Nonlinear Fishbone Dynamics in Spherical Tokamaks with Toroidal Rotation

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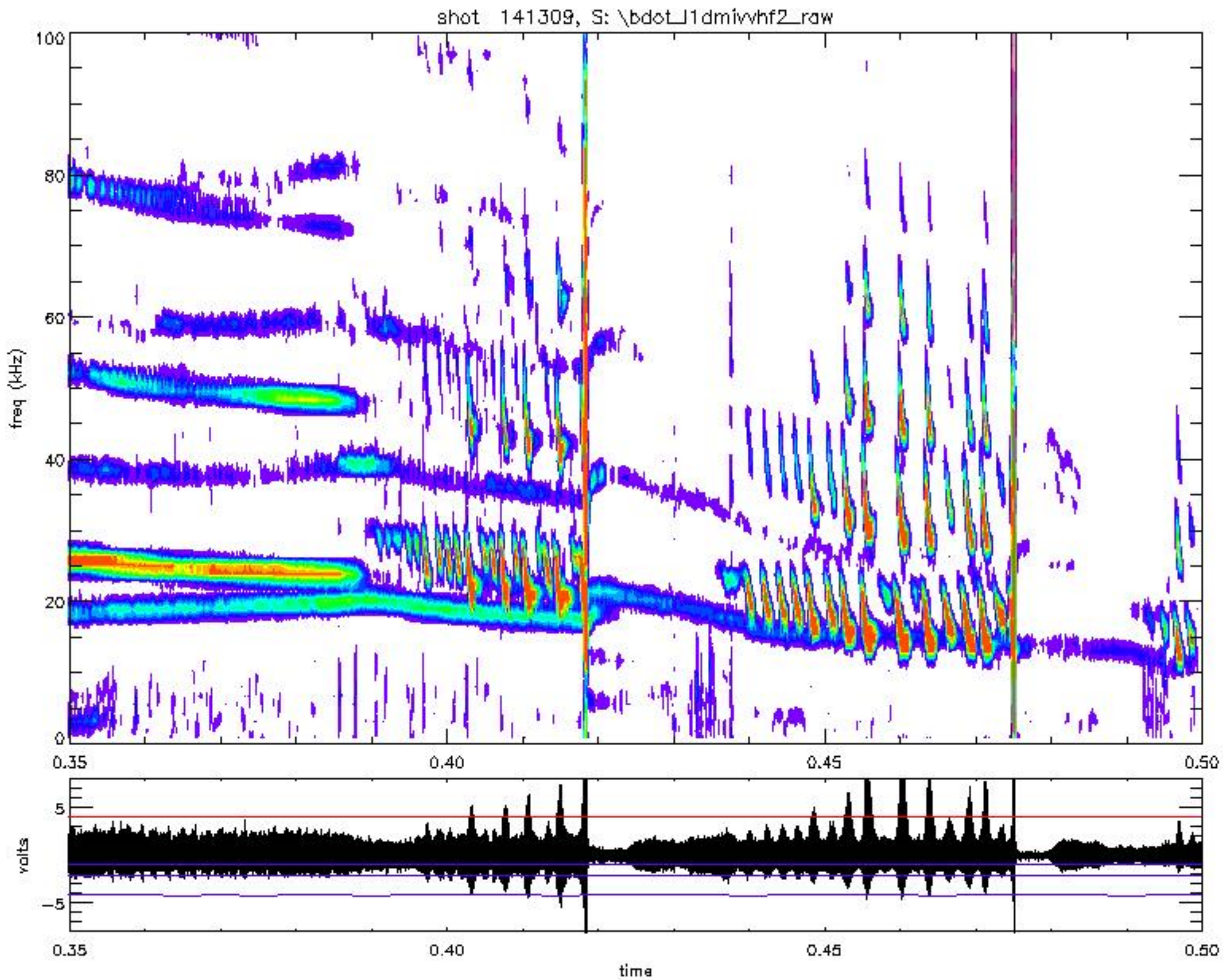
Outline

1. Motivation and introduction
2. Fishbone linear stability with toroidal rotation
3. Fishbone nonlinear dynamics
4. Conclusions

Motivation

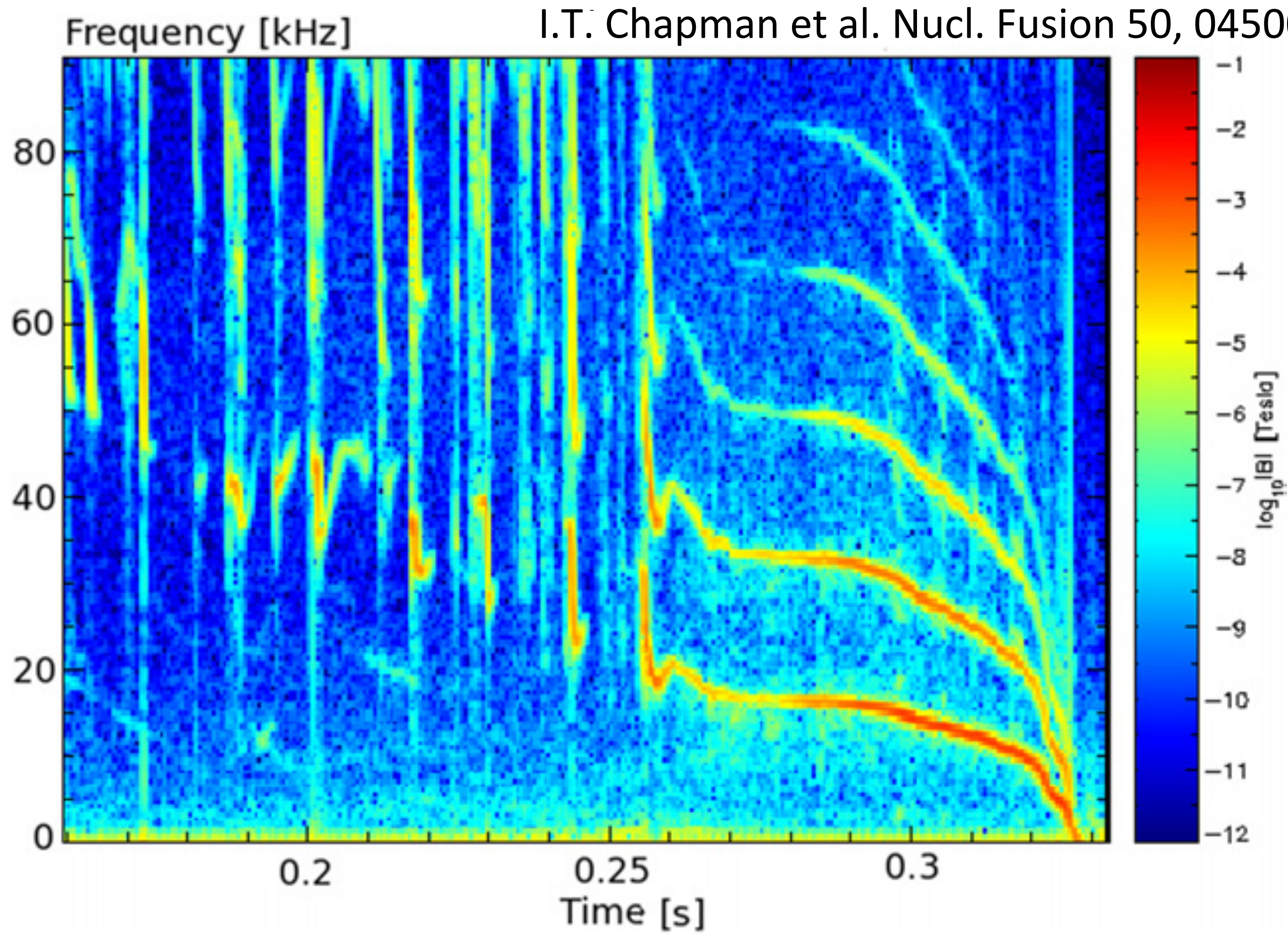
- Energetic particle (EP)-driven instabilities can induce significant alpha particle redistribution and losses to the first wall of fusion reactors;
- Energetic particle can interact with thermal plasma strongly: affect equilibrium, stability and transport. EP physics is a key element for understanding and controlling burning plasmas.
- Fishbone is one of the most important energetic particle driven mode in tokamak plasmas, which has global mode structure, and can limit plasma performance.
- M3D-K simulations of beam-driven modes in NSTX are carried out for code validation and physics understanding.

Beam-driven fishbones are routinely observed in NSTX



Fishbone and NRK (LLM) were observed in STs and tokamaks

I.T. Chapman et al. Nucl. Fusion 50, 045007 (2010)



M3D-K is a global nonlinear kinetic/MHD hybrid simulation code for toroidal plasmas

G.Y. Fu, J. Breslau, L. Sugiyama, H. Strauss, W. Park, F. Wang et al.

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

$$\mu_0 \mathbf{J} = \nabla \times \mathbf{B}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{J}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\rho \frac{d\mathbf{v}}{dt} = \mathbf{J} \times \mathbf{B} - \nabla p + \mu \nabla^2 \mathbf{v}$$

$$\frac{dp}{dt} = -\gamma p \nabla \cdot \mathbf{v} + \rho \nabla \cdot \left(\kappa \cdot \nabla \frac{p}{\rho} \right)$$

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{J} \times \mathbf{B} - \nabla \cdot \mathbf{P_h}$$

$$\mathbf{P_h} = P_\perp \mathbf{I} + (P_\parallel - P_\perp)\mathbf{bb}$$

$$P_\parallel(\mathbf{x}) = \int M v_\parallel^2 \delta(\mathbf{x} - \mathbf{X} - \rho_\mathbf{h}) F(\mathbf{X}, v_\parallel, \mu) d^3\mathbf{X} dv_\parallel d\mu d\theta$$

$$P_\perp(\mathbf{x}) = \int \frac{1}{2} M v_\perp^2 \delta(\mathbf{x} - \mathbf{X} - \rho_\mathbf{h}) F(\mathbf{X}, v_\parallel, \mu) d^3\mathbf{X} dv_\parallel d\mu d\theta$$

$$F = F(\mathbf{X}, v_\parallel, \mu) = \sum_i \delta(\mathbf{X} - \mathbf{X_i}) \delta(v_\parallel - v_{\parallel,i}) \delta(\mu - \mu_i)$$

$$\frac{d\mathbf{X}}{dt} = \frac{1}{B^{**}} \left[v_\parallel \left(\mathbf{B}^* - \mathbf{b_0} \times \left(\langle \mathbf{E} \rangle - \frac{1}{e} \mu \nabla (B_0 \langle \delta B \rangle) \right) \right) \right]$$

$$m \frac{dv_\parallel}{dt} = \frac{e}{B^{**}} \mathbf{B}^* \cdot \left(\langle E \rangle - \frac{1}{e} \mu \nabla (B_0 - \langle \delta B \rangle) \right)$$

$$\dot{\mu} = 0$$

- The energetic particle stress tensor, P_h, is calculated using drift kinetic or gyro-kinetic equation via PIC.
- Mode structures are evolved self-consistently including non-perturbative effects of energetic particles.
- Include plasma rotation.

G.Y. Fu et al, PHYSICS OF PLASMAS 13, 052517 (2006)

Previous work:

Linear stability and nonlinear dynamics of the fishbone mode in spherical tokamaks

F. Wang, G.Y. Fu, J. Breslau, J.Y. Liu, Phys. Plasmas 2013

- We consider NSTX plasmas with a weakly reversed q profile and q_{min} close but above unity. For such q profile, fishbone and non-resonant kink mode (NRK) have been observed in NSTX and MAST.

- M3D-K simulation results show that both NRK and fishbone can be unstable in such profile. A fishbone instability preferentially excited at higher $q_{min,}$ which consistent with the observed appearance of the fishbone before the "long-loved mode" in MAST and NSTX experiments.

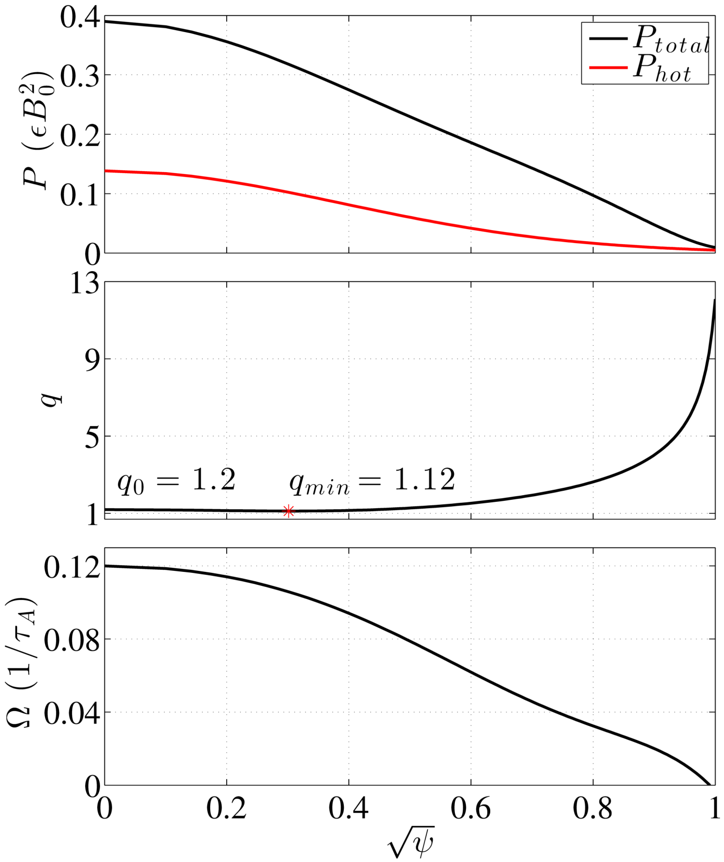
- Nonlinear simulations show that an m/n=2/1 magnetic island is found to be driven by the fishbone instability, which could provide a trigger for the NTM.

New results in this work

- Effects of toroidal rotation on linear stability.

- Particles nonlinear phase space dynamics, frequency chirping.

Equilibrium profile and parameters



NSTX #124379 at t=0.635s

B_0=0.44T, R=0.86m, a=0.60m

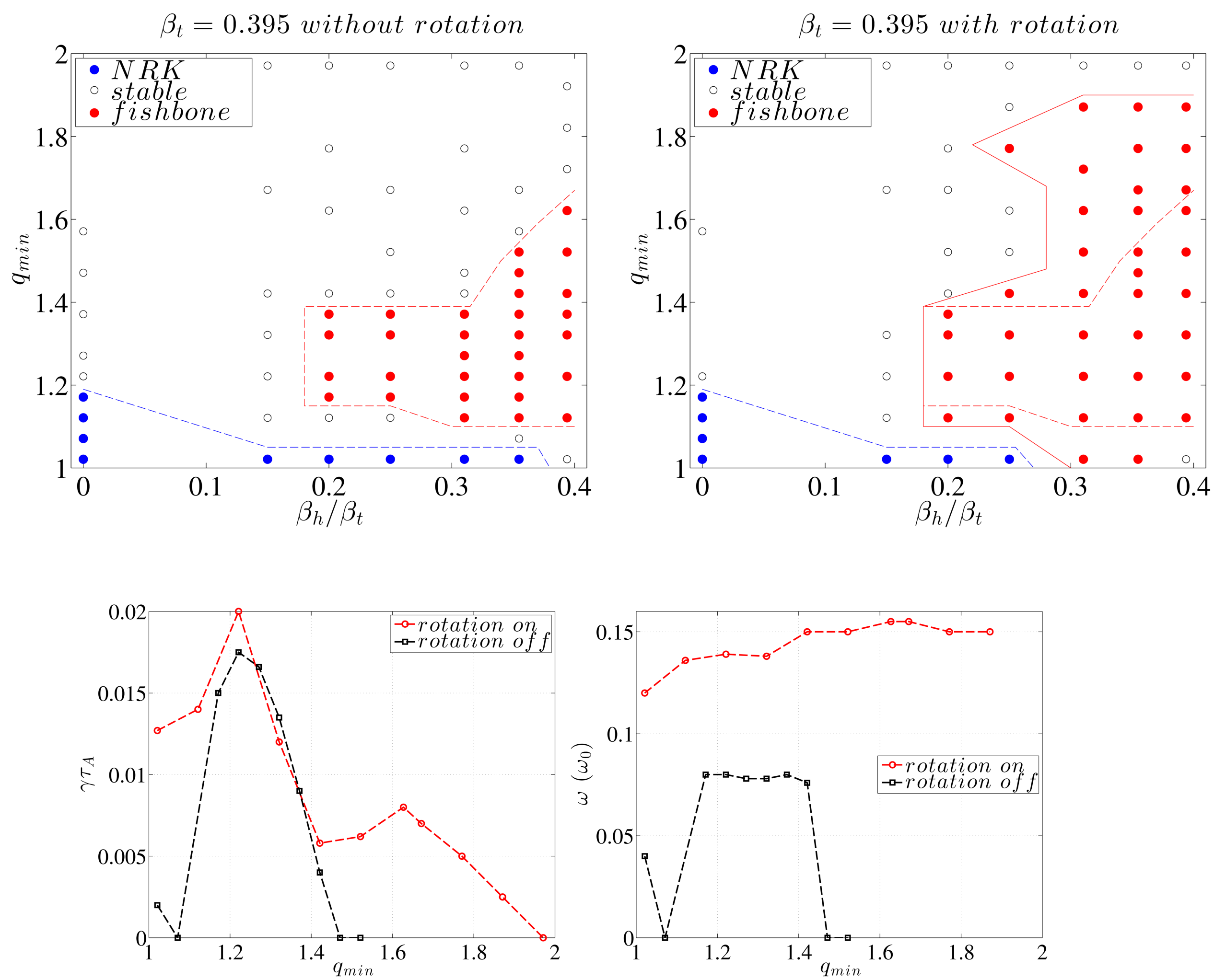
$n_e(0)$=9.3 x 10^{13} cm^{-3}

$\beta_{tot}(0)$=30%

Analytic fast ion distribution with

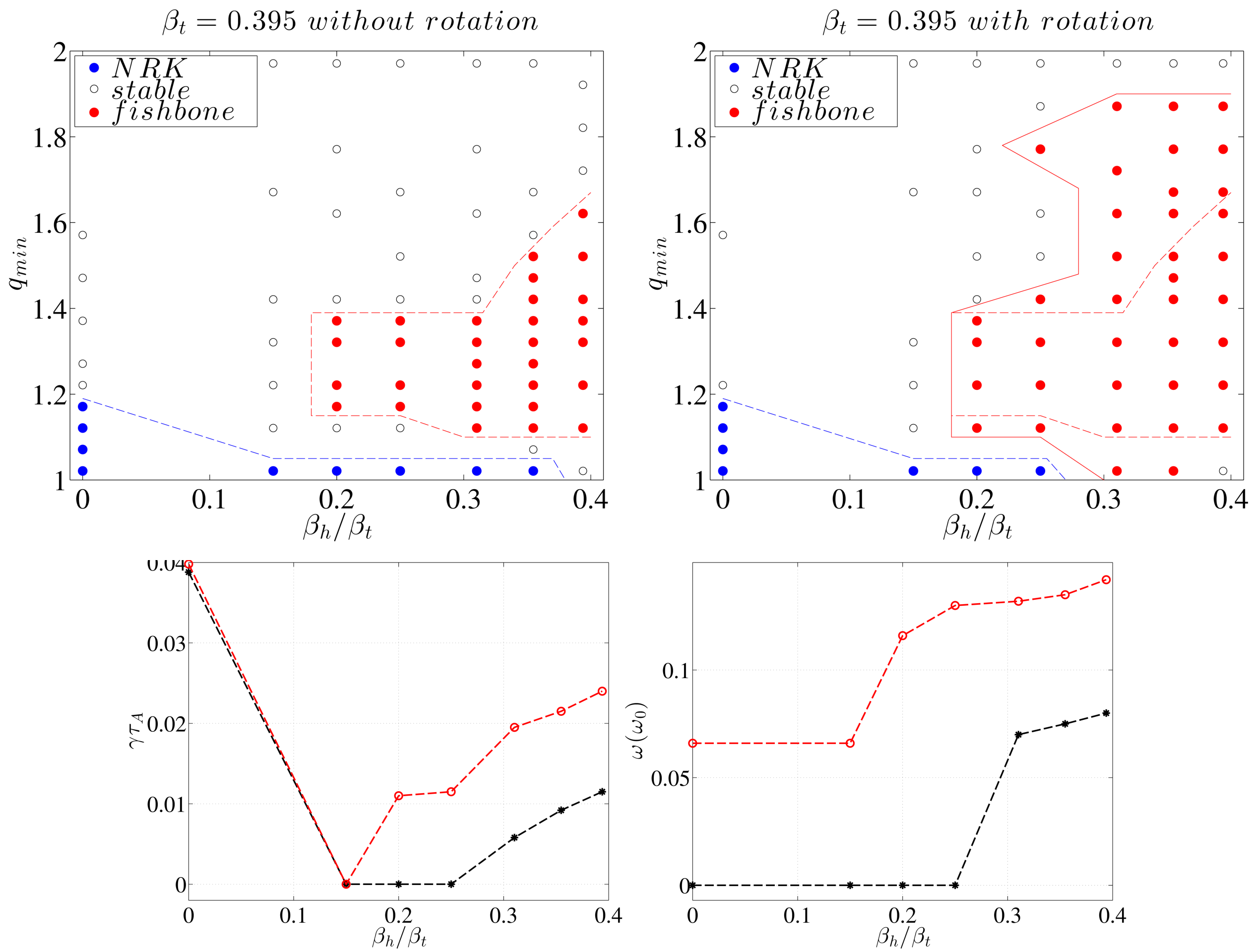
$$\lambda \equiv \frac{v_\parallel}{v} \simeq 0.6$$

Rotation effect is destabilizing for fishbone at higher q_{min} .



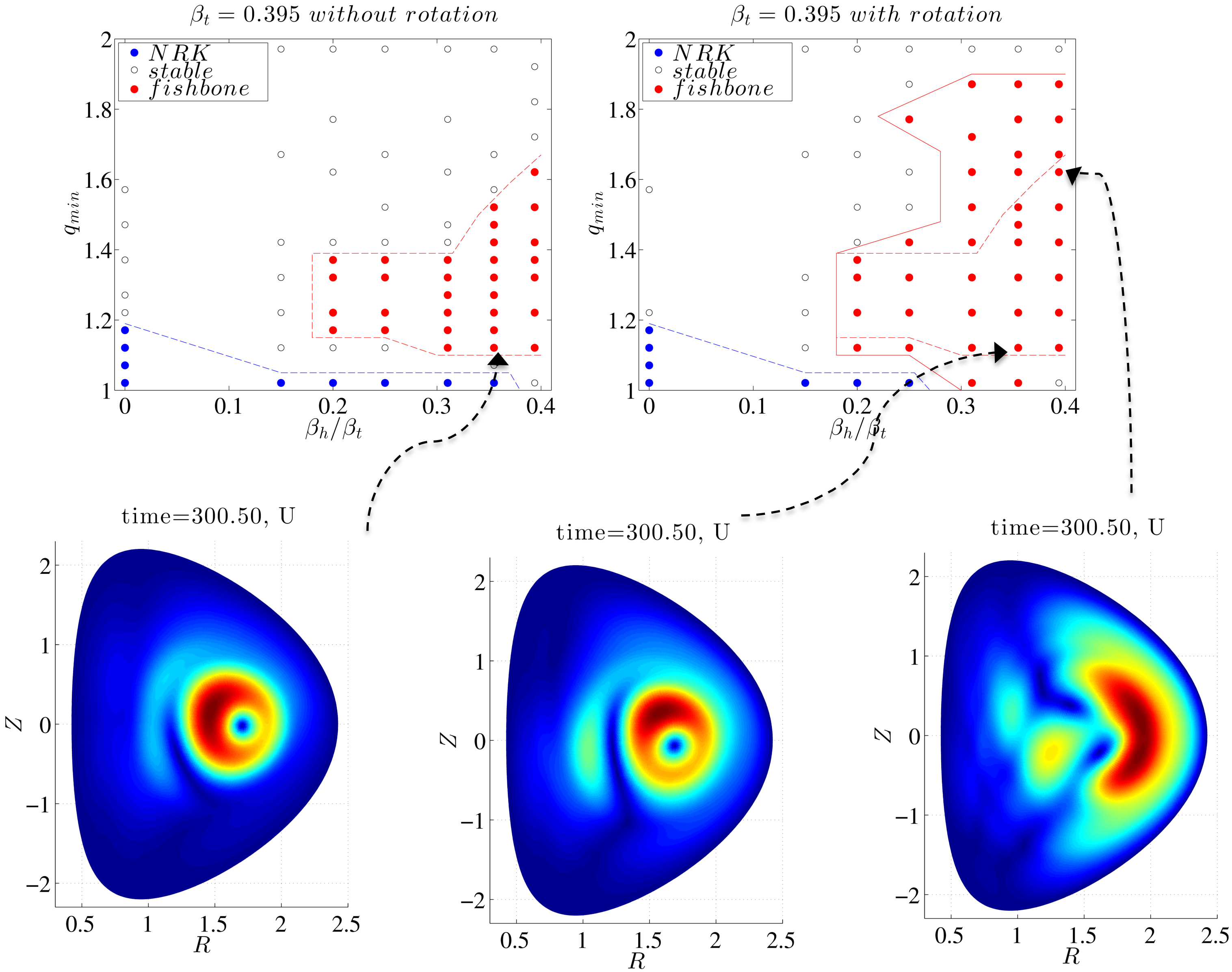
β_h/β_t=0.35

Rotation effect is destabilizing for fishbone at lower q_{min} .

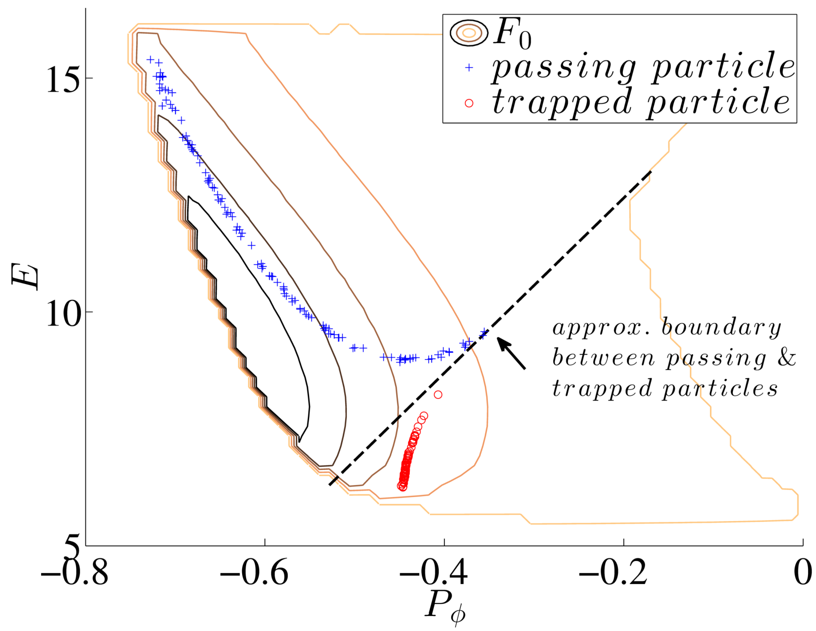


q_{min}=1.121

The mode structure is different at low q_{min} and high q_{min}. At high q_{min}, the m/n=2/1 component becomes more important, and the mode has strong ballooning feature



Passing and trapped linear resonant particles in phase space



$q_{min} = 1.321$, $\beta_h/\beta_t = 0.2$ and $\mu = [7.2, 7.3]$ (E, P_ϕ and μ are in code units).

The main resonance for passing particles is:

$$\omega - \omega_\phi - \omega_\theta = 0$$

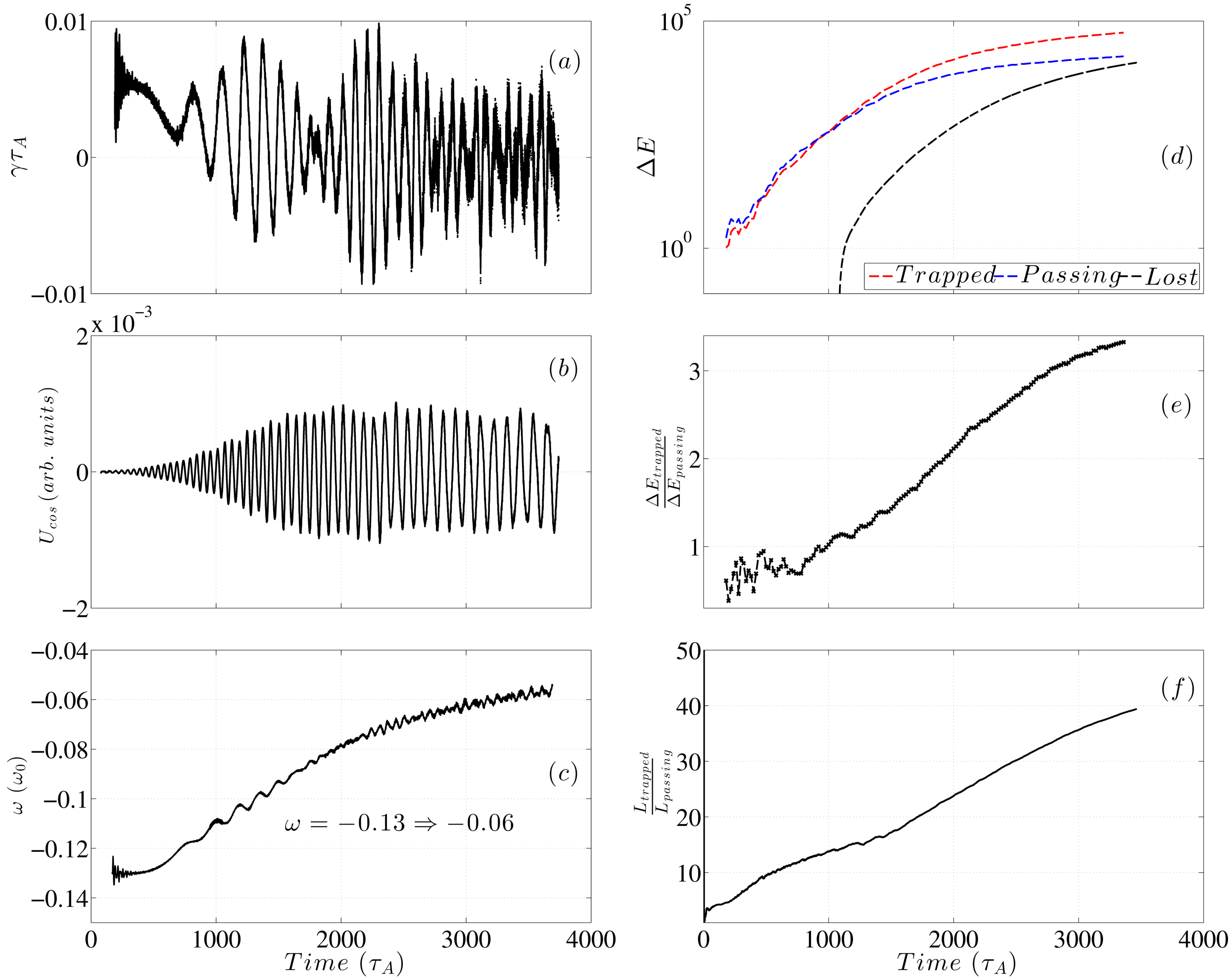
ω_θ and ω_ϕ are poloidal and toroidal transit frequency.

For trapped particles, the main resonance condition is:

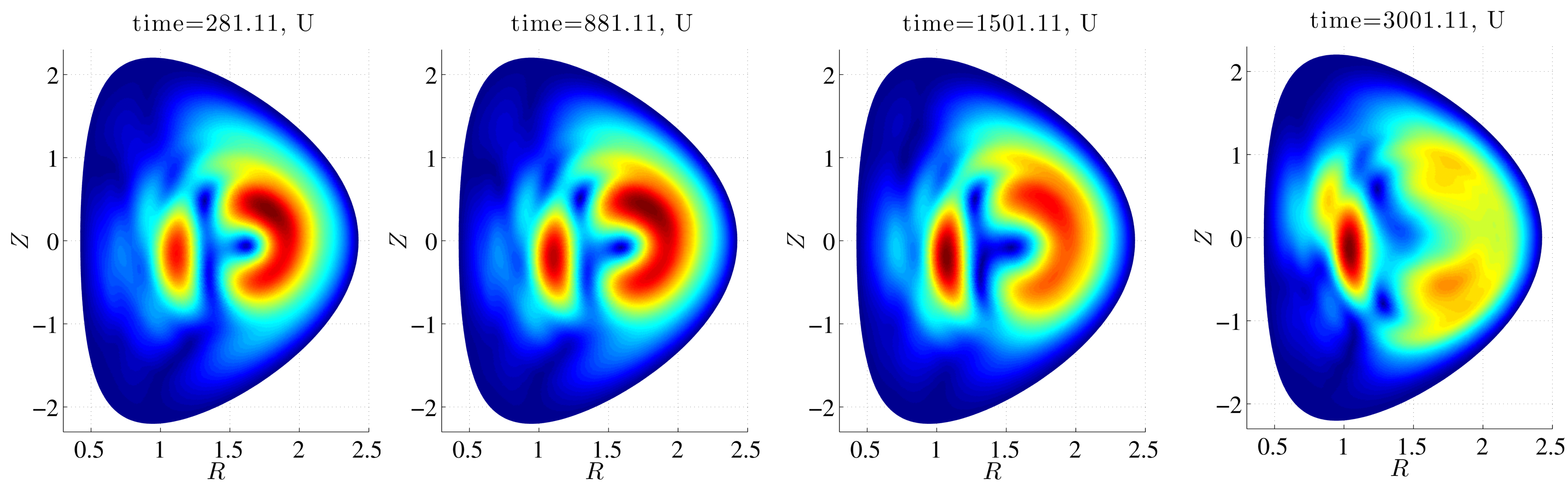
$$\omega = \omega_d$$

where ω_d is the toroidal precession drift frequency.

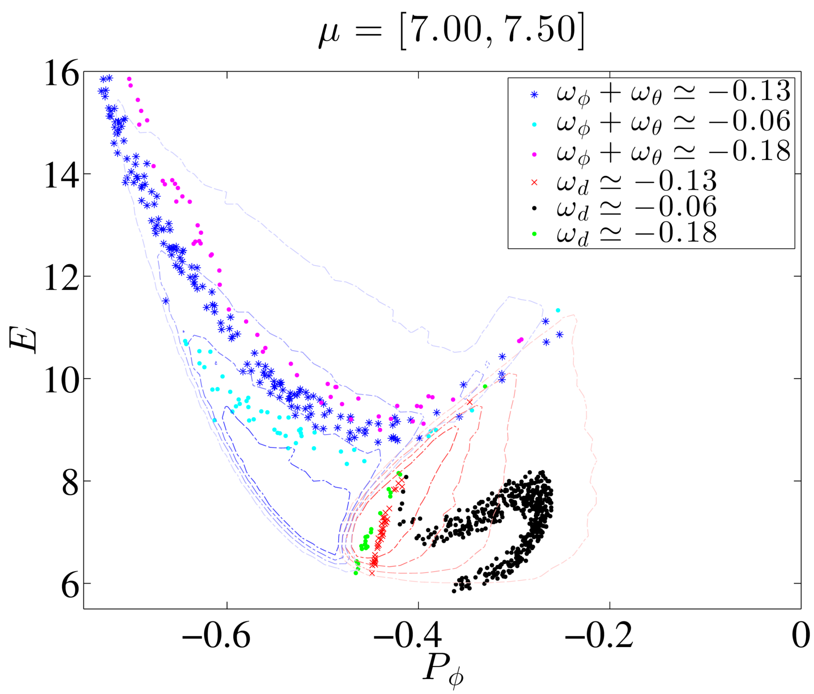
Fishbone nonlinear dynamics
linearly, both passing and trapped particles have contribution to drive the mode.

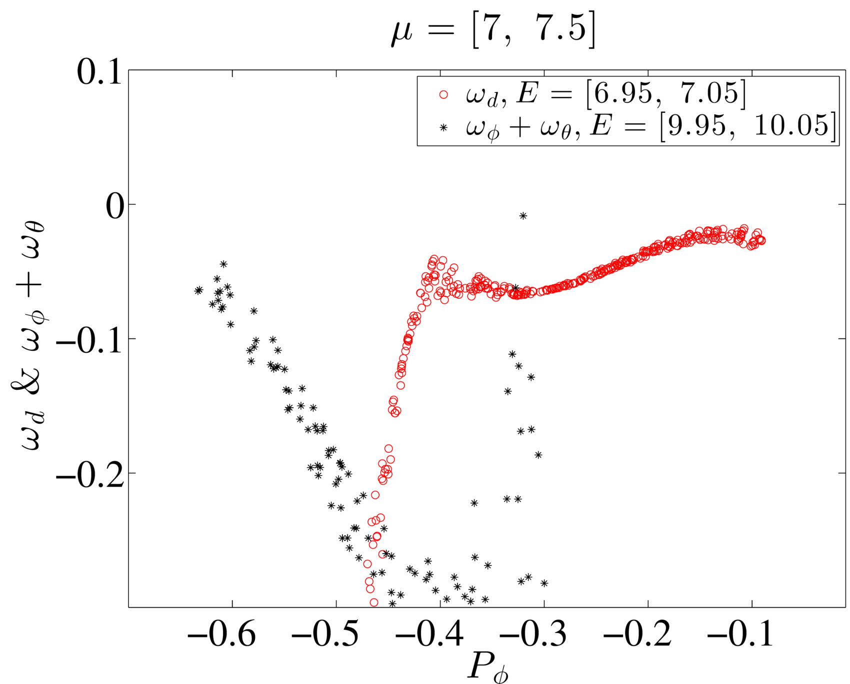


Mode structure broaden at low field side nonlinearly.



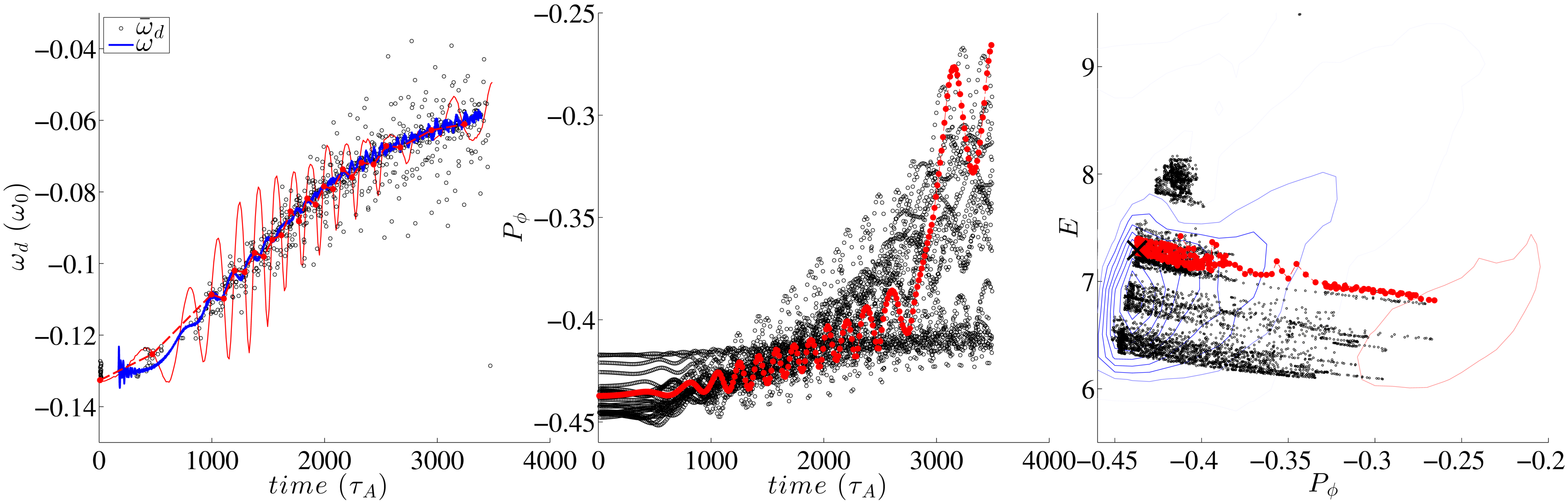
The key difference between passing and trapped particles: trapped particles drift frequency decreases as P_Φ increases, and passing particles are in the opposite.



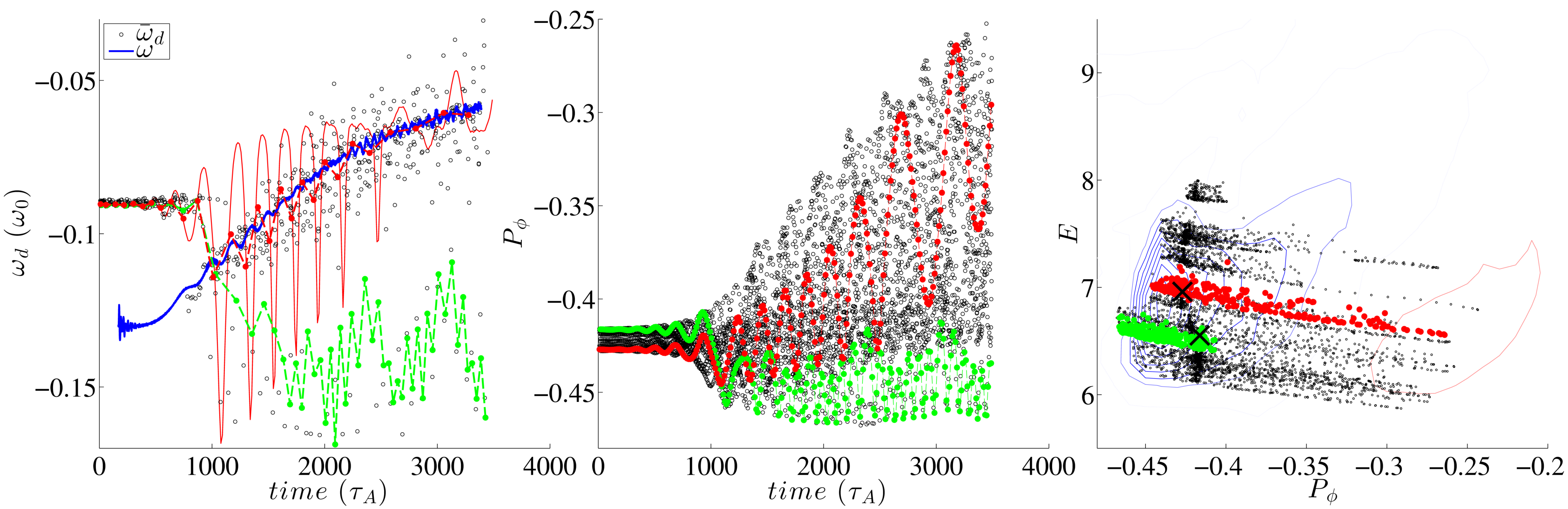


Unperturbed trapped and passing resonance particles and near resonance particles:

Nonlinear dynamic of trapped particles with initial frequency close to the linear mode frequency: almost all of those particles stay in resonance.

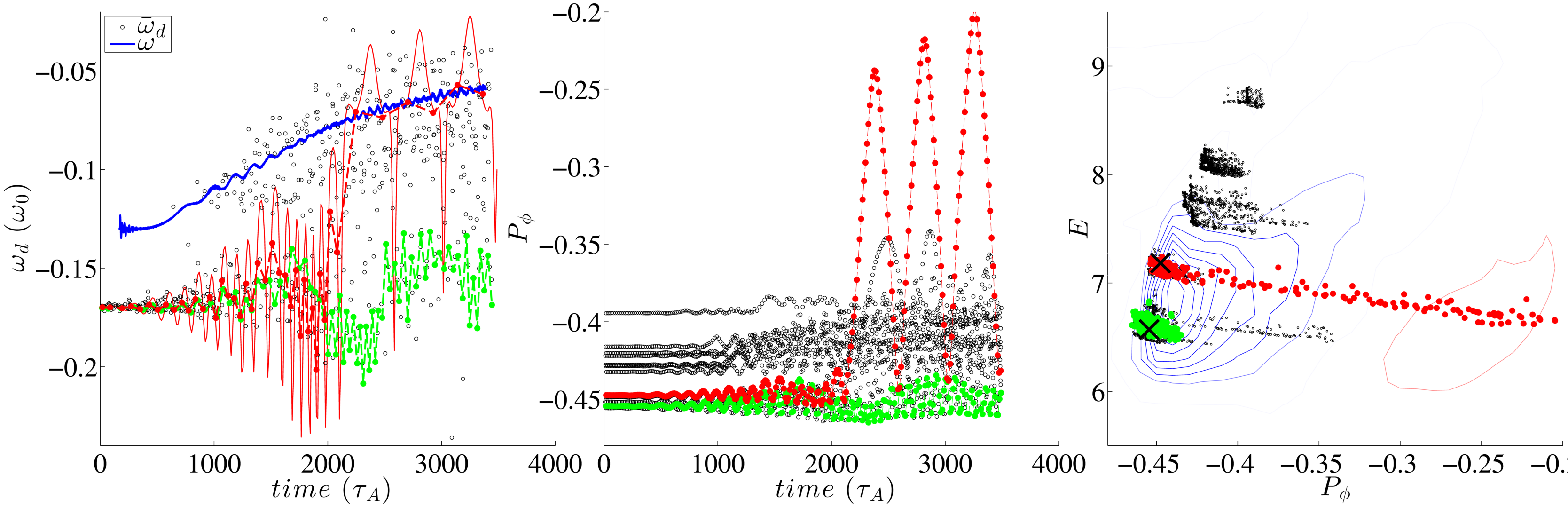


Nonlinear dynamic of trapped particles with initial frequency less than the linear mode frequency, most of those particles become resonant



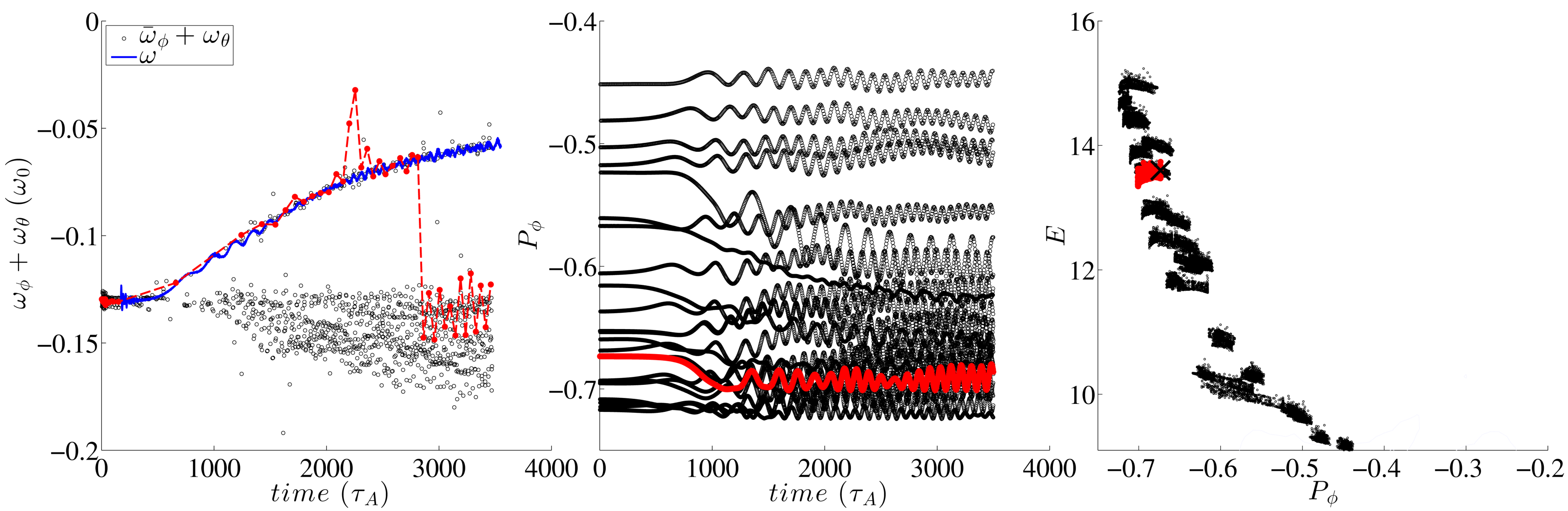
~80% particles turn into resonance

Nonlinear dynamic of trapped particles with initial frequency larger than the linear mode frequency: some of those particles become resonant



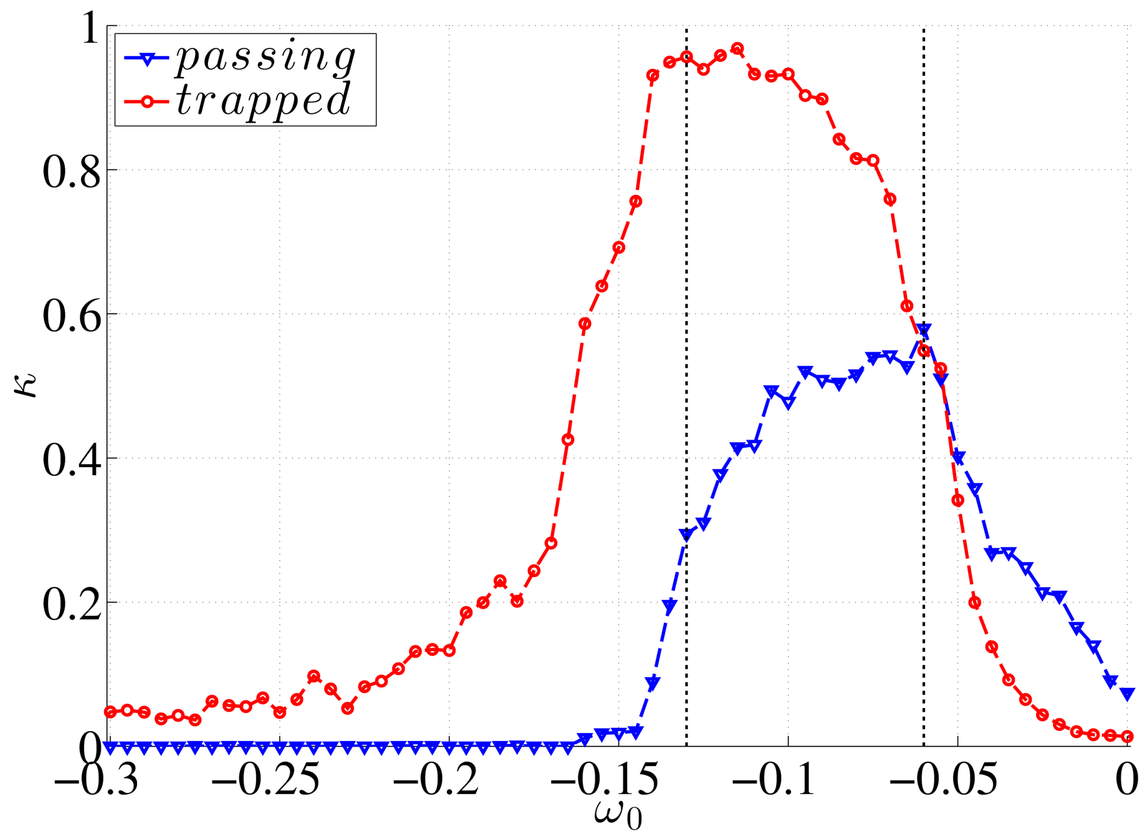
~30% particles turn into resonance

Nonlinear dynamic of passing particles with initial frequency close to the linear mode frequency: some of those particles stay in resonance, and they may also break from resonance.



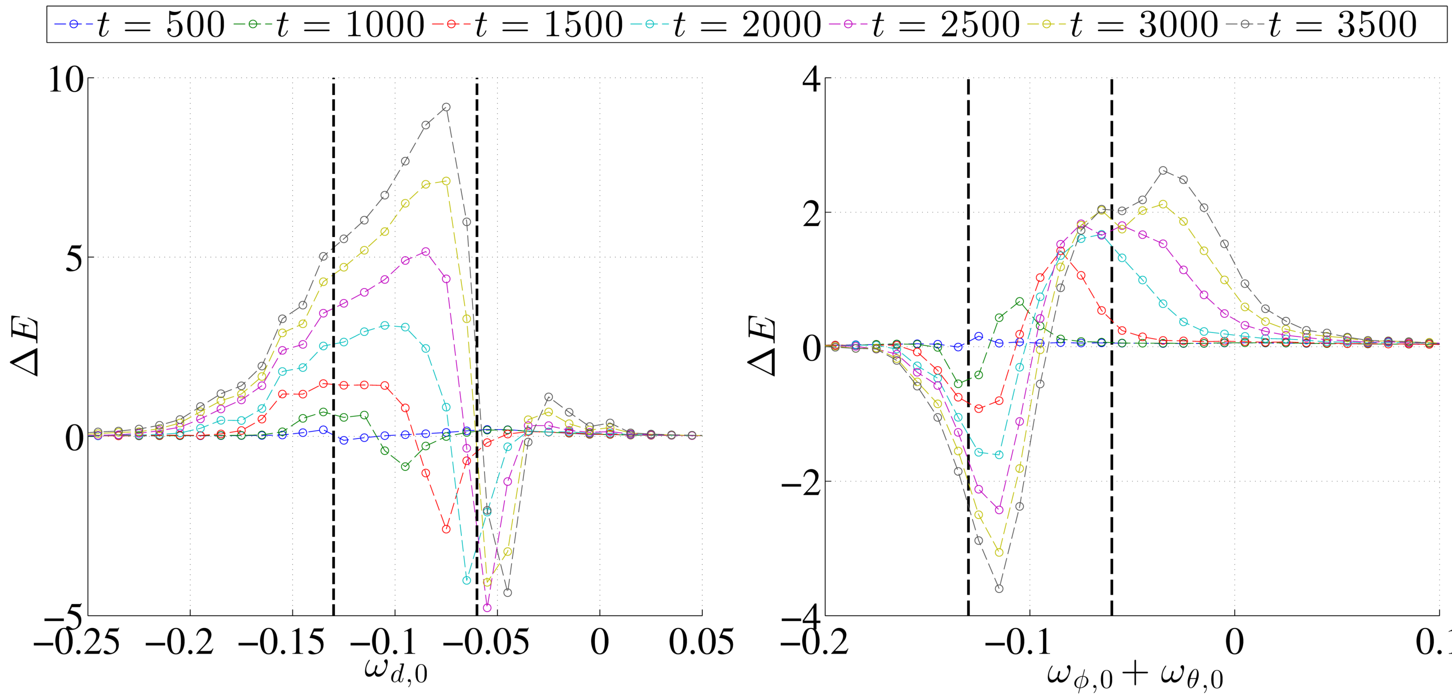
~30% particles turn into resonance

Trapped particles keeping resonance more easily than passing particles, most particles with initial frequency lower than mode linear frequency become resonant nonlinearly.

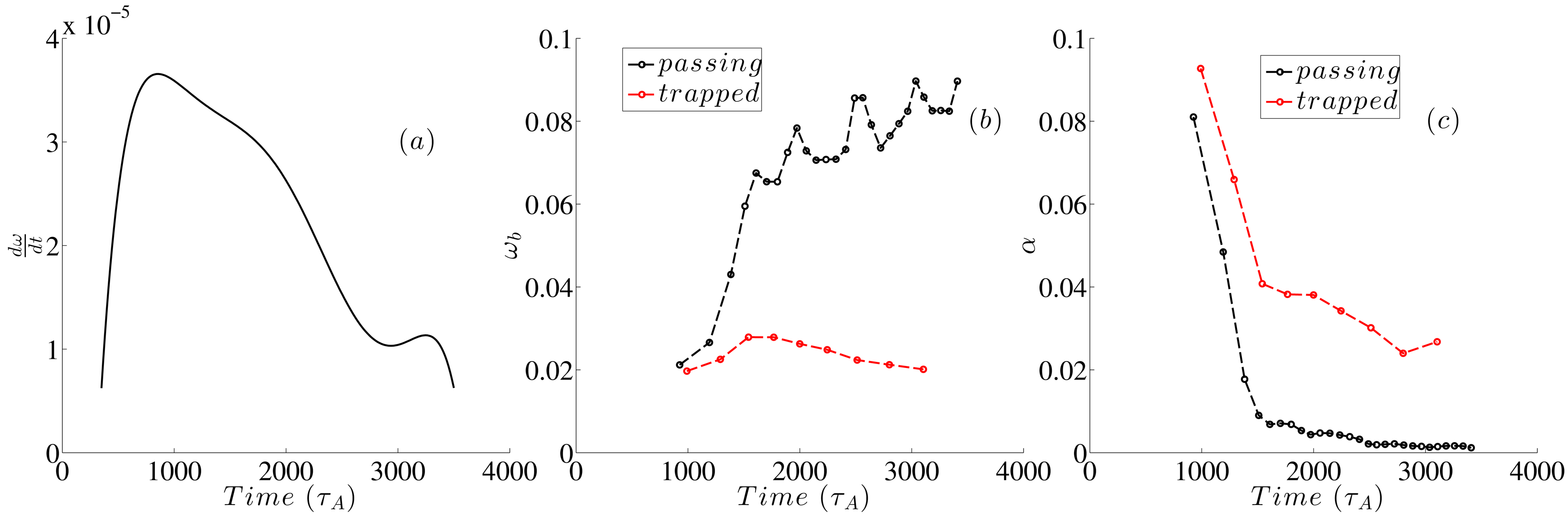


$$\kappa \equiv \frac{Resonant\,particle\,number}{Total\,particle\,number}$$

Particles with initial frequency lower than mode linear frequency can contribute more energy than linear resonant particles in nonlinear phase



The wave particle trapping is in adiabatic regime

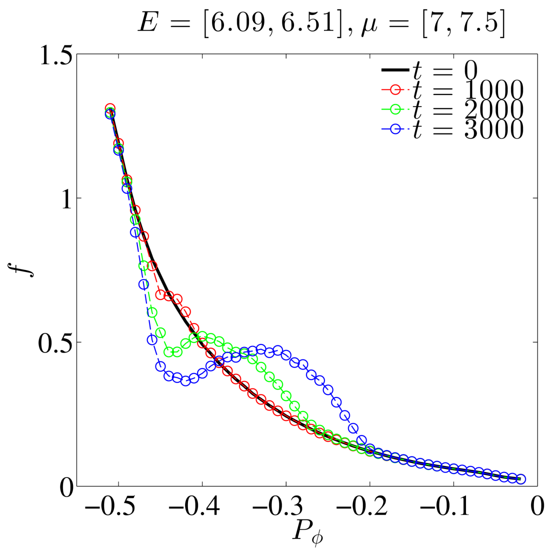


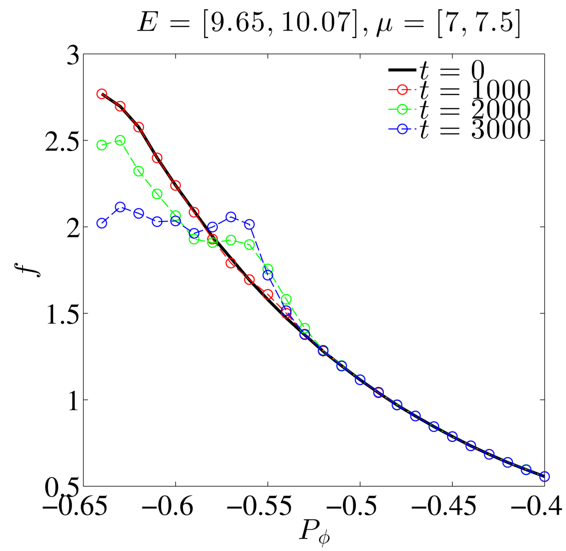
$$\alpha \equiv \frac{d\omega}{\omega_b^2 dt}$$

The distribution function become flat around the resonant region.
Flatting region increases as the mode frequency chirping down

Trapped particles

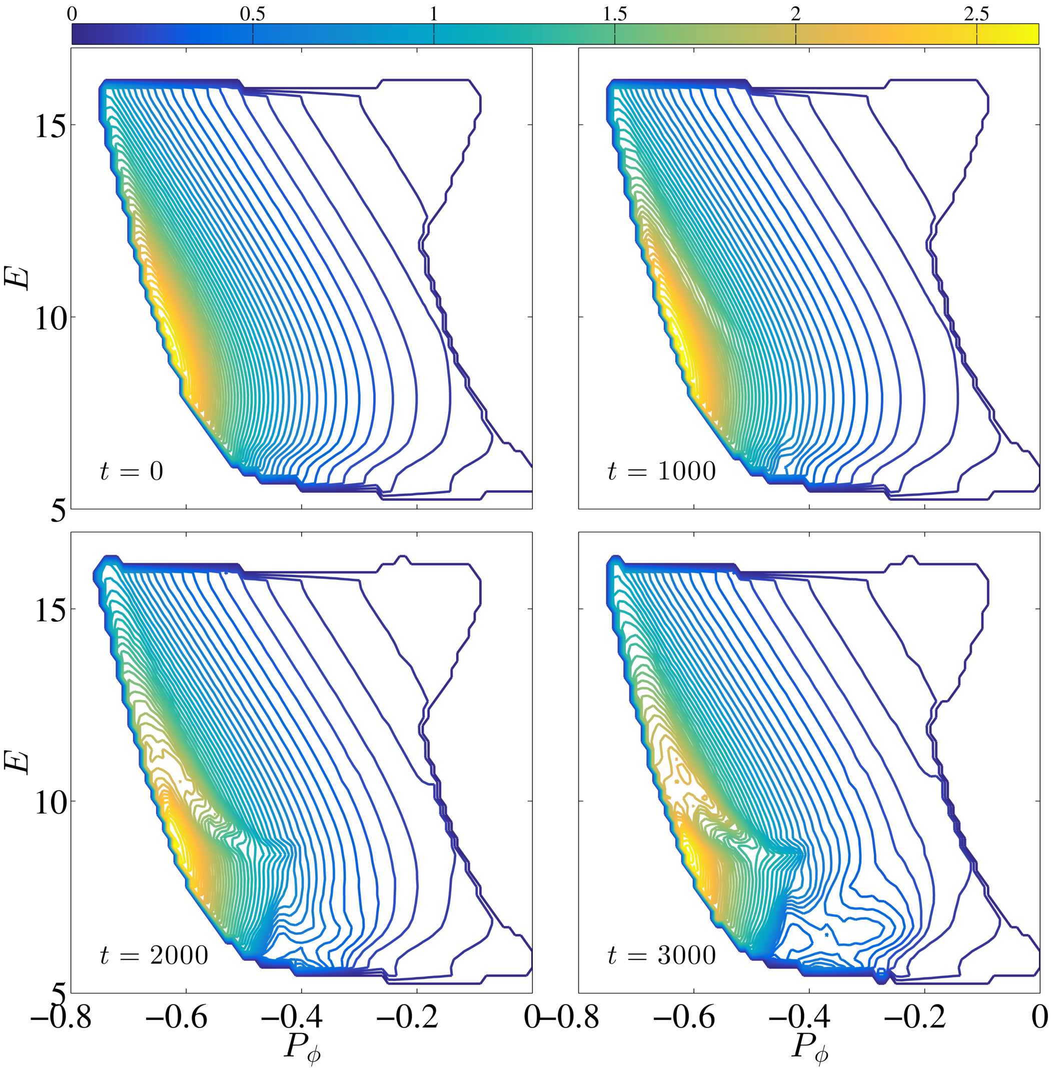
Passing particles





Flatting region increases with resonant particles keep moving out.
The trapped particle induce redistribution has a structure like a clump,
while the resonant island in phase space is wide, comparable with the clump shift distance.

The distribution function become flat around the resonant region, and as the mode frequency chirping down, trapped particles transport from the core to the edge.



Conclusions

- Rotation effect is destabilizing for fishbone at higher and lower q_{min} .
- Linearly, passing particles are important to drive fishbone mode.
- The fishbone nonlinear chirping is mainly due to the trapped resonant particles moving outward radially while keeping resonance with the mode.
- Due to the frequency profile in space, passing particles are difficult to keep in resonance nonlinearly.
- Nonlinearly, as the mode frequency chirping down, linearly non-resonant particles could turn into resonance. This additional factor plays an important role to sustain the mode nonlinearly.
- The phase space island is large in P_{Φ}, and induces a significant flattening region in the distribution function.