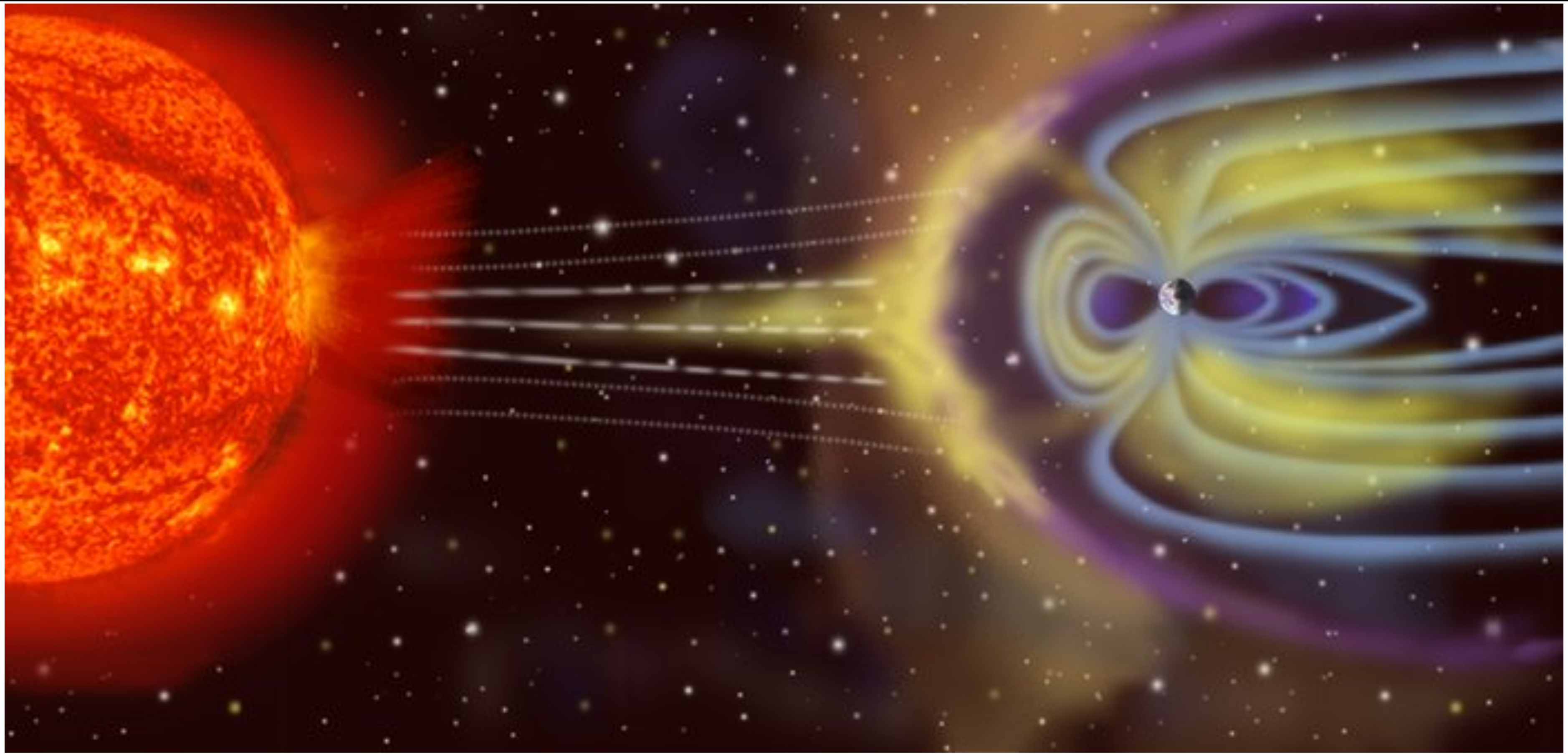
Hybrid simulation study of *high-frequency* H-band EMIC waves in the Earth's magnetosphere

Kyungguk Min, Chungnam National University

ISSS-15, 8 August 2024

EMIC Waves in the Magnetosphere



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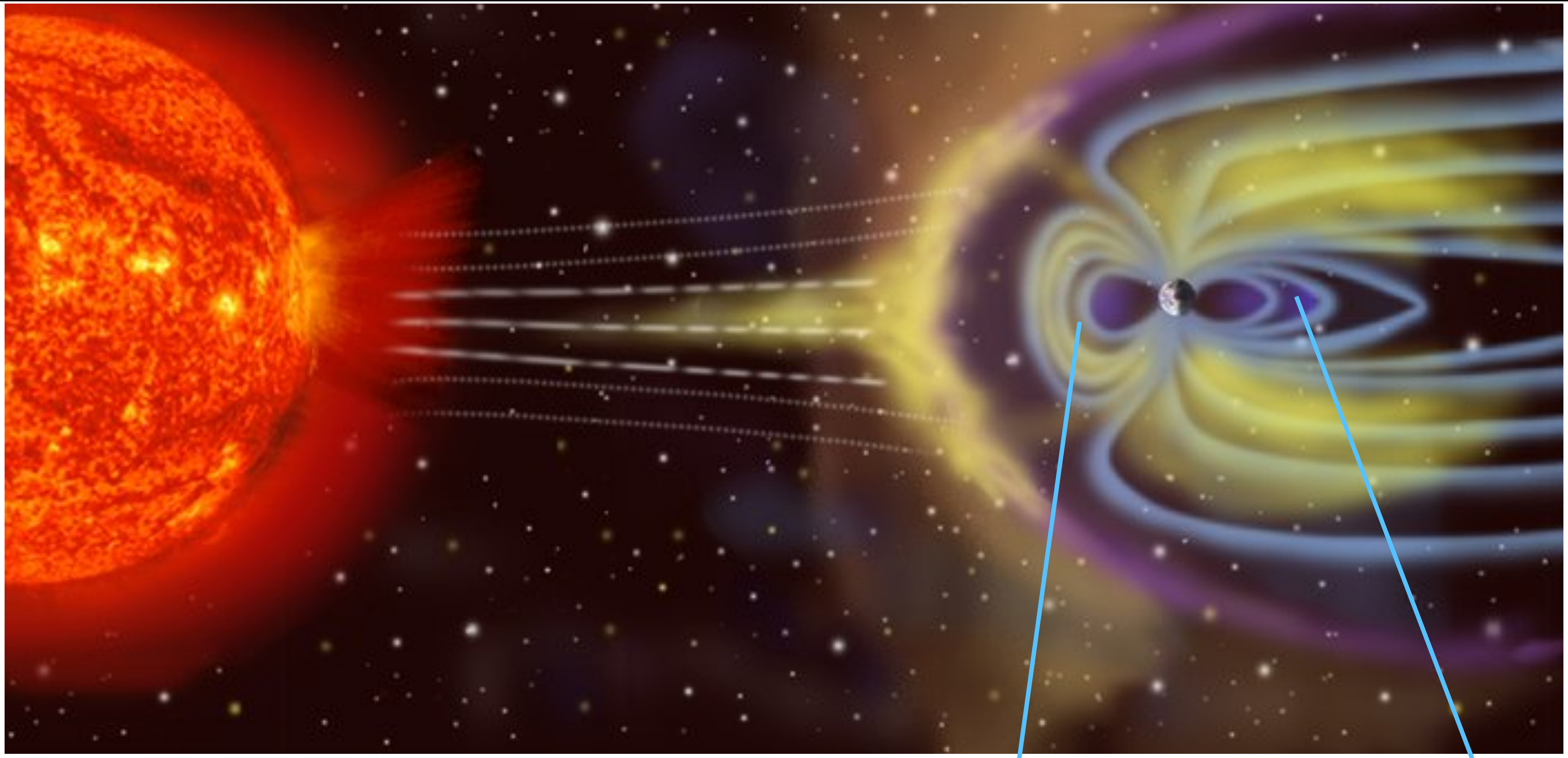
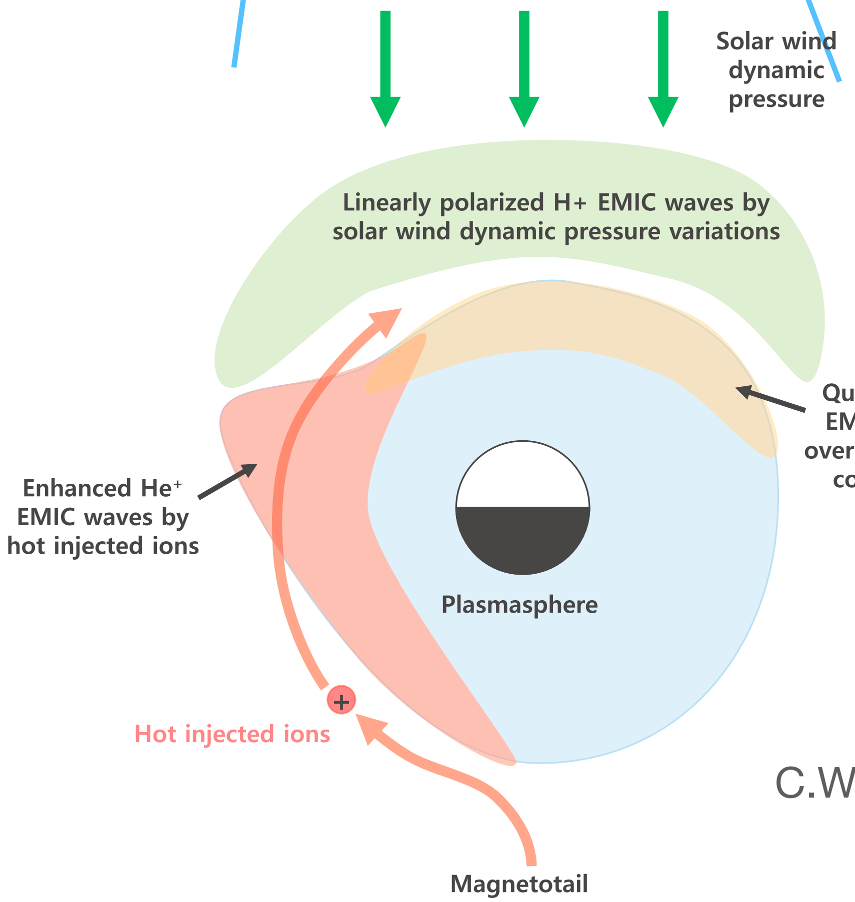
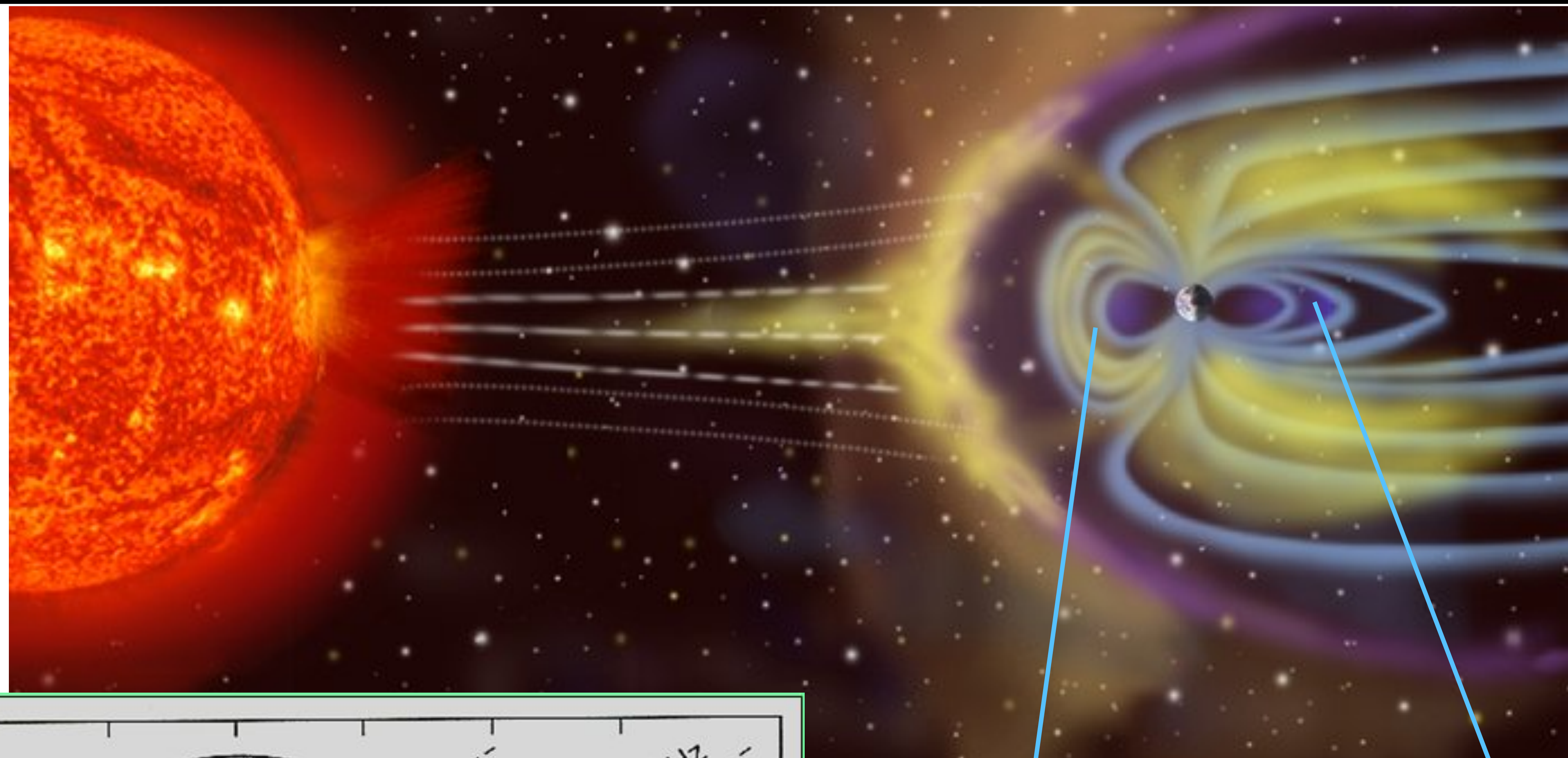
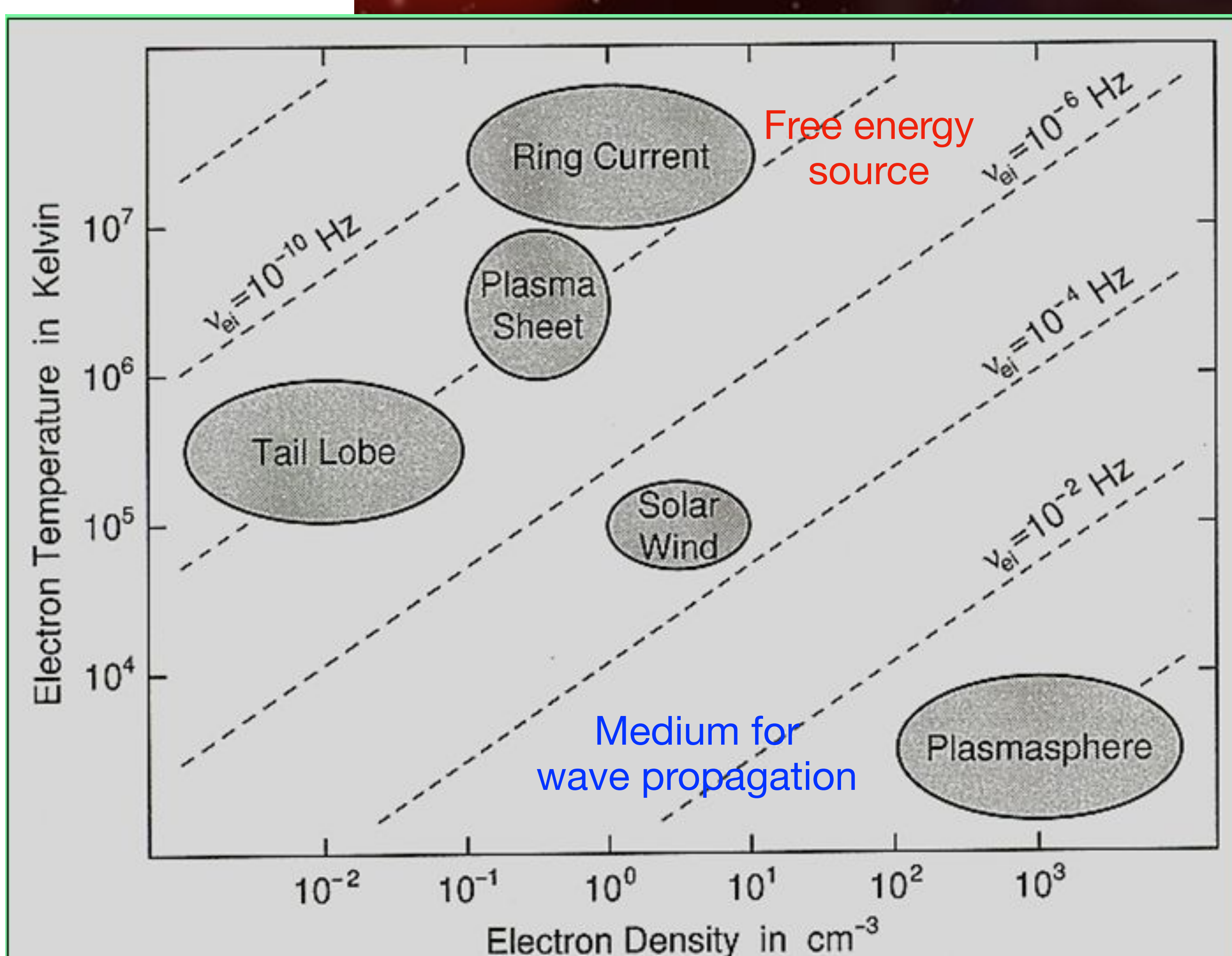


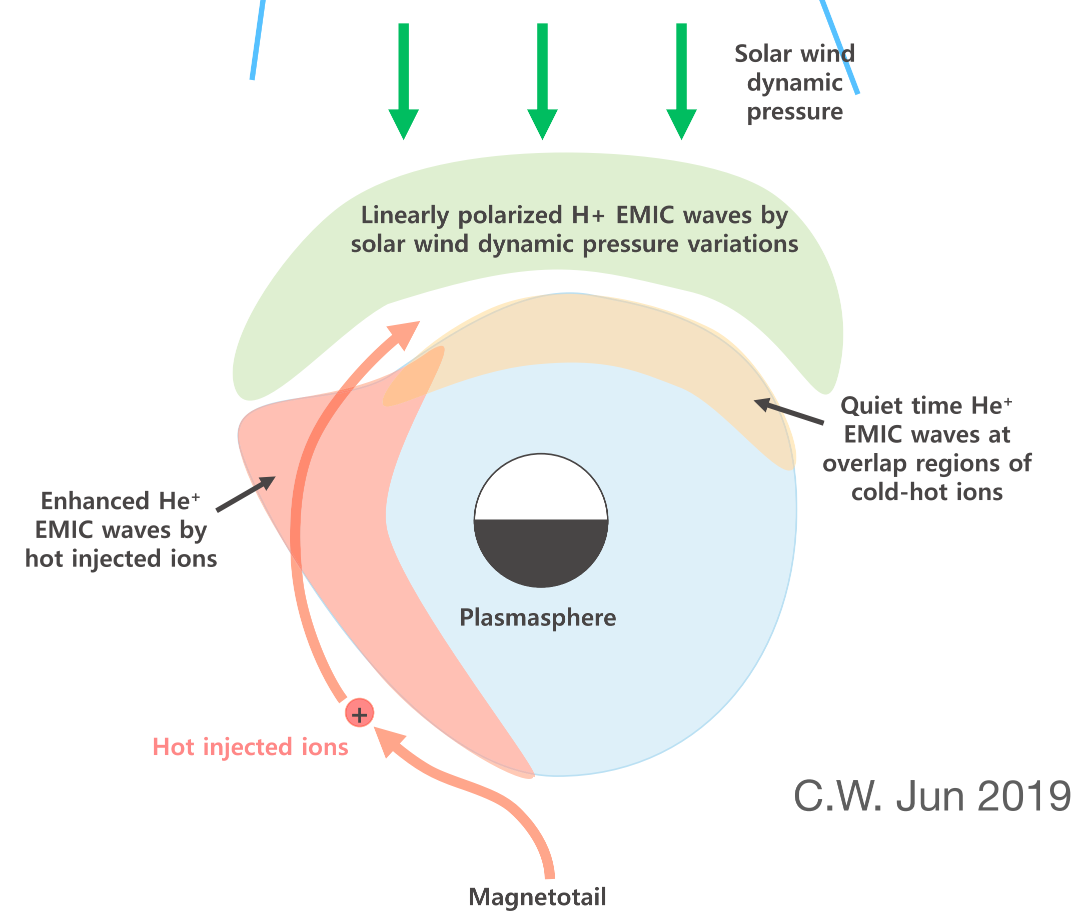


C.W. Jun 2019

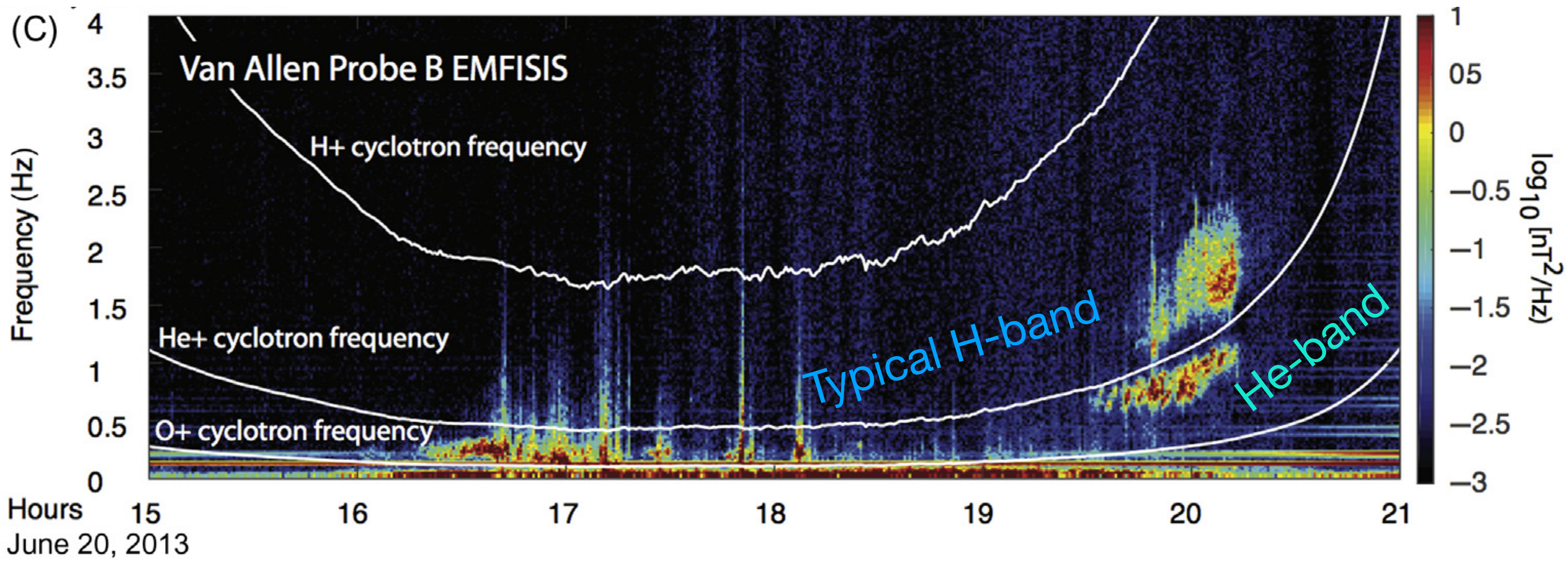
EMIC Waves in the Magnetosphere







Typical vs. *High-frequency* EMIC Waves



Blum+ 2019

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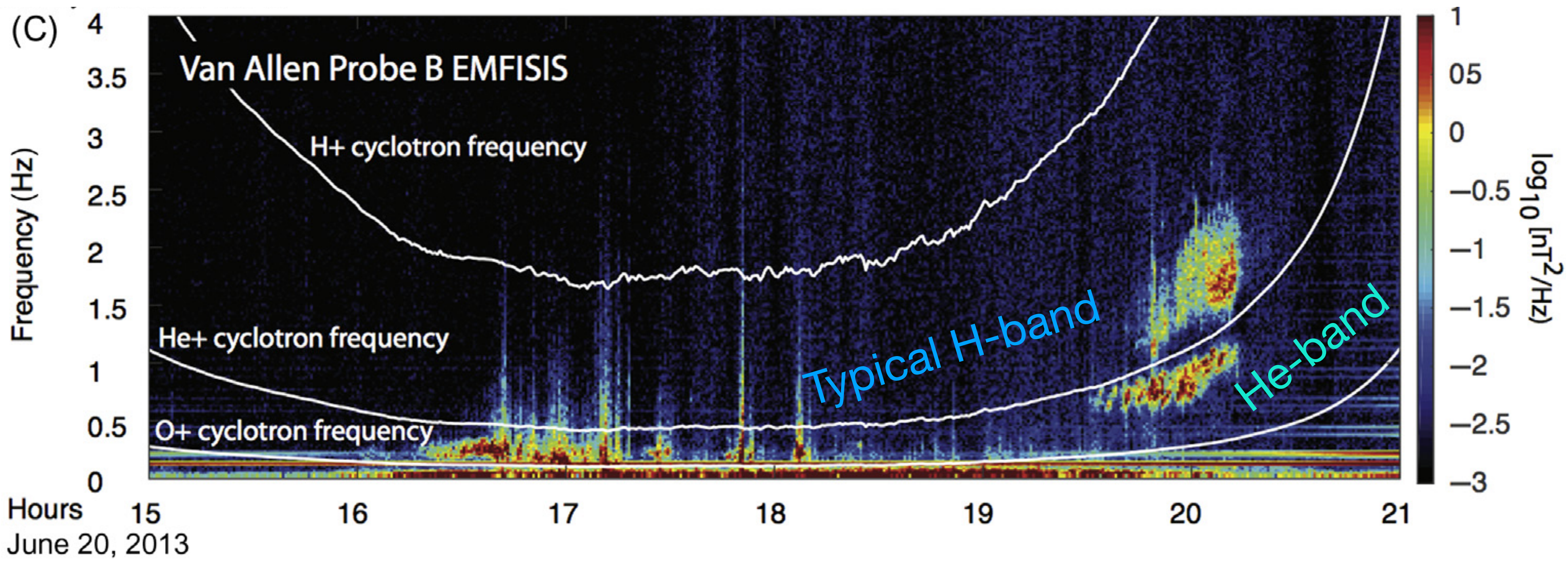
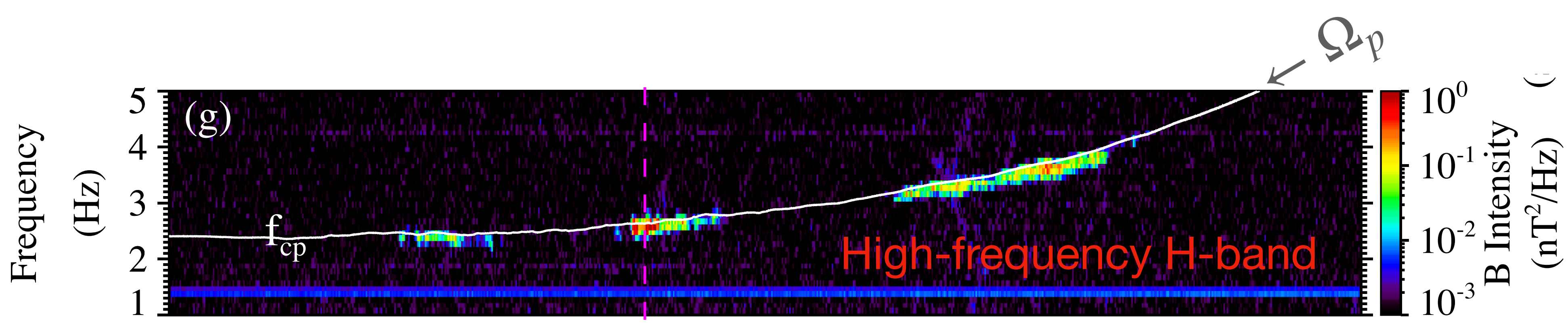


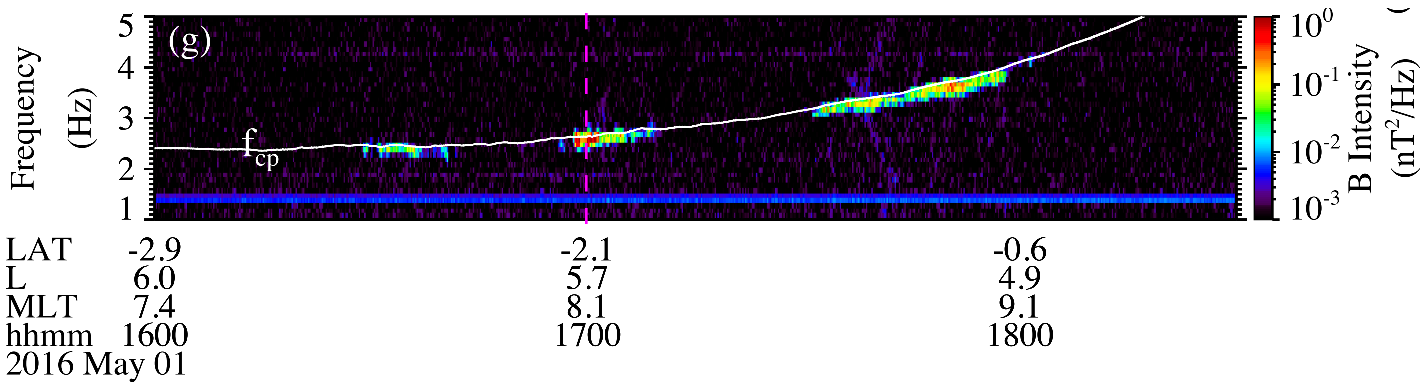
Blum+ 2019

S. Teng+ 2019

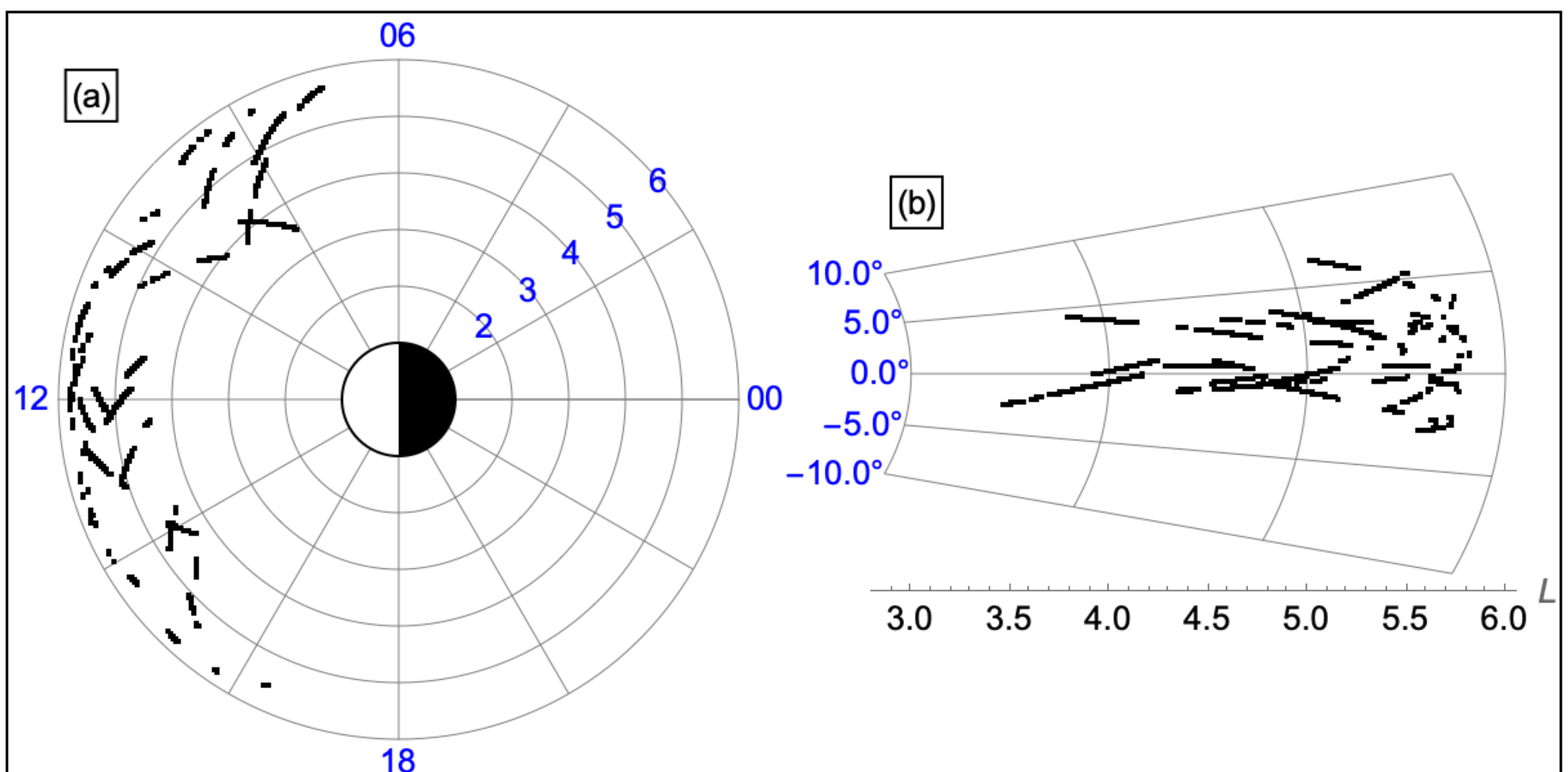


Van Allen Probes Observations

S. Teng+ 2019 (Van Allen Probes)



- ***Relatively rare, recently discovered***



Throughout dayside ***Within ±5° magnetic latitude***

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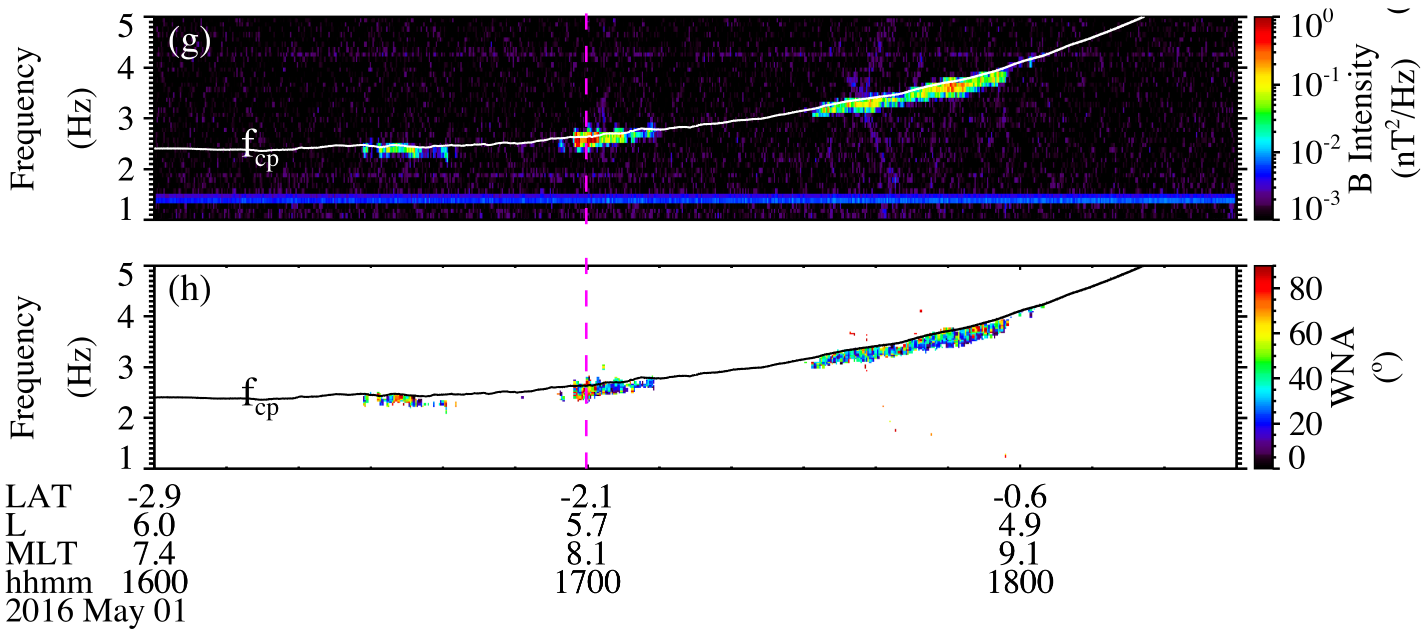
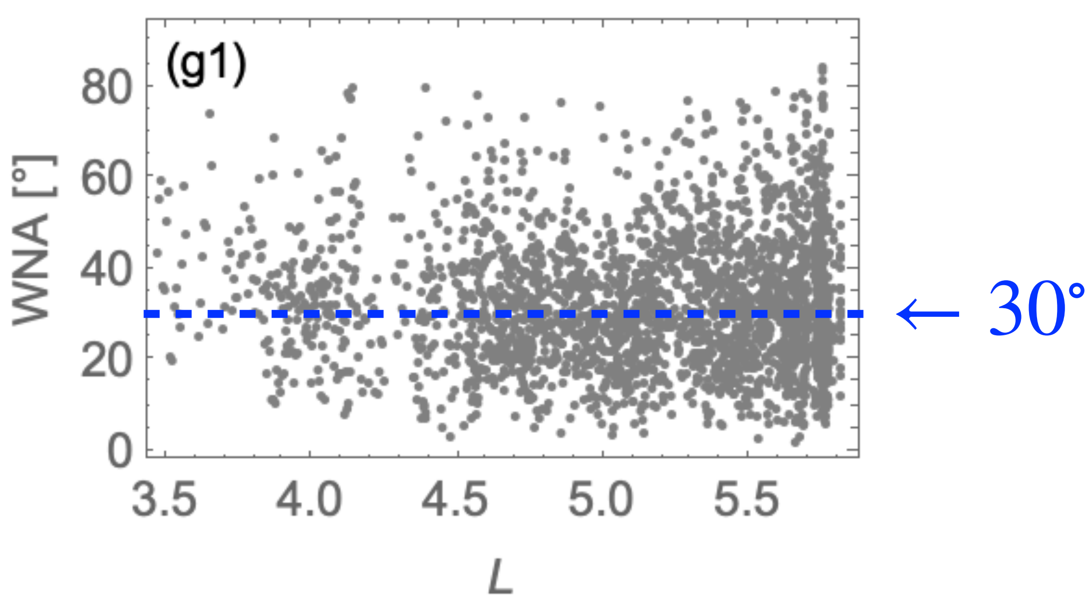
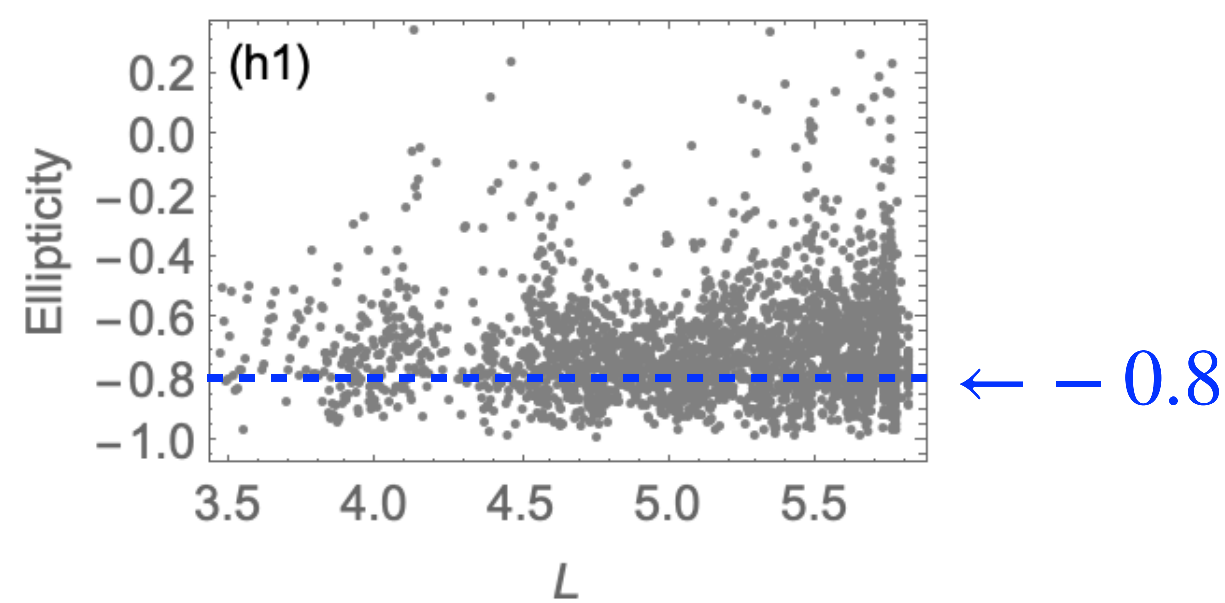


- ***Relatively rare, recently discovered***
- ***LH polarized, quasi-parallel propagation***





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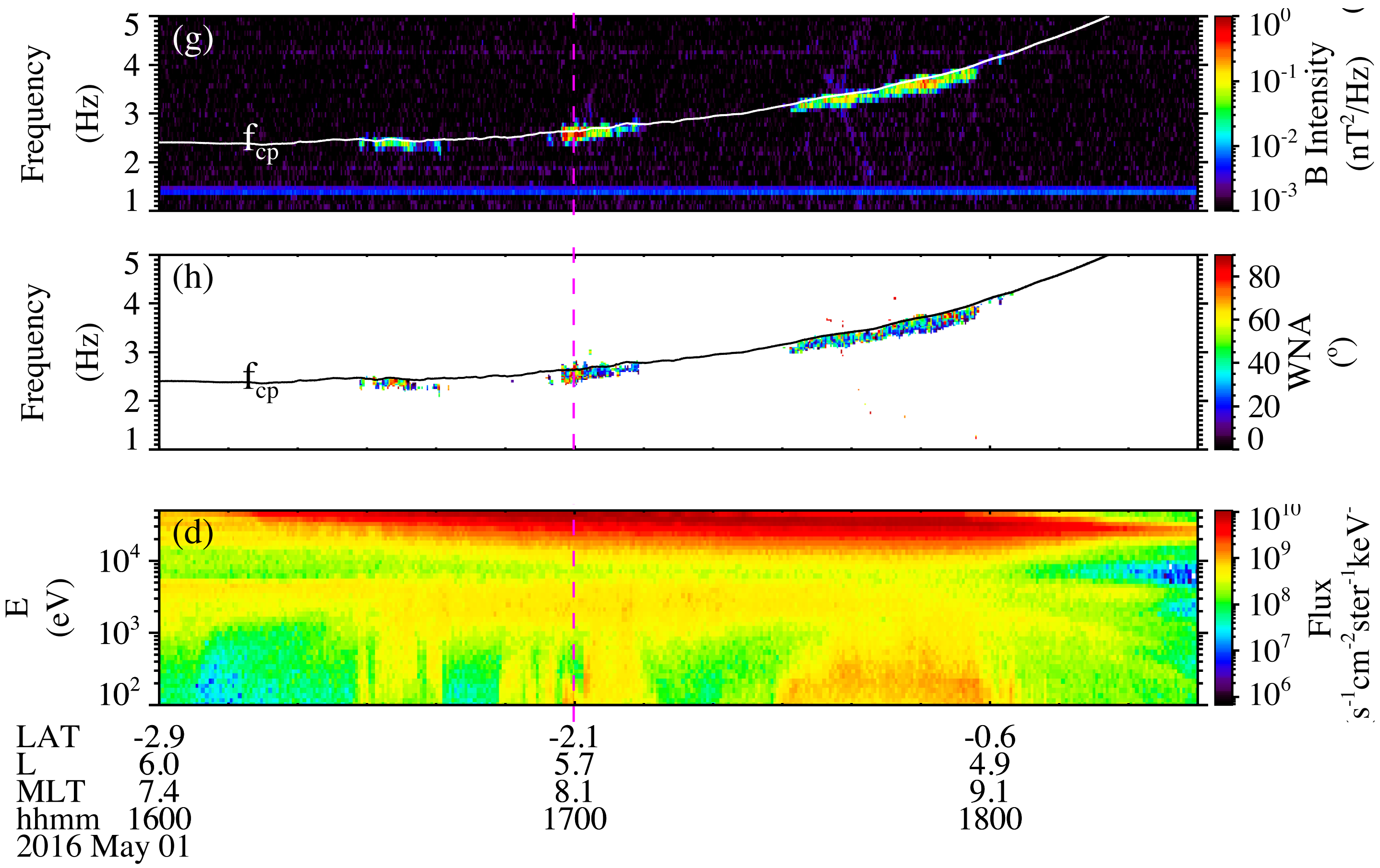

- ***Relatively rare, recently discovered***
- ***LH polarized, quasi-parallel propagation***
- ***Low ($\lesssim 500$ eV) energy proton enhancement***

Van Allen Probes Observations

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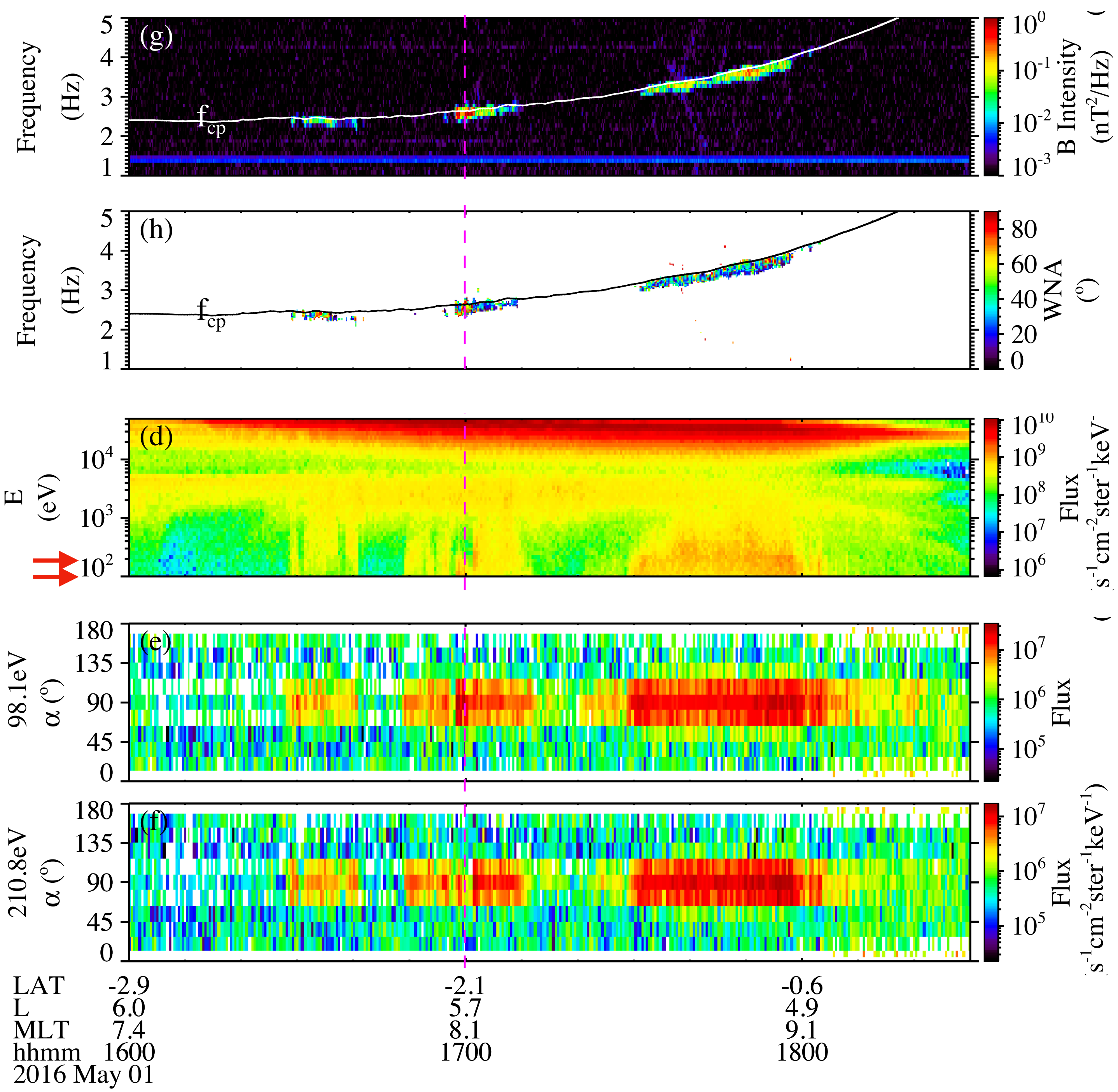
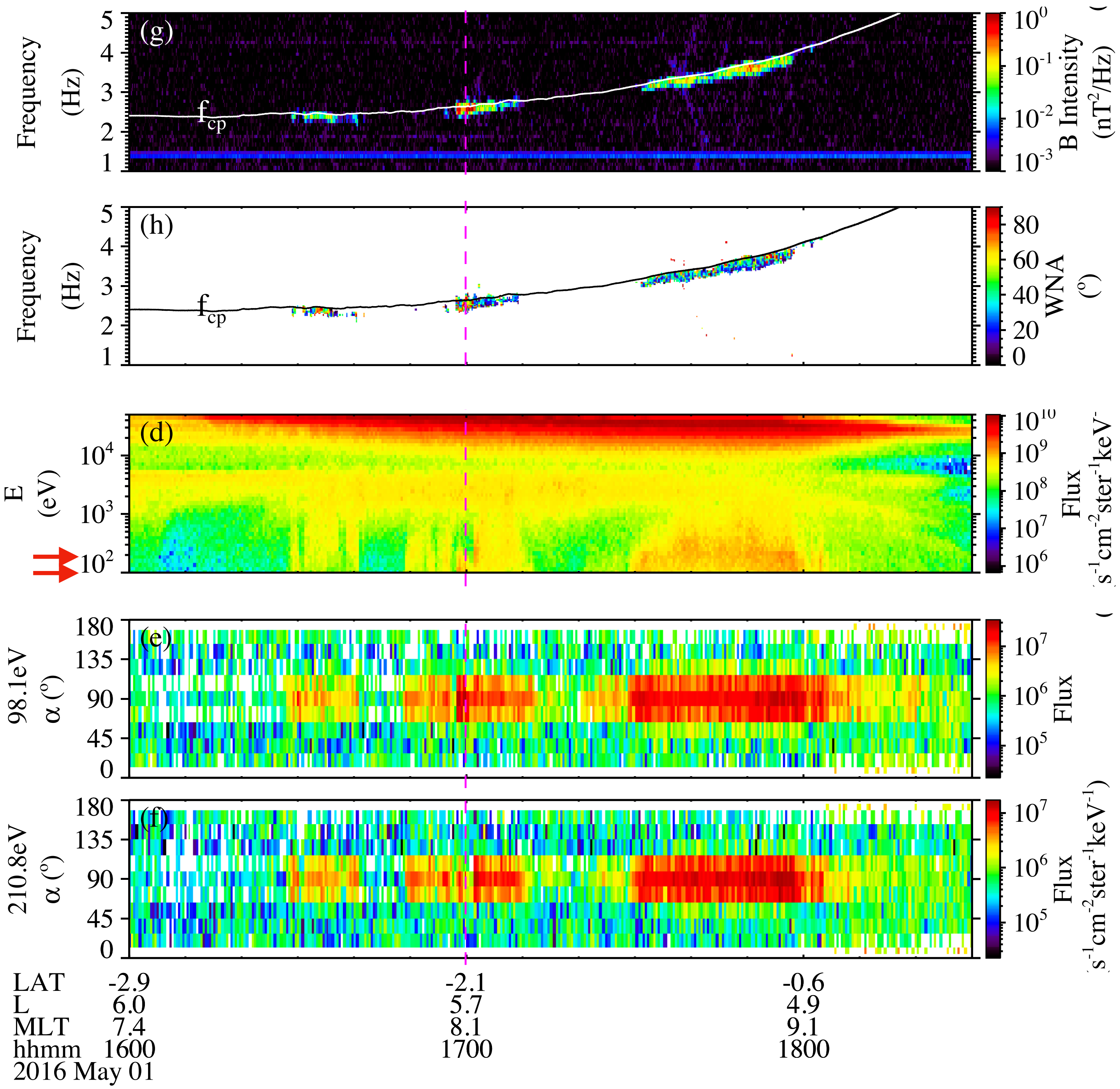


- ***Relatively rare, recently discovered***
- ***LH polarized, quasi-parallel propagation***
- ***Low ($\lesssim 500$ eV) energy proton enhancement***
- ***90°-peaked, very anisotropic low-energy proton pitch-angle distribution***

Van Allen Probes Observations

S. Teng+ 2019 (Van Allen Probes)



- ***Relatively rare, recently discovered***
- ***LH polarized, quasi-parallel propagation***
- ***Low ($\lesssim 500$ eV) energy***

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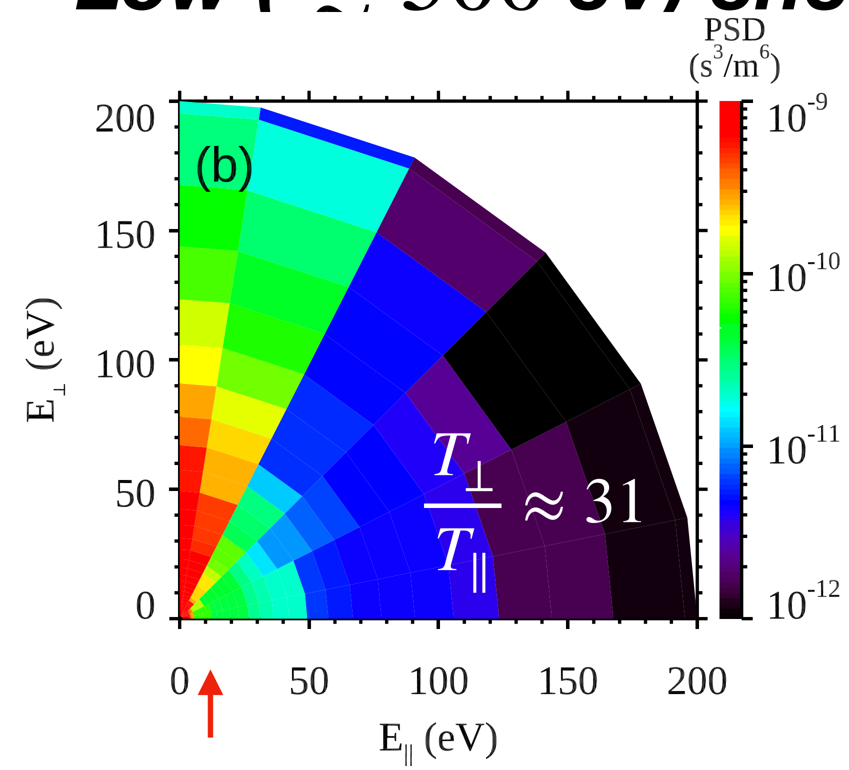
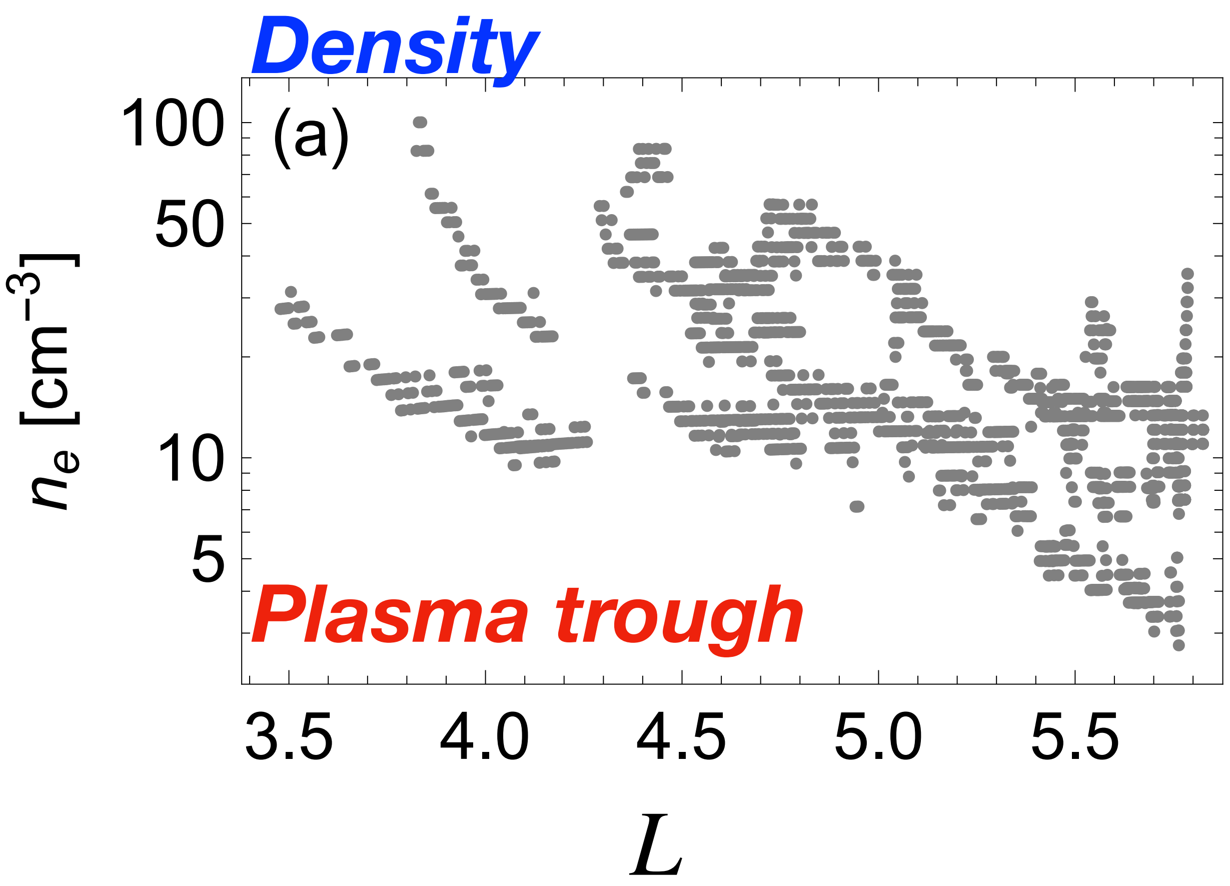
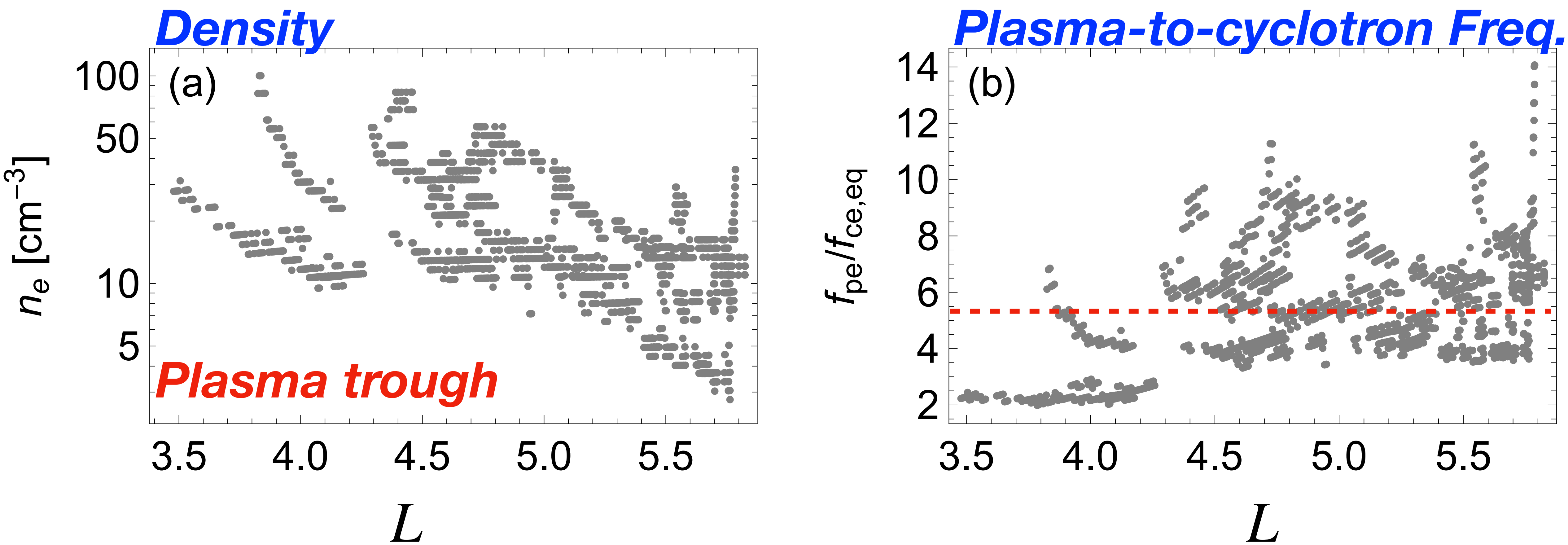


Resonant Energy

Van Allen Probes Observations



Van Allen Probes Observations



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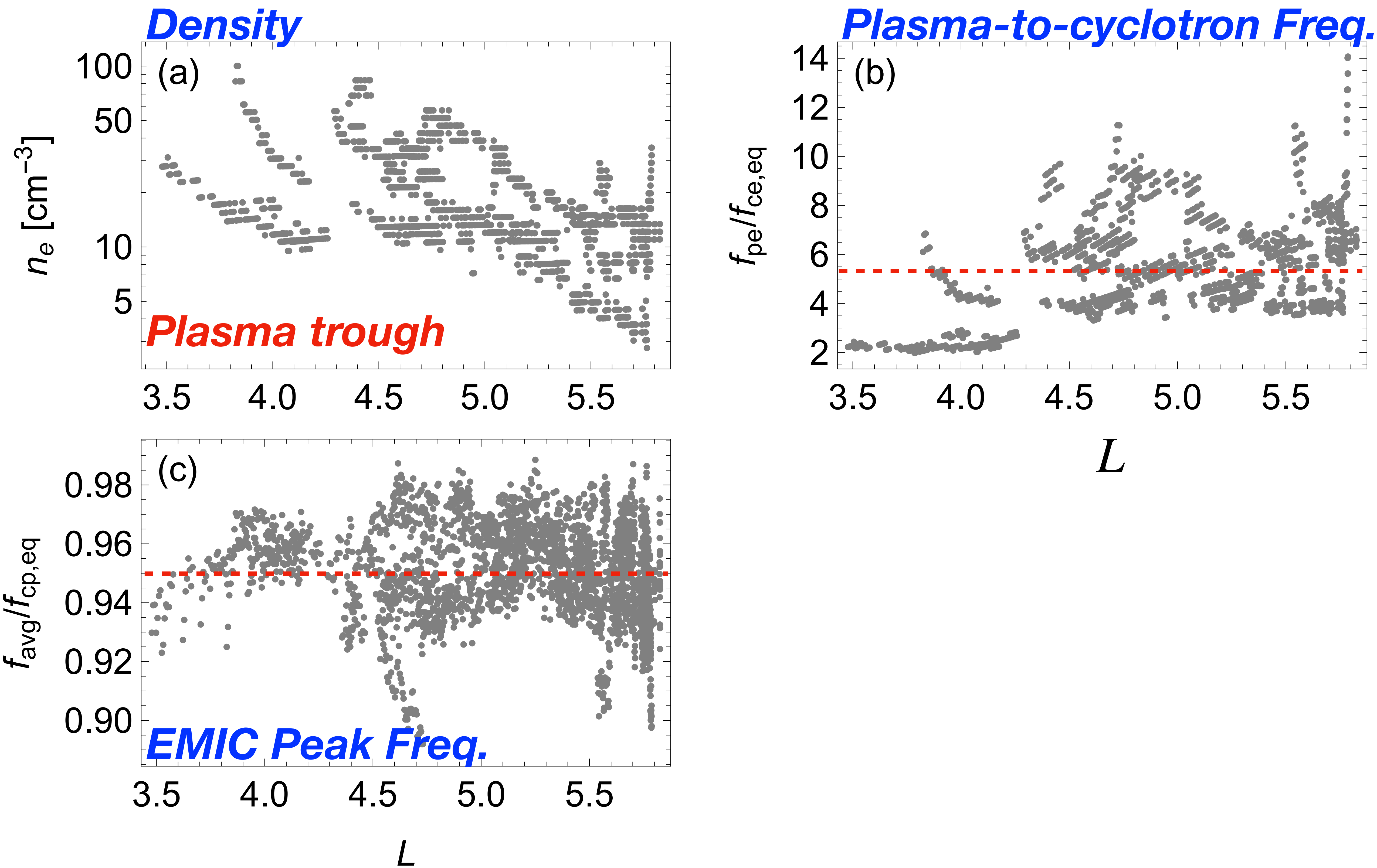

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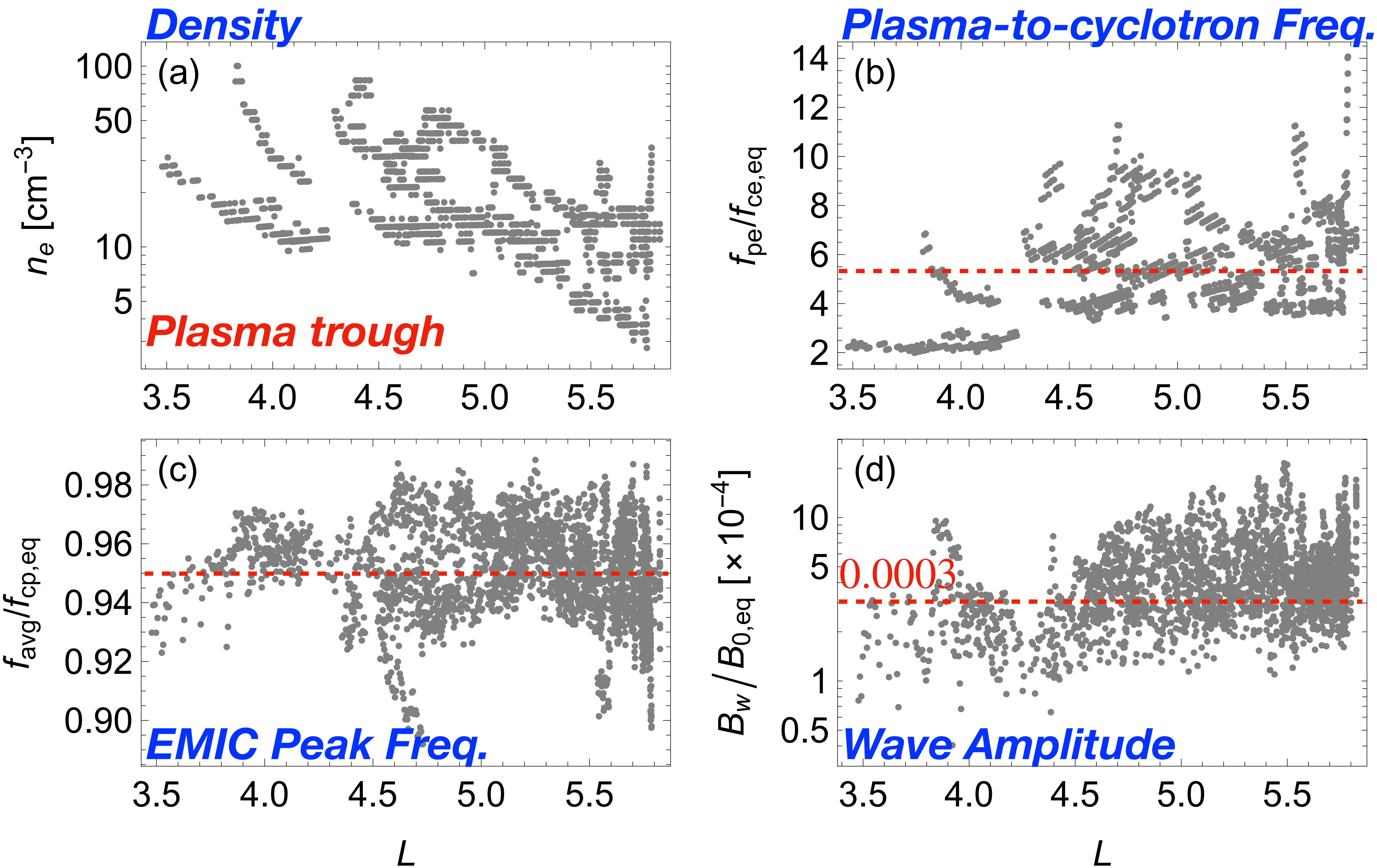
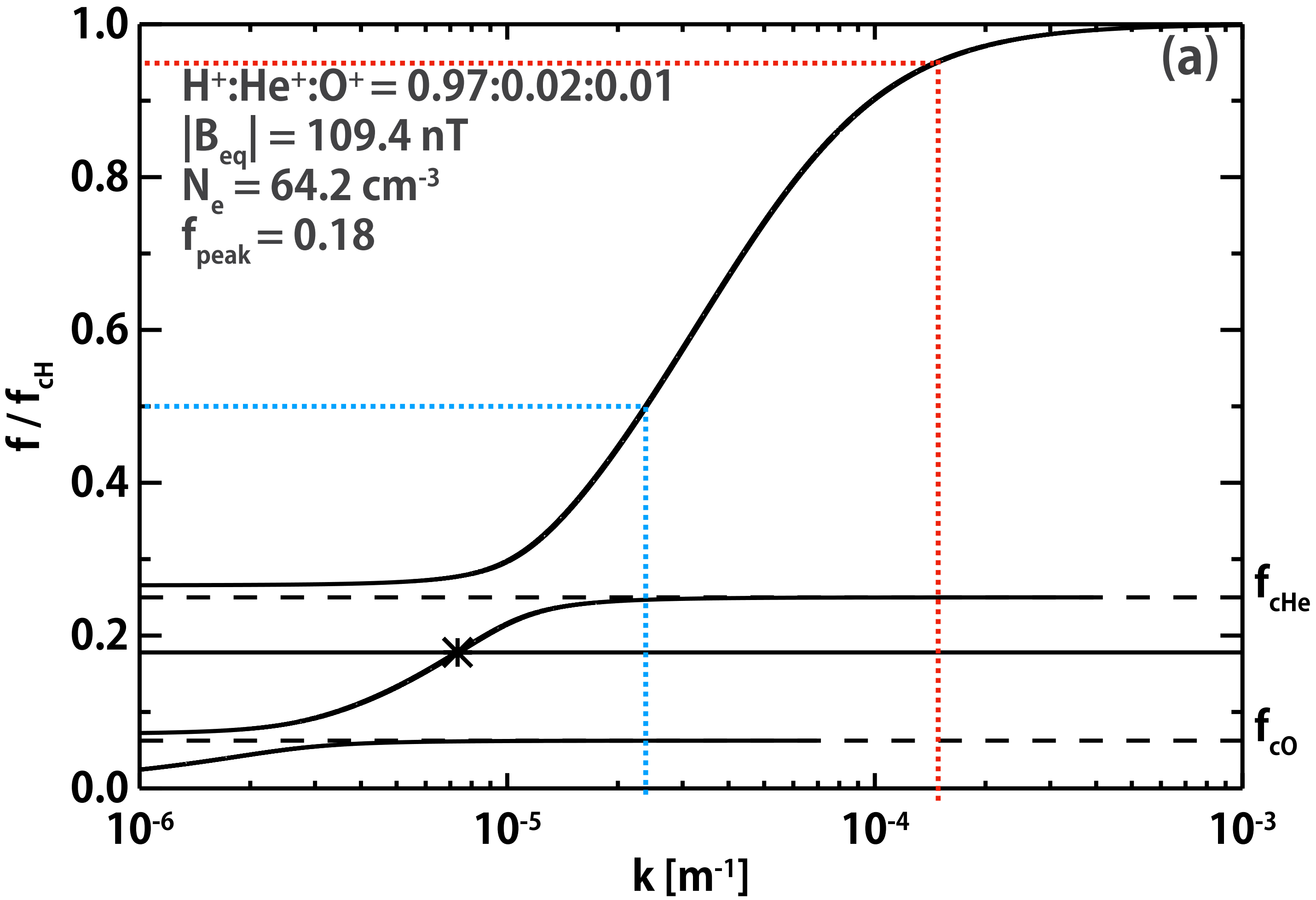


Free Energy Source of HFEMIC

$$\text{Growth Rate} \sim \omega_p^2 \left(A_p + \frac{\omega_r}{\omega_r - \Omega_p} \right) \sqrt{\pi} x_p e^{-x_p^2}$$

(Kennel & Petschek, 1966)

C. W. Jun+ 2023 (assuming parallel propagation)



- ***Anisotropy threshold***

$$A \equiv \frac{T_\perp}{T_\parallel} - 1 \gtrsim \frac{\omega}{\Omega_p - \omega}$$

- ***Typical H-band***:

$$A \gtrsim \frac{0.5}{1 - 0.5} = 1$$

- ***High-frequency EMIC***:

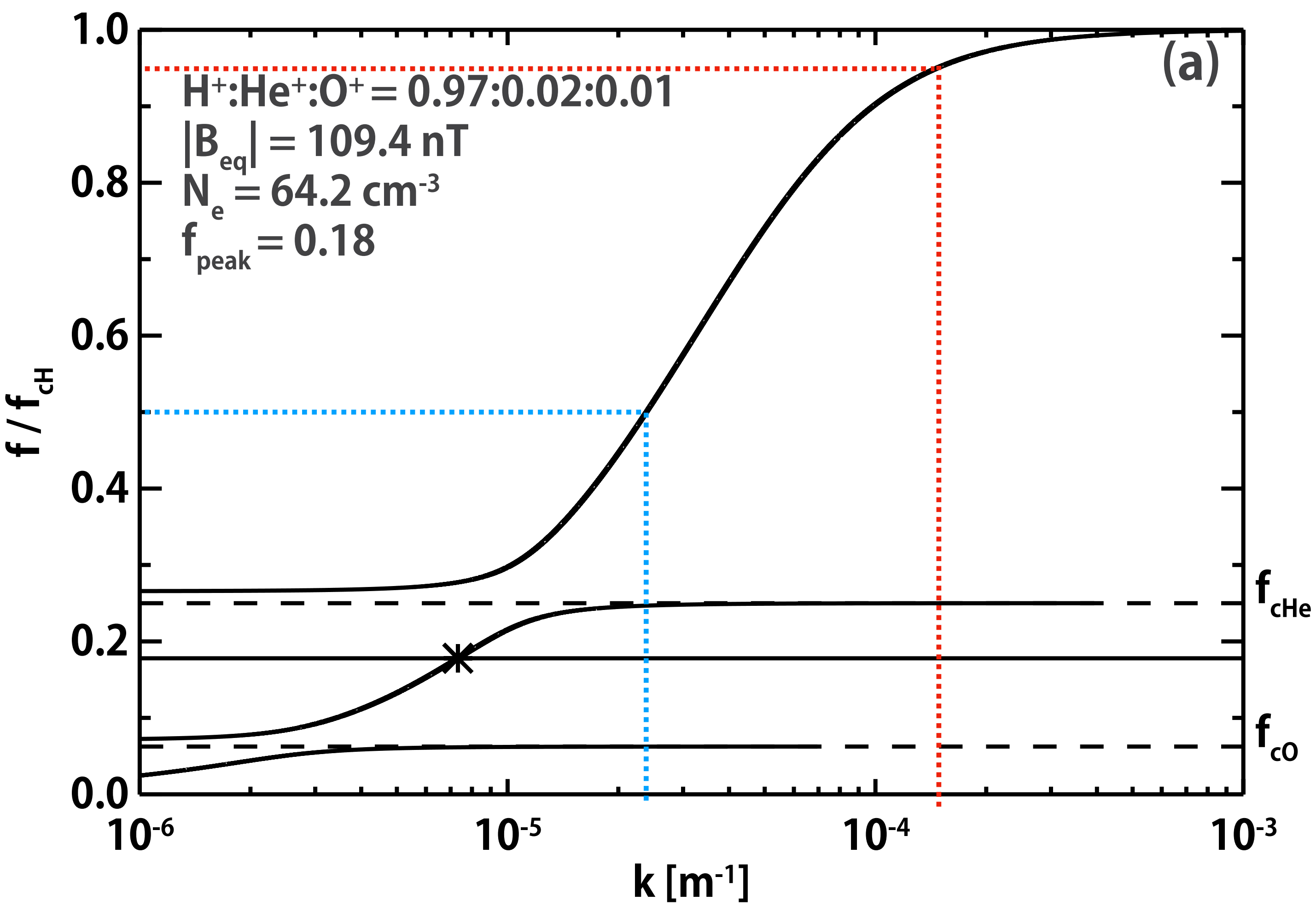
$$A \gtrsim \frac{0.95}{1 - 0.95} = 19$$

- ***The HFEMIC instability requires a large temperature anisotropy.***

Free Energy Source of HFEMIC

Growth Rate ~ $\omega_p^2 \left(A_p + \frac{\omega_r}{\omega_r - \Omega_p} \right) \sqrt{\pi} x_p e^{-x_p^2}$ (Kennel & Petschek, 1966)

C. W. Jun+ 2023 (assuming parallel propagation)



- ***Average resonant energy***

$$\frac{nk_B T_\parallel}{B_0^2/2\mu_0} \propto \frac{v_\parallel^2}{v_A^2} = \frac{(\omega - \Omega_p)^2}{k_\parallel^2 v_A^2}$$

- ***Typical H-band***:

$$\beta_\parallel \sim \frac{(0.5-1)^2}{0.7^2} \approx 0.5$$

- ***High-frequency EMIC***:

$$\beta_\parallel \sim \frac{(0.95-1)^2}{4^2} \approx 0.00016$$

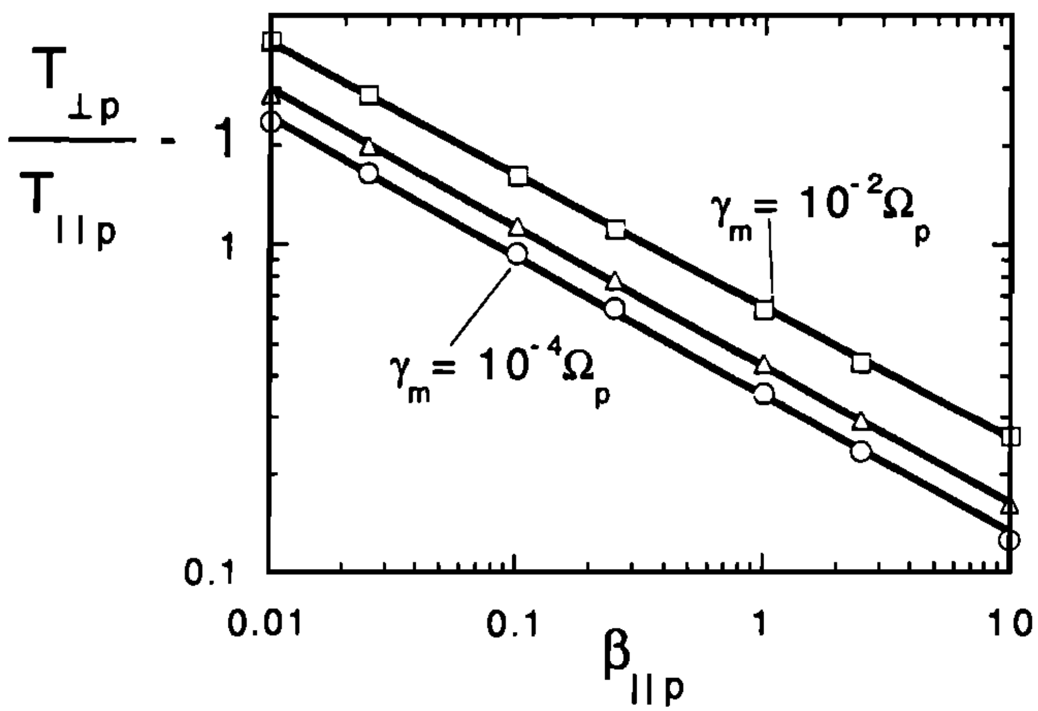
- ***The HFEMIC instability requires very small proton beta, equivalent to $T_\parallel$ ~ 1-10 eV in the magnetosphere.***

Theoretical Anisotropy Threshold

Gary+ 1994

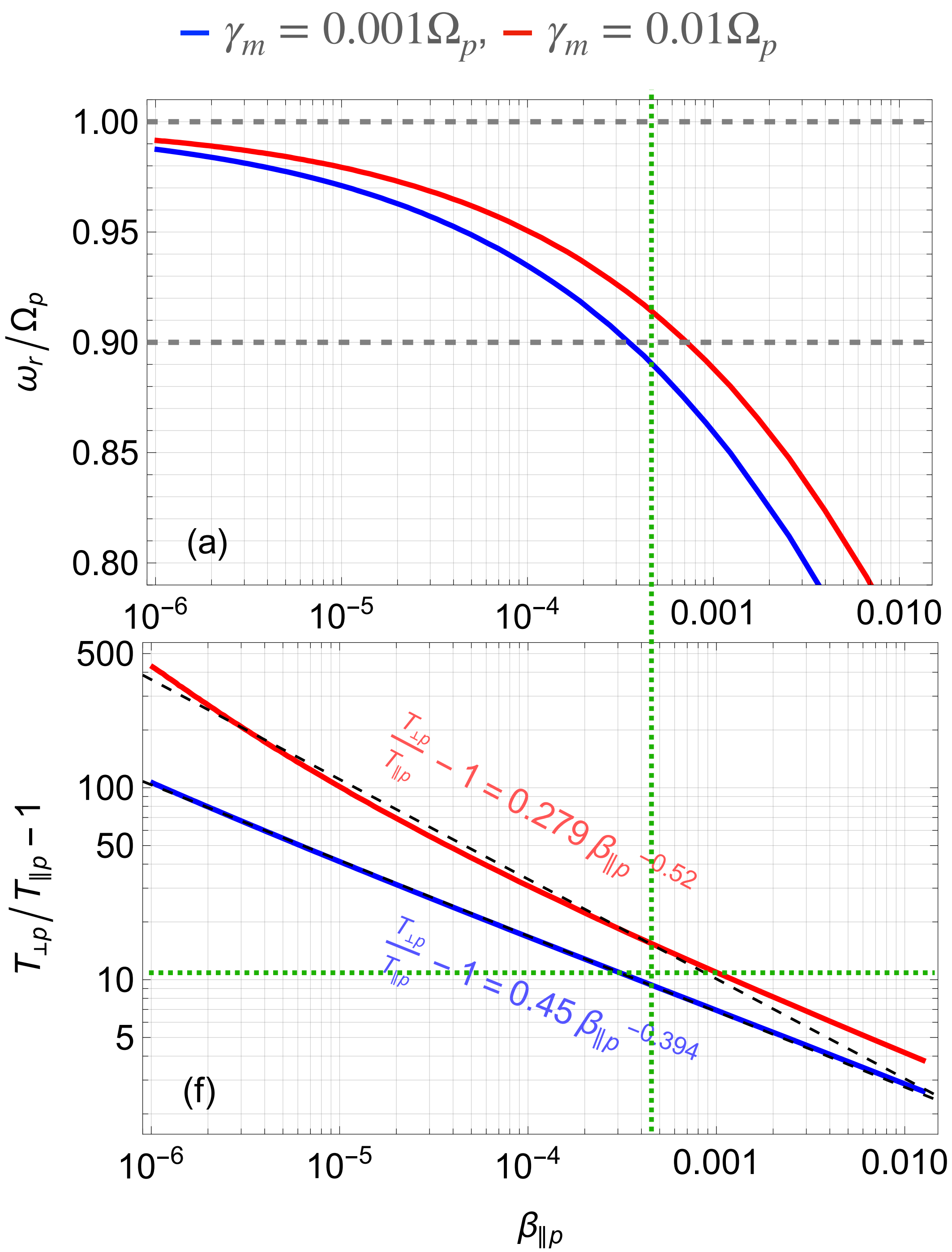
$$\frac{T_{\perp p}}{T_{\parallel p}} - 1 = \frac{0.43}{\beta_{\parallel p}{}^{0.42}} \qquad (\gamma_m = 10^{-3}\Omega_p)$$

$$\frac{T_{\perp p}}{T_{\parallel p}} - 1 = \frac{0.65}{\beta_{\parallel p}{}^{0.40}} \qquad (\gamma_m = 10^{-2}\Omega_p)$$



Typical EMIC wave

Theoretical Anisotropy Threshold



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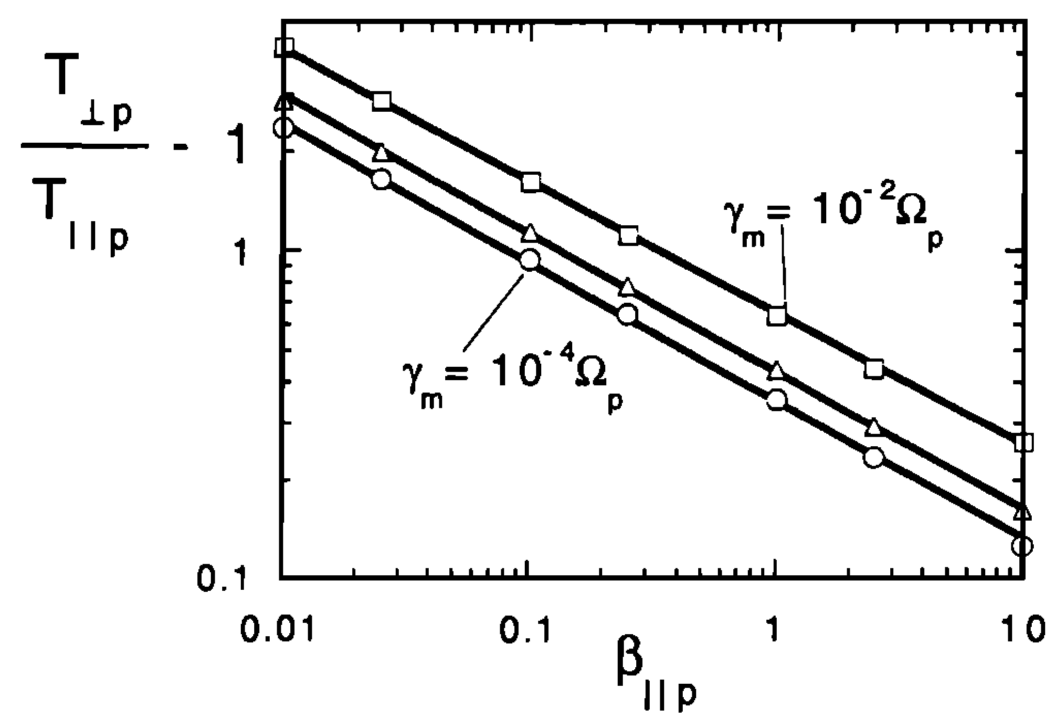
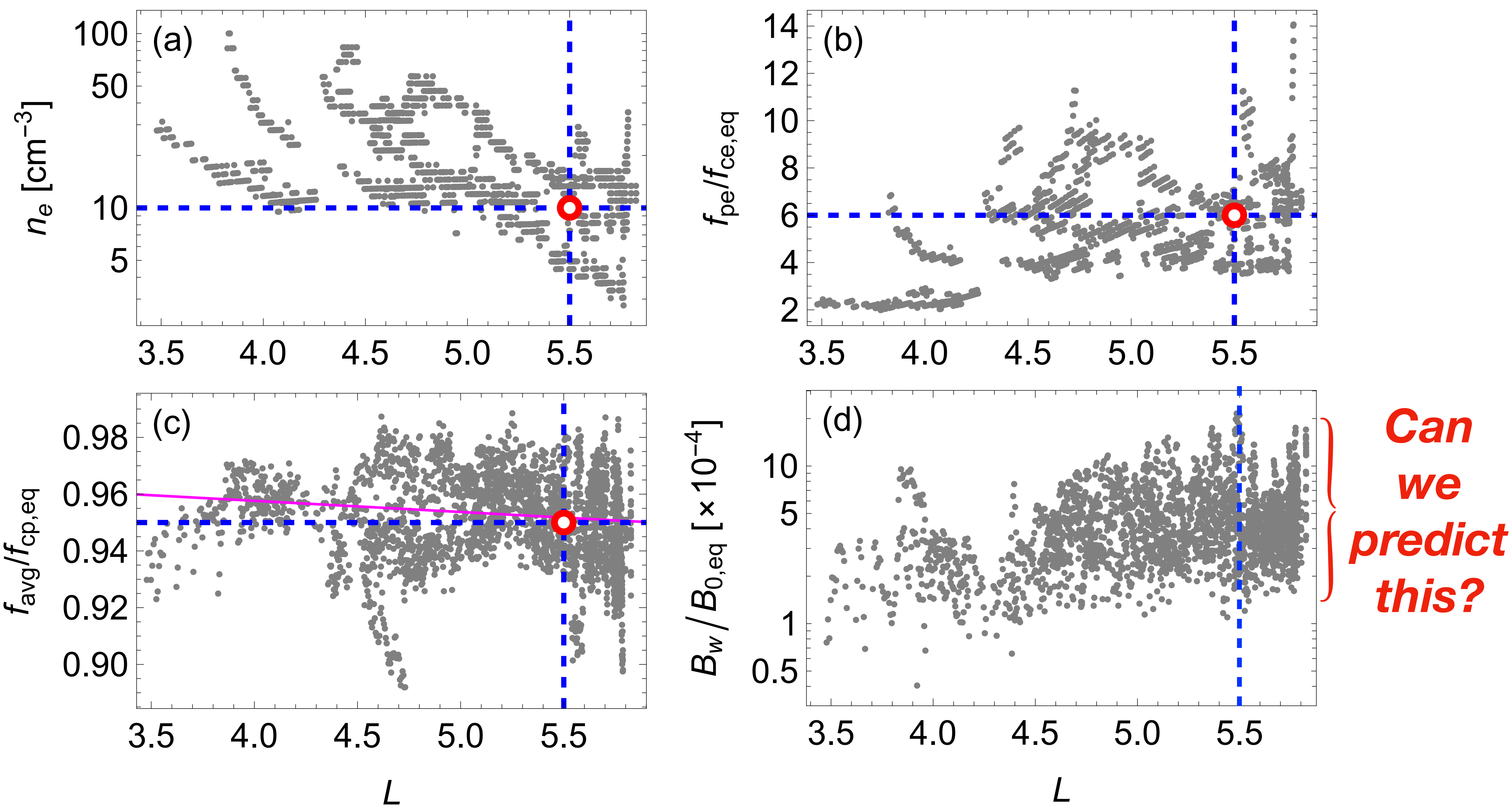


High-frequency EMIC wave

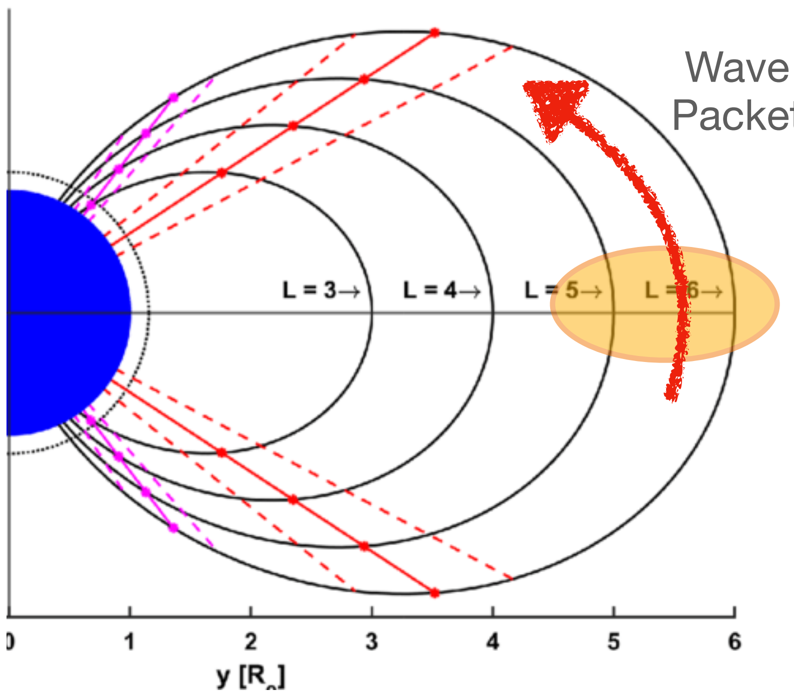
Typical EMIC wave

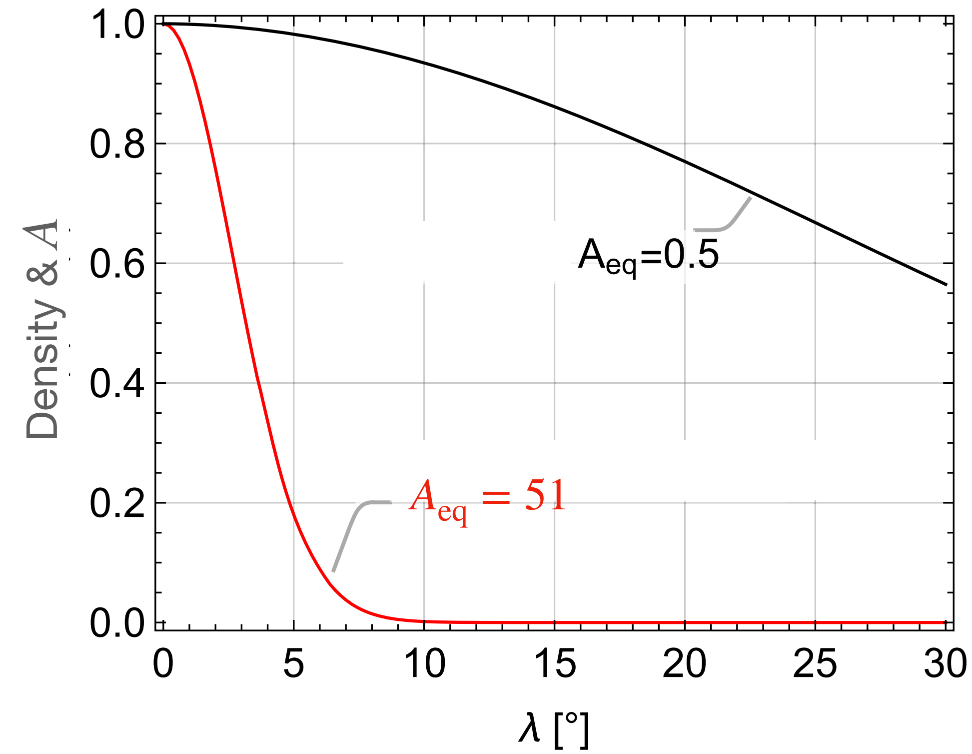
Can HF-EMIC waves by ion cyclotron instability grow in a realistic environment?



Q. Given a plasma condition at L = 5.5 with a reasonable proton distribution that gives rise to wave growth at f = 0.95 fcp according to theory, can we prove wave growth with saturation amplitude commensurate with the observed wave amplitudes?

Earth's Dipole Magnetic Field



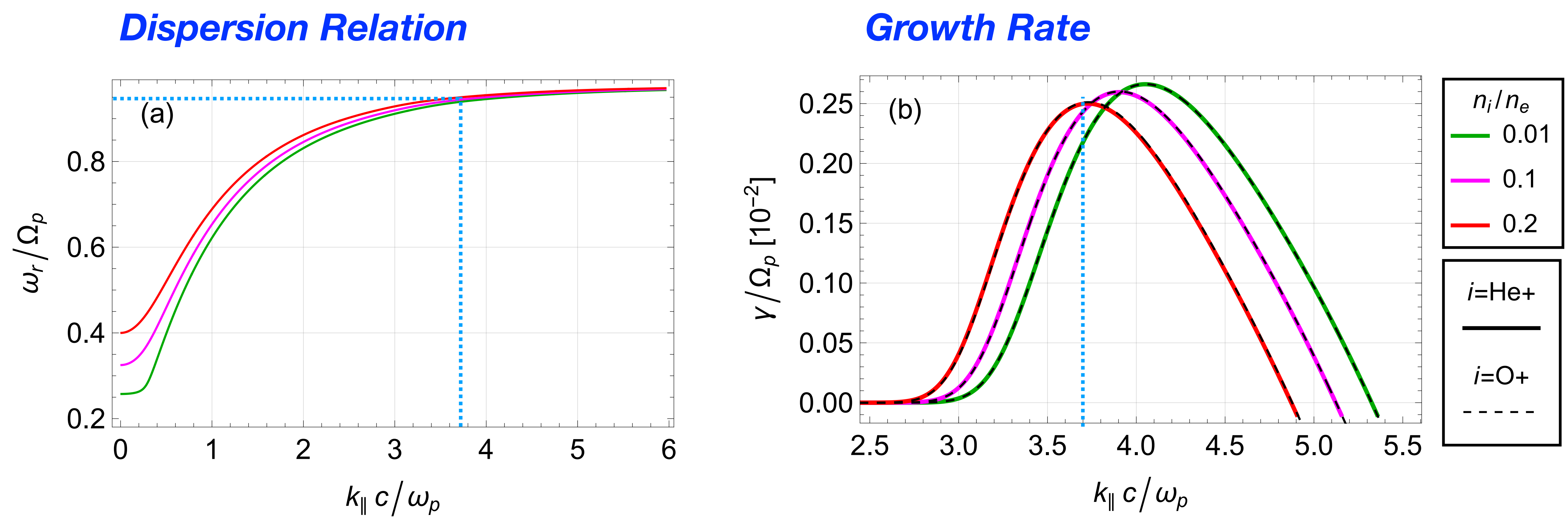


Liouville's theorem:

$$\textbf{density \& anisotropy} \propto \left[\left(1 - \frac{B_{0,\mathrm{eq}}}{B_0(\lambda)} \right) (A_{\mathrm{eq}} + 1) + \frac{B_{0,\mathrm{eq}}}{B_0(\lambda)} \right]^{-1} \quad \textbf{(bi-Maxwellian)}$$

The more anisotropic the initial distribution is,
the narrower the equatorial source region becomes.

Initial distribution



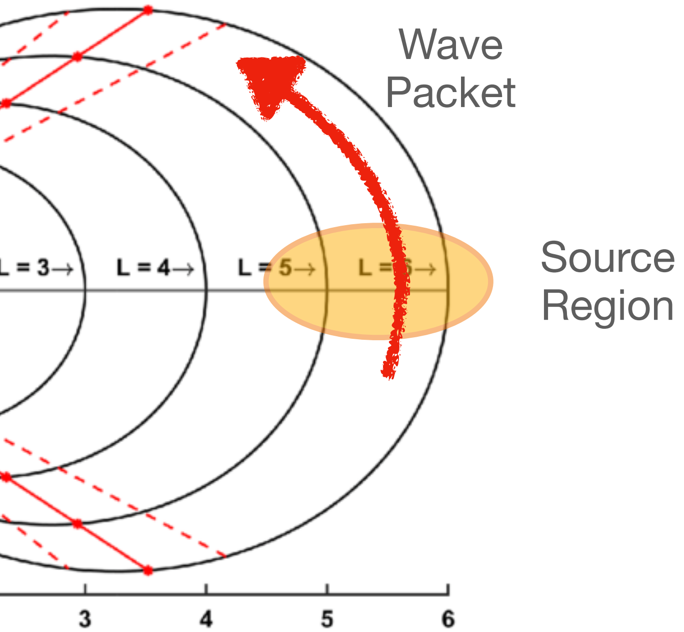
Heavy ion density : 20% (extreme case scenario)

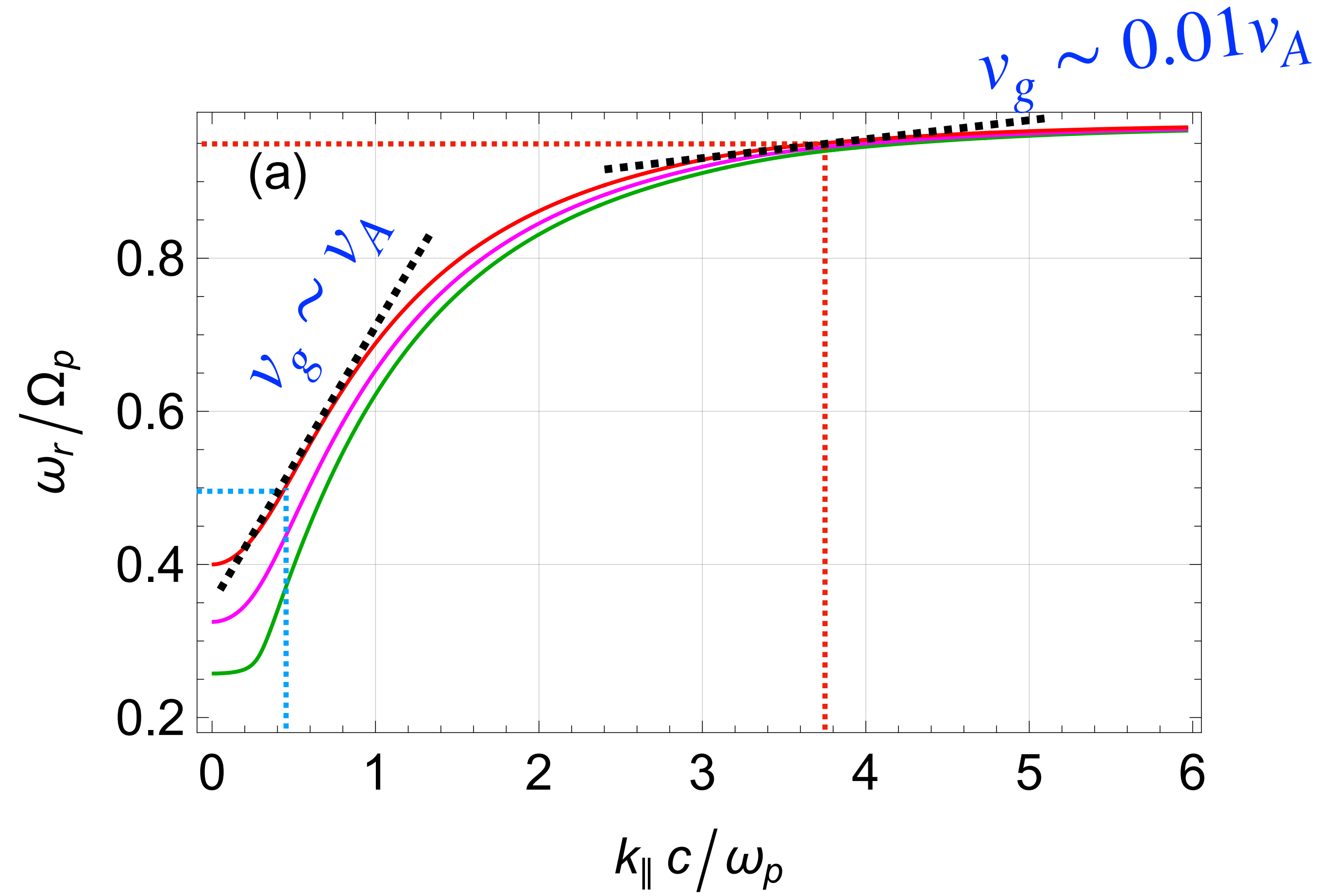
Hot proton density : 20%

Hot proton beta : $\beta_{\parallel hot} = 10^{-4}$ $(\leftarrow f_{\text{peak}} \approx 0.95 f_{cp})$

Hot proton anisotropy : $\dfrac{T_{\perp hot}}{T_{\parallel hot}} \approx 31$ (← Teng+ 2019 estimate)

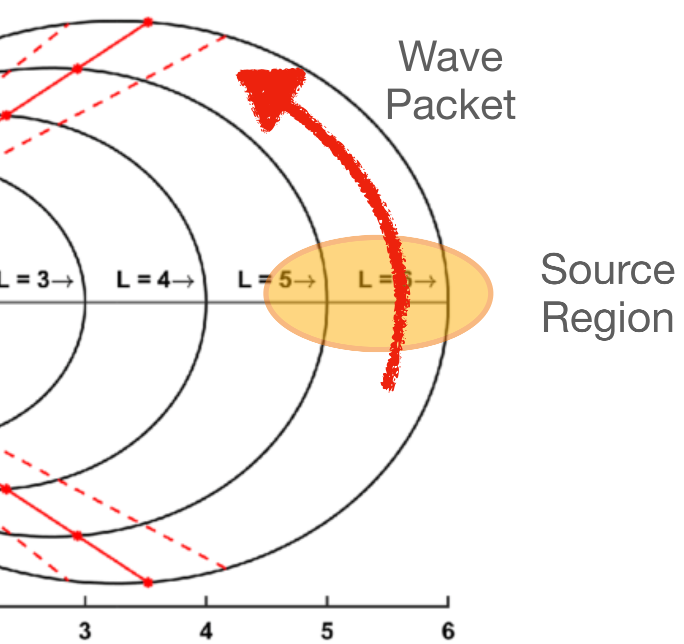
Convective growth rate

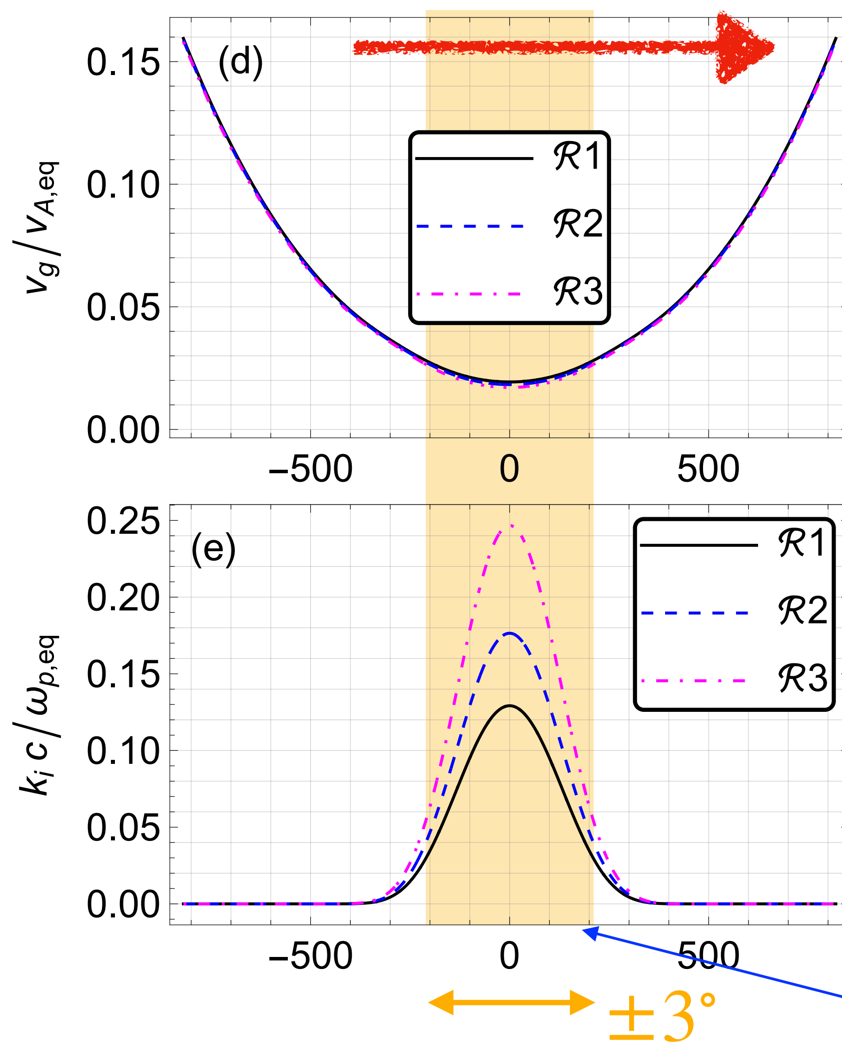


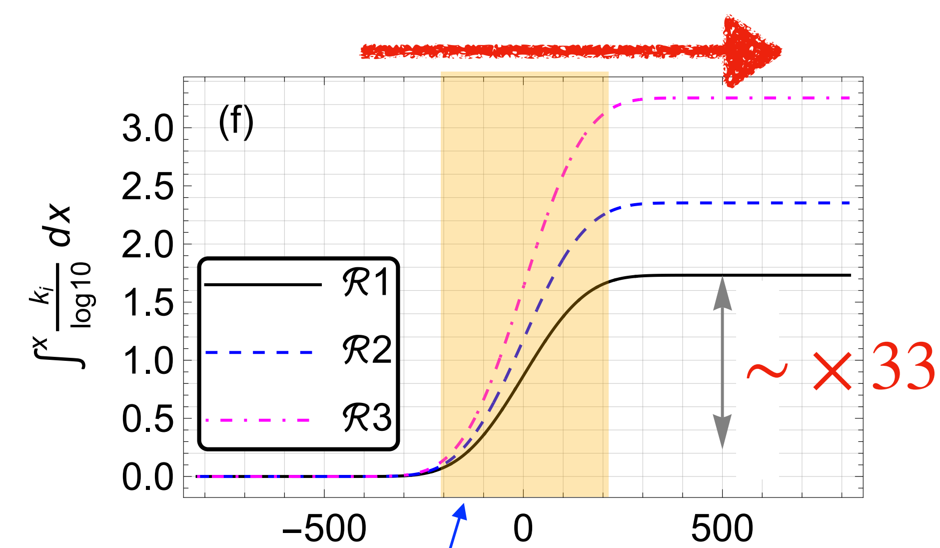


Wave group velocity $: \dfrac{dx}{dt} = v_g \equiv \dfrac{\partial \omega}{\partial k_\parallel}$

Convective growth rate







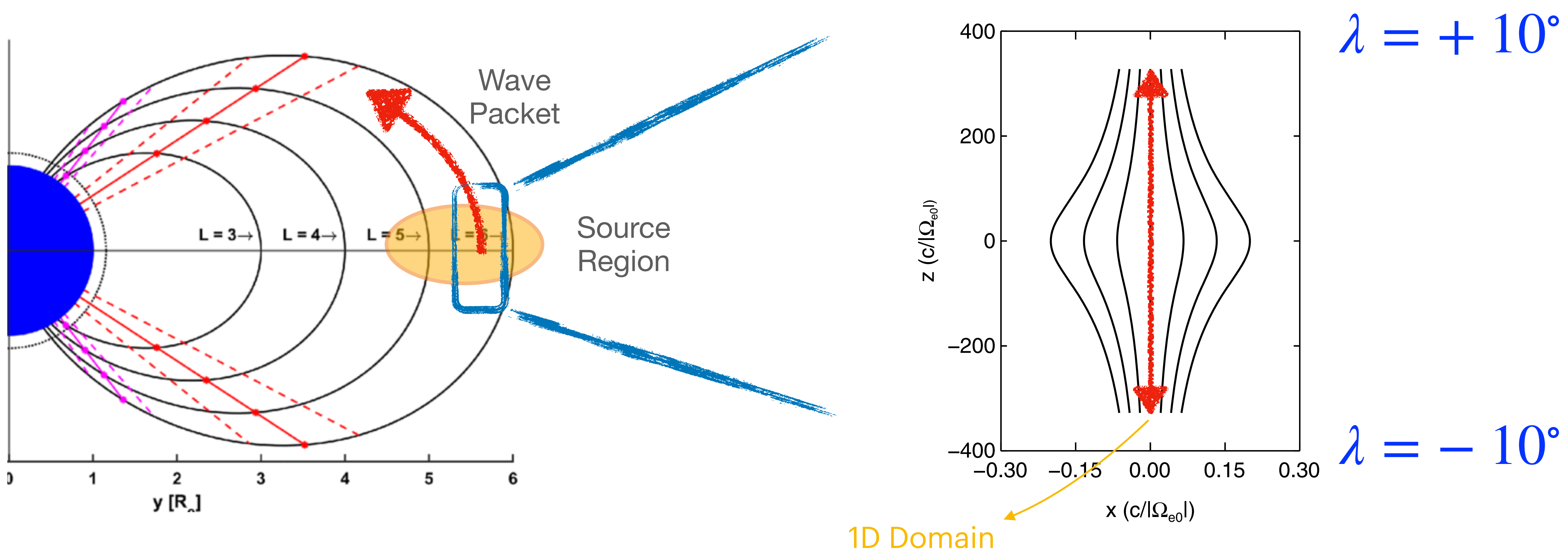
Slowly moving wave packets can (partly) compensates for the narrow source region!

Wave group velocity : $\dfrac{dx}{dt} = v_g \equiv \dfrac{\partial \omega}{\partial k_{\parallel}}$

Convective growth rate : $k_i = \dfrac{\gamma}{v_g}$

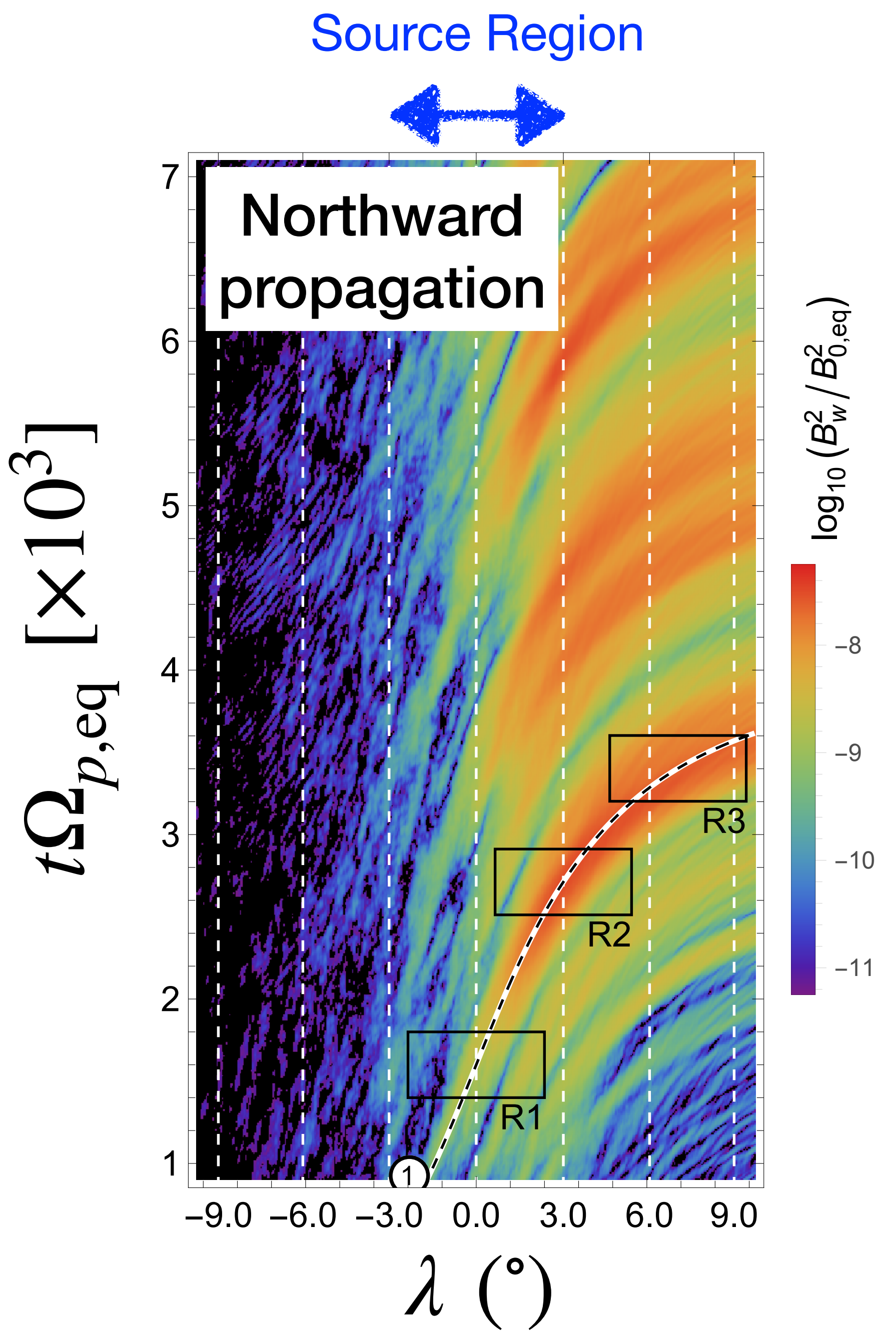
Amplification factor : $\log_{10}\left(\dfrac{B_w}{B_{0,\mathrm{eq}}}\right) = \dfrac{1}{\log 10}\displaystyle\int_{\mathcal{O}}^{x} k_i \,\mathrm{d}x$

1D Hybrid PIC Model



- ***Usual hybrid PIC approach (kinetic ions + massless electron fluid)***
- ***1D domain along the field line (parallel propagation only)***
- $B_{\rm dip} \approx B_{0,\rm eq}\left(1 + \frac{4.5}{L^2}\frac{s^2}{R_E^2}\right)$ ***with*** $L = 5.5$ ***(realistic scale)***
- ***Similar models by Katoh & Omura (2007) and Shoji & Omura (2011)***

Simulation Results



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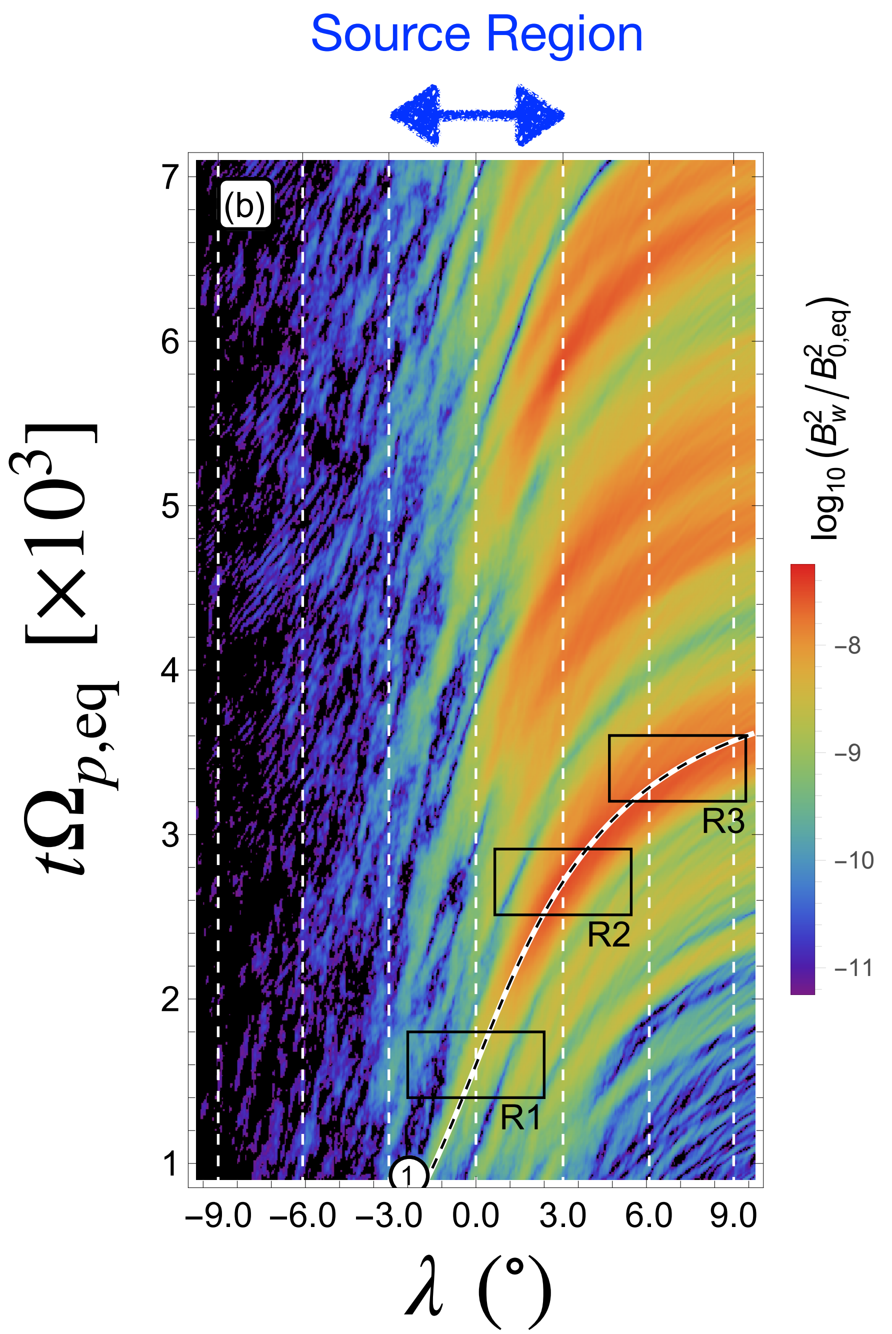
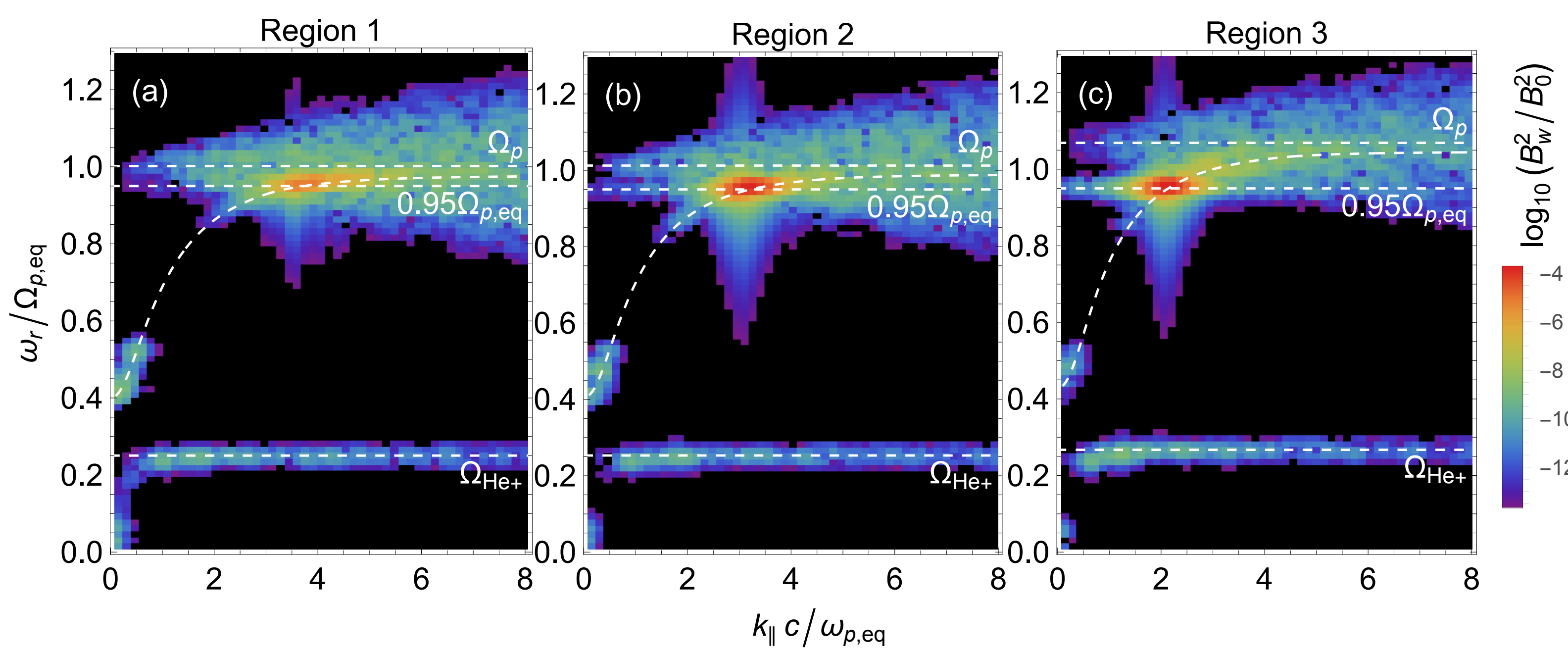
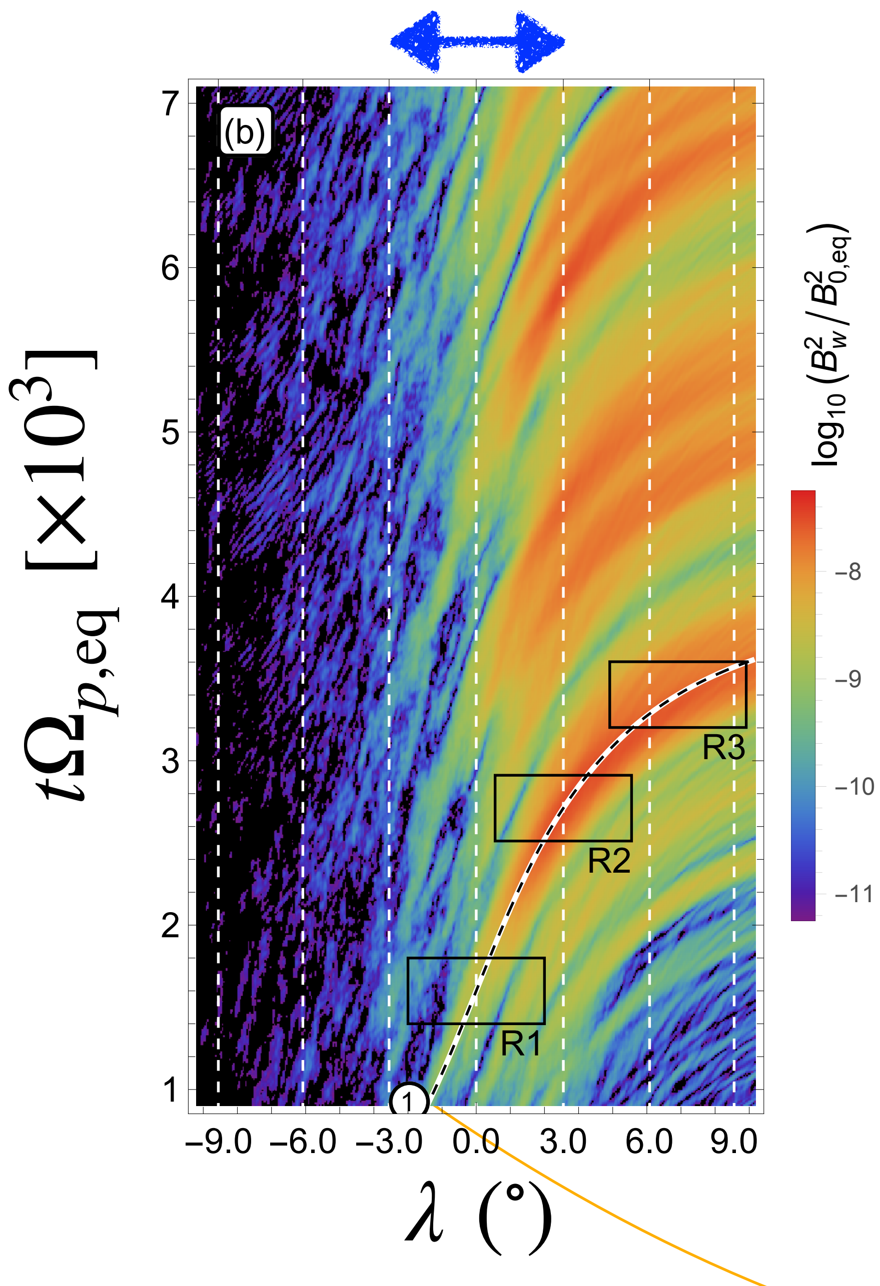


Dispersion Relation



Simulation Results

Source Region



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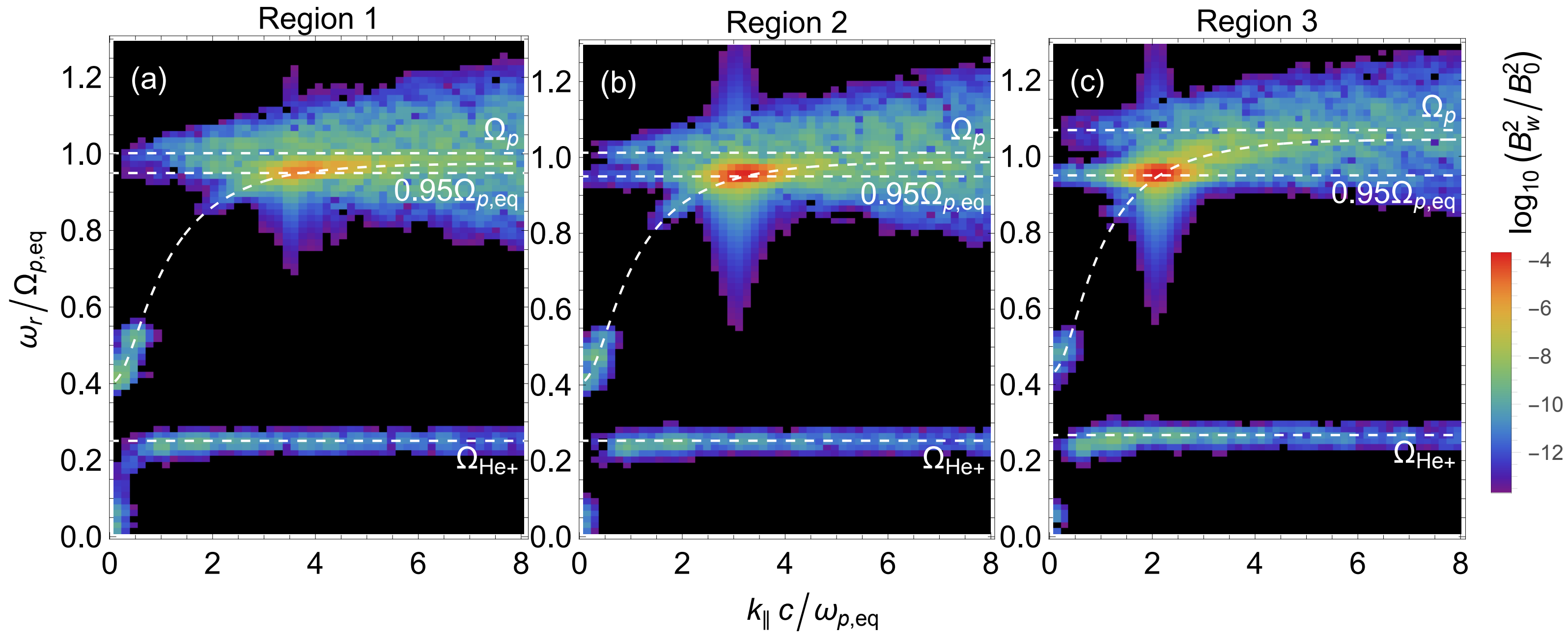
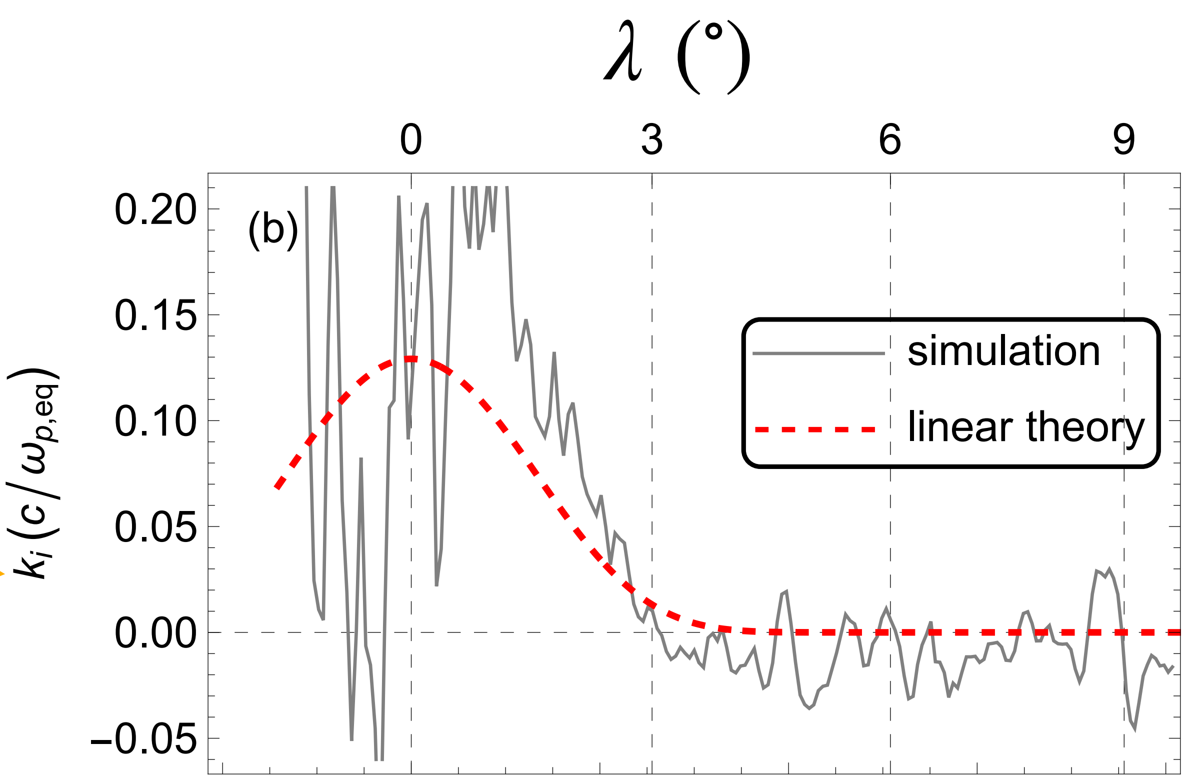
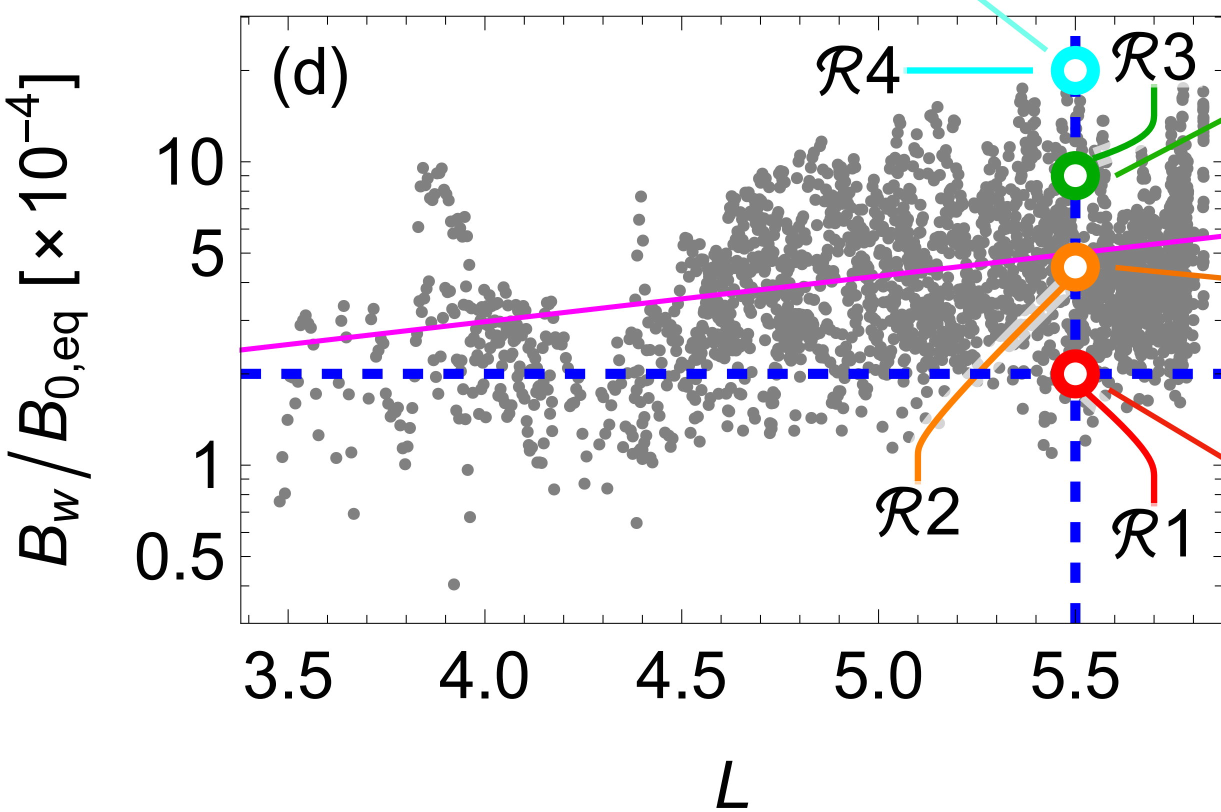


Instantaneous Growth Rate



Theory, Simulation, Observation (1)

$\frac{T_{\perp hot}}{T_{\parallel hot}} \approx 31$ in *uniform field*



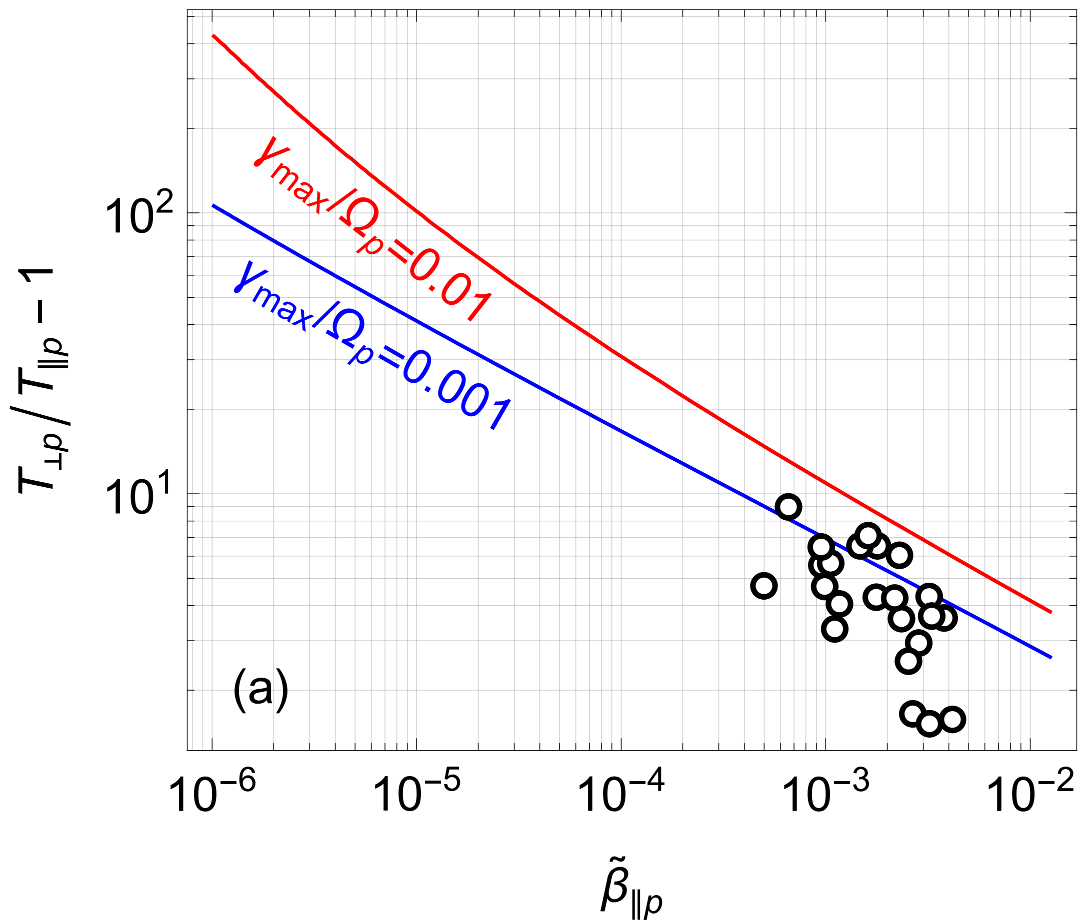
$\frac{T_{\perp hot}}{T_{\parallel hot}} \approx 40$

$\frac{T_{\perp hot}}{T_{\parallel hot}} \approx 35$

$\frac{T_{\perp hot}}{T_{\parallel hot}} \approx 31$ ***S. Teng+ (2019) Estimate***

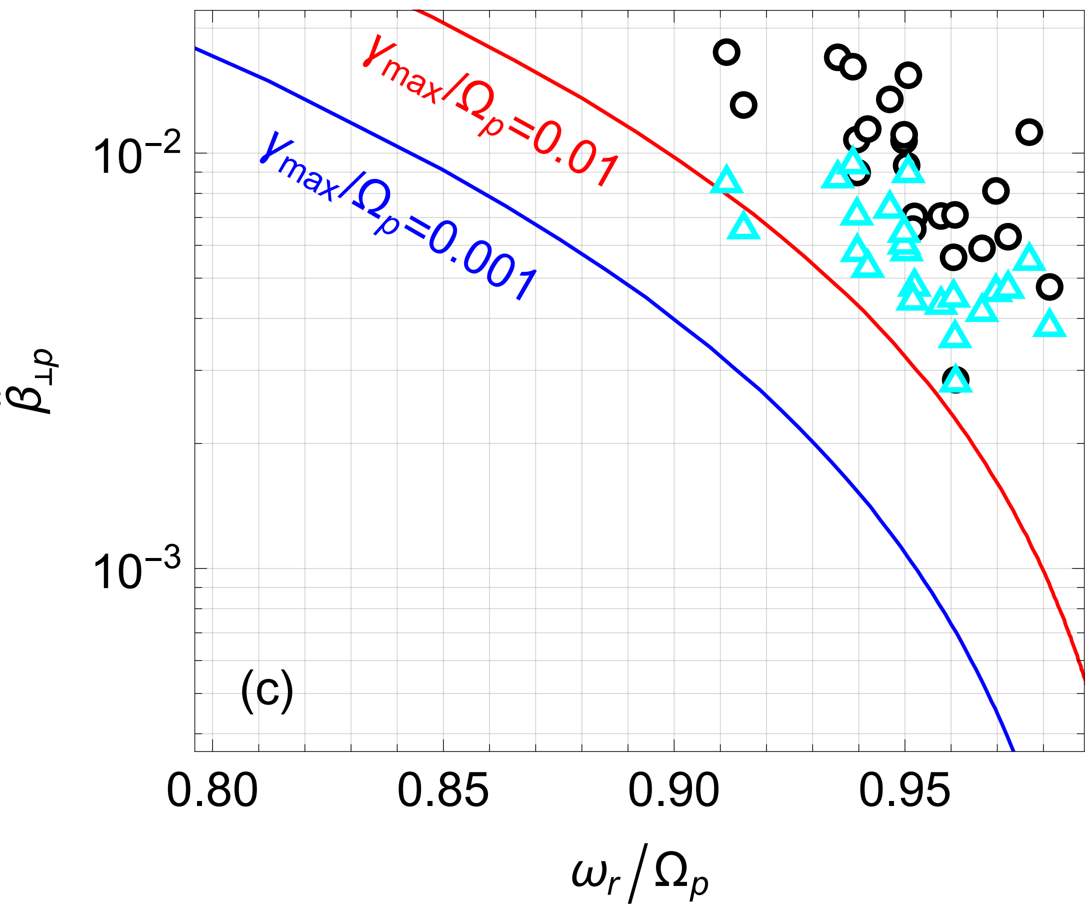
Saturation amplitudes within the range of observation

Theory, Simulation, Observation (2)



Because of very small $T_\parallel \sim 1 - 10$ eV, determination of $\beta_\parallel$ (and anisotropy) is difficult (likely overestimated).

Theory, Simulation, Observation (2)



On the other hand, measurements of $\beta_\perp$ and $f_{\rm peak}$ are more accurate.
The data points seem to line up closely to the curves by the theoretical predictions.

Conclusions

- ***New type of EMIC (HFEMIC) waves***: $f_{\text{peak}} \sim 0.95 f_{cp}, \Delta f \lesssim 0.1 f_{cp}$

  → *Left-hand polarized, quasi-parallel propagating electromagnetic ion cyclotron mode*

- ***Rare in occurrence (mostly outside the plasmasphere), but the anisotropic, low-energy proton population is quite prevalent***

  → *How the latter comes about is an unanswered question!*

- ***The very anisotropic, low-energy proton population is likely the source of free energy***

  → *Qualitative agreement btw/ data and predicted anisotropy threshold*

  → *Hybrid PIC simulations support HFEMIC wave growth wi saturation amplitudes commensurate with the observationa*

Min, K. (2024). Linear theory analysis and one-dimensional hybrid simulations of high-frequency EMIC waves in a dipole magnetic field. Journal of Geophysical Research: Space Physics, 129, e2023JA032387. https://doi.org/10.1029/2023JA032387