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Comprehensive Gyrokinetic Simulations of Tokamak Turbulence at Finite Relative Gyroradius

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Introduction and Motivation

- Global gyrokinetic code GYRO contains all physics of low frequency (<< ion cyclotron) plasma turbulence assuming only that the ion gyroradius is less than magnetic field gradient length
  - Nonlinear and basic ITG with adiabatic electrons
  - Electrons (trapped and passing) electromagnetic and finite β
  - Collisions
  - Real tokamak geometry
  - Finite ρ^*
- Continuum (fluid-like) methods in 5-dimensional space $(r, \theta, n, \varepsilon, \lambda)$
- 2-modes of operation:
  - flux-tube with cyclic boundary conditions
    to be compared with Dorland 's gyrokinetic flux tube code GS2 effectively ρ^* -> 0
    No ExB or profile effects but otherwise identical physics and capability
  - full radius or wedge -tube with non-cyclic BC and Δn=5-10 ρ^* small but finite
- Why global full radius? Shear in the ExB velocity known to have a powerful stabilizing effect. But shear in the diamagnetic velocity can be just as large and cannot be treated at ρ^* = 0. Flux-tube codes at ρ^* -> 0 have only gyroBohm scaling and no non-local effects.

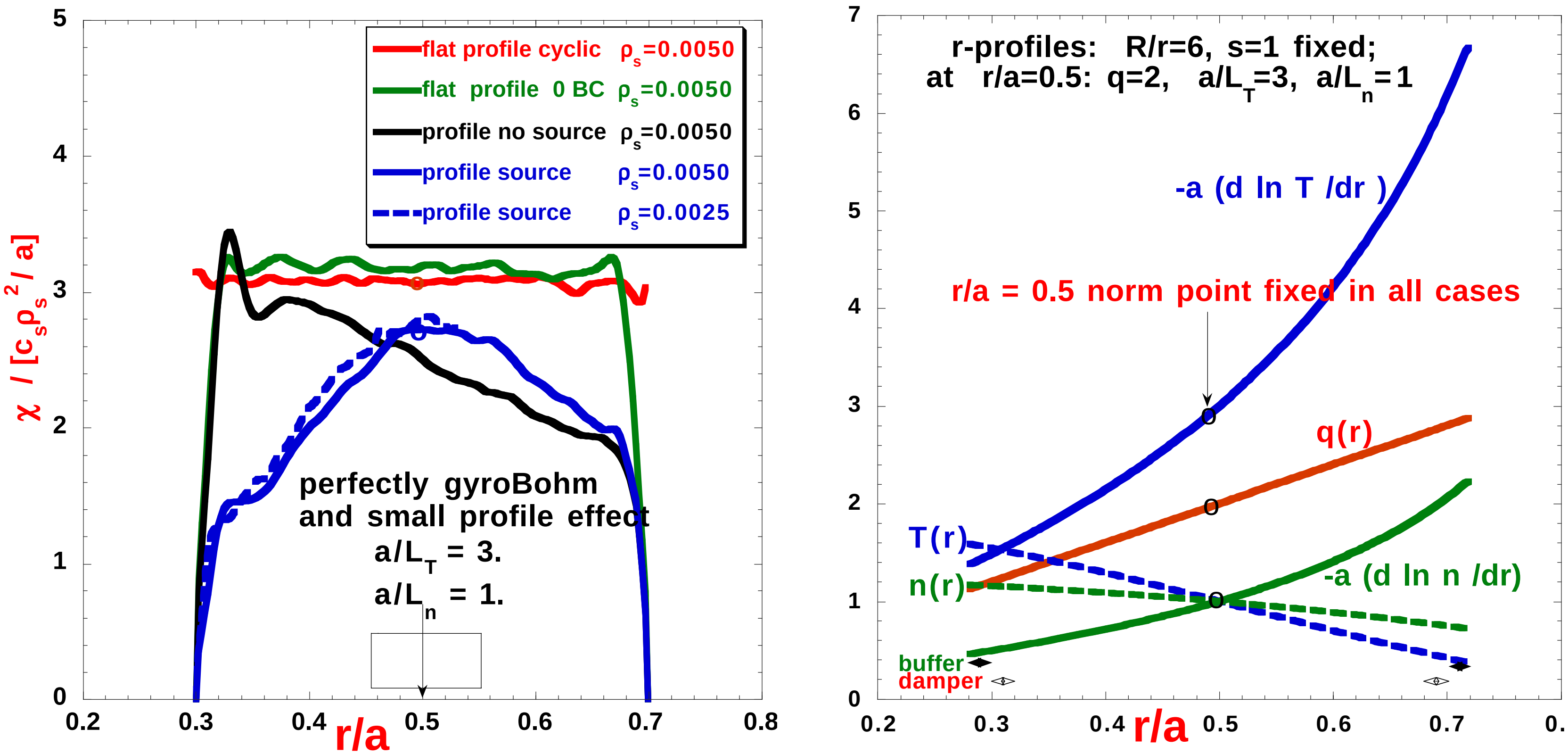
Key questions addressed

- How and where does shear in the diamagnetic mode phase velocities ($\gamma_{shear} \propto \rho*$) break gyroBohm scaling to Bohm or worse?
  - Basic paradigm from Garbet and Waltz (APS '95):

    Velocity shear comparable to linear ballooning mode rate ($\gamma_{shear} > \gamma$) stabilizes, hence expect gyroBohm scaling well above threshold but Bohm or worse near threshold (small γ) with strong shear. There is no single power law in $\rho*$.

    $\chi_{gB} = \rho*\chi_B$ and $\chi \propto \chi_{gB} (1 - \rho* / \rho*_{crit})$ with $\rho*_{crit} = 1 - L_T / L_{Tcrit}$
  - How do correlation lengths and times scale in a Bohm regime?
- Technical questions:
  - How do flux-tube simulations compare with non-cyclic BC simulations without profile variation, i.e. can we find " benign boundary" conditions ?
  - When adding profile variation, do we need to add sources?
  - How large must the radial simulation slice be to get an accurate measure of the local χ ?
- How "local" is turbulent diffusion? Is there any *"action at a distance"* ?
- Initial restriction to ITG with adiabatic electrons s-α circular geometry.

Noncyclic BC radial slice reproduces gyroBohm flux tube diffusion at the slice center for weak profile shear



- 80 ρ_s noncyclic BC radial slice with flat profiles identical to cyclic flux tube gyroBohm result hence zero-value BC with external edge buffer and damper zones are "benign"
- Adding weak profile variation with sources shows only slight profile stabilization and remains gyroBohm at ρ_s = 0.0050 -> 0.0025 (Typical DIII-D)

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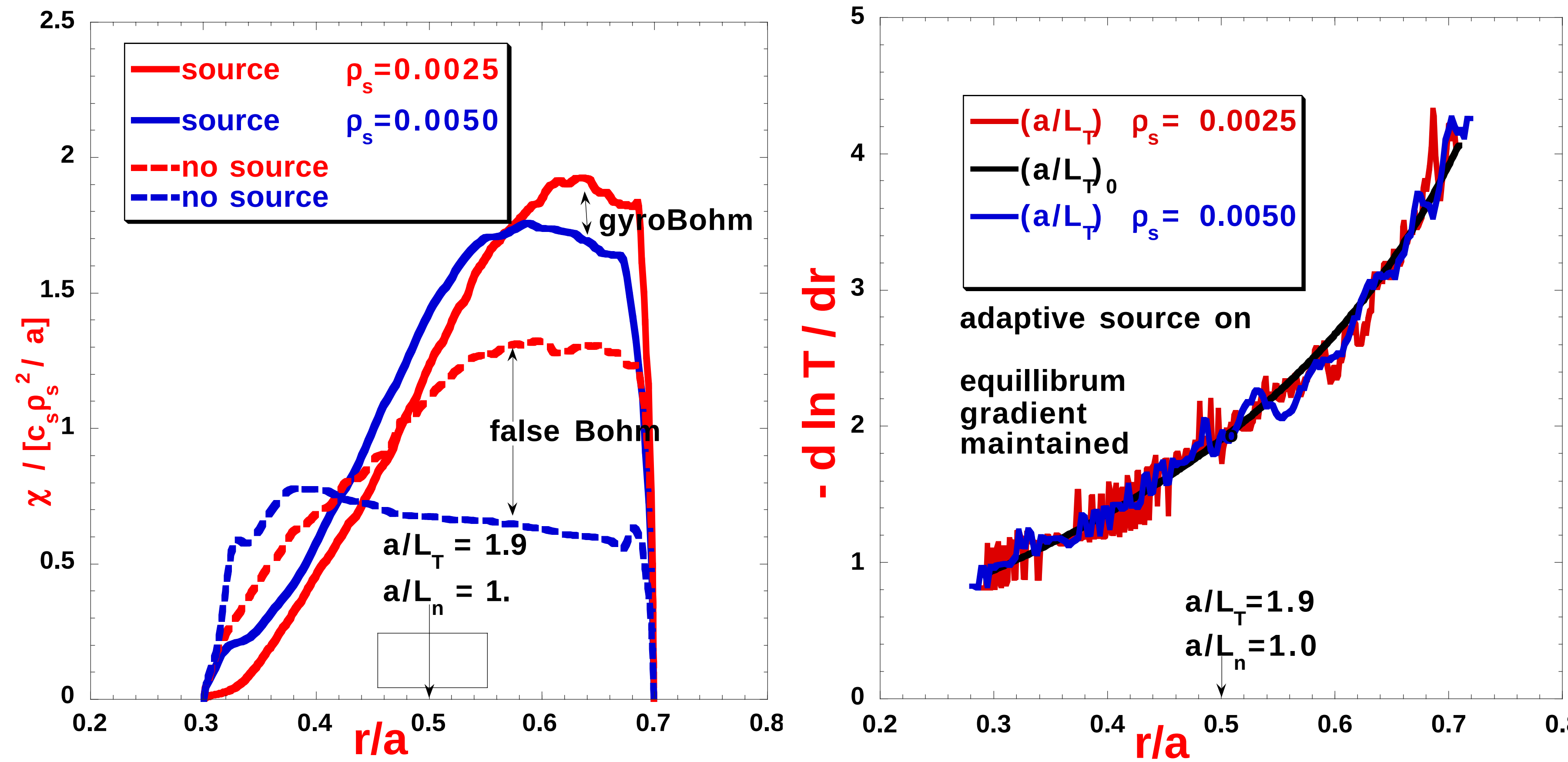
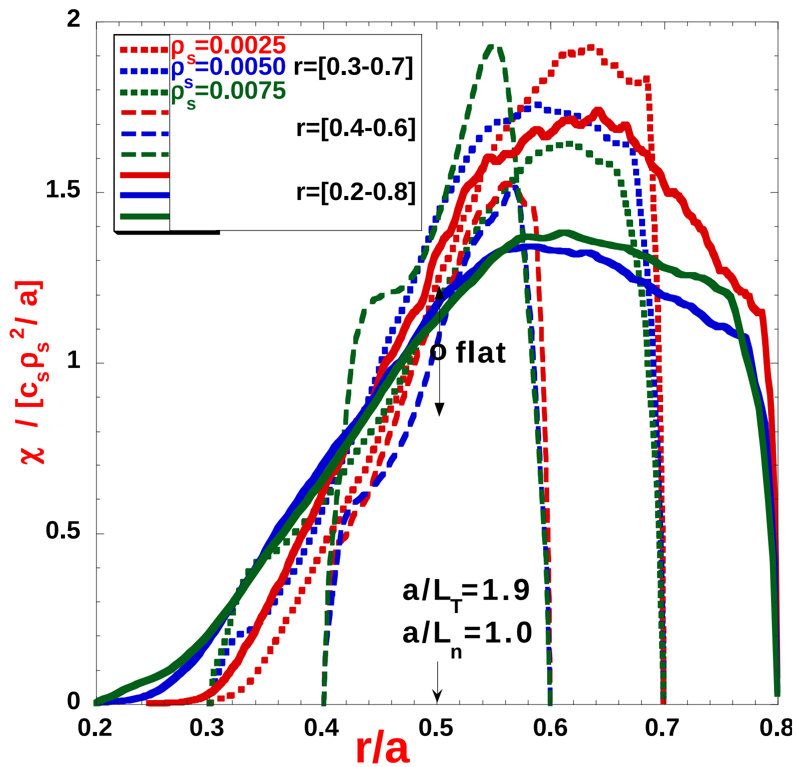
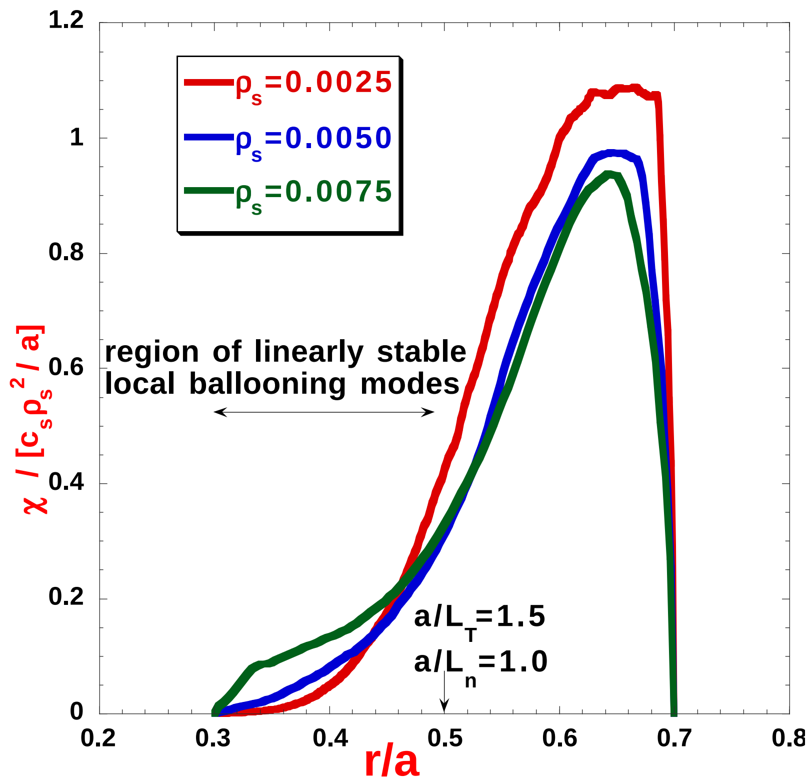
Need adaptive source to prevent “false Bohm scaling”



- Small ρ_s scaled deviations from the equilibrium profiles caused by the n=0 perturbations in the absence of sources can cause "false" Bohm scaling nearer threshold.

Slice approach valid: χ at the norm pt. is unchanged with slice size



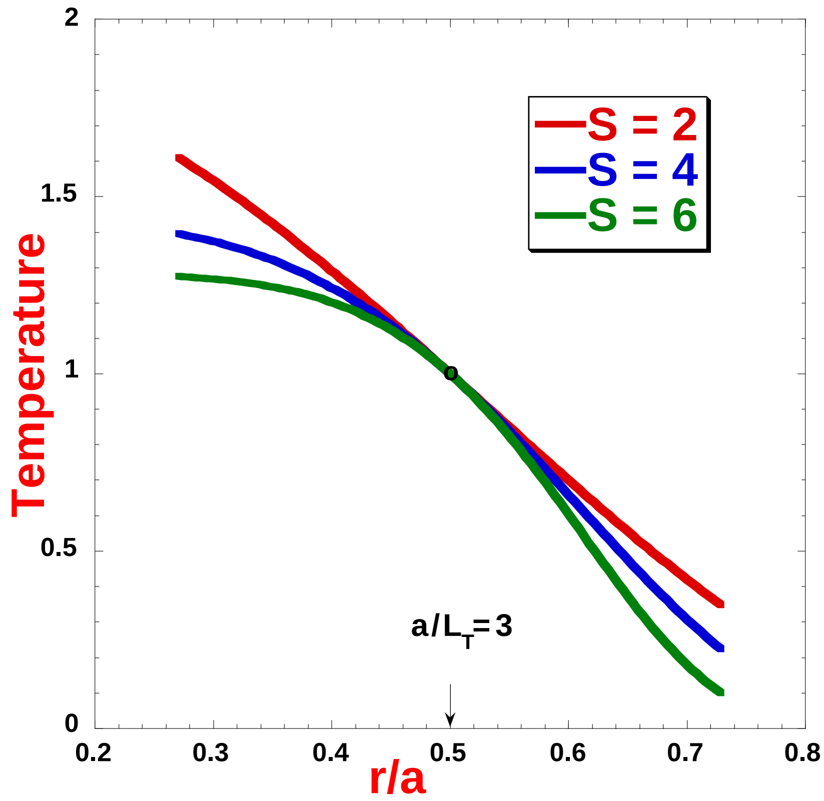


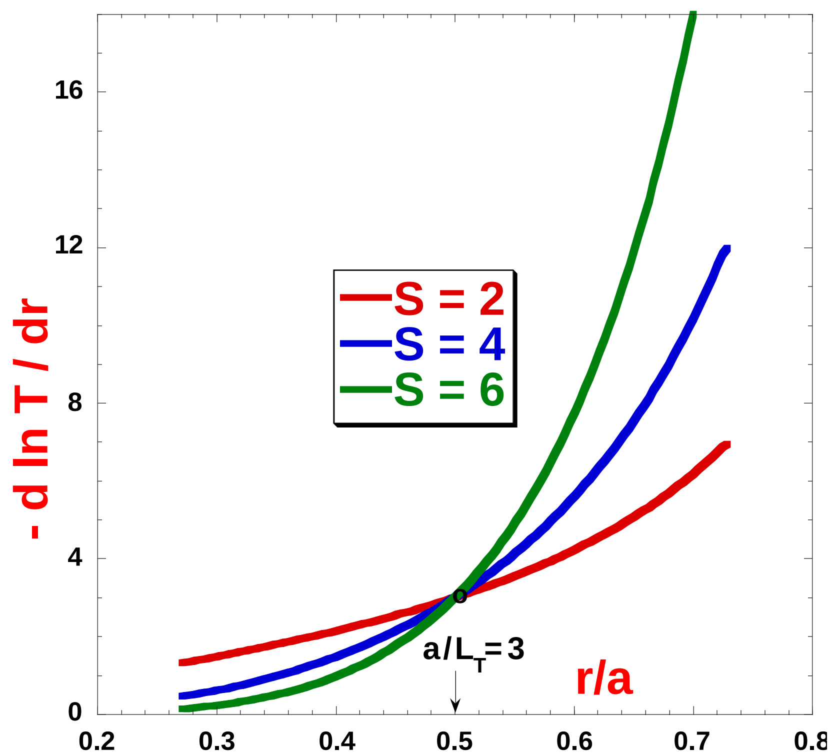
- **In cases without significant profile shear, gyroBohm scaling can persist even close to threshold (a/L_T = 1.9) although we can see a non-local subcritcal turbulence effect at threshold (a/L_T = 1.5) .**

To find Bohm scaling, we increase the density gradient which lowers γ_{max} and increases diamagnetic ExB shear, and we increase the profile shearing S from 2 to 4 and 6

$T(r) = T_0 (1 - r/a^S)^{\alpha_T}$, $n(r) = T_0 (1 - r/a^S)^{\alpha_n}$ keeping a/L_T and a/L_n fixed at r/a =0.5

(a/L_T=3, a/L_n=1) - > (a/L_T=3, a/L_n=2 .5) decrease η_i from 3 to 1.3 & γ_{max} from 0.13 to 0.06





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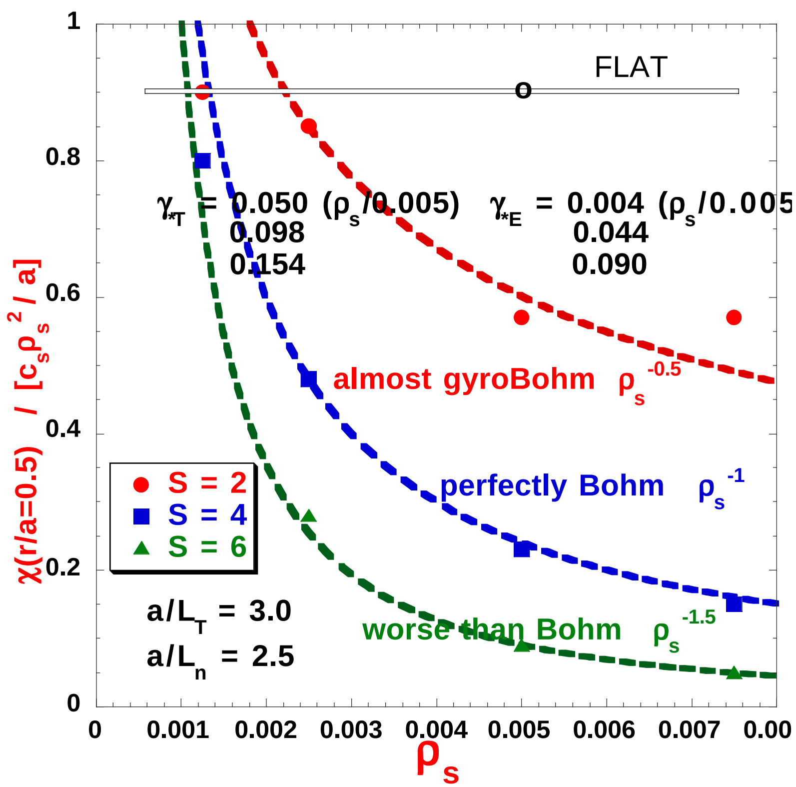
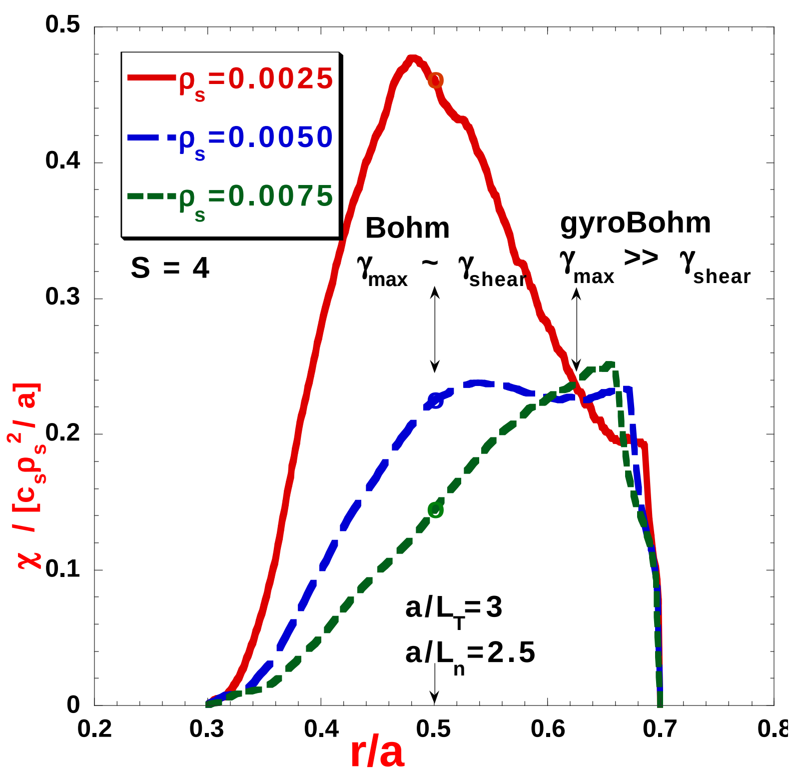
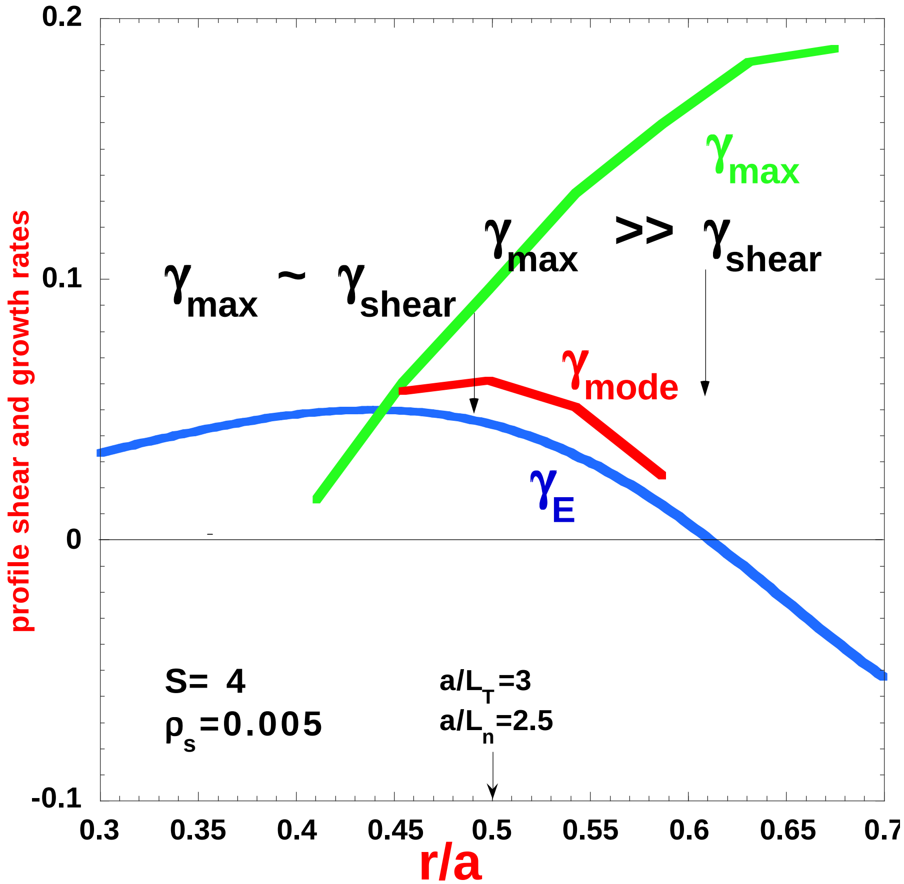
- **Bohm scaling or worse results at the norm point r/a= 0.5 with increased shearing S =4 ->6**
- **At weaker shear and small ρ_s, approach gyroBohm scaled "flat" (no profile) results**
- **GyroBohm scaling still results where profile shearing rates are weak $\gamma_{shear} < \gamma_{max}$**





- Shearing rate approached growth rate only near norm point r/a= 0.5



$$\gamma_{shear} \sim \gamma_{mode} \equiv r/q \;\partial (q/r \; V_{mode\ phase}) / \partial r$$

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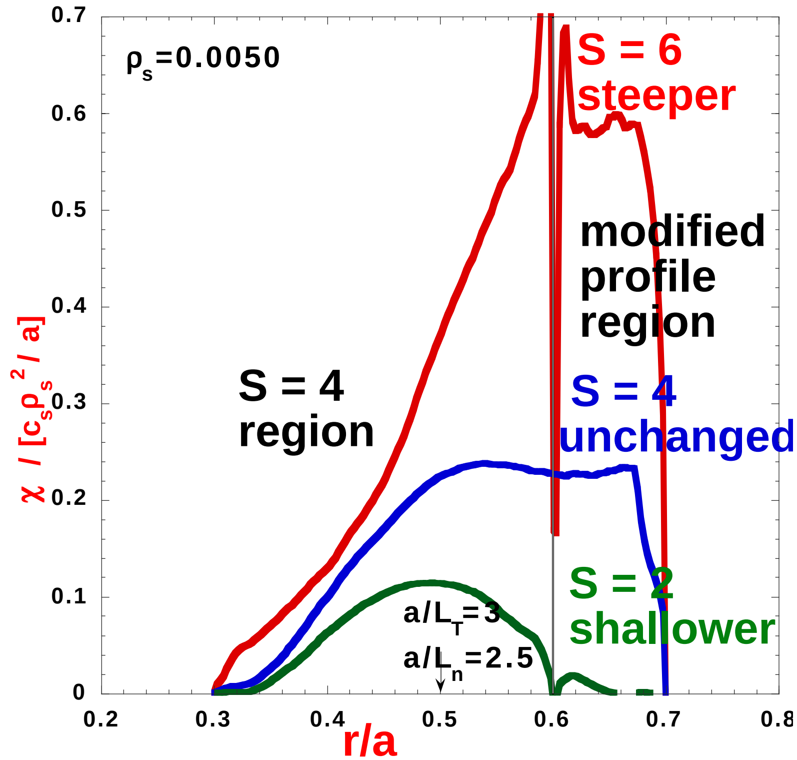
Nonlocal transport "action at a distance" possible



- **Modifying the temperature gradient at a distance of 10x the correlation length can change the local transport in a Bohm scaled regime**

The transport levels are more than 10x lower than where we started at S=2 , a/L_T = 3 , and a/L_n = 1.

Speculate that the non-local effect is mediated by the temperature perturbations associated with the n=0 zonal flows

Conclusions from ITG adiabatic electron simulations

- We have found "benign" noncyclic BC for a radial slice which reproduces the flux tube.
- An "adaptive" source keeps the radial slice equilibrium profiles fixed and prevents "false" Bohm scaling from the build up of long-wave n= 0 zonal flows
- For moderate profile variation, small density peaking, and weak profile shear ($\gamma_{shear} < \gamma_{max}$)
  - profile stabilization is weak and gyroBohm scaling results, and
  - low level transport can be obtained at inner stable radii when outer radii are unstable.
- For strong profile variation, peaked density gradients, strong ExB profile shear ($\gamma_{shear} \approx \gamma_{max}$)
  - profile stabilization is strong and Bohm scaling (or worse) can result
  - although gyroBohm (no profile flux tube-like) results can be approached at low ρ^*
  - Bohm scaled diffusion has τ_c independent of ρ^* and $L_c \propto \rho_s^{0.5}$
- "action at a distance" obtained near threshold

Newest work with comprehensive physics

- Since previous study with ITG adiabatic electrons in s-α circular geometry, we are now treating actual DIIID profiles form the L- mode rho-star scaling experiments with full physics capability of GYRO.
- In particular we have
  - Electrons (trapped and passing), electromagnetic and finite β with collisions.
  - Real tokamak geometry with Miller local equilibria input from experiment.
  - Toroidal velocity profiles for parallel shear driving Kelvin-Helmholtz ITG
  - Computed toroidal viscosity η_ϕ and e-i energy exchange rate (x a^2) as well as energy and particle diffusivities χ_i χ_e D_i D_e
  - Experimental profiles E_r used to compute the very important equilibrium ExB

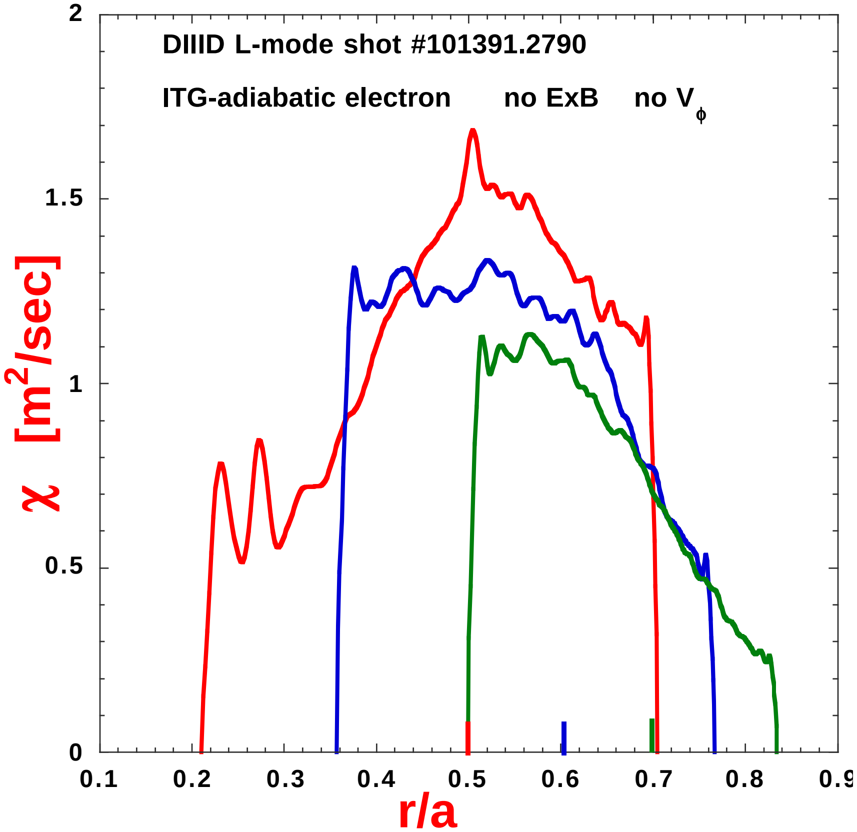
DIIID L-mode rho-star scaling shots: ITG only

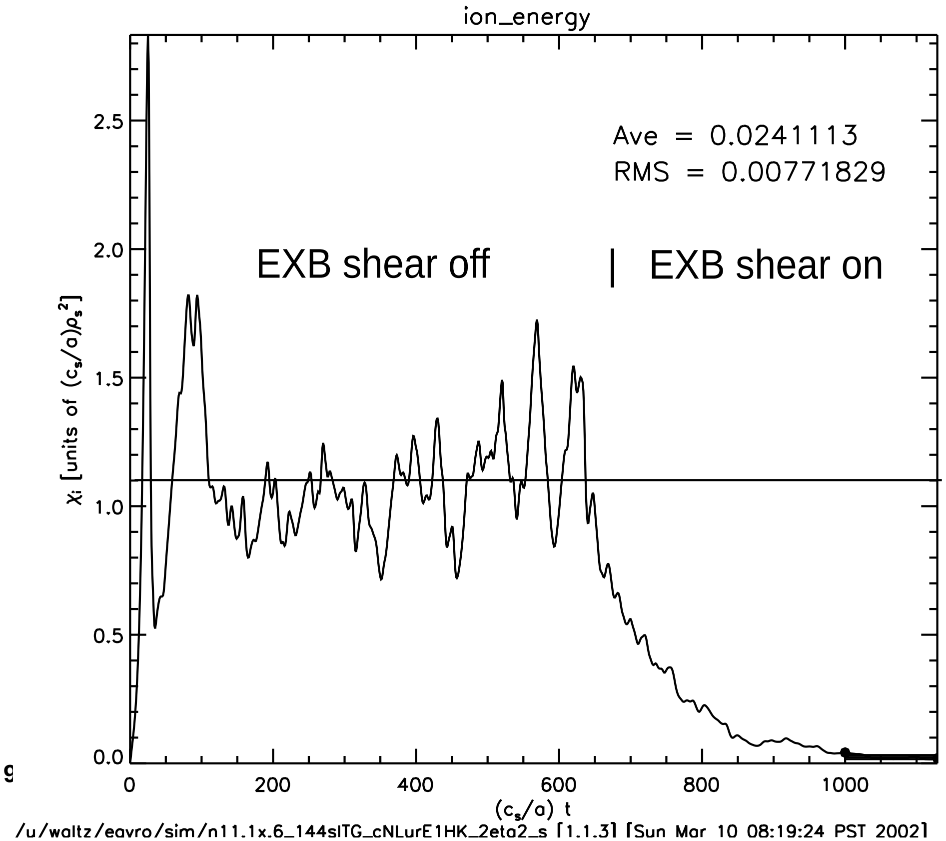
- B=2 .1T low rho_star shot. ITG with no v_ϕ or ExB shear

  -Smaller low-resolution boxes compare well with larger high-resolution boxes.

  -Slices centered at different r/a have "good overlap".

  -With ExB shear (even with dv_ϕ/dr Kelvin-Helmholtz), ITG needs electron drive to get transport





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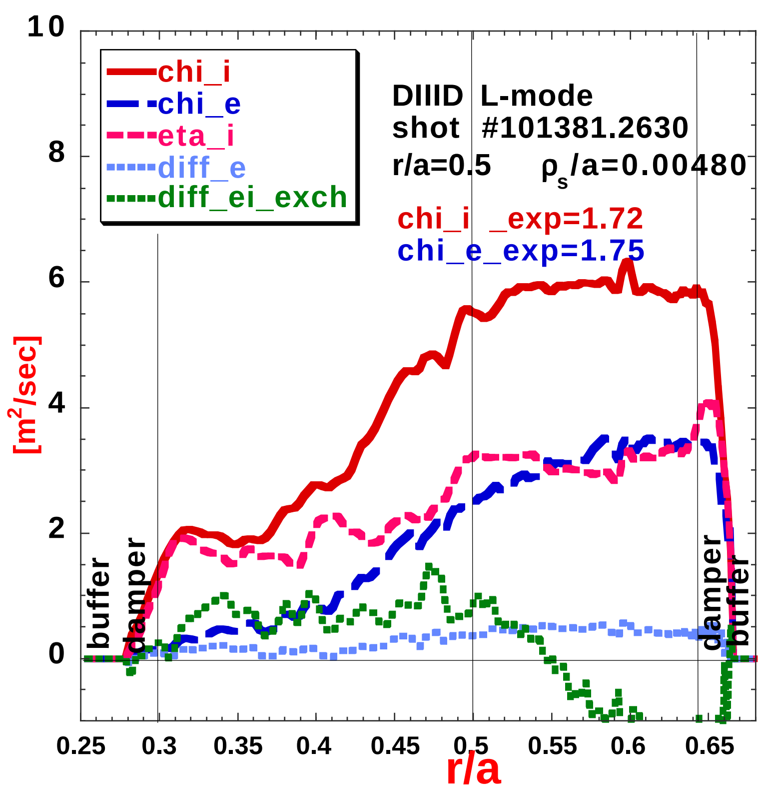
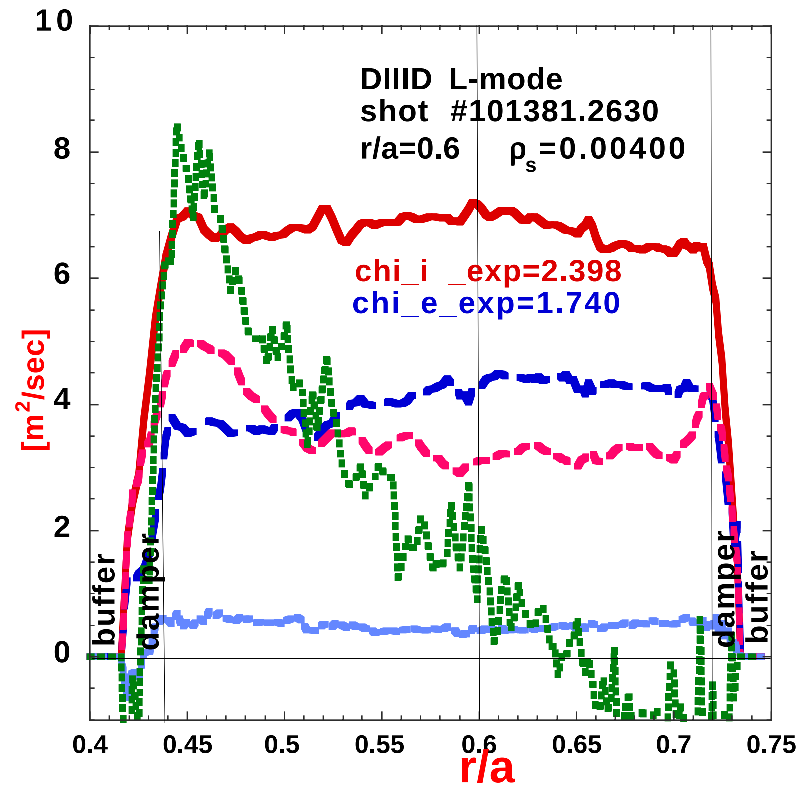
DIIID L-mode rho-star scaling shots: full physics

- **B=1.050 high rho-star shot. Full physics (save collisions)**





Good "overlap" between r/a=0.5 and 0.6 norm centers validates slice approach

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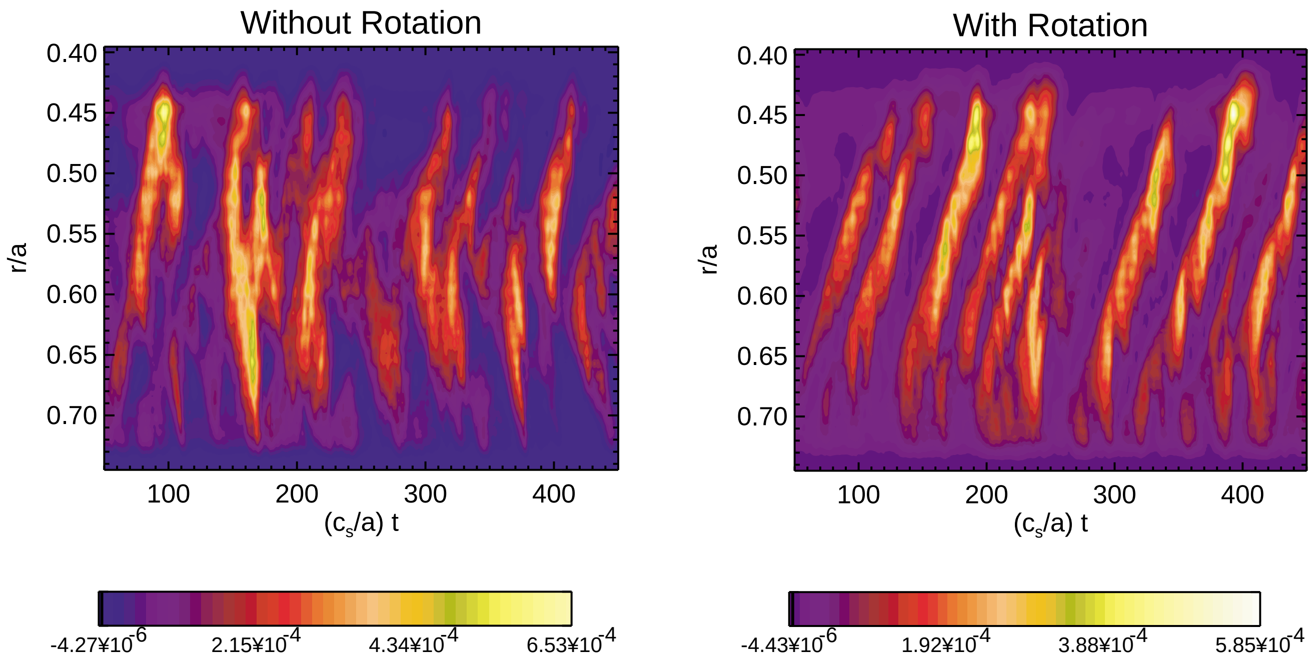
- at r/a = .6 both GRYO runs and experiment close to Bohm scaling ratios

	comment			ratio
B_T	experiment	2.1 T	1.05 T	0.50
$\chi_{i\text{-}gB} = (c_s/a)\rho_s^2$	experimental norm value	1.018 m^2/sec	1.934 m^2/sec	$(0.56)^{-1}$
ρ_s/a	experiment	0.00257	0.00400	$(0.64)^{-1}$
$\chi_i / \chi_{i\text{-}gB}$	experiment	2.34	1.24	0.55
$\chi_i / \chi_{i\text{-}gB}$	full phys	3.9	2.7	0.69
$\chi_i / \chi_{i\text{-}gB}$	no collisions	6.0	3.6	0.60
$\chi_i / \chi_{i\text{-}gB}$	no ExB	5.0	4.2	0.84
$\chi_i / \chi_{i\text{-}gB}$	flux tube noExB	8.1	7.7	0.96

We need a sensitivity study to determine χ^i/χ_{gB} changes with errors in profile. Typically profiles are 10% but gradient lengths are 30%. Very likely < 30% lower temperature gradients and < 30% higher shear rates will compensate.

Rotational shear effect direction of avalanches



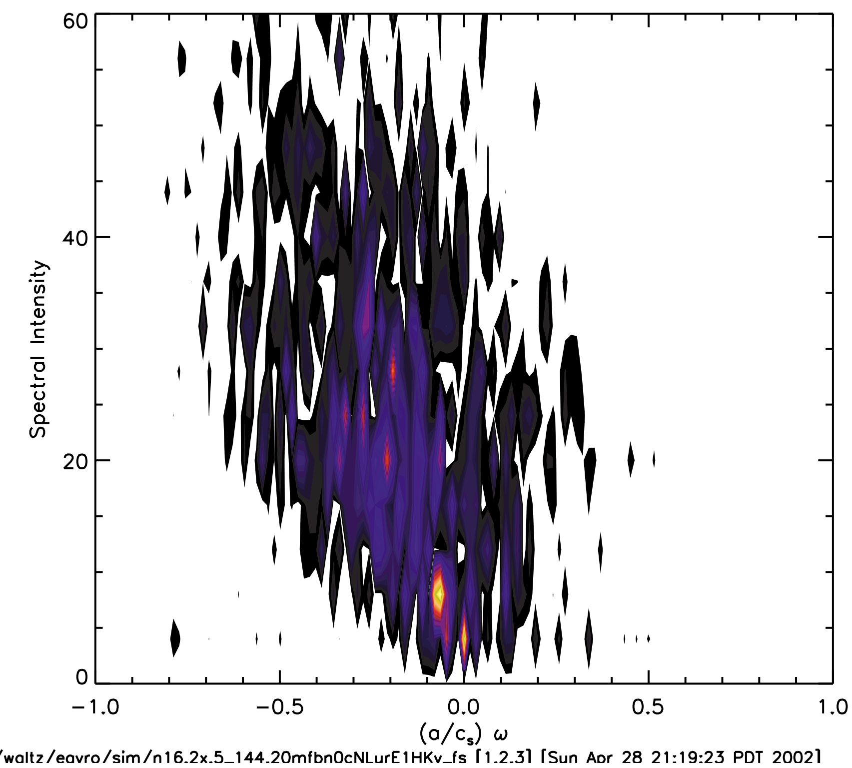
- **Avalanches appear with both Bohm (here) scaling and gyroBohm scaling**
- **Larger rho-star has higher velocity avalanches**

Looking for the trapped electron branch

- **B = 1.05T r/a= .5**

The ITG branch at negative ω is clearly visible in this nonlinear spectrum.

We would love to see the positive ω TEM branch show up !



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Comments and caveats

- Curiously, density correlation lengths scale as ρ* and auto-correlation times as ρ* in contrast to the simple ITG Bohm scaled cases (i.e. $[\rho^*]^{0.5}$ and $[\rho^*]^{0}$).

- This maybe related to another difference: Although the ExB is clearly important, the EXB shear rate in the two shots is nearly the same (by experimental design), i.e. in contrast NOT scaled with ρ*. Hence NOT clear that the mechanism for the broken gyroBohm is the same as the simple ITG cases.

- Runs made with root(m_i/m_e) 20 not 60. We know this does not have much effect on linear stability, but we have not checked nonlinear runs.

- We need to repeat the runs at larger radial slices to be sure non-local effects are small.

- These runs are fairly low beta, but we have not yet seen any magnetic flutter transport beyond a few percent.

- The full physics runs previously took 5-24hr restarts on 128ps seaborg.nersc.gov ....7-10 day turn-around. Recently improved processor scaling to 1024ps have 256ps runs complete in 24hr.

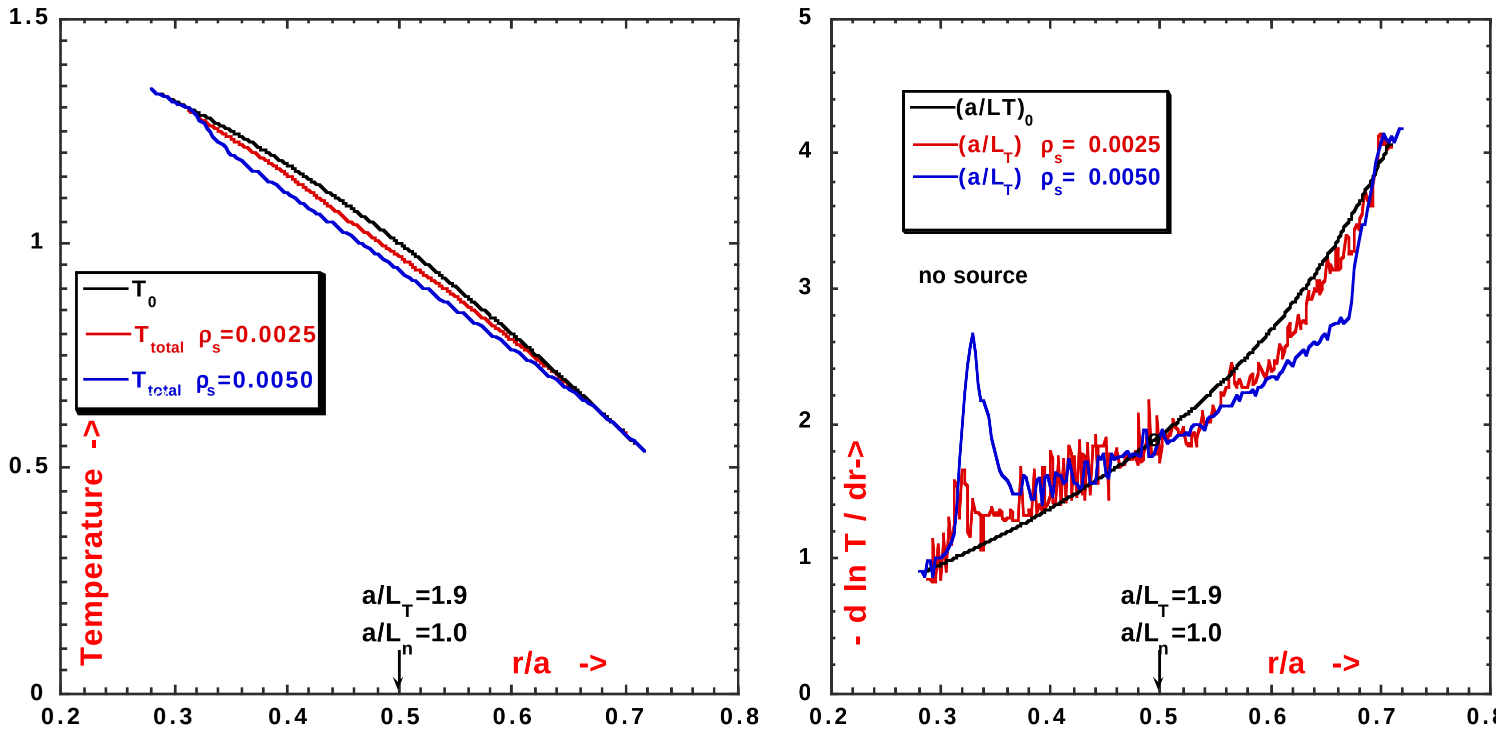
Conclusions

- Need to finish GYRO-GS2 benchmark runs for DIIID shot profiles in the flux-tube no profile or ExB shear limit.
- Work in progress requires detailed experimental error analysis to determine if GYRO power flows are in agreement with experiment within error bars, however
- Preliminary results suggest the Bohm scaling character is in agreement with the Bohm character of L- mode experiments.
- Moving on to understand why H - mode ρ* scaled shots have gyroBohm scaling.

Visit the GYRO web site http://web.gat.com/comp/parallel/ _ for literature and movies.

ADDITIONAL MATERIAL

- **Small ρ_s scaled deviations from the equilibrium profiles caused by the n=0 perturbations in the absence of sources significantly change the temperature gradient.**



- We have constructed an "adaptive source" to preserve the equilibrium:

flux surface average $< >$ n = 0 gyrokinetic equation with source S

$$d < \tilde{f}_0(\varepsilon) > / dt + r^{-1} d / dr\, r [\Gamma(\varepsilon)] = S(\varepsilon)$$

where $\Gamma(\varepsilon) = < \Sigma_{n>0} [\rho_s \, inq/r \, \tilde{\phi}_n]^* \tilde{f}_n(\varepsilon) >$ i s the flux at energy ε

$$S(\varepsilon) = \int_0^t dt' / T_{eq} \exp [(t' - t) / T_{eq}] \; F_{0,1}(\varepsilon)$$

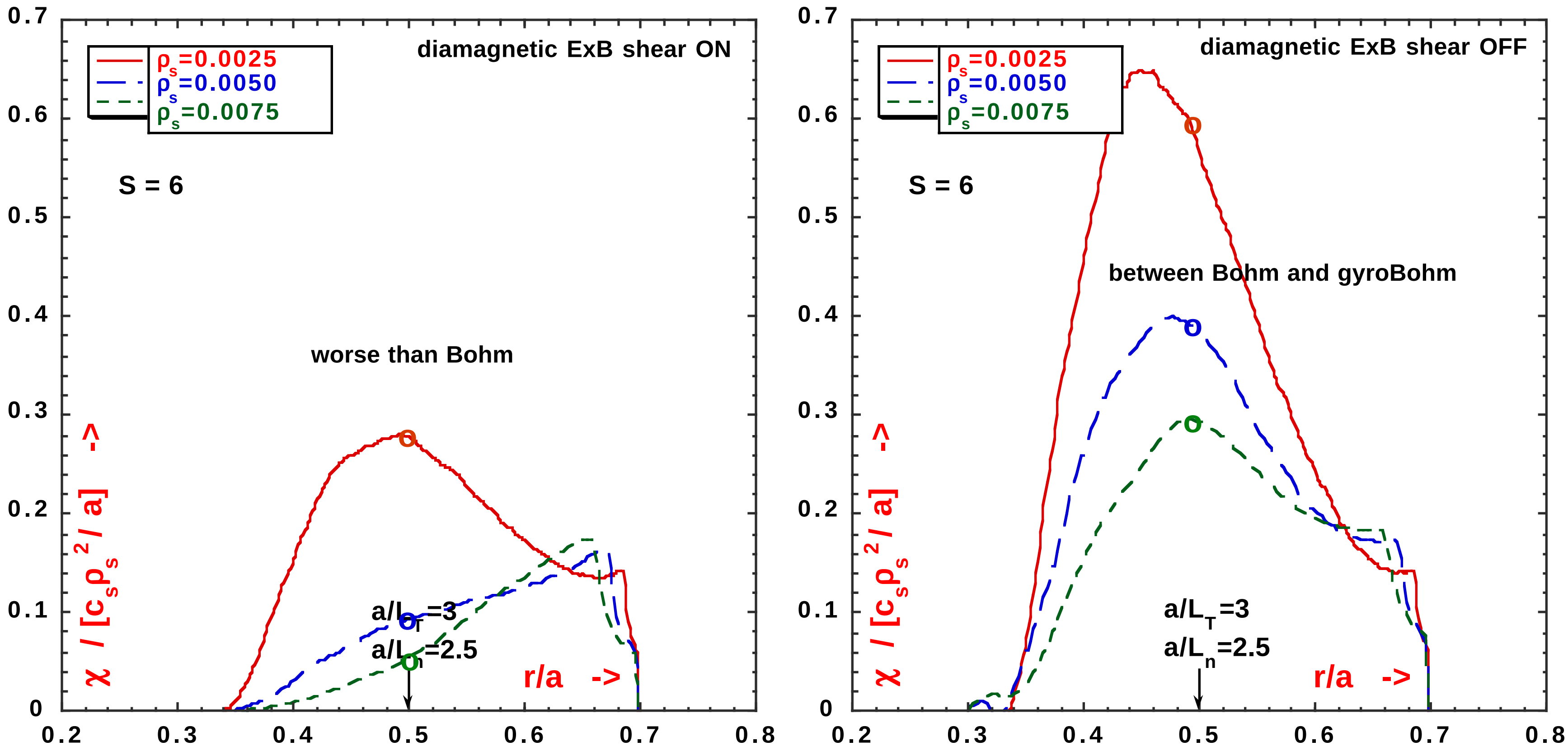
where $F_{0,1}$ is the cos [$(1,2)\pi x/L$] longwave components of $r^{-1} d/dr\, r [\Gamma]$.

$T_{eq} = 50\, a/c_s$ compared to run time $1000\, a/c_s$

- S is "adaptive ": It "can" change fast, but after the nonlinear saturation, it in fact changes only slowly. Restarts with a "frozen" S give the same result.

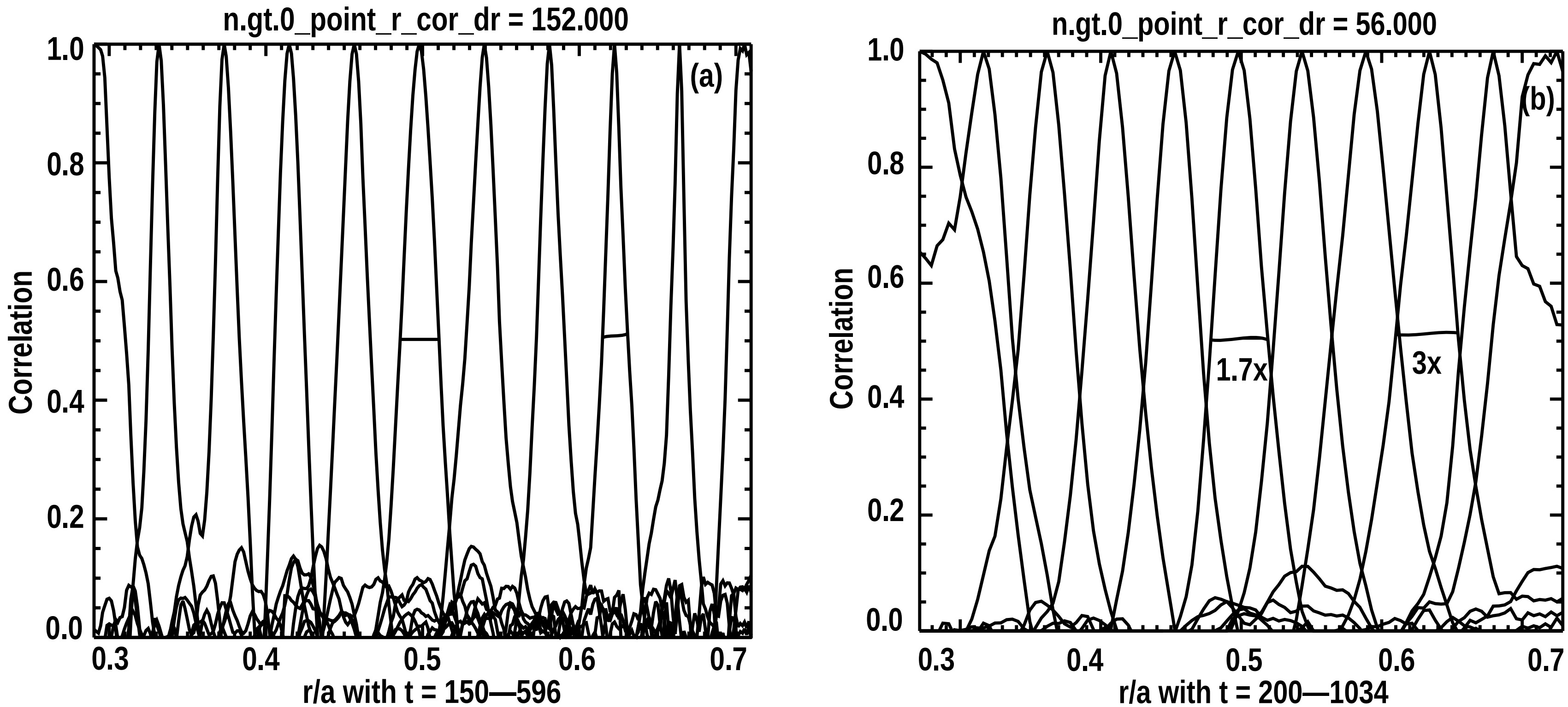
- Being "long wave" and constant in time, the adaptive source acts as a "true " source.

- **Diamagnetic EXB shear is big contributor to breaking gyroBohm and decreasing transport**



- n>0 radial correlation lengths in the Bohm scaled region (r/a = 0.5) scale as $L_c \propto \rho_s^{0.5}$ (i.e. 1.7X)

  gyroBohm scaled region (r/a = 0.65) scale as $L_c \propto \rho_s$ (i.e. 3X)

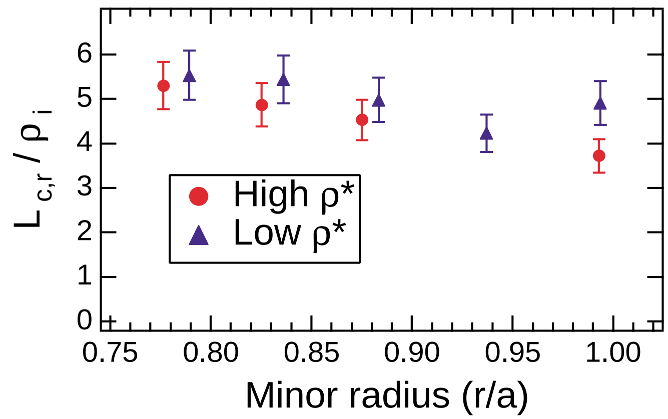


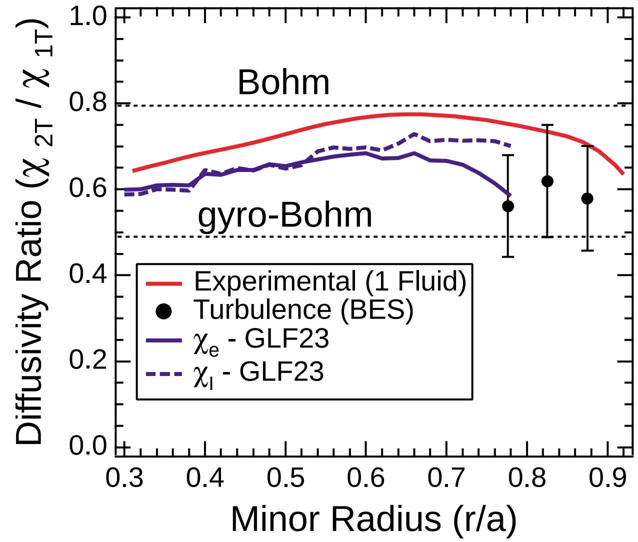
$\rho_s = 0.0025$ $\rho_s = 0.0075$ (i.e. 3X)

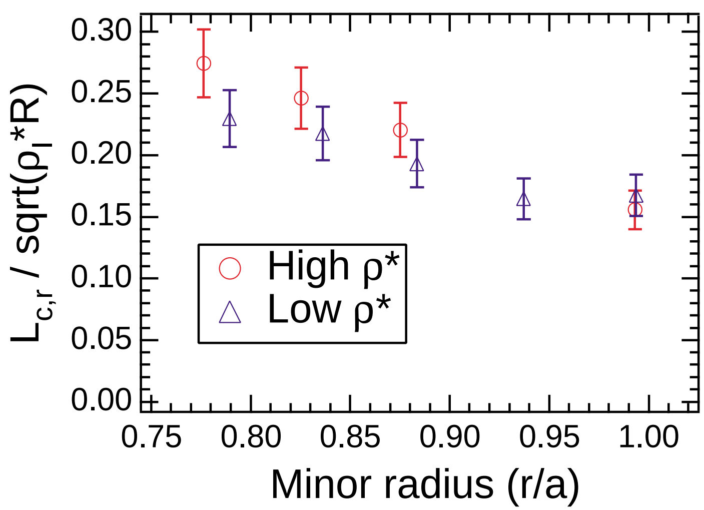
Correlation times τ_c remain invariant to ρ_s, so $\chi \propto L_c^2/\tau_c \propto \rho_s$ consistent with Bohm

[$a/L_T = 3$ $a/L_n = 2.5$ S = 4]

- **DIII-D L-mode ρ^* scans by 1.6 X show no change in τ_c / [c_s/a], L_c^2/τ_c intermediate between Bohm and gyroBohm, and L_c intermediate scaling between ρ_s and $(\rho_s R)^{0.5}$**







G.R McKee, C.C. Petty, R.E.Waltz, et al IAEA 2000 paper EX6 /

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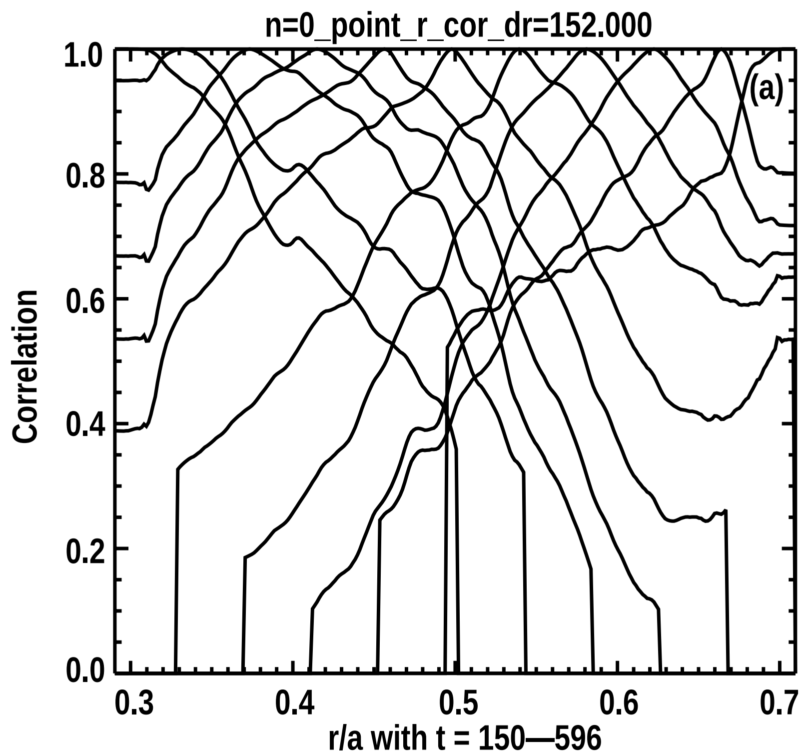
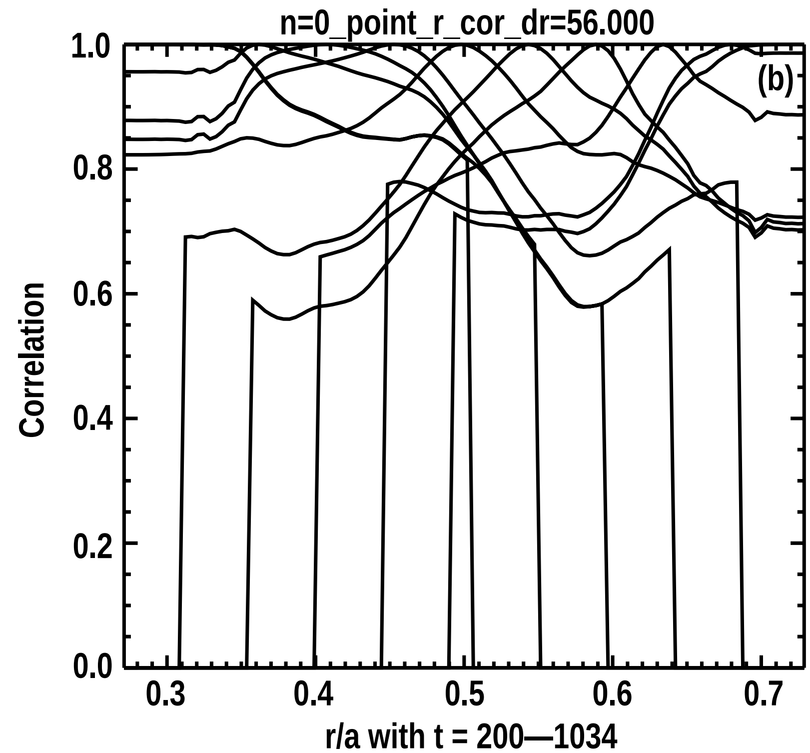
- **Difficult to measure n=0 zonal flow radial correlation lengths large and insensitive to ρ_s**





$\rho_s = 0.0025$ $\rho_s = 0.0075$

[$a/L_T = 3$ $a/L_n = 2.5$ $S = 4$]