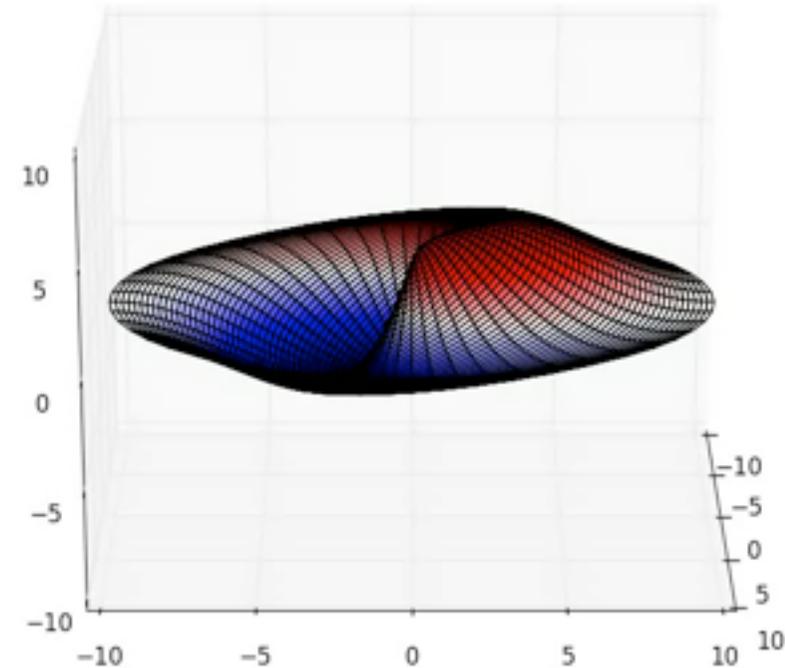


# THE STABILITY OF WARPED PROTOPLANETARY DISCS

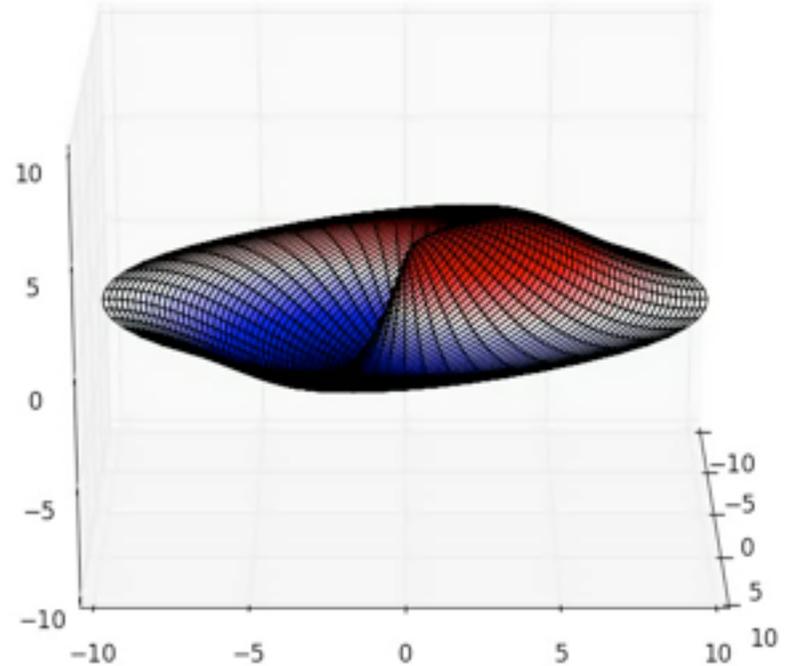


**SIJME-JAN PAARDEKOOOPER**  
**QUEEN MARY, UNIVERSITY OF LONDON**

Together with G. Ogilvie (DAMTP, Cambridge)

# WARPS

- Warp: disc orbital plane varies with radius
- Twist: line of nodes varies with radius



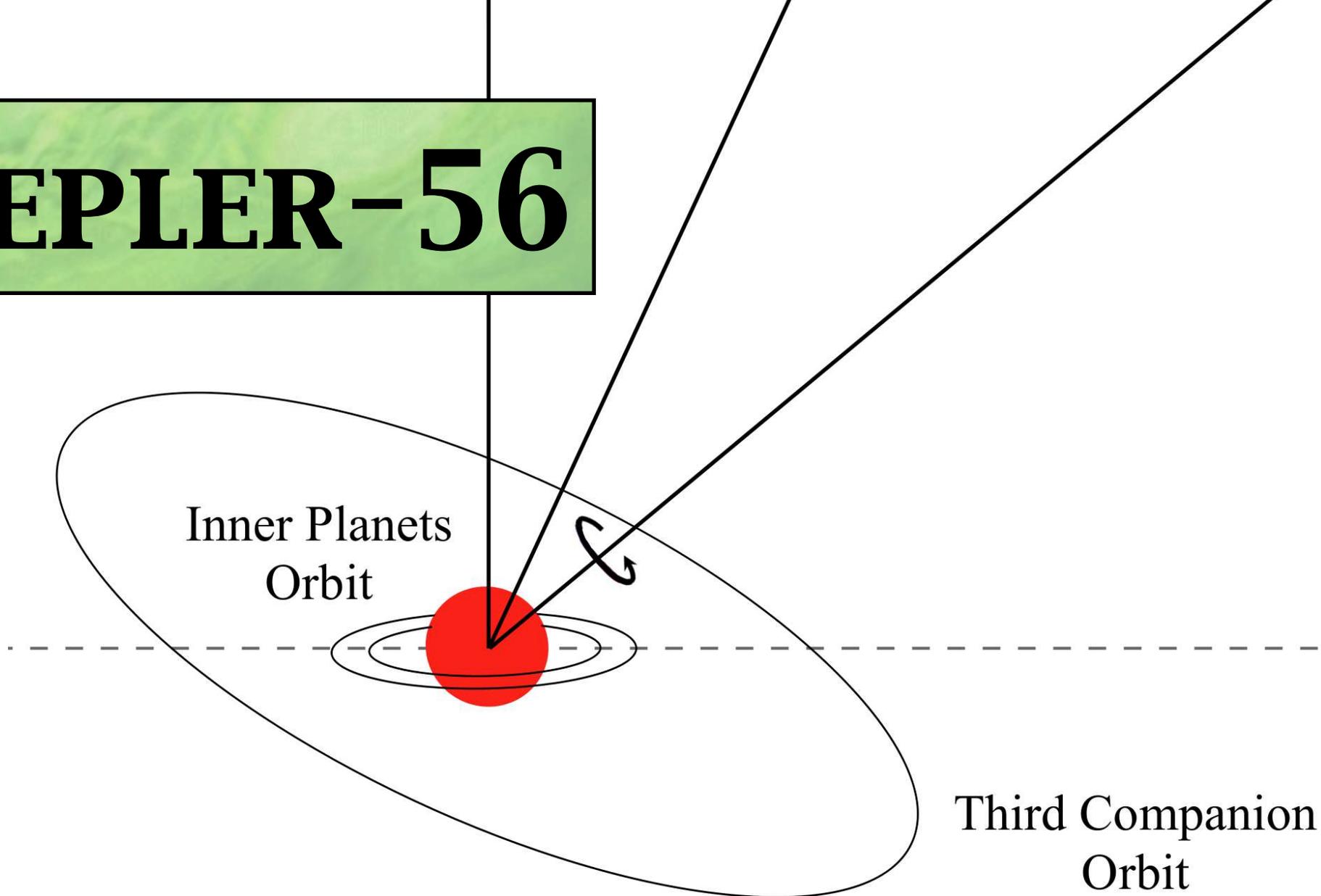
# WARPS

- Possible cause: misalignment in system
- Bardeen-Petterson (1975, black hole discs)
- Inclined planet / companion
- Accretion of material with different angular momentum

# CONSEQUENCES

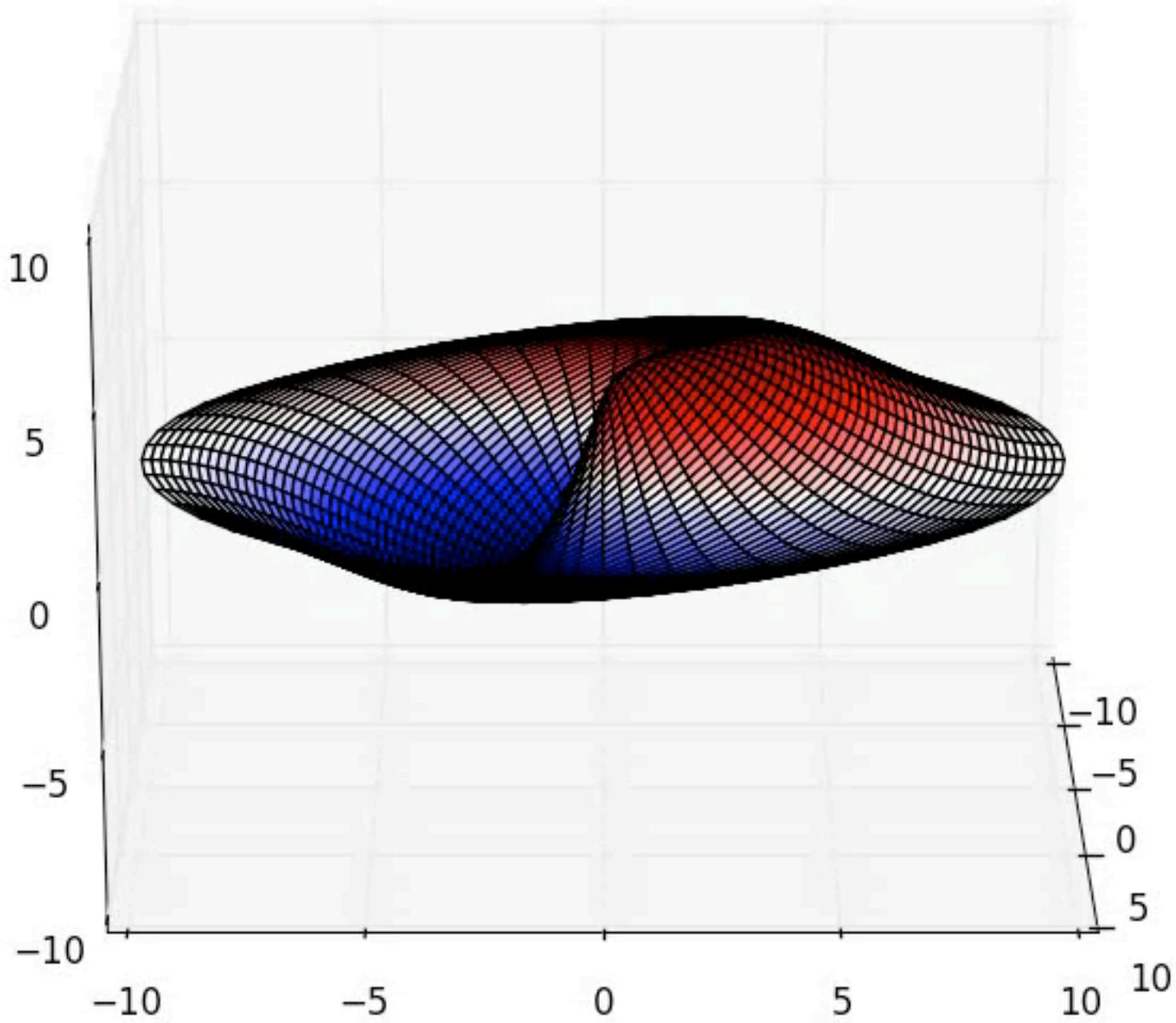
- Some extrasolar planets are observed to orbit inclined with respect to stellar rotation axis
- Was the primordial disc aligned with stellar spin?

# KEPLER-56

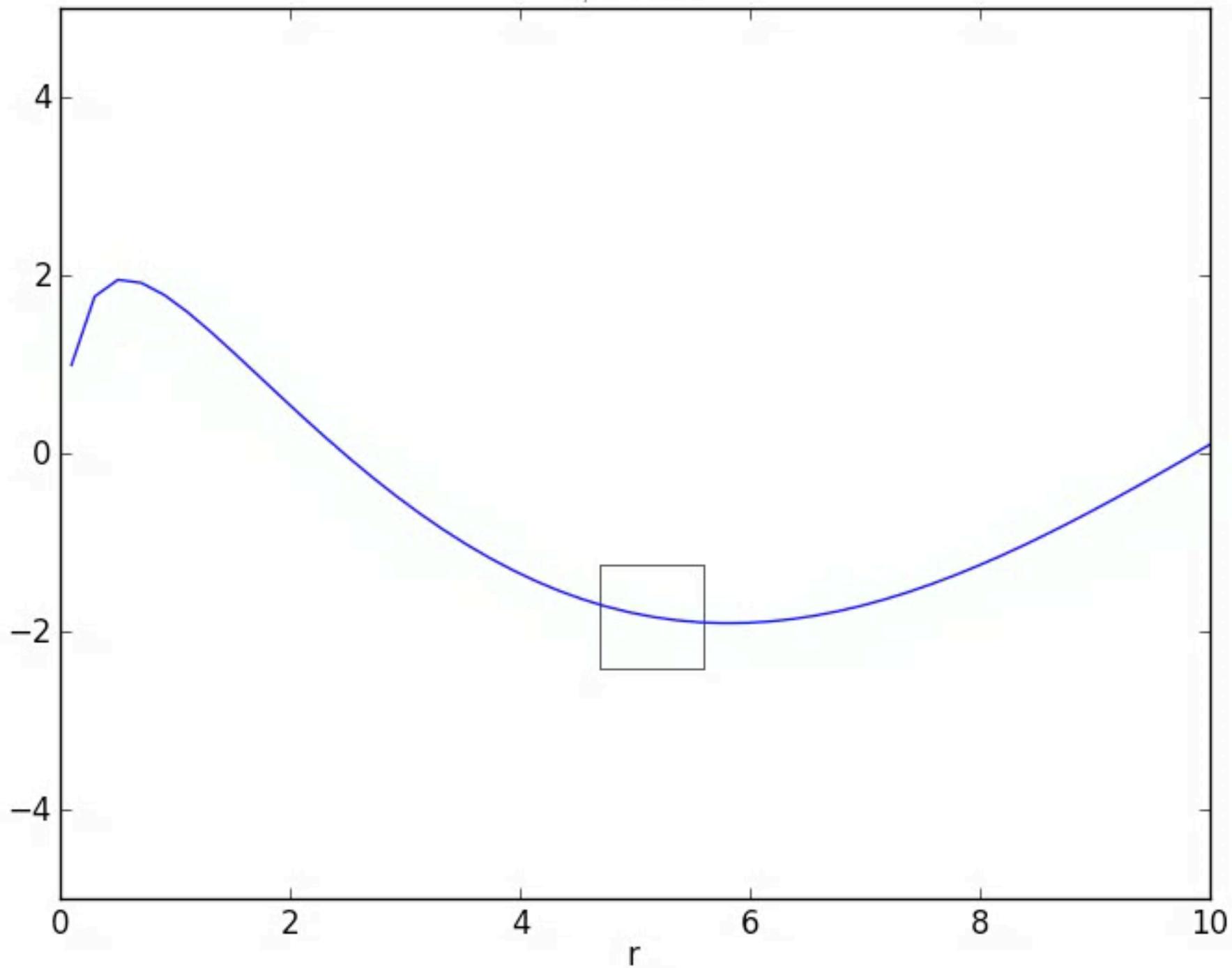


# BASIC QUESTION

- How badly does a disc **resist** warping?
- If it is warped, how long can it stay warped without external forcing?
- Try and come up with a well-controlled numerical experiment
- Warped **shearing box**



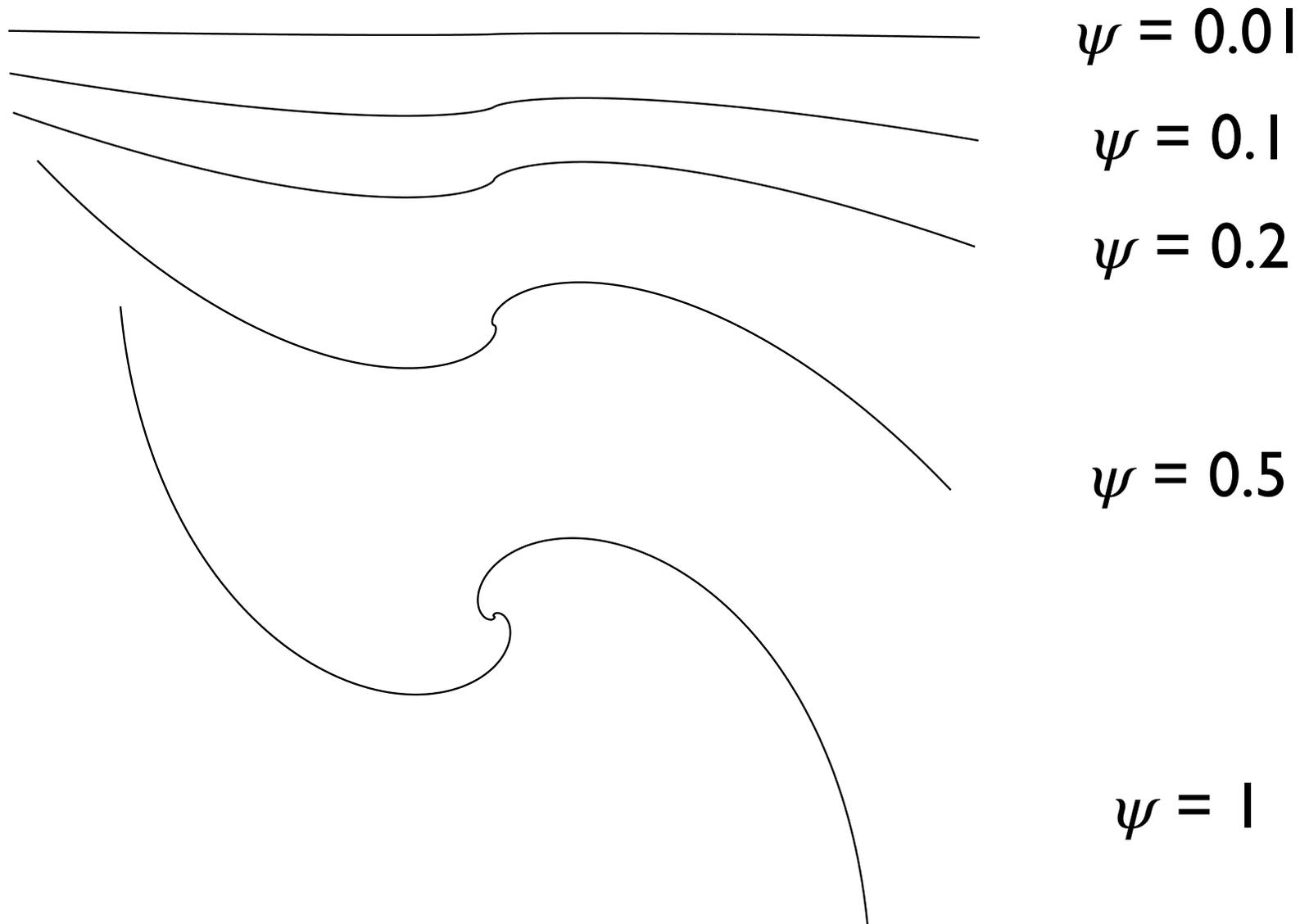
$\phi = 0.0$



# LOCAL MODELS

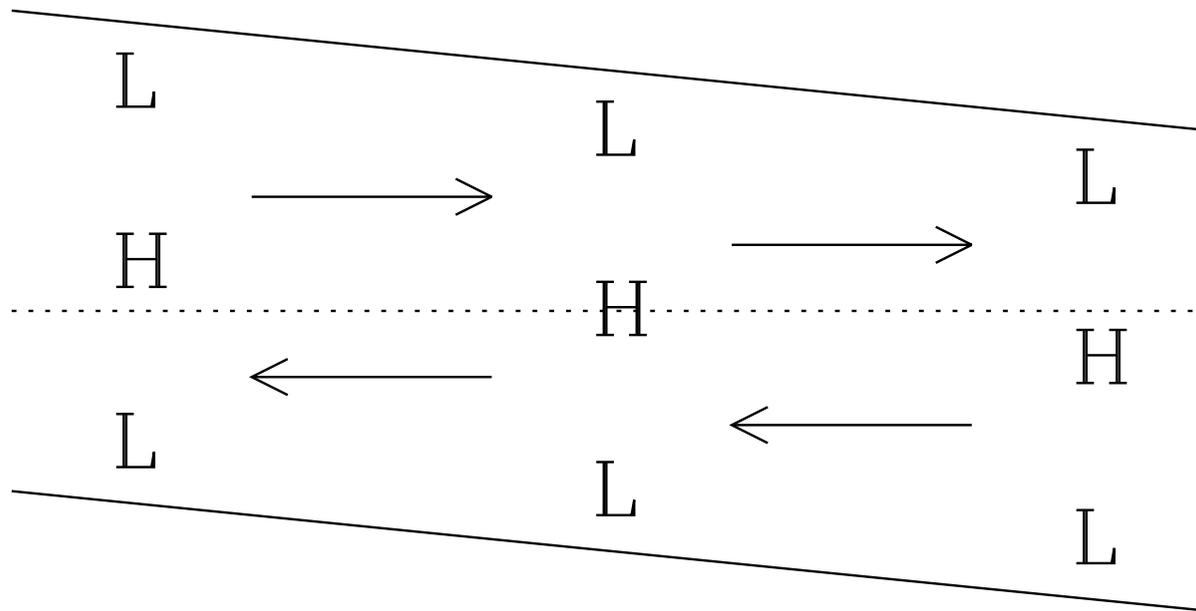
- A shearing box in a warped disc experiences an oscillating geometry
- Oscillation amplitude  $\psi$  (dimensionless warp amplitude)
- Ogilvie & Latter (2013a,b)

# LOCAL MODELS

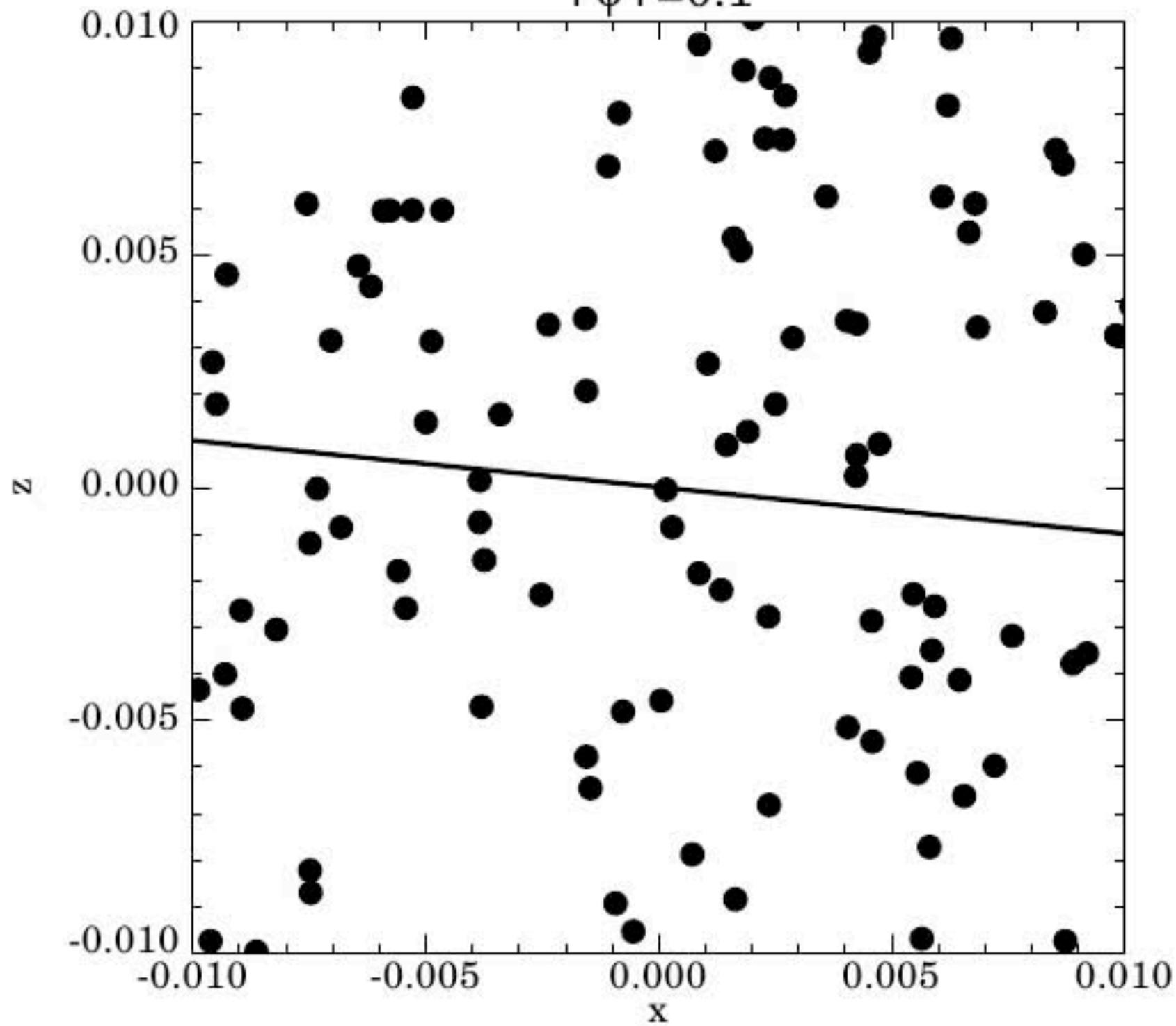


# LAMINAR FLOW

- No warp: velocity only due to shear
- In the presence of a warp, no vertical hydrostatic equilibrium



$$|\psi| = 0.1$$

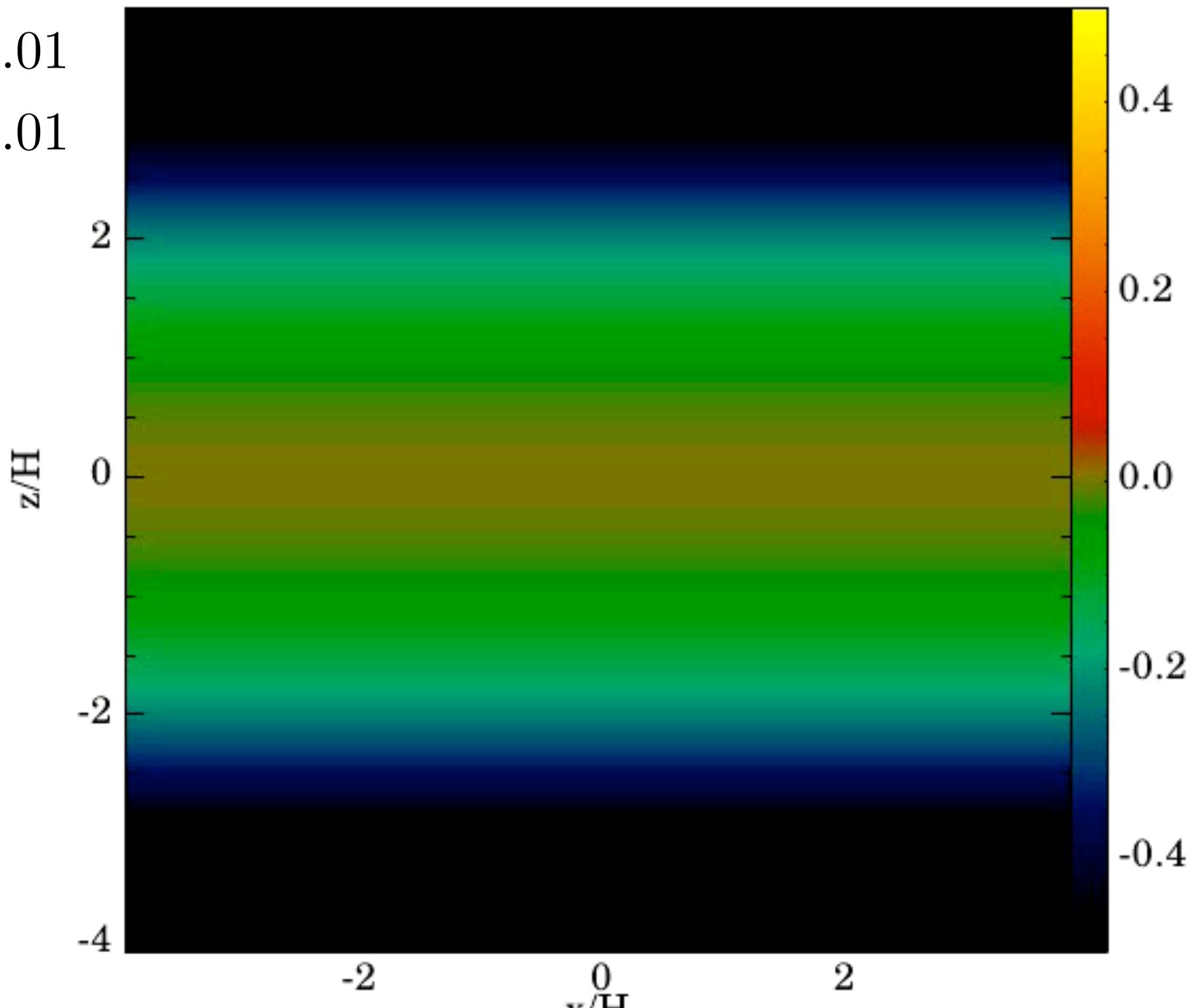


# INTERNAL TORQUES

- Laminar flows give rise to **internal stresses/torques**
- Bad news: warp diffuses  $\alpha^2$  times viscous time scale
- A possible way out: laminar flows can be unstable

$$|\psi| = 0.01$$

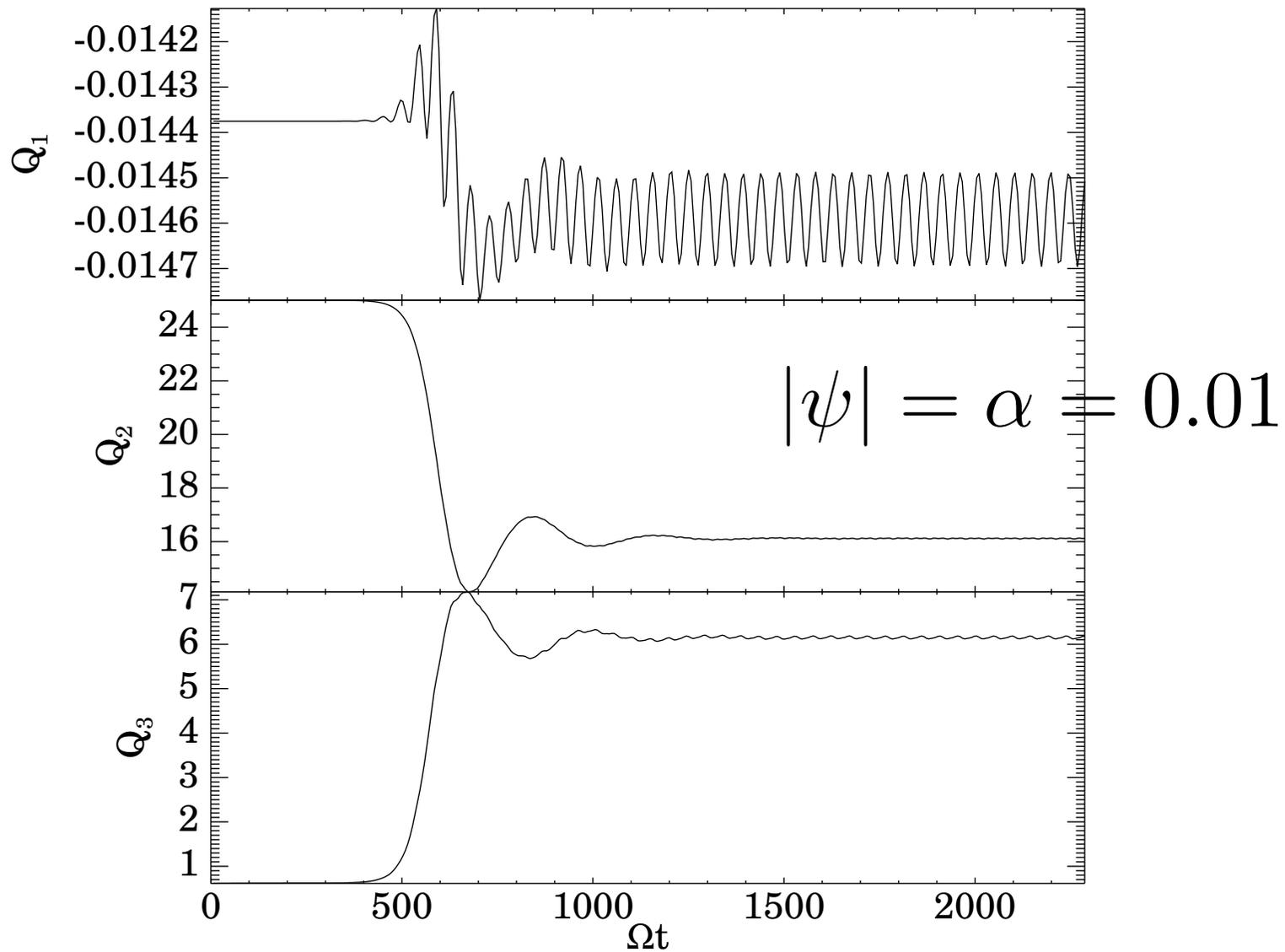
$$\alpha = 0.01$$



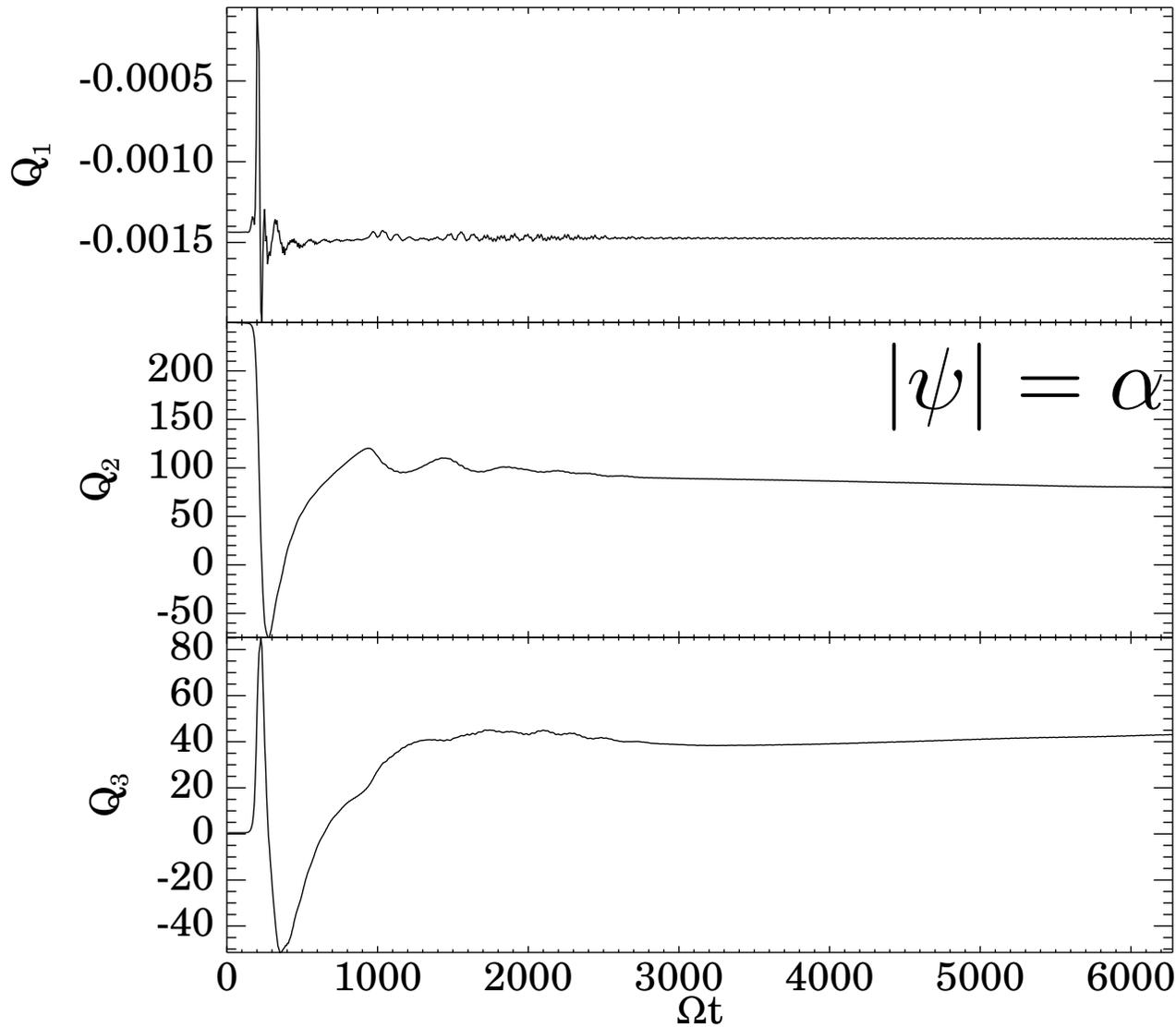
# RESULTS

- Result: “turbulent” state
- Laminar flow is reduced considerably
- This has consequences for internal stresses...

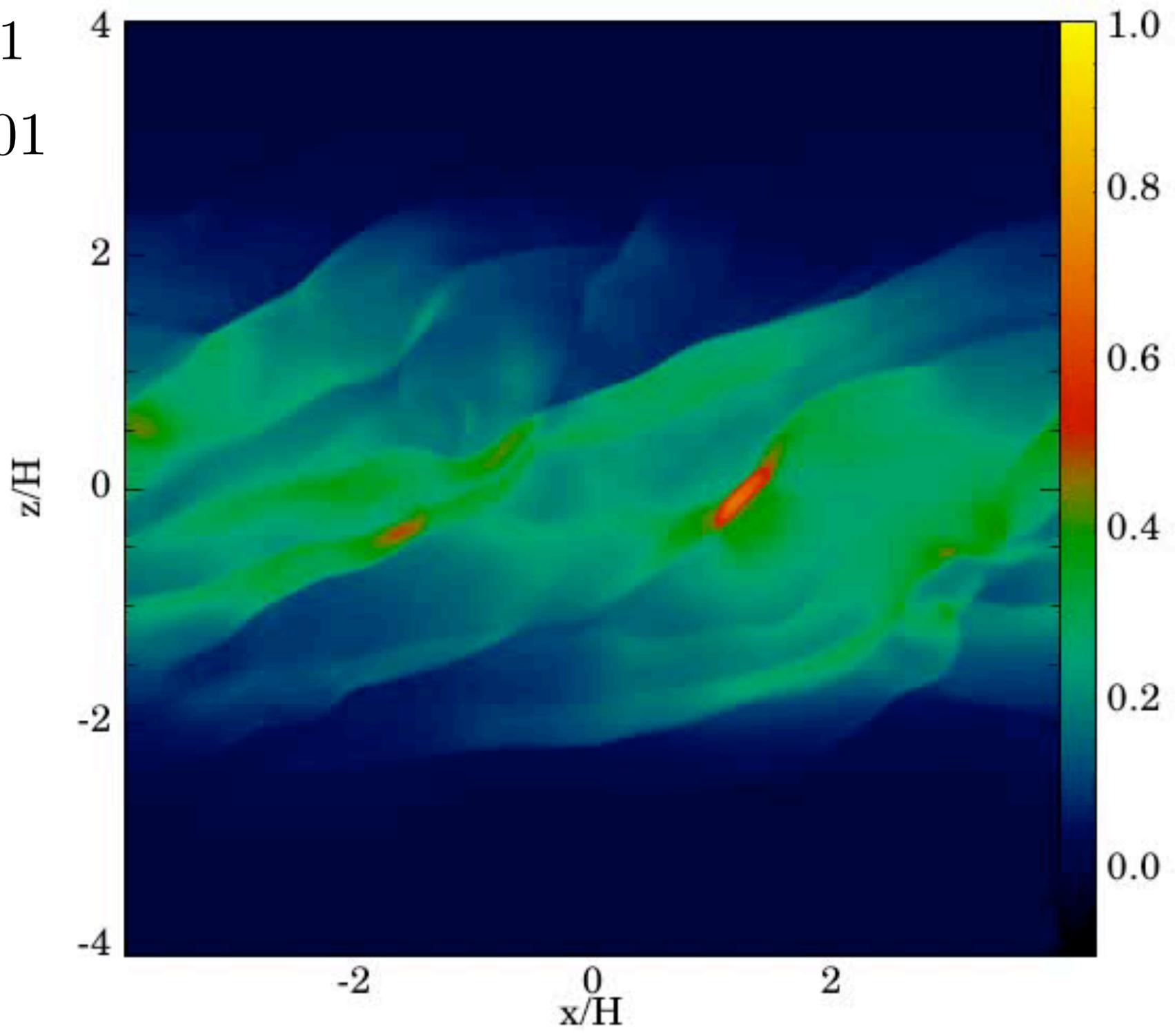
# RESULTS



# RESULTS



$|\psi| = 0.1$   
 $\alpha = 0.001$



# RESULTS

- Warp diffusion slows down by a factor of 2-10 due to turbulence
- Reduction more severe for smaller  $\alpha$
- This will promote warp survival

# OPEN QUESTIONS

- From 2D to 3D
- From isothermal to adiabatic
- Interaction with (MHD) turbulence

# CONCLUSIONS

- It is possible to harness the power of the shearing box to study warped discs
- The laminar flows associated with warped discs are hydrodynamically unstable
- The resulting “turbulence” can promote warp survival