The saturation properties of broadband EMIC waves and the associated heating of cold ions

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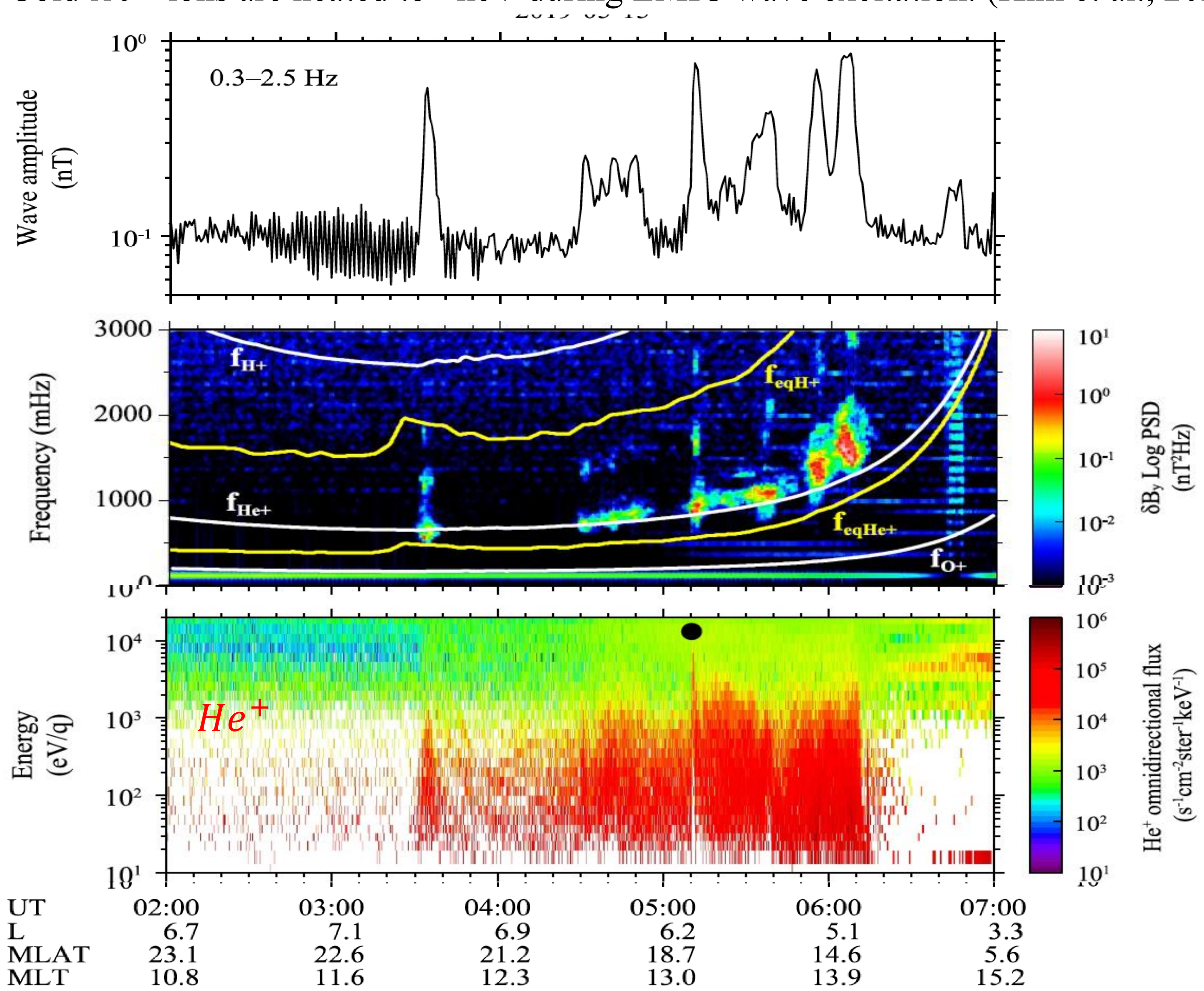
Background & Motivation

- EMIC waves are parallelly propagating electromagnetic waves driven by ring current ion temperature anisotropy, and play essential roles in scattering electrons via gyroresonance (~MeV) and bounce resonance (~100s keV).
- The excitation of EMIC waves is affected by cold ions, e.g., H^+, He^+, O^+.
- EMIC wave growth:

Ring current ions anisotropy (Tperp/Tparp>1) →
- Excite EMIC waves
- Reduce Tperp/Tparp
- Heat background cold plasma

→ EMIC waves reach saturation

- Cold He^+ ions are heated to ~keV during EMIC wave excitation. (Kim et al., 2024)



Science question:
What are the properties of EMIC waves in the H^+-He^+-O^+ plasma after saturation and how do they contribute to the heating of cold ions?

Conclusions

The EMIC wave frequency spectrum shifts toward lower frequencies as a result of the relaxation of hot proton anisotropy. The cold He^+, O^+ ions are heated sequentially due to the wave frequency evolution. He^+ ions are heated to ~keV and O^+ ions are heated to ~100s eV. The cold O^+ ions are heated parallelly to the background magnetic field, while the He^+ ions are heated perpendicularly.

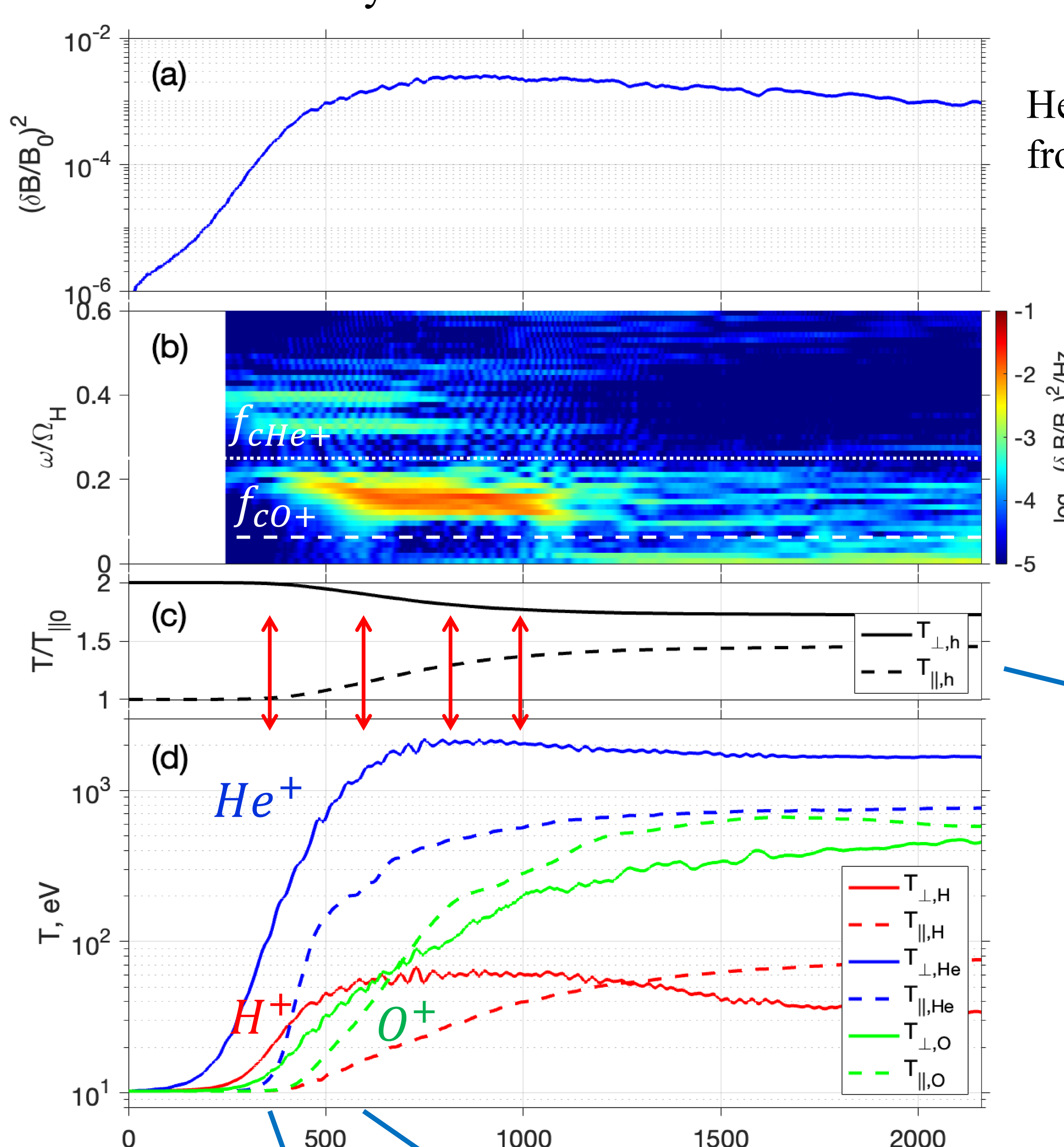
Reference:
Kim et al. (2024). *Observation and numerical simulation of cold ions energized by EMIC waves.*
Winske et al. (2003). Hybrid simulation codes: Past, present and future—A tutorial.
Gendrin. (1981). Gendrin, R. (1981). General relationships between wave amplification and particle diffusion in a magnetoplasma.
Kennel & Petschek. (1966). Limit on stably trapped particle fluxes.

Hybrid Simulations and Analysis

- Simulation Setup (Winske et al., 2003):

Components	Electron (e)	Hot H^+ (h)	Cold H^+ (H)	Cold He^+ (He)	Cold O^+ (O)
	n_e~2.4/cm³	n_h/n_e=5%	n_H = 80%	n_{He}/n_e=5%	n_O = 10%
Parameters	B_0=100 nT	ω_{pe}/ω_{ce}=5	T_{cold}~10eV	$\tilde{\beta}_h$ =10.0	$T_{\perp h}/T_{\parallel h}$=2.0

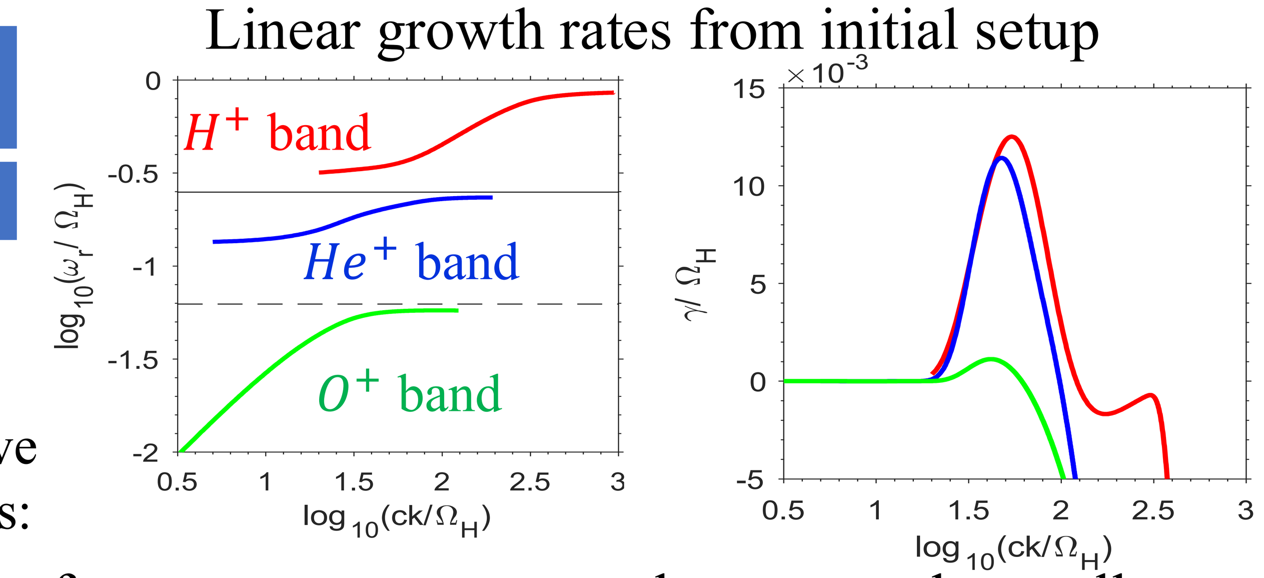
Hybrid simulation results



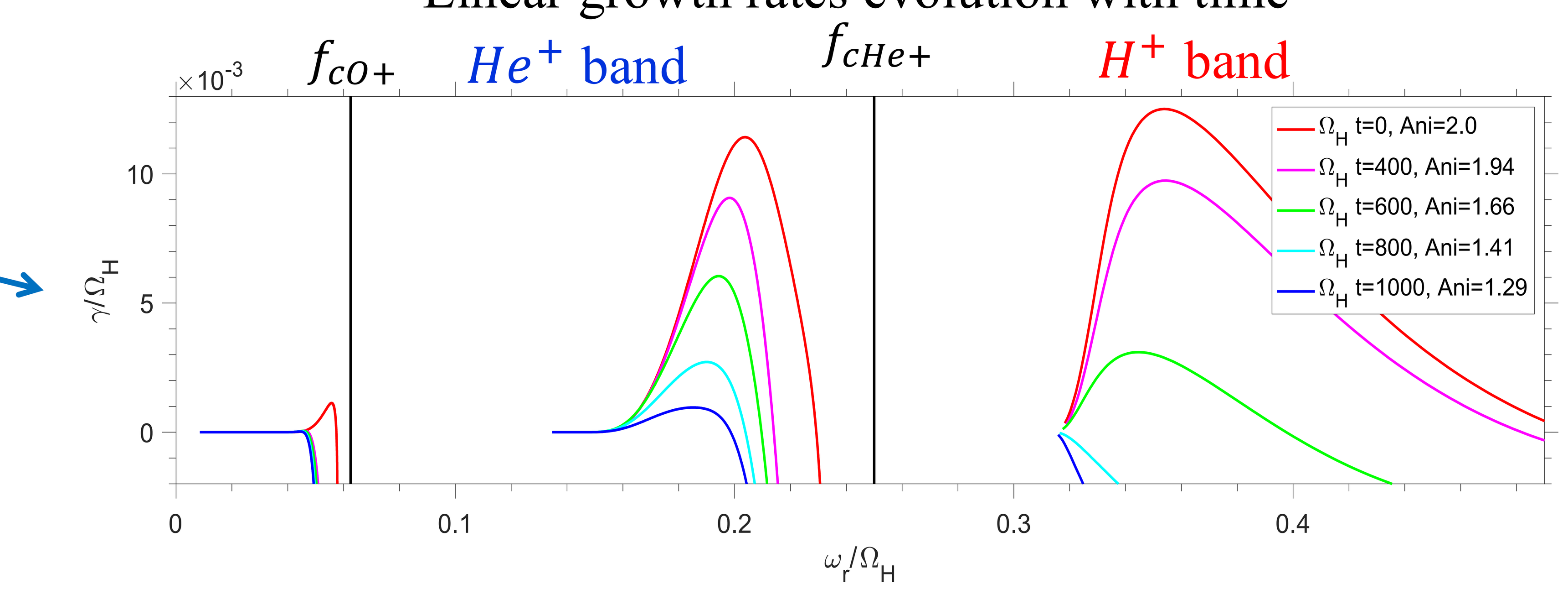
Here are what we observe from the hybrid simulations:

- The EMIC wave frequency spectrum evolves towards smaller frequency;
- The cold He^+, O^+ ions are heated sequentially;
- He^+ ions are heated to ~keV and O^+ ions are heated to ~100s eV.

Linear growth rates from initial setup

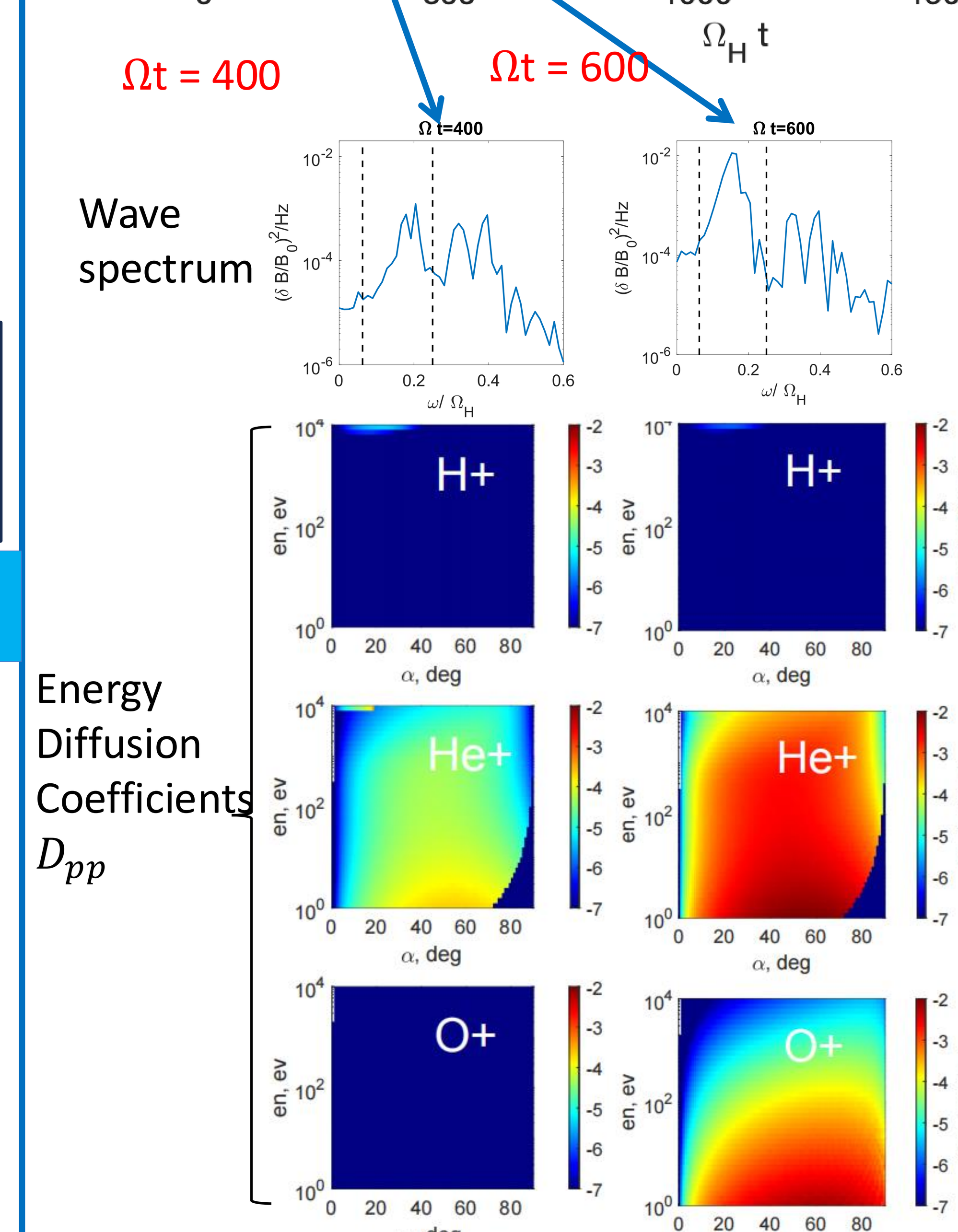


Linear growth rates evolution with time



- The growth rate of H^+ band EMIC waves decreases more sharply than that of He^+ band EMIC waves, with Ani decreasing;
- The relaxation of the temperature anisotropy reduces the maximum frequency of positive linear growth rate. (Kennel & Petschek, 1966)

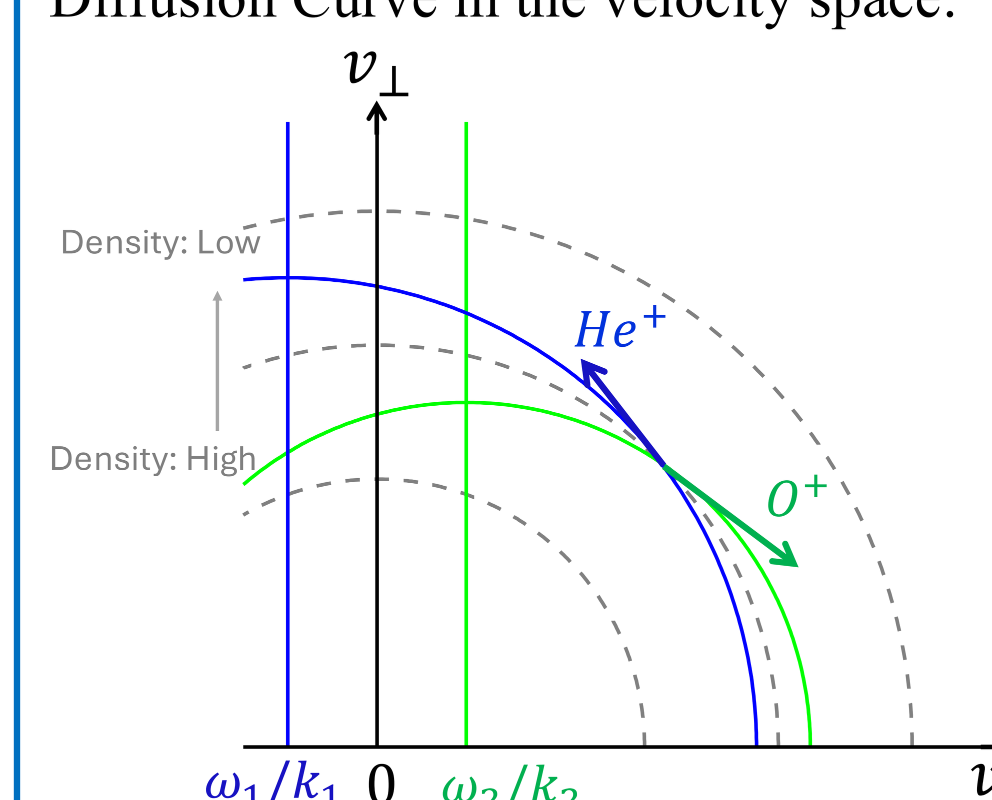
$$\omega_i = \frac{A}{A+1}\Omega$$



- The cold He^+, O^+ ions are heated sequentially due to the wave frequency evolution.

Resonance Condition: $\omega - k_{//}v_{//} = \Omega$ (Gendrin 1981)

Diffusion Curve in the velocity space: ${v_\perp}^2 + (v_{\parallel} - \omega/k)^2 = const$



In the frame moving with the wave, at the phase velocity ω/k, wave associated electric field E_w vanishes, meaning the particle's energy is conserved in the reference frame. Due to their differing masses, the resonance conditions for He^+ and O^+ are different, resulting in their unique diffusion curves.

- He^+ ions undergo perpendicular heating, while O^+ ions are heated parallelly.