Accretion of Gas Giants Constrained by the Tidal Barrier

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Introduction

During their formation, emerging protoplanets tidally interact with their natal disks (Goldreich & Tremaine 1980). Lin & Papaloizou (1986) shows that tidal perturbation of planets with mass ratio exceeding the thermal limit is sufficiently strong to induce the formation of a gap in the disk near the protoplanet's orbit and quench its own growth. If the gas depletion timescale is quite short, the asymptotic mass of gas giants near the ice line in protostellar disks (PSD) similar to the Minimum Mass Solar Nebula (MMSN) are comparable to that of Jupiter (Lin & Papaloizou 1993, Bryden et al. 1999).

On the other hand, many hydrodynamical simulations show that gas continues to flow across the planet's orbit even after the planet reaches the gap-opening mass (e.g. Fung+2014, Durmann & Kley 2015, Szulagyi+ 2014). and prescriptions for the undepleted gap density (Kanagawa+ 2015, Duffell & MacFadyen 2013) have been applied to infer gas giant planets' growth limit in the modified gap-opening paradigm (Tanigawa & Tanaka 2016, Rosenthal+ 2020).

The asymptotic mass (in disks with moderate viscosity) obtained in these studies is typically an order of magnitude higher than the classical scenario, and they predict an excess of 10 M_J planets around solar-type star systems. The prolific production of such high-mass planets is incompatible with the observed ceiling in the mass distribution obtained from radial velocity surveys of long-period planets (Marcy+ 2005, Mayor+ 2011).

In contrast, Dobbs-Dixon+ (2007) has shown that despite the residual flow through the gap, the gas may not be so efficiently accreted onto the protoplanets. In an inviscid or weakly viscous disk, the vortensity and Bernoulli energy are fully or mostly conserved along streamlines. This leads to a vortensity mismatch between the horseshoe streamlines and the outer region of circumplanetary disk (CPD) which prevent horseshoe materials from entering the circumplanetary region in the low-viscosity limit exponentially.

Solid lines in Fig 1 show the predictions for planet accretion rate as a function of planet mass, in a MMSN disk at a_p =5AU, with scale height at planet location, h_p=0.05, viscosity alpha=0.004, from three papers. The symbols are from numerical simulations (blue: D'Angelo + 2003, Red: Bodenheimer+ 2013), where disk eccentricity is *not* excited.

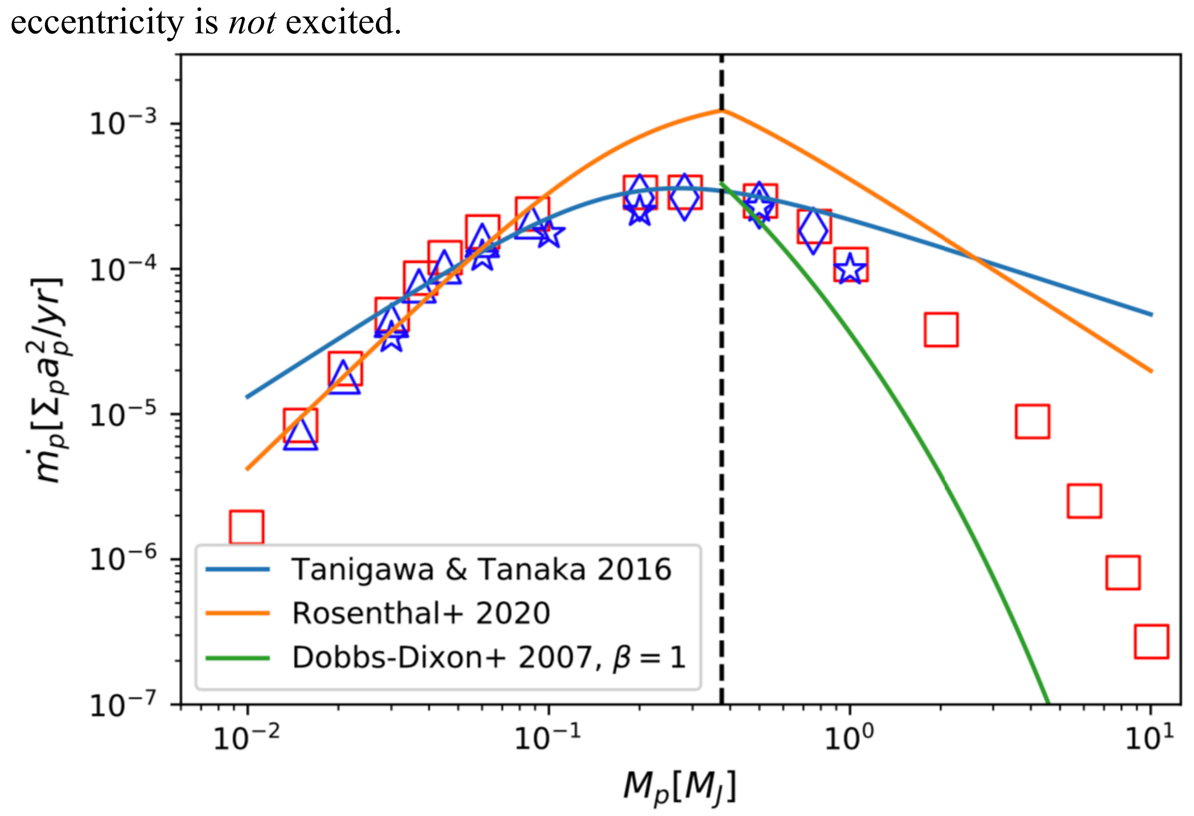

Figure 1

While the fallout of accretion rate from Bodenheimer+ 2013 seem closer to the Dobbs-Dixon prediction, we also note that in realistic scenarios, massive enough planets should be able to excite eccentricity in the disk and give rise to an increased accretion rate (Kley & Dirksen 2005, Teyssandier & Ogilvie 2017). More extensive numerical simulations should be applied to study this further.

Results

We performed high-resolution simulations with LA-COMPASS (Li+ 2005) for a variety of disk (scale height & viscosity) and planet mass parameters. The accretion rate results are presented in Fig 2. In the main runs, we set the fiducial gas surface density to be 0.001 in the default unit system (G=M_*=1), corresponding to a fiducial accretion rate. But the results of accretion rate in surface density units are generic as long as self-gravity is not invoked. We have also identified cases with large long-term fluctuations in the planets' accretion rates, they correspond to excited eccentricity of the disk, and we plot the medium value of accretion rate with solid red points and indicate the upper and lower bound with error-bars.

We use four color bands to show representing the range for planet mass doubling timescale between 1Myr and 3Myrs. The orange color band represents the fiducial gas surface densit. In comparison, the blue band represent the less massive MMSN model. We also use pink, and green color bands to represent PSDs with given disk accretion rates of 1e-8 and 1e-9 M_{sun}/yr.

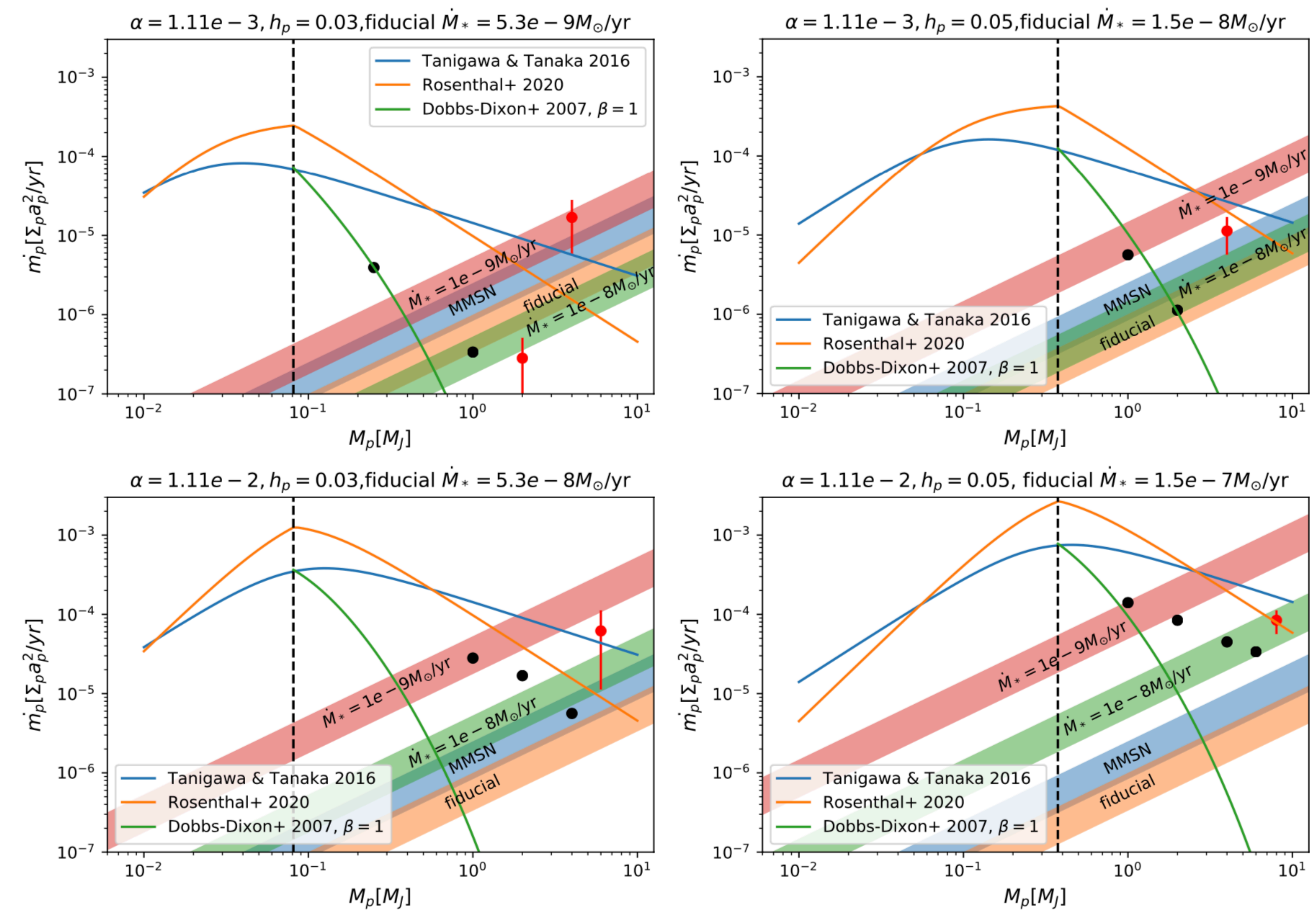

Figure 2

CONCLUSION: In weakly viscous disks, protoplanets' accretion rate steeply decreases with their masses above the thermal limit, constrained by the tidal/vortensity barrier. the relation between stable-eccentricity accretion rate and planet mass conform more with exponential decay, than the linear scalings from previous works. As the planets' growth time scale exceeds the gas depletion time scale, their masses reach asymptotic values comparable to that of Jupiter.

But, in relatively thick and strongly viscous disks, the barrier is overcome by dissipation, the growth rate will first be linear and protoplanets' asymptotic masses can exceed several times that of Jupiter. Such massive protoplanets does NOT continue to accrete steadily, but they strongly excite the eccentricity of nearby streamlines, destabilize orderly flow, substantially enhance the diffusion rate across the tidal barrier, and elevate their growth rate until their natal disk is severely depleted. Based on the upper fall-off in the observe mass distribution of known exoplanets, we suggest their natal disks had relatively low viscosity, modest thickness and limited masses (comparable to MMSN).

Physical Picture

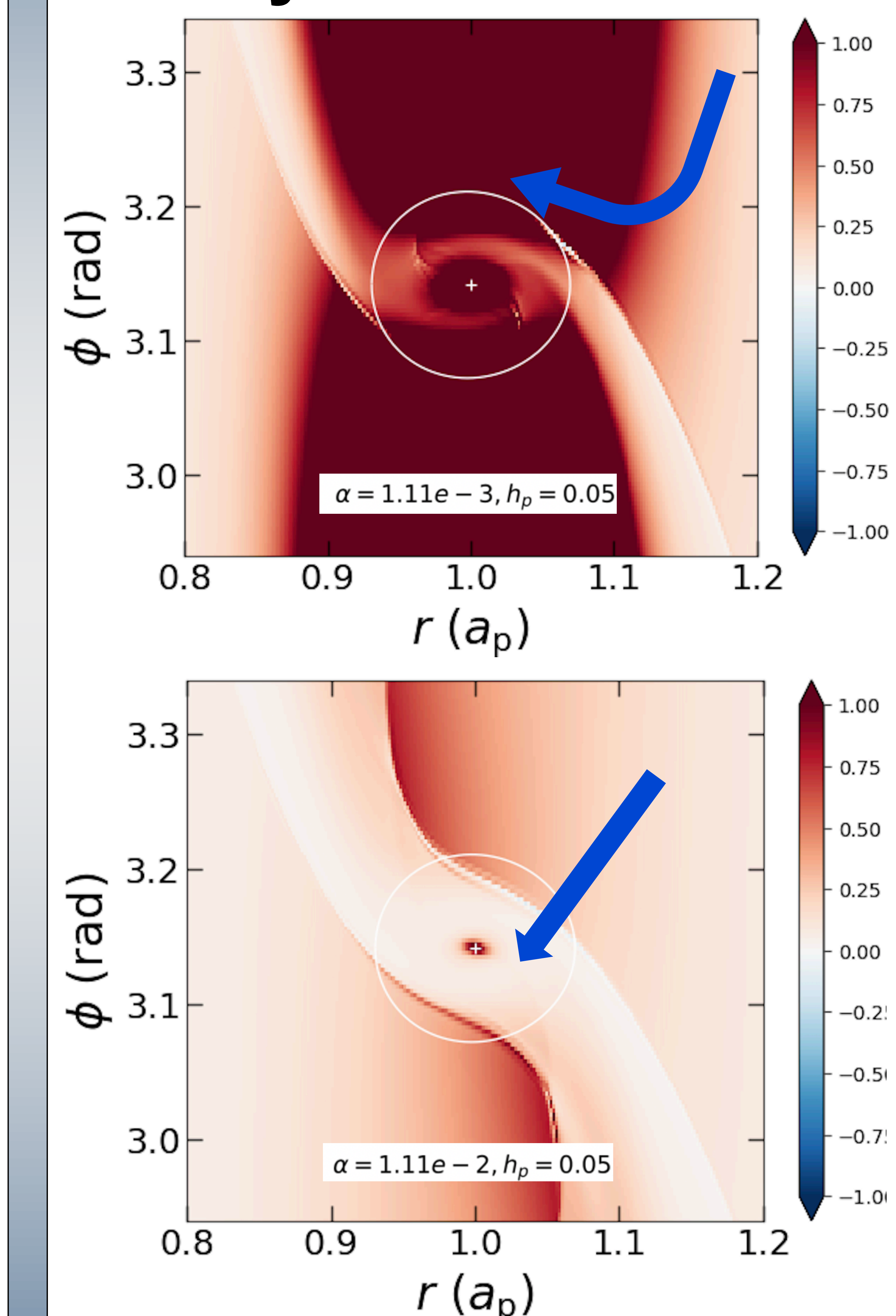

Figure 3

In Fig 3 we demonstrate the effect of tidal barrier by plotting the vortensity distribution around the planet for the high and low viscosity case.

In the low viscosity case (upper), vortensity is not strictly but approximately conserved along streamlines. Sharp transitions in the vortensity distribution across the CPD-horseshoe interface deflect incoming streams (blue arrow). However, for large viscosity (lower) case, viscous transport and energy dissipation smooth the distribution of vortensity across these interfaces and materials are easier to be accreted (blue arrow).