# Turbulence/Neoclassical interaction through poloidal convective cells

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# Magnetic confinement fusion

- High T
- High n

$\rightarrow$ Pressure Gradient

- **Good confinement**

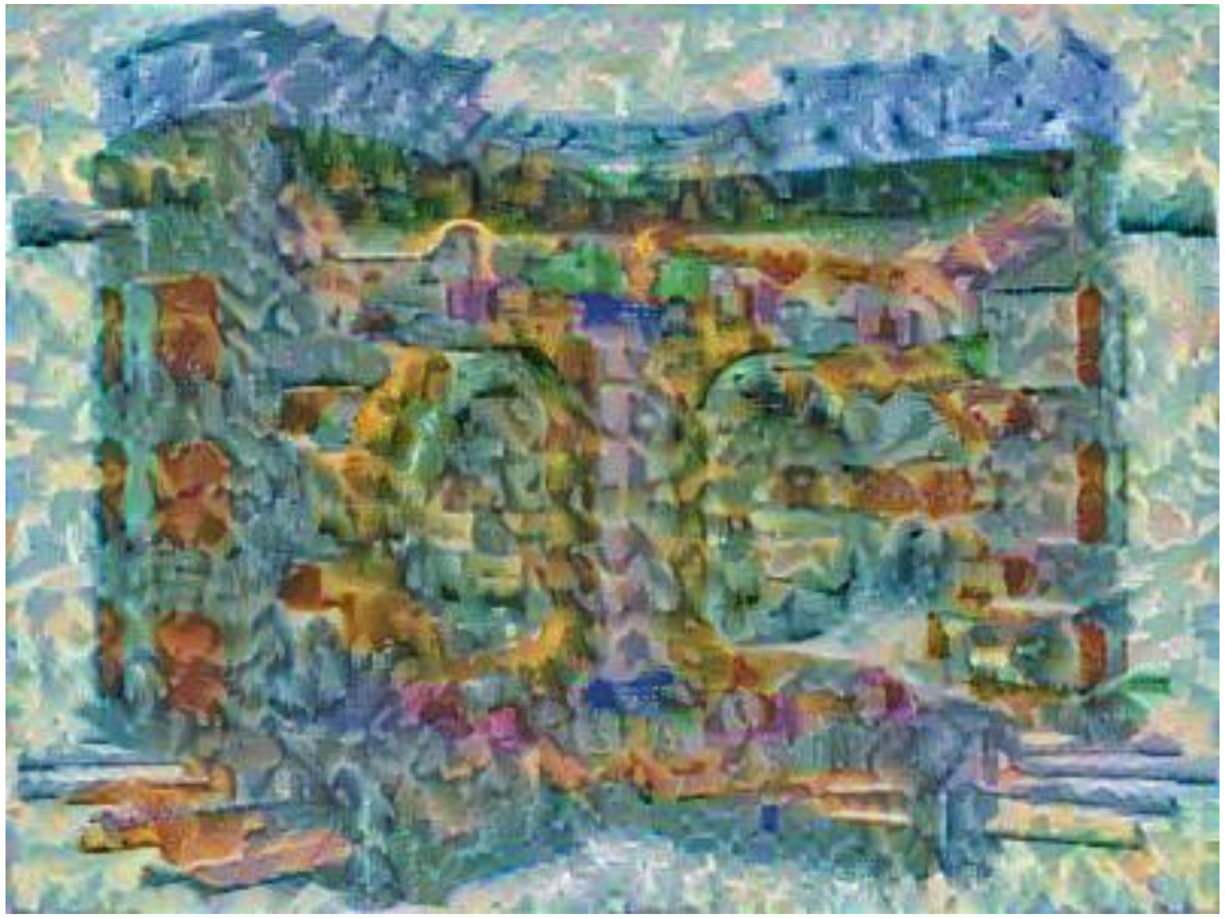
$$\mathbf{F} = D \nabla G$$

$\mathbf{F}$ :Flux （particle、heat）

$G$ :Gradient（density、temperature）

$D$ :Diffusion coefficient

**ITER in Cezanne style**



30 m

**Better understanding of transport phenomenon**

# Charged particle motion in magnetic field

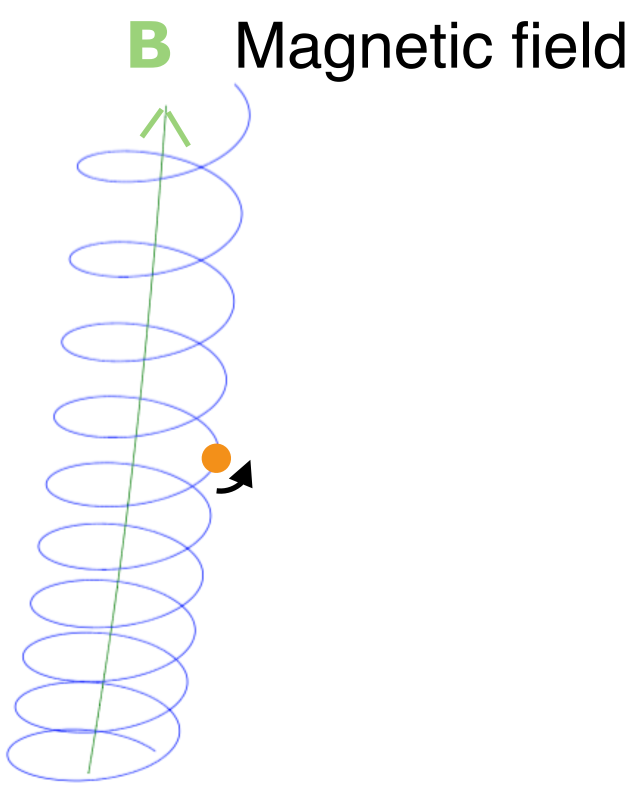
## Equation of motion

$$m\frac{d\mathbf{v}}{dt} = e\left(\mathbf{v}\times\mathbf{B}\right) + \mathbf{F}$$

F: external force

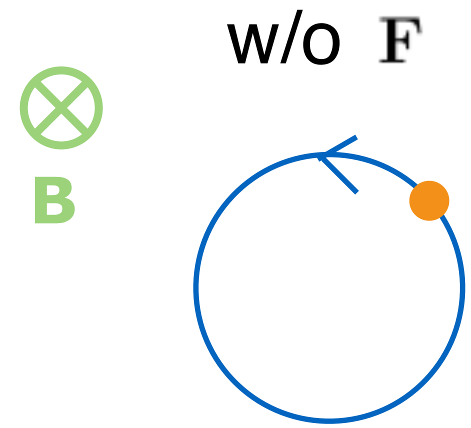
### Larmor motion

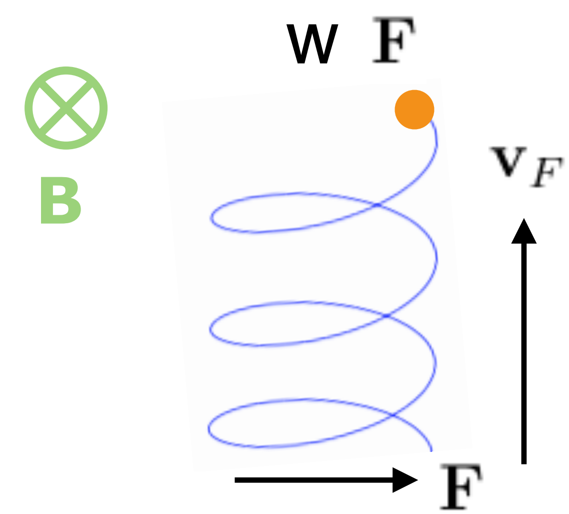
$$m\mathbf{v}_0 = e\left(\mathbf{v}_0\times\mathbf{B}\right)$$




### Drift motion

$$\mathbf{v}_F = \frac{\mathbf{F}\times\mathbf{B}}{eB^2}$$

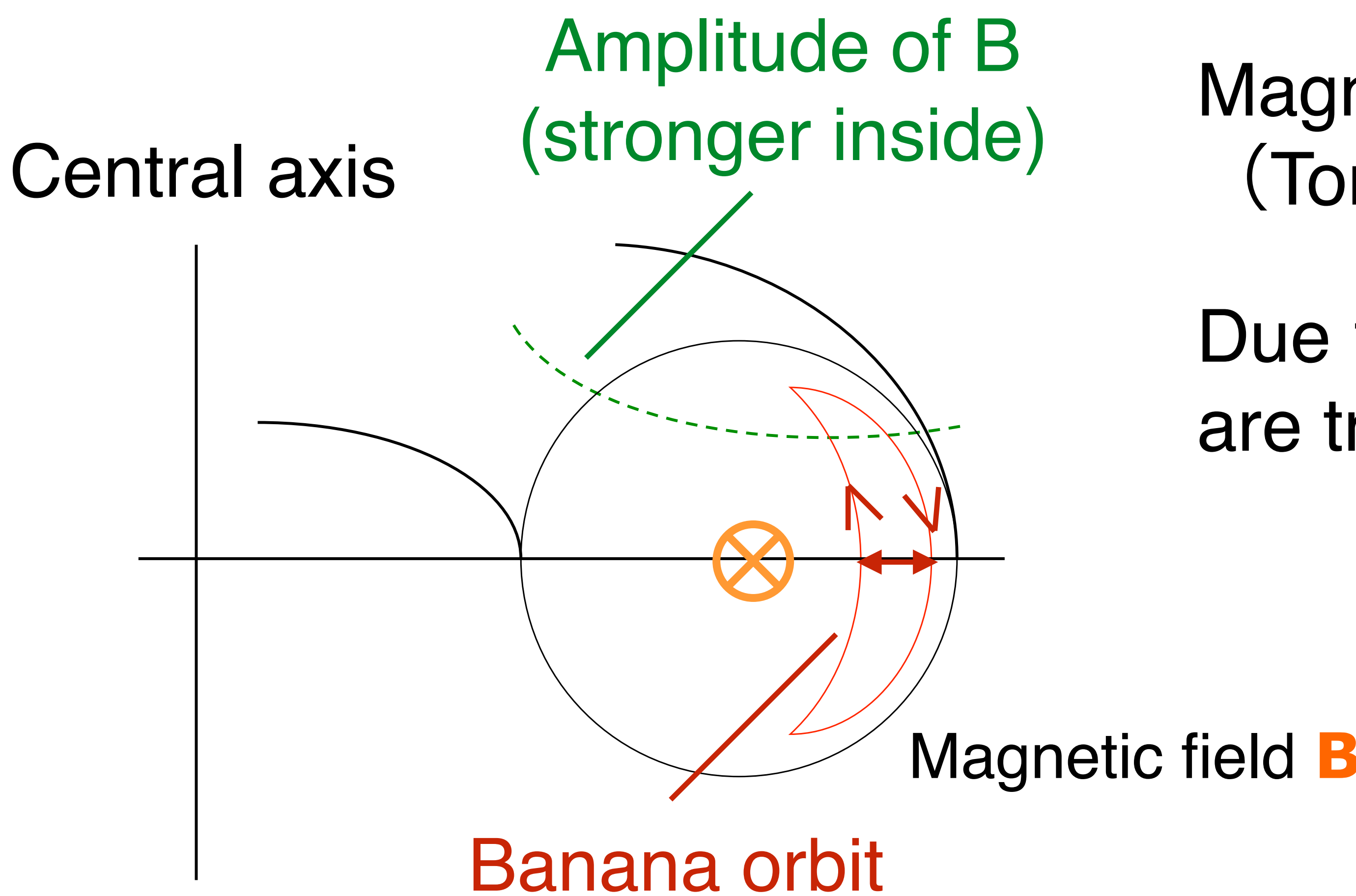



- **ExB drift** (electric field)
- **Magnetic drift** (curvature, grad B)

- **Traverse the magnetic field line** due to drift motion $\mathbf{v}_E + \mathbf{v}_D$
- These traverse motions can **harm confinement property**

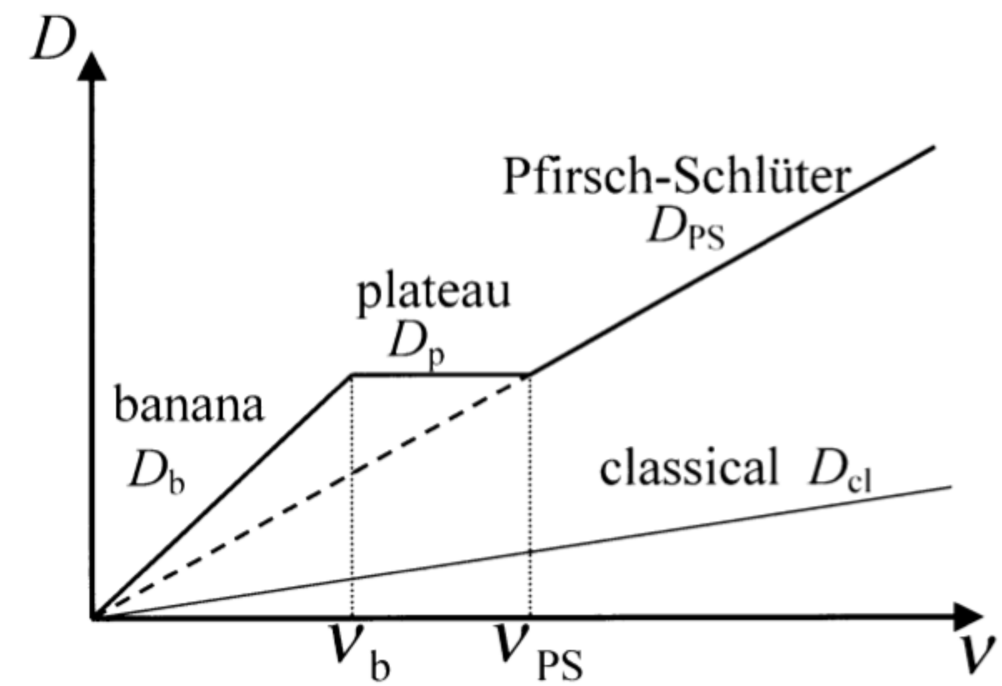
# Neoclassical transport




Projection to poloidal cross section

Magnetic field stronger inside
(Toroidal magnetic field $B \sim B_\phi \propto 1/R$ )

Due to magnetic mirror, a part of particles are trapped (**Trapped particles**)

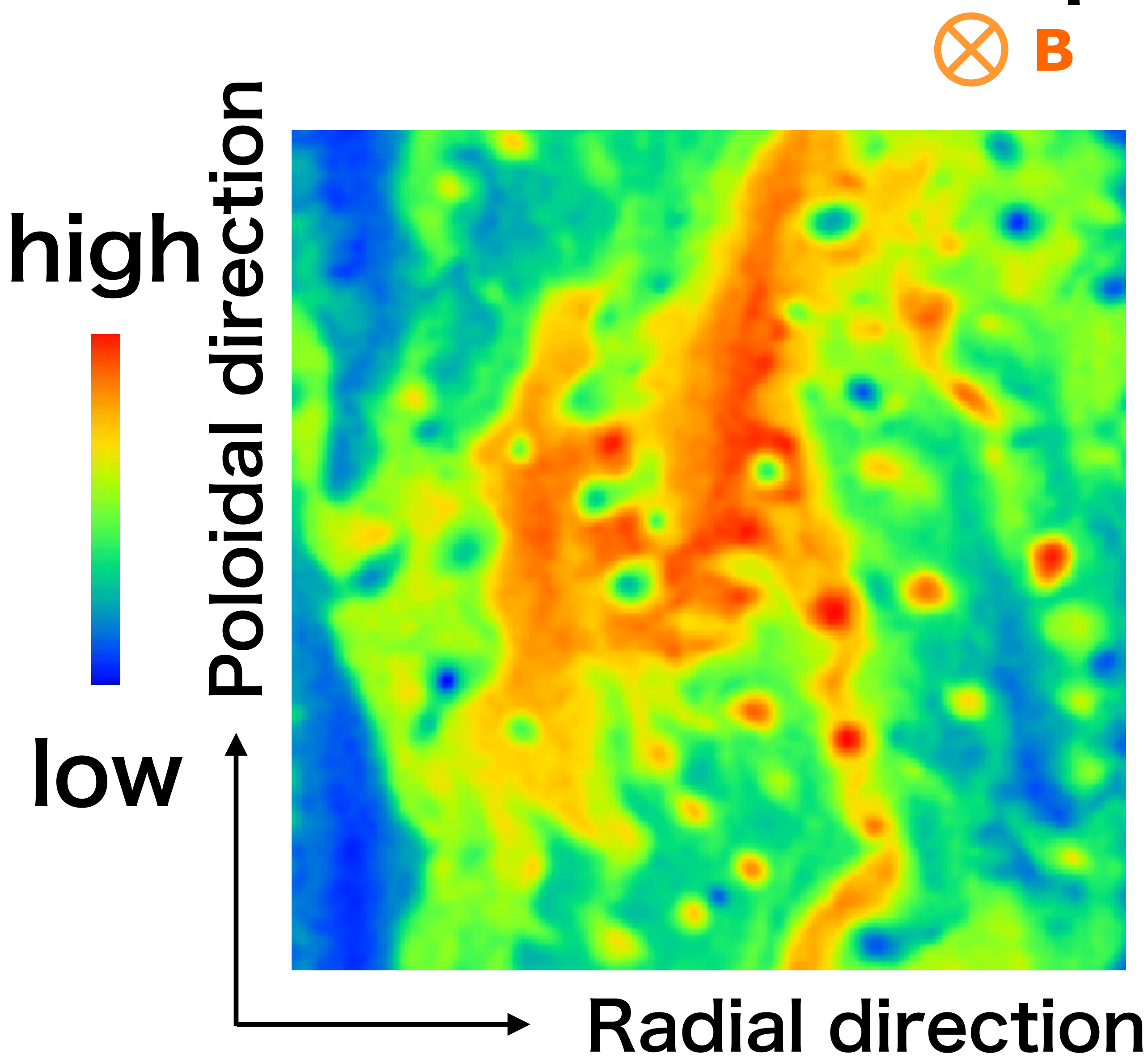



**Banana width** $\Delta r_{\mathrm{b}} \sim (q\rho_{\mathrm{ts}})/\sqrt{\epsilon} > \rho_{\mathrm{ts}}$

- Step width larger than the Larmor radius in classical transport
- Caused by the spatial dependence of magnetic drift $\mathbf{v}_D$

# Turbulent transport

## Potential Color map




- Characteristic length

$$\xi_{\boldsymbol{k}r} \sim \left( \frac{cE_{\boldsymbol{k}\theta}}{B} \right) \delta\tau_{c\boldsymbol{k}}$$

travel distance of a particle by **ExB drift** $\mathbf{v}_E$

- Correlation time

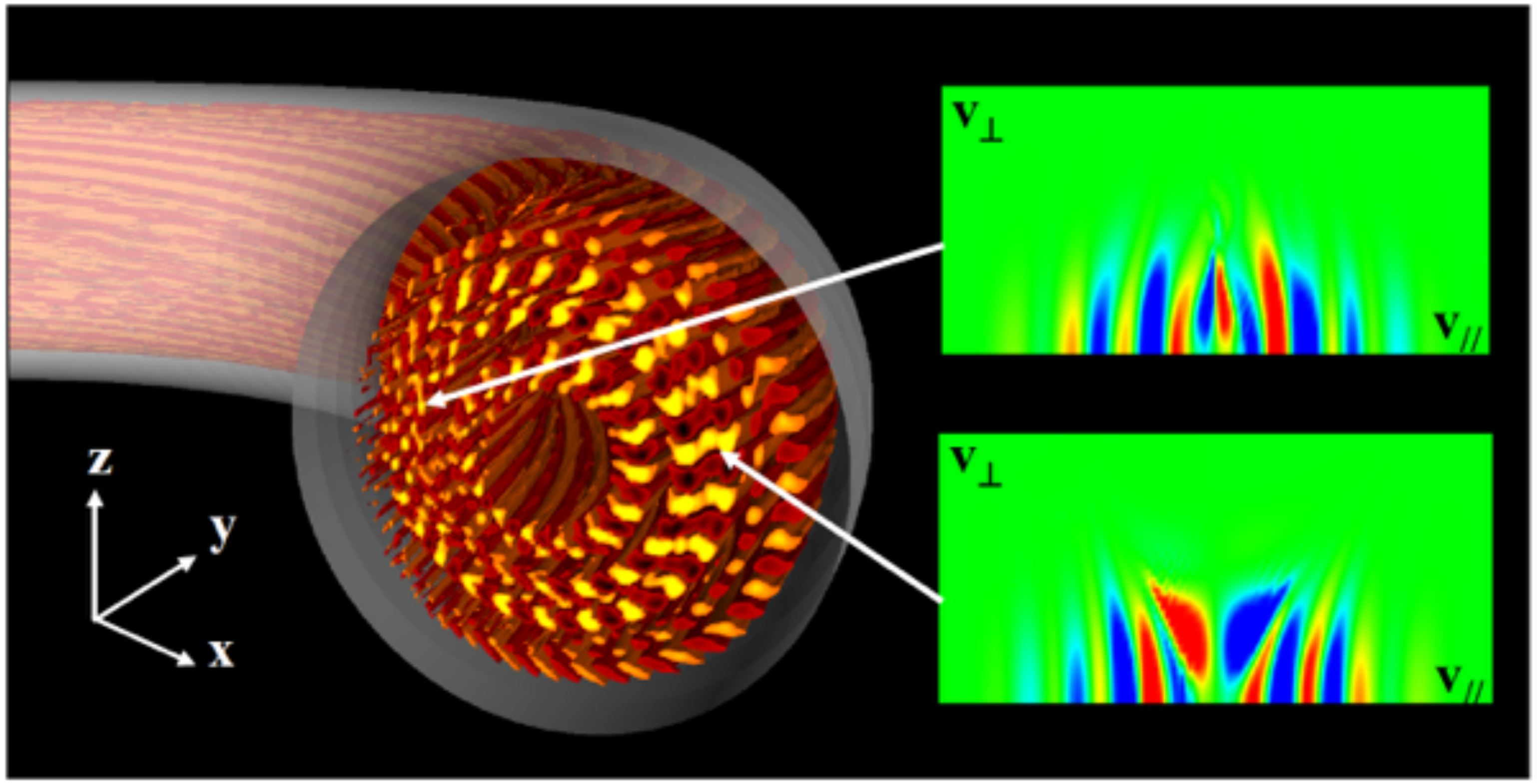
$\delta\tau_{c\boldsymbol{k}}$

generation/annihilation of a vortex

- Heat flux from high T region to low T region by random walk

Ishizawa, et al

# Plasma turbulence simulation




Each grid point has structure in real space (x, y, z) and velocity space ($v_{\parallel}$, $v_\perp$)

⟶ **5D** stencil computations

**Problem size:** $\sim 10^{10}$

[Idomura et al., Comput. Phys. Commun (2008); Nuclear Fusion (2009)]

**The fusion plasma performance is dominated by plasma turbulence**

- Predicting performance of future fusion machines ITER/DEMO

**First principle full-f 5D gyrokinetic model is employed for plasma turbulence simulation**

- Resolving machine scale (~ m) with turbulence scale mesh (~ cm)
- Solving profile and fluctuation without scale separation (full-F approach)

  **Neoclassical + Turbulence** transport

# full-F gyrokinetic simulations

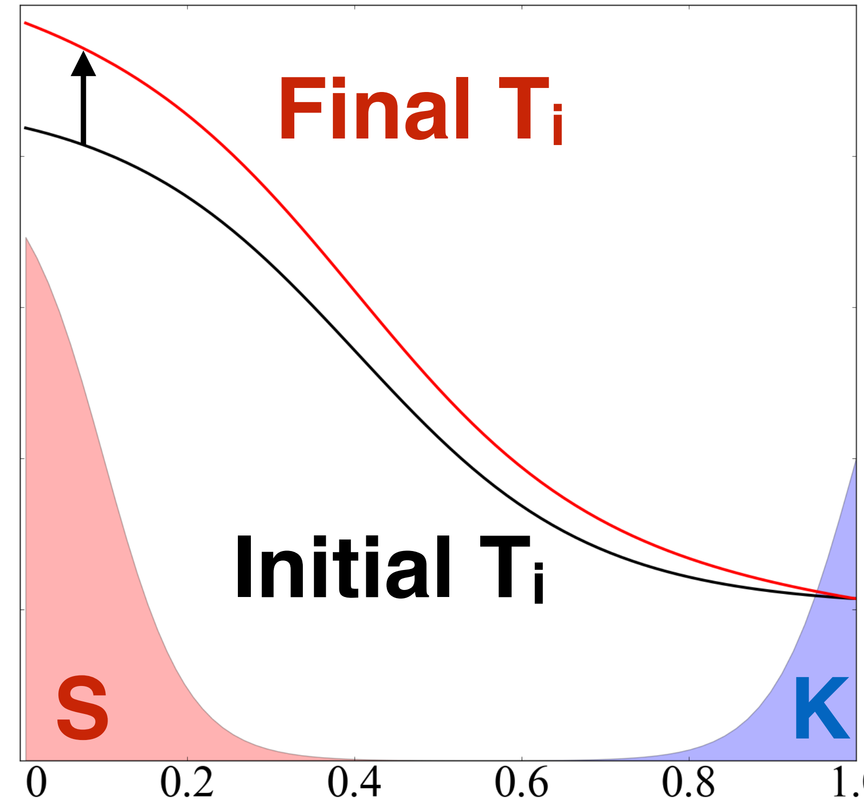
**Gyrokinetic equation: Solve f**

$$\partial_t f - [H, f] = C + S + K$$

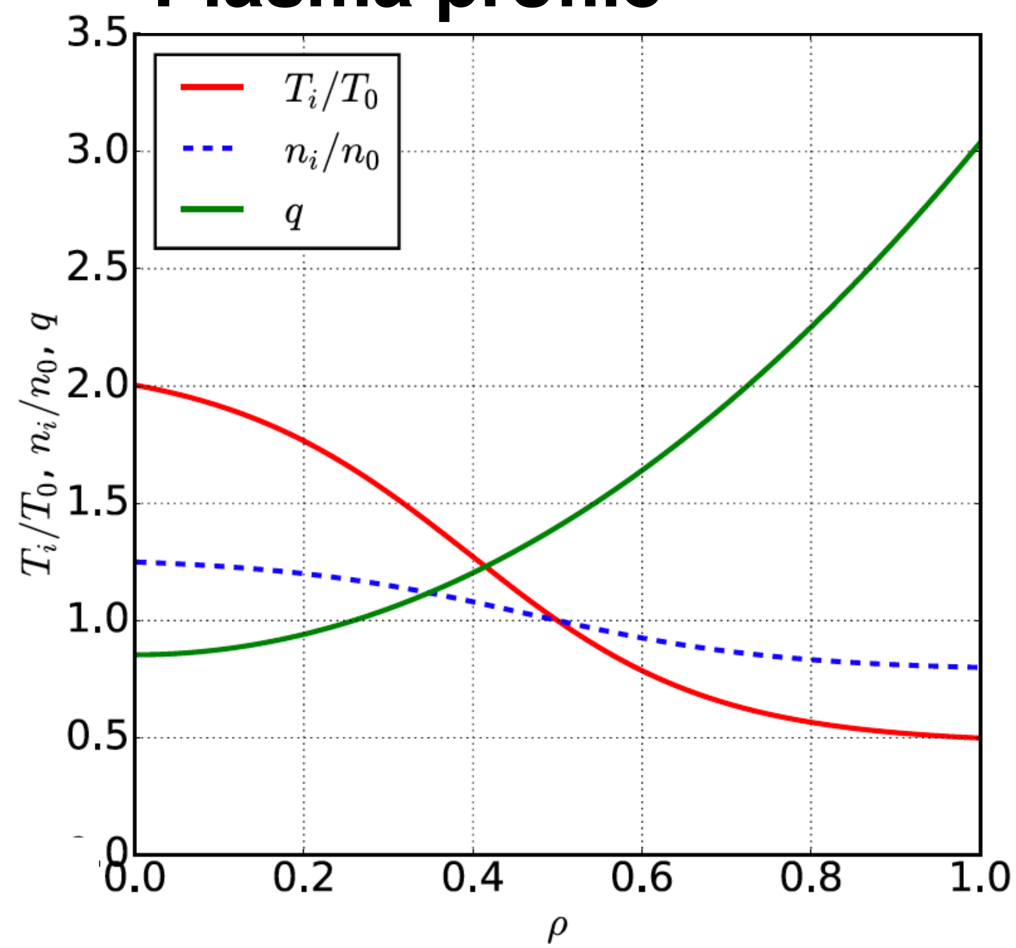
$C$ : collision $S$ : source $K$ : sink

**Poisson equation: Solve electric field**

$$-\nabla_\perp \cdot (P_1 \nabla_\perp \phi) + P_2 (\phi - \langle\phi\rangle) = \rho[f]$$




Plasma profile




- Solving **profile, fluctuation consistently (full-F approach)**

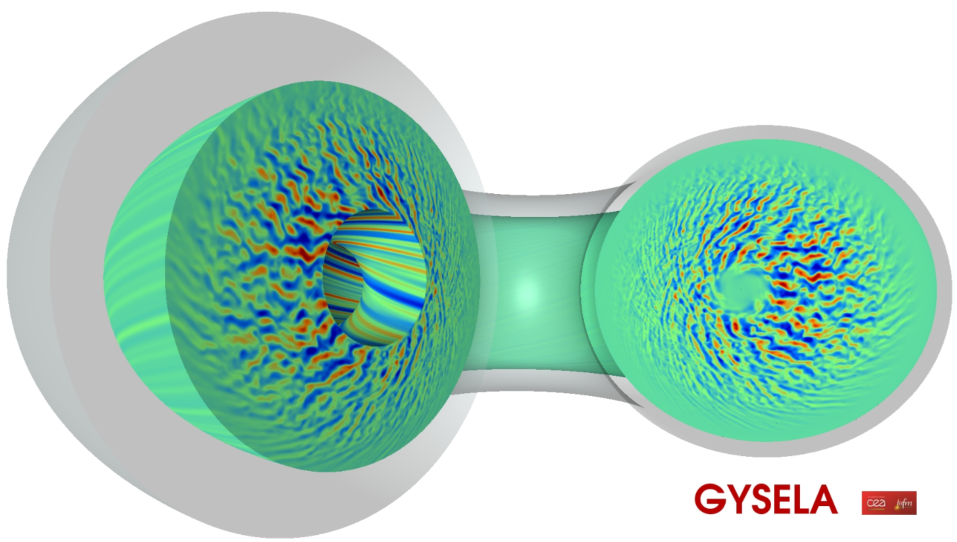
  ORB5 (PIC), XGC1 (PIC), GKNET (Euler), **GYSELA (Semi-Lagrangian)**, GT5D (Euler)

- Fixed heat source + sink (krook) + collisions (neoclassical transport)

- Simulate **self-organisation** induced by **plasma turbulence**

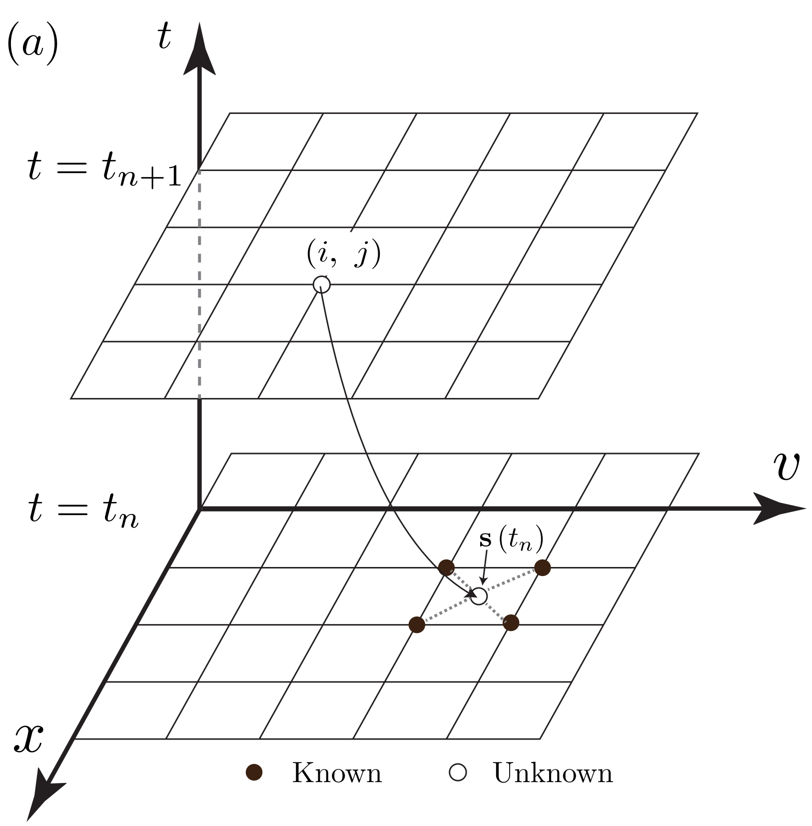
# GYSELA code

## Physics




- Modeling ITG turbulence in Tokamak
- **Flux-driven full-F gyrokinetic** model
- Solving 5D Vlasov + 3D Poisson eqs.
- Neoclassical physics by collision op.
- Full kinetic or trapped kinetic electrons (Adiabatic electrons in this work)

## Numerics




- **Semi-Lagrangian** scheme to solve Vlasov
- Interpolation of footpoints: Spline/Lagrange
- Parallelisation: MPI + OpenMP
- 3D domain decomposition by MPI

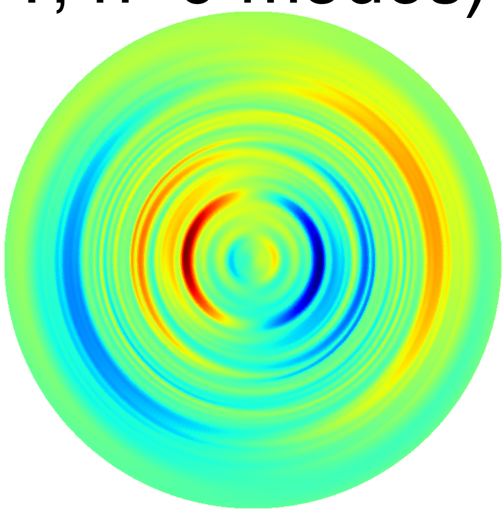
$$N_{\mathrm{MPI}} = p_r \times p_\theta \times N_\mu$$

- Good scalability up to 450 kcores

[1] V. Grandgirard, et al, CPC (2016)

# Poloidal asymmetry matters

**Flow asymmetries (CCs)**
(m>=1, n=0 modes)



Negligible in standard neoclassical theory

**Particle transport [2,3,4]**

- Neoclassical coefficient of heavy impurity transport enhanced or decreased by **one to two orders** of magnitude

**Momentum transport [5]**

- Neoclassical angular momentum flux enlarged even when asymmetry is small

**Drive of convective cells**

- RF heating
- Centrifugal force by toroidal rotation
- **Reynolds Stress (RS)** by **Plasma turbulence [1]**


[1] P. Donnel, et al., PPCF, (2018)
[2] C. Angioni et al, PPCF, (2014)
[3] S. Breton et al, NF, (2018)
[4] P. Donnel, et al., PPCF, (2019)
[5] S. K. Wong, Phys Plasmas, (2009)


**Convective cells are instrumental in neoclassical transport**

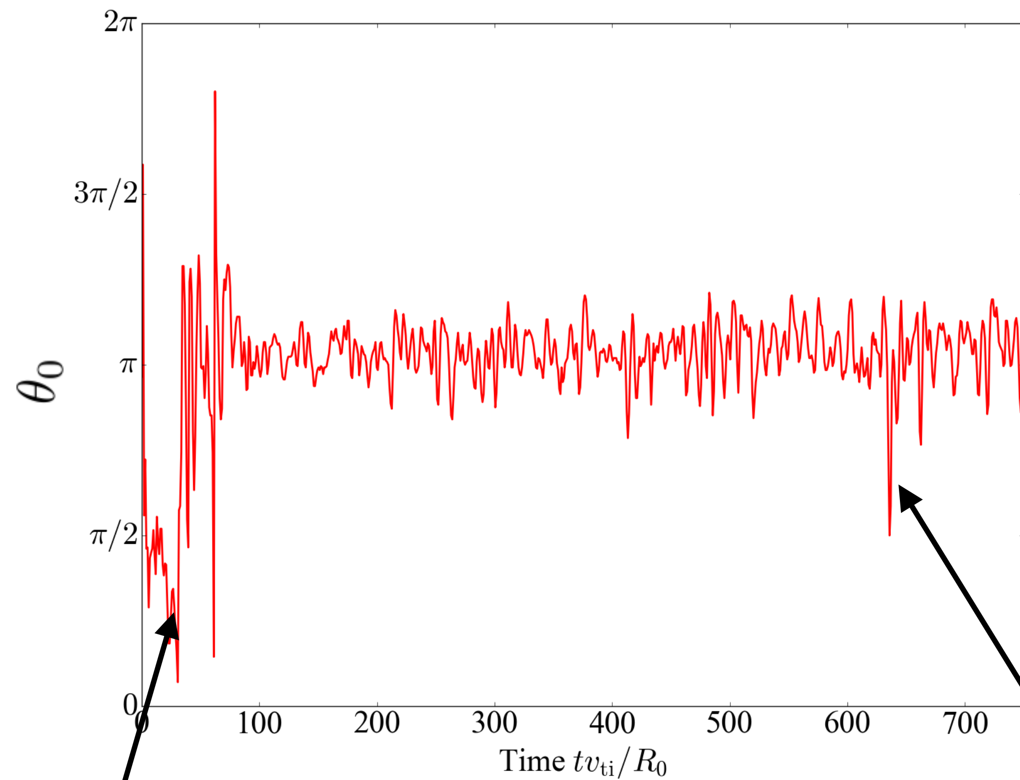
# Dynamics of phase of CCs

**Up-down asymmetry**
**(Perp Compressibility**

**GAM limit**

$$\frac{\omega}{\omega_{\rm th}} = \mathcal{O}(1)$$

$$\longrightarrow \hat{\phi}_{\omega,-1} = -\hat{\phi}_{\omega,1}$$

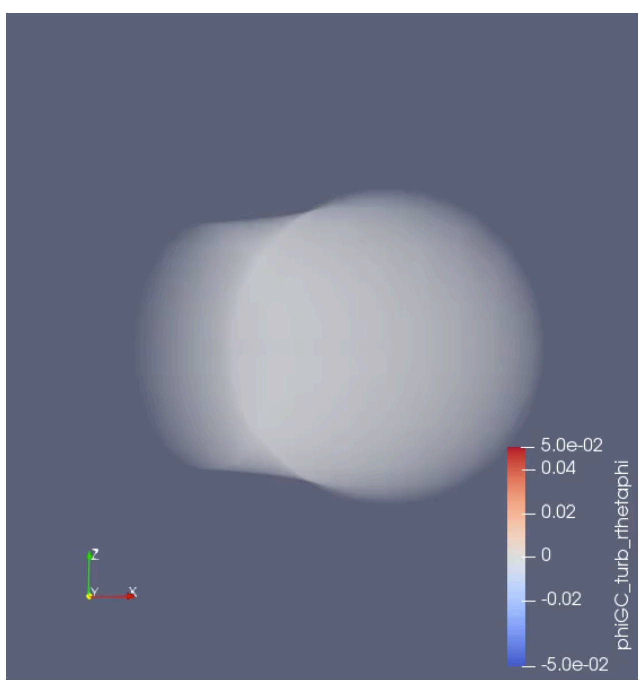



**In-out asymmetry**
**(Reynolds stress)**

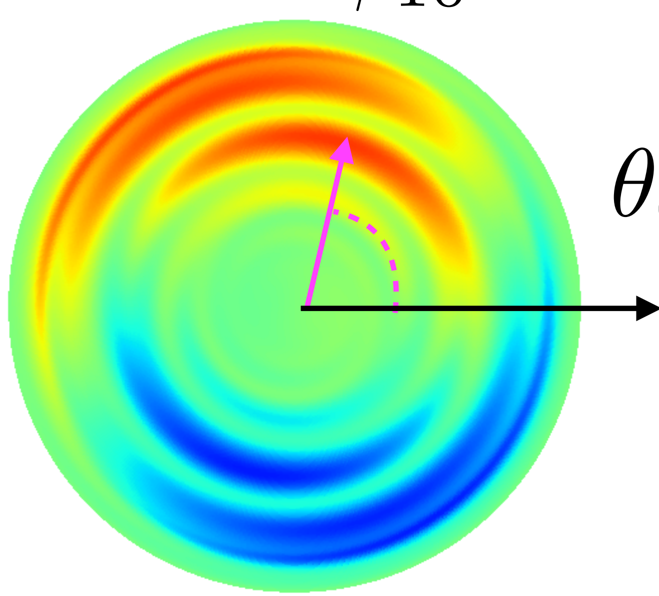
**Convective cell limit**

$$\frac{\omega}{\omega_{\rm th}} \ll (k_r\rho_{\rm ti})^2$$

$$\longrightarrow \hat{\phi}_{\omega,-1} = \hat{\phi}_{\omega,1}$$

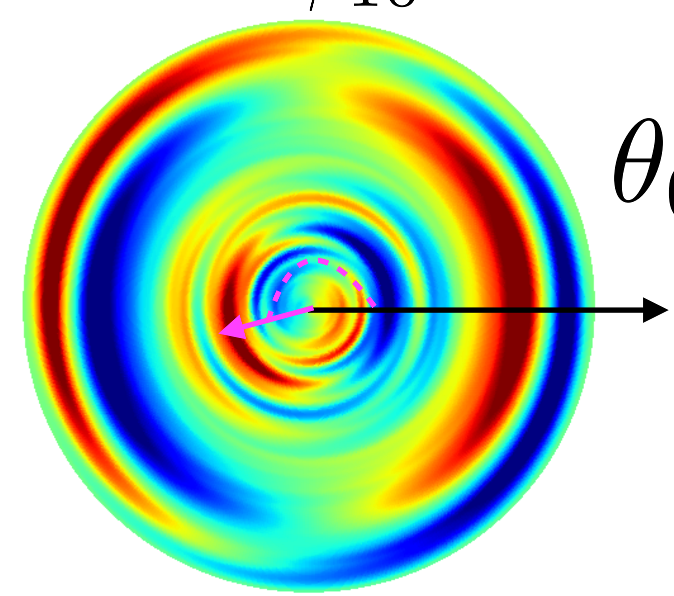



$\phi_{10}$



$\theta_0 \sim \pi/2$

$\phi_{10}$



$\theta_0 \sim \pi$

- **Up-down asymmetry (GAM) to in-out asymmetry (Conv cells)**

[1] P. Donnel, et al., PPCF, (2018)

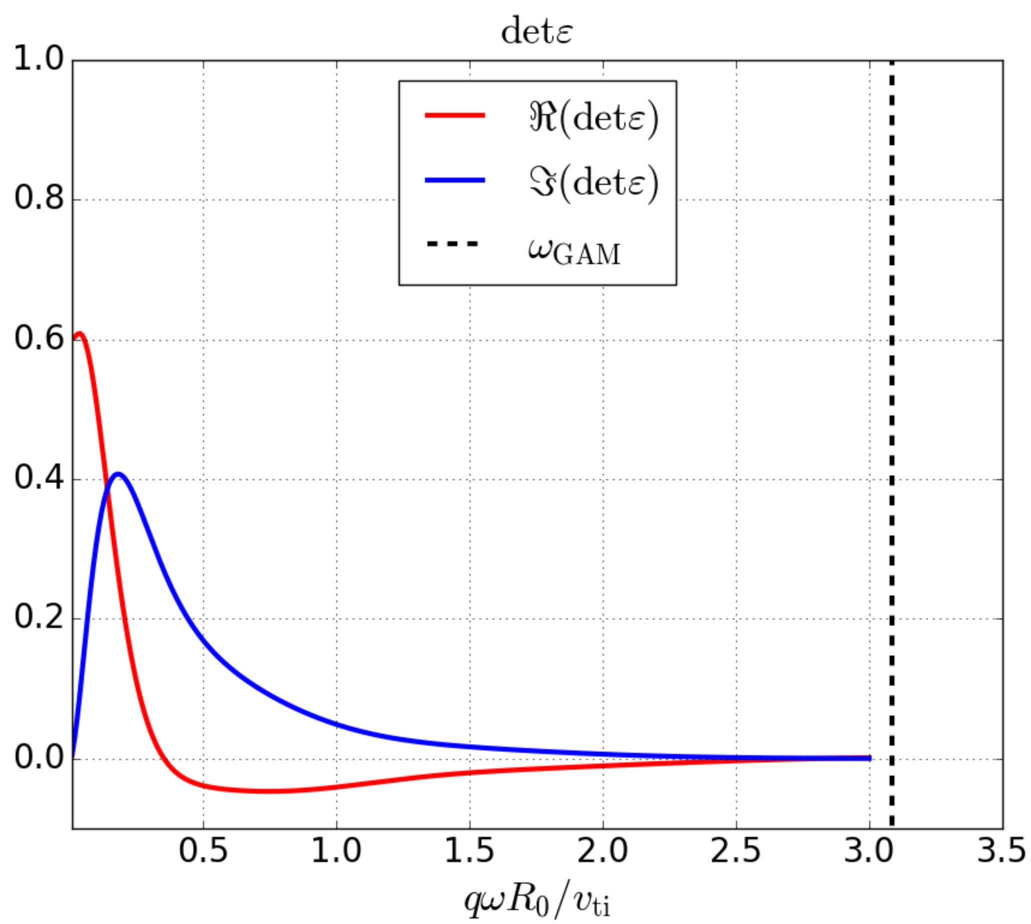
# Generation of Convective cells

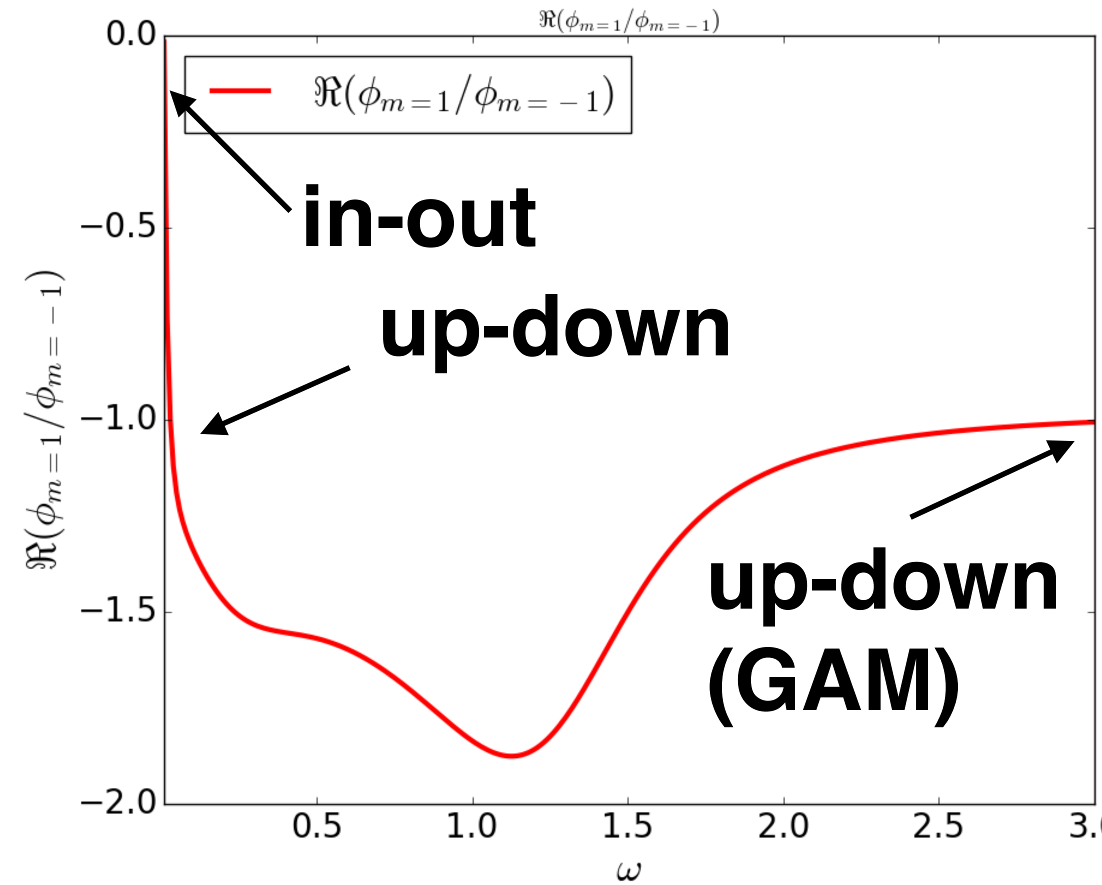
**Gyrokinetic equation coupled with QN eq.** $\varepsilon \cdot \hat{\phi} = \mathrm{S}$

Keeping m = -1, 0, 1 modes only

$$\underbrace{\boxed{\frac{N_{eq}}{T_{eq}}\left[1+(1-\delta_{m,0})\,\tau\right]\begin{pmatrix}\hat{\phi}_{\omega,-1}\\ \hat{\phi}_{\omega,0}\\ \hat{\phi}_{\omega,1}\end{pmatrix}}}_{\textbf{Vorticity}} + \underbrace{\boxed{i\omega\int d^3vG^{-1}\frac{F_{eq}}{T_{eq}}\mathcal{J}^2\begin{pmatrix}\hat{\phi}_{\omega,-1}\\ \hat{\phi}_{\omega,0}\\ \hat{\phi}_{\omega,1}\end{pmatrix}}}_{\textbf{Coupling}} = \underbrace{\boxed{-\int d^3vG^{-1}\mathcal{J}\begin{pmatrix}\mathcal{N}_{\omega,-1}\\ \mathcal{N}_{\omega,0}\\ \mathcal{N}_{\omega,1}\end{pmatrix}}}_{\textbf{Source term}}$$

$q = 1.5, \ \tau = 1$



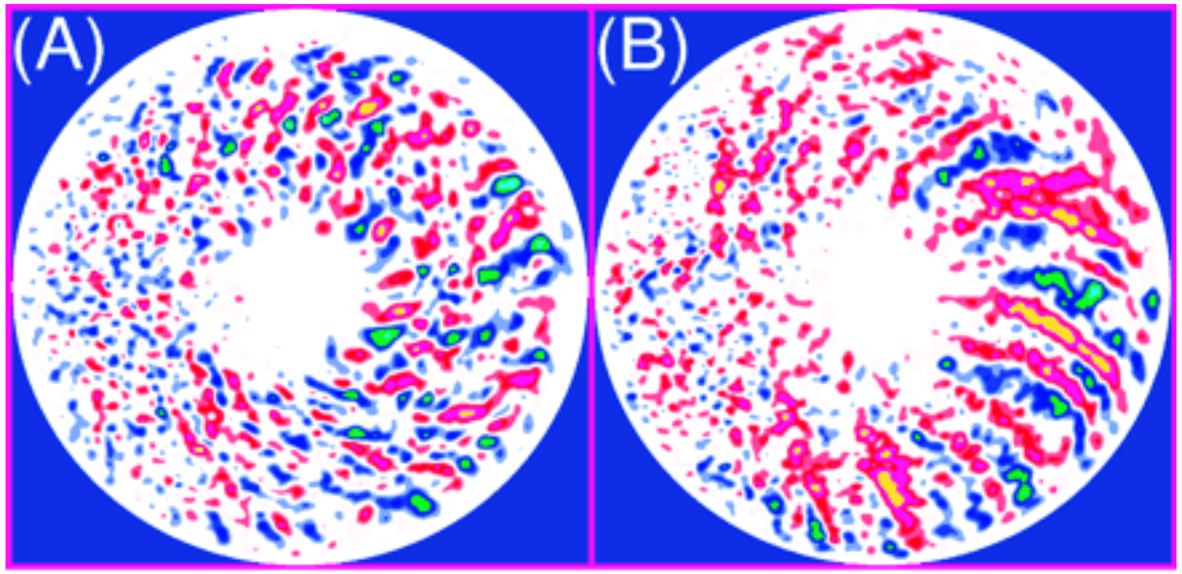

- Analytically $\det\varepsilon = 0$ gives the GAM frequency
- Symmetry changes depending on the frequency (up-down to in-out)



[1] P. Donnel, et al., PPCF, (2018).

# Impact of Conv Cells to transport

- Famous pictures from Z. Lin [1] to demonstrate the impact of ZF

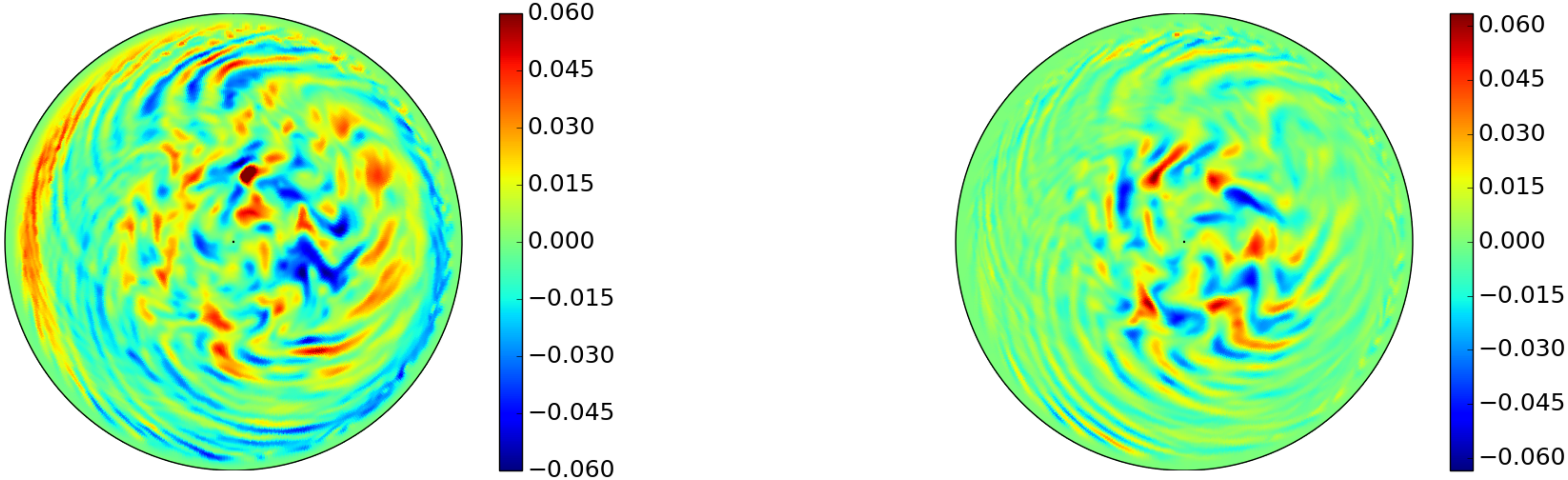



**w ZFs** **w/o ZFs**

**Turbulence regulation by ZFs**

[1] Z. Lin, et al, Science (1998).
[2] Y. Asahi, et al, PPCF (2019).

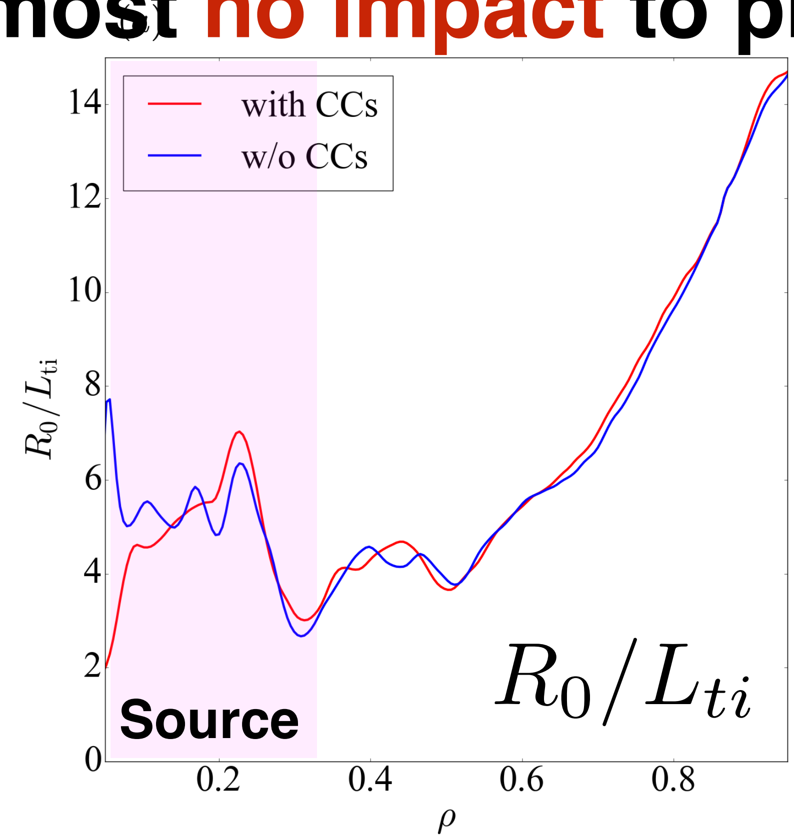
- This work [2]: Impact of **Convective cells** by filter (m>=1, n=0 modes)

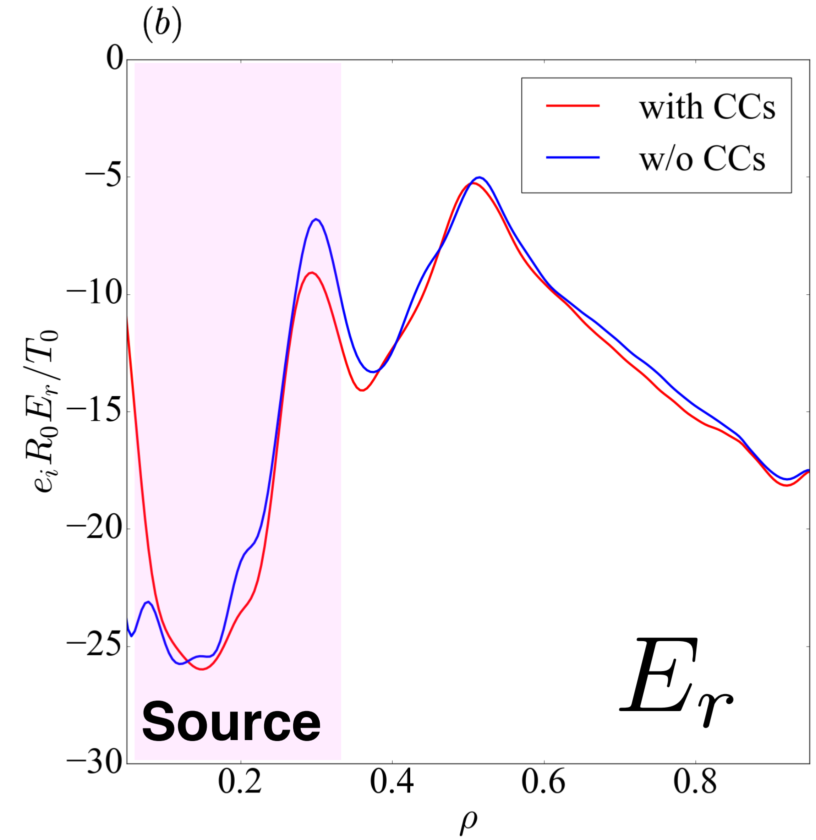



**w CCs** **w/o CCs**

# Turbulence regulation weak

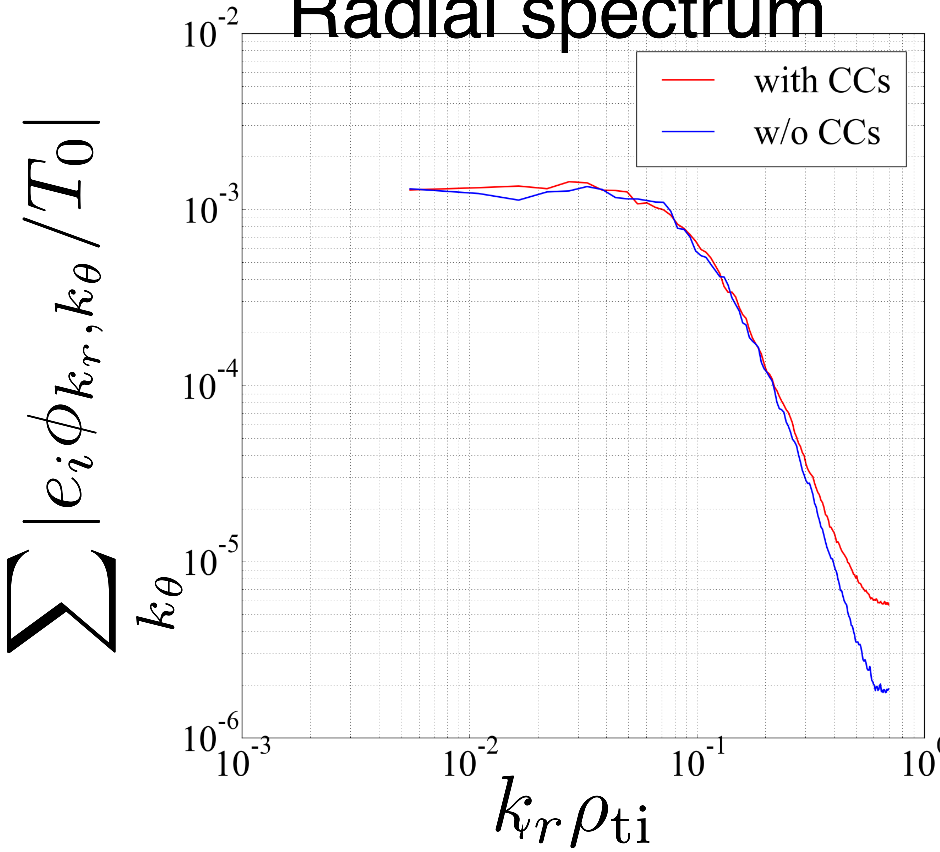
- **Almost** no impact **to profiles**



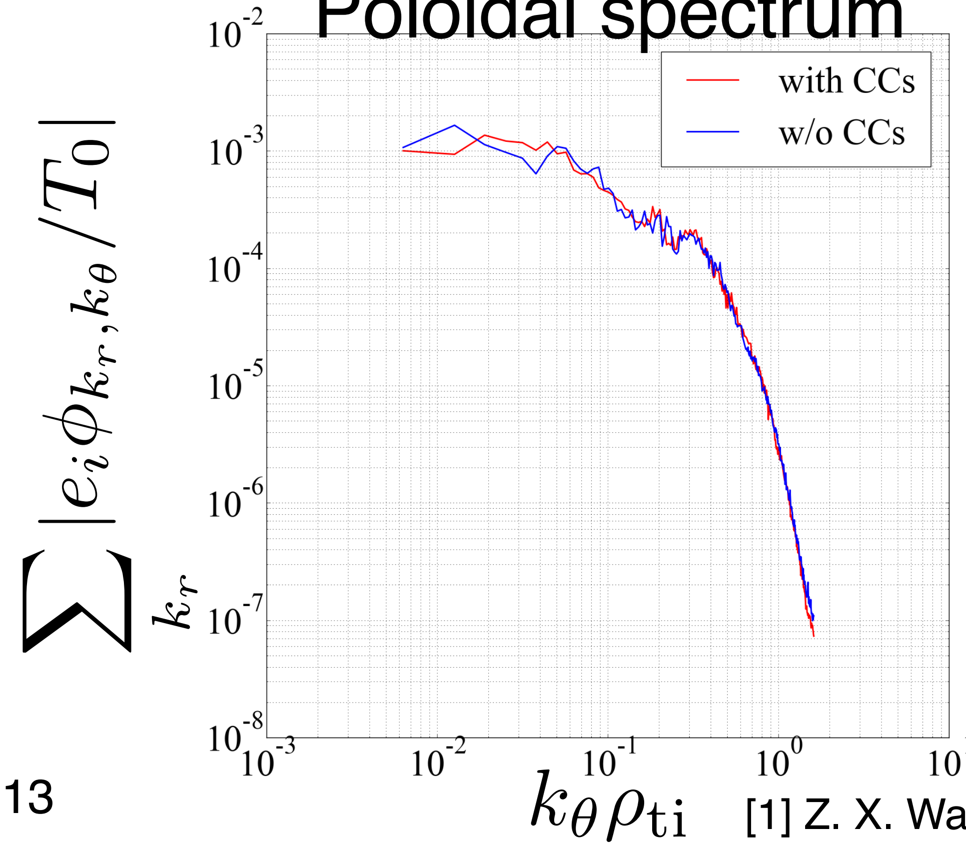




- **Turbulence regulation: vortex shearing (m>=1 mode) [1] weak**

Radial spectrum



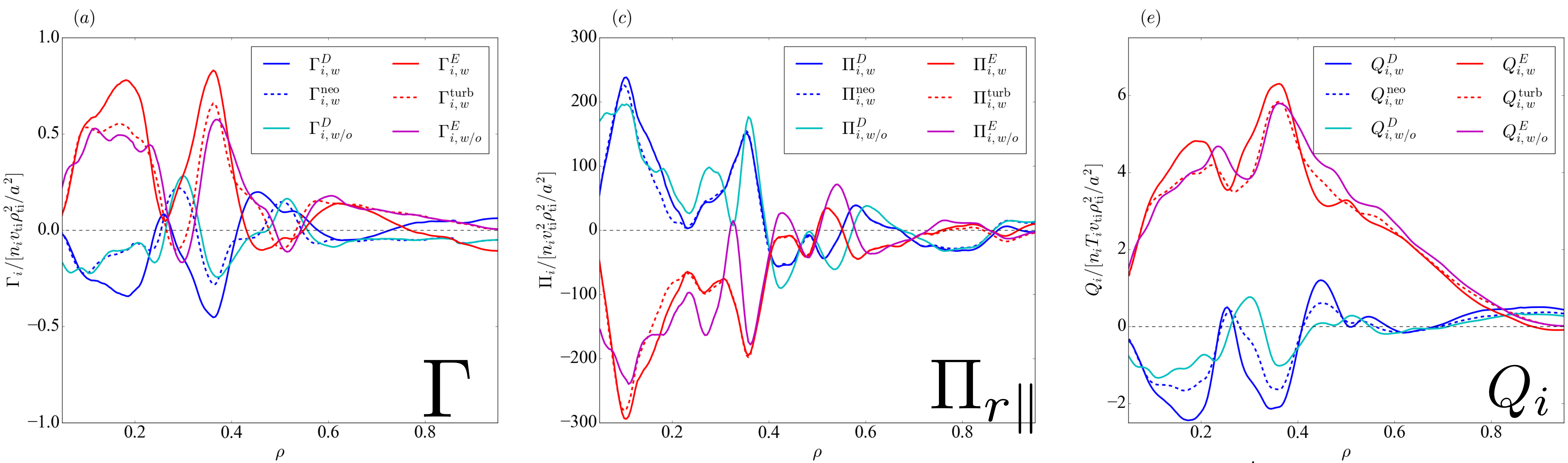

Poloidal spectrum






[1] Z. X. Wang, et al., PRL, (2009)

# Convective cells on transport




**Time average:** $tR_0/v_{\mathrm{ti}} = 600 \sim 750$

**$V_E$ & $V_D$ contribution**

$$\boxed{\Gamma_E = \int d^3\mathbf{v} F \mathbf{v}_E}$$

$$\boxed{\Gamma_D = \int d^3\mathbf{v} F \mathbf{v}_D}$$

**Turbulent&Neoclassical contribution**

$$\boxed{\Gamma_{turb} = \int d^3\mathbf{v} F \mathbf{v}_E^{n\neq 0}}$$ Subtract CC

$$\boxed{\Gamma_{neo} = \int d^3\mathbf{v} F (\mathbf{v}_D + \mathbf{v}_E^{n=0})}$$ Add CC

- **Significant contribution of CCs on particle transport (Solid, dotted lines)**
- **Neoclassical energy transport (blue and cyan)**

# CCs contribute on neoclassical flux

## CCs affect distribution function

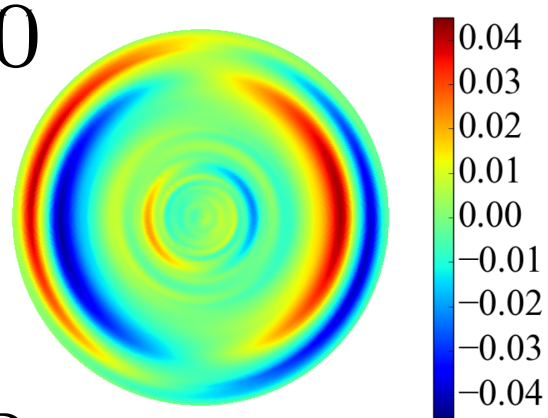
- Enhanced density asymmetry without CCs

$$\hat{f}_{\omega,10} = -\frac{e\hat{\phi}_{\omega,10}}{T}F_{\mathrm{M}} + F_{\mathrm{M}}\frac{\omega-\omega_*}{\omega-\frac{v_\parallel}{qR}}\left[\frac{e\hat{\phi}_{\omega,10}}{T} - \frac{mv_\parallel^2+\mu B_0}{2T}\epsilon\delta\left(\omega\right)\right].$$

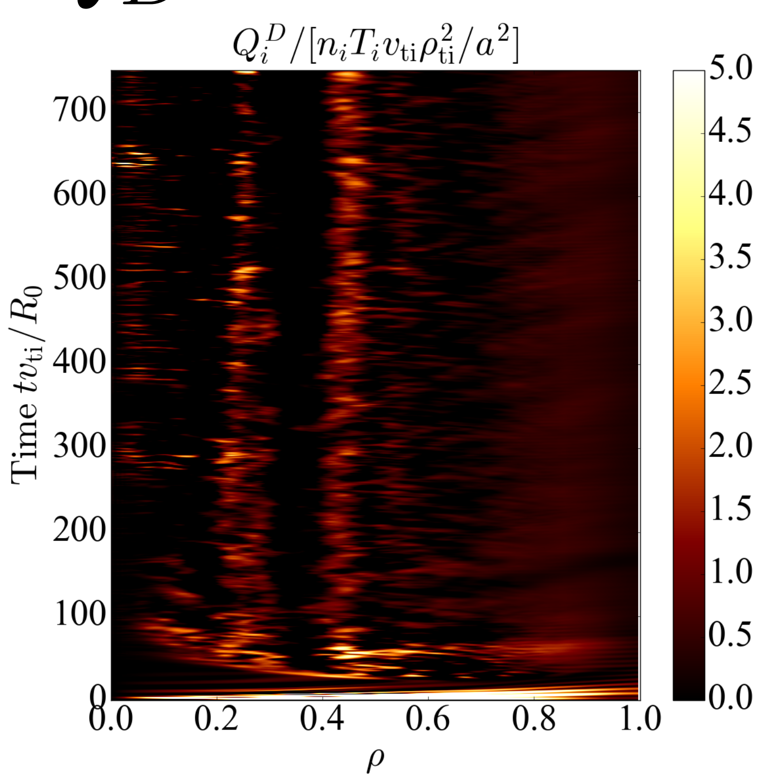
- **Energy flux by magnetic drift decreased by CCs**

**(w CCs)**

$n_{10}$

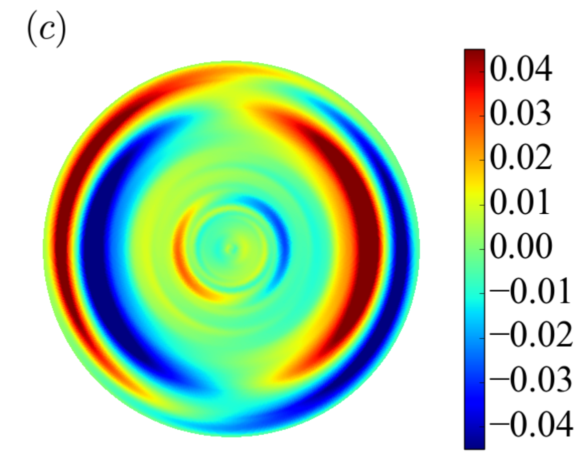



$Q_D$



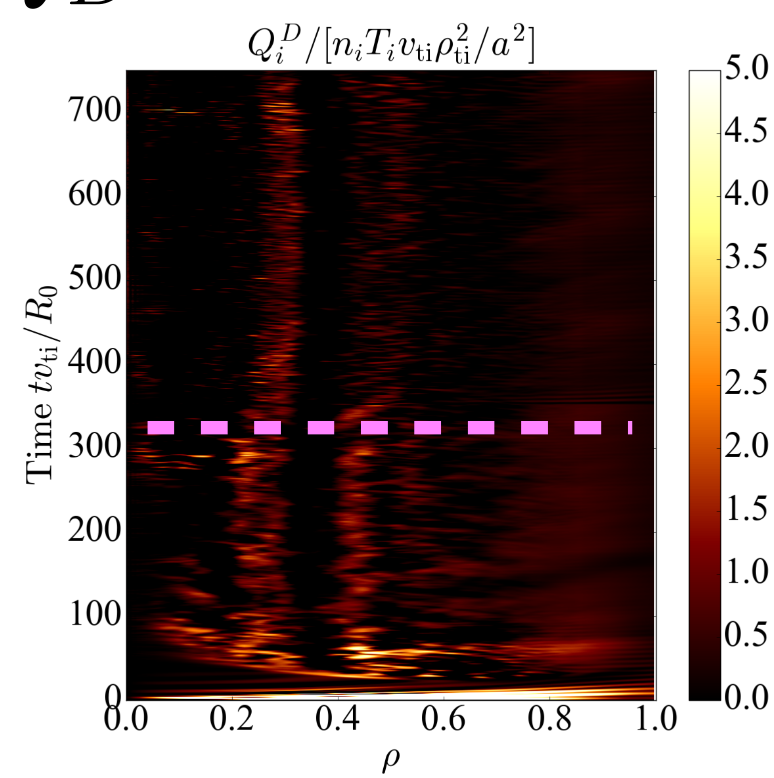

**(w/o CCs)**

$n_{10}$

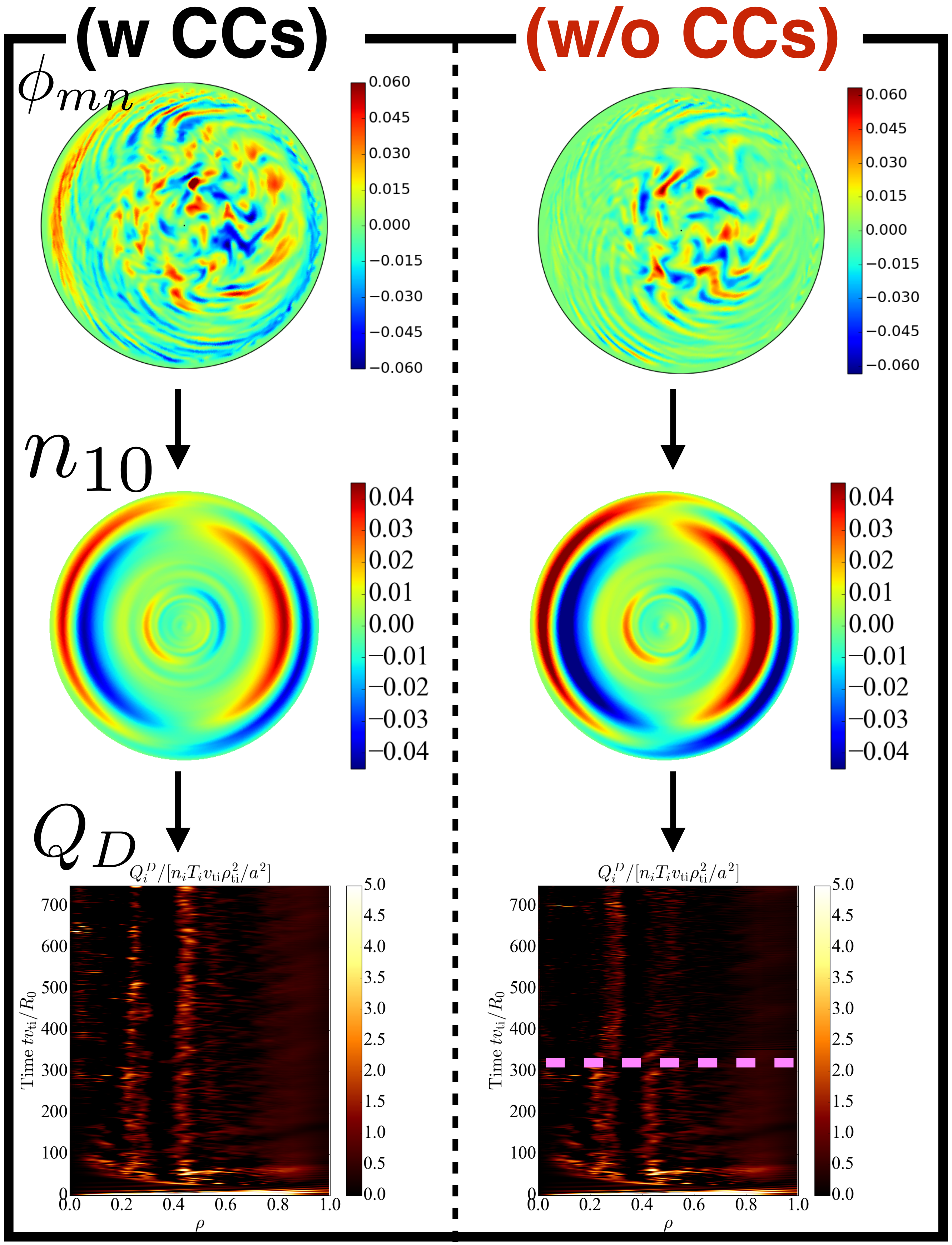



$Q_D$

**Filter on** →



# How CCs affect fluxes




- **Turbulent components of potential not affected**

  ⟶ Profile unchanged,
  Weak vortex shearing

- **Asymmetry in distribution function f enhanced**

  ⟶ Consequence of linear response to potential

- **Reduction in energy flux by magnetic drift**

  ⟶ Neoclassical transport affected through **f**

$$Q_D = \left\langle \int d^3v f \frac{1}{2} m v^2 \mathbf{v}_D \cdot \nabla r \right\rangle$$

# Summary, Future work

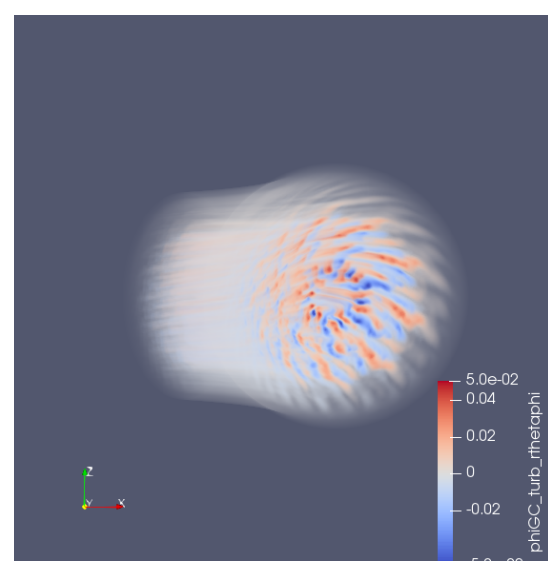
## Turbulence/neoclassical interactions via CCs

- Turbulence can generate convective cells (large scale structure)
  Up-down (GAM) to in-out (Convective cells) asymmetry
- Turbulence regulation weak
  Weak impact on profiles and vortex shearing
- Convective cells can affect neoclassical transport
  Contributions from convective cells are non-negligible

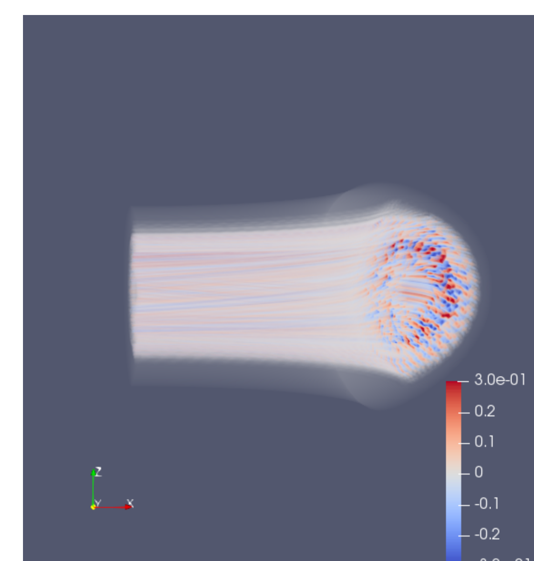
## Future work

- **Impact of kinetic electrons**
- **Circular to Realistic geometry**

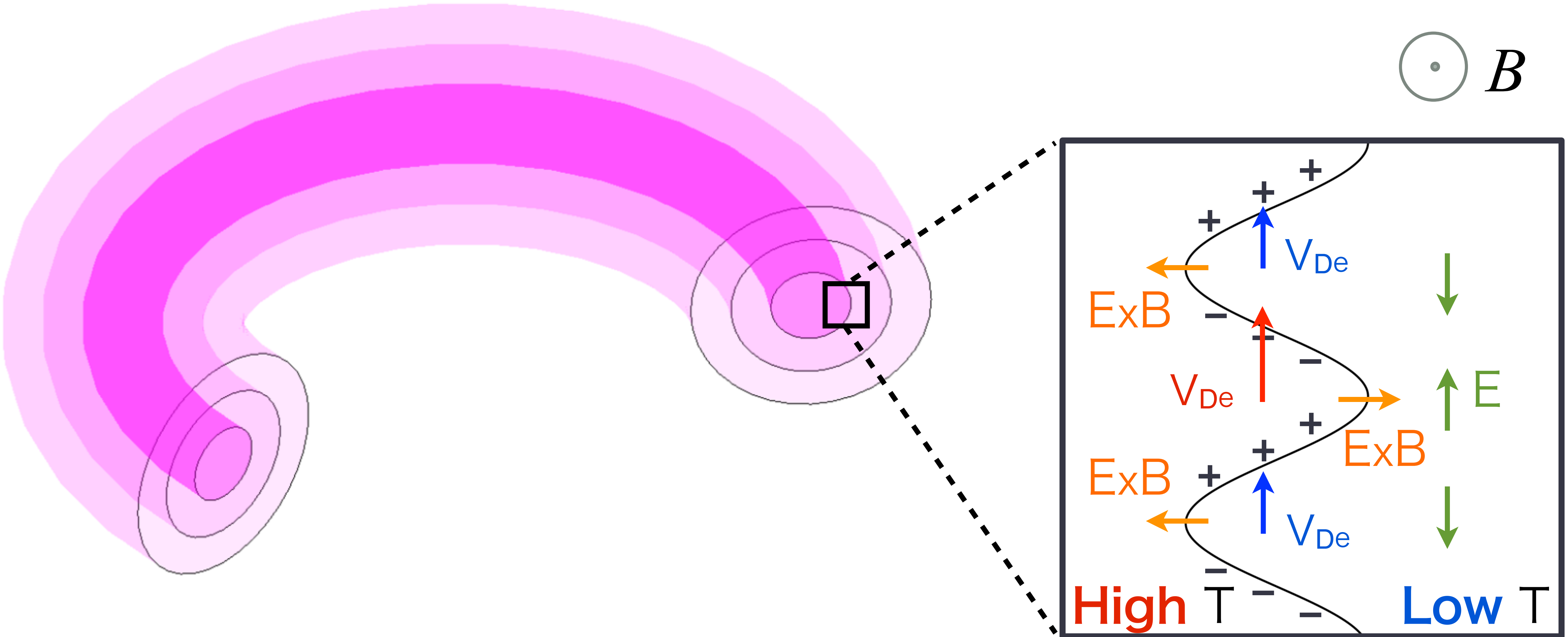
Circular (**KE**)



**JT-60U** (**KE**)



# Electron temperature gradient mode




(1) **Temperature** fluctuation

(2) Speed difference in **$V_{De}$**

(3) Charge seperation

(4) Electric field ➡ **E x B** drift

(5) fluctuation growth

$V_{De}$: **Magnetic drift**

$$\mathbf{v}_{De} = -\frac{1}{eB}\mathbf{b} \times \left[ \frac{m_e {v_\parallel}^2 + \mu B}{B} \nabla B + \frac{m_e {v_\parallel}^2}{cB^2/4\pi} \nabla P \right]$$

Dependence on temperature

toroidal **ETG** mode