La recherche d'émissions radio exoplanétaires avec LOFAR : Jupiter en tant qu'exoplanète

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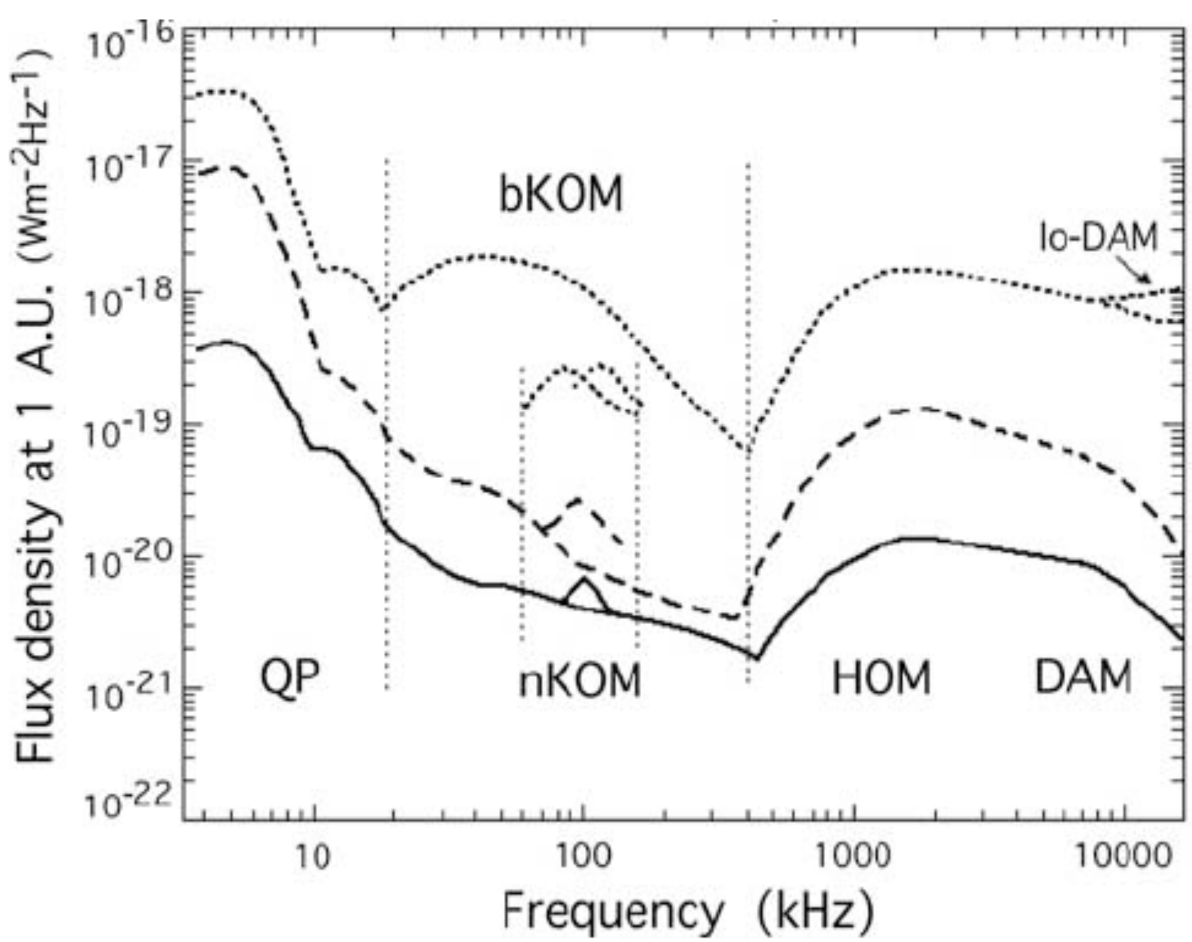
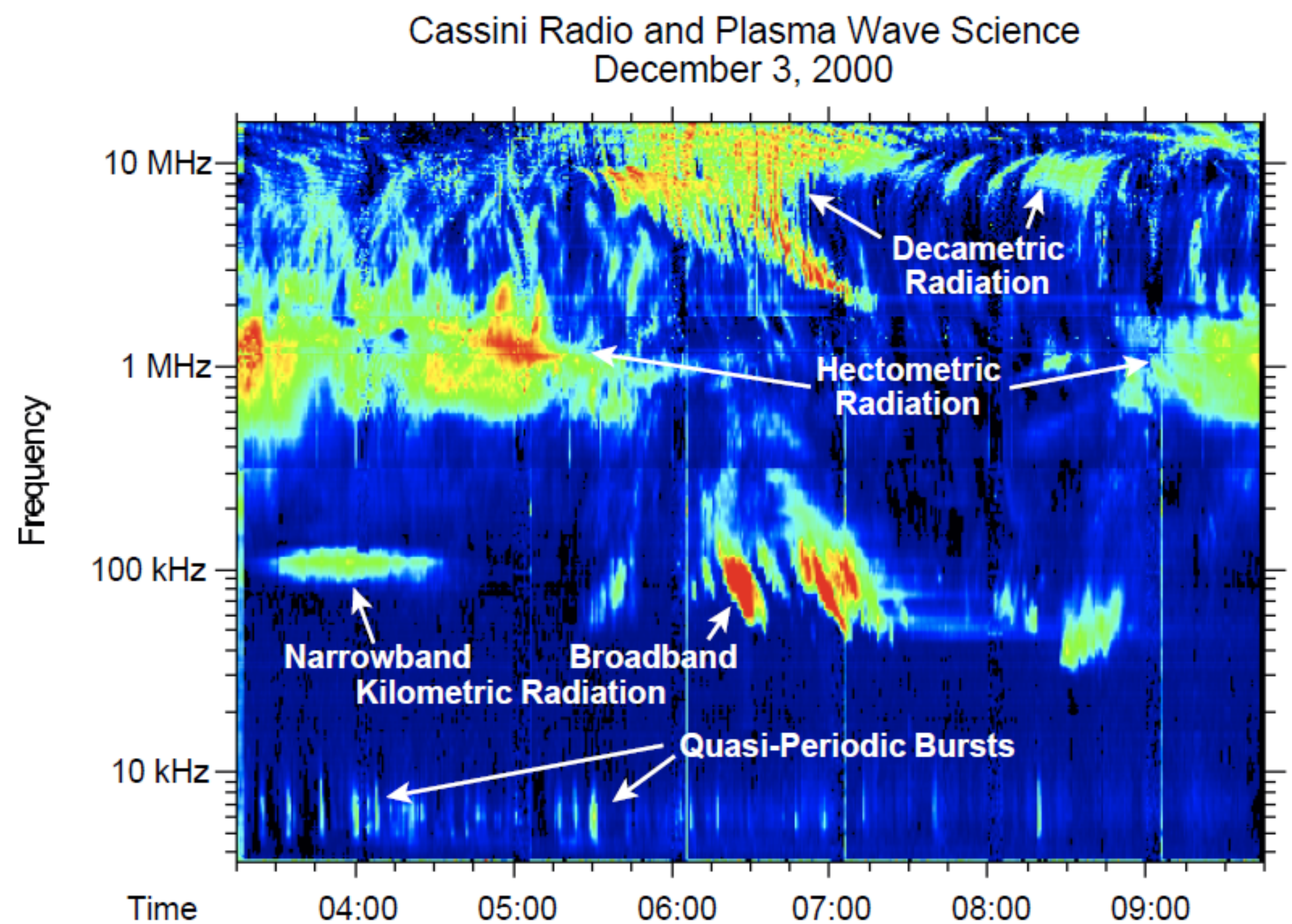
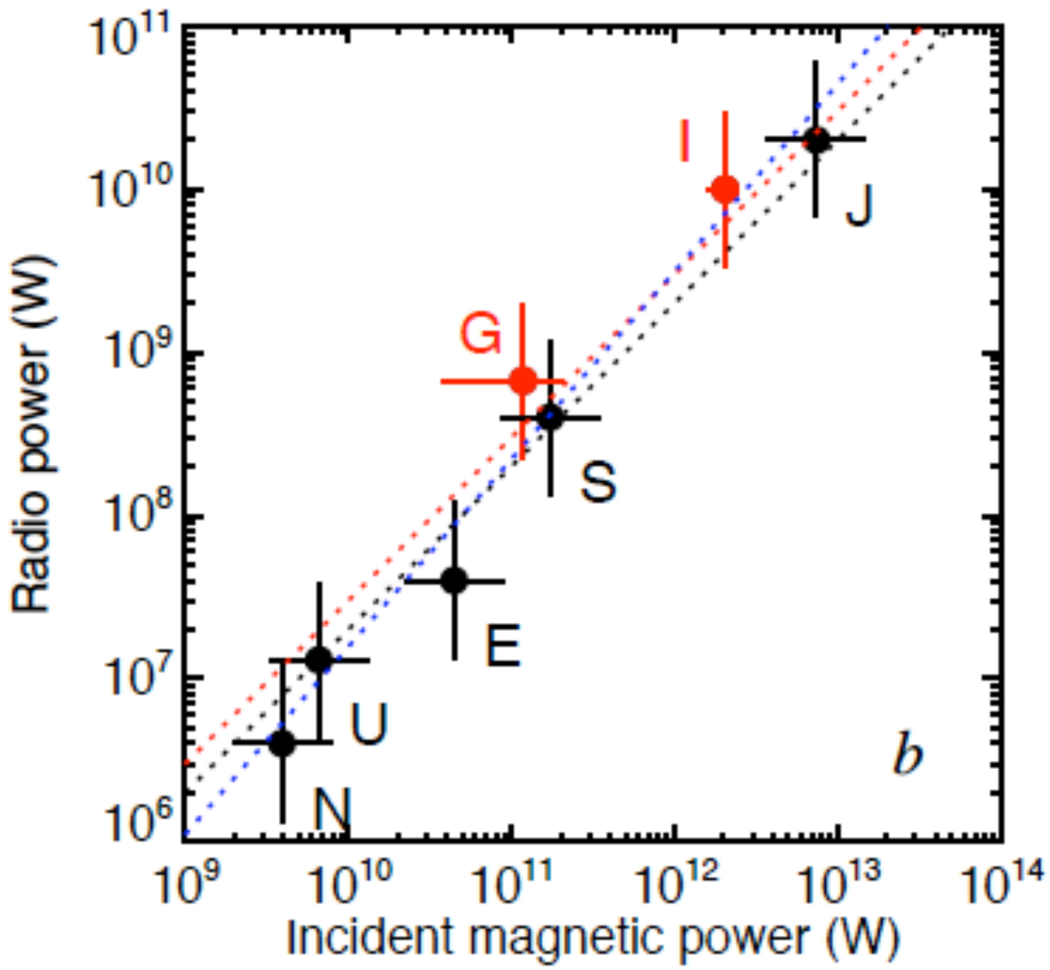
• Jupiter : source of strong polarized (V) radio bursts ≤ 40 MHz

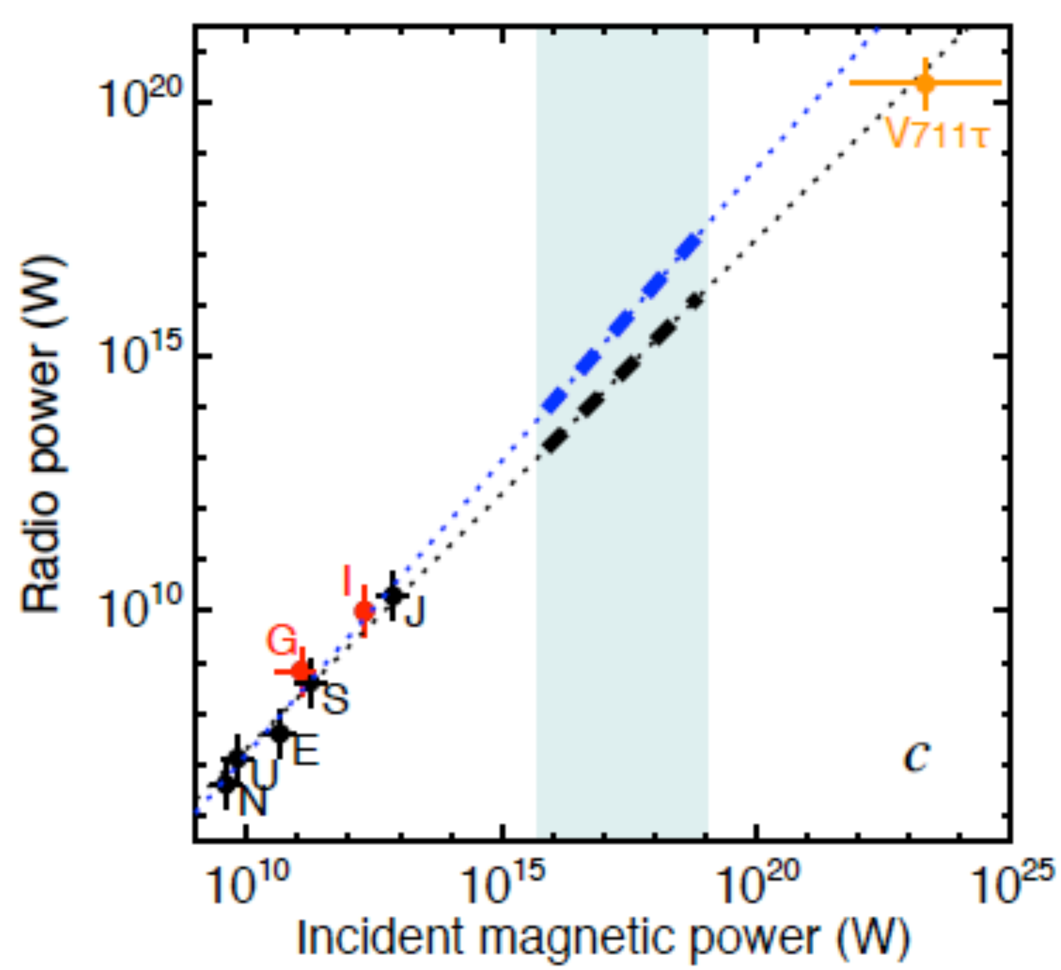




[Zarka et al., JGR 2004]

• Theory : exoplanetary radio emissions up to 10^{3-7} × Jupiter's at f ~ 10-100 MHz ?





[Zarka et al., ASS 2001 ; PSS 2007 ; ... A&A 2018]

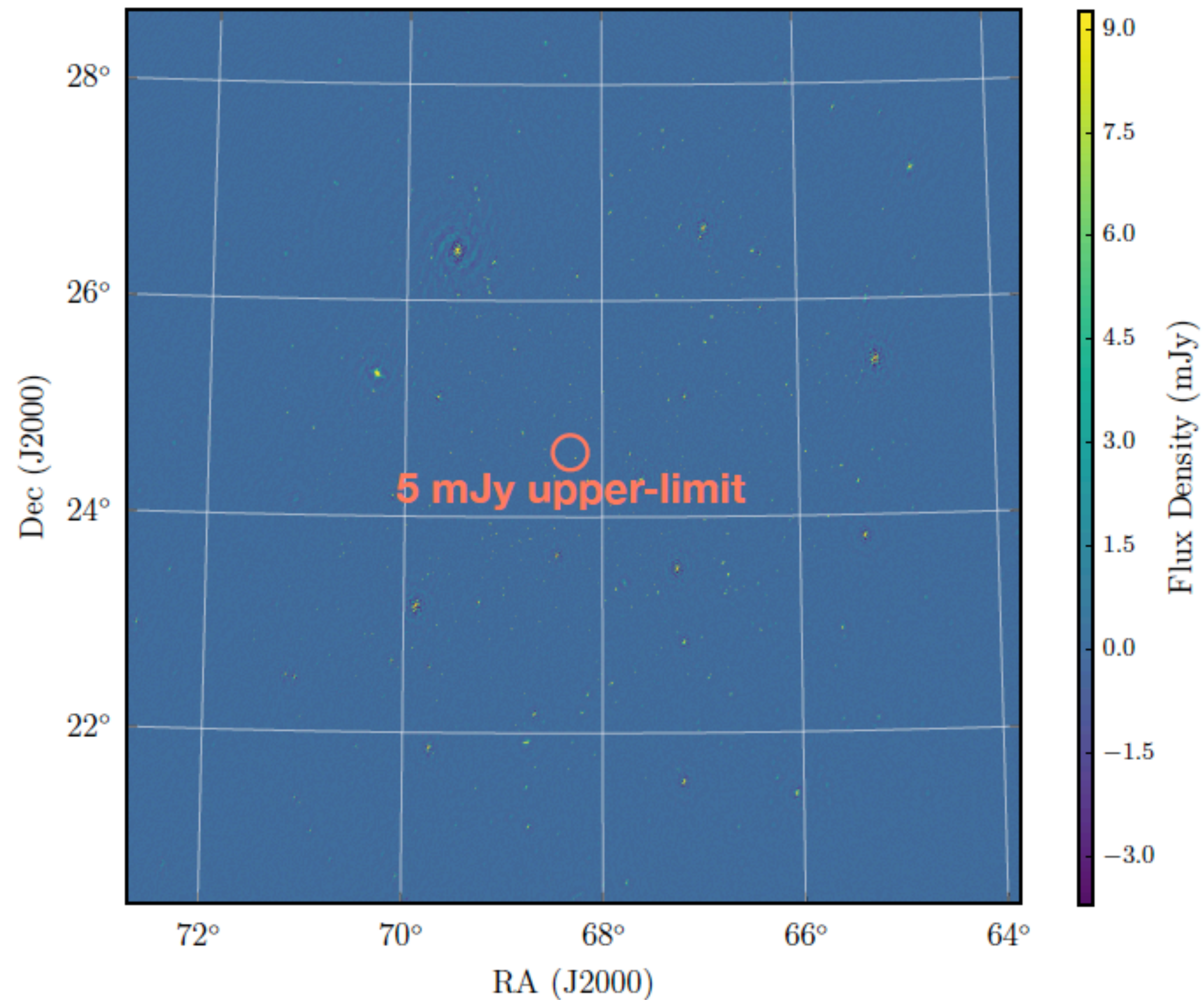
• Goal : exoplanetary B, comparative exo-magnetospheric physics ...

[Hess & Zarka , A&A 2011]

• No confirmed detection yet *[Zarka et al., SKA book 2015]*

- Imaging : steady emission

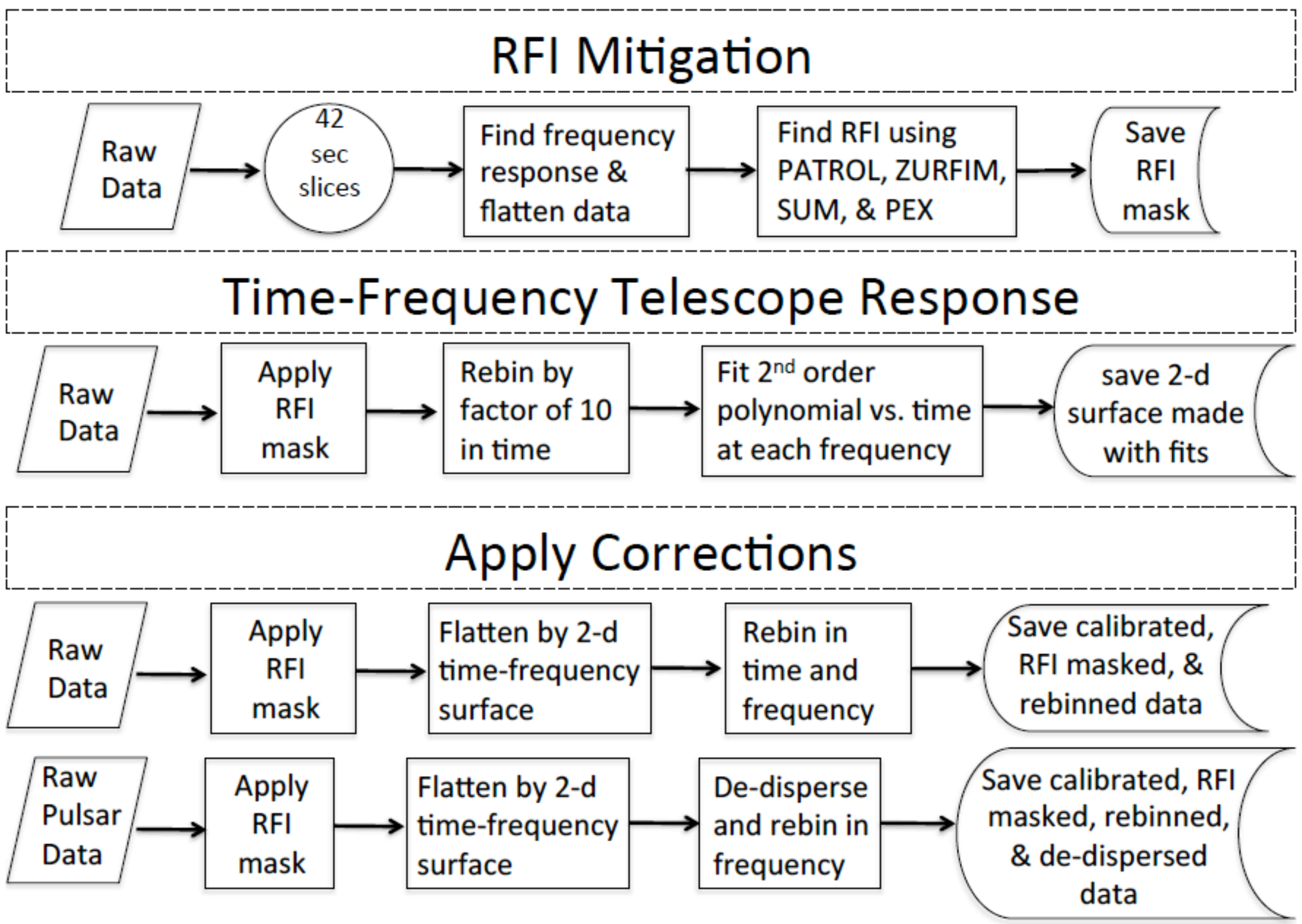
[Loh et al., in prep. 2018]



- Beamformed observations : transients

- LOFAR-LBA beamformed data :
    - poor sensitivity out of the 58 MHz peak
    - heavy pollution (RFI, ionosphere)

- LOFAR-LBA beamformed data :
    - processing pipeline : RFI mitigation, correction of t-f response, smart δt×δf integration



[Turner et al., PRE8 2017]

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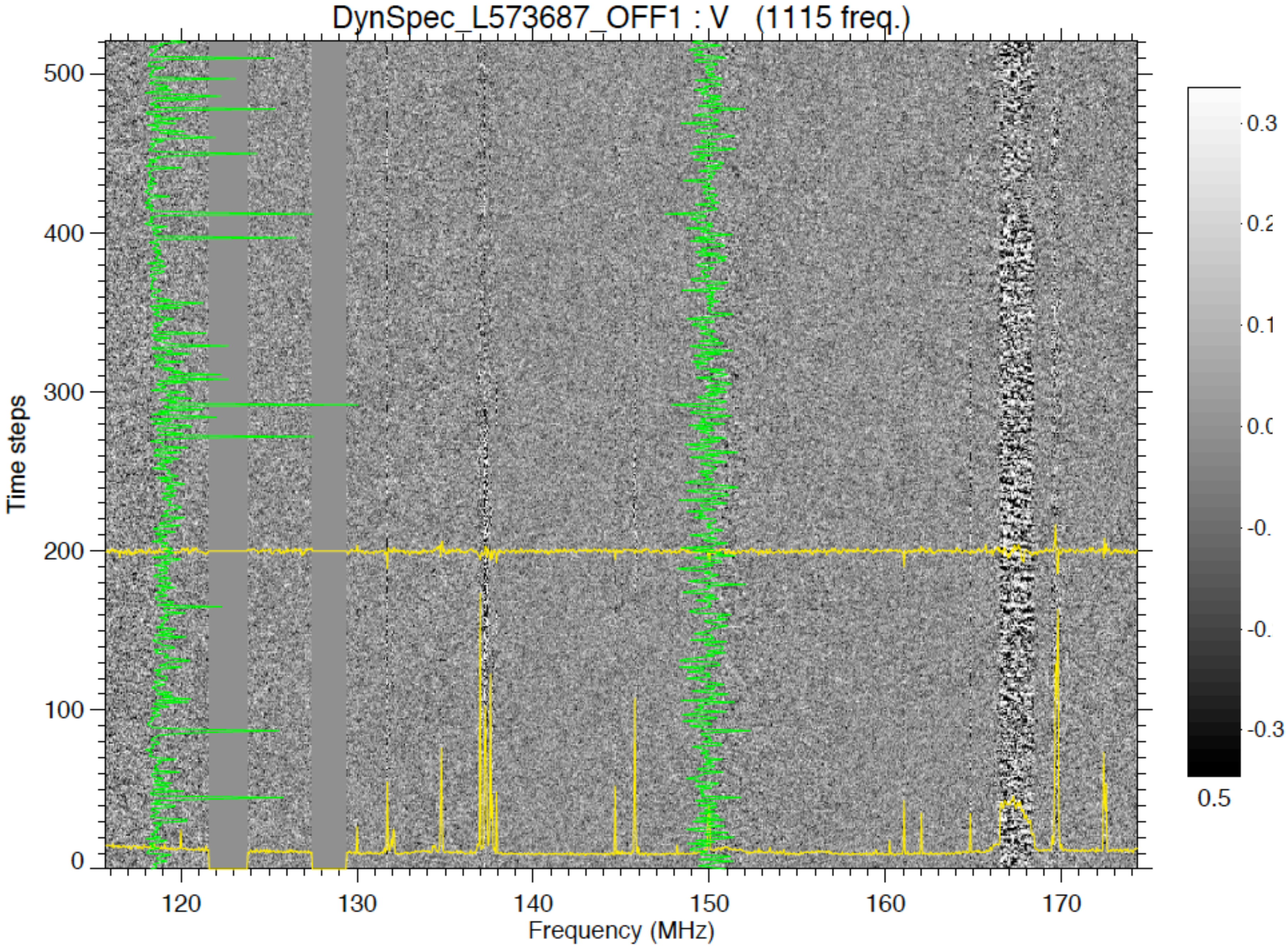

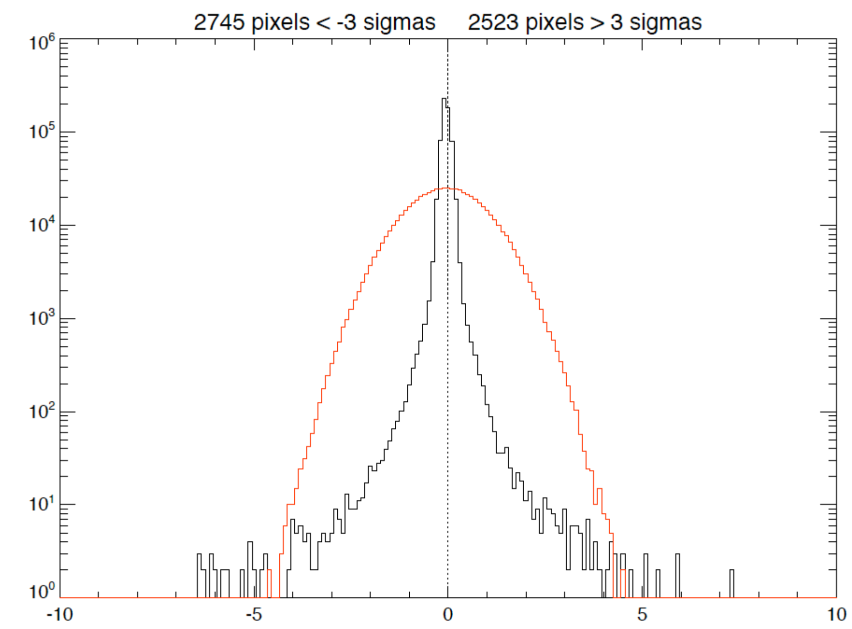

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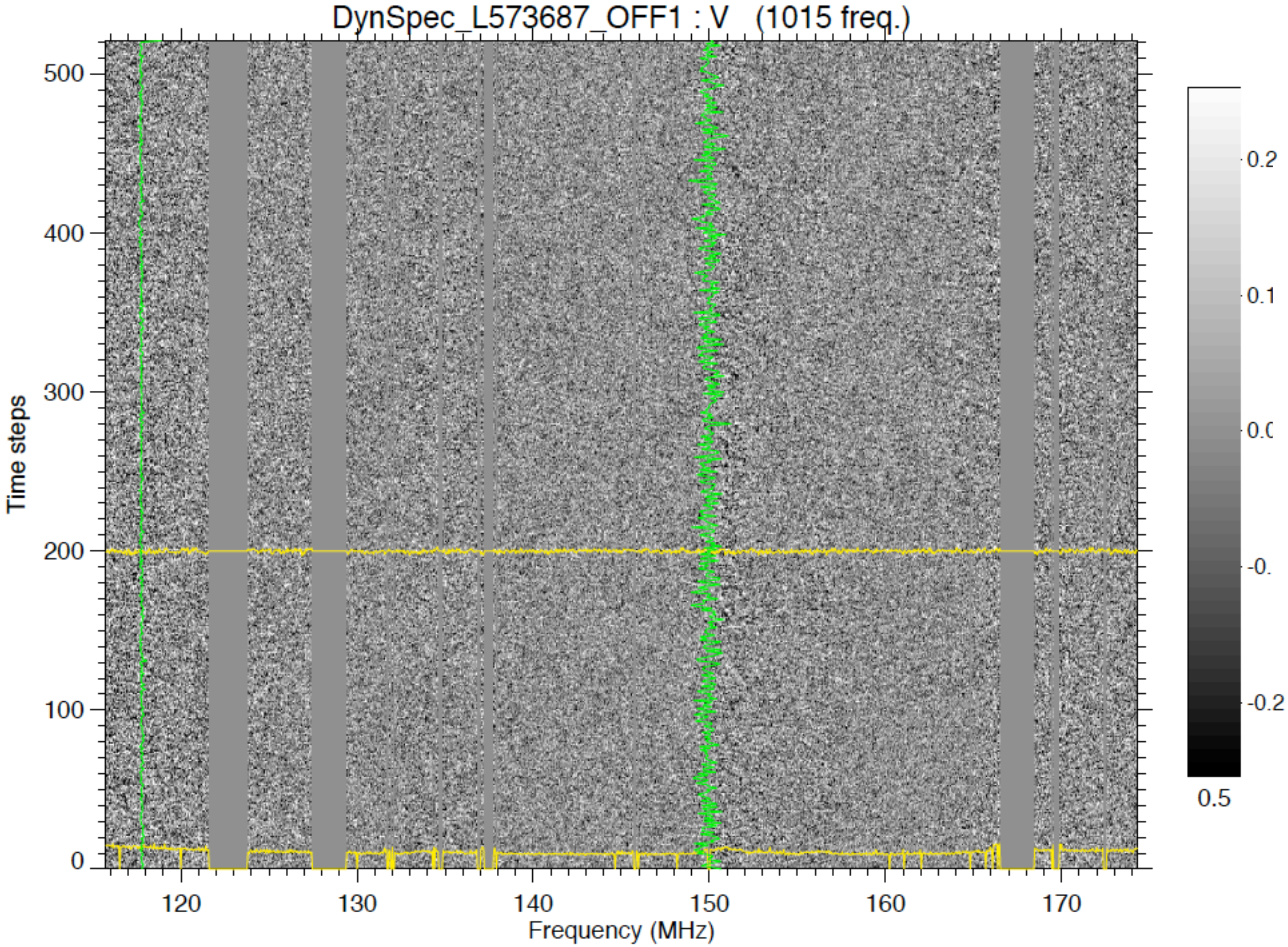
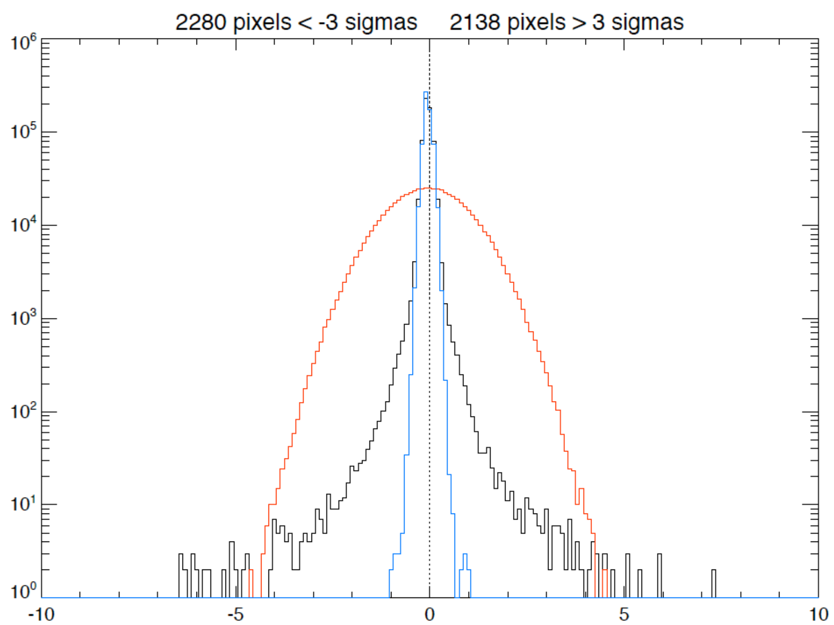




  - post-processing pipeline : high-pass filtering + several observables (Q1-4 below)

- Quantify performance ?

Astronomy & Astrophysics manuscript no. output
July 1, 2018

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

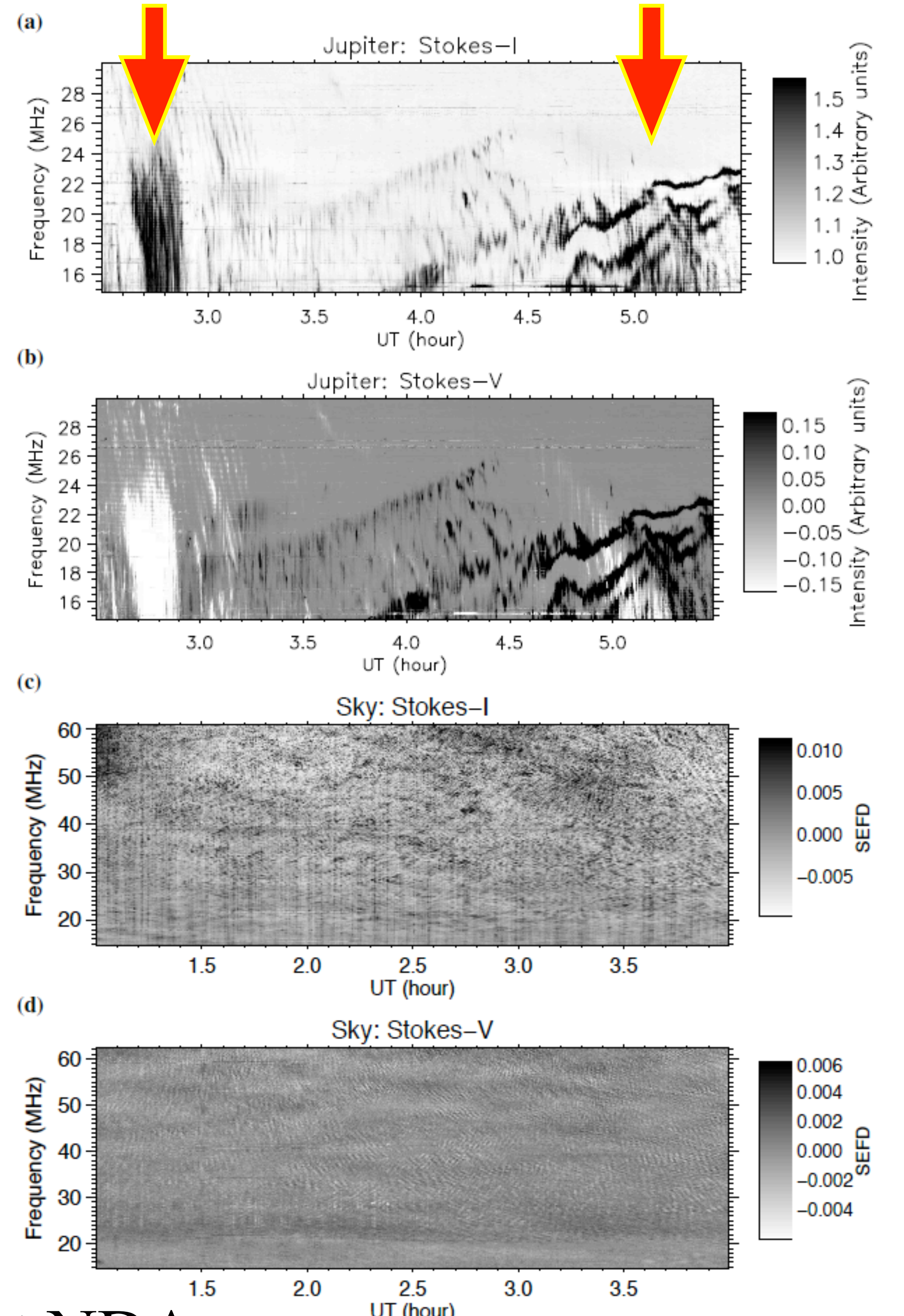
Jake D. Turner[1,2], Jean-Mathias Grießmeier[1,3], Philippe Zarka[4,3], Iaroslavna Vasylieva[5]

- Principle :
  - Build "exoplanet" radio signal as : $\alpha \times$ Jupiter + Sky
  - Apply pipeline → Blind detection On/Off vs. $\mathrm{Off}_1/\mathrm{Off}_2$
  - Stokes I & V + frequency transposition

• Quantify performance ?

Setup of the LOFAR LBA beam-formed observations

Parameter	Value	Units
Array Setup	Core	
# of Stations	24	
Lower Frequency	14.7	MHz
Upper Frequency	62.4	MHz
Channel Bandwidth (b)	3.05	kHz
# of Subbands	244	
Channels per Subband	64	
Time Resolution (τ_r)	10.5	msec
Angular Resolution	9.2	arcmin
Raw Sensitivity[b] (ΔS)	208	Jy
Polarizations	IQUV	



• Simultaneous Jupiter observation at NDA
→ calibrated flux density & polarization

- Some math. for adding attenuated Jupiter signal to sky background, in Stokes I & V, incl. frequency transposition & correction of instrumental response

$$I_{new} = I_{S,2} + \alpha I_{J,2},$$
$$= I_{S,2}\left(1 + \alpha \frac{I_{J,1}}{I_{S,1}} \frac{S_{\text{SEFD},1}}{S_{\text{SEFD},2}}\right)$$
$$I_{new} = I_{S,2}\left(1 + \alpha \frac{I_{J,1}}{I_{S,1}} \left[\frac{max(\lambda_{J,1}, 10m)}{max(\lambda_{S,2}, 10m)}\right]^2 \frac{N_{S,2}}{N_{J,1}}\right)$$

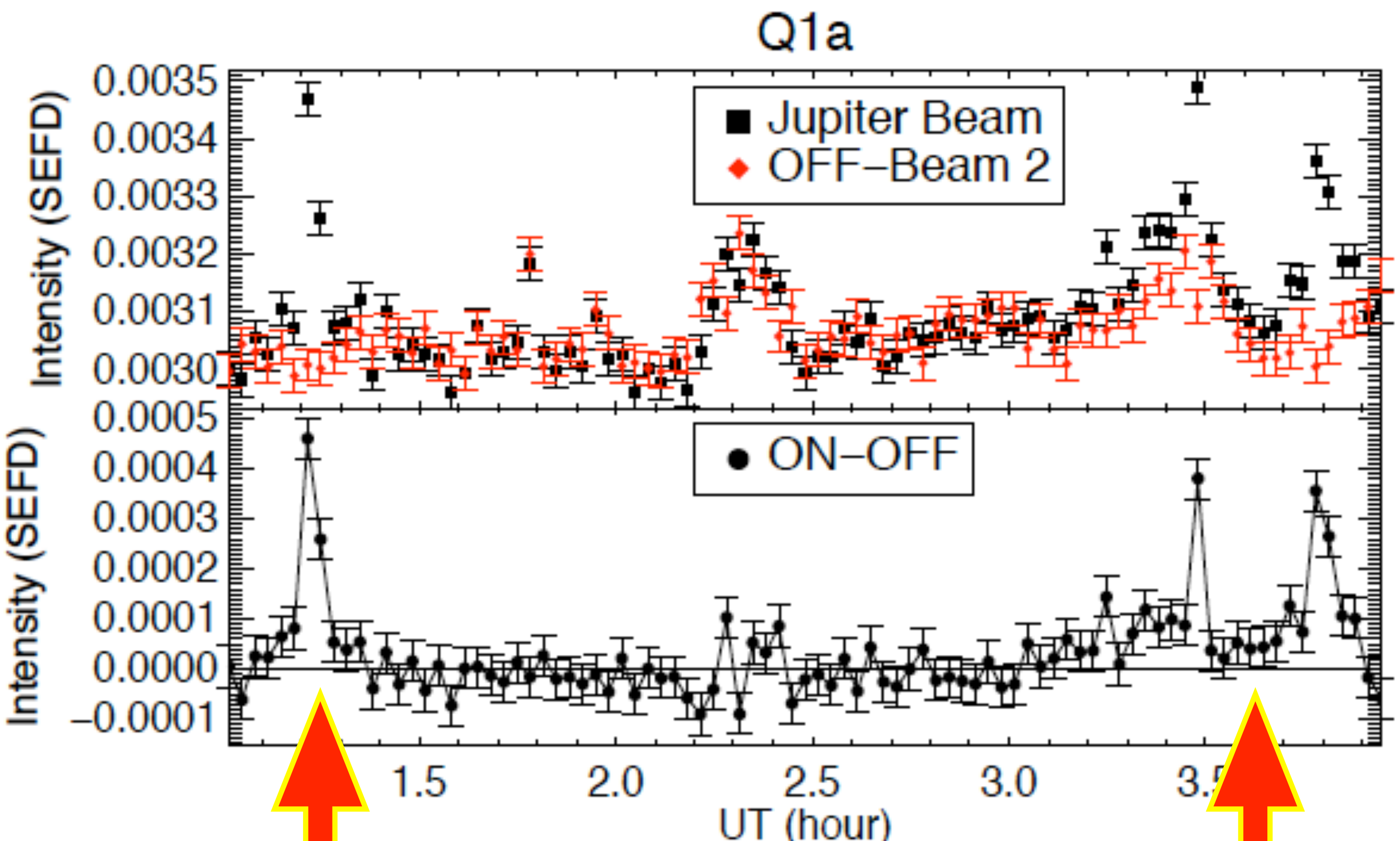
$$V_{new} = V_{S,2} + \alpha V_{J,1}\left(\frac{I_{S,2}}{I_{S,1}}\right)\left(\frac{S_{SEFD,1}}{S_{SEFD,2}}\right)$$

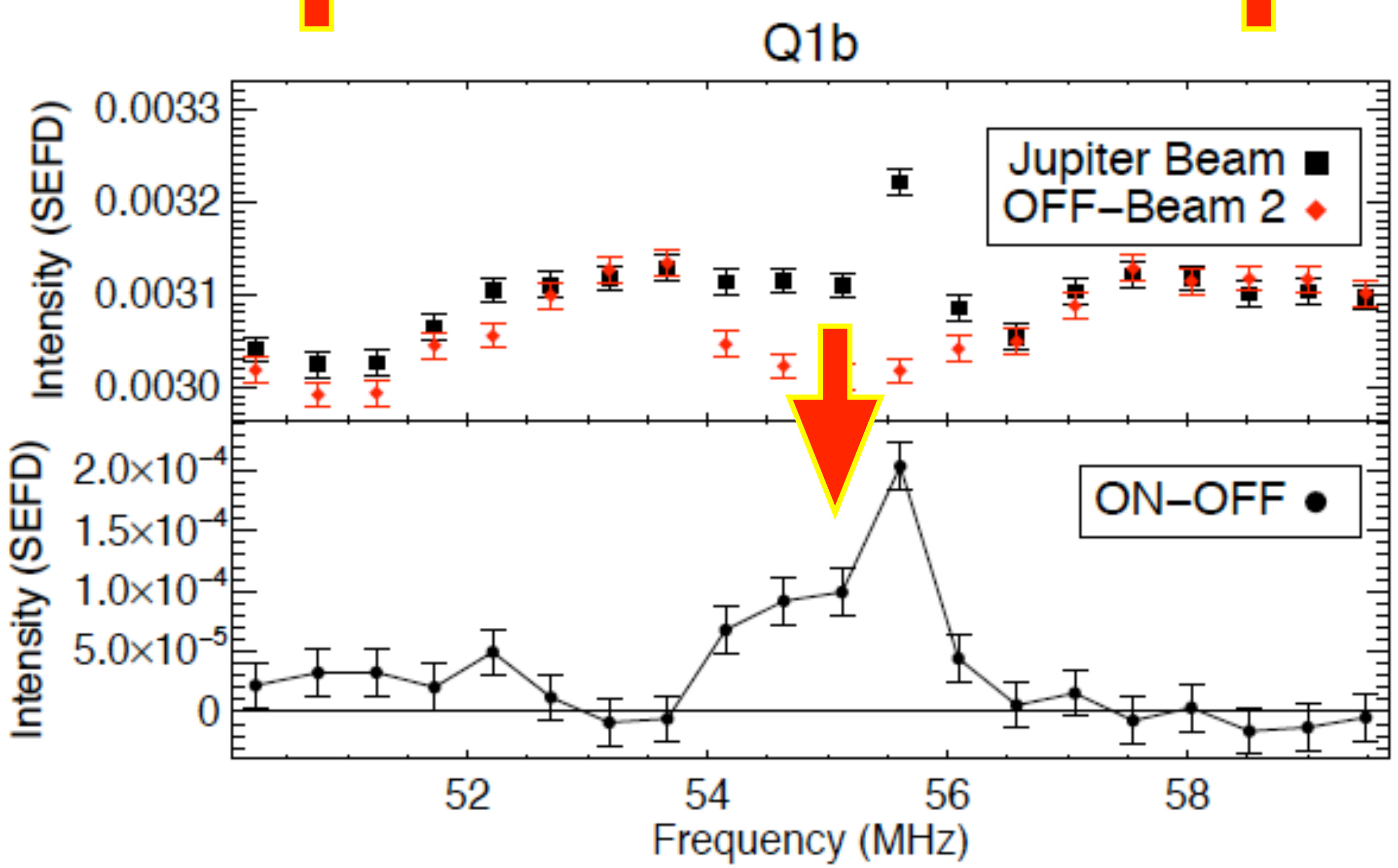
$$V_{new} = V_{S,2} + \alpha V_{J,1} \frac{I_{S,2}}{I_{S,1}} \left[\frac{max(\lambda_{J,1}, 10m)}{max(\lambda_{S,2}, 10m)}\right]^2 \frac{N_{S,2}}{N_{J,1}} \qquad v = \frac{V}{I} \qquad v' = v - \langle v \rangle_t \qquad V' = v' I_{cor}$$

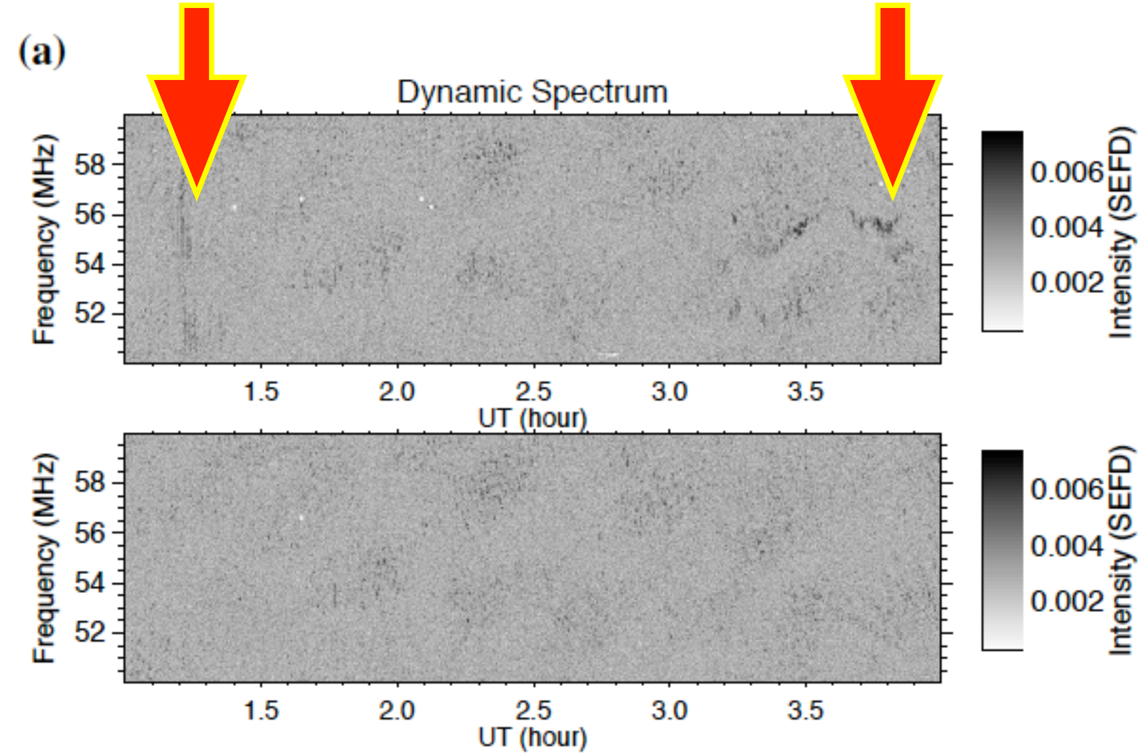
$$V'_{new} = V'_{S,2} + \alpha V'_{J,1}\left(\frac{I_{S,2}}{I_{S,1}}\right).\left(\frac{S_{SEFD,1}}{S_{SEFD,2}}\right)$$

$$|V| \qquad V'+ = \begin{cases} V', & \textbf{if } V' > 0 \\ 0, & \textbf{otherwise} \end{cases} \qquad V'- = \begin{cases} (-V'), & \textbf{if } V' < 0 \\ 0, & \textbf{otherwise} \end{cases}$$

- Observables Q1 : $\delta t \sim$ minutes

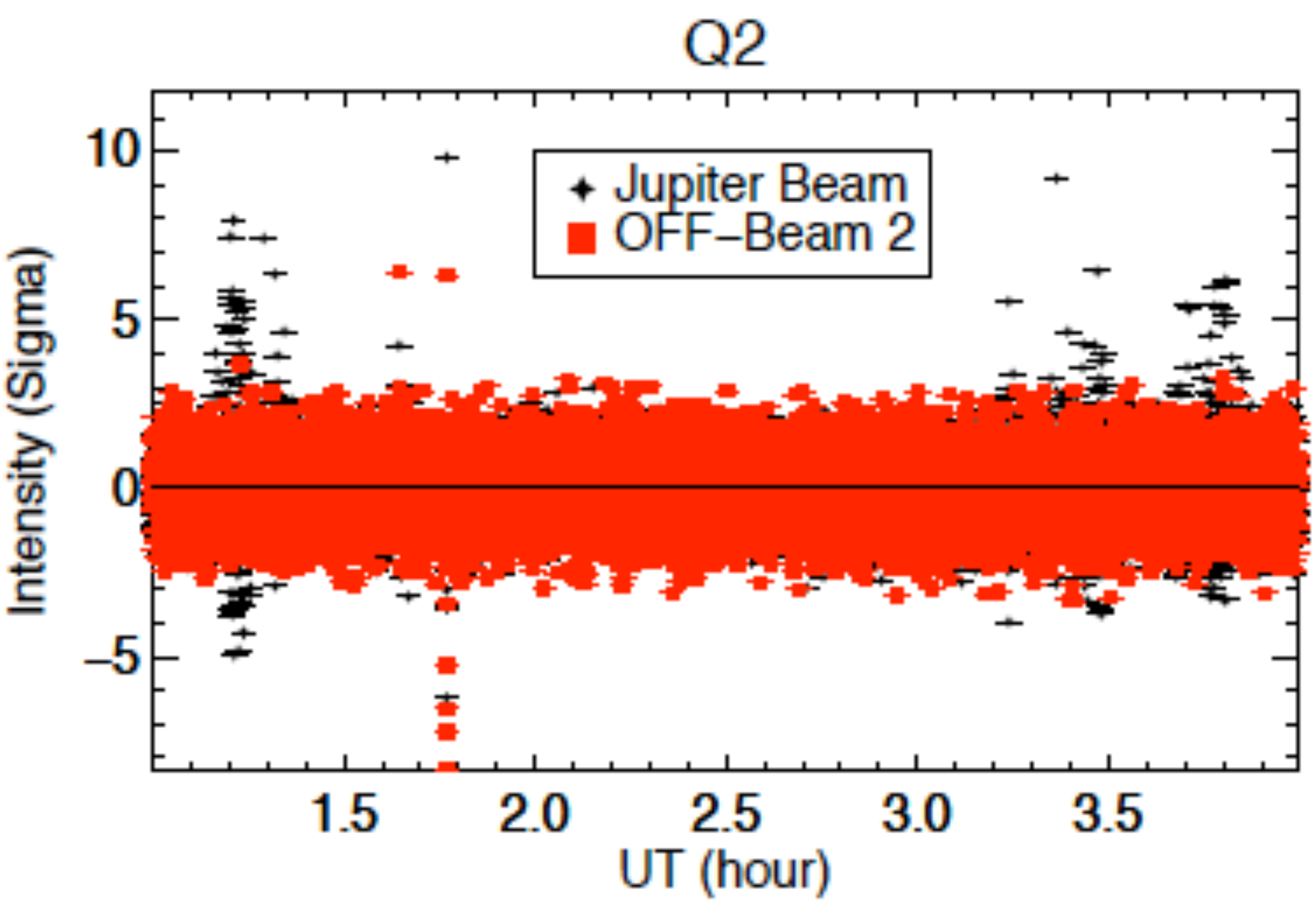


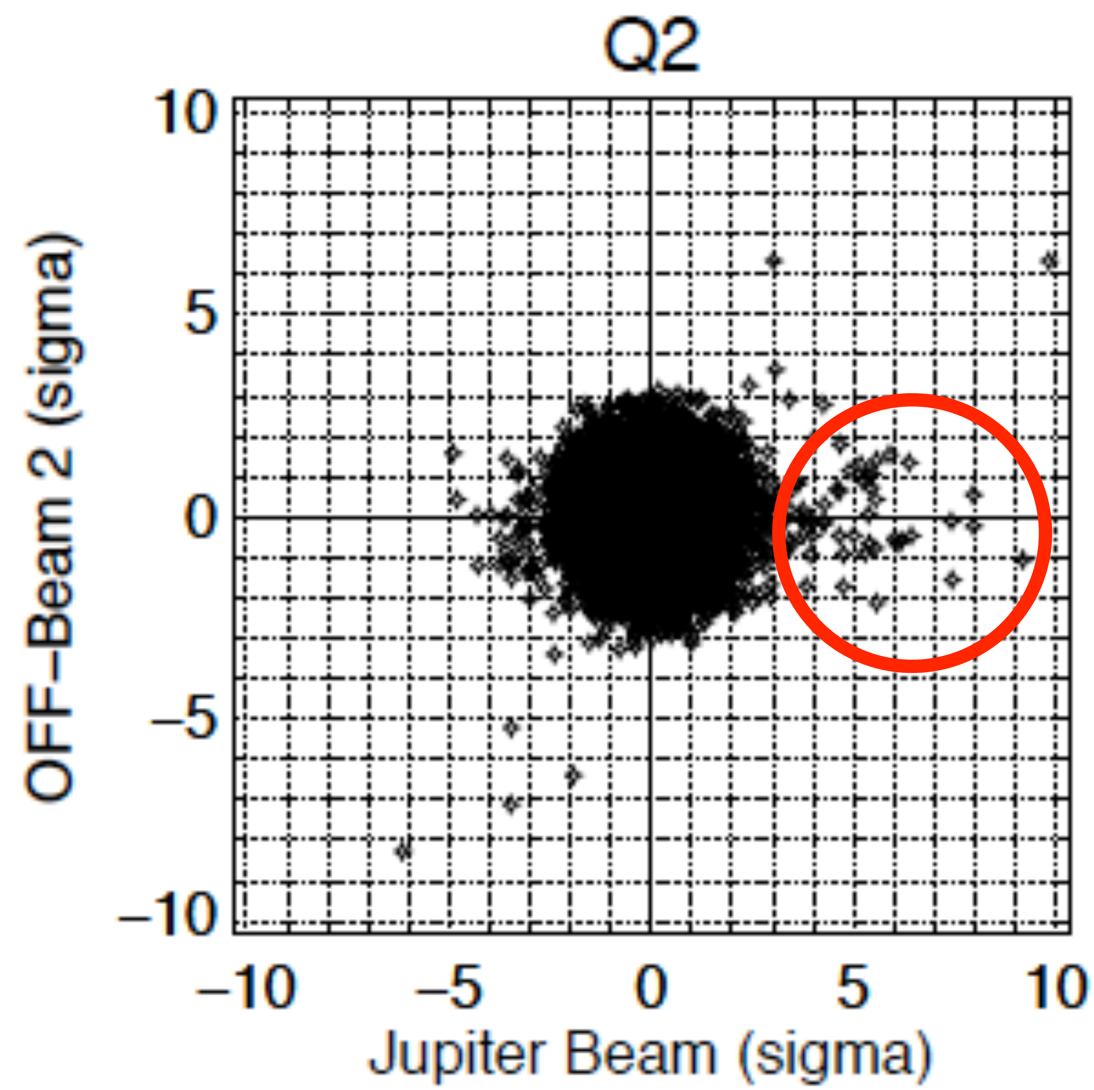




$|V'|, \ \alpha = 10^{-4}$

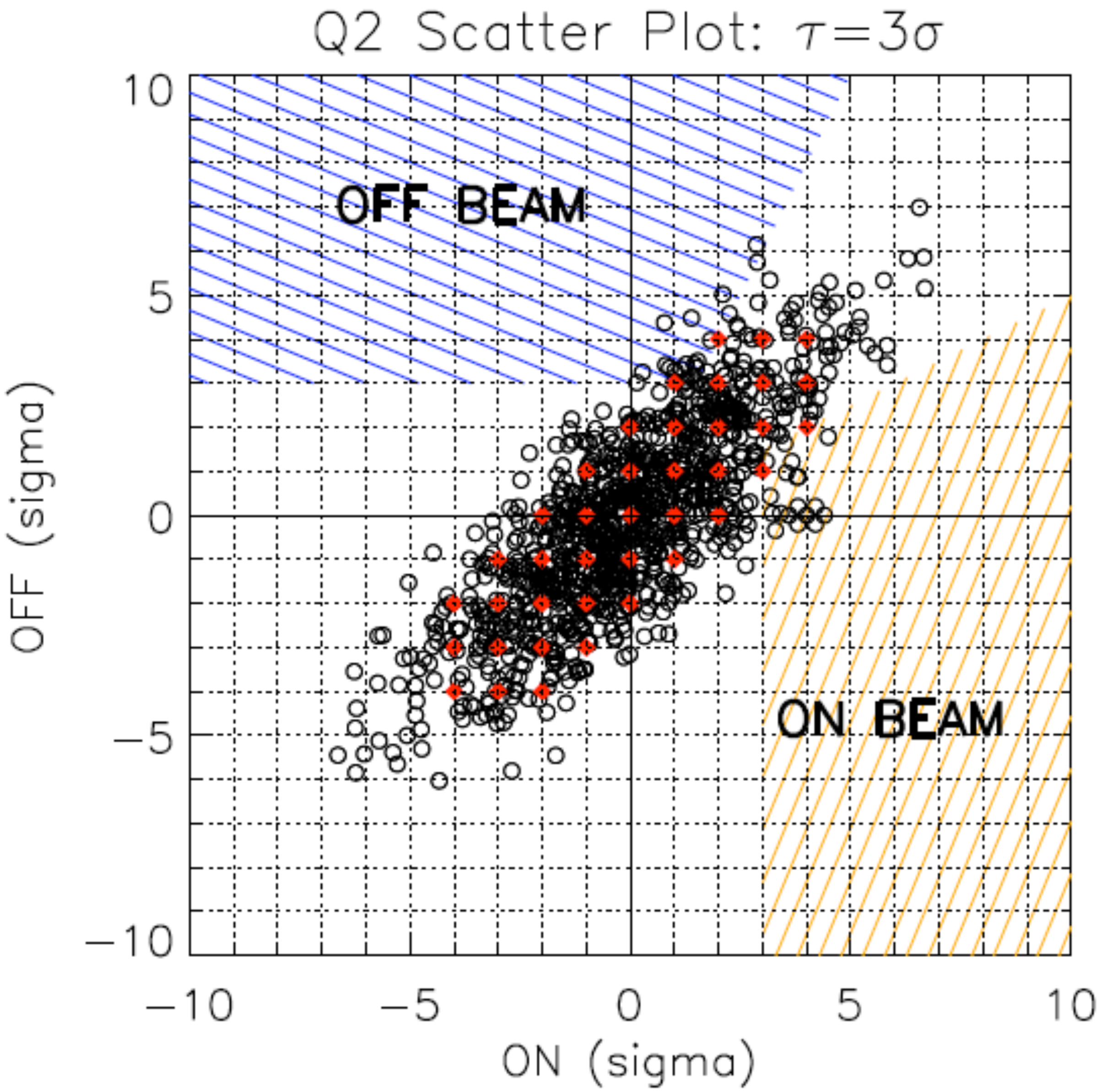
• Q2 : high-pass filtering, normalization (σ), & On vs. Off scatter plot

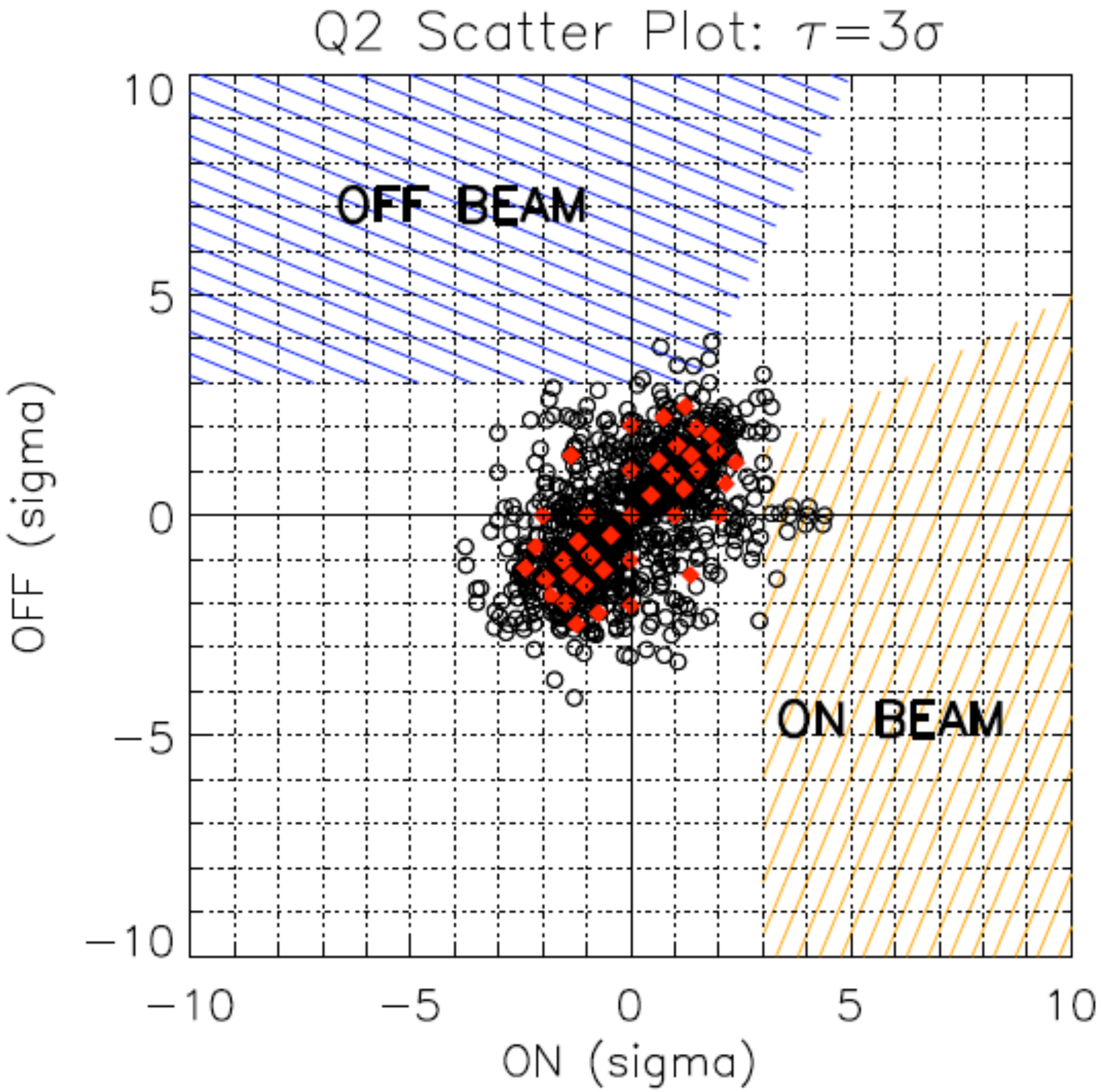




$|V'|, \ \alpha = 10^{-4}$

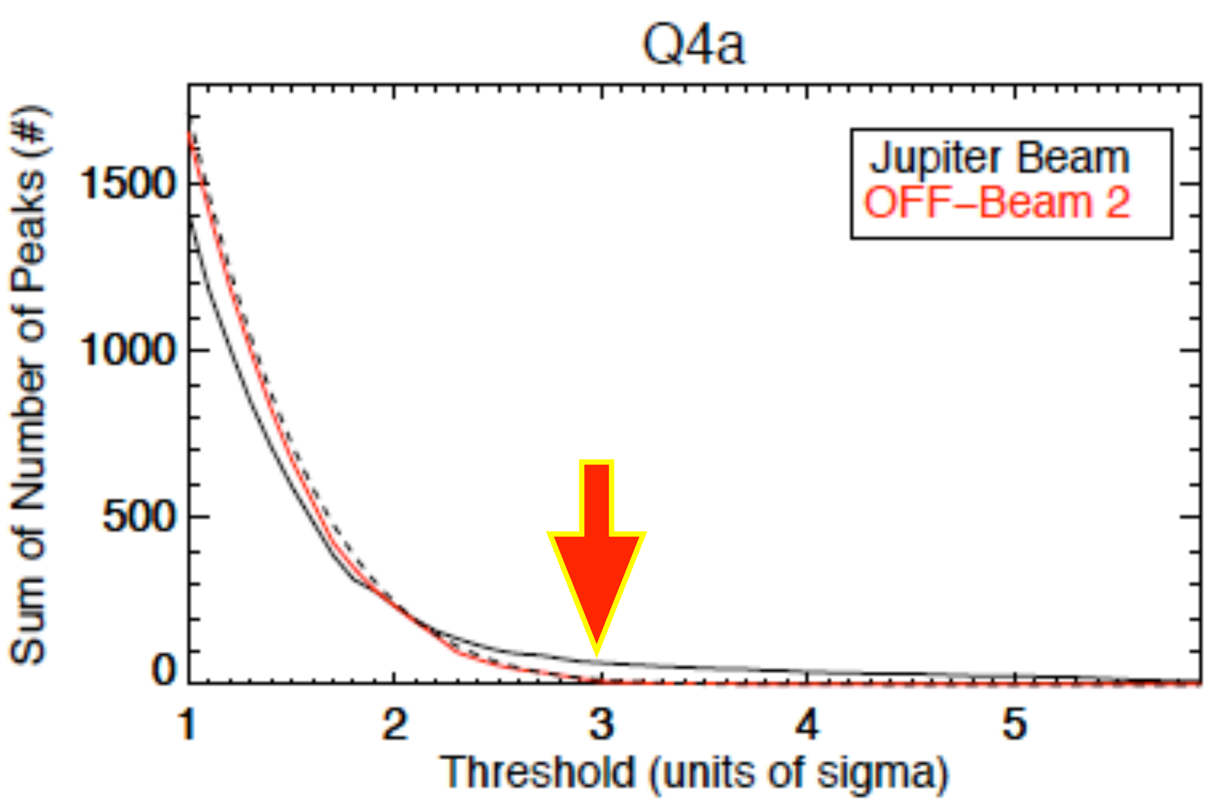
• Elliptical correction

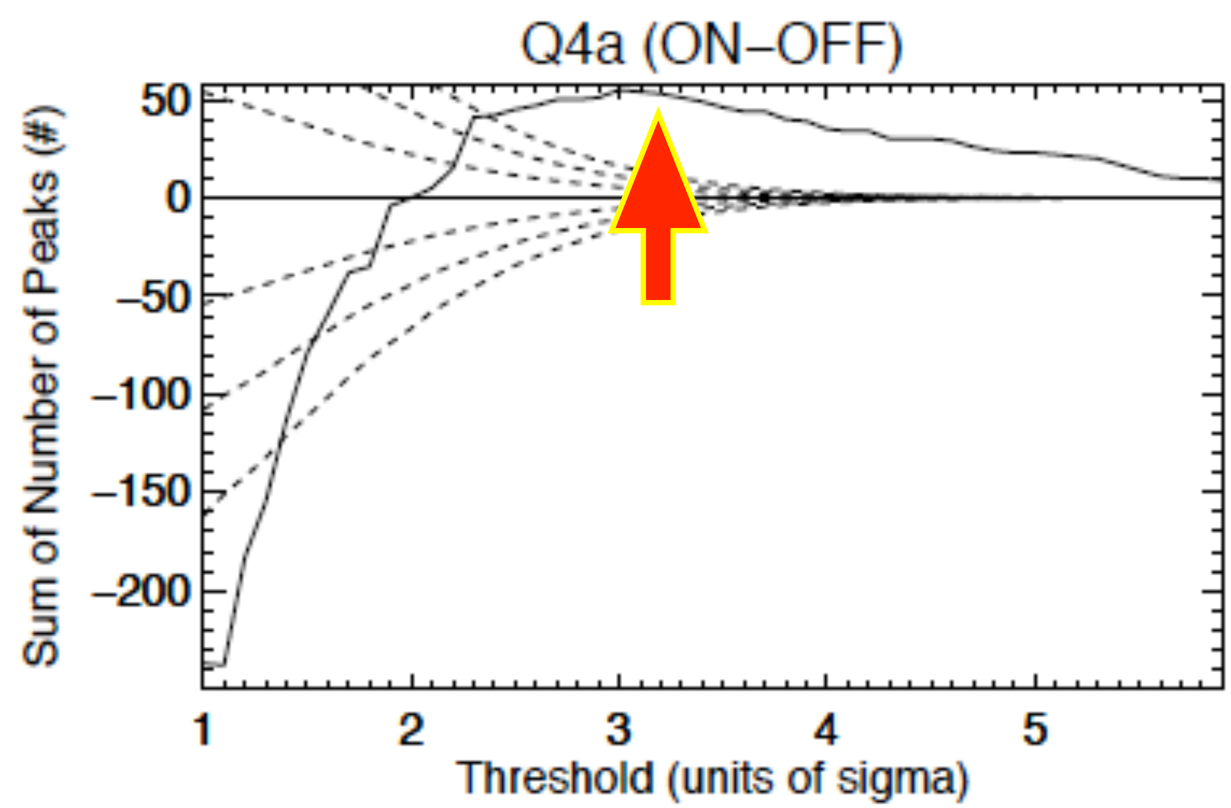




- Q3/Q4 :
  - a - N peaks $\geq \tau$
  - b - Σ peak power for (a)
  - c - (N peaks $\geq \tau$) - (N peaks $\leq -\tau$)   [Asymmetry]
  - d - Σ peak power for (c)
  - e - N peaks On $\geq \tau$ and $\geq 2\times$Off   [Offset]
  - f - Σ peak power for (e)

- Q3 vs. t for fixed τ, Q4 vs τ for all t





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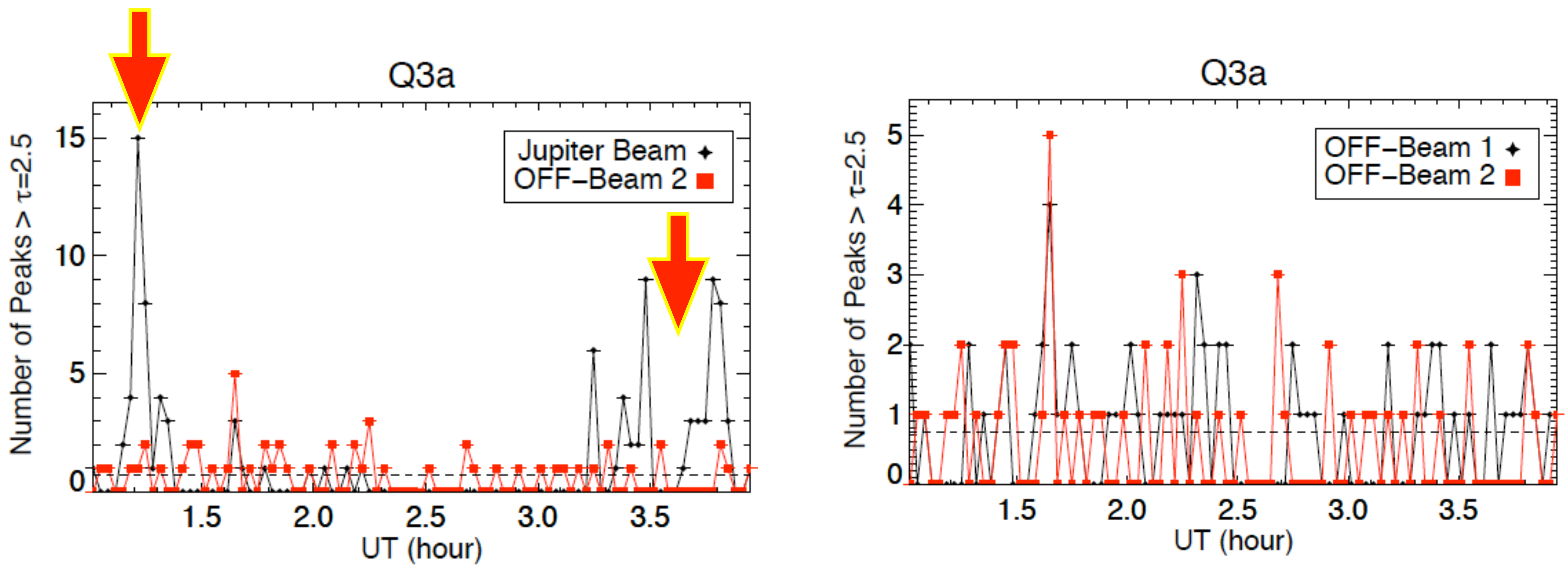
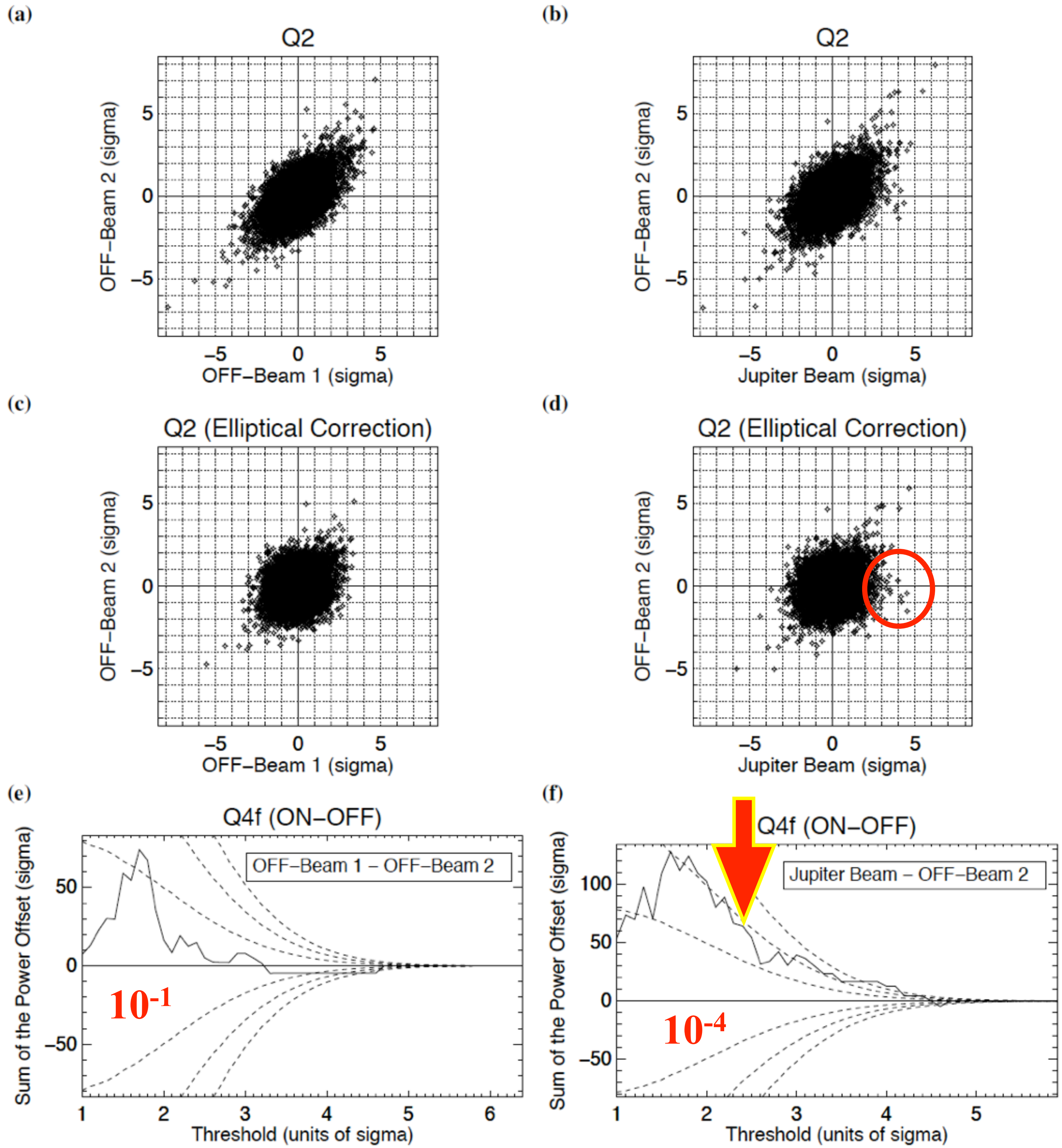


$|V'|$, $\alpha = 10^{-4}$

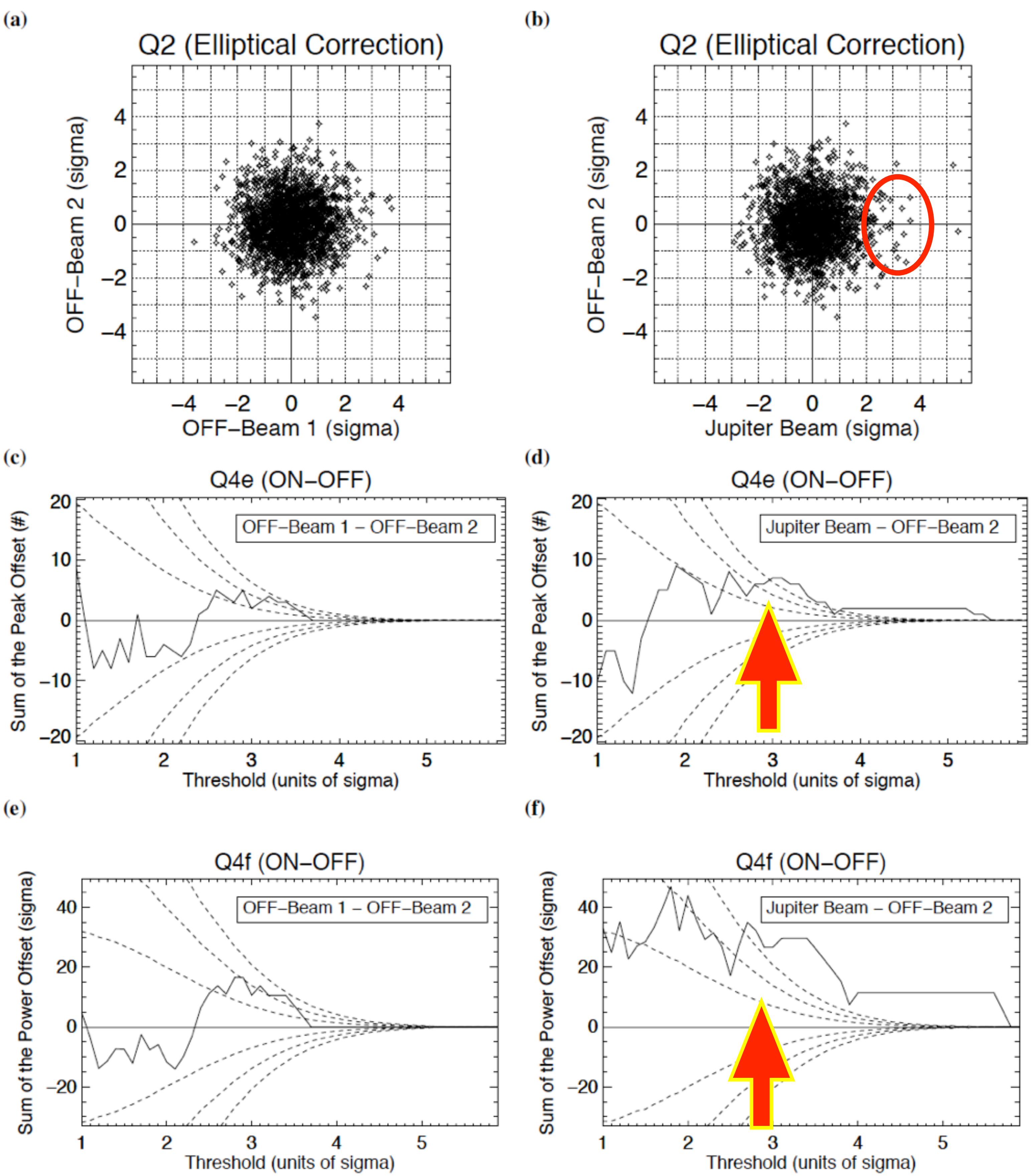
• Results : Stokes I, $\alpha_{min} = 3\times10^{-4}$ for f=[50,60] MHz

Post-processing parameters

Parameter	Value	Units
Width of frequency range ($\Delta\nu$)	10	MHz
Time Range (ΔT)	3	hours
Rebin time of processed data ($\delta\tau$)	1	secs
Mask threshold	90	%
Time interval (TI)	2	minutes
Frequency interval (FI)	0.5	MHz
Low-pass filter smoothing window (w)	10	secs
Threshold (τ) range	1 - 6	sigma

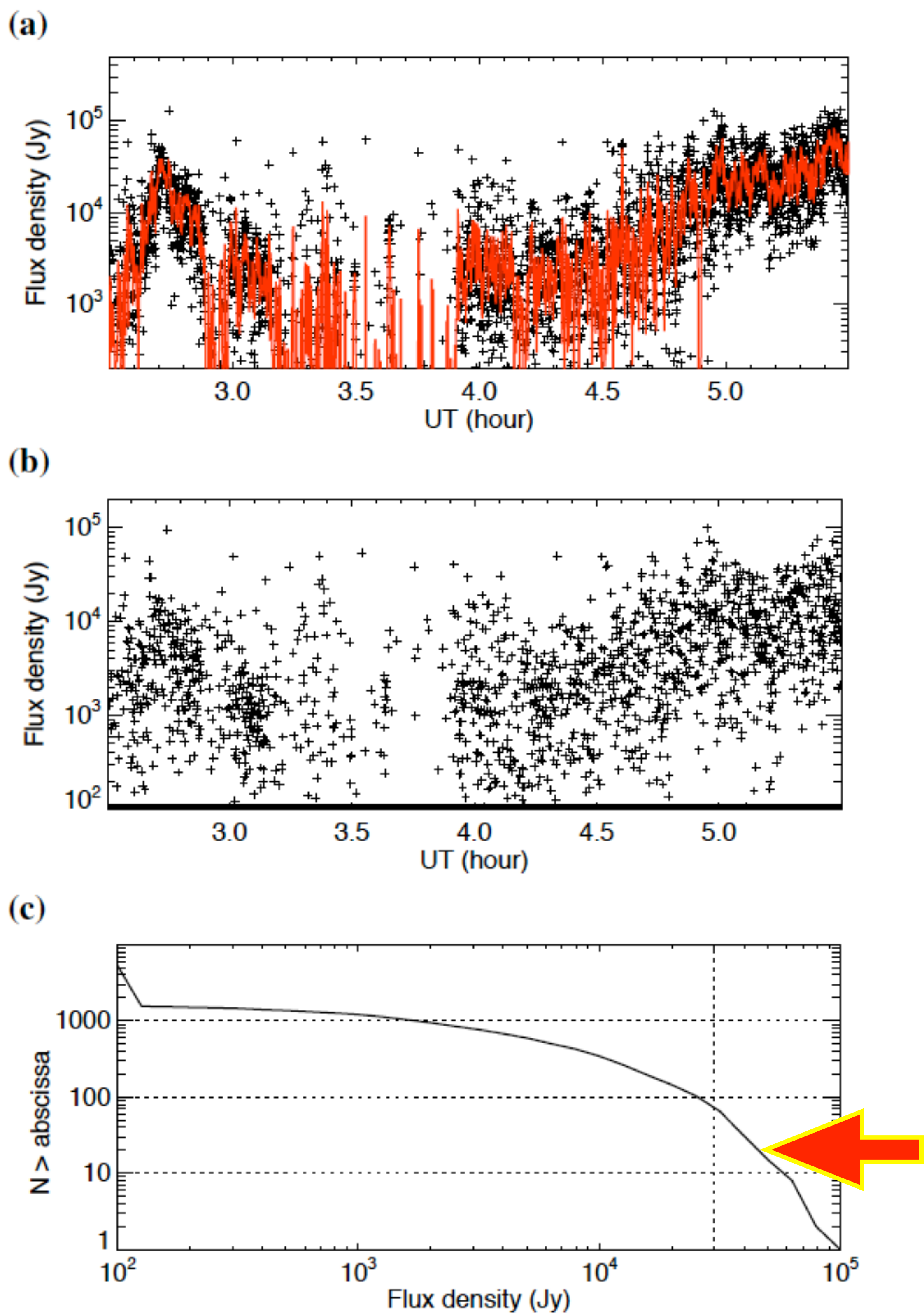


• Results : Stokes V (V'+), $\alpha_{min} = 3\times10^{-5}$ for f=[53.5,56.5] MHz



~30 data points >2σ

- Results : 30 data points $>2\sigma$
  - $\rightarrow$ Jupiter flux $\sim 4\times10^4$ Jy
  - $\rightarrow$ detection threshold $= 4\times10^4\ \alpha_{min} = 1.3$ Jy



$$\sigma_{LOFAR} = \mathrm{SEFD} / N\,(b\tau)^{1/2}$$
$$= 50 \text{ mJy } (2 \text{ min x } 10 \text{ MHz})$$
$$\sim 1 \text{ Jy } (1 \text{ s x } 3 \text{ MHz})$$

- Summary of α_{min} values

Frequency Range (MHz)	Stokes-I α	Stokes-V α
Obs #2		
50 - 60	$10^{-3.5}$	$10^{-4.5}$
40 - 50	10^{-3}	10^{-4}
30 - 40	10^{-3}	10^{-4}
20 - 30	$10^{-2.5}$	$10^{-3.5}$

- Exoplanet detection limits with LOFAR

$$\alpha = \alpha_J \left(\frac{S_J[\text{ref}]}{S_J[\text{obs}]}\right)\left(\frac{5\,AU}{d}\right)^2$$

	S_J(ref) [Jy at 5 AU]	Distance [pc]	Stokes-I α_J	Stokes-V α_J
50% occ.	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
1% occ.	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
peak	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

- Final remarks
  - emission $\sim 10^{4\text{-}5} \times$ Jupiter detectable
  - confident detection down to 2σ
  - confirm detection with signal periodicity
  - application to dynamic spectra from LOFAR surveys' phased-corrected visibilities

    = beamformed data reconstructed from imaging data (sensitivity $\geq \times 2$)

    → massive search
  - NenuFAR, SKA-Low