Planet–disk interaction in VSI-active disks

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Motivation: accretion via hydrodynamic turbulence

The vertical shear instability (VSI) is a mechanism capable of generating hydrodynamic turbulence in protoplanetary disks [1], and has risen in popularity for its potential to drive accretion in the optically thin, rapidly-cooling outer regions of disks [2]. Furthermore, models of synthetic observations suggest that the kinematic signature of the VSI could be observable in the near future. [3]

Methods: numerical simulations

We perform global, high-resolution, 3D numerical simulations of VSI-active protoplanetary disks with embedded planets in a spherical geometry. We focus on models with simple, parametrized cooling.

The VSI: the mechanism and an example

The vertical shear in protoplanetary disks can drive turbulent motion by allowing gas to accelerate along lines of constant angular momentum.
If the gas can cool sufficiently fast to ignore the stabilizing effects of buoyancy, the result is the growth of corrugation modes that span the full vertical extent of the disk.
The turbulent stress generated by this motion results in an accretion channel about the midplane, and has a characteristic signature of vertically elongated eddies of gas.

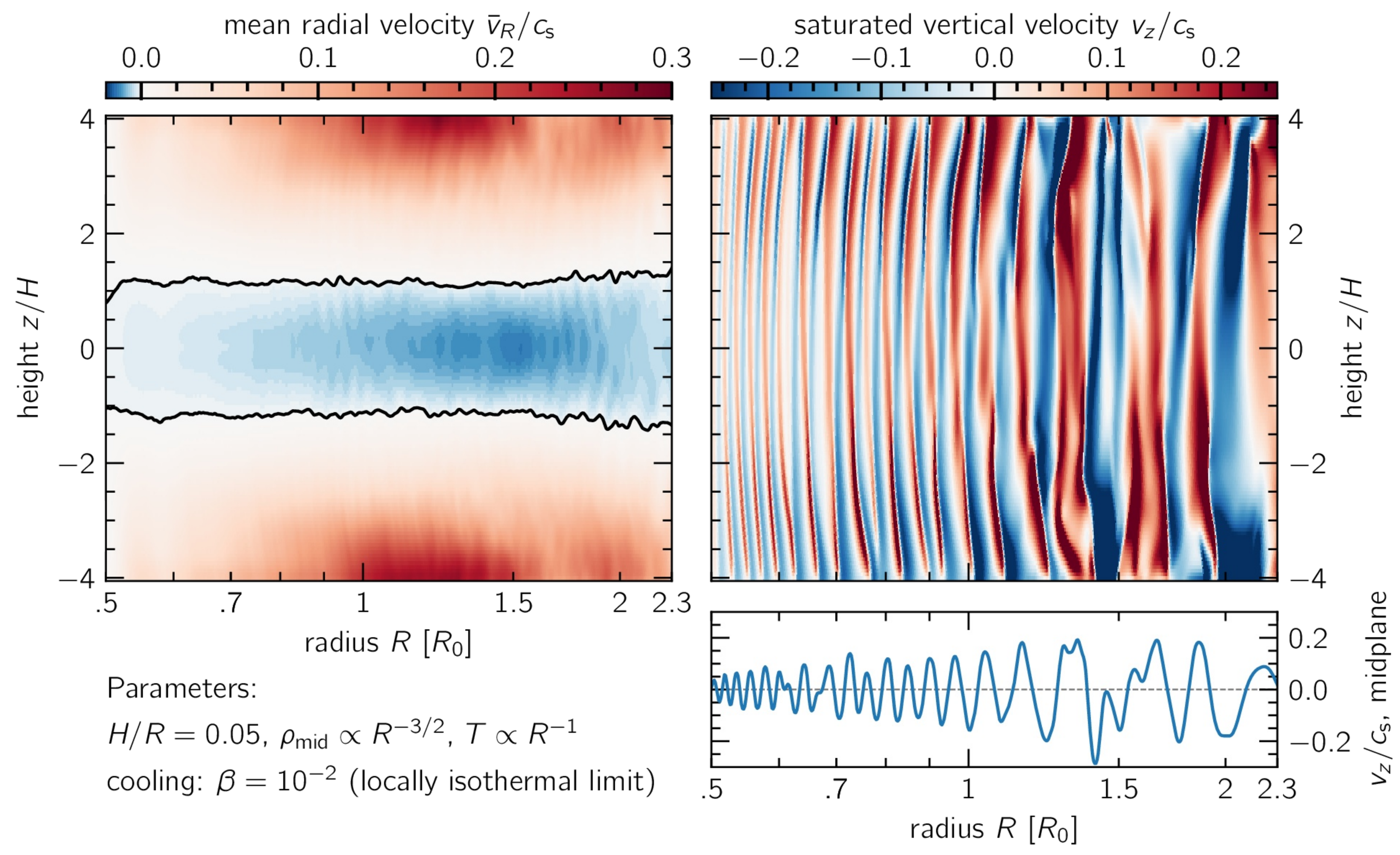

Figure 1: The accretion channel in a VSI-active disk (left) and its kinematic signature (right).

VSI stress: turbulent accretion and mixing

We compute the VSI-generated α by comparing the time- and space-averaged Reynolds stress to classical viscous theory. [4]

$$\nu = \alpha c_s H \approx \frac{W_{R\phi}}{R\,d\Omega/dR}, \quad W_{x\phi} = \langle \delta v_x \delta v_\phi \rangle_{R,\phi,t}$$

$$\text{then:} \quad \alpha_{acc} \approx \frac{2}{3}\frac{W_{R\phi}}{c_s^2}, \quad \alpha_{mix} \approx \frac{W_{z\phi}}{c_s^2}$$

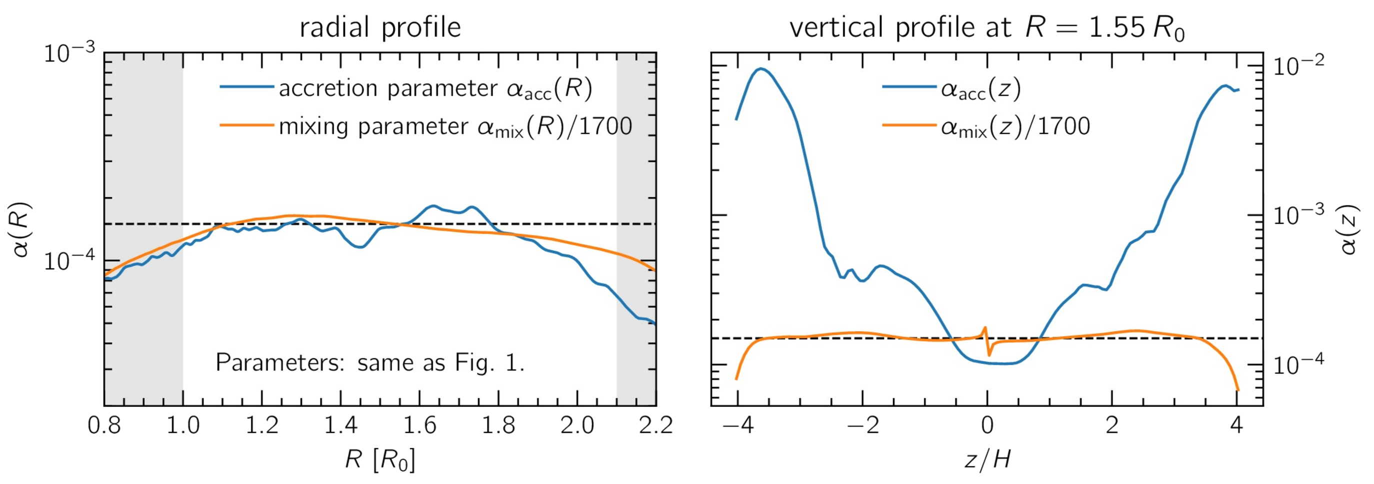

Figure 2: Turbulent stress driven by the VSI. Vertical mixing is 1700x stronger than radial accretion.

Planet-generated features: spirals, gaps, vortices

Planets generate spiral arms. Massive planets can also carve one or more gaps in the gas, driving vortex formation.
In this high-mass regime, the planet impacts a wide region of the disk through multiple planet- and vortex-launched spirals.
These azimuthal features could affect VSI activity.

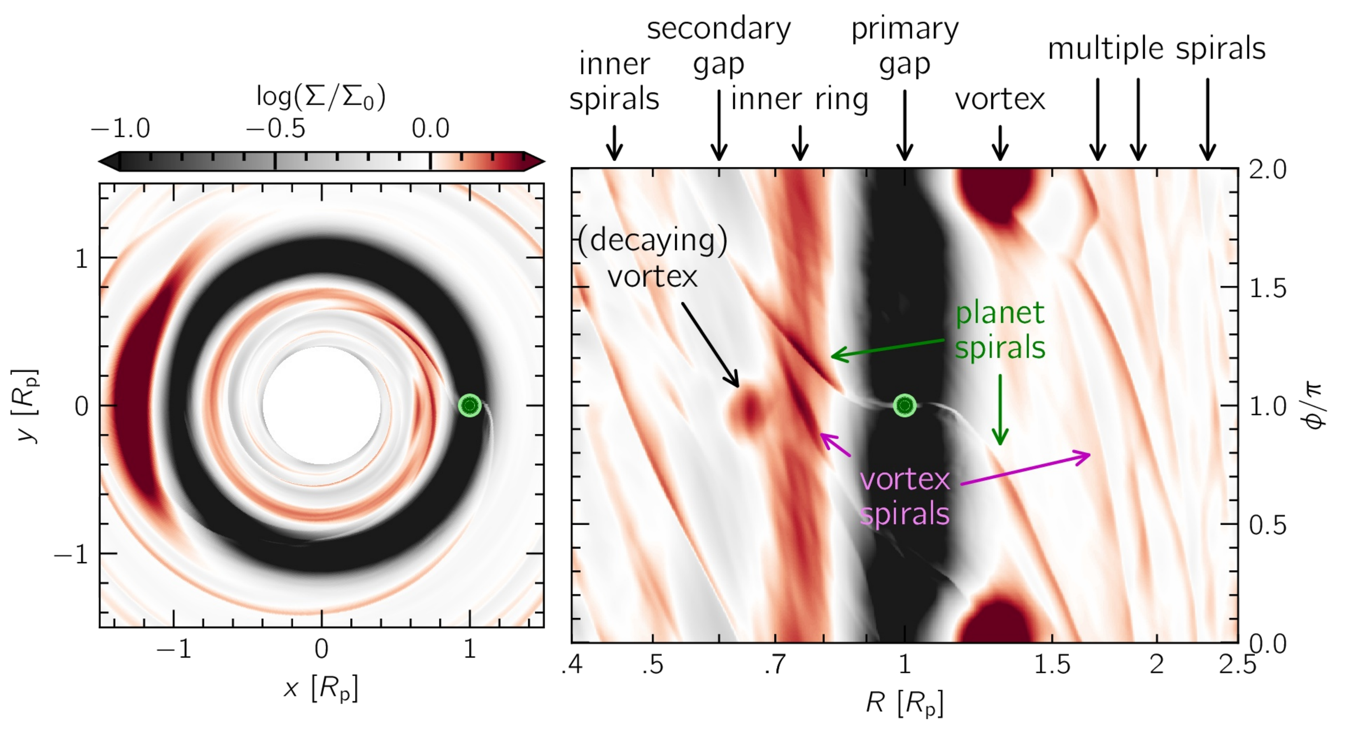

Figure 3: Planet-generated features in the high-mass regime. A low-mass planet only launches weak spirals.

Planet–VSI interaction: azimuthal features weaken VSI activity

In the low-mass regime a planet's spiral arms can interfere with VSI stress, weakening it slightly. In the high-mass case, the presence of more prominent non-axisymmetric features (vortices, stronger spirals) damps VSI activity dramatically.

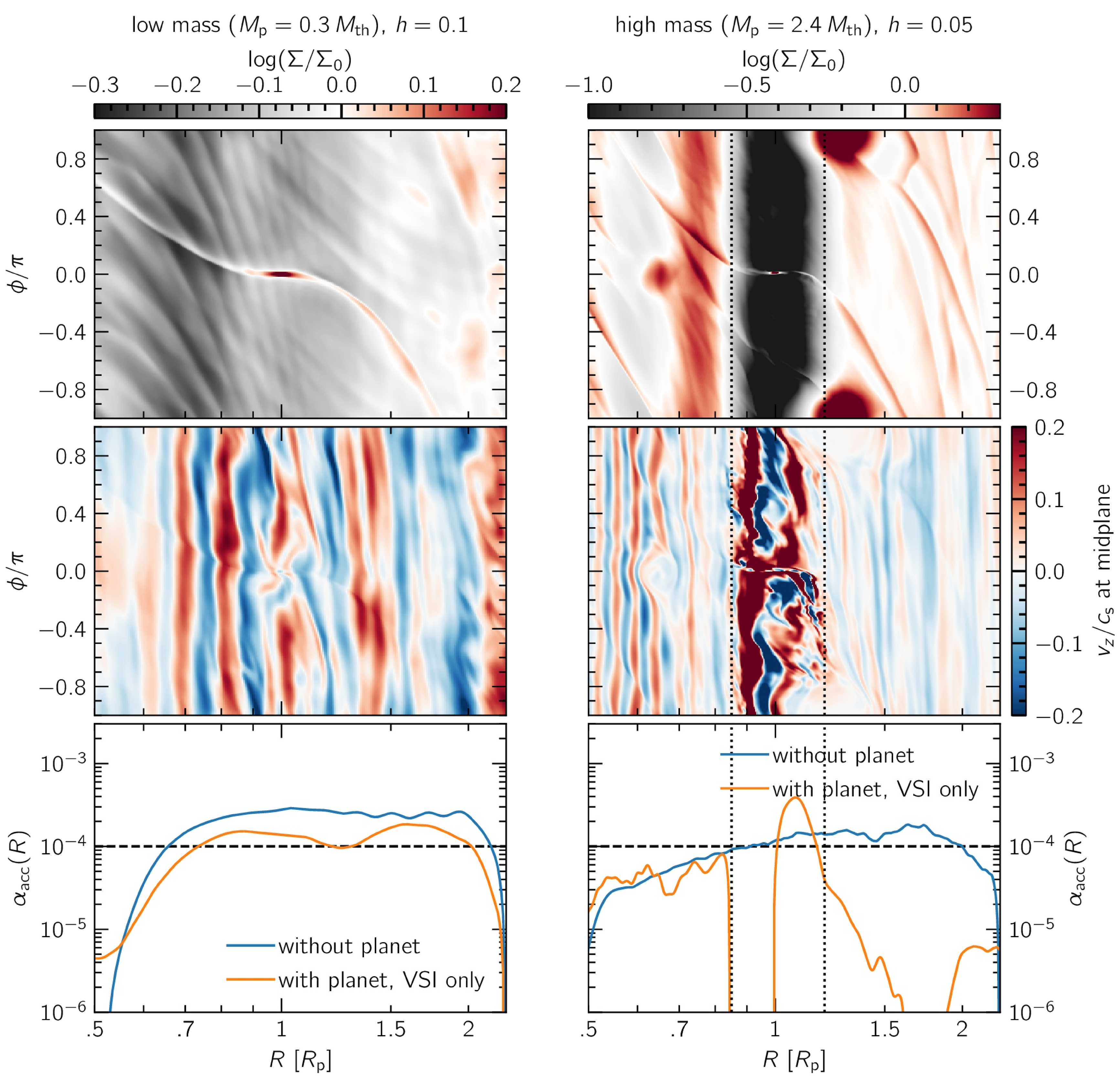

Figure 4: Planets in VSI-active disks. Left: spirals by a low-mass planet slightly diminish VSI stress. Right: the massive planet completely dominates the disk through the presence of gaps, spirals and vortices, eliminating the VSI in the outer disk. The VSI still operates in the relatively more quiet inner disk. Snapshots are taken after 500 planetary orbits.

Weakened VSI activity strongly impacts its mixing capability

While the planet's spirals contribute slightly to the total vertical motion of the disk, the VSI is the dominant mixing mechanism. As a result, disrupting the VSI reduces vertical mixing substantially even though the planet's spirals can continue driving a Reynolds stress radially.

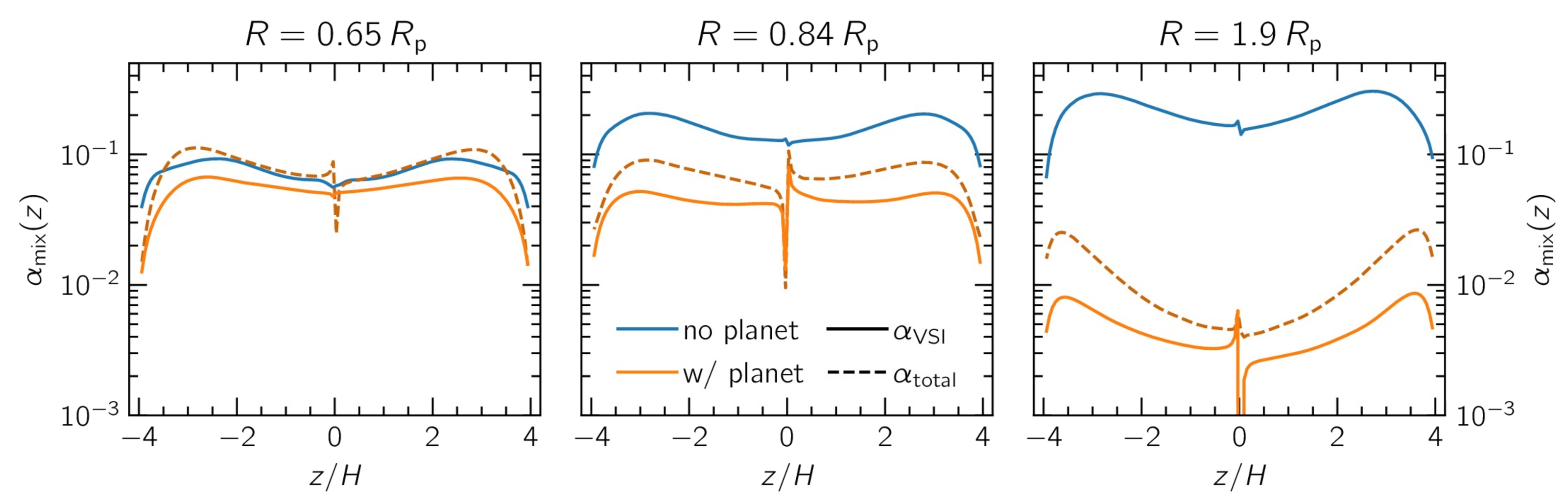

Figure 5: Turbulent mixing stress in a disk with a massive planet (right column of Fig. 4). Left: in the inner disk far from the planet, the VSI is mostly unaffected. Middle: near the planet, VSI activity is maintained albeit slightly reduced. Right: in the outer disk, the combination of planet- and vortex-driven spirals weakens VSI turbulence significantly.

Conclusions

- Unperturbed, the VSI can drive accretion with $\alpha \sim 10^{-4}$ for realistic disk parameters, thus accounting for part of the total observed accretion rates.
- The VSI can coexist with low-mass, non-gap-opening planets, albeit in a slightly weaker state (factor of ~2) due to the planet's spiral arms.
- Massive planets dominate the disk with non-axisymmetric features, significantly weakening VSI accretion and mixing by a factor of 10–100.

Our results suggest that observing VSI signatures with ALMA is extremely unlikely in the presence of massive planets.

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References

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