Finite orbit width effect on the neoclassical toroidal viscosity in the superbanana-plateau regime

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Outline

1. Introduction
2. Numerical verification of NTV by global kinetic simulations
3. Finite orbit width effect on NTV
4. Another application of GT5D for 3D geometry
5. Summary

Background & motivation - 3D effect on tokamak

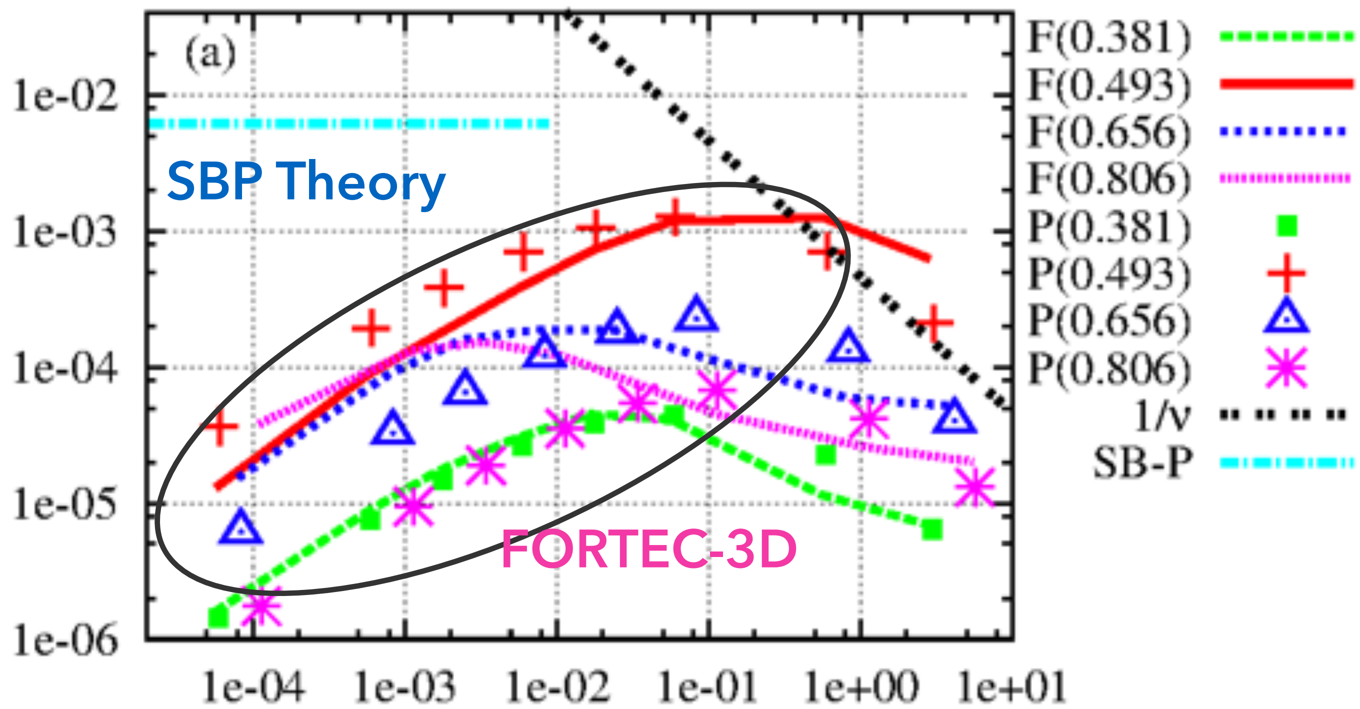
3D effect is a key issue for plasma confinement in tokamaks.

- Small resonant 3D perturbation affects on tokamak plasmas.
    - stability: ELM mitigation
    - transport: **Neoclassical Toroidal Viscosity (NTV)** , Rotation

Discrepancy of NTV prediction: ν_b^*-dependency

- [Shaing ,PPCF2009] ν_b^*-independent NTV (Superbanana-plateau theory)
- [Satake, PRL2011] ν_b^*-dependency by FORTEC-3D code.

ν_b^*-dependency of NTV
from SBP theory and FORTEC-3D.
(Satake, PRL2011)



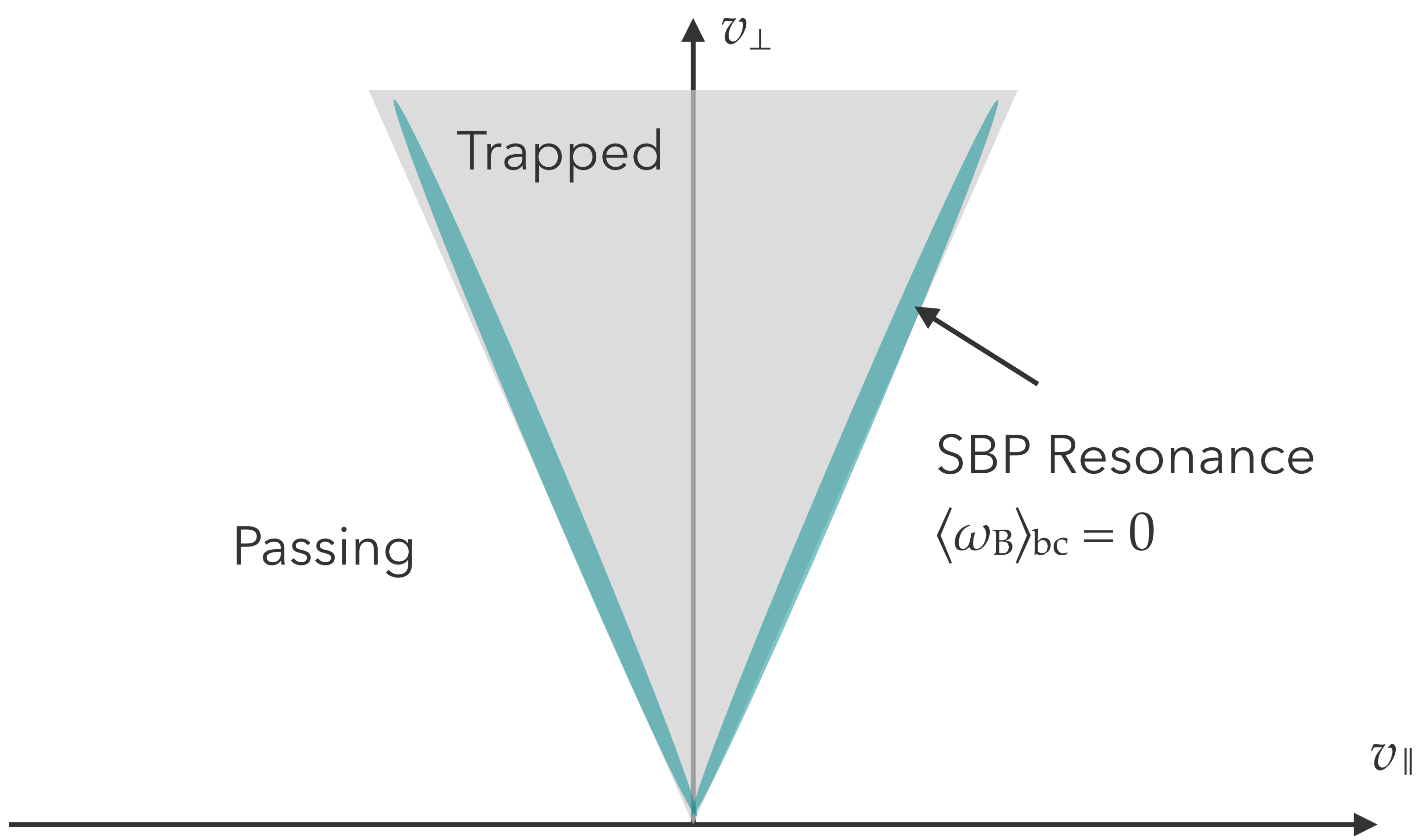
Purpose

Clarify the cause of the discrepancy by using two different types of global kinetic simulations.

Superbanana-plateau theory for NTV

- Local, bounce-averaged drift-kinetic equation.
- Toroidal precession, $\langle \omega_{\mathrm{B}} \rangle_{\mathrm{bc}} = 0$, gives the resonant condition.
- Magnetic shear shifts the resonance κ^2 towards the boundary [Shaing, JPP2015].
- Non-axisymmetric part of δB is only retained through the perturbed radial drift.
- **Independent of collisionality.**

Schematic view of SBP resonance



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Target plasma profiles & numerical tools

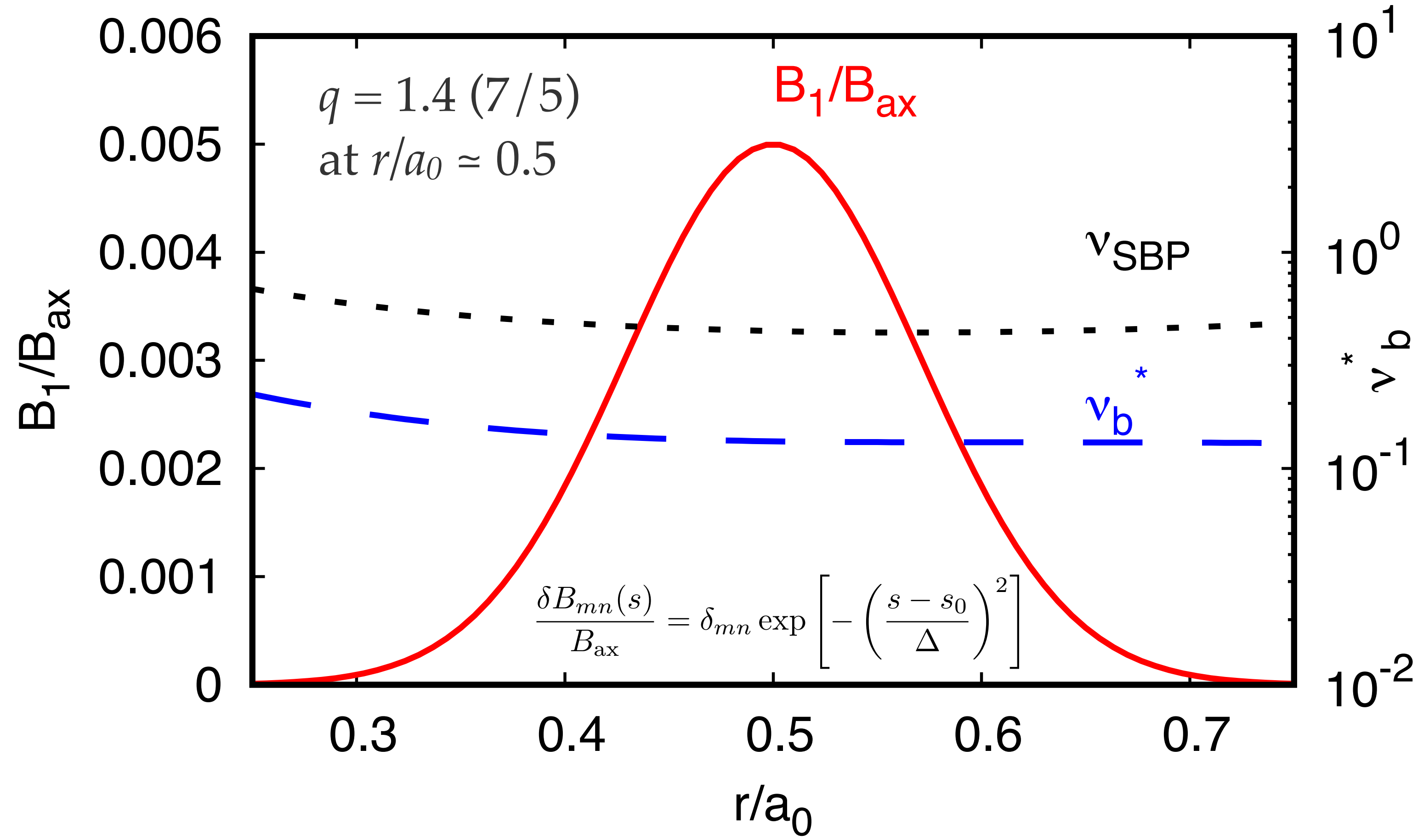
Circular tokamak with δB

- $B_{ax} = 1.91$ T
- $a_0 = 0.47$ m / $R_{ax} = 2.35$ m
- $1/\rho^* = 150$
- $q = 0.854 + 2.184\,(r/a_0)^2$ (positive shear)
- $E_r = 0$ (fixed)
- $\nu_b^* \simeq 0.12$ (base case)

  In the superbanana-plateau regime

  scan: $\nu_b^* \times 0.01, 0.1, 1, 5, 10, 50$
- $\delta B/B_{ax} = 0.5$ % with $m/n = 7/5$
- resonant surface with $q = 1.4$ at $r/a_0 \simeq 0.5$.

Radial profile of perturbation and ν_b^*.



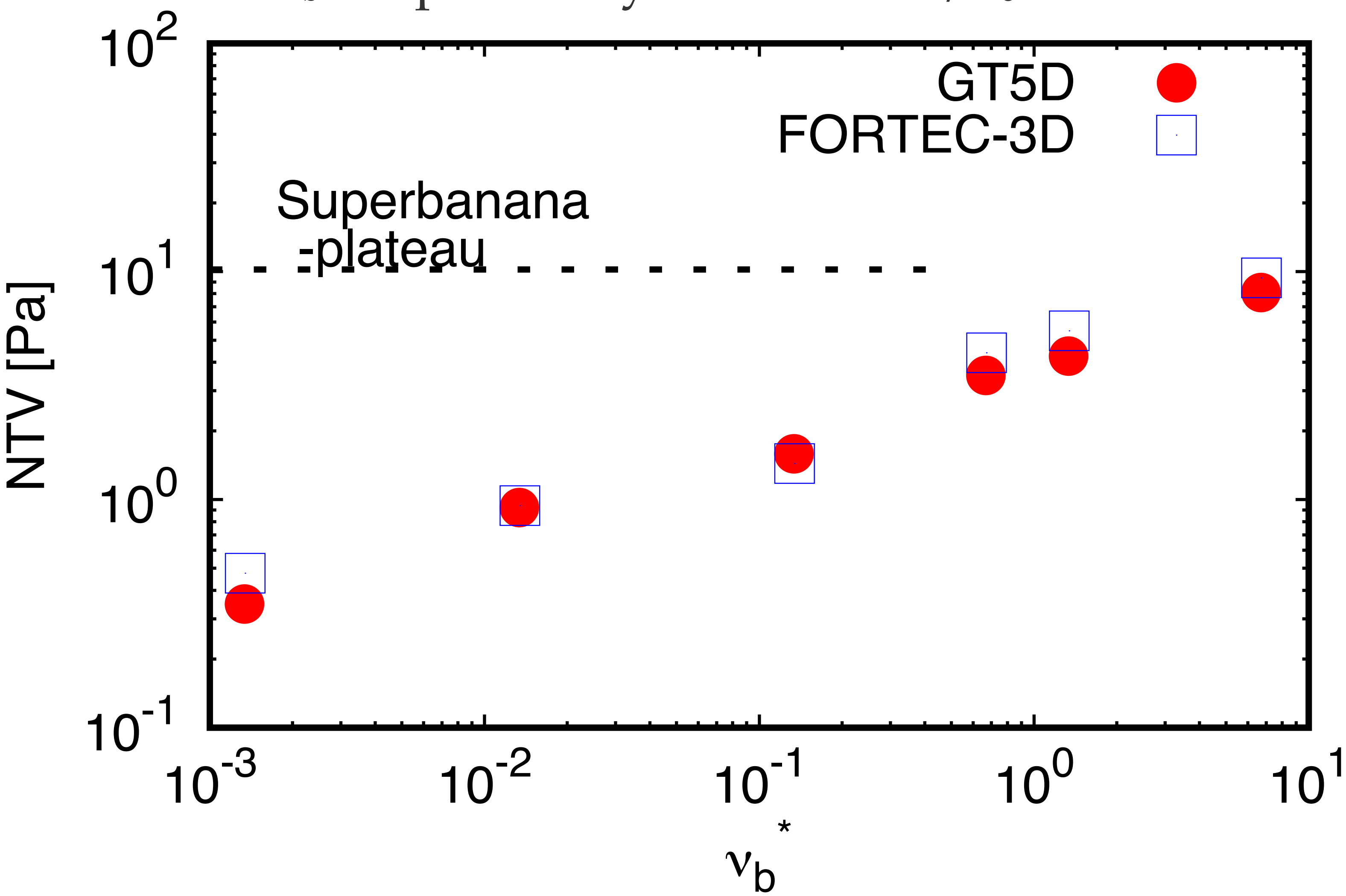
Global kinetic code

- **GT5D**; Full-f Eulerian code for gyrokinetic simulations
- **FORTEC-3D**; δf Monte Carlo (particle) code for drift-kinetic (neoclassical) simulations

ν_b^*-dependency of NTV arises in global sims.

NTV of global kinetic simulations reproduce similar ν_b^*-dependency over the wide ranges of collisionalities.

ν_b^*-dependency of NTV at $r/a_0 \simeq 0.5$



- SBP theory gives constant NTV.
- GT5D/FORTEC-3D gives lower NTV.
- GT5D/FORTEC-3D shows ν_b^*-dependency.

NTV of SBP theory ($E_r = 0$) is evaluated as;

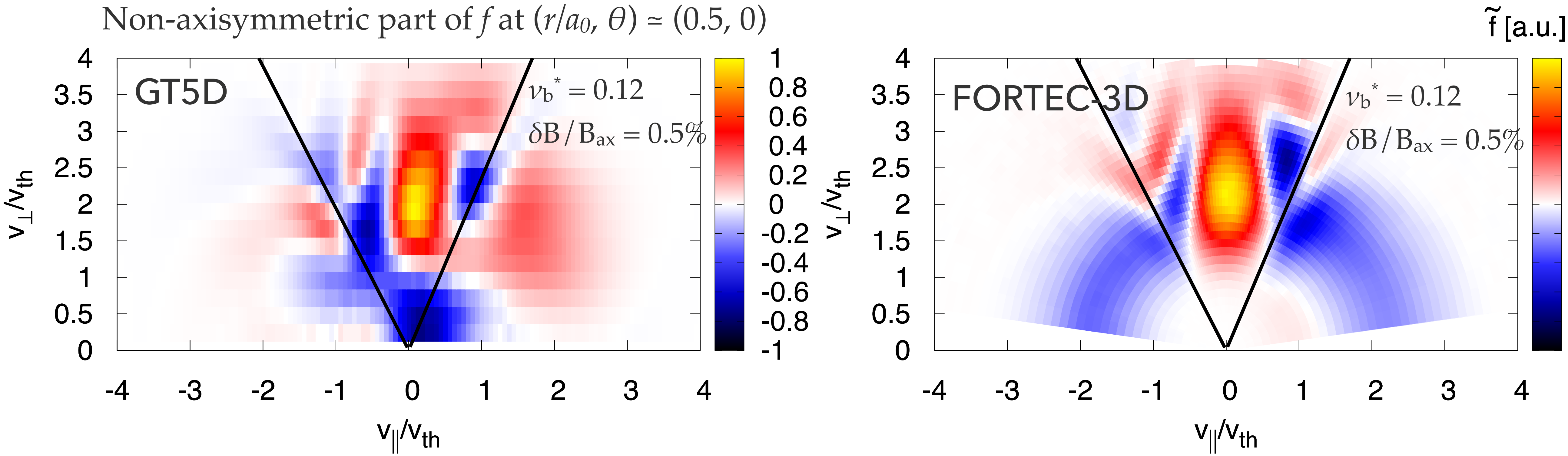
$$\langle \boldsymbol{e}_\zeta \cdot \nabla \cdot \mathsf{P} \rangle = -\eta_1 n_i m_i v_{th}^2 R_{ax} \sqrt{\frac{\epsilon}{2\pi}} \frac{d \ln p_i}{dr}$$

$$\eta_1 = n\Gamma\left(\frac{5}{2}\right) 4K(\kappa_{res})\,\kappa_{res}^2 \left(1-\kappa_{res}^2\right) |\alpha_n^2 + \beta_n^2|$$

$$\kappa_{res} \simeq 0.83$$

No resonant structure in global simulations.

Velocity space structures of non-axisymmetric part of f are successfully verified.



- No resonant structures along the boundary (barely-trapped) region.
- Rather complicated structures are observed.
- Especially, a clear large scale structure appear in trapped region.
- Complicated structures survive for smaller $\delta B \simeq 0.05\ \%$ –> determined by unperturbed orbit.

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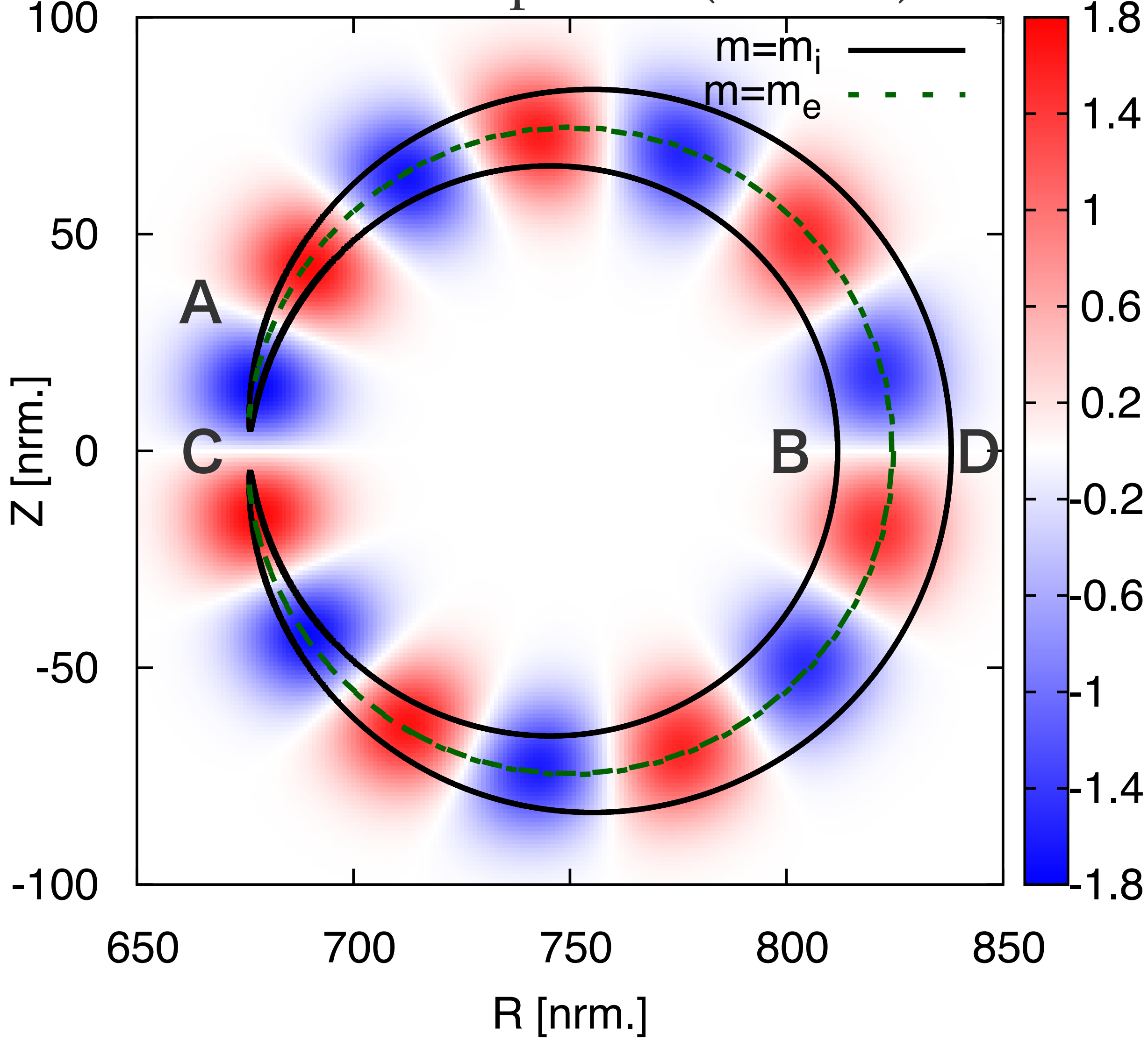
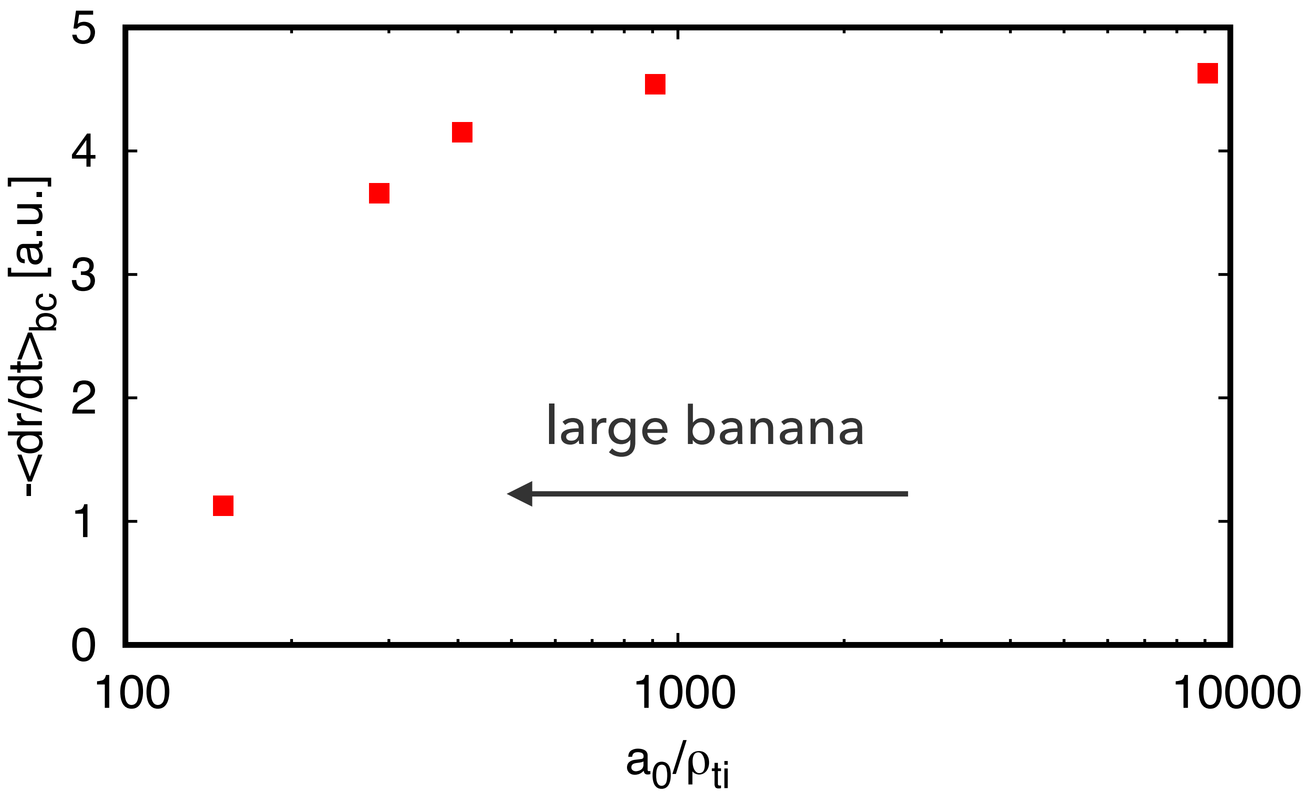
Absence of resonance results from the large finite orbit width of barely-trapped (resonant) particles.

- Banana width $\Delta_b / a_0 \simeq 0.17$ for $v/v_{th} \simeq \sqrt{2}$; variation of $q \simeq 1.2$ - 1.59.
- Barely-trapped particle feel the perturbation only for a fraction of the bounce period.
  - Perturbation becomes less effective.
- Bounce-average of $\mathrm{d}r / \mathrm{d}t$ significantly decreases as m increases.

Barely-trapped particle orbits with contour plot of $(\mathrm{b}\times\nabla \mathrm{B1})\cdot\nabla \mathrm{r}$

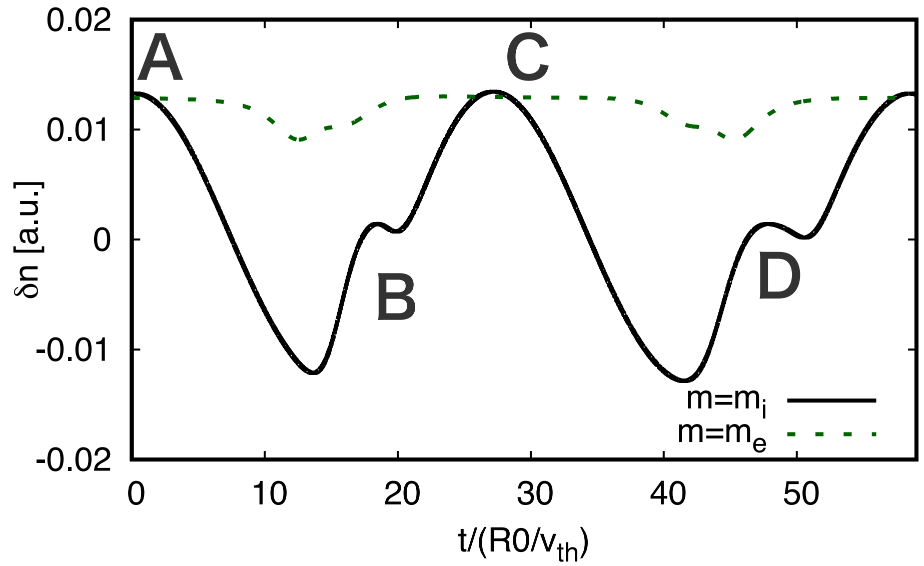


mass (banana-width) dependency of $\langle \mathrm{d}r/\mathrm{d}t \rangle_{bc}$

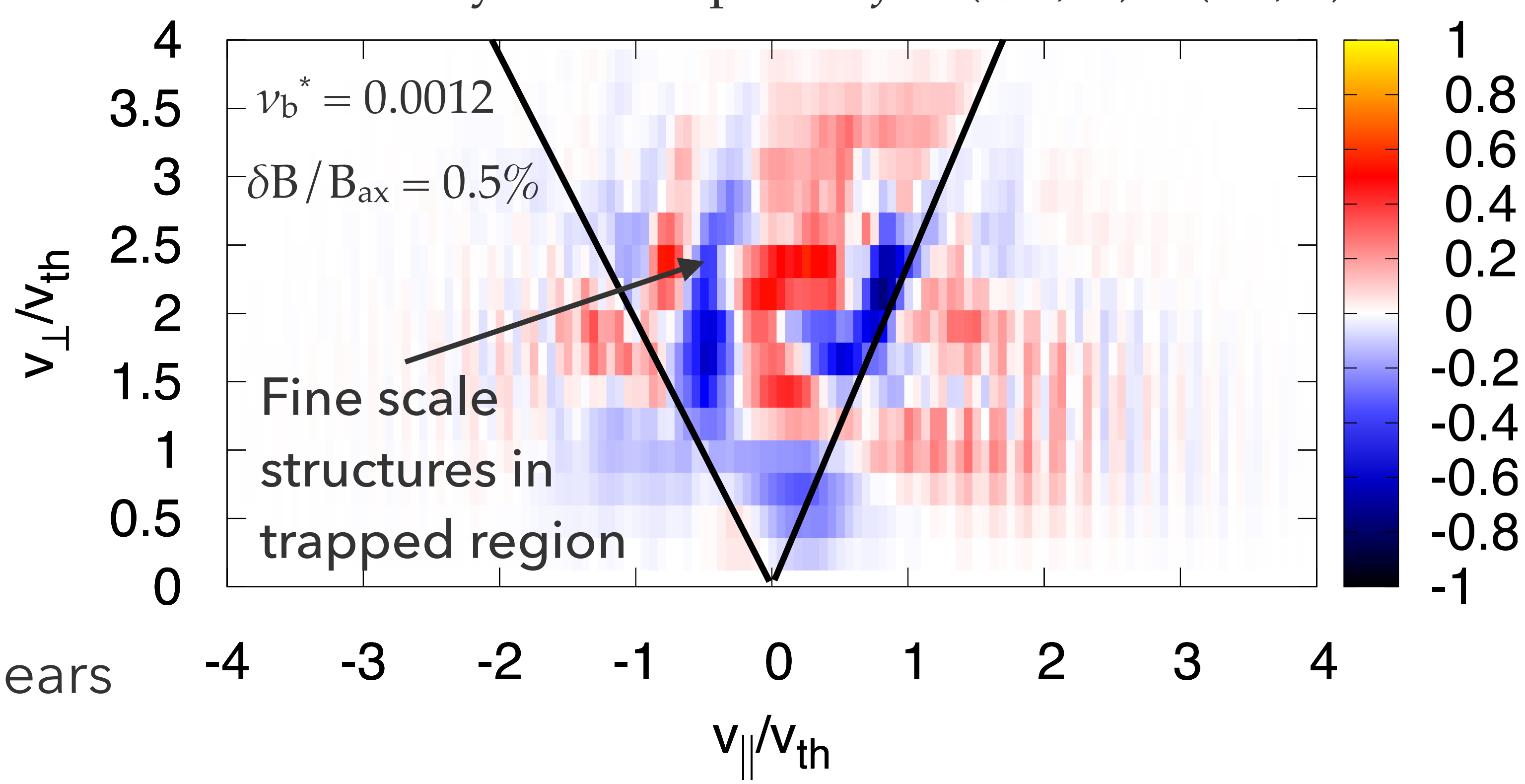


FOW generates finite-l mode, causes phase-mixing.

δn sampled along the bounce motion



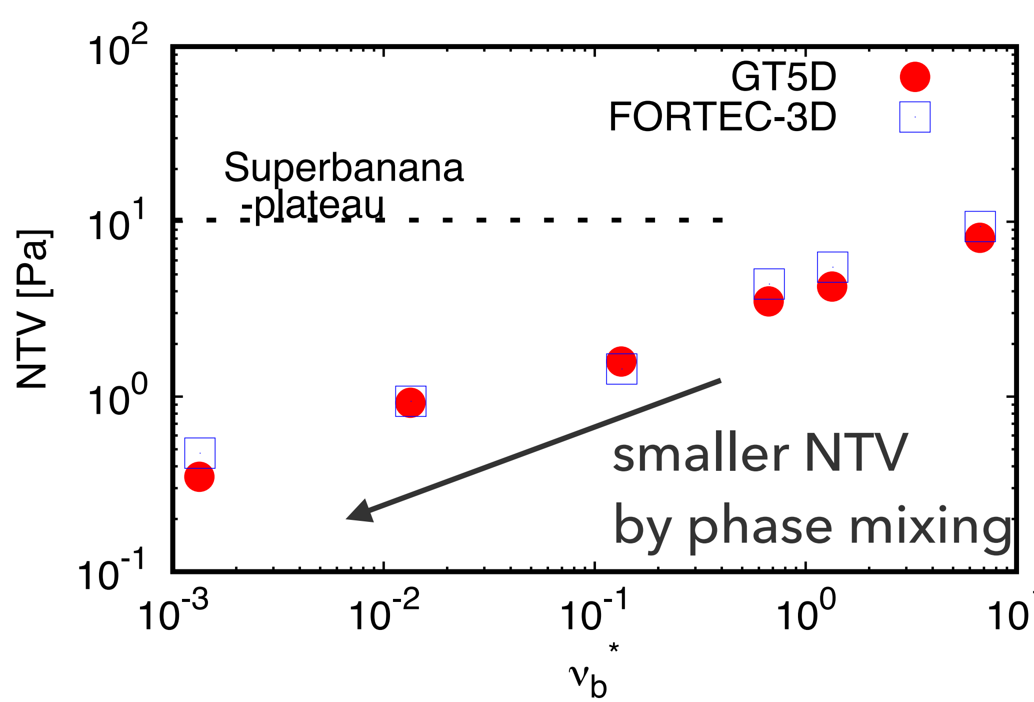
Non-axisymmetric part of f at $(r/a_0, \theta) \simeq (0.5, 0)$



- Non-zero (finite) mode structure appears along the bounce motion.
- Finite-l along the bounce motion causes the phase-mixing as;

$$\partial_t \delta f_l + \mathrm{i} l \omega_{\mathrm{bc}} \delta f_l = 0$$

- Phase mixing generates fine scale structures in lower ν_b^*.
- Makes NTV smaller in lower ν_b^*.



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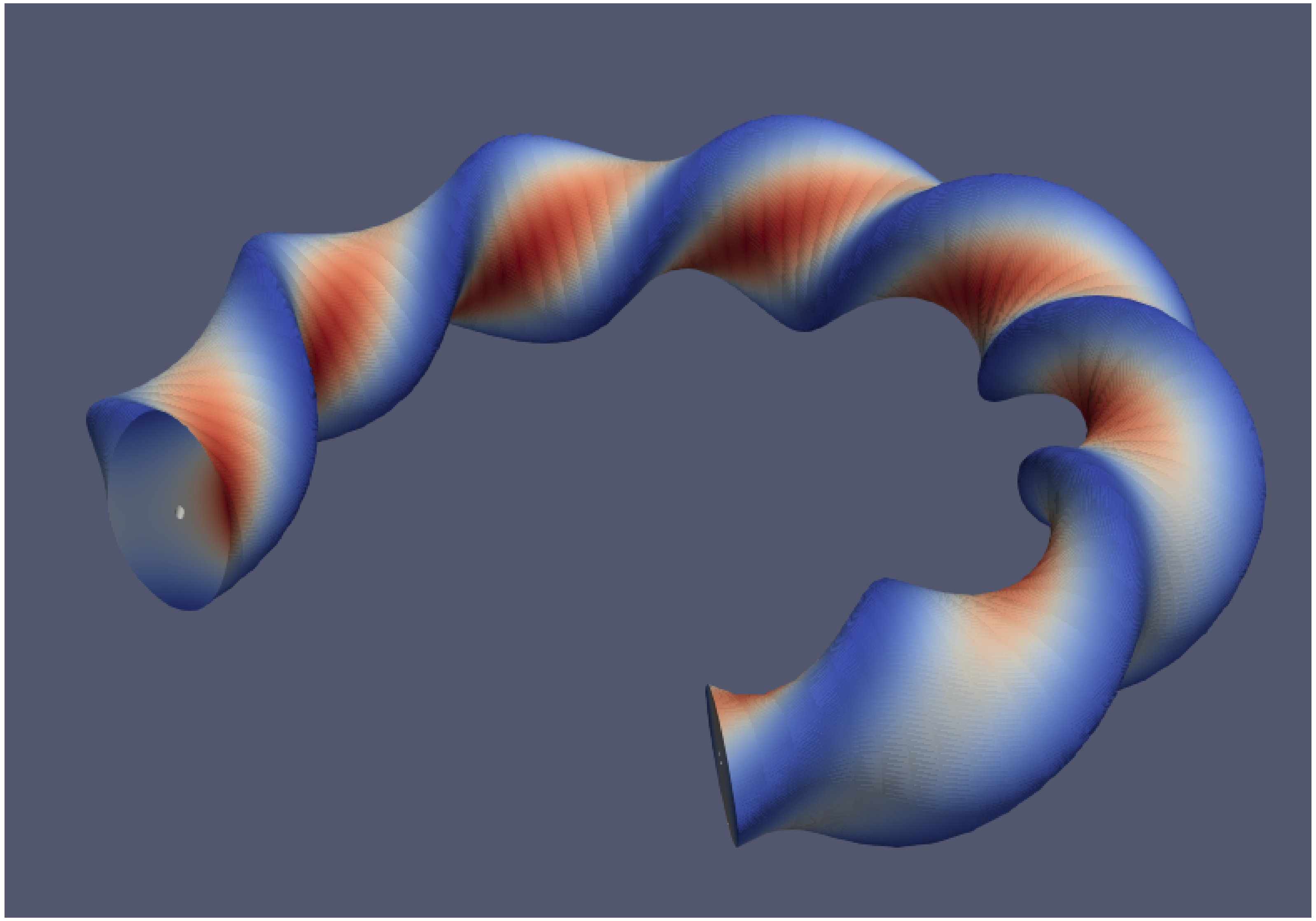
Full-f gyrokinetic simulations for 3D field



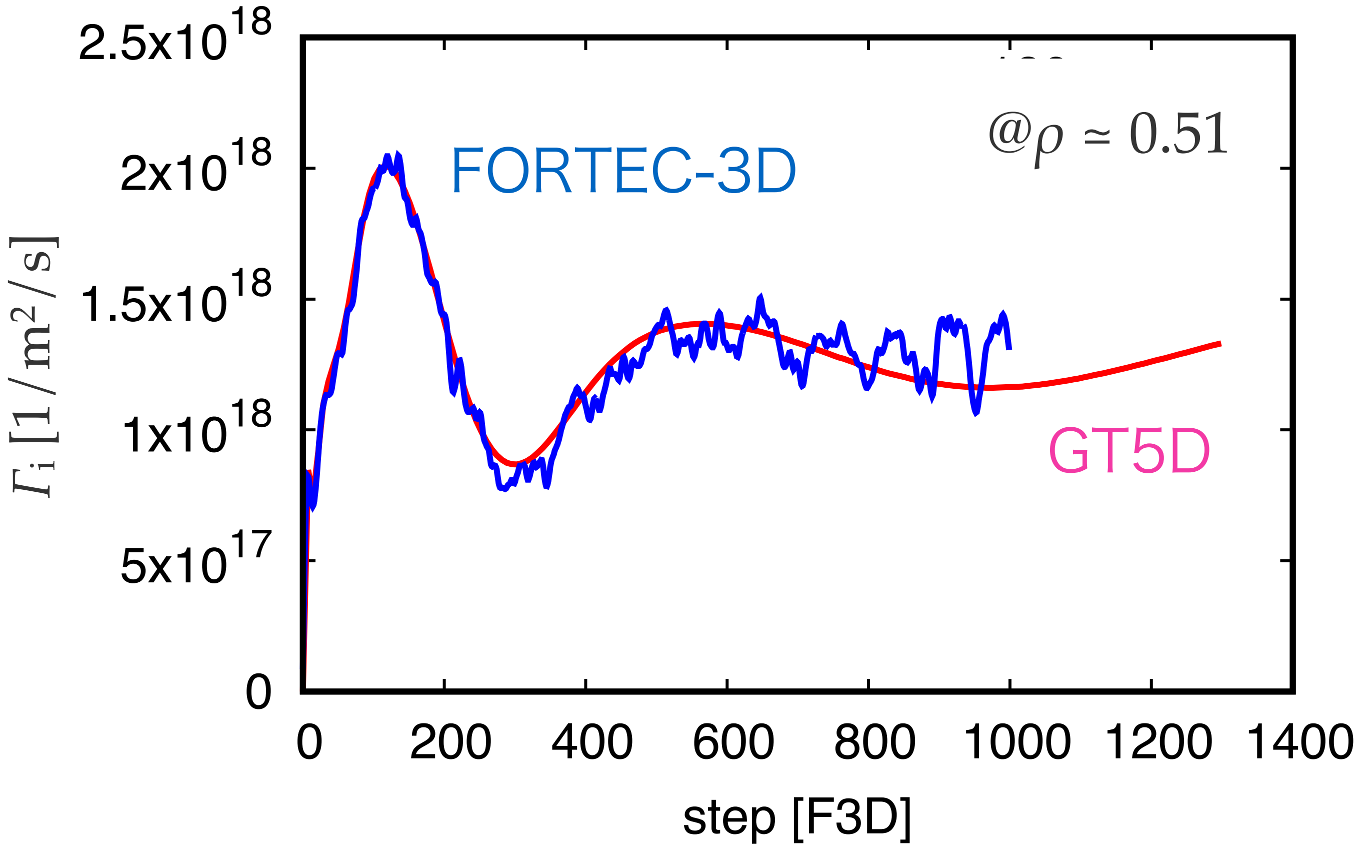
GT5D+VMEC

- Solves gyrokinetic equation.
- Global full-f model.
- VMEC equilibrium for 3D field.
- Eulerian approach.
  - Conservative Morinishi scheme.
- Radial electric field solver.
  - Ambipolar condition of neoclassical transport.
- **Neoclassical benchmark has been initiated.**

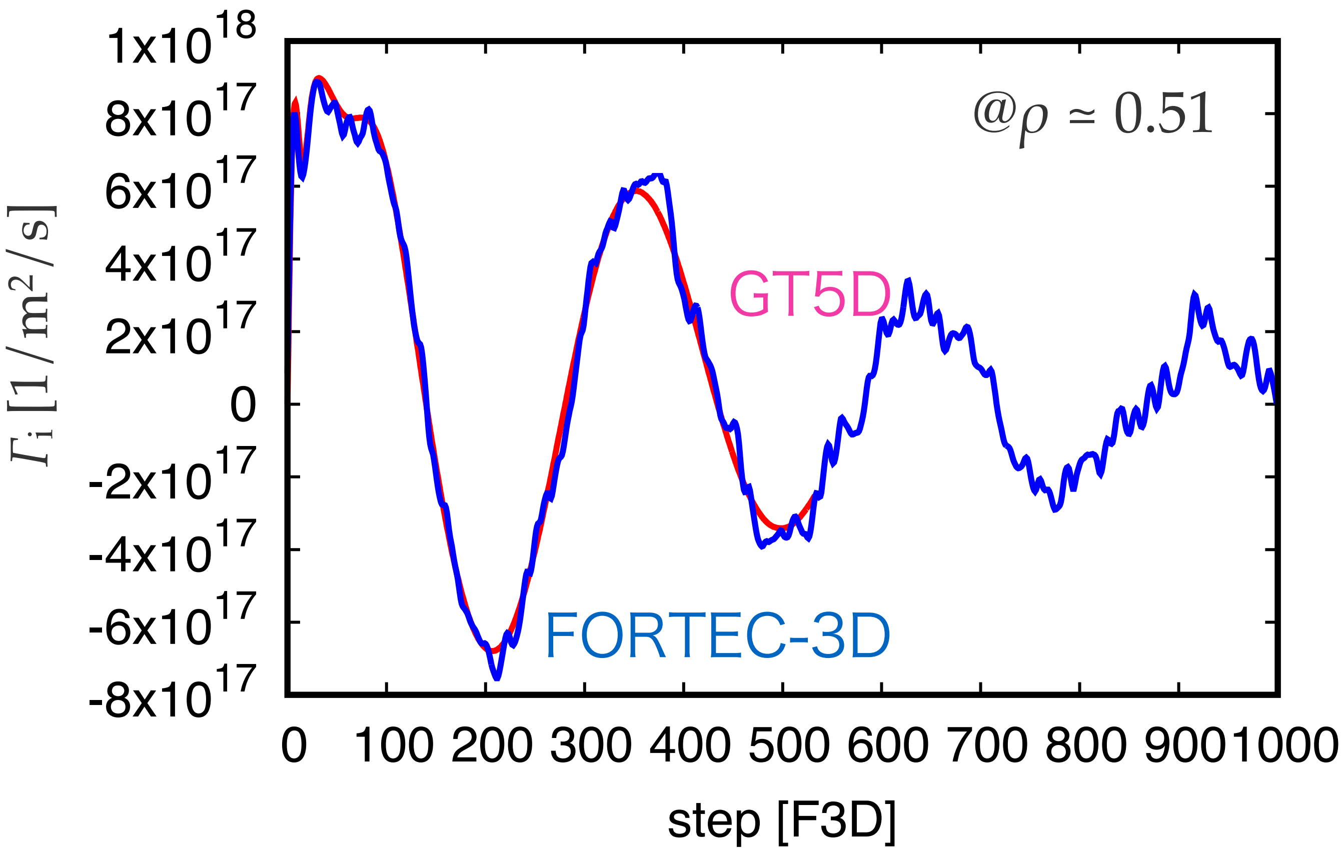
Benchmark case parameters

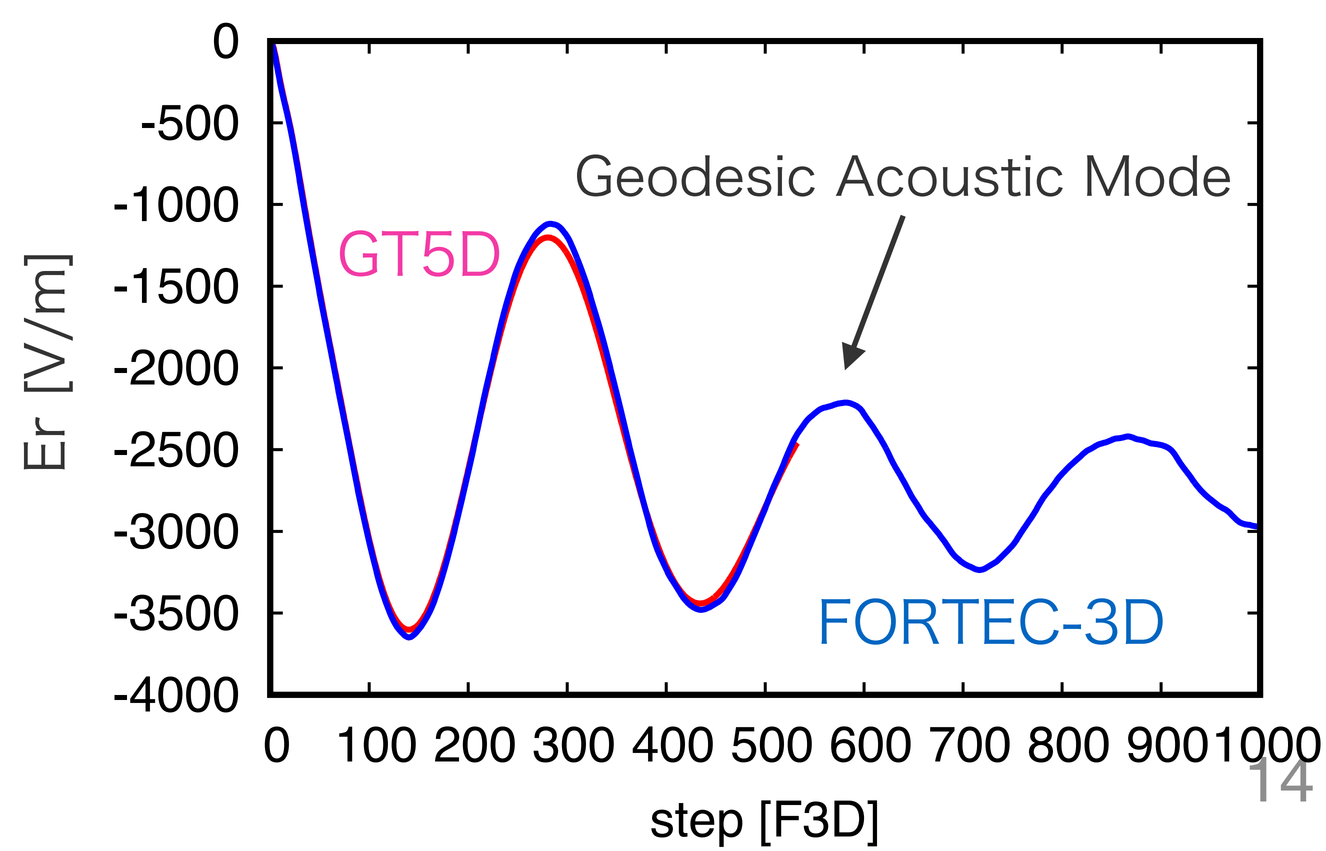
- LHD inward shifted configuration with $R_{\mathrm{ax}} = 3.6\ \mathrm{m}$ and $B_{\mathrm{ax}} = 3.0\ \mathrm{T}$.
- $a_0 = 0.63\ \mathrm{m}$.
- $T_{\mathrm{i,ax}} = 0.91\ \mathrm{keV}$, and $n_{\mathrm{e,ax}} = 3.5\times10^{18}\ \mathrm{m}^{-3}$.

(Preliminary) NC Benchmarks w/ and w/o Er



- **NC particle flux of GT5D+VMEC shows fairly good agreement with FORTEC-3D.**
- $1/\nu$-regime; $\nu_b^* \simeq 0.15$ @ $\rho \simeq 0.51$.
- (bottom) E_r is determined according to the ambipolar condition of Γ.





Summary

FOW effect on NTV in Superbanana-Plateau regime

- NTV of GT5D well reproduces the ν-dependency of NTV and velocity space structure of FORTEC-3D simulations.
- Large banana width of the unperturbed orbit plays a key role in NTV physics.
    1. Radial drift caused by perturbation significantly decreases. —> Smaller NTV.
    2. Finite-l mode along the bounce motion causes the phase mixing —> ν-dependency.

GT5D+VMEC

- Global full-f gyrokinetic simulation code for 3D geometries.
- Equilibrium from VMEC is incorporated into GT5D via the newly developed interface.
- First neoclassical benchmarks w/ and w/o Er show good agreements with FORTEC-3D.