Exoplanet searches in Radio : Theory & Observations from UTR-2 to LOFAR/SKA

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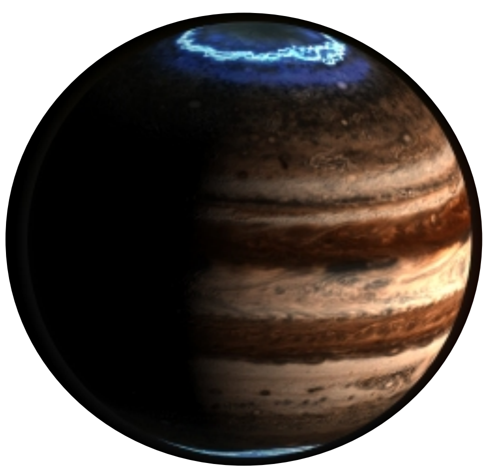
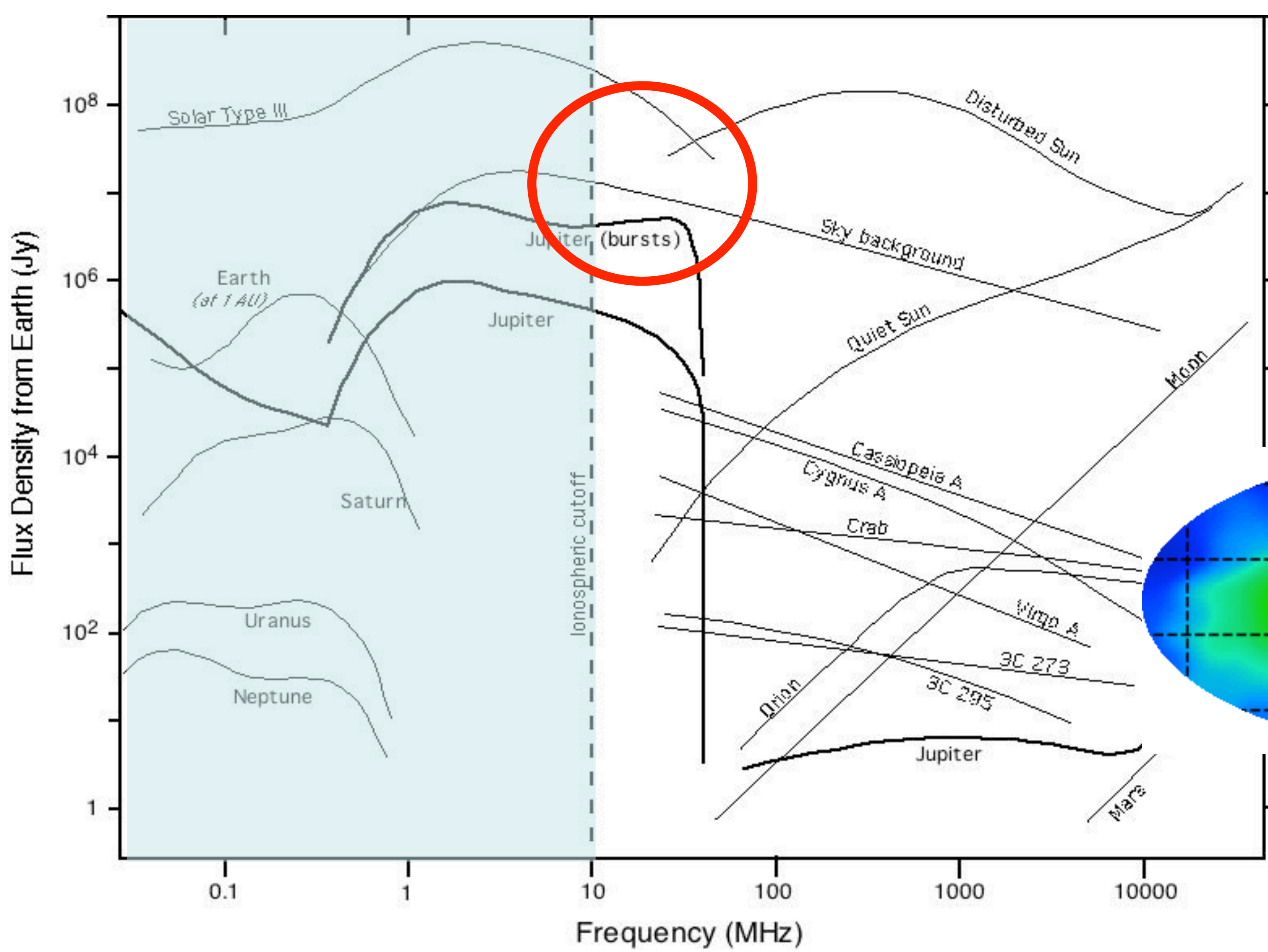
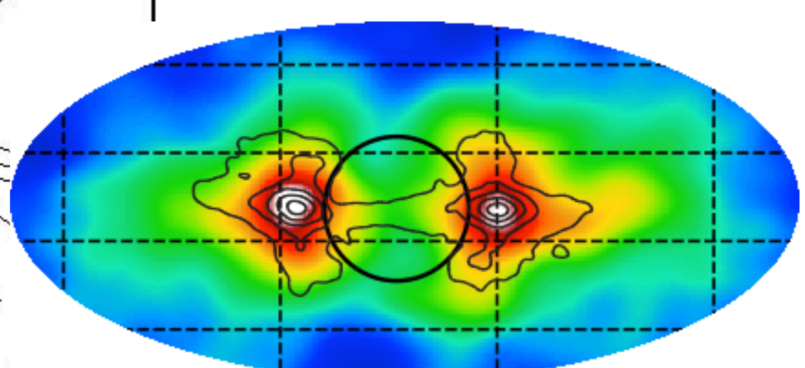
- Jupiter LF radio emission are intense ⇒ discovery & measure of B field (~10G) and rotation period (~10h)
- ∃ similar Terrestrial emissions, ≤1 MHz (B ~ 0.5G)
- Radiation belts emission = synchrotron
- Auroral emissions = Cyclotron-Maser (CMI) : $f=f_{ce}$, keV e-, high T_B, circular polar., narrow beaming, t-f variability
- Contrast Jupiter - Sun ~ 1 → radio search !







[Girard et al., 2012]

- Intense sky background (+ RFI + ionosphere) → detection difficult
- Maximum distance for Nσ sky-limited detection of a source ζ x Jupiter :

$$d_{max} = (\zeta S_J A_e / 2NkT)^{1/2} (b\tau)^{1/4} = 5\times10^{-8} (A_e \zeta)^{1/2} f^{5/4} (b\tau)^{1/4} \quad [pc]$$

ζ = 1	b τ = 10^6 (1 MHz, 1 sec)		b τ = 2×10^8 (3 MHz, 1 min)		b τ = 4×10^{10} (10 MHz, 1 hour)	
	f = 10 MHz	f = 100 MHz	f = 10 MHz	f = 100 MHz	f = 10 MHz	f = 100 MHz
$A_e = 10^4$ m^2 (~NDA)	0.003	0.05	0.01	0.2	0.04	0.7
$A_e = 10^5$ m^2 (~UTR-2, LOFAR)	0.01	0.2	0.03	0.6	0.1	2.2
$A_e = 10^6$ m^2 (~SKA)	0.03	0.5	0.1	2.	0.4	7.

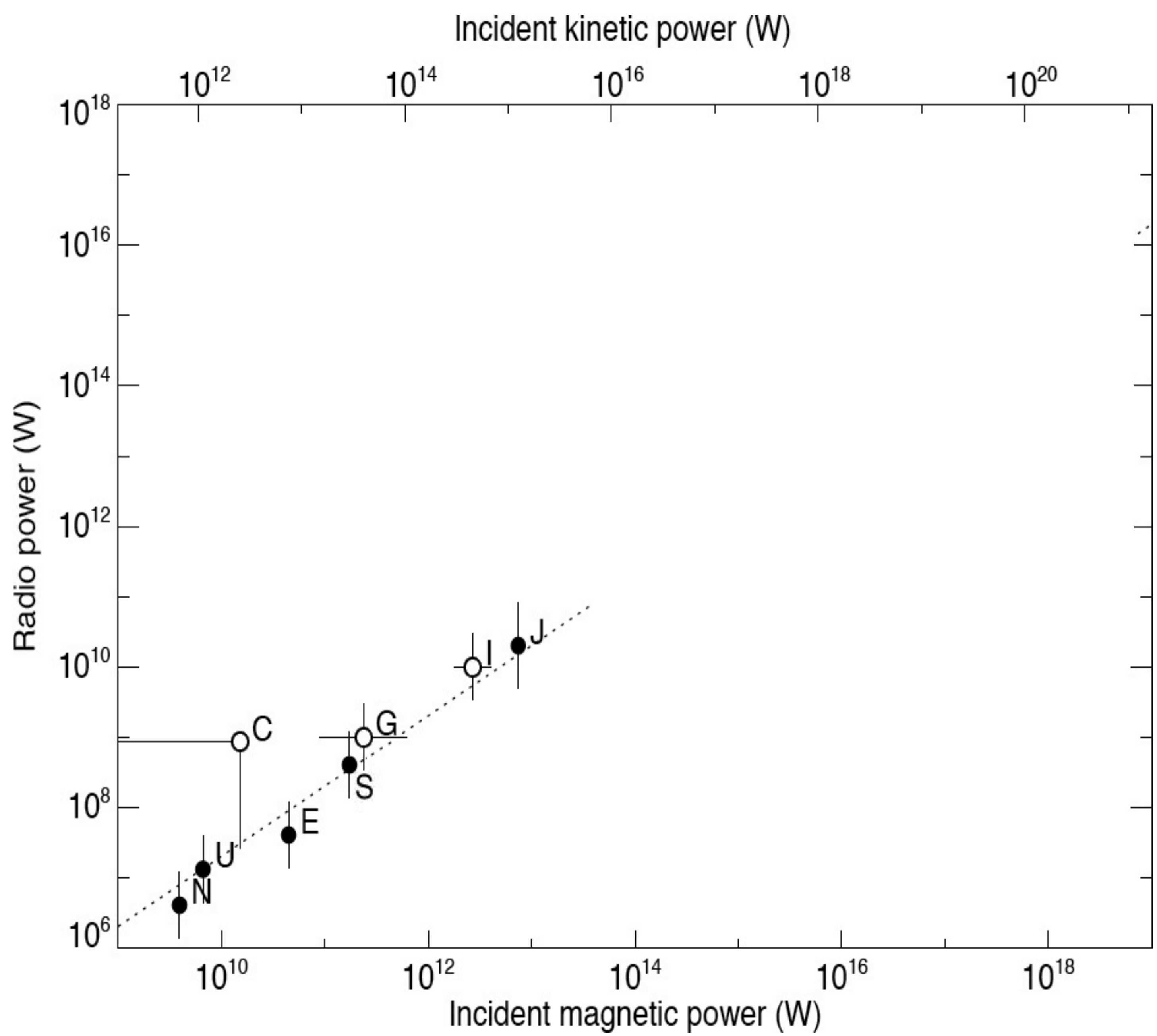
(distances in parsecs)

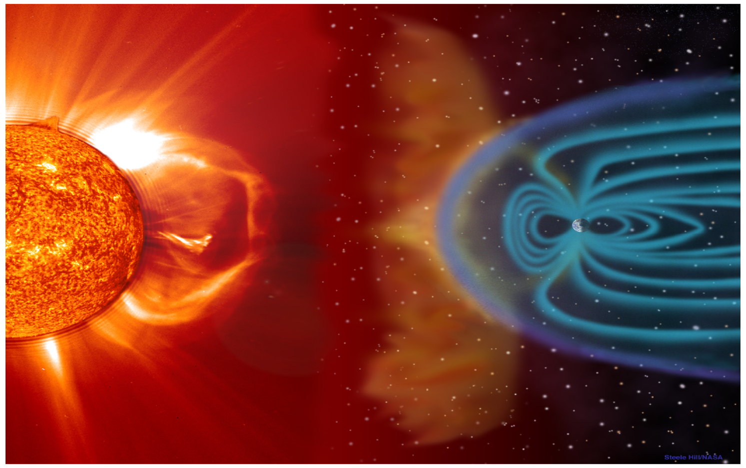
[Zarka et al., 1997]

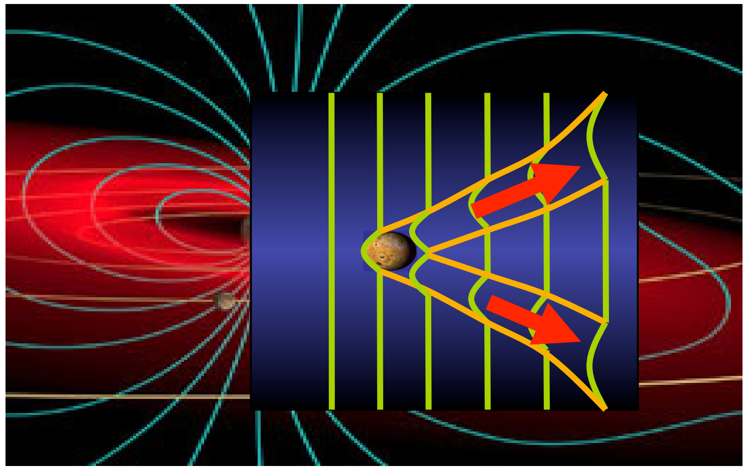
THEORY

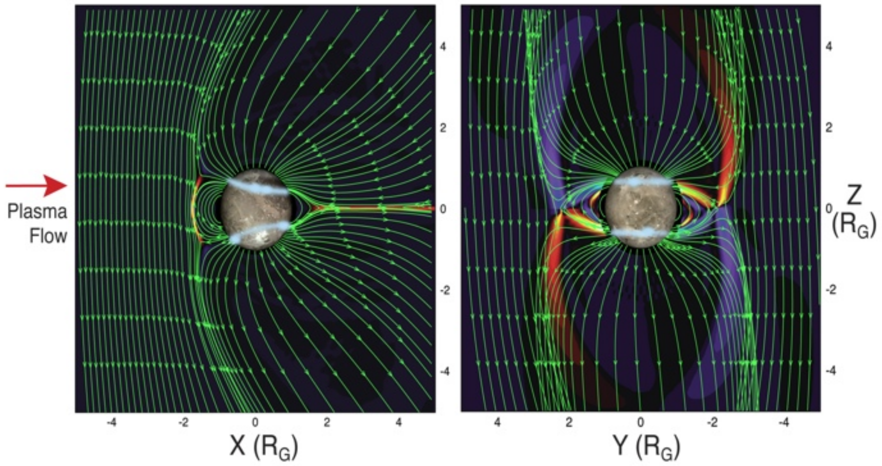
• General frame of flow-obstacle interaction in our Solar system : magnetic reconnection, Alfvén waves, Unipolar interaction

• Empirical radio-magnetic scaling law with ~constant efficiency ε~2-10×10^{-3}





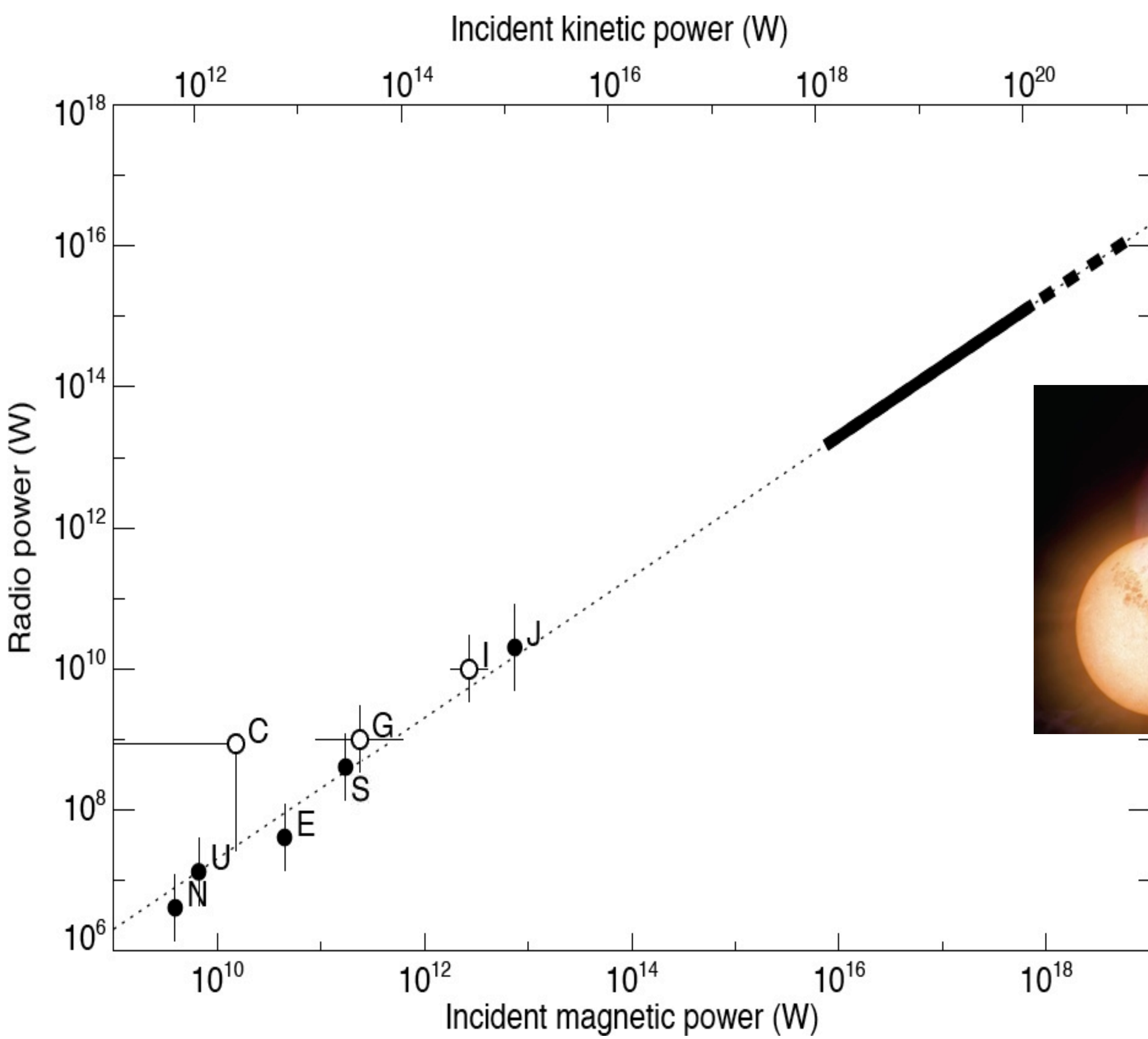




[Zarka et al., 2001 ; Zarka, 2007]

→ Extrapolation to hot Jupiters :

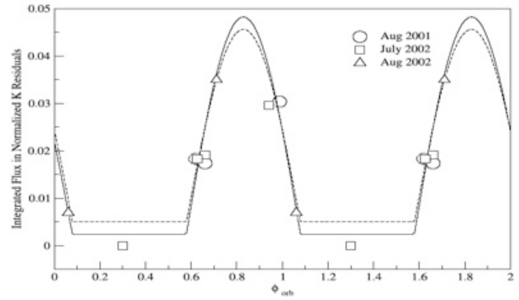
- Magnetospheric radio emission up to 10^5 Jupiter
- Unipolar inductor emission up to $\geq 10^6$ Jupiter at $\geq$30-300 MHz, but requires $B_* \geq$ 10-100B

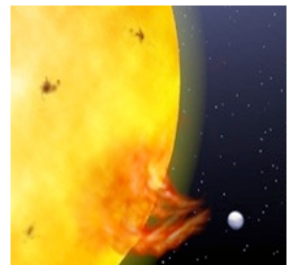


[Zarka et al., 2001 ; Zarka, 2007]

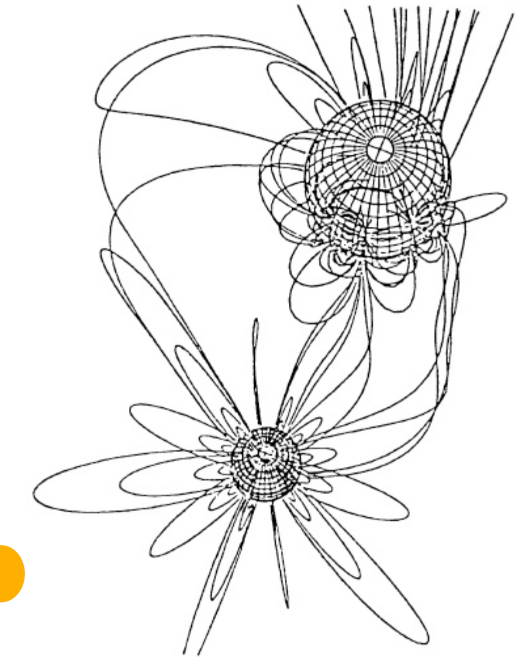
- Measurement of an interacting magnetic binary(RS CVn V711 τ) compatible with extrapolated scaling law [Zarka, 2010]

- + Controversial optical SPI detection

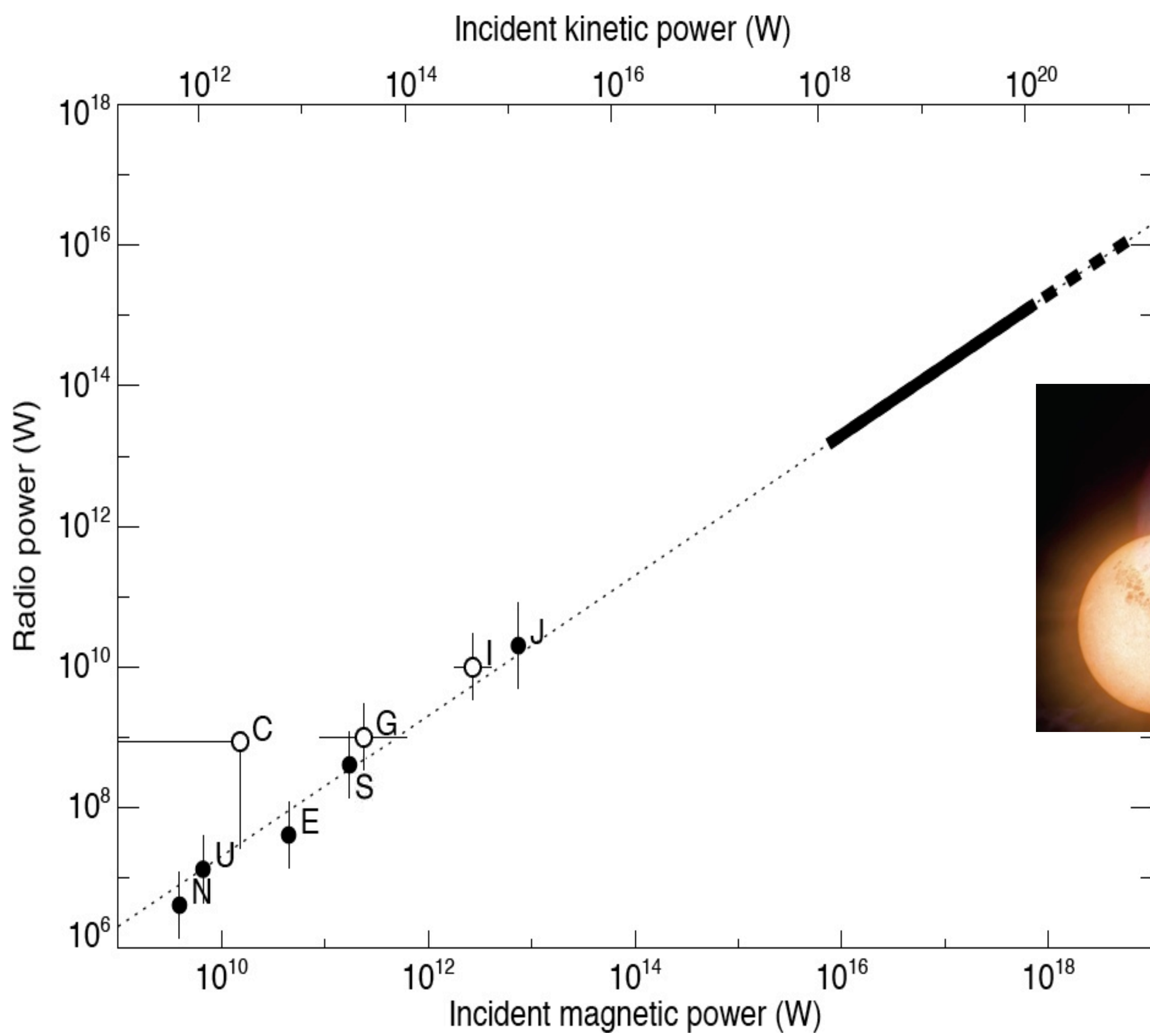




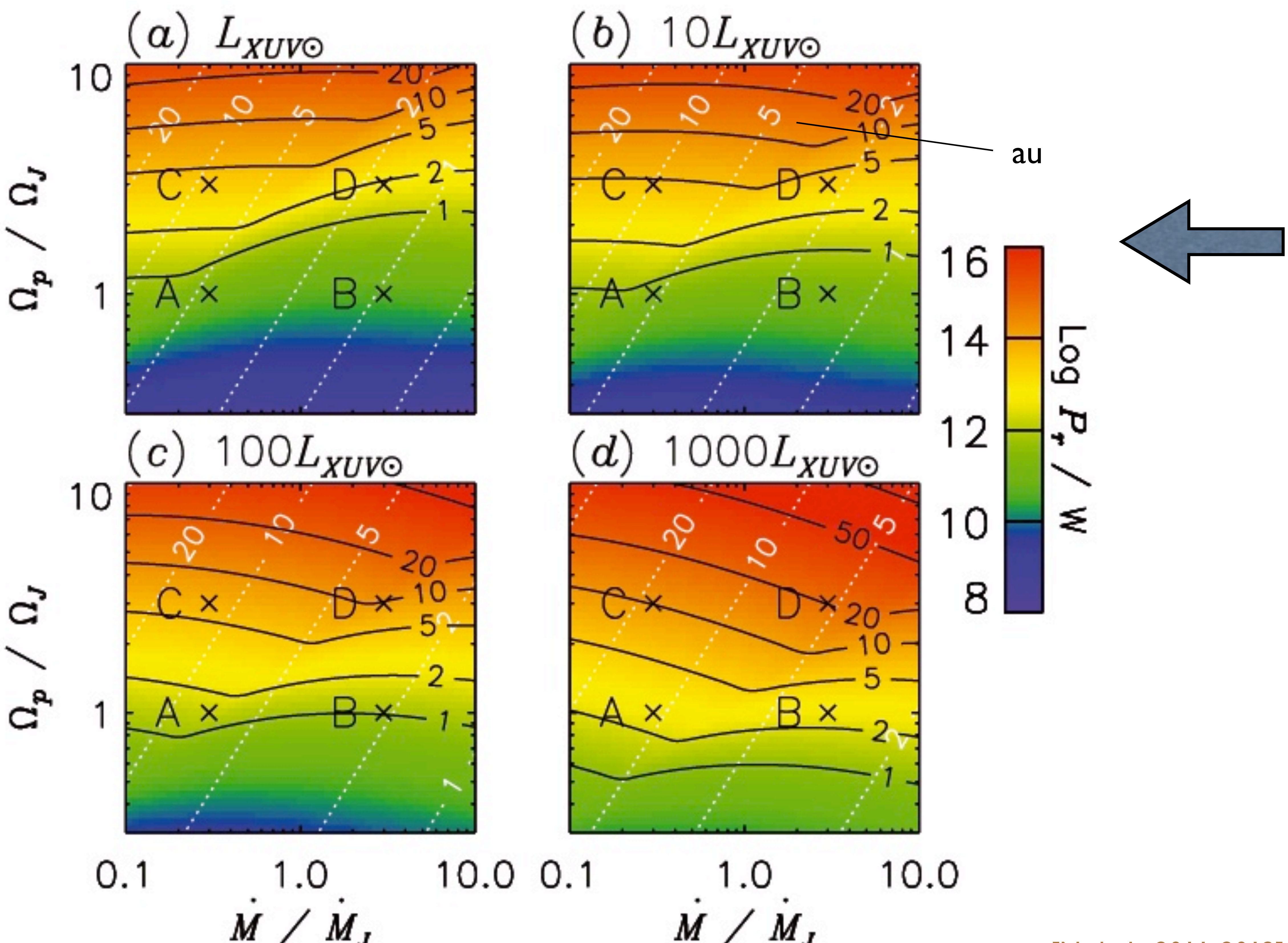
[Shkolnik, 2003-5-8]



magnetic binary
[Budding et al., 1998]



• Internally driven radio emission of normal Jupiters around highly XUV luminous stars → large radio fluxes requires rapid Xo rotation (1-3h)



[Nichols, 2011, 2012]

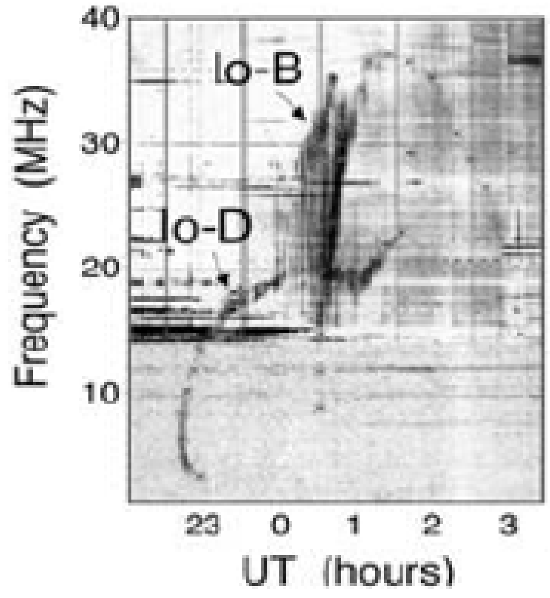
- Maximum distance for Nσ sky-limited detection of a source ζ x Jupiter :

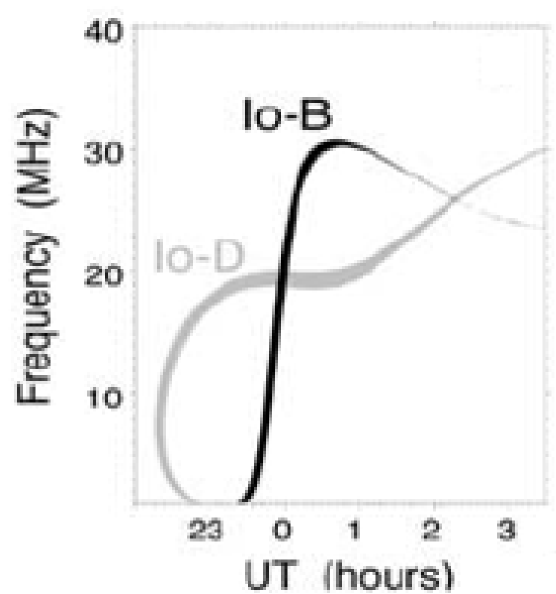
ζ = 10^5	b τ = 10^6 (1 MHz, 1 sec)		b τ = 2×10^8 (3 MHz, 1 min)		b τ = 4×10^{10} (10 MHz, 1 hour)	
	f = 10 MHz	f = 100 MHz	f = 10 MHz	f = 100 MHz	f = 10 MHz	f = 100 MHz
$A_e = 10^4$ m^2 (~NDA)	1	16	3	59	13	220
$A_e = 10^5$ m^2 (~UTR-2, LOFAR)	3	50	11	190	40	710
$A_e = 10^6$ m^2 (~SKA)	9	160	33	600	130	2200

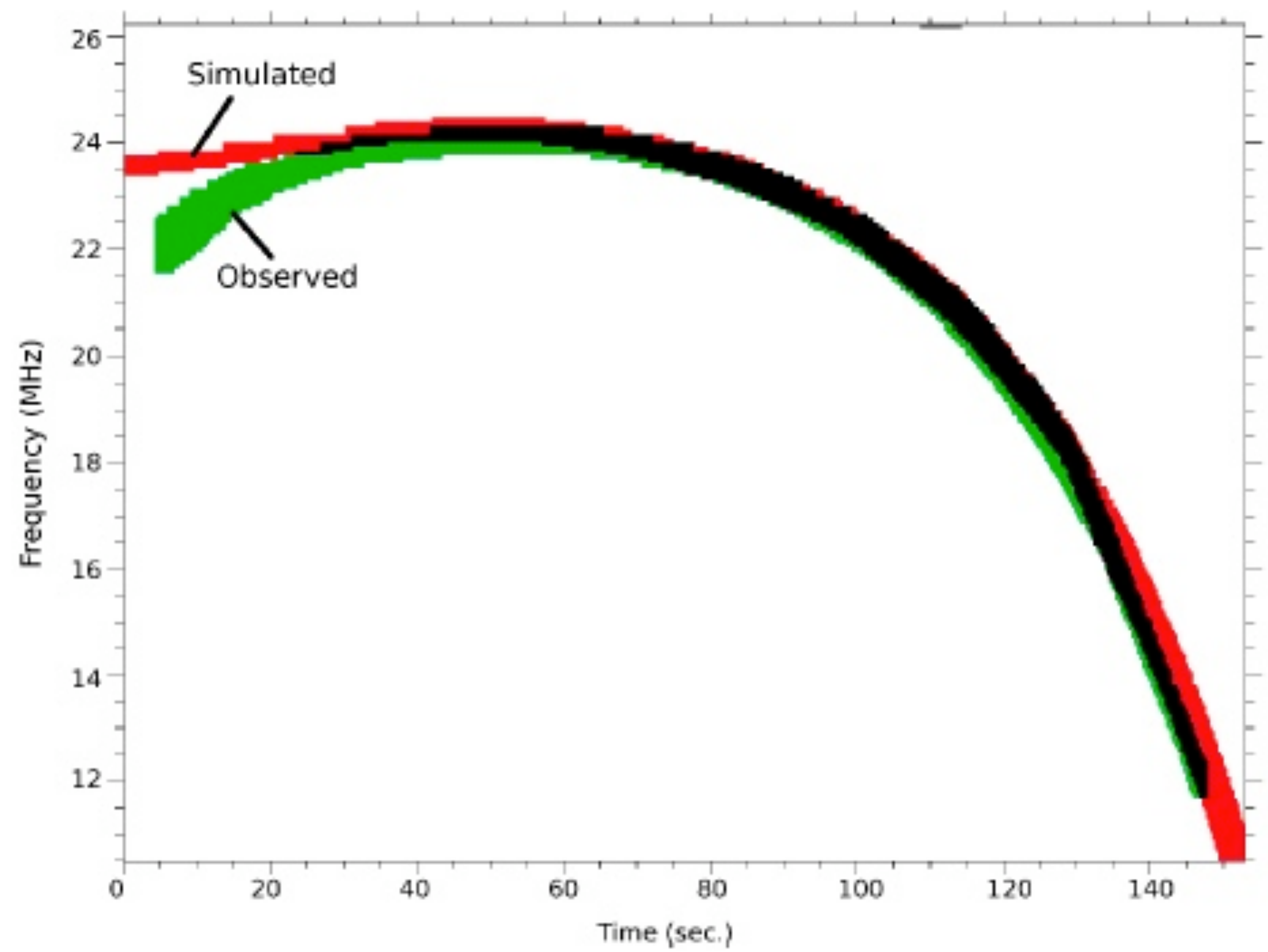
(distances in parsecs)

- turbulence → intermittency [Chian et al., 2010]
- scintillations → radio flux x100 ? [Farrell et al., 1999]

- Predicting radio dynamic spectra from CMI modelling for various SPI scenarii
  - no imaging → t-f morphology reveals physical parameters
  - successful loss-cone driven CMI modelling of Jupiter's radio emissions :
    → Meudon ExPRES code



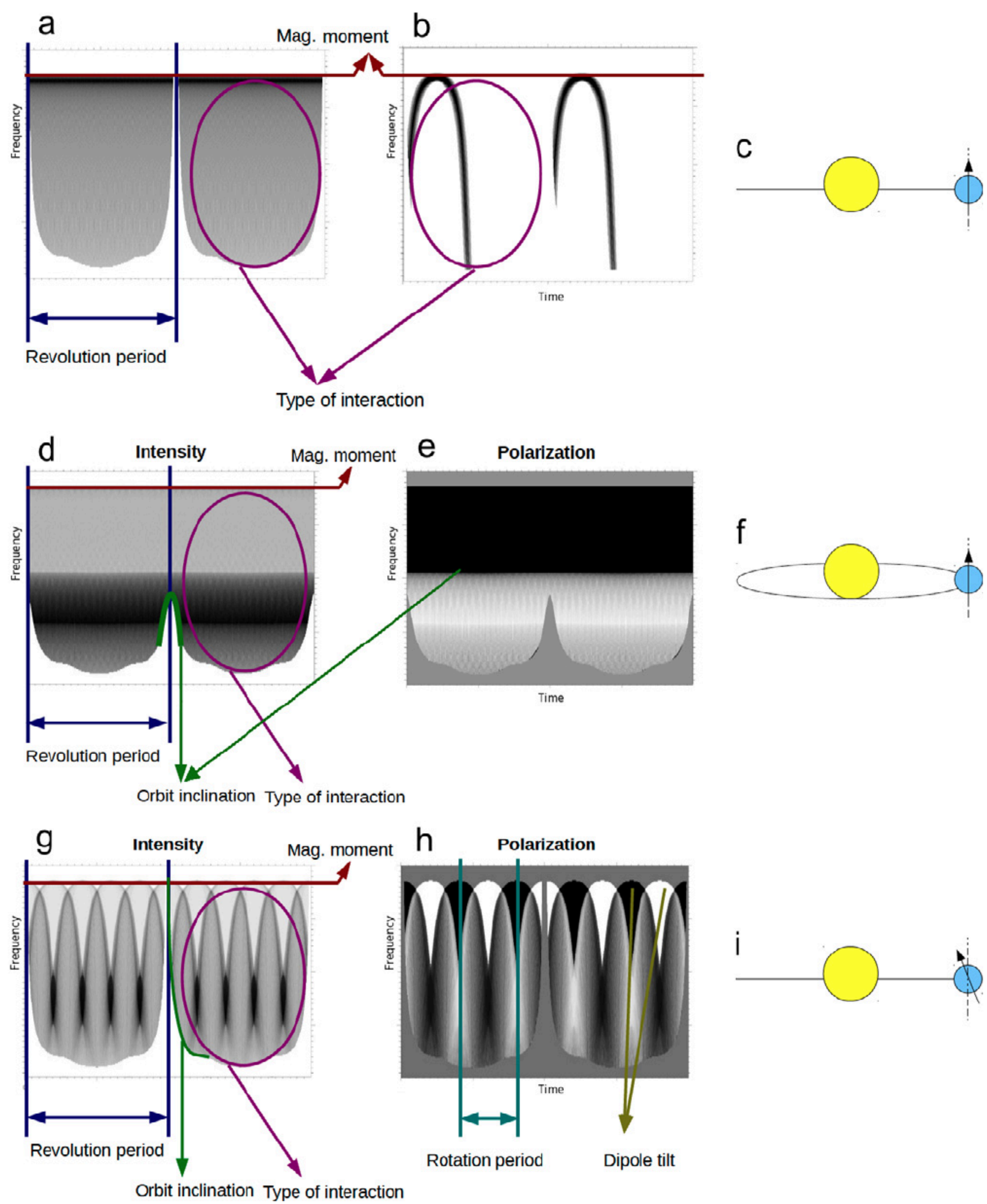




[Hess et al., 2008, 2010, 2013]

• Star-Exoplanet case : parameters (stellar/exoplanet B tilt/offset, orbit inclination), planetary and stellar rotation, planetary orbital period ...

[Hess & Zarka, 2011]



• Study of typical cases (specific modeling post-detection)

• Model predictions scalable to any frequency range (depends on B involved)

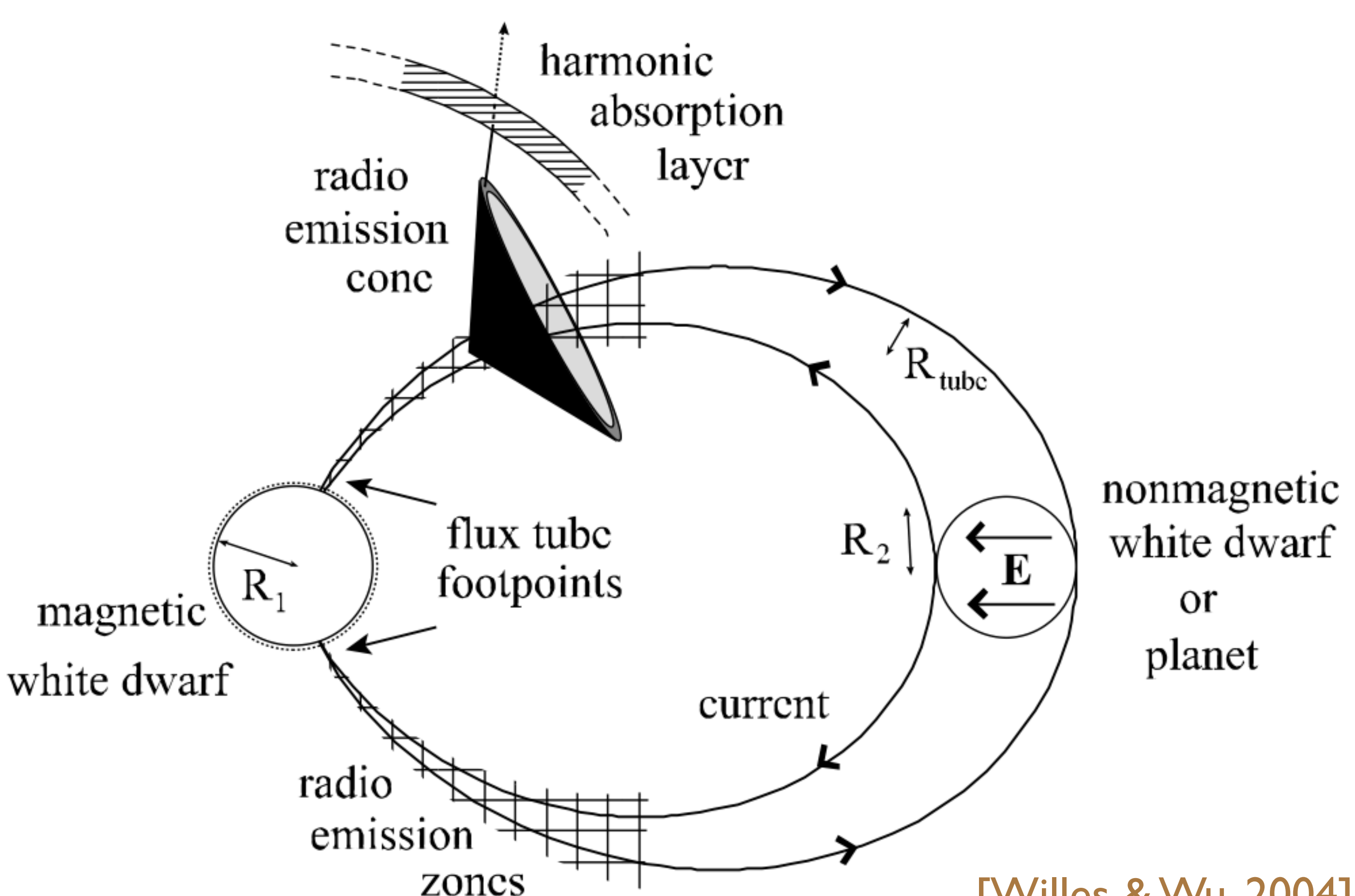
• ≥ a few 10's MHz, LF cutoff becomes negligible except very close to the star & at low inclination (~occultation)

- White dwarf-planet unipolar interaction explains ultrashort period (P<10 min) X-ray sources with antiphase optical emission : X-Ray emission by heated footpoints on magnetic WD + optical emission by irradiation of the companion

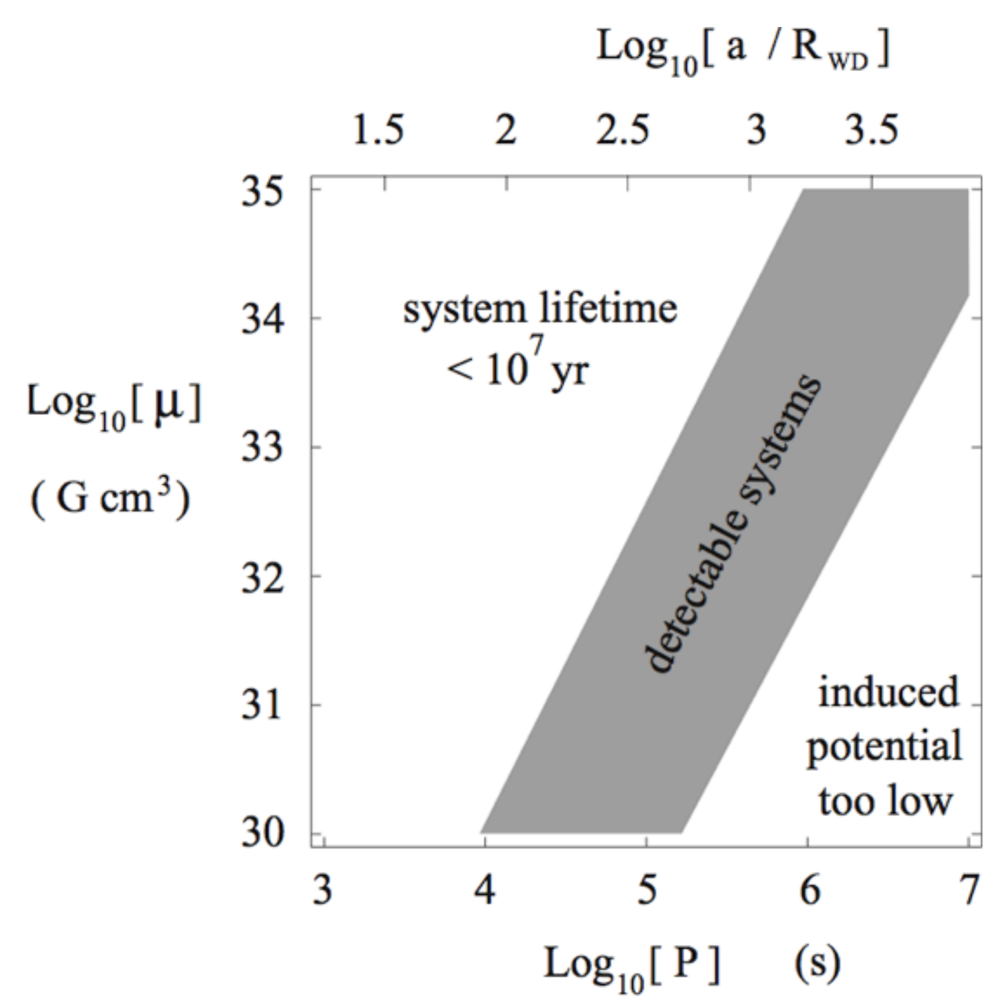
- P decrease consistent with power radiation via unipolar induction
- System lifetime due to gravitational radiation emission

- CMI radio emission ?

  → may reveal Earth-like planets in close orbit around WD (= remnants of main sequence stars with planet surviving the stellar expansion phase and back in stable orbit)



[Willes & Wu, 2004]



- Interest of low-frequency radio observations of exoplanets : immense !

  → Direct detection, discovery ?

  → Measurement of B (only way !)

  ⇒ contraints on scaling laws & internal structure models

  → Planetary rotation period ⇒ tidal locking ?

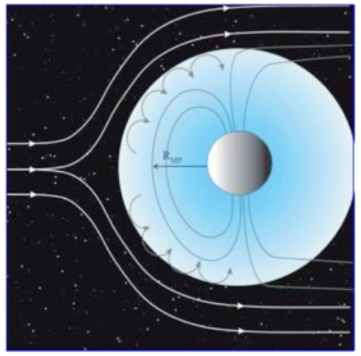
  → Possible access to orbit inclination

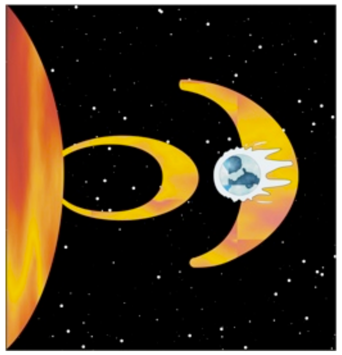
  → Existence / orbital period of satellites ?

  → Comparative (exo)planetary magnetospheric physics = NEW FIELD, theoretical frame ready, we are leading it

  → Magnetosphere favours habitability (limits atmospheric erosion by solar wind & CME, limits destruction of O_3 by cosmic rays)

  [Griessmeier et al., 2004; Khodachenko et al., 2006...]

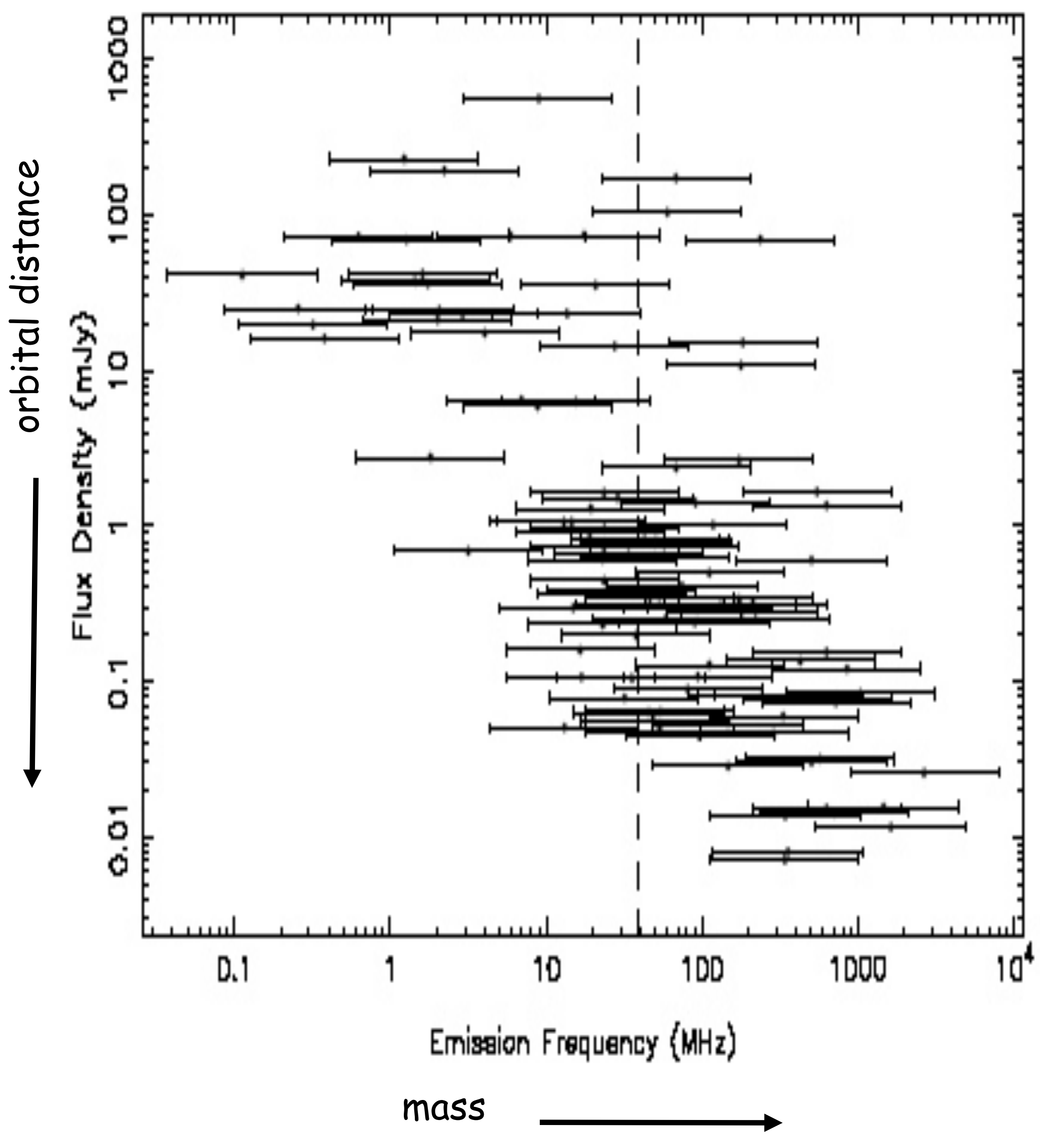




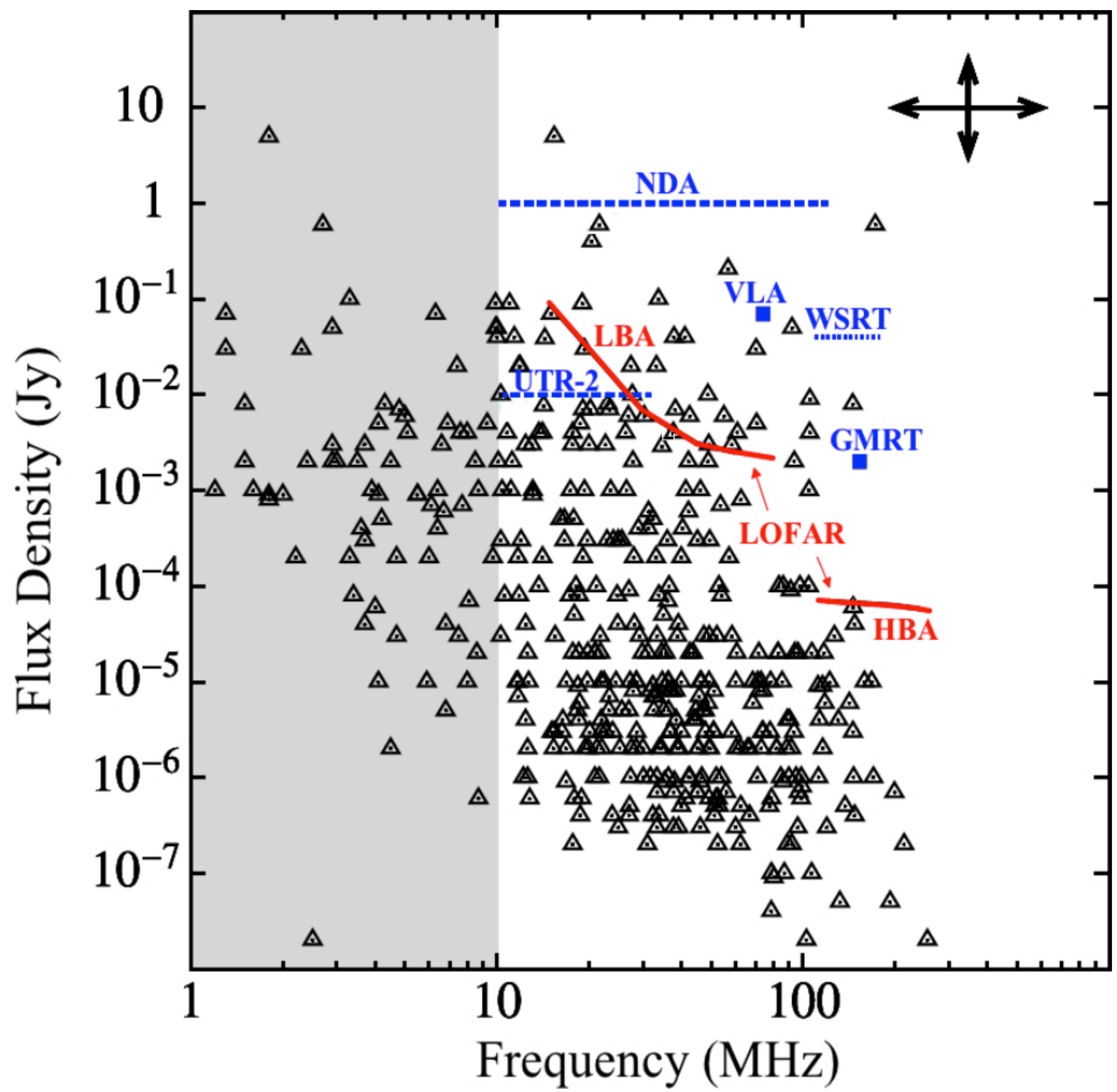
- Synchrotron emission from radiation belts : stable but weak (a few nJy @ 1 pc)

PREDICTIONS

- Application of scaling laws to exoplanet census → target selection



[Lazio et al., 2004]



[Griessmeier et al., 2007, 2011]

- Unipolar inductor CMI radio emission from WD-exoplanet systems

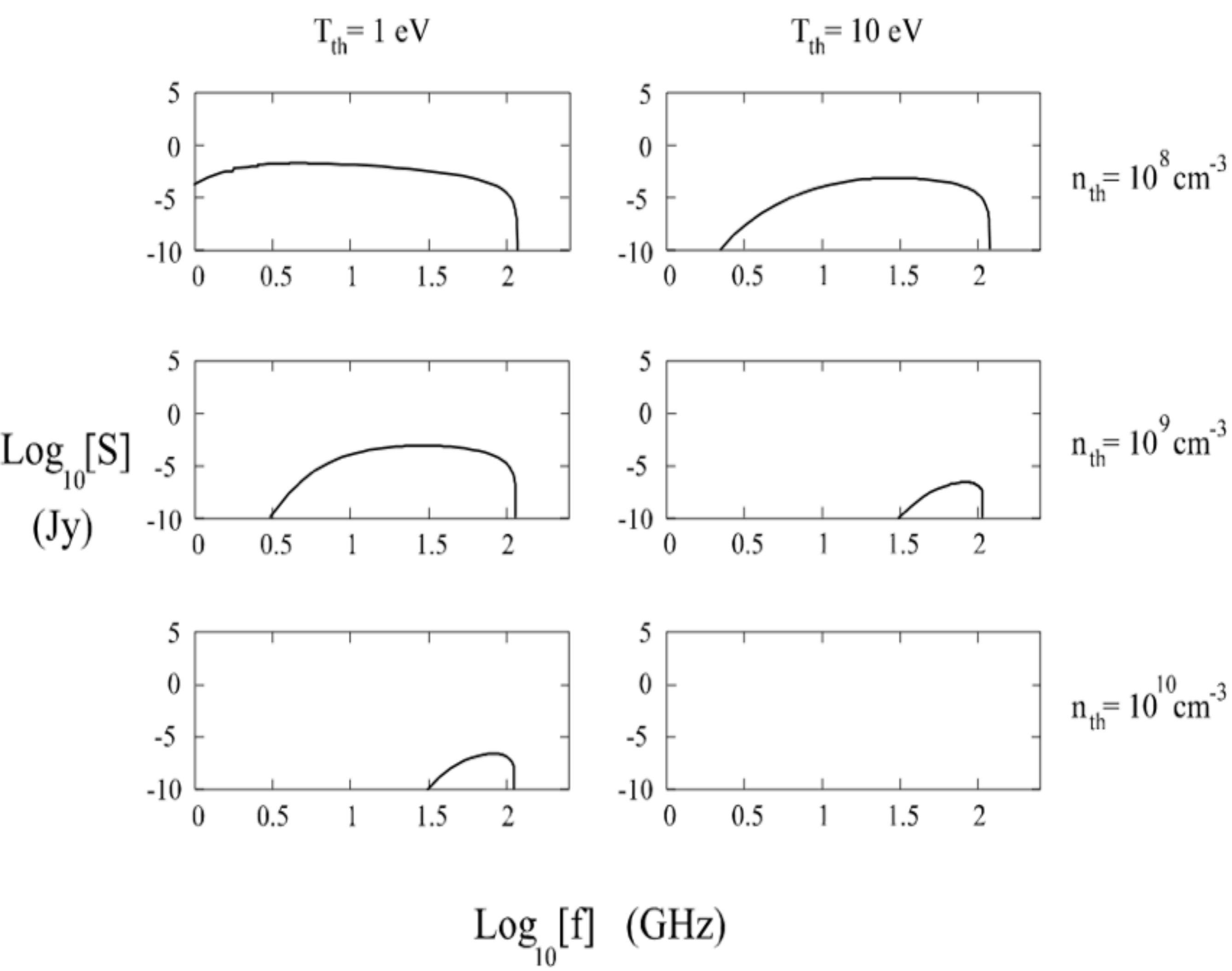
→ broadband emission up to 100 GHz (+ absorption bands), 100% circularly polarized bursts (X mode dominant), modulated at the orbital period

→ orbital period modulation : bursts (~10 min), a few % duty-cycle (beaming)

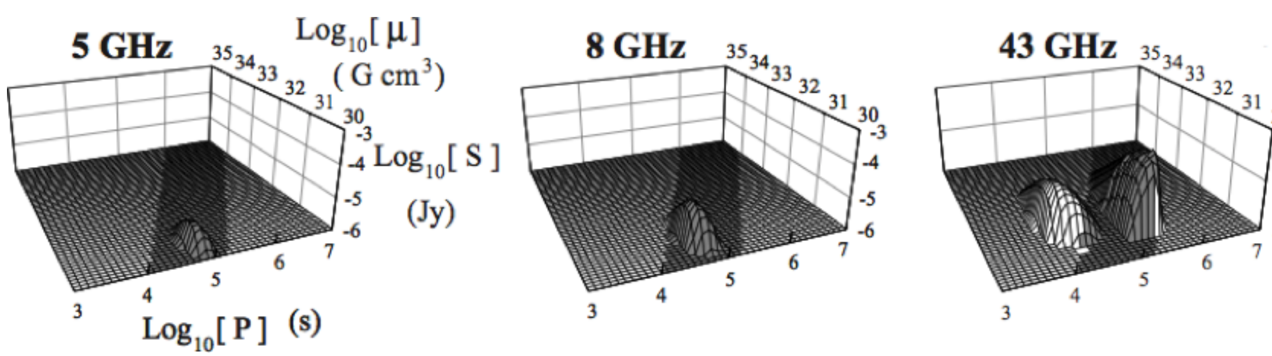
→ order of magnitude predictions (N_e of 1 keV loss-cone e- ×10 → S ×10^4)

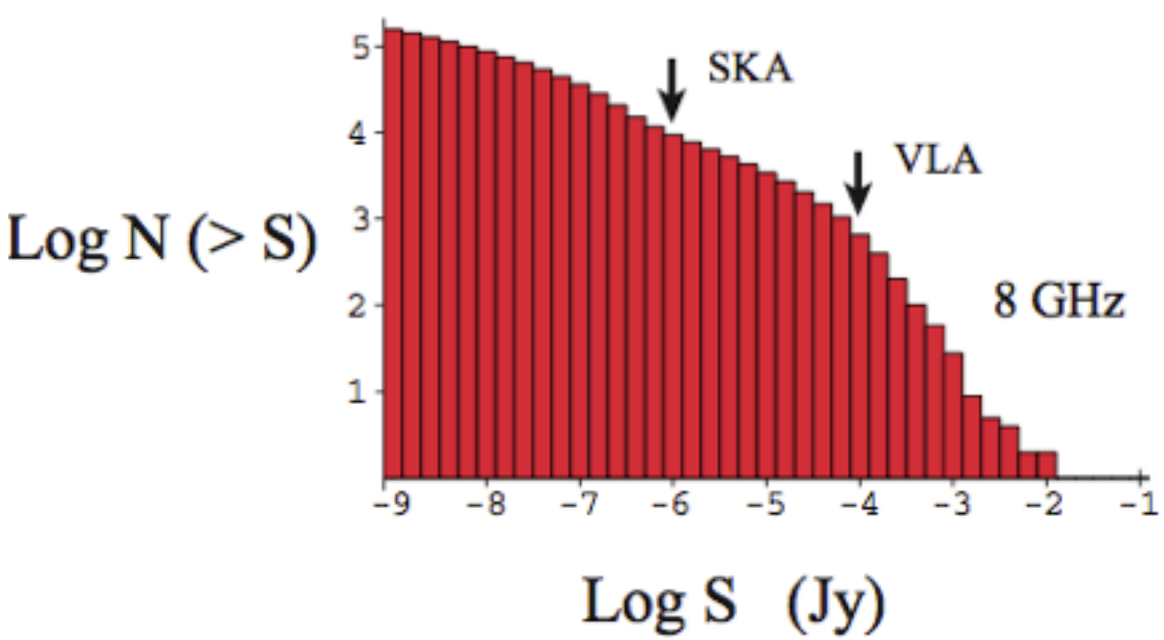
→ Limited unipolar inductor lifetime due to spin-orbit coupling

Flux density spectra @ 100 pc with 1 keV e-

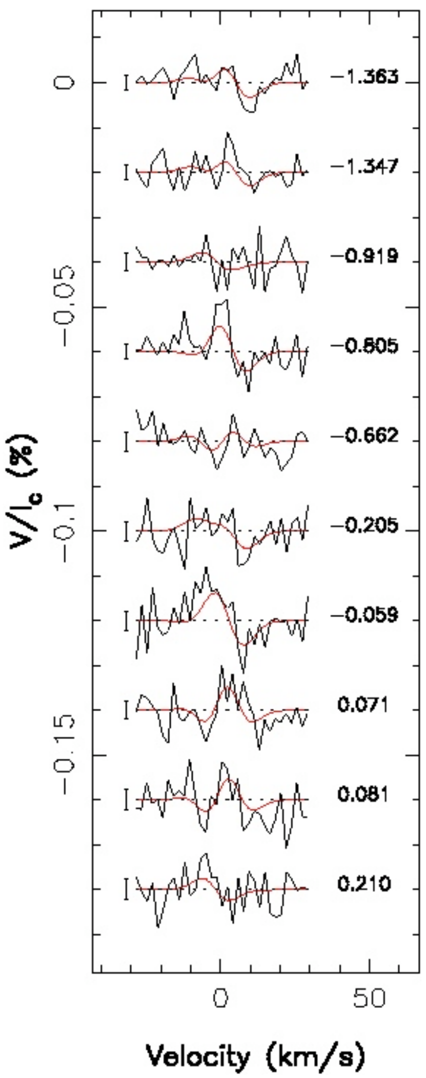


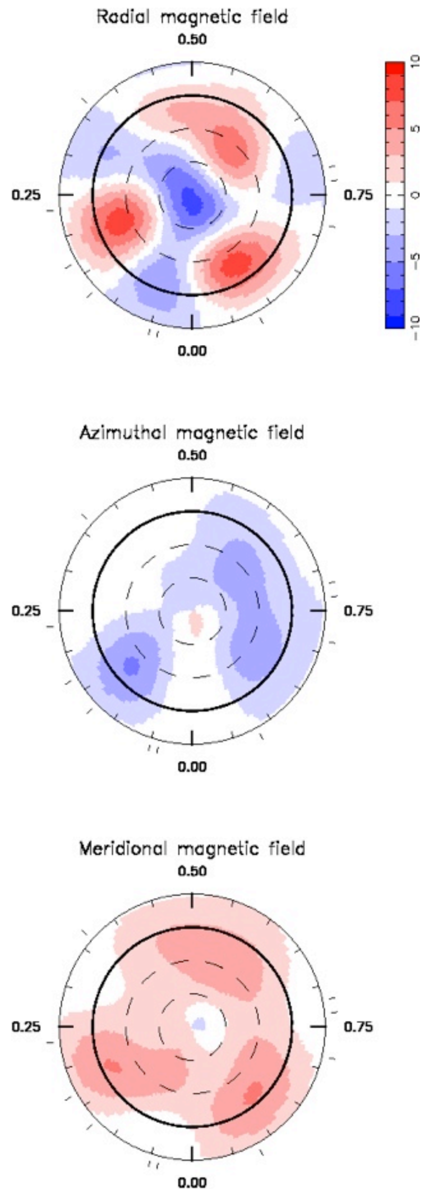
[Willes & Wu, 2004, 2005]





- Stellar B-fields & variable star-planet interaction (SPI)





[Farès et al., 2010]

- Solar B field :

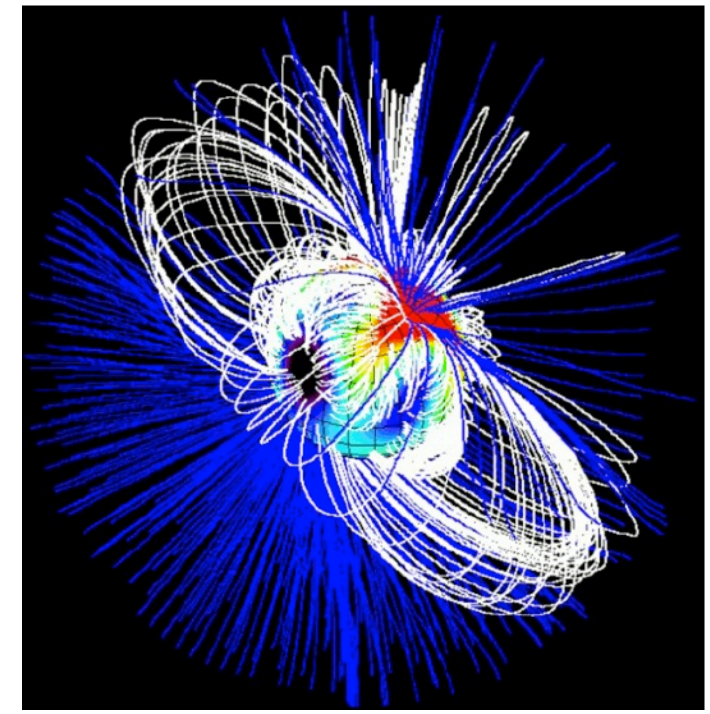
→ large-scale ~1 G

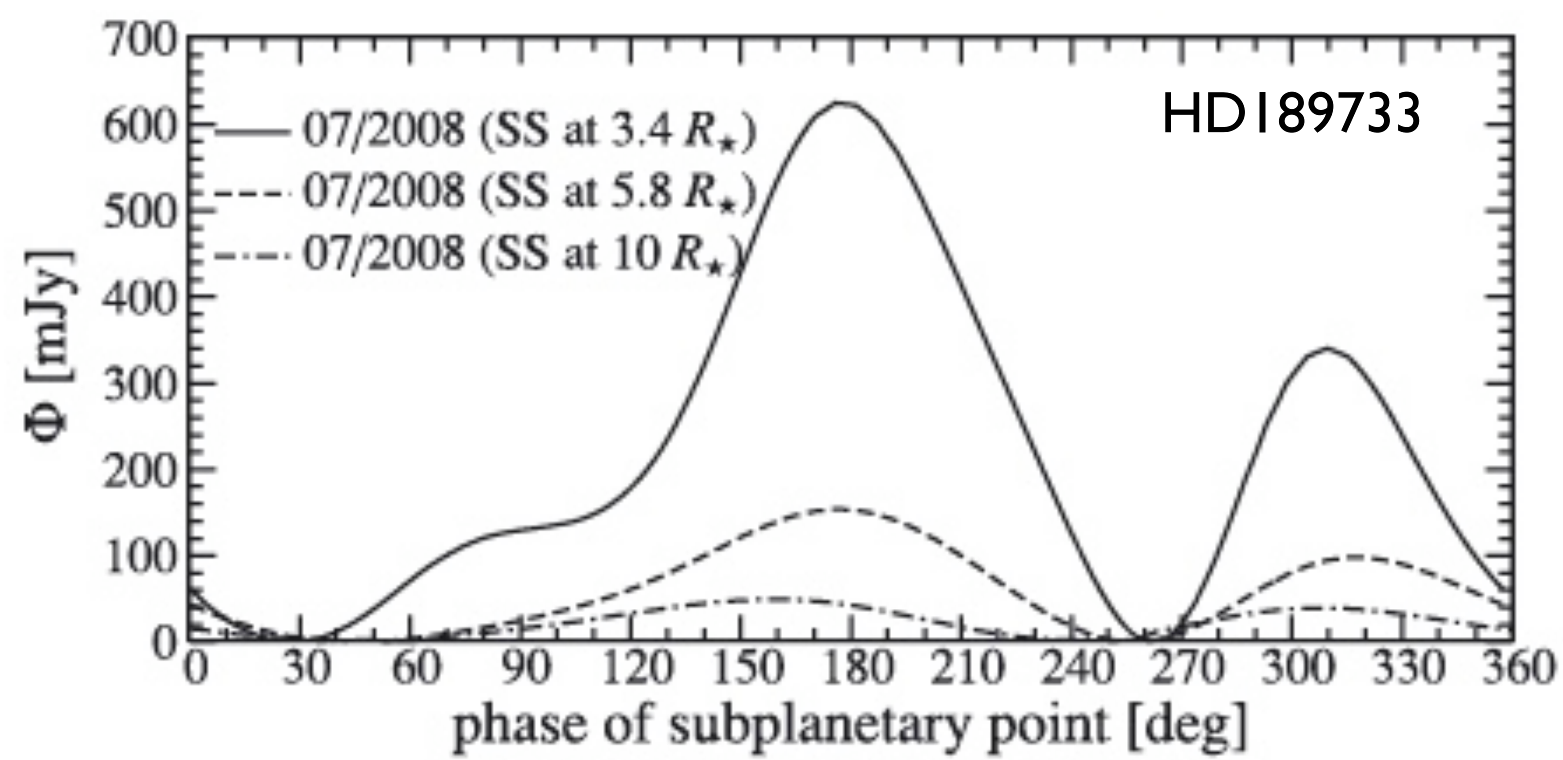
→ mag. loops ~10^3 G

(few % of surface)

- Magnetic stars : > 10^3 G

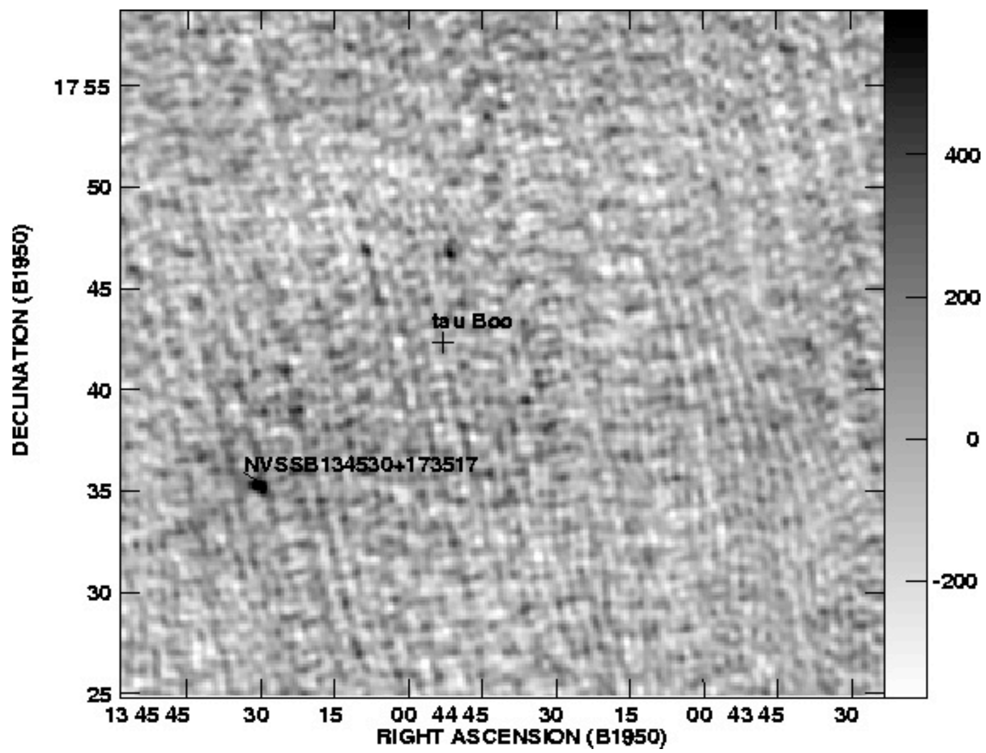
- τ Boo : 5-10 G (10^{-4} T)
- HD 76151 : ~10 G
- HD 189733 : >50 G
- HD 171488 : 500G

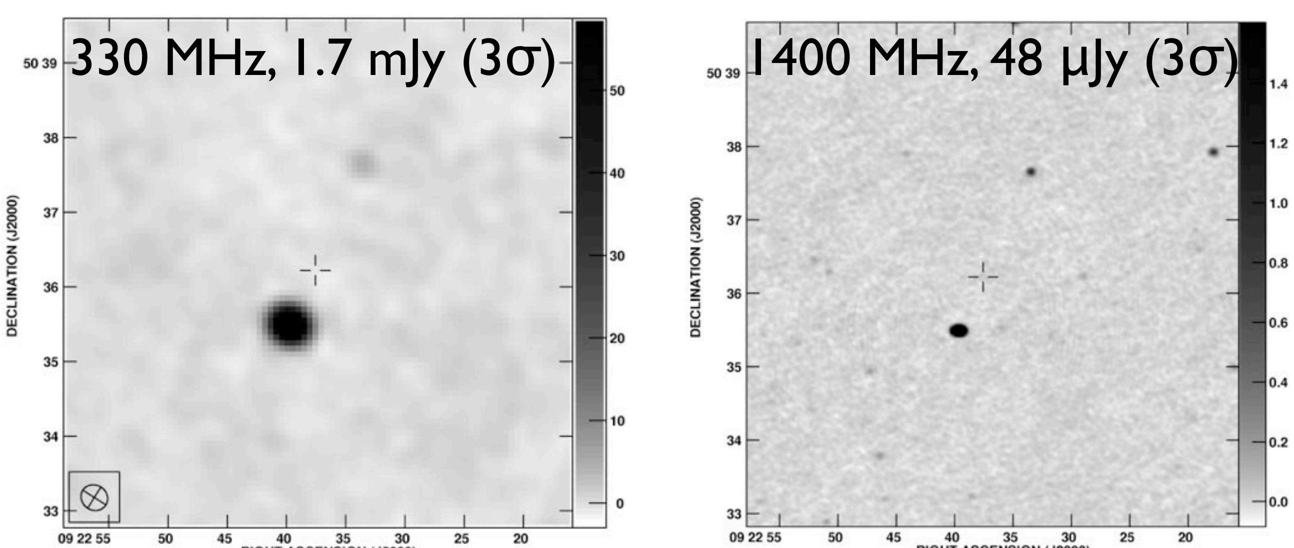




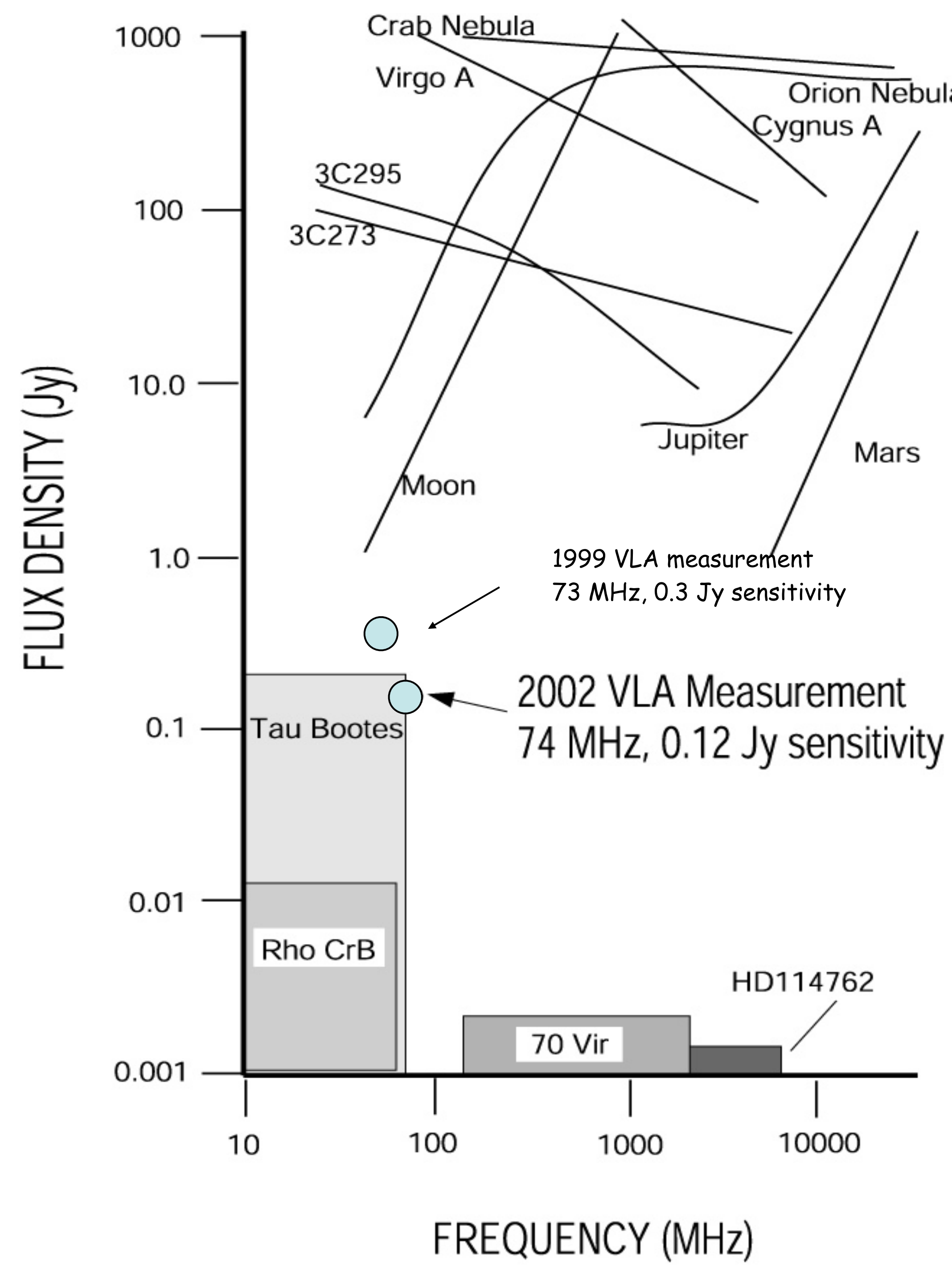
OBSERVATIONS

- Observations at VLA at 74, 330, 1465 MHz
  τ Boo, HD 80606 → no detection (low A_{eff}, 'HF')





HD 80606

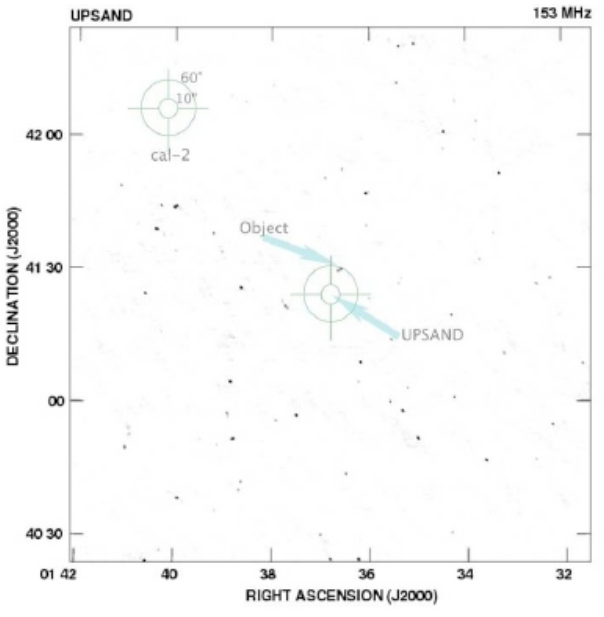


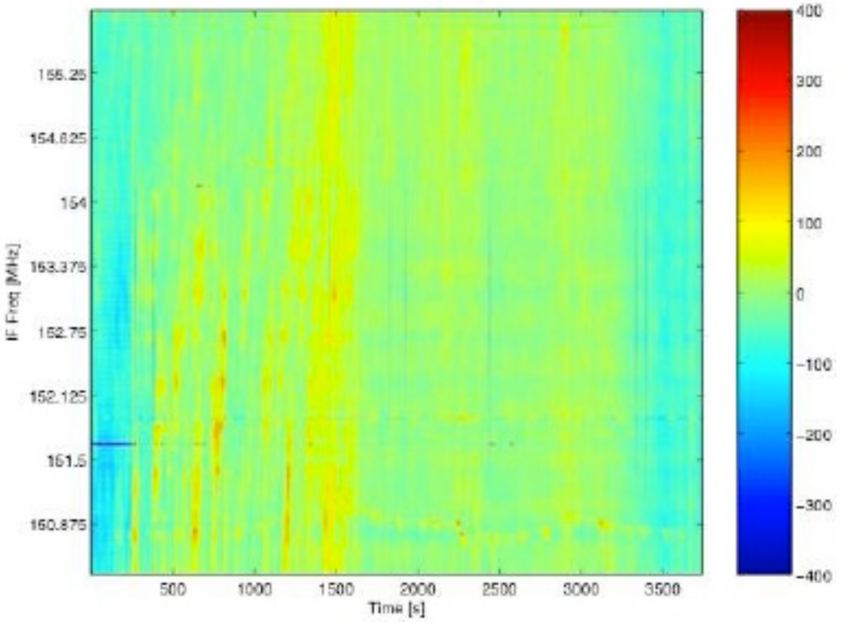
[Winglee et al., 1986; Bastian et al., 2000; Farrell et al., 2003, 2004; Lazio & Farrell, 2007; Lazio et al., 2010]

- Observations at GMRT at 153 MHz

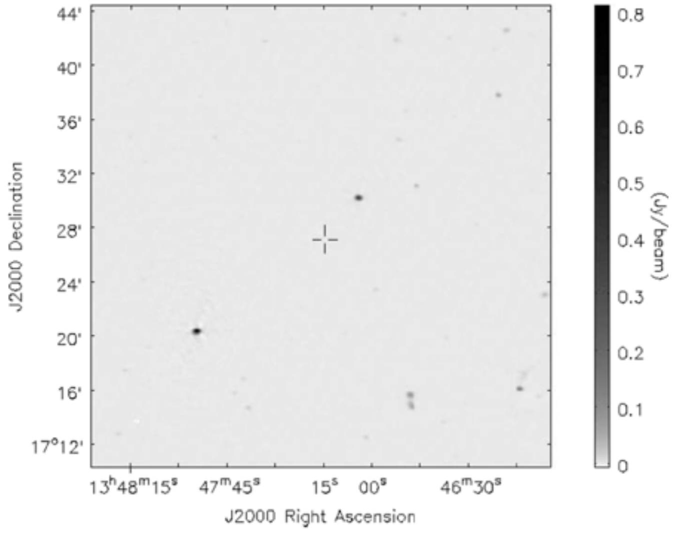
Ups And, ε Eri, HD 128311 → no detection

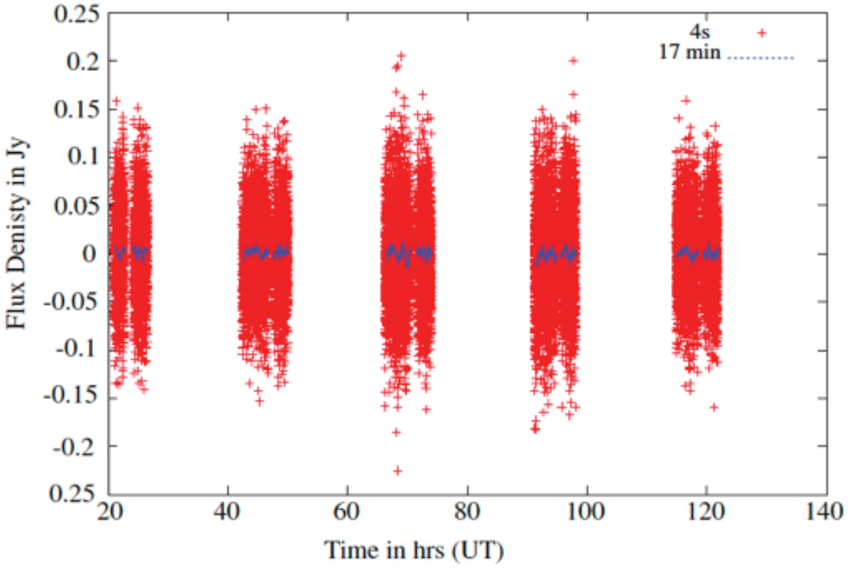
[Winterhalter et al., 2006; Majid et al., 2006; George and Stevens, 2007, 2008]





τ Boo (> $4M_J$, ~0.05 AU, 16 pc, P=79.5h) : 40 h, ~0.4 mJy



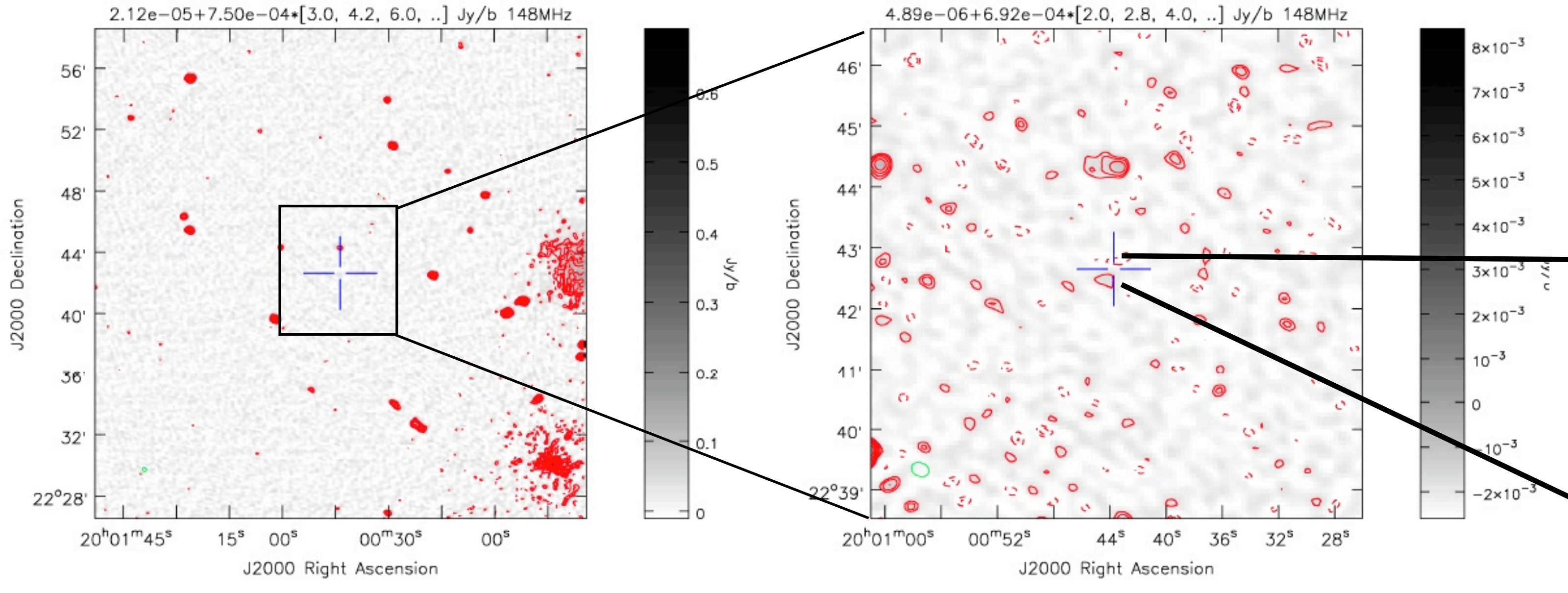


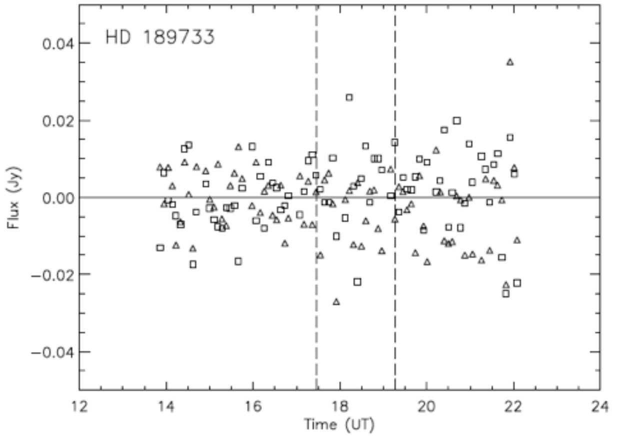
→ no detection

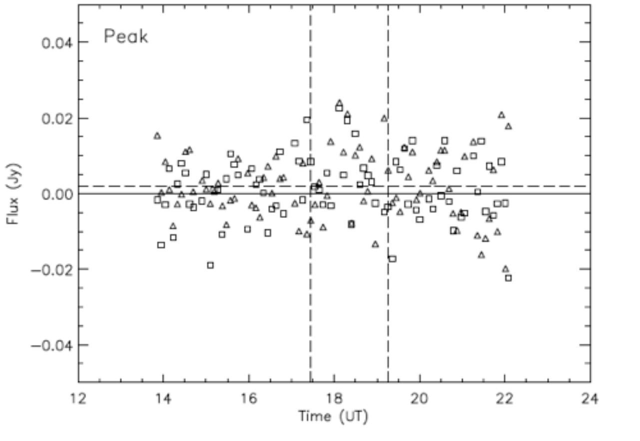
[Hallinan et al., 2013]

→ RFI ? B_{planet} < 50G ? (!) emission too weak ?

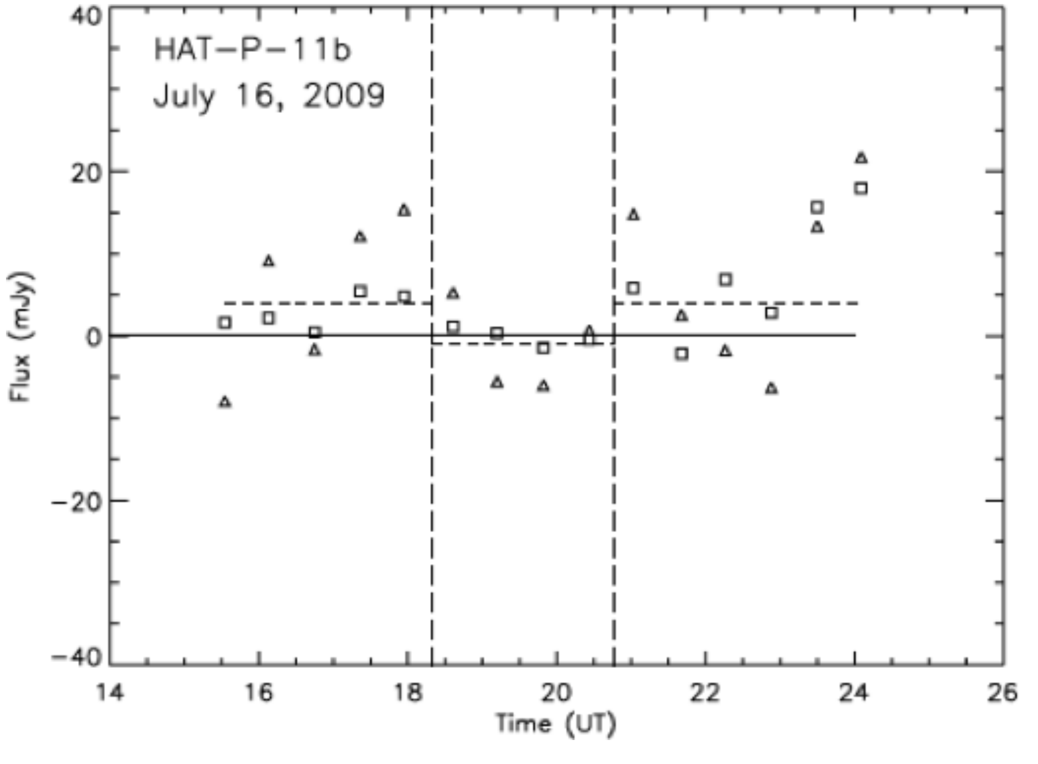
- Observations at GMRT at 153 MHz, 244, 614 MHz
  → anti-transits of HD189733b, HD209458b
  HAT-P-11b







[Lecavelier et al., 2009, 2011]



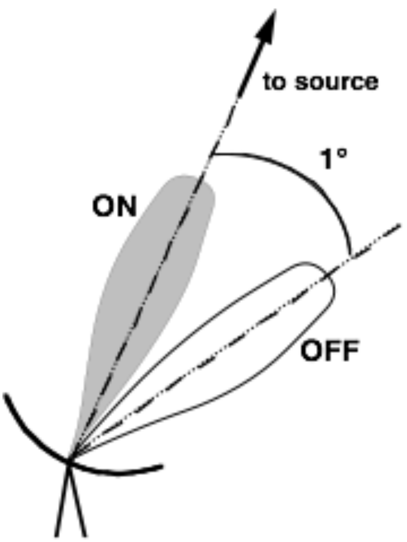
HAT-P-11, 153 MHz
unconfirmed in 2010

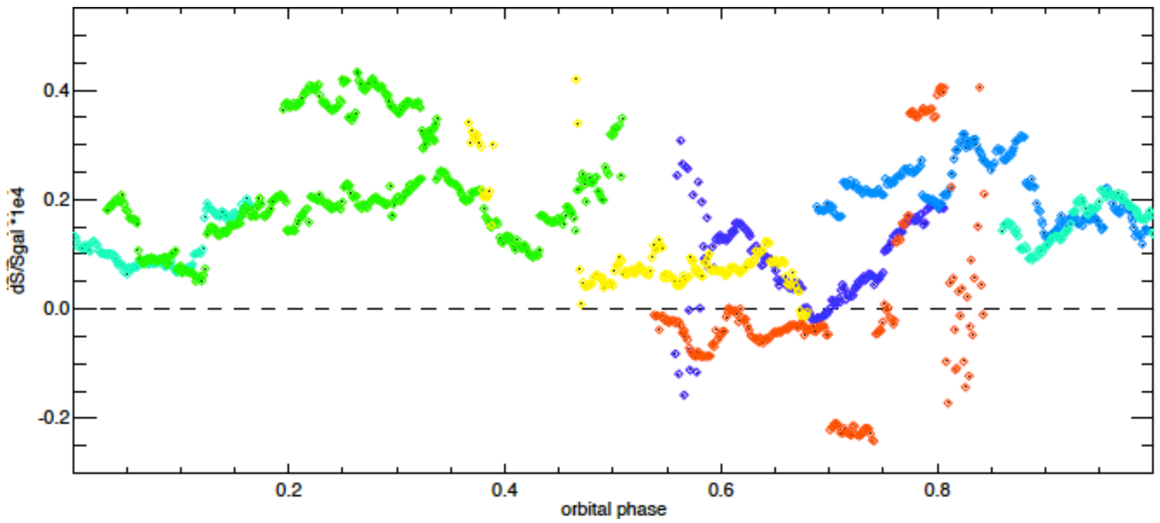
[Lecavelier et al., 2013]

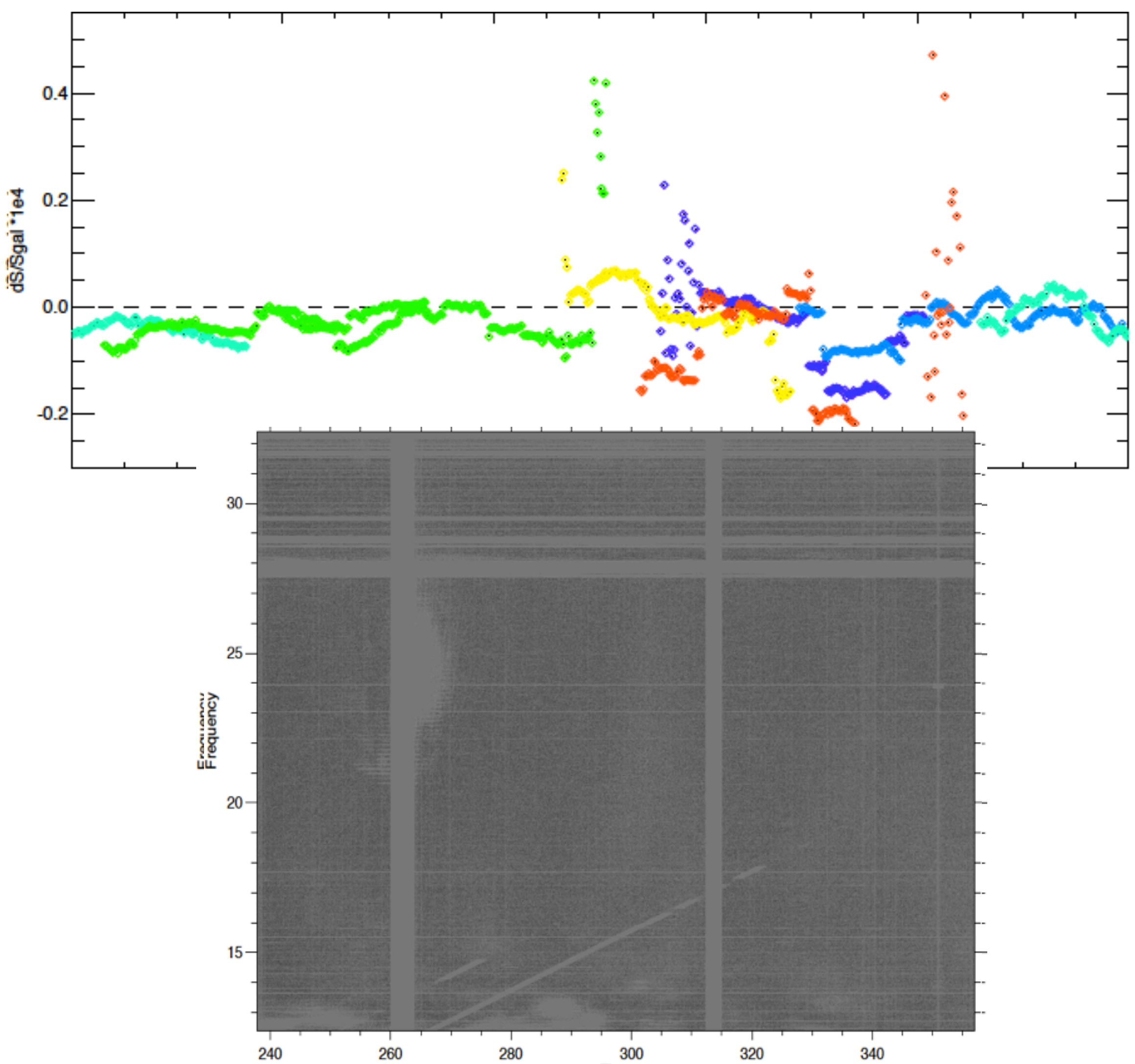
Last minute information :
Recent A&A paper by Sirothia et al.
Several candidate radio exoplanets in GMRT 150 MHz survey.
To be followed, confirmed, but very encouraging.

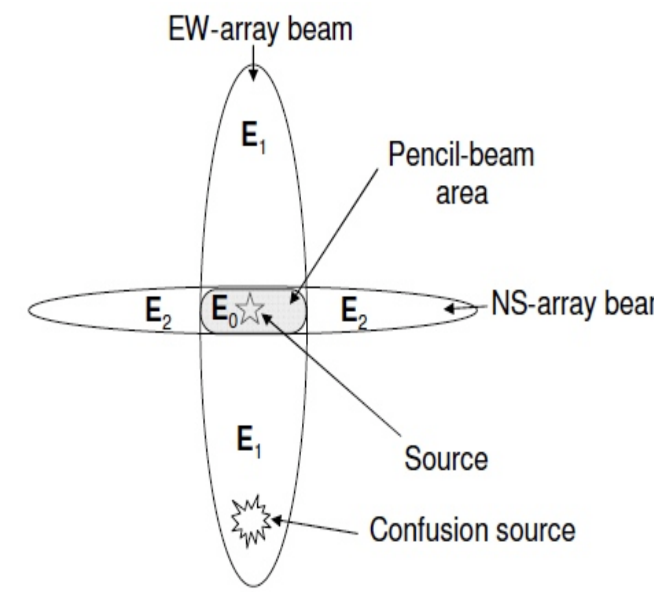
- Observations at UTR-2, 10-30 MHz dual beam, δ f=4 kHz, δ t=20 msec

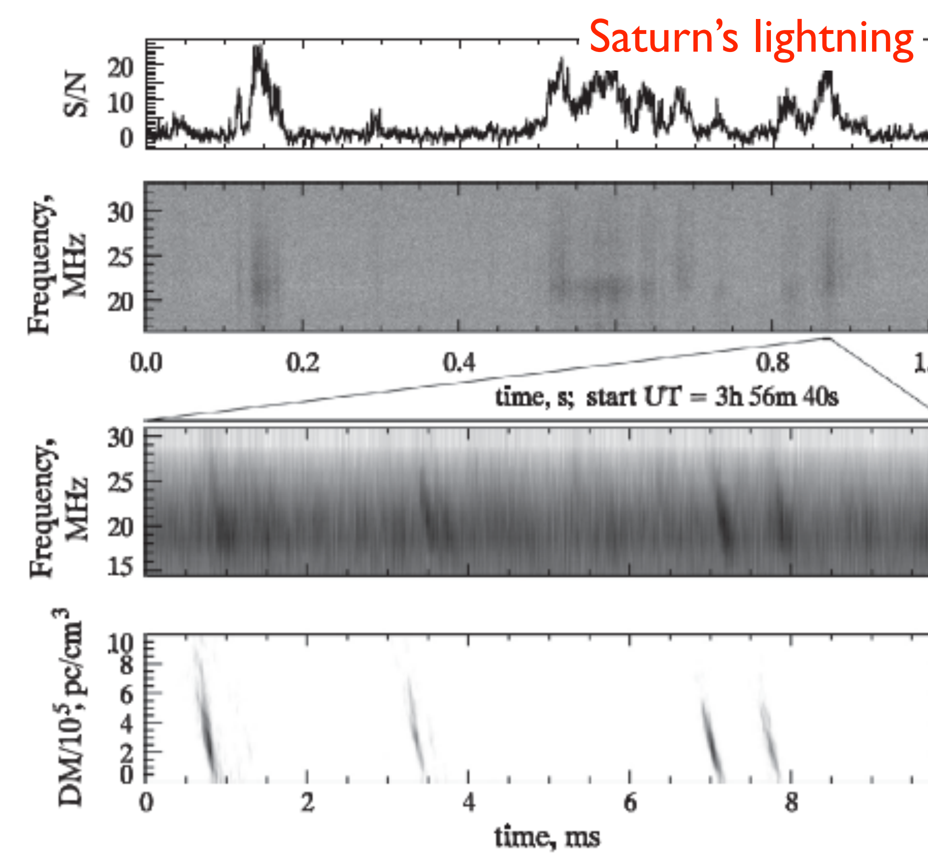
[Ryabov et al., 2004, 2010; Zarka et al., in prep]



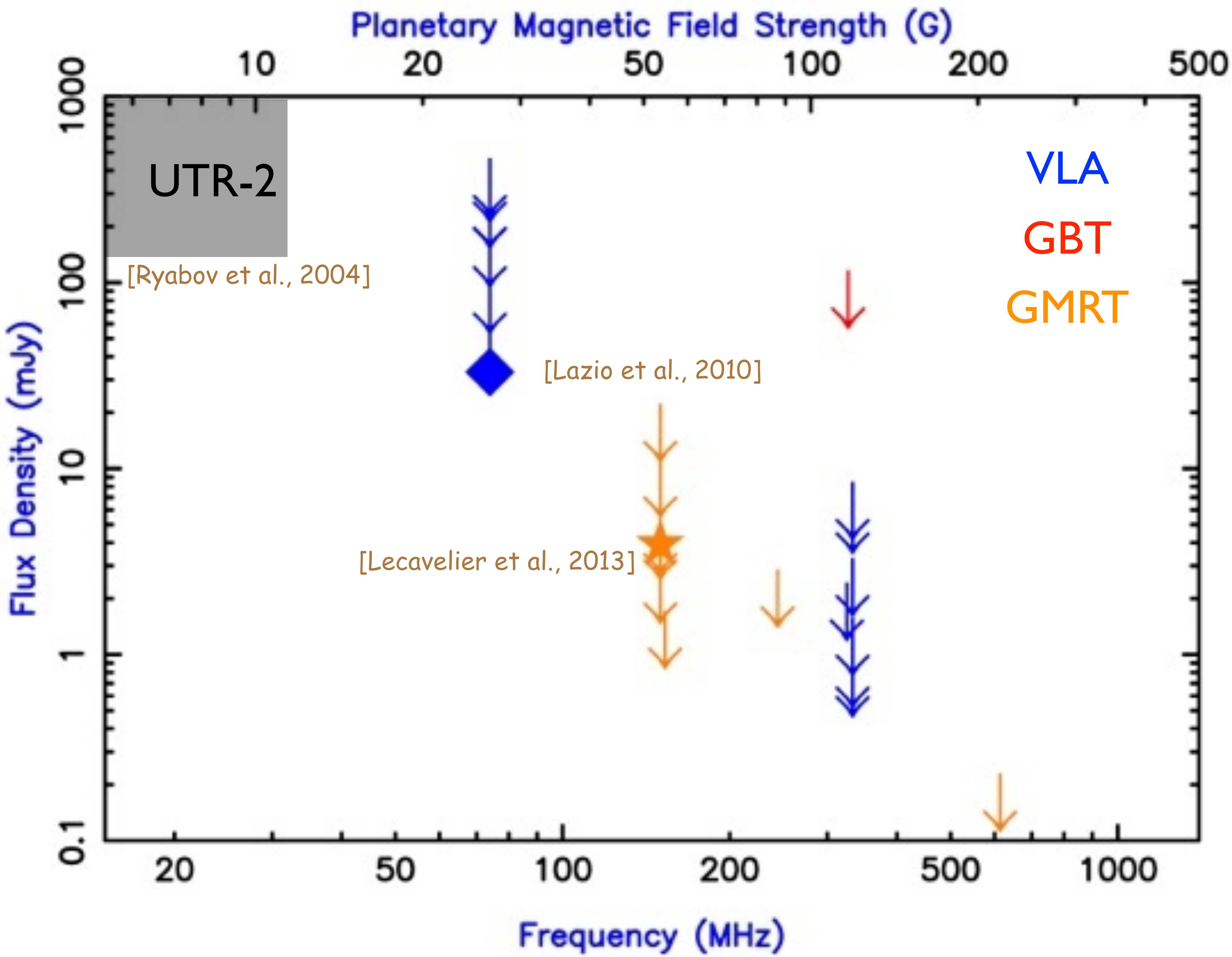








- Inferred limits (from J. Lazio)



- Observations with LWA, 10-88 MHz
  256 antennas, dual beam,
  mJy sensitivity

[Hallinan et al.]

HJUDE – Hot Jupiter Detection Experiment with the LWA ⇒ 5000 hours

A volume-limited survey of known HJs

distance: $d < 50$ pc

semi-major axis: $a < 0.5$ AU

projected mass: $M \sin i > 0.5\ M_J$

location: northern sky

Planet	d (pc)	a (AU)	P_{orb} (d)	M (M_J)	Coordinates (J2000)	Best month	Num. days
Hot Jupiters likely to be tidally locked:							
υ And b	13.49	0.059	4.62	1.4	01^h37^m $+41°24'$	Sep	37
τ Boo b	15.62	0.048	3.31	6.5	13^h47^m $+17°27'$	Mar	43
HD 189733 b	19.45	0.031	2.22	1.13	20^h01^m $+22°43'$	Jun	29
HD 187123 b	48.26	0.042	3.10	> 0.51	19^h47^m $+34°25'$	Jun	31
HD 209458 b	49.63	0.047	3.52	0.69	22^h03^m $+18°53'$	Aug	32
Hot Jupiters less likely to be tidally locked:							
55 Cnc b	12.34	0.116	14.65	> 0.84	08^h53^m $+28°20'$	Dec	30
ρ CrB b	17.24	0.226	39.84	> 1.06	16^h01^m $+33°18'$	Apr	30
70 Vir b	17.99	0.484*	116.69	> 7.46	13^h28^m $+13°47'$	Mar	30
HD 195019 b	38.52	0.137	18.20	> 3.58	20^h28^m $+18°46'$	Jun	30
HD 114762 b	38.65	0.363*	83.89	>11.68	13^h12^m $+17°31'$	Mar	30
HD 38529 b	39.28	0.131*	14.31	> 0.86	05^h47^m $+01°10'$	Nov	30
HD 178911 Bb	42.59	0.345*	71.48	> 7.29	19^h09^m $+34°36'$	Jun	30
HD 37605 b	43.98	0.261*	54.23	> 2.86	05^h40^m $+06°04'$	Nov	30

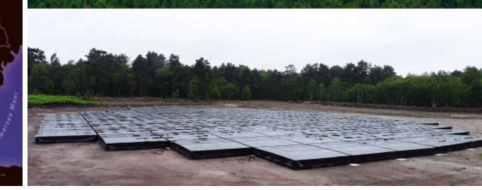
* Sources with eccentricities greater than 0.1.

LWA Long Wavelength Array

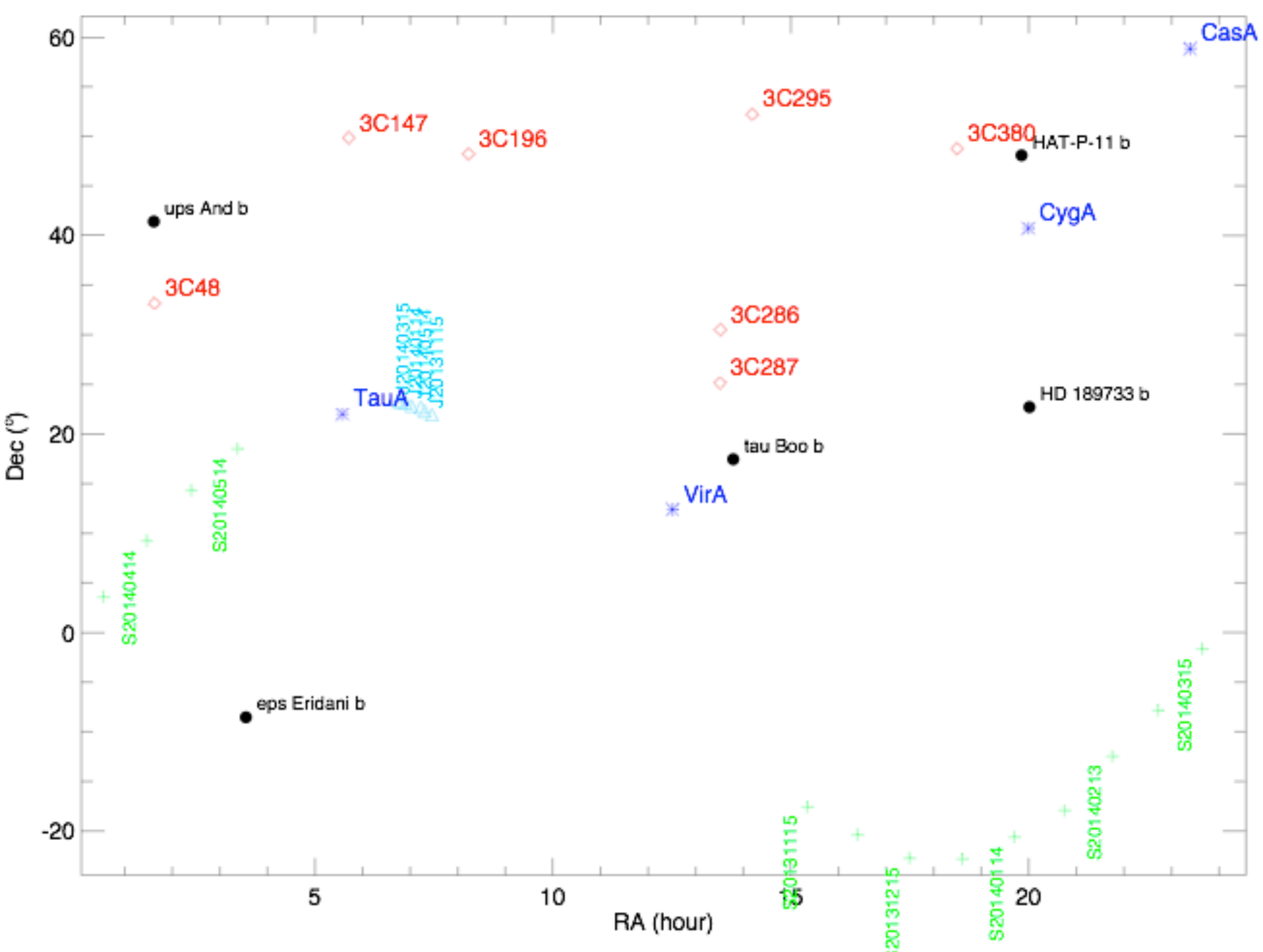
- Observations with LOFAR, 26-62 MHz, imaging + TAB

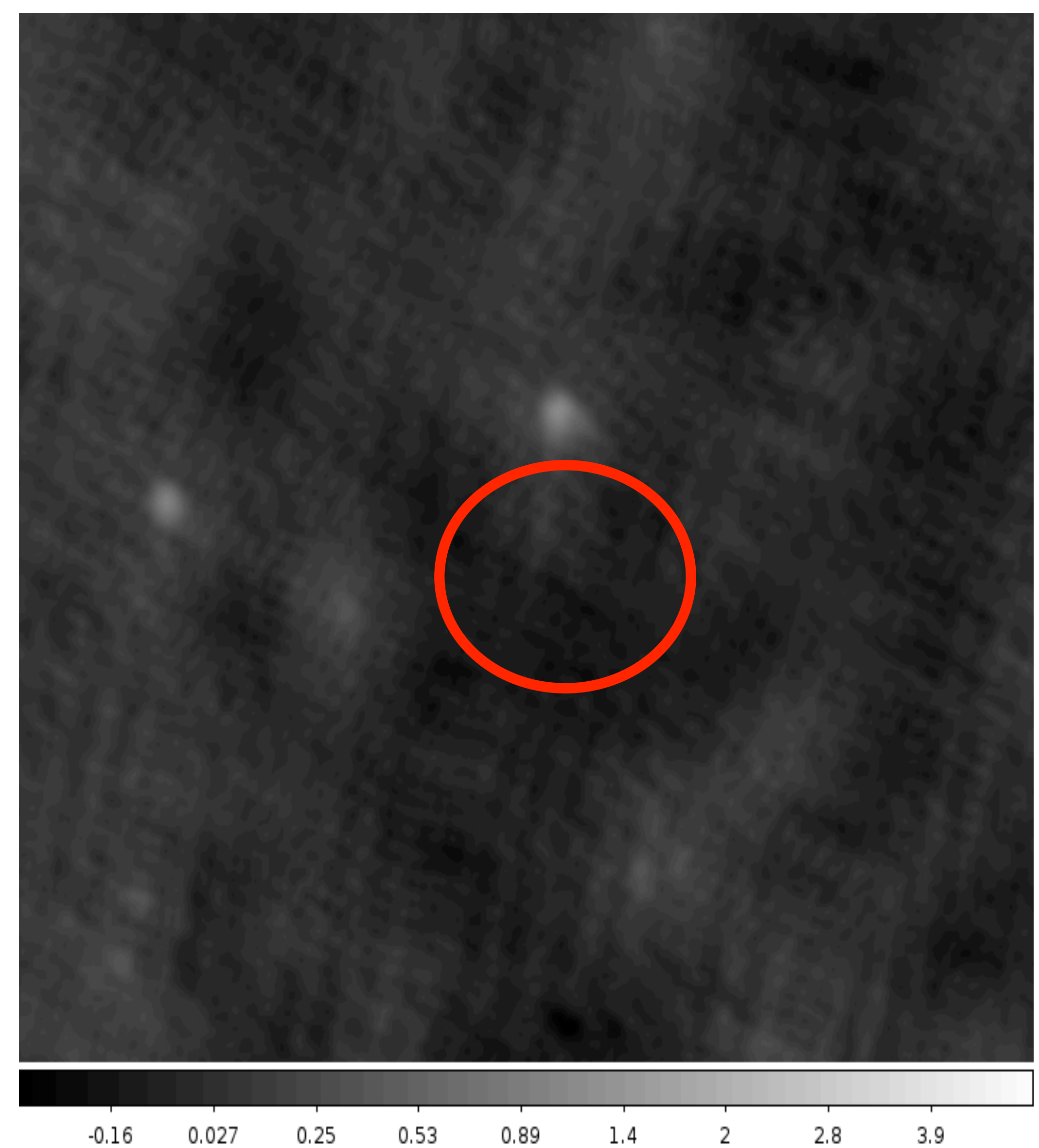
[Zarka et al.]

→ 5 targets observed 30h in cycle 0



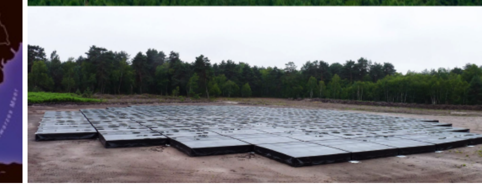
UPS AND, 2013-02-27, 2h, 1SB @ 56 MHz : image = 4096x4096 pixels (5") = 6° x 6°
(u,v) ≤ 5000 wavelengths, CSclean (CASA)



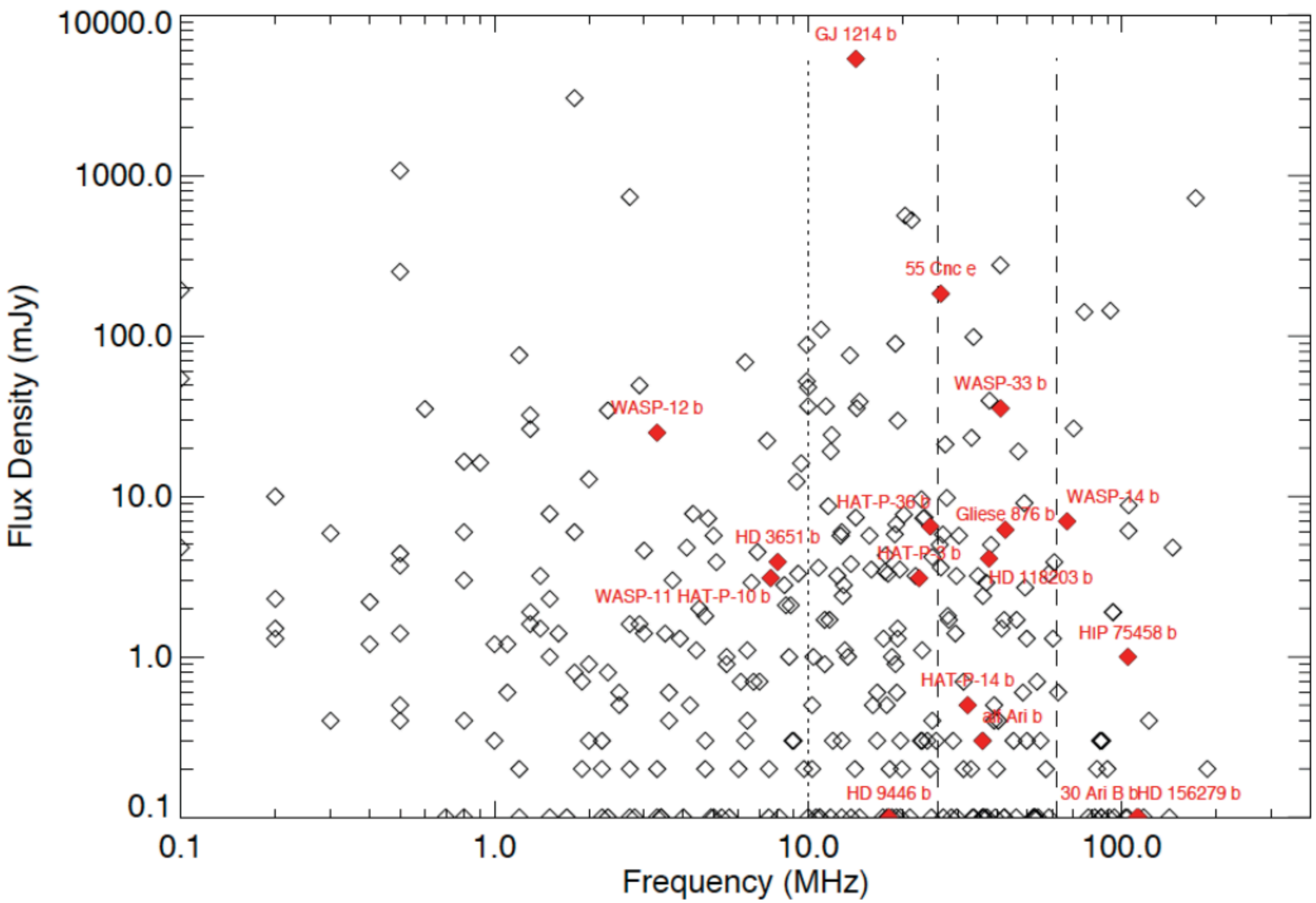


- Observations with LOFAR, 26-62 MHz, imaging + TAB

[Zarka et al.]



→ 17 targets to be observed 17h in cycle 1



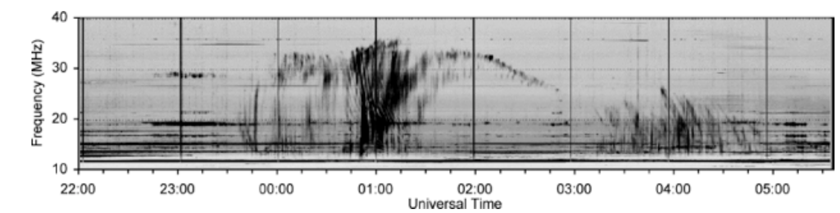
NEXT ?

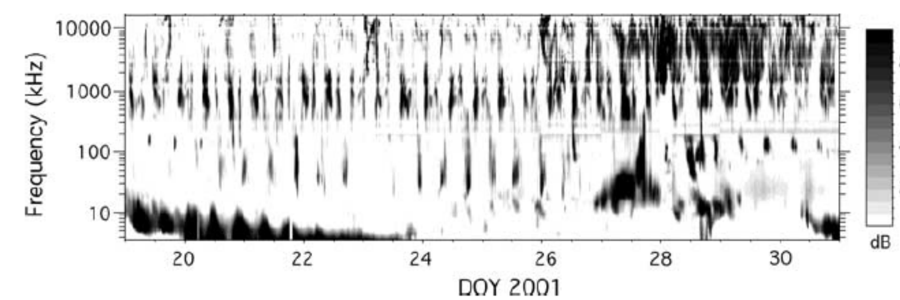
LOFAR :

- Search for transients, « naïve approach » : Images (t), Visibilities (t)
- Search for transients : less naïve approach : FT (image pixels),

Compressed Sensing ⇒ (2D + t) sparse recovery

- Circular / Full polarization





- 1000's candidates
- Time variability due to narrow beaming / visibility
- Need to observe large sample at low frequencies (< 100 MHz)

  to overcome geometrical selection effects ⇒ long duty-cycles

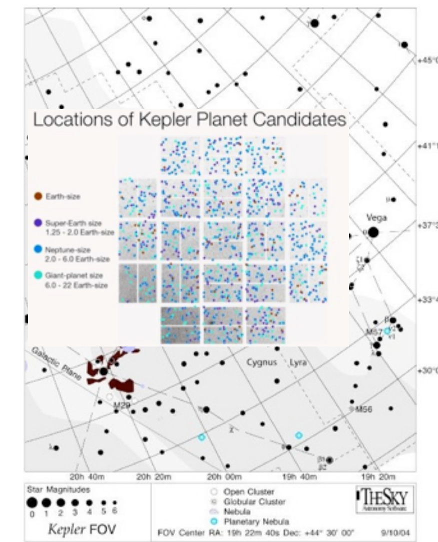
- Commensal observations

OLWA

- all sky LWA

NenuFAR :

- In standalone mode, compact array with very high sensitivity
- 10-88 MHz bandwith, 2 full-band beams + 256 pixels maps within a broad FoV $(8°-60°)^2$



- National instrument ⇒ possibility of very high duty-cycles

  (e.g. Kepler field)

  (including observations in // with LOFAR)

- Very high FoM for exoplanet search

Radio Array	Freq. range (MHz)	Effective area (m^2)	N polar.	% of obs. time	Figure of Merit (FoM)	Field of View ($°^2$)	Resolution
UTR-2 (2040 dipoles)	10-32	~143 000	1	5-10%	157-315	0.25 - 7	30’
VLA 27 dishes (25 m Ø)	73-74.6	~2 000	2	1-5%	<1	68	25"
GMRT 30 dishes (45 m Ø)	149-157	~30 000	2	1-2%	5-10	5	20"
LOFAR low : 48 stations × 48/96 dip.	30-80	100 000 – 14 000	2	5%	180 (60)	10-300	5"-0.9"
LOFAR high : 48 st. × 48/96 × 16 dip.	110-250	70 000 – 20 000	2	5%	180 (60)	4-30	0.6"-0.3"
LSS 48 × 19 dipoles	15-85	47 000 – 4 000	2	20%	384	70-2000	3.8°-0.7°

- Possible synergies with complementary instruments : LF radio (UTR-2, GURT, OLWA), ZD spectropolarimetry (cf. above), UV-X * luminosity …

SKA-LOW

→ Must significantly improve / LOFAR (if no detection)

• Jupiter decameter emission @ 10 pc peaks at ~25 μJy (sec - min timescale) / 3 μJy (hour timescale), (x20 if planet at ~ 1 AU)

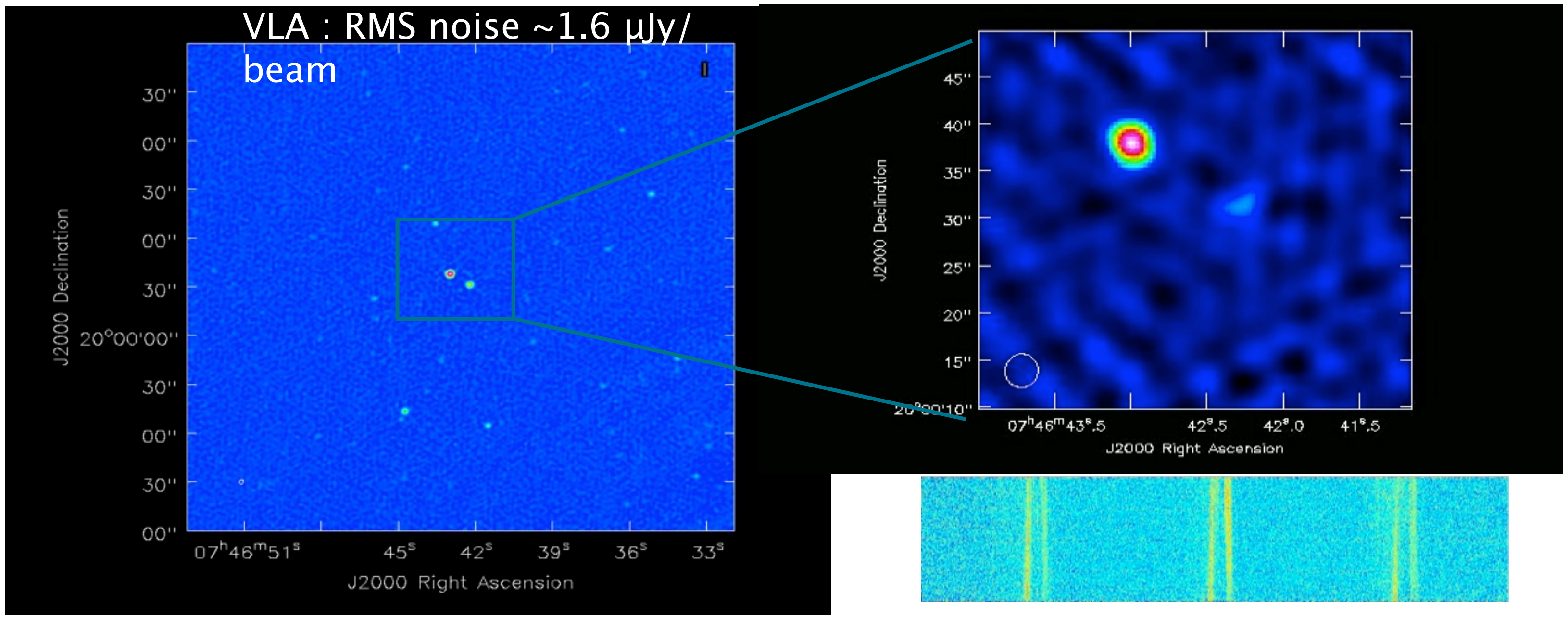
• SKA-low sensitivity: mJy - 10's μJy at timescales from sec to hours
→ no more need of scaling laws, ~Jupiter detectable at 10s of pc

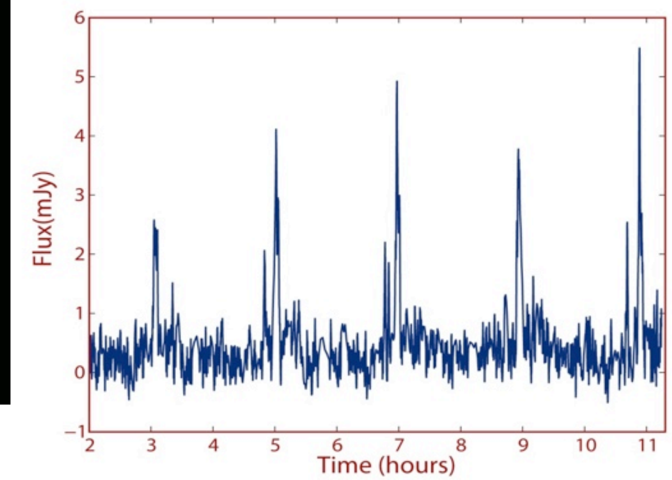
• SKA-low baseline design essentially Ok: broad freq. range ≥50 MHz, broad instantaneous coverage, full polar, 50-100 km baselines, radio quiet site (multi-beam capability ?)

FAST ?

LOFAR on the Moon ?

• Synergies with white / brown / cool dwarfs & flaring stars studies (cf. above)

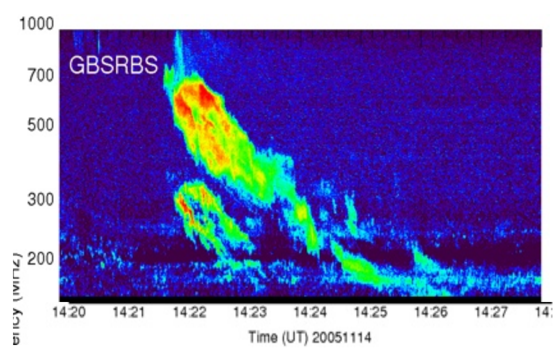


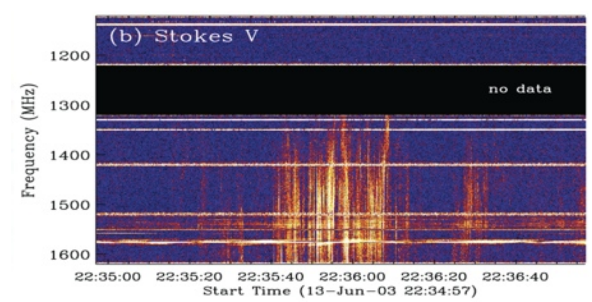


[Hallinan et al., 2007, 2008]

→ Brown dwarfs pulses discovered at GHz frequencies

→ Periodic pulses (~2 h), 100% circularly polarized, $T_B > 10^{15}$ K, |B| ~2 kG





[Osten, Hallinan, et al.]

- from dwarfs to planets (X, H-alpha, T, rotation, transition to stable B geometries)
- lower mass planets more frequent around M dwarfs (habitable?)
- stellar bursts (~type II/III), cause planetary auroras, atmospheric loss
- similar obs. techniques and emission levels (star-planet discrimination via orbital period & polarization)

THIS IS POTENTIALLY A HIGH VISIBILITY HIGH «RETURN» SUBJECT ...