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Group-standing effects on upstream whistlers around the Moon and planetary bow shocks

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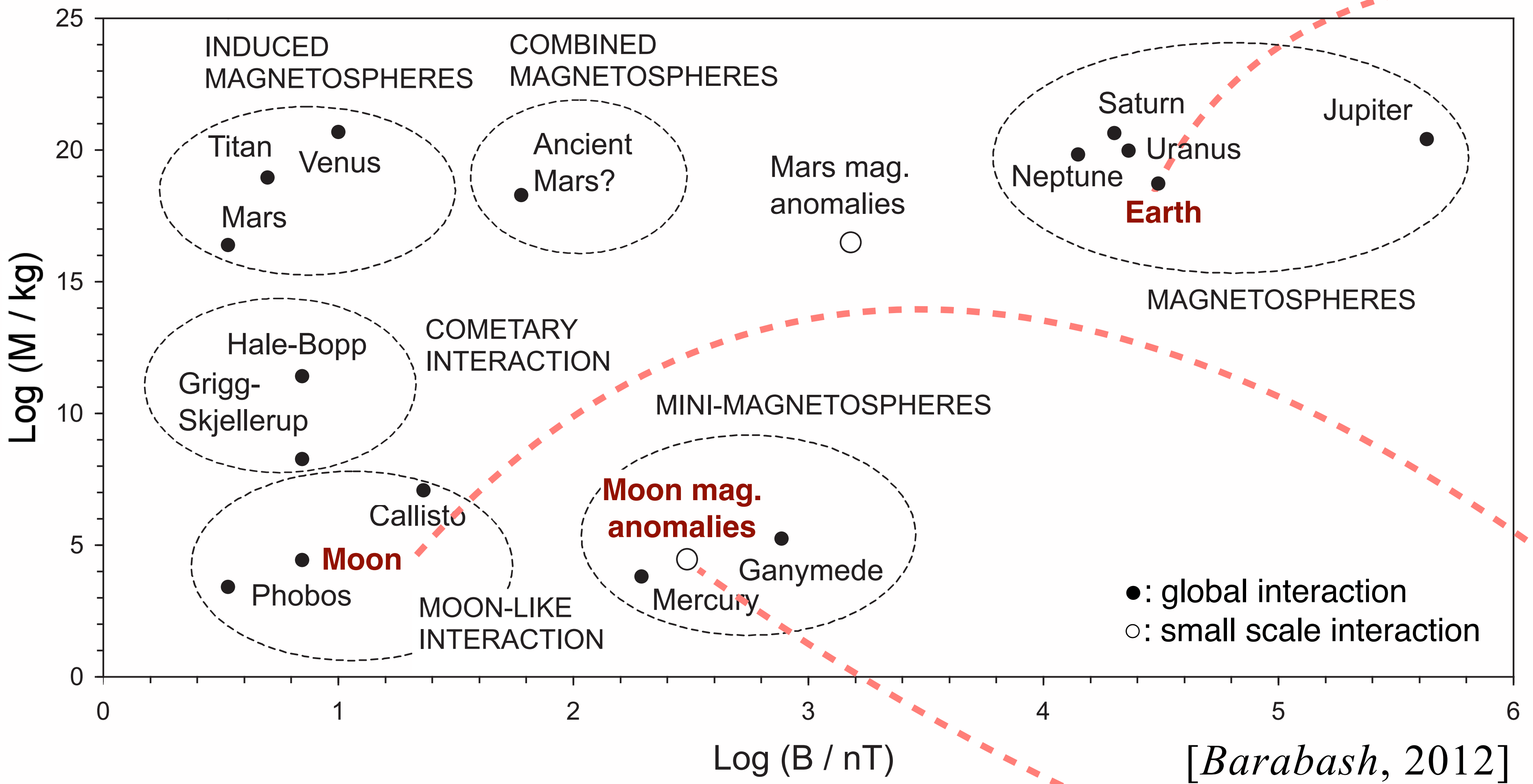
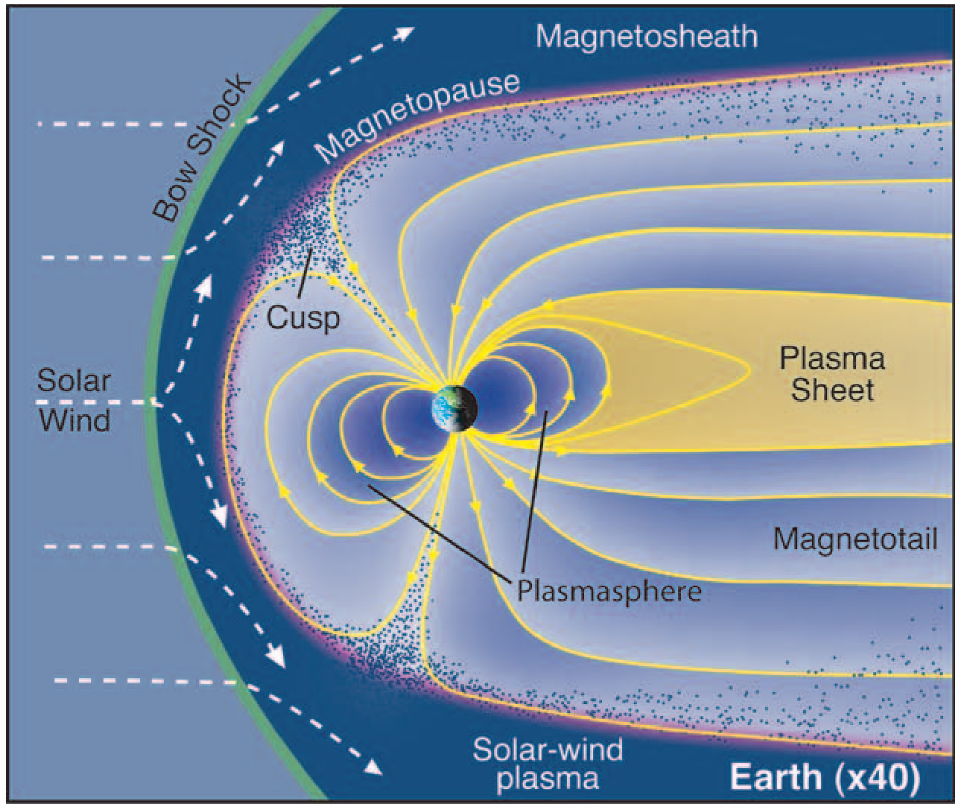
SW interaction with solar system bodies

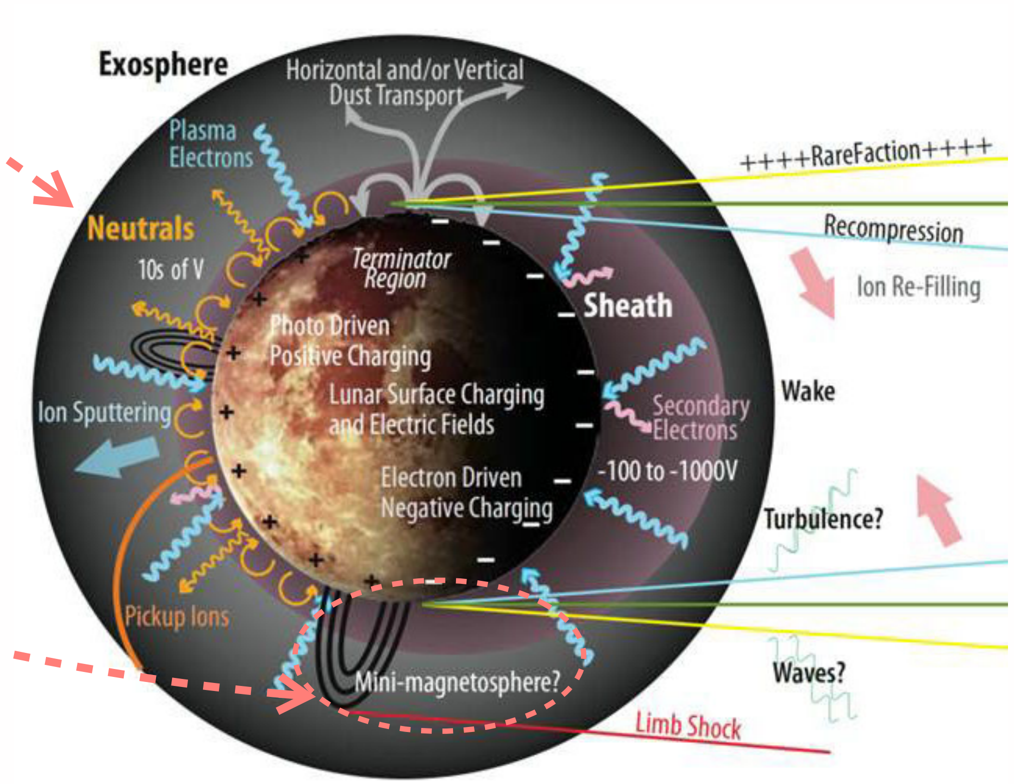
- 300−800 km/s
- 2−30 /cm^3
- H^+ ~ 95 %, He^{2+} ~ a few %
- 10^{4-5} K



[*Barabash*, 2012]



[*Kivelson and Bagenal*, 2007]



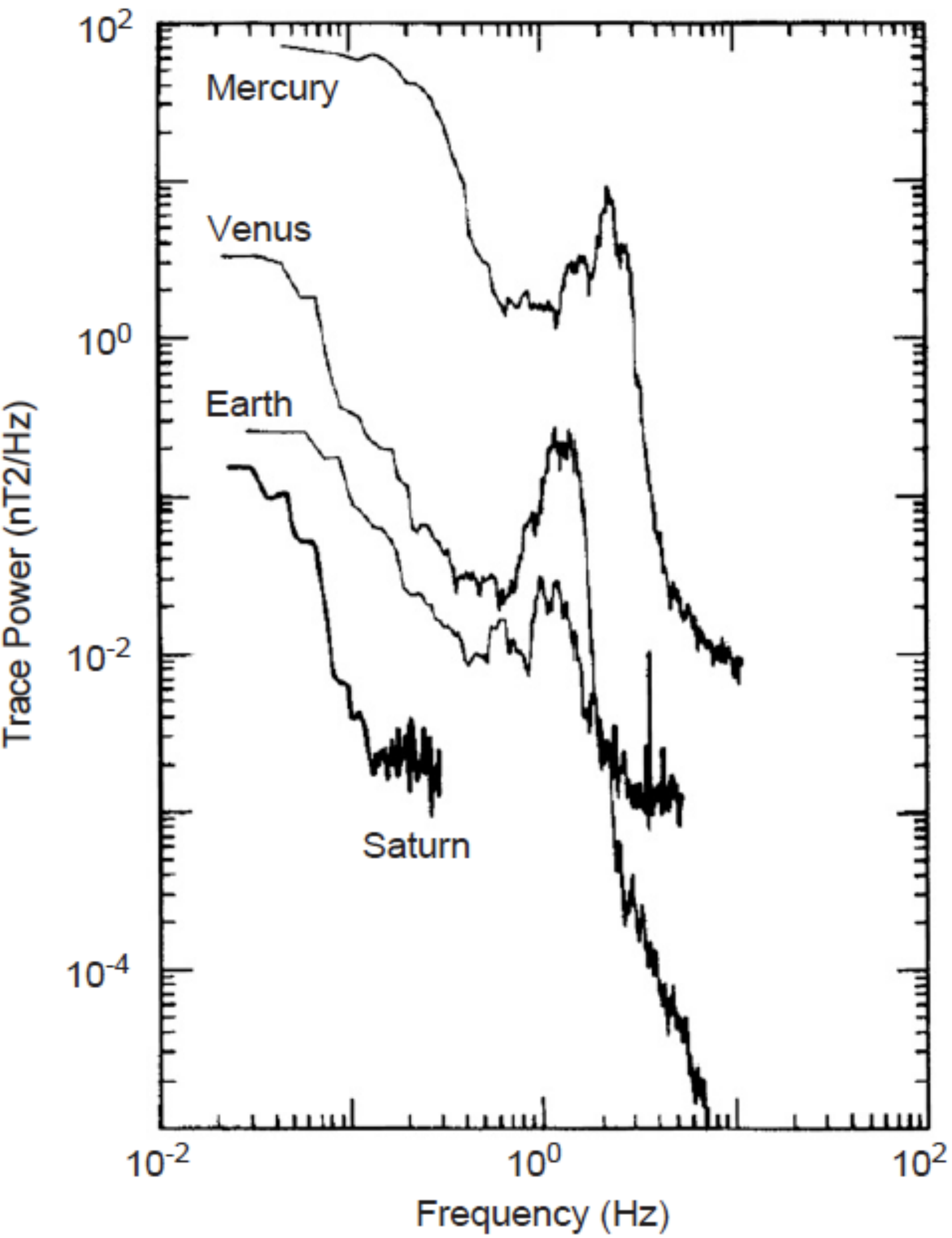
[DREAM project, NASA]

<u>How is the SW energy transformed? & to What?</u>

Grobal vs Local scale, Magnetized vs Unmagnetized

→ upstream waves play a part of the energy

Upstream whistlers

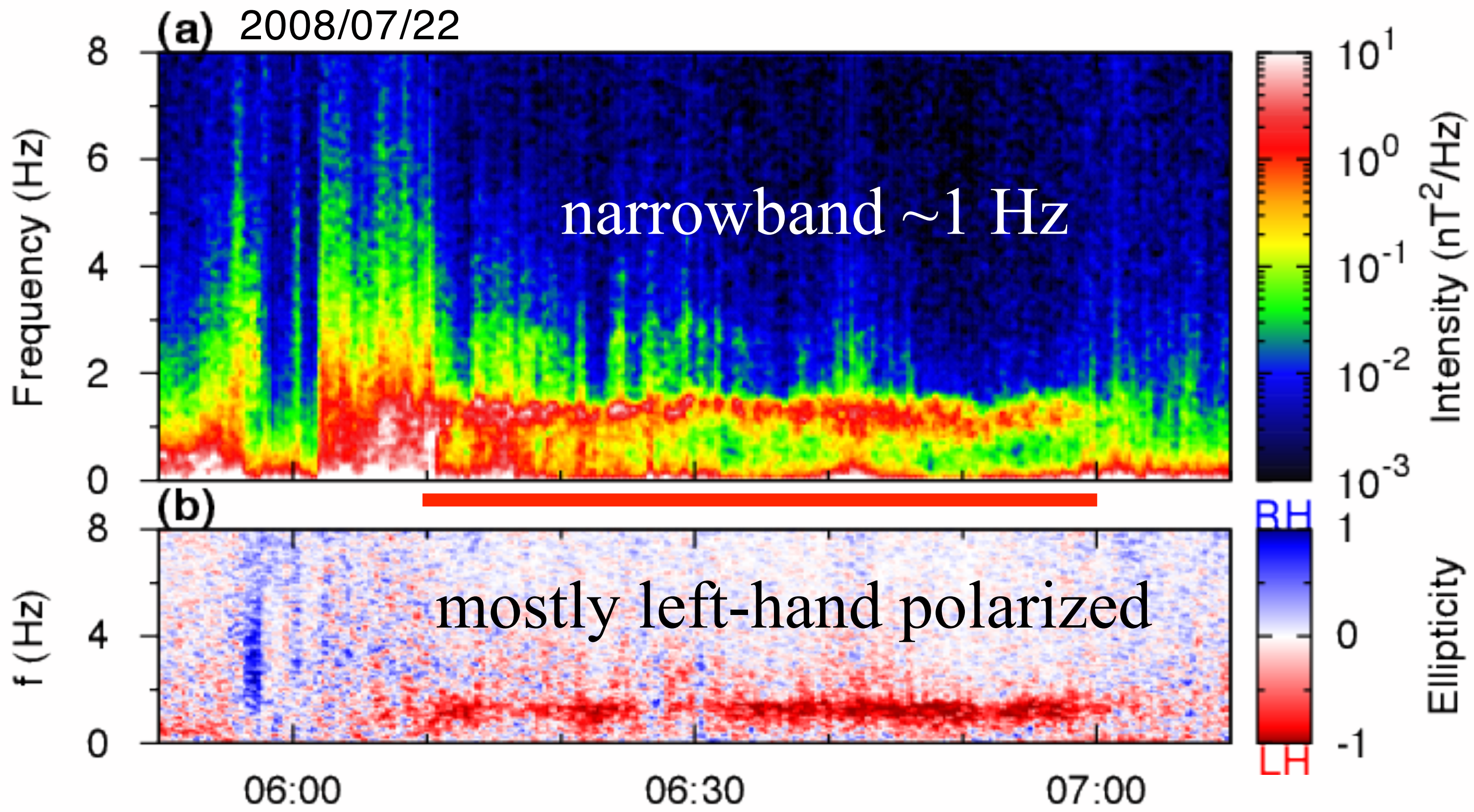


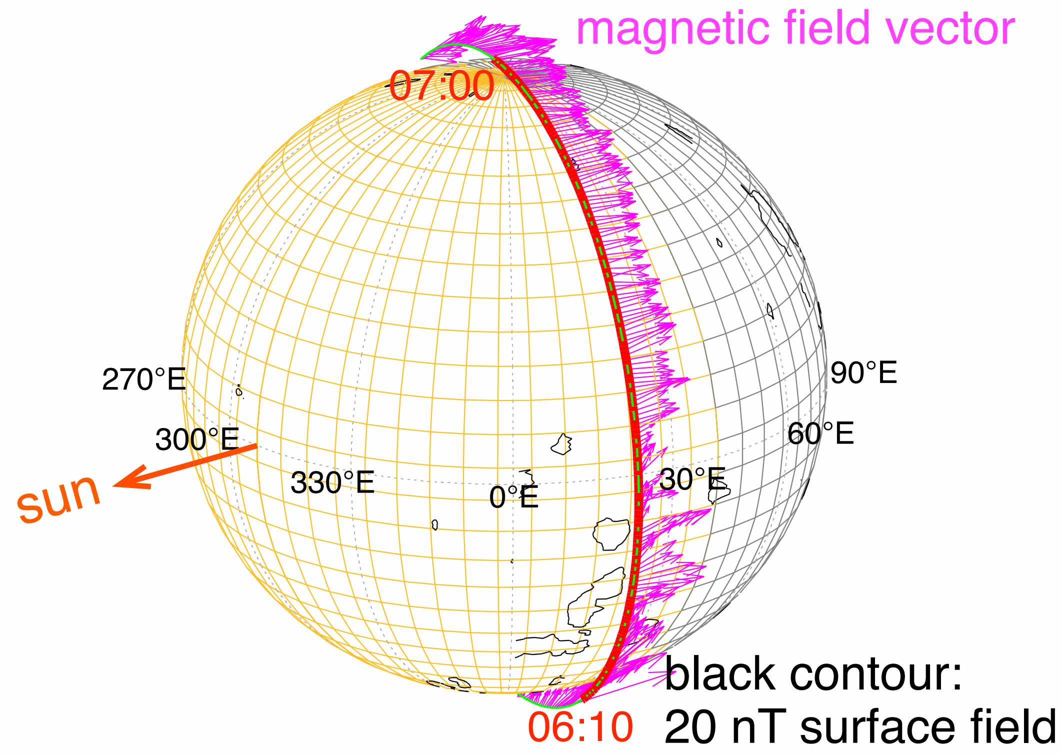
[*Russell*, 2007]

- electromagnetic waves ~**1 Hz** ("1 Hz wave")
- mostly left-hand polarized (LH)
- generally observed upstream of solar system bodies
  - Earth: *Heppner et al.*, 1967; *Fairfield*, 1974, etc.
  - Mercury: *Fairfield and Behannon*, 1976; *Orlowski et al.*, 1990
  - Venus: *Orlowski and Russell*, 1991; *Orlowski et al.*, 1993
  - Mars: *Brain et al.*, 2002
  - Saturn: *Orlowski et al.*, 1992
  - Moon: *Farrell et al.*, 1996; *Nakagawa et al.*, 2003
  - Uranus: *Smith et al.*, 1989, 1991
  - IP shock: *Tsurutani et al.*, 1983
  - comet: *Tsurutani et al.*, 1987
- similar spectral shape under different conditions
- propagate as far as ~30 R_E

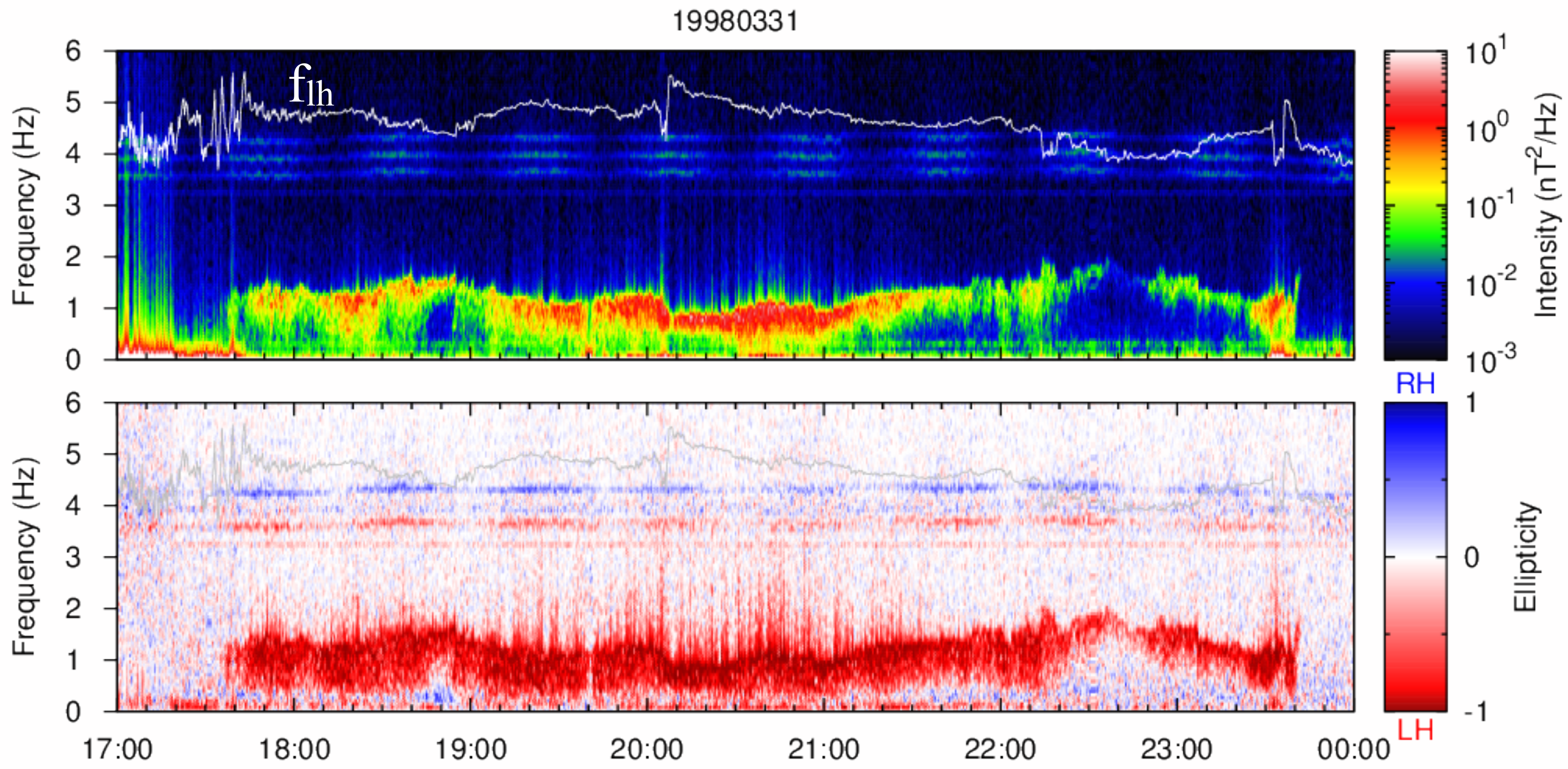
Narrowband upstream whistlers (NR)

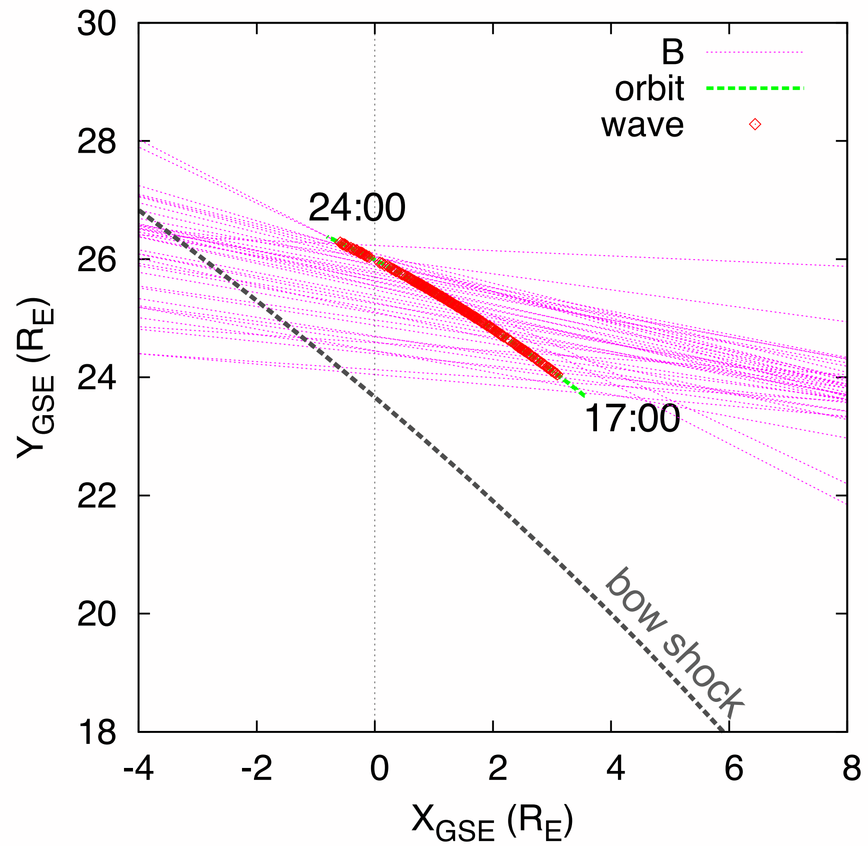
Kaguya





Geotail





Possible sources of upstream whistlers

Upstream local instabilities?

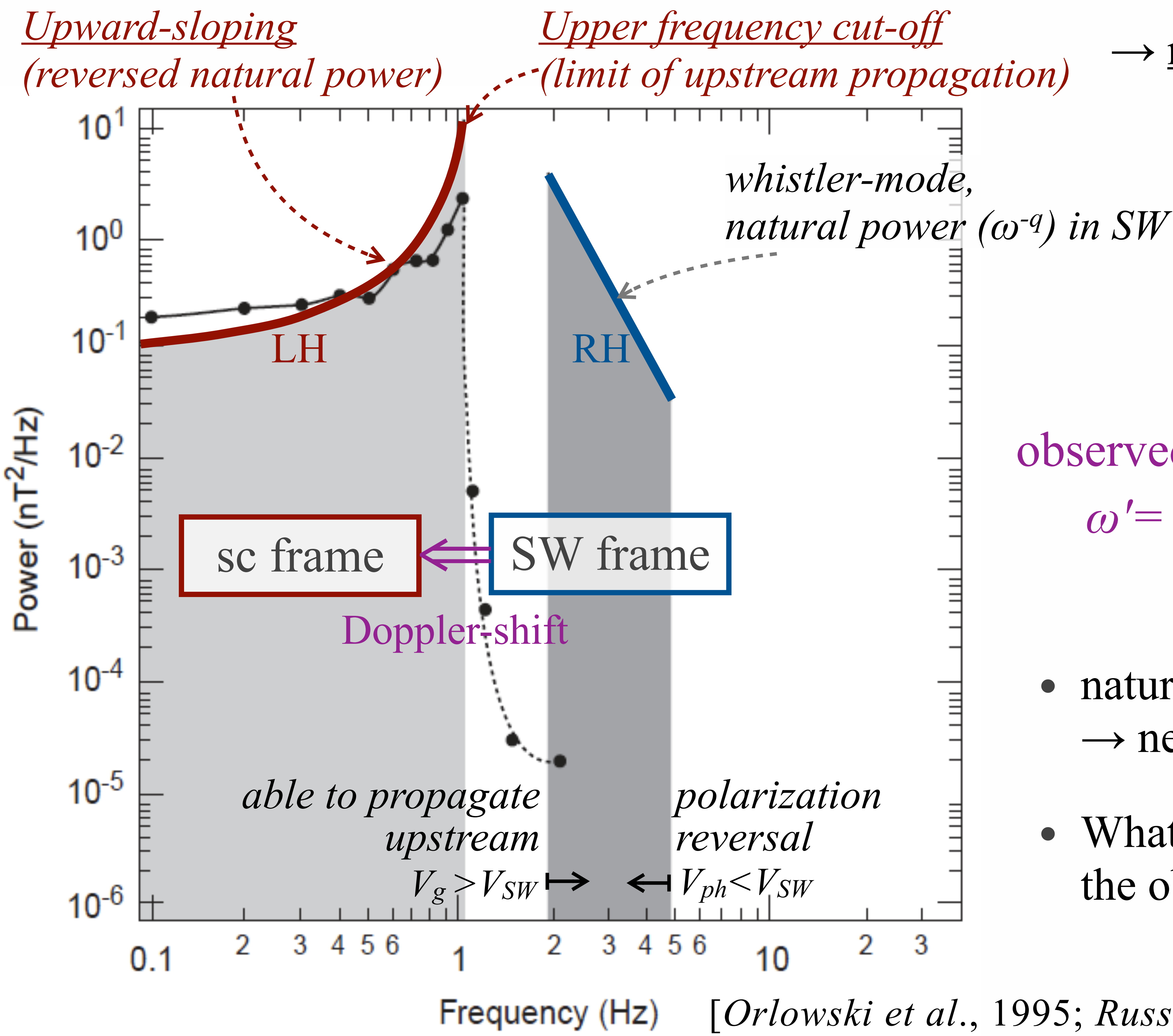
- Reflected ion beams [*Hoppe et al*., 1981; 1982]
- Large pitch angle electrons backstreaming from the shock [*Sentman et al*., 1983]
- Temperature anisotropic ($T_\perp/T_\parallel \gg 1$) proton beams [*Wong and Goldstein*, 1987]
- Gyrating isotropic proton beams [*Wong and Goldstein*, 1988; *Hellinger et al*, 1996]
- Electron temperature anisotropies $T_\perp/T_\parallel > 1$ [*Mace*, 1998]

By or within shock itself?

- Field-aligned $T_\perp/T_\parallel > 1$ electron beams toward magnetosheath within the shock ramp [*Tokar and Gurnett*, 1985]
- Reflected protons which gyrate back to the shock [*Hellinger and Mangeney*, 1997]
- Loss cone or nongyrotropic electron distributions [*Veltri and Zimbardo*, 1993]
- Cross-field drift at the shock [*Orlowski et al*., 1995]
- Shock front perturbations [*Baumgartel et al*., 1995]
- Nonlinear interaction of non-stationary shock front [*Balikhin et al*., 1997; 1999]

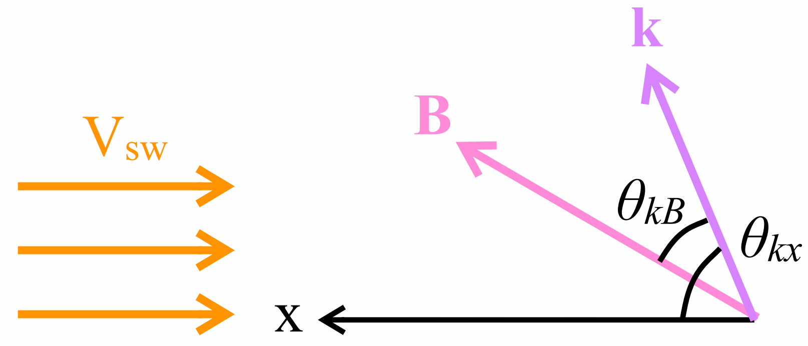
What are required for generation? ↔ for observation?

Spectral formation of NR



[*Orlowski et al.*, 1995; *Russell*, 2007]

→ narrowband LH waves ~ 1 Hz



observed frequency by spacecraft in SW

$$\omega' = \omega + \mathbf{k}\cdot\mathbf{V_{sw}} = \omega - kV_{sw}\cos\theta_{kx}$$

- natural power & upstream propagation → necessary?
- What does determine the observed frequencies?

Modification of spectral density

wave power ↓ ... *spectral density* ↓

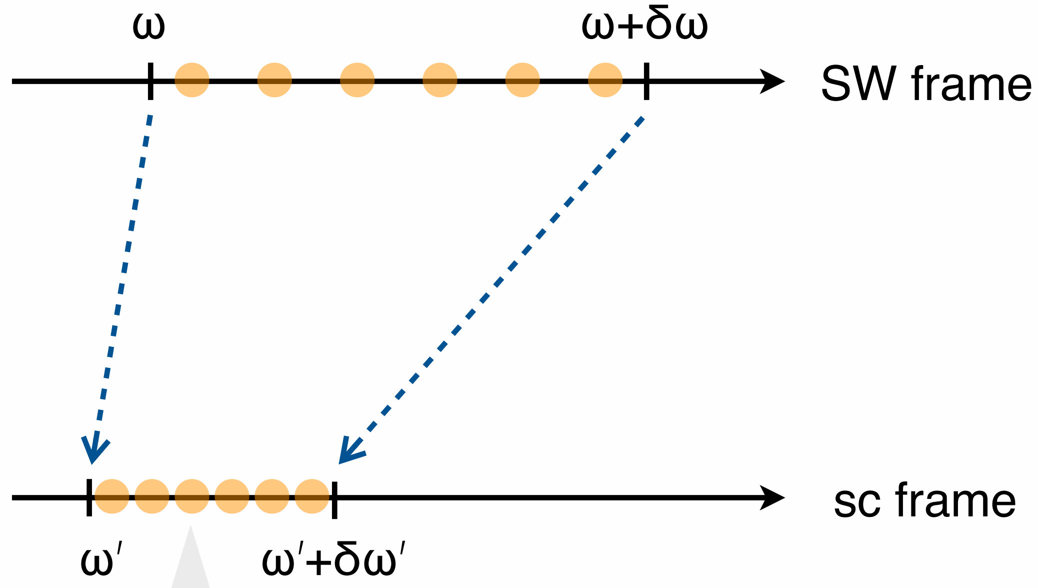
<u>SW frame</u> $$P(\omega, \delta\omega) = \int_{\omega}^{\omega+\delta\omega} S(\nu)d\nu = \langle S(\omega)\rangle\,\delta\omega$$

invariant for a Doppler-shift transformation,

$\omega' = \omega + \mathbf{k}\cdot\mathbf{V_{sw}} = \omega - kV_{sw}\cos\theta_{kx} = \omega - k_x V_{sw}$

[e.g., *Orlowski et al.*, 1995]

<u>sc frame</u> $$P'(\omega', \delta\omega') = \int_{\omega'}^{\omega'+\delta\omega'} S'(\nu)d\nu = \langle S'(\omega')\rangle\,\delta\omega'$$



$$\langle S'(\omega')\rangle = \langle S(\omega)\rangle \frac{\delta\omega}{\delta\omega'} \sim \langle S(\omega)\rangle \frac{V_{g,x}}{V'_{g,x}}$$

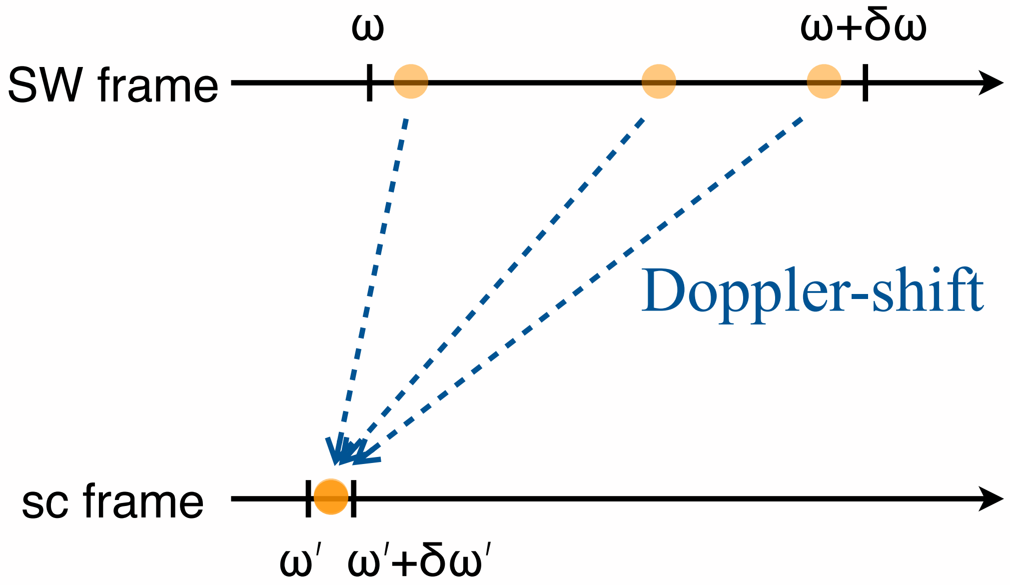
⇓

observed spectral density is modified by $\delta\omega/\delta\omega' \sim V_{g,x}/V'_{g,x}$

Modification of spectral density

$$\langle S'(\omega')\rangle = \langle S(\omega)\rangle \frac{\delta\omega}{\delta\omega'} \sim \langle S(\omega)\rangle \frac{V_{g,x}}{V'_{g,x}}$$

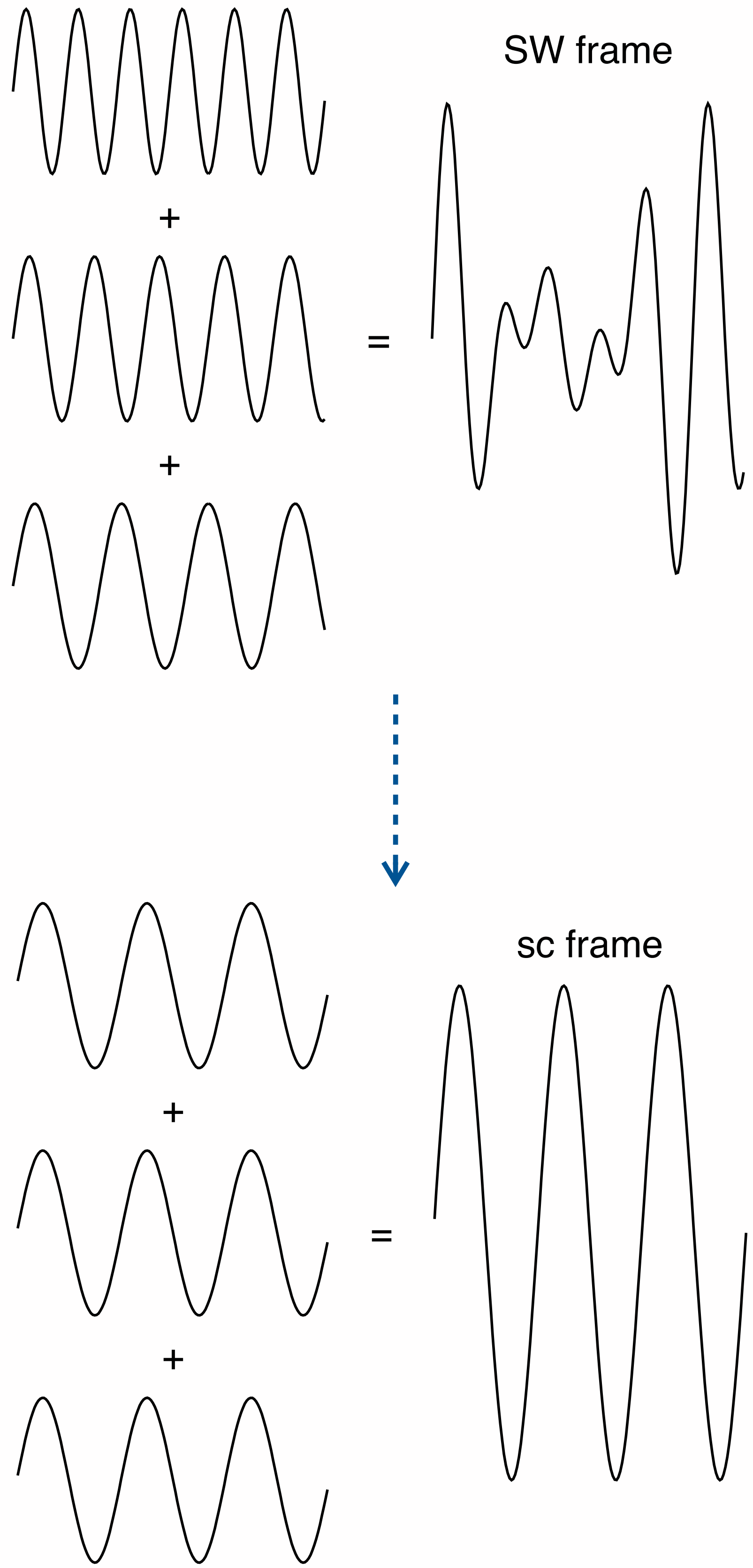
when $V'_{g,x} = V_{g,x} - V_{SW} \to 0$
(stagnate in sc frame = group-standing),
observed spectral density has a peak



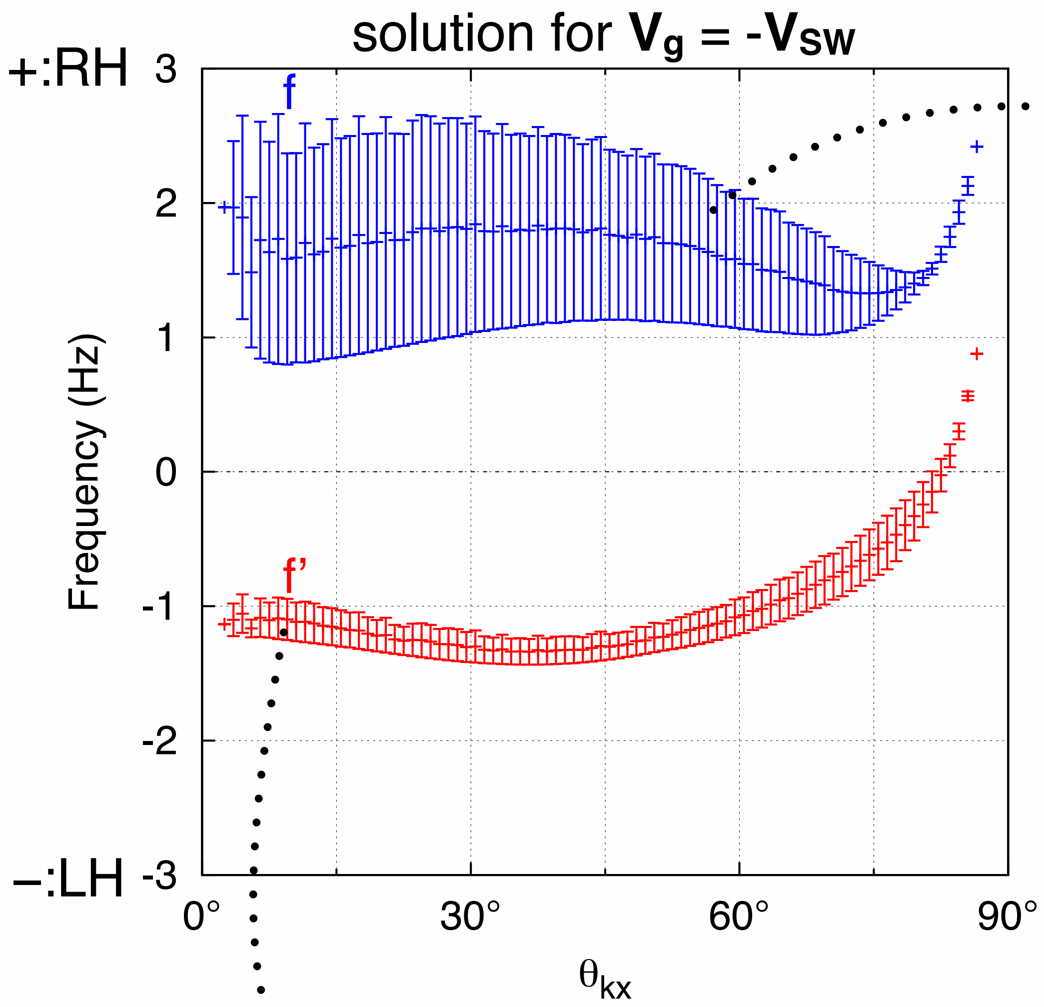
⇓

group-standing effect

- natural power in SW → not required
- propagated upstream ($V'_g > 0$) → nearly stagnated



$$\begin{cases} \mathbf{V_g = -V_{SW}} & \text{.......... } \textbf{group-standing condition} \\ \omega' = \omega - kV_{sw}\cos\theta_{kx} & \text{.......... Doppler shift of frequency} \\ D(\omega, k, \theta_{kB}, n, B) = 0 & \text{.......... whistler-mode in cold plasma} \\ \mathrm{B = 5\ nT,\ n = 5\ cm^{-3},\ V_{SW} = 400\ km/s} & \text{.......... typical SW parameters at 1 AU} \end{cases}$$

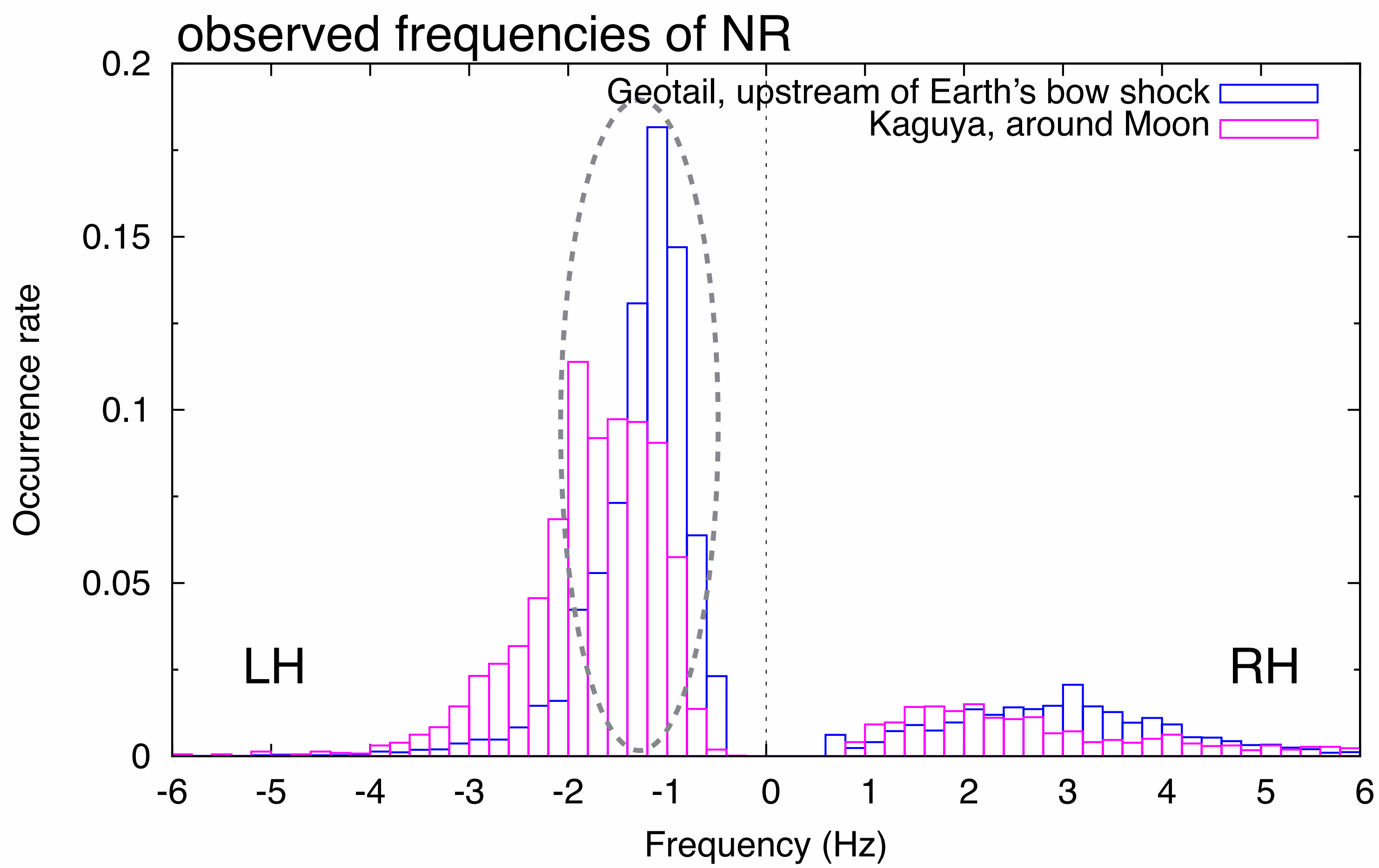


frequency in SW frame: 1−3 Hz

~ lower hybrid freq (f_{lh}), 3.3 Hz

frequency in sc frame: ~1 Hz & LH

→ agree with observed frequency



Upstream whistlers (NR) of other planets

observed values [*Orlowski et al.*, 1995; *Brain et al.*, 2002]

	Mercury	Venus	Earth	Mars	Saturn
f_{obs} (Hz)	2.5−3.0	1.0−1.8	0.8−1.5	0.5−0.8	0.1−0.2
θ_{kx} (deg)	0−37	8−30	9−36	21−38	60−70
θ_{kB} (deg)	7−53	5−51	5−57	19−40	40−60
heliocentric distance (AU)	0.39	0.72	1	1.52	9.55
n (/cm^3)	33.37	10	5	2.15	5.48×10^{-2}
V_{sw} (km/s)	400	400	400	400	400
B (nT)	25.3	8	5.0	2.8	0.4

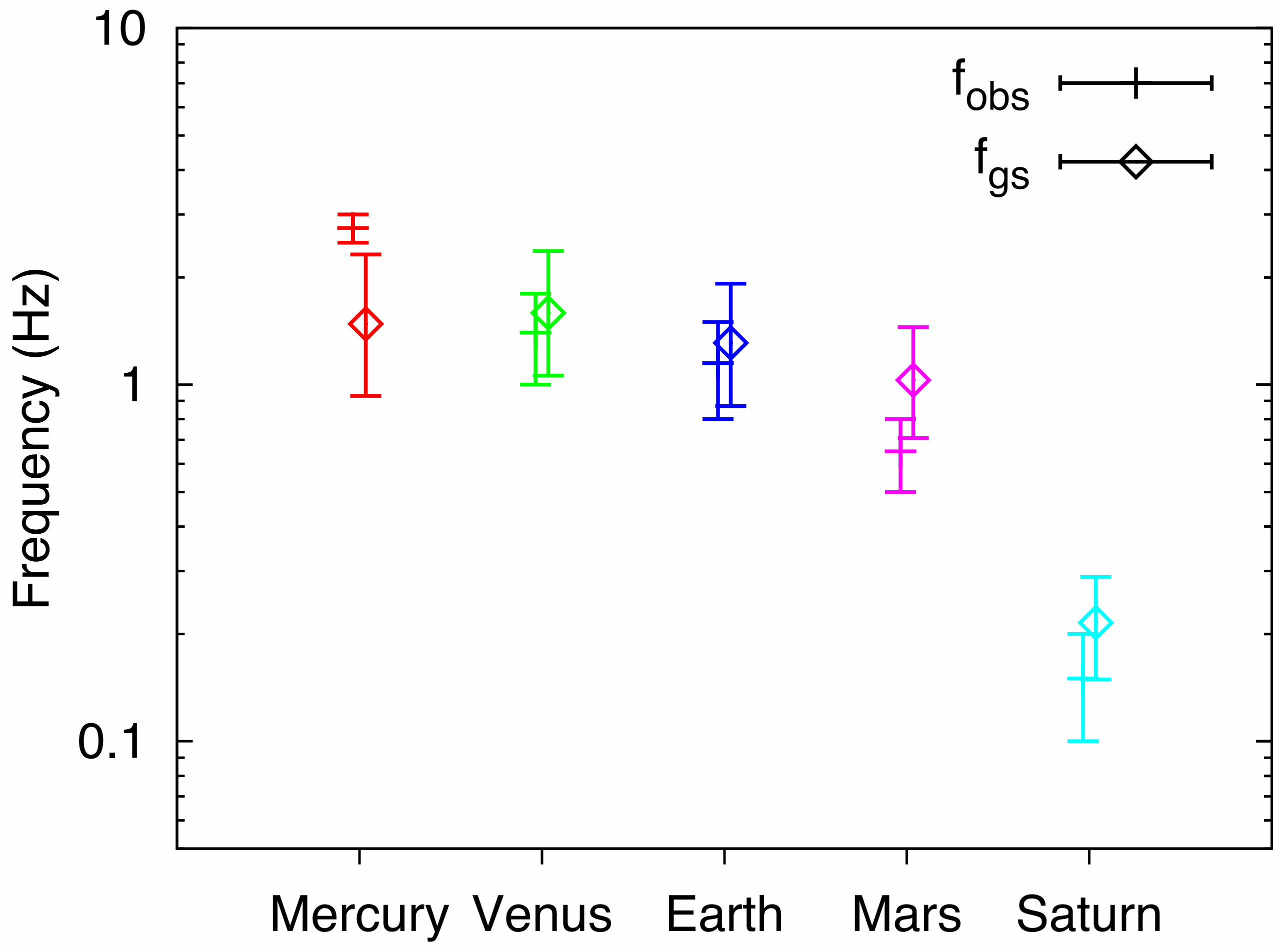
input parameters

±10%

$$n(r) = n_0 \frac{r_0^2}{r^2} \qquad V(r) = V_0$$

$$B(r) = \sqrt{B_r^2 + B_\varphi^2} = B_0 \sqrt{\left(\frac{r_0^2}{r^2}\right)^2 + \left(\frac{\omega_s r_0^2}{ur}\right)^2}$$

[*Meyer-Vernet*, 2007]



$f_{obs} \approx$ estimated f_{gs} even in different conditions

<u>Observed frequency is determined by group-standing effect</u>

⇒ NR is group-standing, and its spectrum is essentially formed by the effects

- concentrate ~1 Hz
- mostly LH
- sharp peak intensity

↓

significantly modified / restricted from generated spectra

NR

group-standing

propagating oblique whistler-mode waves ~f_{lh}

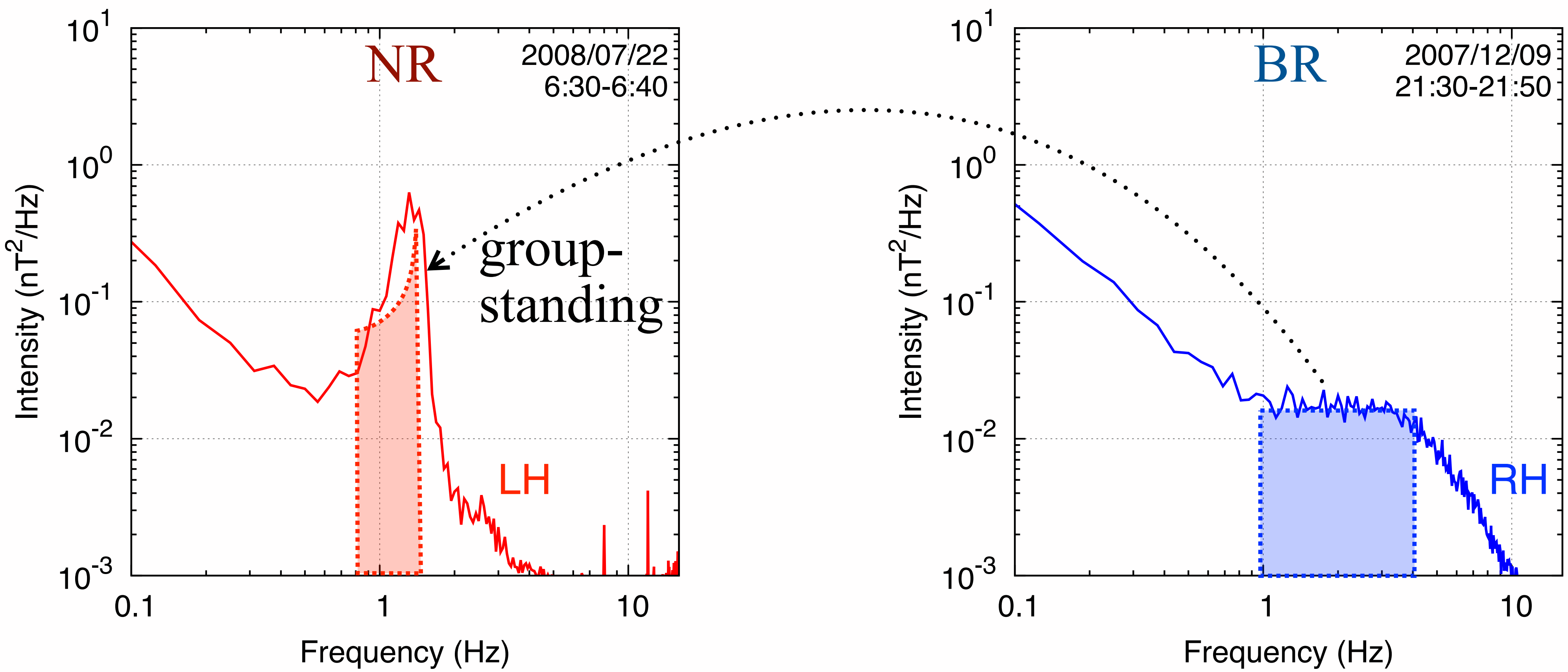
not group-standing

BR

- broadband including ~f_{lh}
- RH with large θ_{kx}
- an order weaker than NR

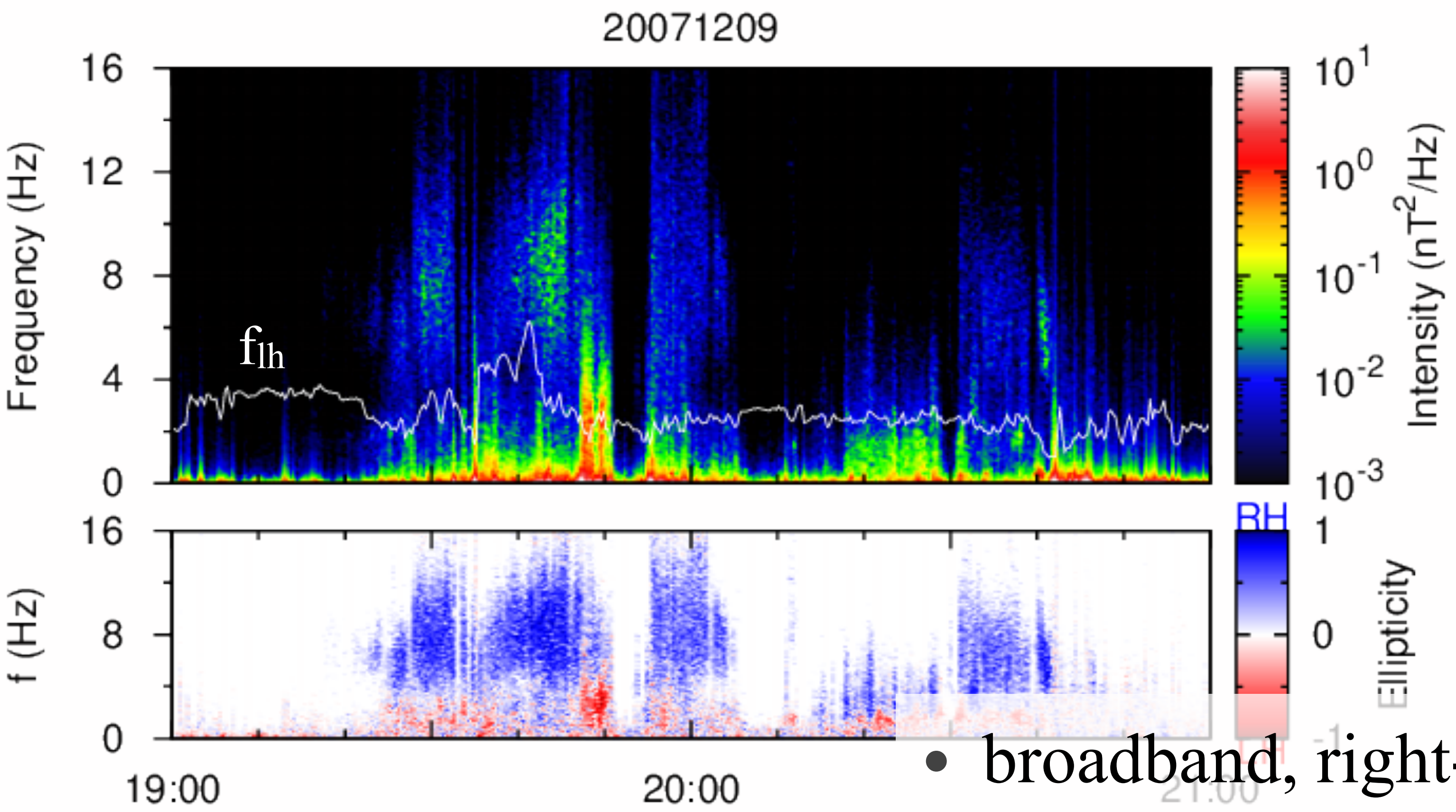
↓

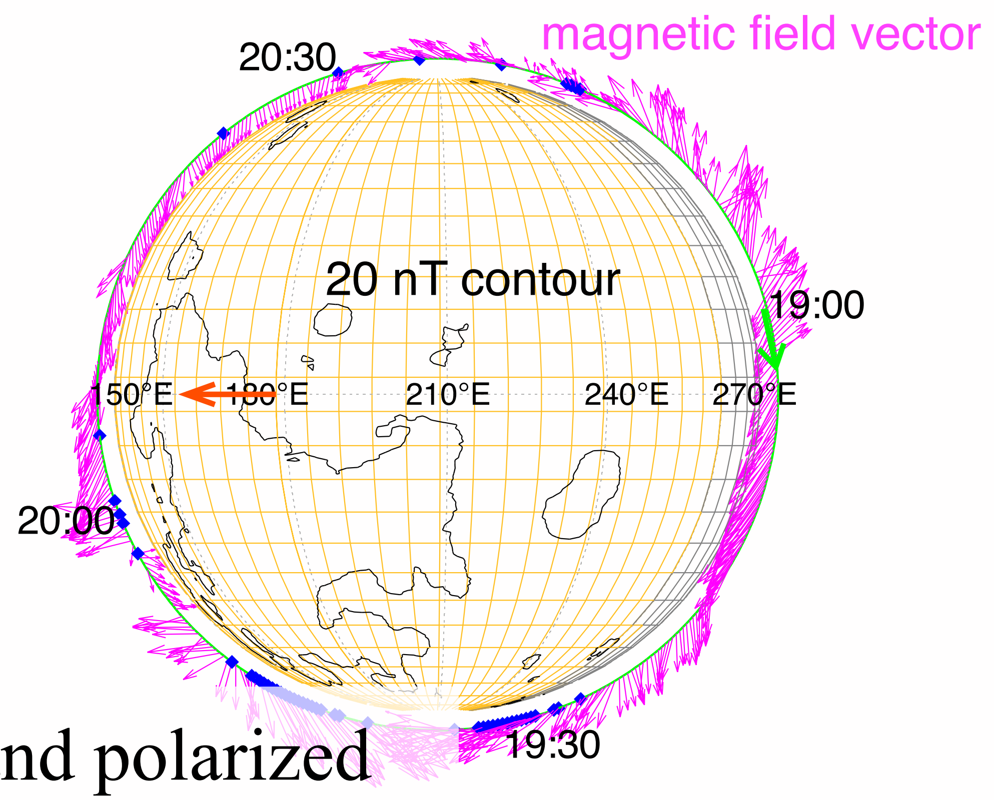
almost not modified from generated spectra



Broadband upstream whistlers (BR)

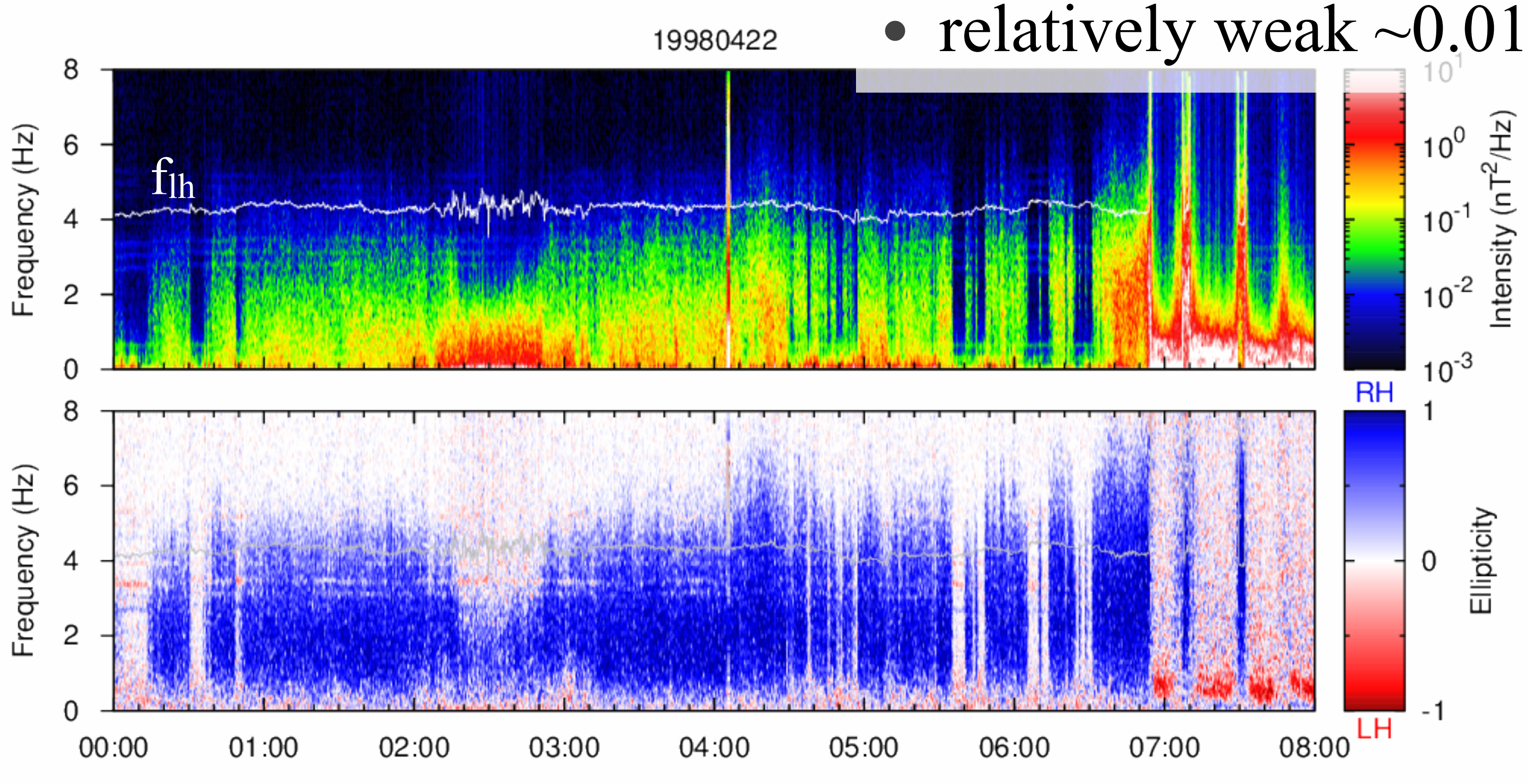
Kaguya

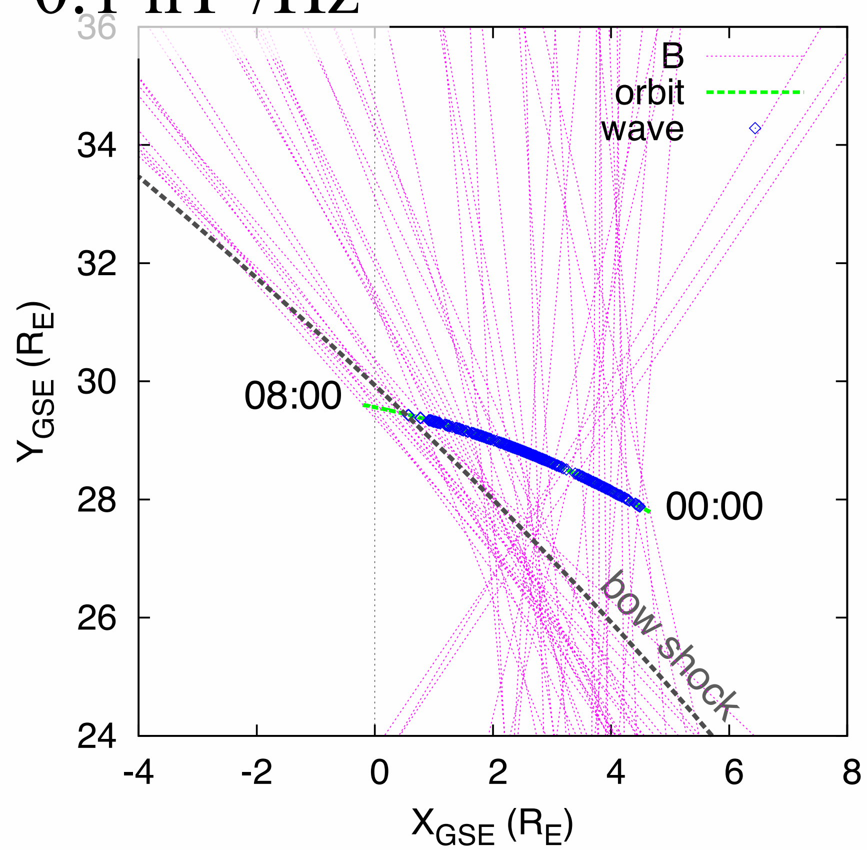


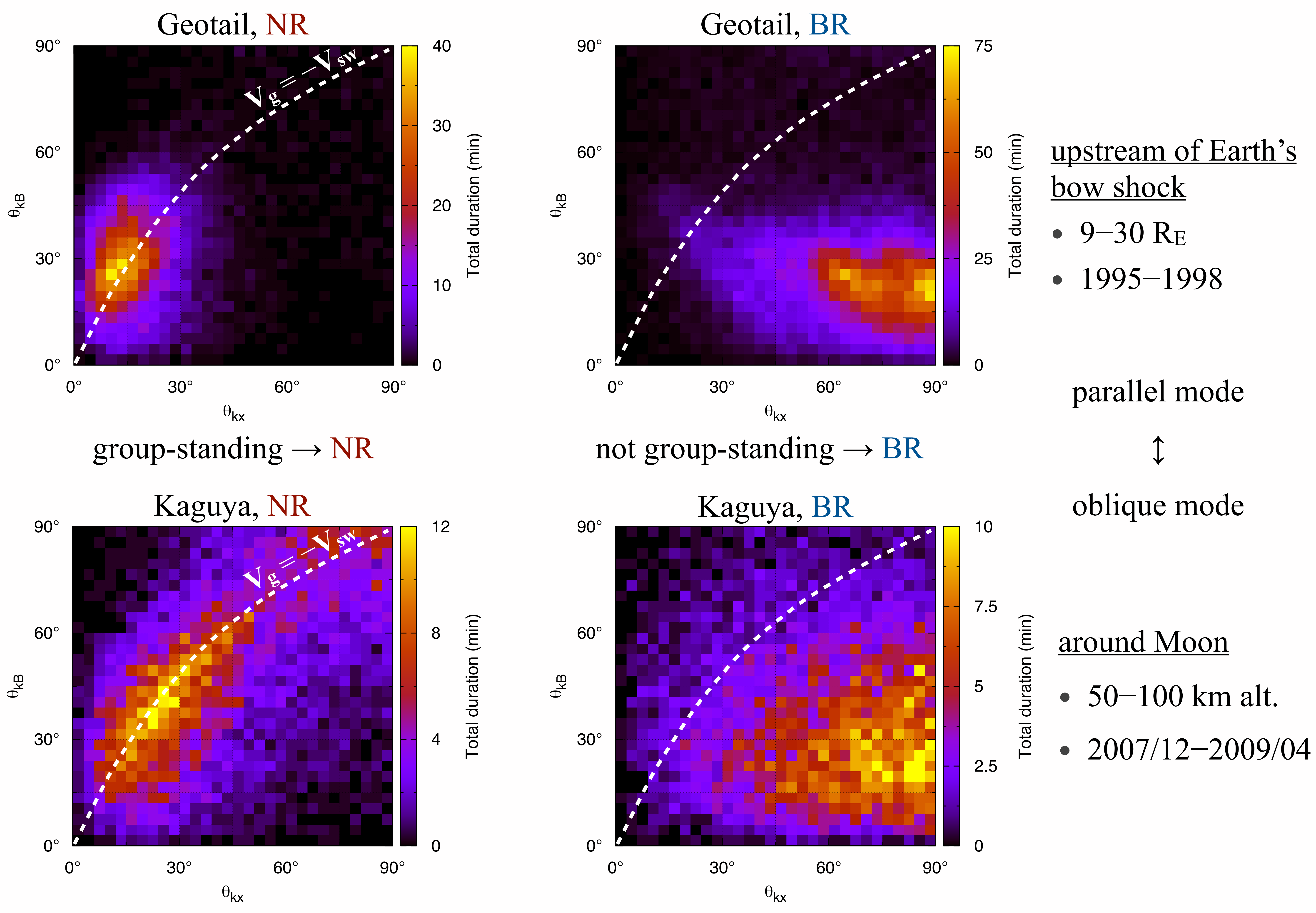


- broadband, right-hand polarized
- relatively weak ~0.01−0.1 nT^2/Hz

Geotail







Geotail, NR
Geotail, BR
Kaguya, NR
Kaguya, BR
V g = −V sw
θkB
θkx
Total duration (min)
upstream of Earth's bow shock
• 9−30 RE
• 1995−1998
parallel mode
↕
oblique mode
group-standing → NR
not group-standing → BR
around Moon
• 50−100 km alt.
• 2007/12−2009/04

Similarities & Differences

	NR (Geotail)		NR (Kaguya)	BR (Geotail)		BR (Kaguya)
occurrence	0.32%		0.51%	0.63%		0.50%
frequency	peak: -1.6−-0.8 Hz	~	peak: -2.1−-1.0 Hz	center: 2.1−3.7 Hz	<	center: 3.1−6.8 Hz
intensity	0.092−0.98 nT^2/Hz	≲	0.17−2.6 nT^2/Hz	0.036−0.28 nT^2/Hz	>	0.013−0.078 nT^2/Hz
θ_{Bx}	small (19°−44°)	~	small (19°−40°)	large (64°−83°)	~	large (46°−77°)
θ_{kx}	small (13°−36°)	≲	small (23°−58°)	large (51°−79°)	~	large (46°−77°)
θ_{kB}	parallel (21°−39°)	<	oblique (32°−66°)	parallel (17°−33°)	<	oblique (47°−78°)

- NR & BR are possibly the same source waves
  group-standing → NR, not group-standing → BR ⇒ general physics through the solar system
- near Earth's bow shock: lower frequency, larger amplitude, more parallel propagation than near Moon
  ⇒ dominant energy sources are different
  e.g., bow shock: ion beam instability, Moon: modified two stream instability

Summary

We proposed the **group-standing** effects to explain upstream whistlers.

- Propagating whistler-mode waves near lower hybrid frequency are observed as NR when they are group-standing, and as BR when they are not group-standing.

- Lower frequency, larger amplitude, smaller θ_{kB} are required for the wave generation near bow shock compared with near the Moon.

$\Downarrow$

The modification of the wave spectra observed in a moving plasma should be considered to understand accurate generation processes.