NSTX Physics Meeting, June 17

XGC1 for NSTX-U

C.S. Chang

on behalf of

S. Ku, J. Lang, R. Hager, D. Stotler, S. Ethier

PPPL

and the *SciDAC Edge Physics Simulation* (EPSI) team

Full-f XGC-DEGAS2 family codes

- XGC0: Drift-Kinetic neoclassical code using a $\Phi(\Psi)$ solver
  - Managed by R. Hager
  - Distributed to KSTAR, Tech-X, GA, Max-Planck, JET, …
- XGCa: Gyrokinetic neoclassical code using a $\Phi(\Psi,\theta)$ solver
  - Managed by R. Hager
- **XGC1 (topic for today): Gyrokinetic turbulence-neoclassical code in a diverted geometry** using a $\Phi(\Psi,\theta, \varsigma)$ solver
  - Managed by S. Ku and J. Lang
  - Distributed to WCI and UCSD, but too large to run
- XGCp: Gyrokinetic turbulence-neoclassical code in circular flux surface geometry
  - Managed by S. Ku
  - Distributed to CEA, WCI, UCSD, …

Outline

- **Introduction**: How different is XGC1 from other GK codes?
- **Edge-core**
  - There is no turbulence shortfall toward pedestal top in XGC1
  - "Turbulence + Heating + Cooling" brings the profile to SOC
- **Central core**: Turbulence spreads into central core
- **Pedestal-SOL**: dominated by neoclassical physics and "blobs"
  - CTEM-type turbulence brings the turbulence back in H-mode layer
  - Momentum transport and particle fueling into core
  - L-H transition
  - Pedestal structure and height: can start from electrstatic
  - H-L back-transition and ELMs: requires E&M
- **3D magnetic perturbation and turbulence**
- **Impurity and turbulence**
- **PMI from plasma side**
  - Scrape-off transport, heat-load footprint and material migration
  - Consistency between scrape-off turbulence and wall-sheath
  - Current circulation

XGC does not use the conventional δf assumptions

- **Gyrokinetic Vlasov equation in full-f**

  df/dt = *L*f= C(f) + **Source + Sink**

$$L = \frac{\partial}{\partial t} + (v_{\|}\mathbf{b} + \mathbf{v}_d + \mathbf{v}_E)\cdot\frac{\partial}{\partial \mathbf{R}} - \mathbf{b}^*\cdot\nabla(\mu B + <\Phi>_\alpha)\frac{\partial}{\partial v_{\|}}$$

$$\mathbf{B}^* = \mathbf{B} + (B v_{\|}/\Omega_s)\nabla\times\mathbf{b}$$

- **Conventional Delta-f codes: Must assume Source=Sink=0**

$L= L_0 + \delta L$, $f=f_0 + \delta f$, $\delta f = w f_0$

$$L_0 = \frac{\partial}{\partial t} + (v_{\|}\mathbf{b} + \mathbf{v}_d)\cdot\frac{\partial}{\partial \mathbf{R}} - \mathbf{b}^*\cdot\nabla(\mu B)\frac{\partial}{\partial v_{\|}}, \qquad \delta L = \mathbf{v}_E\cdot\frac{\partial}{\partial \mathbf{R}} - (\mathbf{b}^*\cdot\nabla <\Phi>_\alpha)\frac{\partial}{\partial v_{\|}}$$

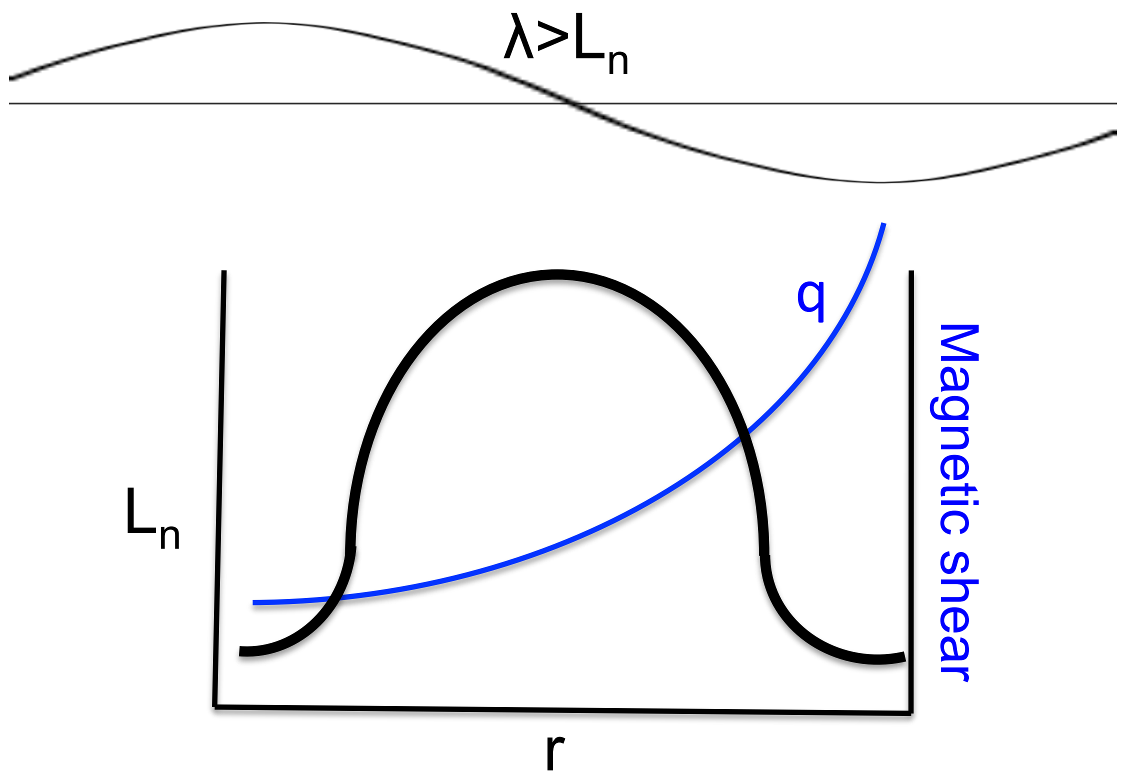
0^{th} order: $L_0 f_0 = C f_0 \rightarrow f_0 = f_M$

$$L\delta f = -Lf_0 + C(f) = \cancel{-L_0(f_0)+C(f_0)} + \delta L f_0 + C(\delta f) = \mathbf{v}_E\cdot\frac{\partial}{\partial r}f_0 - (\mathbf{b}^*\cdot\nabla <\Phi>_\alpha)\frac{\partial}{\partial v_{\|}}f_0 + C(\delta f)$$

$$= \mathbf{V}_{E,r}\,[1/L_n + 1/L_T\,(v^2/v_{th}-3/2)]f_0 - [e v_{\|}E_{\|} + m v_{\|}^2\,(\mathbf{b}\cdot\nabla\mathbf{b})\cdot\mathbf{V}_E]f_0/T + C(\delta f)$$

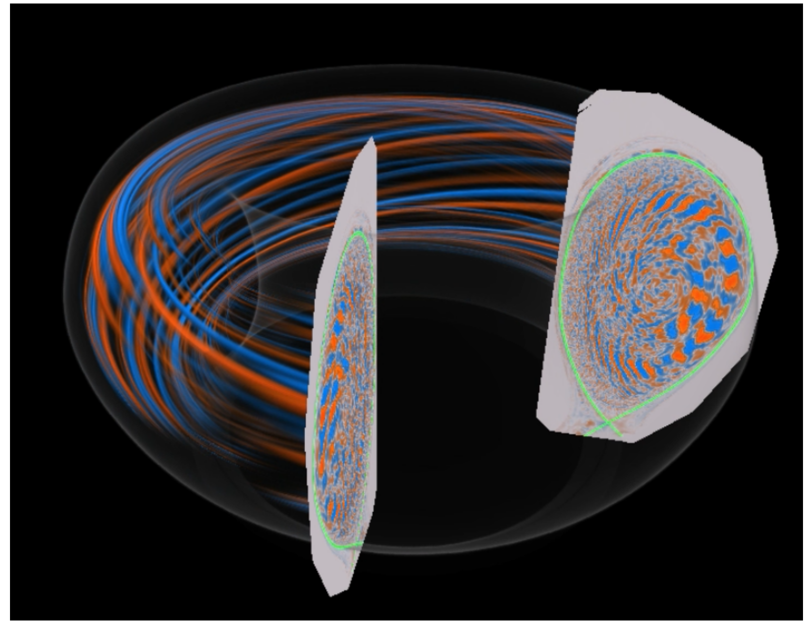
In a local code, RHS is assumed constant, even though it is not constant over a wavelength in ITB or ETB.

Instabilities in ETB or ITB are highly nonlocal.
XGC1 does not use "constant" driving terms or variables.



- If super critical at one point, but subcritical elsewhere, will turbulence survive? Vice versa.
- This question is valid across different modes because longer waves enable coupling/excitation of shorter waves non-locally → Inclusion of longer waves is important.

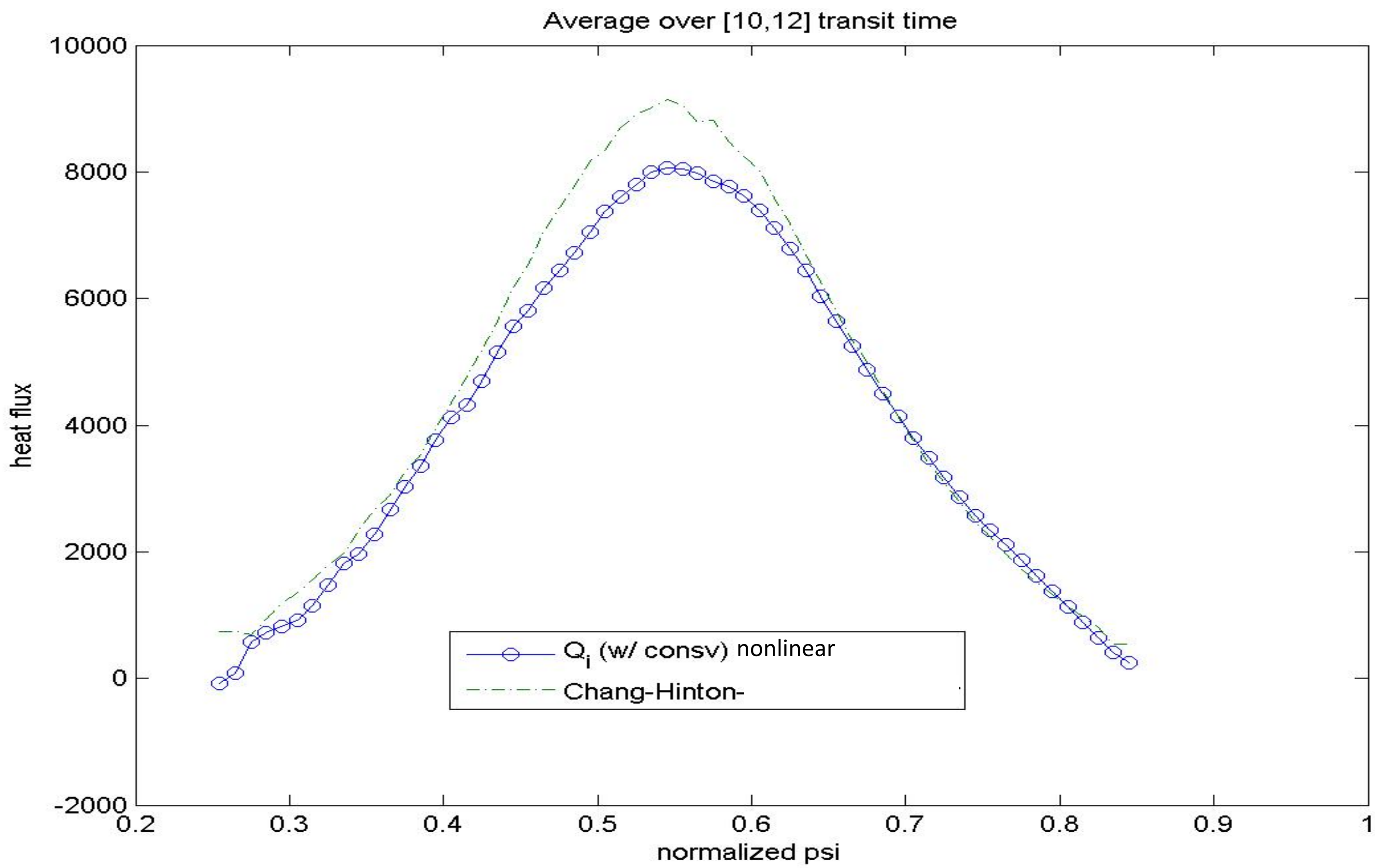
XGC1: X-point included Gyrokinetic Code



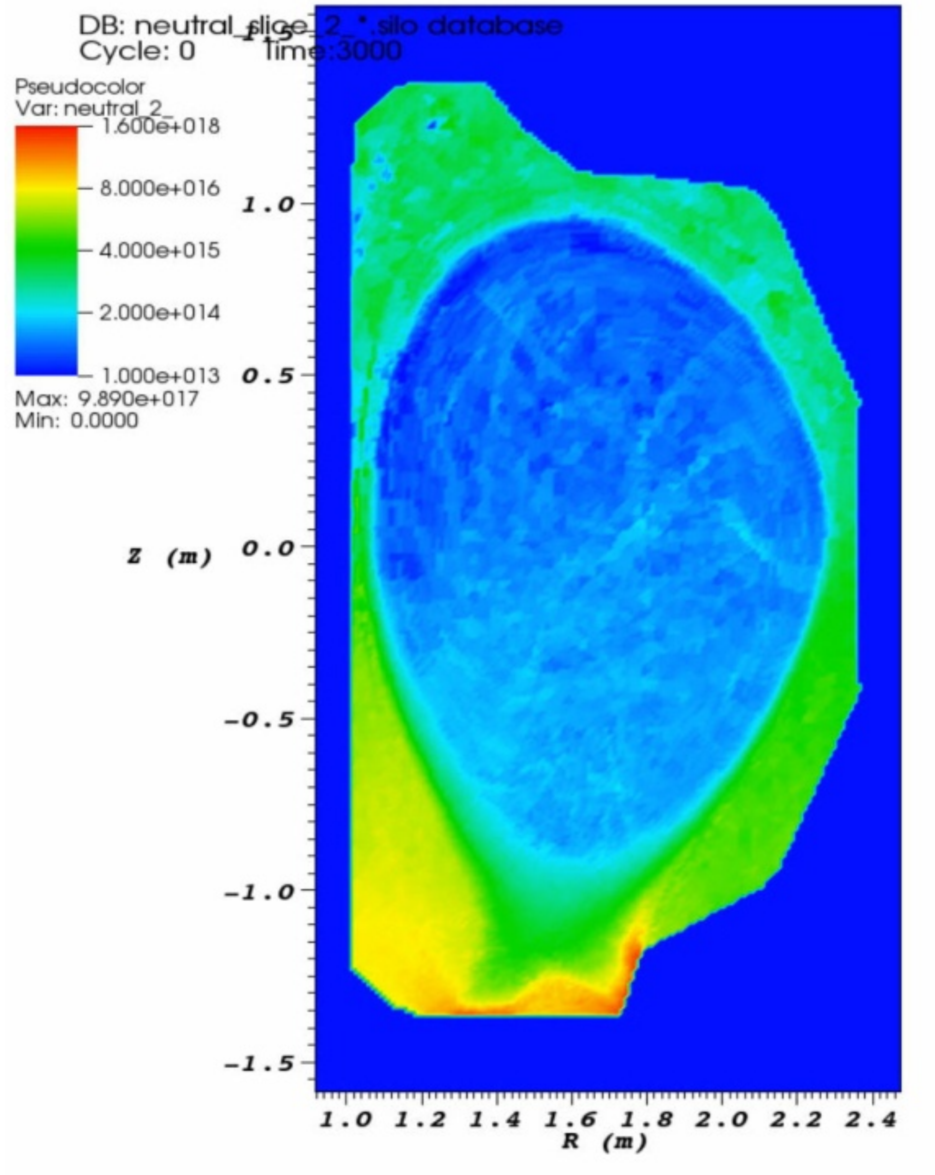
- Uses experimental EFIT data
  - Magnetic fields
  - Divertor and limiter geometry
- Full-f GK ions and drift-kinetic electrons: Neoclassical and turbulence physics together
  - ITG, TEM, resistive ballooning, drift waves, …
  - ETG capable, only more expensive to run
  - E&M (tearing, KBM, ..) to come in ~1 year
- Particle-energy-momentum conserving Coulomb collisions
  - Linear Monte-Carlo collision
  - Fully nonlinear Fokker-Plank-Landau collision on v-space grid
- Neutral Monte-Carlo routine with CX and ionization cross-sections
- Impurity particles, radiation physics: being transferred from XGC0

XGC1 uses a fully nonlinear FPL collision operator

- We have both linear-based Monte Carlo operator and fully non-linear Fokker-Planck-Landau operator, in both XGC0 and XGC1
- Chang-Hinton has been reproduced from nonlinear collisions within <20%



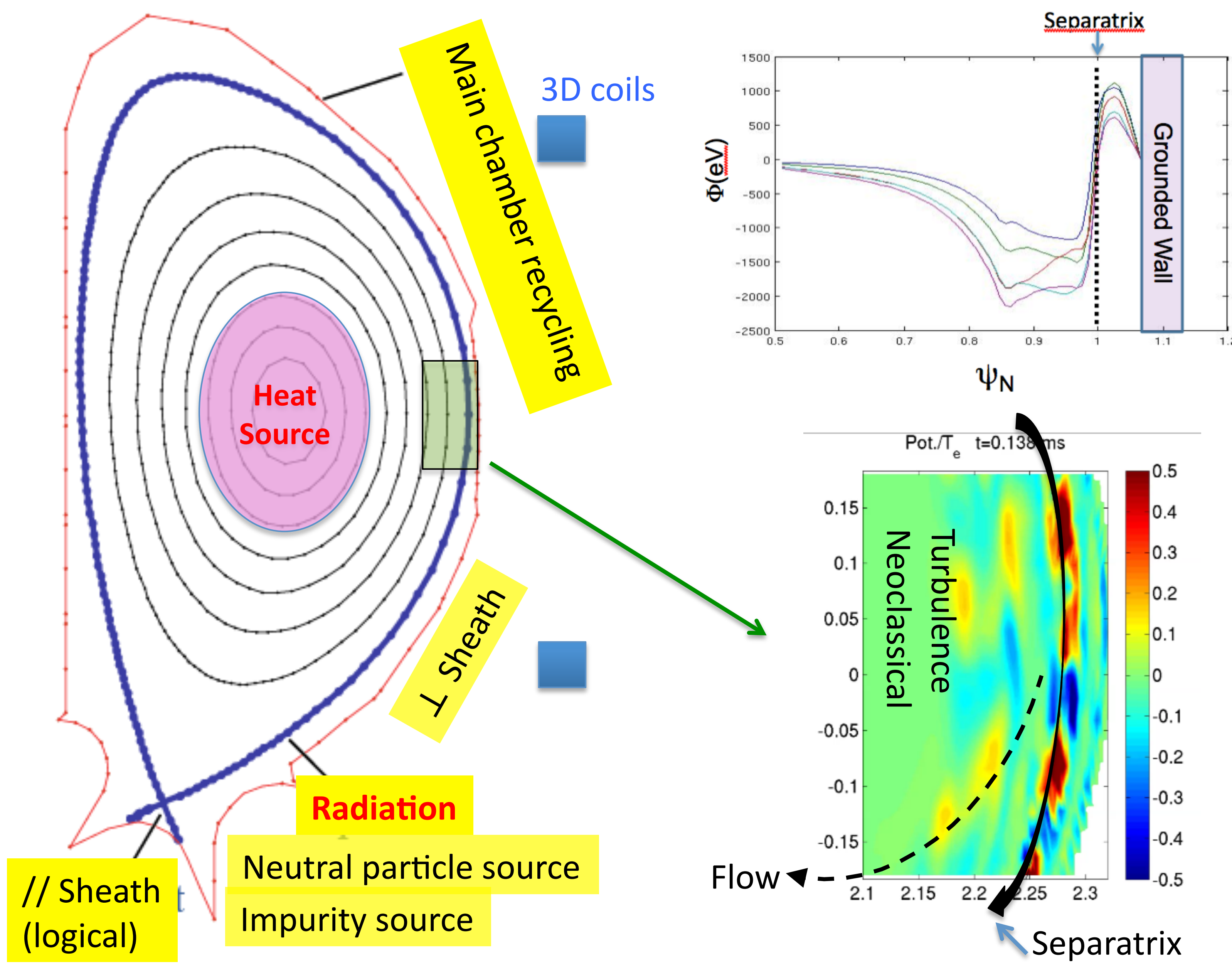
XGC-DEGAS2



Logarithmic plot of 2D deuterium neutral atom density in a DIII-D plasma

(showing the neutral source peaked at the divertor targets, as determined by the poloidal profile of XGC particle losse to wall).

Multi-physics in XGC1



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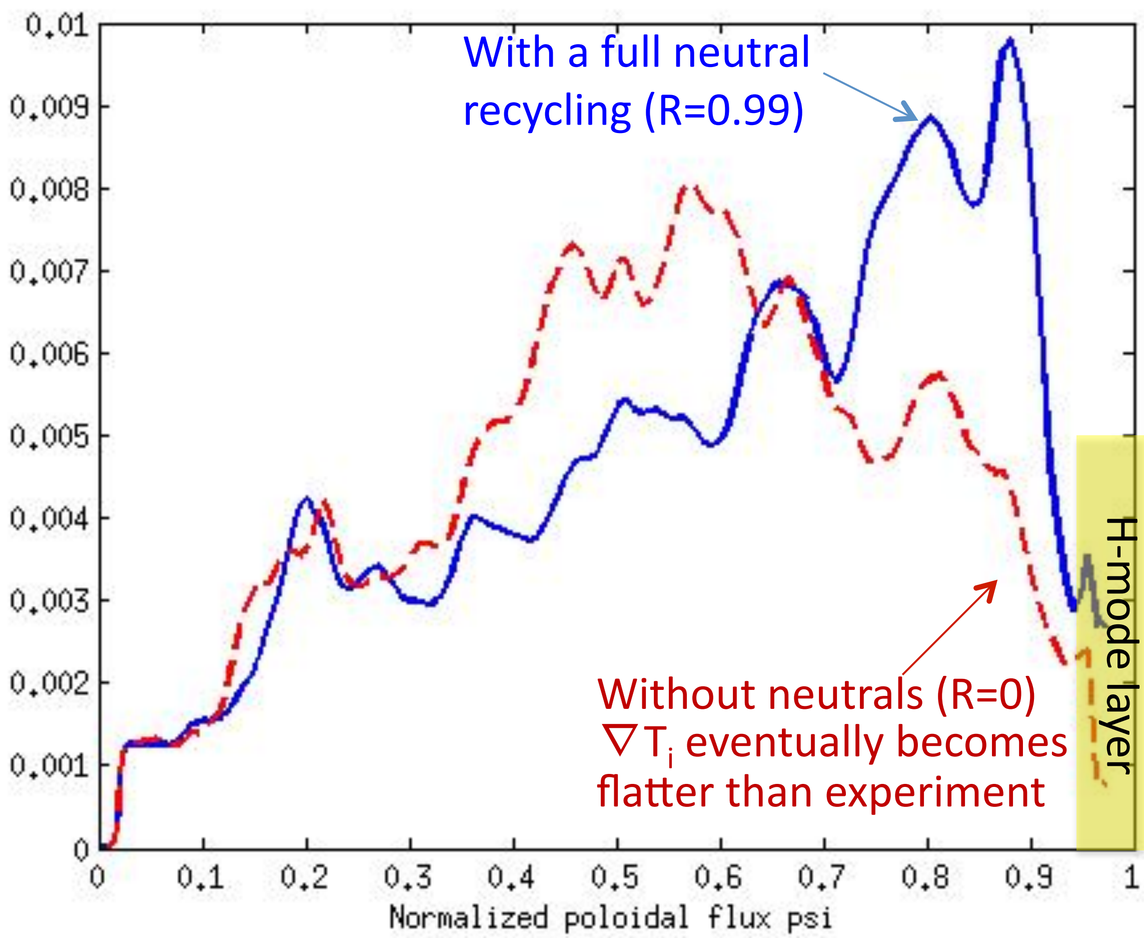
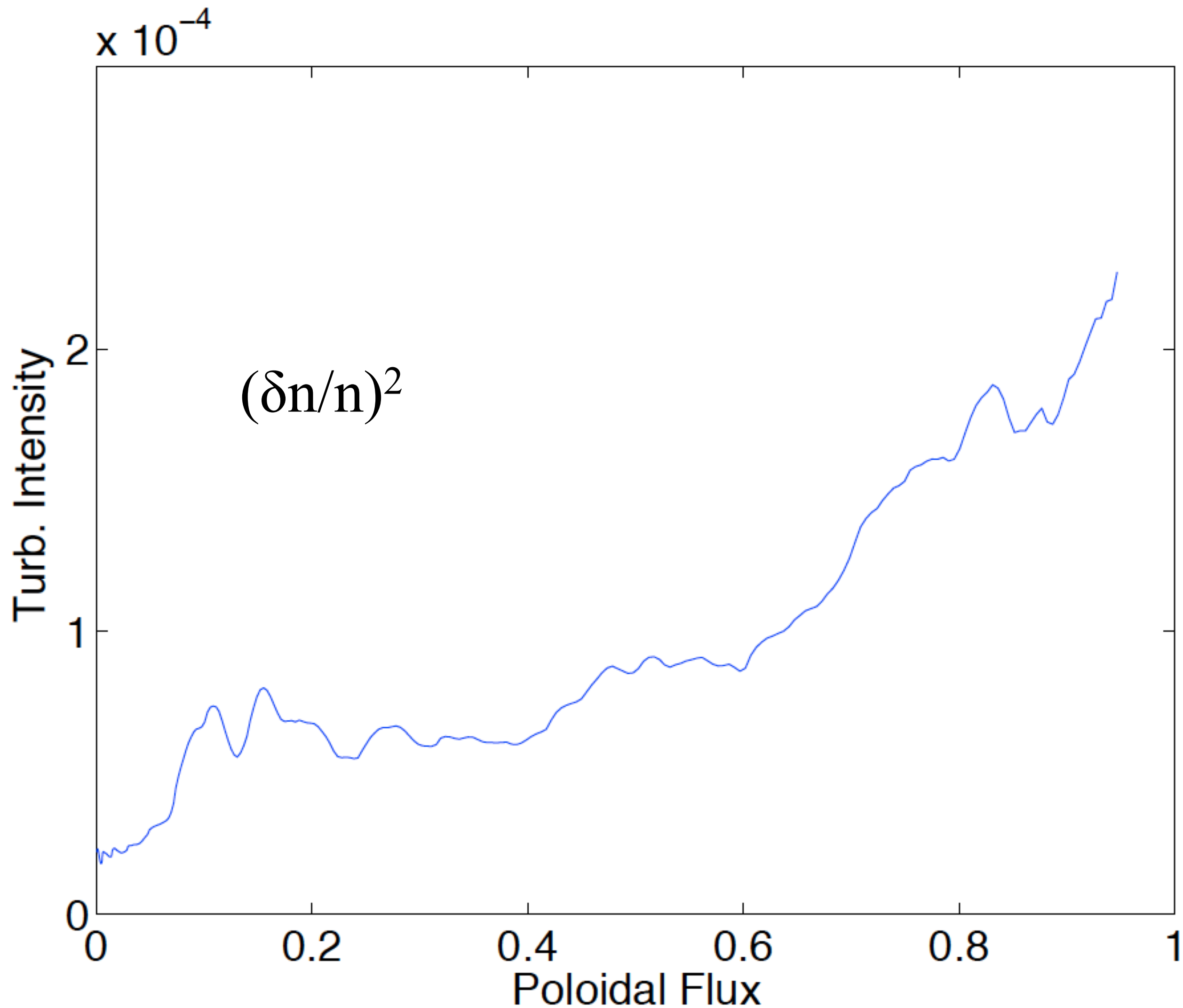
XGC1 does not have the "turbulence short falls" even with ITG turbulence alone

(Natural BD condition, full-f and driven by heat-flux)

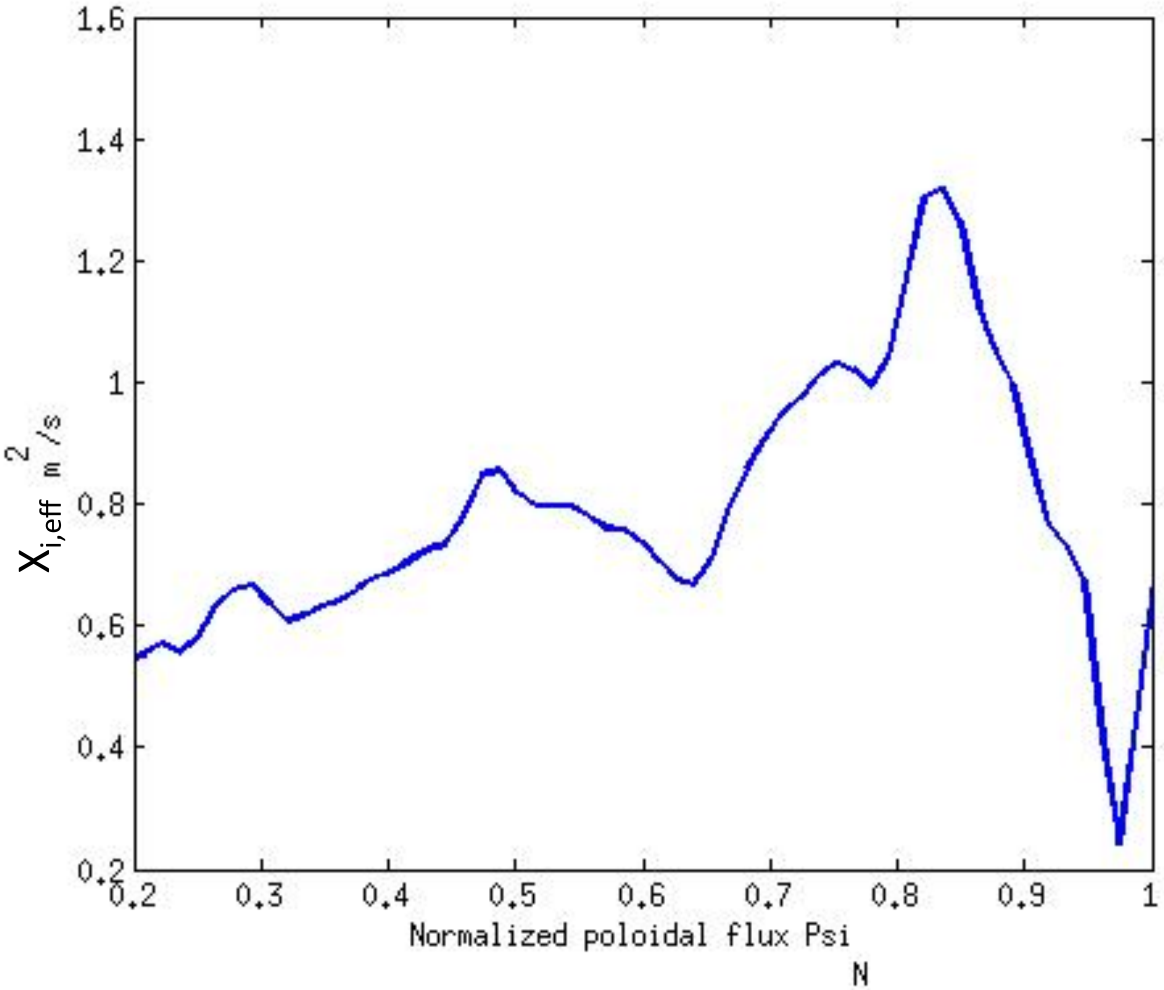


Before the ∇T_i decay without neutrals

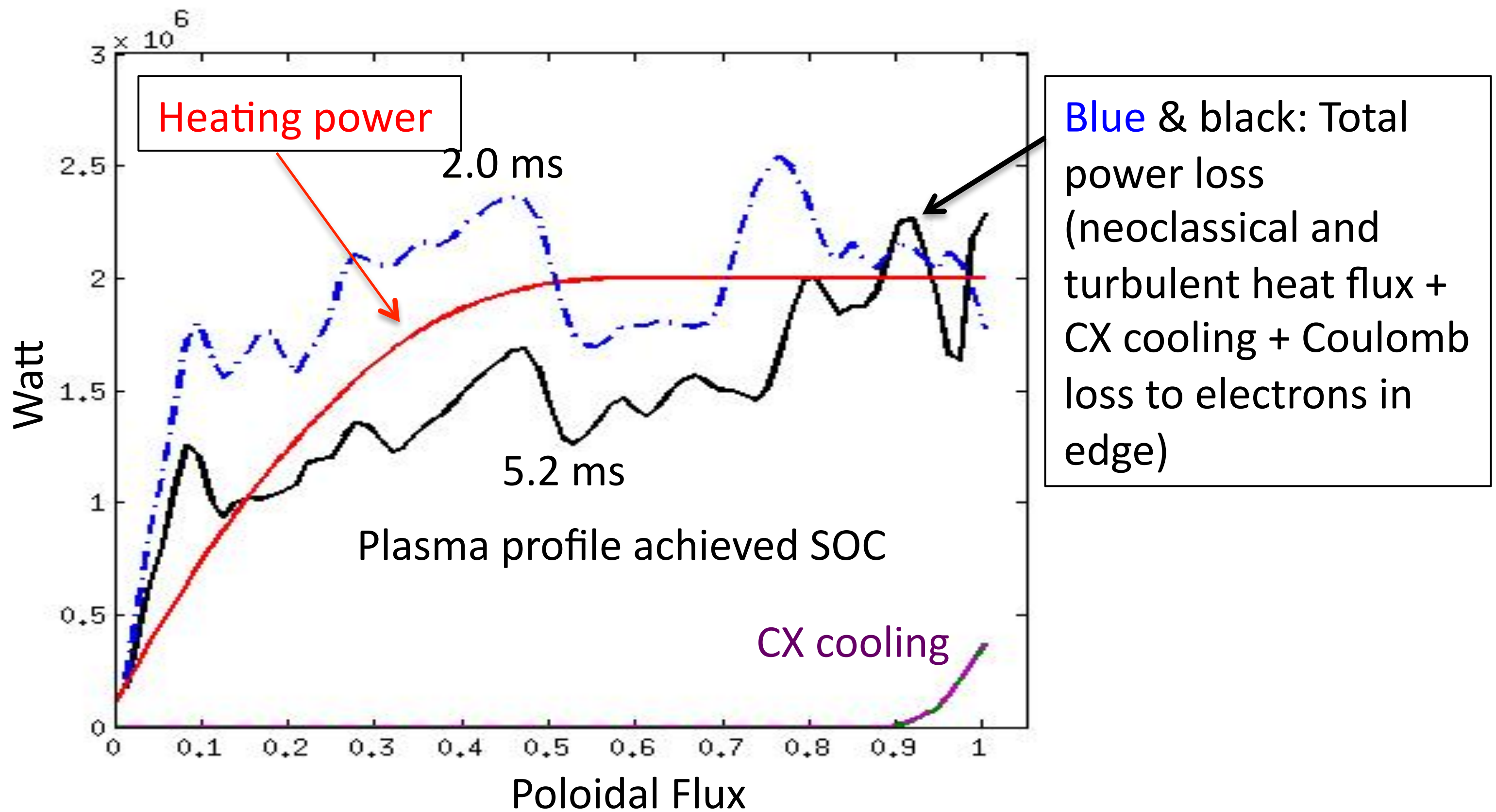
(For comparison with a delta-f code)



$\chi_{i,eff}$ from ITG turbulence in a DIII-D H-mode plasma



Radial ion power balance achieved with ITG turbulence (it is a ms-type dynamic balance!)



Red: Total heating power

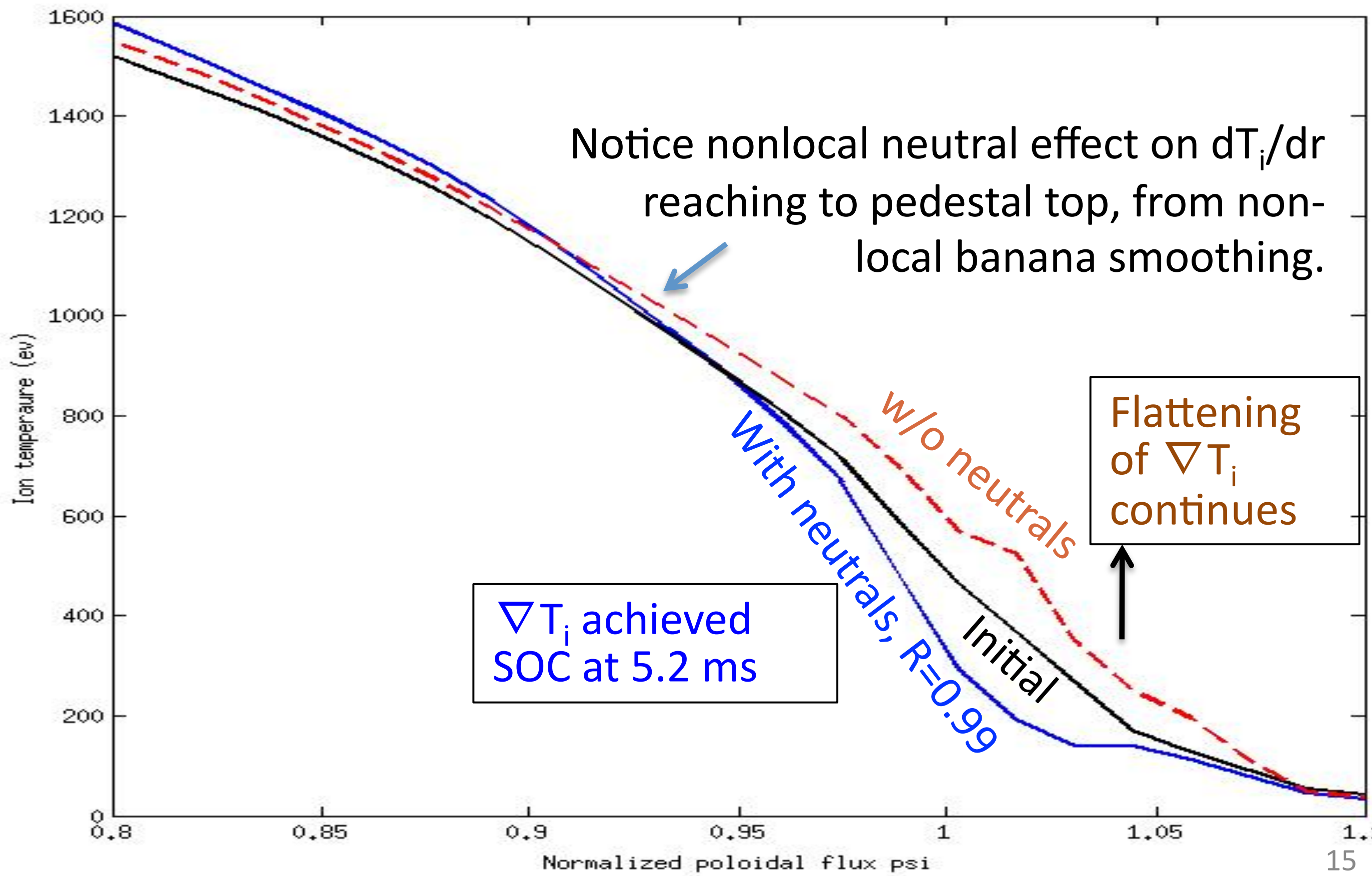
Black: Total power loss at 5.2 ms (heat flux + CX cooling + loss to electrons)

Blue dashed: Total power loss at 2.0 ms, showing large bursty time variation

Purple: CX cooling at 2.0 ms

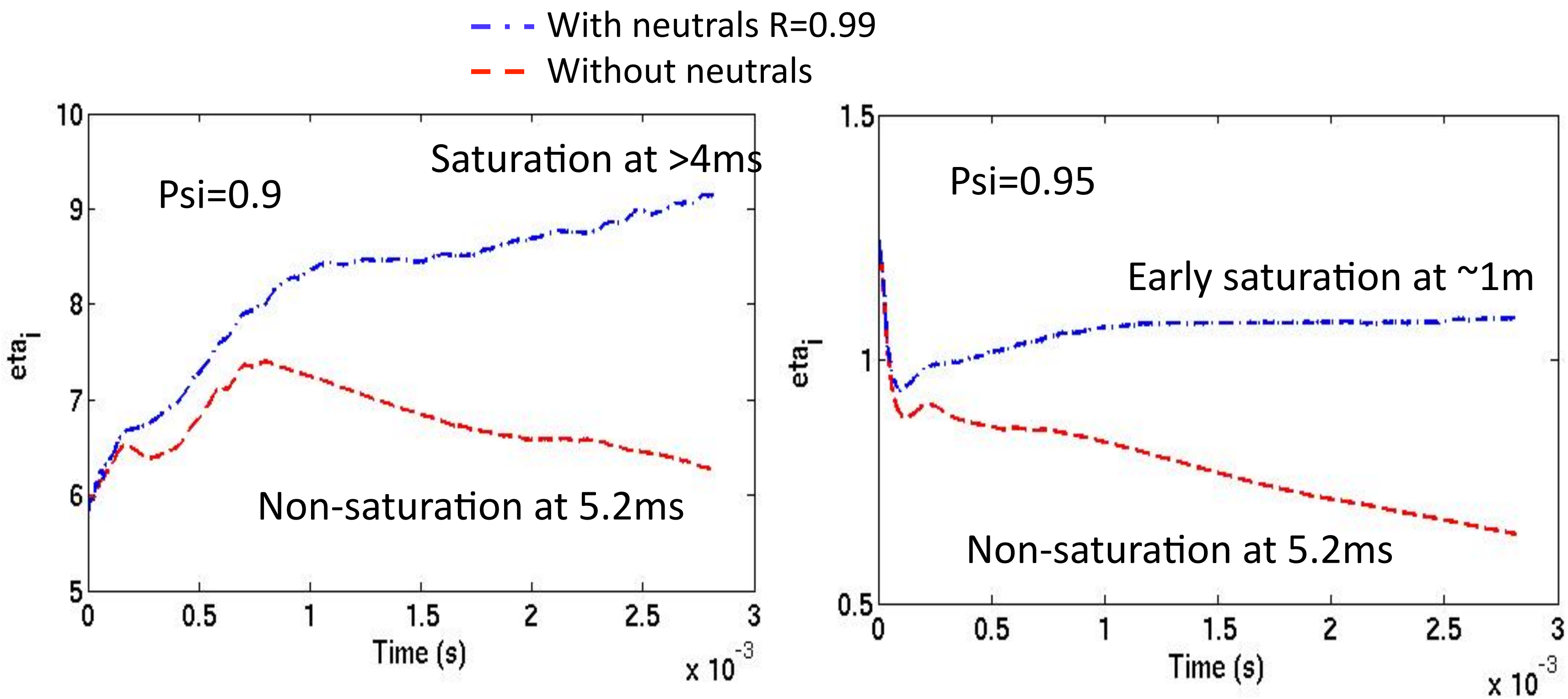
Green: CX cooling at 5.2 ms: shows a quick saturation of CX loss

Saturated T_i profile is different without neutrals in XGC1



Neutrals increase η_i at density pedestal top

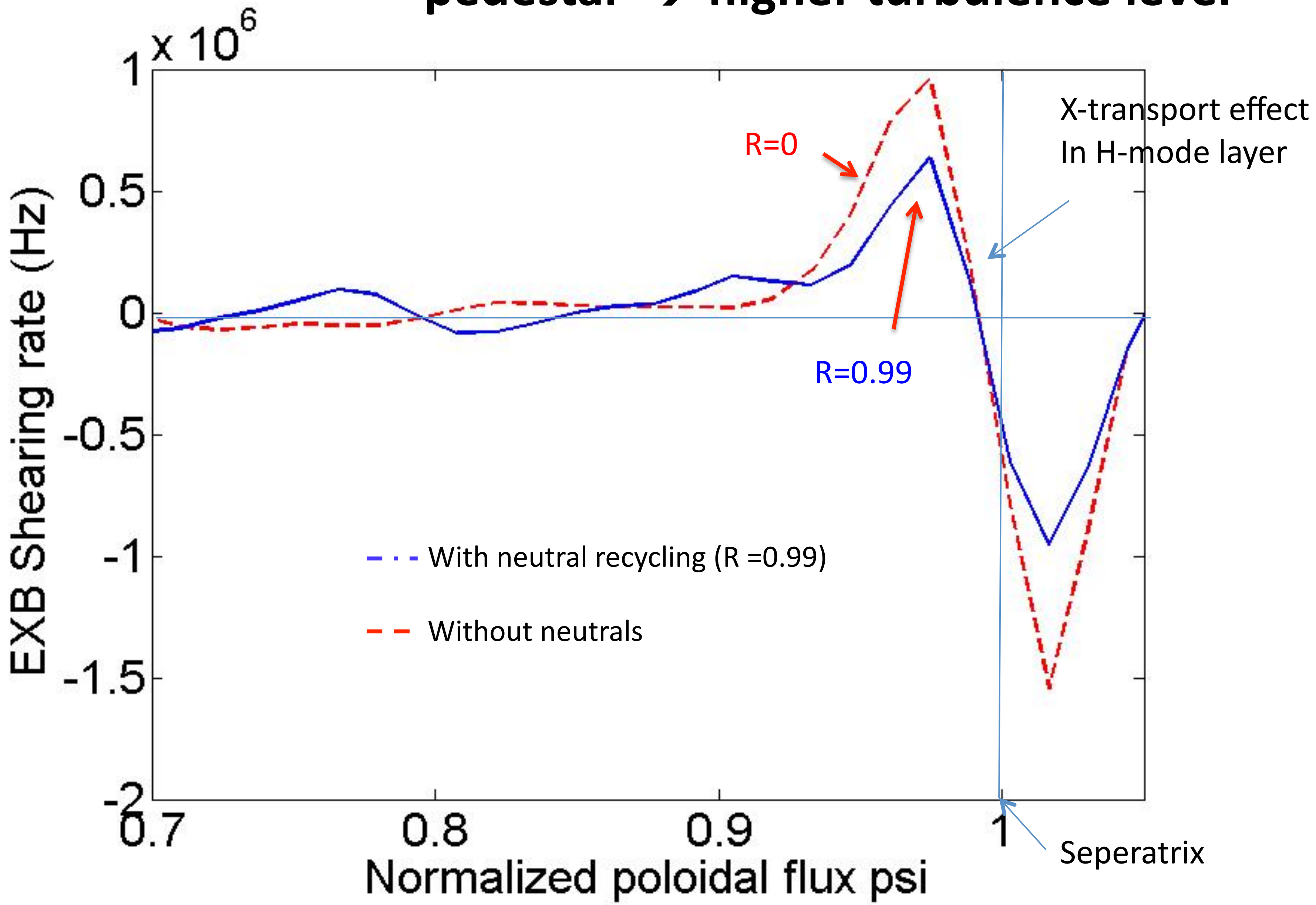
In steep H-mode gradient region, η_i stays low ~1



→ Neutrals produce stronger T_i pedestal

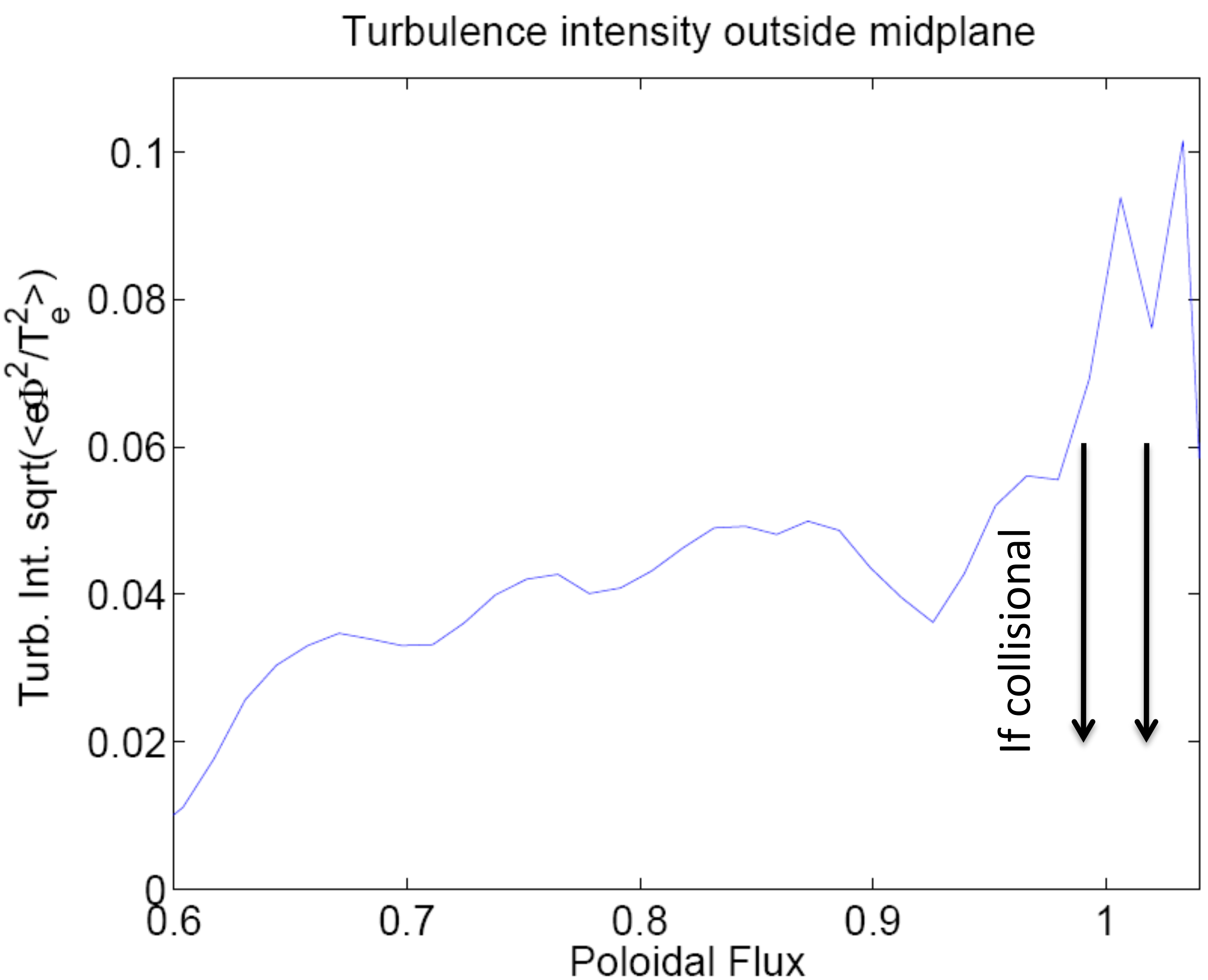
→ Stronger turbulence source at density pedestal top Psi~0.9

EXB shearing rate is weaker with neutrals in the edge pedestal → higher turbulence level



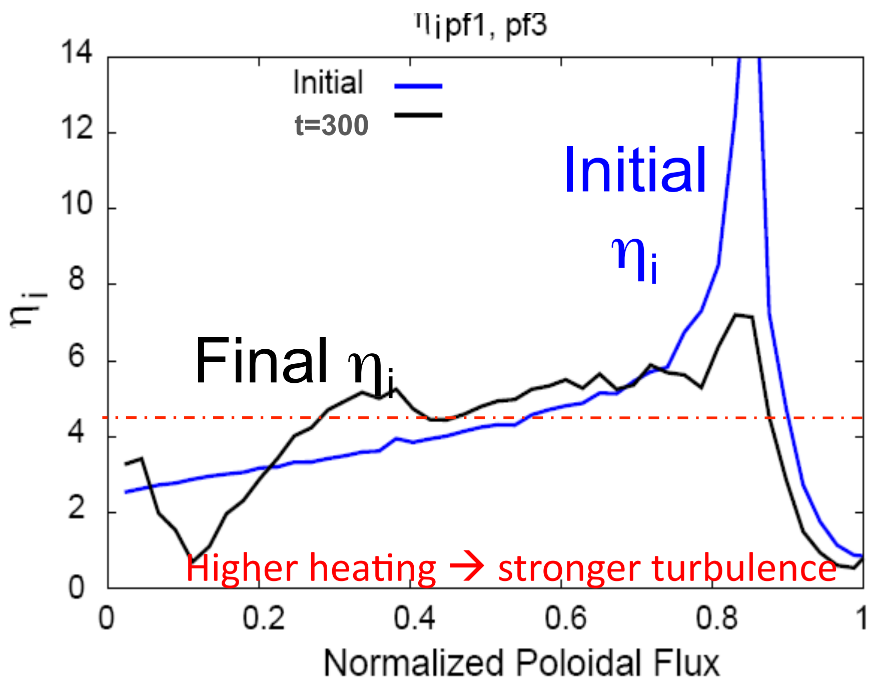
XGC1 shows that the edge turbulence is even stronger with nonlinear ITG+CTEM interaction.

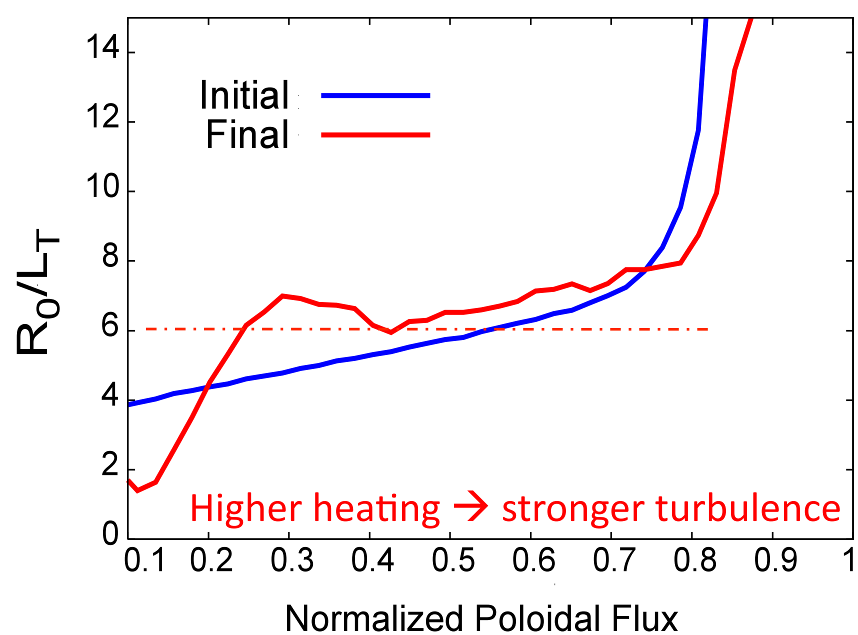
(Natural BD condition, full-f and flux driven)



T_i advances to stiff self-organized criticality

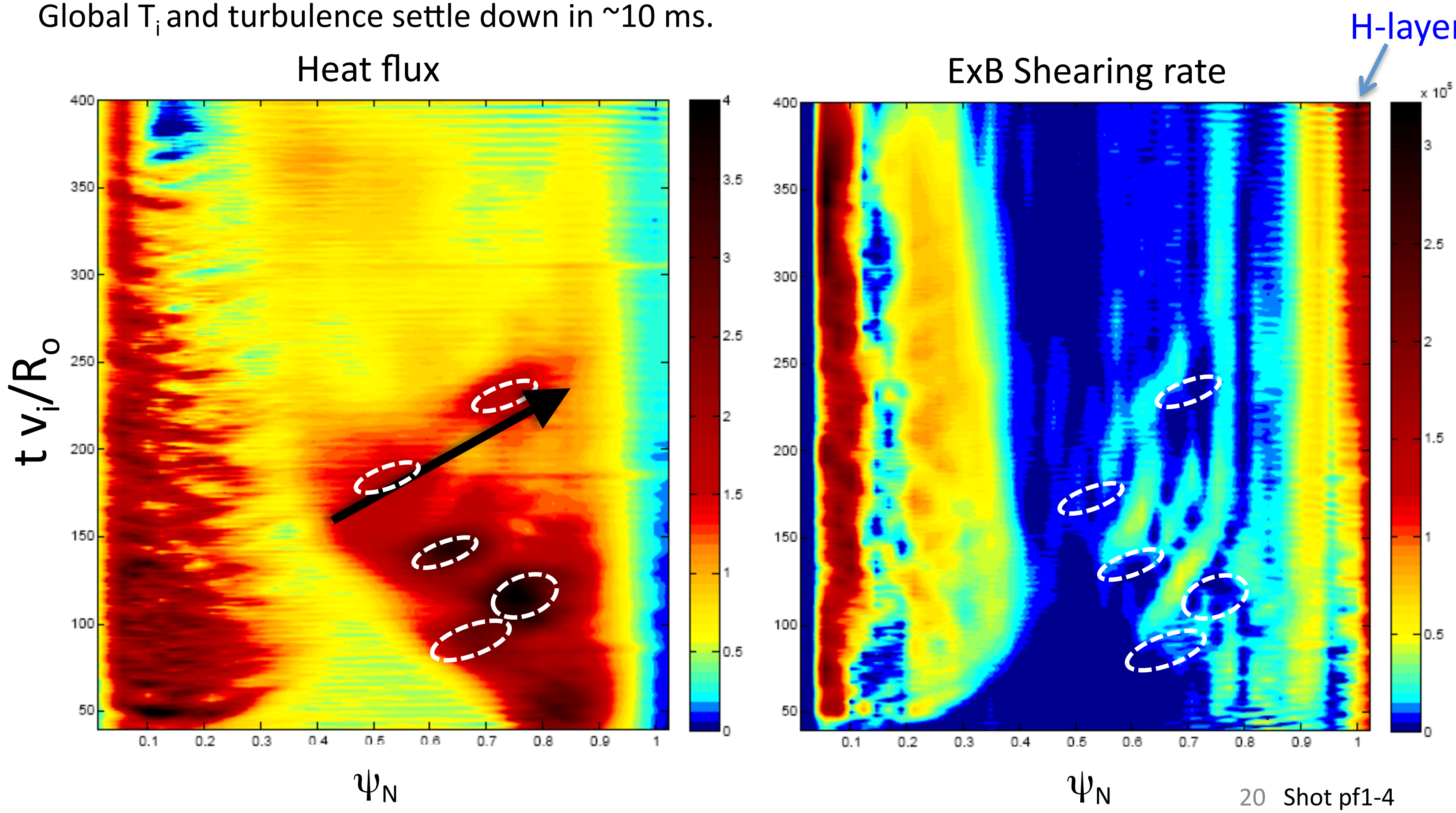
- TRIGINITY, TGYRO, etc: "Scale separation assumption. Turbulence simulation in small regions of the space-time grid, embedded in a coarse grid on which fluid transport equations are evolved" [M. Barns et al, PoP2010]
- XGC1: f contains all scale turbulence and transport physics without scale separation, together with heat/torque source and neutral particles
- Plasma profile in XGC1 evolves while maintaining "stiff" self-organized criticality: **Edge T_i determines core T_i.**





Self-organizing interaction between outward heat bursts by turbulence and E'xB control of turbulence

- The self-organizing interactions can be clearly seen in the bursty initial stage
- Similar interactions at smaller scale exists at later time in the form of avalanche
- Temperature perturbation information at edge propagates to core in this fashion, taking <5 ms in DIII-D: cold/hot pulse experiment, propagation speed ~ 0.3 km/s ~ 1.7 $\rho_{(i,0.6)} v_{(i,0.6)} / R_0$ ~ 0.4 V_*
- Global T_i and turbulence settle down in ~10 ms.



 Shot pf1-4

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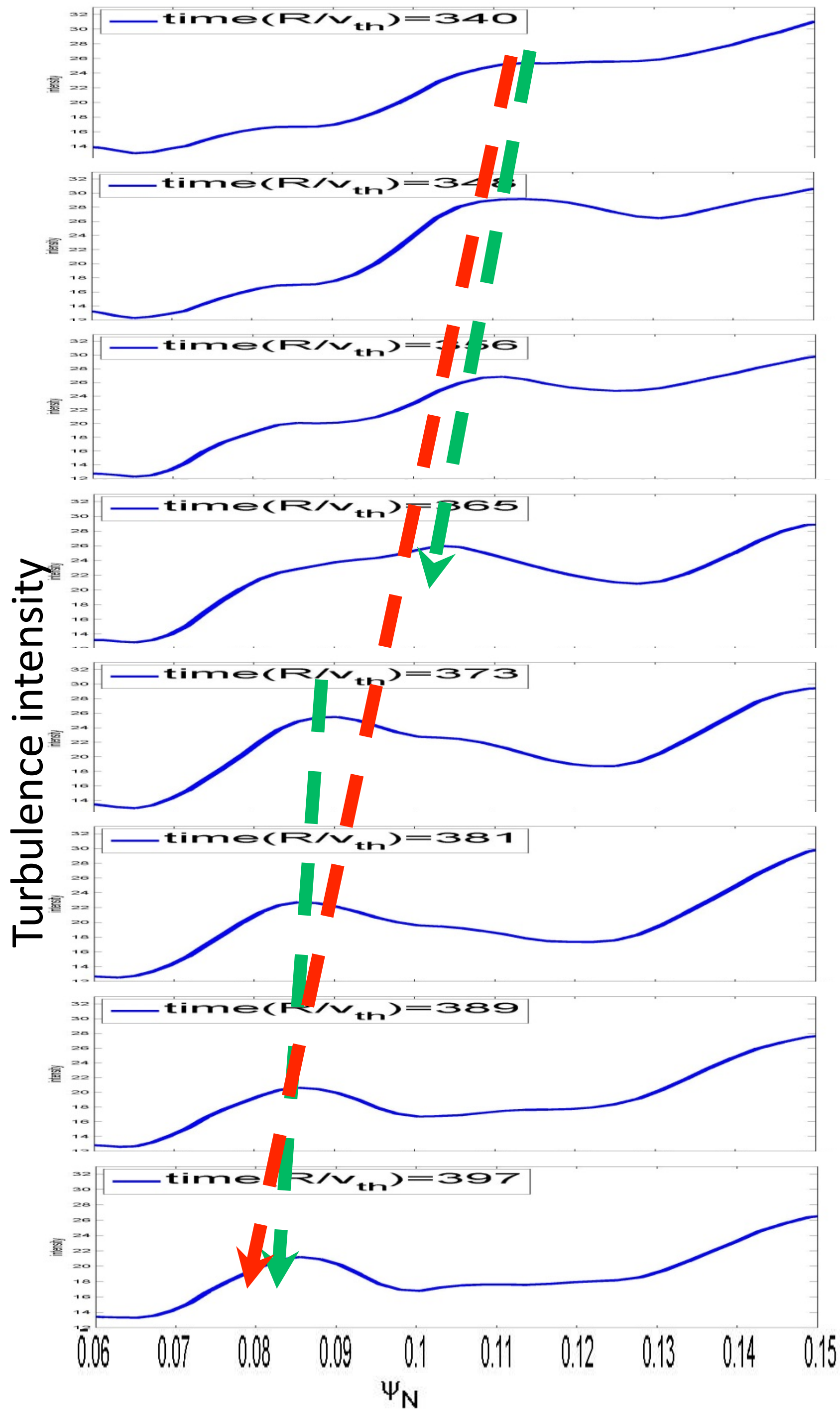
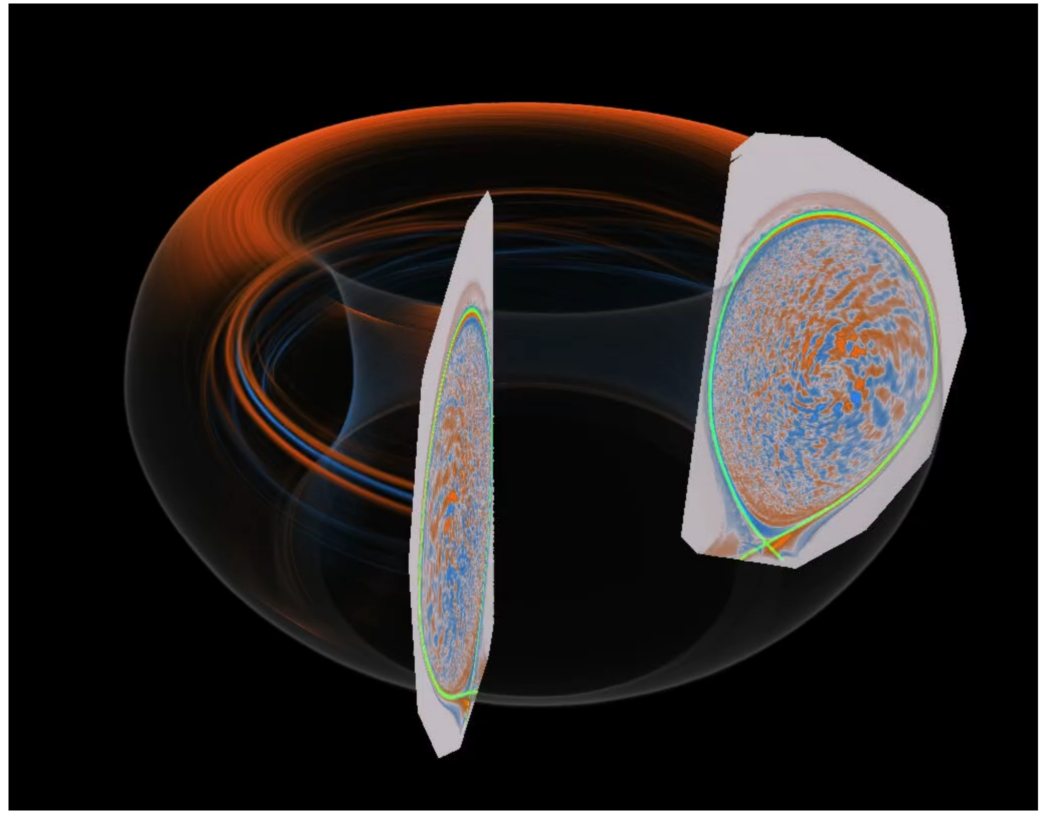


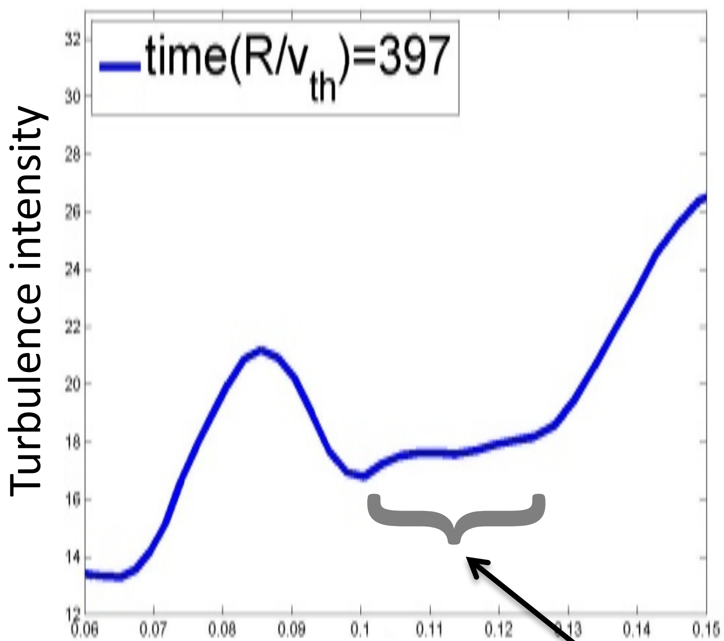
Turbulence exists in central core where the turbulence drive is subcritical.



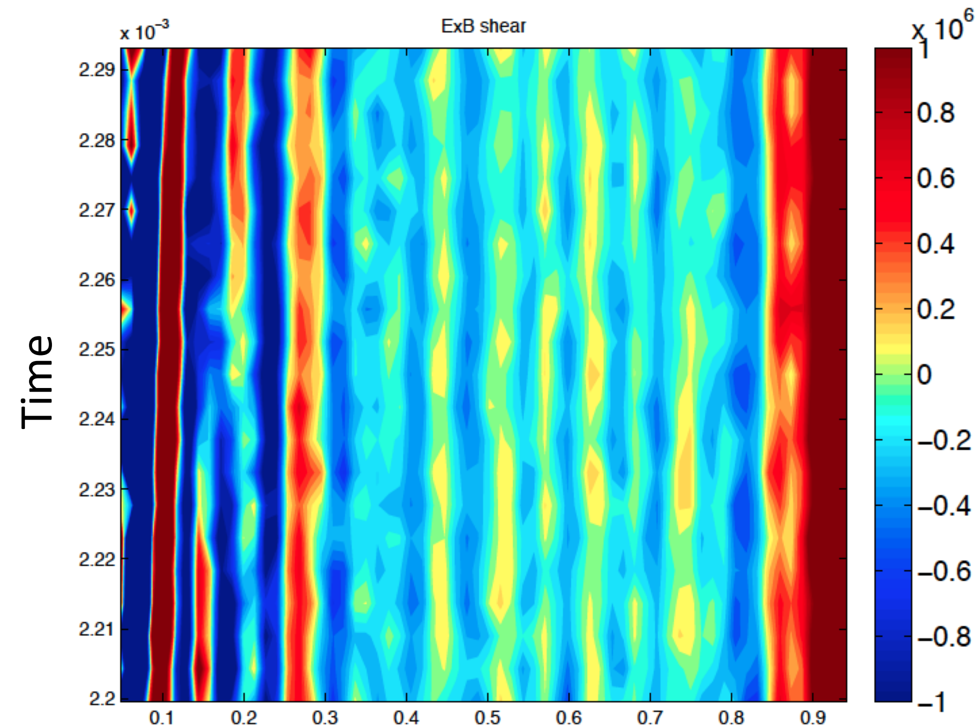
Inward spreading from turbulent region.

Many interesting physics to be studied, including internal transport barrier.

A sign of internal transport barrier formation at the boundary between the subcritical and SOC regions!



ExB shearing rate the final time window



Drop in turbulence intensity

Strongly sheared ExB layer

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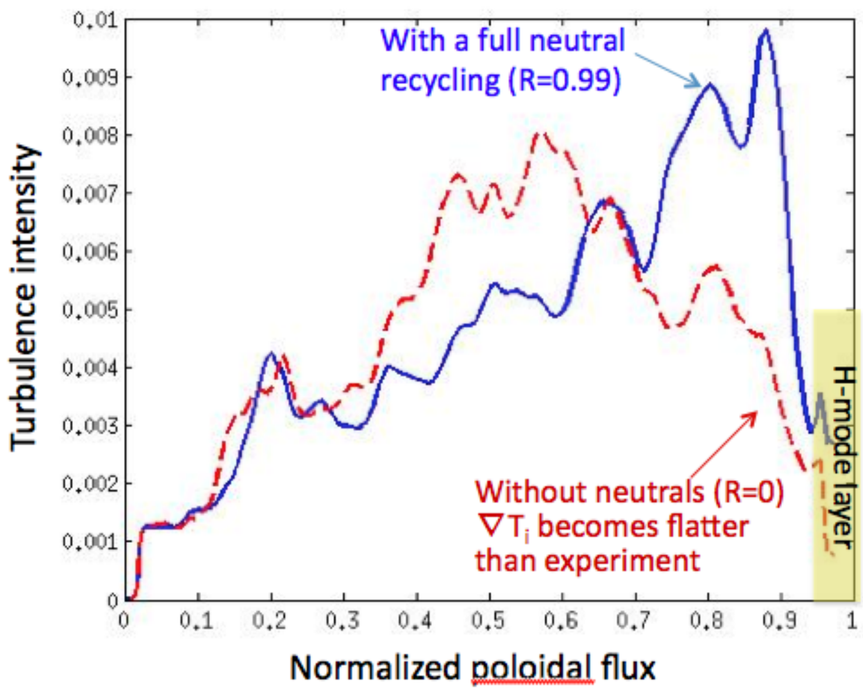
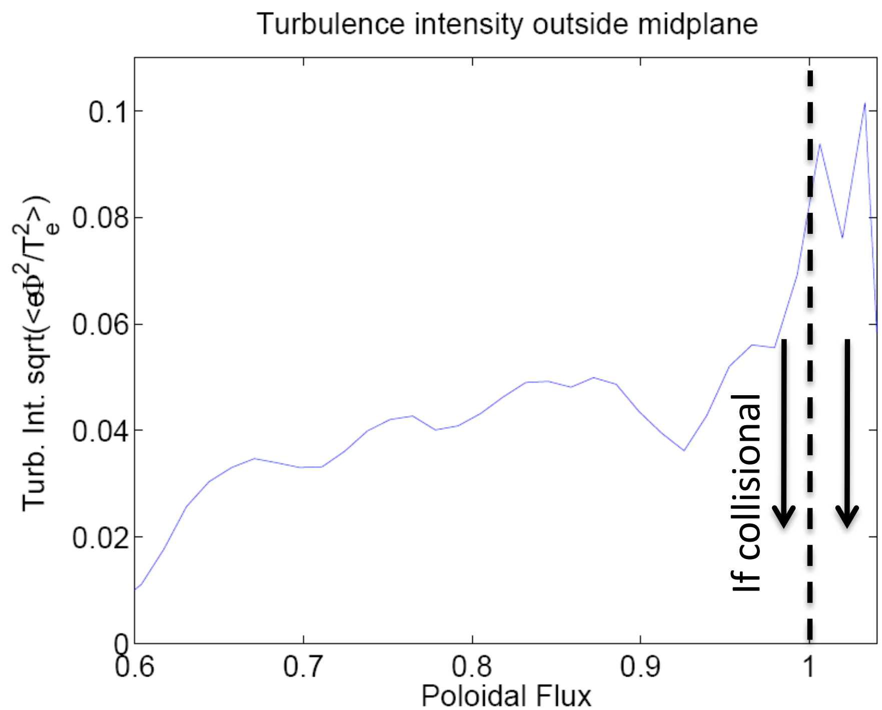
XGC1 finds that, unlike ITG alone, the nonlinear ITG+CTEM turbulence can fill up the H-mode layer.

(A little different plasma profile between these two)



With adiabatic electrons

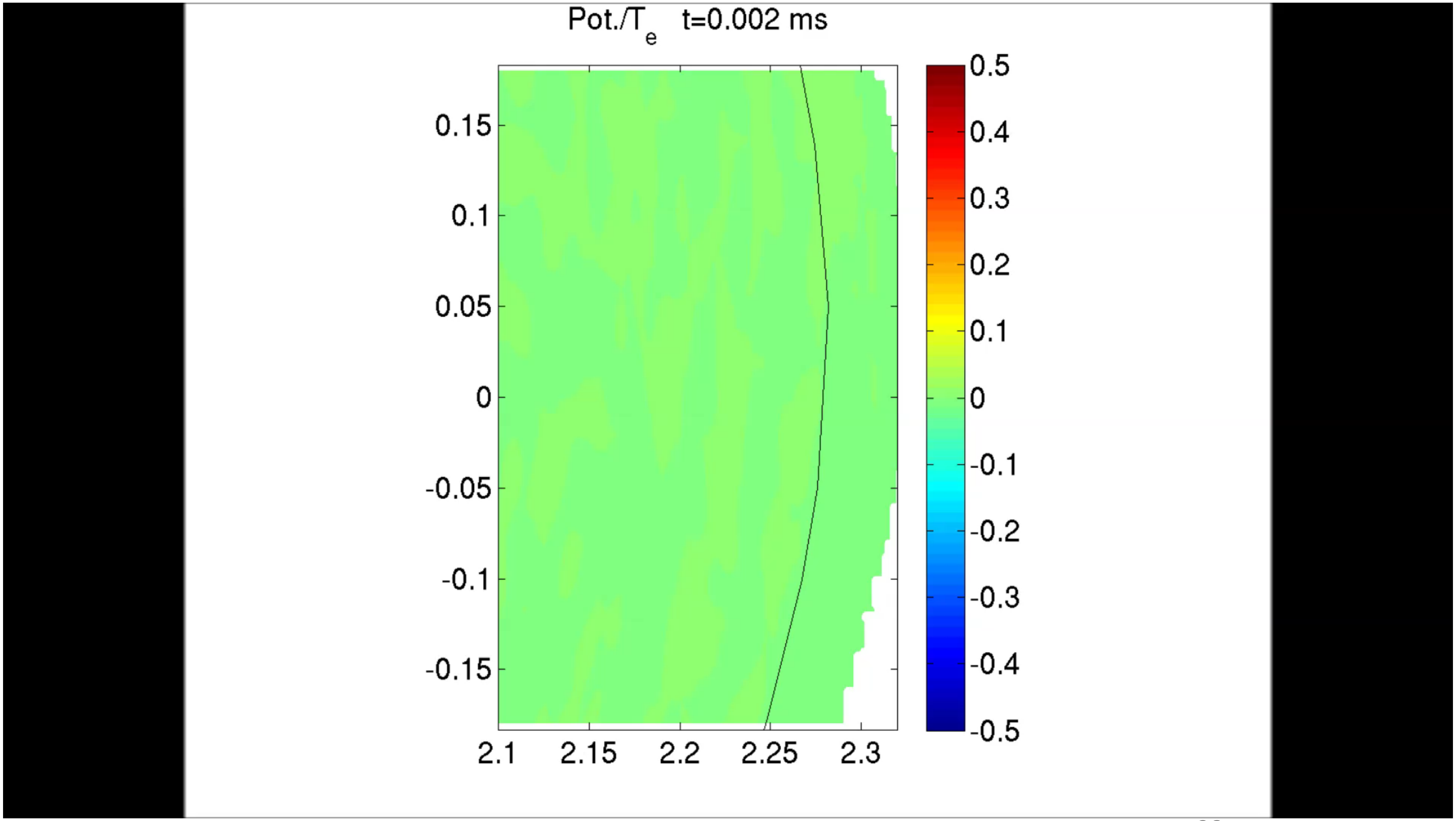


With collisionless kinetic electrons

Could this mean that 1) ITG is dominant right after L-H transition, and that 2) as edge T-pedestal grows, the CTEM type turbulence (with E&M effect) makes turbulence to come back in the H-layer? Relation with ELMs?

Gyrokinetic dynamics of nonlinear coherent potential structures ("blobs") across separatrix at outside midplane.

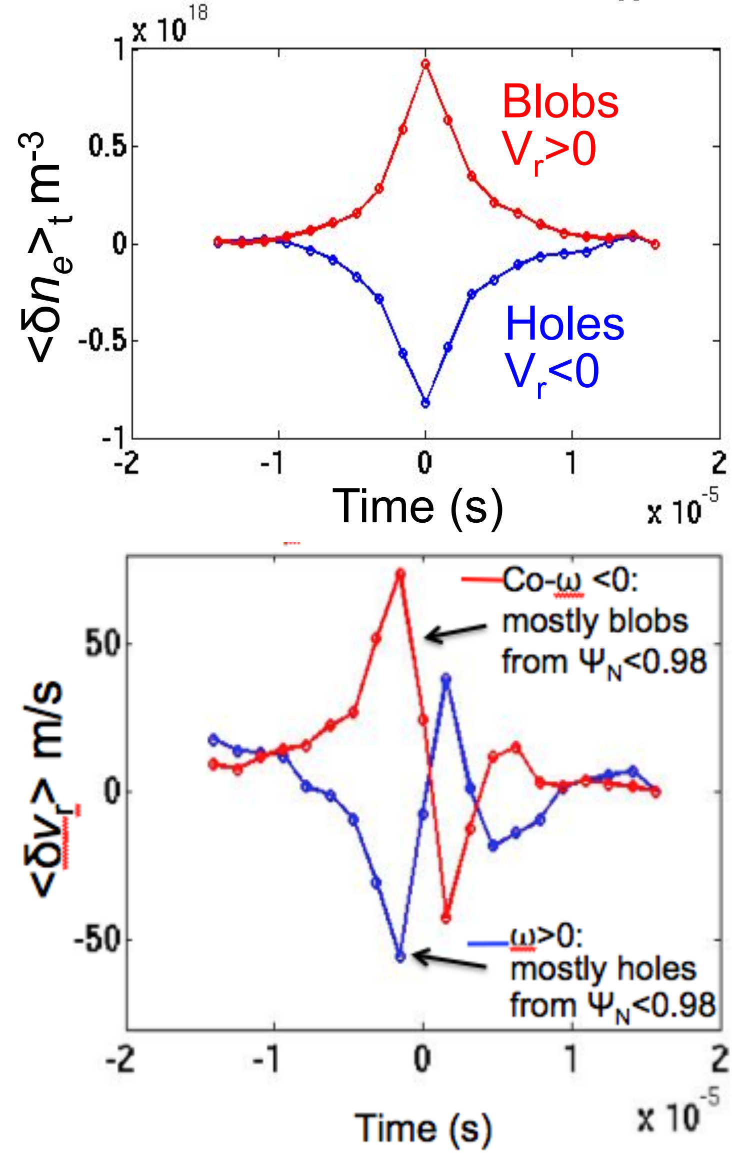
Notice that the blob amplitude is ~50%



The nonlinear coherent structures are composed of blobs and holes

- **Blobs** move radially **outward** and **holes** move **inward**
- Similar to observations from HL-2A experiment
  - M. Xu et. al., IAEA 2012
- Blobs and holes **carry physics information** with them
  - **mass, heat, and momentum**

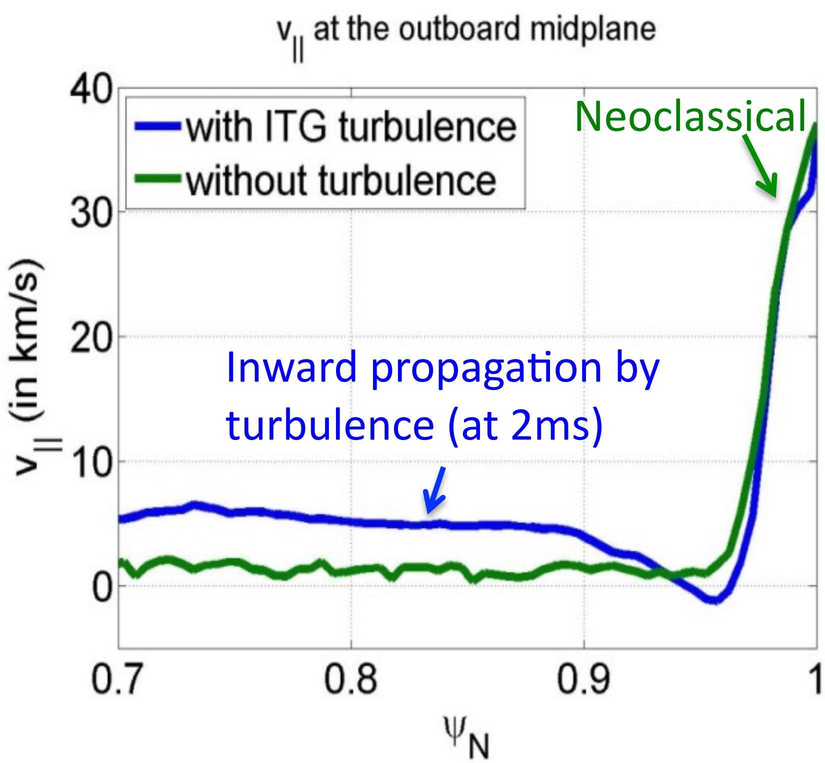
Measured at $0.96<\Psi_N<1$

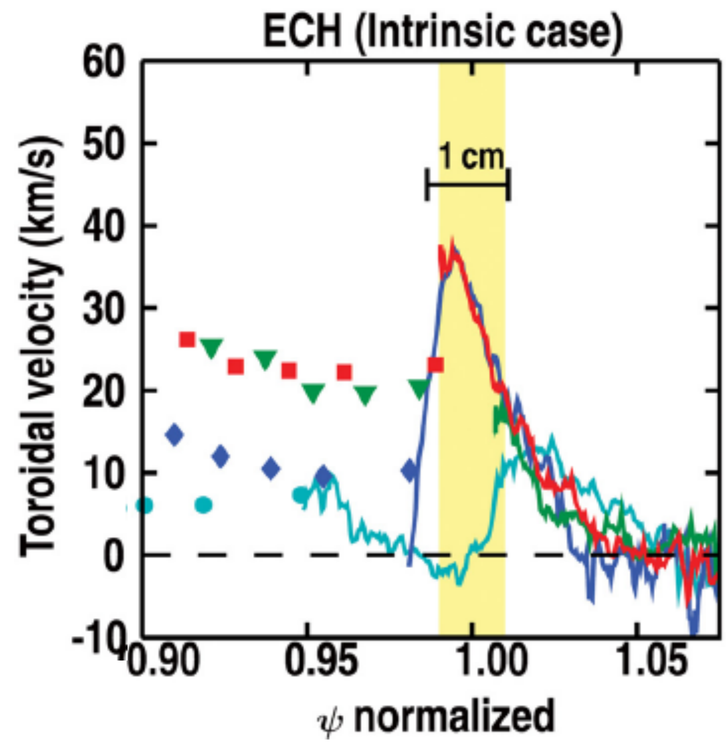


Rotation is generated at edge and pinched inward in XGC1 (& in experiments: Rice et al)

- **Strong neoclassical co-rotation at edge: Pfirsch-Schulter and orbit loss**
- **Turbulent residual-stress driven inward pinch of edge rotation (by holes)**

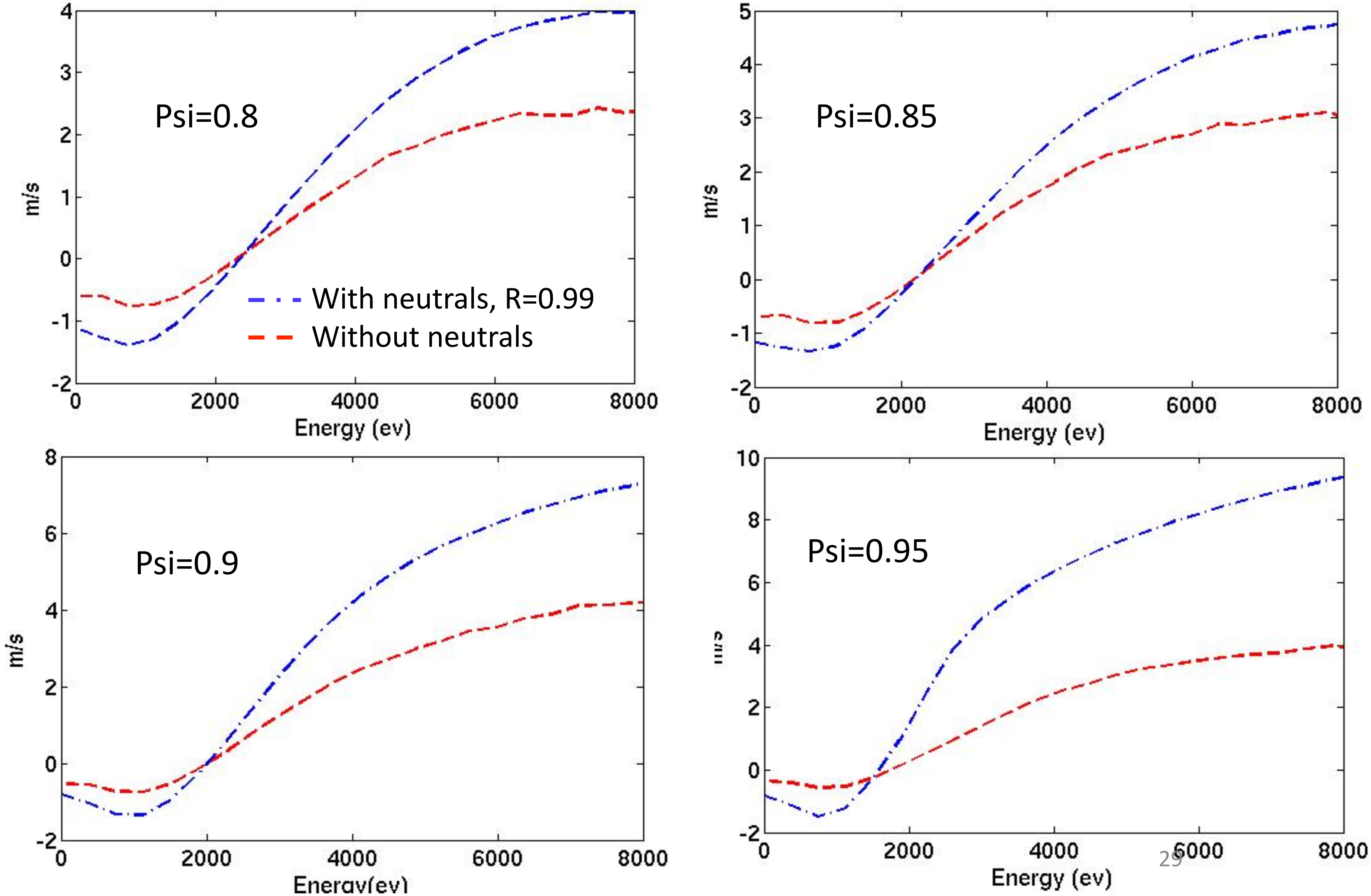
S. Muler et al, PoP 2011, L-H transition





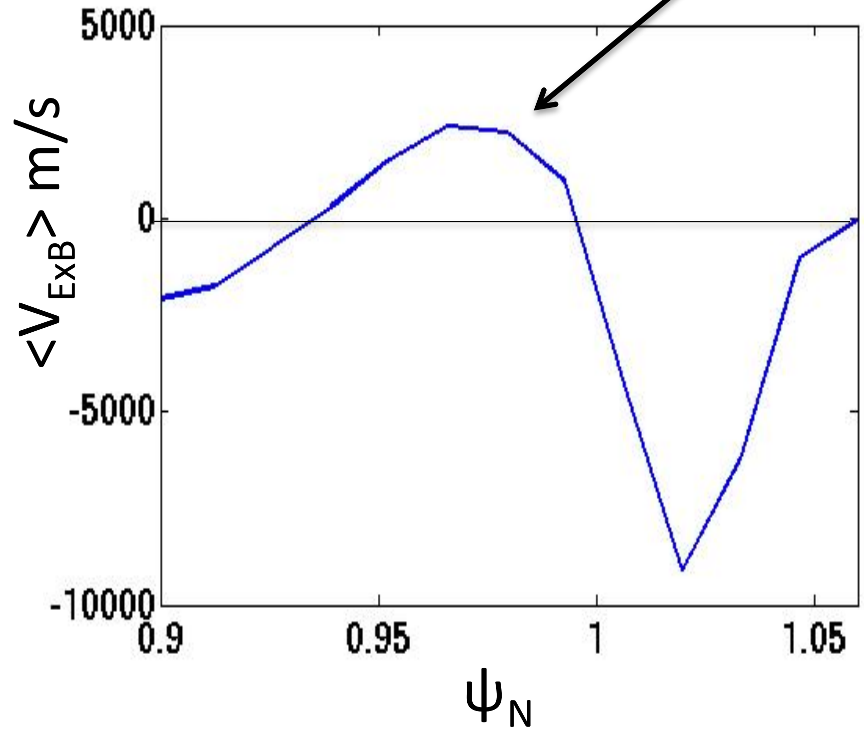
Holes carry the co-rotation inward

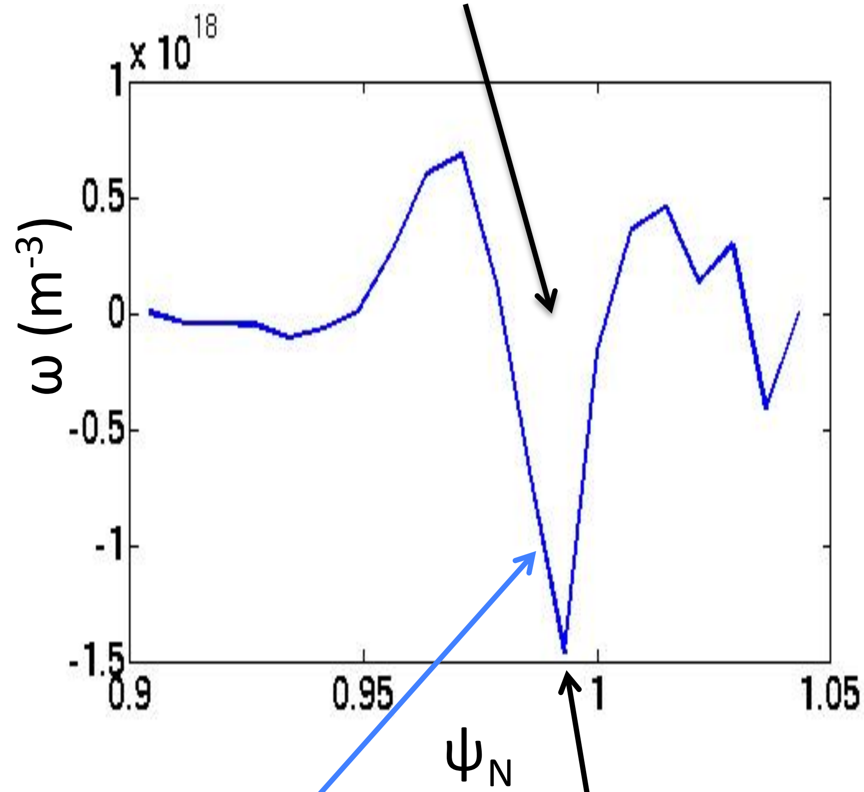
Inward cold-particle pinch at $\Psi>0.8$: It increases with neutral particles: Holes are colder. (Figures are from ITG turbulence)



Mean V_{ExB} and vorticity ω from XGC1 in the presence of blobs and holes

Stronger negative vorticity means stronger ExB shearing rate in H-layer

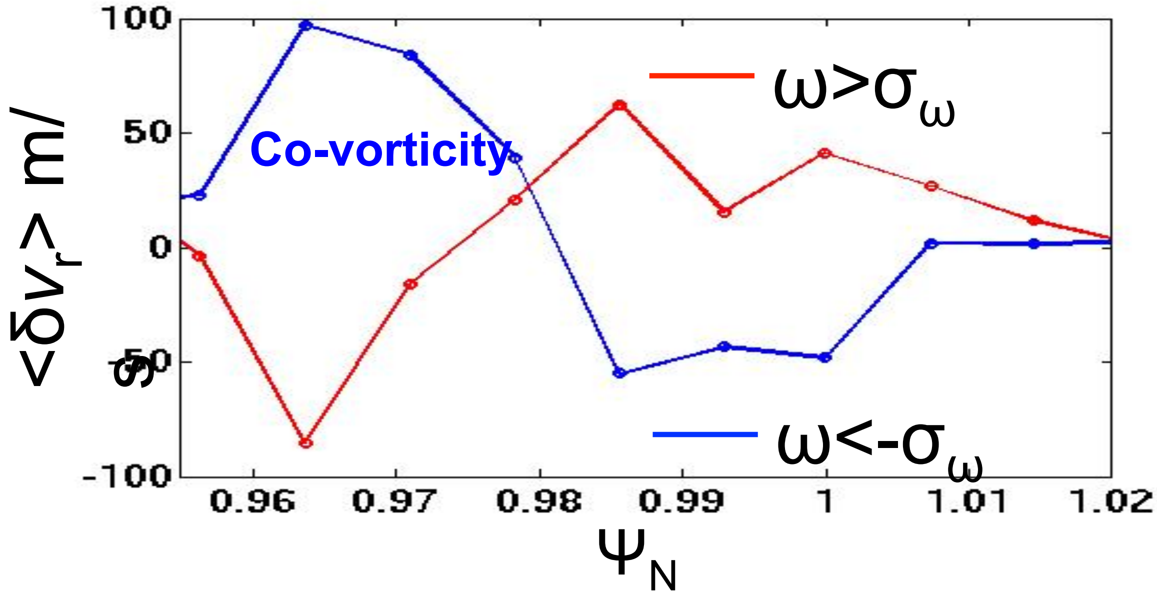




Co-vorticity is defined as ω<0

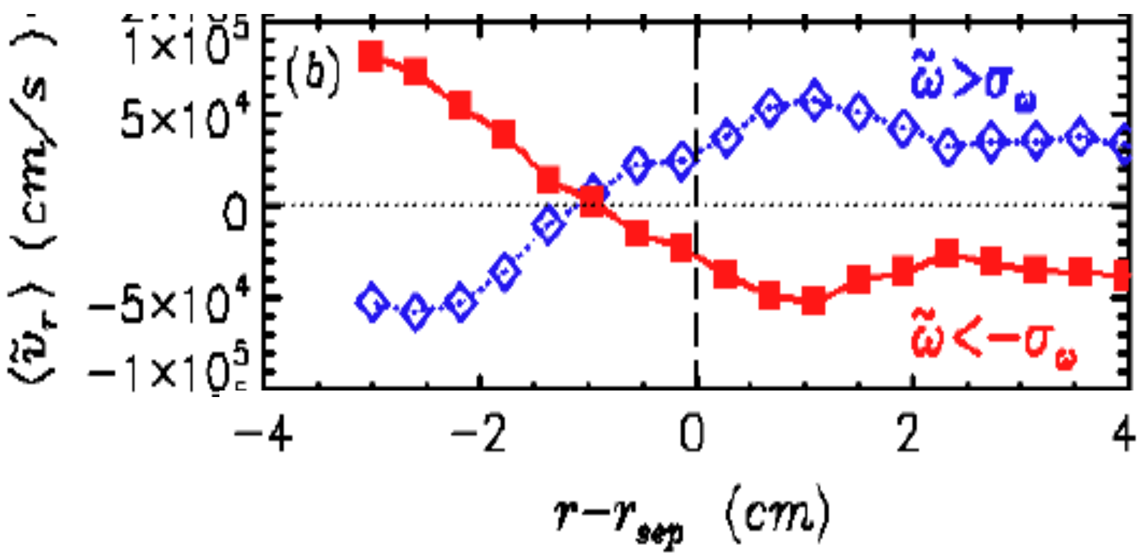
Min(ω) at $\Psi_N \approx 0.99$

The negative vorticity merges to $\Psi_N \approx 0.98$, strengthening the neoclassical EXB shearing rate.



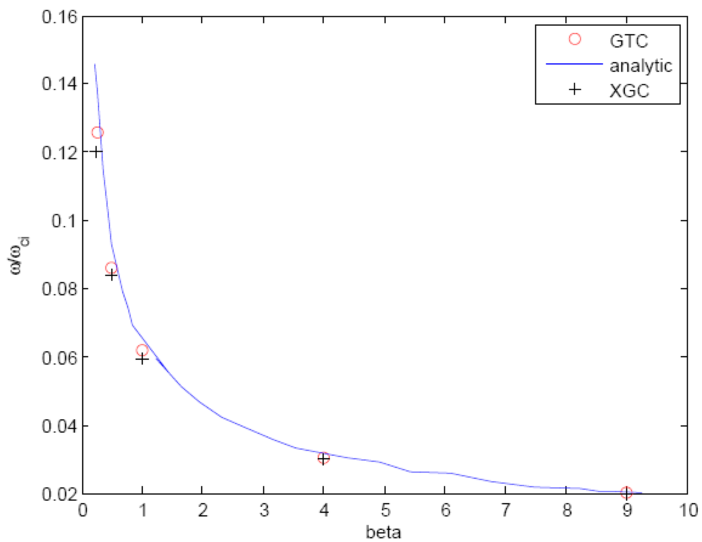
Vorticity merging from XGC1 in a DIII-D plasma.

Highly plausible trigger of L-H transition [a la, Diamond et al]

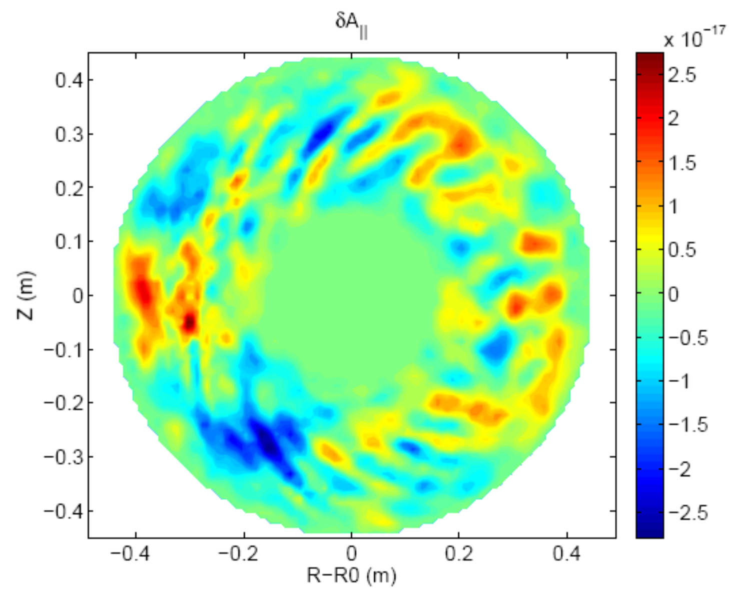


Vorticity merging observed on HL-2A, M. Xu, IAEA2012

Electro-Magnetic turbulence capability in XGC1



Cross verification of fluid Alfven wave frequency in fluid-particle hybrid scheme



Low beta ITG turbulence in electromagnetic split-weight scheme

- Currently both algorithms are in XGC1
- KAM verification is on the next action item
- These two E&M methods to be converted to diverted geometry
- Gyrokinetic tearing-ELM capability is on our next plan in XGC1 (J. Lang with U. Colorado).

Validation of the basic neoclassical + turbulence capabilities of XGC1 on NSTX → Application to NSTX-U

- How well (badly) do the full-f neoclassical + electrostatic turbulence compare with the existing NSTX data in edge-core, scrape-off layer, and in the central core? [Ku, Lang, Hager]
- Can we understand the L-H transition physics with neoclassical + electrostatic turbulence? [in 2013, S. Ku, J. Lang and Hager]
  - Pedestal structure?
- How much improvement will we get if we add the E&M turbulence? [in 2014, S. Ku]
- What if we add impurities? [work in progress, K. Kim]
- What if we add 3D field? [work in progress, Hager and Ku]
- Understand ELMs from gyrokinetic physics? [2014, J. Lang]
- Circulation current in SOL?

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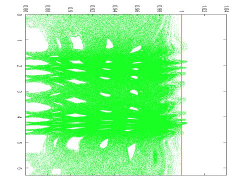
3D perturbations affect global turbulence and transport.

They must be included for quantitative understanding of NSTX and NSTX-U plasma property.

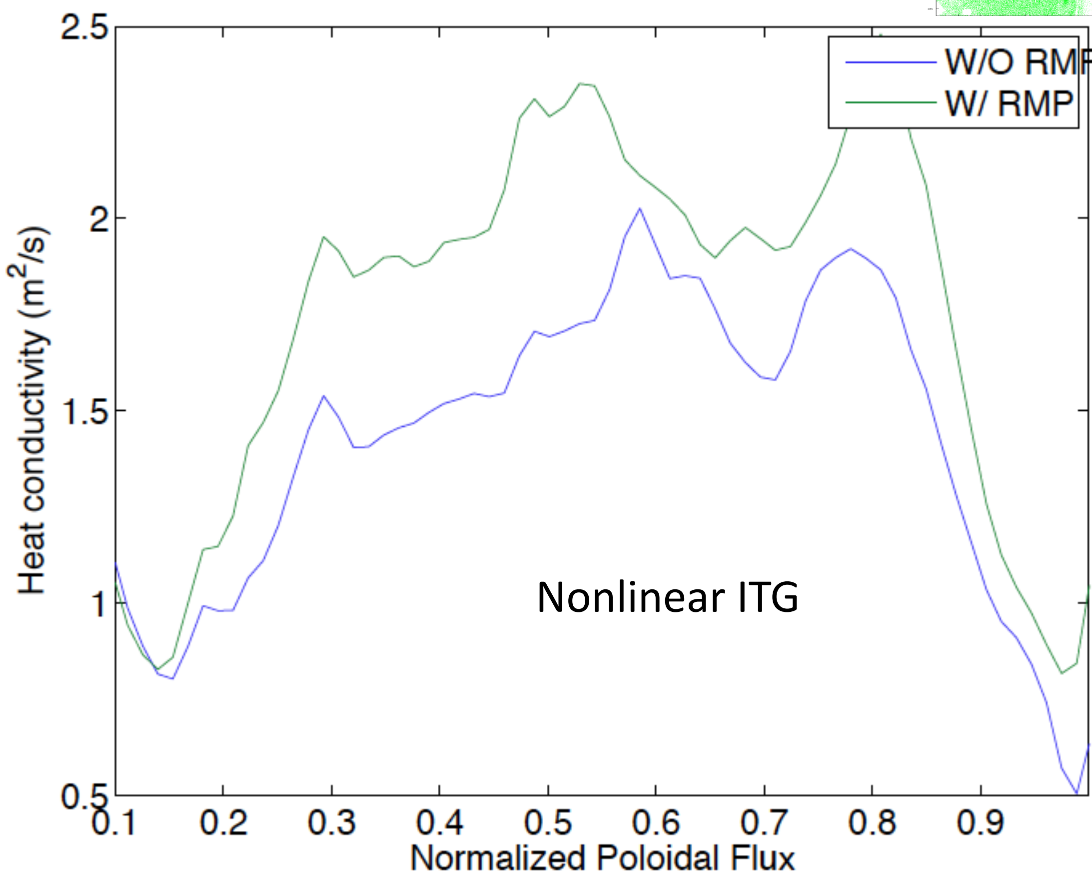


Example: RMP effect on ITG turbulence

- RMPs with plasma response has been solved in XGC0
- The perturbed B-field is imported into XGC1
- Damping of ExB shearing by 3D enhances turb. level

A strong RMP-effect on background plasma has been well-verified [XGC0].

A comprehensive RMP study: XGC0 → XGC1



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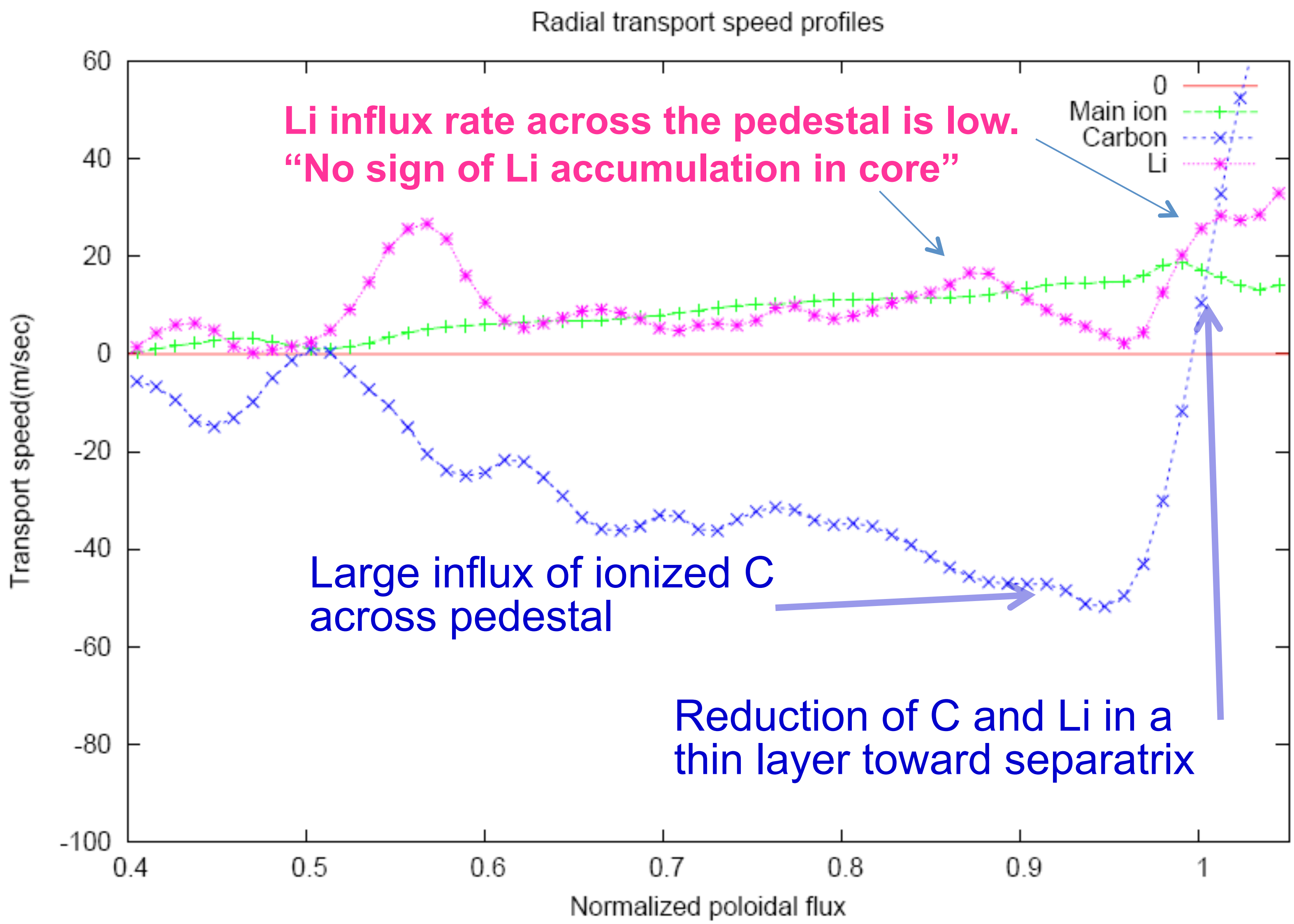
  - Current circulation

XGC0 says, at n_C/n_e=10%, Li moves outward while C^{+6} moves inward at ψ_N<1.

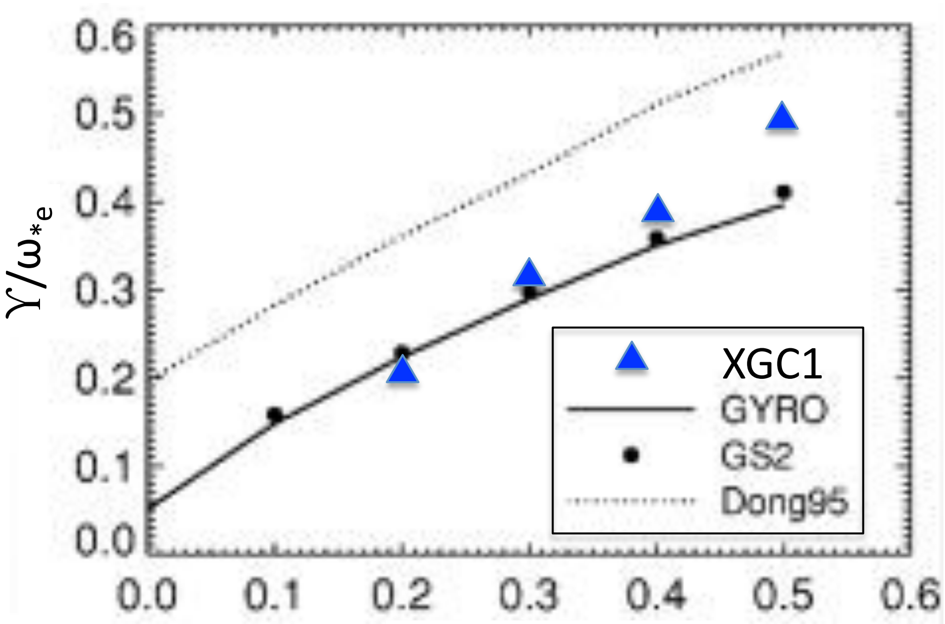


Impurity ions can affect turbulence significantly ITG → Impurity modes

In addition to the neoclassical impurity capability, a turbulence impurity physics capability is being added to XGC1.

- A cross-verification with GYRO, GS2, and Dong-Horton has been reasonably successful.
- Impurity collision and radiation routines are being moved from XGC0

[Kyuho Kim, part of PhD thesis research, KAIST]



Carbon fraction

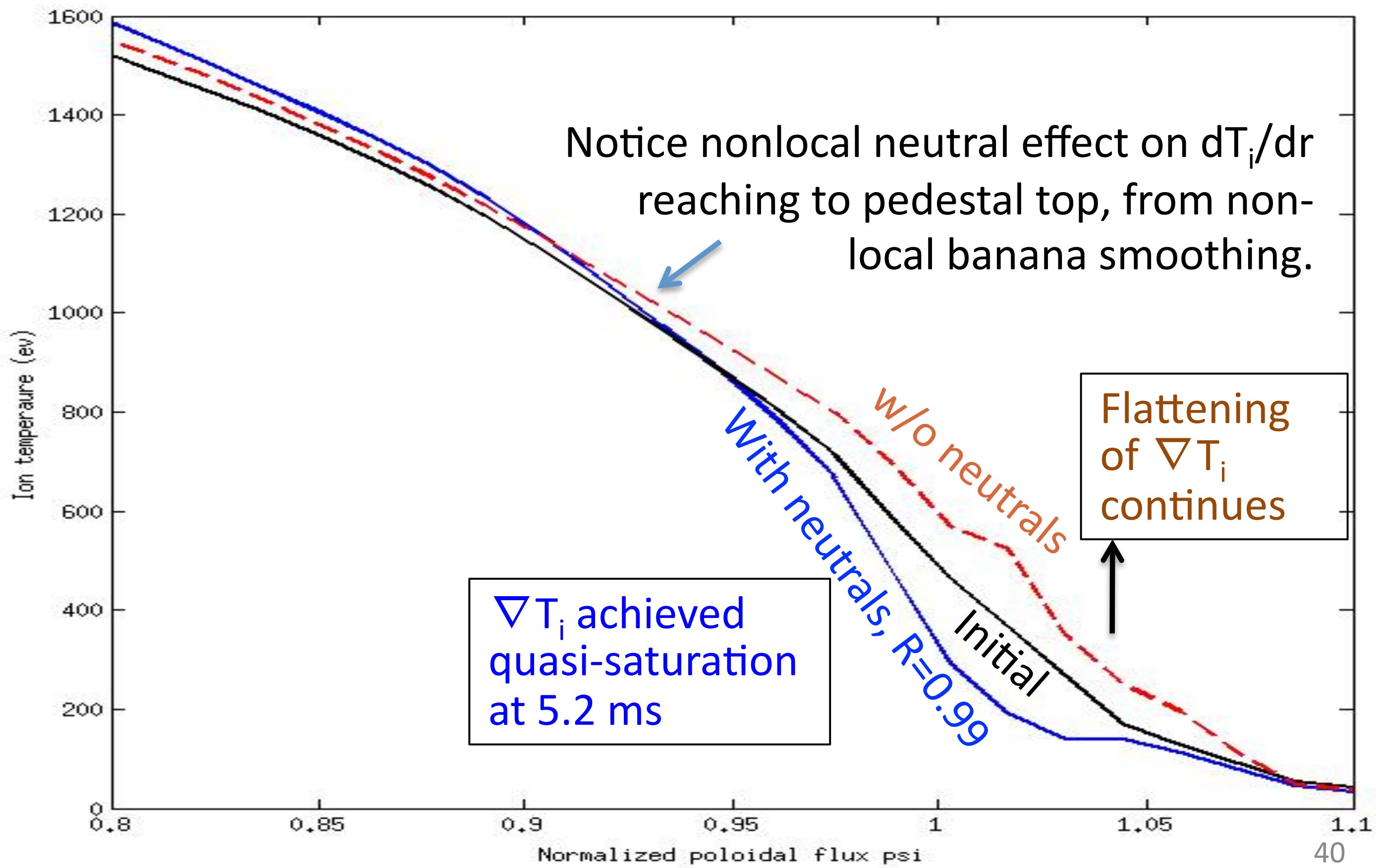
Multiple aspects of Li transport and its effects on plasma confinement can be studied in XGC1

- Li transport itself is influenced by neoclassical and turbulence
- Radiation
- Through effect on neutral particle recycling
  - Neutrals can affect plasma profiles
  - Neutrals can affect plasma turbulence

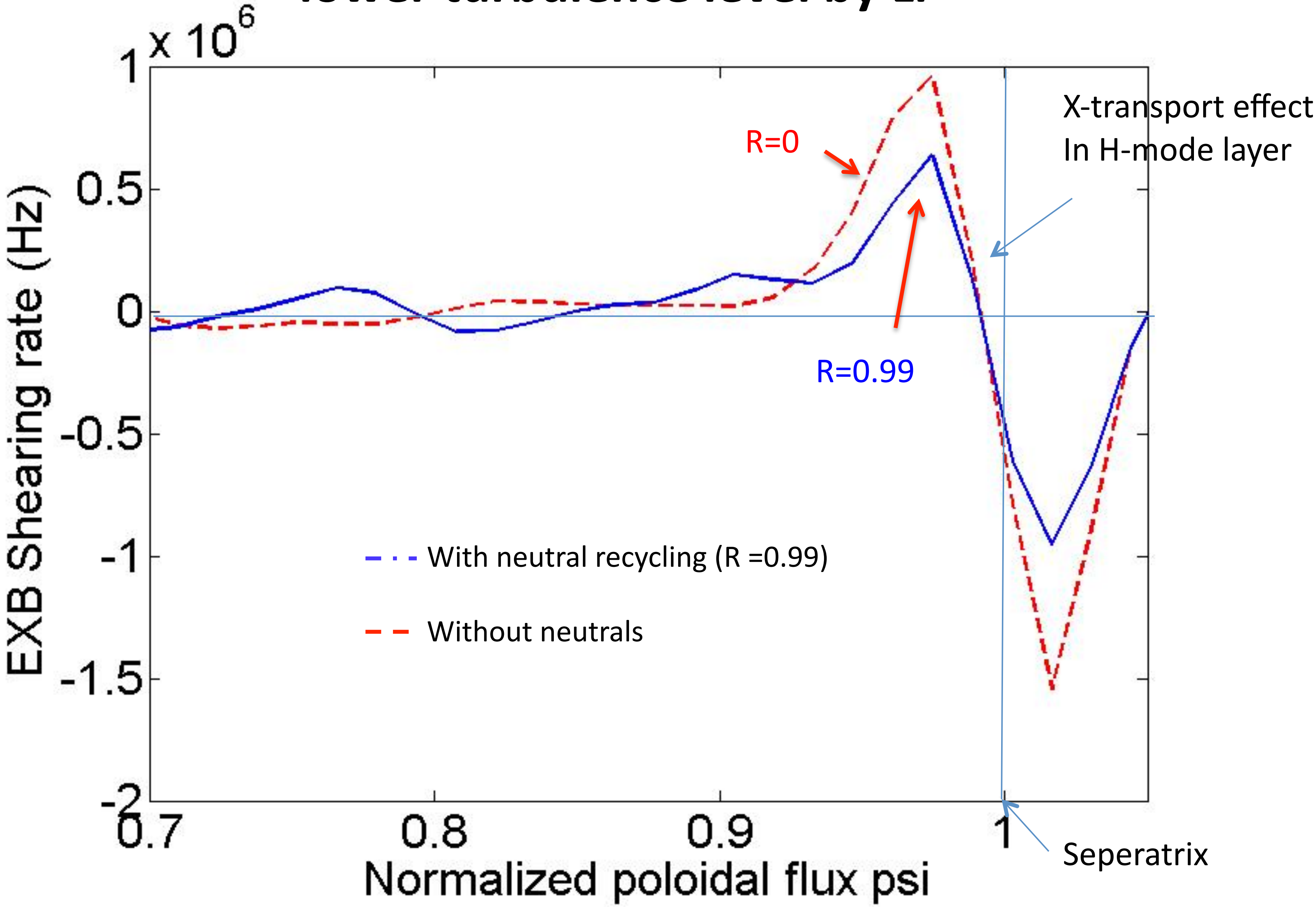
  → Li transport
- Through direct effect on turbulence
  - Generation of impurity modes
  - Effect on other turbulence modes

  → Li transport
- Plasma aspect of Li PMI
  - Neoclassical and turbulence consistent // and ⊥ sheath potential
  - Globally consistent plasma impingement on the wall
  - Li migration in scrape-off
- XGC1 can easily be converted to MAGNUM-PSI geometry for code validation
- A reliable PMI model/data is needed

Indirect effect of Li on plasma profile, through modification of neutral recycling, can be studied in XGC1: both neoclassical and turbulent

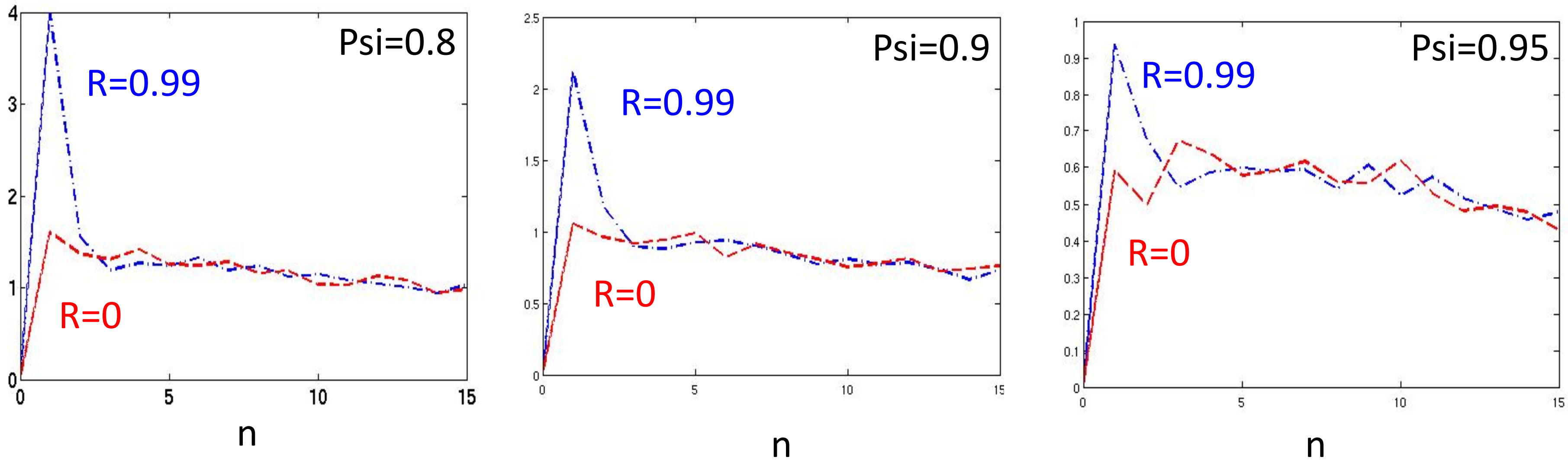


Li effect on EXB shearing rate can be validated → lower turbulence level by Li



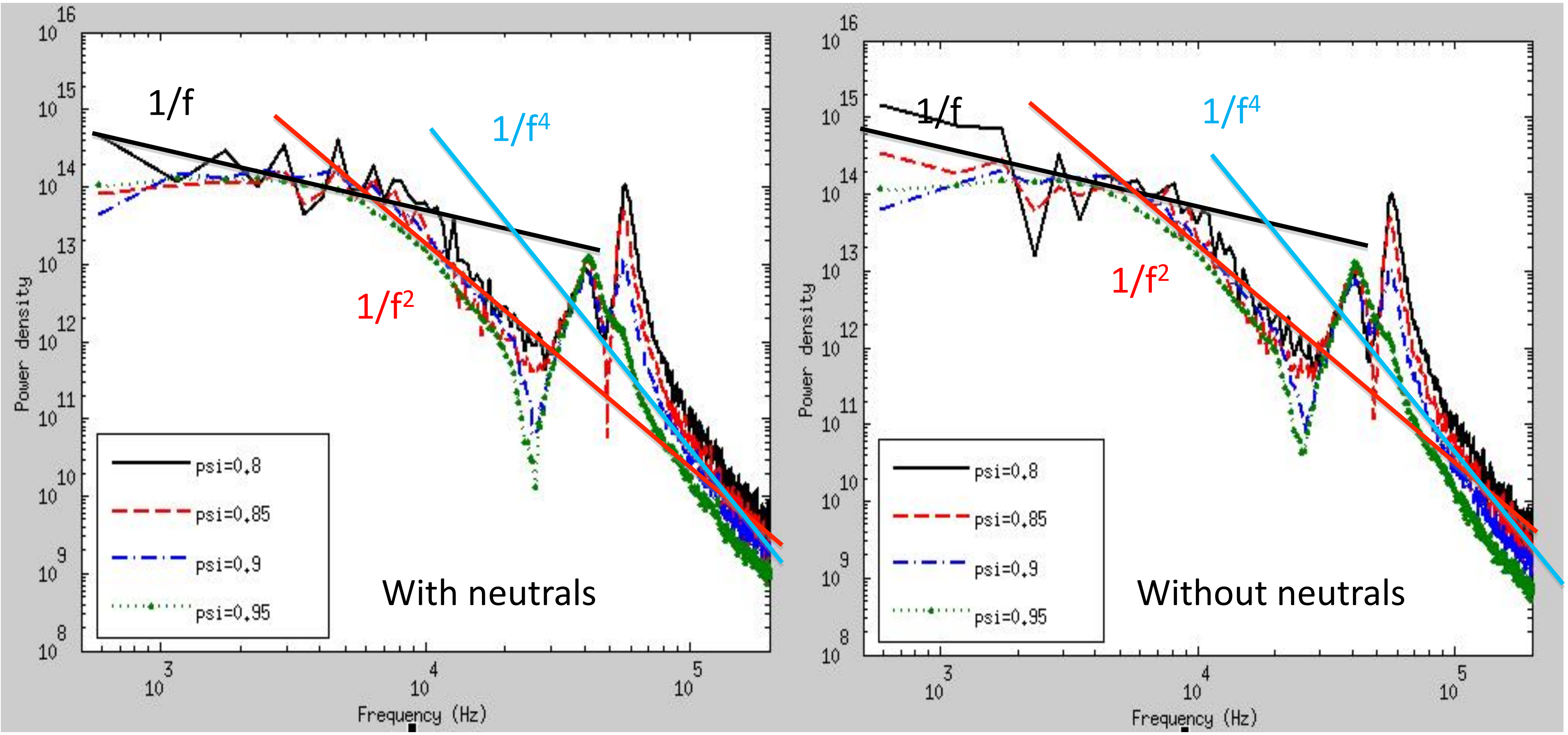
Li effect on the k-spectrum of edge turbulence can be validated in NSTX/NSTX-U

Turbulence spectrum in toroidal mode number n shows that the neutrals shift the turbulence to the long wavelength structure.



Li effect on turbulence frequency spectrum

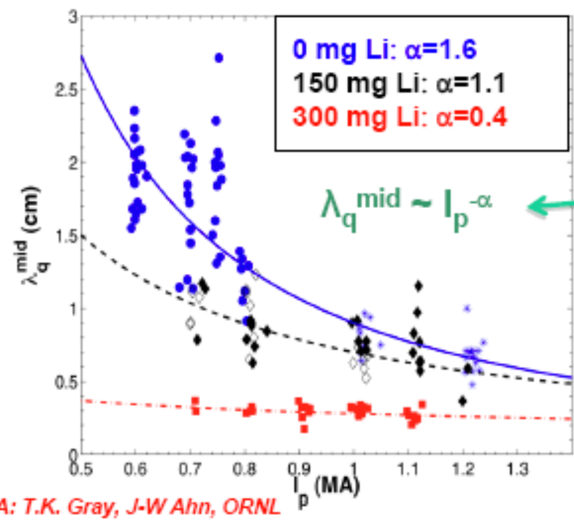
Heat transport spectrum at low frequency is reduced by neutrals, though.



$$f_{GAM} \approx 60 \ \ \mathrm{KHz}$$

XGC0 shows that neoclassical physics sets the basis for the $1/I_p^{\alpha}$ heat flux width behavior (2010 JRT)

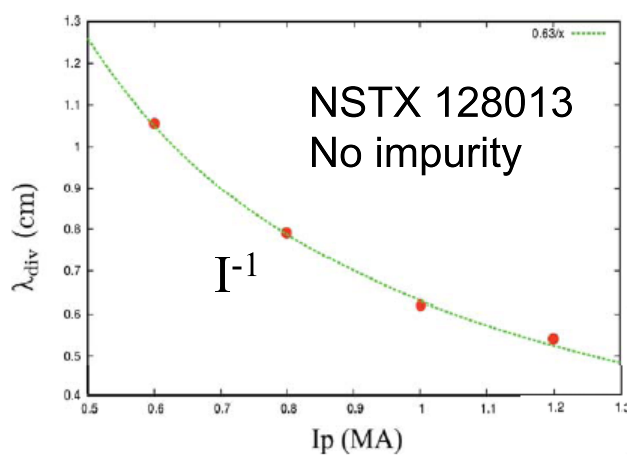
**Joint Research Target (3 U.S. Facilities)*



IAEA: T.K. Gray, J-W Ahn, ORNL

- Divertor heat flux width decreases with increased plasma current I_P
  - Potentially major implications for ITER
  - NSTX: λ_q^{mid} further decreases with Li

→ **NSTX Upgrade with conventional divertor (LSN, flux expansion of 10-15) projects to very high peak heat flux up to 30-45MW/m²**



Neoclassical physics:
XGC0 shows $\lambda_q^{mid} \propto I_P^{-\alpha}$, where α is function of collisionality, with some broadening by radial anomalous transport.

Outline/Summary

- Introduction: How different is XGC1 from other GK codes?
- Edge-core
  - There is no turbulence shortfall toward pedestal top in XGC1
  - "Turbulence + Heating + Cooling" brings the profile to SOC
- Central core: Turbulence spreads into central core
- Pedestal-SOL: dominated by neoclassical physics and "blobs"
  - CTEM-type turbulence brings the turbulence back in H-mode layer
  - Momentum transport and particle fueling into core
  - L-H transition
  - Pedestal structure and height: can start from electrstatic
  - H-L back-transition and ELMs: requires E&M
- Penetration of 3D magnetic perturbation and turbulence
- Impurity and turbulence
- PMI from plasma side
  - Scrape-off transport, heat-load footprint and material migration
  - Consistency between scrape-off turbulence and wall-sheath
  - Current circulation