Helical and non-helical large-scale dynamos in thin accretion disks

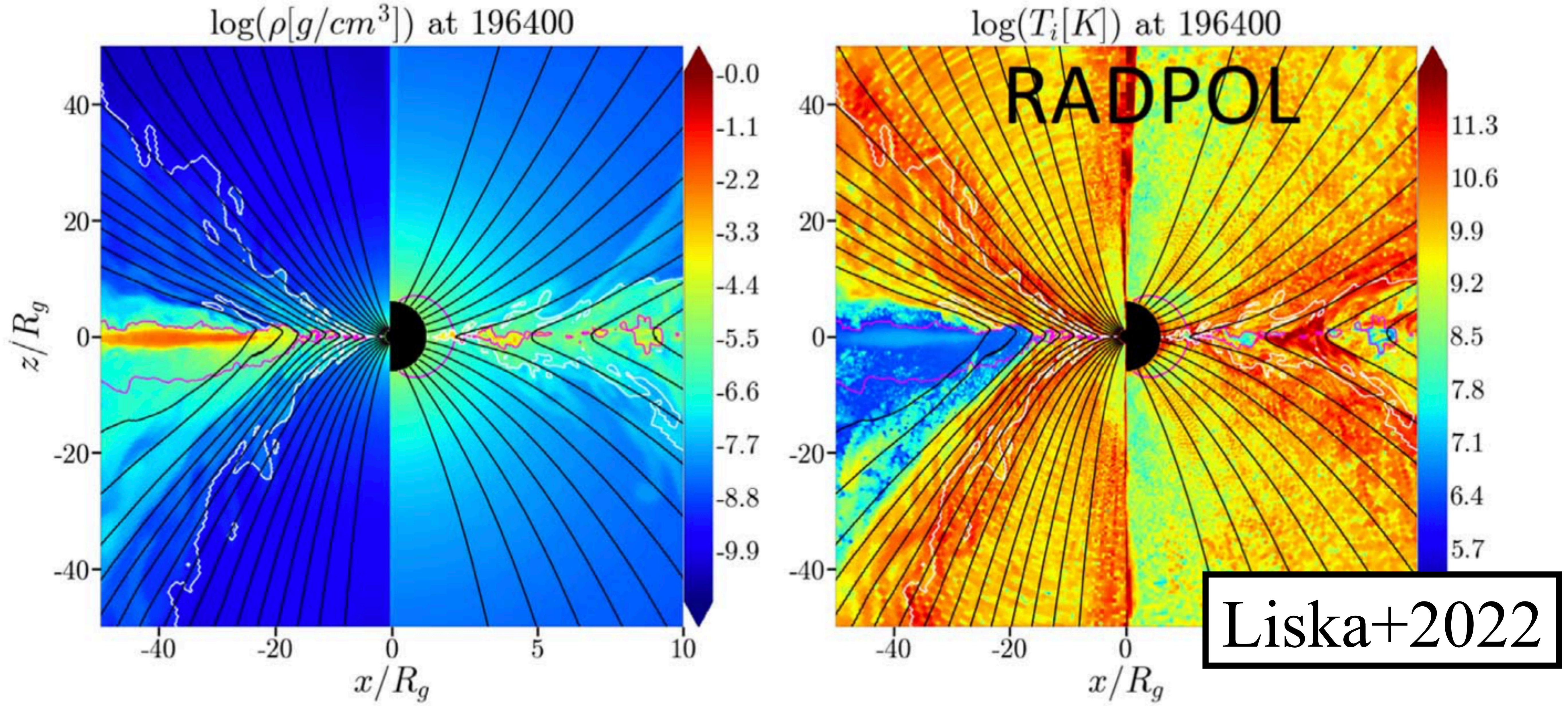
Hongzhe Zhou (周竑喆)

The 32nd Texas Symposium on Relativistic Astrophysics, Dec. 15, 2023

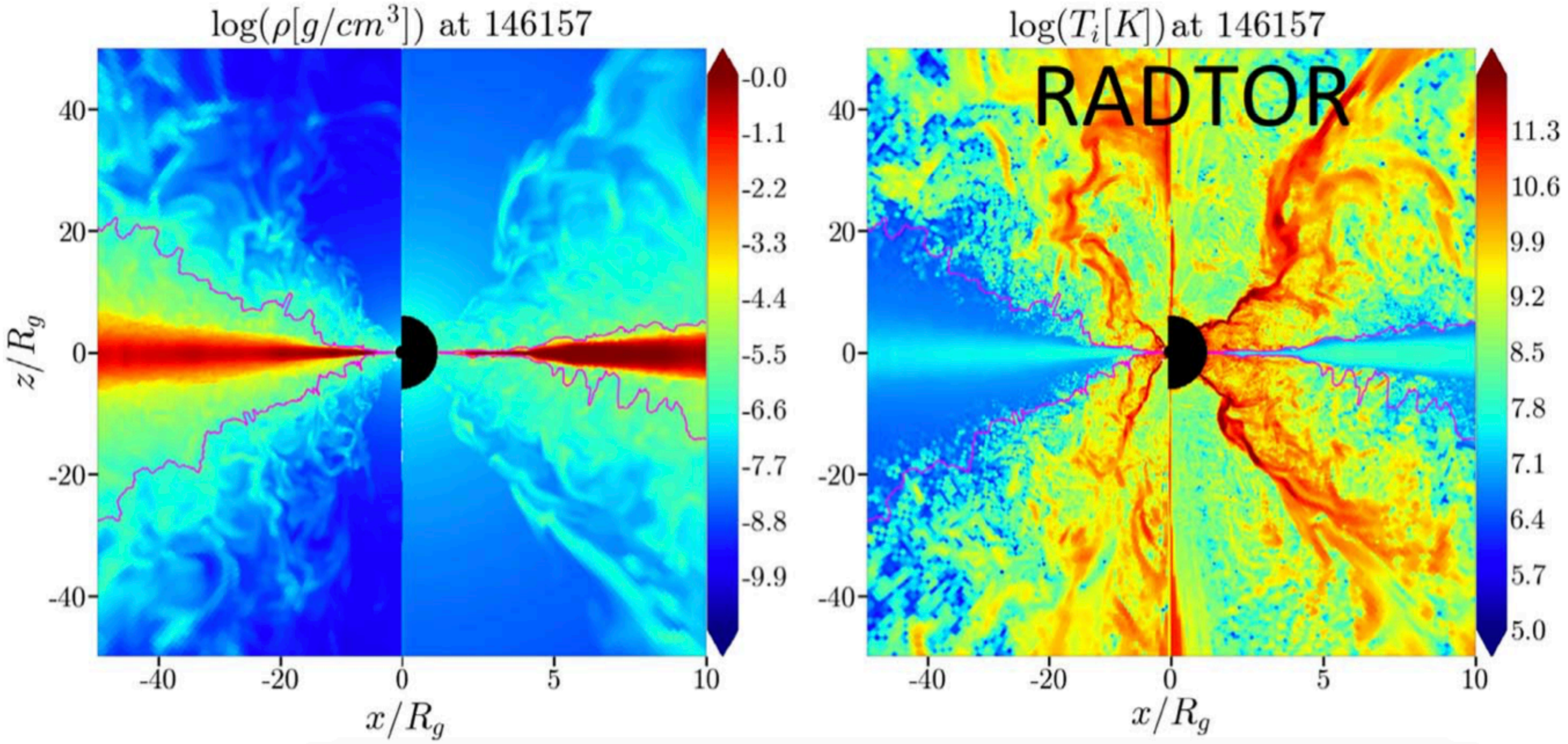
李政道研究所
TSUNG-DAO LEE INSTITUTE

Initial B determines MAD/SANE states

- Thin disk + poloidal flux
  → MAD



- Thin disk + toroidal flux
  → SANE



Challenge in realizing large-scale dynamos in GRMHD simulations

- Self-consistent amplification of B in disks: dynamo

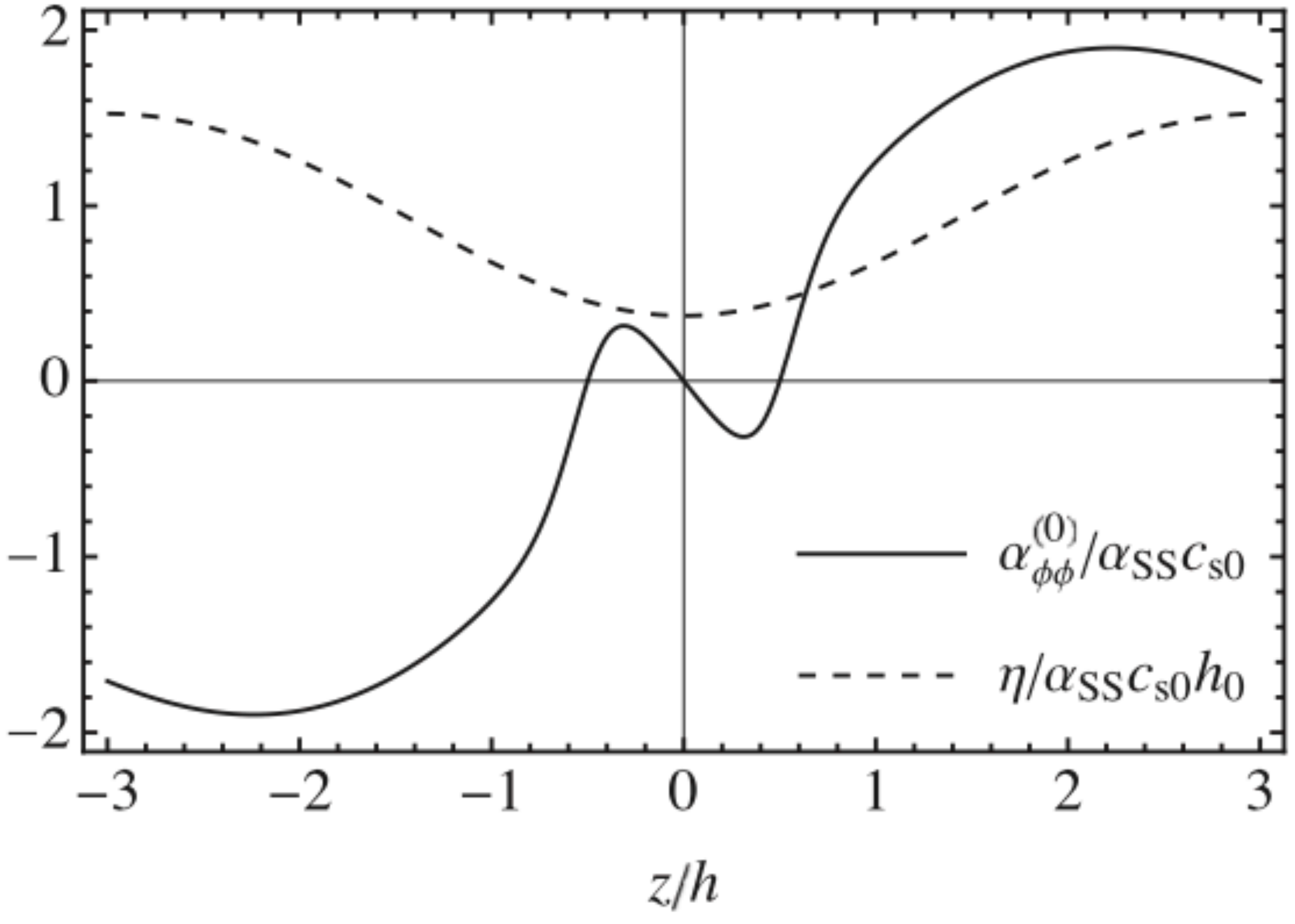
- Why not: requires a well-resolved turbulence with fairly extended inertial range,
  $N_\theta \geq \# \times B_{ini}^{-1}$

- Needs a very high resolution + quite long simulation time — too expensive

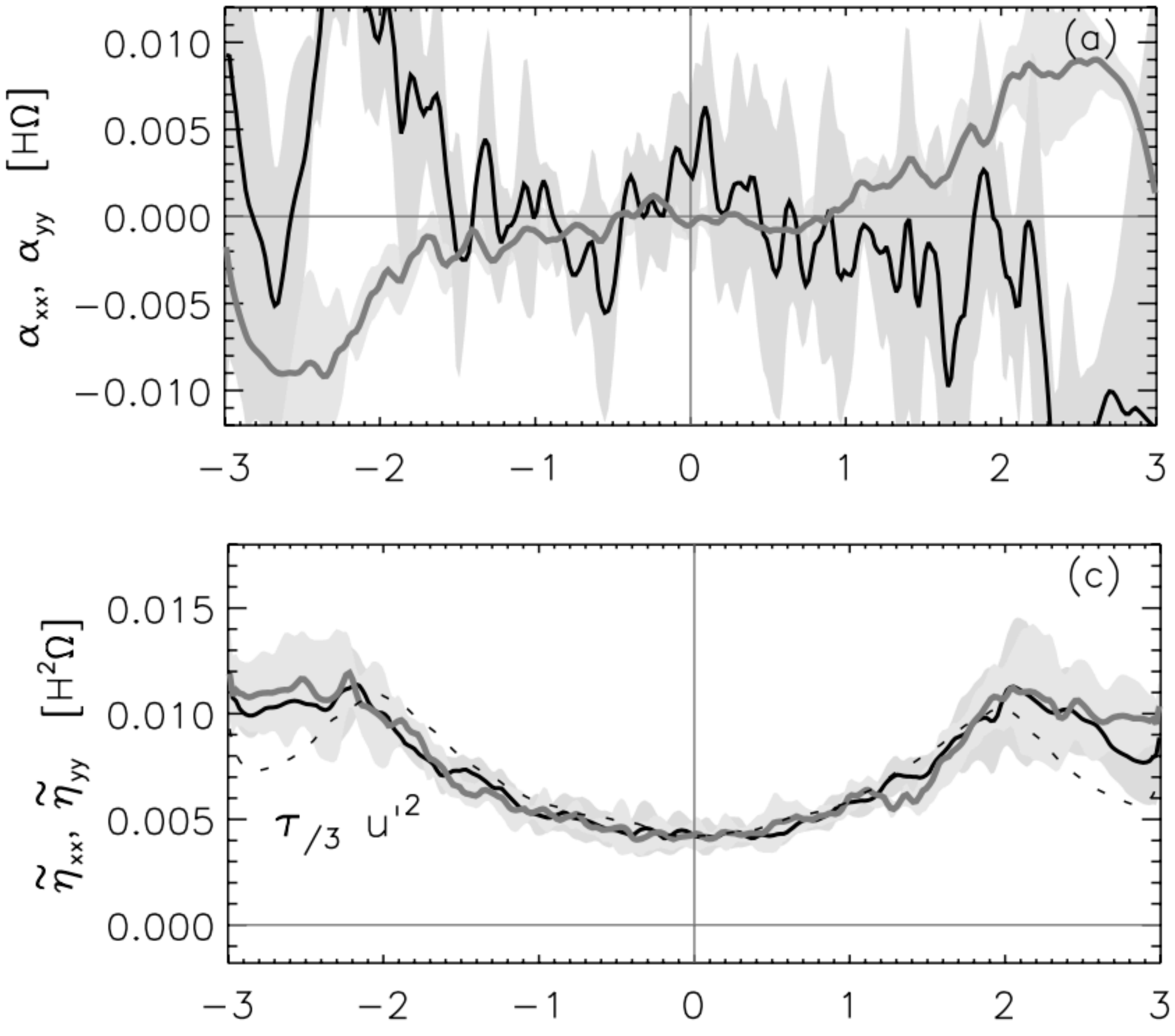
- **Workaround**: use extra terms in low-resolution simulations to mimic mean-field amplification that is only available in high-resolution simulations — subgrid modeling
  $\partial_t B = \nabla \times (U \times B + \alpha B - \eta J) + \nu_M \nabla^2 B$

α and η profiles: semi-analytical v.s. direct numerical simulation

HZ2024



Gressel 2010



$$\alpha \propto \frac{z}{h}\left(\alpha_{SS} - \frac{2}{3\alpha_{SS}\beta}\right)c_s$$

Stratification

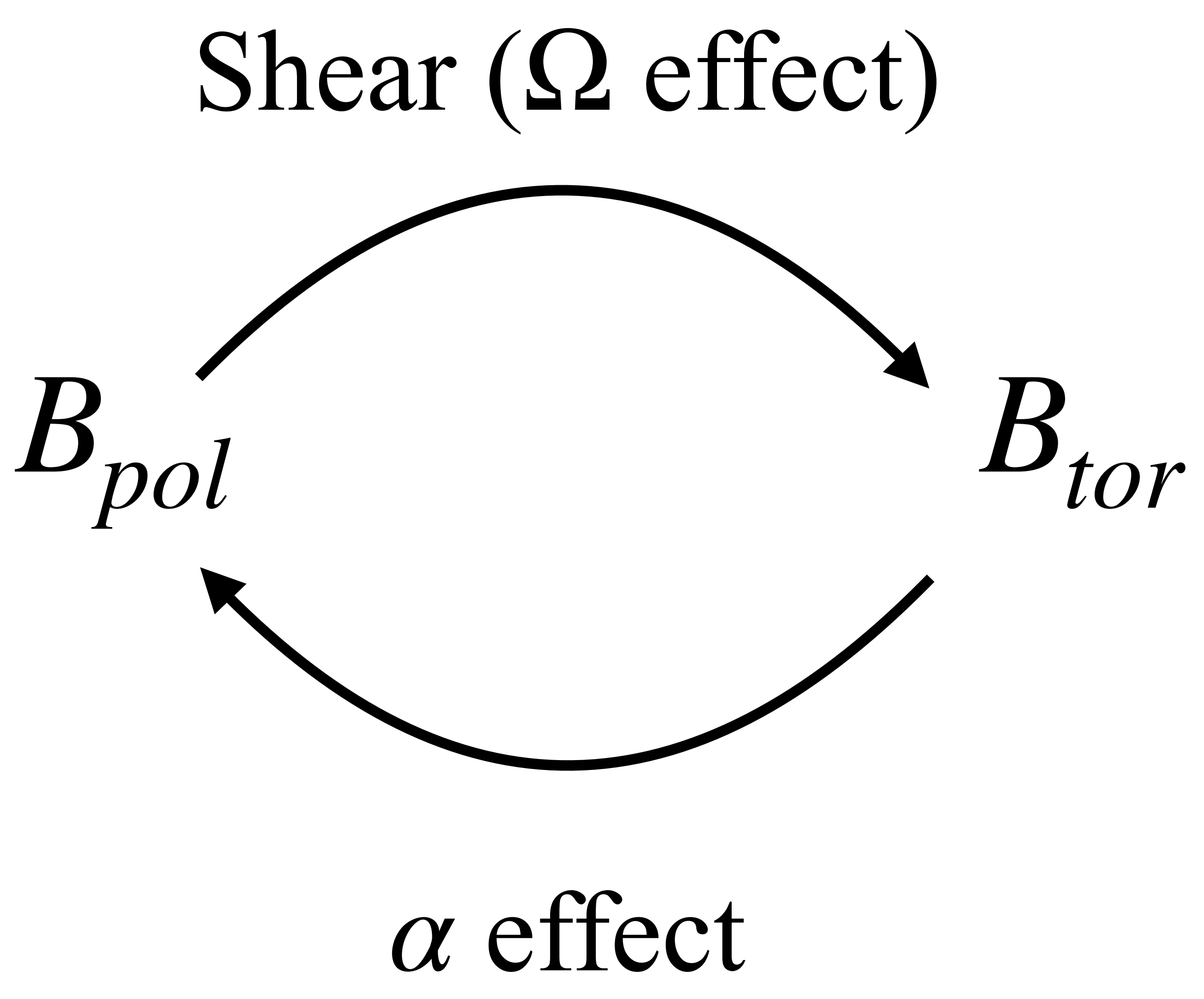
Viscosity parameter (Shakura+Sunyaev 1973)

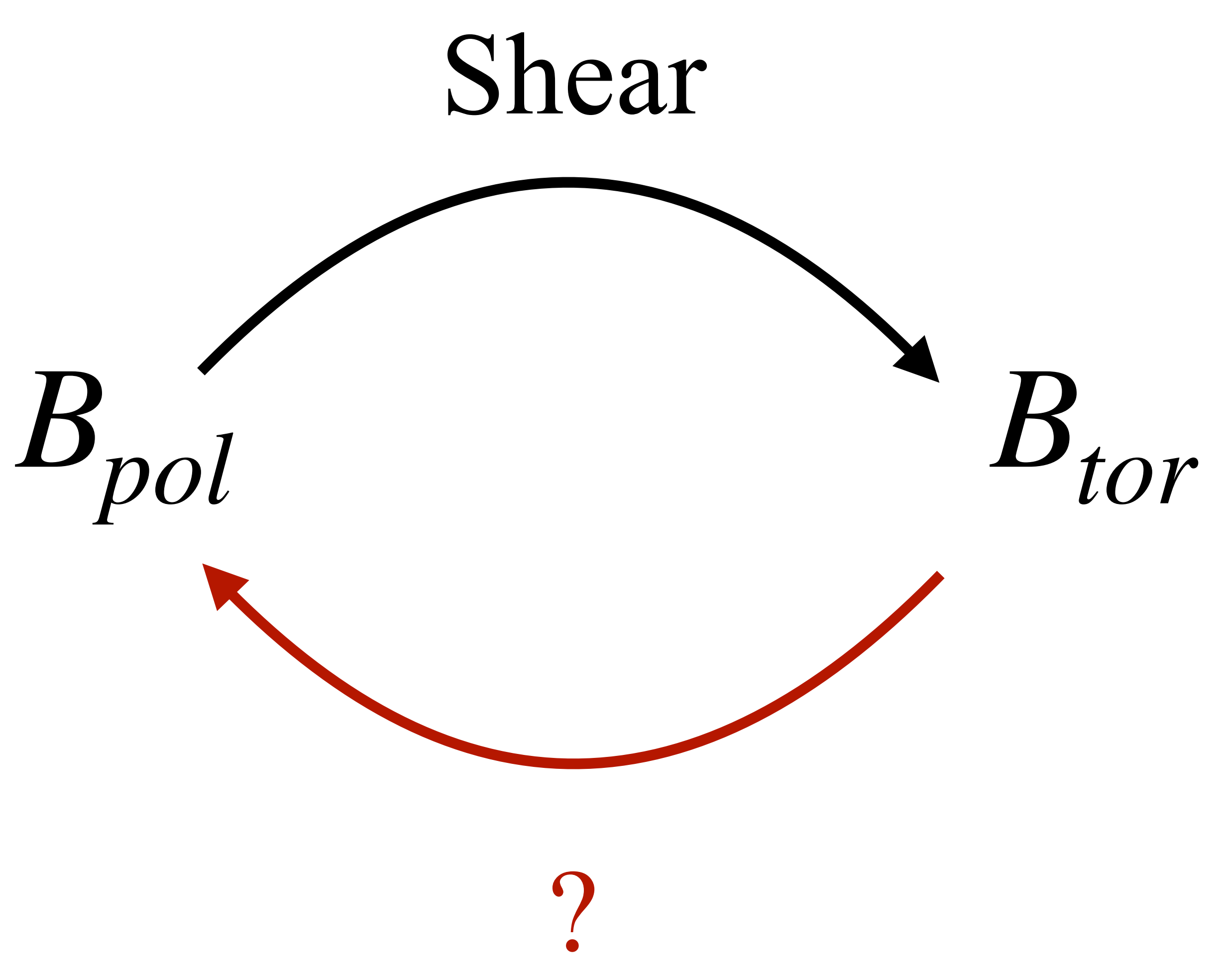
Feedback due to magnetic helicity evolution

Sound speed

Other possibilities: Shear dynamo terms in a thin-disk model

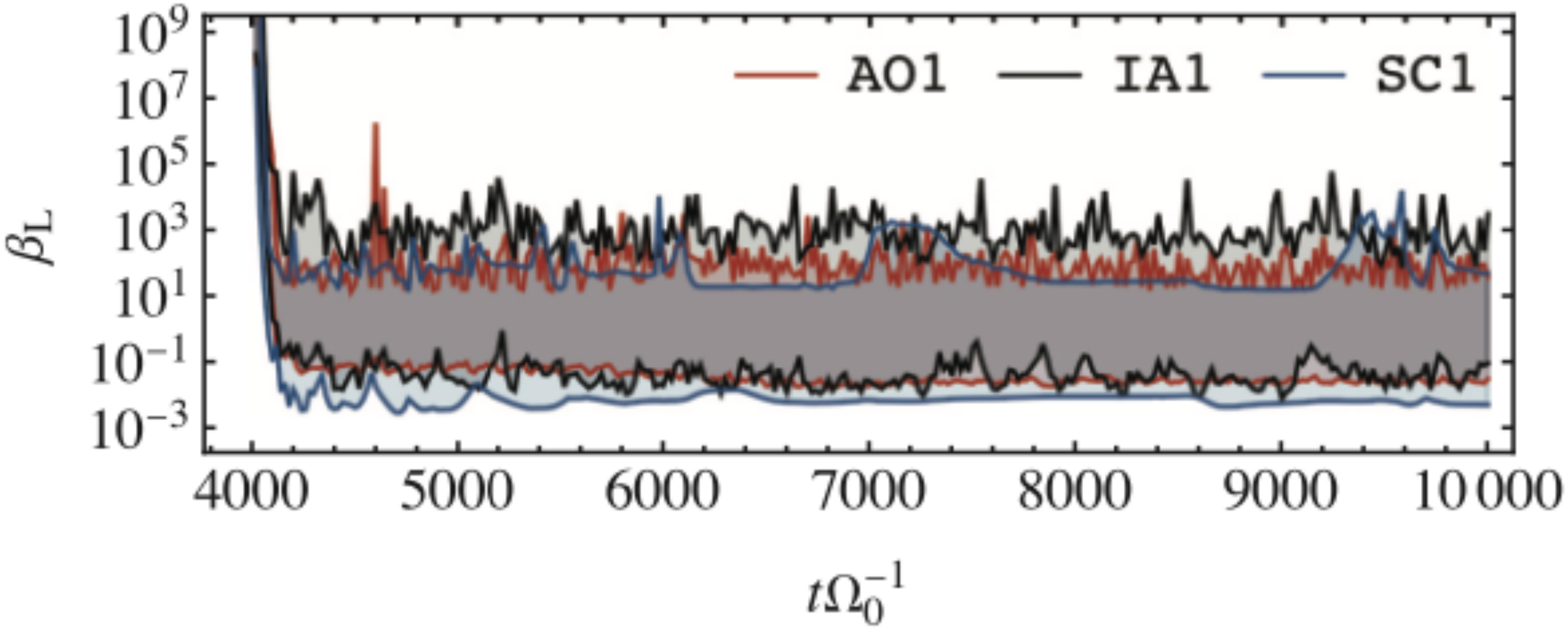
- These are **nonhelical** models which might dominate in weakly stratified flows (ADAFs)
- **Incoherent α effect**: α fluctuations around 0
- **Shear-current effect**: anisotropic turbulent diffusivity
- Both supported in shearing-box analysis





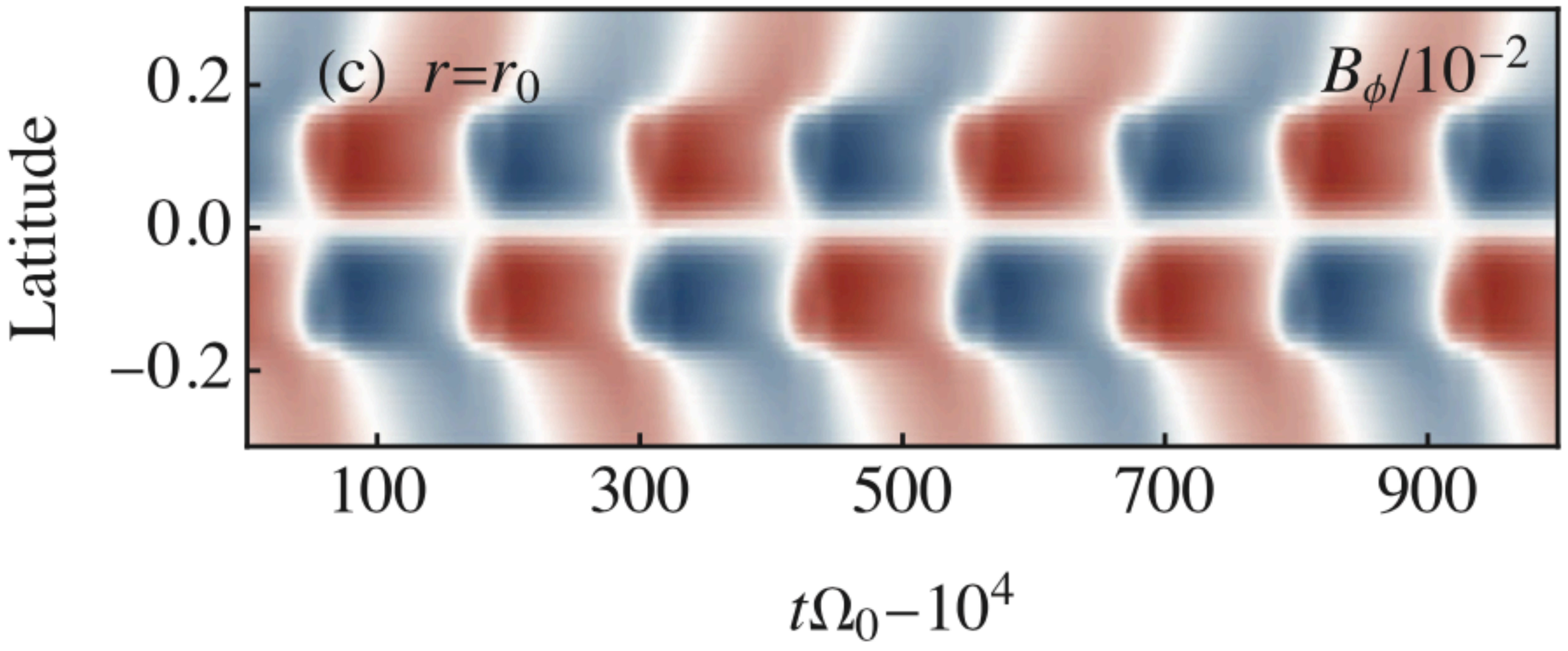
2D axisymmetric Newtonian disk with subgrid dynamos (HZ2024)

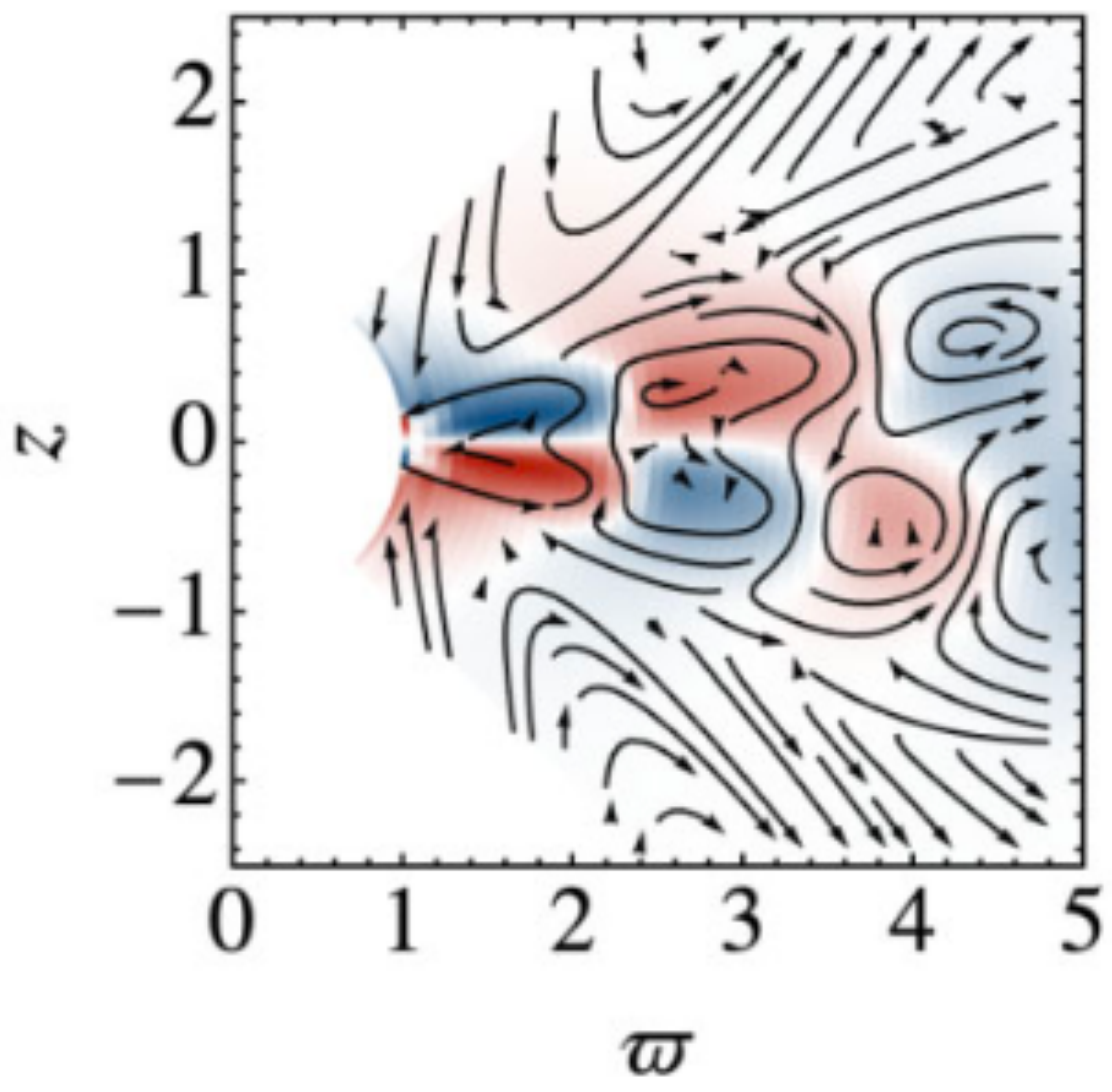
- Thin disk, $h/r \simeq 0.1$; azimuthal magnetic field, $\beta_{ini} > 10^9$



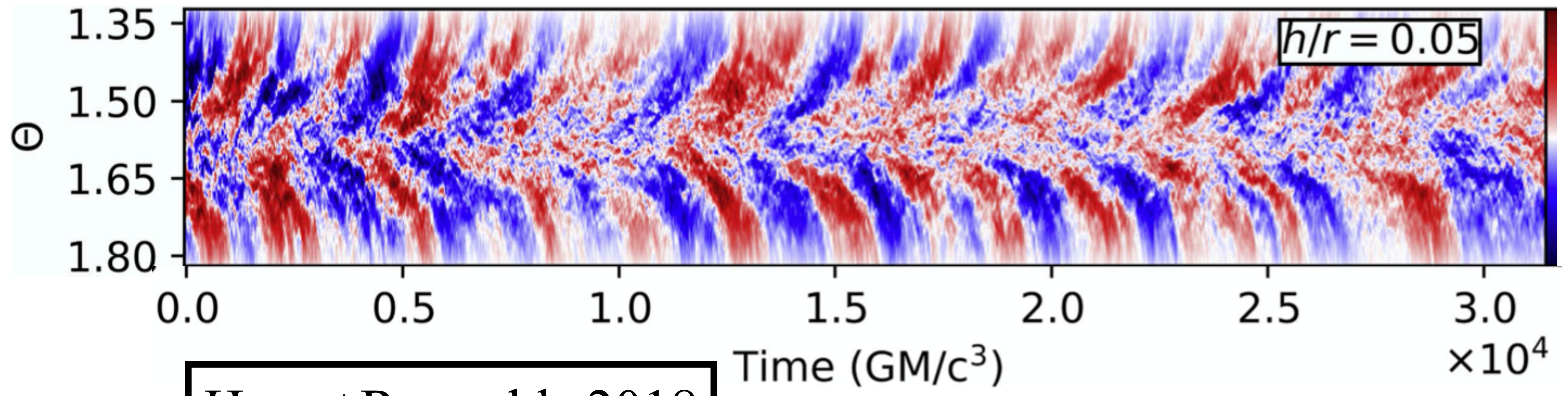
- Plasma β in the disk 0.1-200; average a few tens

Helical models: reproduce results in direct numerical simulations

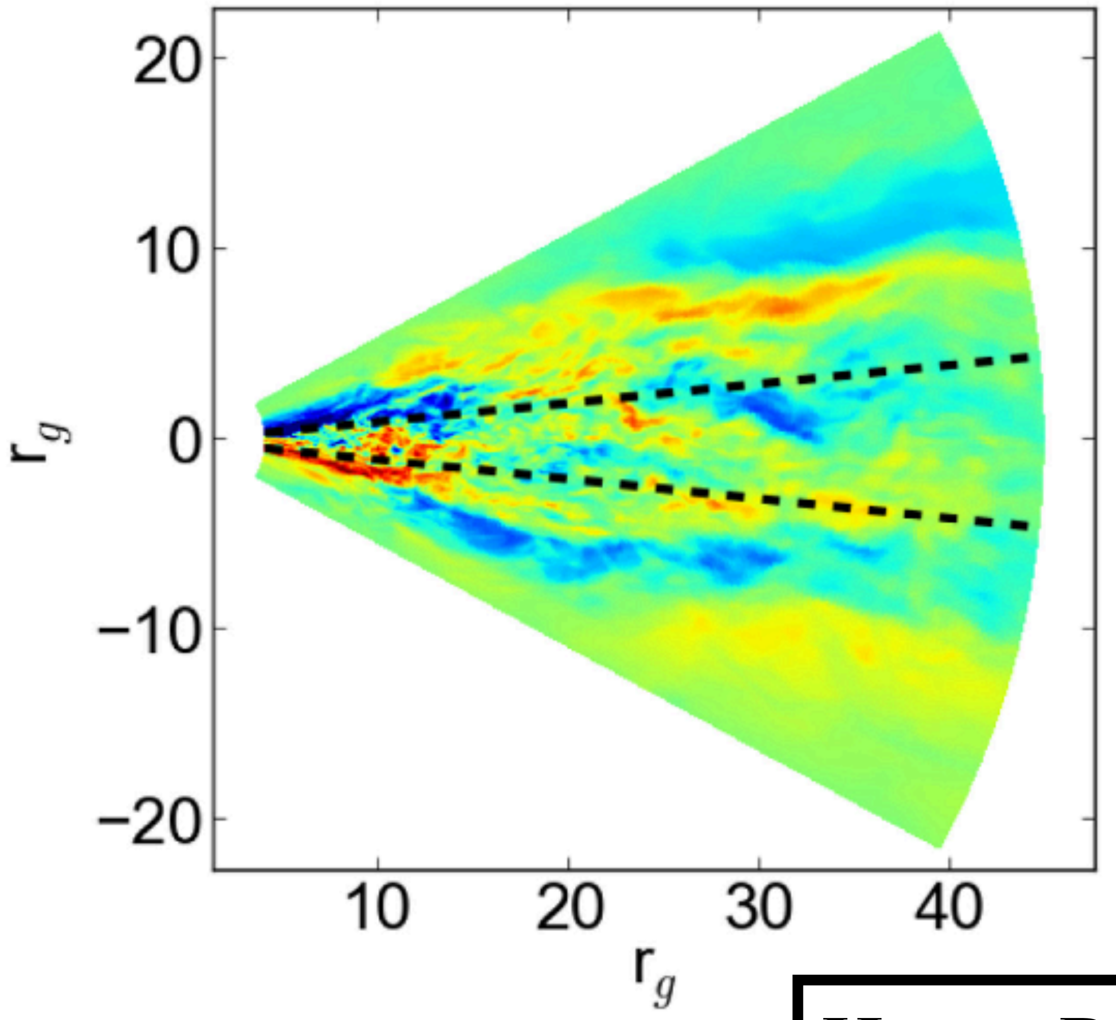




- Dipolar
- Cycle period ~ $40t_{Kep}$
- Coherent lengths $L_{radial} \simeq 30h$



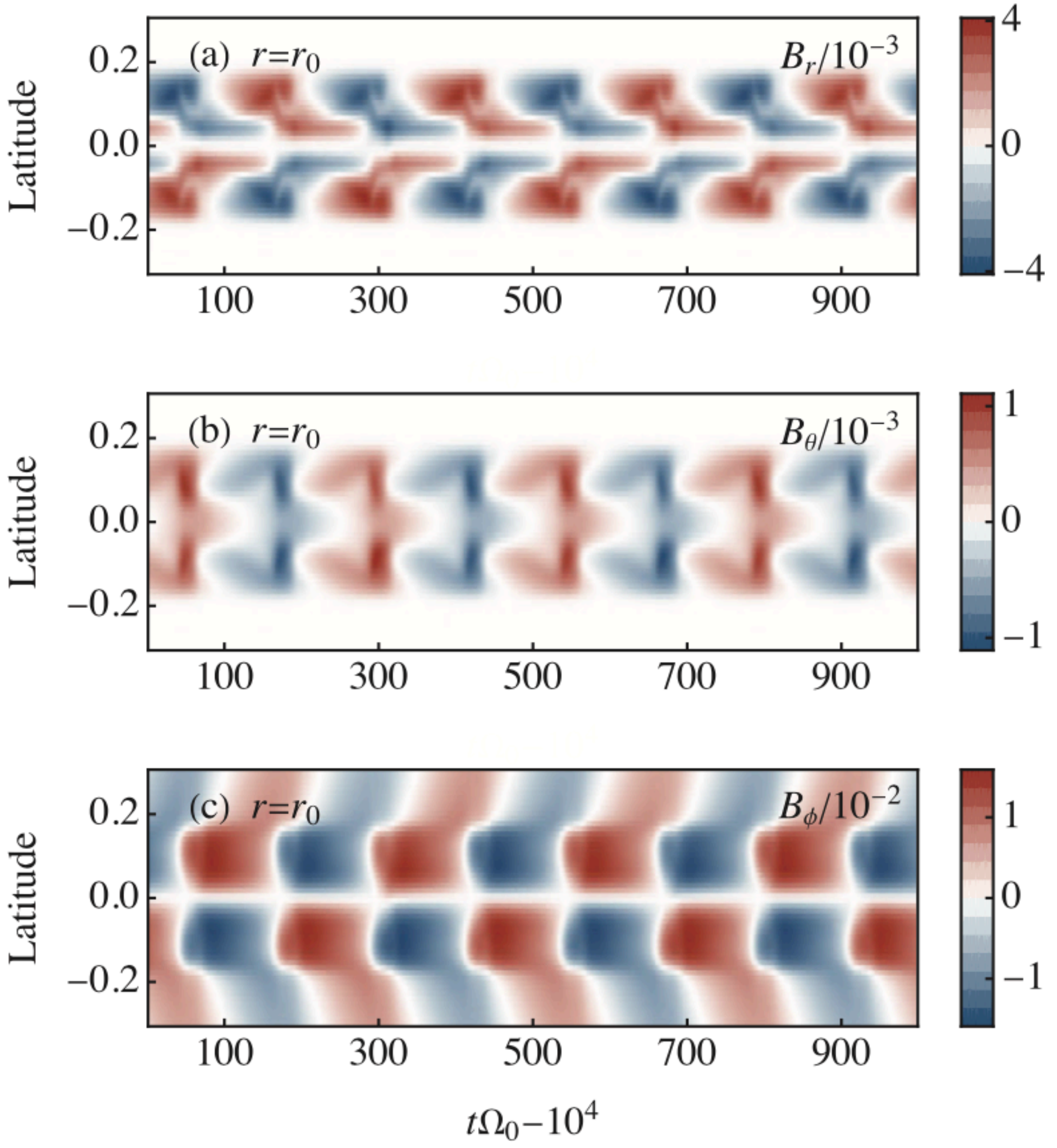
Hogg+Reynolds 2018



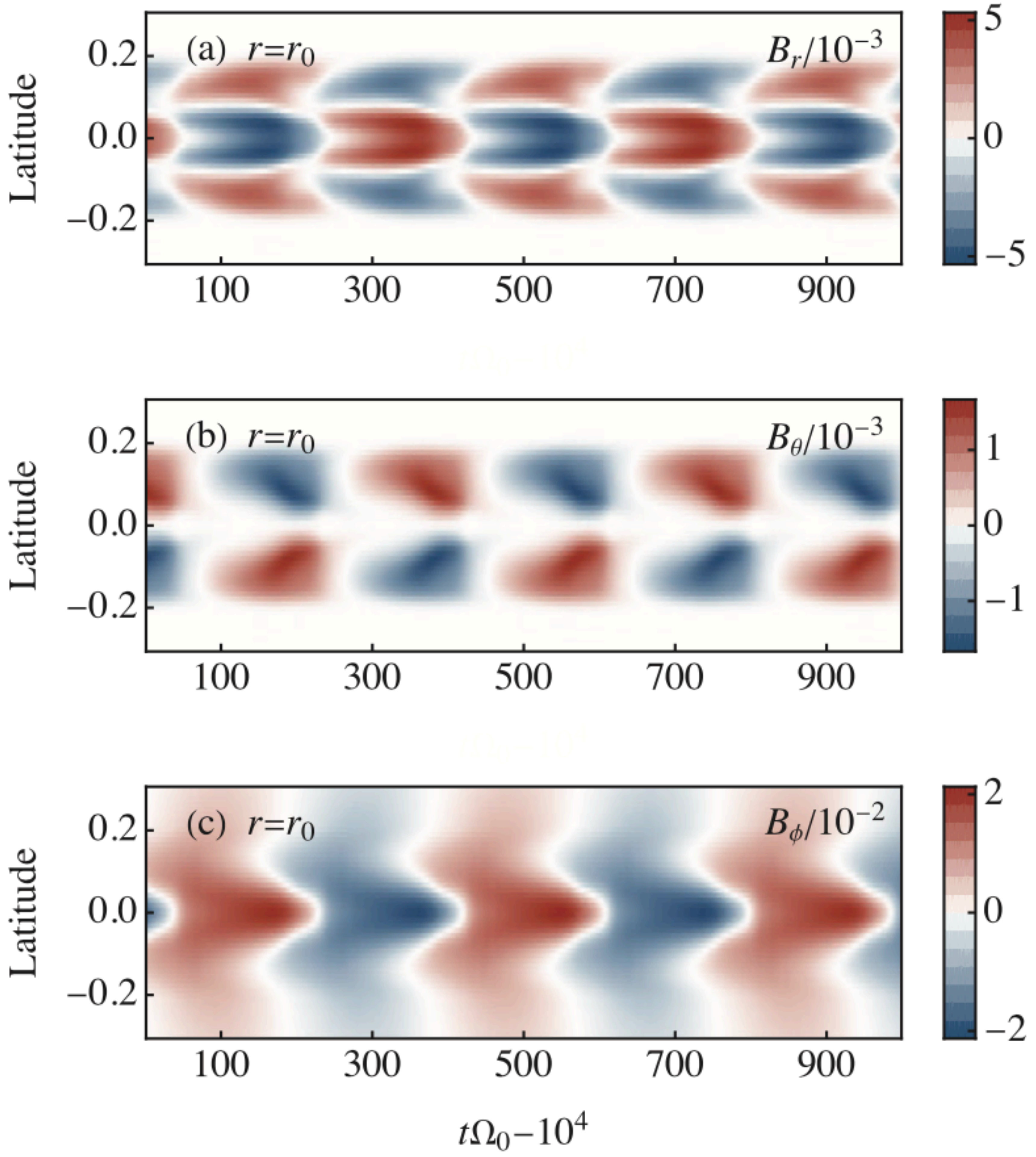
Hogg+Reynolds 2016

Helical models: effect of quenching prescription

This work: dynamo quenching derived from magnetic helicity evolution—dipole

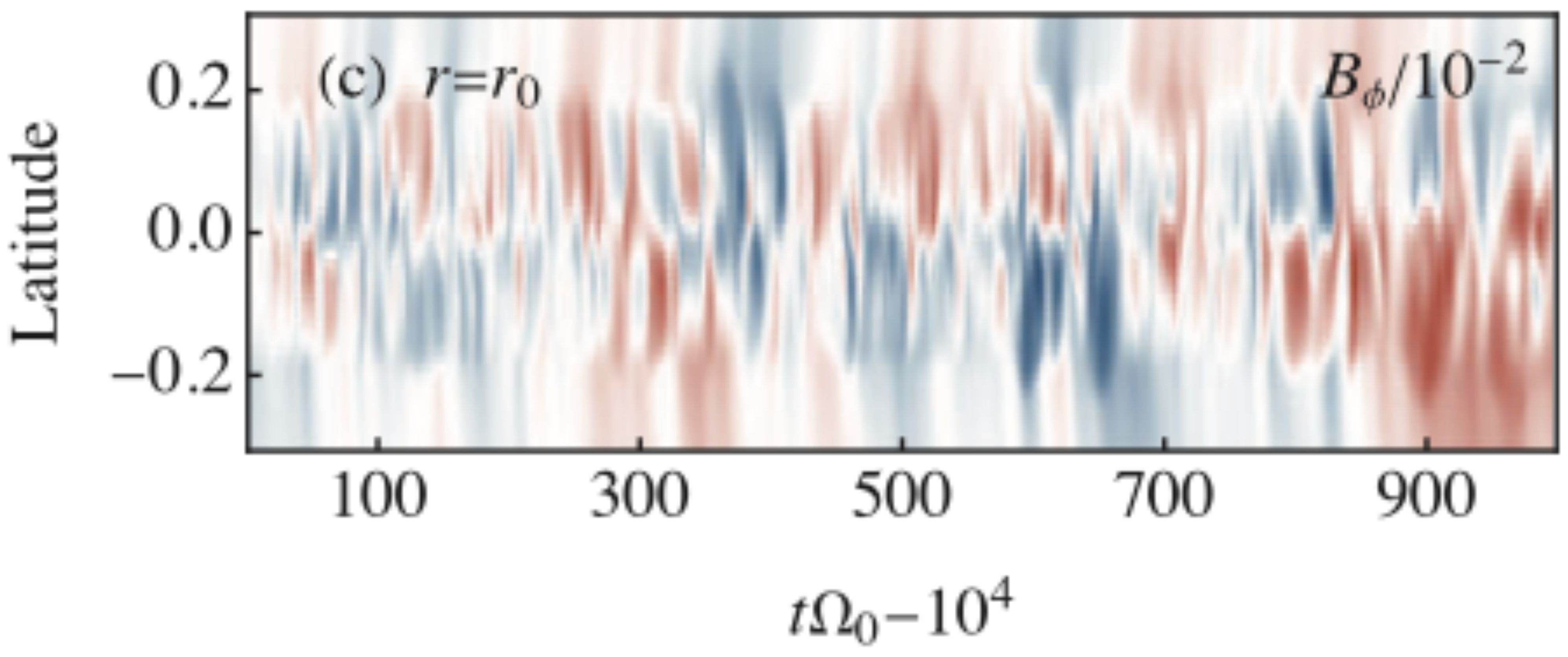


Previous parameterized/algebraic quenching $\alpha(B) \sim 1/(1+B^2/B_{eq}^2)$ produces quadruple field

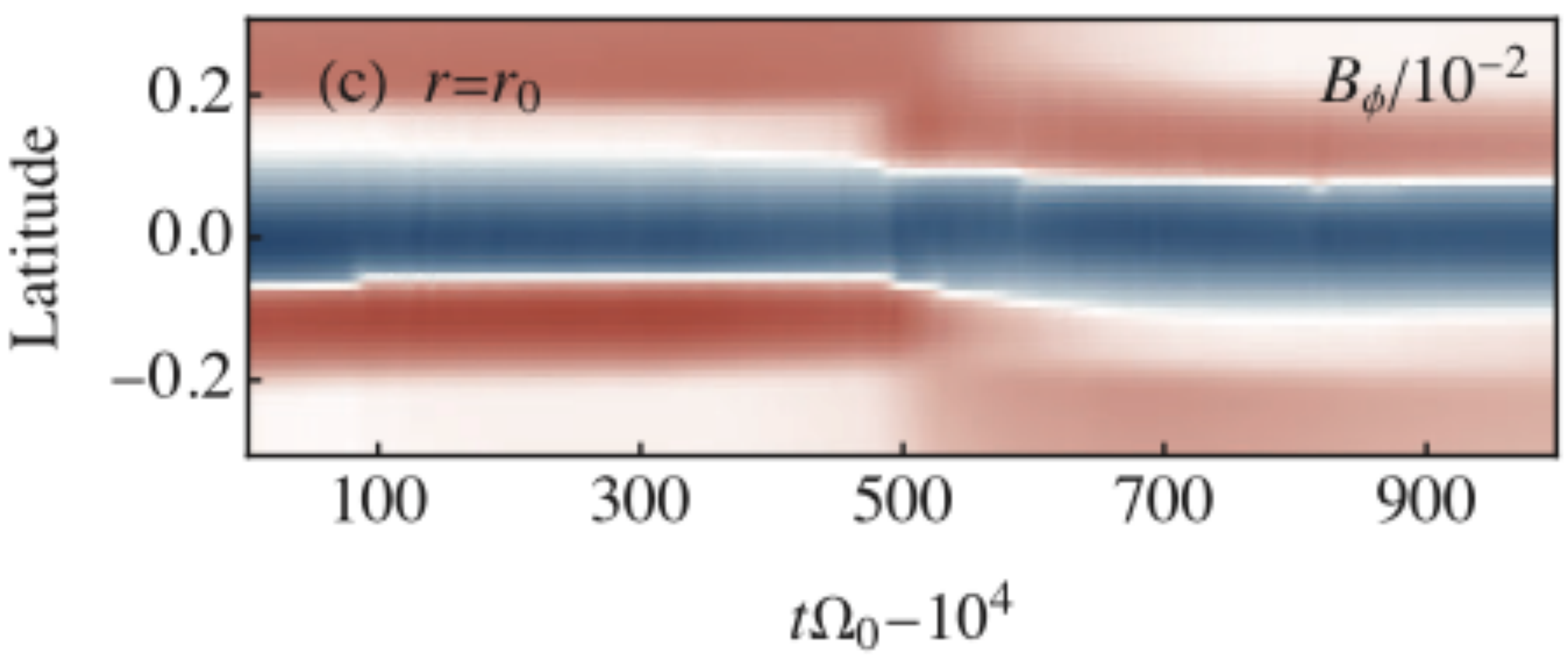


Nonhelical mechanisms: likely subdominant in MRI turbulence

Incoherent α effect: strong fluctuations



Shear-current effect: strong field, no cycles



- Both in disagreement with shearing-box results
- Might operate in thin disks, but likely subdominant

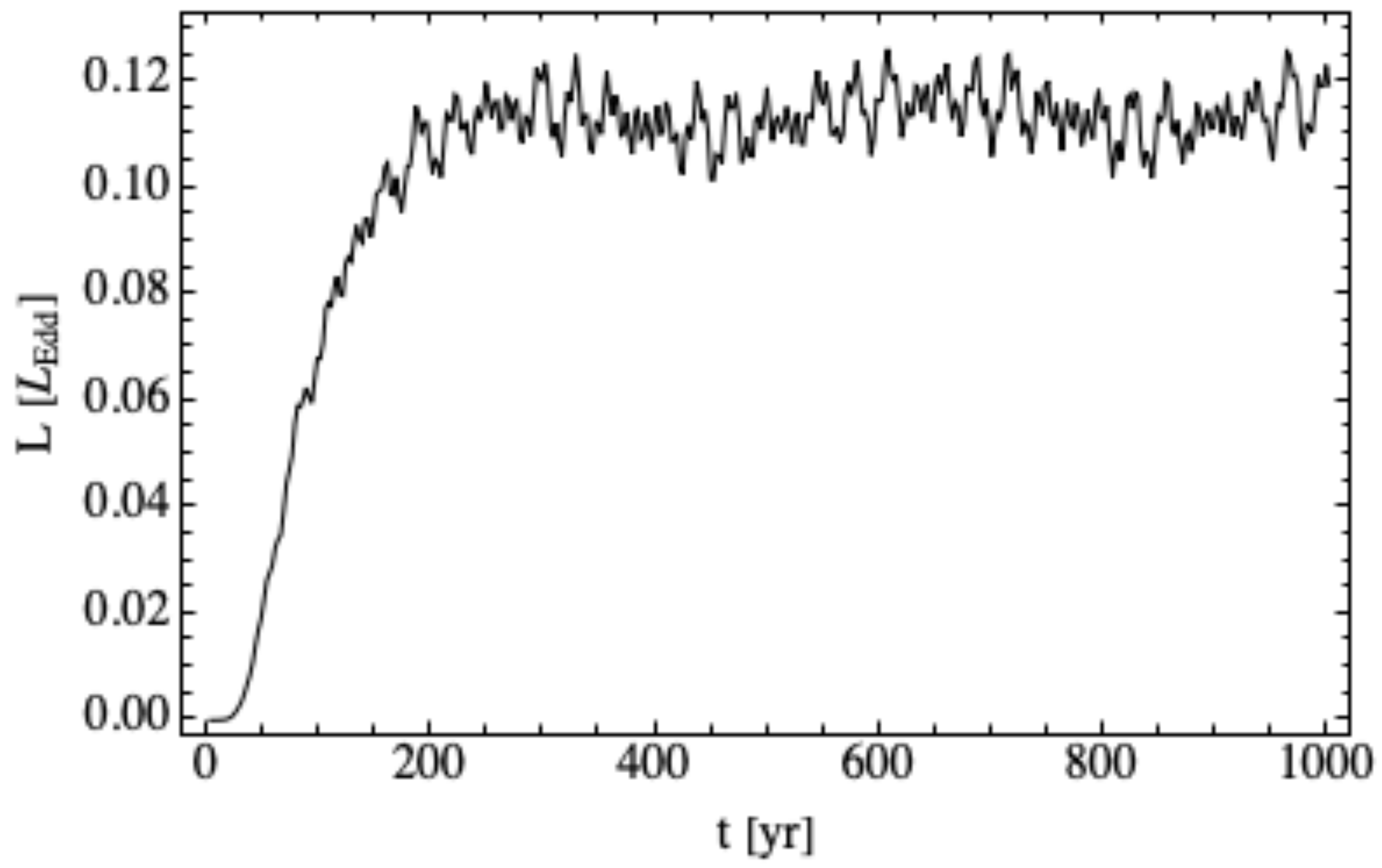
Implications of a periodic disk magnetic field

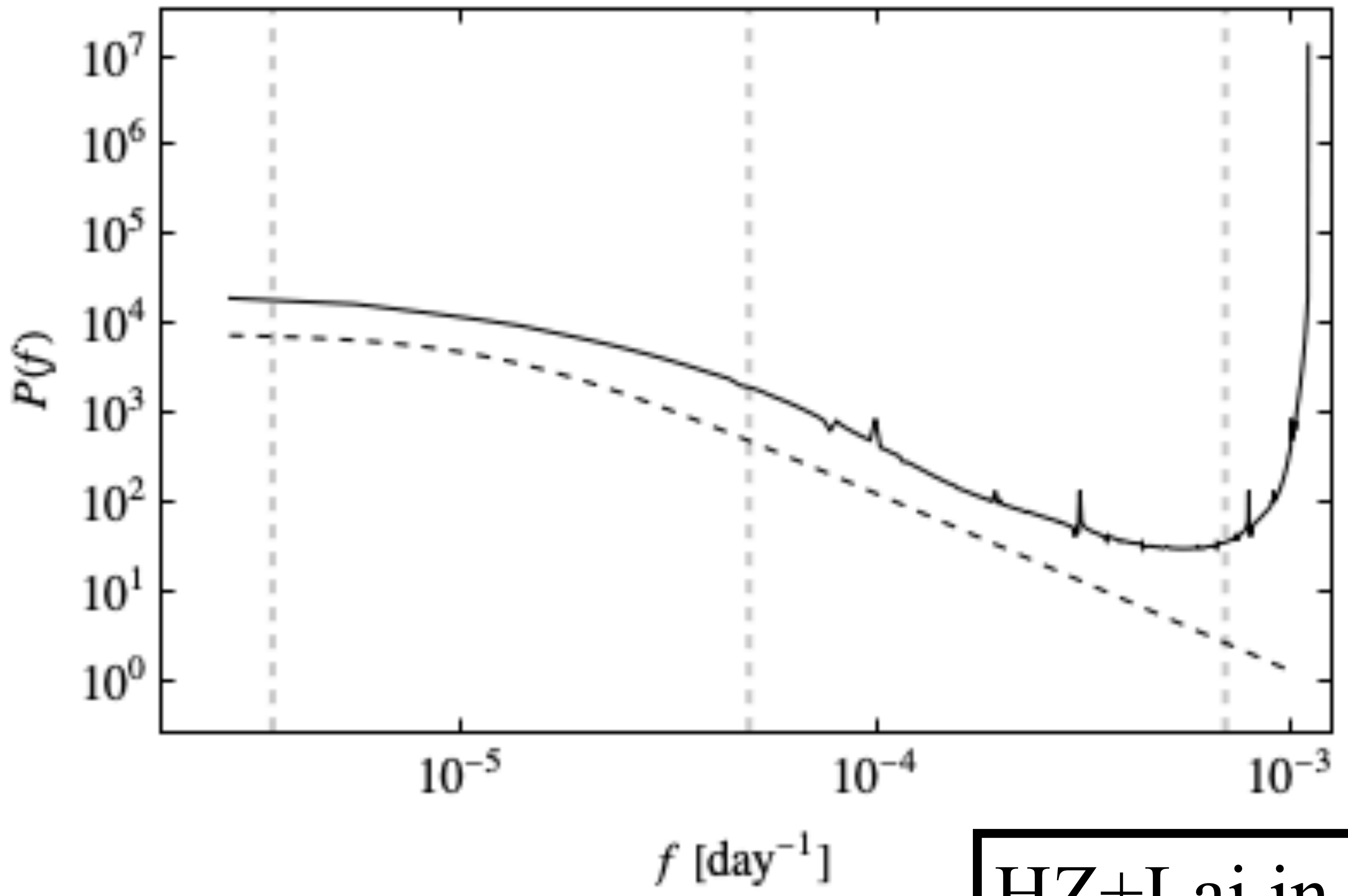
Outflows:

- Alternating polarity → reconnection near the BH and flares
- Insufficient net poloidal flux → weak and/or episodic jet
- Changing of dynamo mechanism near the BH: truncated disk / gravitomagnetic dynamo

AGN variability:

- Varying B → MRI strength → turbulent viscosity → local mass accretion rate and emission
- Preliminary: can lead to DRW spectrum but too long cut-off time scale





HZ+Lai in prep.

Take-home messages

- With the help of **subgrid dynamo models**, low-resolution GRMHD simulations can self-consistently amplify large-scale B field.

- Helical and nonhelical dynamo terms in a thin disk are constructed, by applying lessons learned in local calculations/simulations:

  Helical models: Include (i) MRI-specific α profile, (ii) dynamical quenching, and (iii) helicity fluxes. Resulting field: dipole, $P_{cyl} \simeq 50T_{kep}$, $L \simeq 30h$

  Nonhelical models (incoherent α effect and the shear-current effect): Newly applied to disks. Inconsistent with direct numerical simulations and might dominant in thick disks.

- Although dynamo-amplified fields are periodic, the induced luminosity variations exhibits more complicated fluctuations — red noise with $P(f) \sim 1/f^2$