Interplay of collisional and turbulent transport processes

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Motivation

- Orders of magnitude in tokamaks (ions)

$$D_{cl} = \nu_{coll}\rho_c^2 \simeq 0.01 m^2 s^{-1}$$
$$D_{neo} = D_{cl} \times \text{geometrical factor} \simeq 0.1 m^2 s^{-1}$$
$$D_{turb} = \frac{v_T}{a}\rho_c^2 \simeq 1 m^2 s^{-1}$$

- Neoclassical= collisional transport enhanced by geometry and resonant processes

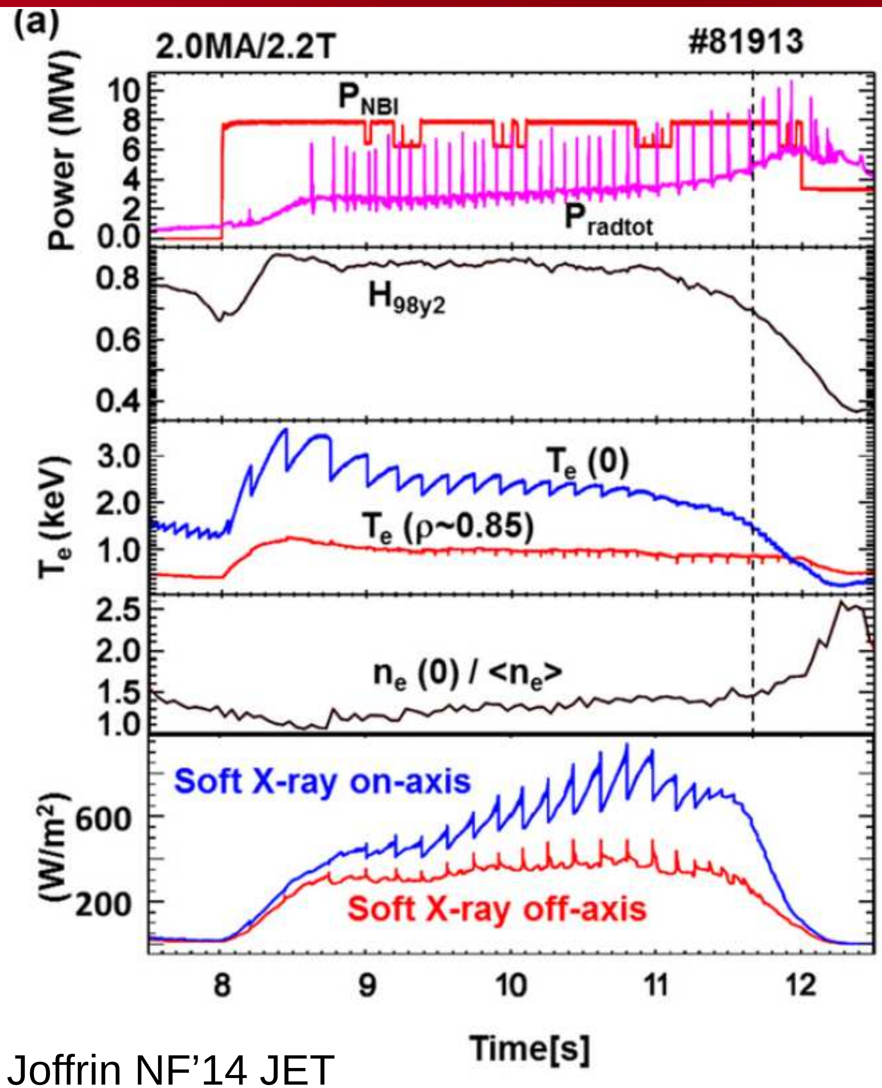
- Two consequences

  - $D_{neo} \ll D_{turb}$ $\rightarrow$ collisional transport is often neglected

  - When calculated, neoclassical and turbulent fluxes are considered as additive and uncorrelated.

Why is collisional transport back on scene?

- Tungsten plasma facing components
  → renewed interest in collisional transport
- Tendency to accumulate in the plasma core
- Neoclassical transport coefficients are enhanced by poloidal asymmetries
  Romanelli 98, Helander 98, Fülöp 99, Casson 14, Angioni 14, Belli 14, Breton 16
- Momentum transport is sensitive to collisional processes Parra 10, Barnes 13, Idomura 14



Joffrin NF'14 JET

Outline

Is there an interaction between neoclassical (≈collisional) and turbulent transport?

1) Relationship between collisional transport and flow symmetries

2) Recent results

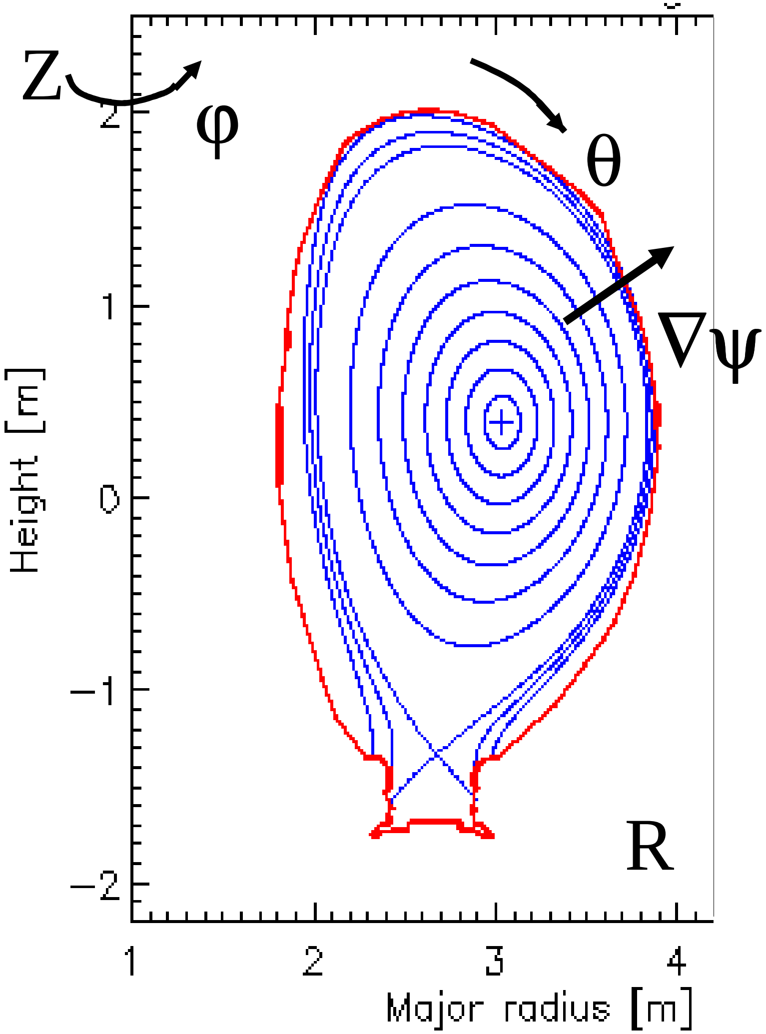
3) Anti-correlation of fluxes: artefact or fact?

What do you have to know about tokamak plasmas?

- Weakly collisional plasmas in a toroidal magnetic configuration
- Field lines generate magnetic surfaces $\psi(R,Z)$=cte
- "Modes" ~ $e^{i(n\varphi+m\theta)}$

- n,m: toroidal and poloidal wave numbers

- n=0: axisymmetric modes



Gyrokinetic approach is the appropriate framework to compute collisional and turbulent transport

- Gyrokinetic Fokker-Planck equation

Coordinates $\mathbf{z}=(\mathbf{x}_G, v_{//}, \mu)$

$$\frac{\partial F}{\partial t}+\frac{1}{J}\frac{\partial}{\partial \mathbf{z}}\cdot\left(\frac{d\mathbf{z}}{dt}JF\right)=C(F)$$

Multi-species collision operator,

Catto 77, Xu & Rosenbluth 91, Brizard 04, Abel 08, Sugama 08, Belli 08, Esteve 15

+ Maxwell equations

- Guiding-center velocity

$$\frac{d\mathbf{x_G}}{dt}=\mathbf{v}_D+\mathbf{v}_E+v_\parallel \mathbf{b}$$

motion along the field lines

Curvature and ∇B drift velocity ≈ vertical

ExB drift velocity $\mathbf{v}_E=\frac{\mathbf{E}\times\mathbf{B}}{B^2}$

Radial fluxes: diffusion and pinch velocities

- Particle flux

$$\mathbf{\Gamma} = \int d^3\mathbf{v} F(\mathbf{v}_D + \mathbf{v}_E + v_\parallel \mathbf{b})$$

- Look for fluxes vs gradients, e.g.

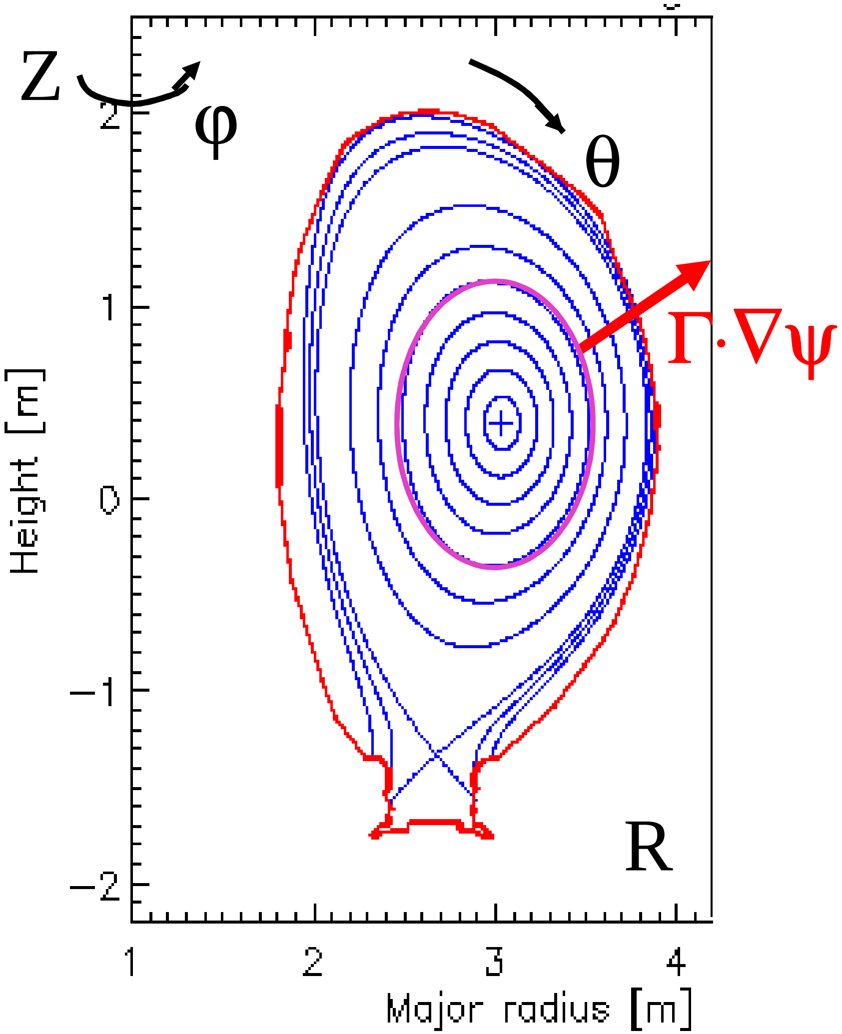
$$\Gamma^\psi = \langle \mathbf{\Gamma} \cdot \nabla\psi \rangle$$

average over magnetic surfaces

- Multi-species → several thermodynamic forces

→ pinch velocity

$$\Gamma^\psi = -D\frac{d\langle N\rangle}{d\psi} + V\langle N\rangle$$



How can turbulence and collisional contributions be identified ?

- Usual definitions of particle fluxes

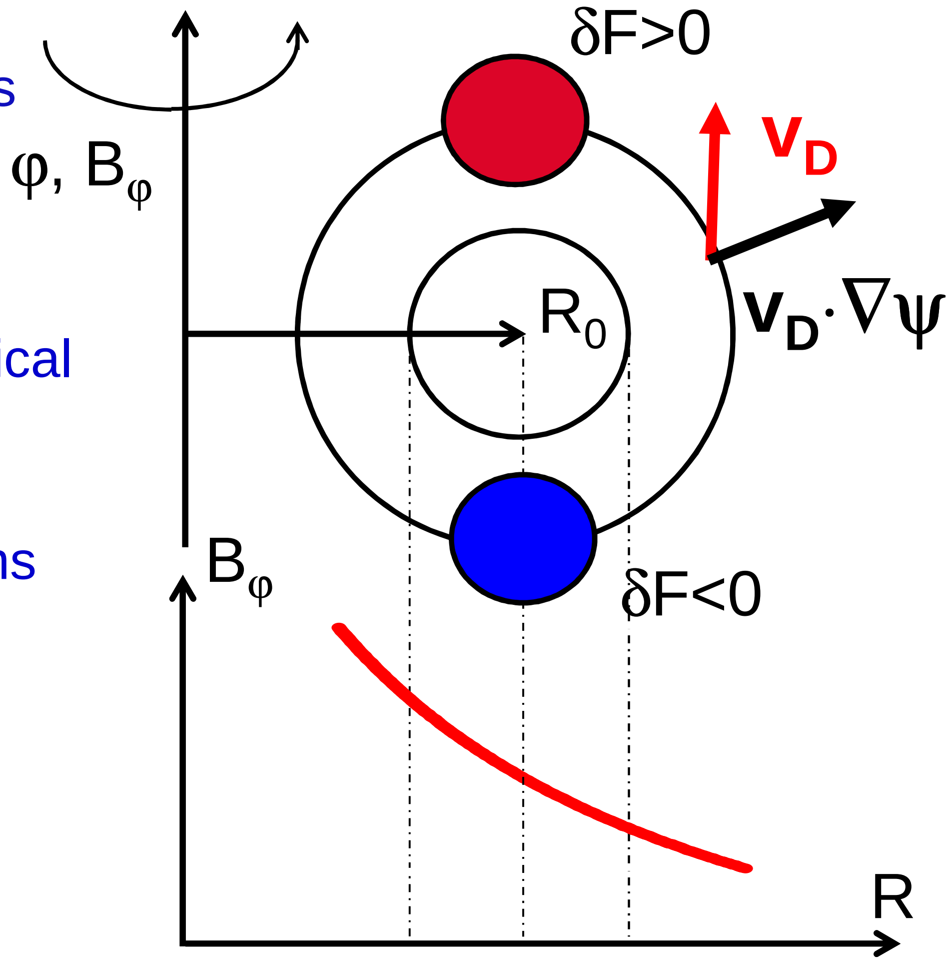
$$\Gamma_E = \int d^3\mathbf{v} F \mathbf{v}_E \qquad \approx \text{ turbulent}$$

$$\Gamma_D = \int d^3\mathbf{v} F \mathbf{v}_D \qquad \approx \text{ neoclassical}$$

- $\langle \Gamma_D \cdot \nabla\psi \rangle = 0$ without collisions

- $\mathbf{v}_D \cdot \nabla\psi \simeq v_D \sin\theta$

→ neoclassical flux is related to up-down asymmetries of F



Collisional particle fluxes are proportional to the parallel drag force

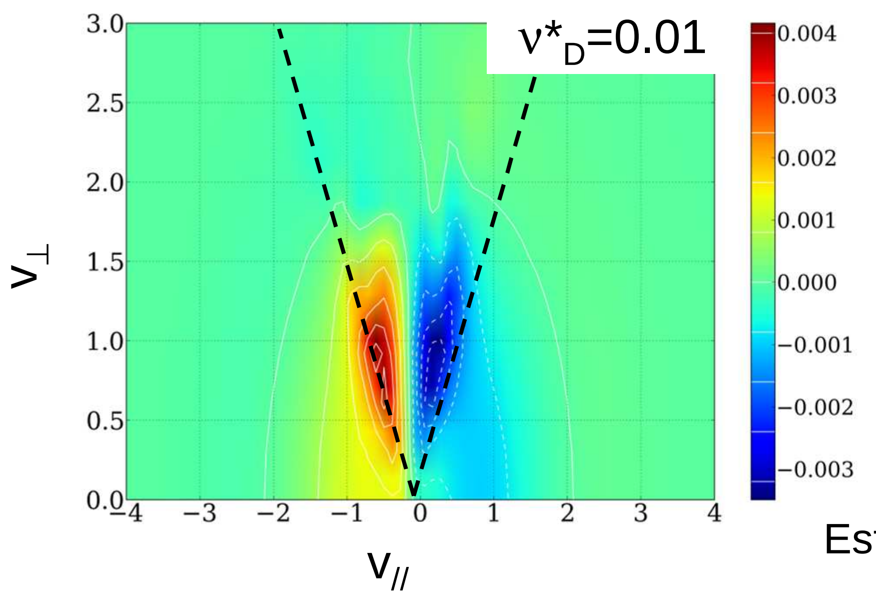
- Neoclassical flux

$$\Gamma^{\psi} = -\frac{B_T R}{e}\left\langle \frac{R_{\parallel}}{B} \right\rangle$$

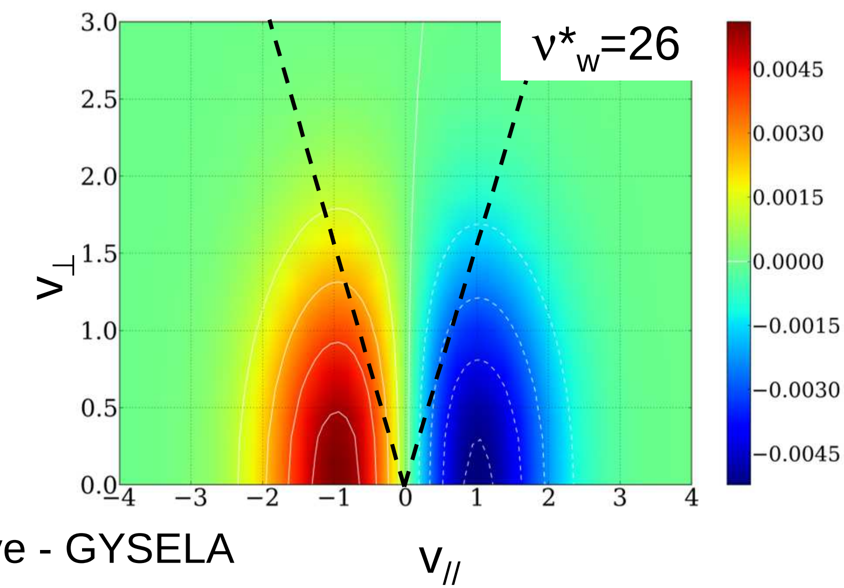
$R_{//}$ is the collisional drag force $$R_{\parallel} = \int d^3\mathbf{v}\, m v_{\parallel} C(F)$$

- Depends on the shape of the distribution function in phase space

F-F_{maxw} Deuterium



F-F_{maxw} Tungsten



Esteve - GYSELA

Neoclassical transport is related to large scale flow cells

- Poloidal asymmetries are essential
- Fluid drag force (impurities)

$$\Gamma^{\psi} = -\frac{B_T R}{e}\left\langle \frac{R_{\parallel}}{B} \right\rangle$$

depends on θ

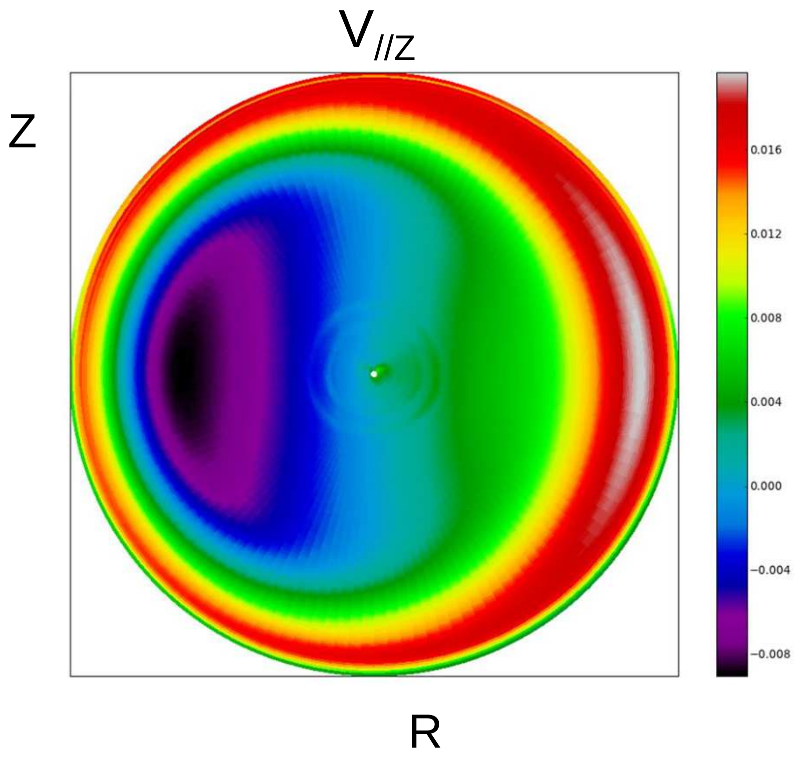
$$R_{\parallel Zi} = -N_Z m_Z \nu_{Zi}\left[V_{\parallel Z} - V_{\parallel i} + C_Z \frac{q_{\parallel i}}{N_i T_i}\right]$$

friction — thermal force

- Pfirsch-Schlüter convection cell due to perpendicular compressibility Pfirsch & Schlüter 1962, Hinton & Hazeltine 76

$$\nabla \cdot \Gamma = 0$$

- Relates parallel flows to perp. gradients



Interplay of collisional and turbulent fluxes: a brief history

- Interplay via kinetic processes : turbulence responsible for scattering in the velocity space McDevitt 13
- Interplay via large scale flows:

- mean flows: i) neoclassical flow → stress tensor → toroidal spin-up Parra 10, Barnes 13, ii) turbulence → stress tensor → poloidal spin-up Dif-Pradalier 09
- zonal flows sensitive to collisions Vernay 12, Oberparleiter 16
- poloidal flow asymmetries → modify fluxes Esteve 16

- Anti-correlated fluxes: toroidal momentum Abiteboul 11, Idomura 14, particles Esteve 16, heat transport near threshold Vernay 12

Momentum transport

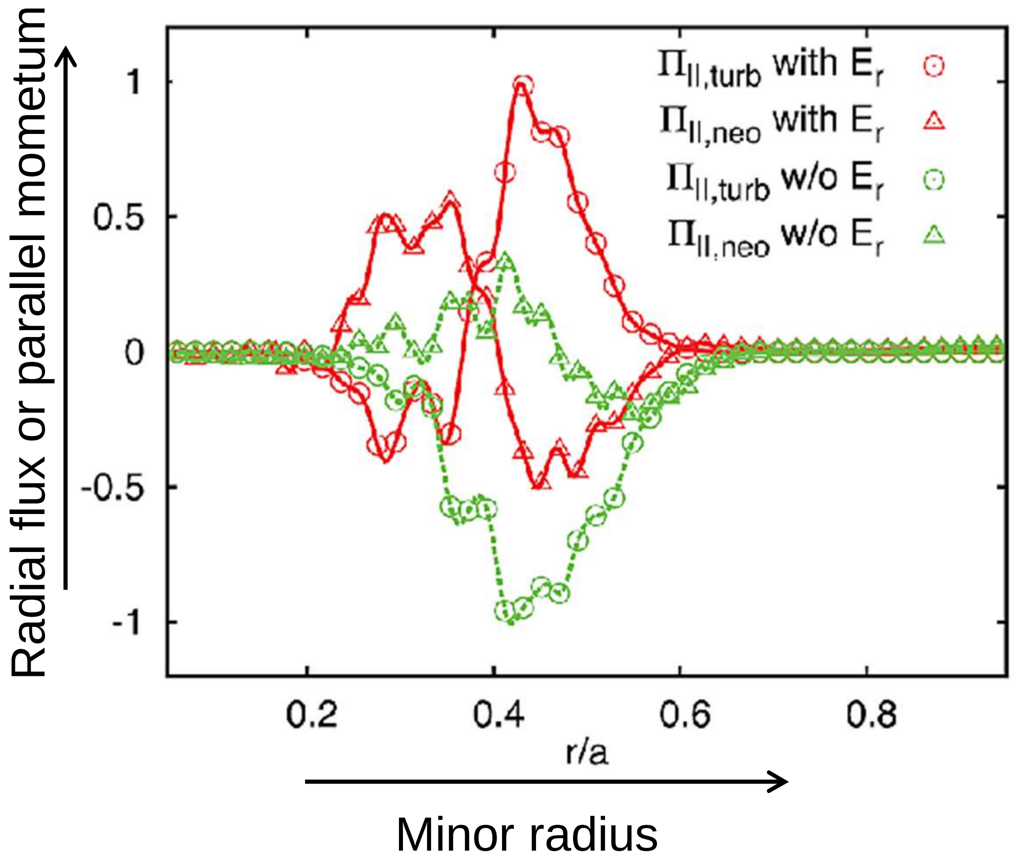
- Near cancellation of neoclassical and turbulent momentum fluxes of parallel momentum Abiteboul 11, Idomura 14

$$\Pi^{\psi}_{E\parallel} = m\int d^3\mathbf{v} F v^{\psi}_{E} v_{\parallel}$$

$$\Pi^{\psi}_{D\parallel} = m\int d^3\mathbf{v} F v^{\psi}_{D} v_{\parallel}$$

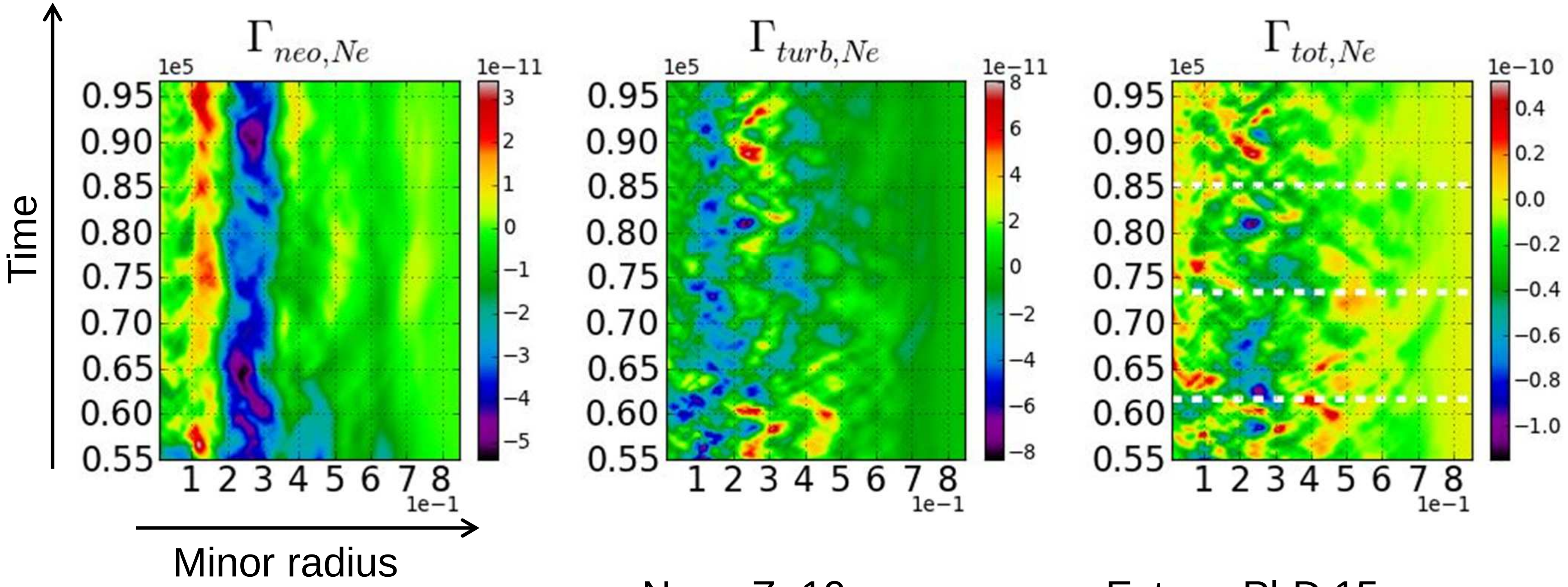
- Seems to be related to the mean radial electric field

Idomura 14



Particle transport

- Competition at medium Z: neoclassical ≈ turbulent transport.
- Negative correlation of turbulent and neoclassical fluxes



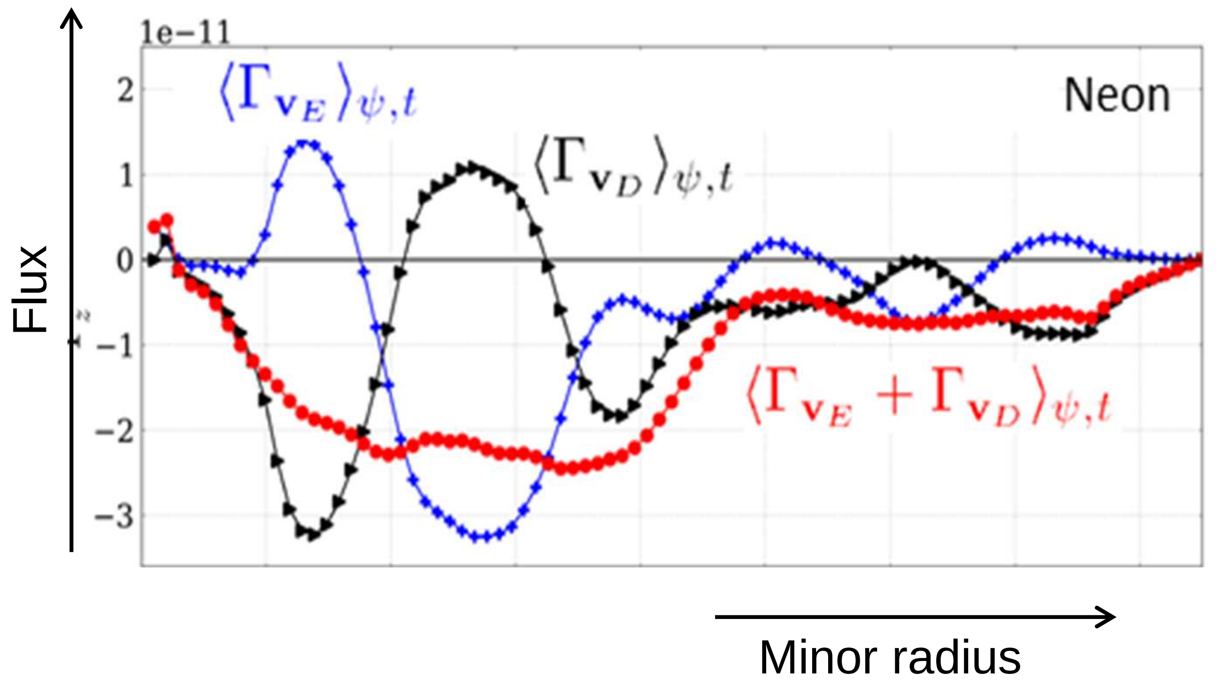
Neon Z=10

Esteve PhD 15

Evidence of flux anti-correlation

- Anti-correlation quite visible for medium Z impurities
- Less pronounced for high Z particles

Esteve PhD 15

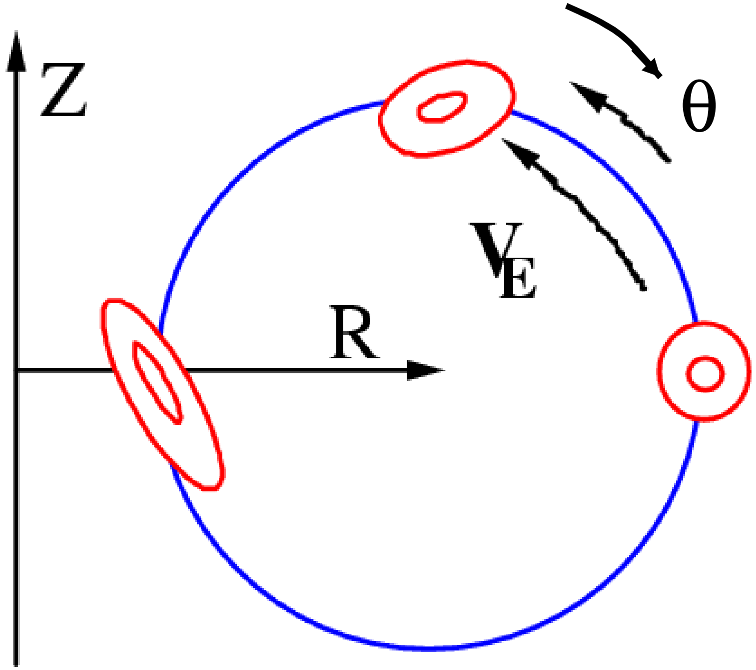


Components of the turbulent Reynolds stress are correlated

- Mean radial and parallel wavenumbers are correlated for a given symmetry breaking mechanism

$$K_\psi = K_\theta \theta_{\mathbf{k}}$$
$$K_\parallel = C_k K_\theta \theta_{\mathbf{k}}$$

Symmetry breaking ~$\mathbf{V_E}$'



- Correlated turbulent fluxes of poloidal and parallel momentum

$$\Pi_{E\theta}^{\psi} = m \int d^3\mathbf{v} F v_E^\psi v_{E\theta}$$
$$\Pi_{E\parallel}^{\psi} = m \int d^3\mathbf{v} F v_E^\psi v_\parallel$$

Poloidal spin-up
→ poloidal flow

Flux of // momentum

A quasi-linear calculation predicts anti-correlated momentum fluxes

- Turbulence intensity is inhomogeneous in the poloidal plane

→ Reynolds stress is modulated

→ poloidal asymmetries of E×B flow → F

→ neoclassical flux of parallel momentum

$$\Pi^{\psi}_{D\parallel} = m \int d^3\mathbf{v} F v^{\psi}_{D} v_{\parallel}$$

- Correlated radial fluxes of parallel momentum

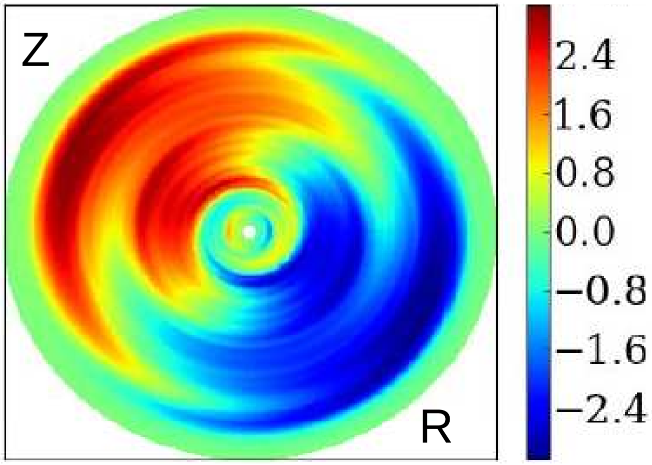
$$\Pi^{\psi}_{D\parallel} = qm \sum_{\mathbf{k}} |v_{E\mathbf{k}}|^2 \theta_{\mathbf{k}}$$

$$\Pi^{\psi}_{E\parallel} = -\pi m \sum_{\mathbf{k}} \tau_{\mathbf{k}} (\mathbf{k} \cdot \mathbf{v}_D) |v_{E\mathbf{k}}|^2 \theta_{\mathbf{k}}$$

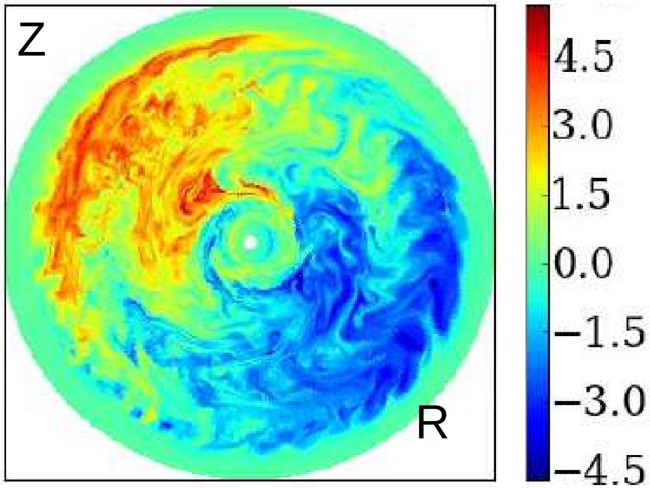
Anti-correlation ← $-$; $\tau_{\mathbf{k}} (\mathbf{k} \cdot \mathbf{v}_D) \approx 1$

Esteve 15

n=0 impurity density



n≠0 impurity density



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Conclusion

- Interplay of collisional and turbulent transport – several possible reasons:

- diffusion in the velocity space → anisotropy of the distribution function

- large scale flows: mean, zonal and poloidal asymmetries

- Indications of anti-correlated neoclassical and turbulent fluxes

- effect is large for momentum flux, moderate for particle flux (Z dependent), small for heat transport

- likely related to poloidal asymmetries of the flow

- can be explained by quasi-linear theory

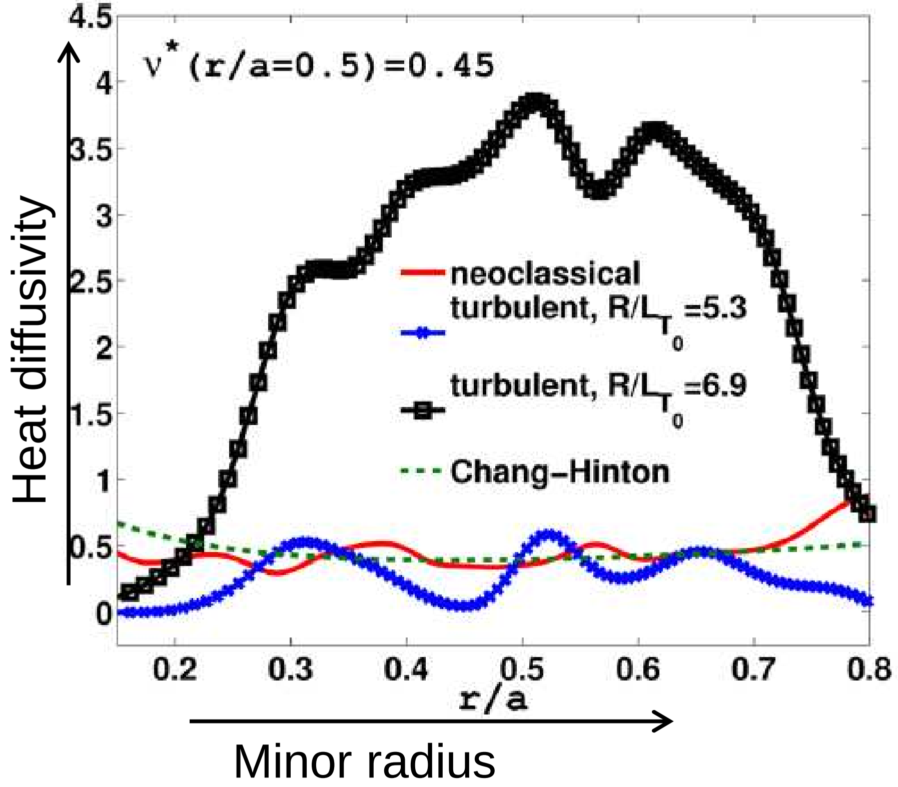
An illustration of "non-additivity"

- Non additivity of ion diffusivities
  Vernay 12

$$\chi_H^{\rm tot}(\nu^*) > \chi_H^{\rm turb}(\nu^*=0) + \chi_H^{\rm neo}(\nu^*)$$

- Explained by the effect of collisions on zonal flow dynamics
- Some hint of anti-correlated fluxes.

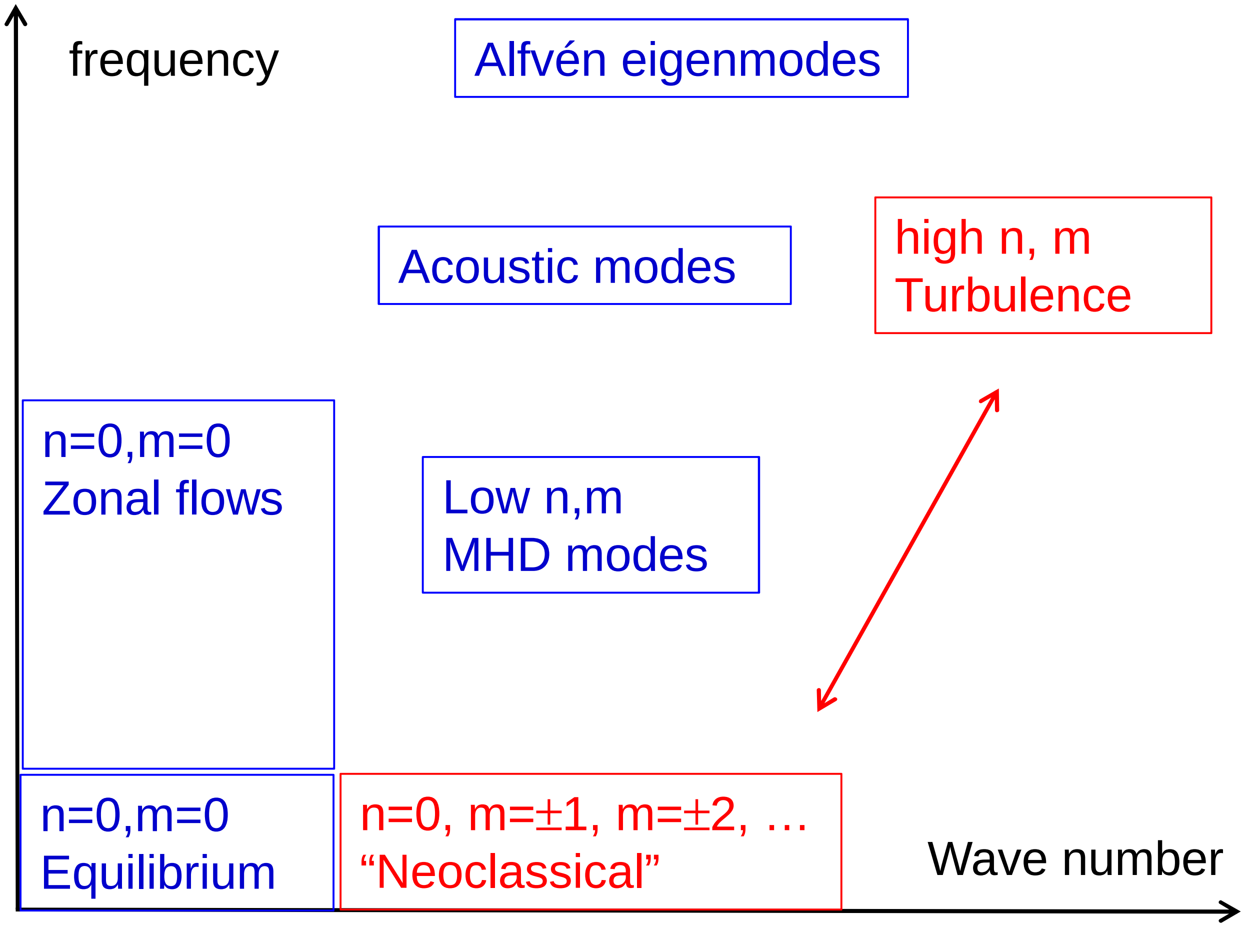
Vernay 12



Scale separation and additivity principle

- Disparate scales in a tokamak
- Multiscale problem
- Scale separation → fluxes are additive

$$\Gamma_{\psi} = \Gamma_{\psi,neo} + \Gamma_{\psi,turb}$$



n,m = toroidal, poloidal wavenumbers

Collision operator

$$C_{ab} = C_{v,ab} + C_{d,ab} + C_{R,ab} + C_{\parallel,ab} + C_{pol,ab}$$

$$C_{v,ab}(\bar{F}_a) = \frac{1}{2}\frac{1}{B_\parallel^*}\frac{1}{v_\perp}\frac{\partial}{\partial v_\perp}\left[B_\parallel^* F_{M0a}\nu_{v,ab}v_\perp^2\left(v_\perp\frac{\partial \bar{g}_a}{\partial v_\perp} + v_\parallel\frac{\partial \bar{g}_a}{\partial v_\parallel}\right)\right]$$
$$+\frac{1}{2}\frac{1}{B_\parallel^*}\frac{\partial}{\partial v_\parallel}\left[B_\parallel^* F_{M0a}\nu_{v,ab}v_\parallel\left(v_\perp\frac{\partial \bar{g}_a}{\partial v_\perp} + v_\parallel\frac{\partial \bar{g}_a}{\partial v_\parallel}\right)\right],$$

$$C_{d,ab}(\bar{F}_a) = \frac{1}{2}\frac{1}{B_\parallel^*}\frac{1}{v_\perp}\frac{\partial}{\partial v_\perp}\left[B_\parallel^* F_{M0a}\nu_{d,ab}v_\perp v_\parallel\left(v_\parallel\frac{\partial \bar{g}_a}{\partial v_\perp} - v_\perp\frac{\partial \bar{g}_a}{\partial v_\parallel}\right)\right]$$
$$+\frac{1}{2}\frac{1}{B_\parallel^*}\frac{\partial}{\partial v_\parallel}\left[B_\parallel^* F_{M0a}\nu_{d,ab}v_\perp\left(-v_\parallel\frac{\partial \bar{g}_a}{\partial v_\perp} + v_\perp\frac{\partial \bar{g}_a}{\partial v_\parallel}\right)\right],$$

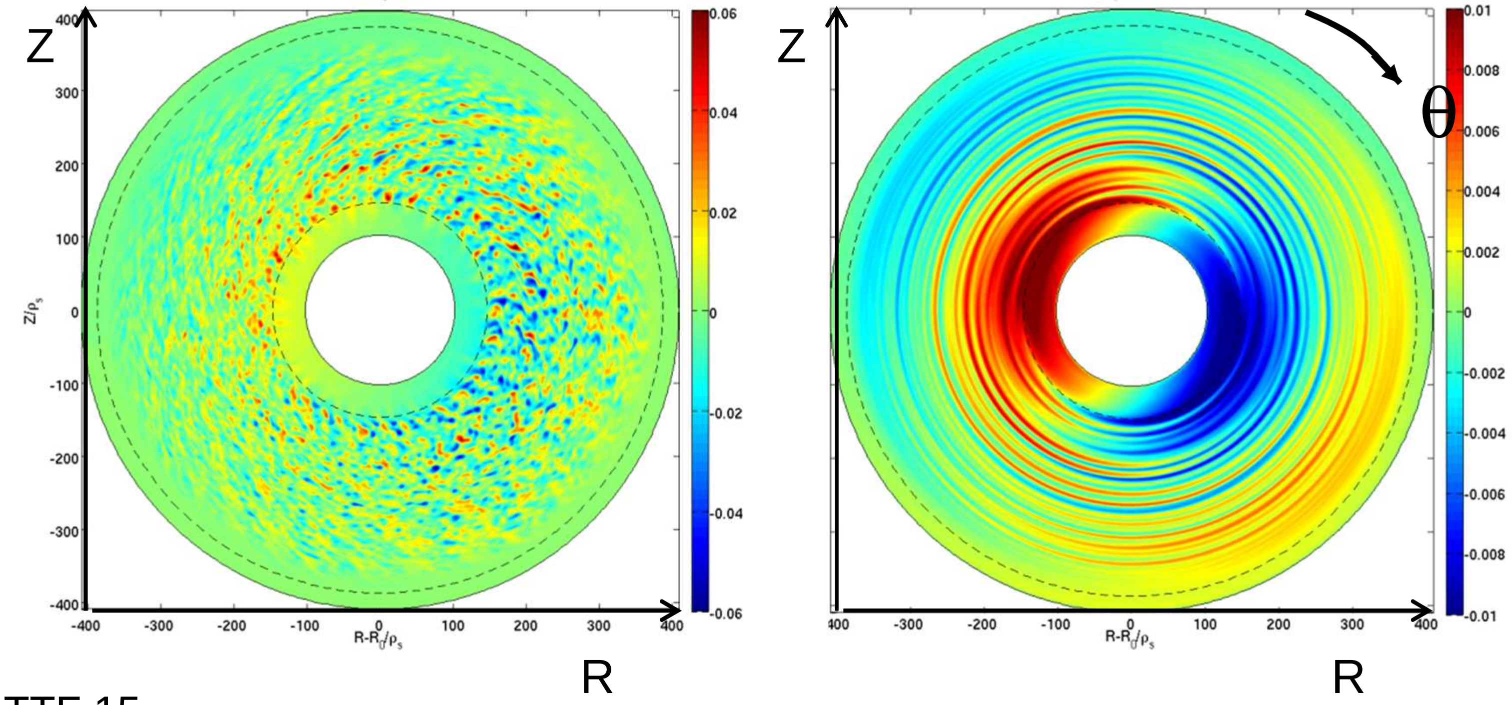
$$C_{\parallel,ab}(\bar{F}_a) = -\nu_{s,ab}\frac{m_a}{T_a}\langle \mathbf{v}\cdot(\mathbf{U}_{d,a} - \mathbf{U}_{ba})\rangle_\gamma F_{M0a}$$

$$\bar{g}_a = \bar{f}_a - \frac{m_a}{T_a}\langle \mathbf{v}\cdot\mathbf{U}_{d,a}\rangle_\gamma - \frac{m_a v^2}{2T_a}J\cdot q_{ba}$$

Poloidal asymmetries of the flows seem to be involved

- Momentum sources + Reynolds stress drive flow poloidal asymmetries

Electric potential (m, n≠0 modes) | Electric potential (m=1, n=0 mode)



Sarazin TTF 15

Collision operator