

# Low-frequency radio emissions from stellar and exoplanetary systems

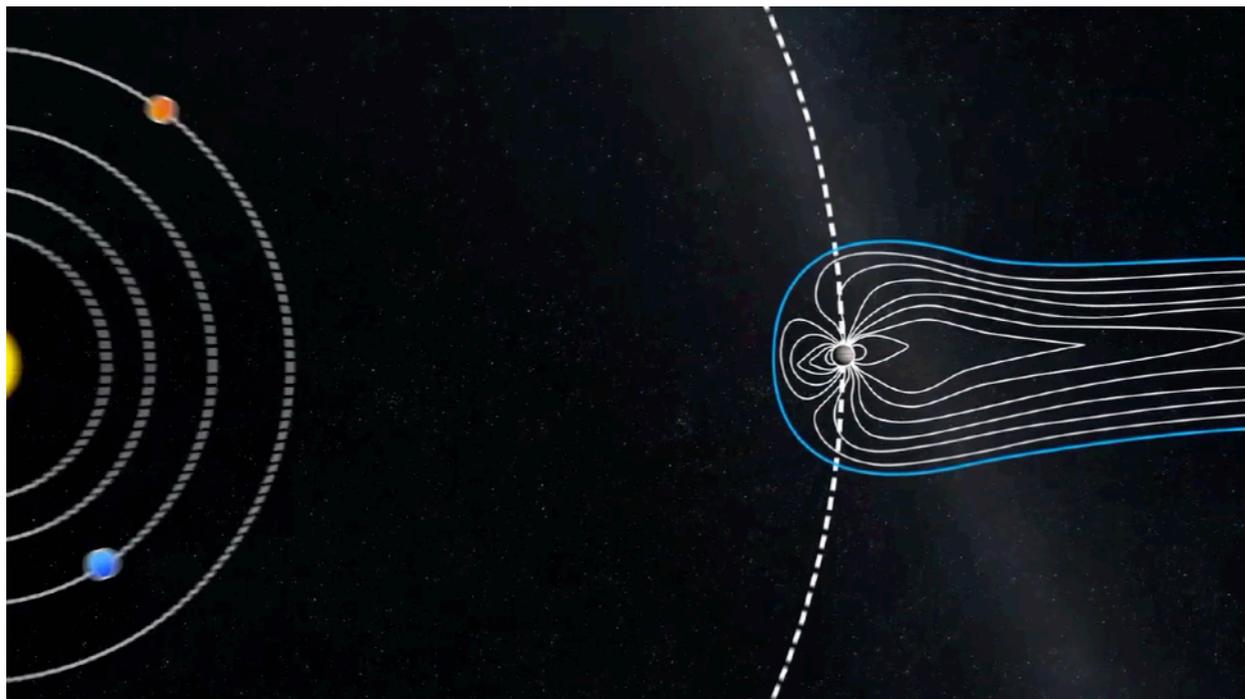
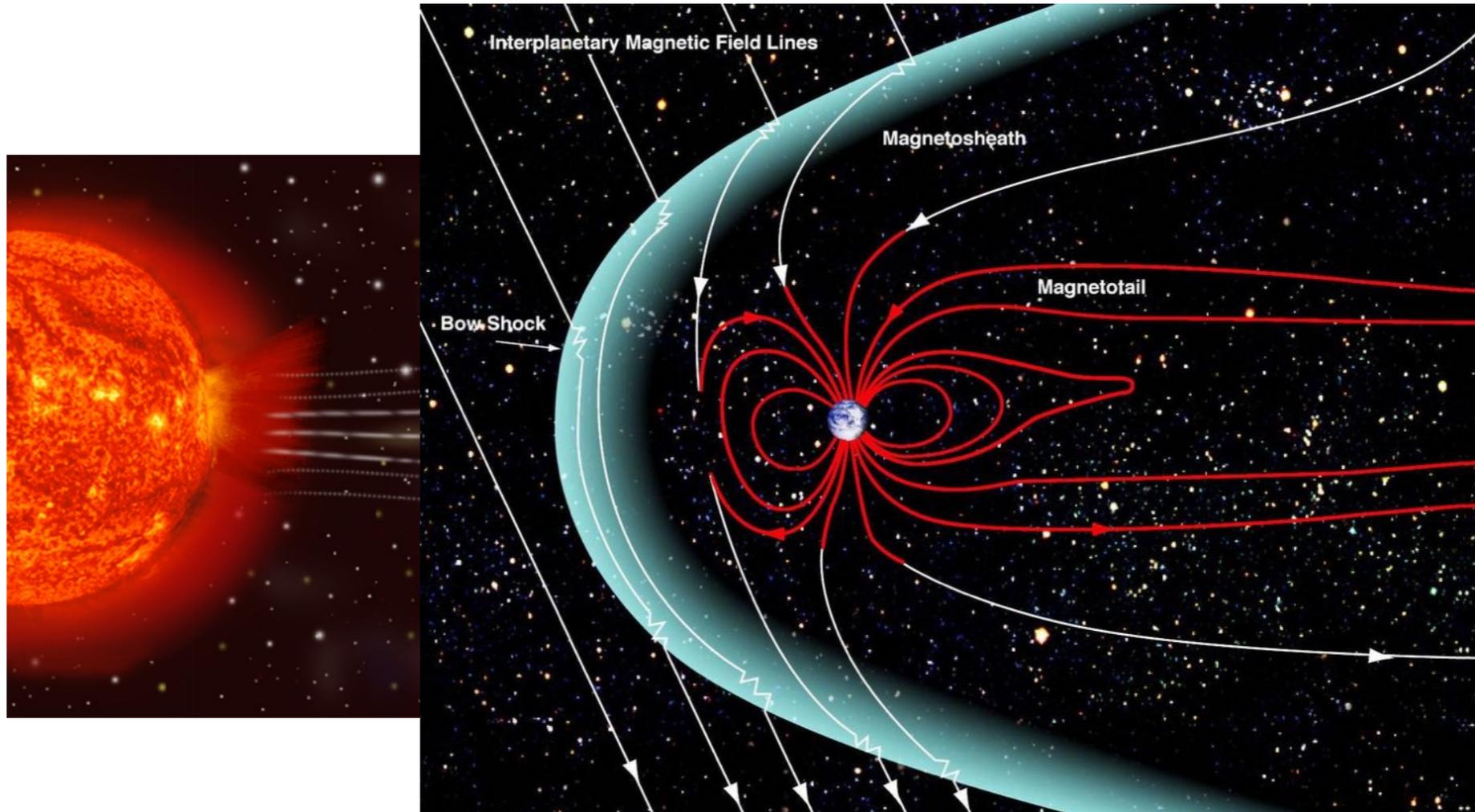
**Philippe Zarka**

*LIRA, CNRS - Observatoire de Paris - PSL*  
[philippe.zarka@obspm.fr](mailto:philippe.zarka@obspm.fr)

+ C. Tasse, X. Zhang, C. Louis, E. Mauduit, J.-M. Griessmeier, J. Turner,  
L. Lamy, J. Girard, A. Loh, Q. Duchêne, and B. Poux-Bouret  
+ thanks to H. Vedantham, J. Callingham, T. Shimwell, M. Hardcastle ...

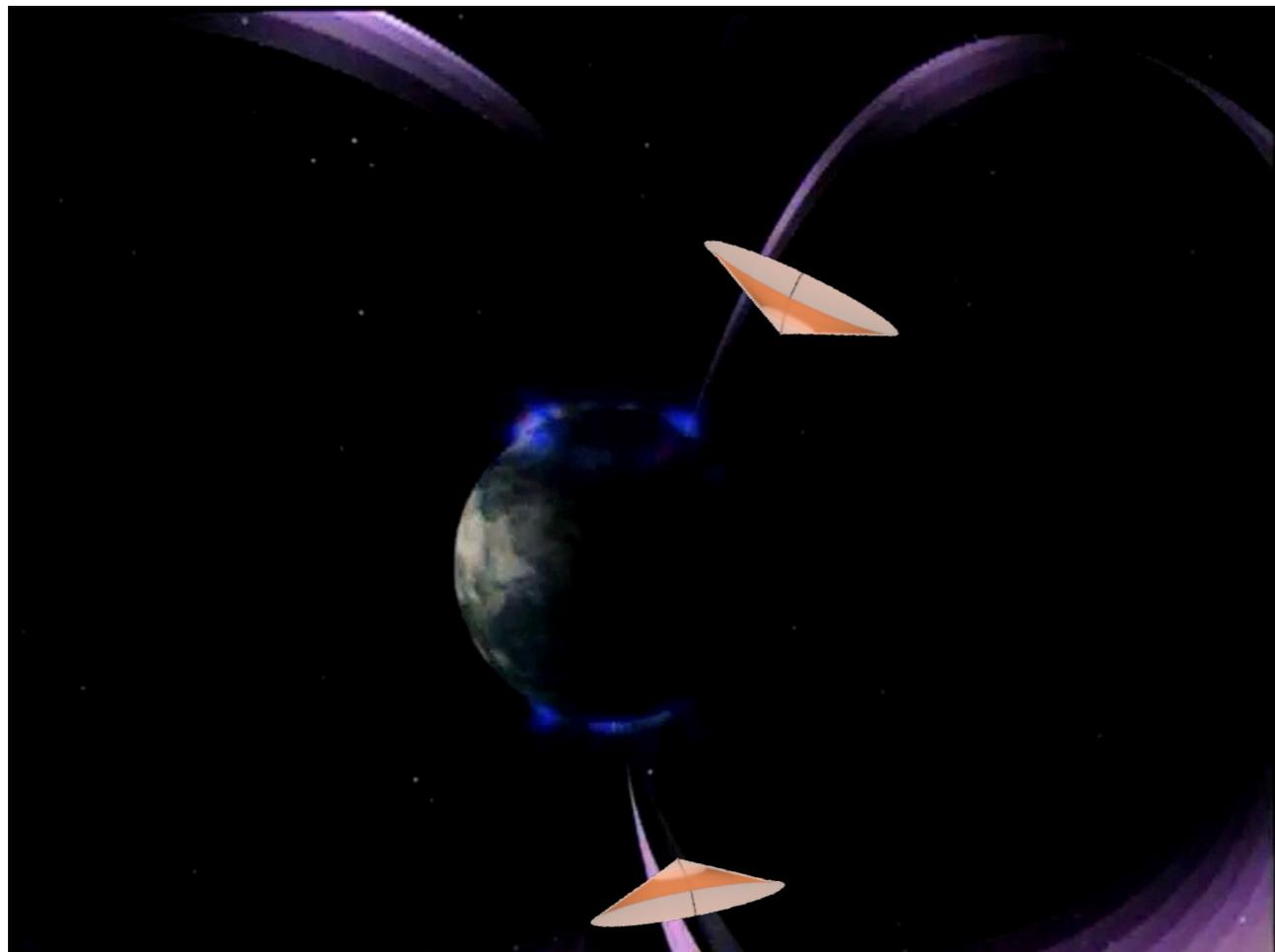
erc

# Context : Planetary Magnetospheres

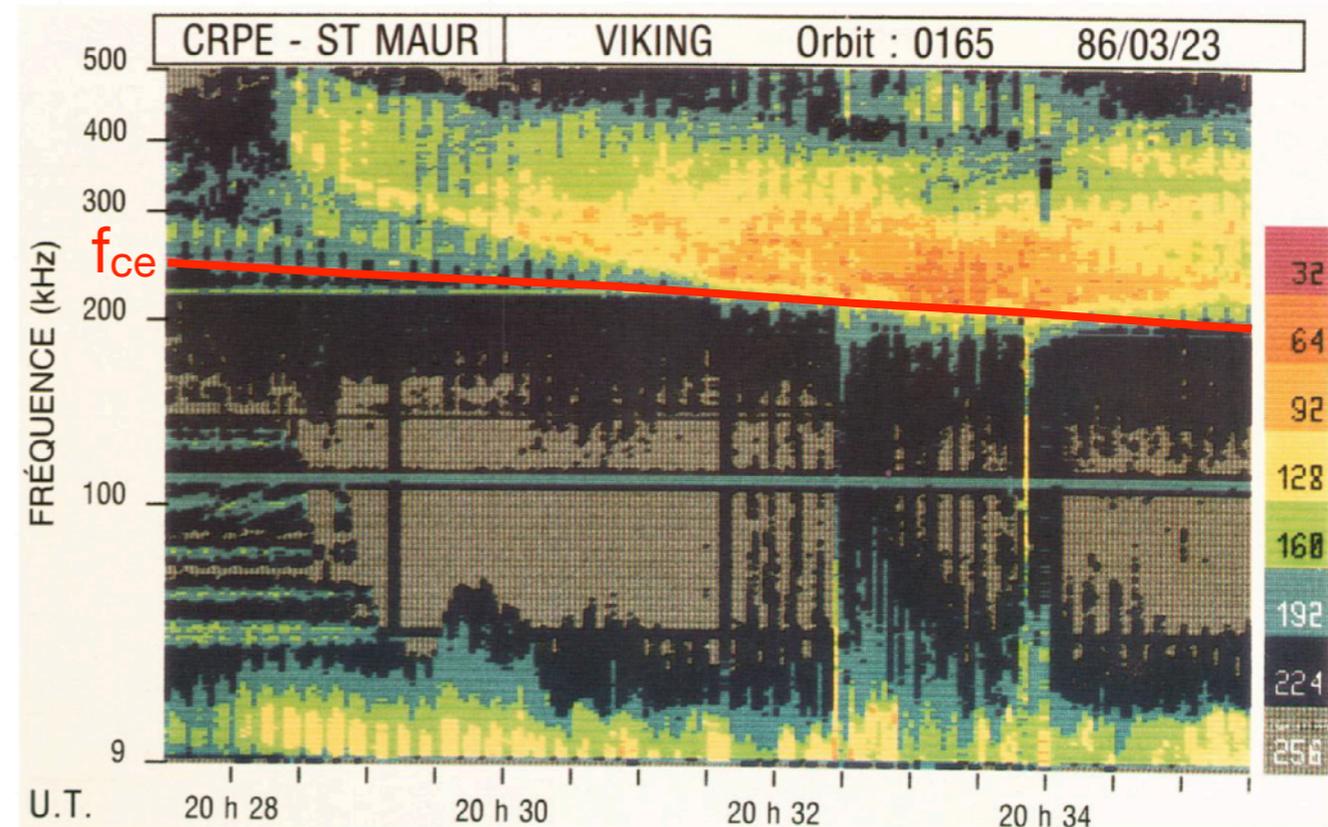
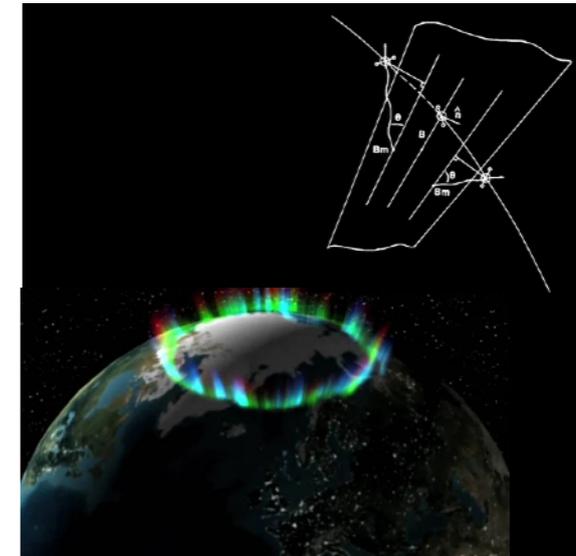


# Planetary Radio Emissions ①

"Solar Wind - Magnetosphere" Auroras: UV & Radio



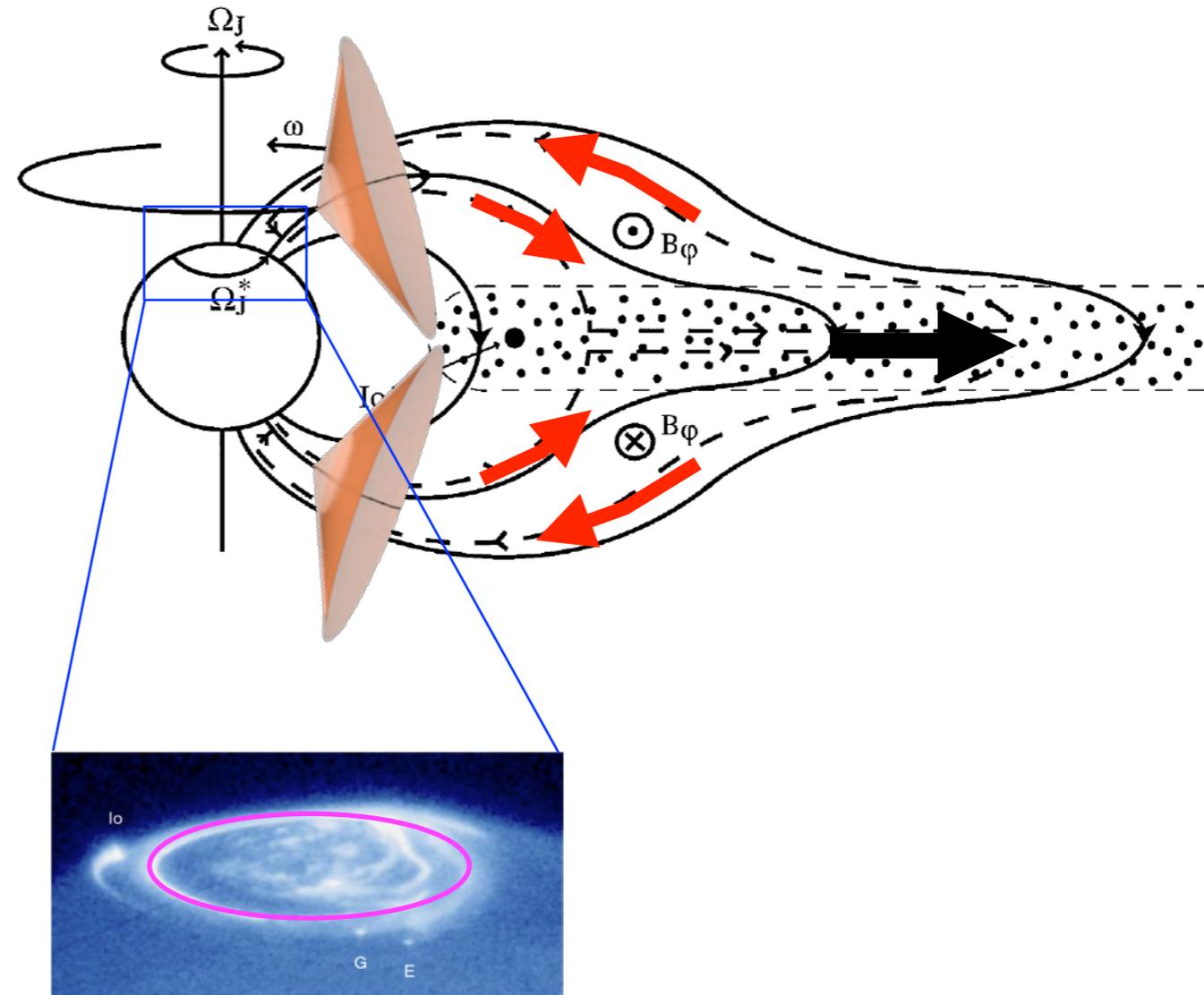
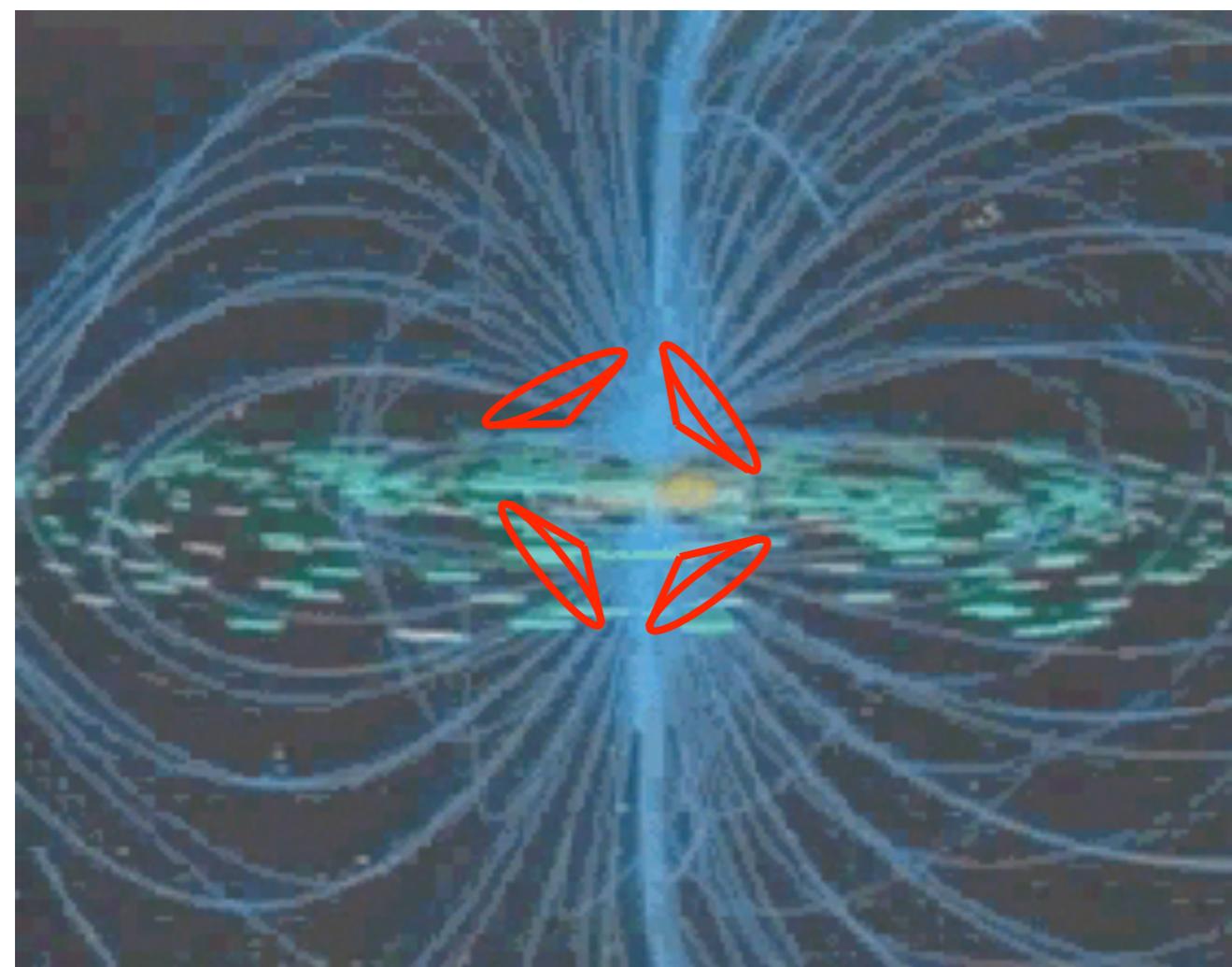
[Dungey 1961]



studied in-situ at Earth, Jupiter, Saturn

# Planetary Radio Emissions ②

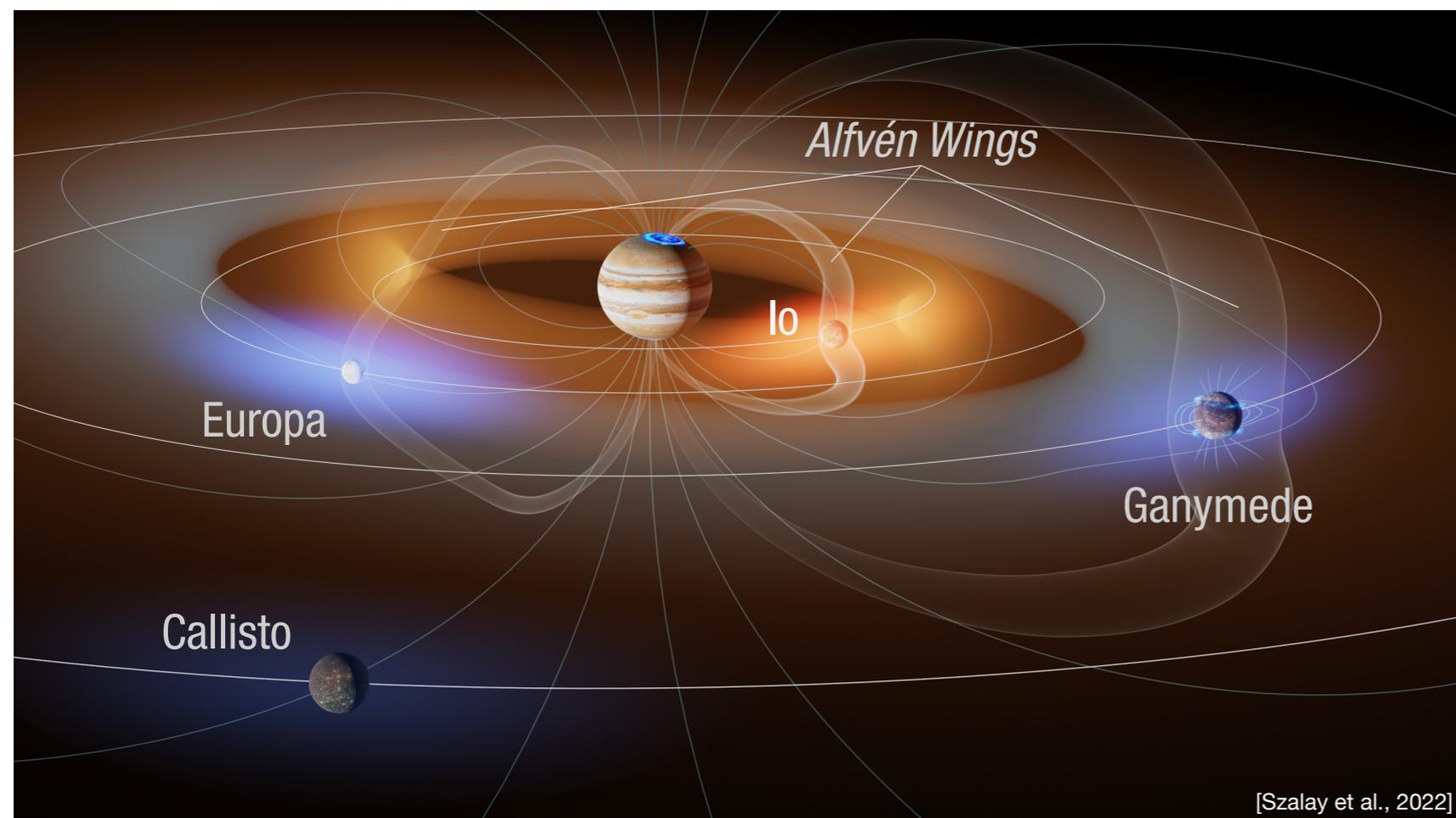
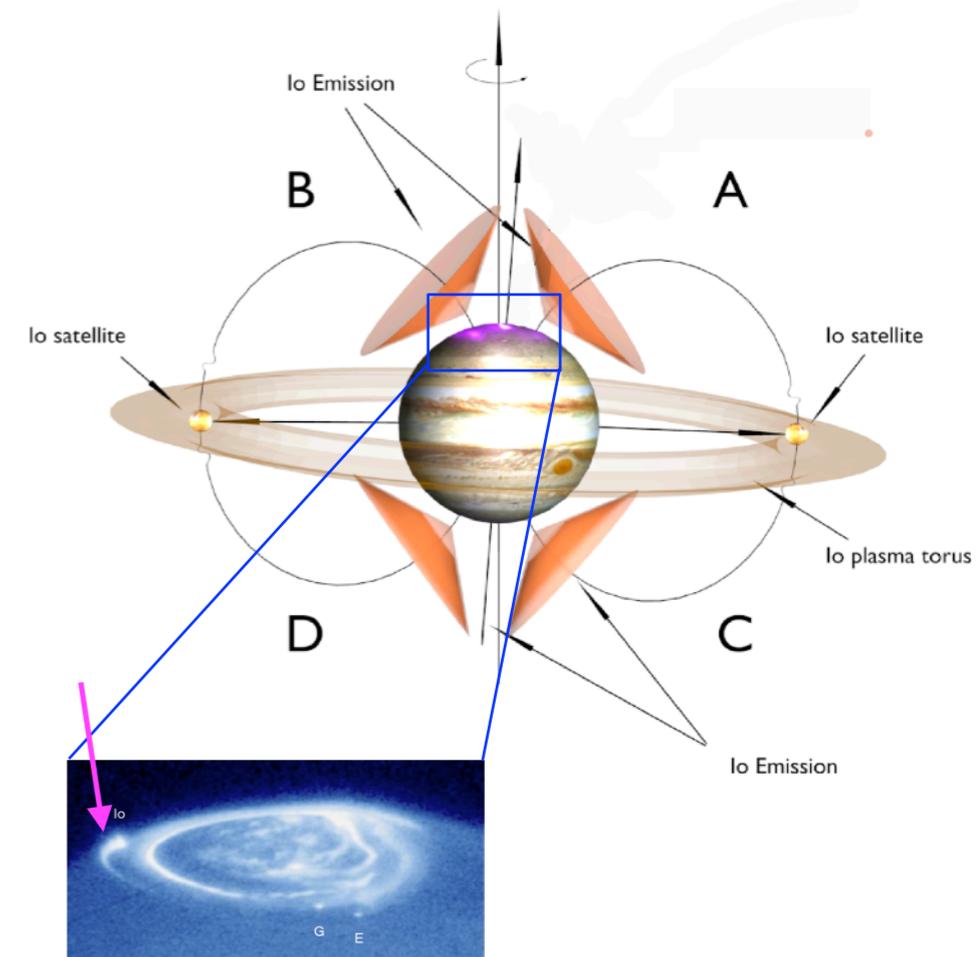
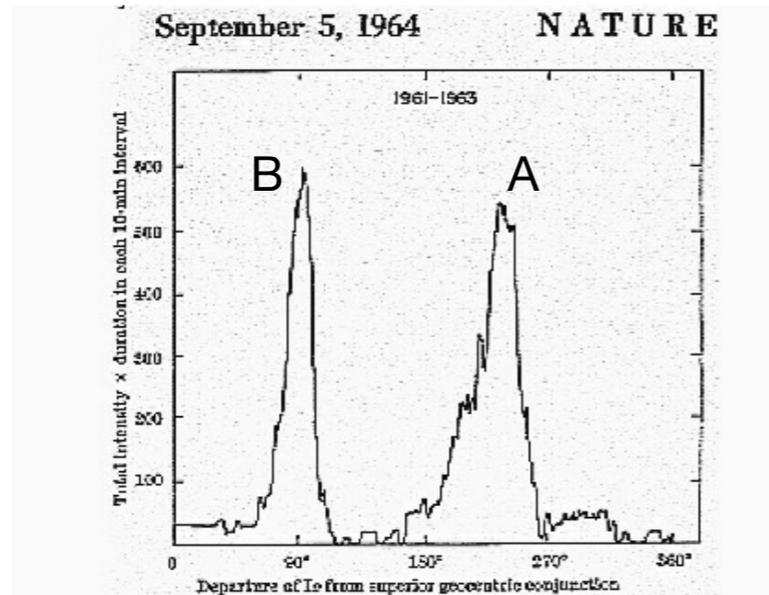
## "Rotational" Auroras: UV & Radio



[Cowley & Bunce 2001]

# Planetary Radio Emissions ③

## Satellites - Magnetosphere Interactions

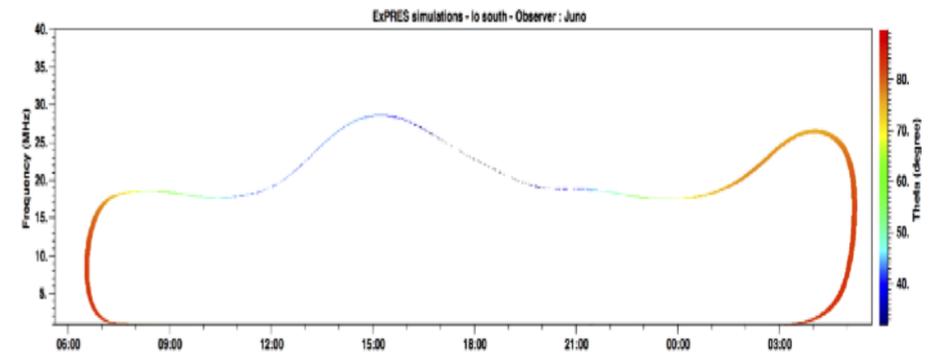
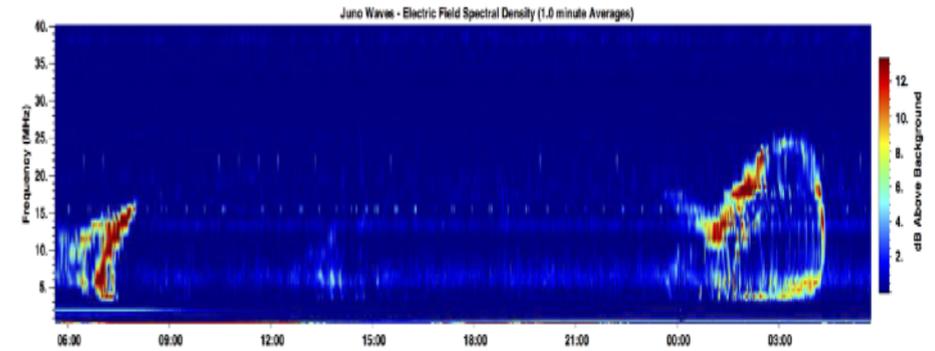
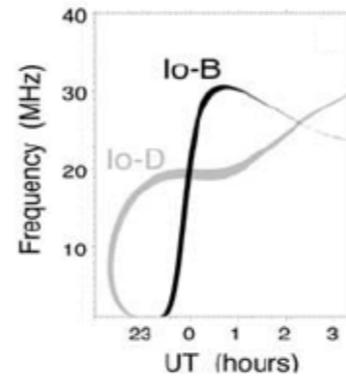
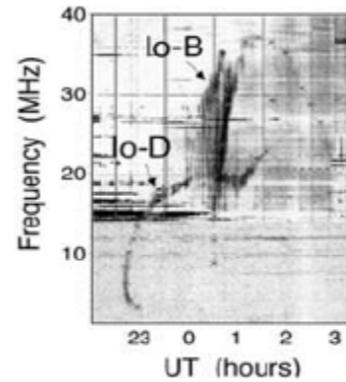


Io: [Bigg 1964]  
Ganymede: [Louis+ 2017, Zarka+ 2018]  
Europa: [Jacome+ 2022]

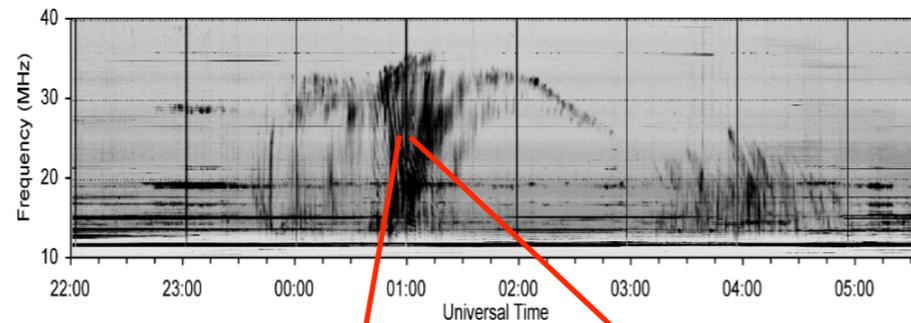
# Emission Process : Electron Cyclotron Maser

Observations  
(ground & space)

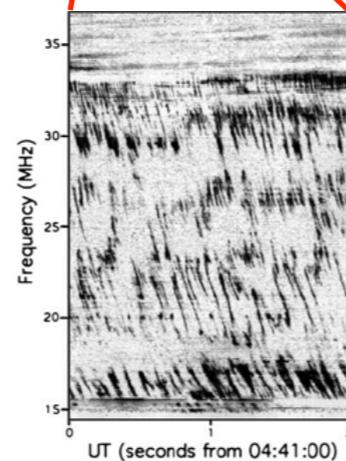
Theory  $\Rightarrow$  Simulation



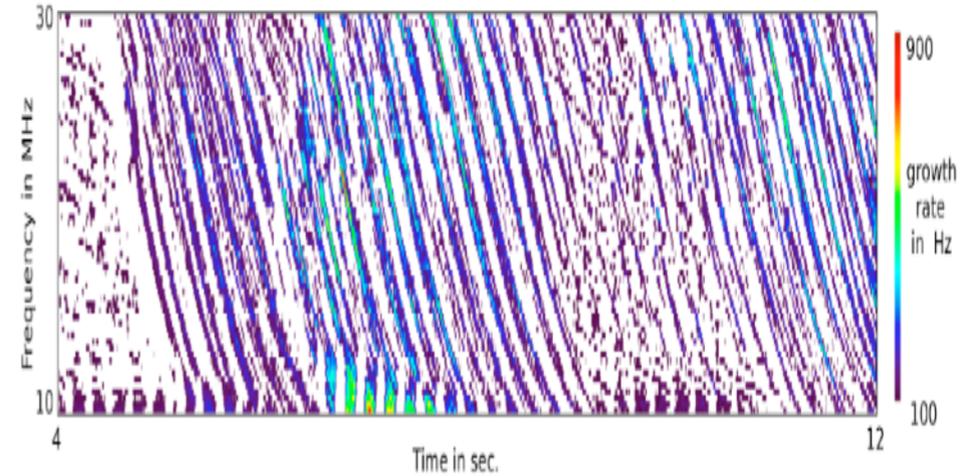
[Zarka 2004, Hess+ 2008, 2009, Louis+ 2017, 2019]



Observations  
(S-bursts)

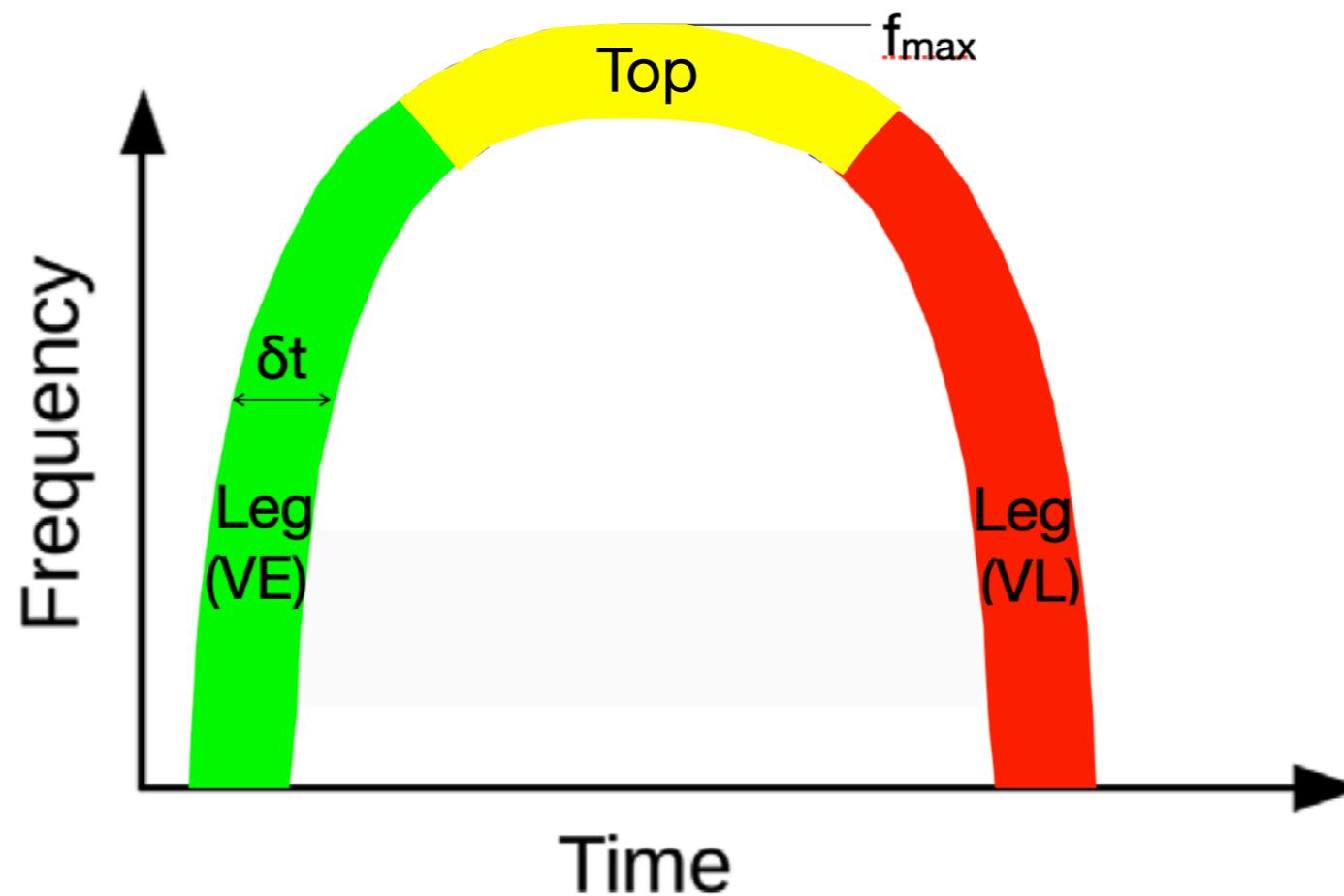
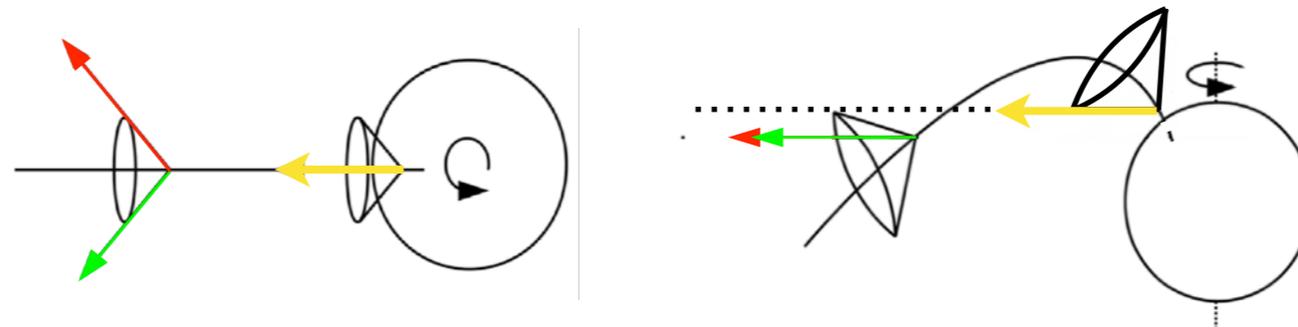


Theory  $\Rightarrow$  Simulation

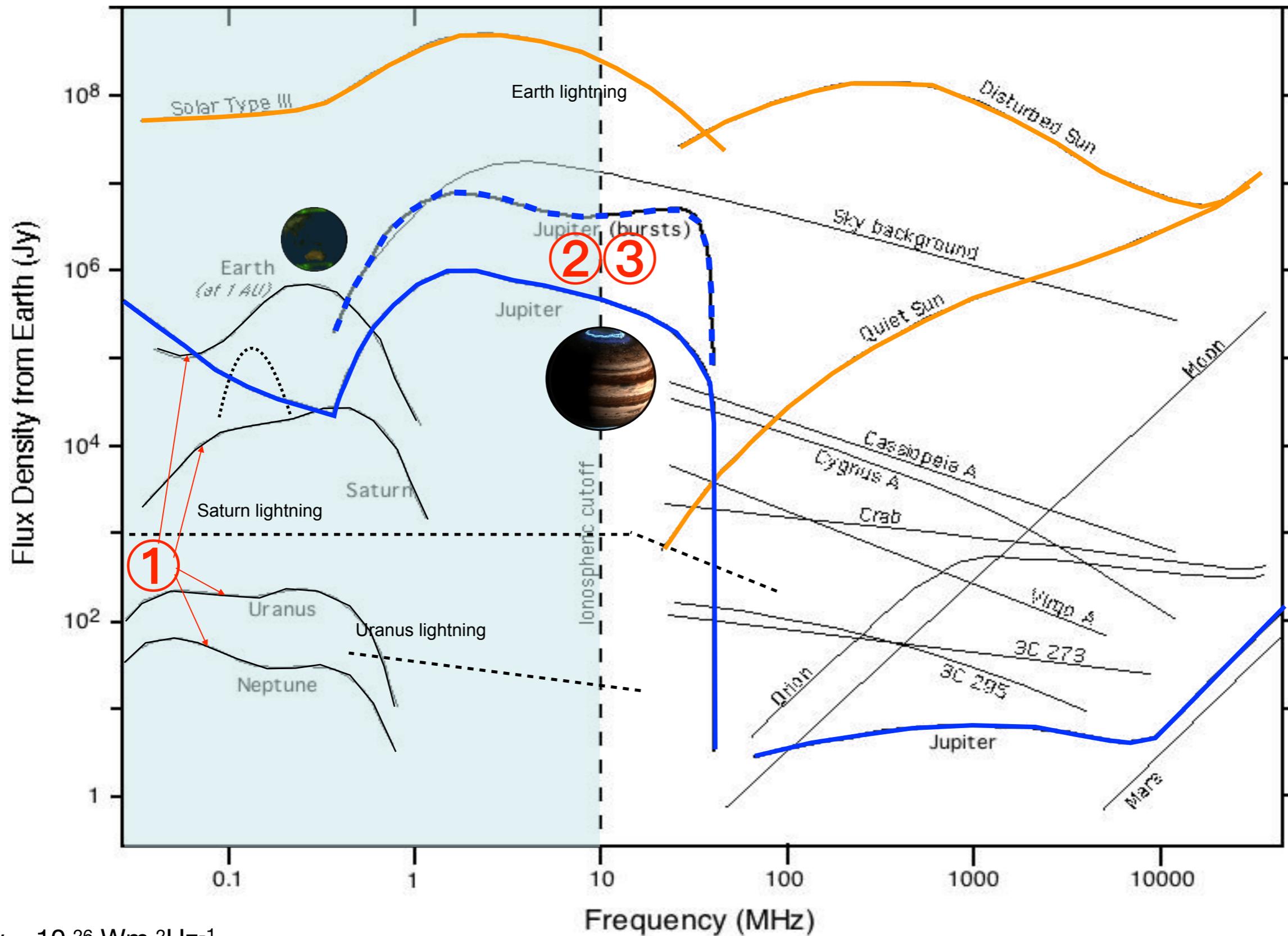


# A fundamental ECM prediction

for a rotating field line / flux tube

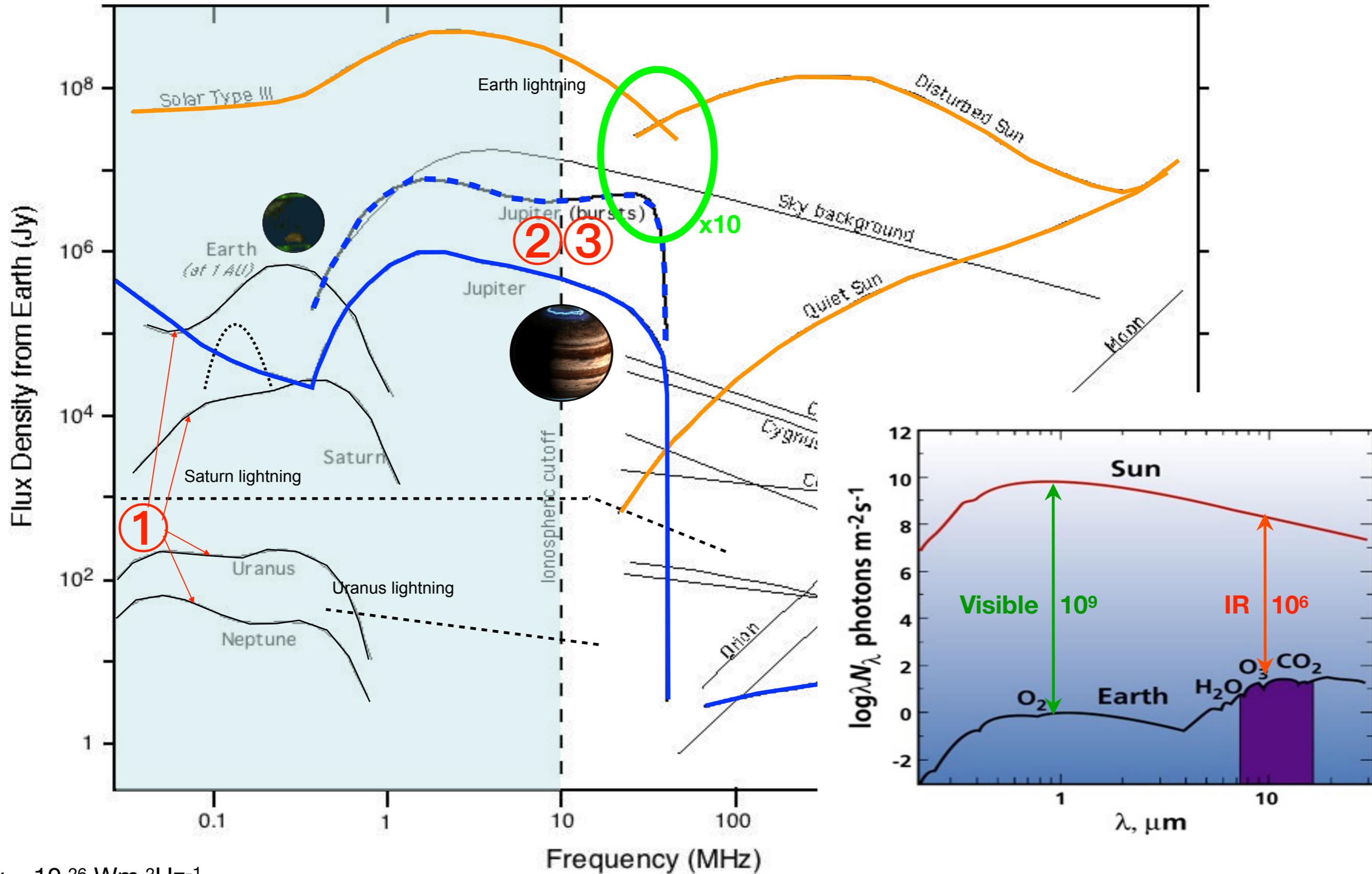


# Planetary Radio Emissions ①②③



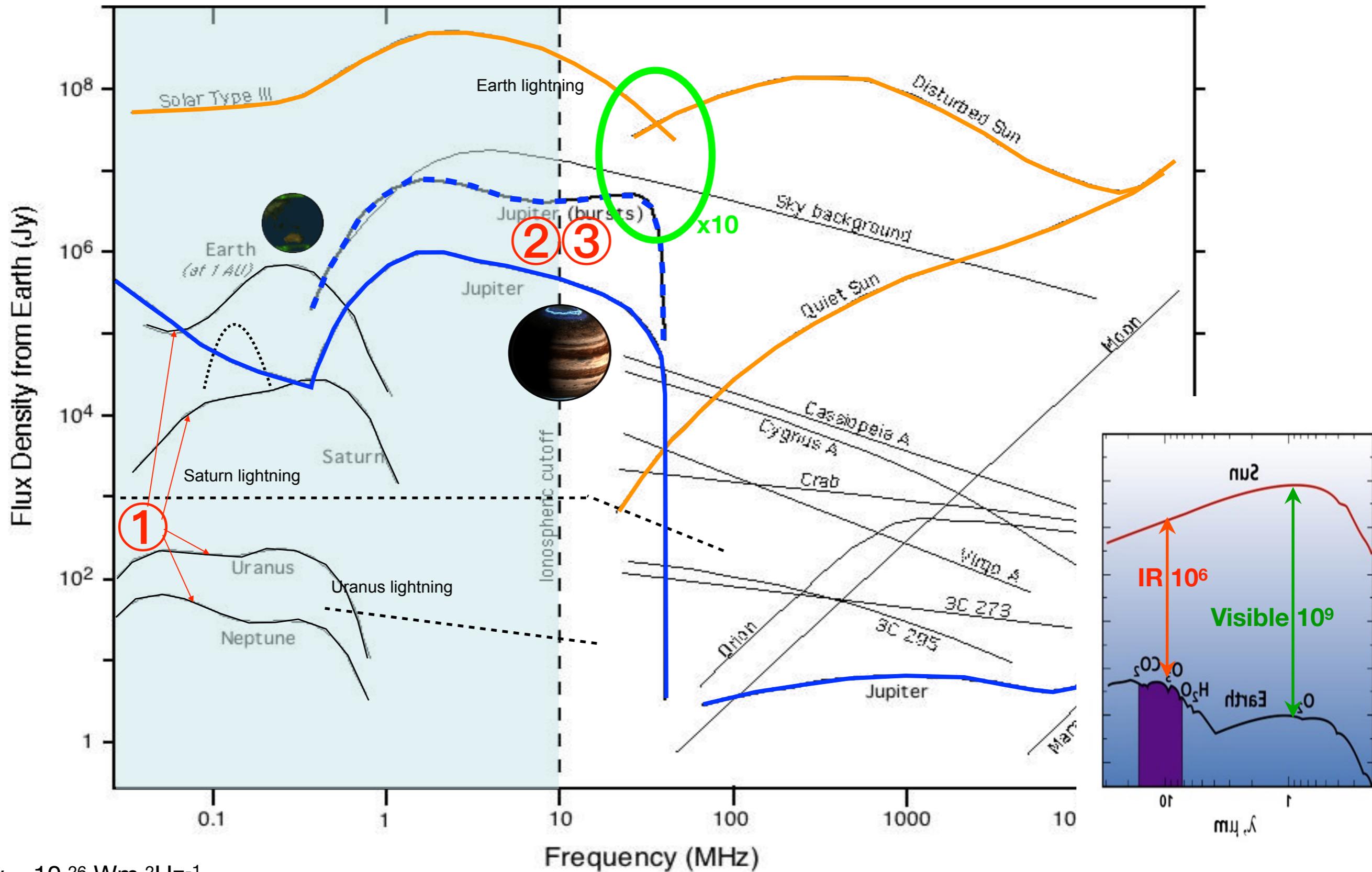
1 Jy =  $10^{-26}$  Wm<sup>-2</sup>Hz<sup>-1</sup>

# Favourable contrast in radio / visible, IR



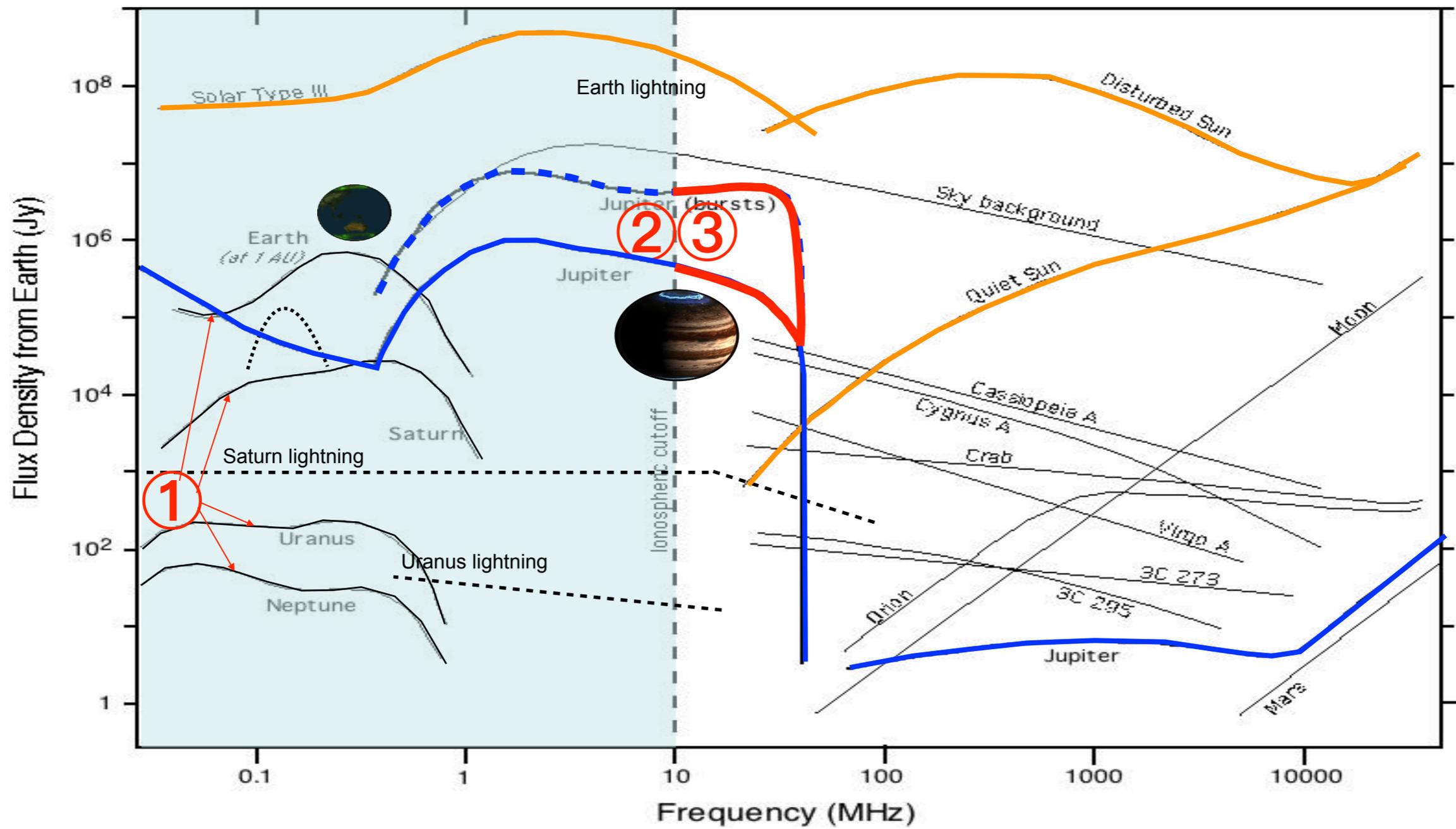
1 Jy =  $10^{-26} \text{ Wm}^{-2}\text{Hz}^{-1}$

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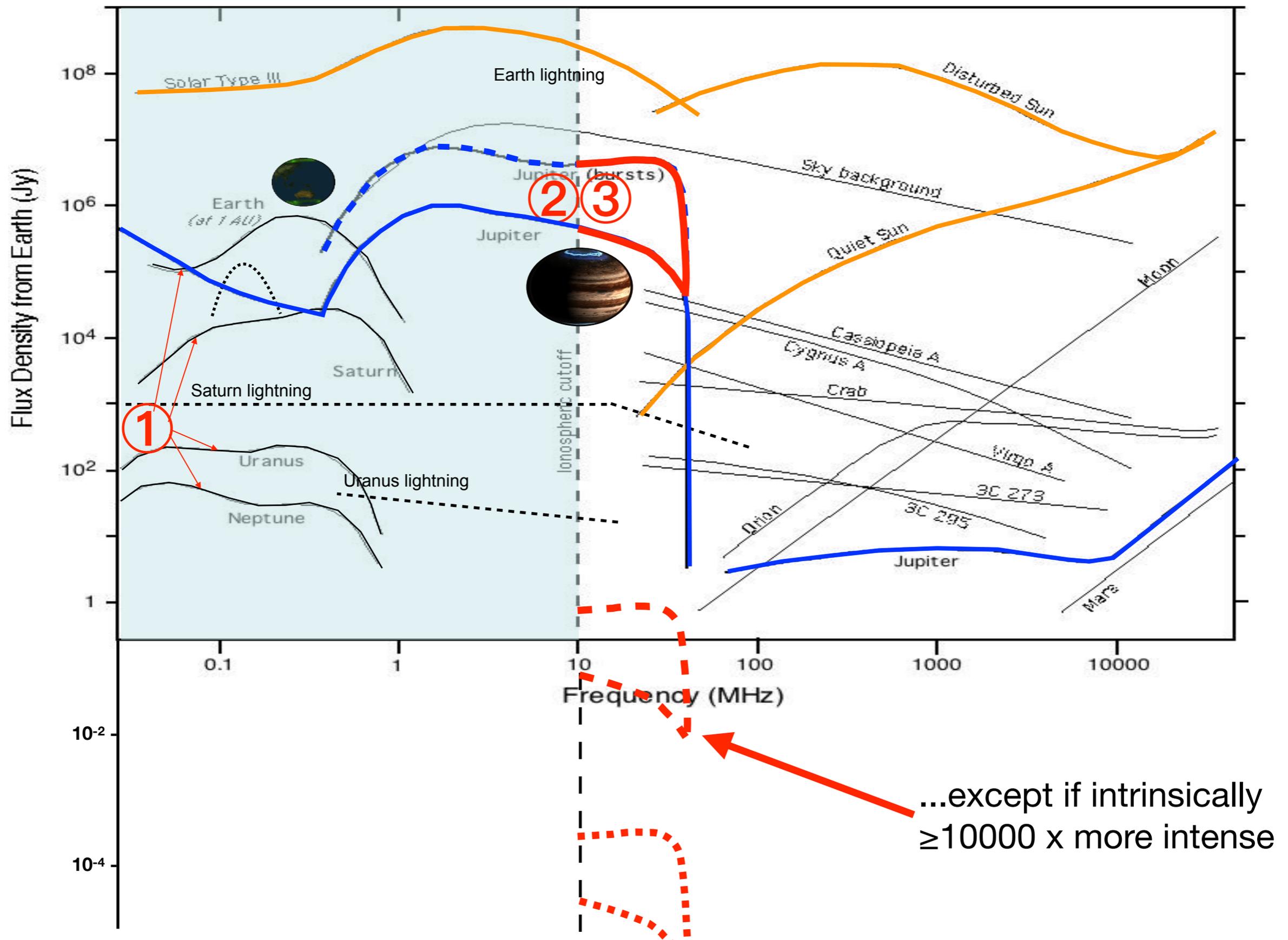


1 Jy =  $10^{-26}$  Wm<sup>-2</sup>Hz<sup>-1</sup>

# But

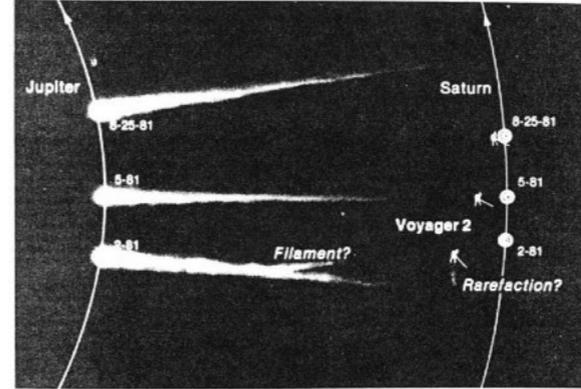
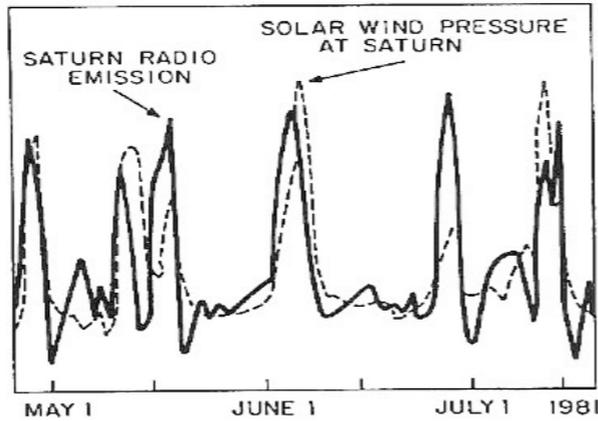
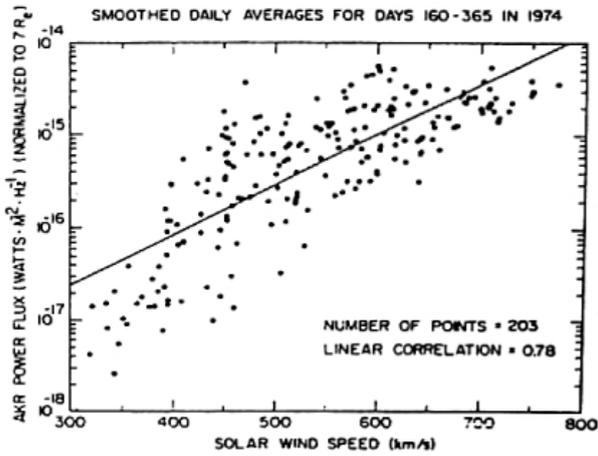


# But ~undetectable at stellar distances



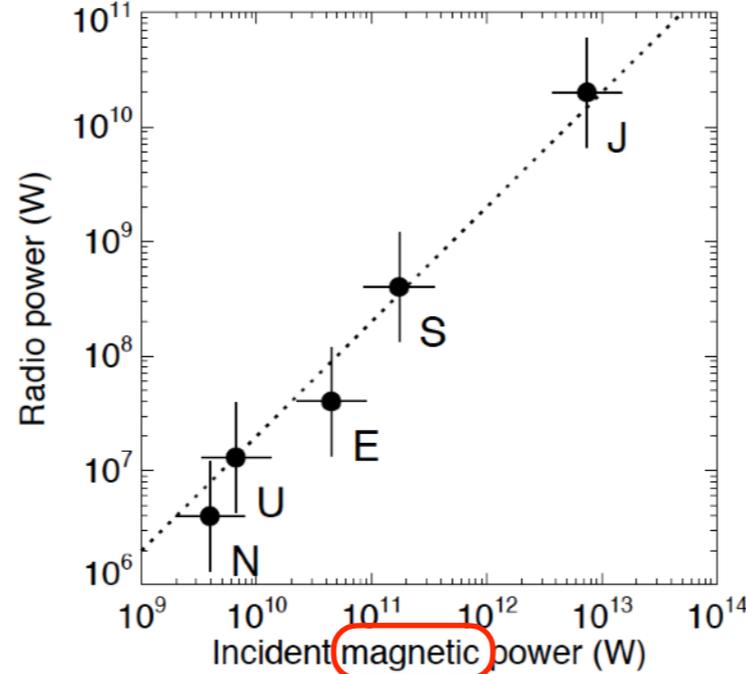
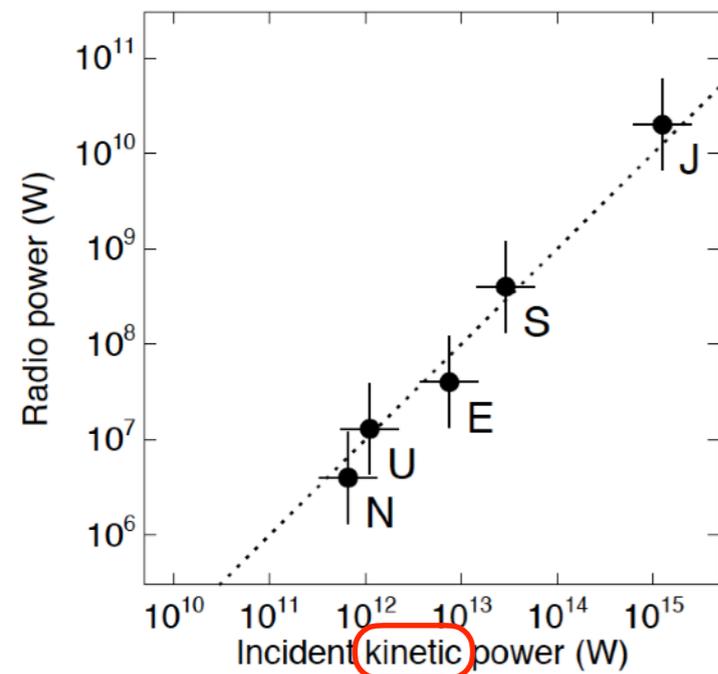
# Exoplanetary Radio Emissions

## ① Super strong "Solar Wind - Magnetosphere" Auroras ?



$\eta \sim 10^{-5}$

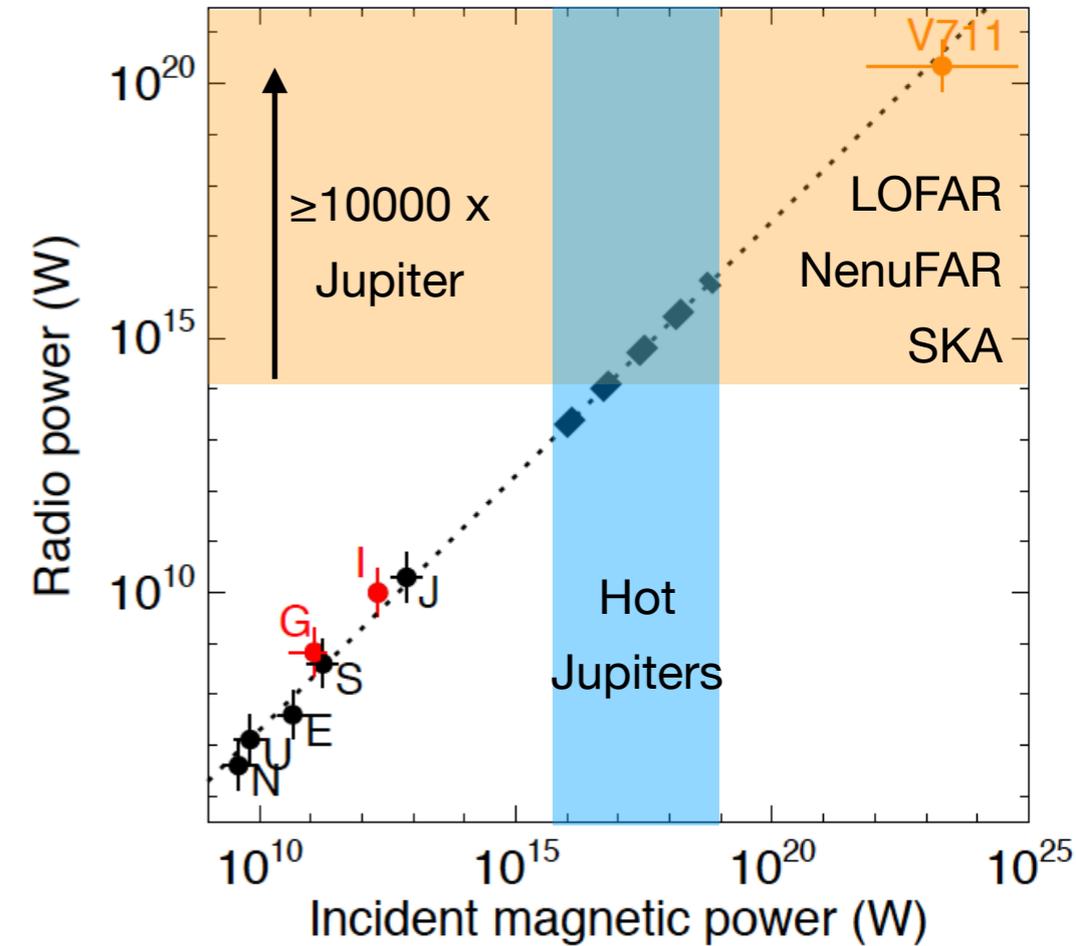
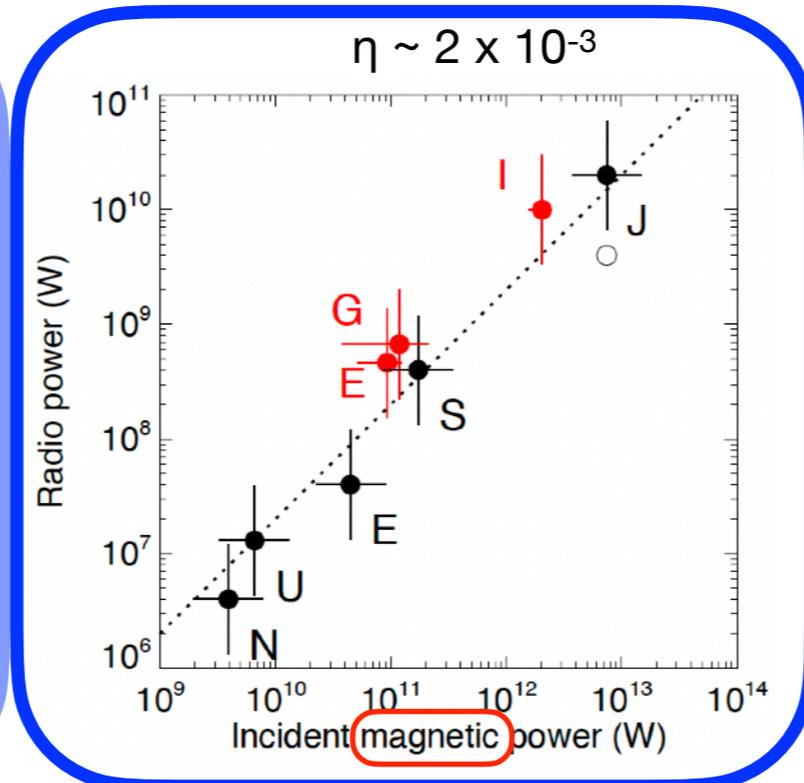
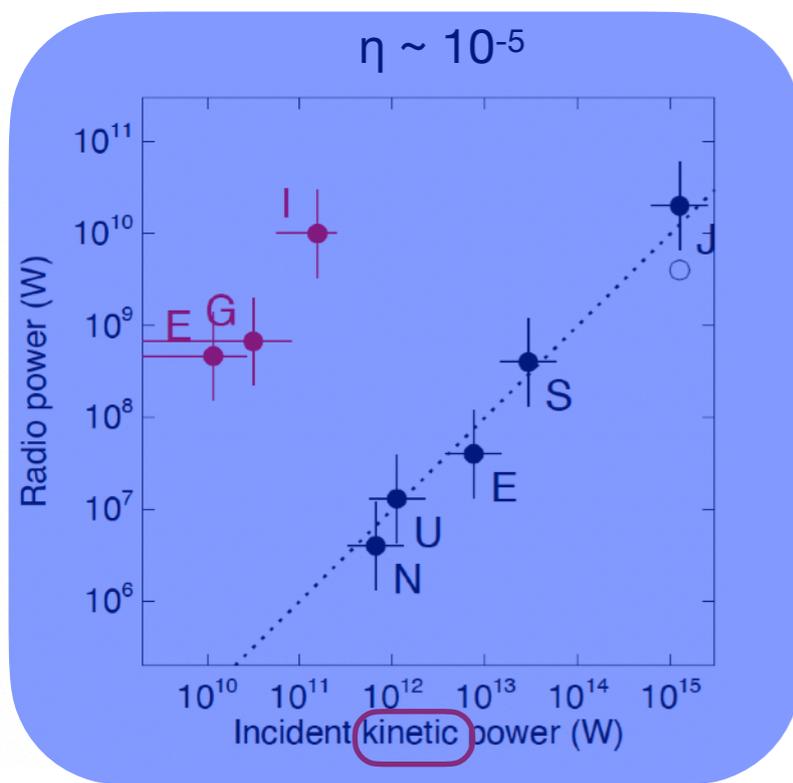
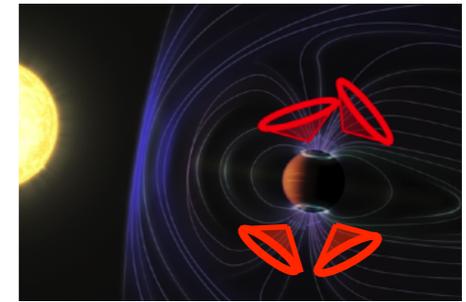
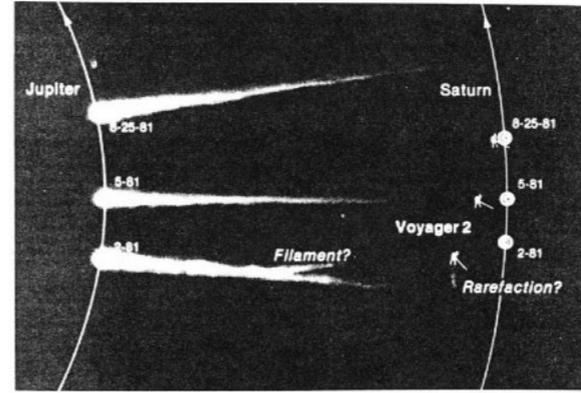
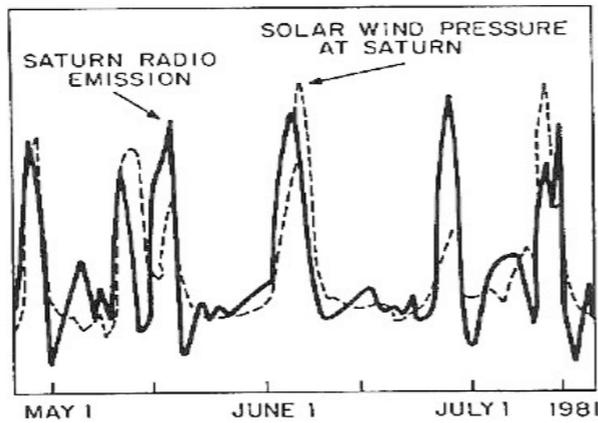
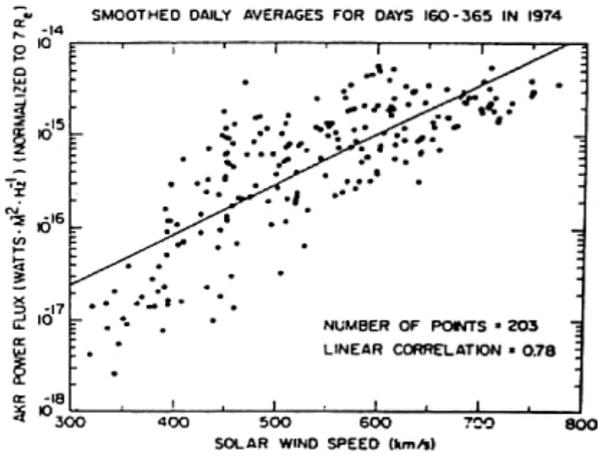
$\eta \sim 2 \times 10^{-3}$



Scaling Law ?

# Exoplanetary Radio Emissions

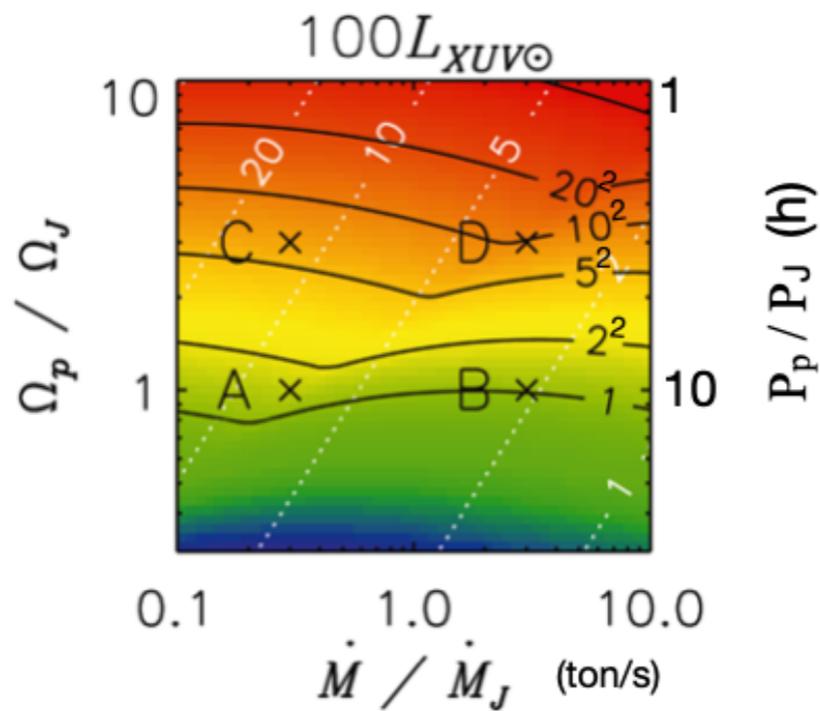
## ① Super strong "Solar Wind - Magnetosphere" Auroras ?



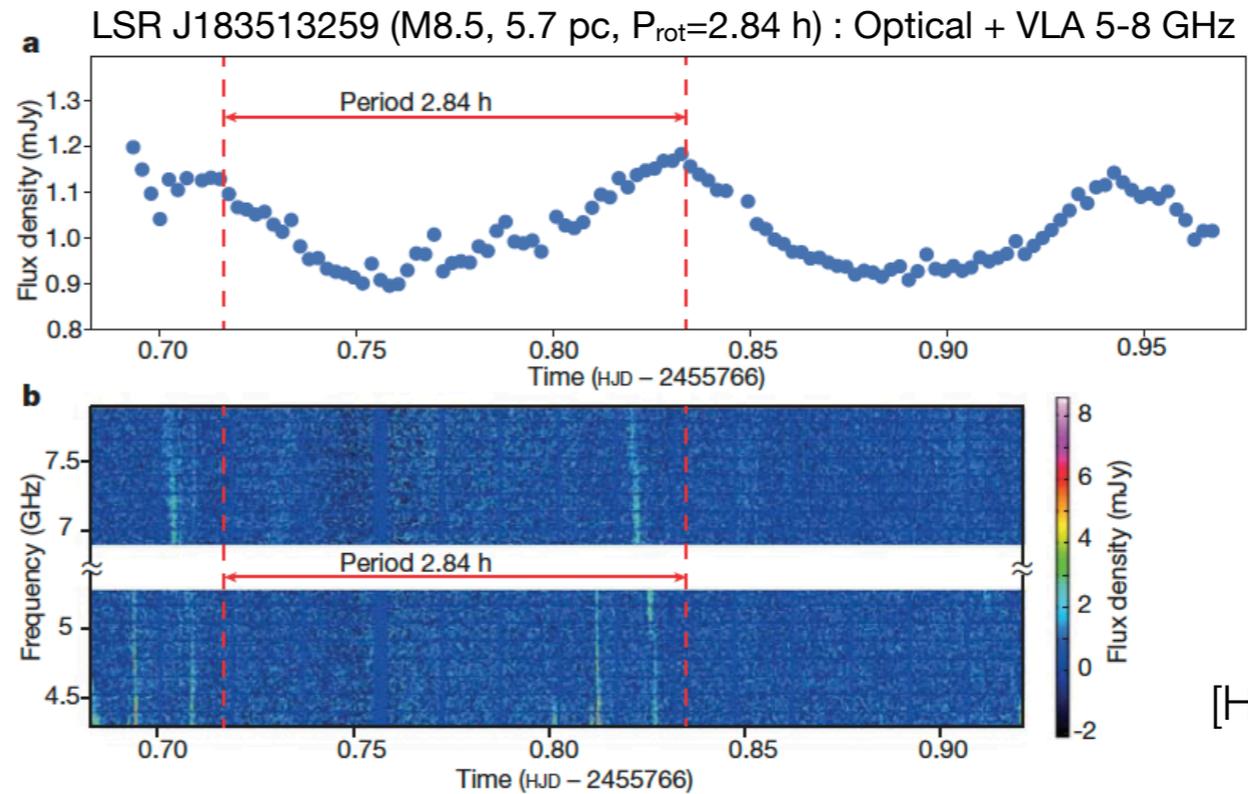
→ Radio-Magnetic Scaling Law

# Exoplanetary Radio Emissions

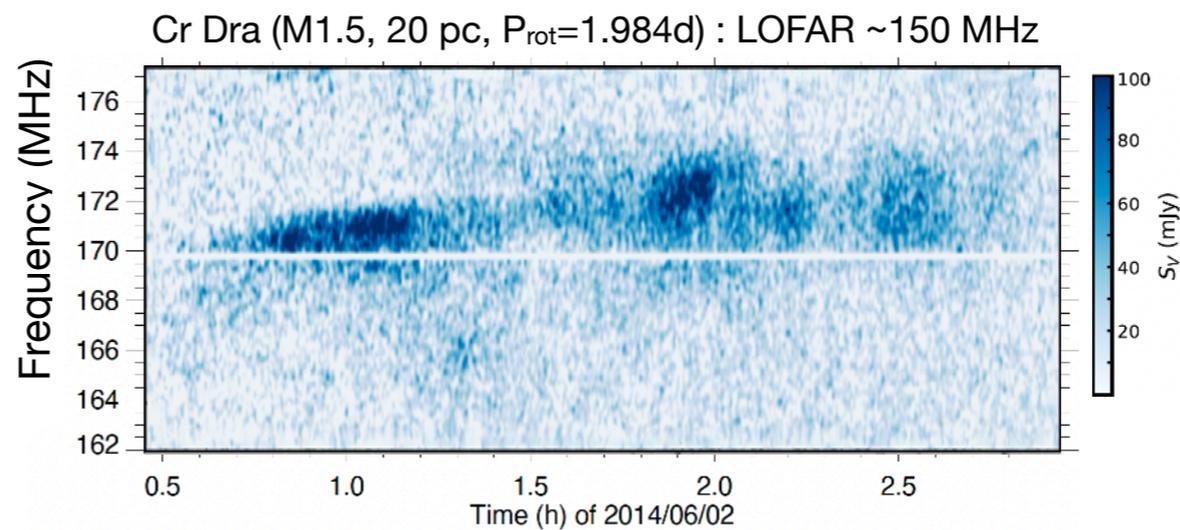
## ② Super strong "Rotational" Auroras ?



[Nichols 2011]



[Hallinan+ 2015]

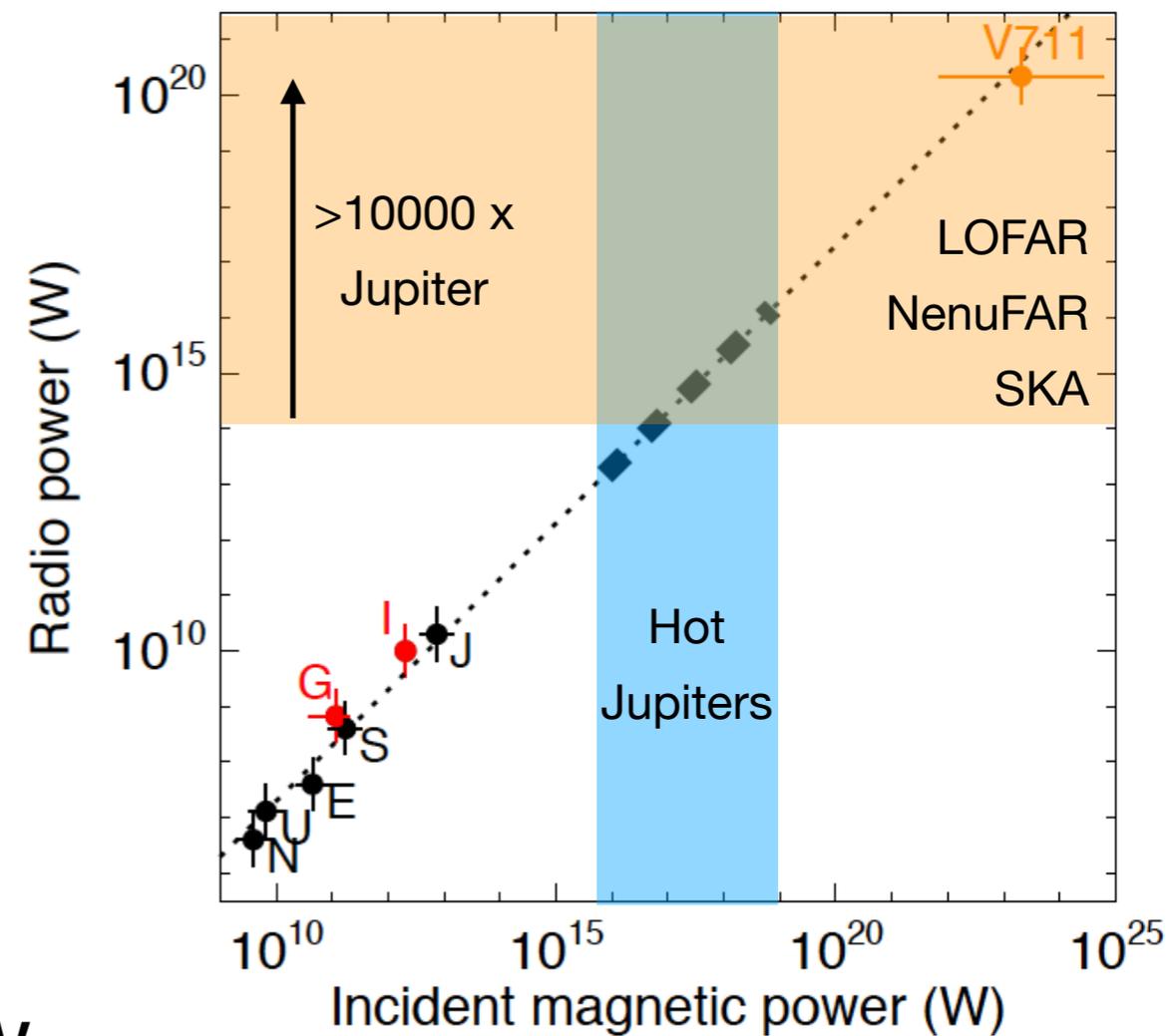
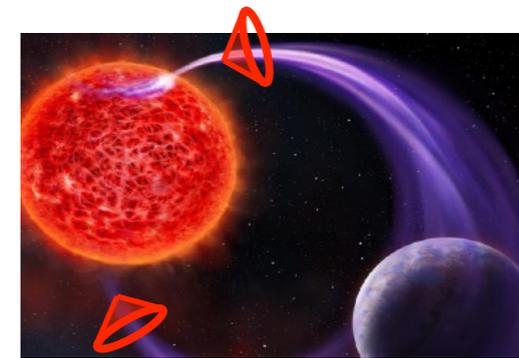
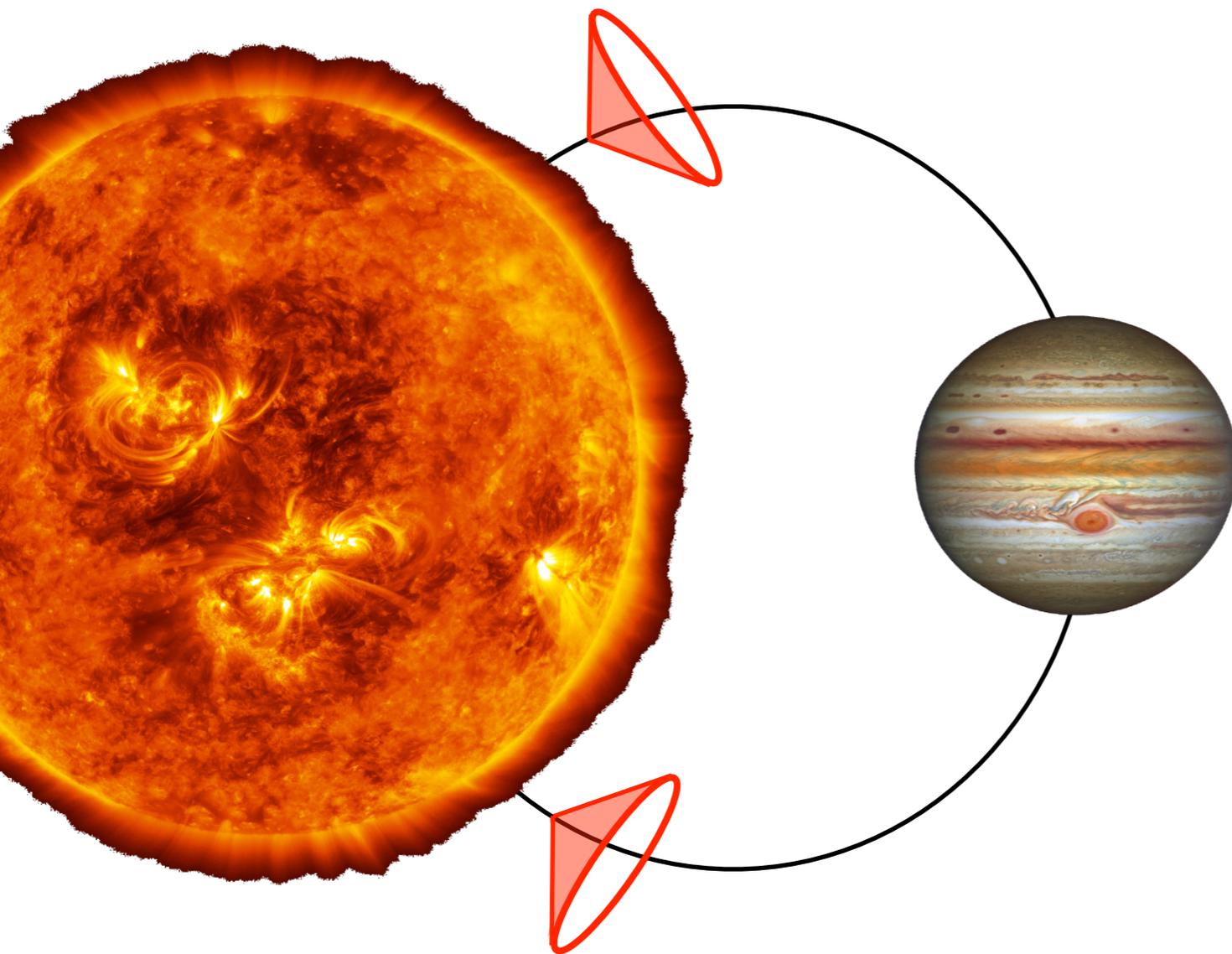


[Callingham+ 2021]

→ Unlikely for planets, likely observed for stars

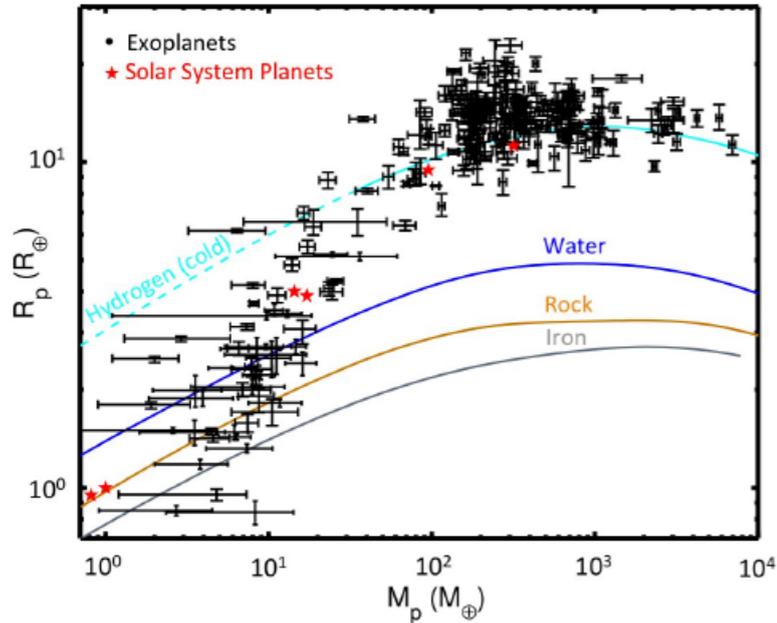
# SPI Radio Emissions

- ③ Star-Planet (magnetic) Interaction =  
Super strong analog to Satellite-Magnetosphere interaction

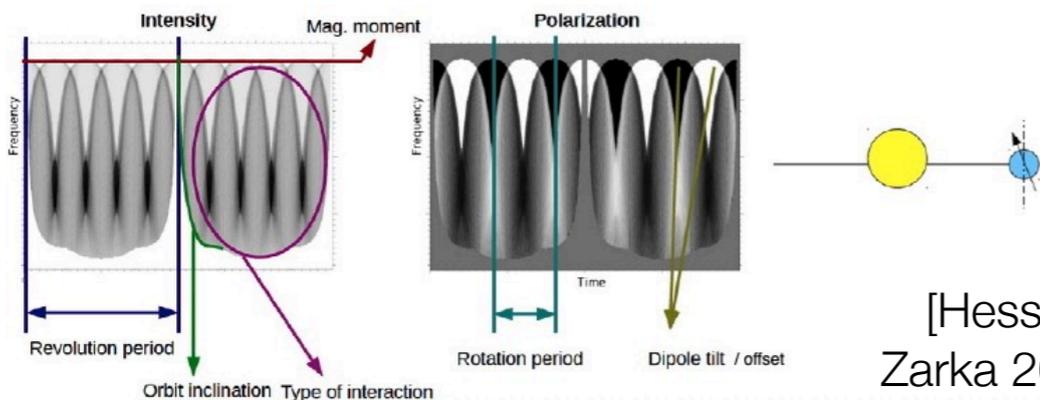
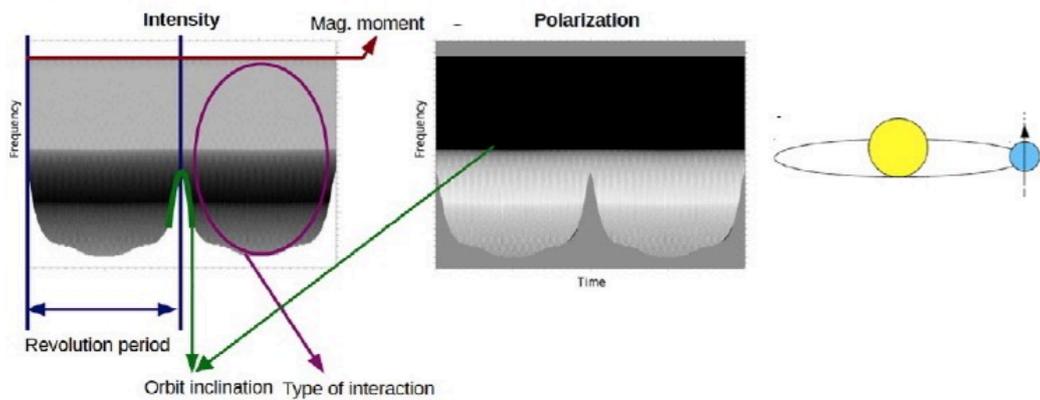
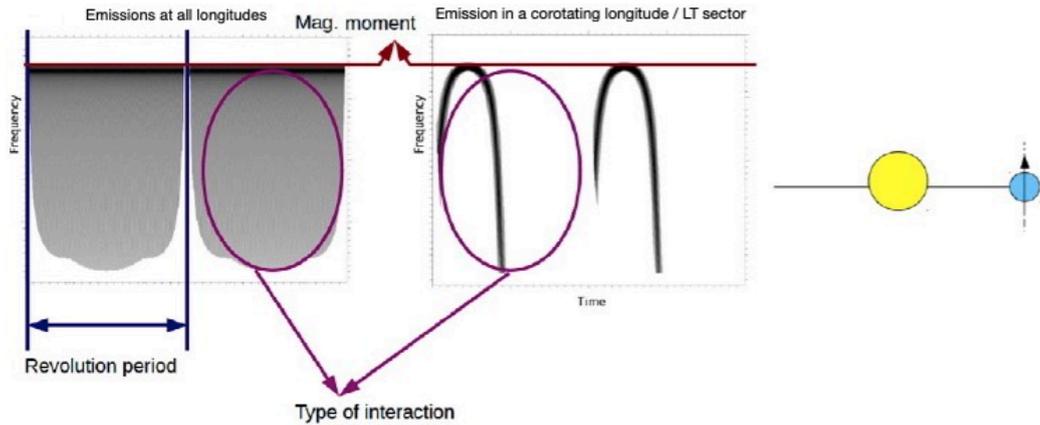
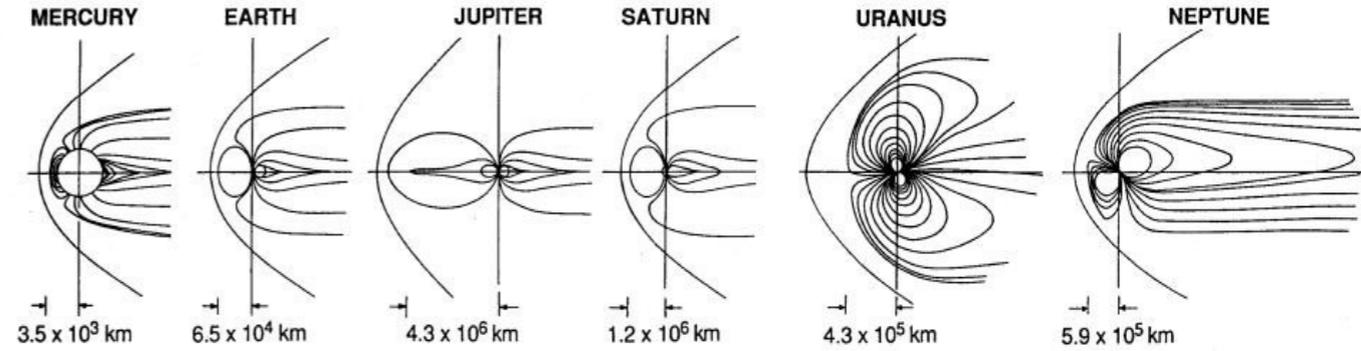


→ Radio-Magnetic Scaling Law

# Motivations



[Seager + 2007]



[Hess & Zarka 2011]

- |B| & tilt  $\Rightarrow$  dynamo  $\Rightarrow$  internal structure
- Planetary rotation  $\rightarrow$  spin-orbit locking ?
- Orbit inclination
- SPI energetics
- Implications for atmosphere evolution (escape / erosion, CR bombardment / O<sub>3</sub> destruction, CME...) & habitability
- **Comparative exo-magnetospheric physics** (population studies - all SS MS have  $\neq$  structure & dynamics)
- **Exo-space weather** (incl. extreme cases: strongly magnetized dwarfs or active stars)
- Discovery tool ?

# Past observations ( $\leq 2014$ )

- UTR-2 10-32 MHz



- LWA 10-88 MHz



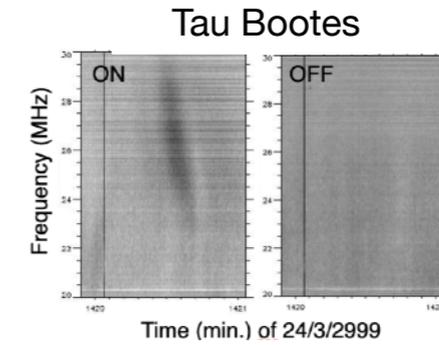
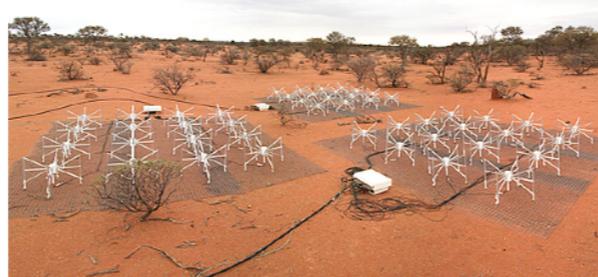
- VLA 74 MHz



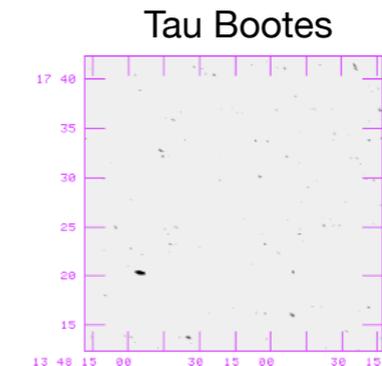
- GMRT 150 MHz



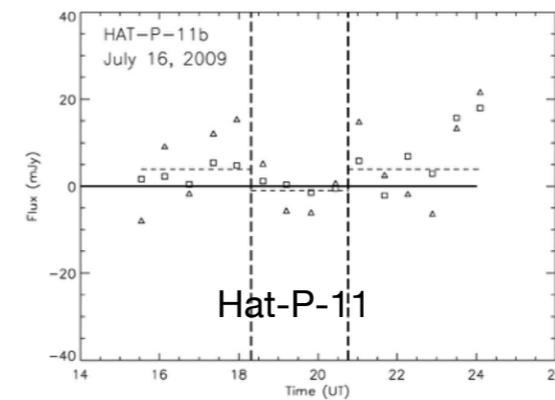
- MWA 163-231 MHz



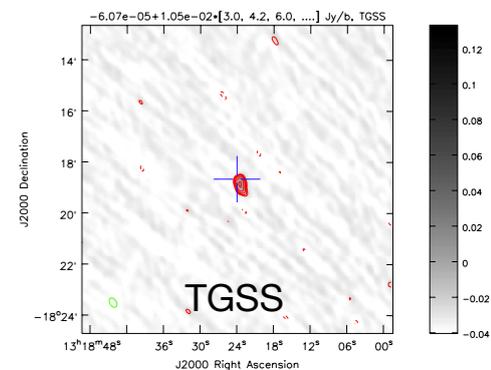
[Zarka+ 1997,  
Ryabov+ 2004]



[Farrell+ 2003, 2004]



[Lecavelier+ 2013, Sirothia+ 2014]



[Lenc+ 2018]

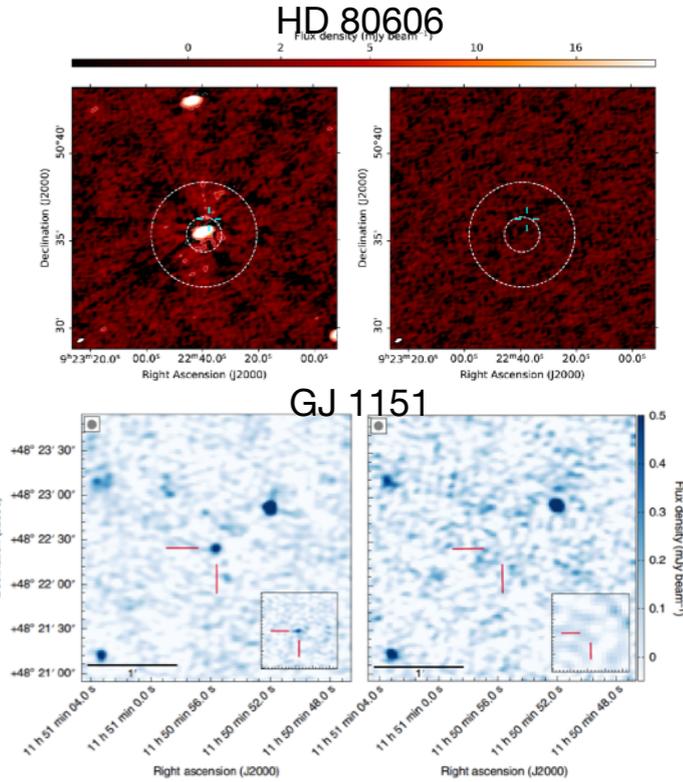
⇒ no confirmed detection

# Recent observations (imaging)

- LOFAR 15-78 MHz

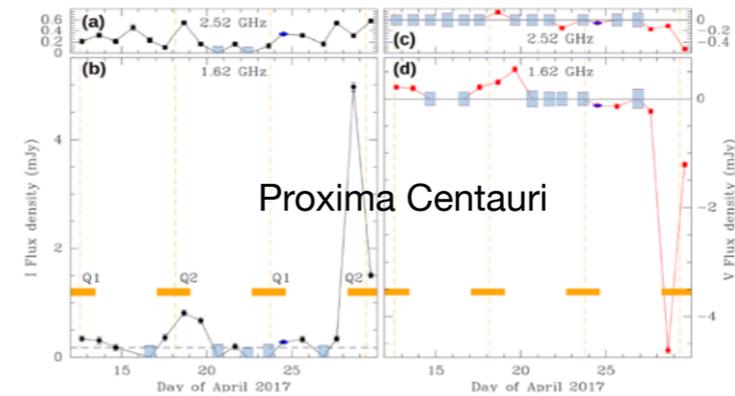
[deGasperin+ 2020, Vedantham+ 2020]

- LOFAR 120-170 MHz



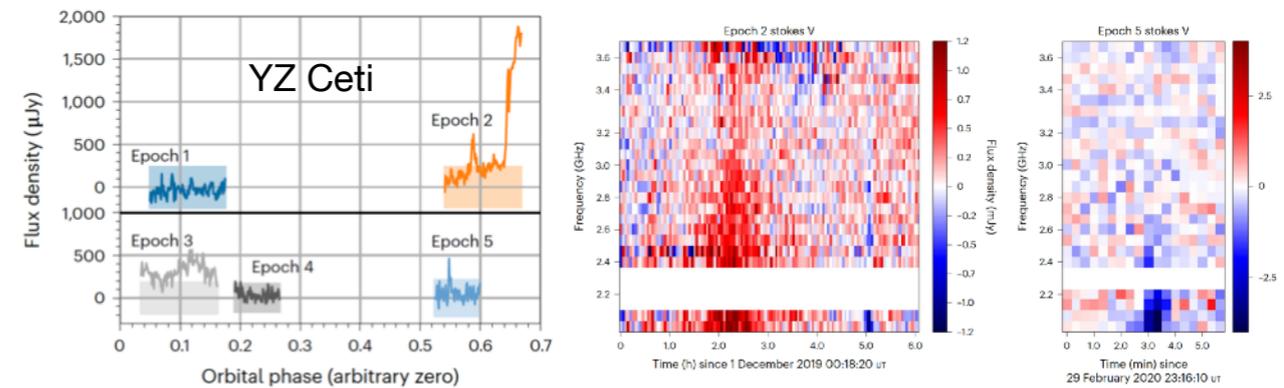
- ATCA 1.6-2.6 GHz

[Perez-Torres+ 2021]



- VLA 2-4 GHz

[Pineda & Villadsen 2023]



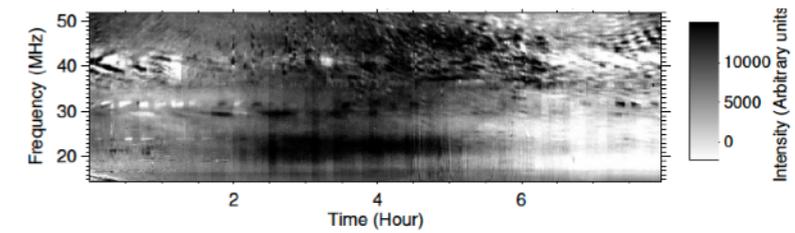
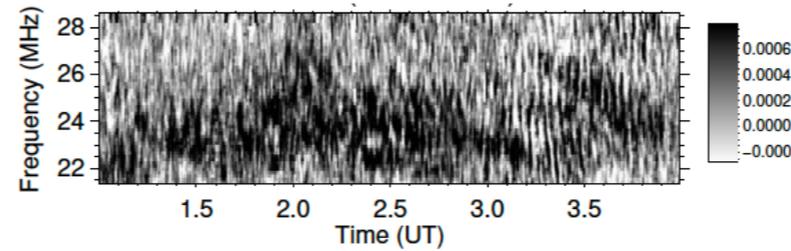
⇒ first detection (stars ?)

# Recent observations (t-f)

- LOFAR & NenuFAR 10-85 MHz

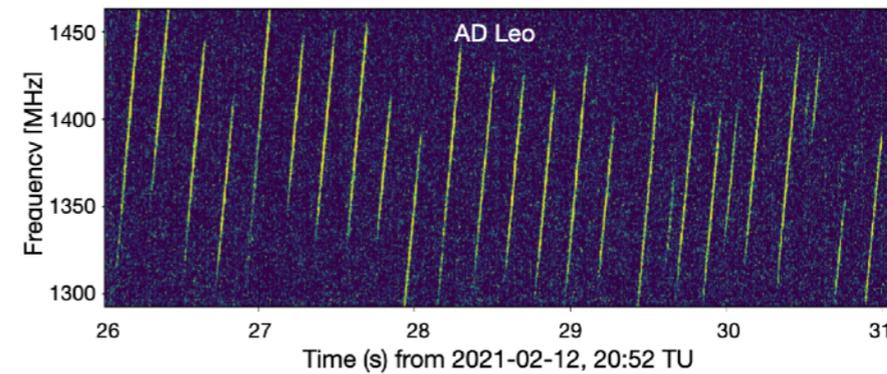


[Turner+ 2021]



⇒ no confirmed detection

- FAST 1-1.5 GHz

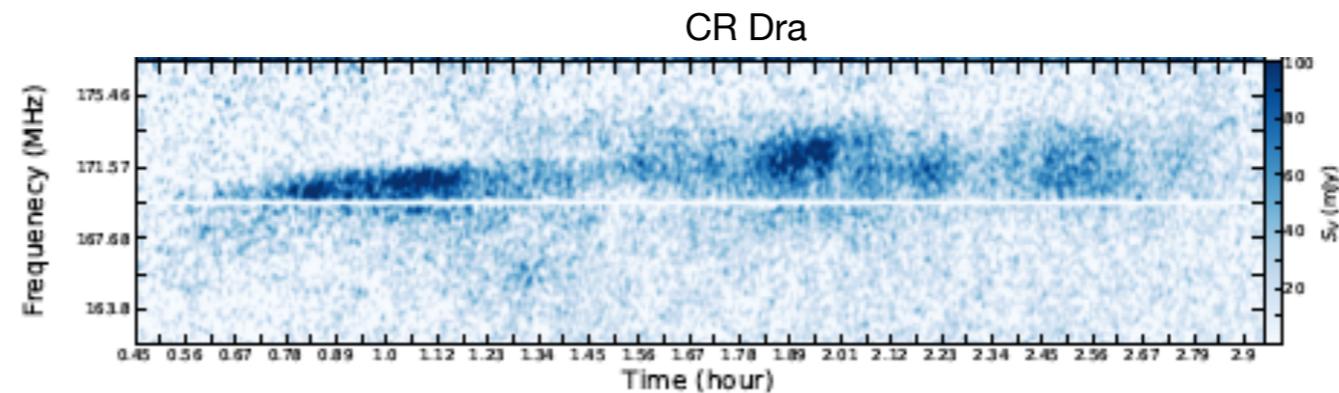


[Zhang+ 2023]

⇒ stellar bursts

# Simultaneous Imaging & t-f analysis

- Limitations of imaging :
  - limited sensitivity to transients
  - low information on unresolved sources
- Summing interferometric visibilities :
  - dynamic spectrum (t-f) at phase center



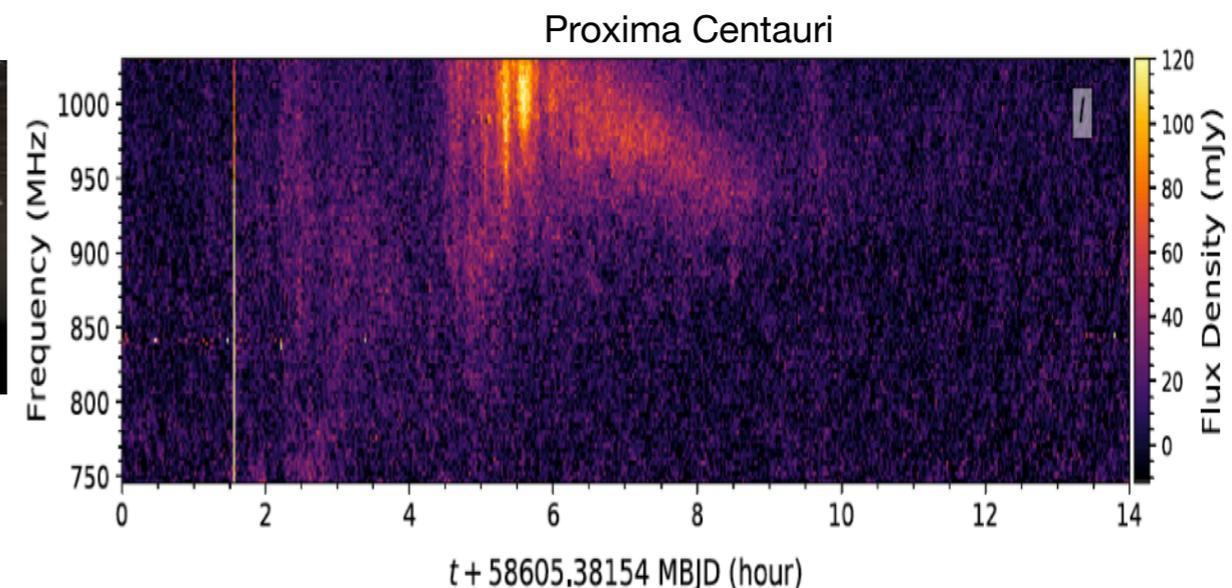
[Callingham+ 2021]

- LOFAR 120-170 MHz

- ASKAP 0.7-1.8 GHz



[Zic+ 2020]

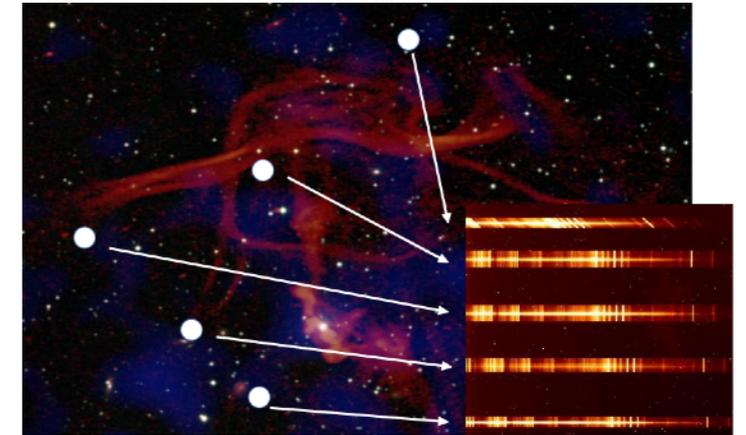
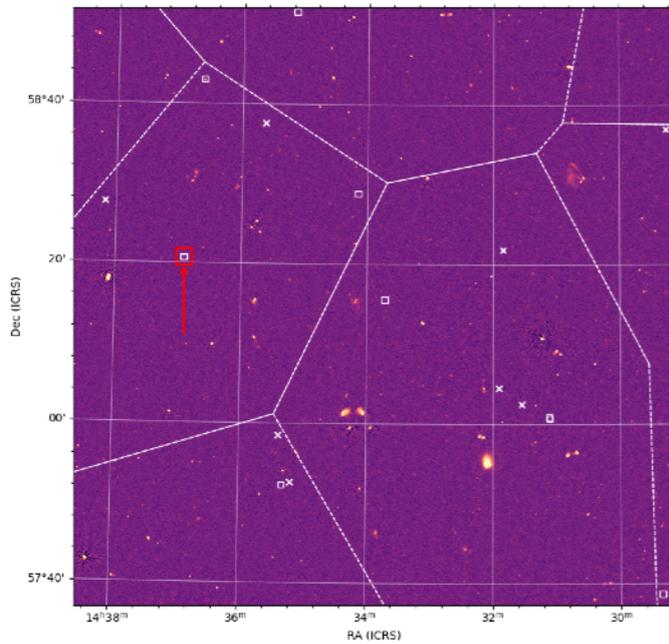


# Simultaneous Imaging & t-f analysis

- New technique : **RIMS**

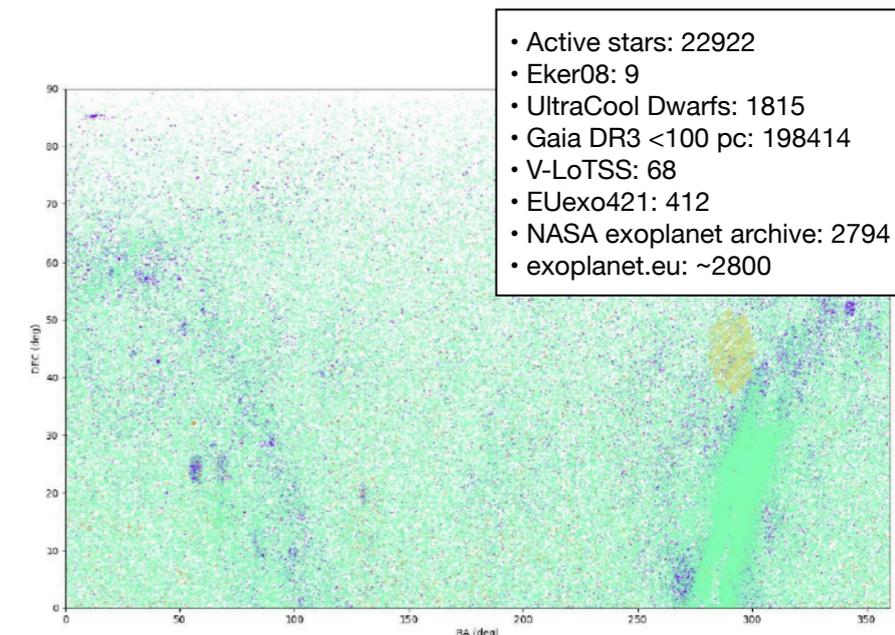
[Tasse+ 2026]

- Summing interferometric visibilities with phase terms
- dynamic spectrum (t-f) toward any directions in the FoV, simultaneously

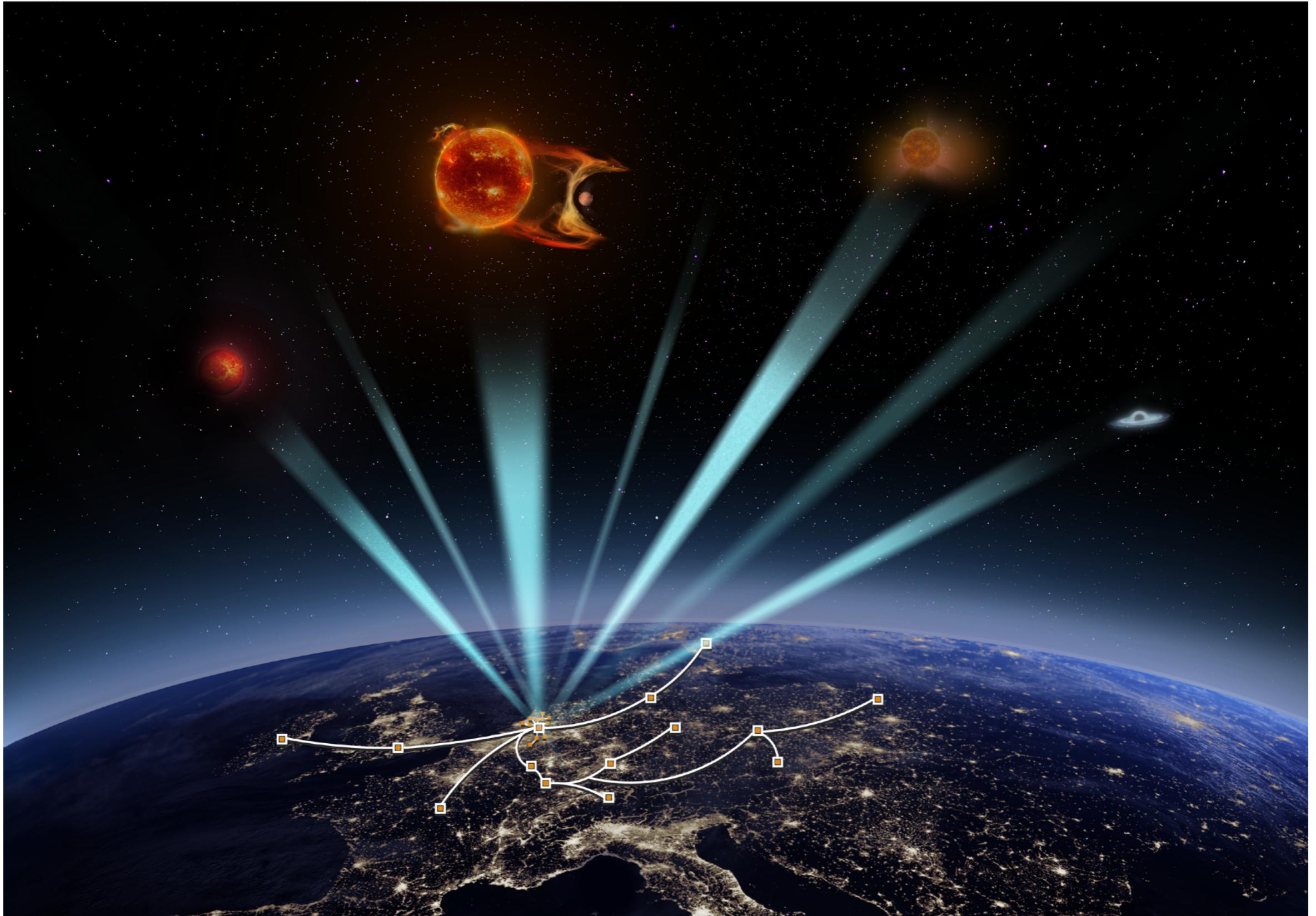


Radio Interferometric Multiplexed Spectroscopy  
= Integral Field dynamic spectroscopy, digital

- Input catalog of exoplanets, stars, dwarf, active, Gaia ( $\leq 100$  pc)  $\sim 227000$  objects
- Application to LoTSS  $\Rightarrow$  generation of  $\sim 500000$  t-f dynamic spectra (targets + random Offs)



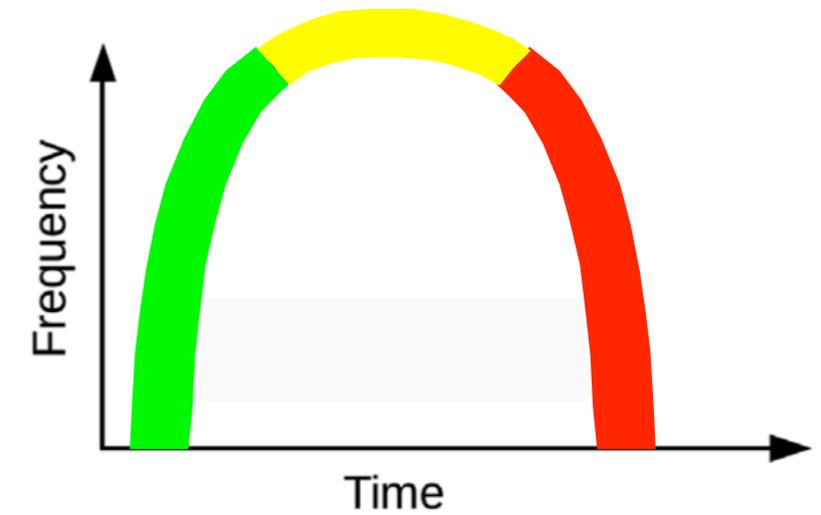
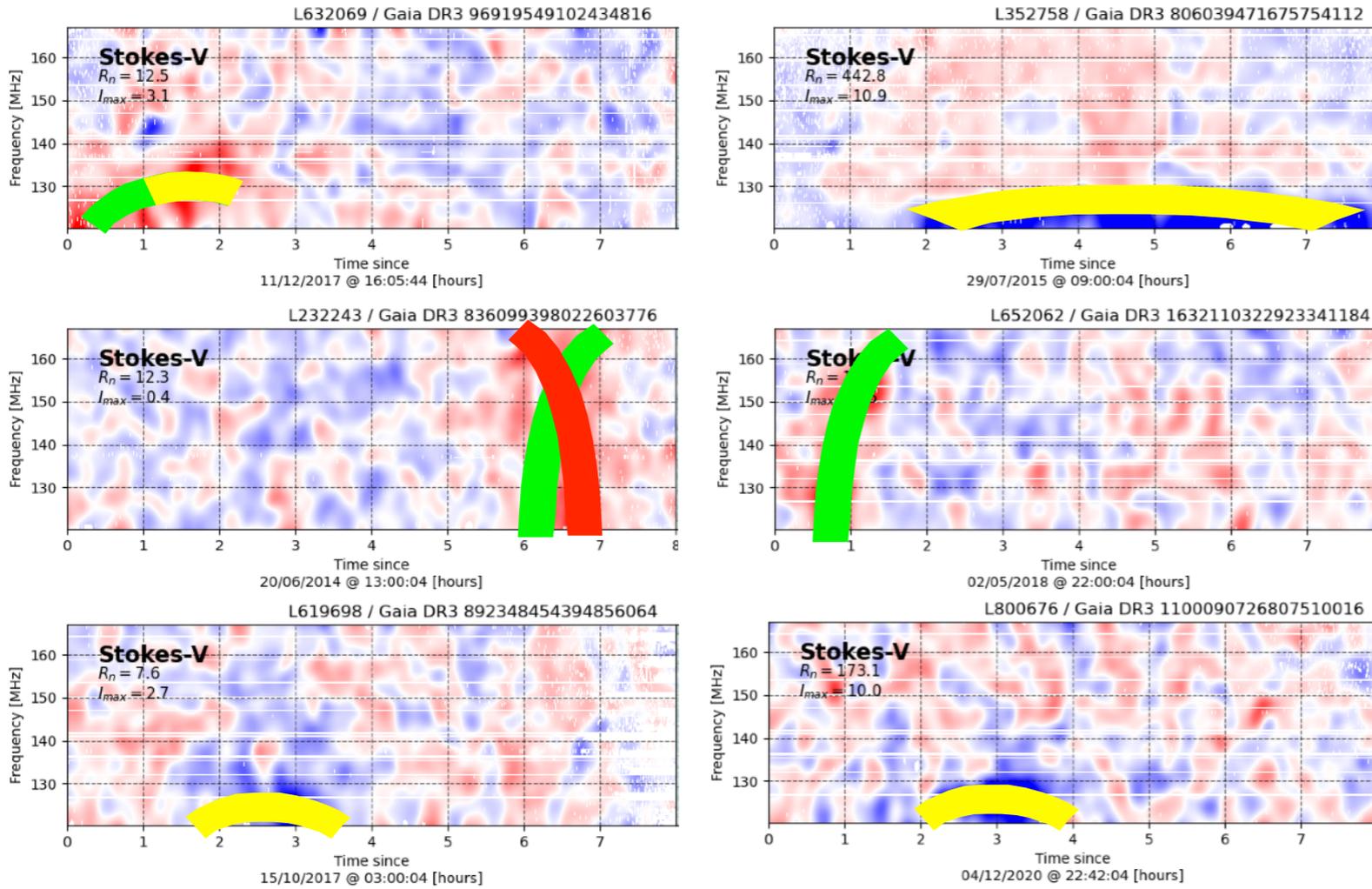
# RIMS



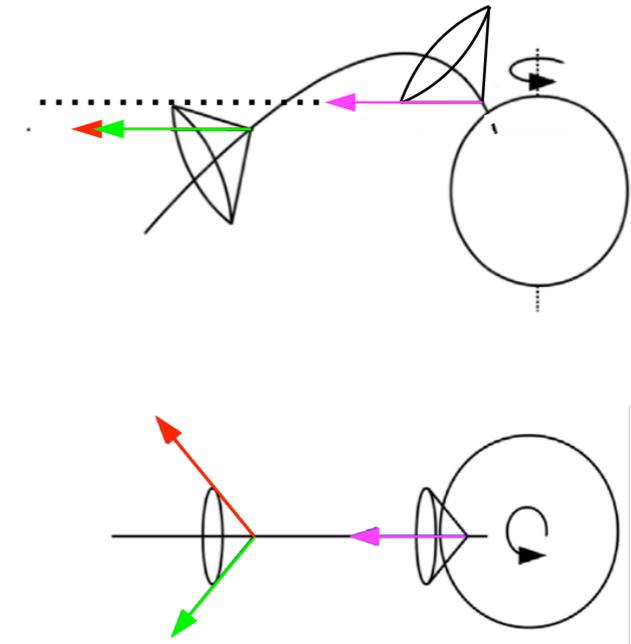
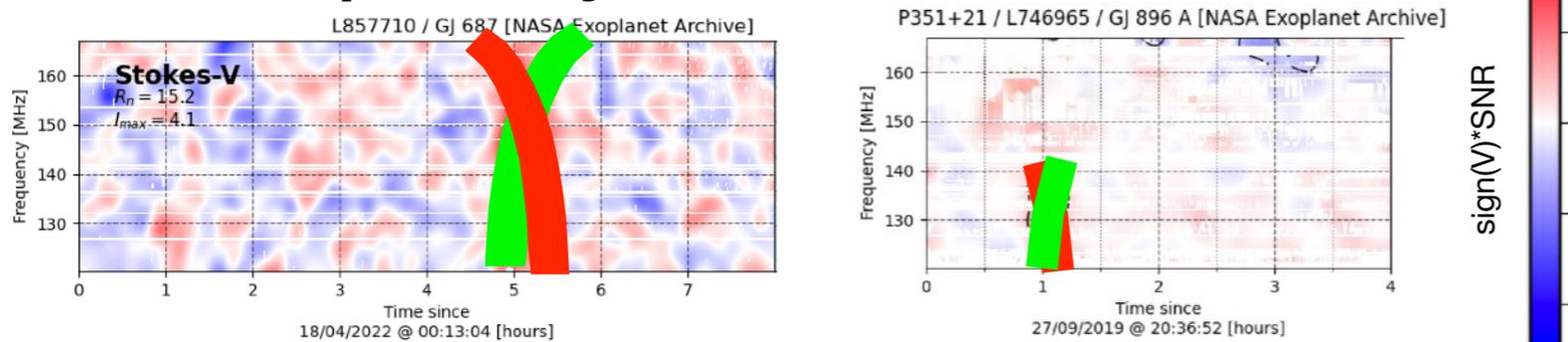
# Multi-object dynamic spectroscopy with LOFAR

- Post-processing of t-f dynamic spectra  $\Rightarrow$  score revealing the presence of bursts

## Stars

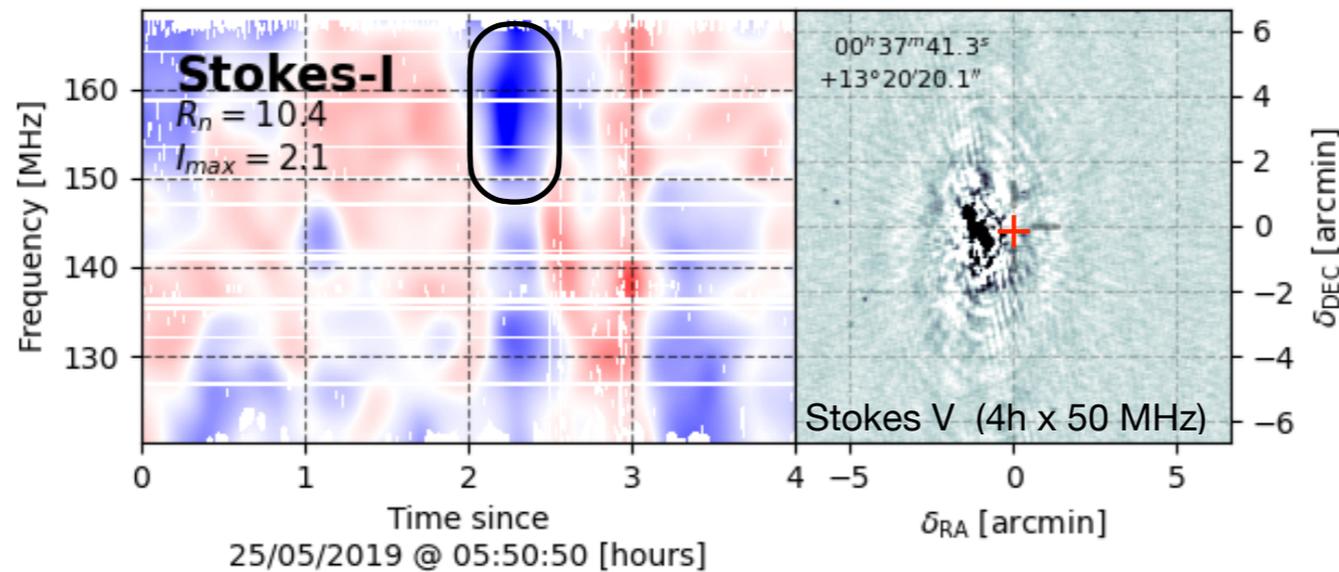


## Star-Exoplanet systems

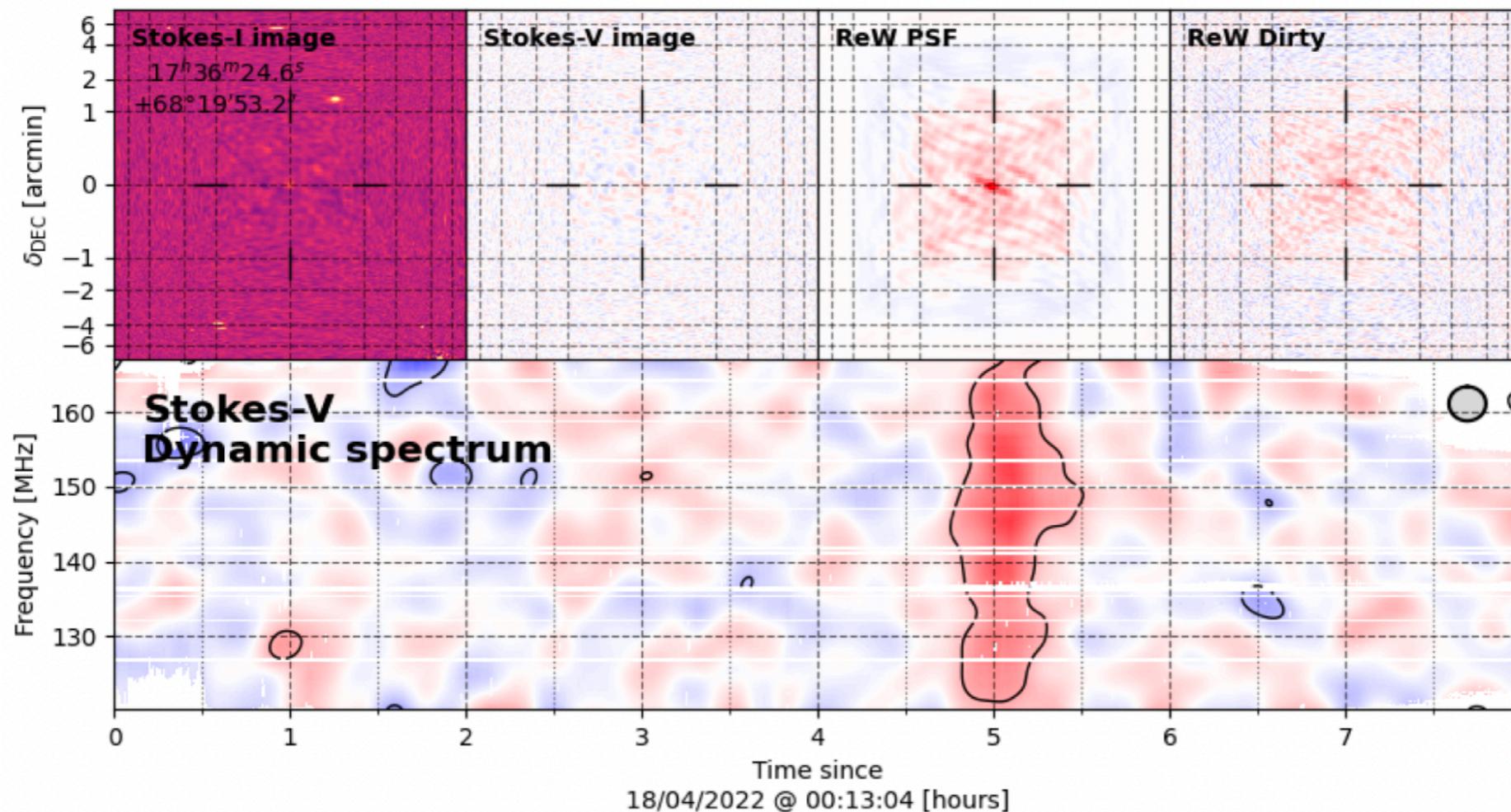


# Confirmation of detections

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

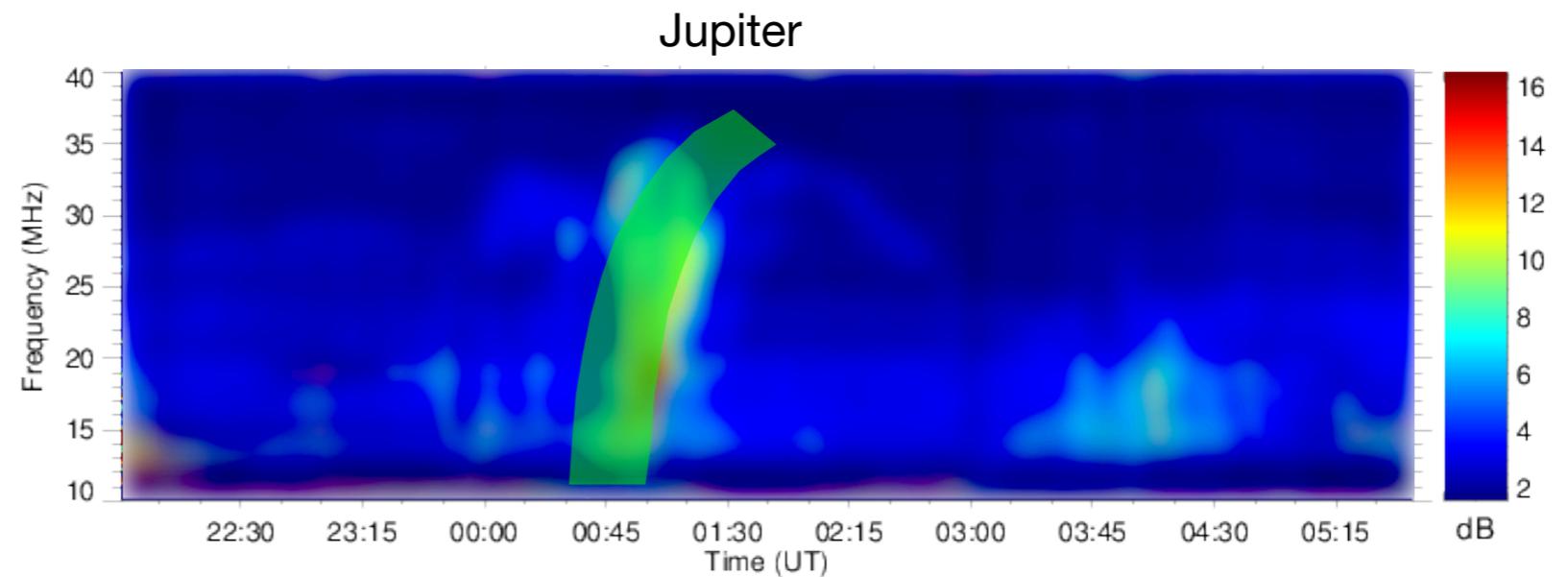
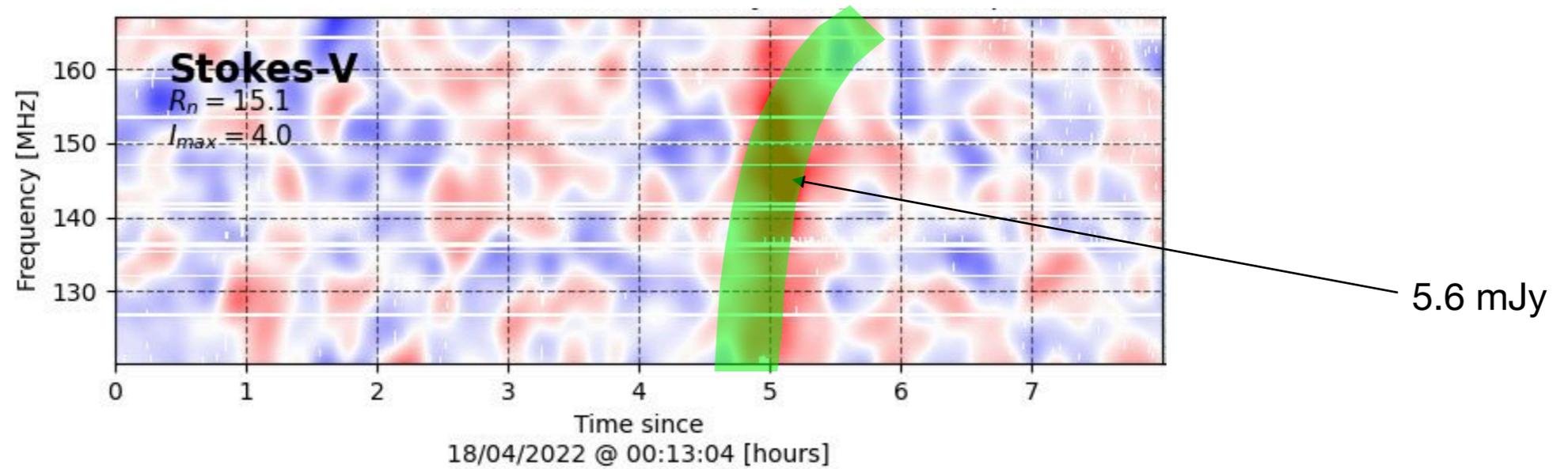


⇒ spurious



⇒ confirmed

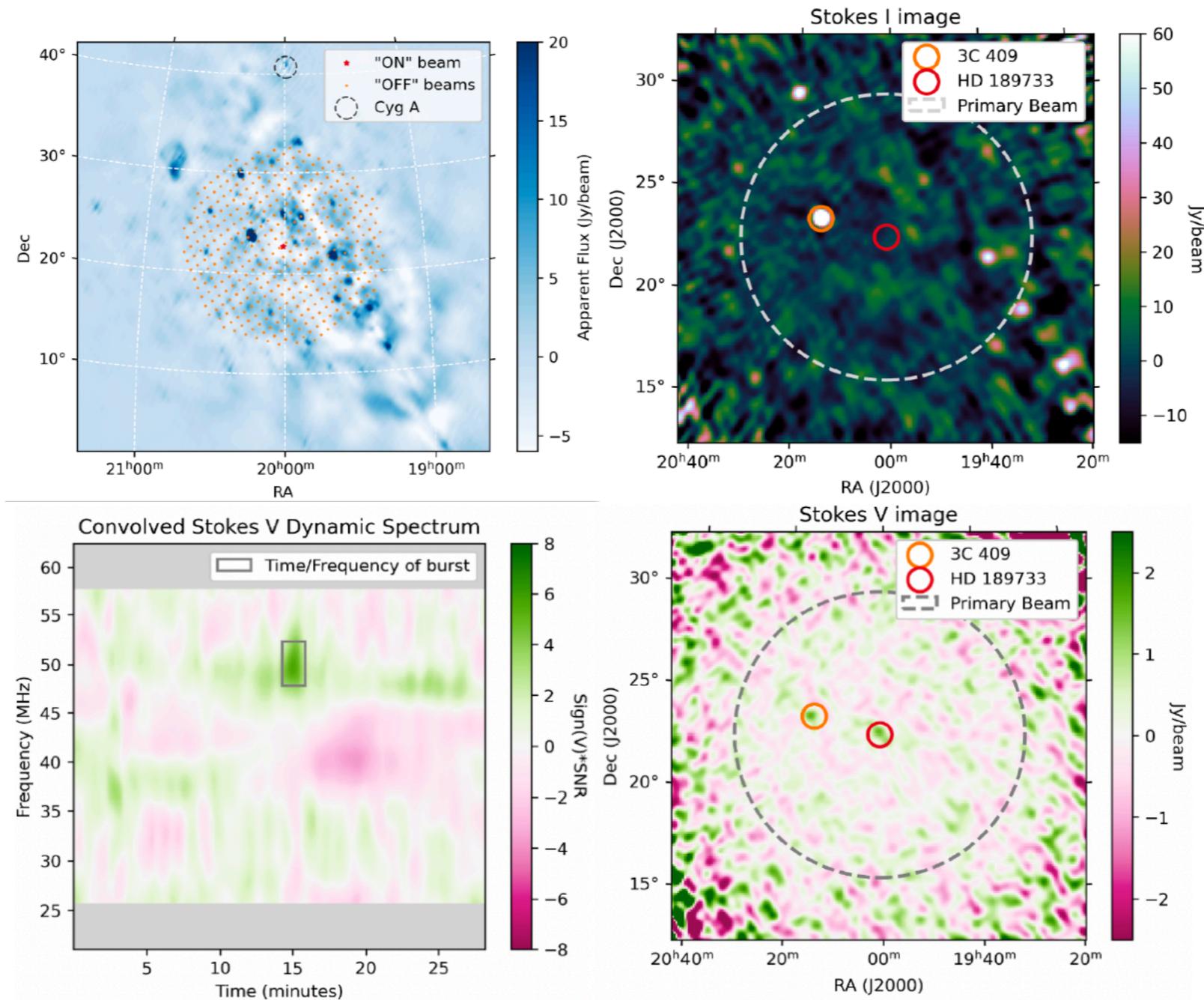
# A case study : GJ 687



- Stellar system hosting a hot Neptune
- Detected flux compatible with predictions from the Radio-Magnetic Scaling Law for SPI

# Detection of HD 189733 with NenuFAR

- 103 observation hours
- 1 burst detected, 1.5 Jy, circularly polarised

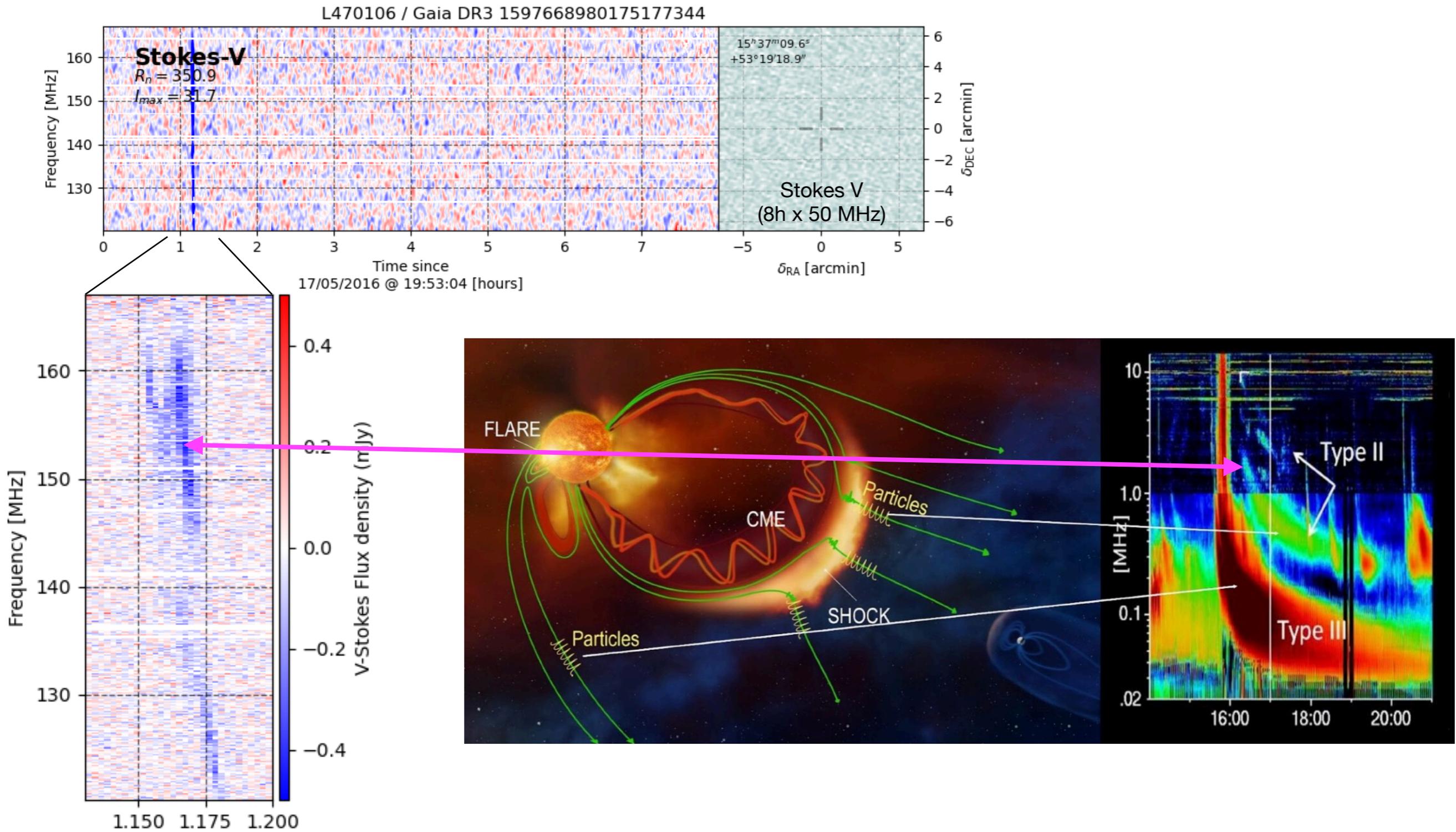


[Zhang+ 2025]

- many more to come soon ...

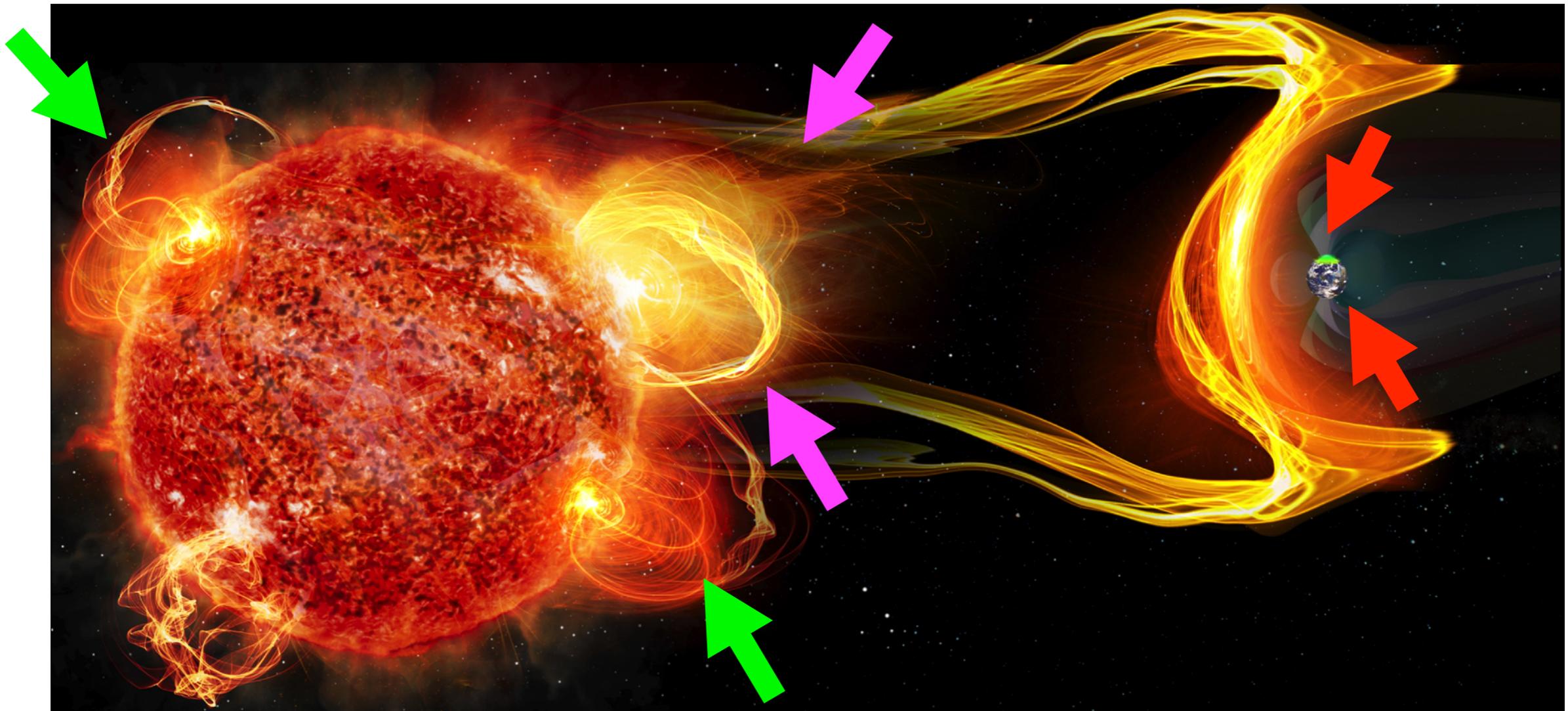
[Zhang+ in prep.]

# Bonus : detection of the 1<sup>st</sup> stellar CME with LOFAR



# Origin of Star-Exoplanet radio emissions ?

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

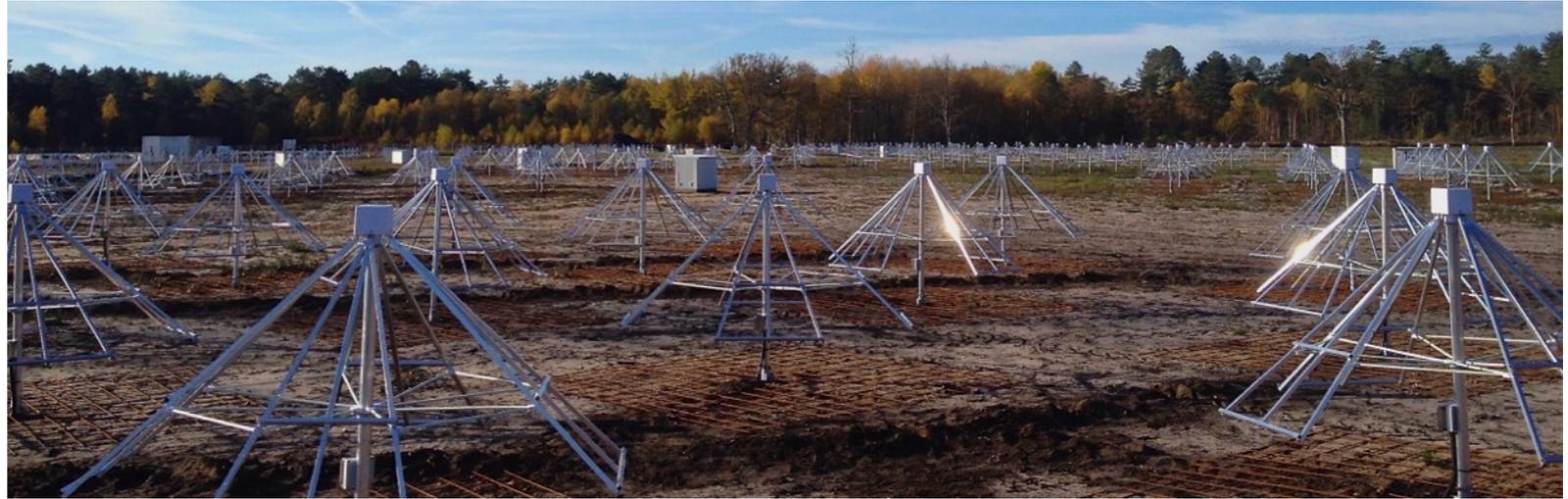


⇒ Need for long time series of radio measurements

⇒ Search for signal periodicities (planetary orbit, star's rotation, synodic)

# Future observations

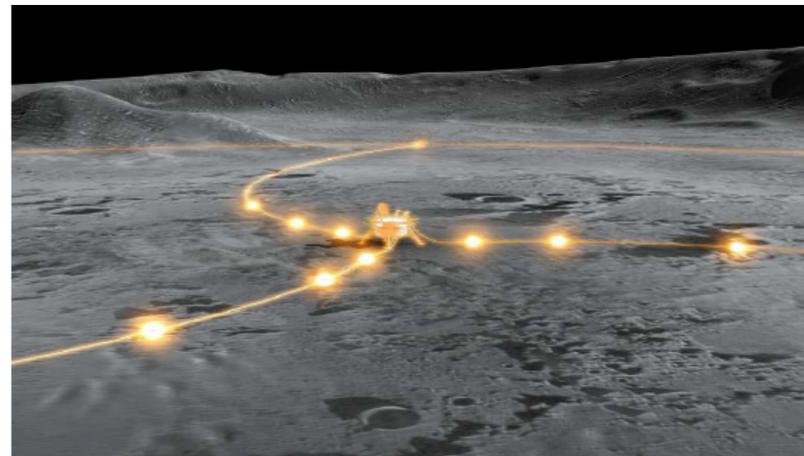
- NenuFAR : 10-85 MHz
- LOFAR 2.0 : 30-250 MHz



- SKA : 50 MHz - >15 GHz

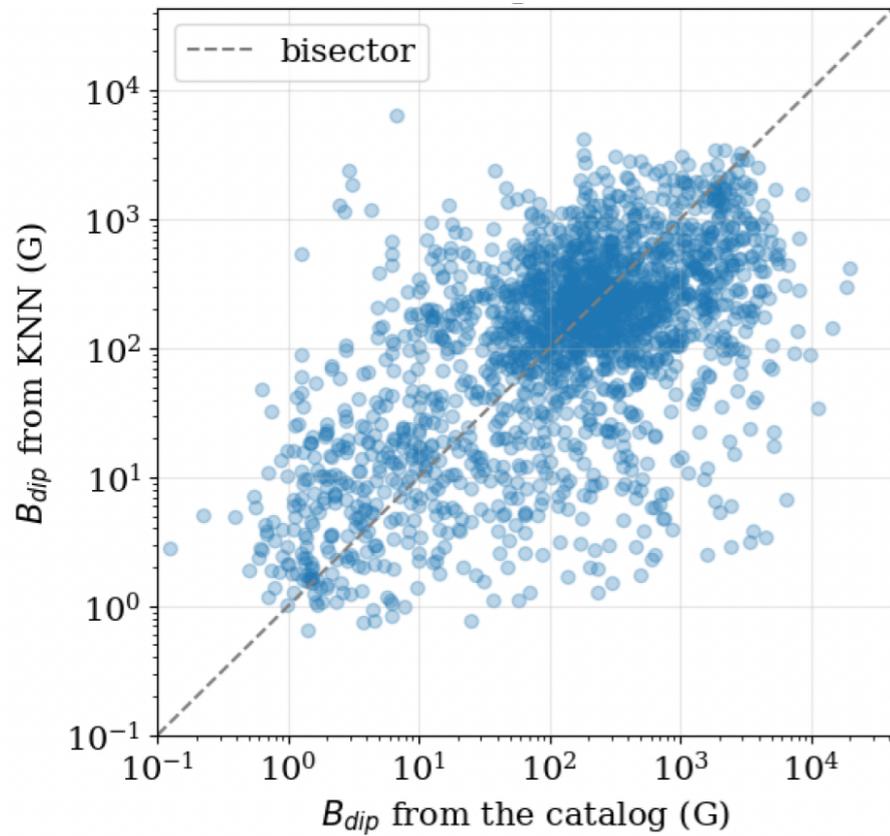


- LOFAR-on-the-Moon : 0.1-100 MHz ?



# Ensemble predictions

Stellar magnetic field database  
+ extrapolation method

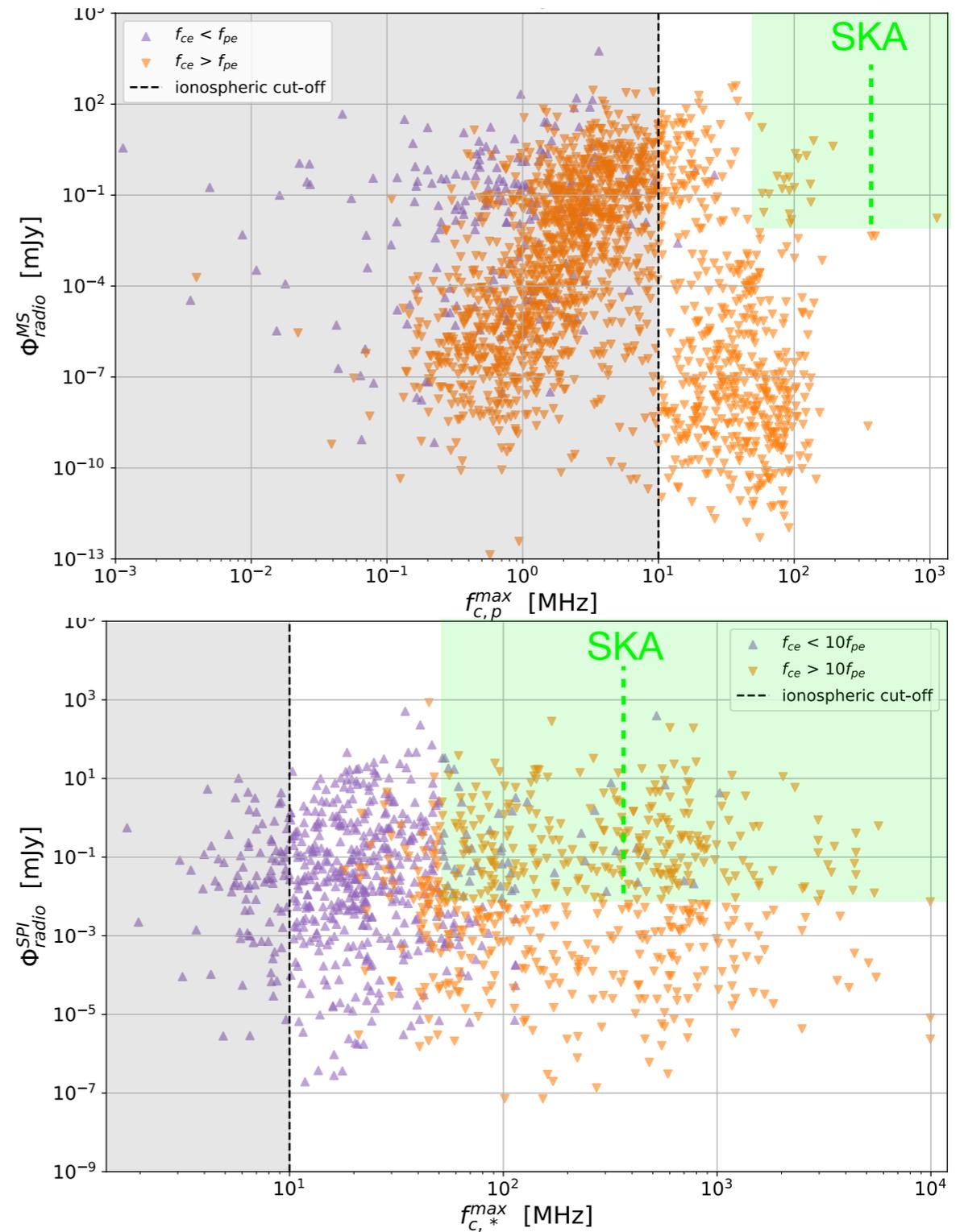


[Duchêne+ submitted]

→ SKA should be very  
successful for SPI radio  
burst detection ... if  
RIMS is implemented at  
SDP level !

+

"Palantir" code (RMSL-based)



[Mauduit+ in prep.]

**Thank you.**

**Questions ?**