Hydrodynamic activity in protoplanetary disks

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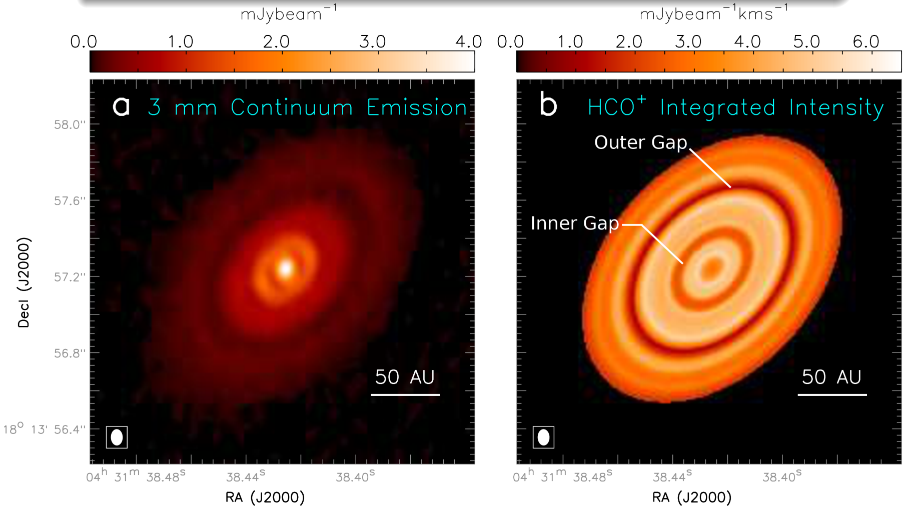
A new era for planet formation

Planets form in protoplanetary accretion disks around young stars



(HL Tau, Yen et al., 2016)

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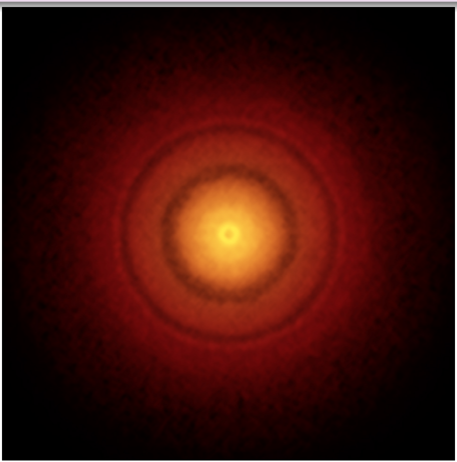
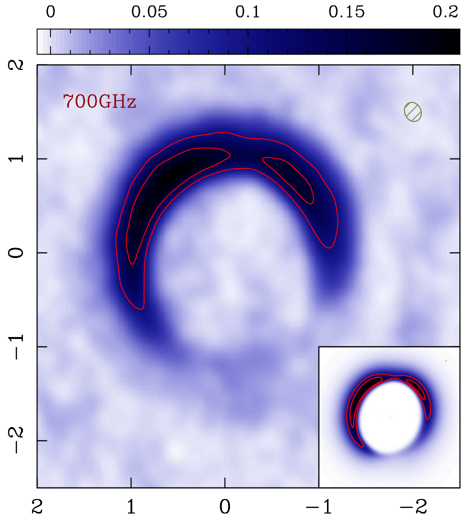


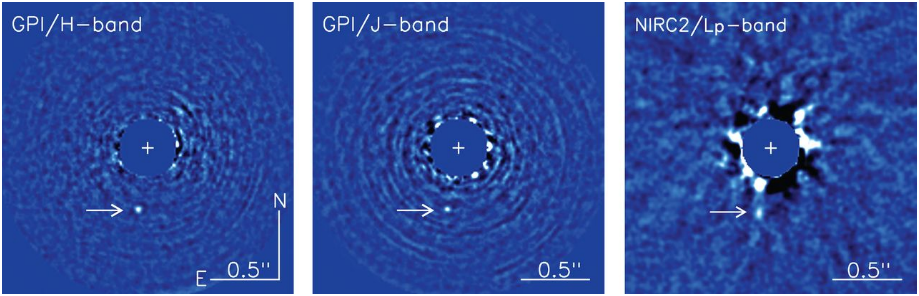
(TW Hydrae, Andrews et al., 2016)

Asymmetric transition disks



(HD142527, Casassus et al., 2015)

Directly imaged planets



(51 Eridani, Macintosh et al., 2015)

Planet formation theory builds on accretion disk theory

Fundamental gas dynamics of protoplanetary accretion disks

- How do disks transport angular momentum and accrete?
  - Turbulent transport?
  - Spiral arms from self-gravity?
  - Magnetic winds?

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- What are the sources of turbulence in disks?
  - Hydrodynamic, gravitational, or magneto-hydrodynamic?
  - Where and when do these operate?

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- Origin of large-scale structures? Rings, gaps, asymmetries/vortices, spirals
  - Planet induced?
  - Fluid instabilities?

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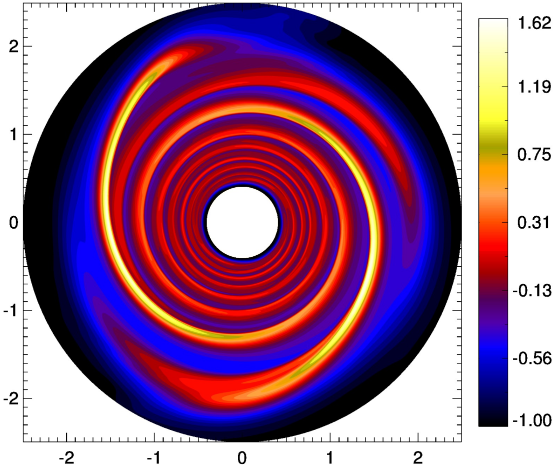
- Origin of large-scale structures? Rings, gaps, asymmetries/vortices, spirals
  - Planet induced?
  - Fluid instabilities?
- How do large-scale structures affect planet formation?
  - Dust-trapping mechanisms (enhance planetesimal formation)?
  - Dynamical interaction with planets?

Hydrodynamical processes in protoplanetary disks

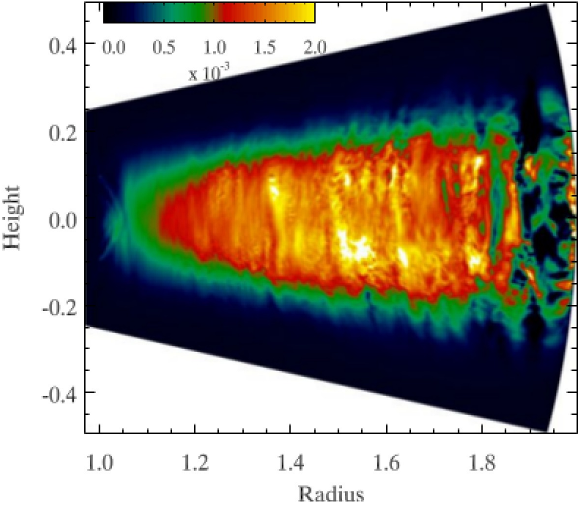
- Gravitational instabilities in young, massive PPDs
  - Going beyond Toomre and Lin-Shu analyses (Lin & Kratter, submitted)



(M.-K. Lin, Fargo simulations, density perturbation)

Hydrodynamical processes in protoplanetary disks

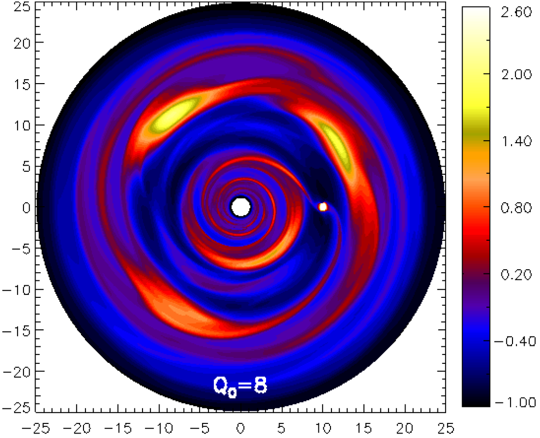
- Vertical shear instability and hydrodynamic turbulence
  - Does it occur in realistic PPDs? (Lin & Youdin, 2015)



(VSI simulation, Nelson et al., 2013, turbulent stresses)

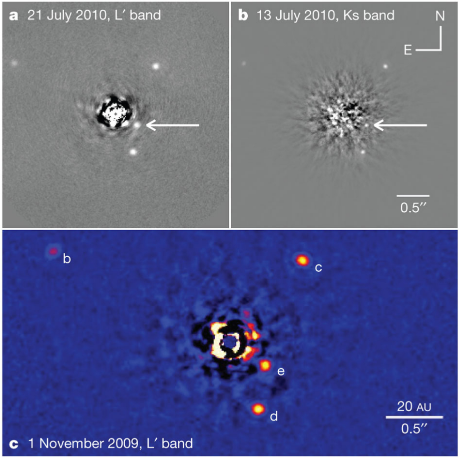
Hydrodynamical processes in protoplanetary disks

- Large-scale vortices in PPDs as dust-traps
  - 3D effects in self-gravitating disks (Lin et al., in prep.)



(Zeus simulation, Lin, 2012b, density perturbation)

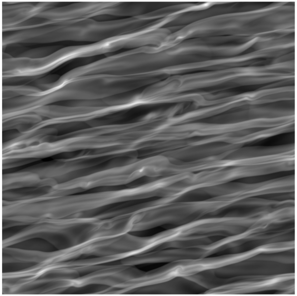
Directly imaged wide orbit planets/brown dwarfs



(Marois et al., 2010)

Disk instability theory

- Young, massive protoplanetary disks can fragment under its own gravity



Fragmentation conditions from simulations

- Massive disk

$$Q \equiv \frac{c_s\Omega}{\pi G\Sigma} \lesssim 2 \text{ or } M_{\rm disk} \gtrsim 0.1M_*$$

- Fast cooling

$$t_{\rm cool}\Omega \lesssim 3$$

The cooling criterion is empirical!

When do realistic protostellar disks fragment?

Work out $\Sigma(R)$, $T(R)$..etc., then ask

1. Where/when is Toomre $Q \lesssim 2$?
2. Where/when is $t_{\rm cool}\Omega \lesssim 3$?

WARNING

Critical cooling depends on the numerical simulation!

(resolution, 2D/3D, local/global, particle-based or grid-based simulations)

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Motivation 1:

Assess disk fragmentation without input from hydrodynamic simulations

Beyond classical gravitational instability

Modern simulations (c. 2010)

- Cooling physics, e.g.

$$\frac{\partial E}{\partial t} = -\frac{E}{t_{\mathrm{cool}}}$$

- Turbulent/viscous, e.g.

$$\nu = \alpha \frac{c_s^2}{\Omega}$$

Analytic toolbox (c. 1960)

Lin-Shu dispersion relation, Toomre Q

$$\omega^2 = \kappa^2 - 2\pi G\Sigma|k| + c_s^2 k^2$$

$$Q \equiv \frac{c_s \kappa}{\pi G \Sigma}$$

- Isothermal/adiabatic (no cooling)
- Laminar (inviscid)

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Motivation 2:

Generalize analytic treatment of GI to include cooling, irradiation and viscosity

$$\omega = \omega(k; Q, t_{\mathrm{cool}}, \alpha)$$

Quantifying cooling

Dispersion relation **with cooling**

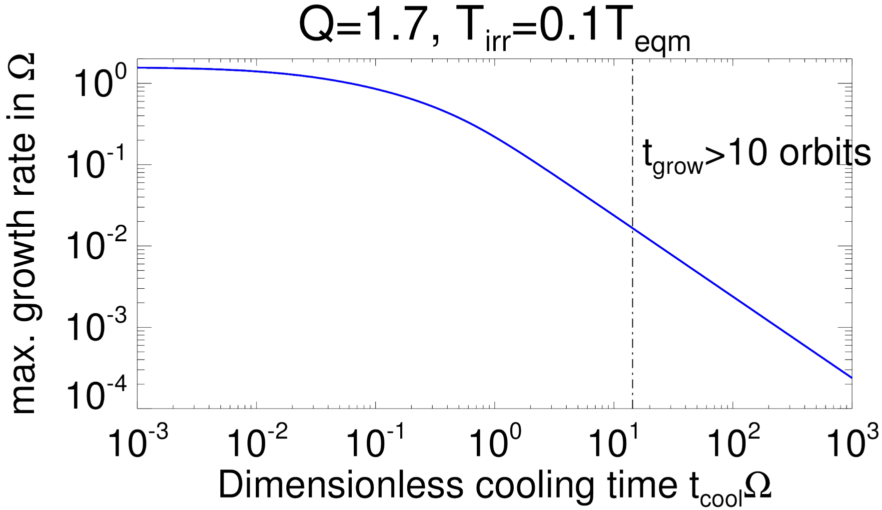
$$\underbrace{s^2}_{\text{growth}} = \underbrace{2\pi G\Sigma|k|}_{+\text{gravity}} \quad \underbrace{-\Omega^2}_{-\text{rotation}} \quad \underbrace{-\left(\frac{T_{\mathrm{irr}}/T + \gamma t_{\mathrm{cool}} s}{1 + t_{\mathrm{cool}} s}\right) c_s^2 k^2}_{-\text{modified pressure}}$$

(Lin & Kratter, sumbitted)

- T_{irr}: irradiation or floor temperature
- **Can be unstable even for $Q > 1$** (cf. $Q < 1$ for classic GI)

Cooling changes the fundamental nature of disk GI

Cooling-driven gravitational instability

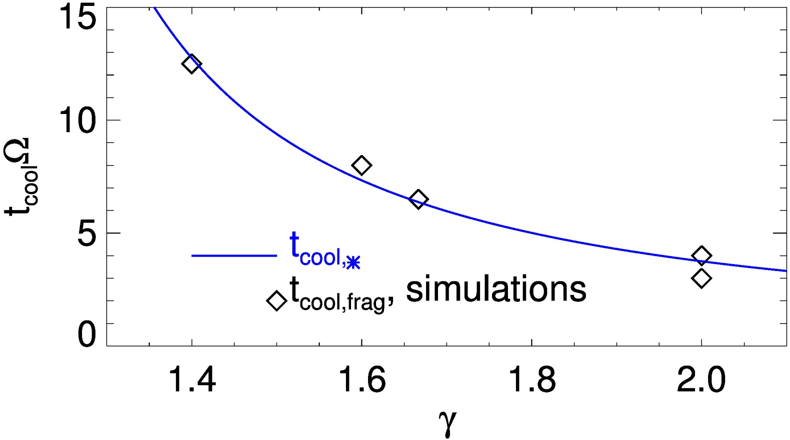


(Lin & Kratter, sumbitted)

Understanding simulations

Cooling timescale to remove pressure over a lengthscale $\sim H$

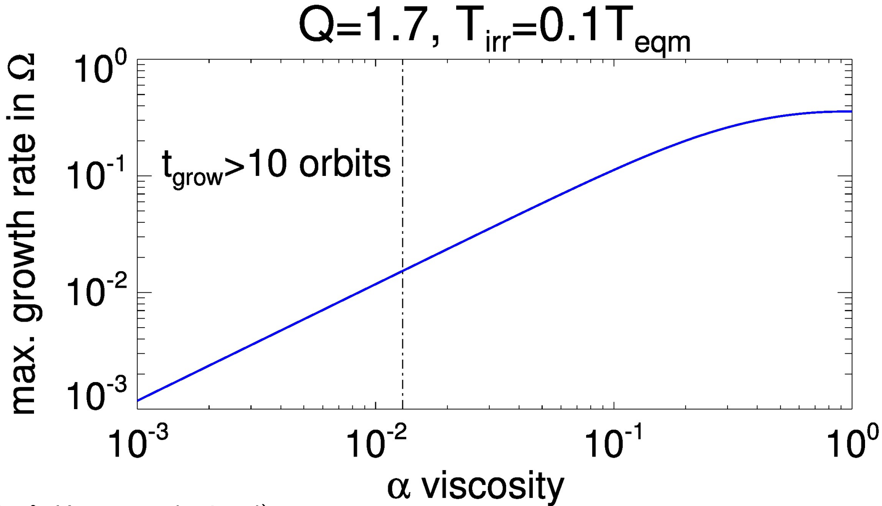
$t_{\mathrm{cool},*} = \left(\sqrt{\gamma} - 1\right)^{-3/2} \Omega^{-1}$ (Lin & Kratter, sumbitted)



Simulations: Gammie (2001); Rice et al. (2005, 2011); Paardekooper (2012)

Viscous gravitational instability

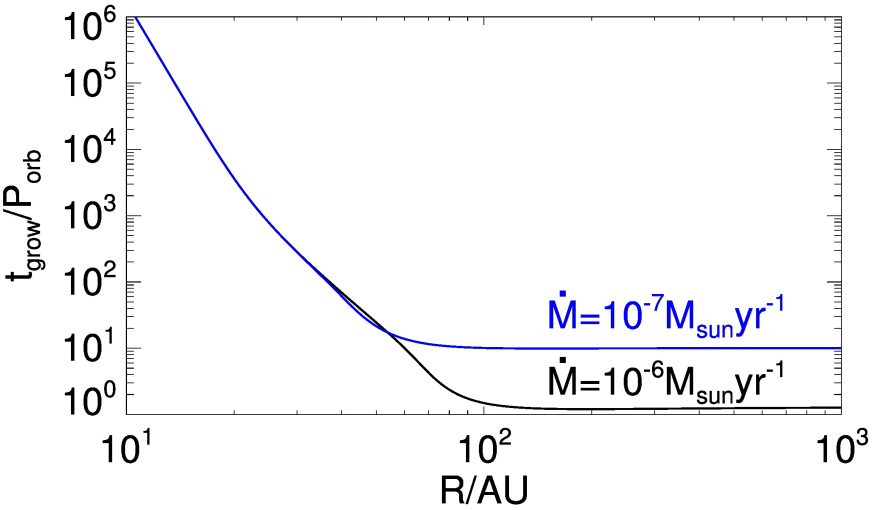
- Viscosity/friction can remove rotational stabilization (Lynden-Bell & Pringle, 1974)



(Lin & Kratter, submitted)

Putting it all together: application to protoplanetary disks

- Input physical disk model with cooling and viscosity — get growth timescales



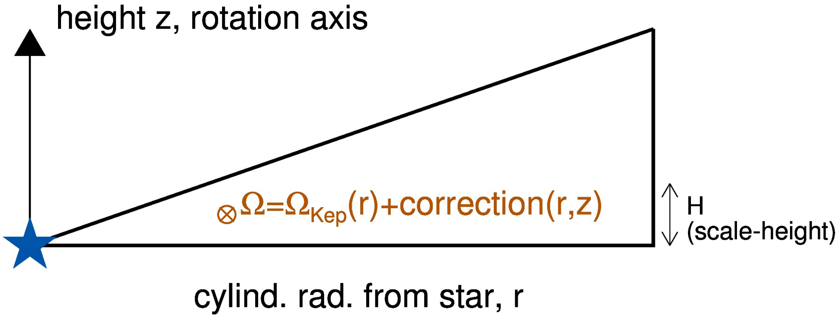
(Lin & Kratter, submitted)

- High $\dot{M}$ disk fragments $\gtrsim$ 60AU, growth times $\sim$ one orbit

What's next for disk GI theory?

- Global analyses with cooling and viscosity
  - Mass infall
  - Disks with radial structure
  - Large-scale spiral instabilities
- Magnetic effects: good or bad for stability?
  - Extend Lin (2014) to include cooling/viscosity

Astrophysical disks have vertical shear



$$\boxed{\frac{\partial \Omega}{\partial z} \neq 0}$$

(Because $\nabla P \times \nabla \rho \neq 0$)

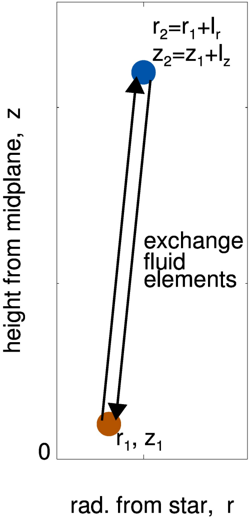
- Vertically isothermal thin-disk with $T \propto r^q$,

$$r\frac{\partial \Omega}{\partial z} \simeq \left(\frac{qz}{2H}\right) \times \frac{H}{r}\Omega_{\mathrm{Kep}}$$

- $H/r \sim 0.05$ in PPDs

Vertical shear instability

$\partial_z \Omega \neq 0 \Rightarrow$free energy$\rightarrow$instability?



- Change in kinetic energy:

$$\Delta E \sim l_r^2 \left(\Omega^2 + \frac{l_z}{l_r} \cdot r \frac{\partial \Omega^2}{\partial z} \right)$$

- Vertical shear is weak, **BUT**

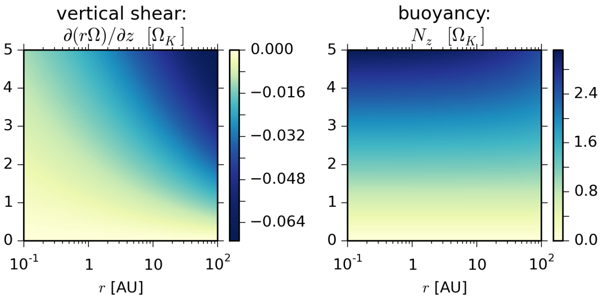
$$\Delta E < 0 \quad \text{if} \quad |l_z| \gg |l_r|$$

$\Rightarrow$ **INSTABILITY**

- Energy released for vertically elongated disturbances.

VSI needs to fight buoyancy in real disks

$$\underbrace{r\partial_z\Omega}_{\text{destabilizing vert. shear}} \quad \text{v.s.} \quad \underbrace{N_z}_{\text{stabilizing vert. buoyancy}}$$



- Vertical shear is weak, $\boxed{r\partial_z ln\Omega \sim O(h) \ll 1}$ (so need $l_z/l_r \gg 1$)
- Vertical buoyancy is strong, $\boxed{N_z/\Omega \sim O(1)}$

Ultra-fast cooling can overcome buoyancy forces

(Lin & Youdin, 2015) : quasi-global analyses of the VSI

- Including energy equation with finite cooling timescale t_{cool}

For $T \propto r^q$ disk, find that VSI requires:

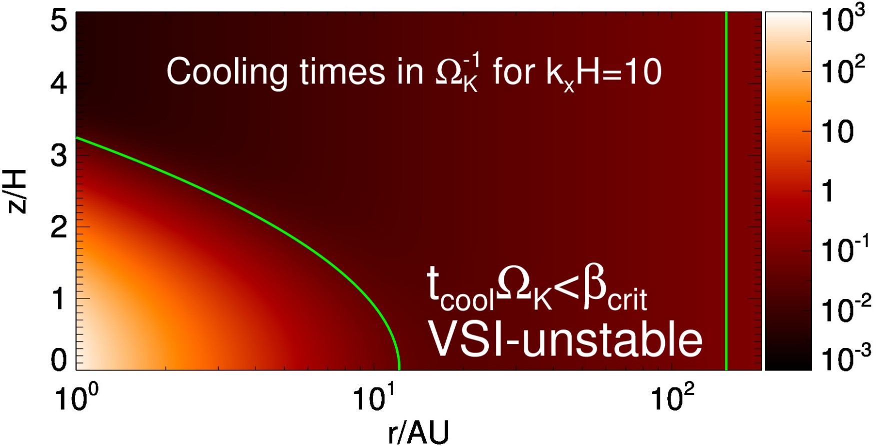
$$t_{\mathrm{cool}}\Omega_{\mathrm{K}} < \frac{h|q|}{\gamma - 1}$$

- $h|q|$: vertical shear ($h \equiv H/r \ll 1$) — destabilizing
- $\gamma - 1$: vertical buoyancy — stabilizing
- $t_{\mathrm{cool}}\Omega_{\mathrm{K}} \ll 1$ required, i.e. rapid cooling
- As seen in high res. numerical simulations
  e.g. Nelson et al. (2013) find VSI only for $t_{\mathrm{cool}}\Omega_{\mathrm{K}} \lesssim 0.06$

Do protoplanetary disks actually develop VSI?

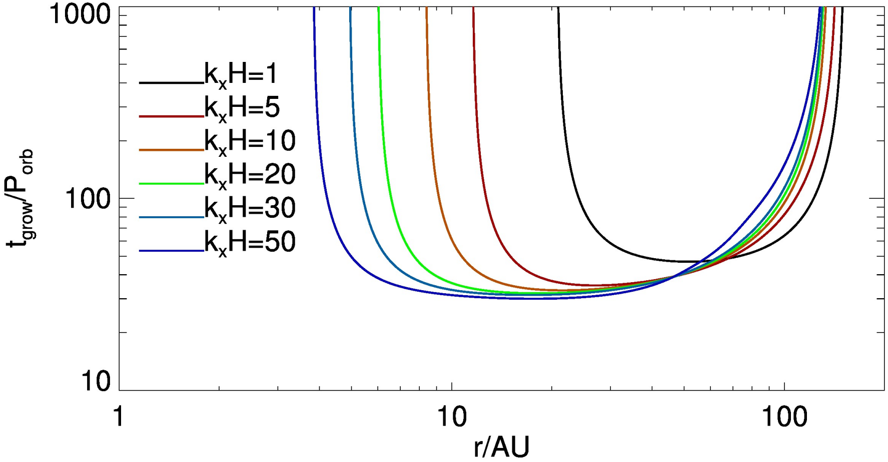
Cooling via dust-opacity ($\propto T^2$) in the Minimum Mass Solar Nebula (Chiang & Youdin, 2010)

$$\beta_{\rm crit} \equiv \frac{h|q|}{\gamma - 1}$$



Typical VSI growth times in the Solar Nebula

- Solve the full linearized fluid equations in the radially local approximation, with radiative diffusion/optically-thin cooling



- VSI is most active in the outer disk 10—100AU
- Forced to develop on smaller scales towards inner disk

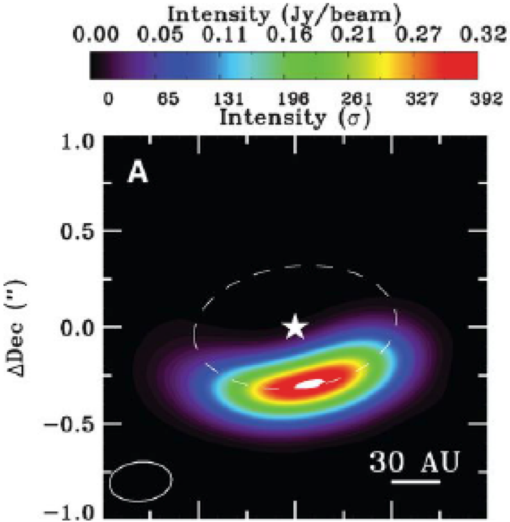
What's next for VSI theory?

Vertical shear in dusty fluids

$$r\frac{\partial \Omega^2}{\partial z} = \frac{c_s^2}{\left[1+\left(\frac{\rho_{\mathrm{dust}}}{\rho_{\mathrm{gas}}}\right)\right]^2}\left[\frac{\partial \ln \rho_{\mathrm{gas}}}{\partial z}\frac{\partial}{\partial r}\left(\frac{\rho_{\mathrm{dust}}}{\rho_{\mathrm{gas}}}\right) - \frac{\partial \ln \rho_{\mathrm{gas}}}{\partial r}\frac{\partial}{\partial z}\left(\frac{\rho_{\mathrm{dust}}}{\rho_{\mathrm{gas}}}\right)\right]$$

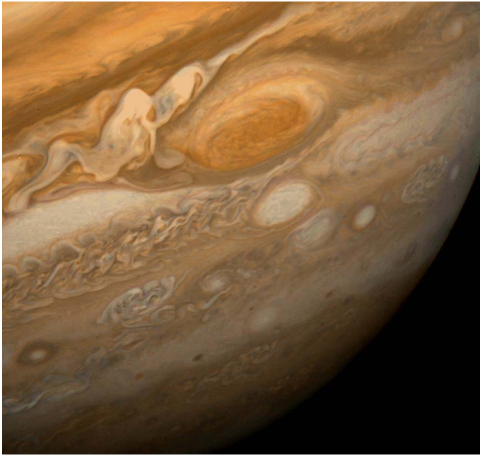
- Develop linear theory for VSI with perfectly-coupled, small dust particles
- Any students interested?

Transition disk asymmetries: vortices?



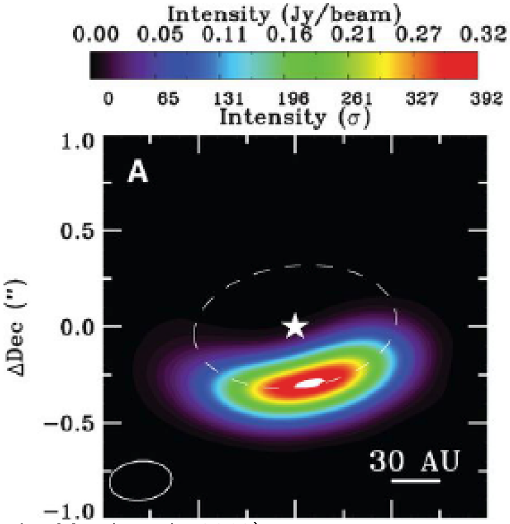
(Oph IRS 48, van der Marel et al., 2013)

Transition disk asymmetries: vortices?



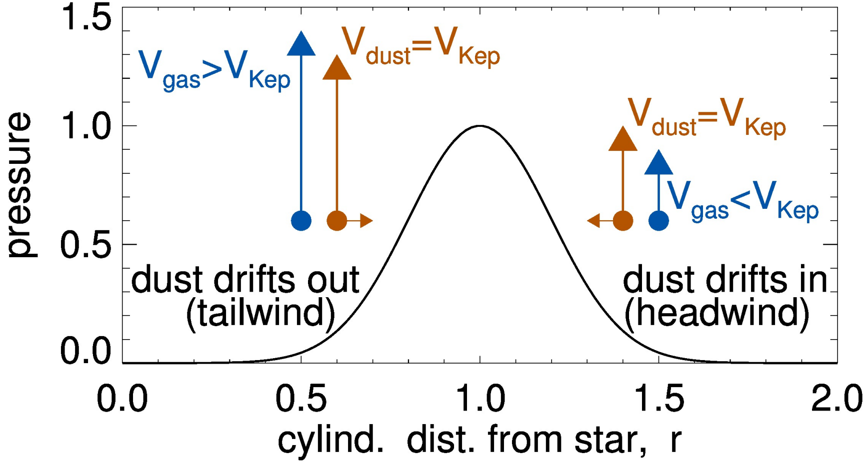
Jupiter's Great Red Spot

Transition disk asymmetries: vortices?



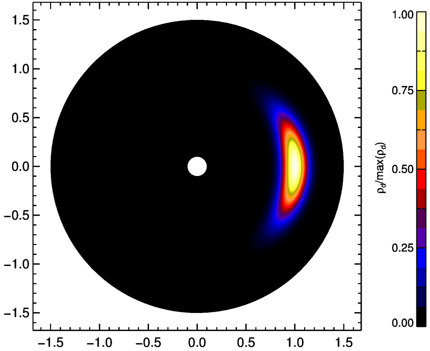
(Oph IRS 48, van der Marel et al., 2013)

Dust-trapping at pressure maxima



- Drag forces cause dust to accumulate at pressure bumps

Dust distribution in disk vortices



$$\rho_d(a) \propto \exp\left(-\frac{a^2}{2H_v^2}\right),$$

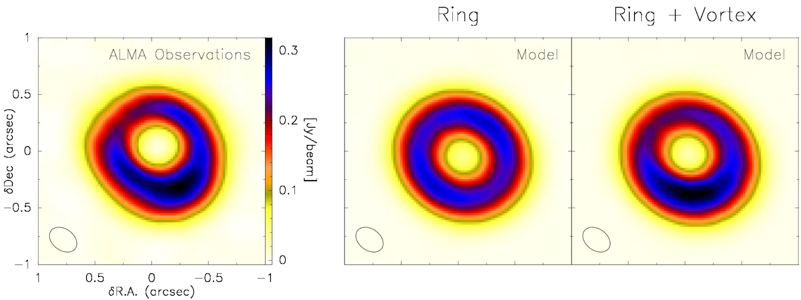
- a: distance from the vortex center

(Lyra & Lin, 2013)

$$H_v(\chi, \delta, \mathrm{St}) = \frac{H_g}{f(\chi)}\sqrt{\frac{\delta}{\delta + \mathrm{St}}}.$$

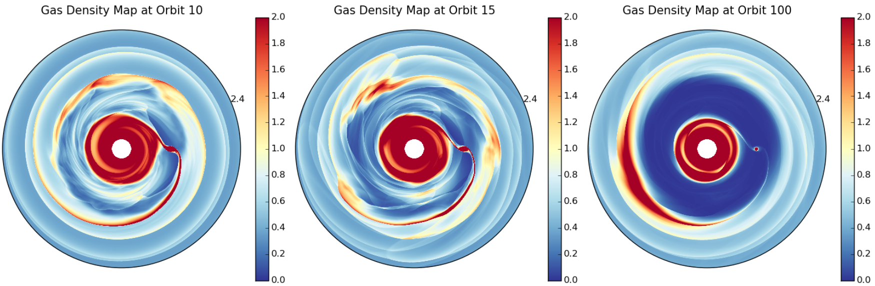
- χ: vortex aspect-ratio
- δ: turbulence in the vortex
- St: Stokes number (dust-gas friction)
- H_g: gas scale height

Application to observations



(SAO 206462, Pérez et al., 2014)
$\chi_{\rm obs} \sim 7$, model+ data $\rightarrow v_{\rm turb} \sim 0.22 c_s$.

Gap edges as sites for vortex formation

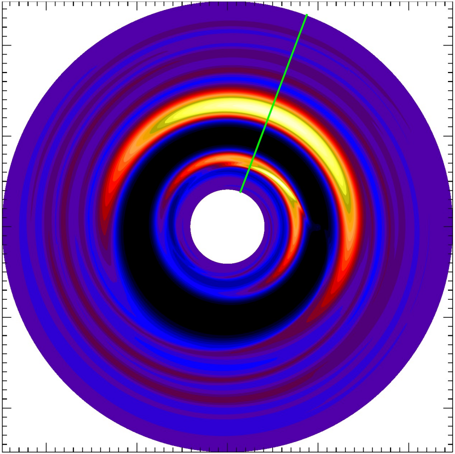


(Credits: UA grad. student M. Hammer, 'Vortices and orbital migration')

- Disk-planet interaction → gaps
- Surface density maxima at gap edges, or PV minima due to strong shear
- Rossby wave instability → edges 'roll up' into vortices (Li et al., 2001)

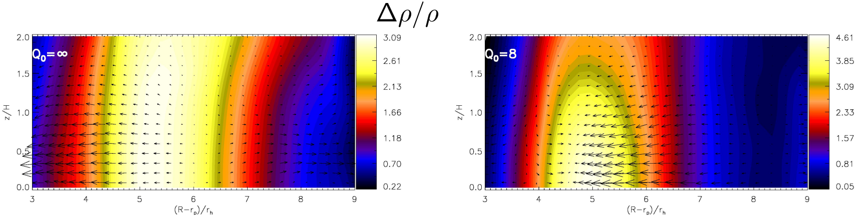
Gap edges as sites for vortex formation

Basic theory is 2D, but PPDs are 3D



Take a look in the (r, z) plane through the vortex

Rossby vortices are vertically global



↑ NO self-gravity

↑ WITH self-gravity

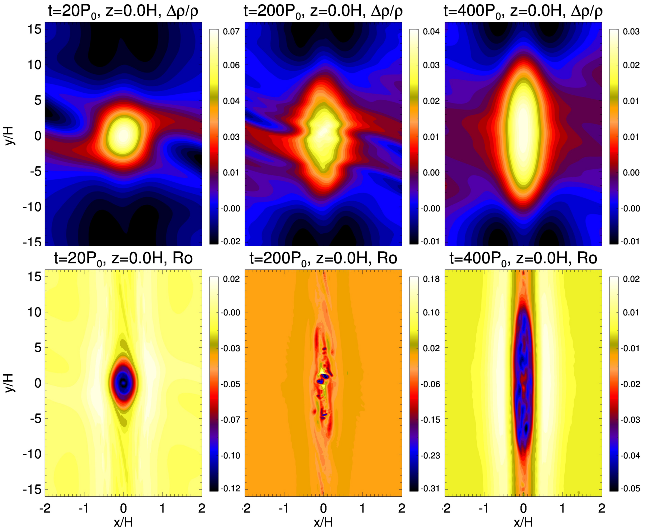
- Global 3D Zeus simulations (Lin, 2012b)
- Consistent with 3D linear theory (Lin, 2012a, 2013a,b)
- Vortex evolution is sensitive to disk vertical structure (Lin, 2014)

Elliptic instability of 3D vortices: shortened vortex lifetimes

- A 3D instability that weakens/destroys vortices (Lesur & Papaloizou, 2009)

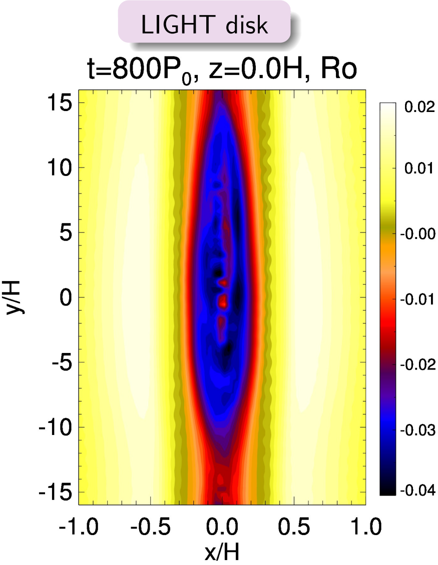
Density pert.

Vorticity/2Ω

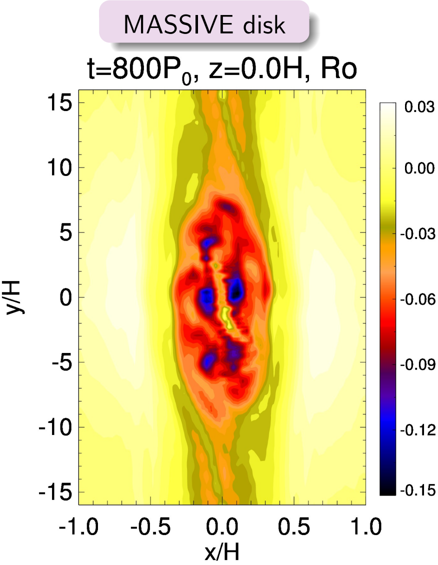


Athena simulations (Lin et al., in prep.)

Elliptic instability & self-gravity (Lin et al., in prep.)

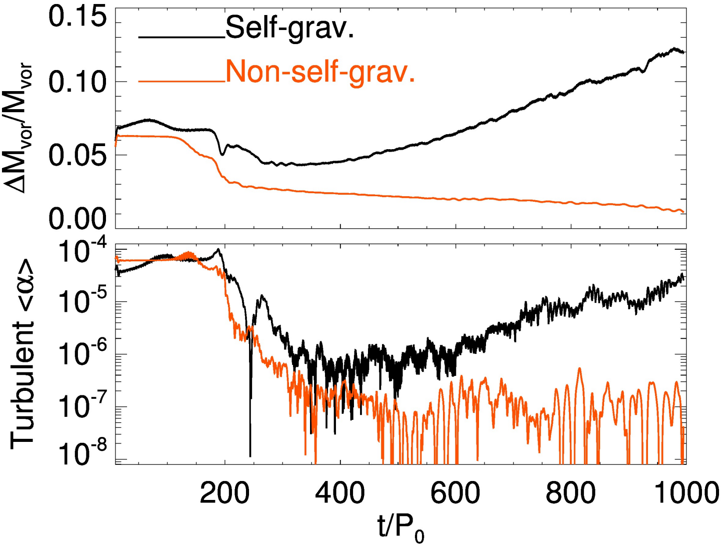


$(Q = 100)$



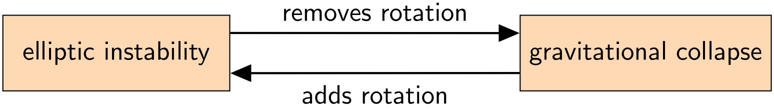
$(Q = 3)$

Elliptic instability & self-gravity (Lin et al., in prep.)



- Self-gravitating vortex collapse correlates with increasing internal turbulence

Conjecture, ongoing, and future work



- Analyze data and design further experiments to verify the effect of self-gravity
- Parameter study: vortex size/shape, box size, resolution
- Implement 'vortex-forming' process in simulations

Summary

Generalized gravitational instability

- Cooling: reduces thermal support
- Viscosity: reduces rotational support
- Fragmentation: GI due to cooling and/or turbulent stresses (viscosity)

Vertical shear instability

- Feeds off free energy in $\partial_z \Omega \neq 0$
- Enabled by ultra-fast cooling in PPDs
- VSI possible in the outer PPD between 10—100AU

Vortices in massive 3D disks

- Self-gravity helps vortex survival, but with a turbulent core?

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