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Properties of the generation and propagation of whistler-mode chorus emissions in the Earth's inner magnetosphere

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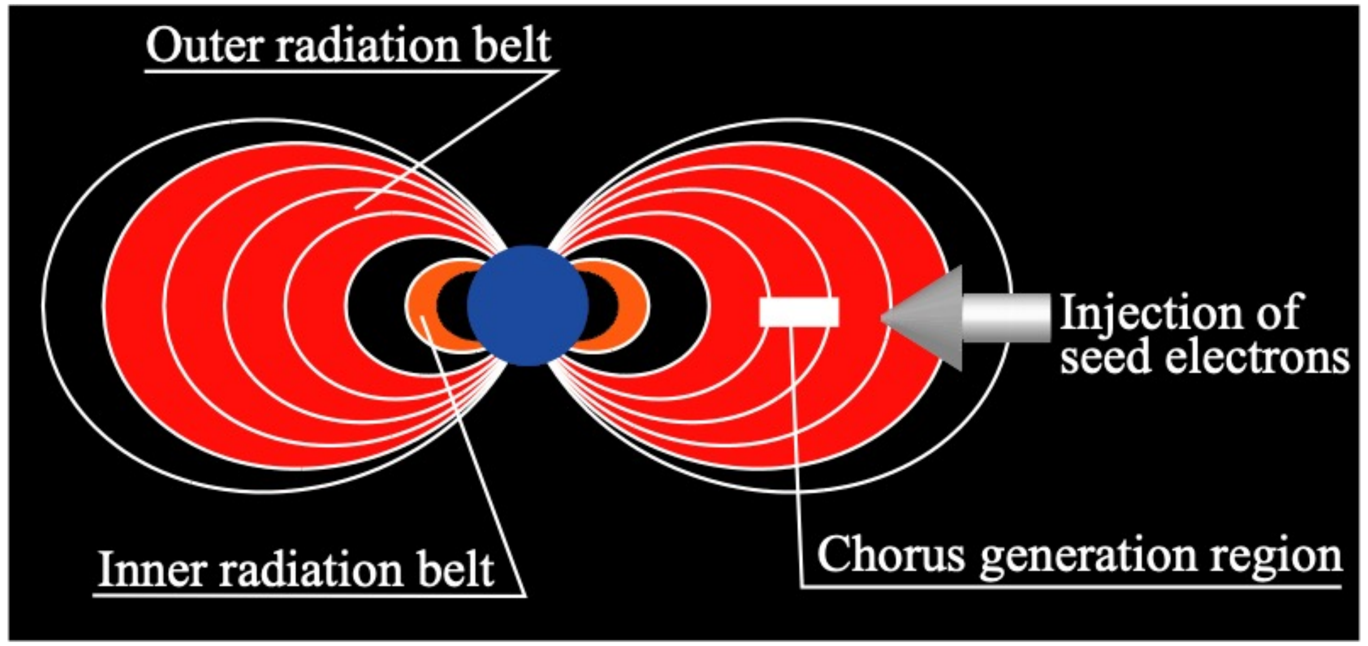
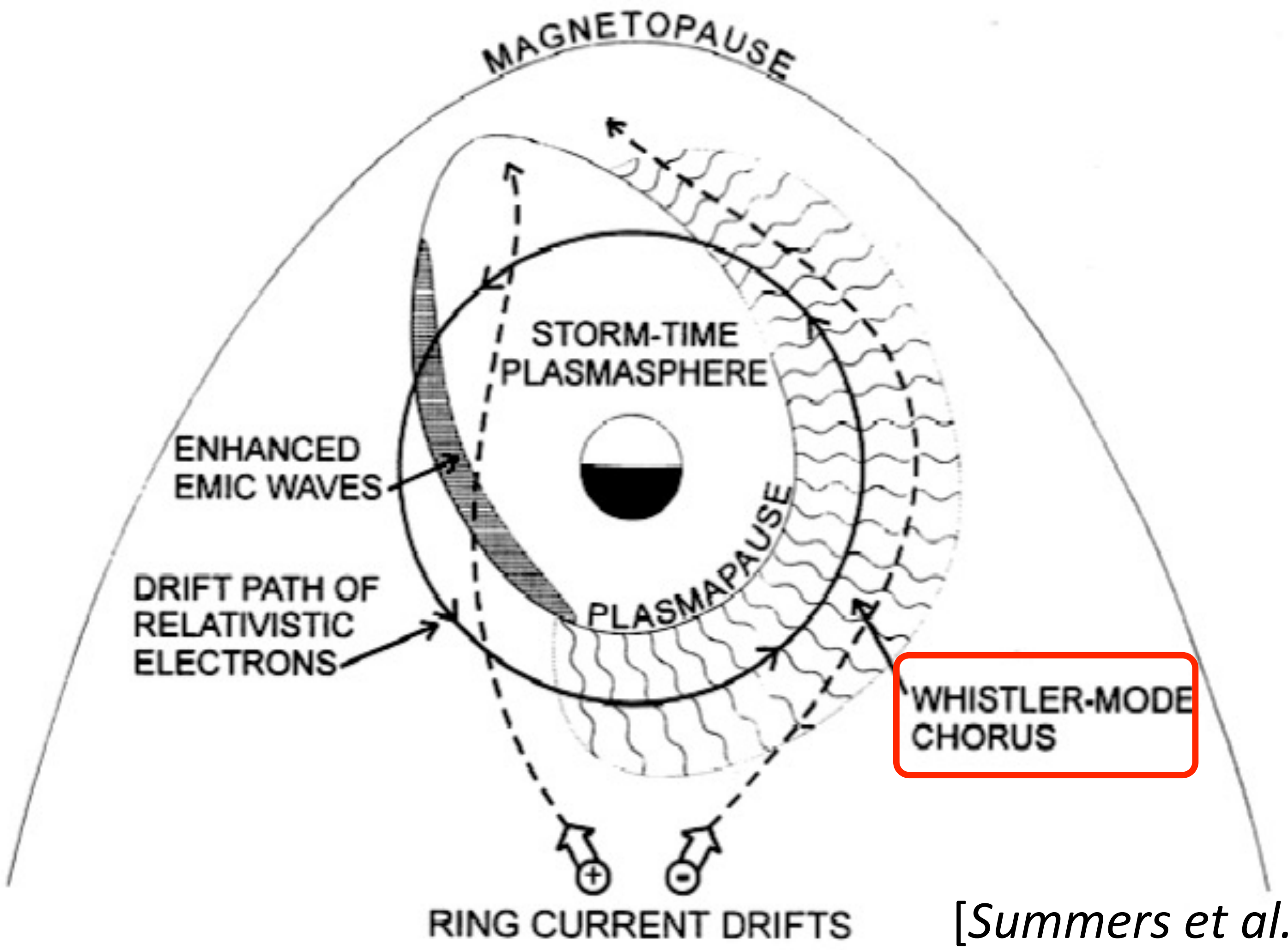
Outline

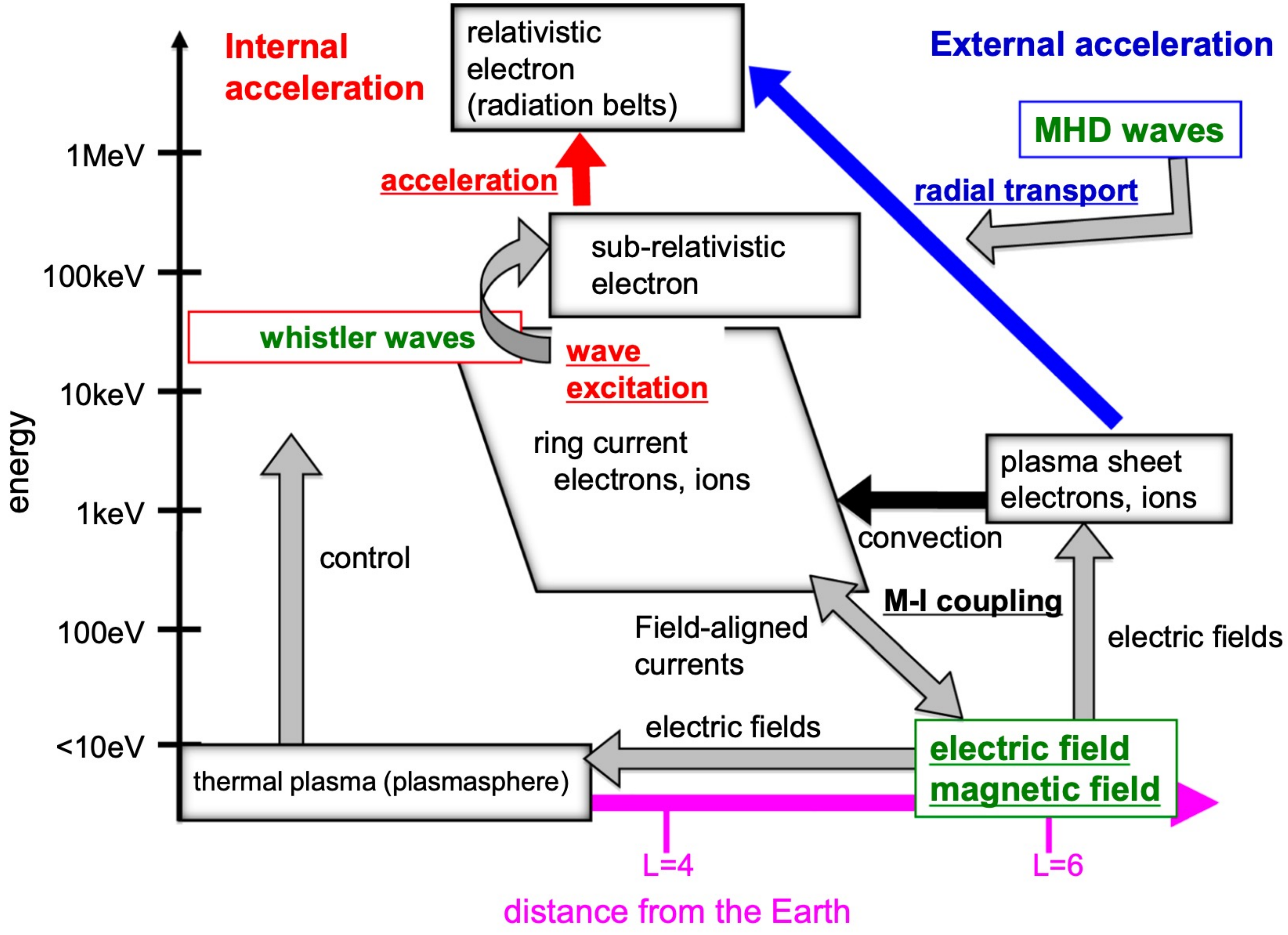
1. Introduction
2. Electron hybrid code simulation of whistler-mode chorus generation
3. Properties of chorus generation process
4. Propagation of chorus in the magnetosphere
5. Summary

Whistler-mode chorus: nonlinear wave-particle interactions in Geospace





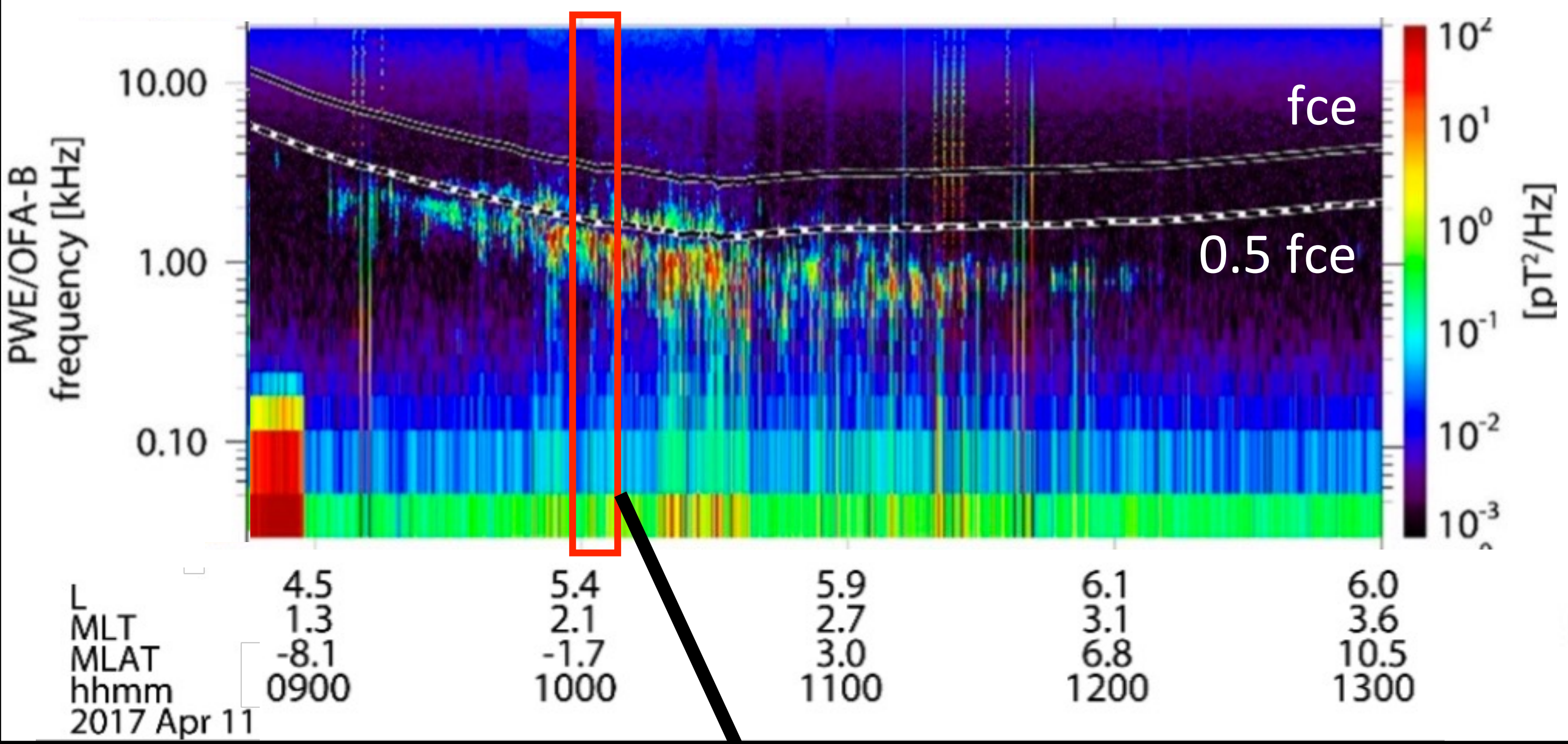
[*Summers et al.*, JGR 1998]

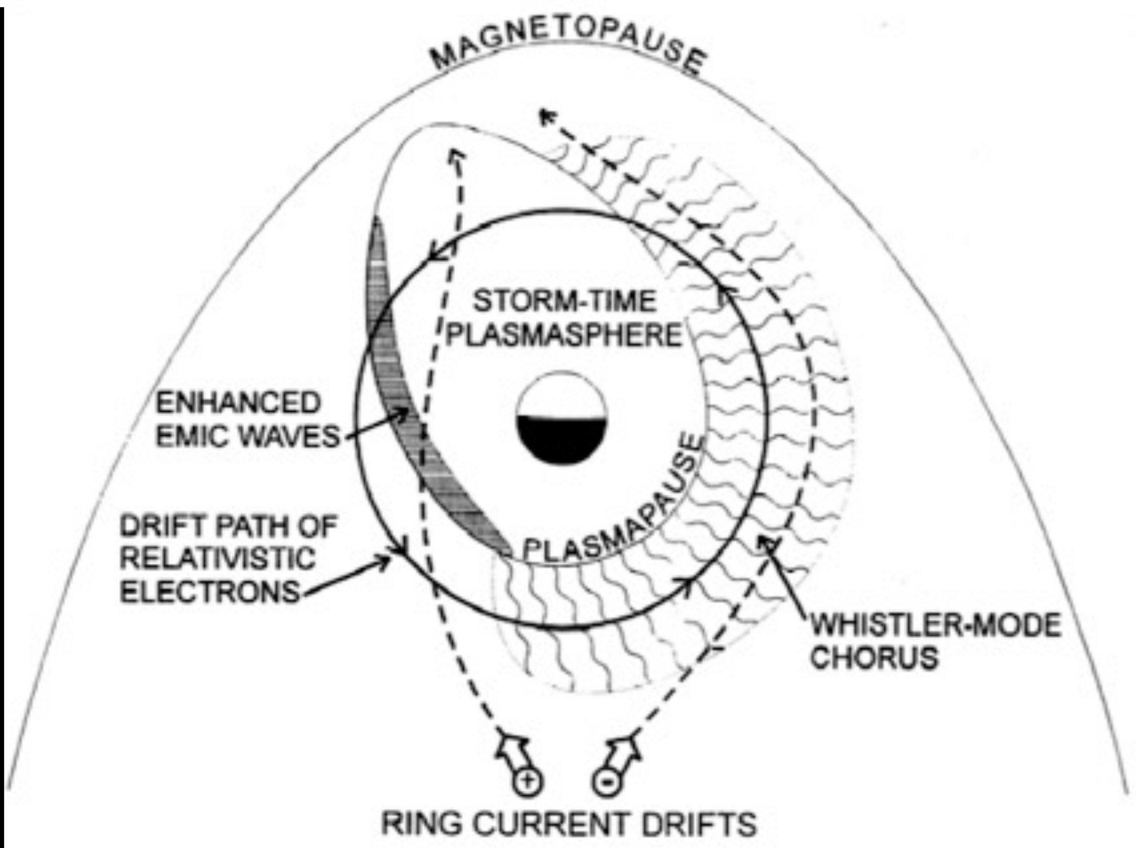


[*Miyoshi et al.*, EPS 2018]

Whistler-mode chorus in the Earth's magnetosphere

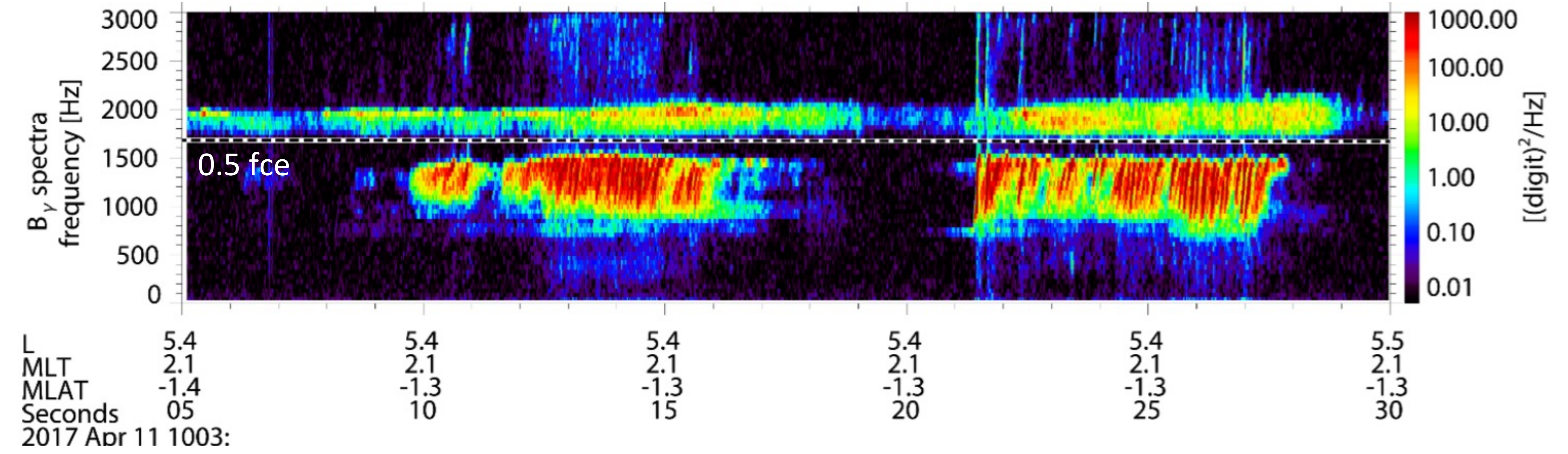
Arase (ERG) [*Kasahara et al.*, EPS 2018]





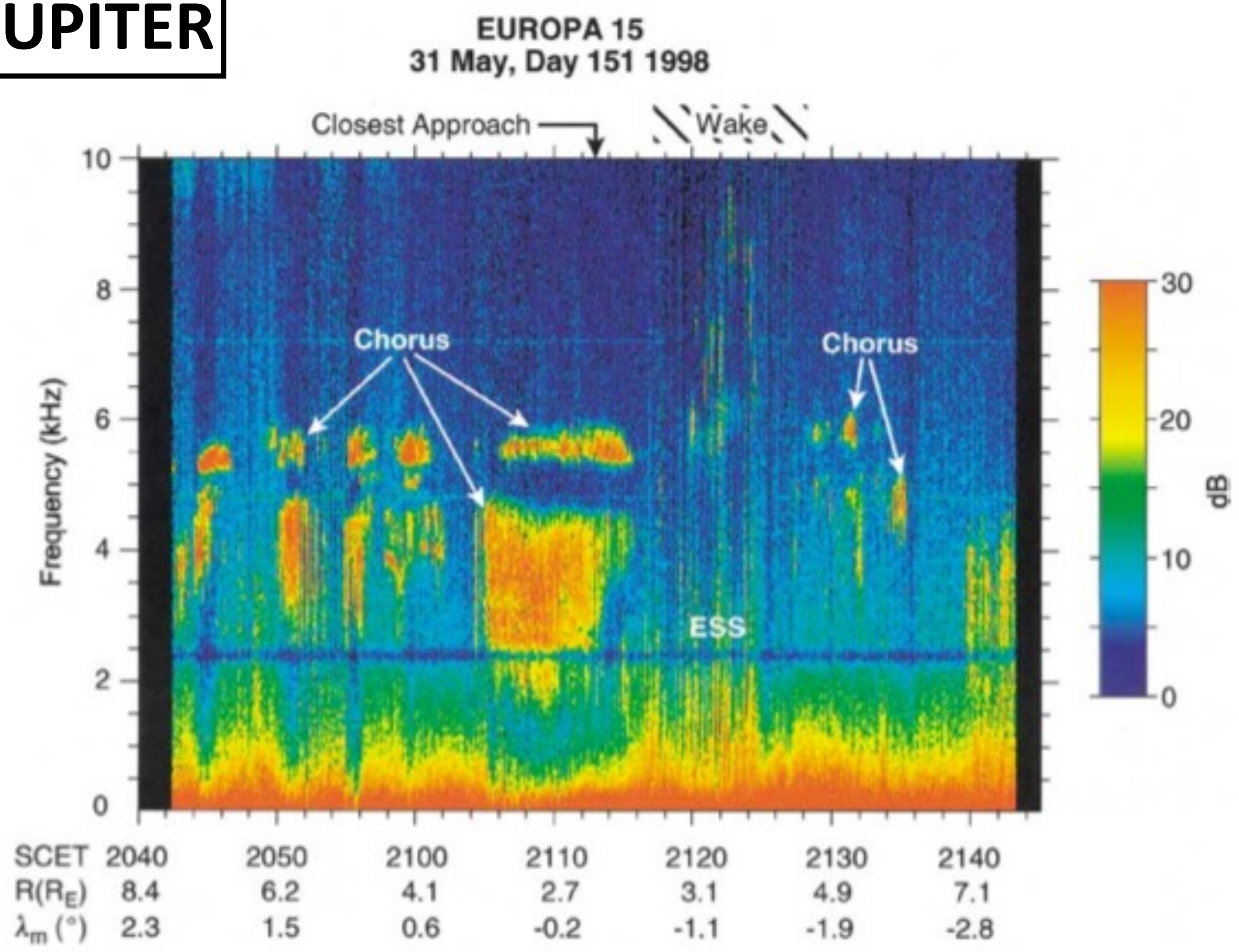
[*Summers et al.*, 1998]

Arase PWE/WFC (Chorus burst)



Chorus in planetary magnetospheres

JUPITER

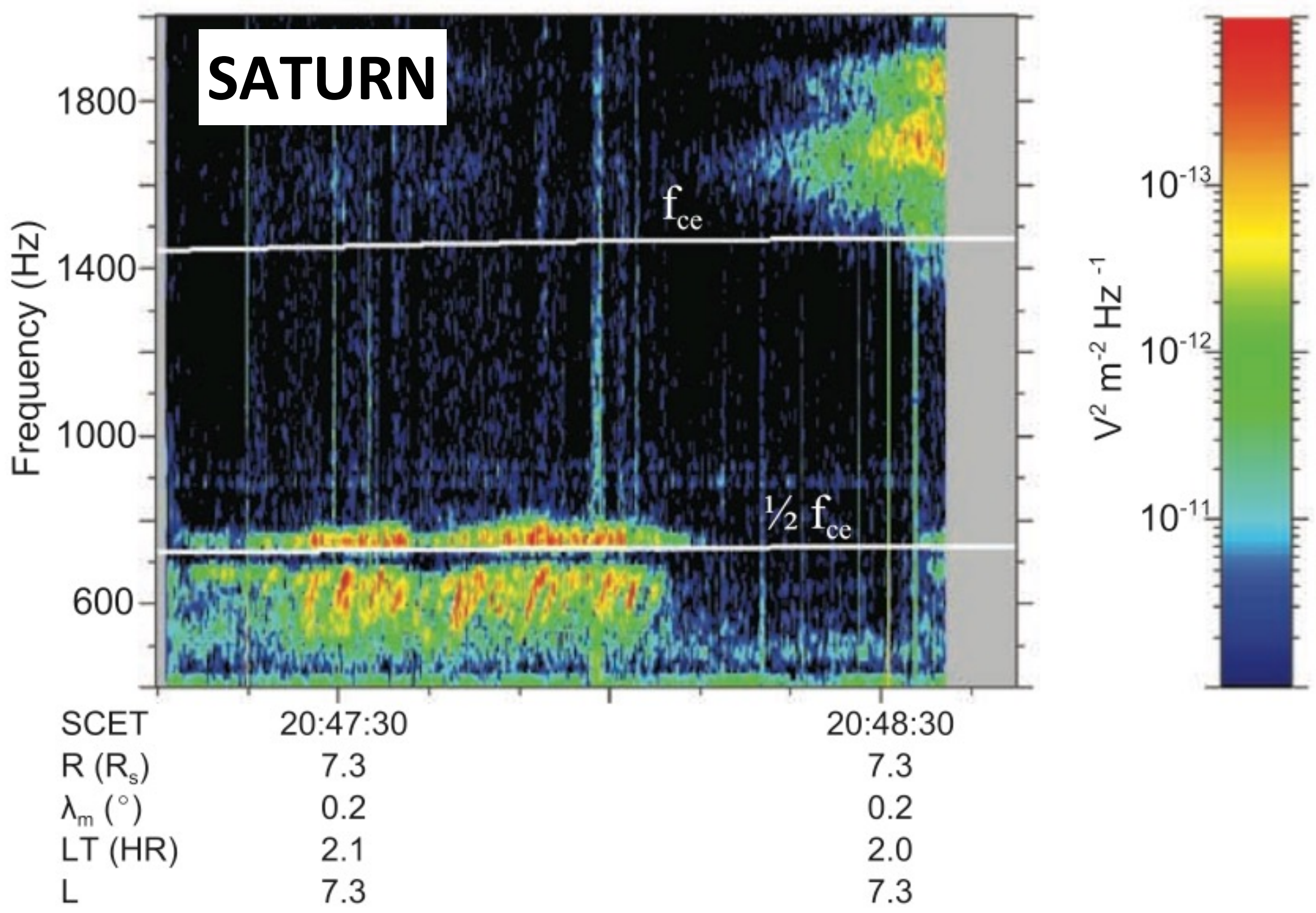


Chorus emissions observed by Galileo in the equatorial region of the Jovian inner magnetosphere

[*Kurth et al.*, PSS 2001]

Typical example of chorus emissions observed by Cassini/RPWS during injection events in Saturn's magnetosphere

[*Hospodarsky et al.*, JGR 2008]



Generation process of whistler-mode chorus

1) Linear growth phase

$$f(v_\parallel, v_\perp, \psi), \quad \partial f/\partial\psi = 0$$

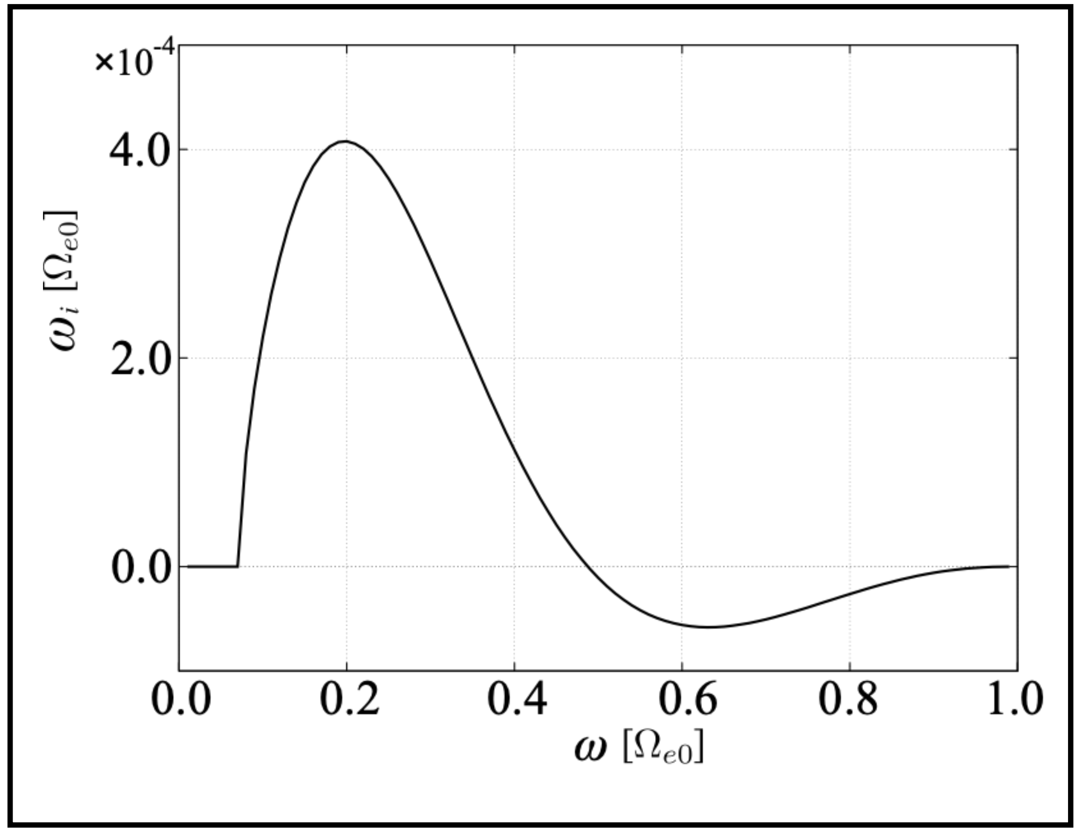
$$\omega - k v_\parallel = \Omega_e/\gamma$$

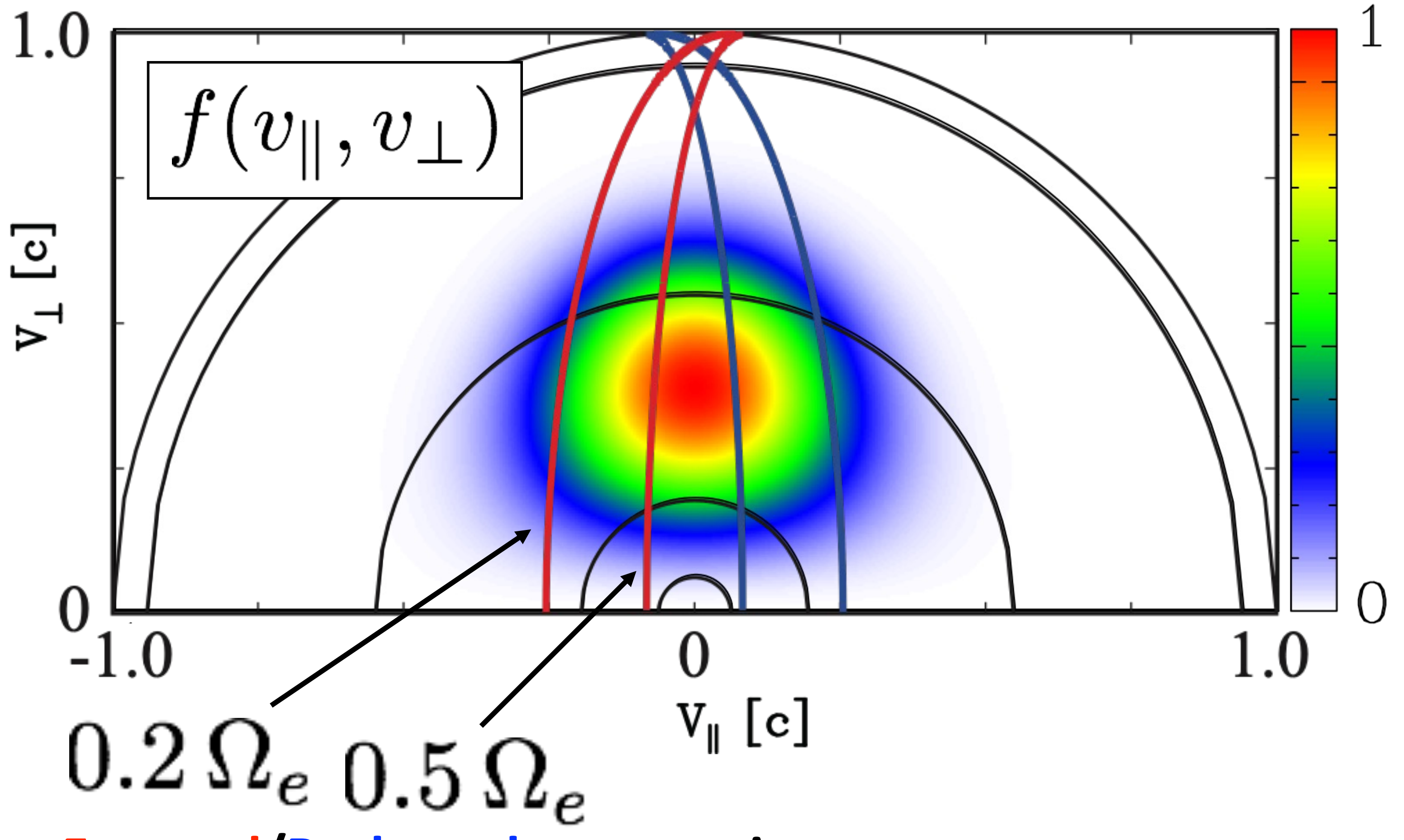
Excitation of a band of whistler-mode waves through the instability driven by a temperature anisotropy of energetic electrons

$$\omega_i \propto \int_0^\infty 2\pi v_\perp f(V_R, v_\perp) dv_\perp$$

$$V_R = \frac{\omega - \Omega_e/\gamma}{k}$$

[cf., *Kennel and Petschek, 1966*]





Forward/Backward propagating waves

--> A finite amplitude coherent wave element emerges from the band of waves

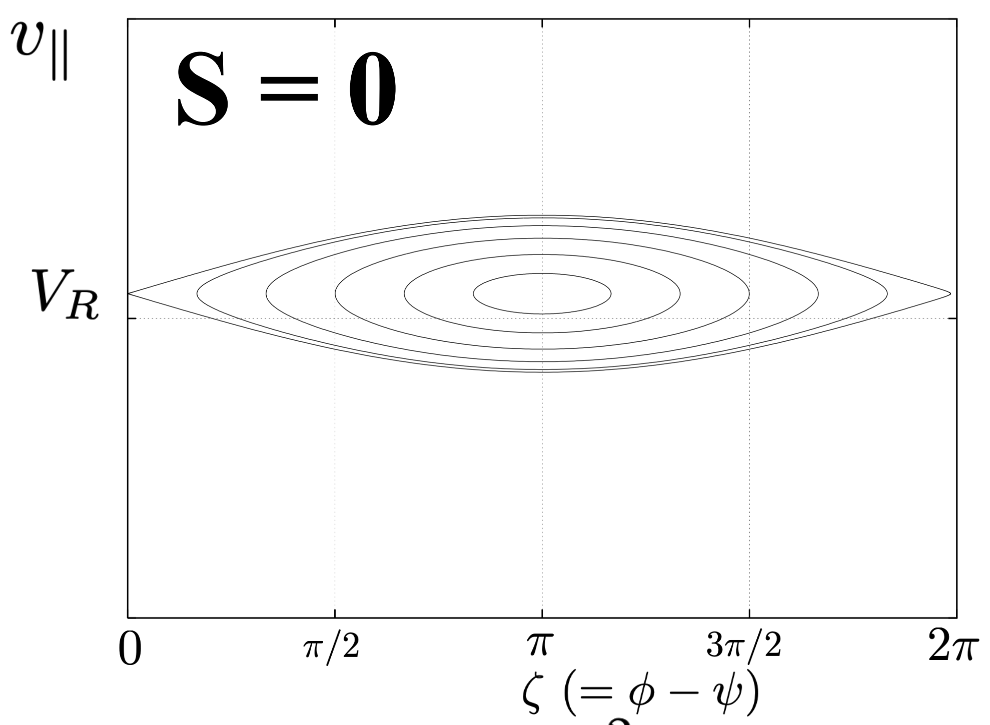
Generation process of whistler-mode chorus

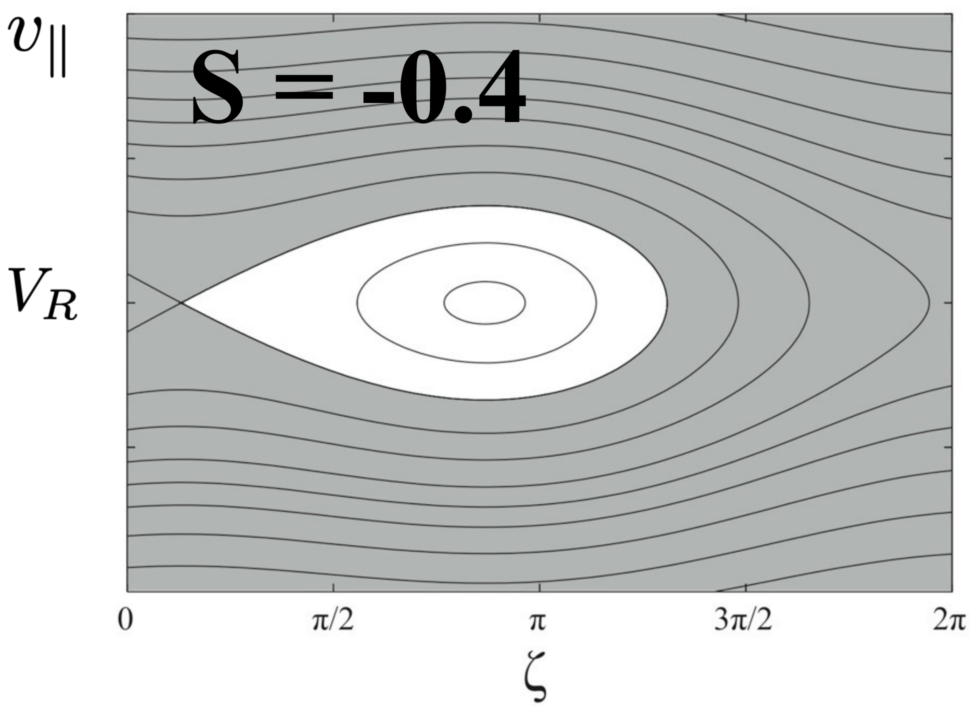
2) Non-linear phase

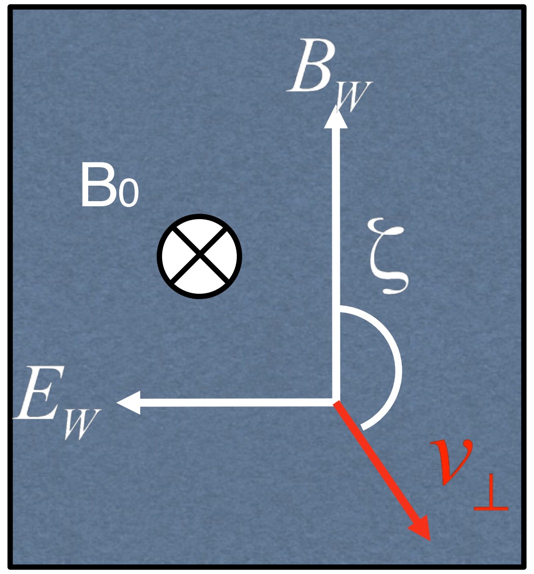
$$f(v_\parallel, v_\perp, \psi), \quad \partial f / \partial \psi \neq 0$$

$$\omega - k v_\parallel = \Omega_e / \gamma$$

Resonant electrons are trapped/untrapped by a coherent wave element, resulting in the formation of "resonant current" [cf., *Omura, EPS 2021*]







$$J_E = \int_{-\infty}^{\infty} \int_0^{\infty} \int_0^{2\pi} [-q v_\perp \sin\zeta] f(v_\parallel, v_\perp, \zeta) v_\perp dv_\parallel dv_\perp d\zeta$$

$$\frac{\partial B_w}{\partial t} + V_g \frac{\partial B_w}{\partial h} = -\frac{\mu_0 V_g}{2} J_E$$

Numerical simulation plays crucial roles in understanding nonlinear properties of the chorus generation process

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1. Introduction
2. Electron hybrid code simulation of whistler-mode chorus generation
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Electron Hybrid code: Basic equations

[e.g., *Katoh et al.*, EPS 2005; *Katoh and Omura,* JGR 2004]

Cold electrons are treated as a fluid
Energetic electrons are treated as particles

$$\frac{\partial \boldsymbol{V}}{\partial t} = -(\boldsymbol{V} \cdot \nabla)\boldsymbol{V} + \frac{q}{m}(\boldsymbol{E} + \boldsymbol{V} \times \boldsymbol{B})$$

Finite-Difference scheme

$$\frac{d(m\boldsymbol{v})}{dt} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

Buneman-Boris method

$$\boldsymbol{J} = qN\boldsymbol{V} + \sum_i q n_i \boldsymbol{v}_i$$

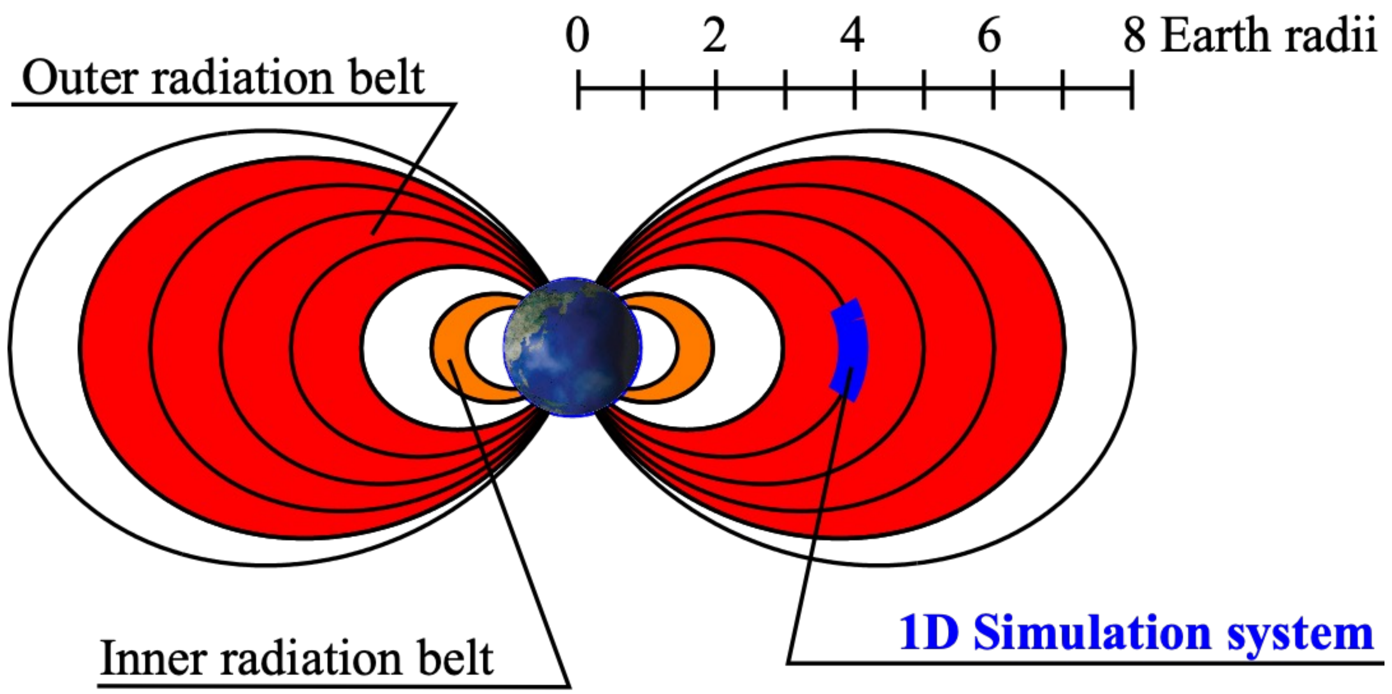
Particle-In-Cell method

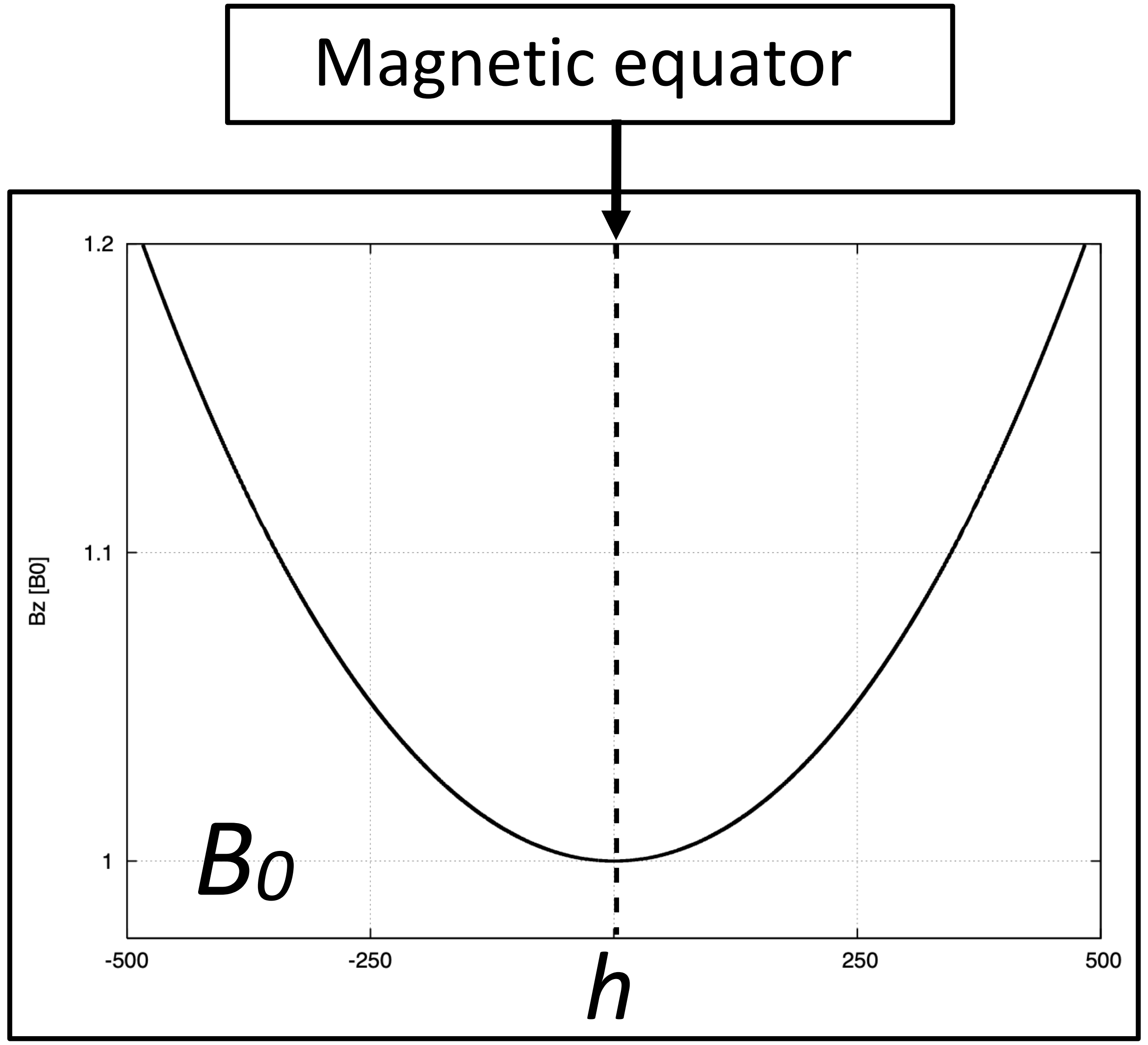
$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

$$\frac{\partial \mathbf{E}}{\partial t} = \frac{1}{\mu_0 \varepsilon_0} \nabla \times \mathbf{B} - \frac{1}{\varepsilon_0}\mathbf{J}$$

Finite-Difference scheme

Simulation model & initial settings



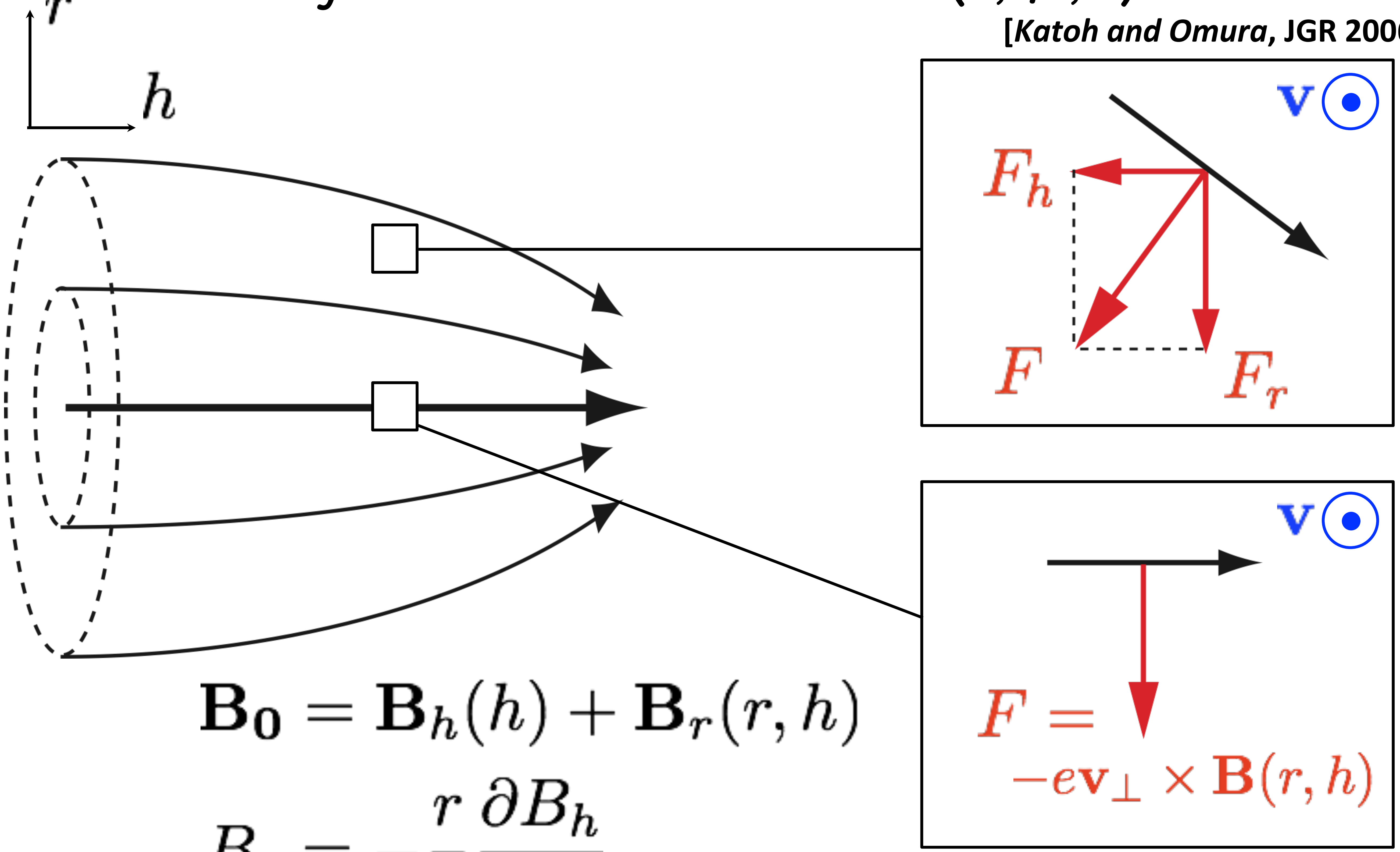


- Electron Hybrid code
- 1D, field aligned system
- Loss-cone velocity distribution with a temperature anisotropy
- neglecting electrostatic waves

Energetic electrons are trapped in the magnetosphere: mirror motion along a field line

Mirror motion of electrons in 1D simulation: Cylindrical field model B(r, ϕ ,h)

[*Katoh and Omura*, JGR 2006]

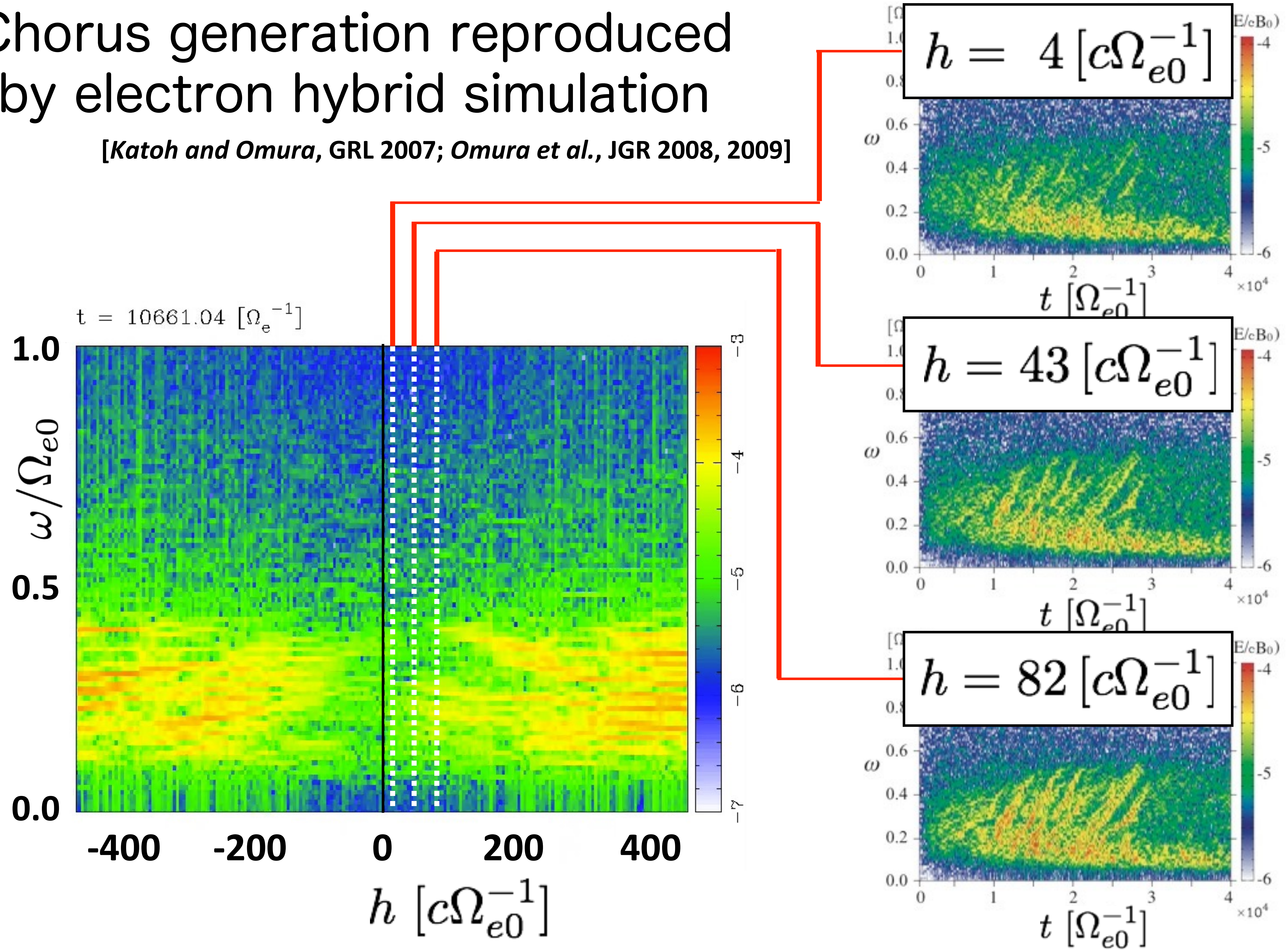


$$\mathbf{B_0} = \mathbf{B}_h(h) + \mathbf{B}_r(r,h)$$

$$B_r = -\frac{r}{2}\frac{\partial B_h}{\partial h}$$

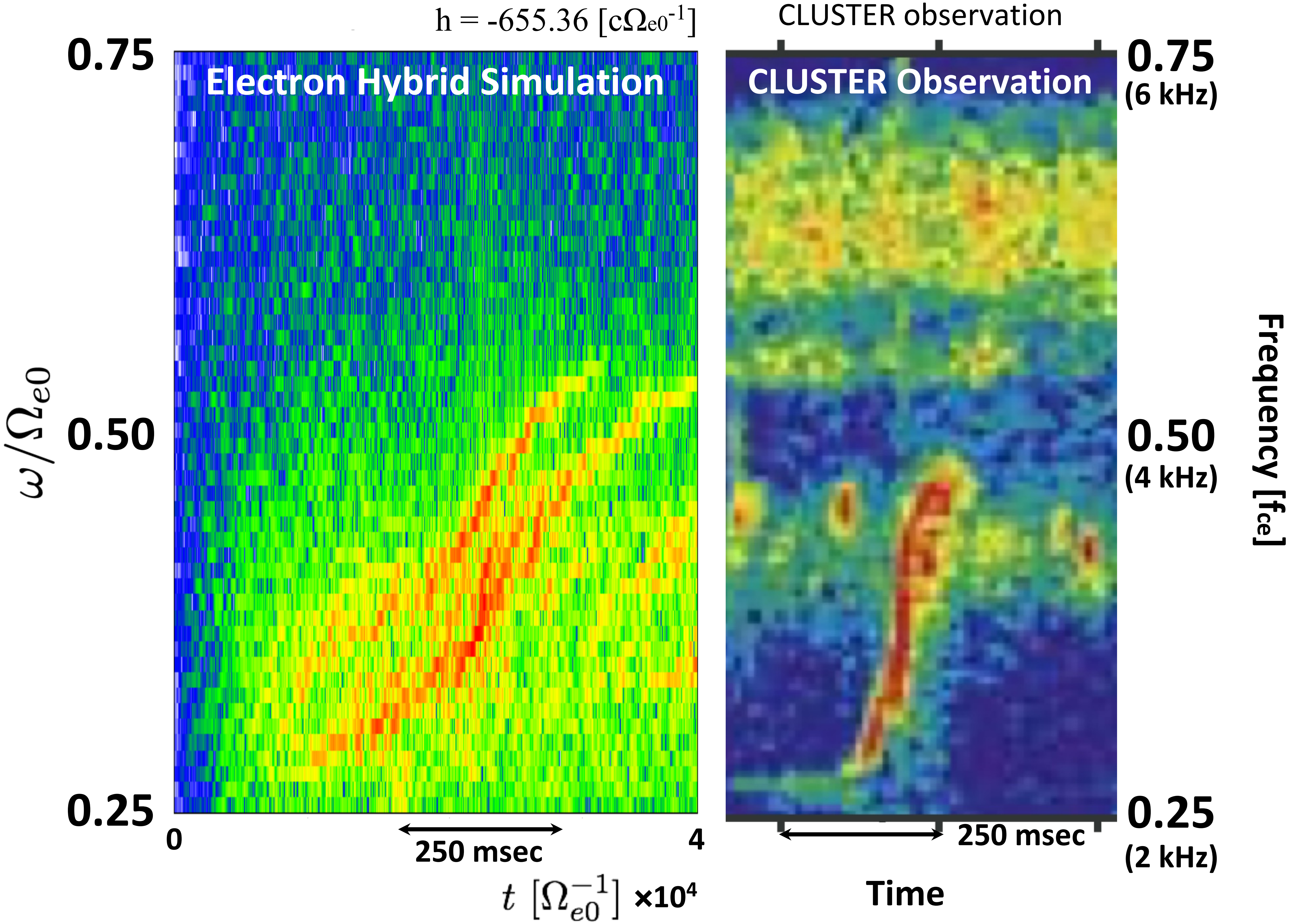
Chorus generation reproduced by electron hybrid simulation

[*Katoh and Omura*, GRL 2007; *Omura et al.*, JGR 2008, 2009]



Simulation/CLUSTER observation results comparison

[*Katoh and Omura*, EPS 2016]



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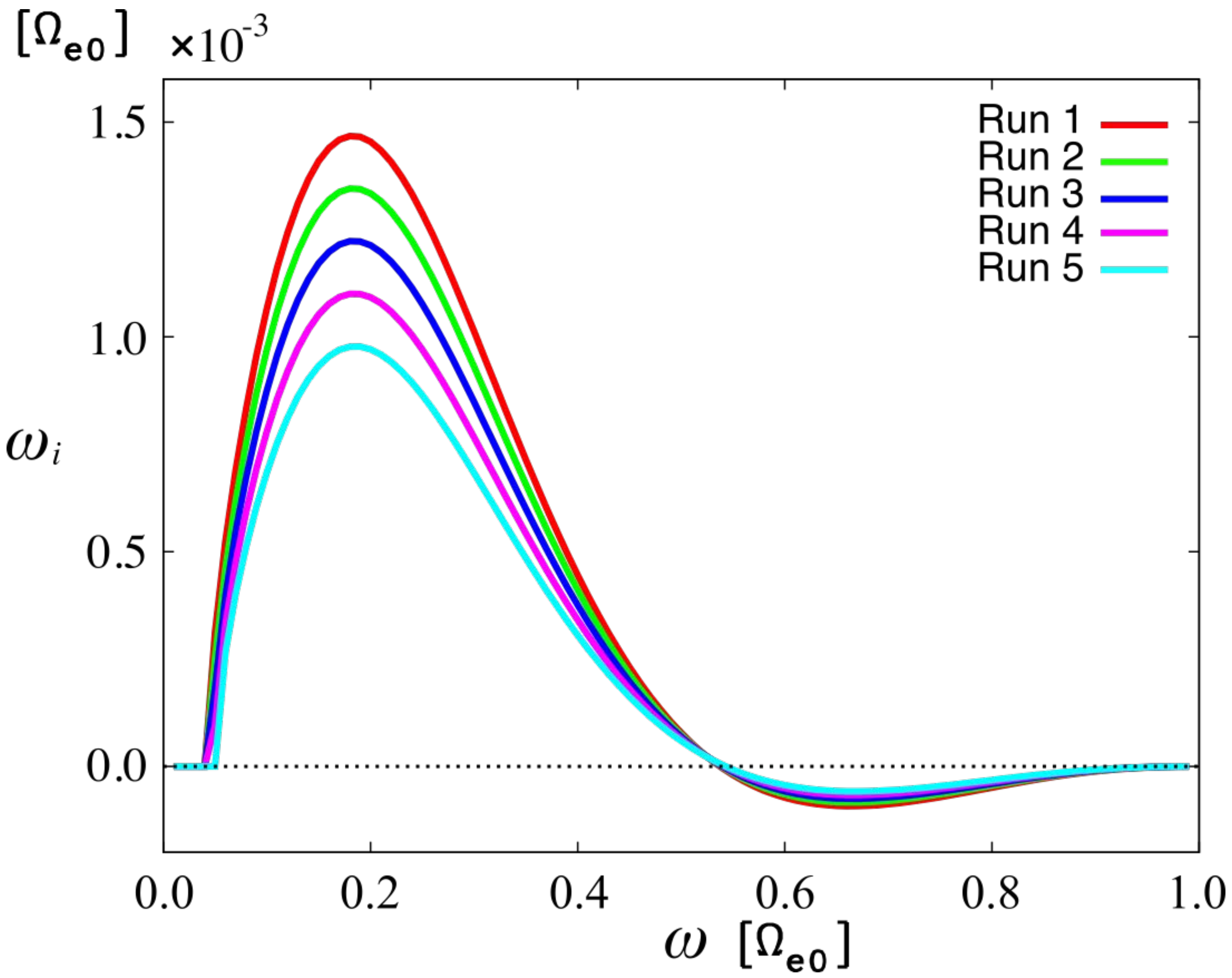
Case 1: number density of energetic electrons

- **Run 1: N_h +20%**
- **Run 2: N_h +10%**
- **Run 3: $N_h = 8 \times 10^{-4} N_{cold}$**
- **Run 4: N_h -10%**
- **Run 5: N_h -20%**

$$\omega_{pe} = 4\,\Omega_{e0} \qquad v_{th,\parallel} = 0.225c$$
$$v_{th,\perp} = 0.6c$$
$$T_\perp / T_\parallel = 7.1$$

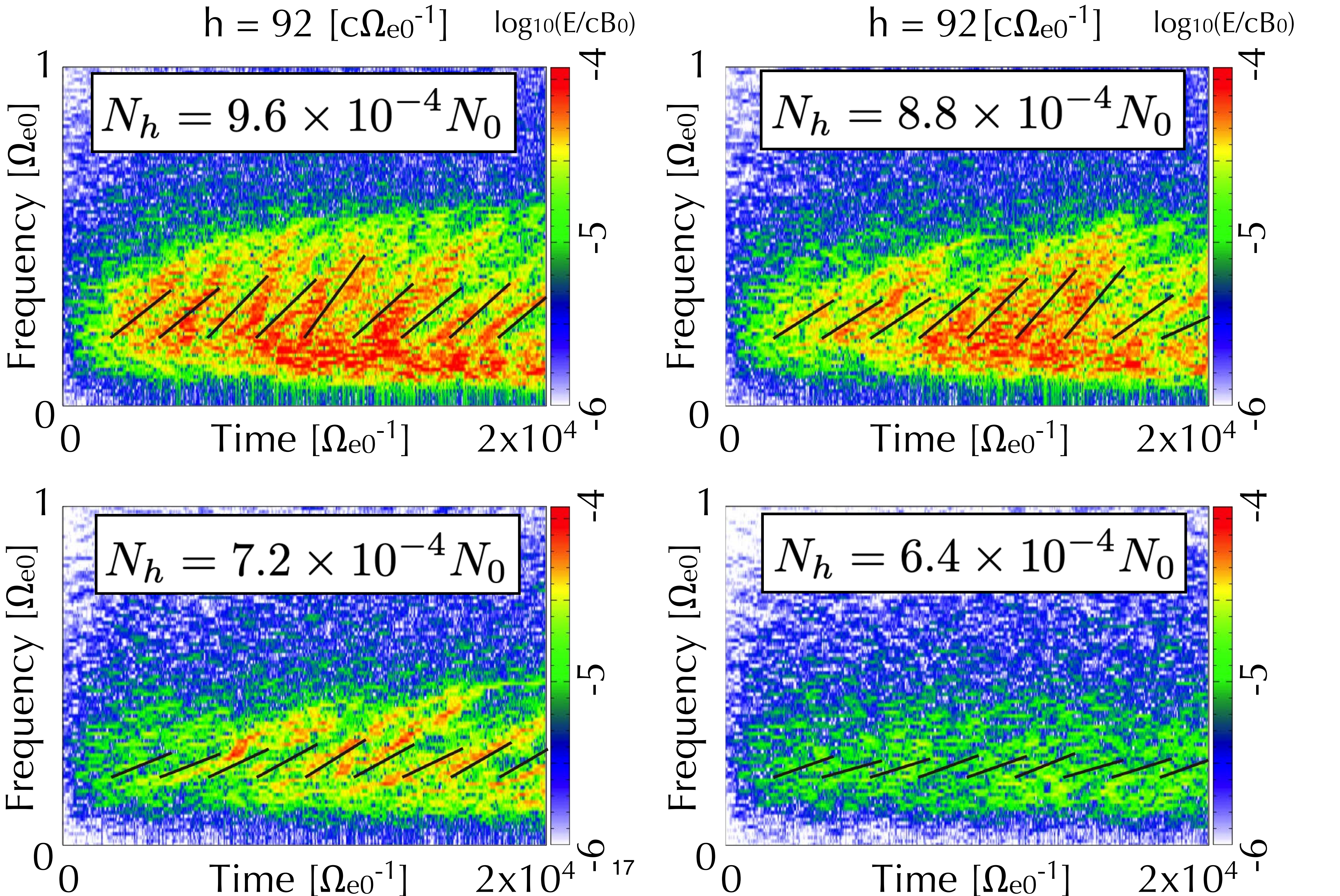


Linear growth rates for Run 1-5

(cf. *Xiao et al.*, 1998)

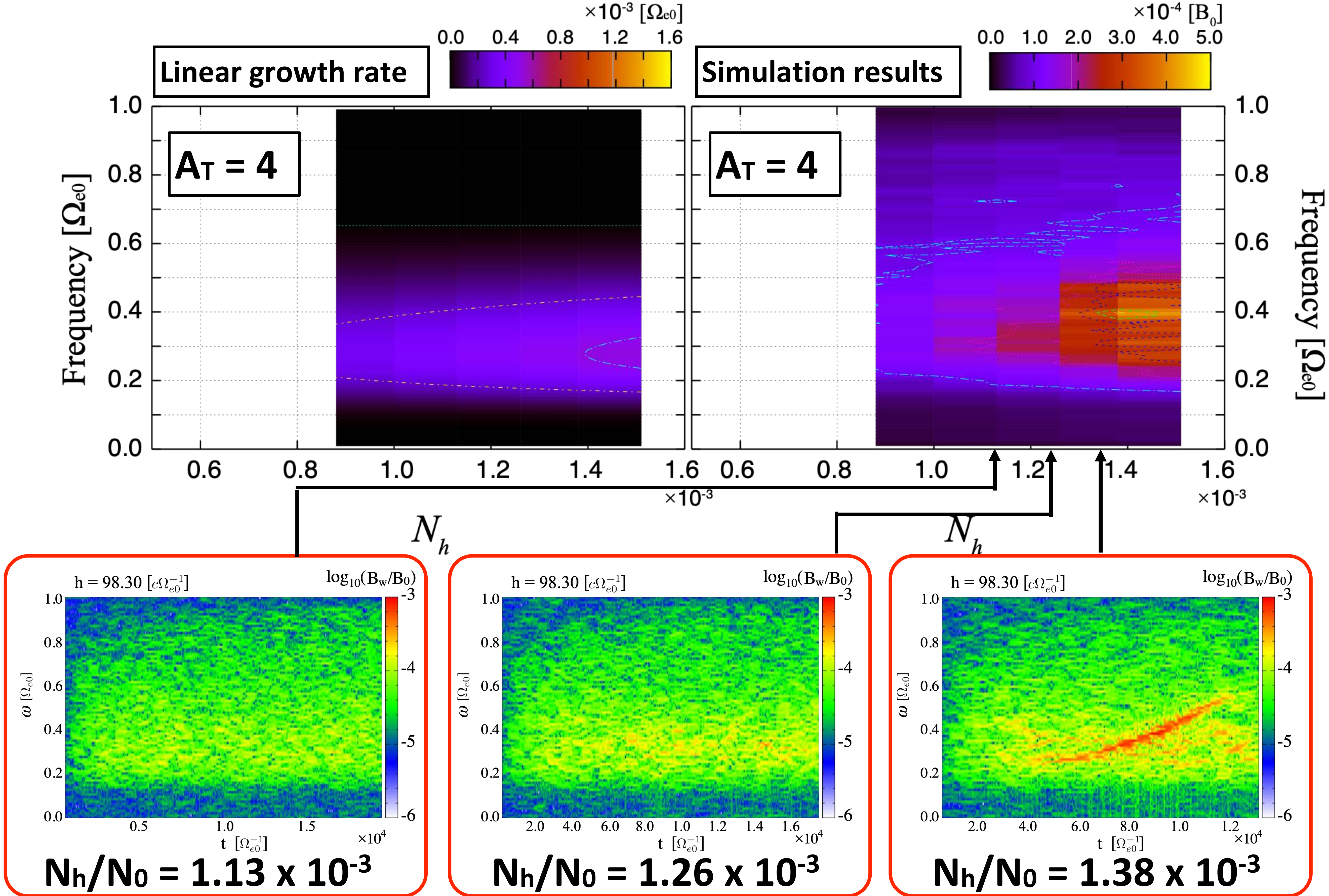
Simulation results with different velocity distribution function

[*Katoh and Omura*, JGR 2011]



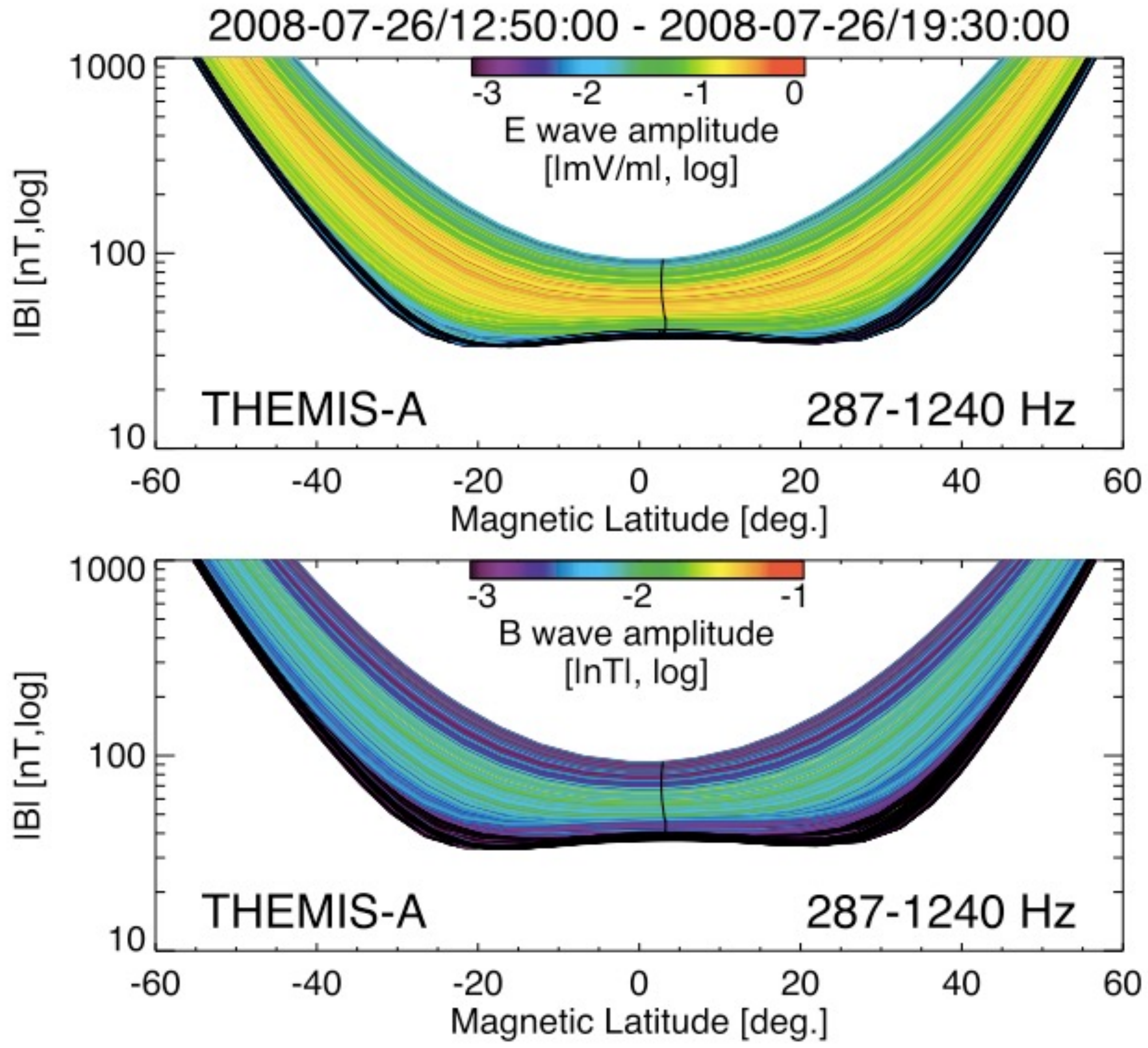
Simulation results with different velocity distribution function

[*Katoh et al.*, JGR 2018]



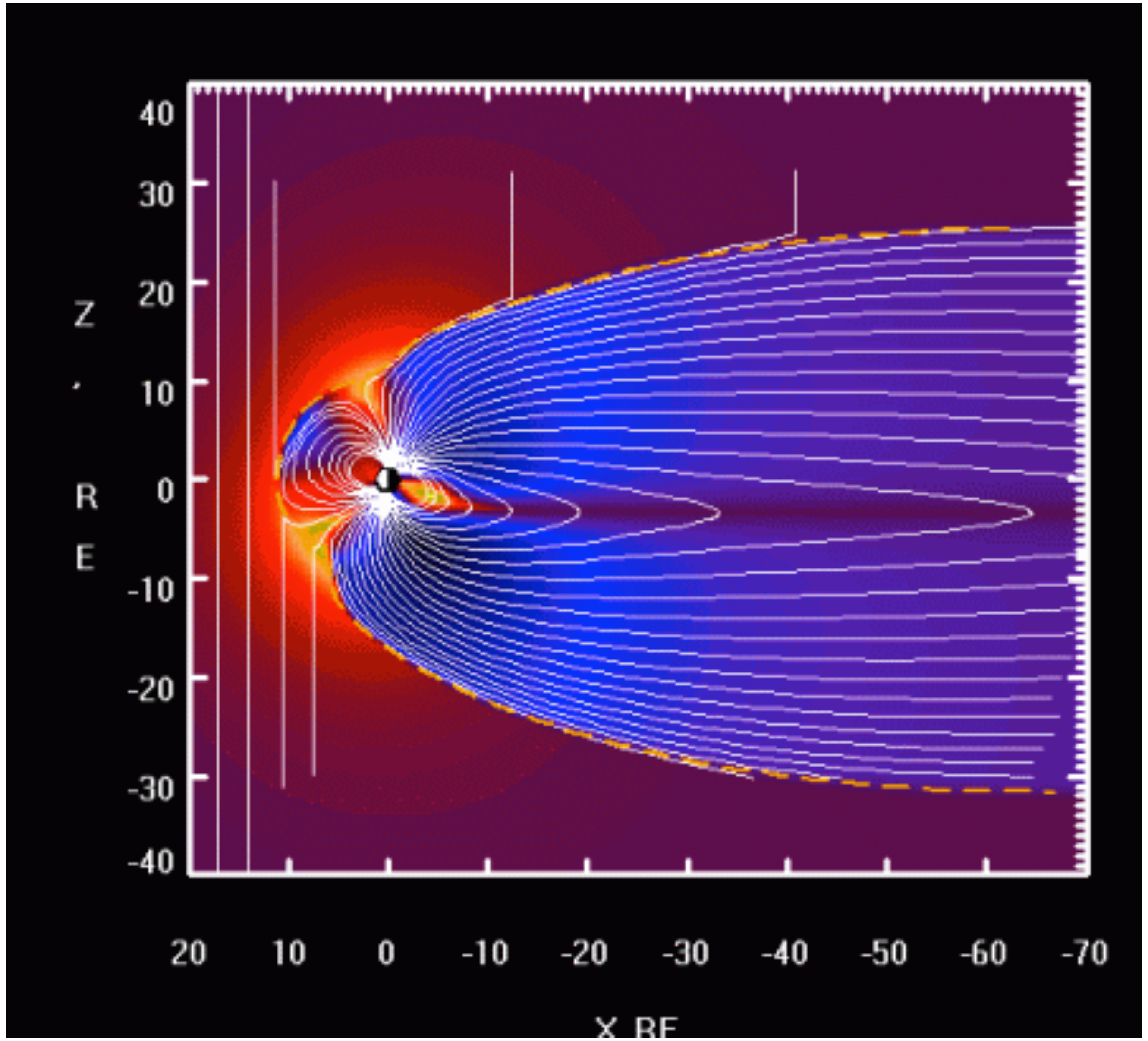
Case 2: Simulations of the same initial condition of energetic electrons and different background magnetic field

- Dayside: magnetospheric configuration is distorted by solar wind compression



[*Keika et al.*, 2012]

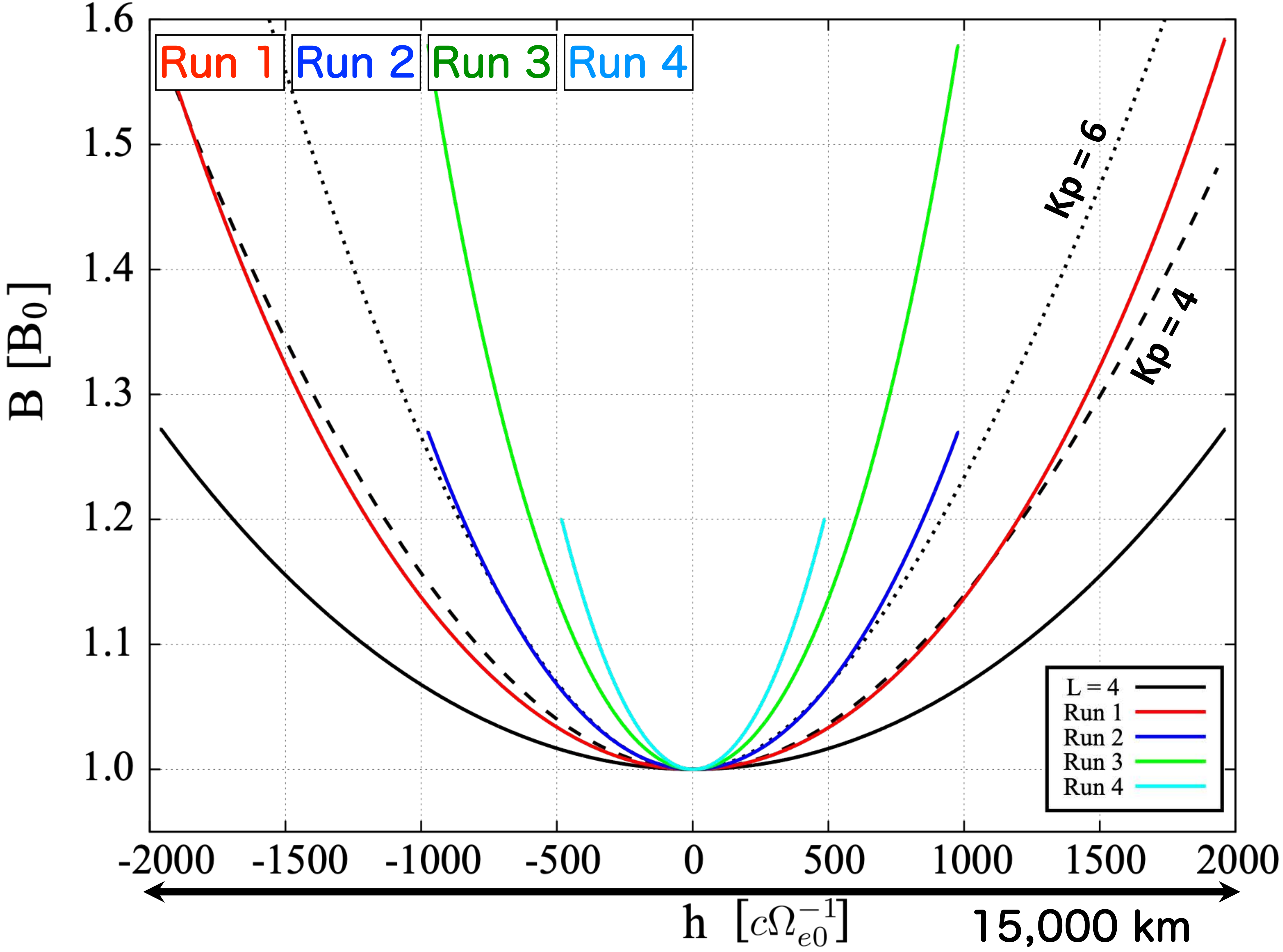
- Nightside: magnetic field lines are stretched during a disturbed time



[*Tsyganenko*, 1989]

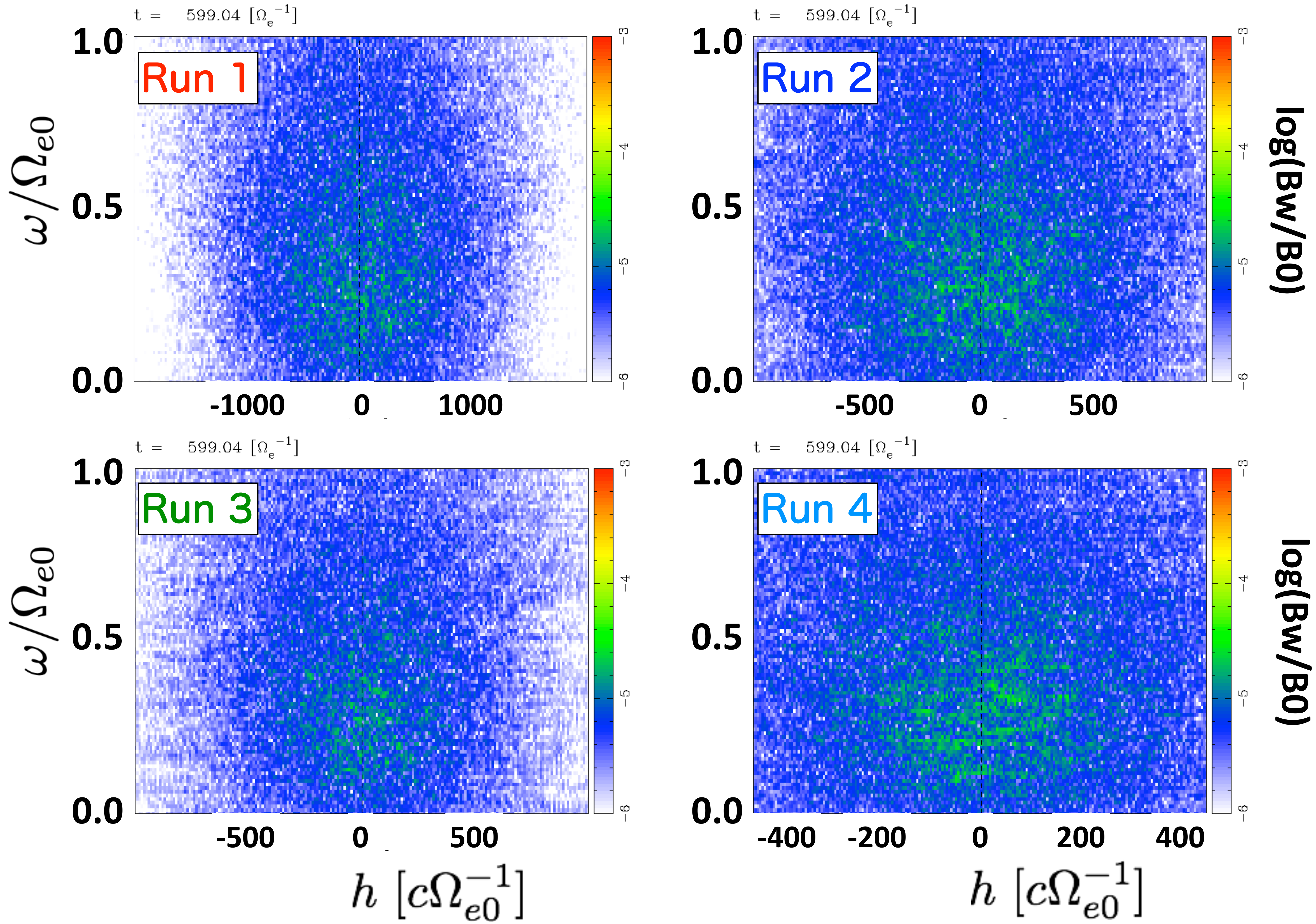
Case 2: Simulations of the same initial condition of energetic electrons and different background magnetic field

[*Katoh and Omura*, JGR 2013]

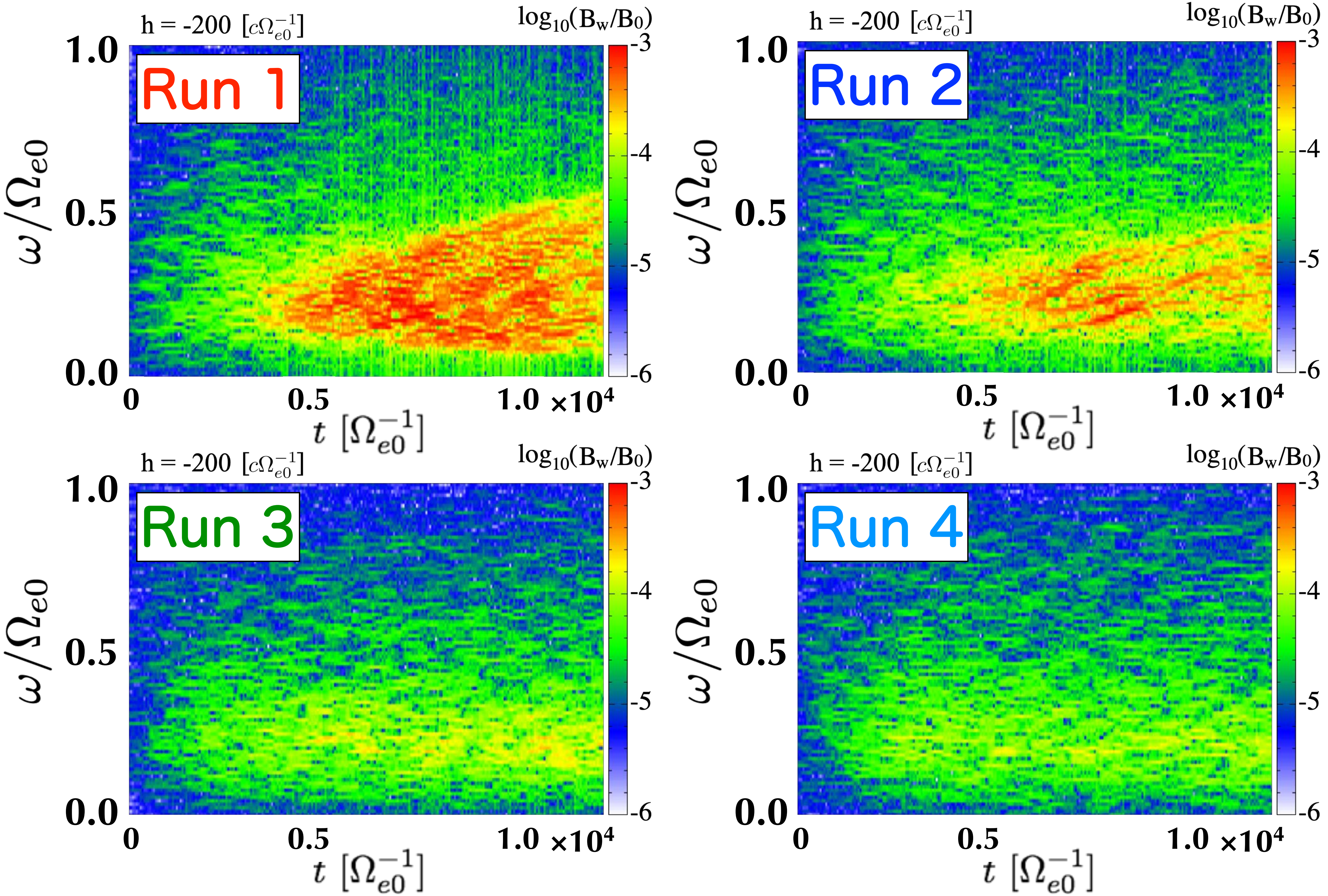


Calculated by
Tyganenko 1989 model
Midnight meridian plane

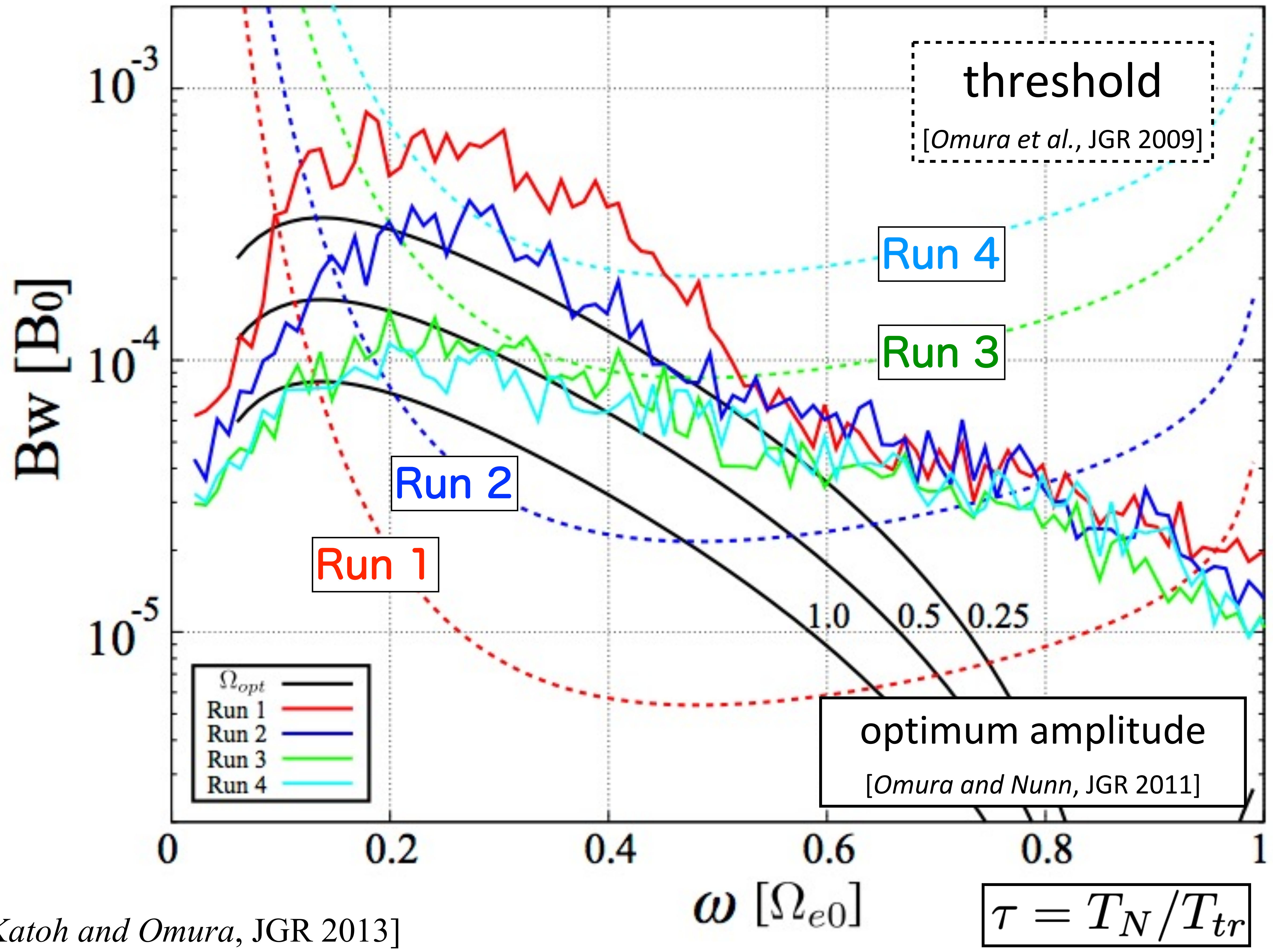
Case 2: Simulation results with different magnetic field gradient



Case 2: Simulation results with different magnetic field gradient



Comparison of theories and results
(different magnetic field gradient)



[*Katoh and Omura*, JGR 2013]

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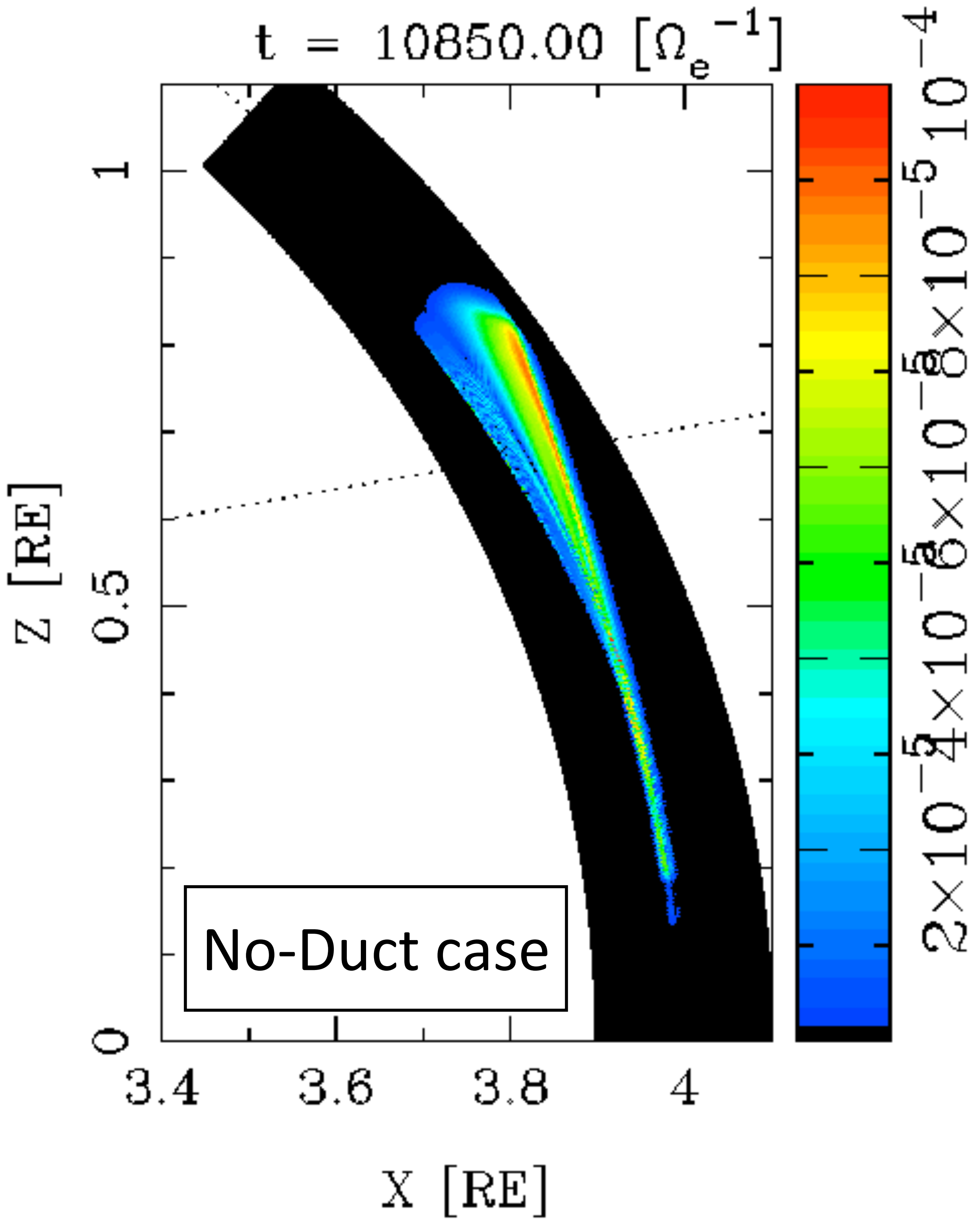
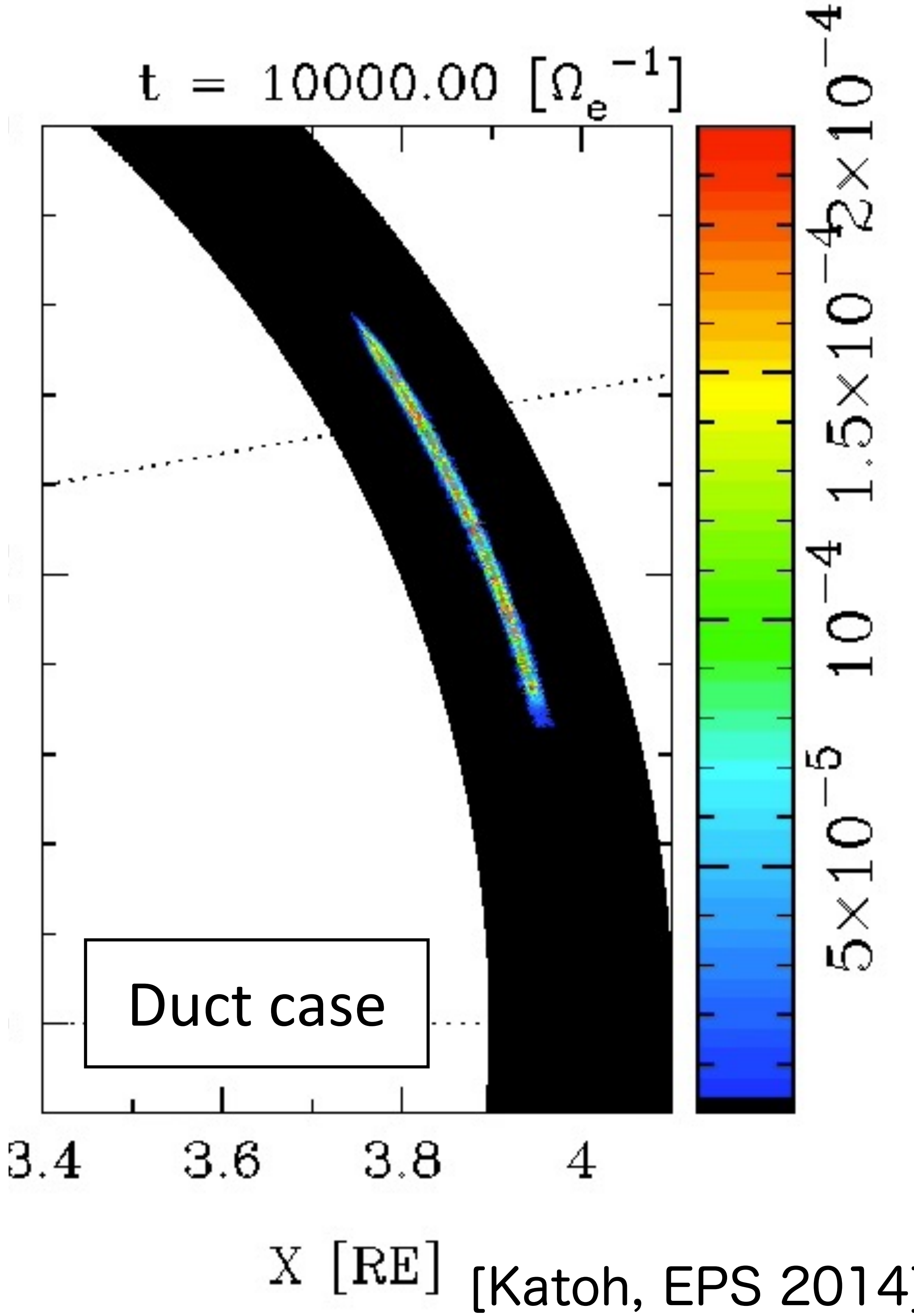
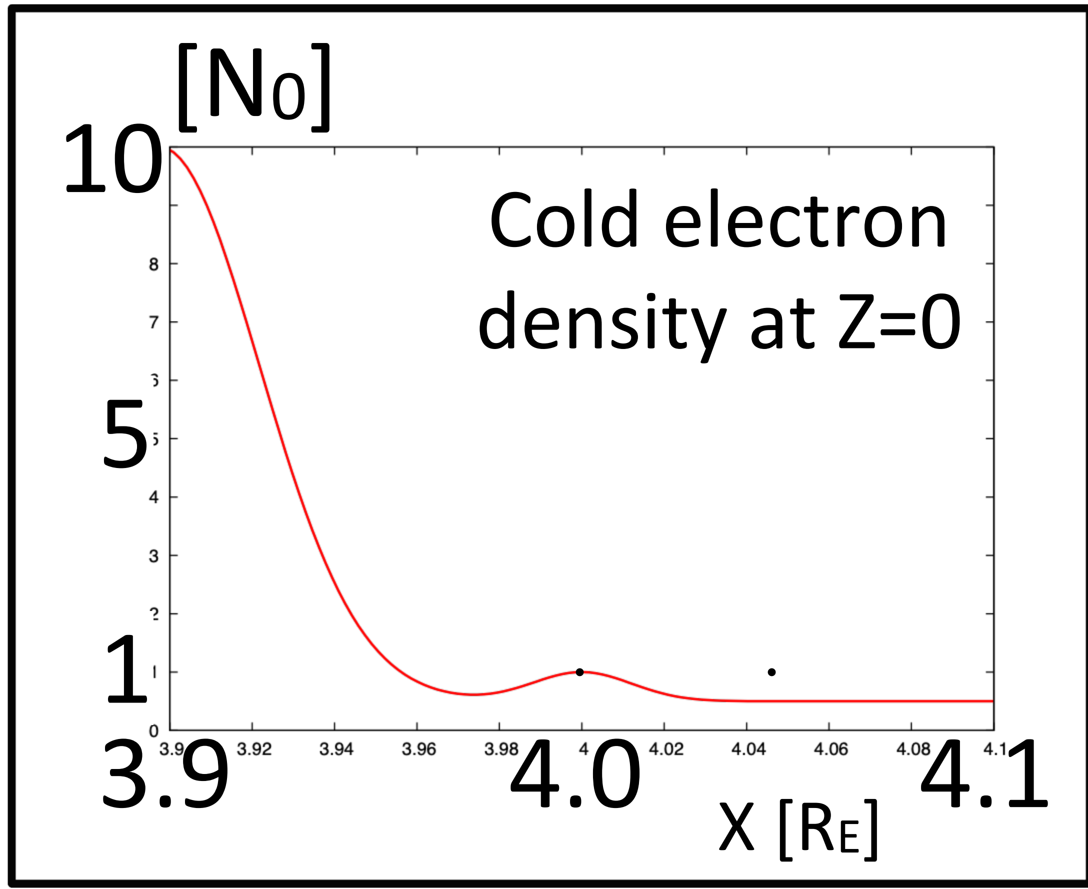
2D simulation of propagation of a rising-tone whistler-mode chorus emission in the magnetosphere





[Katoh, EPS 2014]

- Without a density duct, whistler-mode waves deviate from the field line at ~10°
- Density duct guides waves up to 30-40° magnetic latitude



2023-2027 JSPS KAKENHI project [PI: Yuto Katoh, Tohoku Univ]

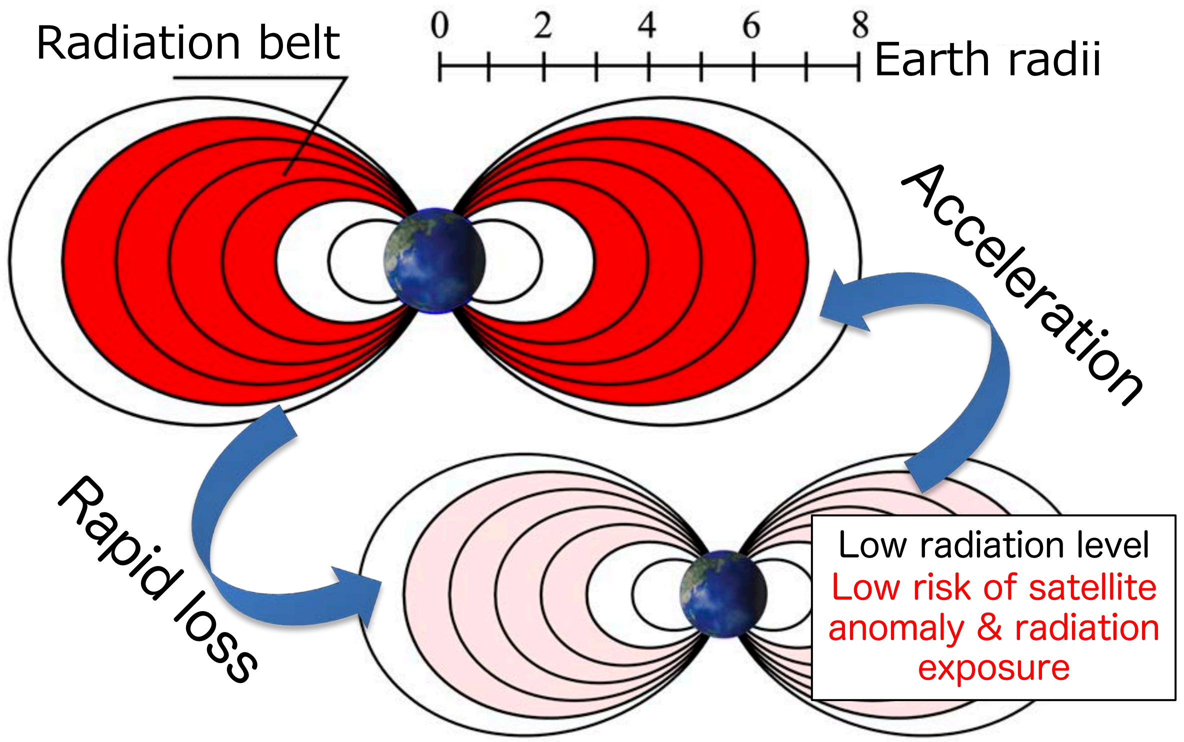
PCUBE (Probing, Controlling, and Understanding of radiation Belt Environments)

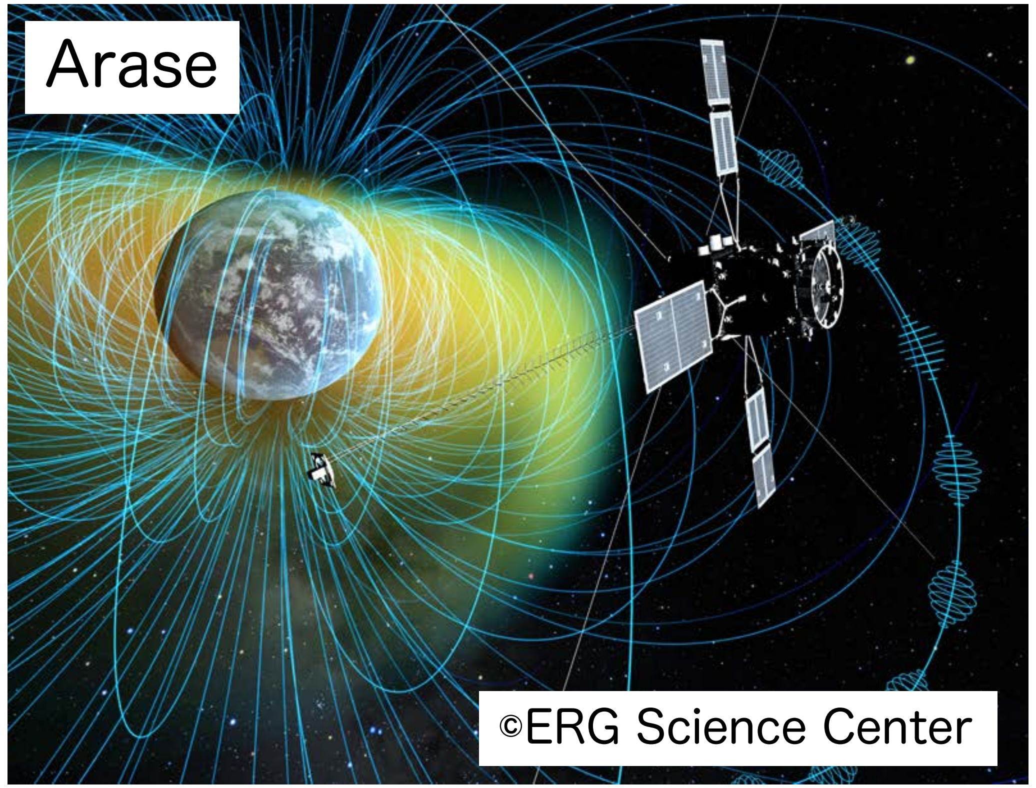
We investigate the rapid loss process of radiation belt electrons by

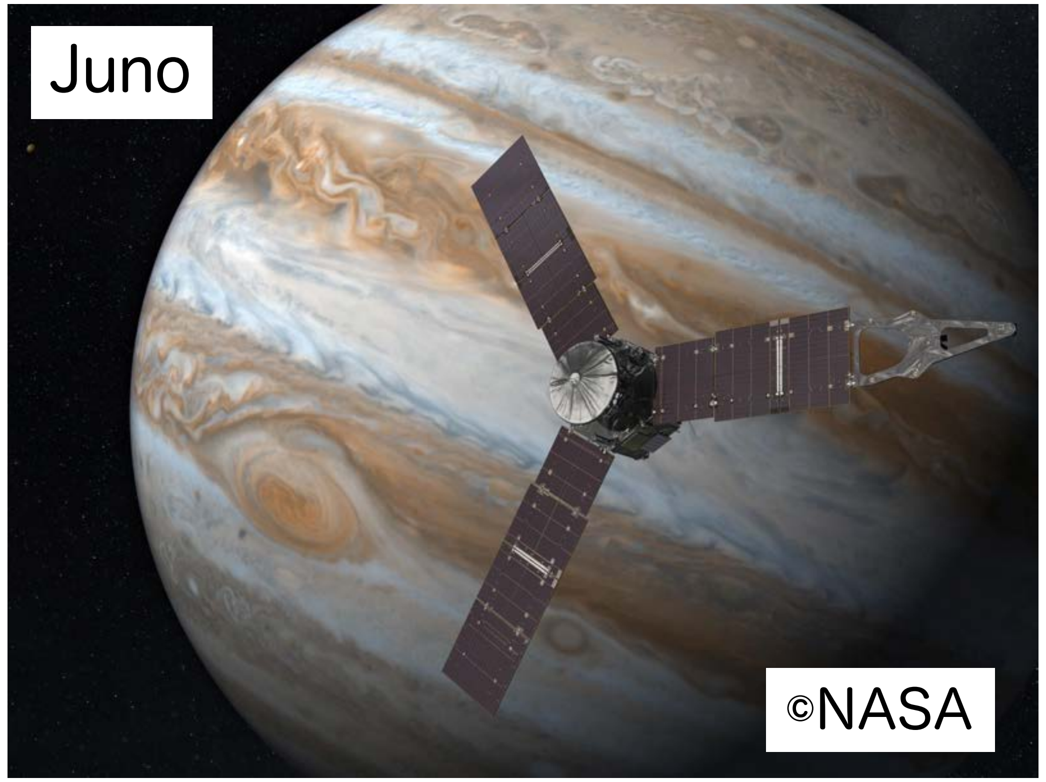
(1) developing a radiation belt model fully incorporating nonlinear wave-particle interactions

(2) measuring the radiation belt loss process by originally developed instruments onboard a CubeSat (to be launched in 2026)

(3) analyzing spacecraft data measured in terrestrial and Jovian magnetospheres







Summary

- We conducted a series of electron hybrid simulations to study dependencies of the generation process of whistler-mode chorus emissions
- Simulation results revealed that chorus emissions are triggered when the wave amplitude exceeds the threshold amplitude derived from the nonlinear wave growth theory
- In the propagation process of whistler-mode waves in the magnetosphere, duct structure guides waves along a field line
- Future work: radiation belt modeling fully incorporating nonlinear wave-particle interactions