Validation studies on local gyrokinetic simulations of tokamak ITG-TEM driven turbulent transport

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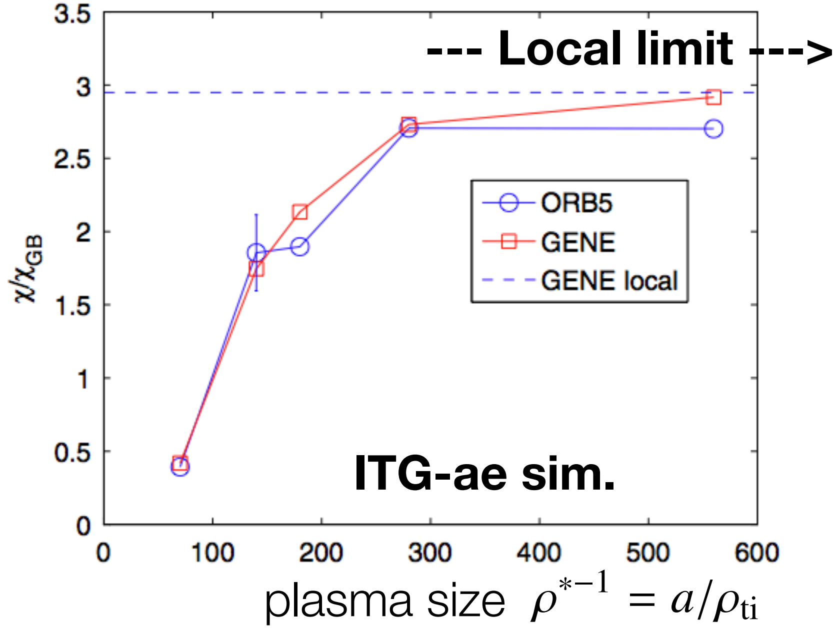
Motivations: Local GK sim. approach for future devices

- First principle based gyrokinetic simulation is a promising method to predict transport properties in future devices, such as ITER and DEMO.

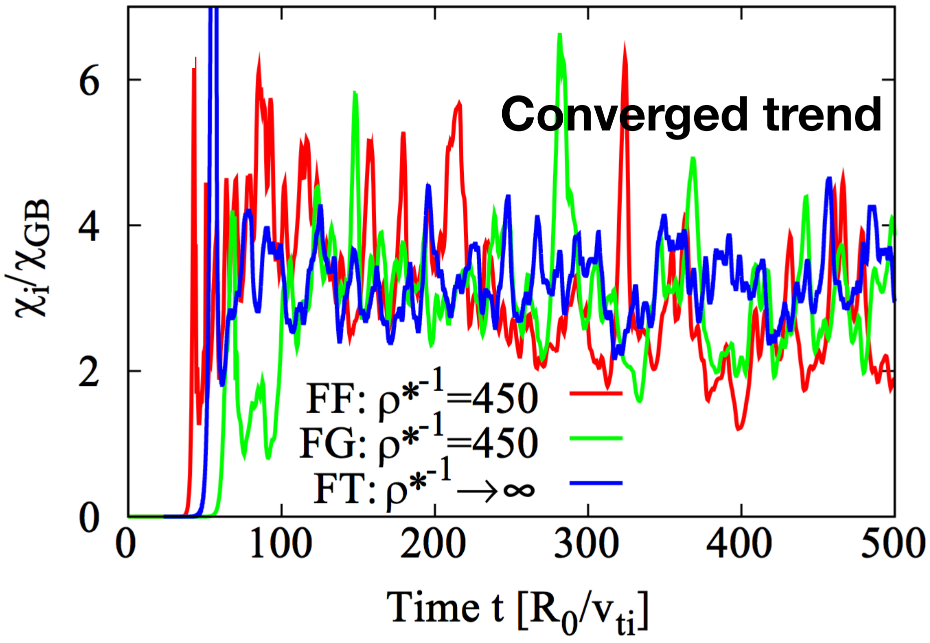
Size scaling of turbulent transport
McMillan PRL2010



--- Local limit --->

ITG-ae sim.

Local(FT) vs. Global(FG/FF) on χ_i/χ_{GB}
Nakata NF2013



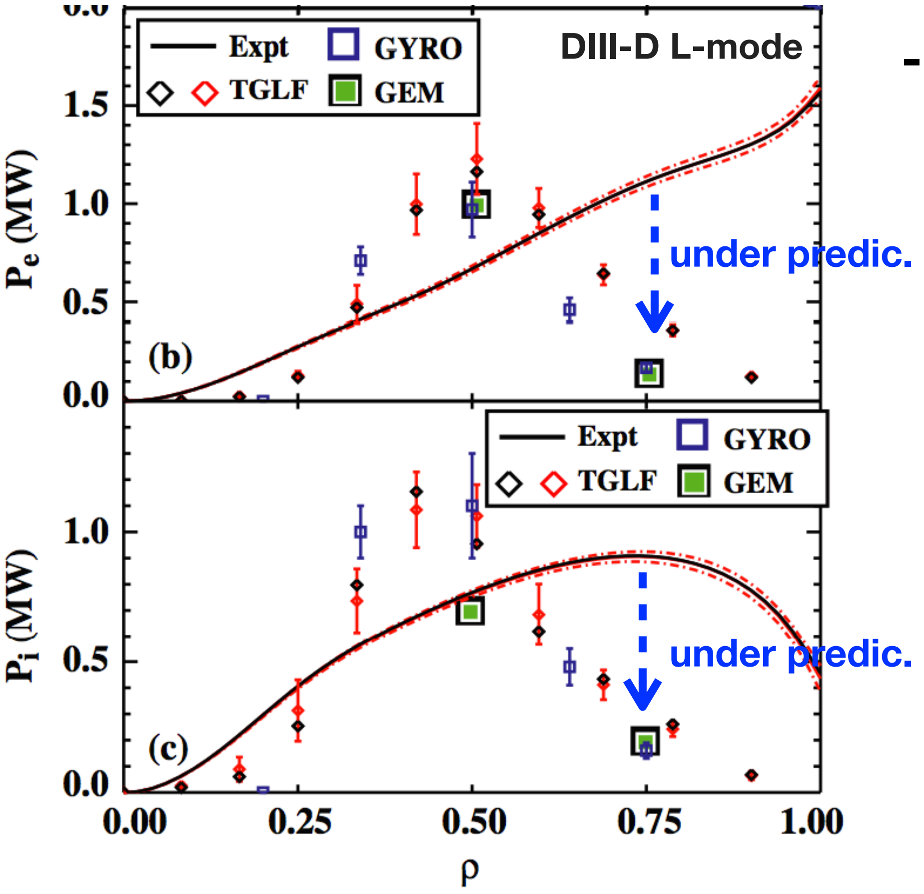
Converged trend

---> ITG-ae global simulation results are well converged to local ones, and suggest that "Local" simulation approach is well applicable for sufficiently large plasmas with $\rho^{*-1} > 300$.

Lin PRL2002, Candy, PoP2004, McMillan PRL2010, Nakata NF2013

Motivations: Validations on ITG-TEM turb. beyond ITG-ae

GK/GF validations on DIII-D Exp.
Rhodes NF2011



- Validation studies on ITG/TEM turb. with kinetic electrons are indispensable for realistic tokamaks.

- Transport shortfall (for outer core) is often reported:

Rhodes NF2011, Told PoP2013

---> Under-predicted transport levels even with "numerically converged" codes

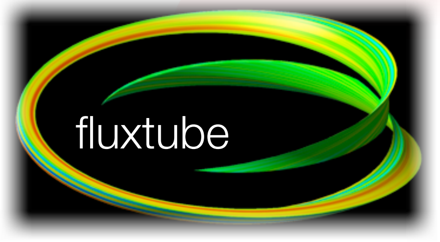
---> Device dependent: DIII-D, C-Mod, AUG, etc

---> Sometimes sensitive against experimental error-bars

---> Prediction capability for tokamak ITG-TEM driven transport on the developed GK-codes should be carefully examined against existing experiments.

In this study, the first validation studies on JT-60U tokamak are carried out, and ITG/ITG-TEM/TEM turbulent transport properties are investigated.

Multi-species electro-magnetic turbulence code: GKV



- A local fluxtube 5D gyrokinetic simulation code

---> δf-model: fixed-background

---> Eulerian (Continuum) solver: spectral in 2D (kx,ky)-space, Finite-Difference in 3D (z, $v_{\|}$, μ)-space

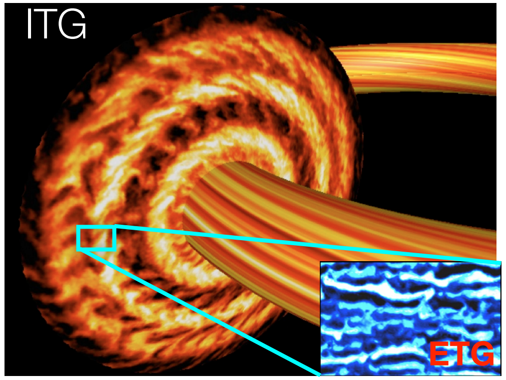
---> Powerful computational performance on PETA-scale system

---> Electro-static, Electro-magnetic fluctuations

---> Multi-species(MS) with kinetic electrons incl. MS-collisions

---> Realistic geometries for Tokamak and Helical systems

---> Entropy balance/transfer diagnostics



[e.g., Watanabe NF2006(original), Watanabe PRL2008, Nunami PFR2011, Nakata PoP2012, Maeyama CPC2013, Maeyama PoP2014, Nakata PFR2014, Ishizawa PoP2014, etc.]

- Multi-species(MS) GK model including kinetic electrons and MS-collisions:

Nakata and Nunami et al, 2014

$$\left(\frac{\partial}{\partial t} + v_{\|}\boldsymbol{b}\cdot\nabla + i\omega_{\mathrm{Da}} - \frac{\mu\boldsymbol{b}\cdot\nabla B}{m_{\mathrm{a}}}\frac{\partial}{\partial v_{\|}}\right)\delta h_{\mathrm{a}\boldsymbol{k}_\perp} - \frac{c}{B}\sum_{\Delta}\boldsymbol{b}\cdot(\boldsymbol{k}'_\perp\times\boldsymbol{k}''_\perp)\,\delta\psi_{\mathrm{a}\boldsymbol{k}'_\perp}\delta h_{\mathrm{a}\boldsymbol{k}''_\perp}$$

$$= \frac{e_{\mathrm{a}}F_{\mathrm{Ma}}}{T_{\mathrm{a}}}\left(\frac{\partial\delta\psi_{\mathrm{a}\boldsymbol{k}_\perp}}{\partial t} + i\omega_{*T\mathrm{a}}\delta\psi_{\mathrm{a}\boldsymbol{k}_\perp} + v_{\|}\frac{\mu\boldsymbol{b}\cdot\nabla B}{T_{\mathrm{a}}}J_0\delta\phi_{\mathrm{a}\boldsymbol{k}_\perp}\right) + \sum_{\mathrm{b}}\oint\frac{d\varphi}{2\pi}e^{i\boldsymbol{k}_\perp\cdot\boldsymbol{\rho}_{\mathrm{a}}}\left\{C^{\mathrm{TS}}_{\mathrm{ab}}[e^{-i\boldsymbol{k}_\perp\cdot\boldsymbol{\rho}_{\mathrm{a}}}\delta h_{\mathrm{ak}_\perp}] + C^{\mathrm{F}}_{\mathrm{ab}}[e^{-i\boldsymbol{k}_\perp\cdot\boldsymbol{\rho}_{\mathrm{b}}}\delta h_{\mathrm{bk}_\perp}]\right\}$$

Extension for realistic tokamak MHD equilibria

- GKV is connected to MHD/Integrated-transport solvers thorough a newly developed interface IGS.

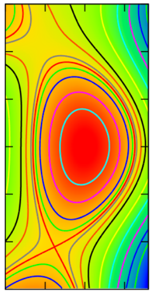
M. Nakata and A. Matsuyama et al., PFR2014

MEUDAS (EQDSK form)

Free-boundary G-S solver

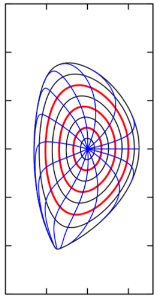
TOPICS (EQDSK form)

Integrated transport solver



$\Psi(R,Z), P(\Psi), I(\Psi)$

IGS (interface)

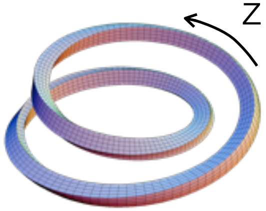


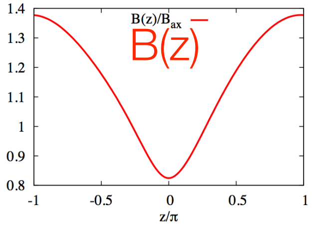
Flux coordinate Interface

Interpolation, tracing flux surfaces

Constructing Axisymmetric, Hamada, and Boozer coordinates

$g^{ij}(z), \mathcal{J}(z), B(z)$





GKV

Local fluxtube code

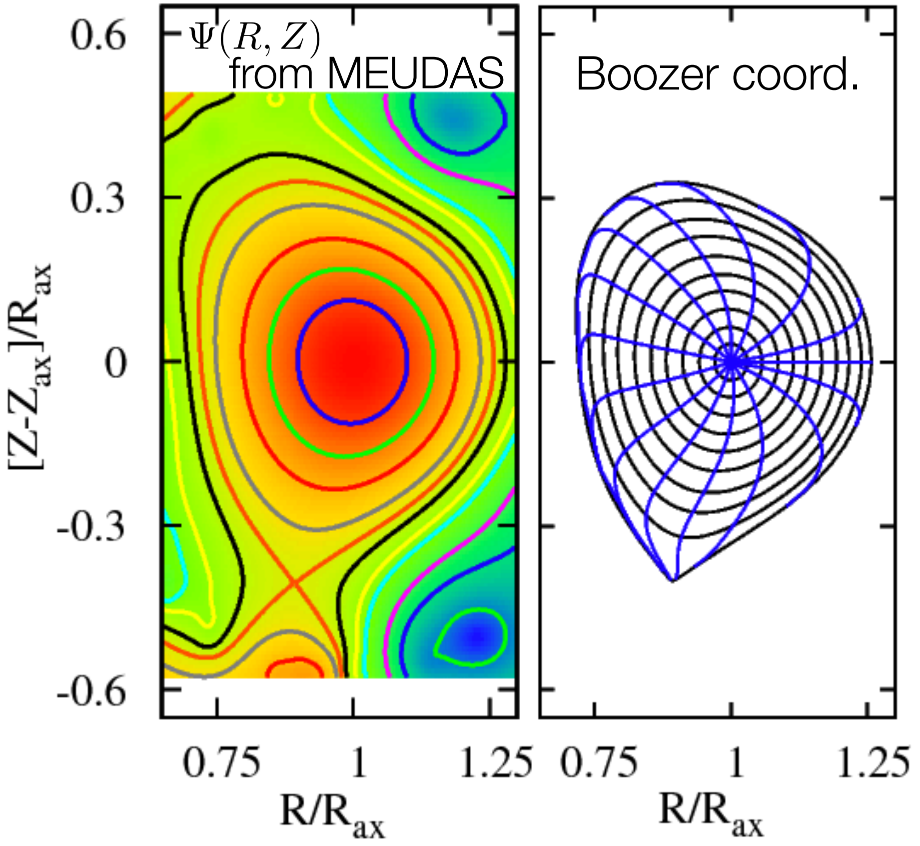
Calculating metric components and advection operators

Turbulence simulation

---> GKV-TOPICS/MEUDAS cooperative study enables the detailed experimental analyses and optimizations on micro-stability/turbulence.

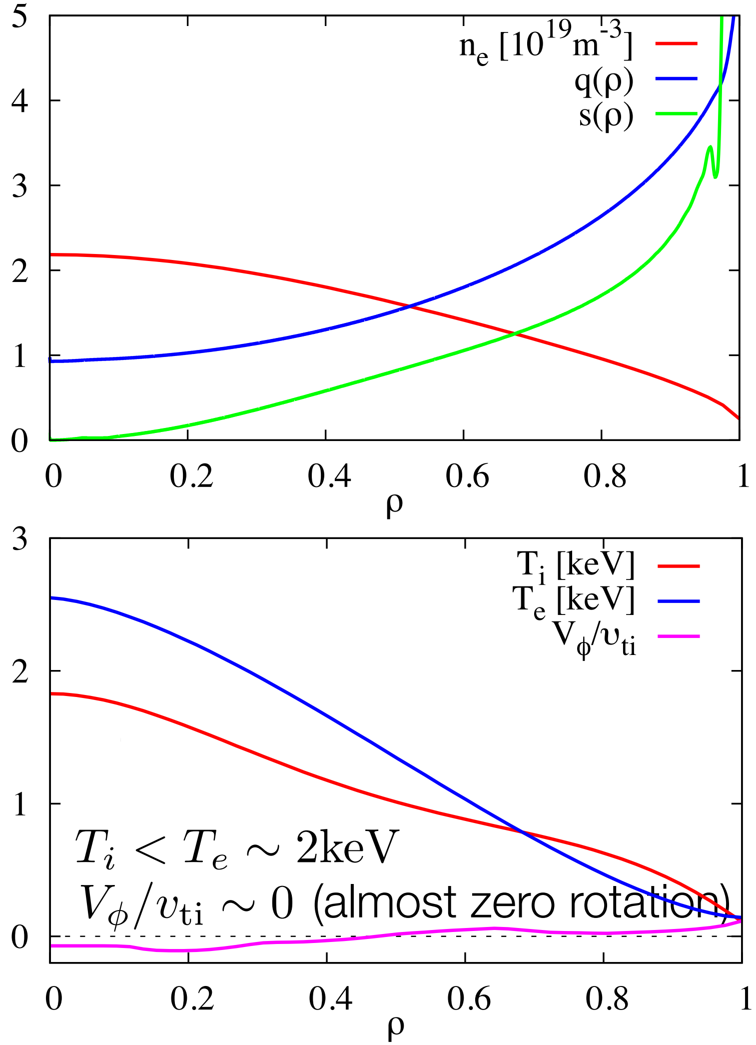
L-mode plasma on JT-60U investigated

JT-60U L-mode plasma: E45072T1010 [Yoshida, PPCF2006]



$$R_{\rm ax} = 3.37{\rm m},\ a = 1.02{\rm m},\ V = 66.8{\rm m}^3,$$
$$B_{\rm ax} = 2.67{\rm T},\ q_{\rm ax} = 0.55,\ q_{95} = 4.04,$$
$$\beta_{\rm iax} = 0.23\%,\ I_{\rm p} = 1.20{\rm MA},\ P_{\rm NB} = 2{\rm MW}$$

Plasma profiles



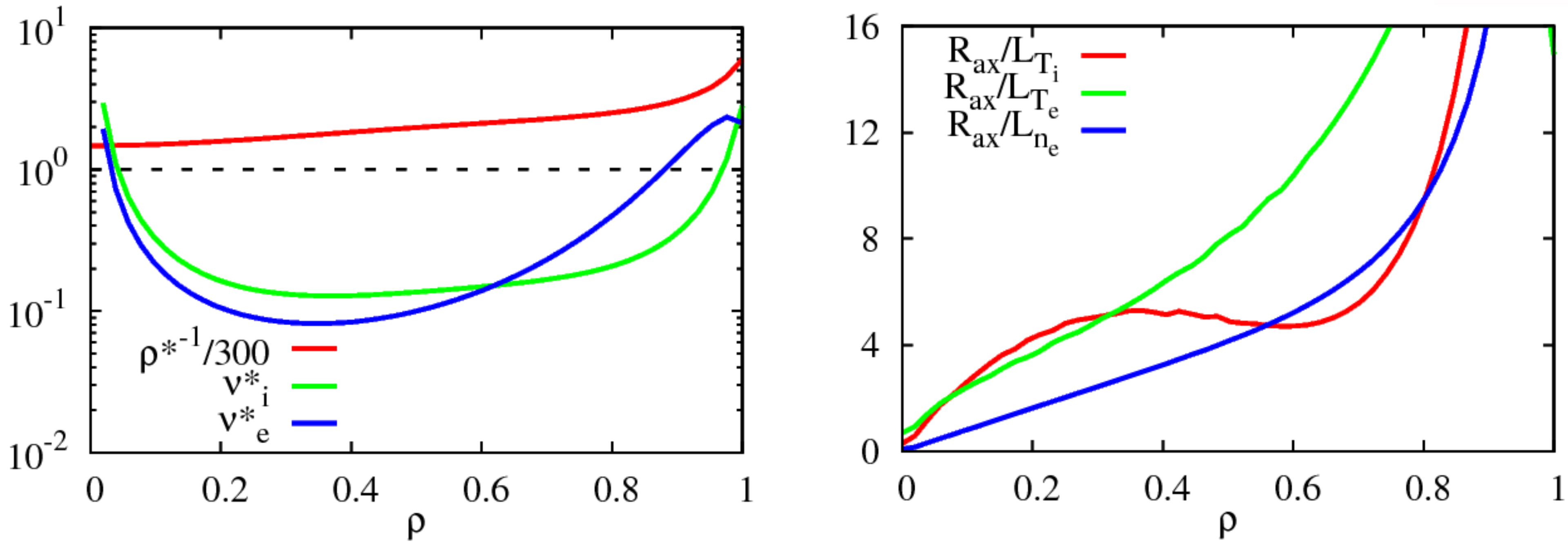
$T_i < T_e \sim 2$keV

$V_\phi/v_{\rm ti} \sim 0$ (almost zero rotation)

Transport relevant profiles and parameters

Normalized plasma size and collisionality

Density and temperature gradients



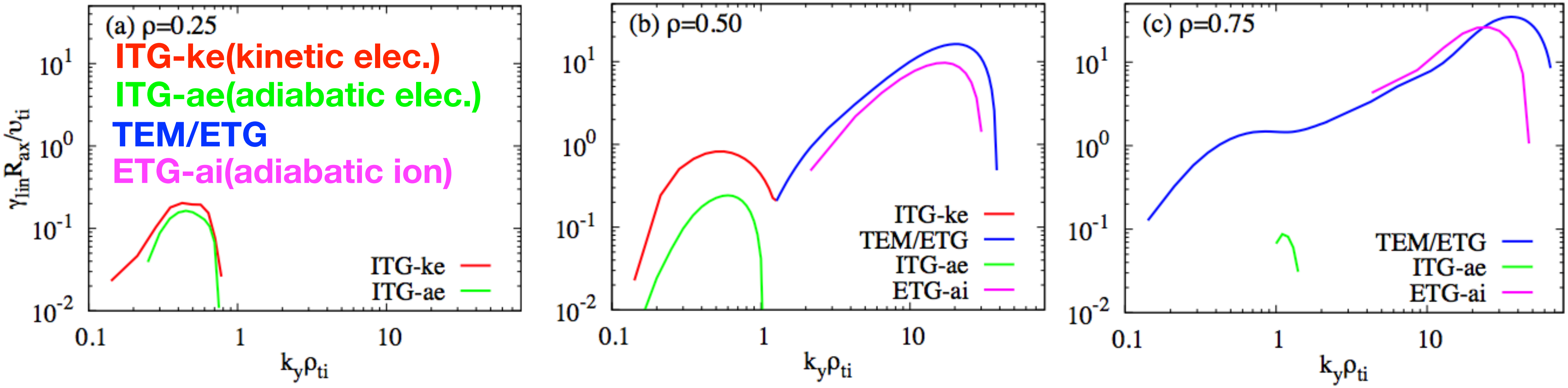
- **sufficiently large normalized plasma size ρ^{*-1} :** $1/\rho^* = a/\rho_{\mathrm{ti}} \sim 500$
- **moderate collisionality(still banana-plateau) :** $\nu^*_{\mathrm{i/e}} \sim 0.1$
- **weak mean Er-shear :** $\gamma_{Er} \sim 0.1 R_{ax}/v_{ti} < \gamma_{lin}$

---> Target discharge is carefully chosen such that “Local limit condition” is well satisfied for the (L-mode) plasma investigated here.

Linear micro-stability analyses

- **GKV results on linear micro-stabilities at ρ=0.25, 0.50, 0.75**

JT-60U L-mode D-plasma: E45072T1010



ρ=0.25: ITG (TEM&ETG stable) **ρ=0.50: ITG-TEM (-ETG)** **ρ=0.75: TEM (-ETG)**

(weak impact of kinetic(trapped) elec.) (strong impact of kinetic elec.)

---> Different mode-structures depending on radial positions: ITG --> ITG-TEM --> TEM

---> Adiabatic electron approximation is valid only for the inner core region.

---> Quasilinear flux ($\propto \gamma/k^2$) increases towards outer region.

Nonlinear turbulence simulations

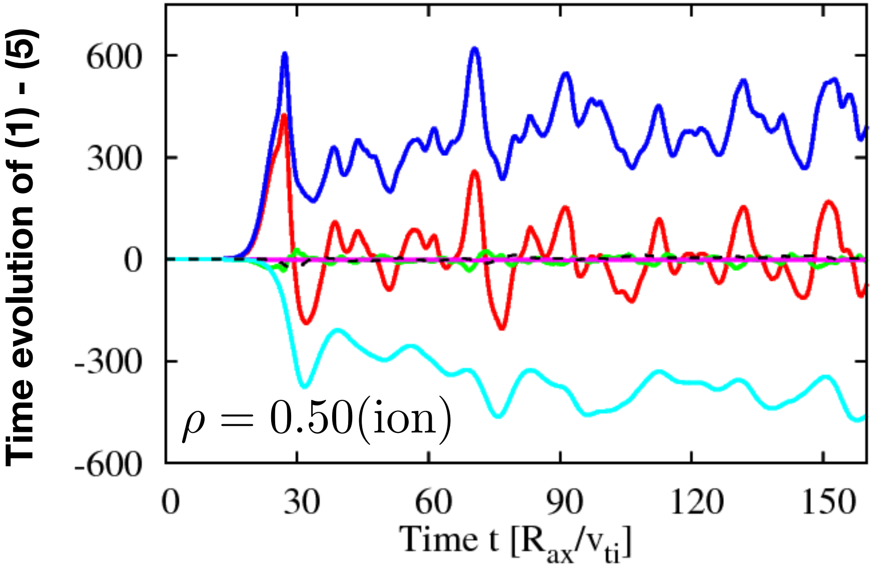
- Numerical resolution for Deuterium-electron system (No-impurities here)

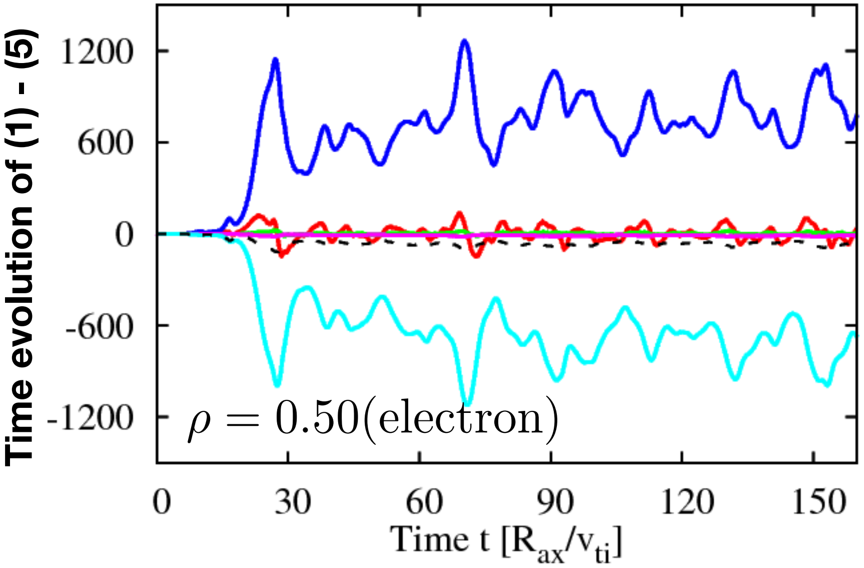
($168k_x$, $32k_y$, 64z, 64v, 32m)-grids, $0.07<k_y\rho_{ti}<2.2$, $0.09<k_x\rho_{ti}<7.90$, $\Delta t = 6.5\times10^{-4}\ R_{ax}/v_{ti}$

- Entropy balance/transfer relations are accurately satisfied in nonlinear simulations:

$$\underline{\frac{d}{dt}\delta S_{\rm s}} + \underline{R_{\rm s}} = \underline{\sum_k J^{\rm es}_{k{\rm s}} X_{k{\rm s}}} + \underline{\sum_k J^{\rm em}_{k{\rm s}} X_{k{\rm s}}} + \underline{D_{\rm s}}, \quad {\rm s}=({\rm i},{\rm e}), \quad k=(n,\,T)$$

(1)entropy variation **(2)field-particle interaction** **(3)electro-static fluxes** **(4)electro-magnetic fluxes** **(5)collisional dissipation**





---> Kinetic turbulent dynamics for both ion and electron is accurately resolved:

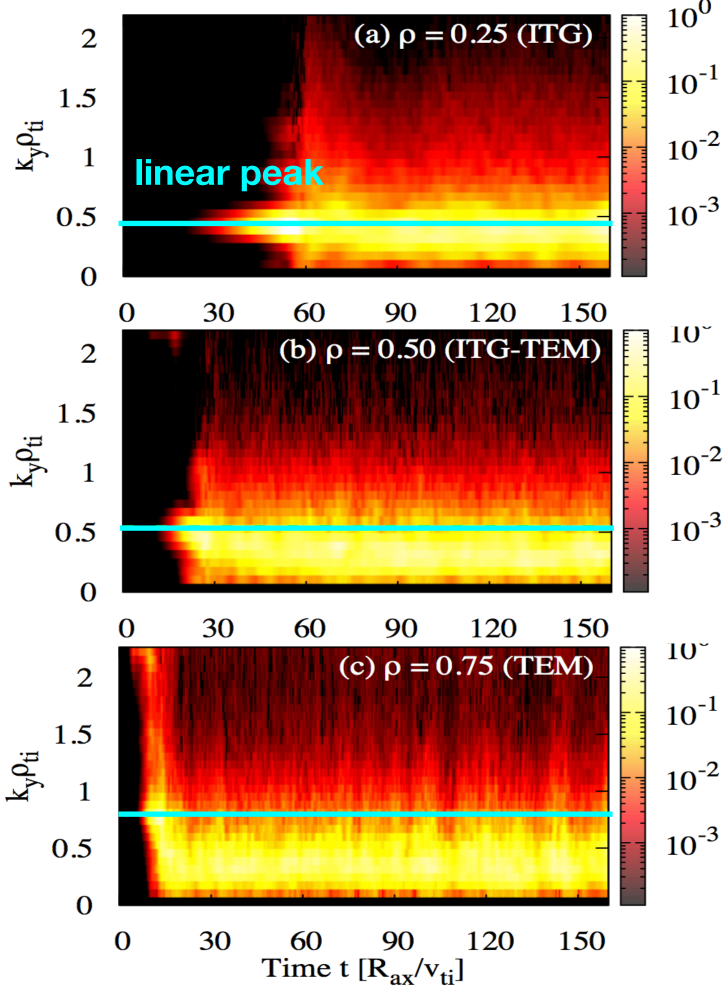
Relative error $|\Delta_i/D_i| <$ ~1% for ions, $|\Delta_e/D_e| <$ ~6% for electrons

---> Not only transport levels, detailed nonlinear interactions among turbulent vortices and zonal flows(ZF) can be quantified.

ITG-TEM simulations and its comparisons with EXP.

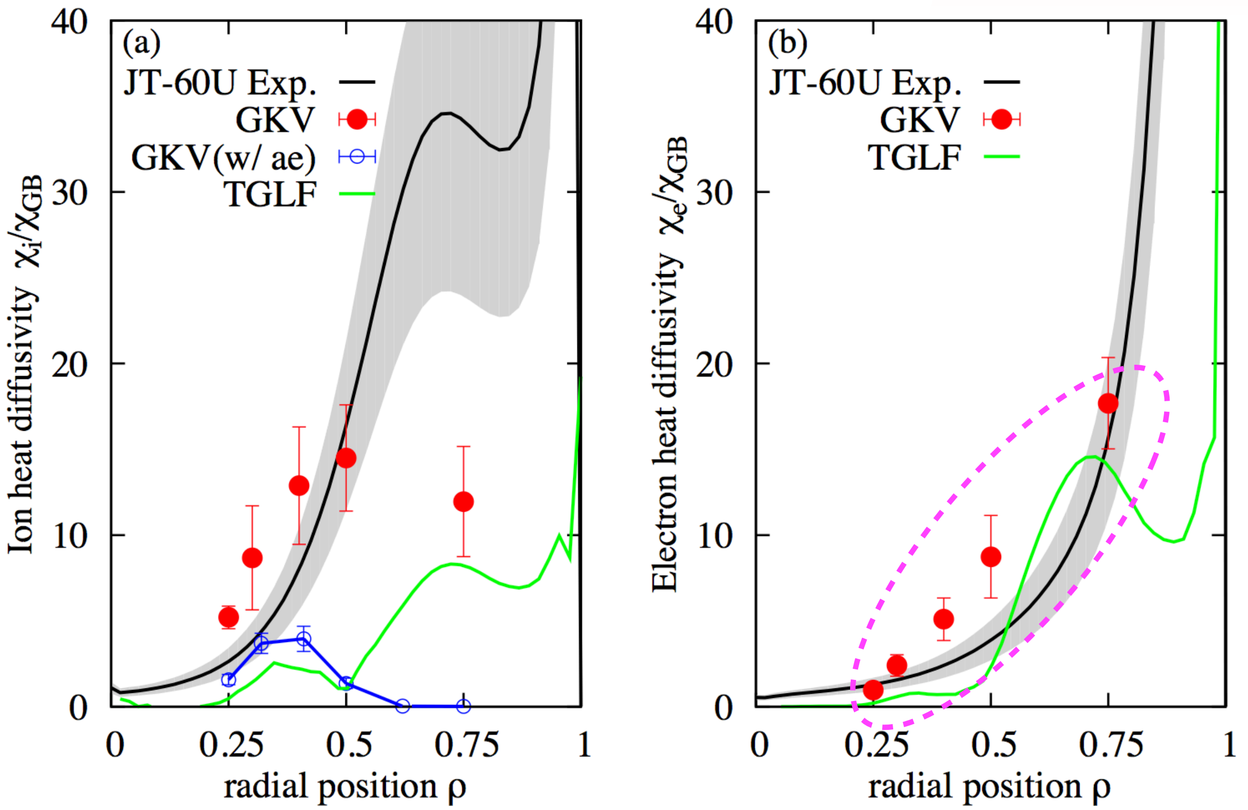
JT-60U L-mode D-plasma: E45072T1010

- Spectral-temporal evolution of ion heat flux



---> Low-k (<1) modes dominates turbulent fluxes.

- Comparisons of ion & electron heat diffusivity



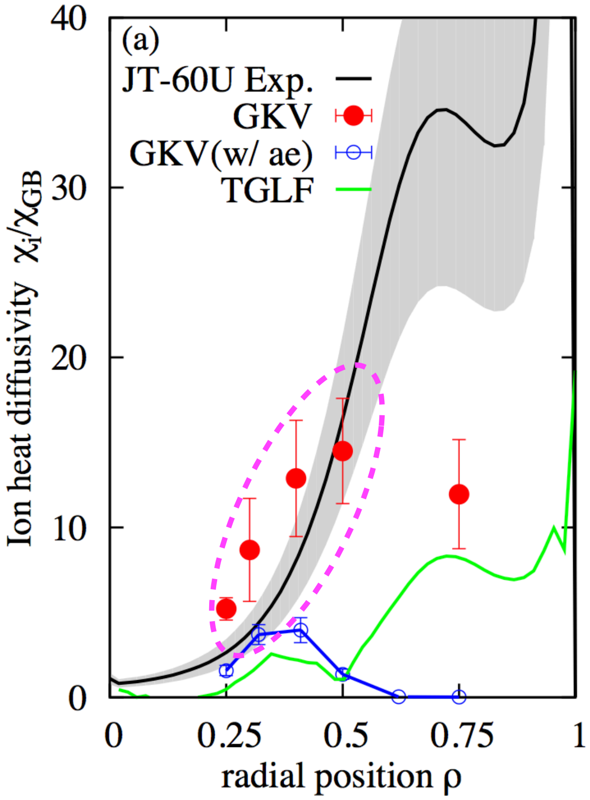
---> GKV with kinetic elec. shows good agreement with EXP. in core region (ρ<~0.5), while TGLF does only qualitatively.

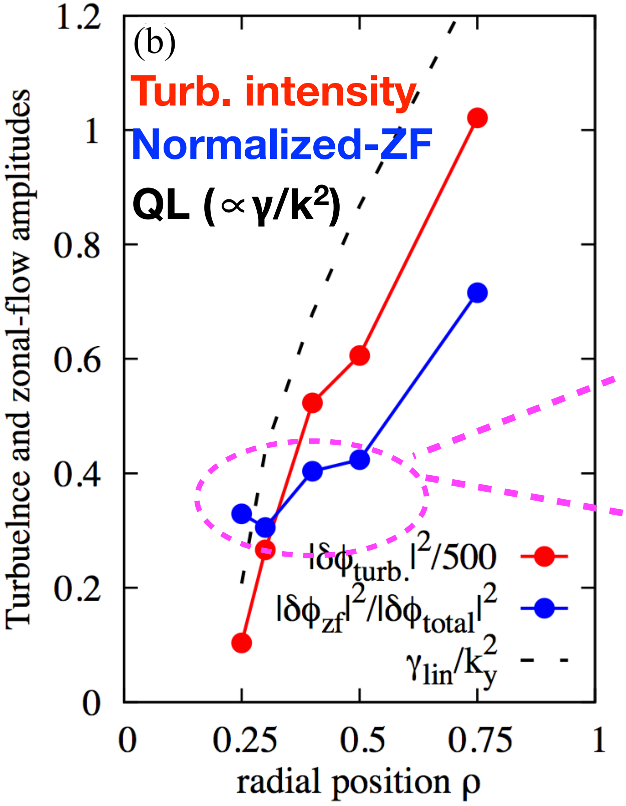
---> "Transport shortfall" appears in χ_i in the outer region (ρ~0.75).

Turbulence intensity and ZF-generations in core region

JT-60U L-mode D-plasma: E45072T1010

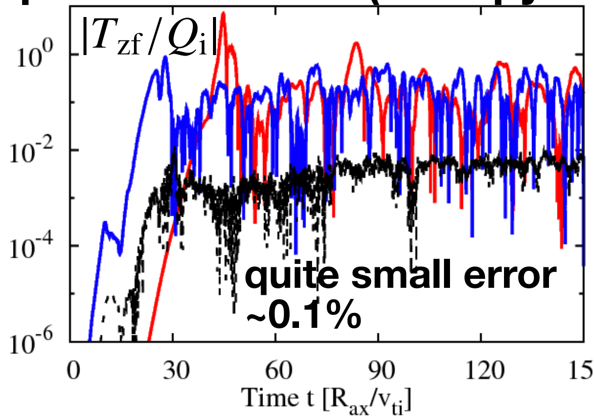
- Radial profile of mean turb. intensity and normalized-ZF.





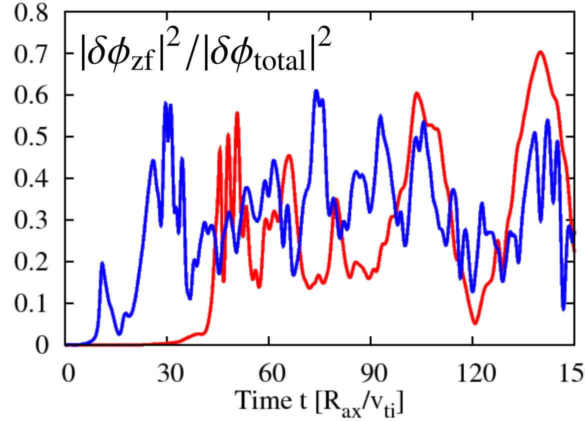
ρ=0.30(ITG) **ρ=0.50(ITG-TEM)**

ZF production rate (entropy transfer)



quite small error ~0.1%

Normalized ZF-amplitude



---> ZF production rate and amplitude are similar in the core region of ITG/ITG-TEM: (ITG-comp. is dominant.)

---> Stronger ZF generation for outer region, while Turb.-intensity ∝ γ/k^2. (discussed later)

Different impact of zonal flows on each transport channel

- To identify the ZF-dependence on multiple transport channels is useful for deeper understanding of transport processes.

cf. Nunami et al, PoP2013

---> We apply a nonlinear functional technique for core ITG-TEM turbulence sim. data.

$$\mathcal{F}[T,Z] = c_T T^{\alpha_T}(1 + c_Z Z^{\alpha_Z}/T)^{-1}, \text{ where } T = \sum_{k_\perp(\mathrm{trb})} k_\perp^2|\delta\phi_{k_\perp}|^2,\ Z = \sum_{k_\perp(\mathrm{zf})} k_\perp^2|\delta\phi_{k_\perp}|^2$$

C_T, C_Z: const. α_T, α_Z: exponents (Turb. energy) (ZF energy)

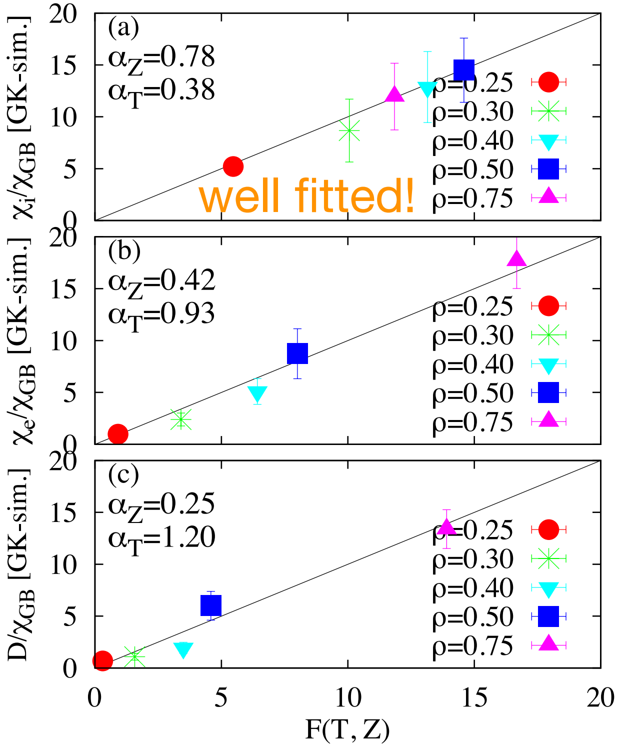
- If F[T, Z] reproduces each transport level on simulations, the exponents α_T/α_Z give nonlinear turbulence/zonal-flow dependence for each transport channels:

ion thermal transport χ_i/χ_{GB}: $\alpha_T = 0.38$, $\alpha_Z = 0.78$

electron thermal transport χ_e/χ_{GB}: $\alpha_T = 0.93$, $\alpha_Z = 0.42$

particle transport D/χ_{GB}: $\alpha_T = 1.20$, $\alpha_Z = 0.25$

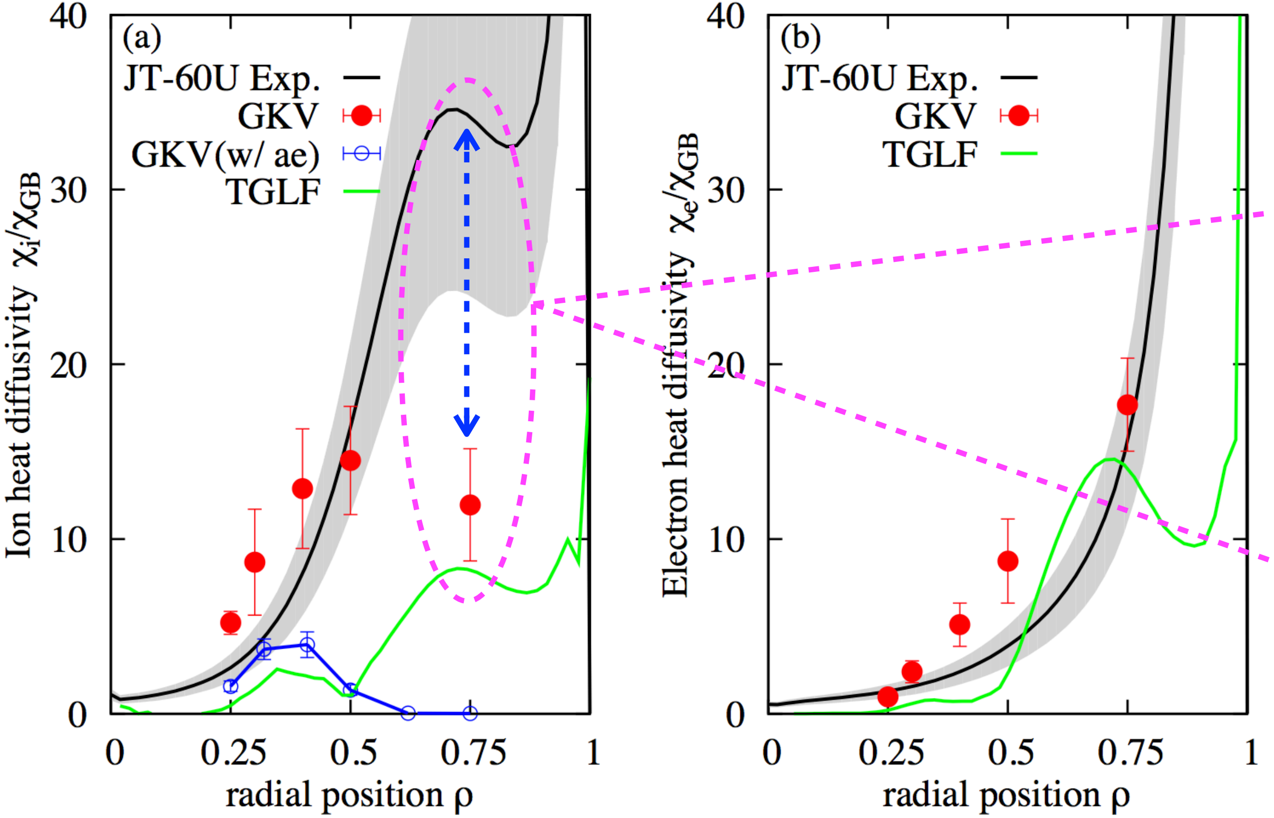
---> Distinct ZF-impact (α_Z) on heat/particle transport is newly identified, i.e., weaker impact on D and χ_e compared to χ_i. (useful insights for transport modeling)



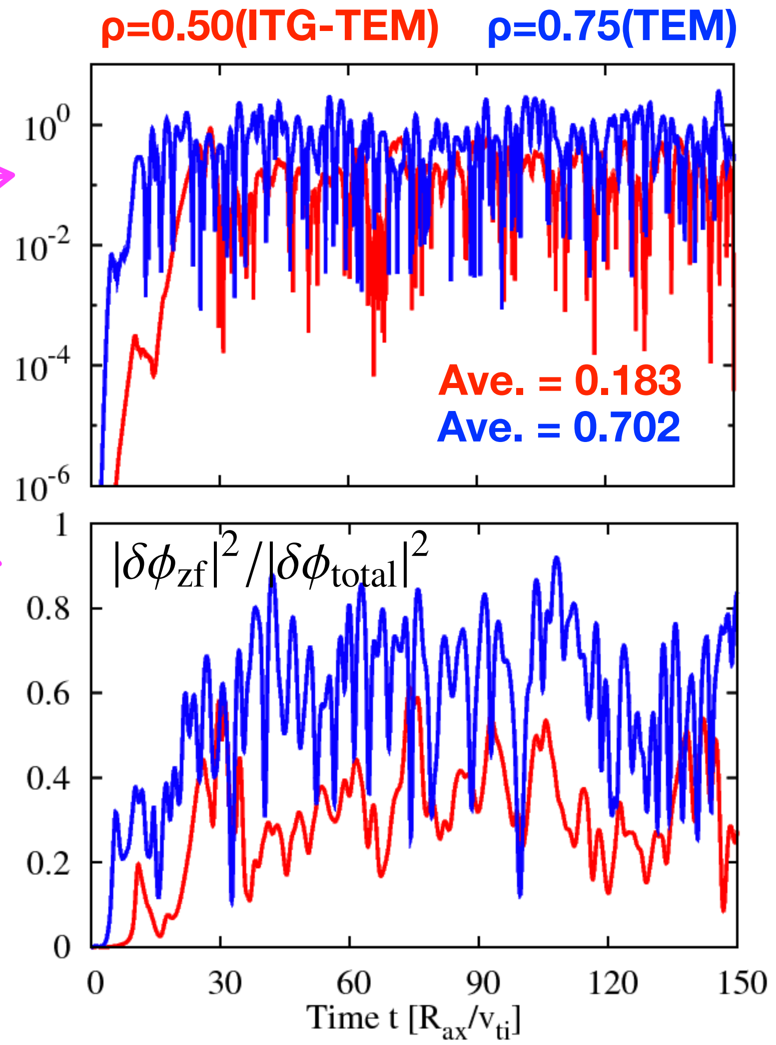
well fitted!

Transport shortfall in outer region

- Comparisons of ion & electron heat diffusivity



- ZF production rate and amplitude

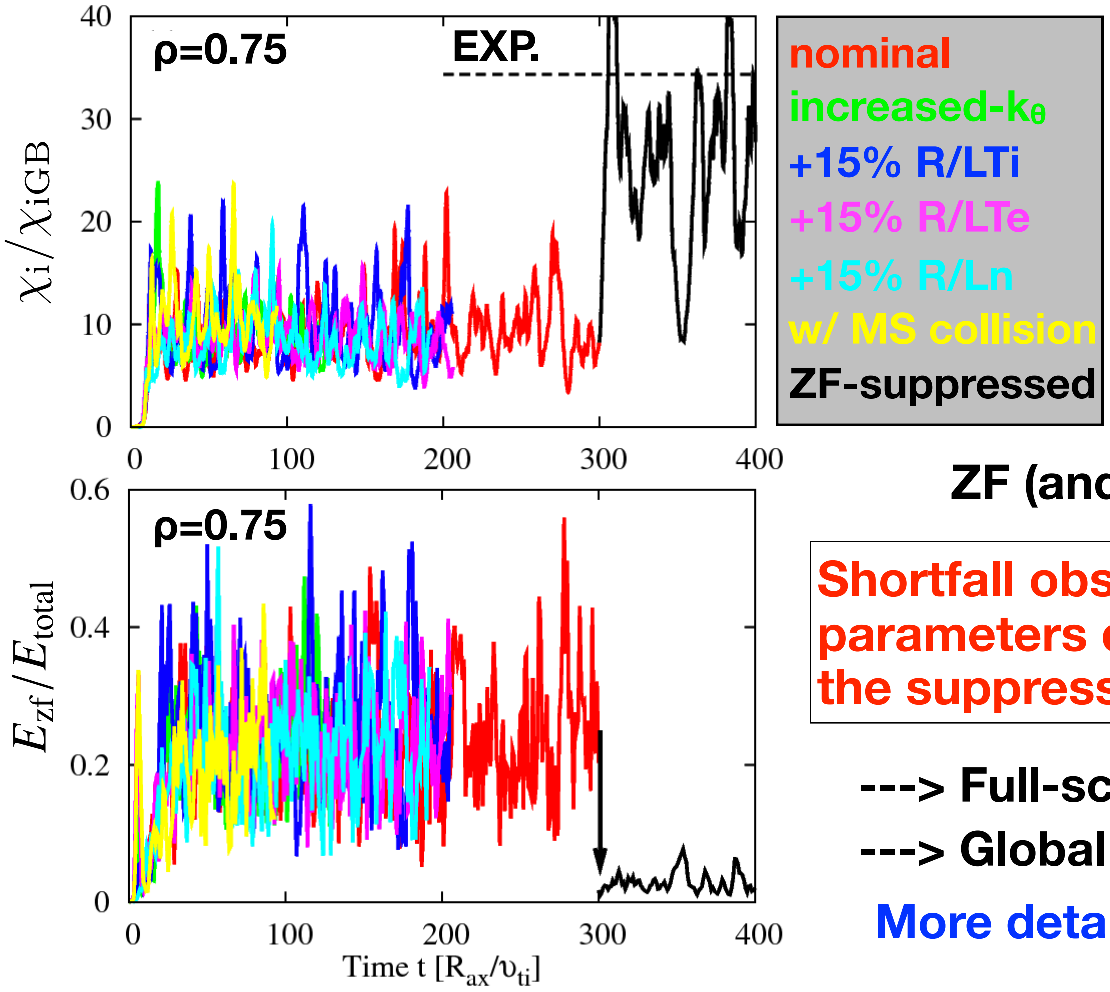


---> TEM turbulence at shortfall region(ρ~0.75) shows more efficient ZF generation compared to ITG region.

---> ZF oscillation is significant for TEM in the outer region.

Parameter Sensitivity on Transport shortfall

- To identify the shortfall property, nonlinear scans with respect to equilibrium gradient parameters and maximum fluctuation scale, etc. are carried out. (cf. Told PoP2013)



Comparison of χ_i between QL and NL

ρ	$\gamma_{\text{lin(max)}}$	$\sum \gamma_{\text{lin}}/k_\theta^2$	χ_i/χ_{iGB}	$\lvert\delta\phi_{zf}\rvert^2/\lvert\delta\phi_{total}\rvert^2$
0.50	0.69	31.4	14.5 (~EXP.)	0.41
0.75	1.59	71.2	11.6 (shortfall)	0.71

ZF (and/or GAM) is a key for the present shortfall

Shortfall observed here is rather insensitive to equilibrium parameters due to strong generation of TEM-driven ZF: the suppressed-ZF gives a recovery of ion heat transport.

---> Full-scale spectra? (cf. Maeyama IAEA2014)

---> Global propagation of ZF? (cf. Miyato PPCF2006)

More detailed investigations are left as a future work

Summary

- In this work, the first validation study against JT-60U tokamak experiments(L-mode) are carried out using a local gyrokinetic code GKV incorporating realistic magnetic geometry and fully-gyrokinetic electrons.

---> GKV simulations show good agreement with experimentally observed ion and electron transport levels in the core region, where the conventional adiab.-elec.- and TGLF models indicate some deviations.

---> Distinct nonlinear ZF dependence on multiple transport channels is identified, i.e., weaker impact on the electron heat and particle transport compared to the ion heat one.

---> In the outer region, transport shortfall is observed also in JT-60U case;
it is found that strong ZF and/or GAM generation dominantly contributes to it,
and the sensitivity on equilibrium parameters is weakened.

These findings on good agreement with core experimental results, including the ZF-impact contribute to more improvement of the prediction capability and reduced transport model.