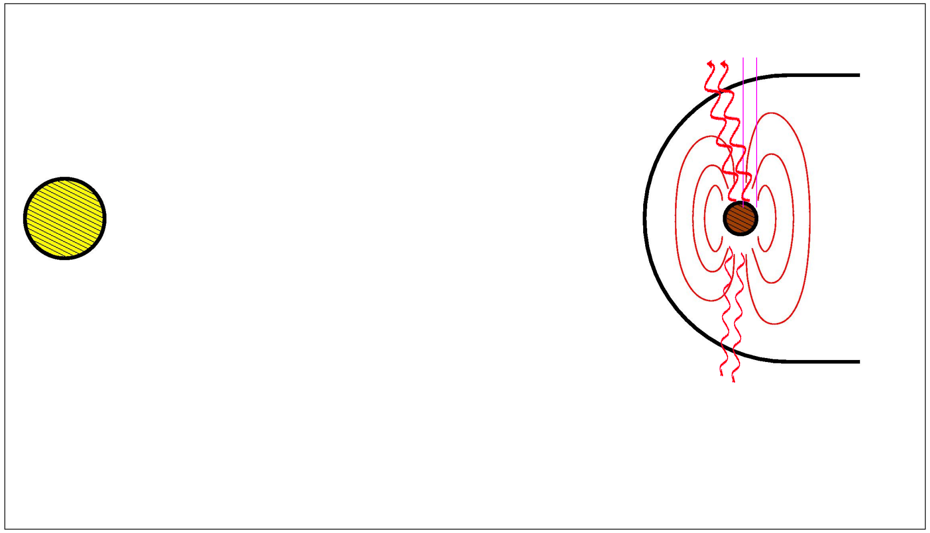
Mechanisms of radio emission from exoplanets



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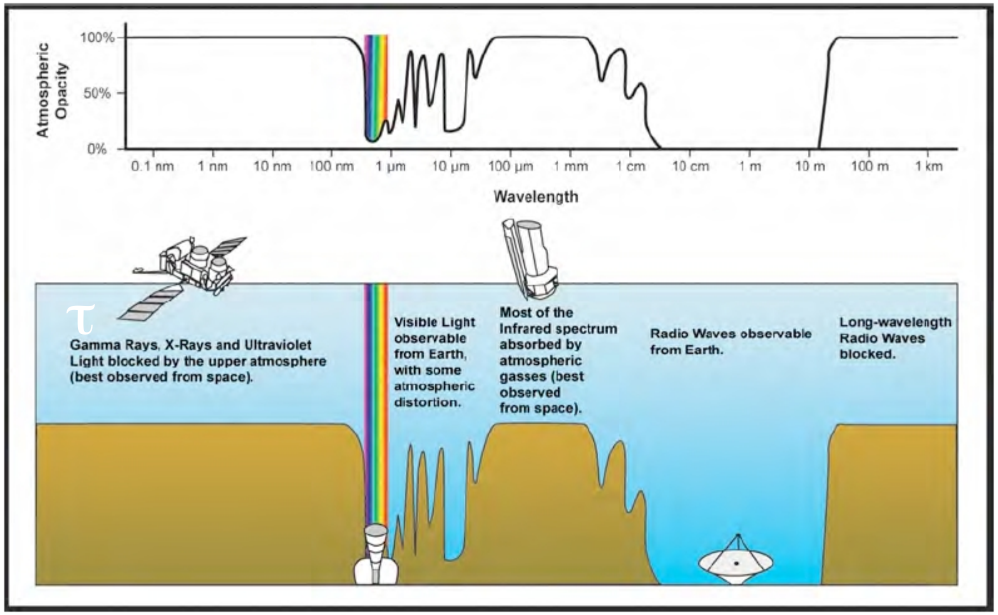
Outline

- radio emission in astrophysics (and planets)
- radio emission of solar system planets
- radio emission of exoplanets
- observational methods
- observations (past, present and future)
- why do we do this?

Radio astronomy

From a technical point of view:

A different kind of astronomy!



- measurement of E-field instead of photon count
- huge range! 3 orders of magnitude in frequency (techniques very different for different frequencies)

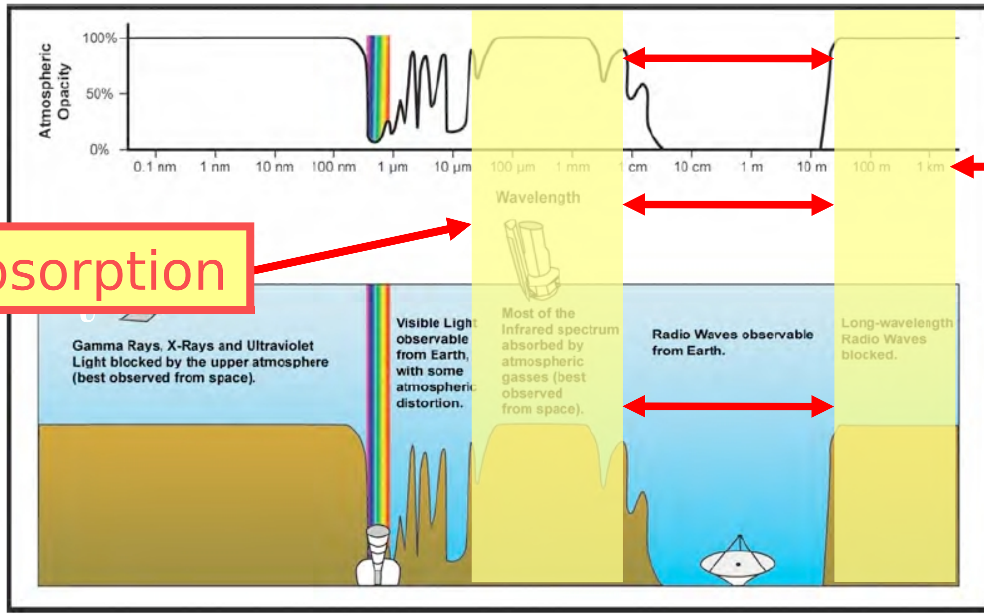
Ground-based radio astronomy

From a technical point of view:

A different kind of astronomy!

absorption

ionosphere



30 GHz

10 MHz

Physics: How to create radio emission

From a physical point of view:
Radio is just some part of the electromagnetic spectrum!

How is electromagnetic emission produced?

Physics: How to create radio emission

From a physical point of view:
Radio is just some part of the electromagnetic spectrum!

How is electromagnetic emission produced?

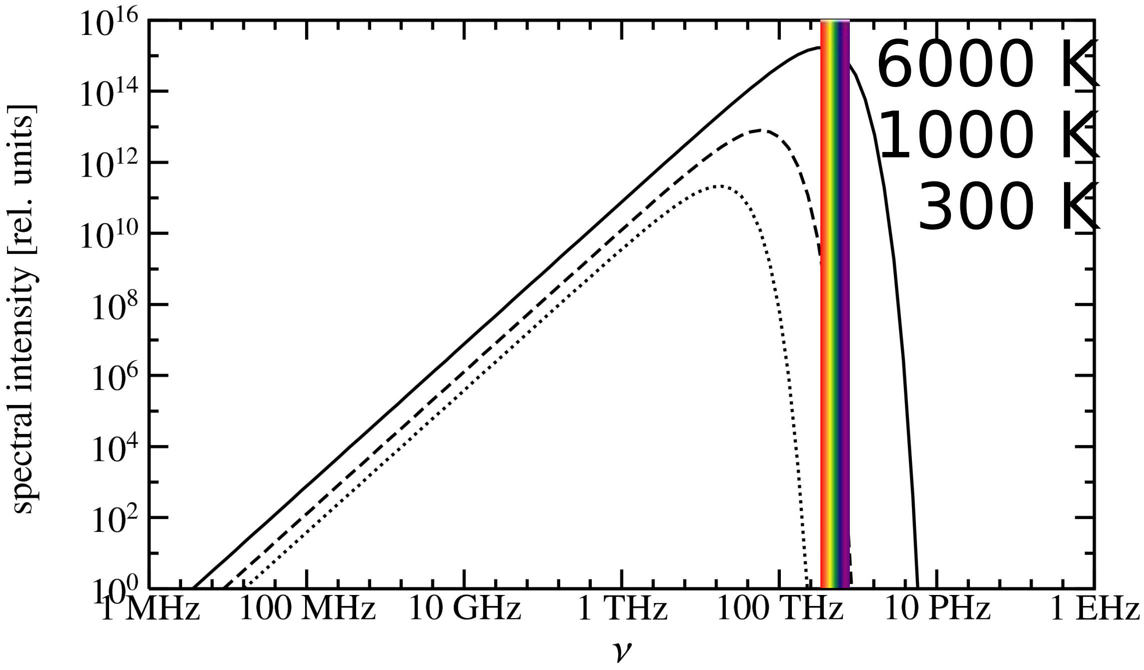
- blackbody radiation
- QM transitions (principal quantum number, angular quantum number, nuclear spin/electron spin, molecular rotation, molecular vibration)
- accelerated charges (synchrotron radiation)

Radio emission from planets?

- blackbody radiation
- lightning emission
- synchrotron emission
- magnetospheric emission

Thermal blackbody emission

low T: blackbody radiation seen in radio (not in visible)



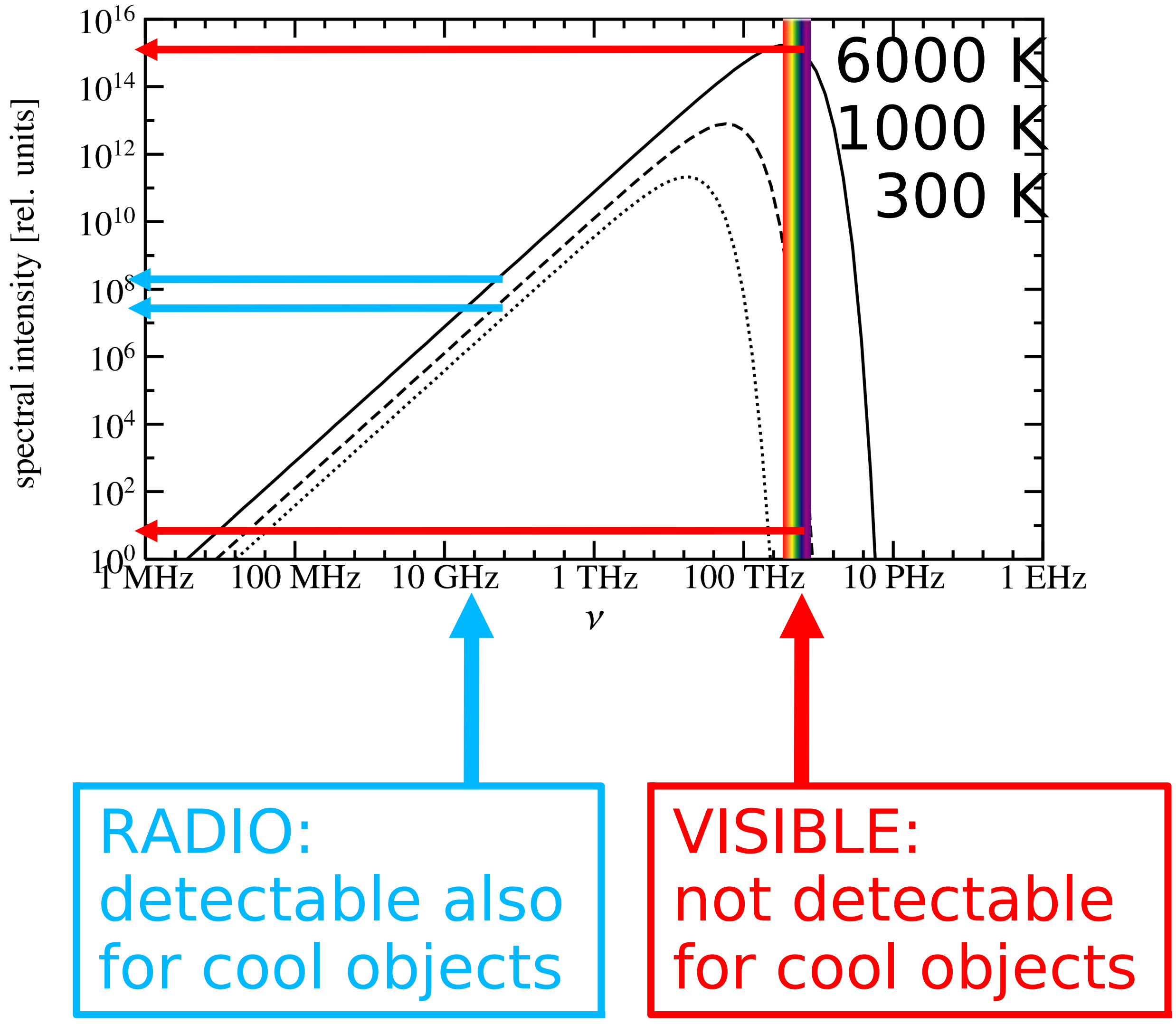
Planck’s law:

(resultats from quantum mechanics)

$$B_\nu(T) = \frac{2h\nu^3/c^2}{\exp(h\nu/kT) - 1}$$

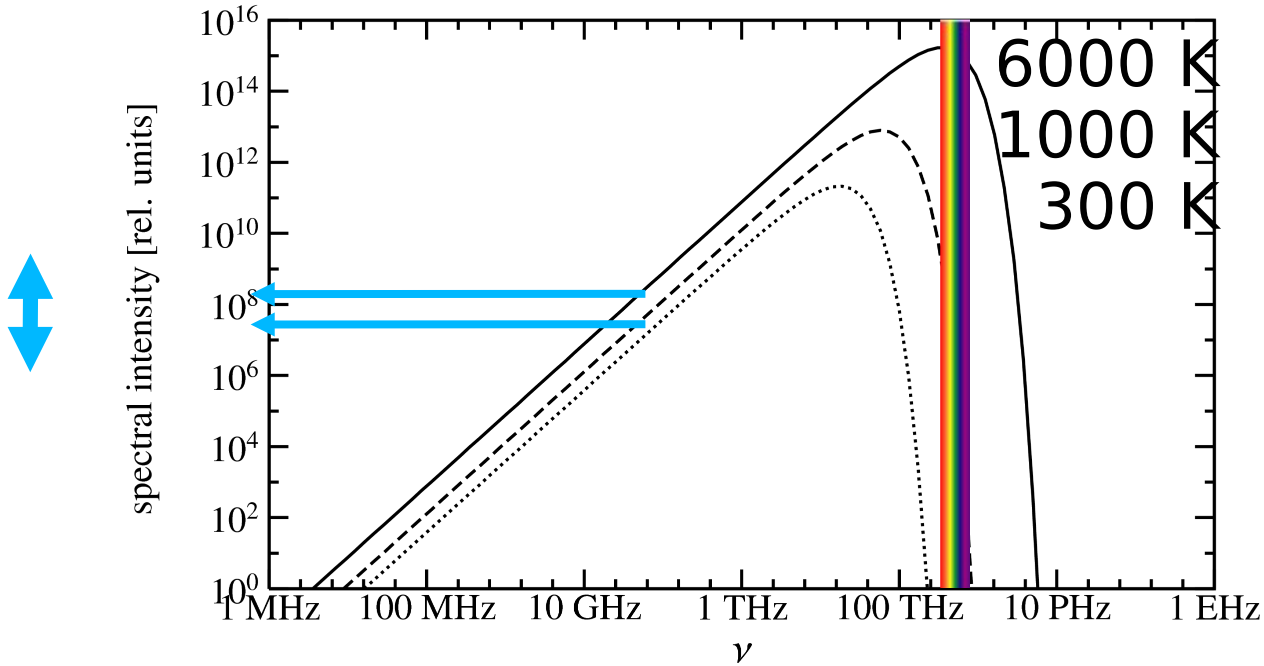
Thermal blackbody emission

low T: blackbody radiation seen in radio (not in visible)



Thermal blackbody emission

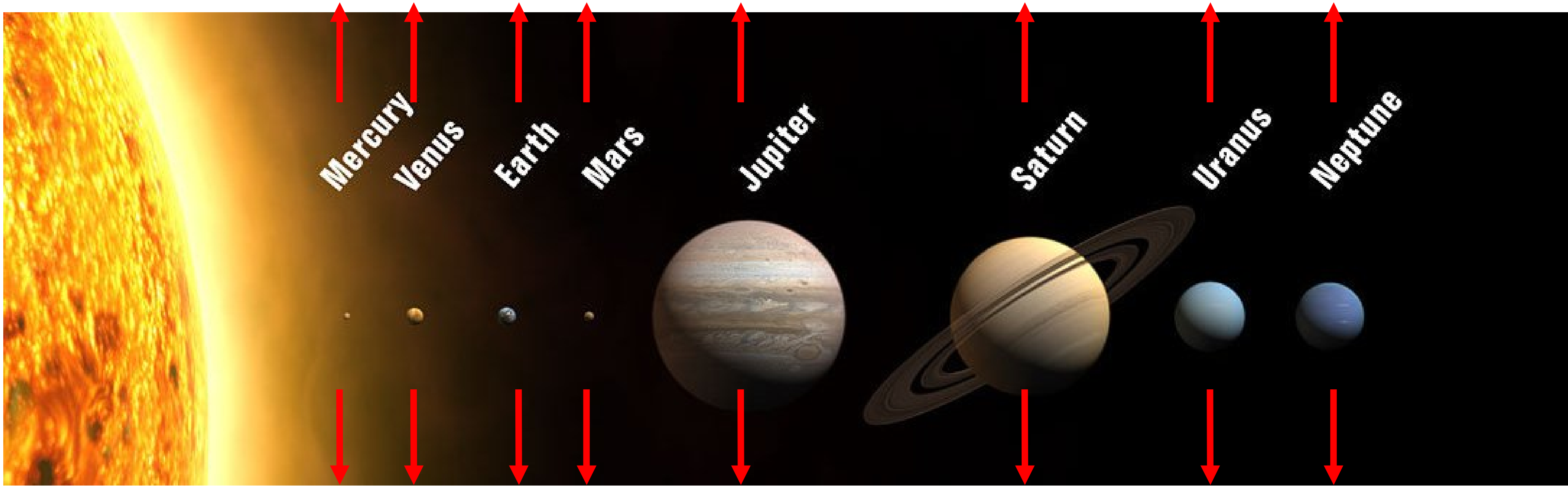
low T: blackbody radiation seen in radio (not in visible)



Can be used to determine temperature!

Planetary radio emission

thermal
(blackbody)



Thermal blackbody emission

Venus

radio (375 GHz)	700 K
IR	225 K

Thermal blackbody emission

Venus

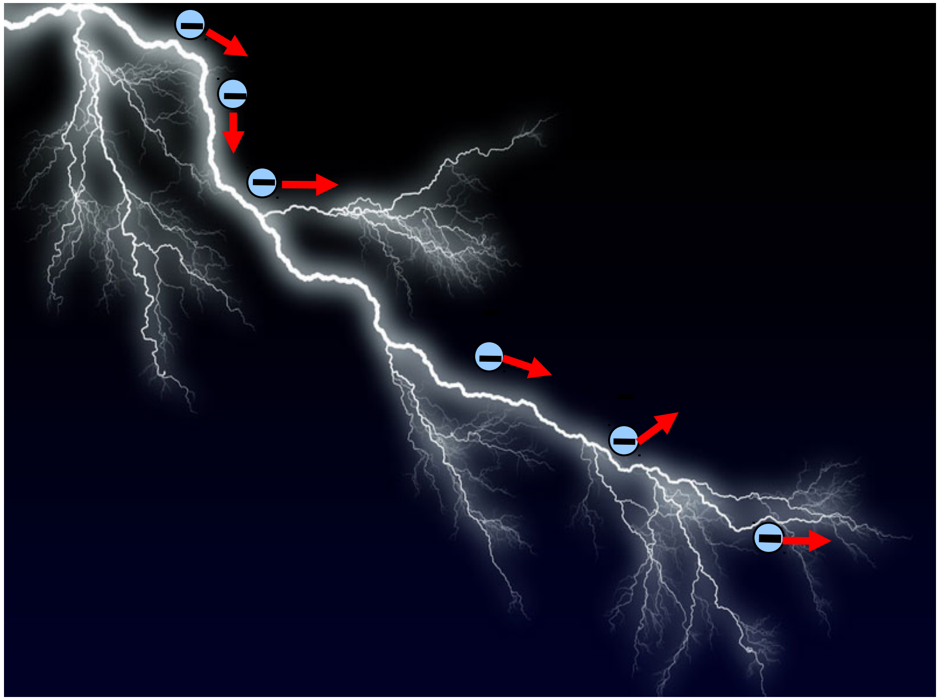
radio	(375 GHz)	700 K (surface temperature)
IR		225 K (cloud temperature)

Greenhouse effect (high CO_2, H_2O, SO_2)
Emission first measured 1956

Radio emission from planets?

- blackbody radiation
- lightning emission
- synchrotron emission
- magnetospheric emission

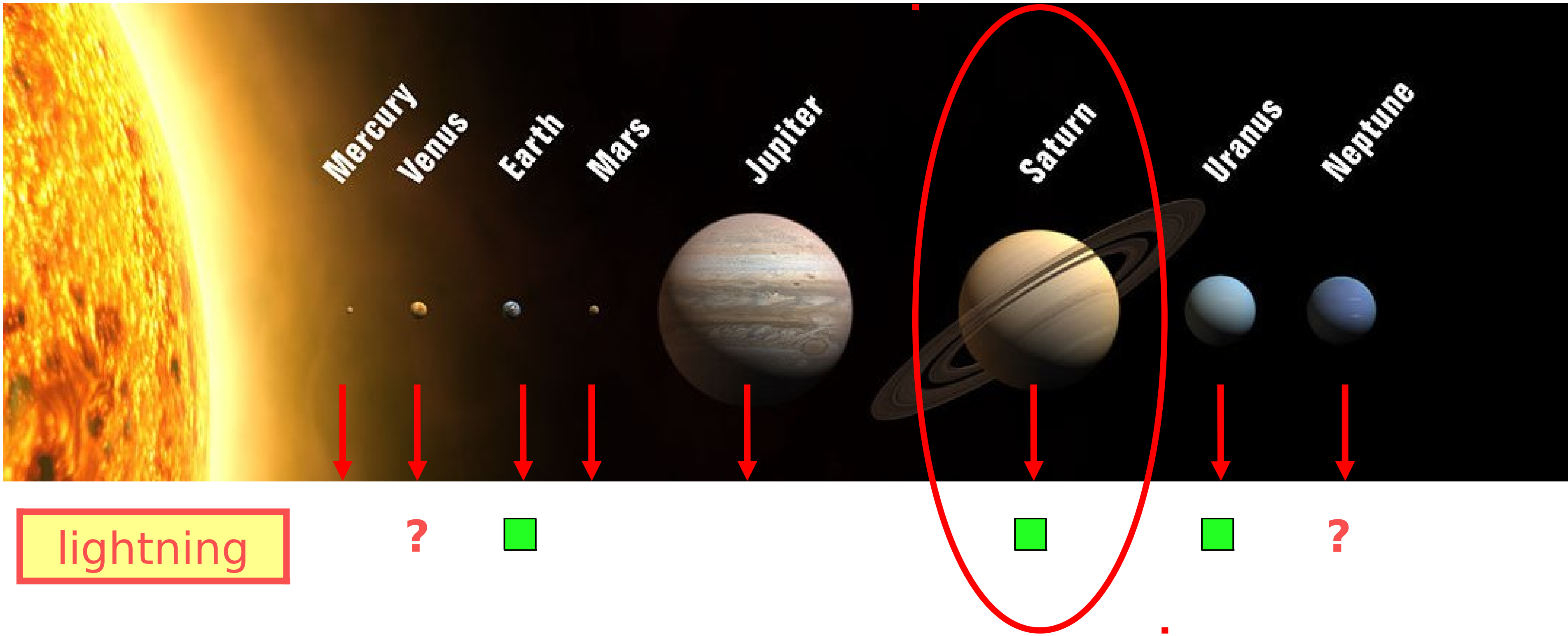
Lightning



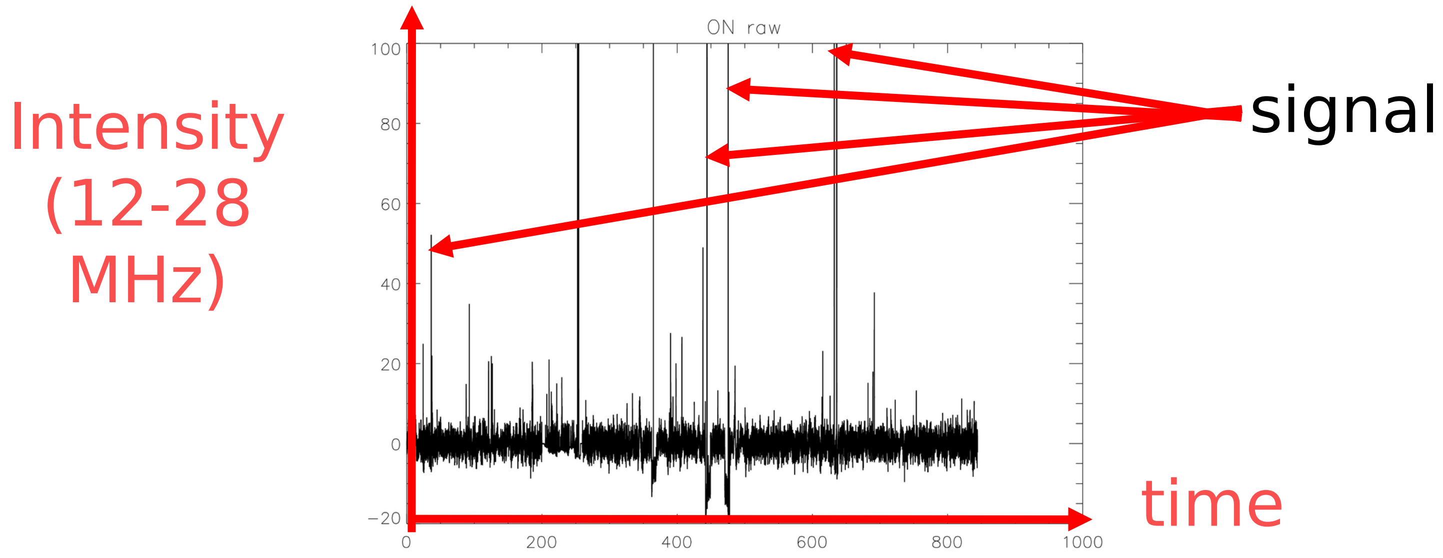
acceleration of charges

⇒ electromagnetic radiation

Lightning emission



Planetary lightning



Radiobursts are:

- weak (no ground detection until 2006)
- short (~15-400 msec)
- broadband (20 kHz-40 MHz)
- transient (OFF since 2011!)

Lightning as a radiosource

Radiosource: lightning activity in corotating storm system

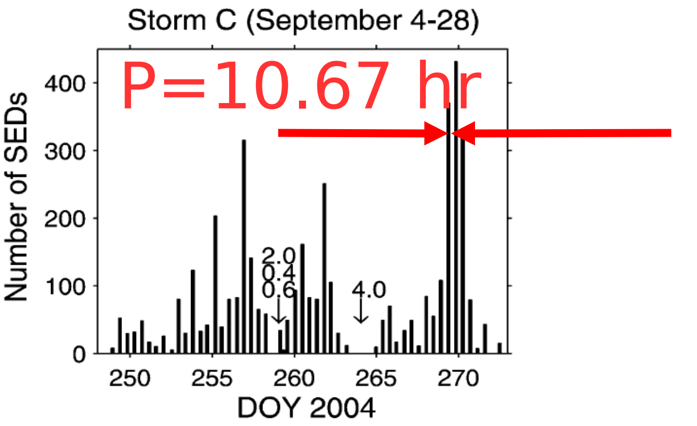
How do we know?

Lightning as a radiosource

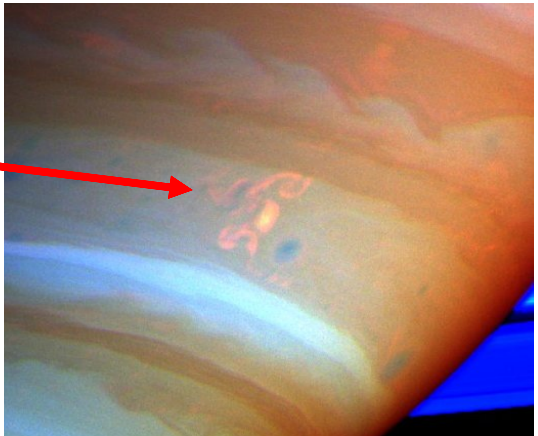
Radiosource: lightning activity in corotating storm system

How do we know?

⇒ episodes repeat after one planetary rotation



⇒ we see the storms in IR (e.g. “Dragon storm”, 2004)



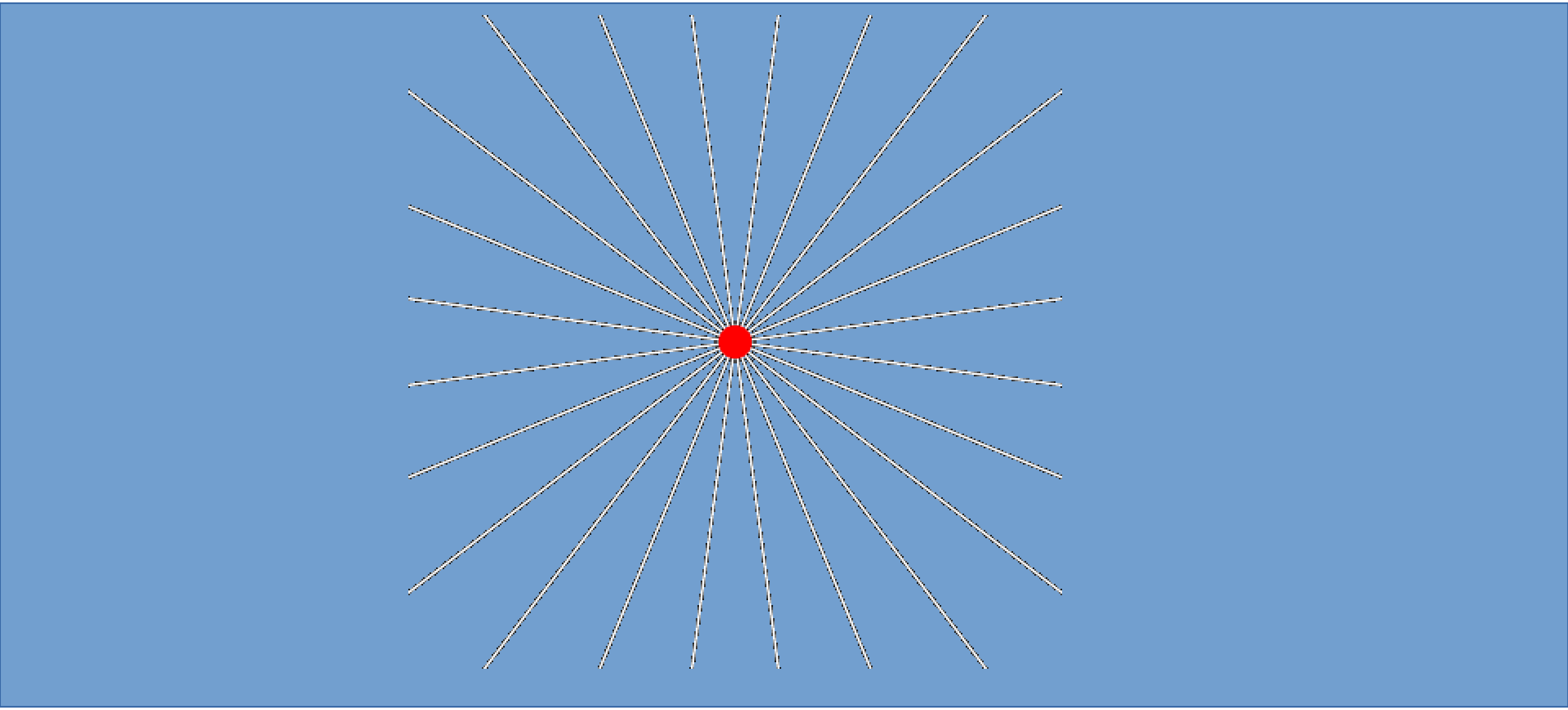
Radio emission from planets?

- blackbody radiation
- lightning
- synchrotron emission
- magnetospheric emission

Accelerated charges

Why should accelerated charged particles create electro-magnetic fields?

A simple experiment (non-relativistic case)



Emitted energy

Electrodynamics: Radiation of an accelerated electron:

$$P_{\text{em}} = \frac{2e^2}{3c^3}\gamma^4\left(a_\perp^2 + \gamma^2 a_\parallel^2\right)$$

where a is the acceleration.

$\gamma = 1/\sqrt{\left(1-\beta^2\right)}$ $\beta = v/c$

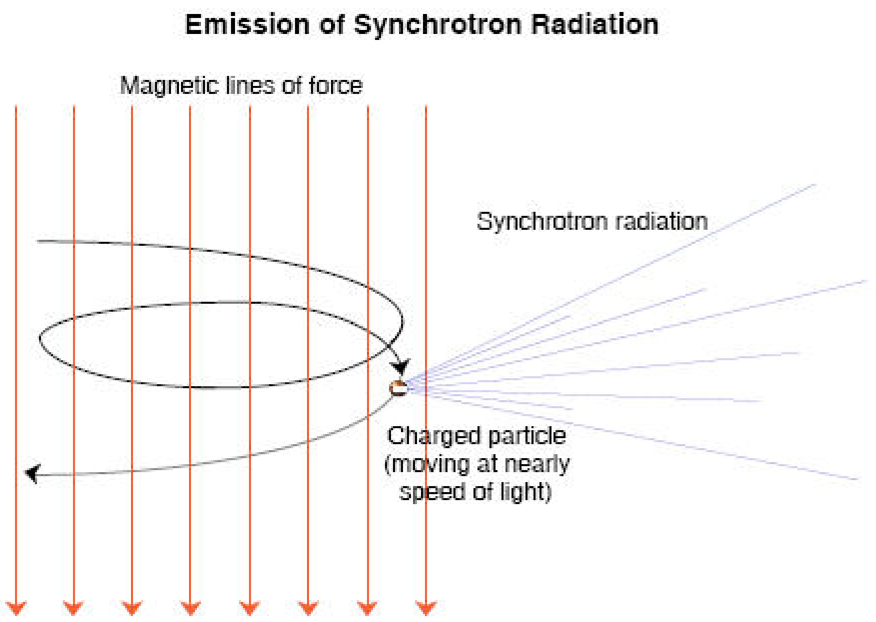
→ cyclotron emission

→ synchrotron emission

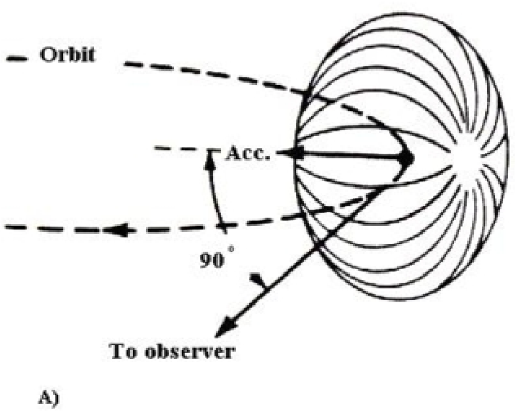
Emission from accelerated charges

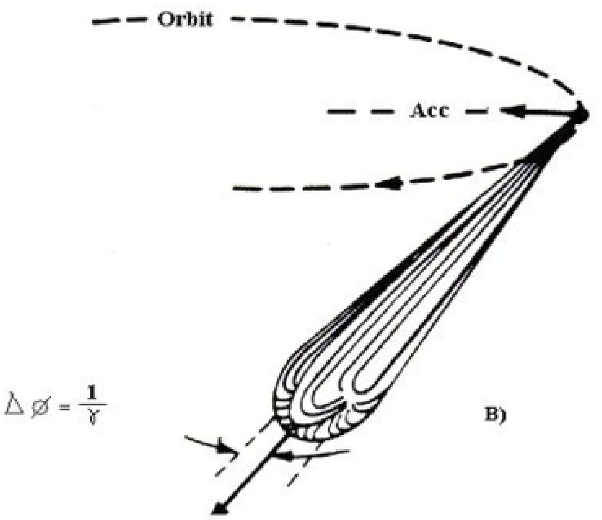
Cyclotron emission: created by non relativistic electrons in a magnetic field

Synchrotron emission: created by relativistic electrons in a magnetic field



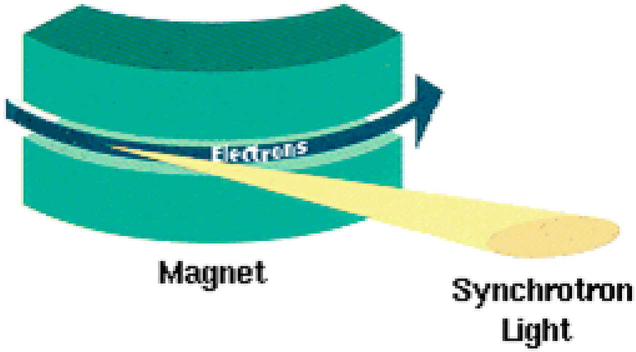
Beaming





Anisotropic beaming:

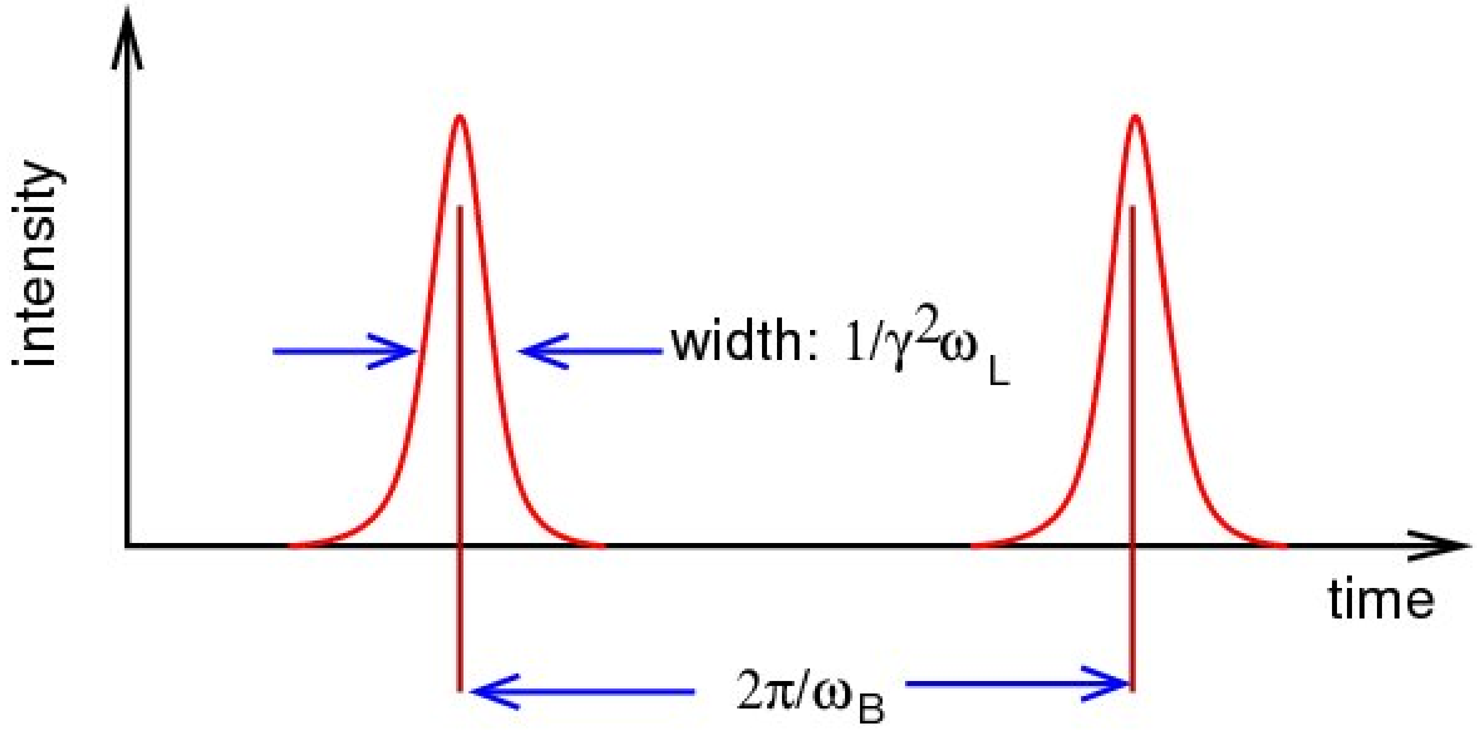
$$\theta_c = \frac{1}{\gamma}\left(\frac{w_c}{w}\right)^{1/3}$$



(results from relativistic electrodynamics)

Emission spectrum of one electron

E(t)

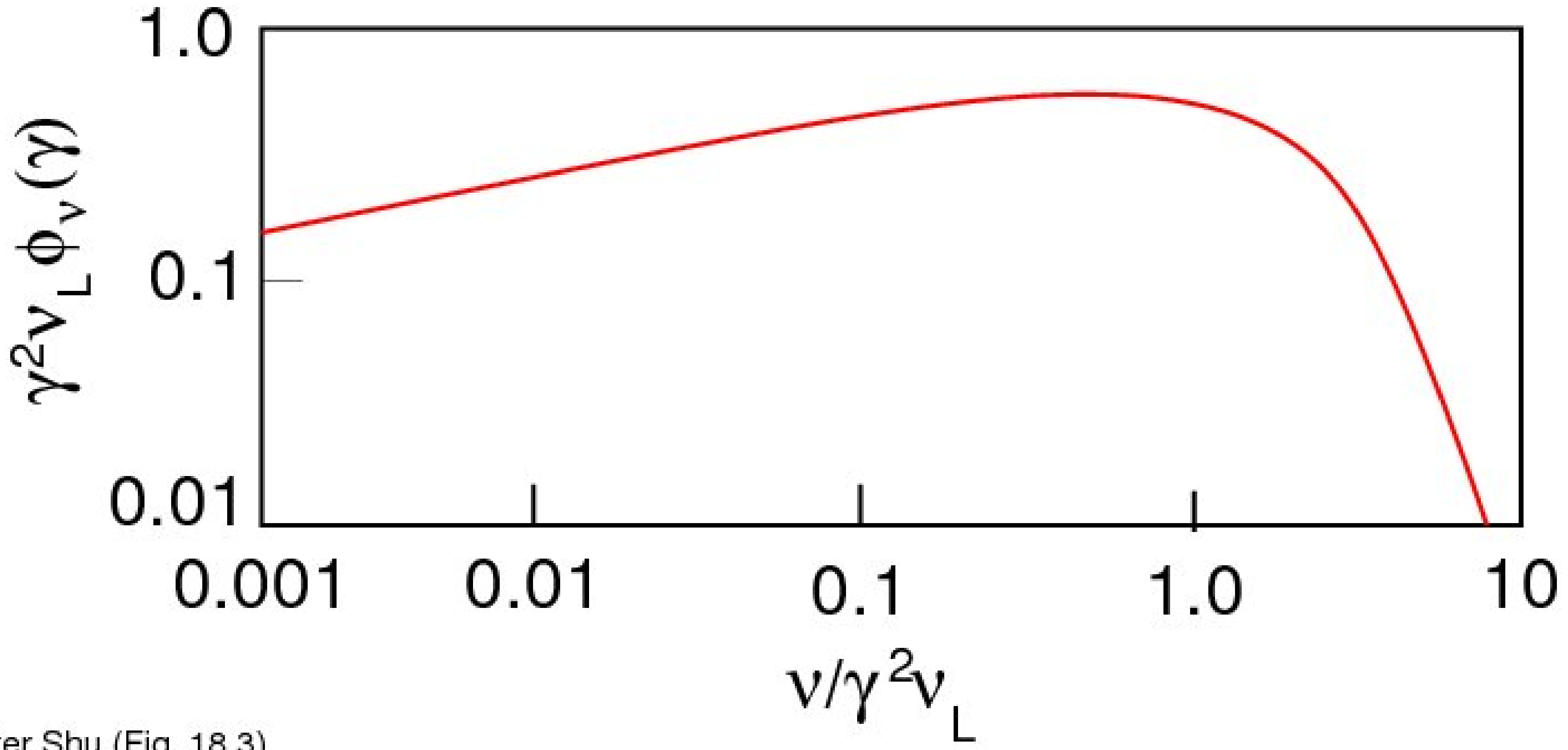


after Shu (Fig. 18.2)

The observed time-dependent E-Field, $E(t)$, from one electron is a sequence of pulses of width τ, separated in time by Δt.

Emission spectrum of one electron

E(ω)=FT{E(t)}

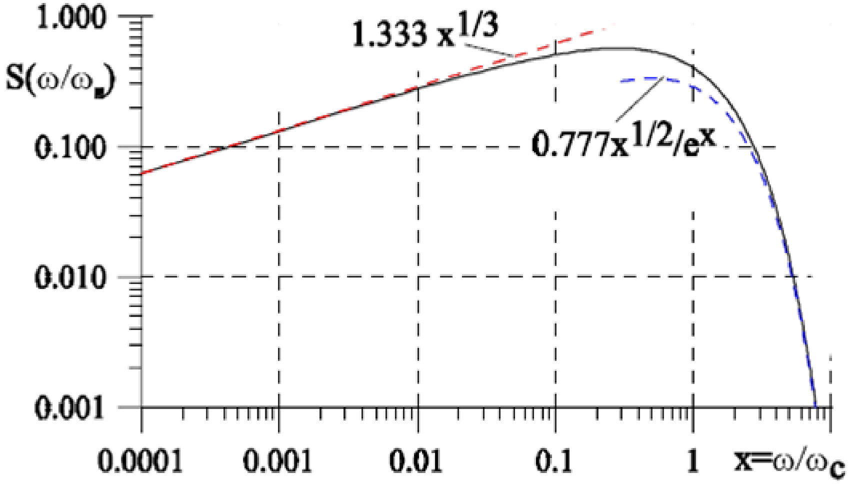


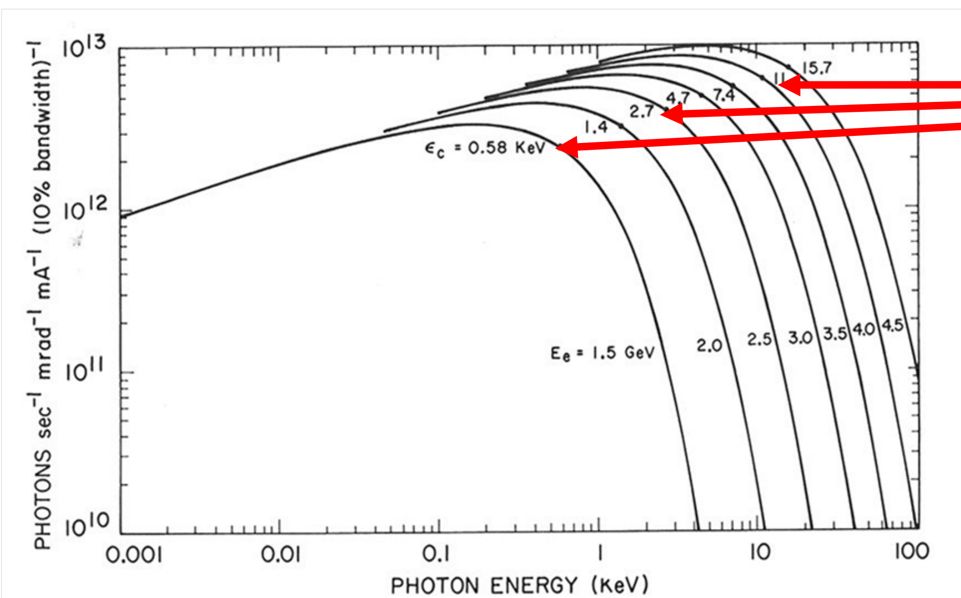
after Shu (Fig. 18.3)

Derive spectrum by Fourier-transforming $E(t)$

τ small $\Longrightarrow$ relevant frequency range quite large.

Emission spectrum of one electron





characteristic frequency/energy

$$\varepsilon_c = \hbar w_c = \frac{3}{2}\frac{\hbar c}{\rho}\gamma^3$$

Cyclotron vs synchrotron: frequency

- cyclotron
  - each location: mono-energetic
  - multiple locations: broad-band up to f_{max}

$$f_c = \frac{eB}{m_e}$$

- synchroton
  - each location: broad-band
  - much higher frequency ($\gamma > 1$)

Cyclotron vs synchrotron: intensity

- cyclotron

  each location: mono-energetic

  → coherent emission possible

- synchrotron

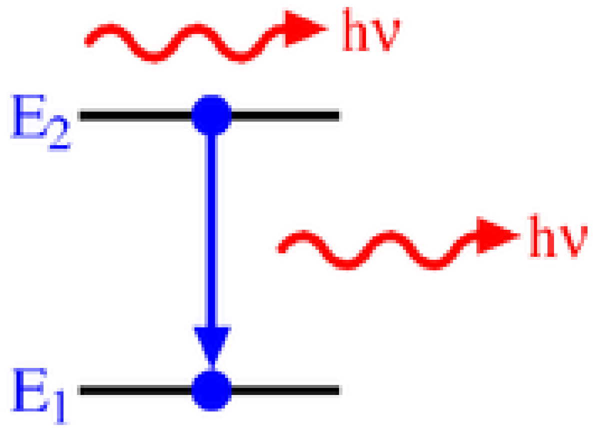
  high intensity

  incoherent emission

  → isotropic emission of planetary environment

Cylotron MASER emission

- monochromatic, induced emission
- similar to LASER
- amplifies within active medium

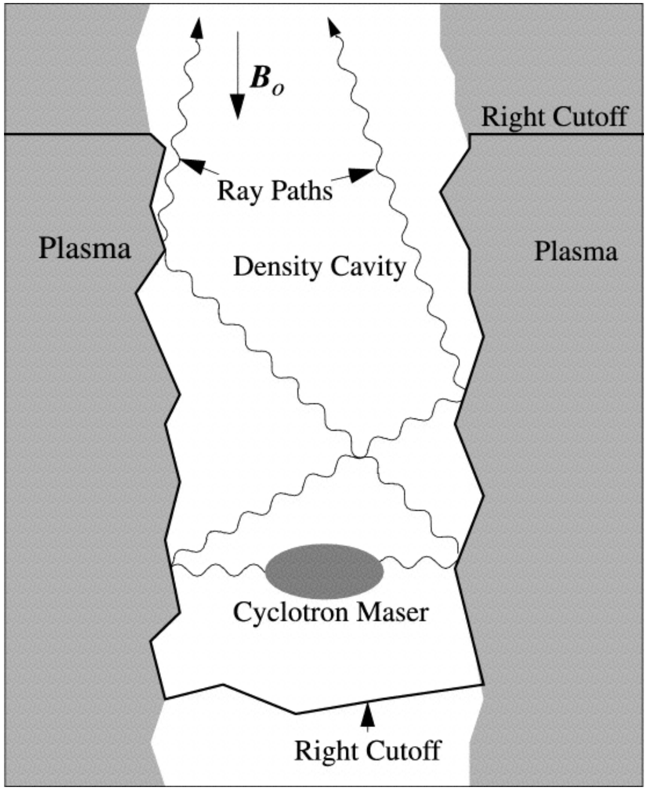


$$\left(\frac{dn_1}{dt}\right)_{B_{21}} = B_{21} n_2 \rho(\nu) \qquad \rho(\nu) = \frac{2h\nu^3}{c^2(e^{h\nu/kT} - 1)}$$

Magnetospheric radio emission

- high latitudes (auroral fieldlines at 2-4 r)
- electrons gyrating in magnetic field
- energy input through stellar wind

- mechanism: cyclotron maser instability



[Ergun et al 2000]

Cyclotron Maser Instability

Imaginary part of wave frequency:

$$\omega_i = \frac{\pi^2 \omega_p^2}{4\omega_r} \int\limits_{-\infty}^{+\infty} dv_\parallel \int\limits_{0}^{+\infty} dv_\perp v_\perp^2 \delta\left(\omega_r - \frac{\omega_c}{\Gamma} - k_\parallel v_\parallel\right) \omega_c \frac{\partial f_0}{\partial v_\perp}$$

condition for growth:

$$\omega_i > 0$$

required:

$$\omega_r - \frac{\omega_c}{\Gamma} - k_\parallel v_\parallel = 0$$

$$\frac{\partial f_0}{\partial v_\perp} > 0$$

[Wu and Lee 1979]

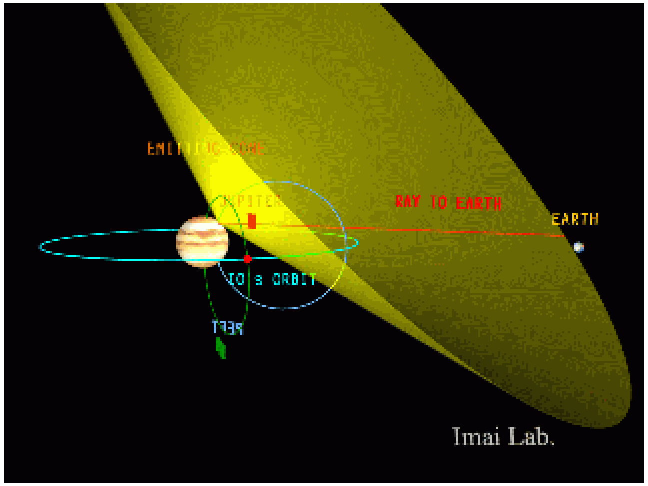
Cyclotron Maser Instability

Imaginary part of wave frequency:

$$\omega_i = \frac{\pi^2 \omega_p^2}{4\omega_r} \int_{-\infty}^{+\infty} dv_\parallel \int_0^{+\infty} dv_\perp v_\perp^2 \delta\left(\omega_r - \frac{\omega_c}{\Gamma} - k_\parallel v_\parallel\right) \omega_c \frac{\partial f_0}{\partial v_\perp}$$

⇒ … ⇒ strong beaming!

emission on a hollow cone

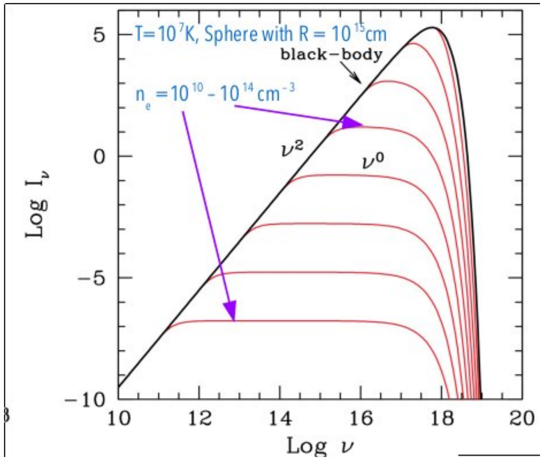


Cyclotron vs synchrotron: intensity

- cyclotron
  each location: mono-energetic
  coherent emission possible
  → strongly beamed

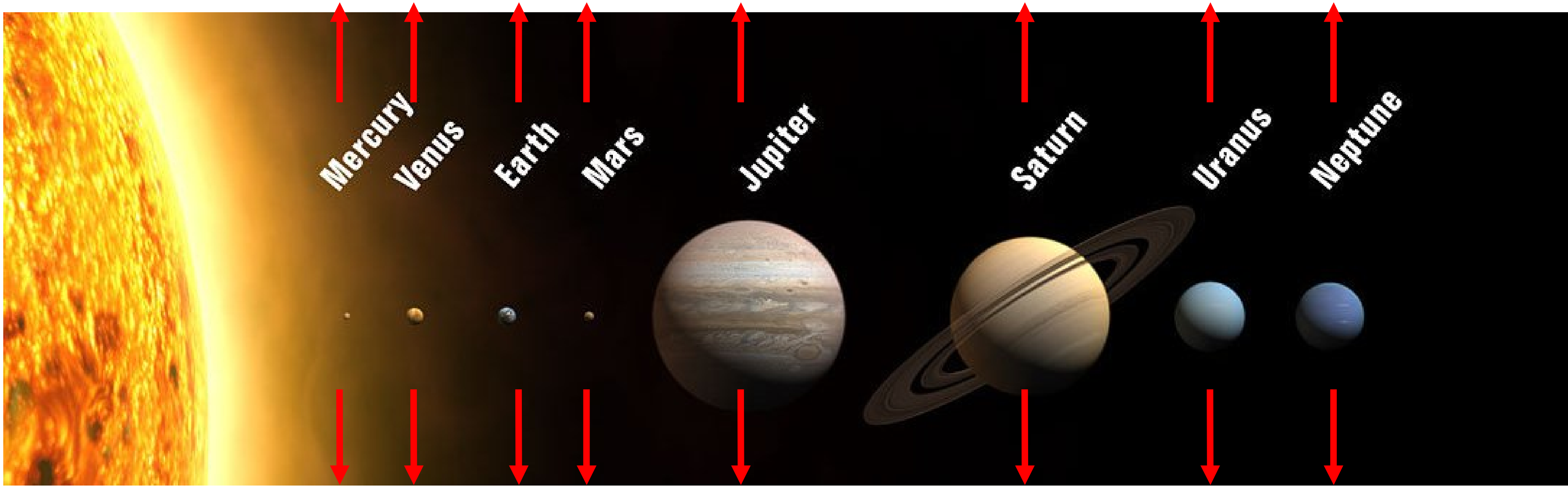
- synchrotron
  high intensity
  incoherent emission (limited by LTE)
  → isotropic emission of planetary environment

- both will exist!
- synchrotron "saturates" (opt. thick)
- cyclotron can be "arbitrarily strong"

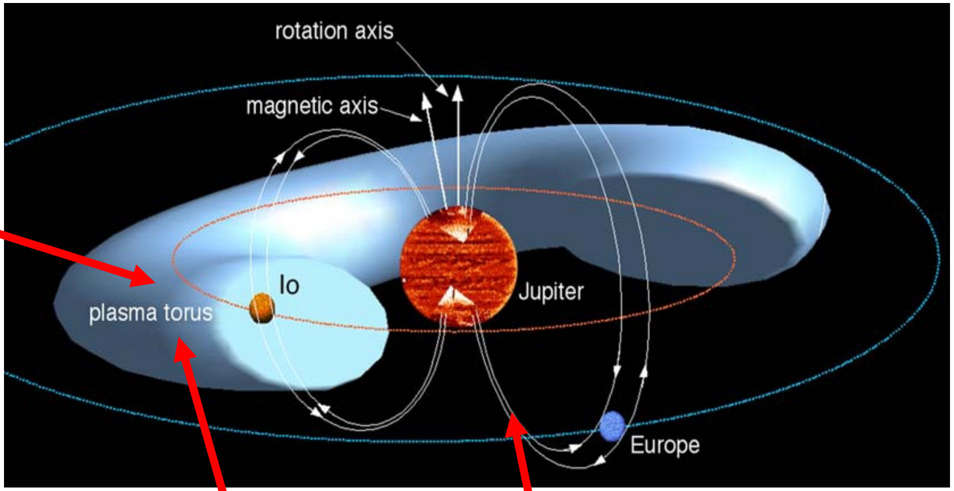


Planetary radio emission

synchrotron



Jupiter

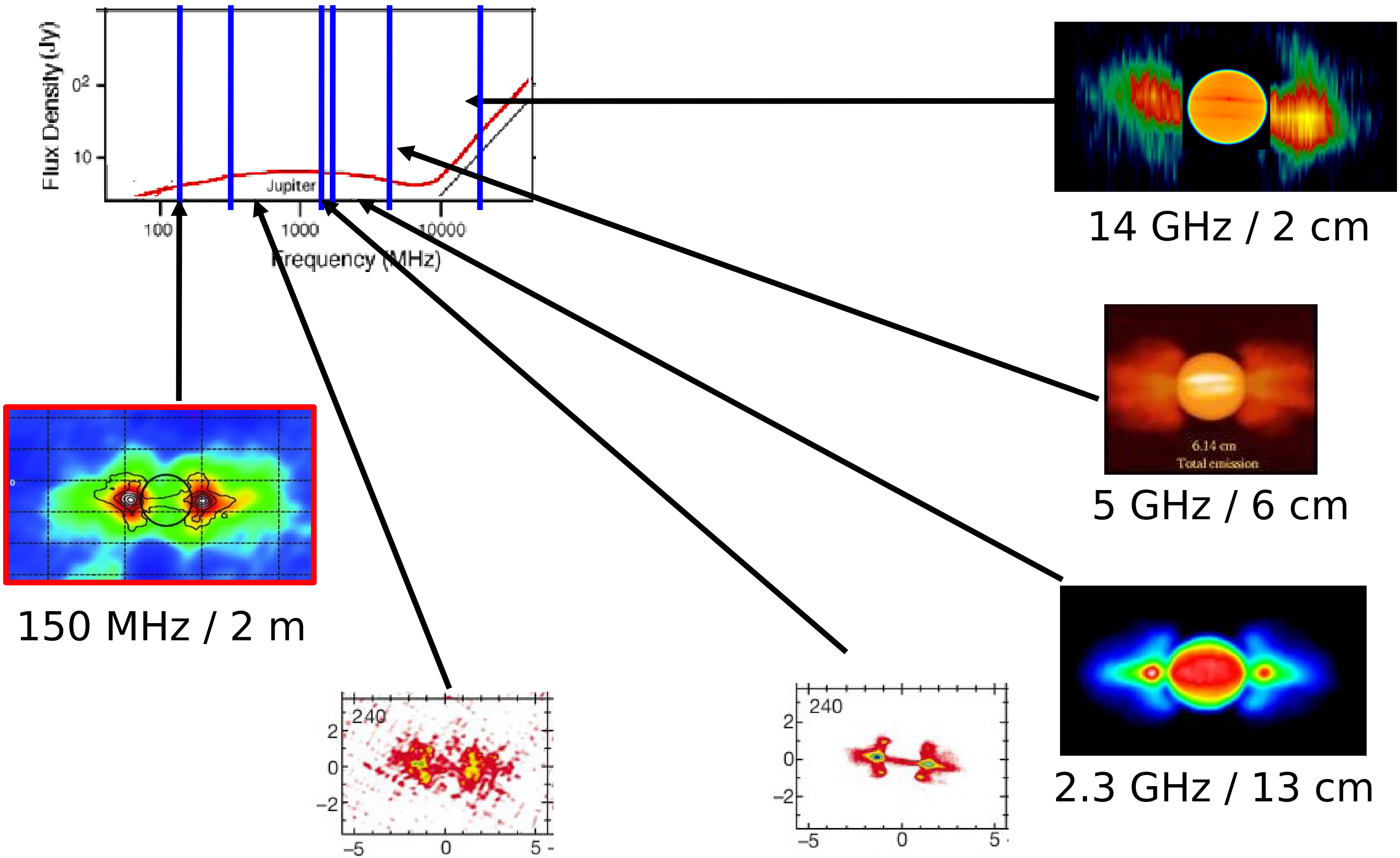


Io plasma torus

magnetic field

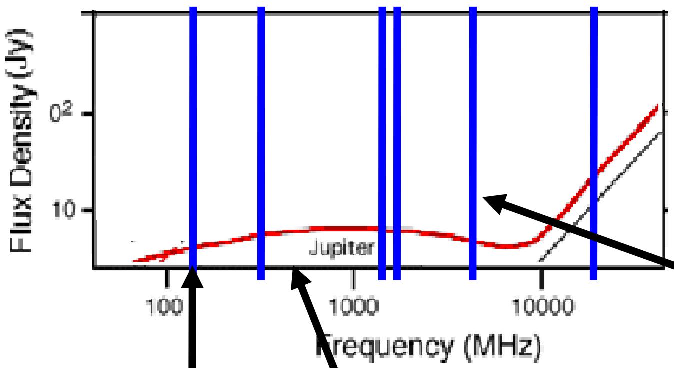
relativistic particles (1-100 MeV)

Jupiter

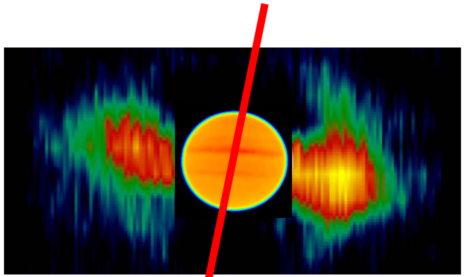


Flux Density (Jy)
10
Jupiter
100
1000
10000
Frequency (MHz)
14 GHz / 2 cm
6.14 cm
Total emission
5 GHz / 6 cm
2.3 GHz / 13 cm
150 MHz / 2 m
240
333 MHz / 90 cm
1.4 GHz / 20 cm

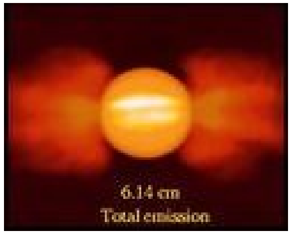
Jupiter



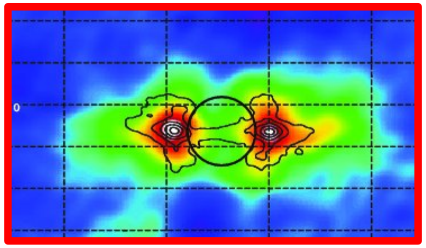
tilt of magnetic axis



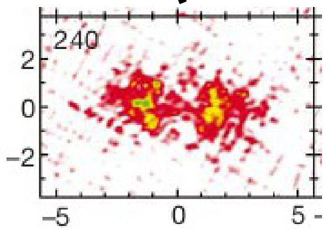
14 GHz / 2 cm



5 GHz / 6 cm

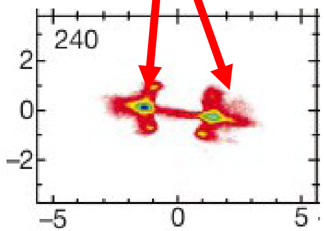


150 MHz / 2 m

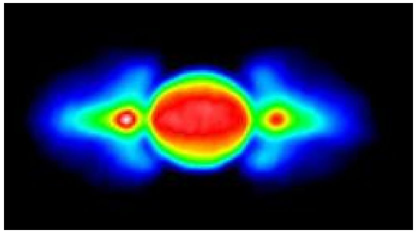


333 MHz / 90 cm

Io plasma torus

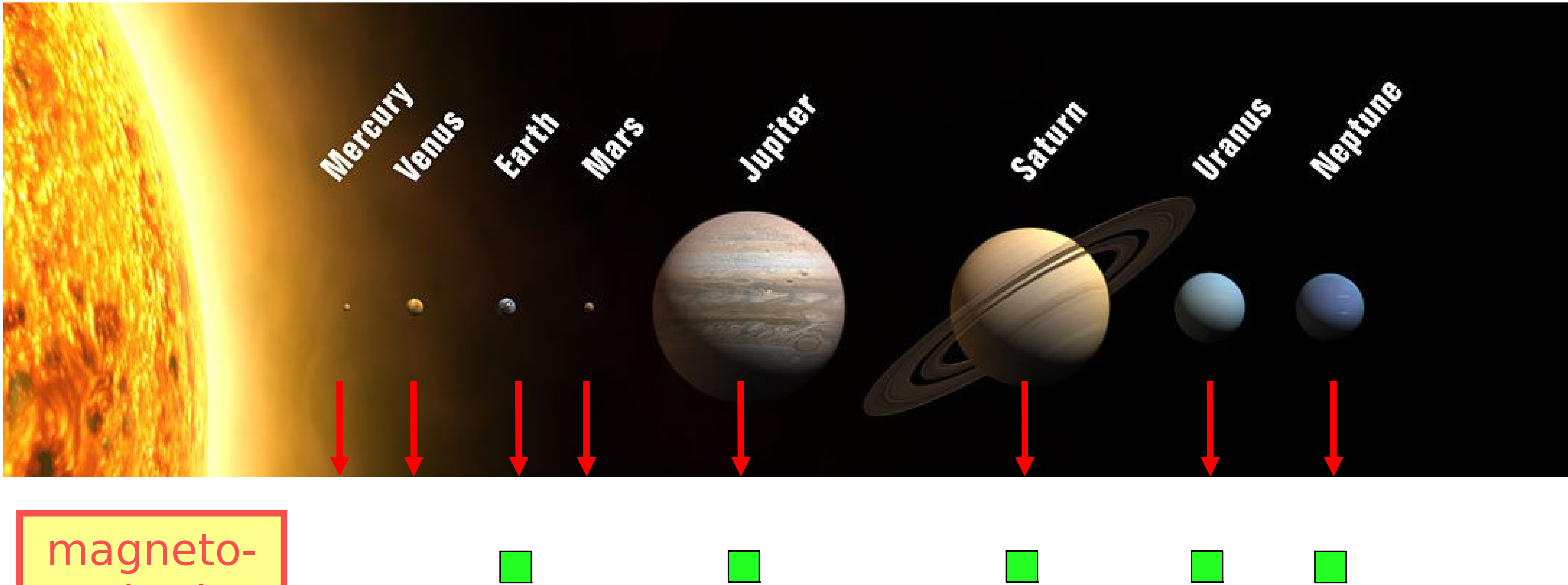


1.4 GHz / 20 cm



2.3 GHz / 13 cm

Magnetospheric emission



magneto-spheric

Magnetospheric radio emission

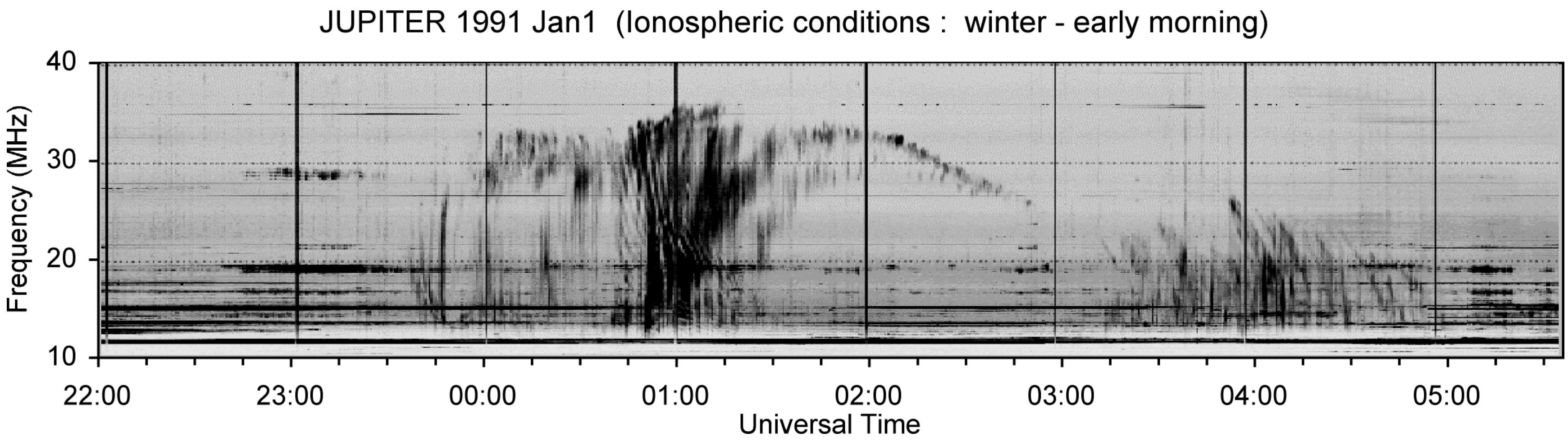
First radio observations:

• Jupiter:	DAM	1955	(ground observation)
• Earth:	AKR	1965	(Elektron-2)
• Saturn:	SKR	1980	(Voyager 1)
• Uranus:	UKR	1986	(Voyager 2)
• Neptune:	NKR	1989	(Voyager 2)

$\Rightarrow$ all strongly magnetized planets are nonthermal radio emitters!

Jupiter’s radio emission

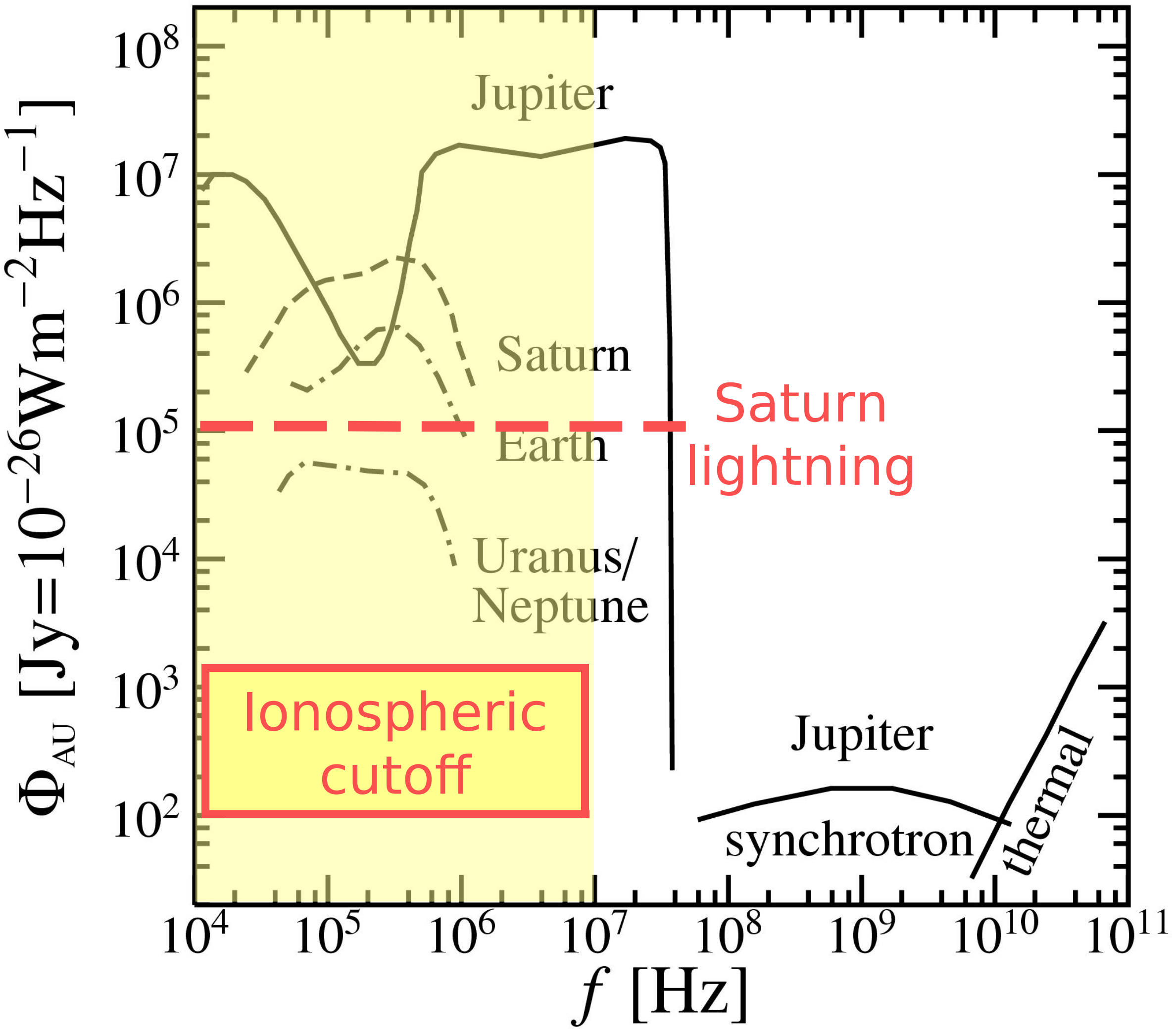
Decametric radio emission of Jupiter



- series of intense radio bursts
- f < 40 MHz
- cyclotron maser emission
- generated in planetary magnetosphere
- timescales: ms (intrinsic) to h (geometry)

$$f_c \propto \frac{eB}{m_e}$$

Radio emission: Comparison



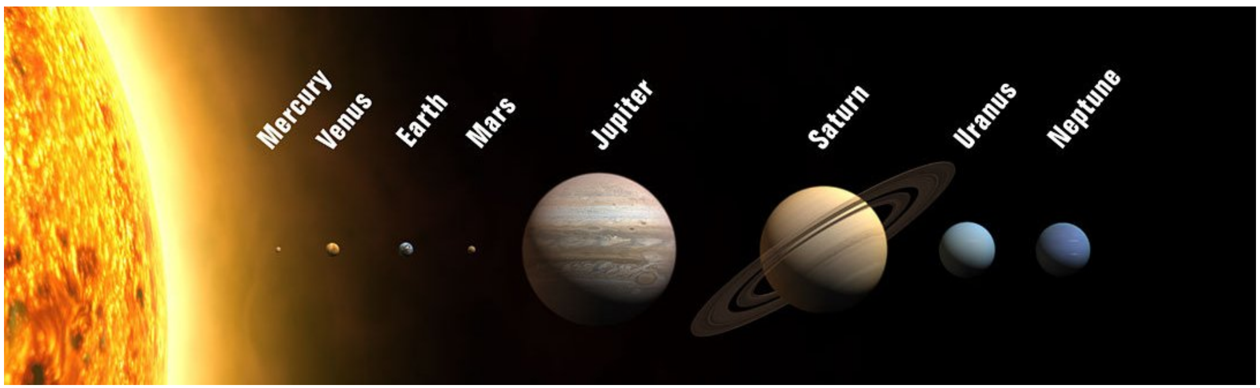
magnetospheric emission much brighter than thermal, lightning or synchrotron emission!

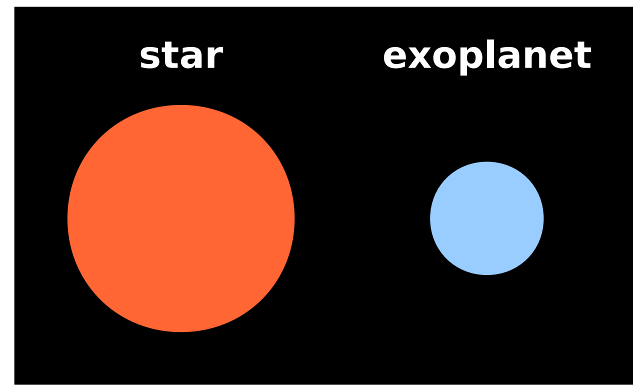
flux normalized to 1 AU

Extrasolar planets

thermal (blackbody) ?

synchrotron ?



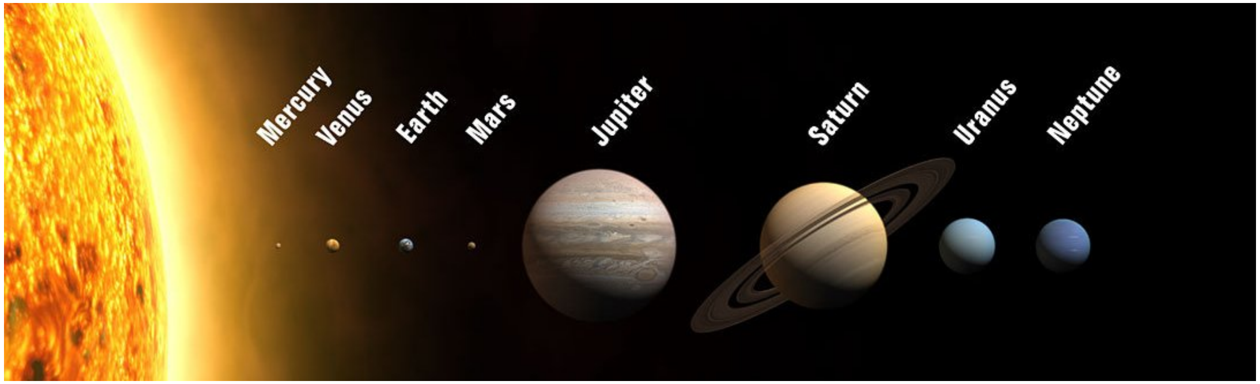


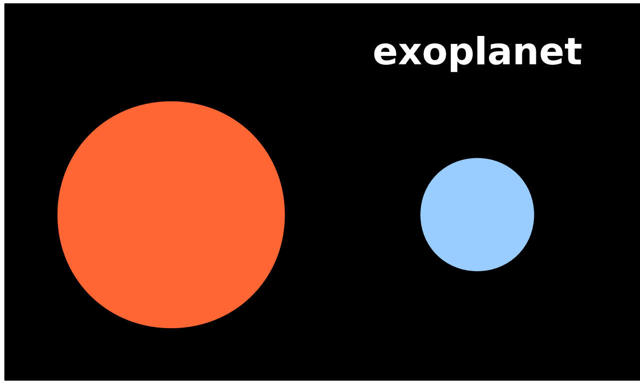
? ? lightning ?

magneto-spheric ?

Extrasolar planets

Sounds easy? It isn't!

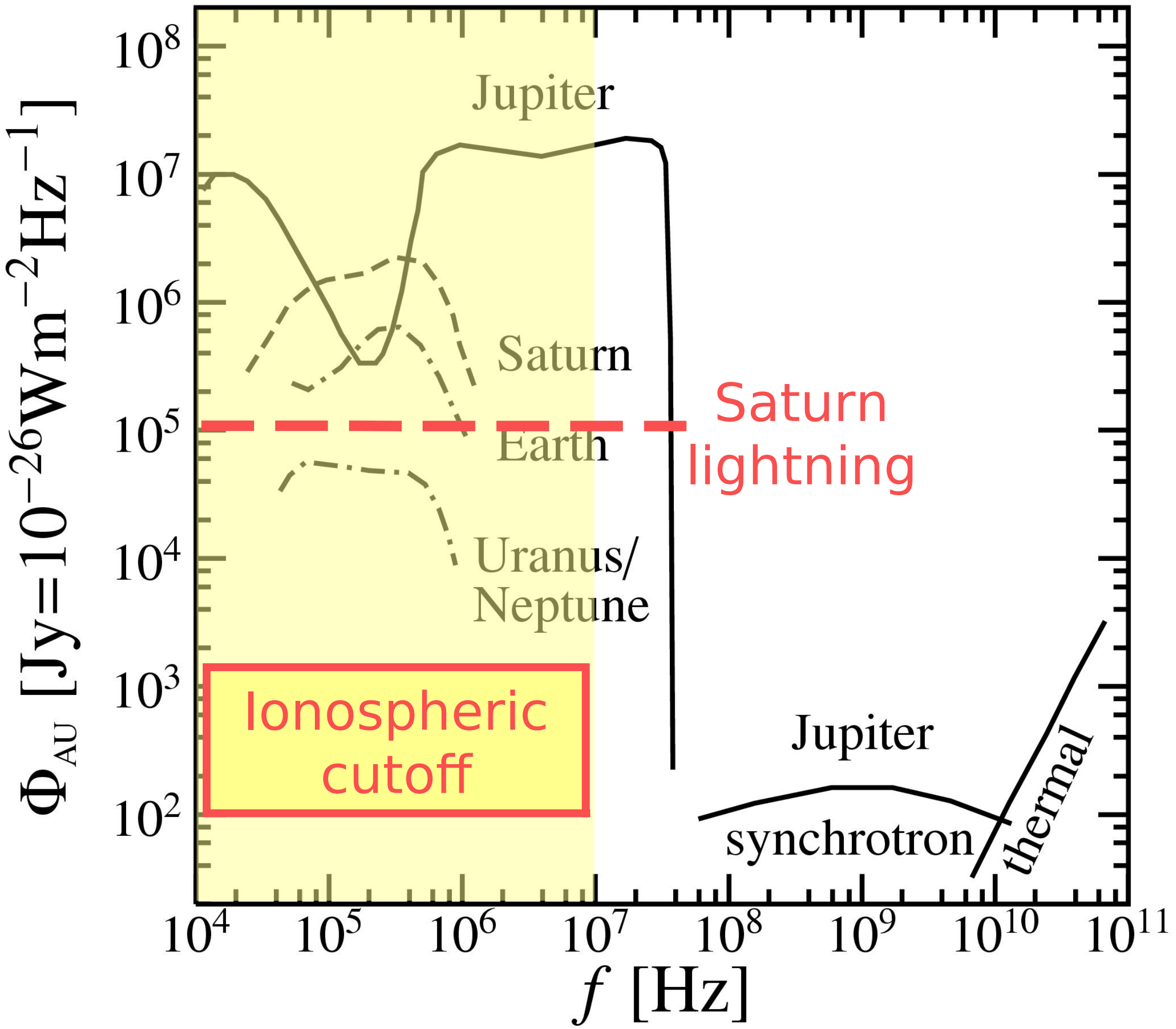




distance = 10^{12} m
rel. signal = 1

distance = 10^{17} m
rel. signal = 10^{-10}

Radio emission of exoplanets



faint
⇓
need large telescopes
⇓
> 10 MHz
(ionospheric cutoff)

flux normalized to 1 AU

Extrasolar planets

astronomical distances:

rel. signal = 10^{-10}

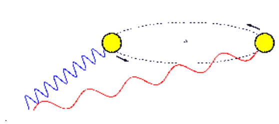
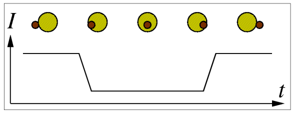
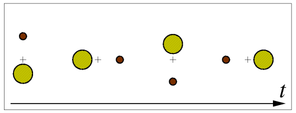
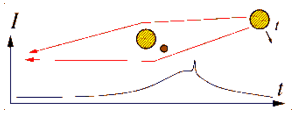
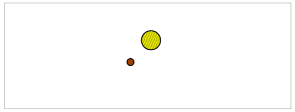
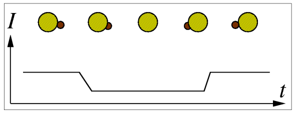
- blackbody radiation?
- synchrotron emission?
- lightning emission?
- magnetospheric emission?

Extrasolar planets

astronomical distances: rel. signal = 10^{-10}

- blackbody radiation? → too faint & star too close
- synchrotron emission? → too faint
- lightning emission? → too faint
- magnetospheric emission? → maybe?

Why do we do this?

Doppler shift	Transit	Astro-metry	Micro-lensing	Direct obs.	Second. Transit
					
1995 (51 Peg b)	2000 (HD209458b)	2002 ? (Gl 876 b)	2003 (O235/M53)	2004 (2M1207)	2004 (HD209458b)
>1000	>3000	20?	>200	>200	>80

Radio emission as additional source of information?

Why do we do this?

$$f_c \propto \frac{eB}{m_e}$$

if B=0 → no emission!

Why do we do this?

Superflares	[Rubenstein 2000; Schaefer 2000]
Planetary migration	[Lovelace 2008]
H_3^+ emission	[Skholnik 2006]
Gas giant mass loss	[Lammer 2009]
Chrom. emission	[Saar 2004]
Early ingress	[Fossati 2010]
Transit profiles (ENAs)	[Holmström 2008]
Radio emission	
Atmospheric loss	[Grießmeier 2010; Driscoll 2013]
Cosmic rays	[Grießmeier 2005, 2009]
Comet-like exosphere	[Mura 2011]

$$f_c \propto \frac{eB}{m_e}$$

if B=0 → no emission!

Why do we do this?

other effects have similar signature

Observation	Expected effect	False positives?
Superflares	Weak or none	Yes [Maehara 2012; Shibayama 2013]
Planetary migration	Weak	Yes [Lovelace 2008; Vidotto 2009, 2010]
H_3^+ emission	Yes?	Yes [Skholnik 2006]
Gas giant mass loss	Yes	Yes [Lammer 2009; Khodachenko 2012, 2015]
Chrom. emission	Yes	Yes [Saar 2004; Preusse 2006; Kopp 2011]
Early ingress	Yes	Yes [Fossati 2010; Lai 2010; Bisikalo 2013a,b]
Transit profiles (ENAs)	Yes	No? [Holmström 2008; Ekenbäck 2010; Kislyakova 2014]
Radio emission	Yes	No
Atmospheric loss	Yes	Yes [Grießmeier 2010; Driscoll 2013]
Cosmic rays	Yes	Yes? [Grießmeier 2015; Tabataba-Vakili 2015]
Comet-like exosphere	Yes	No? [Mura 2011; Guenther 2011]

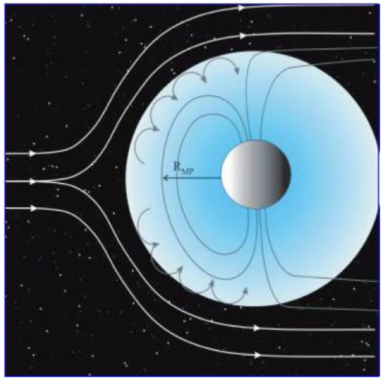
[Grießmeier 2015]

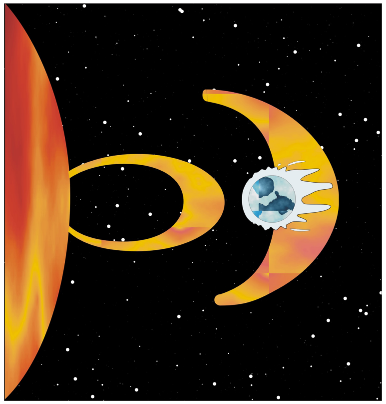
radio emission is the most promising way to find exomagnetospheres

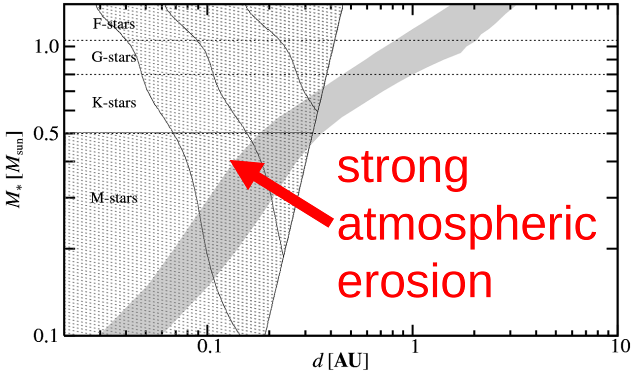
Why do we do this?

- planetary migration!
- protect against stellar wind + CMEs!
- protect against cosmic rays!
- explain observed transit curves!
- understand solar system planets!
- understand star-planet interaction!

need B_s (ZDI) and B_p (→ ?)

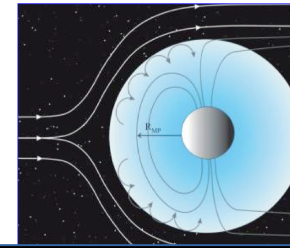


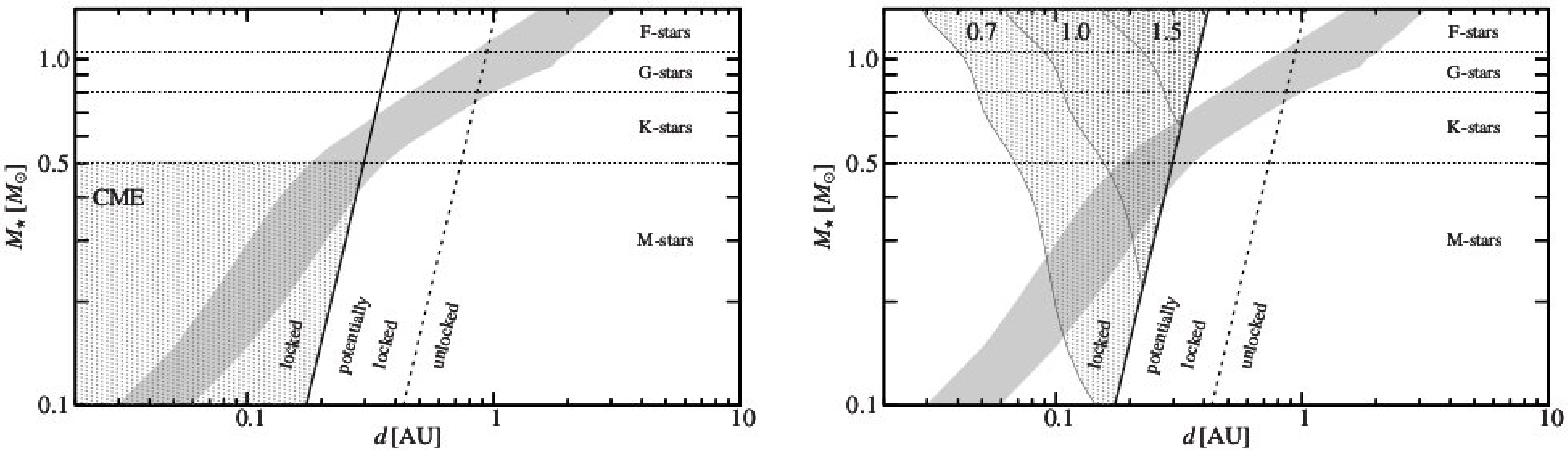




[e.g. Grießmeier 2015]

Atmospheres





(a) Atmospheric erosion by CMEs. (b) Atmospheric erosion by stellar wind.

⇒ habitable zone reduced!

[Grießmeier et al. 2004,
Khodachenko et al. 2007,
Griessmeier et al. 2010]

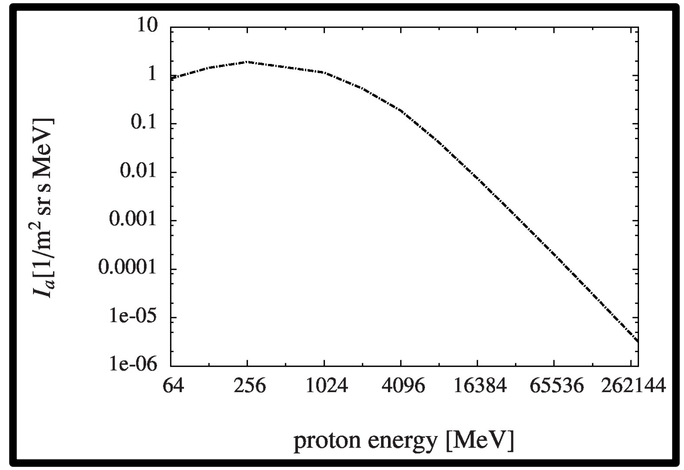
Cosmic rays

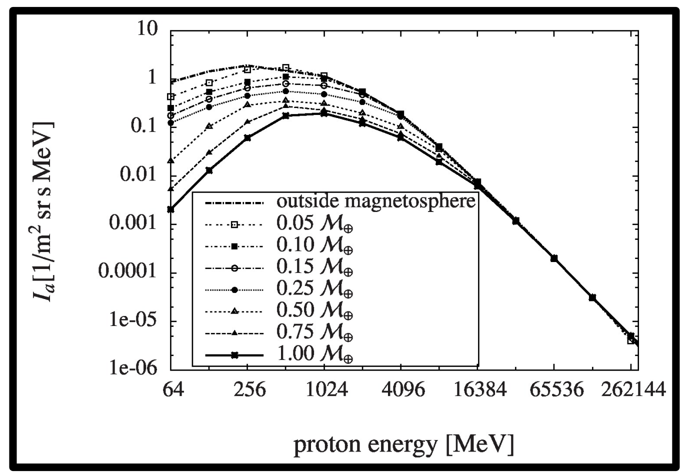
astrosphere

magnetosphere

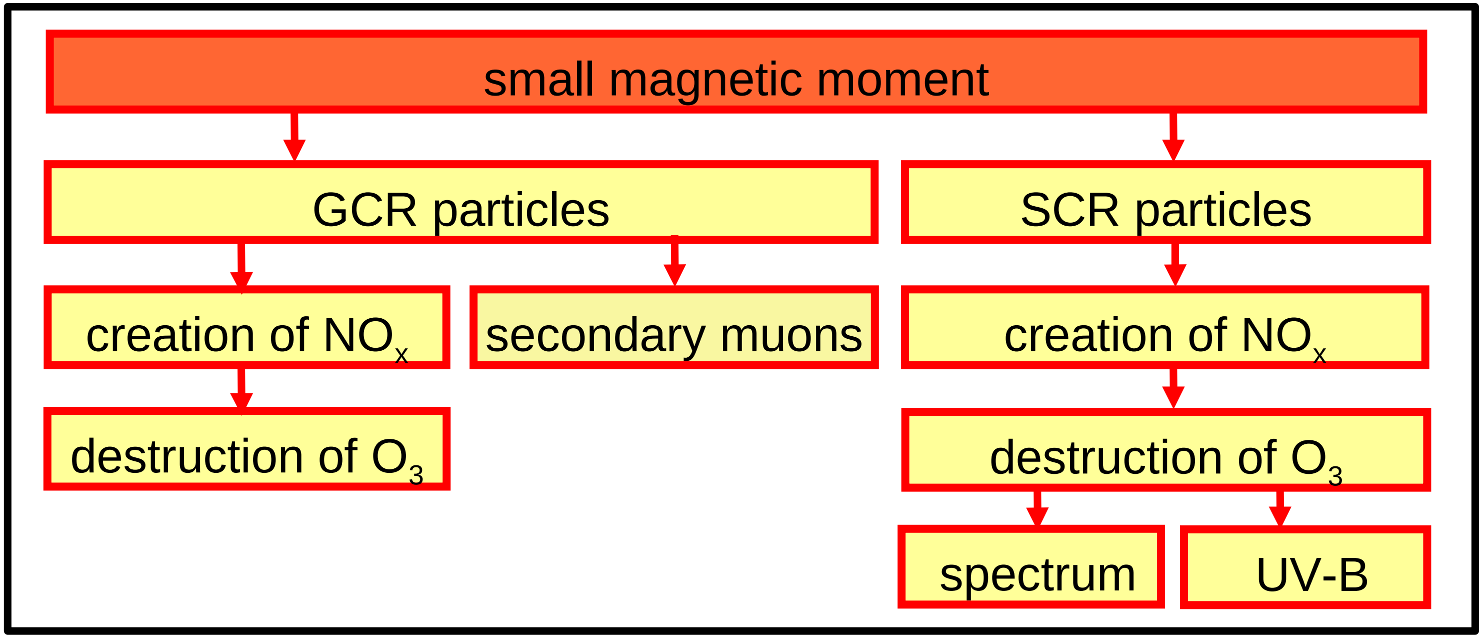
atmosphere

surface



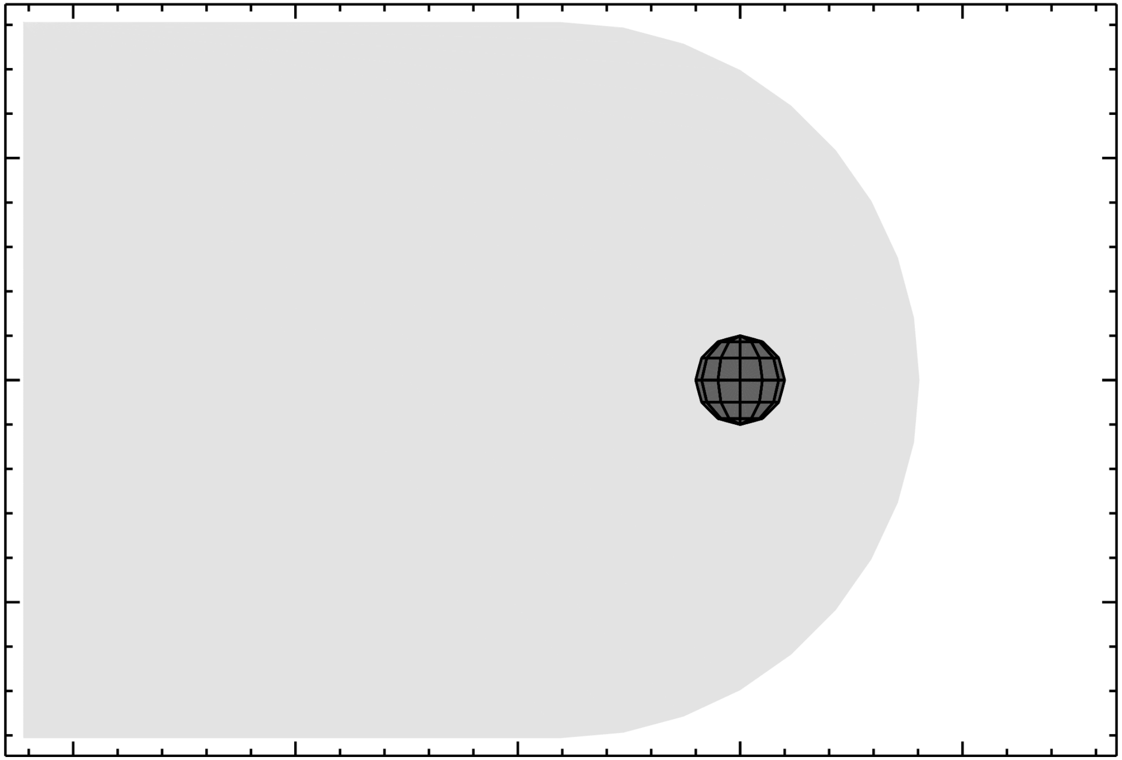


Cosmic rays



small magnetic moment
GCR particles
SCR particles
creation of NOx
secondary muons
creation of NOx
destruction of O3
destruction of O3
spectrum
UV-B

Cosmic rays



[Grießmeier et al. 2005,
Stadelmann et al. 2010]

Cosmic particles:
galactic protons
16 MeV<E<524 GeV

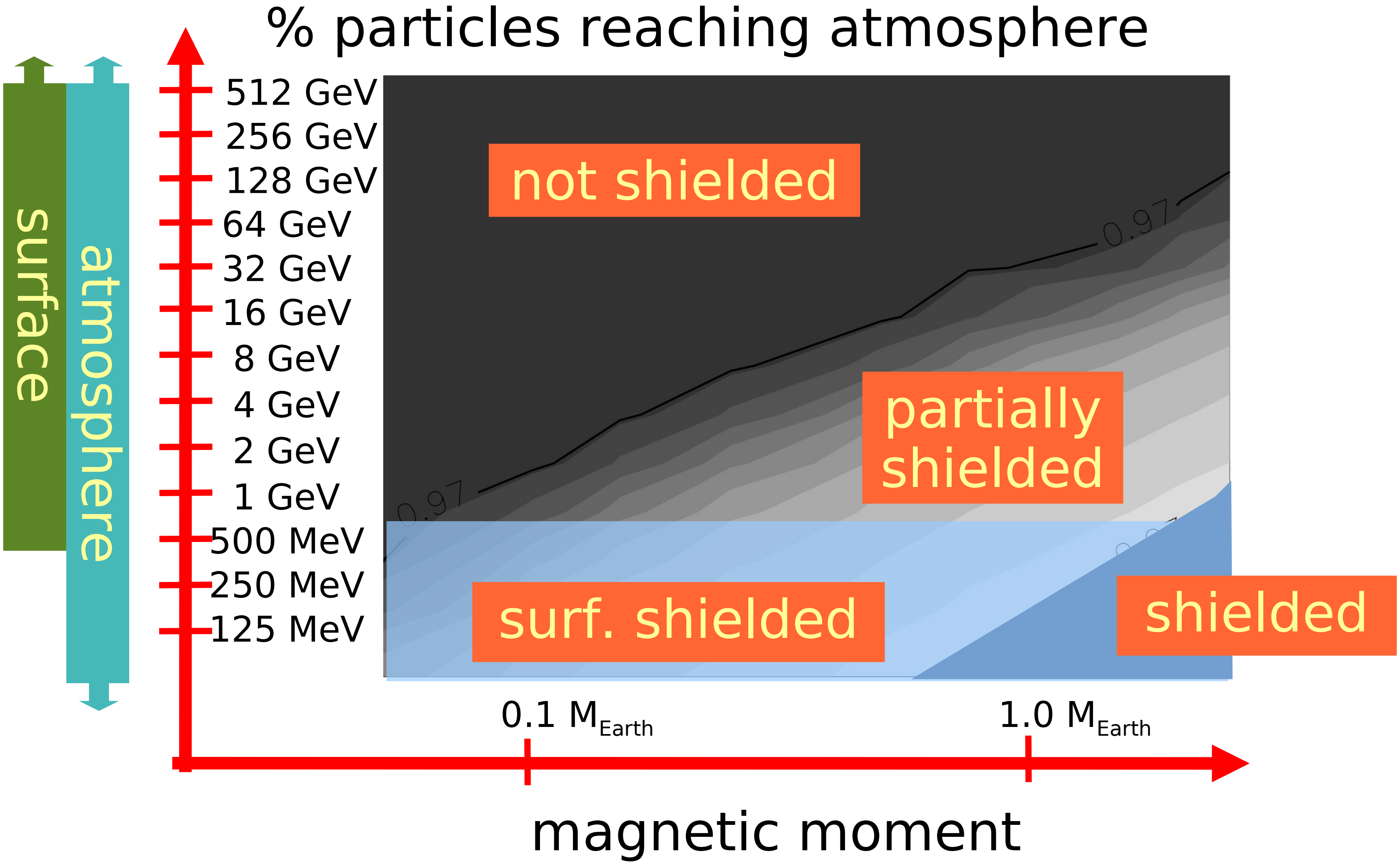
↓

Follow 28 Mio.
trajectories per energy

↓

Count particles
reaching the
atmosphere

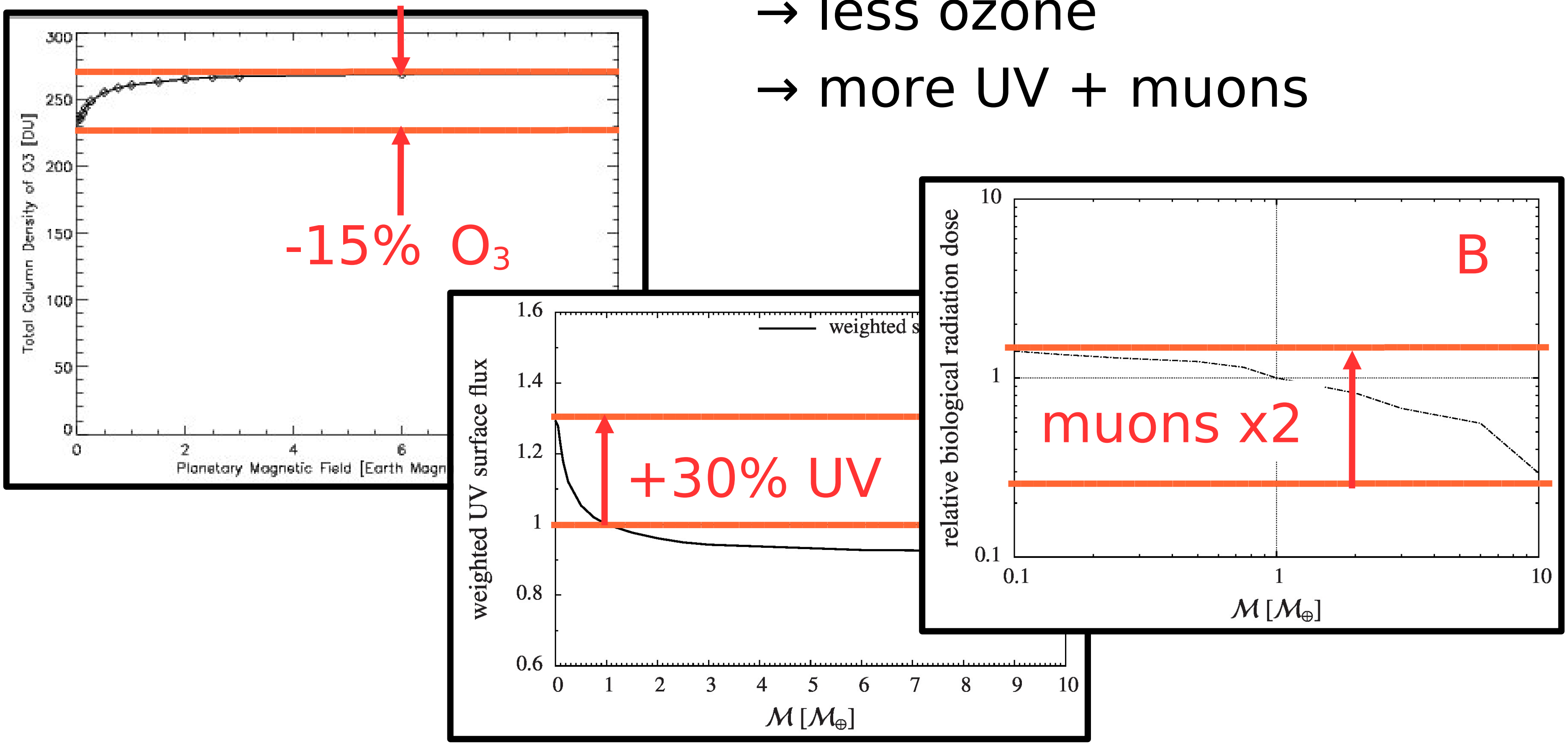
Cosmic rays



[Grießmeier et al. 2015, 2016]

Cosmic rays

• magnetic field probably weak → large flux of GCR
→ less ozone
→ more UV + muons



[Grießmeier et al. 2005; Grenfell et al. 2007; Grießmeier et al. 2009, 2015, 2016; Atri et al. 2013, 2017]

Cosmic rays

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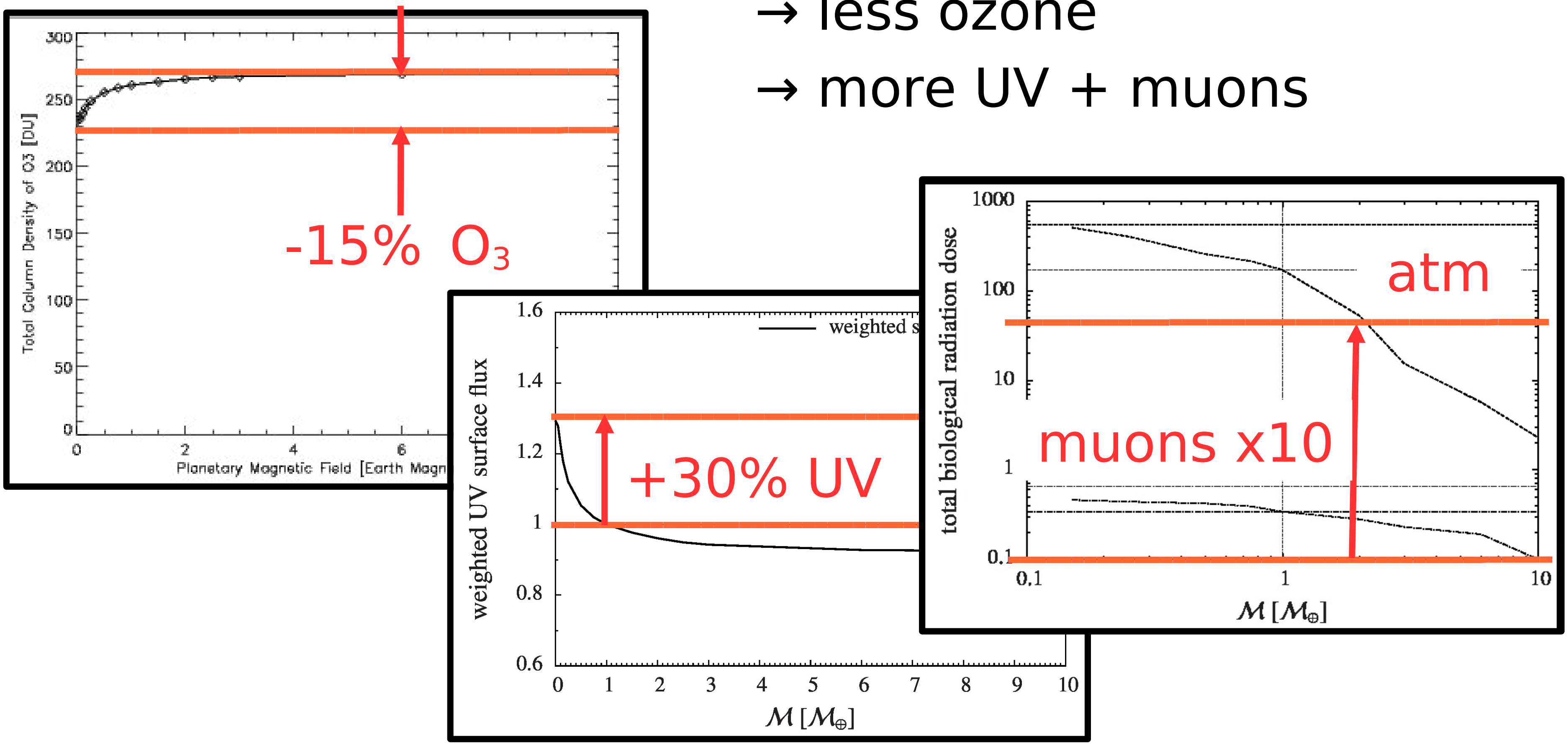


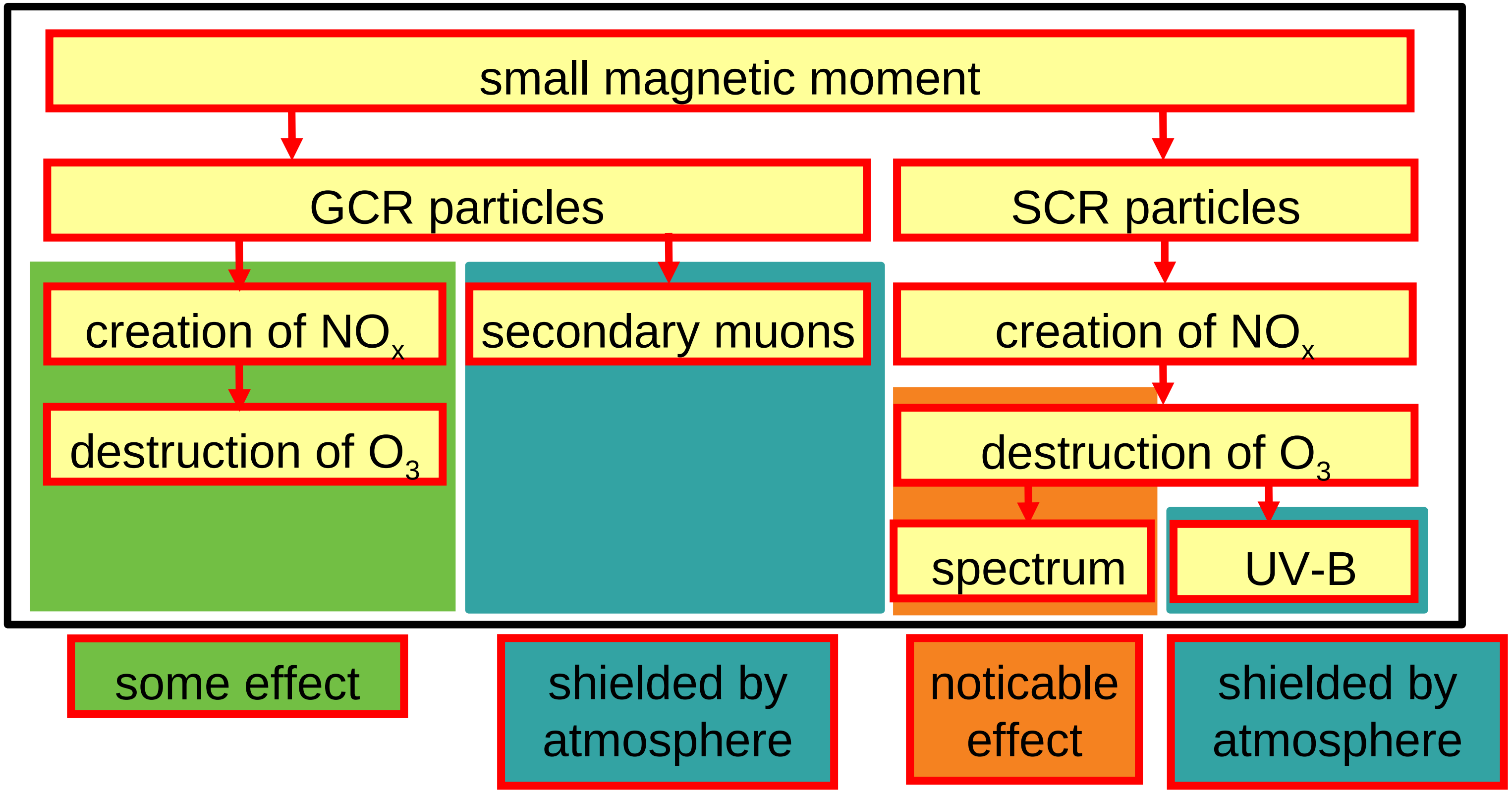
[Grießmeier et al. 2005; Grenfell et al. 2007;
Grießmeier et al. 2009, 2015, 2016; Atri et al. 2013, 2017]

Stellar cosmic rays

biol. weighted surface UV [rel. units]	quiescent UV	long UV flare
Earth	1	
quiescent M star	0.01	1.2
flaring M star	0.2	40

[Grenfell et al. 2012,
Tabataba-Vakili et al. 2016]

Cosmic rays

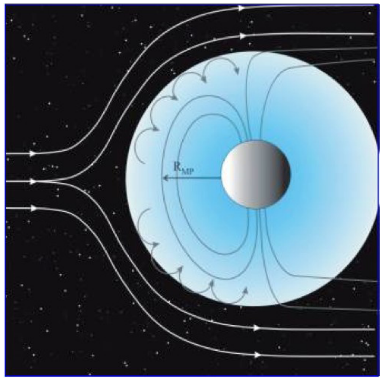


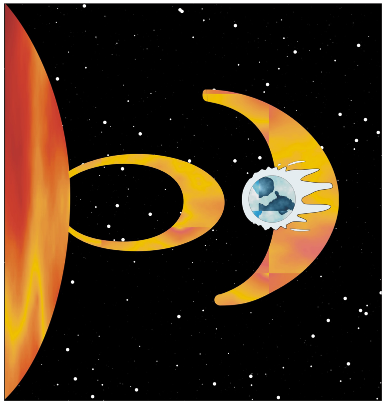
small magnetic moment
GCR particles
SCR particles
creation of NO_x
secondary muons
creation of NO_x
destruction of O_3
destruction of O_3
spectrum
UV-B
some effect
shielded by atmosphere
noticable effect
shielded by atmosphere

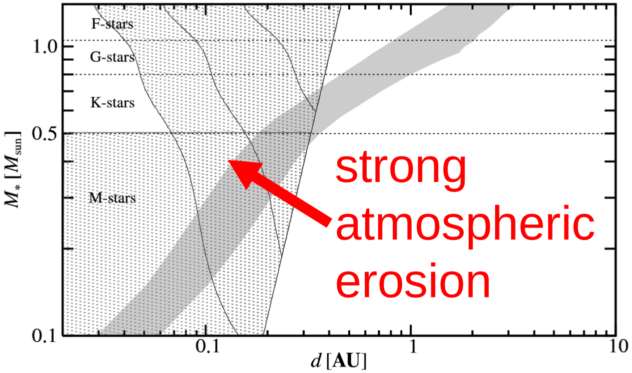
Why do we do this?

- planetary migration!
- protect against stellar wind + CMEs!
- protect against cosmic rays!
- explain observed transit curves!
- understand solar system planets!
- understand star-planet interaction!

need B_s (ZDI) and B_p (→ ?)

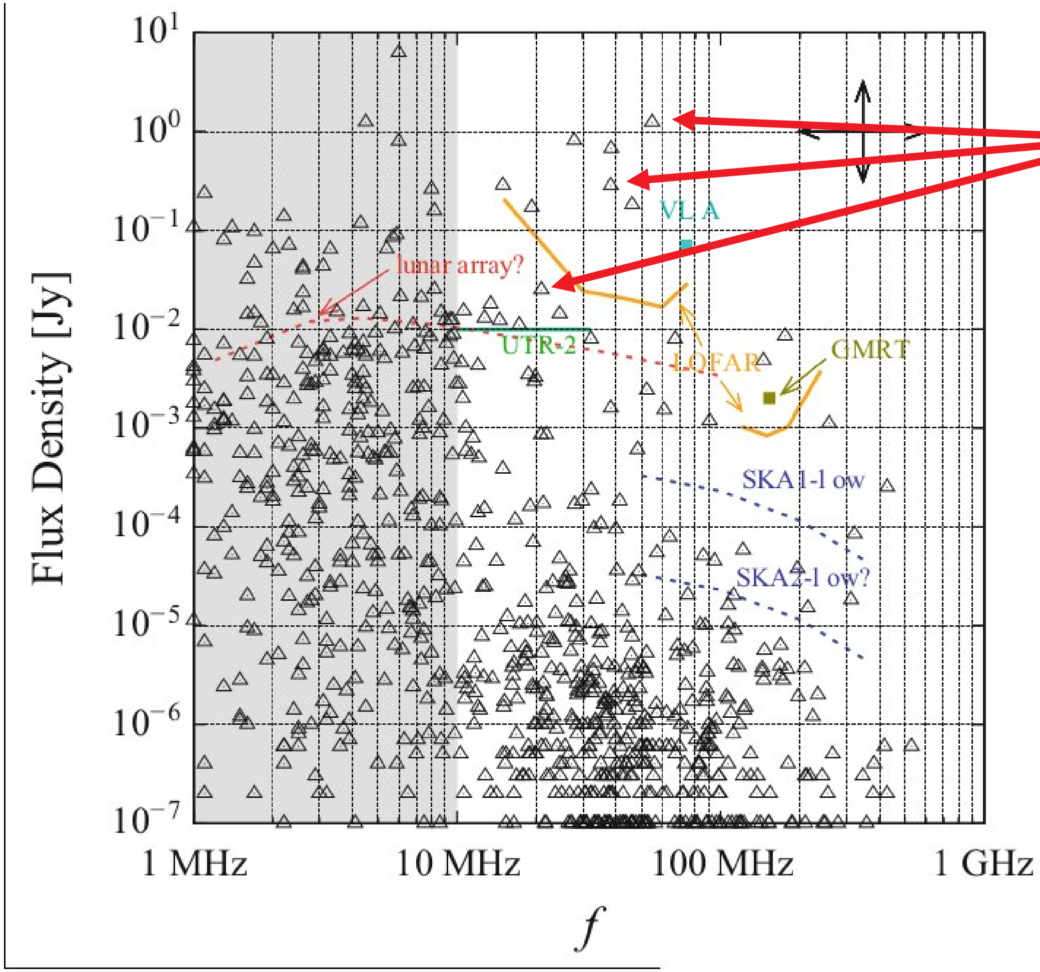






[e.g. Grießmeier 2015]

Theoretical sensitivity limit



estimates for all known exoplanets (comparing different theories) [Grießmeier et al. 2007, 2011, 2018]

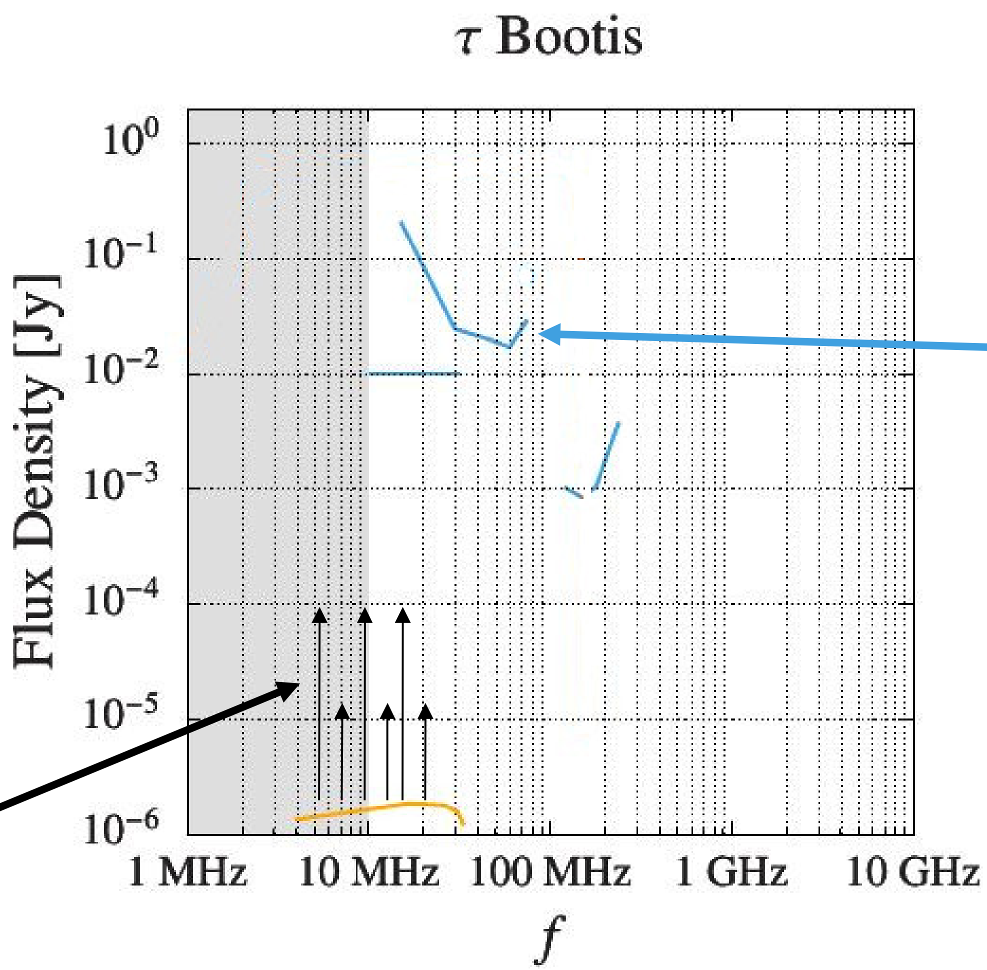
based on magnetic scaling [Zarka et al. 2001, 2006, 2007]

- more planets
- B_s (ZDI) and B_p (young planets)
- exoplanetary ionosphere

→ has to be updated [Mauduit et al. in prep.]

Jupiter emission

Jupiter
at
15.6 pc



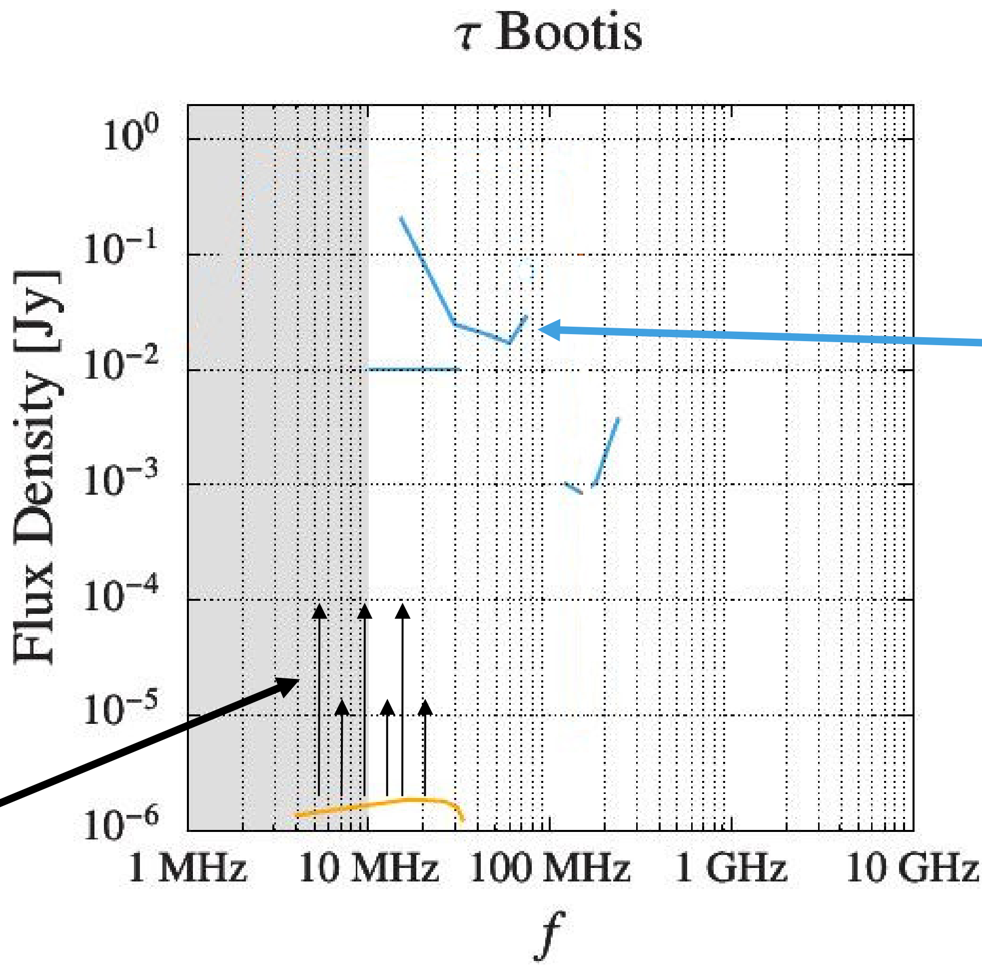
LOFAR-
LBA

Jupiter
bursts:
x10, x100

2 to 4 orders of magnitude too low…

Jupiter emission

Jupiter
at
15.6 pc



LOFAR-
LBA

theoretical
detection
limits

Jupiter
bursts:
x10, x100

2 to 4 orders of magnitude too low…
unless emission can be "boosted"

Power input

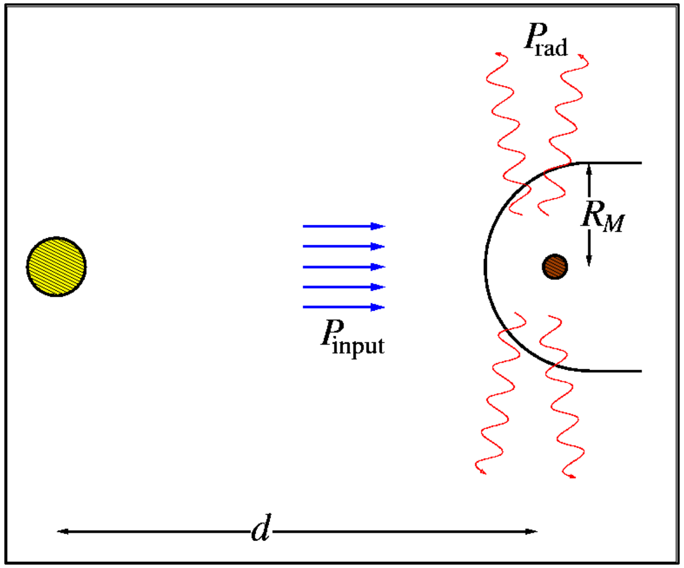
Is exoplanetary radio emission observable?

Power input: (stellar wind)

$$P_{\mathrm{input}}$$

Emitted radio power:

$$P_{\mathrm{rad}} \propto P_{\mathrm{input}}$$



⇒ Strong emission for close-in planets

Magnetospheric radio emission

solar wind

⇩

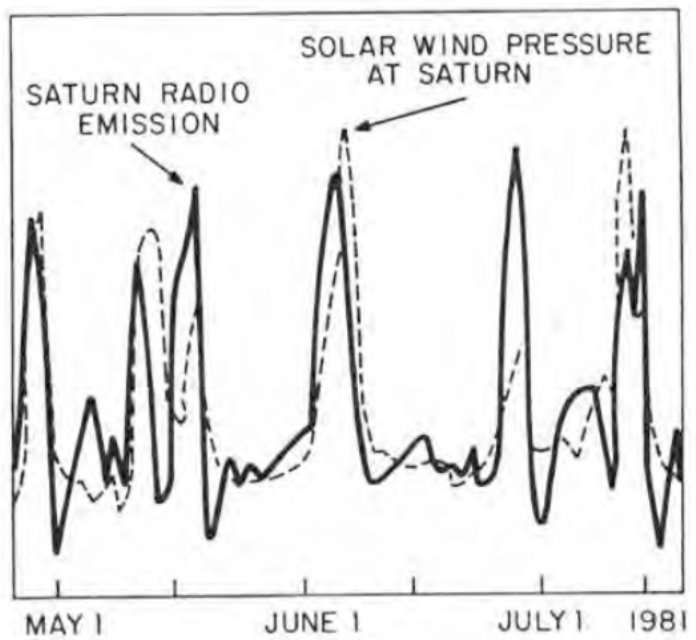
particles enter the planetary magnetic field

⇩

electrons spiral around fieldlines

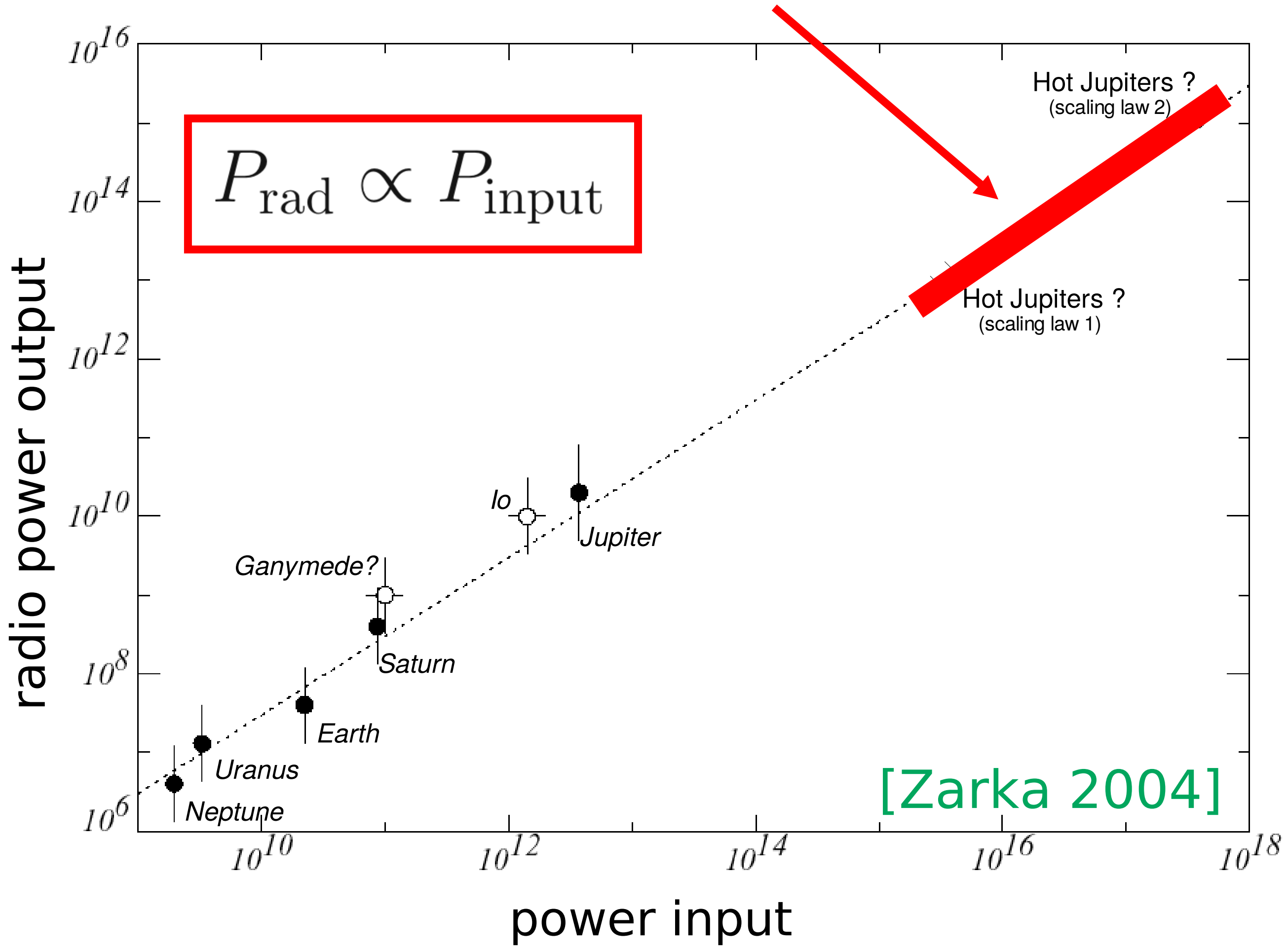
⇩

radio emission (gyrofrequency)

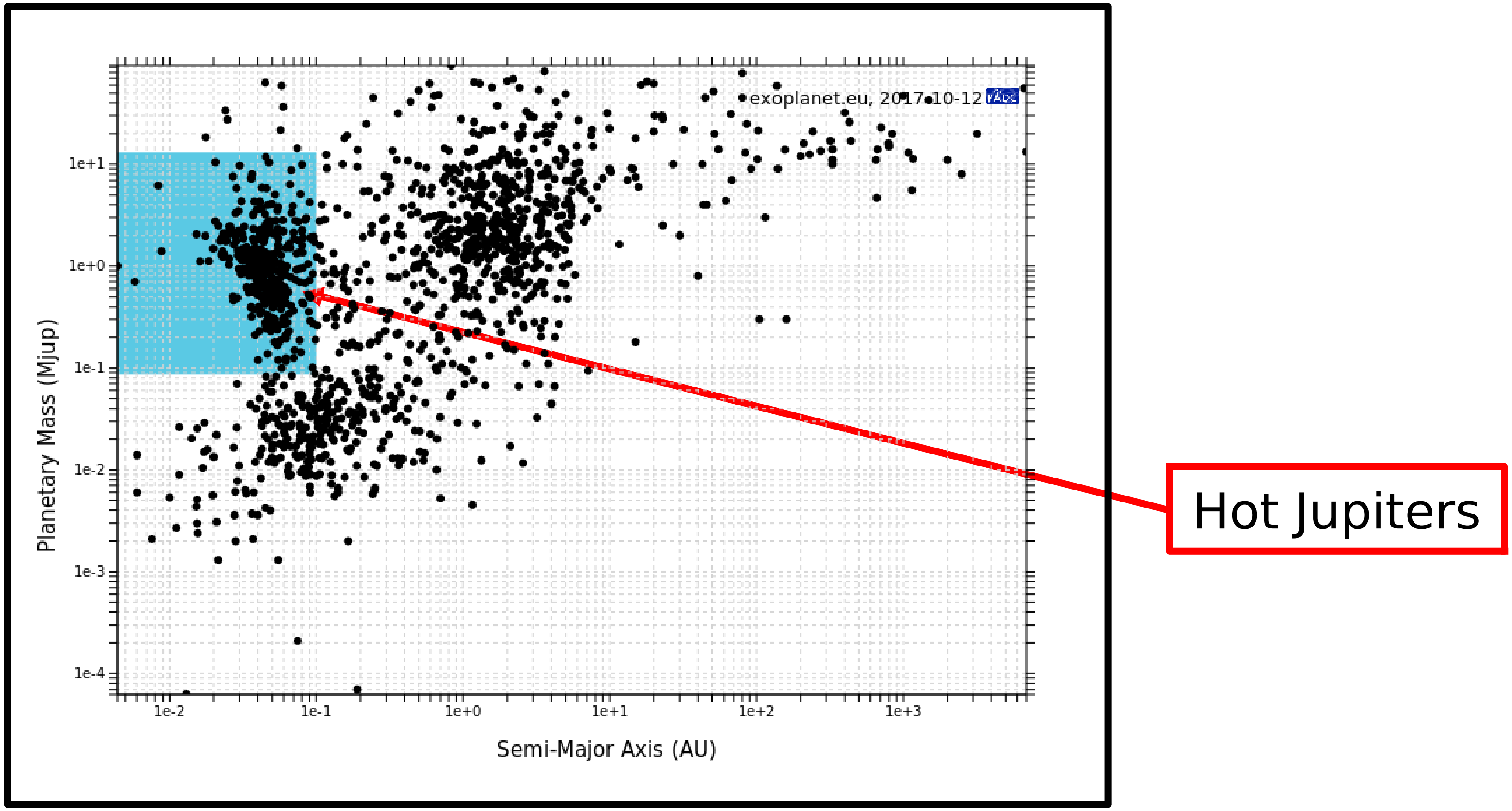


Power output

Strong emission for
planets close to their star!



Exoplanets: Orbital radii

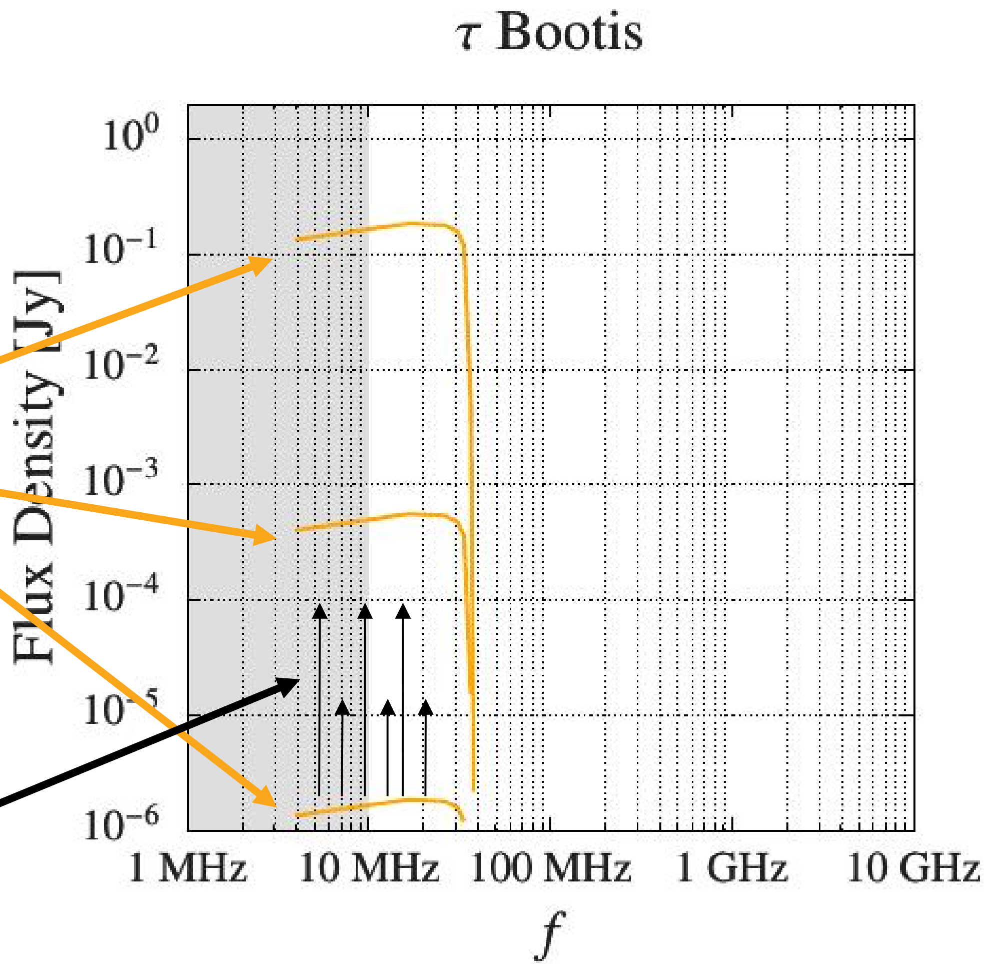


[http://www.exoplanet.eu]

Beyond the solar system

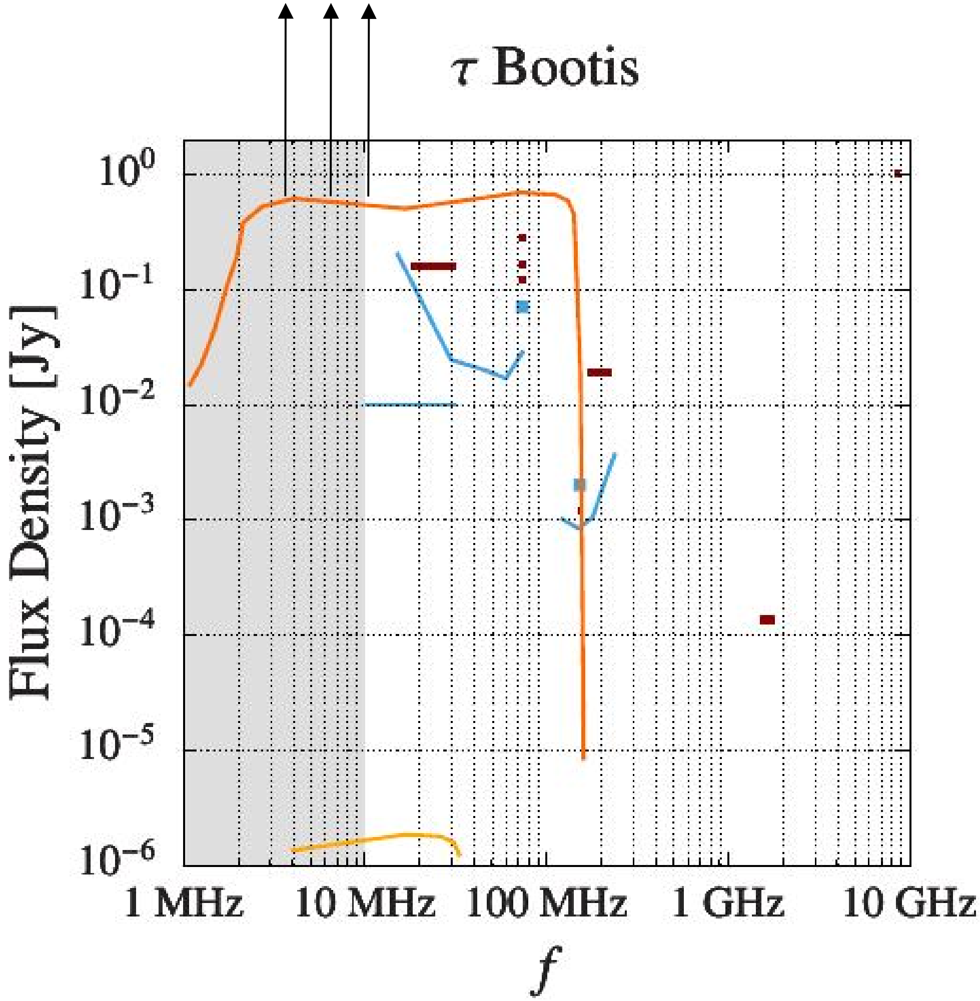
Jupiter at 15.6 pc:
x 10^5
x 300
x 1

Jupiter bursts:
x10, x100



theoretical studies: intense emission is possible (up to Jupiter x10^5...10^6)

Tau Bootis A b



theoretical detection limits

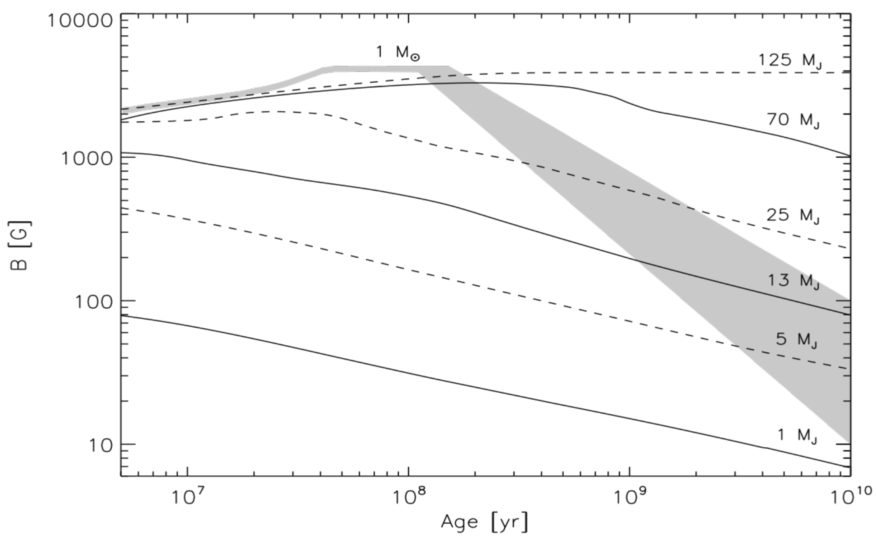
Not all planets are equal

Planetary magnetic fields

- Radio detection : f > 10 MHz → $B_{max\text{-}surface} \geq 4$ G
- Spin-orbit synchronisation (tidal forces) → ω↓
- $M \propto \omega^{\alpha}$ with $½ \leq \alpha \leq 1$ → M ↓
- Young planets? B(t) decay

→ lecture by Daniele

- Internal structure + convection models



Planet name	Planet mass $[M_{\rm Jup} \sin i]$	a [AU]	d^1 [pc]	$\dot{M}$ $[\dot{M}_\odot]$	Age [Gyr]	$B_{\rm dip}^{\rm pol}$ [G]
Jupiter	1.00	5.20		1.0	4.5	9
eps Eridani b	1.55	3.39	3.2	25.9	1.7	19
Gliese 876 b	1.93	0.21	4.7	0.1	2.4	23
Gliese 876 c	0.56	0.13	4.7	0.1	2.4	6
GJ 832 b	0.64	3.40	4.9	0.2	2.0	7
HD 62509 b	2.90	1.69	10.3	0.3	5.6	24
Gl 86 b	4.01	0.11	11.0	9.4	2.9	40
HD 147513 b	1.00	1.26	12.9	150.4	0.8	15
ups And b	0.69	0.06	13.5	20.2	1.4	10
ups And c	1.98	0.83	13.5	20.2	1.4	30
ups And d	3.95	2.51	13.5	20.2	1.4	58
gamma Cephei b	1.60	2.04	13.8	1.1	3.6	16
51 Peg b	0.47	0.05	14.7	0.2	6.2	3
tau Boo b	3.90	0.05	15.0	198.5	0.8	58
HR 810 b	1.94	0.91	15.5	103.9	0.8	30
HD 128311 b	2.18	1.10	16.6	39.9	0.9	33
HD 128311 c	3.21	1.76	16.6	39.9	0.9	48
HD 10647 b	0.91	2.10	17.3	22.9	1.4	14
GJ 3021 b	3.32	0.49	17.6	170.2	0.8	49
HD 27442 b	1.28	1.18	18.1	1.9	2.7	14
HD 87883 b	1.78	3.60	18.1	2.6	3.3	19
HD 189733 b	1.13	0.03	19.3	17.3	1.7	14
HD 192263 b	0.72	0.15	19.9	7.1	2.5	8

[Farrell et al. 1999; Sanchez-Lavega, 2004; Grießmeier et al. 2014; Reiners & Christensen, 2010; Yadav & Thorngren, 2017]

Stellar magnetic fields

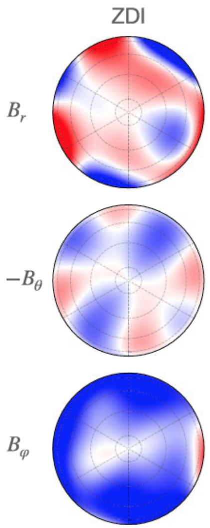
emission determined by B_* (ZDI) and B_p (young planets)

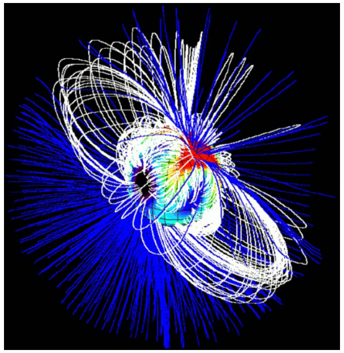
Spectropolarimetry / Zeeman Doppler Imaging → B_*

+ Extrapol. magnetic topology up to planetary orbit

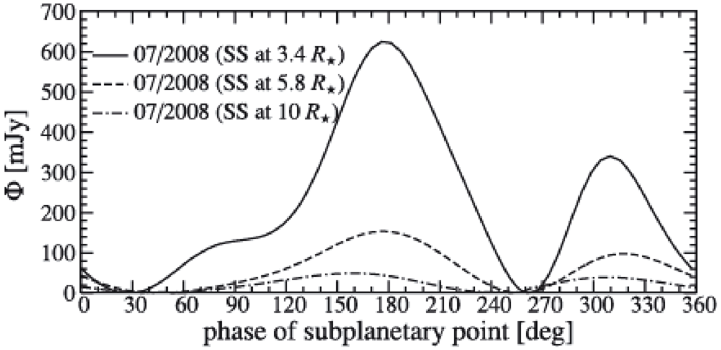
→ time variability of expected SPI signal

→ lecture by Rim





HD 189733



[Farès et al., 2010; Strugarek et al., 2022]

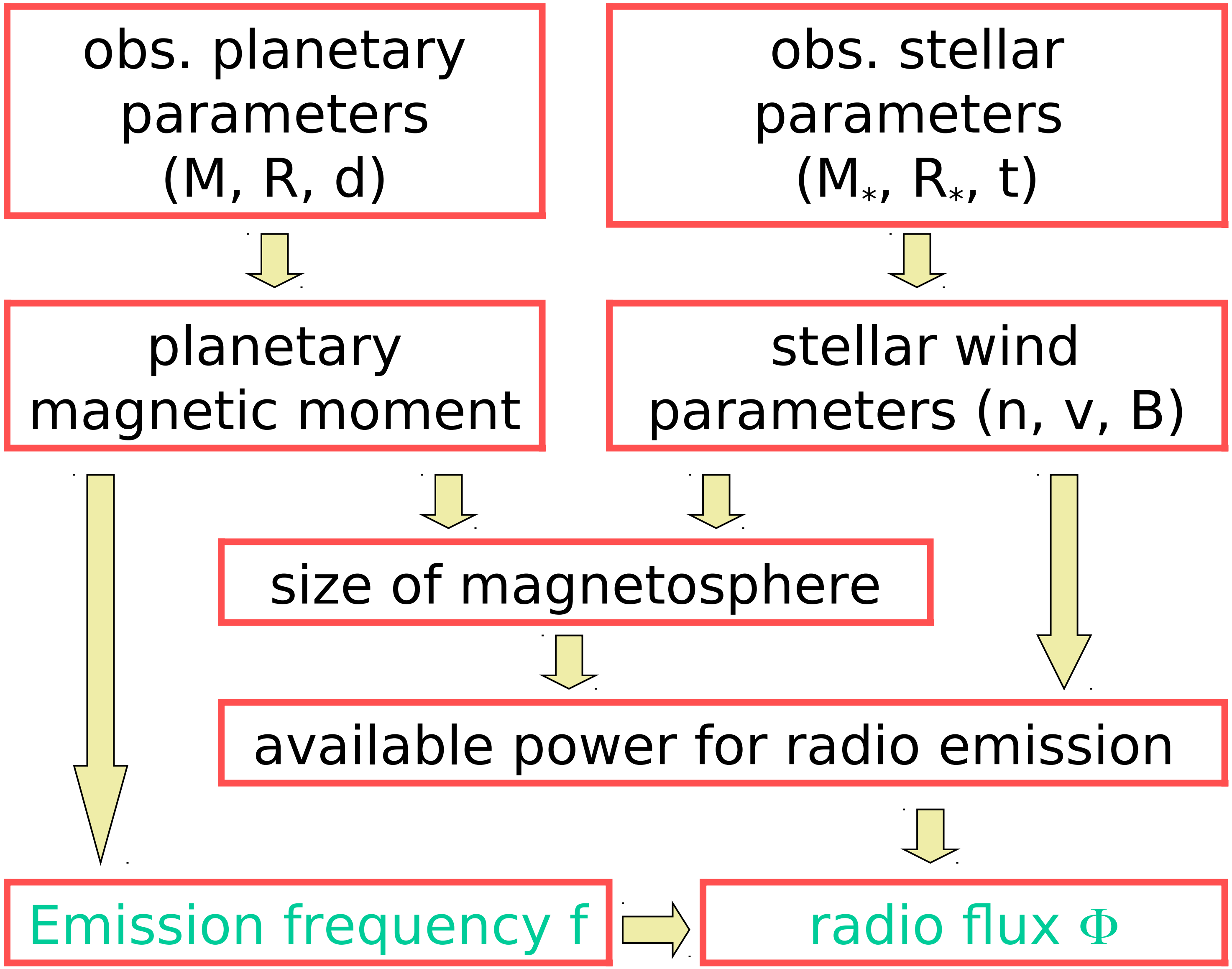
Theory: Condition for radio emission

- low mass Hot Jupiters → extended atmosphere
  → radio emission not possible
  e.g. HD 209458b, HD 189733b [Weber et al. 2017a, 2017b]
- massive Hot Jupiters → compact atmosphere
  → radio emission is possible
  e.g. τ Bootis b [Weber et al. 2018]
- υ Andromedae b → mass unknown!
  if radio emission is detected, $M_p > 2.25\ M_J$
  [Erkaev et al. 2022]
- A problem for many planets!
  [Grießmeier 2023]

Radio emission: Theoretical studies

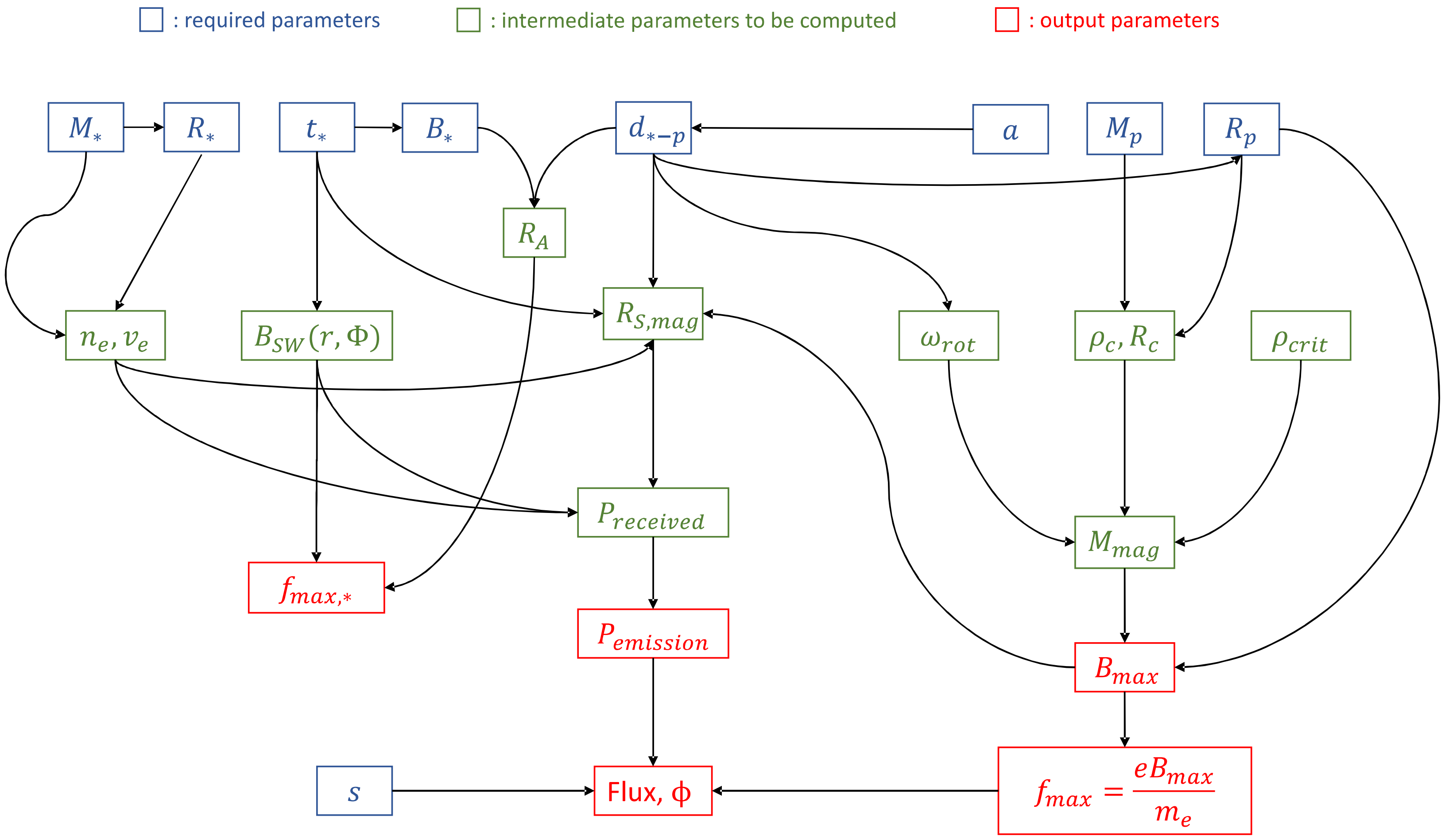
mech-anisms	• kinetic interaction	[Zarka et al 1997, Farrell et al 1999]
	• comparison to stellar emi.	[Zarka et al 1997, Grießmeier et al 2005]
	• magnetic interaction	[Zarka et al 2001]
	• unipolar interaction	[Zarka 2007]
	• acceleration of electrons	[Jardine et al 2008]
	• planets with plasma sources	[Nichols 2011, 2012, Noyola et al 2014, 2016]
	• Dungey-cycle-like interaction	[Nichols et al 2016]
planet	• planetary magnetic field	[Grießmeier et al 2004, Grießmeier 2015]
	• target list	[Lazio et al 2004, Griessmeier et al 2007b, 2011, Driscoll et al. 2011, Nichols 2012]
	• orbital distance	[Grießmeier et al 2007a]
	• orbital inclination	[Hess et al 2011]
star	• influence of stellar age	[Stevens 2005, Grießmeier et al 2005]
	• influence of stellar CMEs	[Grießmeier et al 2006, 2007a]
	• stellar magnetic field	[Fares et al 2010, Vidotto et al 2012, 2015, See et al 2015, Alvarado-Gómez et al 2016]
ab-sorption	• absorption close to star	[Grießmeier et al 2007b, Hess et al 2011]
	• absorption close to planet	[Weber et al 2017, Erkaev et al 2022]
special cases	• white dwarfs	[Willes et al 2005]
	• evolved stars	[Ignace et al 2010, Fujii et al 2016]
	• T Tauri stars	[Vidotto et al 2010]
	• A stars	[Katarzyński et al 2016]
	• rogue planets	[Vanhamäki et al 2011]

Radio flux estimation



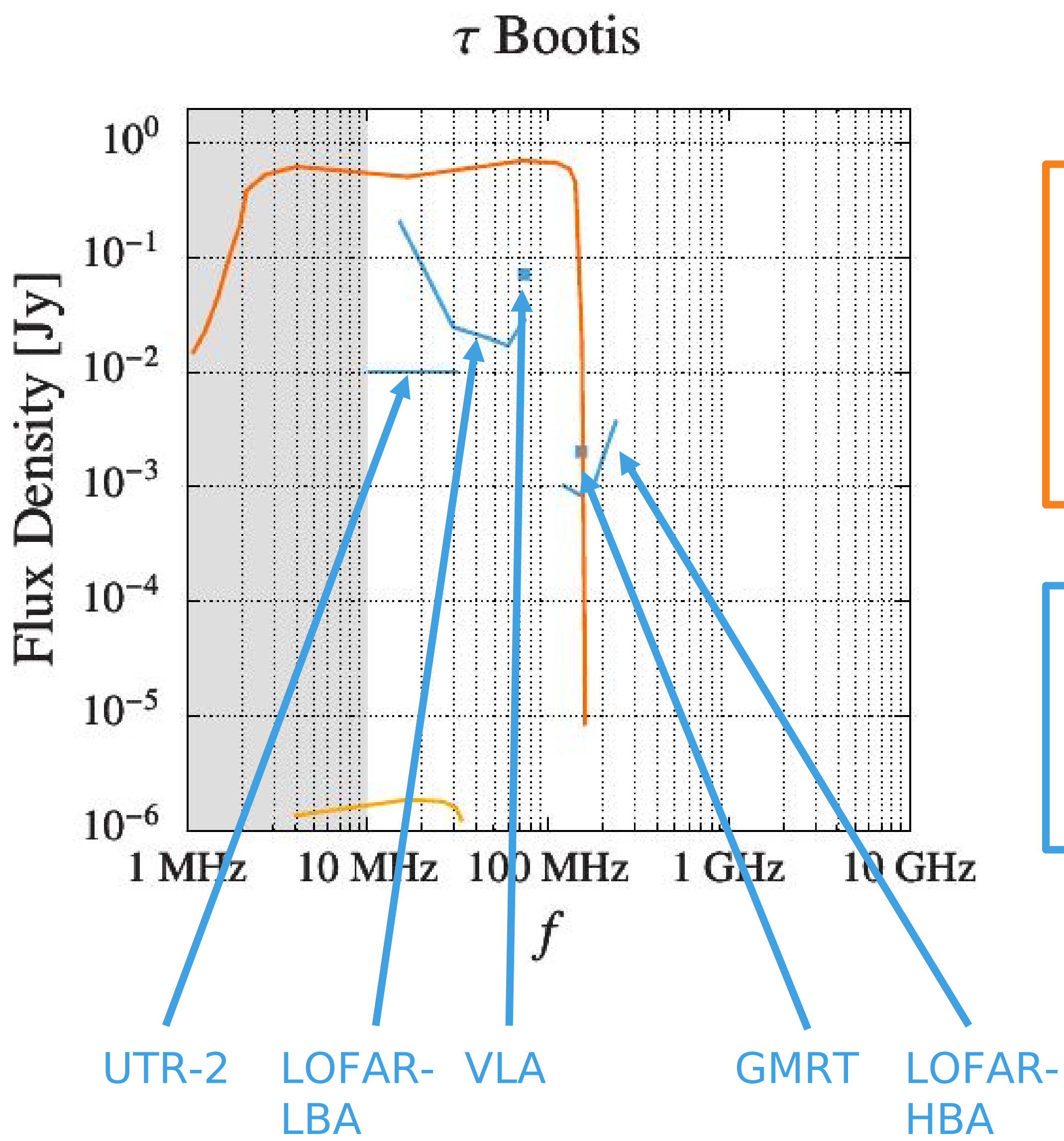
[Grießmeier et al. 2007, 2011, 2017]

Radio prediction code PALANTIR



[Mauduit et al. 2023; 2024 in prep.]

Expect detectable emission



theoretical predictions for τ Bootis

theoretical detection limits

Jupiter at 15.6 pc

Radio emission: Observational studies

- Clark Lake [Yantis et al 1977]
- VLA [Winglee et al 1986, Bastian et al 2000, Farrell et al 2003, Lazio et al 2004, 2007, 2010a, 2020b]
- UTR-2 [Zarka et al 1997, Ryabov et al 2004, Zarka 2011]
- Effelsberg [Guenther et al 2005]
- Mizusawa [Shiratori et al 2005]
- GMRT [Winterhalter et al 2006, Majid et al 2006, George et al 2007, Lecavelier et al 2009, 2011, 2013, Hallinan et al 2013, Sirothia et al 2014]
- GBT [Smith et al 2009]
- LOFAR [Zarka et al 2011, Turner et al 2021, 2024]
- MWA [Murphy et al 2015]
- WSRT [Stroe et al 2012]
- NenuFAR [Turner et al 2023]

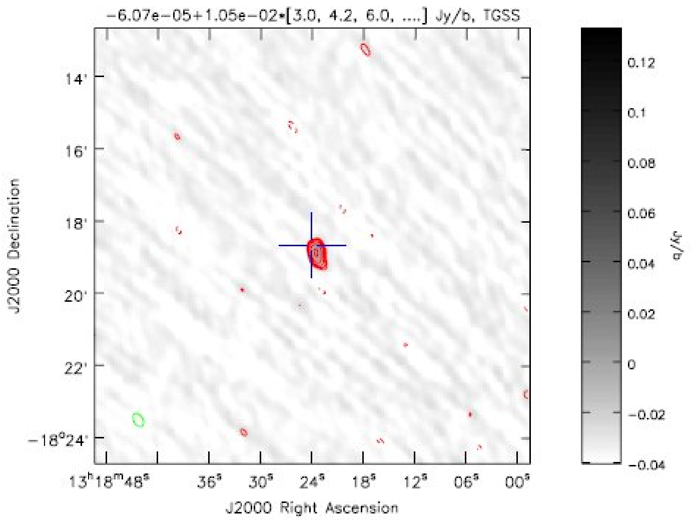



- no (firm) detection yet
- sensitivity ~ predictions
  → observations ongoing

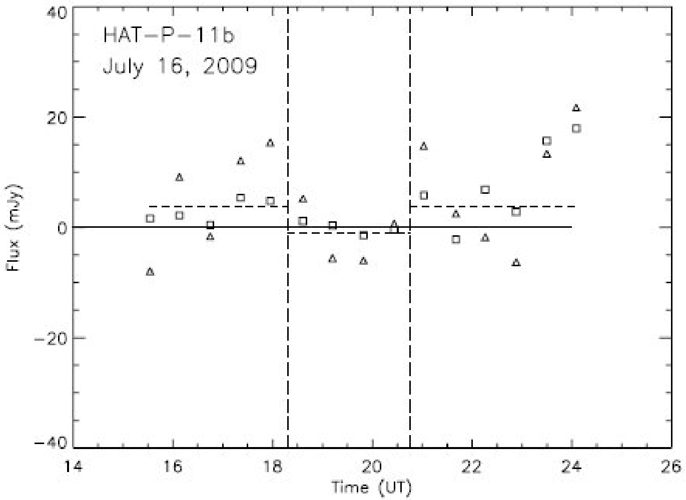
Types of observations

- imaging
  - \- computationally expensive
  - \- good for continuous emission or slow variation
  - \- needs good calibrators
  - \+ decorrelate RFI if distant telescopes
- stacked images (same target)
- stacked images (different targets)
- beamformed observations
  - \- computationally cheap
  - \+ good for bursty emission
  - \+ fine RFI filtering
  - \- ionospheric effects
- reconstructed beamformed

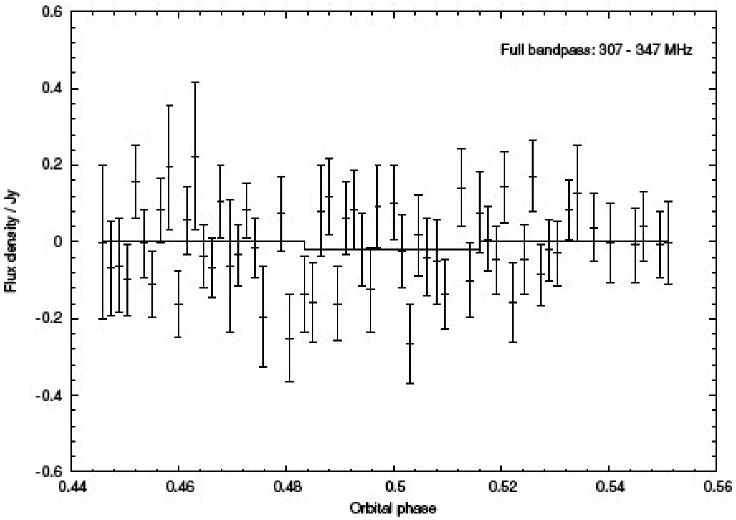
Radio emission: Observational studies



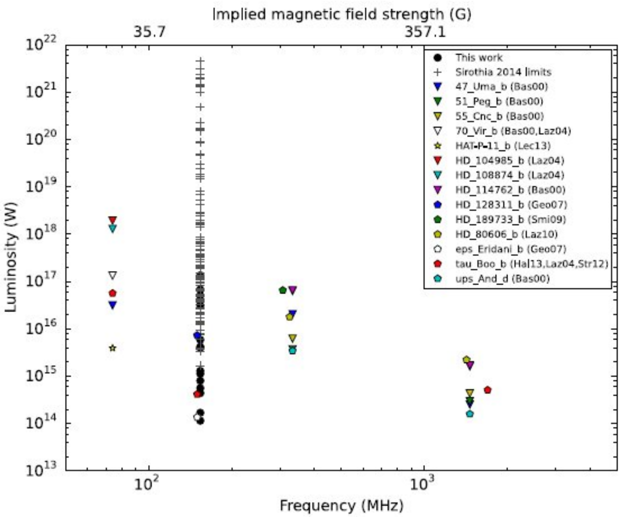
[Sirothia et al., 2014]



[Lecavelier et al., 2013]



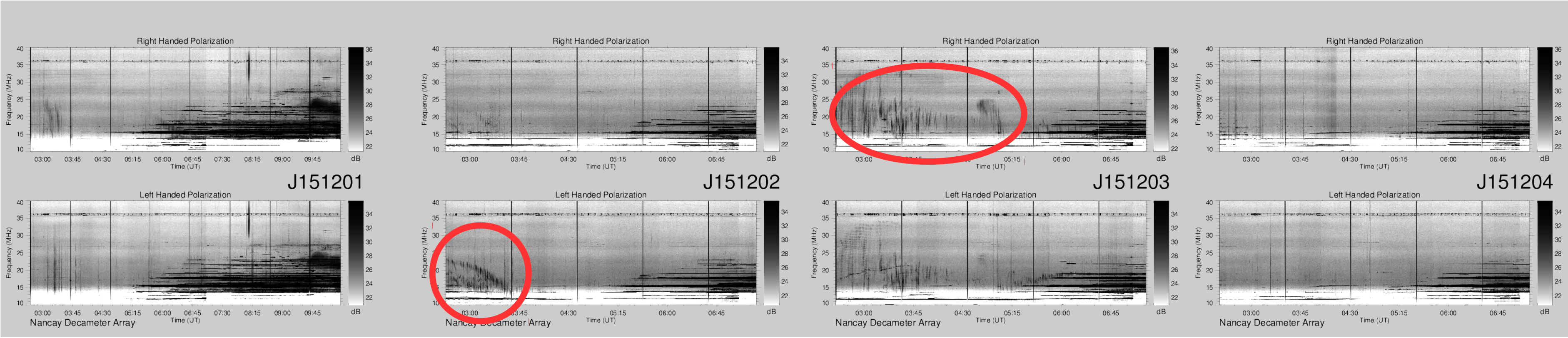
[Smith et al., 2009]



[Murphy et al., 2015]

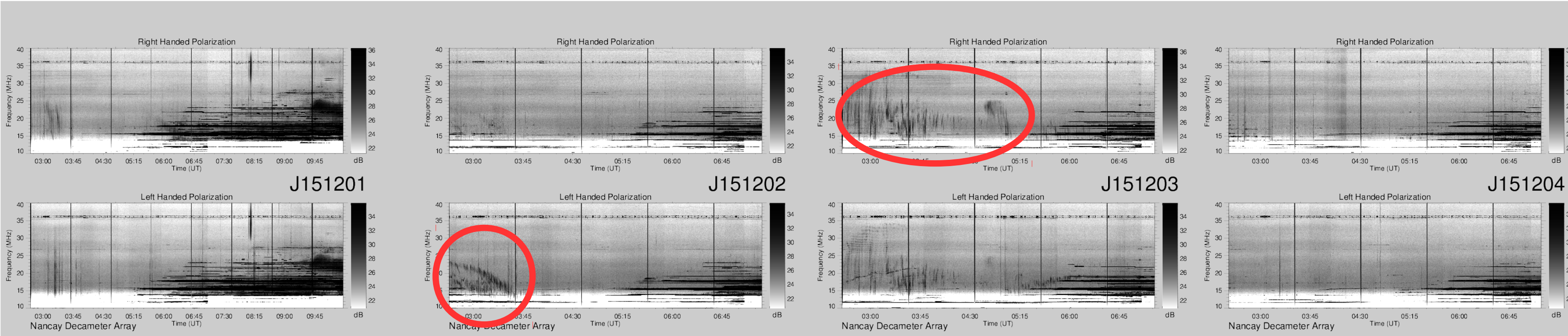
Observing once is not enough

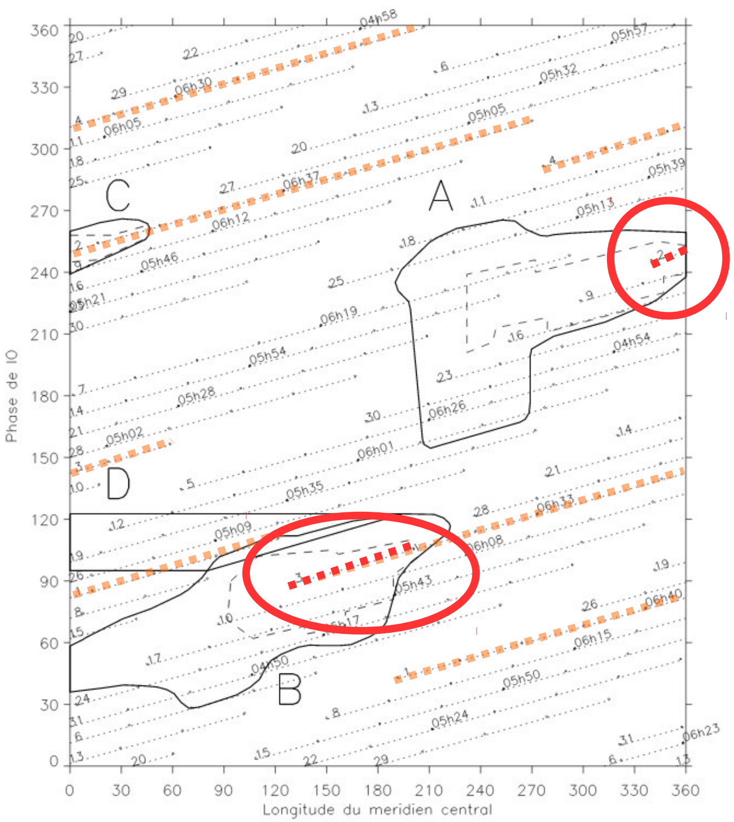
Orbital phase



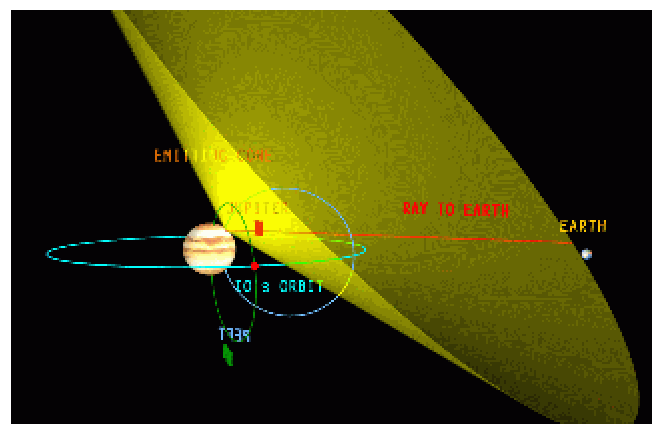
- for Jupiter, random observations only give 10-20% detections!

Orbital phase



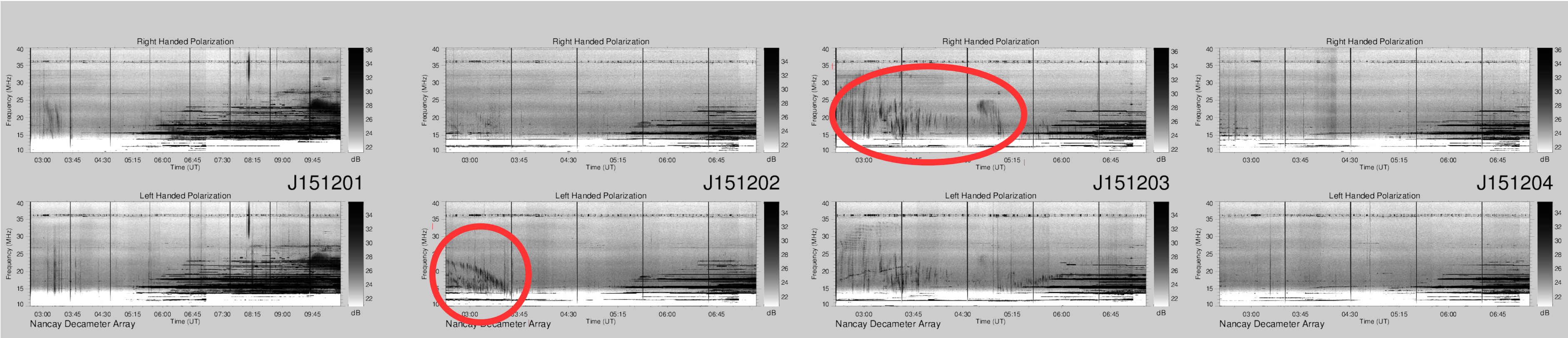


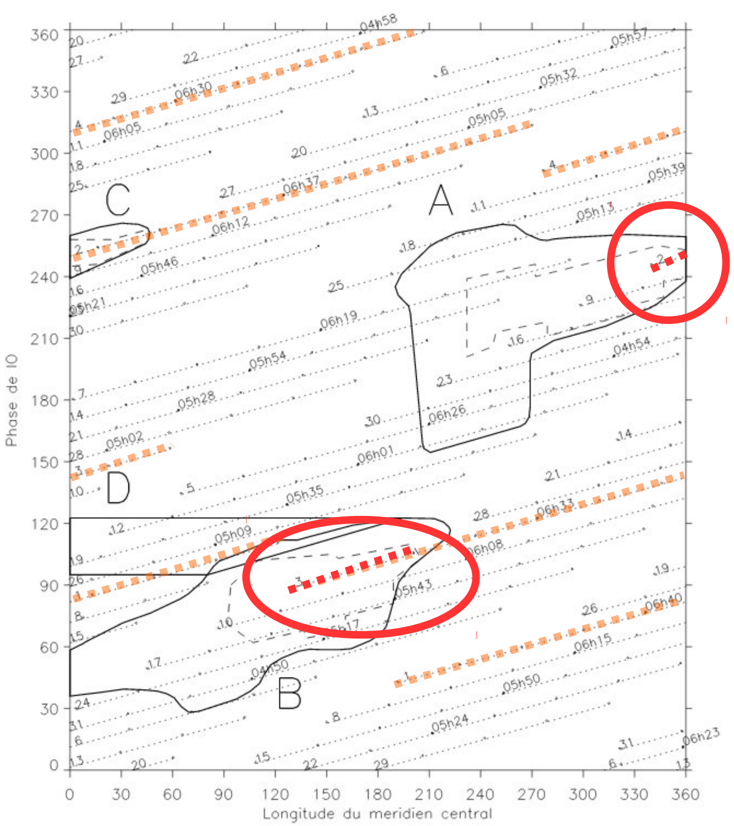
- for Jupiter, random observations only give 10-20% detections!
- emission is always on
- emission is strongly beamed



[Imai Lab., Kochi National College of Technology]

Orbital phase

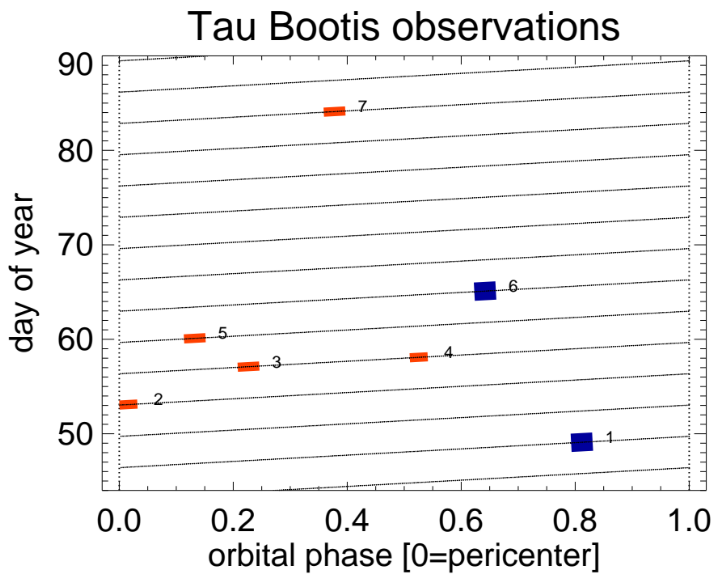


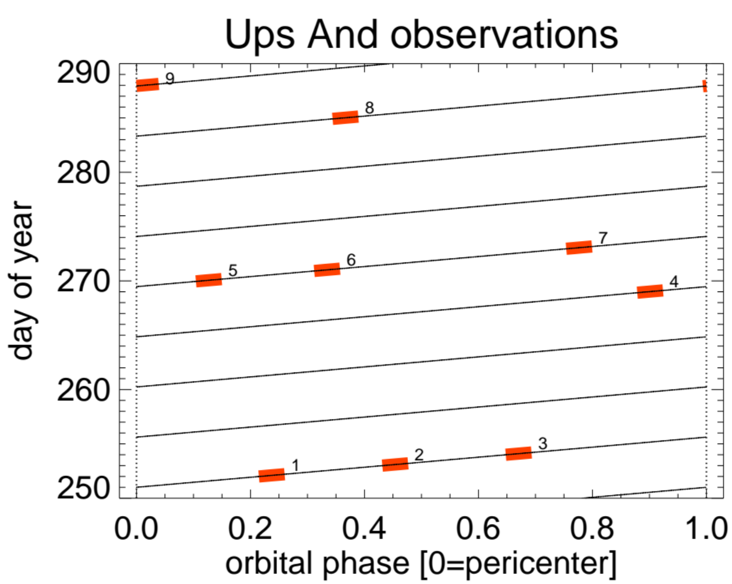


- for Jupiter, random observations only give 10-20% detections!
- emission is always on
- emission is strongly beamed

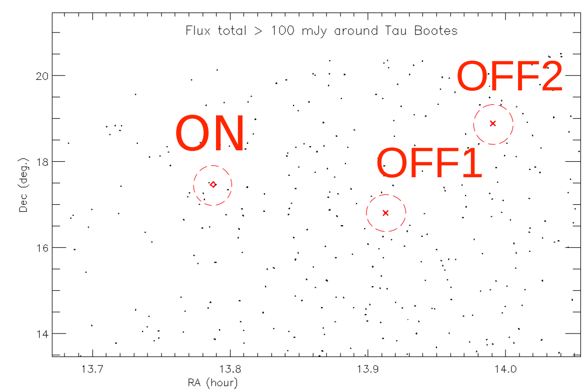
- for exoplanets: have to cover orbit
- else: non-detections meaningless

Observations: 55 Cnc, υ And, τ Boo





- theoretical prodictions → selection of 3 targets
- 20-45h / target
- distance 12-15 pc
- spread observations to cover orbital period
- multiple tied array beams → search for rapid bursts (1s)



Theoretical detection limit

- are simple detection limits realistic?
- how were they obtained?

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$$\Delta S = S_{sys}/(N\sqrt{n_{pol}\tau_r b})$$

- how well do we know the telescope?
- how well do we know the emission?

Theoretical detection limit

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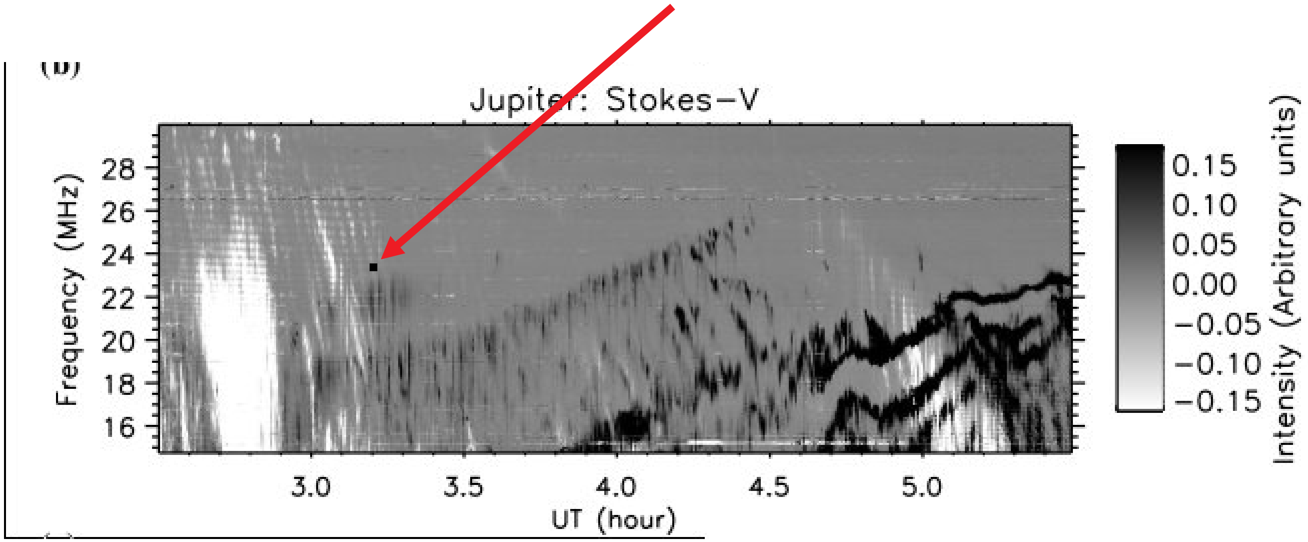
- how were they obtained?

$$\Delta S = S_{sys}/(N\sqrt{n_{pol}\tau_r b})$$

→ ΔS=200 Jy (per t-f "pixel" of 10 ms x 3 kHz) ...but...
→ ΔS= 5 Jy (rebinned "pixel" of 1 s x 45 kHz) ...but...



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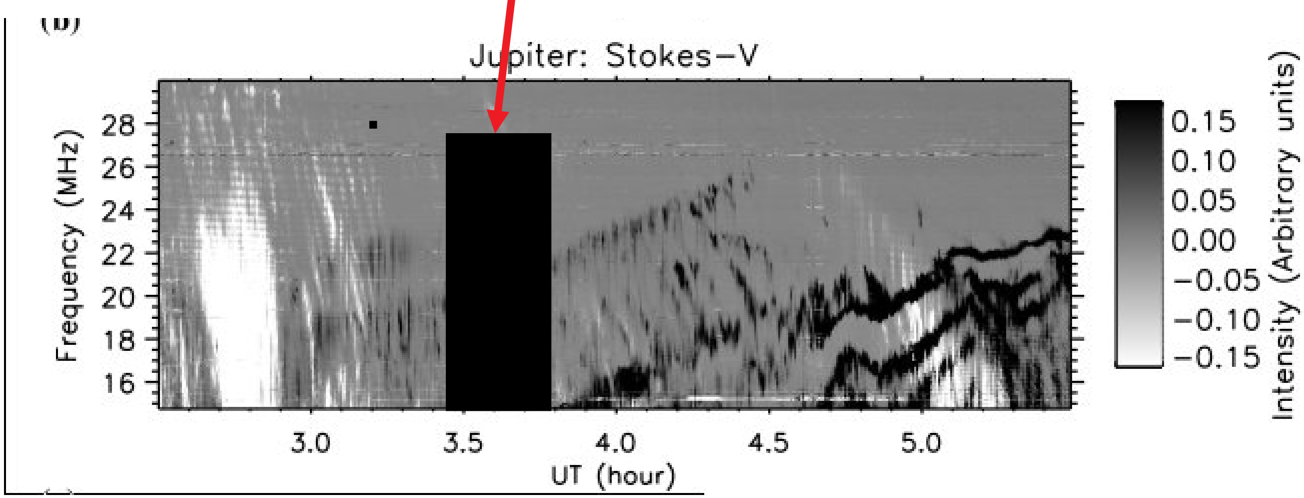

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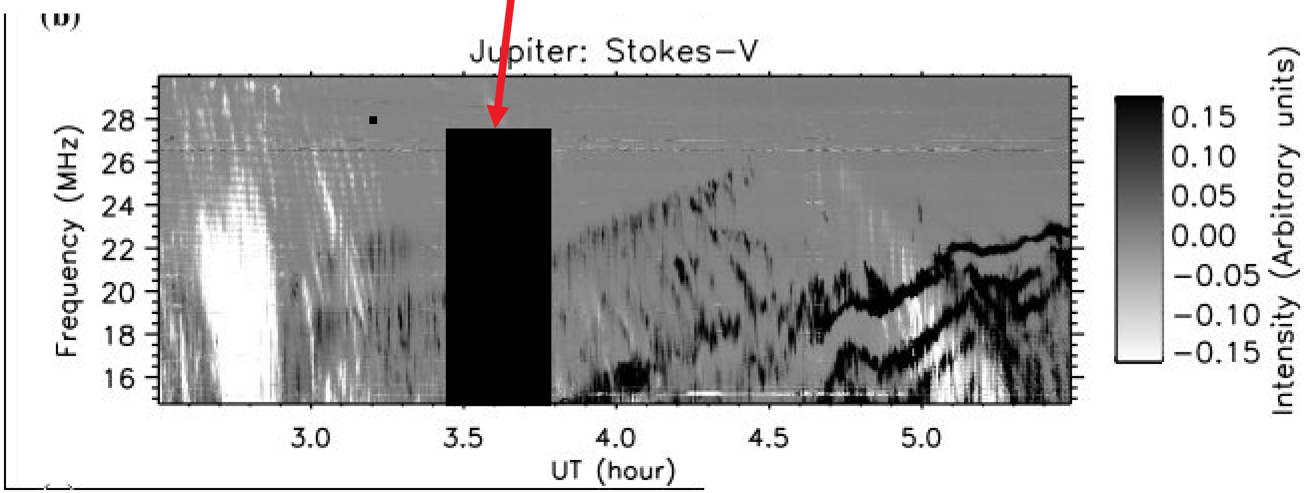
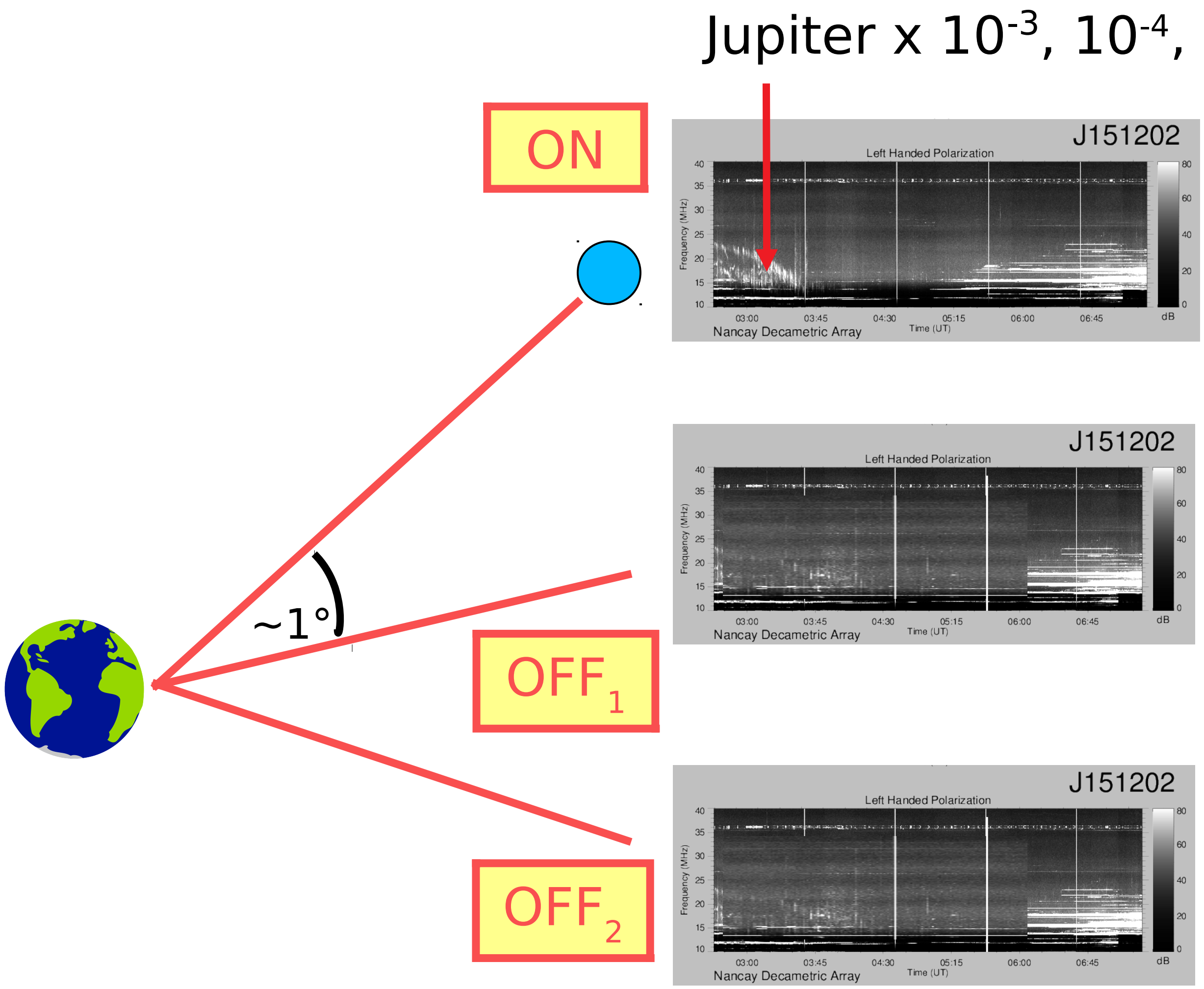


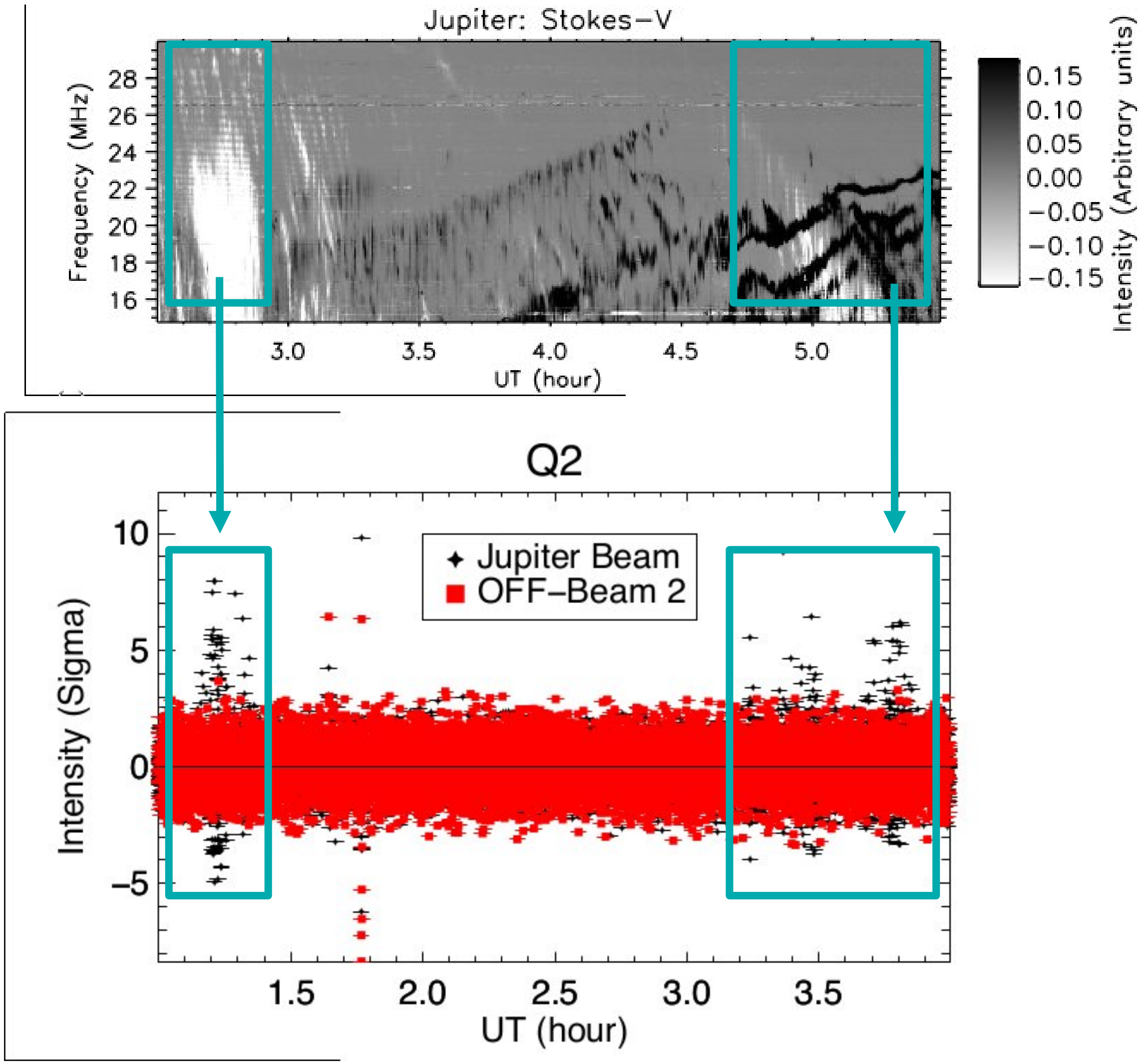
for bursty emission: theoretical detection limit = misleading!
→ need to benchmark telescope + pipeline

Measure the detection limit!



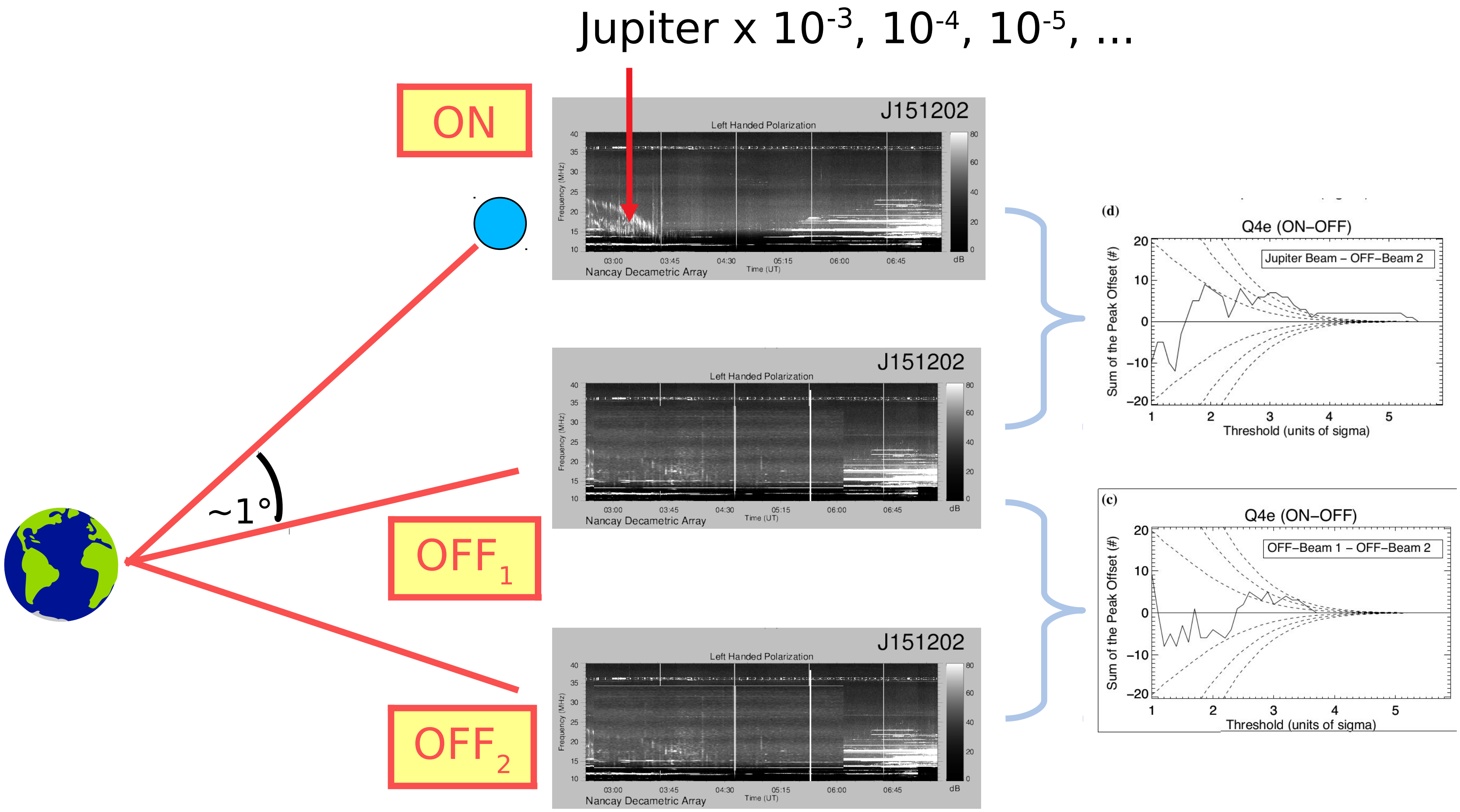
→ check if pipeline detects Jupiter x 10^{-3}
→ check if pipeline detects Jupiter x 10^{-4} ...

Measure the detection limit!

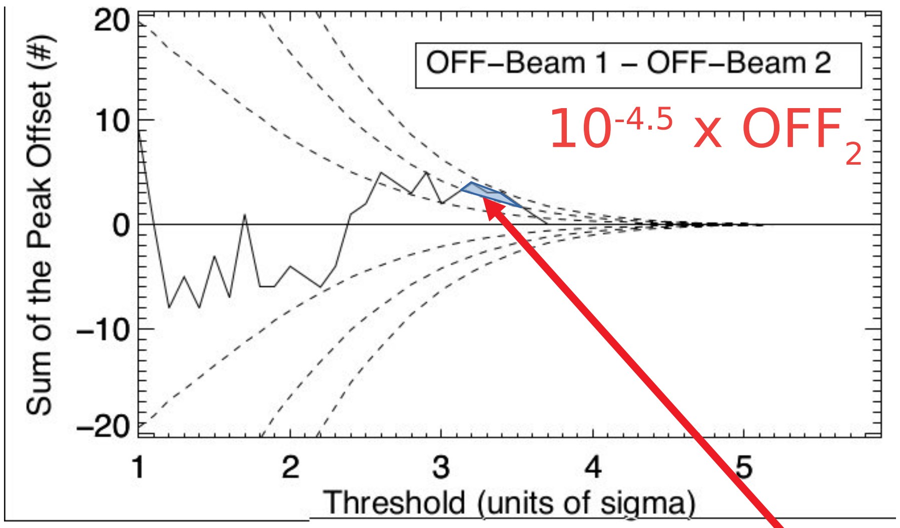


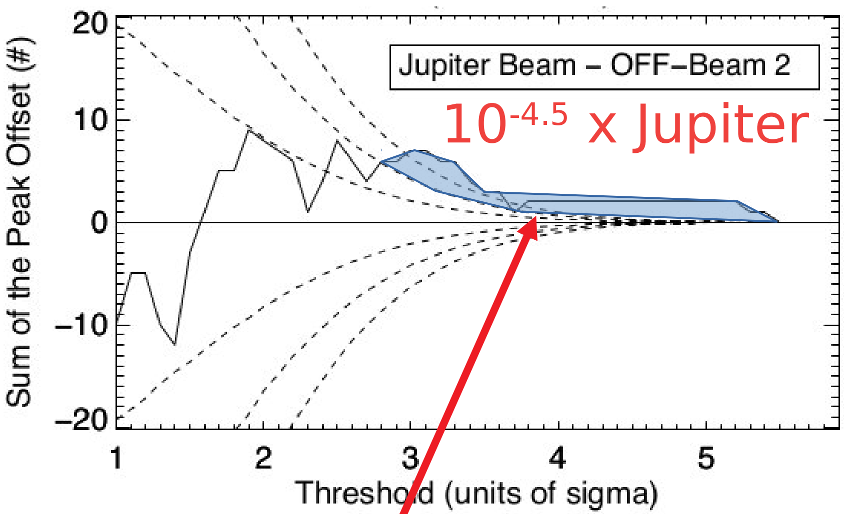
- Jupiter’s emission is bursty
- search bursts of 1-10 s duration

Measure the detection limit!



Measure the detection limit!





false positive probability 0.1

10^{-4}
(3.9 σ detection)

LOFAR detection limit

planet	rel. signal
Jupiter	1
exo-Jupiter	10^{-10}
Hot Jupiter	$10^{-10} \times 10^{5}$

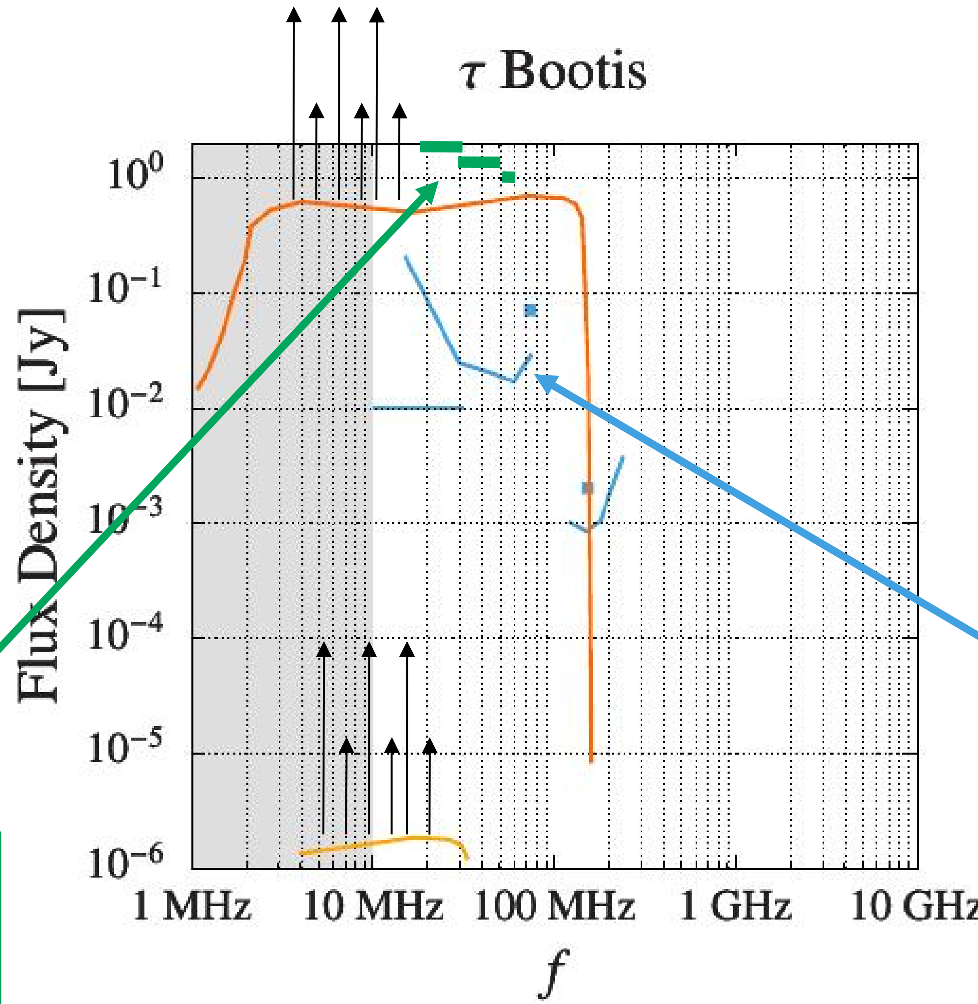
Question: can we detect an emission of Jupiter x10^{-5}?

Answer: at least Jupiter x$10^{-4.5}$

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	$10^{-2.5}$	$10^{-3.5}$

[Turner et al. 2019]

Tau Bootis A b



Jupiter at 15.6 pc

theoretical predictions for τ Bootis

theoretical detection limits

measured detection limits (1s bursts)

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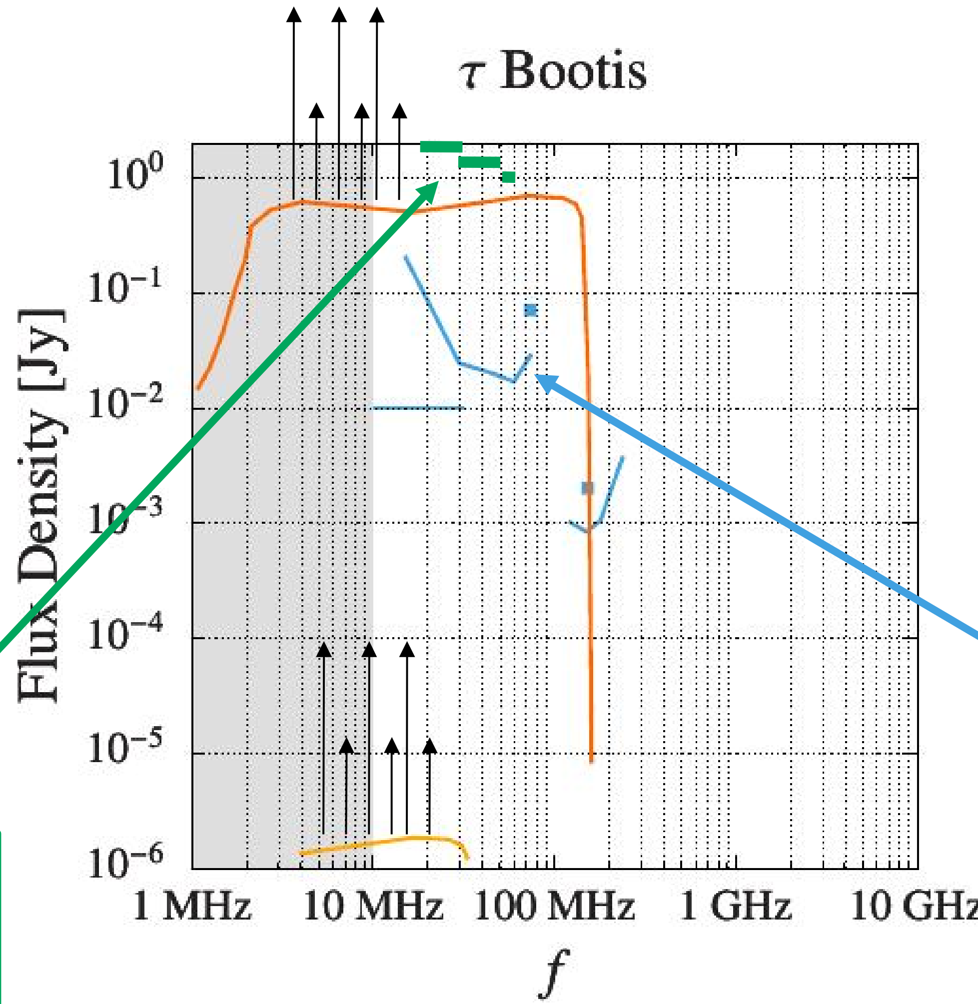

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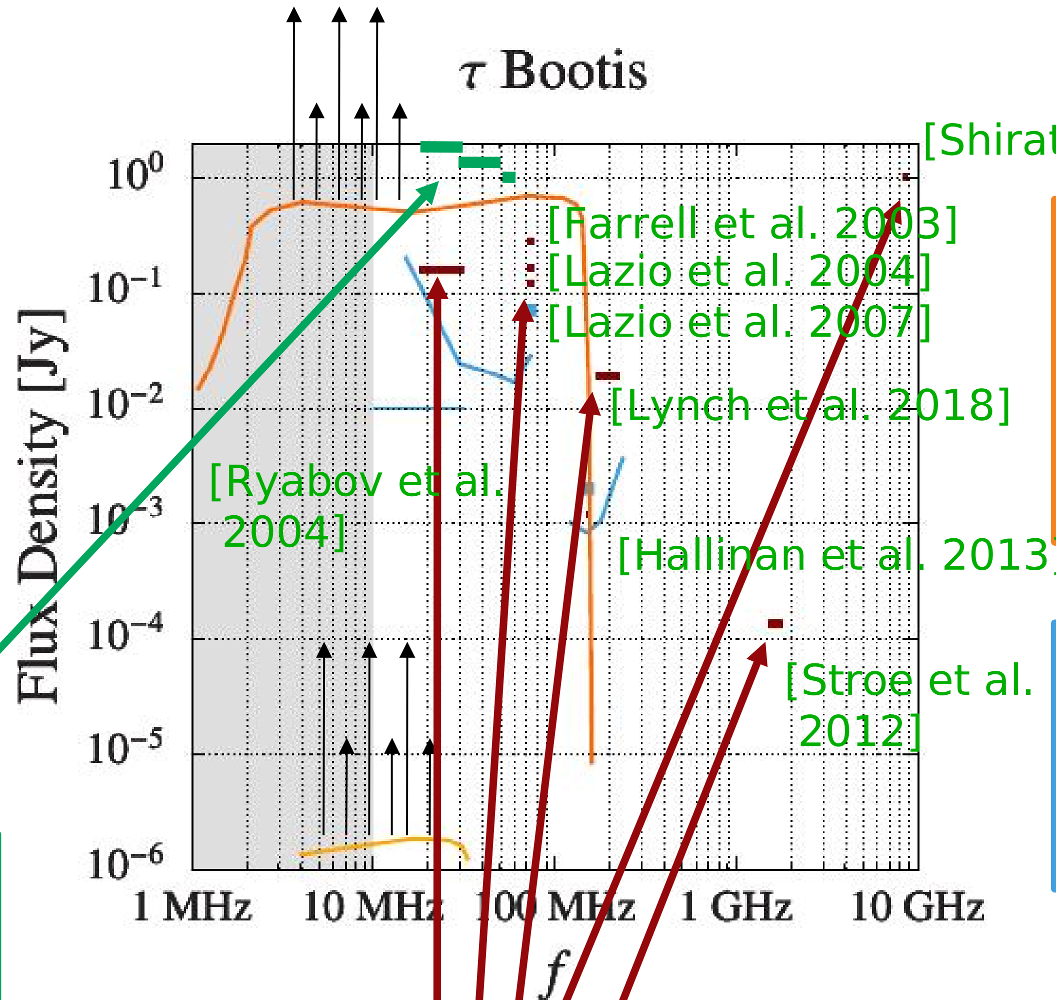
→ bright bursts are detectable!

Tau Bootis A b



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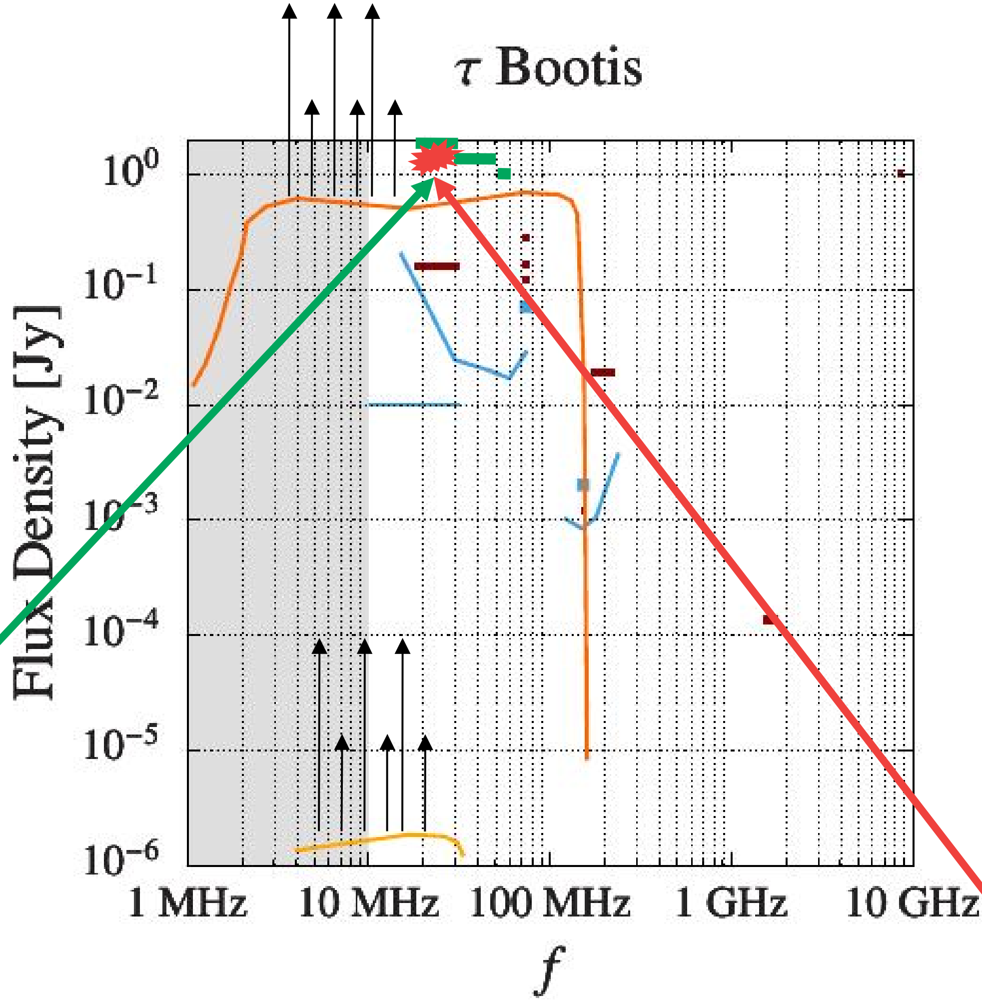

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new observations of τ Bootis

Tau Bootis A b

- 2017: A tentative detection (LOFAR)!
  [Turner et al. 2021]

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are were sure the signal is real? → 3σ
is it the star?
is it the star via SPI?
is it the planet? → circular pol.

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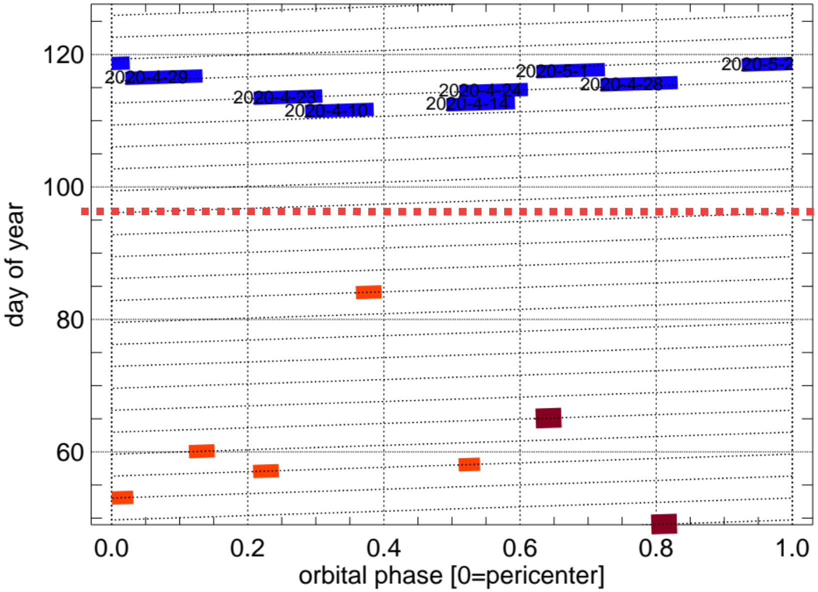
"Extraordinary claims require extraordinary evidence"

→ try to repeat observation
aims:
- increase significance
- periodicity? (orbital period, stellar rotation, beat period)

→ lecture by Rim

τ Boötis: follow-up observations



- confirm origin (planet τ Boötis b)
- → set up follow-up campaign
- multiple telescopes: LOFAR, LWA, UTR-2, NenuFAR
- improved phase coverage

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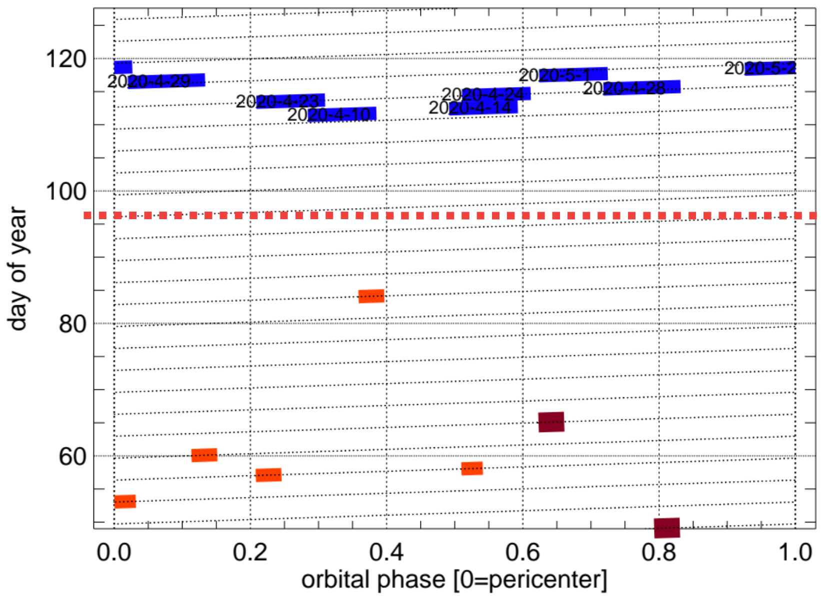

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No signal! [Turner et al. 2023, 2024]

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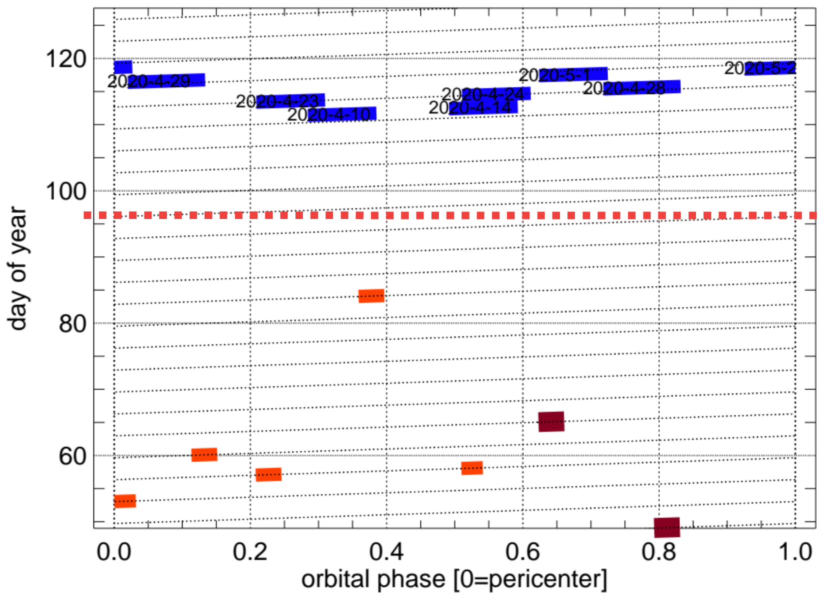

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  No signal! [Turner et al. 2023, 2024]
  Why?
  - original detection false positive?
  - CMI condition not always fulfilled (evapor. atm.)?
  - magnetosphere depleted?
  - variable emission
    (stellar rotation, stellar magnetic cycle)?

τ Boötis: follow-up observations

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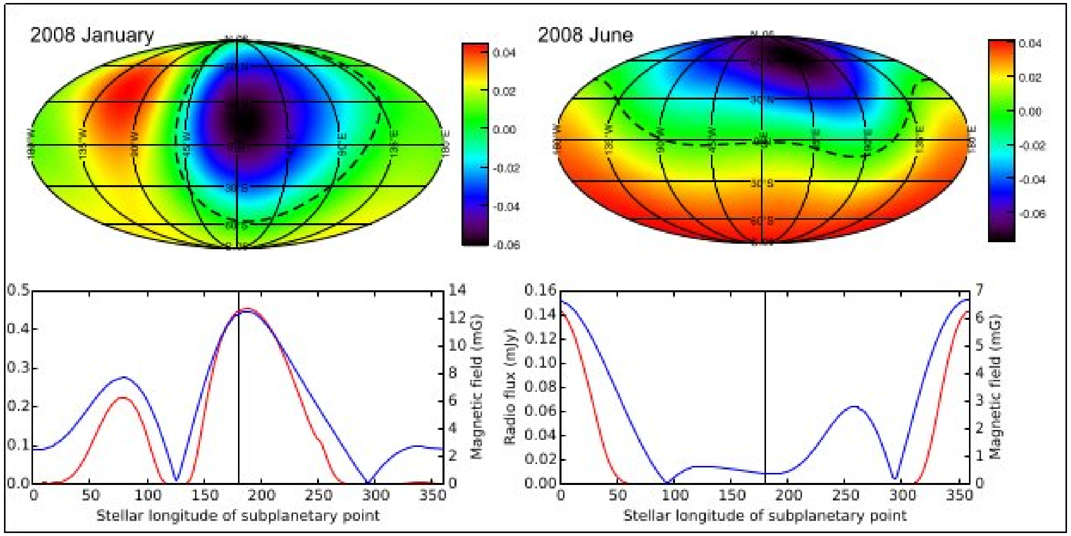
  (stellar rotation, stellar magnetic cycle)?



[See et al. 2015]

τ Boötis: follow-up observations

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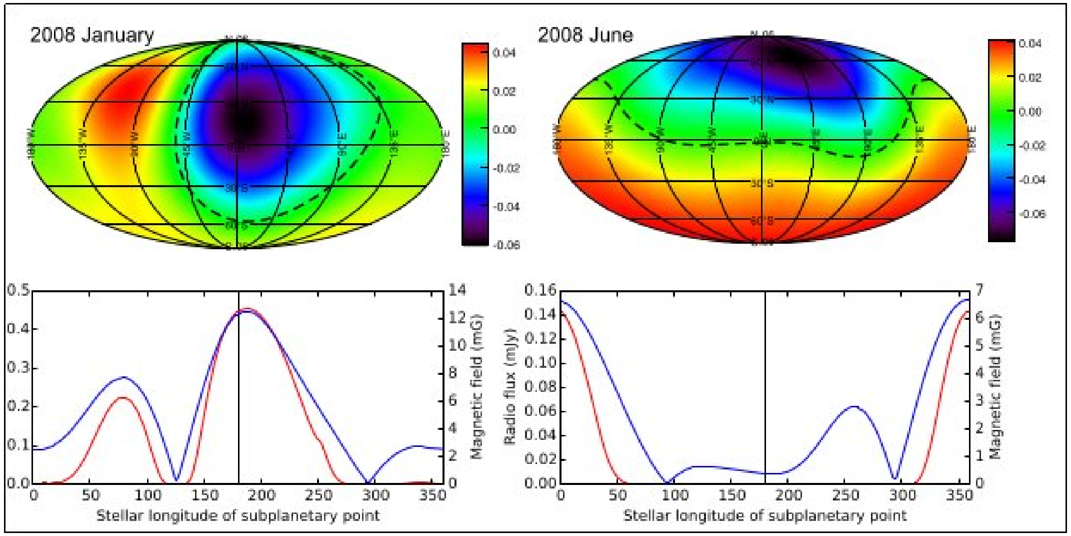

[See et al. 2015]

- If we knew the stellar magnetic field, we could...

  → rule this out in case of non-detection!

  → nterpret result in case of detection!

- all we need is ZDI observations

→ lecture by Rim

τ Boötis: follow-up observations

- 2023 observations (NenuFAR, TBL)!
  [Turner et al., in prep.]

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  (I'll work on this this afternoon, I promise!)

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- LOFAR2.0 ("Exloo collaboration", 2026+),
  SKA (SWG "Cradle of Life", 2030+),
  observations from the Moon (20??+)
  ...