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Global Transport of Energetic Particles due to Hole-Clump Production

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Particle Transport Mechanisms of Interest

- **Neoclassical:** Large excursions of resonant particles (banana orbits) + collisional mixing
- **Quasilinear:** Phase-space diffusion over a set of overlapped resonances
- **Convective:** Transport of phase-space holes and clumps by modes with frequency chirping

Important Issue: Individual resonances are narrow. How can they affect every particle in phase space?

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Outline

- Quasilinear relaxation near instability threshold
- Phase space holes and clumps (reminder)
- Remnants of frequency sweeping events
- Recurrent production of holes and clumps
- Global redistribution of fast particles

Quasilinear Equations for Bump-on-Tail Instability

- Kinetic equation for fast particles:

$$\frac{\partial F}{\partial t} - \frac{\partial}{\partial V} D \frac{\partial F}{\partial V} = -\nu\left(F - F_0\right)$$

- Wave kinetic equation:

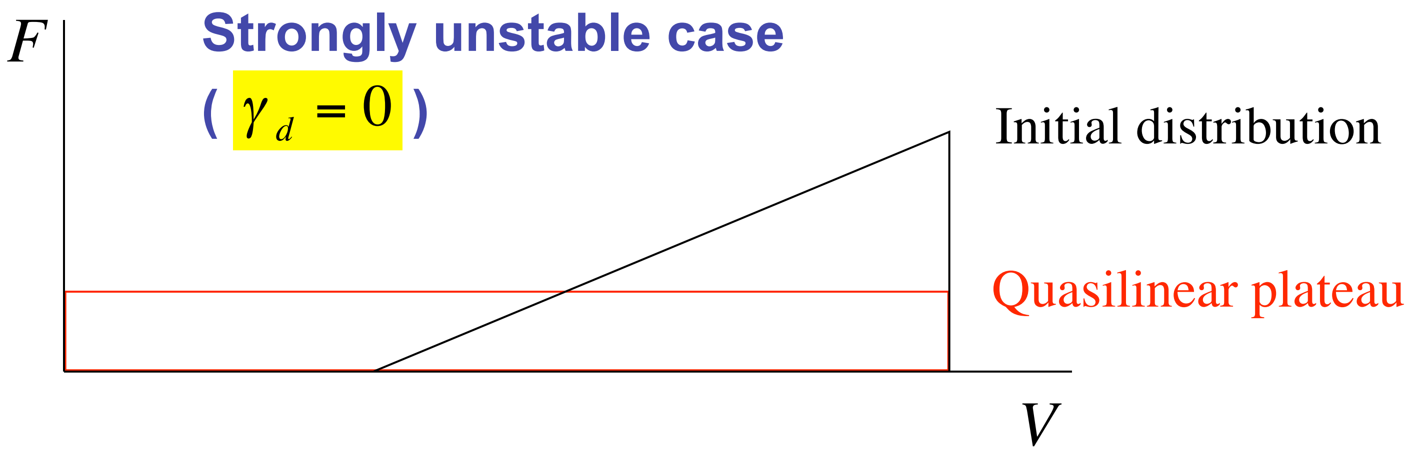
$$\frac{\partial D}{\partial t} = 2\left(\gamma_L - \gamma_d\right) D$$

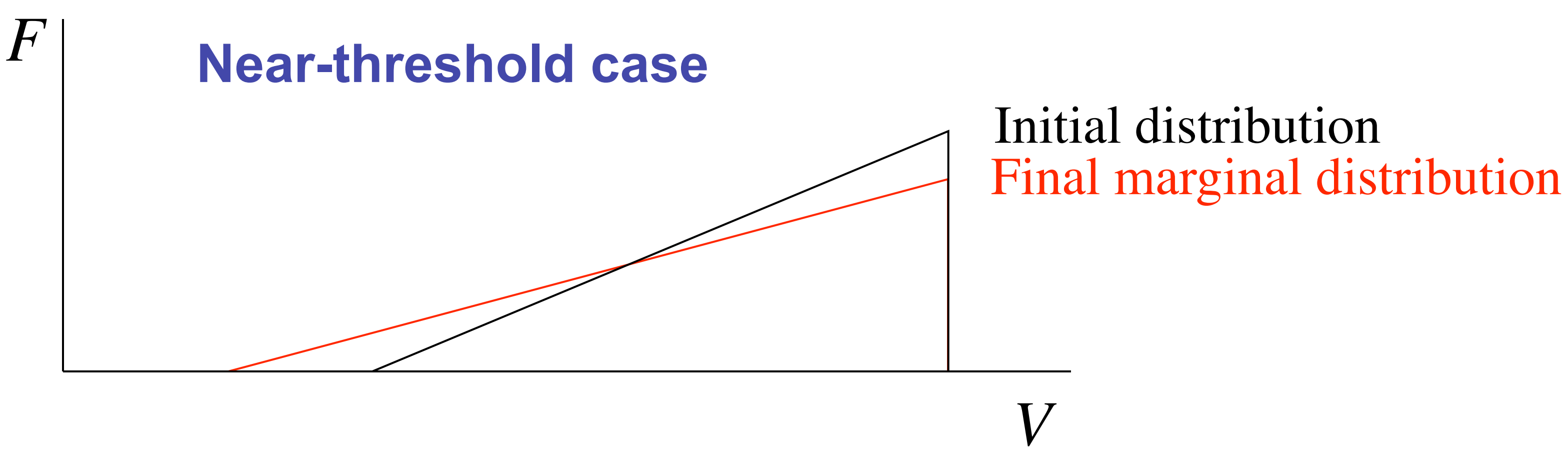
- Instability drive:

$$\gamma_L = \omega_p \frac{\pi}{2n} V^2 \frac{\partial F}{\partial V}$$

- Background damping: γ_d

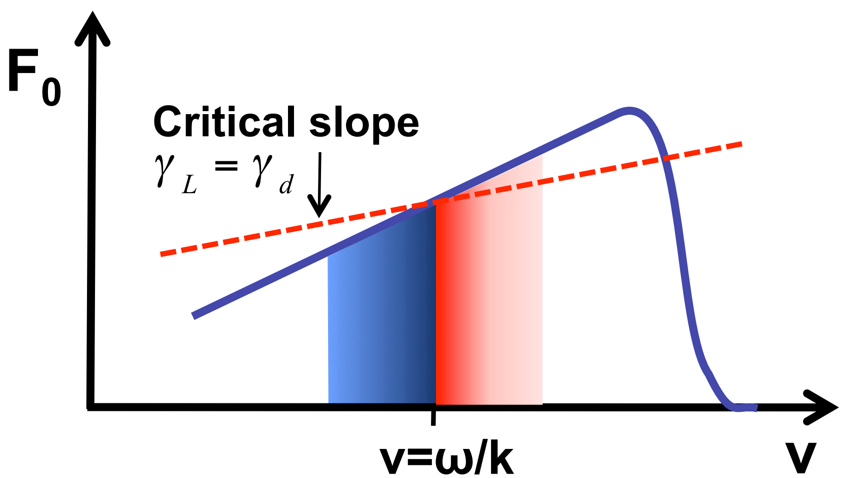
Quasilinear Relaxation

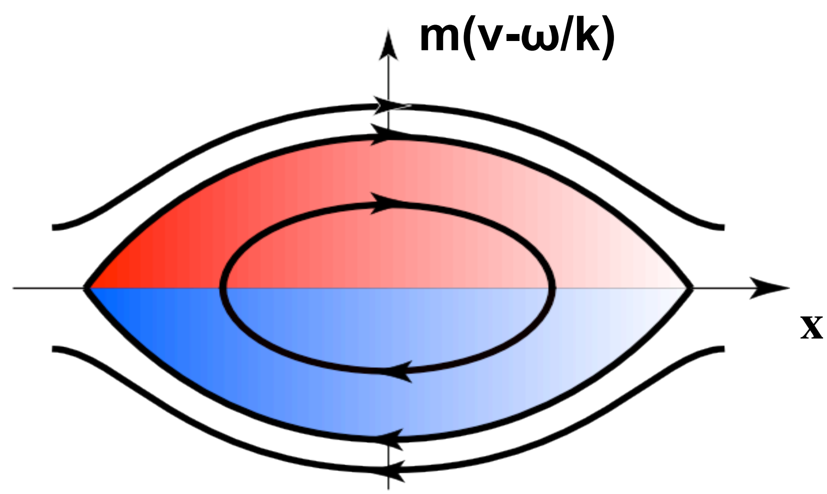




Single Mode Theory

- Unstable initial distribution of energetic particles $F_0(v)$.
- One linearly unstable mode.
- Instability drive, γ_L, due to wave-particle resonance (ω-kv=0).
- Background dissipation rate, γ_d, determines the critical gradient for the instability.





Single Mode Formalism

$$\frac{\partial F}{\partial t} + u\frac{\partial F}{\partial \zeta} + \frac{ek}{2m}\left[\hat{E}(t)e^{i\zeta} + \text{c.c.}\right]\frac{\partial F}{\partial u}$$

$$= \left[\nu^3 \frac{\partial^2}{\partial u^2} + \alpha^2 \frac{\partial}{\partial u} - \beta\right]\left(F - F_0\right)$$

$$\frac{\partial \hat{E}}{\partial t} = -4\frac{\omega}{k^2}\pi e\int f_1\, du - \gamma_d \hat{E}$$

$$u \equiv k\text{v} - \omega$$

$$\zeta \equiv kx - \omega t$$

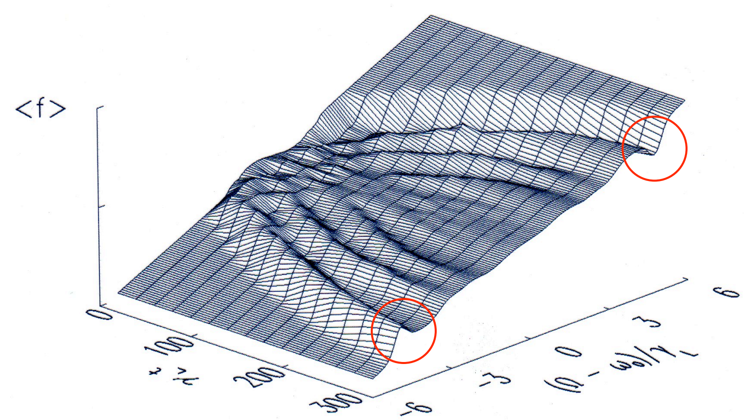
$$F = F_0 + f_0 + \sum_{n=1}^{\infty}\left[f_n \exp(in\zeta) + c.c.\right]$$

$$E = \frac{1}{2}\left[\hat{E}(t)e^{i\zeta} + \text{c.c.}\right]$$

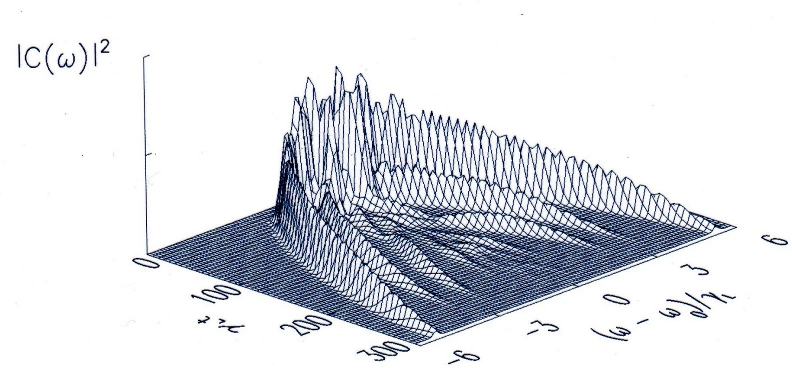
Spontaneous Chirping of Weakly Unstable Mode

- Simulation of near-threshold bump-on-tail instability *(N. Petviashvili, 1997)* reveals spontaneous formation of coherent phase space structures (clumps and holes) with time-dependent frequencies.
- The phase space structures seek lower energy states to compensate energy losses due to background dissipation.
- Clumps move to lower energies and holes move to higher energy regions.

Spatially averaged distribution function



Mode power spectrum



Global Transport Mechanism

- A single hole or clump affects only a small fraction of the energetic particle phase space.

- A sweeping event leaves a dent/bulge in the particle distribution function after the wave field decays.

- Global redistribution requires either many coexisting modes (quasi-linear diffusion scenario) or many sweeping events (this work).

- Holes and clumps can be generated continuously without a source until the distribution changes globally.

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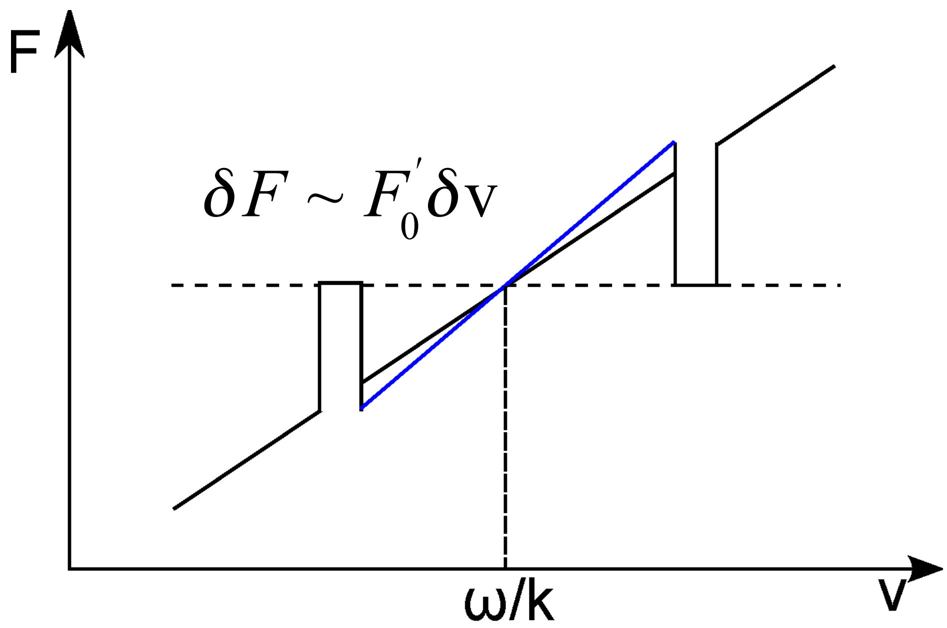
Dynamics of Holes and Clumps at Early Times

- Holes/clumps are the original resonant particles
- They move slowly compared to the bounce period



- The wave amplitude is constant:

$$\omega_B = \left(16/3\pi^2\right)\gamma_L$$

- Particles cant get inside separatrix.
- Hole/clump gets deeper/ higher as it moves:

$$\delta\omega = \left(16/3\pi^2\right)\gamma_L\sqrt{2\gamma_d t/3}$$

H.L. Berk, B.N. Breizman, N.V. Petviashvili, Phys. Lett. A ***234****, 213 (1997)*

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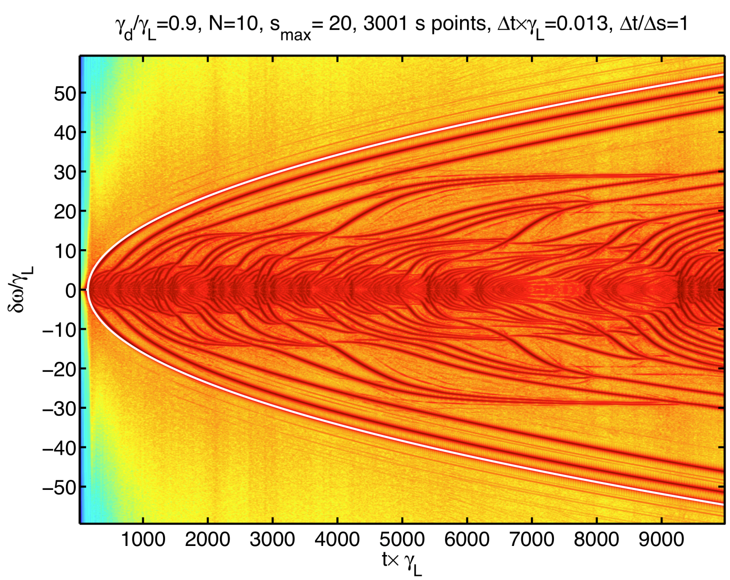
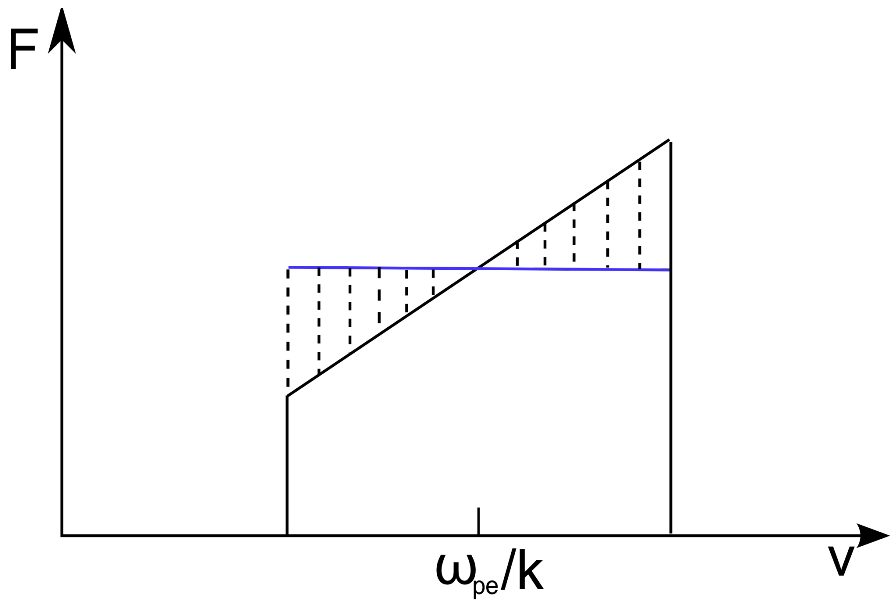
Global Relaxation via Recurrent Sweeping

- Sweeping modes arise continuously without a source
- Each mode creates a narrow distortion in the particle distribution
- The distribution remains perturbed after the mode dies
- ”Stacked up” holes and clumps modify the distribution globally





M.K. Lilley, B.N. Breizman, S.E. Sharapov, Phys. Plasmas (2010)

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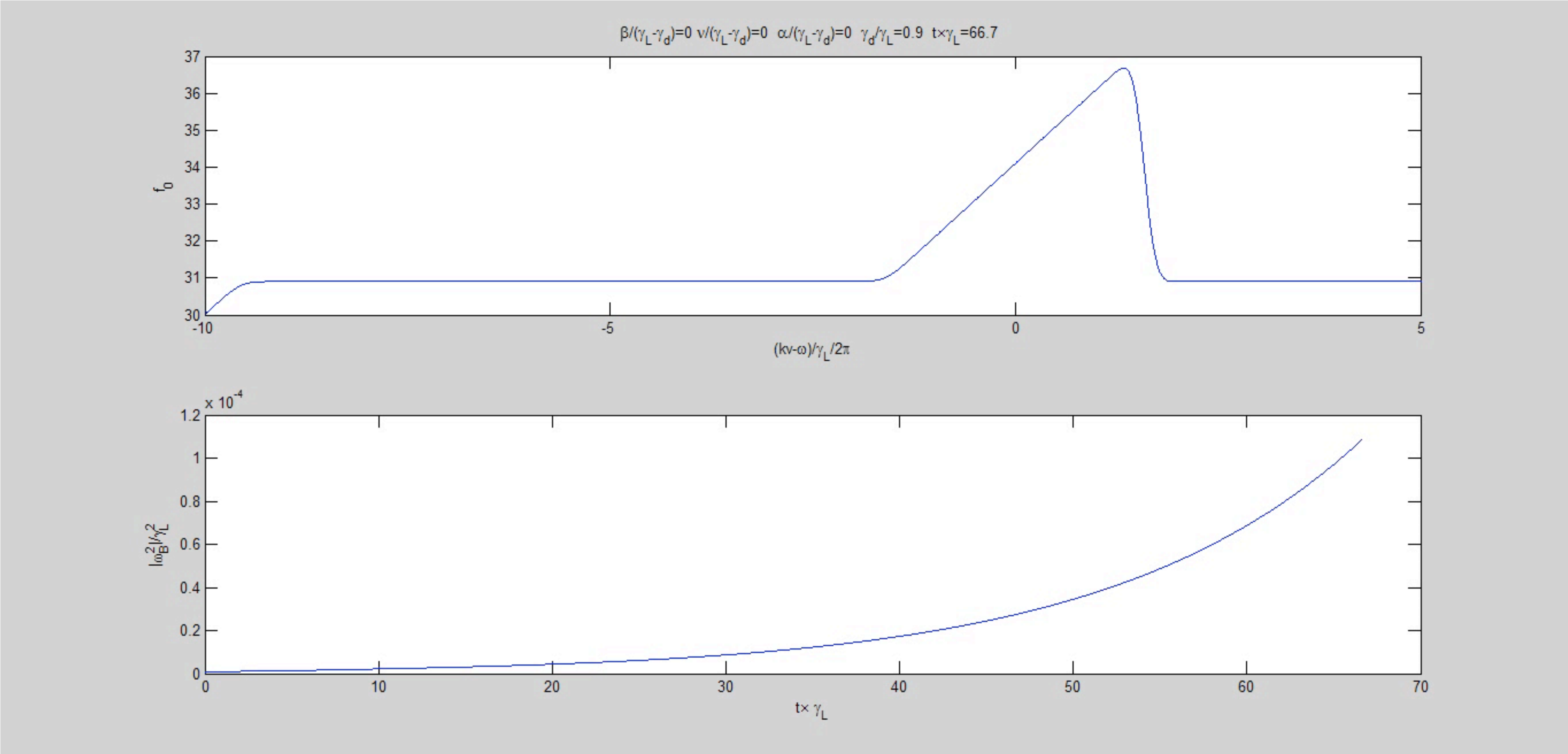
Dynamics of Global Relaxation



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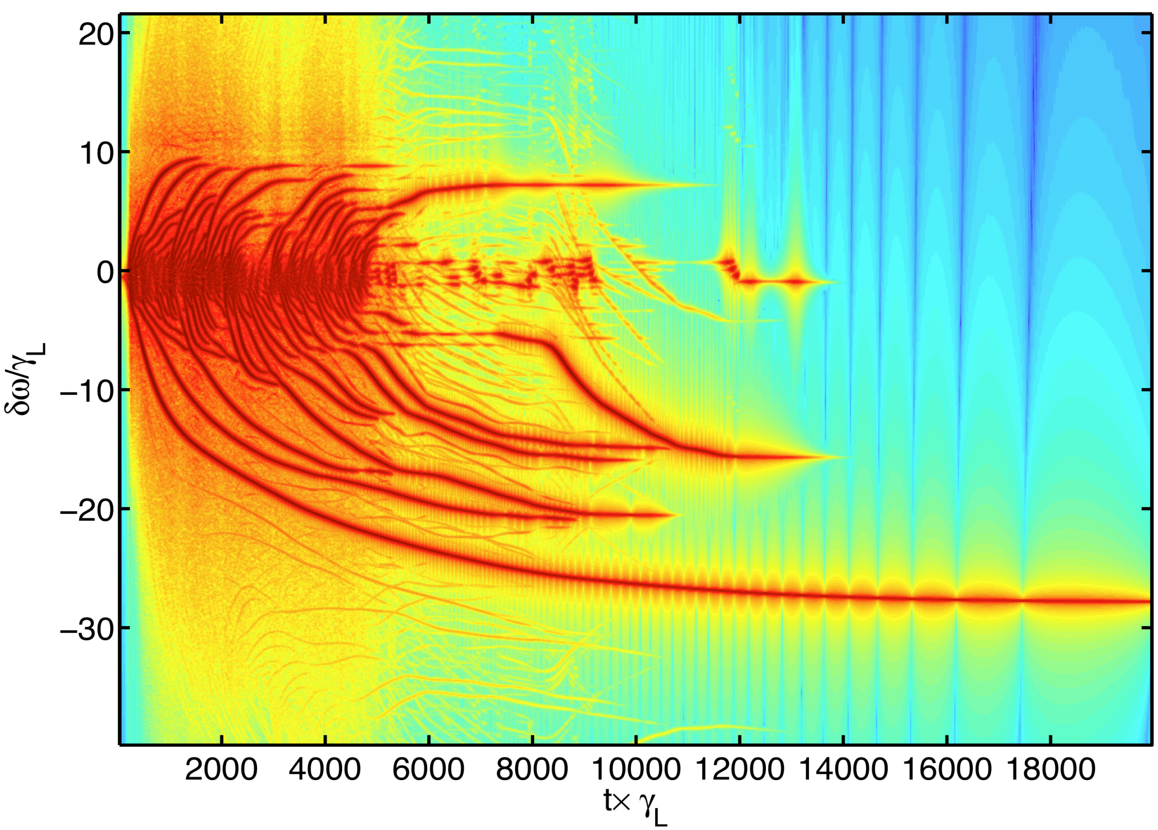
Wave Spectrum During Global Relaxation



Conclusions

- ❑ An isolated resonance can generate recurrent frequency sweeping events that lead to global change in the fast particle distribution.

- ❑ This transport mechanism is convective and it can be more efficient than quasilinear diffusion in the near-threshold regime.

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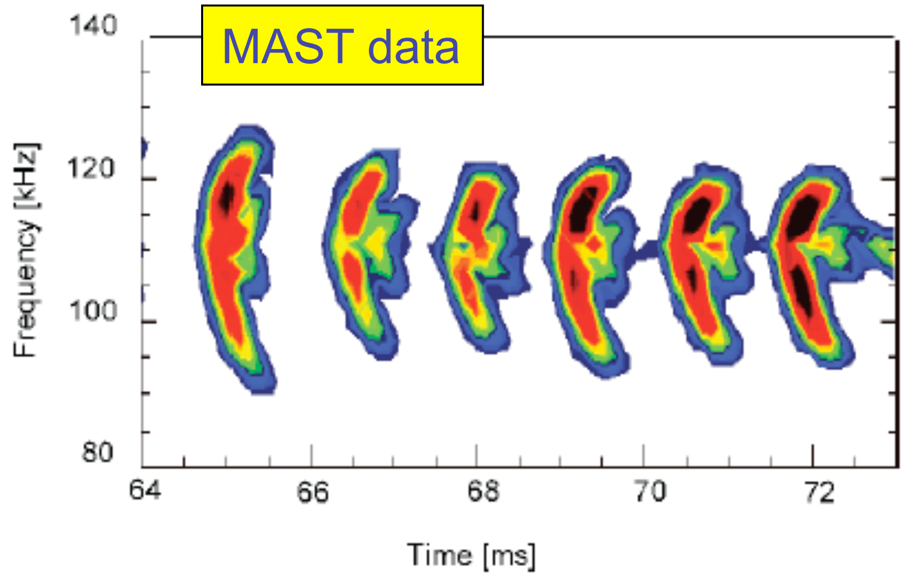
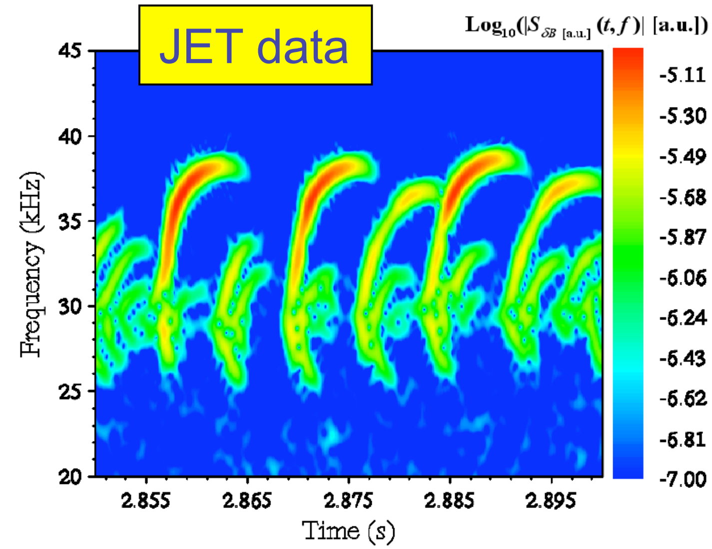
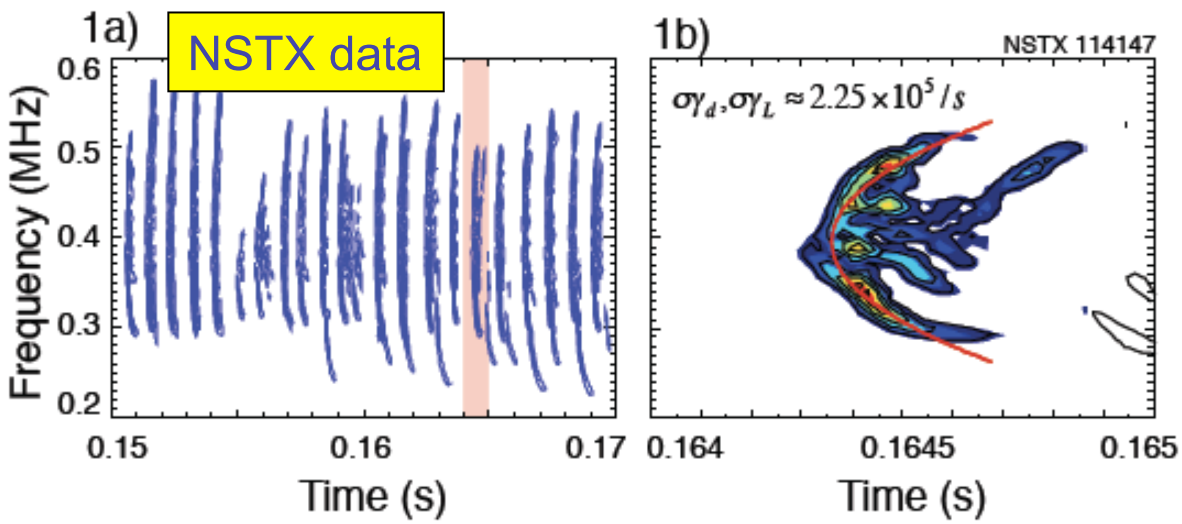
Rapid Frequency Chirping Events







The ms timescale of these events is much shorter than the plasma energy confinement time

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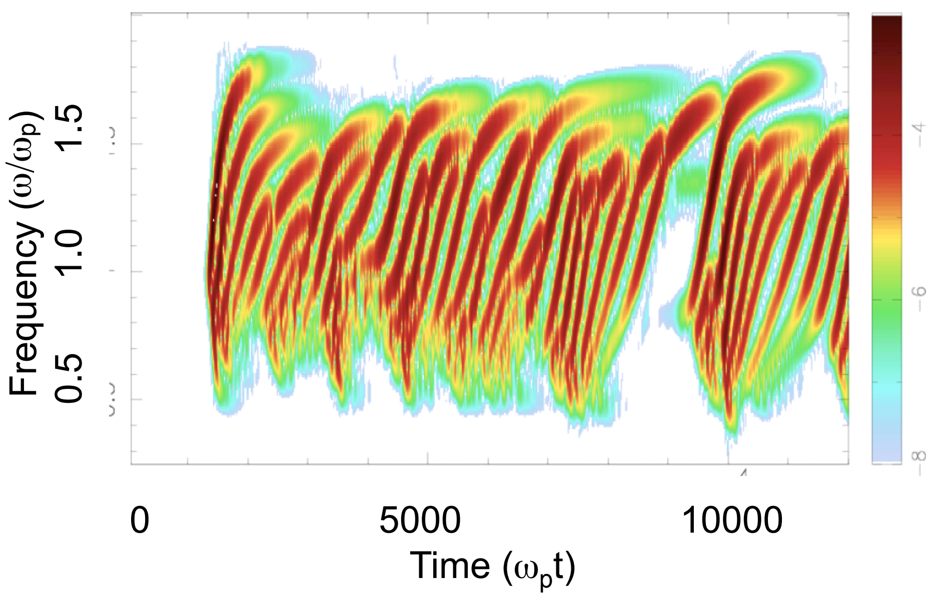
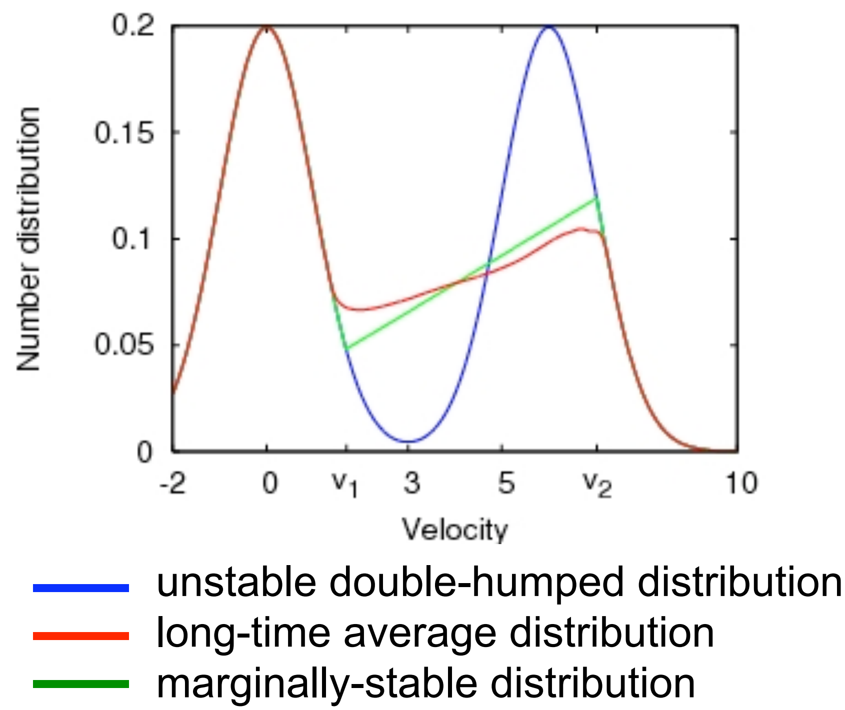
Recurrent Chirping Events Maintain Marginally Stable Distribution

Relaxation of unstable double-humped distribution, with source,sink, and background plasma dissipation.

R.Vann, et al., PRL ***99,*** *025003 (2007)*





Chirping events facilitate energy exchange between the energetic particles and the bulk plasma.

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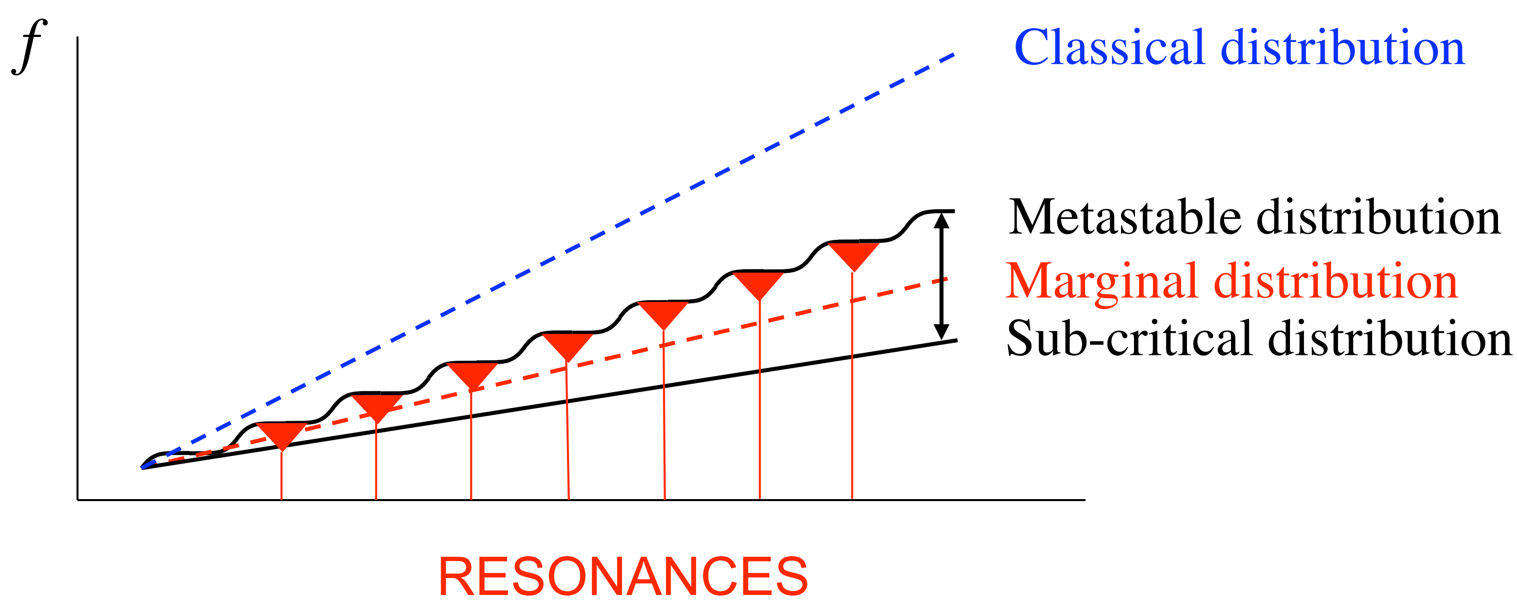
Intermittent Quasilinear Diffusion

A weak source (with insufficient power to overlap the resonances) is unable to maintain steady quasilinear diffusion

Bursts occur near the marginally stable case



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Time Scales and Mode Evolution Phases

γ_L - linear growth rate due to resonant particles

γ_d - background damping rate due to bulk plasma

ω_b - trapped particle bounce frequency

1. Linear near-threshold instability
(excitation of a plasma eigenmode)

$$\tau_1 \sim 1/(\gamma_L - \gamma_d) << 1/\omega_b$$

2. Explosive nonlinear growth of the mode
Formation of phase-space holes and clumps with trapped particles
Initiation of frequency sweeping

$$\tau_2 \sim 1/\gamma_L \sim 1/\omega_b$$

3. Slow (adiabatic) evolution of phase-space holes and clumps
Significant frequency sweeping
Transition from the bulk plasma eigenmode to a beam mode

$$\tau_3 >> 1/\gamma_L \sim 1/\omega_b$$

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