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TEMPEST simulations of the neoclassical transport in a single-null tokamak geometry

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Acknowledgments: E. Belli, K. Bodi, J. Candy, P. Colella, M. R. Dorr, J. A. Hittinger, G. D. Kerbel, S. Krasheninnikov, P. B. Snyder, M. V. Umansky, Z. Xiong

Presented at

2009 APS April Meeting and the Sherwood Fusion Theory Conference

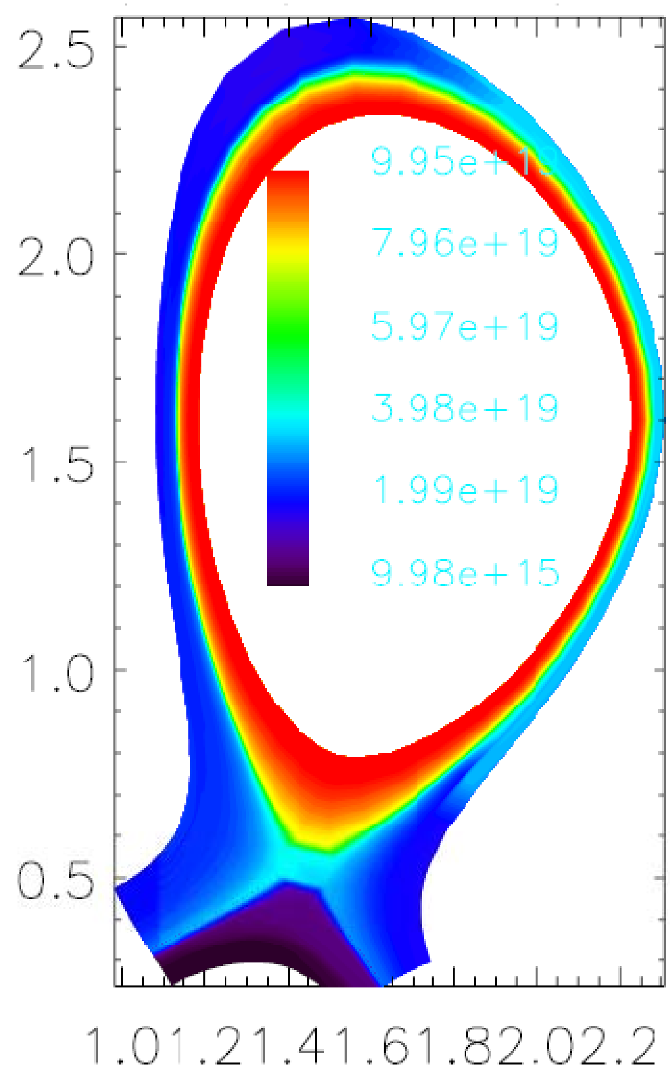
May 2 – 5, 2009

Denver, Colorado

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

TEMPEST: fully nonlinear (full-f) continuum gyrokinetic transport and turbulence code

- **Solve for the particle distribution function $f(\psi,\theta,\xi,E,\mu,t)$ (avg. over gyration: 6D → 5D)**
- **2D or 3D configuration space**
- **2D – velocity space (E_0,μ)**
- **Solving GK field equations for $\Phi(\psi,\theta,\xi,t)$ using HYPRE**
- **Realistic toroidal geometry, kinetic ions & electrons, electrostatic fluctuations, collisions, sophisticated algorithms.**

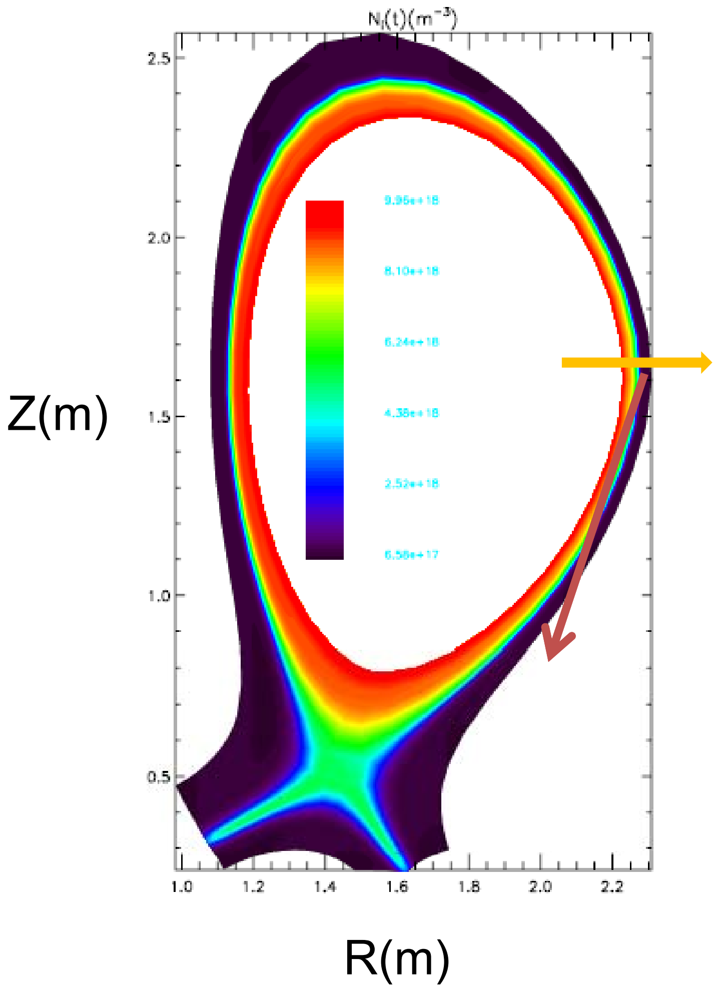


In this talk, we focus on 4D and divertor geometry

X. Q. Xu, Z. Xiong, M. R. Dorr, J. A. Hittinger, et al., Nuclear Fusion 47, 809-816(2007).
X. Q. Xu, PHYSICAL REVIEW E, V. 78, 016406 (2008).

TEMPEST neoclassical simulations with an anomalous radial diffusion coefficient D (k-uedge)

Single ion dynamical species with no ϕ and no recycling



Radial neoclassical + anomalous D

Kinetic parallel flow

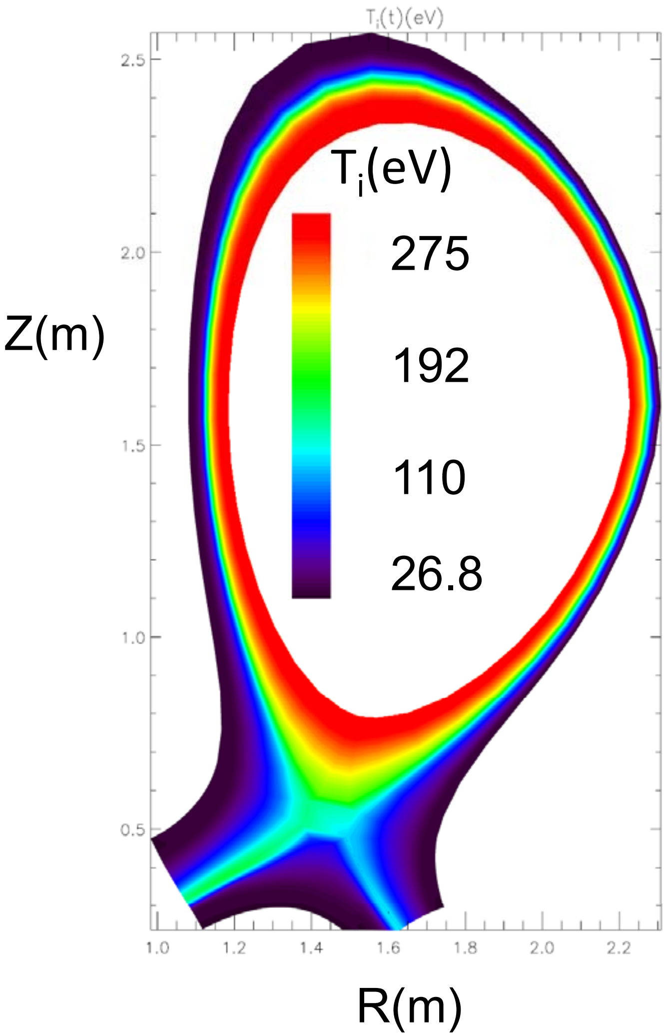
Boundary conditions:

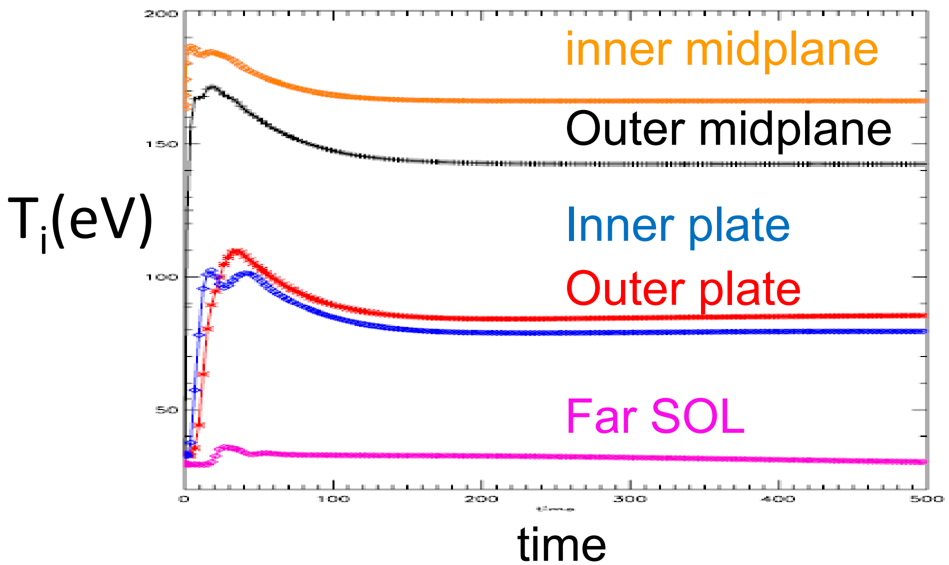
F_M with fixed Ni, Ti and $U_{||i}$=0 at core side
Zero radial gradient: dF/dψ=0, at the wall and PVT

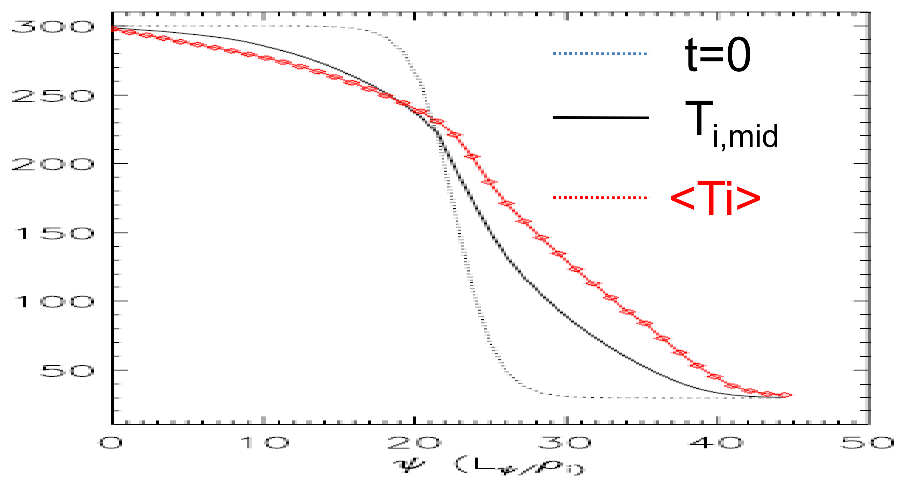
Absorbed divertor plates boundary condition

For given boundary conditions, the goal is to
Find a steady state kinetic solution in pedestal

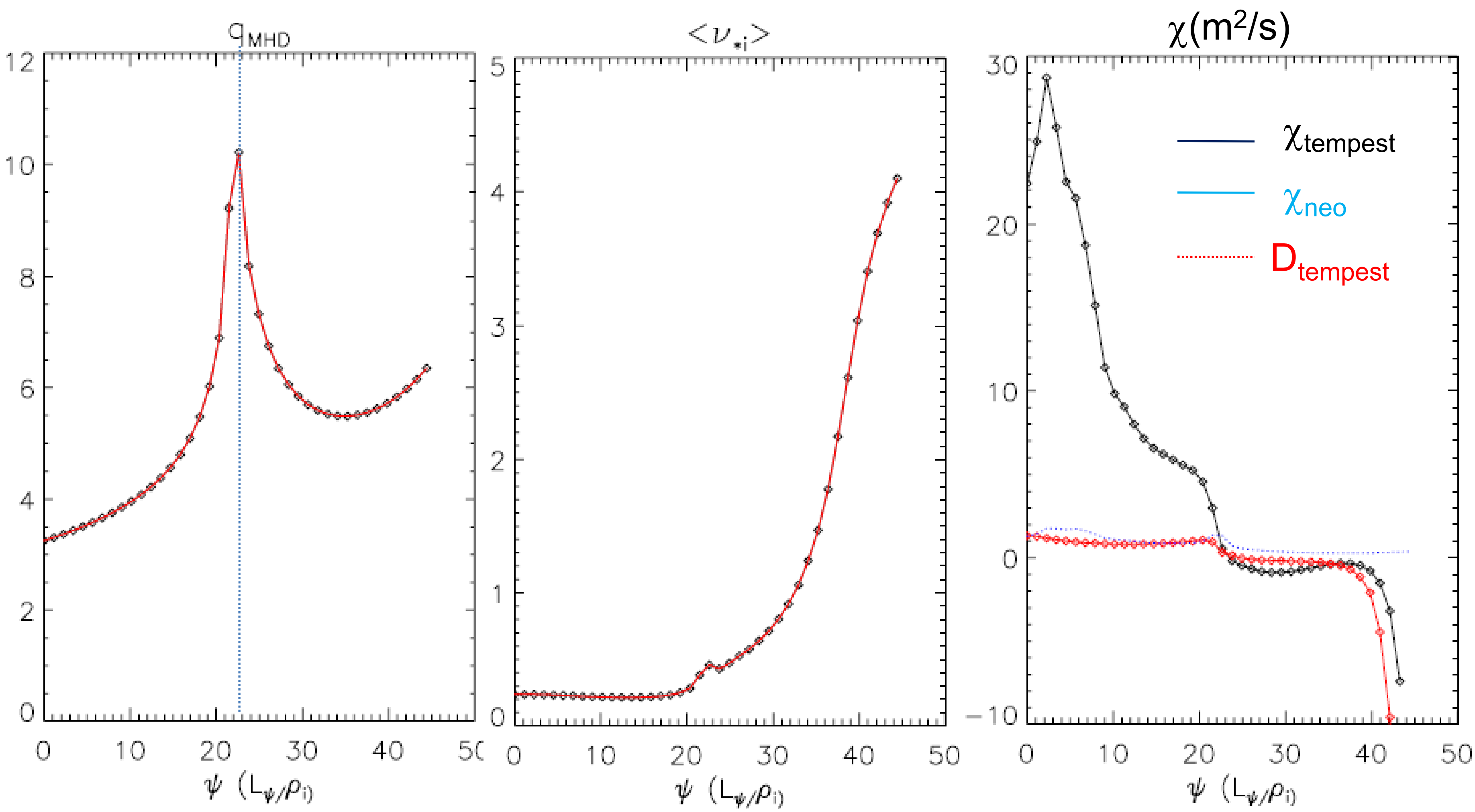
TEMPEST shows a steady state T_i with an anomalous D=1.0 m^2/s and $N_i=1x10^{19}/m^3$







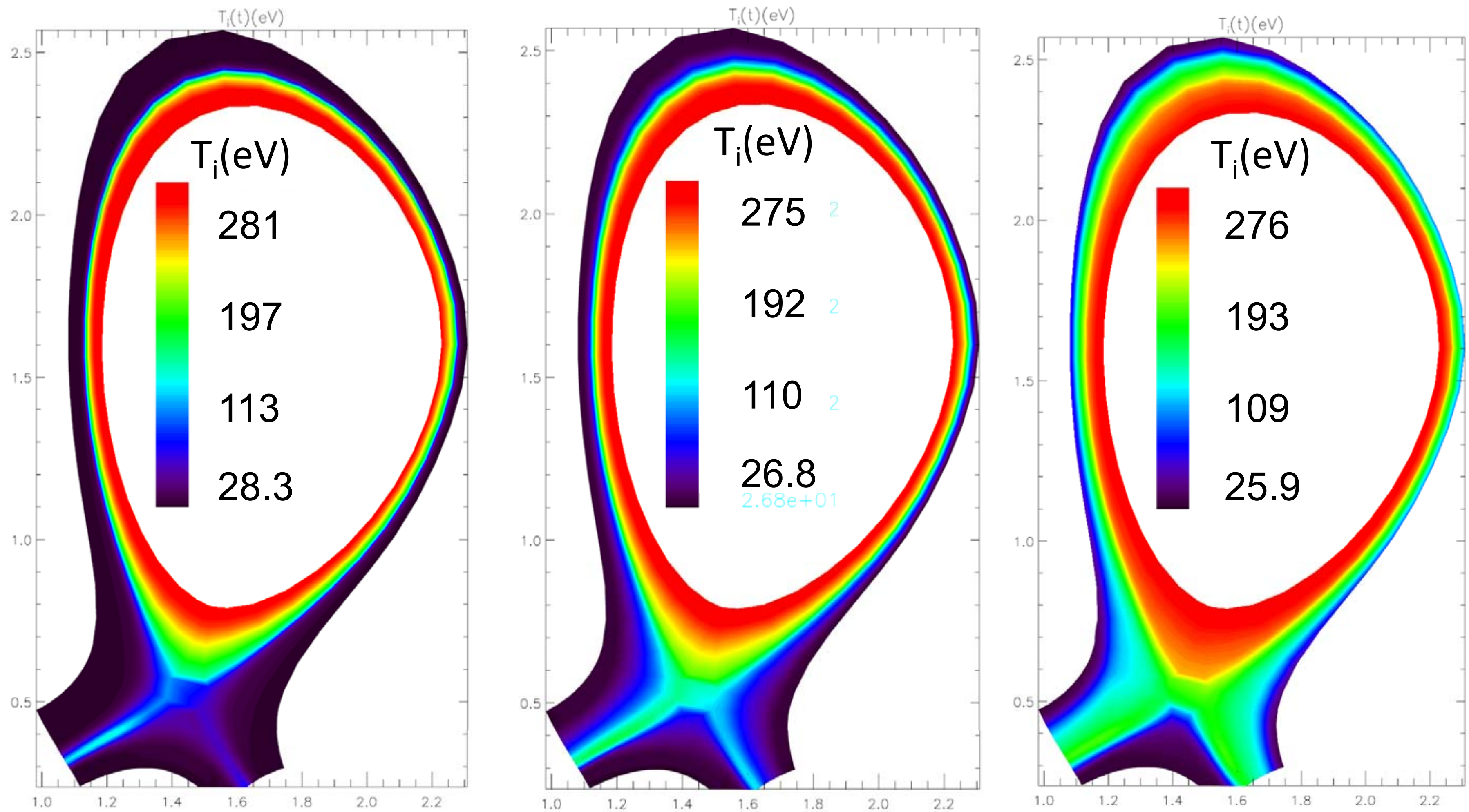
TEMPEST shows a different ion neoclassical transport coefficients for D and χ



The D-scan of ion temperature T_i profile

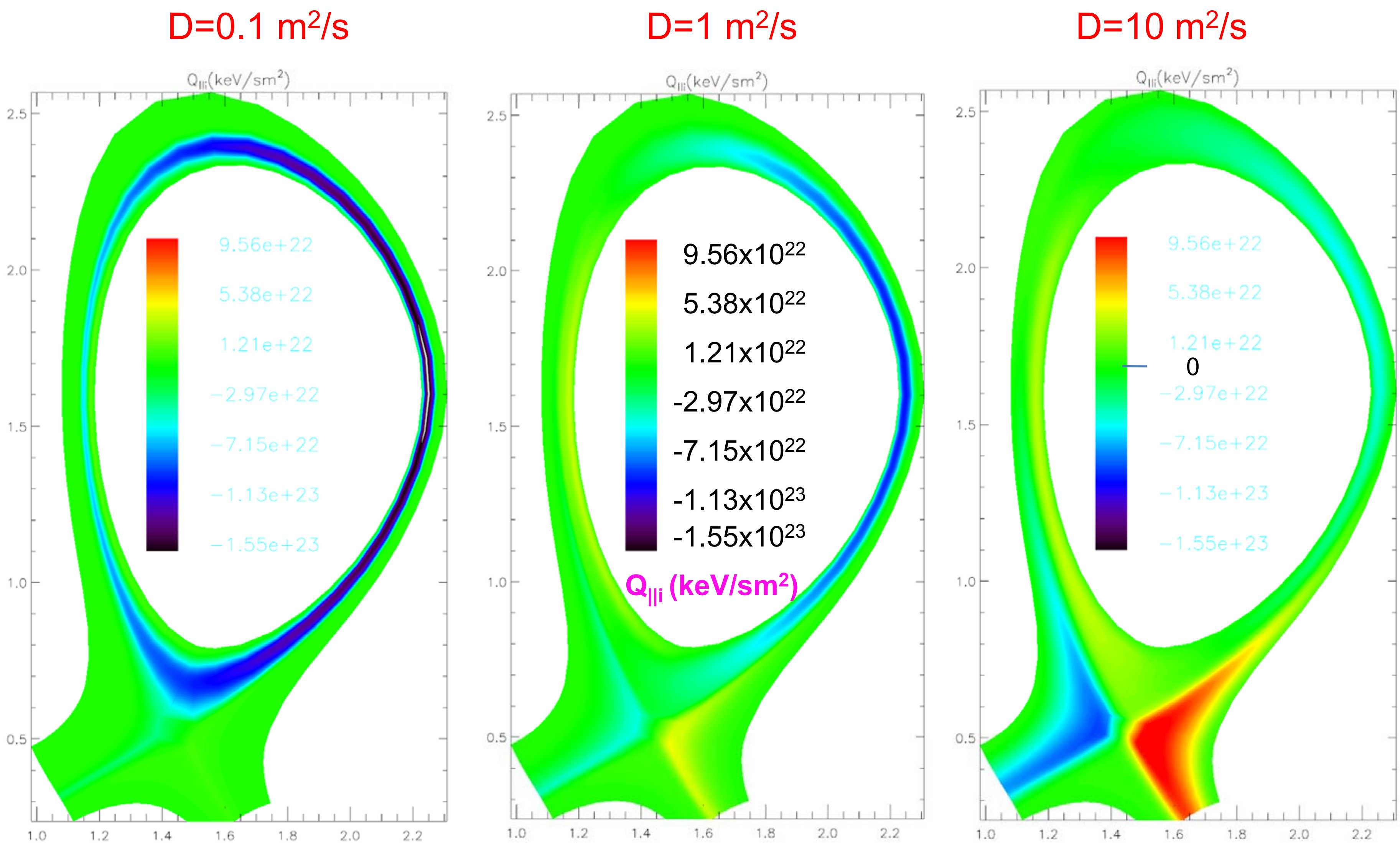
large D spreads heat on the divertor plates

D=0.1 m²/s　　D=1 m²/s　　D=10 m²/s



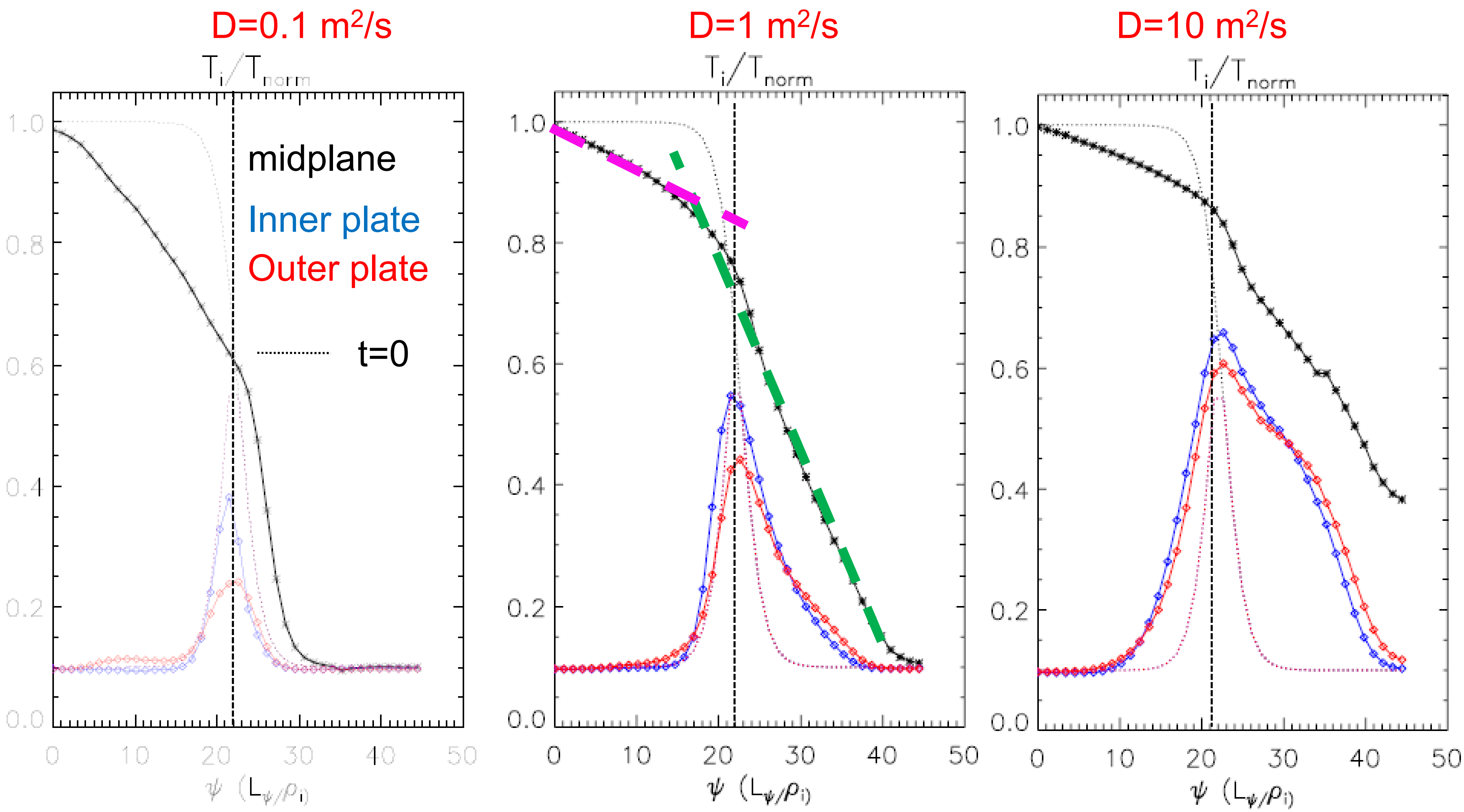
The D-scan of ion parallel heat flux $Q_{||i}$

large D spreads heat on the divertor plates



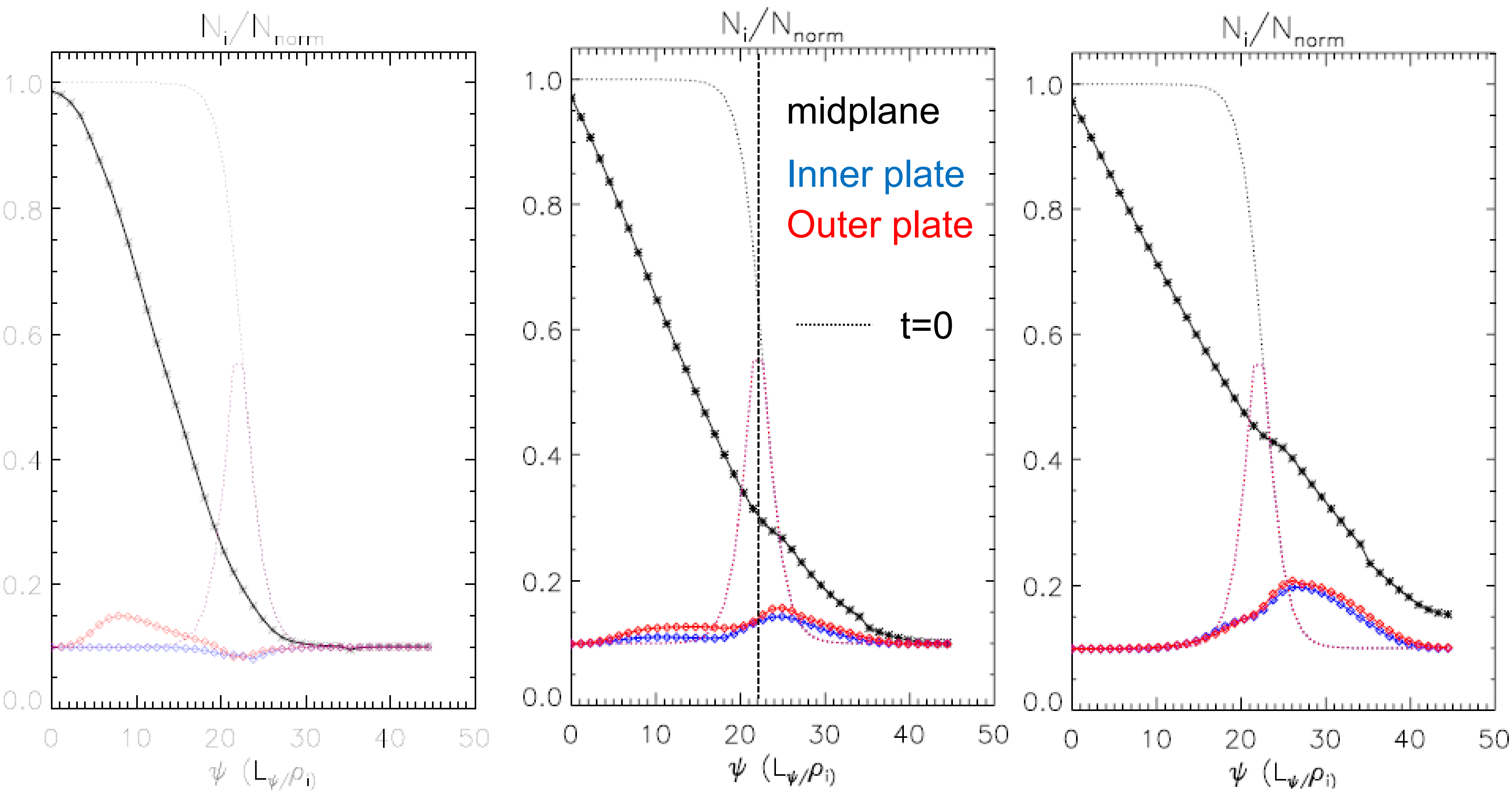
The large D broadens radial ion temperature profiles both at midplane and at plates

two spatial scales at midplane across the separatrix



The large D broadens radial density profiles both at midplane and at plates and makes the plates denser

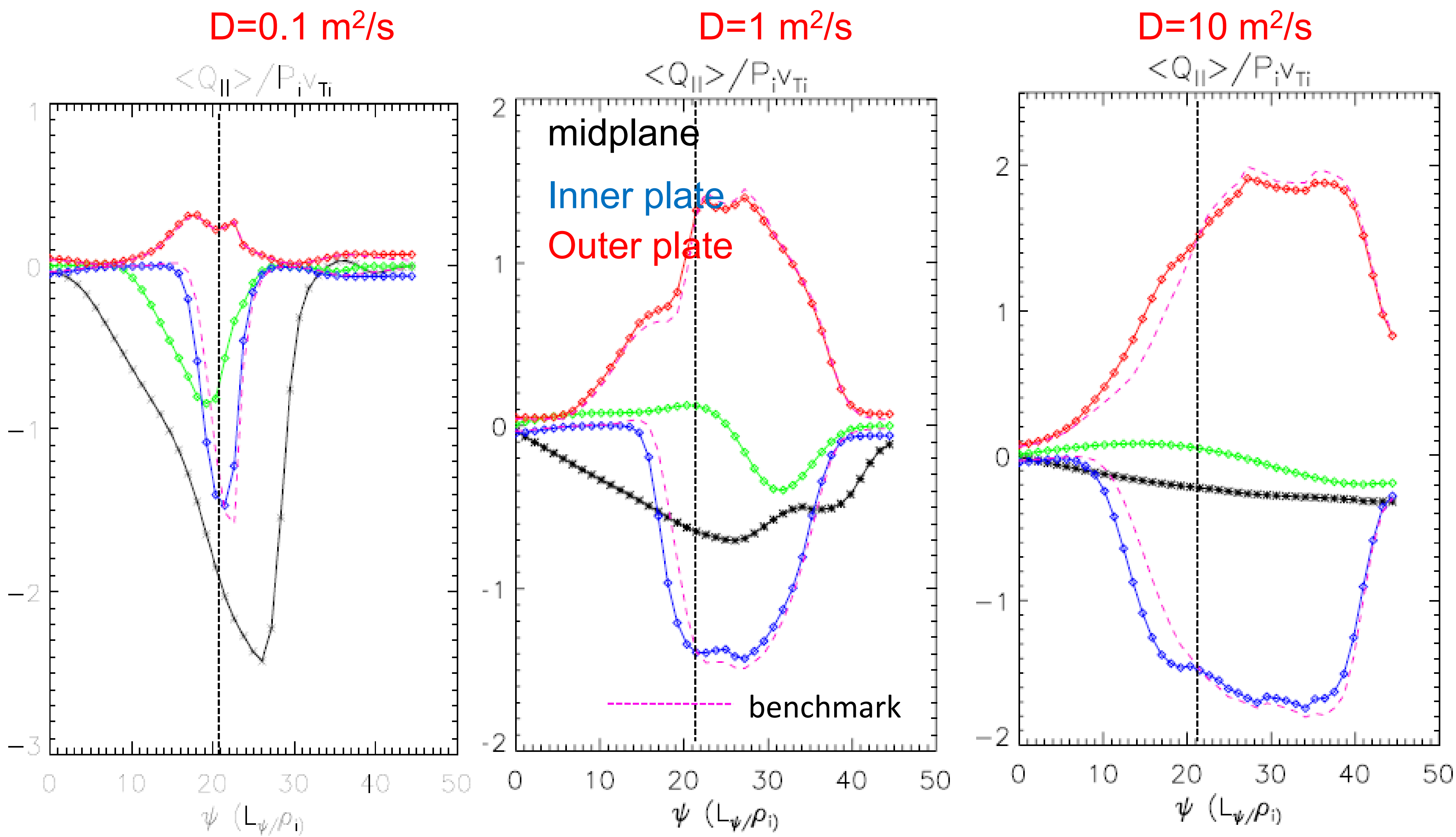
D=0.1 m^2/s D=1 m^2/s D=10 m^2/s



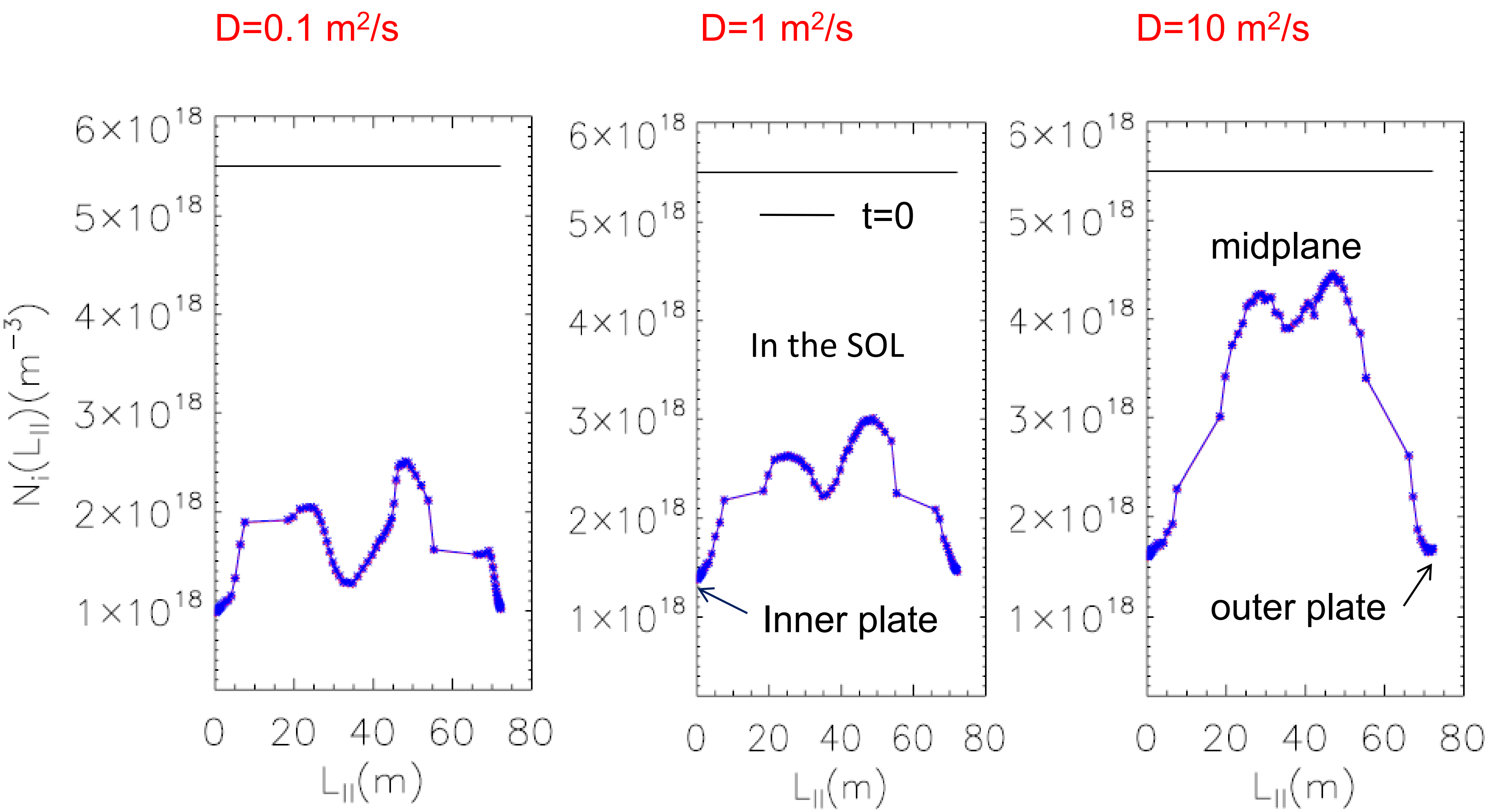
The large D broadens radial parallel heat flux $Q_{||i}$ profiles

both at midplane and at plates

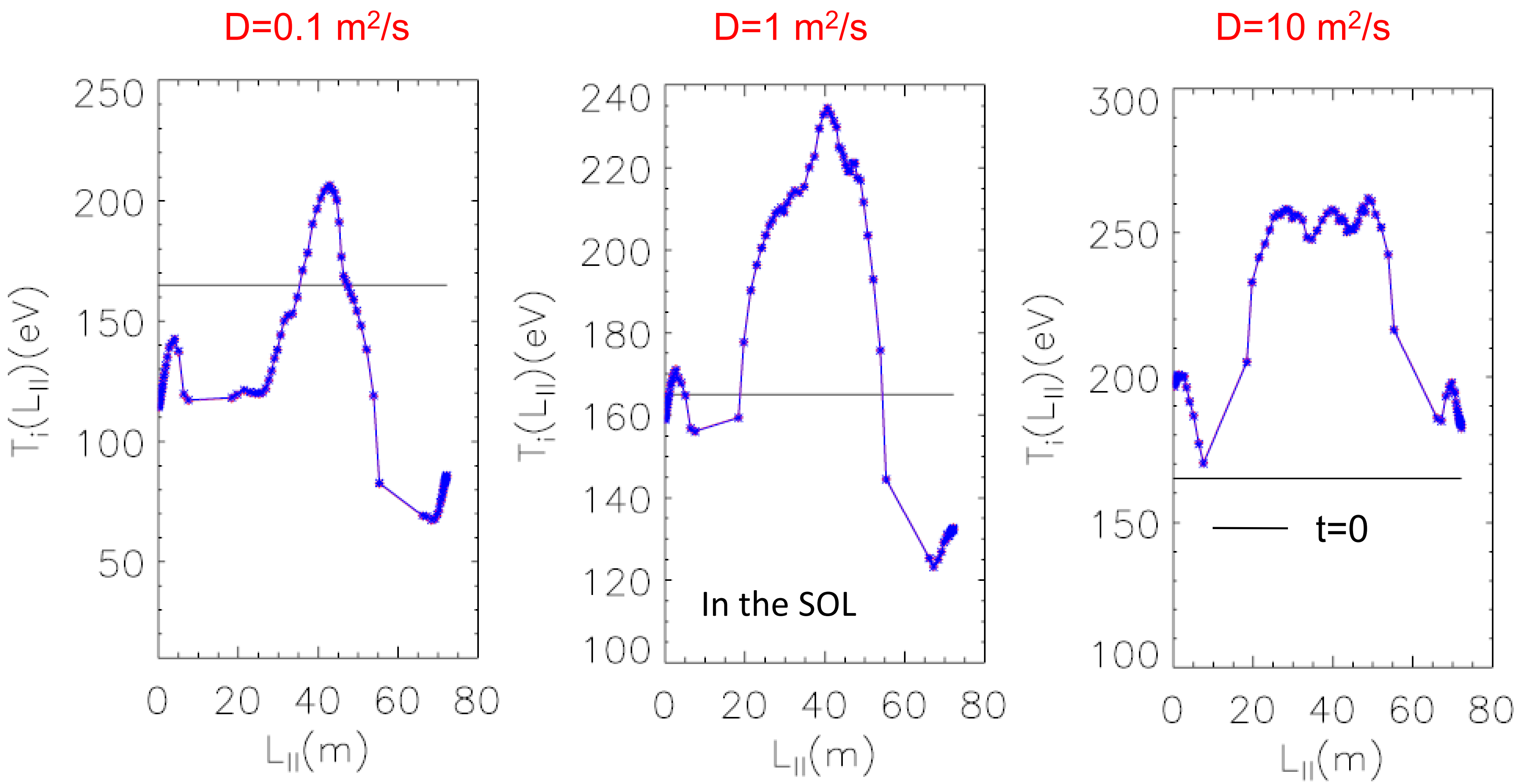
Peak heat flux is further in the SOL due to finite orbit size



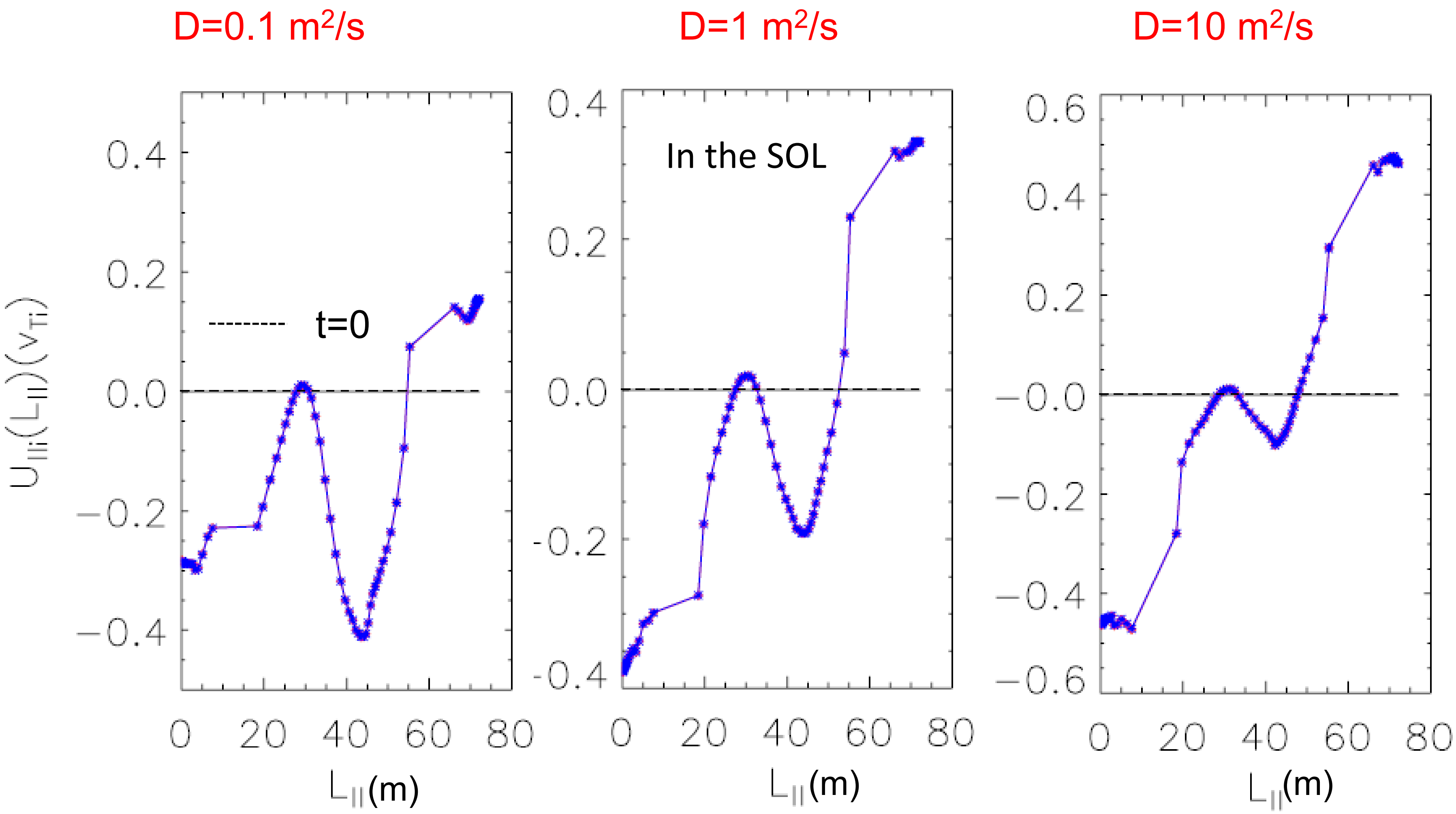
The large D increases poloidal uniformity of density profile in the bulk plasma; possibly due to the relative role of diffusion vs convection/radial drift



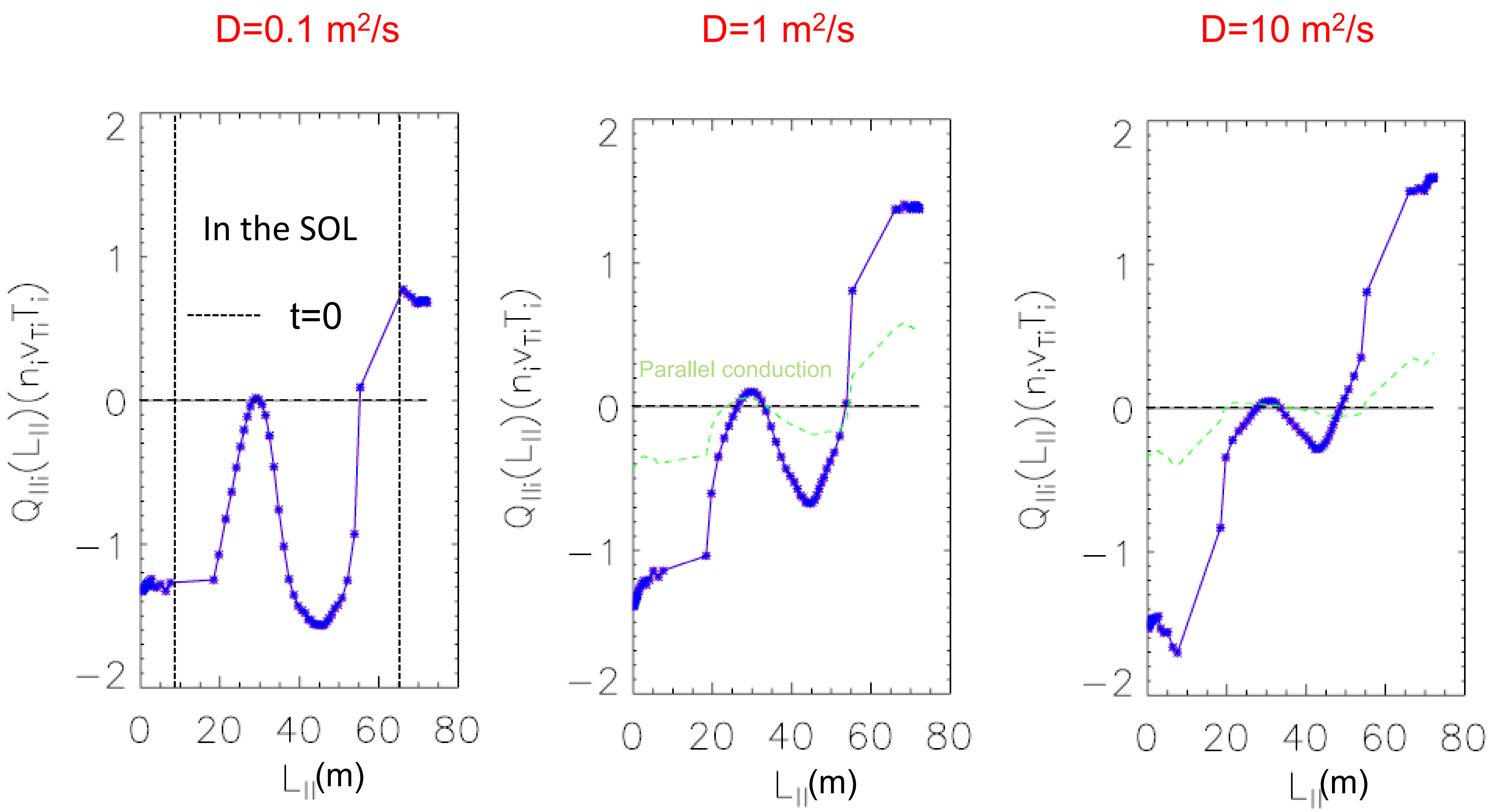
The large D increases poloidal uniformity of T_i profile in the bulk plasma;
possibly due to the relative role of diffusion vs convection/radial drift
T_i increases towards the plates below x-point



The large D decreases $U_{||i}$ at midplane due to flattening profiles and increases $U_{||i}$ at plates (leading to fluid results)



The large D decreases $Q_{||i}$ at midplane due to flattening profiles and increases $Q_{||i}$ at plates (leading to fluid results)



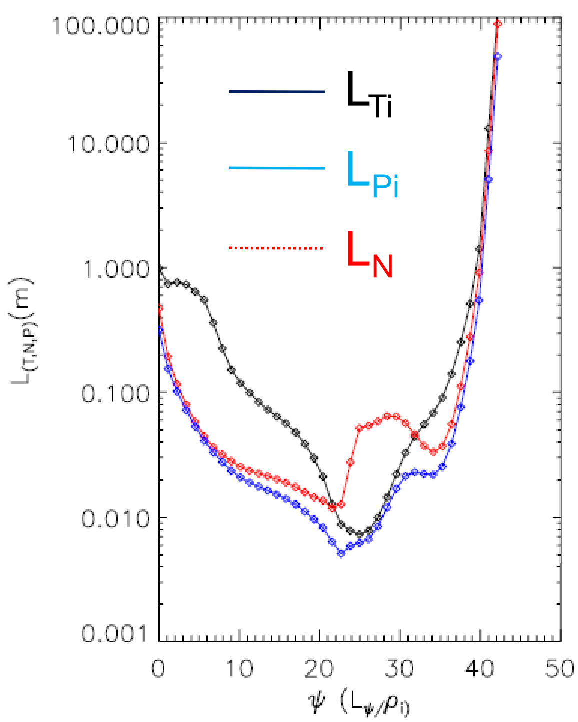
The anomalous D plays a role as collisional de-correlation, which makes transition from kinetic to fluid regime

$\tau_b = qR/(\varepsilon^{1/2} v_{ti}) \approx 100\mu s$ vs $\tau_D = L_{pi}^2/D$

D=0.1 m^2/s

$\tau_D/\tau_b \sim 10$

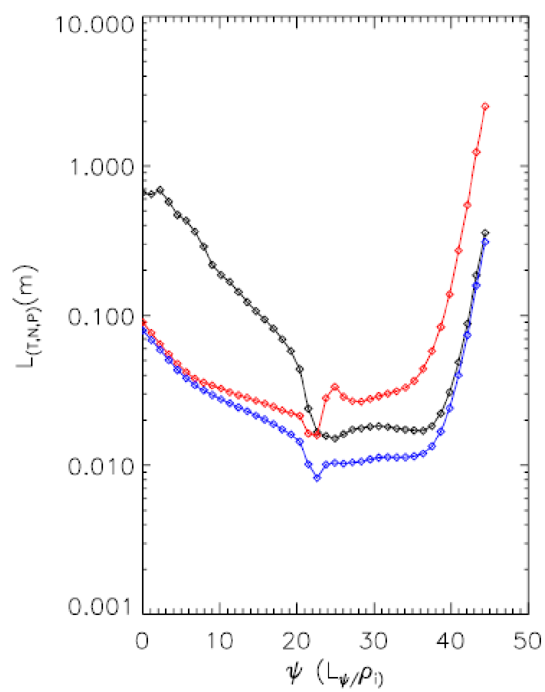
Effective banana regime



D=1 m^2/s

$\tau_D/\tau_b \sim 1$

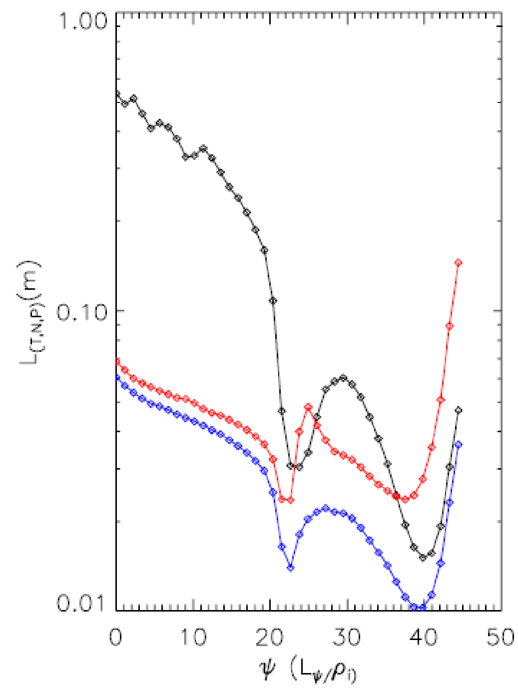
Effective plateau regime



D=10 m^2/s

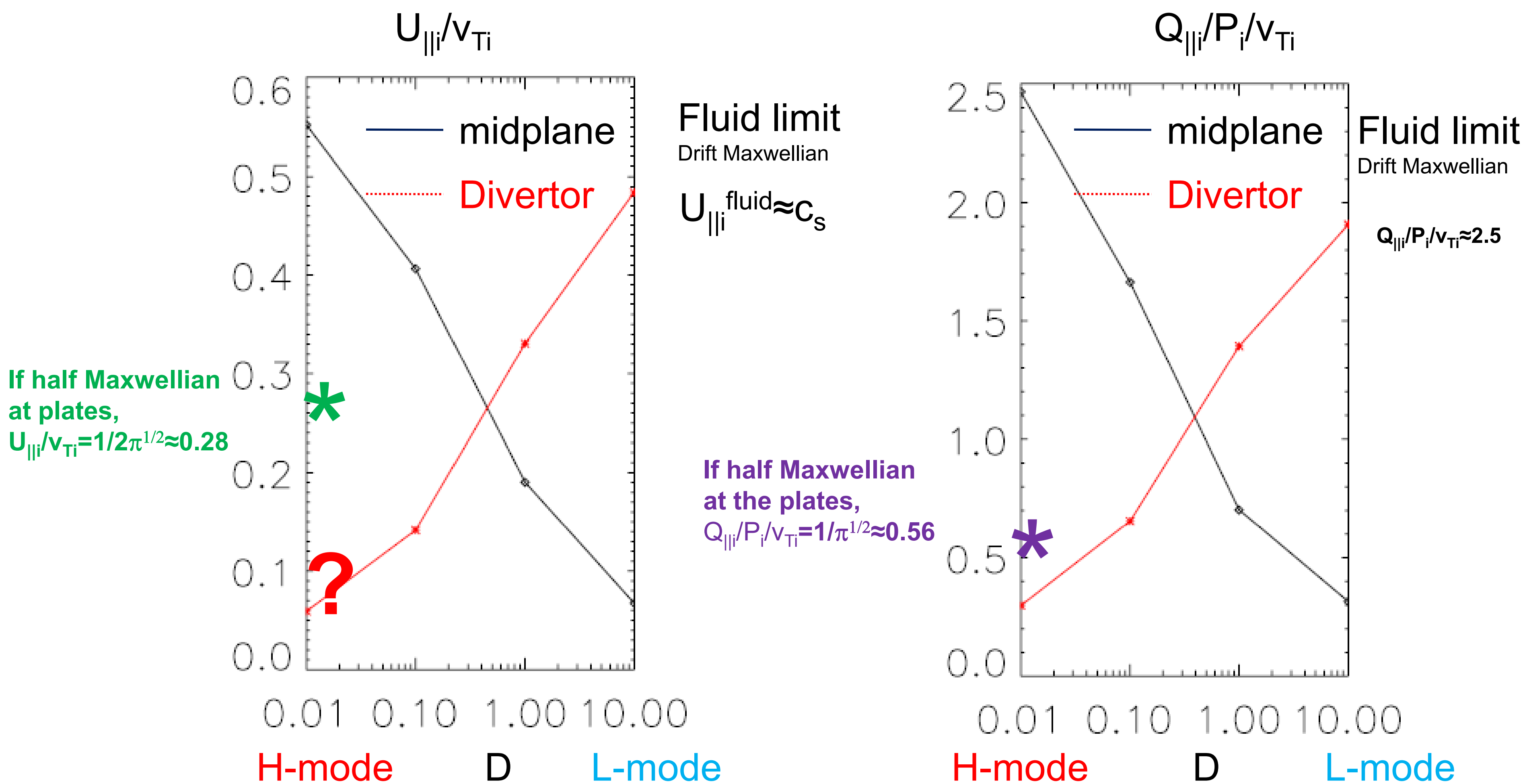
$\tau_D/\tau_b \sim .1$

Effective collisional regime

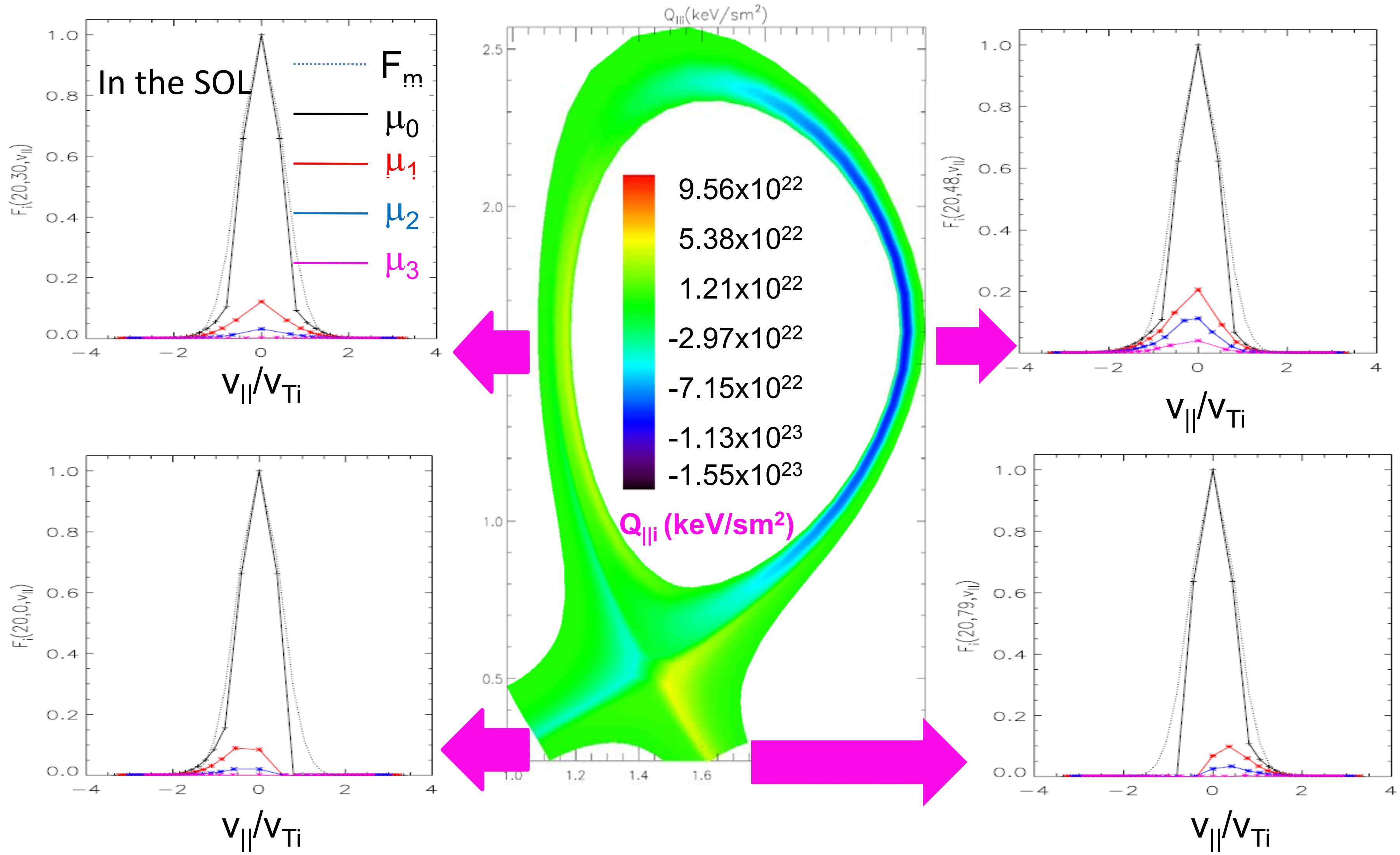


The anomalous D plays a role as collisional de-correlation, which makes transition from kinetic to fluid regime

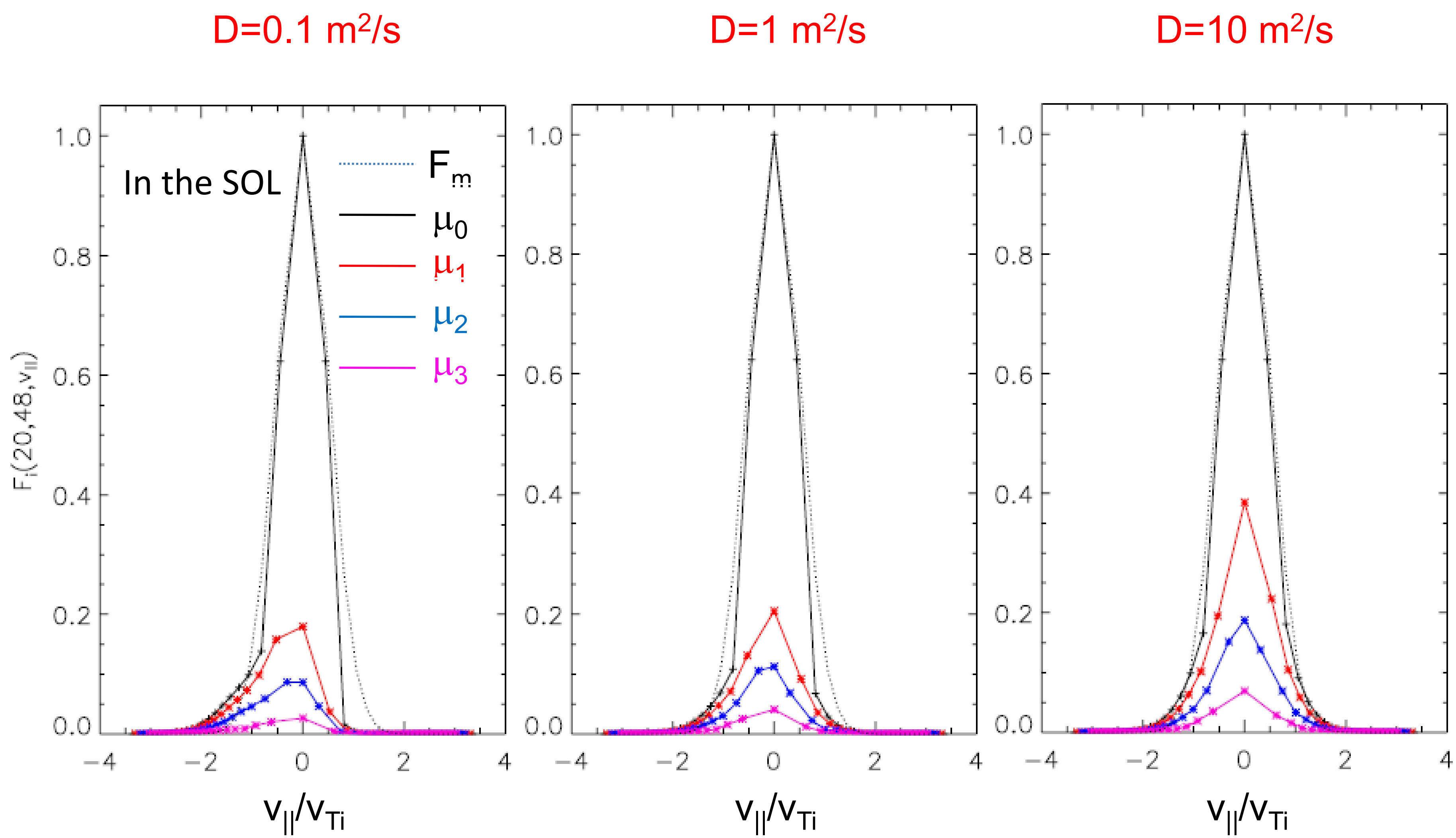
Parallel fluxes at midplane follows neoclassical, while at divertor plates follows fluid



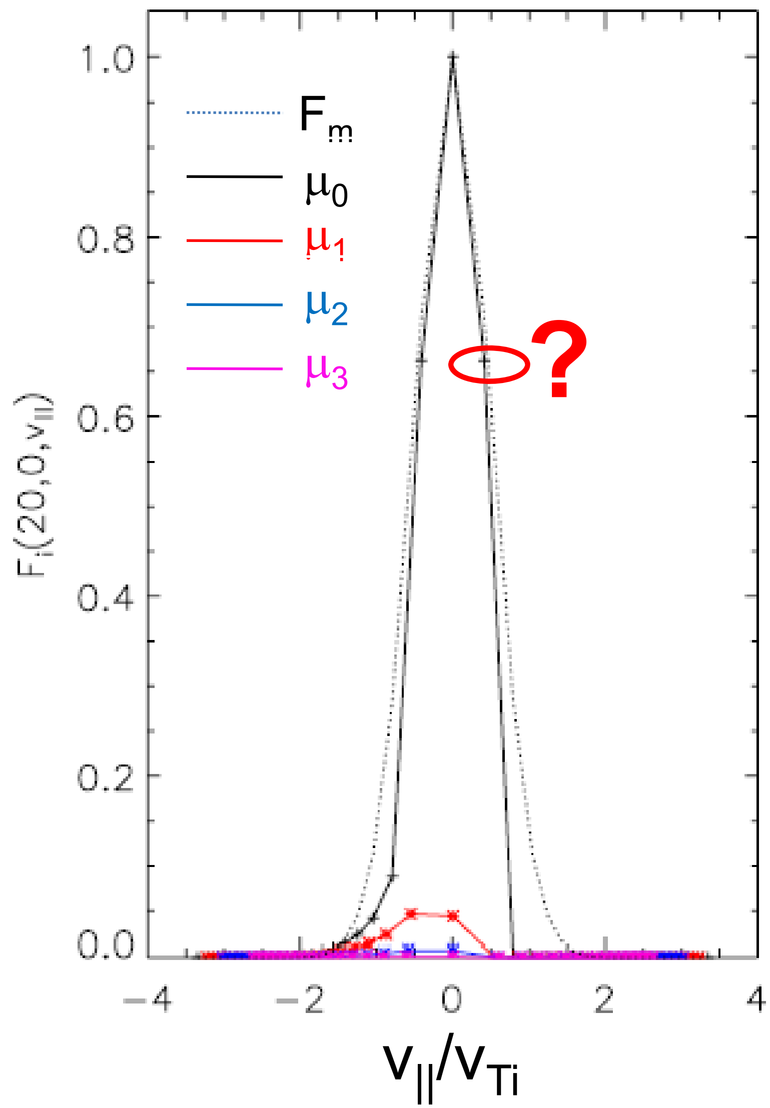
TEMPEST shows a steady state non-Maxwellian F_i with an anomalous $D=1.0\ m^2/s$ and $N_i=1\times10^{19}/m^3$

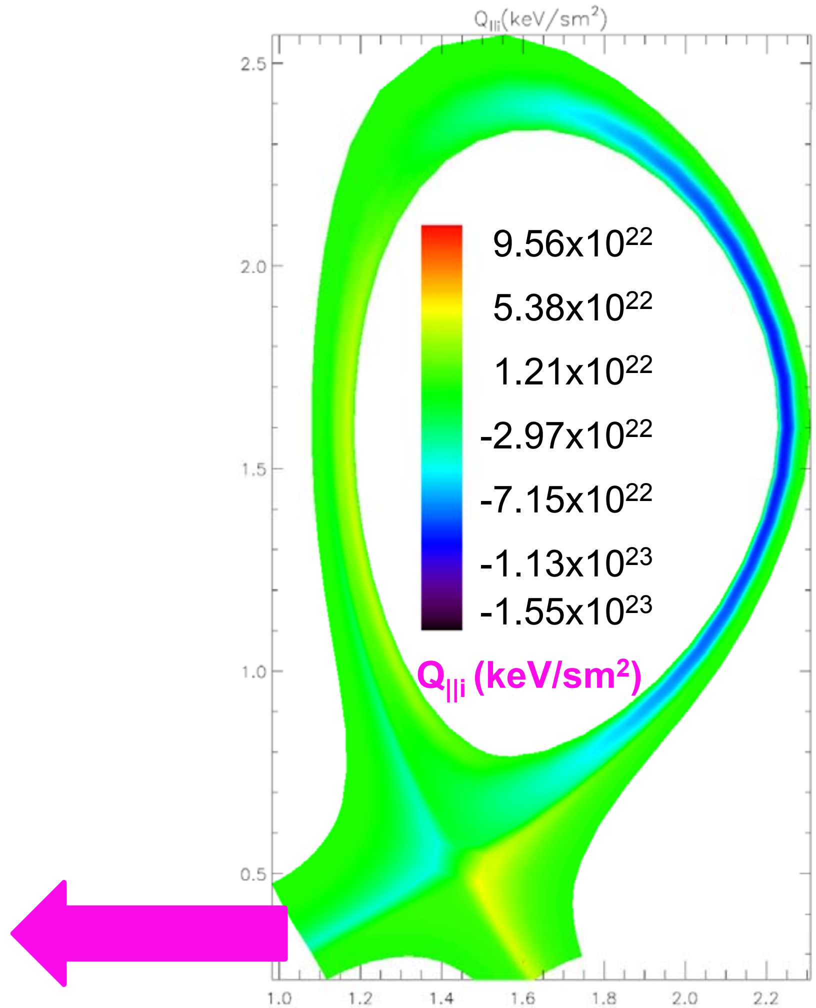


The D-scan of ion distribution function F_i at midplane
TEMPEST shows that large D leads to Maxwellianization

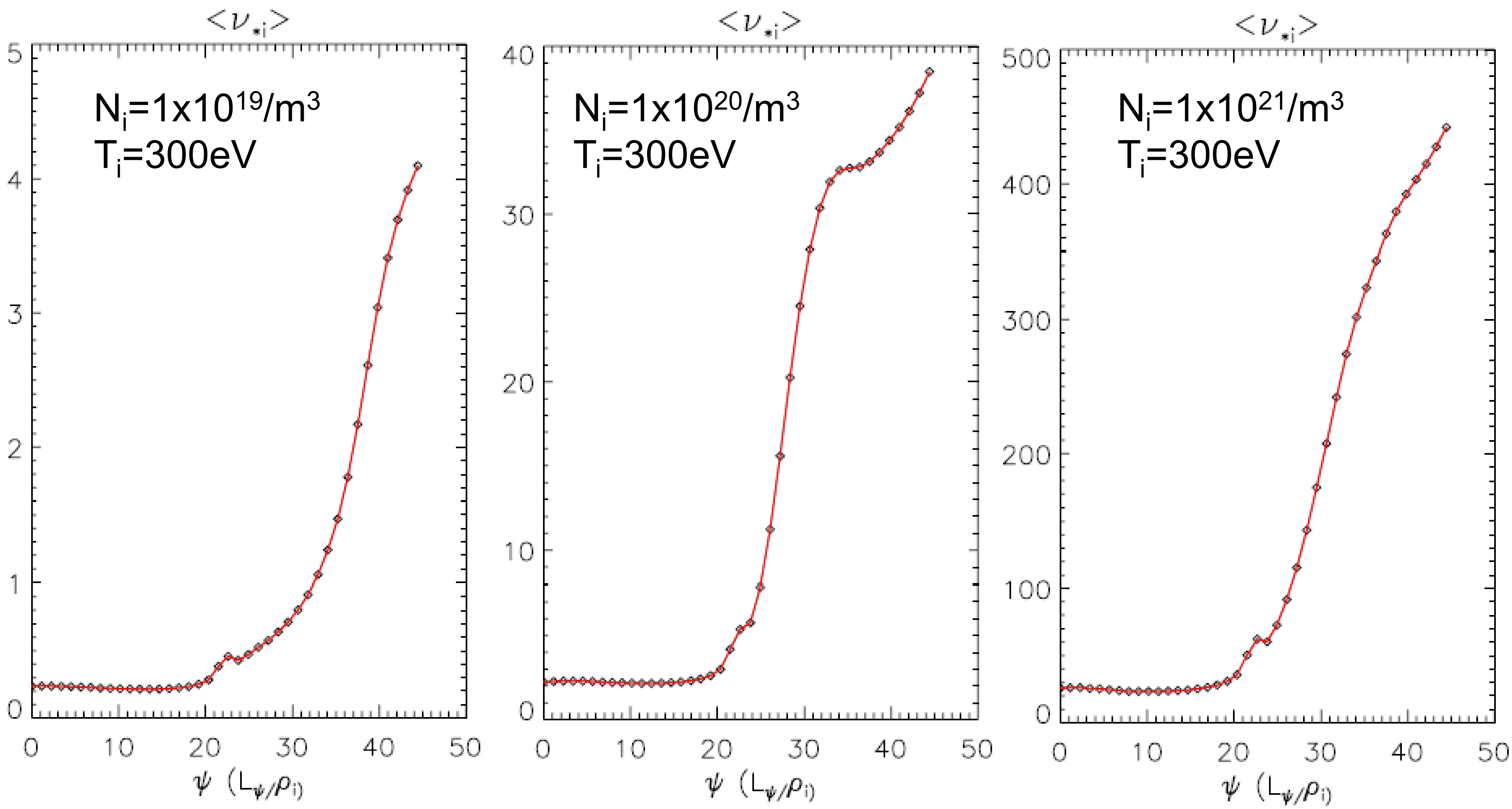


TEMPEST shows a steady state non-half-Maxwellian F_i at plates, possibly due to residual collision from slow particles & exotic orbits



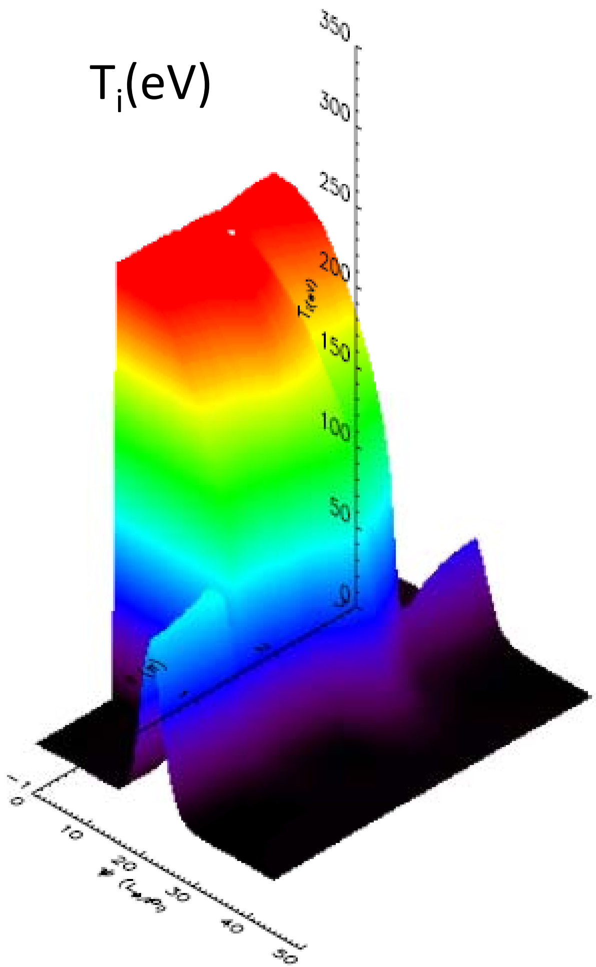


TEMPEST neoclassical simulations with anomalous D span from banana to collision regimes

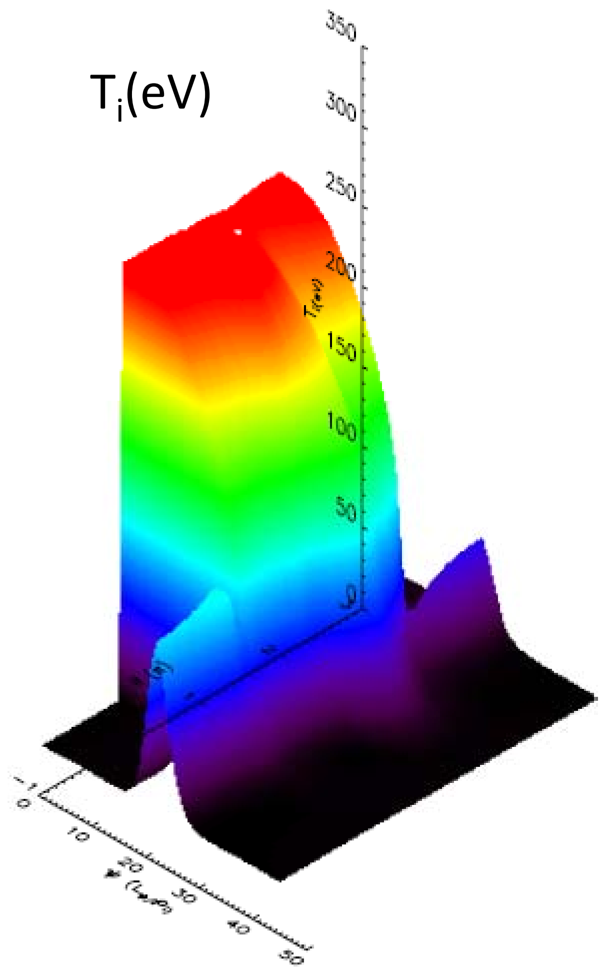


The higher density→higher collision yields a similar T_i steady state as the large D

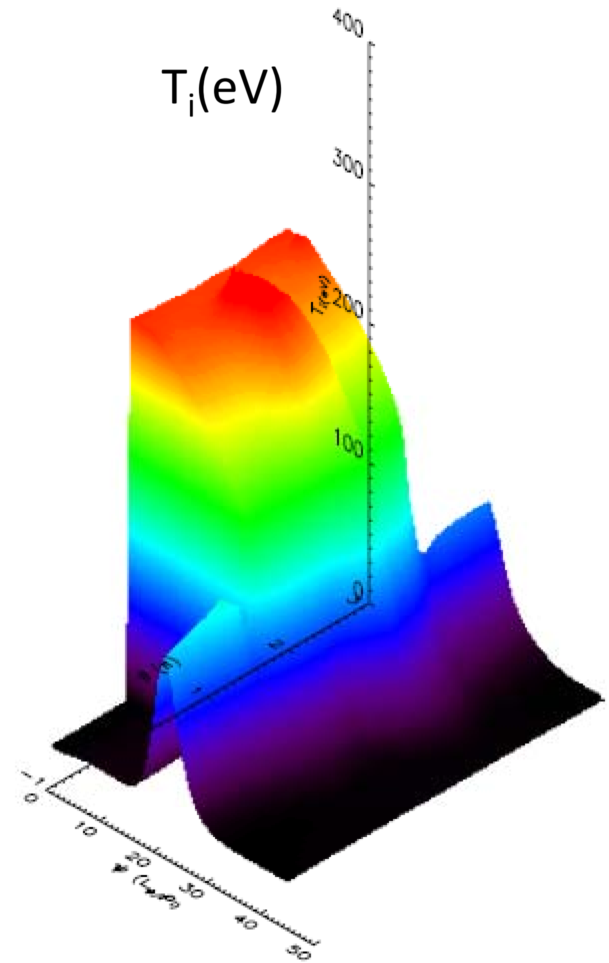
$Ni=1X10^{19}/m^3$
$D=0.1\ m^2/s$



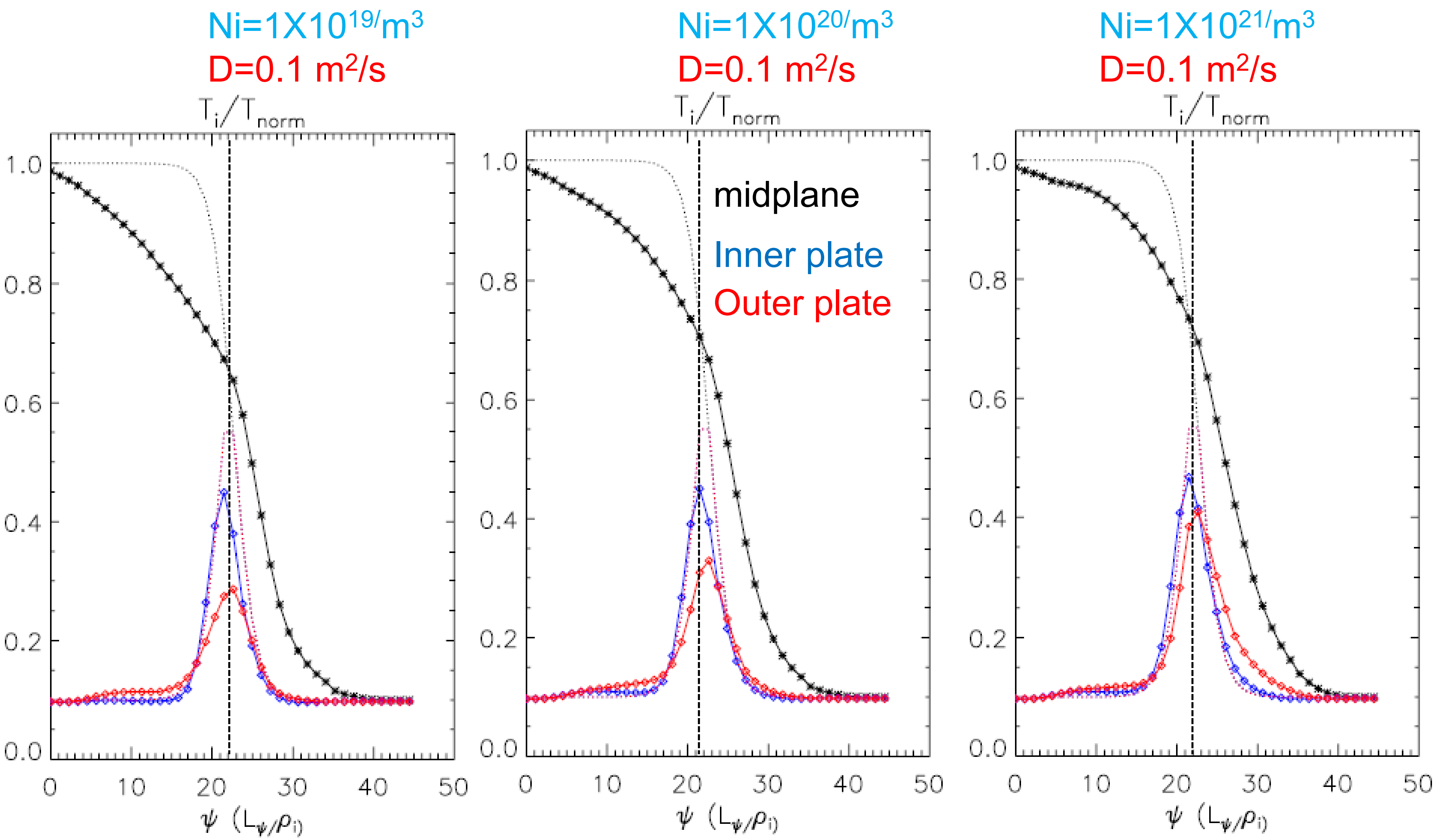
$Ni=1X10^{20}m^3$
$D=0.1\ m^2/s$



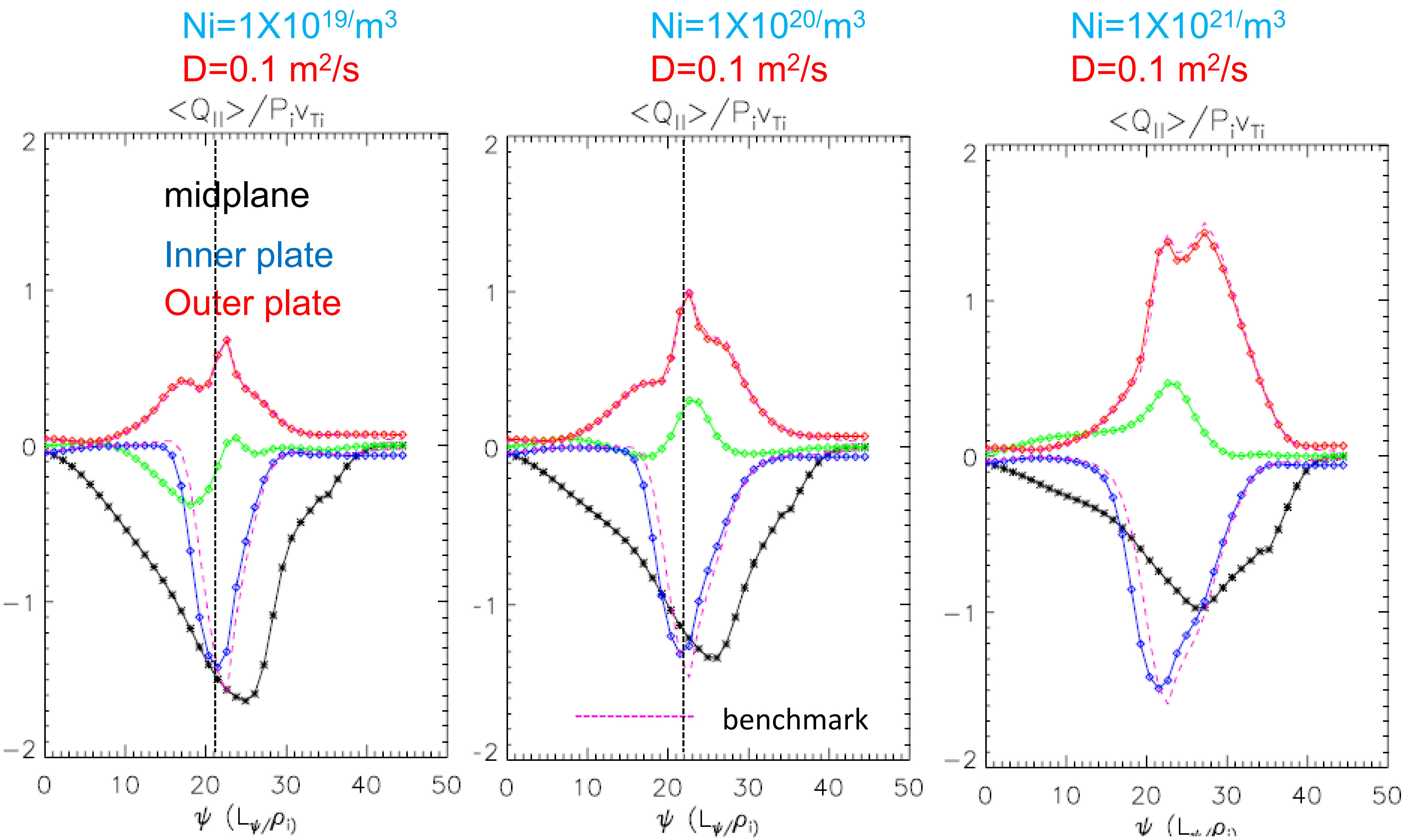
$Ni=1X10^{21/}m^3$
$D=0.1\ m^2/s$



The higher density→higher collision yields a similar T_i steady state as the large D



The higher density→higher collision yields a similar $Q_{||i}$ steady state as the large D



Summary

- **TEMPEST calculates steady state ion distribution function using a full-f code in divertor geometry with sources and sinks at boundaries.**

- **TEMPEST shows**
  - **T_i is broader than density due to finite ion orbit size, with two spatial scales at midplane across the separatrix due to the endloss**
  - **The anomalous D plays a role as collisional de-correlation, large radial diffusion coefficient D leads to Maxwellianization**
  - **large D decreases $U_{||i}$ and $Q_{||i}$ at midplane (following neoclassical relationship), increases $U_{||I}$ and $Q_{||i}$ (leading to conventional fluid relationship) at plates**
  - **higher density→higher collision yields a similar T_i steady state as the large anomalous diffusion coefficient D**

- **Activating, benchmarking and validating Tempest's multiple species features will lead to a full kinetic edge simulation code, including impurities and neutrals with different charge Z. and mass M**