Test Particle Simulation of Relativistic Proton Acceleration by Electromagnetic Ion Cyclotron Waves in the Inner Jovian Magnetosphere

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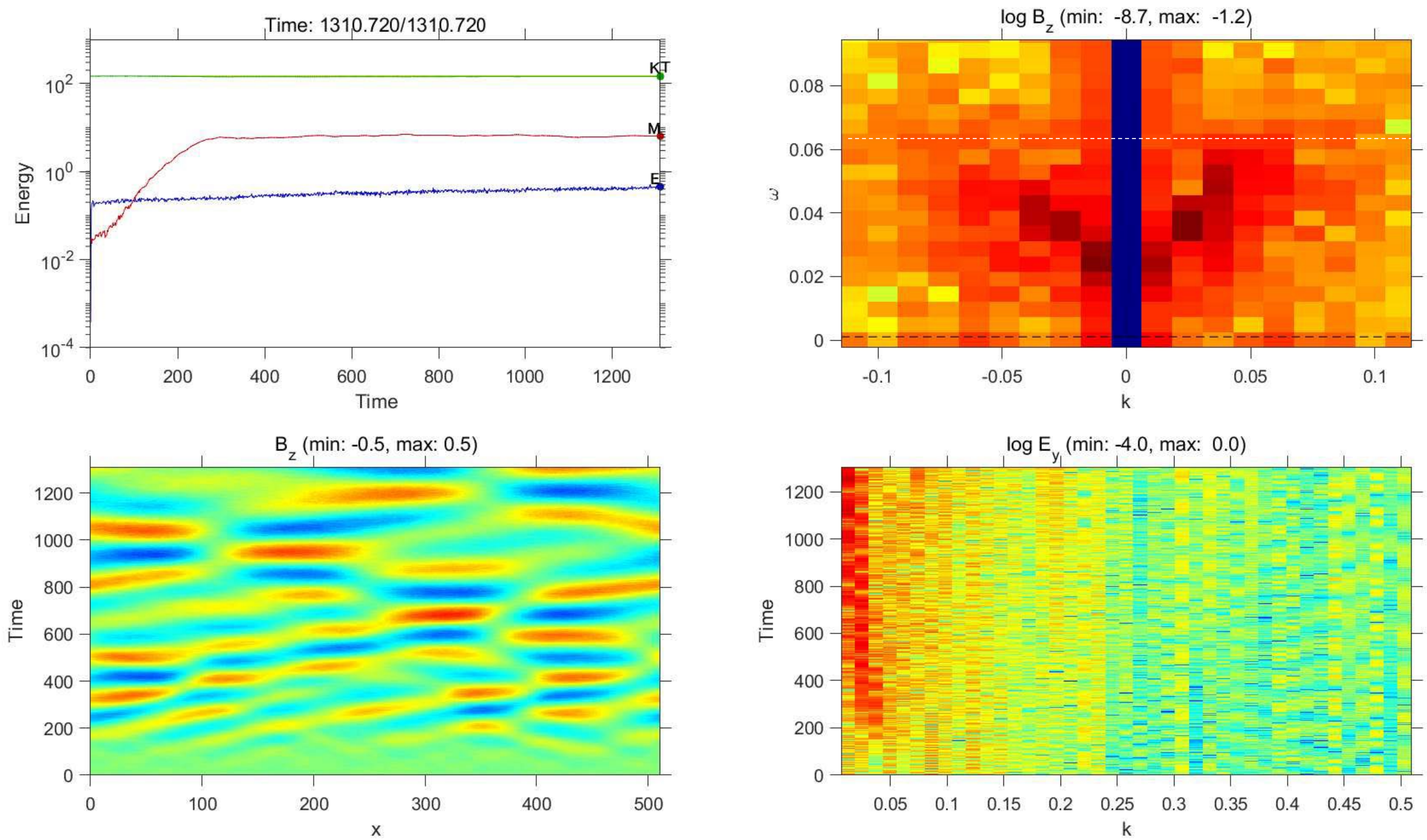
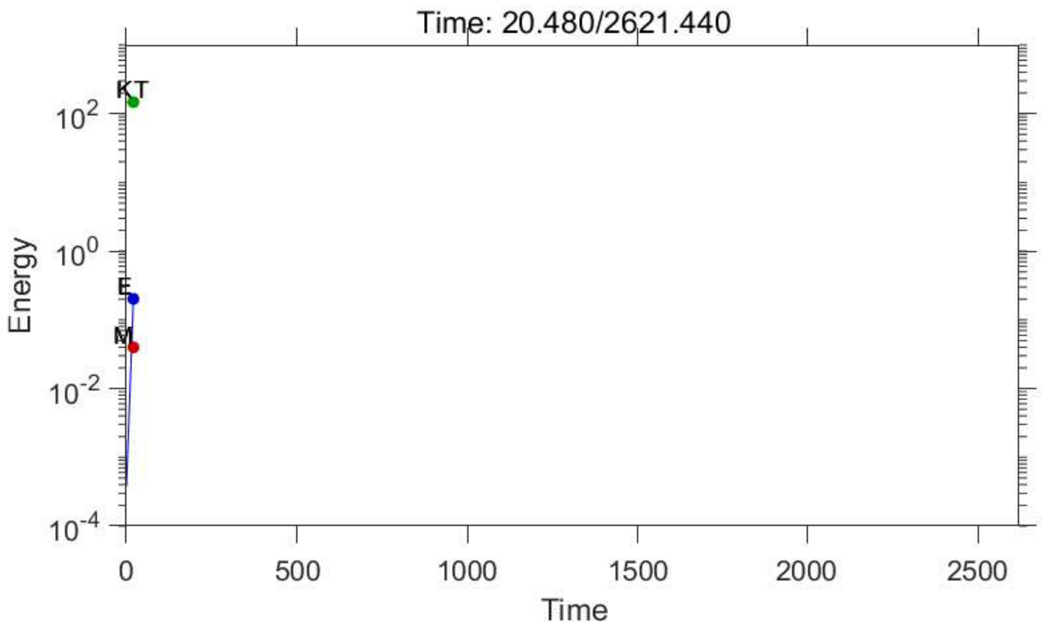
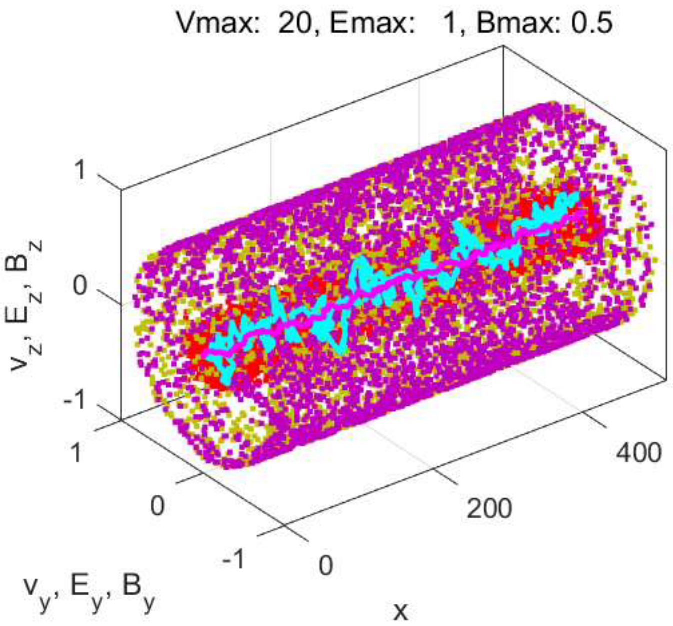
EMIC Wave Instability Driven by Ion Temperature Anisotropy



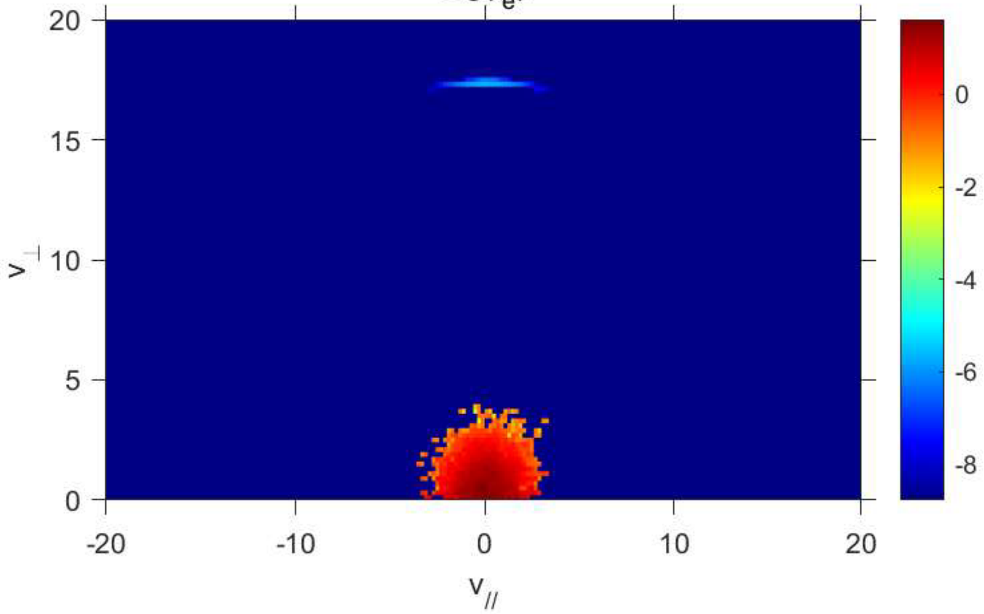
KEMPO1: ISSS-15 PIC Hands-on



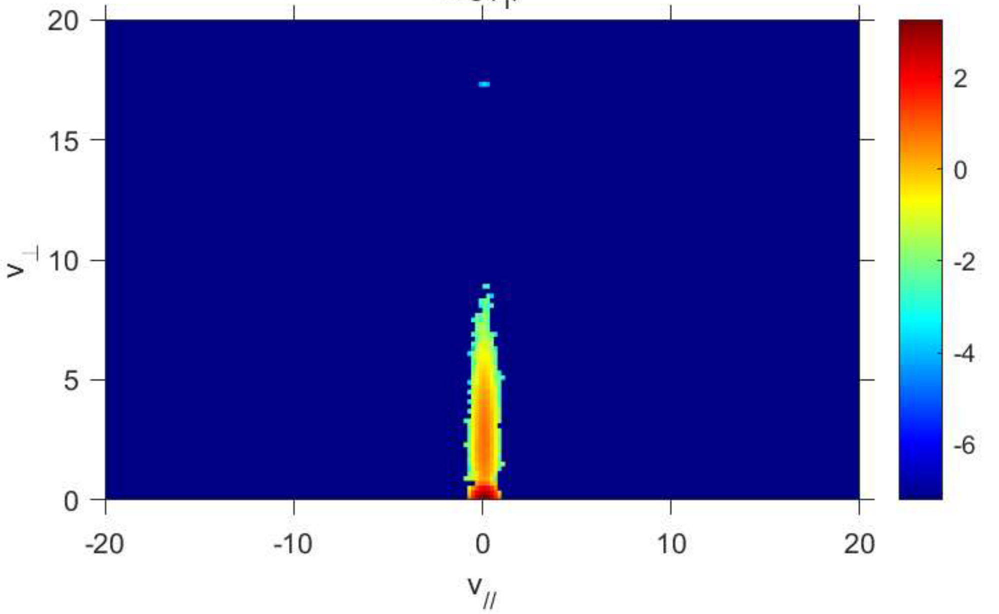


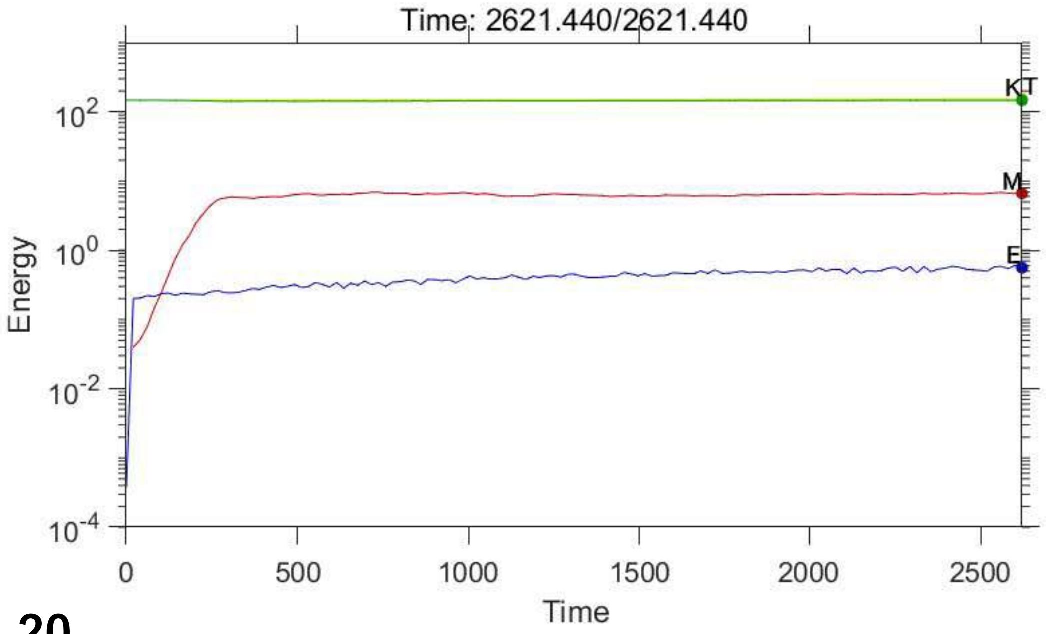
CV = 20

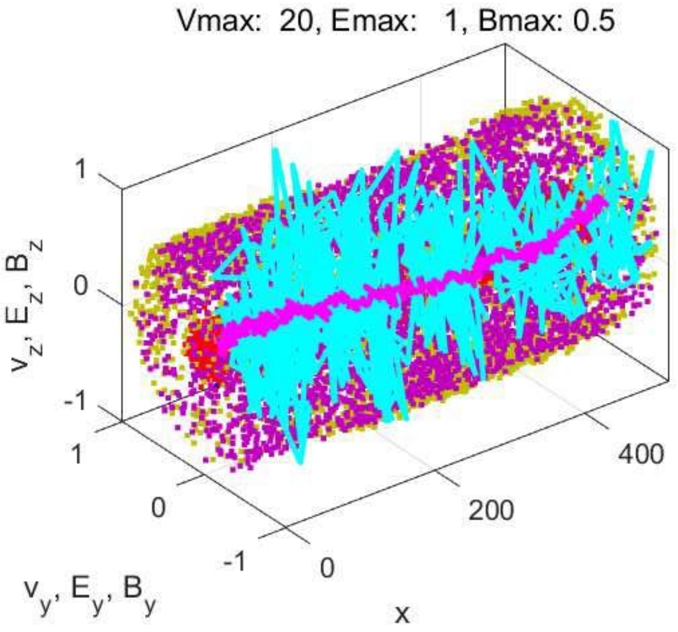
Electrons



Ions

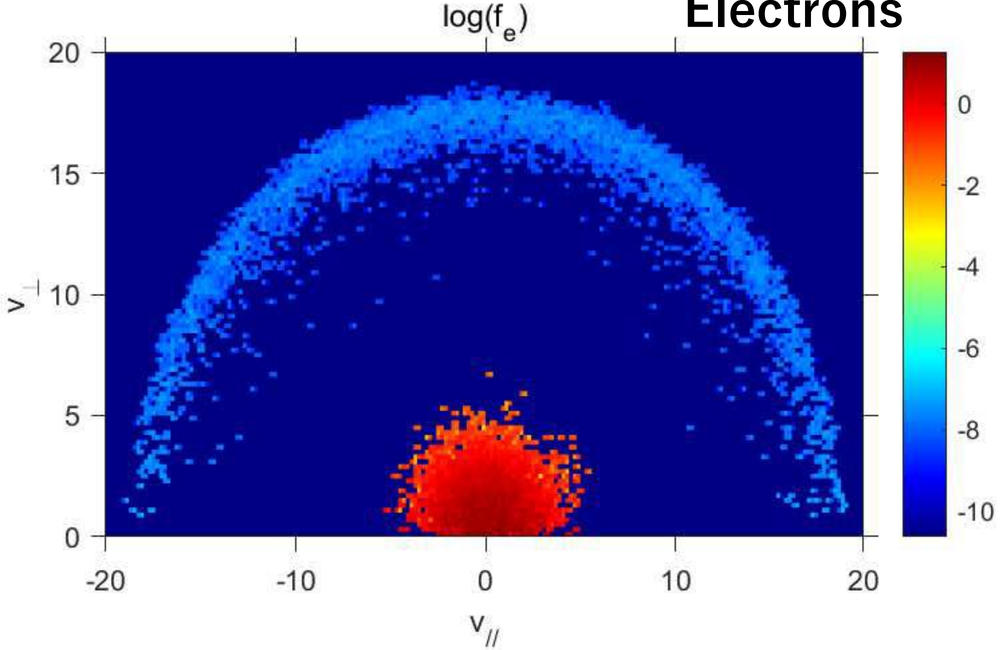




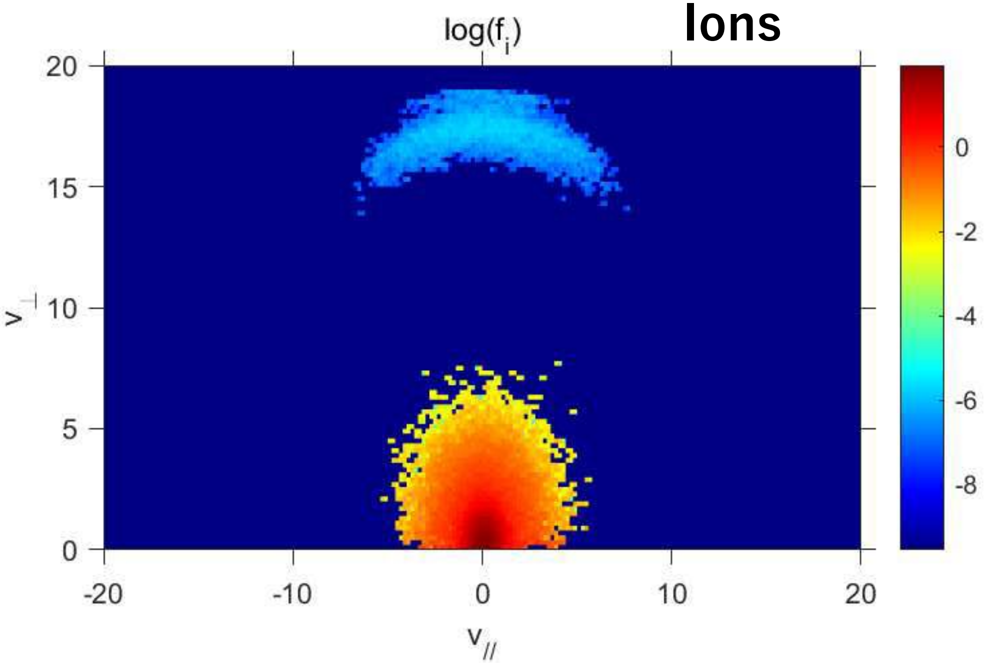


CV = 20

Electrons



Ions



Nonlinear EMIC Wave-Proton Interaction

$$\frac{\mathrm{d}\zeta}{\mathrm{d}t} = -k\left(v_{\|} - V_R\right)$$

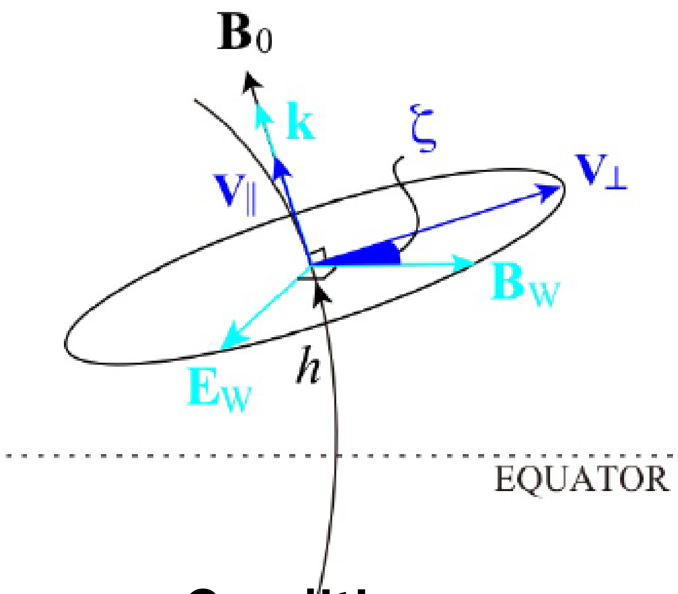
$$V_R = \frac{\omega}{k}\left(1 - \frac{\Omega_{\mathrm{H}}}{\omega\gamma}\right)$$

$$\frac{\mathrm{d}^2\zeta}{\mathrm{d}t^2} = \omega_{tr}^2\left(\sin\zeta + S\right)$$

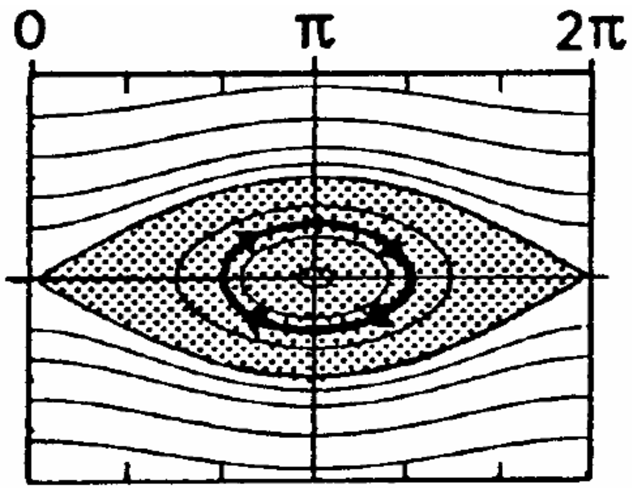
$= 0$ **: Second-order Resonance Condition**

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

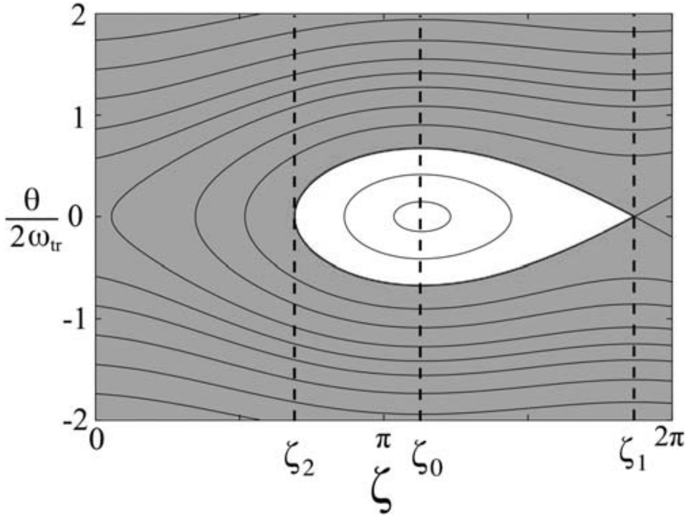
$$\theta = k(v_{\|} - V_R)$$



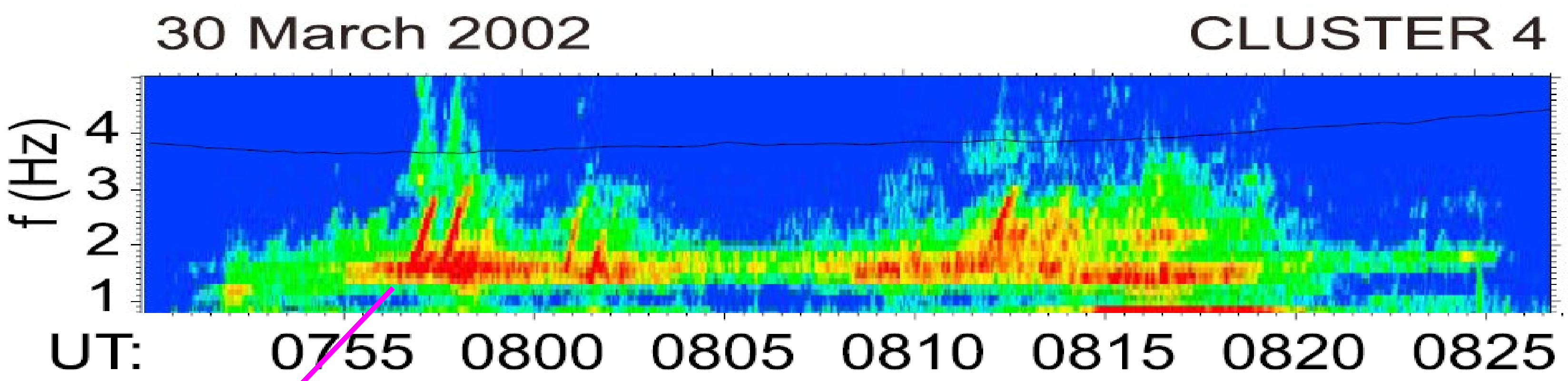
$S = 0$



$S = 0.4$

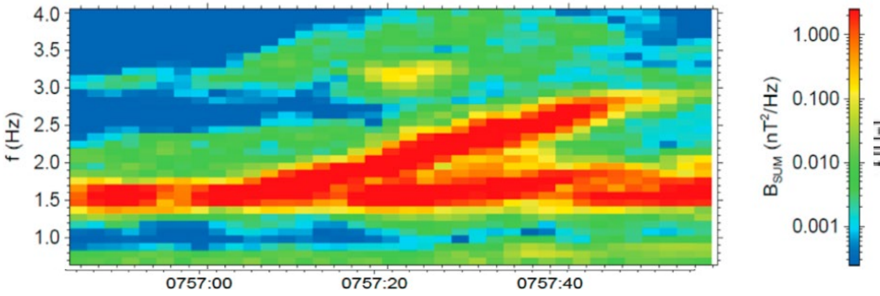


Electromagnetic Ion Cyclotron (EMIC) Waves



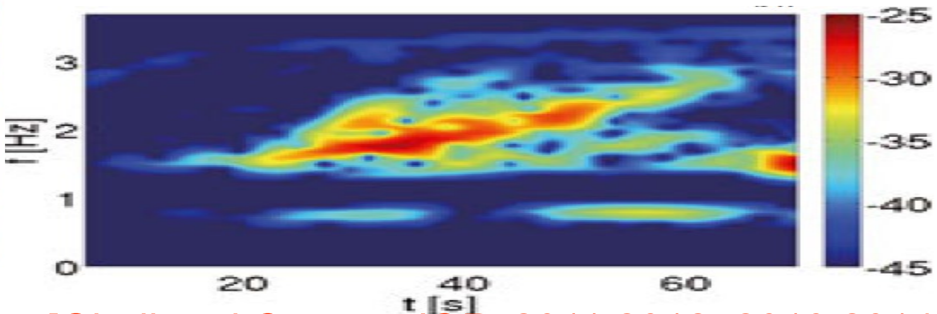
[*Pickett et al., GRL, 2010*]

Nonlinear Wave Growth Theory



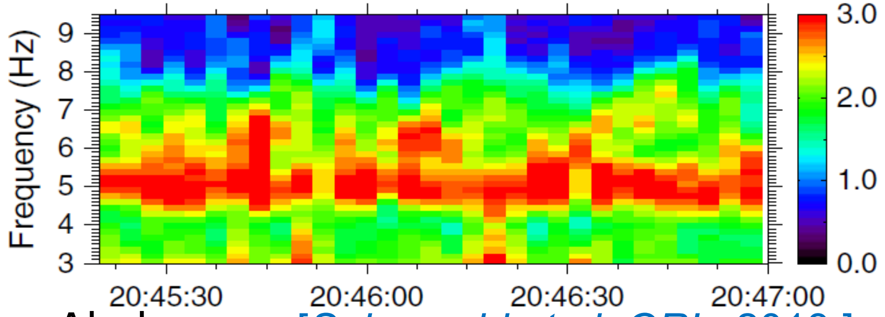
[*Omura et al.,JGR,* 2010]

Hybrid Code Simulations



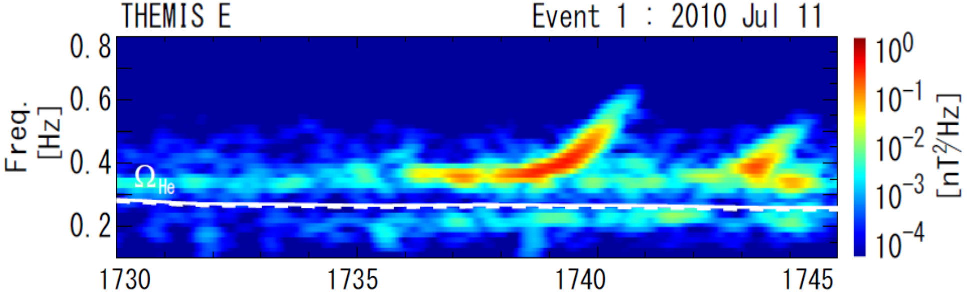
[*Shoji and Omura, JGR,* 2011,2012, 2013,2014]

Radiation Belt Slot Region



Akebono [*Sakaguchi et al.,GRL,* 2013]

Outside Plasmapause



[*Nakamura et al., JGR,* 2014]

Relativistic Turning Acceleration (RTA) by EMIC Waves

Kinetic Energy Variation

$$\frac{\mathrm{d}K}{\mathrm{d}t} = m_{\mathrm{H}}c^2\frac{\mathrm{d}\gamma}{\mathrm{d}t} = -qE_w v_\perp \sin\zeta$$

$$\frac{\mathrm{d}^2\zeta}{\mathrm{d}t^2} = \omega_{tr}^2(\sin\zeta + S) = 0$$

$$\frac{\mathrm{d}K}{\mathrm{d}t} = \frac{m_{\mathrm{H}}\omega\Omega_w v_\perp}{k}S$$

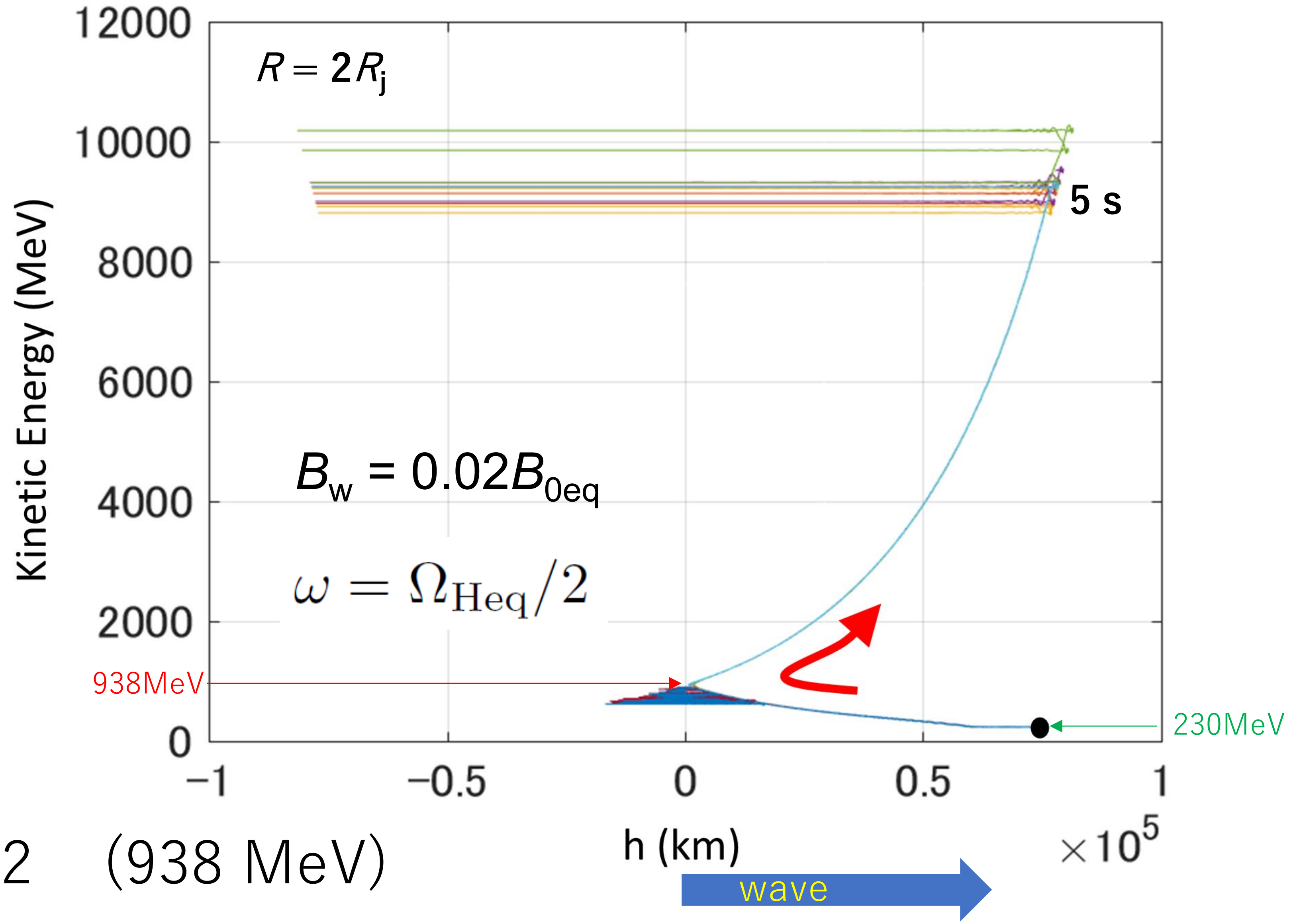
$$S = \frac{1}{\omega_{tr}^2}\left(s_1\frac{\partial\omega}{\partial t} + V_p s_2\frac{\partial\Omega_{\mathrm{H}}}{\partial h}\right)$$

Turning Point

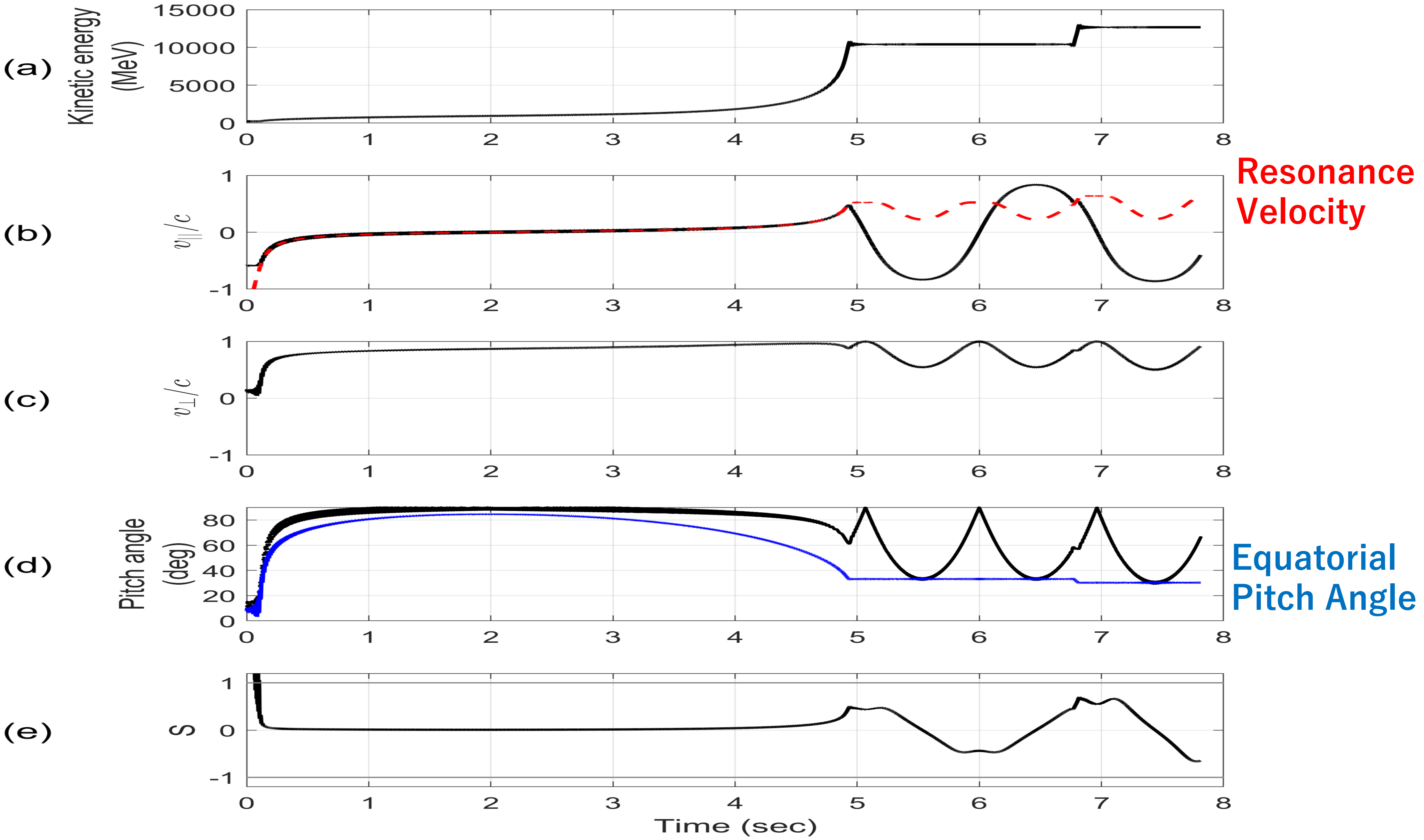
$$V_R = \frac{\omega}{k}\left(1 - \frac{\Omega_{\mathrm{H}}}{\omega\gamma}\right) = 0$$

$$\gamma \simeq \frac{\Omega_{\mathrm{Heq}}}{\omega} = 2 \quad (938\ \mathrm{MeV})$$

Trajectories of 8 Protons with Different Initial Phase Angles



Trajectory of Trapped Resonant Particle



Anomalous Trapping at Low Pitch Angles

Initial Pitch Angle: $\alpha_0 = 10$ degrees

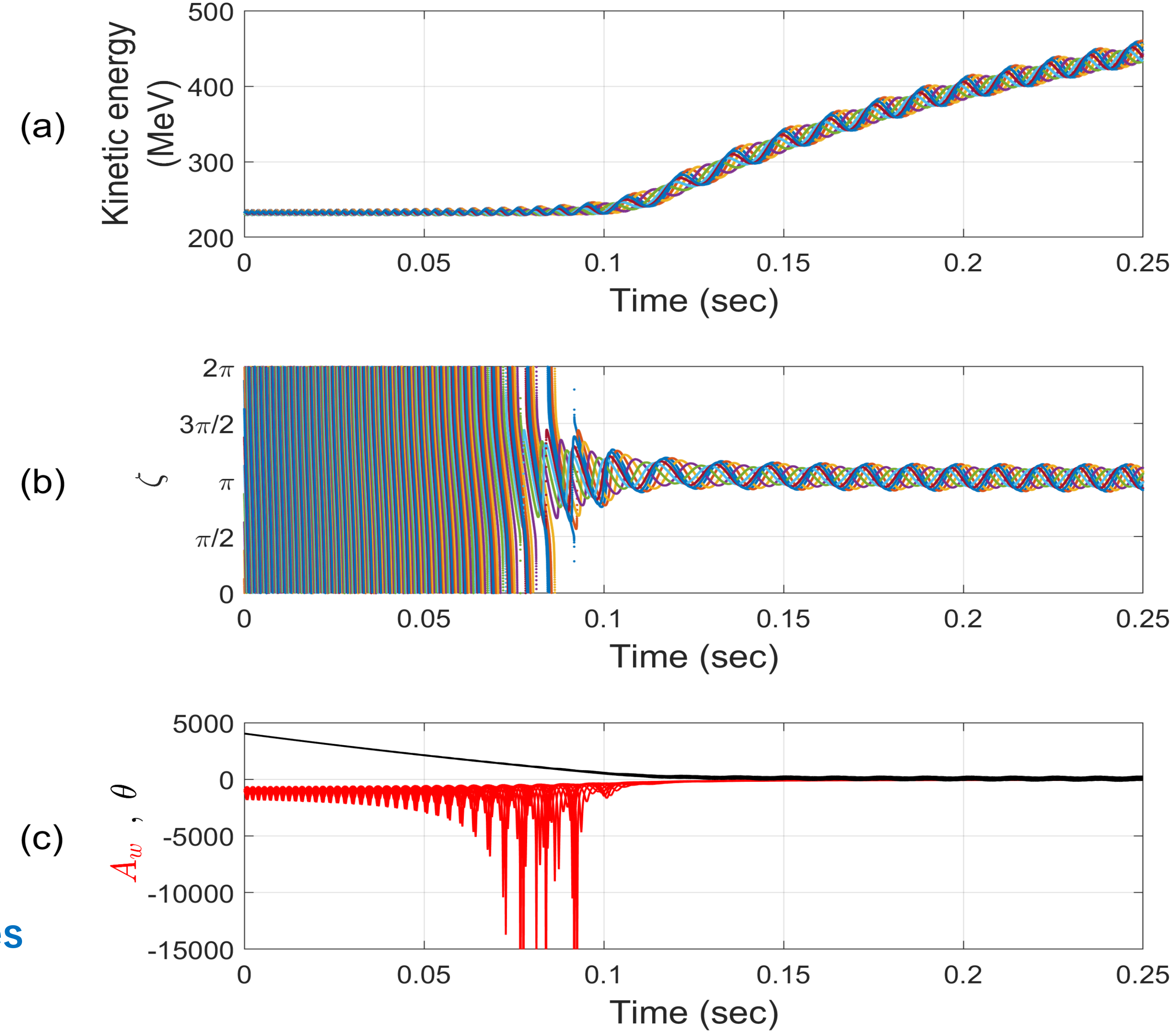
$$\frac{\mathrm{d}\zeta}{\mathrm{d}t} = \boxed{A_w} \cos\zeta - \theta$$

$$\boxed{A_w} = \frac{\Omega_w}{\gamma v_\perp}\left(v_\parallel - \frac{\omega}{k}\right)$$

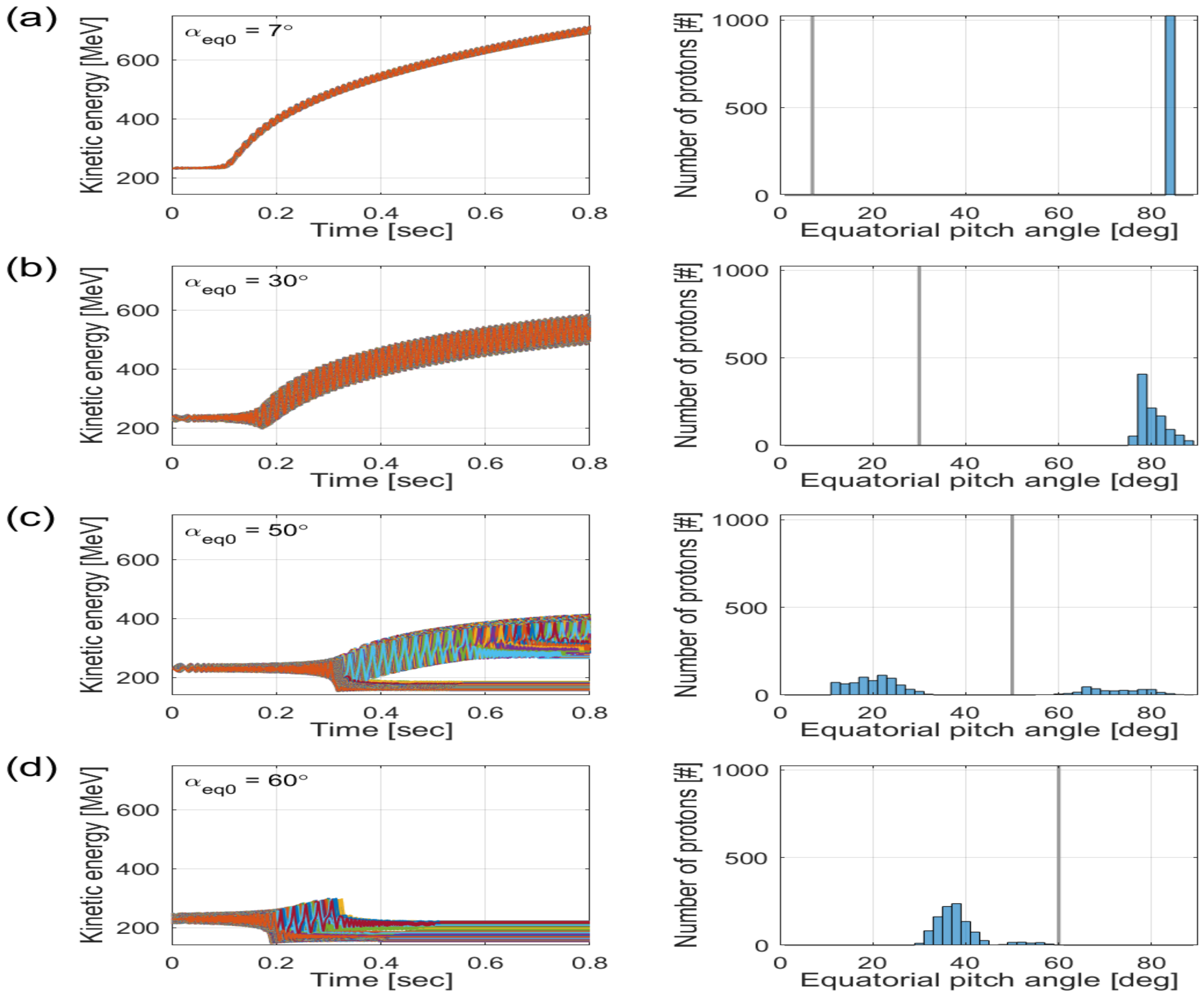
$$\frac{\mathrm{d}^2\zeta}{\mathrm{d}t^2} = \omega_{tr}^2(\sin\zeta + S)$$

$$S = \frac{1}{\omega_{tr}^2}\left(s_1\frac{\partial\omega}{\partial t} + V_p s_2 \frac{\partial\Omega_\mathrm{H}}{\partial h}\right)$$

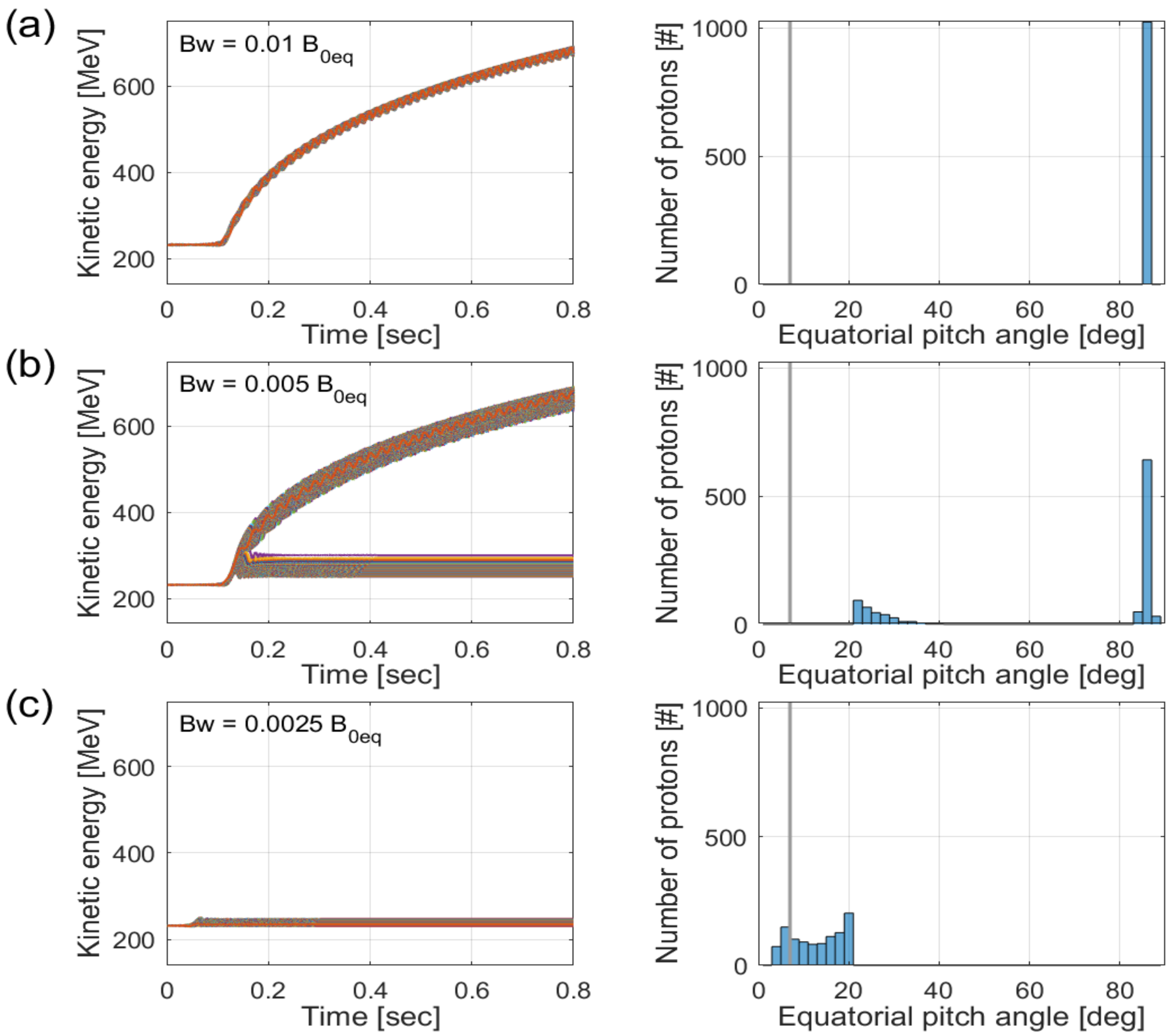
Anomalous trapping of low pitch angle electrons by coherent whistler mode waves
[*Kitahara and Katoh, JGR*, 2019]



Dependency on Initial Pitch Angles α_0



Dependency on Wave Amplitude B_w

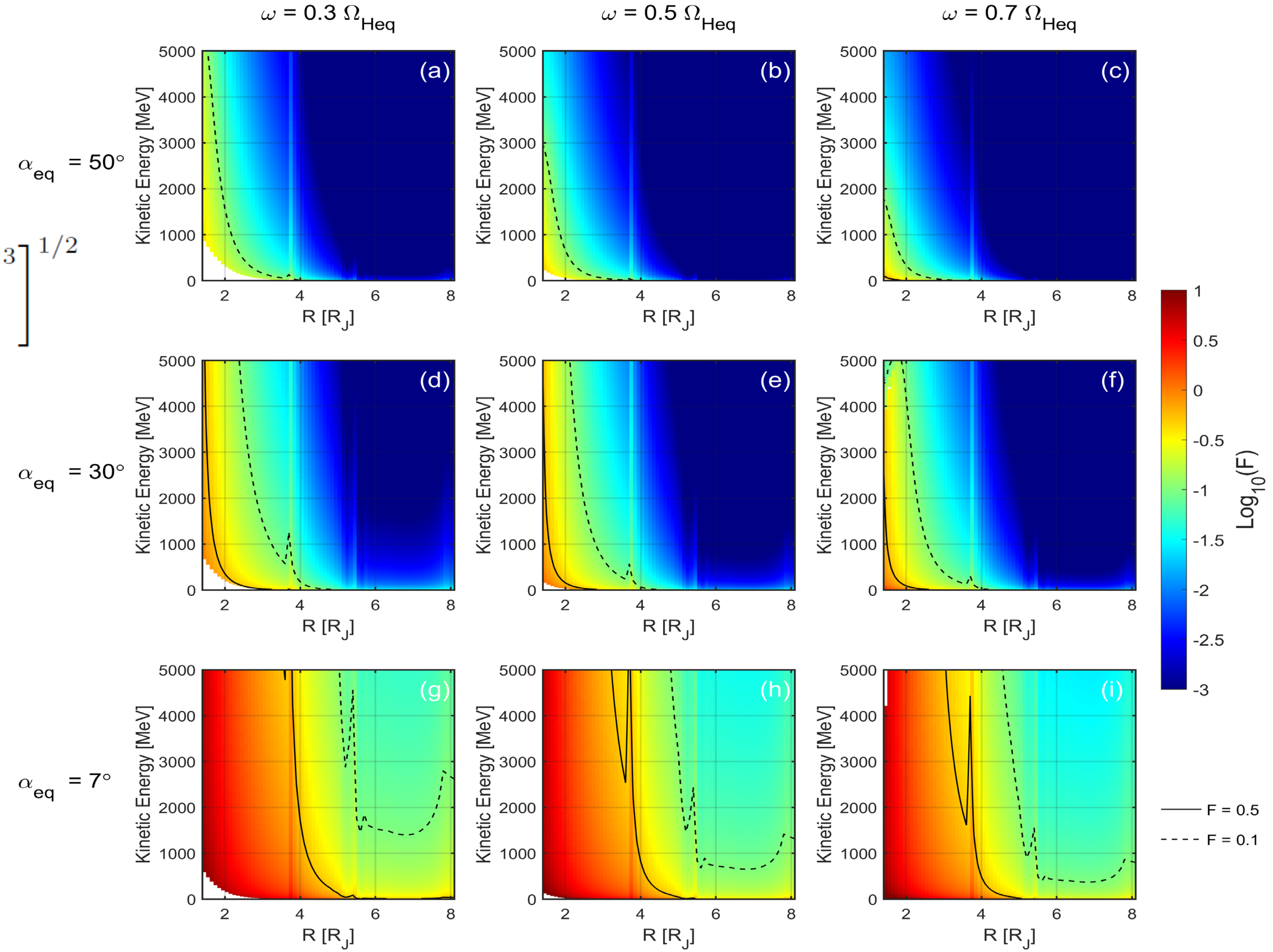


Anomalous Trapping Factor F

$$\frac{d\zeta}{dt} \sim -\left(F\cos\zeta + 1\right)\theta$$

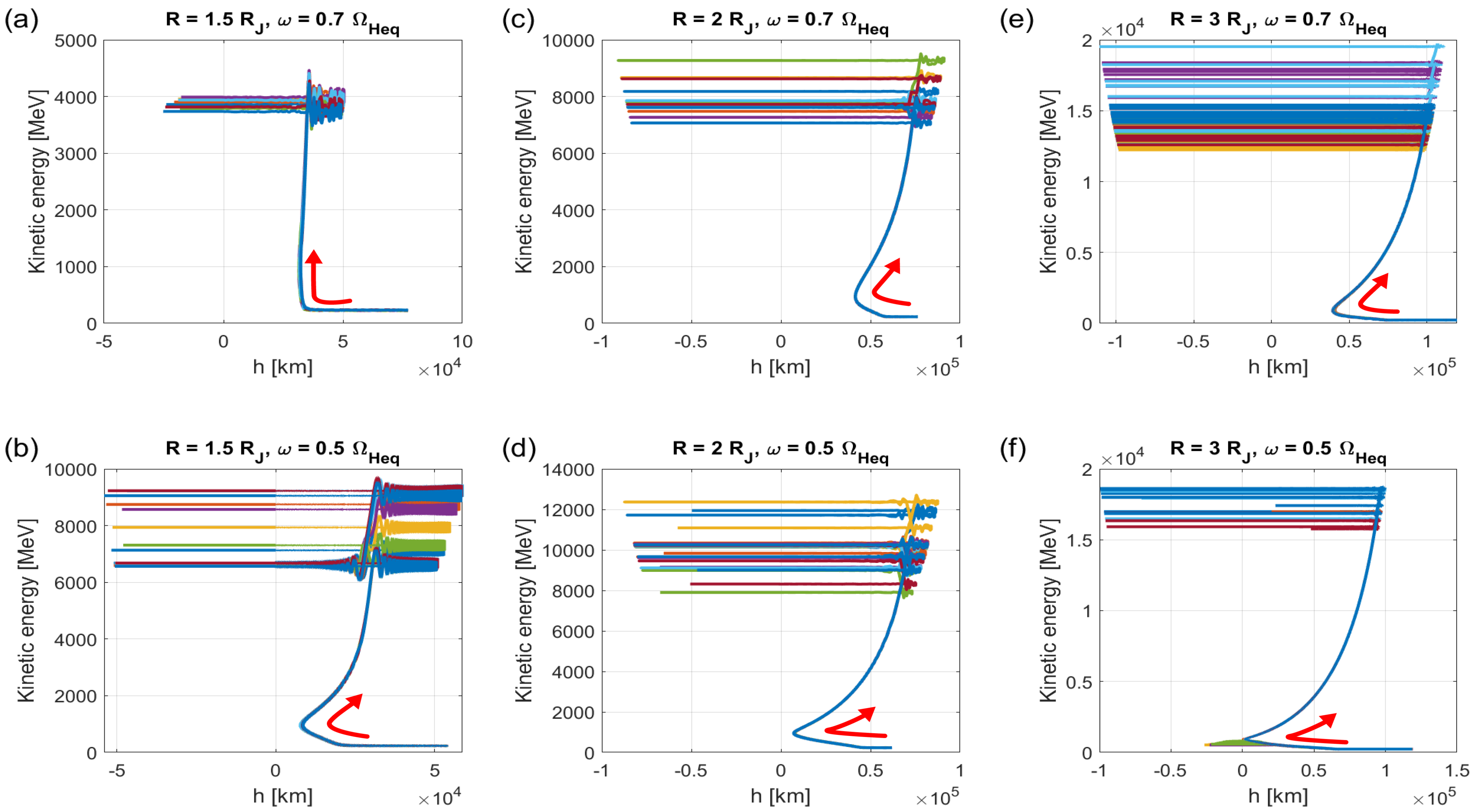
$$F = \frac{\Omega_H \Omega_w^{1/2}}{(\gamma k v_\perp)^{3/2}} = \left[\frac{\Omega_w}{\Omega_H}\left(\frac{V_p - V_R}{v_\perp}\right)^3\right]^{1/2}$$

$F << 1$:
No Anomalous Trapping



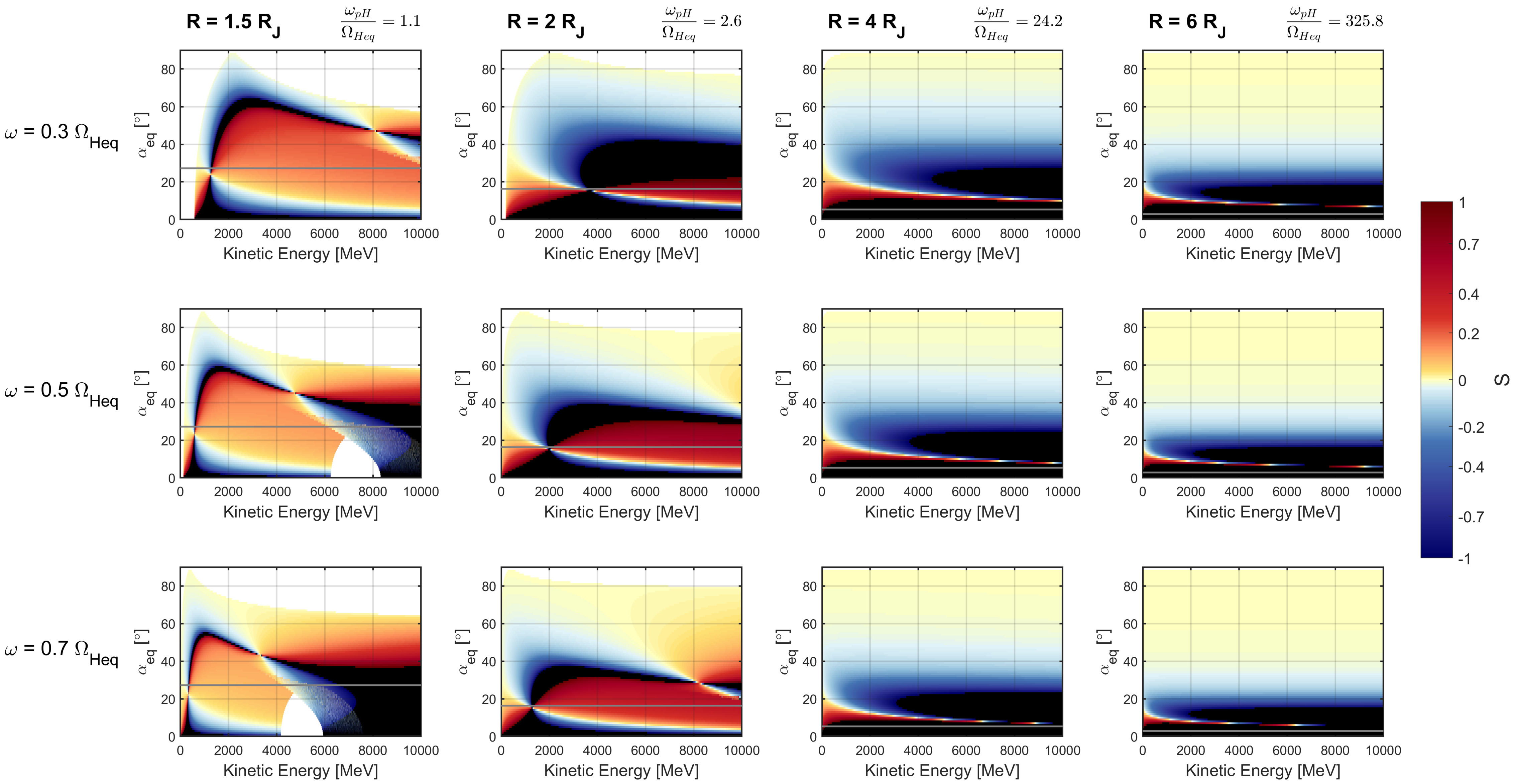
RTA Dependency on Frequency and Radial Distance

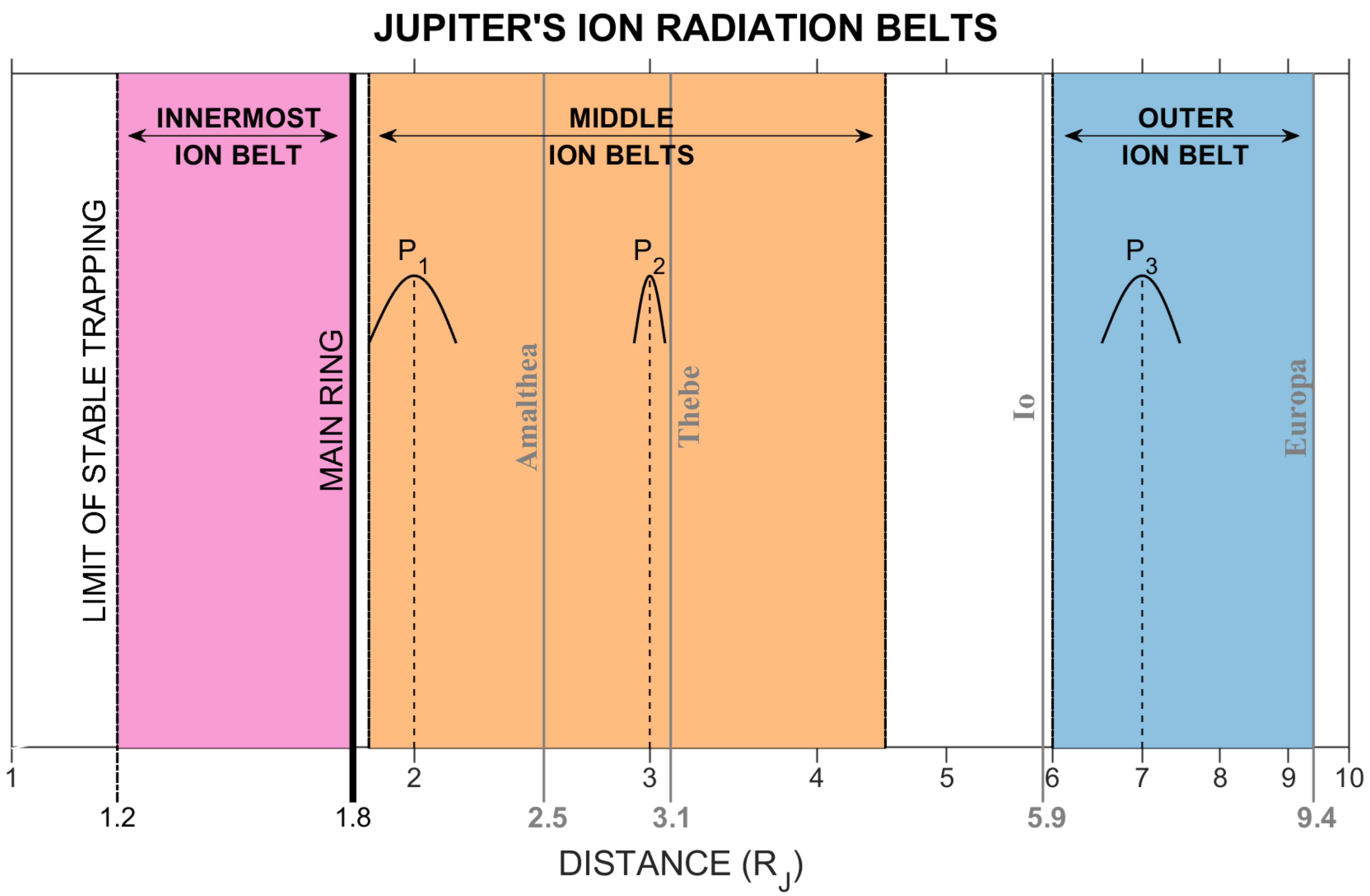
$B_w = 0.02 B_{0eq}$



Inhomogeneity Factor S for Nonlinear Trapping

$$S = \frac{\gamma v_\perp}{2\Omega_H \Omega_w \chi^2} \frac{\partial \Omega_H}{\partial h}$$





JUPITER'S ION RADIATION BELTS
INNERMOST ION BELT
MIDDLE ION BELTS
OUTER ION BELT
LIMIT OF STABLE TRAPPING
MAIN RING
P_1
P_2
P_3
Amalthea
Thebe
Io
Europa
1
2
3
4
5
6
7
8
9
10
1.2
1.8
2.5
3.1
5.9
9.4
DISTANCE (R_J)

Summary

- We have conducted test particle simulations of proton acceleration by EMIC waves in the Jovian magnetosphere.
- Protons with initial energy 240 MeV are accelerated to 10 GeV in by relativistic turning acceleration at $R = 2\ R_j$.
- Effective acceleration is enhanced by anomalous trapping at low pitch angles, while it is limited in the parameter space.

[*Sekine, Omura, Summers, Hsieh, Nakamura, JGR , 2024*]