Nonlinear Dynamics of Toroidal Alfvén Eigenmodes driven by Trapped Energetic Particles

Farah Atour

Supervisors: Xin Wang, Sergio Briguglio
Academic supervisor: Philipp Lauber

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HMGC

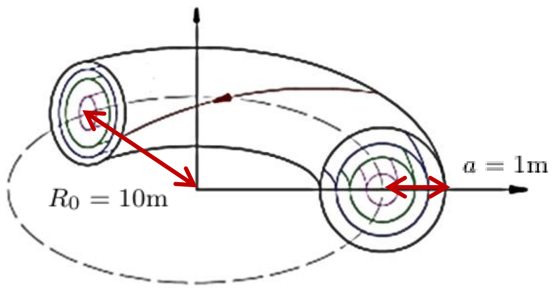
Hybrid **M**HD **G**yrokinetic **C**ode

reduced O($\in^3$) (**MHD**) equations
including **resistivity** and **viscosity**

nonlinear **gyrokinetic** Vlasov equation
(*Drift kinetic limit*)

Pressure coupling

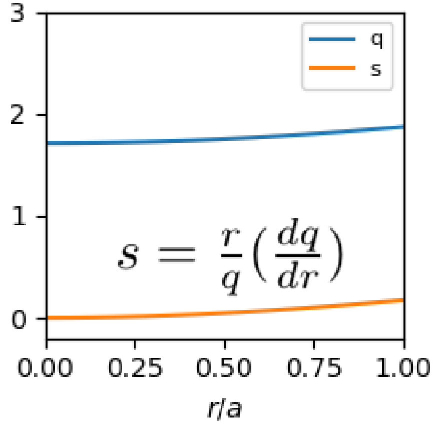
International Tokamak Physics Activity (ITPA) Benchmark



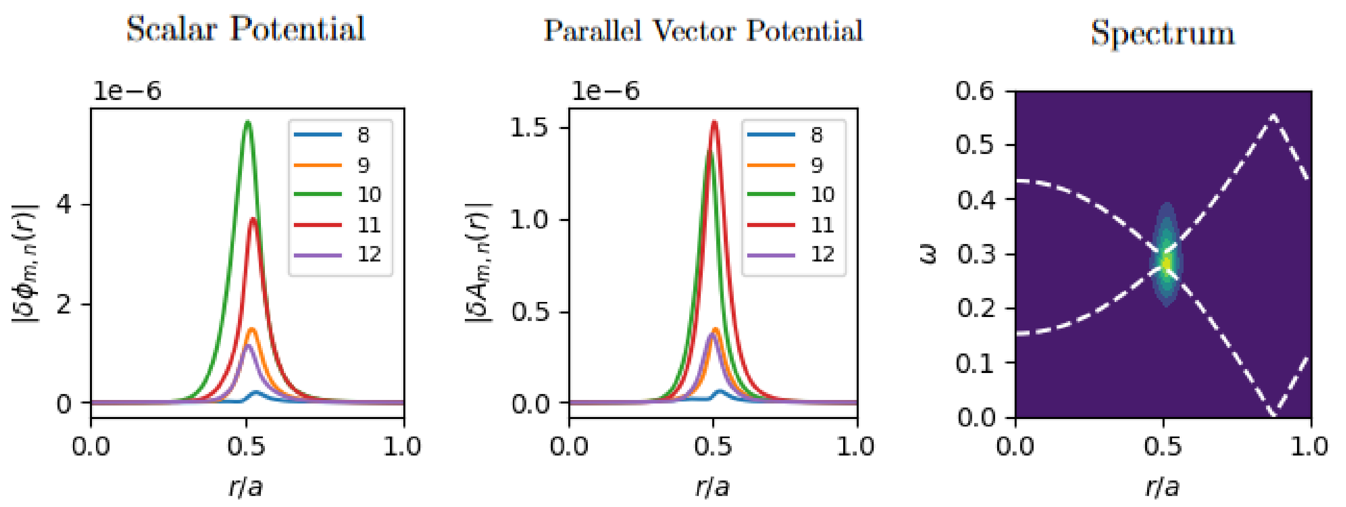
Safety Factor

$q = q_0 + (q_a - q_0)\left(\frac{r}{a}\right)^2$

$q_0 = 1.71 \qquad q_a = 1.87$



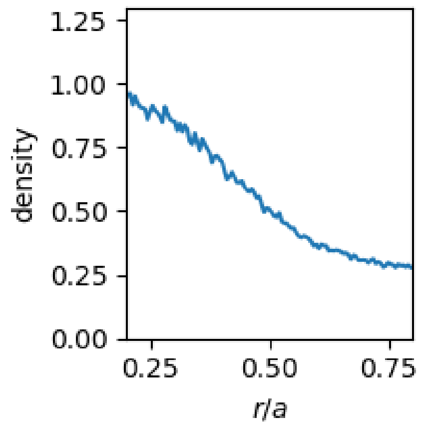
Geometric Properties



Waves Properties

Maxwellian distribution

$F_{H0}(s,E) = \left(\frac{m_h}{2\pi T_H}\right)^{\frac{3}{2}} n_H(s) e^{-\frac{E}{T_H}}$



Particles Properties

In our case the only difference with the typical ITPA case is the distribution function.

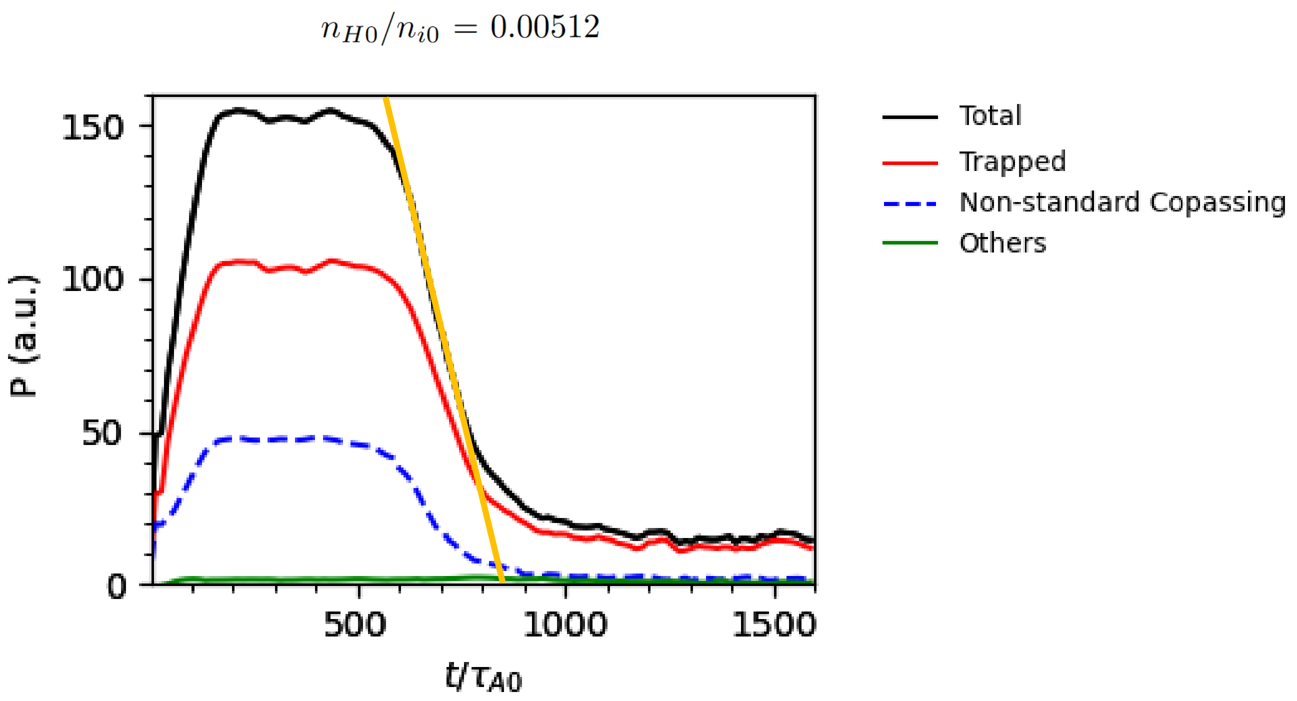
→ Anisotropic Distribution Function

$$\cos\alpha_0 = \frac{v_{\|}}{\sqrt{2E/m_H}} = 0$$

* See our paper for the full expression.

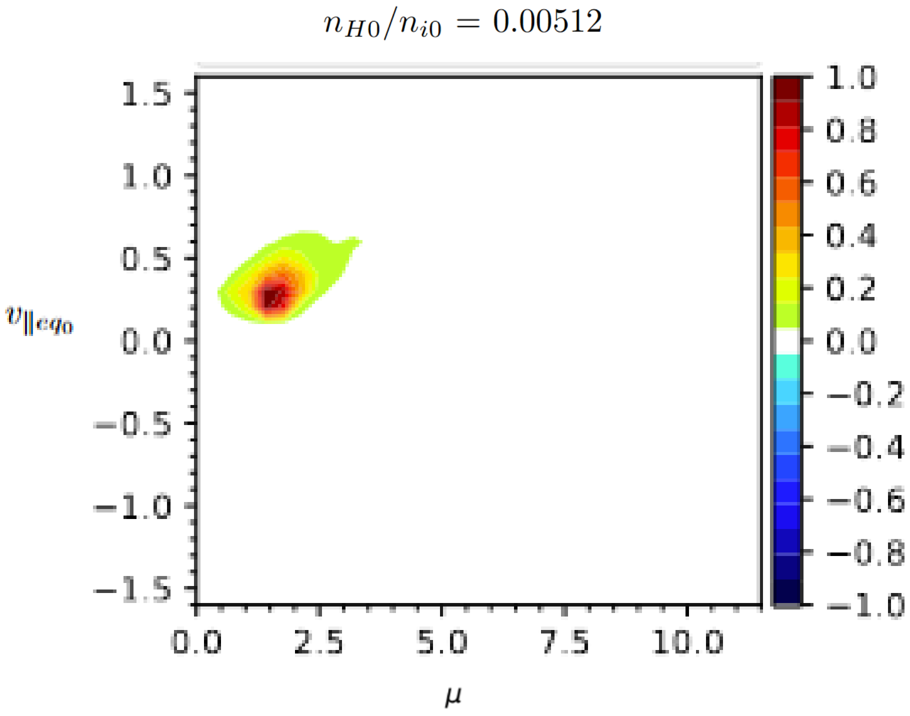
Before we begin our analysis, let's first check that using this distribution function truly shows that trapped particles are the main contribution of mode destabilization!

Full Population Power Transfer



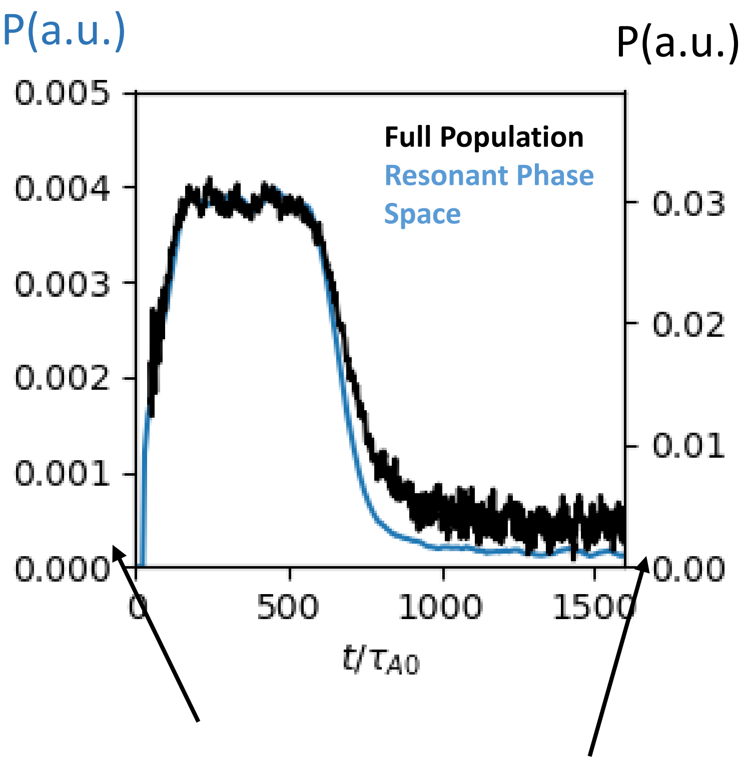
- Trapped particles are indeed the main driver of mode destabilization!
- What we are interested in is understanding the cause of the fast fall dynamics which we will refer to its timing as t_{fall}.

Search for Resonant Phase Space Structure

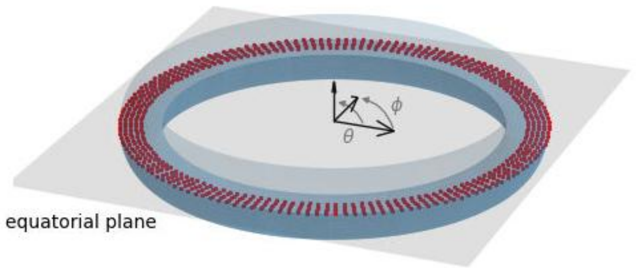


(integrated over all other coordinates)

The dominant point is (1.42,0.30)

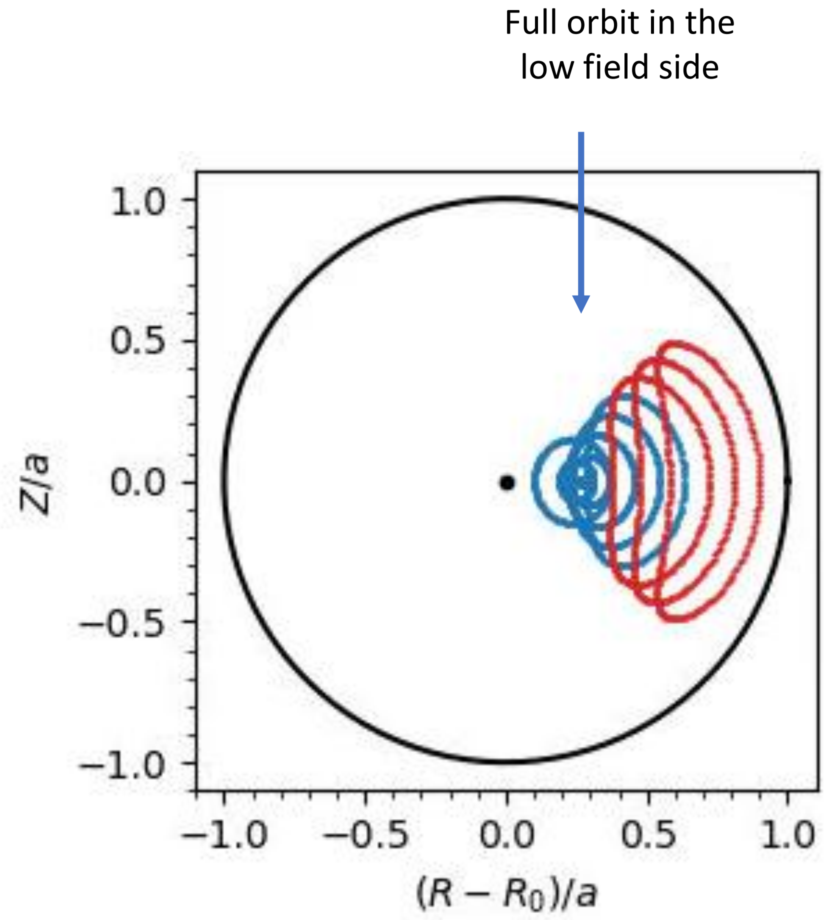


Different scale but approximately the same behaviour!



*We start another simulation with a set of test-particles all distributed along the equatorial plane

Particles' orbits

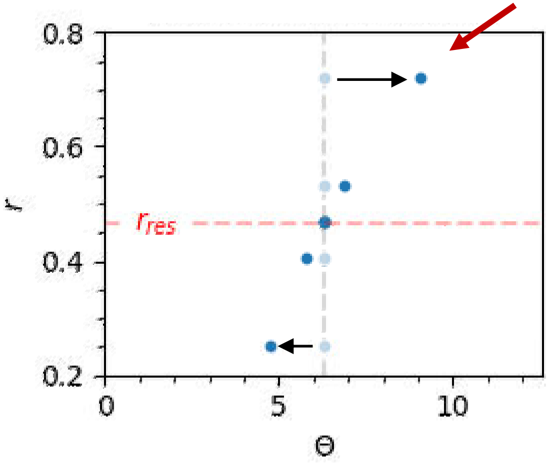


Previous Analysis for CoPassing Particles

Previous Analysis for CoPassing Particles

Linear phase

After one poloidal orbit

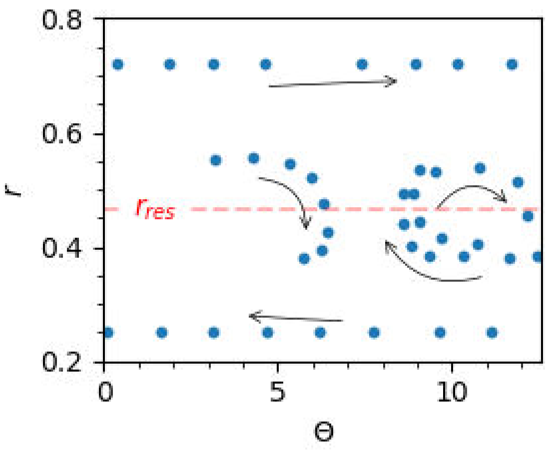


Wave phase

Nonlinear phase

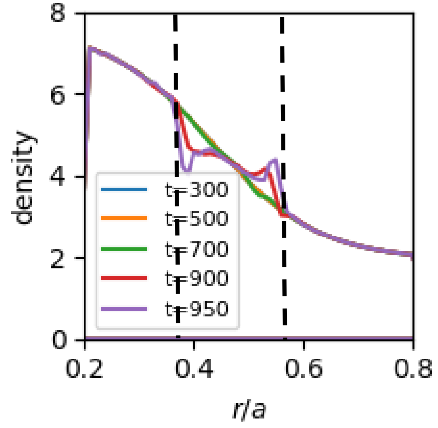
While the resonant particles will move radially

In nonlinear phase the perturbation fields becomes important

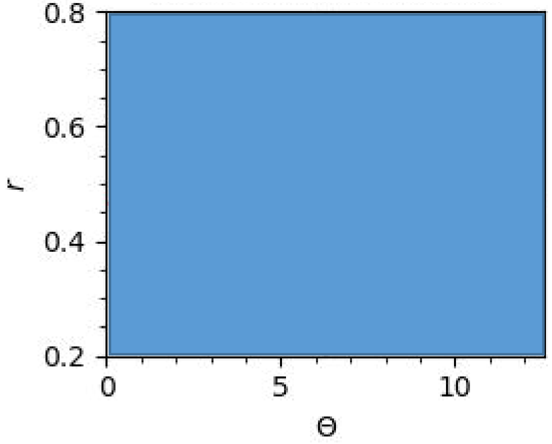


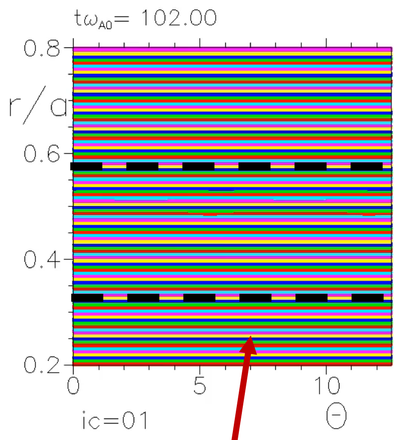
Particles far from resonance will not have radial variation

Previous Analysis for CoPassing Particles



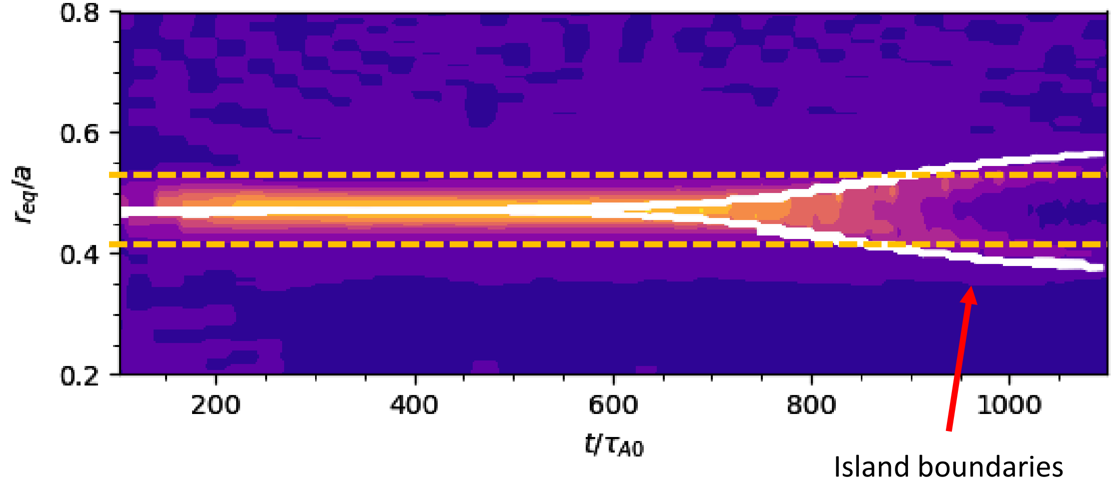
How about more particles?





Coloured depending on the initial r position

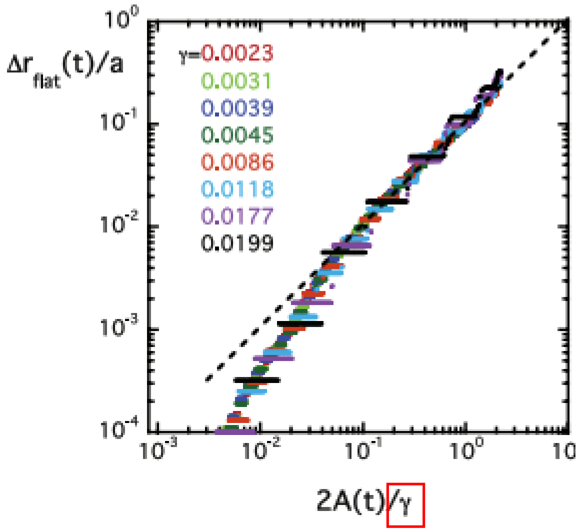
Power exchange

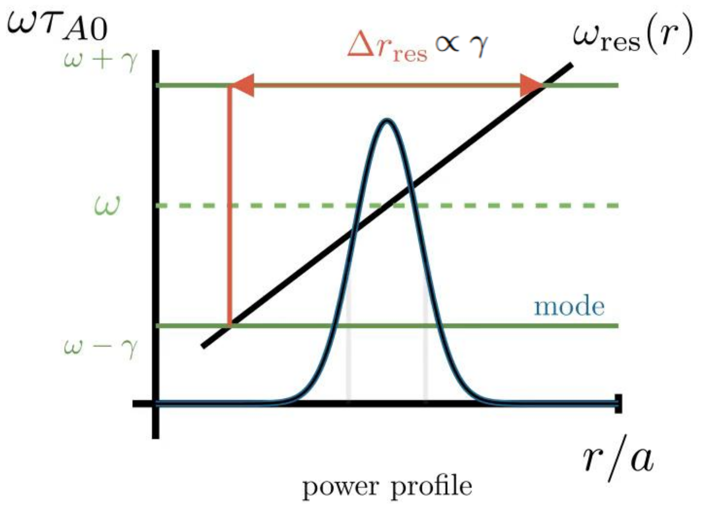


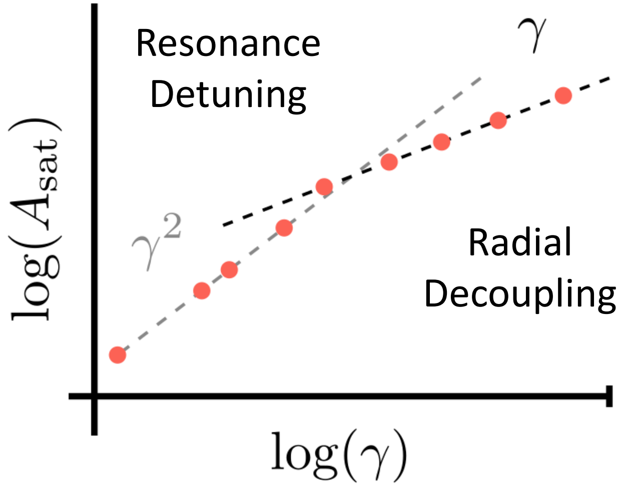
Island boundaries

Previous Analysis for CoPassing Particles

$$\text{(passing particles)} \qquad \omega_{\text{res}} = n\omega_d + k\omega_b + (n\bar{q} - m)\sigma\omega_b$$
$$\text{(trapped particles)} \qquad \omega_{\text{res}} = n\omega_d + k\omega_b$$





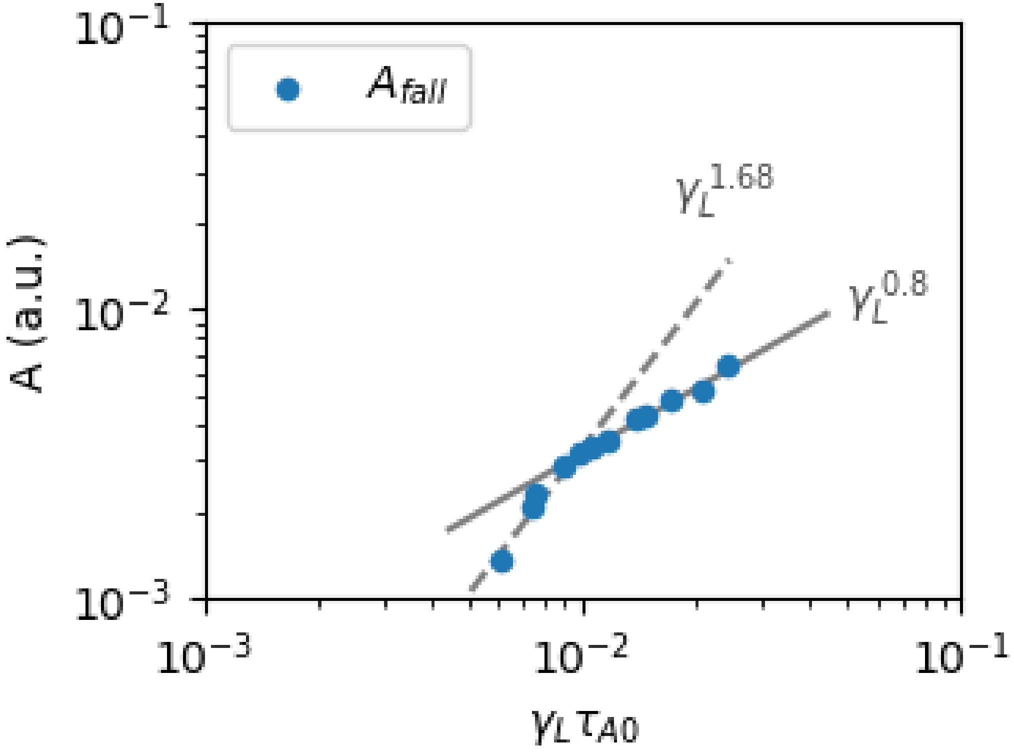


Taken from: S. Briguglio, M. Schneller, X. Wang, C. D Troia, T. Hayward-Schneider, V. Fusco, G. Vlad, and G. Fogaccia. Saturation of alfven modes in tokamak plasmas investigated by hamiltonian mapping techniques. Nuclear Fusion, 57(7):072001, mar 2017.

$$\Delta r_{\text{flat}} \approx \min[\Delta r_{\text{res}}, \Delta r_{\text{mode}}]$$

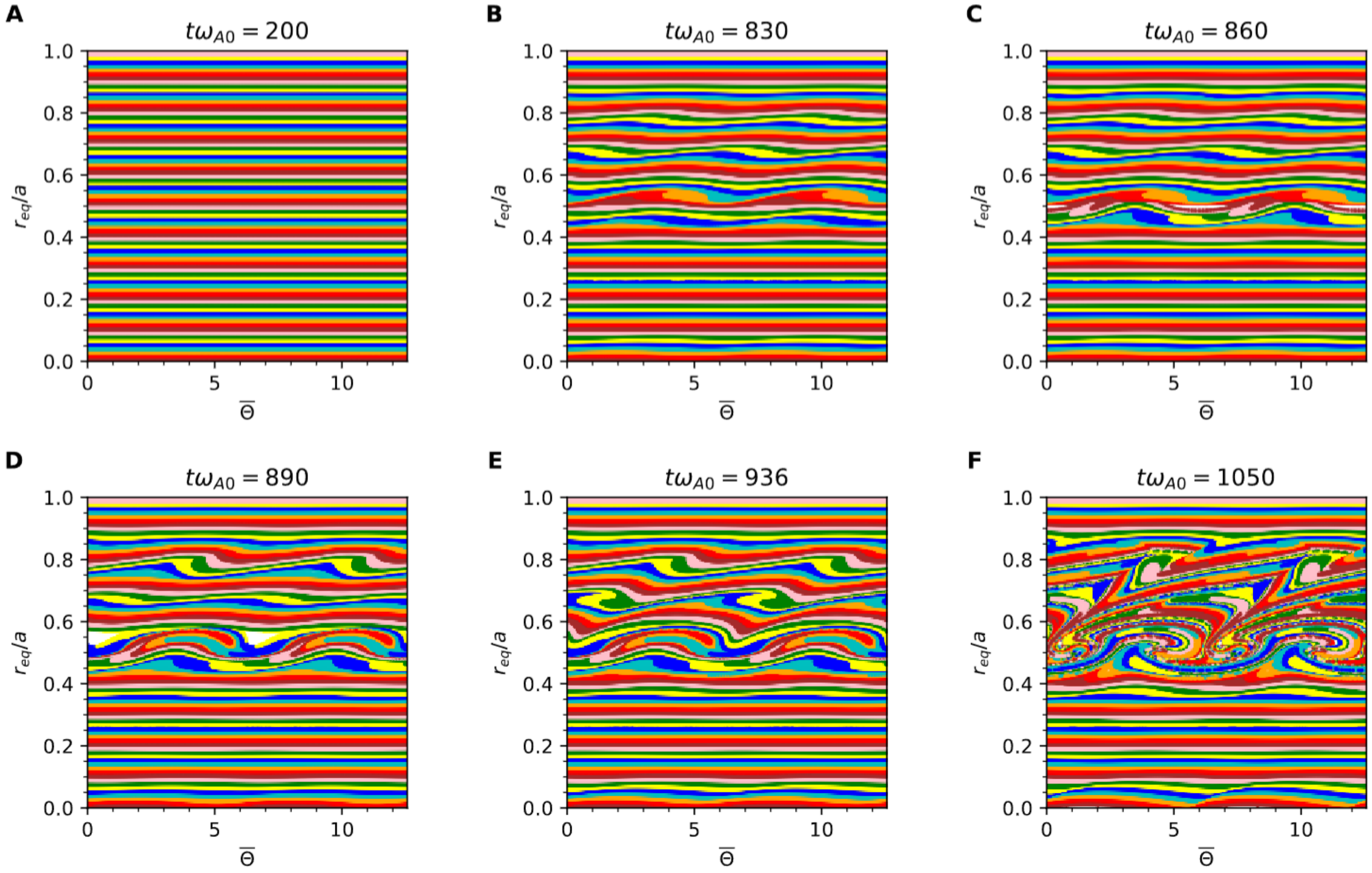
Now back to our problem!

Amplitude Scaling



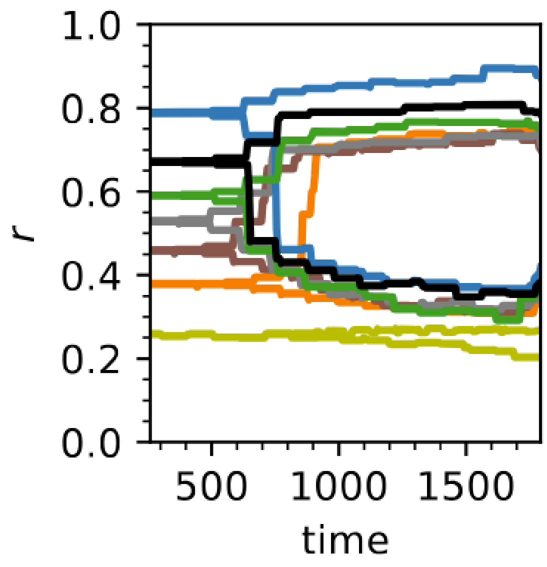
Let's first focus our analysis on high growth rate values and then return to the lower values.

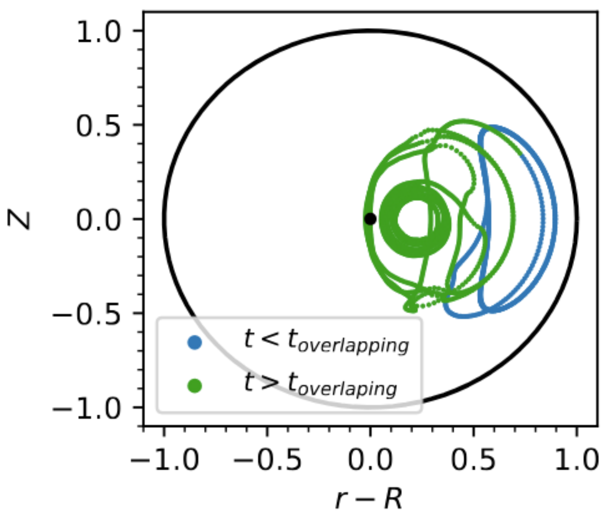
Hamiltonian Mapping

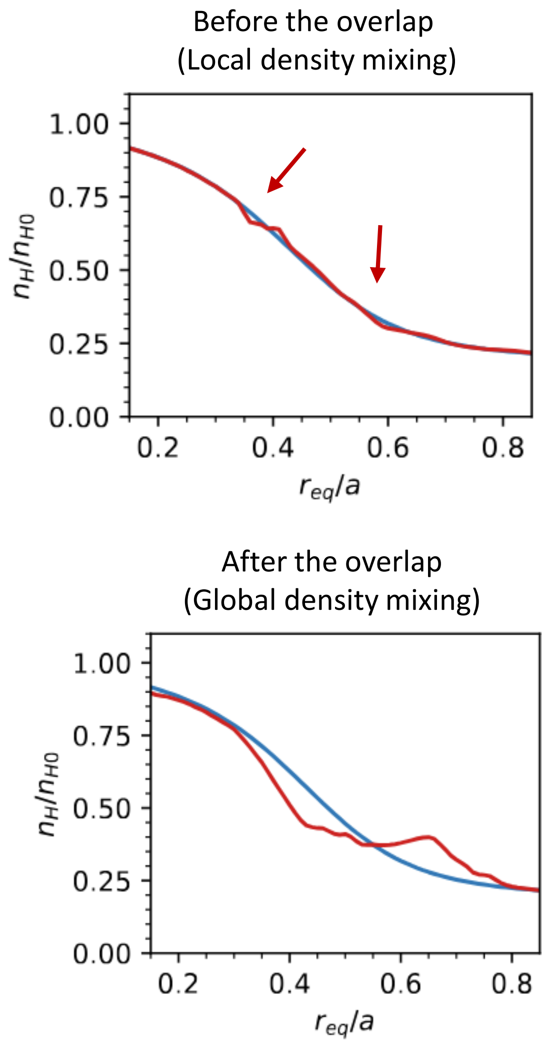


Overlapping Islands

But why do multiple islands form in the first place?



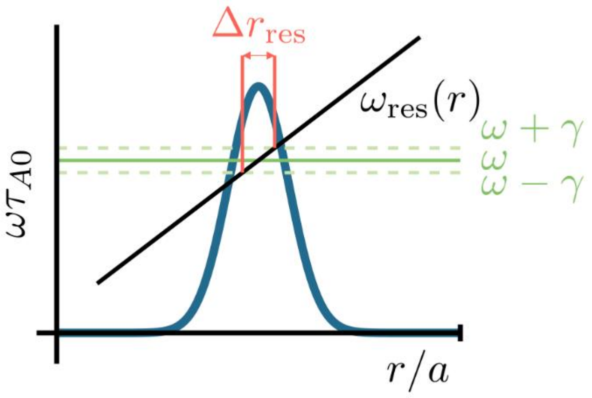


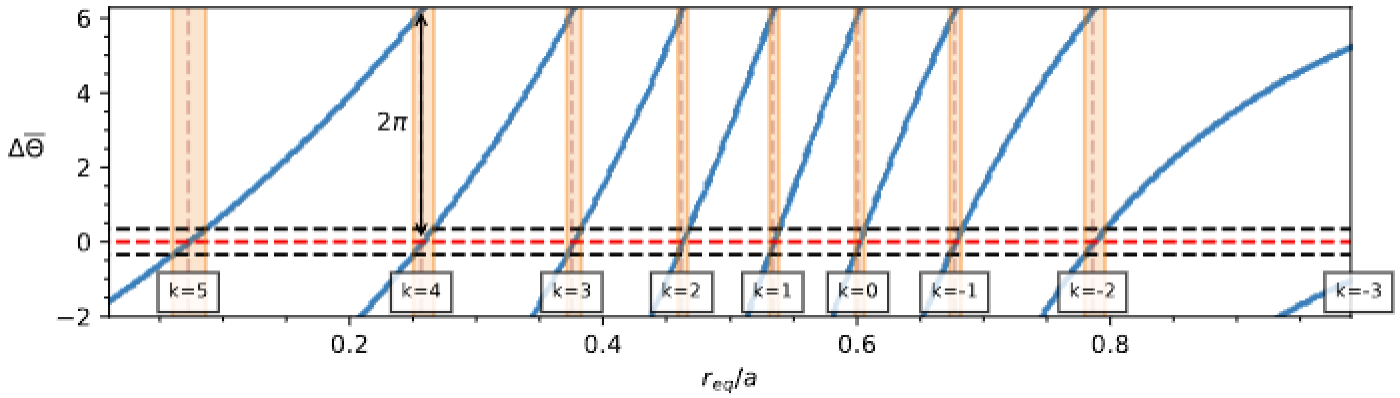


Multiple Resonances

(trapped particles) $\omega_{\text{res}} = n\omega_d + k\omega_b$

Passing particles





$|\Delta r_{\text{transit}}| \sim a$

$\Delta r_{\text{bounce}} \sim 0.1\, a.$

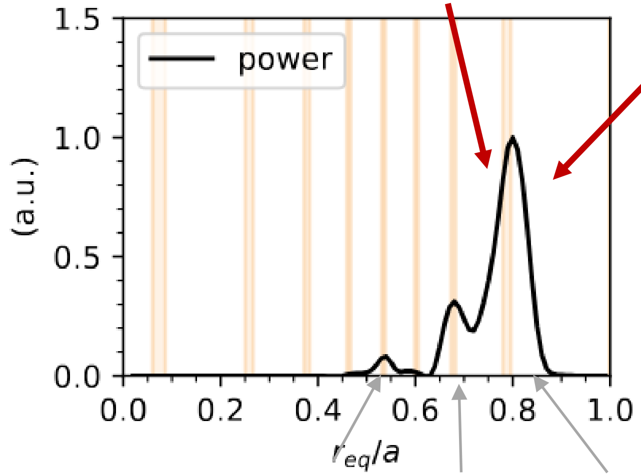
* See our paper for the derivations.

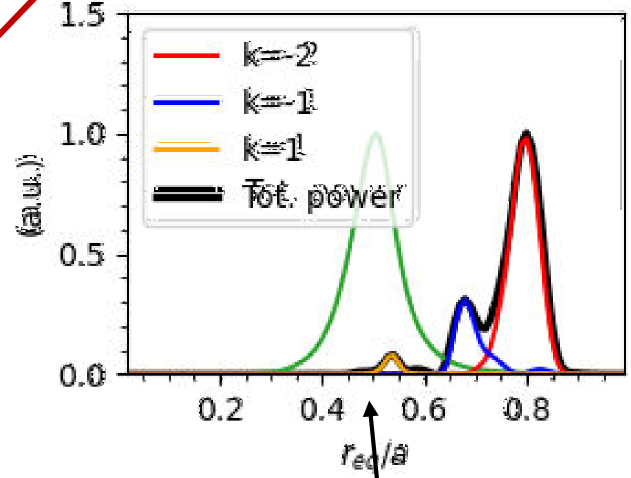
Power Exchange Profile

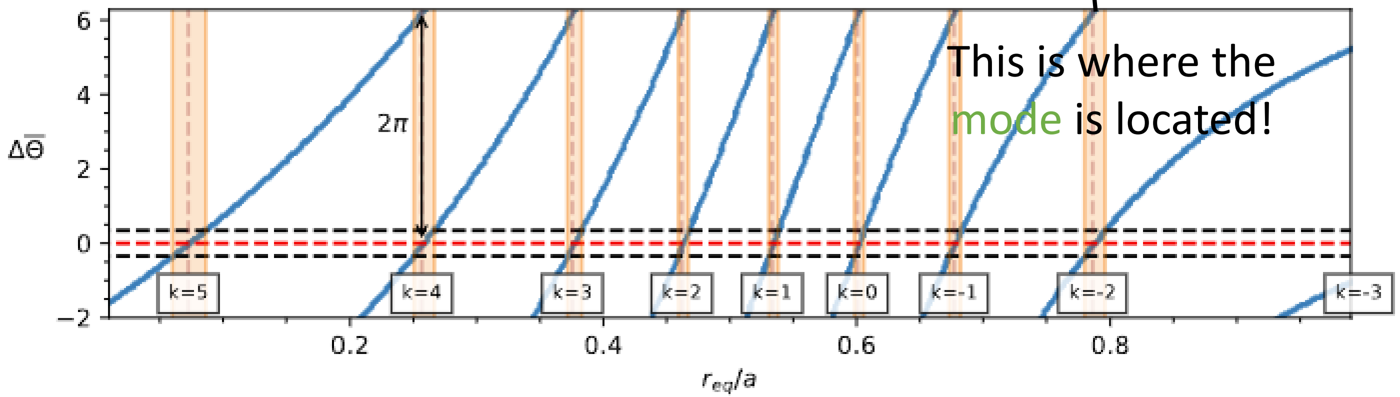
Notice how the power profile is not limited by Δr_{res}

Let's focus on the most dominant harmonic

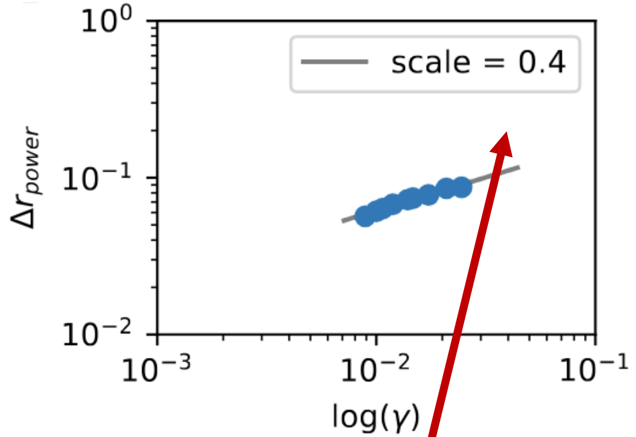
What is happening? And why the highest power exchange is in the outer positions?



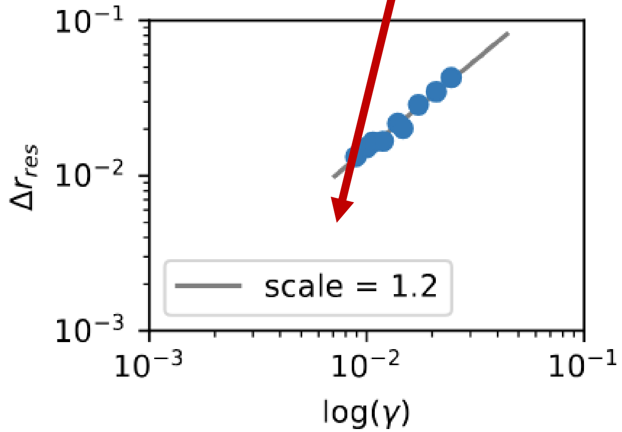




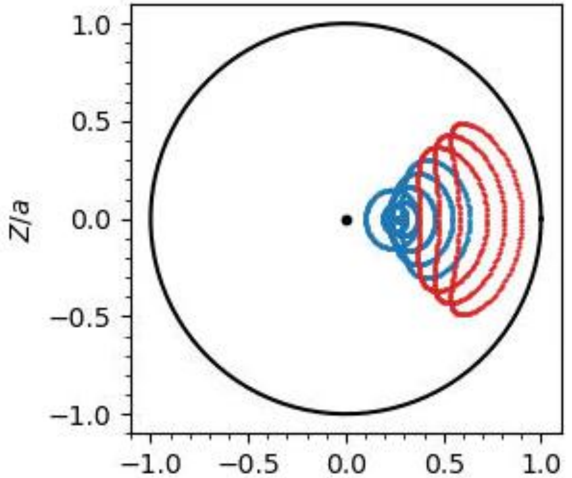
This is where the mode is located!

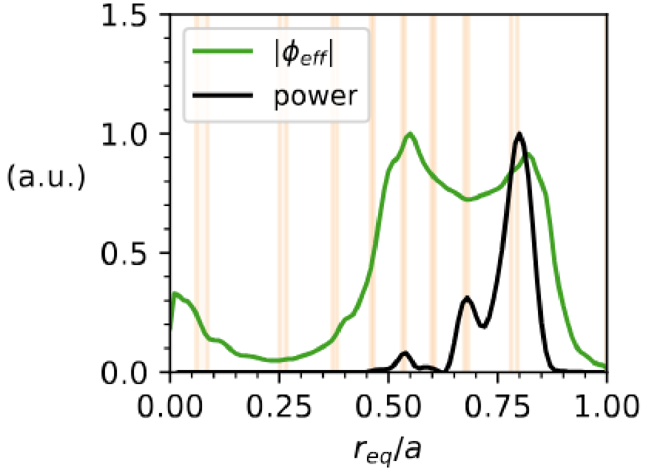


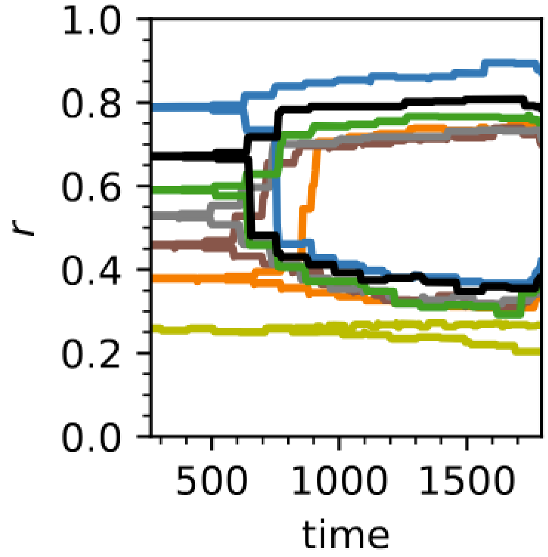
Not even close

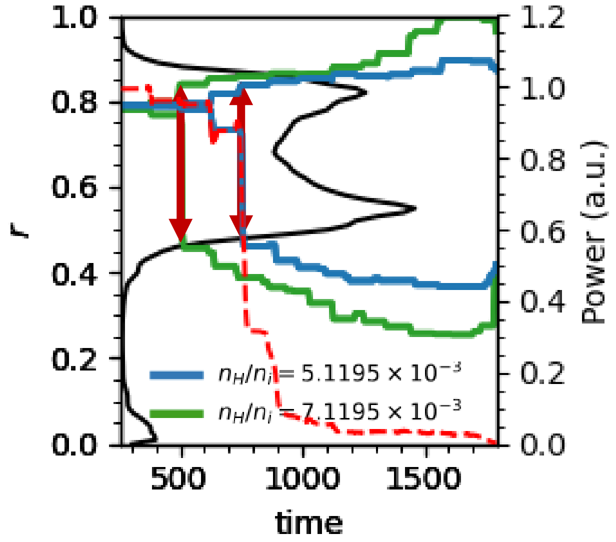


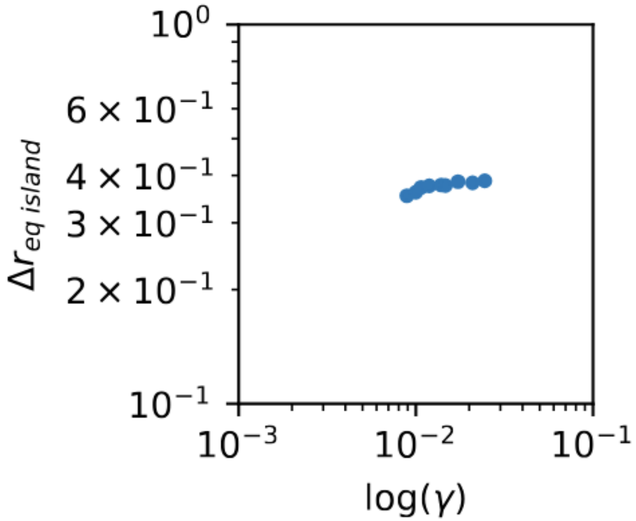
Effective Field



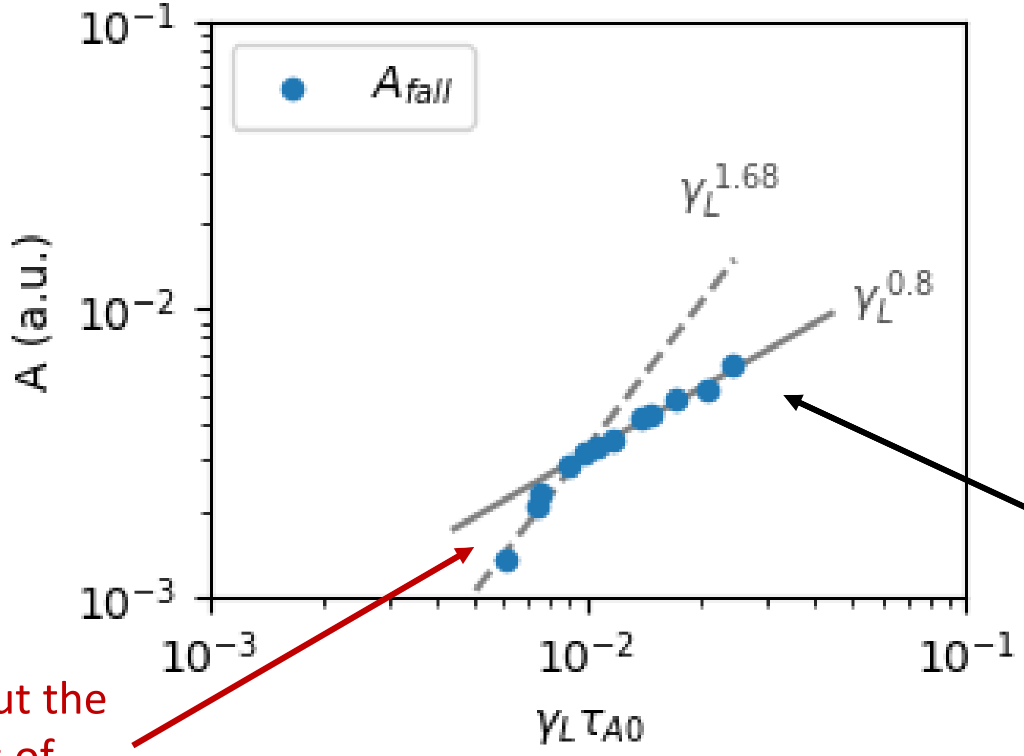








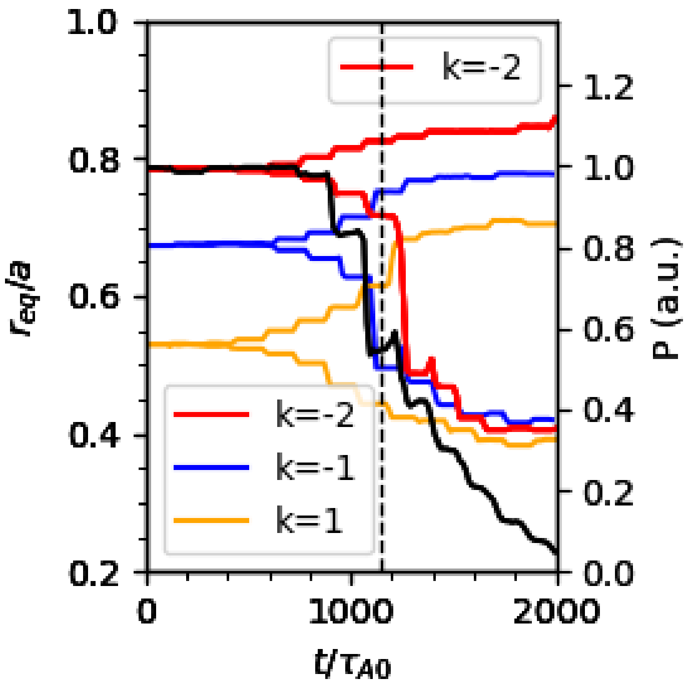
In conclusion

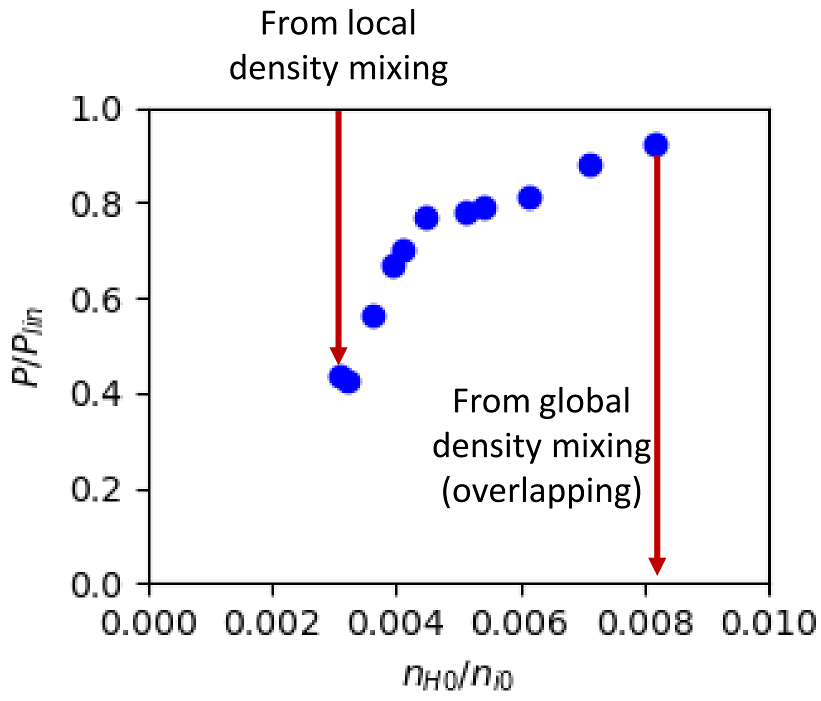


What about the low values of growth rate?

So for **high growth rate** values the mode amplitude grows until island overlap extends density flattening across the entire power exchange area, dictated by the **effective field** which resembles the **radial decoupling regime**

Impact of Local Density Mixing on Power Transfer





Summary

TABLE I. Summary of key findings.

	Islands involved	Density mixing	Saturation amplitude's scaling	Density mixing limiting width
Low n_{H_0}/n_{i_0}	Single island	Local	$\gamma_L^{1.68}$	Single bounce-harmonic power width
Large n_{H_0}/n_{i_0}	Overlapping islands	Global	$\gamma_L^{0.8}$	Effective field

Thank you!