My primary research interest is theoretical astrophysical fluid dynamics with application to accretion disks and planet formation theory. I employ a combination of computer simulations, analytic and semi-analytic methods to rigorously establish and understand new results. I summarize below previous works, and describe in more detail recent projects and future research topics.

1. Research areas

1.1. Structures in protoplanetary disks as signposts of planet formation

It is now possible to directly observe detailed sub-structures in protoplanetary disks (PPDs), such as gaps, rings, or spirals, which may be signposts of planets or the planet formation process itself. Understanding physical processes that lead to structured PPDs is essential to explain observations and further 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 for such asymmetries is the formation of pressure bumps associated with large-scale vortices, towards which dust particle drift due to drag forces. An analytic description of dust-trapping by disk vortices, developed by Lyra & Lin (2013), can indeed model such observations (Pérez et al. 2014). This idea also plays a prominent role in planetesimal formation (Barge & Sommeria 1995). Thus, disk vortex dynamics is an integral part of modern planet formation theory.

Vortices in PPDs may also be evidence of already-formed, but unseen giant planets. I developed a semi-analytic theory that explains, in detail, how a giant planet can open disk gaps that are in fact hydrodynamically unstable (Lin & Papaloizou 2010), and used numerical simulations to show the outcome of instability is vortex formation. This scenario, including subsequent dust-trapping, has since been validated by others (e.g. Zhu & Stone 2014).

I generalized the theory of planet-induced gap instabilities to self-gravitating disks (Lin & Papaloizou 2011a,b). I showed, through mathematical analysis and numerical simulations, that disk self-gravity (DSG), while commonly ignored in models of disk-planet interactions, has *profound* effects on gap stability. In particular, vortex formation is discouraged in with increasing DSG, and is eventually replaced by a new 'gravitational edge instability', signified by large-scale spiral features associated wtih disk gaps.

I show in Fig. 1 numerical simulations that demonstrate this trend with DSG (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 DSG in spherical co-ordinates. More recently, I applied the `PLUTO` code (Mignone et al. 2007) to show that vortex-formation is sensitive to how the mass-accretion rate within the disk depends on the height from the disk midplane (Lin 2014b), which can be expected in realistic PPD models (e.g., Landry et al. 2013; Bai 2015; Simon et al. 2015; Gressel et al. 2015).

It is clear from these studies that observable disk morphologies are intimately linked to the underlying disk/planet properties. For example, the observation of a single large-scale vortex implies the disk mass is low — a property that is diffult to directly infer. Thus, the continuous development of theoretical models of PPD structures is neccessary, in conjunction with observational data, to expose actual conditions for planet formation.

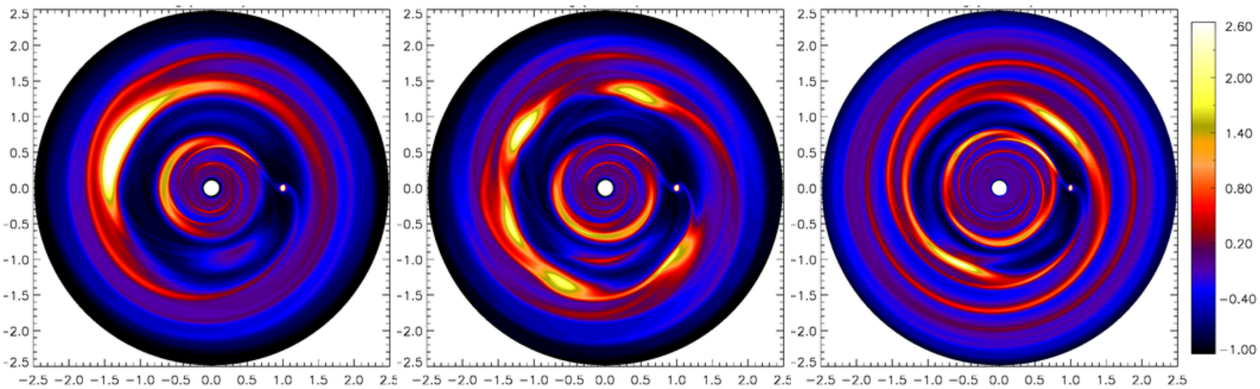

Fig. 1.— *Numerical simulations of 3D self-gravitating disk-planet interaction using the* `ZEUS-MP` *code. Shown here are gap instabilities as a function of disk-to-star mass ratio M_d/M_*. In low mass (left, $M_d/M_* = 0.021$) or moderately massive disks (middle, $M_d/M_* = 0.056$), gap edges undergo 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 instead. The colorbar shows the relative density perturbation.*

1.2. Disk-planet interaction and orbital migration

It is well-known that the gravitational interaction between proto-planets and the gaseous PPD lead to orbital migration (Goldreich & Tremaine 1979; Lin & Papaloizou 1986). In standard, featureless disk models, the planet typically migrate towards the central star. However, with the observational evidence that complex structures may be commonplace in PPDs, it is now necessary to study orbital migration in such disks. This problem is artifically surpressed in most mdoels that attribute disk asymmetries as of planetary origin.

Using direct hydrodynamic simulations, I showed that gap-edge vortices in fact cause giant planets to undergo episodic orbital migration leaving complex sub-structures behind (Lin & Papaloizou 2010). In massive disks where the gap edges develop global spiral patterns (Fig. 1, right panel), I showed that *outwards* orbital migration becomes possible due to the spiral instability (Lin & Papaloizou 2012). This work was further expanded through the 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 quite generic to giant planets that open gaps in self-gravitating disks. This 'spiral-planet' interaction also explains outward migration in massive disks seen by other authors (Zhu et al. 2012; Stamatellos 2015).

1.3. Theory of astrophysical fluid instabilities

The 'vortex-forming' instability described above is in fact applicable to any accretion disks that contain radial structure. Apart from disk gaps, the transtion between actively accreting and 'dead' zones in PPDs are also possble sites for this 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 have thus extended the linear theory of the vortex instability to 3D disks with varied thermodynamics (Lin 2012a, 2013b). A major effort in this work is the development of simple spectral and pseudo-spectral methods/algorithms to solve the associated partial differential equation eigenvalue problem (e.g. Lin 2013a), which are notoriously difficult to tackle. I found that, depending on the disk thermodynamics, vortices can have signigicant vertical structure, with potentially observable consequences (e.g. lifting dust particles to the disk atmosphere). These calculations have been confirmed with non-linear hydrodynamic simulations performed by myself, 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, starting with linear analyses of disks that permits both gravitational instability (GI) and magneto-rotational instability (MRI), including non-ideal effects (Lin 2014a). I found that their interaction can be non-trivial. These include the stabilization MRI by disk self-gravity for some perturbations, but MRI density flucuations can also be enhanced by self-gravity in other cases. Importantly, using this framework, I am able to identify parameter regimes in which MRI-GI interaction is strongest, which will provide an important guide for future non-linear simulations of magnetized, massive PPDs which I intend to pursue.

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, $\partial_z\Omega \neq 0$. It is then possible to tap into this free energy through a *vertical shear instability* (VSI, Urpin & Brandenburg 1998; Urpin 2003). The VSI has gained considerable interest as a route to hydrodynamic turbulence in PPDs (Nelson et al. 2013; Stoll & Kley 2014; McNally & Pessah 2015; Barker & Latter 2015; Mohandas & Pessah 2015). The VSI is requires a short cooling timescale in order to overcome the stabilizing influence of buoyancy forces in typical disks, but a quantitative criteria has yet been determined — until now.

In this work, I performed a detailed analysis of the VSI, focusing on its thermodynamic requirements and derived the remarkably simple result,

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

for efficient VSI. Here, t_{cool} is the cooling timescale, h is the disk aspect-ratio, q is the local (logarithmic) radial temperature gradient and γ is the adiabatic index. Since $h \ll 1$ in PPDs, this requirement explains why $\beta \ll 1$ is needed to observe VSI in direct numerical simulations (Nelson et al. 2013). This criteria was also verified numerically.

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 estimating cooling timescales based on dust opacity, we show that the VSI is indeed viable in realistic PPDs, with maximum activity between 5 and $50AU$ (Fig. 2). Our simple criterion also potentially allows one to incoporate the VSI in 1D or analytic accretion disk models.

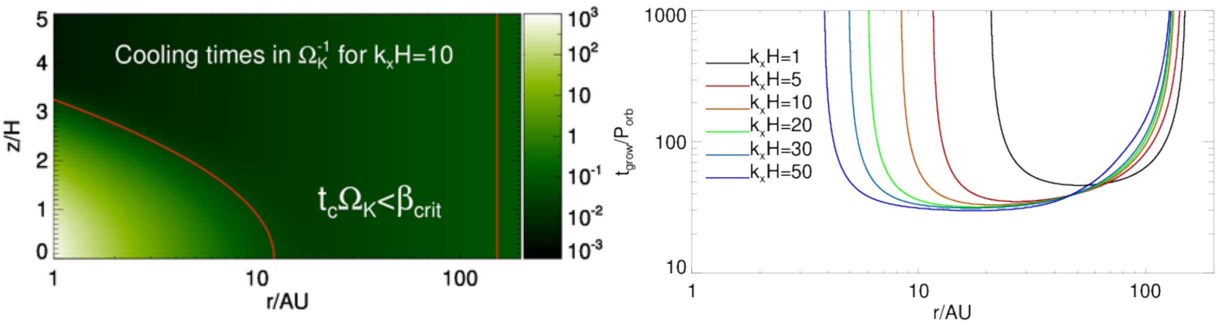

Fig. 2.— *Left: estimated cooling times in a standard PPD — the 'Minimum Mass Solar Nebula' (Chiang & Youdin 2010) — compared with the requirement presented by Eq. 1 (red lines) for the VSI to operate. Right: growth timescales explicitly calculated from linear stability analysis, showing that VSI is most active at intermediate radii, consistent with Eq. 1 (i.e. left plot).*

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

A widely used disk model in the study of dynamics in PPDs, such as disk-planet interaction, is the *locally isothermal disk*, in which the temperature is a prescribed function of position. Such models physically represent the situation where heating is dominated by an external source, e.g. the outer parts of PPDs (beyond few tens of AU) illuminated by stellar irradiation (Stamatellos & Whitworth 2008).

I showed that the propagation of waves in such a thermodynamically-forced disk is non-trivial. In particular, non-axisymmetric waves are able to undergo instability by extracting angular momentum from the background disk, a process mediated by the imposed temperature gradient. I described this new instability mechanism analytically, and used direct hydrodynamic simulations (with three independent codes: `FARGO`, `ZEUS-MP` and `PLUTO`) in both 2D and 3D to demonstrate how this effect can lead to the formation of one-armed or eccentric patterns (Fig. 3). This process may be relevant to PPDs are large radii, where large-scale spiral patterns are indeed observed. This work also made use of a newly developed Poisson solver for disk gravity for the `PLUTO` code.

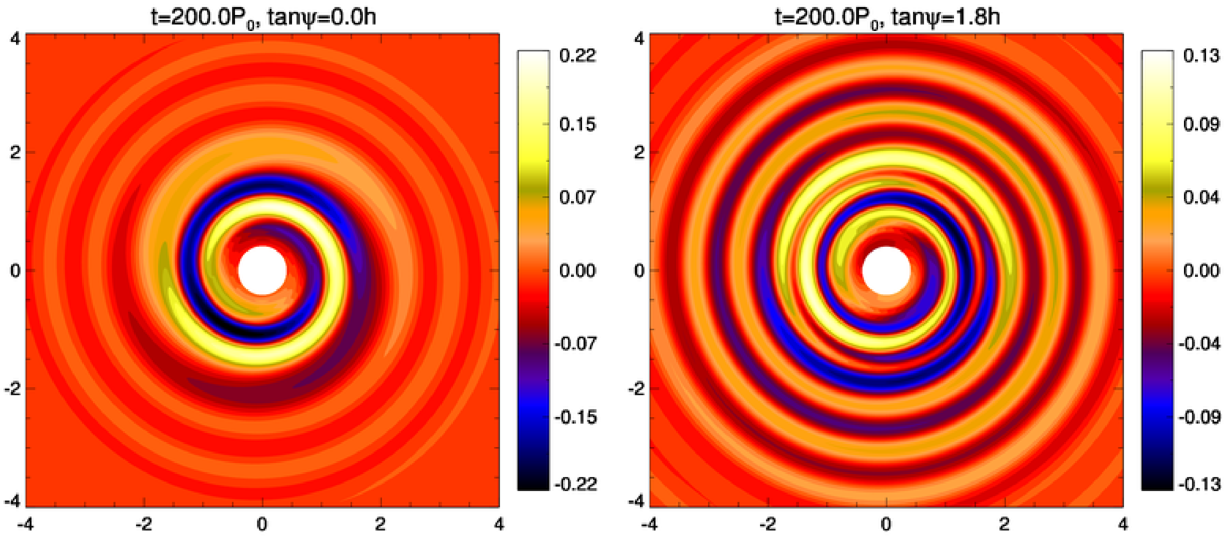

Fig. 3.— *Non-linear numerical simulation of a self-gravitating, locally isothermal 3D disk, using the* `PLUTO` *hydrodynamics code. The component of the density field with azimuthal wavenumber* $m = 1$ *at the midplane (left) and approximately two scale-heights above the midplane (right) is shown.*

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 associated with planet-induced gaps in non-isothermal disks. This is an important issue because all such previous studies have employed locally isothermal disks. Through carefully-designed numerical experiments using the `FARGO` 2D 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 rate (Fig. 4). We showed that there exists an optimal cooling rate that maximizes the lifetime, and hence observability, of such vortices. This result has subsequently been verified independently (Lobo Gomes et al. 2015). I will extend this study to 3D disks.

3. Research proposal

3.1. Analytical fluid dynamics and applications

Modern astrophysical MHD make substantial use of direct numerical simulations to reveal new phenomena. On the other hand, physical understanding is often better revealed through analytical or semi-analytical methods. Such calculations are *essential* to verify and guide computer simulations, but are not always provided. This is particularly important when studying fluid dynamical instabilties, which are fundamental to many astrophysical processes. As numerical simulations become increasingly sophisticated, so too must analytical models.

For example, the importance of disk thermodynamics on gravitational instabilities in PPDs

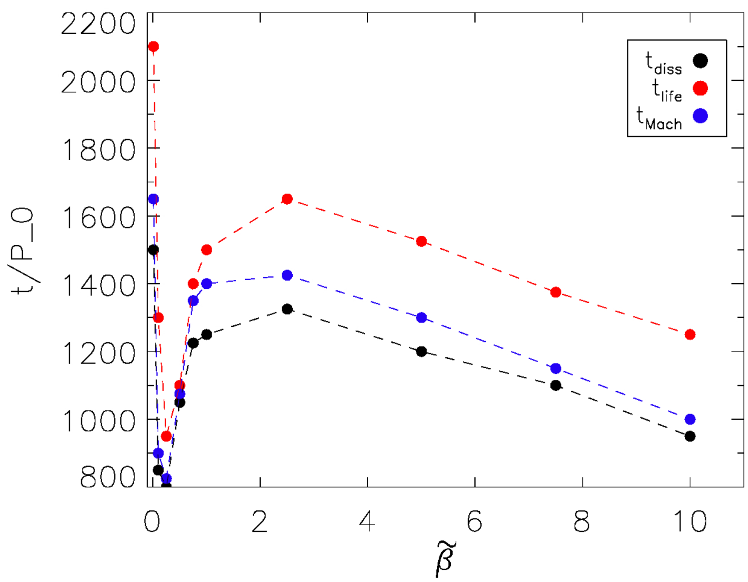

Fig. 4.— *Lifetimes of gap-edge vortices (in orbits) as a function of the dimensionless cooling time imposed in the disk. Colors indicate different metrics for the vortex lifetime, all of which display non-monotonic dependence on the cooling time.*

is evident from numerical simulations (e.g. Gammie 2001; Rice et al. 2005; Meru & Bate 2011; Paardekooper 2012). However, such studies still refer to the classic Toomre Q parameter to characterize self-gravitational instabilities, which is formally derived for idealized, isothermal disk models.

Recently, in collaboration with K. Kratter, we have begun to revisit the stablity problem by expanding the analytical framework to match the more complex physical processes that modern simulations account for. I show a preliminary calculation in Fig. 5 where growth rates of unstable modes are computed accounting for heating, cooling and turbulence in the disk (Lin & Kratter, in preparation). These calculations will be applied to actual PPDs, e.g. determine where the disks are unstable and characteristic lengthscales of the emerging structures. This approach allows a wide range of parameters to be surveyed, which is impractical by direct simulation.

The goal of this line of work is the development of simplified PPD models based on rigorous analytical theory that offer in-depth understanding. This neccessarily involves treatment of various fluid instablities expected in PPDs. Additional physics to these problems include, but not limited to: self-gravity, non-ideal MHD, realistic thermodynamics, global and non-axisymmetric geometries.

3.2. Elliptical vortices in 3D self-gravitating disks

As discussed above, vortices in PPDs are an attractive explaination for observed disk structures, and they can play crucial roles in planetesimal formation by acting as dust-traps. I will advance theoretical models of disk vortices to include more realistic physics, begining with self-gravity, which

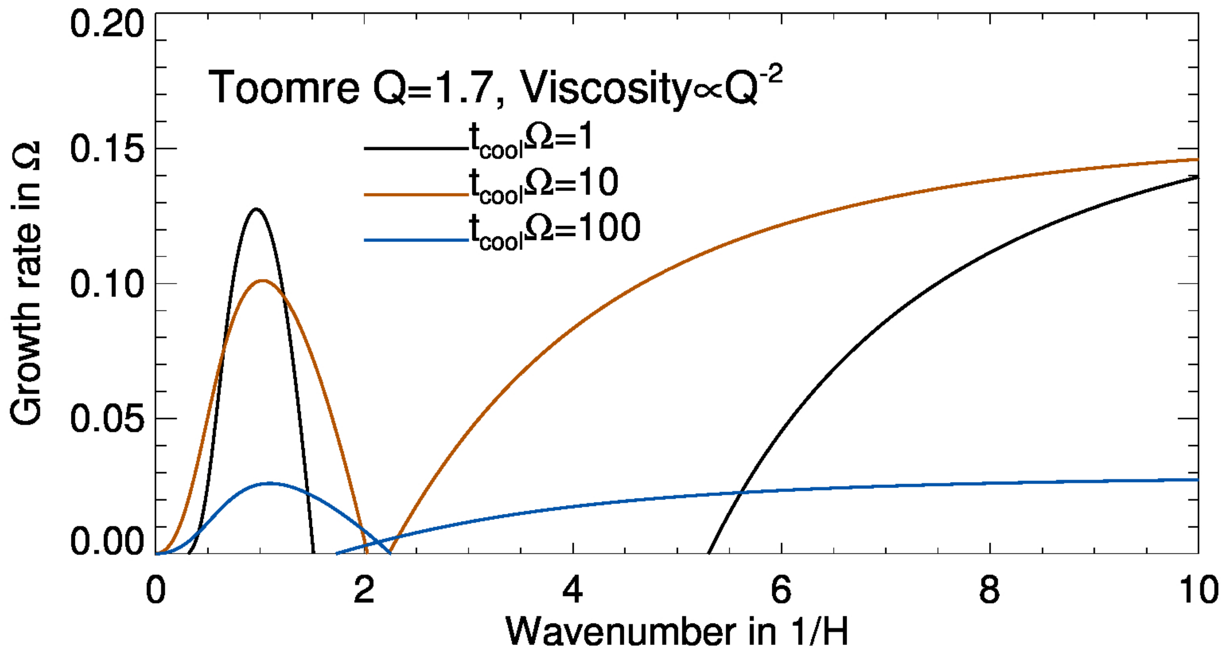

Fig. 5.— *Analytically-determined growth rates of unstable modes in a self-gravitating, non-isothermal, turbulent accretion disk model. The horizontal axis is the radial wavenumber of the perturbation under consideration. Colors indicate different imposed cooling timescales. Turbulence is modeled through an effective viscosity, here assumed to be of self-gravitational origin, so that viscosity increases with decreasing Toomre Q of the background disk.*

is commonly neglected for simplicity. However, several analytical and numerical studies show that self-gravity cannot be neglected for vortex dynamics *even when self-gravity is deemed unimportant* according to the classic Toomre Q parameter (Lin 2012b; Lovelace & Hohlfeld 2013). Furthermore, self-gravity is expected to be generally important in the early evolution of PPDs, during which vortex formation can also be expected (Bae et al. 2015). These considerations motivate a proper study of the structure and evolution of vortices in vortices in 3D self-gravitating disks.

I show in Fig. 6 two preliminary simulations carried out with the `ATHENA` code (Stone et al. 2008). Here, a vortex is initialized in a local patch of an accretion disk and allowed to evolve. Both disks are gravitationally stable, but the vortex structure depends on the strength of self-gravity, which is expected to affect its long term evolution.

A major focus will be vortex stability. It is well-known that secondary, elliptic instabilities act to destroy non-self-gravitating vortices in 3D (Lesur & Papaloizou 2009; Railton & Papaloizou 2014). It is important to understand how this picture is modifed in massive disks, and hence the expected vortex lifetimes in, for example, young PPDs. I will also explore the gravitational instability of vortices, possibly mediated by hydrodynamic turbulence due to the elliptic instability (Gammie 1996). I will begin with ideal, local disk models, which permit higher numerical resolution, before moving onto global simulations.

I will also investigate dust-dynamics in self-gravitating 3D vortices. As seen in Fig. 6, the vortex attains vertical structure in massive disks. This is expected to affect vertical dust-settling. Related to this problem is the stability of elliptical dusty-fluid distributions, which I plan to pursue analytically in conjunction with numerical simulations. These issues are expected to affect planetesimal formation in disk vortices (Fu et al. 2014; Crnkovic-Rubsamen et al. 2015).

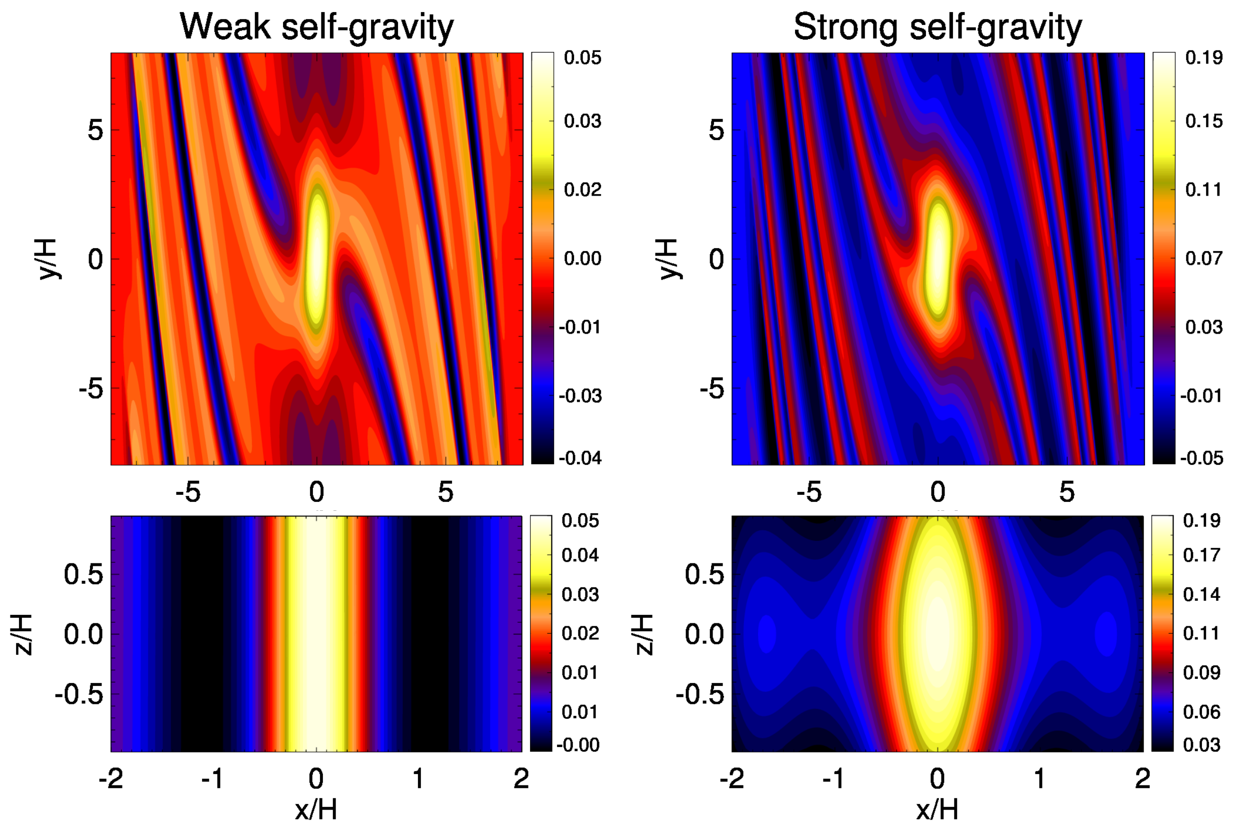

Fig. 6.— *Quasi-steady state vortex formed by initializing shearing-box simulations with a vortex perturbation for a weakly self-gravitating disk (left) and a strongly self-gravitating, but stable disk (right). The colorbar shows the relative density perturbation at the midplane (top) and in the meridional plane (bottom).*

3.3. Giant planet orbital migration and eccentric disks

A well-known problem in planet formation theory is that in typical disk models, proto-planets migrate inwards rapidly and are lost to the central star, thereby preventing the formation of gas giant planets. Thus, recent theoretical focus have been on halting or reversing the inwards orbital migration of low-mass protoplanets (see e.g., Baruteau et al. 2014, for a recent review).

The outwards migration of *giant* planets have received much less attention. Only a limited number of studies have explored this possibility (Pepliński et al. 2008; Crida et al. 2009; D'Angelo & Marzari 2012). However, such mechanisms offer a potential explanation for 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 mechanisms for the outwards orbital migration of giant planets. I will go beyond previous efforts and consider self-gravitating disks, as appropriate for outer regions of PPDs, and improved thermodynamics.

Giant planets may also lead to globally distorted, eccentric disks (Papaloizou et al. 2001; Kley & Dirksen 2006; Dunhill et al. 2013). In Fig. 7, I show preliminary calculations that improve upon these studies by including disk self-gravity and/or non-adiabatic thermodynamics. I will study eccentric disk morphologies in relation to disk and planet properties. A related issue is that 3D eccentric disks are known to be hydrodynamically unstable (Papaloizou 2005b,a; Barker & Ogilvie 2014). I will study this instablity in the context of planet-induced eccentric disks by performing global 3D numerical simulations.

3.4. Magnetized self-gravitating disks

Magneto-hydrodynamic (MHD) turbulence and gravitational instability (GI) are the two robust transport mechanisms that underly accretion disks. These processes are typically studied in isolation (Turner et al. 2014). There are, however, conditions where they simultaneously develop: in the formation phase of PPDs (Inutsuka et al. 2010) and in layered-accretion models (Landry et al. 2013), PPDs can be both self-gravitating and magnetized. Most models that account for both effects have done so implicitly through a viscosity prescription (Armitage et al. 2001; Zhu et al. 2010b,a; Martin et al. 2012).

The goal of this project is to develop theoretical models of self-gravitating PPDs including *explicit* MHD. Key questions include to what extent does MHD and GI influence one another, how is angular momentum transport by GI affected by MHD and vice versa, and how does MHD turbulence influence the direct formation of giant planet via disk fragmentation?

There have been a limited number of attempts at this problem (Fromang et al. 2004c,a,b), but despite being from over a decade ago, these studies still present the latest simulations. A major effort here will be to perform direct simulations of magnetized, self-gravitating disks that go beyond early numerical limitations with modern computational resources. This includes high numerical resolution and long-term simulations.

I will begin with local, shearing-box simulations with the `ATHENA` code, using Lin (2014a) to benchmark and guide the results. I will then move onto global disk simulations using the `ZEUS` and/or `PLUTO` codes. These will also serve as basis for studying disk-planet interaction in young PPDs which are massive and magnetized.

Analytical work will continue to play a pivotal role in this study. I will continue to develop the magnetized, self-graviating disk models presented in Lin (2014a). Specifically, improved treatment of disk thermodynamics (including heating and cooling processes) will be implemented in order to properly study gravitational instabilities.

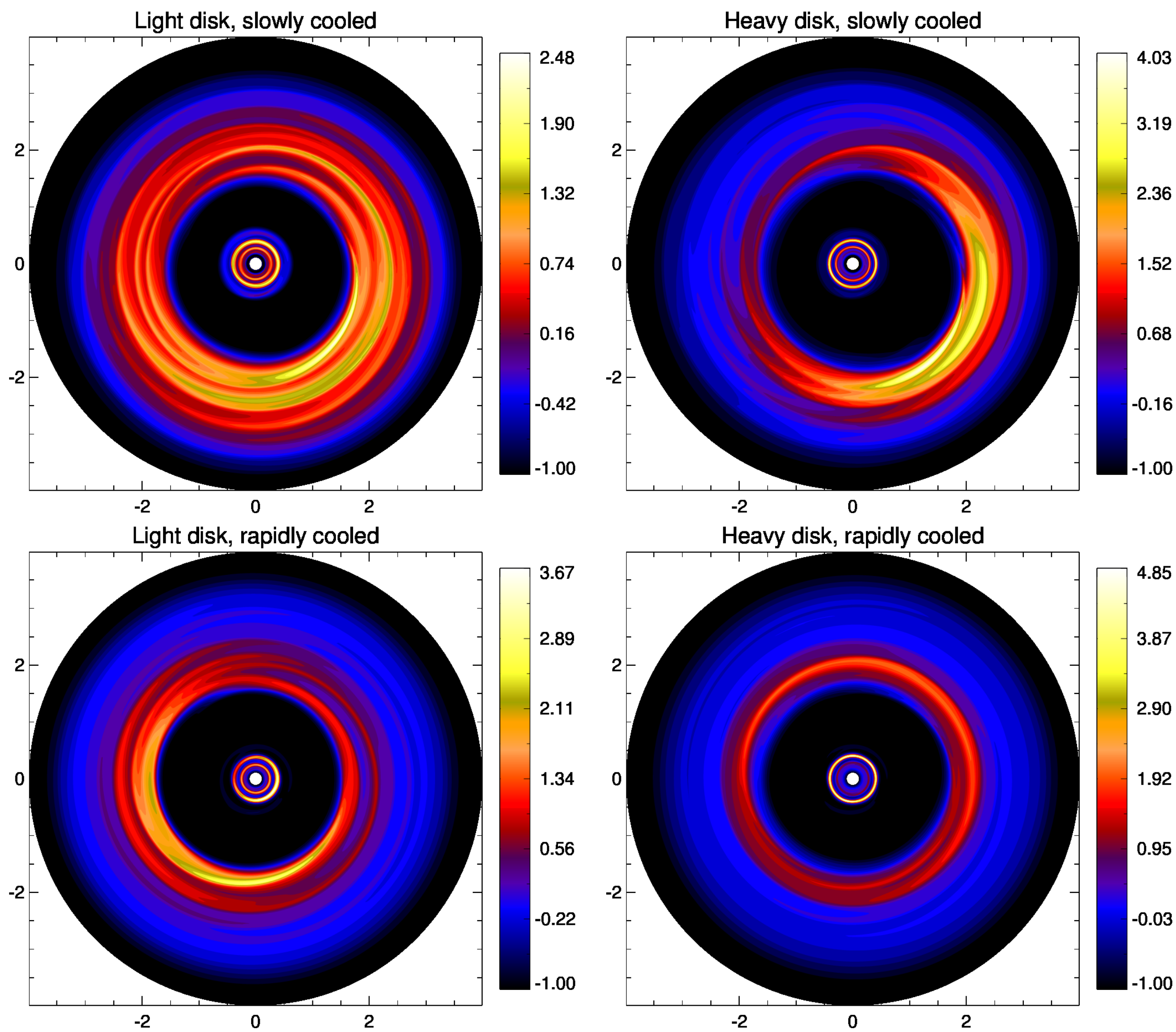

Fig. 7.— *Formation of eccentric gaps due to disk-planet interaction. Here, a 5-Jupiter mass planet is inserted into a self-gravitating, non-isothermal disk and held on a fixed, circular orbit. Top panels: slowly-cooled disks with* $t_{\rm cool} = 10\Omega^{-1}$*; bottom panels: rapidly cooled disks with* $t_{\rm cool} = 0.1\Omega^{-1}$. Left panels: light disks with $M_d \simeq 0.0002M_*$; right panels: heavy disks with $M_d \simeq 0.05M_*$.

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