Supercritical stability of the Large Helical Device plasmas due to the kinetic thermal ion effects

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PLASMA SIMULATOR

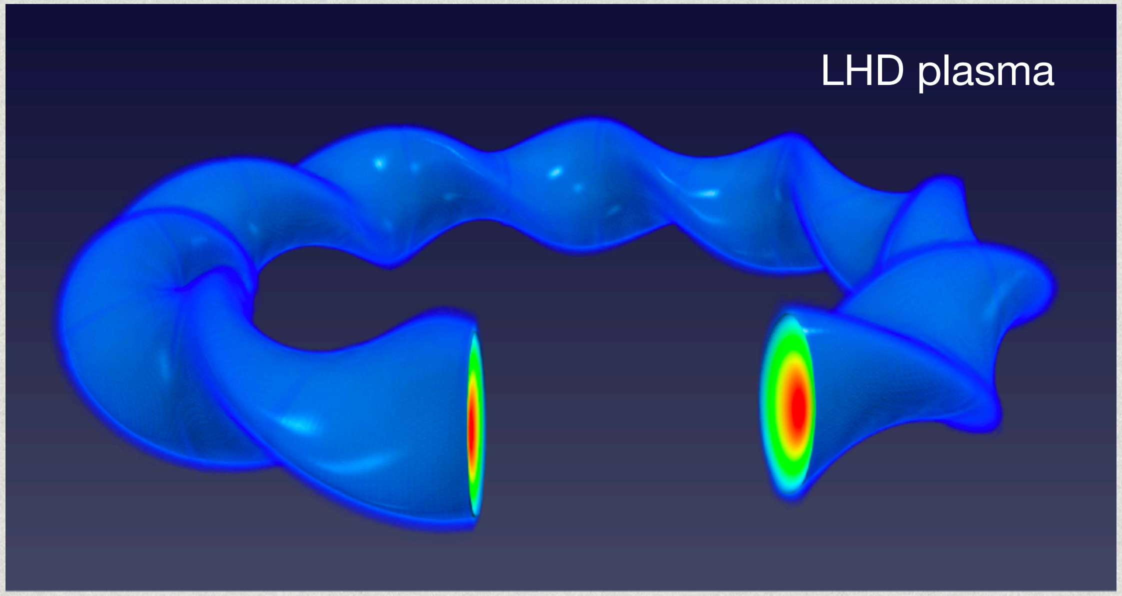
Outline

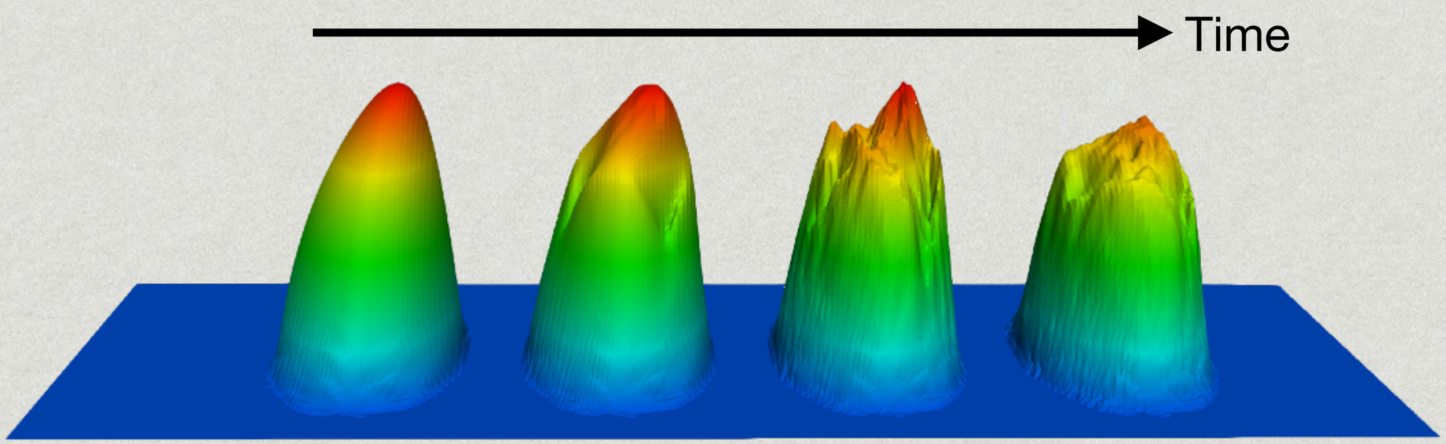
- Motivation
- Numerical model
- Simulation results
  - Linear stability
  - Nonlinear evolution
- Summary

Why high beta plasmas can be stably obtained in the LHD experiments?

- In the Large Helical Device (LHD) experiments, the volume averaged beta value has achieved 5% without large MHD activities.

- Such high beta LHD plasmas have a magnetic hill in the plasma peripheral region.
  ➡ MHD instabilities are unstable.



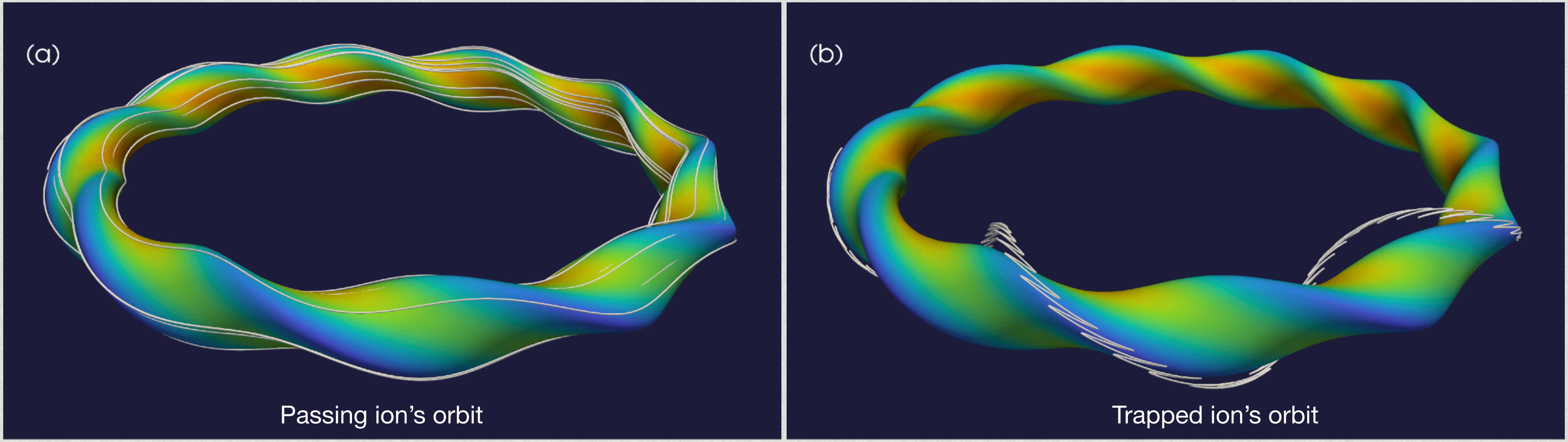


Time evolution of pressure profile in a poloidal cross section obtained from a simulation based on the MHD model.

- Simulations based on the MHD model can not reproduce the LHD experimental results showing that the high beta plasma is maintained.
  ➡ Improving the simulation model is necessary.

Kinetic effects of thermal ions on MHD instabilities

In this study, the stability analysis of MHD instabilities in LHD plasmas has been carried out by numerical simulation based on the kinetic MHD model where thermal ions are simulated with the drift-kinetic model.



Magnetic field strength and orbits of (a) a passing ion and (b) a trapped ion in the LHD.

It is found that the trapped ions play an important role in the suppression of the MHD instabilities.

Hybrid simulation (MEGA code)

$\mathbf{B}, \mathbf{E}, P_e$

Ion : Drift kinetic model (PIC method)

$$\frac{d\mathbf{x}}{dt} = \mathbf{v},$$

$$m_i v_\parallel \frac{dv_\parallel}{dt} = (\mathbf{v}_\parallel^* + \mathbf{v}_C) \cdot (q_i \mathbf{E}^* - \mu \nabla B),$$

$$\frac{dw_j}{dt} = -V_j \left[(\mathbf{v}_E + v_\parallel (\mathbf{b} - \mathbf{b}_0) \cdot \nabla + \frac{d\epsilon}{dt} \frac{\partial}{\partial \epsilon} \right] f_0,$$

where

$$\mathbf{v} = \mathbf{v}_\parallel^* + \mathbf{v}_E + \mathbf{v}_B + \mathbf{v}_C,$$

$$\mathbf{v}_\parallel^* = \frac{B}{B^*} v_\parallel \mathbf{b},$$

$$\mathbf{v}_E = \frac{1}{B^*} (\mathbf{E}^* \times \mathbf{b}),$$

$$\mathbf{v}_B = -\frac{1}{q_i B} (\mu \nabla B \times \mathbf{b}),$$

$$\mathbf{v}_C = \frac{m v_\parallel^2}{q_i B^*} \nabla \times \mathbf{b},$$

$$B^* = B(1 + \rho_\parallel \mathbf{b} \cdot \nabla \times \mathbf{b}), \;\; \rho_\parallel = \frac{m_i v_\parallel}{q_i B},$$

$$\mathbf{E}^* = -\mathbf{u} \times \mathbf{B} - \frac{m_i}{q_i \rho} \nabla_\parallel P_e,$$

- The number of particles : 64 / mesh

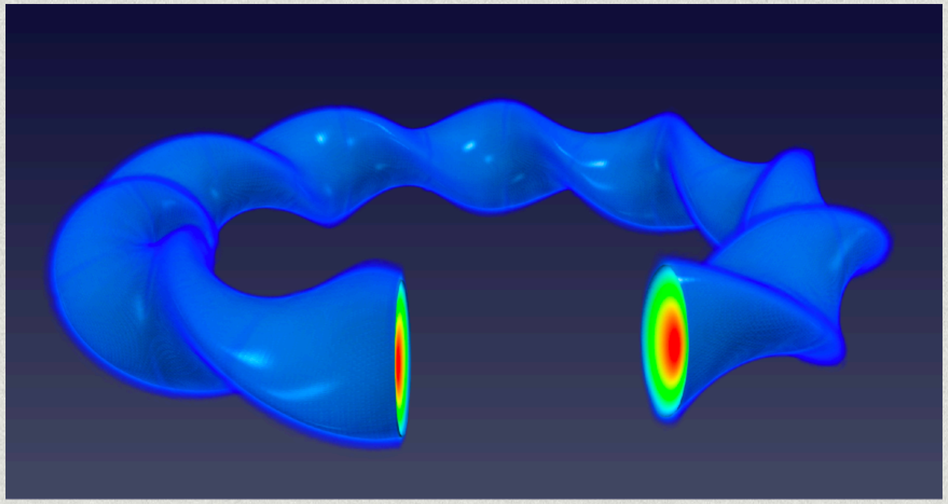
Fluid model (Finite difference method)

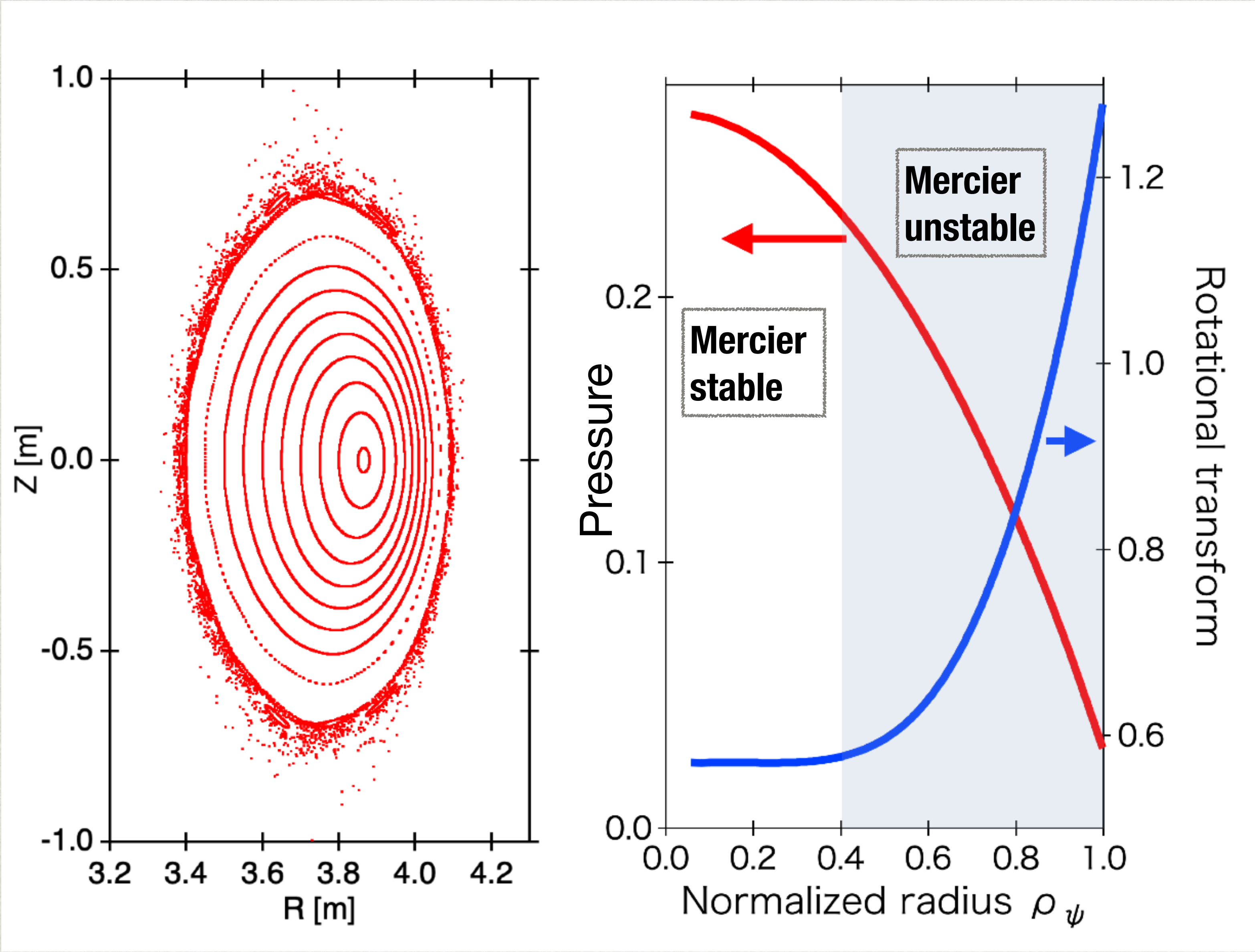
$$\begin{aligned}
\rho \frac{\partial \mathbf{u}_\perp}{\partial t} &= -\rho[(\mathbf{u}_\perp + u_\parallel \mathbf{b}) \cdot \nabla] \mathbf{u}_\perp \\
&\quad -\nabla_\perp (P_e + P_{i\perp}) - (P_{i\parallel} - P_{i\perp})(\mathbf{b} \cdot \nabla) \mathbf{b} \\
&\quad +\mathbf{j} \times \mathbf{B} \\
&\quad -\nu \rho \nabla \times (\nabla \times \mathbf{u}_\perp) + \frac{4}{3} \nu \rho \nabla (\nabla \cdot \mathbf{u}_\perp), \\
\frac{\partial \mathbf{B}}{\partial t} &= -\nabla \times \mathbf{E}, \\
\frac{\partial P_e}{\partial t} &= -\nabla \cdot [P_e (\mathbf{u}_\perp + u_\parallel \mathbf{b})] \\
&\quad -(\Gamma - 1) P_e \nabla \cdot (\mathbf{u}_\perp + u_\parallel \mathbf{b}) \\
&\quad +(\Gamma - 1) \nabla \cdot [(\chi_\perp \nabla_\perp + \chi_\parallel \nabla_\parallel)(P_e - P_{e,eq})], \\
\mathbf{E} &= -\mathbf{u}_\perp \times \mathbf{B} + \eta (\mathbf{j} - \mathbf{j}_{eq}), \\
\mathbf{j} &= \frac{1}{\mu_0} \nabla \times \mathbf{B}
\end{aligned}$$

- The number of Meshes : 128x128x640

$\rho, u_\parallel, P_{i\parallel}, P_{i\perp}$

High beta LHD equilibrium is constructed by HINT code

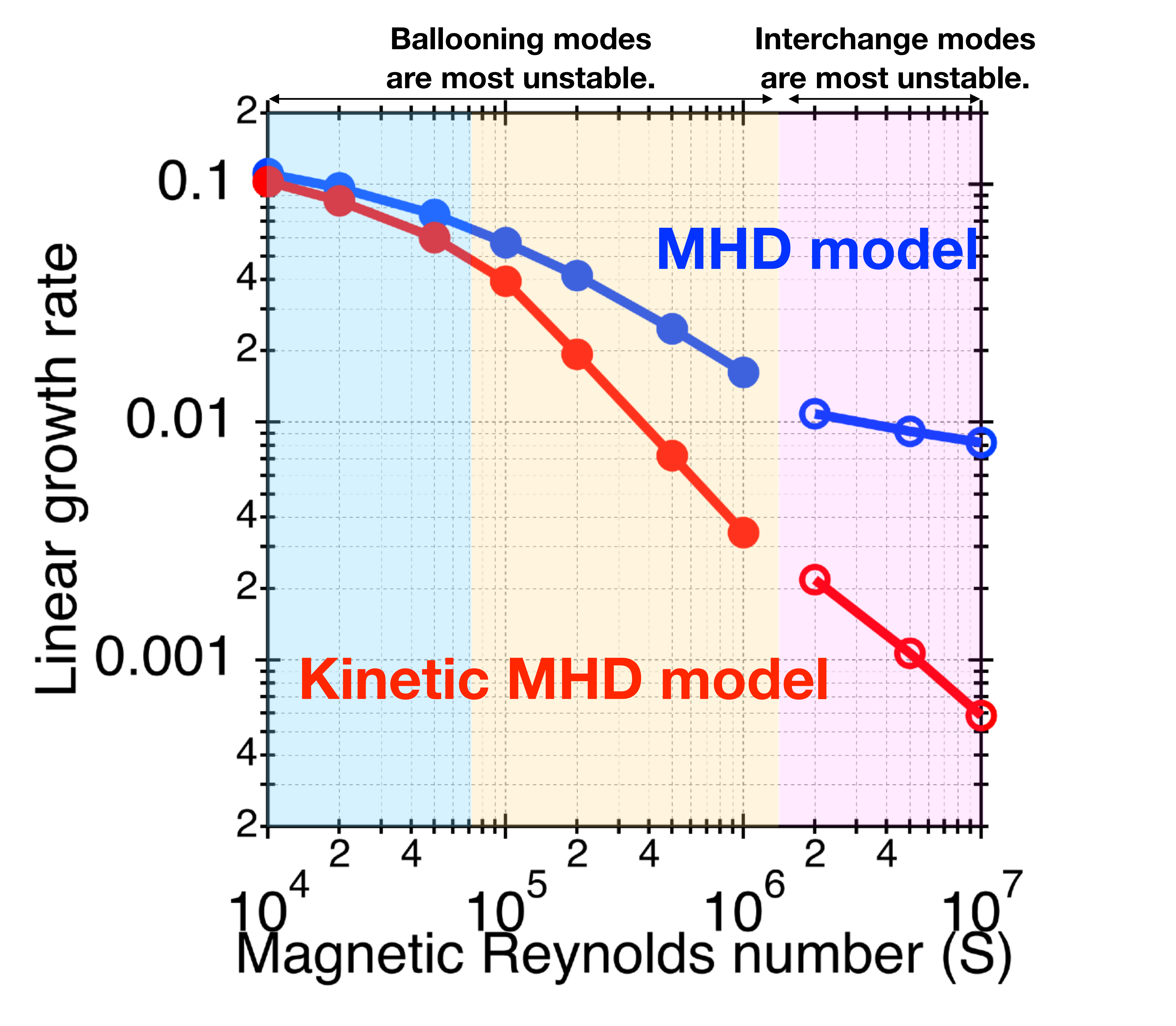




- MHD equilibrium is constructed by HINT code.
- The central beta : β_0=7.4%.
- $P_{e,eq}=P_{i\|,eq}=P_{i\perp,eq}=P_{HINT}/2$.
- Density : Uniform profile
- Ion : Maxwell distribution function

Ion kinetic effects reduce linear growth rates

M. Sato and Y. Todo, J. Plasma Phys. (2020)



Effects of gradient B & curvature drifts

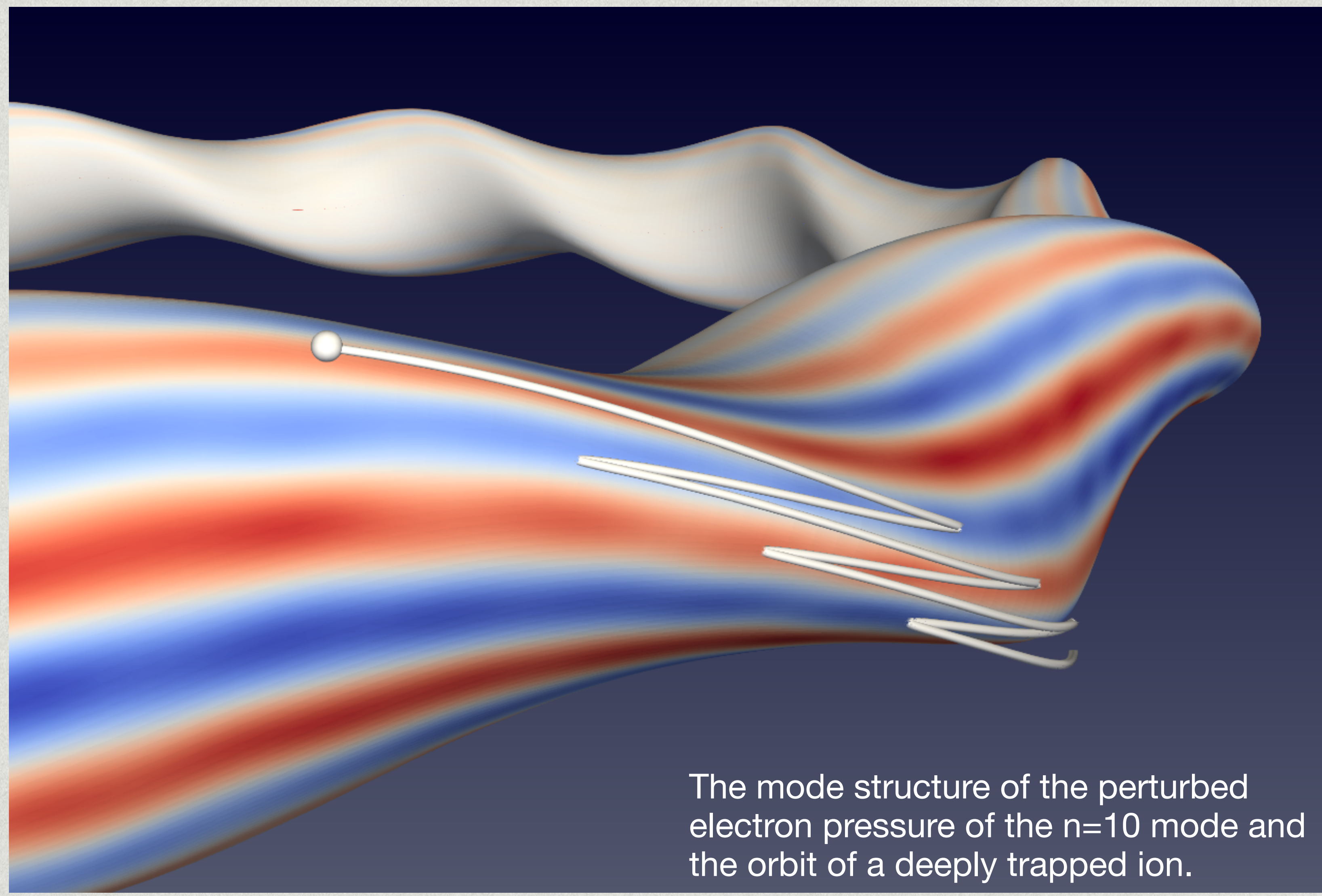
$$\mathbf{v} = \mathbf{v}_{\parallel}^{*} + \mathbf{v}_E + \quad (\mathbf{v}_B + \mathbf{v}_C)$$

$$\mathbf{v}_{\parallel}^{*} = \frac{B}{B^{*}} v_{\parallel} \mathbf{b}$$

$$\mathbf{v}_E = \frac{1}{B^{*}} (\mathbf{E}^{*} \times \mathbf{b}),$$

$$\mathbf{v}_B = -\frac{1}{q_i B} (\mu \nabla B \times \mathbf{b})$$

$$\mathbf{v}_C = \frac{m v_{\parallel}^2}{q_i B^{*}} \nabla \times \mathbf{b}$$



The mode structure of the perturbed electron pressure of the n=10 mode and the orbit of a deeply trapped ion.

Effects of gradient B & curvature drifts

M. Sato and Y. Todo, Nucl. Fusion (2019)

Introducing α_d for controlling the gradient B & curvature drifts

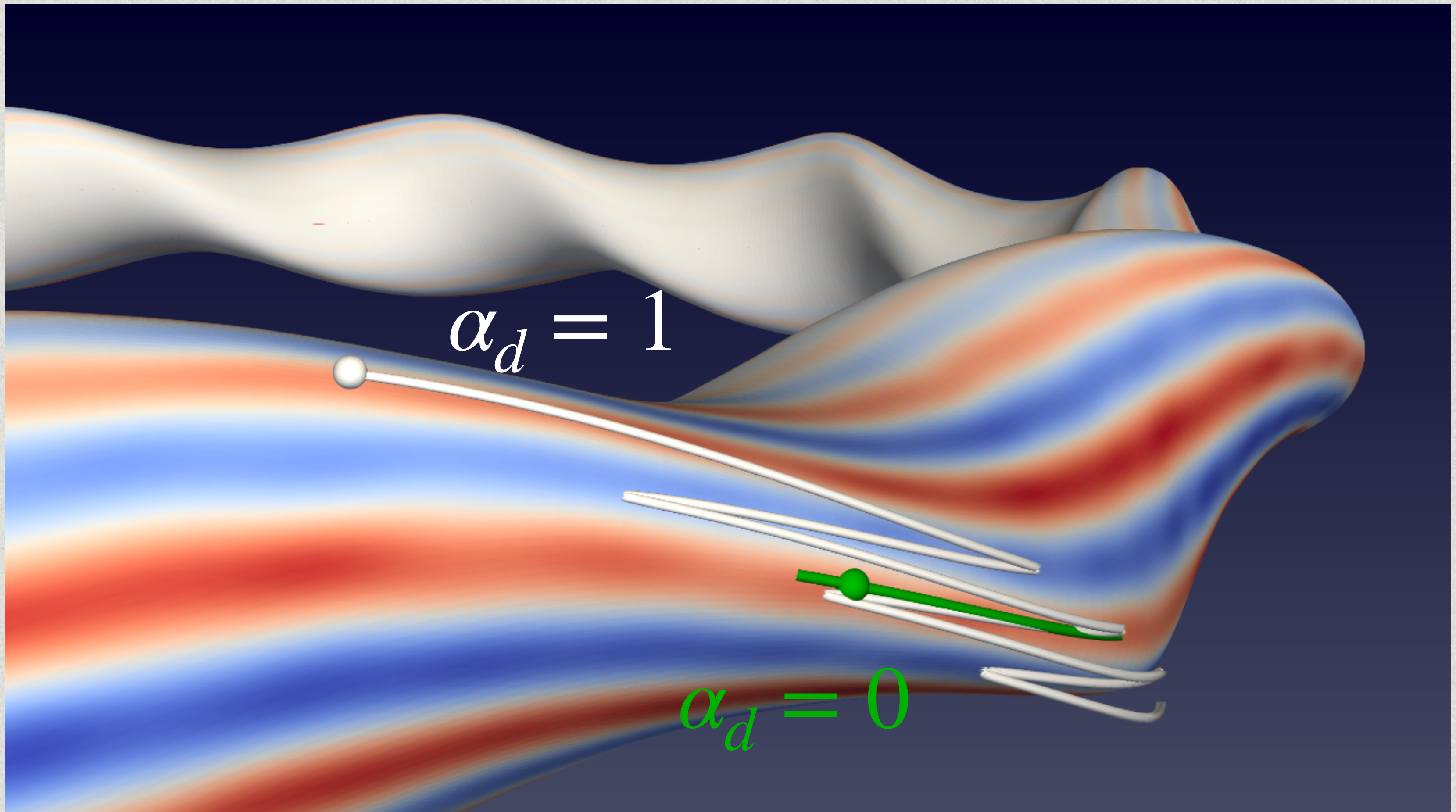
$$\mathbf{v} = \mathbf{v}_\parallel^* + \mathbf{v}_E + \alpha_d(\mathbf{v}_B + \mathbf{v}_C)$$

$$\mathbf{v}_\parallel^* = \frac{B}{B^*} v_\parallel \mathbf{b}$$

$$\mathbf{v}_E = \frac{1}{B^*}(\mathbf{E}^* \times \mathbf{b}),$$

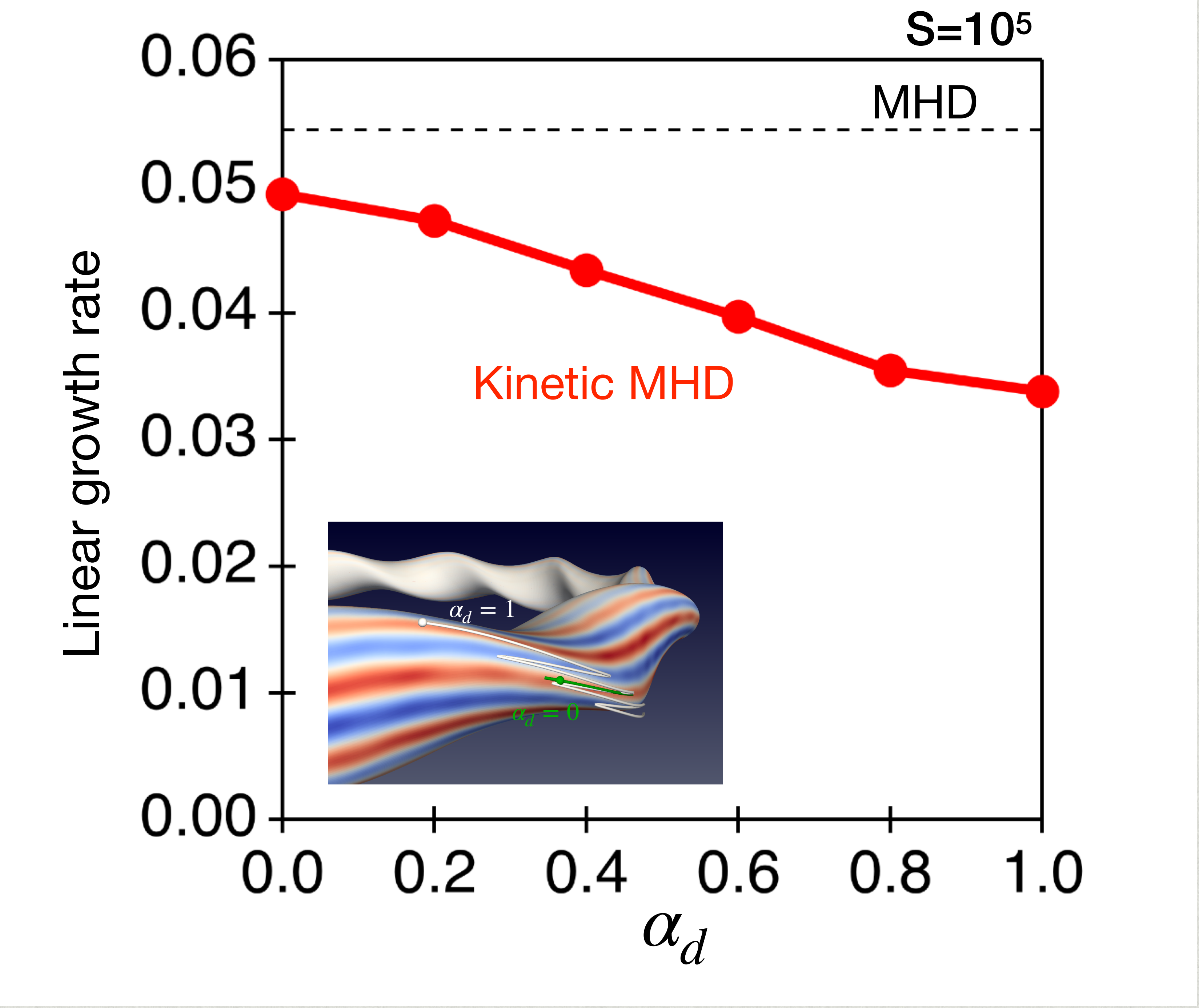
$$\mathbf{v}_B = -\frac{1}{q_i B}(\mu \nabla B \times \mathbf{b})$$

$$\mathbf{v}_C = \frac{m v_\parallel^2}{q_i B^*} \nabla \times \mathbf{b}$$



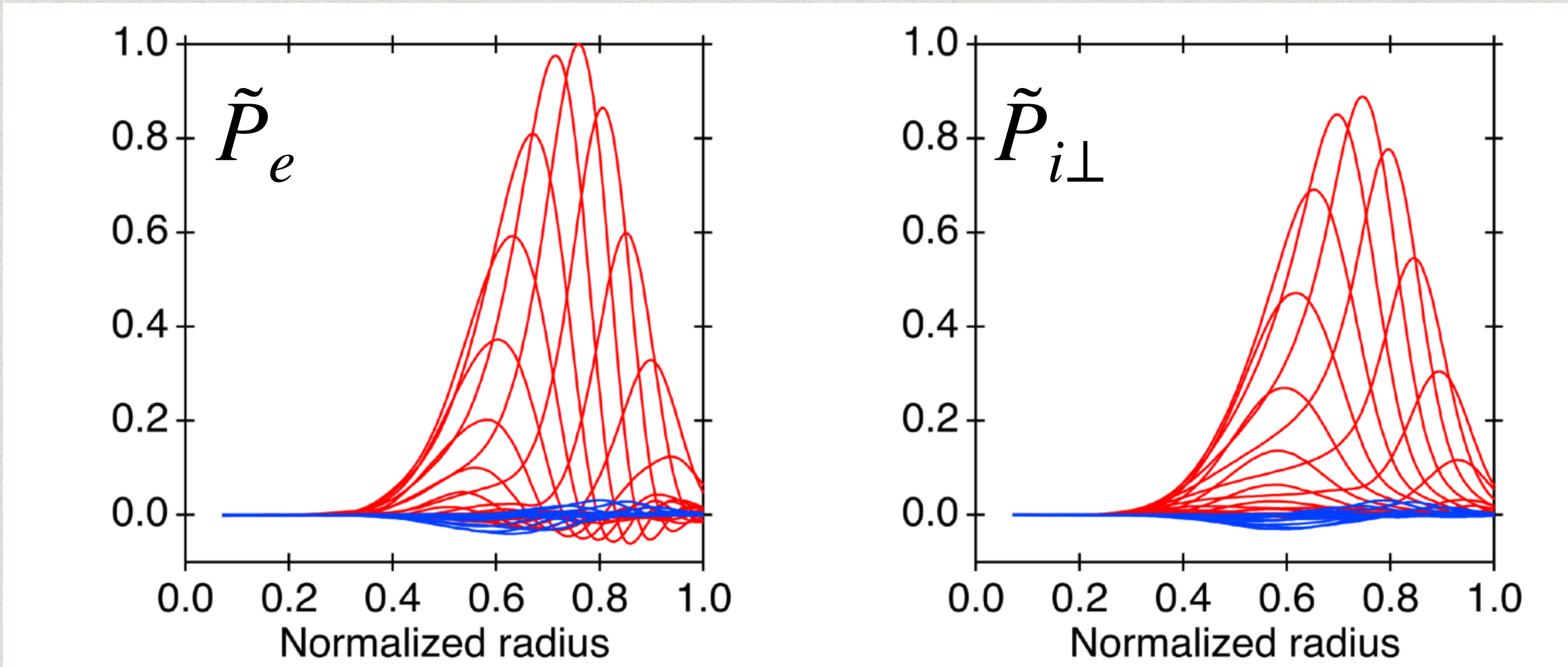
The mode structure of the perturbed electron pressure of the n=10 mode and the orbit of a deeply trapped ion.

Gradient B & curvature drifts reduce the linear growth rate

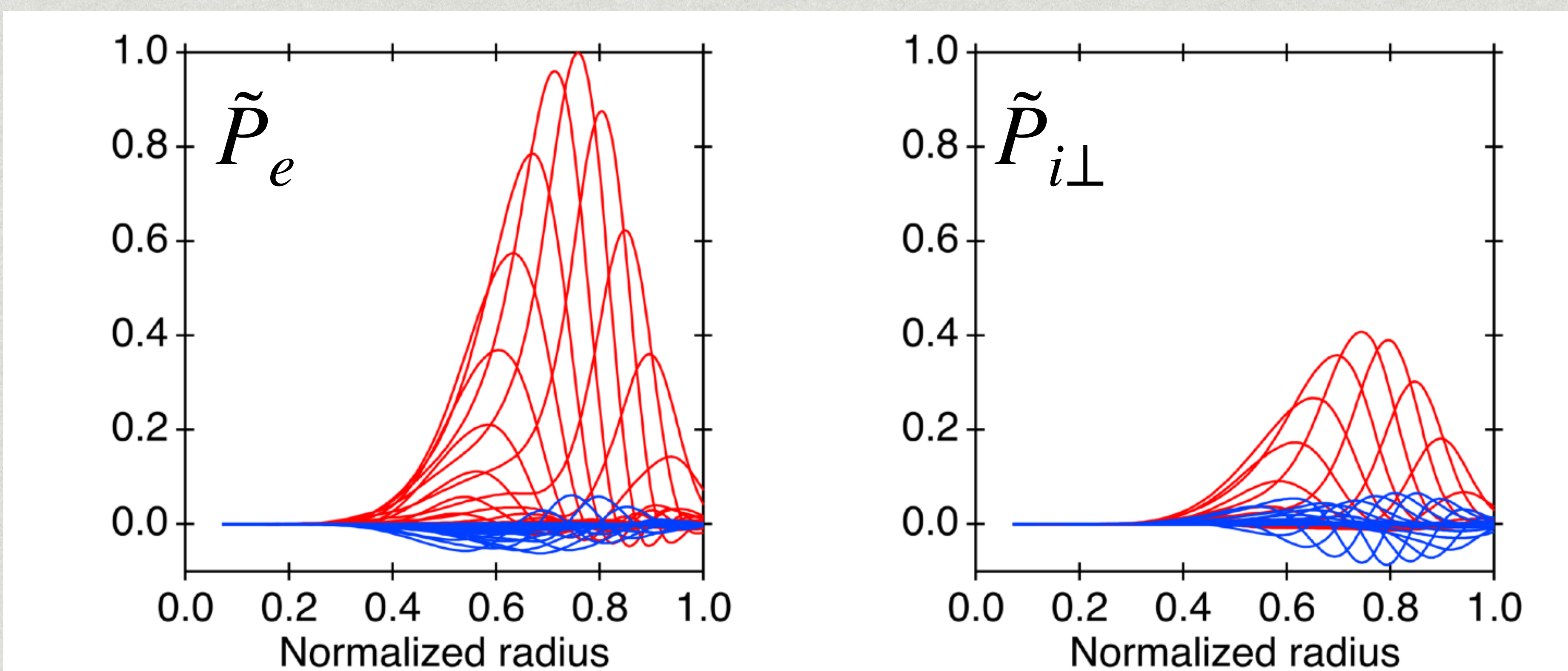


Gradient B & curvature drifts suppress $\tilde{P}_{i\perp}$

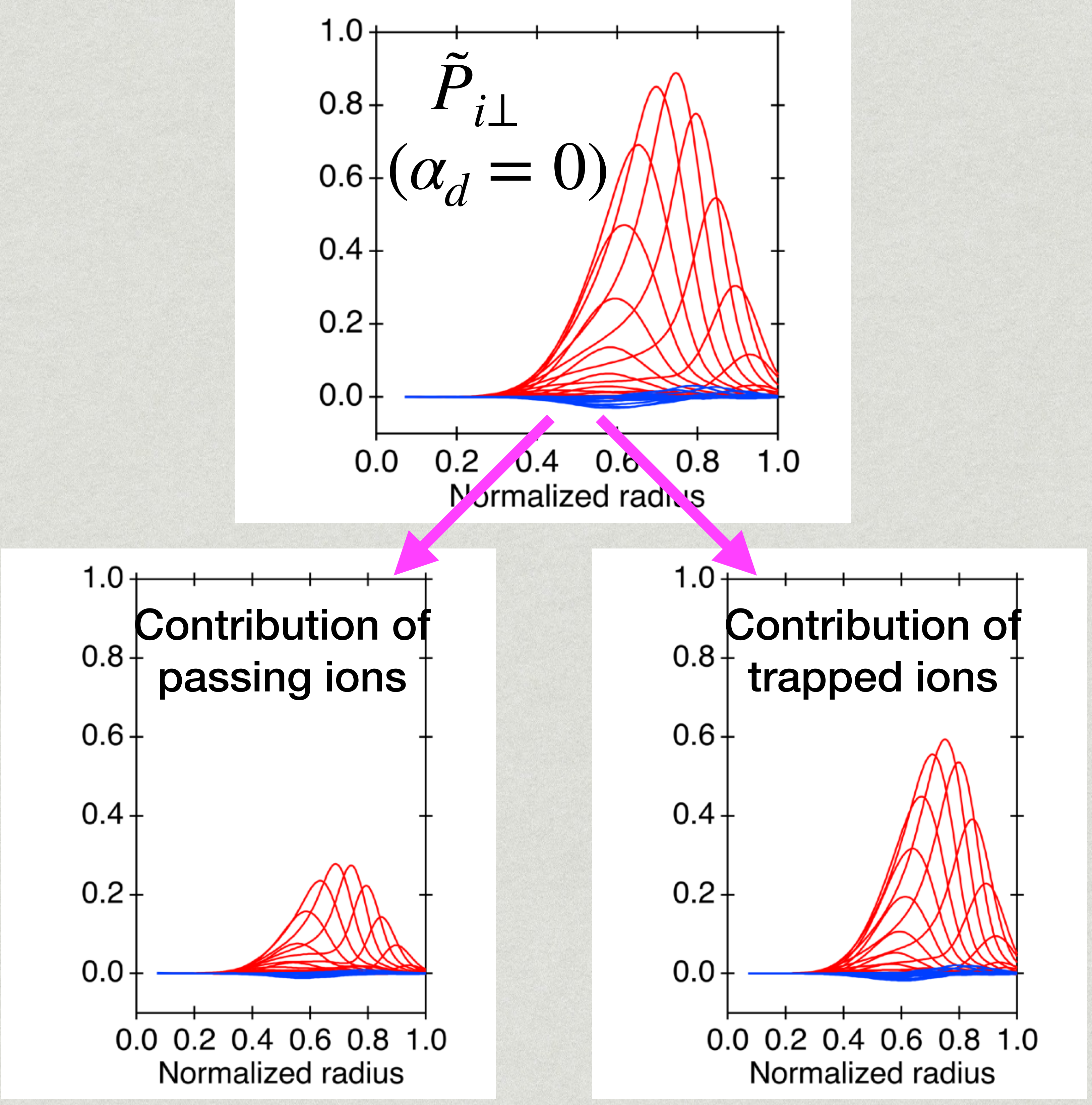
$\alpha_d = 0$



$\alpha_d = 1$

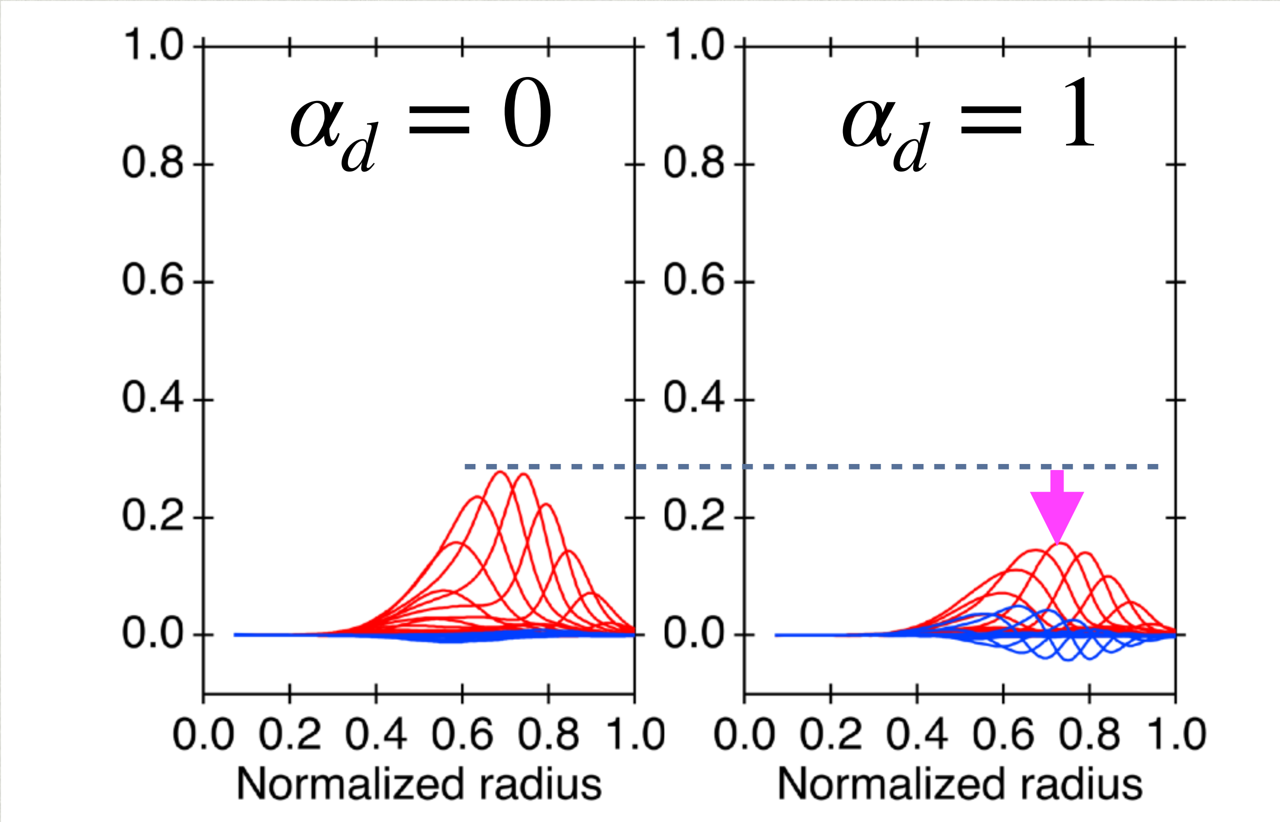


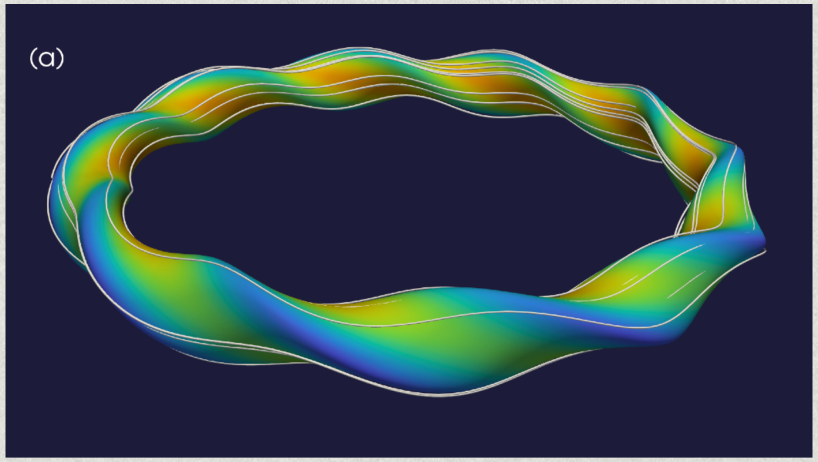
Contributions of passing ions and trapped ions



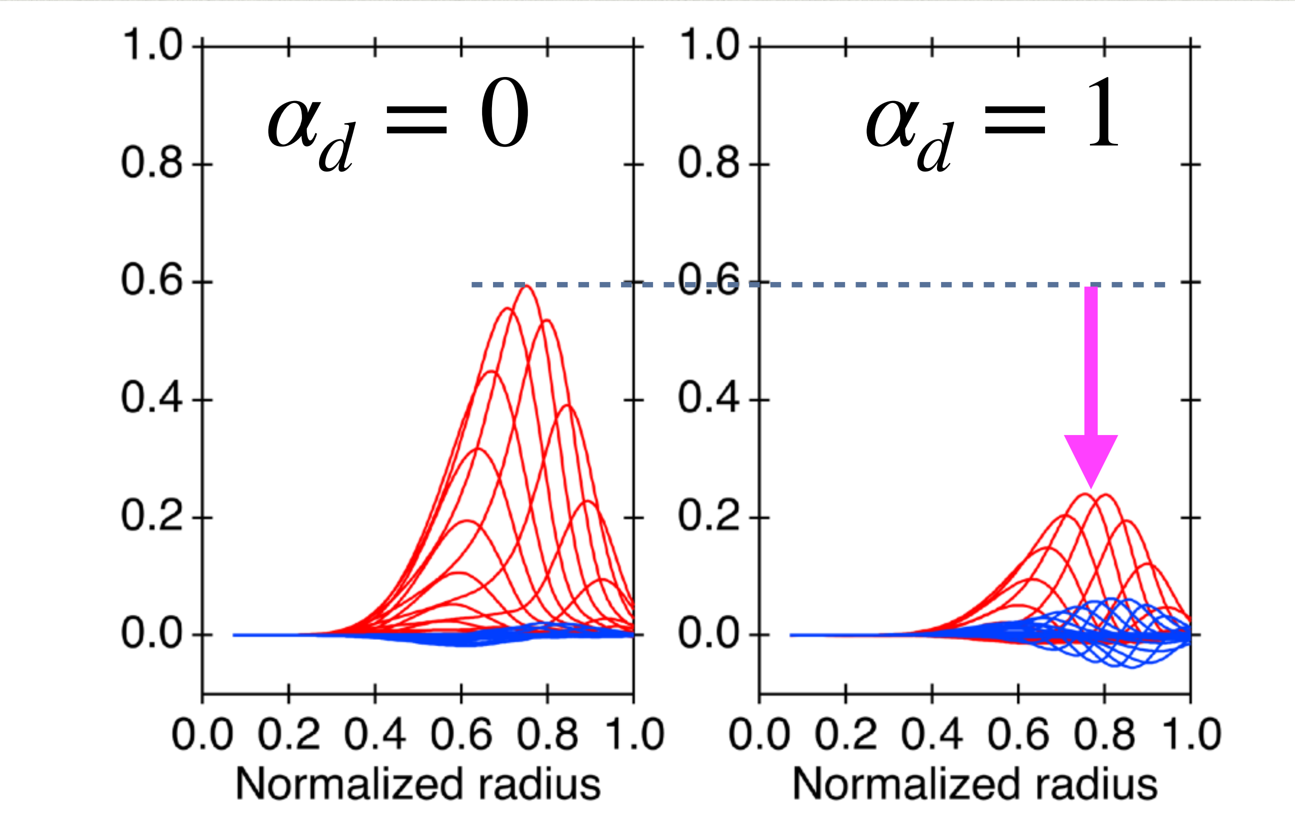
Gradient B & curvature drifts significantly suppress the contribution of trapped ions

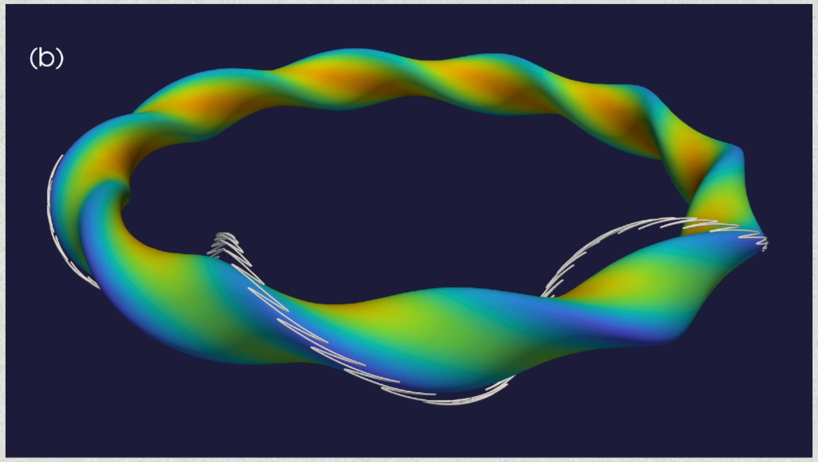
Passing ions



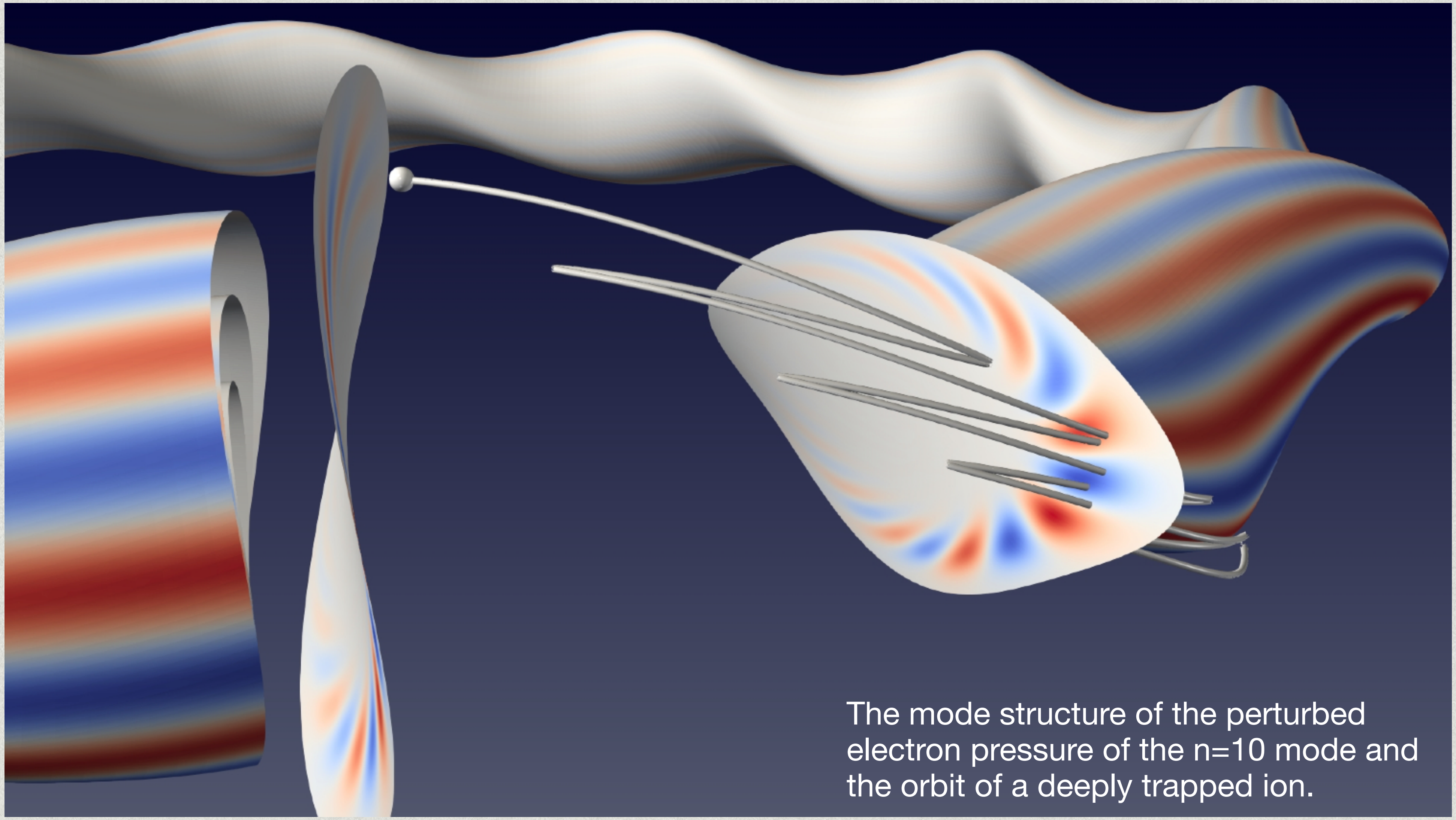


Trapped ions





Suppression mechanism due to the precession drift motion of trapped ions



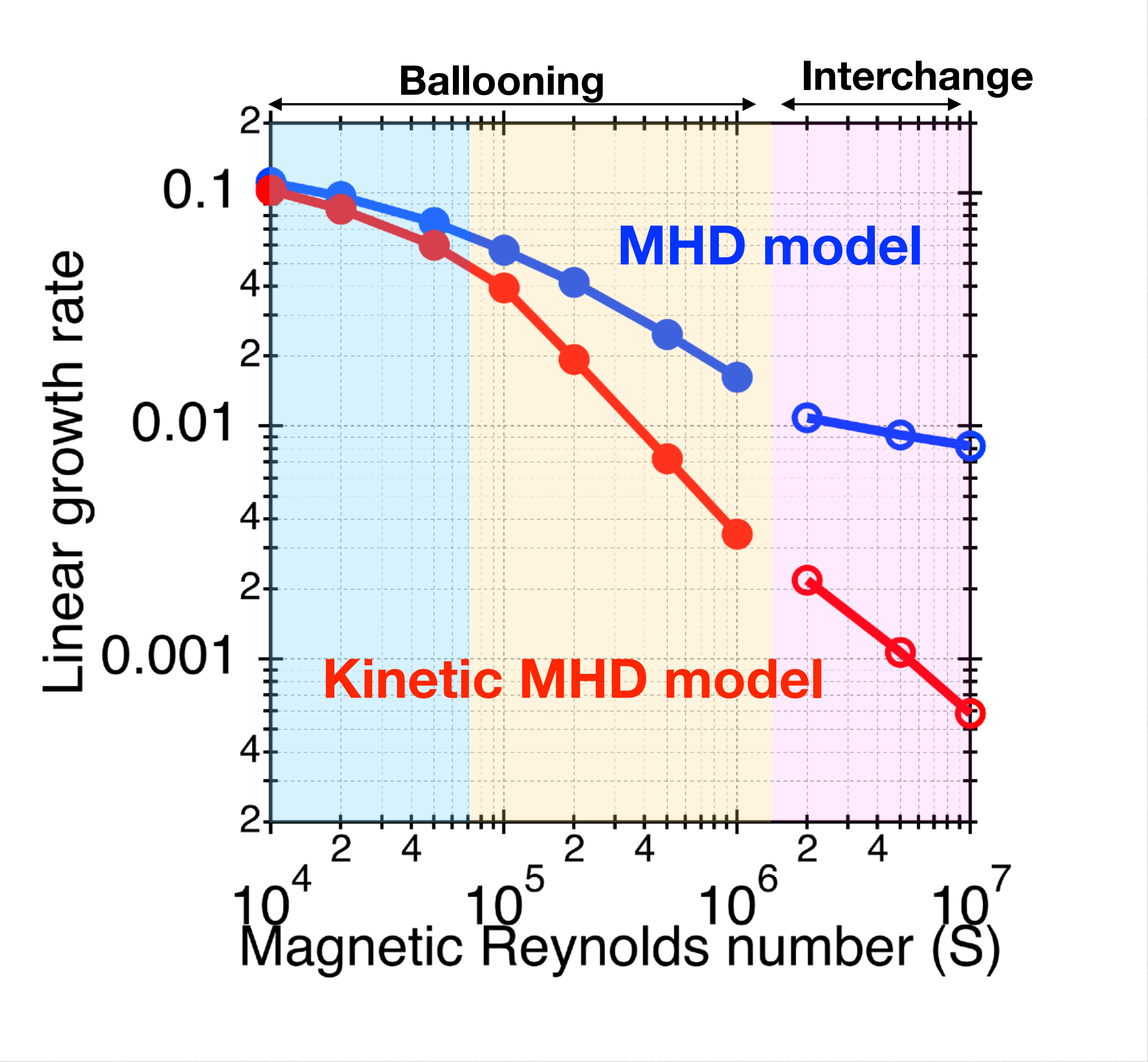
The mode structure of the perturbed electron pressure of the n=10 mode and the orbit of a deeply trapped ion.

The trapped ions can move through both positive and negative perturbations of the instabilities in the growth phase of the instabilities.

When “the precession drift frequency of the trapped ions with respect to the mode phase” is larger than the linear growth rate of the instabilities, the response of the trapped ions to the instabilities is weakened.

The contribution of the ion pressure gradient to the energy source for driving the instabilities becomes weaker.

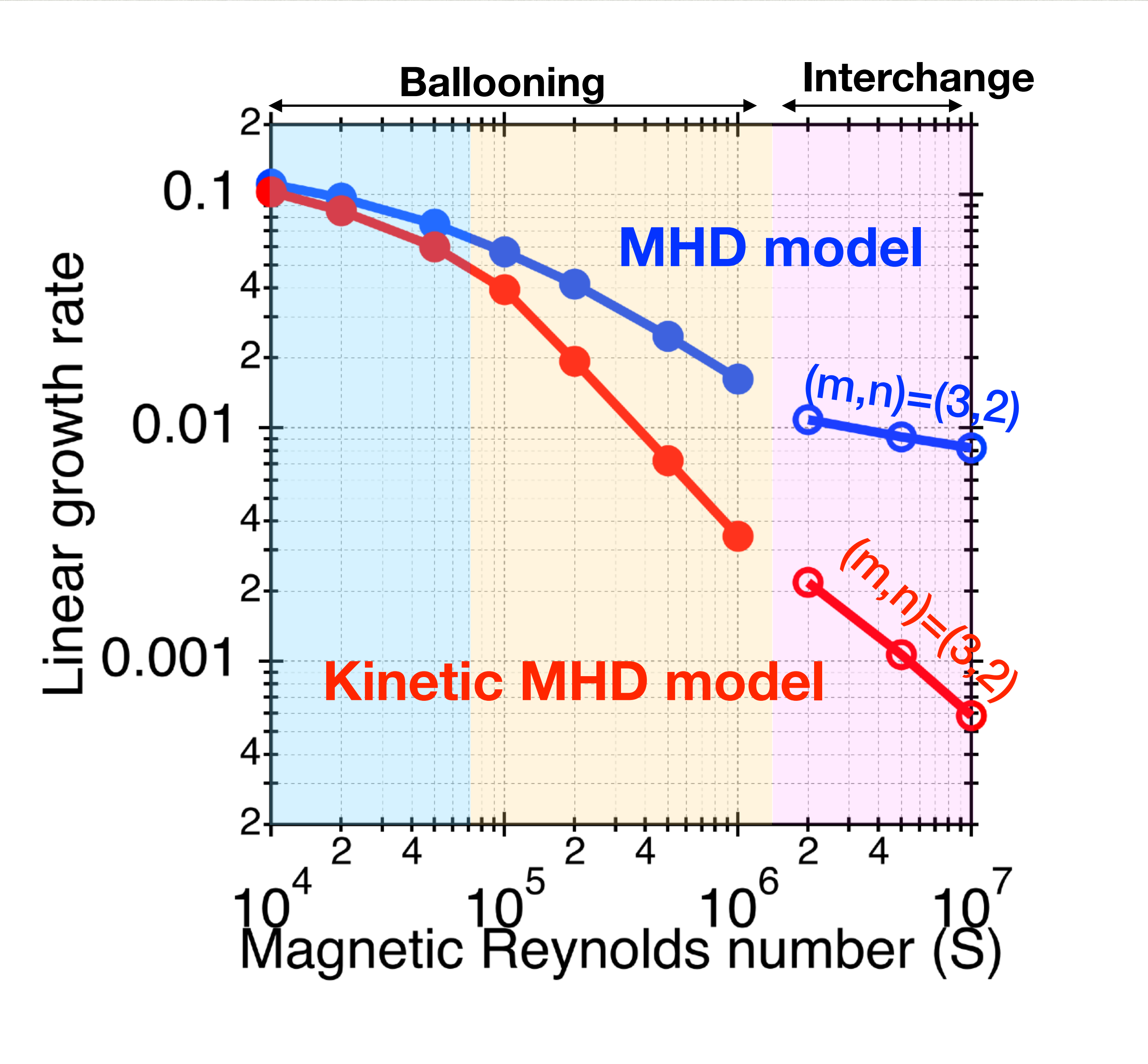
Linear growth rate vs. precession drift frequency with respect to the mode phase

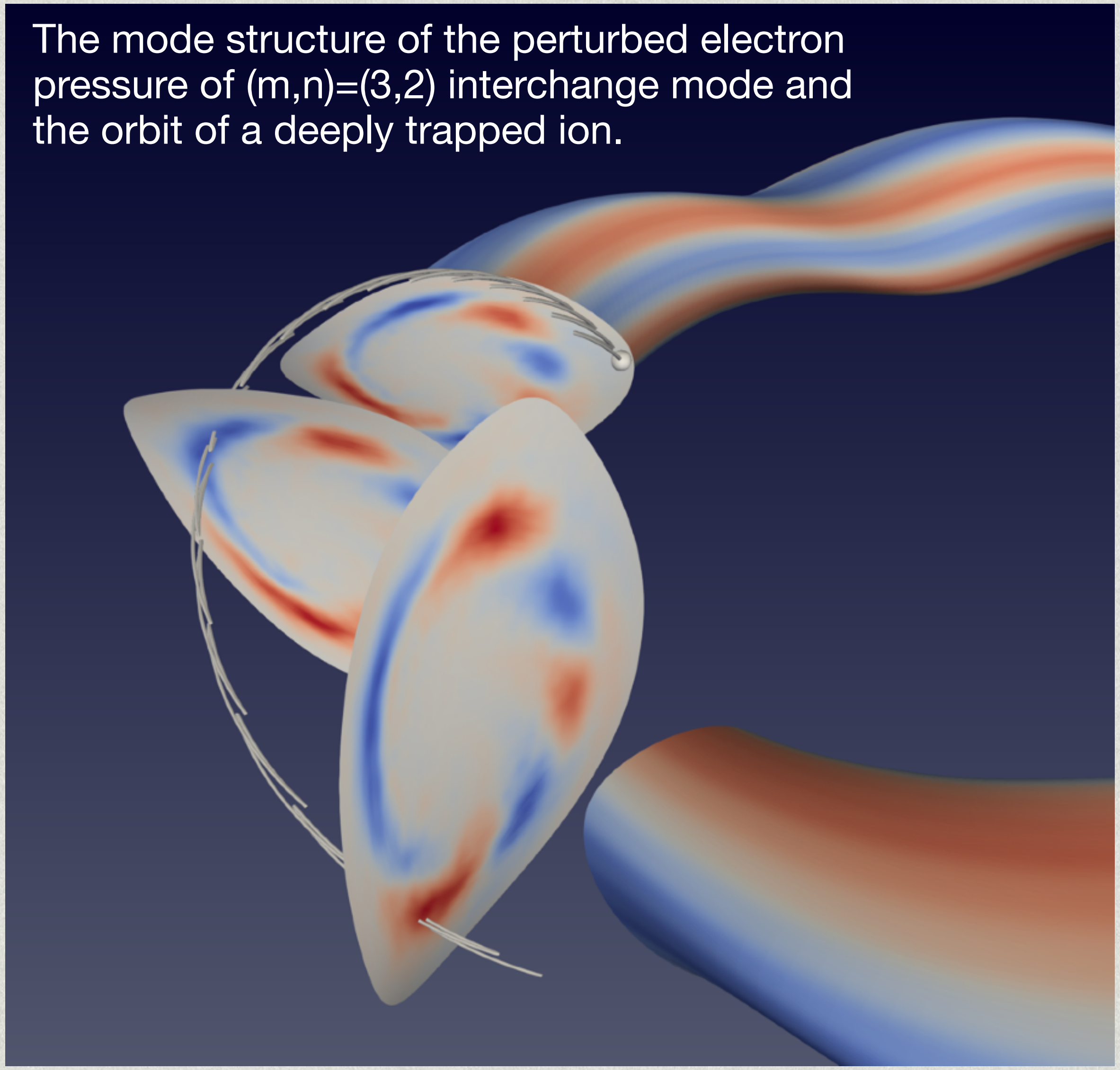


Linear growth rate

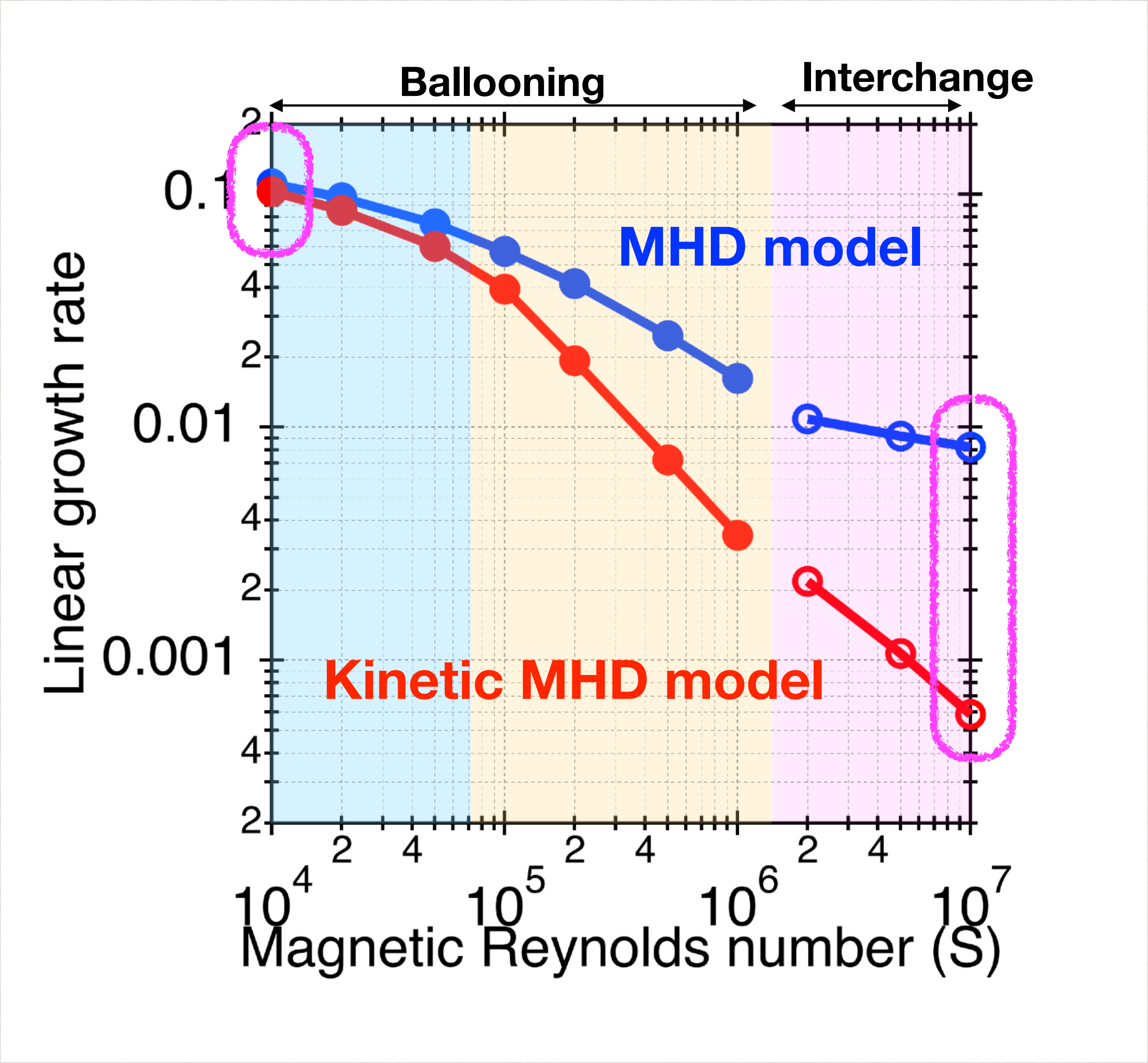
Precession drift frequency of trapped ions with mode phase

Interchange modes with low mode number can be stabilized by ion kinetic effects





Nonlinear evolution : MHD vs. Kinetic MHD



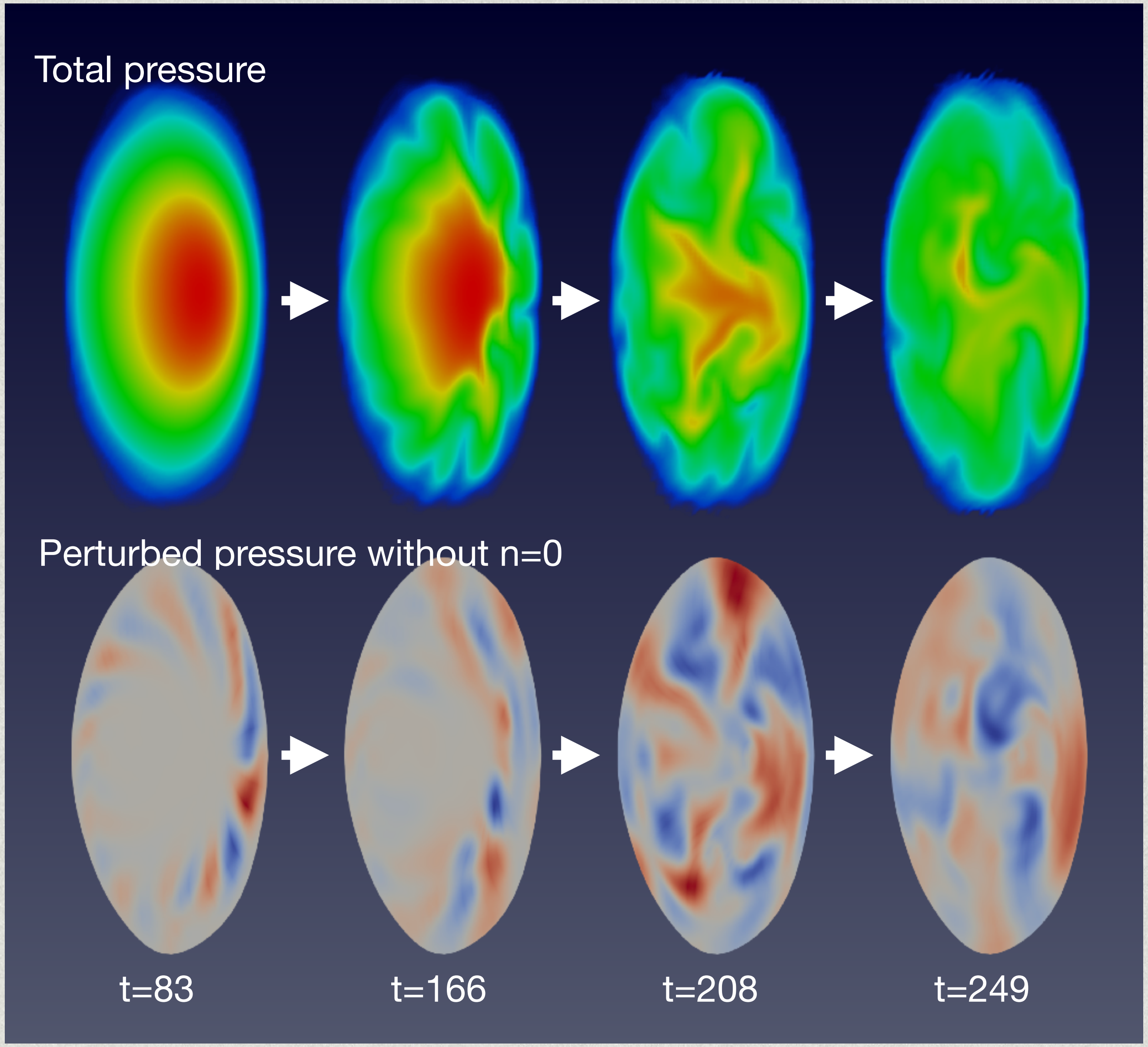
(1) S=10^4

(2) S=10^7

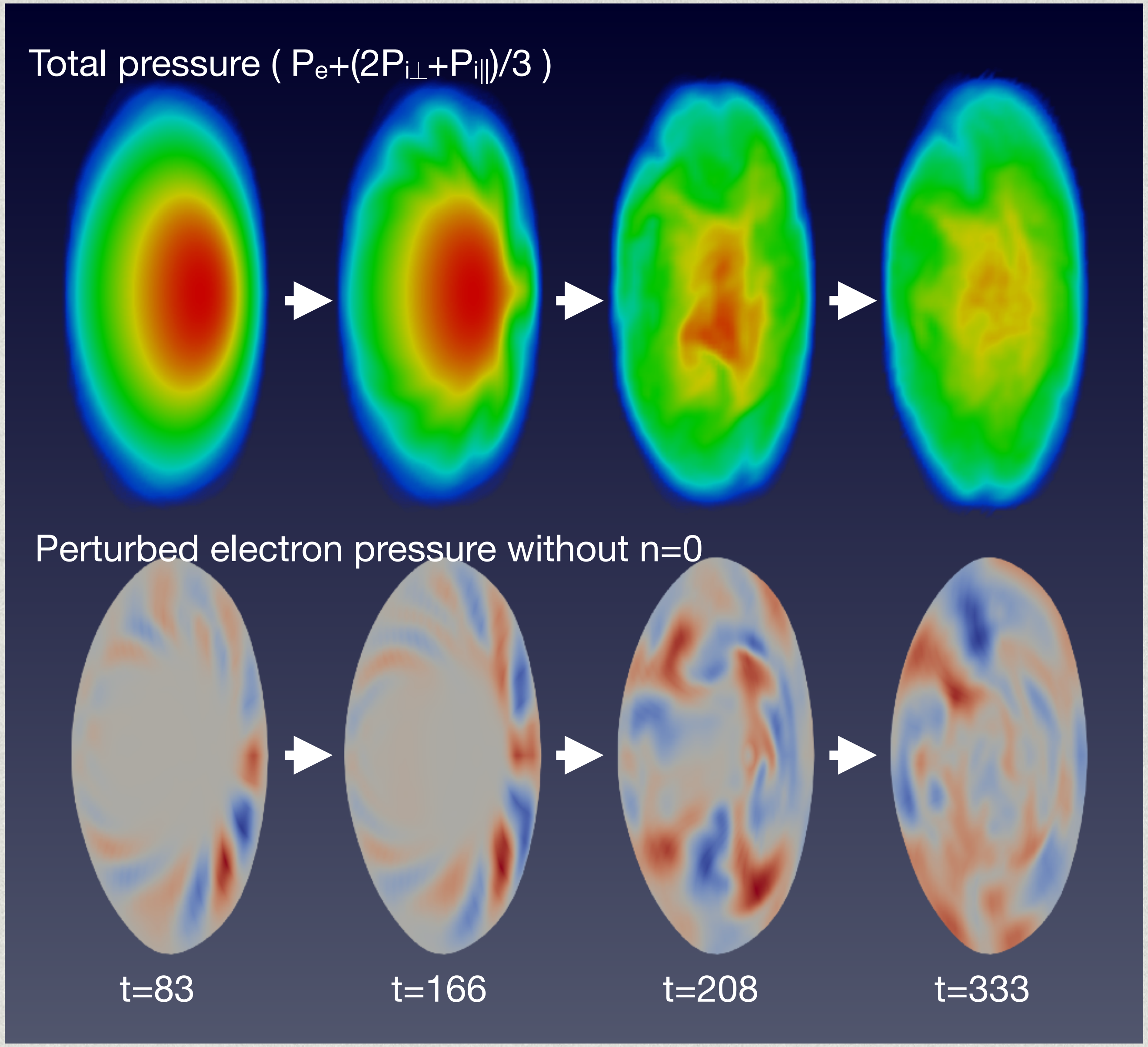
For low S, the central pressure significantly decreases in both models

- Nonlinear evolution of the pressure profile on a poloidal cross section for $S=10^4$ obtained from the MHD model and the kinetic MHD model.

MHD model

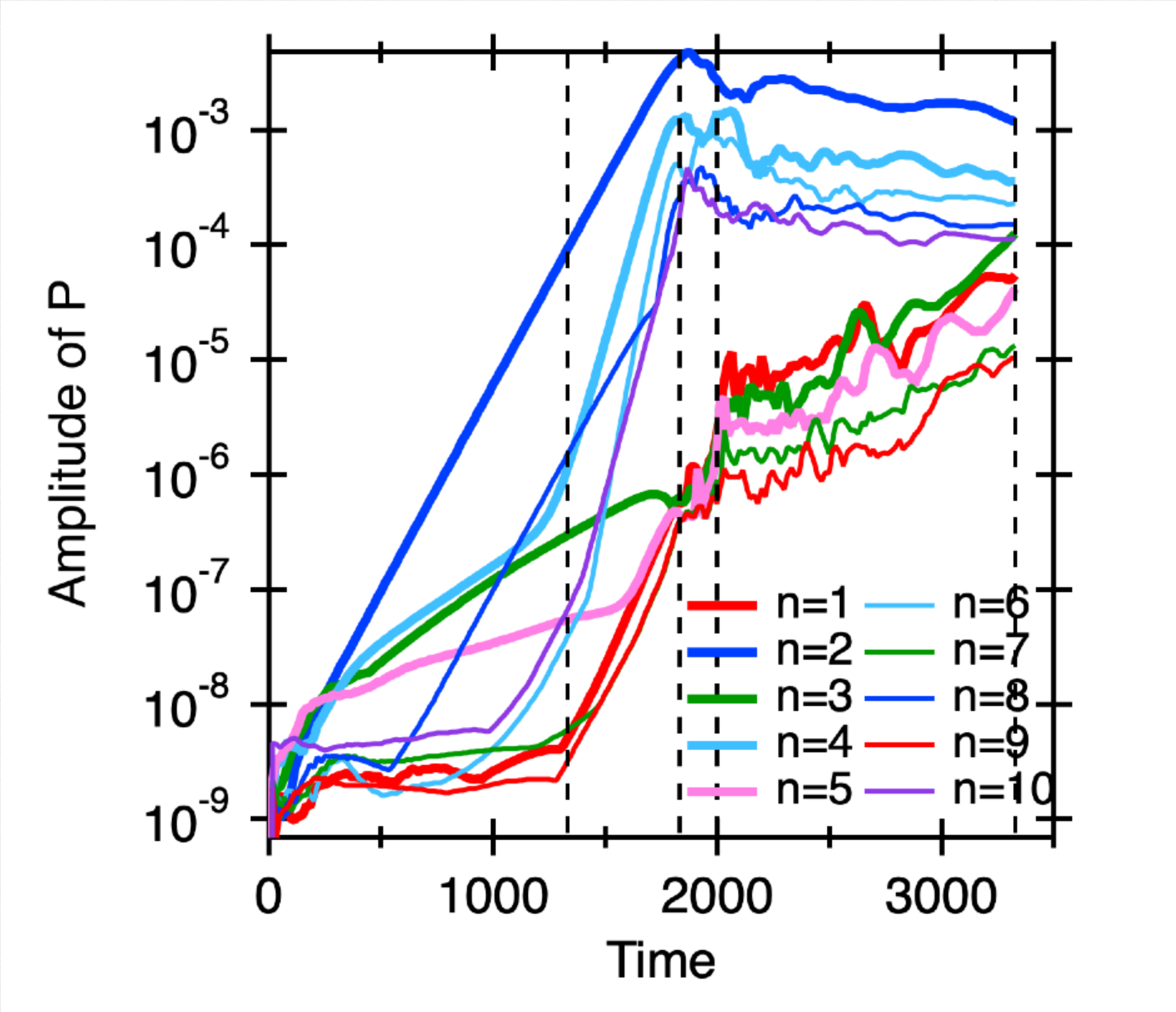


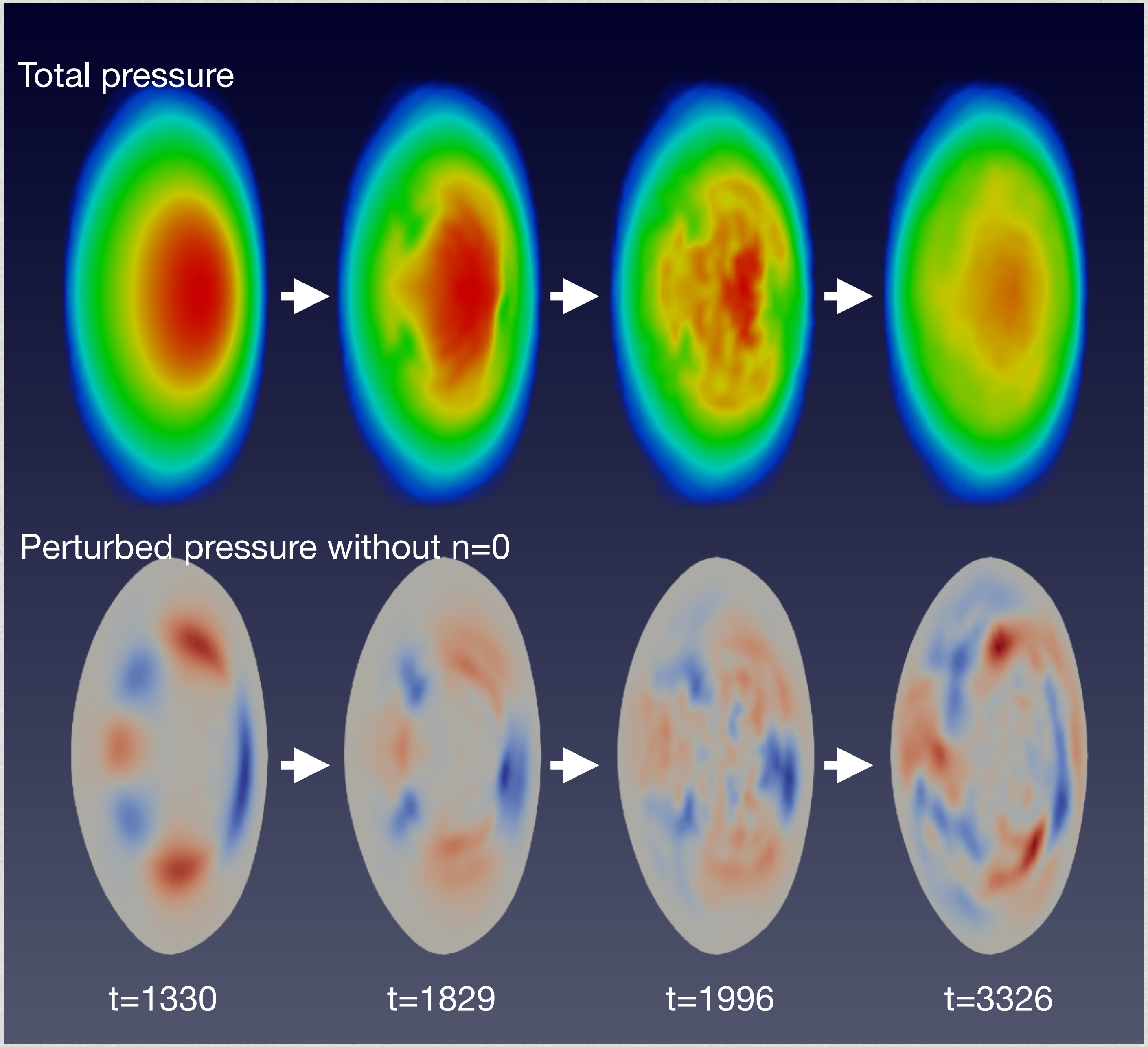
Kinetic MHD model



High beta is not maintained for high S number in the MHD model

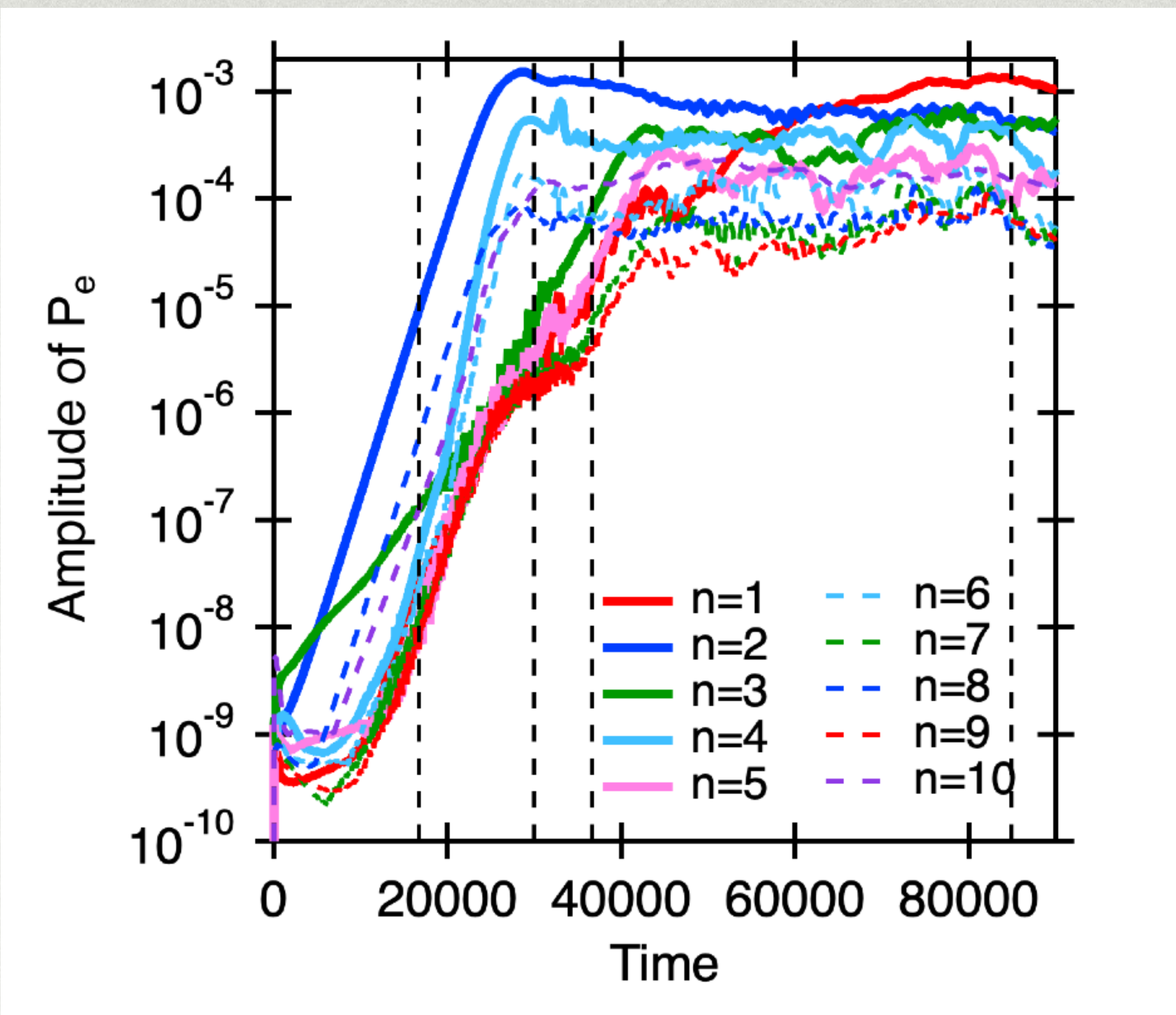
- Nonlinear evolution for $S=10^7$ obtained from the MHD simulation.

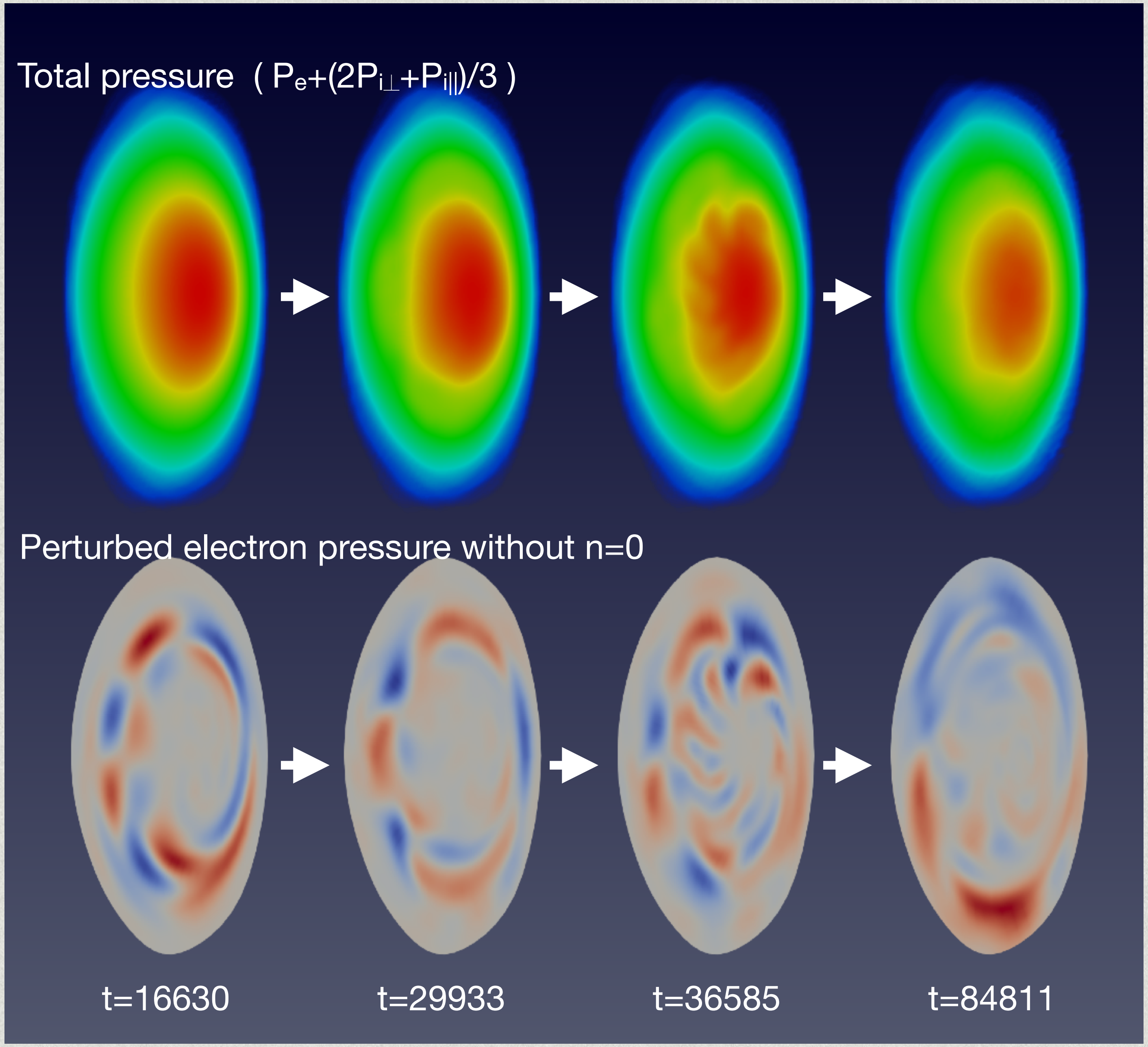




High beta is maintained for high S number in the kinetic MHD model

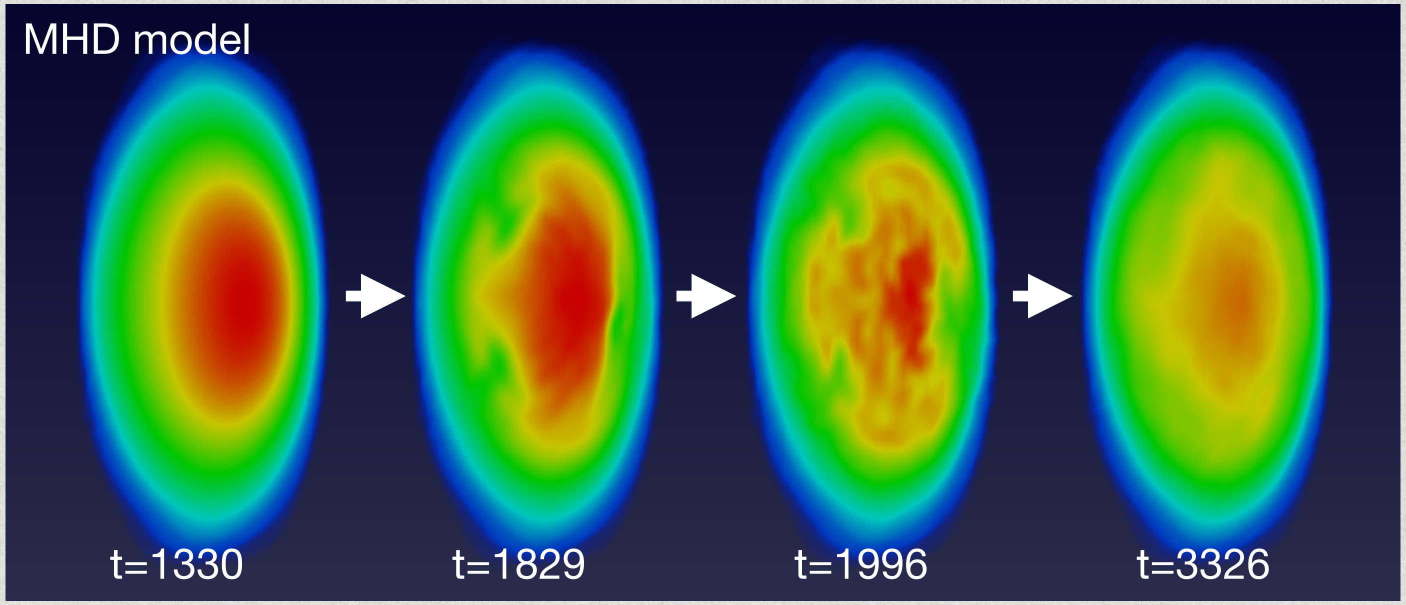
- Nonlinear evolution for S=10^7 obtained from the kinetic MHD simulation.

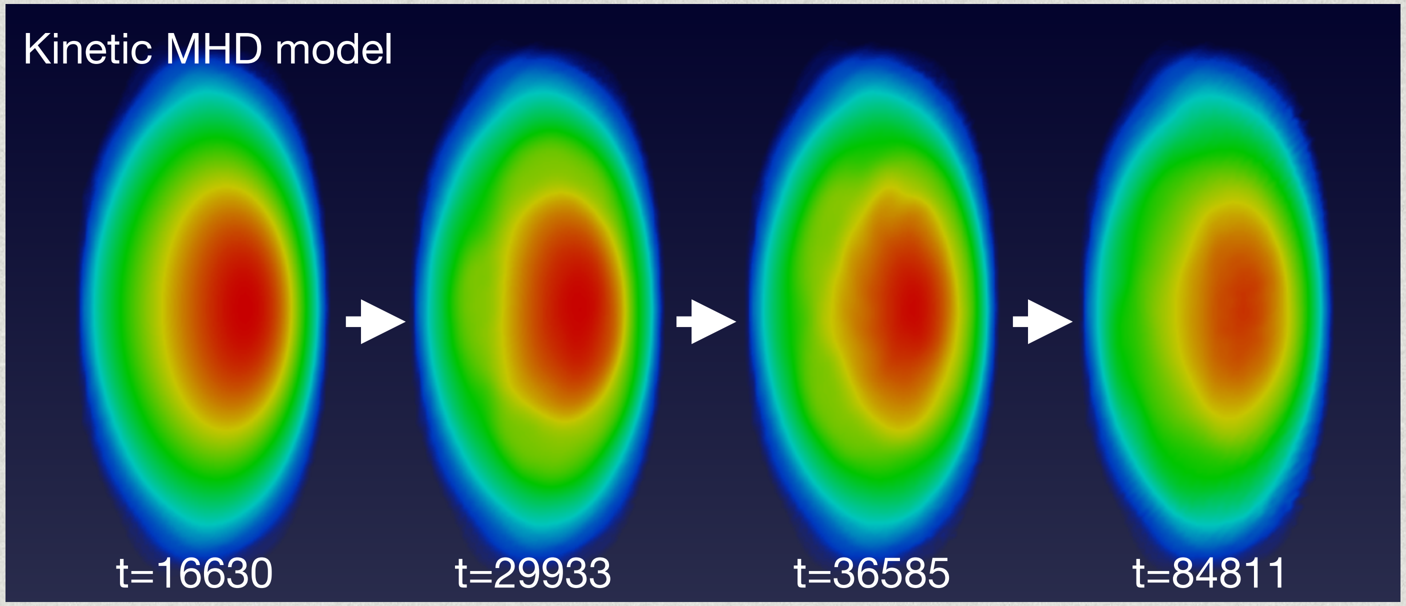


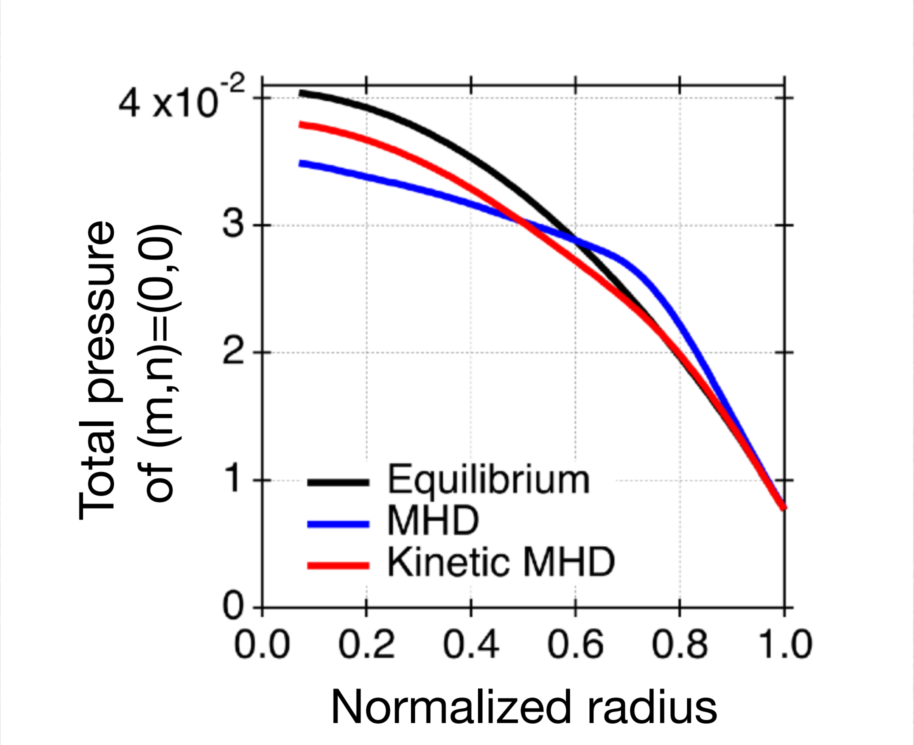


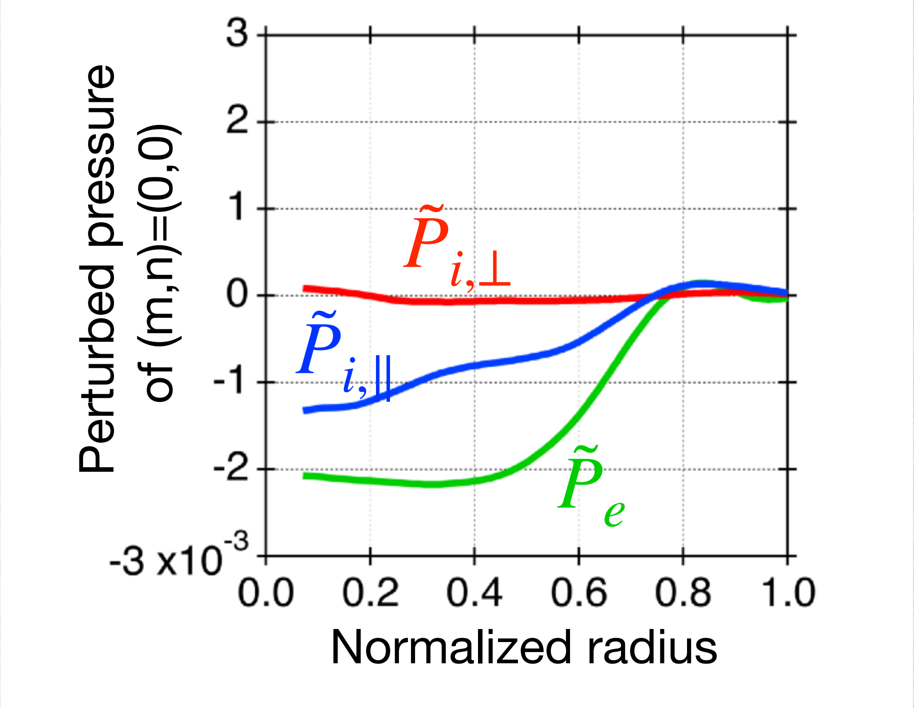
Ion kinetic effects significantly suppress $\tilde{P}_{i\perp}$ at the saturated state

- S=10^7

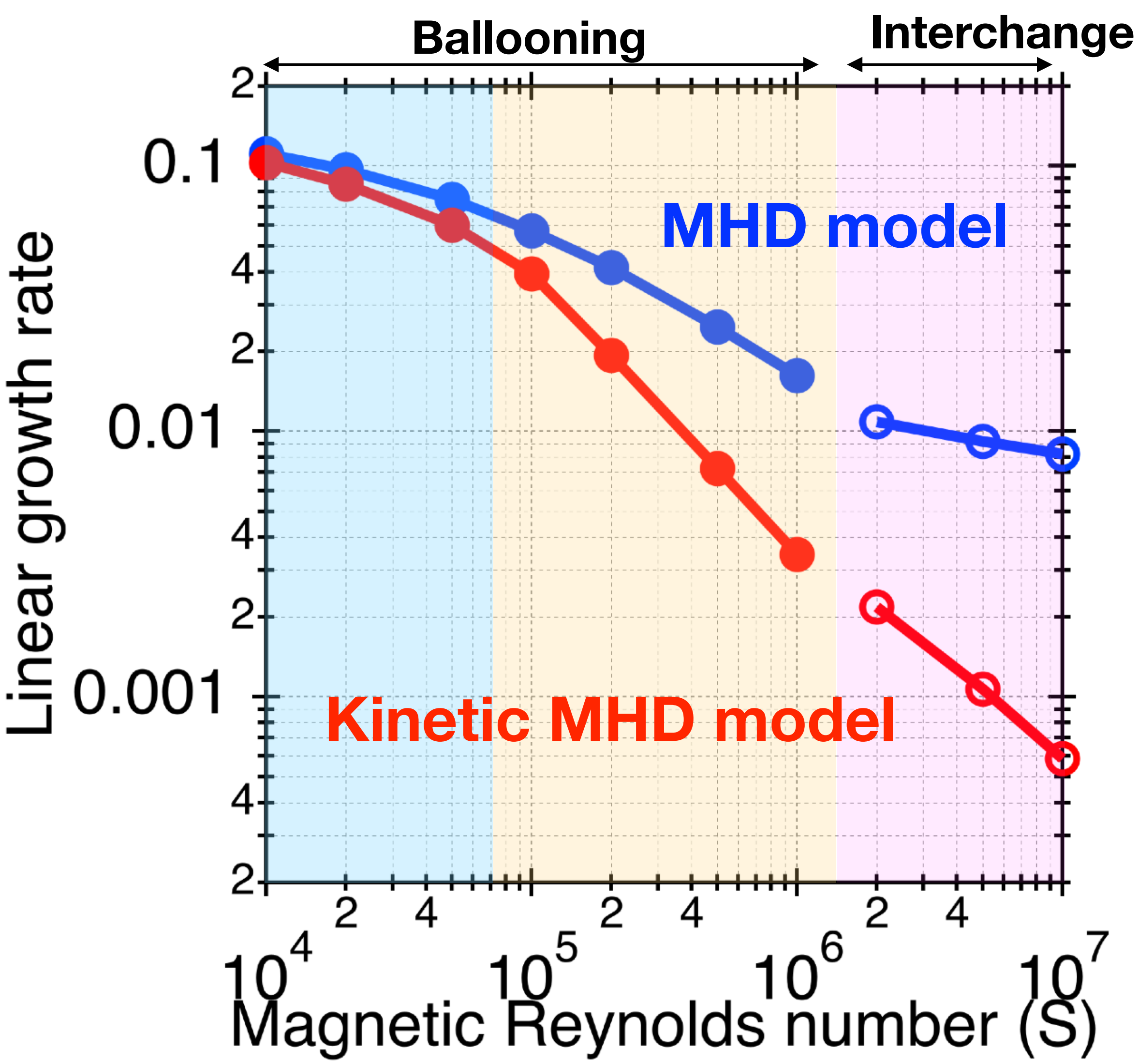


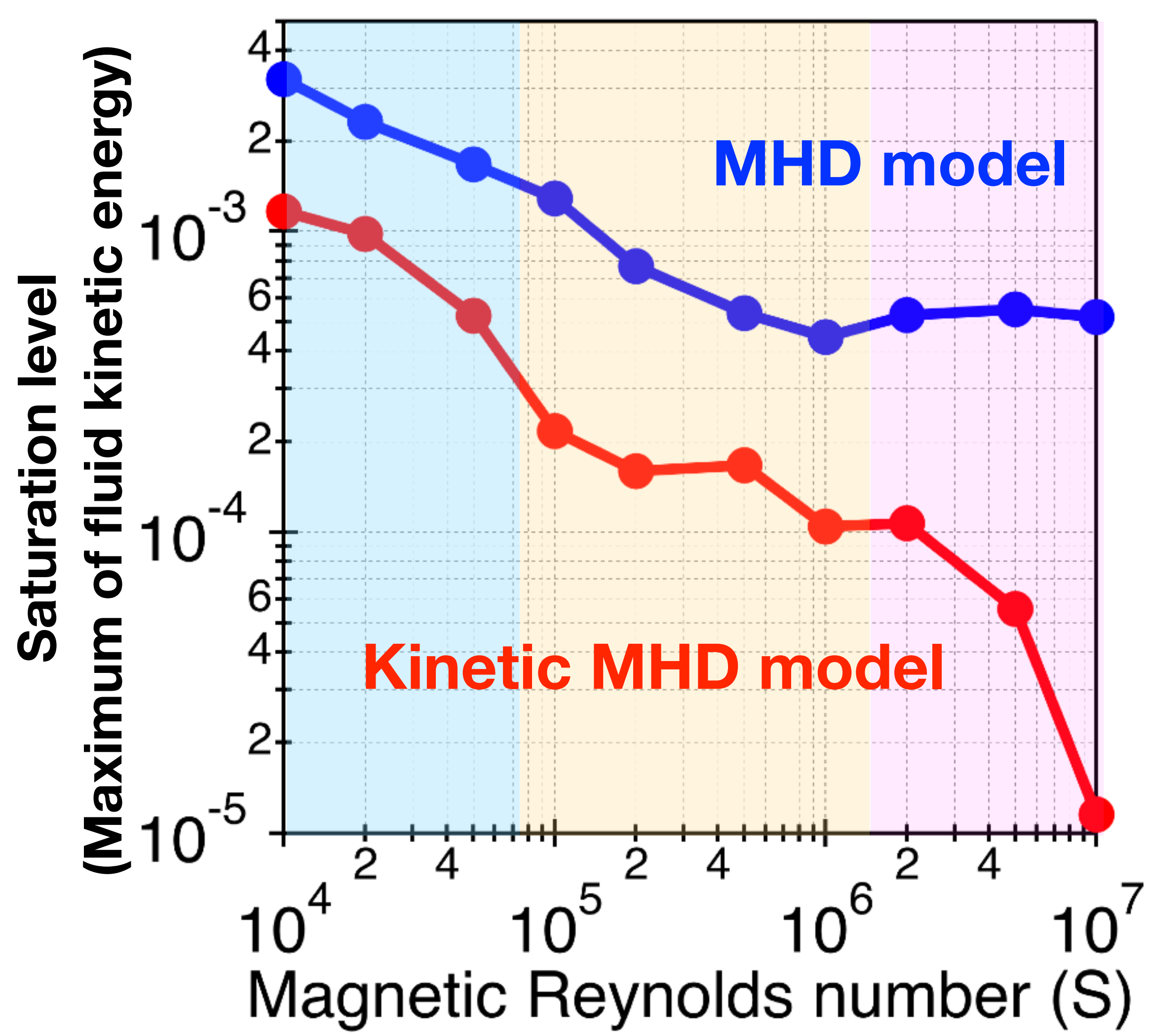






Saturation level for high S number is significantly suppressed by kinetic ion effects





Summary

- Numerical simulations based on the kinetic MHD model with kinetic thermal ions have succeeded in reproducing the LHD experimental results showing that high beta plasma is maintained.
- This results from the fact that the response of the trapped ions to the instabilities is weakened by the precession drift motion of the trapped ions.
  - When “the precession drift frequency of the trapped ions with respect to the mode phase” is larger than the linear growth rate of the MHD instabilities, the response of the trapped ions to the MHD instabilities becomes weakened. As a result, the MHD instabilities become suppressed since the MHD instabilities can not use the driving energy source contributed from the ion pressure.
- The supercritical stability of the LHD plasmas well above the Mercier criterion can be attributed to the precession drift motion of the trapped ions in the three-dimensional magnetic field.