The search for exoplanets in radio

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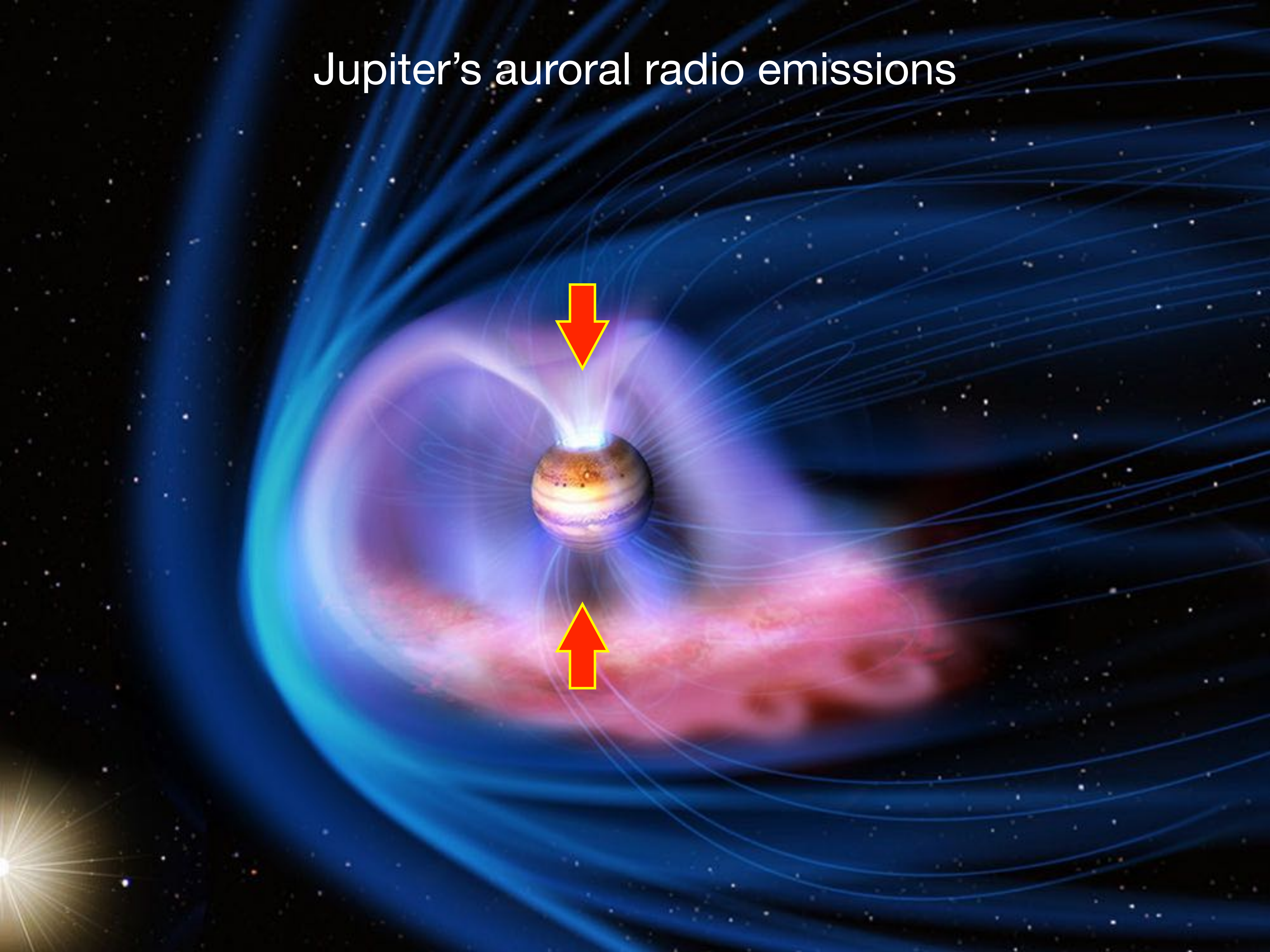
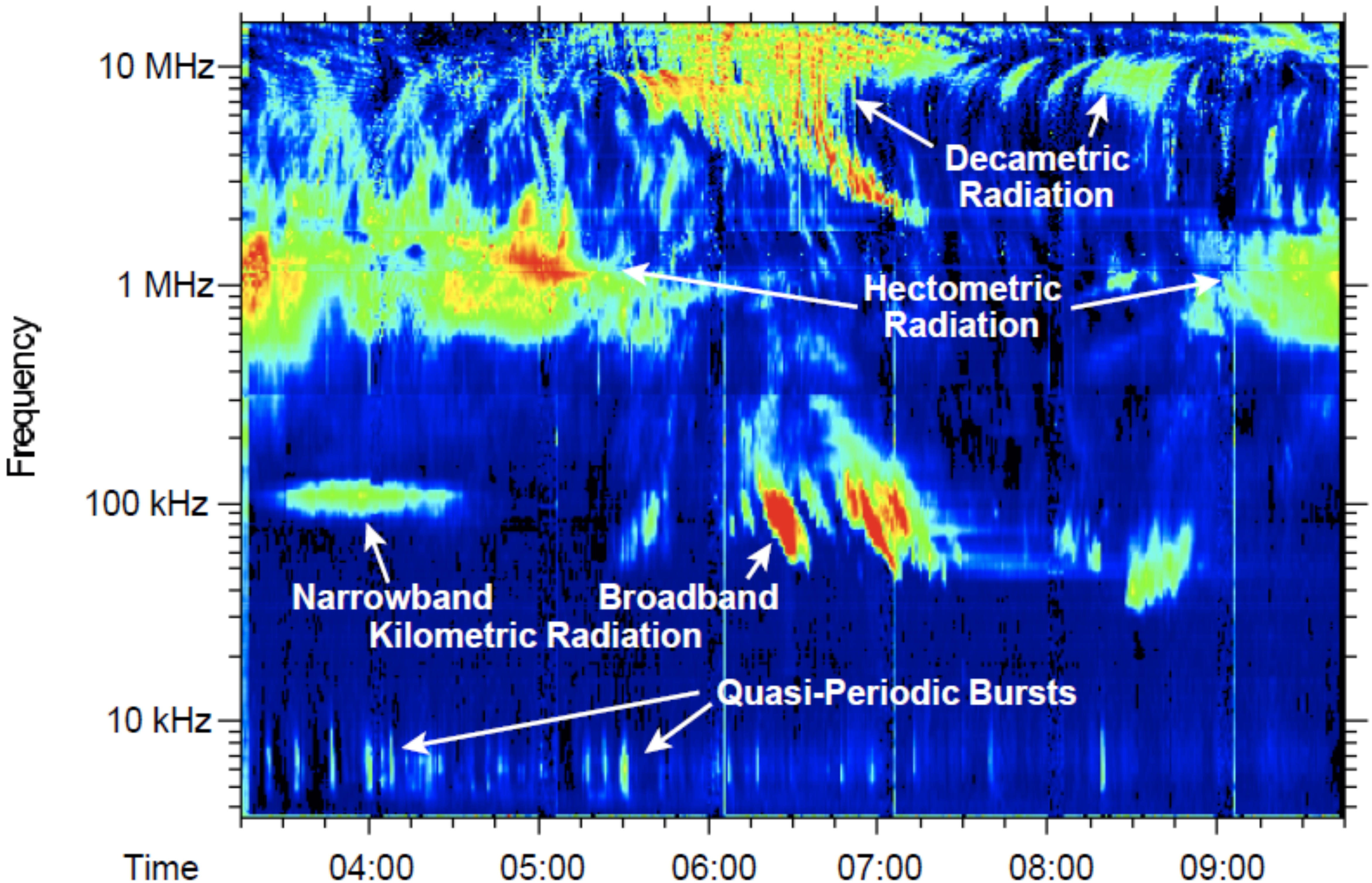
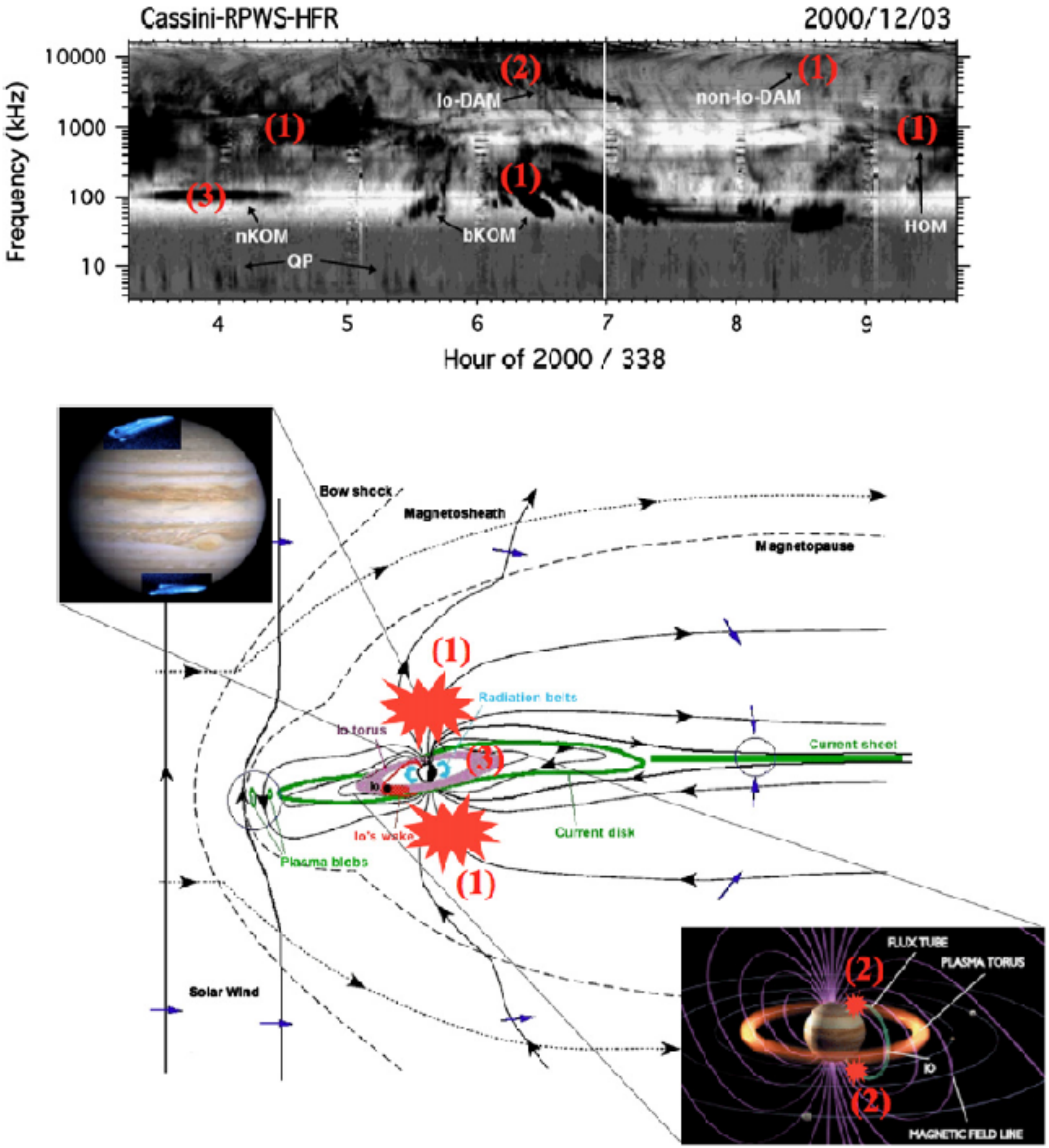
Special thanks to Jake Turner & Jean-Mathias Grießmeier

Jupiter’s auroral radio emissions



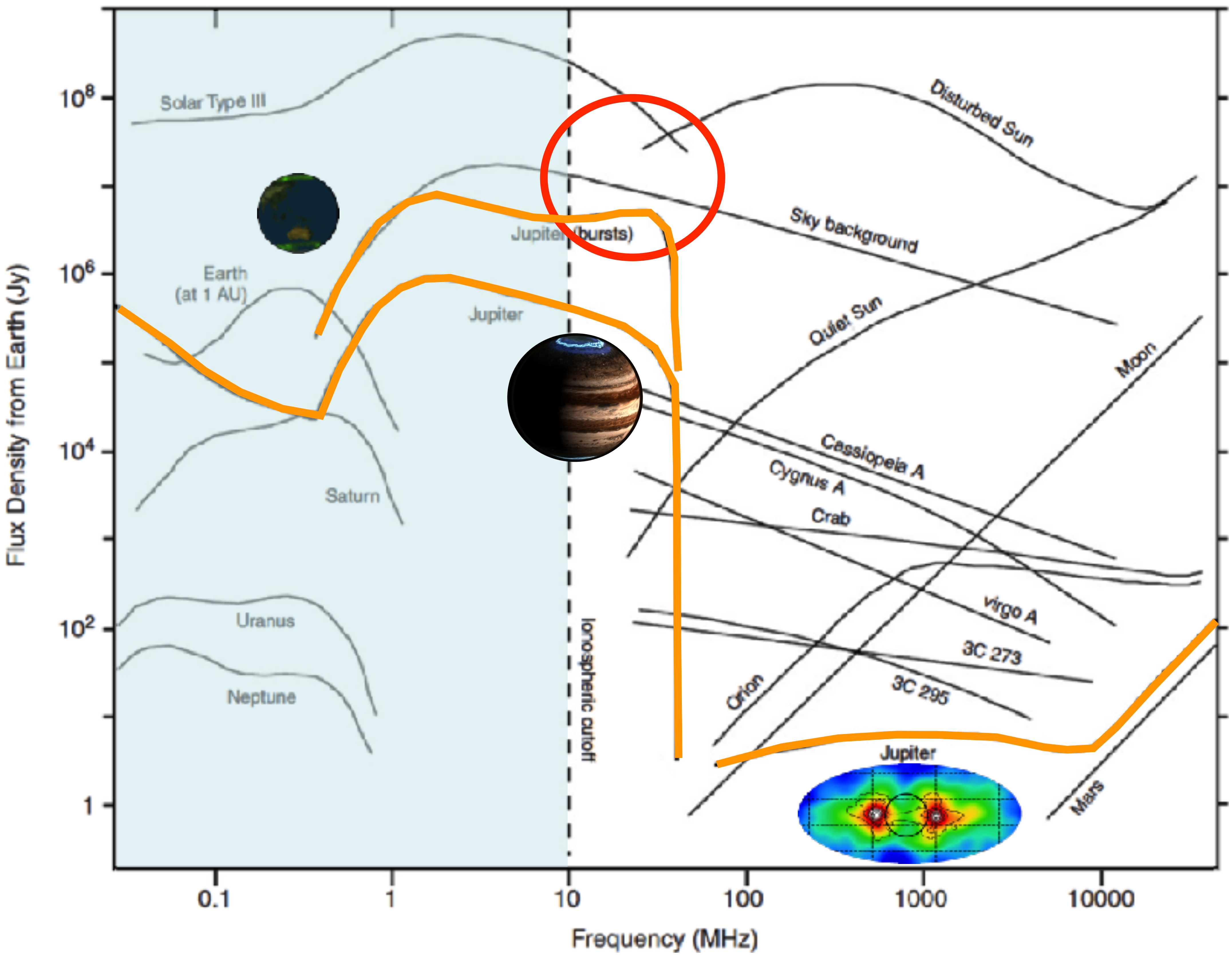
Cassini Radio and Plasma Wave Science
December 3, 2000





[Zarka et al., 2004, 2012]

Jovian decameter emission as intense as solar emissions



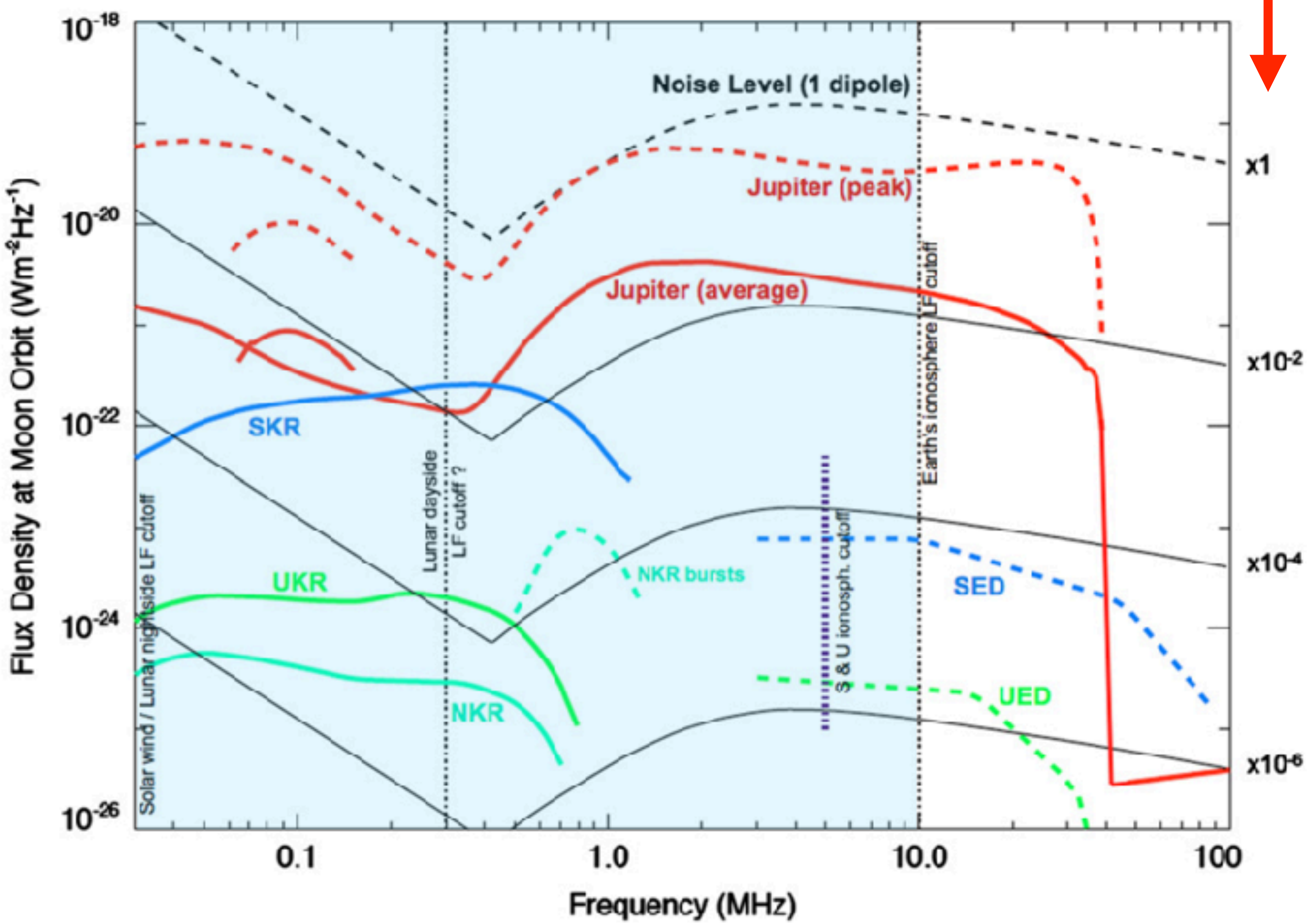
[Zarka et al., 2007, 2015]

Detectability

$$S_{noise}(Wm^{-2}Hz^{-1}) = 2kT_{noise}/A_{dipole} = 2kT_{noise}\Omega/\lambda^2$$

$$S_{min} = S_{noise}(A_{eff}/A_{dipole})^{-1}(bt)^{-1/2} \quad \text{with} \quad A_{eff} \sim N \times A_{dipole}$$

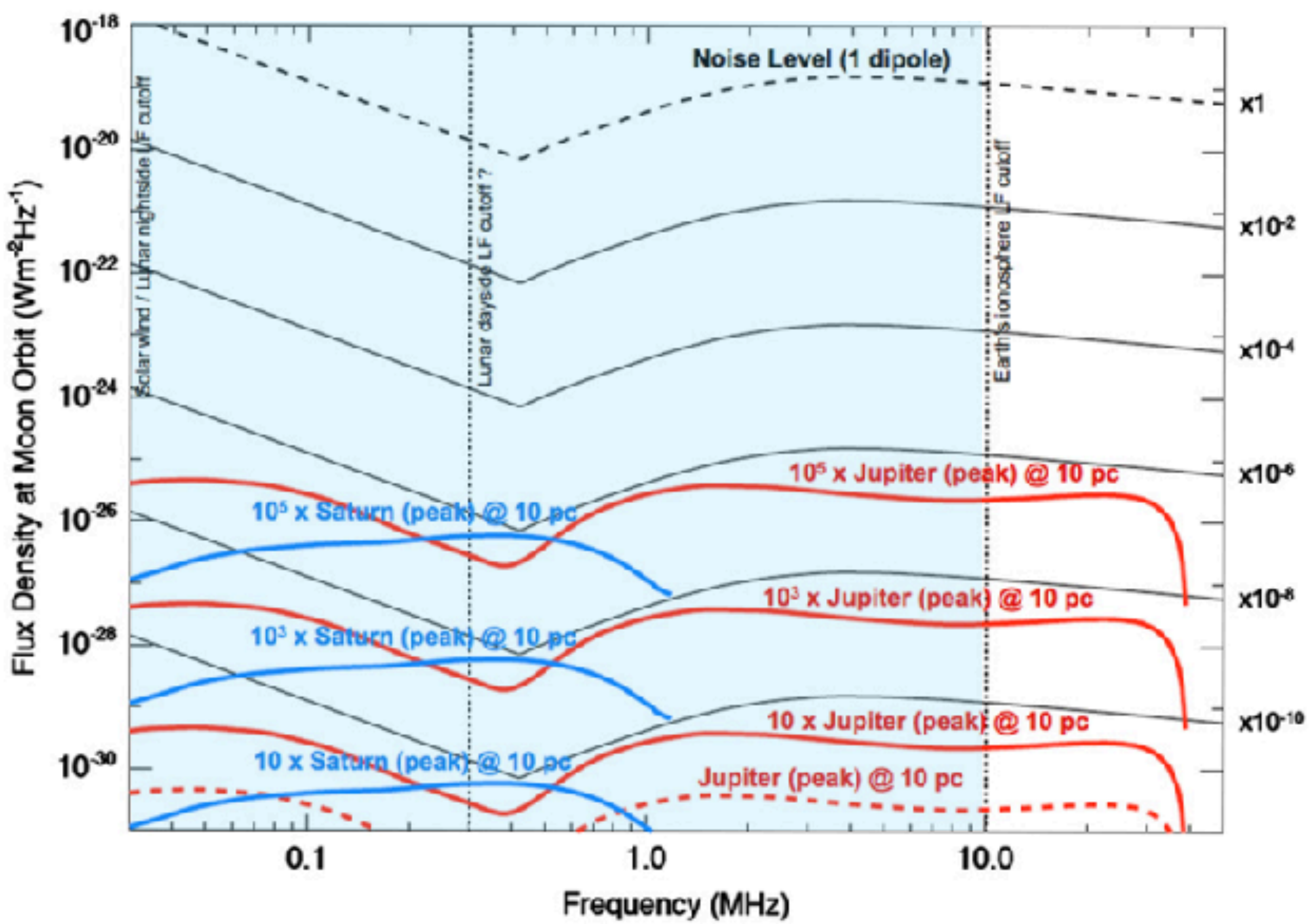
$$\text{thus } S_{min} \sim S_{noise}/[N(bt)^{1/2}] = S_{noise}/C \quad \text{with} \quad C = N(bt)^{1/2}$$



[Zarka et al., 2012]

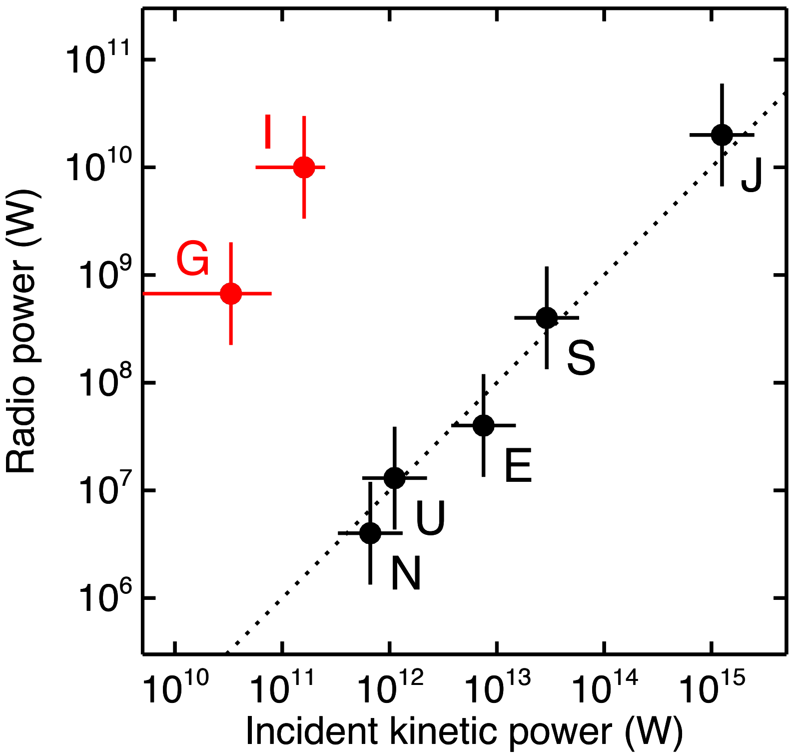
Detectability

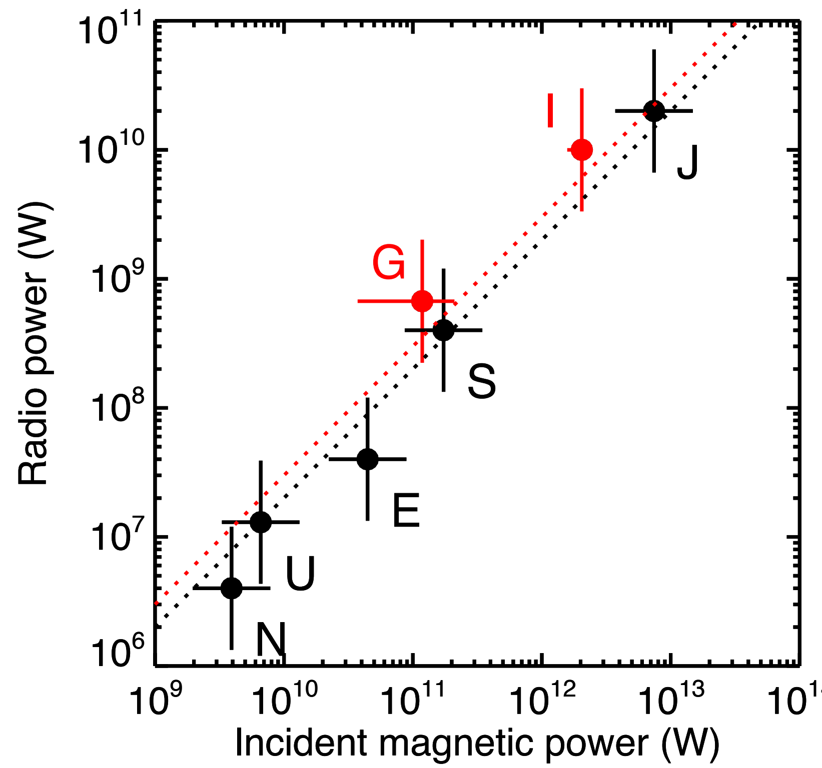
Radio emission	C	N (dipoles)	b (kHz)	τ
Jovian radio components	10^1–10^2	1	10	1 s
			100	10 ms
SKR	10^2–10^3	1	100	1–10 s
UKR and NKR	10^4–10^5	1	200–500	10–60 min
		10^1–10^2	100	10 s
SED	10^5	10^2	10^4	300 ms
UED	10^6	10^3	10^4	300 ms
Radio-exoplanet	10^7	100–500	10^3–10^4	10–60 min
		~10	2×10^4	1 day



[Zarka et al., 2012]

Scaling law & Predictions

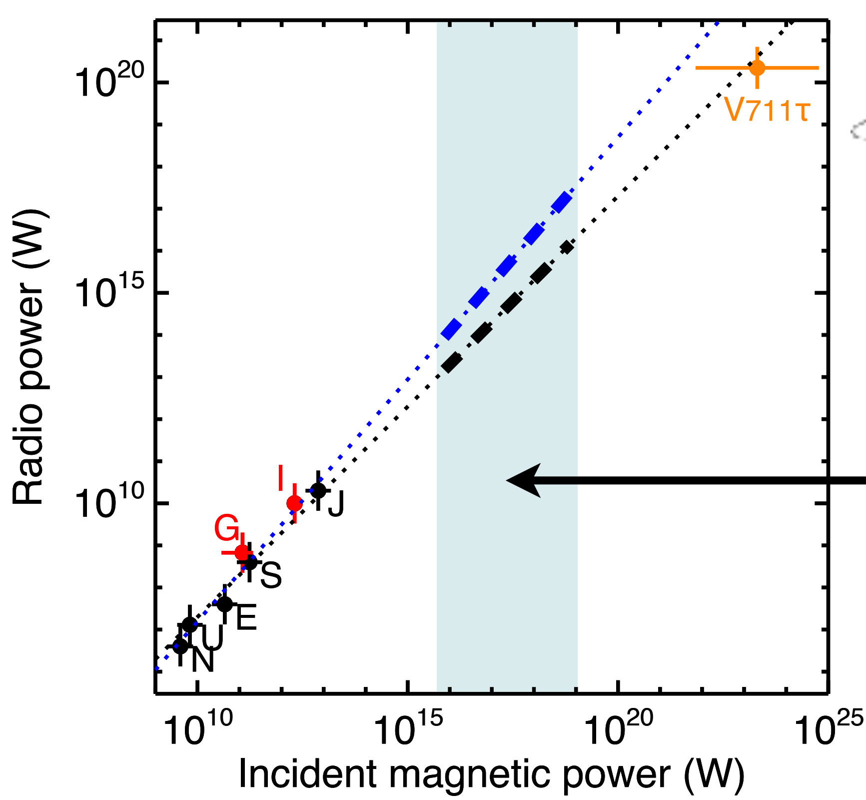




$$P_d = \varepsilon \, (V_{flow} B_{\perp}^2 / \mu_o) \, \pi R_{obs}^2$$

$$P_r = \beta \, (V_{flow} B_{\perp}^2 / \mu_o) \, \pi R_{obs}^2 = \beta \, P_d / \varepsilon$$

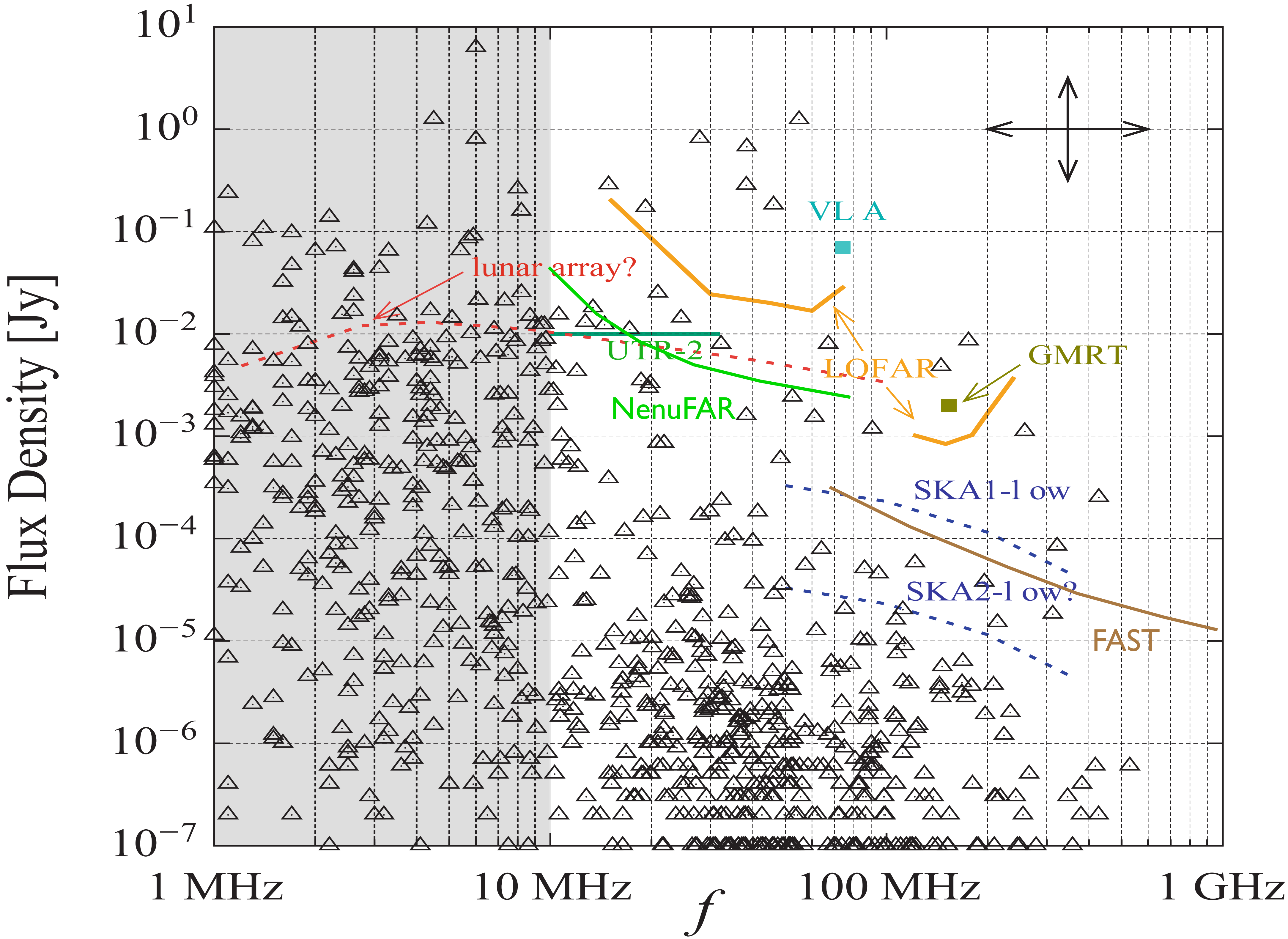
→ General flow - obstacle interaction



hot Jupiters : magnetospheric emission and Io-induced emission x 10^{3-6}

[Zarka et al., 2001, 2007, 2018]

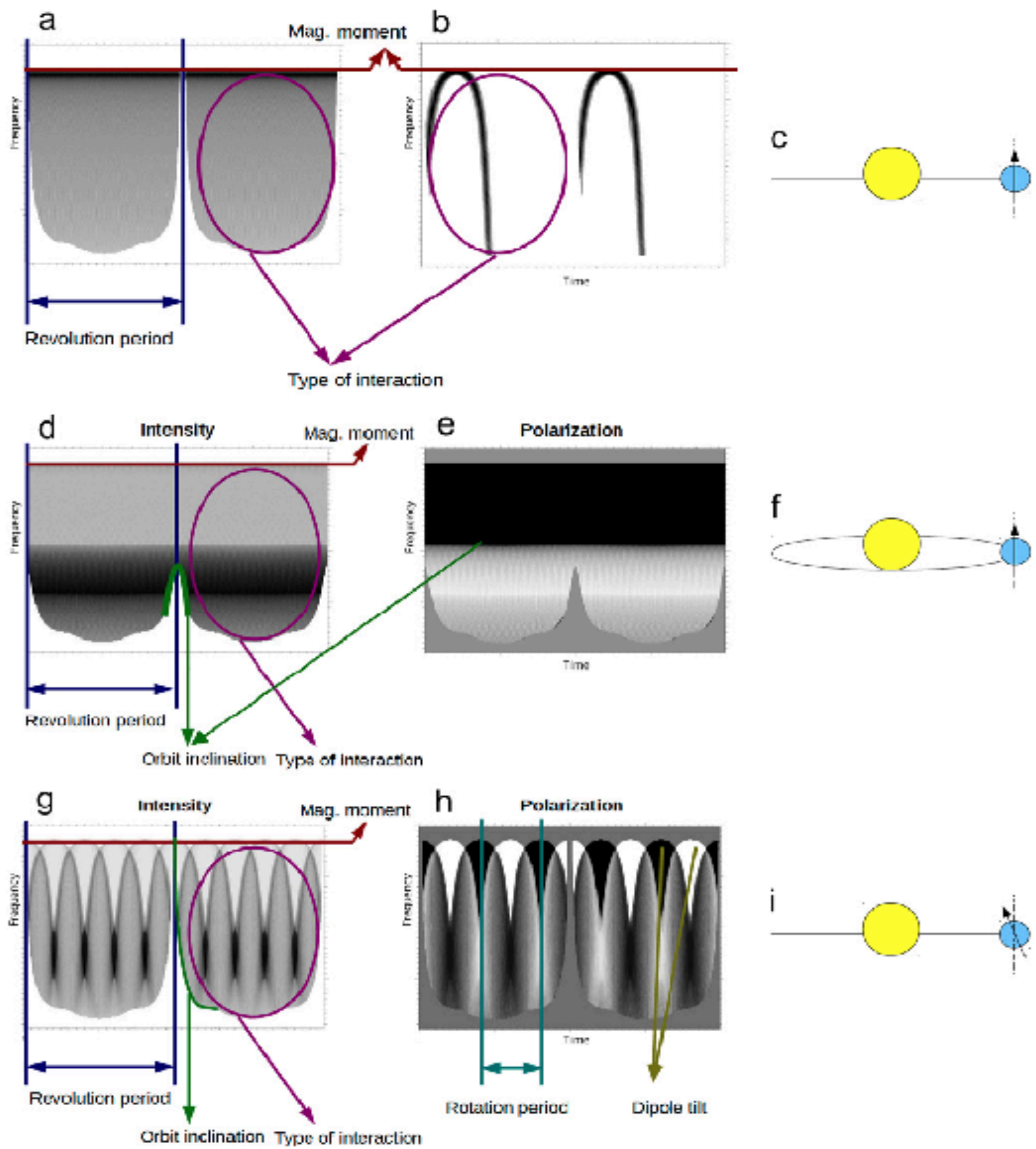
Potentially detectable signals with LOFAR, UTR-2, NenuFAR



[Grießmeier et al., 2011; Grießmeier, 2018]

Motivations

B, internal structure, exo-magnetospheric physics, SPI, habitability ...

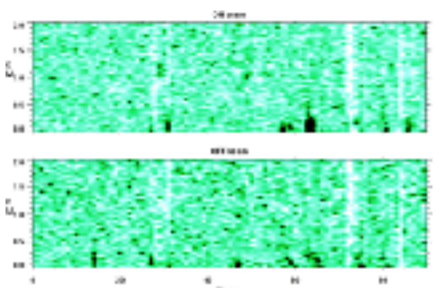


[Hess & Zarka, 2011]

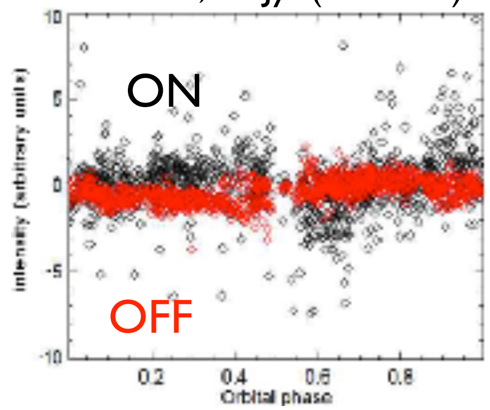
Intense observational efforts, no confirmed detection until recently

UTR-2 10-32 MHz

ρ Cr, 160 mJy (On / Off)



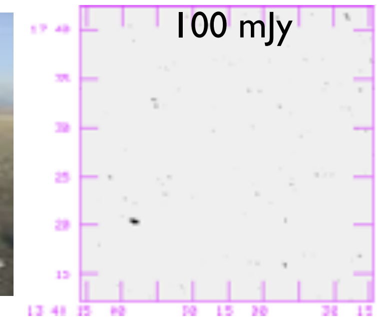
Corot 7, ~1 Jy (On / Off)



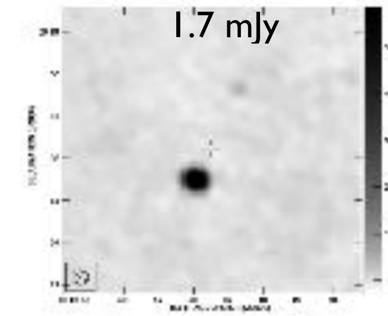
[Ryabov et al., 2004 ;Vasylieva et al., 2016]

VLA 74 MHz

τ Boo, 74 MHz, 100 mJy

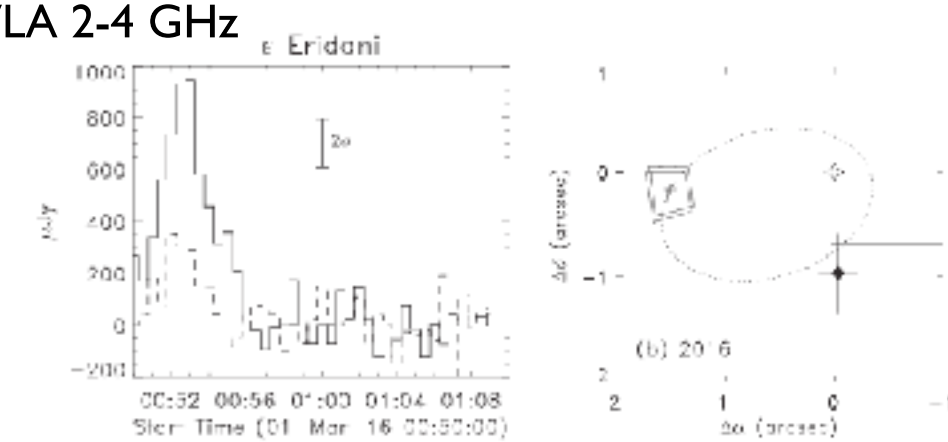


HD80606, 330 MHz, 1.7 mJy



[Farrell et al., 2003, 2004 ; Lazio & Farrell, 2007]

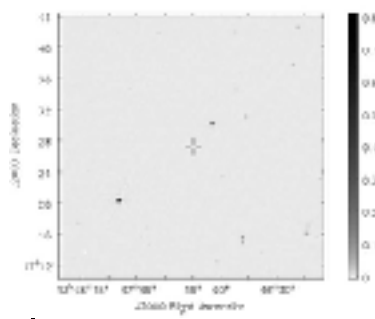
VLA 2-4 GHz



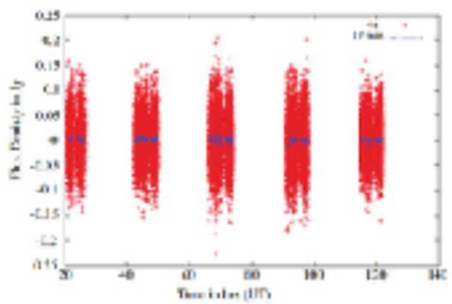
[Bastian et al., 2018]

GMRT 150 MHz

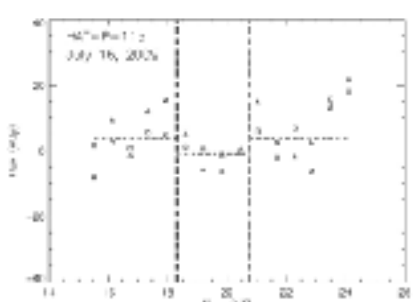
τ Boo, 150 MHz, 1 mJy



[Hallinan et al., 2013]



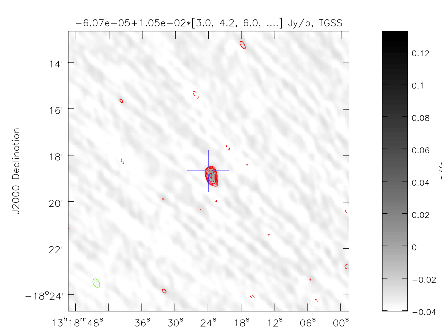
Hat-P-11, 150 MHz, 3.9 mJy



[Lecavelier et al., 2013]

TGSS → 4 candidates out of 175 exoplanetary systems, ~ 18-120 mJy

[Sirothia, et al., 2014]



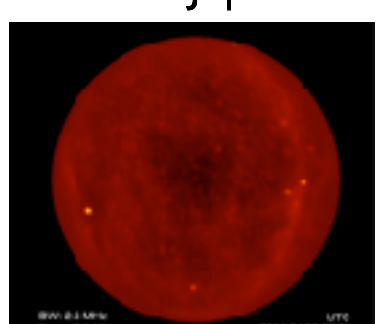
MWA 163-231 MHz

Proxima Centauri,V, 18 mJy ?

[Lenc et al., 2018]

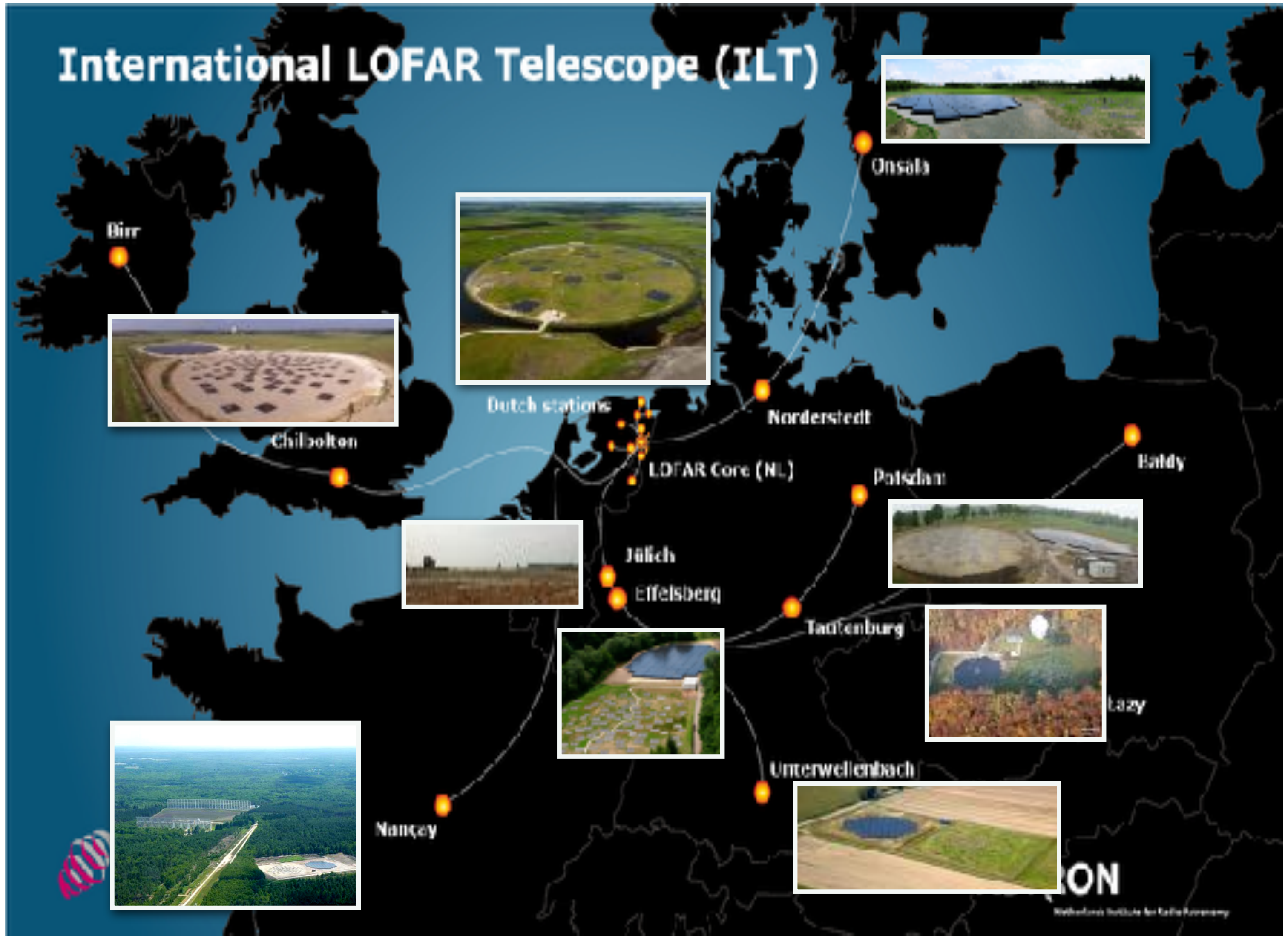
LWA (+ OLWA) 10-88 MHz

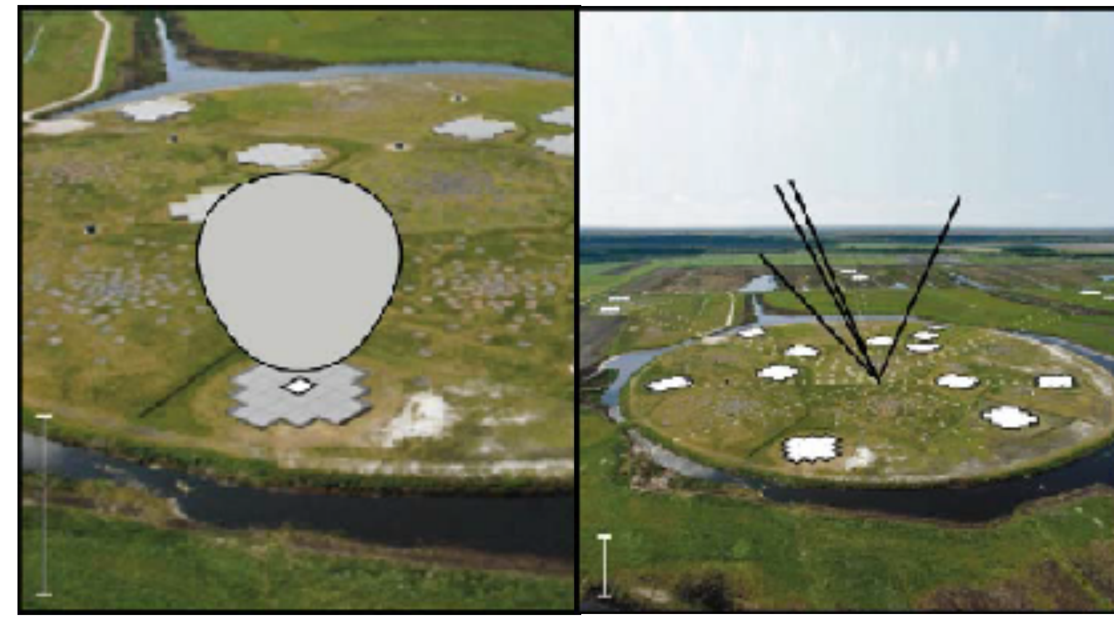
~5000+ h on ~12 Hot Jupiters

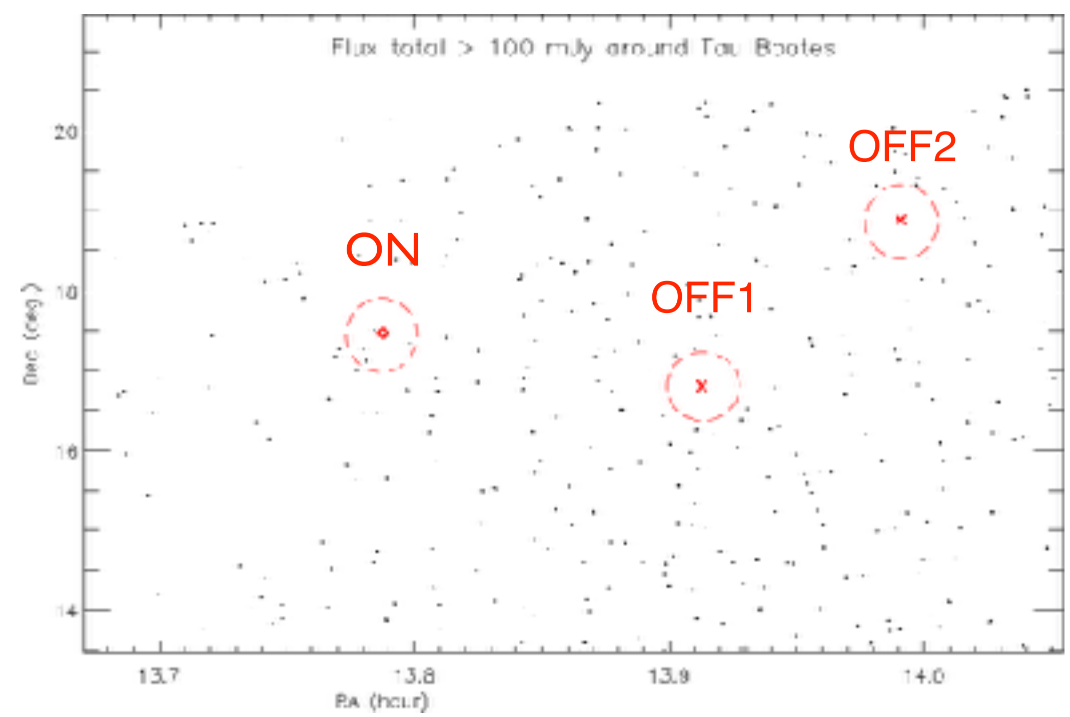


[Hartman, Hallinan, et al.]

Beamformed observations with LOFAR







Phased array (beamformed) mode, core only

24 stations x 48 dipoles = 1152 antennas

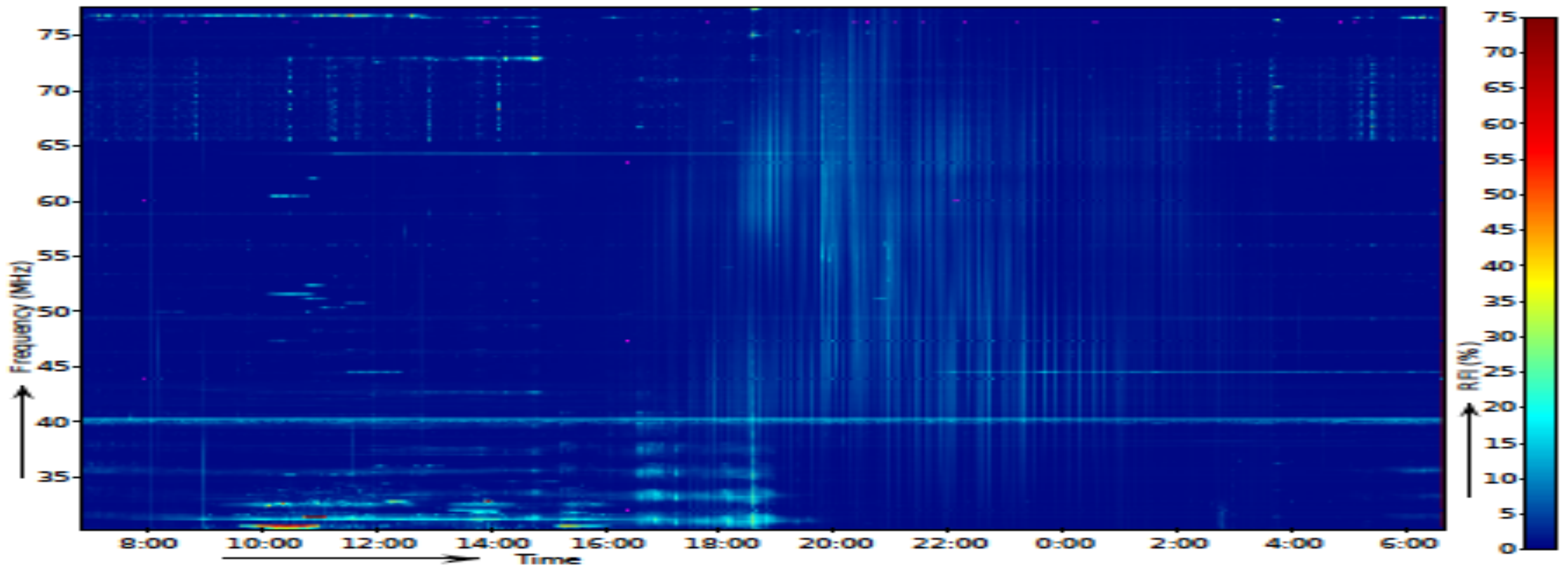
15-74 MHz, IQUV

multi-beam (1 ON, 2 OFFs), 2-3° apart

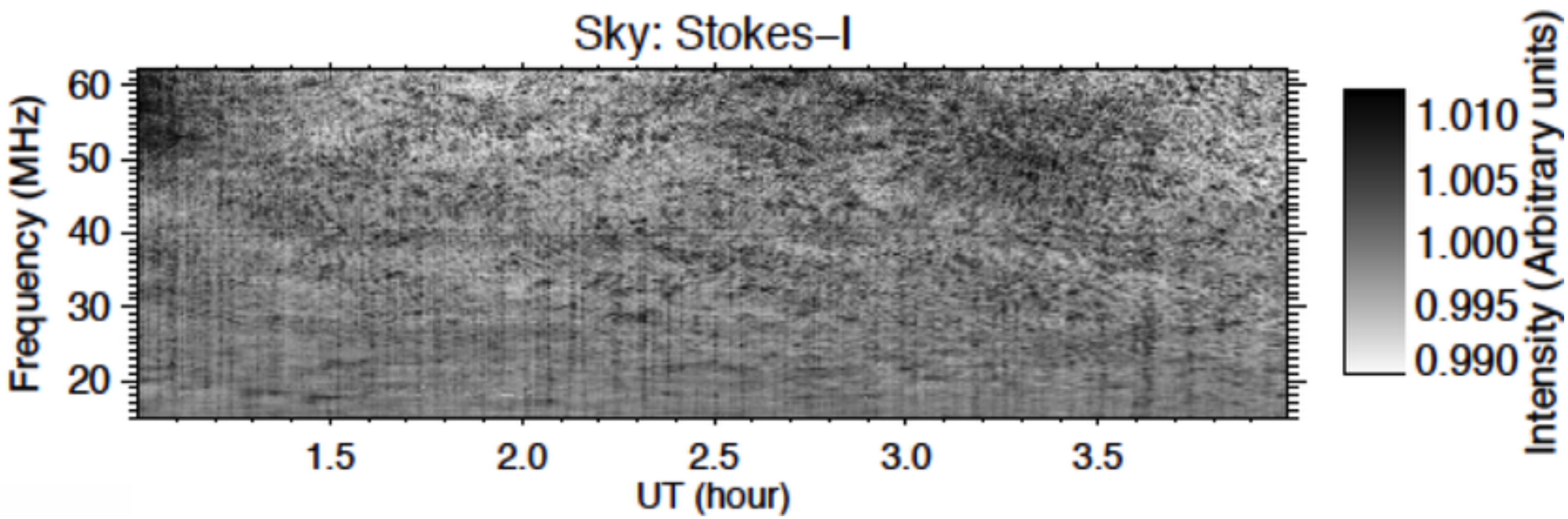
high time-frequency resolutions ⟹ RFI mitigation

[Turner et al., 2017]

Beamformed observations with LOFAR : strongly disturbed at low frequencies



[Offringa et al., 2013]



[Turner et al., 2017]

« Benchmarking » on Jupiter

[Turner et al., 2017]

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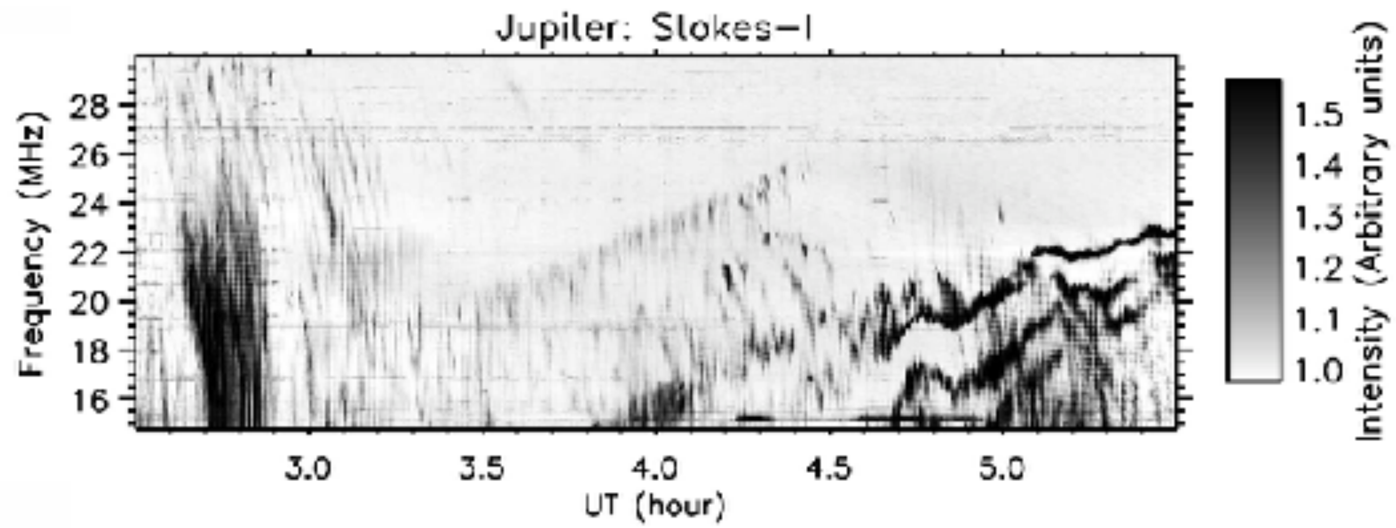
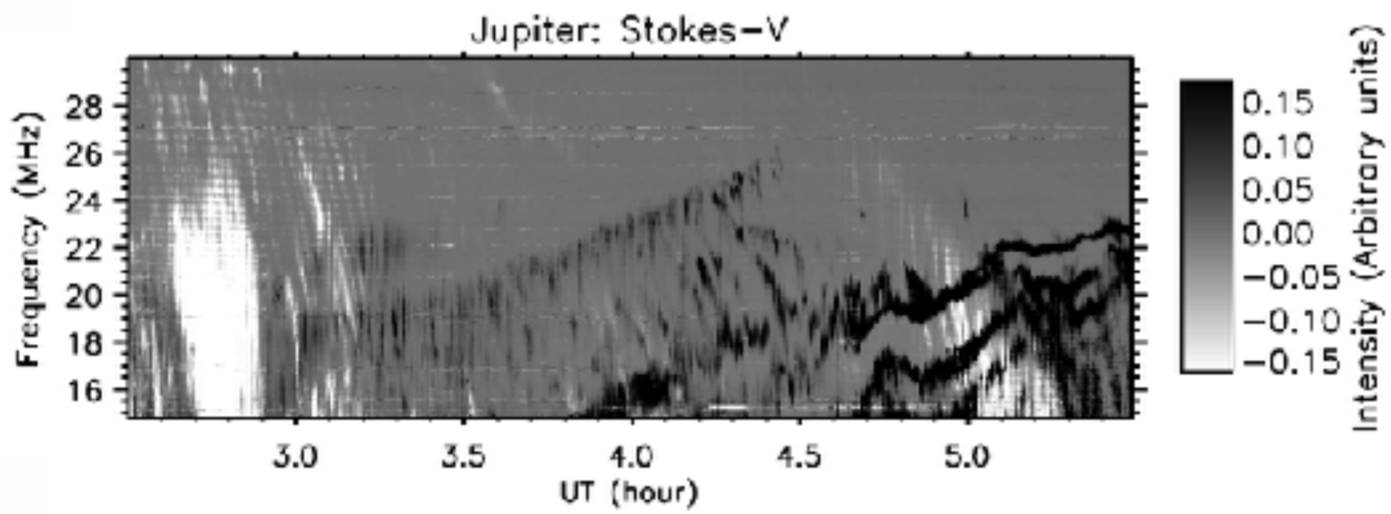
Astronomy & Astrophysics

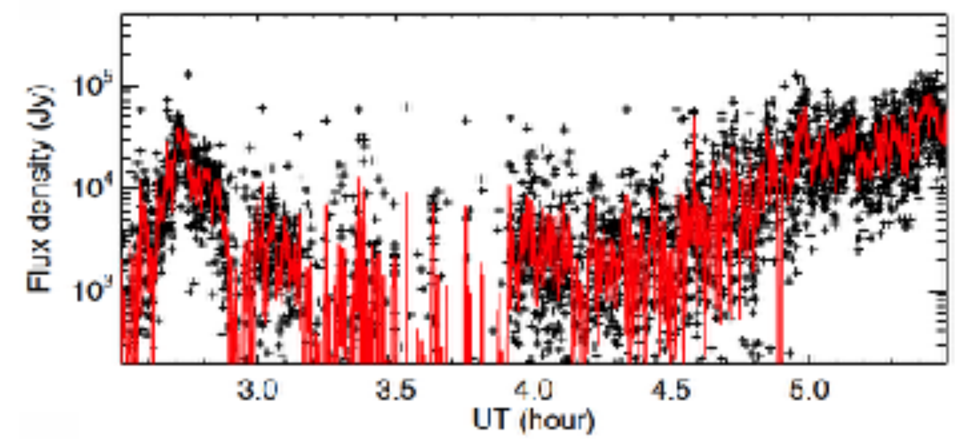
The search for radio emission from exoplanets using LOFAR beam-formed observations: Jupiter as an exoplanet

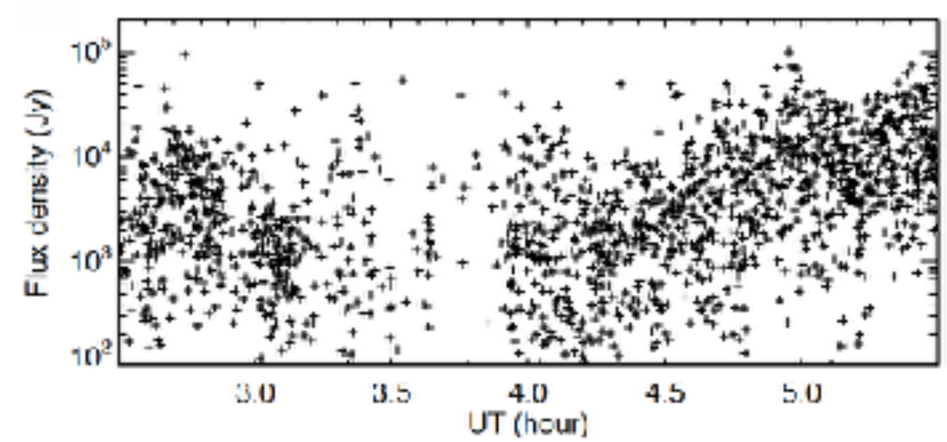
Jake D. Turner[1,2,3], Jean-Mathias Grießmeier[1,4], Philippe Zarka[4,5], and Iaroslavna Vasylieva[6]

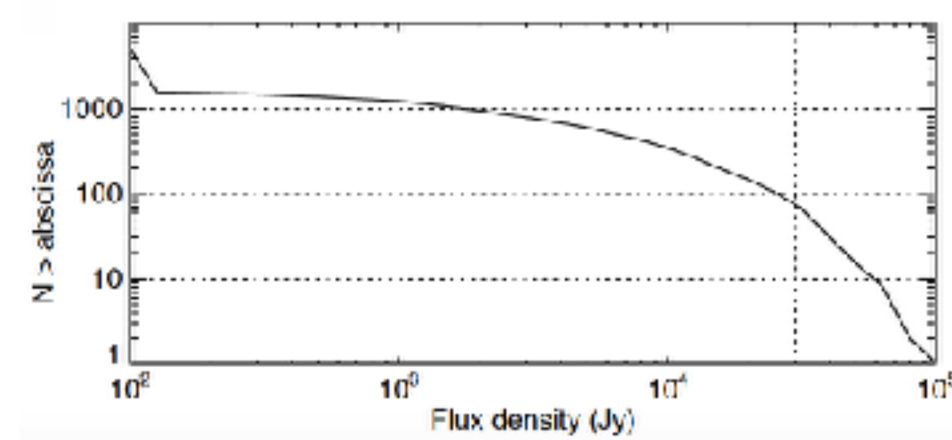
Jupiter observation with LOFAR & NDA





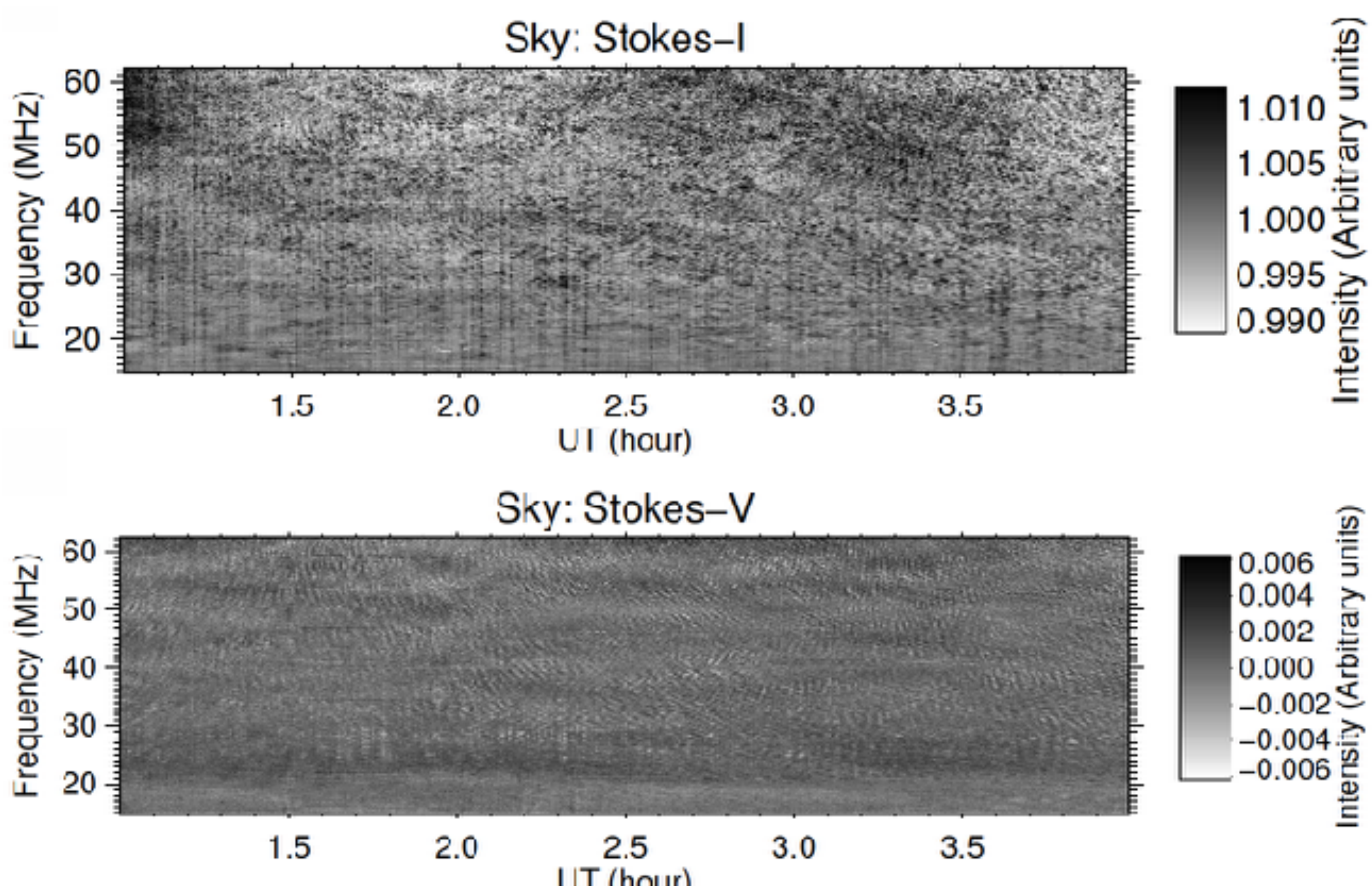






Jupiter observation & exoplanetary targets with LOFAR

Parameter	Obs #1	Obs #2	Obs #3	Obs #4
LOFAR OBS ID	L568467	L570725	L569123	L547645
Date (UT)	February 11, 2017	February 18, 2017	February 26, 2017	September 28, 2016
Time (UT)	02:30–05:30	01:12–04:12	01:16–04:16	23:00–04:00
Target	Jupiter	Tau Bootis	Tau Bootis	Upsilon Andromedae
ON-beam RA (2000)	13:27:49.42	13:47:15.74	13:47:15.74	01:36:47.84
ON-beam Dec (2000)	−07:39:01.70	+17:27:24.90	+17:27:24.90	+41:24:19.60
OFF-beam 1 RA (2000)	13:25:51.27	13:54:44.95	13:54:44.95	01:40:00
OFF-beam 1 Dec (2000)	−09:35:11.94	+16:49:29.20	+16:49:29.20	+38:00:00
OFF-beam 2 RA (2000)	13:35:55.97	13:58:10.366	13:58:10.366	01:30:00
OFF-beam 2 Dec (2000)	−09:05:16.10	+19:00:01.37	+19:00:01.37	+48:00:00



Transposition of the Jovian signal in Stokes I & V and in frequency

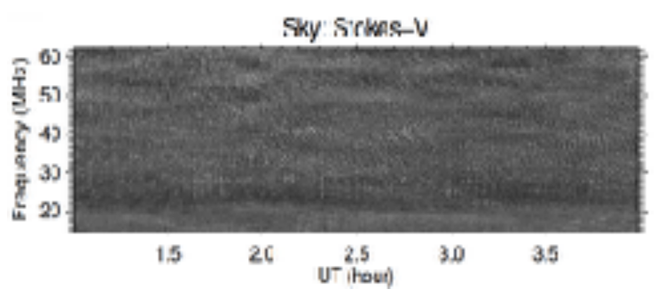
$$I_{\rm sim} = I_{\rm S2} + \alpha I_{\rm J2},$$
$$= I_{\rm S2}\left(1 + \alpha \frac{I_{\rm J1}}{I_{\rm S1}} \frac{S_{\rm S1}}{S_{\rm S2}}\right)$$

$$\mu_{10} \sim \mu - 1.3\sigma_g$$

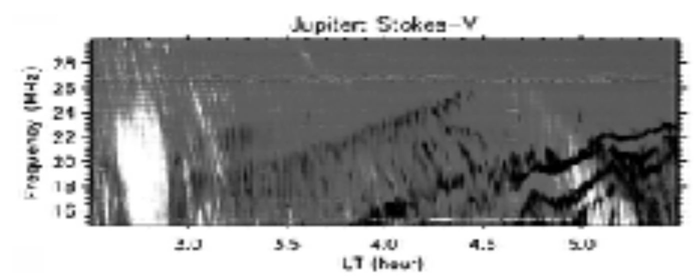
$$I_{\rm S1} = \mu = \mu_{10}\left(1 - \frac{1.3}{\sqrt{n_{\rm pol}\, b\, \tau_r}}\right)^{-1}$$

$$V_{\rm sim} = V_{\rm S2} + \alpha V_{\rm J1}\left(\frac{I_{\rm S2}}{I_{\rm S1}}\right)\left(\frac{S_{\rm S1}}{S_{\rm S2}}\right)$$

+ correction of the instrumental response in polarization



+ α



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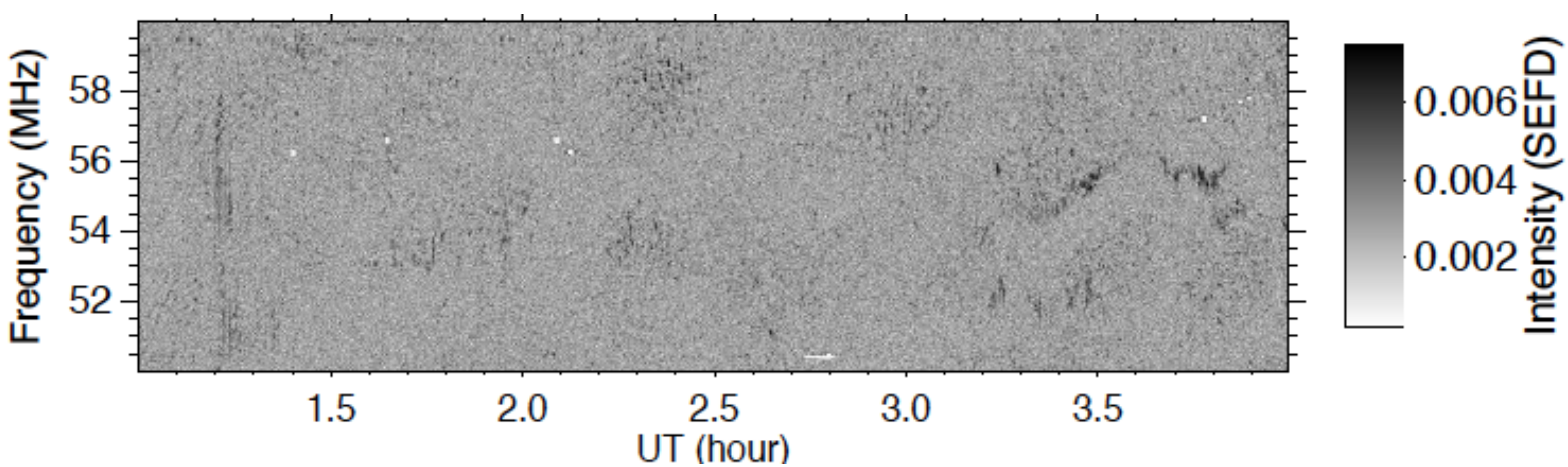
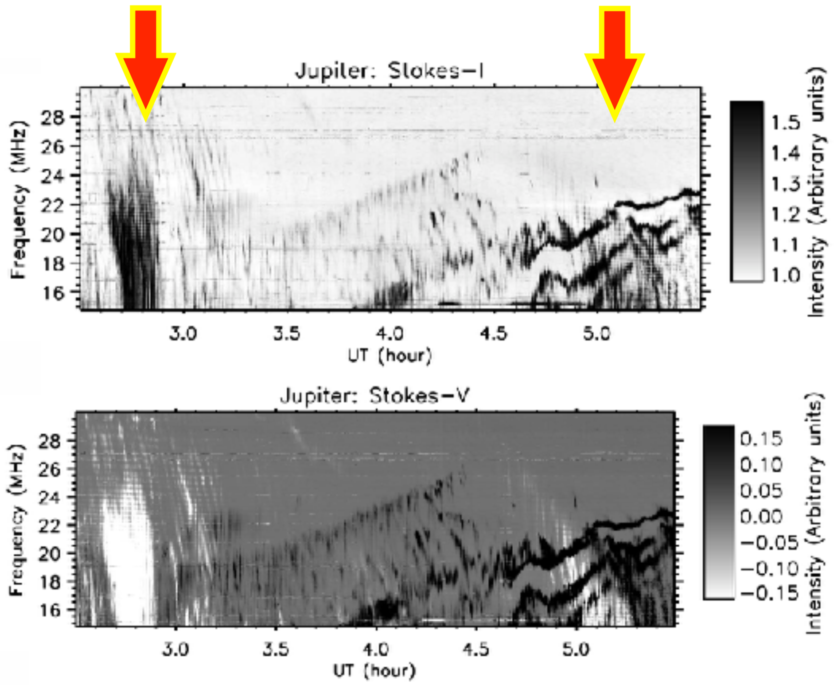
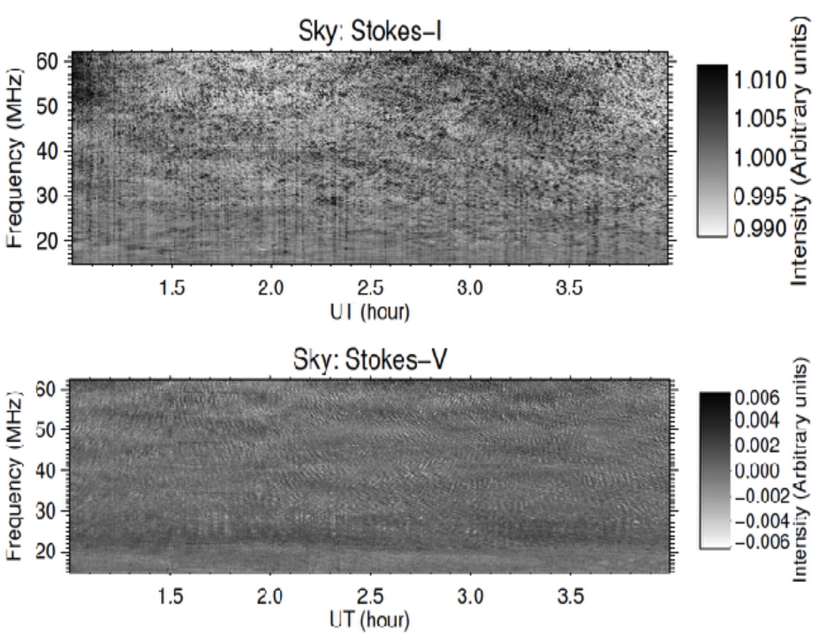
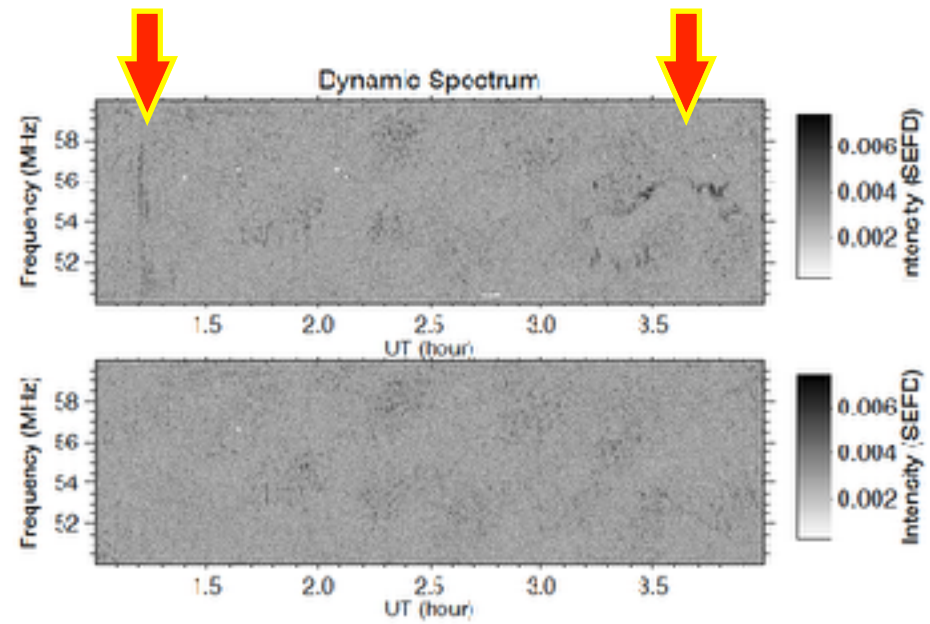


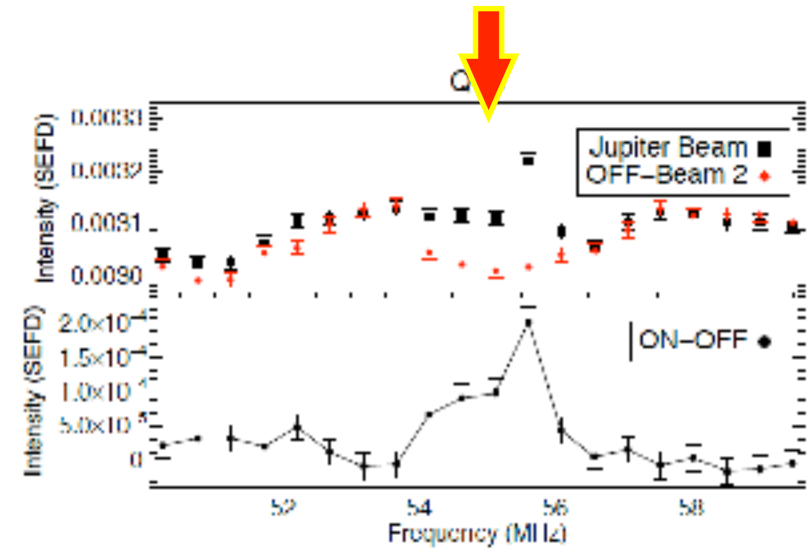
Detection of attenuated signal: slowly varying (minutes)

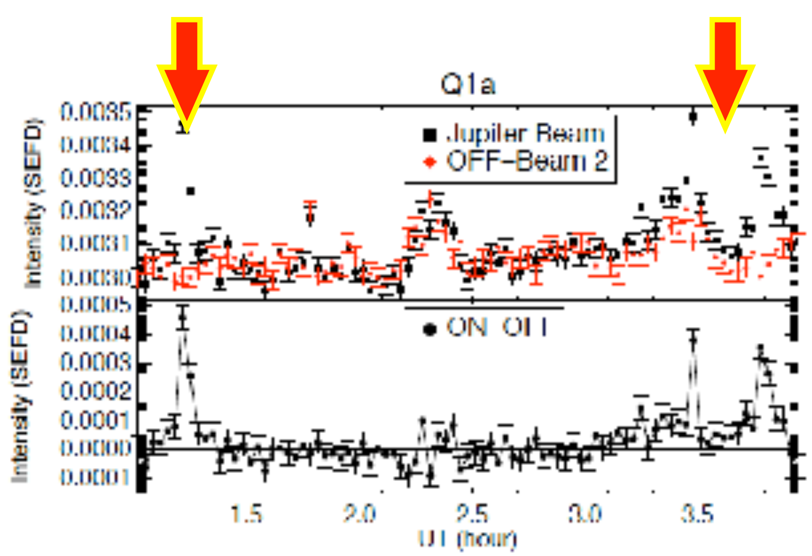




$|V|,\ \alpha = 10^{-4}$

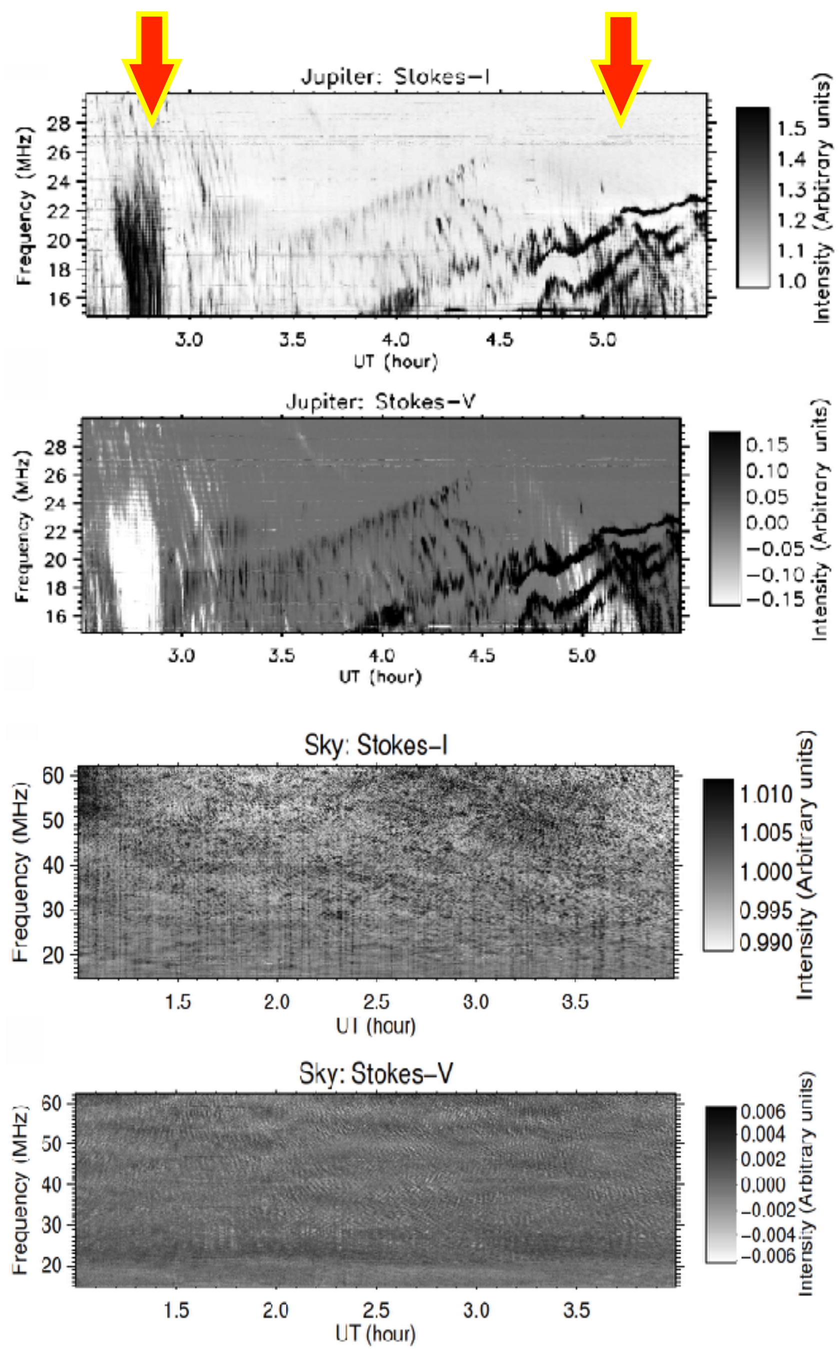




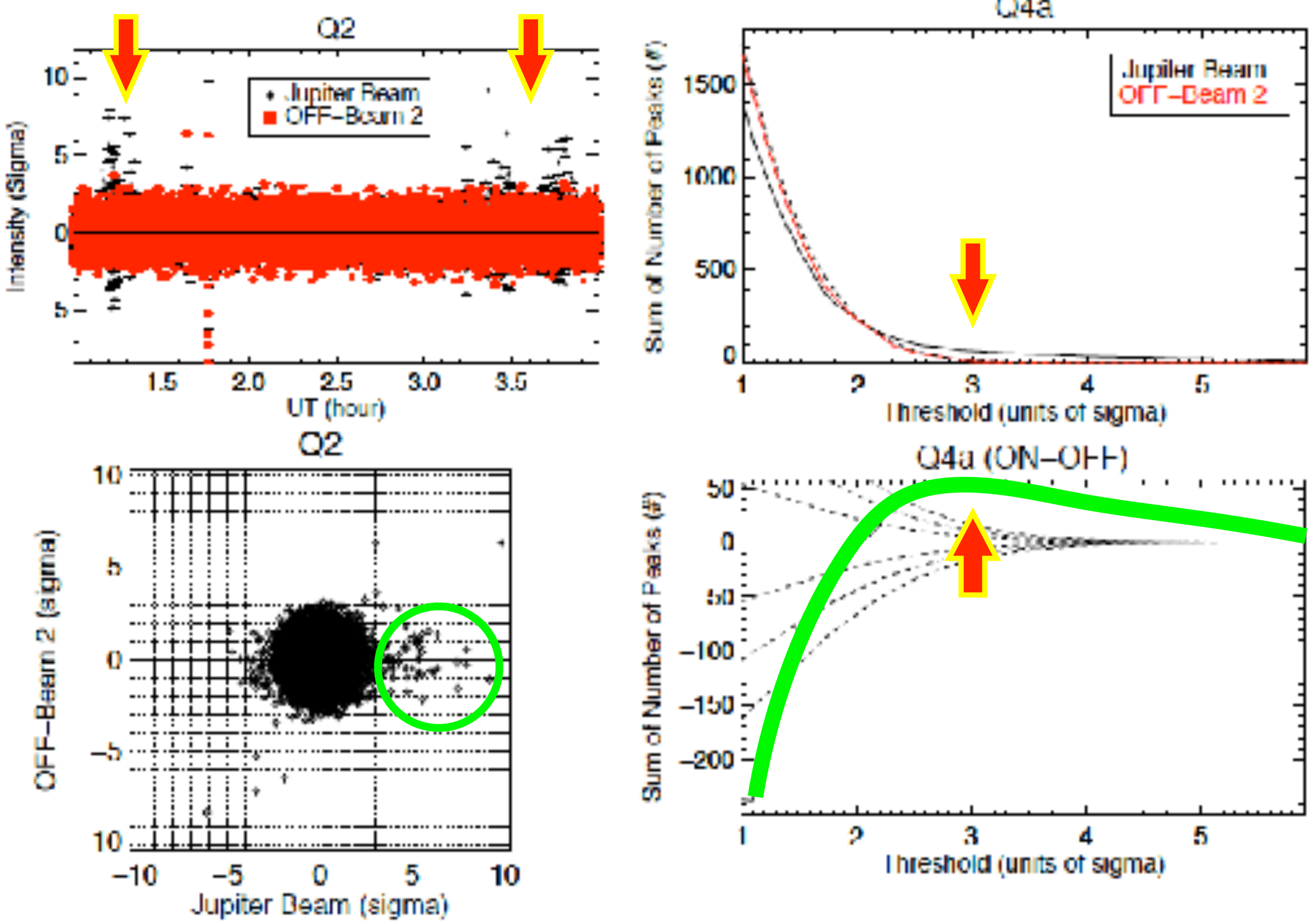


→ slowly varying emissions

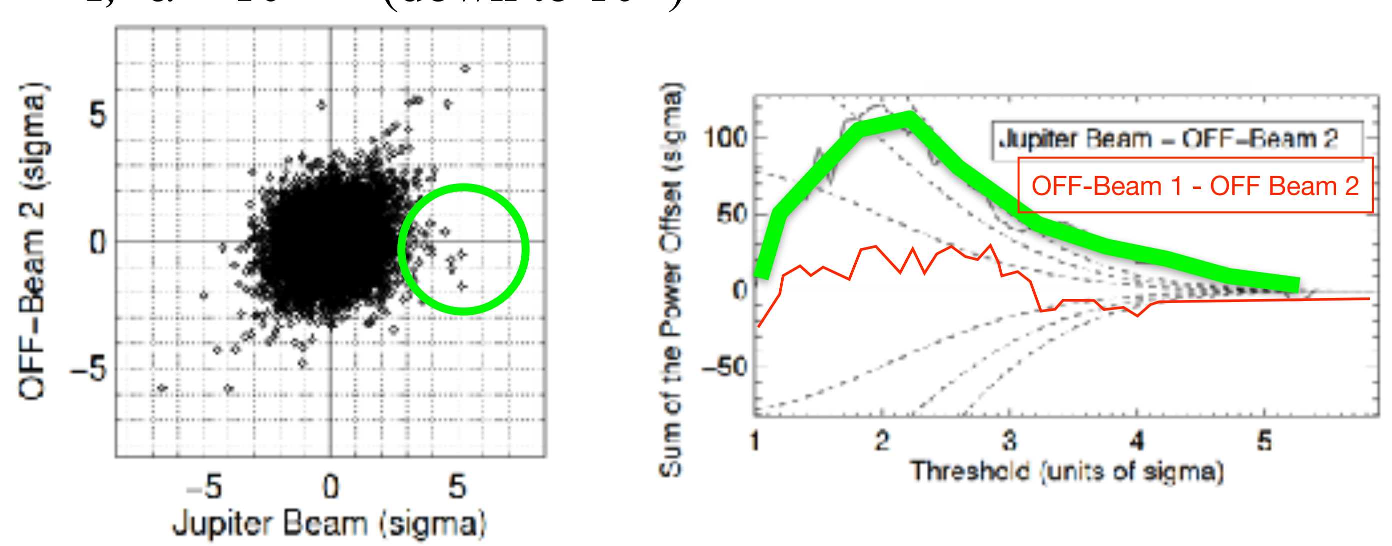
Detection of attenuated signal: bursts (~1 sec)



$|V|$, $\alpha = 10^{-4}$ (down to $10^{-4.5}$)



I, $\alpha = 10^{-3.5}$ (down to 10^{-4})



→ bursty emissions

Detection limit

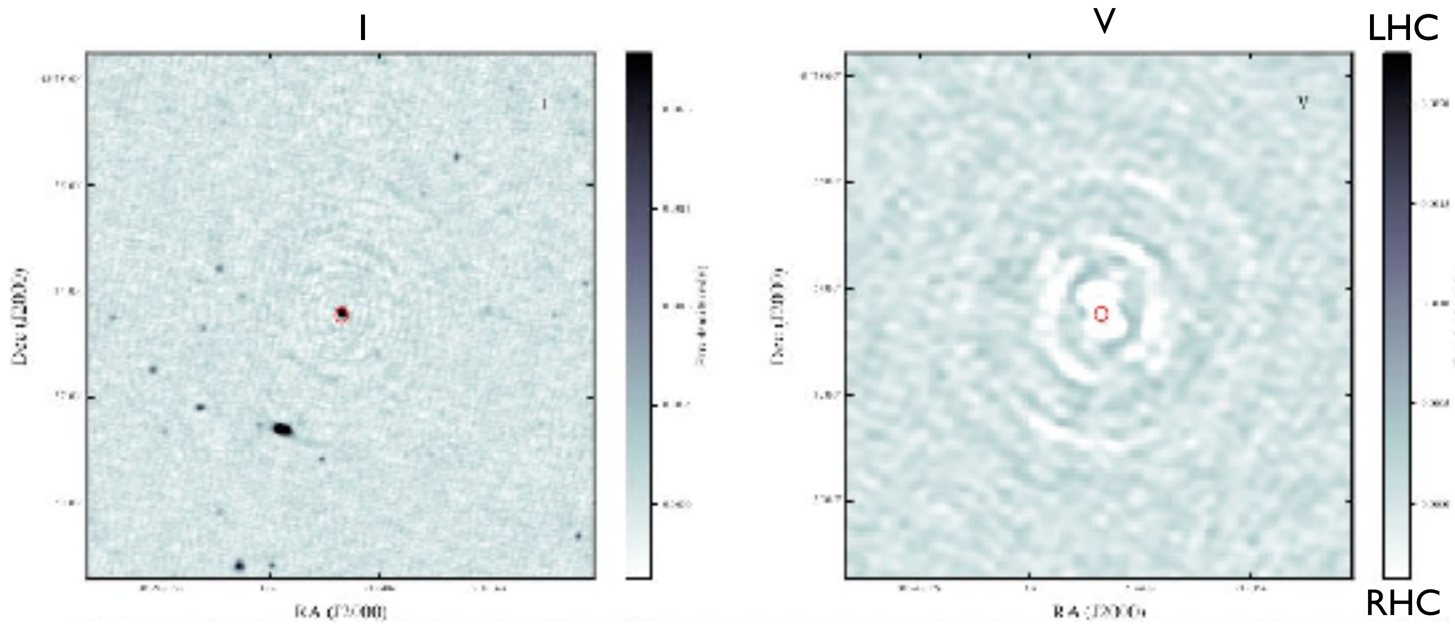
Table 5. Detection limit of LOFAR LBA beam-formed observations found by observing "Jupiter as an exoplanet".

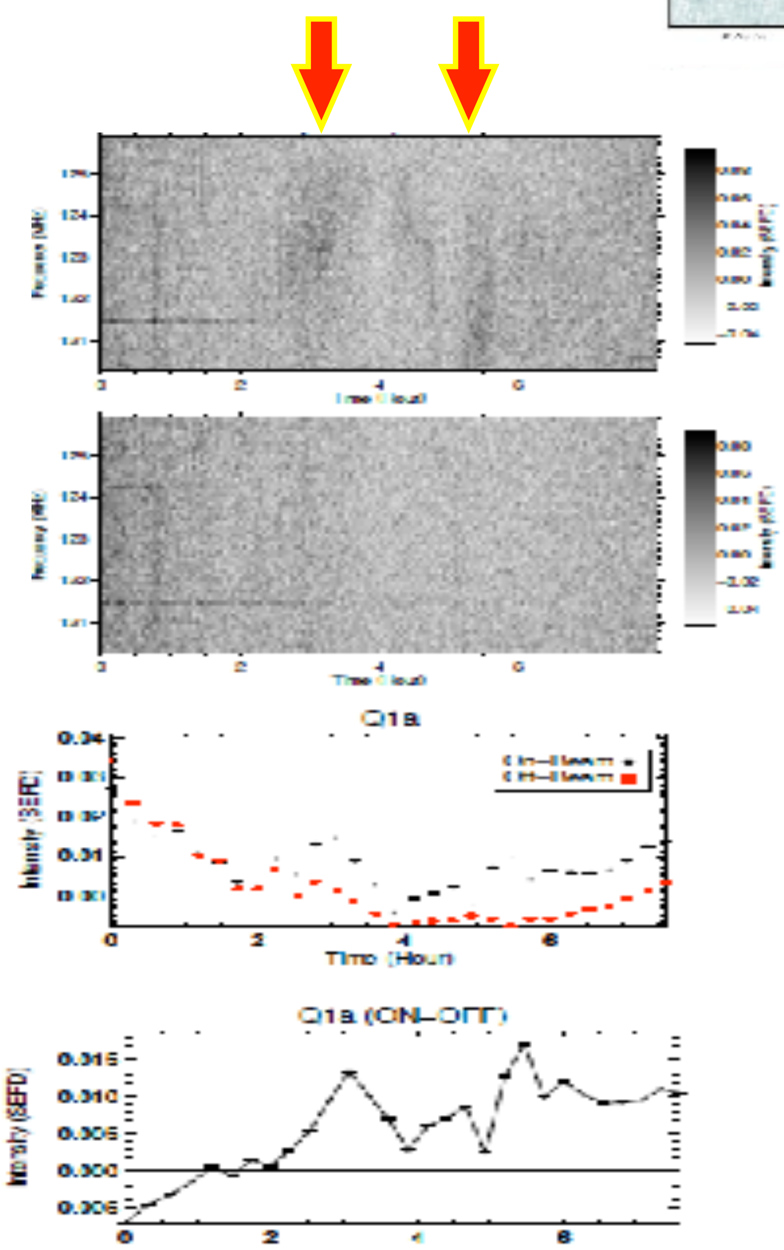
S_J(ref; Jy at 5 AU)	Distance (pc)	Stokes-I α_J	Stokes-V α_J
4×10^{4} [(a)]	5	1×10^{7}	1×10^{6}
"	10	4×10^{7}	4×10^{6}
"	20	2×10^{8}	2×10^{7}
4×10^{5} [(b)]	5	1×10^{6}	1×10^{5}
"	10	4×10^{6}	4×10^{5}
"	20	2×10^{7}	2×10^{6}
6×10^{6} [(c)]	5	6×10^{4}	6×10^{3}
"	10	3×10^{5}	3×10^{4}
"	20	1×10^{6}	1×10^{5}

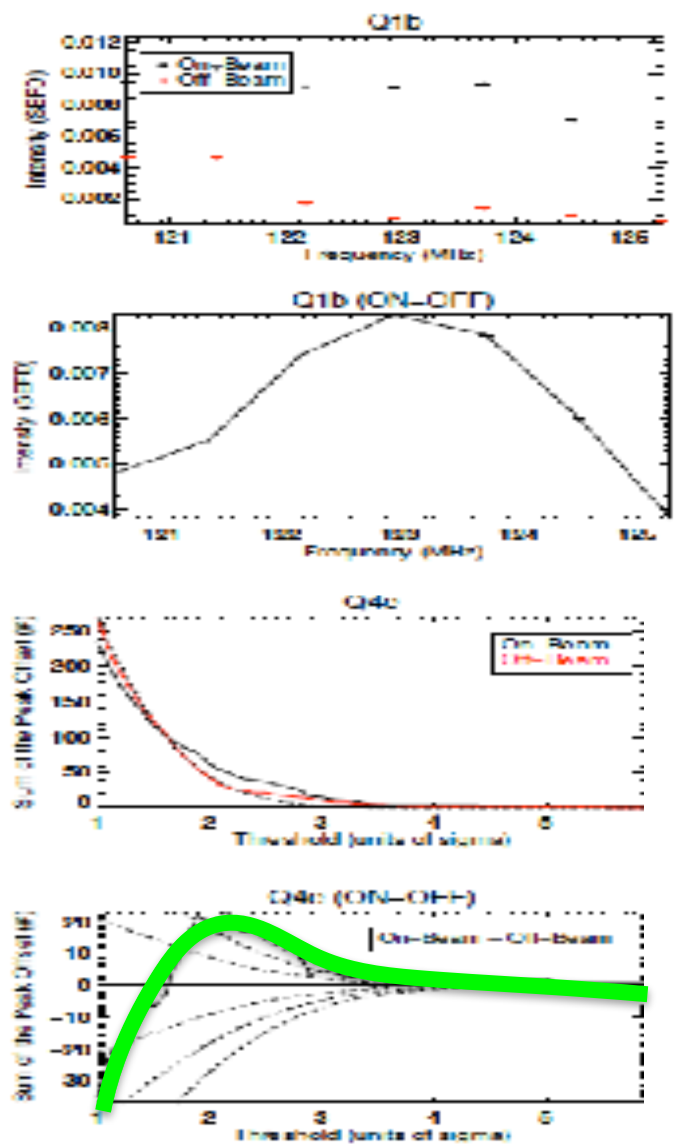
Notes. All calculations were done with Eq. (21) where the scaling factor $\alpha = 10^{-3.5}$ for Stokes-I and $\alpha = 10^{-4.5}$ for Stokes-V and $S_J(\mathrm{obs}) = 3\times10^{4}$ Jy (Sect. 3.1, Fig. 2). [(a)]The level of Jupiter's burst emission exceeded in ≥50% of Jupiter bursts (Zarka et al. 2004, Fig. 7). [(b)]The mean level of Jupiter's burst emission exceeded in ~1% of Jupiter bursts. [(c)]Maximum peak of Jupiter's S-burst emission (Queinnec & Zarka 2001).

→ 10^4 to 10^5 x Jupiter's bursts detectable at 5-20 pc range

Test on LOFAR survey data







→ LP 212-62 :
rotationally variable star
Stokes V, RHC bursts
10's sec - min timescales, 120-126 MHz
S ~10's mJy

$P = S\ 2\pi\ d^2\ \Delta f \sim 10^{15}$ W
($d = 18.2$ pc)
$S = k\ T_B\ \omega / \lambda^2$
$\Rightarrow T_B \sim 10^{13}$ K for a 1 R_S ∅ source
$B_{surface} \sim 45$ G
if Cyclotron-Maser emission

[Tasse et al., 2020, in preparation]

Observations of 55 Cnc, υ And, τ Boo

[Turner et al., 2017]

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Astronomy & Astrophysics

The search for radio emission from the exoplanetary systems 55 Cancri, υ Andromedae, and τ Boötis using LOFAR beam-formed observations

Jake D. Turner[1,2], Philippe Zarka[3,4], Jean-Mathias Grießmeier[3,5], Joseph Lazio[6], Baptiste Cecconi[3,4], J. Emilio Enriquez[7,8], Julien N. Girard[9,10], Ray Jayawardhana[1], Laurent Lamy[4], Jonathan D. Nichols[11], and Imke de Pater[12]

	units	55 Cnc b	55 Cnc e	υ And b	τ Boo b
* type		G8V[a]	G8V[a]	F9V	F7V
d	[pc]	12.5[b]	12.5[b]	13.5[b]	15.6[b]
$t_\star$	[Gyr]	10.2 ± 2.2[a]	10.2 ± 2.2[a]	3.8±1[b]	1.0±0.6[b]
a	[AU]	0.114[a]	0.0156[a]	0.057[c]	0.0462[c]
M_p	[M_J]	0.81[a]	0.024[a]	≥0.68[c]	≥3.87[c]
R_p	[R_J]	unknown	0.194[a]	unknown	unknown
ν_{max}^{NR}	[MHz]	20[d]	30[d]	14[d]	74[d]
Φ_{max}^{NR}	[mJy]	2.9[d]	150[d]	75[d]	170[d]
ν_{max}^{R}	[MHz]	3.3[d]	19[d]	2.2[d]	15[d]
Φ_{max}^{R}	[mJy]	5.3[d]	170[d]	140[d]	290[d]

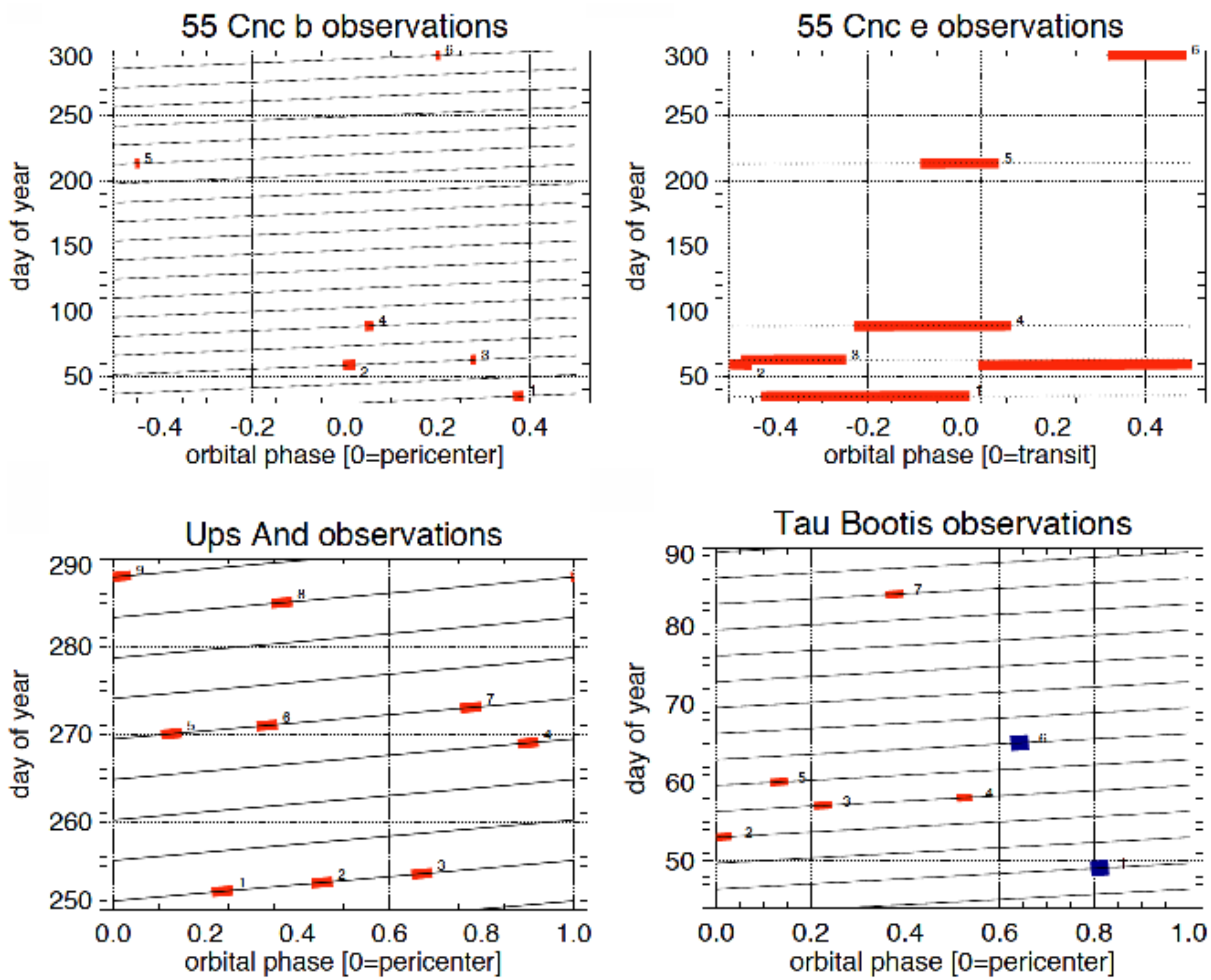
Observations of 55 Cnc, υ And, τ Boo

[Turner et al., 2017]

Choice of 3 targets from scaling law predictions

Distance ~12-15 pc

Coverage of orbital phase with 20-45 hours / target



Observation of τ Boo (7 sessions)

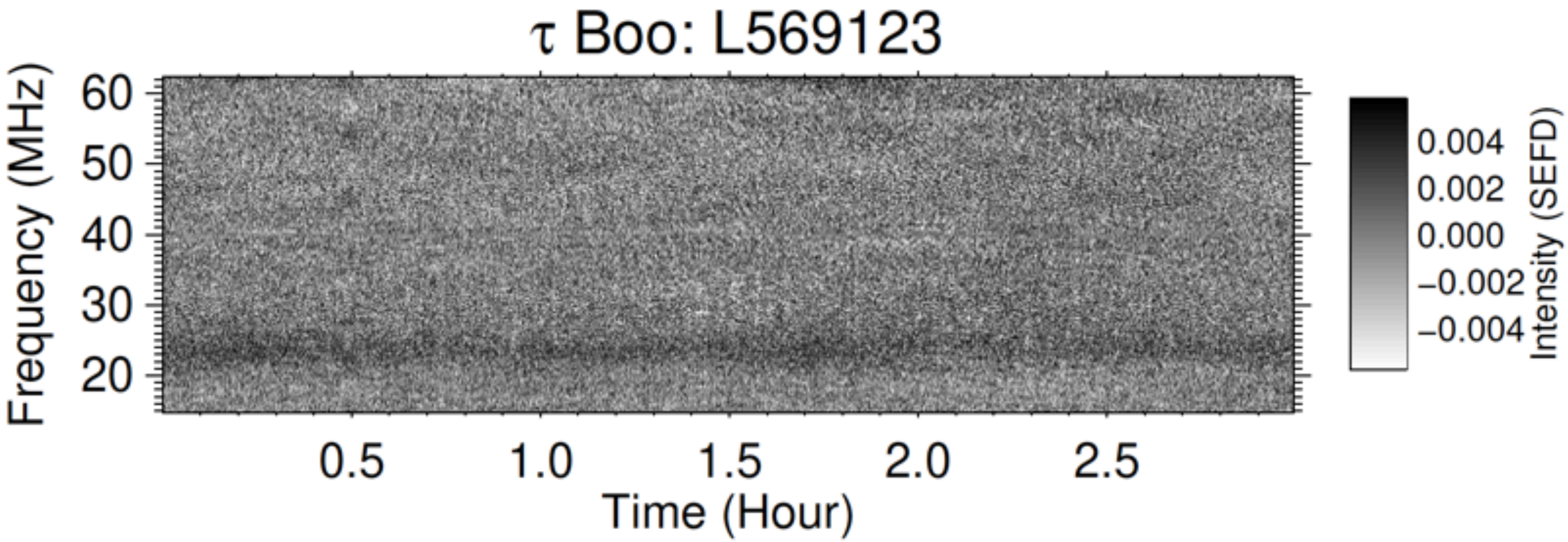
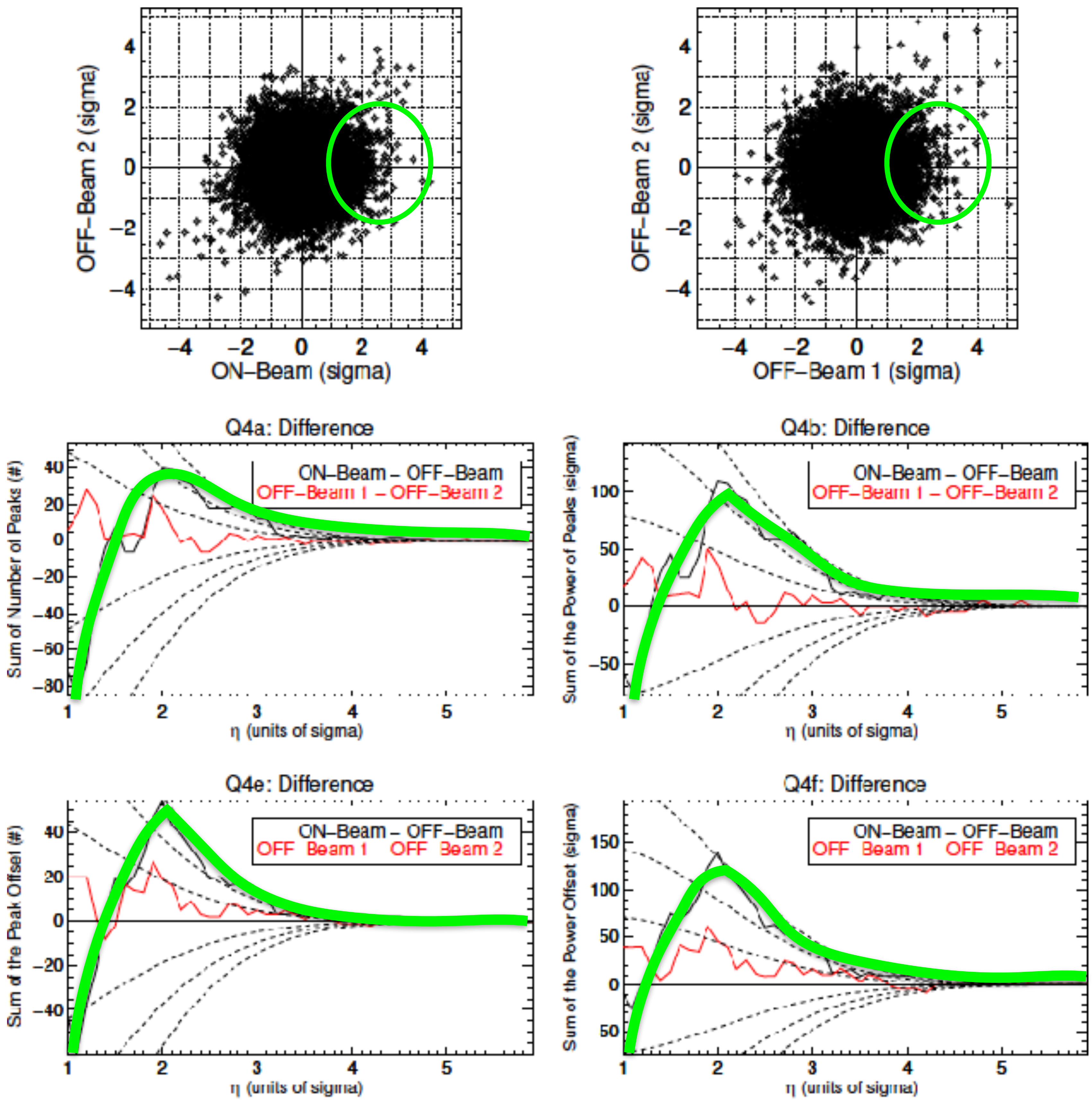


Table 3: Parameters for the post-processing pipeline.

Parameter	Value	Units
Frequency ranges	26-74, 26-50, 50-74[a]	MHz
	15-62, 15-38, 38-62[b]	MHz
Q1 Time bins (δT)	2	minutes
Q1 Frequency Bins (δF)	0.5	MHz
Q2-Q4 rebin times ($\delta\tau$)	1, 10	sec
Mask threshold	90	%
Smoothing window for high-pass filtering	10	$\delta\tau$
Threshold (η) range	1 - 6	σ

[a] Frequency ranges for the 55 Cnc observations.
[b] Frequency ranges for the υ And and τ Boo observations.

Possible detection of bursts from τ Boo (session #1)



Reality and origin of the radio signal ?

Stokes V, LHC

« Objective » detection

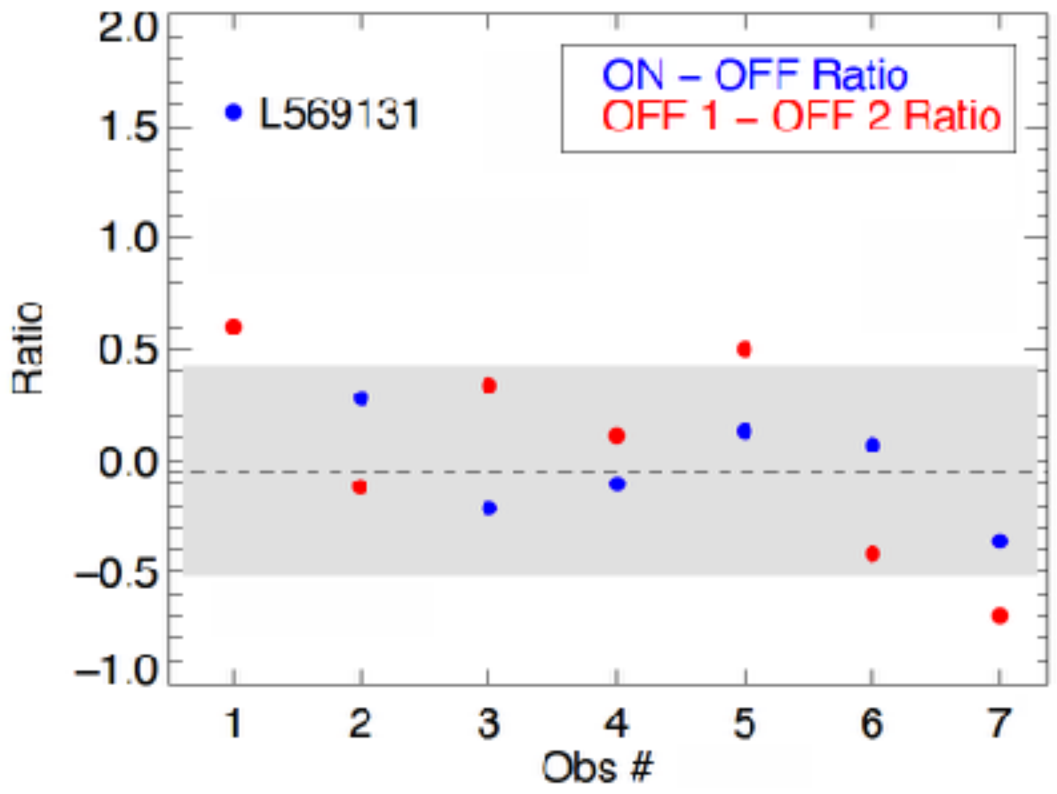
no simultaneous Jupiter emission

A few tens bursts ~1 sec (not at 10 sec)

15-21 MHz , S≥890 mJy

Confidence level 3.2σ

ON & OFF curves ≠ with 98% probability (K-S test)



No large flare from τ Boo A

B = 1.7-3.9 G (ZDI)

Flares from τ Boo B M-dwarf ?

Requires strong coronal B field

Scaling law

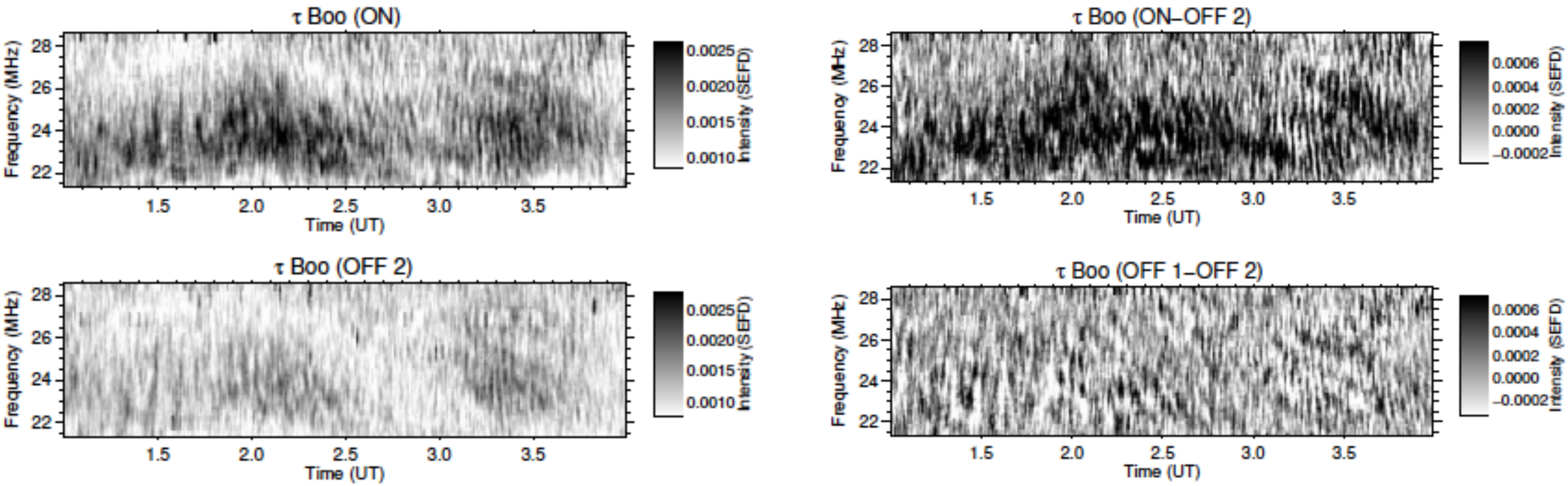
If τ Boo b, $B_{surface}$ = 5.4-7.5 G

$P = S\,\Omega d^2\,\Delta f \sim 10^{15}$ W ⇒ ~ 10^5 x Jupiter

$S = k\,T_B\,\omega / \lambda^2$ ⇒ $T_B \sim 10^{18}$ K for a 1 R_J ∅ source

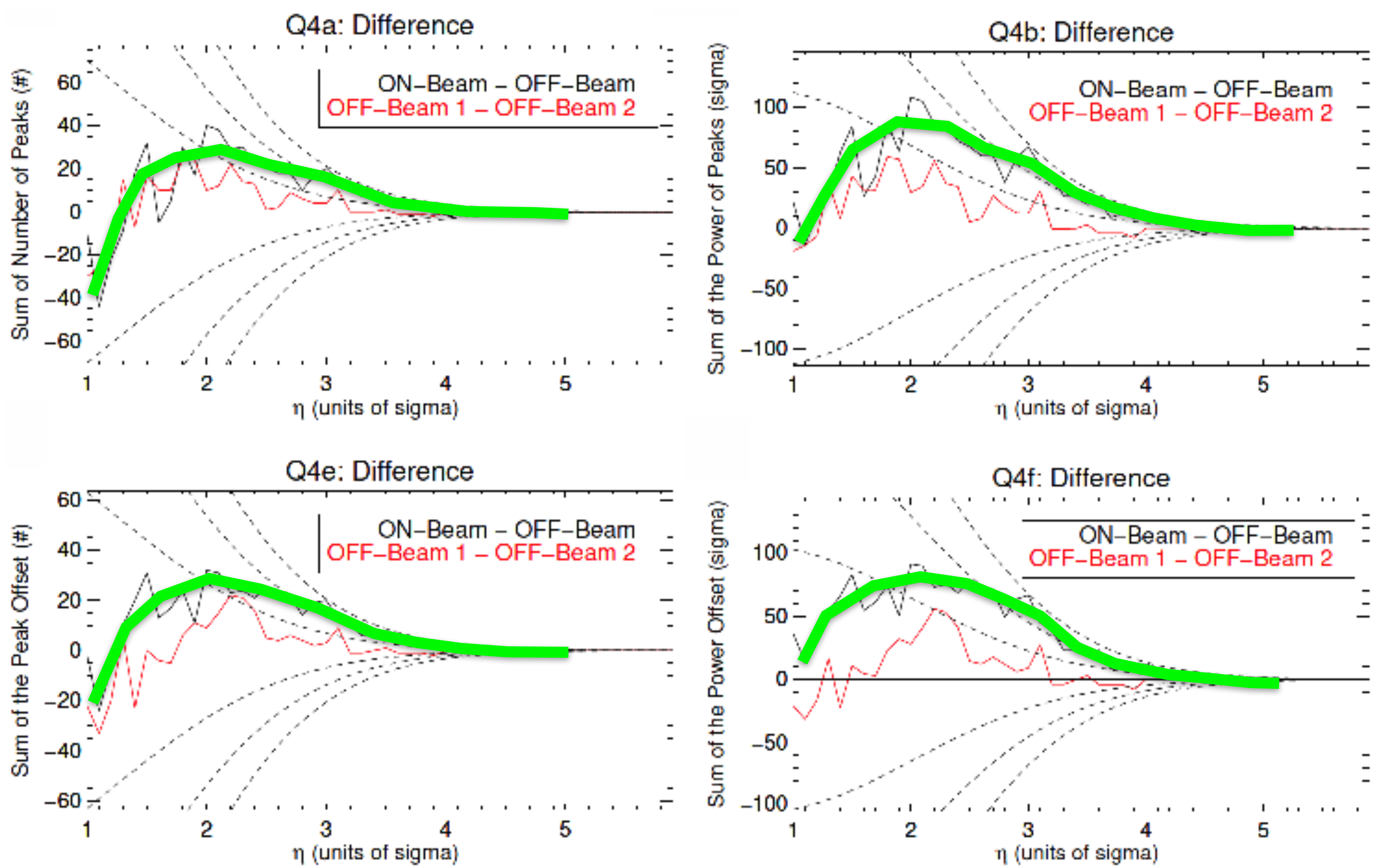
⇒ ~Jupiter for a 10-100 km ∅ source

Slowly variable emission of τ Boo ? (session #6)



⇒ likely spurious but unexplained origin

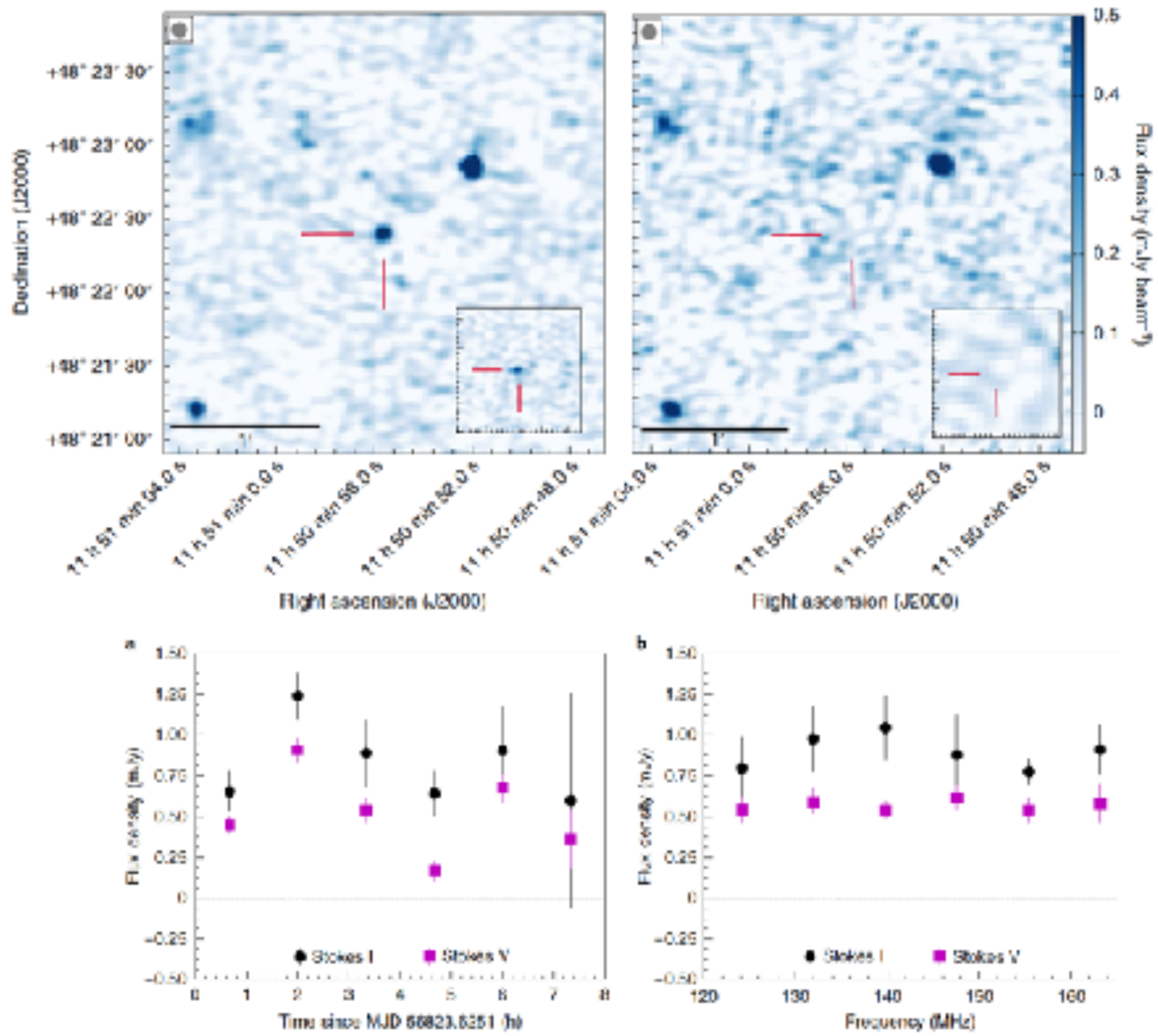
Marginal detection of bursts from υ And



υ And : marginal detection ~2σ

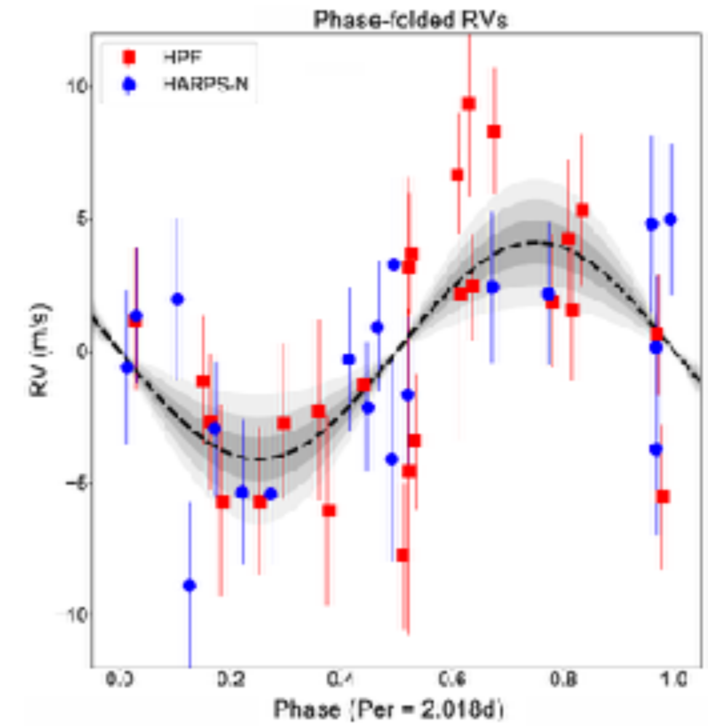
55 Cnc : no detection of bursts

In parallel : LOFAR imaging survey results

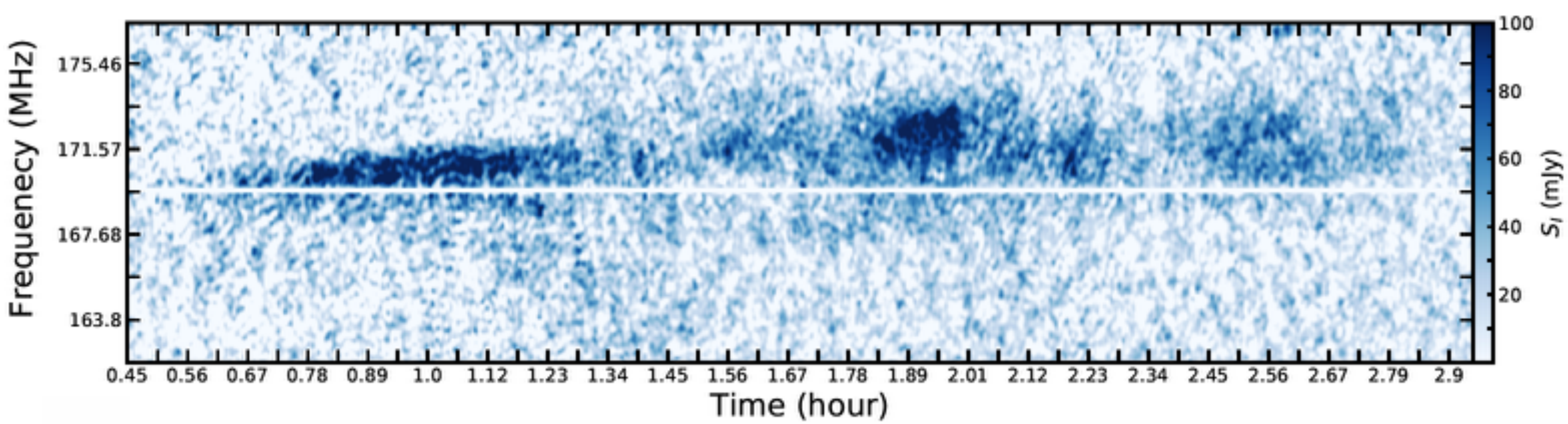


[Vedantham et al., 2020]

GJ 1151



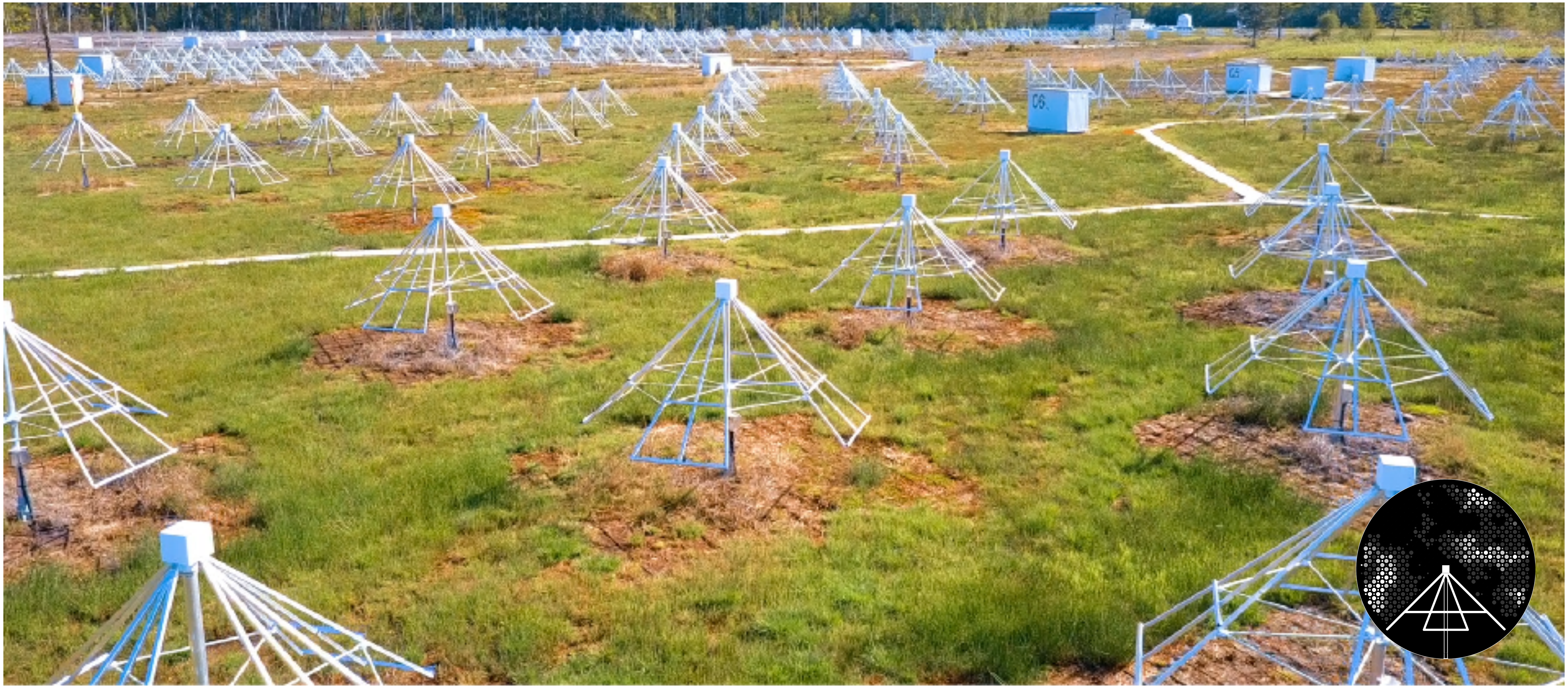
[Mahadevan et al., 2021]



CR Dra

[Callingham et al., 2021]

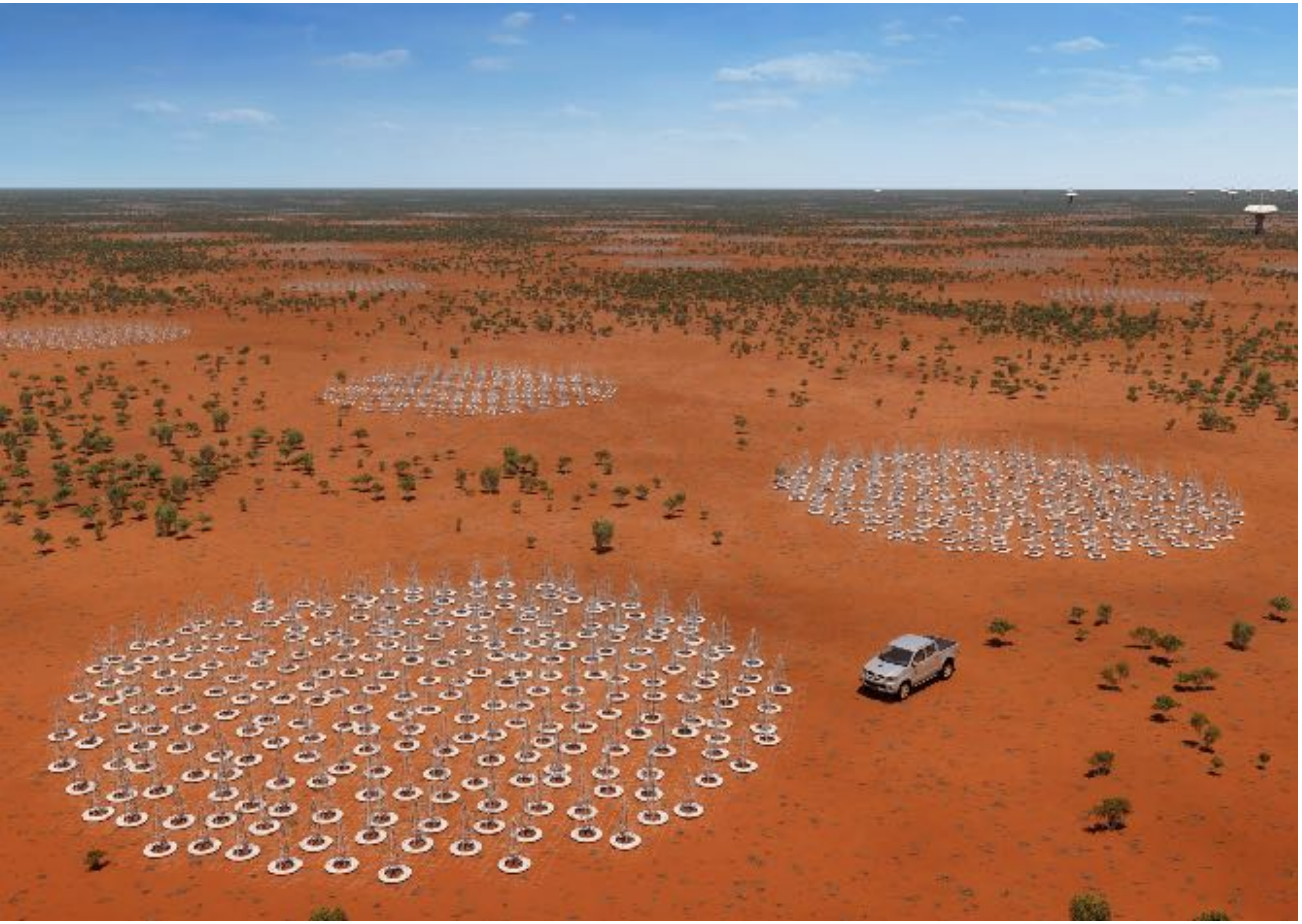
Ongoing ...

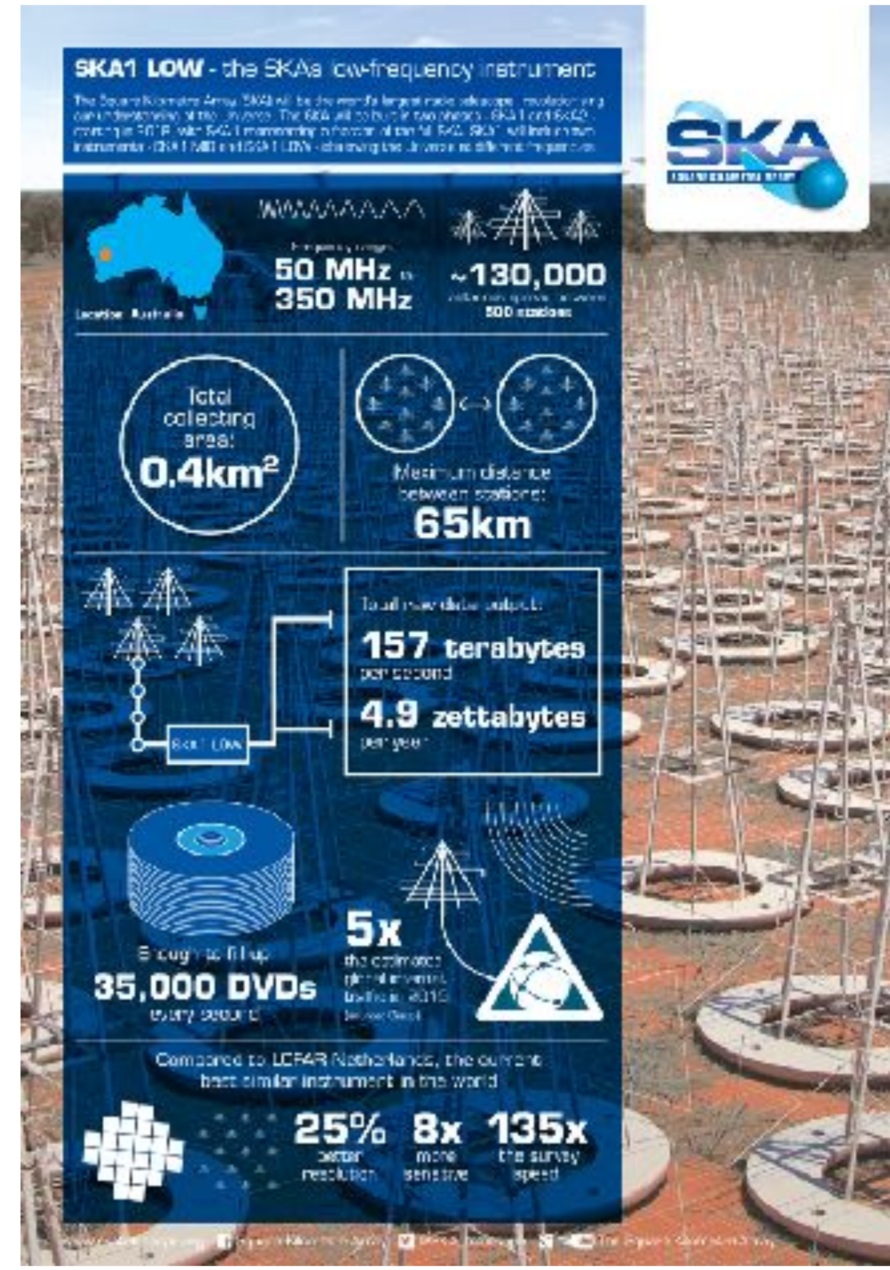


NenuFAR, 10-85 MHz

Massive observations ⇒ orbital / rotational radio period ?

Perspective





SKA (Low), 50-350 MHz, 2027-30 ?

Even before the discovery of the first exoplanet in 1995, radio observations inspired by the intensity of Jupiter's radio emissions had begun. They proved to be extremely difficult, but also motivated the development of ever larger antenna arrays. The theory rather predicts emissions at low radio frequencies and of very low intensity. But the predictions are subject to large uncertainties on both intensity and emitted frequencies, and there was no guarantee that these radio emissions could be detected before the advent of SKA. **In recent months, several papers have suggested that the tip of the radio detection iceberg is now emerging above the galactic background.** If these detections are confirmed, they will open up **a new and promising field of study: comparative exo-magnetospheric physics**, i.e. the physics of star-planet plasma interactions. In this field, we know only 6 planetary magnetospheres in the solar system, all quite different from each other. **The detection of tens or hundreds of analogs will be a revolution comparable to the one that the discovery of exoplanets' orbital parameters has brought to solar system formation models.** I will make a brief review of the theoretical bases of this research, an inventory of the observations with emphasis on recent detections, and I will give some perspectives.