# Research statement

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My primary research interest is astrophysical fluid dynamics with application to accretion disk physics and planet formation theory. I employ a combination of analytical methods and numerical simulations to rigorously establish and understand new results. I summarize previous works in §1, describe recent projects, including future directions in §2, and discuss new research topics in §3.

## 1. Research areas

### 1.1. Signposts of planet formation in protoplanetary disks

It is now possible to directly observe detailed sub-structures in protoplanetary disks (PPDs), such as gaps, rings, or spirals. These may be signatures of planets or the planet-formation process itself (Pohl et al. 2015; Dong et al. 2015a,b). It is essential to explore formation mechanisms for such structures to explain observations and advance planet formation theory.

Many PPDs show lopsided dust distributions (e.g., Casassus et al. 2015; Pinilla et al. 2015; van der Marel et al. 2015, and references therein). The leading explanation is the presence of large-scale vortices, which are associated with pressure maxima and act as dust-traps due to drag forces. Indeed, an analytic description of this process, developed by Lyra & Lin (2013), has been successfully applied to interpret such observations (Pérez et al. 2014; Marino et al. 2015). Dust-traps may also play a prominent role in planetesimal formation (Barge & Sommeria 1995). Vortex dynamics is thus an integral part of modern planet formation theory (Surville & Barge 2015).

Vortices in PPDs may also be indirect evidence of unseen giant planets (van der Marel et al. 2013). I developed a detailed semi-analytic theory to explain how a giant planet can open disk gaps that are in fact hydrodynamically unstable, and used numerical simulations to show the outcome of instability is vortex formation (Lin & Papaloizou 2010), which subsequently collect dust (e.g. Fu et al. 2014; Zhu & Stone 2014). I generalized the theory of gap instabilities to self-gravitating disks (Lin & Papaloizou 2011a,b). I used mathematical analysis and numerical simulations to show that disk self-gravity has *profound* effects on gap stability, even though it is usually neglected in such studies. Vortex formation is discouraged with increasing disk mass, and in very massive disks a new 'gravitational edge instability' instead develops at the gap edge.

Fig. 1 show disk-planet simulations of gap instabilities as a function of disk mass (Lin 2012b). In this study, I extended the above thin-disk calculations to full 3D disk models by adapting the `Zeus-MP` code (Hayes et al. 2006) to compute disk self-gravity in spherical co-ordinates. More recently, I applied the `Pluto`[1] code (Mignone et al. 2007) to show that vortex formation is sensitive to the dependence of the mass accretion rate on the height from the disk midplane (Lin 2014b). This complication is expected in realistic PPD models (e.g., Bai 2015; Simon et al. 2015; Gressel et al. 2015), so the existence of vortices in PPDs indirectly constrain the vertical disk structure.

Observable disk morphologies are thus intimately linked to the underlying disk and planet properties. For example, dependence on self-gravity means that the observation of a single large-scale vortex implies the disk mass must be low — a property that is difficult to directly infer, but crucial to planet formation. Thus developing realistic models to explain PPD sub-structures are necessary, in conjunction with observational data, to expose actual conditions for planet formation.

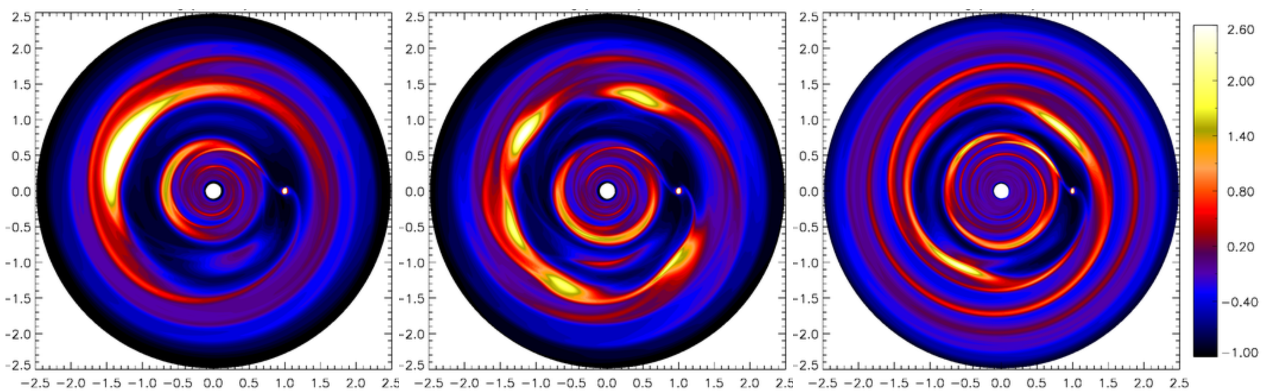

Fig. 1.— *Numerical simulations of 3D self-gravitating disk-planet interaction using the* `Zeus-MP` *code. Shown here are gap instabilities as a function of disk-to-star mass ratio* $M_d/M_*$*. In low mass (left,* $M_d/M_* = 0.021$*) or moderately massive disks (middle,* $M_d/M_* = 0.056$*), gap edges undergo vortex formation, but the number of vortices increase with* $M_d$*. In very massive disks (right,* $M_d/M_* = 0.08$*), a spiral instability develops at the gap edge instead. The colorbar shows the relative density perturbation.*

### 1.2. Disk-planet interaction and orbital migration

The gravitational interaction between proto-planets and the surrounding gaseous PPD leads to orbital migration of the planet (Goldreich & Tremaine 1979; Lin & Papaloizou 1986). In standard, *smooth* disk models, disk-planet interaction typically causes orbital decay. With the observational evidence of complex large-scale structures in PPDs, it is now necessary to study orbital migration in *non-smooth* disks. This is further motivated by recent theoretical models that successfully attribute observed disk asymmetries to disk-planet interaction, but these in fact neglect orbital migration (e.g. Ataiee et al. 2013; Pinilla et al. 2015).

I used numerical simulations to show that gap-edge vortices cause giant planets to undergo episodic orbital migration, leaving sub-structures behind (Lin & Papaloizou 2010). In massive disks, I found that global spiral arms associated with unstable gaps (Fig. 1, right panel), can cause *outwards* orbital migration (Lin & Papaloizou 2012). This work was further expanded through the

[1] http://plutocode.ph.unito.it/

2012 CITA Summer Student Program in which I supervised an undergraduate student to examine the role of planet mass (Cloutier & Lin 2013). We found that outwards orbital migration is generic to gap-opening companions in self-gravitating disks. This 'spiral-planet' interaction also explains outward migration observed in simulations of massive disks performed by other authors (Zhu et al. 2012; Stamatellos 2015).

### 1.3. Theory of astrophysical fluid instabilities

The 'vortex instability' described above is applicable to any astrophysical disk that contain localized radial structure. Apart from disk gaps, the transition between actively accreting and 'dead' zones in PPDs are also possible sites for instability (Varnière & Tagger 2006; Lyra & Mac Low 2012). The original theory was developed for 2D, razor-thin disks (Li et al. 2000), but real PPDs are three-dimensional.

I developed the theory of the vortex instability in 3D disks with varied thermodynamics (Lin 2012a, 2013b). I devised spectral and pseudo-spectral methods/algorithms to solve the associated complex partial differential equation eigenvalue problem (Lin 2013a). I found the 3D instability can have significant vertical structure with potentially observable consequences (e.g. lifting dust particles to the disk atmosphere). These calculations have been confirmed with direct hydrodynamic simulations (Lin 2013b), and used by other researchers to benchmark their simulations (Meheut et al. 2012; Richard et al. 2013).

I have also begun to study magnetized self-gravitating disks with linear analyses of disks subject to both gravitational instability (GI) and magneto-rotational instability (MRI), including non-ideal effects (Lin 2014a). I showed that their interaction can be non-trivial, e.g., MRI can be stabilized or enhanced by disk self-gravity depending on the parity of perturbation considered. Most importantly, this framework allows one to easily identify parameter regimes in which MRI-GI interaction is strongest. This provides an important guide to future non-linear simulations (§3.4).

## 2. Recent projects

### 2.1. Vertical shear instability in protoplanetary disks (Lin & Youdin 2015)

Astrophysical disks are generally *baroclinic* — surfaces of constant pressure and density do not coincide. Consequently, the disk's orbital frequency depends on the height from the disk midplane, $\partial_z\Omega \neq 0$. This free energy can be tapped through a *vertical shear instability* (VSI, Urpin & Brandenburg 1998; Urpin 2003). The VSI has thus gained considerable interest as a route to purely hydrodynamic turbulence in PPDs (Nelson et al. 2013; Stoll & Kley 2014; McNally & Pessah 2015; Barker & Latter 2015; Mohandas & Pessah 2015), which is expected to play an important role in weakly ionized PPDs. While vertical shear is generic, in realistic, stably-stratified disks the VSI also requires a short cooling timescale to overcome buoyancy forces. However, a quantitative thermodynamic criteria has not been determined until now.

I performed a detailed semi-global analysis of the VSI and derived the remarkably simple result,

$$\beta \equiv t_c \Omega < \frac{h|q|}{\gamma - 1}, \tag{1}$$

as the thermodynamic requirement for efficient VSI. Here, $t_c$ is the cooling timescale, $h$ is the disk aspect-ratio, $q$ is the local logarithmic radial temperature gradient and $\gamma$ is the adiabatic index. Since $h \ll 1$ in PPDs, this criterion explains why $\beta \ll 1$ was needed to observe instability in the first numerical simulations of the VSI (Nelson et al. 2013). This criteria was also verified in our numerical stability calculations.

Eq. 1 allows one to immediately assess the importance of the VSI across a wide range of disk parameters without resorting to costly computer simulations. By calculating cooling timescales based on dust opacity, we showed that the VSI is indeed viable in realistic PPDs, with maximum activity between 5 and 50AU (Fig. 2), and smaller (larger) scale structures are expected in the inner (outer) disk.

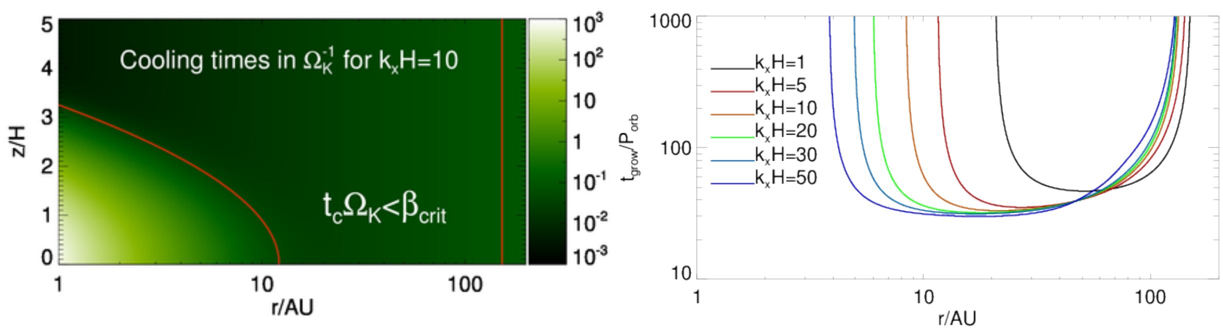


Fig. 2.— *Left: estimated cooling times in a standard PPD — the 'Minimum Mass Solar Nebula' (Chiang & Youdin 2010) — compared with the VSI requirement presented by Eq. 1 (red lines). Right: growth timescales (in local orbits) explicitly calculated from linear stability analysis, showing that VSI is most active at intermediate radii, consistent with Eq. 1 (i.e. left plot). Here $k_x$ is the radial wavenumber of the perturbation, and $H$ is the disk pressure scale height.*

This work presents a significant advance in the theoretical understanding of the VSI. However, further development is still necessary. I will develop a theory for the VSI in fully global, non-axisymmetric disk models with a realistic treatment of heating and cooling processes (e.g. inclusion of viscous heating and radiative diffusion, Latter & Ogilvie 2006). Alternative sources of vertical shear will also be explored (e.g. mass infall from an envelope, Harsono et al. 2011).

### 2.2. Eccentric modes in thermodynamically-forced accretion disks (Lin 2015)

The *locally isothermal disk*, in which the temperature is a prescribed function of position, is a widely used model for PPDs in studies such as disk-planet interaction. These models physically represent disks in which heating is dominated by an external source, e.g. the outer parts of PPDs illuminated by stellar irradiation (Chiang & Goldreich 1997; Stamatellos & Whitworth 2008).

I showed that the propagation of waves in such a thermodynamically-forced disk is non-trivial: non-axisymmetric waves can undergo instability by extracting angular momentum from the background disk, a process mediated by the temperature gradient. I described this new instability mechanism analytically, and used hydrodynamic simulations (with three independent codes: `Fargo`, `Zeus-MP` and `Pluto`) in both 2D and 3D to demonstrate how this mechanism can lead to the formation of one-armed or eccentric patterns (Fig. 3). This phenomenon may be relevant to PPDs at large radii, where large-scale spiral patterns are indeed observed (Rameau et al. 2012; Casassus et al. 2012; Muto et al. 2012; Grady et al. 2013; Benisty et al. 2015; Wagner et al. 2015), and is a conceptually novel route to forming eccentric disks. For this work I also developed a Poisson solver for the `Pluto` code to simulate 3D self-gravitating disks.

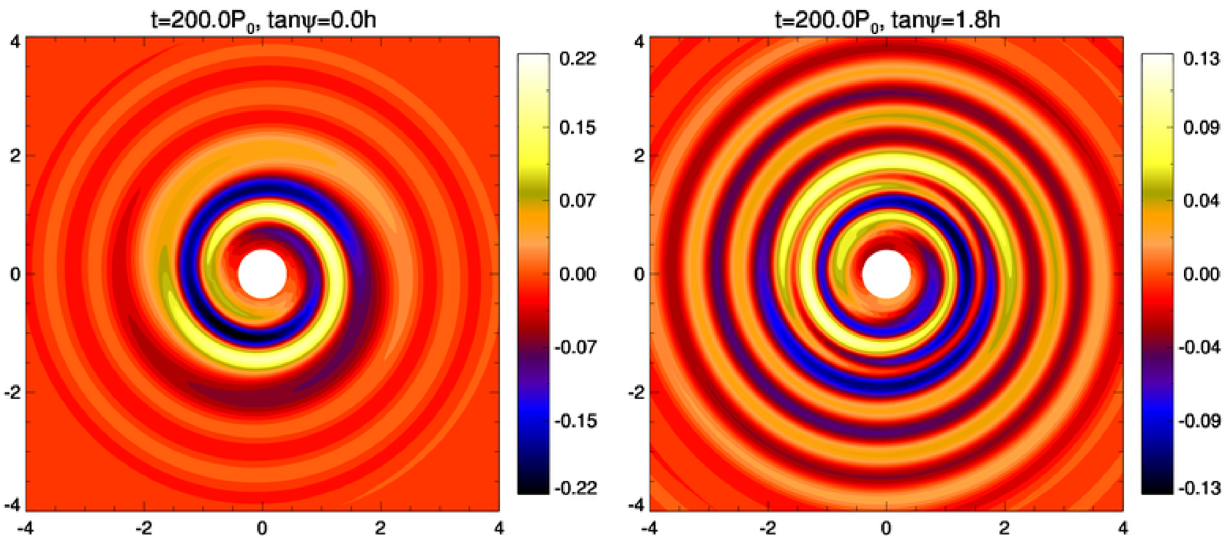


Fig. 3.— *Non-linear numerical simulation of a self-gravitating, locally isothermal 3D disk, using the* `Pluto` *hydrodynamics code. The component of the density field with azimuthal wavenumber $m = 1$ at the midplane (left) and approximately two scale-heights above the midplane (right) is shown.*

In the locally isothermal disk model, heating/cooling timescales are formally zero. I will generalize this work to finite thermal timescales by including an appropriate energy equation, in order to quantify the thermodynamic requirement for this new instability, and better constrain its application to PPDs. This will be done through both theoretical analysis as well as direct simulations, including extended calculations to explore its impact on the long term disk evolution.

### 2.3. Vortices in non-isothermal disk-planet simulations (Les & Lin 2015)

This project was undertaken by an undergraduate student as part of the 2014 CITA Summer Student Program, whom I directly supervised. We studied vortex formation through non-isothermal disk-planet interactions, generalizing previous such studies which have all employed locally isothermal disks. Through carefully designed numerical experiments using the `Fargo` code (Masset 2000), we showed that slowly-cooled disks are more stable against vortex formation than rapidly-cooled disks. However, the overall lifetime of gap-edge vortices have a non-monotonic dependence on the cooling time (Fig. 4): there is an optimal cooling time that maximizes the lifetime, and hence observability, of such vortices. This result was later verified independently by Lobo Gomes et al. (2015). This means that observations of vortices puts an indirect constrain on disk thermodynamics.

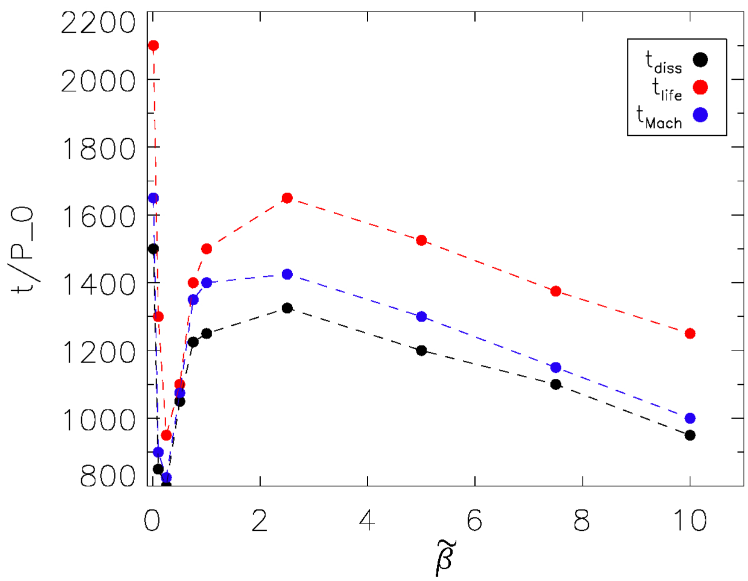


Fig. 4.— *Lifetimes of gap-edge vortices (in orbits) as a function of the dimensionless cooling time imposed in the disk. Colors indicate different metrics for the vortex lifetime, all of which display non-monotonic dependence on the cooling time.*

This project offers excellent research opportunities for students. I am interested in working with undergraduate or graduate students to extend this work to include disk self-gravity, 3D (using the new `Fargo3D` code[2]) and/or orbital migration.

## 3. Research proposal

### 3.1. Analytical fluid dynamics and applications

Modern astrophysical fluid dynamics make substantial use of direct numerical simulations to reveal new phenomena. However, physical understanding is better clarified through analytical or semi-analytical methods. Such calculations are also *essential* to verify and guide computer simulations. This is particularly important when studying fluid dynamical instabilities, which are fundamental to many astrophysical processes. As numerical simulations become increasingly sophisticated, so too must analytical models.

For example, the importance of heating/cooling processes on the gravitational stability of

[2] http://fargo.in2p3.fr/

PPDs has been stressed through numerical simulations (e.g. Gammie 2001; Rice et al. 2005; Meru & Bate 2011; Paardekooper 2012). However, such studies and semi-analytical models (e.g. Rafikov 2015) still refer to the classic $Q$ parameter, which formally characterizes self-gravity in isothermal disks (Toomre 1964).

Recently, I have revisited this stability problem by developing an analytical framework to match the complex physics that modern simulations include. I show a preliminary result in Fig. 5 where growth rates of unstable modes in a self-gravitating disk are properly calculated with the inclusion of heating, cooling and turbulence (Lin, Kratter & Youdin, in preparation). This framework will be applied to to actual PPDs to determine regions of instability, characteristic lengthscales of the emerging structures, and address disk fragmentation. Our model naturally leads to a characteristic cooling time, $t_c\Omega \sim (\sqrt{\gamma}-1)^{-3/2}$, which reproduces the fragmentation boundary reported in the literature (Gammie 2001; Rice et al. 2005, 2011).

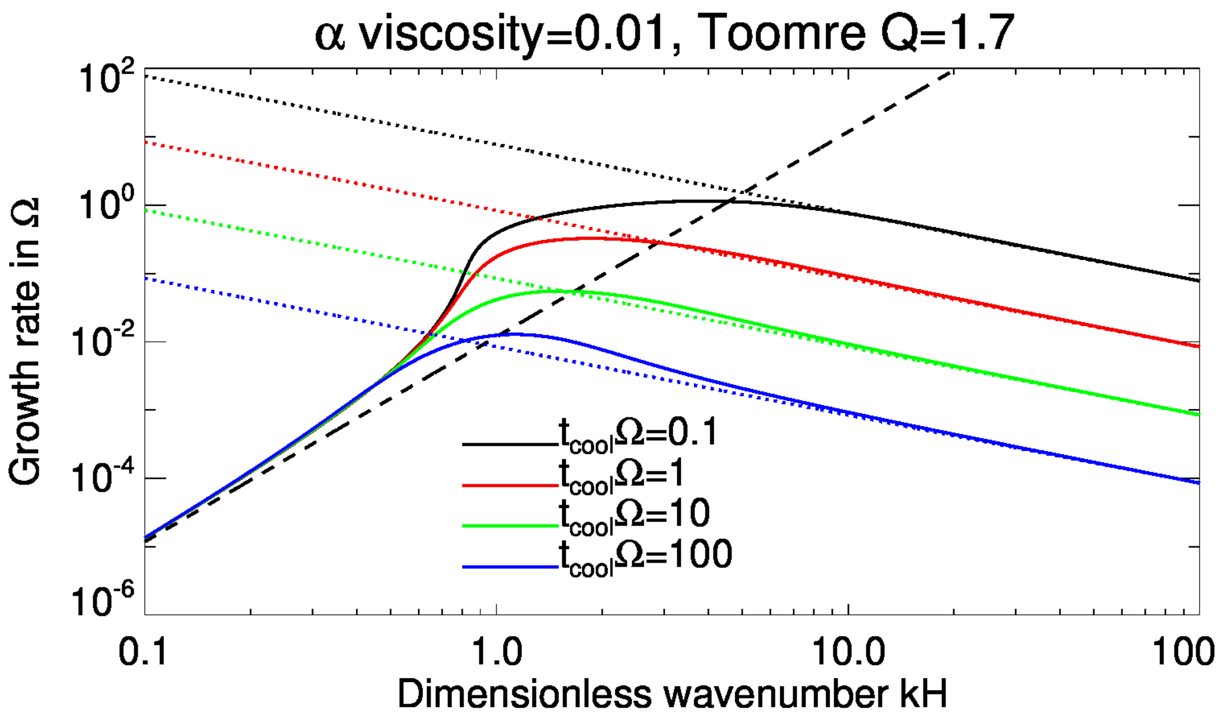


Fig. 5.— *Growth rates of unstable modes in a self-gravitating, non-isothermal, turbulent accretion disk. The horizontal axis is the radial wavenumber of the perturbation under consideration. The disk is subject to optically-thin cooling with timescale* $t_{\rm cool}$*, and turbulence is modeled through an effective alpha viscosity. Broken lines correspond to analytic asymptotic behaviors at small and large scales.*

The goal of this line of work is to develop simplified PPD models based on rigorous analytical theory. This approach enables large parameter surveys to be carried out, which are impractical by direct simulation. Here, a necessary effort is a detailed treatment of various fluid instabilities in PPDs (Turner et al. 2014), such as the vortex and vertical shear instabilities discussed above, among others (e.g. the recently discovered 'convective over-stability', Klahr & Hubbard 2014; Lyra 2014; Latter 2015). Generalizations include, but not limited to: self-gravity, non-ideal MHD, realistic thermodynamics, global geometry, and non-axisymmetric disturbances (including transient dynamics, Umurhan et al. 2006; Rebusco et al. 2009; Shtemler et al. 2010; Razdoburdin & Zhuravlev 2012).

### 3.2. Elliptical vortices in 3D self-gravitating disks

Vortex formation is a promising candidate to explain observed sub-structures in PPDs, and they can enhance planetesimal formation by acting as dust-traps. Most models of vortices do not account for its self-gravity. However, several recent studies have shown that self-gravity cannot be neglected for vortex dynamics even when the disk is not massive (Lin 2012b; Lovelace & Hohlfeld 2013; Zhu & Baruteau 2015). Furthermore, self-gravity is dynamically significant in the early evolution of PPDs, during which vortex formation can be expected (Bae et al. 2015).

These considerations motivate a proper study of the structure and evolution of vortices in 3D self-gravitating disks. I show in Fig. 6 two preliminary simulations carried out with the `Athena`[3] code (Stone et al. 2008). Here, a local vortex is initialized in an accretion disk and allowed to evolve. Both disks are gravitationally stable, but the vortex structure is clearly modified by self-gravity.

A key focus will be vortex stability. It is well-known that secondary, elliptic instabilities can destroy non-self-gravitating vortices in 3D (Lesur & Papaloizou 2009; Railton & Papaloizou 2014). I will study how this picture is modified in self-gravitating disks, and hence determine the expected vortex lifetimes in realistic, young PPDs. I will also explore the gravitational instability of elliptical vortices, possibly mediated by hydrodynamic turbulence from the elliptic (Gammie 1996). I will begin with local disk models to allow high numerical resolution, before moving onto global models where vortex migration can also be simulated (Paardekooper et al. 2010).

I will investigate dust-dynamics in self-gravitating 3D vortices in connection to planetesimal formation. Key issues to address include how vertical dust settling is modified by disk self-gravity, the condition for gravitational instability of elliptical dust distributions (Lyra & Lin 2013), and the impact of drag forces on the hydrodynamic/gravitational stability of gaseous vortices.

I will pursue these issues using both numerical simulations (with the `Athena` and/or `Pluto` codes) and analytical modeling. The latter demands application of mathematical methods from the fluid dynamics field; in particular the extension of techniques for analyzing elliptical flow (Kerswell 1994) to include the Poisson equation.

### 3.3. Giant planet orbital migration and eccentric disks

Recent efforts in the theory of disk-planet interaction have focused on halting or reversing the (typical) inwards orbital migration of low-mass planets (see e.g., Baruteau et al. 2014, for a recent review), which would otherwise prevent the formation of gas giant planets.

The *outwards* migration of *giant* planets, however, have received little attention. Only a limited

[3]https://trac.princeton.edu/Athena/

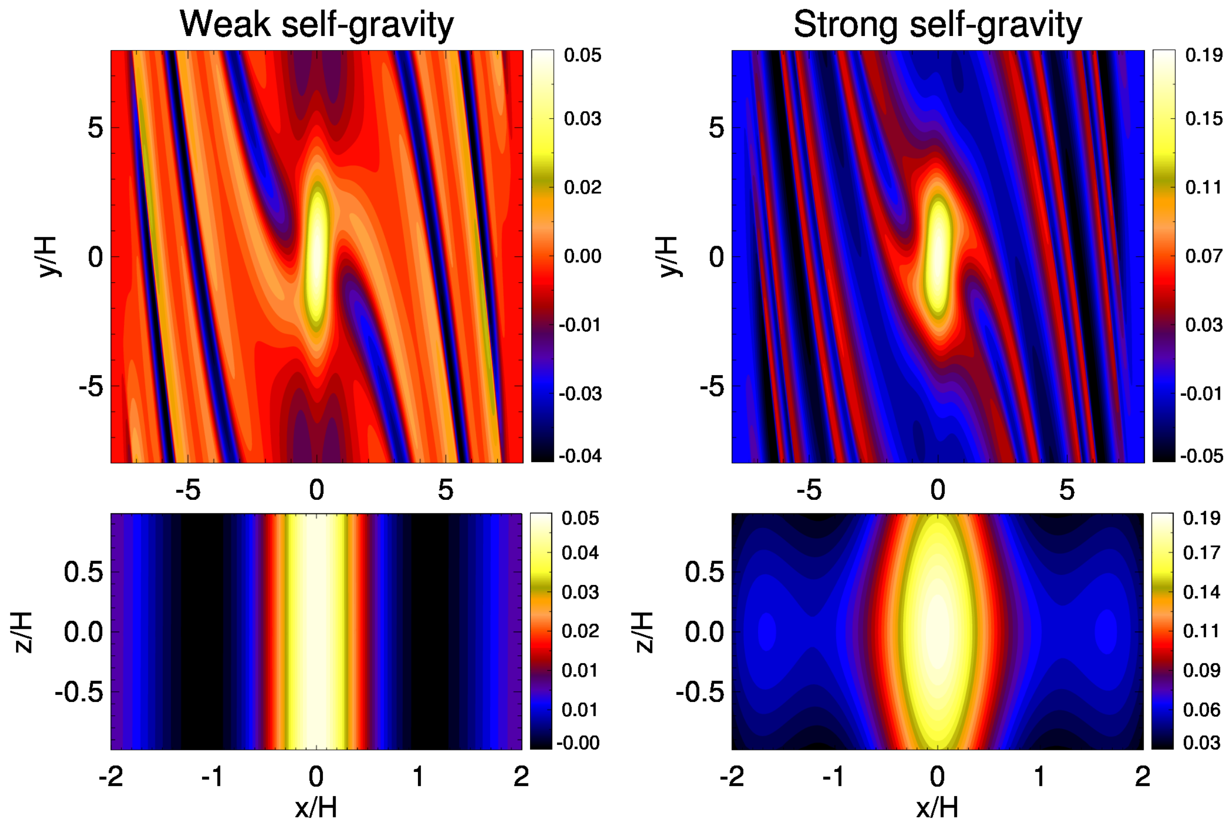


Fig. 6.— *Quasi-steady state vortex formed by initializing shearing-box simulations with a vortex perturbation for a weakly self-gravitating disk (left, with Toomre* $Q \simeq 160$*) and a strongly self-gravitating, but stable disk (right, with* $Q \simeq 1.6$*). (Local gravitational instability in 3D requires* $Q \lesssim 0.8$*, Mamatsashvili & Rice 2010, .) The colorbar shows the relative density perturbation at the midplane (top) and in the meridional plane (bottom).*

number of studies have examined this possibility (Pepliński et al. 2008; Crida et al. 2009; D'Angelo & Marzari 2012). However, such mechanisms can potentially explain the increasing population of directly-imaged giant planets or companions on wide orbits (Marois et al. 2008; Lagrange et al. 2010; Rameau et al. 2013; Kuzuhara et al. 2013; Bailey et al. 2014; Galicher et al. 2014; Kraus et al. 2014; Mawet et al. 2015; Macintosh et al. 2015).

I will use 2D and 3D hydrodynamical simulations to study disk-planet interaction with focus on the outwards orbital migration of giant planets. I will go beyond previous efforts and consider non-isothermal self-gravitating disk models as appropriate for outer regions of PPDs. The key goals are to identify conditions under which outwards migration can occur (e.g. disk and planetary masses, heating/cooling processes, turbulence levels), analyze its underlying mechanism, and determine how far can such mechanisms bring giant planets away from its host star.

Giant planets may also lead to globally distorted, eccentric disks (Papaloizou et al. 2001; Kley & Dirksen 2006; Dunhill et al. 2013; Duffell & Chiang 2015). In Fig. 7, I show preliminary simulations including disk self-gravity and cooling. I will quantify eccentric disk morphologies in relation to its self-gravity and non-ideal thermodynamics. A related issue is that eccentric disks are known to be hydrodynamically unstable to 3D disturbances (Papaloizou 2005b,a; Barker & Ogilvie 2014). I will study this instability in the context of planet-induced eccentric disks by performing global 3D numerical simulations (using the `Pluto` and the new `Fargo3D` codes), with the objective of quantifying the expected disk/planet eccentricities in realistic PPDs. Orbital migration of giant planets in globally eccentric 3D disks will also be simulated.

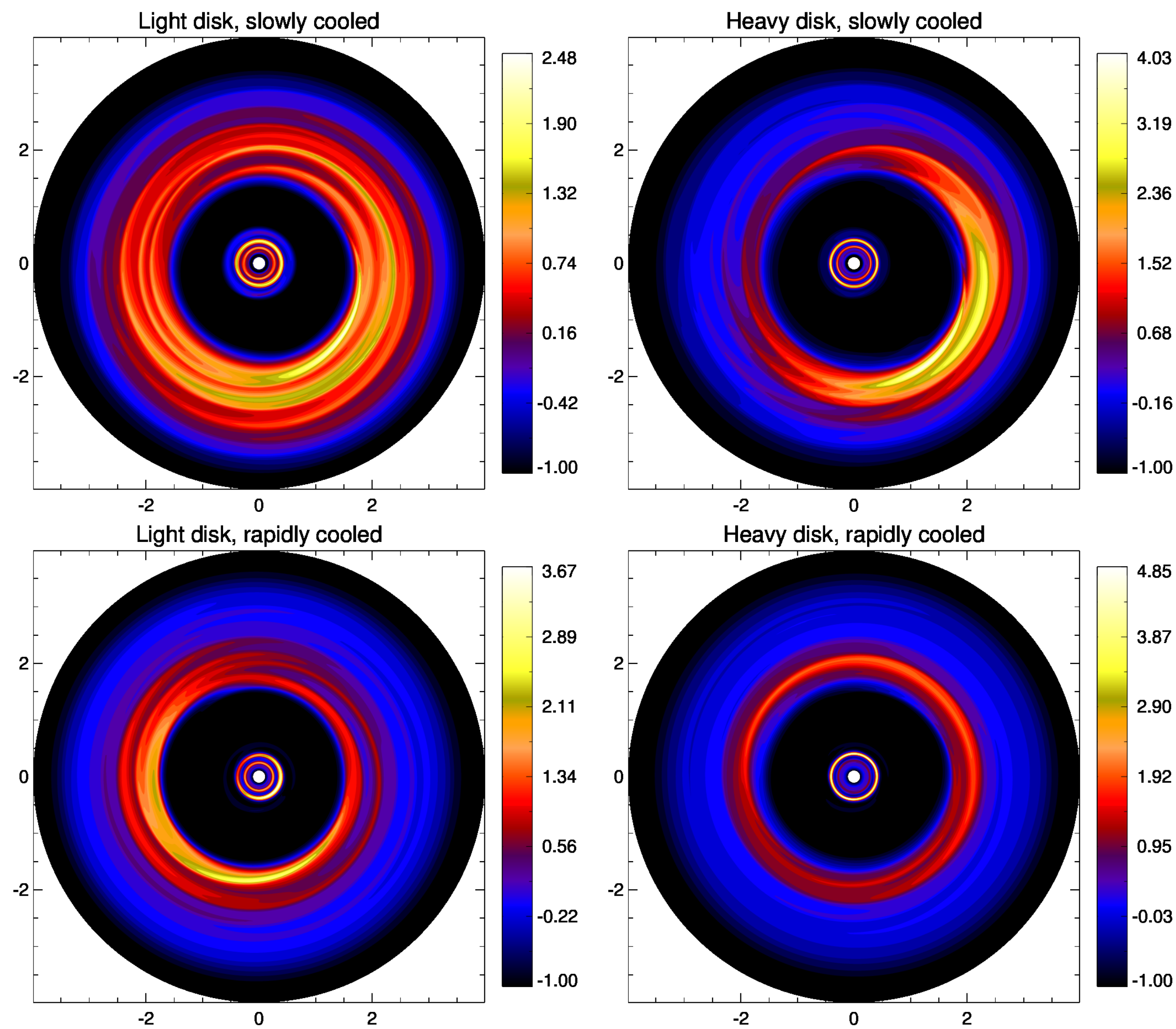


Fig. 7.— *Formation of eccentric gaps due to disk-planet interaction. Here, a 5-Jupiter mass planet is inserted into a self-gravitating, non-isothermal disk and held on a fixed, circular orbit. Top panels: slowly-cooled disks with* $t_{\rm cool} = 10\Omega^{-1}$*; bottom panels: rapidly cooled disks with* $t_{\rm cool} = 0.1\Omega^{-1}$*. (Here, 'cooling' refers to relaxation towards a prescribed temperature profile.) Left panels: light disks with* $M_d \simeq 0.0002M_*$*; right panels: heavy disks with* $M_d \simeq 0.05M_*$*. The colorbar shows the relative surface density perturbation.*

### 3.4. Magnetized self-gravitating disks

Magneto-hydrodynamic (MHD) turbulence and gravitational instability (GI) are the two robust mechanisms for angular momentum transport and powering accretion disks. These processes are typically studied in isolation (Turner et al. 2014). However, in young PPDs (Inutsuka et al. 2010), layered-accretion models (Landry et al. 2013) (which include circum-planetary disks, Lubow & Martin 2012) the disk is simultaneously self-gravitating and magnetized. The traditional approach to account for both effects is implicitly through a viscosity prescription (Armitage et al. 2001; Zhu et al. 2010a,b; Martin et al. 2012; Rafikov 2015).

The goal of this project is to develop models of self-gravitating PPDs including *explicit* MHD. This self-consistent framework allows the study of the earliest evolution of PPDs, and hence determine the initial conditions for planet formation. I will begin with simulating local, 3D disk models with the `Athena` code. I will study how MHD and GI interact to affect disk stability (using Lin 2014a, to benchmark and guide the simulations) and characterize turbulent activity as a function of self-gravity, magnetization, and non-ideal effects such as resistivity.

I will also explore magnetized disk fragmentation including cooling. I will address whether magnetic effects help fragmentation (through turbulence) or oppose it (through magnetic pressure). This is a necessary step beyond previous studies in the hydrodynamic limit, in order to assess giant planet formation by disk fragmentation, which is expected in young, massive PPDs, but these are also likely magnetized. I will then move onto global disk simulations (using the `Zeus-MP` and/or `Pluto` codes) to study realistic transport rates and large-scale structure formation (e.g. vortices and spirals). These models will be the basis for studying magnetized disk-planet interaction.

I will take full advantage of high performance computing resources at the University. This is expected to enable significant improvements from previous efforts (Fromang et al. 2004a,b; Fromang 2005) in terms of numerical resolution and integration times. However, complementary analytical work will be continually developed, starting with generalizations of Lin (2014a) to account for explicit heating/cooling and non-axisymmetric disturbances, in order to fully model the linear dynamics of magnetized self-gravitating disks and compare with simulations.

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