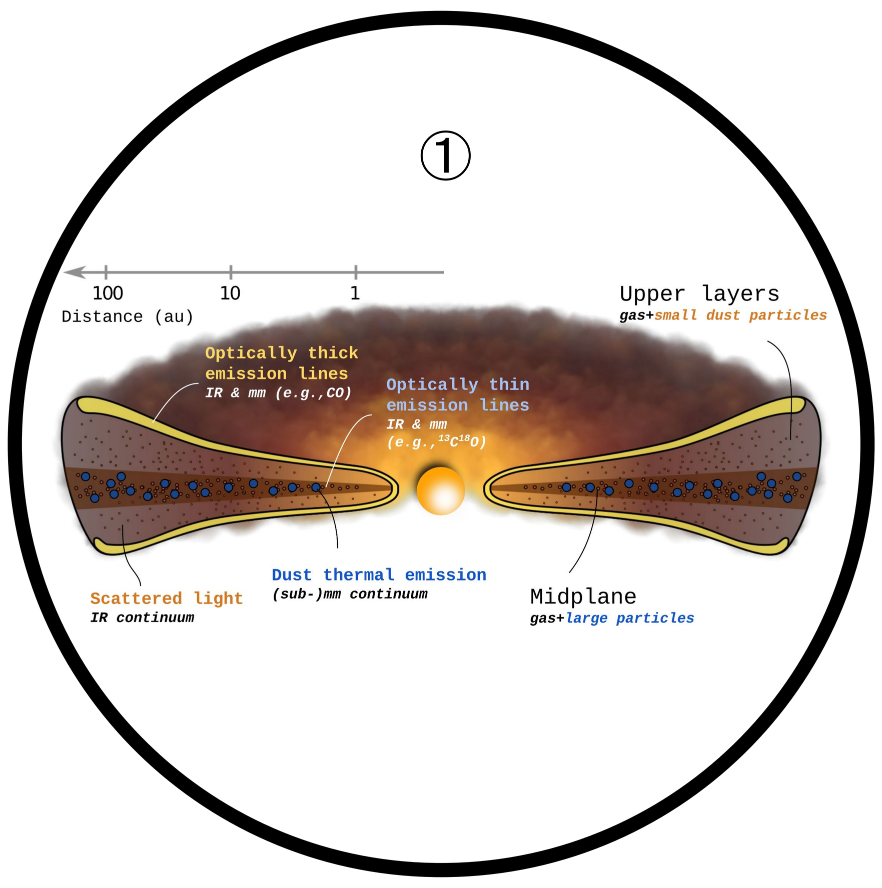
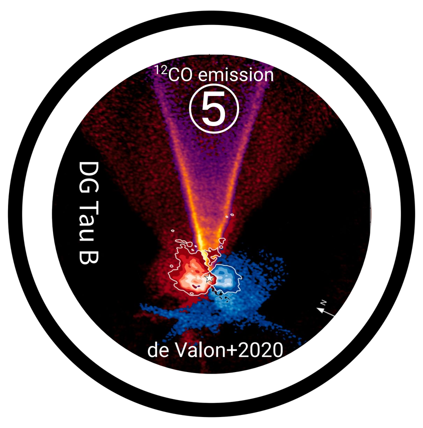
The magnetized fate of massive protoplanets: **PLANET-DISK-WIND** interaction





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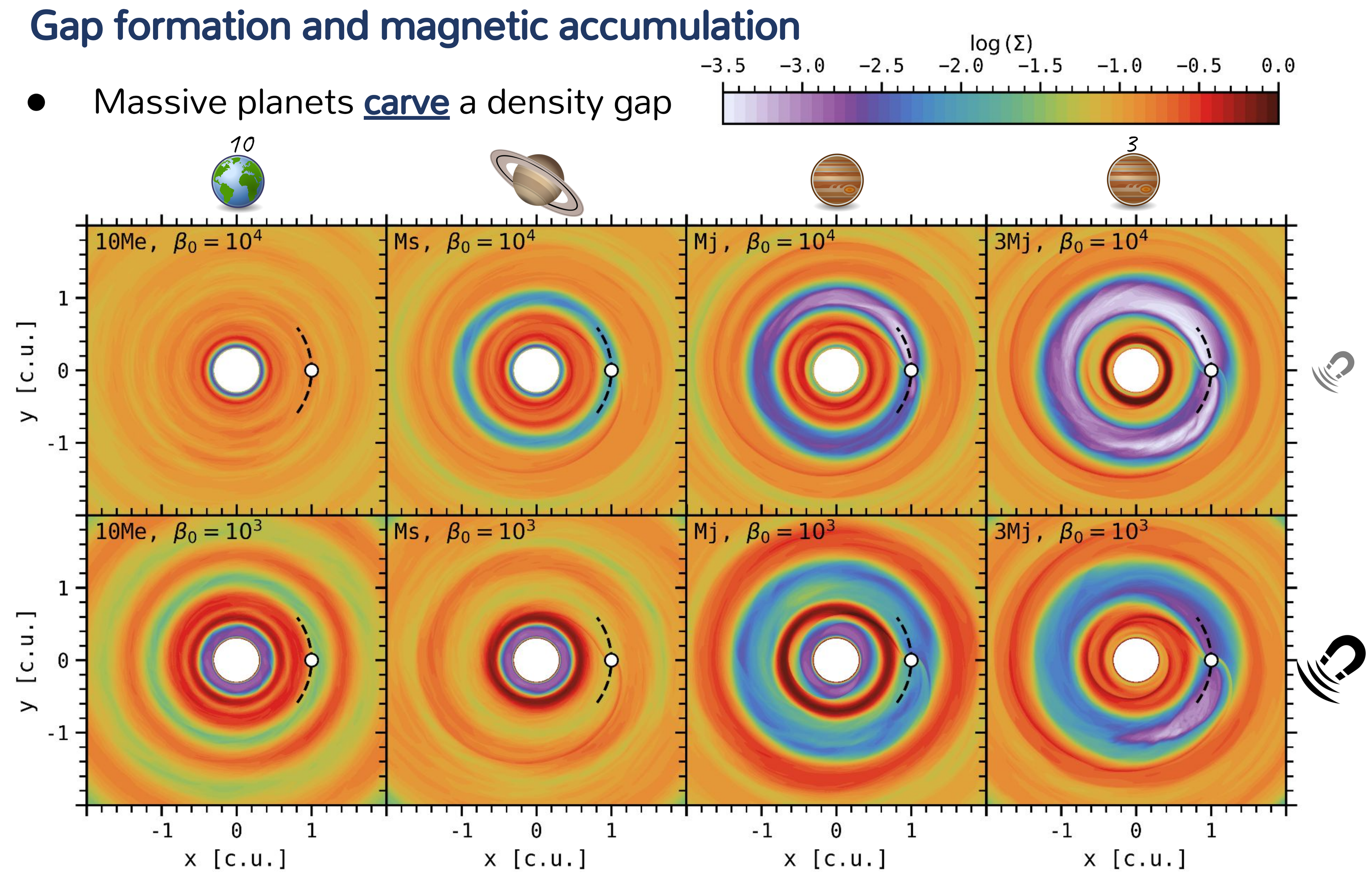
Context and numerical methods

- Protoplanetary disks① are composed of gas and dust, and encompass the primitive phase of planetary systems. Substructures are commonly detected in different observational tracers, via the dust thermal emission in radio②, molecular gas emission lines and scattered light in IR③: spirals, bright and dark rings, cavities, crescents, ...
- Various models are proposed to account for this diversity, with e.g. the presence of planet(s)④ disturbing the disk. In general, planet/disk interaction models rely on an α prescription of gas accretion in 2D/3D hydrodynamic simulations, with a turbulence resulting from the non-linear saturation of the magneto-rotational instability. This scenario of turbulent radial transport of mass is now challenged by non-ideal MHD simulations, but also by the detection of winds⑤ in the disks' emission. Accretion would then be partly due to a vertical extraction of angular momentum (**AM**) by MHD winds leading to a laminar radial transport of mass.
- To study planet/disk interactions in such an environment, we performed 8 non-ideal MHD simulations (with ambipolar diffusion), in cylindrical geometry, at high resolution (640 x 2048 x 384, i.e. 16 pts per scale height at the planet position), with a large-scale vertical magnetic field. 4 planet masses Mp in fixed circular orbit are chosen (10 Me, 1 Ms, 1 Mj, 3Mj) and 2 initial disk magnetizations ($\beta_0 = 10^4, 10^3$ for the initial plasma parameter, defined as the ratio of the thermal pressure over the magnetic pressure).

We use the GPU-accelerated code IDEFIX⑥ (https://github.com/idefix-code/idefix) to integrate the compressible equations of MHD via a finite volume method with a Godunov scheme. Simulations were carried out in parallel on the GPU architecture of the Jean-Zay machine (IDRIS).

Gap formation and magnetic accumulation

- Massive planets carve a density gap

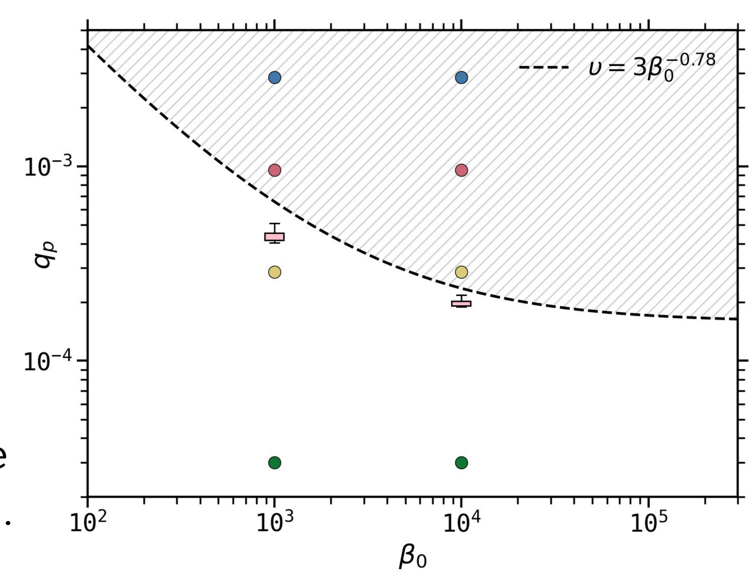


- Gap opening criterion with accretion dominated by MHD winds

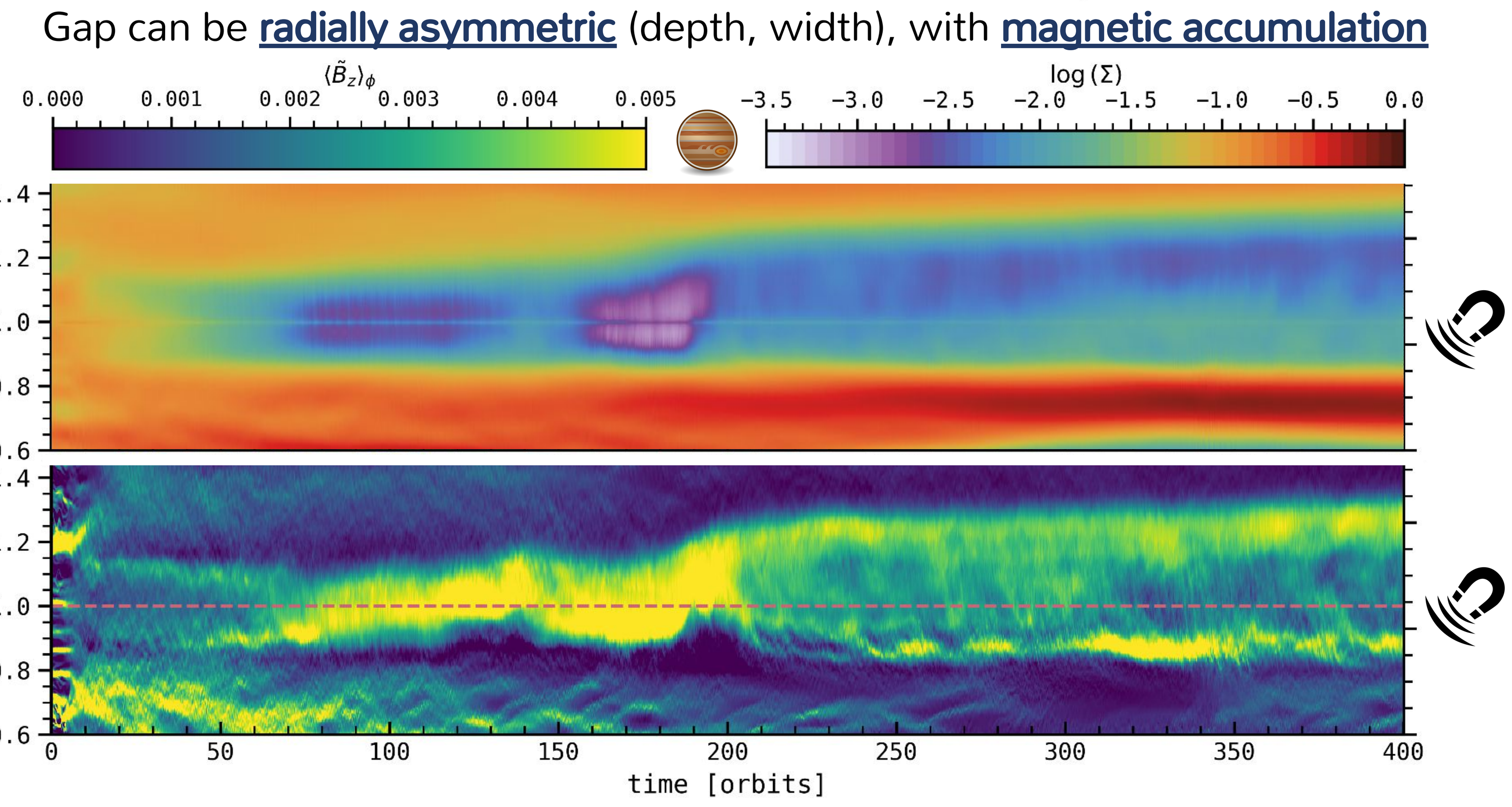
$$\frac{3h}{4(q_p/3)^{1/3}} + \frac{2h\upsilon}{(q_p/3)^{2/3}} < 1$$

υ magnetic wind torque
h aspect ratio
q_p planet-to-primary mass ratio

→ Harder for a given planet to carve a gap at higher initial magnetization.

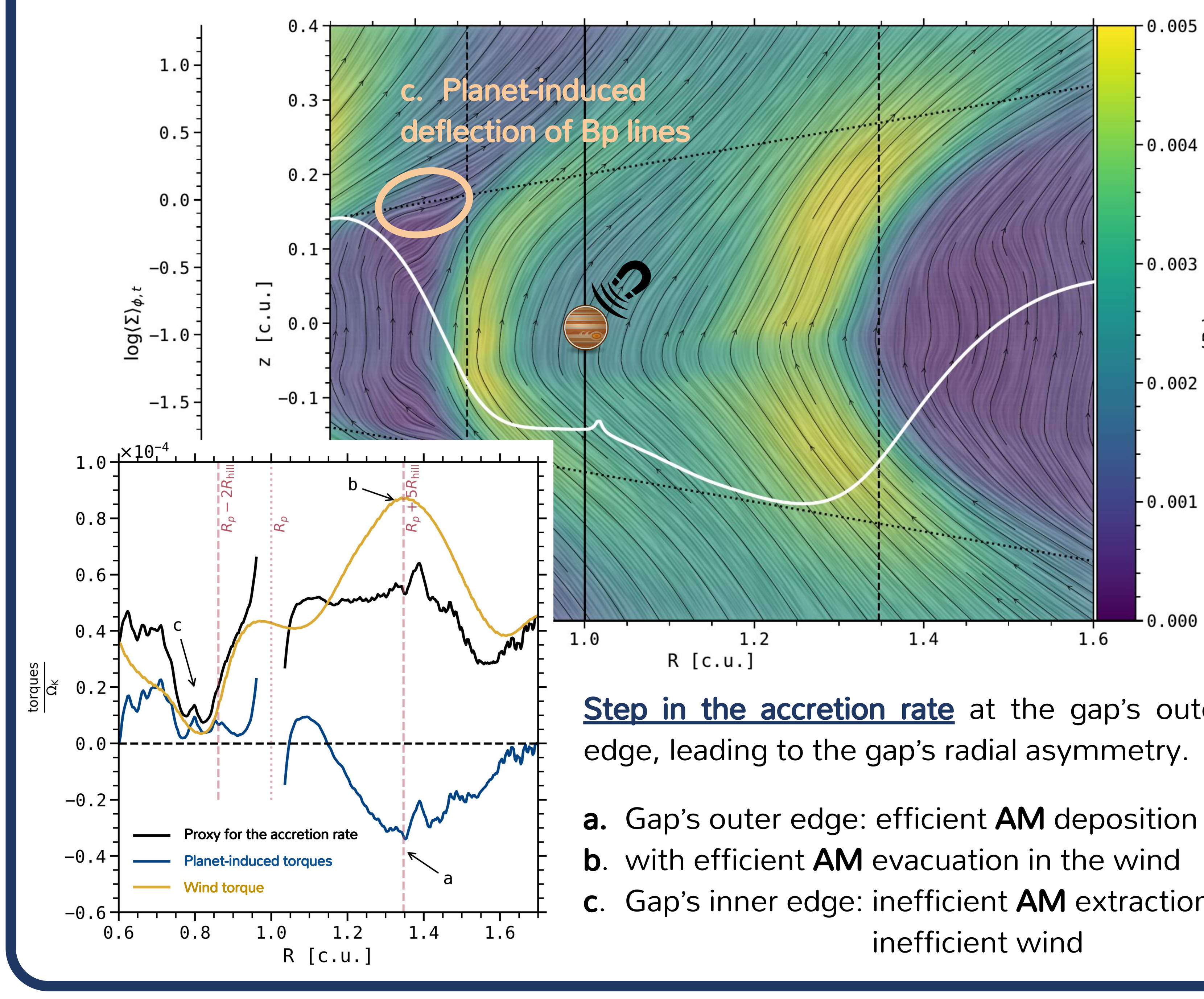


- Gap can be radially asymmetric (depth, width), with magnetic accumulation



Enhanced/Diminished wind torque above the gap's outer/inner edge

Double accumulation of the poloidal magnetic field, but asymmetric wind torque due to the planet-induced deflection of magnetic field lines at the disk surface.

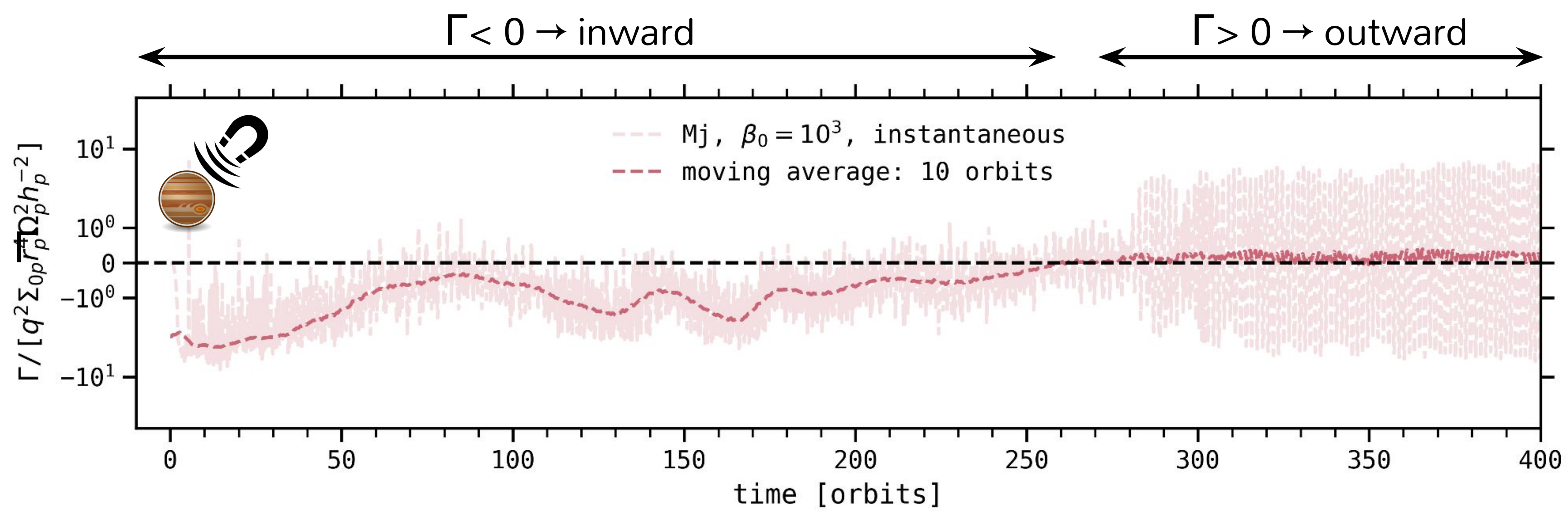


Step in the accretion rate at the gap's outer edge, leading to the gap's radial asymmetry.

a. Gap's outer edge: efficient **AM** deposition
b. with efficient **AM** evacuation in the wind
c. Gap's inner edge: inefficient **AM** extraction inefficient wind

Asymmetric gap and outward migration

Γ gravitational torque by the gas onto the planet → direction+amplitude of migration



Because the gap is asymmetric (the planet is closer to the gap's inner edge), we expect the external (negative) Lindblad torque to weaken, leading to an increasingly slower inward migration, and even a potential reverse migration (after 270 orbits).

Summary and conclusion

- Gaps:
  → deeper when Mp increases and the initial magnetization decreases.
  → for Saturn-mass planets, more massive planets if higher initial magnetization.
  → radially asymmetric (width, depth) as it drifts outward.
  → privileged region for the accumulation of large-scale magnetic field.
- MHD wind torque above the gap:
  → outer edge: enhancement fed by the planet torque.
  → inner edge: decrease due to planet-induced deflection of **B** lines at disk's surface.
- Migration:
  → asymmetric gap reduces the outer Lindblad torque.
  → potentially reversed for Jovian planets in magnetized disks (> a few 100 orbits).
- MHD winds affect planet/disk interaction (flow kinematics, protoplanet migration).
- Planet torque ↔ Wind torque ↔ Magnetic field transport.
- Predictions from "effective" models with parameterized wind torques are not recovered (gap formation criteria, migration direction and speed).

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