Advances in Comprehensive Gyrokinetic Simulations of Transport in Tokamaks

R. E. Waltz, J. Candy, and F.L. Hinton

General Atomics

C. Estrada-Mila

University of California at San Diego

J. E. Kinsey

Lehigh University

2004 FEC IAEA-CN-116/TH/8-2

GENERAL ATOMICS

GYRO is the most physically comprehensive global nonlinear gyrokinetic code

- GYRO is an Eulerian (continuum) [not PIC (Lagrangian)] 5D gyrokinetic code. Development began in 1999 and design milestones completed in early 2003.
- GYRO operates both as a cyclic flux tube code (flat profiles at vanishing ρ_*) or near full radius slice 0 boundary condition global code (profile variation with finite ρ_*).
- GYRO is very versatile with all the physics needed for physically realistic simulations of all transport channels in a tokamak core plasma:
  - toroidal ITG mode physics
  - real tokamak geometry
  - trapped and passing electrons
  - finite beta
  - e-i pitch angle collisions
  - equilibrium sheared ExB and toroidal rotation profiles
  - inputs real experimental profiles

  == “full physics”

Some limitations and fundamentals about GYRO, global gyrokinetic codes, and broken gyroBohm scaling at finite ρ_*

- Standard gyrokinetic & Poisson-Ampere equations assume leading order in small ρ_* only.

  Typically ρ_* and $\tilde{n}/n_0$ < O(1%) [see Frieman & Chen 1982; Antonsen & Lane 1980]

- GYRO consistently retains only this leading order in ρ_* : Thus in GYRO,

  all finite ρ_* effect breaking gyroBohm scaling result from profile variation alone.

- GYRO will likely be inaccurate in a steep gradient pedestal where $\tilde{n}/n_0$> O(10%). Consistently relaxing these small ρ_* approximations likely require 6D Vlasov equations.

- For flat profiles and all ρ_* , global GYRO with 0 BC gives the same gyroBohm scaled transport as the flux-tube GYRO with cyclic BC, i.e. the boundary conditions are "benign".

- With profile variation, going from small to very small ρ_* , the local diffusivity from a global code approaches the the gyroBohm scaled diffusivity from a local flux tube code.

GENERAL ATOMICS

The mystery since the first 1990 IAEA DIII-D experiments:
tokamak transport is always gyroBohm sized, but
_Why are L-modes Bohm scaled at such small experimental values of ρ_* ?
_Why are H-modes (and Ohmic) discharges typically gyroBohm scaled ?

Outline:

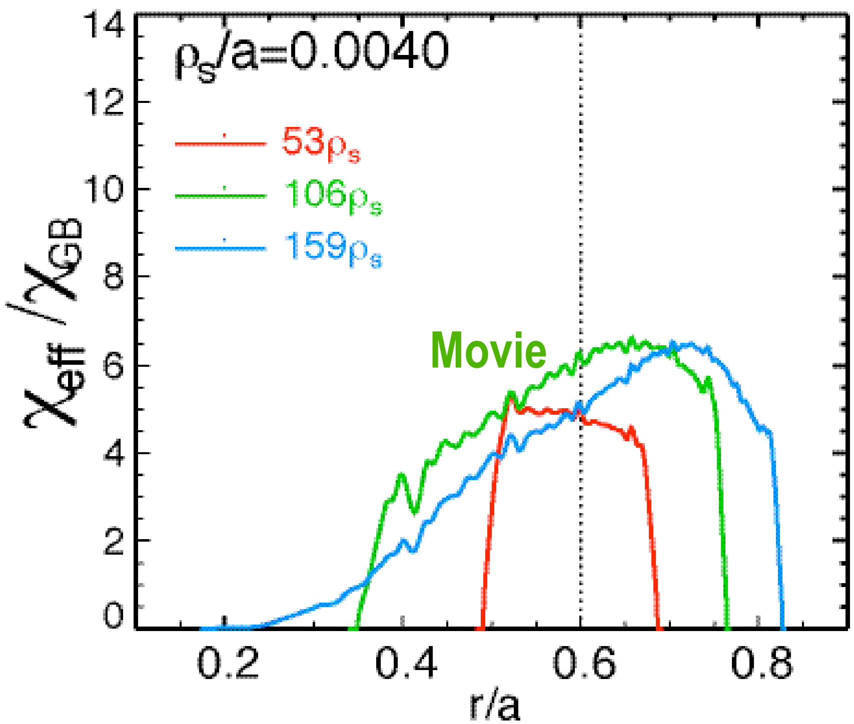
- Realistic simulation of Bohm scaled DIII-D L-mode ρ_* pair
- First steps to a steady state core gyrokinetic transport code
- Mechanisms breaking gyroBohm scaling: local versus non-local
- Heuristic theory/model for non-local transport
- Corrugated flux surface “equilibrium” profiles and local dynamos
- Neoclassical flows embedded in turbulence
- ExB shear quenching of electron driven turbulence
- Plasma and impurity flow pinches

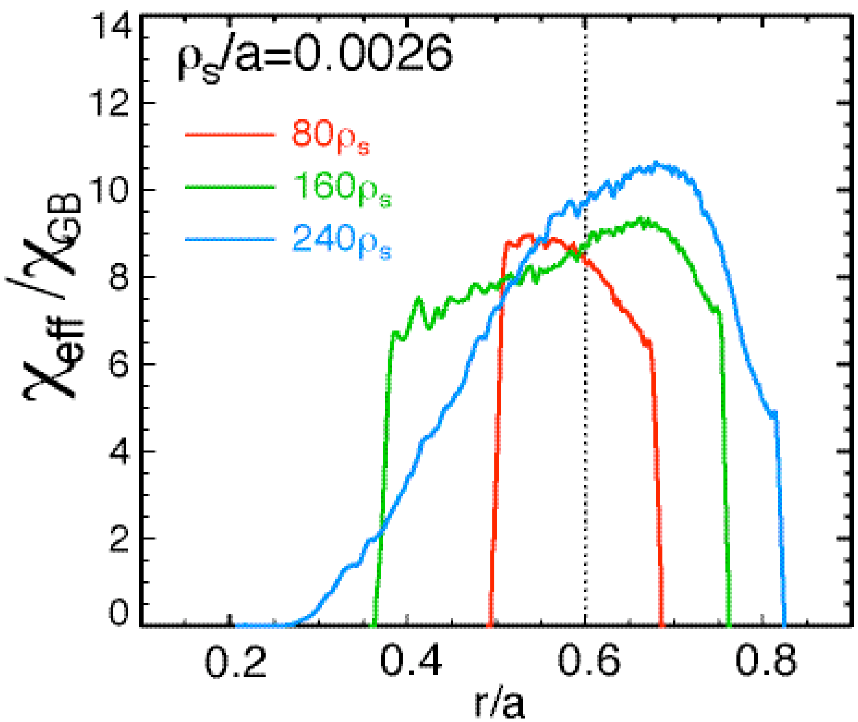
Realistic simulation of Bohm scaled DIII-D L-mode ρ_* pair

Transport at slice center nearly independent of slice size suggests non-local effects are small and not responsible for Bohm scaling here.

$$\chi_{eff} = (\chi_i + \chi_e)/2 \qquad \chi_{GB} = (c_s/a)\rho_s^2 \qquad \rho_* \equiv \rho_s/a \qquad \rho_s \equiv c_s/\Omega_i$$

- **Bohm scaling is** $\chi/\chi_{GB} \quad 1/\rho_*$ $\qquad \rho_*(1.05T)/\rho_*(2.10T) = 0.0040/0.0026 \approx 8/5$

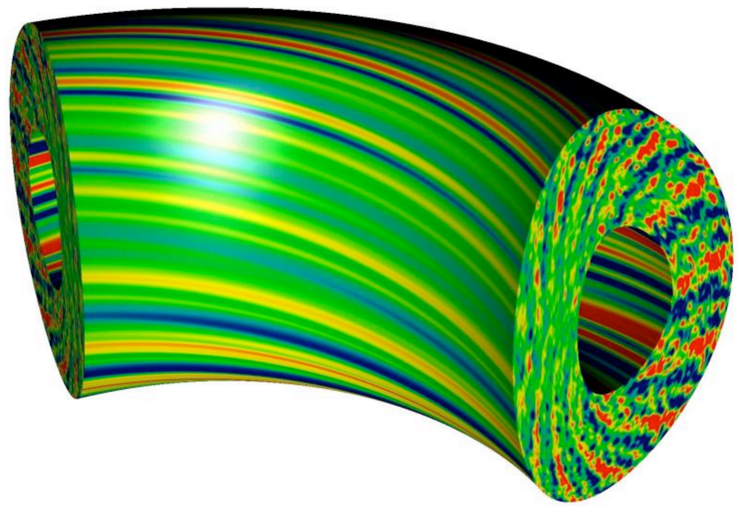




- **"Full physics" except $\sqrt{m_i/m_e}$ =20 not 60 which is difficult for large slices sizes here.**
- **Transport 4x experimental levels for 20 but 2x experimental for physical $\sqrt{m_i/m_e}$ = 60.**

GENERAL ATOMICS

B=1.05T ρ_* = 0.004 medium slice simulation movie



- Movie is DIIID L-mode discharge #101381 with "full physics" except $\sqrt{m_i / m_e} = 20$
- Halo is separatrix
- Stagnation point at r/a=0.6 corresponds to movie reference frame with E_r=0
- GYRO movie downloads at http://Fusion.gat.com/comp/parallel/

GENERAL ATOMICS

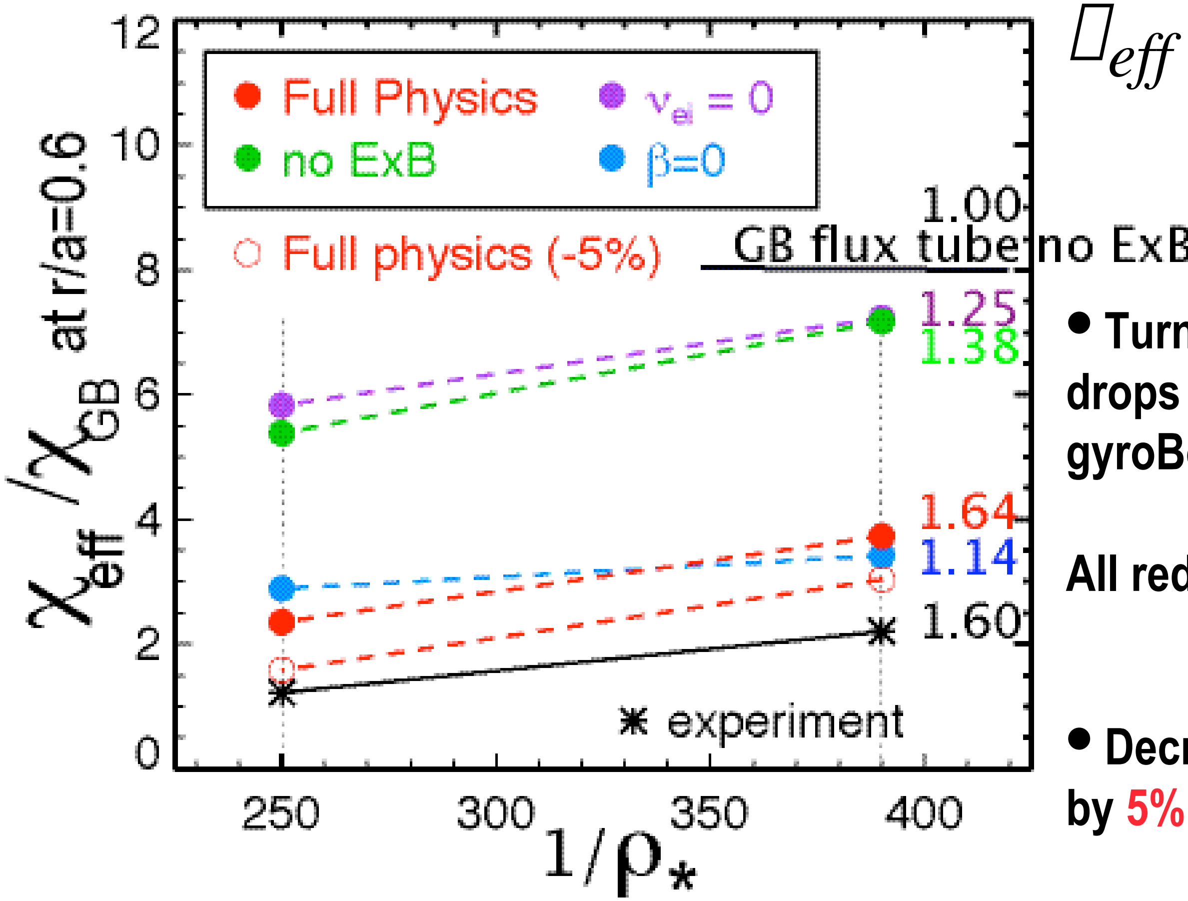
B=1.05T ρ_* = 0.004 medium slice simulation movie

Code: GYRO

Authors: Jeff Candy and Ron Waltz

Get within 2x of experimental diffusivity with Bohm scaling only if retaining “Full Physics” (and real electron mass).

$\sqrt{m_i / m_e} = 20 \to 60 \quad \chi_{eff} / \chi_{GB}\ ratio : 8/5 \to 3.6/2.2$ **= 1.64**



$\chi_{eff} / \chi_{GB}(flux\ \ tube\ \ no\ \ ExB) = 8$

- Turning off ExB, or e-i collisions, or beta drops from Bohm ratio 1.64 toward gyroBohm scaling ratio 1.00

All reduce $\gamma_{net} = \gamma_{max} - \alpha\gamma_E$

- Decreasing the ion temperature gradient by 5% gets to 1.5X exp.

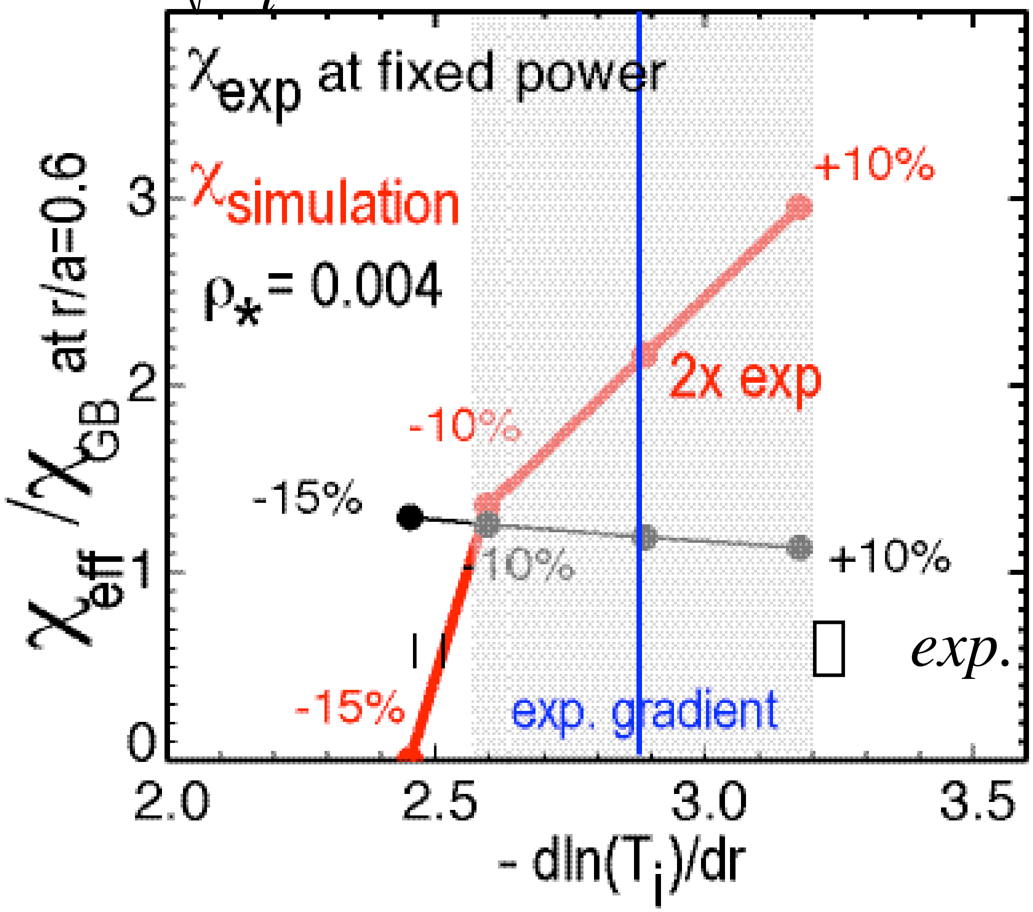
GENERAL ATOMICS

The DIIID core is very stiff:

Transport power flow is very sensitive to temperature gradient.

A small 10% reduction brings simulation into agreement with experiment

$\sqrt{m_i / m_e} = 60$ **"Full Physics"**



$\approx$ *exp. error ?*

- **To fully test a stiff transport model against experiment , one must predict the temperature profile from given experimental power flows;**

rather than

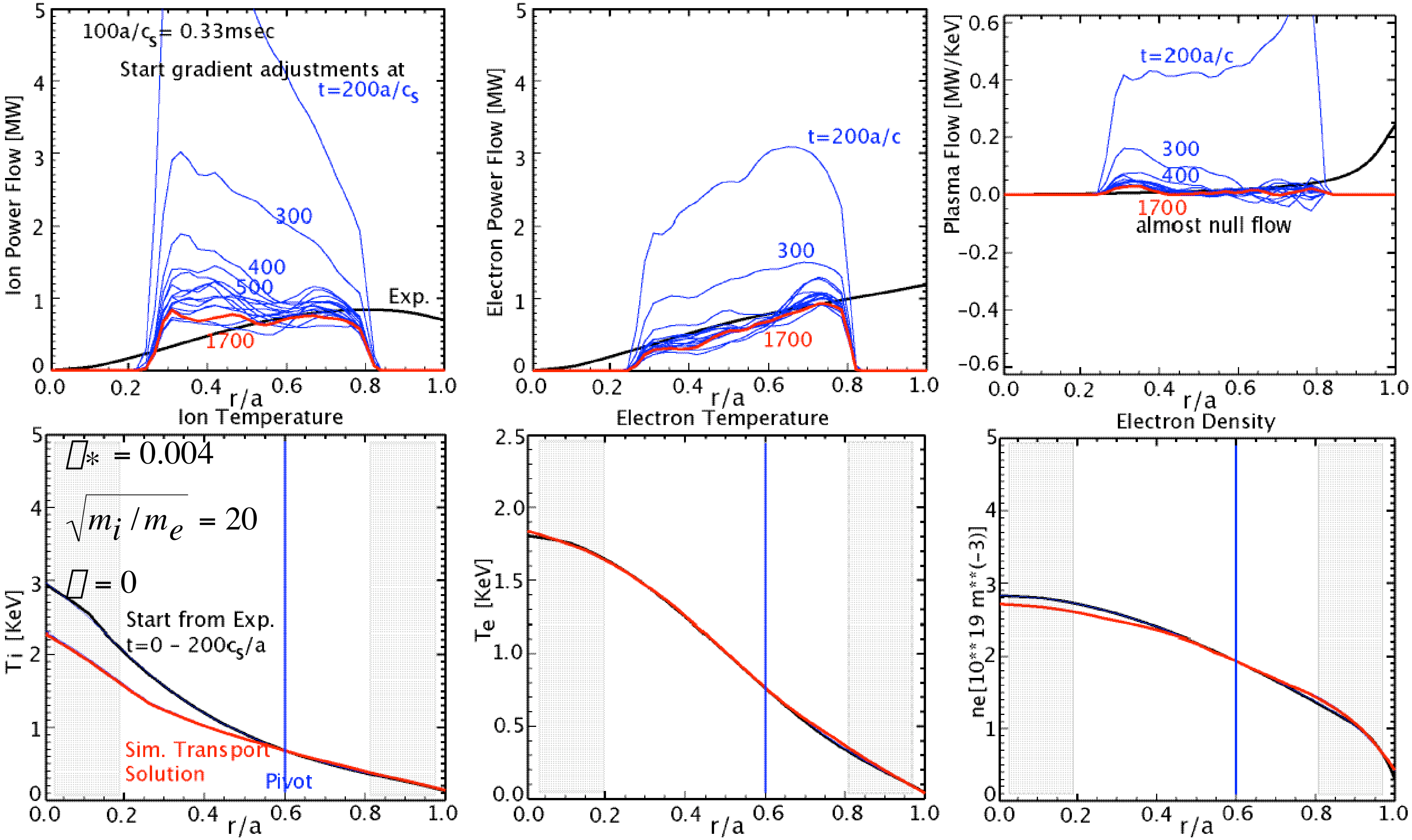
predict the power flow from the given experimental temperature profile.

We need a gyrokinetic transport code !

First steps to a steady state core gyrokinetic transport code

At every radius, use a negative feedback adjustment in the gradients to drive the simulation flows to the experimental flows: $\square grad_{sim} / grad_{\exp} = \square\square_{FB}[flow_{sim} \square flow_{\exp}]/ flow_{\exp}$

Integrate up and down the simulation gradient from a fixed pivot to get the simulation profile.



- Within the next two years, we hope to have a gyrokinetic steady state core transport simulation with self-consistent fusion power for an ITER scale burning plasma given an H-mode pedestal boundary condition.

Local mechanisms breaking gyroBohm scaling

- The profile of maximum growth rate γ_{max} and ExB shear rate γ_E are exquisitely matched, so Bohm scaling is not due to experimental dissimilarity.
- Mode phase velocity shear rates $\gamma_s = |\gamma_* \pm \gamma_E|$ can have a ρ_* dependence.

  When $\gamma_s / \gamma_{max} \sim \rho_* / \alpha \sim O(1)$ there can be a significant stabilizing effect breaking gyroBohm scaling: $\chi \sim \chi_{GB}(1 - \gamma_s / \gamma_{max}) \sim \chi_{GB}(1 - \rho_* / \alpha) \approx \chi_{GB}(\alpha / \rho_*)$

Contrast with empirical Mixed Bohm/gyroBohm Model: $\chi \sim \chi_{Bohm} \alpha / (1 + \rho_* / \alpha)$

- This local shearing mechanism was previously discussed [Waltz et al IAEA 1996] and illustrated with ITG-ae simulations [Waltz, Candy & Rosenbluth APS 2001 and IAEA 2002]

However for the DIII-D L-mode ρ_* pair realistic “full physics” simulation

- The ρ_* dependence of the velocity shearing rate γ_S seems too weak, to quantitatively account for the Bohm scaling.

Non-local mechanisms breaking gyroBohm scaling

- Linear toroidal coupling between singular surfaces gives a non-local mechanism which drains turbulence from unstable regions and spreads turbulence into stable (or less unstable regions).

  This non-local mechanism breaks gyroBohm scaling toward Bohm in the unstable regions:

  $$\chi \sim \chi_{GB}(1 - \rho_* / \Delta)$$

  and toward super-gyroBohm in the stable (or less unstable) regions:

  $$\chi \sim \chi_{GB}(1 + \rho_* / \Delta)$$

- This non-local mechanism was found to give a small breaking effect in ITG-ae simulation using realistic profiles with a central stable core but could account for transport in linearly stable central core plasmas or ITBs [Waltz, Candy & Rosenbluth APS 2001 and IAEA 2002]

- Lin, Hahm et al [APS 2001 and IAEA 2002] using unphysical flat profiles with stable central core and edge, showed Bohm scaled ITG-ae simulations at ρ_* =0.008 (about 2x DIII-D values).

However the DIII-D L-mode ρ_* pair realistic "full physics" simulation had no stable edge and the stable core was not covered by the smaller simulation slices…yet Bohm persisted.

- Thus it seems unlikely to us that this non-local mechanism gives a quantitative explanation.
- Nevertheless non-local effects can be important, and we have developed a heuristic model for including them into gyroBohm local transport models like GLF23 [Waltz et al IAEA 1996]

GENERAL ATOMICS

Summary and Conclusions

- GYRO is the most physically comprehensive gyrokinetic code with the "full physics" presently thought required to realistically simulate core tokamak transport in all channels.
- Bohm scaled transport in DIII-D L-modes in matched ρ_*-pairs has been obtained.
- ExB shear appears to be important in obtaining Bohm scaling in DIII-D L-mode.

  The simulated gyroBohm scaled DIII-D H-modes have much lower ExB shear rates.
- Core transport is stiff. Simulated core power and plasma flows can be matched with to experimental flows with small (10%) adjustments in the ion temperature gradients.
- We demonstrated the first steps to a core gyrokinetic transport code.
- We have investigated both local velocity shear and non-local drainage mechanisms for breaking gyroBohm scaling.

  ……But neither appear to give quantitatively accurate accounts of the Bohm scaling in the realistic DIII-D L-mode simulations.

Other recent conclusions (discussed in paper & poster)

- **Simulations demonstrated a heuristic theory (model) for incorporating non-local transport in local gyroBohm models (like GLF23) . The theory is based on linear toroidal coupling of singular surfaces and the partial formation of global modes broken up by zonal flows.**
- **The model locally averages local growth rates over a length L**

$$L/a \approx 1/[T_{glob}\gamma_E] \approx (\rho_* / \hat{s})(a/R)/[\gamma_{loc}^{net}/(c_s/a)]^{1/2}$$

- **GYRO has shown that the equilibrium flux-surface averaged radial gradient (and divergence) profiles are highly corrugated on the scale of a few ion gyroradii and tied to singular surfaces.**

  "Dynamo" current density corrugations may affect tearing stability but do not produce much net current beyond the neoclassical current voltage relation

- **Ion-ion collisions and the neoclassical curvature drift drive was added to GYRO.**

  Even with large orbit effects (finite ρ_*), the "cross-talk" between turbulent and neoclassical flows appears to be weak.

- **The EXB shear quench rule: $\gamma_E/\gamma_{max} = 2 \pm 0.5$ (s-α geometry) has been extended from ITG to trapped electron mode (TEM) turbulence.**

  For purely toroidal rotation, a large parallel shear rate $\gamma_p = (Rq/r)\gamma_E$ can drive up $\gamma_{max}(\gamma_p)$ faster than γ_E and no quench may result.

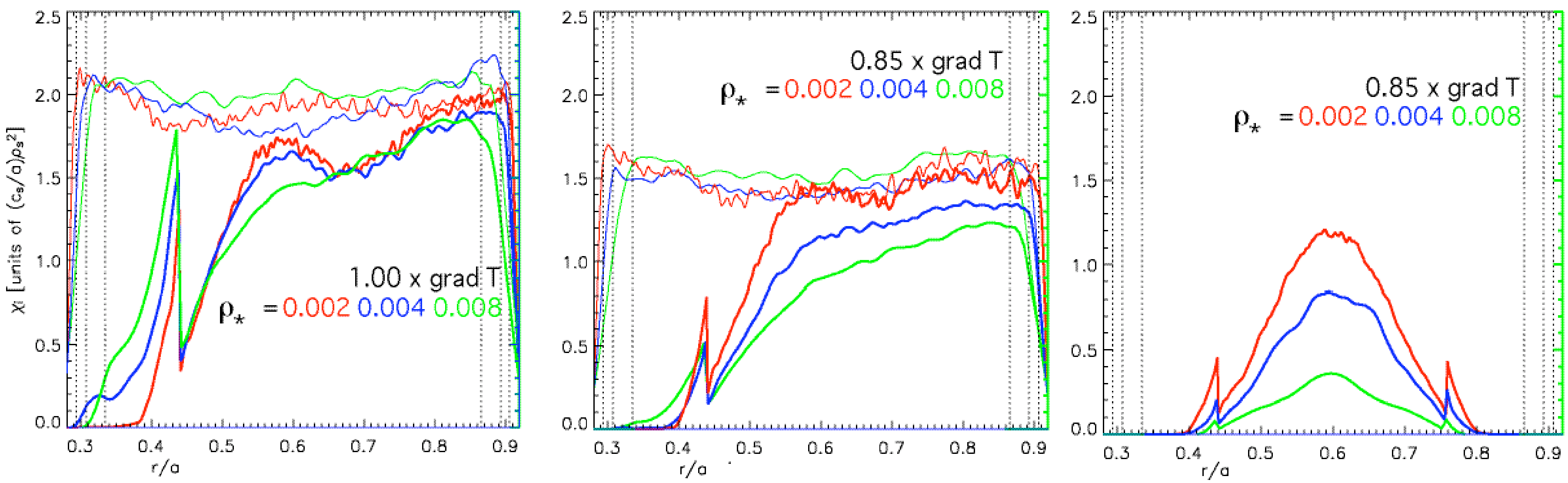
- **Multi-species have been added to GYRO. Thermally pinched plasma flows and impurity pinches are found to be in good agreement with the 1996 GLF23 model.**

GENERAL ATOMICS

Simulations with non-local transport

- Simplified ITG-ae simulations with flat and piecewise flat profiles.

  ……. a/L_T reduced 4-fold in left quarter of radial slice to get a stable region



- Lower driving rate increases the “non-local connection length” L

……….easier to get Bohm scaling nearer to threshold

- Adding an unphysical stable edge region to the right, doubles the drainage from the unstable region and makes Bohm scaling easier to get

Heuristic theory (model) for non-local transport

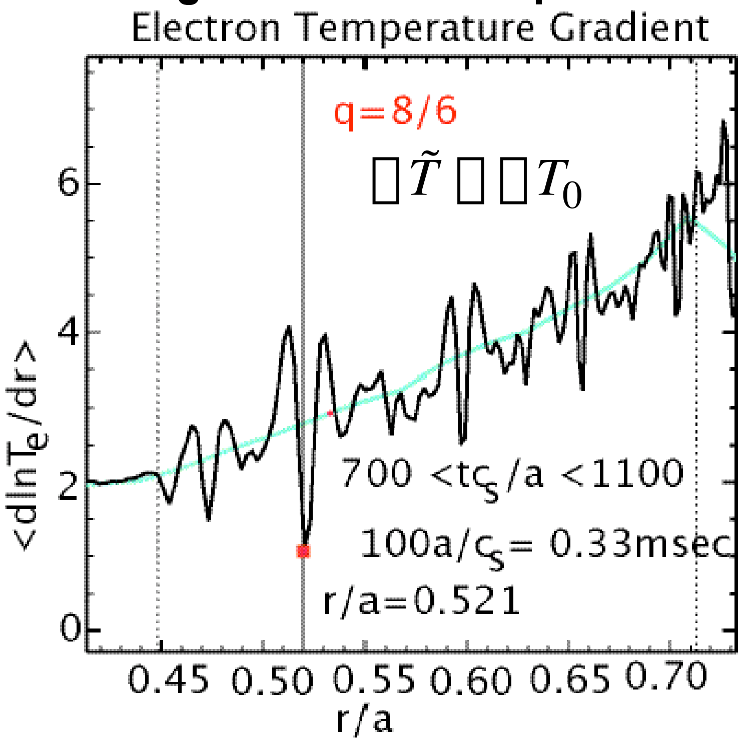
- **Local transport models (like GLF23) use quasilinear theory with the gyroBohm spectral weight** $I_k(x) = [(e|\tilde{\phi}_k|/T_e)/\rho_*]^2 \quad \propto \gamma^{net}_{k\_loc}/[c_s/a]$
- **We propose to replace the local (net) growth rate** $\gamma^{net}_{k\_loc}$ **by a non-local growth rate from radially averaging over the whole plasma (with a localized weight) :**

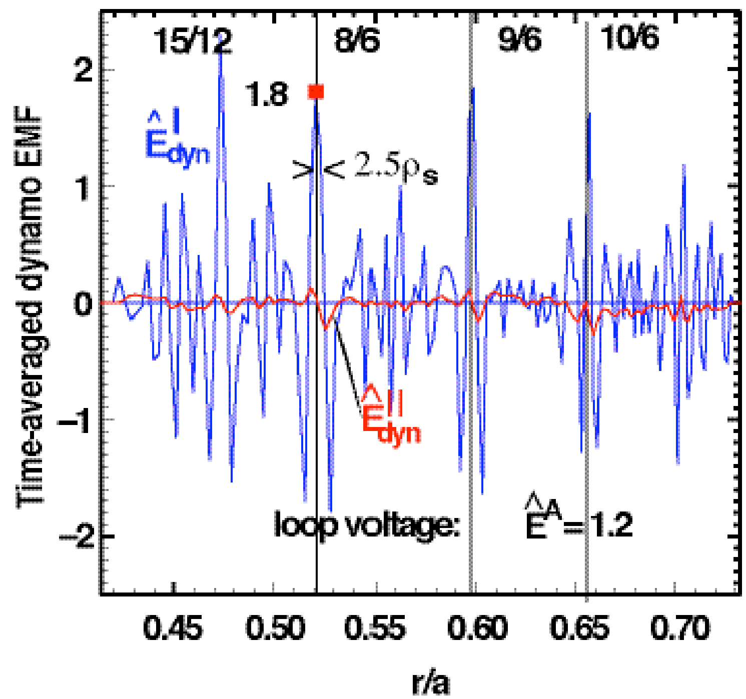
$$\gamma_k^{net}(x) = \int_{-\infty}^{\infty} dx'/[2L(x')]\gamma^{net}_{k\_loc}(x')\exp[-|x-x'|/L(x')]$$

- **BC:** $\gamma^{net}_{k\_loc}(x'<0) = \gamma^{net}_{k\_loc}(0)$ **and** $\gamma^{net}_{k\_loc}(x'>a) = \gamma^{net}_{k\_loc}(a)$
- **If** $L/a \gg$ **then** $\gamma_k(x) \to \gamma_{k\_glob}(x)$ **the global eigenmode growth rate. Both** $\gamma^{net}_{k\_loc}$ **and** $\gamma^{net}_{k\_glob}$ **are independent of** ρ_* **.**
- **But for small** ρ_* **plasmas, global eigenmodes take a long time to form** T_{glob}**, and if the turbulence is more strongly driven, the zonal flows have larger ExB shearing rates** γ_E **and more quickly break up the global modes before they fully form.**
- **Our heuristic theory argues** $L/a \sim 1/[T_{glob}\gamma_E] \sim (\rho_*/\hat{s})(a/R)/[\gamma^{net}_{loc}/(c_s/a)]^{1/2}$ **which explains the piecewise flat profile simulations.**

Profile Corrugations and dynamos

- "Equilibrium" flux-surface averaged radial profiles of gradients (and divergences) are highly corrugated on the scale of a few ion gyroradii.
- The corrugations are "components of zonal flows" tied to low order singular surfaces



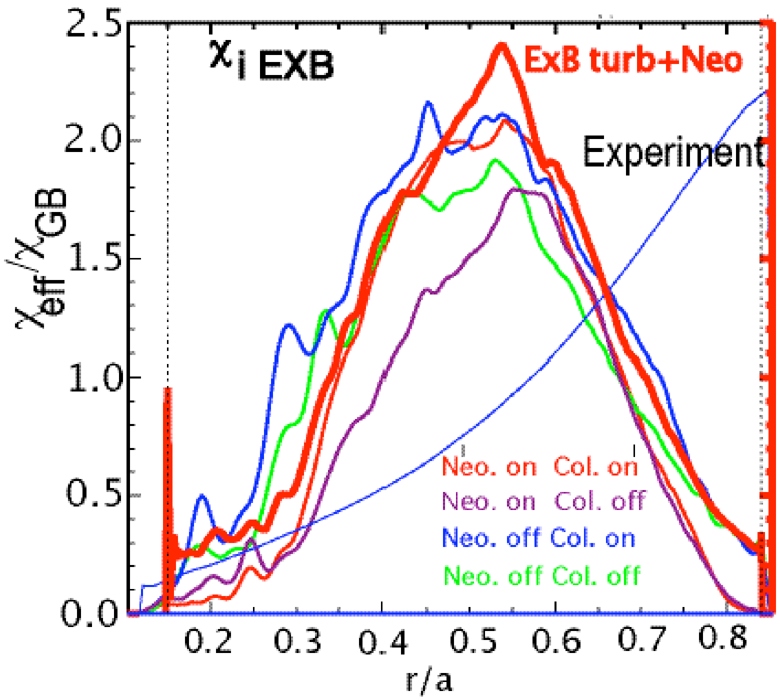


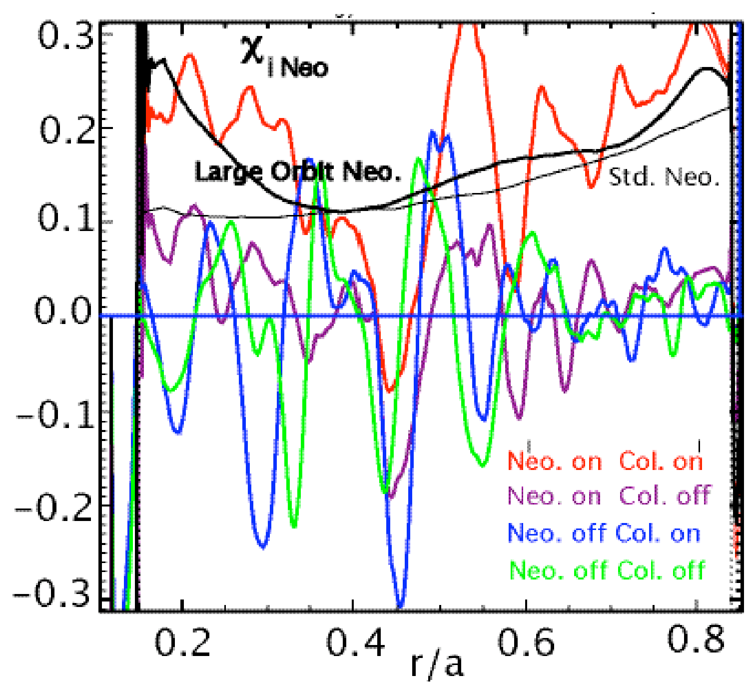
- There are current density corrugations $j_{dyn}/j_0 = E_{dyn}/E^A$ responding to dynamo EMF's which drive little net current but may effect tearing mode stability.
- EMF(I) is from magnetic flutter (like the MHD □ - dynamo) and EMF(II) is electrostatic.

“Cross-talk” between neoclassical and turbulent flows

- **GYRO now has a conserving Krook ion-ion collisions and a neoclassical driver term to n=0 equation giving the O(ρ_*) poloidal deviation to the equilibrium. Neoclassical flows result.**
- **At ρ_* -->0 there is no “cross talk” between turbulent and neoclassical flows….they are additive.**

For finite - ρ_* the cross talk appears to be small if any.





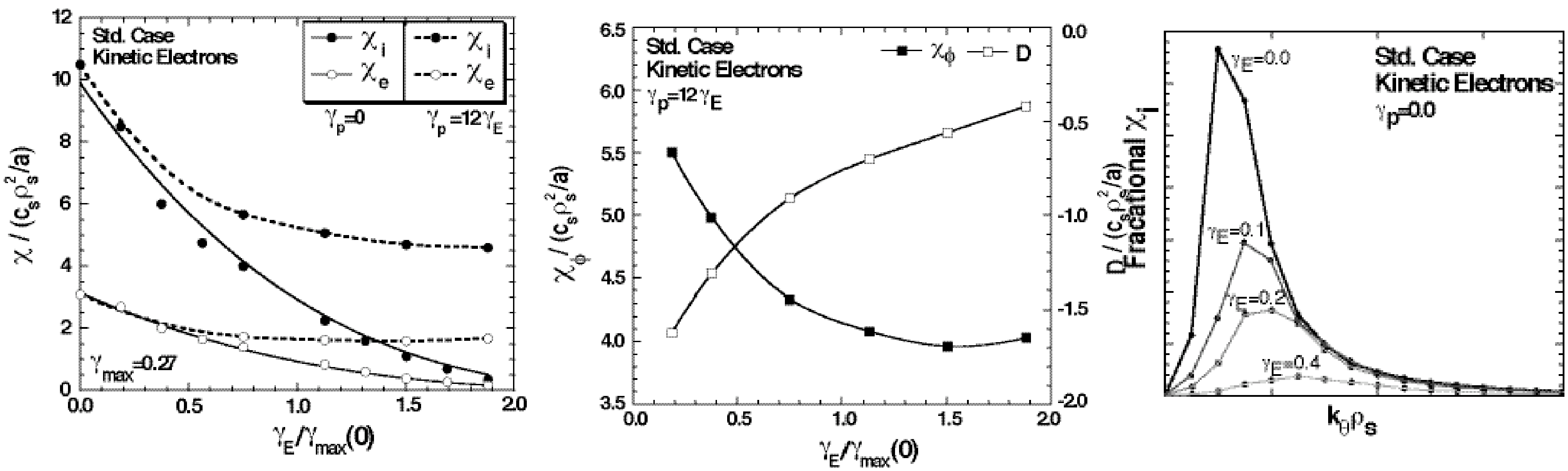
- **The “turbulent” neoclassical flows $\left\langle (\tilde{f} + ze\tilde{\phi}/T)_{n=0} \Box_{Dx}(\Box) \right\rangle$ are radial averages of the large orbit neoclassical flows (which deviate somewhat from the standard ρ_* -->0 flows .**

- **Plasma flow (not shown) is ambipolar (with conserving Krook and non-adiabatic part only)**

EXB shear quenching and trapped electron driven modes

- **The EXB shear quench rule: $\gamma_E / \gamma_{max} = 2 \pm 0.5$ (s-α geometry) has been extended from ITG to trapped electron mode (TEM) turbulence: GA-Std case $a/L_T = 3, a/L_n = 1, R/a = 3, q = 2, s = 1$**

  For purely toroidal rotation, a large parallel shear rate $\gamma_p = (Rq/r)\gamma_E$ can drive up $\gamma_{max}(\gamma_p)$ faster than γ_E and no quench may result.

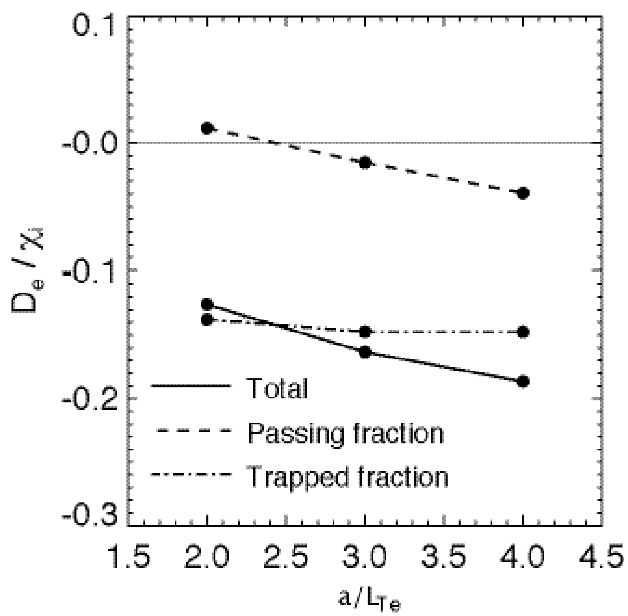


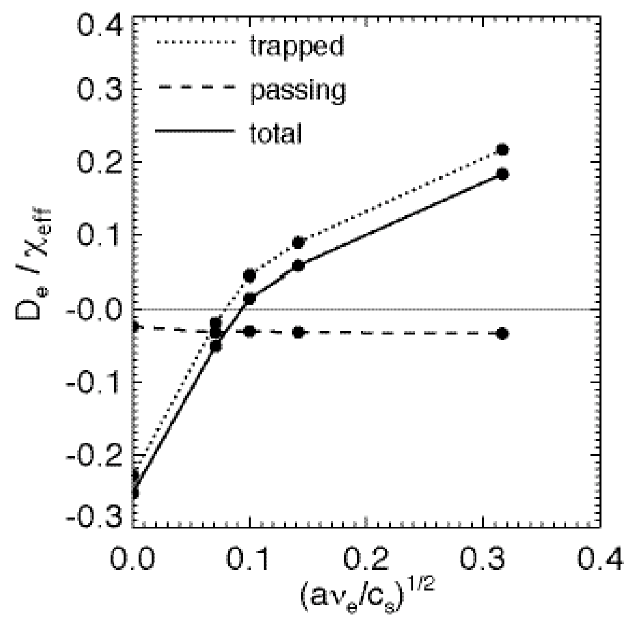
$\gamma_p = \gamma_E = 0$	L_n / L_T	$[\gamma_{max}, \omega]$	χ_i / χ_{GB}	χ_e / χ_{GB}	D / χ_{GB}
ITG-ae	3/1	0.13, -0.31	3.54 ± 0.37		
ITG/(TEM)	3/1	0.27, -0.33	10.7 ± 2.6	3.2 ± 0.6	-1.9 ± 0.5
ITG/TEM	2/2	0.28, -0.014	11.0 ± 2.2	11.3 ± 2.2	4.0 ± 0.8
TEM	2/3	0.43, +0.029	23.9 ± 3.7	27.7 ± 4.5	5.6 ± 0.9

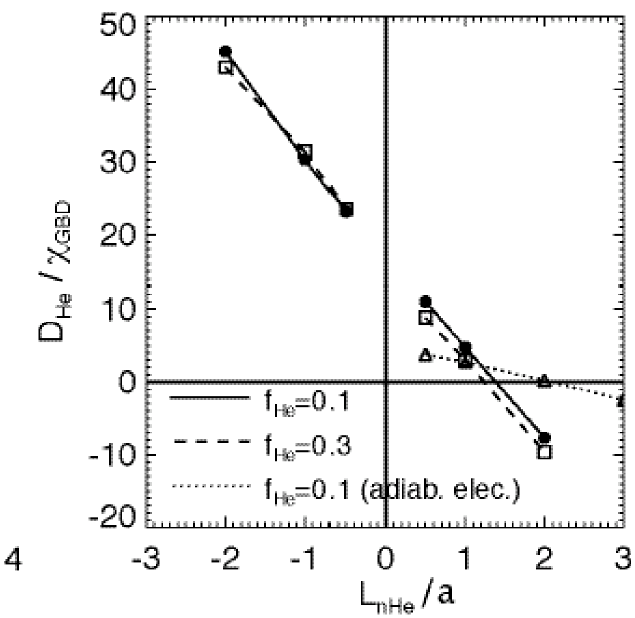
Plasma and impurity flow pinches

- Multi-species have been added to GYRO. Thermally pinched plasma flows and impurity pinches are found to be in good agreement with the 1996 GLF23 model.
- Pure plasma thermal pinch driven by trapped electrons.
- Adding e-i collisions move null flow point to higher $\eta_e = L_n / L_{Te}$

  The thermal pinch allows some peaking of null flow cores.
- Helium transport described by D-V paradigm: $\Gamma_{He} = D_{He} n_{He} / L_{He} = n_{He} [D^d{}_{He} / L_{He} - V_{He}]$







GA Std. Case: $a/L_T = 3, a/L_n = 1, R/a = 3, q = 2, s = 1$

GENERAL ATOMICS