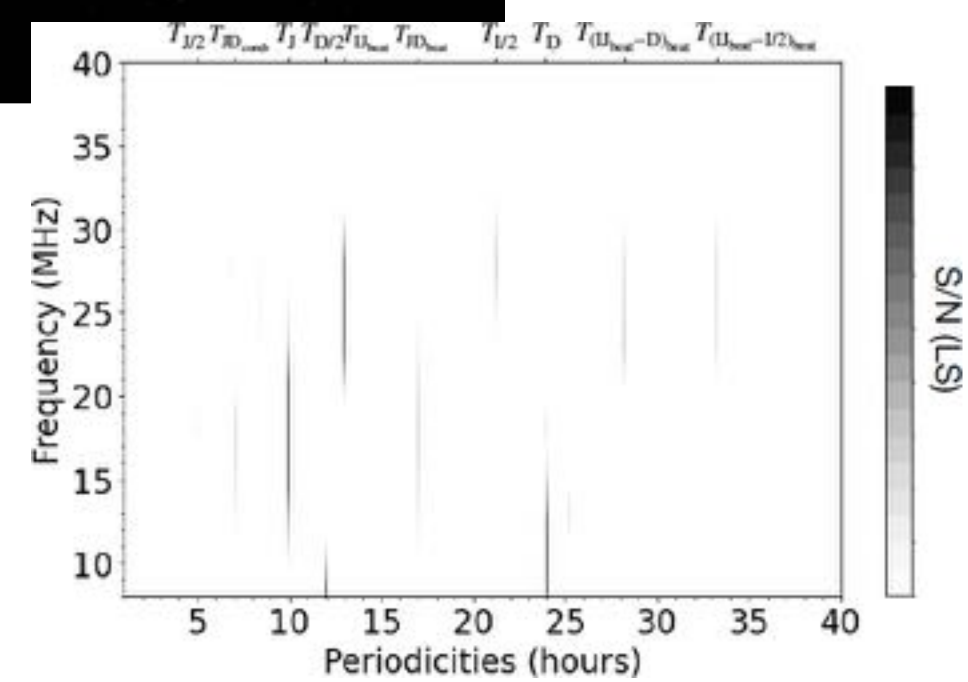


Origin of the signals : stellar / SPI / exoplanet ?

- Stellar flare ?
- Exoplanetary (magnetospheric, auroral) emission ?
- SPI : emission induced by exoplanet in stellar magnetic field ?



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



[Louis+ 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)

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