Interplay between collisions and turbulence in gyrokinetic simulations

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A foreword on the tool: Gysela

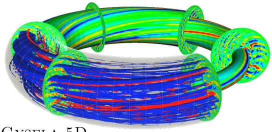
Guiding-centre

$$\partial_t \bar{f} + \mathbf{v}_E \cdot \boldsymbol{\nabla}_\perp \bar{f} + \mathbf{v}_D \cdot \boldsymbol{\nabla}_\perp \bar{f} + v_\parallel \nabla_\parallel \bar{f} + \dot{v}_\parallel \, \partial_{v_\parallel} \bar{f} = \mathcal{C}(f)$$

Particles

$$-\frac{1}{n_0(r)} \boldsymbol{\nabla}_\perp \cdot \left[\frac{n_0}{B\,\omega_c} \boldsymbol{\nabla}_\perp \phi \right] + \frac{e}{T_e(r)} \left(\phi - \langle \phi \rangle \right) = \frac{2\pi B}{m n_0} \iint d\mu \, dv_\parallel J_0 \left(f - f_{init} \right)$$

- ☹ electrostatic, adiabatic electrons
- ☺ global & *full–f*



Gysela 5D

Include NC physics to GK ➠ discussion on $\mathcal{C}(f)$

Neoclassical theory with GYSELA

Neoclassical ≡ ion–ion collisions (adiab. electrons)

➠ $\nu_\star \equiv \nu_{\star\,i} = \dfrac{\text{collision freq.}}{\text{transit freq.}} \equiv \dfrac{qR_0}{v_{th,\,i}} \dfrac{\nu_{ii}}{\epsilon^{3/2}}$; with $\nu_{ii} = \dfrac{4\sqrt{\pi} n_i Z^4 e^4 \log \Lambda}{3\, m_i^2\, v_{th,\,i}^3}$

Small causes...

$\chi_{NC} \ll \chi_{turb} \sim \chi_{exp}$; $\tau_{NC} \gg \tau_{turb}$

...with strong possible effects

collisions ➠ linear damping {MF+ZF} ➠ transport level

Ultimately: $\nu_\star^{Iter}$ ➠ impact on transport ?

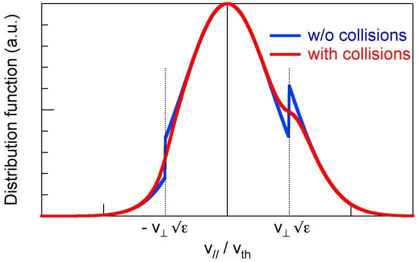
Friction force between trapped and passing

trapped $\langle v_\theta \rangle = 0$ (sym.) $\neq$ passing

➠ preferred interaction: loss cone

➠ regularisation in $v_{||}$

modelisation : **friction force**



Complex general framework: **Mini. model ➠ max. physics ?**

❶ relax. $f \longrightarrow f_{Maxwell}$ ➠ *full–f* (bulk+fluct.)

❷ model the boundary layer ➠ diffusion

❸ analytically ➠ exact neoclassical regimes

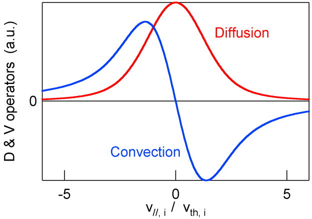
Adopted operator: on $v_\parallel$ only

GYSELA : **efficient parallelisation on μ** (MPI + OpenMP)

➠ operator on $v_\parallel$

$$\frac{\mathrm{d}}{\mathrm{d}t} f = \partial_{v_\parallel} \left(\mathcal{D}\, \partial_{v_\parallel} f - \mathcal{V} f \right)$$

➠ $\dfrac{\mathcal{V}(r, v_\parallel)}{\mathcal{D}(r, v_\parallel)} = -\dfrac{v_\parallel}{v_{th}^2}$



➠ exact neoclassical regimes

exact $\nabla \cdot \bar{\bar{\Pi}}_{NC}$

$$mn\, \mathrm{d}_t \boldsymbol{V} = en(\boldsymbol{E} + \boldsymbol{V} \times \boldsymbol{B}) - \nabla p - \nabla \cdot \bar{\bar{\Pi}} - mn\, \nu_{\boldsymbol{i}\,\boldsymbol{e}} (\boldsymbol{V_e} - \boldsymbol{V_i})$$

drawback: parallel dissipation $\nu_{\boldsymbol{i}\,\boldsymbol{e}}$ ➠ $\nu_{\boldsymbol{i}\,\boldsymbol{i}}$ selects $\langle v_{\parallel\, i} \rangle = 0$

❶ Neoclassical transport: results

➠ without turbulence ($\nabla T_i < \nabla T_{i\,c}$)

❷ Interplay: neoclassical effects & turbulence

➠ above ITG threshold

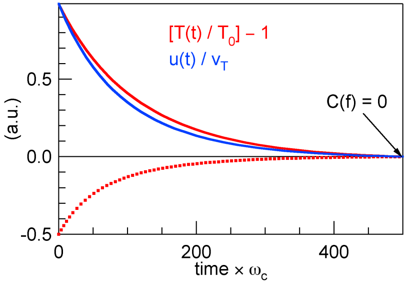
Neoclassical transport: verifications

❶ Operator $\mathcal{C}$ only: $\partial_t f = \mathcal{C}(f)$

- Relaxation towards Maxwellian

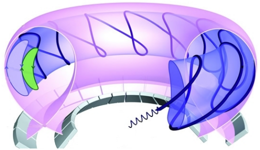
  ➠ guaranteed by $\dfrac{\mathcal{V}}{\mathcal{D}} = -\dfrac{v_\parallel}{v_{th}^2}$

- $\tau_{caract.}$ OK



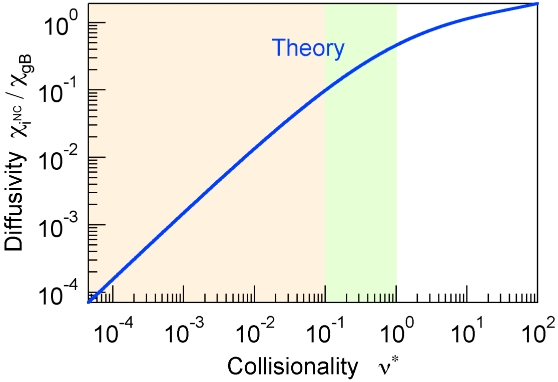
❷ Equilibrium: $\mathrm{d}f_{eq}/\mathrm{d}t = \mathcal{C}(f_{eq})$

$$v_\theta = 0 = v_{E\theta} + v^\star \quad \Rightarrow \quad E_r \propto \nabla p$$



Subtle neoclassical results (1/3)

❸ NC thermal transport: $\chi_{NC} = -Q / n \nabla T$



theoretical prediction: [Chang, Hinton '86]

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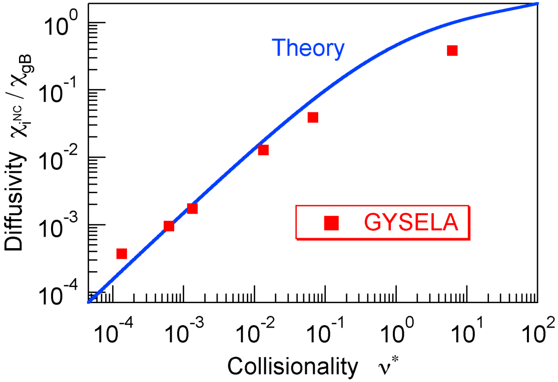

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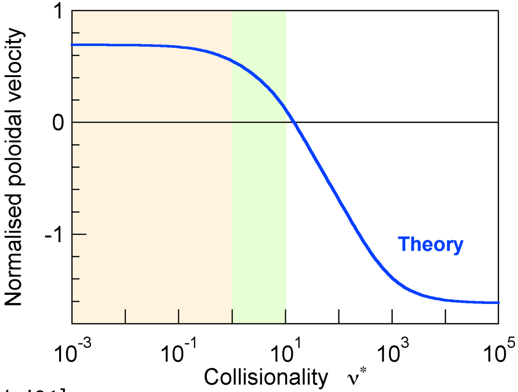
Subtle neoclassical results (2/3)

❹ Ion poloidal rotation $v_{\theta,\ i}$ reverses sign with $\nu_\star$

$$mn\,\mathrm{d}_t \boldsymbol{V} = en(\boldsymbol{E} + \boldsymbol{V} \times \boldsymbol{B}) - \nabla p - \nabla \cdot \bar{\bar{\Pi}} - mn\,\nu_{i\,e}(\boldsymbol{V}_e - \boldsymbol{V}_i)$$

$\nu_{ie}(\boldsymbol{V}_e - \boldsymbol{V}_i)$ ➠ $\nu_{ii}\boldsymbol{V}_i$

exact $\nabla \cdot \bar{\bar{\Pi}}_{NC}$ ➠ v_θ^{NC}



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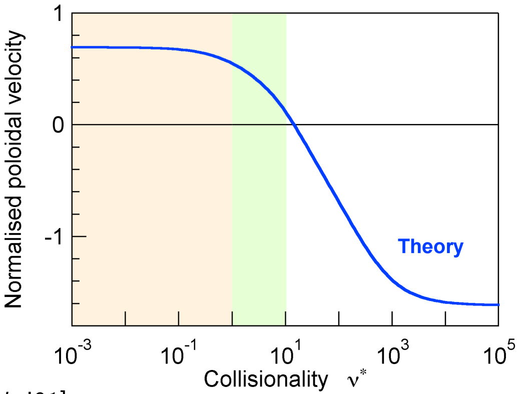
$\nu_{ie}(\boldsymbol{V}_e - \boldsymbol{V}_i) \Rightarrow \nu_{ii}\boldsymbol{V}_i$

exact $\nabla \cdot \bar{\bar{\Pi}}_{NC} \Rightarrow v_\theta^{NC}$



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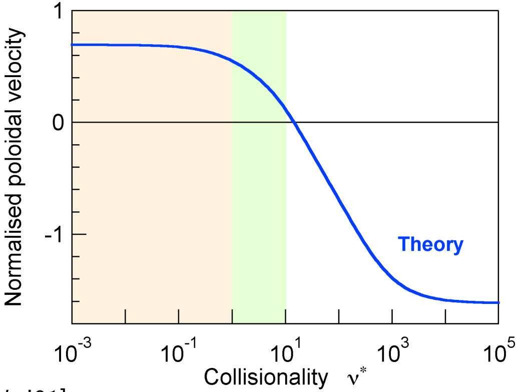

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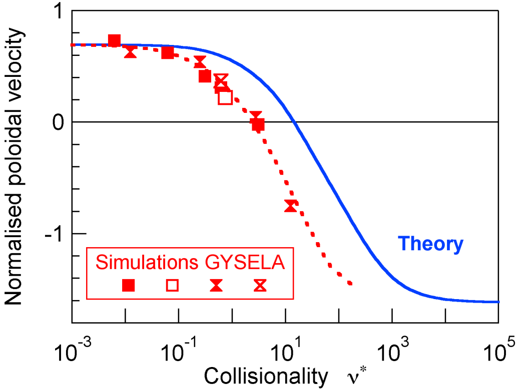
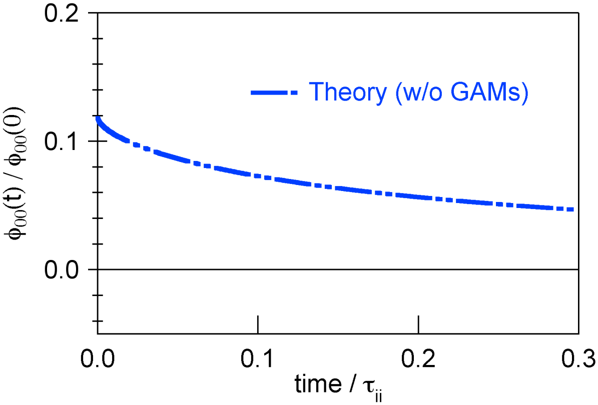


➠ **New result**

Subtle neoclassical results (3/3)

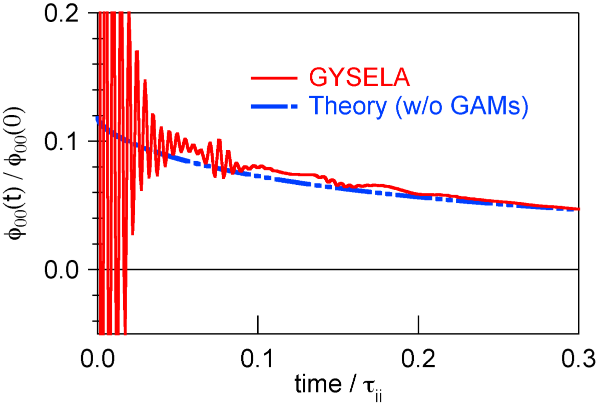
❺ Collisional damping of {zonal + mean} flows



theoretical prediction: [Hinton, Rosenbluth '99]

Subtle neoclassical results (3/3)

❺ Collisional damping of {zonal + mean} flows



➠ **Crucial for synergy (?) with turbulence**

❶ Neoclassical transport: results
➠ without turbulence ($\nabla T_i < \nabla T_{i\,c}$)

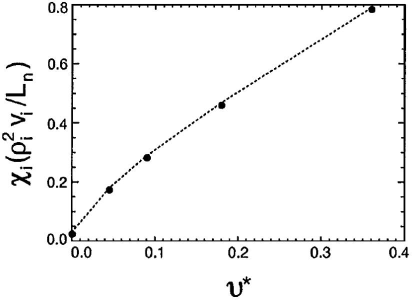
❷ Interplay: neoclassical effects & turbulence
➠ above ITG threshold

Coll. & turbulence: crucial players for transport

Naively : collisions ↗ ➠ dissipation ↗ ➠ turbulence ↘

but . . .

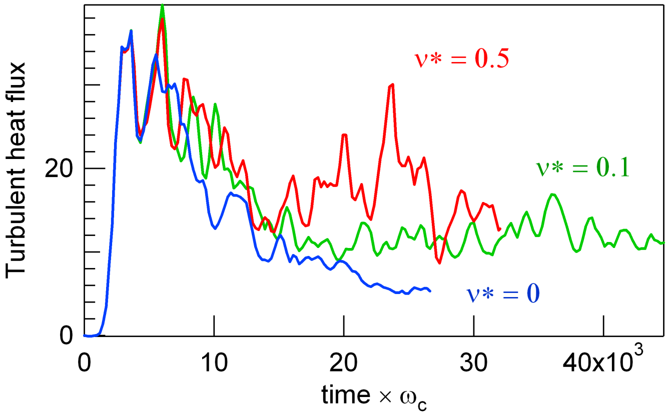
GTC result: [Lin, *et al.* '99]



More efficient: collisions ↗ ➠ {ZF + MF} ↘ ➠ turbulence ↗

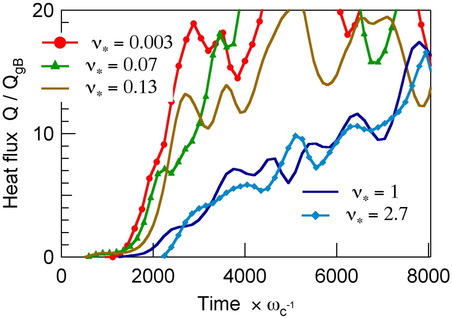
- accurately describe collisional damping {ZF + MF} – **OK**

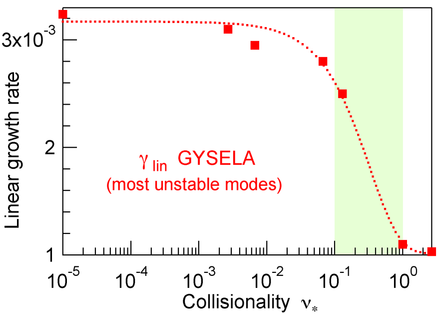
Interplay with the turbulence



➠ **preliminary work: interpretation in progress**

Opposite effects involved





Heuristic model:

$$\chi_{turb} = \frac{\chi_0}{1 + \alpha\, \gamma_{E\times B}^2} \qquad \begin{cases} \nu_\star \nearrow & \chi_0 \approx \gamma_0/\langle k_\perp^2 \rangle - k_\perp^2\, \chi_{NC} \searrow \\ \nu_\star \nearrow & \{MF + ZF\} \searrow \quad \gamma_{E\times B} \searrow \end{cases}$$

Perspectives, open questions

GYSELA is addressing **gyrokinetics** + **neoclassical** theory

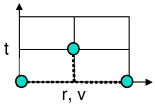
➲ will turbulence significantly affect $\bar{\bar{\Pi}}$ ($v_\theta \neq v_\theta^{NC}$) ?

➲ $\chi^{NC}(turb)$? ; $\chi^{turb}(\nu_\star)$?

➲ if synergy . . . due to ZF ? (distance to lin. threshold ?)

. . .

Numerical strategy in GYSELA



Eulerian

Dissipation

$\Downarrow$

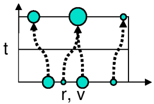
high order scheme

Particle-in-Cell (PIC)

Noise

$\Downarrow$

δf + optimized loading

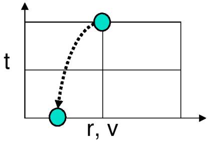


GYrokinetic SEmi-LAgrangian code

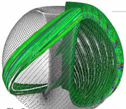
Semi-Lagrangian

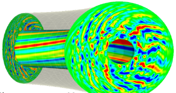
follow trajectories backwards

on fixed grid (weak noise, moderate dissip.)



Full-*f*	**δf**
Flux-tube small scale structures	**Global, Full-Torus** large scale events


Gs2


GYSELA 5D

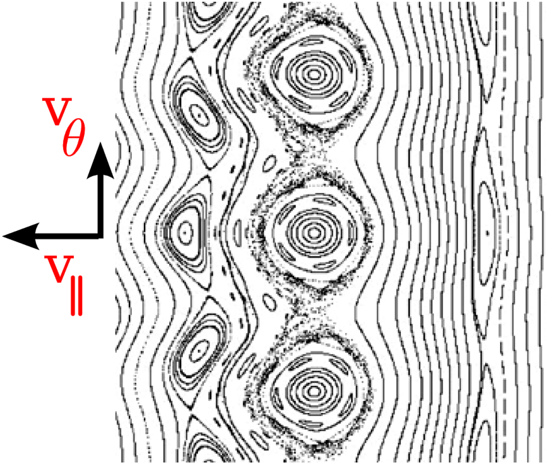
Conservation properties

$$mn\,\mathrm{d}_t \boldsymbol{V} = en(\boldsymbol{E} + \boldsymbol{V} \times \boldsymbol{B}) - \nabla p - \nabla \cdot \bar{\bar{\Pi}} - mn\,\nu_{\boldsymbol{i}\,\boldsymbol{e}}(\boldsymbol{V}_{\boldsymbol{e}} - \boldsymbol{V}_{\boldsymbol{i}})$$

- Momentum conservation: transfert over electrons
  - Adiabatic electrons: $\boldsymbol{V}_{\boldsymbol{e}} = 0$
    - *A priori*, ∞^{ty} of solutions ; GYSELA $\Rightarrow \langle V_{\parallel\, i} \rangle = 0$
      - $j_{\parallel,\,e} \Rightarrow j_{\parallel,\,i}$ ➠ solution with vanishing parallel flow

- Turbulent friction: $\nu_{turb} \gg \nu_{e\,i}$

Friction force in the $v_{\parallel}$ direction



Zonal flows and collisions