Gyrokinetic simulations of ITG turbulence with GYSELA 5D

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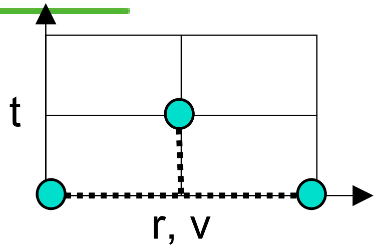
Various strategies for gyrokinetic codes



Eulerian

Dissipation

⇓

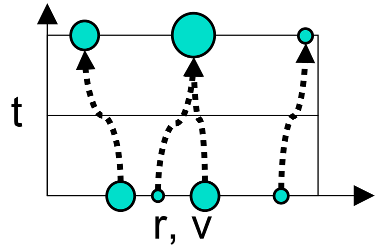
high order scheme

Particle-in-Cell (PIC)

Noise

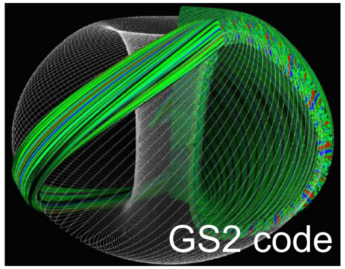
⇓

δf + optimized loading



Full-*f*

δf

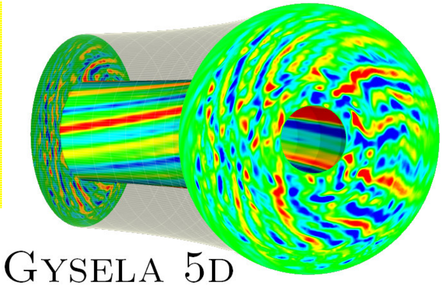


Flux-tube

small scale structures

Global

large scale events



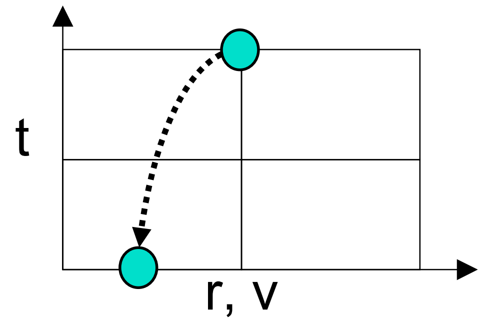
GYSELA 5D

GYrokinetic **SE**mi-**LA**grangian code

Semi-Lagrangian

follow trajectories backwards

on fixed grid (weak noise, moderate dissip.)



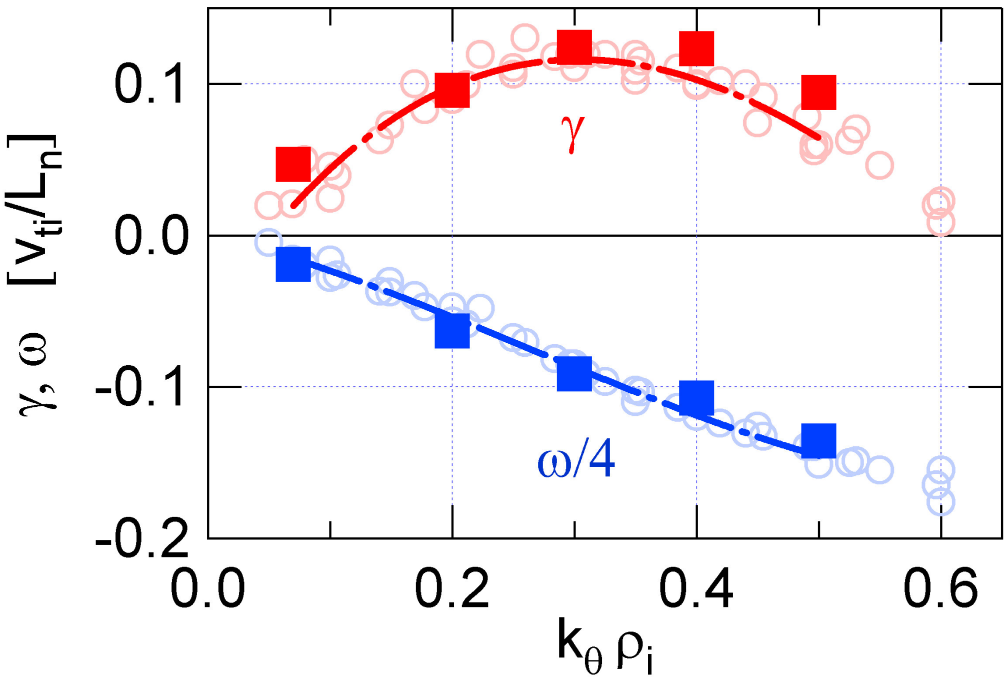
GYSELA: full-f code for toroidal ITG turbulence

- Standard gyrokinetic equation: $f(r,\theta,\varphi,v_{//},\mu,t)$ & $\phi(r,\theta,\varphi,t)$

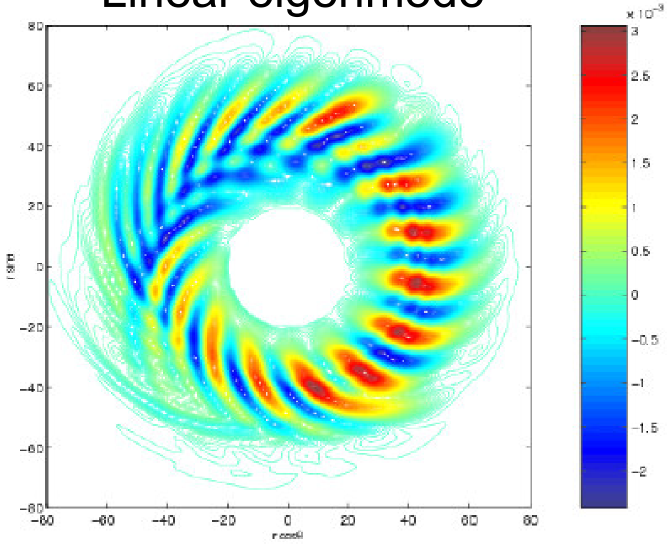
$$\begin{cases} \text{"Vlasov"} & \partial_t f + (\vec{v}_E + \vec{v}_g)\,.\vec{\nabla}_\perp f + v_\parallel \nabla_\parallel f + \dot{v_\parallel}\, \partial_{v_\parallel} f = 0 \\ \text{Electro-neutrality} & \frac{1}{T_e}\left(\phi - \langle\phi\rangle\right) - \frac{1}{n_0}\vec{\nabla}_\perp.\left(n_0 \vec{\nabla}_\perp \phi\right) = \frac{1}{n_0}\int d\Gamma\, J.\left(f - f_{eq}\right) \end{cases}$$

- Linear benchmark with other codes (CYCLONE)

[after Dimits '00]



Linear eigenmode



ZF linearly undamped in collisionless regime

Initial poloidal flow (m,n)=(0,0)

shielded by finite orbit width effects

E-folding decay

GAM oscillations

Residual magnitude

$$\hat{\phi}_{00}(t_0)$$

Sideband coupling

GAMs (m,n)=(±1,0)

Landau-damping

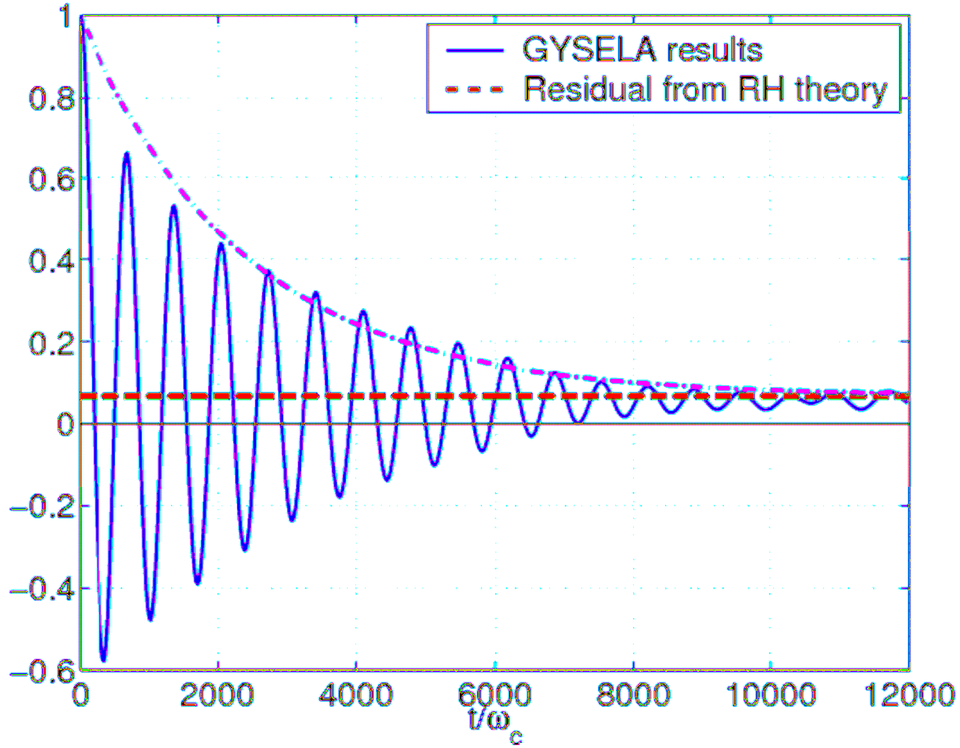
Undamped component

Zonal Flow

$$\hat{\phi}_{00}(t_\infty) = \frac{\hat{\phi}_{00}(t_0)}{1 + 1.6\, q^2/\epsilon^{1/2}}$$

Consistent with theory

[Rosenbluth-Hinton '98, Sugama-Watanabe '07]



Ongoing non-linear benchmark with ORB5

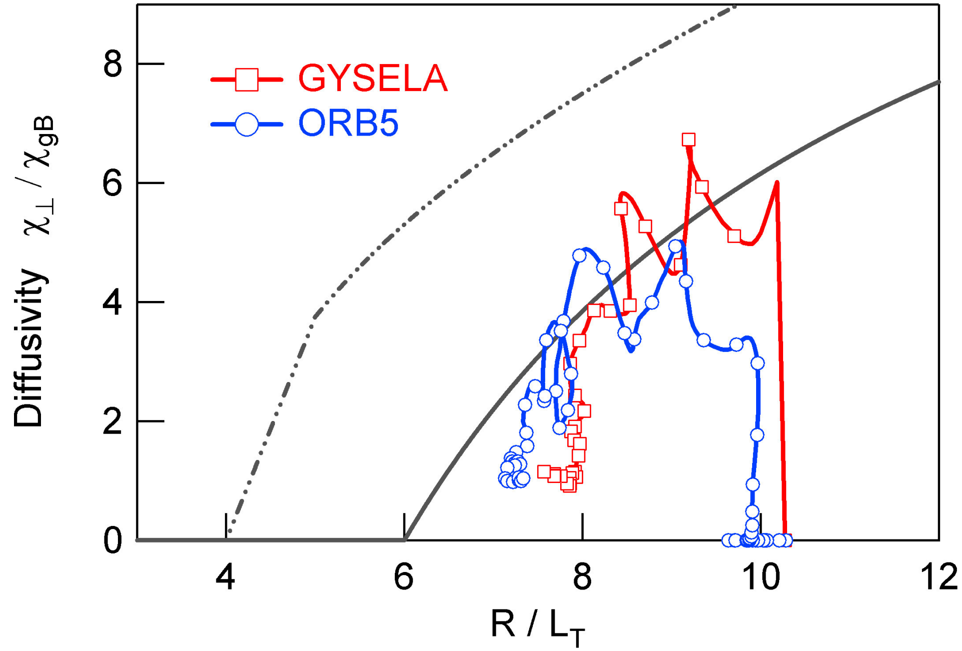
Global 5D gyrokinetic codes - toroidal ITG - adiabatic electrons

GYSELA:

- Full f
- Num. scheme = Semi-Lagrangian
- Poisson solver = Finite differences
- Time evolution = leap-frog

ORB5:

- $\delta f = f - f_{eq}$
- Numerical scheme = PIC
- Poisson solver = Finite elements
- Time evol. = 4th order Runge-Kutta



CYCLONE test case

(within ITM European Task Force)

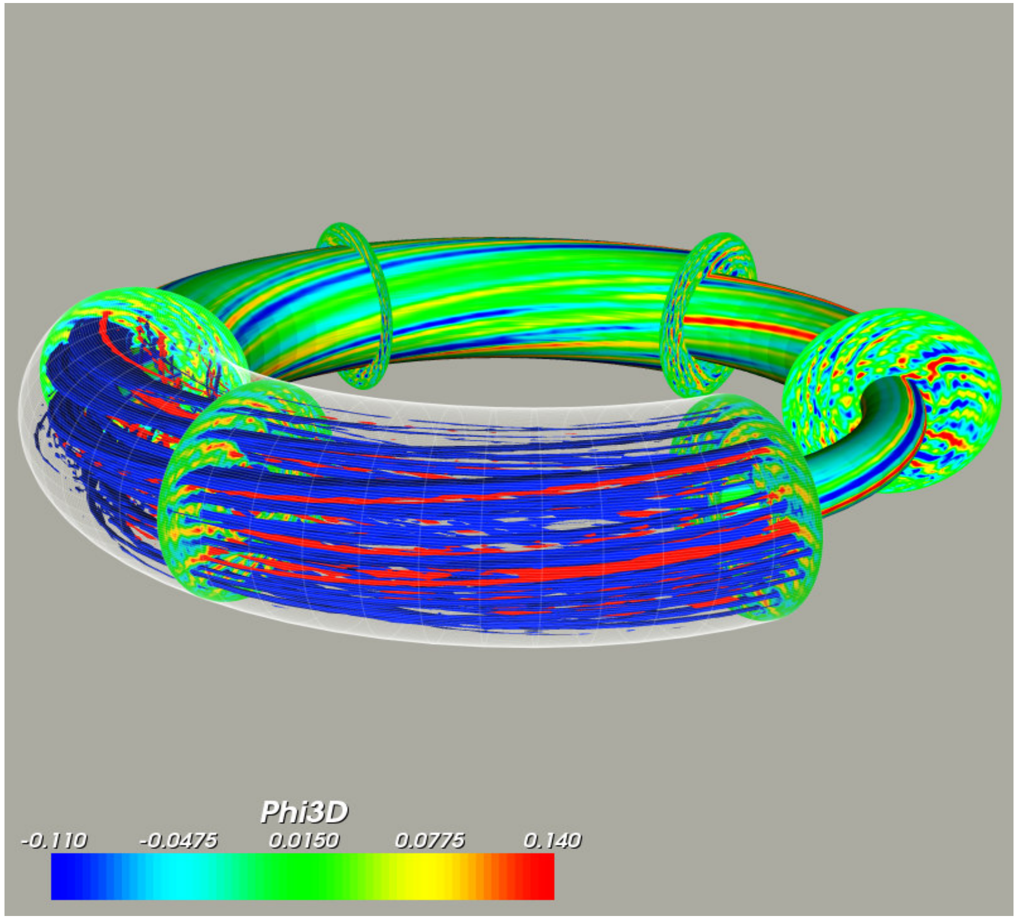
[see poster P. Angelino, this conference]

Transport strongly reduced by zonal flows

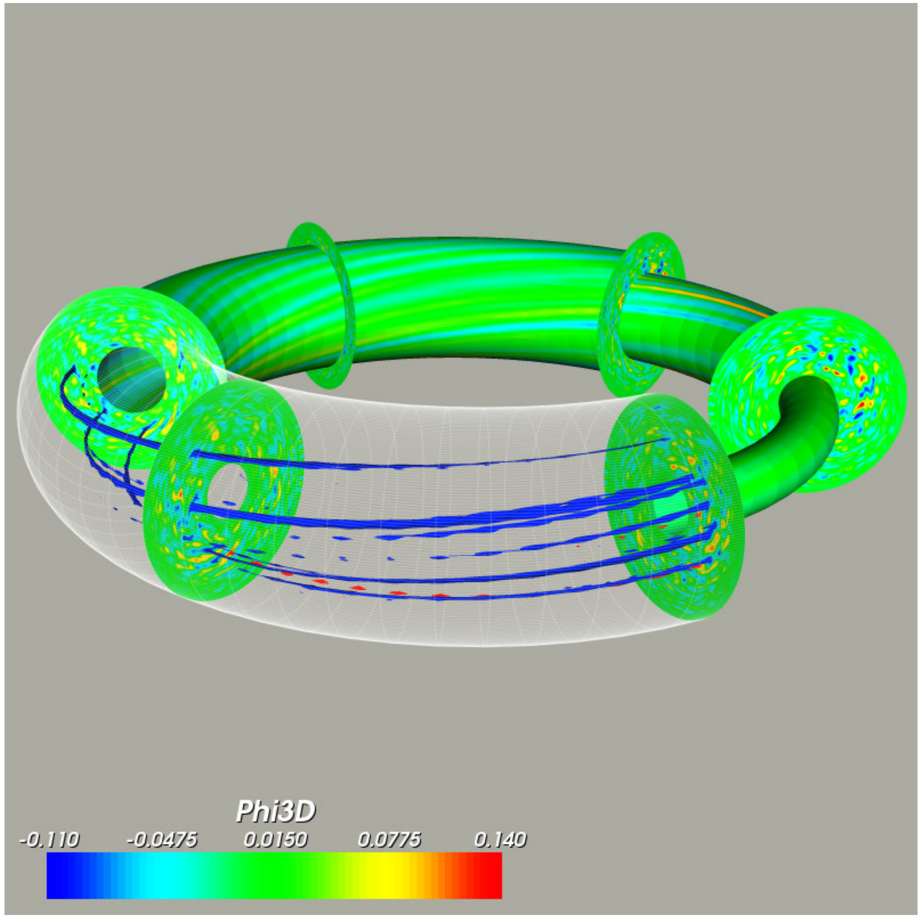
Case $\rho_* = 5.10^{-3}$ | $r \times \theta \times \varphi \times v_{//} \times \mu = 256 \times 256 \times 64 \times 32 \times 8 \rightarrow 2.10^9$ grid points

4 500 h single-proc (64 proc. used)

Without zonal flows



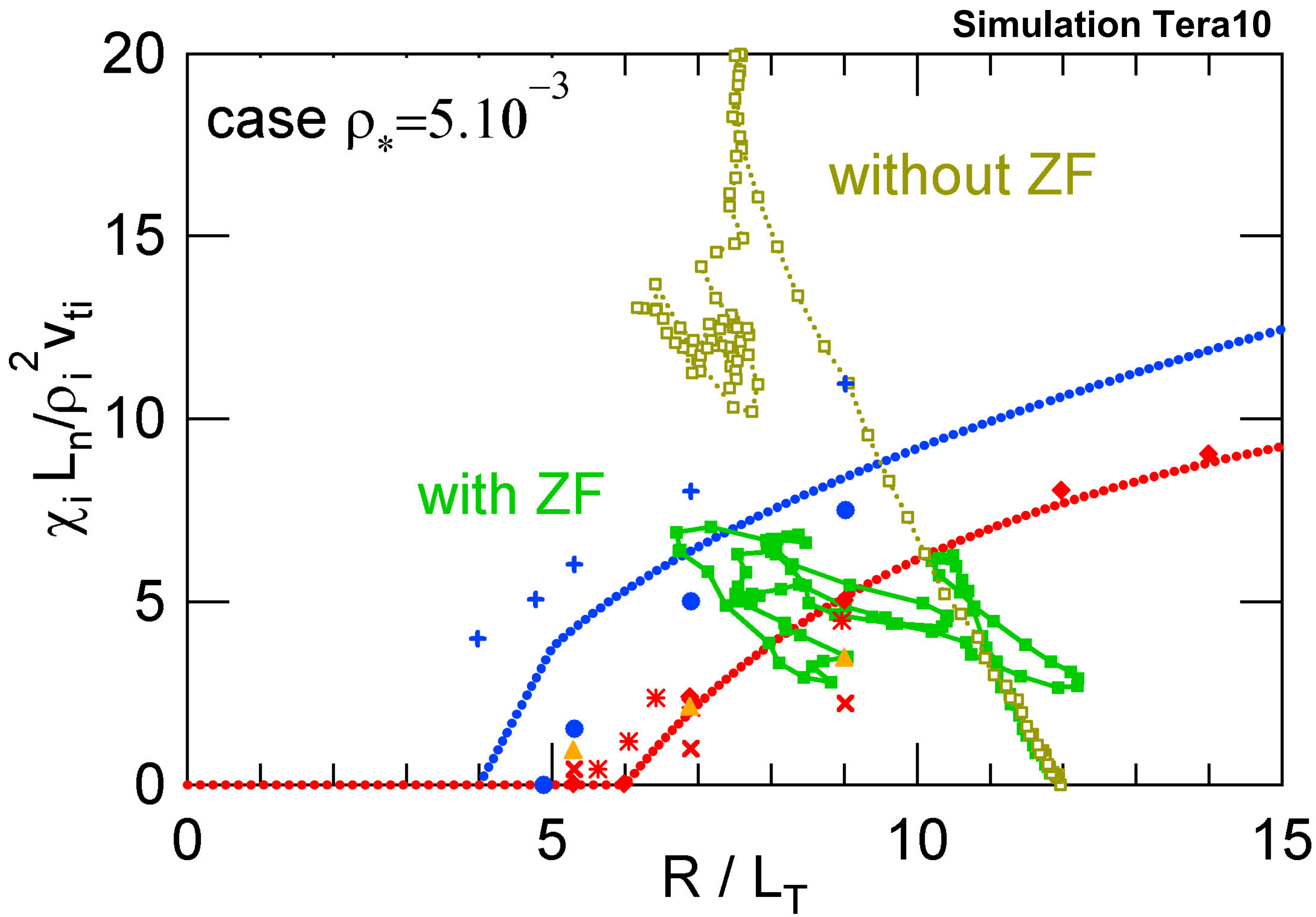
With zonal flows



Transport strongly reduced by zonal flows

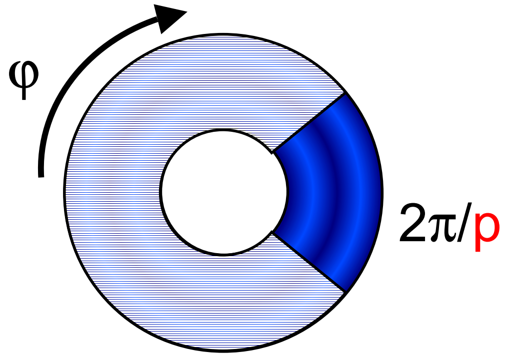
When ZF are allowed to develop:

- ❑ $\chi_\perp$ reduced by a factor of 2-3
- ❑ $\chi_\perp$ consistent with CYCLONE base case



Simulating a fraction of torus only

- $L_\varphi = 2\pi/p$ $\Rightarrow$ modes n={0, p, 2p, 3p, …, N} only (periodicity); all m
- Ratio (nb resonant modes / total nb modes) = Cst



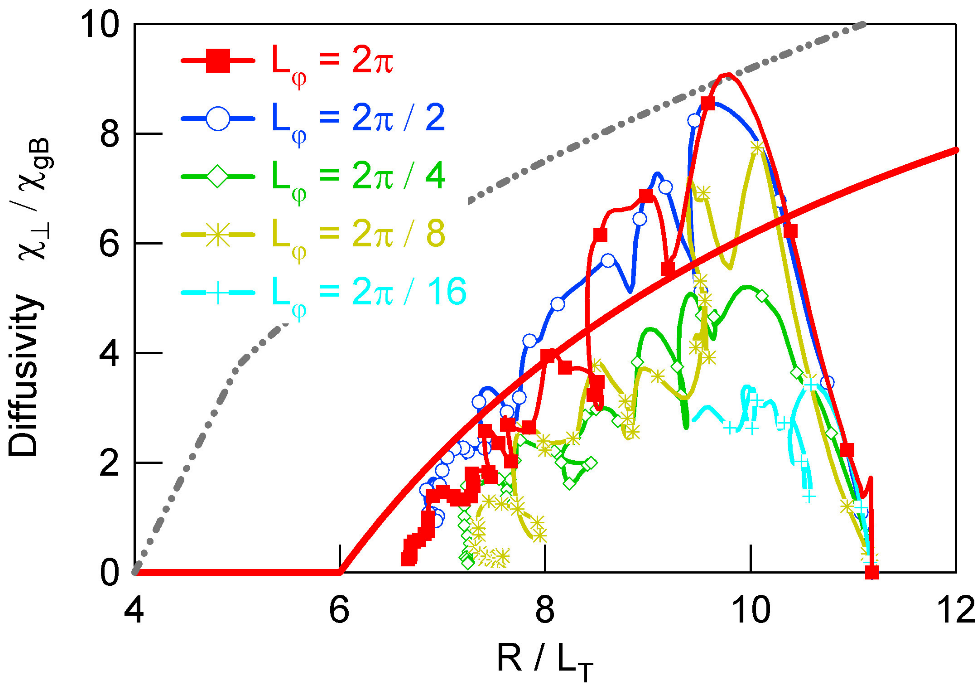
- **Validity scales with ρ_* :**

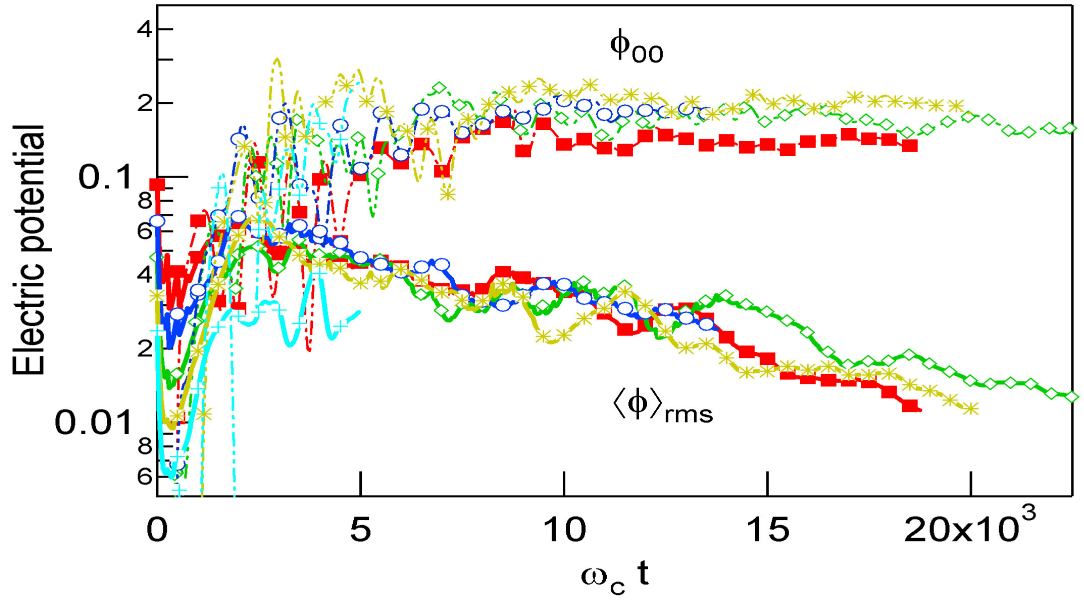
$n \propto k_\theta \rho_i / q\rho_* \;\Rightarrow\;$ Nb unstable modes $\propto (p\,\rho_*)^{-1}$

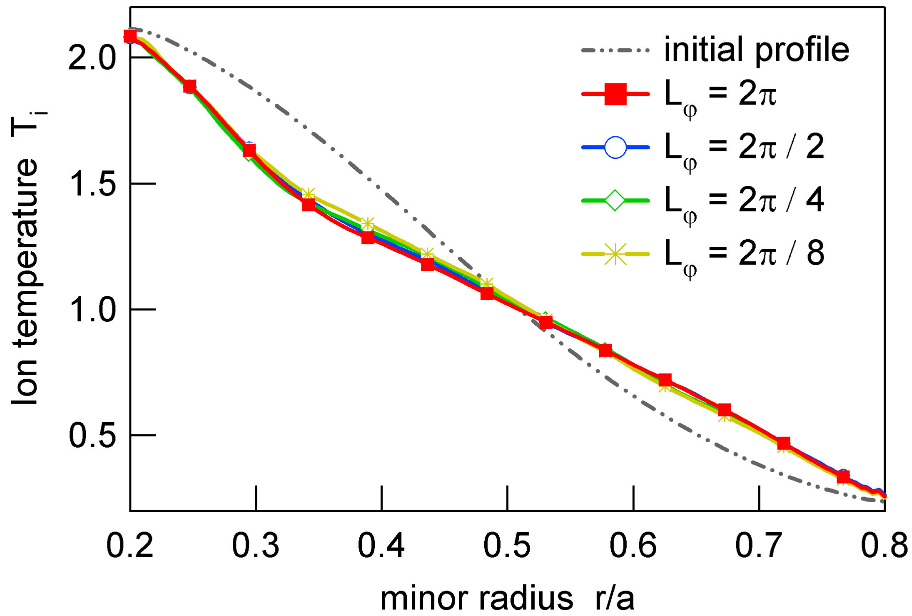
Small fraction of torus (p>>1) all the more valid since ρ_* is small

Fractions of torus at $\rho^* = 10^{-2}$

~ OK up to $2\pi/8$

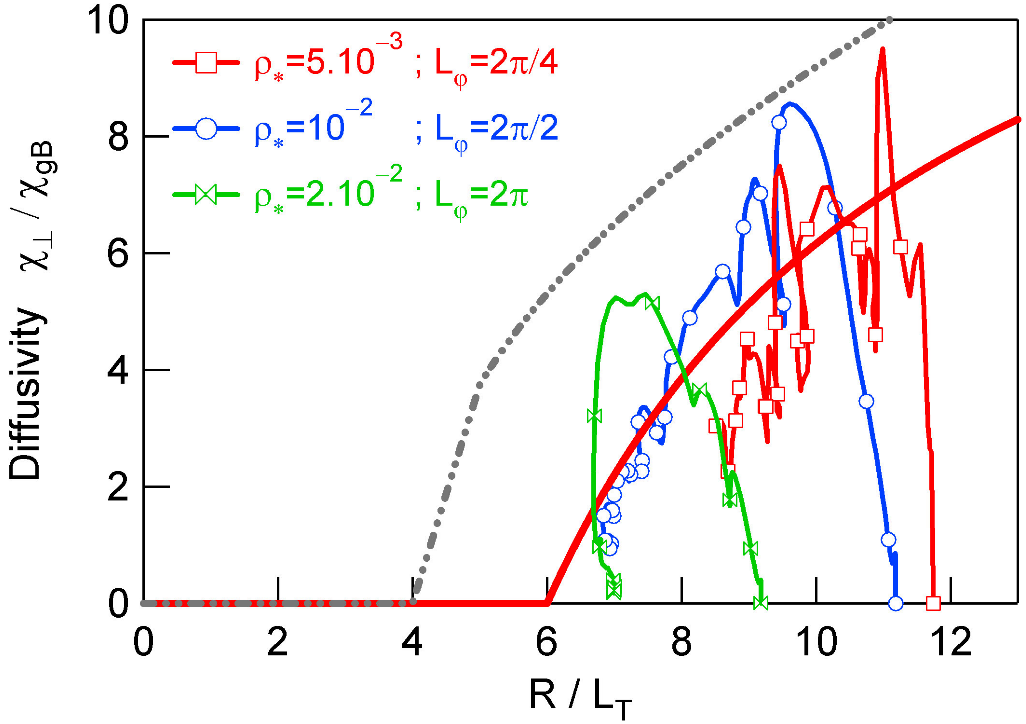






Turbulence scaling with ρ*

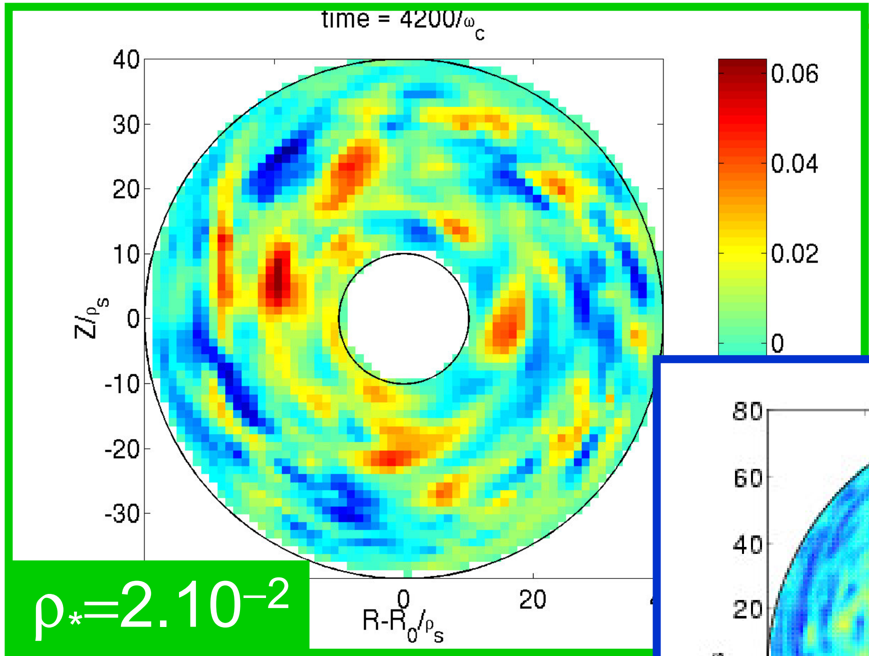
- Motivations:
  - Empirical scaling law $\tau_E \propto \rho_*^{-3}$
  - $\rho_*^{ITER} \approx 2.10^{-3}$ not accessible to present day experiments
  - Transition Bohm → gyroBohm reported in GK simulations: threshold? physical mechanism? [Lin '02, Candy-Waltz '03]
- Difficulty: $\rho_* / 2 \Rightarrow$ grid mesh $\times 2^3$ and $\Delta t / 2$

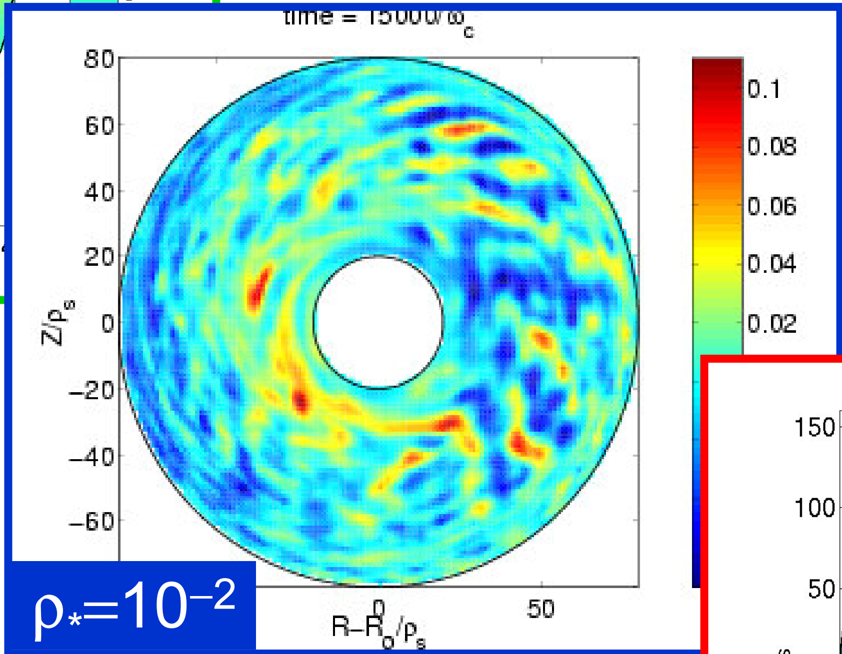


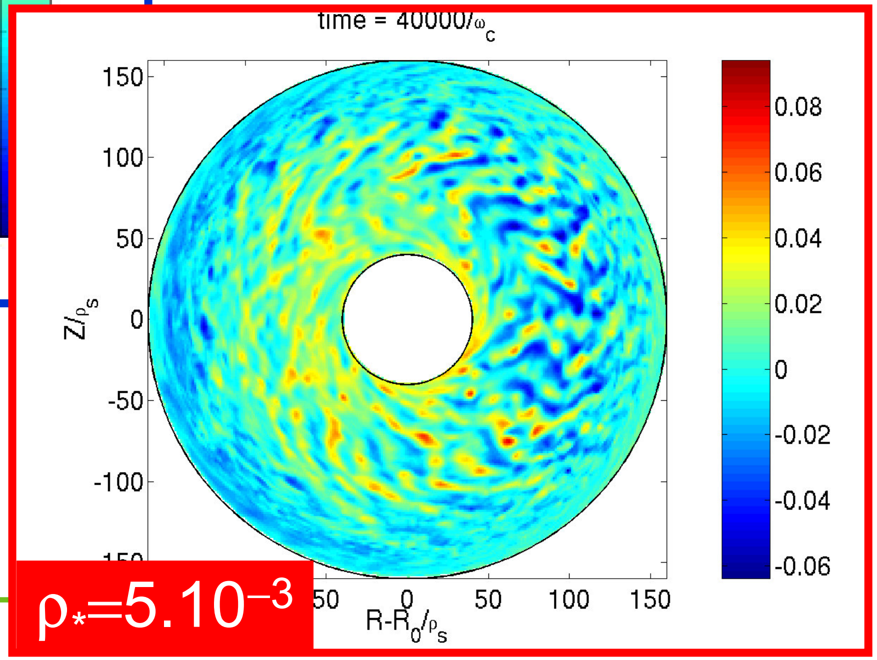
- Preliminary scaling with GYSELA:
  - Large to intermediate ρ_*
  - Different distances to $(R/L_T)^{crit}$
  - Fraction of torus

Transport scaling with ρ_*

Large to intermediate ρ_*







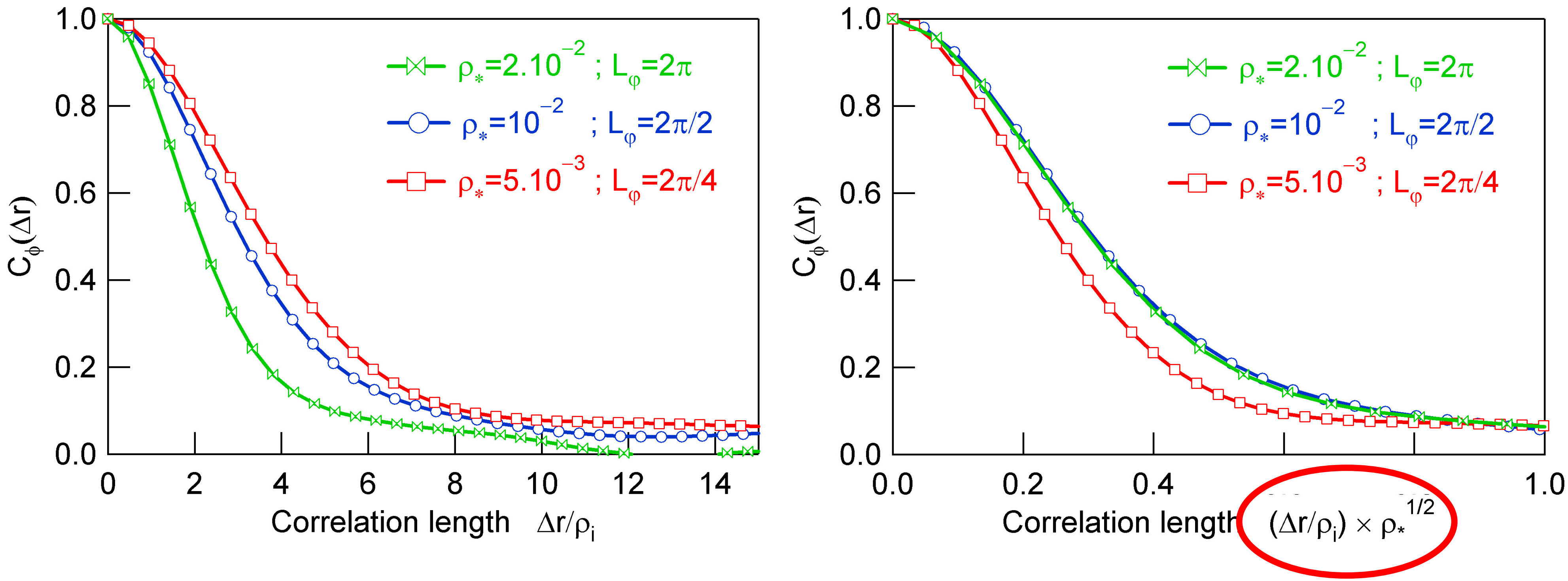
λ_c consistent with Bohm scaling at large ρ_*

and close to the threshold

$$\chi_\perp = \lambda_c^2 / \tau_c = \rho_*^{\alpha}\, \chi_{Bohm}$$

$\omega_c \tau_c \propto \rho_*^{-1}$ and

- $\lambda_c/\rho_i \propto \rho_*^{-1/2} \Rightarrow$ Bohm ($\alpha=0$)
- $\lambda_c/\rho_i \sim$ Cst $\Rightarrow$ gyroBohm ($\alpha=1$)



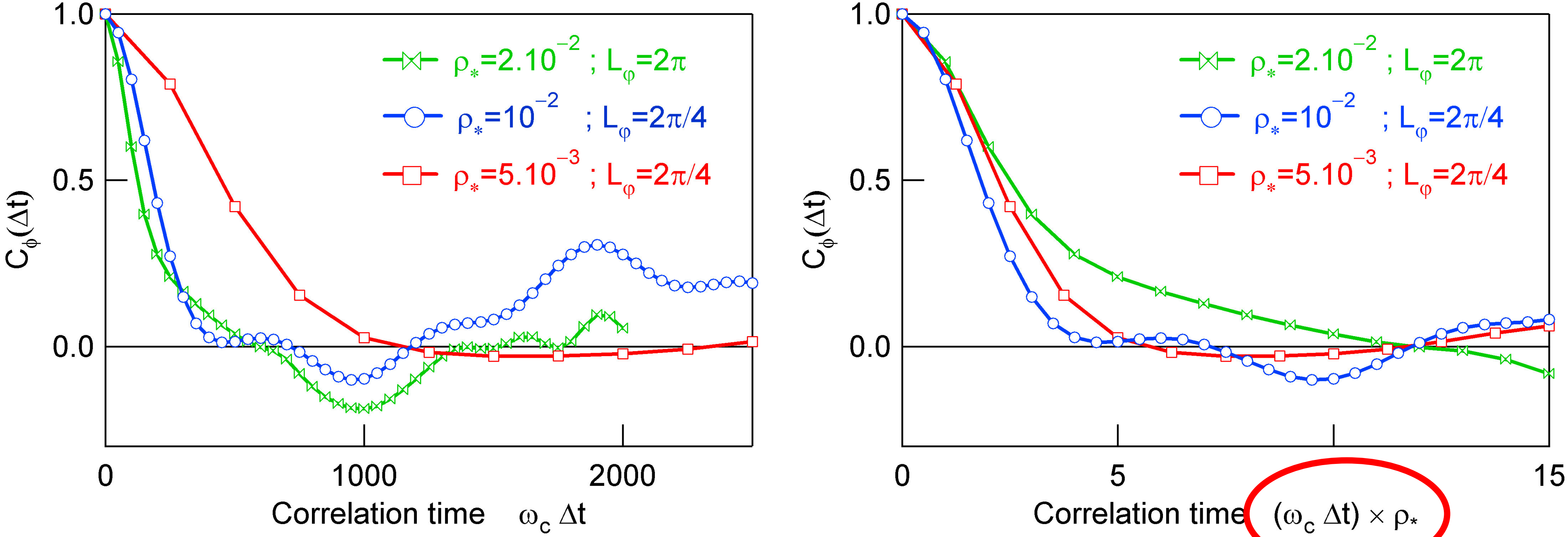
Poor statistics for correlation time τ_c

$$\chi_\perp = \lambda_c^2 / \tau_c = \rho_*^{\alpha}\, \chi_{Bohm}$$

$\omega_c \tau_c \propto \rho_*^{-1}$ and

$\lambda_c/\rho_i \propto \rho_*^{-1/2} \Rightarrow$ Bohm (α=0)

$\lambda_c/\rho_i \sim$ Cst $\Rightarrow$ gyroBohm (α=1)



Conclusions

- GYSELA code:
  - Full-f, global, semi-Lagrangian
  - Canonical equilibrium [Dif-Pradalier '06]
  - Linear & non linear benchmarks (CYCLONE, ORB5)
- Heat diffusivity reduced by 2-3 when Zonal Flows are active
- Correlation length consistent with Bohm scaling at large ρ_* ($>10^{-2}$) and close to the threshold

Parallelisation & performances of GYSELA

- **Parallelisation: MPI & Open-MP**
- **Efficiencies:**
  - Solver Vlasov (4D): 92% on 64 proc.
  - Solver Quasi-Neutrality (3D): 85.5% on 32 proc.