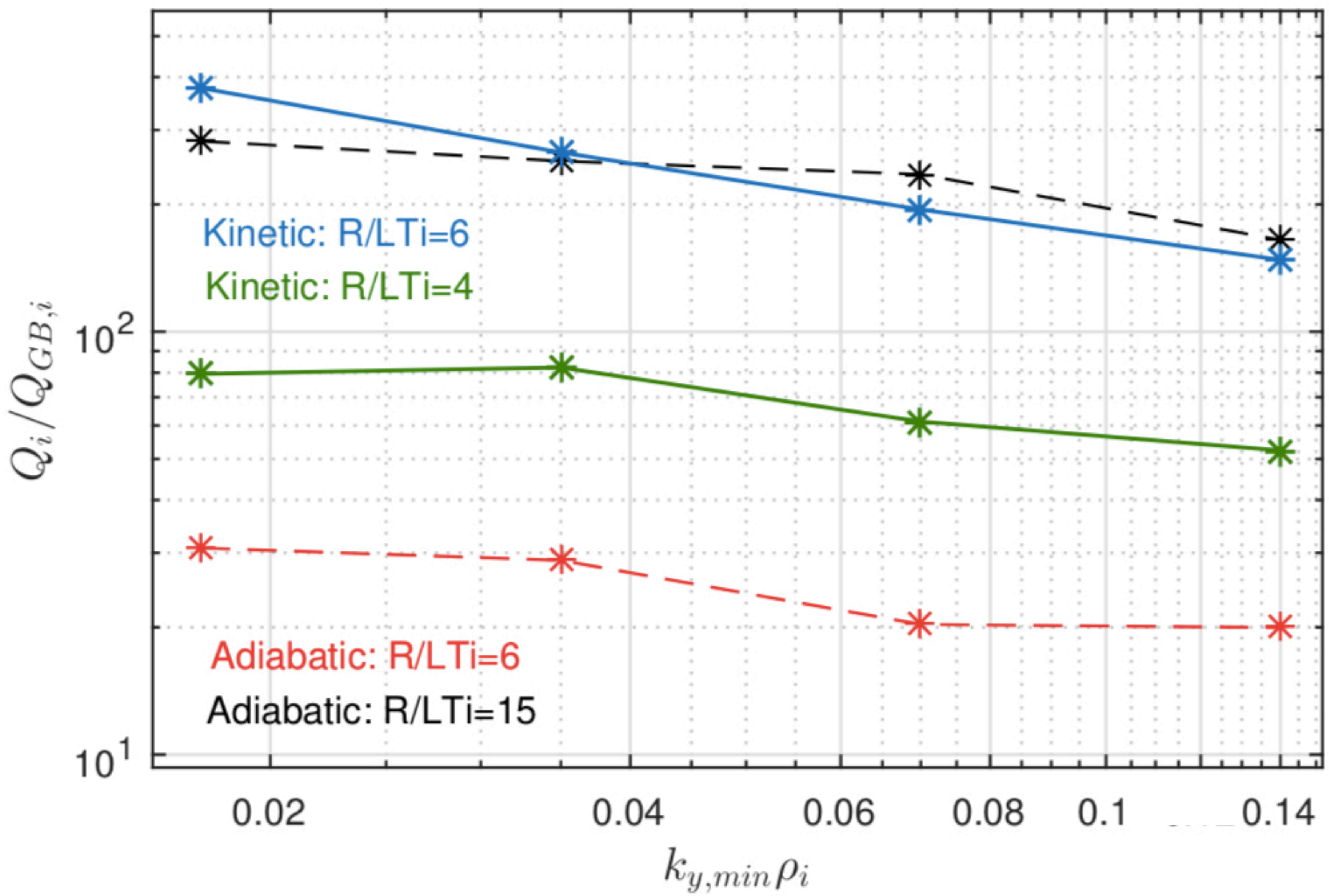
Turbulent self-interaction through the parallel boundary condition in local gyrokinetic simulations



Justin Ball, S. Brunner, and Ajay C.J.

Swiss Plasma Center, EPFL

12th Vienna Plasma Kinetics Working Meeting

1 August 2019

Outline

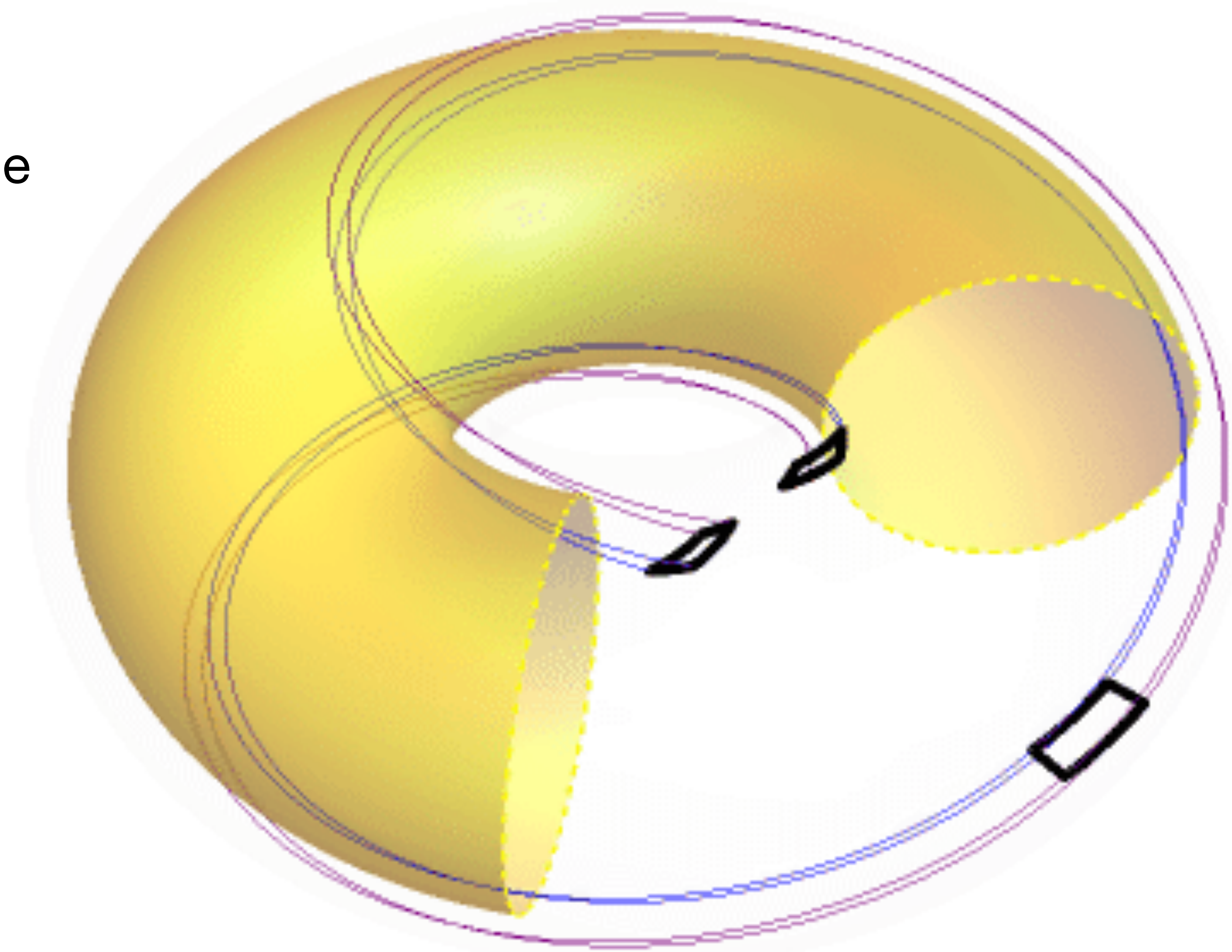
- Understand the parallel boundary condition and how it enables self-interaction
- Explore effects of self-interaction
    - e.g. how it drives intrinsic flow [WORK IN PROGRESS]
- Investigate two strategies for eliminating self-interaction
- Test each strategy to see its impact on heat flux convergence

What’s causing non-convergence?

- Hypothesis: self-interaction through the parallel boundary condition of local simulations

- Typically, the length of the flux-tube is just one poloidal turn

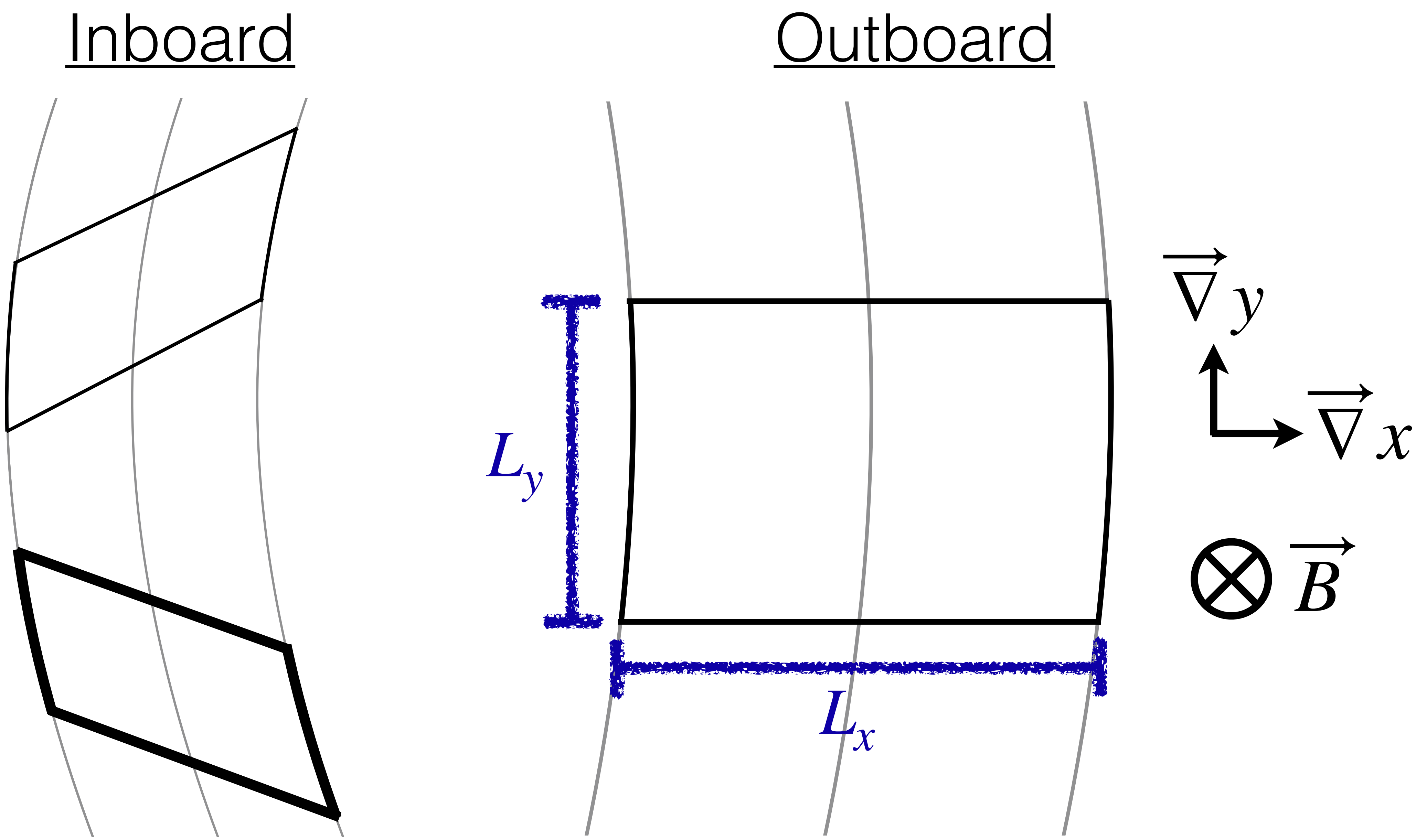
- *Statistical* periodicity is substituted with *exact* periodicity



Parallel boundary condition enables self-interaction

Beer et al. *PoP* (1995).

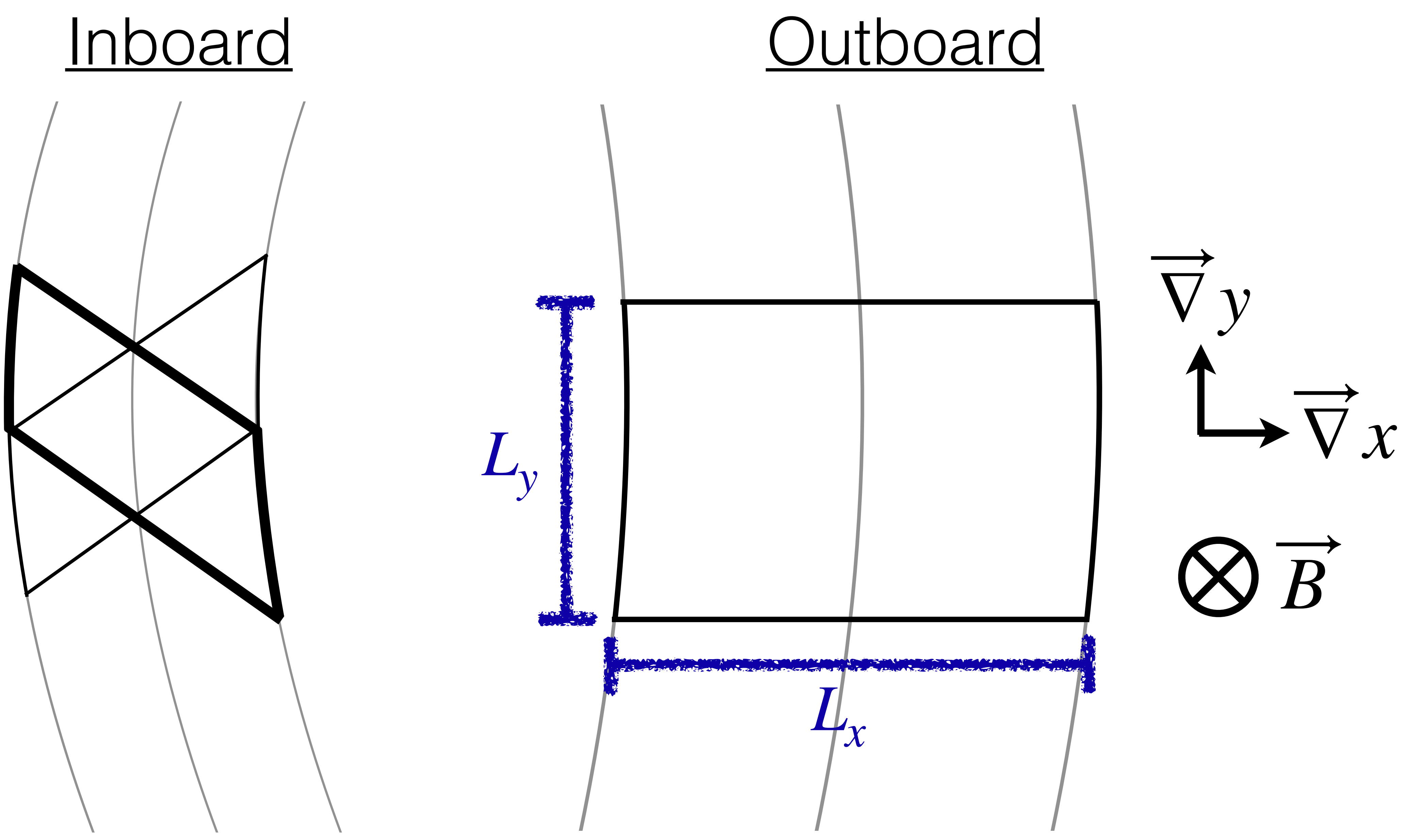
- The magnetic field lines at opposing ends of the domain are connecting using the “twist-and-shift” boundary condition



Parallel boundary condition enables self-interaction

Beer et al. *PoP* (1995).

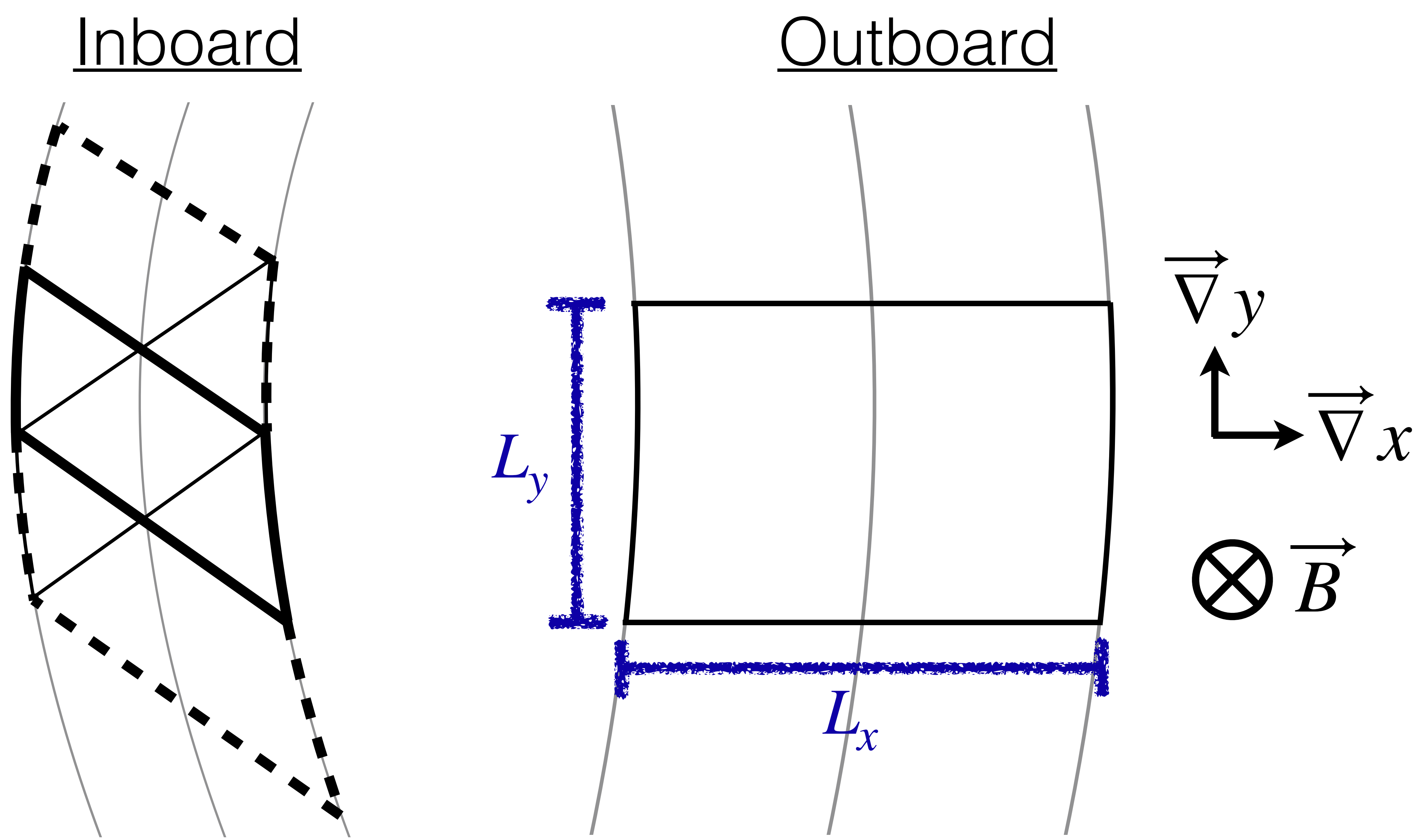
- Align the centers of the parallelograms



Parallel boundary condition enables self-interaction

Beer et al. *PoP* (1995).

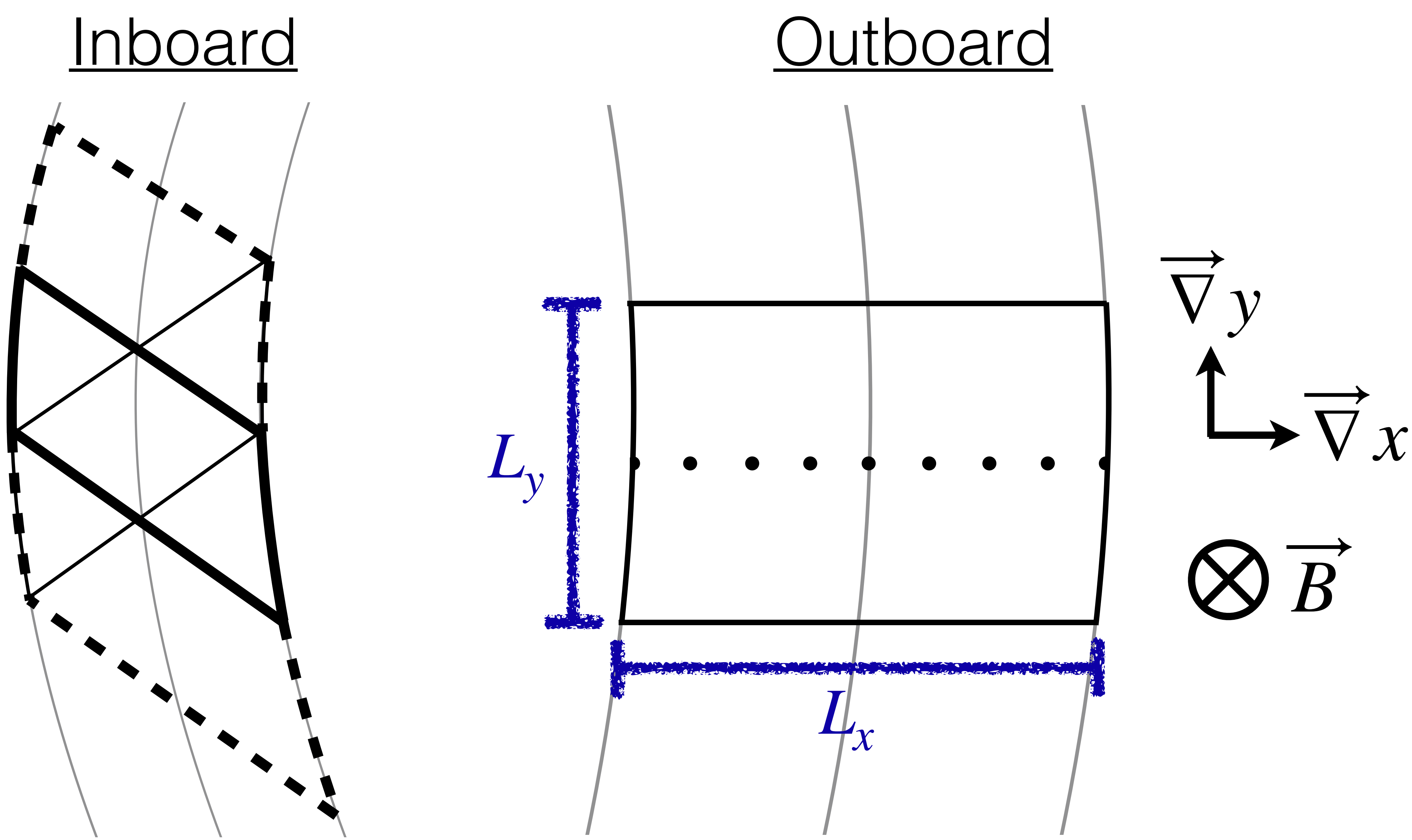
- Use periodic copies to fully cover the opposing boundary



Parallel boundary condition enables self-interaction

Beer et al. *PoP* (1995).

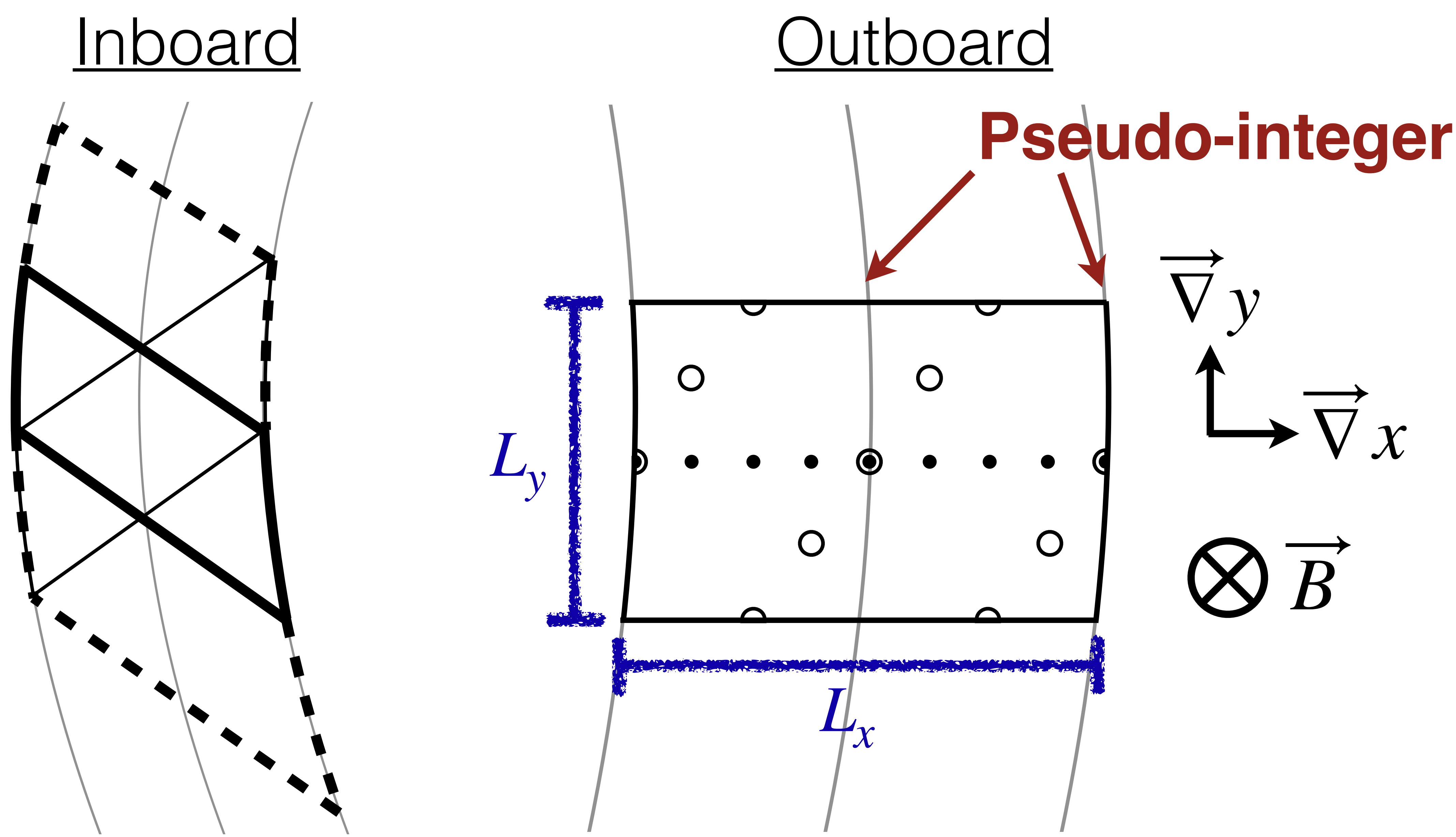
- Follow field lines through the parallel boundary



Parallel boundary condition enables self-interaction

Beer et al. *PoP* (1995).

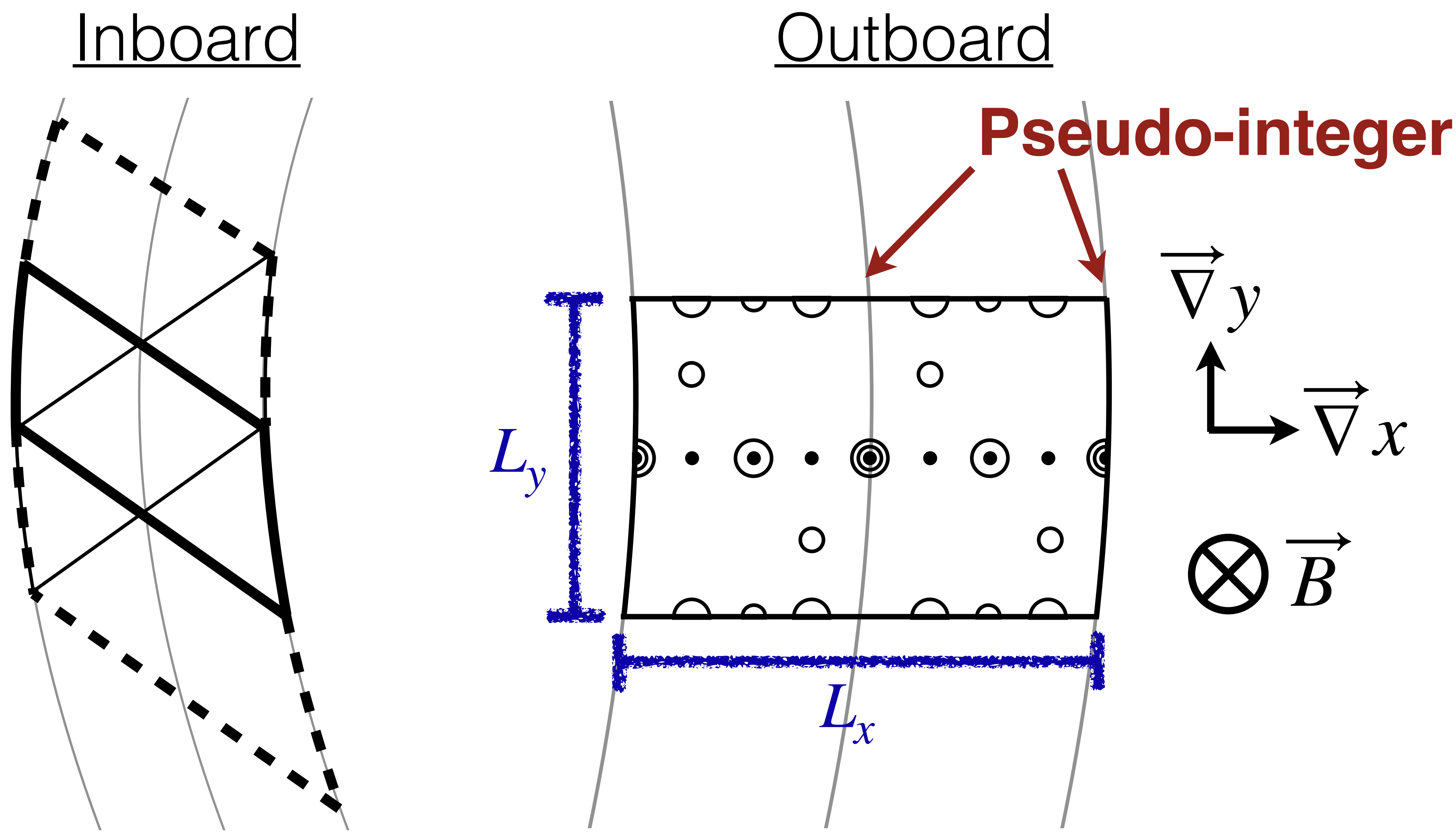
- Applying “twist-and-shift" after just one poloidal turn creates “pseudo-integer” surfaces



Parallel boundary condition enables self-interaction

Beer et al. *PoP* (1995).

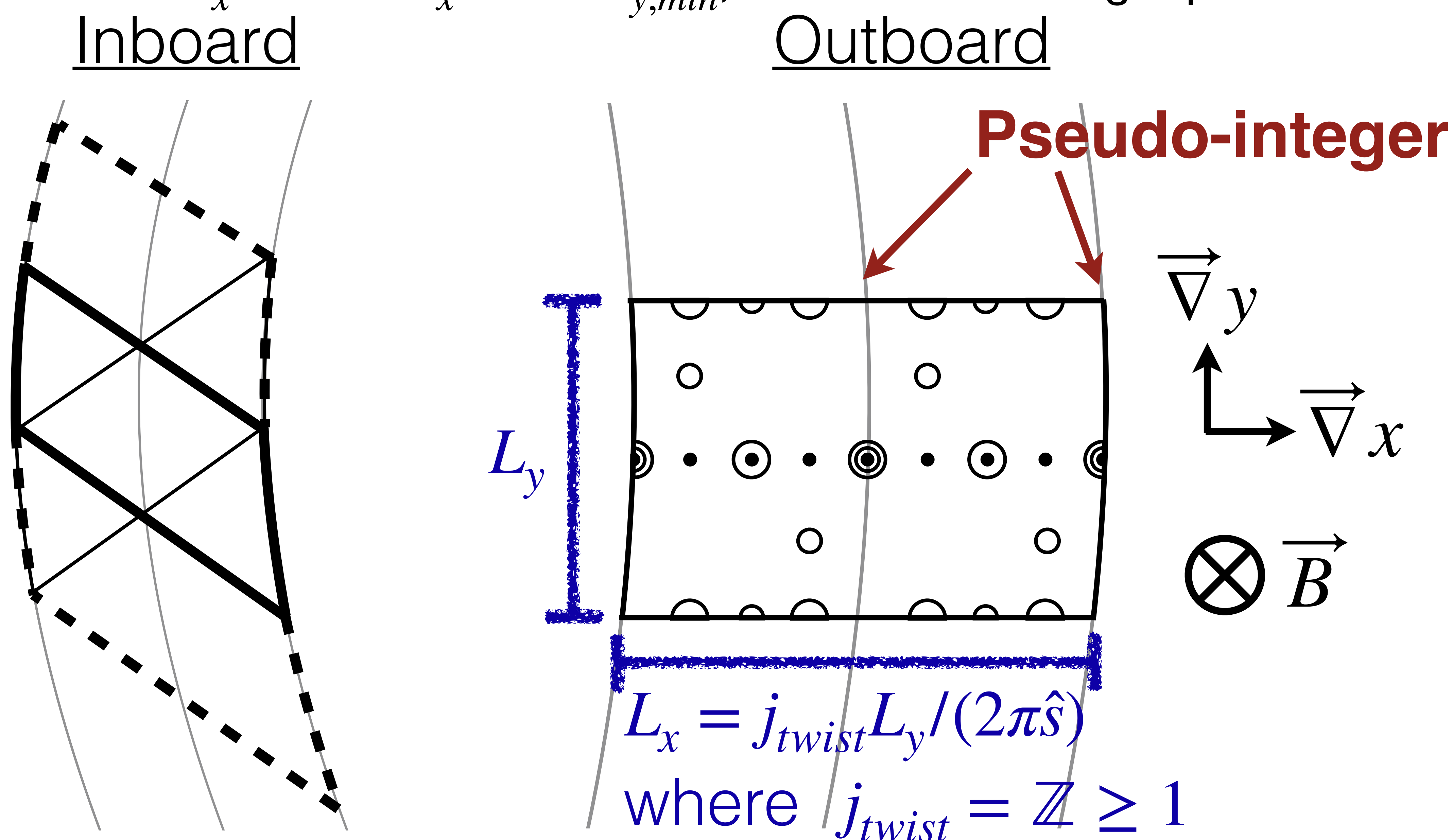
- Applying “twist-and-shift" after just one poloidal turn creates “pseudo-integer” surfaces



Parallel boundary condition enables self-interaction

Beer et al. *PoP* (1995).

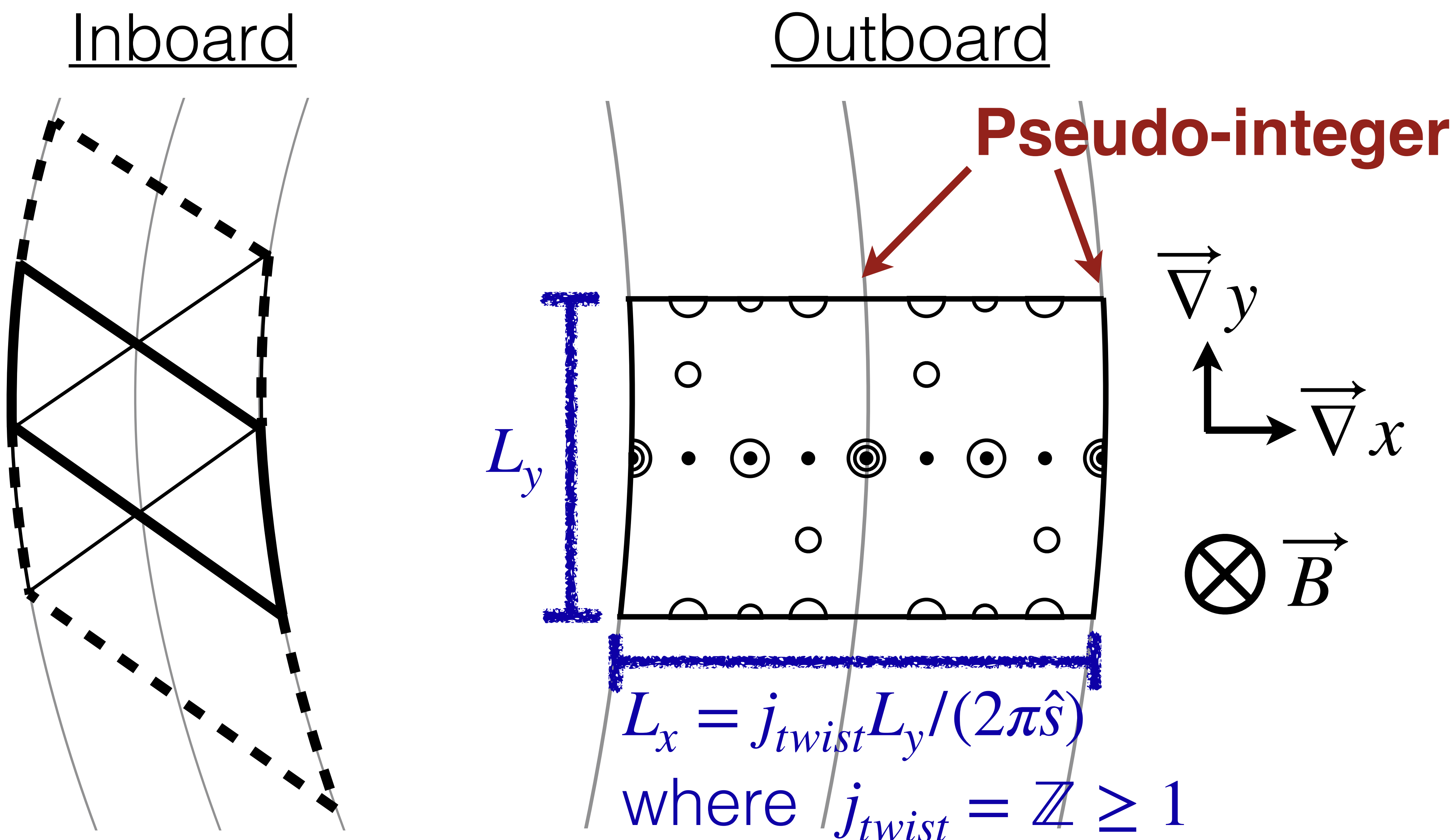
- Using of Fourier representation discretizes the aspect ratio of the domain because $k_x = 0 \rightarrow k_x = 2\pi\hat{s}k_{y,min}$, which must be a gridpoint



Parallel boundary condition enables self-interaction

Beer et al. *PoP* (1995).

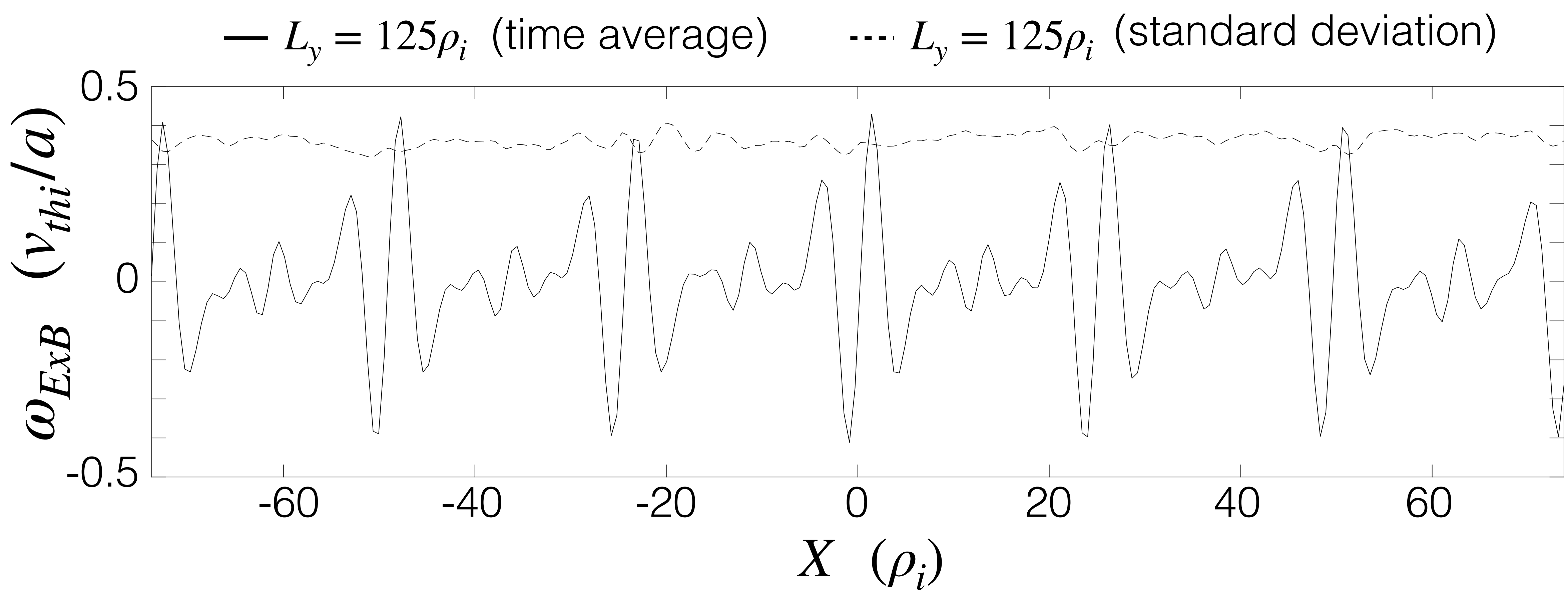
- j_{twist} is the number of pseudo-integer surfaces in the box



Flow shear layers occur at pseudo-integer surfaces

Waltz et al. *PoP* (2006).
Dominski et al. *PoP* (2015).
Weikl, Peeters et al. *PoP* (2019).

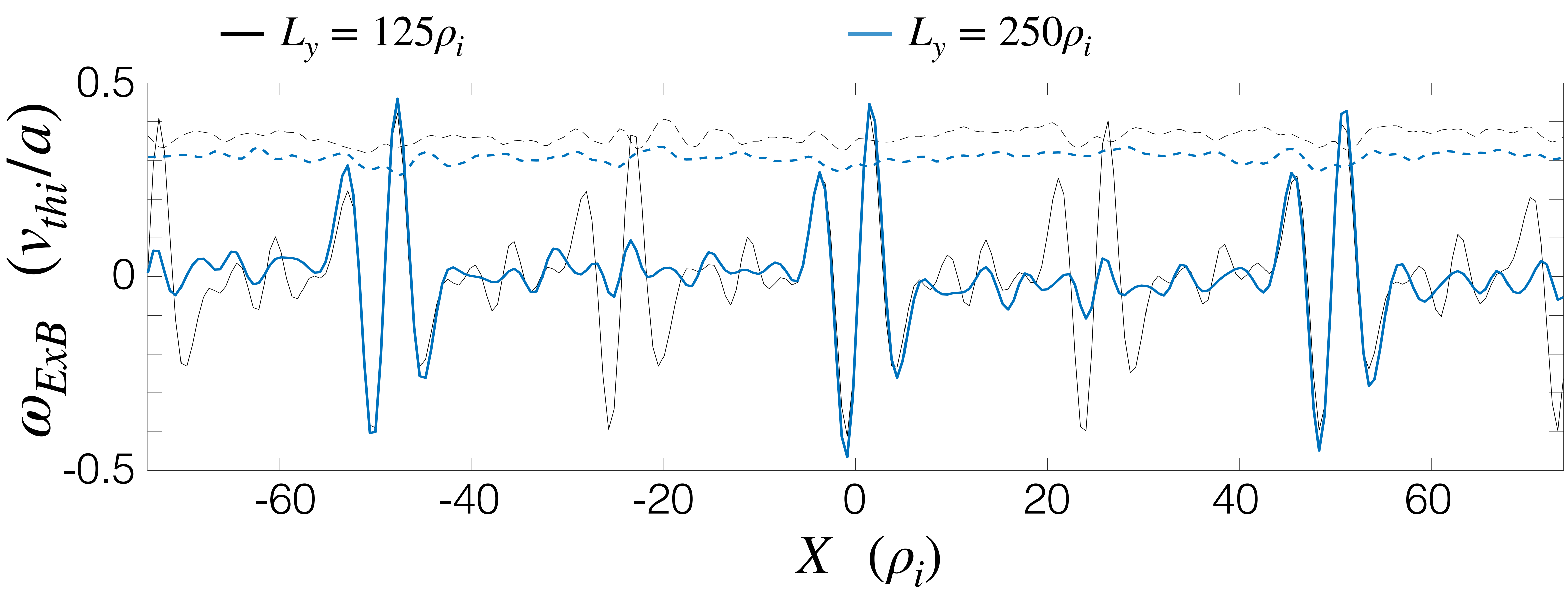
- One symptom is time-constant radially-localized flow shear layers when using kinetic electrons (but not adiabatic electrons)



Flow shear layers occur at pseudo-integer surfaces

Waltz et al. *PoP* (2006).
Dominski et al. *PoP* (2015).
Weikl, Peeters et al. *PoP* (2019).

- One symptom is time-constant radially-localized flow shear layers when using kinetic electrons (but not adiabatic electrons)



- Non-convergence because the spacing of flow shear layers increases with L_y

ASIDE: symmetry-breaking drives flow layers?

Peeters et al. *PoP* (2005).
Parra et al. *PoP* (2011).
Parra et al. *PPCF* (2015).

- Flow is constant, so it can be considered as intrinsic rotation and must be driven by symmetry-breaking
- Symmetry-breaking mechanism is variation in turbulence characteristics (e.g. profile shearing), but at the ρ_i spatial scale
- One of two effects are needed: magnetic drifts or magnetic shear within FLR effects

$$\frac{\partial}{\partial t}\left(h_s - \frac{Z_s e F_{Ms}}{T_s} \underline{J_0\left(k_\perp \rho_s\right)} \phi \right) + v_{||} \hat{b} \cdot \vec{\nabla} h_s + \underline{i \vec{k}_\perp \cdot \vec{v}_{Ms}} h_s + a_{||s} \frac{\partial h_s}{\partial v_{||}} + \left\{ h_s, \underline{J_0\left(k_\perp \rho_s\right)} \phi \right\}$$

$$= i \frac{k_y}{B} \underline{J_0\left(k_\perp \rho_s\right)} \phi F_{Ms} \left[\frac{1}{L_n} + \left(\frac{m_s v^2}{2 T_s} - \frac{3}{2} \right) \frac{1}{L_T} \right]$$

ASIDE: symmetry-breaking drives flow layers?

Peeters et al. *PoP* (2005).
Parra et al. *PoP* (2011).
Parra et al. *PPCF* (2015).

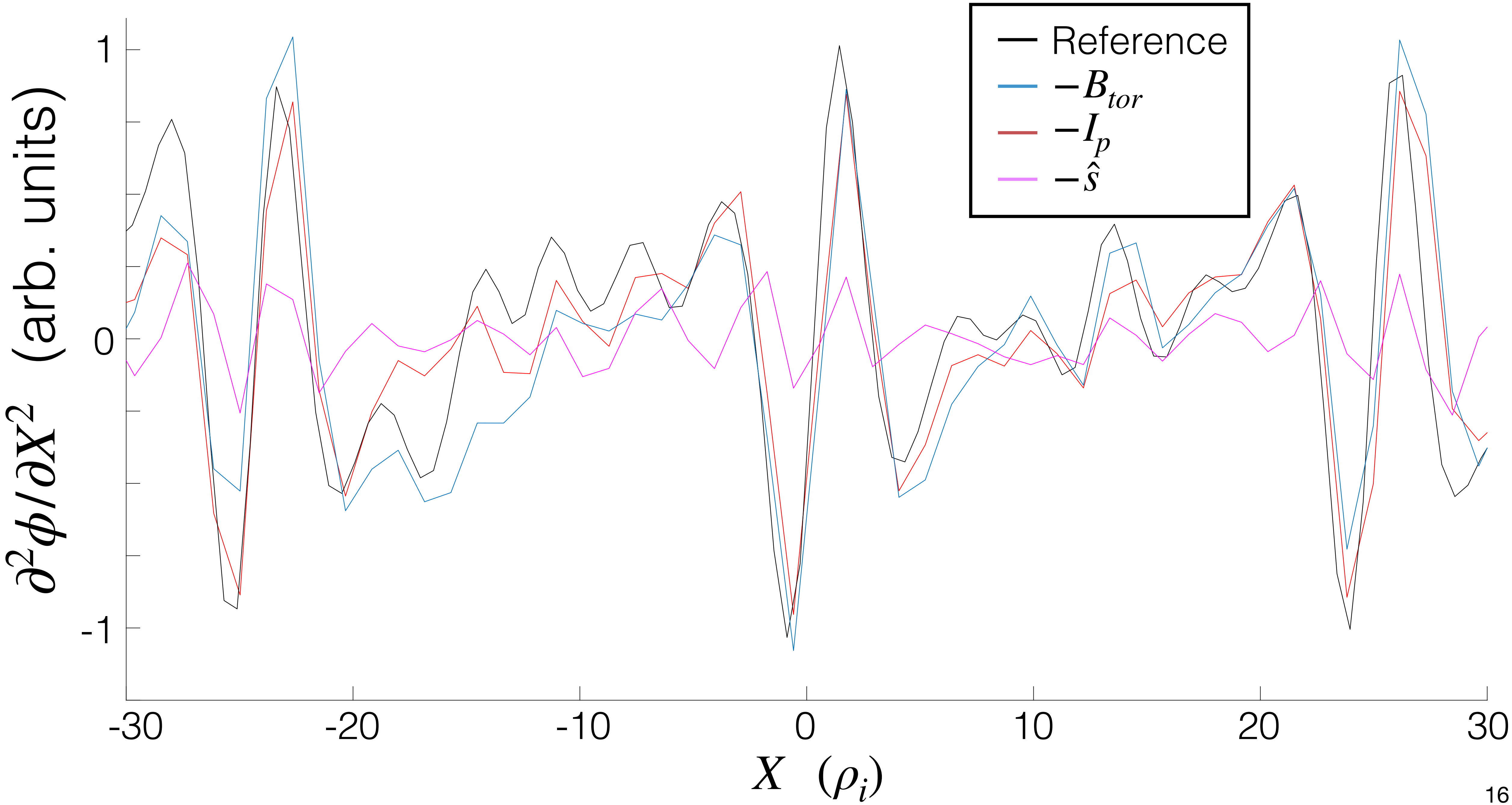
- Flow is constant, so it can be considered as intrinsic rotation and must be driven by symmetry-breaking
- Symmetry-breaking mechanism is variation in turbulence characteristics (e.g. profile shearing), but at the ρ_i spatial scale
- One of two effects are needed: magnetic drifts or magnetic shear within FLR effects

$$\frac{\partial}{\partial t}\left(h_s - \frac{Z_s e F_{Ms}}{T_s} J_0\left(k_\perp \rho_s\right)\phi\right) + v_{||}\hat{b}\cdot\vec{\nabla}h_s + i\,\vec{k}_\perp\cdot\vec{v}_{Ms}h_s + a_{||s}\frac{\partial h_s}{\partial v_{||}} + \left\{h_s, J_0\left(k_\perp\rho_s\right)\phi\right\}$$

$$= i\frac{k_y}{B}J_0\left(k_\perp\rho_s\right)\phi F_{Ms}\left[\frac{1}{L_n} + \left(\frac{m_s v^2}{2T_s} - \frac{3}{2}\right)\frac{1}{L_T}\right]$$

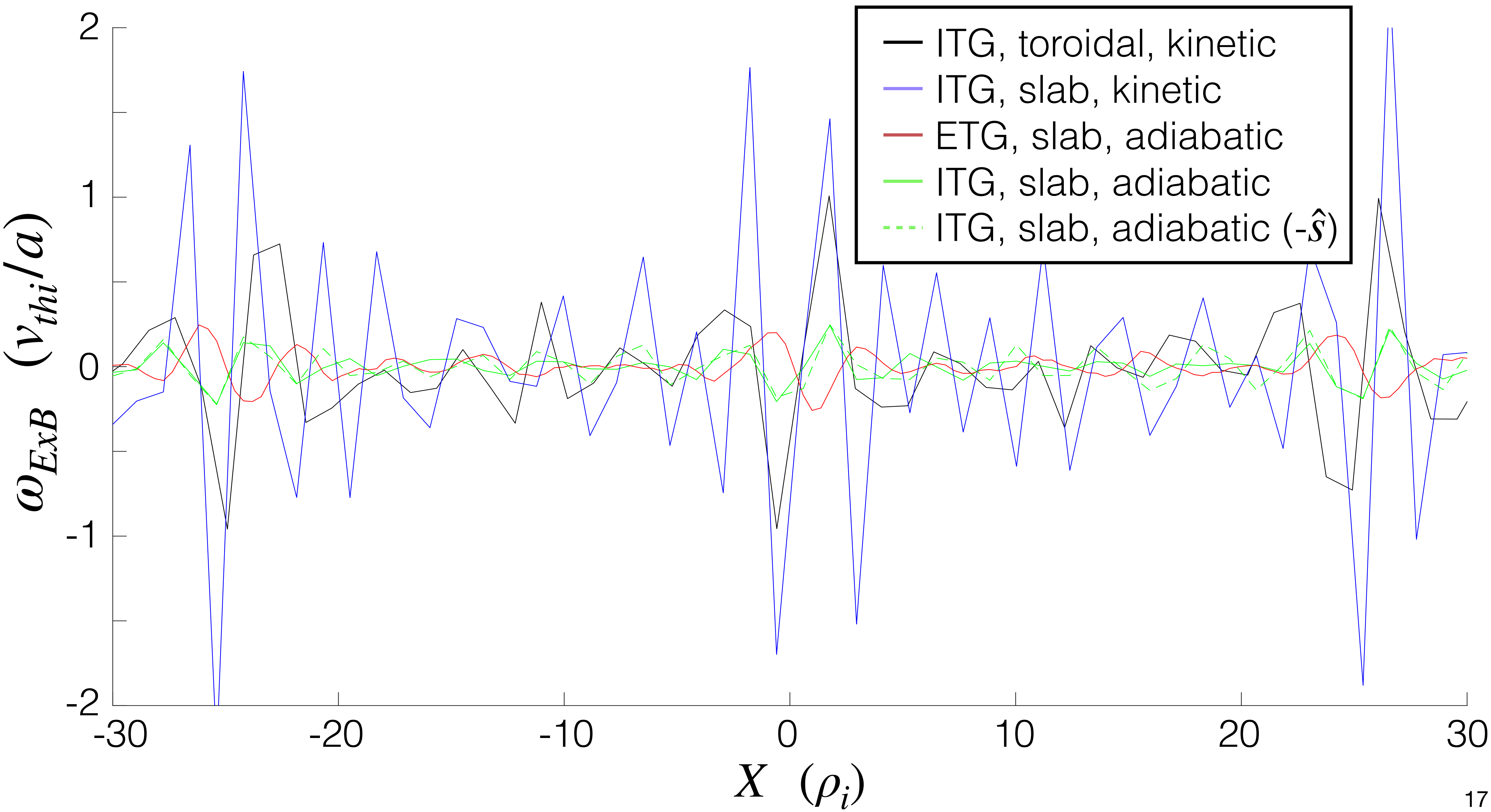
ASIDE: symmetry-breaking drives flow layers?

- Evidence is that they have the correct symmetry properties (I think)…



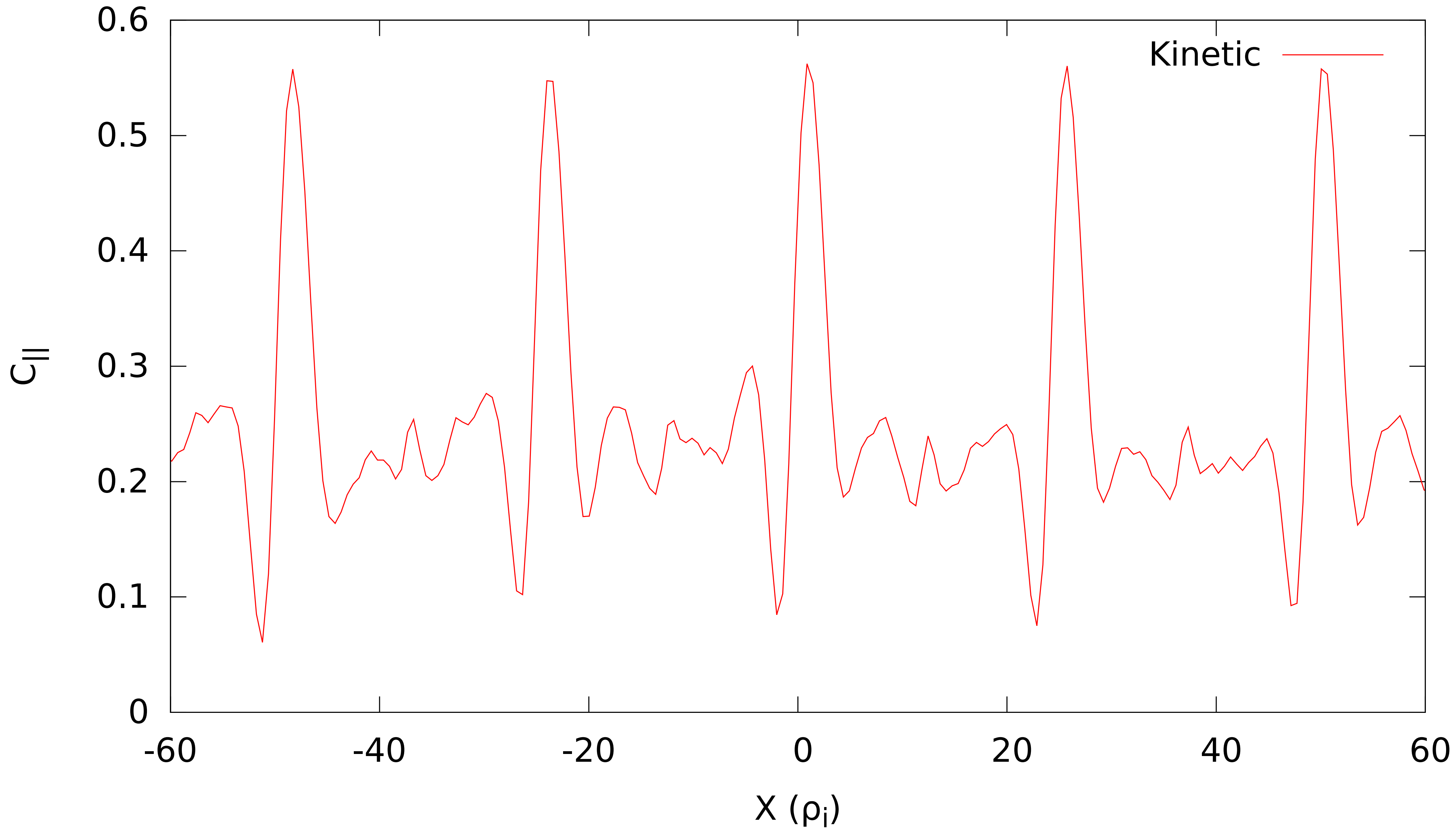
ASIDE: symmetry-breaking drives flow layers?

- …and are fairly universal (but not in toroidal geo. with adiabatic e⁻)



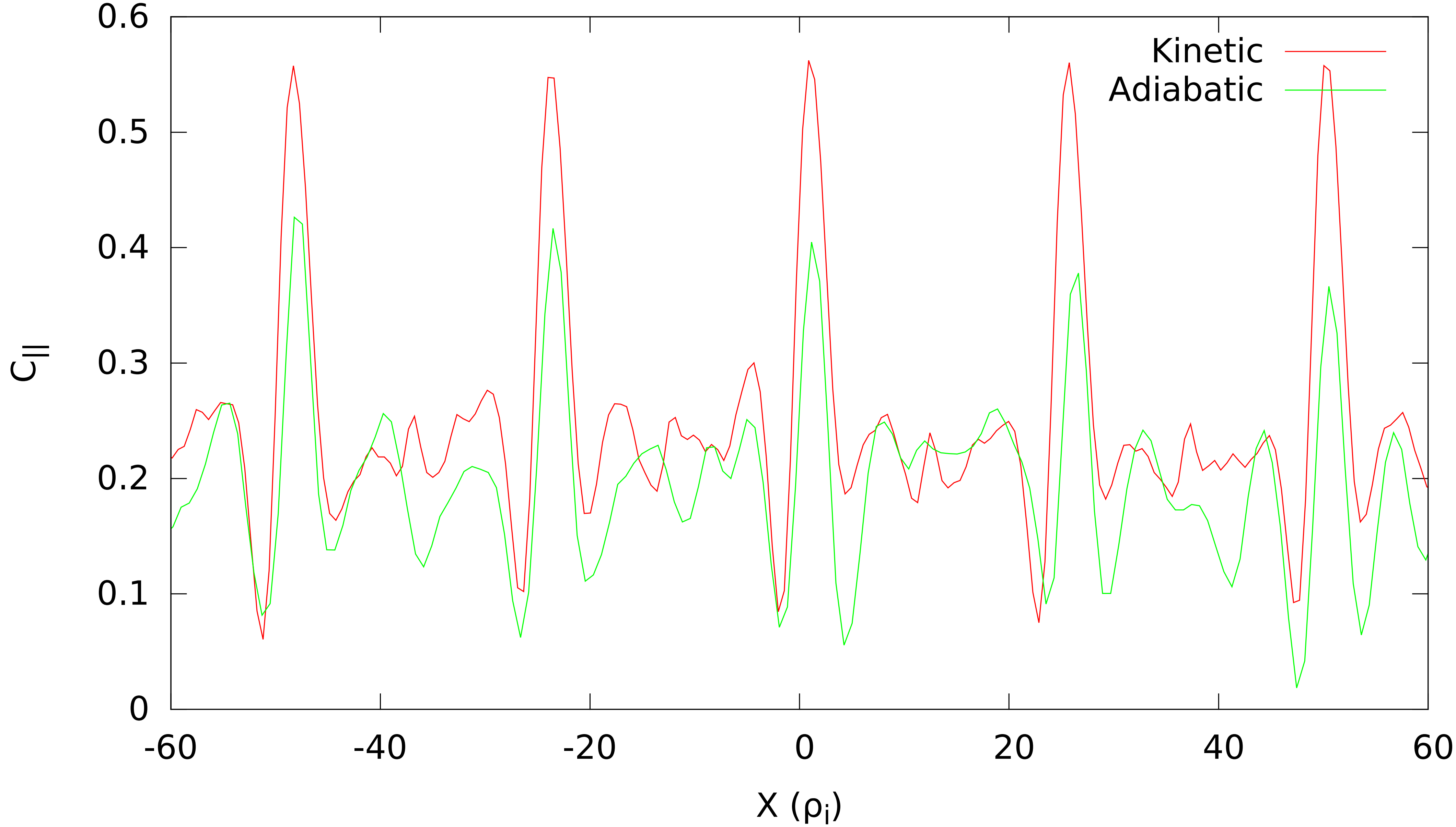
Flow layers are just one type of self-interaction

$$C_{||}(X) \equiv \left\langle \frac{\left\langle \phi_{NZ}(X,Y,Z=0,t)\phi_{NZ}(X,Y,Z=\pi,t)\right\rangle_t}{\sqrt{\left\langle \phi_{NZ}^2(X,Y,Z=0,t)\right\rangle_t \left\langle \phi_{NZ}^2(X,Y,Z=\pi,t)\right\rangle_t}} \right\rangle_Y$$



Flow layers are just one type of self-interaction

$$C_{||}(X) \equiv \left\langle \frac{\left\langle \phi_{NZ}(X,Y,Z=0,t)\phi_{NZ}(X,Y,Z=\pi,t)\right\rangle_t}{\sqrt{\left\langle \phi_{NZ}^2(X,Y,Z=0,t)\right\rangle_t \left\langle \phi_{NZ}^2(X,Y,Z=\pi,t)\right\rangle_t}} \right\rangle_Y$$

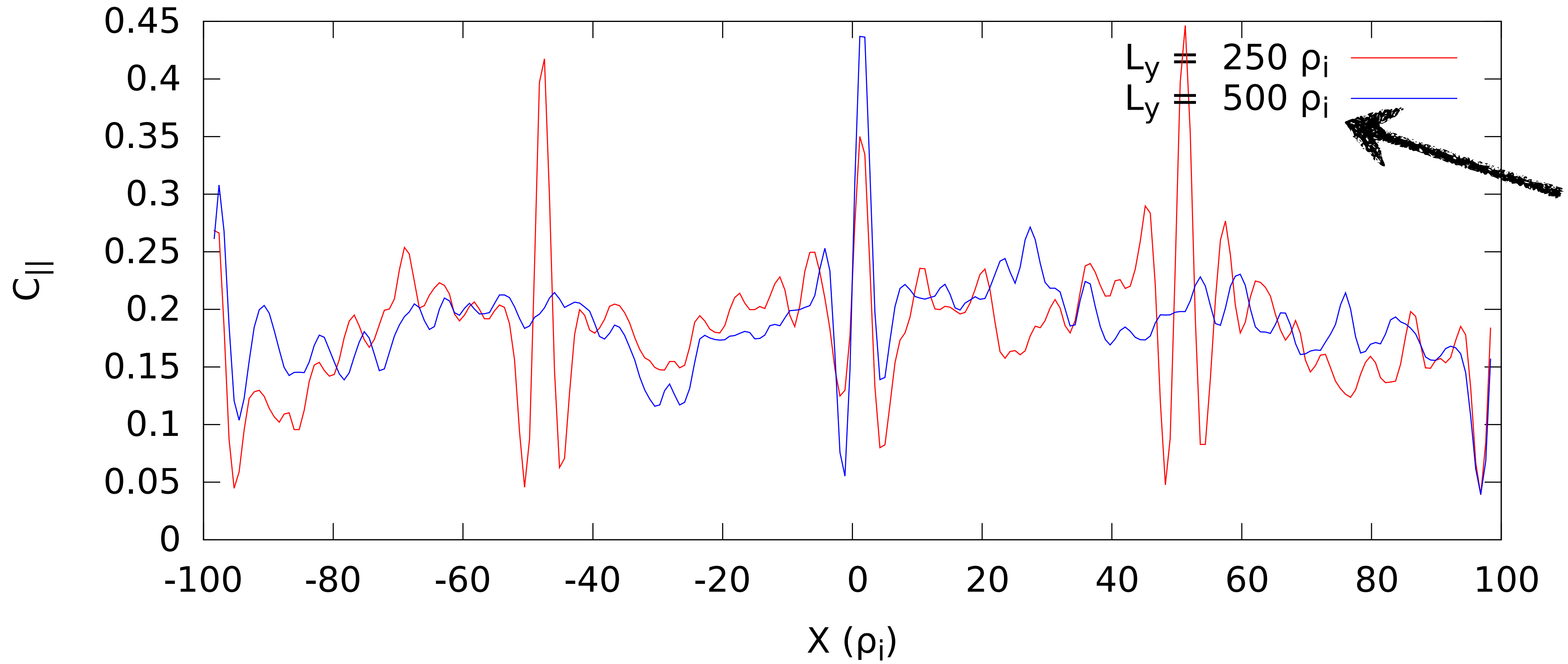


Eliminating self-interaction by increasing L_y

Beer et al. *PoP* (1995).

- Parallel self-interaction is unphysical far from actual integer surfaces:

1. "Dilute" away pseudo-integer surfaces by increasing L_y



DIII-D:
$L_y \approx 1250\rho_i$

- Must increase n_y proportionally and eventually n_x as well

Eliminating self-interaction by increasing N_{pol}

Beer et al. *PoP* (1995).

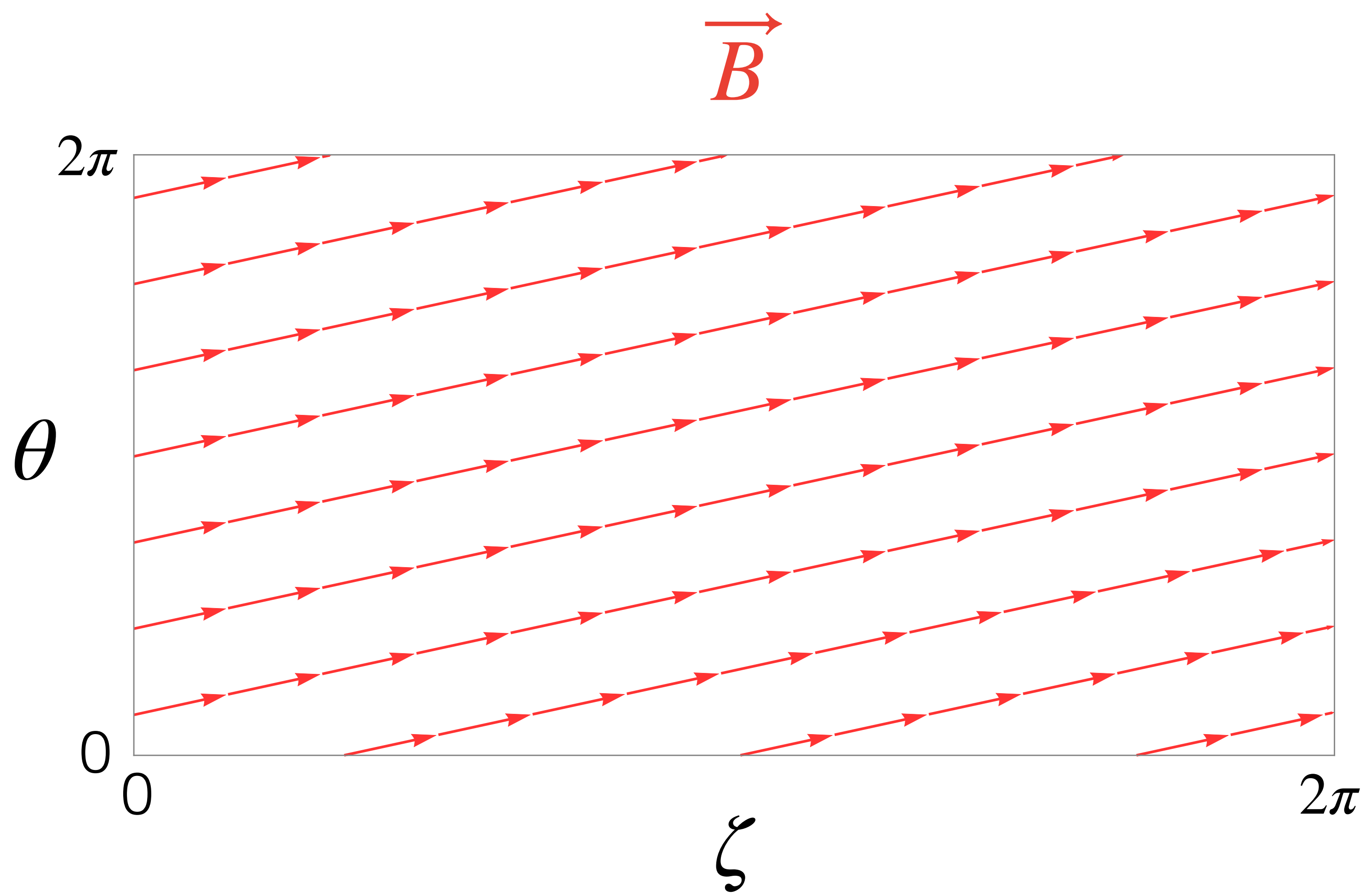
Scott. *PoP* (1998).

- Parallel self-interaction is unphysical far from actual integer surfaces

2. Weaken self-interaction by extending the parallel domain with N_{pol}

- Zonal flows are consistent between the different poloidal turns

- Global consistency is not needed in the $\rho_* \to 0$ limit



Eliminating self-interaction by increasing N_{pol}

Beer et al. *PoP* (1995).

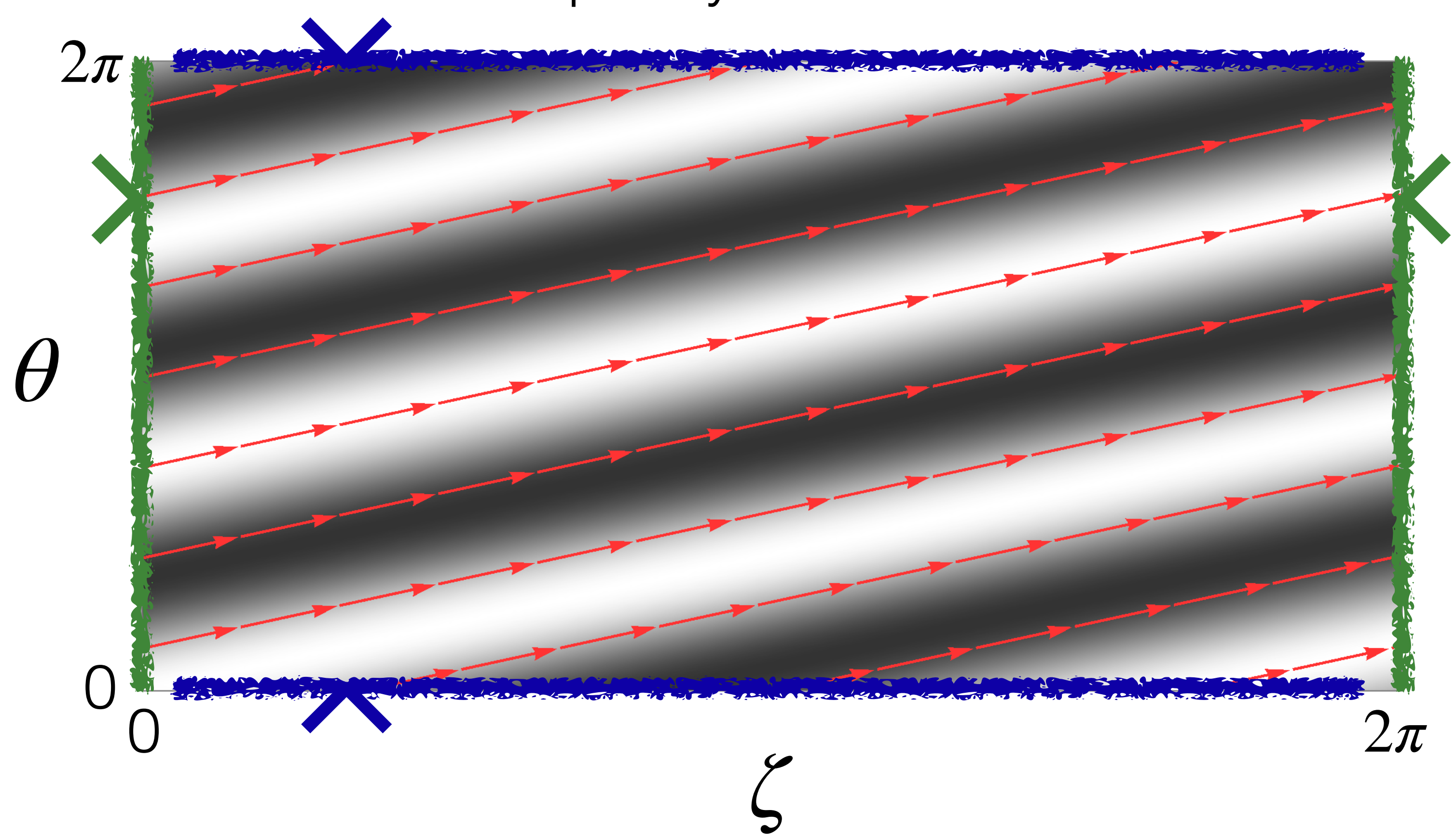
Scott. *PoP* (1998).

- Parallel self-interaction is unphysical far from actual integer surfaces

2. Weaken self-interaction by extending the parallel domain with N_{pol}

   - Zonal flows are consistent between the different poloidal turns
   - Global consistency is not needed in the $\rho_* \to 0$ limit

Specify m and n



Eliminating self-interaction by increasing N_{pol}

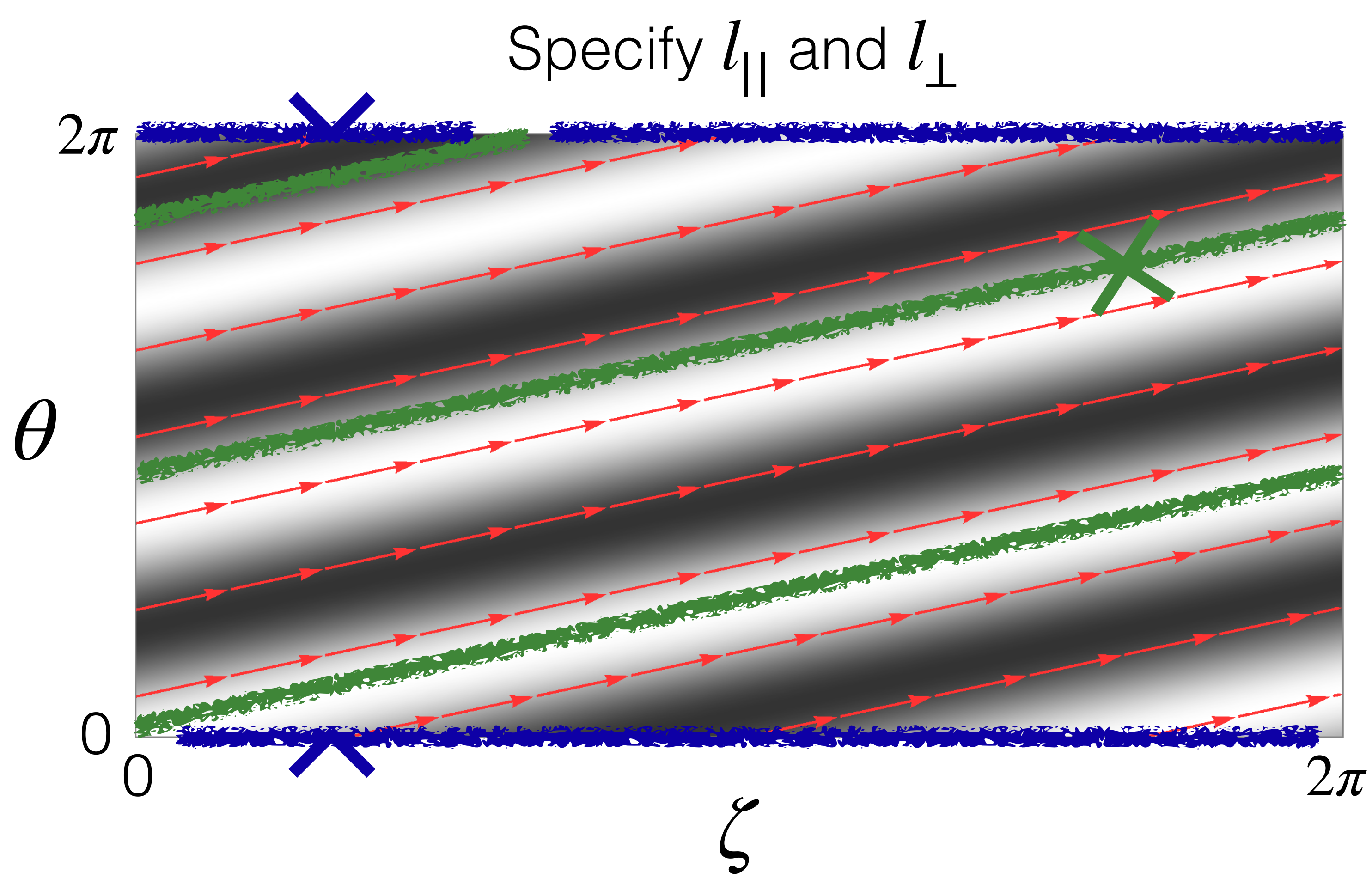
Beer et al. *PoP* (1995).

Scott. *PoP* (1998).

- Parallel self-interaction is unphysical far from actual integer surfaces

2. Weaken self-interaction by extending the parallel domain with N_{pol}

- Zonal flows are consistent between the different poloidal turns
- Global consistency is not needed in the $\rho_* \to 0$ limit



Eliminating self-interaction by increasing N_{pol}

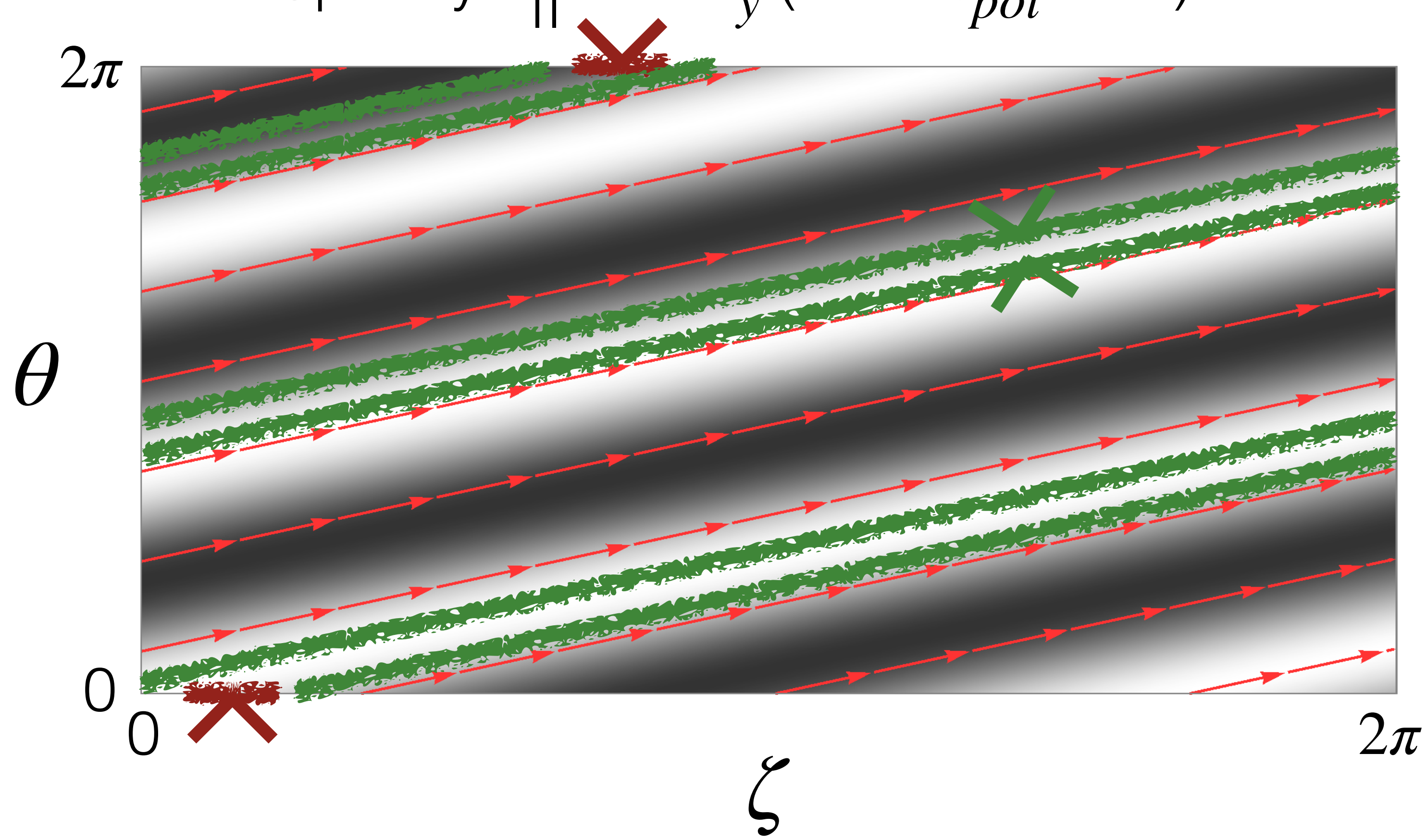
Beer et al. *PoP* (1995).
Scott. *PoP* (1998).

- Parallel self-interaction is unphysical far from actual integer surfaces

2. Weaken self-interaction by extending the parallel domain with N_{pol}

   - Zonal flows are consistent between the different poloidal turns
   - Global consistency is not needed in the $\rho_* \to 0$ limit

Specify $k_{||}$ and k_y (with $N_{pol} = 1$)



Eliminating self-interaction by increasing N_{pol}

Beer et al. *PoP* (1995).

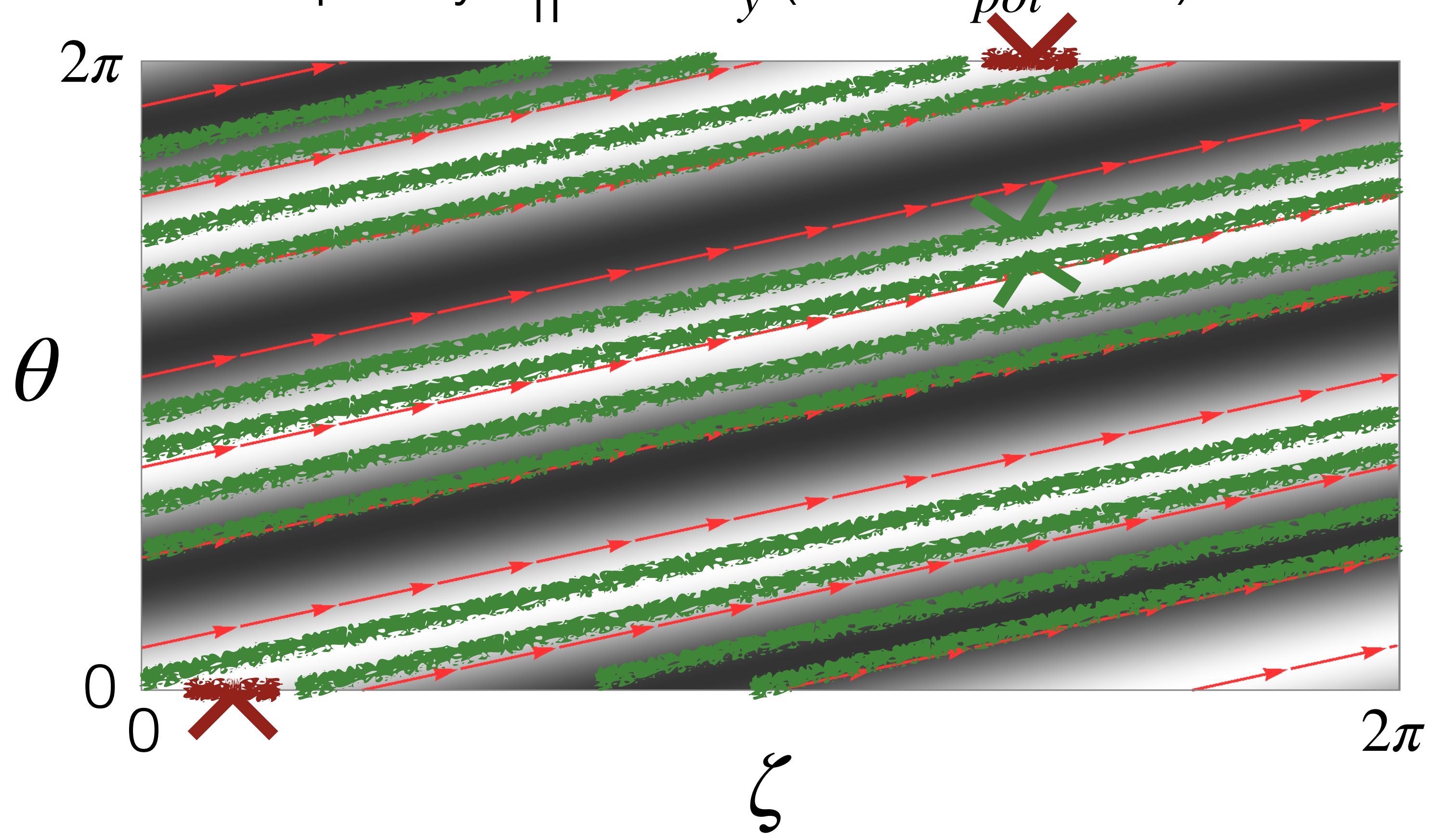
Scott. *PoP* (1998).

- Parallel self-interaction is unphysical far from actual integer surfaces

2. Weaken self-interaction by extending the parallel domain with N_{pol}

   - Zonal flows are consistent between the different poloidal turns
   - Global consistency is not needed in the $\rho_* \to 0$ limit

Specify $k_{||}$ and k_y (with $N_{pol} = 2$)



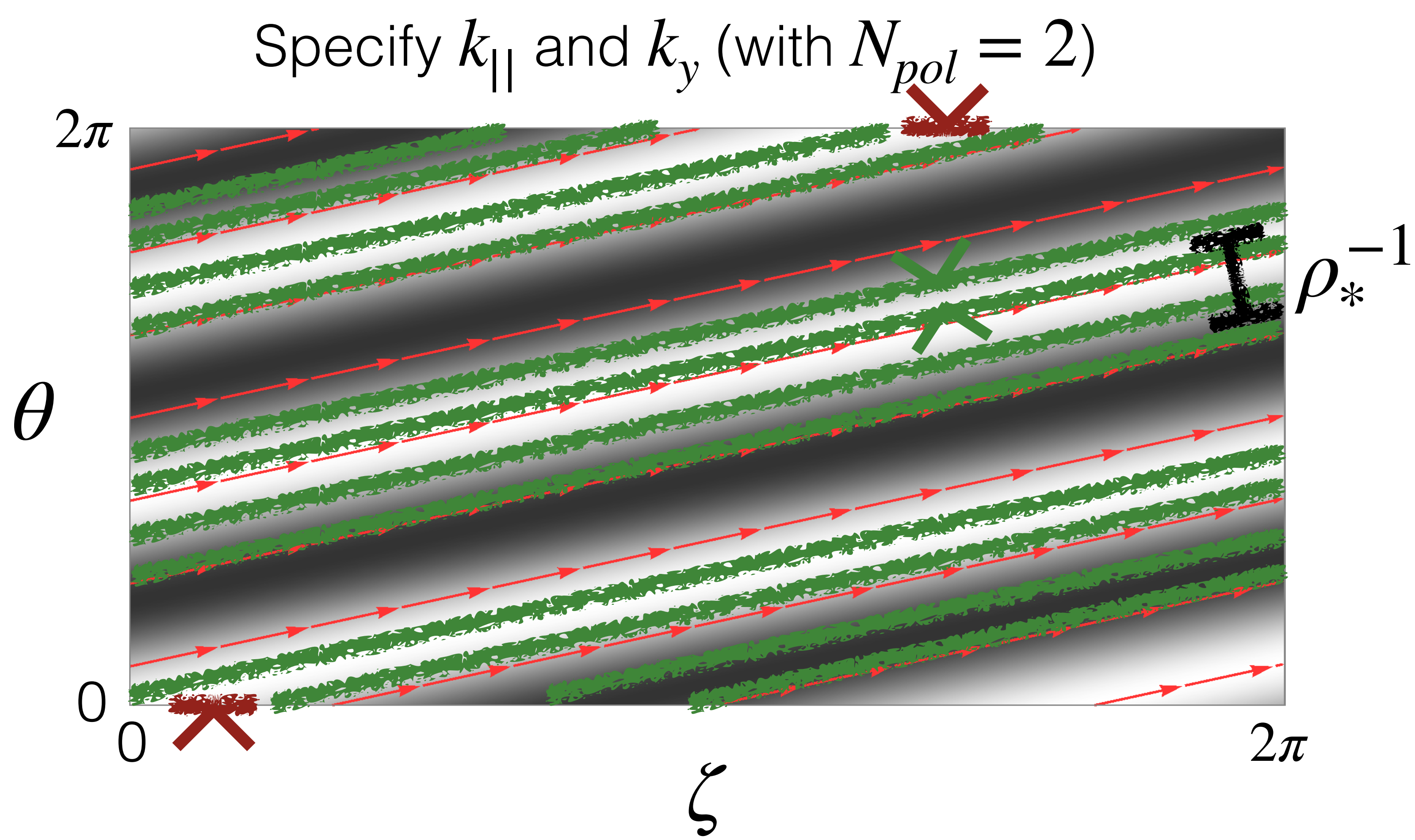
Eliminating self-interaction by increasing N_{pol}

Beer et al. *PoP* (1995).
Scott. *PoP* (1998).

- Parallel self-interaction is unphysical far from actual integer surfaces

2. Weaken self-interaction by extending the parallel domain with N_{pol}

    - Zonal flows are consistent between the different poloidal turns
    - Global consistency is not needed in the $\rho_* \to 0$ limit



Eliminating self-interaction by increasing N_{pol}

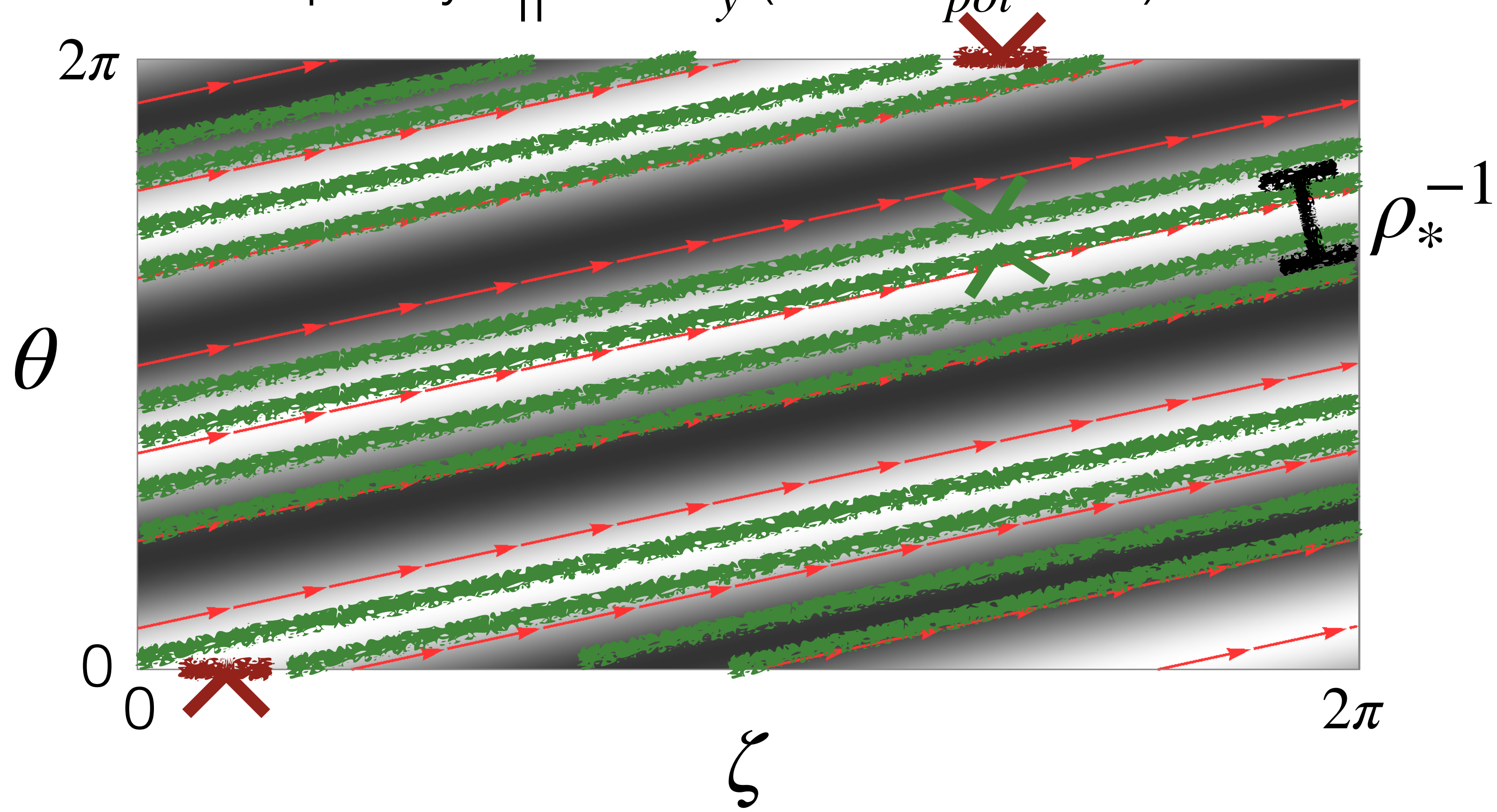
Beer et al. *PoP* (1995).
Scott. *PoP* (1998).

- Parallel self-interaction is unphysical far from actual integer surfaces

2. Weaken self-interaction by extending the parallel domain with N_{pol}

   - Zonal flows are consistent between the different poloidal turns
   - Global consistency is not needed in the $\rho_* \to 0$ limit (no domain self-intersection either)

Specify $k_{||}$ and k_y (with $N_{pol} = 2$)

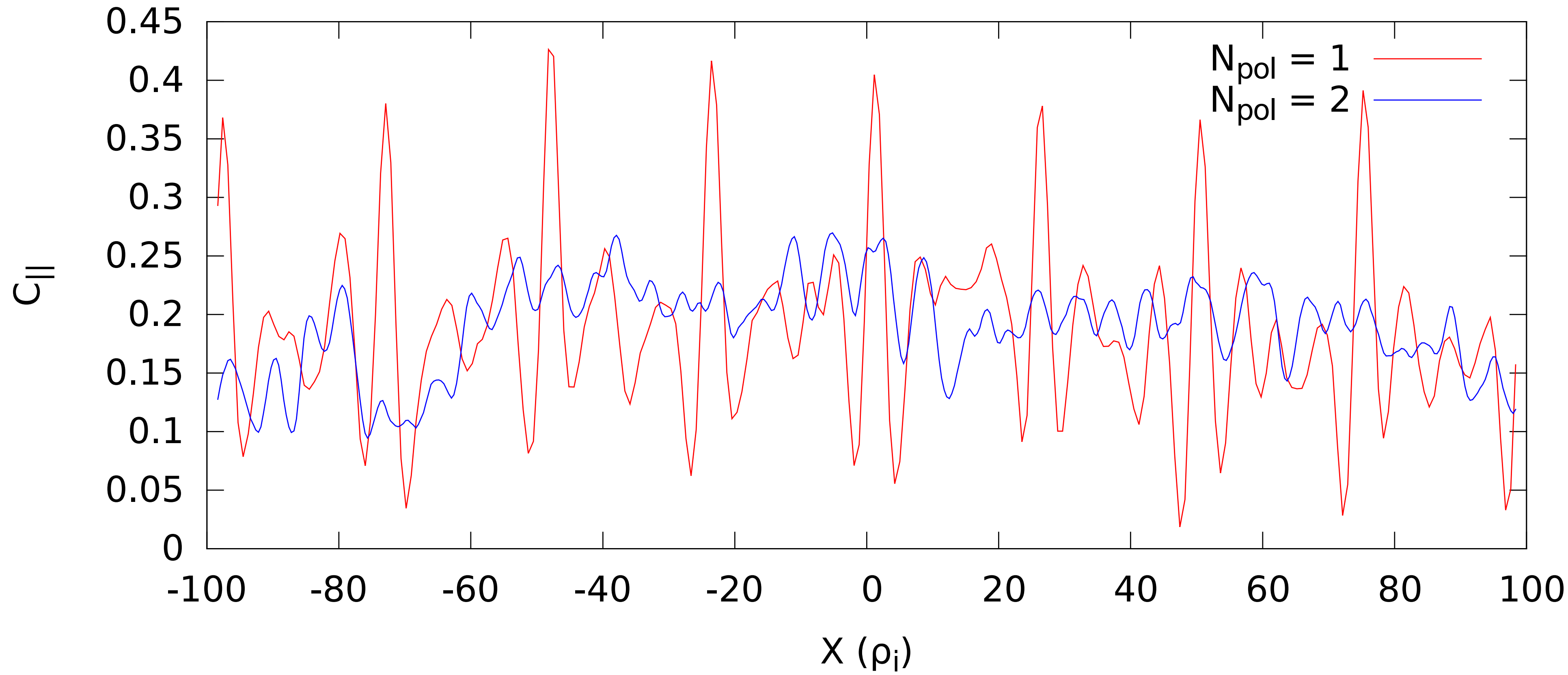


Eliminating self-interaction by increasing N_{pol}

Watanabe et al. *PoP* (2015).

- Parallel self-interaction is unphysical far from actual integer surfaces:

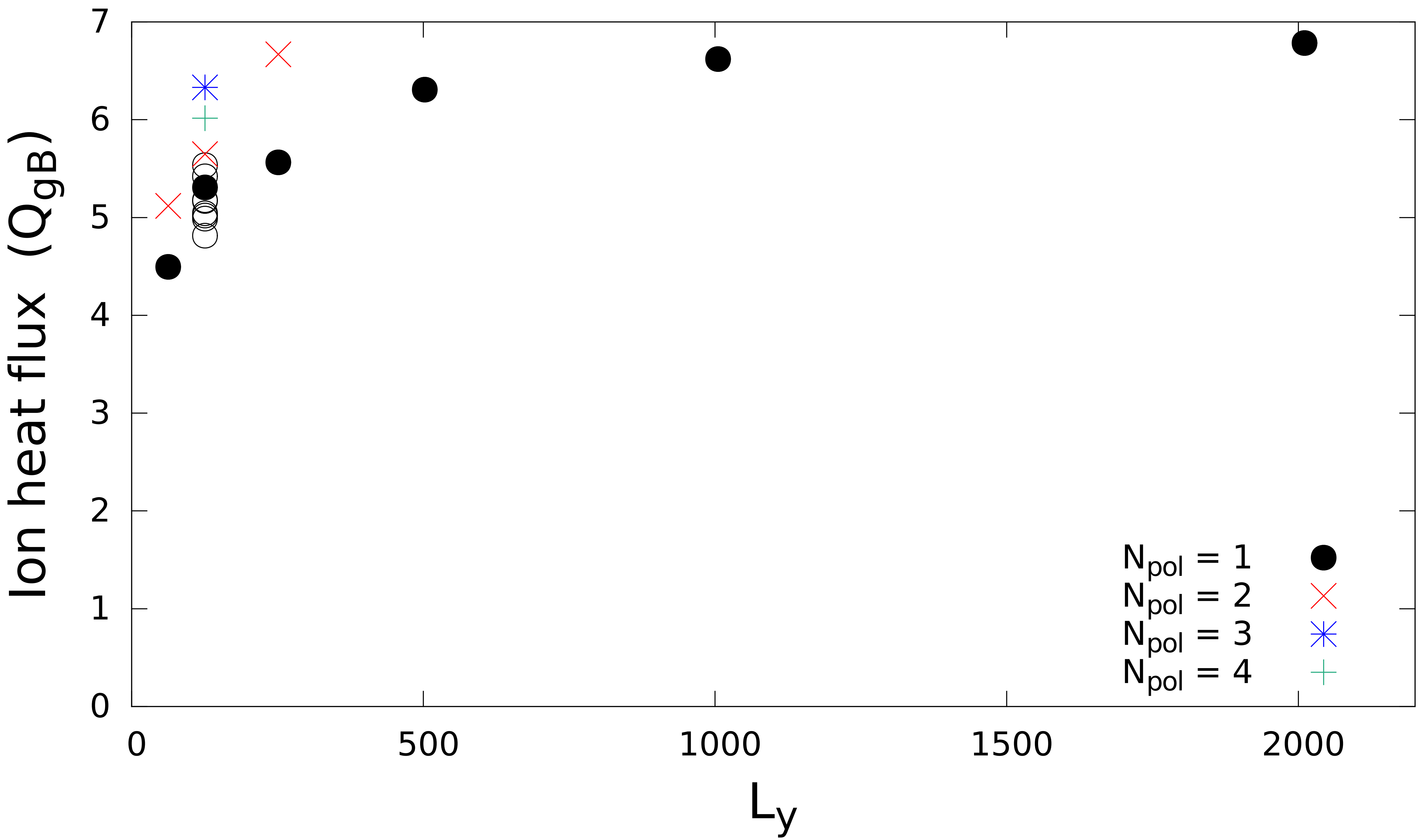
2. Weaken self-interaction by extending the parallel domain with N_{pol}



- Must increase n_z and n_x proportionally (without the "flux-tube train")

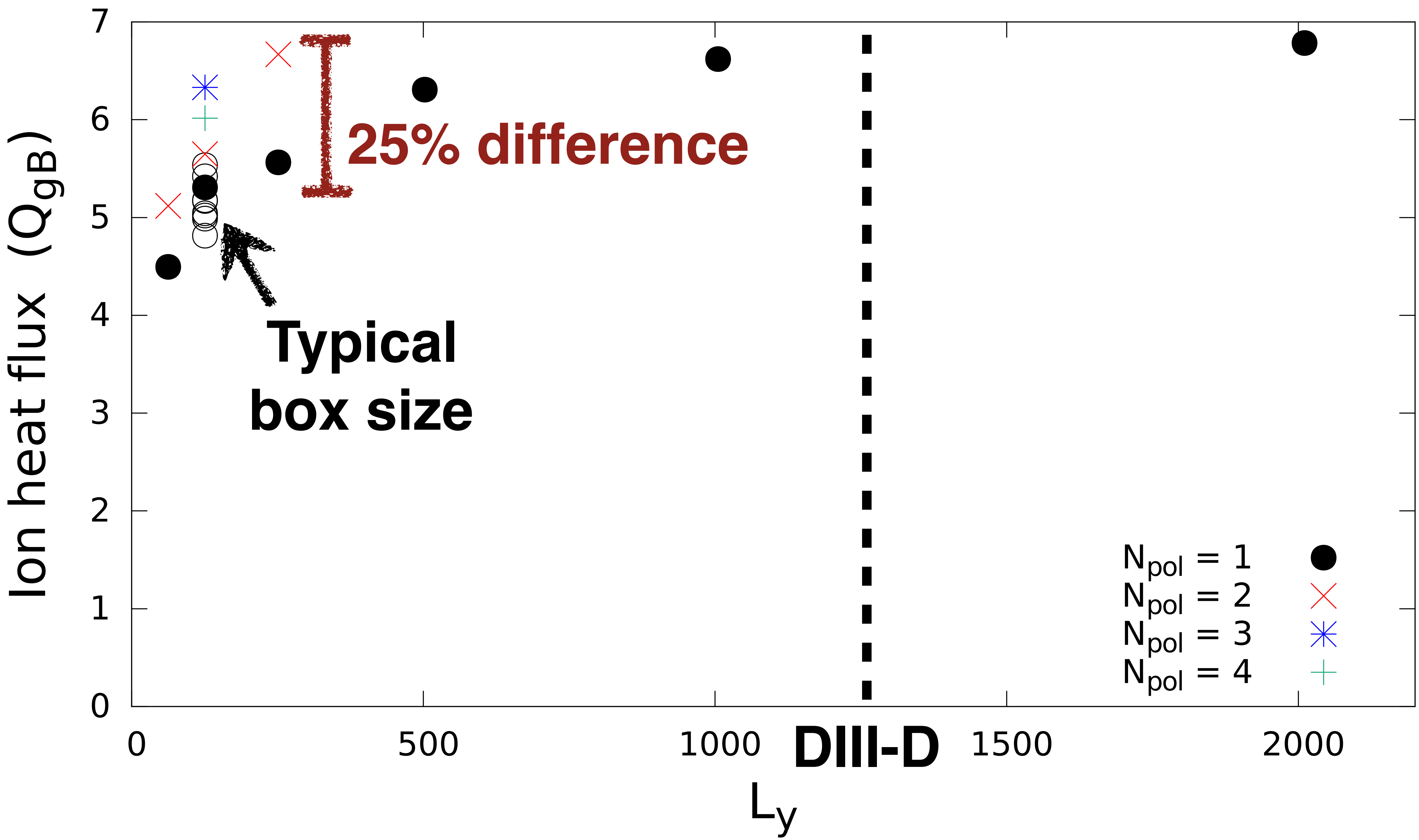
Both converge to same result (adiabatic CBC)

Dimits et al. *PoP* (2000).



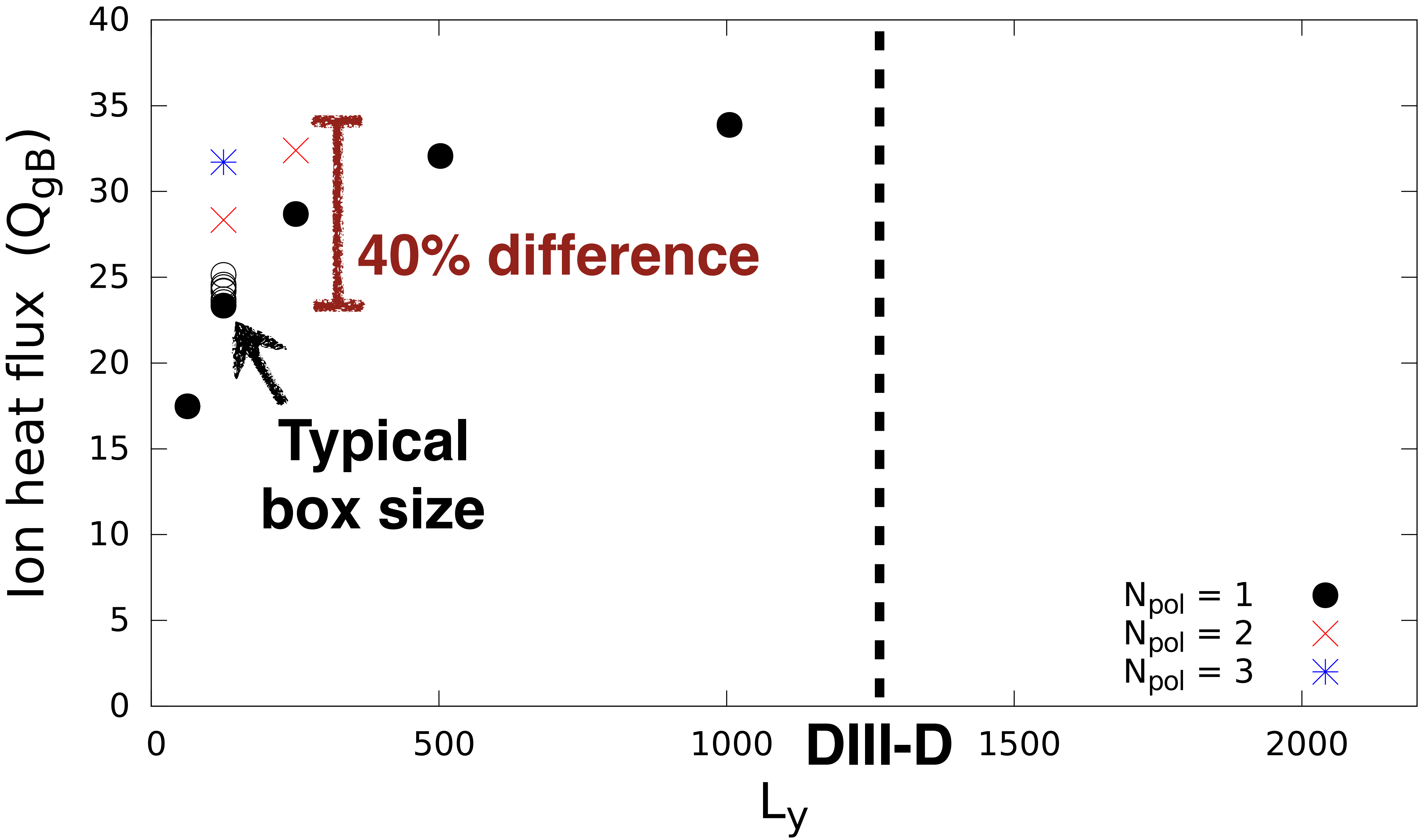
Both converge to same result (adiabatic CBC)

Dimits et al. *PoP* (2000).

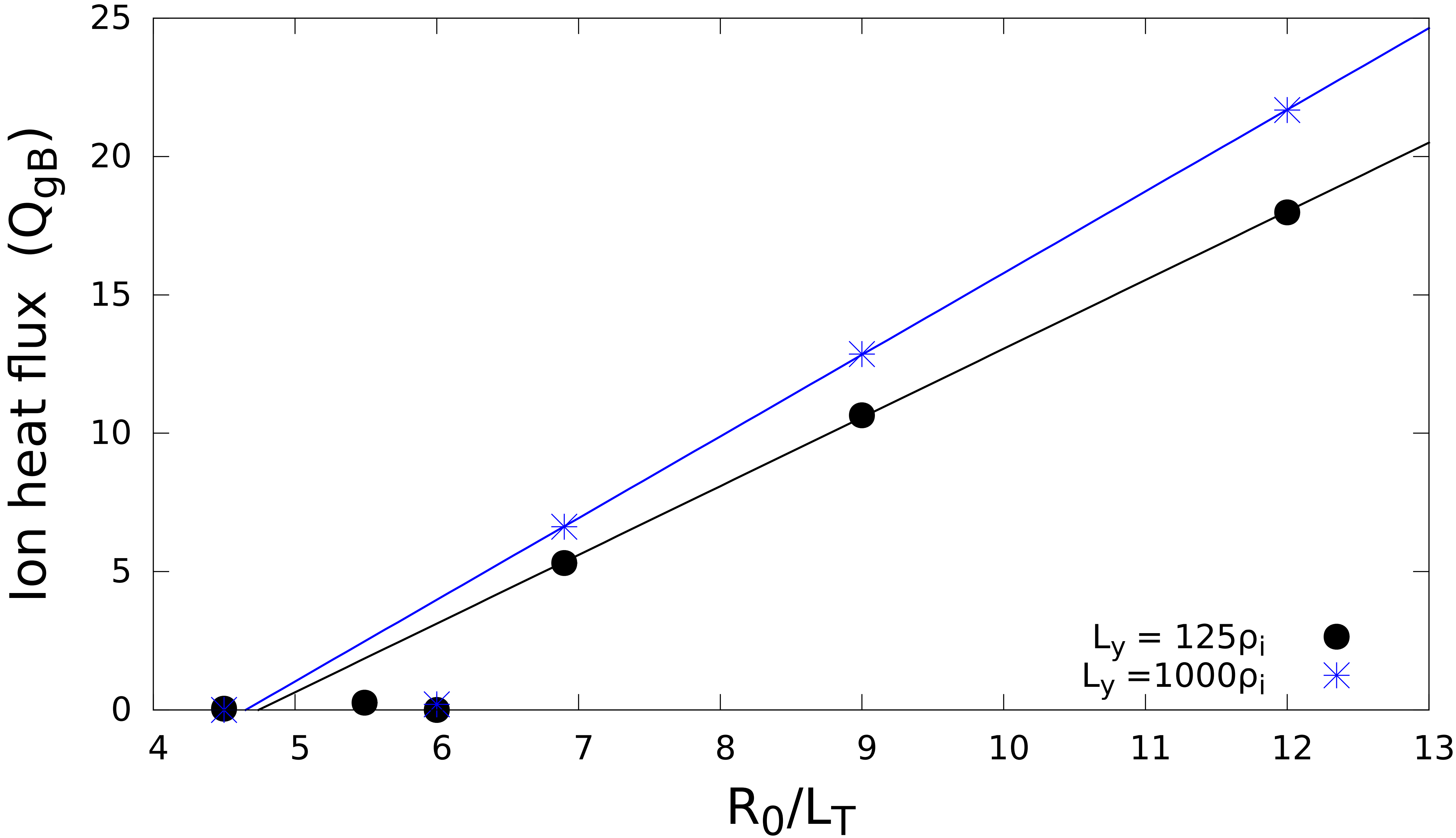


Both converge to same result (kinetic CBC)

Dimits et al. *PoP* (2000).



Critical gradient is affected less (CBC adiabatic)

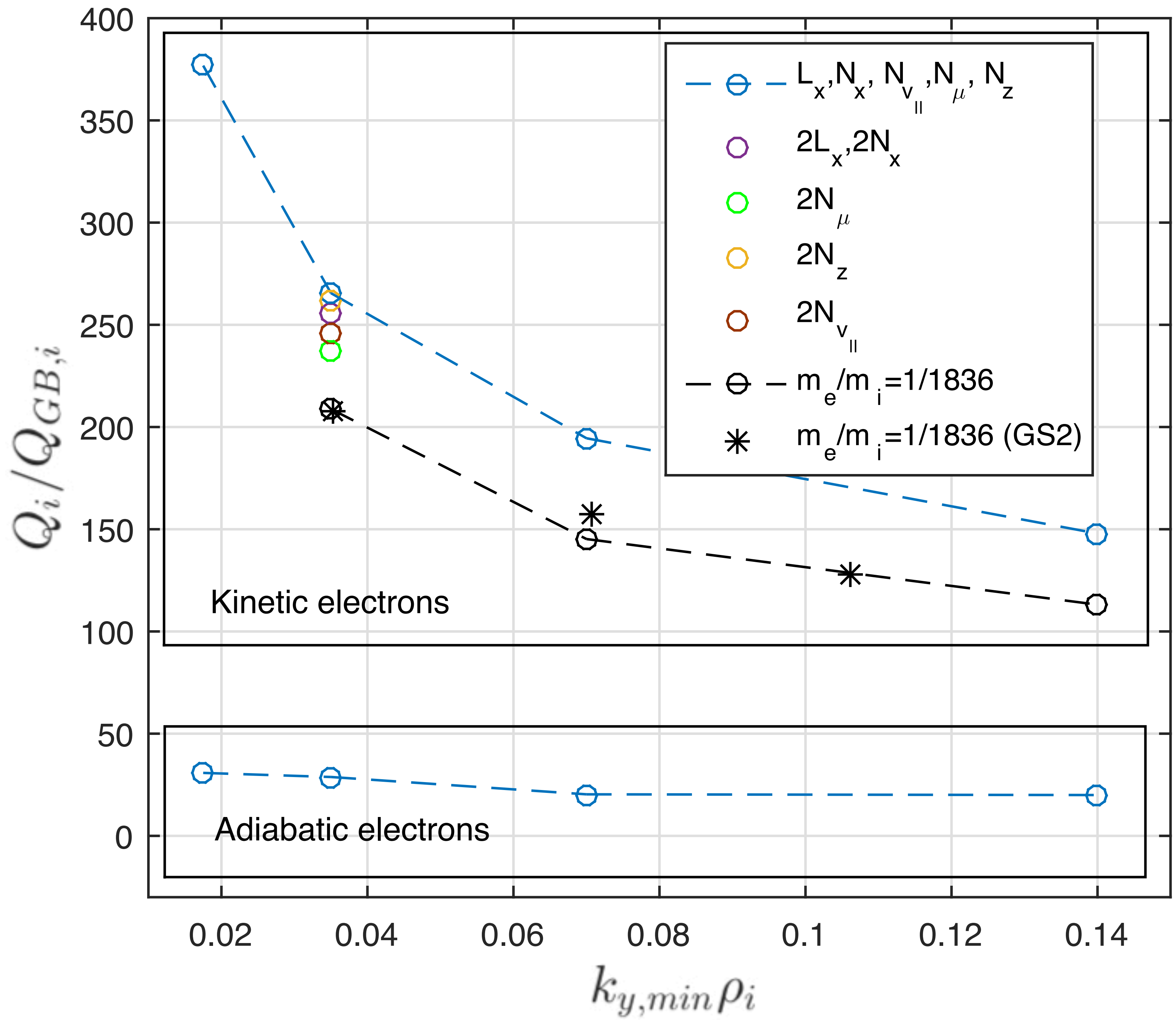


Conclusions

- Self-interaction at pseudo-integer surfaces:
  - drives intrinsic flow
  - *significantly* decreases energy transport
  - can be eliminated by increasing L_y and/or N_{pol} until convergence is achieved
- Implementing the flux-tube train could make converged simulations cheaper

Thank you!

GS2 benchmark

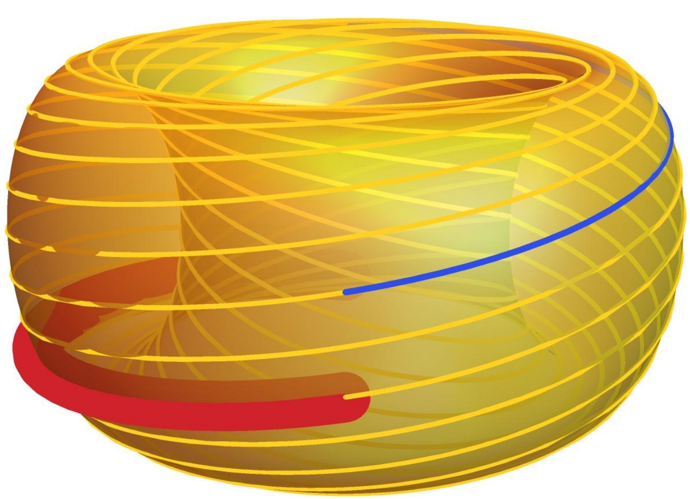


Up-down symmetry breaking mechanisms

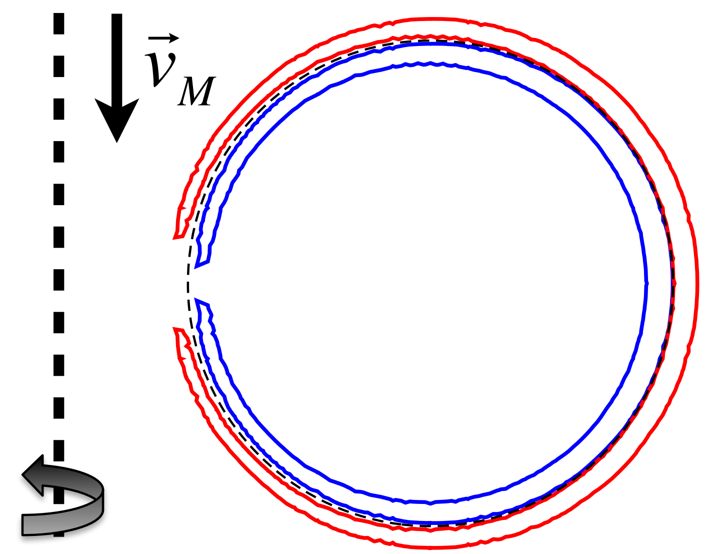
Camenen et al. *Nucl. Fusion* (2011).

- We want to create nonzero rotation from an initially stationary plasma:

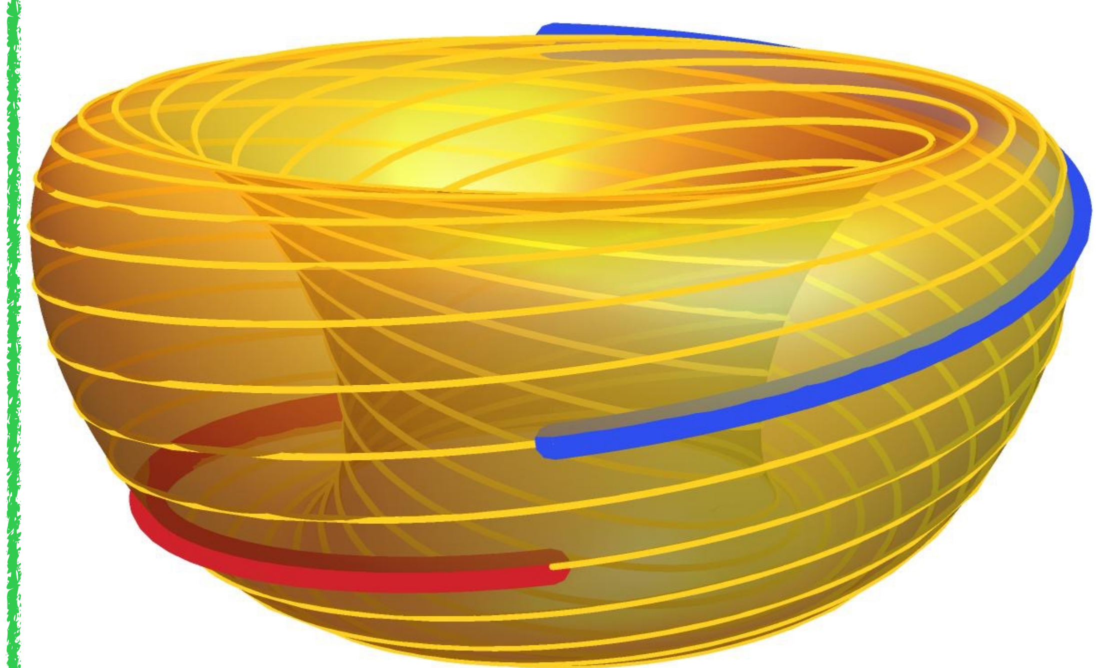
1) Rotation



2) Gradient in rotation



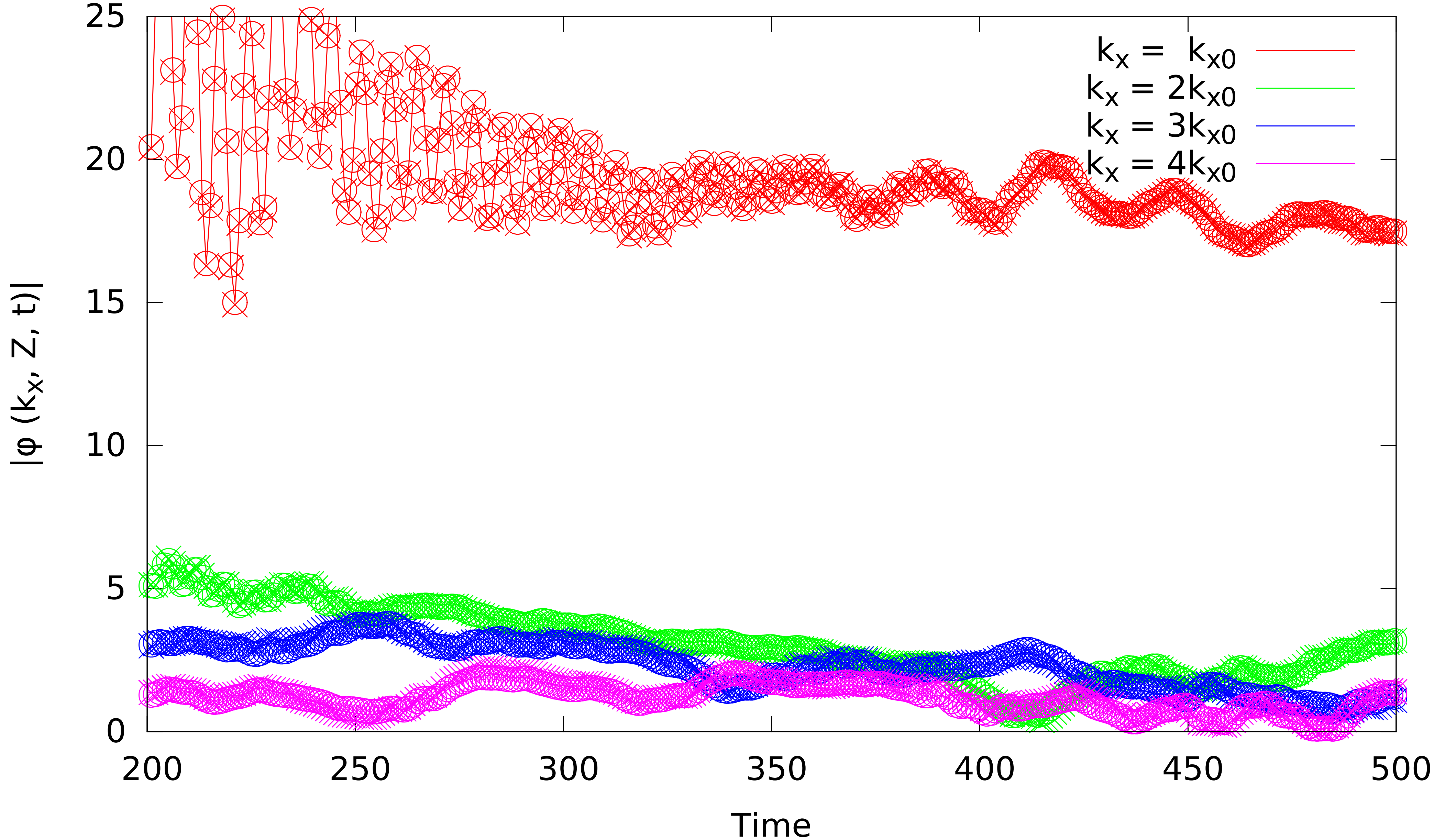
3) Up-down asymmetry



- Order $\rho_* \equiv \rho_i / a$ mechanisms (radial profile variation, neoclassic flows, …) as well as options 1 and 2 likely weaken significantly in future larger machines

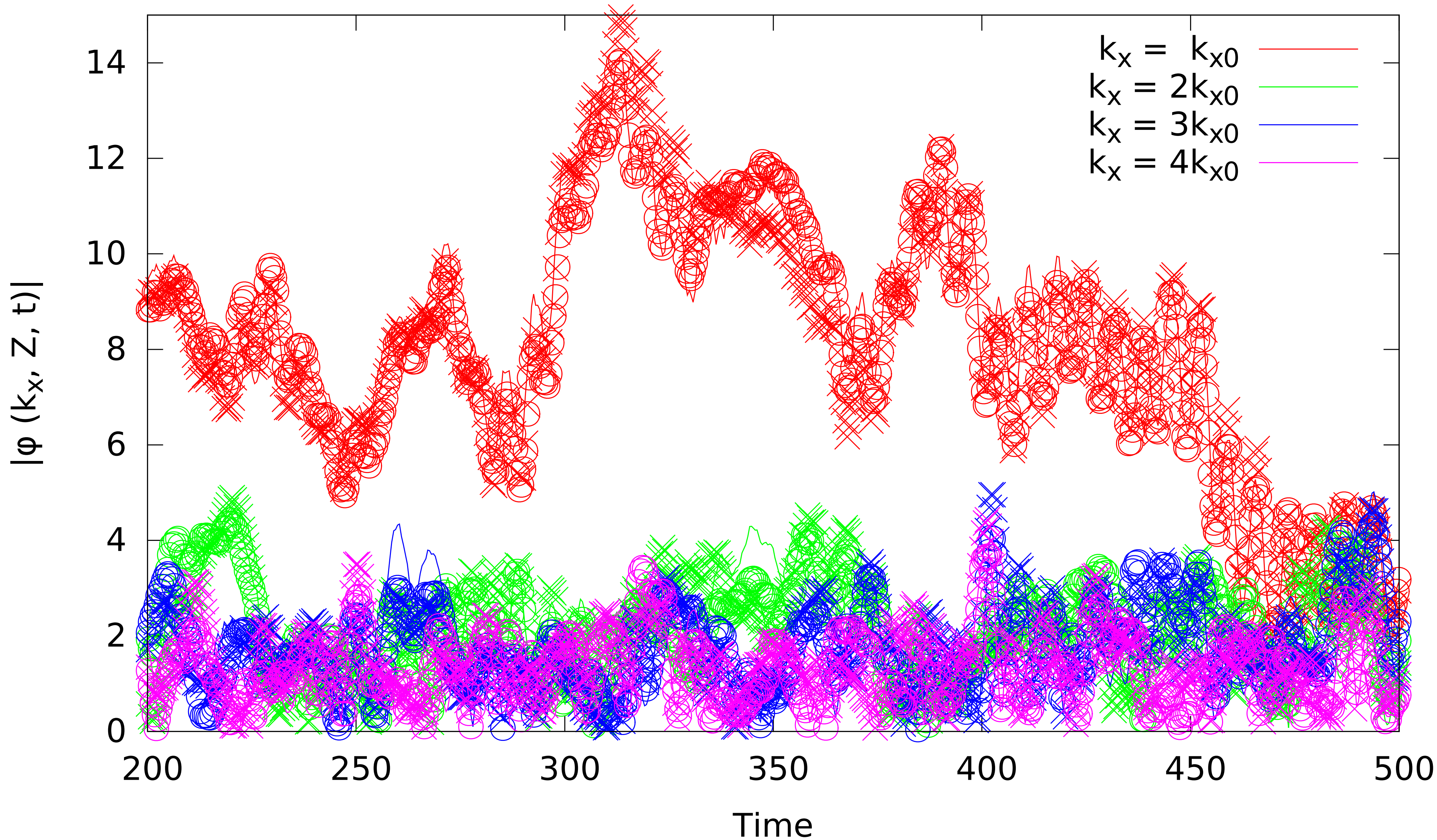
Zonal flow consistency (adiabatic)

- Different symbols (i.e. line, circles, crosses) indicate different toroidal locations at the same poloidal position



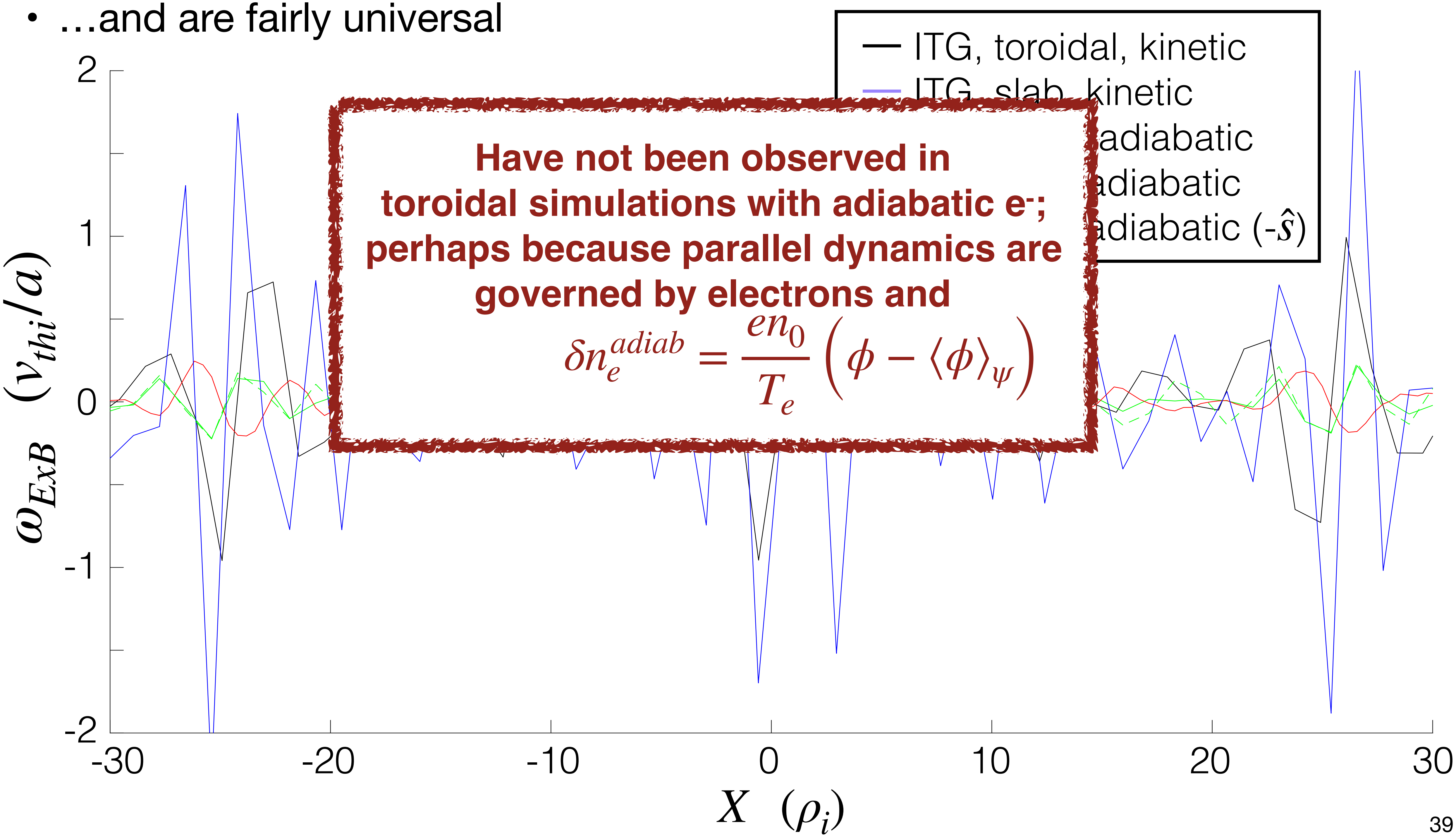
Zonal flow consistency (kinetic)

- Different symbols (i.e. line, circles, crosses) indicate different toroidal locations at the same poloidal position



Symmetry-breaking drives flow shear layers?

- …and are fairly universal



Have not been observed in toroidal simulations with adiabatic e⁻; perhaps because parallel dynamics are governed by electrons and

$$\delta n_e^{adiab} = \frac{e n_0}{T_e}\left(\phi - \langle \phi \rangle_\psi\right)$$