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## Fishbone instability and transport of energetic particles

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## Summary

- **Energetic particles (EP)** known to impact MHD instabilities, potentially inducing EP transport, as discovered experimentally<sup>[1,2]</sup>
- Extensive **theoretical linear works** done over the past decades<sup>[3,4,5,6]</sup>
- **Non-linear hybrid codes**<sup>[9,11,12,13,15]</sup>, verified by comprehensive linear models and codes<sup>[7,8,16]</sup>, are needed to capture the physics of the fishbone induced EP transport
- **Full orbit nonlinear hybrid code**<sup>[15]</sup> useful to investigate the physics of high energy alpha particles

## Comprehensive linear model

The kinetic internal kink dispersion relation<sup>[4,7,8,16]</sup>

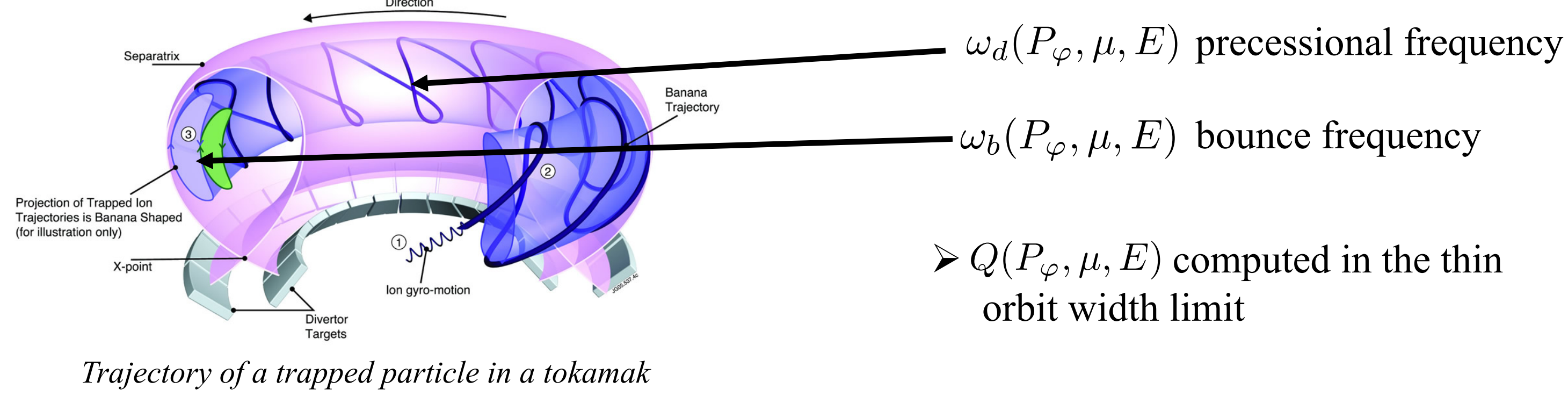
$$D(n_{h,0}, \Omega) = \delta I(\Omega) - i[\delta W_{MHD} + \delta W_K(n_{h,0}, \Omega)] = 0$$

$$\delta I(\Omega) \propto \Omega = \omega + i\gamma \in \mathbb{C}$$

$\delta W_{MHD}$  computed by CHEASE/XTOR-2F<sup>[14]</sup>

Complex resonant kinetic contribution, computed numerically<sup>[4,7,8,16]</sup>

$$\delta W_K \propto \sum_{n_2} \int dP_\varphi d\mu \int_0^{E_\alpha} \frac{Q(P_\varphi, \mu, E)}{\Omega - (n_2 + q\delta_p)\omega_b - \omega_d} dE$$

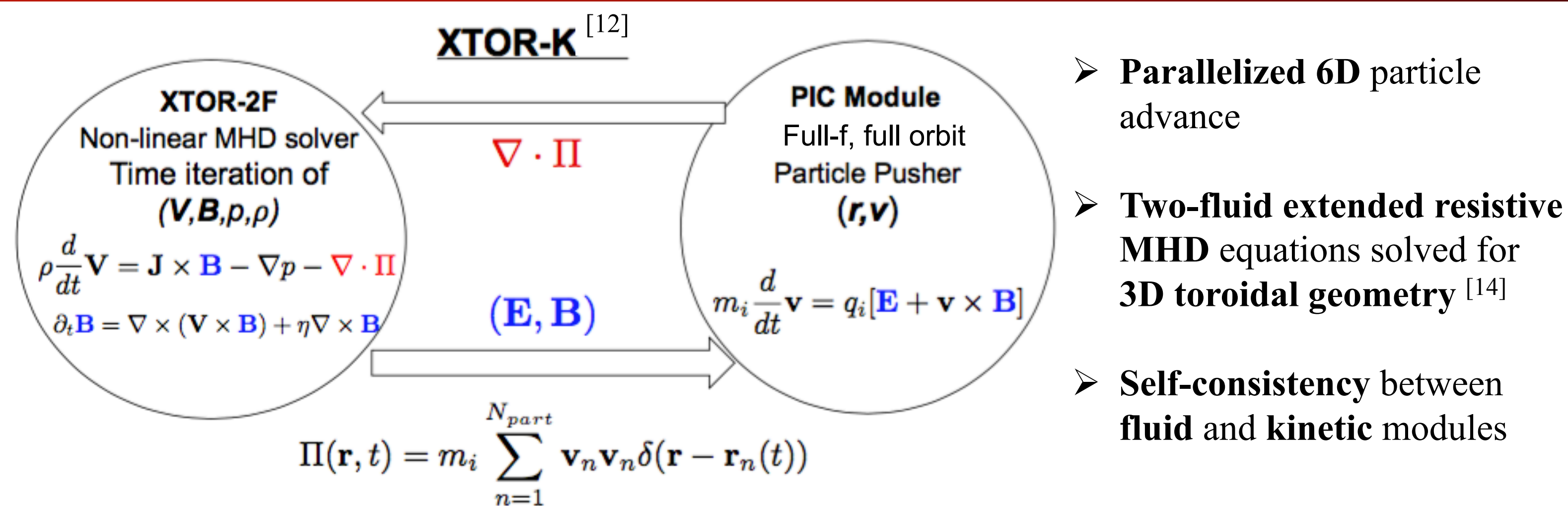


- $\omega_d(P_\varphi, \mu, E)$  precessional frequency
- $\omega_b(P_\varphi, \mu, E)$  bounce frequency
- $Q(P_\varphi, \mu, E)$  computed in the thin orbit width limit

## Specificities of the linear model

- Effects of passing particles taken into account
- Resonant integral solved analytically or numerically
- Fluid terms kept in the kinetic contribution
- Solves non-perturbatively the implicit dispersion relation

## Description of the hybrid code XTOR-K



- Parallelized 6D particle advance
- Two-fluid extended resistive MHD equations solved for 3D toroidal geometry<sup>[14]</sup>
- Self-consistency between fluid and kinetic modules

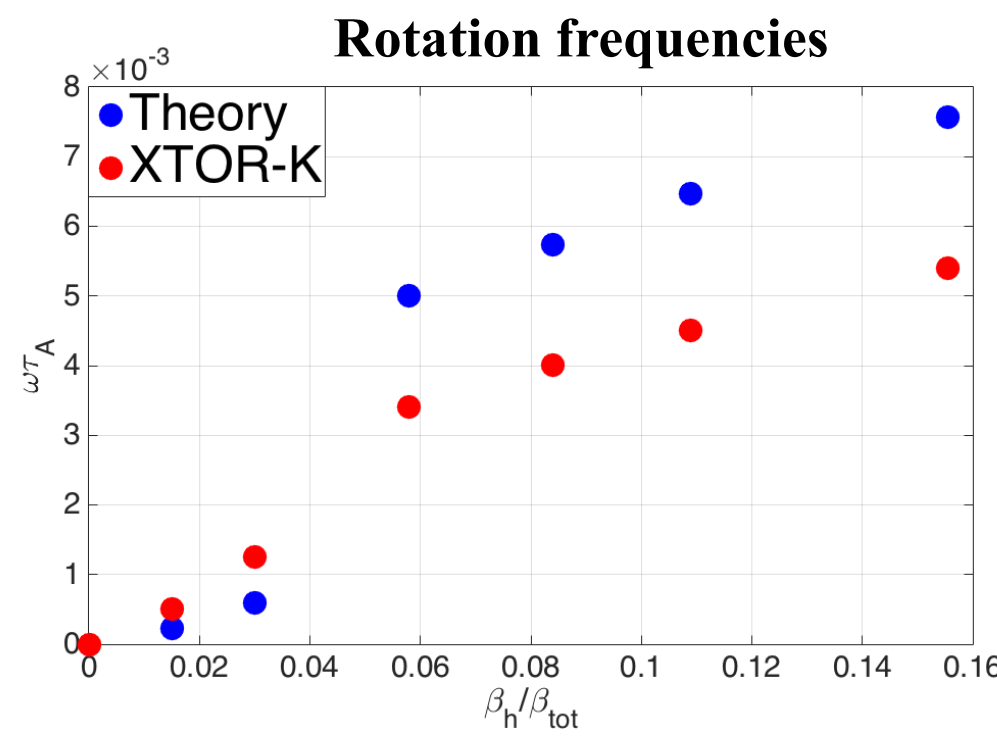
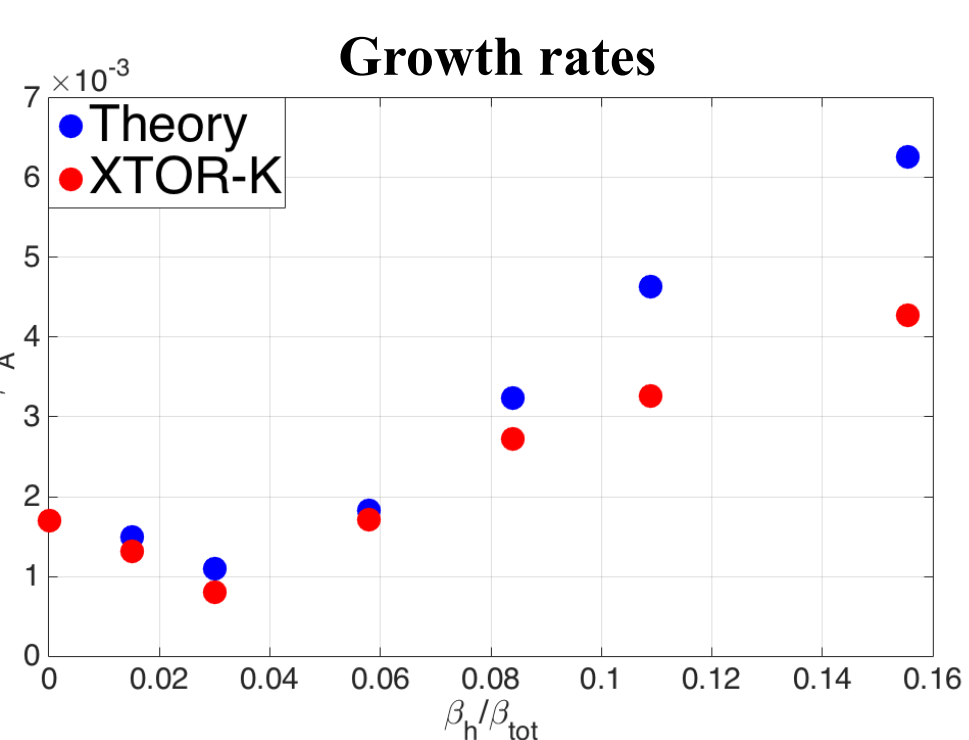
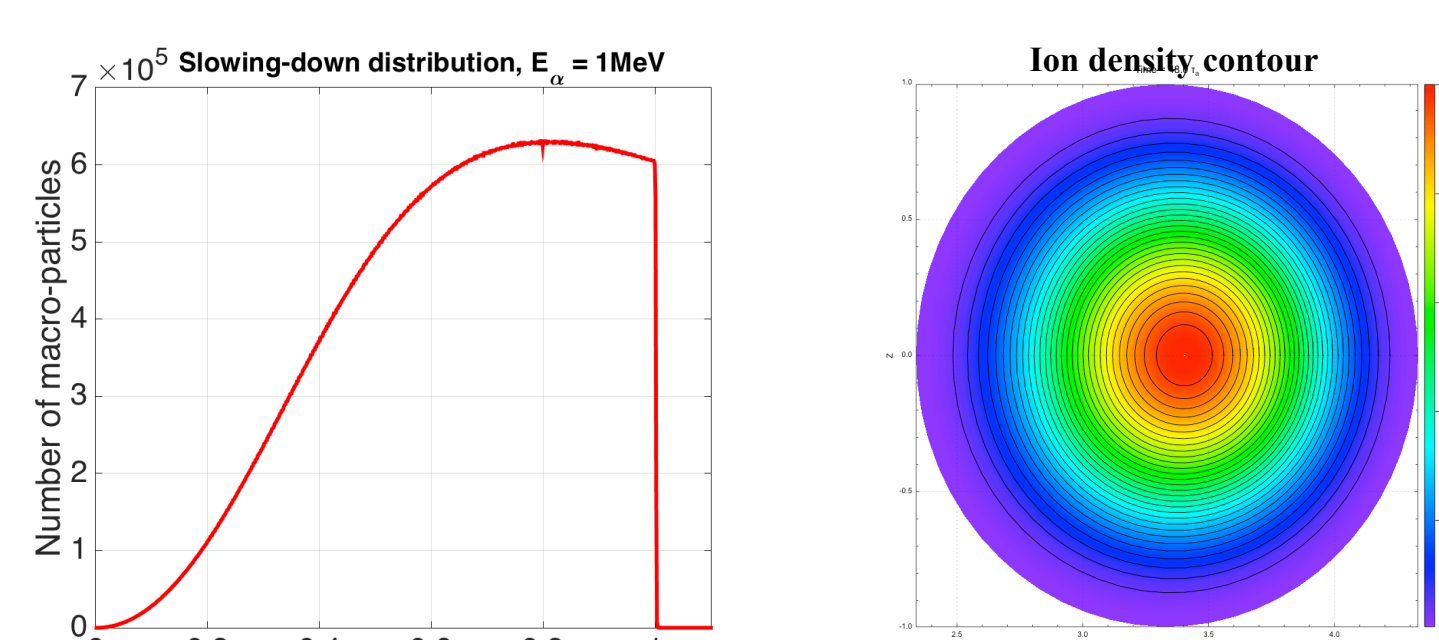
## Linear verification of XTOR-K

- **Isotropic Slowing-Down** distribution of alpha particles at peak energy of 1 MeV

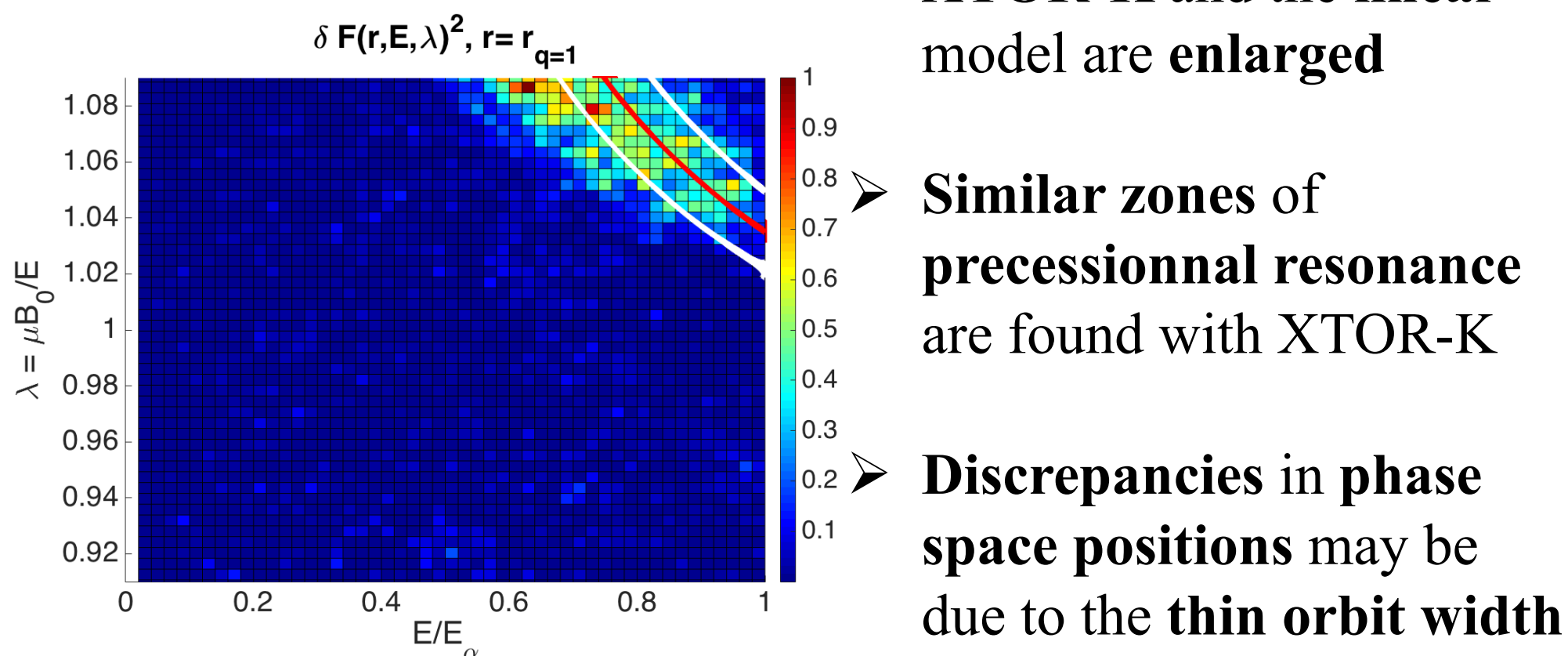
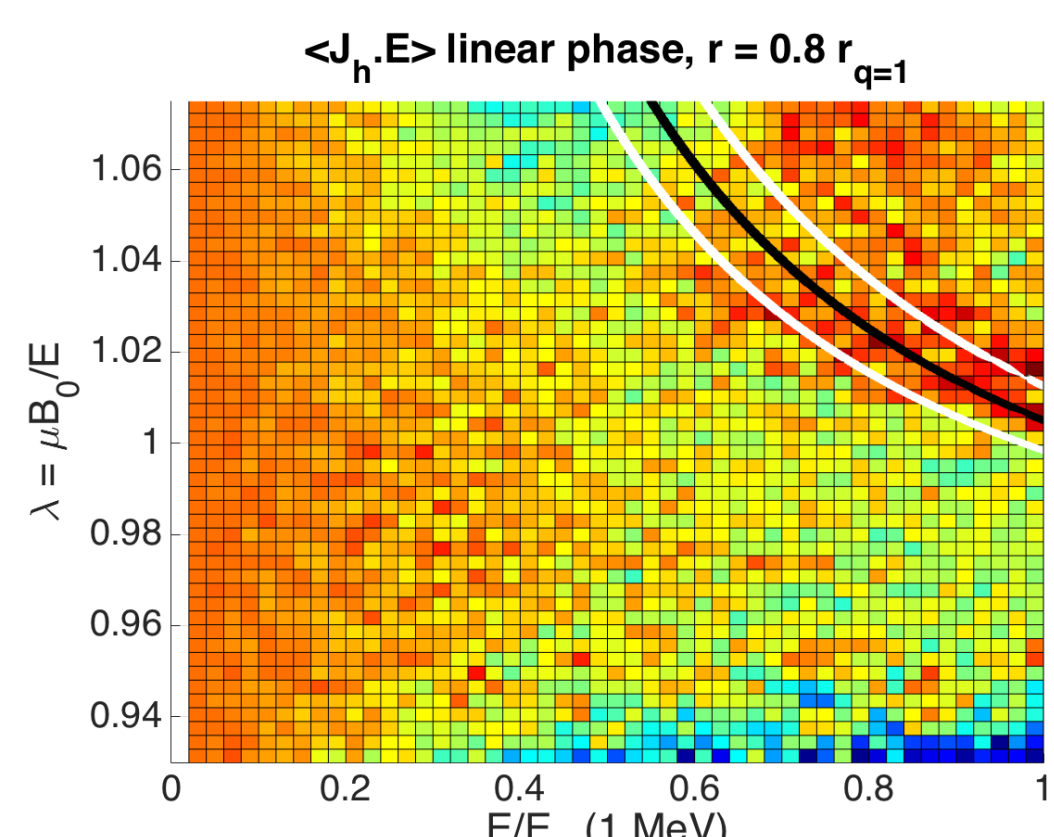
$$F_\alpha(r, E) = C n_\alpha(r) \frac{\theta(E_\alpha - E)}{E^{3/2} + E_c^{3/2}(r)}$$

- Circular magnetic flux surfaces

- Peaked EP profile  $n_\alpha(r) = n_{\alpha,0}(1 - r^2)^6$

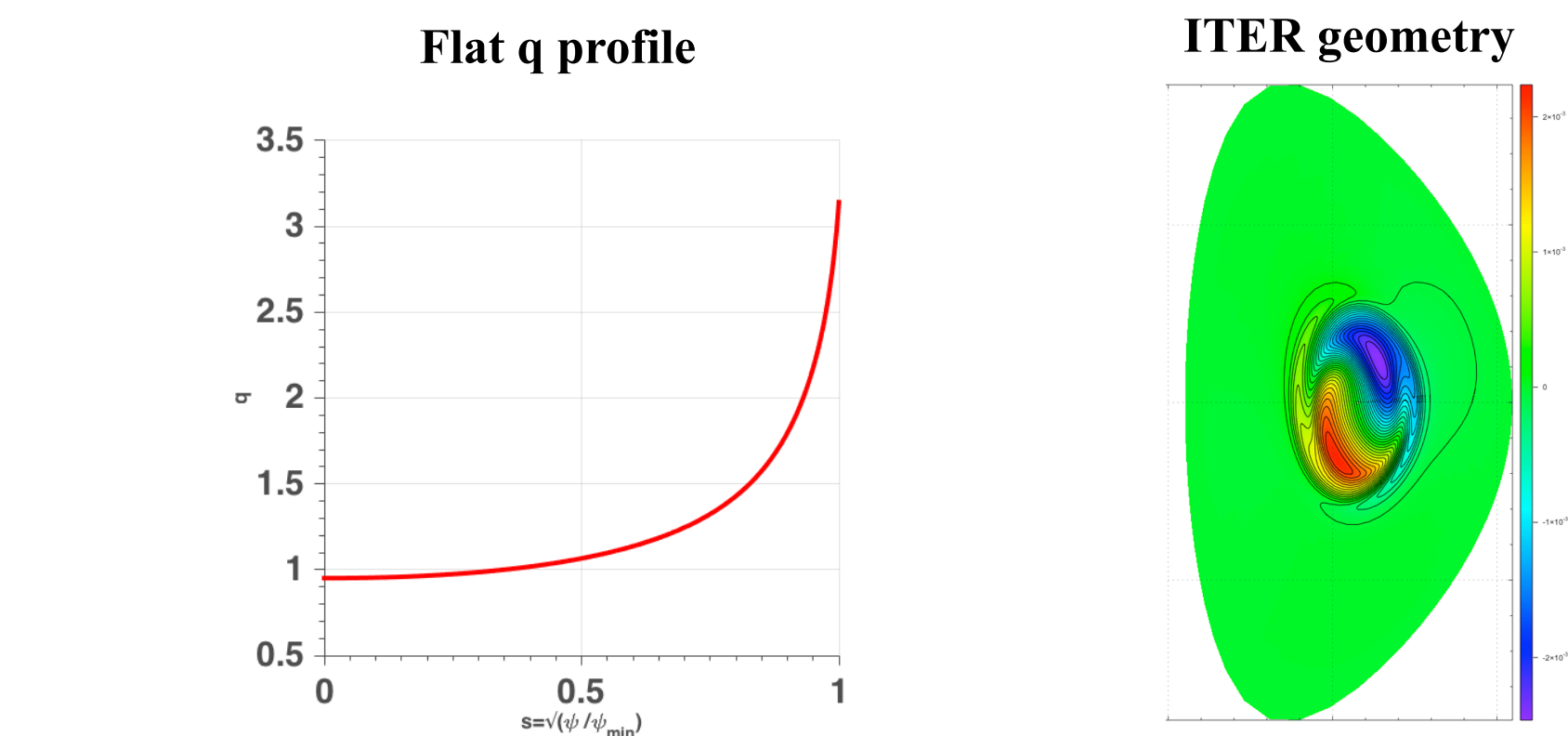
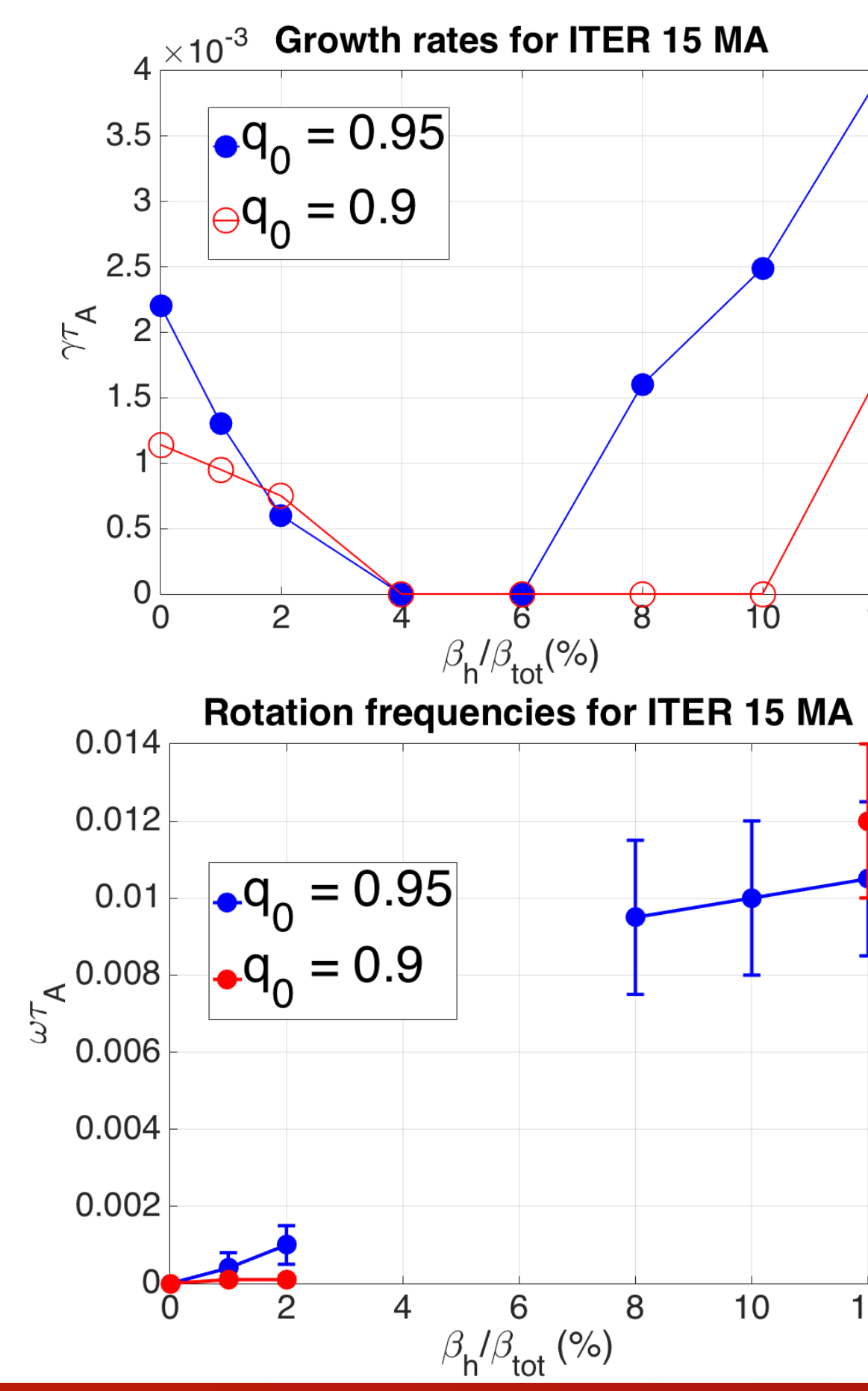


- Linear theory agrees reasonably well with XTOR-K
- Discrepancies arise at higher EP density
- At high density, differences between XTOR-K and the linear model are enlarged



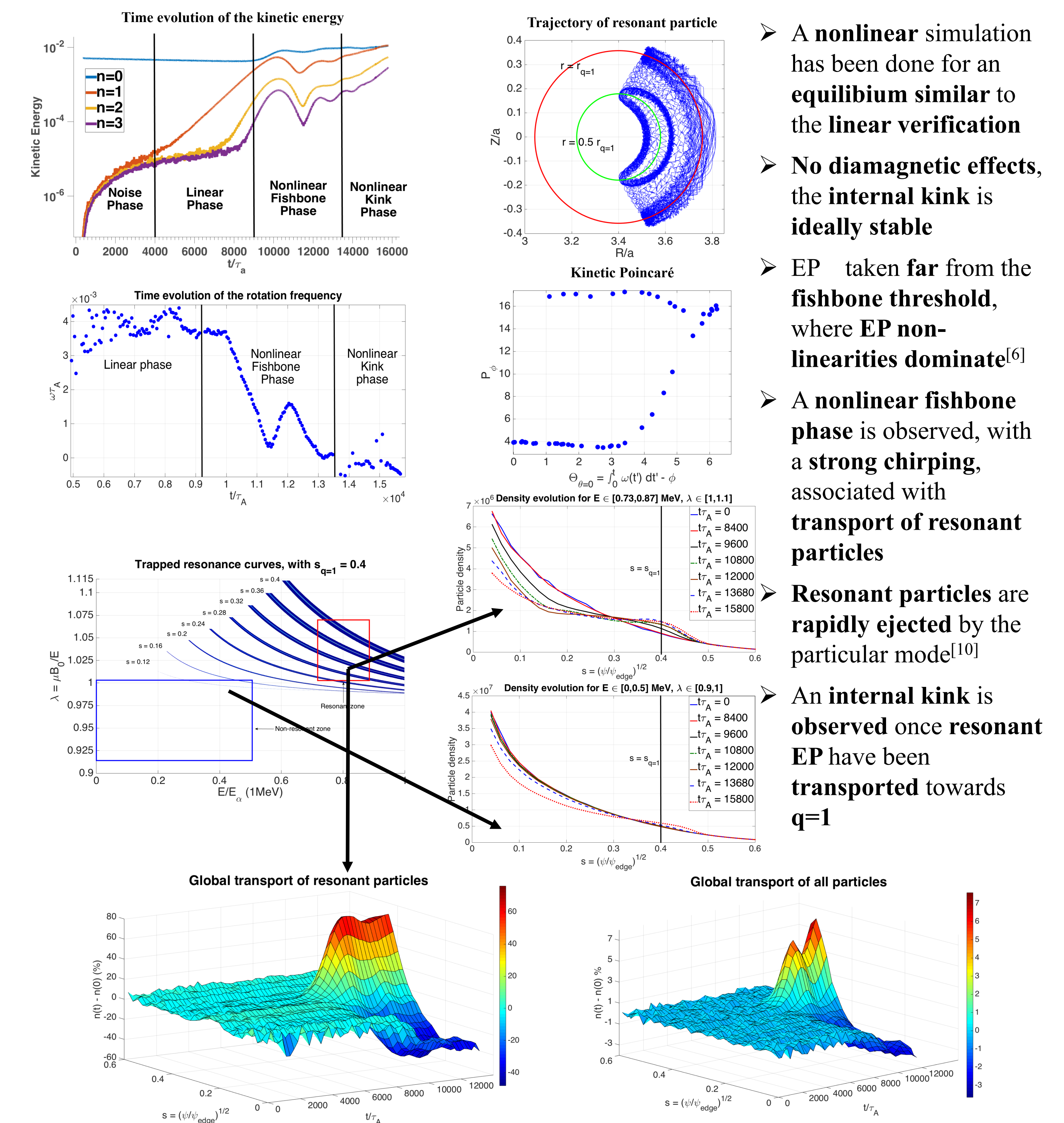
- Similar zones of precessional resonance are found with XTOR-K
- Discrepancies in phase space positions may be due to the thin orbit width assumption

## Linear stability of the ITER 15 MA case



- Linear simulations performed for up-down symmetric ITER geometry, with alpha particles at 3.5 MeV peak energy
- For  $q_0 = 0.95, 0.9$ , thresholds for the fishbone range between 6-10%, where expected ITER beta ratio will be around 15-20% for  $T_i(0) = 23$  keV<sup>[17]</sup>
- ITER can be unstable against fishbone instability for specific equilibria with peaked alpha density profile

## Fishbone nonlinear simulation



- A nonlinear simulation has been done for an equilibrium similar to the linear verification
- No diamagnetic effects, the internal kink is ideally stable
- EP taken far from the fishbone threshold, where EP nonlinearities dominate<sup>[6]</sup>
- A nonlinear fishbone phase is observed, with a strong chirping, associated with transport of resonant particles
- Resonant particles are rapidly ejected by the particular mode<sup>[10]</sup>
- An internal kink is observed once resonant EP have been transported towards  $q=1$

- 50% of resonant EP are transported by the fishbone, whereas total EP fishbone transport is weak (4%)
- EP global transport needs also to be studied near the fishbone threshold, where synchronisation between EP and kink rotation can occur
- At actual 3.5 MeV peak energy, resonances span larger zones of phase space, which could increase EP transport

## Conclusion

- Newly implemented nonlinear hybrid code XTOR-K verified linearly
- ITER 15 MA can be fishbone unstable for specific equilibria
- Global EP transport due to fishbone found weak far from fishbone threshold at 1 MeV
- More advanced kinetic Poincaré diagnostics needed to understand the nonlinear interplay between mode chirping and EP transport
- An other nonlinear simulation needed to generalize results near fishbone threshold for more ITER relevant equilibrium

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