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Gyrokinetic Simulation of Tokamak Edge Plasma

C.-S. Chang[a),b)]

[a)] *Princeton Plasma Physics Laboratory*

Princeton University, USA

PPPL PRINCETON PLASMA PHYSICS LABORATORY

[b)] *SciDAC-3 Center for Edge Physics Simulation*

EPSi Edge Physics Simulation

QUEST Quantification of Uncertainty in Extreme Scale Computations

FASTMATH

SUPER Institute for Sustained Performance, Energy, and Resilience

SDAV

Three codes to be used in this lecture

All 3 codes include magnetic separatrix surface and Monte Carlo neutral particle recycling in the simulation domain.

- XGC0: Drift-kinetic particle-in-cell code
  - $\Phi(\psi)$ solver, RMP penetration capable
- XGCa: Gyrokinetic neoclassical code in X-point
  - Axisymmetric $\Phi(\psi,\theta)$ solver
- XGC1: Gyrokinetic turbulence+neoclassical

  4 versions
  - Full-f gyrokinetic ions + adiabatic electrons (ES)
  - Hybrid δf gyrokinetic ions + drift kinetic electrons (ES)
  - Full-f gyrokinetic ions + fluid electrons (E&M)
  - Split weight kinetic electrons (E&M), not used for production (too expensive in XGC1)

Gyrokinetic Simulation of Edge Physics

Introduction

- Why gyrokinetics for edge physics?
- Local vs nonlocal transport

Part I: Neoclassical and RMP physics without turbulence

- Fundamentals of neoclassical physics
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- Neoclassical physics in steep edge pedestal
- RMPs: penetration and transport

Part II: Addition of turbulence to neoclassical physics: examples

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- Divertor heat-flux width
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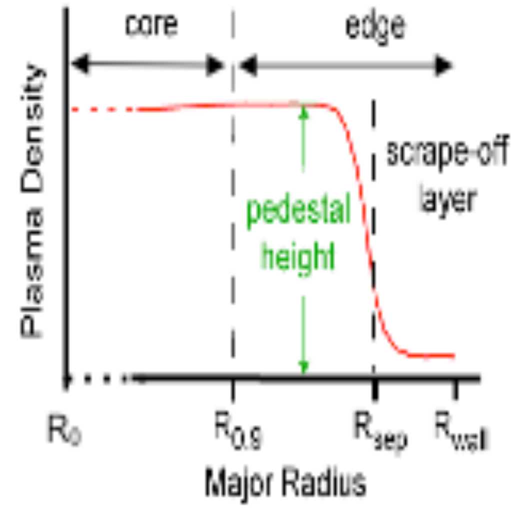
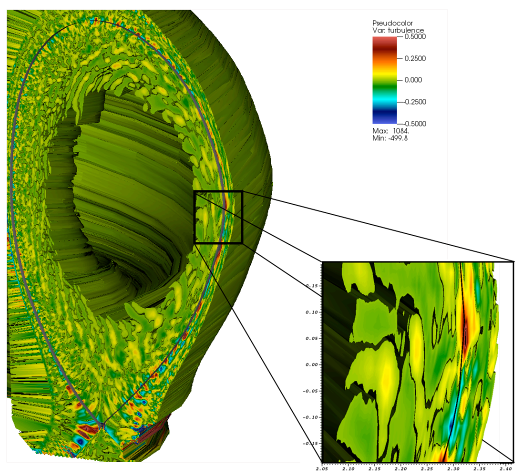
Why does edge plasma need gyrokinetic study?

✧ **Non-equilibrium Thermodynamics**
- Gradient scale length ~ physical mixing length
  - Neoclassical orbit excursion
  - Radial turbulence correlation
  - Gyro-viscosity? Neoclassical viscosity?
- In contact with material wall, X-loss
- Turbulence amplitude >10%
- Difficult to be described with fluid equations
  - Non-Maxwellian plasma
  - Collision effect ~ 0^{th} order
  - Closure terms ~ 0^{th} order
  - Braginskii theory, CGL, etc do not apply

✧ **All the important physics are scale-inseparable→ tightly coupled**
- Space-time scale: Particle dynamics ~ collision ~ turbulence ~ ELM
- Space scale: Mean plasma ~ neutral particles ~ all others above



Edge Pedestal



Large-amplitude blobby edge turbulence

Difficult to solve a tightly coupled system

For example

$d^2x/dt^2 = 2x + 3x^2 + 4y + xy + y^2$

$d^2y/dt^2 = x + 2x^2y + 3y + 4y^2$

We cannot ignore the coupling terms to solve the uncoupled equations, and then to consider the coupling effect using the uncoupled solutions. The solutions can be completely different.

When the coupling is known to be weak, the problem becomes easier.

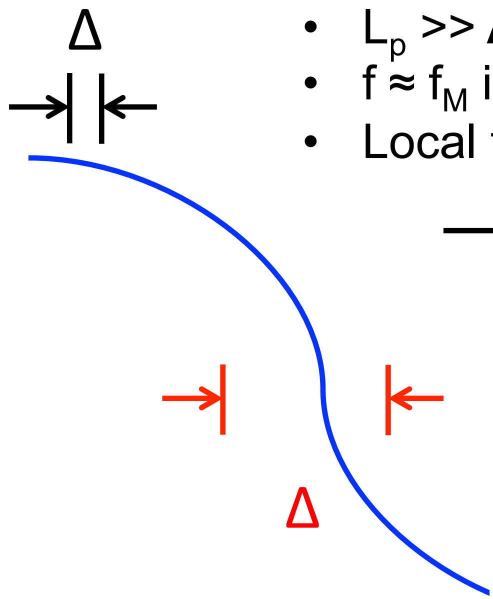
$d^2x/dt^2 = 2x + 3x^2 + \varepsilon(4y + xy + y^2)$

$d^2y/dt^2 = \delta(x + 2x^2y) + 3y + 4y^2$

$\varepsilon, \delta << 1$

- Our fusion plasma is in a self-organized state resulting from a nonlinear multiscale coupling. The edge plasma is an extreme example with many multiscale nonlinear coupling.
- Solving the whole system without the separation assumption is a desirable way.

Local and nonlocal transport



- $L_p >> \Delta$, Information at a local point can define gradient and D.
- $f \approx f_M$ is possible.
- Local transport theory: $\Gamma_r = -D(r)\nabla n(r)$, Fick's law

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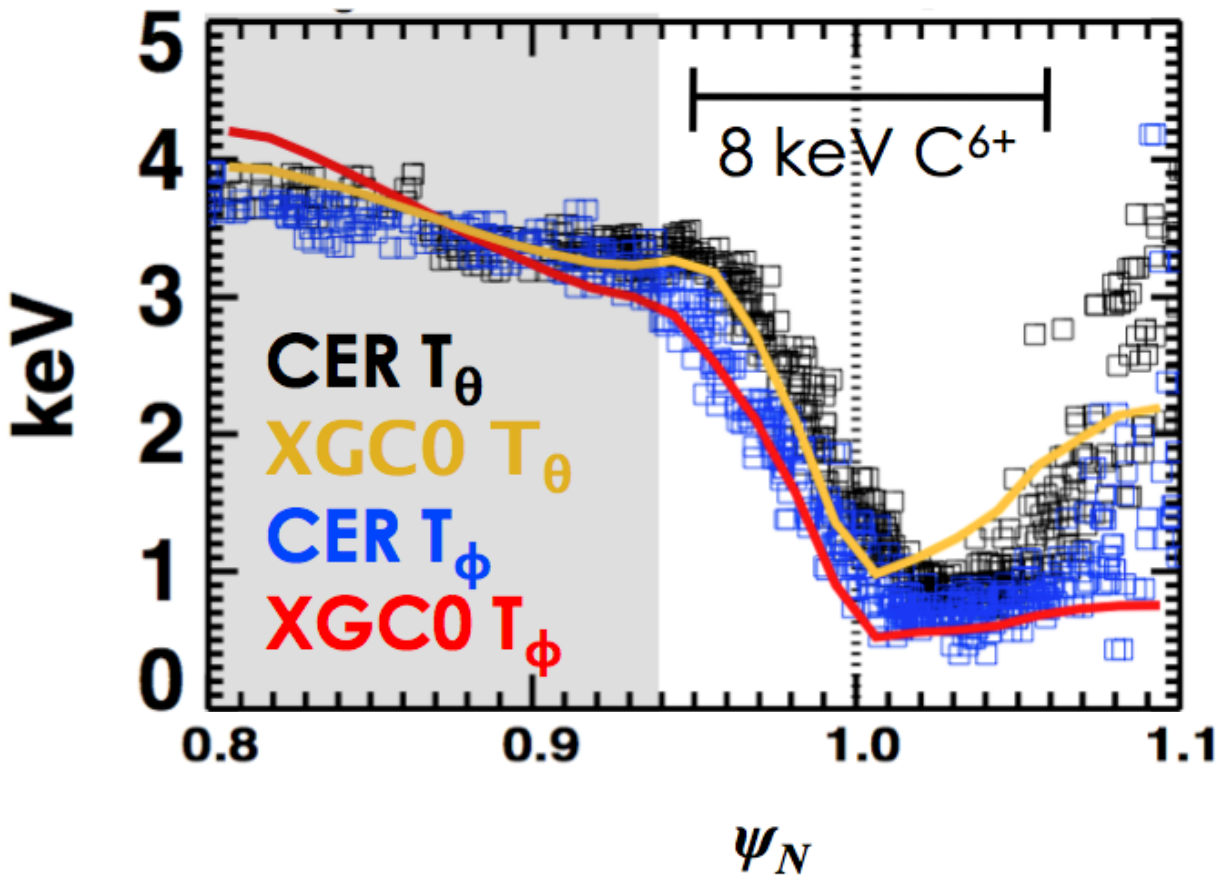
- $L_p \sim \Delta$, Local point information cannot define the gradient and D.
  - Will $L_p << \Delta$ be possible?
    → Neoclassical pedestal width [Chang, PoP 2004]
  - Will $f \approx f_M$ be possible?
- Nonlocal transport theory: fluxes can still be defined.
  - We often define $D_{eff}(r)$ that contains the nonlocal information including n', n", E', etc.
  - D_{eff} is often nonlinear
  - Self-organization between L_p and Δ

- **Let's start with the local case to get the basic idea of the neoclassical theory.**
- **Then, let's get into the nonlocal case: edge pedestal.**

Edge plasma is not in thermal equilibrium



DIII-D edge plasma

Devon Battaglia (APS-DPP 2013, Invited)

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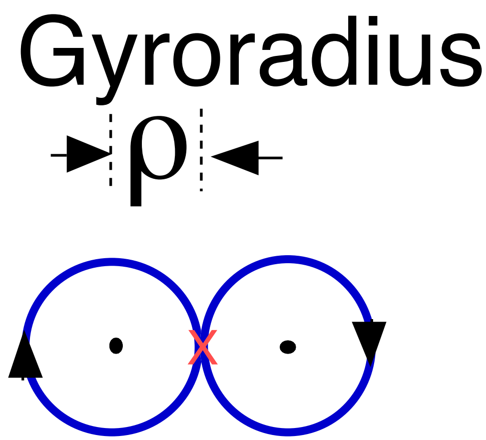
Classical Diffusion in B-field



Random walk argument

$D \approx f\, \gamma \Delta^2$

f : Participating fraction

γ : Random walk frequency

Δ: Step size

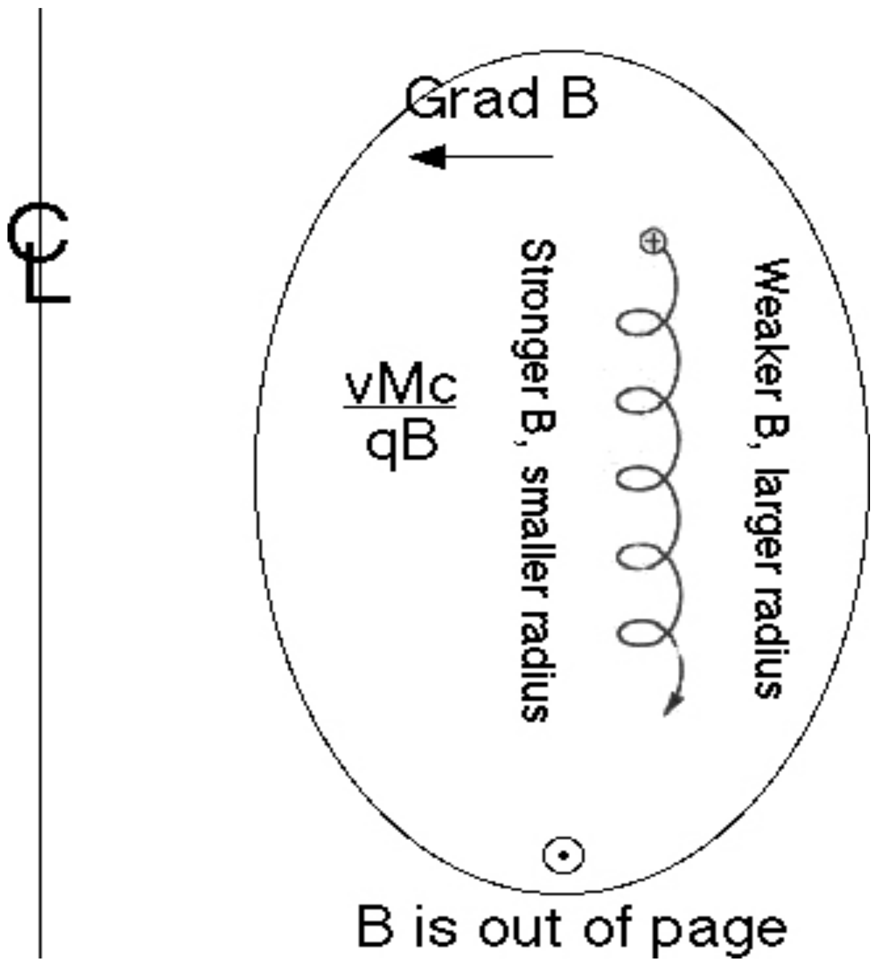
$f=1,\ \gamma=\nu_c,\ \Delta=\rho$

$\Rightarrow D_c = \nu_c \rho^2 \ (\propto B^{-2})$

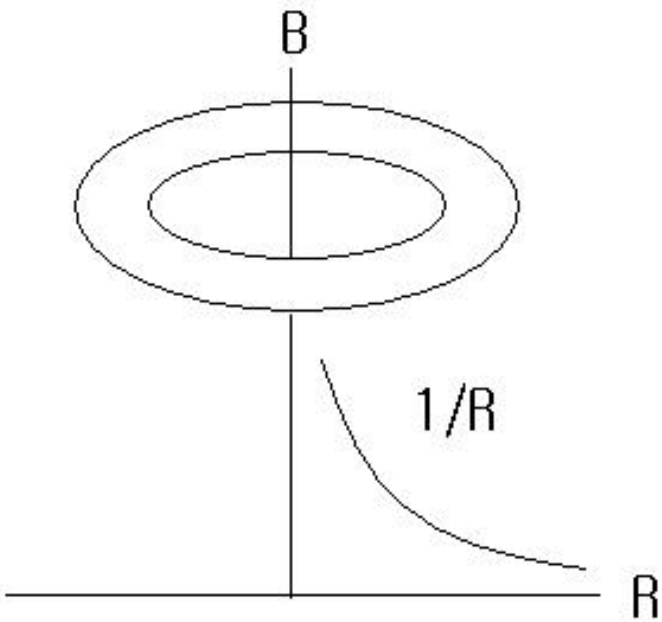
From next slides, let's jump to the local neoclassical transport physics.

Single particle confinement:

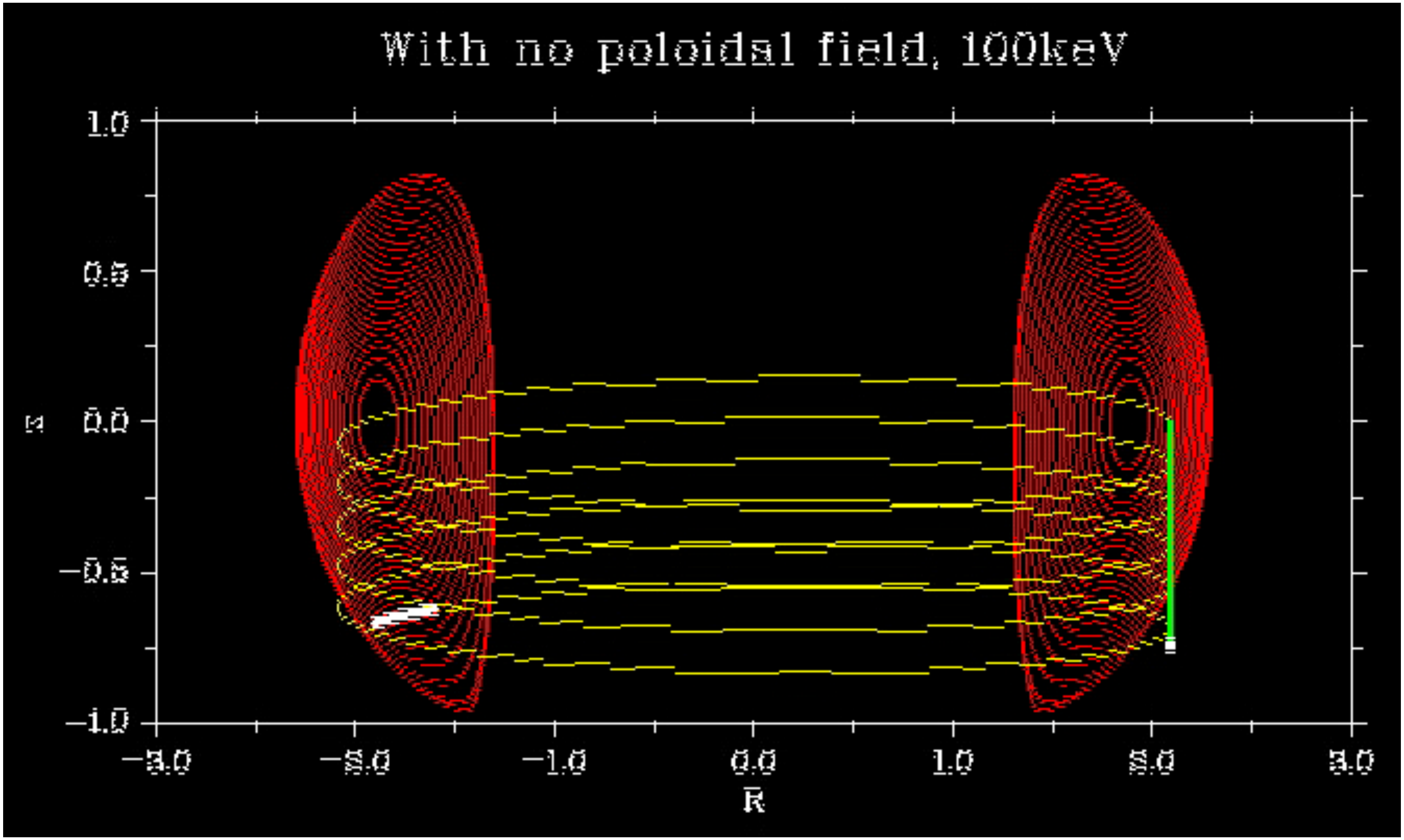
Plasma particles drift up or down.



$|B| \propto 1/R$



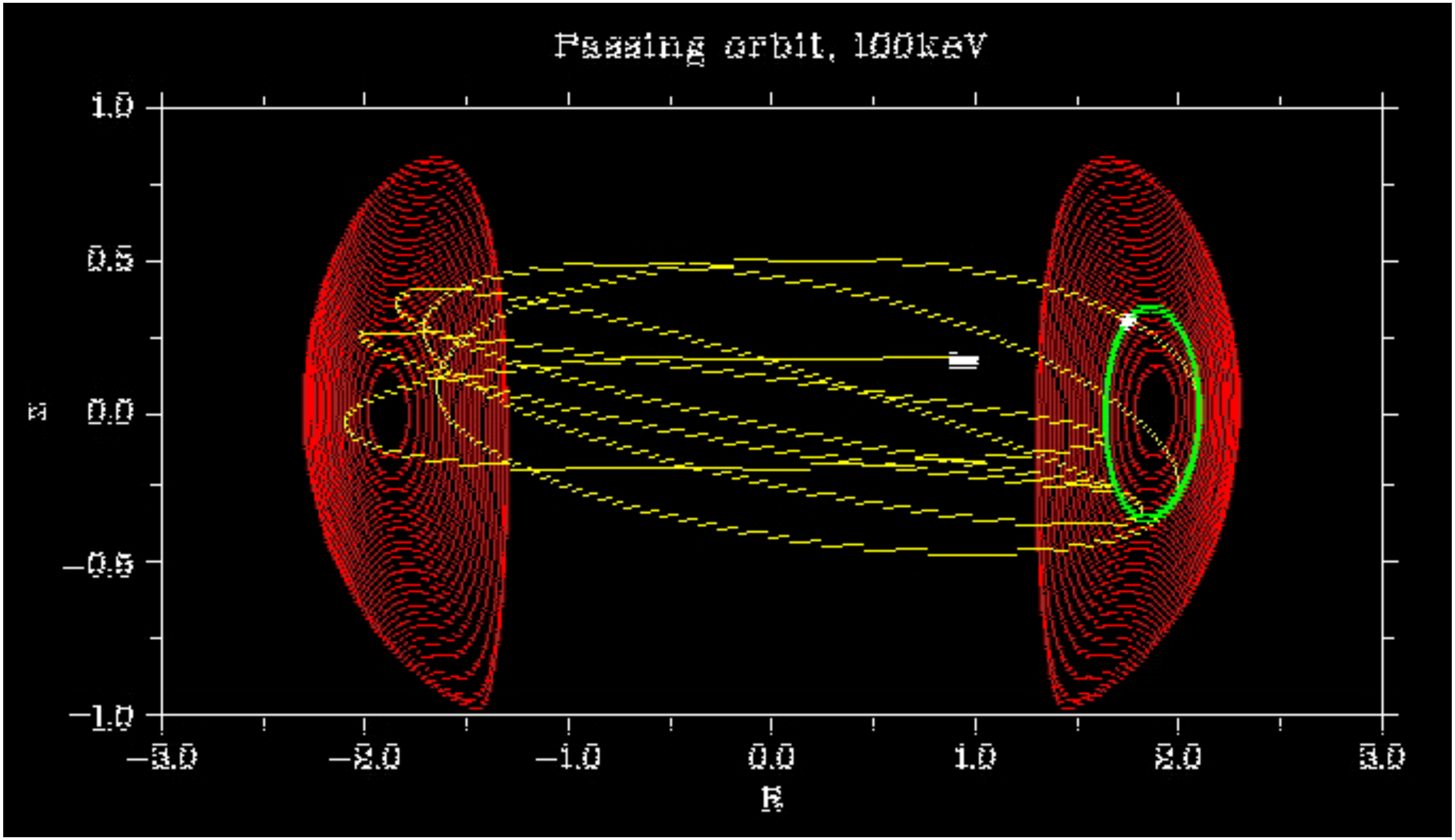
Without poloidal magnetic field, particles are not confined



Gyro motions are not shown.

Visualization by S.H. Hahn

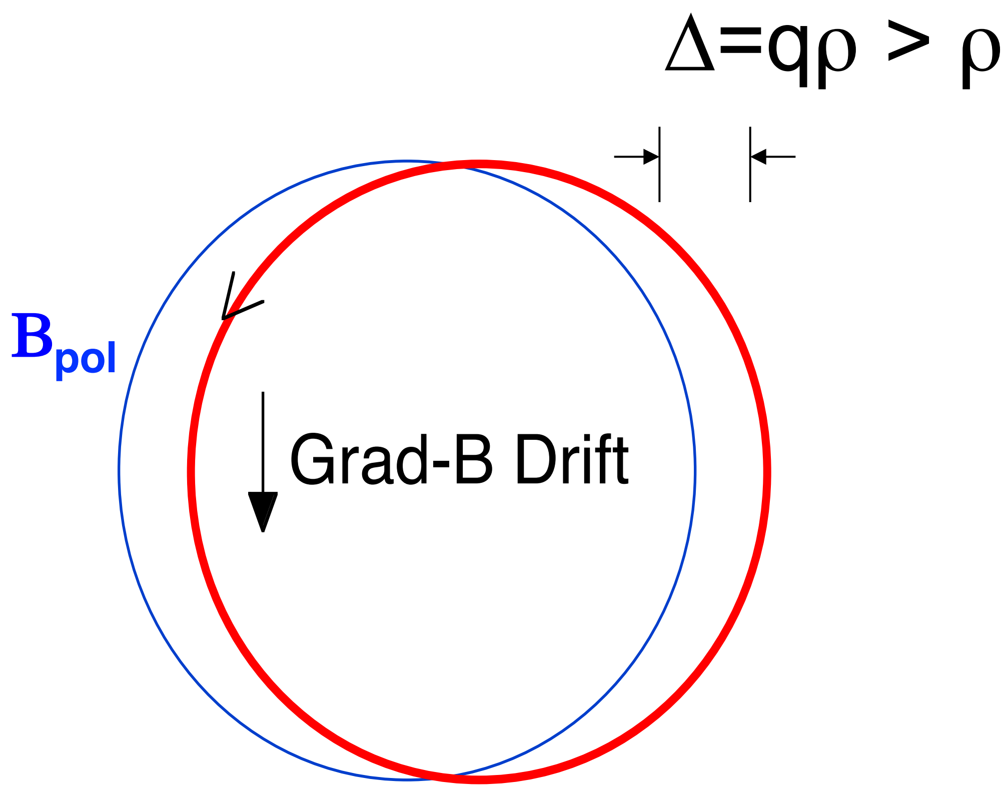
After adding a poloidal magnetic field (B_P/B_T~0.1), plasma particles are well confined.



Gyro motions are not shown.

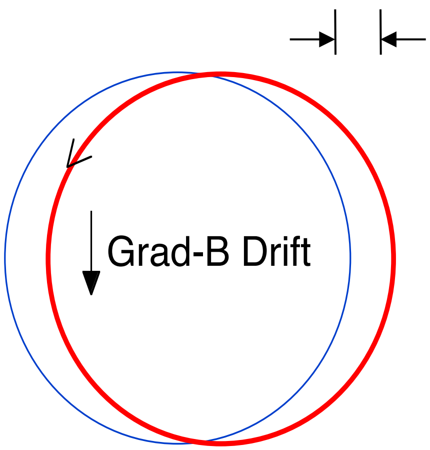
Visualization by S.H. Hahn

B_p gives toroidal confinement. Grad-B + Curvature drifts merely yield orbit shift. Radial excursion brings in the neoclassical transport.



Collisional Neoclassical Diffusion in tokamak (Pfirsch-Schluter diffusion)

$\Delta = q\rho$



Random walk argument

$D \approx f\,\gamma\Delta^2$

- f : Participation fraction
- γ : Random walk frequency
- Δ: Step size

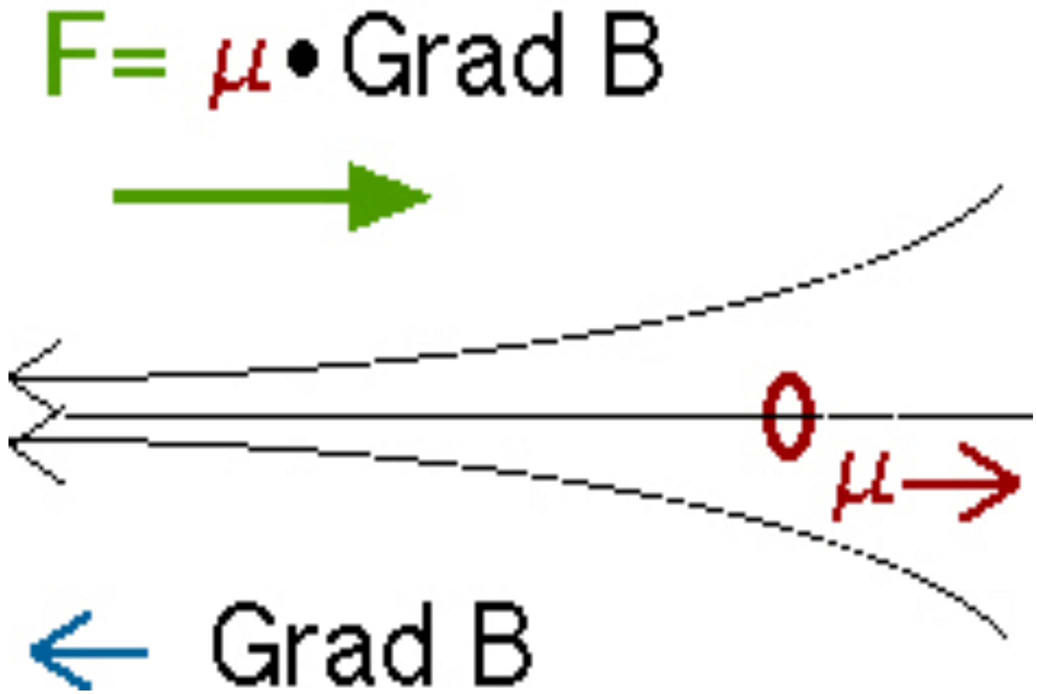
$f=1,\ \gamma=\nu_c,\ \Delta=q\rho$

$$\Rightarrow D_{PS} = \nu_c\, q^2\rho^2 = q^2 D_c \quad (\propto B^{-2})$$

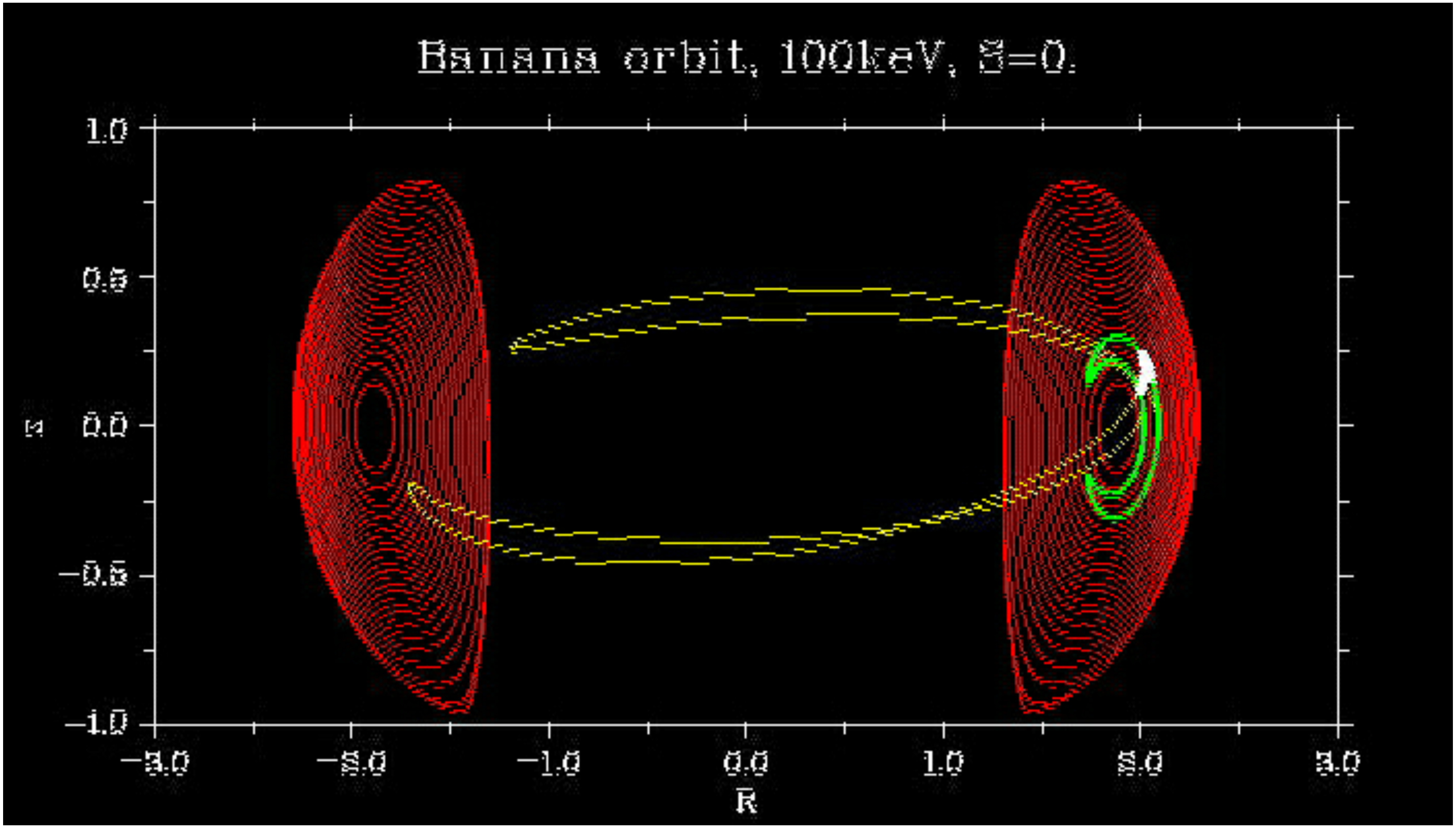
Function of q(r), 1<q<5

Mirror force yields banana orbit

Force on a Magnetic Dipole



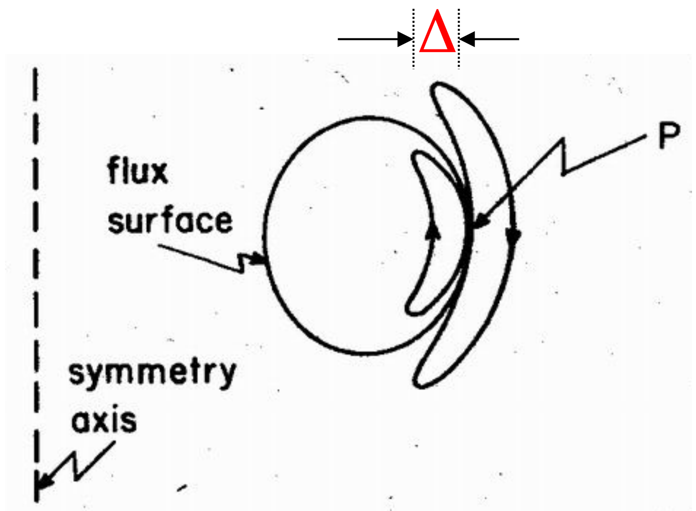
Magnetic mirror force turns particles with small $v_{||}$ into trapped "banana" orbits. → Enhanced nonlocal self-organization, bootstrap current, neoclassical transport

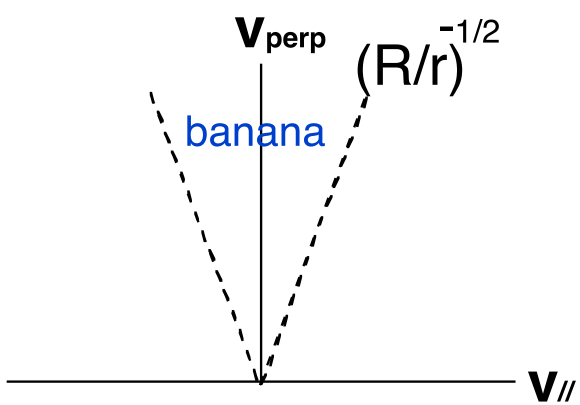


Gyro motions are not shown.

Visualization by S.H. Hahn

∇B and curvature drift with magnetic mirroring $\Rightarrow$ Neoclassical Banana Diffusion





Random walk argument

$D \approx f\, \gamma\, \Delta^2$

f: Participation fraction

γ : Random walk frequency

Δ: Step size

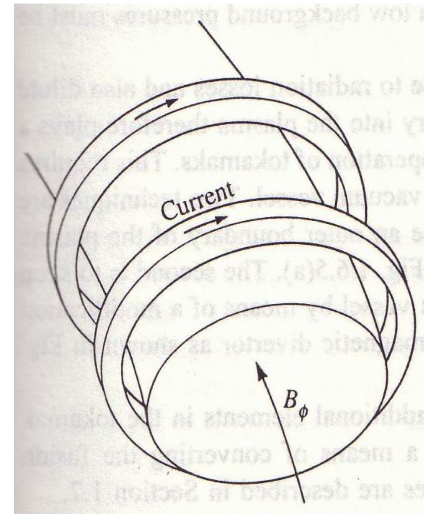
$f=(r/R)^{1/2}$, $\gamma = (R/r)\nu_c$,

$\Delta = \rho\, q (R/r)^{1/2}$

$\Rightarrow D_{NC} = (R/r)^{3/2} q^2 \nu_c \rho^2$ ($\propto \mathbf{B^{-2}}$)

$D_{NC} = (R/r)^{3/2} q^2 D_c \sim 10^2 D_C$

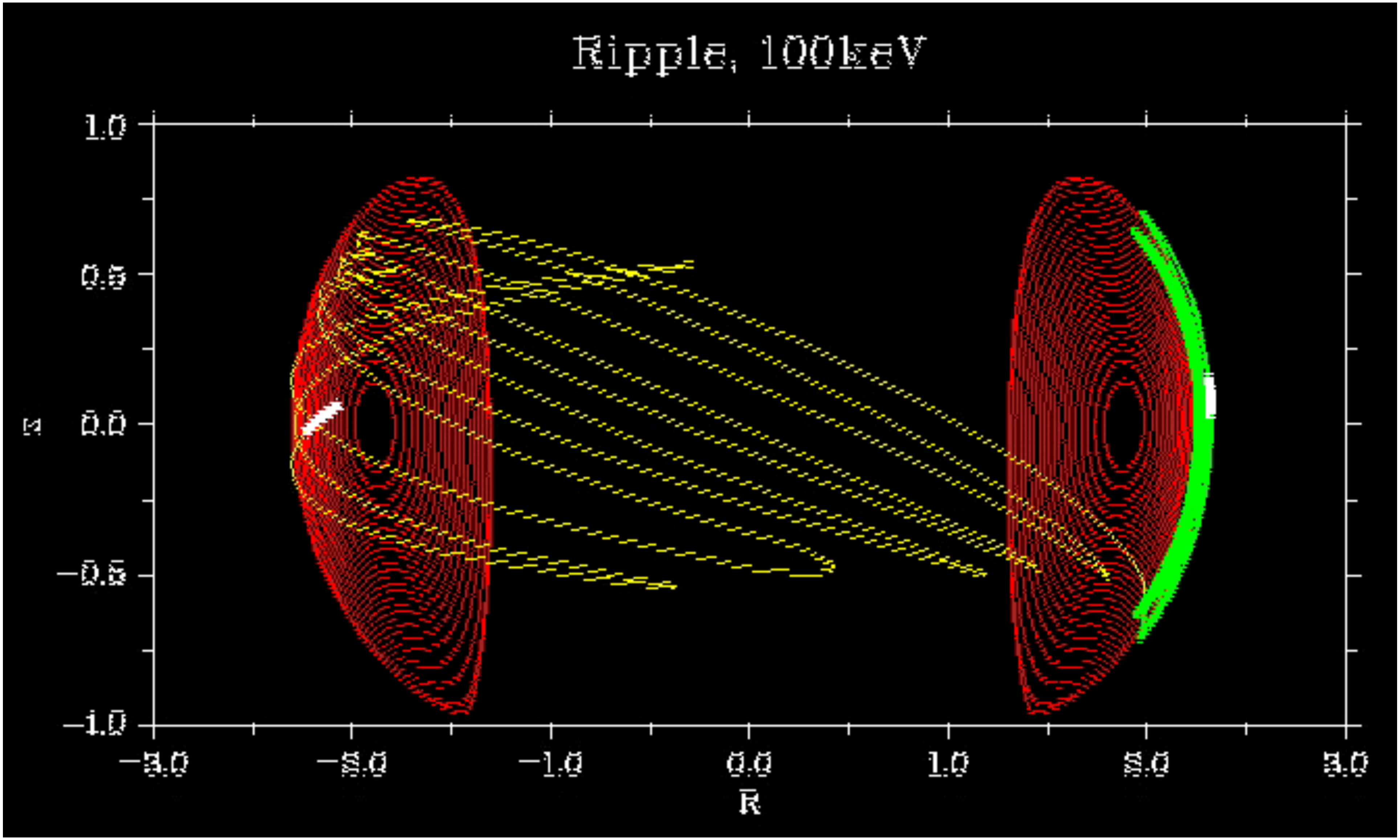
Chaotic Ripple Transport of Hot Ions



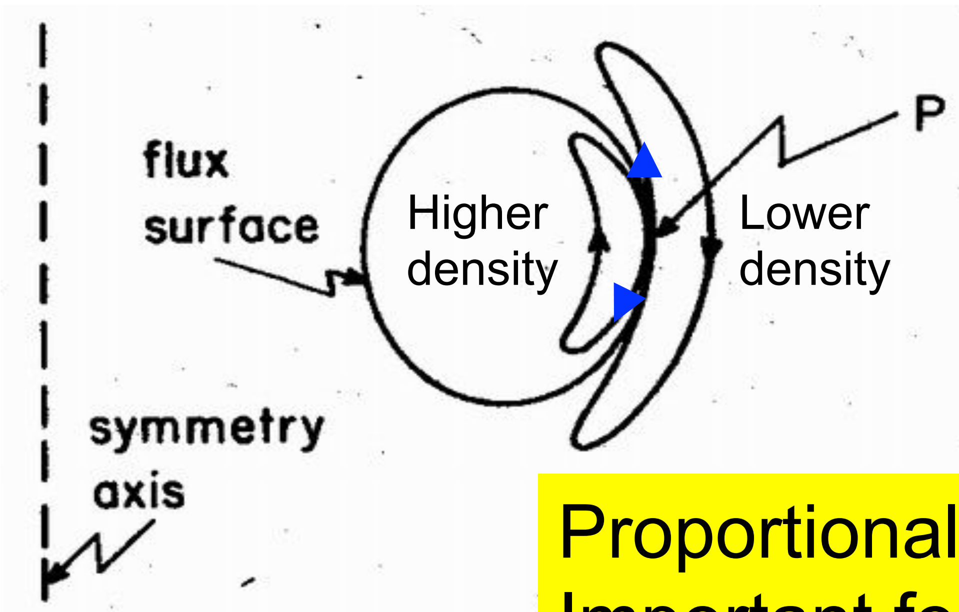
- Steady banana orbits are for axisymmetric system.
- In reality, number N of toroidal field coils is finite.

  There is a small ripple field in the edge $>10^{-3}$
- Chaotic radial random-walk of hot ions in the edge plasma: alpha and helium ash ions, NBI ions, RF tail ions

100 keV Beam Ion dynamics if Ripple in KSTAR is enhanced (from XGC)



Bootstrap current



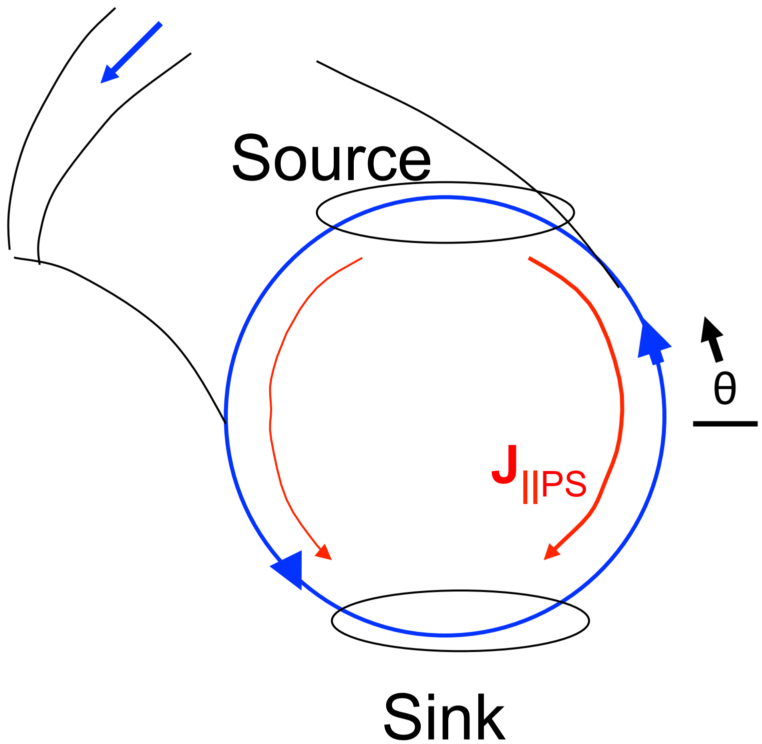
Net electron flow

$\downarrow\downarrow \; + \; \uparrow \; = \; \downarrow$

Proportional to n and T gradient. Important for both equilibrium and steep-gradient instability.

Caution: r-dependence of trapped fraction $f_T \propto (r/R)^{1/2}$ does not produce bootstrap current.
Radially-mapped f_T is homogeneous.

Pfirsch-Schluter current/flow



$nu_\perp = (B_o/\Omega_o)\ \mathbf{b}\mathrm{x}\nabla p/B(\theta)$

$\nabla \bullet nu_\perp \propto \sin\theta$

$J_{||PS} = qnu_{PS} \propto \cos\theta$

- Driven by pressure gradient (part of plasma equilibrium) and can be locally large and important for transport, in steep gradient region.
- Experimental interpretation needs to be careful because of this.

$$J_{||PS} = -cB\ (dp/dpsi)\ [RB_T/B^2 - \langle RB_T\rangle/\langle B^2\rangle]$$

$$\langle J_{||PS}\rangle = 0$$

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2D neutral particles evolve consistenly with plasma

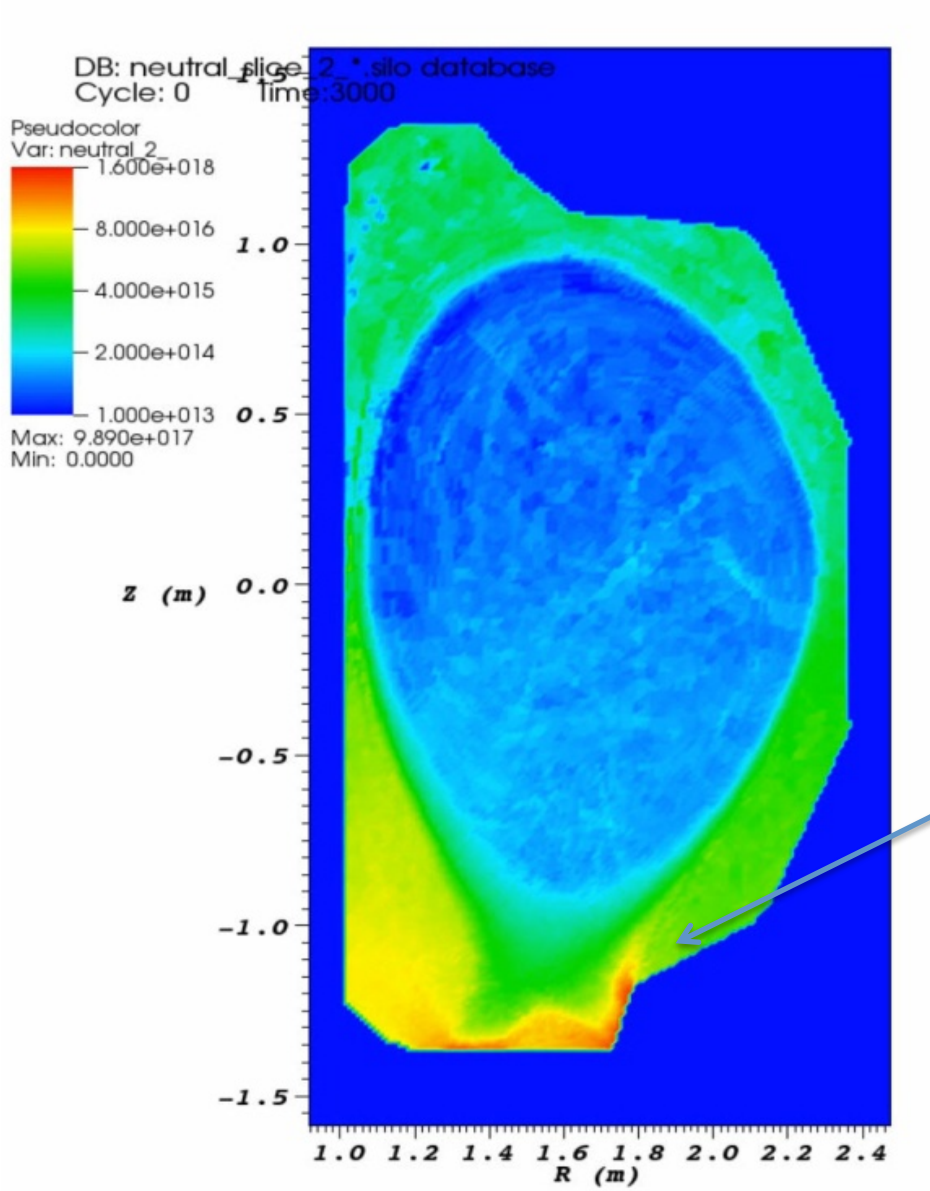


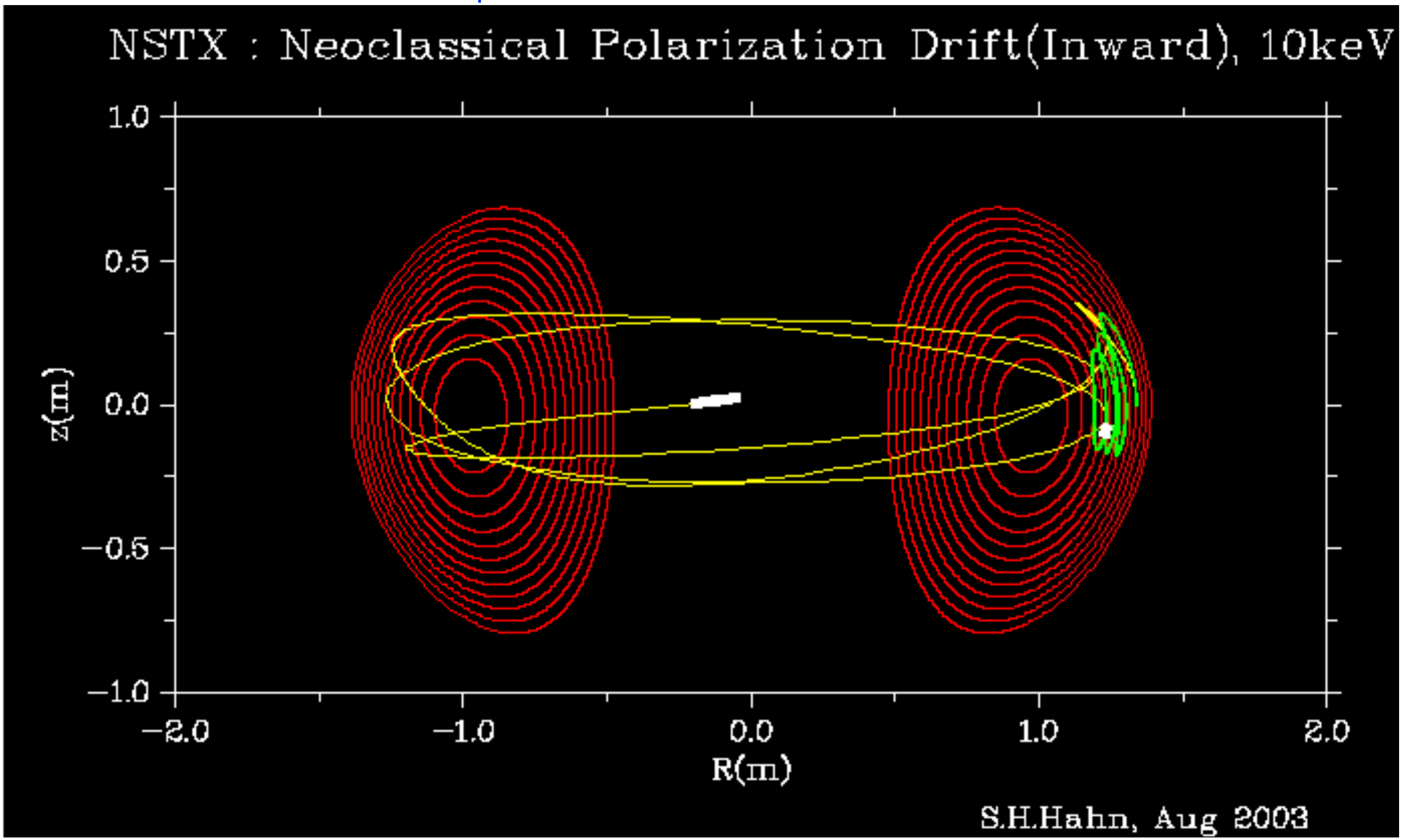
Figure by D. Stotler

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

(showing that that the neutral source is peaked at the divertor targets, as determined by the poloidal profile of XGC ion losses to wall).

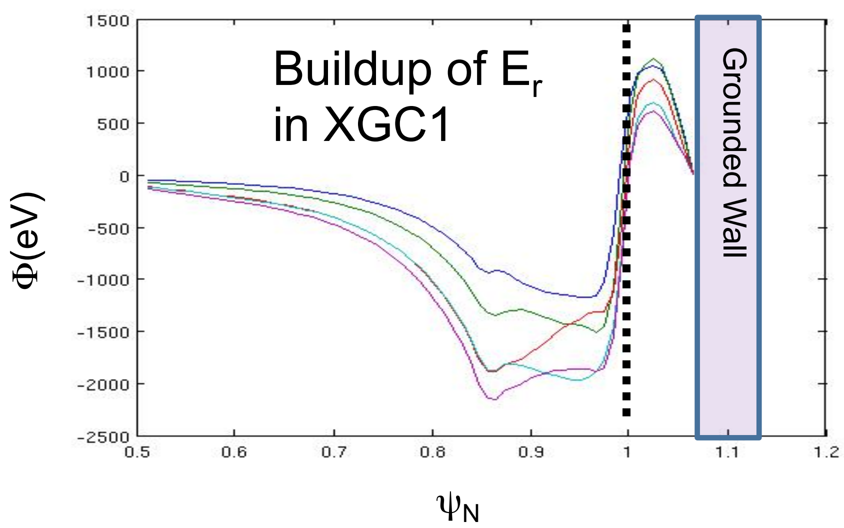
Neoclassical Polarization effect is much stronger than the classical polarization effect. Needs to be handled correctly when E_r is non-negligible.

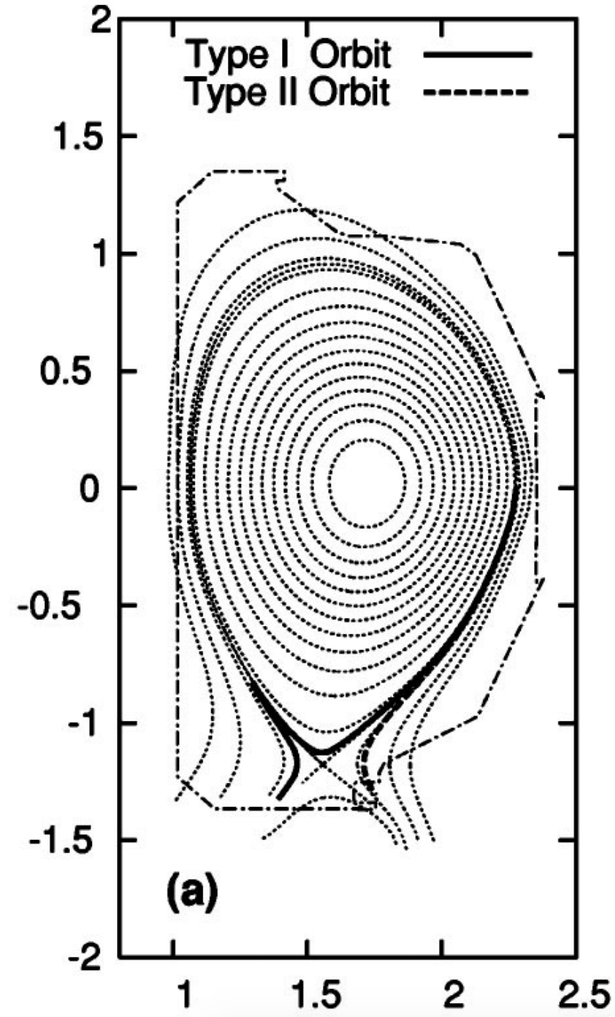
An $dE_r/dt < 0$ case is shown below.



X-transport as a base for E_r-layer and steep ∇p formation

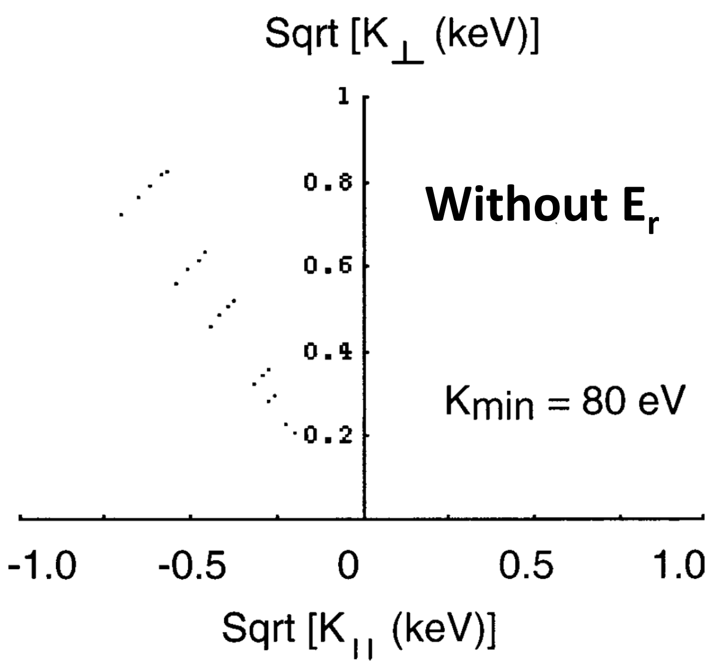
- B_P=0 at magnetic X-point and is small around it.
  - Weak poloidal ion rotation
  - Confinement is lost → ion orbit loss
  - Negative charge within ion banana width Δ_b inside separatrix → strong E_r<0 in Δ_b layer
- Strong V_{ExB} restores poloidal rotation and restores the ion confinement
  - Stops further build-up of E_r
- Strong E_r creates steep ∇p (force balance, electrostatic confinement) → pedestal

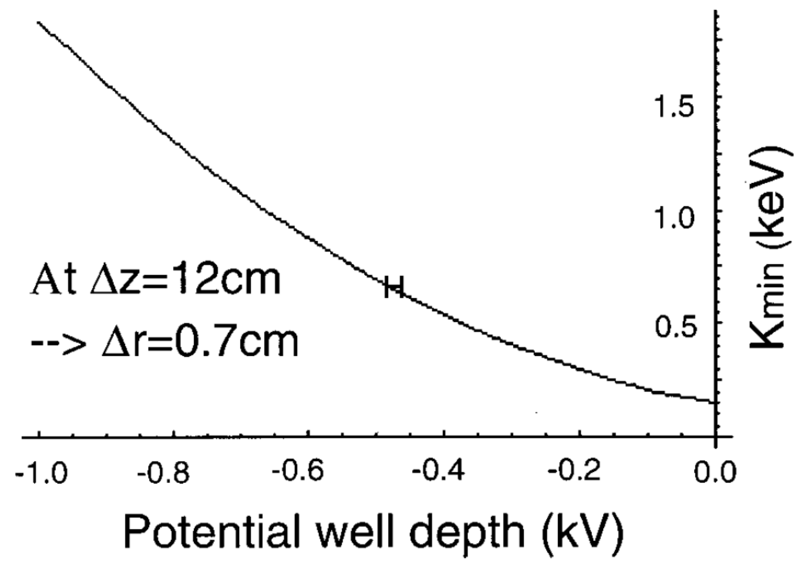




Typical ion loss orbits, from XGC

X-loss energy in pedestal is raised by the self-organizing ExB to achieve ambipolar transport → X-transport [Chang Phys. Plasmas 2002]





Myths about the neoclassical X-loss/X-transport physics

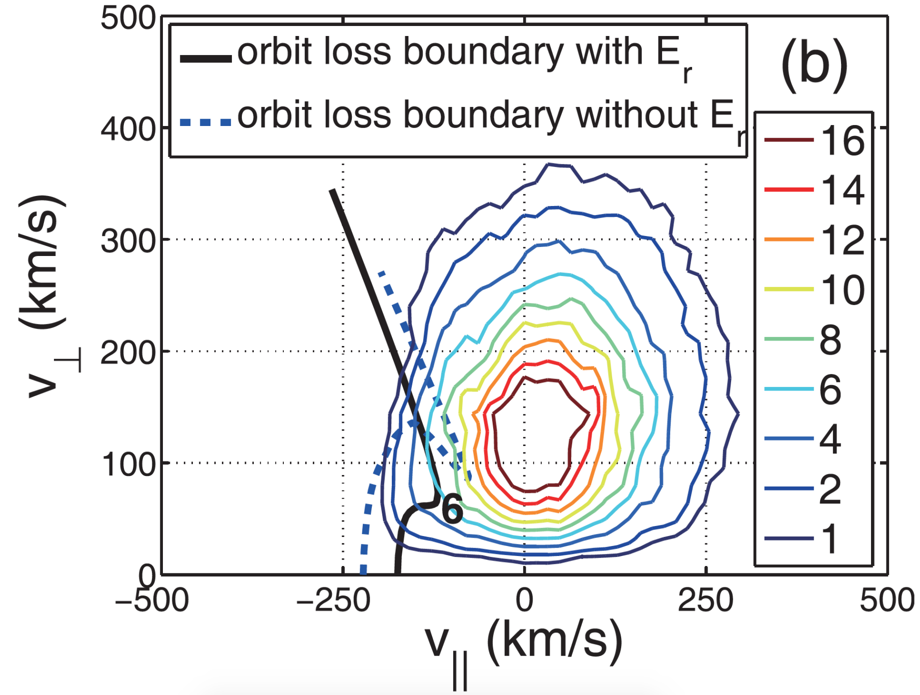
Myth #1: Is the X-transport theory the same as the previous orbit loss theories?

No. The previous orbit loss theories assumed that there is a large empty hole. In the X-transport theory, there is an unconventional transport process that closes the non-ambipolar v-space hole by ExB rotation and makes the collisional (+ turbulent) transport ambipolar [Chang, Phys. Plasmas 2002]

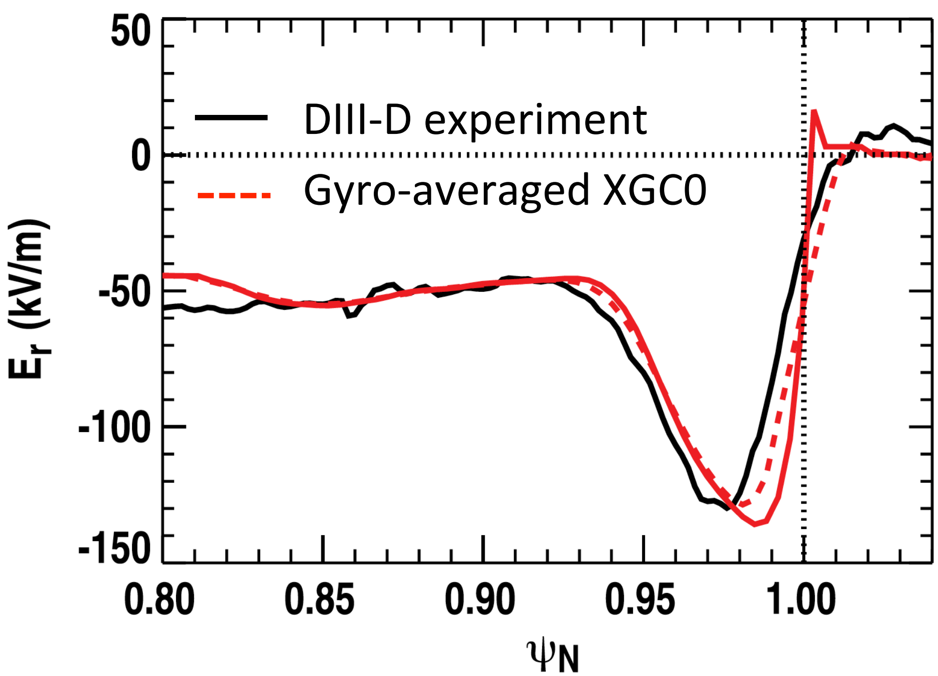
Myth #2: Is there strong momentum source from the X-loss?

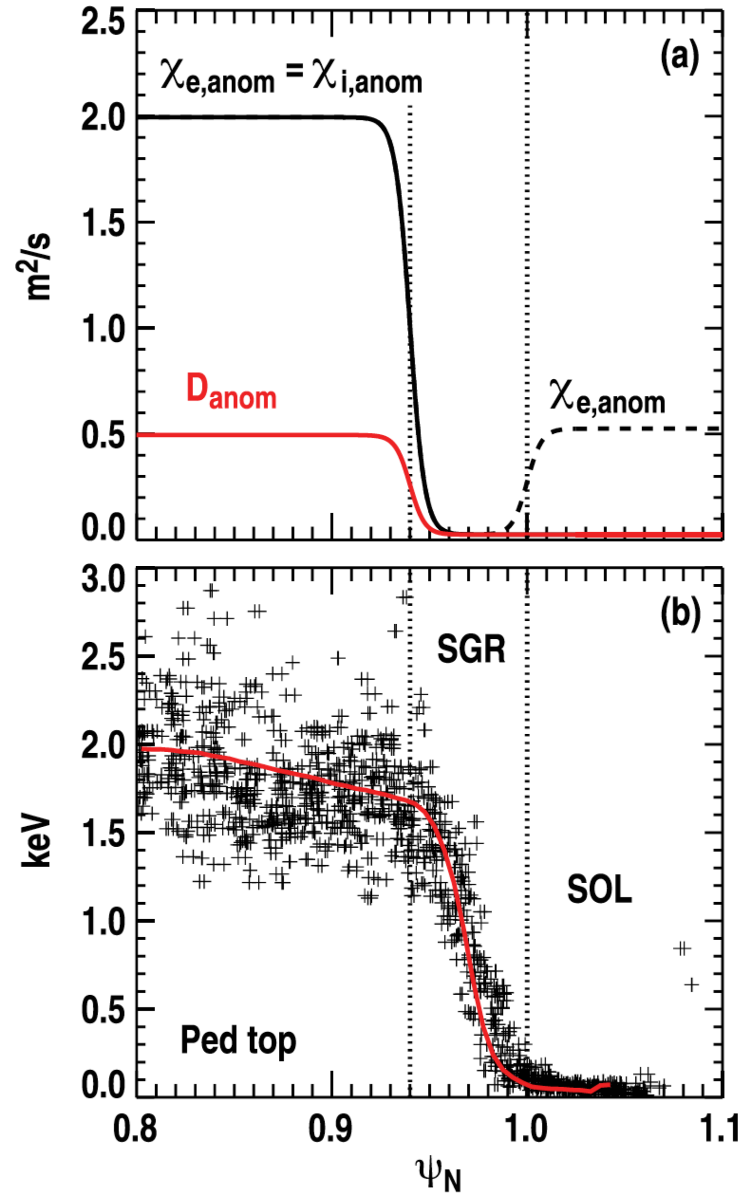
No, only a little. The X-loss energy is raised so that the original v-space hole that can contribute to the momentum loss is closed [Seo, Phyis. Plasmas 2014]

→ Turbulence is needed to spread *f* into the higher energy loss hole.

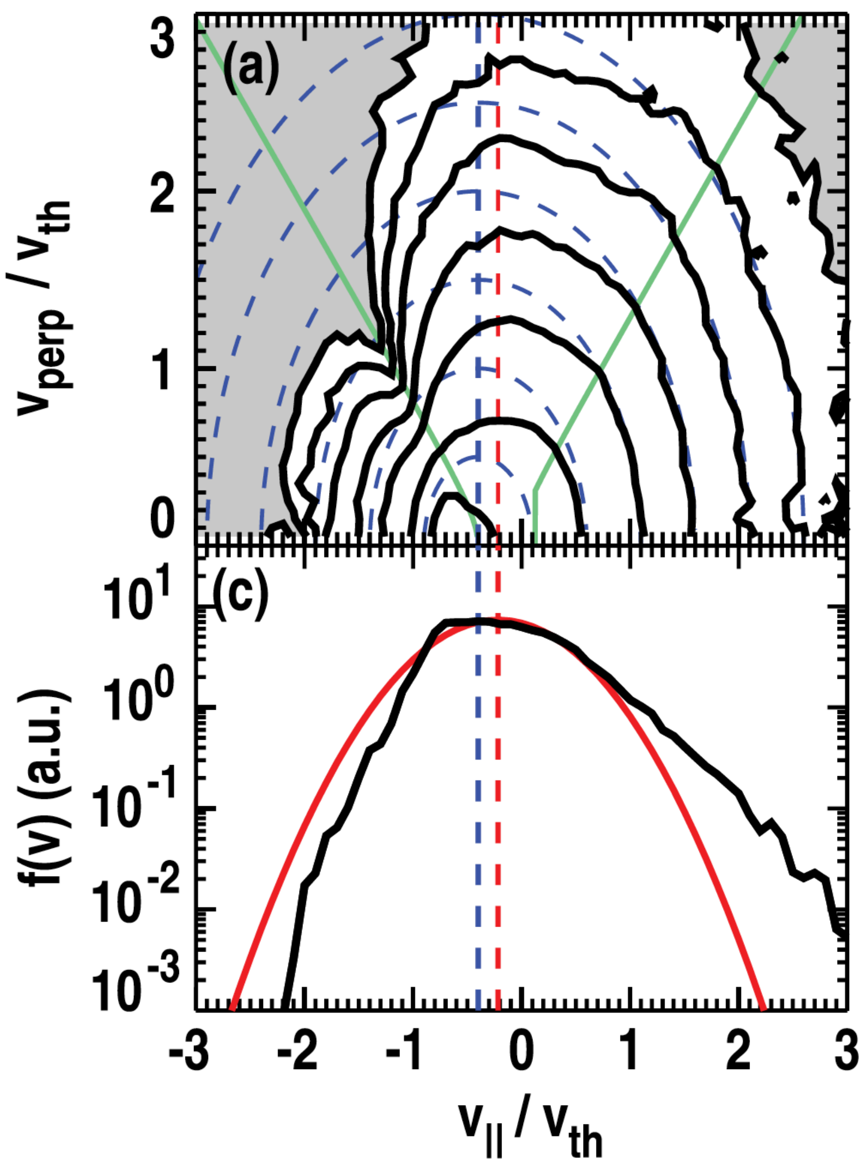


Battaglia et al. reported that the experimental H-mode E_r can be reproduced to the zeroth order by neoclassical XGC0 without introducing much anomalous diffusion [PoP2014].





Neoclassical particle distribution at the top of the outboard midplane pedestal, showing the mixed effects from ion orbit loss and Pfirsch-Schluter physics.

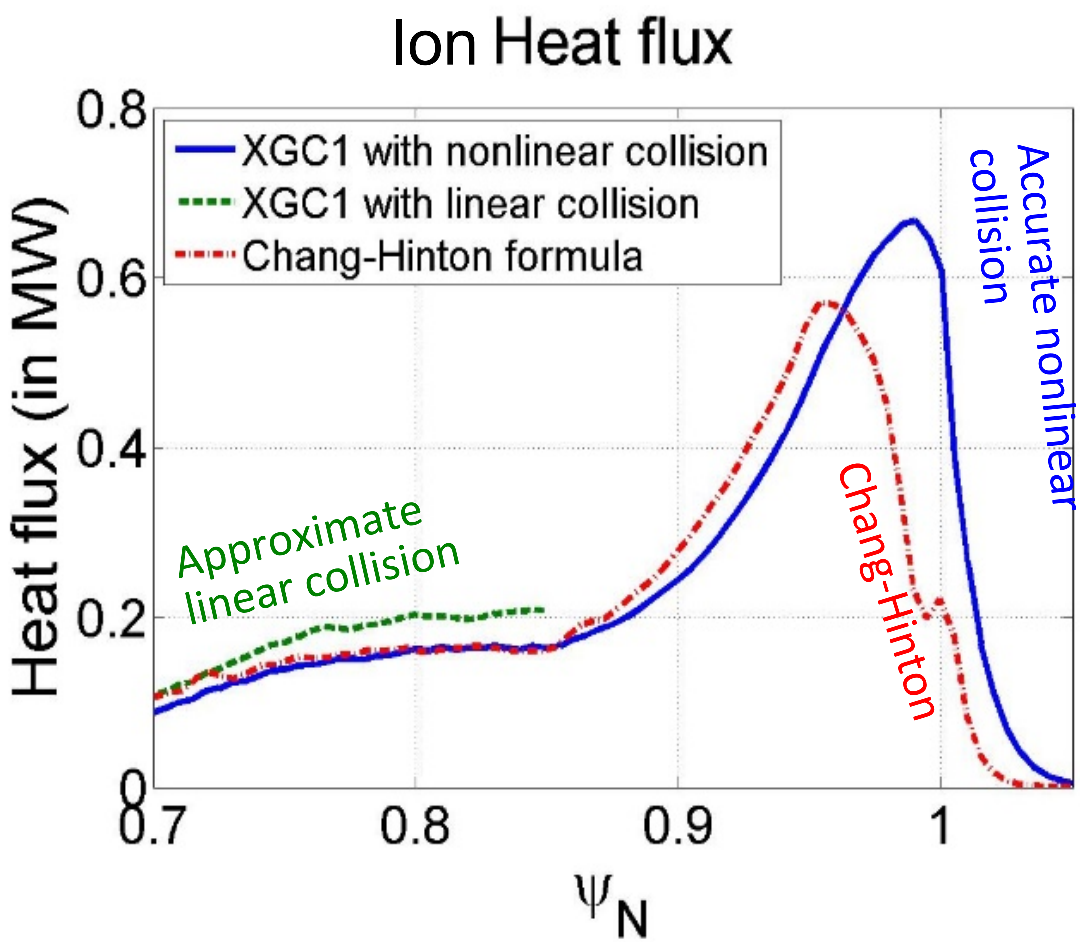


Battaglia [Phys. Plasmas 2004]

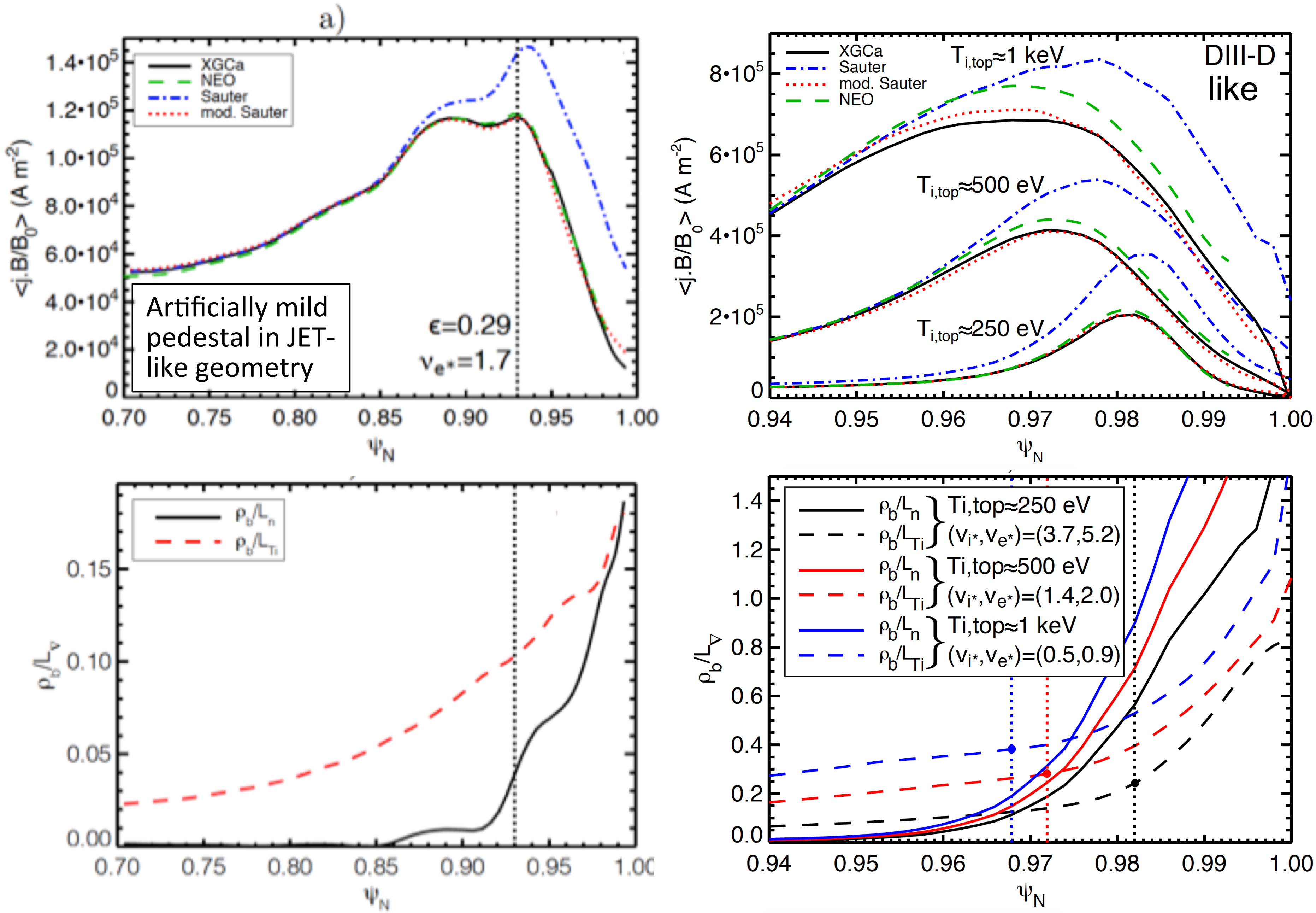
Turbulence changes this picture.
Seo et al. [Phys. Plasmas 2004]

Neoclassical Transport Physics in Edge Pedestal

- Single particle confinement in pedestal-SOL is not subject to "tokamak physics"
- Most analytic neoclassical theories do not apply to the edge pedestal and SOL
  - Non-equilibrium: Nonlocal orbits, X-transport, open field, non-Maxwellian, …
- Pfirsch-Schluter flow & current are fluid quantities and still valid in pedestal

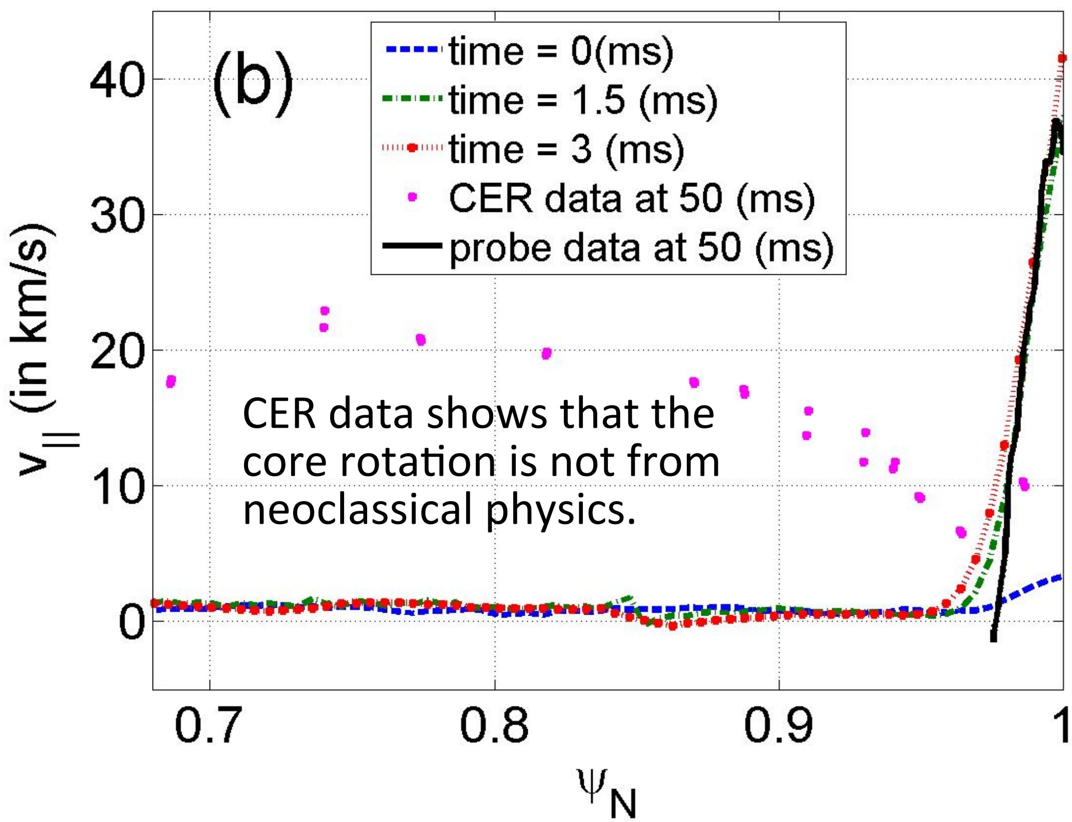


Bootstrap current in steep pedestal shows the nonlocal behavior



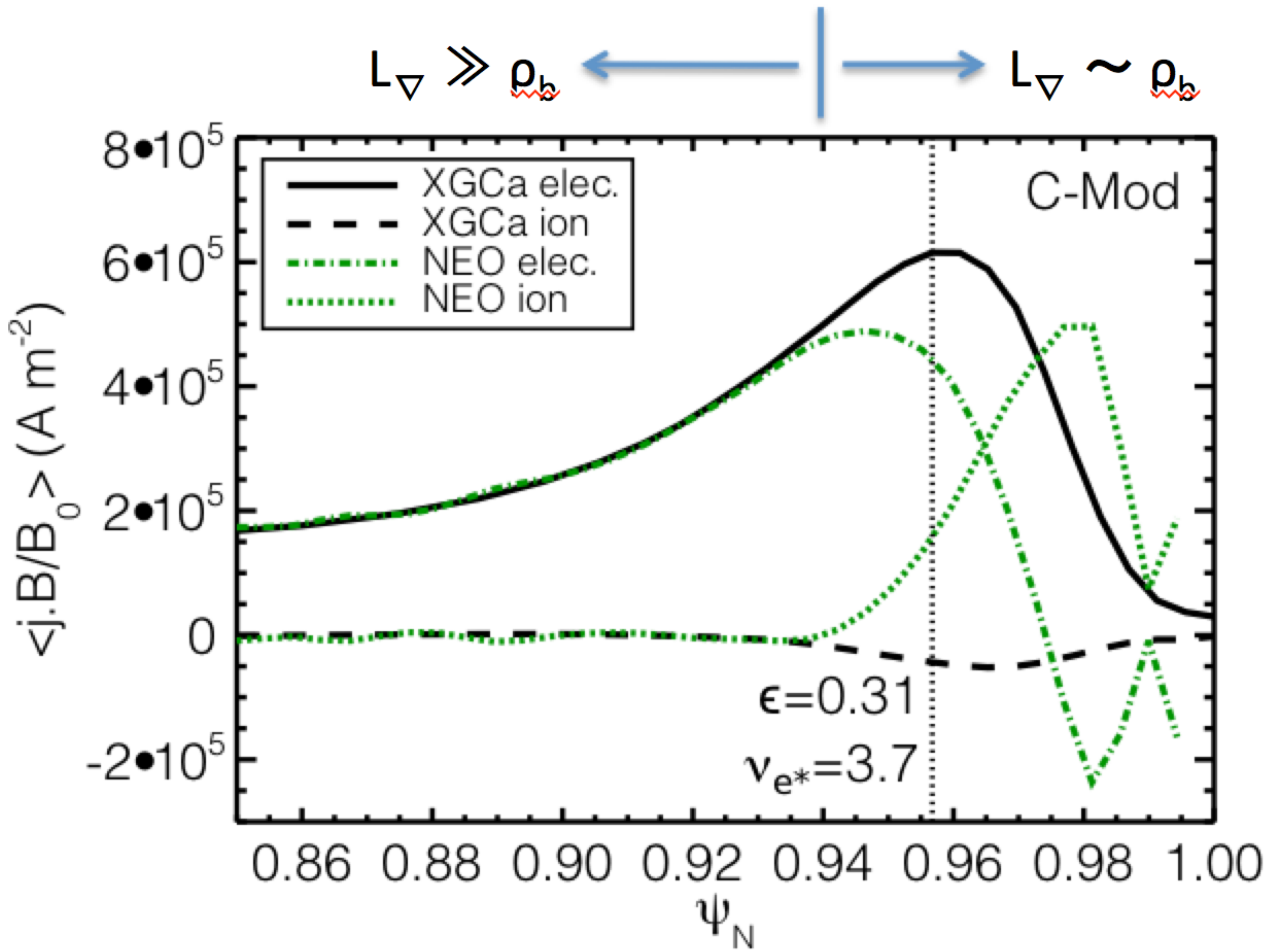
Pfirsch-Schluter flow & current are fluid quantities and still valid in a steep edge pedestal

- They are large and important, but its flux-surface average vanishes.
- Experimentalists measuring the flow and the current at outboard midplane often get confused, and consider them from "turbulence" or "anomalous."



Experimental probe data (black line) in DIII-D agrees with the neoclassical Pfirsch-Schluter flow measurement from XGC1 (green and red dots)

Plasma flow in a steep pedestal is different from what is expected from local physics



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Physics of kinetic RMP penetration and transport in realistic diverted plasma

- RMP penetration and plasma transport have strong kinetic components, influenced by neoclassical dynamics
- Kinetic RMP simulation is a difficult task: Assume small $\delta B \lesssim 10^{-3}$
  - ψ_0 plays it role: Cantori (partially stochastic and/or sticky surfaces)
  - Take a step-by-step approach

1. Use XGC0
   - Turbulence-free: Assume RMP-driven transport >> turbulence transport. Use anomalous radial random walk model when needed.
   - Assume existence of time-asymptotic, quasi-steady solution: $\tau_{RMP}/\tau_{Alfven} \rightarrow \infty$, $\partial A_{||}/\partial(t/\tau_{Alfven}) \rightarrow 0$
   - Assume $\Phi=\Phi(\Psi_0) \rightarrow E_{||}$ is from $b \cdot \nabla_{\psi}\Phi$
2. Use XGCa: Remove the $\Phi=\Phi(\Psi_0)$ condition, but still turbulence-free
3. Use XGC1: Include turbulence

Advantage of the XGC0 kinetic RMP simulation over fluid/MHD

- Parallel conductivity, viscosity, anisotropic transport, pressure anisotropy, and toroidal rotation are self-consistent with the RMP dynamics.
- Trapped-passing dynamics is included
- Self-consistent, sheared ExB dynamics
- Velocity-dependent kinetic electron dynamics and collision processes in stochastic magnetic field
- $J_{||}$ experiences a significant broadening from the kinetic electrons in stochastic B-field and magnetic islands: nonlocal $J_{||}$

  → Physics of the KAM surfaces is more natural than MHD/fluid, in which $J_{||}$ response is localized to narrow mode rational surfaces → hard to destroy KAM surfaces between the mode rational surfaces

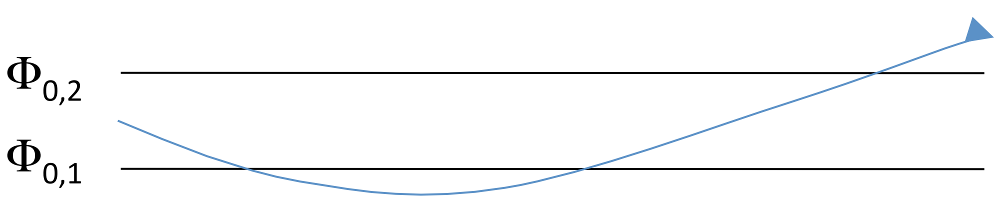
  (Ideal MHD cannot produce stochastic magnetic perturbation or island.)
- Transport is consistent with RMP penetration

5D drift-kinetic code XGC0 with $\Phi(\Psi_0)$ solution

- Realistic Diverted geometry:EFIT
- Marker particles: Lagrangian guiding-center motion
- Magnetic equilibrium and perturbation solver from M3D-omp: $\delta\psi(\delta J_T)$
- Monte Carlo neutral particles with wall-recycling
- Logical sheath at wall
- Experimental level of heat and momentum source at core-edge boundary
- Random-walk modeling of anomalous transport to reproduce pre-RMP plasma

Assumptions used for the RMP study

- Small 3D $\delta B << B_0$
- Quasi-steady solution exist $\partial A_{||}/\partial(t/\tau_{Alfven}) \rightarrow 0$,   ($\mathbf{E} = -\nabla\Phi - \partial\mathbf{A}/\partial t$)
- $\nabla\Phi(\psi_0)$ and $\nabla p(\psi_0)$ are supported in partial stochasticity and the ψ_0-aligned cantori $\rightarrow$ $E_{||}$ is from $b \cdot \nabla_\psi \Phi$
- Assume that turbulence-driven transport is small compared to RMP-driven transport



$B=B_0+\delta B$

$E_{||} = -\nabla\Phi_0 \bullet \delta B_r/B_0$

Kinetic penetration and transport model

- Two coupled systems with the BD condition $\delta\Psi = \delta\Psi^V$ at far scrape-off:

XGC0 $$\frac{\delta J_{\|}}{B} = F(\delta\psi)$$

Solver $$\Delta^* \delta\psi = \mu_0 I \frac{\delta J_{\|}}{B} = \mu_0 I \sum_m \left(\frac{\delta J_{\|}}{B}\right)_{mn} e^{i(m\theta - n\varphi)}$$

where the operator *F* denotes the Vlasov-Poisson system XGC0 and the second equation means the Ampere's law solver of M3D, and Δ^* is the Grad-Shafranov operator (Laplacian in toroidal geometry).

- Obtain implicit iterative solution of the coupled system
  - ✓ Use implicit damped iteration scheme

$$\delta\psi^{induced}_{k+1,mn} = \delta\psi^{induced}_{k,mn} + c_d \Delta\psi_{k,mn},$$

$$c_d = \mathrm{Min}\left[1, \underset{\mathrm{m,i}}{\mathrm{Min}}\left|\delta\psi_{k,mn}(r_i) / \Delta\psi_{k,mn}(r_i)\right|\right], \quad \delta\psi^{induced}_{k,mn} = \delta\psi_{k,mn} - \delta\psi^{vacuum}_{mn}$$

$$\delta\psi_{k+1,mn} = \frac{\delta\psi^{vacuum}_{mn} + \delta\hat{\psi}^{induced}_{k+1,mn}}{1 + \chi_{mn}(k)}, \ \delta\psi^{induced}_{k+1,mn} = \delta\overline{\psi}^{induced}_{k+1,mn} + \delta\hat{\psi}^{induced}_{k+1,mn}, \ \chi_{mn}(k) = -\frac{\delta\overline{\psi}^{induced}_{k+1,mn}}{\delta\psi_{k,mn}}$$

RMP simulation for weakly collisional, low density DIII-D pedestal

Partial results published in Huijsmans , C. S. Chang , N. Ferraro et al, PoP 2015

Modeling DIII-D 126006 RMP shot, n=3

- ITER-like low collisionality (~0.1) H-mode

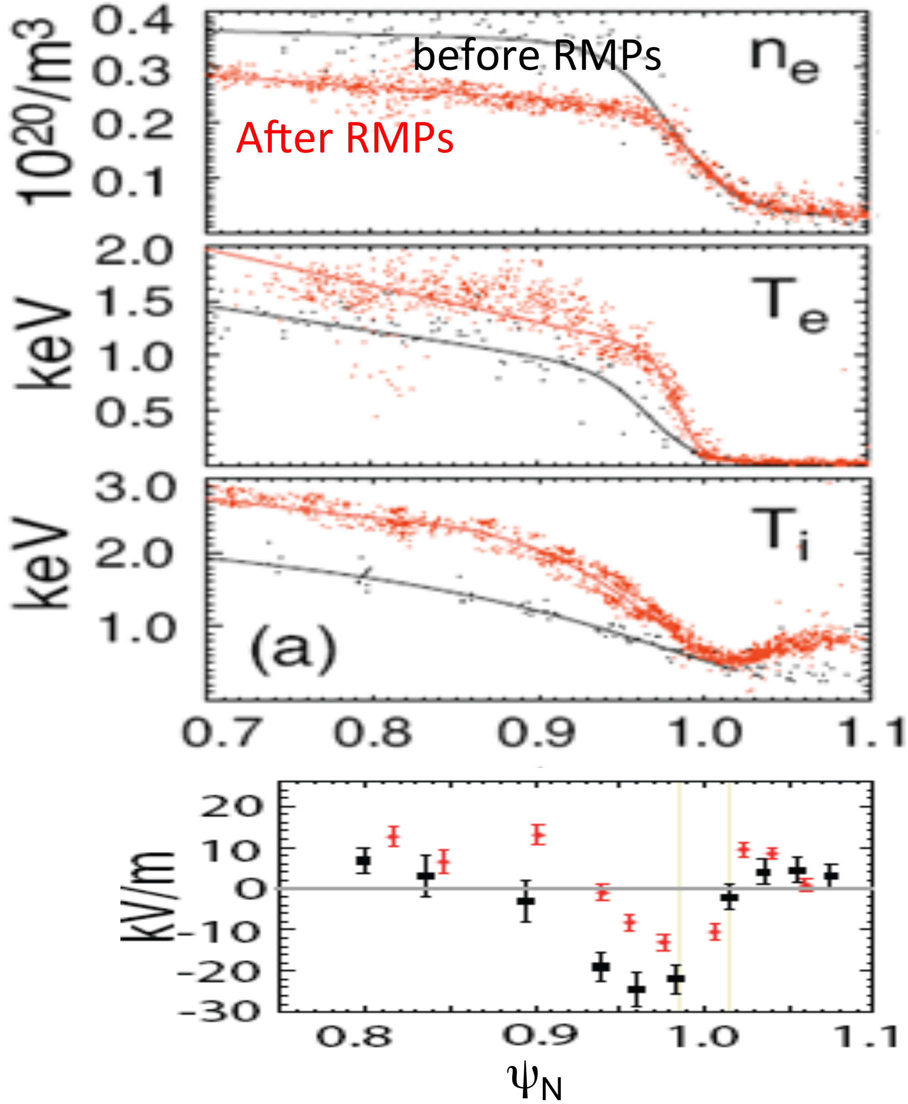
6 MW of heat and 4 N-m of torque at inner boundary (ψ_N=0.8)

Ad-hoc anomalous transport is included using a random walk method to fit the pre-RMP plasma profile, and is assumed unchanged by RMPs ($D \approx \chi_e \approx \chi_i \approx \chi_\phi \approx 0.2\ m^2/s$)

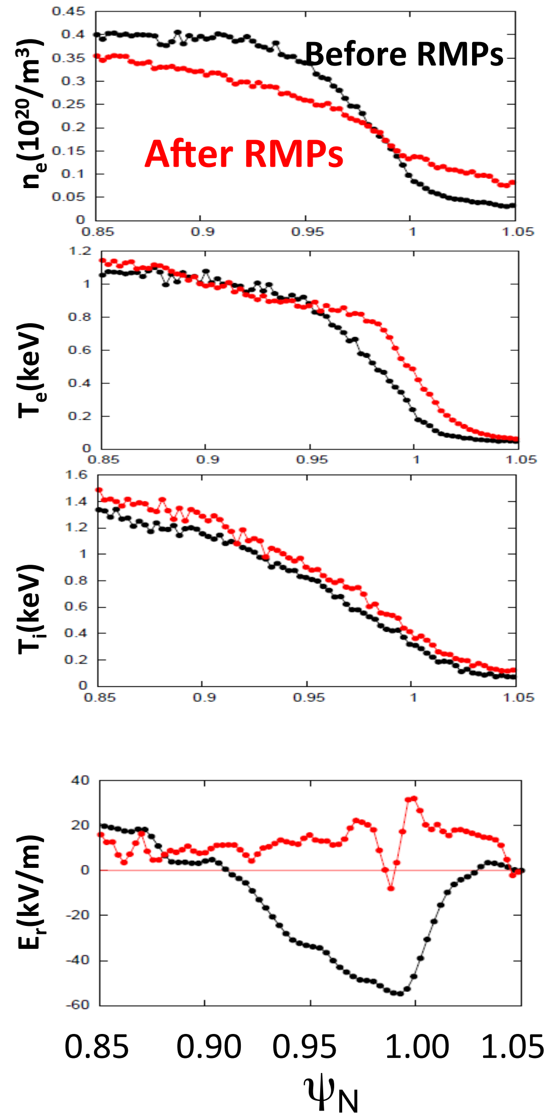
- The RMP driven transport is found to be much greater than the ad-hoc anomalous transport

Vacuum RMP boundary condition at $\psi_N \approx 1.06$

Simulation reproduces all the qualitative features of experiment, inside the ELM suppression window (q_{95}=3.58)



DIII-D Experiment 126006 at ~100 ms after RMPs



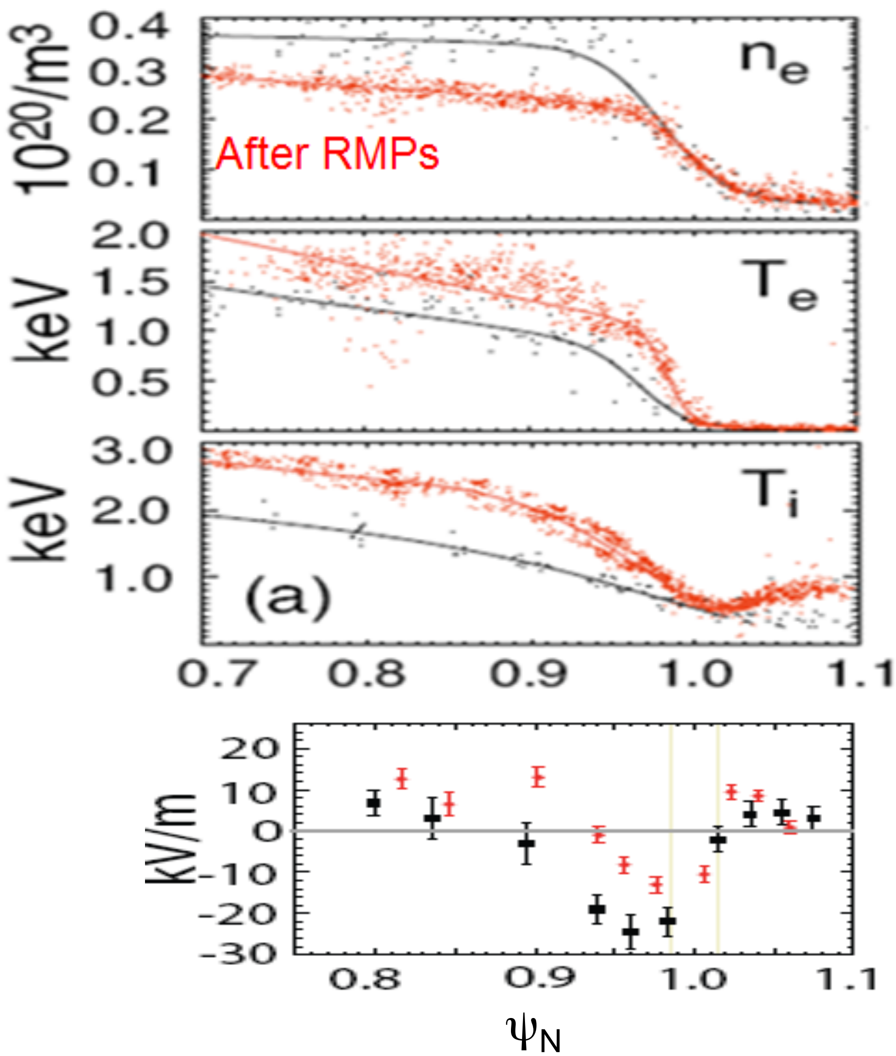
Density pump-out

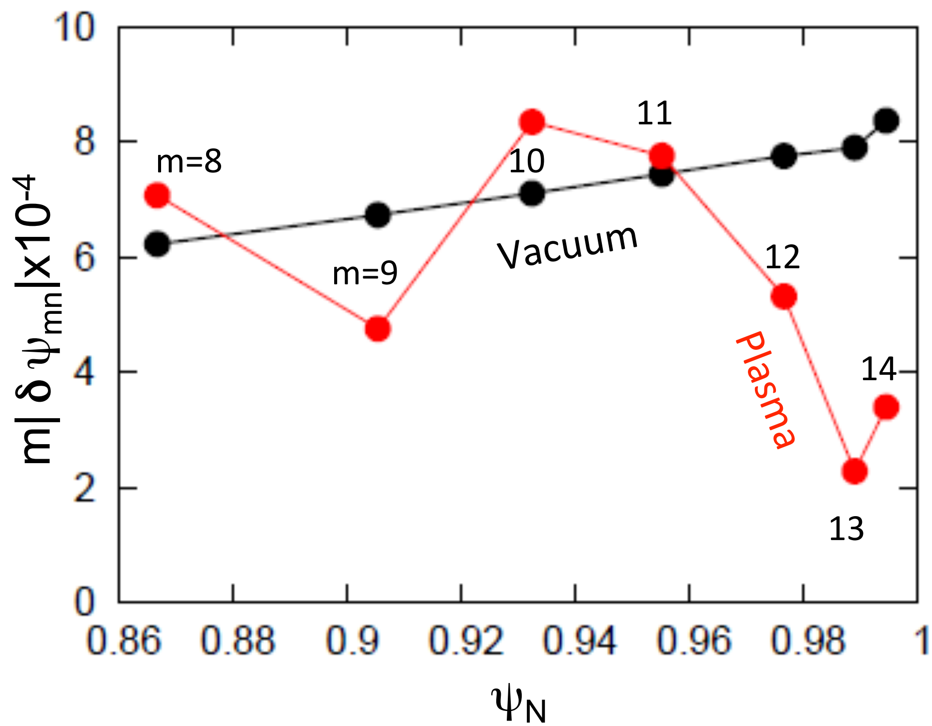
∇Te shifted radially or steepens when radiation included

Er shearing rate survives

Simulation reached quasi steady-state at 4ms after the RMP turn-on.

Resonant components are suppressed around Ψ_N~0.97-1.0 → survival of transport barrier. But, back to ~vacuum level stochasticity/islands at Ψ_N<0.96

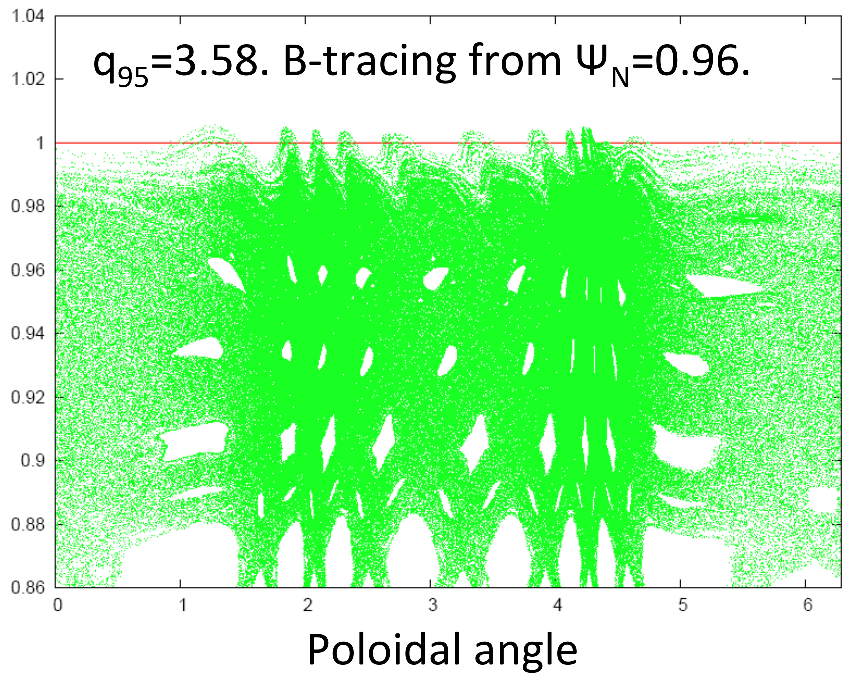




Amplitude of the resonant components v.s. radius in the ELM-suppression q_{95}-window

As a result of the $J_{||}$ broadening and the nonlinear interaction, XGC0 does not show KAM surfaces at pedestal top.

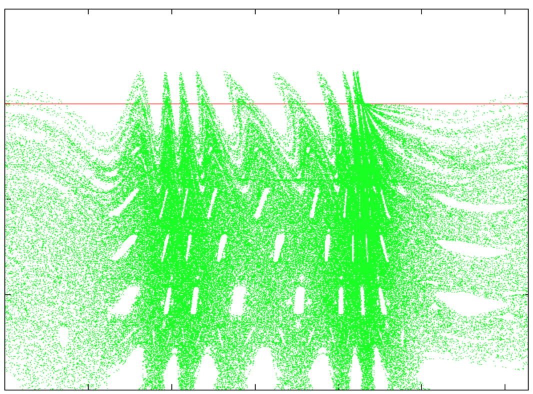
Chirikov parameter >1 at all radii in the q_{95} suppression window.



Field line mappings started at Ψ_N=0.96.

Field line puncture plot, starting from ψ_N=0.96, shows that robust vacuum B-stochasticity/islands remain closer to separatrix in the ELM suppression

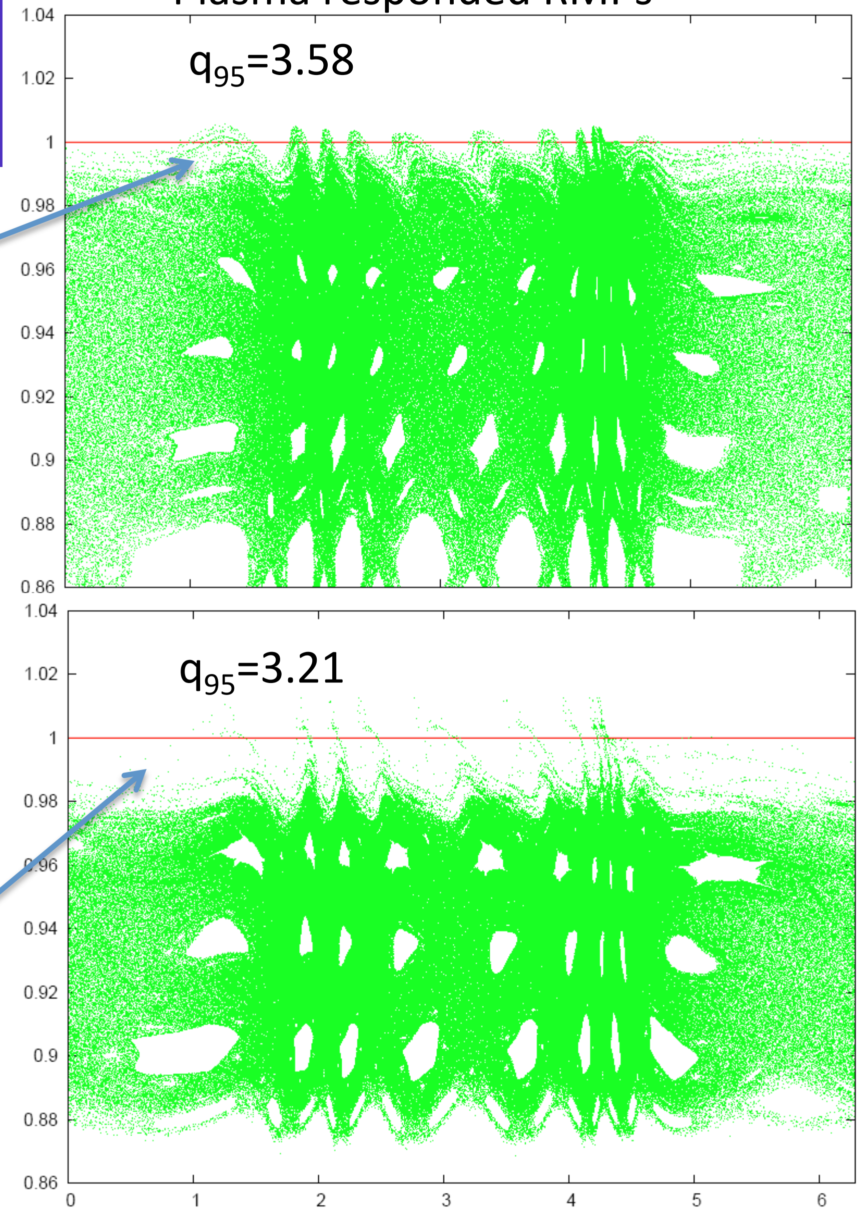
Inside the q_{95} window: Field line connection between plasma and wall is stronger



Vacuum RMPs with
B_T =1X $B_{T,EQDSK}$, q_{95}=3.69

ψ_N

Plasma responded RMPs



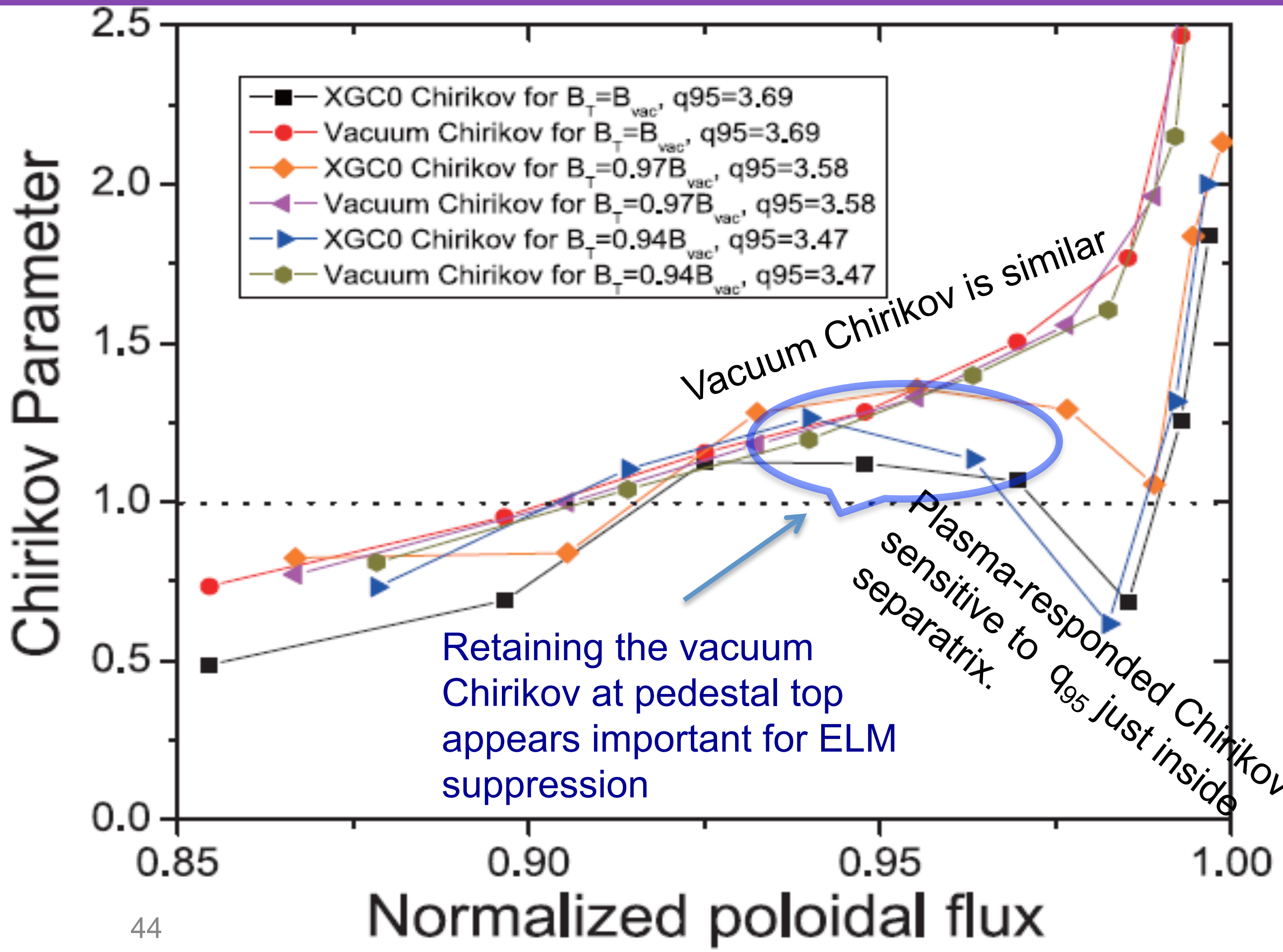
Poloidal angle

Out-of-window: Field connection between plasma and wall is weak

Vacuum Chirikov is similar, but the plasma-responded Chirikov is a sensitive function of q_{95} around 3.58.

Near q_{95} =3.58, Chirikov ≥1 everywhere. Otherwise, Chirikov<1 just inside the separatrix surface ψ_N~0.98.

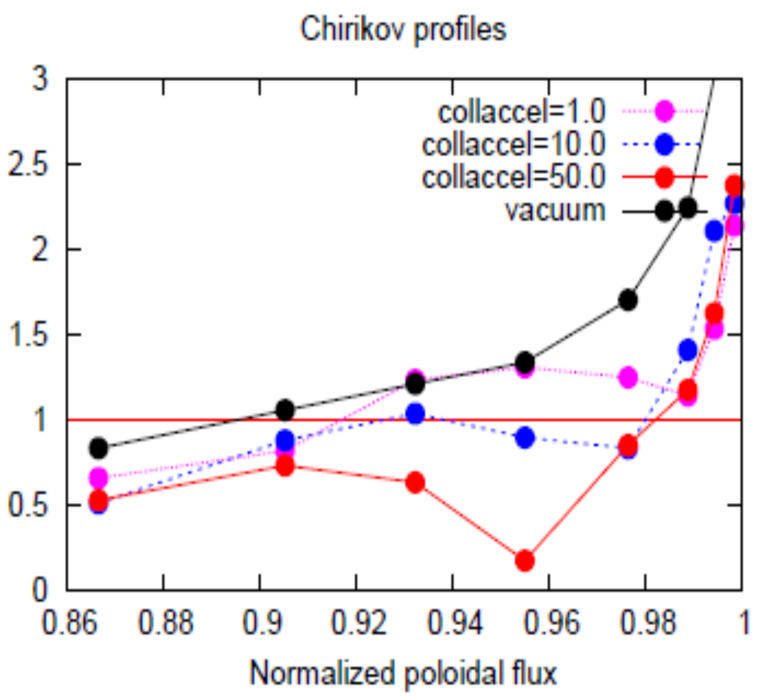
→ "Vacuum Chirikov>1 is only a necessary condition."

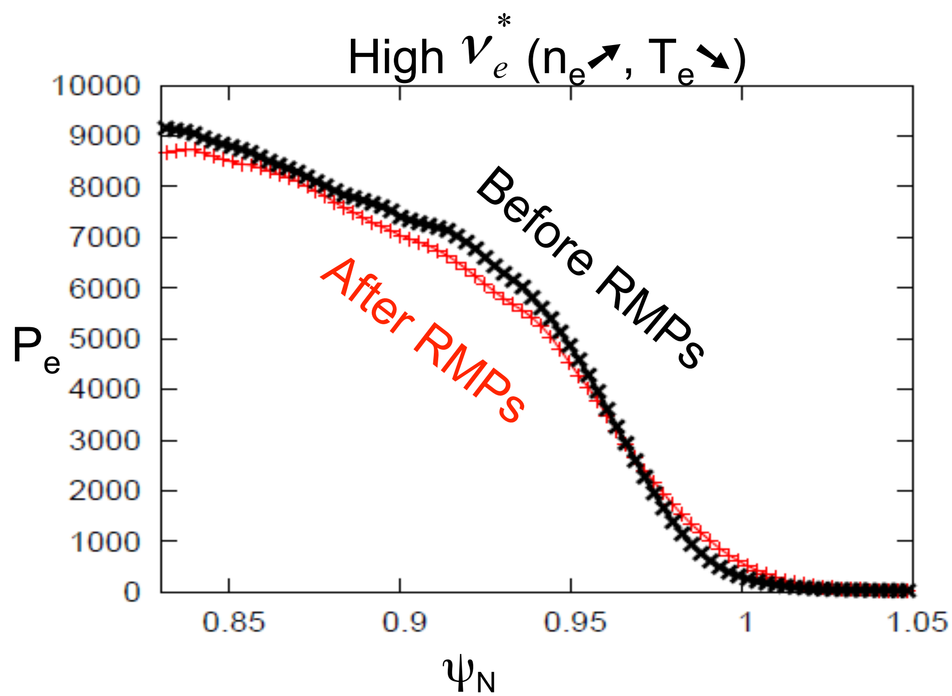


Effect of collisionality

Experiment: As ν_{e*} increases, RMP-driven transport becomes weak (and the ELM suppression is lost in most cases; often mitigation).

Simulation: As ν_{e*} increases, RMP penetration becomes weak, thus RMP-driven transport is reduced.





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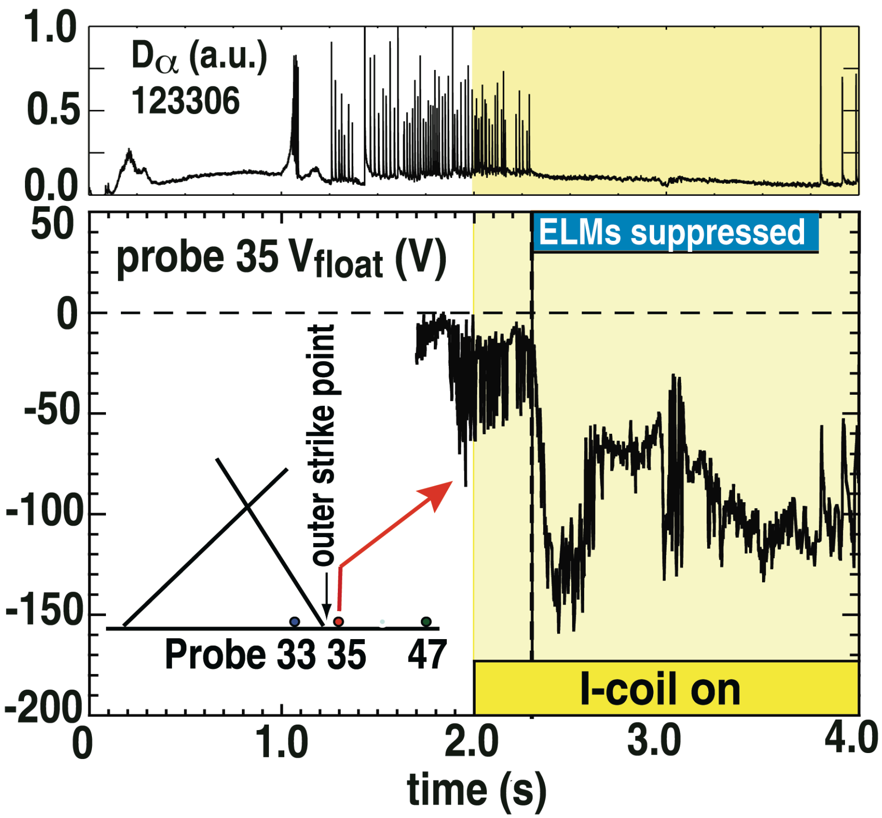
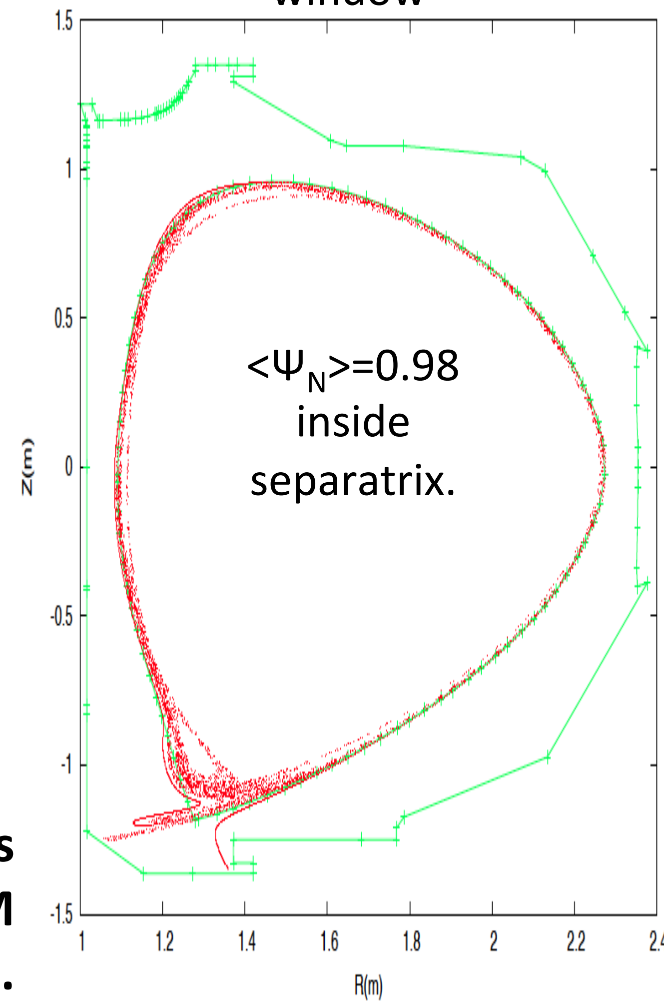
Experimental indication of field line connection from pedestal to divertor in ELM suppression window



J. Watkins, et al., J. Nucl. Mater., **363-365** (2007) 708

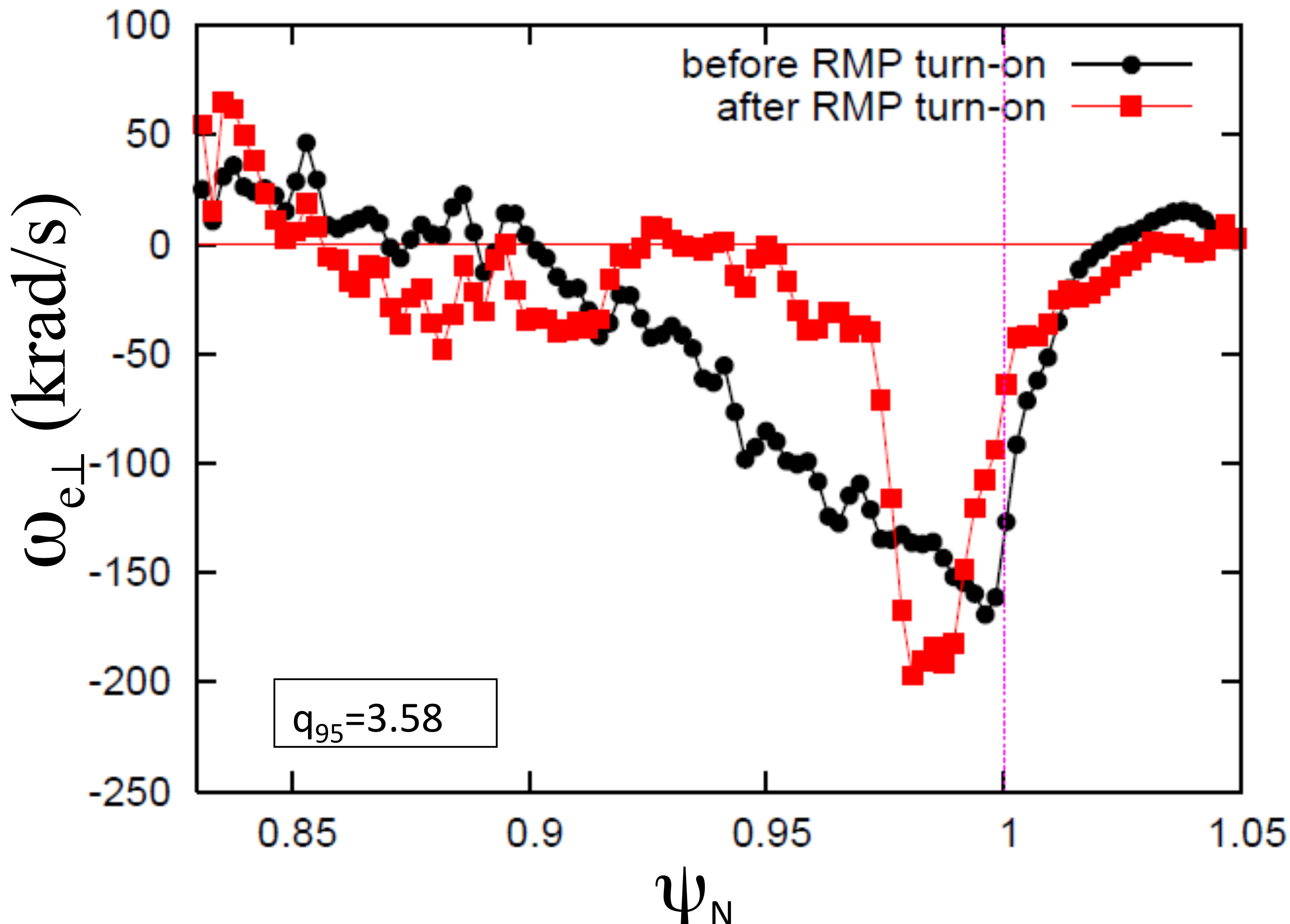
Agrees with implication from XGC0 kinetic simulation in q95 window



This connection to inside separatrix does not happen if q_{95} is out the ELM suppression window.

XGC0 finds large $|V_{e\perp} = V_{e*} + V_{ExB}|$ in the barrier-survival region (shielding layer), and zero/small $V_{e\perp}$ in the enhanced transport region

Large $|V_{e\perp}|$ just inside the separatrix is supported by the robust X-transport effect.

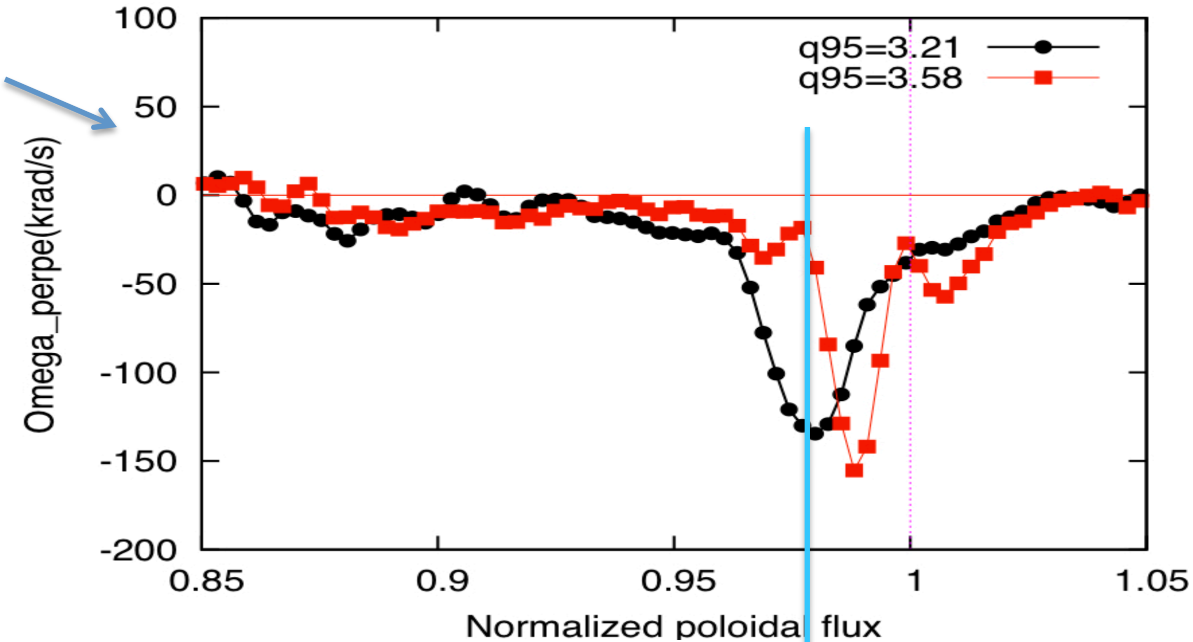


Similar result seen in experiment [Moyer]

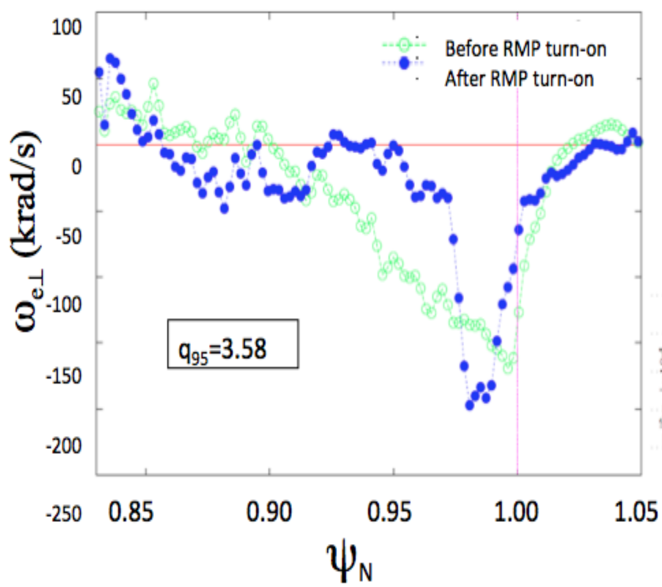
Cf., Fitzpatrick's flow shielding theory

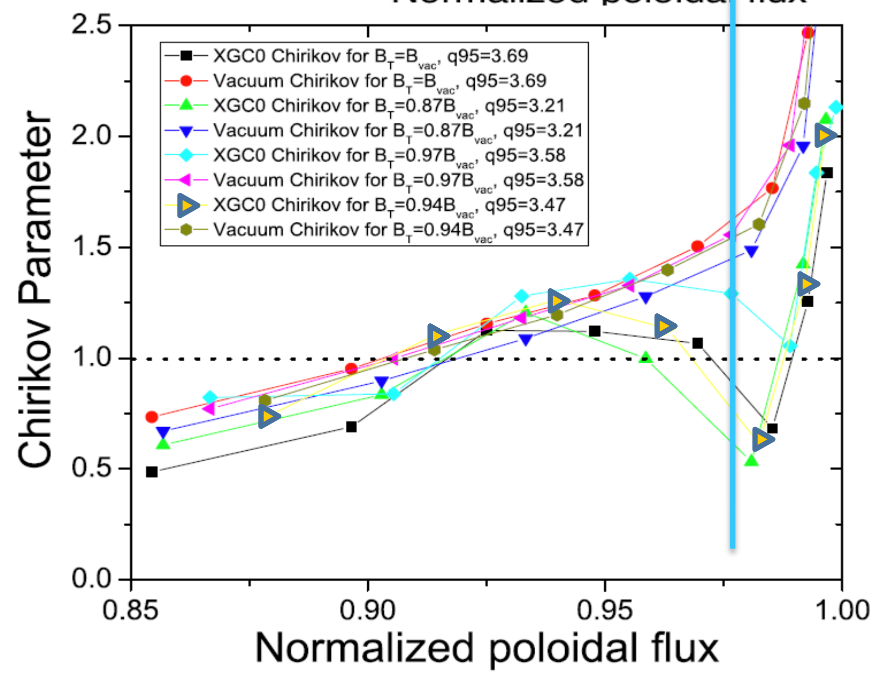
The small $V_{e\perp}$ region moves outward in the ELM suppression window

$V_{e\perp}$ in and out of q-window



$V_{e\perp}$ before and after RMPs

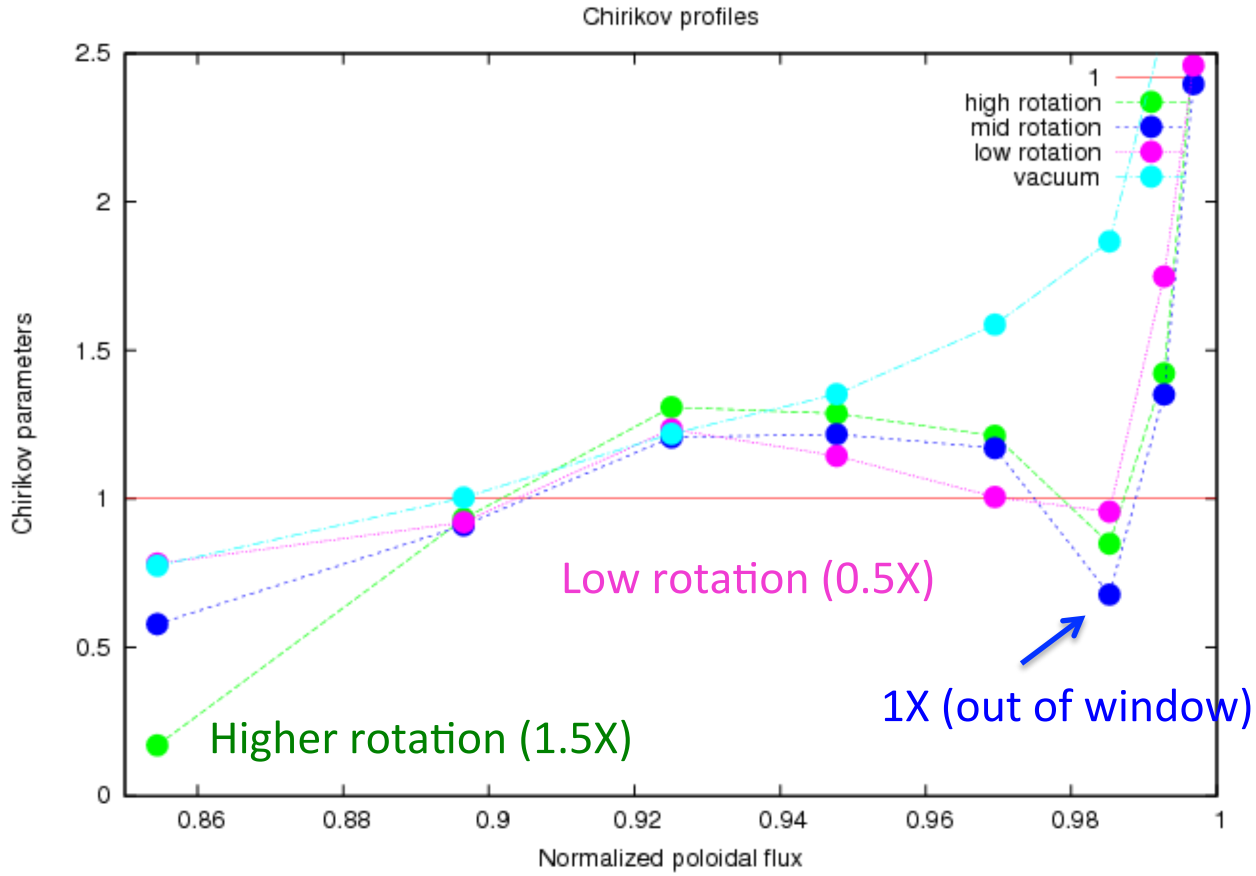




Rotation effect on stochasticity

Effect of a slower rotation on the penetration of islands/stochasticity into edge pedestal top is minimal due to strong "edge physics effect (X-loss)" → good news for ITER.
However, it does not suppress the vacuum RMPs in deep core.

50% higher rotation significantly suppresses the RMPs in the core, not at pedestal top.



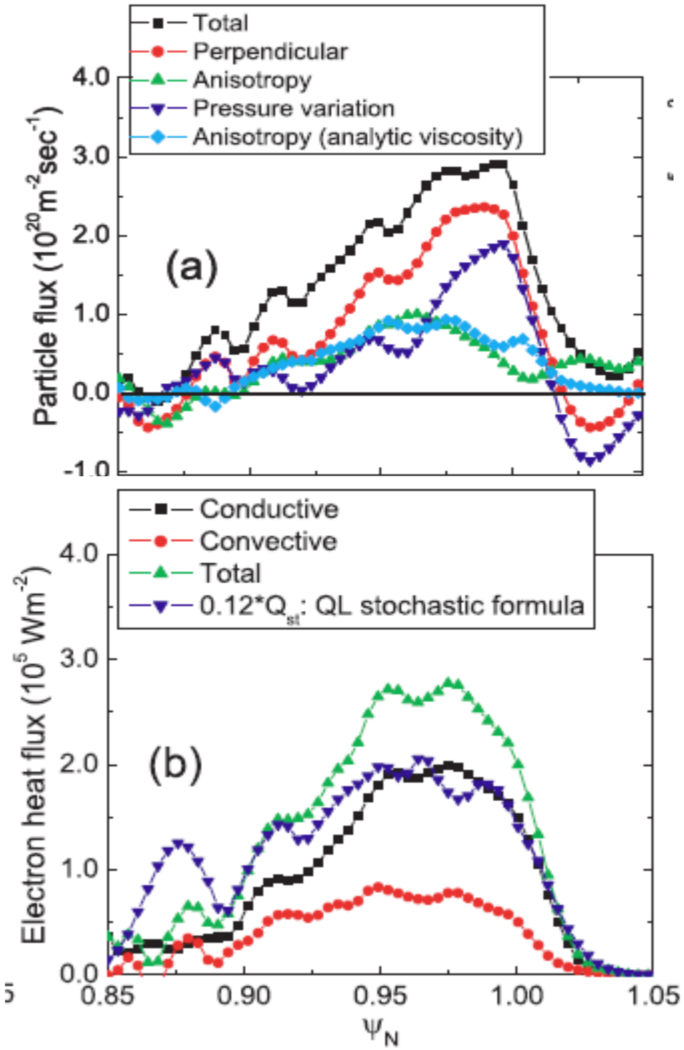
Basic tokamak particle and heat transport mechanism in stochastic 3D magnetic field ≠ Rechester-Rosenbluth

[G. Park, C.S. Chang, et al, Phys. Plasmas **17**, 102503 (2010)]

- **Particle flux follows 3D ion radial Transport**
  - Negligible Γ_r is true only in axisymmetric E_{r0}
  - A non-axisymmetric δB generates $\Delta E_r = E_r - E_{r0}$
  - ΔE_r drives Γ_r via toroidal friction of trapped ions against passing ions: $\Gamma_r = F_T x B/B^2$
  - General analytic neoclassical theory

$$\left\langle \vec{\Gamma} \cdot \nabla\psi \right\rangle = -\frac{I}{e}\left\langle \frac{\nabla_{\|}P_{\|}}{B} \right\rangle + \frac{I}{e}\left\langle \frac{(P_{\|} - P_{\perp})\nabla_{\|}B}{B^2} \right\rangle$$

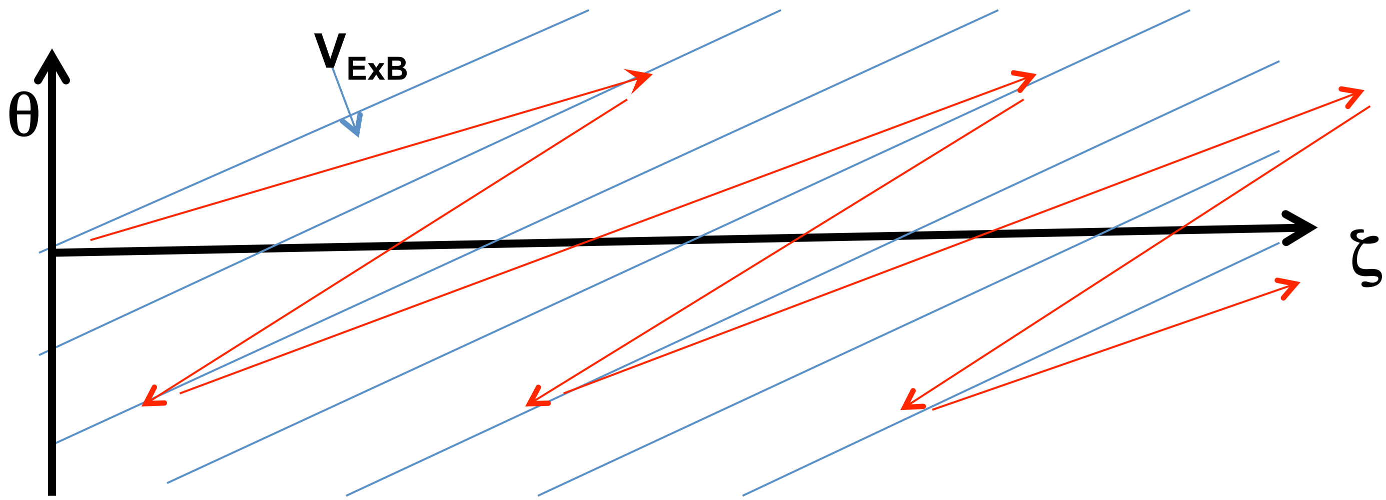
- **Electron heat flux**
  - Q_e is only 10^{-1} of the Rechester-Rosenbluth
  - Due to trapped particles, E_r & $\perp$ drifts
  - Conductive electron heat loss is ~convective loss!



Particle and heat transport in fixed stochastic B

[G. Park, C.S. Chang, et al, Phys. Plasmas **17**, 102503 (2010)]

- Particle transport is significantly enhanced by
  $\Delta E_r = E_r - E_{r0}$(Axisymmetric)
  - Trapped particles experience a net toroidal drift by ΔE_r while the passing par ticles experience little. → Toroidalf Friction F_T → raidal $F_T x B_p$ drift



- Parallel electron heat transport is observed to be ~ particle transport) << Rechester and Rosenbluth
  - Trapped particles (~3/4) are not subject to Rechester-Rosenbluth
  - Passing particles deviate from Rechester-Rosenbluth due to ExB and GraB drifts
  - Ambipoar Er also playes an important role in reducing electron transport

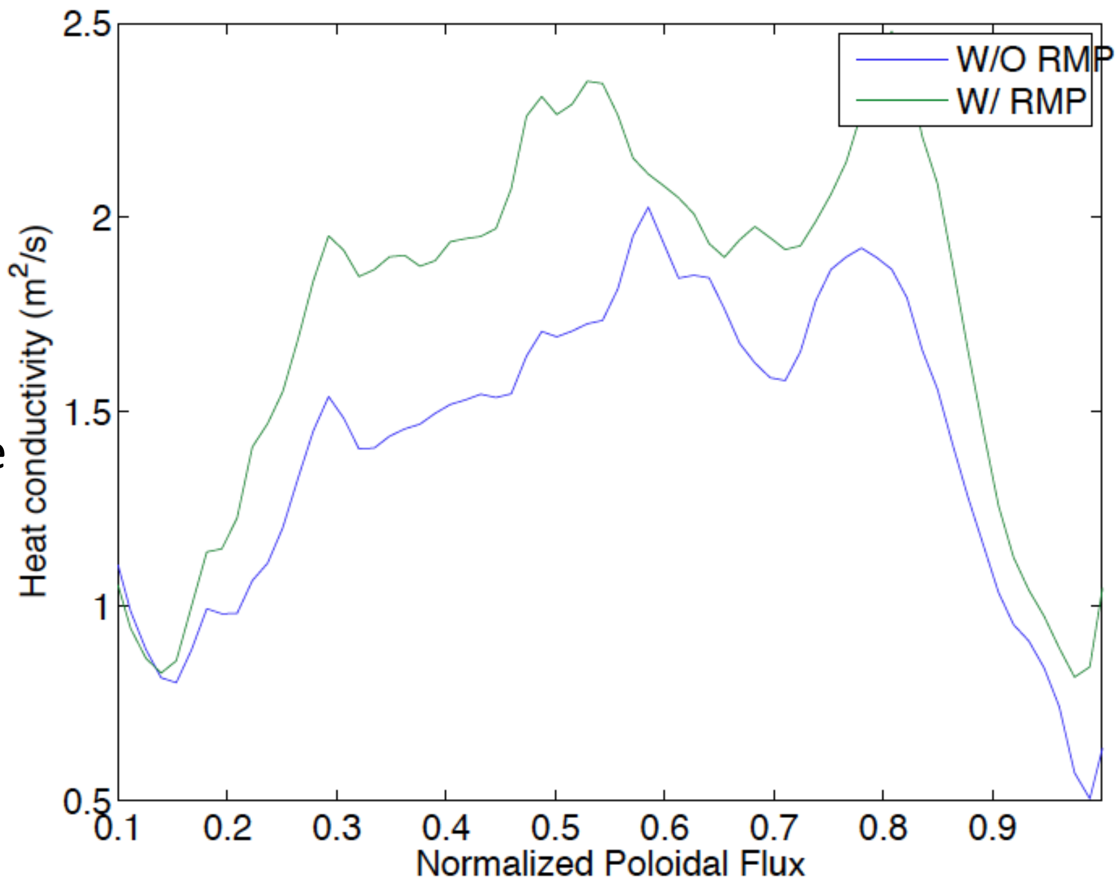
3D perturbations affect global turbulence and transport.

3D must be included for quantitative understanding of turbulence.

Example: RMP effect on ITG turbulence in XGC1

- RMPs with plasma response has been solved in XGC0
- The perturbed B-field is imported into XGC1
- ExB shearing is reduced by RMPs, enhancing turbulence

A comprehensive 3D field penetration study capability will move from XGC0 to XGC1: turbulence with kinetic electrons-ions-neutrals, RMPs, ripple, error field, transport, profile response, etc



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PIC simulation of Tokamak plasmas: Total-f and reduced-δf

- Total-f (Full-f): Solve f directly without manipulation
  - $Df / Dt = C(f) + \mathrm{Source} - \mathrm{Sink}$
  - Used in the original GK ion XGC1 with adiabatic electrons
- Reduced-δf in thermal equilibrium plasmas & for $\rho/L_P \rightarrow 0$
  - $f = f_M$(fixed analytically) + δf

    $$\frac{D\delta f}{Dt} \cong -\frac{D^* f_M}{D^* t} + C(\delta f), \text{ where D* is the reduced D: } \frac{D^* f_M}{D^* t} = v_E \cdot \nabla f_M$$
  - No free energy from grad-B/Curvature drift on RHS
  - Scale separation between mean (f_M) and perturbed δf assumed
  - Main plasmas are described in this way in many well-known δf codes applied to the tokamak core region

- The reduced-δf method assumes scale-separation $\rho/L_P \rightarrow 0$ and thermal equilibrium background plasma; and possesses other restrictions.
- But, it is still popular because it can
  – save compute time and
  – reduce particle noise.
- Question: Can we perform the total-f simulation while keeping these advantages, but removing the disadvantages?

Known (f_M) → Unknown ($f_{0,grid}$)

\+ Unknown

Let's put the coarse-grained quantity on coarse-grained continuum grid.

- **Less restricted by memory than the fine-grained 5D continuum method**
- **The scalability is achieved by particles.**

The naive total-δf particle method

- Total-δf
  - $f = f_0 + \delta f$, f_0 is a time-constant analytic function

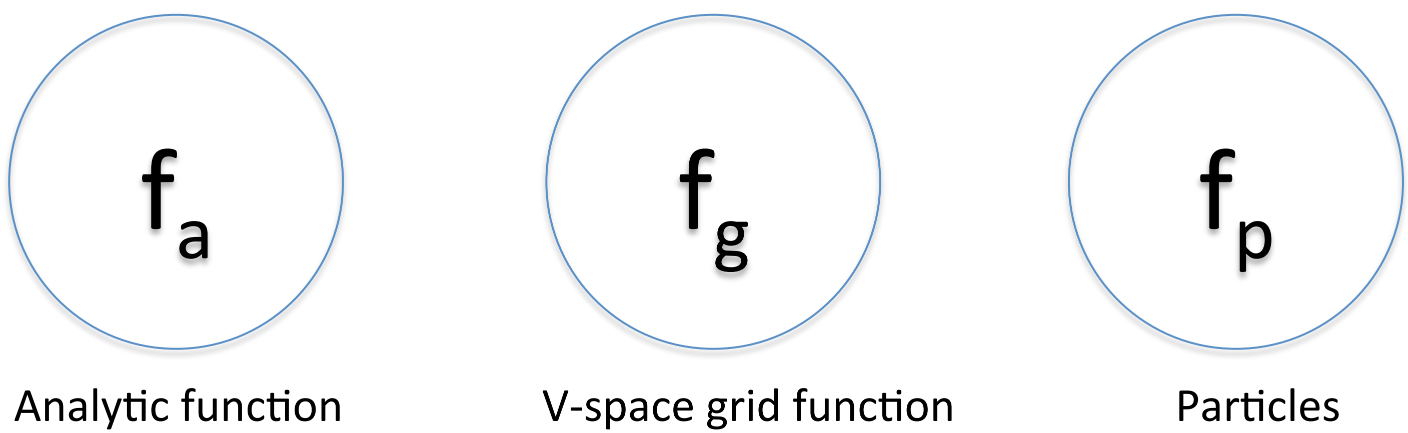
$$\frac{D\delta f}{Dt} = -\frac{Df_0}{Dt} + C + \mathrm{Source} - \mathrm{Sink}$$

  - **Mathematically identical to total-f**
  - Mean and perturbed physics are solved together
  - δf can can become large due to strong V_B drive from finite ρ_i/L_p, wall loss, sources, or long time simulation.

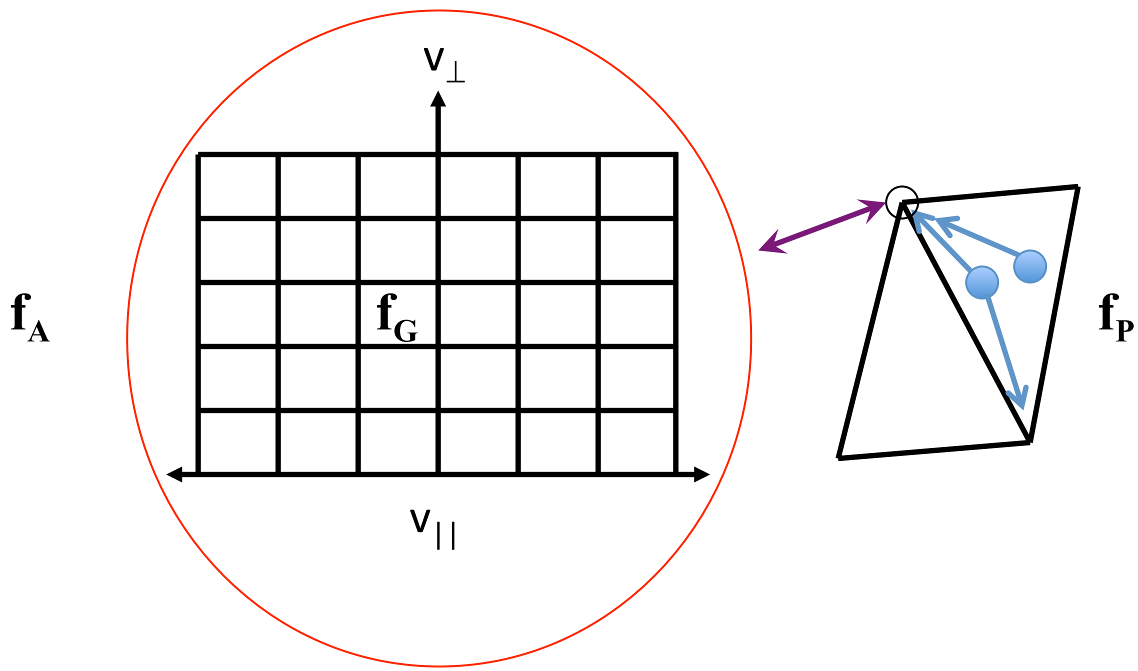
    → Growing weight and noise problem
  - Difficult to handle wall loss, non-linear collision, and sources and sinks

New hybrid-δf scheme [Ku et al. JCP, submitted]

- Solve the total-δf eq.
- $f = f_0 + f_P = f_a + f_g + f_P$, enables simulation of non-thermal equilibrium
- f_0 contains slowly varying physics.
- f_a is a fixed analytic distribution function (e.g. Maxwellian).
- f_g is the deviation from f_a on 5D grid. f_g can be partially updated into f_M
- f_P represents the δf particles, driven by the free energy in ∇f_a and ∇f_g.
- All physics information can be on the continuum grid, if f_p is also placed on the v-grid → physics data size << particle data size



$$f = f_a + f_g + f_p$$



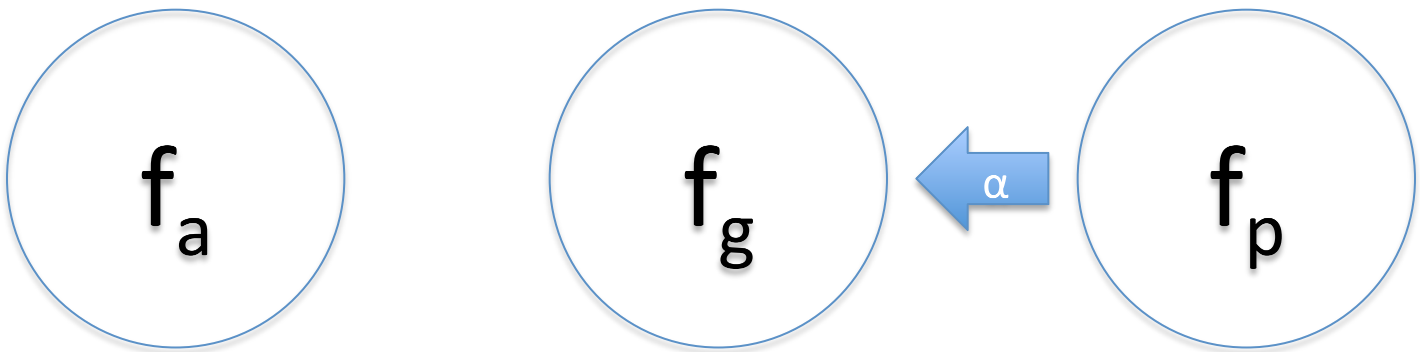
The new hybrid Lagrangian scheme

- Time evolution:
  - Step 1: Solve the particle motion and the weight evolution as in the naïve total-δf scheme, with the S operation (collision, ionization, CX, …) in v-grid

$$\frac{Df_P}{Dt} = -\frac{D(f_a + f_g)}{Dt} + S(\text{v-grid})$$

  - Step 2: Redefine f_P and f_g with the following operation ($\alpha \ll 1$)

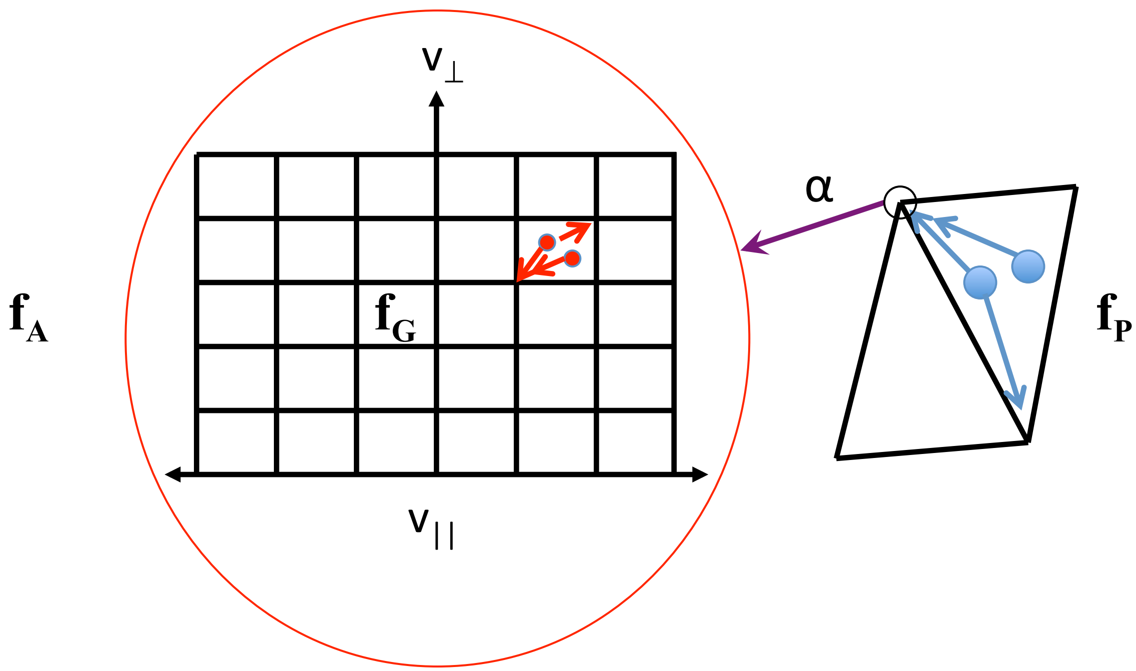
$$f_P \Leftarrow [1-\alpha(X,V)]f_P \ , \quad f_g \Leftarrow f_g + \alpha(X,V)f_P$$



Slowly varying in time

Fast varying in time

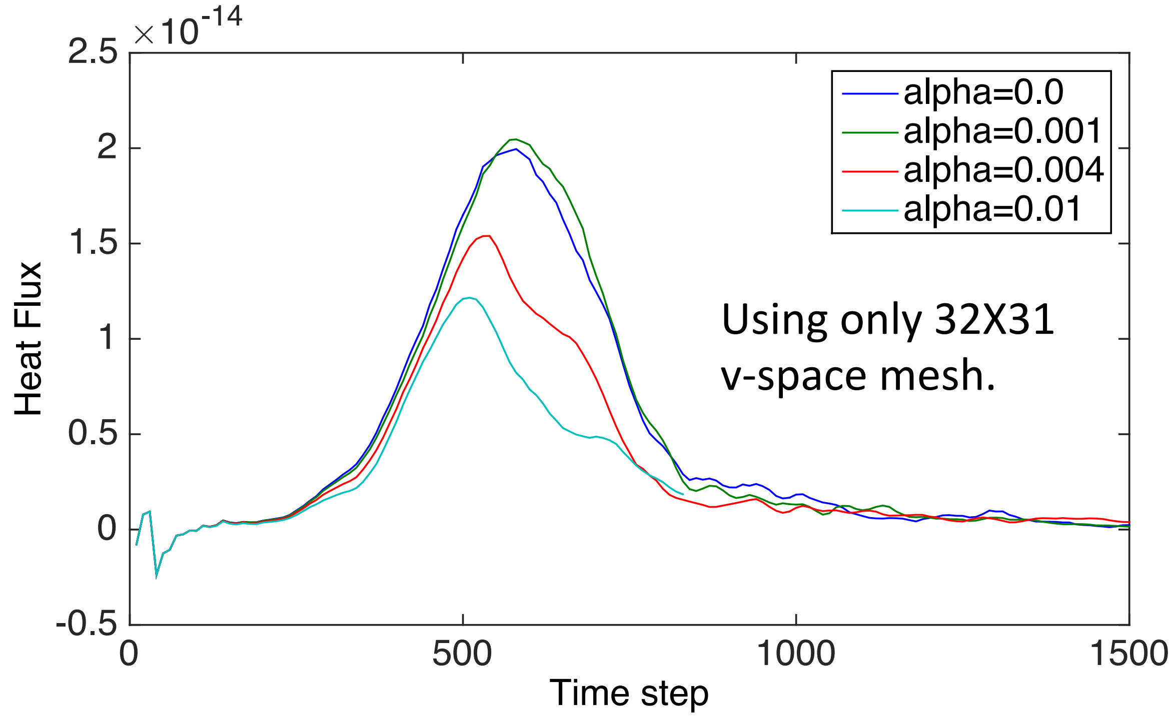
$$f = f_a + f_g + f_p$$



The α factor and the numerical dissipation

$$f_P \Leftarrow (1-\alpha) f_P$$

$$f_g \Leftarrow f_g + \alpha f_P$$



- A simple example case: hybrid-δf simulation with zero heating
  - Turbulence driver decays as the background profile relaxes
- The particle to v-space operation gives numerical dissipation from interpolation (damping of Landau resonance).
- A too large α reduces turbulence and time integrated heat flux
- More refined v-space mesh allows greater α.
- Optimal α ~ C(Δv) Δt/[turbulence correlation time scale]

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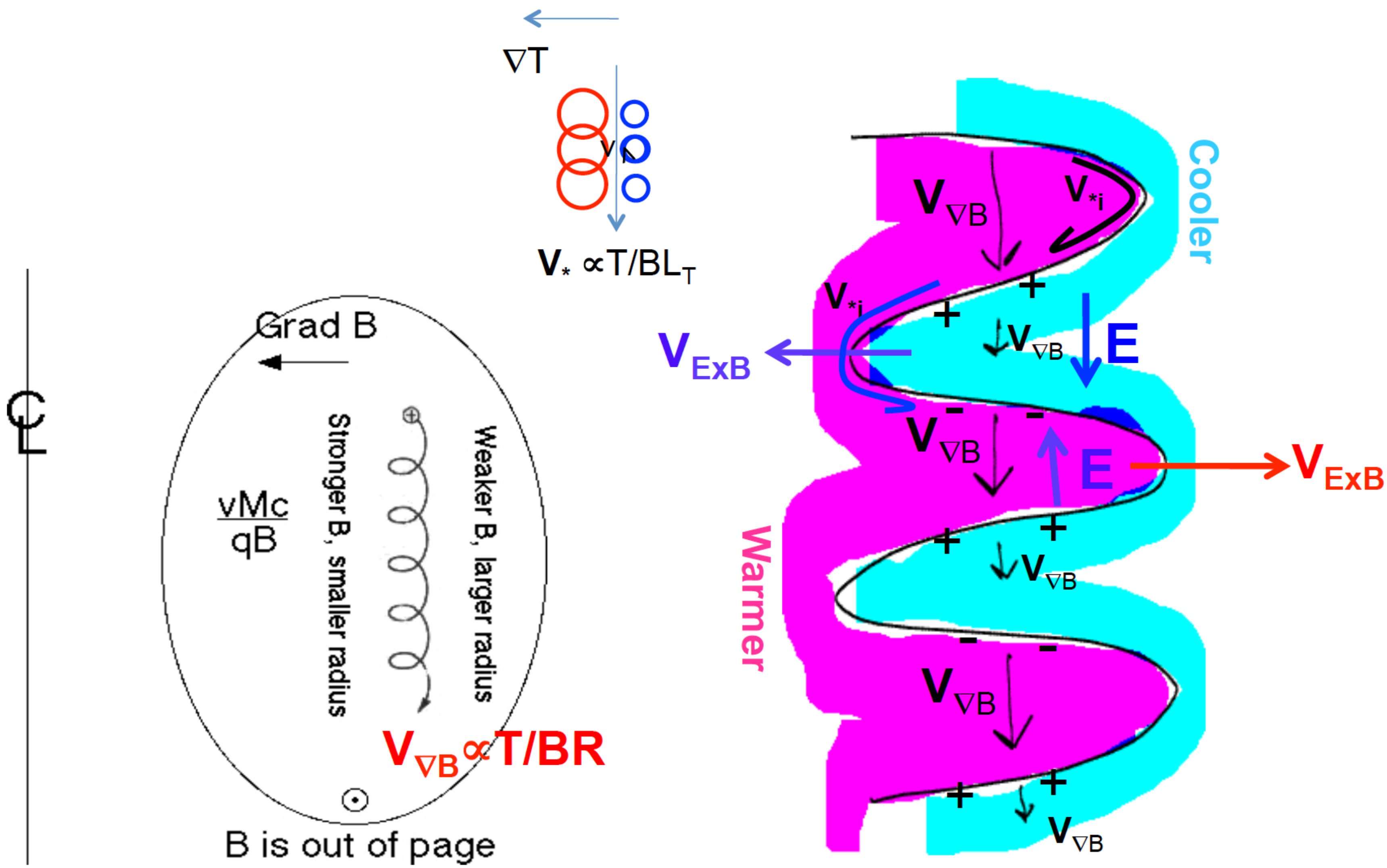
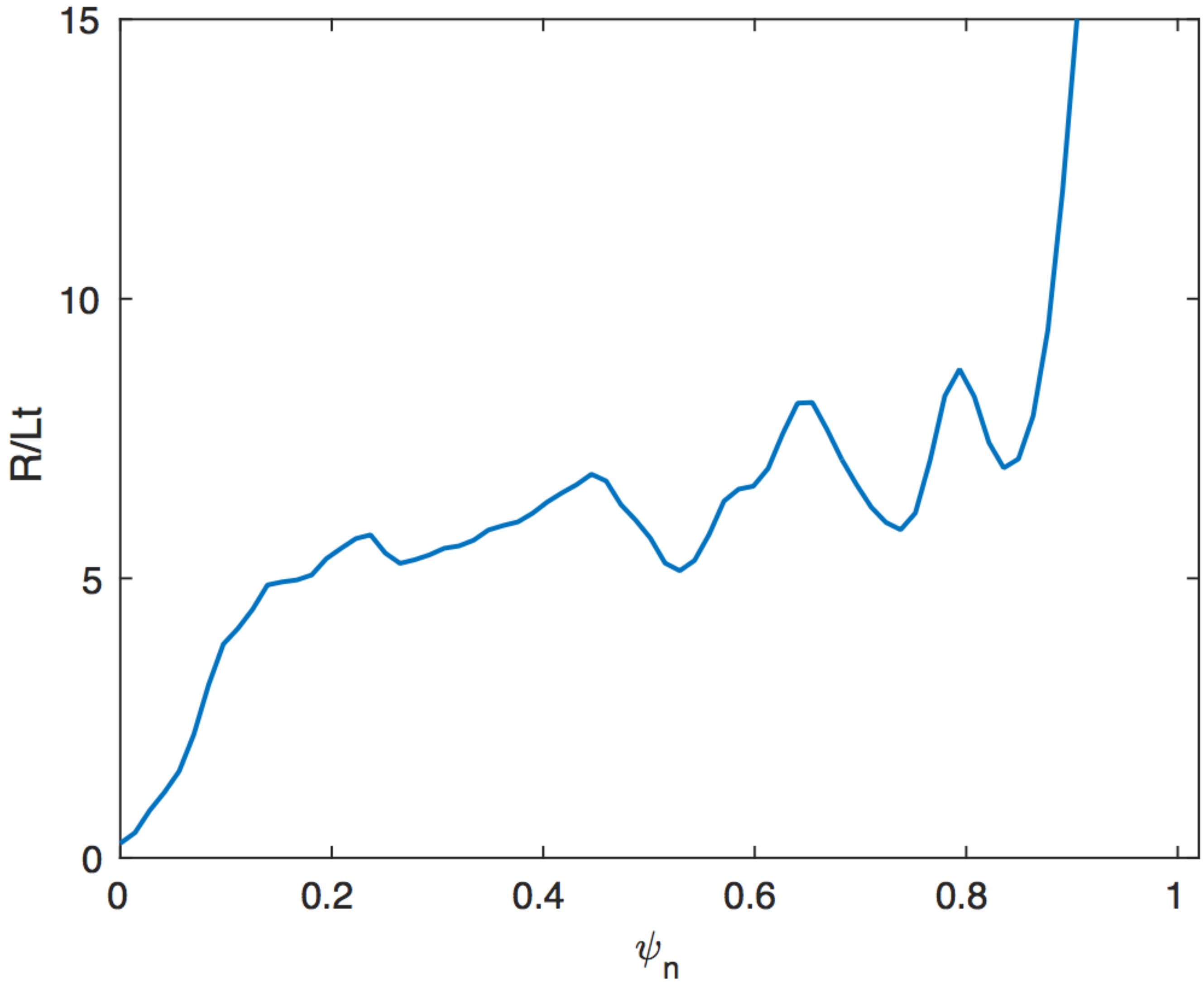
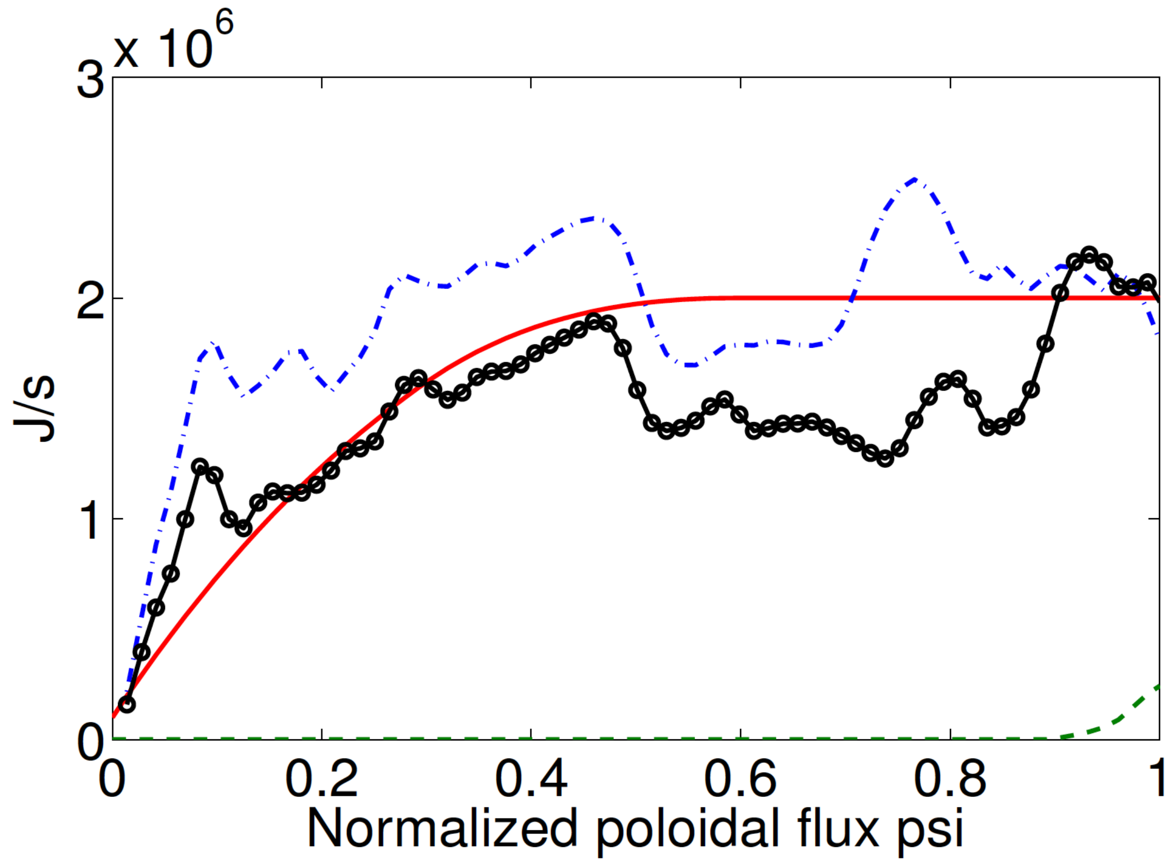
ITG (Ion Temperature Gradient) modes

(Plasma interchange without frozen-in B)



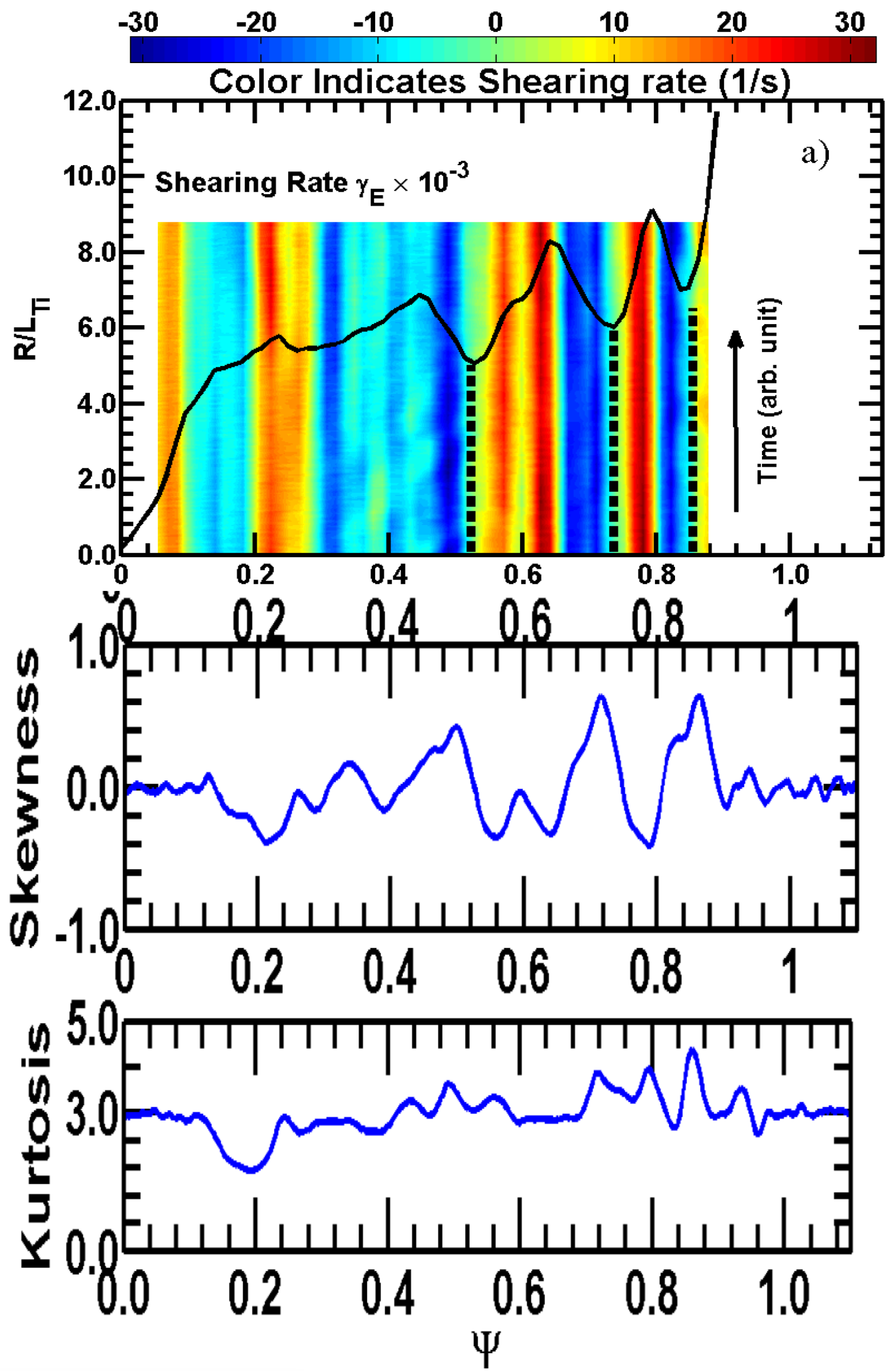

15
10
5
0
R/Lt
0
0.2
0.4
0.6
0.8
1
ψ_n



x 10^6
3
2
1
0
J/s
0
0.2
0.4
0.6
0.8
1
Normalized poloidal flux psi

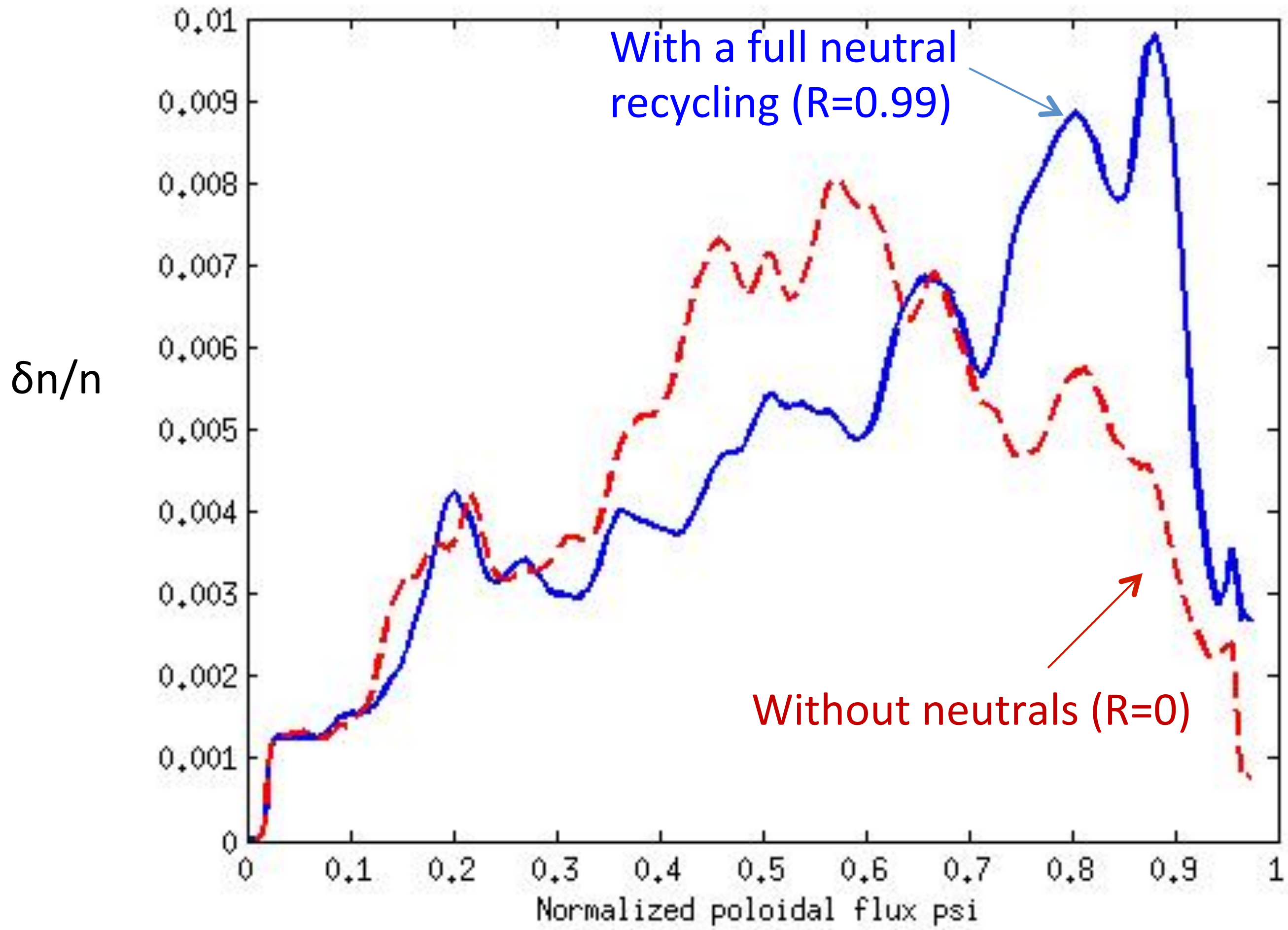
In the global self-organized state

- Self-organization is regulated by spontaneous ExB flow shearing, through non-local staircase T or corrugated ∇T profile interactions
- Sheared ExB flow and ∇T corrugation keeps the turbulence to be just right for to expel a proper amonut of heat-flux
- Non-Gaussian turbulence



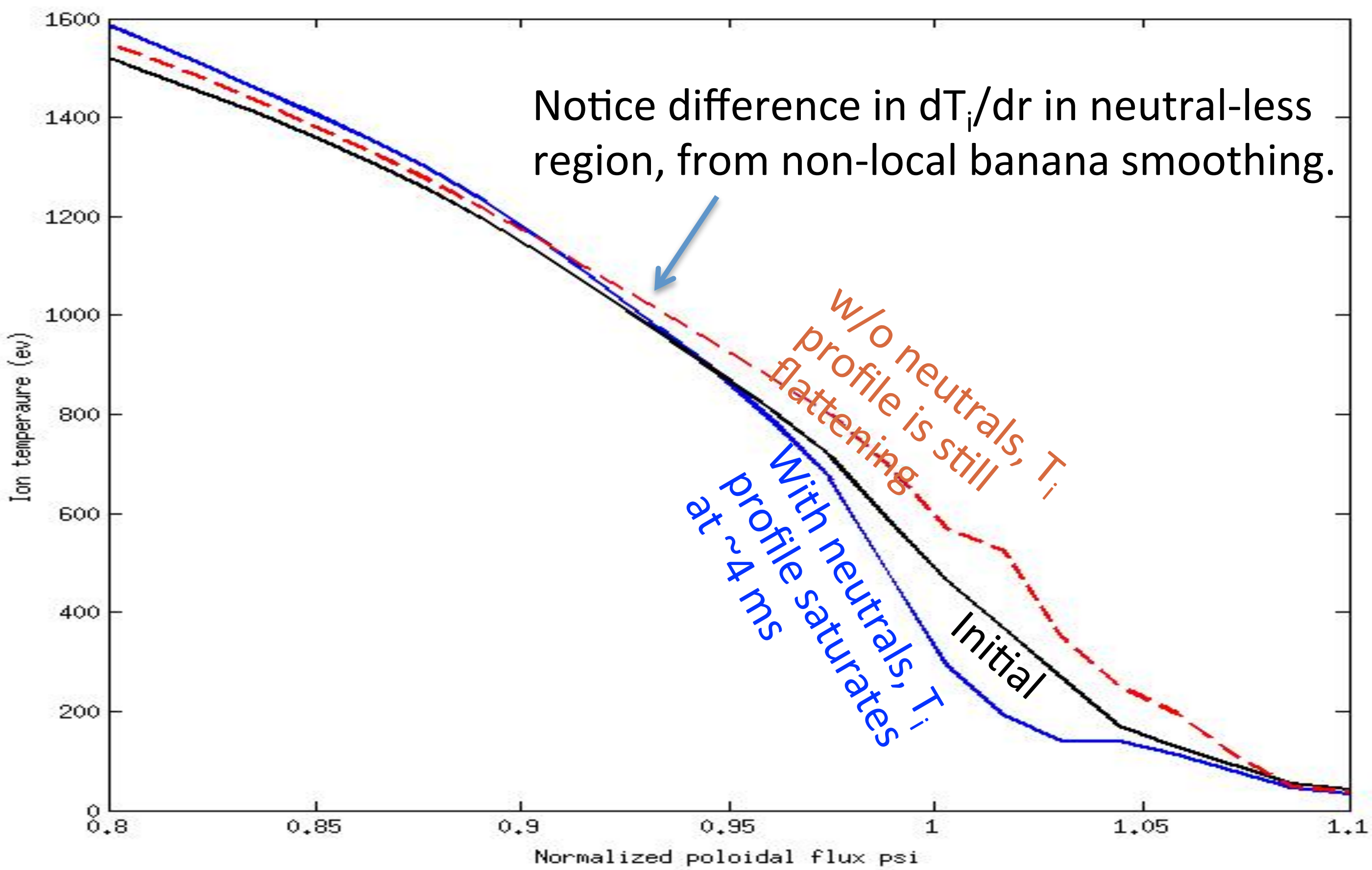
XGC1 showes that ITG turbulence is sensitive to neutral atomic physics

- Cooling of T_i in pedestal slope → A higher turbulence drive (η_i) at pedestal top
- Damping of ExB shearing rate by neutrals

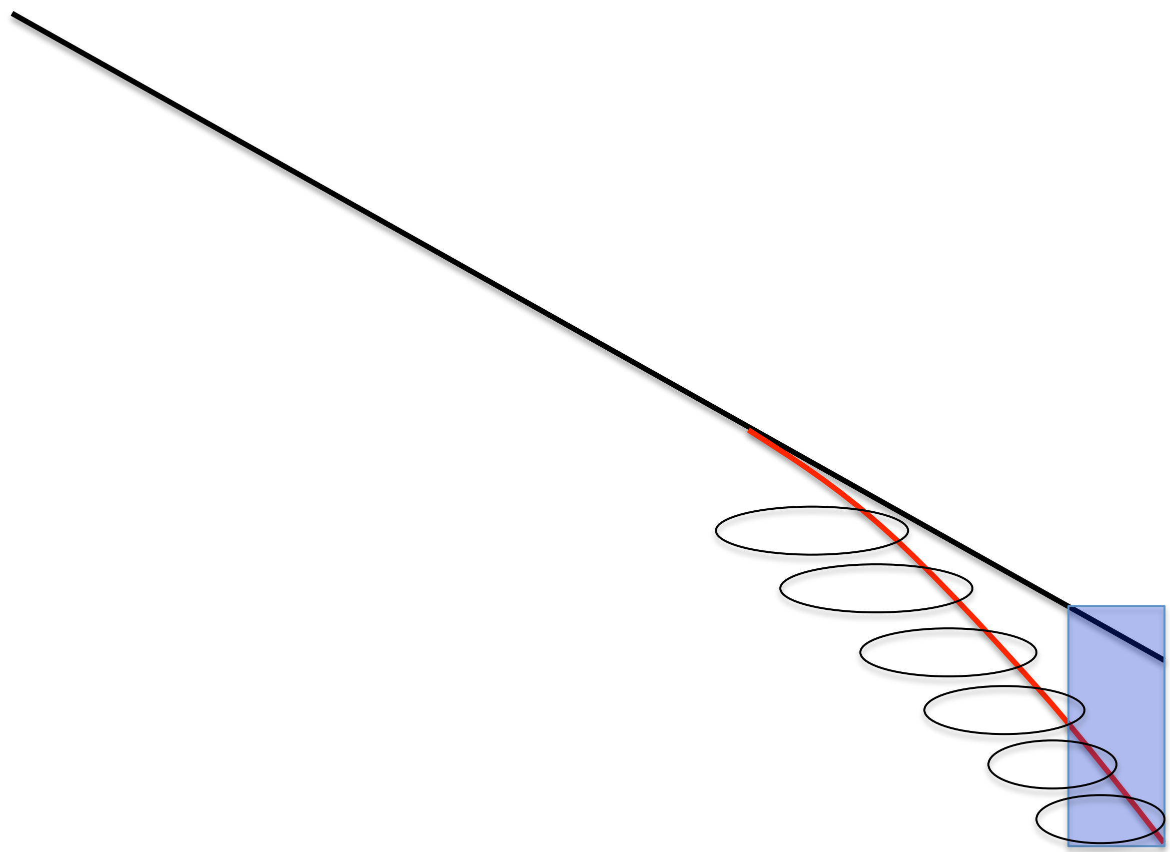


Neutral particles at outer part of pedestal affect η_i at pedestal top due to ion orbit smoothing

- Edge T_i profile saturates at steeper gradient with neutral particle recycling
- Maintaining adequate η_i and high edge ITG turbulence is difficult without neutrals

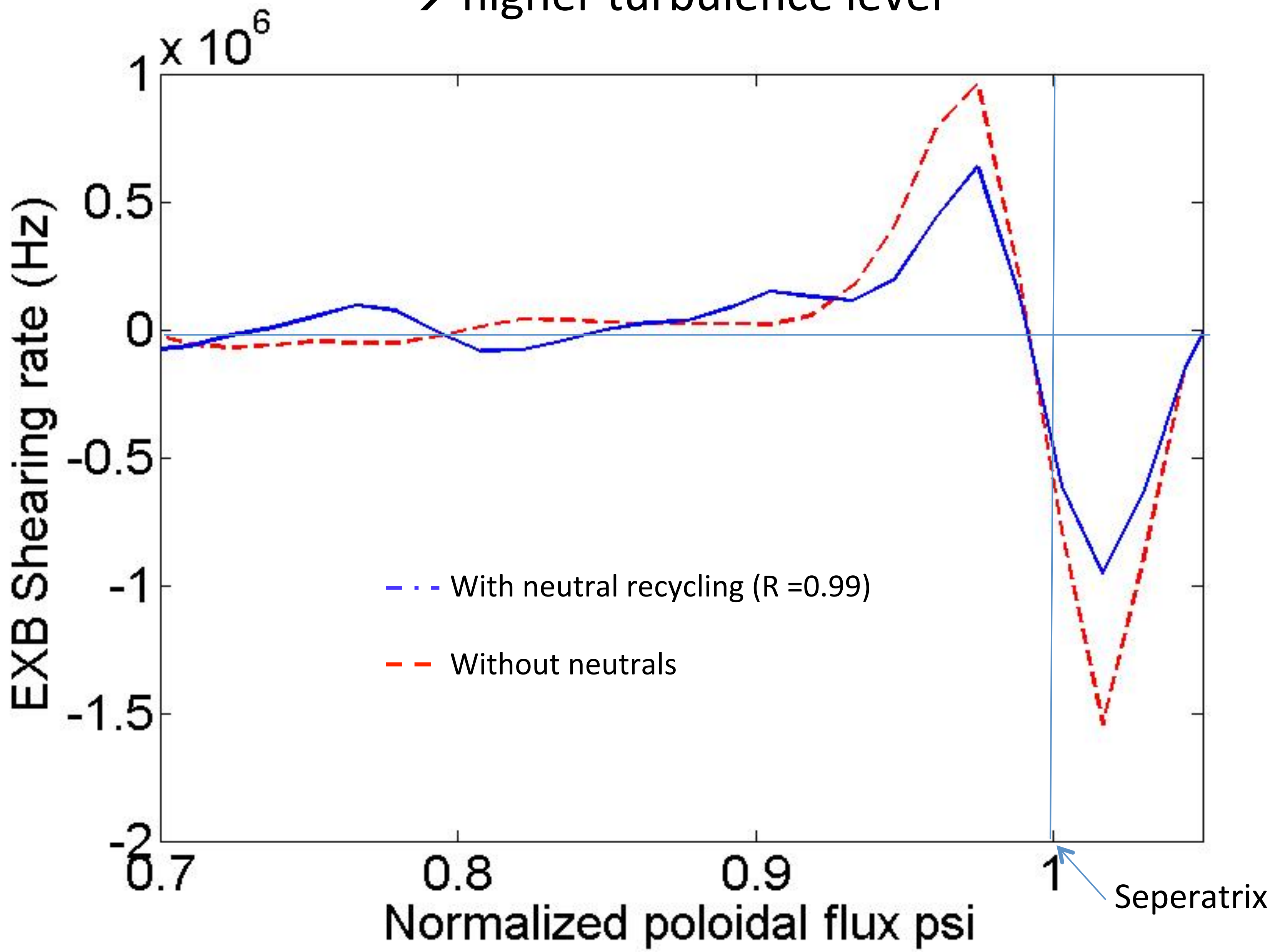


Cartoon picture of how neutral cooling "bends" down the edge T_i profile through radial orbital mix



EXB shearing rate is weaker with neutrals in the edge pedestal

→ higher turbulence level



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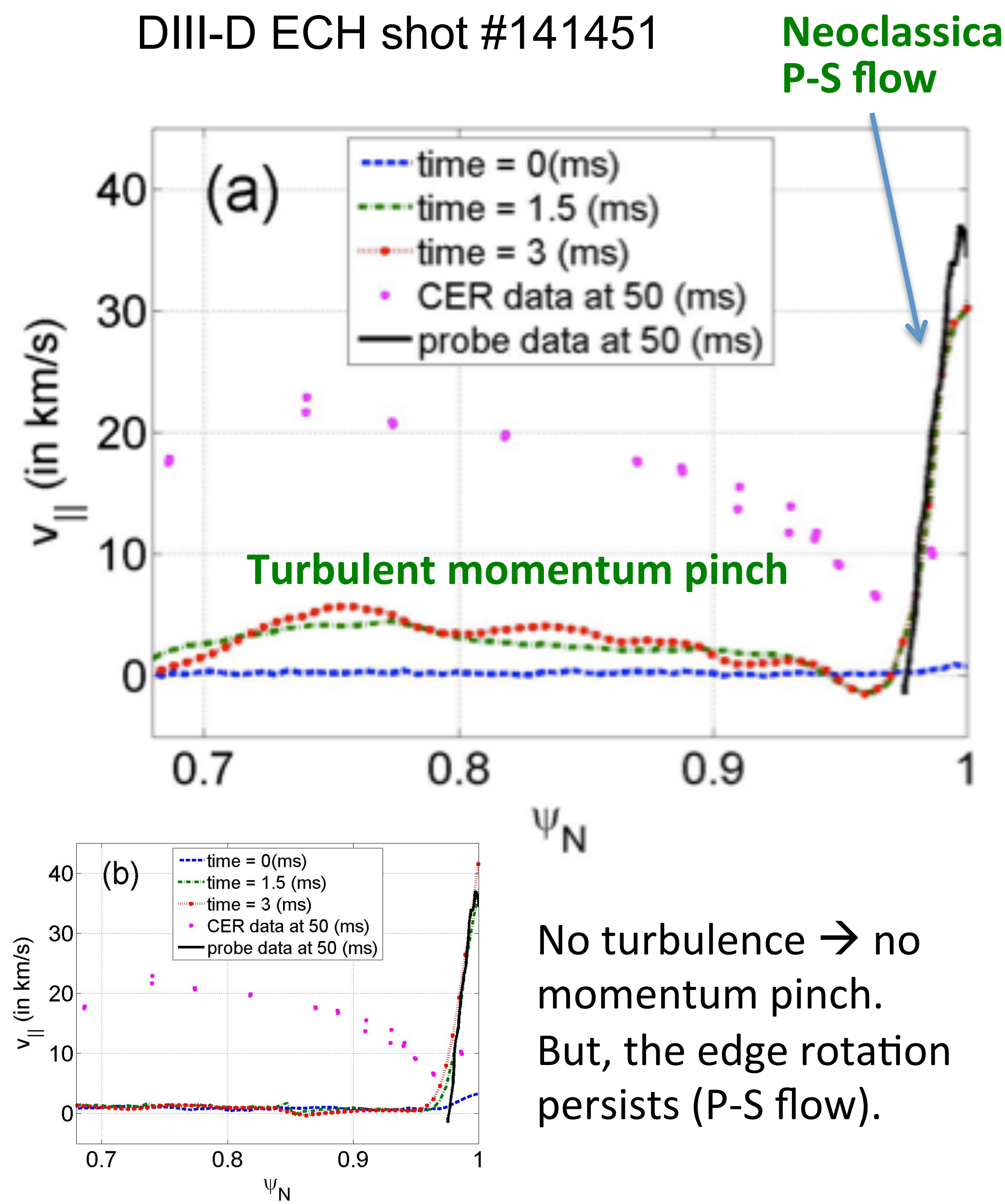
Edge rotation source and inward momentum pinch

- Detailed experimental measurement exists [S. Muller, PRL & PoP, 2011]
  - Conventional δf turbulent Reynolds stress could not explain experiment
- The full-f XGC1-produced edge rotation profile and inward momentum pinch speed agreeing with the experimental data
  - Edge rotation is from PS flow, not from turbulence as speculated by experimentalists.
  - Momentum pinch: In addtion to the conventional theory, full-f interaction between turbulence and neoclassial orbits is needed

DIII-D ECH shot #141451



No turbulence → no momentum pinch.
But, the edge rotation persists (P-S flow).

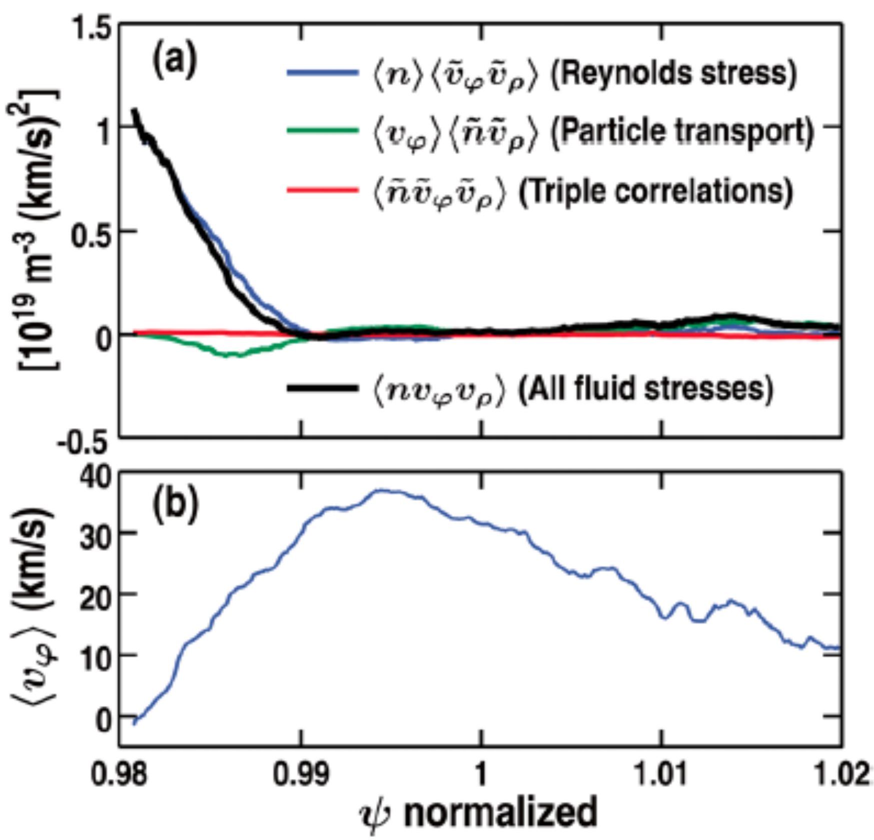
Validation of the edge momentum source and the inward momentum flux in DIII-D edge plasma

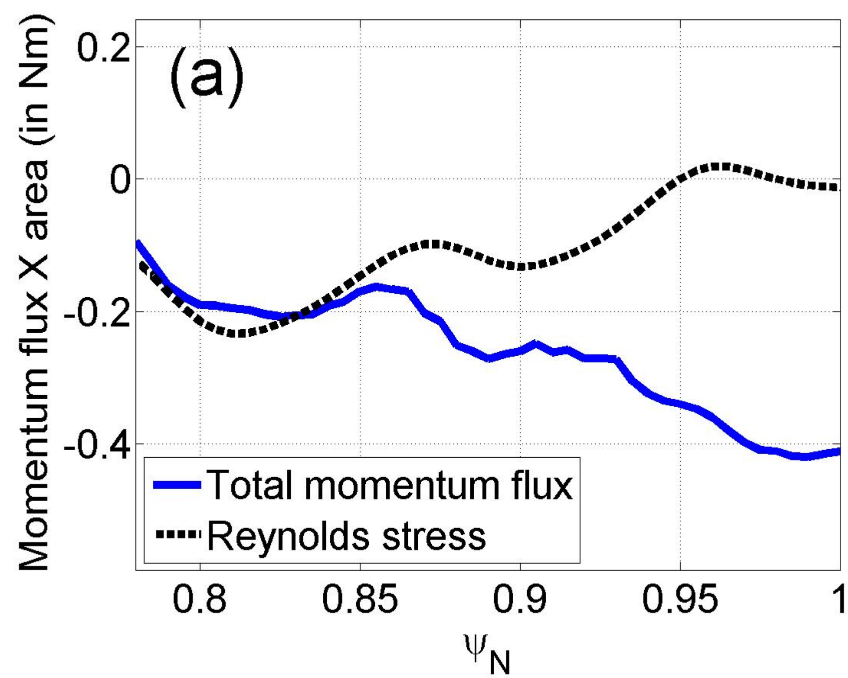
Experiment (Muller et al., PRL2011)

- Edge momentum source is seen
- Measured turbulent Reynolds stress cannot explain either edge momentum source or inward momentum transport

XGC1 simulation (Seo et al., PoP2014)

- Similar momentum source is seen and identified to be from neoclassical physics
- Total momentum flux from full-f ITG + neoclassical orbits is inward, with a correct magnitude.





Gyrokinetic Simulation of Edge Physics

Introduction

- Why gyrokinetics for edge physics?
- Local vs nonlocal transport

Part I: Neoclassical and RMP physics without turbulence

- Fundamentals of neoclassical physics
- Neutral particles
- Neoclassical physics in steep edge pedestal
- RMPs: penetration and transport

Part II: Addition of turbulence to neoclassical physics: examples

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- Edge momentum source by X-loss and turbulence
- Electrostatic blobby edge turbulence (hybrid delta-f)
- Divertor heat-flux width
- Electromagnetic XGC1

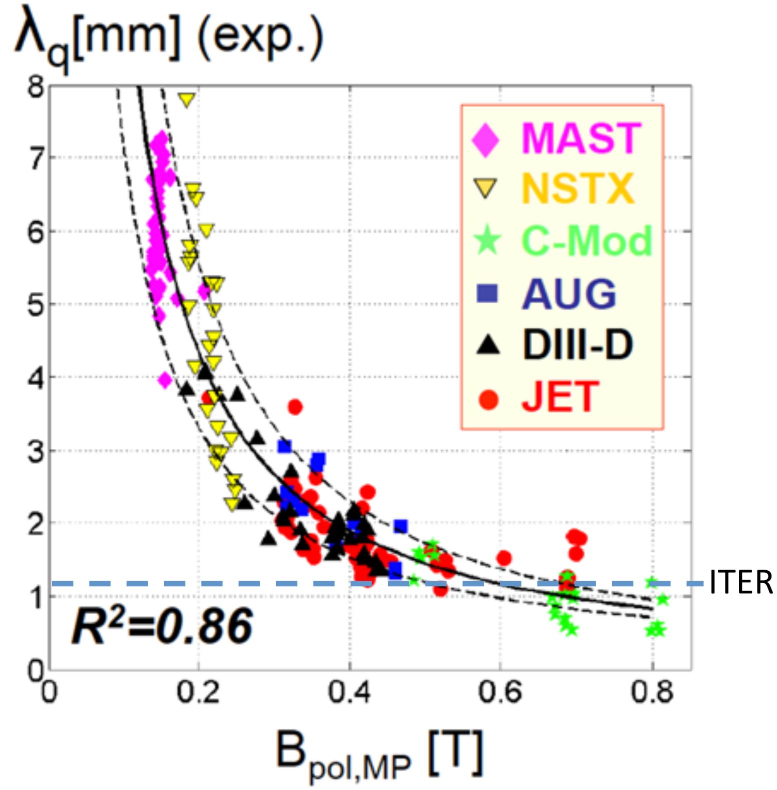
Blobby turbulence and divertor heat load

- For divertor heat-flux width, both neoclassical and blobby turbulence physics could be important
- Neoclassical dominant models [XGC0 results and Goldston model] yield

  $\lambda_q \propto 1/I_p^{\gamma}$, $\gamma \sim 1$

  - Appears to be working for the present-day tokamaks
- Will this be true in ITER? Δ_{banana}/a is smaller in ITER than that in the present tokamaks, but the blob size may be larger: $\Delta_{blob} \sim (a\rho_i)^{1/2}$
- Edge plasma is in non-equilibrium kinetic state: non-Maxwellian

→ **Requires extreme scale computing**



T. Eich et al., NF 2013

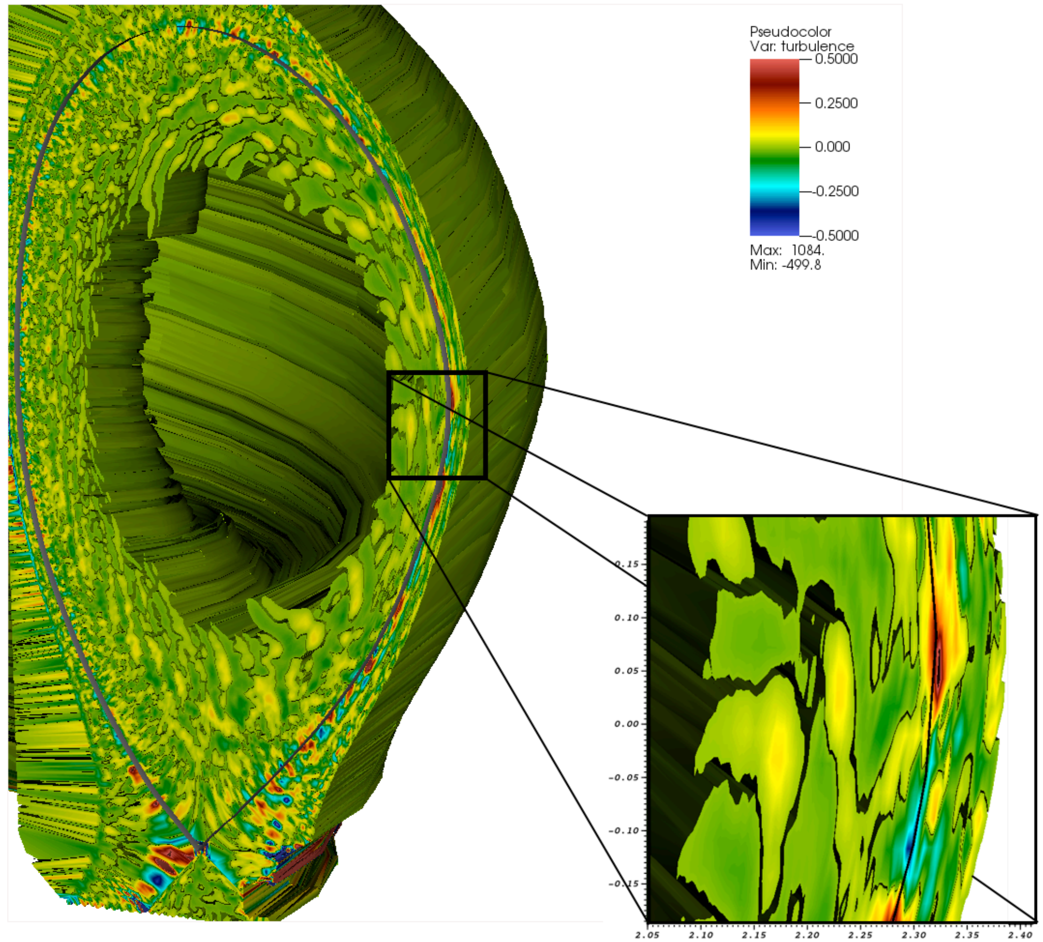
Ability for the nonlinear “blobby” edge turbulence + orbit dynamics is a pre-requisite for heat-flux study

2013-2014 INCITE, using 90% (16,384+ nodes~24pF) of heterogeneous Titan

IAEA2014 Talk

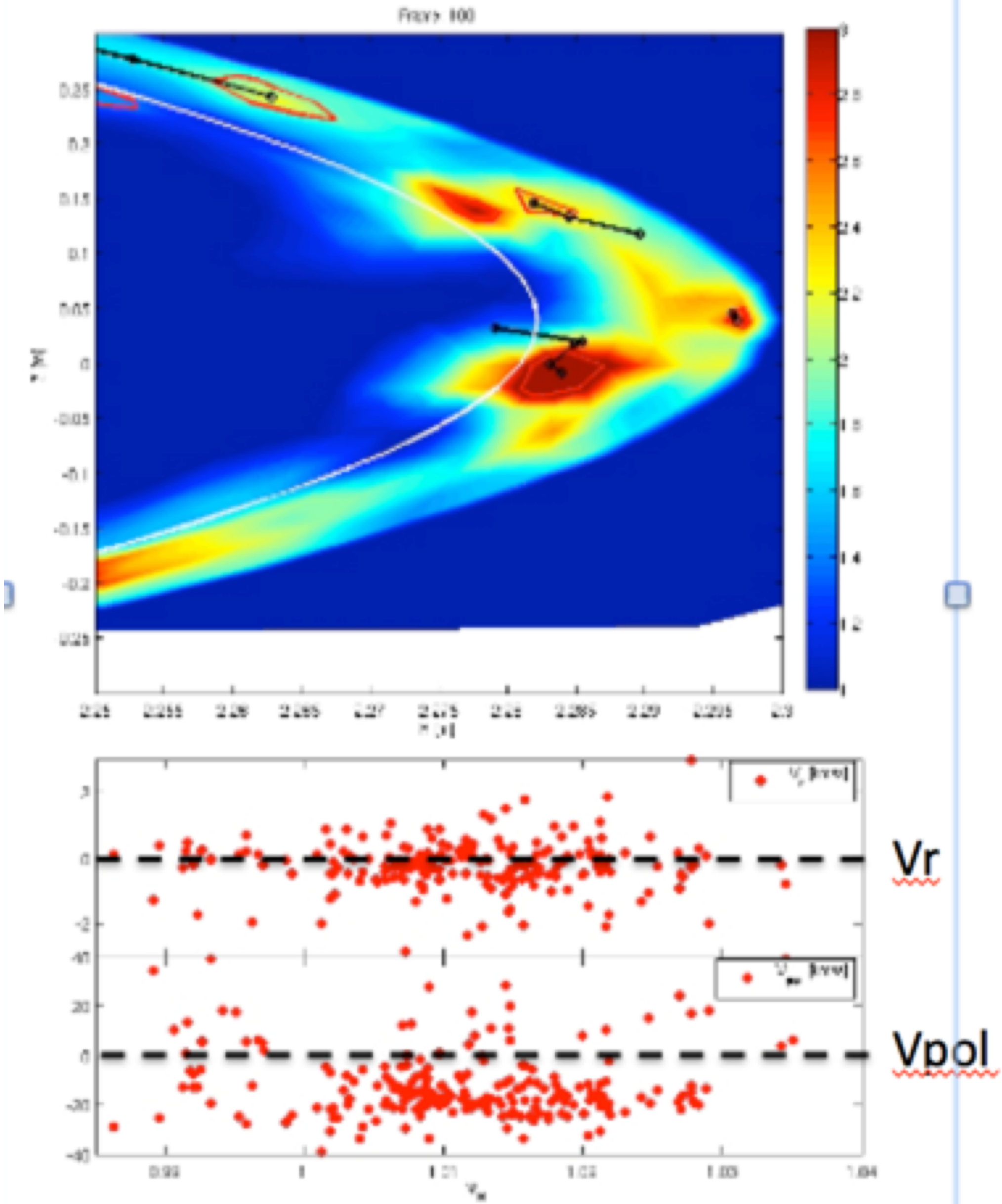
Gyrokinetic XGC1-simulation of edge blobs in DIII-D plasma

- Gyrokinetic ions
- Drift-kinetic electrons
- Neutral particle recycling
- Nonlinear Fokker-Planck-Landau collisions



Simulation by S. Ku,
Visualization by D. Pugmire

Blob dynamics in DIII-D like H-mode edge

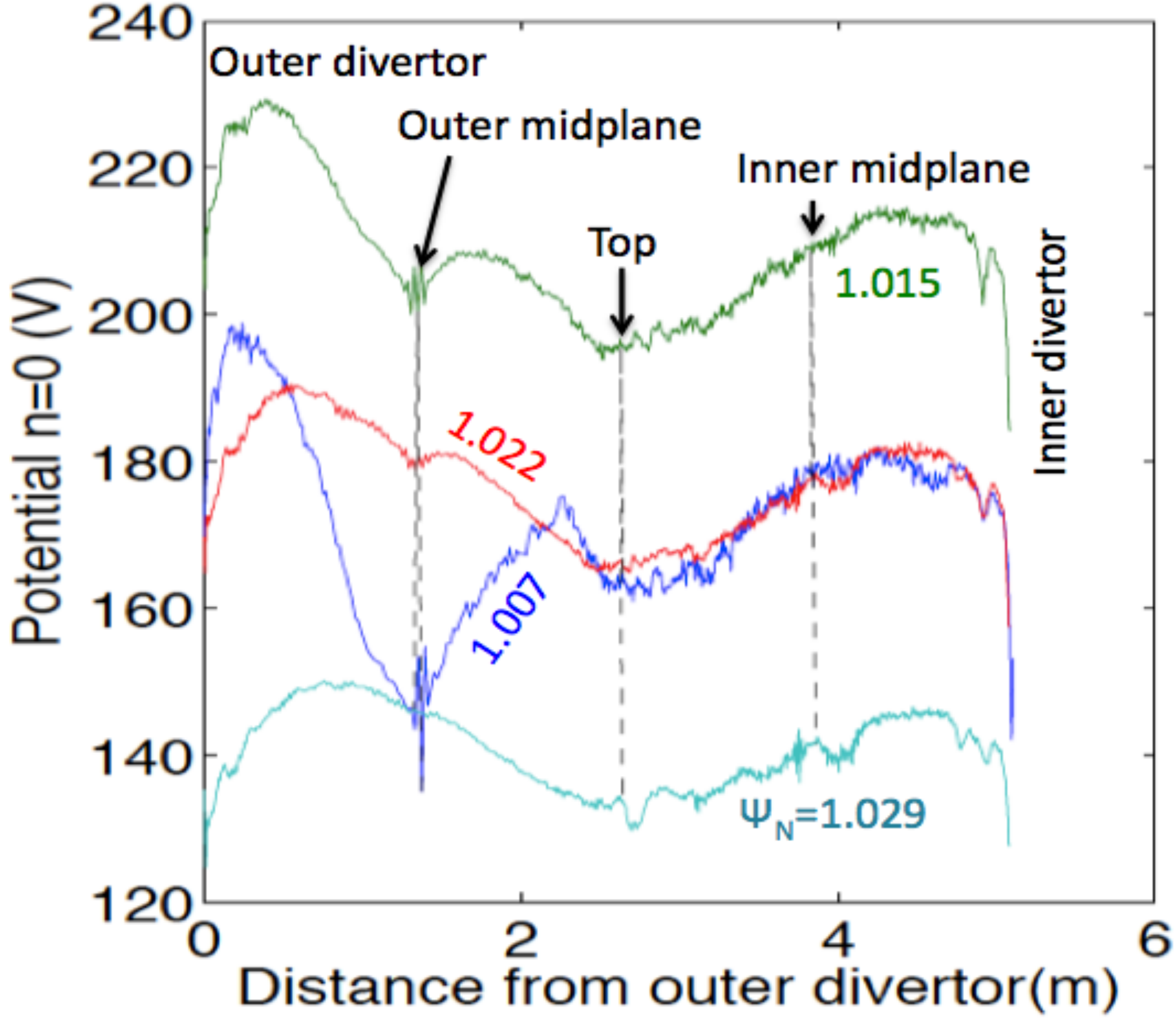


Blob radial velocity stays below 2 km/s.

Poloidal ExB blob motion is in the electron diamagnetic direction (upward) in the pedestal, and changes sign in the scrape-off layer toward the divertor (~20 km/s).

Poloidal potential variation in the scrape-off layer is calculated in XGC1 for self-consistent SOL physics. Notice the strong pre-sheath in front of the divertor plates.

With nonlinear collisions and neutral recycling



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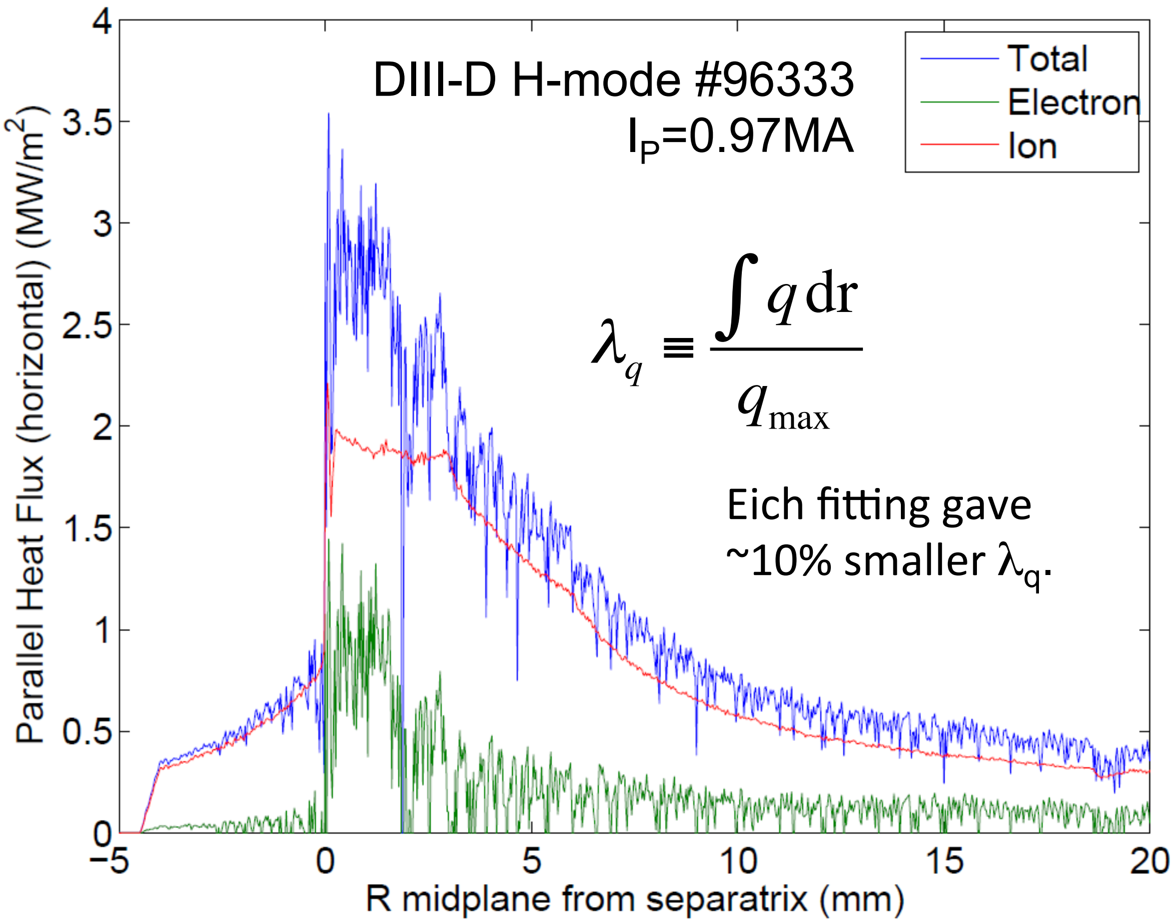
λ_q is dominated by ions in this DIII-D like edge plasma

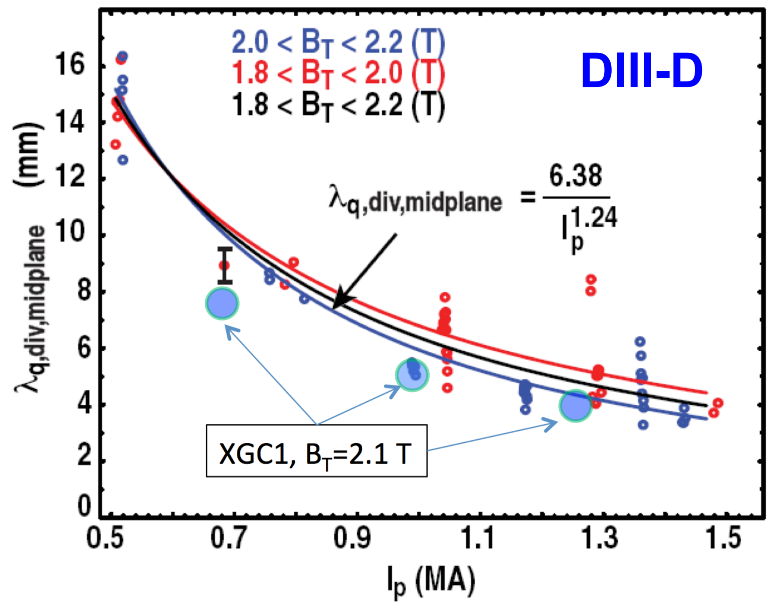
$K_e < K_i$ in scrape-off, and ions (electrons) gain (lose) kinetic energy in the pre-sheath

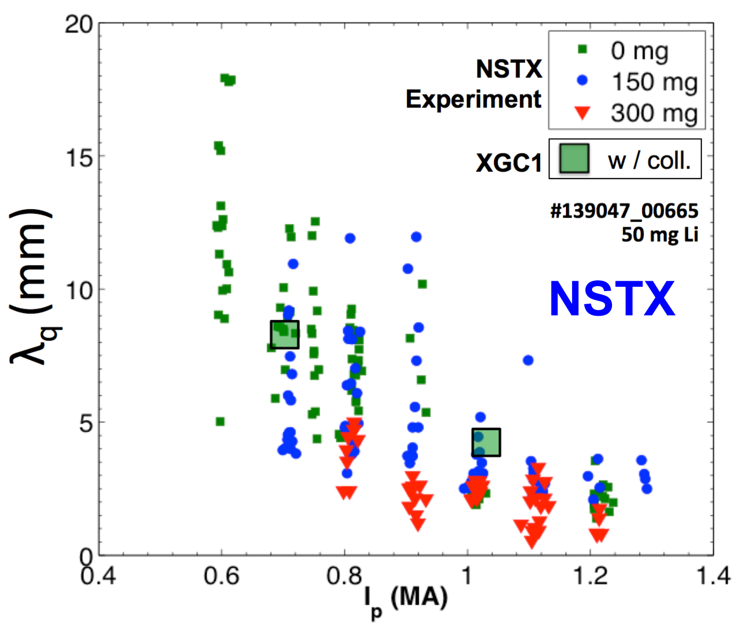


- λ_q =5.1 mm at I_P=0.97MA
  - Enhancement by neutral particles is only ~10%
- λ_q is closer to ion orbit spreading width than the radial blob size (≳1cm)

Heat-load spreading by **blobs** (represented by λ_{qe} ~2mm in the figure) is masked by the ion orbital spreading.

$\lambda_{q,mid}$ predictions for DIII-D & NSTX are in the right ballpark





- $\lambda_{q,mid}$ is calculated after mapping the heat-flux distribution from divertor to midplane.
- $\lambda_{q,mid}$ from XGC1 in the right ball-park with experimental values from two very different tokamak devices
  - ✧ DIII-D for conventional aspect ratio
  - ✧ NSTX for tight aspect ratio
- Broadening of $\lambda_{q,mid}$ by $\gtrsim$1cm blobs is found to be insignificant in the present-day machines.
- Will the blobs survive and saturate the $1/I_p$ scaling when the ion orbit width physics becomes les significant in ITER?

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Motivation and Introduction

- Steep edge pedestal can be susceptible to electromagnetic turbulence and MHD/fluid like modes
- Complete understanding of ELMs may require integrated gyrokinetic simulation
  - There are many features of ELMs that do not resemble MHD/Fluid modes: e.g., ELM precursors, ELMs that are not of Type-I.
  - Interplay among turbulence, ELMs, 3D magnetic perturbation
- We are building a version of XGC1 that can handle turbulence (including KBMs), low-n kink modes, peeling-ballooning modes, low-n tearing modes, etc → **Equilibrium pedestal limit and ELMs**
  - **Phase I: Reduced-MHD type, exclude trapped electron modes.** We are using the Phase-I XGC1 to study E&M modes in realistic tokamak edge plasma
  - **Phase II: Include trapped electron modes** by getting closures from kinetic electrons.
  - **Phase III: Switch completely to kinetic electrons using the hybrid-Lagrangian scheme**

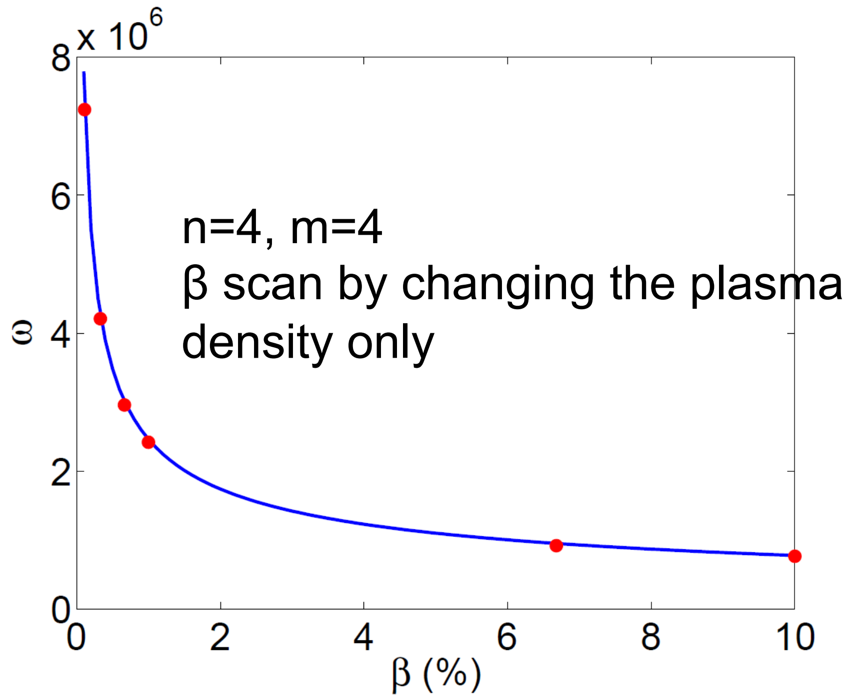
Present Status of E&M in Fluid-Electron XGC1

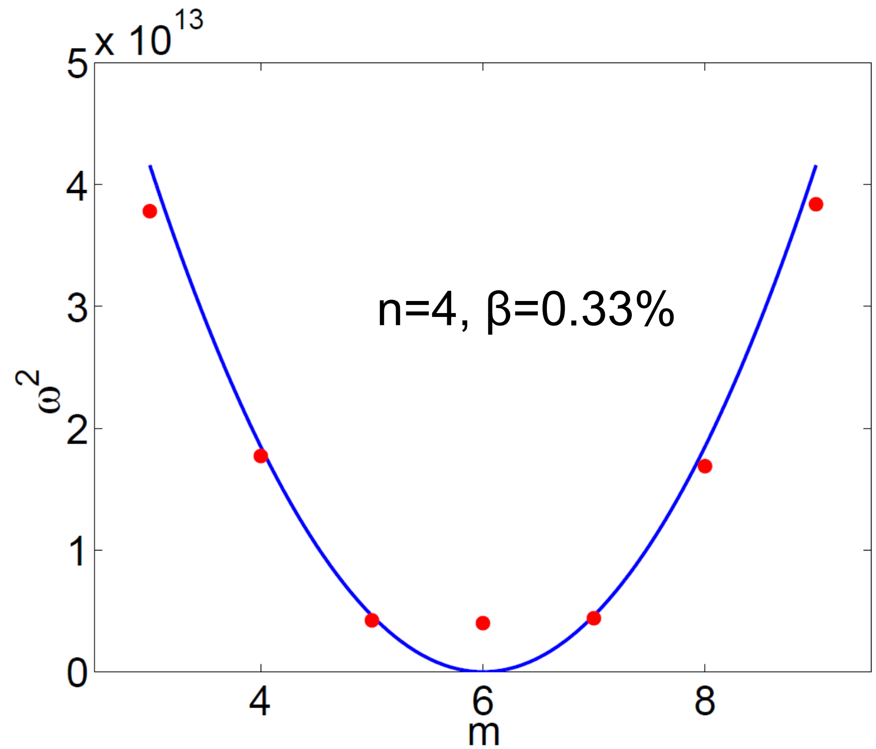
- Verification of linear E&M modes
  - Kinetic shear-Alfven modes
  - Low-n Tearing modes
  - Transition from ITG to KBM

- Edge E&M modes in
  - NSTX magnetic geometry
  - DIIID magnetic geometry

[Reference: Notable Outcome Report, 2015, PPPL]

Verification of shear Alfvén waves (cyclone geometry)





- In the figures shown here, the ion response enters through the polarization response only.
- Cyclone geometry

ITG-KBM Verification in cyclone geometry

- Cyclone base case equilibrium

$$q(r) = 0.854 + 2.184(r/a)^2$$

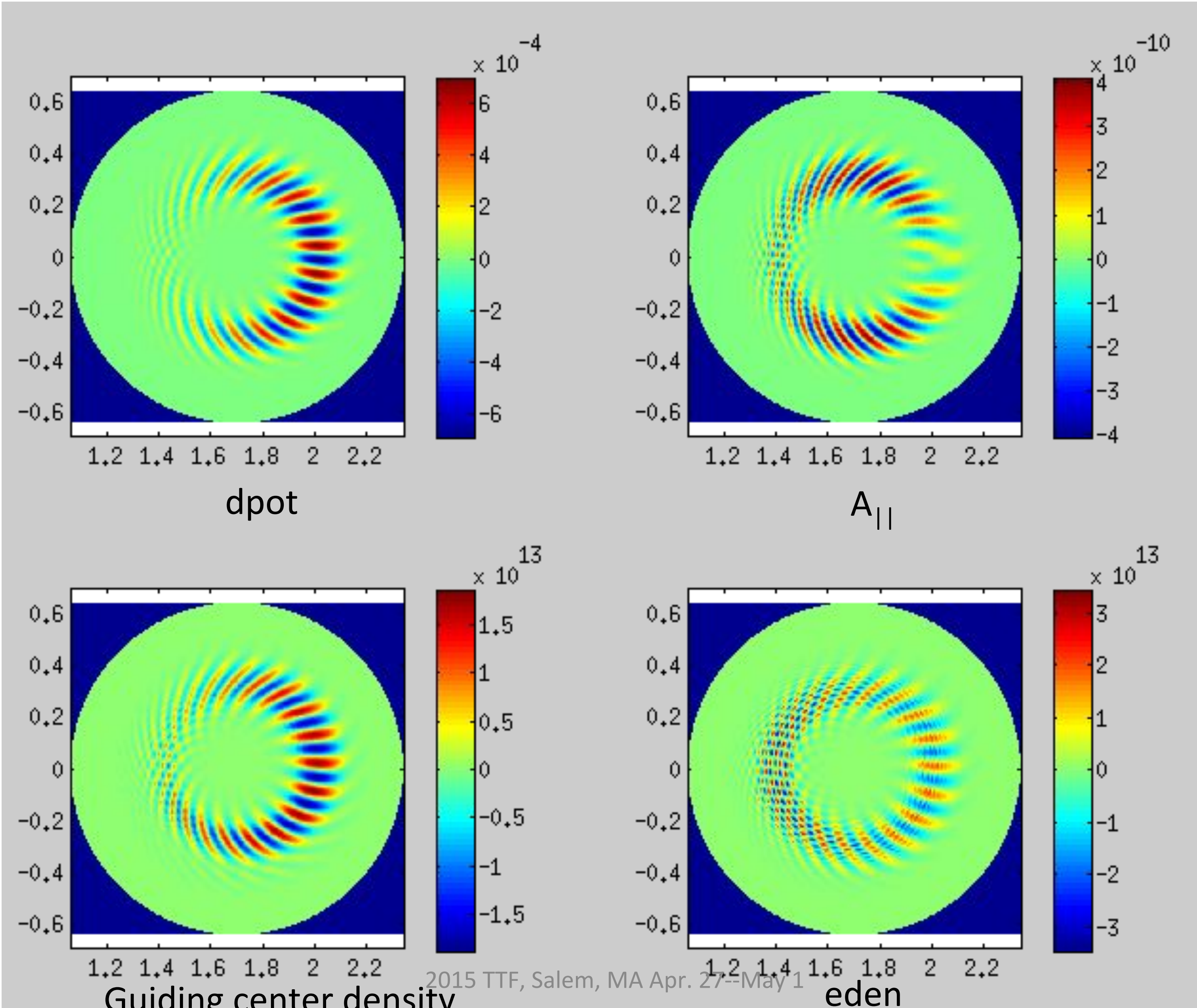
a/R0=0.358 R0/Ln=2.22 R0/LTi=6.92
B0=1.9 T R0=1.7 m Ti=Te=3Kev

- Global single n-mode simulation

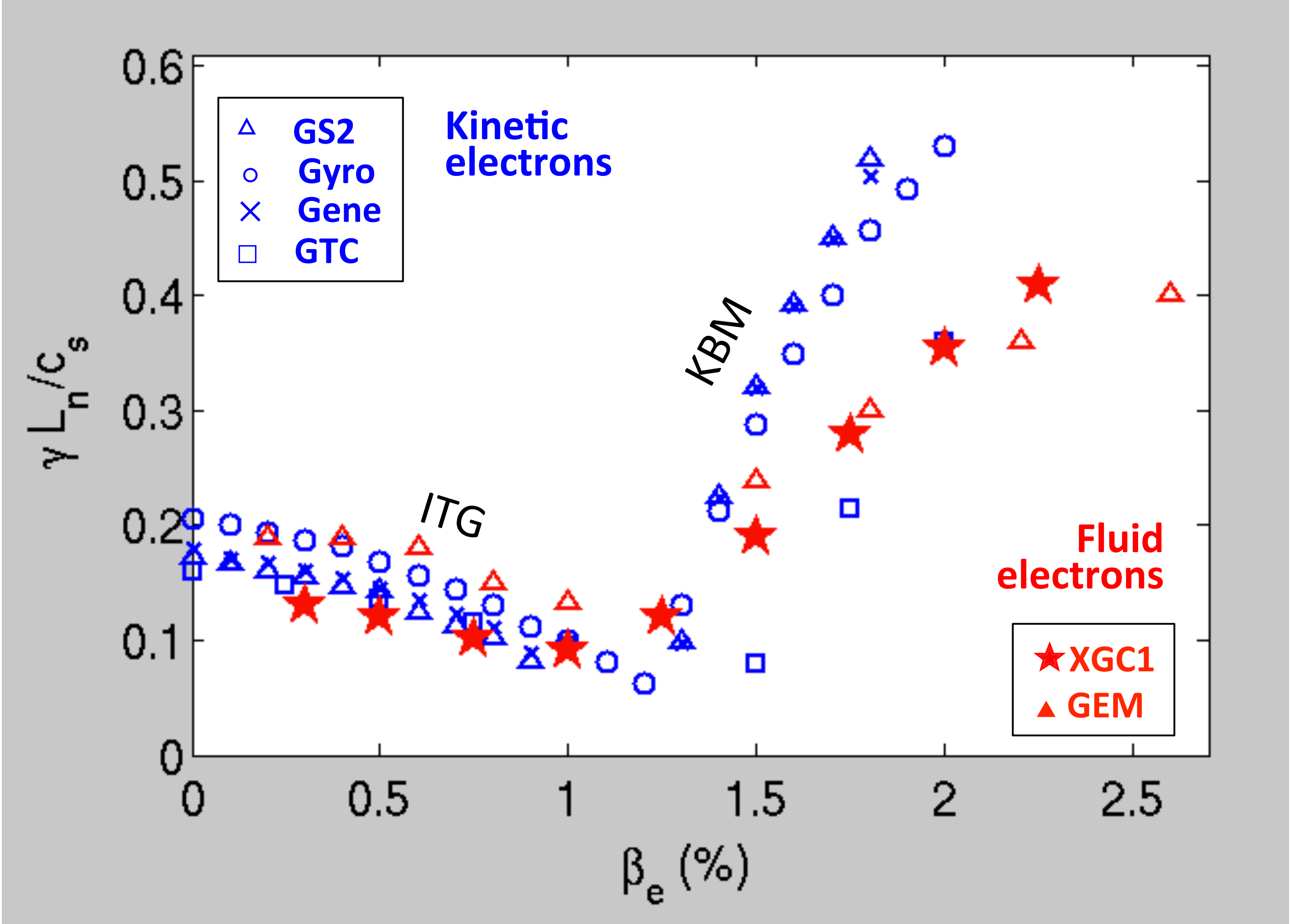
n=15, D ions, 32 poloidal planes. 4mm grid size

- For the β' scan, only plasma density is varied with the plasma gradient and the magnetic equilibrium fixed.

KBM at higher beta (3.33%)

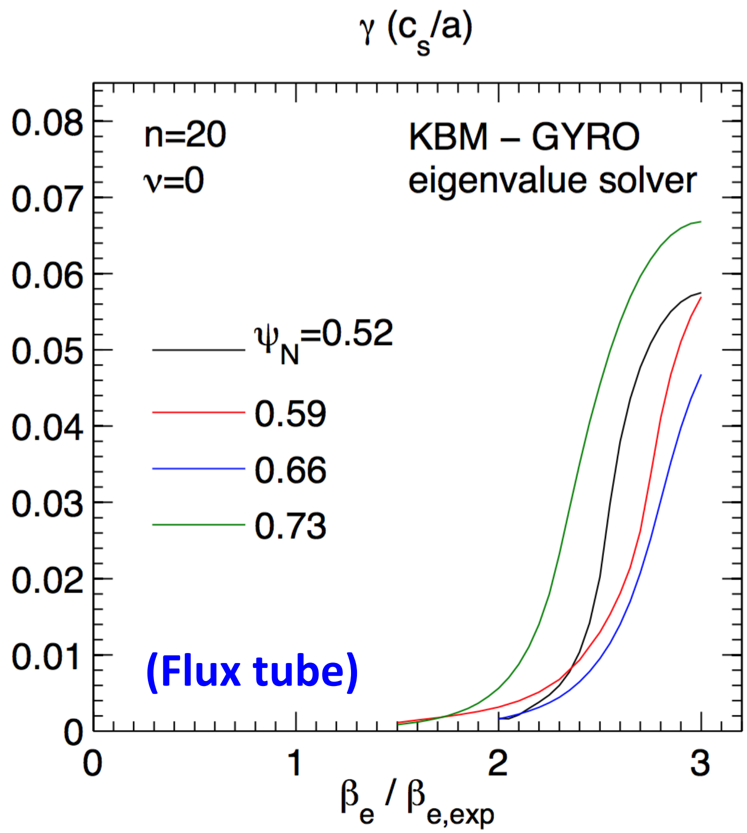


ITG-KBM Transition Verification

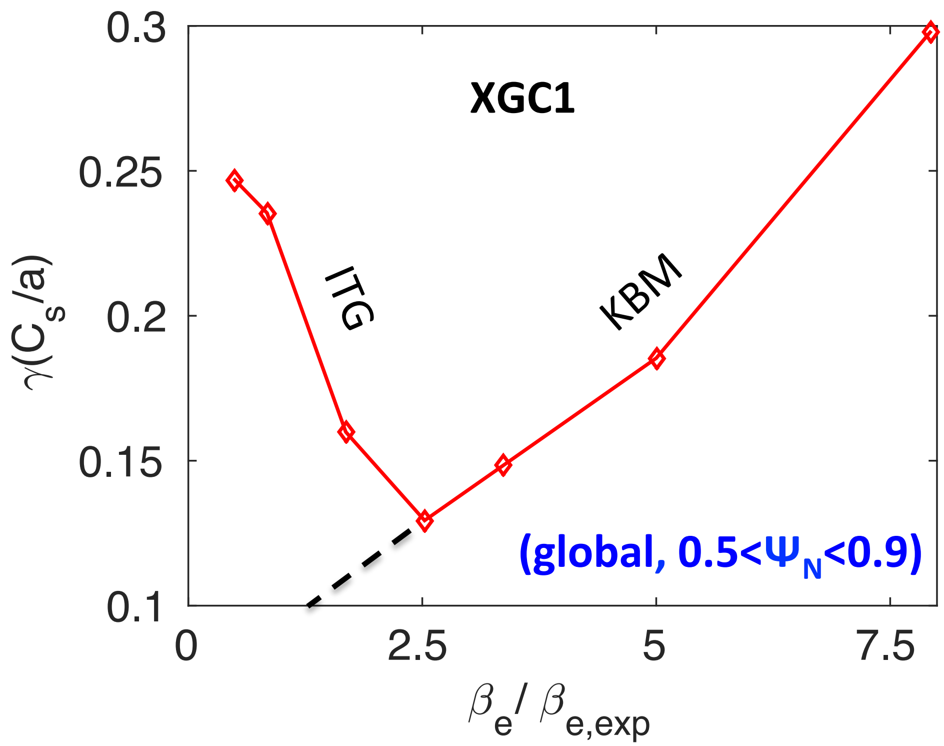


GEM: S. Parker, Y. Chen and C. Kim, *Comp. Phys. Comm.* 127, 59 (2000)
GTC: I. Holod and Z. Lin, *Phys. Plasmas* 20, 032309 (2013)
GYRO: E. A. Belli and J. Candy, *Phys. Plasmas* 17, 112314 (2010)
GS2 and Gene: Moritz Puschel, Thesis (2009)

Gyro's local Eigenvalue solver also shows that KBMs are stable at the NSTX pedestal top at experimental β_e.



Credit: W. Guttenfelder



(Note: If ITGs are weaker, then KBMs could show up at experimental beta.)

Resistive Tearing Modes in XGC1, (m=2, n=1) shown here