Mutual Interaction Between Micro-Turbulence and Collisionless Tearing Mode in Toroidal Geometry

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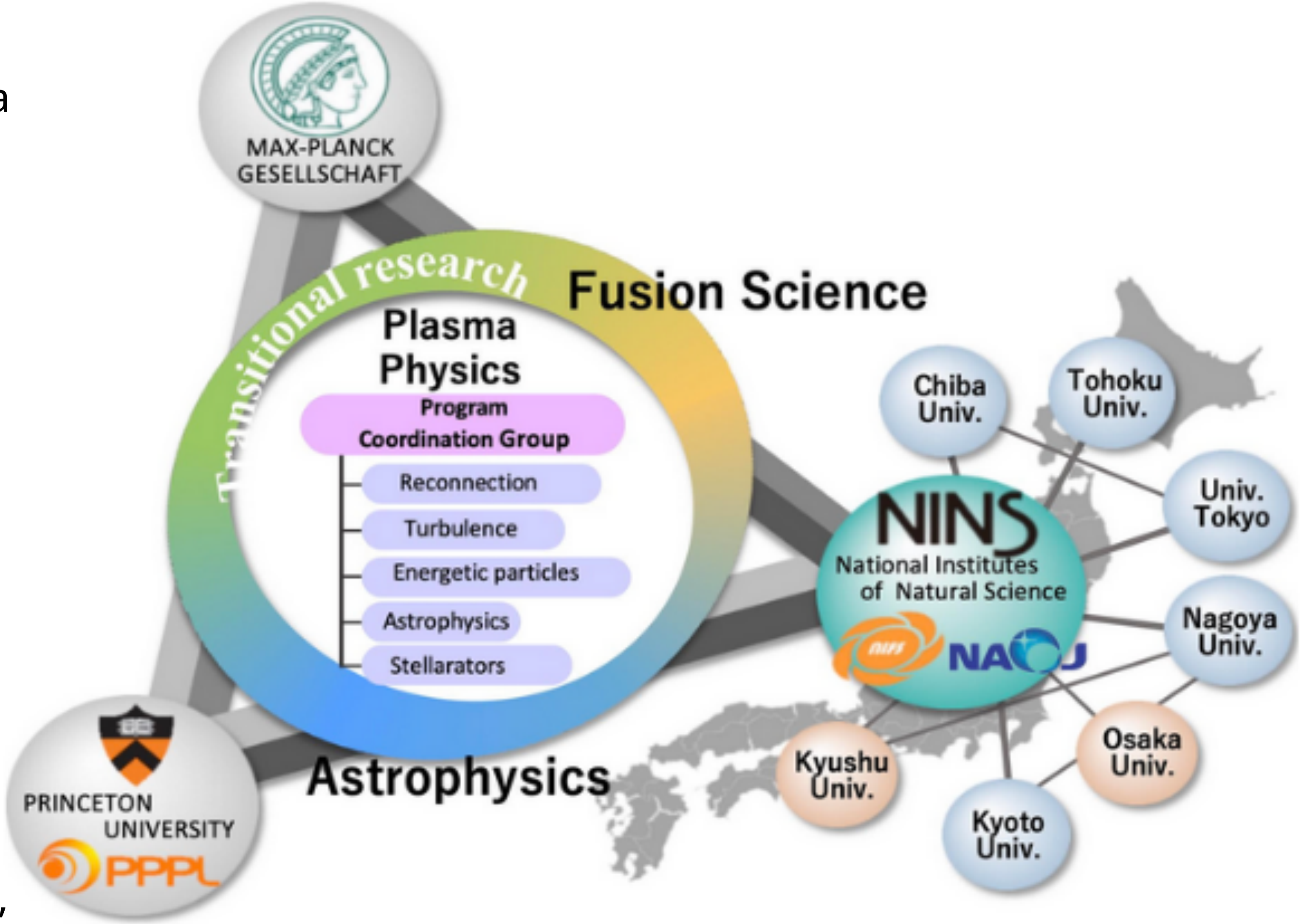
NINS–IRCC: Research Unit for Astro-Fusion Plasma Physics (AFP)

- Promote new research activities
  Merge fusion and astronomical plasma
- Establish plasma physics Japan-EU-US international research collaborations

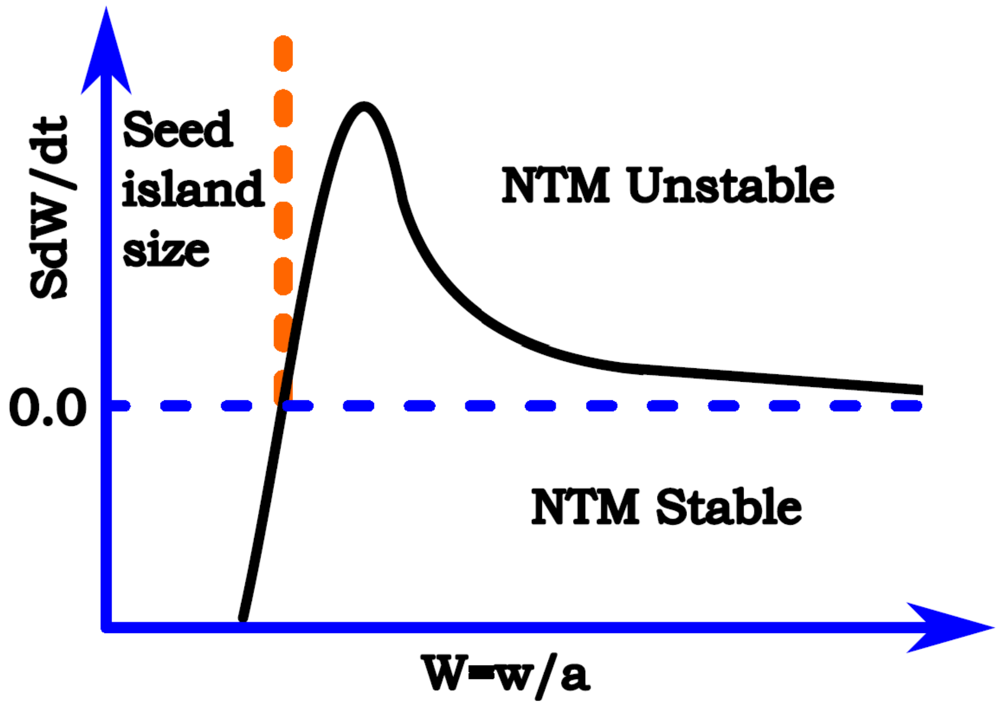


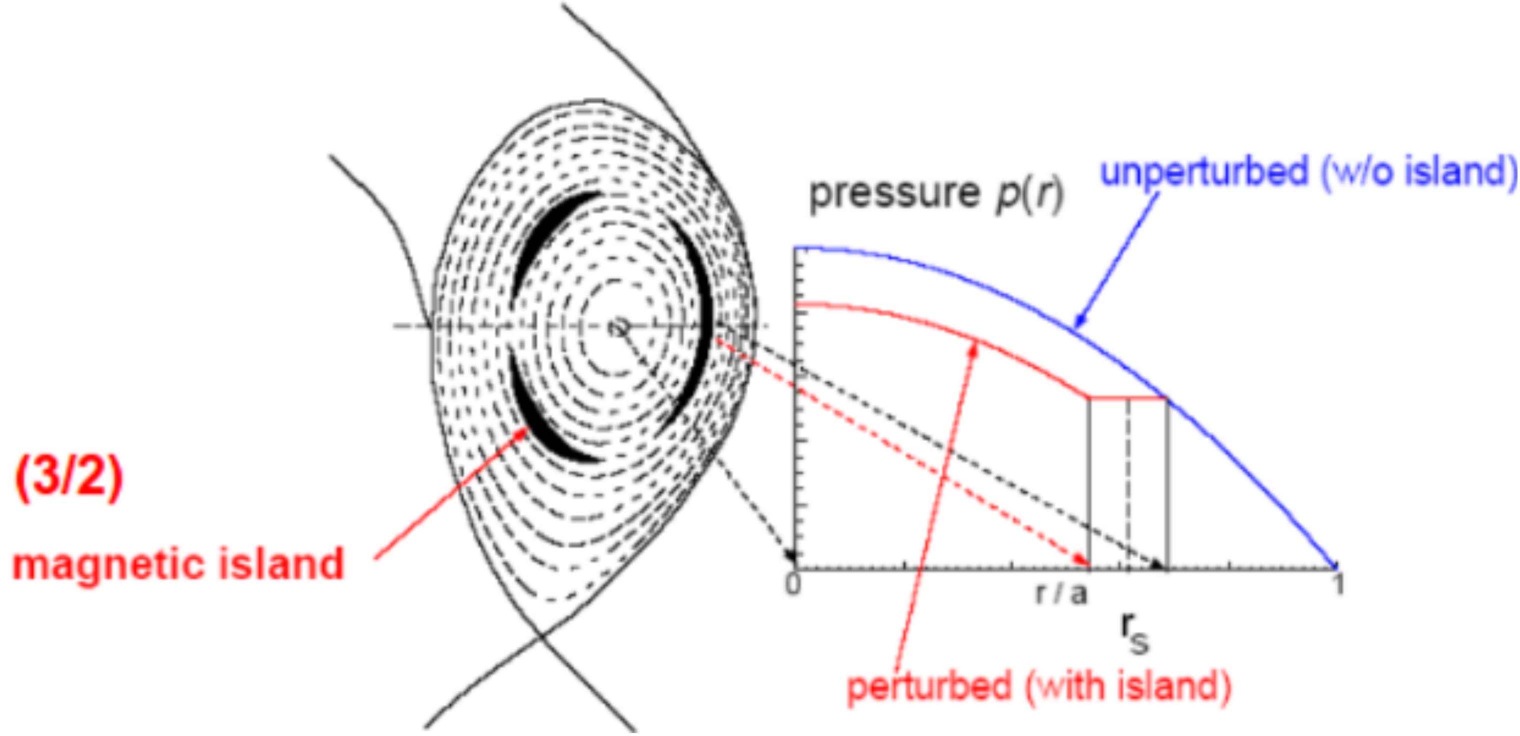
Research Project

- Turbulence–tearing mode interactions collisional and collisionless regime.
- GK simulations in toroidal geometry and astrophysics.
- Find cross-application between fusion and astrophysics:
  Bi-coherence, energy, entropy transfer, reduced models, ...

- Neo-Classical Tearing Mode (NTM) driven by bootstrap current $\propto \nabla P$
- Linearly stable $(\Delta' < 0)$, need a seed to flatten the pressure profile (Carrera 86)
- Control of NTM understood and efficient (Sauter 10, Widmer 19)
- Mechanism of seed need to be calrified
- **Turbulence can be a player in the NTM seeding** (Agullo 17, Ishizawa 19)
- Non-linear evolution by generalised Rutherford equation (Rutherford 73, Widmer 19)

$$\frac{0.82\mu_0 a^2}{\eta}\frac{dW}{dt} = a\Delta' + a\Delta'_{bs} + a\Delta'_{GJJ} + a\Delta'_{ctrl} + \dots$$





Gyrokinetic PIC Code ORB5 (Lanti (2020))

- GK average of fast particle gyration, reduces 6D to 5D
- Strongly magnetized unperturbed plasmas $\rho_s \nabla \boldsymbol{B}/\boldsymbol{B} = \rho_s/R \ll 1$
- Field fluctuations at gyro-radius scale

$$k_\perp \rho \cong 1 \qquad k_{||}/k_\perp \ll 1$$

GK relevant from micro- to macro-scale

- 5D Lagrangian PIC code
- Solves the GK Vlasov-Maxwell system of equations
- Multispecies, fully kinetic electrons
- Distribution function split between background variate F_0 and time dependent variation f_{1s}

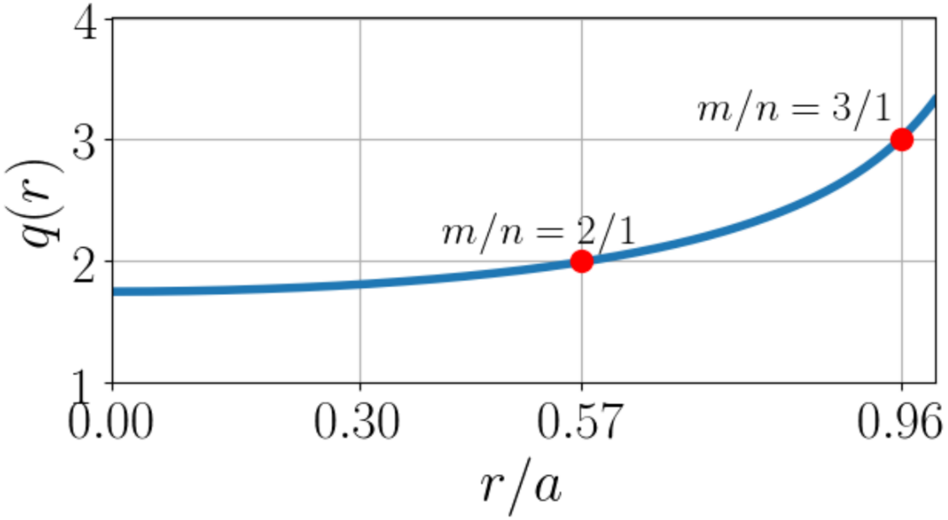
$$\frac{\partial f_{1s}}{\partial t} + \dot{\boldsymbol{R}} \cdot \frac{\partial f_{1s}}{\partial \boldsymbol{R}} + \dot{v}_{||} \frac{\partial f_{1s}}{\partial v_{||}} = -\dot{\boldsymbol{R}}^{(1)} \cdot \frac{\partial F_{0s}}{\partial \boldsymbol{R}} - \dot{v}_{||}^{(1)} \frac{\partial F_{0s}}{\partial v_{||}}$$

- Quasi-neutrality and Ampère's law linearized about an equilibrium distribution function

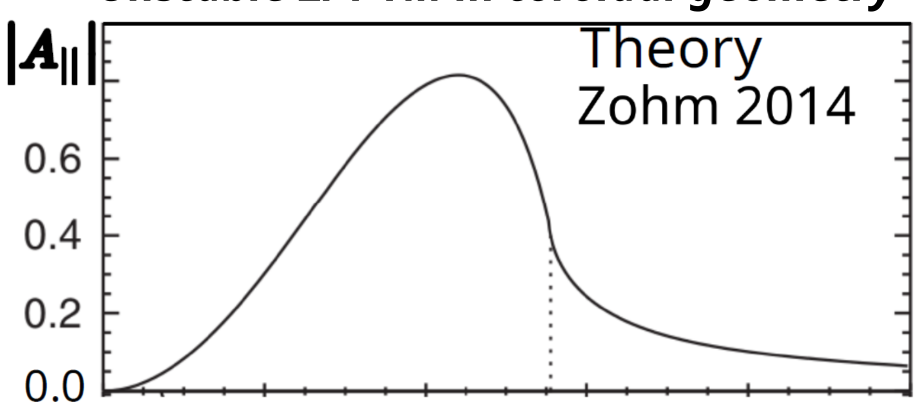
Tearing Mode Initialisation in Toroidal Geometry

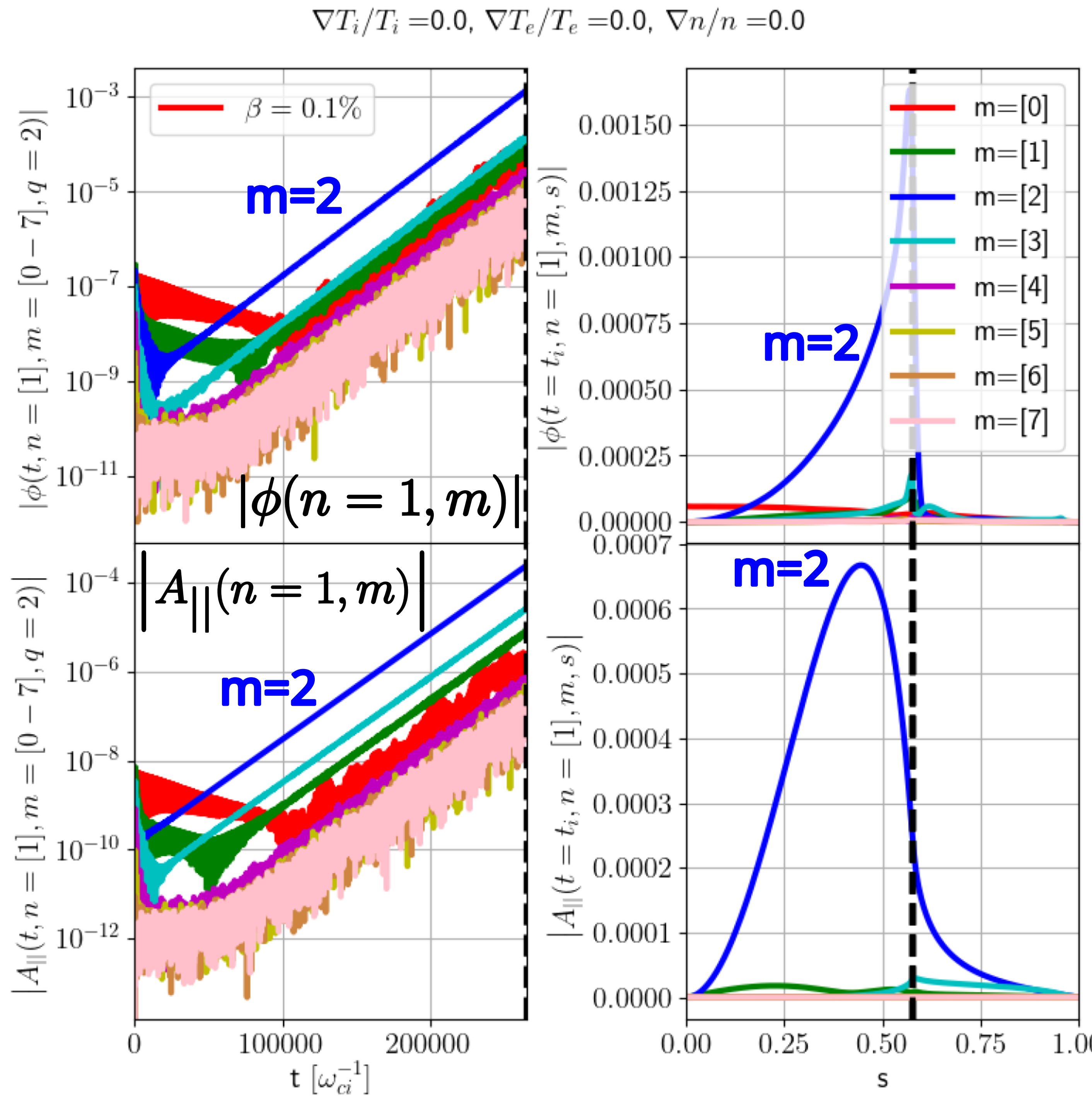
- Shifted Maxwellian for the electrons produces $\boldsymbol{J}$ consistent with $\boldsymbol{q}$
- Mass ration m_i/m_e=200
- Large aspect ratio R_0/a=10

$\rho^* = \rho/a = 1/100$



Unstable 2/1 TM in toroidal geometry

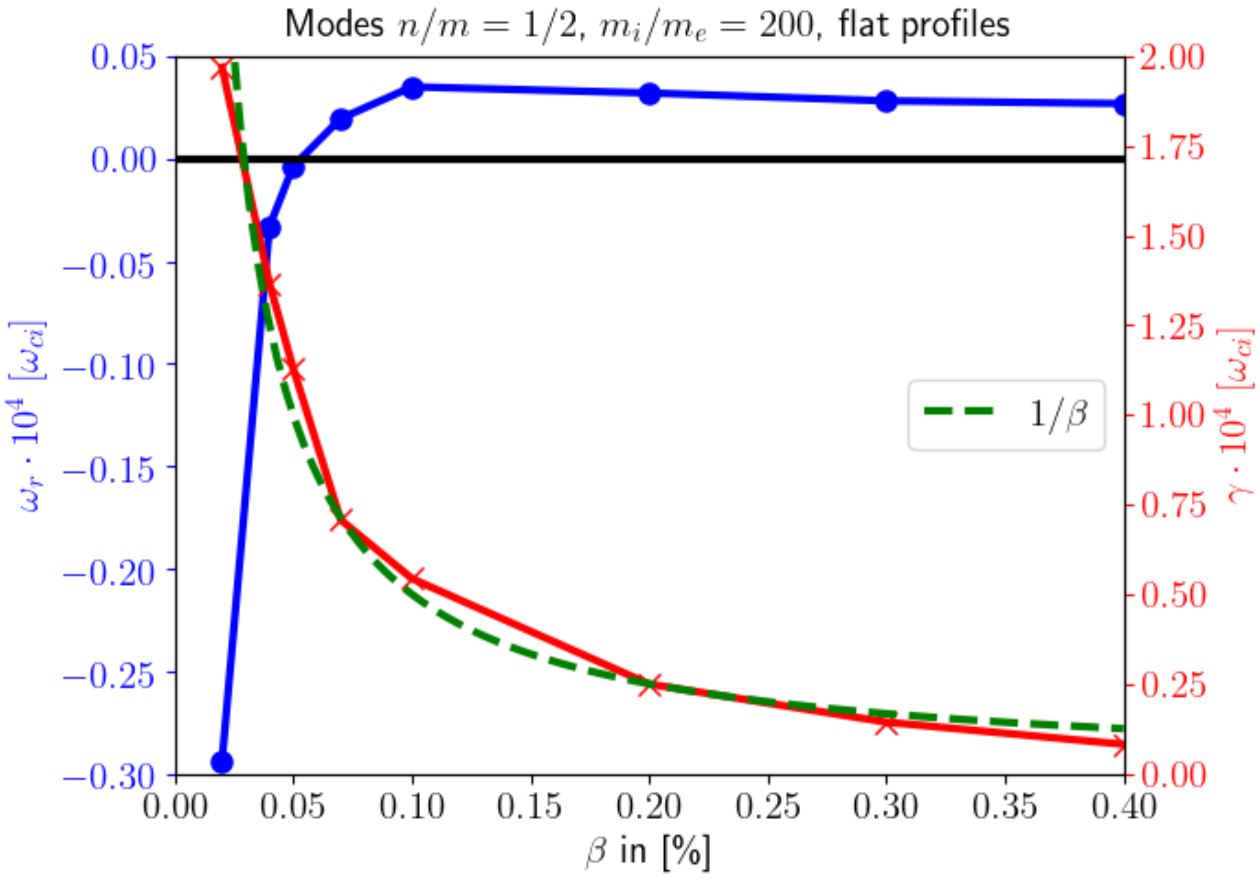




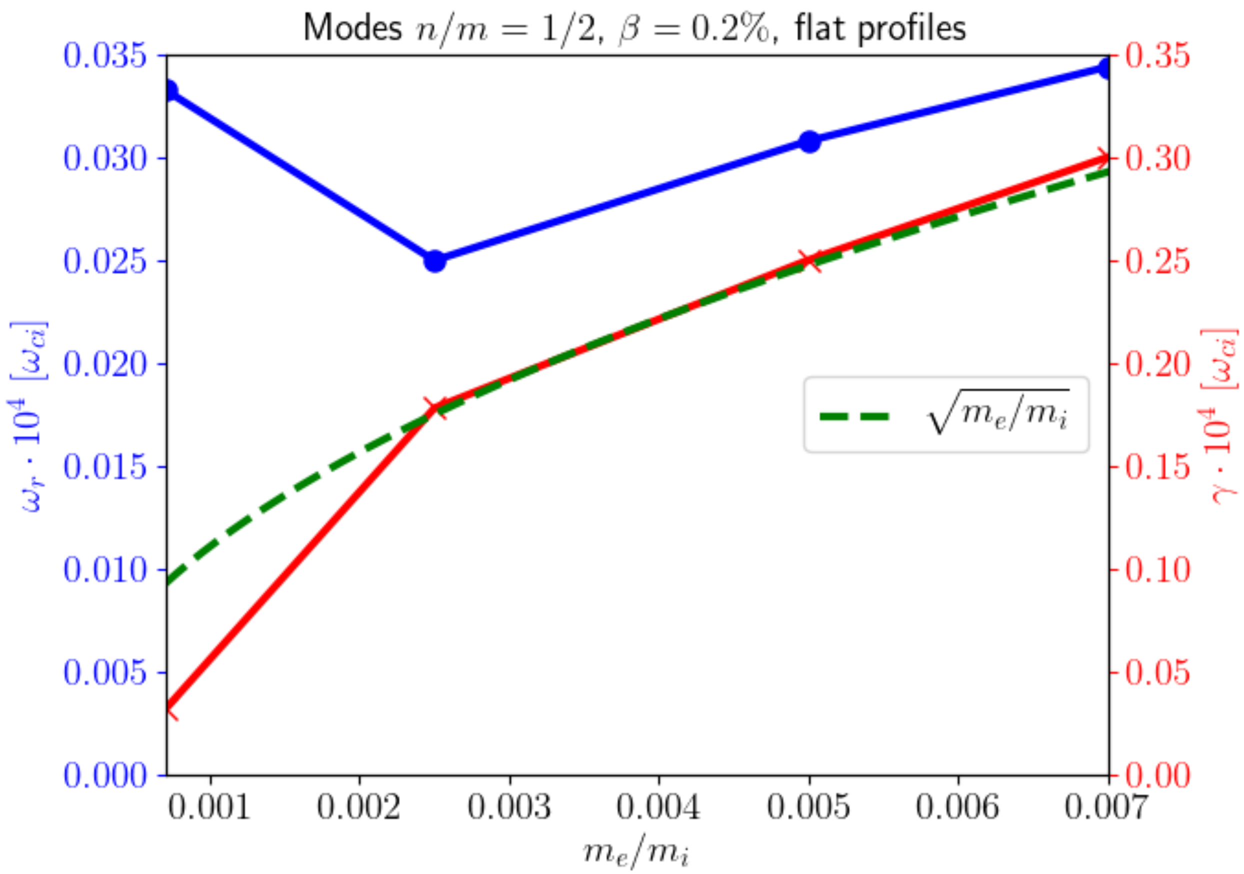
- Kinetic estimation of the growth rate (Rogers 2007)
- $\gamma_{cl}/\gamma_{ci} = \Delta' \rho_{se} k_\theta \rho_{se} \left(\frac{m_e}{m_i}\right)^{1/2} \frac{1}{T_e^{1/2}} (T_e + T_i)^{1/2} \frac{1}{\beta_e}$ Validity: $m_e/m_i < \beta$

Linear simulations with flat density and temperature profiles in agreement

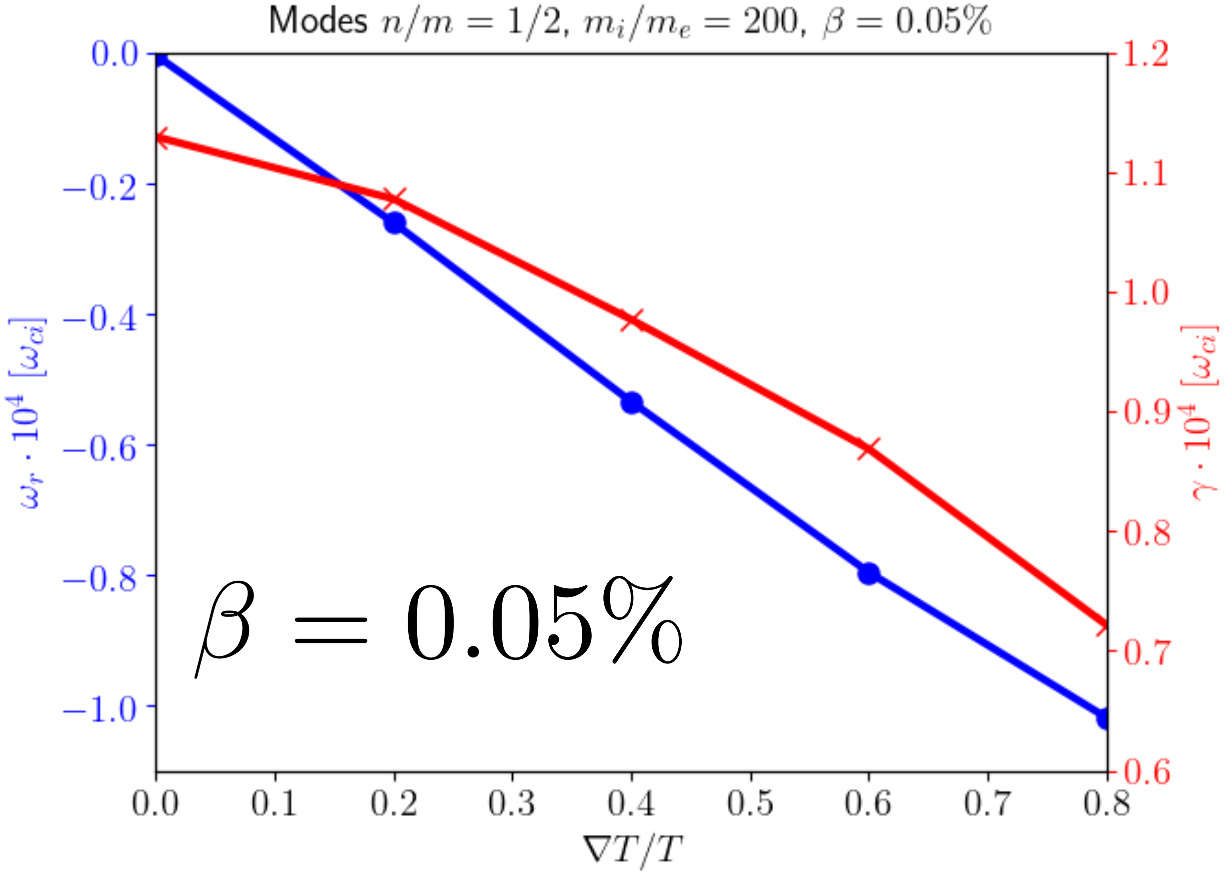
- β-scan, fixed T_e=T_i and m_e/m_i = 0.005

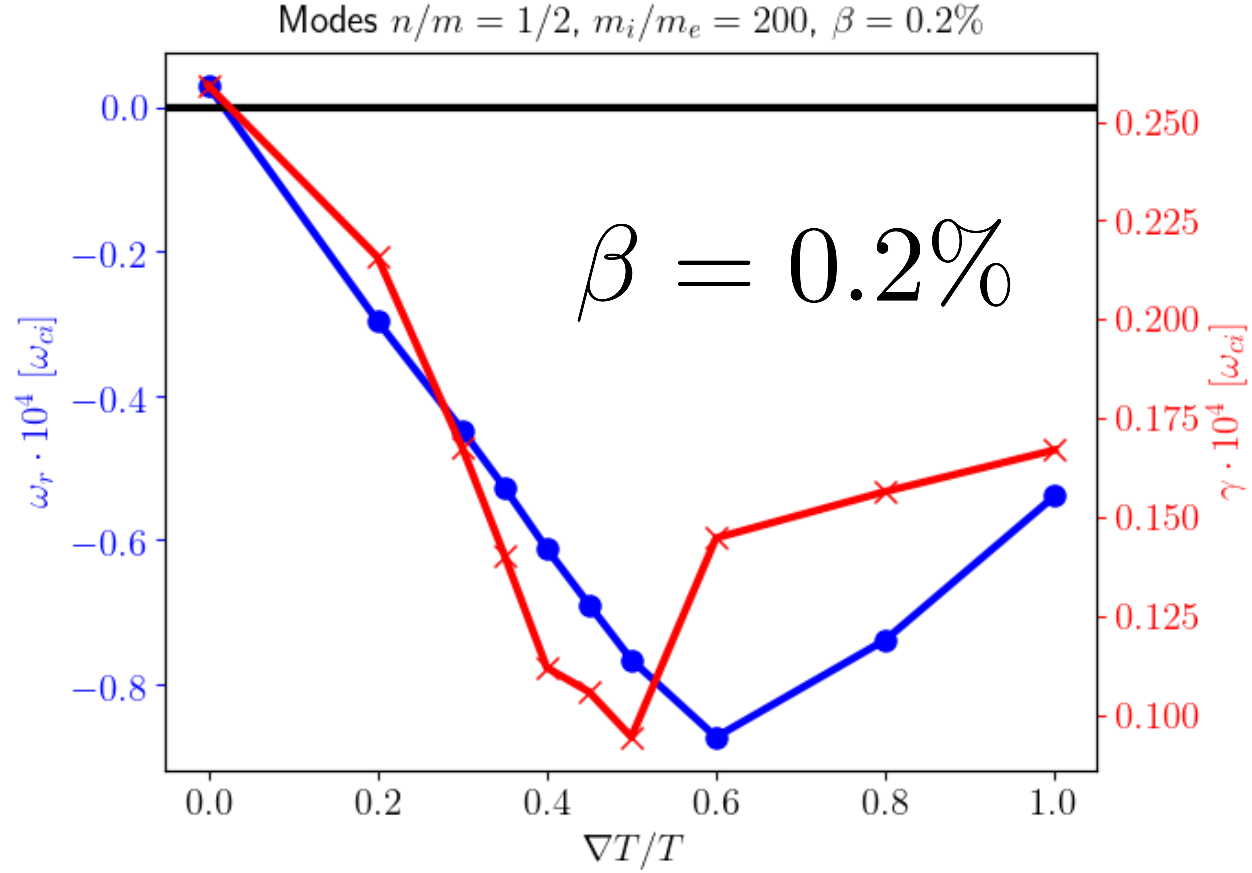


- Mass scan, fixed T_e=T_i and β =0.2%

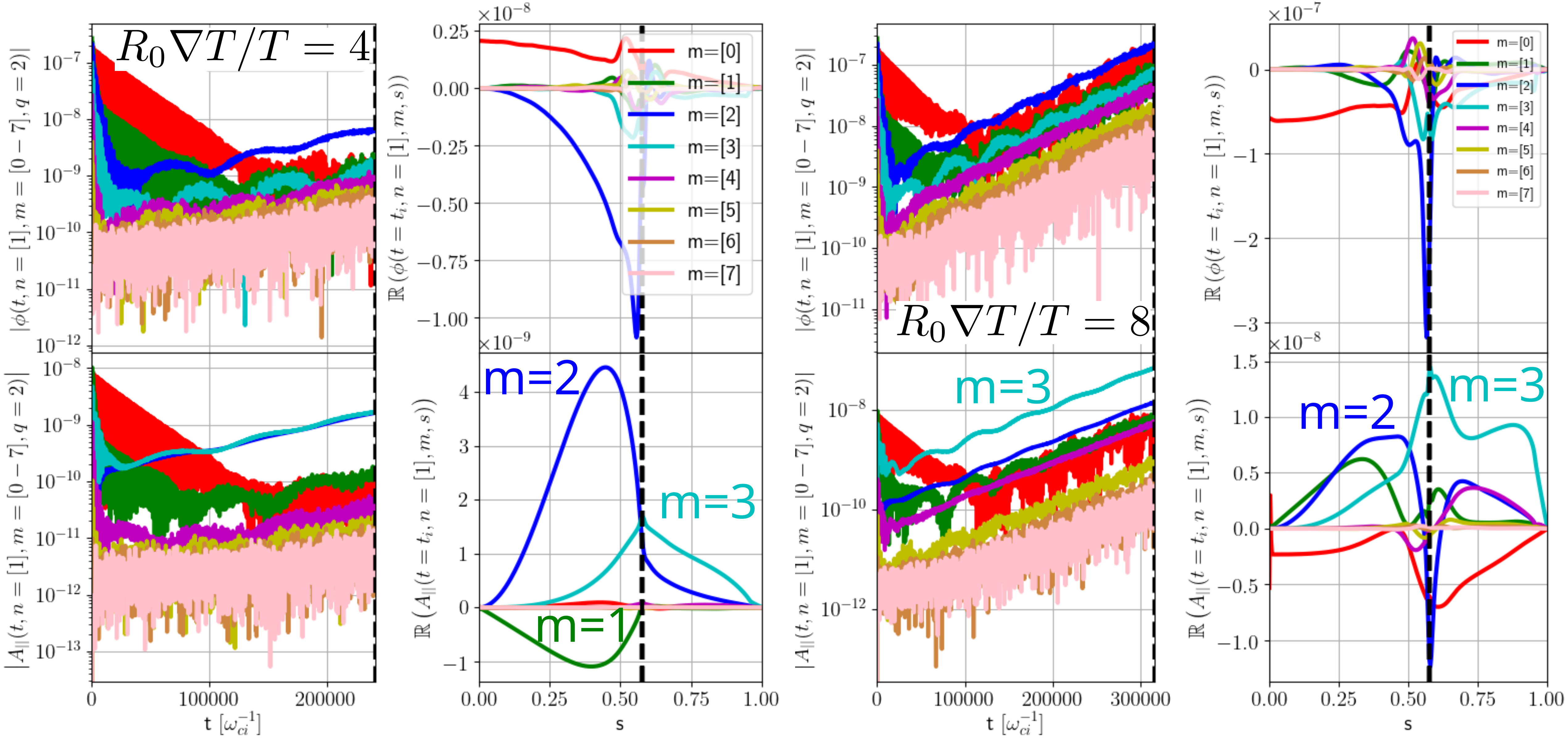


- Kinetic theory ($\omega_D^* = 0$) (Drake and Lee (1977)): γ no change, $\omega_r = \omega_n^* + \omega_{T_e}^*/2$
- Gyrokinetic (fluid collisions) (Connor et al. (2012)): γ reduced by $\nabla P = \nabla(n_i T_i + n_e T_e)$
- Gyro-fluid (Tassi et al. (2010)): $\gamma^2 \approx \gamma_0^2 - 0.5\omega_e^*(1 - T_i/T_e)$
- Two-fluids (Nishimura et al. (2008)): $\omega_r \cong \omega_n^* + \alpha\omega_T^* + \omega_{\boldsymbol{E}\times\boldsymbol{B}} + \omega_B^* + \omega_\eta^*$



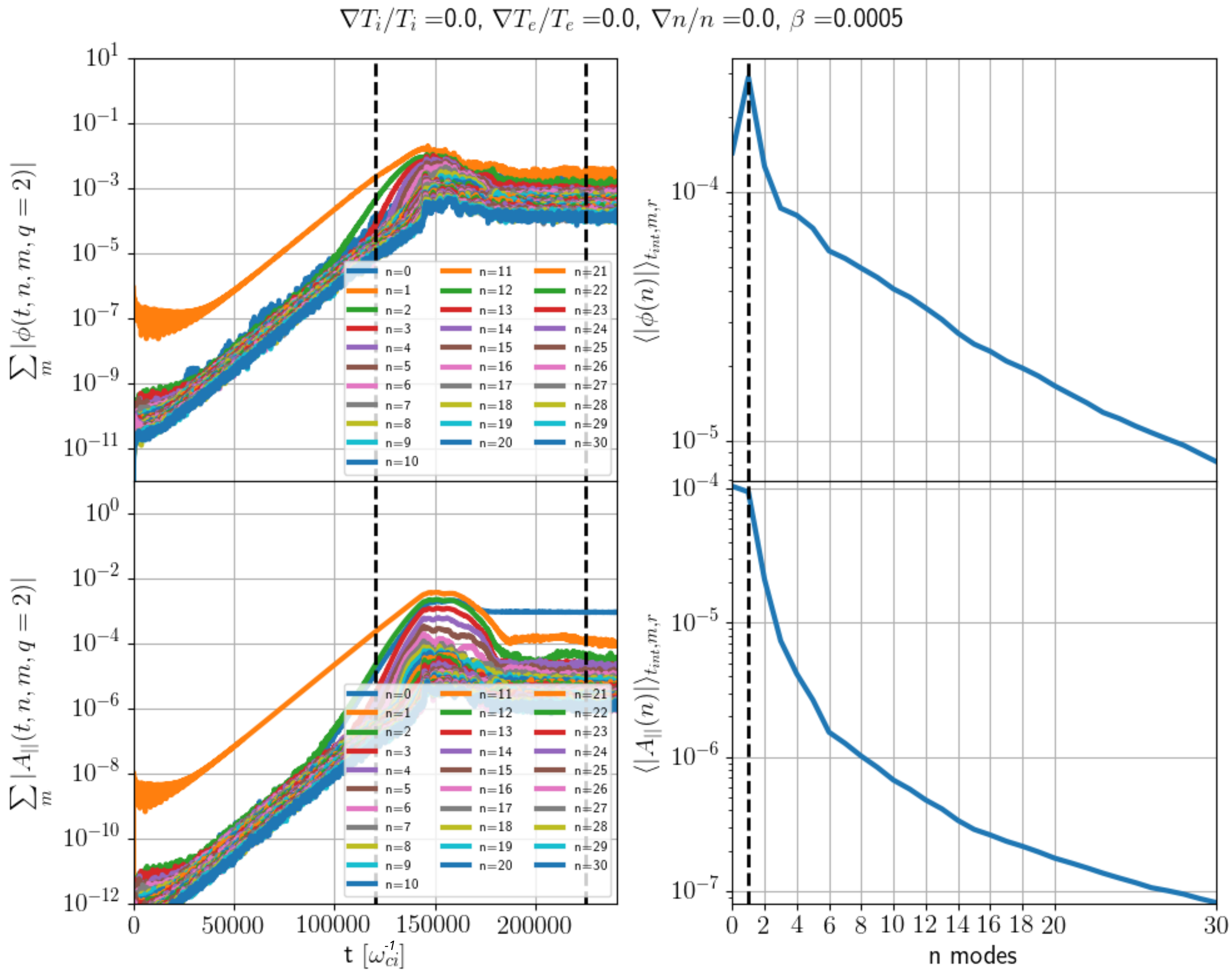


- $R_0 \nabla n / n = 0 \; \beta = 0.2\%$

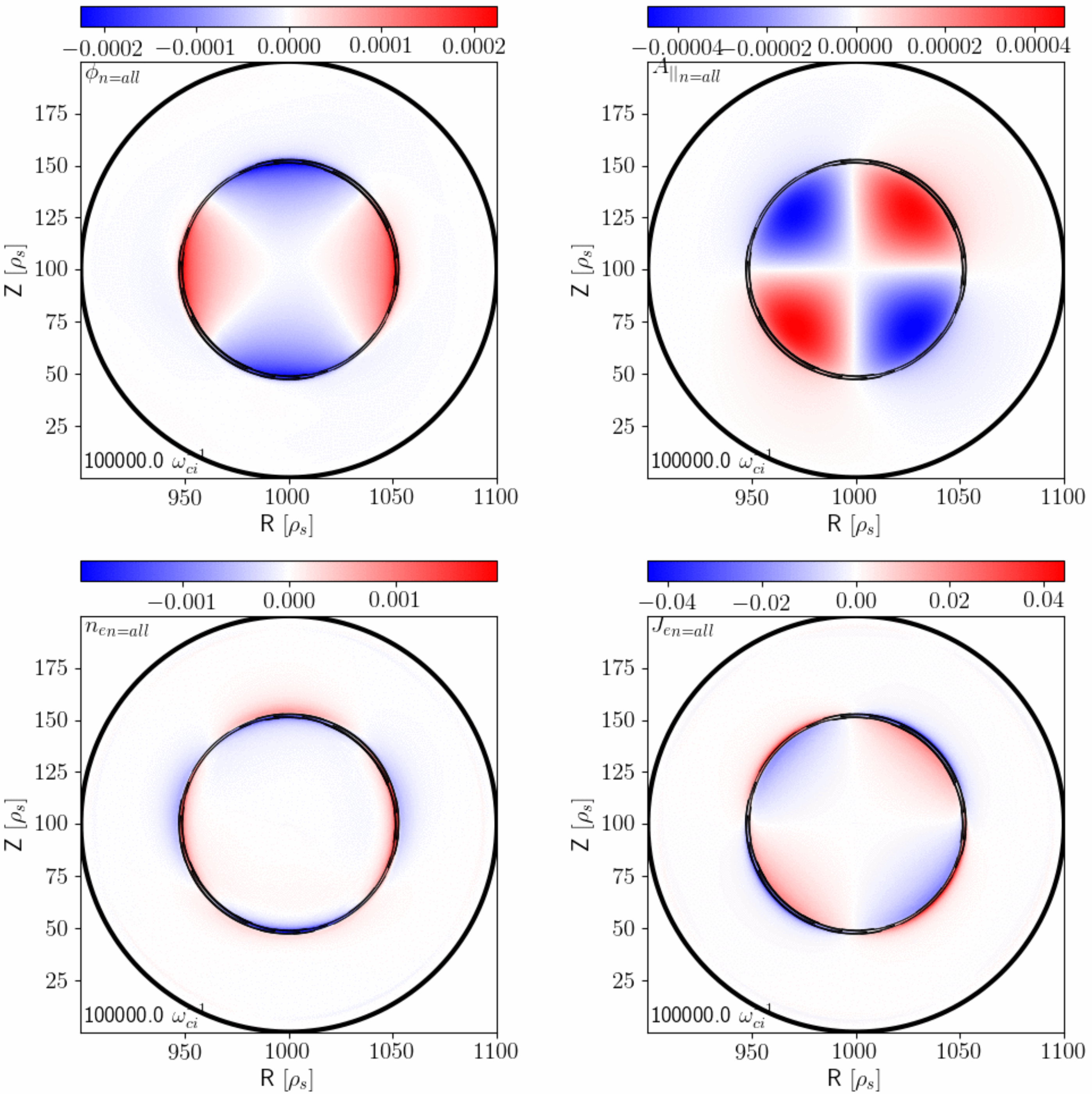


Toroidal Mode Time Evolution and Spectrum, Flat Profiles

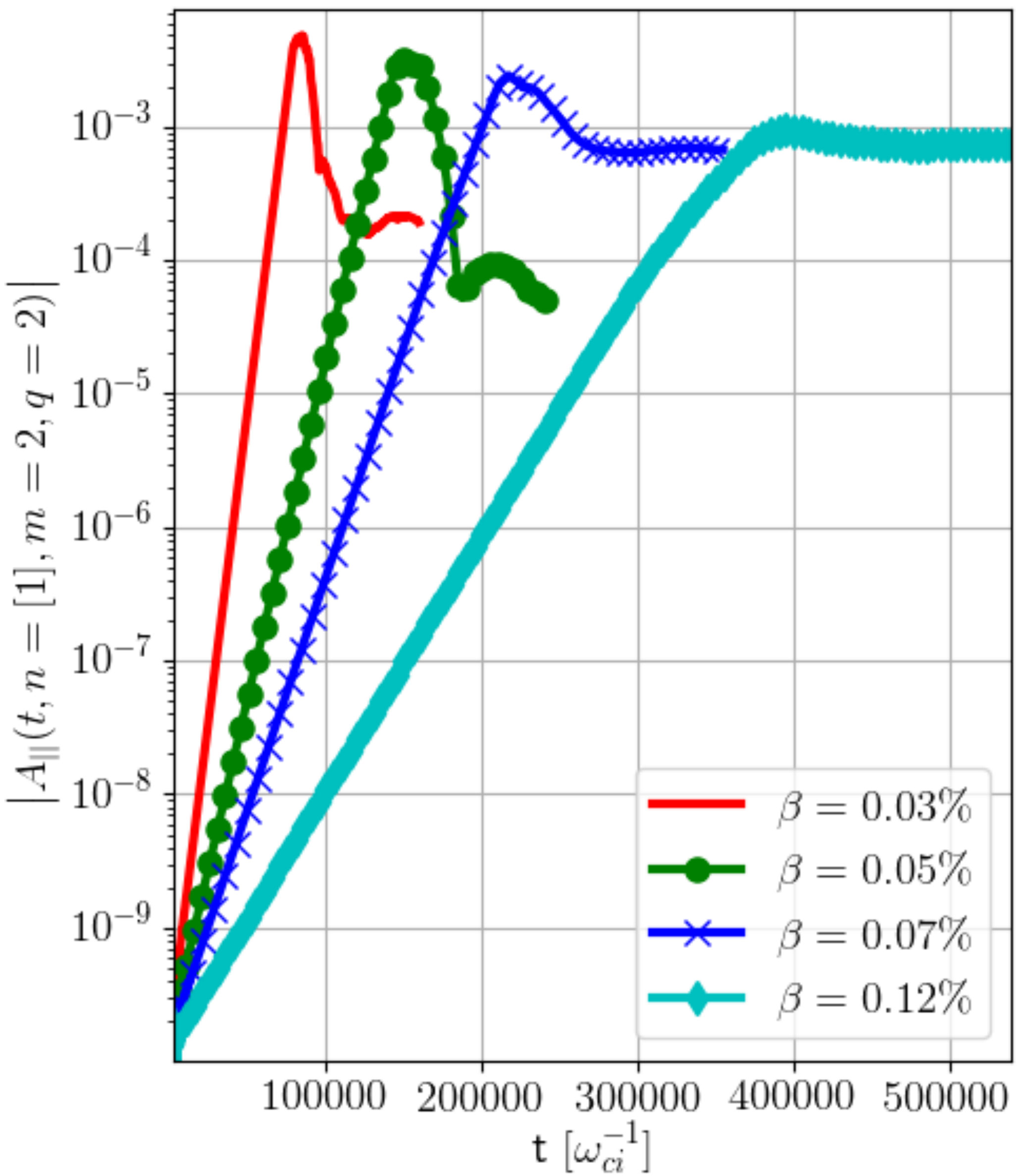
- n summed over m
- TM initially perturbed
- Noise following TM growth
- At ~t=9e5 larger n interacts
- Island size w_s~$A_{||}$ reduced after overshoot

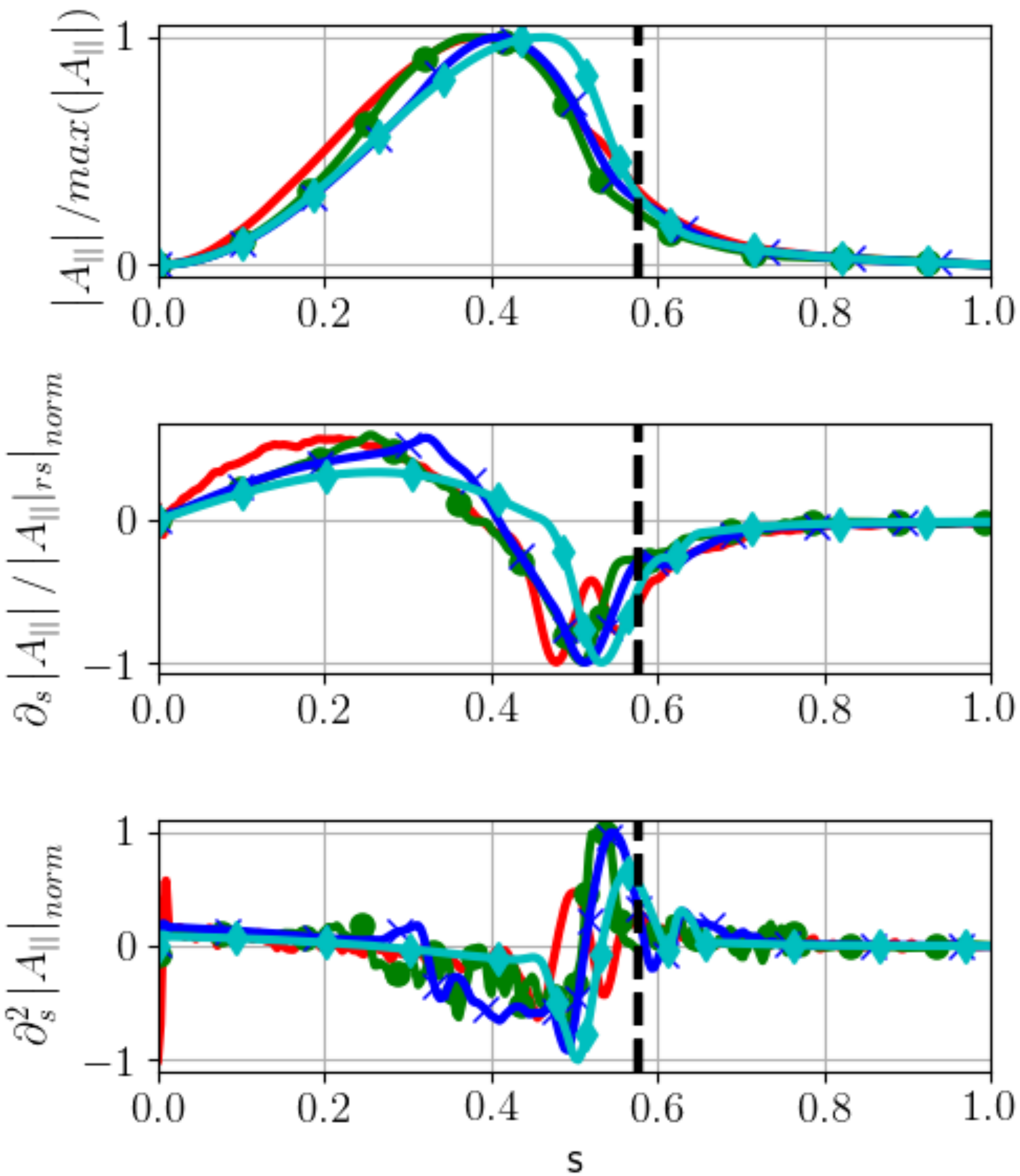


- Electrostatic turbulence at the island separatrix
- Density fluctuation generates local turbulence, starting at X-point
- Strong zonal current due to large island.



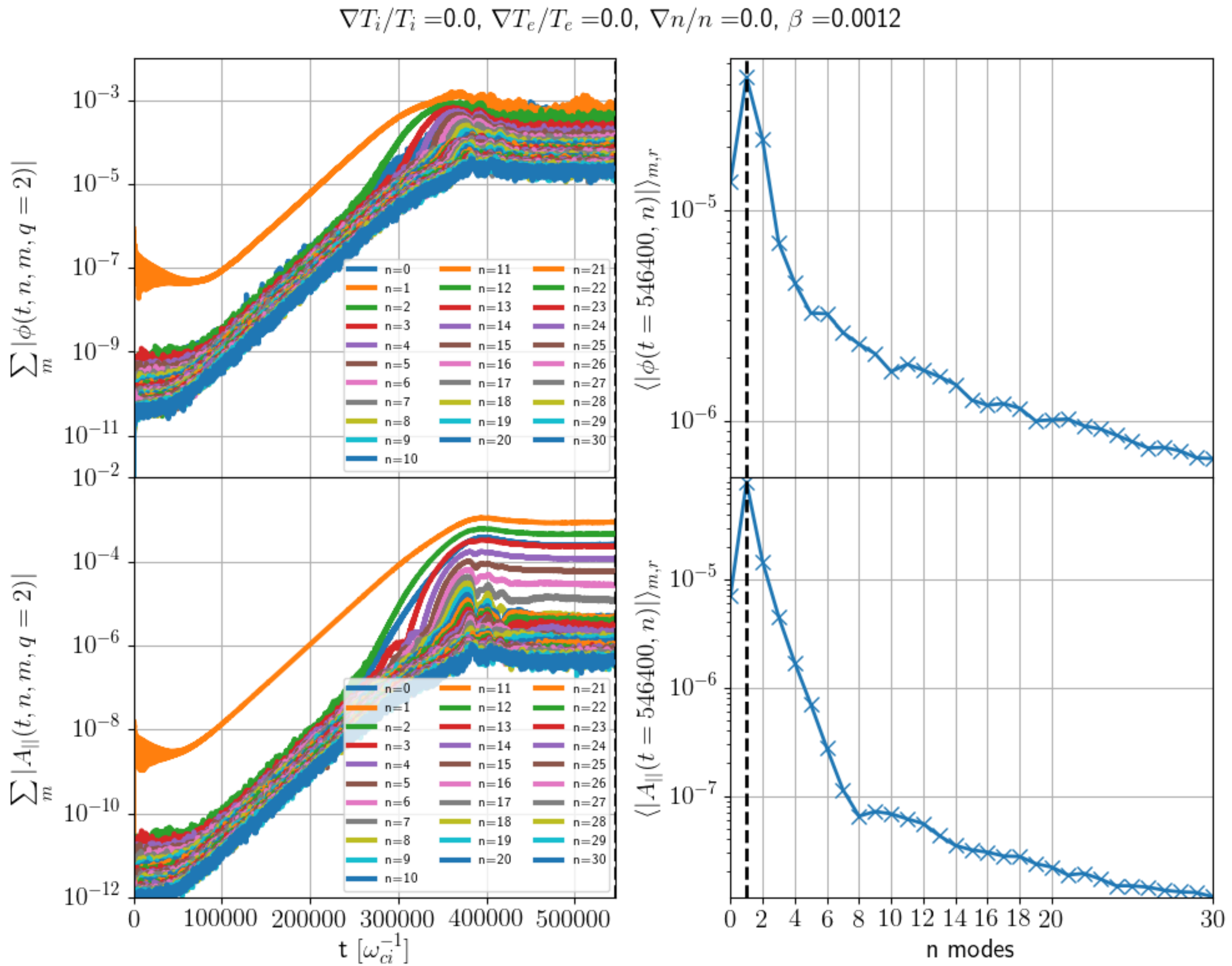
- Plasma-beta reduces the linear growth of the tearing
- Increased plasma-beta reduced the overshoot





Toroidal Mode Time Evolution and Spectrum, Flat Profiles

- TM initially perturbed
- Noise following TM growth
- At ~t=2.2e5 larger n interacts
- Island size w_s~$A_{||}$ not reduced
- $A_{||}$ n=1 dominates at saturation

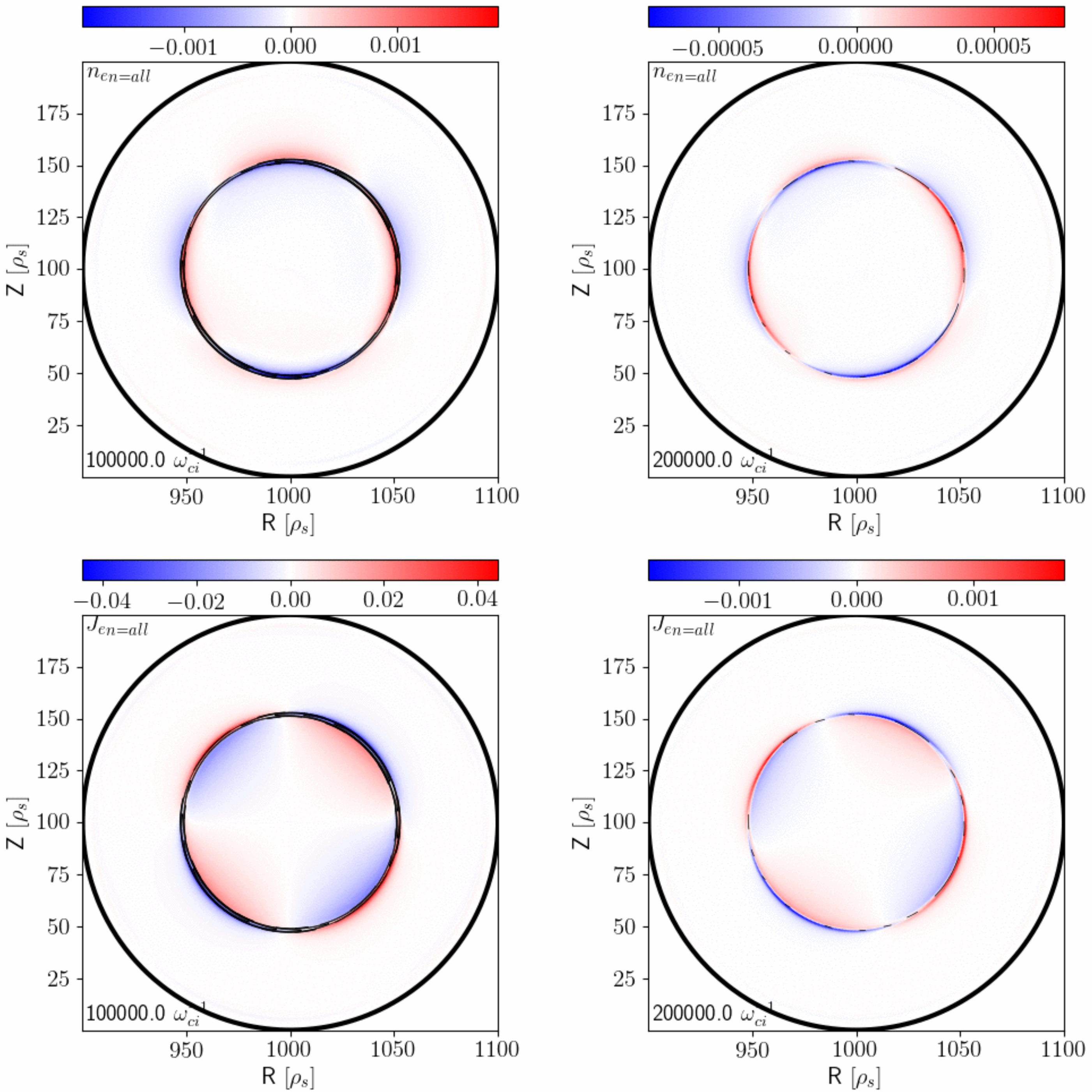


Poloidal Cut Comparing beta=0.05% and 0.12%

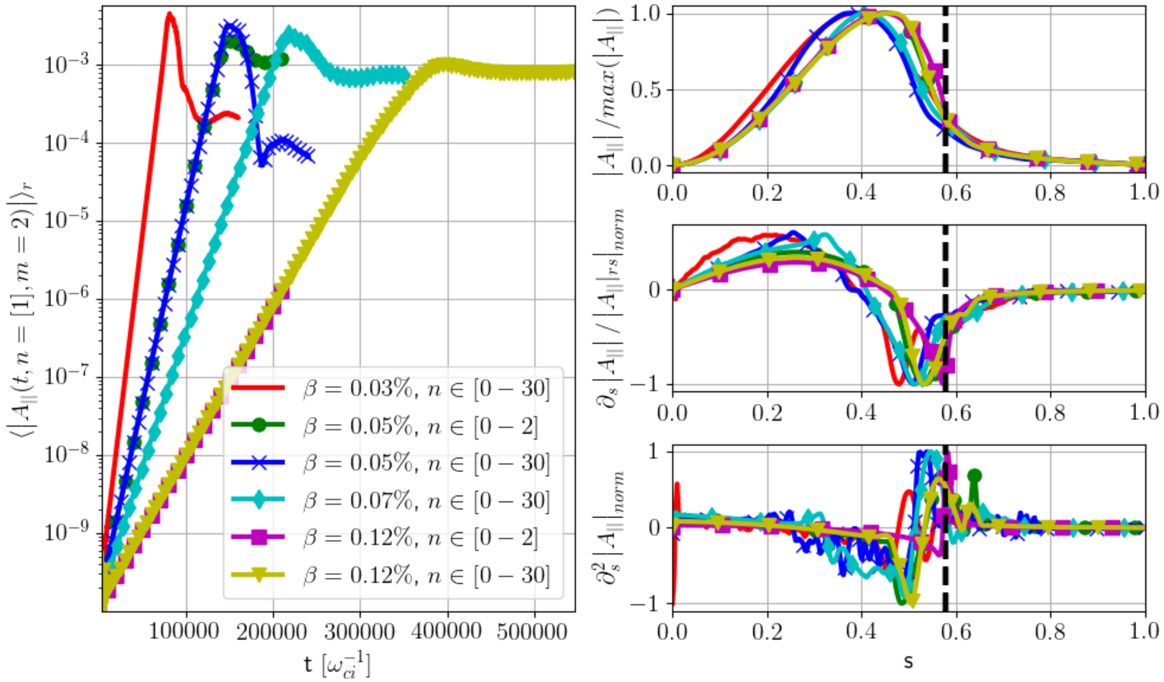
- No-shrinking of the island for beta=0.12%
- Density fluctuations one order magnitude less for beta=0.12%
- Current density fluctuations ~5x smaller at beta=0.12%

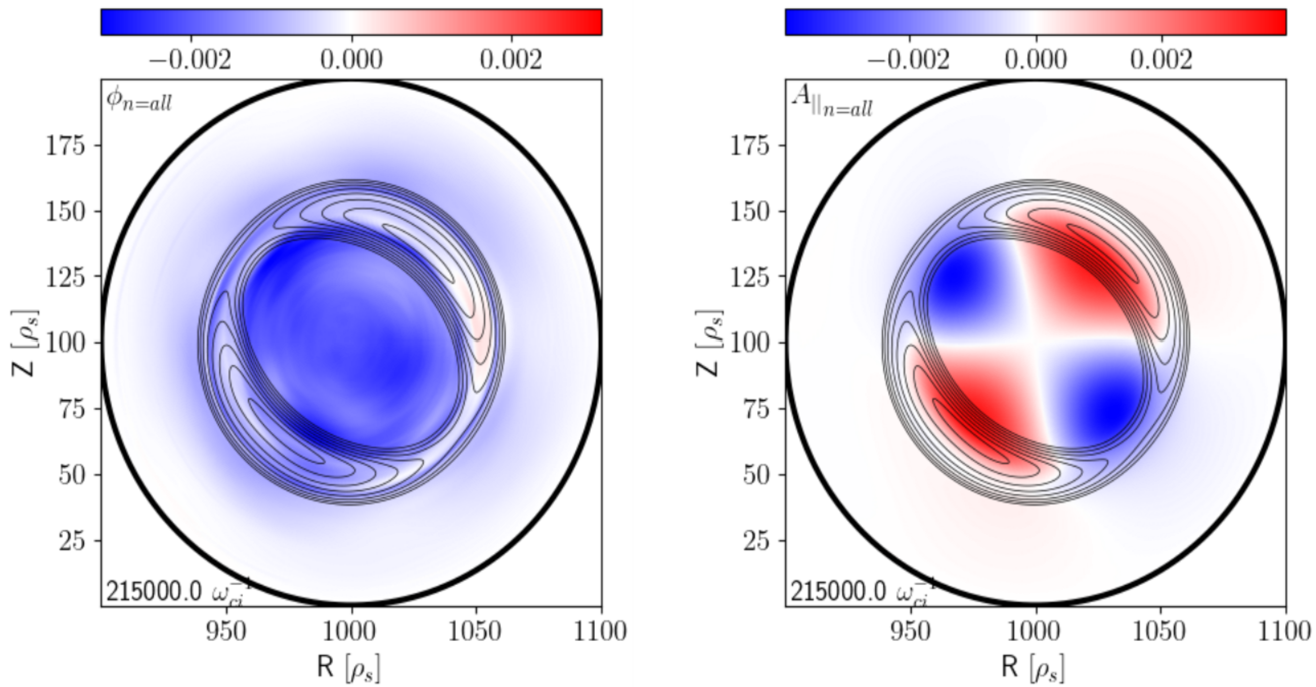
$$\gamma_{cl}/\gamma_{ci} = \Delta' \rho_{se} k_\theta \rho_{se} \left(\frac{m_e}{m_i}\right)^{1/2} \frac{1}{T_e^{1/2}} \left(T_e + T_i\right)^{1/2} \frac{1}{\beta_e}$$

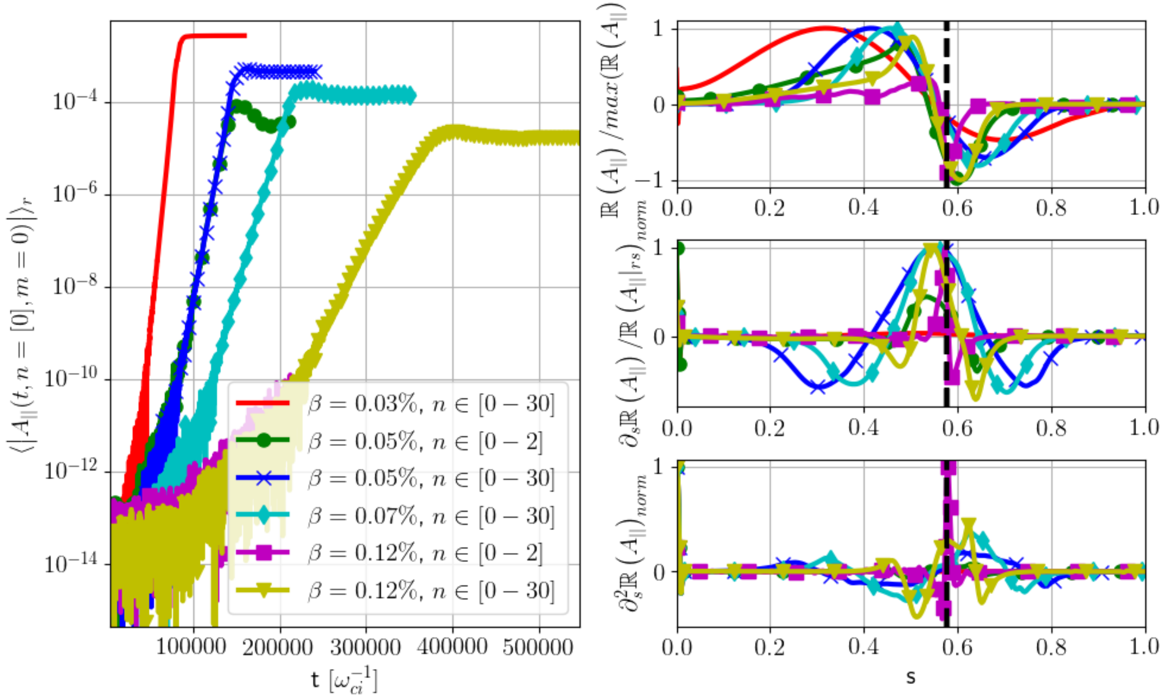
$$\beta_e = \frac{\mu_0 q_e N_0 T_0}{B_0^2} \qquad N_0 = \langle n_e \rangle \qquad T_0 = T_e(s)$$

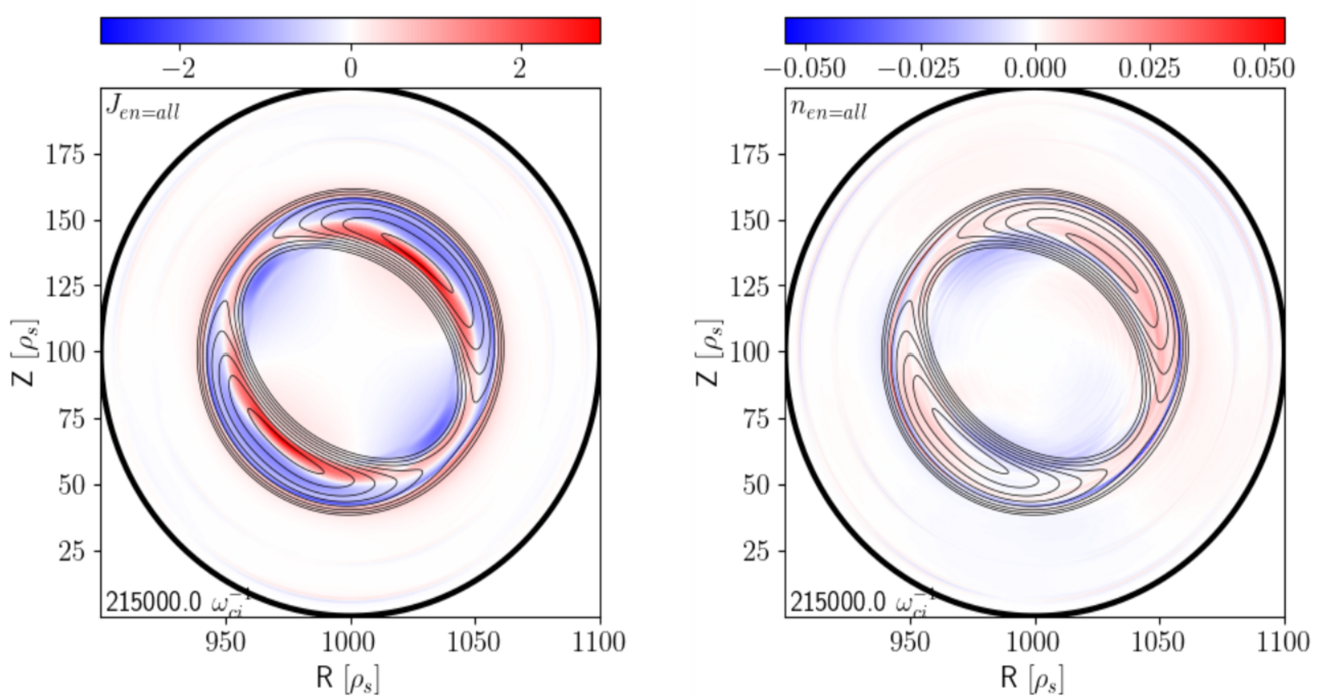


Time evolution of $A_{||}$ m/n=2/1 and 0/0









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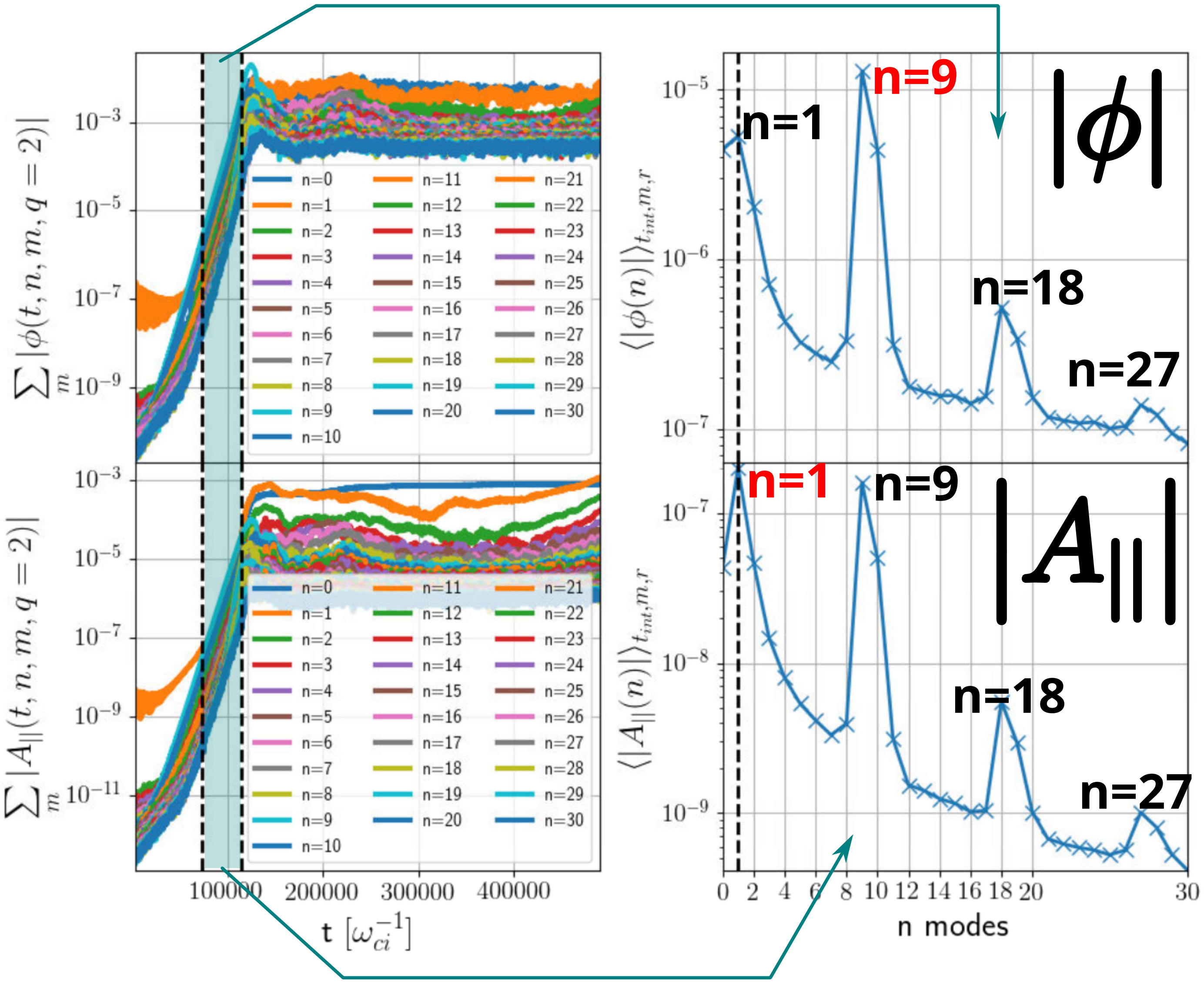
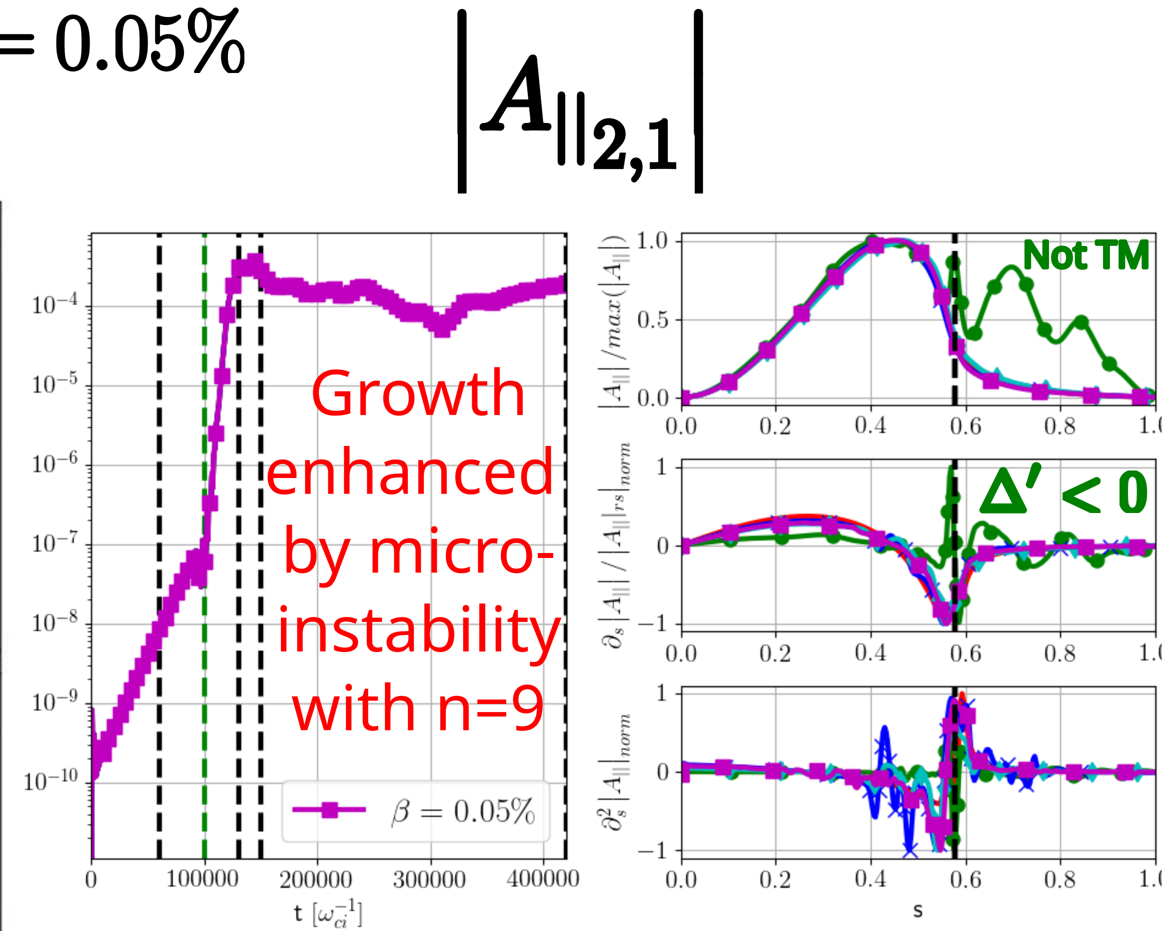
CTM growth enhanced by ITG turbulence

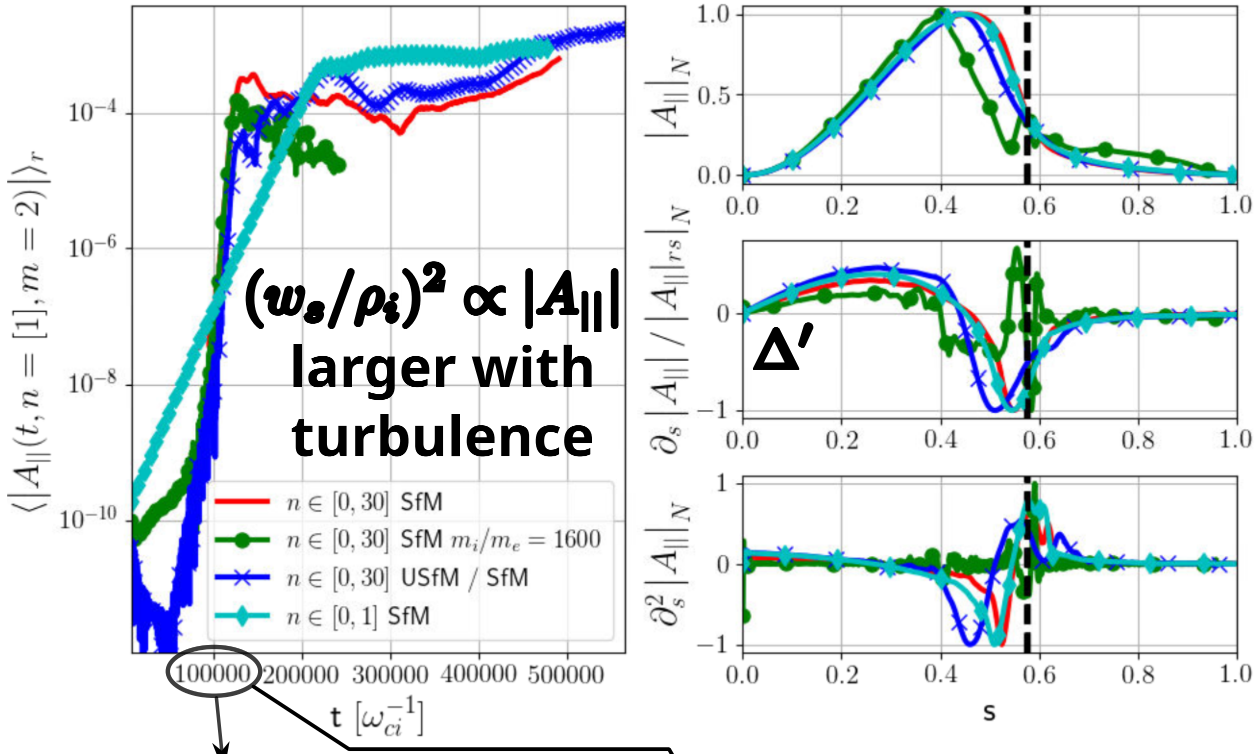
- $R_0\nabla T/T = 6,\ R_0\nabla n/n = 1,\ \beta = 0.05\%$

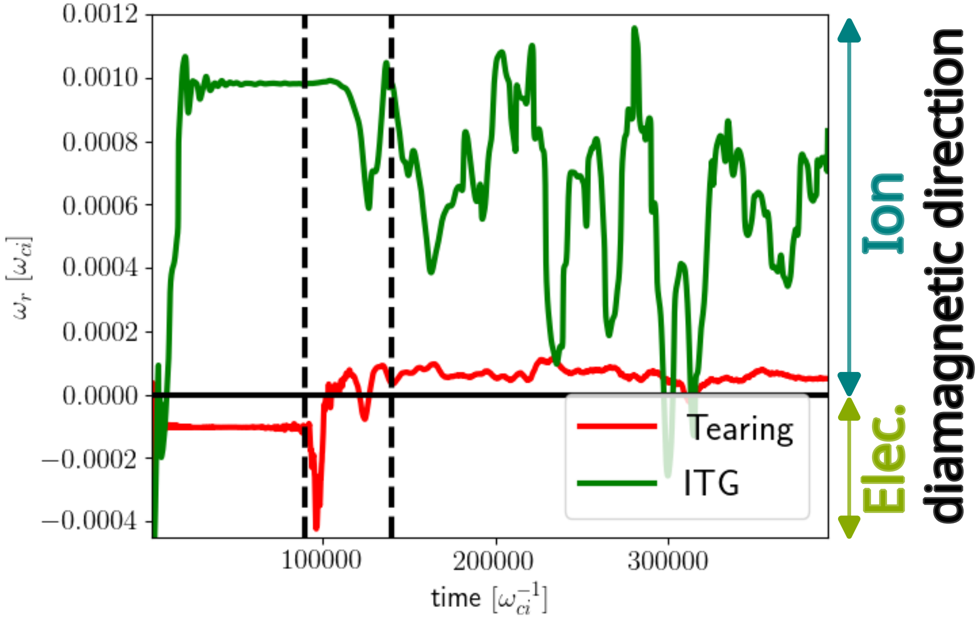




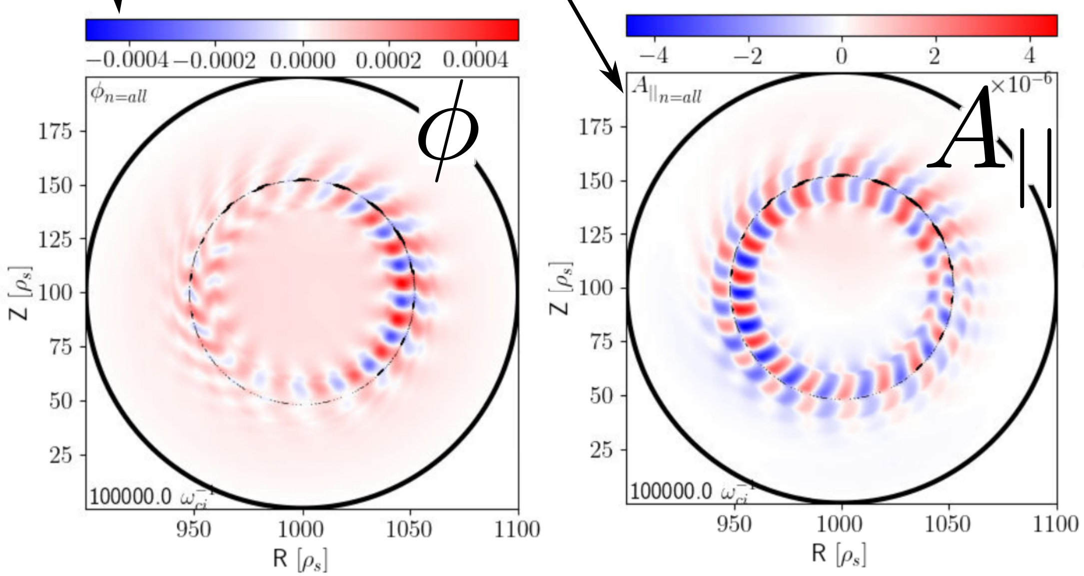
- TM symmetry broken by ITG but restored at saturation
- Time needed for island to establish Related to strong zonal field?

How Turbulence Modifies the Growth and Island Saturation

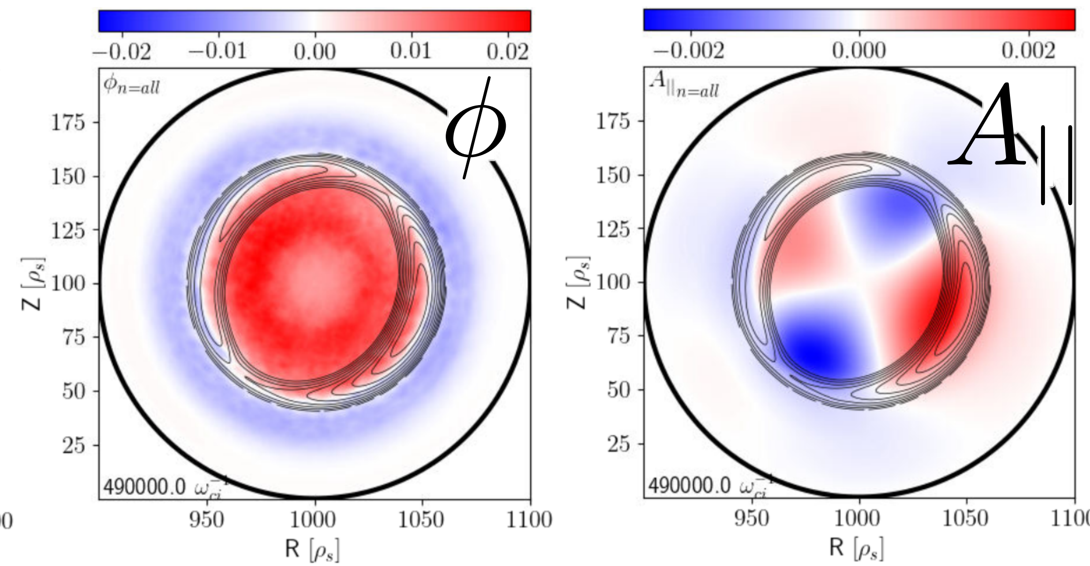




Turbulence changes the TM frequency from electron (w_r<0) to ion (w_r>0) diamagnetic drift directions



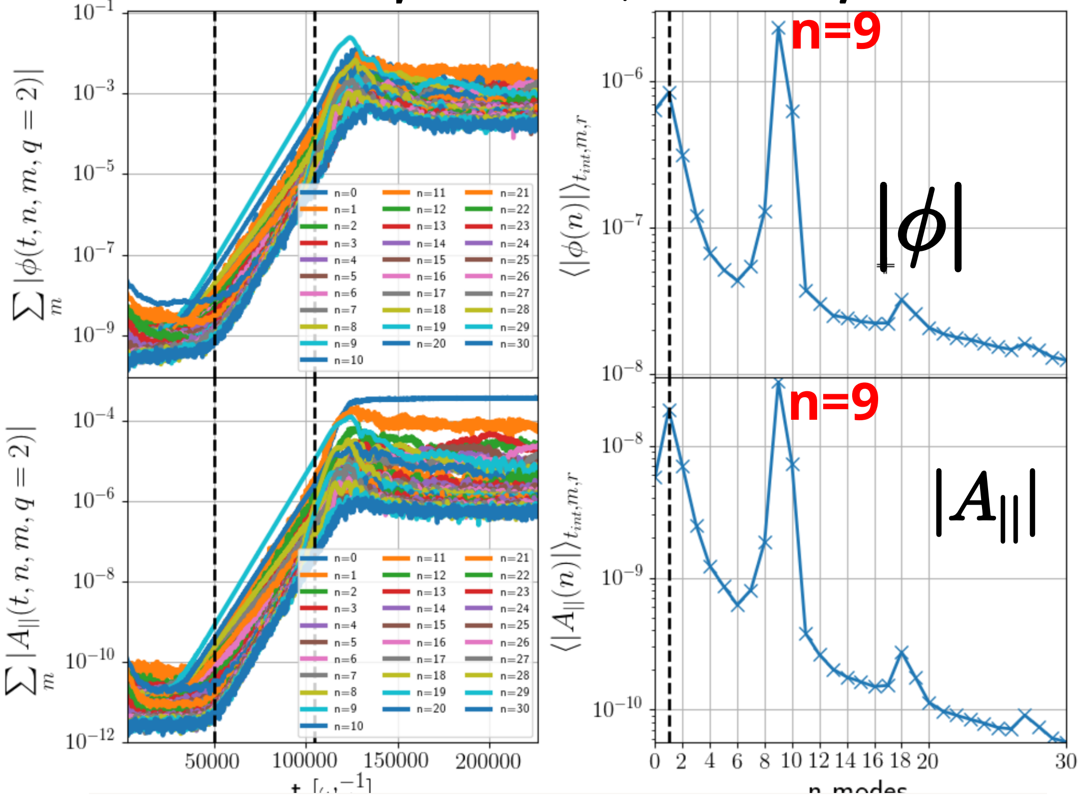
Time when TM interact with micro-instability identified as ion temperature gradient (ITG) modes

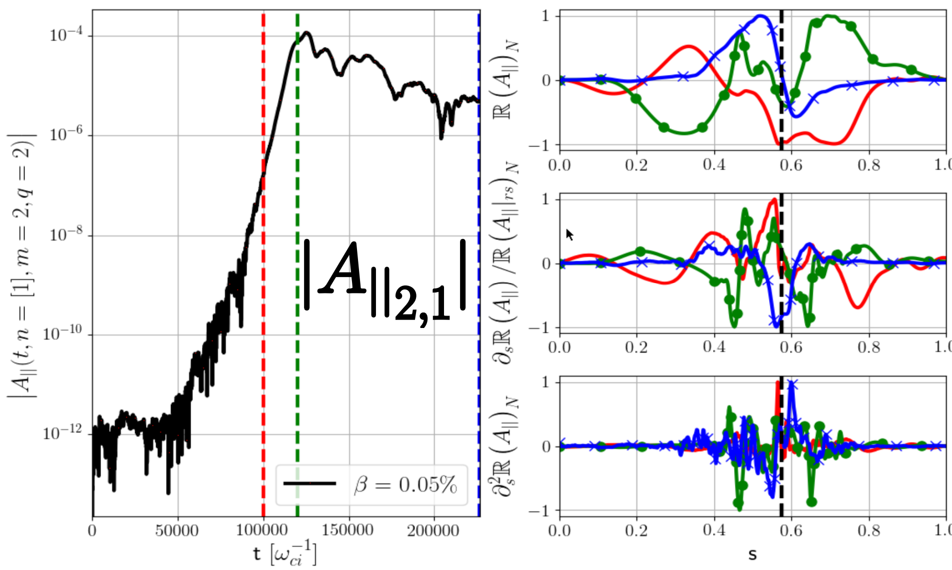


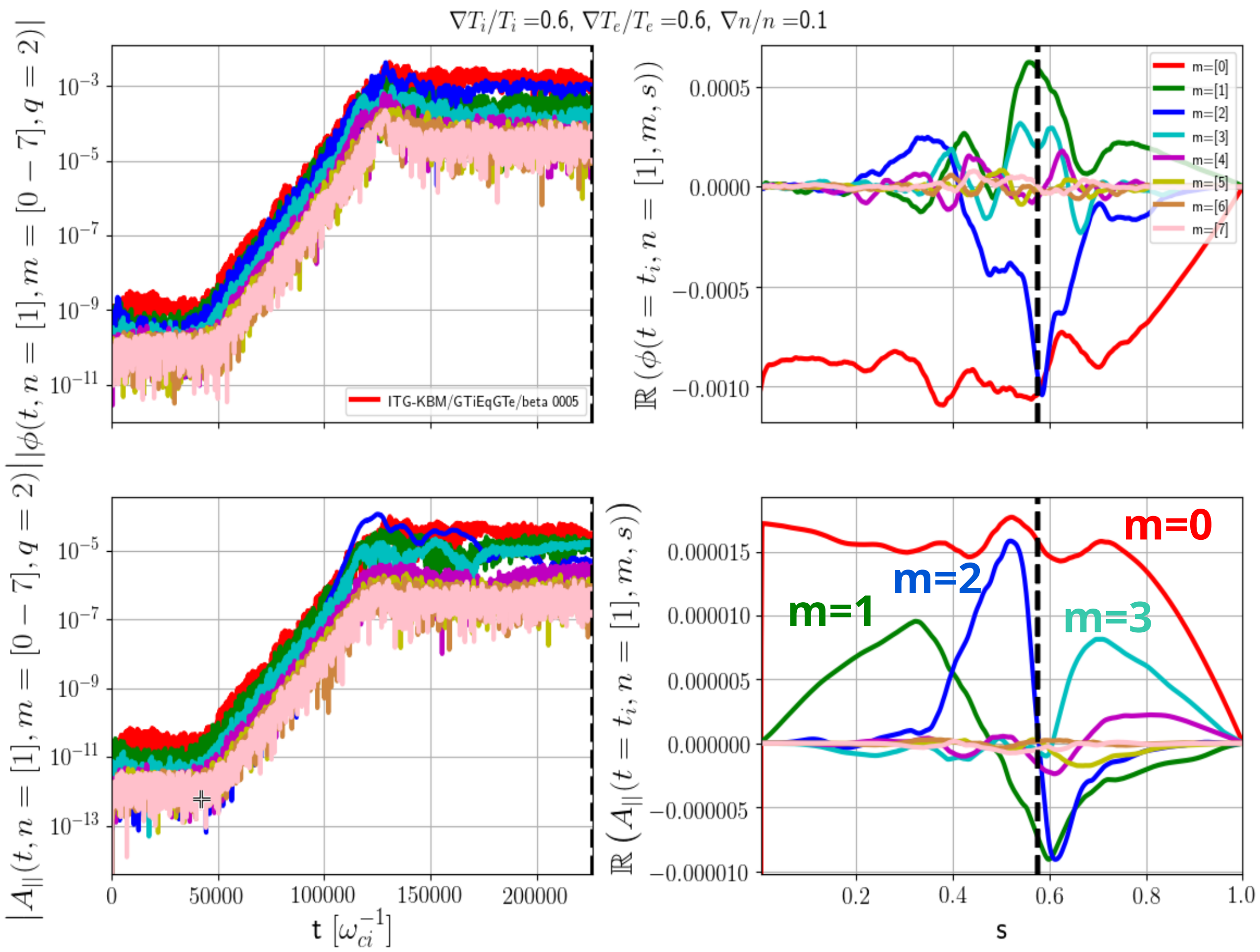
At turbulence saturation time magnetic islands regulate turbulence

Large n initialised Turbulence with RLT_e=RLT_i: No Reconnection Yet

$$R_0 \nabla T_s / T_s = 6,\ R_0 \nabla n / n = 1$$





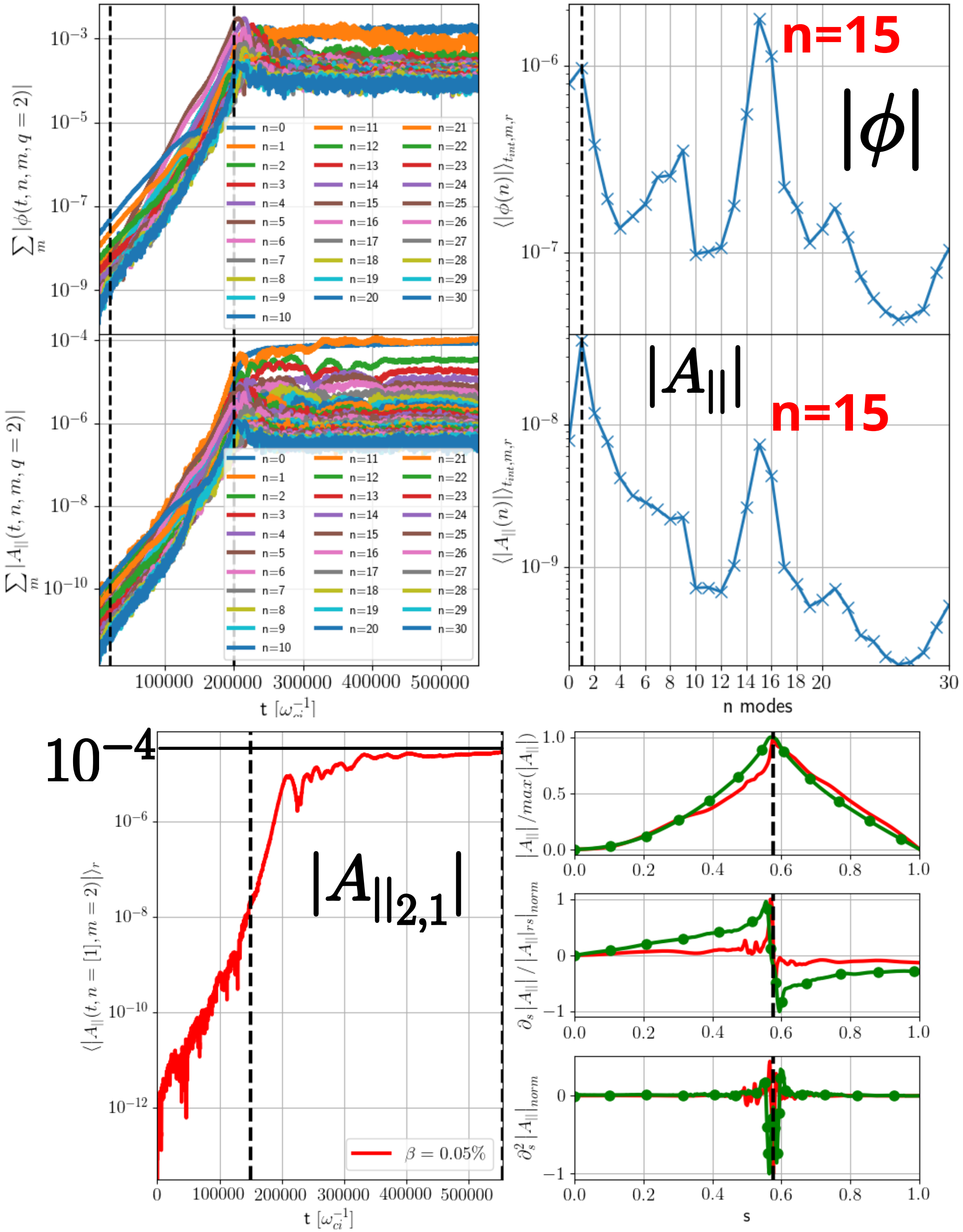


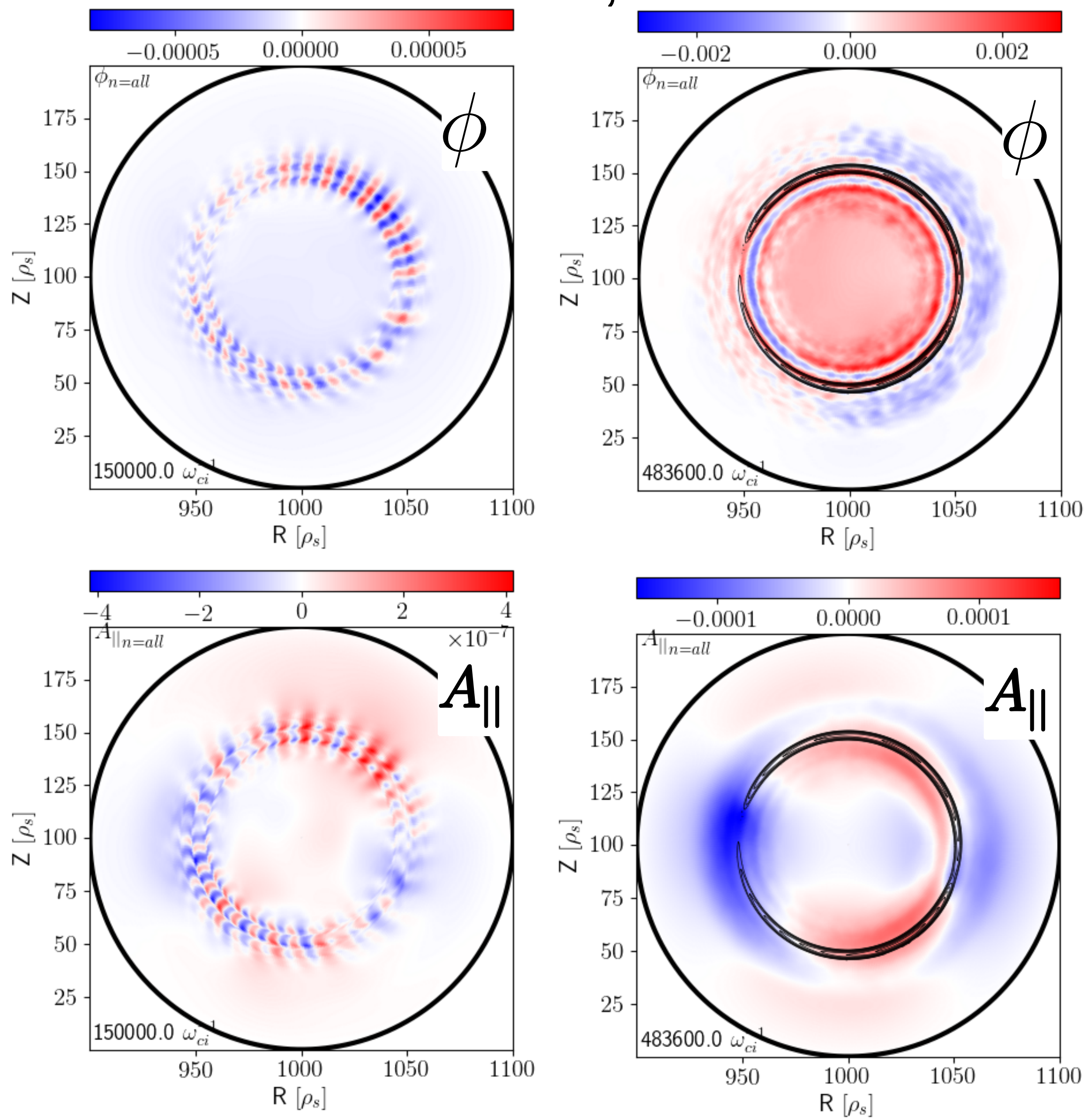
Large n initialised Turbulence with nabla Te: Reconnection

$R_0\nabla T_e/T_e = 6$, $R_0\nabla T_i/T_i = 0$, $R_0\nabla n/n = 1$, $\beta = 0.05\%$

- Small magnetic island out of turbulence

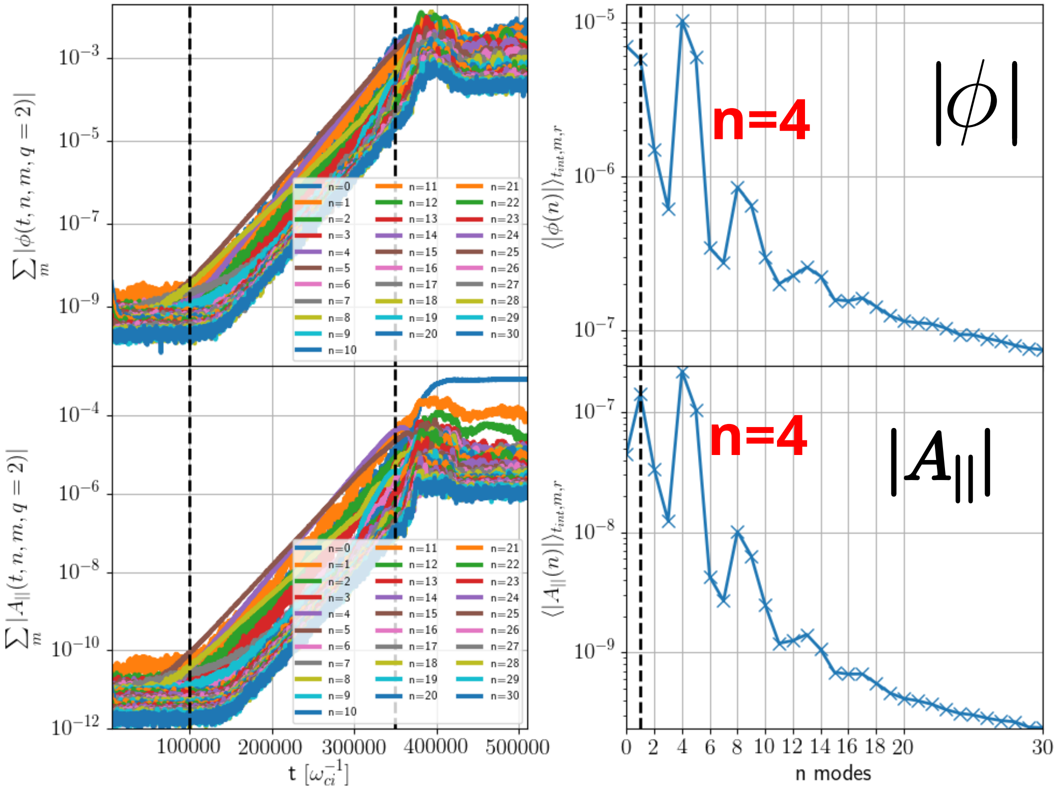
$w_s^2 \propto |A_{\|2,1}| \cong 10^{-4}$

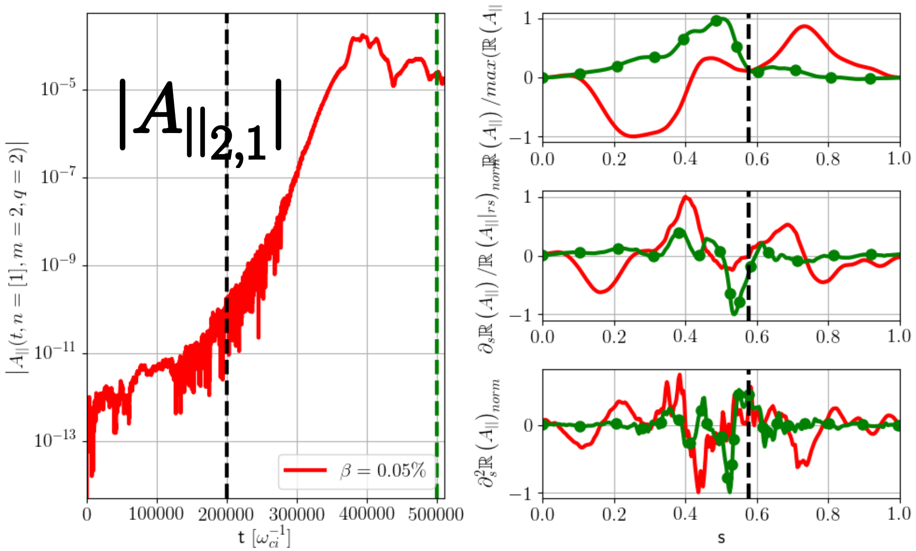




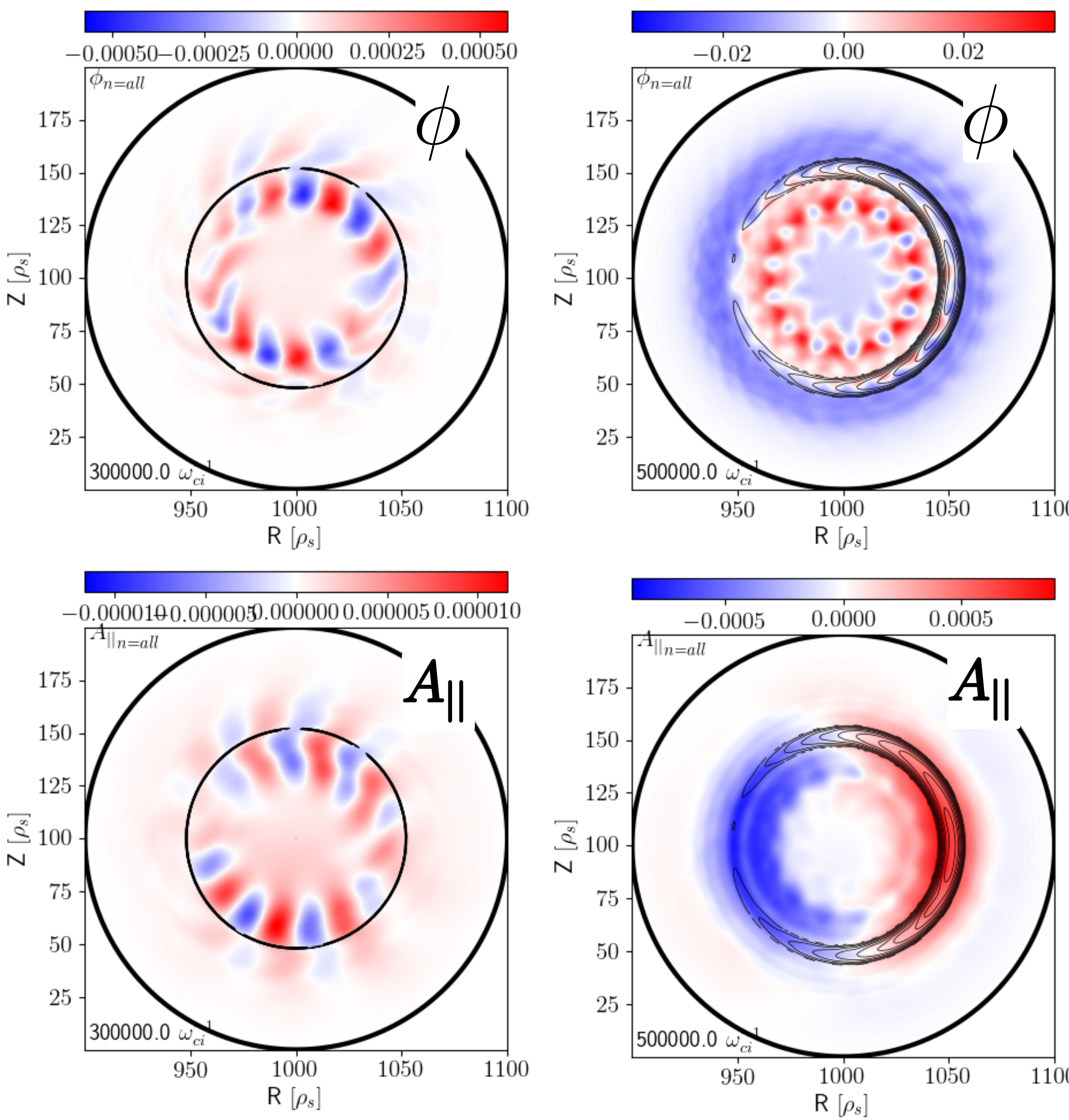
Large n initialised Turbulence with nabla Ti: No Reconnection Yet

$R_0\nabla T_e/T_e = 0,\ R_0\nabla T_i/T_i = \mathbf{6},\ R_0\nabla n/n = 1,\ \beta = 0.05\%$





No islands visible **at the moment**



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Summary

- ORB5 Linear TM simulations in agreement with kinetic theory
- Growth rate reduced by increased plasma-beta, increased gradient
- Existence of another instability at large pressure gradient
- Non-linear simulations with flat density and Temperature profiles
  - Strong drive leads to large islands
  - The island saturation size not only proportional to tearing parameter
  - Turbulence develops at the island sepratrix
  - Strong density fluctuations leads to the shrinking of island and strong zonal current formation
- Non-linear simulations with finite density and temperature gradients
  - ITG Turbulence is found to enhance the tearing growth when initially unstable
  - Initial turbulence:
    No reconnection with small n driven turbulence for the moment
    Reconnection for large n driven turbulence
- Threshold exists defining different type of reconnection