Exoplanet searches in Radio (I) : theory & searches with UTR2, GMRT and LOFAR

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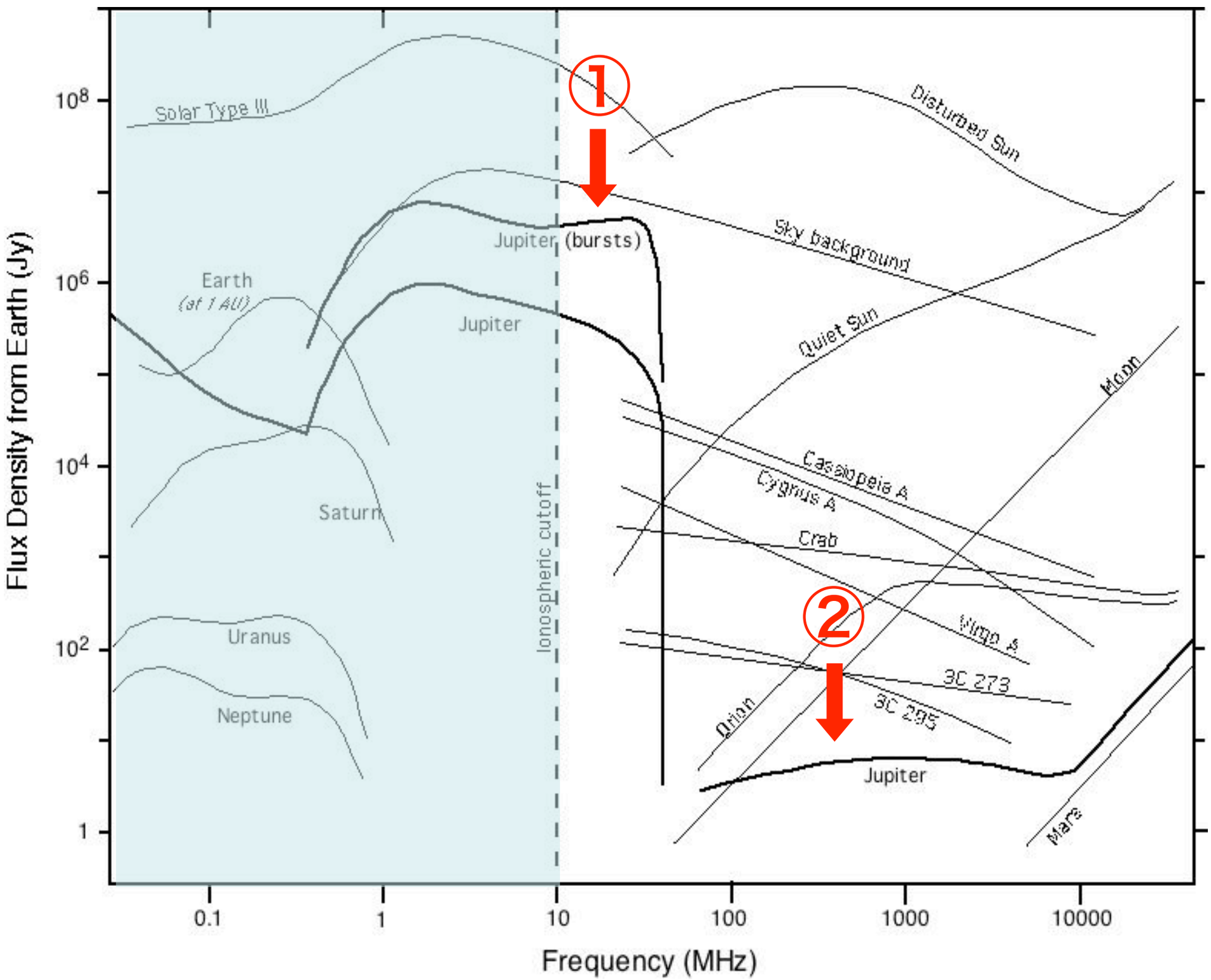
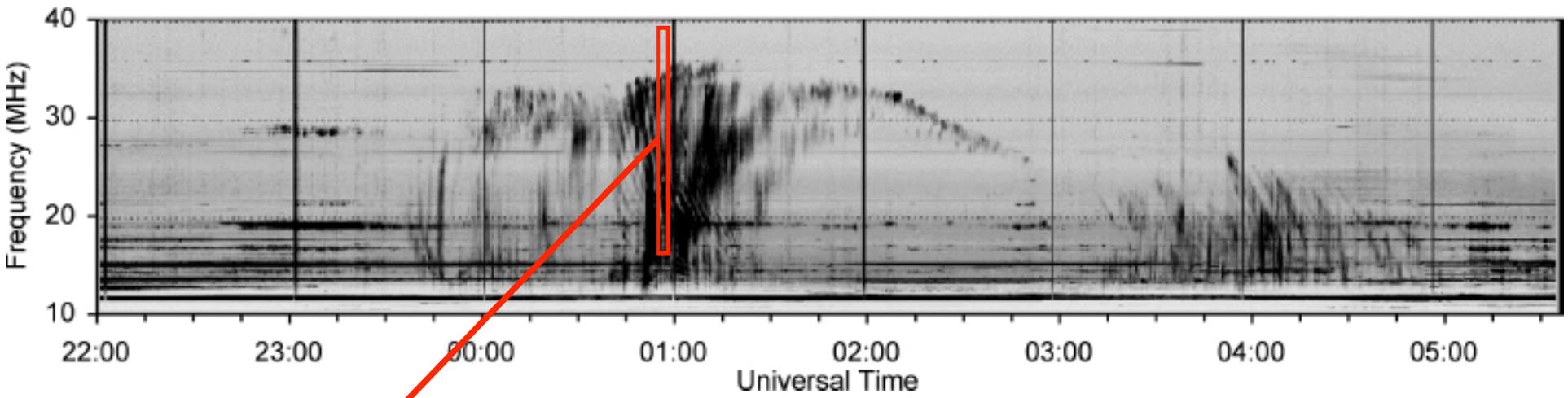
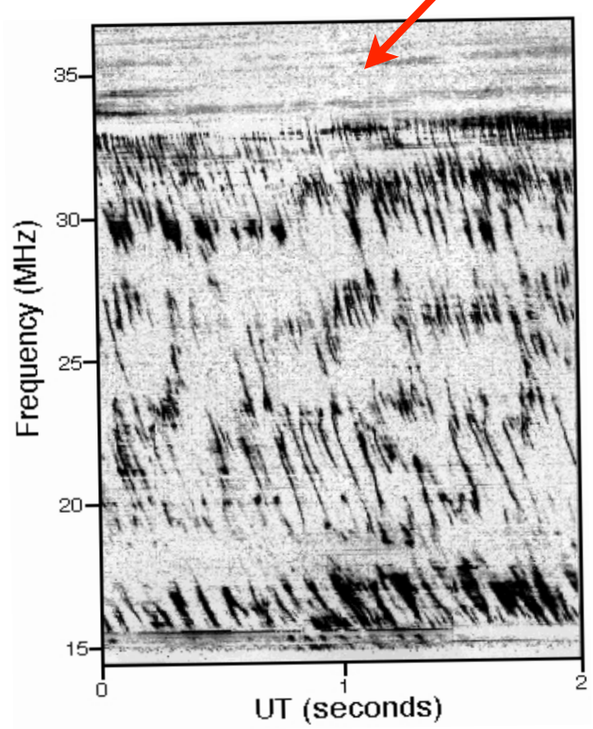
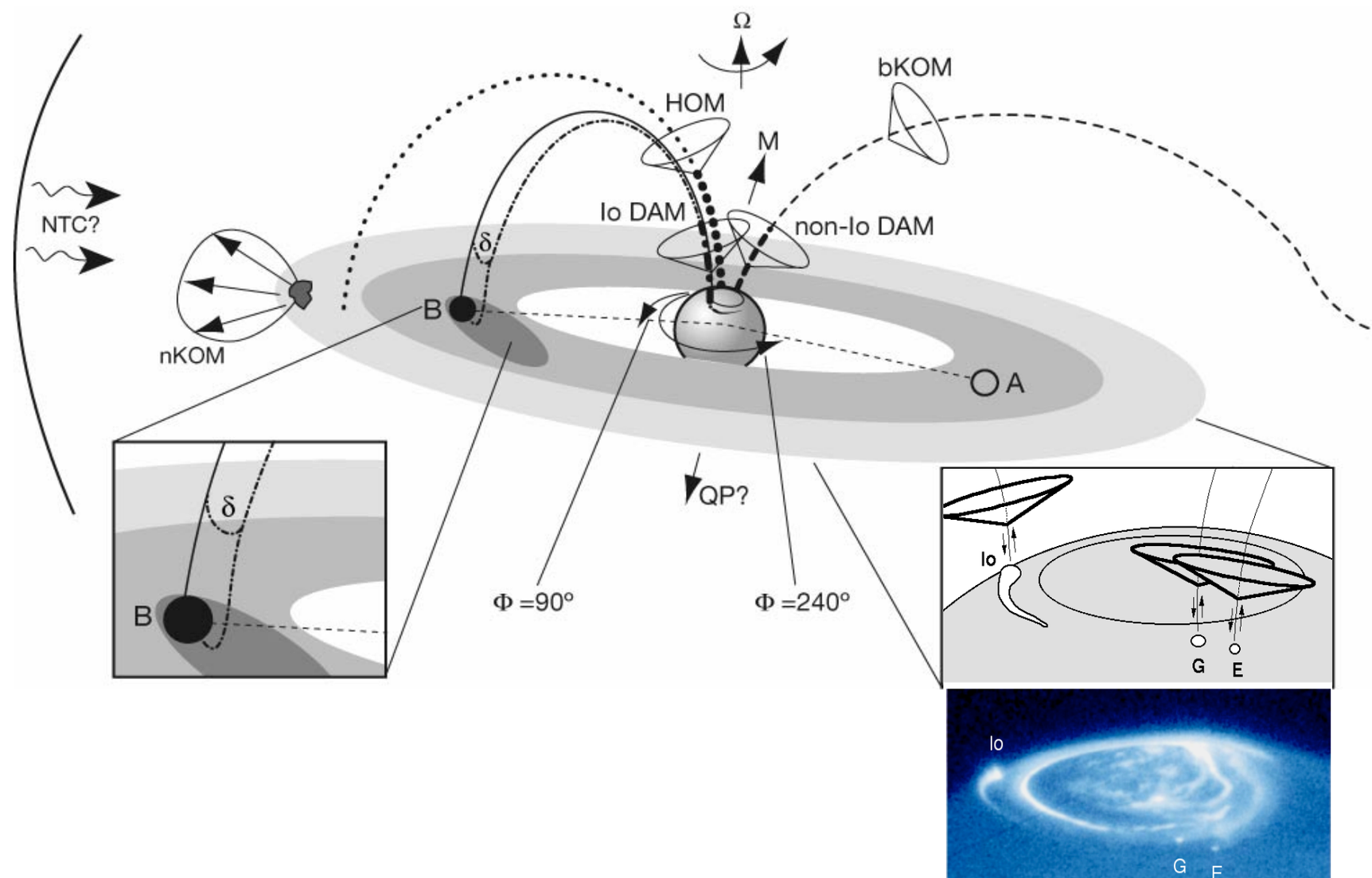
- Jupiter LF radio emission are intense



① Decameter-wave magnetospheric (auroral & satellite-induced) emissions





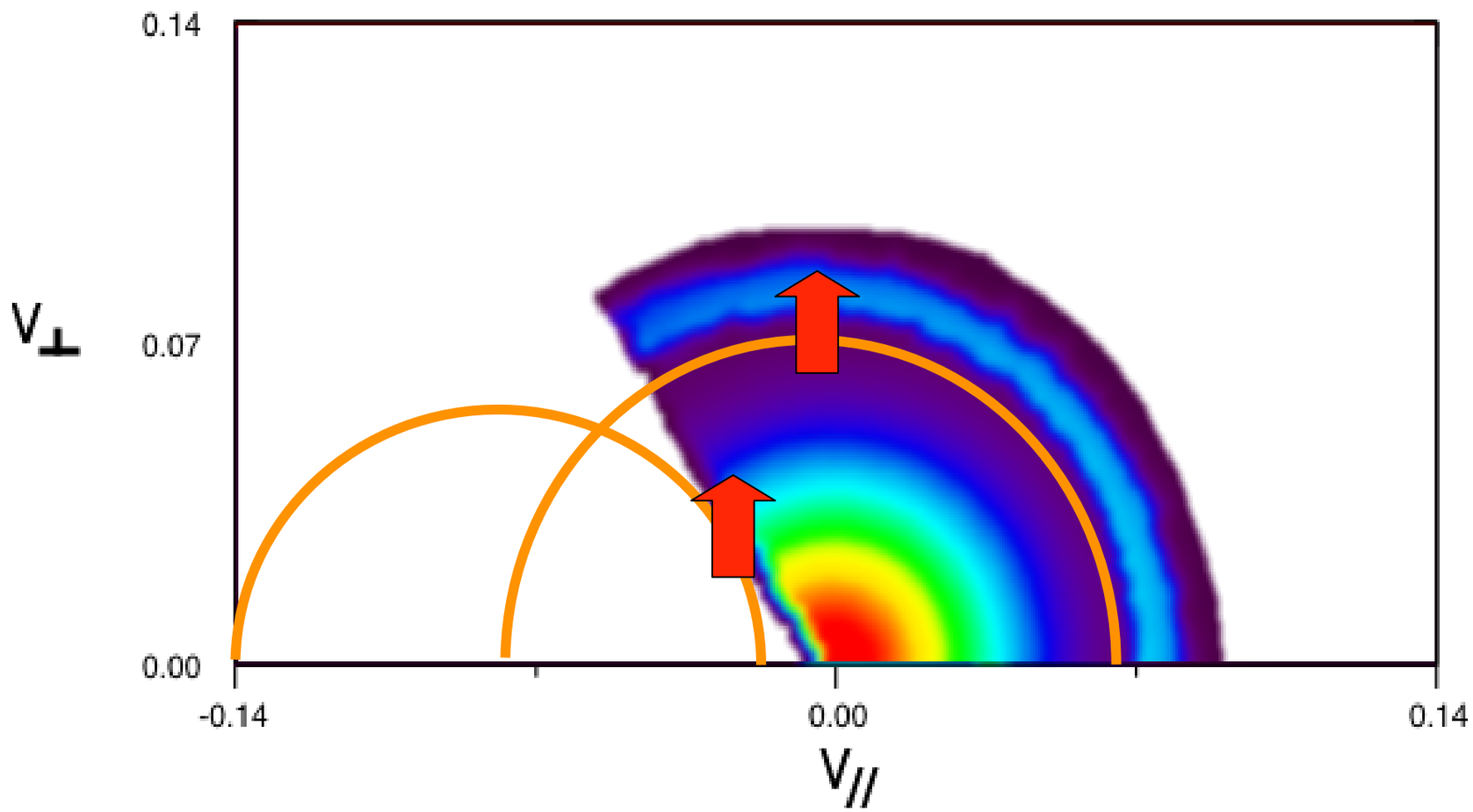


① Decameter-wave magnetospheric (auroral & satellite-induced) emissions

→ attributed to Cyclotron-Maser Instability (CMI)

Resonance condition : $\omega = \omega_c/\Gamma - k_{\|} v_{\|}$

Growth rate : $\gamma = \frac{\omega_p^2 c^2}{8\omega_c} \int_0^{2\pi} v_\perp^2(\theta) \nabla_{v_\perp} f(\mathbf{v}_0, \mathbf{R}(\theta)) d\theta$



[Wu, 1985 ; Treumann, 2006 ; Hess et al., 2008]

→ Sources where strong B, $f_{pe} << f_{ce}$, non Maxwellian keV e-

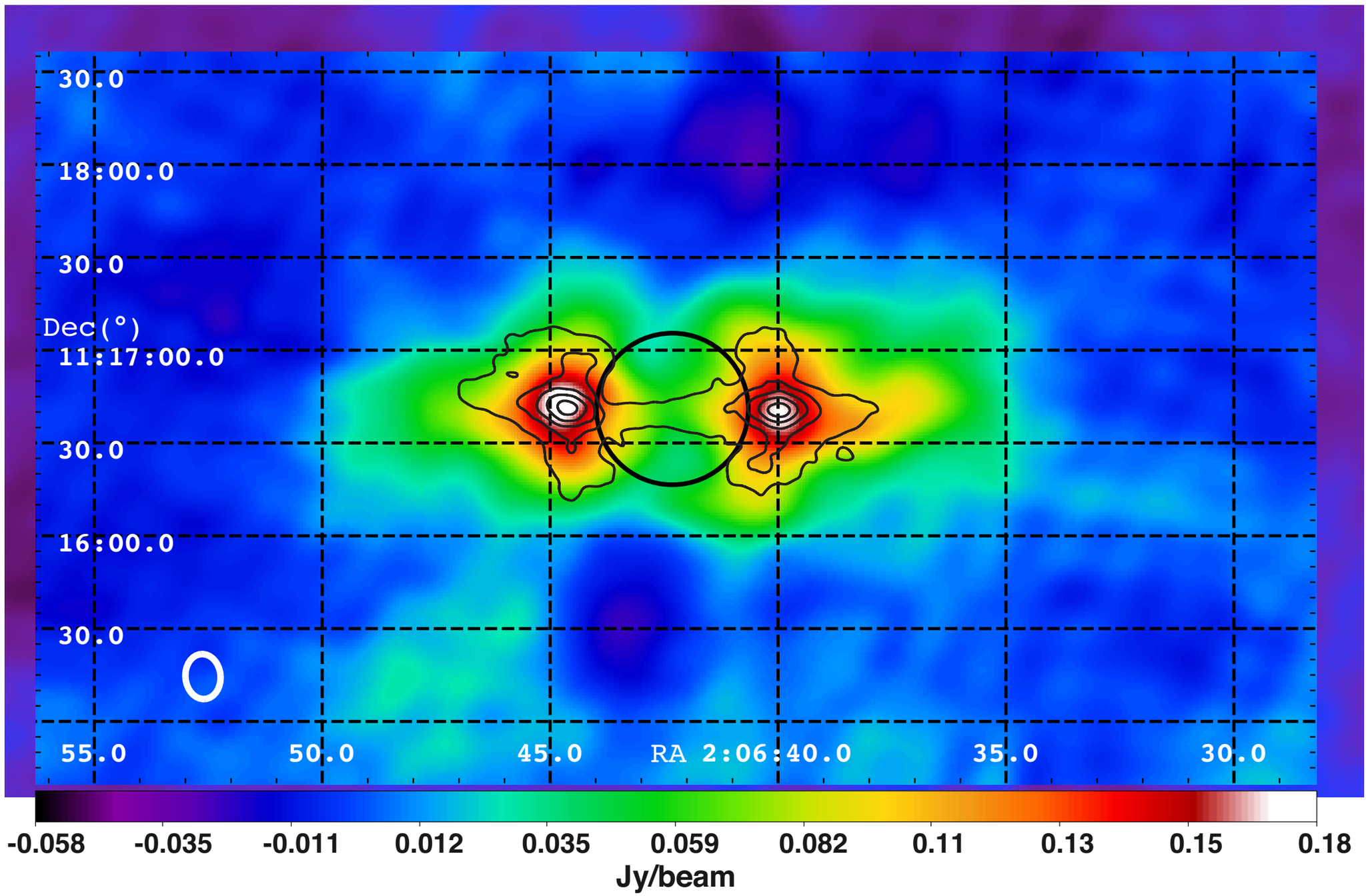
→ high T_B, 100% circularly polarized, narrow beaming, fine structures

② Decimeter emission from the radiation belts : synchrotron

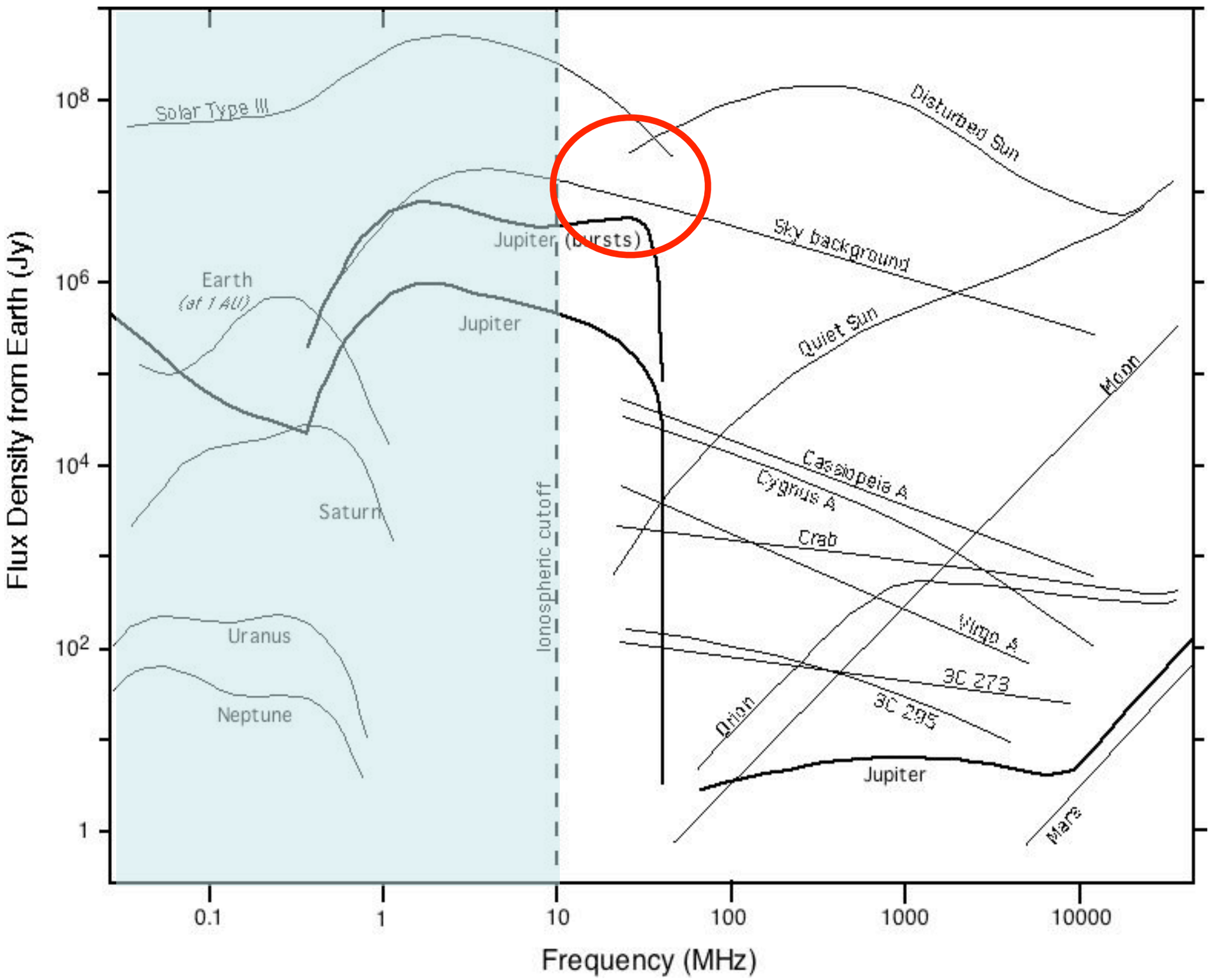
LOFAR : Δf = 127-172 MHz, Δt = 7h, Beam = 17.8”x15.5”, Pixel = 1", Jupiter disk = 49’‘

[Girard et al., 2013]

Contours : VLA @ 15 GHz [de Pater & Dunn, 2003]



- Jupiter-Sun contrast favourable at LF radio (CMI >> plasma emission)



→ radio search = natural idea, but ...

- Intense sky background + RFI + ionosphere → difficult !

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

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

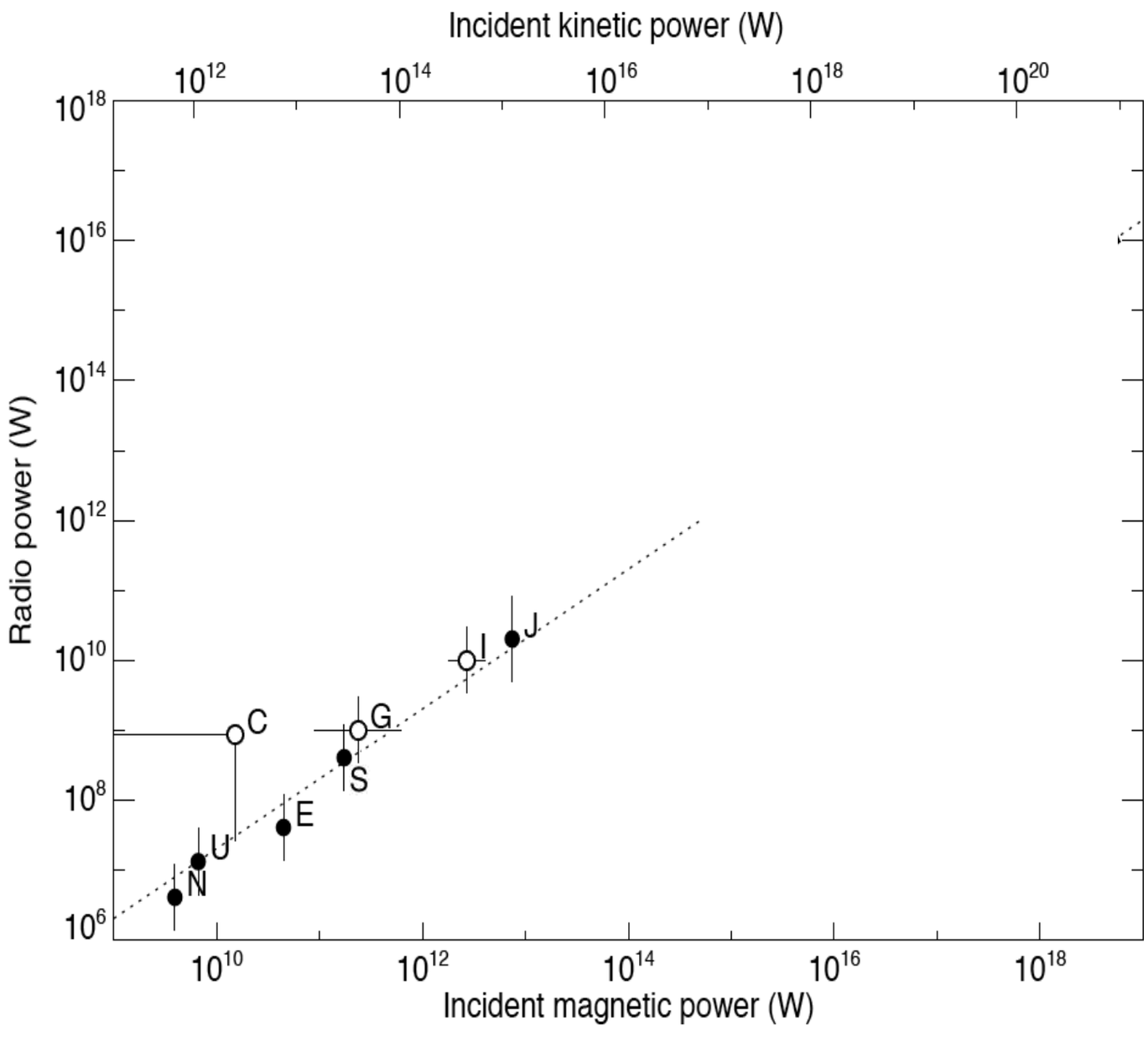
$\zeta = 1$	$b\tau = 10^6$ (1 MHz, 1 sec)		$b\tau = 2\times10^8$ (3 MHz, 1 min)		$b\tau = 4\times10^{10}$ (10 MHz, 1 hour)	
	f = 10 MHz	f = 100 MHz	f = 10 MHz	f = 100 MHz	f = 10 MHz	f = 100 MHz
$A_e = 10^4\ m^2$ (~NDA)	0.003	0.05	0.01	0.2	0.04	0.7
$A_e = 10^5\ m^2$ (~UTR-2, LOFAR)	0.01	0.2	0.03	0.6	0.1	2.2
$A_e = 10^6\ m^2$ (~SKA)	0.03	0.5	0.1	2.	0.4	7.

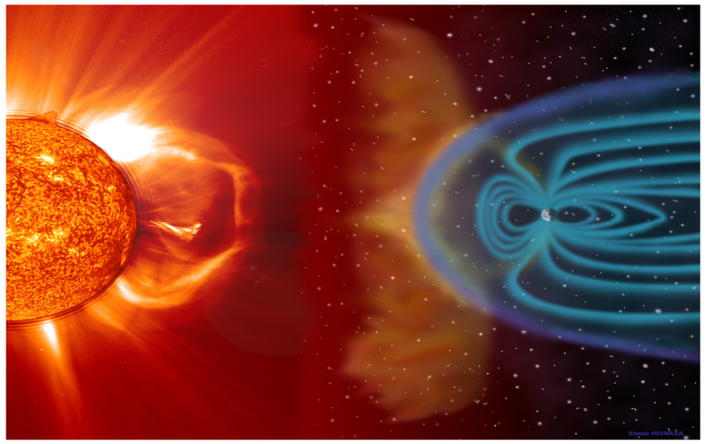
(distances in parsecs)

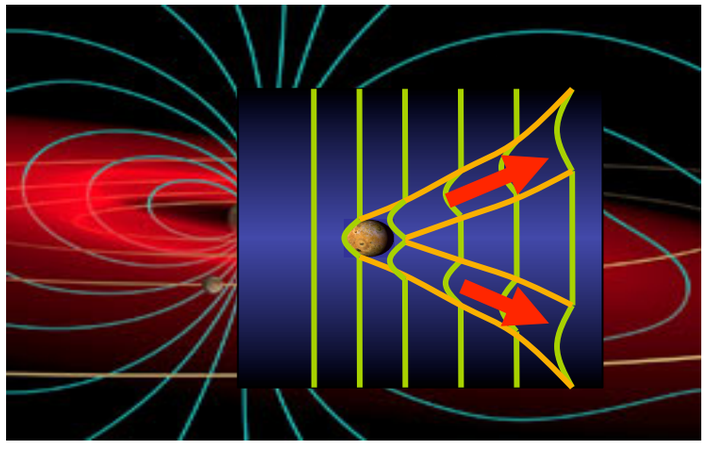
[Zarka et al., 1997]

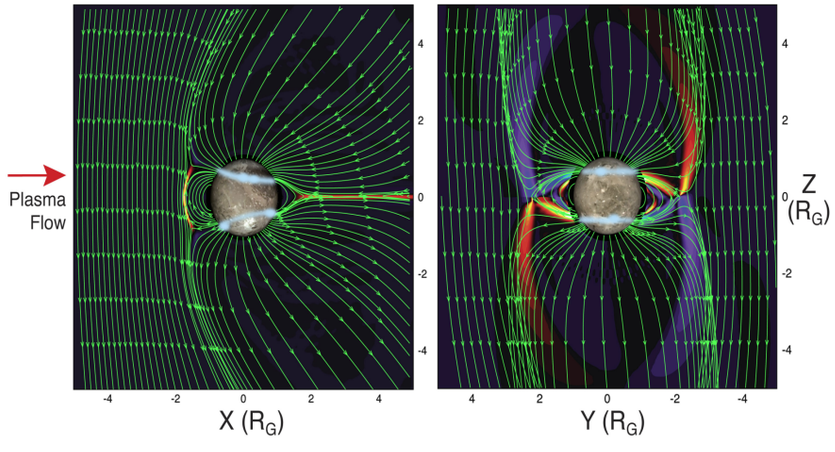
THEORY

- General frame of flow-obstacle interaction in our Solar system (SW-MS & satellite-MS interactions, with magnetized or unmagnetized satellite = dipolar or unipolar interaction)
- Empirical radio-magnetic scaling law with ~constant efficiency $\varepsilon \sim 2\text{-}10 \times 10^{-3}$





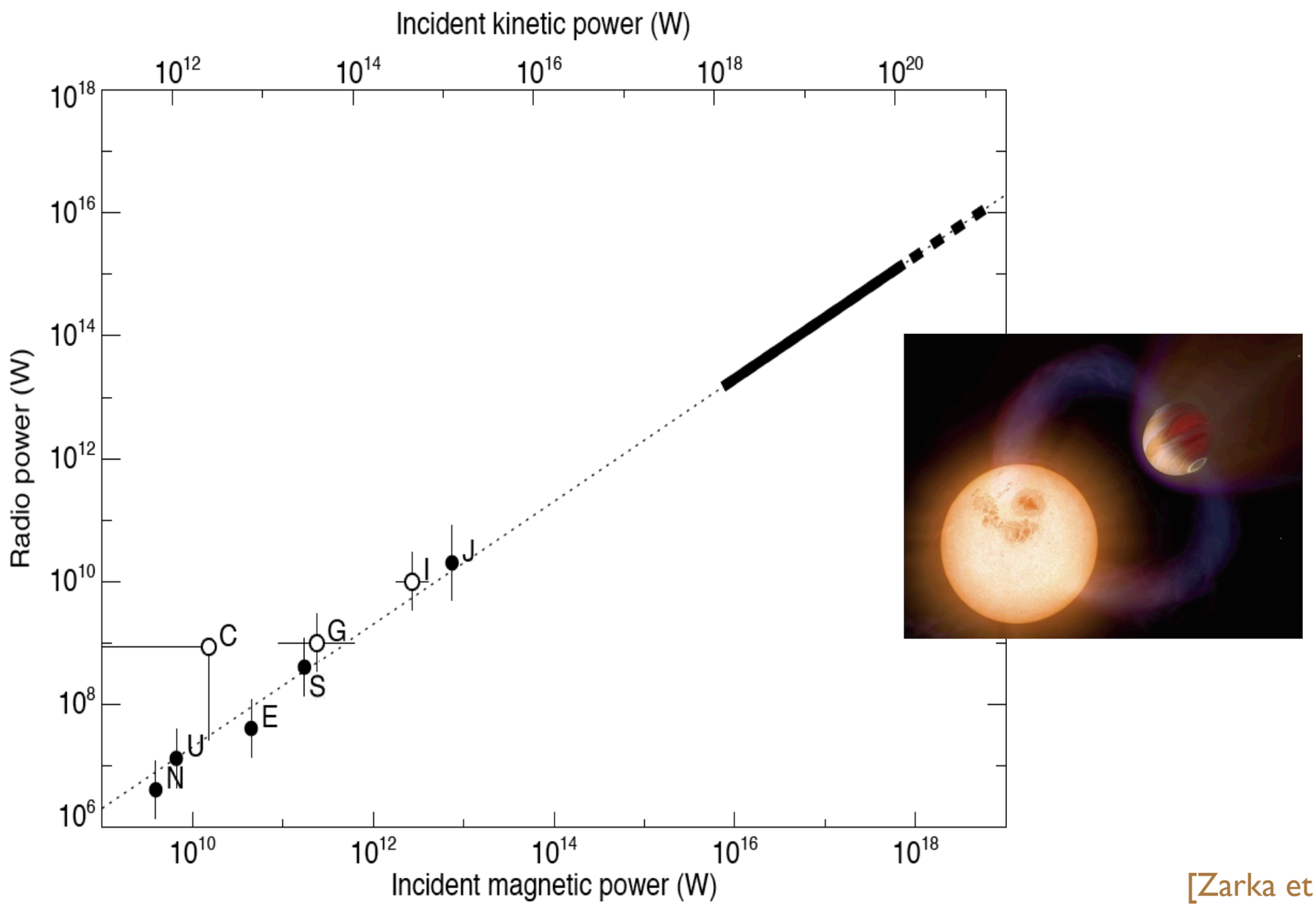




[Zarka et al., 2001 ; Zarka, 2007]

→ 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]

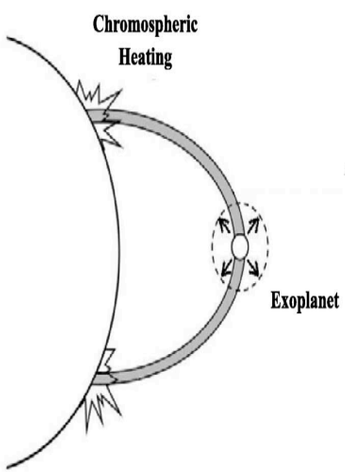
- B decay for spin-orbit synchronized systems ?

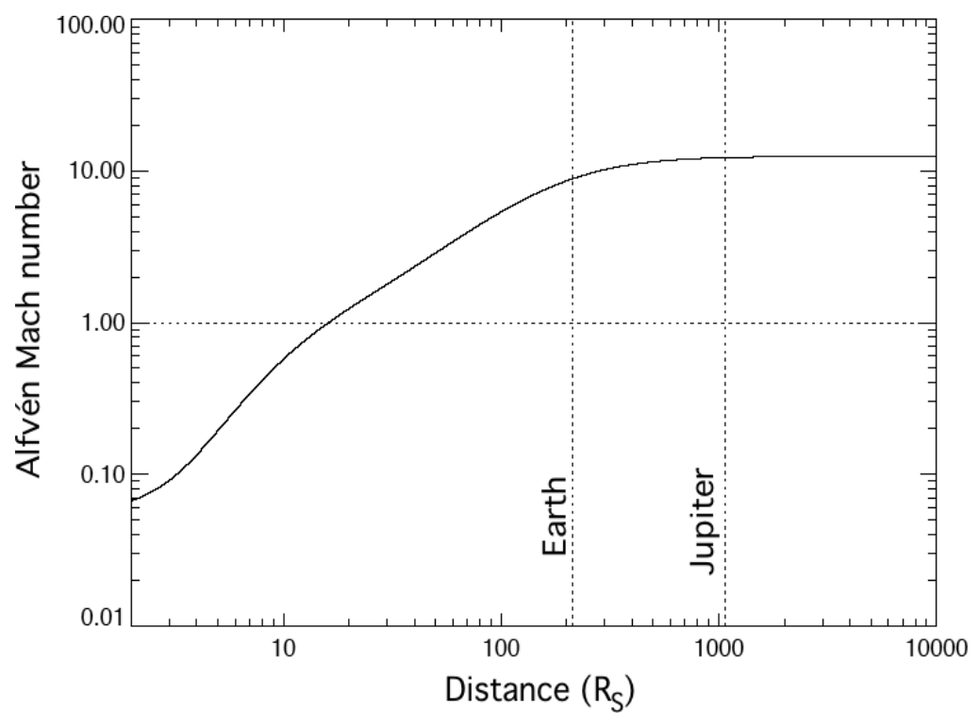
$\mathcal{M} \propto \omega^{\alpha}$ with $\frac{1}{2} \leq \alpha \leq 1$ $\omega\downarrow \rightarrow \mathcal{M}\downarrow$?

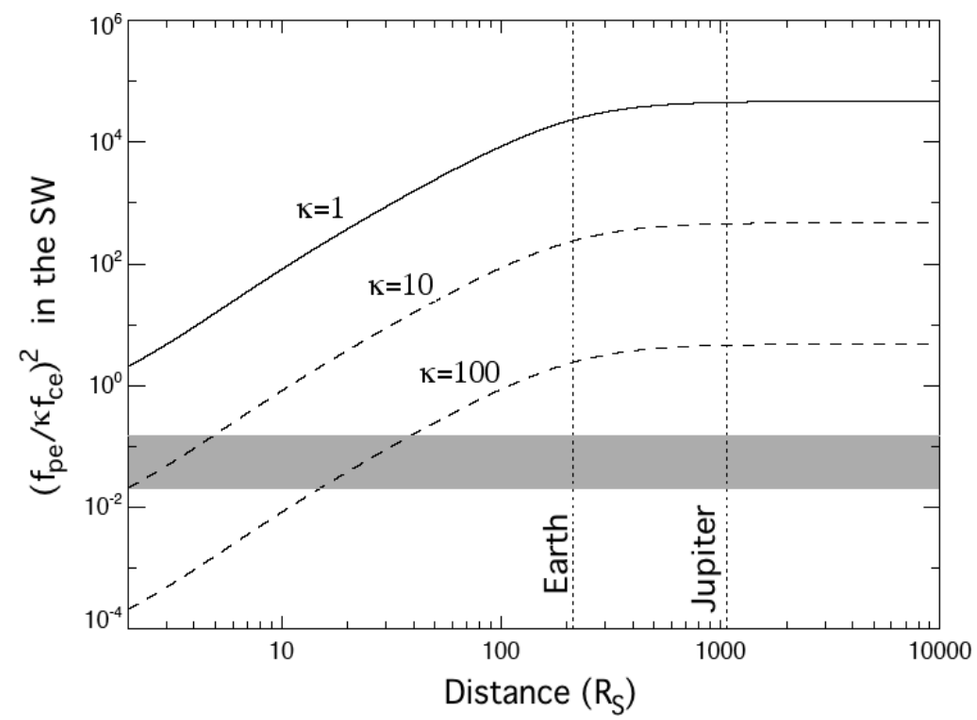
- Internal structure + convection models → self-sustained dynamo

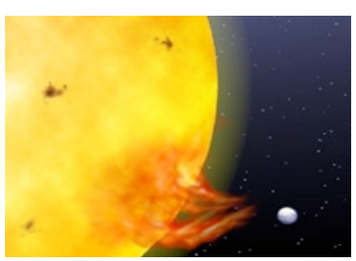
→ $\mathcal{M}$ could remain ≥ a few $G.R_J^3$ [Sanchez-Lavega, 2004 ; Reiners & Christensen, 2010]

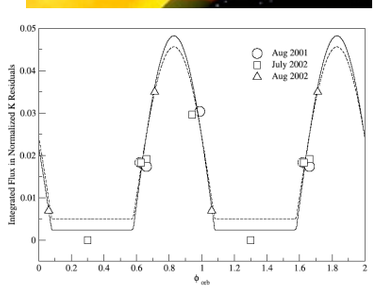
- If no strong planetary B → giant Io-Jupiter-like interaction ? (Unipolar inductor)











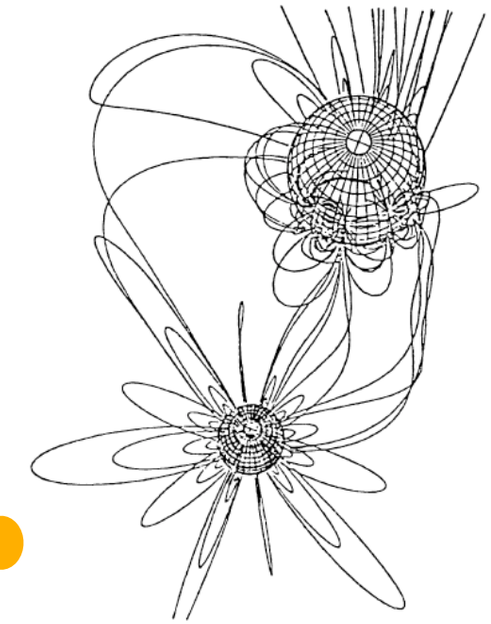
$f_{pe}/f_{ce} << 1$ → B ~ 10-100 B_{sun}

→ emission ≥ 30-300 MHz from 1-2 R_S

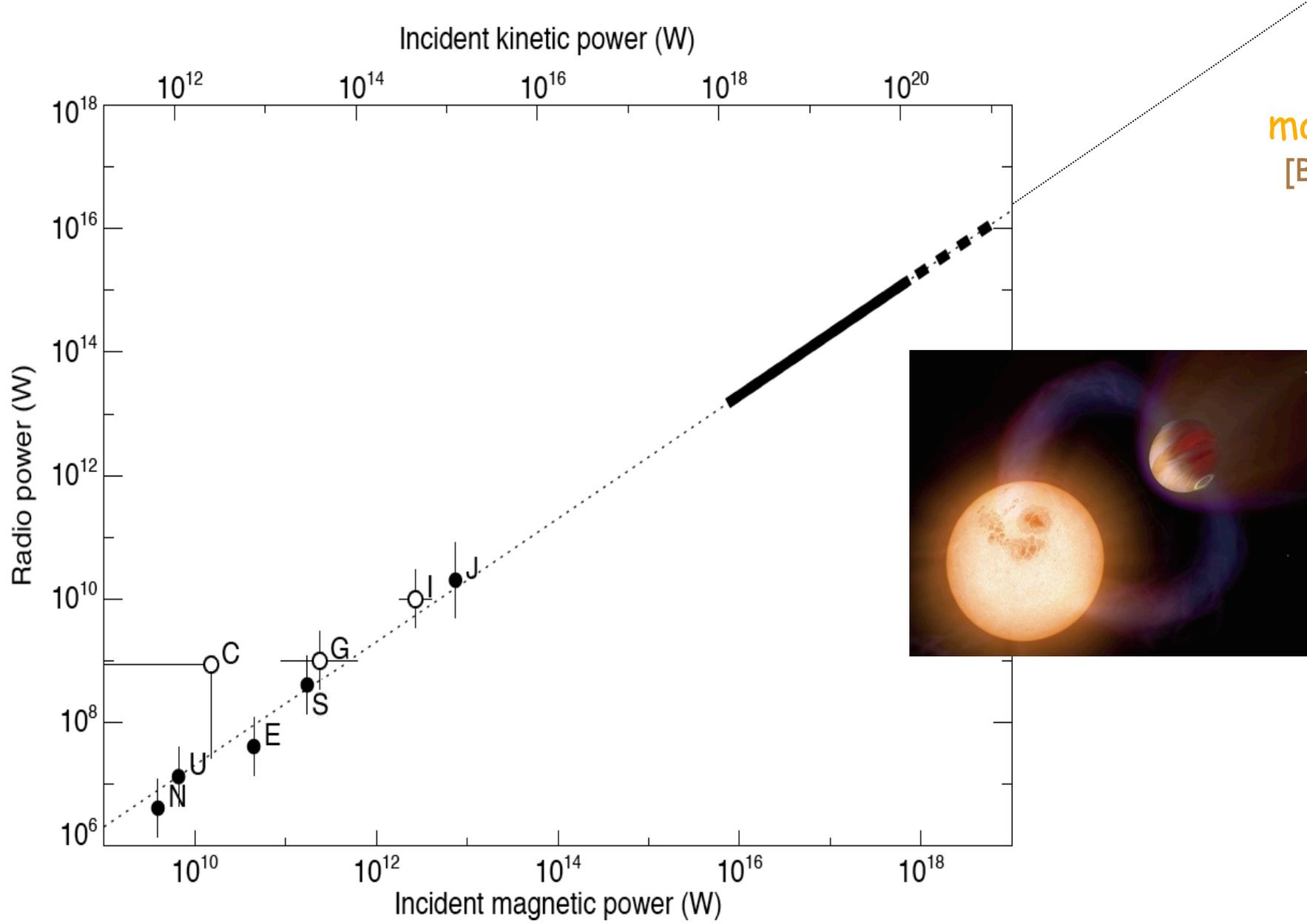
[Shkolnik et al., 2003,2005,2008]

[Zarka, 2007]

- Measurement of an interacting magnetic binary (RS CVn V711 τ [Budding et al., 1998]) compatible with extrapolated scaling law



magnetic binary
[Budding et al., 1998]

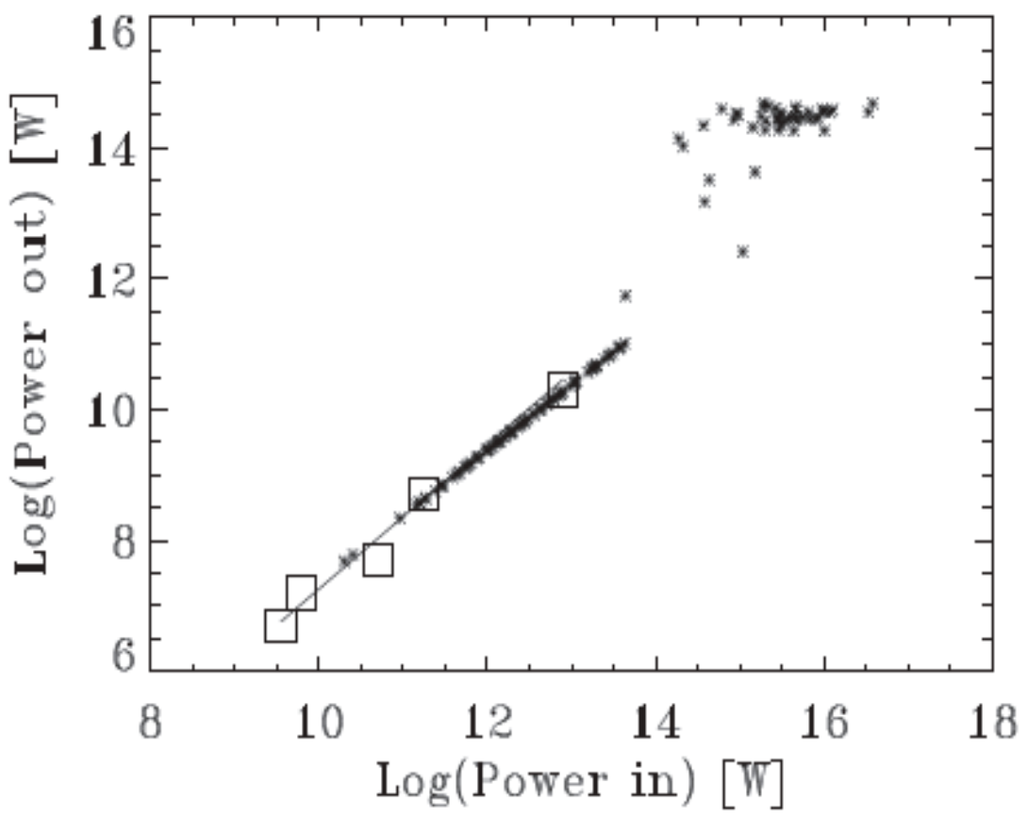


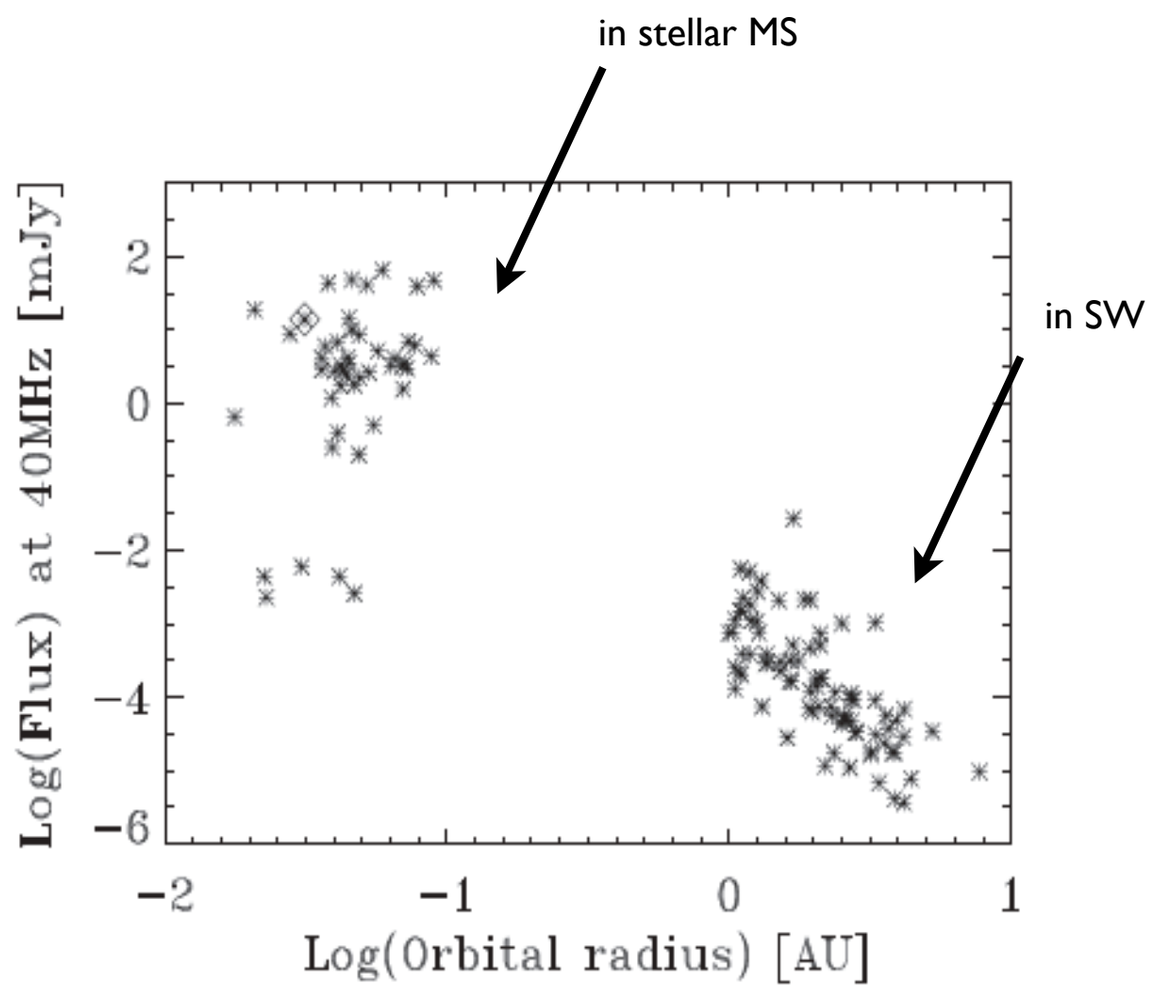
[Zarka, 2010]

- Possible justification of scaling law

Magnetic reconnection and electron acceleration at the magnetopause ?

- Computation of parallel E field (assuming $B_* = 1G$)
- Number and energy of runaway electrons
- Parametrization by "efficiency" η





[Jardine & Cameron, 2008]

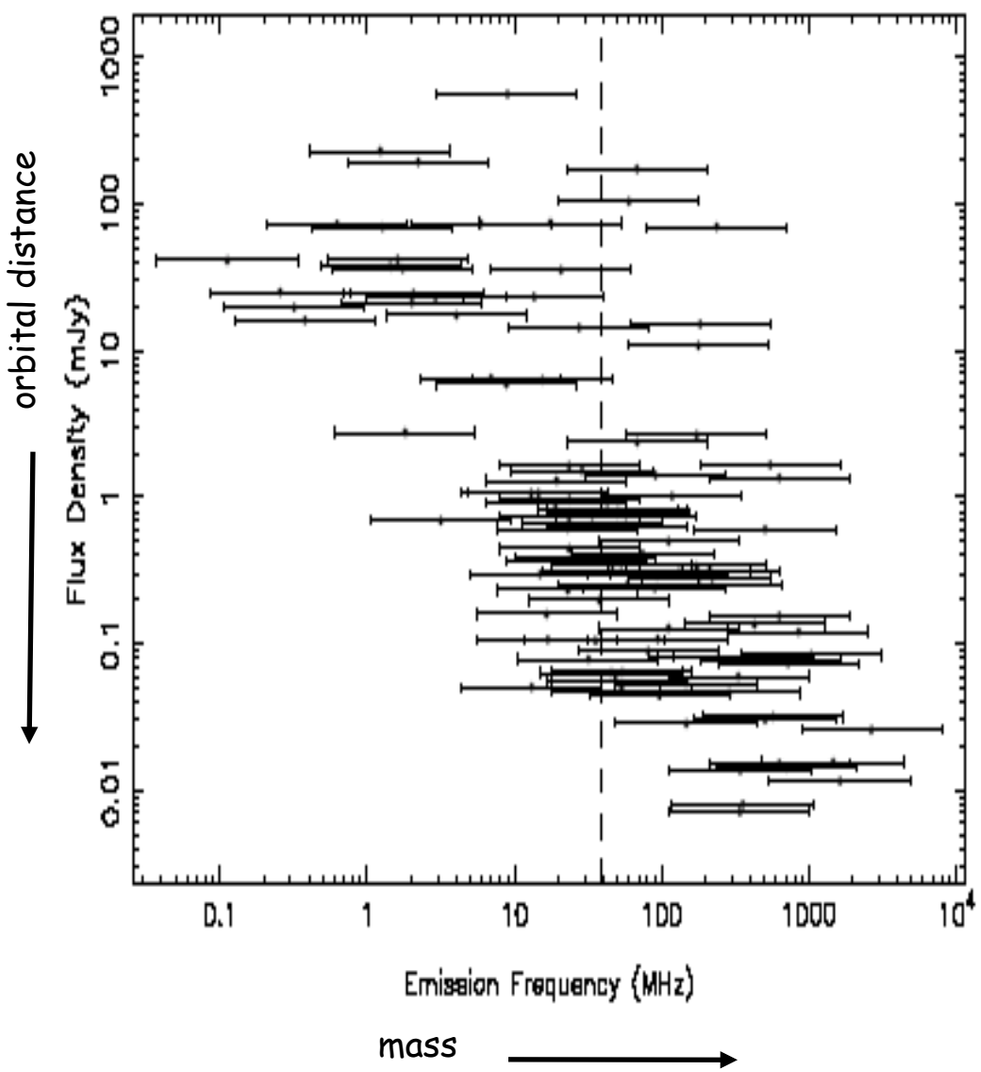
- Maximum distance for Nσ sky-limited detection of a source ζ x Jupiter :

$\zeta = 10^5$	$b\,\tau = 10^6$ *(1 MHz, 1 sec)*		$b\,\tau = 2\times10^8$ *(3 MHz, 1 min)*		$b\,\tau = 4\times10^{10}$ *(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

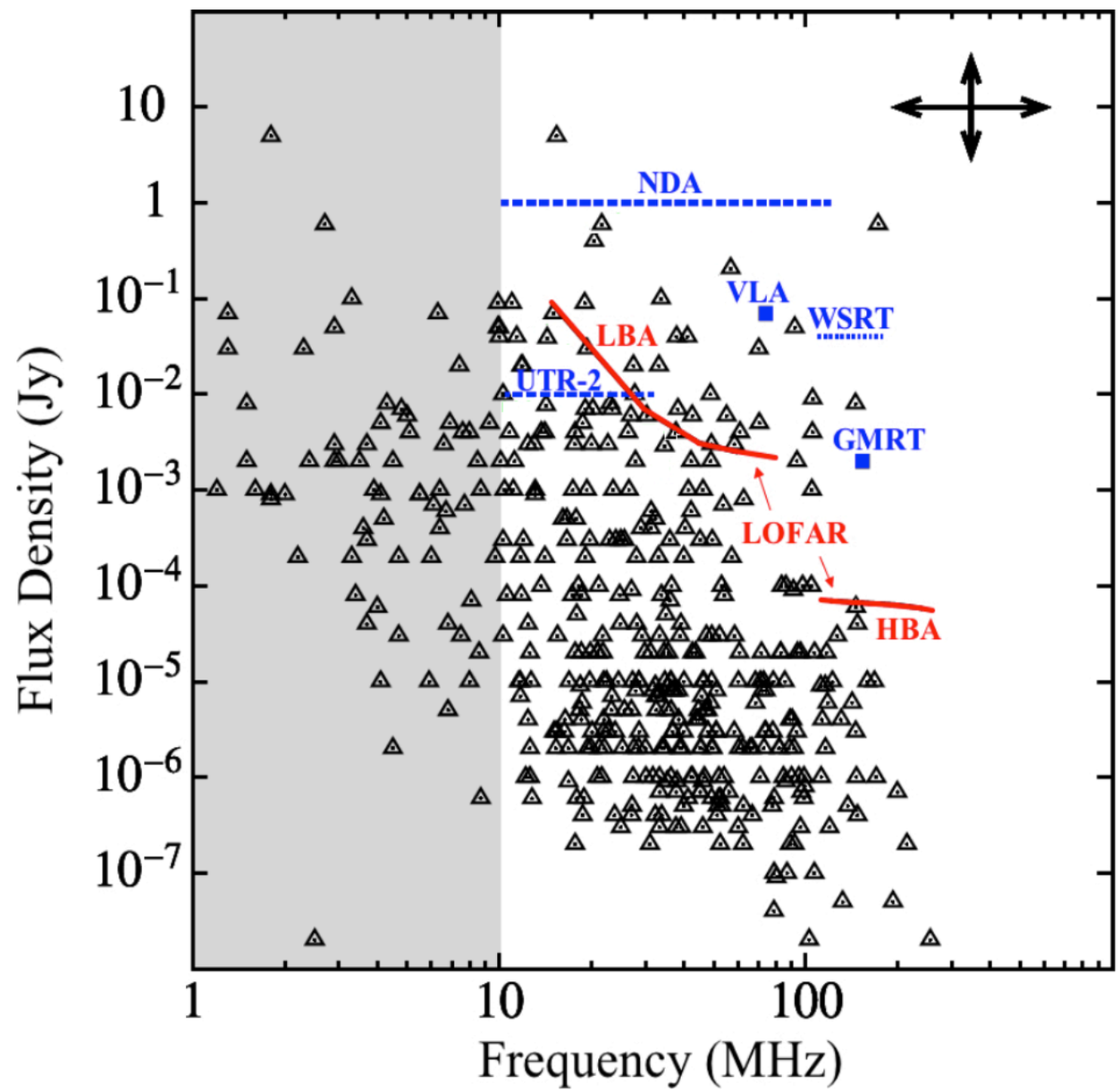
(distances in parsecs)

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

- Application of scaling laws to exoplanet census

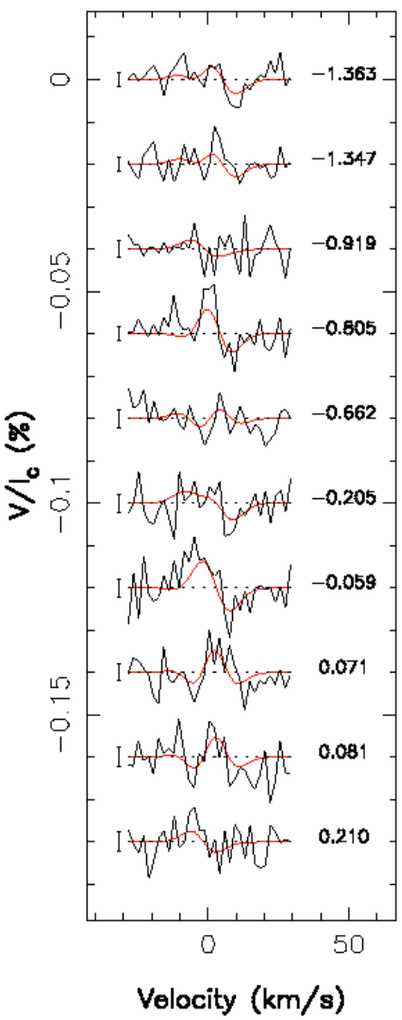


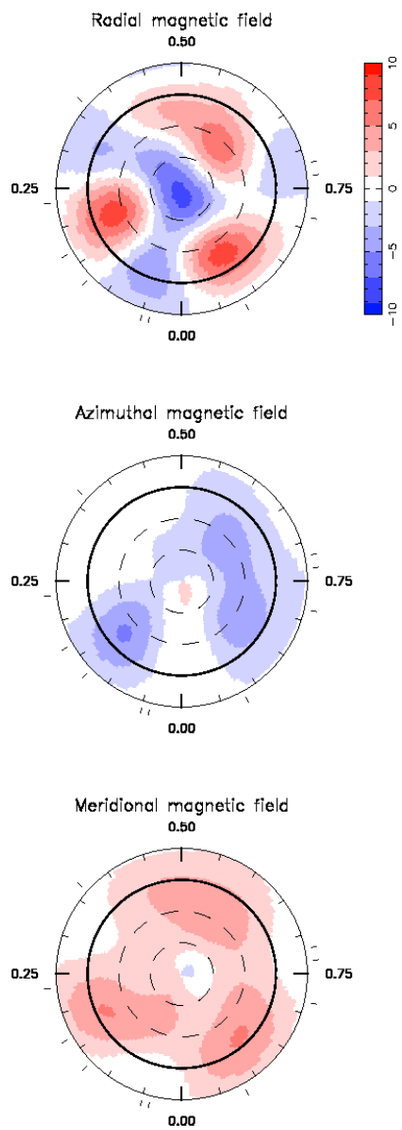
[Lazio et al., 2004]



[Griessmeier et al., 2007, 2011]

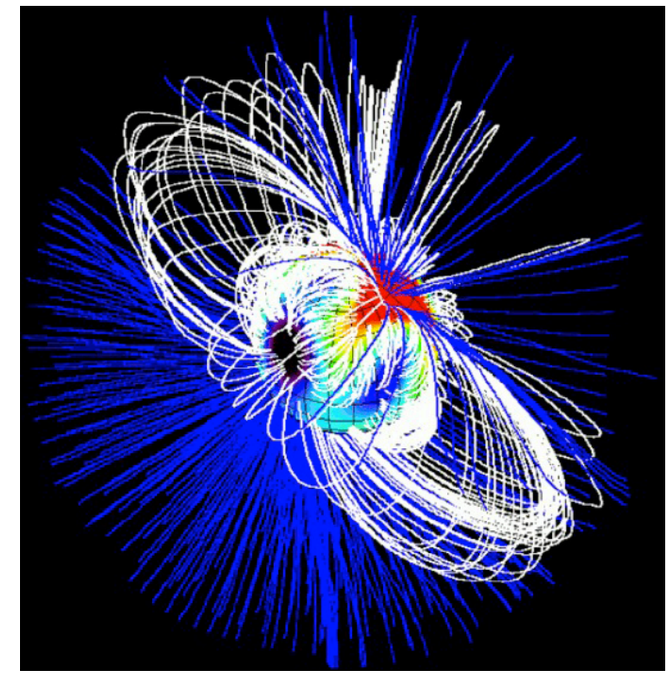
• Stellar B-fields & variable star-planet interaction (SPI)

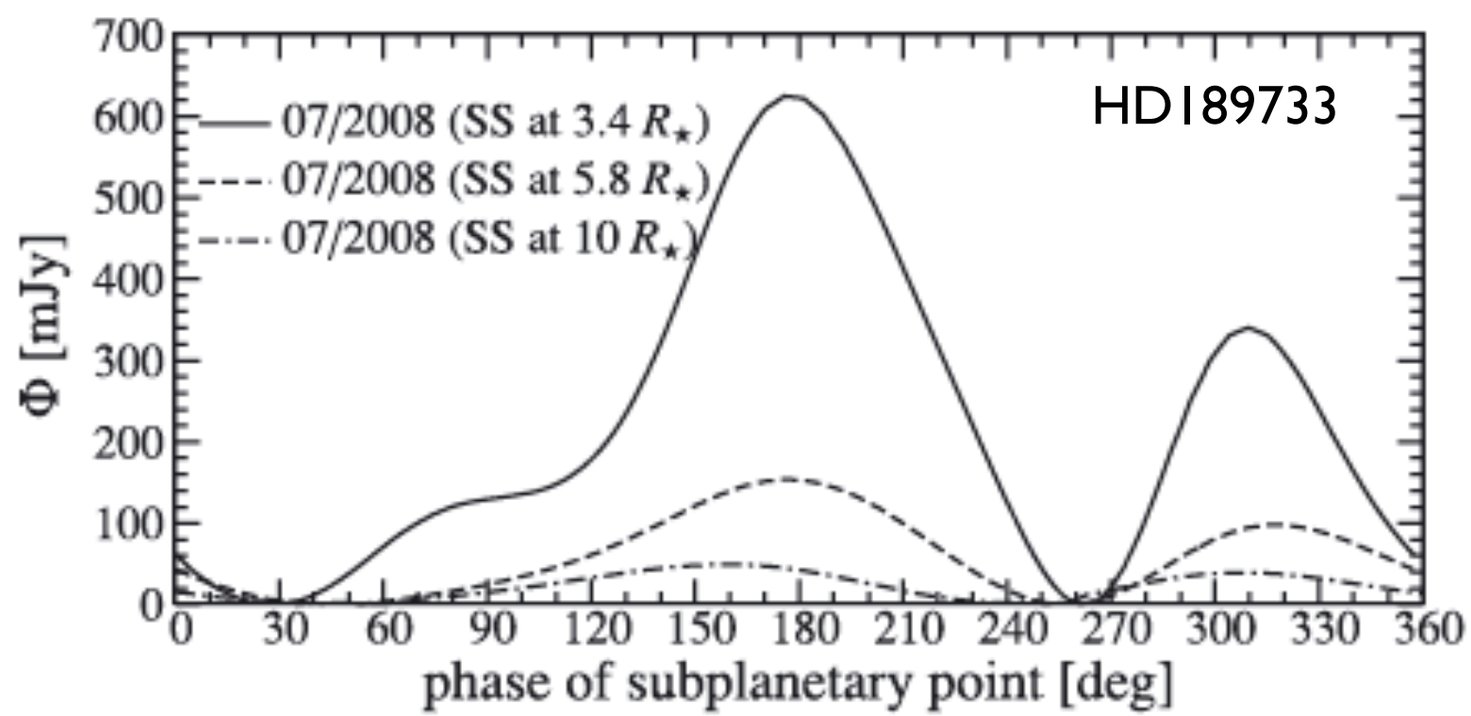




- Solar B field :
→ large-scale ~1 G
→ mag. loops ~10^3 G
(few % of surface)
- Magnetic stars : > 10^3 G

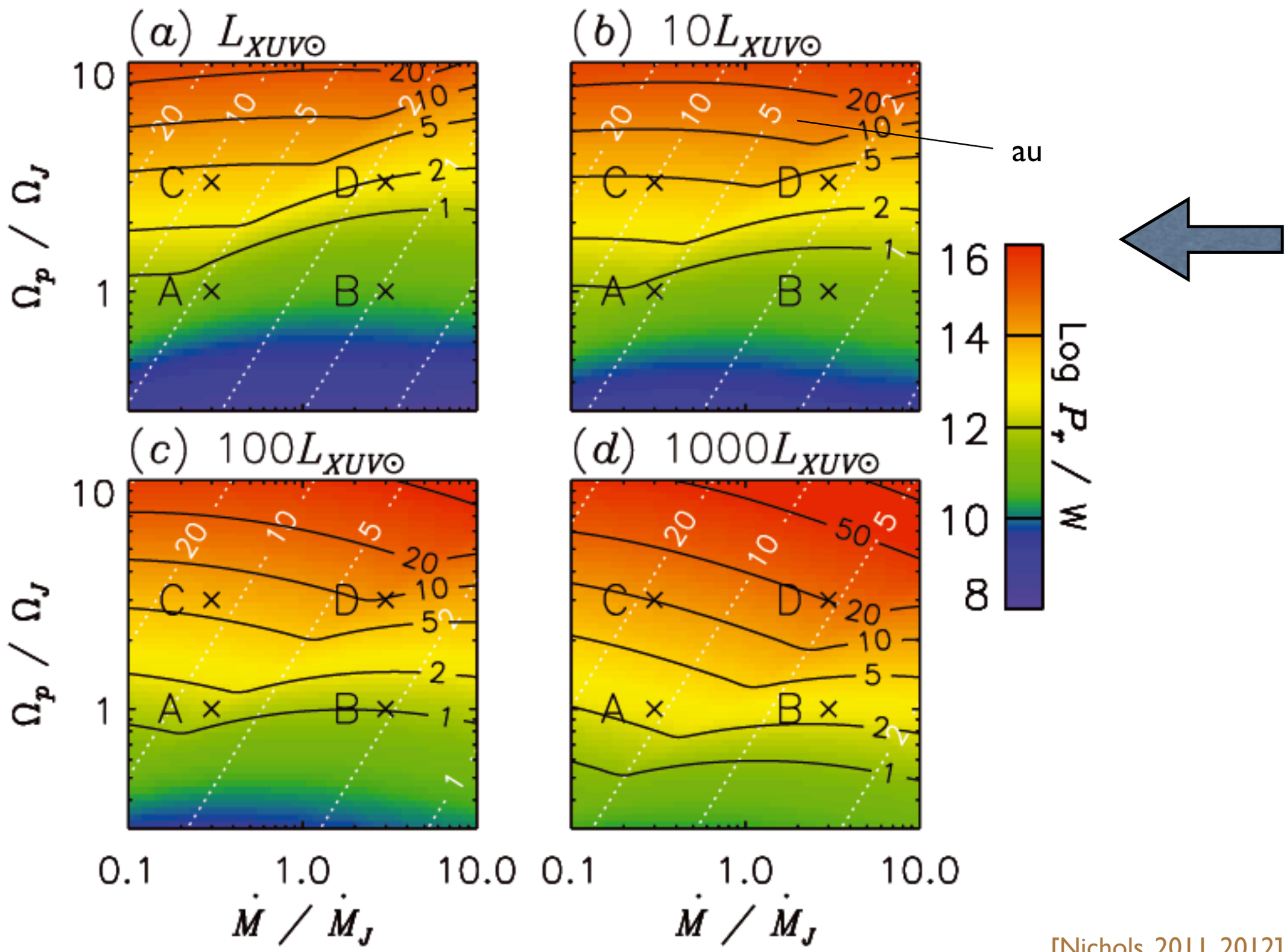
- τ Boo : 5-10 G (10^{-4} T)
- HD 76151 : ~10 G
- HD 189733 : >50 G
- HD 171488 : 500G





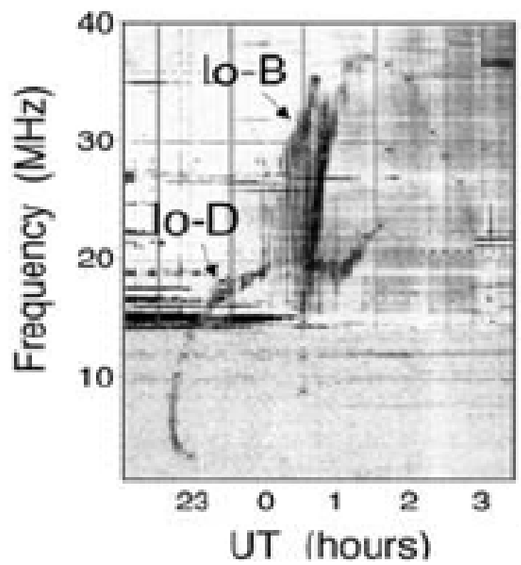
[Farès et al., 2010]

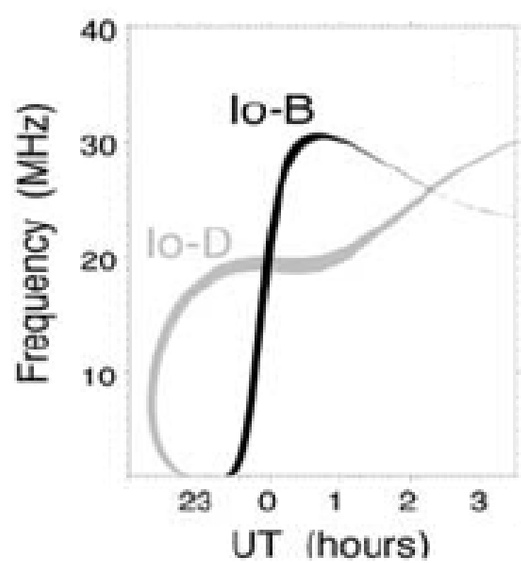
• Internally driven radio emission of normal Jupiters around highly XUV luminous stars → large radio fluxes requires rapid Xo rotation (1-3h)

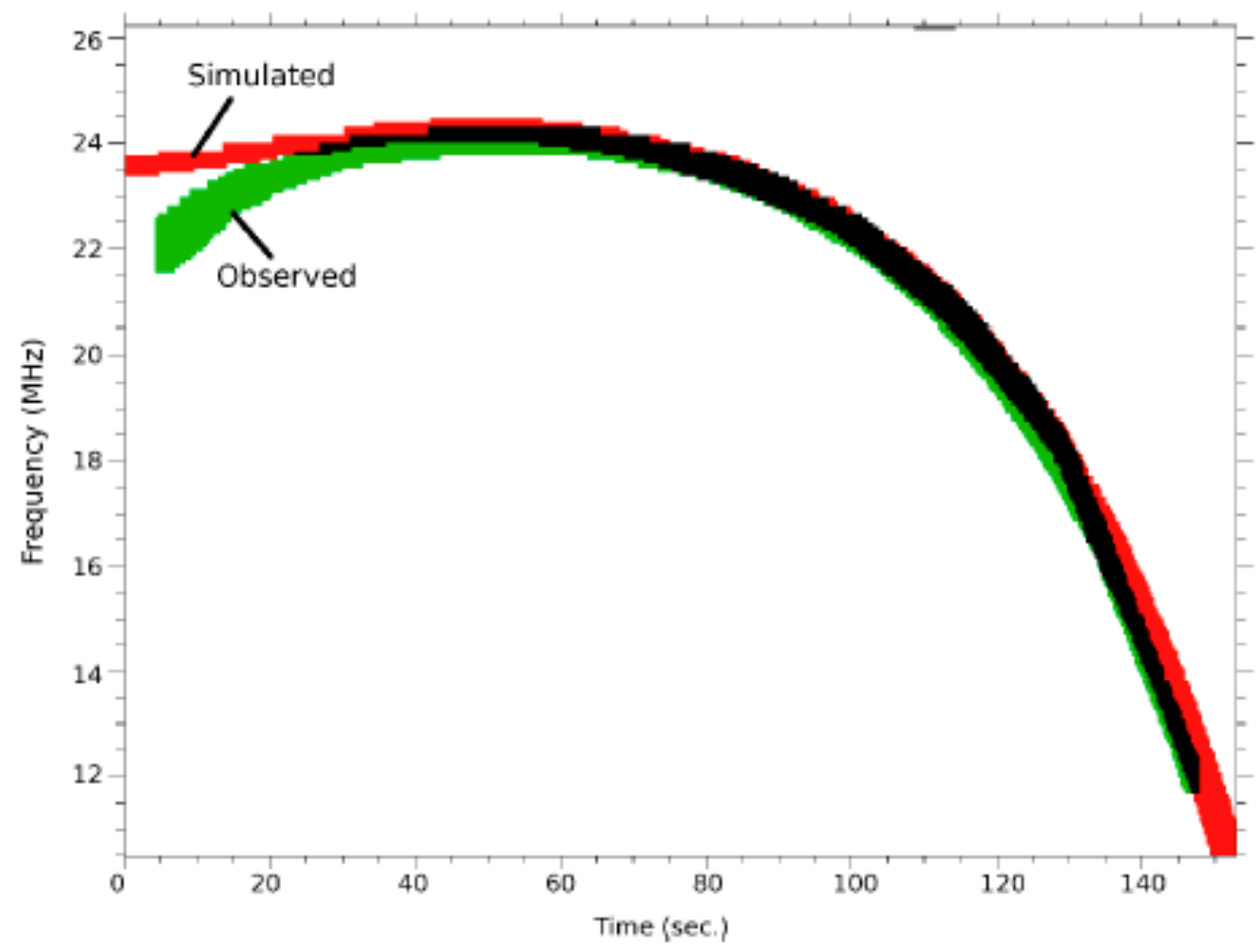


[Nichols, 2011, 2012]

- Predicting radio dynamic spectra from CMI modelling for various SPI scenarii
  - imaging cannot resolve *-Xo or WD-Xo or WD-WD systems
  - t-f morphology reveals system's physical parameters
  - successful loss-cone driven CMI modelling of Jupiter's radio emissions :
    → ExPRES code



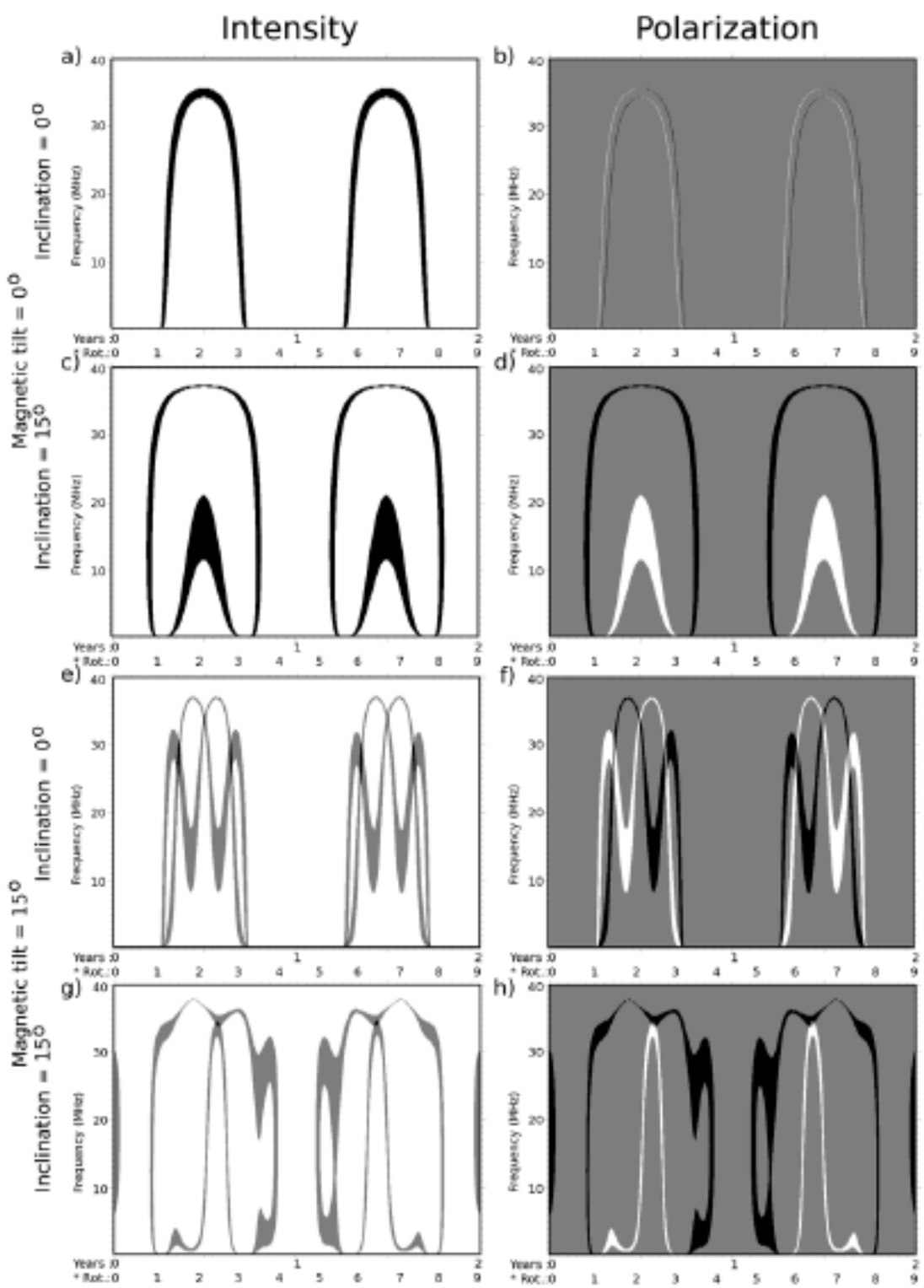




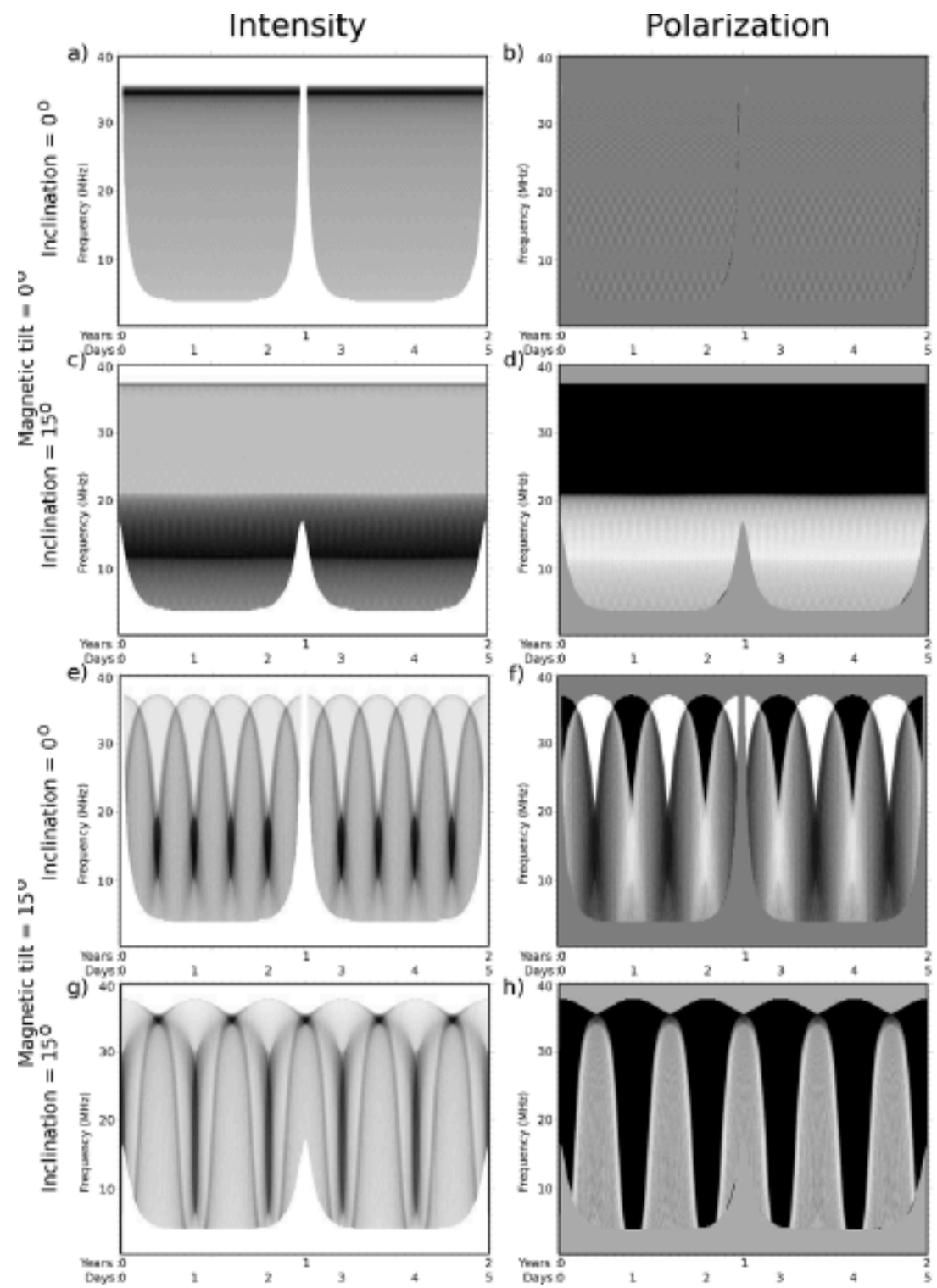
[Hess et al., 2008, 2010, 2013]

- Star-Exoplanet case : interaction scenario (auroral or unipolar inductor emission)

[Hess & Zarka, 2011]



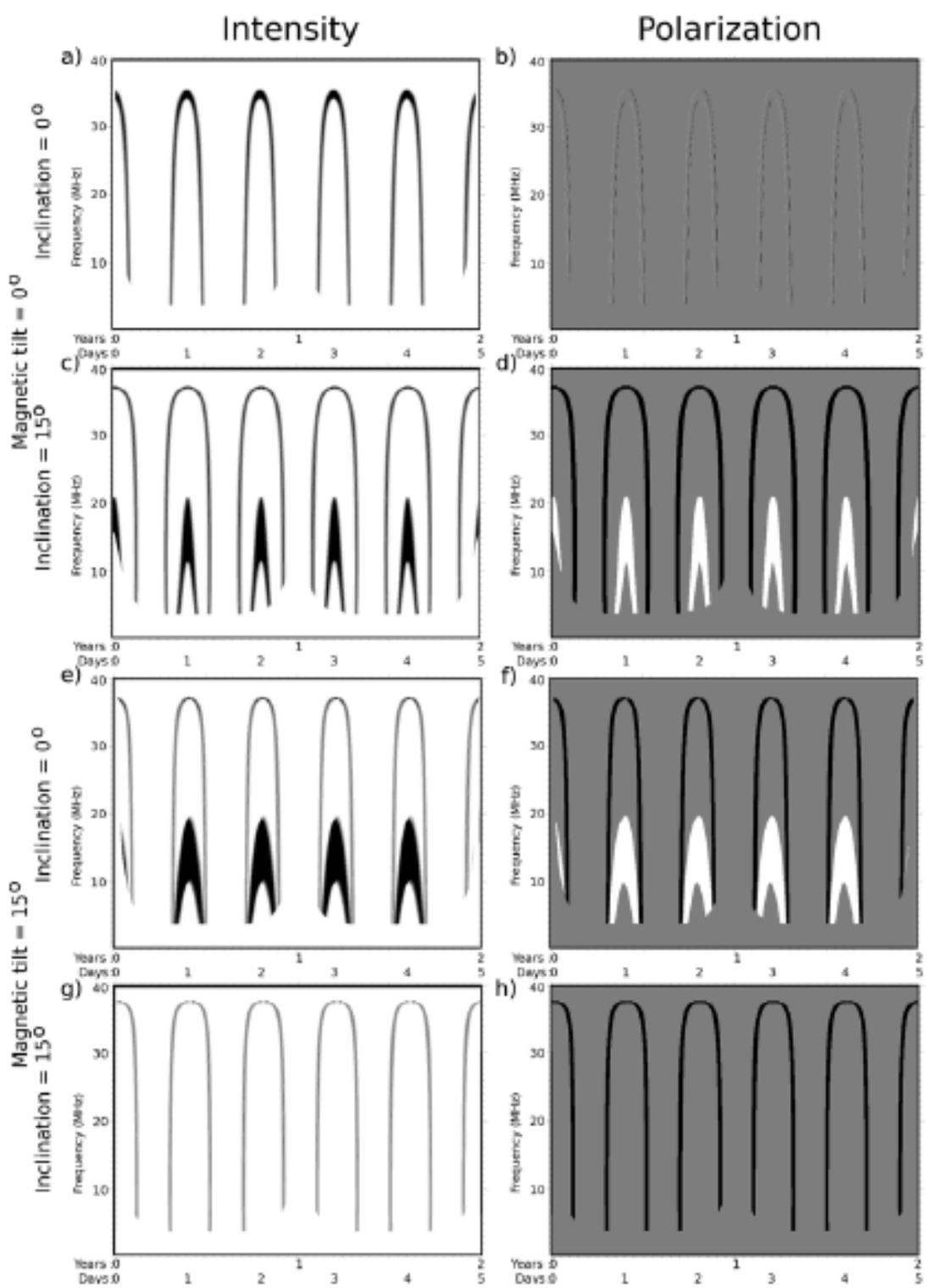
Xo-induced radio emission in stellar B field



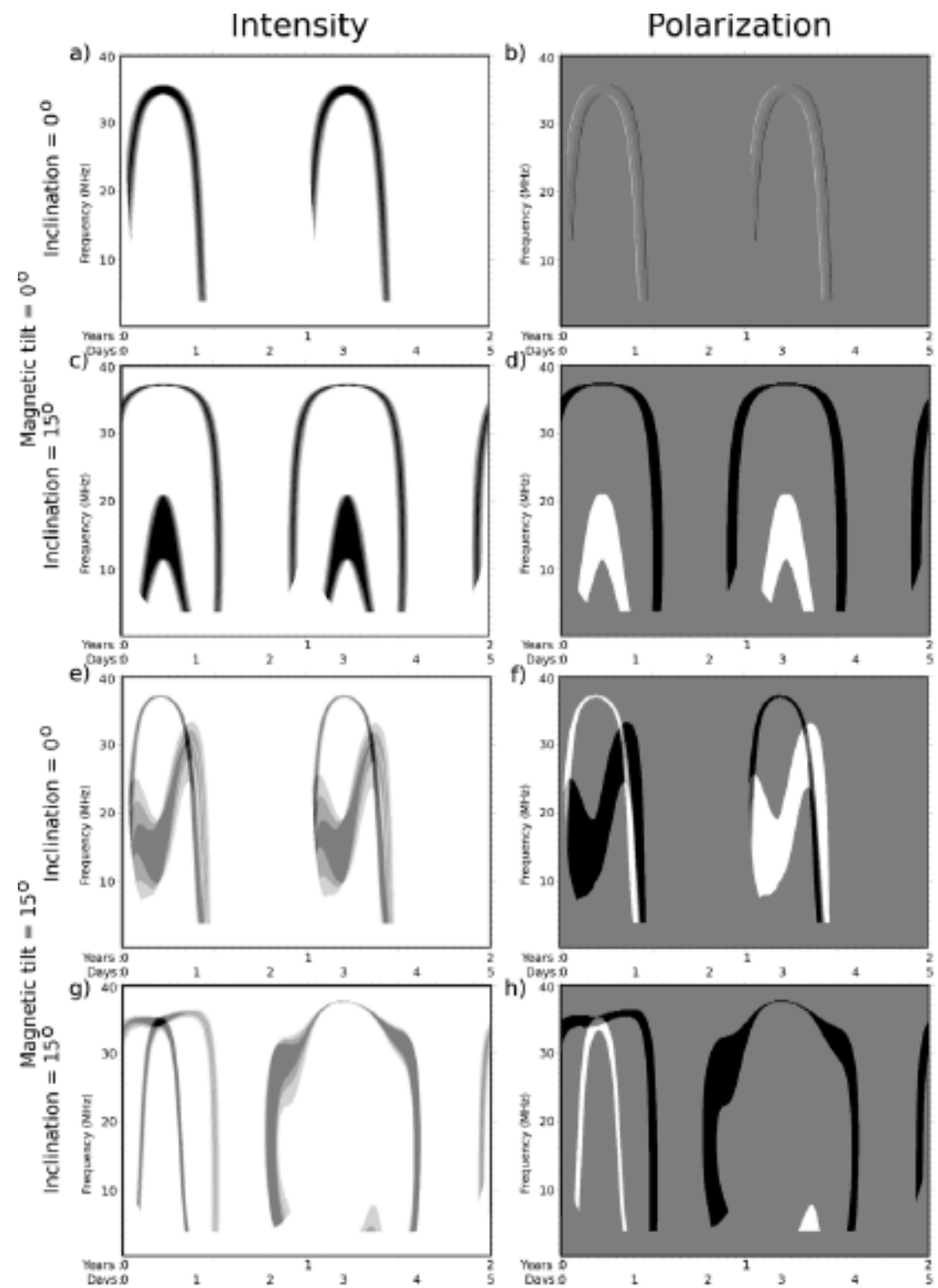
exoplanet emission : full oval

- Star-Exoplanet case : interaction scenario (auroral or unipolar inductor emission)

[Hess & Zarka, 2011]



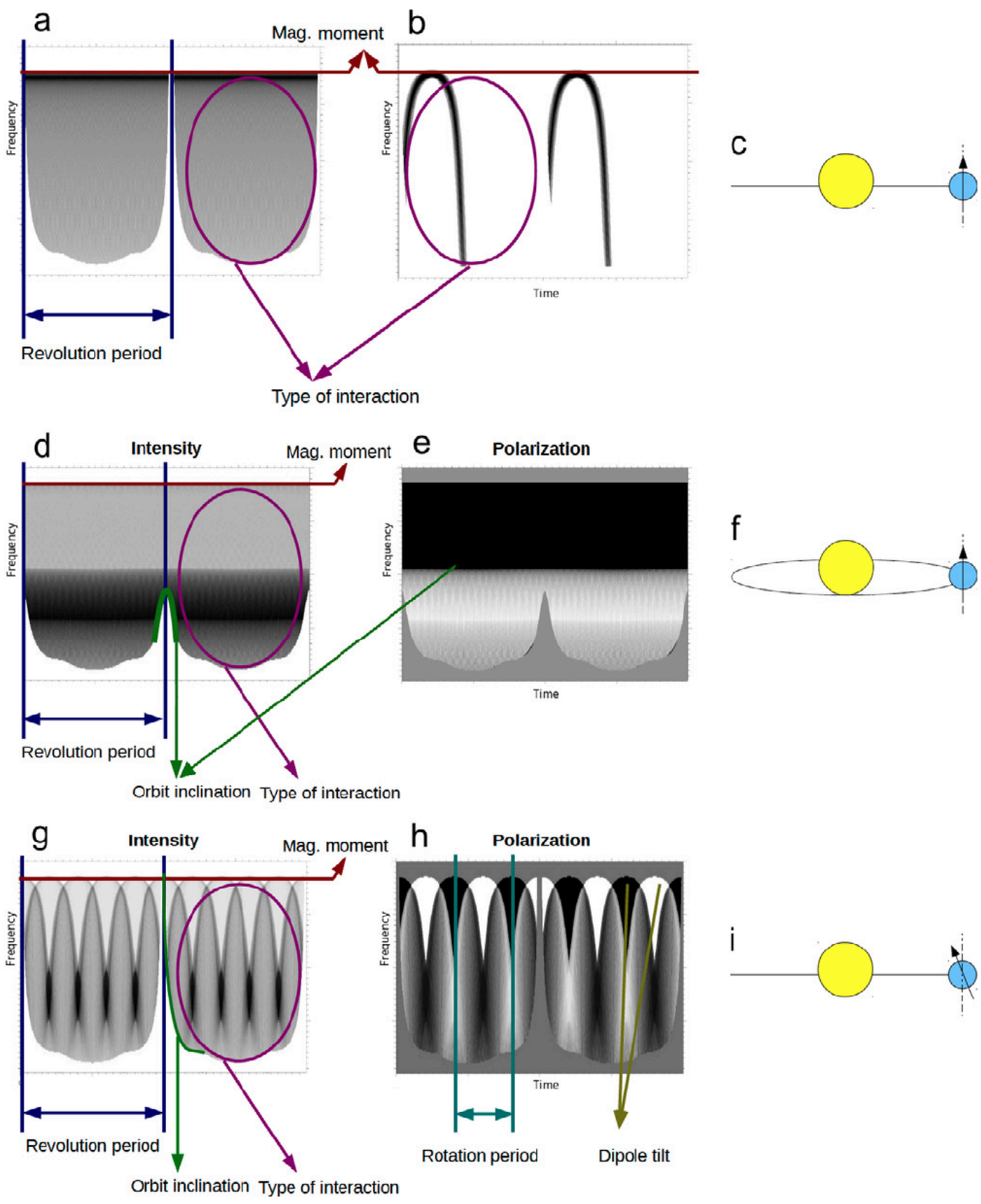
exoplanet emission : longitude sector



exoplanet emission : LT sector

• 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 possible / easy post-detection)

• Model predictions easy to scale to any frequency range (depends on magnetic fields involved)

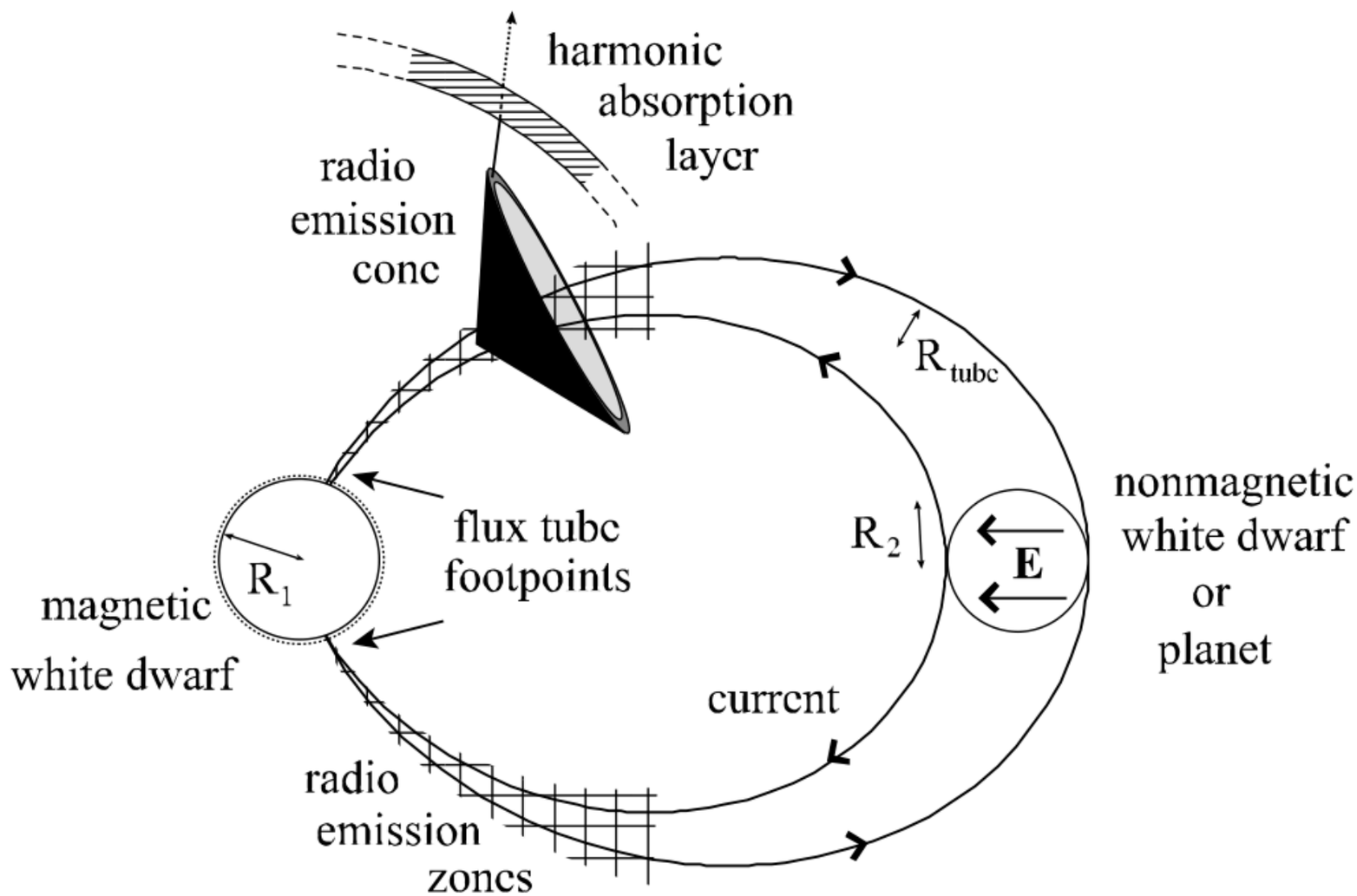
• ≥ a few 10's MHz, LF cutoff becomes negligible except very close to the star & at low inclination (~occultation)

• Magnetic WD - Non-Magnetic WD systems in synchronous rotation to explain ultrashort period (P<10 min) X-ray sources with antiphase optical emission

→ unipolar inductor interation ~ Io-Jupiter

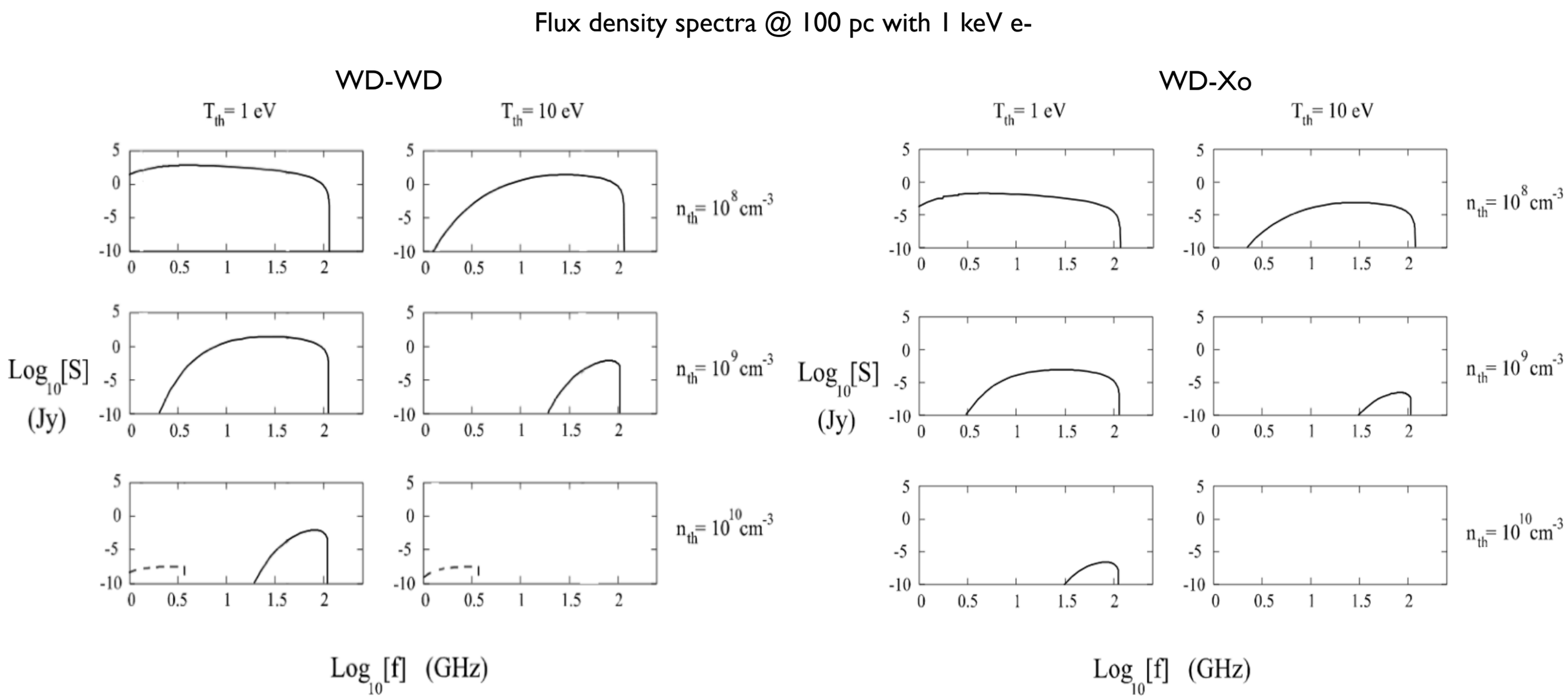
→ X ray emission at footpoints = heating on magnetic WD + optical emission by irradiation of the non-magnetic WD

• P decrease consistent with power radiation via unipolar induction



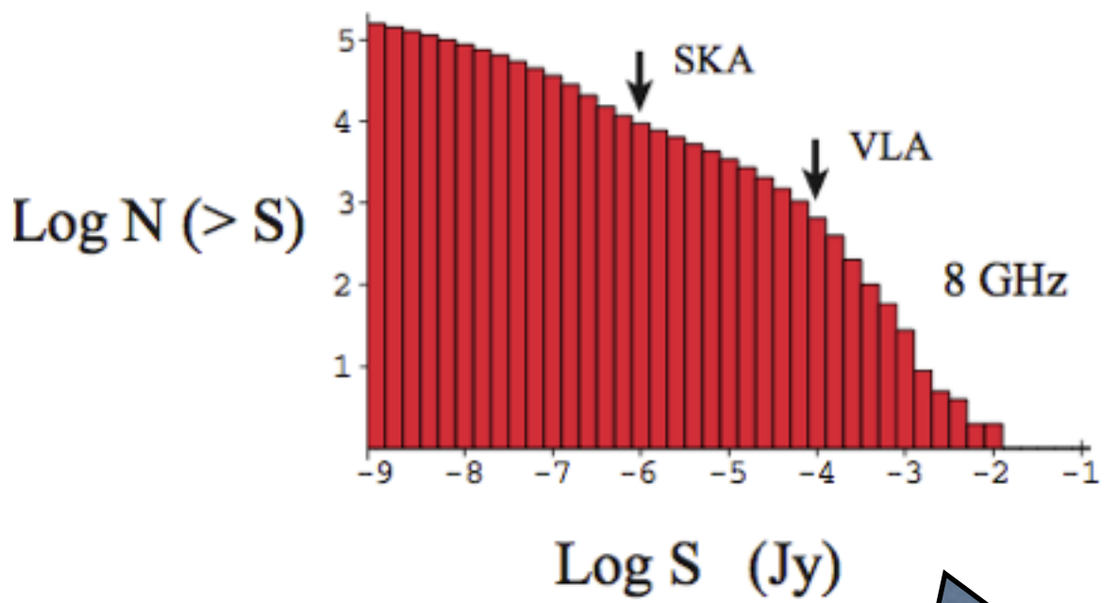
[Willes & Wu, 2004]

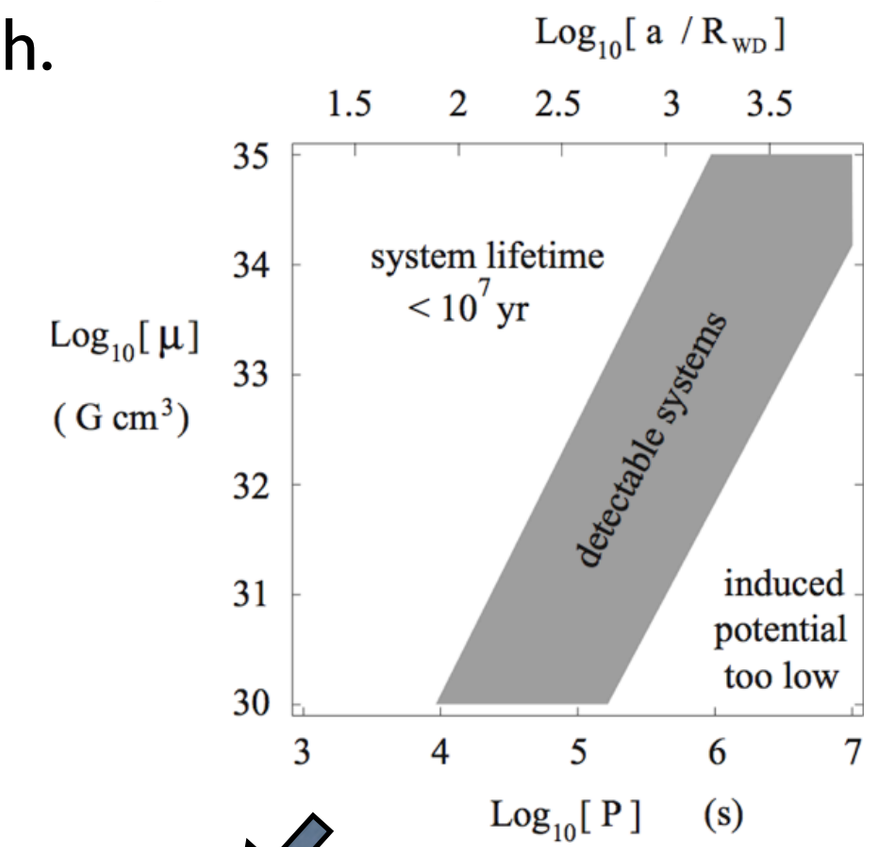
- Unipolar inductor CMI radio emission from WD-WD & WD-exoplanet systems
  - → broadband emission up to 100 GHz + absorption bands, X mode dominant
  - → bursts (~10 s for WD-WD systems, ~10 min for WD-Xo systems)
  - → duty cycle ~ a few % (due to beaming)
  - → order of magn. predictions (density of 1 keV loss-cone e- ×10 → S ×10^4)
  - → higher power in WD-WD systems due to higher magnetic moment

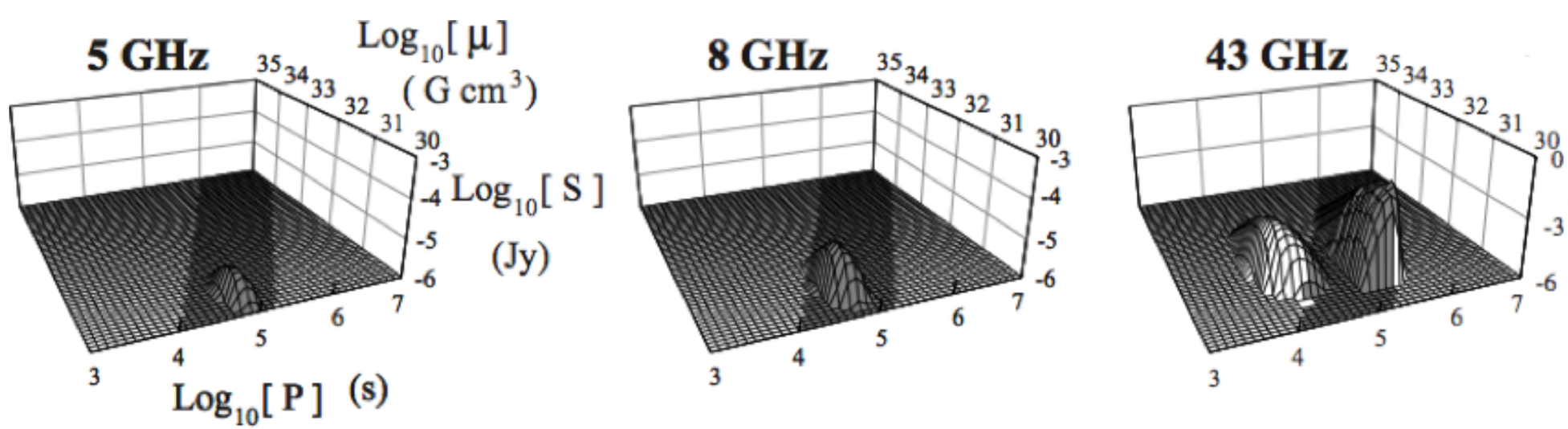


[Willes & Wu, 2004]

- Limited unipolar inductor lifetime due to spin(of magnetic WD)-orbit coupling
  - → ~10^4 years for WD-WD
    (system lifetime ~10^6 years due to gravitational radiation emission)
    ~1% detection probability per unipolar inductor phase
  - → ~$10^{7\text{-}9}$ years for WD-Xo with $P_{orbital}$=10-30 h.







[Willes & Wu, 2004, 2005]

→ Radio emission up to 100 GHz, 100% circularly polarized bursts, modulated at the orbital period

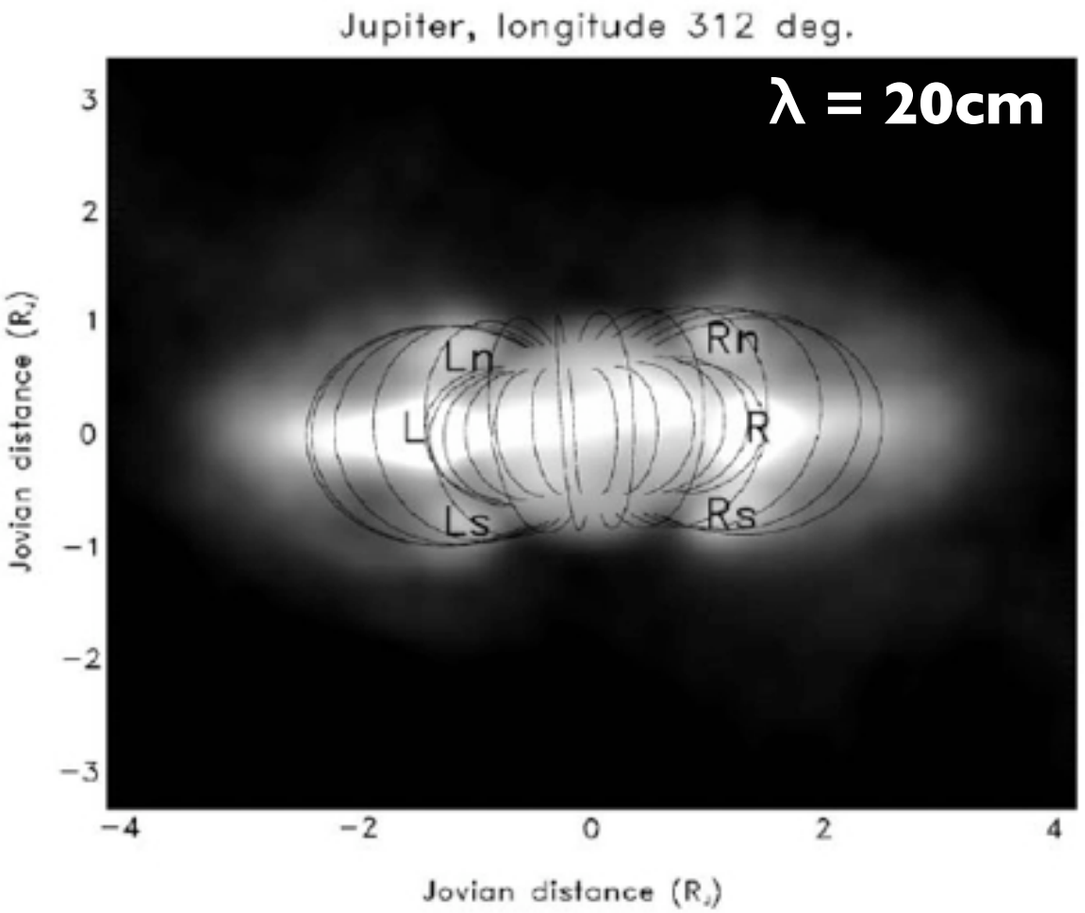
→ may reveal Earth-like planets in close orbit around WD (= remnants of main sequence stars with planet surviving the stellar expansion phase and back in stable orbit)

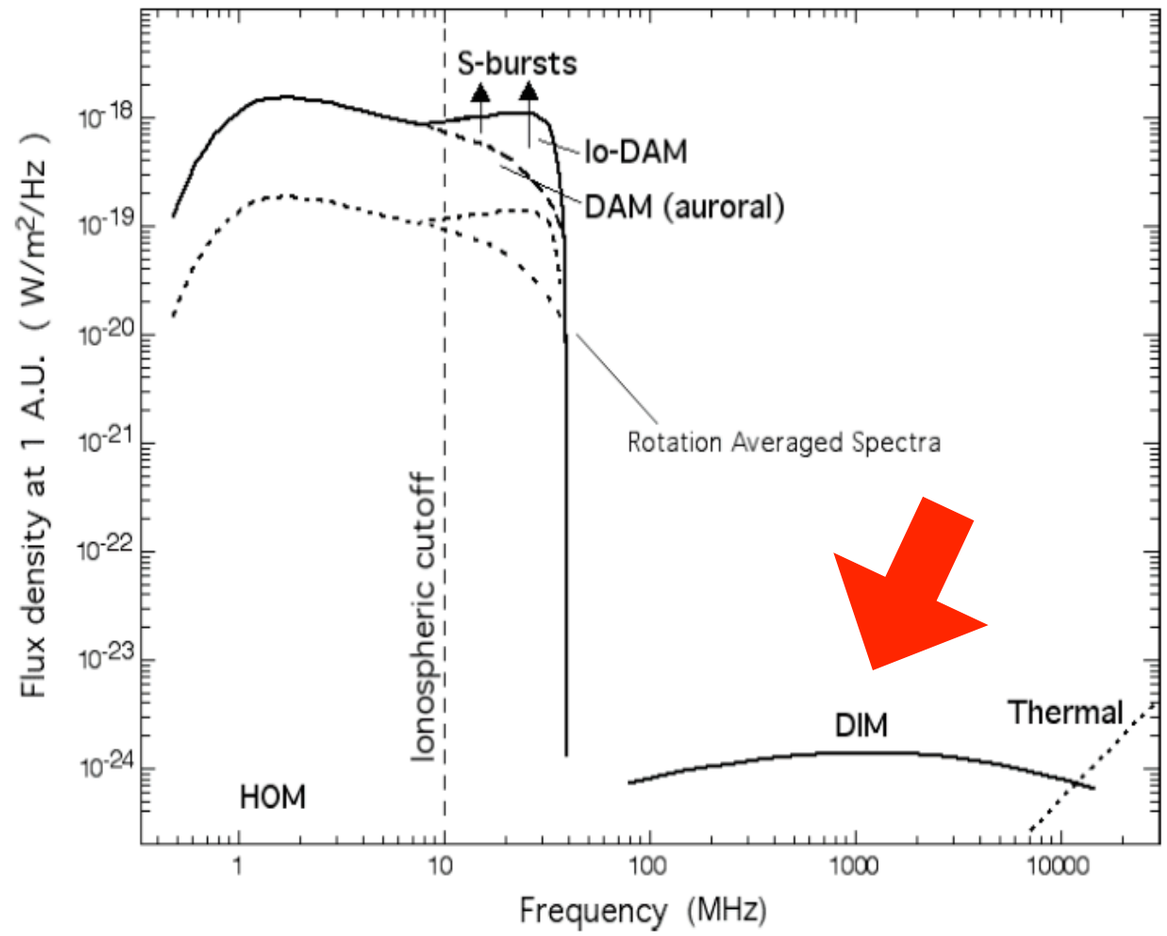
[Willes & Wu, 2004, 2005]

- Generalized unipolar inductor analysis, with non-zero Xo resistivity (self-consistent model)

[Laine, 2013]

- Synchrotron emission from radiation belts





[de Pater, 2004 ; Zarka, 2004]

- Stable emission, allowing for long integration times, but weak
- Jupiter's synchrotron emission ~100 Jy @ 1 AU at 1 GHz → 0.0025 μJy @ 1 pc
- SKA1-Low sensitivity ~ 2kT/[A(bτ)1/2] ~ 10 μJy

with A/T~1000, b=10 MHz, τ=1 hr

→ detectability of 1000× Jupiter at pc range only

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

→ Direct detection

→ Measurement of B

⇒ contraints on scaling laws & internal structure models

→ Planetary rotation period ⇒ tidal locking ?

→ Possible access to orbit inclination

→ Existence / orbital period of satellites ?

→ Comparative magnetospheric physics : <u>theoretical frame ready</u>

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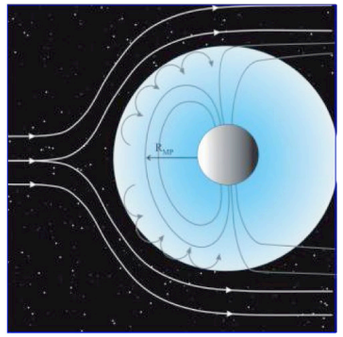

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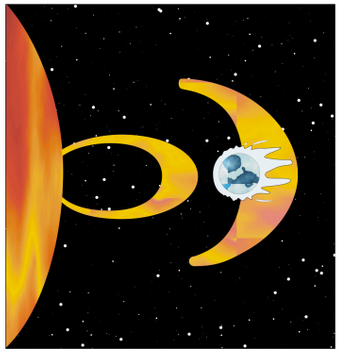


[Griessmeier et al., 2004; Khodachenko et al., 2006...]

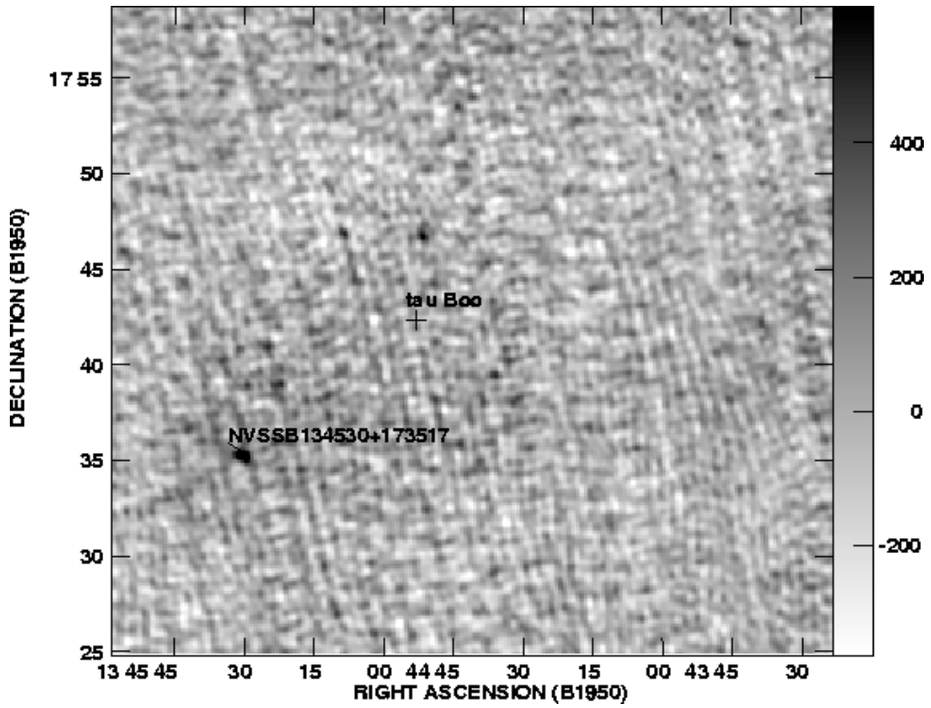
OBSERVATIONS

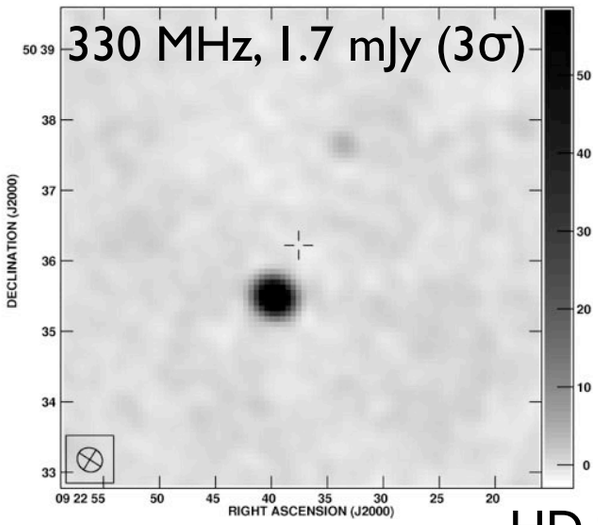
- Limited angular resolution (λ/D) $\Rightarrow$ no imagery (of the target)

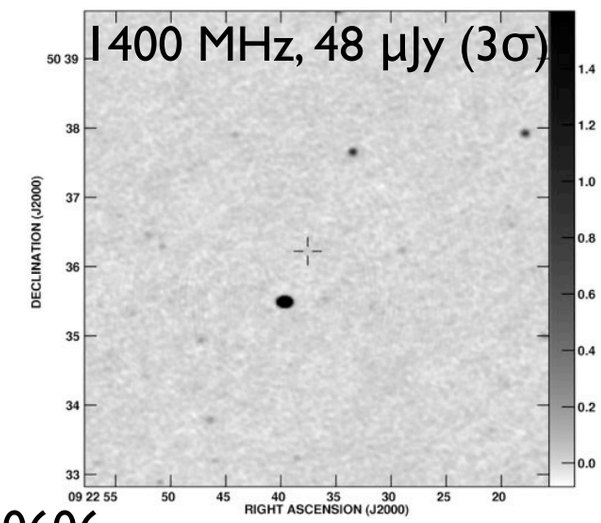
$\rightarrow$ (1) detect a signal, (2) star or planet ?

$\rightarrow$ discriminate via emission polarization + periodicity (orbital)

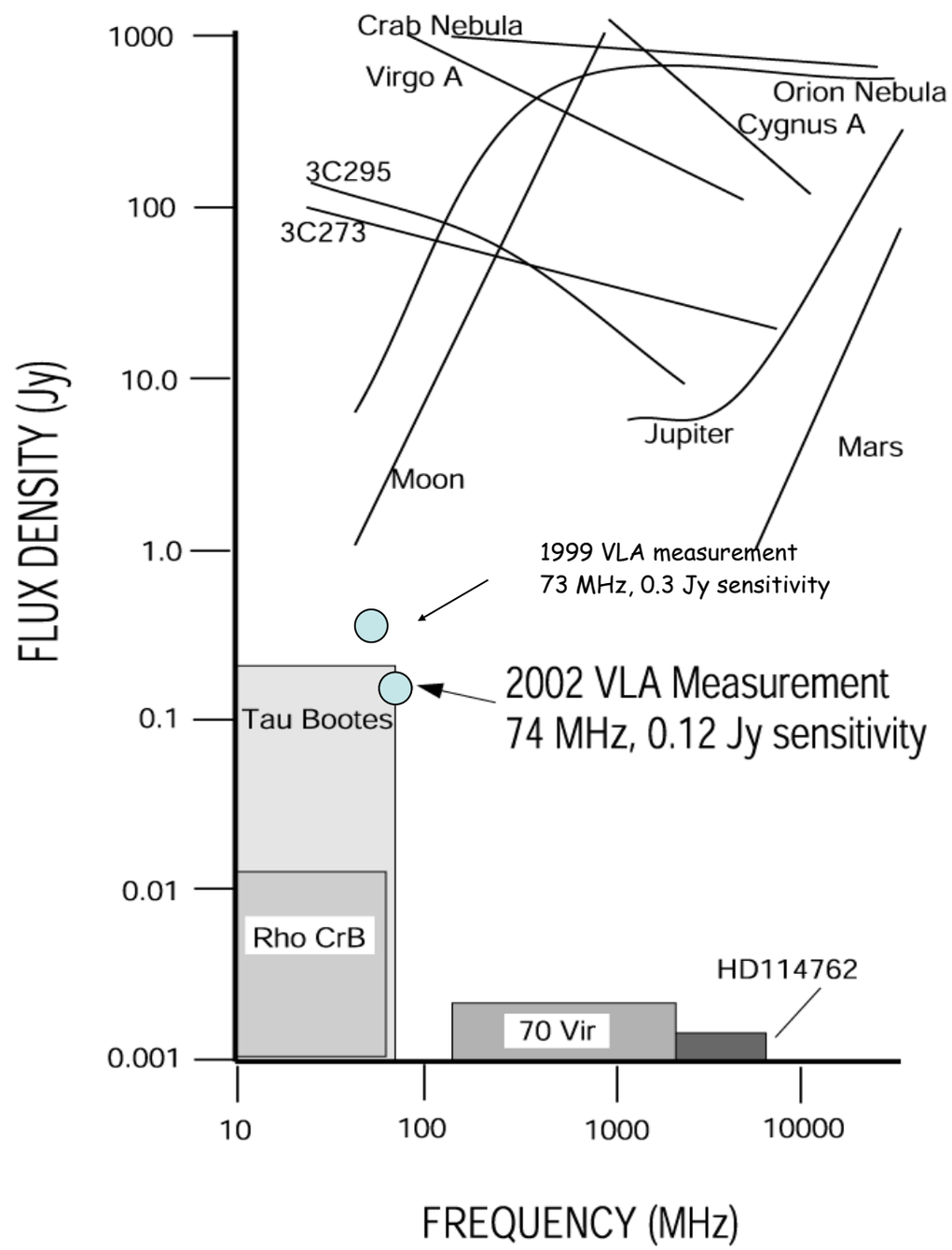
- Observations at VLA at 74, 330, 1465 MHz
  τ Boo, HD 80606 → no detection
  (but low A_{eff} / high frequency)







HD 80606

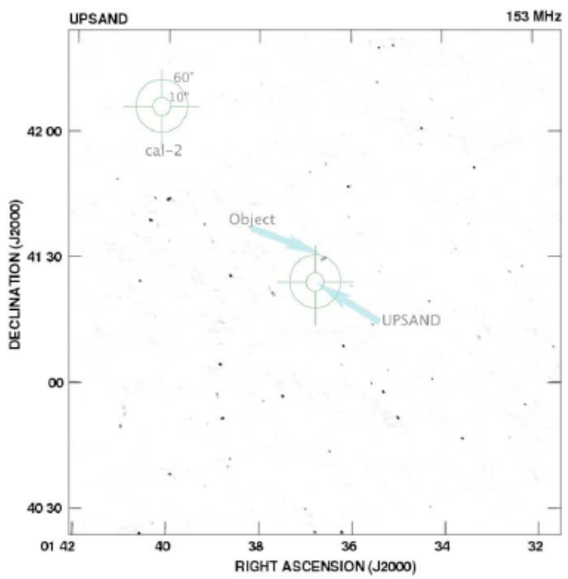


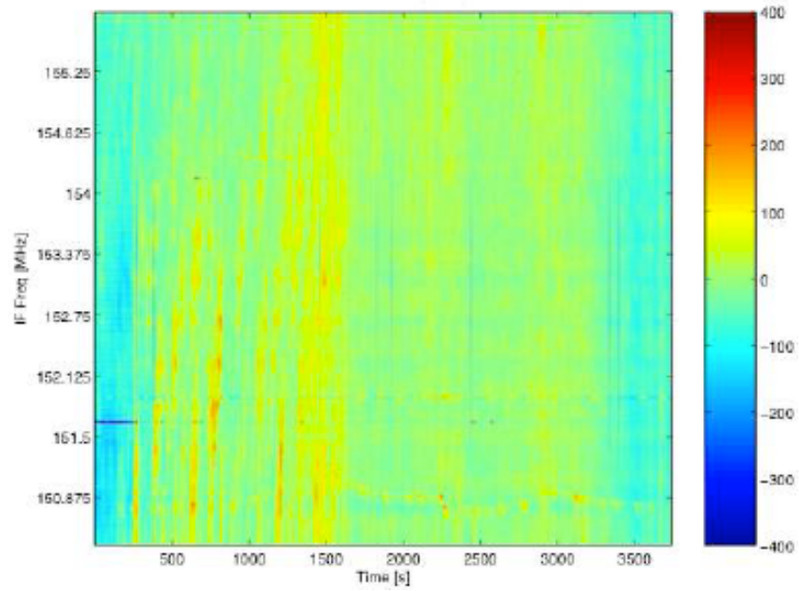
[Winglee et al., 1986; Bastian et al., 2000; Farrell et al., 2003, 2004; Lazio & Farrell, 2007; Lazio et al., 2010]

- Observations at GMRT at 153 MHz

Ups And, ε Eri, HD 128311 → no detection

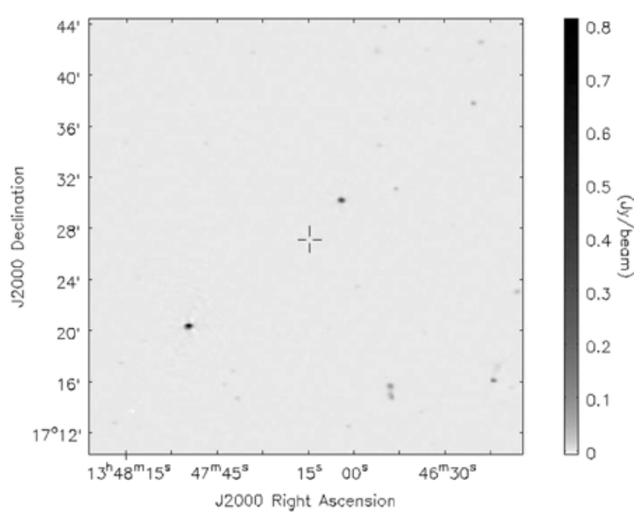
[Winterhalter et al., 2006; Majid et al., 2006; George and Stevens, 2007, 2008]

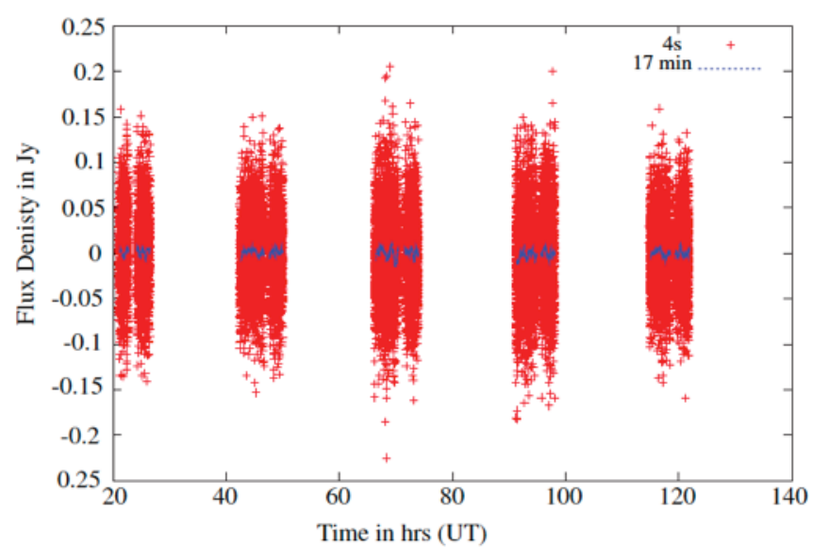




τ Boo (40 h, ~0.4 mJy) → no detection

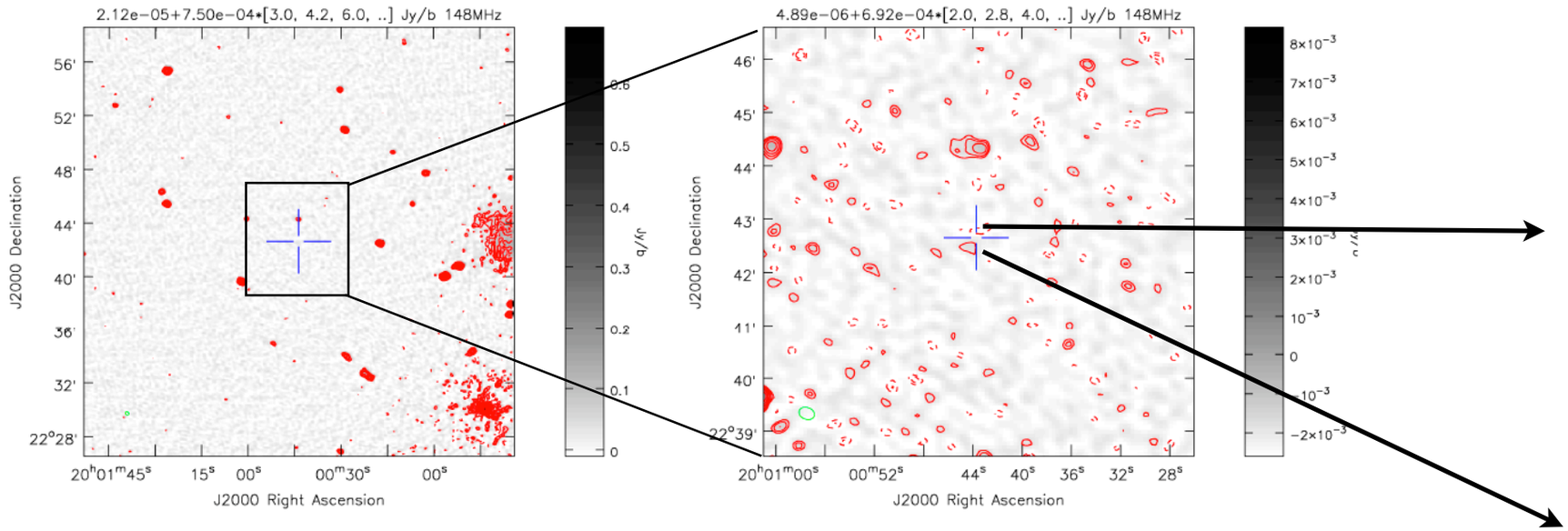
[Hallinan et al., 2013]

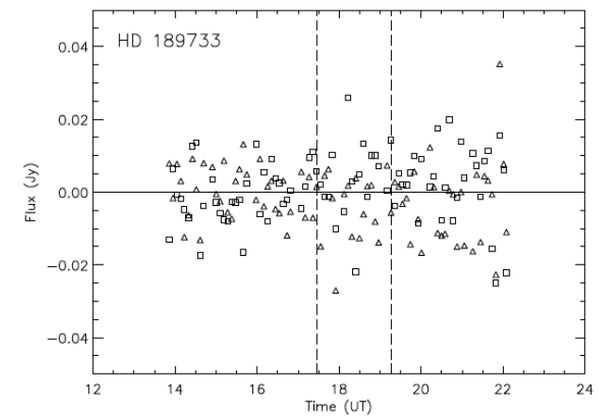


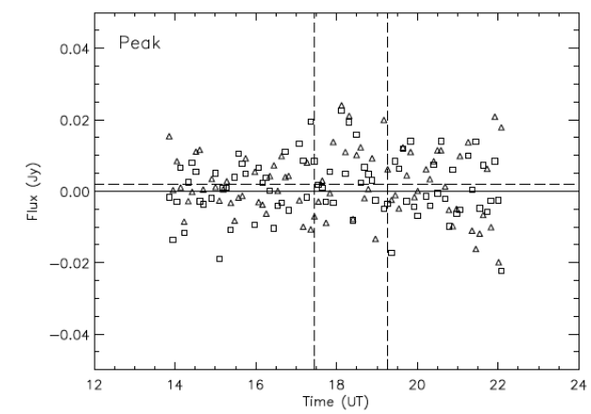


→ RFI ? B_{planet} < 50G ? emission too weak ?

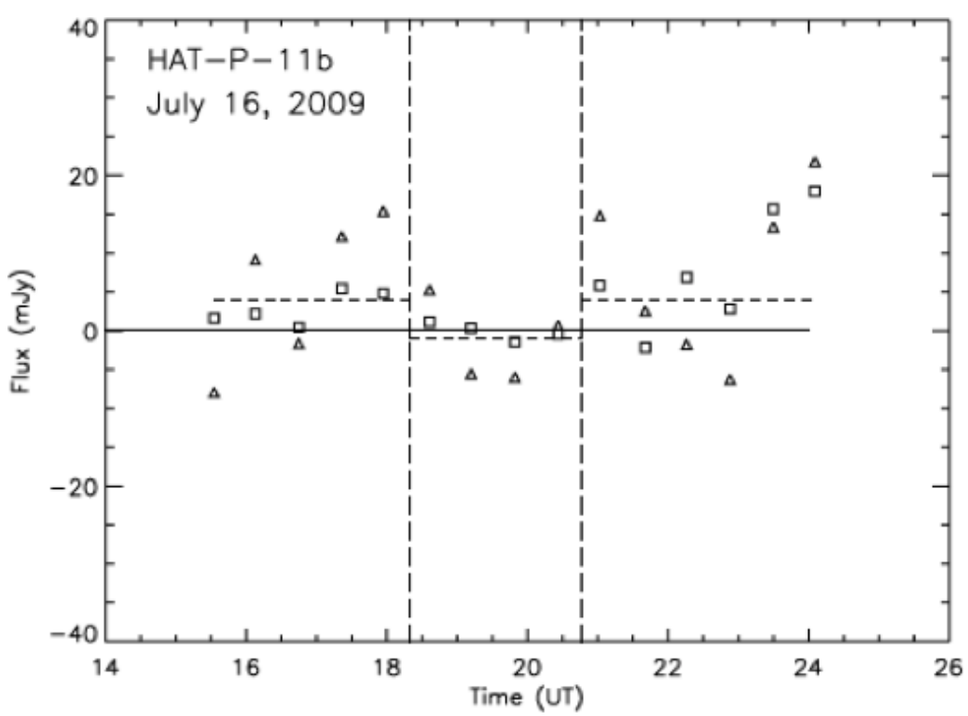
- Observations at GMRT at 153 MHz, 244, 614 MHz
  → anti-transits of HD189733b, HD209458b
  HAT-P-11b







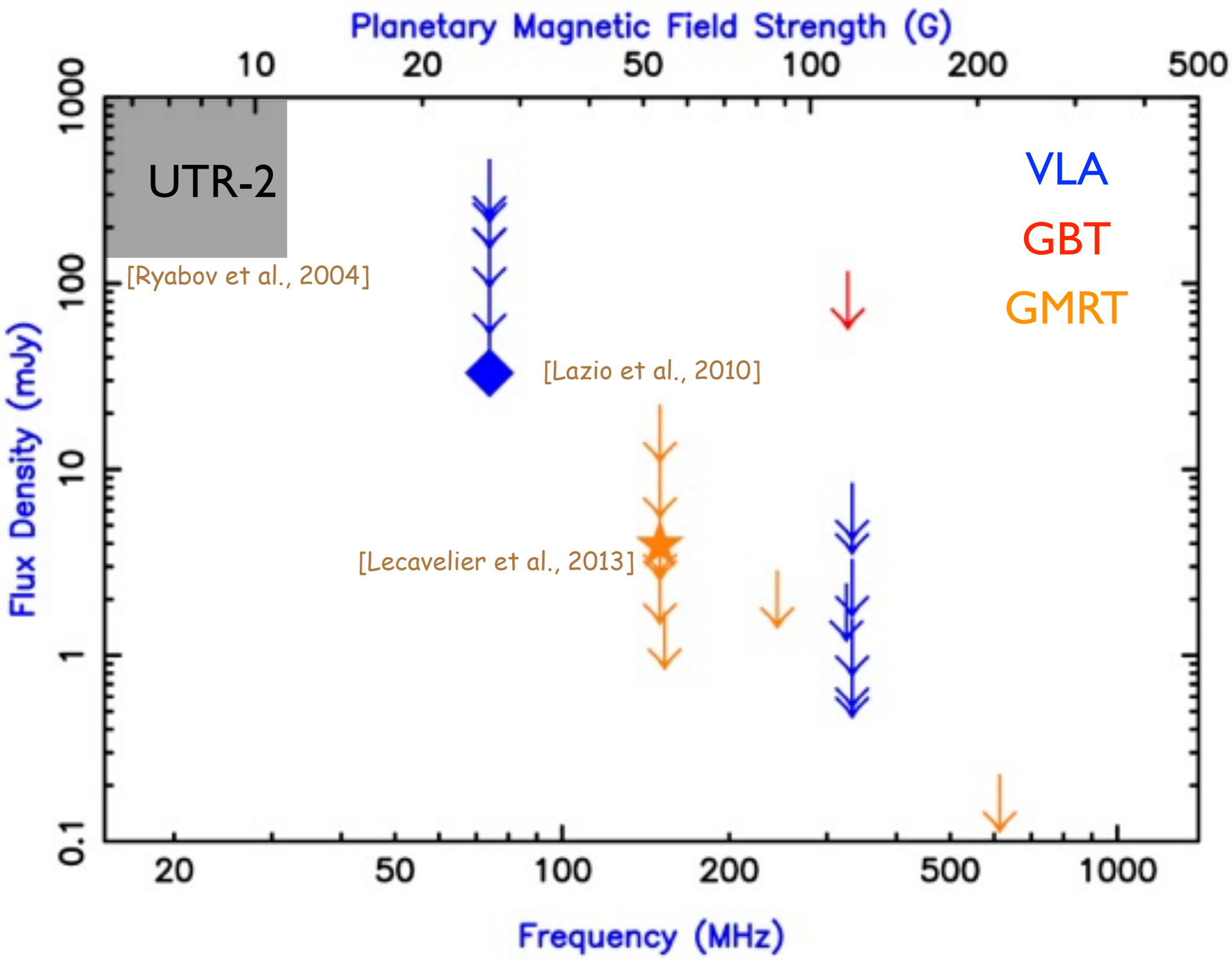
[Lecavelier et al., 2009, 2011]



HAT-P-11, 153 MHz
unconfirmed in 2010

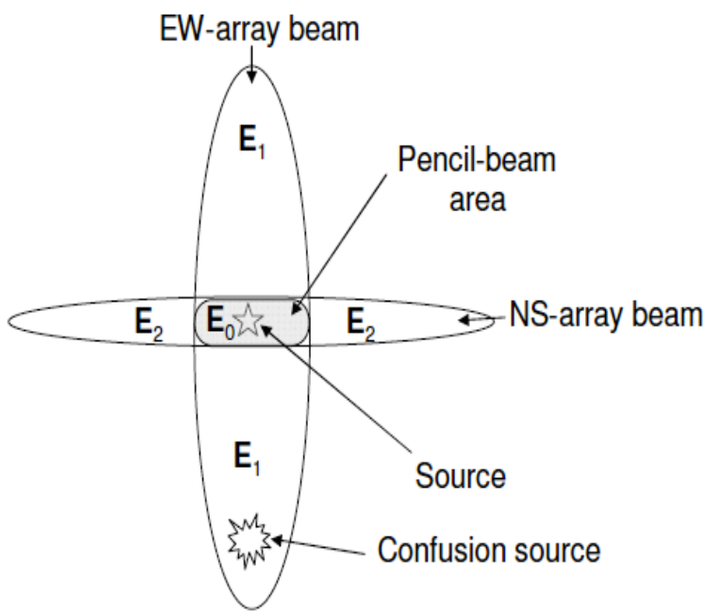
[Lecavelier et al., 2013]

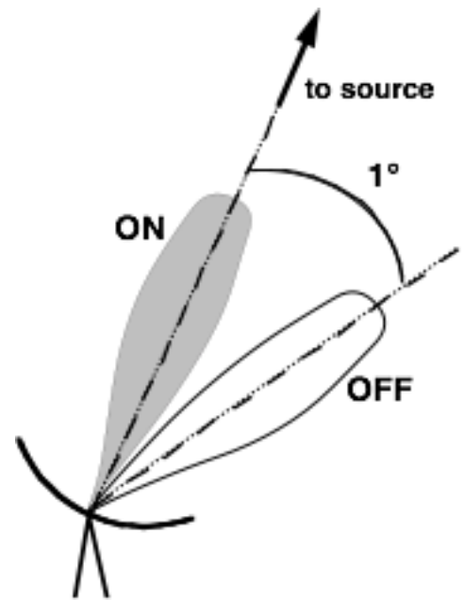
- Inferred limits (from J. Lazio)

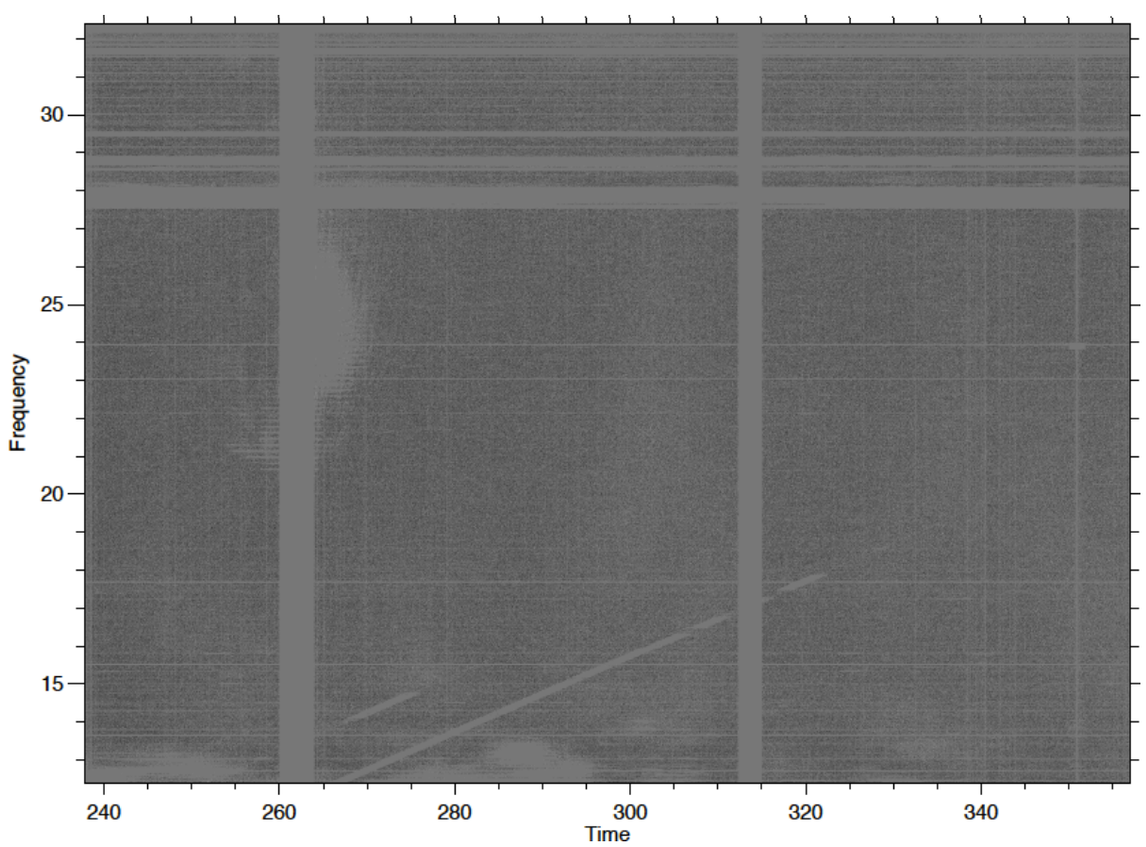


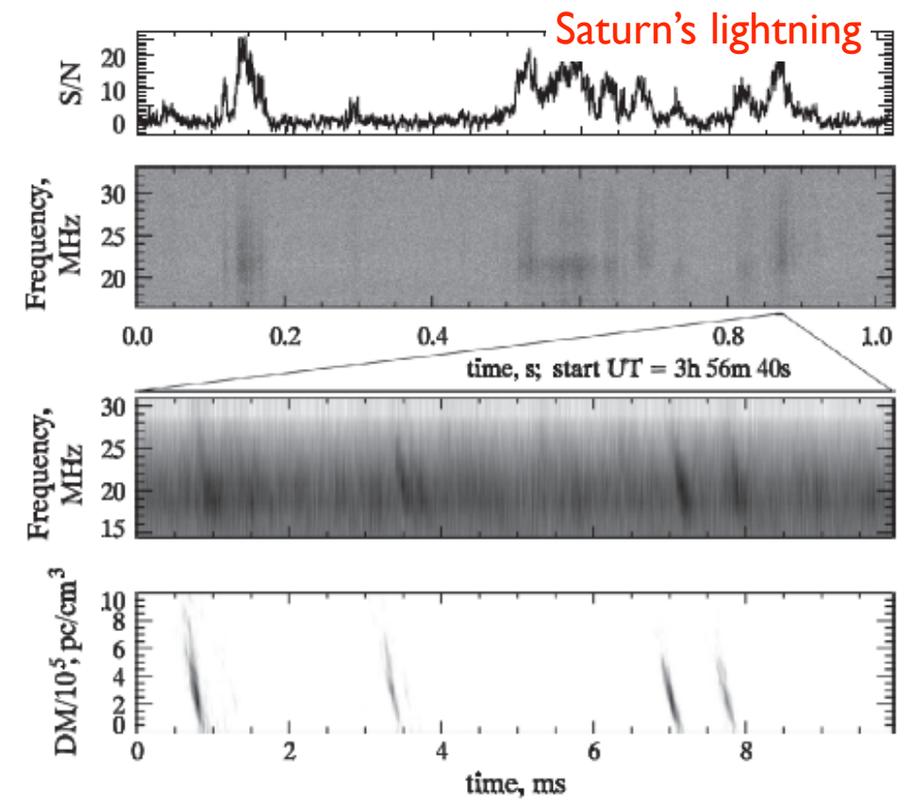
- Observations at UTR-2, 10-30 MHz dual beam, δ f=4 kHz, δ t=20 msec

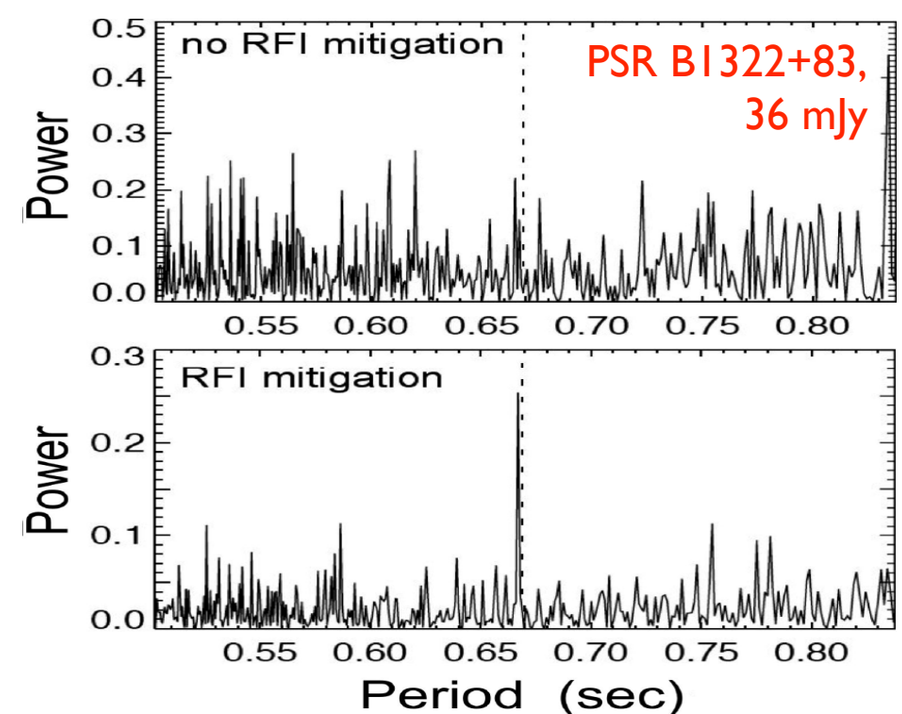
[Ryabov et al., 2004, 2010; Zarka et al., in prep]



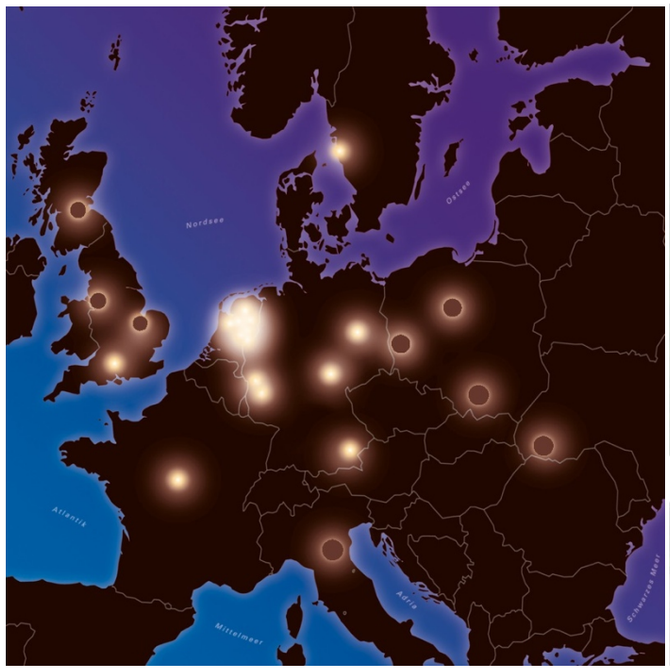


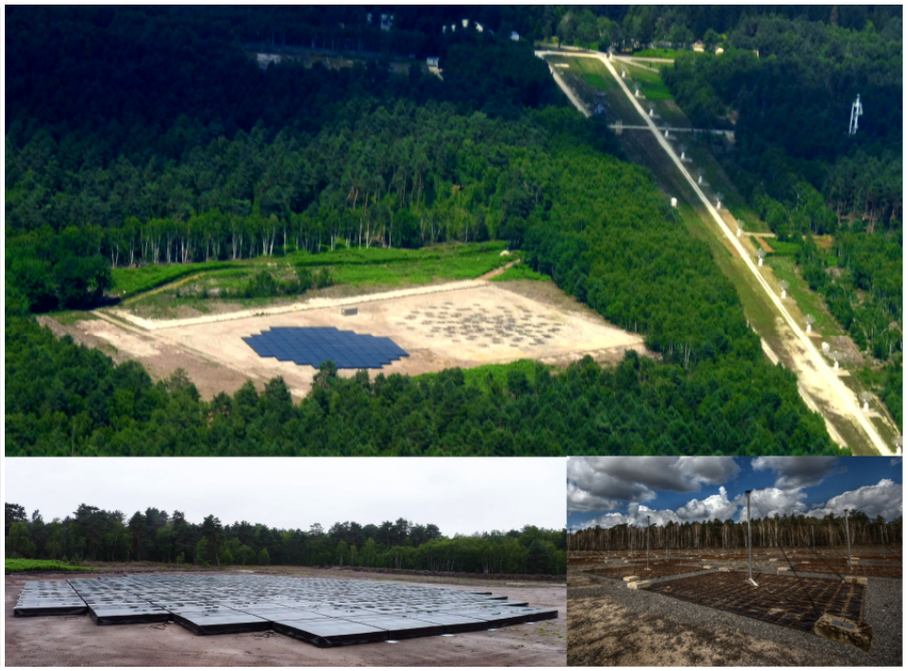


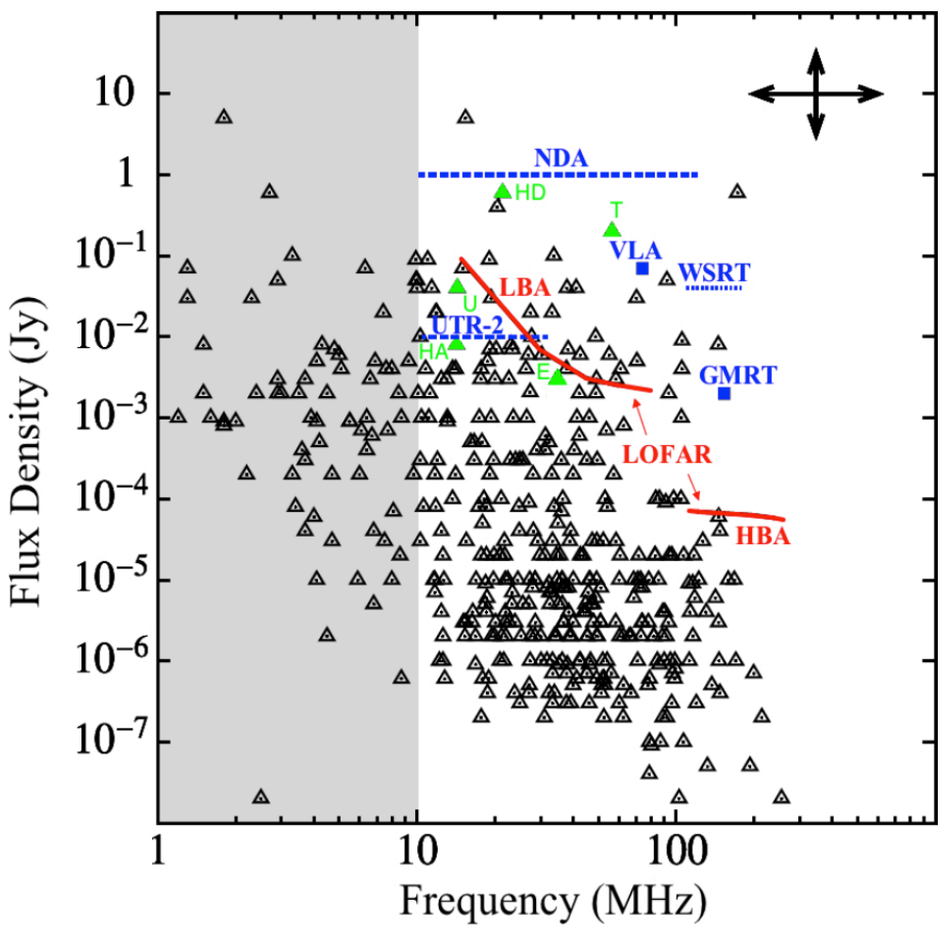


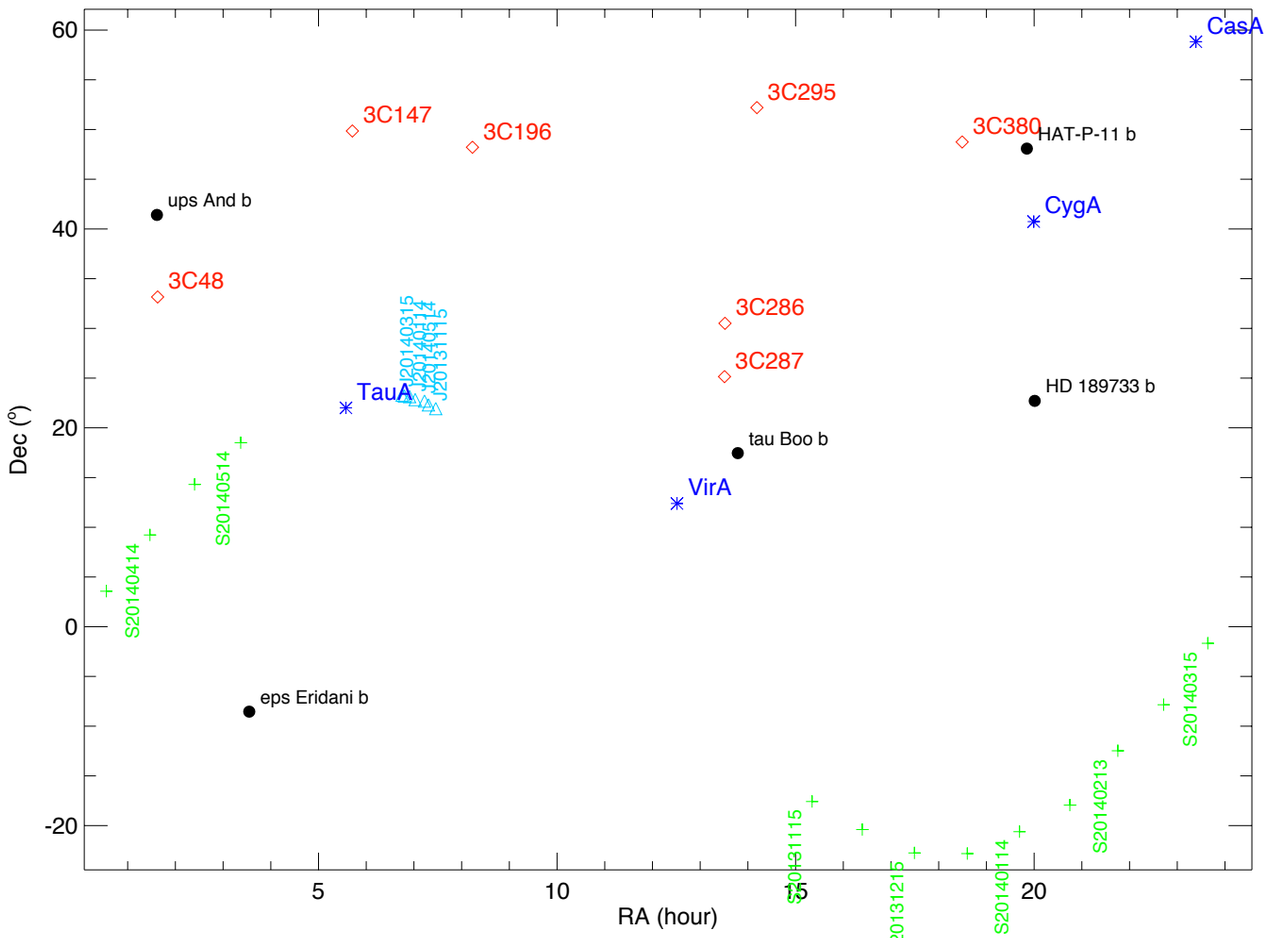


- Observations with LOFAR, 30-250 MHz, imaging + tied-array beams
  → a few targets observed in cycle 0 (Zarka et al., 30h, Lazio et al., 30h)









- Next ?

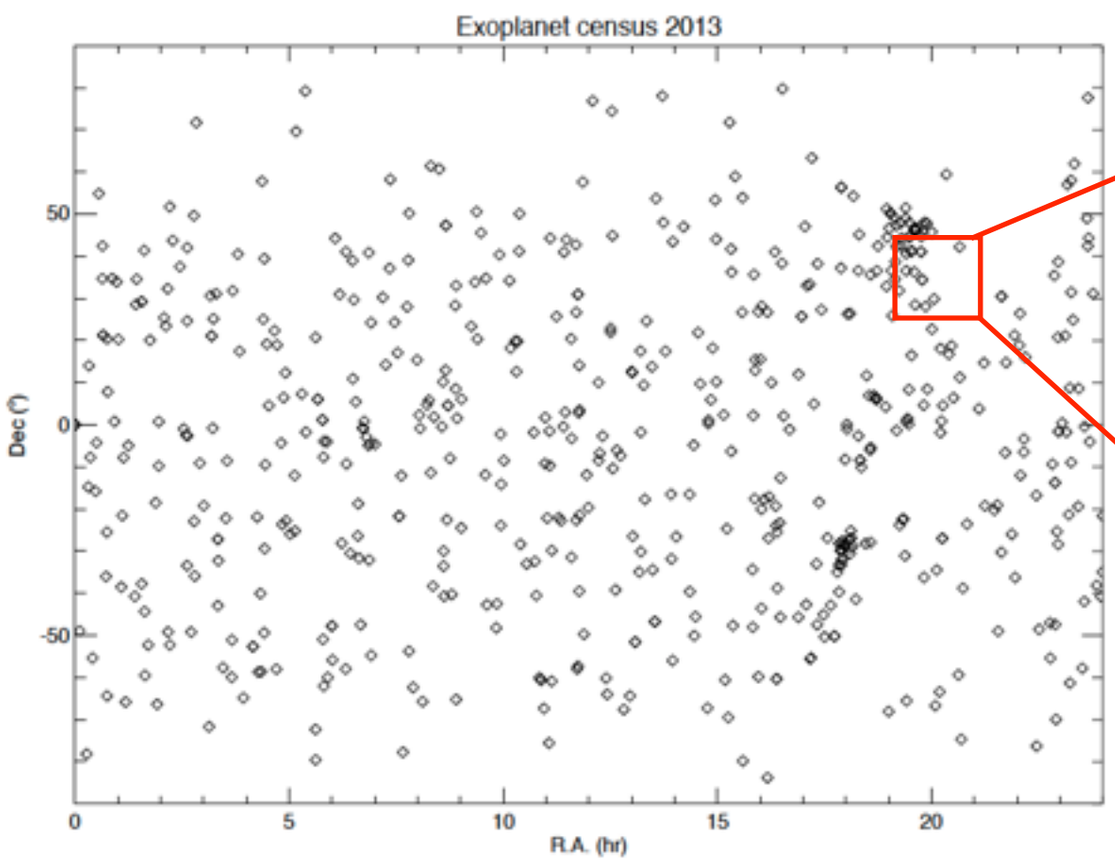
exoplanet.eu : 16 known Xo systems < 10 pc, ~235 < 50 pc, ~360 <100 pc …

1-10 Xo per 1hr × 10° field

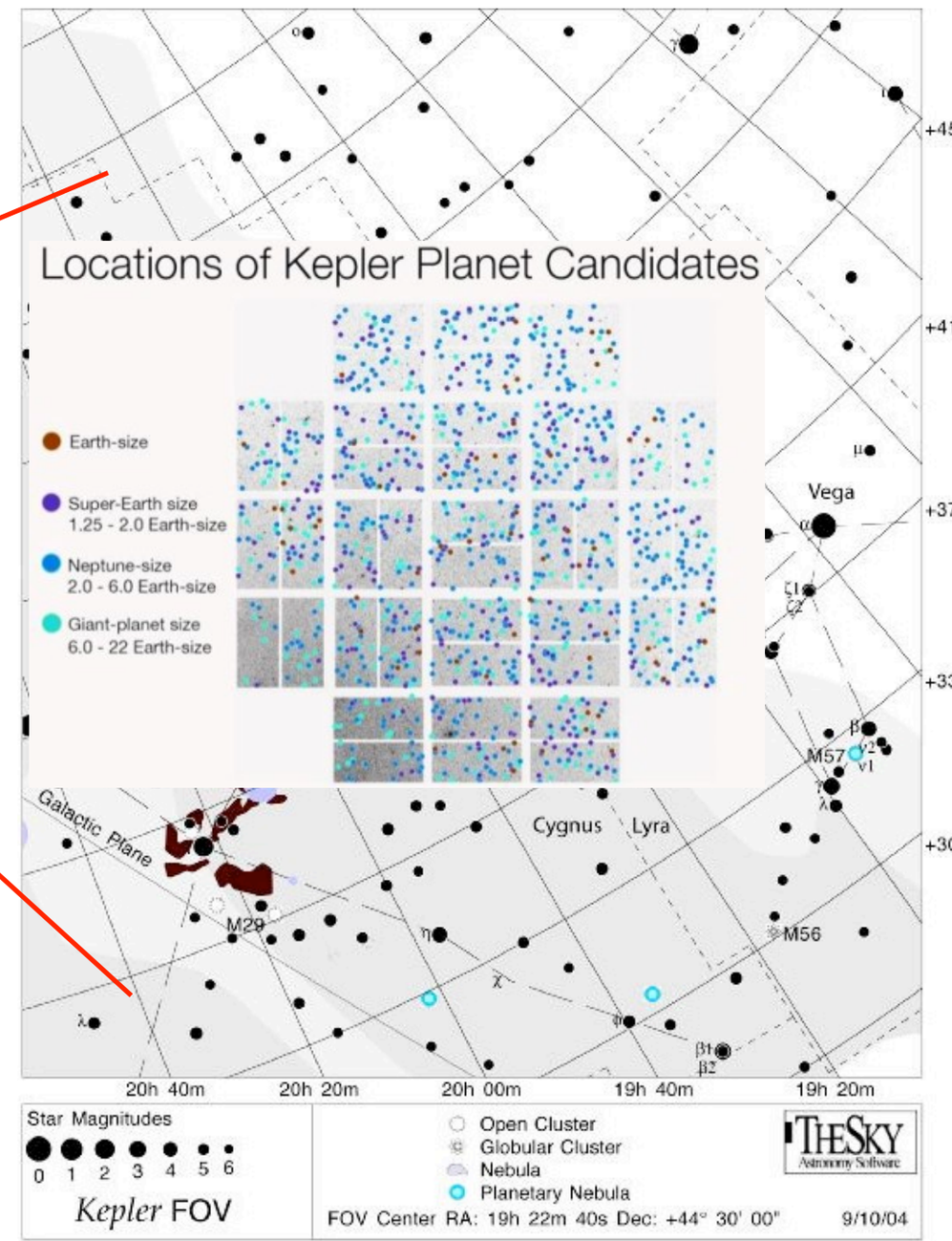
100's of Xo confirmed / candidates in ~10° Kepler field

40 stars up to 5 pc, 1000 up to 10 pc …

coordinated obs. (UTR-2, ZD polarimetric imaging, UV-X …)



~700 Xo systems



DISCUSSION

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

→ Direct detection

→ Measurement of B

⇒ contraints on scaling laws & internal structure models

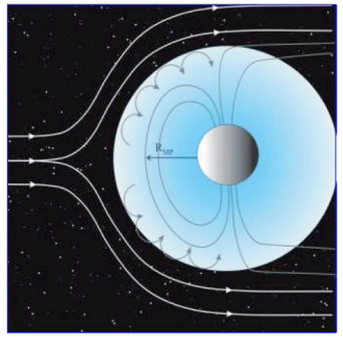
→ Planetary rotation period ⇒ tidal locking ?

→ Possible access to orbit inclination

→ Existence / orbital period of satellites ?

→ Comparative magnetospheric physics : <u>theoretical frame ready</u>

→ Magnetosphere limits atmospheric erosion by the solar wind & CME



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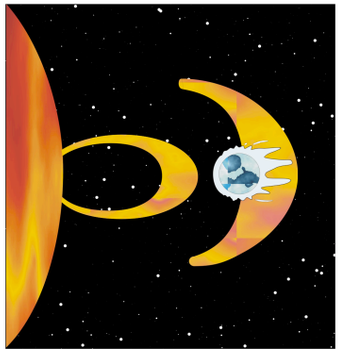

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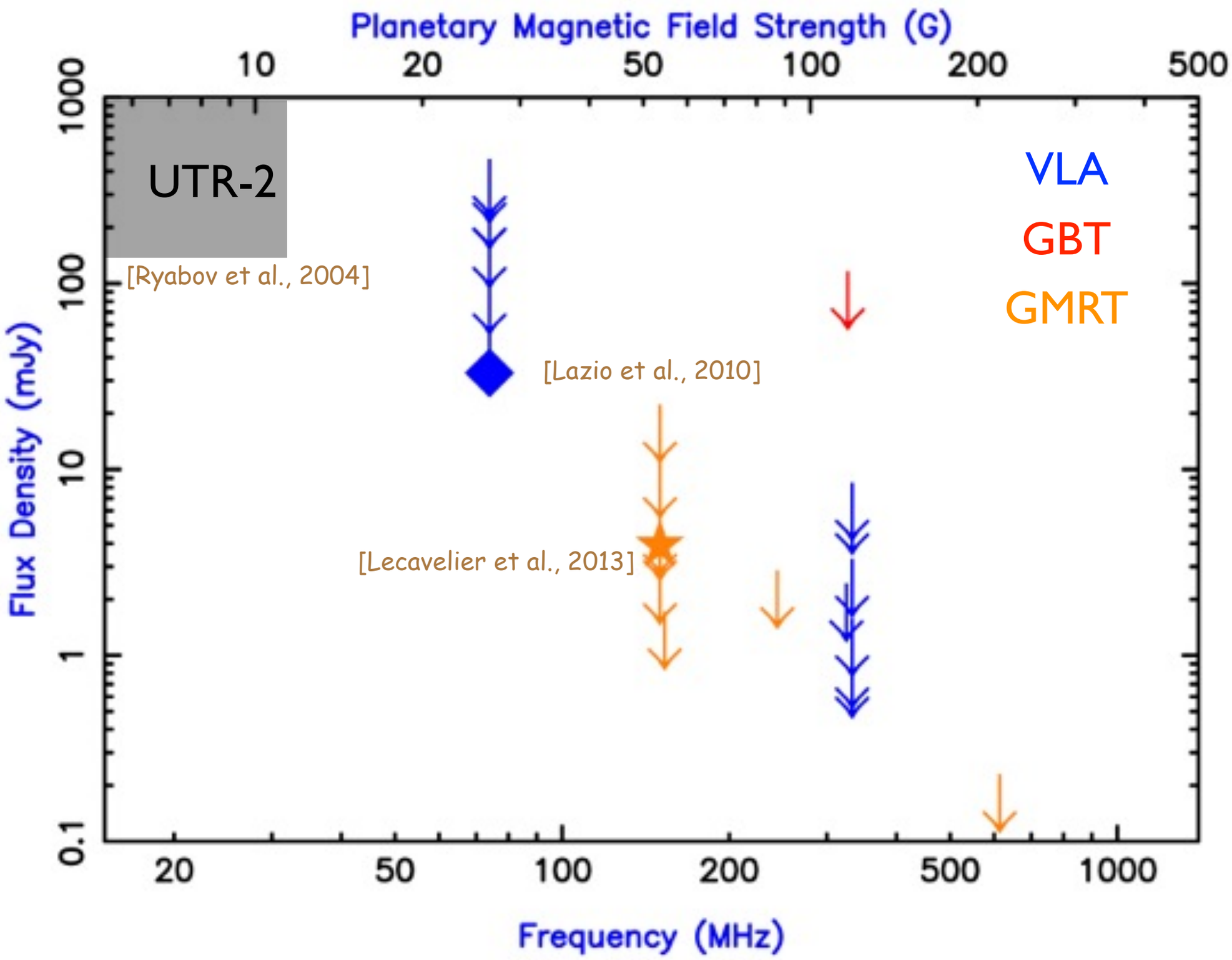
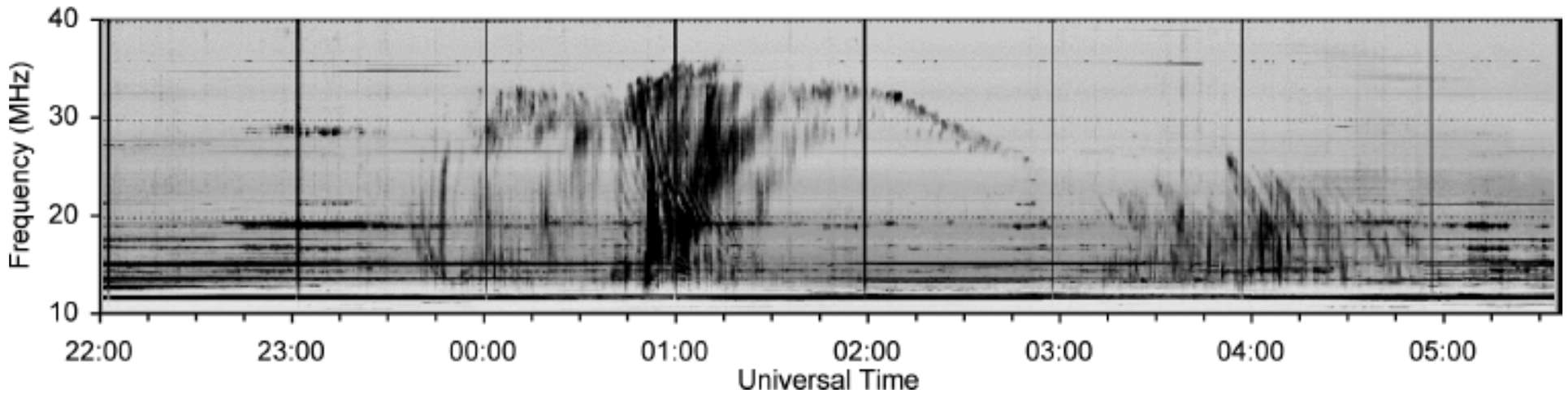
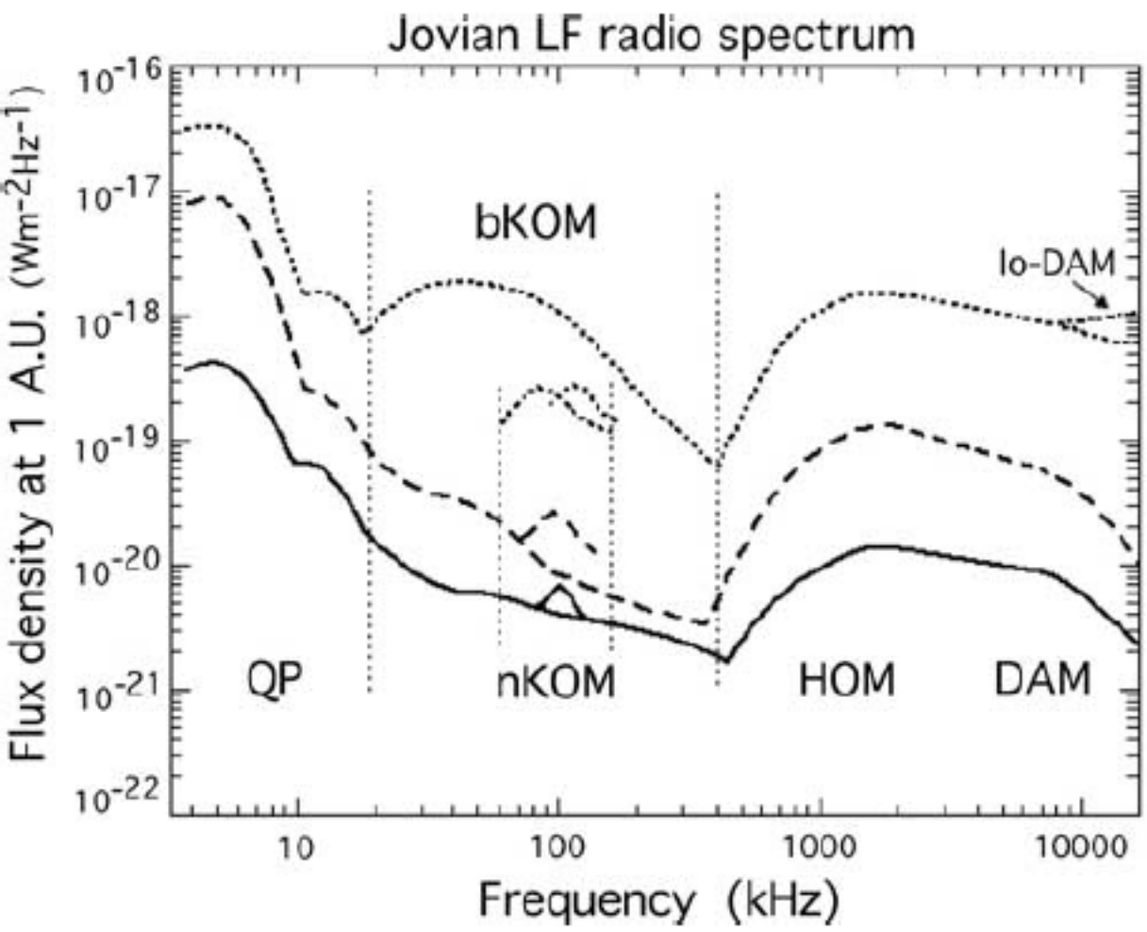
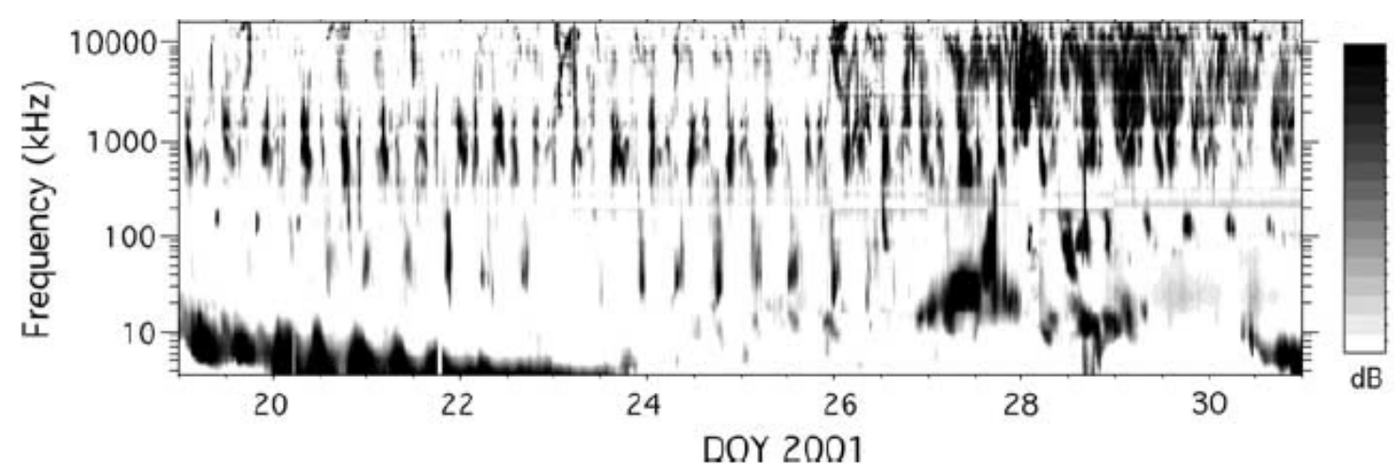


- Jupiter's radio spectrum & timescales







- Some requirements for SKA searches of Xo MS and/or SPI radio emissions

→ Must significantly improve / LOFAR (if no detection)

- High sensitivity : mJy - 10's μJy at timescales from sec to hours
  flux density limited by emission processes and distance
  timescales limited by narrow beaming / visibility window of expected emission
  Jupiter decameter emission @ 10 pc peaks at ~25 μJy (sec - min timescale)
  3 μJy (hour timescale)
- Broad frequency range, from 50 MHz to >> GHz
- Broad instantaneous frequency coverage
- Circular / Full polarization
- Need to observe many targets many hours
  (5°x5° FoV, multi-beam (several fields) capability ?, high duty cycles,
  coordinated programs (EoR, transients ?), commensal obs. ?)

• Some requirements for SKA searches of Xo MS and/or SPI radio emissions

→ Must significantly improve / LOFAR (if no detection)

- SKA1-low baseline design essentially Ok
  (hierarchical distribution of log-per. dipoles)
- 50-100 km max. baselines : low enough confusion, peeling... ?
  → high dynamic range observations needed
- RFI mitigation (very low RFI level @ SKA-Low site)
- Imaging 5°x5° field(s) at ~1 sec time resolution + multi-timescales search
- Multi-beam (multi-field) capabiliyty in SKA-Low ?
- Go to frequencies < 50 MHz ?

• Synergies with cool / dwarf / flaring stars studies (with possible strategies for post-flare exoplanet search, VLBI observations...), & with SETI