NSTX Physics Meeting
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XGC code framework in CPES for application to NSTX physics

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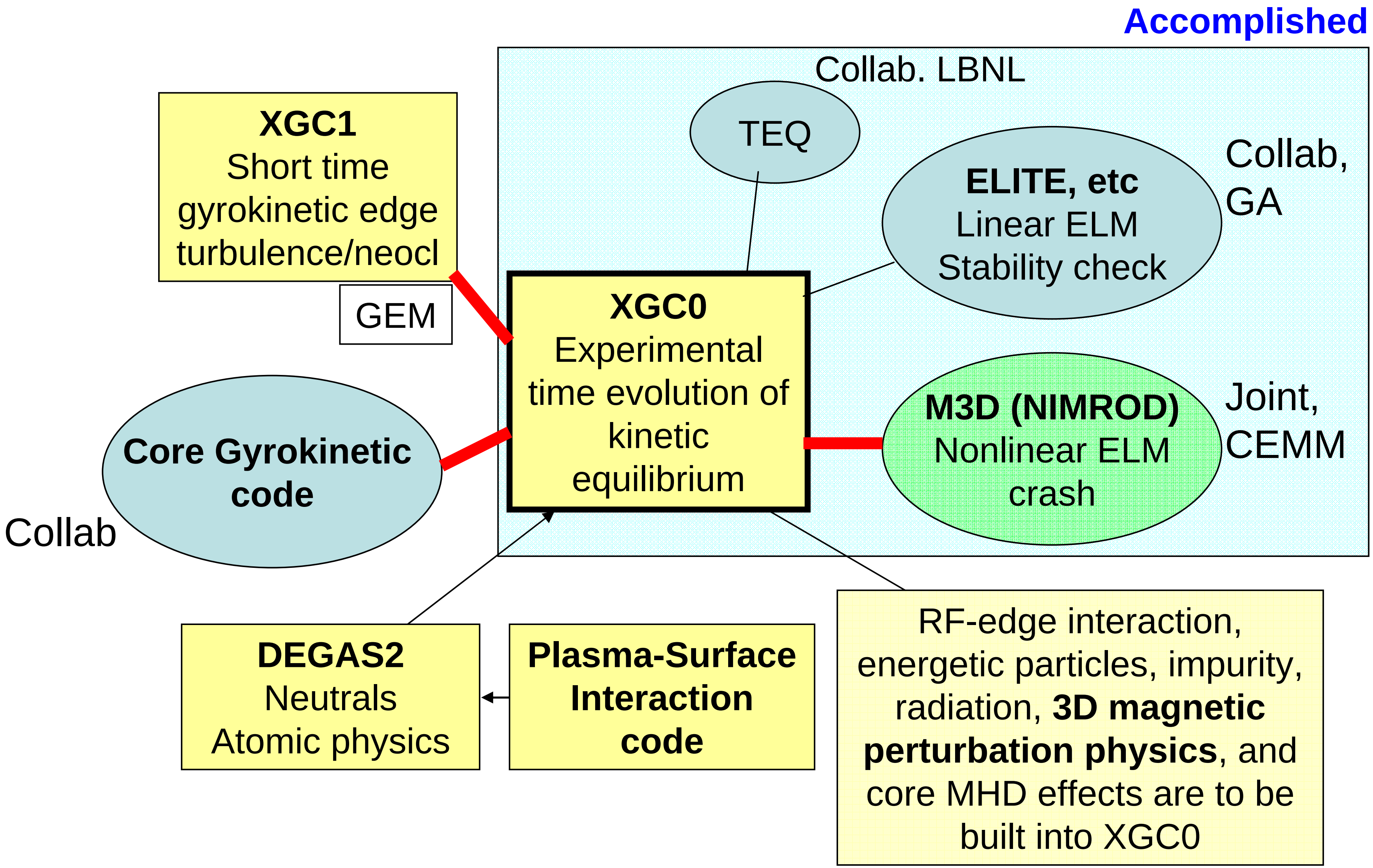
CPES
Center for Plasma Edge Simulation

Outline

1. Building integrated XGC framework in CPES
2. The base code XGC0 (with classical transport)
3. XGC1 gyrokinetic edge turbulence code
4. Coupled XGC0-Elite-M3D framework
5. What critical physics can CPES study together with NSTX (before the XGC1 era)?

1. Automated multiscale code integration framework in CPES



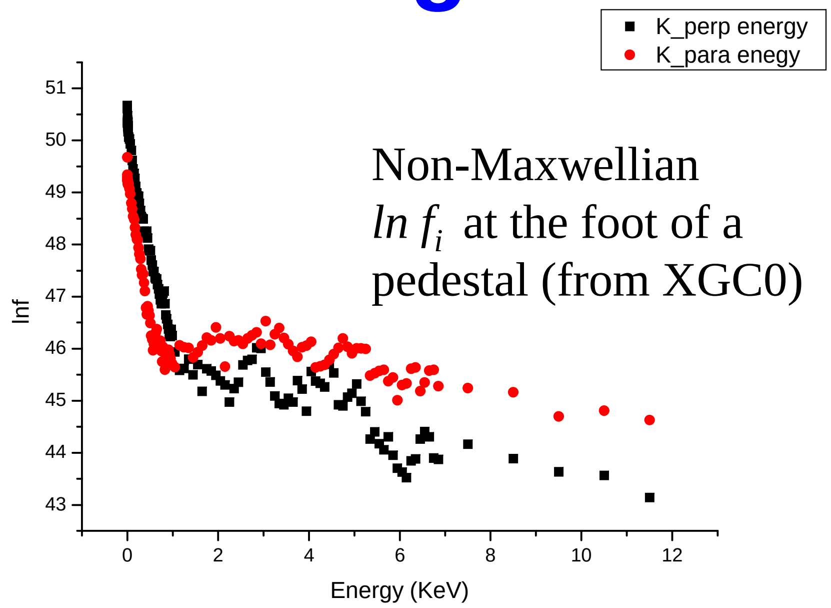
The problem requires time dependent, integrated understanding of

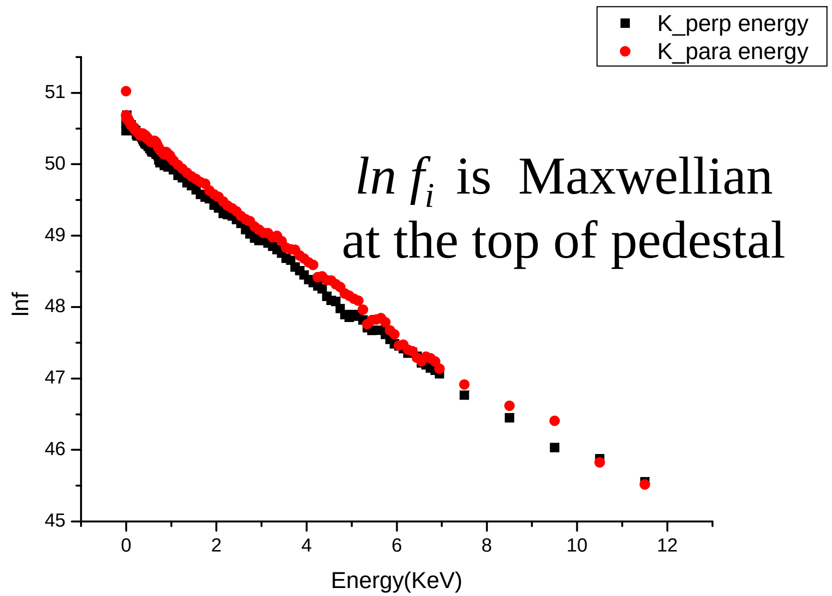
- Edge kinetic* neoclassical physics
- Edge kinetic turbulence physics
- Core turbulence and MHD physics
- Large scale edge localized modes (ELMs)
- Neutral, impurity and atomic physics
- Scrape-off physics
- Wall load, neutral recycling, and sputtering
- Energetic particle influx from core
- RF interaction of edge plasma
- 3D magnetic field effects

*Edge ions have steep gradient and are non-Maxwellian.

Kinetic plasma in the edge

- Orbit loss (X-loss)
- Non-Maxwellian ions in pedestal and near scrape-off due to steep gradient
- Non-Maxwellian ions and electrons due to open field lines
- Not a conventional neoclassical plasma
- J_{boot} works (marginally) in pedestal due to low U_i

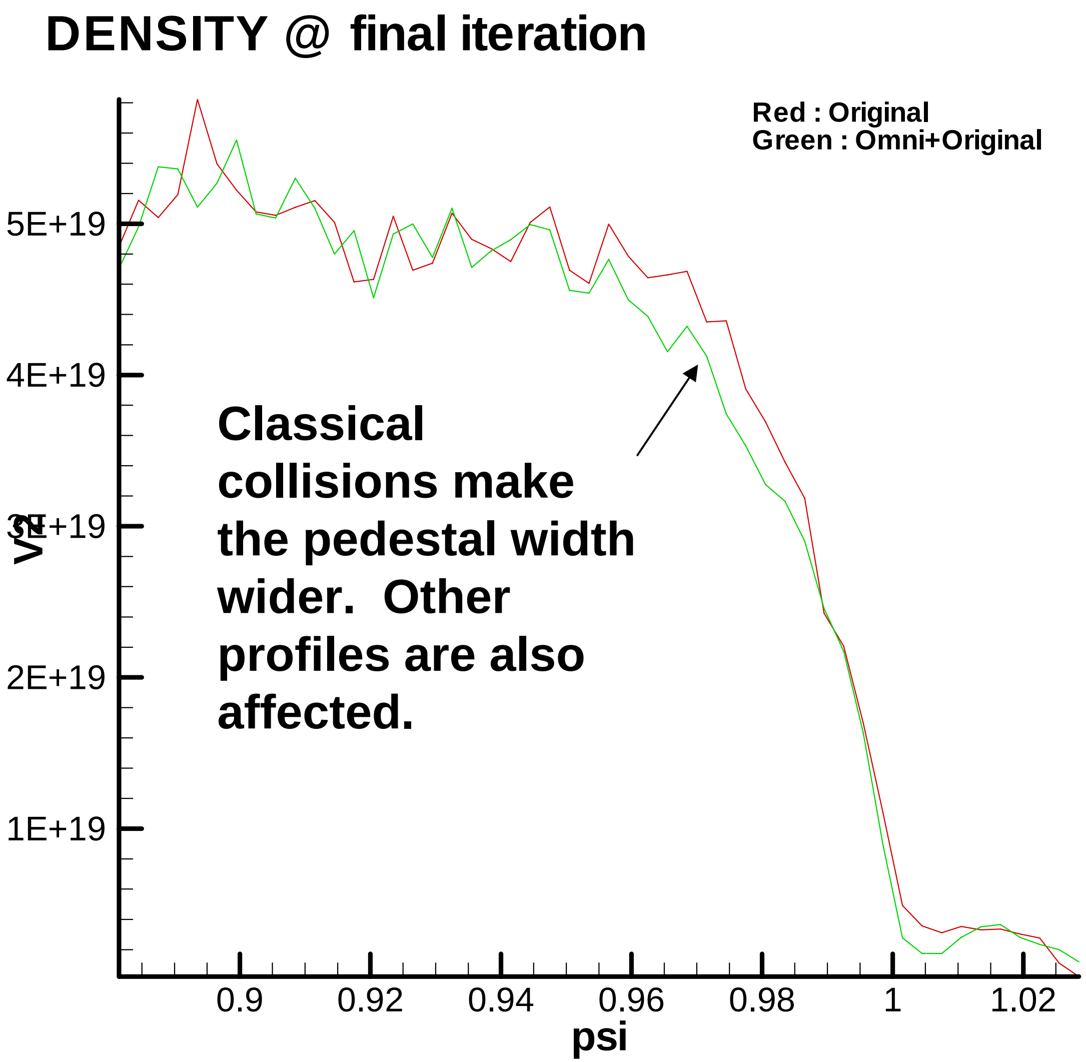




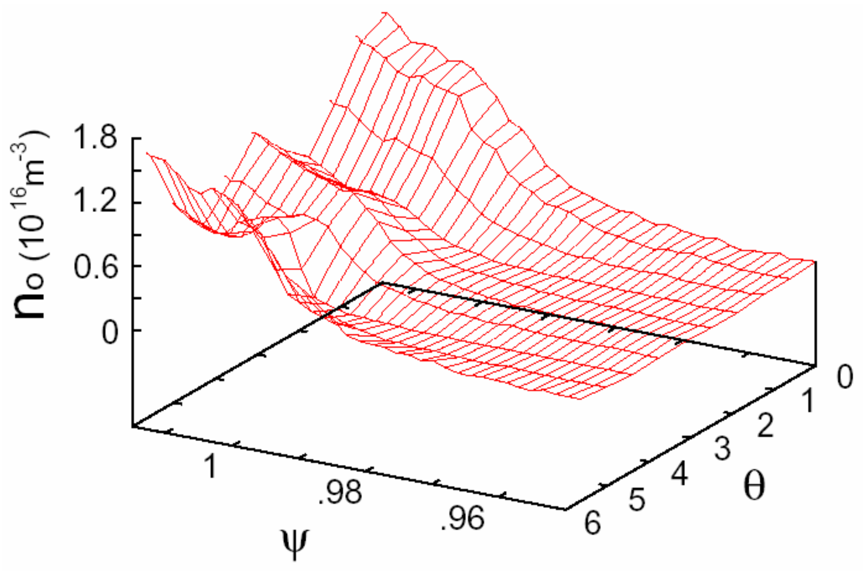
2. XGC0 is the base code for integration

- Long time f90 simulation of kinetic equilibrium and transport
- Ion/electron/neutral, **full-f**, 5D guiding center dynamics
- Z_{eff} in the current version
- Conserving collisions
- $\Phi(\psi)$ electric potential solver
- Finite gyroradius collision effect (Omni) included for ST
- XGC0 will integrate in all the other physics components
- XGC0 evaluates kinetic bootstrap current, and the corresponding Grad-Shafranov equilibrium B evolution
- Kepler integration framework for automatic coupling of XGC0-Elite-M3D is established for pedestal-ELM cycle
- $\Phi(\psi)$ in scrape-off is less accurate (needs XGC1 verification)
- Integration of DEGAS2 into XGC0 is to produce the first fully kinetic, edge plasma-neutral transport code.

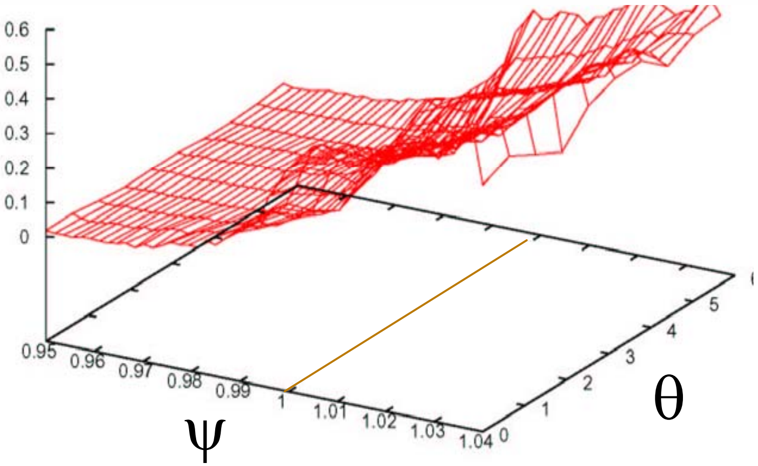
Effect of classical physics on pedestal can be significant in NSTX

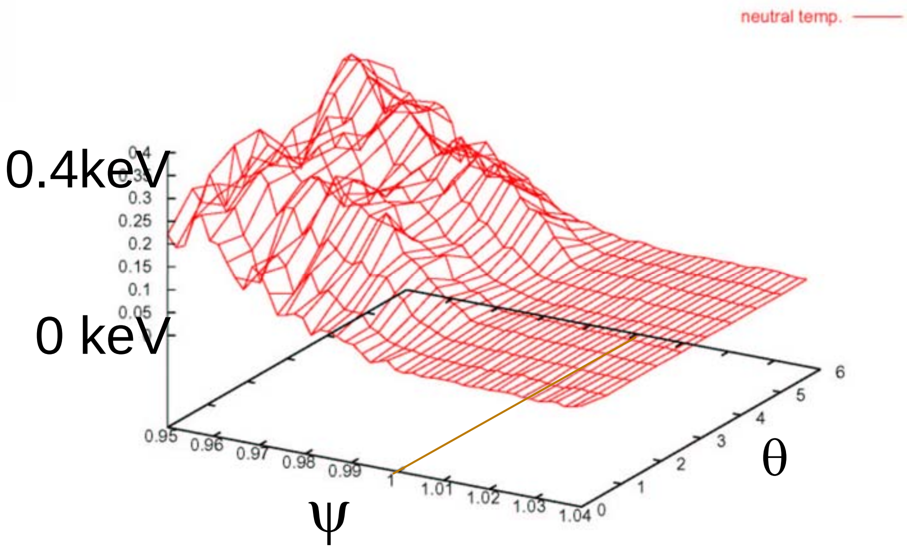


Neutral density and temperature distribution in DIII-D



If constant poloidal source distribution

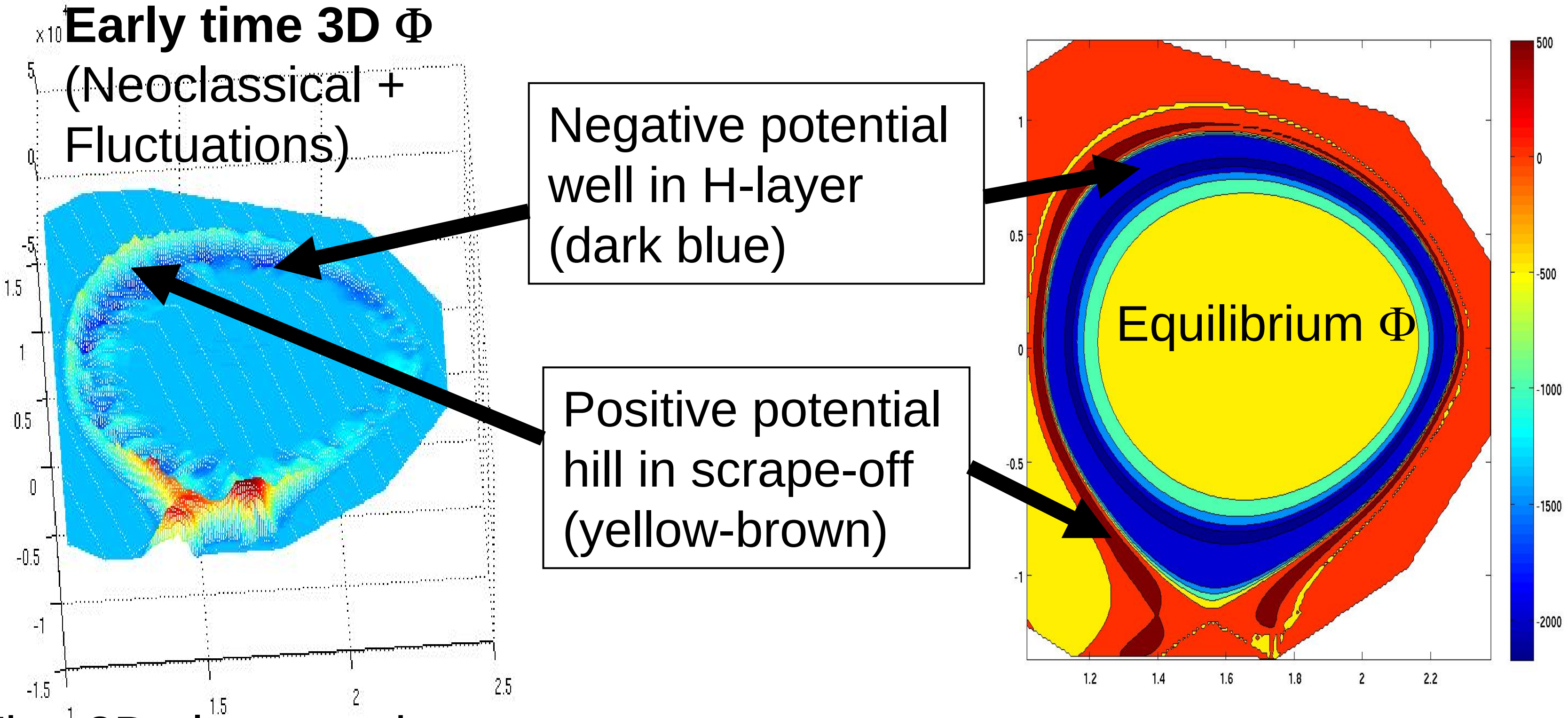




3. XGC1 Edge Gyrokinetic Code

- Particle-in-cell 5D gyrokinetic code in f90
- Integrated neoclassical and turbulence
- Unstructured mesh
- Realistic numerical g_eqdsk geometry with X-point
- Conserving collisions
- Full-f ions and electrons (neutrals with recycling)
- Can run in a mixed-f mode
- (Noise dissipation by physical collisions)
- Heat (particle) flux from core
- Particle source from neutral ionization
- (Heat/particle sink through transport, atomic physics and wall interaction)
- Solver: $E_r \neq 0$ at inside and $\Phi=0$ at wall

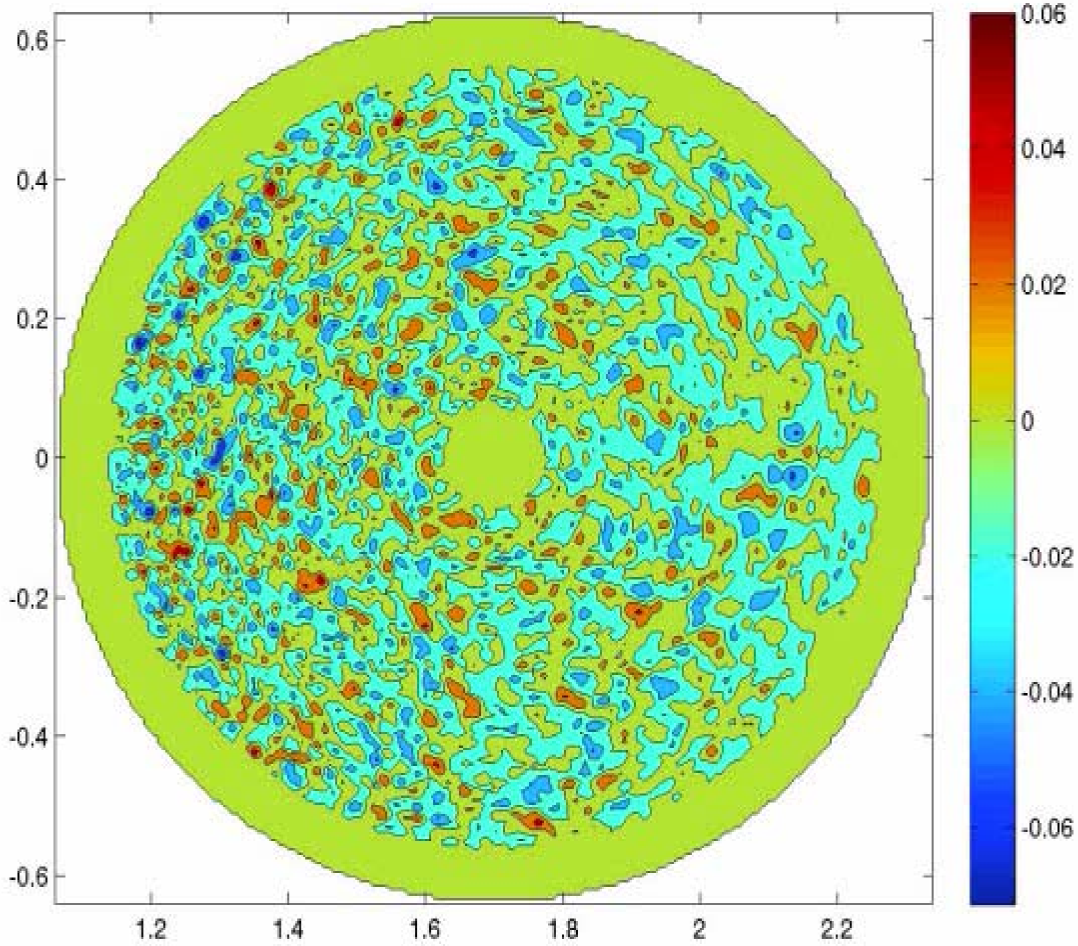
XGC1: Short time Turbulence/Neoclassical gyrokinetic code, will provide turbulence flux to XGC0



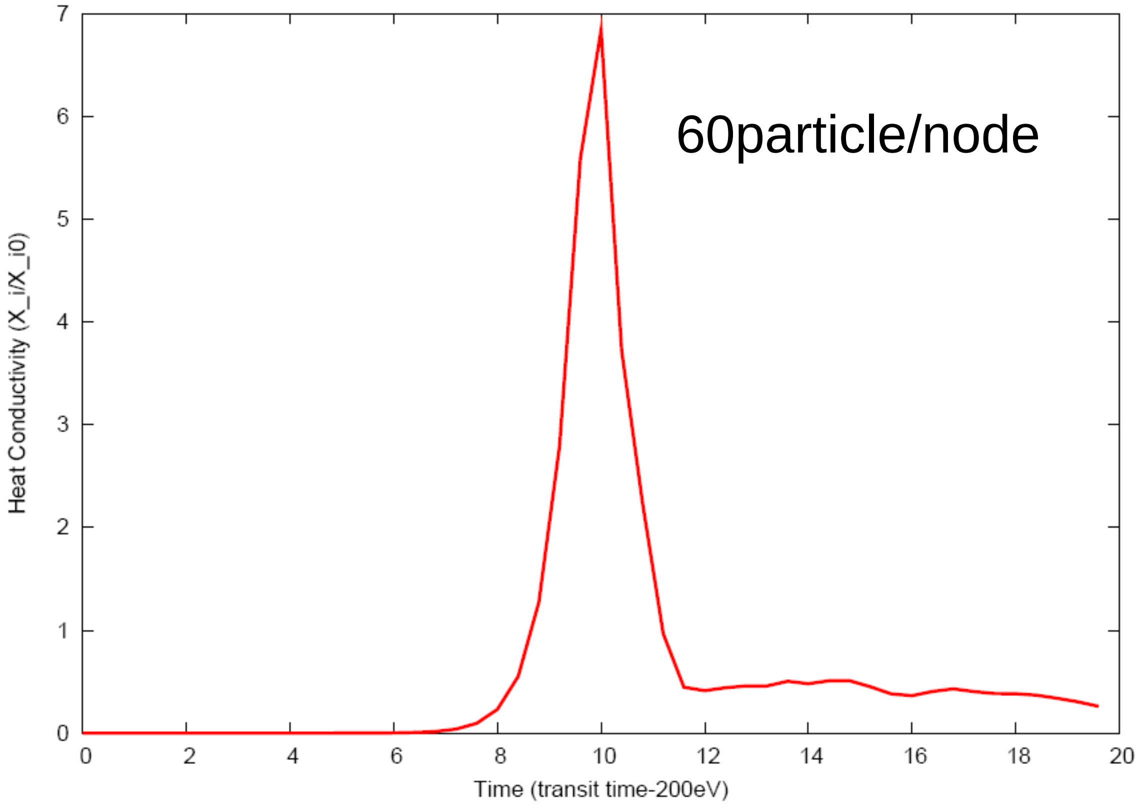
First 3D electrostatic solution across separatrix has been obtained from XGC1. What fraction of the fluctuation is numerical?

2D neoclassical potential distribution has been extracted from 3D by toroidal averaging and poloidal-time smoothing

XGC1 verification in cyclone plasma: Time evolution of turbulent potential



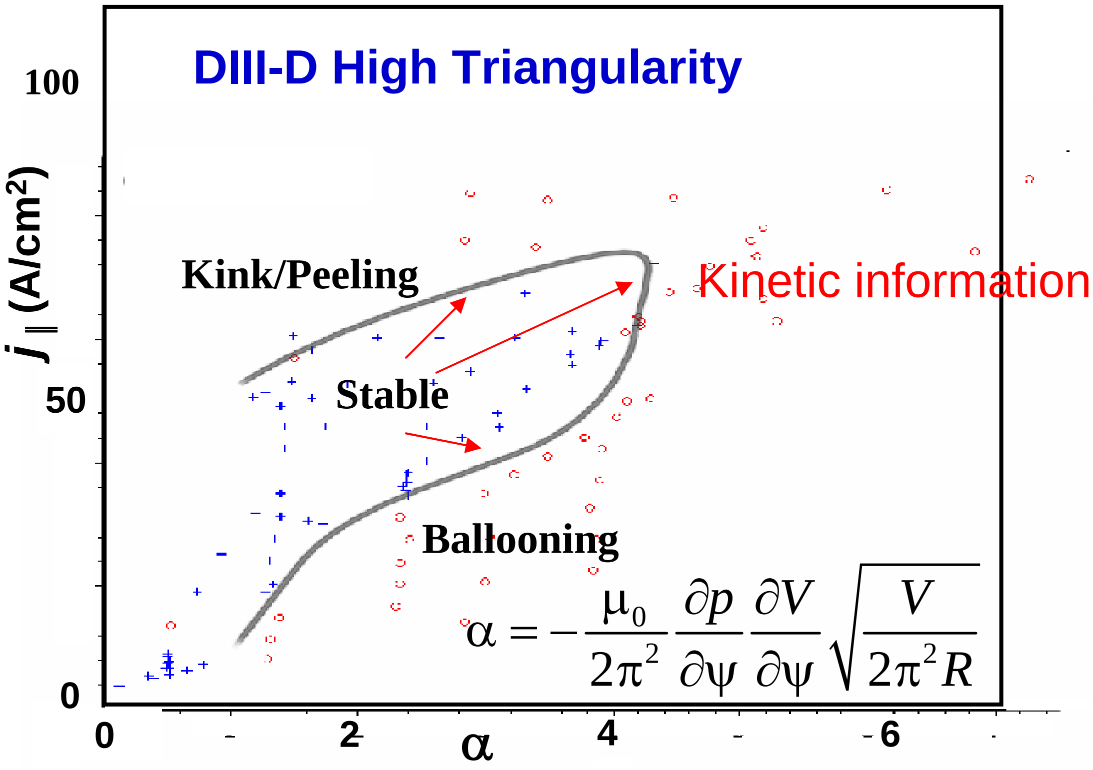
Time dependence of ITG turbulence diffusion coefficient in XGC1 (decays after plateau)



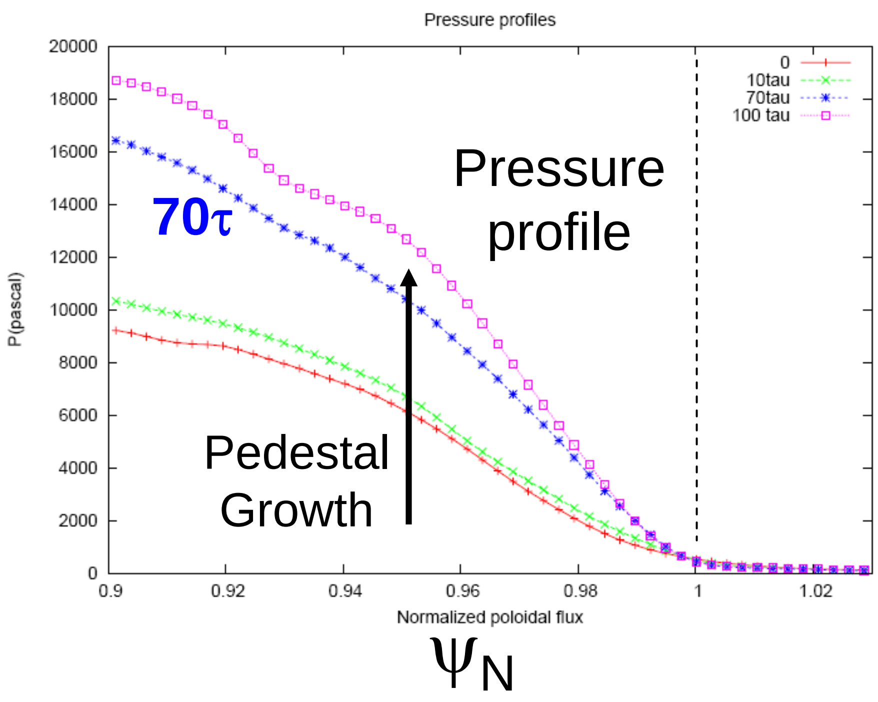
(For verification in cyclone geometry: δf_i and adiabatic electrons)

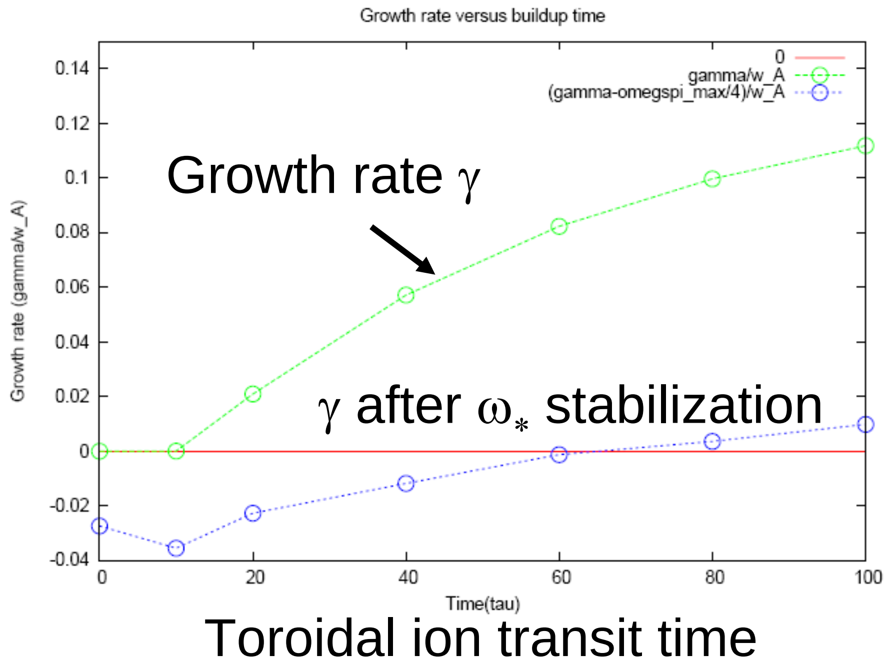
4. Coupling with the Elite linear stability code

- Authors: P. Snyder and H. Wilson
- Intermediate to high n (> 5) ideal MHD instabilities
- Extension of the ballooning formalism through two orders in 1/n
- Peeling-ballooning stability bounds



Elite stability monitoring of kinetic XGC0 pedestal growth





Neoclassical dominant pedestal growth (D_{Anom}= 0.05m²/s, ballooning)

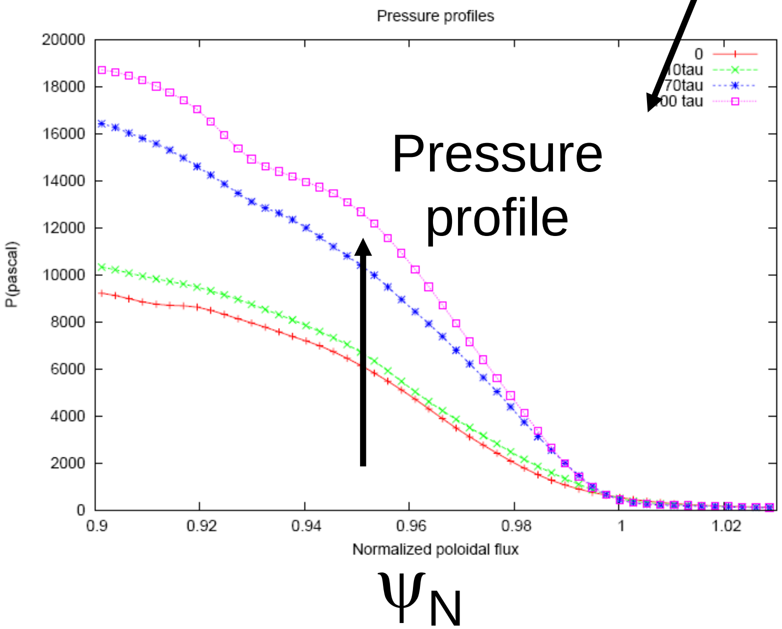
Type-I ELM unstable around 70τ

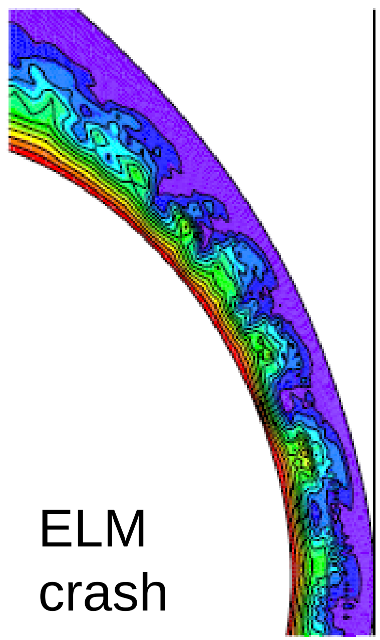
Coupled XGC0-MHD simulation of ELM cycle

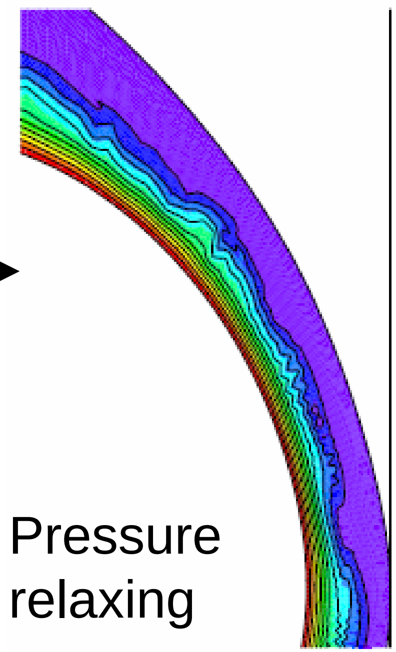
Linear stability check (Elite)

Pedestal buildup by XGC0

ELM crash by M3D







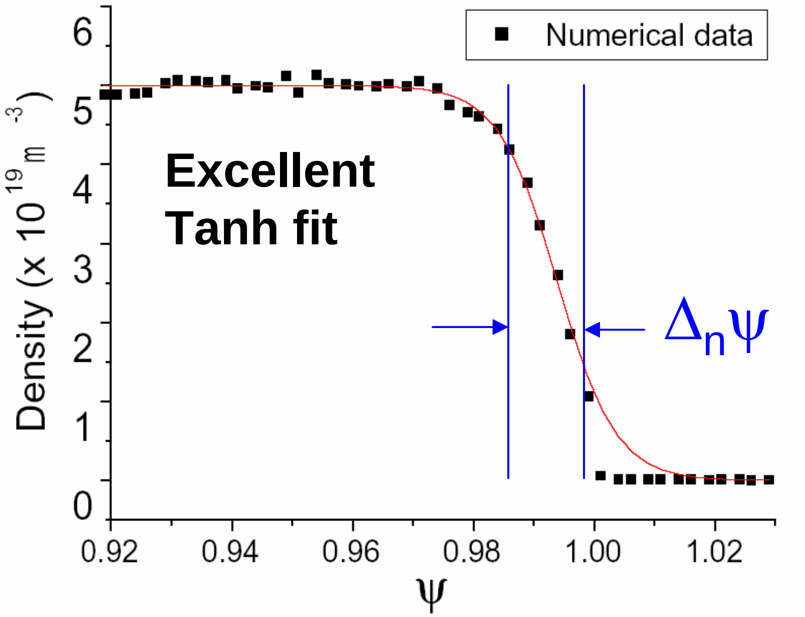
What can CPES do in collaboration with NSTX experiments?

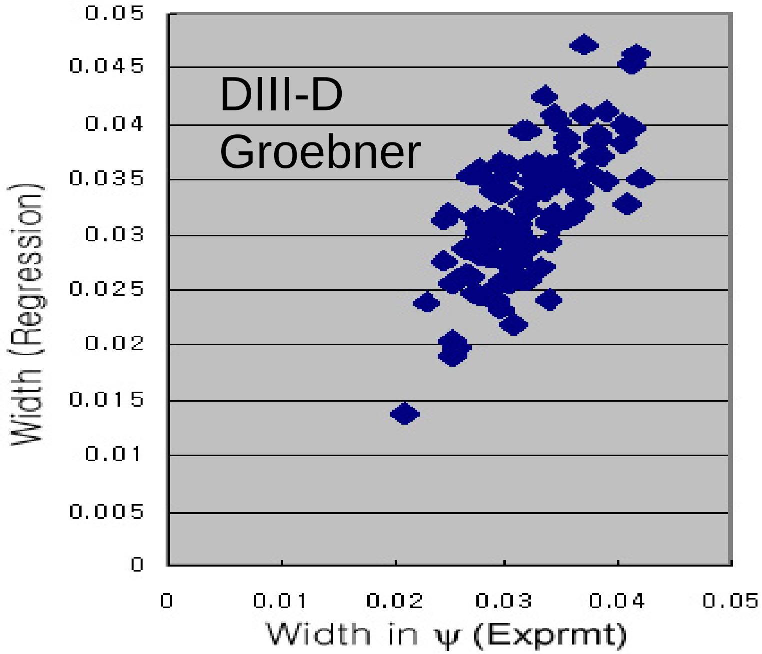
NSTX

- There are many critical NSTX/ITER physics issues we can study together even before the completion of XGC1.
- Two-sided goal of CPES
  - First principles understanding (extreme computing)
  - **Practical modeling by improving the transport matrix**

- Estimate how large D_{Anom} is in pedestal
- Investigate pedestal scaling law
- Test D_{Anom} models for H-mode transition
- Fundamental 0th order physics (fi, ExB rotation, etc)
- RMP studies for ELM control
- Neoclassical rotation sources in the edge
- Kinetic modeling of the whole plasma under heating/momentum source models and D_{Anom} models
- Divertor heat load, and others

- How large is the turbulence transport component in pedestal?
- Can we get a reliable pedestal scaling law without full understanding of turbulence?





XGC finds neoclassical density pedestal width scaling

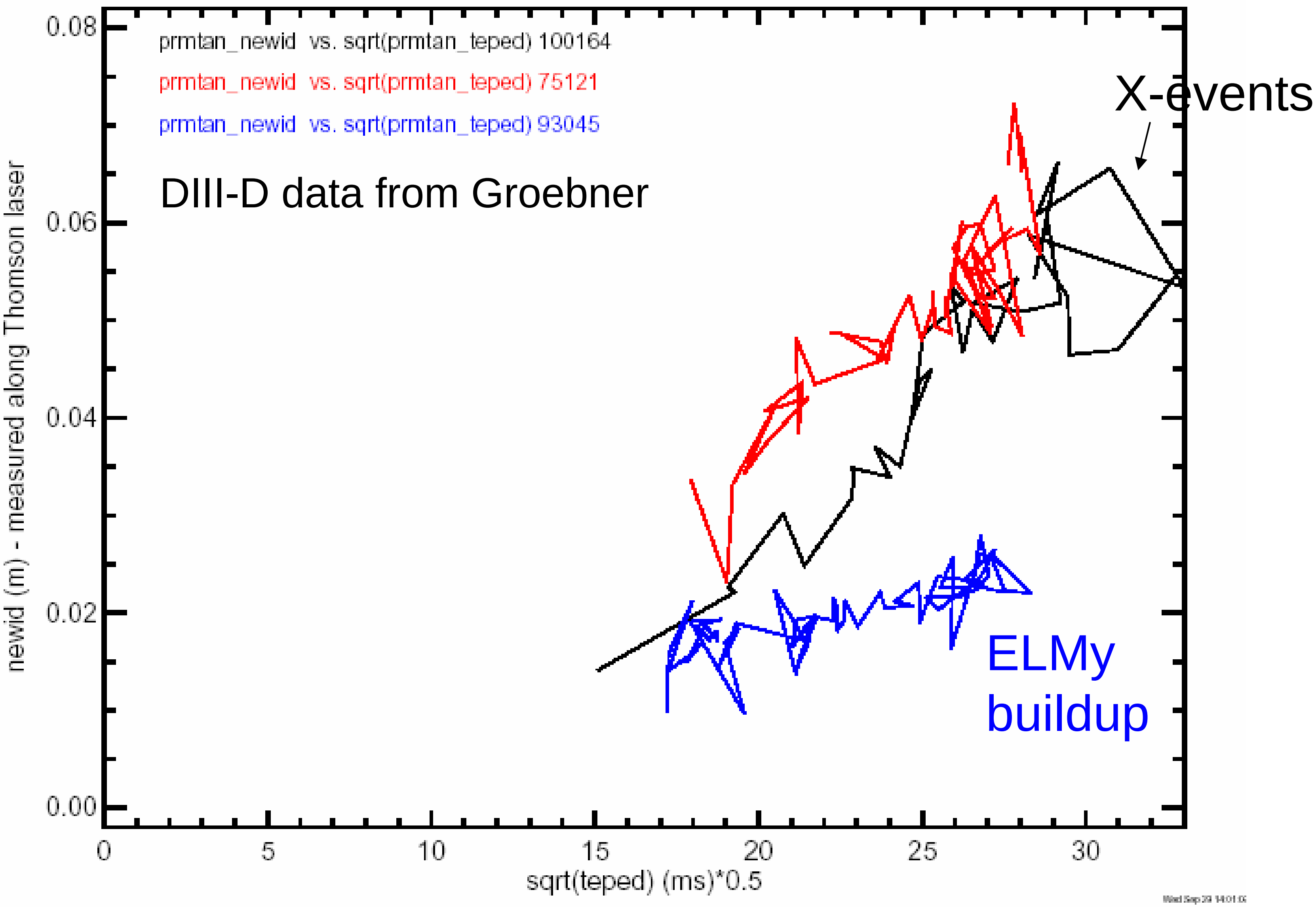
$$\Delta_n\psi(\text{neo}) \propto M_i^{1/2}\,(T_i^{0.5}-0.23)\,/B_T$$

DIII-D data shows

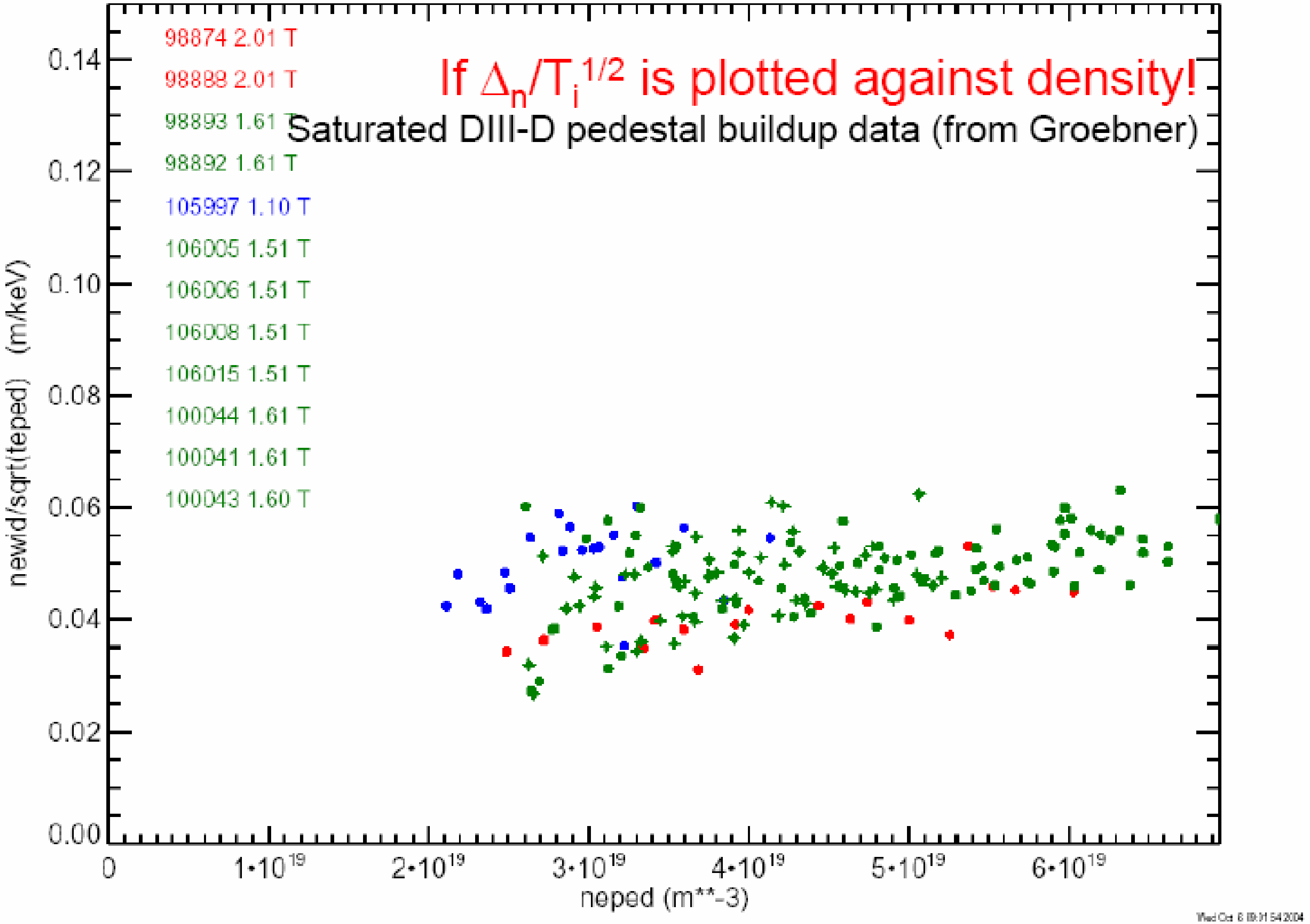
$$\Delta_n\psi(\text{exp}) = 0.075\,(T_i^{0.5}-0.22)/B_T + 0.0092\,n/q$$

Neoclassical **Anomalous (10 - 20%)**

Δ_n increases with Sqrt($T_{e,ped}$) during buildup

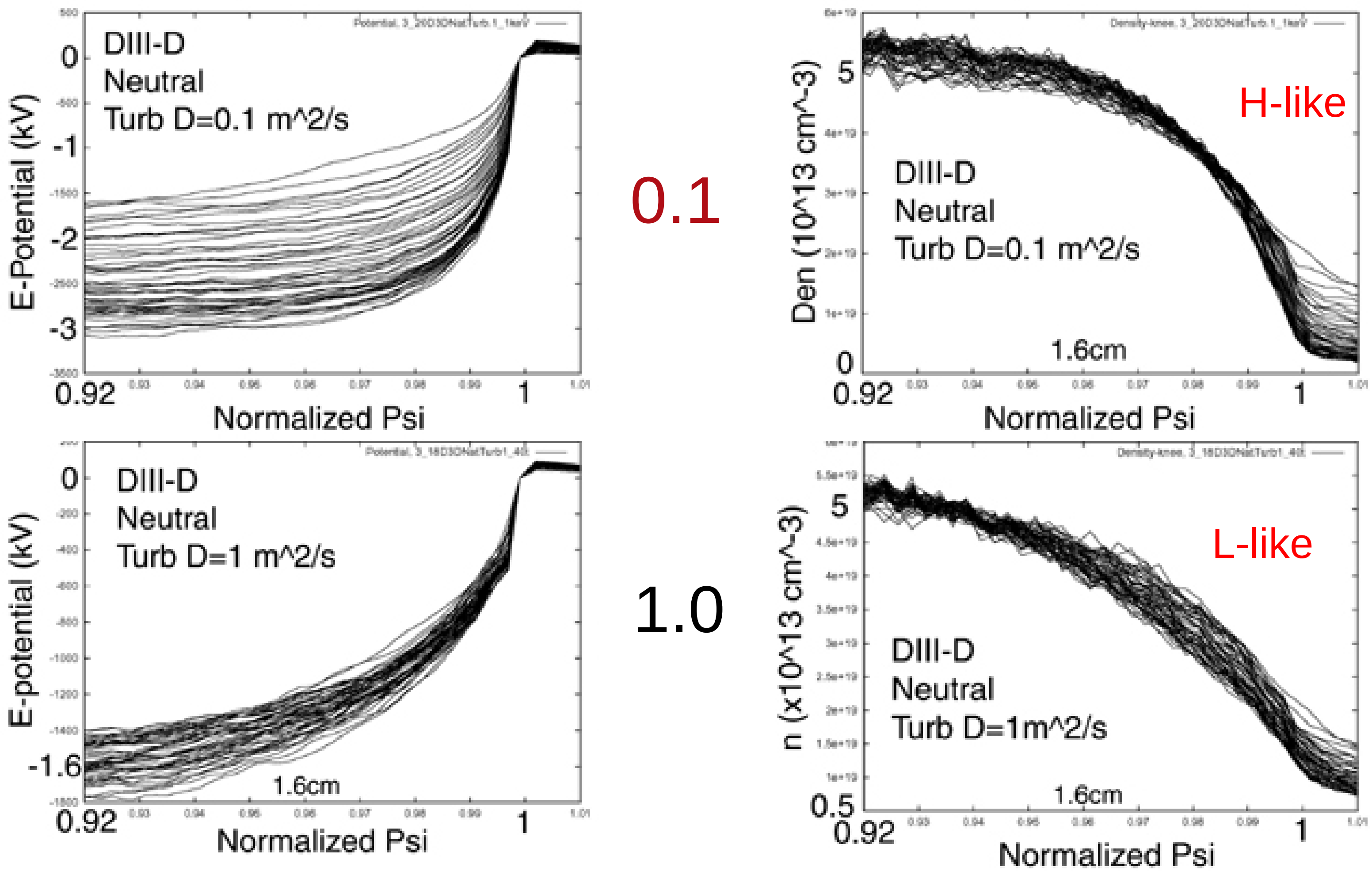


Weak anomalous transport effect shows up



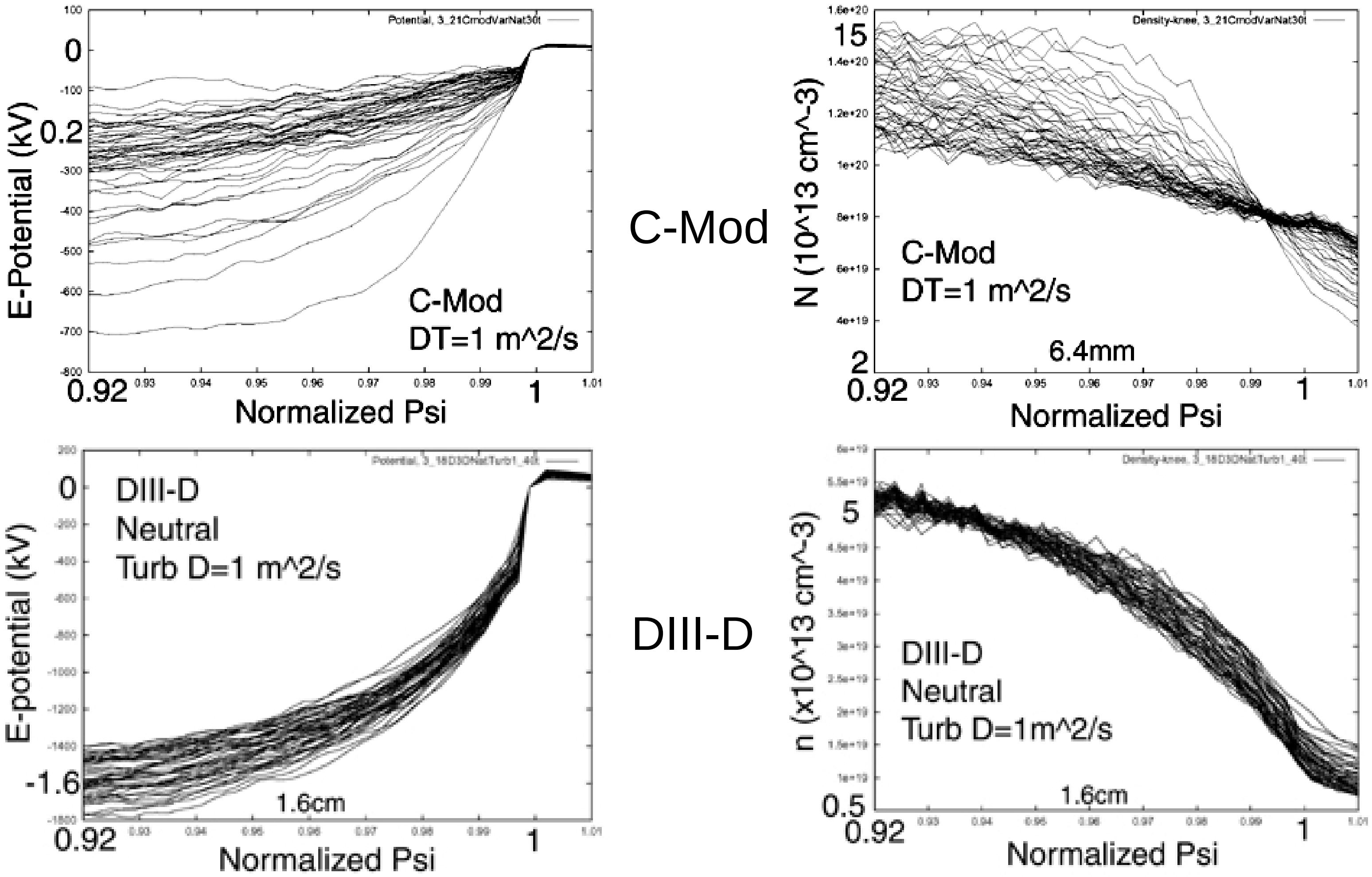
Reduce $D_{Anom} \Rightarrow$ pedestal sturcture

$D = 0.1\ m^2/s$ (δ_r=0.4 mm), T_i= 1 keV

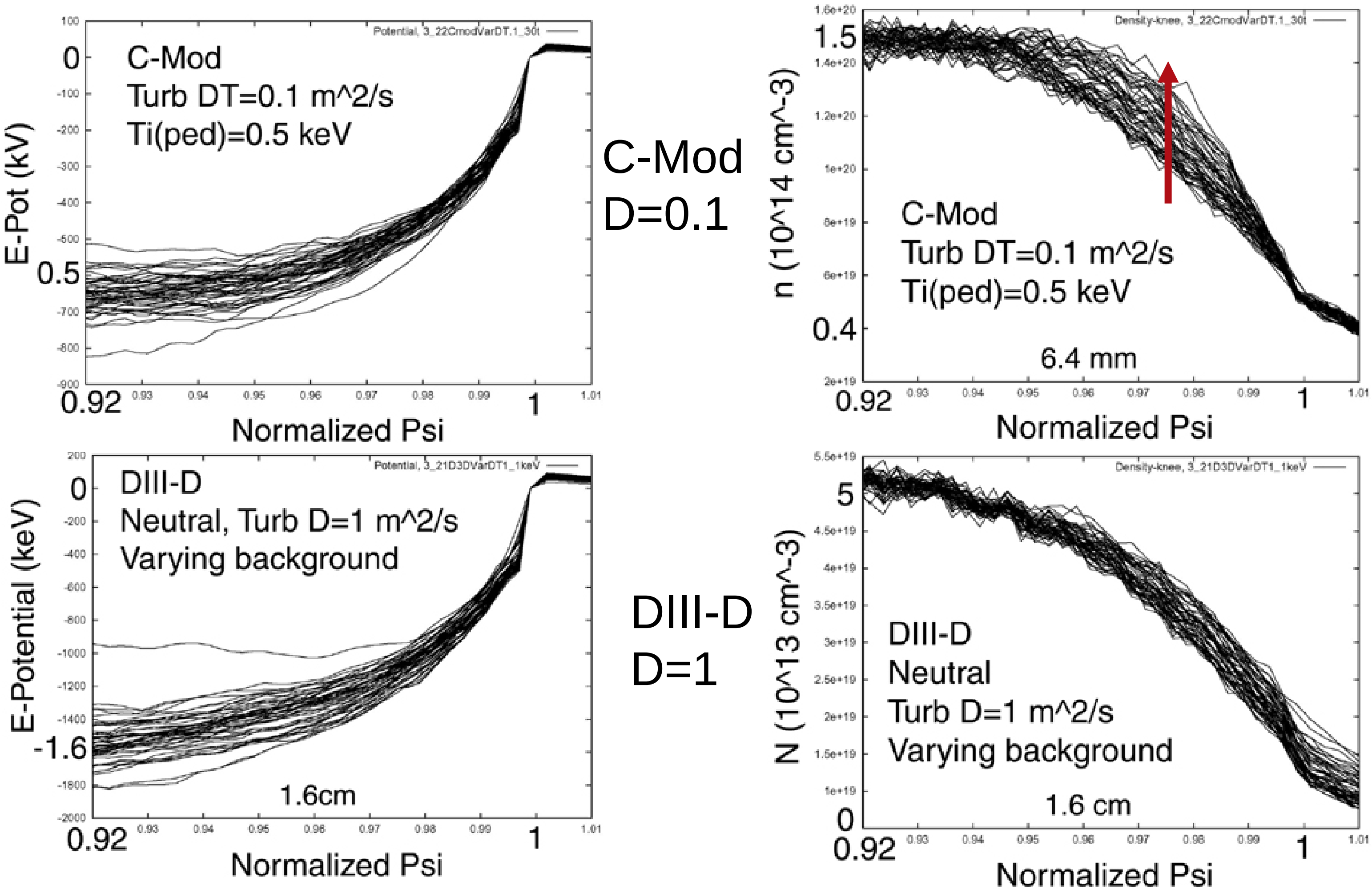


DIII-D **vs** C-Mod

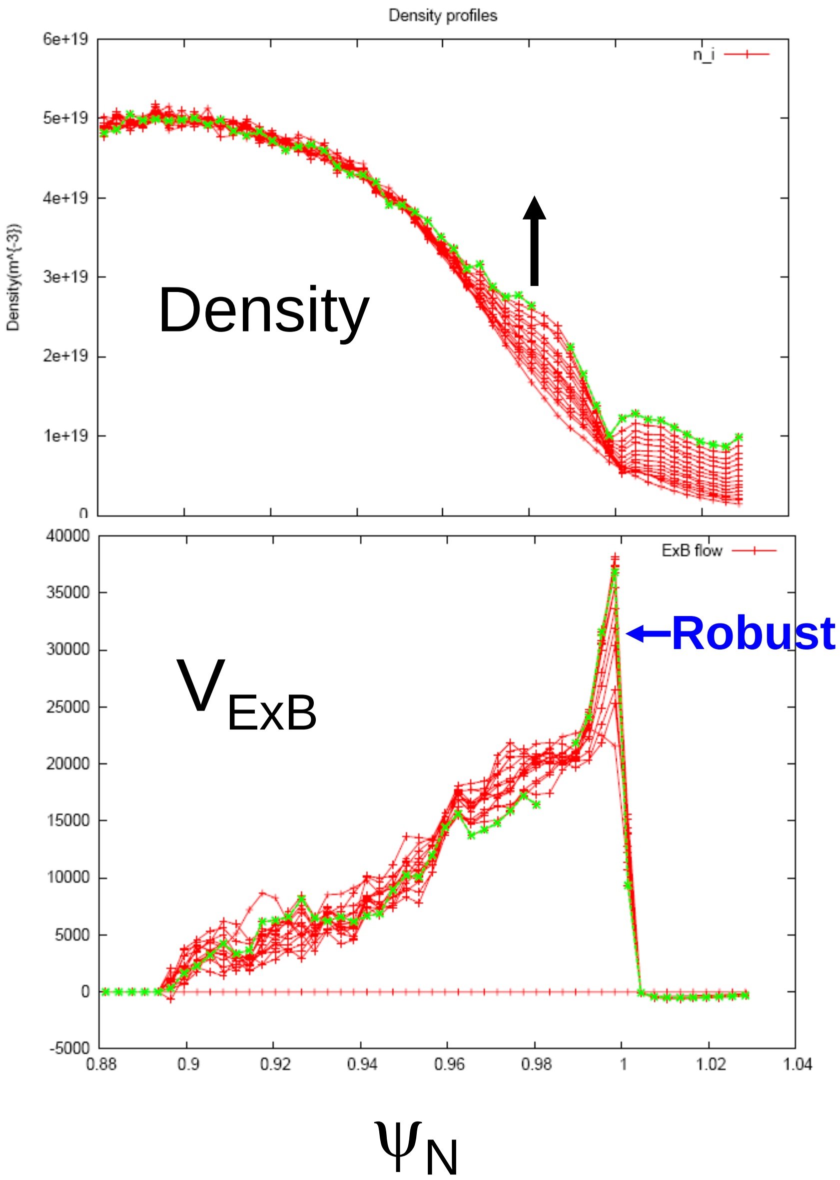
C-Mod plasma has smaller D_{Turb}

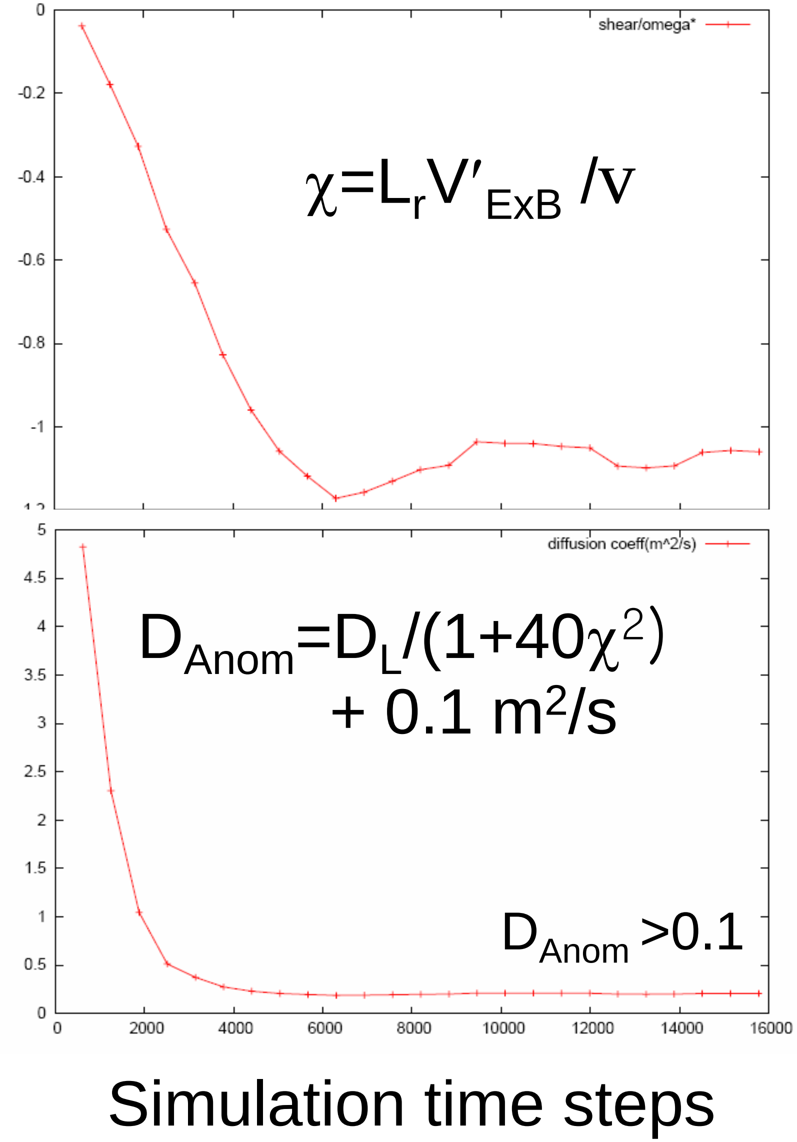


Reduced D_{turb} in C-Mod yields better comparison.
Test if Bohm or GyroBohm?

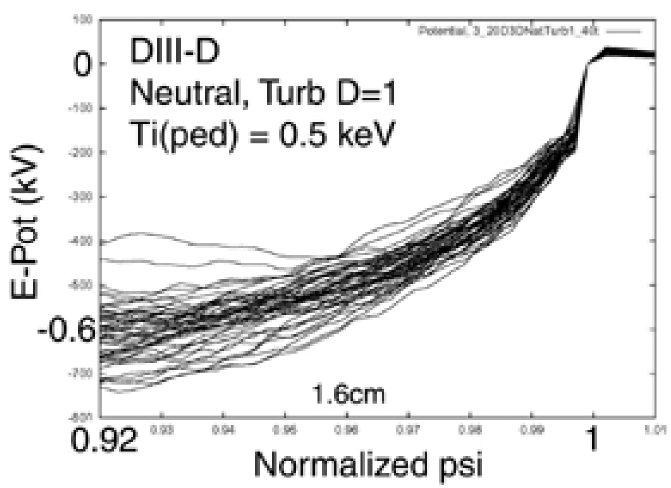


- Test of analytic turb diffusion model in XGC0

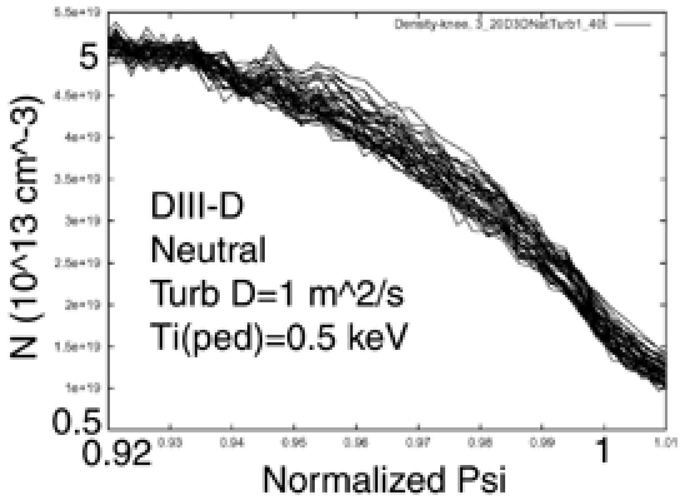


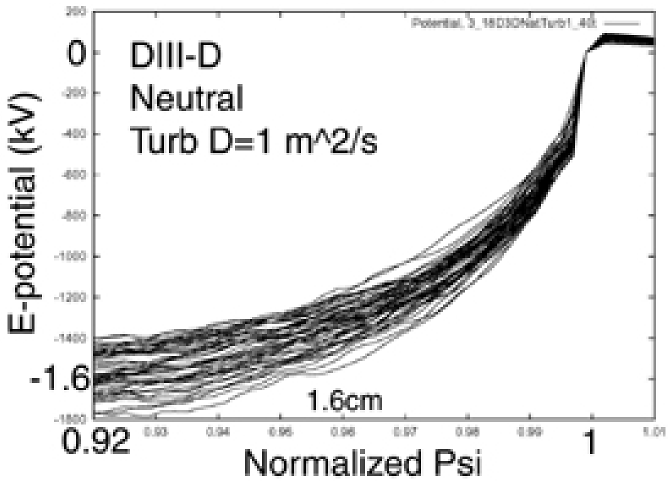


E_r increases with T_i (ped) under Turbulence diffusion (D=1 m^2/s)

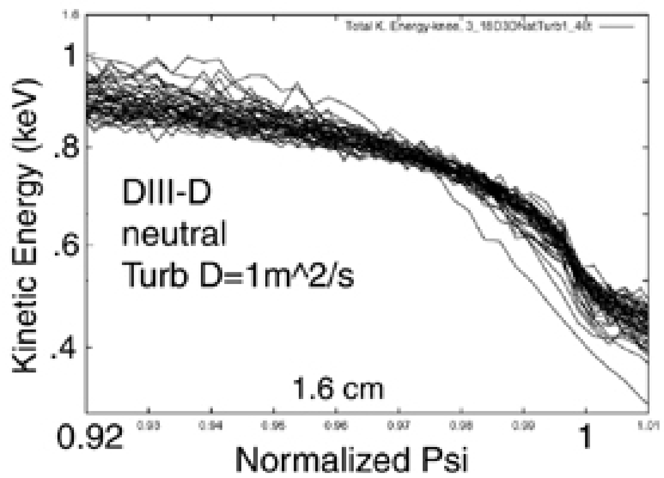


T_i=
0.5 keV



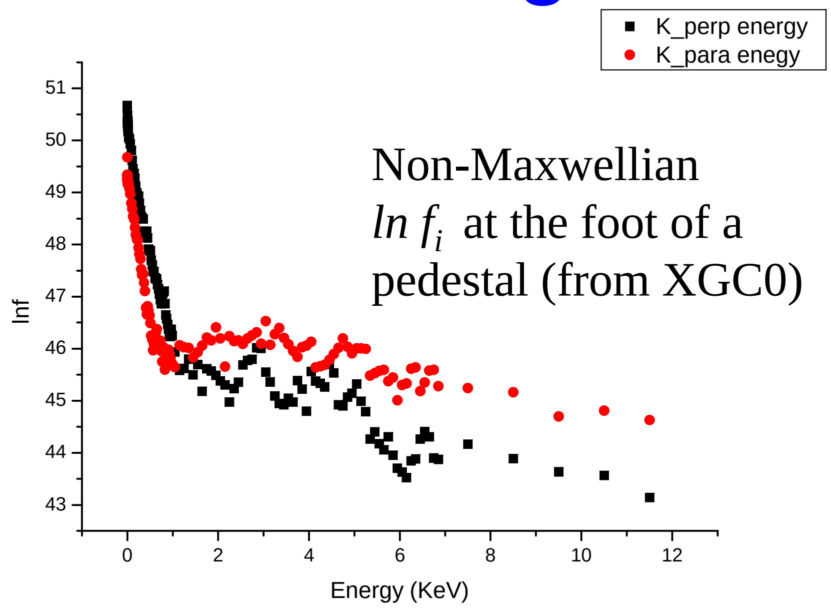


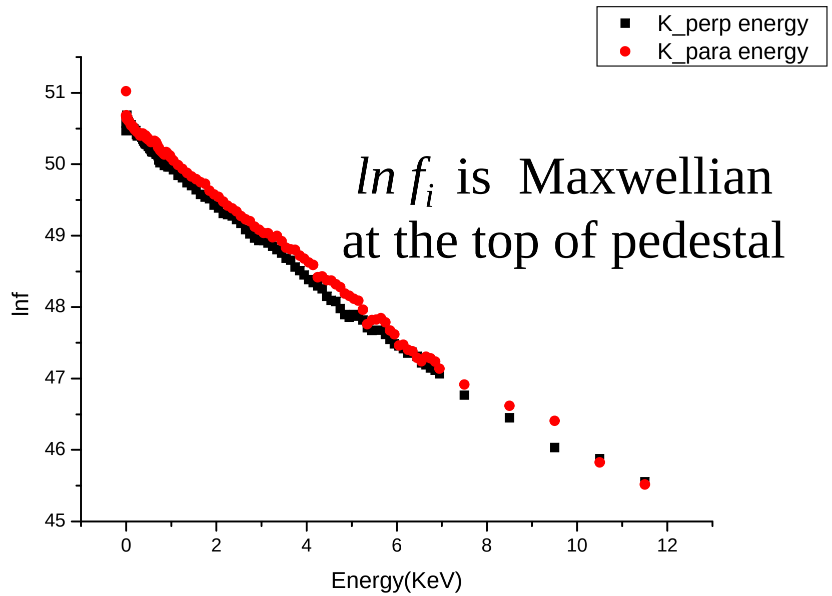
1 keV



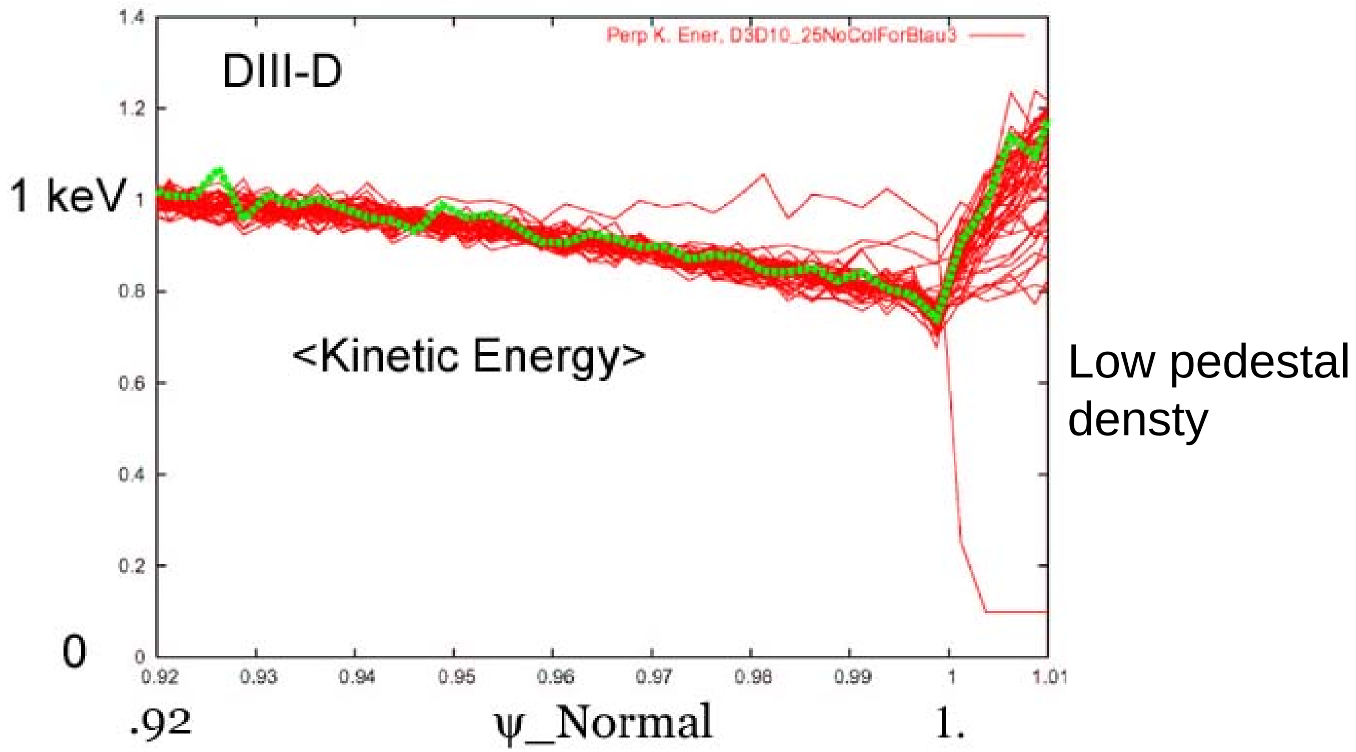
- Zero-th order physics in the edge

- Orbit loss (X-loss)
- Non-Maxwellian ions in pedestal and near scrape-off due to steep gradient
- Non-Maxwellian ions and electrons due to open field lines
- Not a conventional neoclassical plasma
- J_{boot} works (marginally) in pedestal due to low U_i

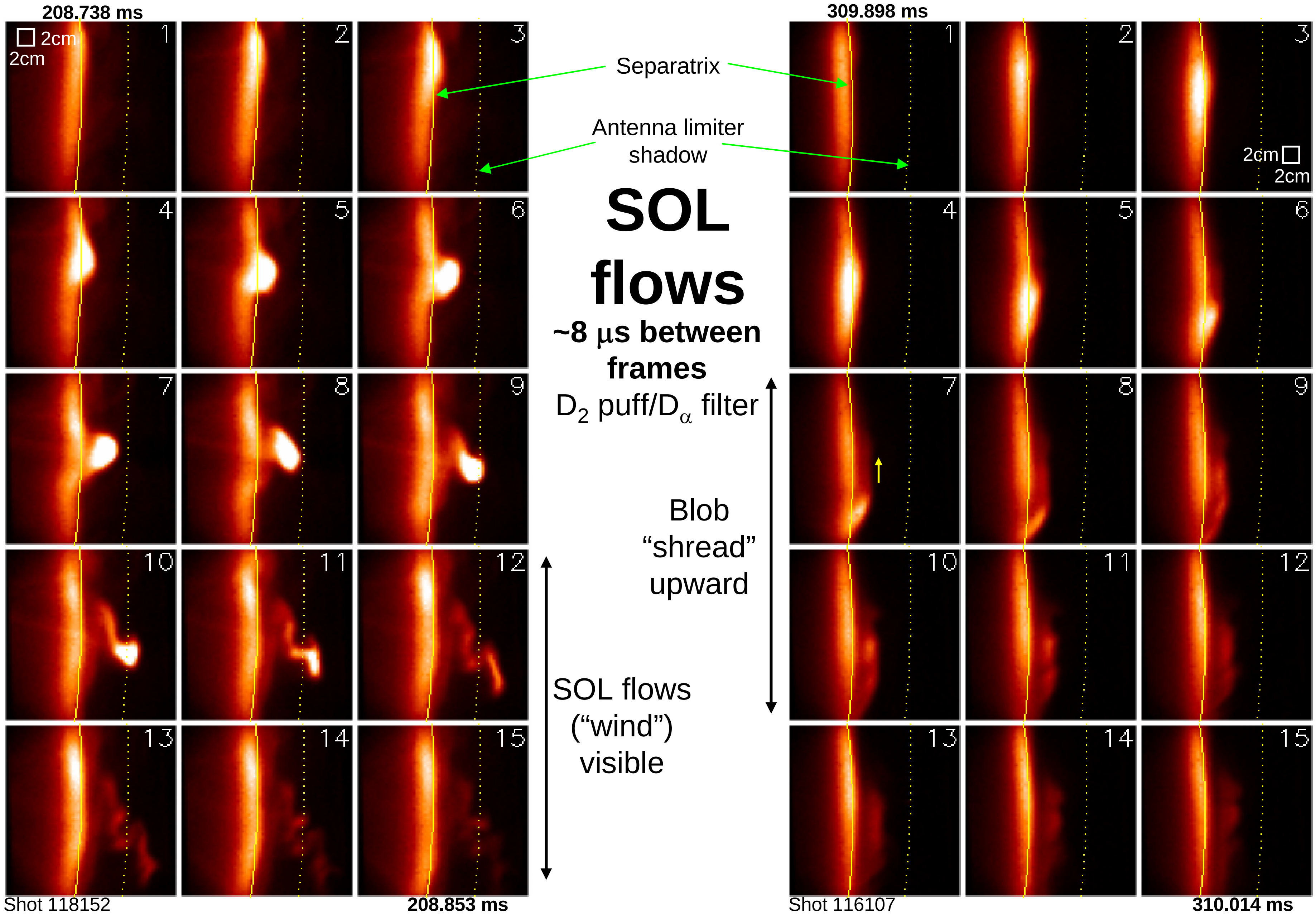




Edge ions are NonMaxwellian

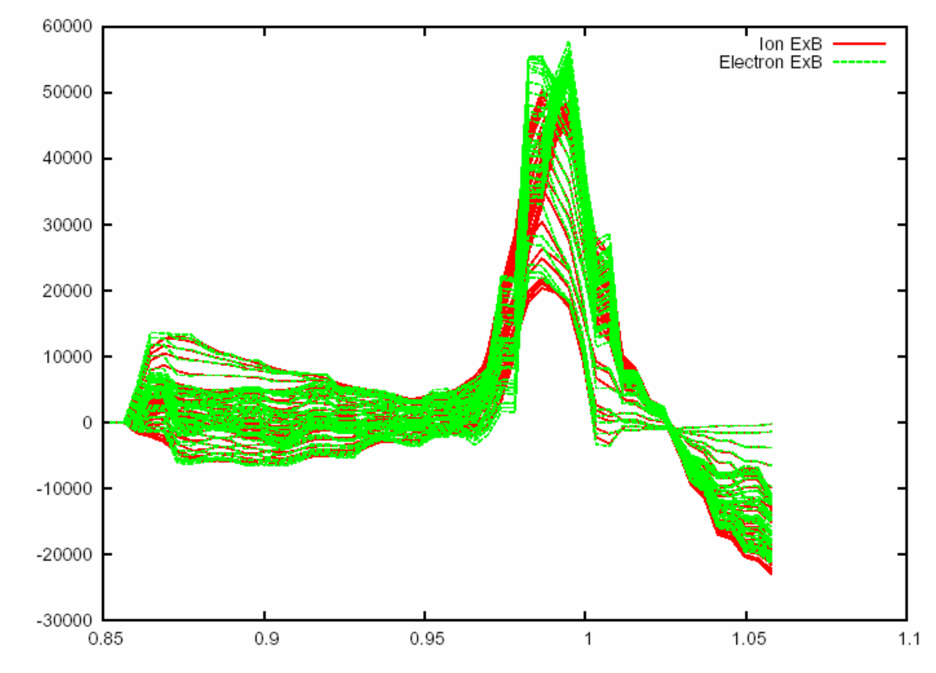


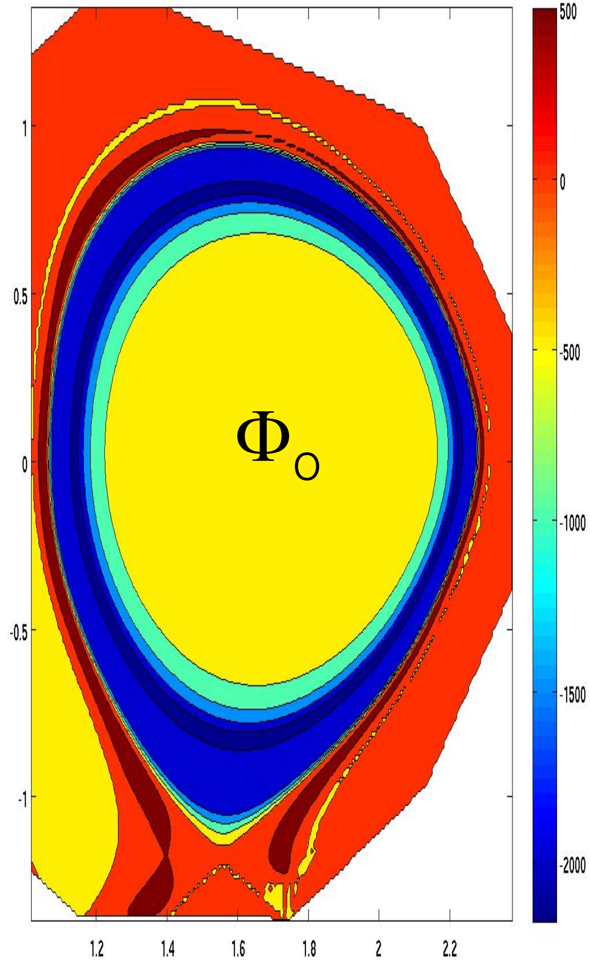
High scrape-off density relaxes the non-Maxwellian feature



Maqueda-Zweben-NSTX

Strongly sheared ExB rotation in the whole edge





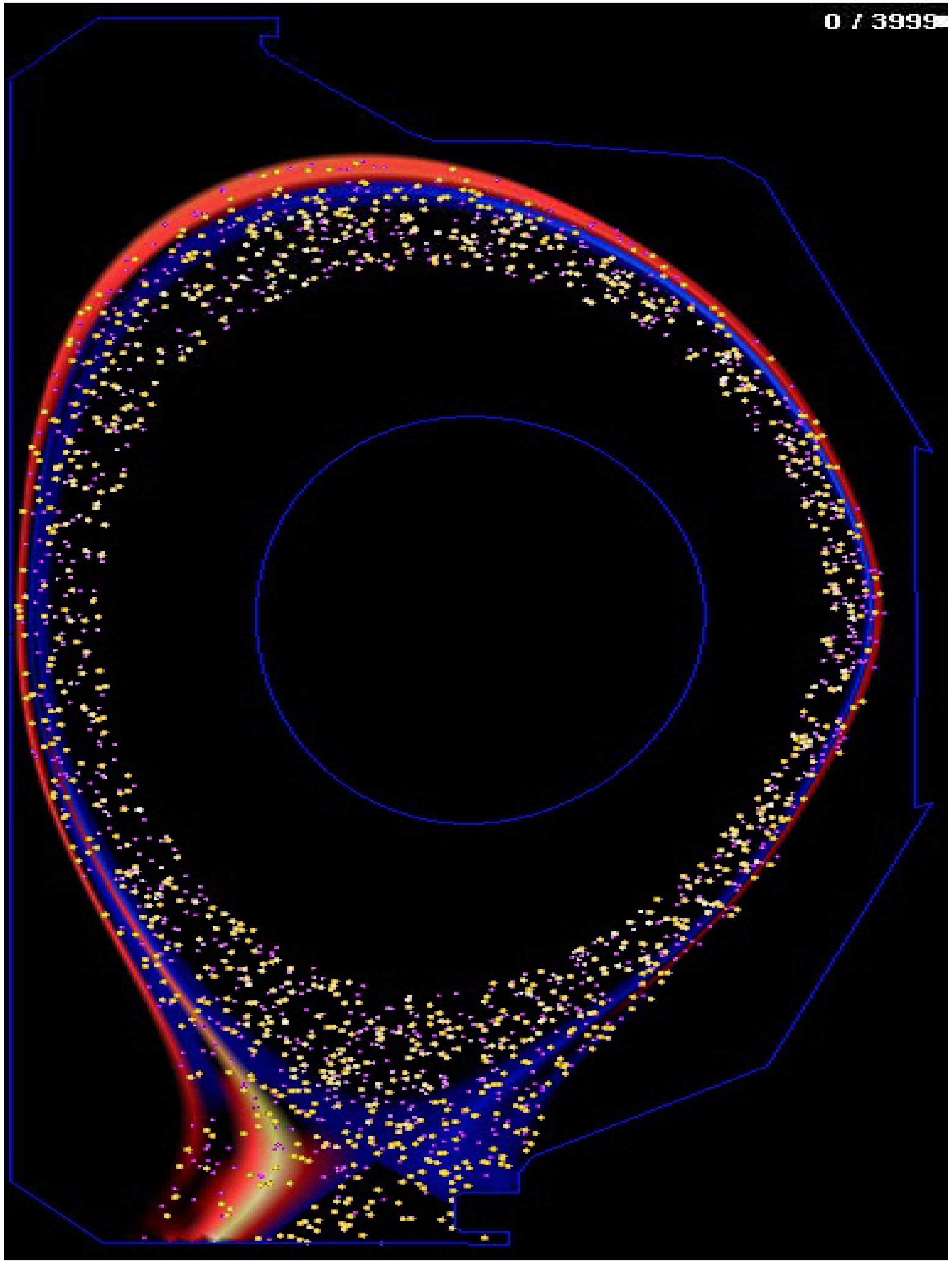
Gyrokinetic particle motions in the poloidal plane (XGC1)

ions

electrons

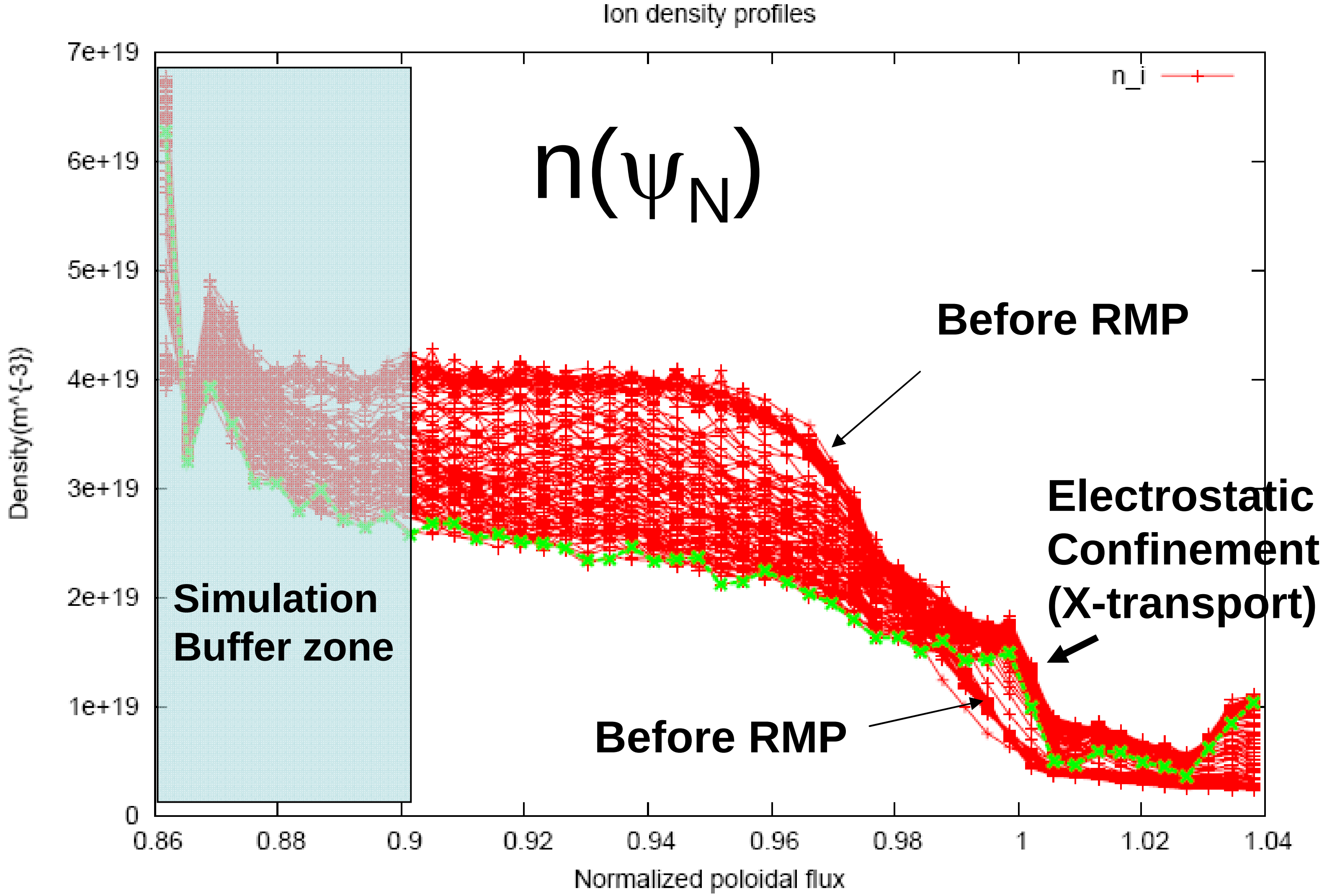
$V_{||} > 0$

$V_{||} < 0$

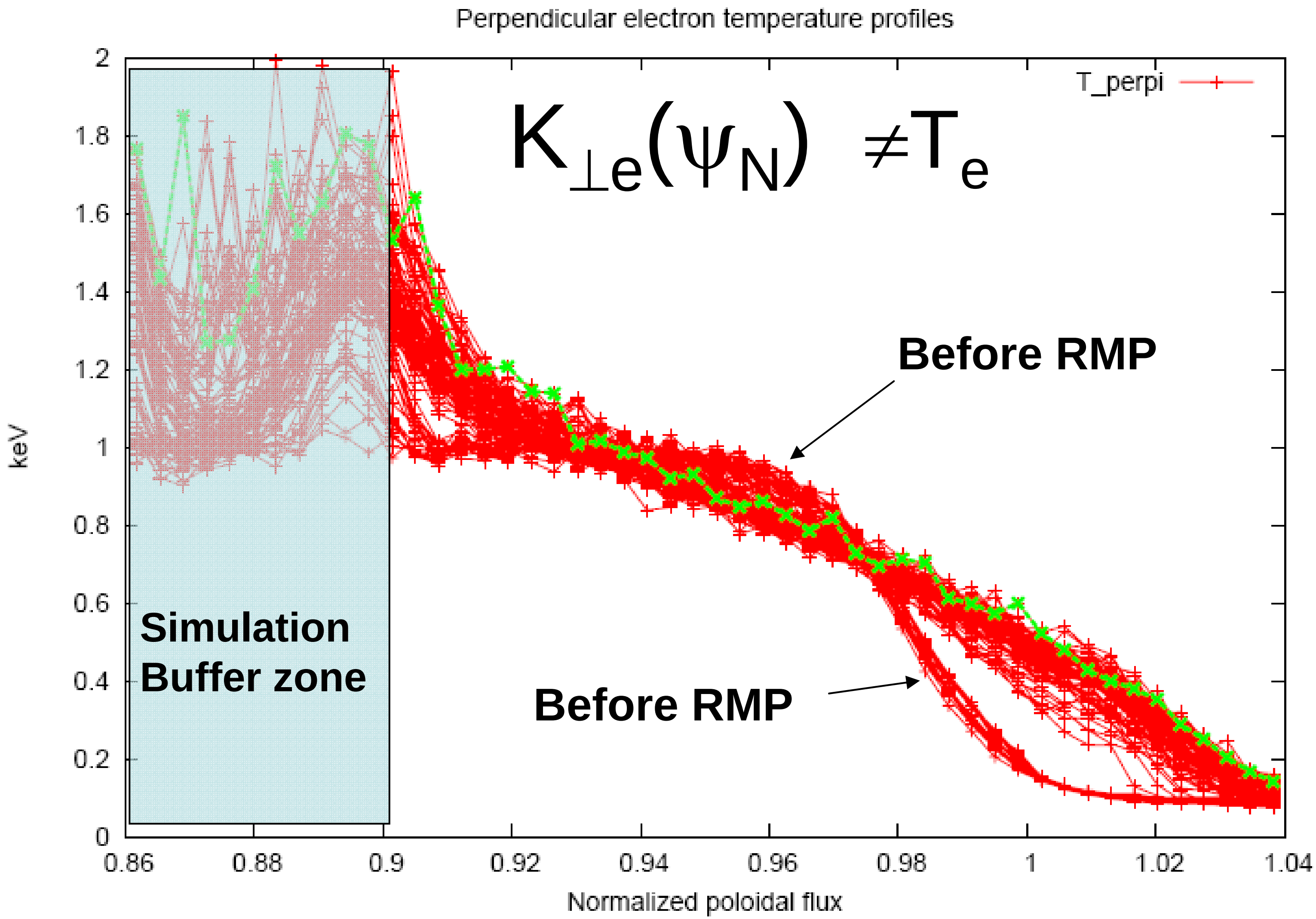


Significant density reduction occurs for all (vacuum) RMP events studied in XGC0

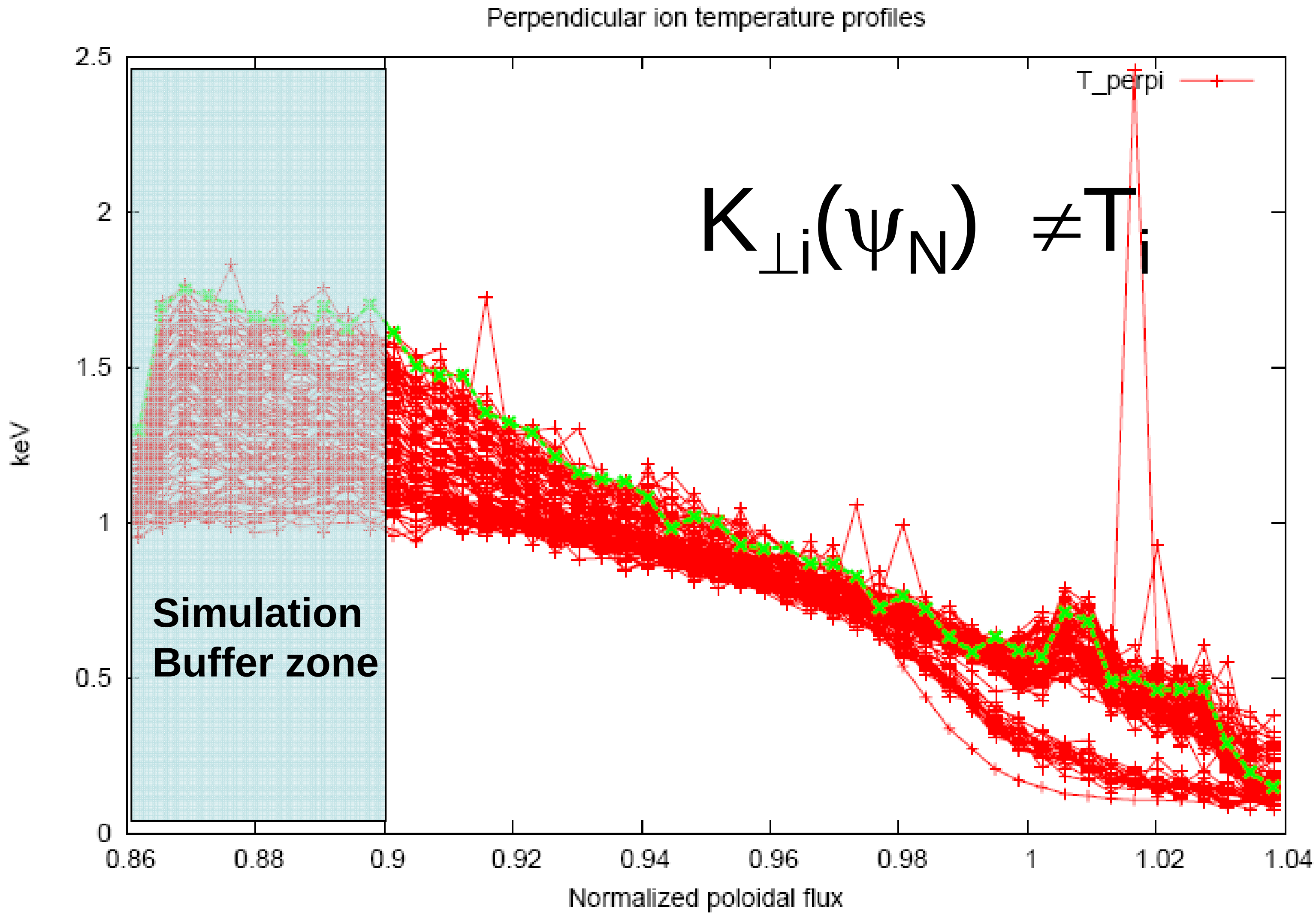
⇒ More stable to ballooning mode



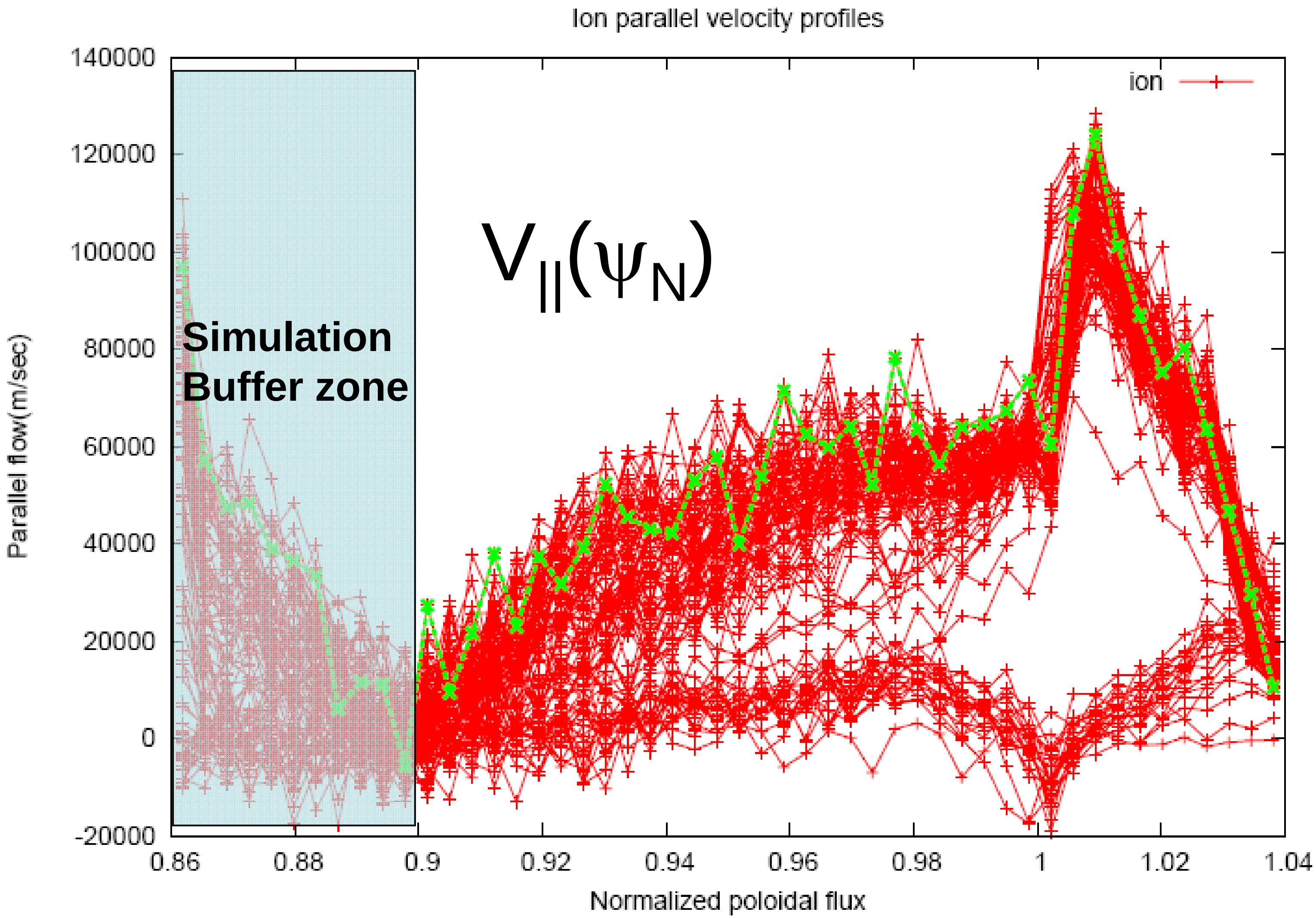
K_e may or may not increase by RMP events depending on power to electrons



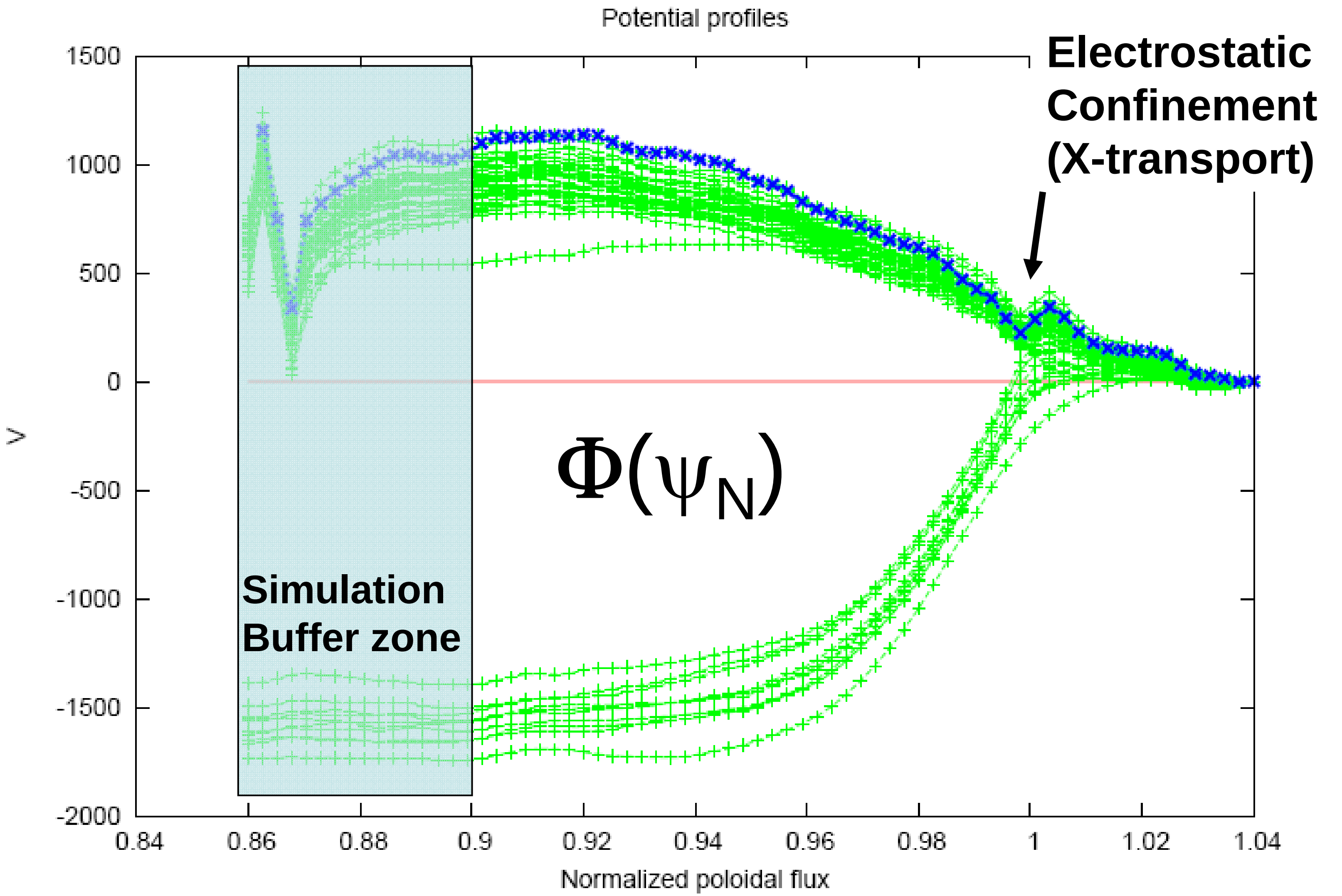
Average ion kientic energy increases due to RMP density reduction in XGC0



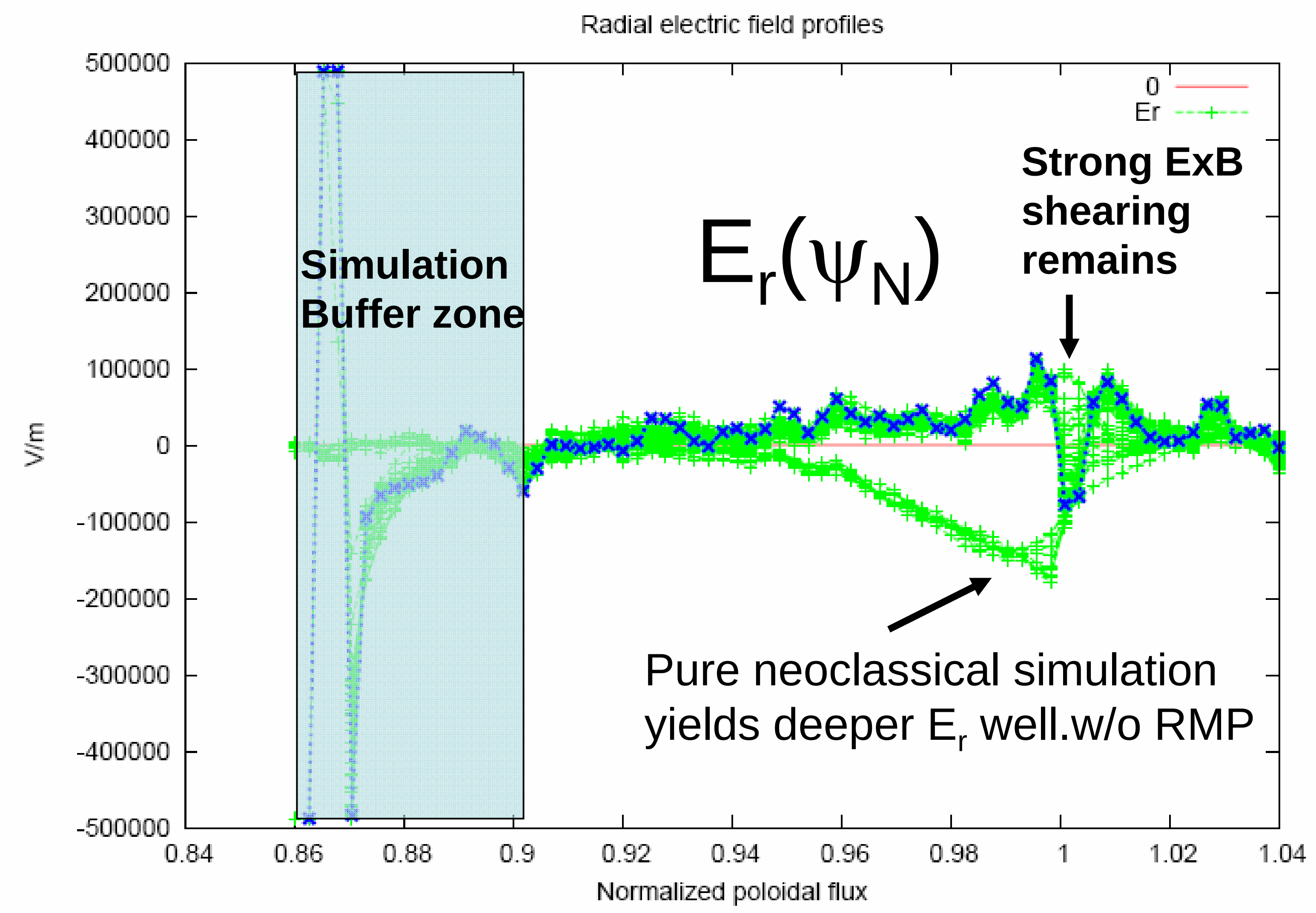
$V_{||}$ increases significantly into co-current direction (to inner divertor) by RMP in XGC0



Φ>0 by RMP, but the X-loss remains robust if D_{anom} is small (0.2 m^2/s within ±20º)



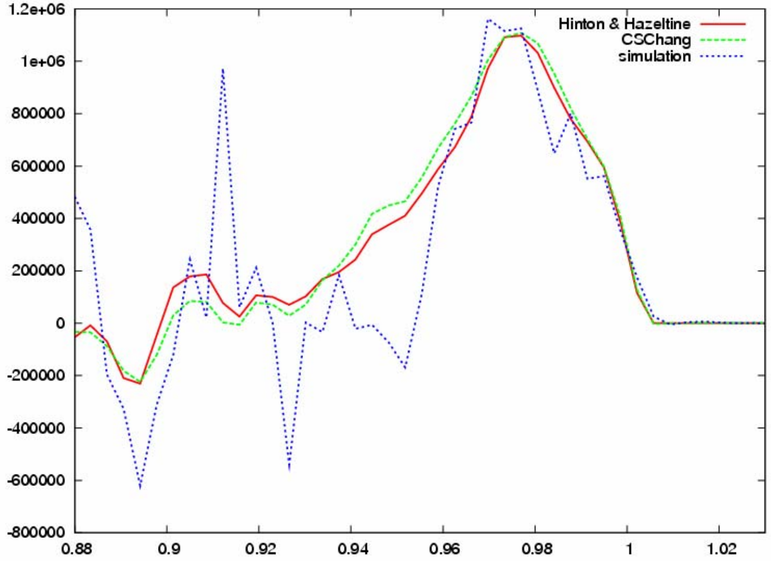
E_r>0 by RMP, but the X-loss remains robust if D_{anom} is small (0.2 m²/s within ±20°)

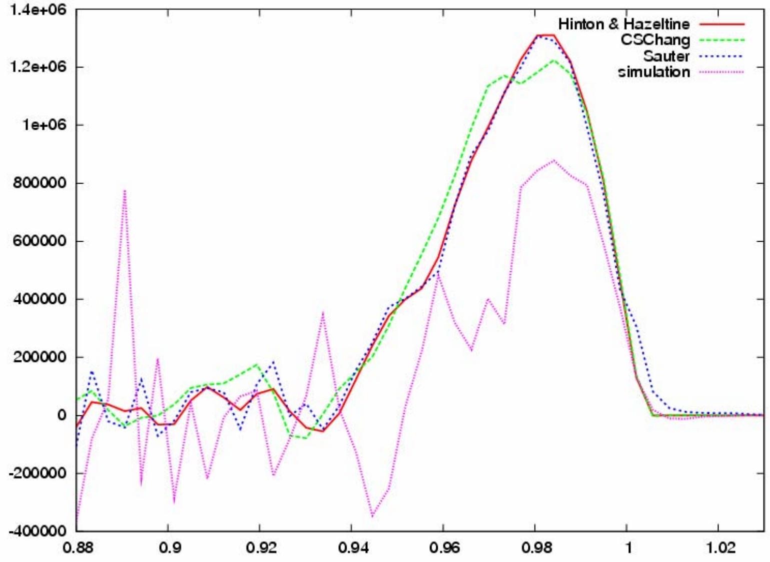


Verification of the analytic bootstrap current models (150K ions and electrons)

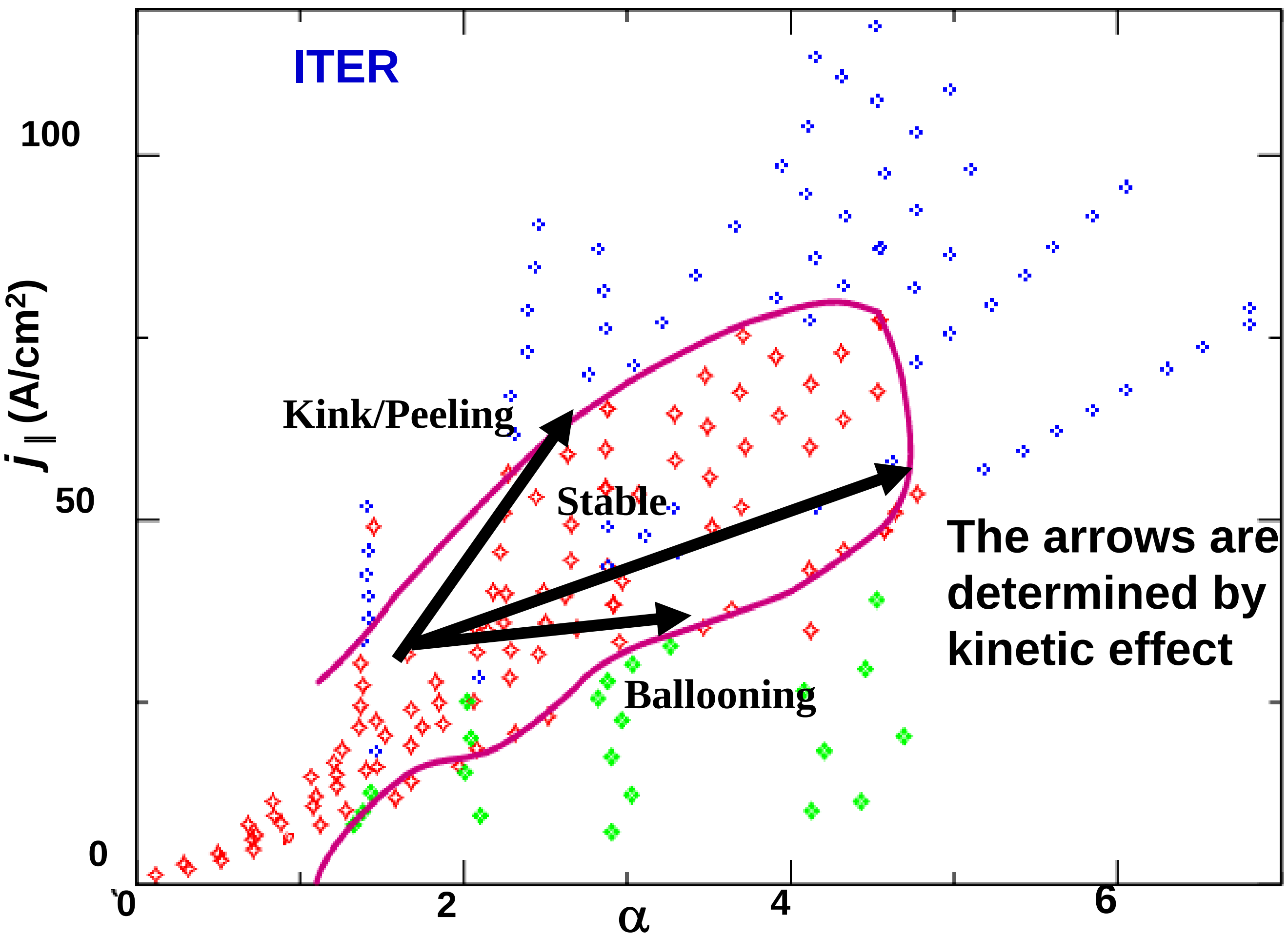
$\Delta_n = 1.5$ cm

$\Delta_n = 0.75$ cm



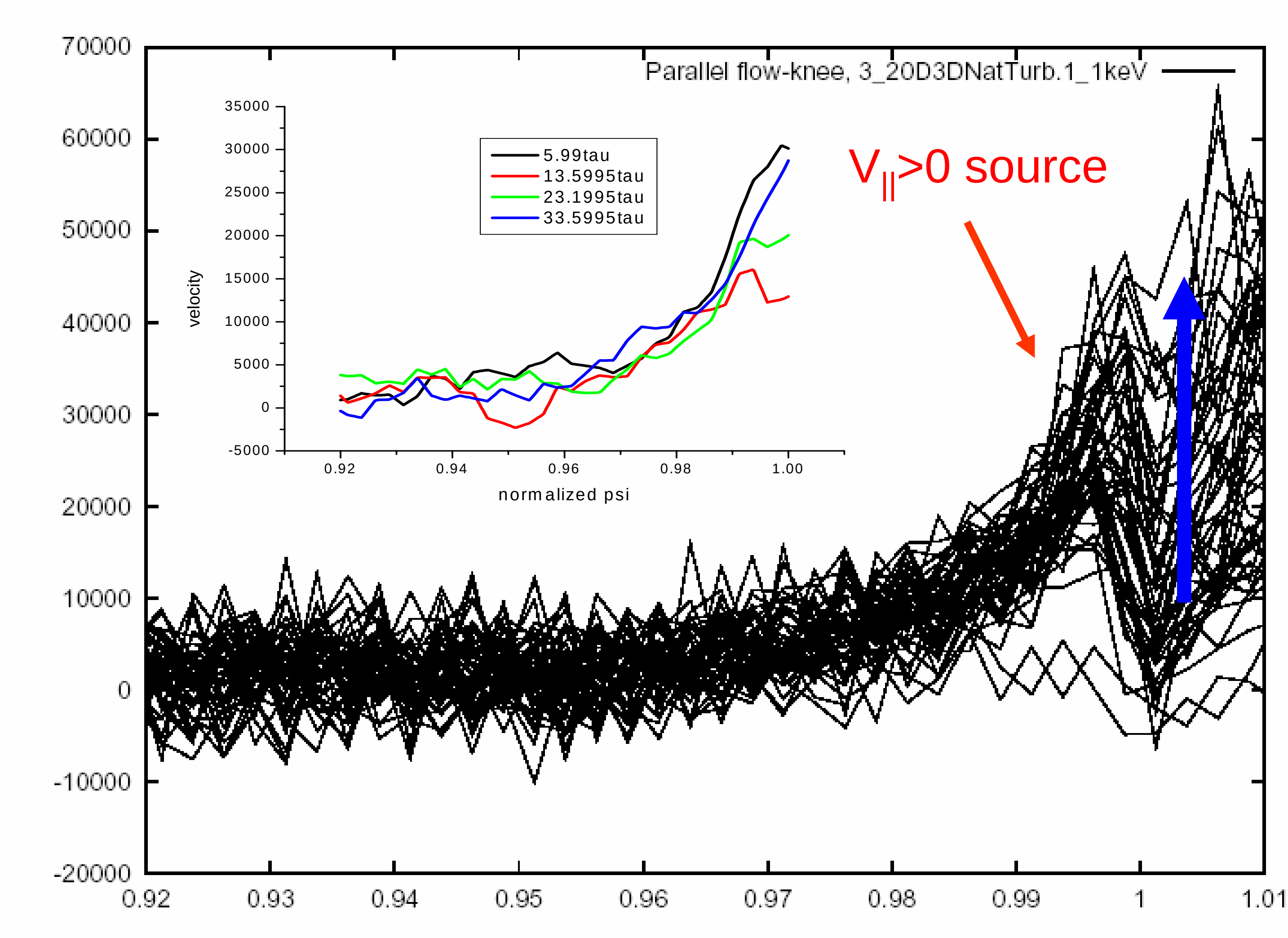


Kinetic control of ELM stability



The arrows are determined by kinetic effect

There is a rotation source in the edge
(D_{turb} = 0.1 m^2/s around outside midplane)



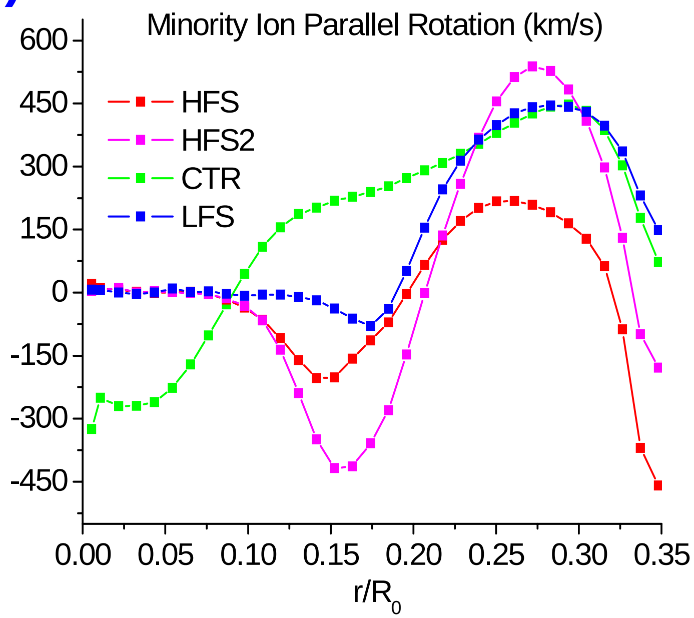
Er & Flow generation by rf in circular geometry tokamak
(J. Kwon)

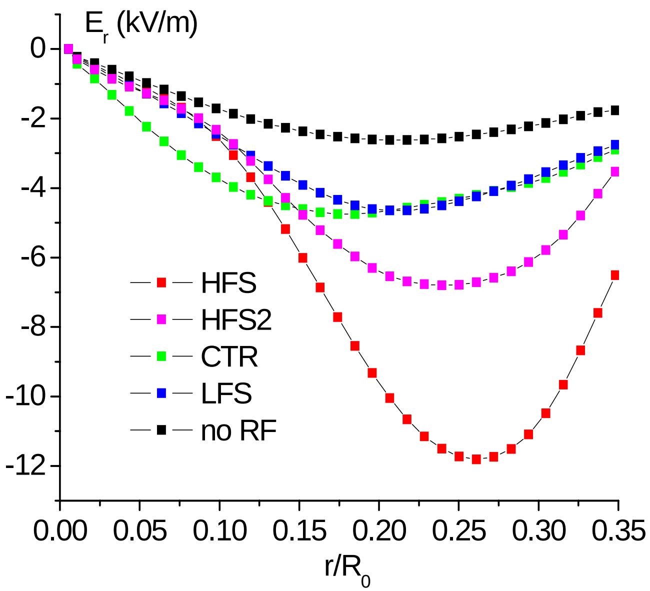
E_r and main ion parallel flow Profiles at t = 174ms.

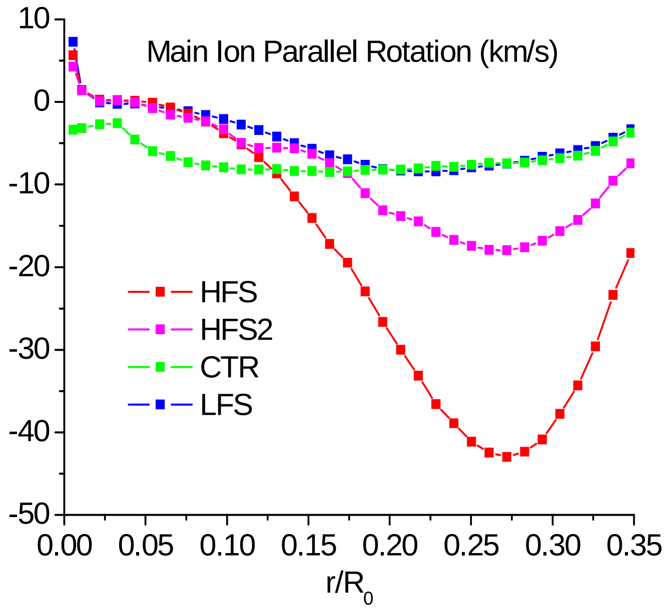
large orbit width and strong radial diffusion driven by RF for HFH

=> A large main ion flow shear for HFH

=> heavy boundary loss and recycling of minority ions (flow sign change at the edge)







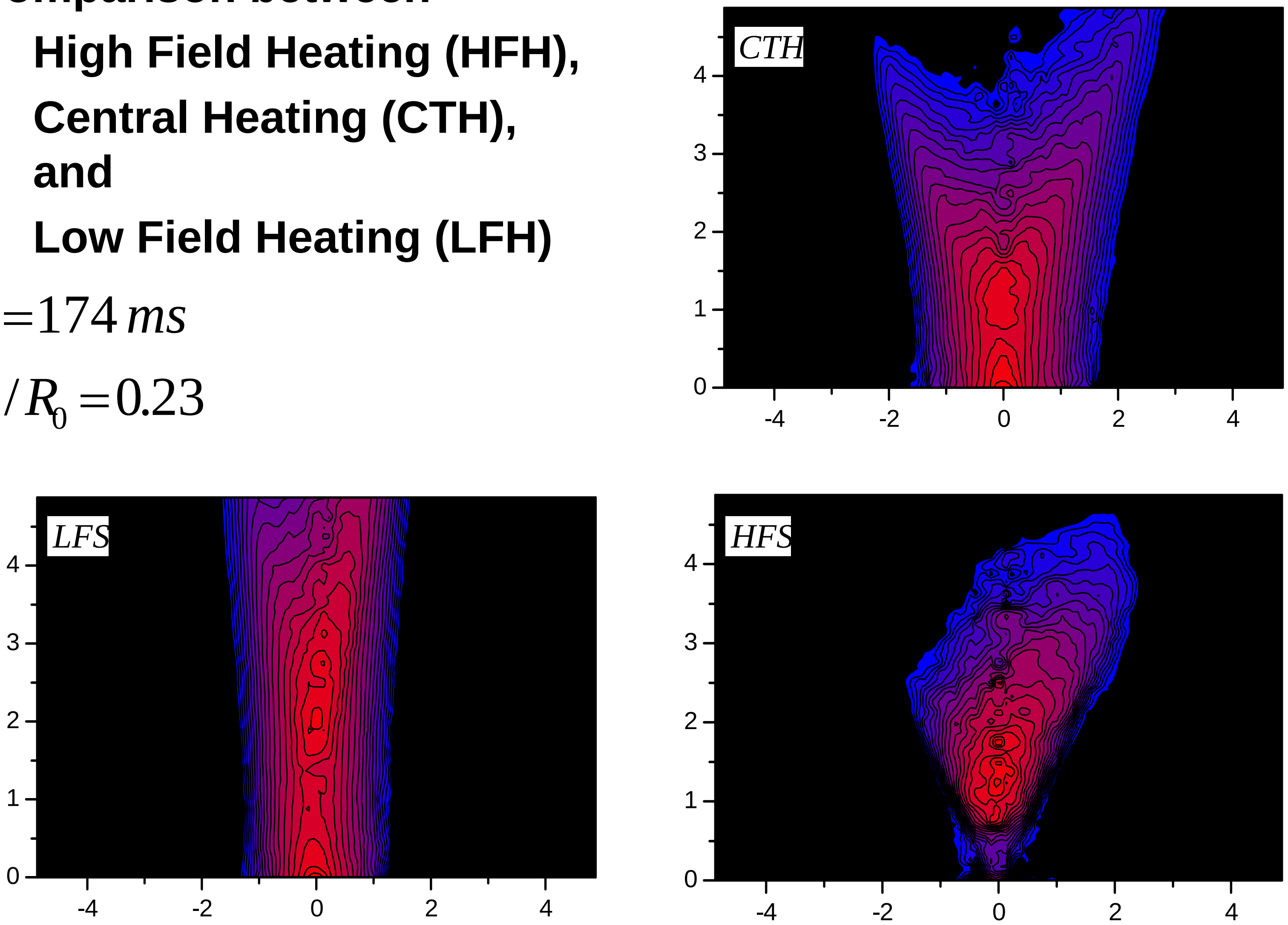
XGC-RF: self-consistently with background Er and rotation

Comparison between

- **High Field Heating (HFH),**
- **Central Heating (CTH), and**
- **Low Field Heating (LFH)**

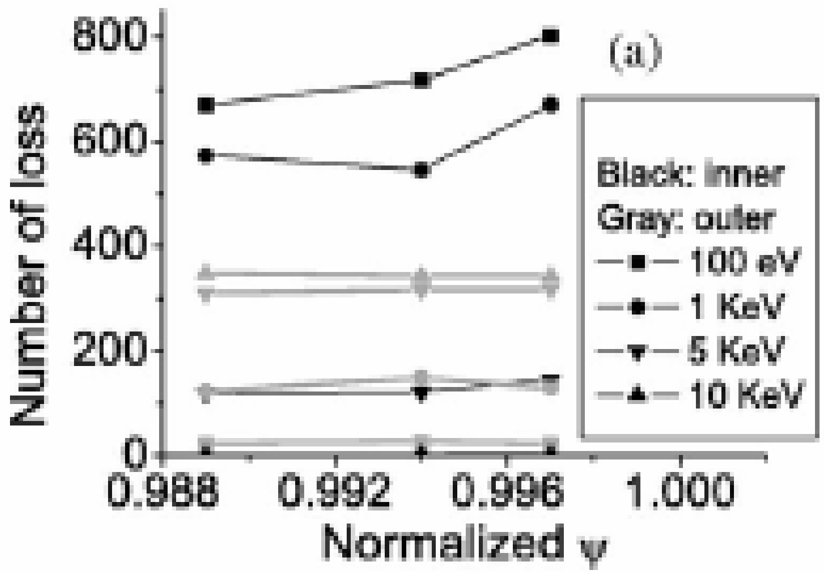
$$t = 174\, ms$$

$$r/R_0 = 0.23$$

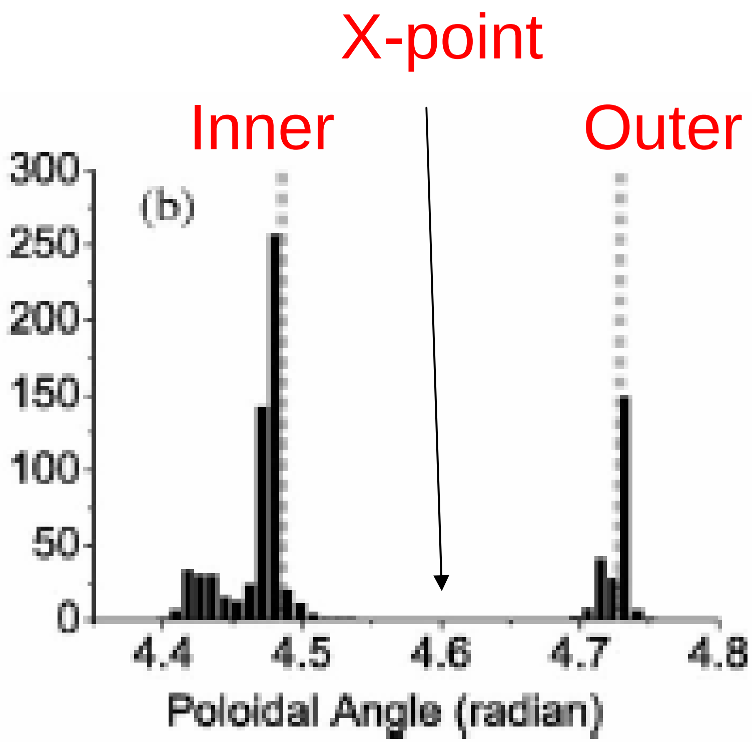


Wall distribution of particle and heat load

(D_A=10 m^2/s in DIII-D magnetic/wall geometry)



Energy dependence
from different flux surfaces

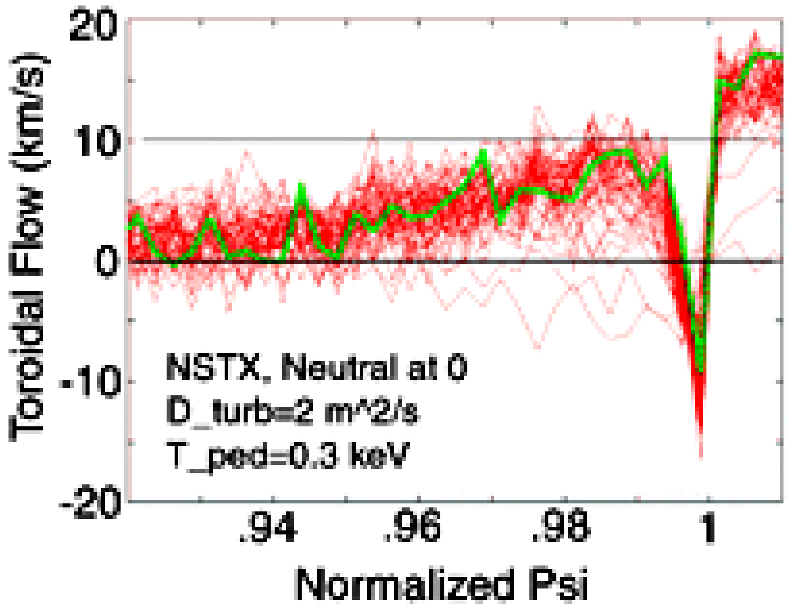


Poloidal angle dependence
of wall ion load

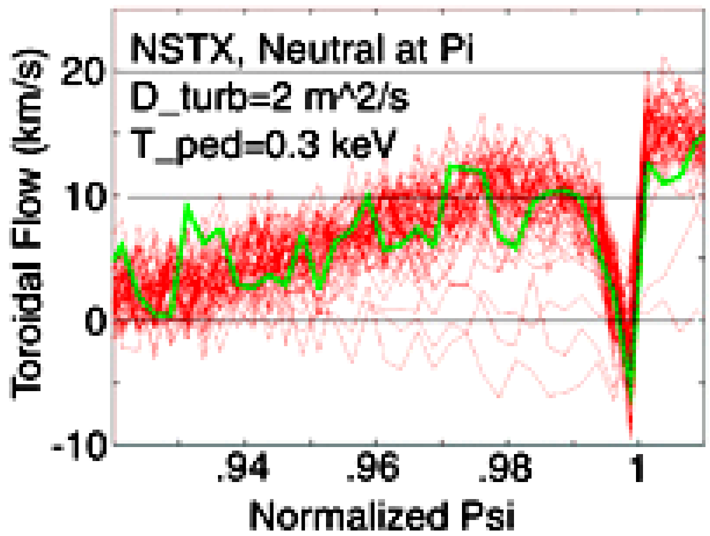
Inside vs Outside Fueling in NSTX

Inside gives ~50% higher <V_ϕ>

Outside



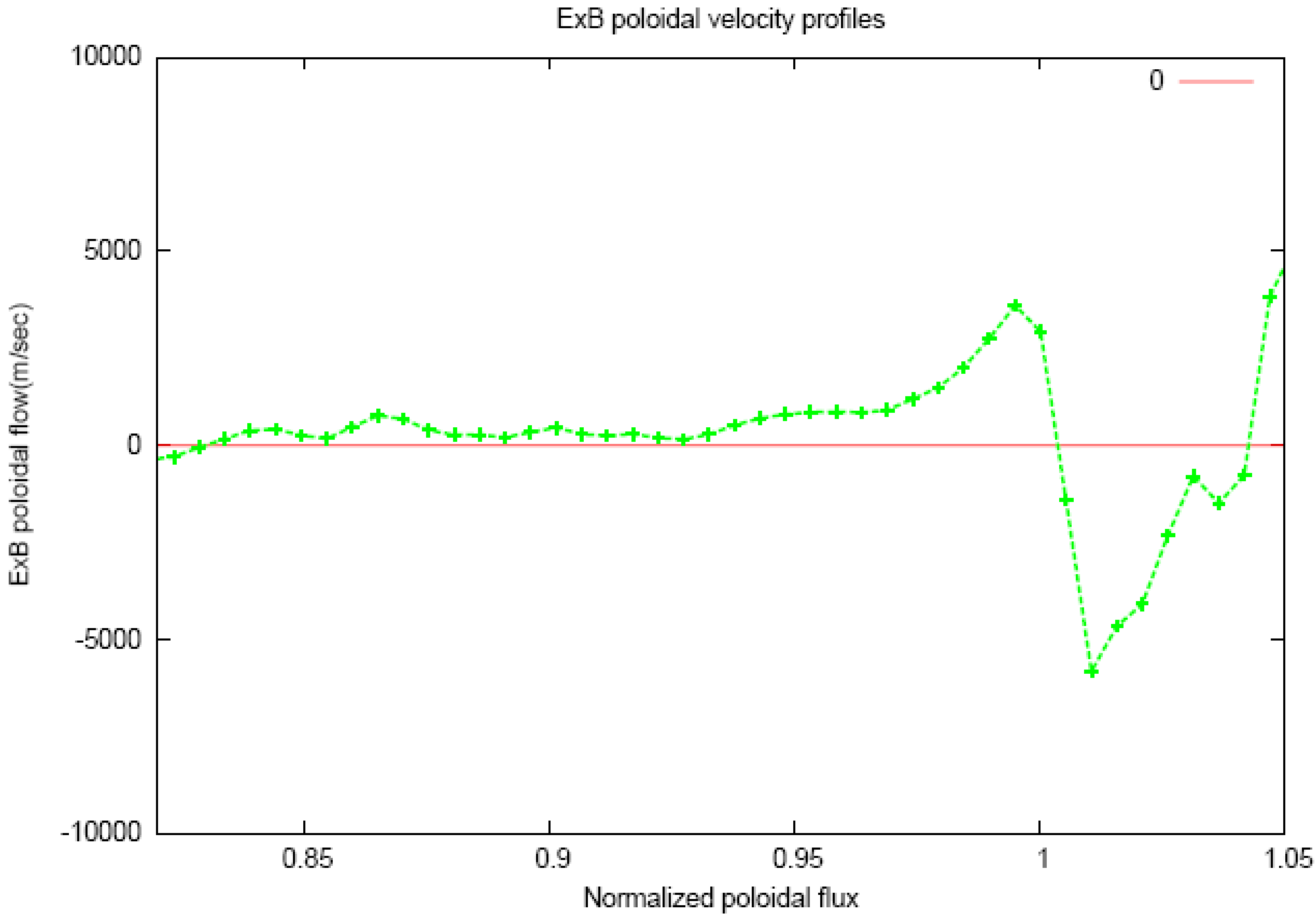
Inside



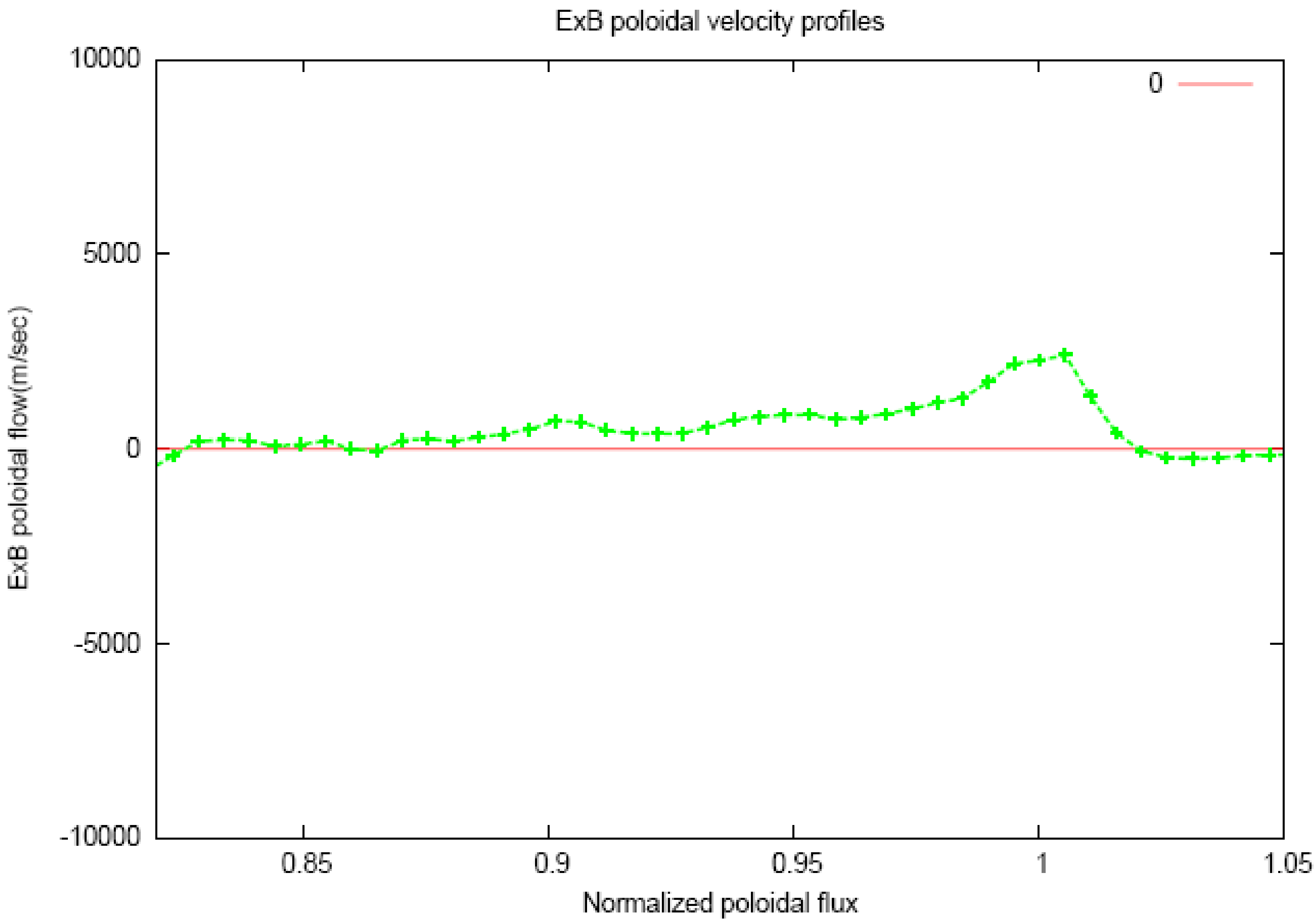
ExB profile comparison between upper and lower single nulls in NSTX

- This study was done without any external momentum source (NBI or rf)
- Lower single null case (forward ∇B) yields stronger ExB flow shear
- Further refinement with the toroidal flow or momentum source is needed.
- XGC is to be modified for double null study

V_{ExB} in lower single null



V_{ExB} in upper single null



Conclusion

NSTX

- XGC0 kinetic equilibrium and transport code is to provide an alternative to the fluid transport models.
- XGC0 can simulate the whole plasma together (core, pedestal and SOL)
- XGC0 and the integrated XGC0-Elite-M3D Kepler framework is ready for experimental validation and collaboration (with analytic turbulence diffusion models until XGC1 is ready)
- DEGAS2 is being integrated into XGC0 for the first all kinetic plasma-neutral-atomic physics
- New physics understandings are to emerge in the near future.