Collisionality dependence of neoclassical toroidal viscosity in superbanana-plateau regime by full-f gyrokinetic simulations

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Outline

- **Background & Purpose**
- **Full-f gyrokinetic simulation for perturbed tokamak; GT5D**
- **Numerical results**
  - Benchmark for axisymmetric tokamak ($\delta B = 0$)
  - NTV benchmark for perturbed tokamak
  - Comparison to SB-P theory of Shaing
- **Summary**

Background

- Momentum transport and plasma (intrinsic) rotation are an important issue for ELM mitigations by RMPs, confinement performance through E×B flow shear, etc.

- There may be non-axisymmetric (3D) field perturbations in a realistic tokamaks due to an error field, RMPs, MHD activities.

- The neoclassical viscosity induced by the symmetry breaking acts as an additional torque and/or damping term in the momentum transport; leading to an offset rotation.

$$\frac{\partial}{\partial t}\left(m_{\mathrm{i}} n_{\mathrm{i},0}\left\langle R^2 \Omega_{\mathrm{t}}\right\rangle\right) \simeq -\left\langle \boldsymbol{e}_\zeta \cdot \nabla \cdot \pi_{\mathrm{i},\parallel}\right\rangle - \frac{1}{V'}\frac{\partial}{\partial s}\left(V' \Pi_{\mathrm{i}}^{turb}\right)$$

Neoclassical viscosity — **Turbulence; diffusion, pinch, residual stress**

Goal of this work

- Using full-f gyrokinetic simulations;
- Investigating the role of NTV in the momentum transport.
- Evaluation of the plasma rotation in a realistic tokamak.

As a first step;

- Model of an asymmetric (3D) field perturbation appropriate for full-f gyrokinetic simulations in GT5D.
- Benchmarks for neoclassical toroidal viscosity (NTV) with a NC transport code, FORTEC-3D, via ν-dependence.
- Comparison to Shaing's SB-P theory.

Gyrokinetic simulations by GT5D

Global full-f gyrokinetic code; GT5D

Gyrokinetic eq. $$\frac{\partial f}{\partial t} + \{\boldsymbol{R}, H\} \cdot \frac{\partial f}{\partial \boldsymbol{R}} + \{v_\parallel, H\} \frac{\partial f}{\partial v_\parallel} = 0$$

GK Poisson eq. $$\frac{1}{\lambda_{\mathrm{D,e}}^2}\left[\Phi - \langle\Phi\rangle\right] - \nabla_\perp \cdot \frac{\rho_{\mathrm{ti}}^2}{\lambda_{\mathrm{D,i}}^2} \nabla_\perp \Phi = 4\pi q_i \int f_1 \delta\left(\boldsymbol{R} + \boldsymbol{\rho}_i - \boldsymbol{x}\right) d\boldsymbol{z}$$

Linearized collision operator w/ conservation laws.
Neoclassical physics is properly included*.

Neoclassical toroidal viscosity in gyrokinetic simulations.

Similarly to the DKE framework, the leading order stress tensor has a CGL-form in gyrokinetics.
Its toroidal components becomes: $\left\langle \boldsymbol{e}_\zeta \cdot \nabla \cdot \mathsf{P}^{\mathrm{CGL}} \right\rangle = \left\langle \left(P_\parallel + P_\perp\right) \frac{\partial B}{\partial \zeta} \right\rangle$

*Satake, *et al.*, CPC **181**, 1069 (2010).

Coordinate system in GT5D and F3D

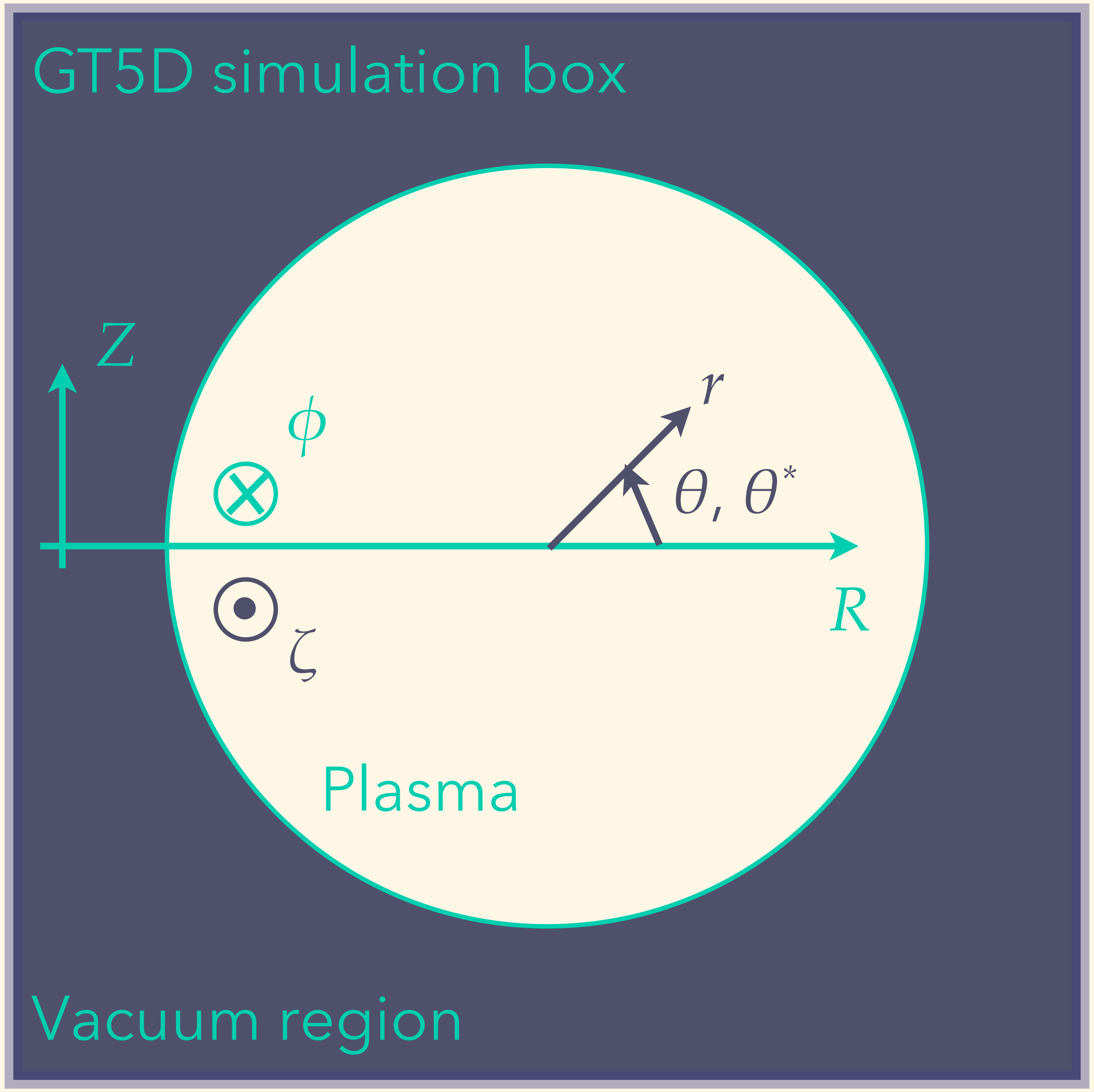
GT5D

GT5D solves GKE in entire region using (R, ϕ, Z) and (r, θ^*, ζ).

θ^* is a straight field line coords, in axisymmetric tokamak.

FORTEC-3D

F3D solves DKE in flux-surface geometry.
Equilibrium field in Boozer coordinates $(\Psi, \theta_\mathrm{B}, \zeta_\mathrm{B})$.



(r, θ^*, ζ) and $(\Psi, \theta_\mathrm{B}, \zeta_\mathrm{B})$ coincides in axisymmetric limit.

δB model for benchmark w/ F3D

Magnetic field perturbation by vector potential

Vector potential $\boldsymbol{A}$ needs to be determined for GT5D,
due to the requirement for $\nabla \cdot \boldsymbol{B} = 0$.

This causes several difficulties numerically and physically in GT5D.

Magnetic field perturbation, only in its magnitude

Here, the perturbation is introduced via the magnitude of B.

Lagrangian of GT5D and FORTEC-3D is rewritten formally:

$$L = e\left(\psi + \frac{mv_\parallel}{eB} I\right)\dot{\theta}* + e\left(-\chi + \frac{mv_\parallel}{eB} G\right)\dot{\zeta} - \boxed{H(B+\tilde{B})} \qquad \text{for GT5D}$$

$$L = e\left(\psi + \frac{mv_\parallel}{e\boxed{\left(B+\tilde{B}\right)}} I\right)\dot{\theta}* + e\left(-\chi + \frac{mv_\parallel}{e\boxed{\left(B+\tilde{B}\right)}} G\right)\dot{\zeta} - \boxed{H(B+\tilde{B})} \qquad \text{for FORTEC-3D}$$

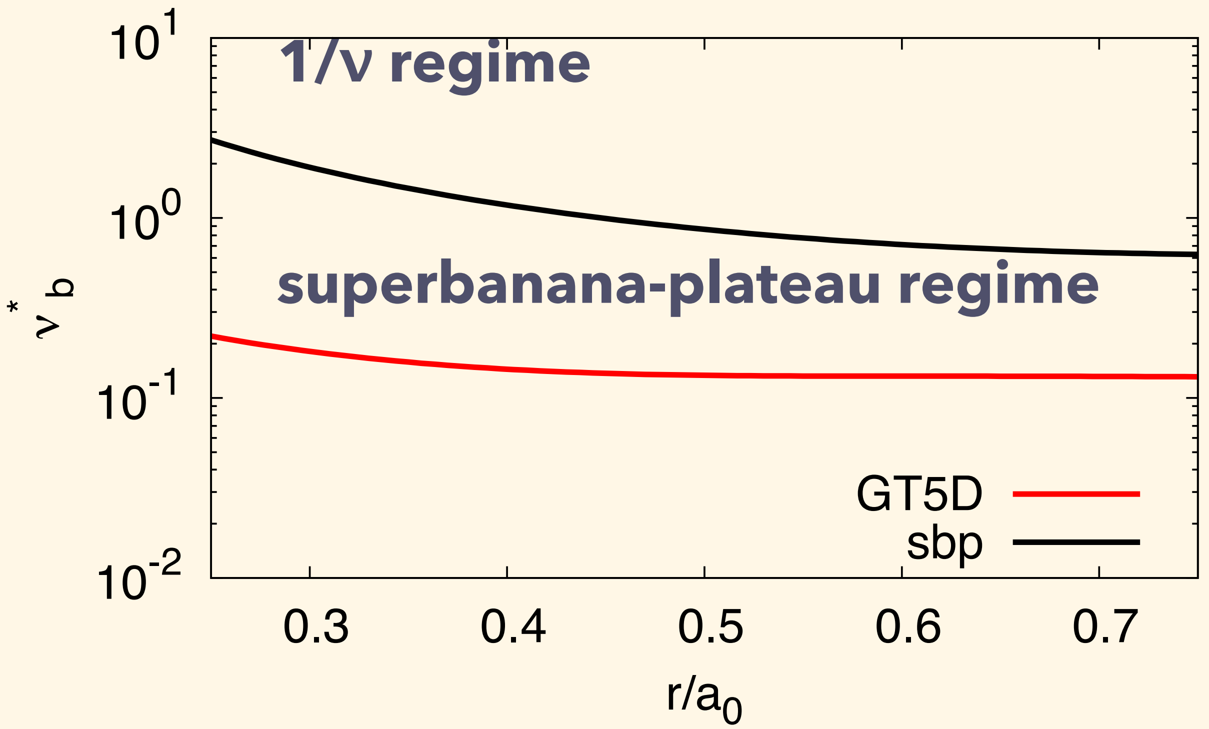
Assuming equilibrium field (current, flux) is kept axisymmetric.

Target plasma

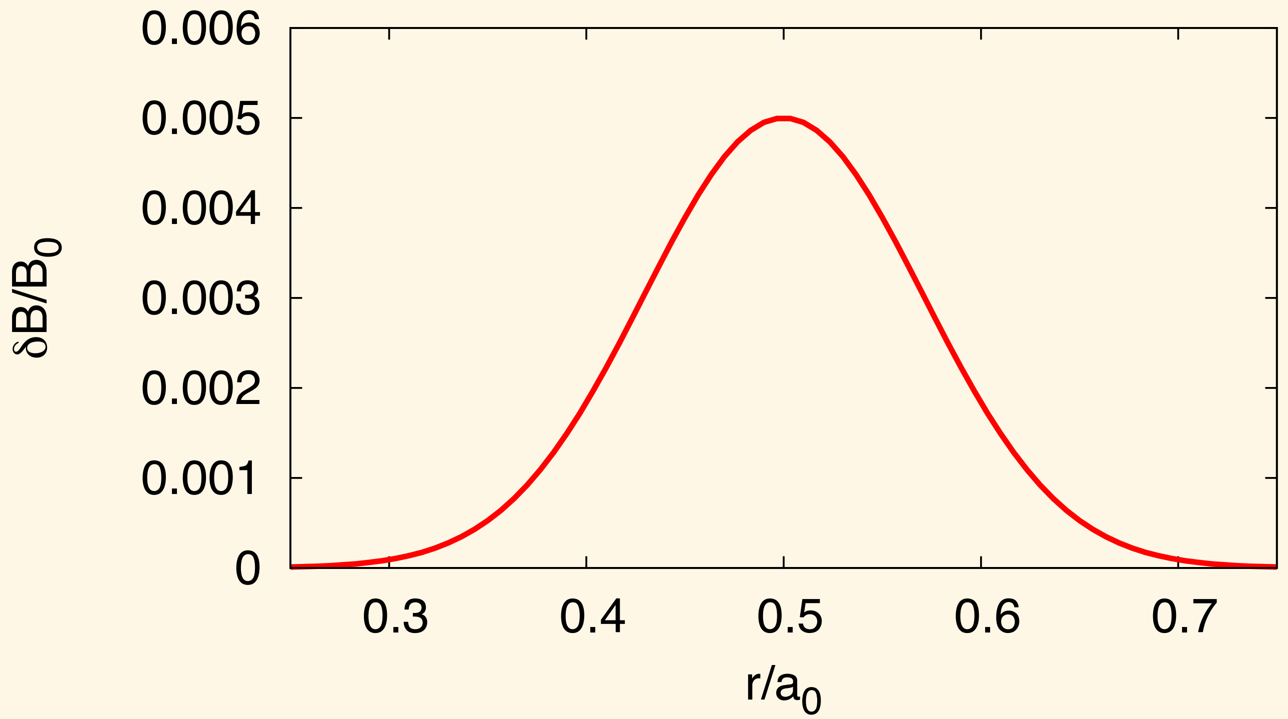
Basic parameters

- $B_0 = 1.91$ T
- $a_0 = 0.47$ m, and $R_0 = 2.35$ m
- $1/\rho^* = 150$
- $q = 0.854 + 2.184s^2$
- m=7, n=5 (resonant at s=0.5)
- $E_r = 0$ (fixed)
- $1/\nu$-regime
- $\delta_{mn} = 0.005$, $s_0 = 0.5$, $\Delta=0.1$

$$\frac{\delta B_{mn}(s)}{B_0} = \delta_{mn} \exp\left[-\left(\frac{s-s_0}{\Delta}\right)^2\right]$$

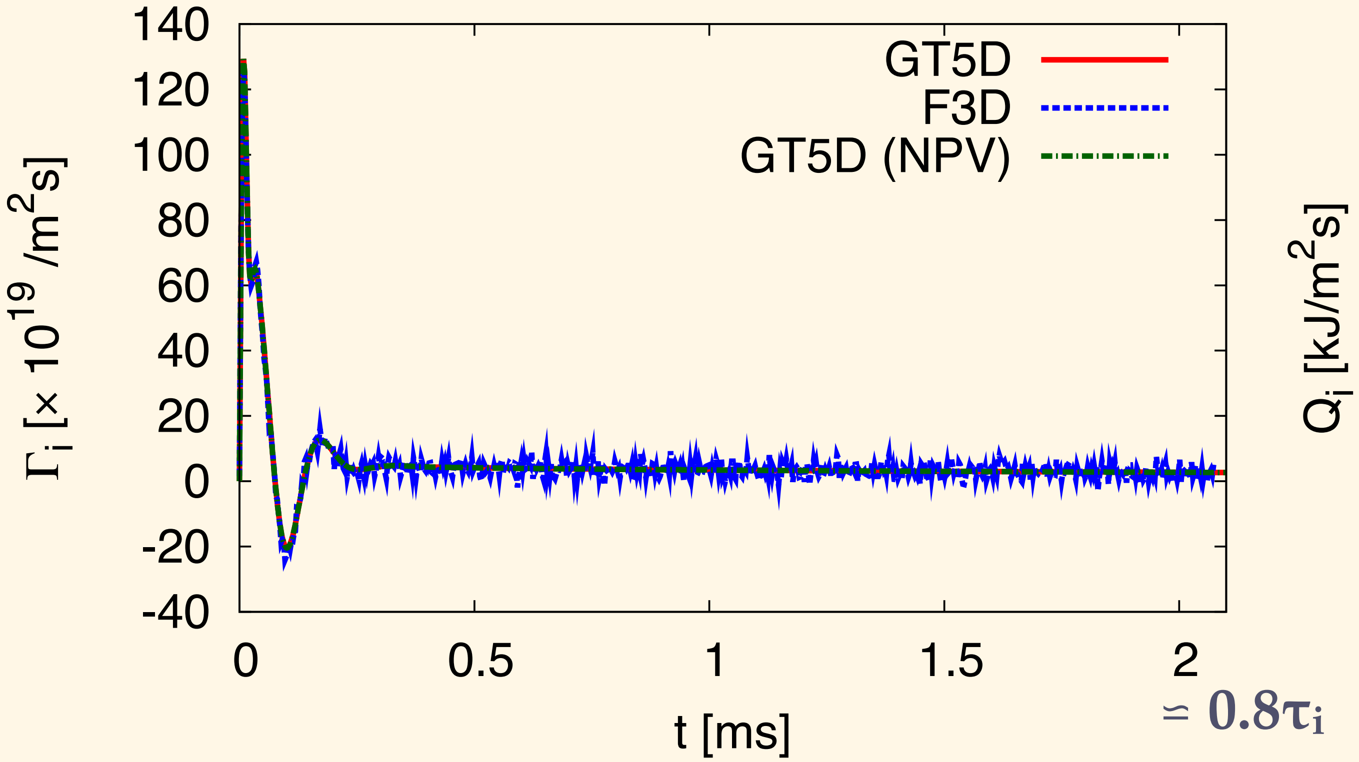


Radial profile of perturbation field

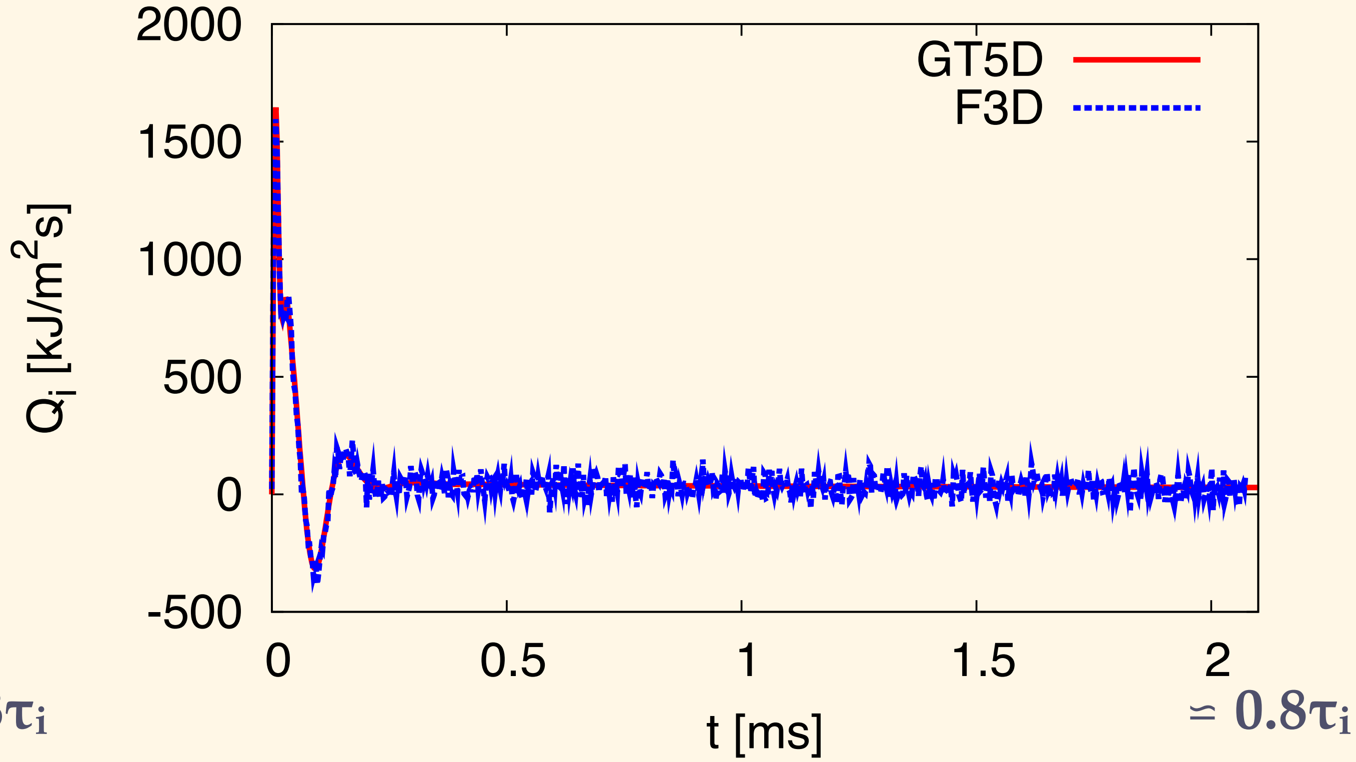


Benchmark w/o perturbation 1.

Particle flux @r/a_0 = 0.5



Energy flux @r/a_0 = 0.5

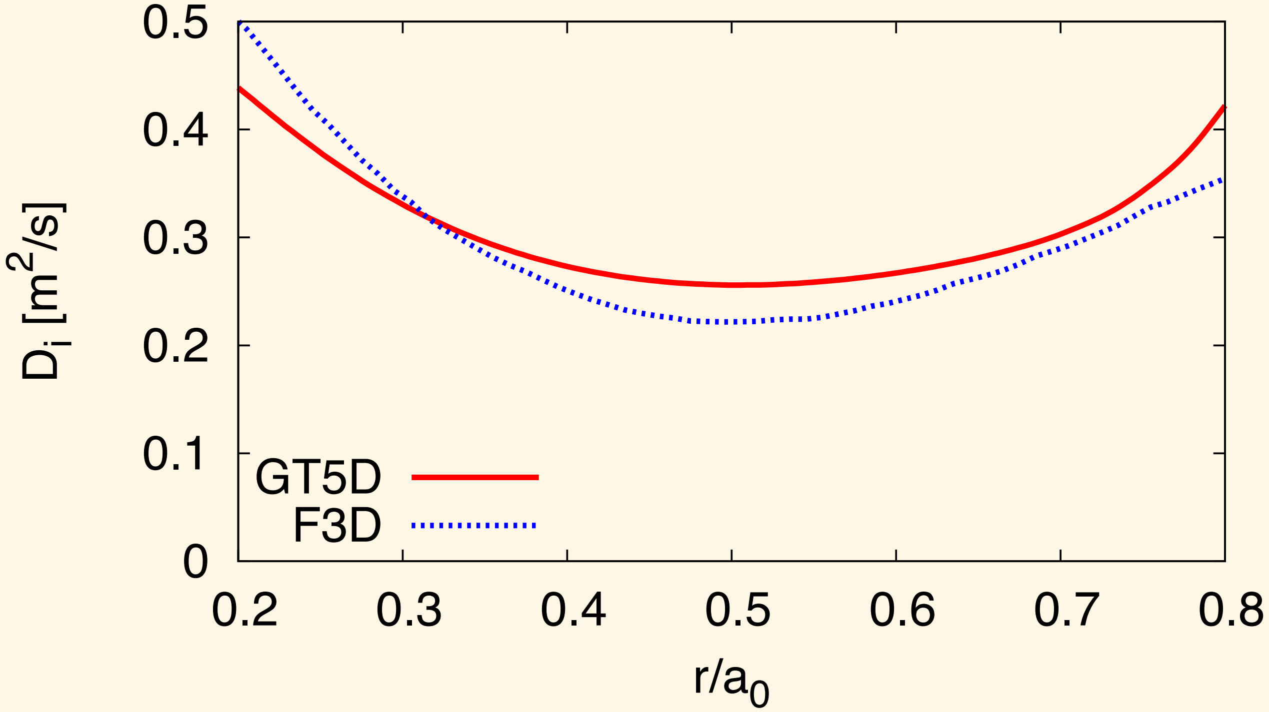


Time evolutions of the radial NC transport of GT5D and F3D well agree for axisymmetric case.

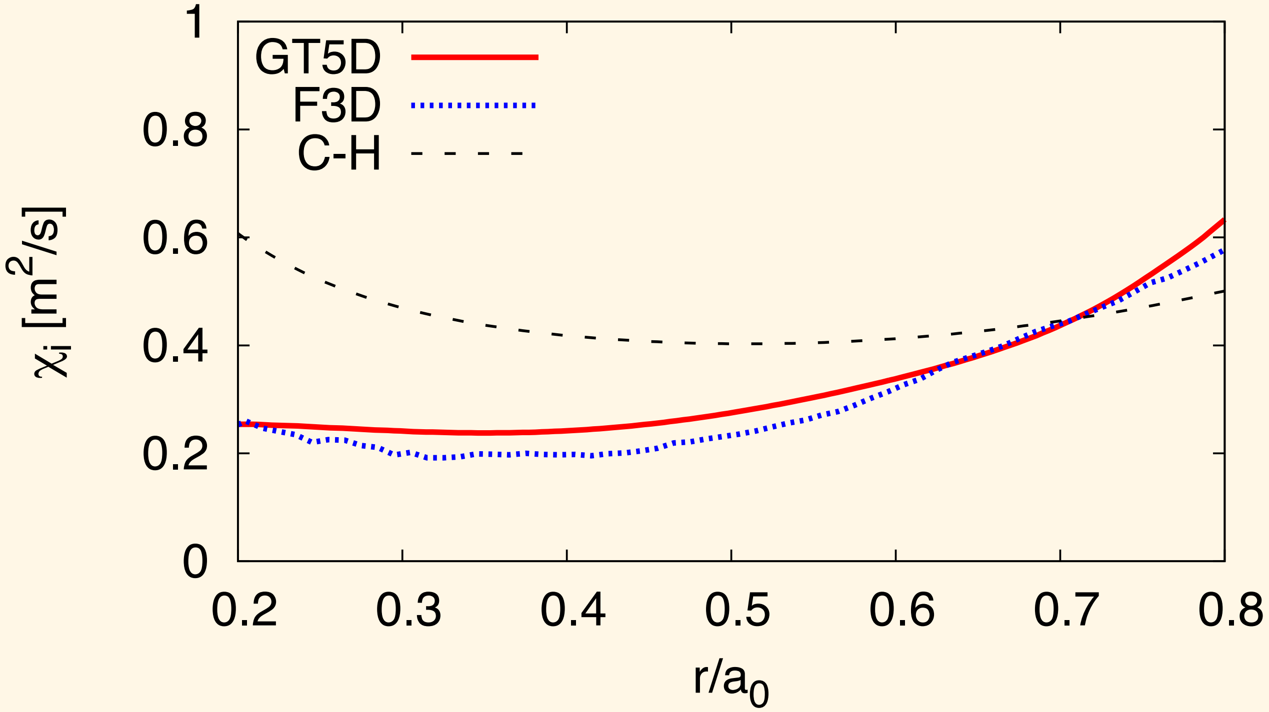
In addition, the particle flux evaluated from NPV also reproduces the radial particle flux of GT5D.

Benchmark w/o perturbation 2.

D_i



χ_i

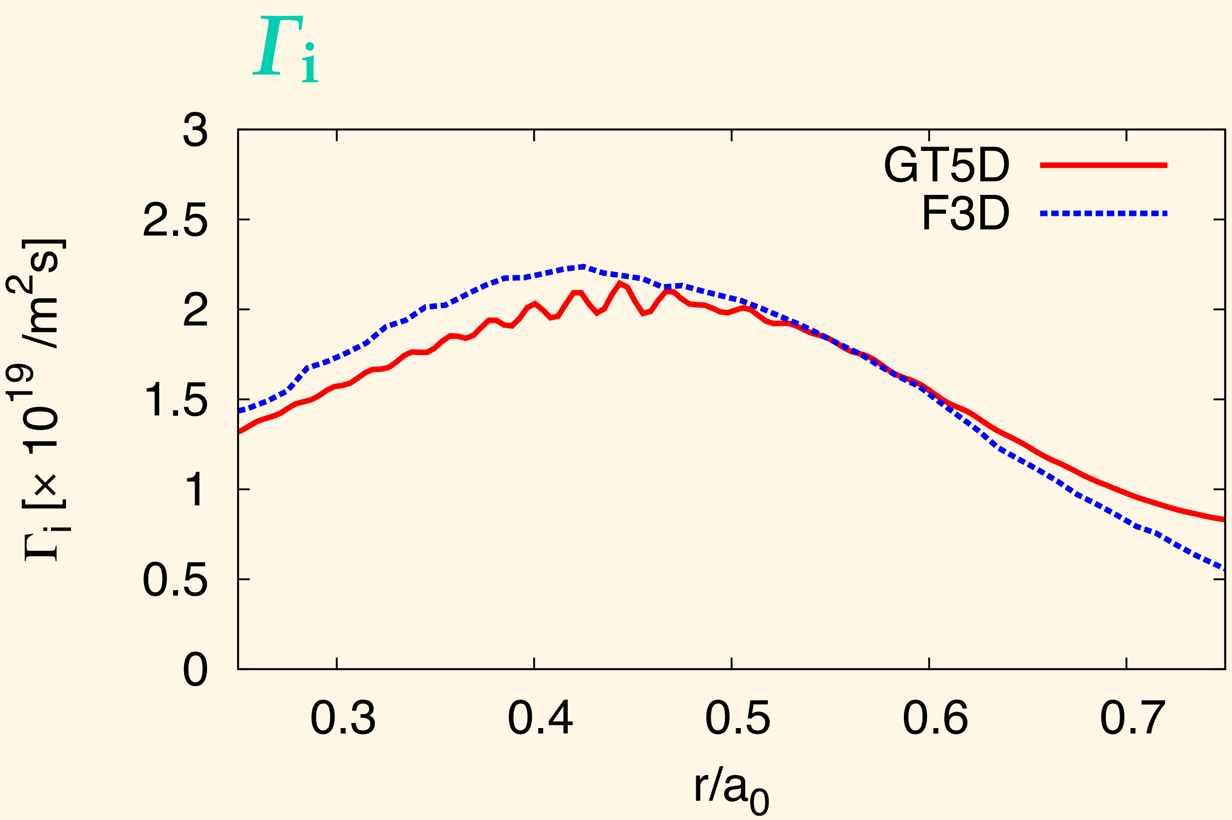


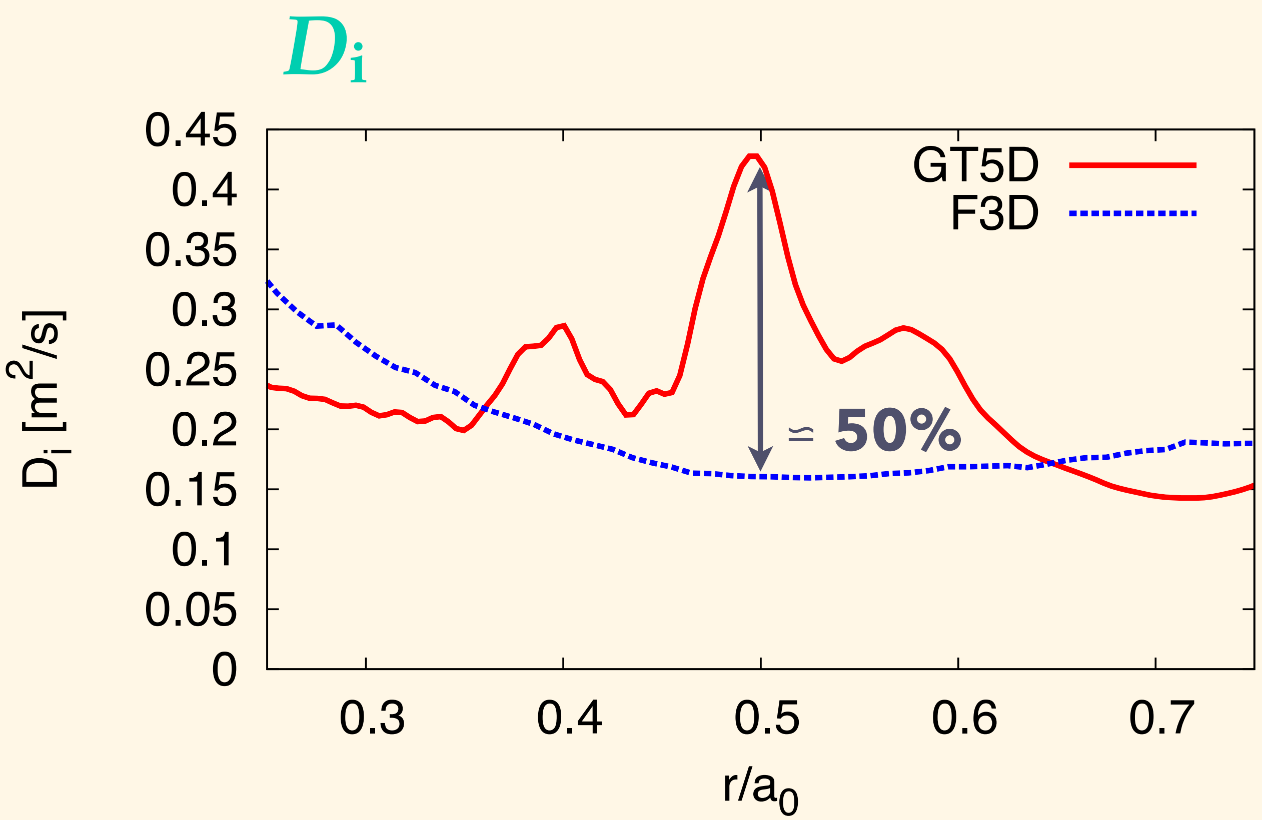
Time-average b/w t = 1.4 and 2.1 [ms]

→ quasi-steady state for the neoclassical radial transport.

For fixed E_r ($E_r = 0$),
good agreements for the particle/heat diffusivities
of F3D and GT5D are confirmed.

NC transport with δB : particle flux





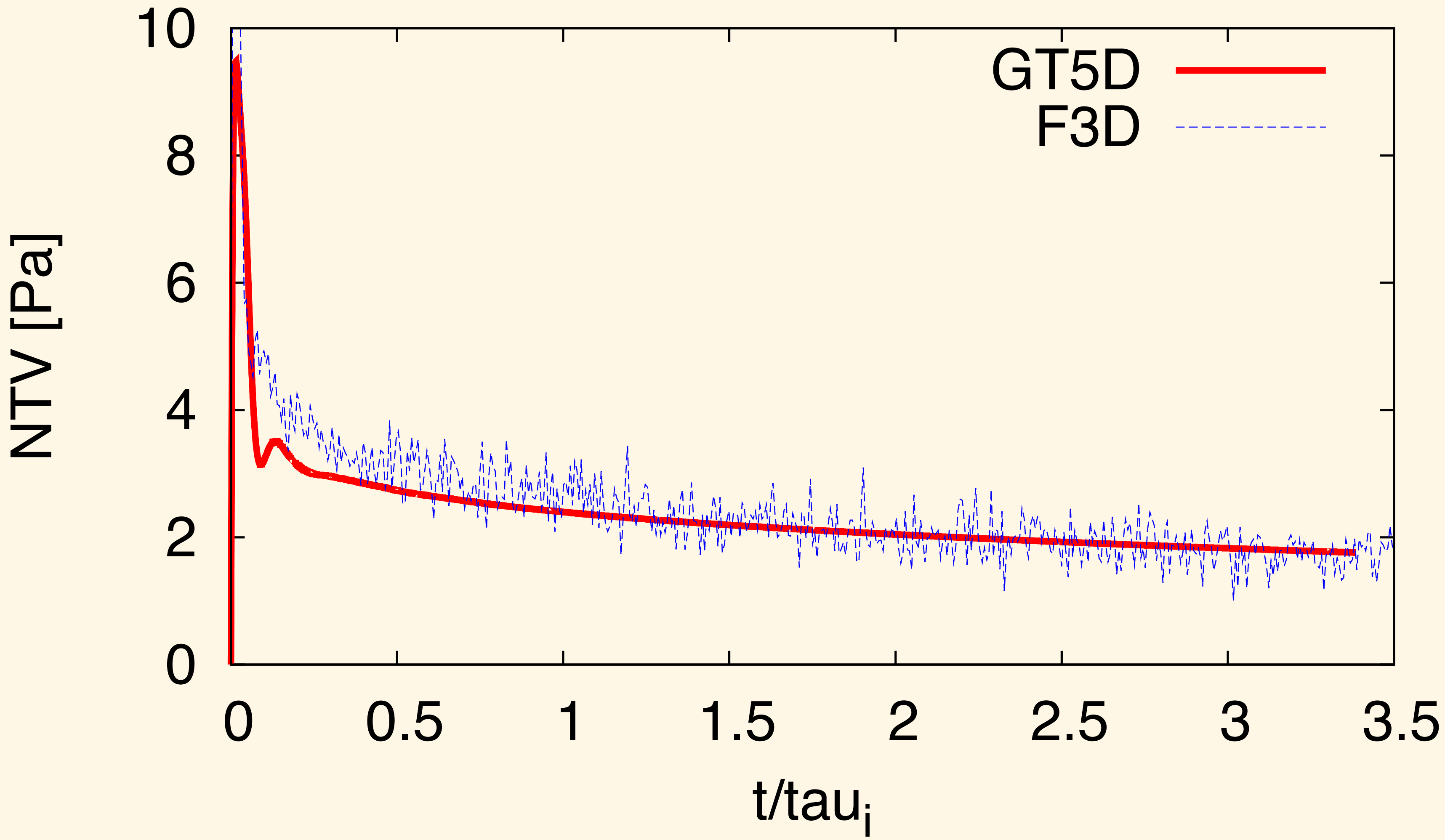
NC radial particle fluxes of GT5D show similar as FORTEC-3D.

The difference becomes larger in D_i.

This indicates that the profile change in GT5D affects the flux, especially around $r/a_0 \simeq 0.5$ (resonant for m/n = 7/5).

The initial n_i, T_i-profiles are varied by the large neoclassical transport driven by δB due to its full-f feature of GT5D.

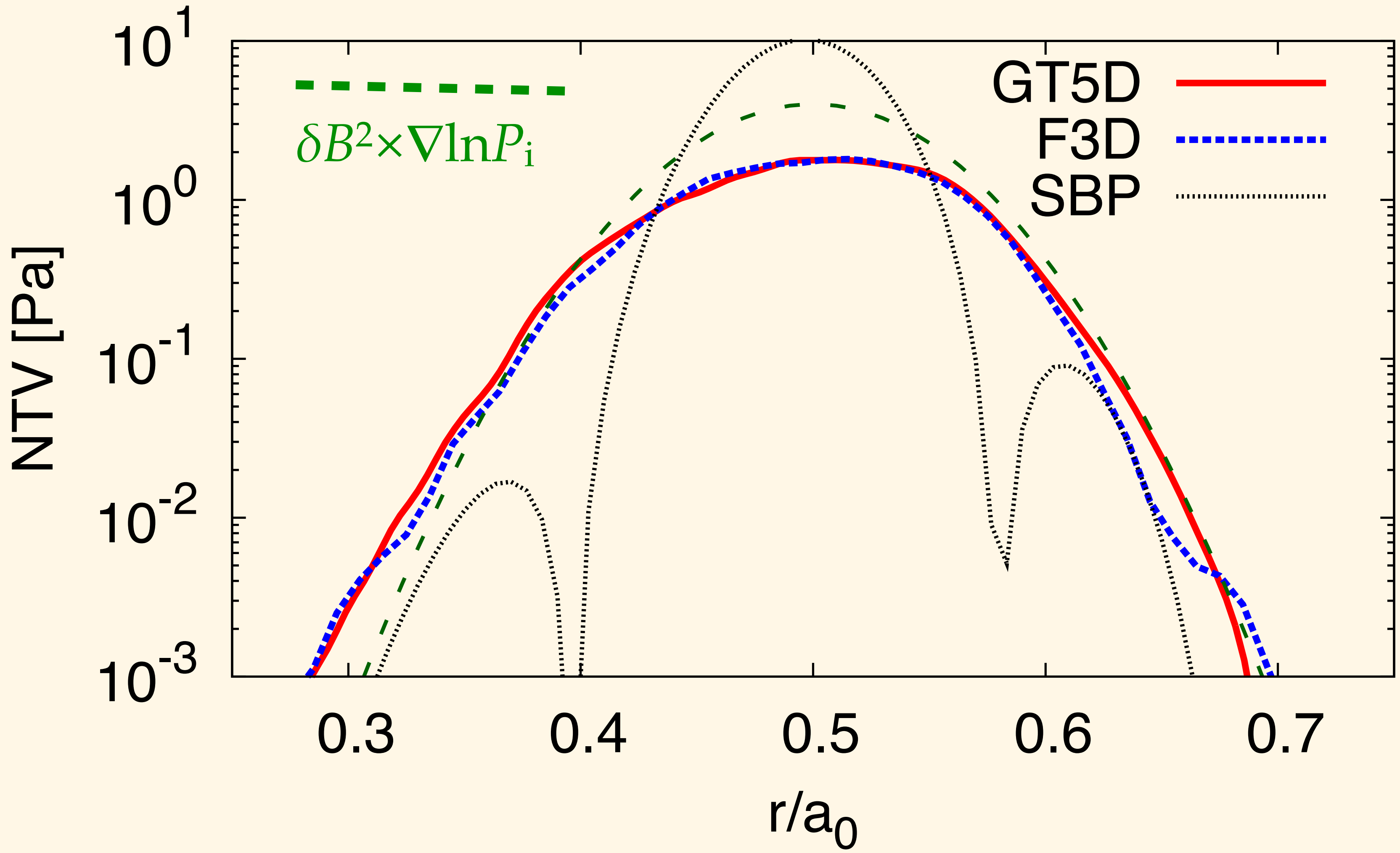
Time dev. of NTV driven by δB



$r/a_0 \simeq 0.5$
resonant surface of
$(m,n) = (7,5)$

NTV of GT5D driven by small δB reproduces that of FORTEC-3D except for the initial phase.

Radial profile of NTV driven by δB



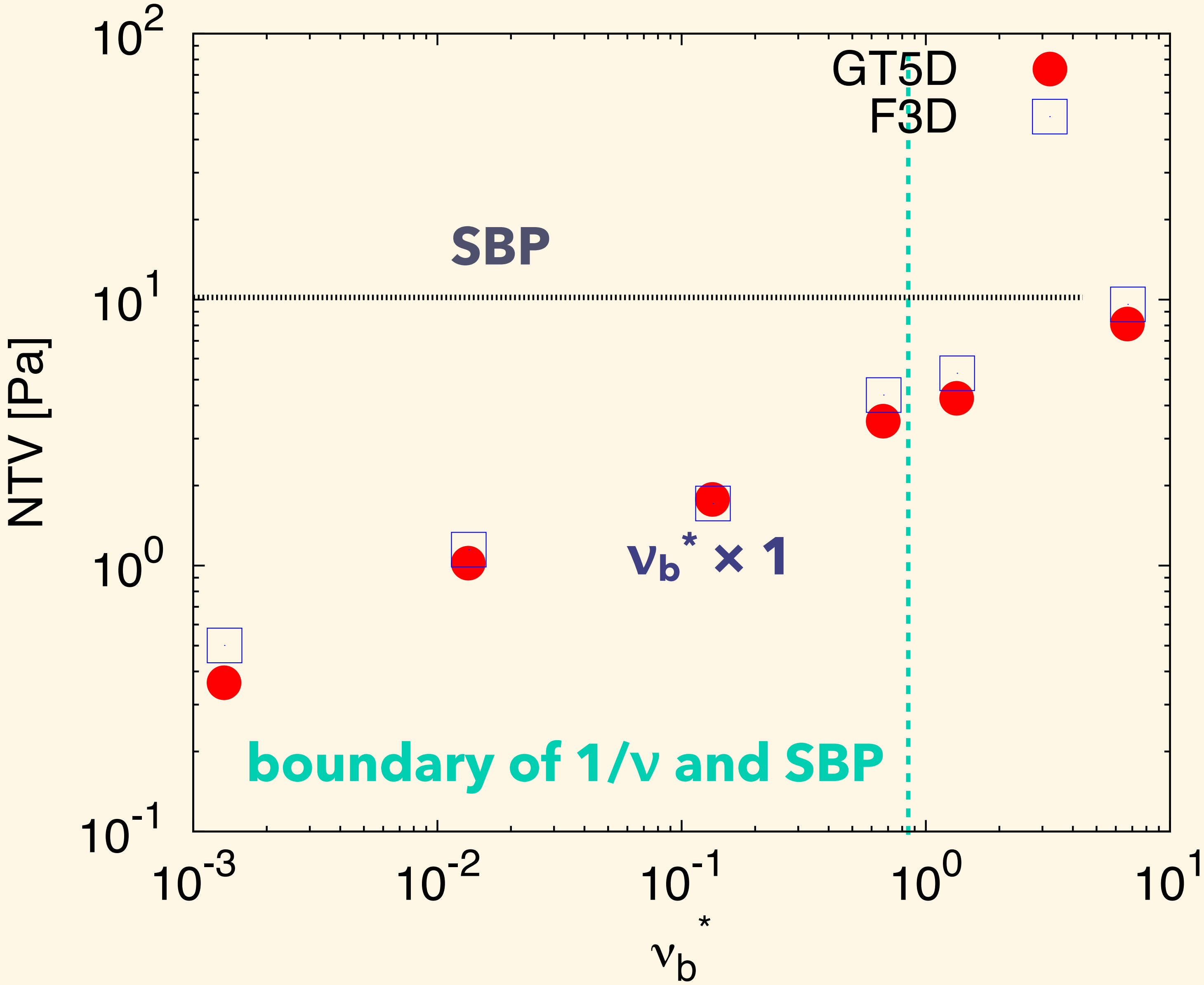
NTV shows the similar profile as $\delta B^2 \times \nabla \ln P_{\rm i}$.

NTV $\propto$ δB^2 approximately.

NTV of GT5D driven by small perturbation shows fairly a good agreement with F3D, and it also reproduces the same order of magnitude as the SB-P theory.

ν_b^* dependence of NTV

NTV @r/a_0=0.5 (resonant surface of m/n = 7/5)



ν_b^* range:
× 0.01, 0.1, 1, 5, 10, 50

The tendency at $\nu_b^* = 0.01$ - 10 is similar to what was already reported in Satake*.

Although NTV in both codes shows a good agreement to SB-P theory near the boundary ($\nu_b^* \simeq 1$), ν-dependence is different from the theory.
→ NTV decreases towards low collisionality.

*Satake, *et al.*, PRL **107**, 055001 (2011), Satake, *et al.*, PPCF **53**, 054018 (2011)

Summary

- **Numerical simulations for NTV caused by a perturbative field are successfully performed using the full-f gyrokinetic code, GT5D.**
- **As a benchmark, NTV of GT5D well reproduces that of FORTEC-3D.**
  - Although δB is treated differently in GT5D from FORTEC-3D, it does not affect the steady-state NTV so much.
- **ν*-dependence of NTV is investigated.**
  - NTV of both codes well agrees to the SB-P value at $\nu_b^* \fallingdotseq 1$.
  - NTV decreases towards low-ν; different from SB-P theory.
  - Shaing's resonant behavior is observed, but it quickly dissipates.

Future works

- **Finite E_r case**
- **Comparison with connected NTV formula.**
- **Benchmark with fixed steady-state profiles should be performed.**