DE LA RECHERCHE À L'INDUSTRIE

Impact of **asymmetries** on **transport** in **tokamak plasmas**

(flux driven gyrokinetic simulations)

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Outline

- **Basics & critical issues of transport in tokamak plasmas**
  - Transport & confinement
  - Transverse drifts & gyrokinetic framework

- **Impact of large scale asymmetries on core impurity transport**
  - Poloidal asymmetries: experimental evidence & issues
  - Turbulence-driven asymmetry… & anisotropy
  - Impact on collisional impurity transport

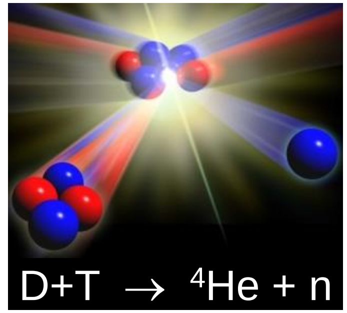
- **Impact of asymmetric boundary layer on edge turbulence**
  - Modelling the unconfined "Scrape-Off Layer"
  - The tail & the dog…

Fusion & confinement

- **Fusion viability** (self-heating) → **Lawson criterion**

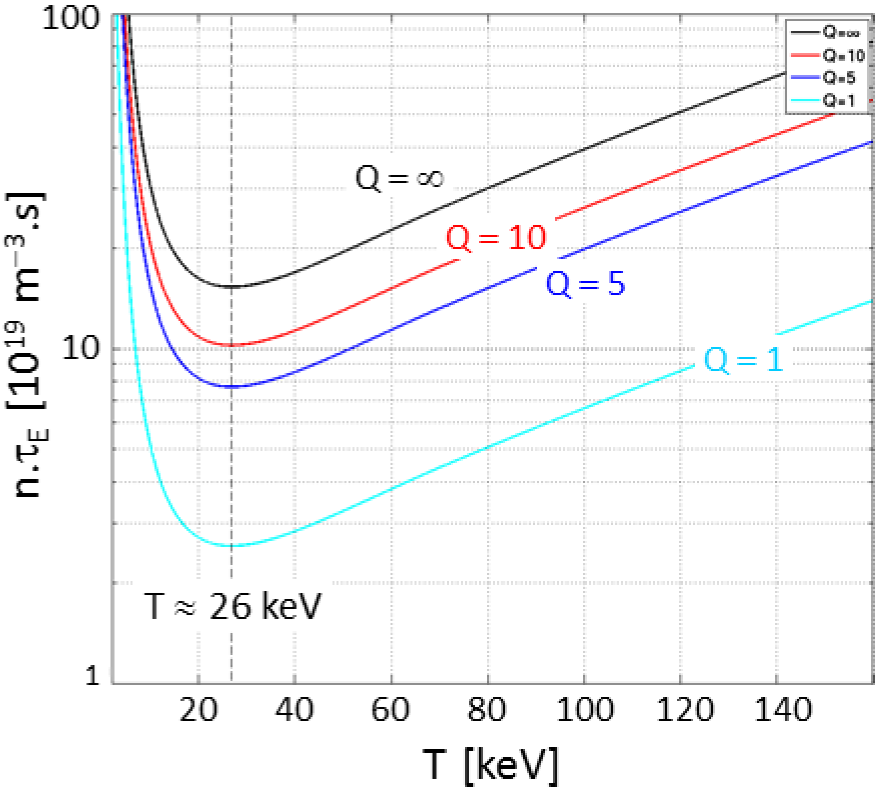
$n_i\ \tau_E > F(T)$

- Governed by reaction rate $\langle\sigma v\rangle$
- Depends on temperature T only
- Minimal at $T \approx 26$ keV



Energy confinement time:

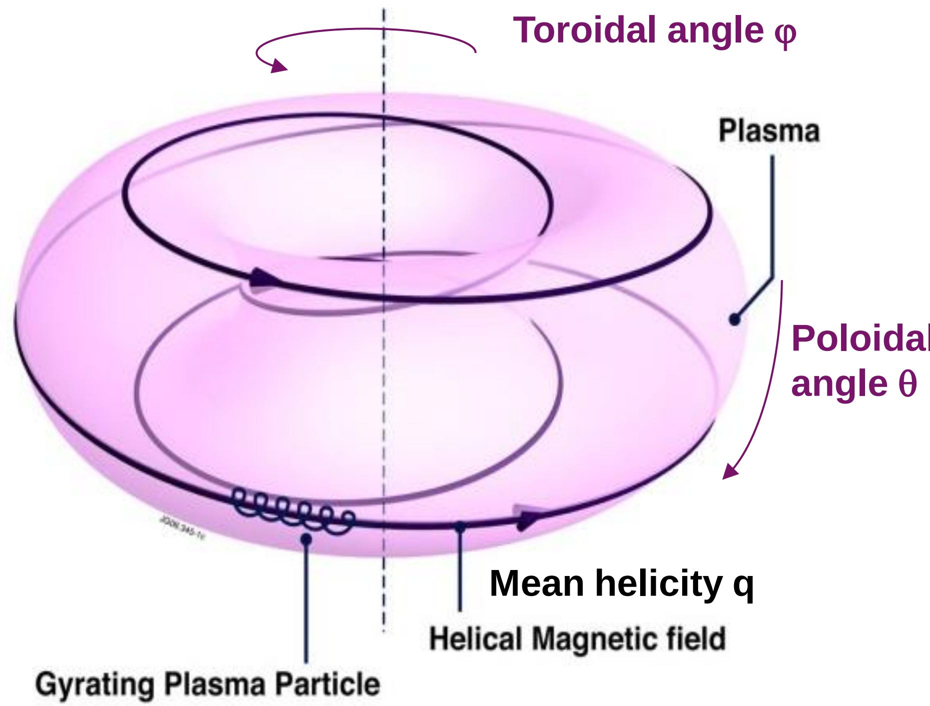
$$\tau_E = \frac{\text{Energy Content}}{\text{Lost Power}}$$



- **Magnetic confinement:**
  - Aim = maximizing τ_E (≈ 5 s)
  - $n_i \approx 10^{20} m^{-3}$ constrained my macroscopic instabilities

Tokamaks: confinement & transport

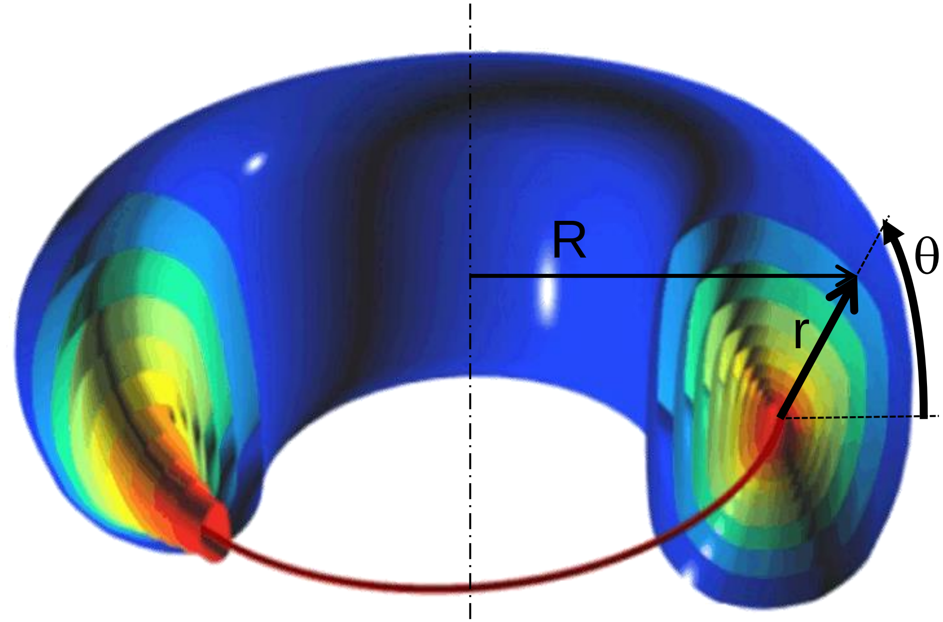
- **Tokamak**
  - Helical magnetic field lines on nested toroidal surfaces ψ=cst
  - Constant **j**, P on magnetic surfaces ($\mathbf{j}\times\mathbf{B}=\nabla P$ ↔ Geostrophic balance)



$$\rho_* \equiv \rho_i / a \approx 2.10^{-3} << 1$$

Tokamaks: confinement & transport

- **Tokamak**
  - Helical magnetic field lines on nested toroidal surfaces ψ=cst
  - Constant **j**, P on magnetic surfaces ($\mathbf{j}\times\mathbf{B}=\nabla P \leftrightarrow$ Geostrophic balance)
  - Intrinsic in/out asymmetry $B(r,\theta)\propto R^{-1}$ $\Rightarrow$ passing & trapped orbits



$\rho_* \equiv \rho_i / a << 1$

- **3 motion invariants + 3 periodic directions $\Rightarrow$ confinement**
  - ~~If axisymmetry: $P_\varphi=-e\psi+mRv_\varphi$~~ $\rightarrow$ Broken by Turbulence
  - ~~If steady **E** and **B** fields: $\mathcal{E}$~~
  - ~~If collisionless: $\mu=\mathcal{E}_\perp/B$~~ $\rightarrow$ Broken by Collisions

  $\Rightarrow$ Transport

Particle trajectories: adiabatic limit

$$\frac{d\mathbf{v}}{dt} = \frac{e_s}{m_s}\left\{\mathbf{E}(\mathbf{x}(t),t) + \mathbf{v}\times\mathbf{B}(\mathbf{x}(t),t)\right\}$$

- Adiabatic limit framework:
  Magnetic field evolves slowly with respect to ω_{ci} and ρ_s

$$\partial_t \log B \sim \mathbf{v}\cdot\nabla \log B \ll \omega_c \;\Rightarrow\; \frac{\rho_s}{R} \sim \frac{mv_\parallel}{eBR} \sim \frac{mv_\perp}{eBR} \ll 1$$

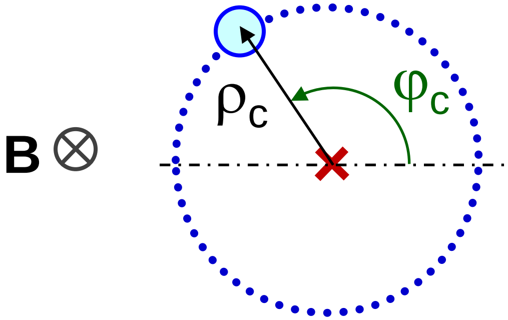
- Scale separation: gyro-average = average over fast time scale

$$\begin{cases} \mathbf{v} = \mathbf{v}_G + \tilde{\mathbf{v}} \\ \mathbf{B} = \mathbf{B}_G + \tilde{\mathbf{B}} \\ \mathbf{E} = \mathbf{E}_G + \tilde{\mathbf{E}} \end{cases}$$

with

$$\langle\tilde{\mathbf{y}}\rangle \doteq \oint \frac{d\varphi_c}{2\pi}\tilde{\mathbf{y}} = 0$$

$$\tilde{\mathbf{B}} / \mathbf{B}_G << 1$$



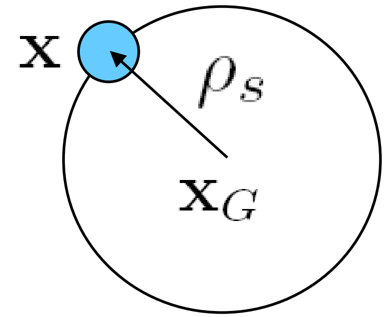
- Perturbation theory – Solving at leading orders in $\epsilon = \rho_s / R \ll 1$

$$\rho_* = \rho_i / a << 1$$

Scale separation: gyro-motion + drifts

- Fast motion → cyclotron motion ($\mathbf{B}_G \approx \mathbf{B}(\mathbf{x}_G)$):

$$\frac{\mathrm{d}\tilde{\mathbf{v}}}{\mathrm{d}t} = \frac{e}{m}\tilde{\mathbf{v}} \times \mathbf{B}_G \longrightarrow \tilde{\mathbf{v}} = \frac{e}{m}\boldsymbol{\rho}_s \times \mathbf{B}_G \doteq \mathbf{v}_c$$



- Slow motion → transverse drifts:

$$\frac{\mathrm{d}\mathbf{v}_G}{\mathrm{d}t} = \frac{e}{m}\left\{\mathbf{E}_G + \mathbf{v}_G \times \mathbf{B}_G + \underbrace{\langle \tilde{\mathbf{v}} \times \tilde{\mathbf{B}} \rangle}_{= -\frac{\mu}{e}\nabla B_G}\right\}$$

with $\tilde{\mathbf{B}} \simeq (\boldsymbol{\rho}_s \cdot \boldsymbol{\nabla})\mathbf{B}_G$

$$\mathbf{E}_G = \langle \mathrm{e}^{\boldsymbol{\rho}_s \cdot \boldsymbol{\nabla}} \rangle \, \mathbf{E}$$

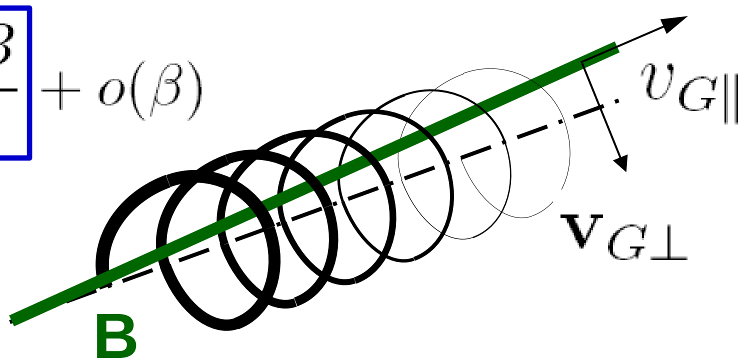
Gyro-average $J(k_\perp \rho_s)$

Adiabatic invariant $\mu = \dfrac{m v_c^2}{2B}$

Projection on ⊥ plane:

$$\mathbf{v}_{G\perp} \simeq \boxed{\frac{\mathbf{B} \times \boldsymbol{\nabla}\langle\phi\rangle}{B^2}} + \boxed{\frac{m {v_{G\parallel}}^2 + \mu B}{eB}\,\frac{\mathbf{B} \times \boldsymbol{\nabla} B}{B^2}} + o(\beta)$$

electric drift $\mathbf{v}_E$ — curvature & ∇B drifts $\mathbf{v}_d$

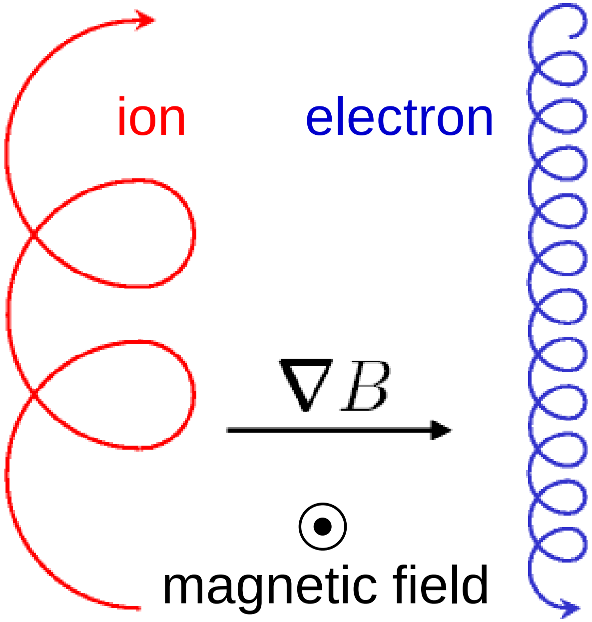


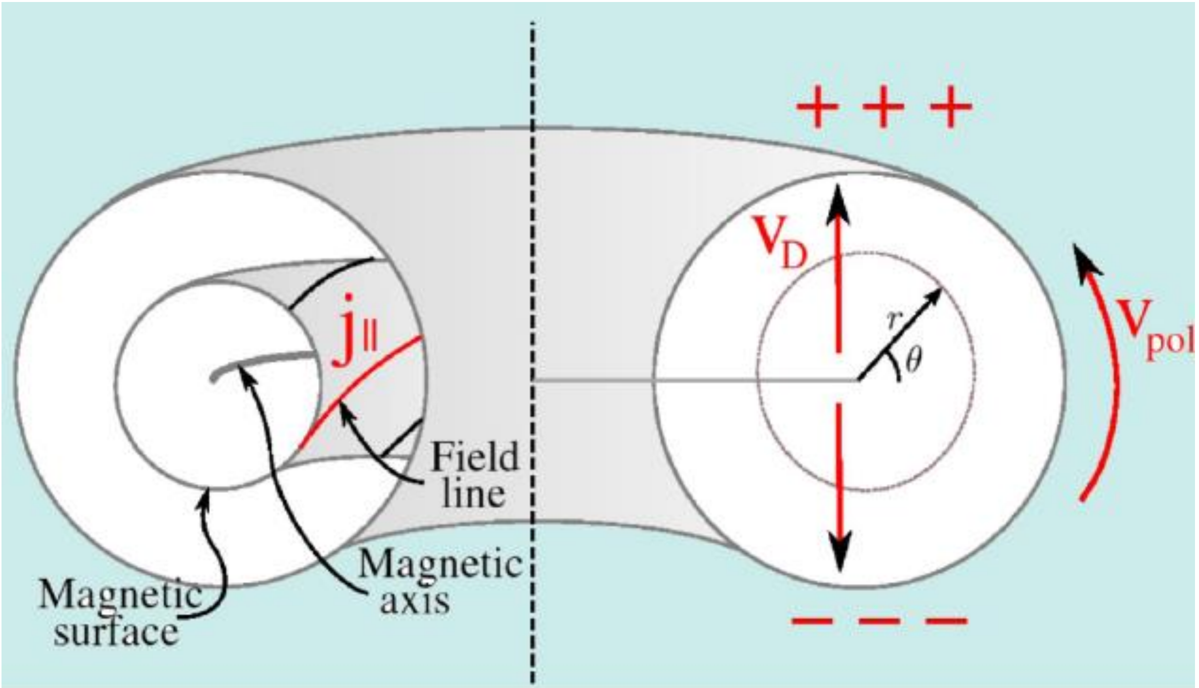
Physics of Curvature & ∇B Drifts

$$\mathbf{v}_d = \frac{m v_{G\parallel}^2 + \mu B}{eB} \frac{\mathbf{B} \times \nabla B}{B^2} + \frac{m v_{G\parallel}^2}{eB} \frac{\nabla \times \mathbf{B}}{B} \Big|_\perp$$

⇒ Vertical charge separation (poloidal asymmetry)

$$\approx \frac{\rho_i}{R} v_T$$



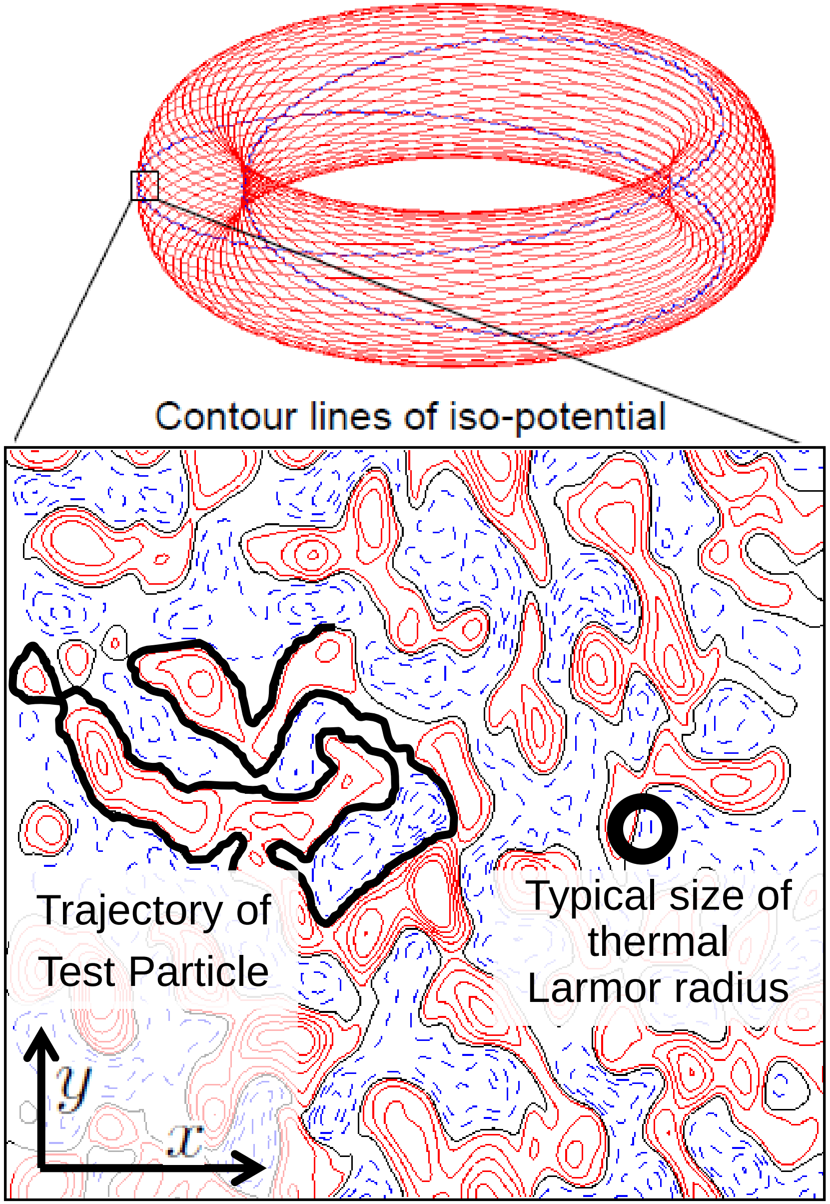


- Return currents: parallel electron current (Pfirsch-Schlüter)
  polarization ion current

Physics of Electric Drift

$$\mathbf{v}_E = \frac{\mathbf{B} \times \nabla \langle \phi \rangle}{B^2}$$ $\Rightarrow$ Turbulent transport

$$v_E \approx (k_\perp \rho_i) \frac{e\phi}{T} v_T$$



- ϕ analogous to stream function in neutral fluid dynamics
- At leading order,
  particles move at $\phi=c^{st}$ (if $\partial_t \phi=0$ & $B=C^{st}$)

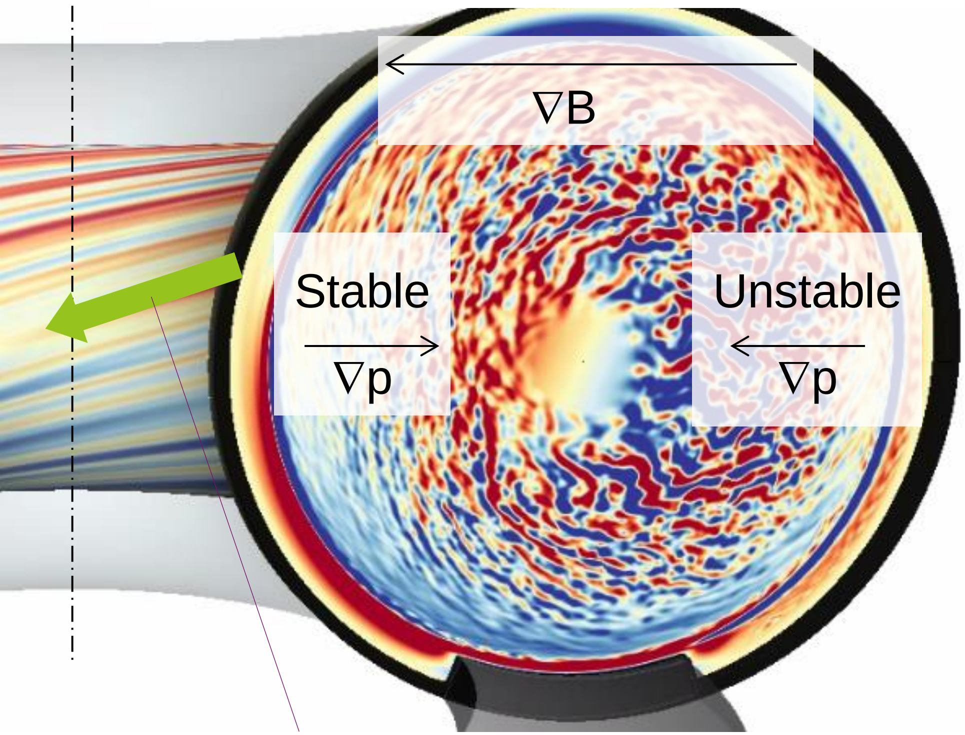
$$d_t \mathbf{x}_\perp = \mathbf{v}_E$$

(y, x) are canonically conjugated for the Hamiltonian $H = \phi/B$

Turbulence: interchange instability

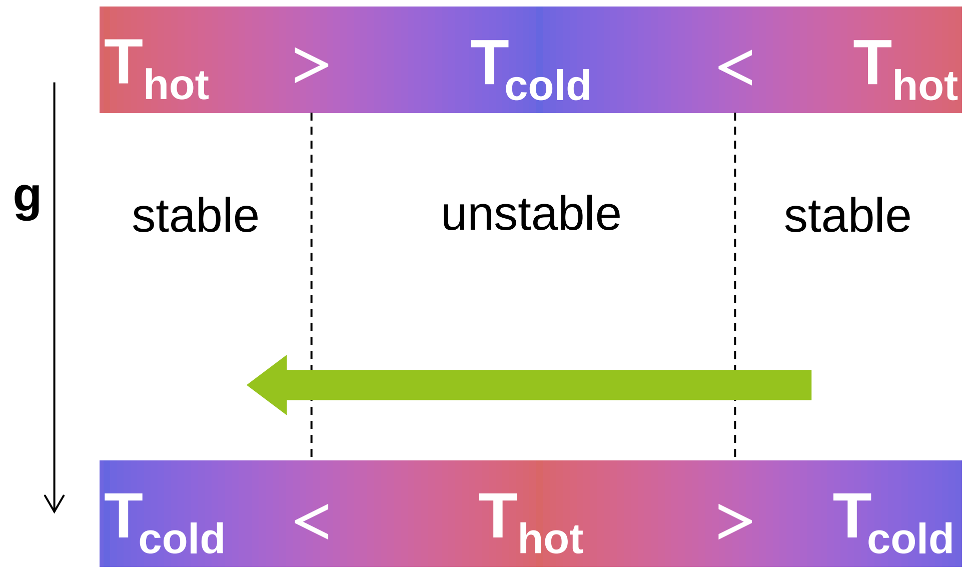
- **Pressure gradient + Field line curvature ⇒ instabilities ⇒ micro-turbulence**
  - Interchange: instability if $\nabla p . \nabla B > 0$
  - Fluctuations of **E** & **B** fields

Interchange



Stable/unstable coupling through // current

Rayleigh-Bénard



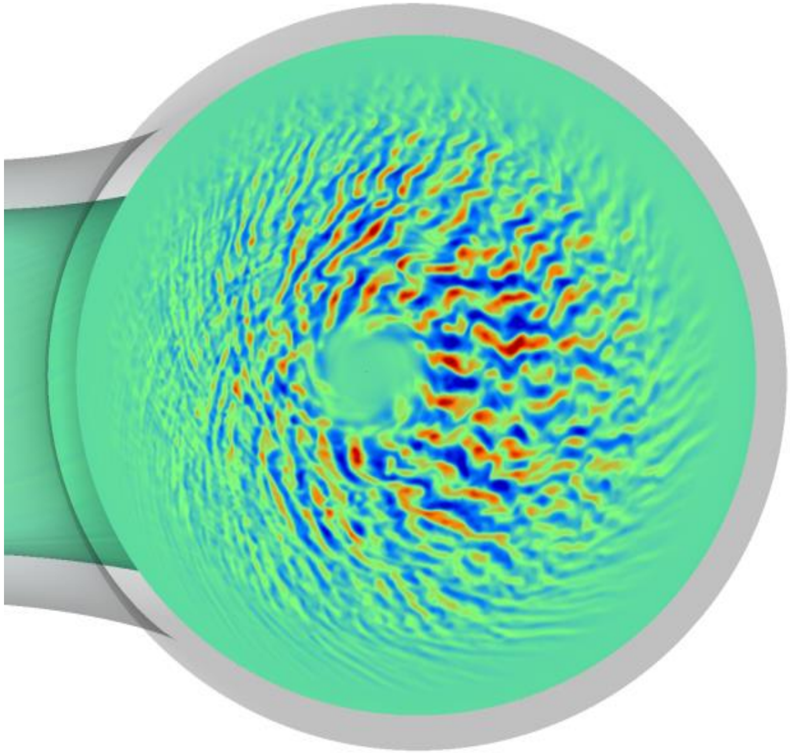
Heat ⊥ transport = thermoconvection

Tokamak plasma turbulence

- Ballooned: in/out asymmetry
- Anisotropic turbulence (quasi-2D):
  $k_{//} qR \sim k_{\perp}\rho_i < 1$
- Small ⊥ scale: $\rho_* << 1$ $(\lambda_{corr} \sim a\, \rho_*)$
  Fluid analogue: Rossby $Ro = U / \Omega_0 L << 1$
- Time scale:
  $\nu_{coll} \approx 10^3 << \omega_{turb} \approx 10^5 << \omega_{ci} \approx 10^8\ s^{-1}$

Governs **heat** (& particle, momentum) **transport**
(effective diffusivity $\approx 1 m^2/s$)

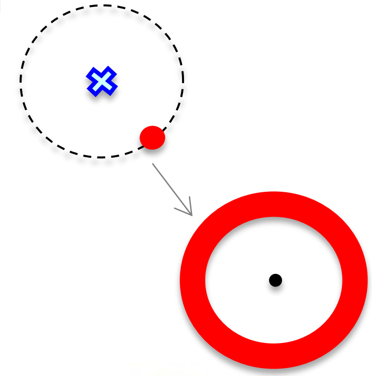
Fluctuations of electric potential
GYSELA
[Grandgirard CPC 2016]



Adequate framework: gyrokinetics

Core plasma **weakly collisional** (λ_{mfp}~10^4 m)
Trapped electron turbulence ⇒ **Kinetic description** mandatory
Fluid assumes long wavelength $k_\perp \rho_s << 1$

[Littlejohn PoF 1981; Brizard-Hahm RMP 2007; Tronko-Brizard PoP 2015]



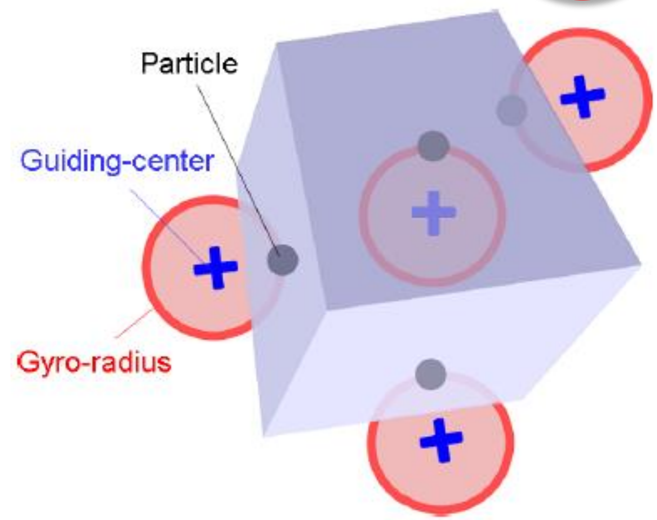
- From **6D kinetics** to **5D gyrokinetics** via **phase space reduction**
  - Particle → Gyro-center
  - Vlasov f($\mathbf{x}$,$v_{//}$,μ,φ_c,t) → Gyrokinetic equation f_G($\mathbf{x}_G$,$v_{G//}$,μ,t)

$$\frac{\partial \bar{f}}{\partial t} + (\mathbf{v}_{G\perp} + \mathbf{v}_{G\parallel}).\boldsymbol{\nabla} \bar{f} + \frac{dv_{G\parallel}}{dt}\frac{\partial \bar{f}}{\partial v_{G\parallel}} = C(\bar{f}) + S$$

- **Maxwell's eqs** involve PARTICLE density & current
  - Requires non-trivial link between f & f_G
  - **Quasi-neutrality** $n_e(x,t) = \Sigma_i Z_i n_i(x,t)$

$$\int d^3v\, f_{Ge} = \int d^3v\, J.f_{Gi} + n_{pol}$$

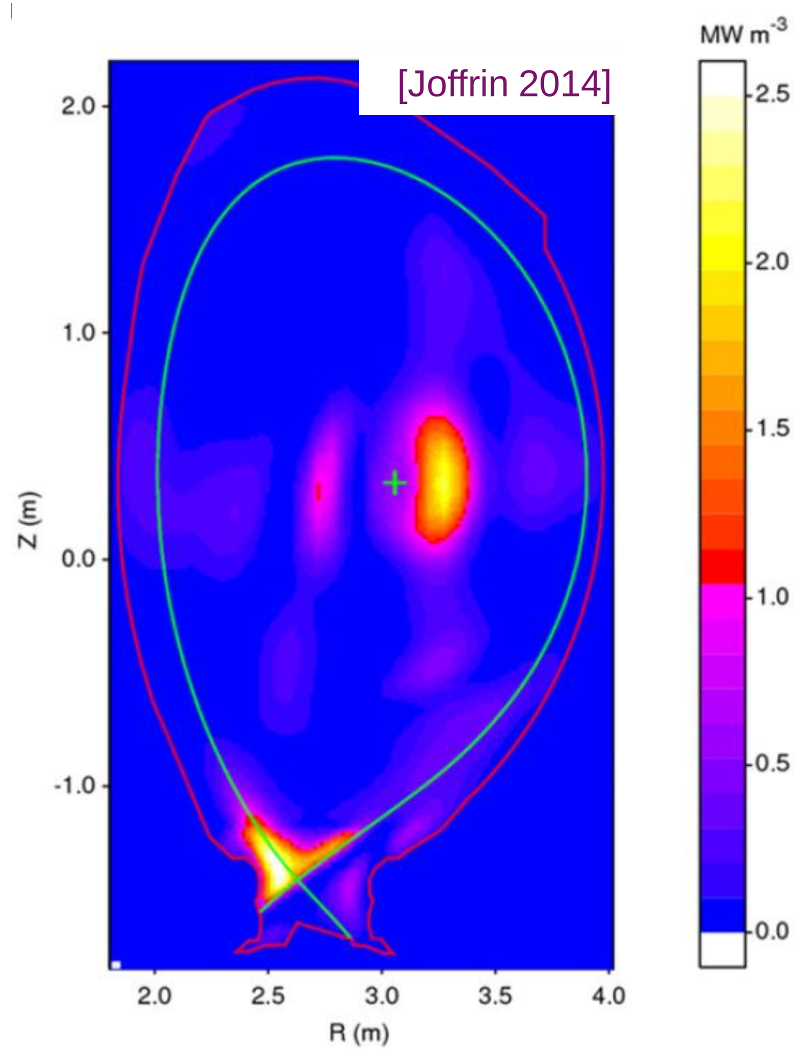
$$\simeq n_{eq,s}\, \rho_s^2 \nabla_\perp^2 \left(\frac{e_s \phi}{T_s}\right)$$



Motivations: impurities

- Understanding / predicting / controlling impurity transport
  - Dilution at low Z
  - Radiation at large Z (tungsten)

⇒ Synergy turbulent/collisional transport: role of poloidal asymmetries?



Motivations: impurities & edge

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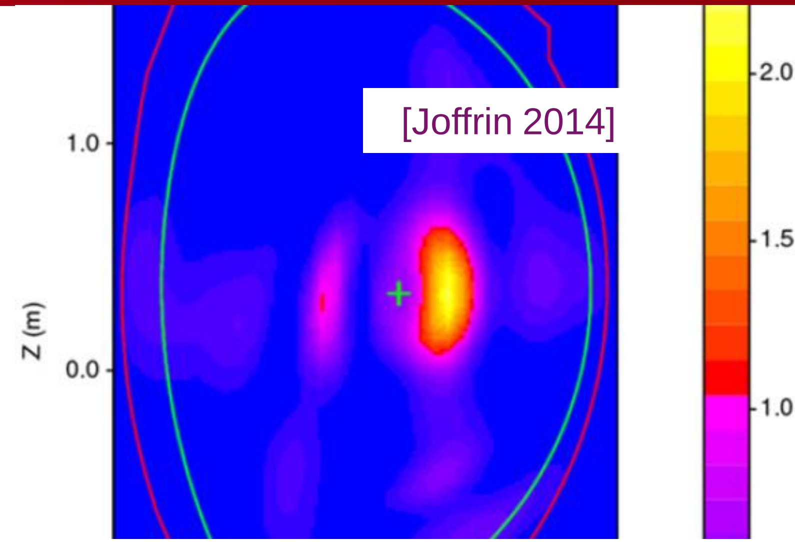
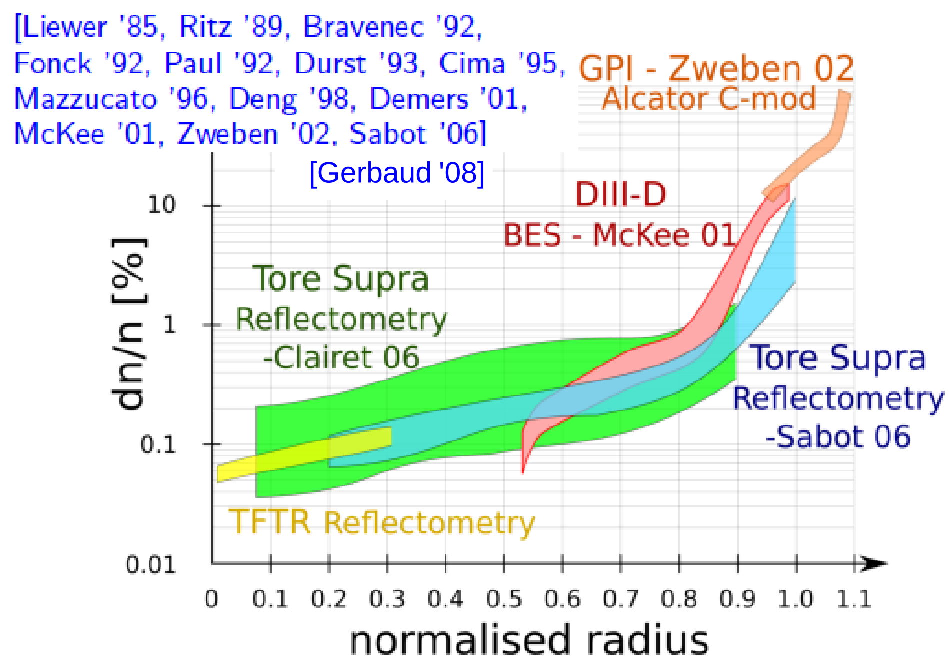


- Large edge fluctuations in all tokamaks



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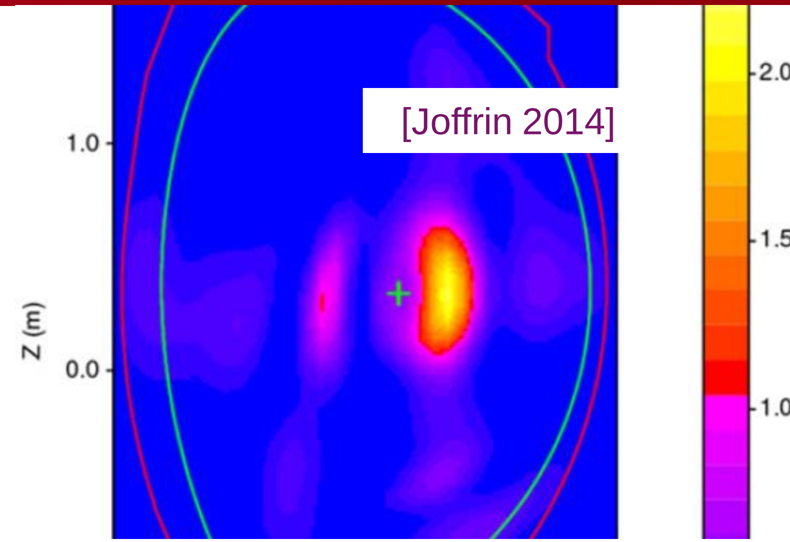


- Large edge fluctuations in all tokamaks
  - Local gyrokinetic models fail…

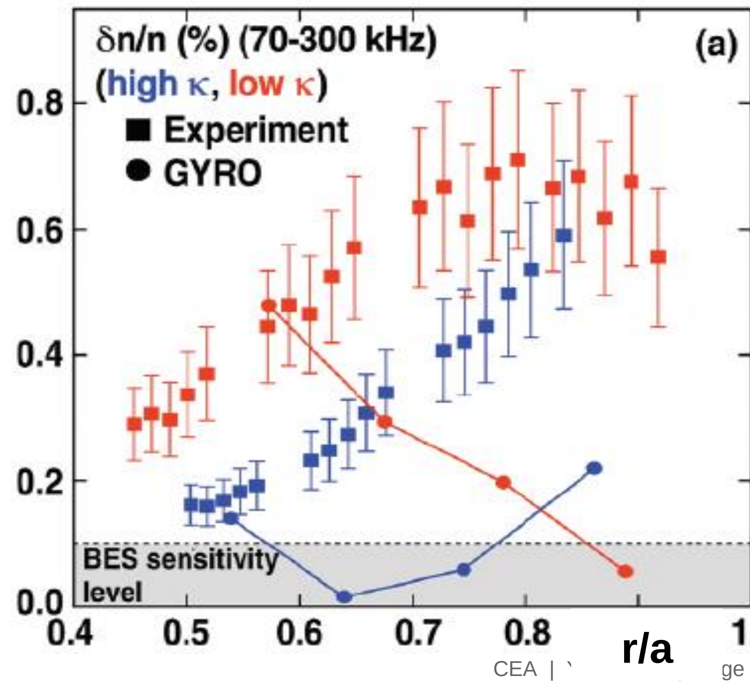
    … unless invoking large error bars

    [Holland PoP 2011, Goerler PoP 2014, Waltz APS 2017]

⇒ Role of asym. flows in unconfined region?

⇒ Role of turbulence spreading core→edge and/or SOL→edge?

[Mattor-Diamond PoP 1994, Garbet NF 1994]



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  - Poloidal asymmetries: experimental evidence & issues
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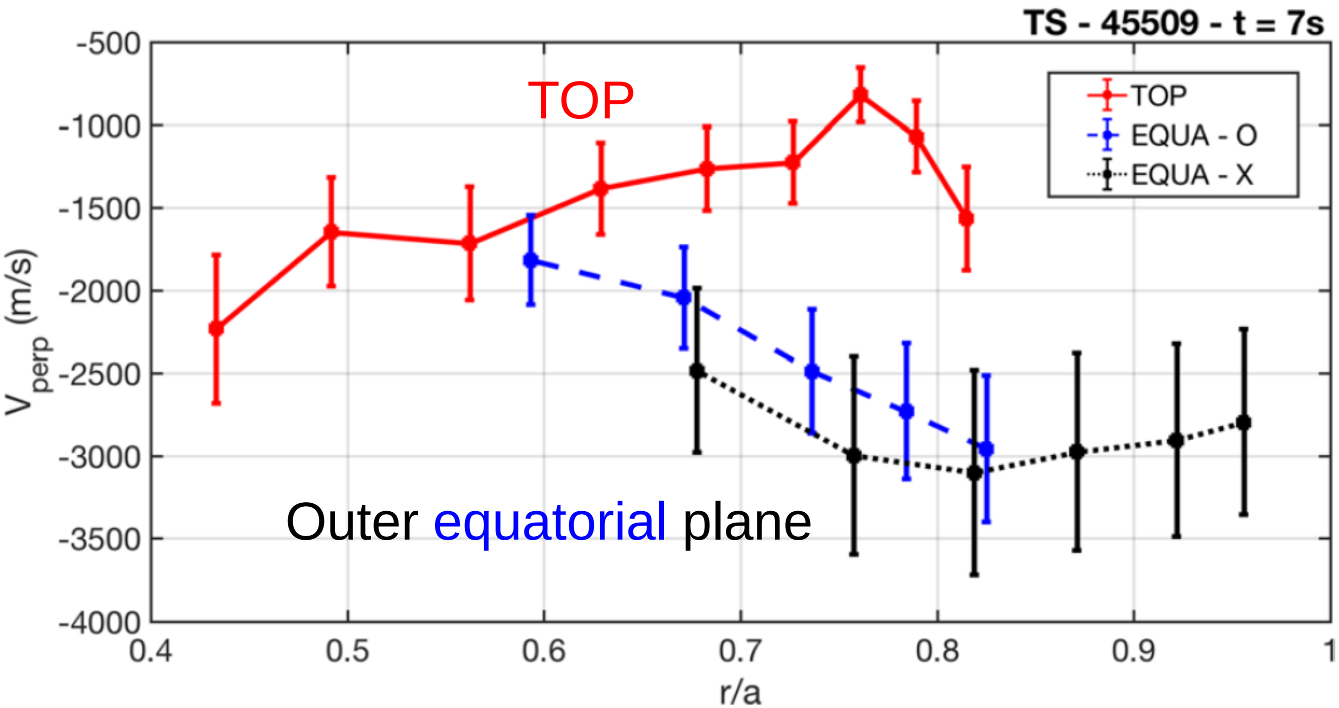
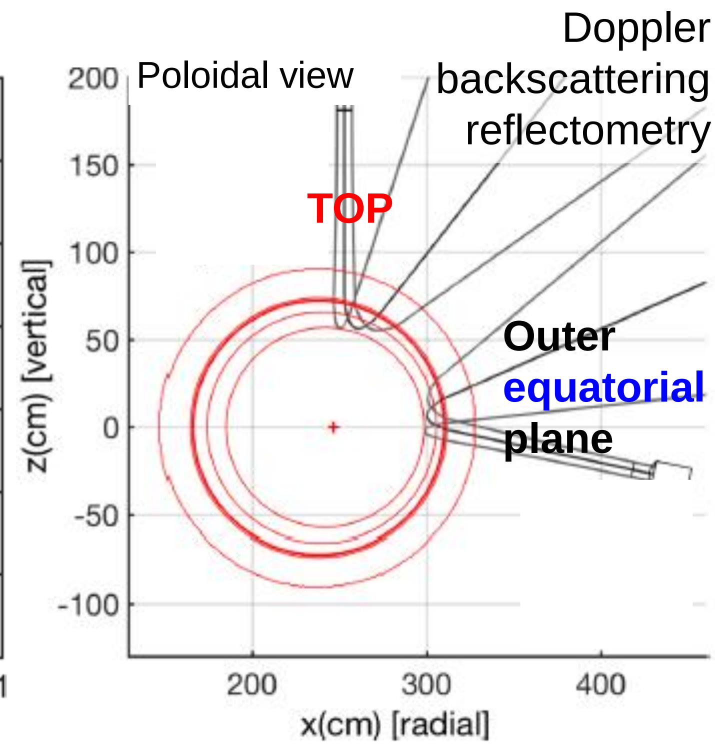
Asymmetries: experimental evidence

- **Faster edge poloidal rotation** of turb. at **outer equatorial plane** than **on top**

  Cannot be explained by B inhomogeneity $v_{E\theta} \sim \partial_r \langle \phi \rangle / B(r,\theta)$

[Vermare, PoP 2018]





- **Open issues:**
  - Possible origin: turbulence-driven?
  - Impact on impurity transport?

Asymmetry & impurity transport

- Convective cells can lead to density asymmetry through adiabatic (Boltzmann) response of trace impurities (charge Z):

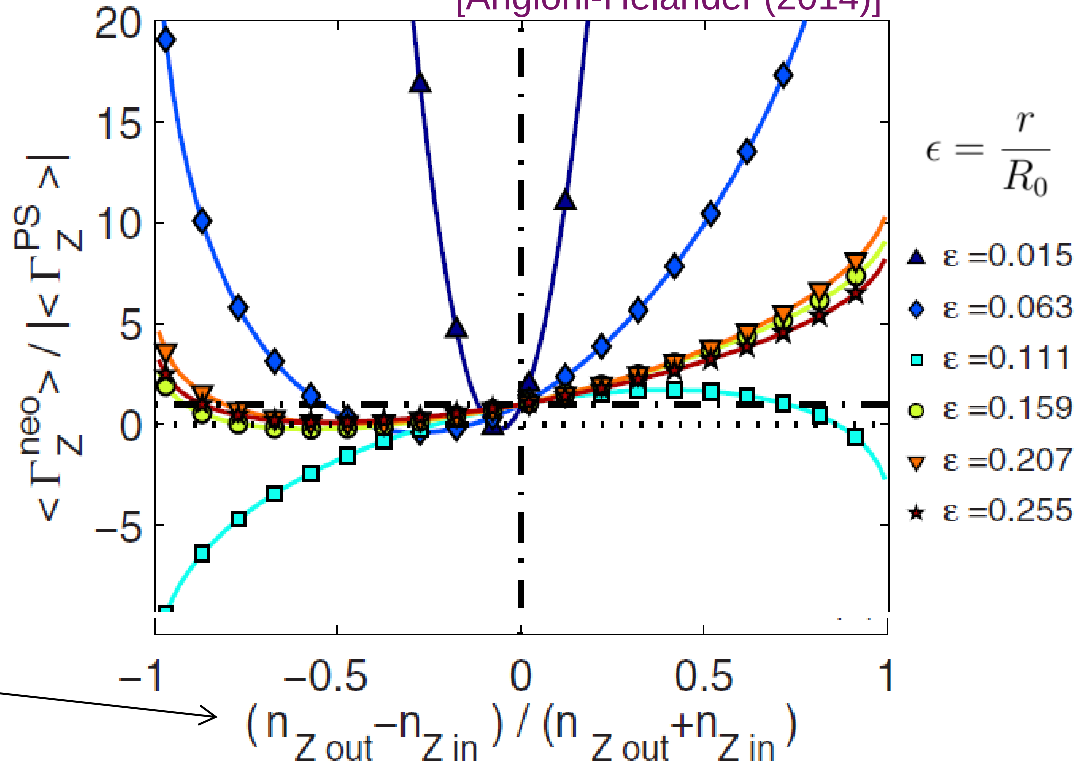
$$\frac{N_z - \langle N_z \rangle_\psi}{\langle N_z \rangle_\psi} \propto \exp\left[-\frac{eZ}{T_z}\left(\phi - \langle \phi \rangle_\psi\right)\right]$$

Poloidal asymmetry

- Asymmetric density
  $\Rightarrow$ neoclassical prediction of impurity flux strongly modified

Ratio of neoclassical impurity flux with & without n_Z asymmetry

[Angioni-Helander (2014)]

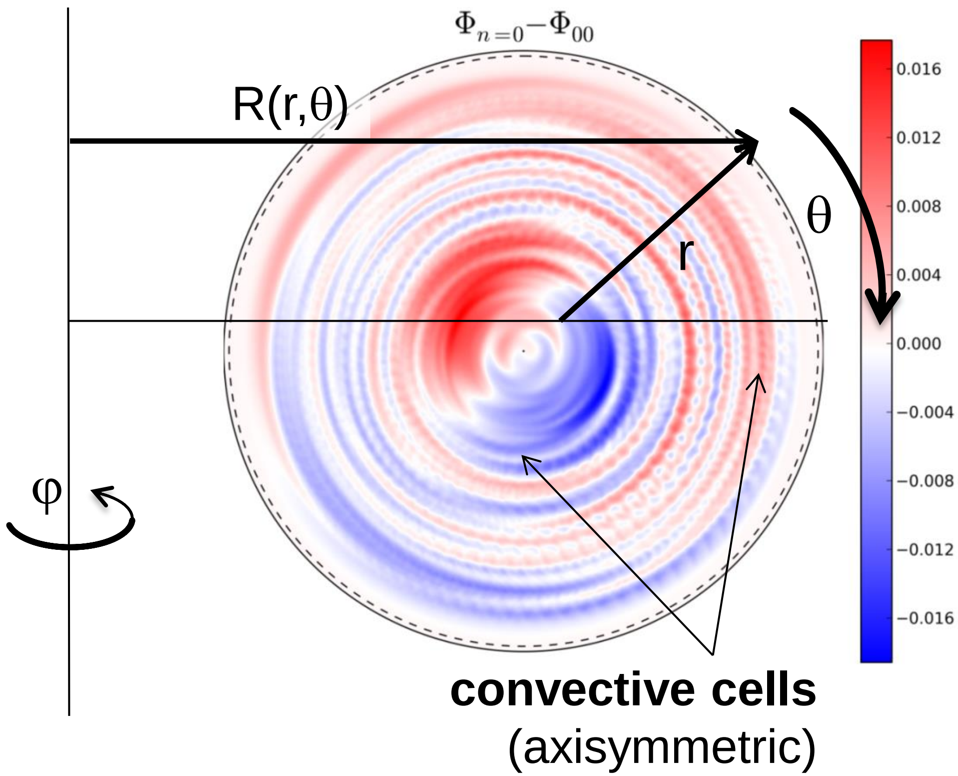


Convective Cells (CC)

- **Convective cells**: large scale (m=±1) axisymmetric (n=0) modes of electric potential *at intermediate to low frequencies* ($\omega << \omega_{GAM} \sim c_s/R$)

$$\phi = \sum \phi_{m,n} \exp\{i(m\theta + n\varphi)\} \longrightarrow \phi_{CC} = \phi_{CC0}(r,t)\ \sin(\theta + \theta_{CC})$$

- Possible origins of poloidal asymmetries
  - Asymmetric heat sources
  - **B**-field inhomogeneity: B ~ 1/R(r,θ)
    - At equilibrium → motion invariants
    - In turbulent regime → transport
- Open issues:
  - Amplitude?
  - Phase θ_{CC} (sin. *vs* cos)?
  - Frequency?



Drives & damping of convective cells

- Turbulence → (m≠0,n≠0) **ZFs**, (0,0) **GAMs** (m=0±1,0) & low freq. **Convective Cells** (m=±1,0)

- Conservation of Potential Vorticity $\Omega = \phi - \langle\phi\rangle - \rho_i^2 \nabla_\perp^2 \phi$ (at constant density n)

  - Neglecting // dynamics and B-inhomogeneity

$$\partial_t \Omega + \mathbf{v}_E . \nabla \Omega = 0 \longrightarrow \partial_t \langle v_{E\theta} \rangle = \langle v_{Er} \Omega \rangle = -\nabla_r \langle \tilde{v}_{Er} \tilde{v}_{E\theta} \rangle$$

Zonal Flows   PV flux   Reynolds' force

[Taylor 1915, McIntyre "Festival book" 2013]

  - Tokamak plasmas: // dynamics + vertical drift (B inhomogeneity)

$$(\partial_t + v_\parallel \nabla_\parallel + \mathbf{v}_D . \nabla)\Omega = -\mathbf{v}_E . \nabla \Omega$$

Landau damping — ⊥ compression — Turbulent nonlinear source

$$\mathbf{v}_D . \nabla \sim v_{D0} \left(\sin\theta\, \partial_r + \frac{\cos\theta}{r} \partial_\theta \right)$$ ⇒ poloidal coupling

Drives & damping of convective cells

- Matrix form for (m,n)=(0±1,0) components of gyro-averaged potential $\bar{h} = e\mathcal{J}\phi$

$$\frac{N_{\rm eq}}{T_{\rm eq}}\begin{pmatrix} E_a & -\mathrm{i}E_c & E_d \\ \mathrm{i}E_c & E_b & -\mathrm{i}E_c \\ E_d & \mathrm{i}E_c & E_a \end{pmatrix}\begin{pmatrix} \bar{h}_{-1,\Omega} \\ \bar{h}_{0,\Omega} \\ \bar{h}_{1,\Omega} \end{pmatrix} = \frac{1}{\Omega}\begin{pmatrix} S_{1,0} + \mathrm{i}(S_{0,-1} - S_{2,-1} - S_{2,1}) \\ -\mathrm{i}S' - S_{1,-1} + S_{1,1} + 2\mathrm{i}S_{2,0} \\ -S_{1,0} + \mathrm{i}(S_{0,1} - S_{2,-1} - S_{2,1}) \end{pmatrix}$$

Linear operator (Time evol. + advection) | Convective Cells & ZF | Nonlinear source terms (turbulence)

[Donnel PPCF 2019(a)]

$$E_a = 1 + \tau + L_0(\Omega) - L_2(\Omega)$$
$$E_b = \langle 1 - \mathcal{J}^2\rangle_v + 2L_2(\Omega)$$
$$E_c = L_1(\Omega)$$
$$E_d = -L_2(\Omega),$$
$$L_j(\Omega) = \left\langle \frac{\Omega^{2-j}\Omega_D^j}{\Omega_+\Omega_- + 2\Omega_D^2}\mathcal{J}^2 \right\rangle_v$$

$$S' = \int \mathcal{J}[\tilde{\bar{v}}_E \cdot \nabla \tilde{\bar{g}}]_{0,\Omega} \mathrm{d}^3v$$

~ Symmetric Reynolds' stress

$$S_{j,M} = \int \frac{\Omega^{2-j}\Omega_D^j}{(\Omega_+\Omega_- + 2\Omega_D^2)}\mathcal{J}[\tilde{\bar{v}}_E \cdot \nabla \tilde{\bar{g}}]_{M,\Omega} \mathrm{d}^3v$$

~ Ballooned Reynolds' stress

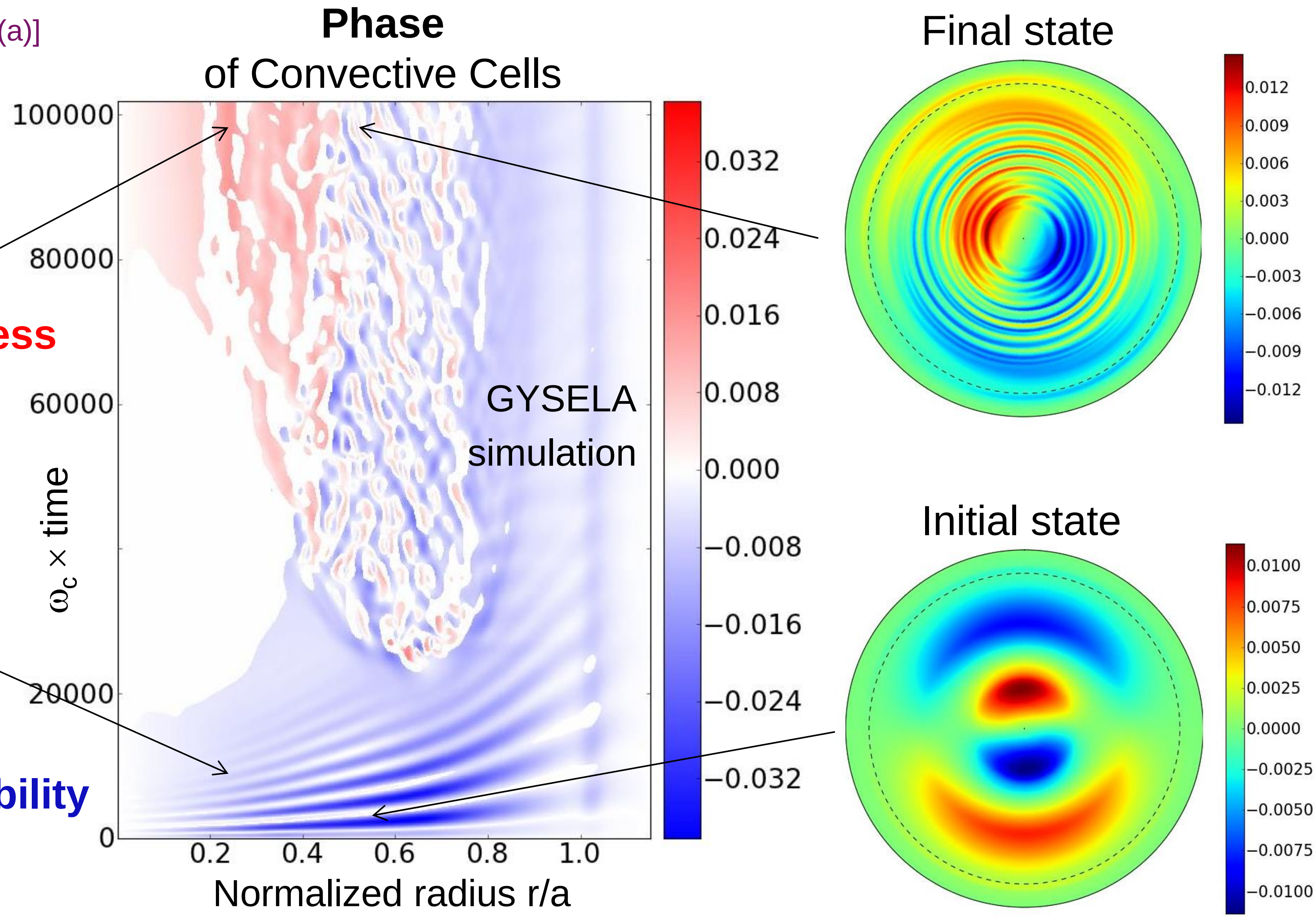
// and v_D dynamics

Phase dynamics of Convective Cells

[Donnel PPCF 2019(a)]

In-out asymmetry (|θ|<20°)

Reynolds stress ballooning



Up-down asymmetry (θ=90°±20°)

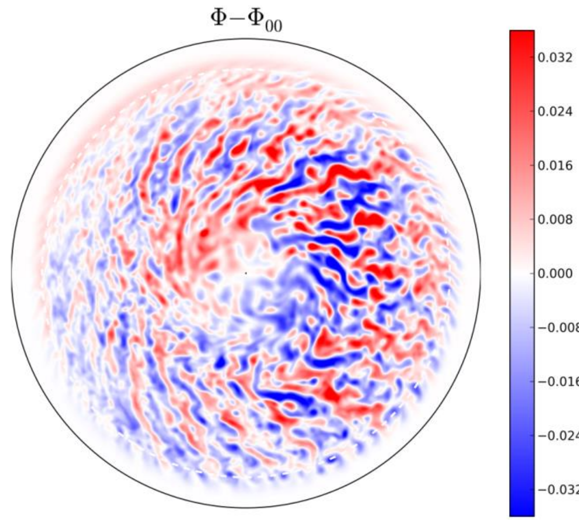
⊥ Compressibility

Impurity transport weakly affected by CC

- GYSELA simulation with Tungsten

  D+W (Z=40), ρ_*=1/190, trace limit ($\alpha = \frac{Z^2 N_Z}{N_i} \approx 10^{-3}$)

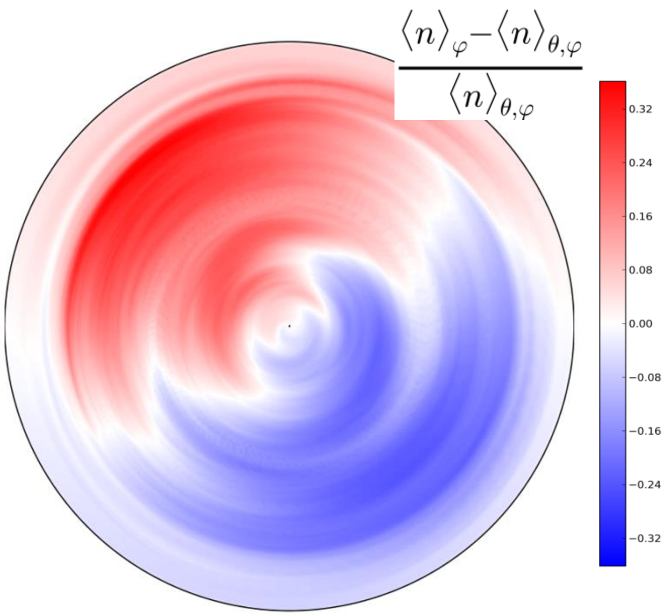
  no torque injection, isotropic heat Source



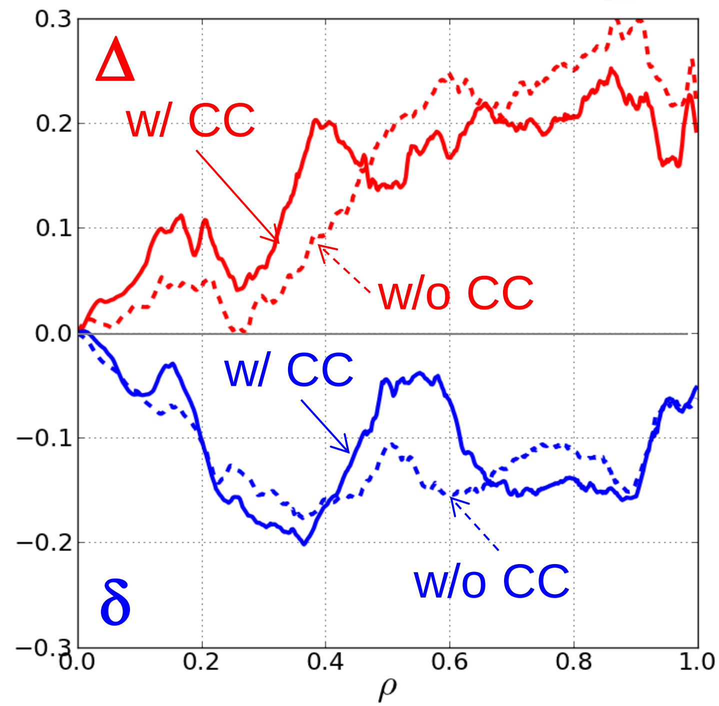
- Poloidal asymmetry of n_Z …

  Parametrized by δ & Δ:

$$\frac{n_z - \langle n_z \rangle}{\langle n_z \rangle} = \delta \cos\theta + \Delta \sin\theta$$



… Marginally due to convective cells



Recovering neoclassical impur. Flux

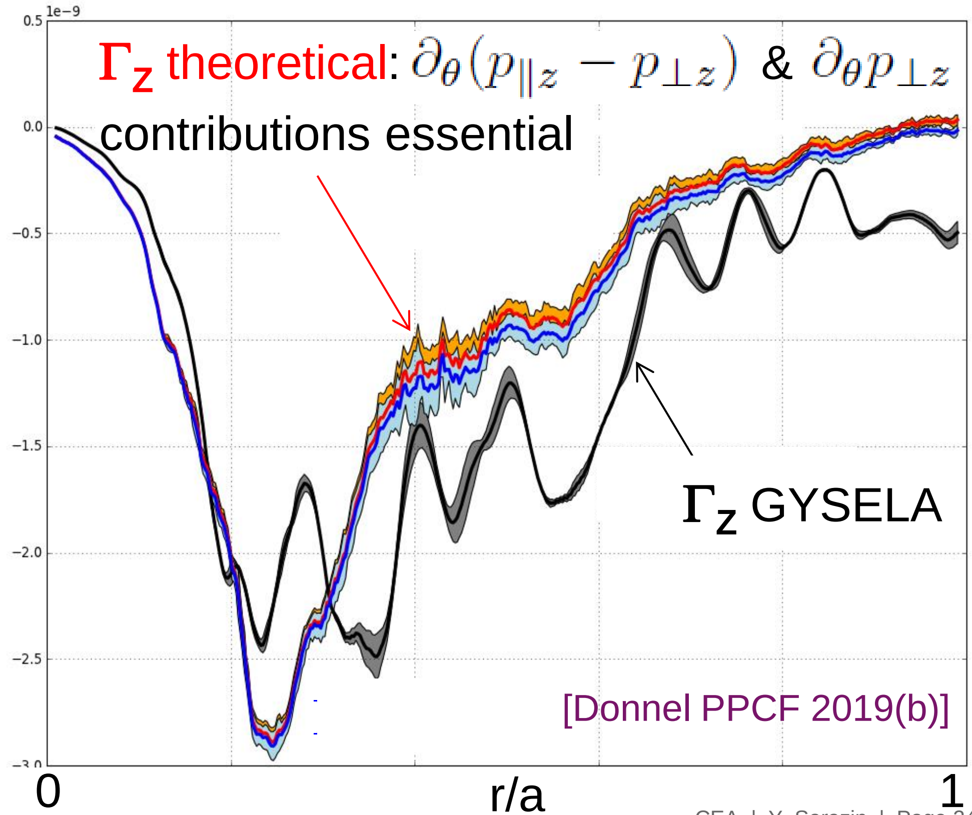
- Convective Cells NOT sufficient to account for
  - Experimental flow asymmetry
  - GYSELA asymmetry of n_Z

- **Generalization**: same analysis for non-adiabatic part g of $f = \left(1 - \frac{e\phi}{T}\right) f_{eq} + g$

$$(\partial_t + v_{\parallel}\nabla_{\parallel})g_{m,0} + [\mathbf{v}_D.\boldsymbol{\nabla} g]_{m,0} = \frac{f_{eq}}{T_{eq}}\,\partial_t(e\phi_{m,0}) - [\tilde{\mathbf{v}}_E.\boldsymbol{\nabla}\tilde{g}]_{m,0}$$

$\Rightarrow$ Poloidal asymmetry possible even without Convective Cells

- Governs **asymmetric pressure anisotropy** (CGL pressure tensor)
  - Effective contribution to impurity flux (in ITER relevant low collisionality regime)
  - Consistent with GYSELA results



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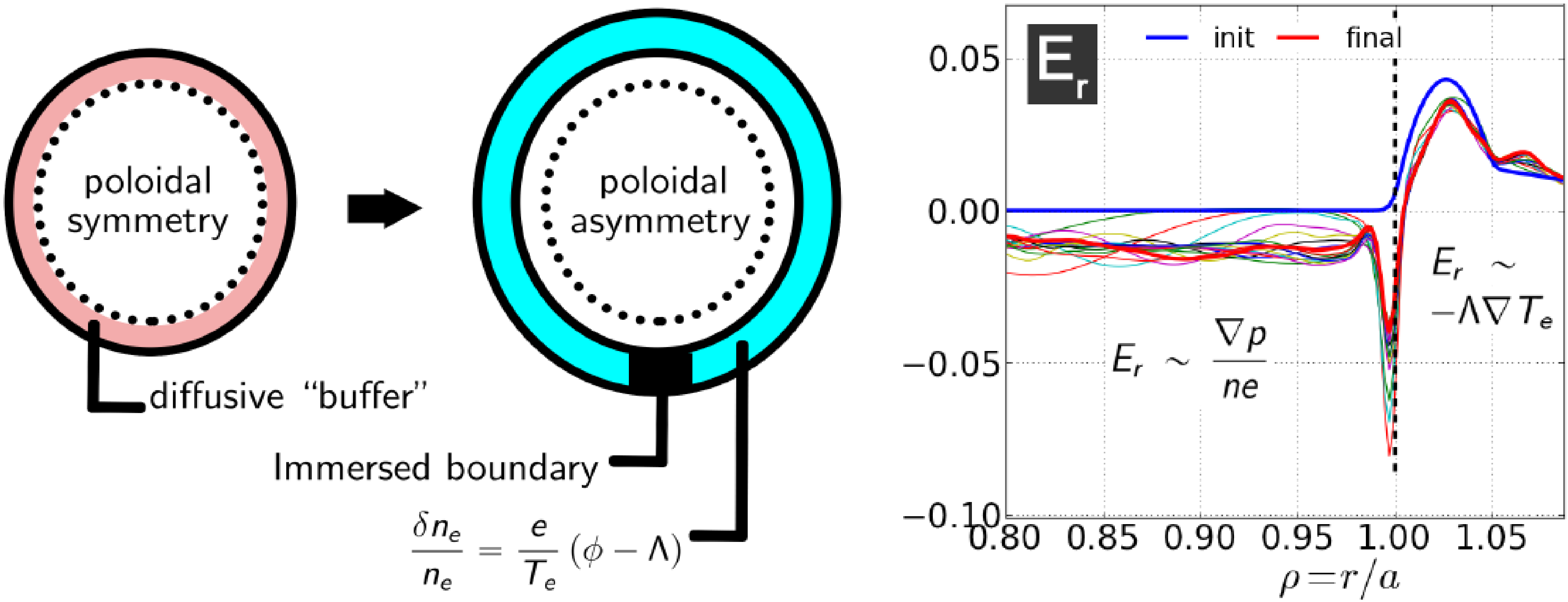
- **Impact of asymmetric boundary layer on edge turbulence**
  - Modelling the unconfined "Scrape-Off Layer"
  - The tail & the dog…

Modelling the SOL region in GYSELA

- **SOL = Scrape-Off Layer:**
  - Region where magnetic surfaces are open
  - Field lines intercept the wall $\Rightarrow$ parallel boundary condition governed by different electron-ion mobility $\Rightarrow$ $\phi = T_e \Lambda / e$ (Bohm criterion)



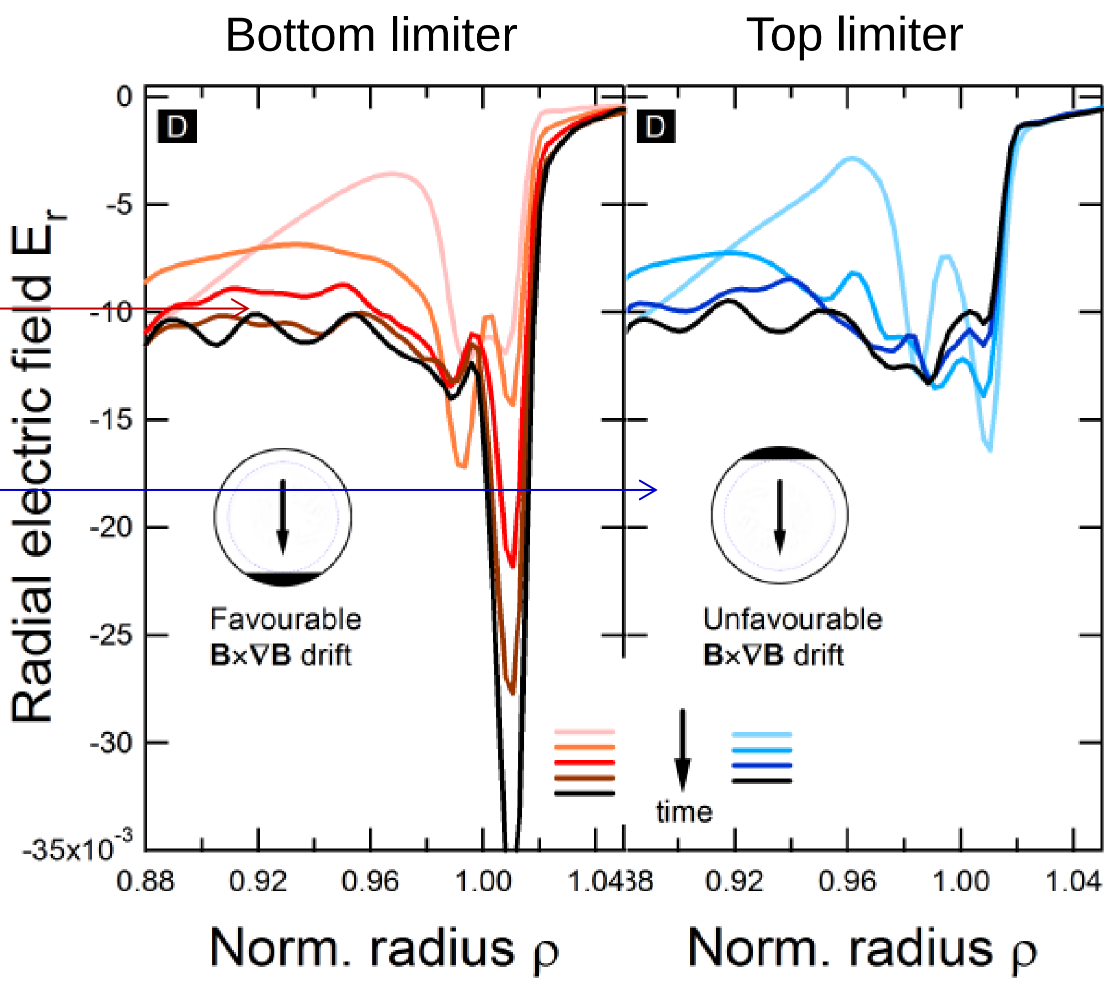
E_r well at separatrix

- Ion orbit drift efficiently contribute to the establishment of E_r well at separatrix:
  - E_r strongly negative when v_{Di} towards limiter

    The opposite holds when v_{Di} away from limiter

Consistent with L-H power threshold lower (~3) in "favorable grad-B drift"

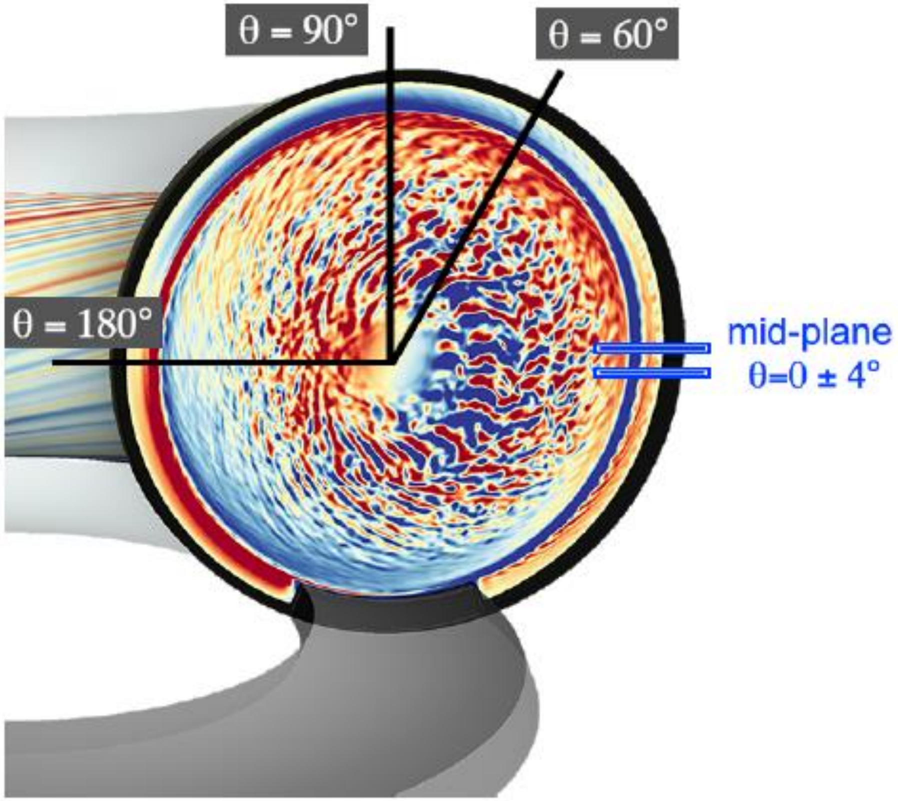
[ASDEX NF 1989; Carlstrom PoP 1996; Labombard NF 2004; Meyer NF 2006]

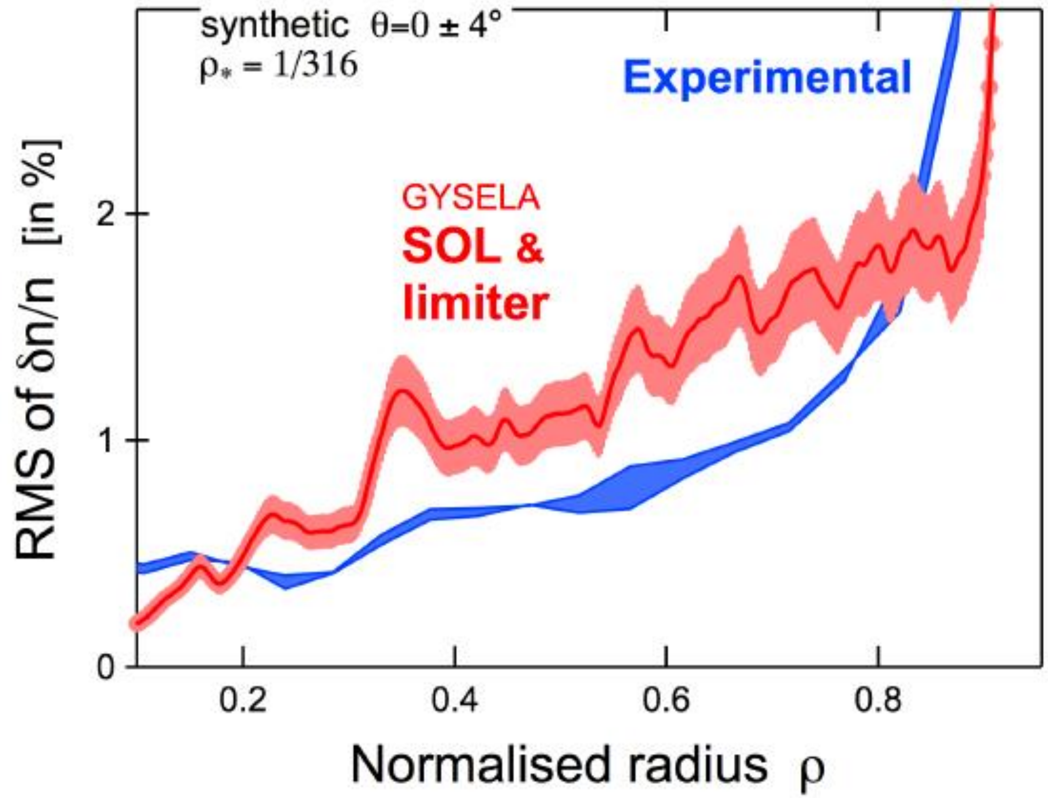


- Top / bottom limiter: governs poloidal asymmetry of fluctuations (caveat: still not at steady state)

Recovering density fluctuation increase

- Highly resolved fast-swept reflectometry measurement of density fluctuation profile in Tore Supra (#45511) [Clairet RSI 2011]
- Mimic exp. conditions in simulation: | $T_e \neq T_i$, n_e, q, s, ν_*, S_{heat}, 75% ρ^*
  Synthetic diagnostic $\theta=0\pm4°$





Core-edge-SOL interplay is key!

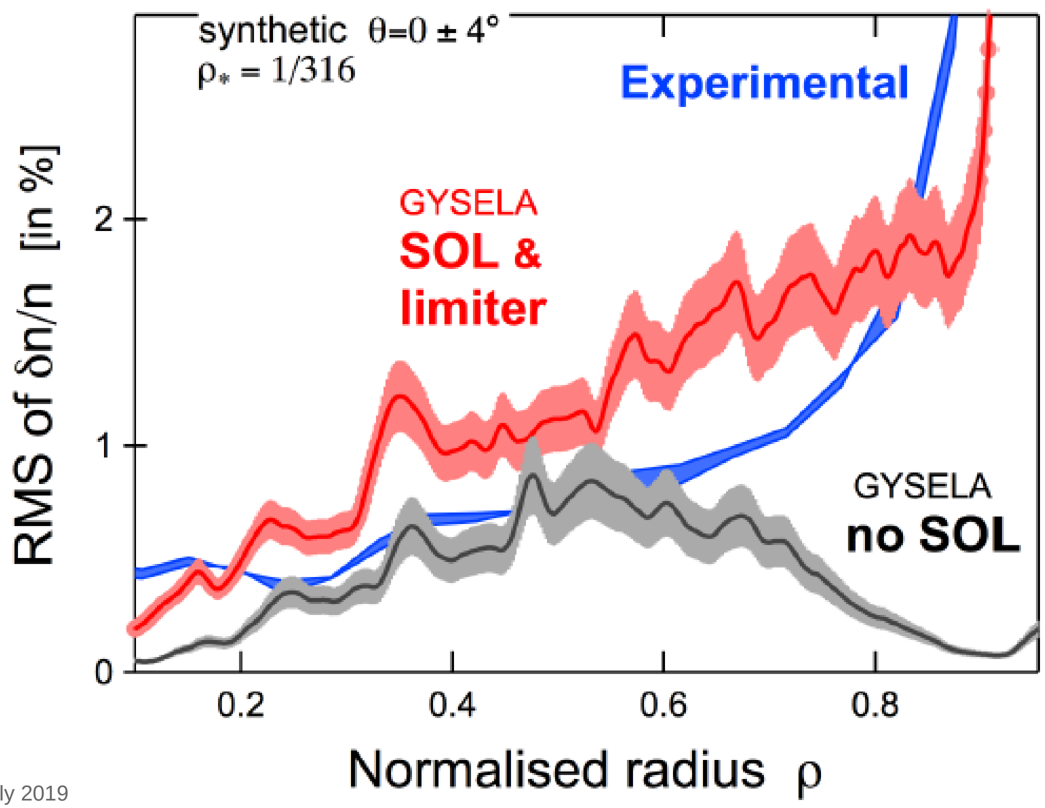
- Inclusion of asymmetric SOL-like boundary condition is key:

  No SOL ⇔ No fluctuation increase at the edge

  → Beach effect** reveals insufficient

[Mattor-Diamond PoP 1994; Gürcan NF 2013]

** Conservation of generalized vorticity $\Omega \rightarrow$ beach effect
Long wavelength approx.: $\Omega \sim n\nabla_\perp^2\phi \Rightarrow \nabla_\perp^2\phi \uparrow$ when $n \downarrow$ (edge)

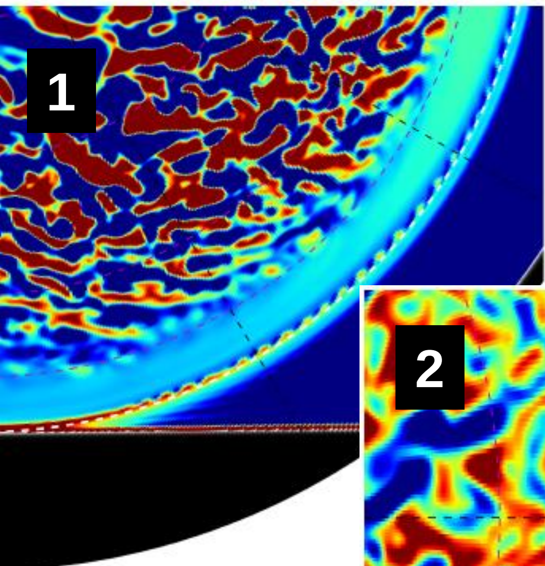


Edge instability & turbulence spreading

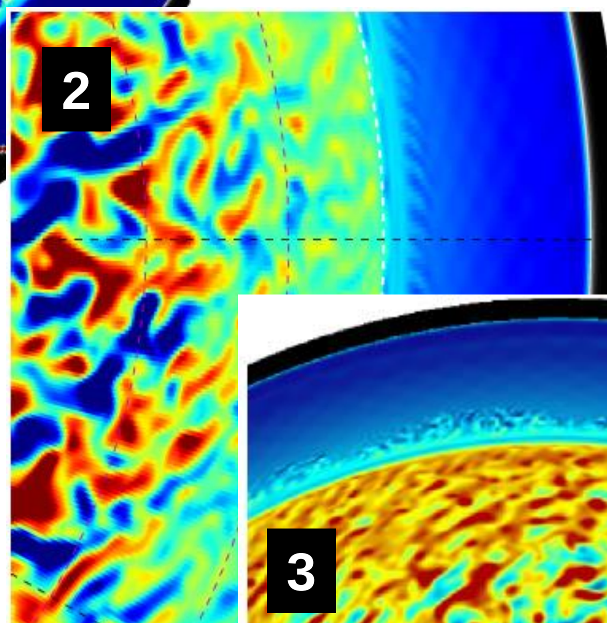
- Initially: weak / No turbulence at the edge
- Then: instability develops at separatrix (Kelvin-Helmholtz in this case)

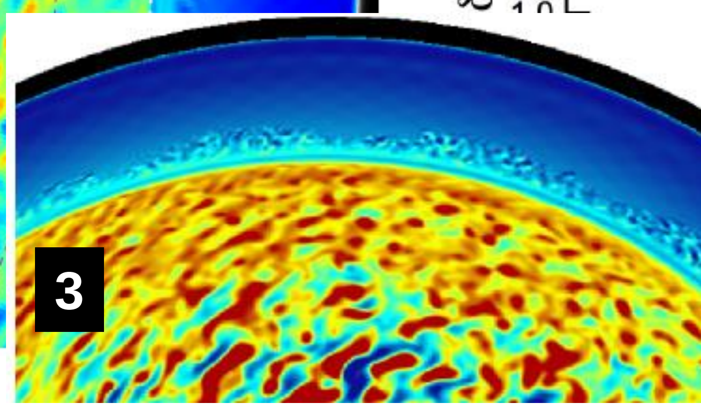
  ⇒ Complex spreading pattern – mostly inward

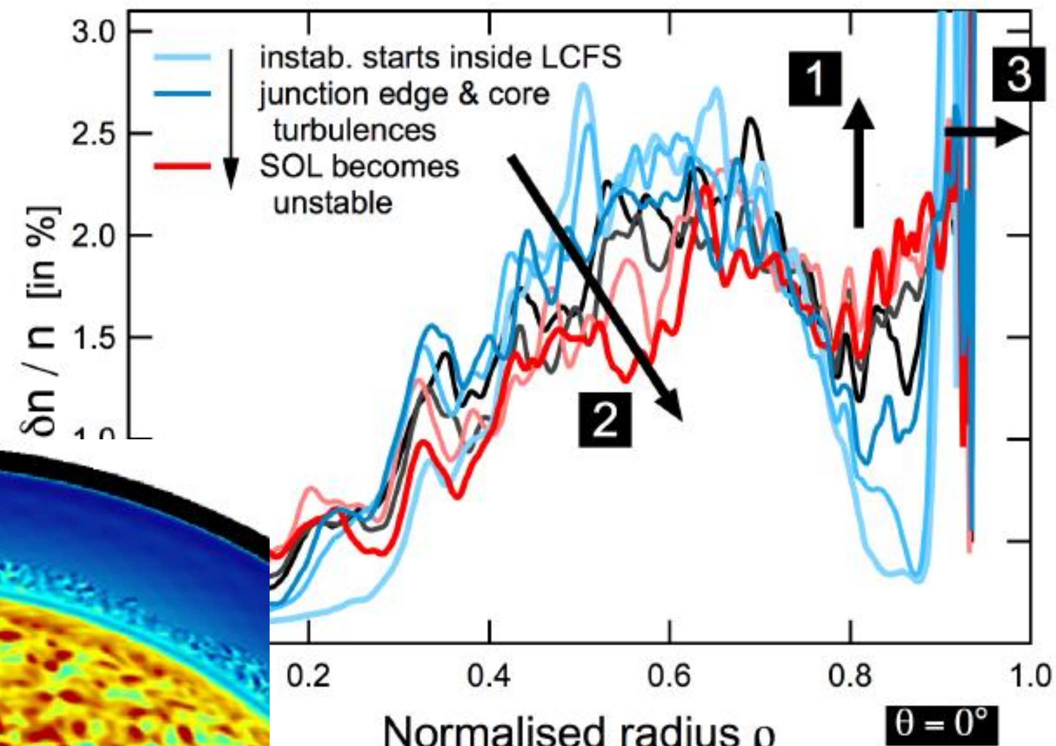
[Kadomtsev 1965; Garbet NF 1994; Hahm PoP 2005]



- Final state: edge & core turb. meet → spreading in & out







Poloidal entrainment & spreading

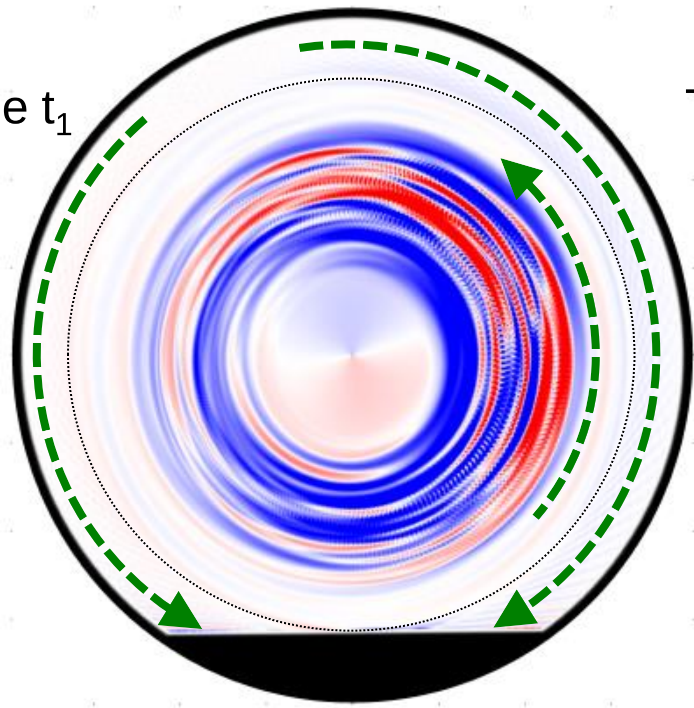
- Drift & limiter → poloidal asymmetry (+ K-H instability in certain regimes)
- Symmetric & asymmetric poloidal flows → advection of fluctuations
- Transport of turbulent intensity (~ fluctuation entropy) into marginally stable edge:

$$\left(\frac{\partial}{\partial_t} + \bar{\mathbf{v}}_{E,\theta}\frac{\partial}{\partial_\theta}\right)[nI] + \nabla\cdot\Gamma = \mathrm{Inj}-\mathrm{Diss.}$$

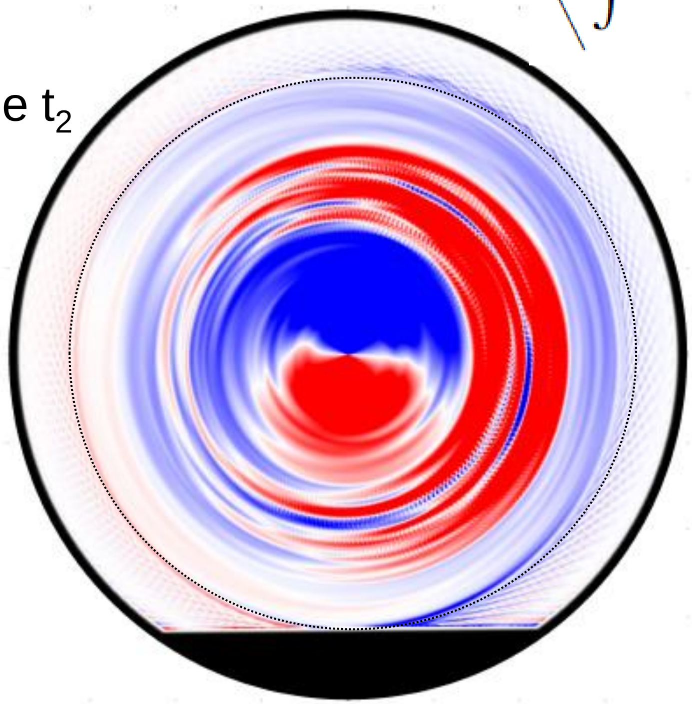
[Mattor PRL 1994; Gürcan NF 2013]

$$\Gamma(r,\theta,t) \equiv \langle \mathbf{v} nI \rangle = \left\langle \int \mathbf{v}_{ExB,r}\frac{\tilde{f}^2}{F_M} \right\rangle$$

Time t_1



Time t_2



Radial flux of turbulent intensity $\Gamma(r,\theta,t)-\Gamma(r,\theta,t_0)$

red ≡ outwards

blue ≡ inwards

Conclusions

- **Core confinement & performance → Gyrokinetic** modelling
  - Dominant drift wave instabilities
  - Complemented by reduced models (large fluctuations & gradients; edge / SOL)

- Impurity contamination → **Turbulence-driven asymmetries**
  - Source = turbulent "Reynolds' stress" + ballooning or ⊥ flow compression
  - Asymmetric flows are only part of the (not the whole) story
  - General theory for pressure asymmetry & anisotropy → consistent with GYSELA impurity flux ++ likely important to predict ITER W transport

- Wall heat flux → **SOL asymmetry** (limiter configuration – simplified modelling)
  - Critical to recover experimental increase of $\delta n/n$ at the edge
  - Poloidal entrainment + inward/outward spreading are keys

Back-up slides

Prediciting phase of Convective Cells

- Polarity (cos *vs* sin) of Convective Cells changes with time scale:
  - Intermediate freq. $\Omega \leq \Omega_D \rightarrow \frac{\phi_{1,\Omega}}{B_{eq}} = -\frac{\phi_{-1,\Omega}}{B_{eq}} = -K_r \rho_i \frac{\Pi_{RS,0}(\Omega)}{(1+\tau)\,\frac{v_T}{R_0}}$

    ⇒ up-down (sin θ) asymmetry

    Main drive = transverse compressibility of the flow
  - Low freq. $\Omega \leq \Omega_D K \rho_i \rightarrow \frac{\phi_{1,\Omega}}{B_{eq}} = \frac{\phi_{-1,\Omega}}{B_{eq}} = -i K_r^2 \rho_i^2 f_{bal} \frac{\Pi_{RS,0}(\Omega)}{(1+\tau)\,\Omega}$

    ⇒ in-out (cos θ) asymmetry

    Main drive = ballooned character of Reynolds' stress

[Donnel PPCF 2019(a)]

- **GYSELA simulation**: Polarity of Convective Cells changes from up-down to in-out when turbulence develops

⇒ Qualitatively consistent with theoretical predictions

Prediciting level of Convective Cells

- Fourier decomposition: $\phi = \sum \phi_{m,n} \exp\{i(m\theta + n\varphi)\}$

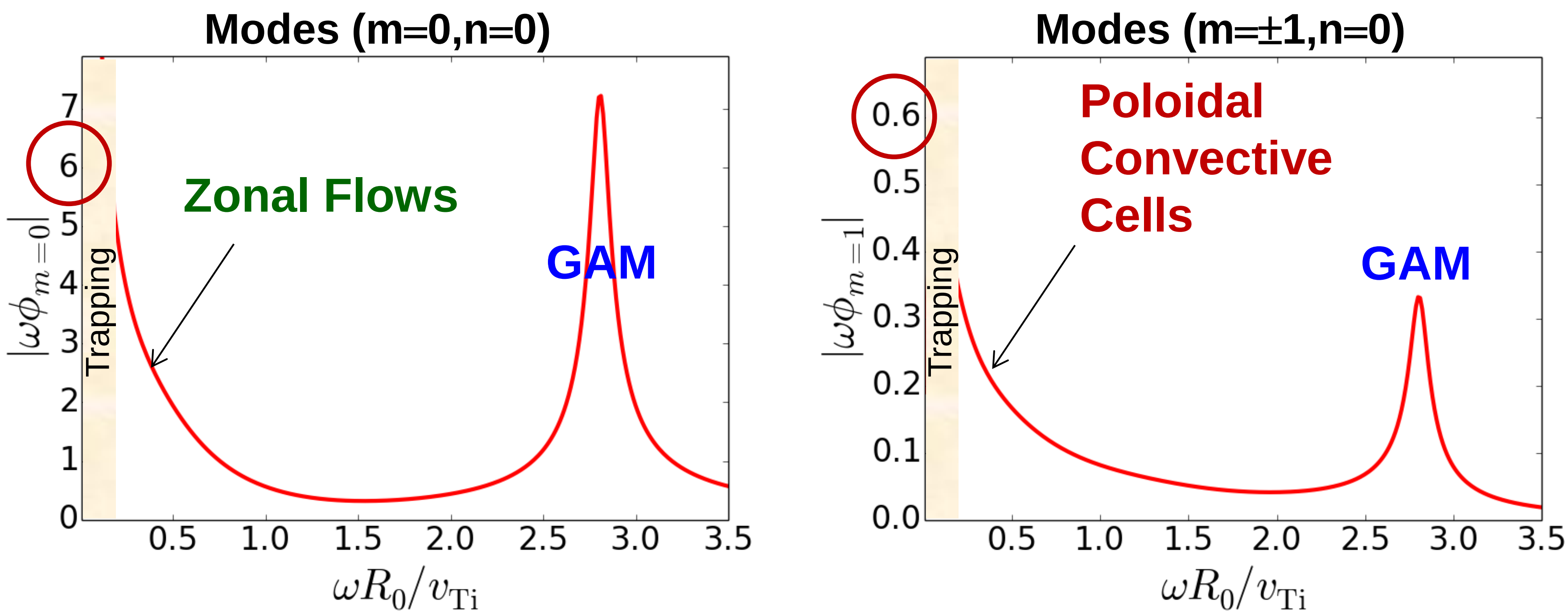
  Turbulence → **ZFs**, **GAMs** and low freq. **Convective Cells**

  (m≠0,n≠0) (0,0) (m=0±1,0) (m=±1,0)

- Assuming Lorentzian spectrum of turbulence ($\Delta\omega = 0.1 v_{Ti}/R_0$)

  ⇒ Generation of Convective Cells can be estimated

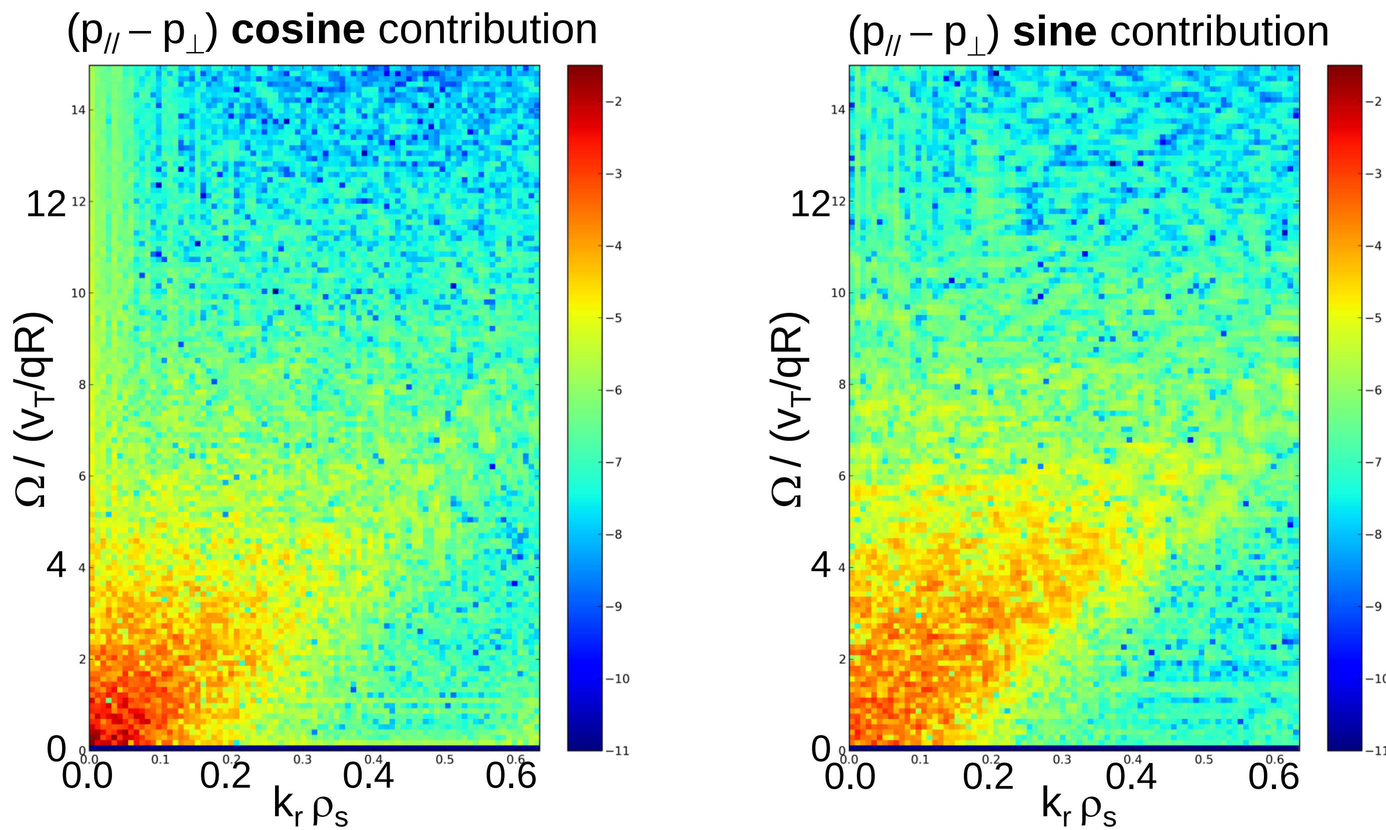
  [Donnel PPCF 2019(a)]



Asymmetric pressure anisotropy

- Turbulence also found to generate asymmetric pressure anisotropy $p_{//} \neq p_{\perp}$

- $(p_{//} - p_{\perp})$ much larger than predicted by neoclassical theory…



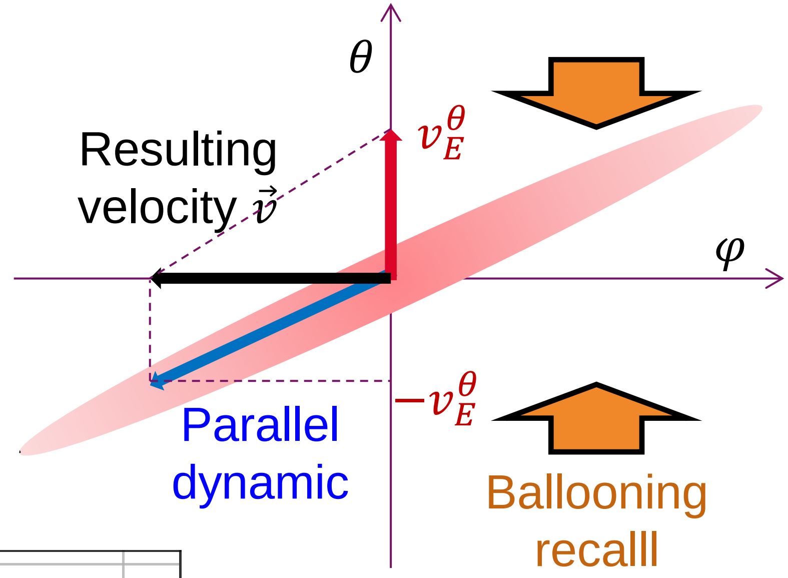
- … which in turn drives additional transverse current:

$$\mathbf{j}_{dia} = \frac{\mathbf{B} \times \nabla p_{\perp}}{B^2} + (p_{\parallel} - p_{\perp}) \left(\frac{\mathbf{B} \times \nabla B}{B^3} + \left. \frac{\nabla \times \mathbf{B}}{B^2} \right|_{\perp} \right)$$

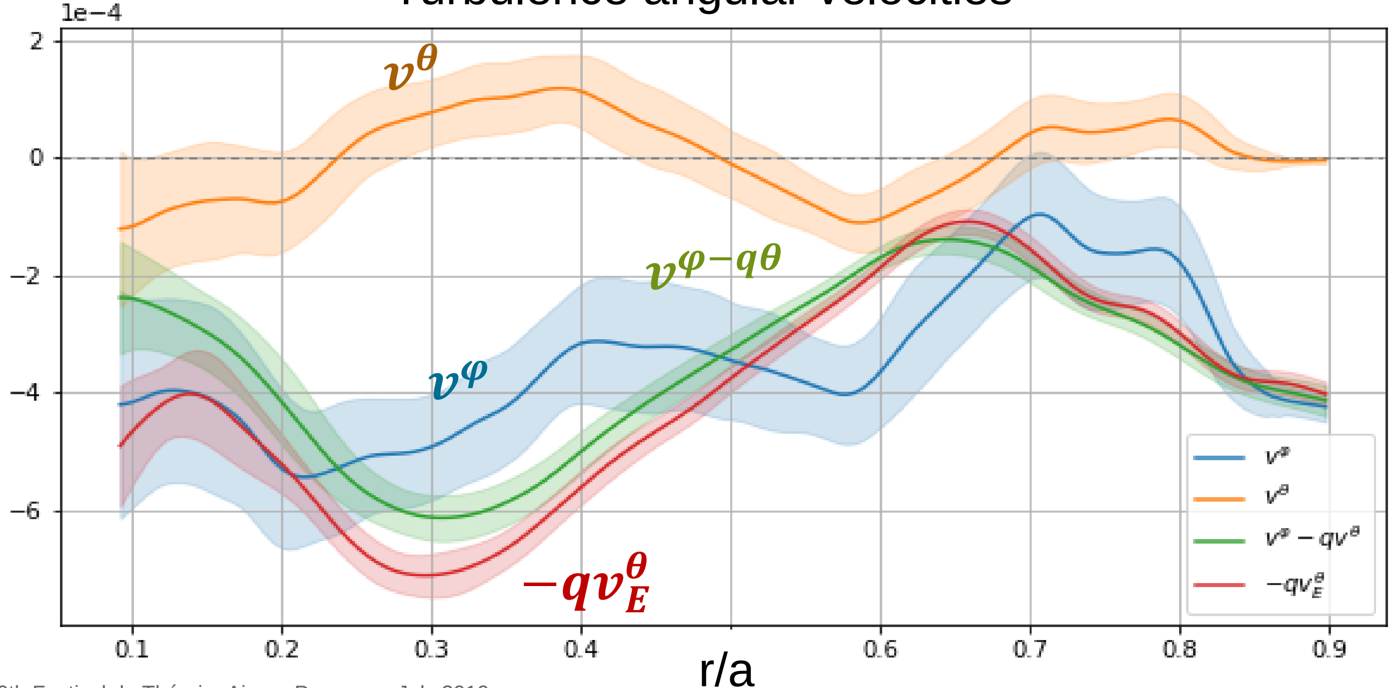
Ballooning ensured despite mean poloidal flow

- 3D velocity of turbulent eddies:
  - $v^r(t,r)$, $v^\theta(t,r)$, $v^\varphi(t,r)$
  - Computed by registration of 3D snapshots (Minimizing $\iint \left|\partial_t \phi + \vec{v}.\vec{\nabla}\phi\right|^2 R d\theta d\varphi$)

$\Rightarrow$ Parallel motion ensures ballooning



Turbulence angular velocities



[Gillot (2019)]