STEシミュレーション研究会@神戸
2017年9月6-8日

惑星磁気圏でのホイッスラーモード・コーラス放射発生過程についての電子ハイブリッド・MHD連成計算

加藤雄人[1], 深沢圭一郎[2], 八木学[3]

1: 東北大学 大学院理学研究科
2: 京都大学 学術情報メディアセンター
3: 理化学研究所 計算科学研究機構

Outline

1. Introduction: whistler-mode chorus emissions in planetary magnetospheres

2. Electron hybrid - MHD cross reference simulations

3. Simulation results of chorus generation in the magnetospheres of the Earth, Jupiter, and Mercury

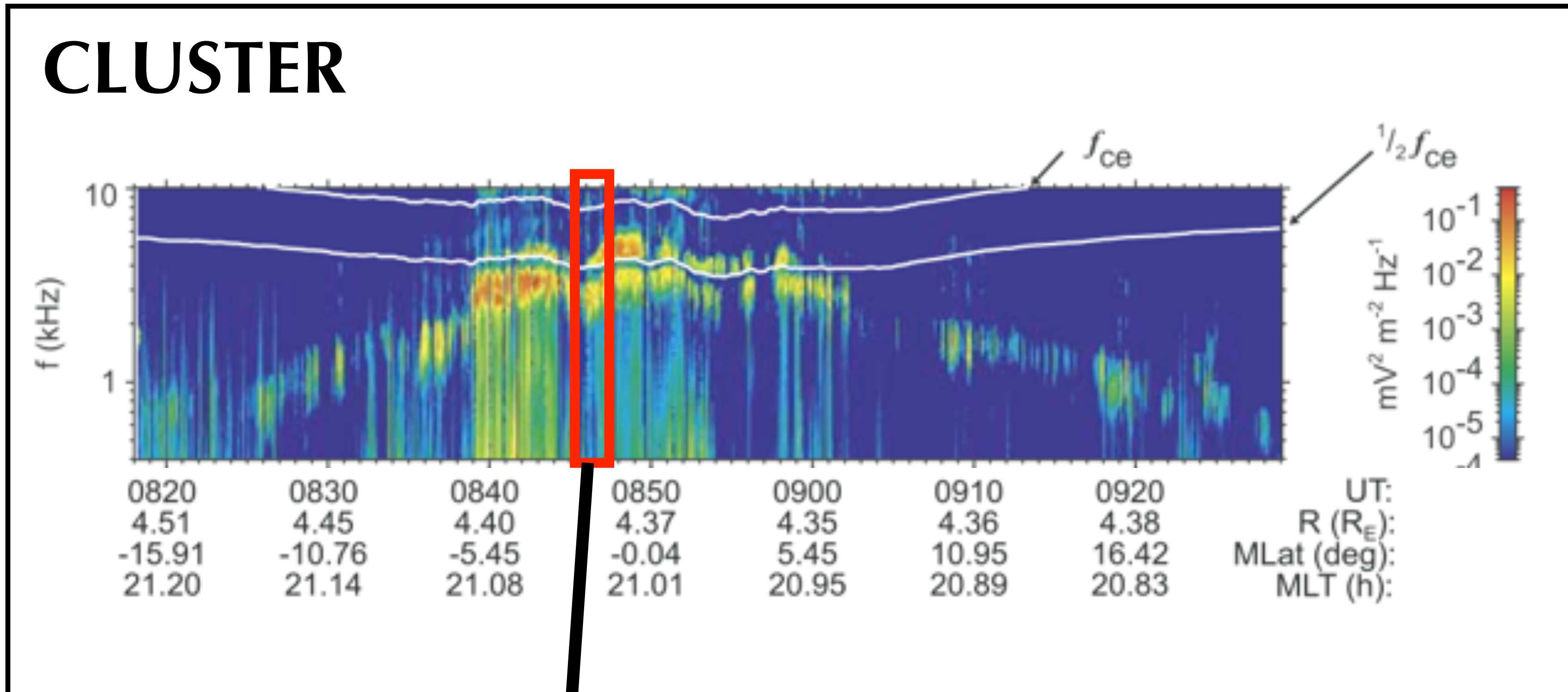
4. Summary

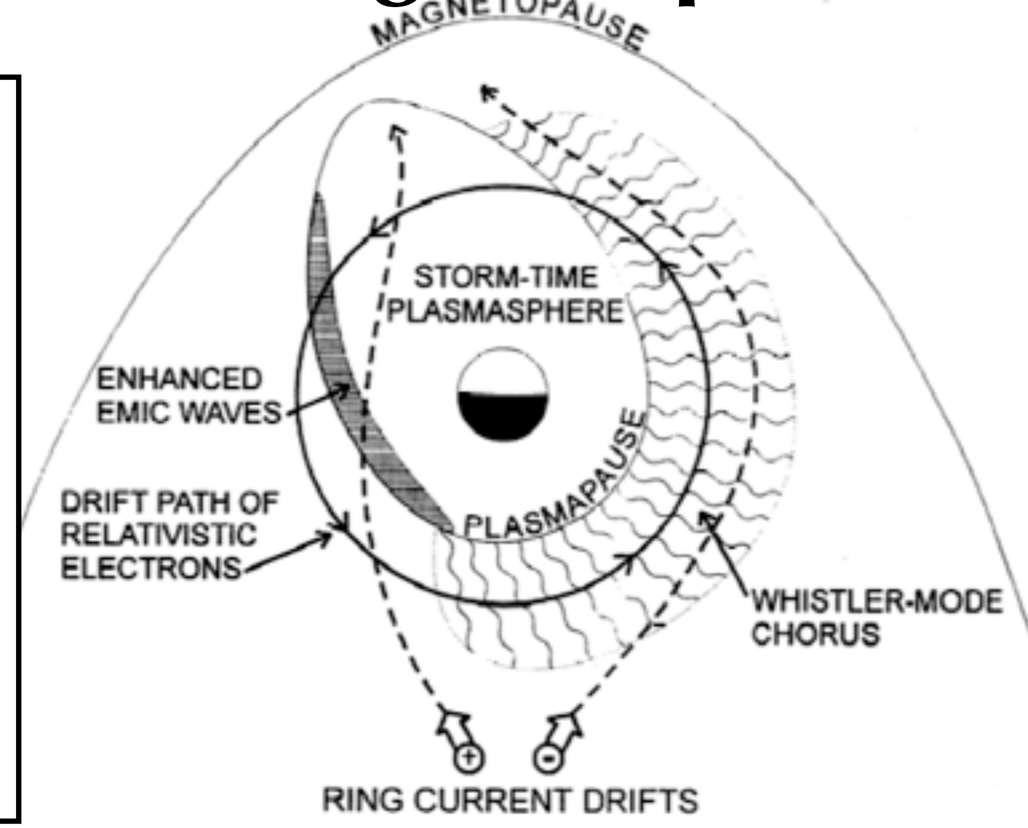
ARASE

(ERG; Exploration of energization and Radiation in Geospace)

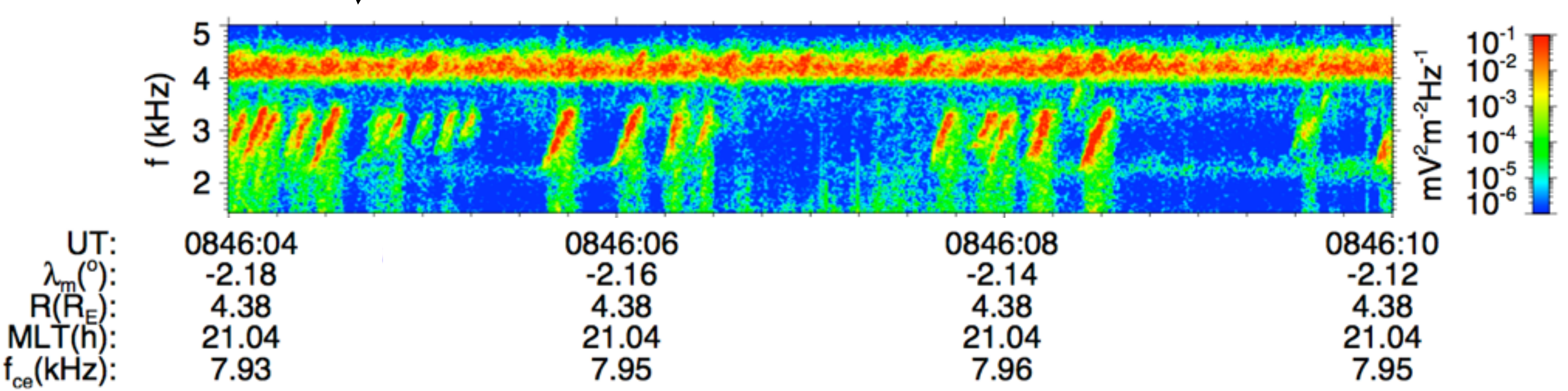
- Science operation started from 29 Mar 2017
- Electric field: DC - 10 MHz
- Magnetic field: DC - 100kHz
- Electrons: 10 eV - 20 MeV
- Ions: 10 eV/q - 180 keV/q
- Software-type Wave-Particle Interaction Analyzer

Whistler-mode chorus in the terrestrial magnetosphere



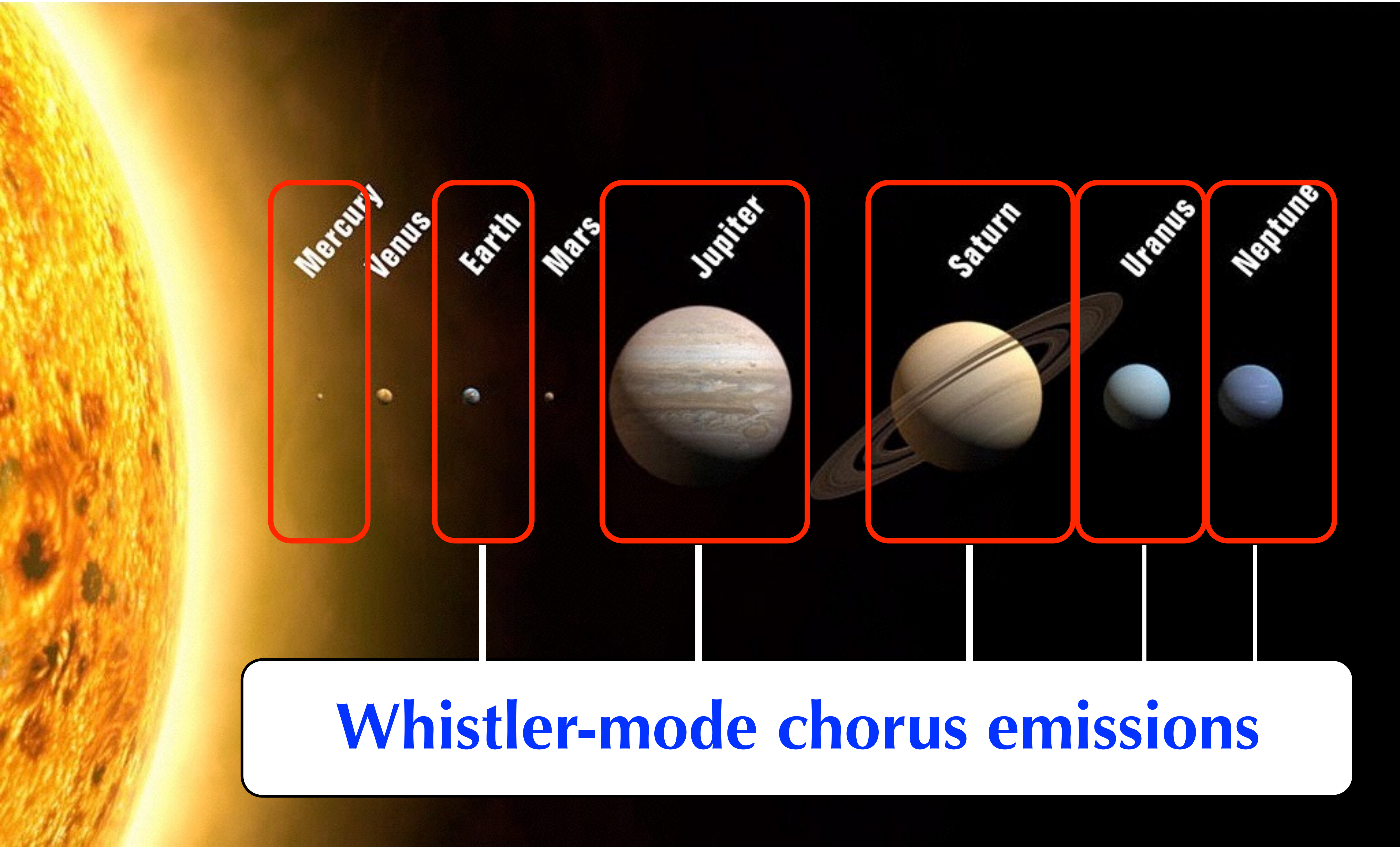


[*Summers et al.*, 1998]



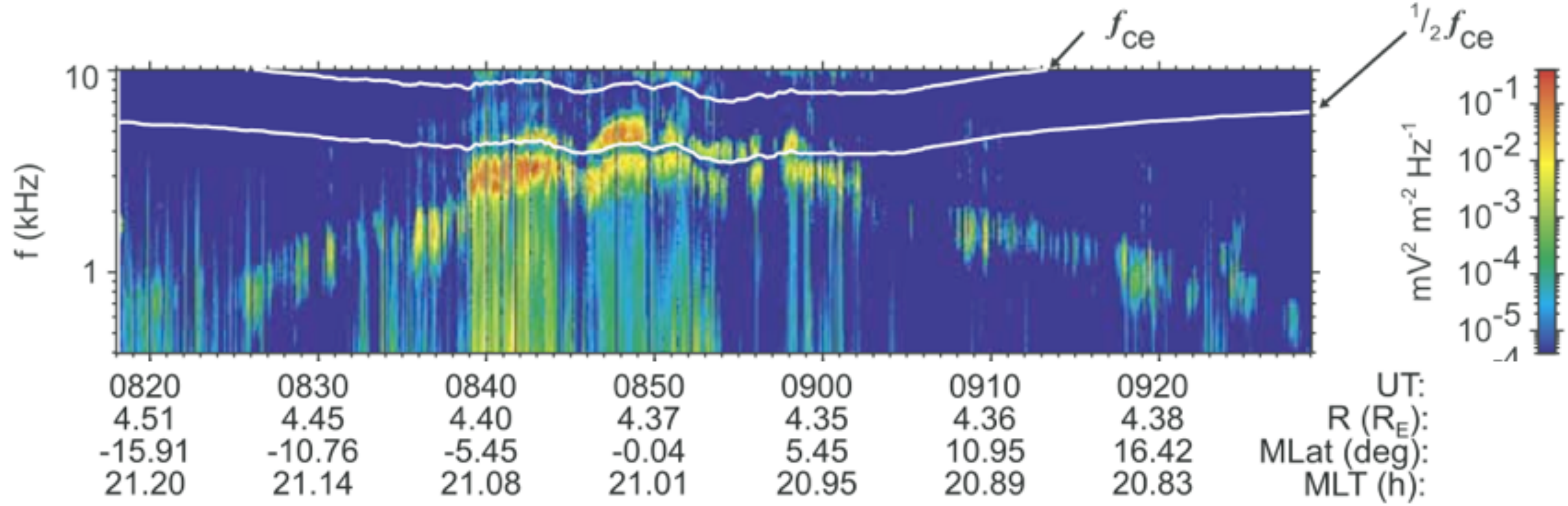
[*Santolik et al.*, 2008]

“Magnetized” planets in the solar system



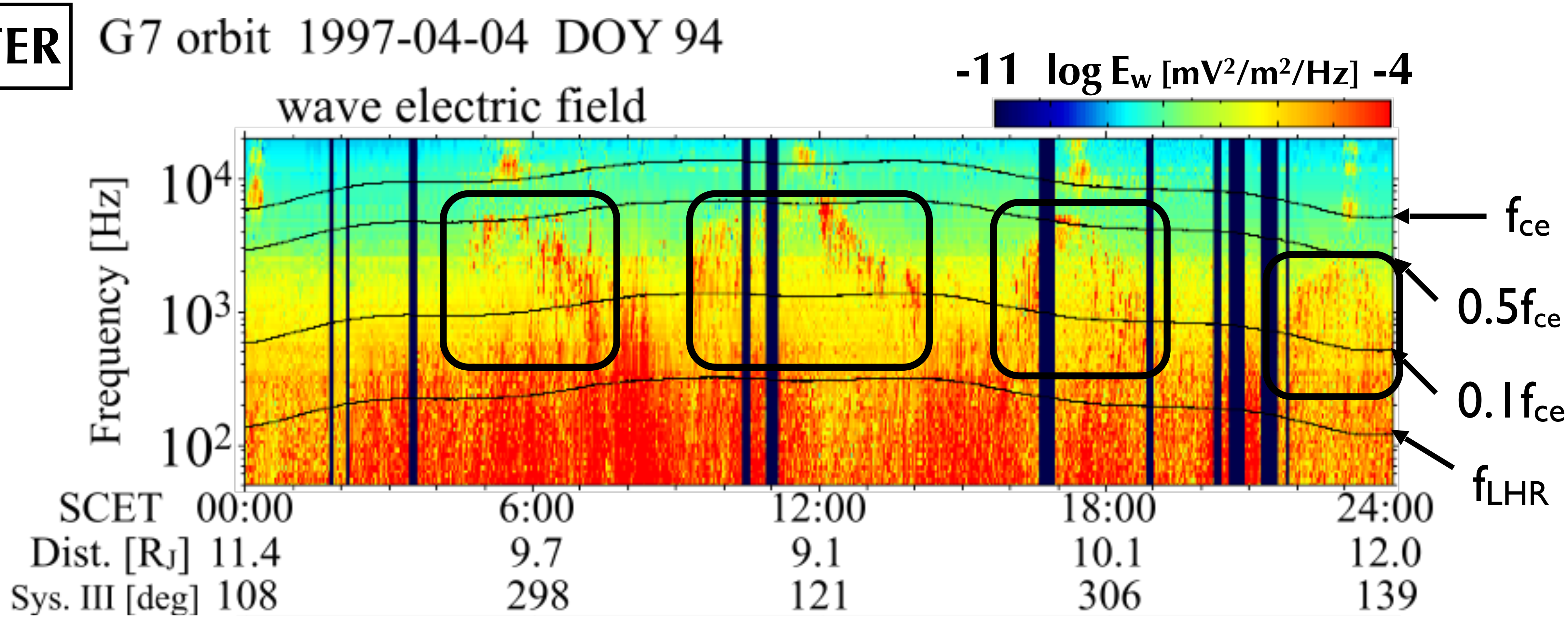
Chorus in planetary magnetospheres

EARTH



[*Santolik et al.*, GRL 2004]

JUPITER



[*Katoh et al.*, JGR 2011]

Purpose of the present study

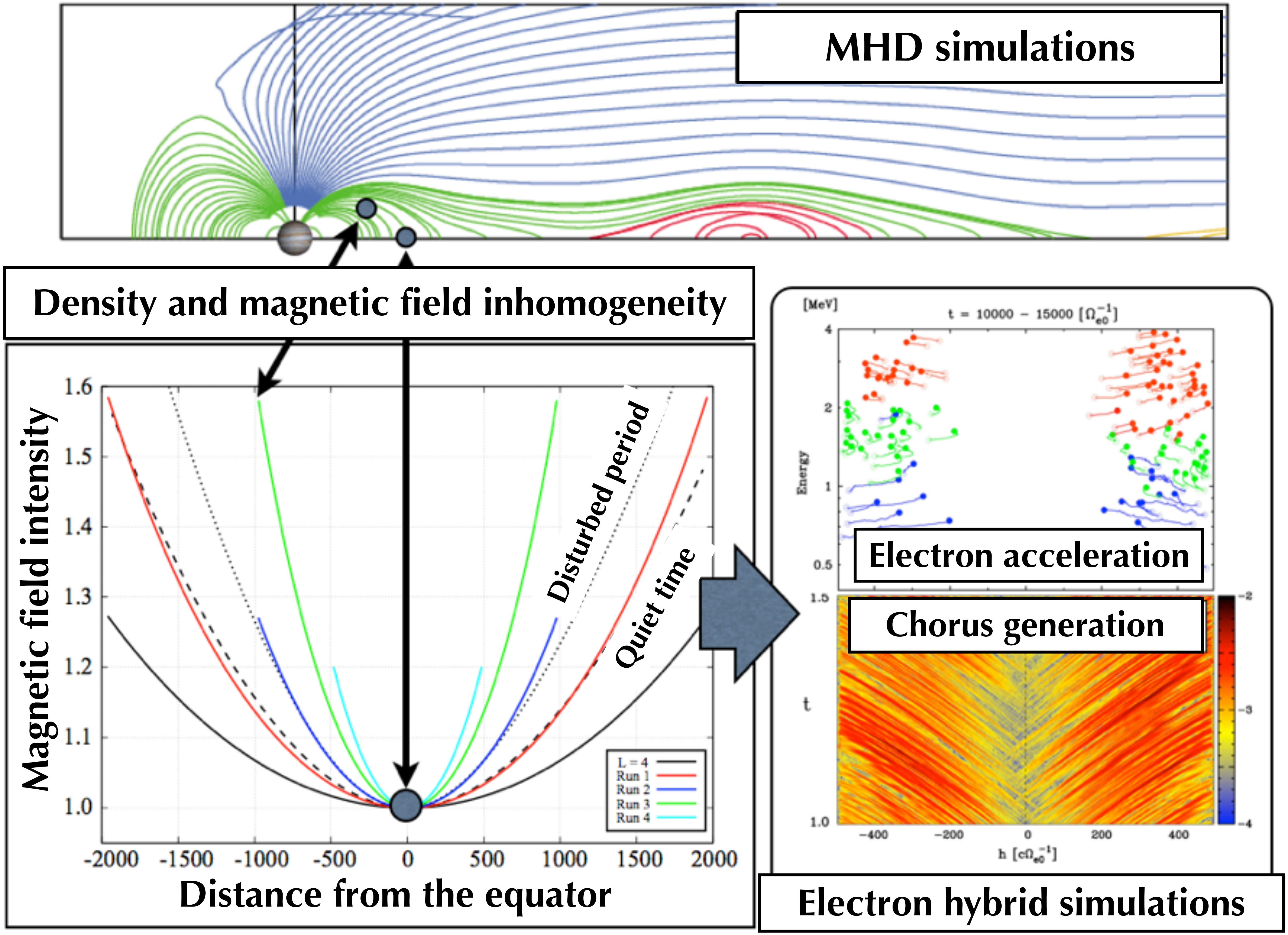
- Understanding differences/similarities of chorus generation process in planetary magnetospheres

- We conduct a series of electron hybrid simulations of the chorus generation and reveal properties on the magnetic field inhomogeneity and velocity distribution function of energetic electrons
- In particular, we focus on the chorus generation process in the magnetospheres of the Earth, Jupiter, and Mercury, by referring the results of MHD simulations

Outline

1. Introduction: whistler-mode chorus emissions in planetary magnetospheres
2. Electron hybrid - MHD cross reference simulations
3. Simulation results of chorus generation in the magnetospheres of the Earth, Jupiter, and Mercury
4. Summary

Electron hybrid – MHD cross-reference simulations



Electron Hybrid code: Basic equations

[e.g., *Katoh and Omura*, JGR 2004, GRL 2007]

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

$$\frac{\partial \mathbf{v}_f}{\partial t} = -(\mathbf{v}_f \cdot \nabla)\mathbf{v}_f + \frac{q_f}{m_f}(\mathbf{E} + \mathbf{v}_f \times \mathbf{B})$$

$$\frac{d(m_p \mathbf{v}_p)}{dt} = q_p(\mathbf{E} + \mathbf{v}_p \times \mathbf{B})$$

$$\mathbf{J} = q_f n_f \mathbf{v}_f + \sum_p q_p \mathbf{v}_p$$

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

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

Simulation model & initial settings

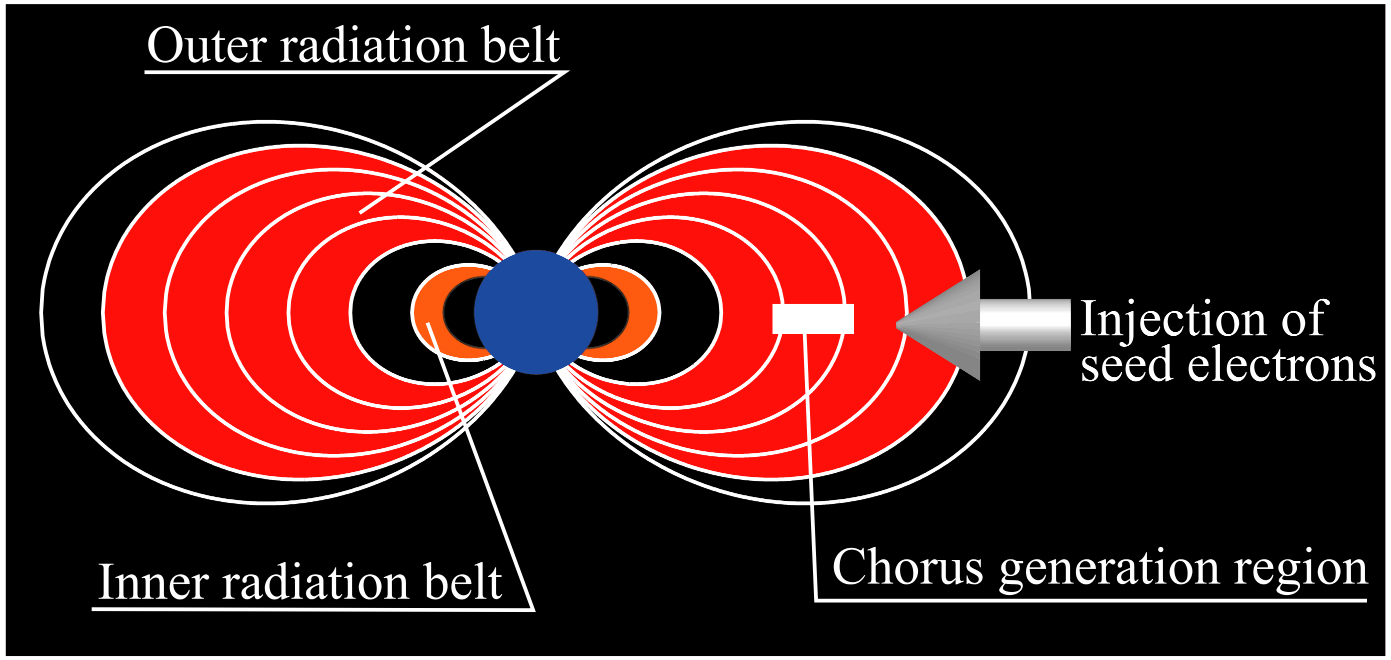
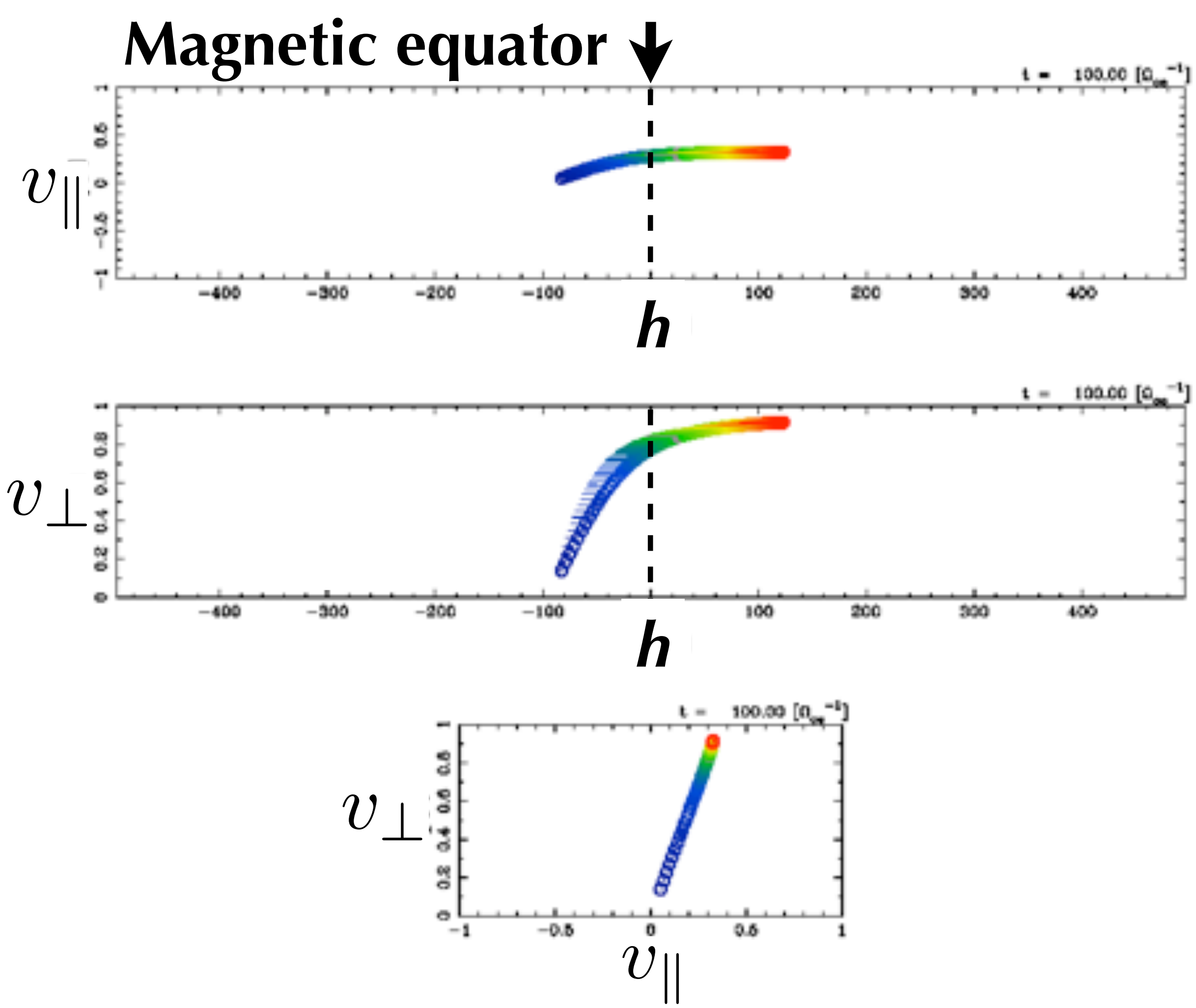
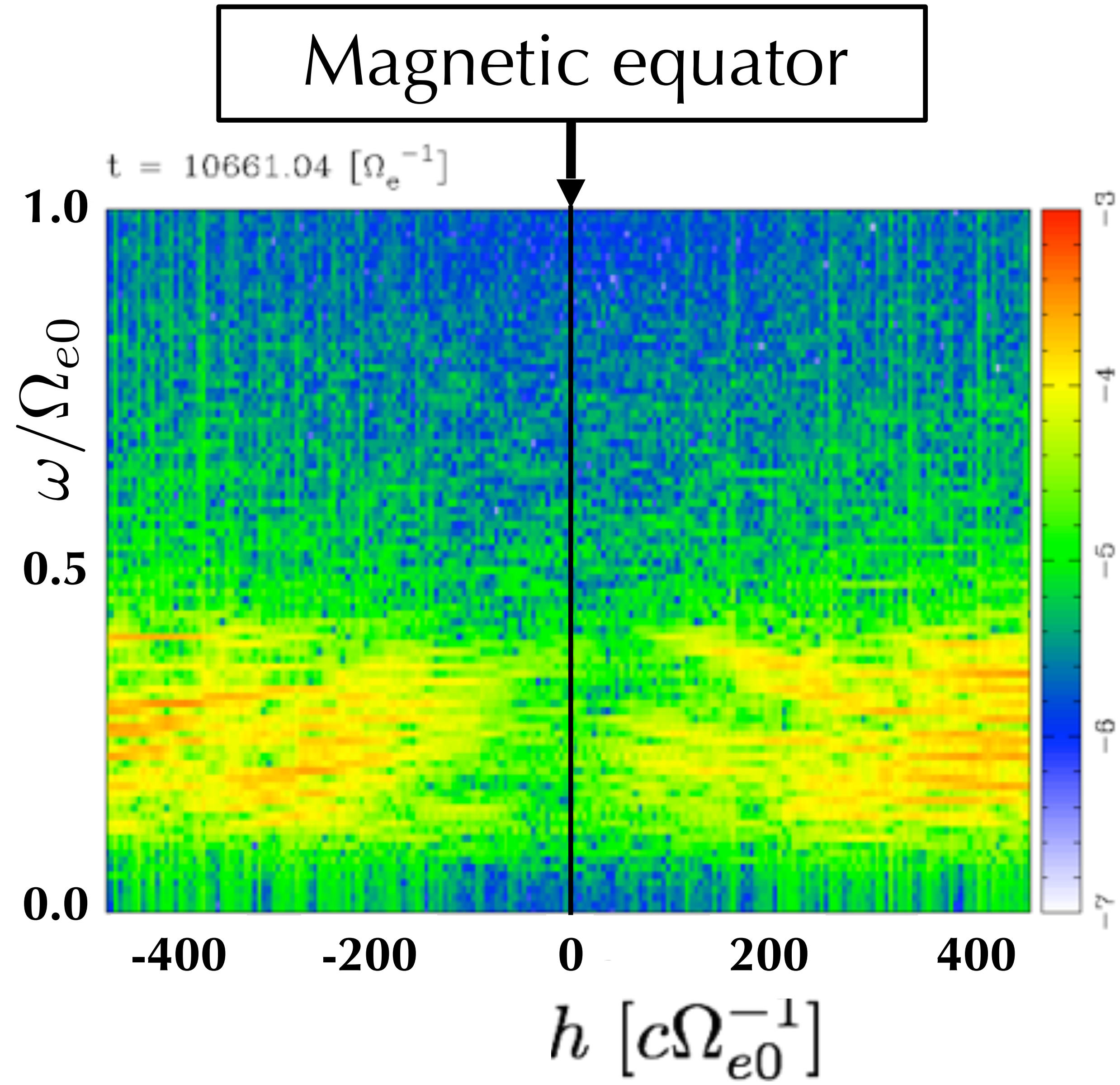


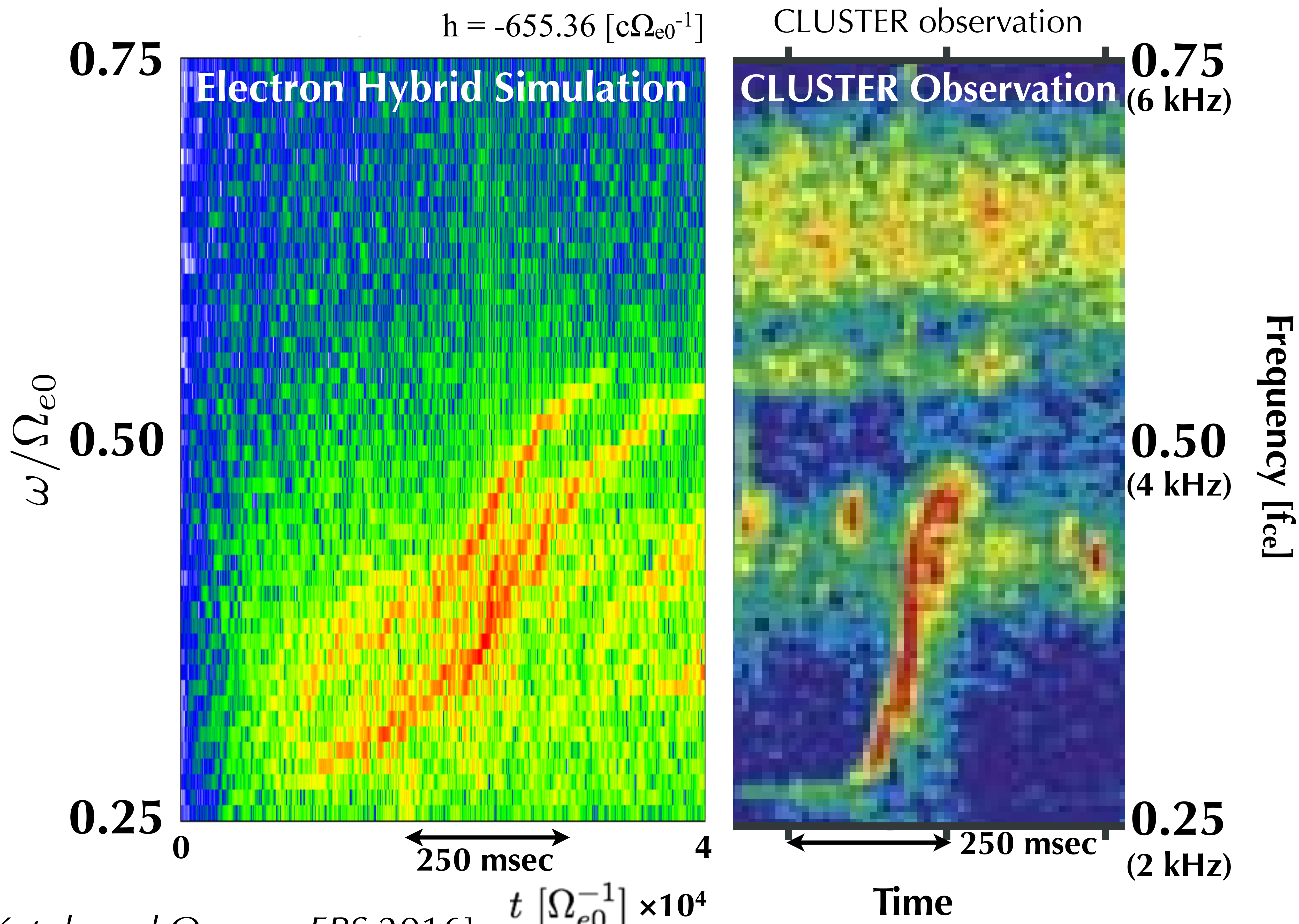
Fig: Schematic illustration of radiation belts



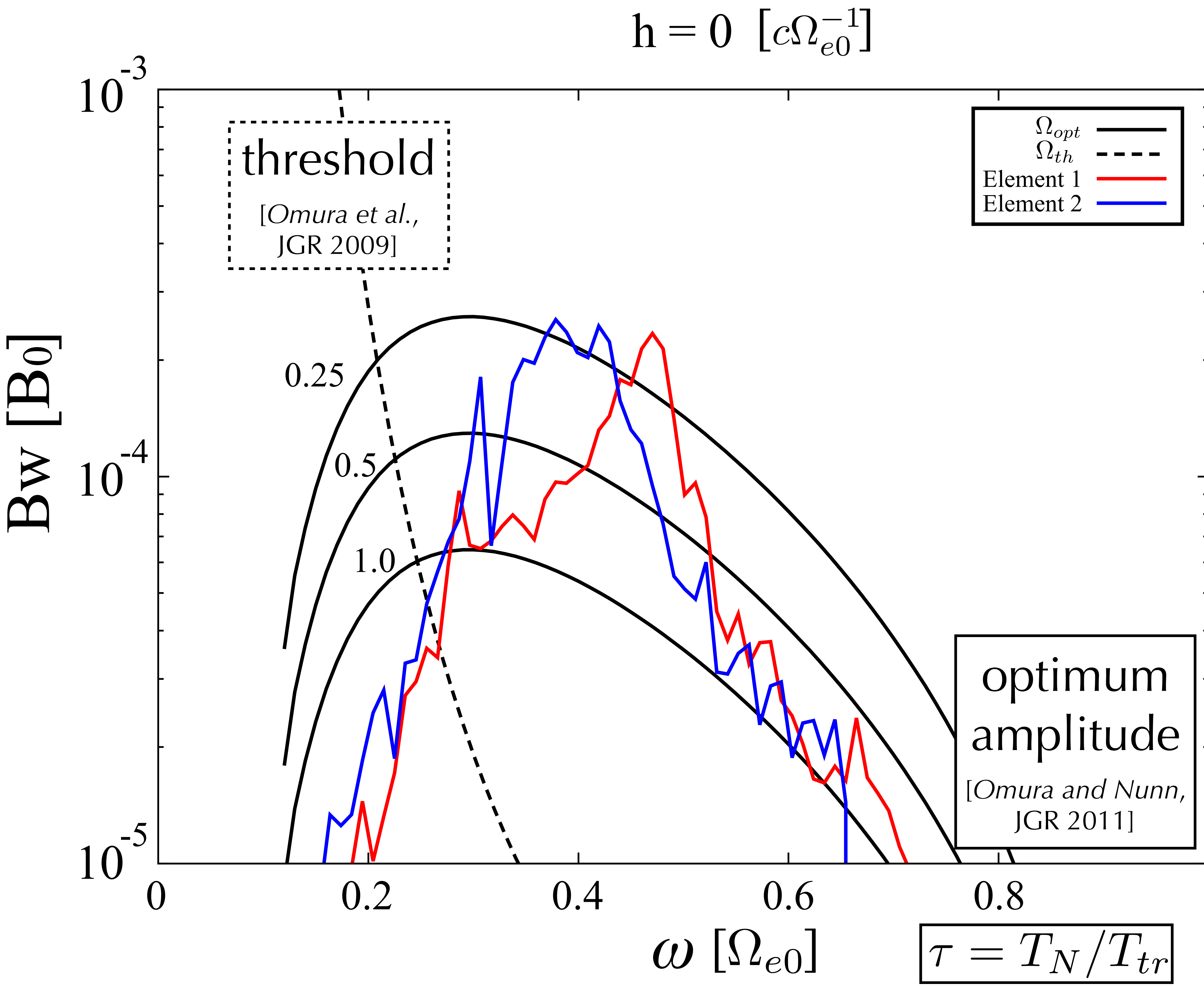


- 1D, field aligned system
- mirror motion of electrons is taken into account
- neglecting electrostatic waves

Simulation/CLUSTER observation results comparison



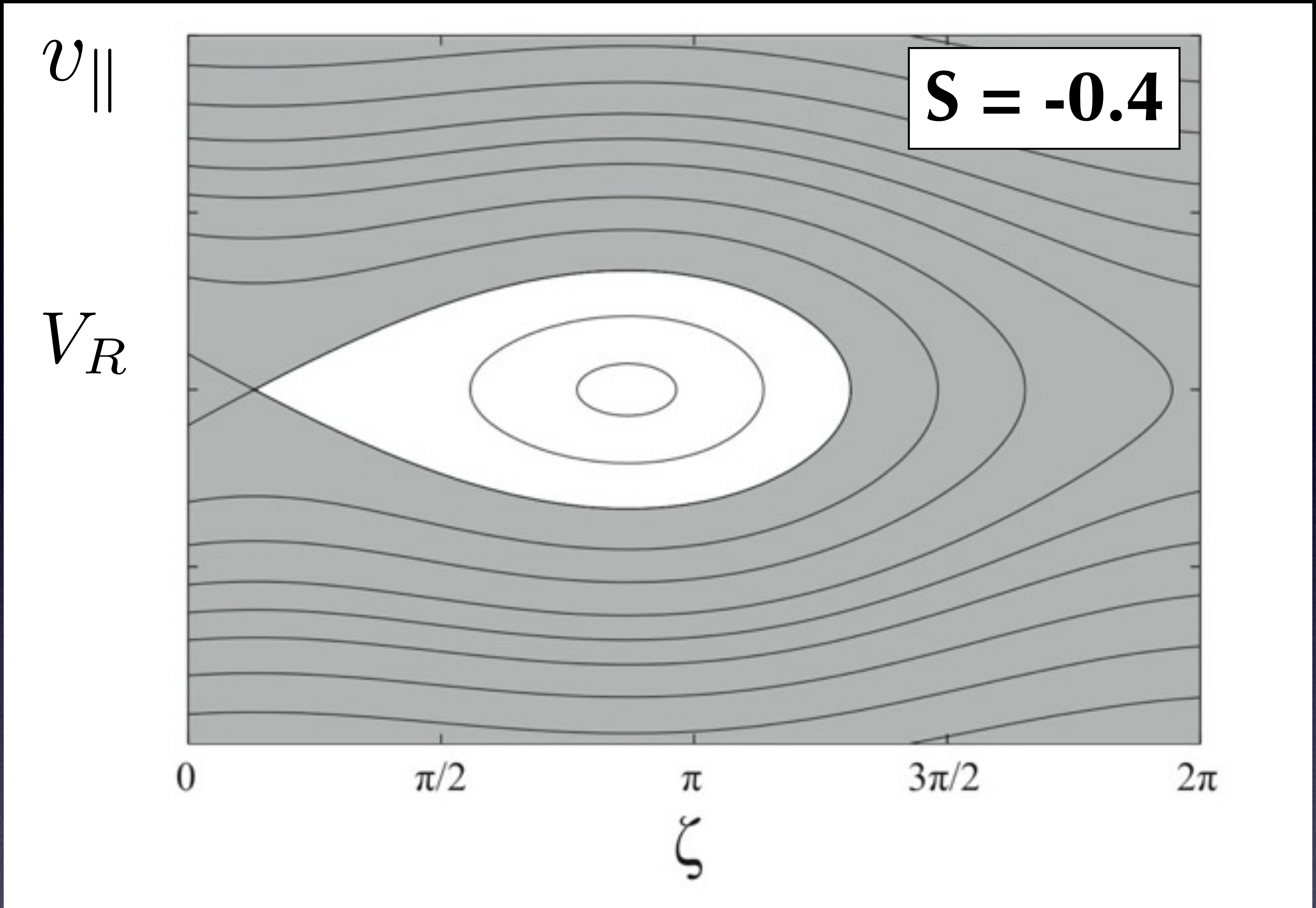
[*Katoh and Omura, EPS* 2016]



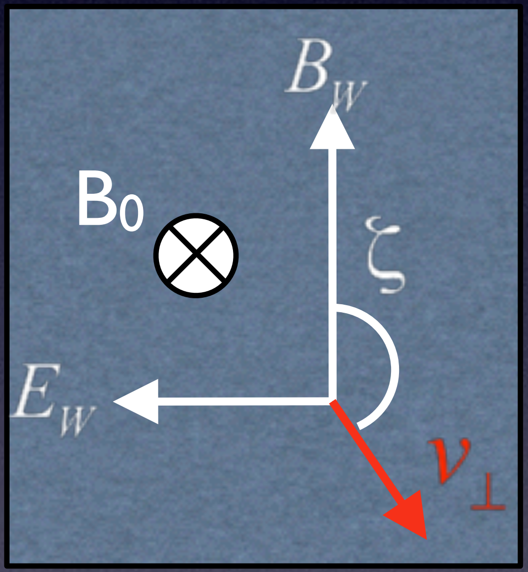
h = 0 [$c\Omega_{e0}^{-1}$]
10^{-3}
10^{-4}
10^{-5}
Bw [B0]
threshold
[Omura et al., JGR 2009]
0.25
0.5
1.0
Ω_{opt}
Ω_{th}
Element 1
Element 2
optimum amplitude
[Omura and Nunn, JGR 2011]
0
0.2
0.4
0.6
0.8
1
ω [Ω_{e0}]
$\tau = T_N/T_{tr}$

Nonlinear wave growth theory for chorus generation

[*Omura et al.*, 2008, 2009]



phase bunching caused by the balance between **Lorentz force** ($\mathbf{v}_\perp \times \mathbf{B}_W$) and **mirror force**

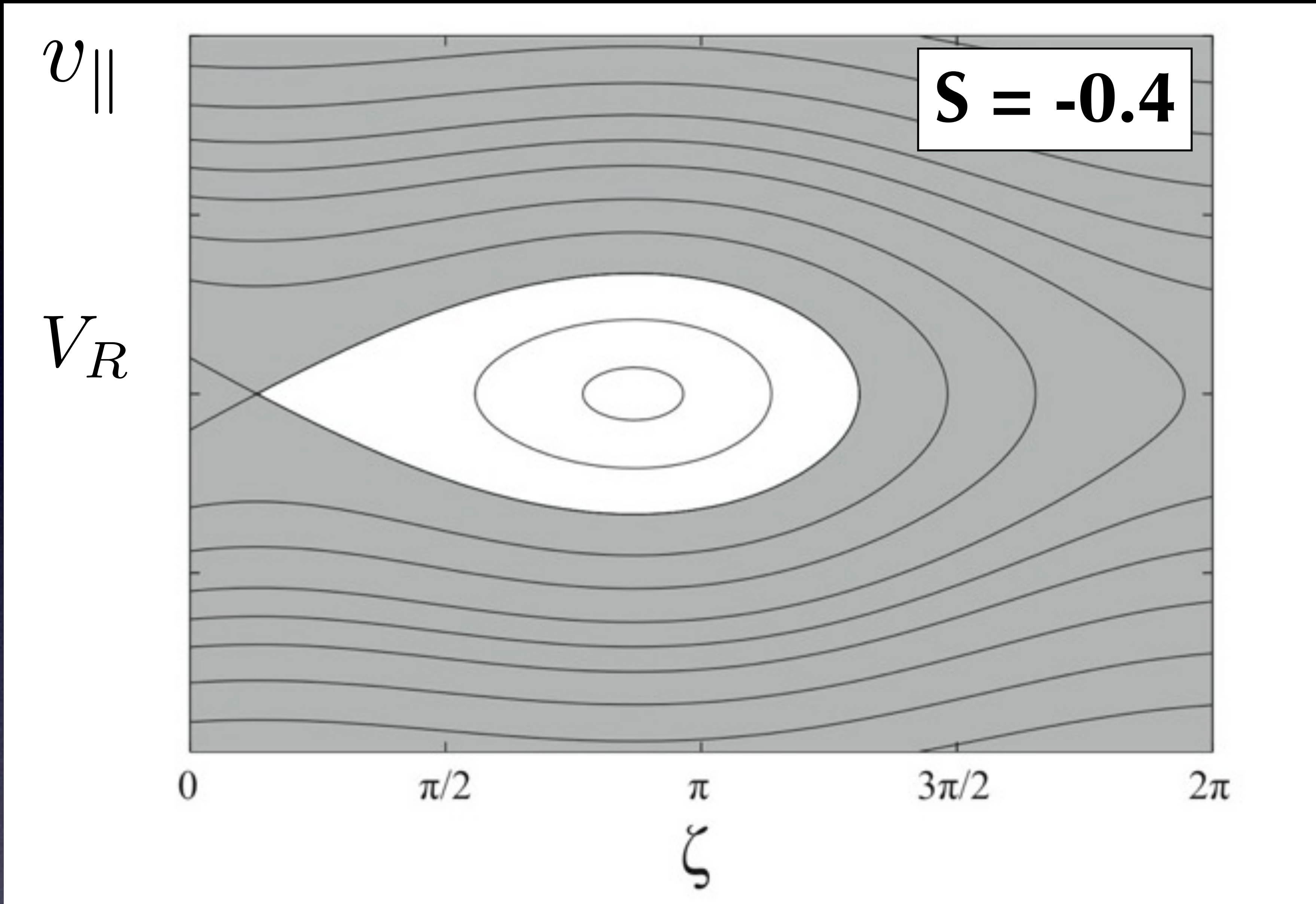


Trajectories of trapped/untrapped electrons in the wave phase space

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

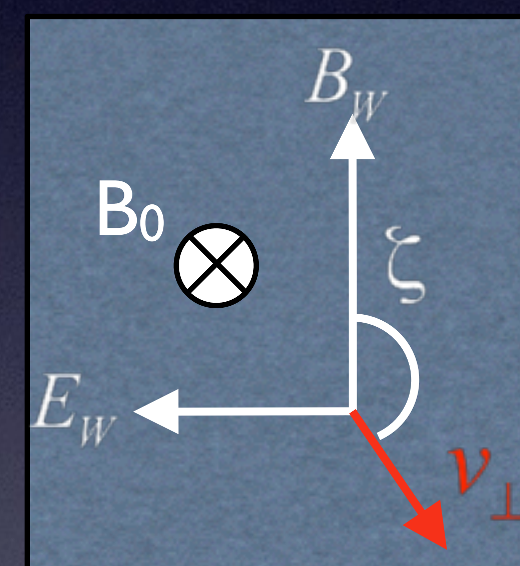
Nonlinear wave growth theory for chorus generation

[*Omura et al.*, 2008, 2009]



phase bunching caused by the balance between **Lorentz force** $(\mathbf{v}_\perp \times \mathbf{B}_W)$

and **mirror force**



Trajectories of trapped/untrapped electrons in the wave phase space

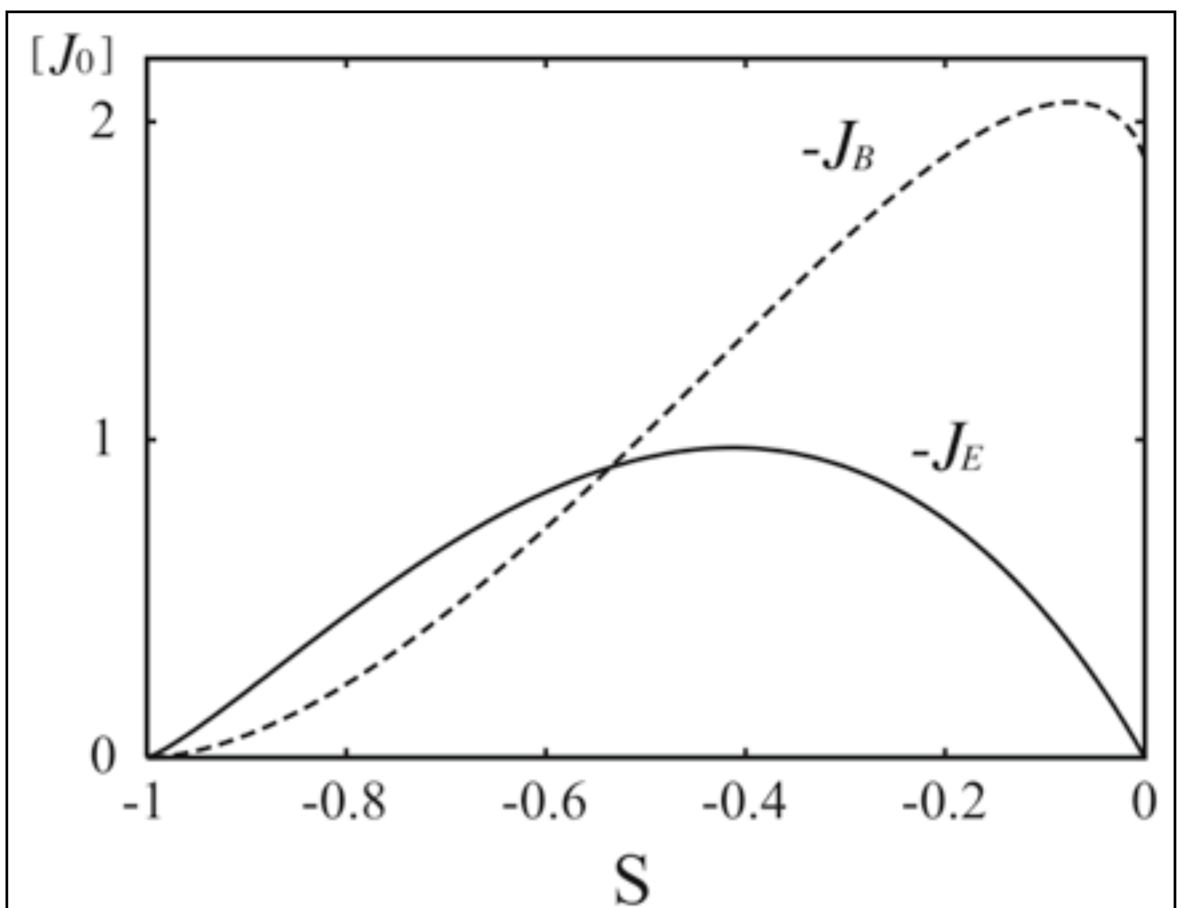
$$S = -\frac{1}{s_0 \omega \Omega_w} \left(s_1 \frac{\partial \omega}{\partial t} + c s_2 \frac{\partial \Omega_e}{\partial h} \right)$$

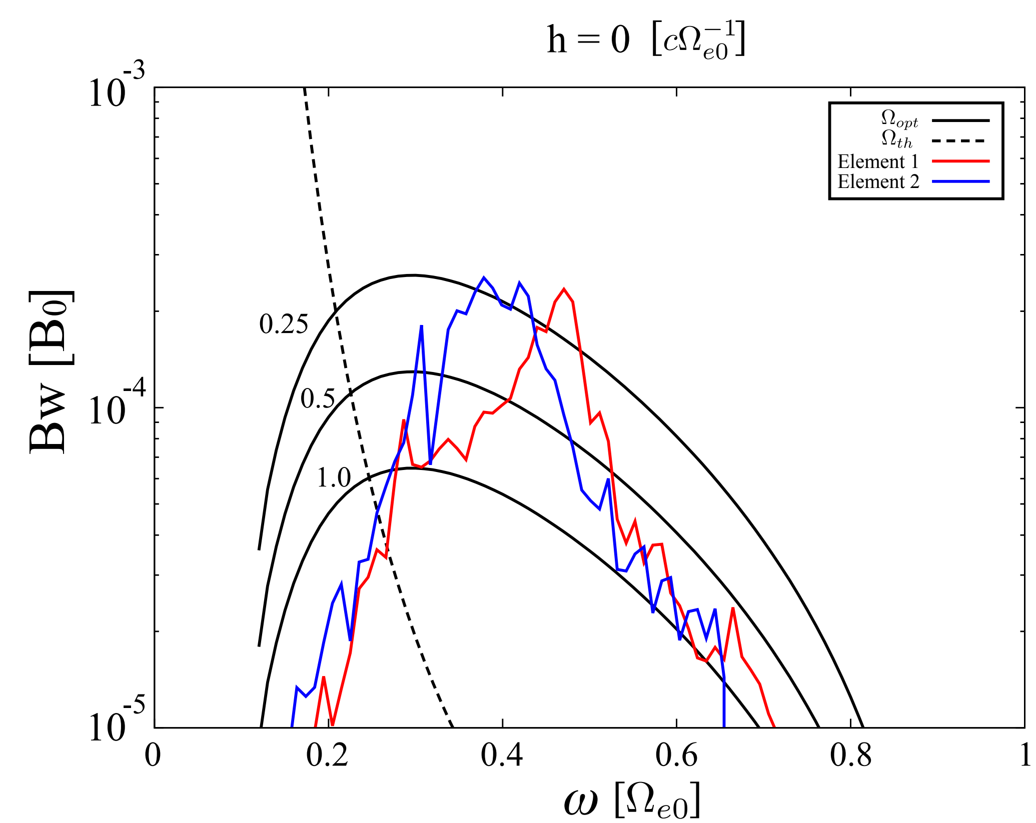
Frequency variation and magnetic field inhomogeneity play the same role

非線形波動成長理論に基づくコーラス発生条件：閾値とoptimum wave amplitude

- **閾値**(B_{th})　[*Omura et al.*, 2009]
  - 非線形成長をもたらす共鳴電流はS=-0.4で最大
  - Sの値は「周波数変化率」と「背景磁場空間勾配」が影響
  - chorusの伝搬過程でS=-0.4が保たれる波動振幅がB_{th}

$$\tilde{\Omega}_{th} = \frac{100\pi^3\gamma^3\xi}{\tilde{\omega}\tilde{\omega}_{ph}^4\tilde{V}_{\perp 0}^5\chi^5}\left(\frac{\tilde{a}s_2\tilde{U}_{t\parallel}}{Q}\right)^2 \exp\left(\frac{\gamma^2\tilde{V}_R^2}{\tilde{U}_{t\parallel}^2}\right)$$





非線形波動成長理論に基づくコーラス発生条件：閾値とoptimum wave amplitude

- **optimum wave amplitude** (B_{opt})　[*Omura and Nunn*, 2011]
  - 共鳴電流J_Eは振幅成長、J_Bは周波数変化をもたらす
  - ある時間幅T_Nの間にJ_Bによる周波数変化量ω_1を考える
  - 磁気赤道でS=-0.4となる周波数変化率dω/dtは波動振幅で決まる
  - T_Nはtrapping period (T_{tr})程度の時間と想定
  - ω_1/T_Nがdω/dtと等しくなる波動振幅がB_{opt}

$$\left(\frac{\partial}{\partial t} + v_g \frac{\partial}{\partial x}\right) B_W = -v_g \frac{\mu_0}{2} J_E$$

$$\left(\frac{\partial}{\partial t} + v_g \frac{\partial}{\partial x}\right) \phi = -v_g \frac{\mu_0}{2} \frac{J_B}{B_W}$$

$$\tilde{\Omega}_{wo} = 0.81\pi^{-5/2} \frac{Q}{\tau} \frac{s_1 \tilde{V}_g}{s_0 \tilde{\omega} \tilde{U}_{t\parallel}} \left(\frac{\tilde{\omega}_{ph} \tilde{V}_{\perp 0} \delta}{\gamma}\right)^2 \exp\left(-\frac{\gamma^2 \tilde{V}_R^2}{2\tilde{U}_{t\parallel}^2}\right)$$

$$\tau = T_N / T_{tr}$$

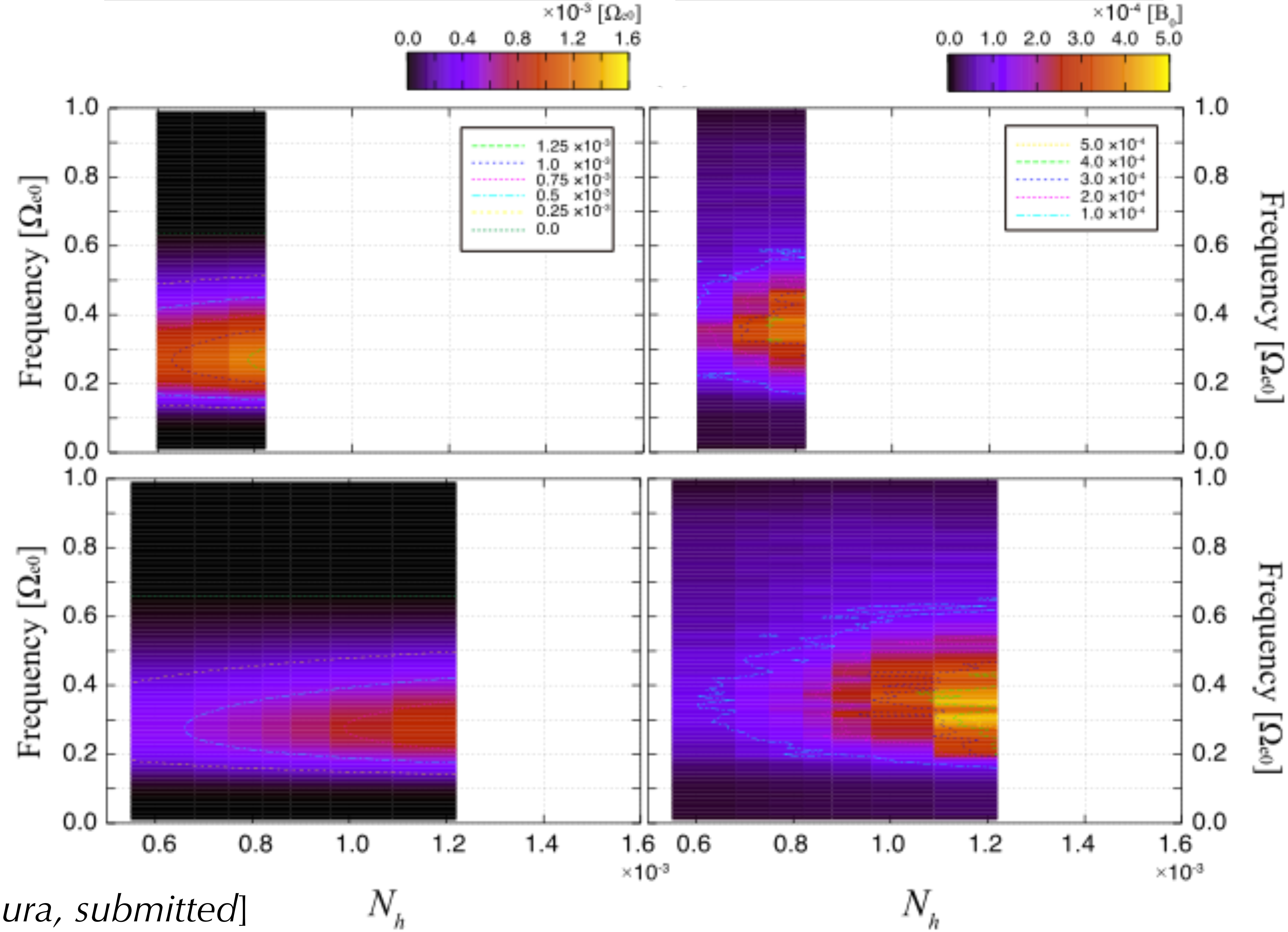
Dependence of chorus generation process on temperature anisotropy

Linear growth rate

Simulation results

$A_T = 9.0$

$A_T = 4.0$

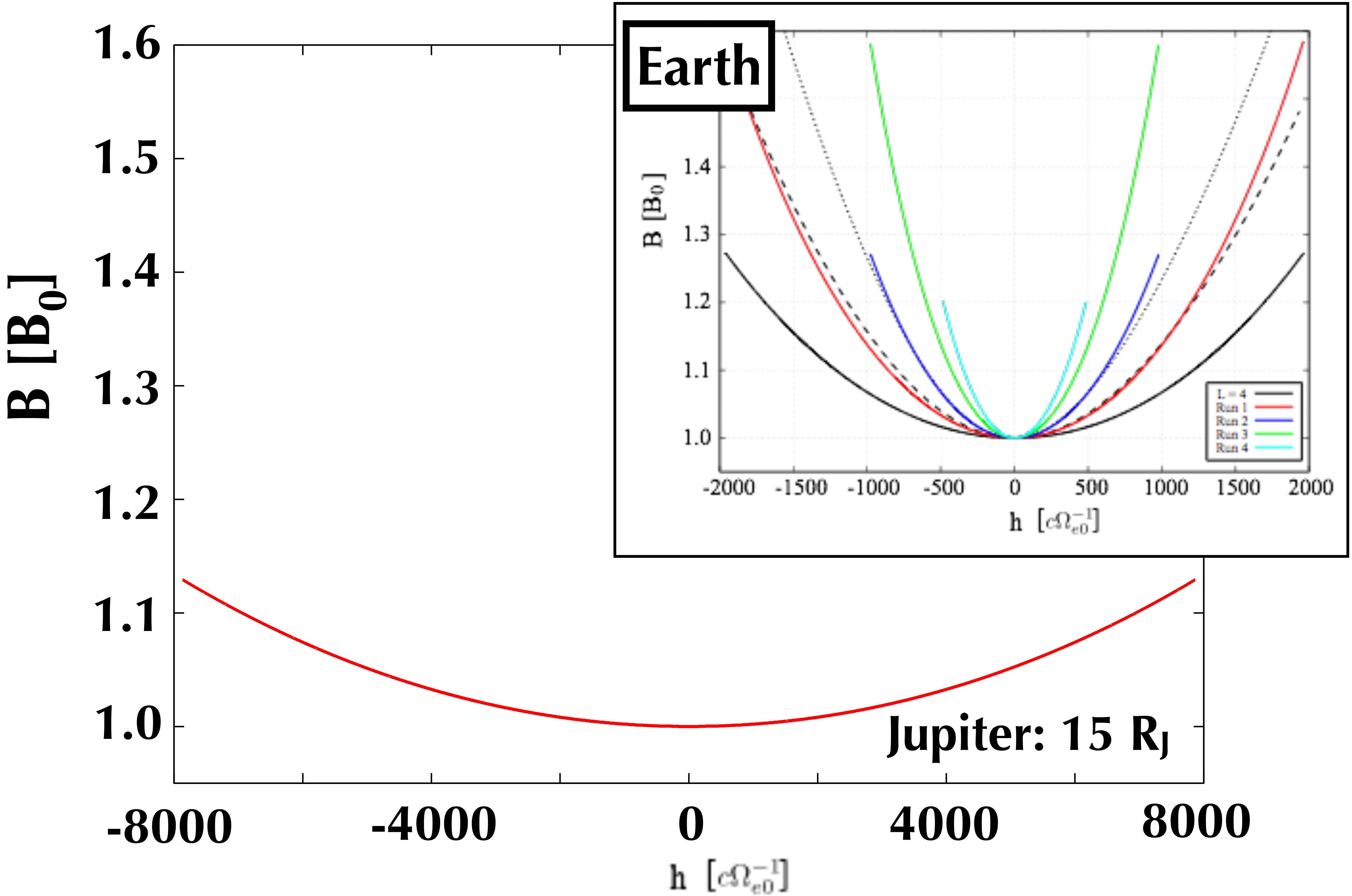


[*Katoh and Omura, submitted*]

Outline

1. Introduction: whistler-mode chorus emissions in planetary magnetospheres
2. Electron hybrid - MHD cross reference simulations
3. Simulation results of chorus generation in the magnetospheres of the Earth, Jupiter, and Mercury
   - Jupiter
   - Mercury
4. Summary

Background magnetic field: Jupiter



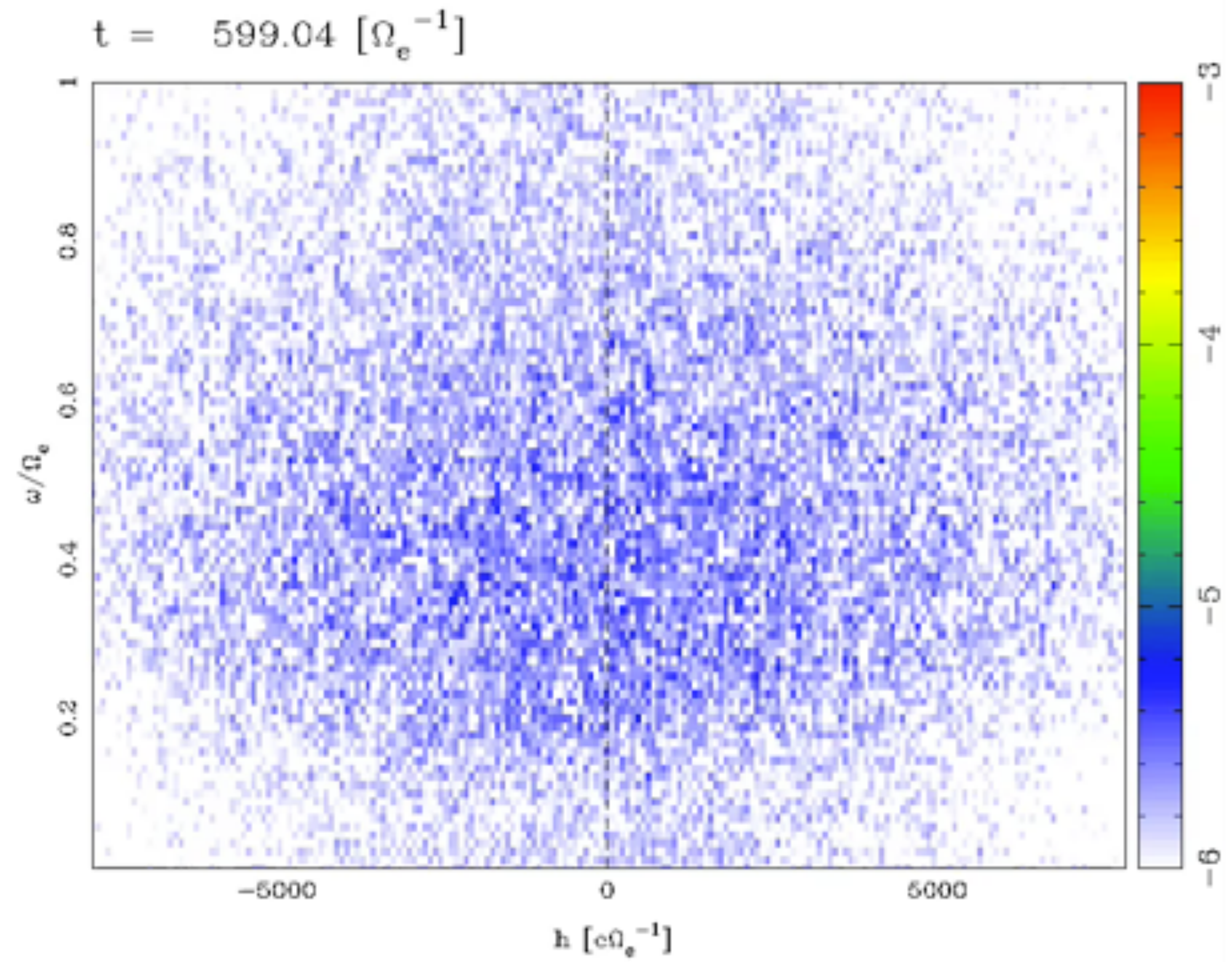
Simulations in the Jovian magnetospheric configuration

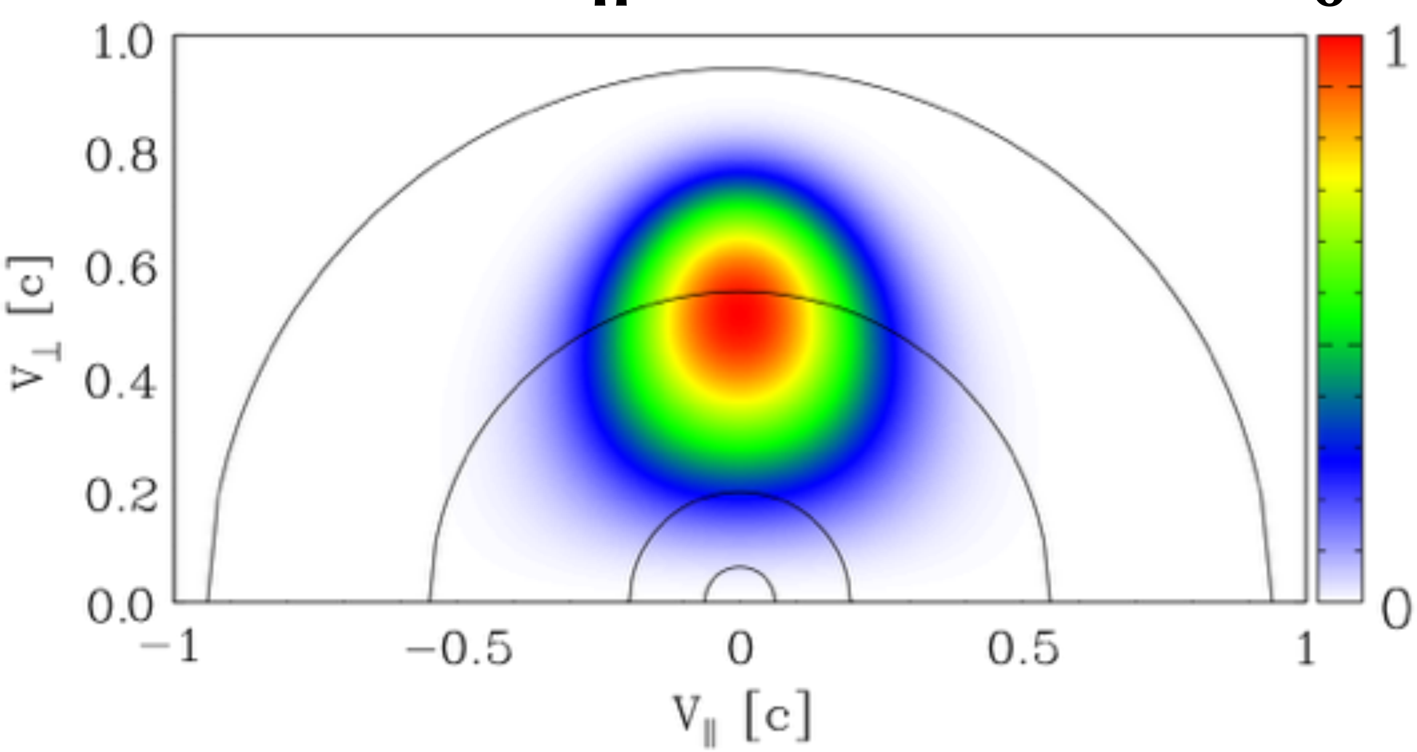
fp/fc = 4　　**A_T = 9.0**

$$A_T = (1+\beta)\frac{U_{t\perp}^2}{U_{t\|}^2} - 1$$

[*cf. Tang et al.*, AnG 2014]

- **Run 1: $N_h = 1.3 \times 10^{-5} N_0$**
- **Run 2: $N_h = 6.0 \times 10^{-5} N_0$**
- **Run 3: $N_h = 1.3 \times 10^{-4} N_0$**



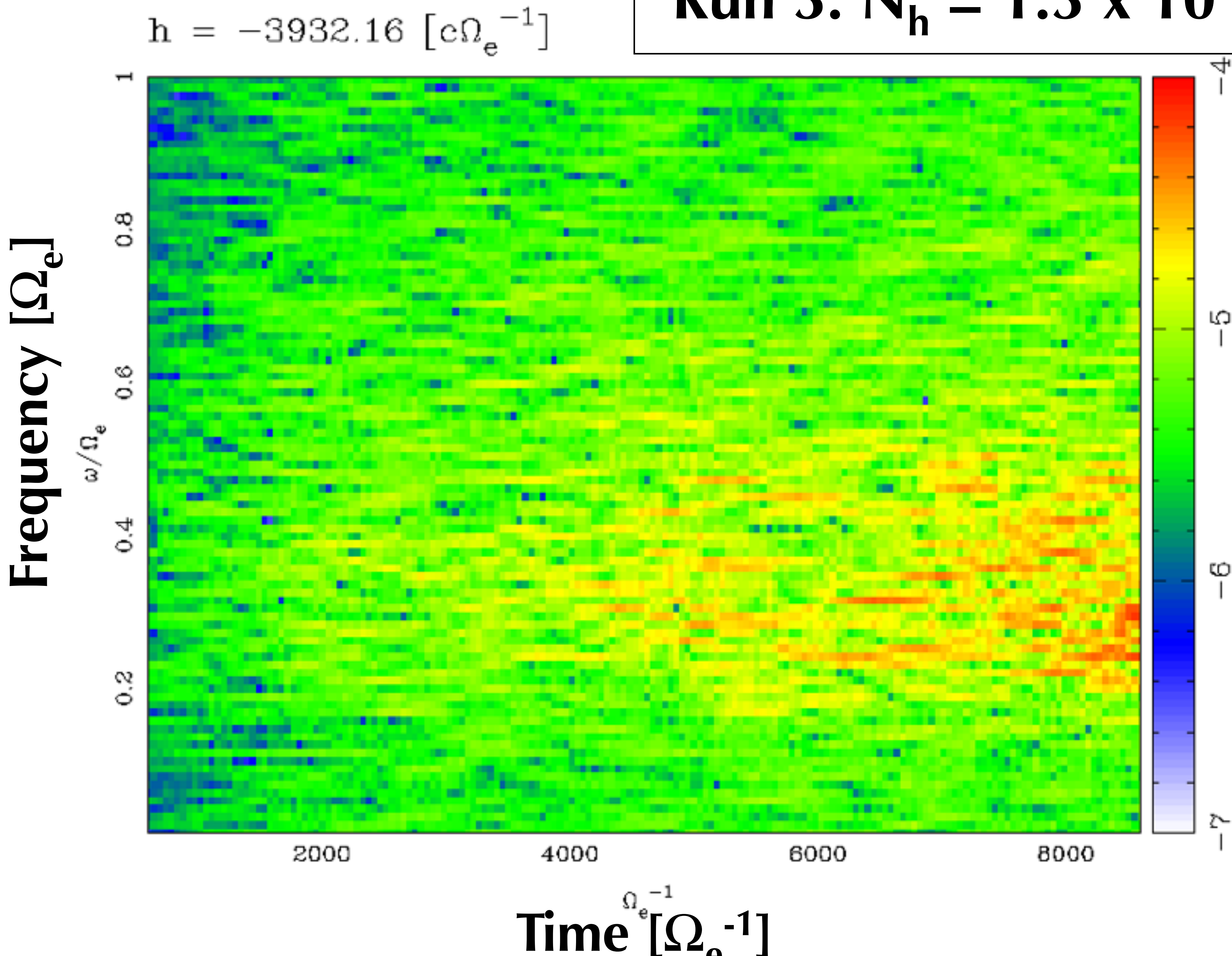


Initial velocity distribution of energetic electrons at the magnetic equator

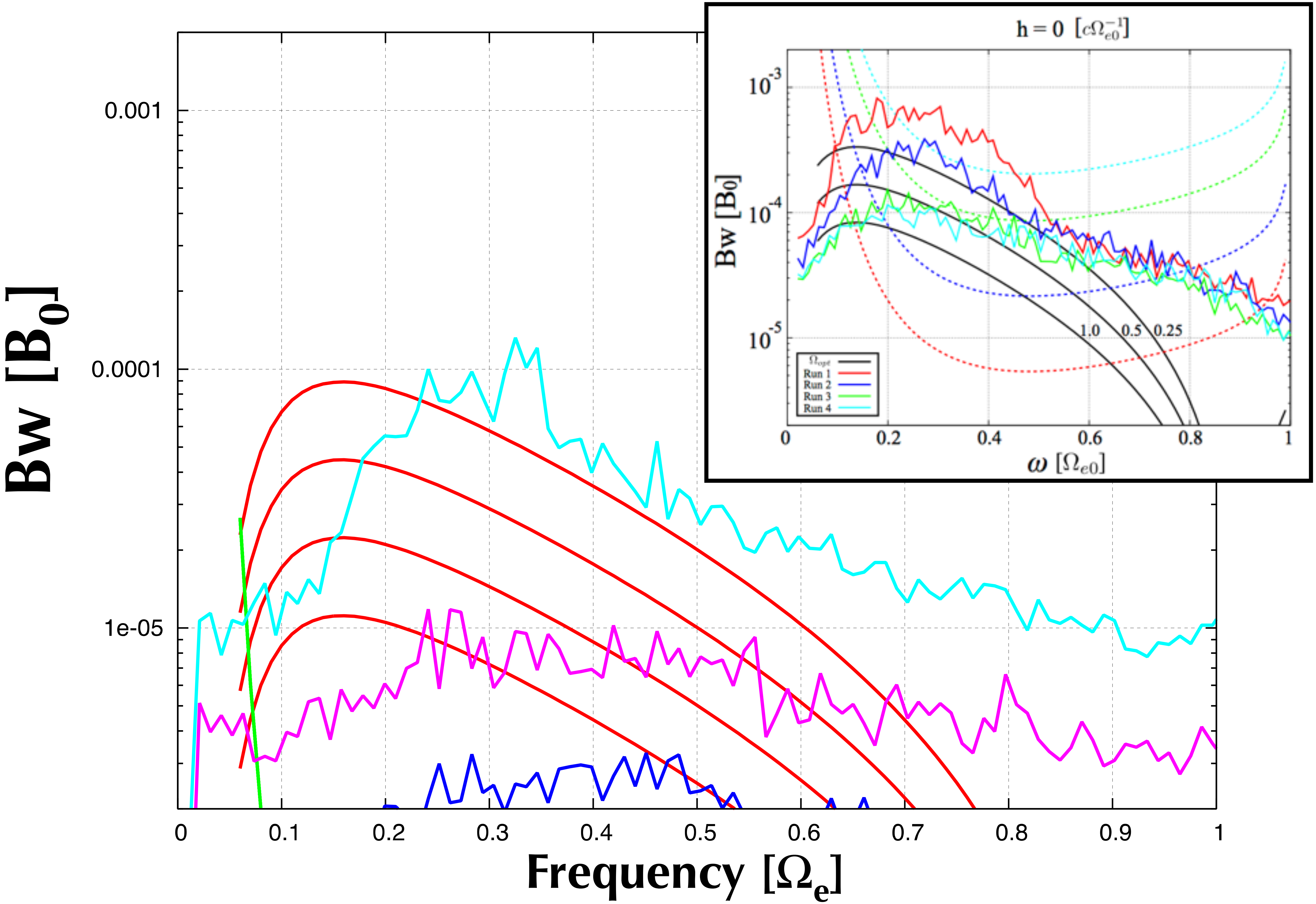
- 15 RJ (Ganymede's orbit)
- 262,144 grids
- 1.1x10^9 particles
- 1536 cores, 2 weeks (FX10, Kyushu Univ.)

Simulations in the Jovian magnetospheric configuration

Run 3: N_h = 1.3 x 10^{-4} N_0



Comparison of simulation results with theories



Outline

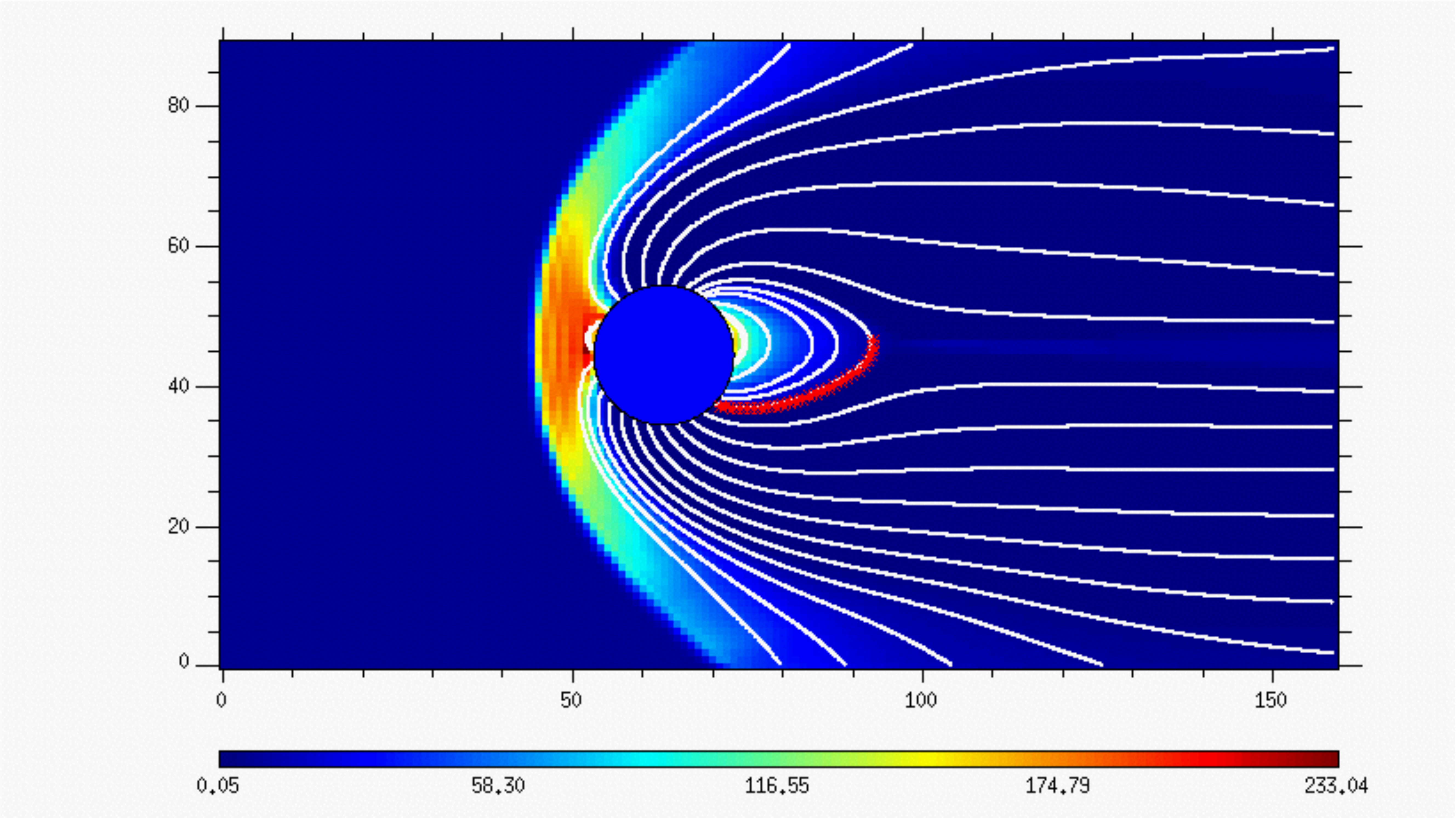
1. Introduction: whistler-mode chorus emissions in planetary magnetospheres

2. Electron hybrid - MHD cross reference simulations

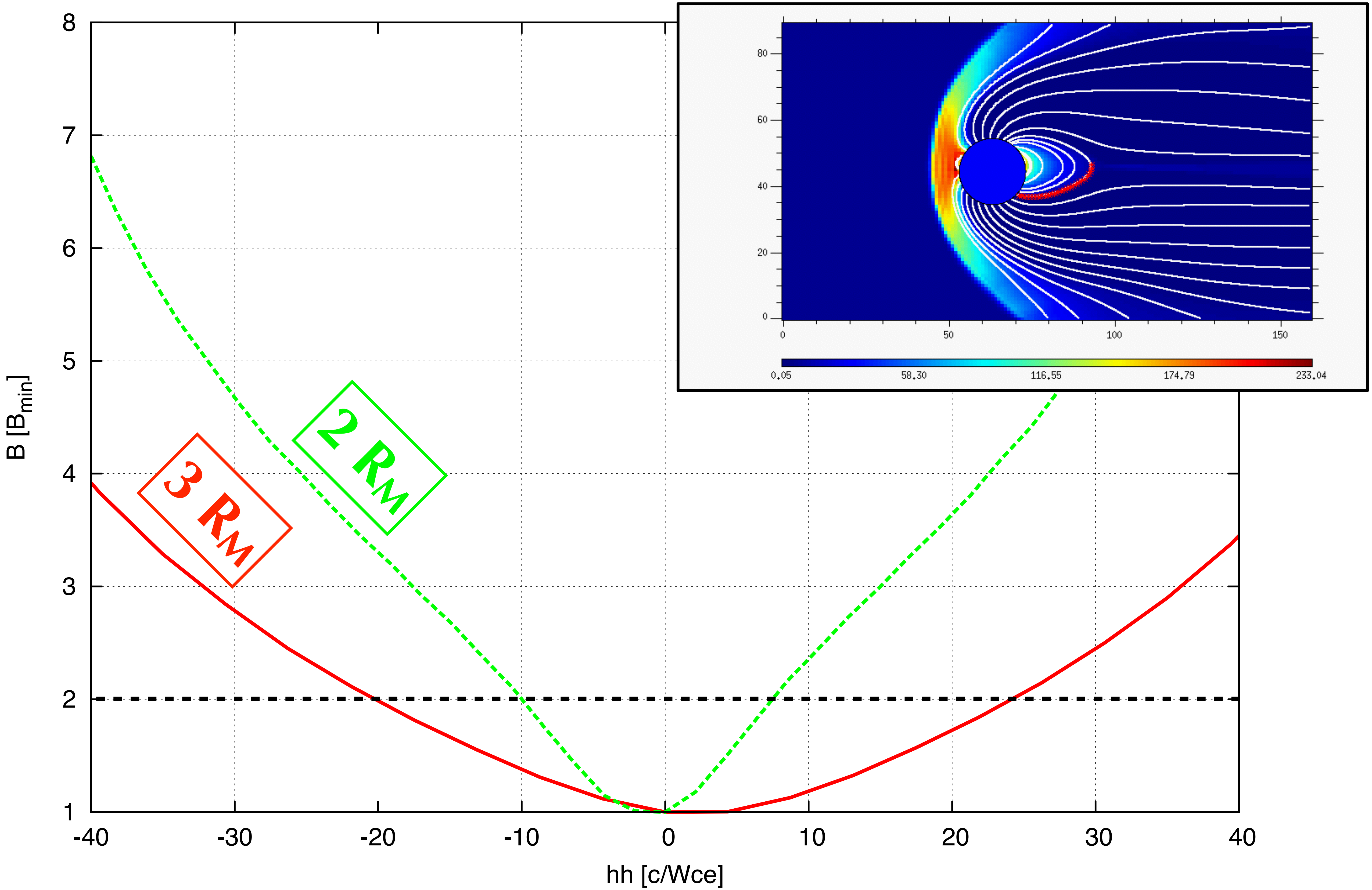
3. Simulation results of chorus generation in the magnetospheres of the Earth, Jupiter, and Mercury
   - Jupiter
   - Mercury

4. Summary

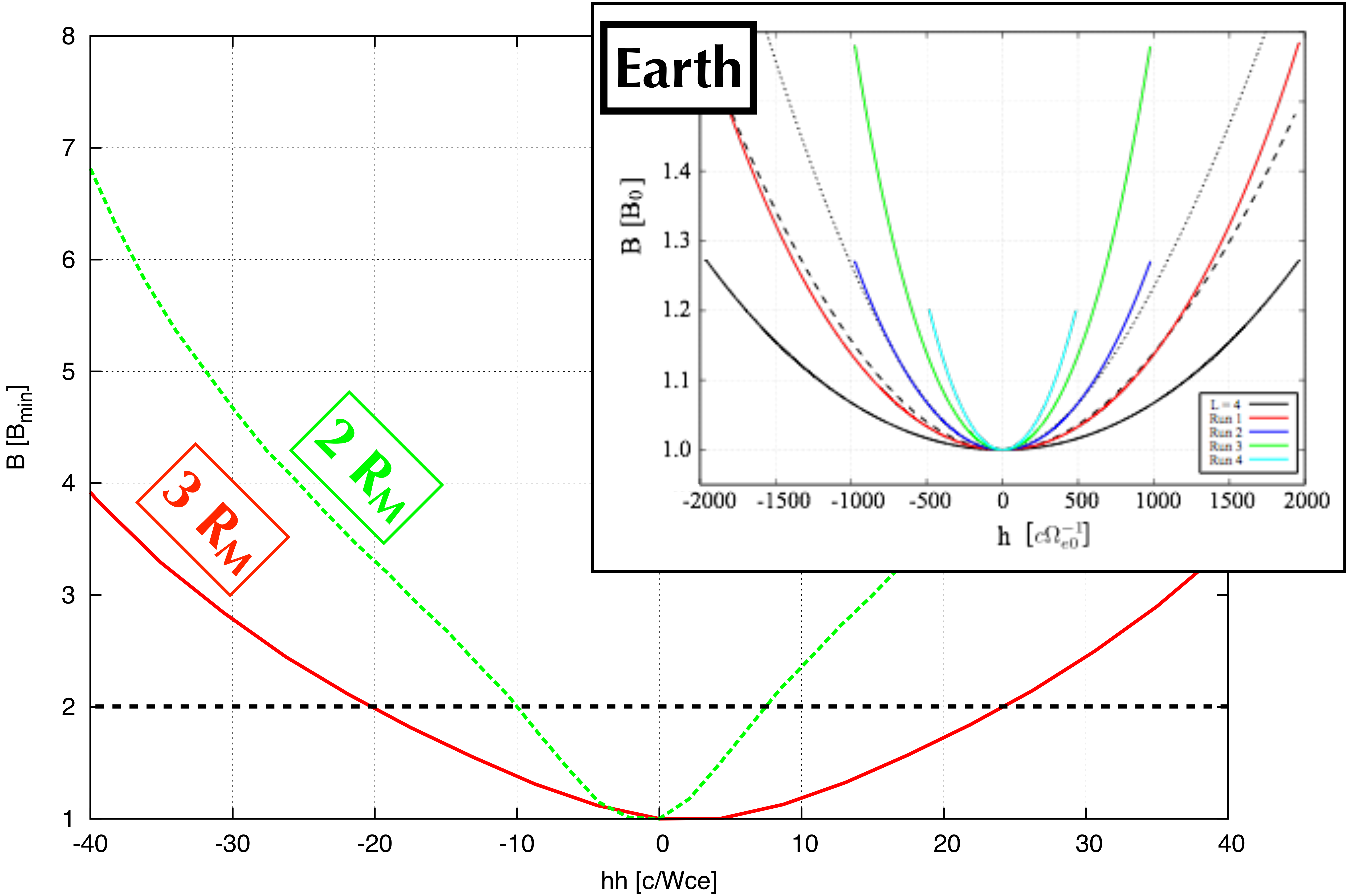
Mercury's magnetic field inhomogeneity: an example of MHD simulation results



Mercury's magnetic field inhomogeneity: an example of MHD simulation results

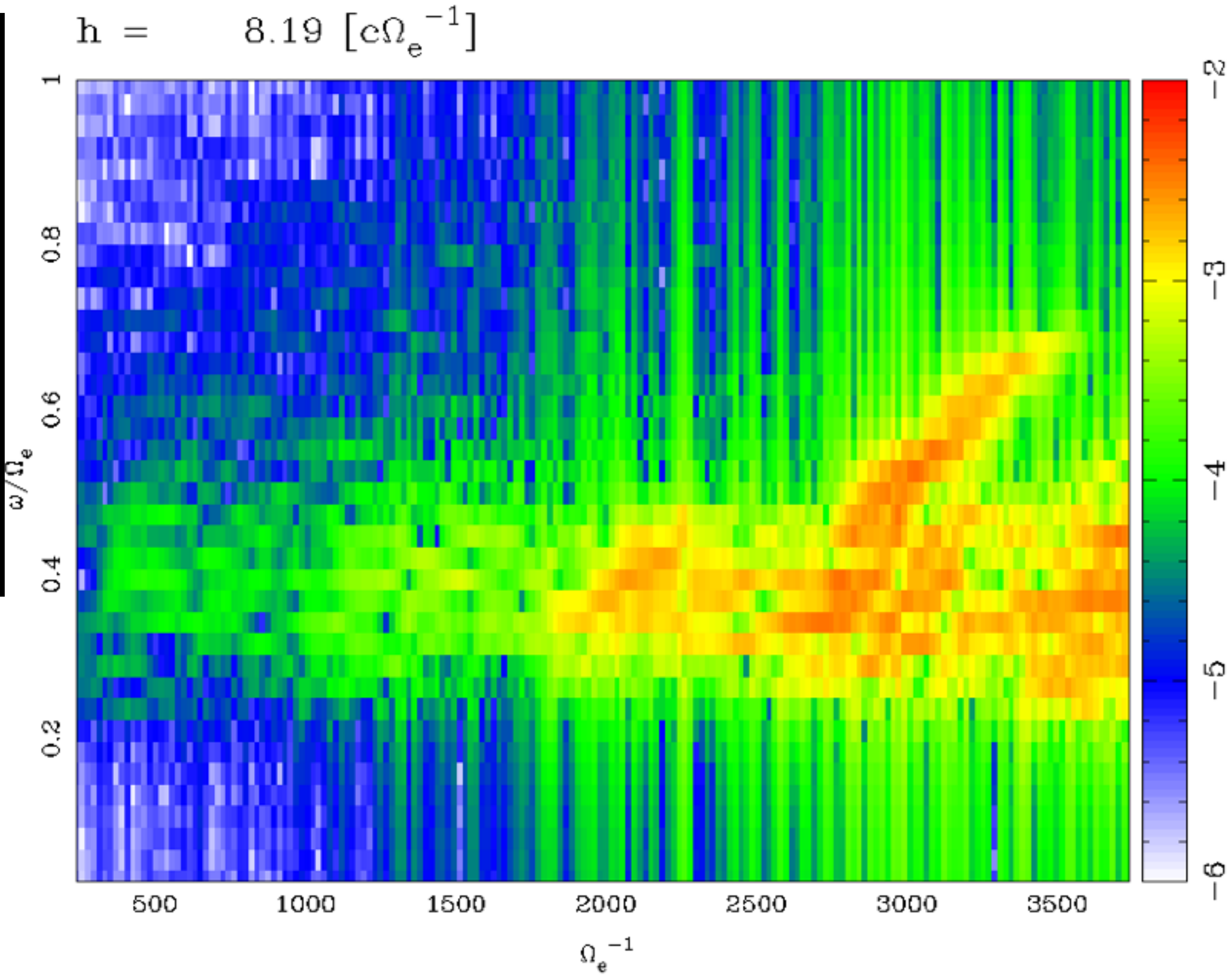


Mercury's magnetic field inhomogeneity: an example of MHD simulation results



Simulation result of chorus in the Mercury's magnetosphere configuration

2 $R_{M,eq}$
fc = 840 Hz
fp = 8.4 kHz
(~1 /cc)
$A_T = 9$
$N_h = 10^{-3} N_0$
20 keV



Summary

- We carried out *"cross-reference"* simulations by MHD and electron hybrid simulations for the study of whistler-mode chorus generation in the planetary inner magnetospheres
- By a series of electron hybrid simulations, we reproduced the enhancement of whistler-mode emissions in the Jovian magnetosphere
- We reproduced chorus in the Mercury's magnetospheric configuration by electron-hybrid code
- These properties should be evaluated by further numerical experiments by cross-reference simulations and by *in situ* measurements in the magnetospheres of the Earth (Arase, VAPs, …), Jupiter (Voyager, Galileo, JUICE), and Mercury (BepiColombo)