MRI in Rotating Flows: Implications for the Solar Tachocline and Dynamo Processes

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Matter - Dynamics, Mechanisms and Control

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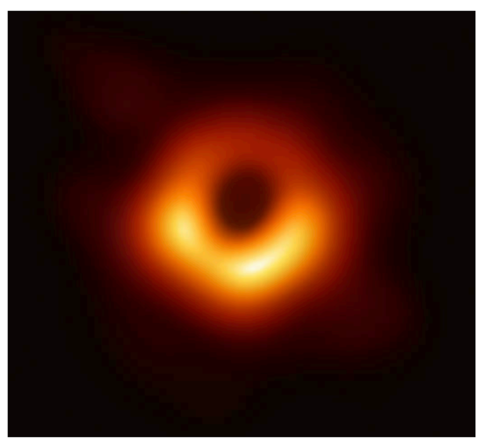
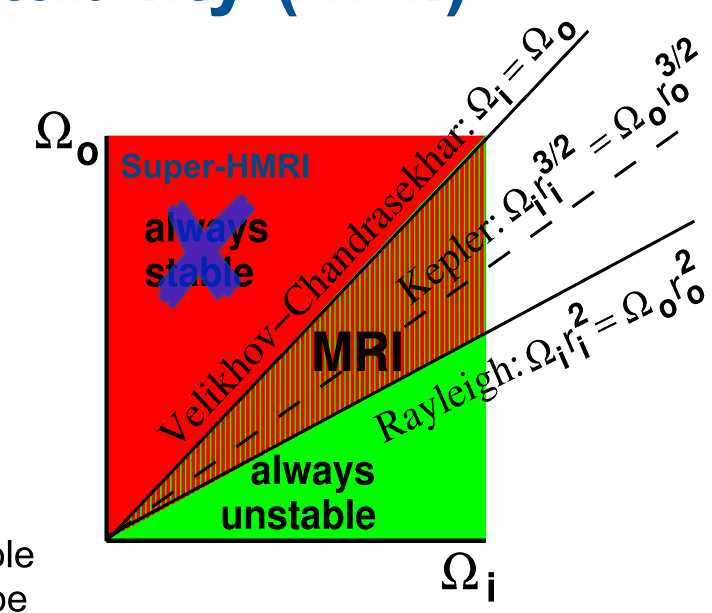
Magnetorotational instability (MRI)

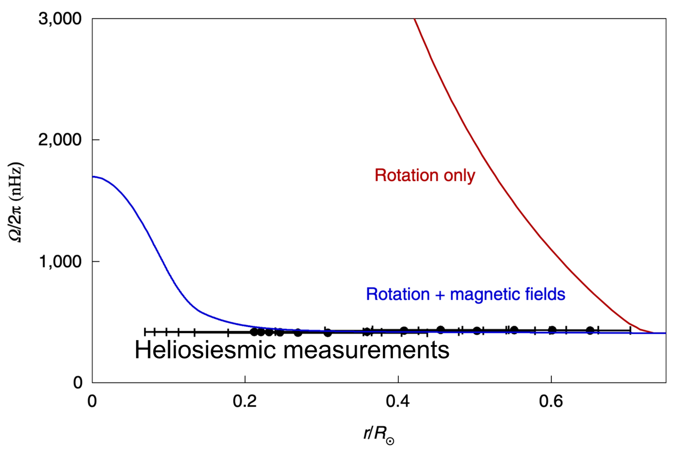
Accretion disks around black hole (NASA)



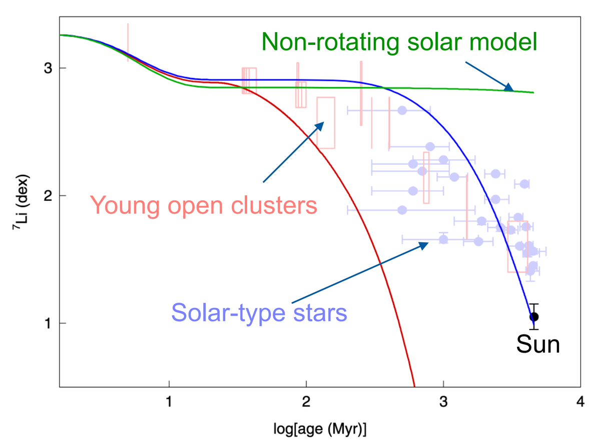
Observation of M87 black hole from Event Horizon Telescope



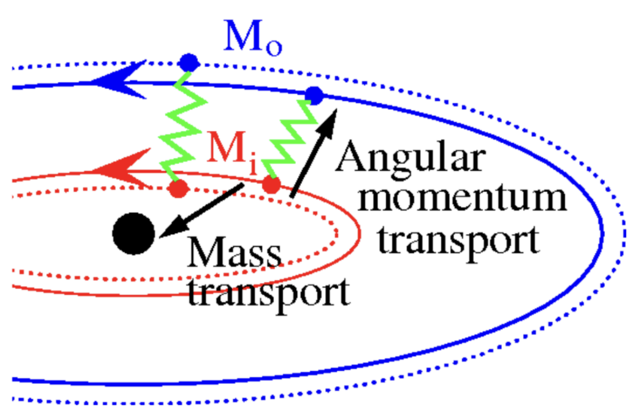
- Magnetorotational instability (MRI) is a powerful dynamical instability in rotational flows arising as a result of the combined action of differential rotation (shear) of the flow and an anchored magnetic field.
- MRI is amongst the most important instabilities in astrophysics, driving angular momentum and mass transport in various cosmic objects and can drive dynamo action.
- **Relevance to the Sun**: MRI may also explain ^{7}Li mixing and angular momentum transport in the solar tachocline. Meduri et al., A&A.683, A12 (2024)



Rotation profiles in the solar radiative interior



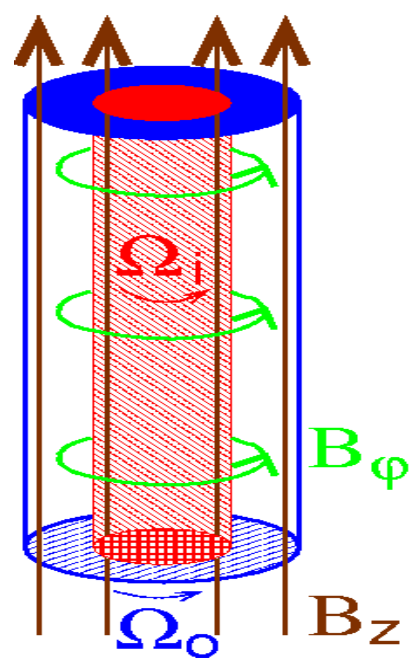
Lithium surface abundance as a function of age for different solar models. Eggenberger et al., Nature Astron. 6, 788 (2022)

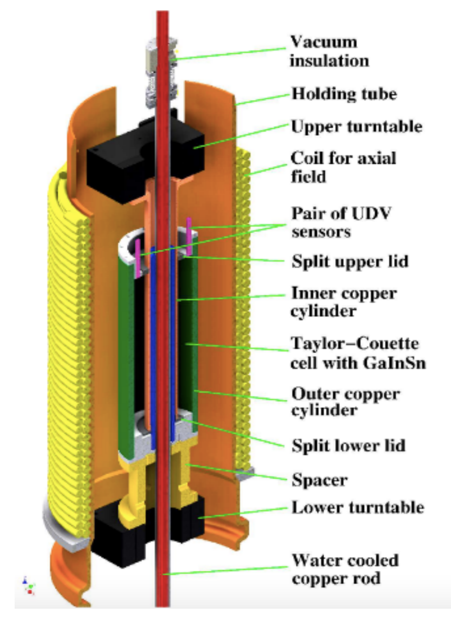


Spring-Mass analogy of MRI

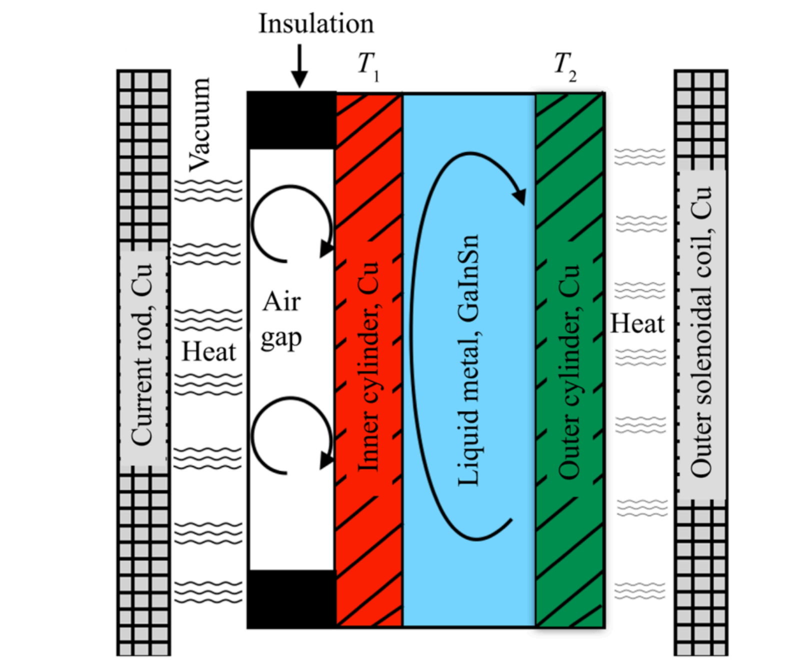
MRI in the lab — PROMISE experiment

Taylor-Couette (TC) flow of a liquid metal between two coaxial rotating cylinders subject to external azimuthal B_ϕ and axial B_z magnetic fields is, due to its analogy with accretion disks, a basic experimental setup to detect and study MRI in the lab.

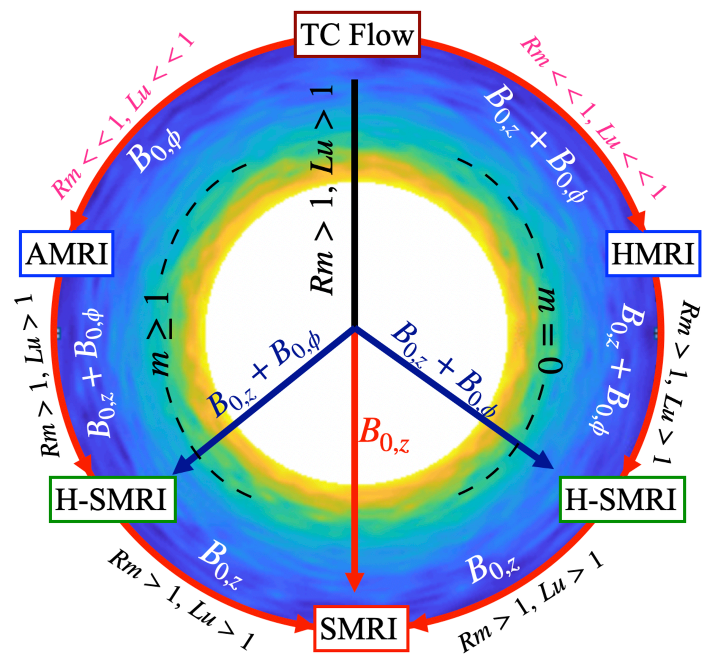




PROMISE (Potsdam ROssendorf Magnetic InStability Experiment) facility at HZDR consisting of a TC device filled with galinstan (GaInSn).



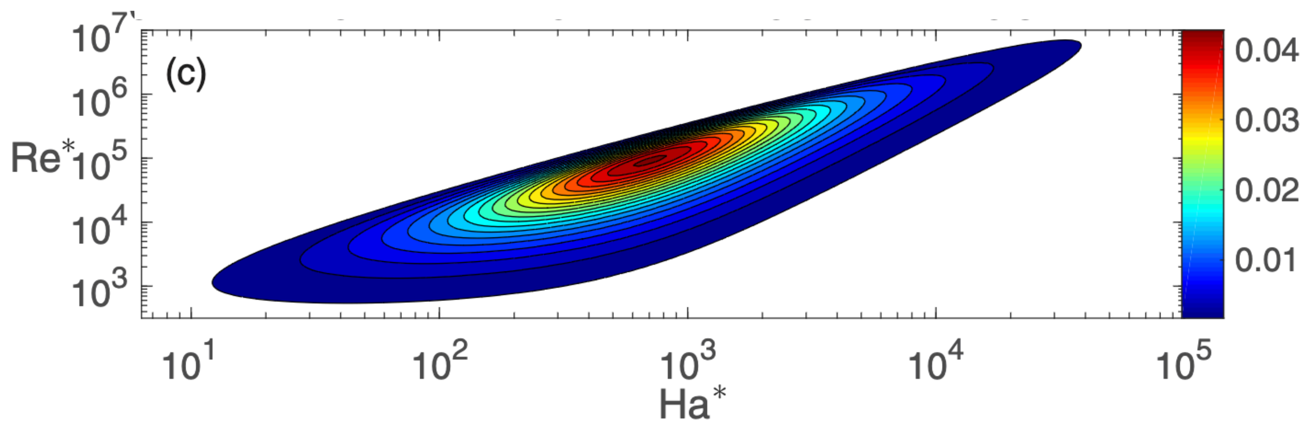
First experiment to incorporate magnetic field, rotation and thermal convection.



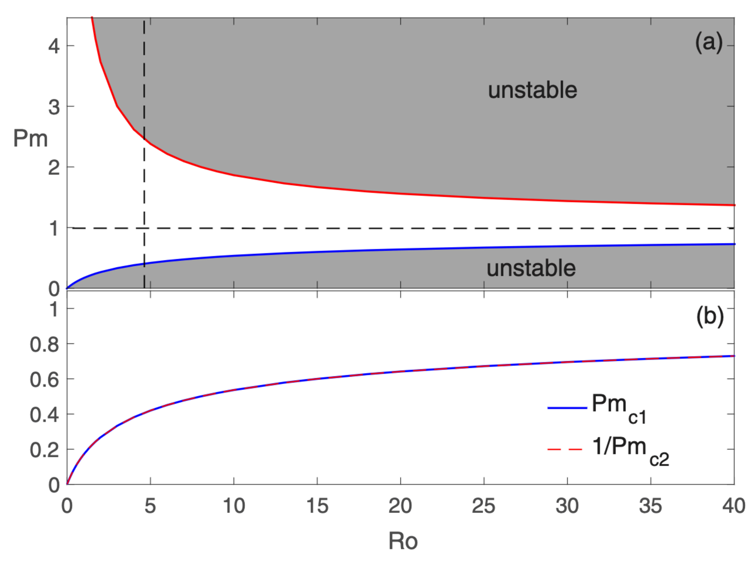
MRI and its variants in TC device

MRI Variants and Angular Momentum Transport in the Solar Interior

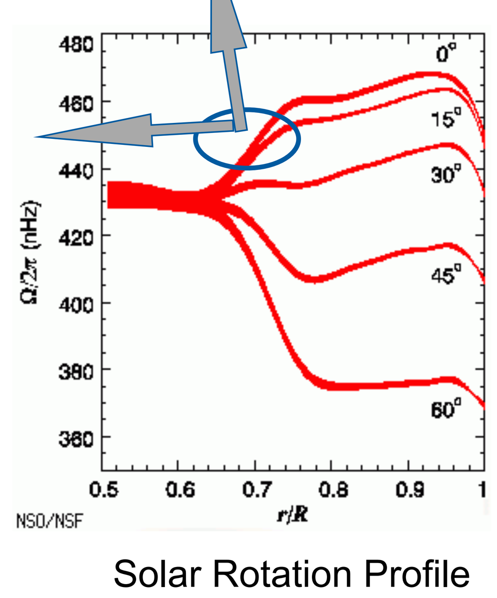
Super-Helical MRI



Instability growth rate as a function of Ha* and Re* at Ro = 1.5 and Pm=10^{-6}.



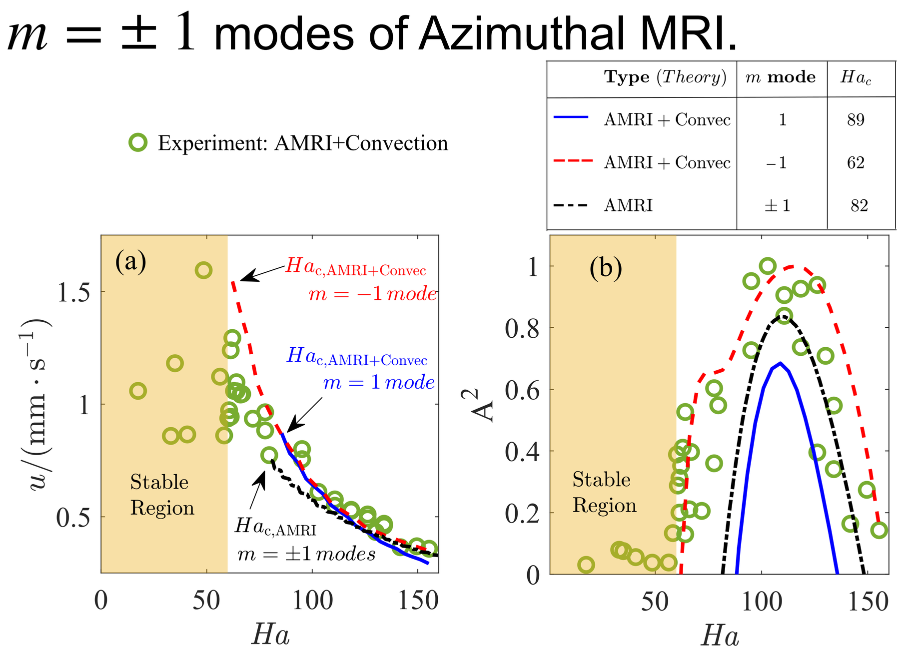
Super-HMRI (grey) at radially increasing angular velocity, or positive shear. Mamatsashvili et al., PRF. 4, 103905 (2019)



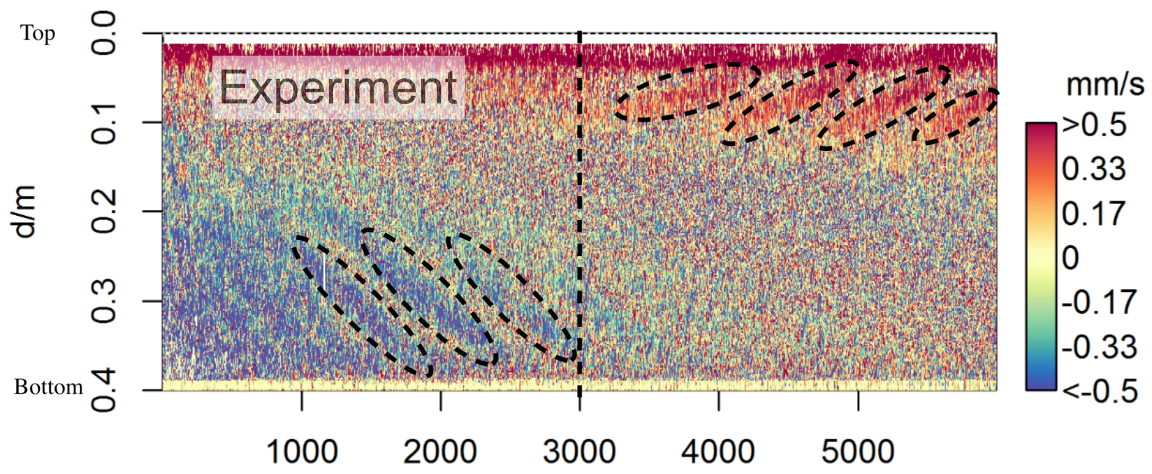
Solar Rotation Profile

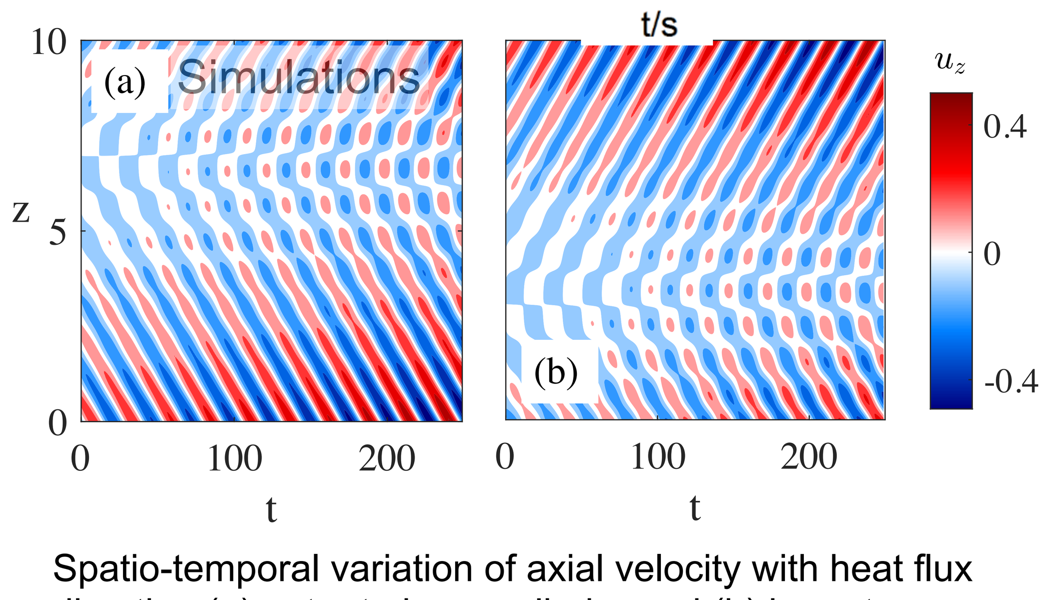
Azimuthal MRI in the presence of thermal convection

- MRI in the presence of thermal convection is experimentally explored for the first time.
- We show that the critical Hartmann number (Ha) for the onset of AMRI is reduced by convection.
- Convection breaks symmetry between $m=\pm 1$ modes of Azimuthal MRI.



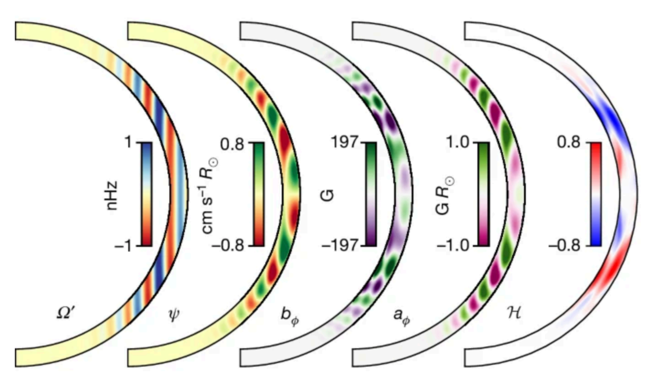
(a) Phase velocities and (b) normalized energy content A^2 of the absolute AMRI in the presence of convection at Re=1480.





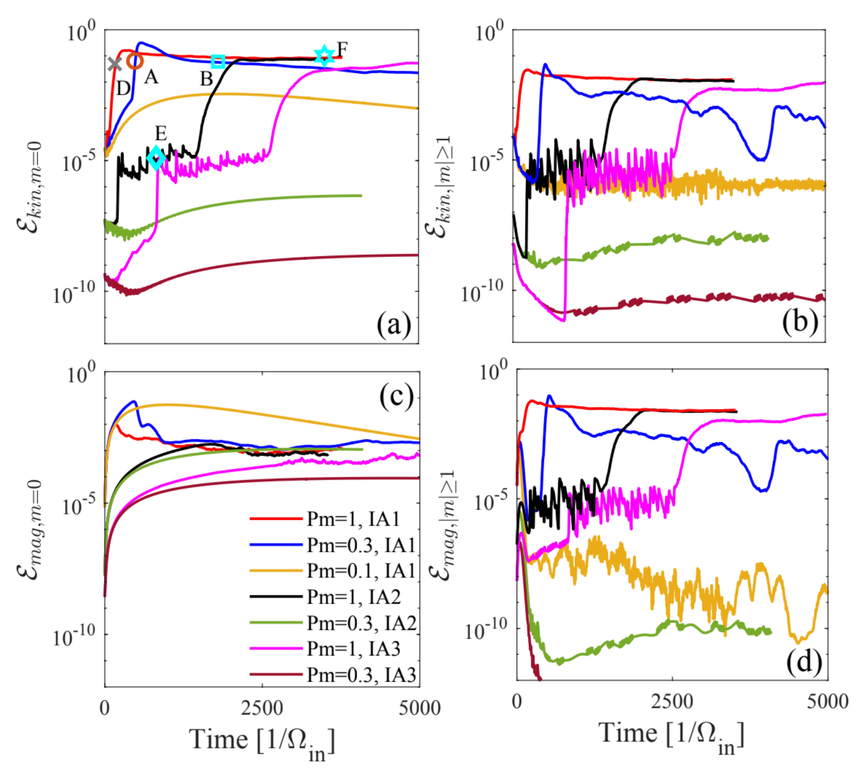
Spatio-temporal variation of axial velocity with heat flux direction (a) outer to inner cylinder and (b) inner to outer cylinder. Mishra et al., JFM, 992:R1, (2024)

MRI-driven magnetic dynamo at small magnetic Prandtl number (Pm ≤ 1)

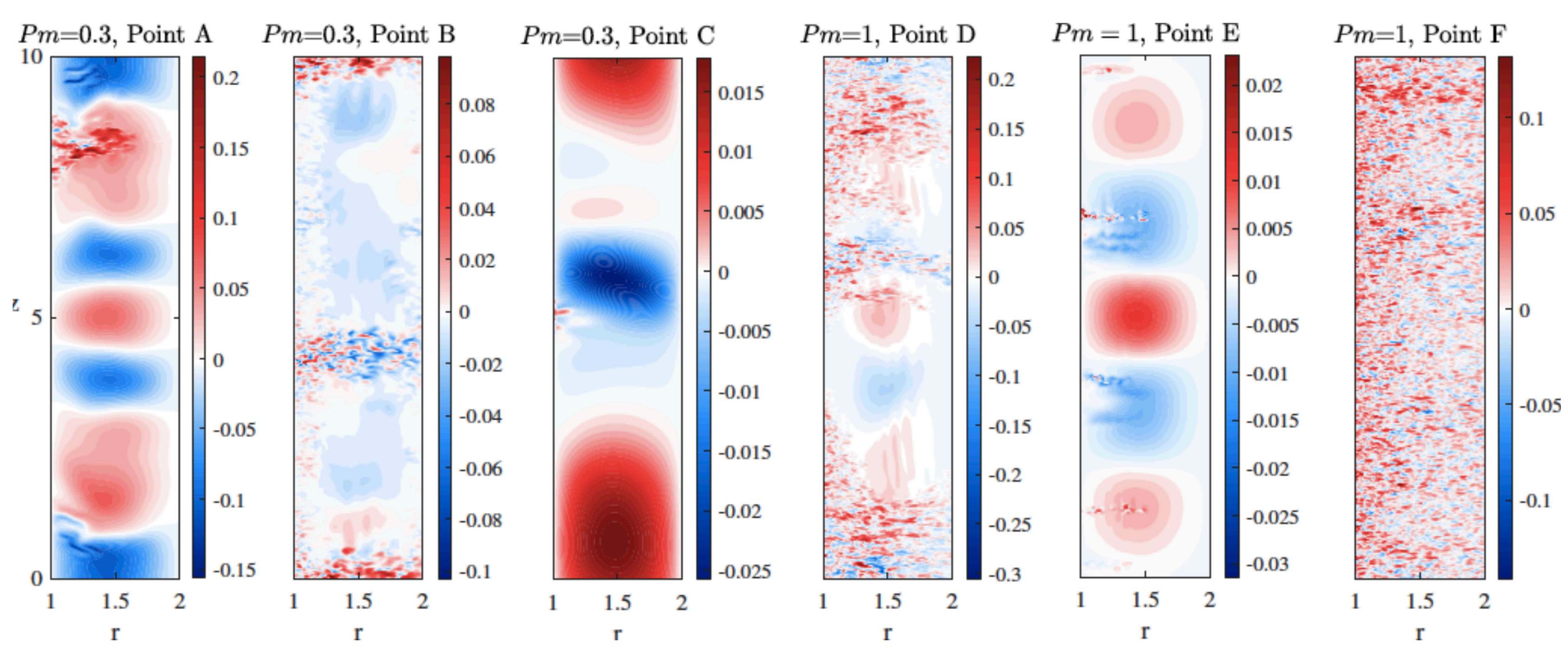


Solar dynamo driven by MRI starts near the surface. Vasil et. al., Nature, (2024)

- MRI driven dynamo amplifies and sustains large-scale magnetic fields.
- We demonstrate the existence of a nonlinear MRI-driven dynamo in a TC flow at low magnetic Prandtl numbers (Pm ≤ 1), relevant to solar conditions where Pm is typically very small.



Evolution of kinetic and magnetic energy at different initial amplitude and Pm.



Structure of the azimuthal field Bφ in the (r, z)-plane at a given azimuthal angle φ and the characteristic time moments A, B, C for Pm = 0.3 and D, E, F for Pm = 1. Namely, the moments A and D correspond to the growth stages, while the moments B and F to the strong and the moments C and E to the weak dynamo states. Mishra et al., PRL, *under revision* (2025)