Planet signatures in transition disks

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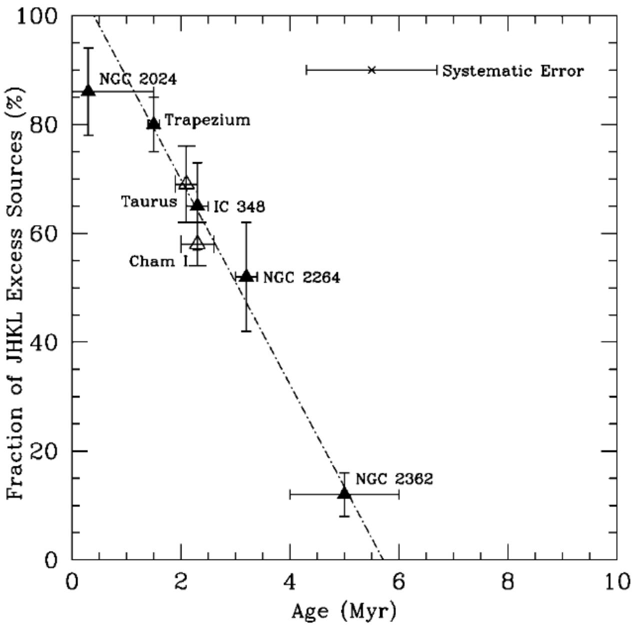
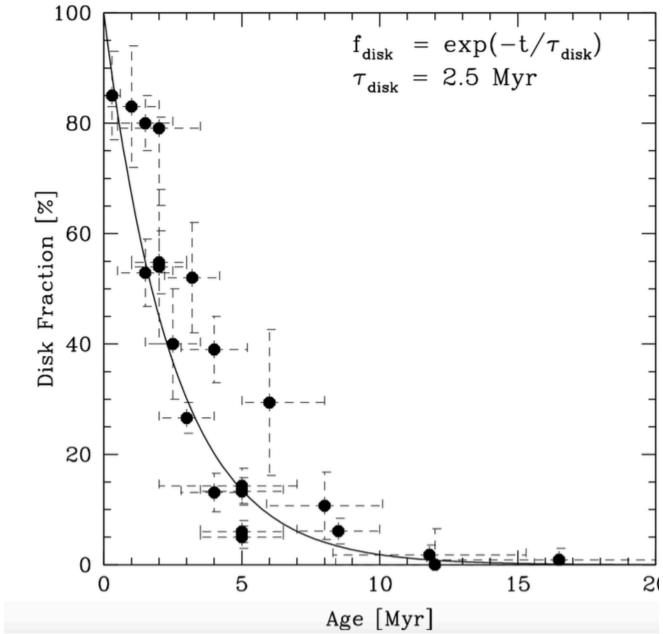
Nagoya University, Dec 18th, 2015

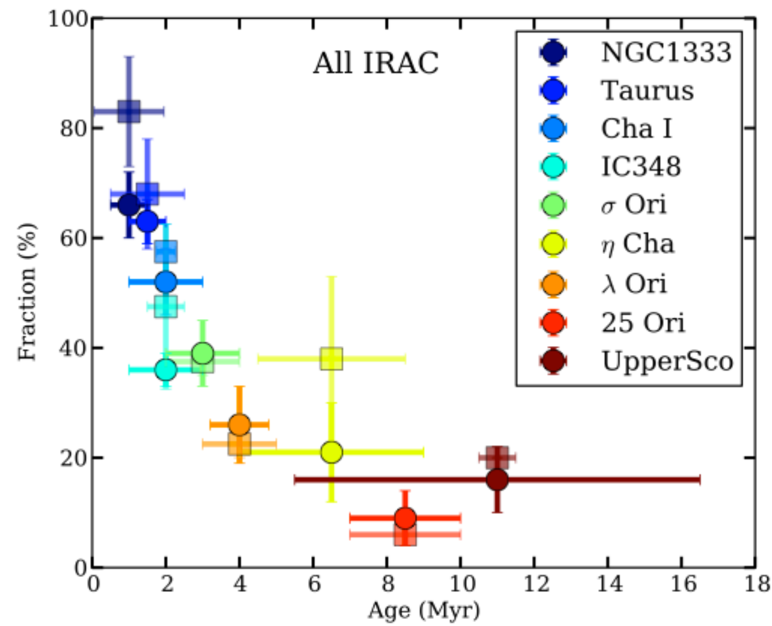
Disk lifetime



(Haisch et al. 2001)



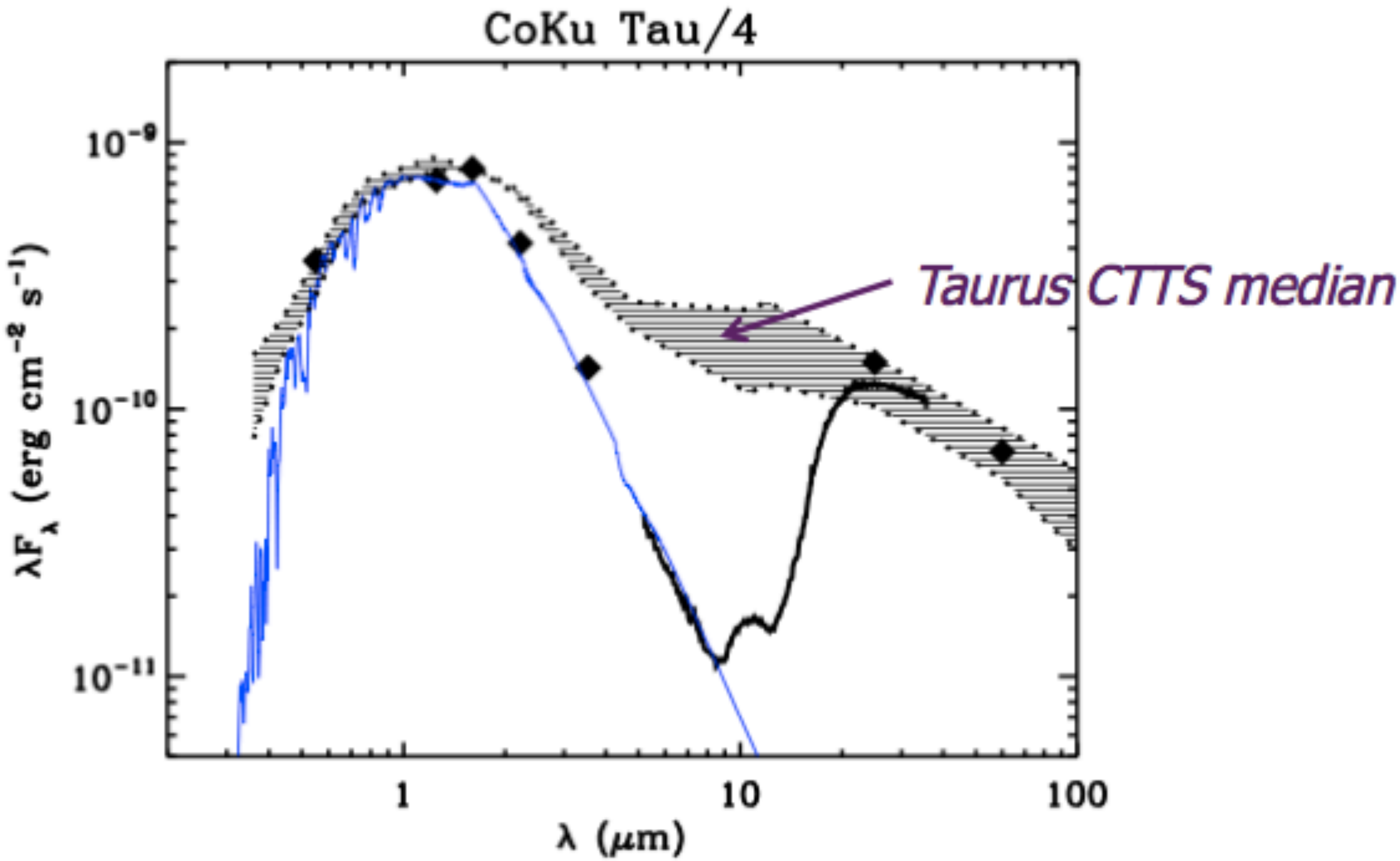
(Mamajek et al. 2009)



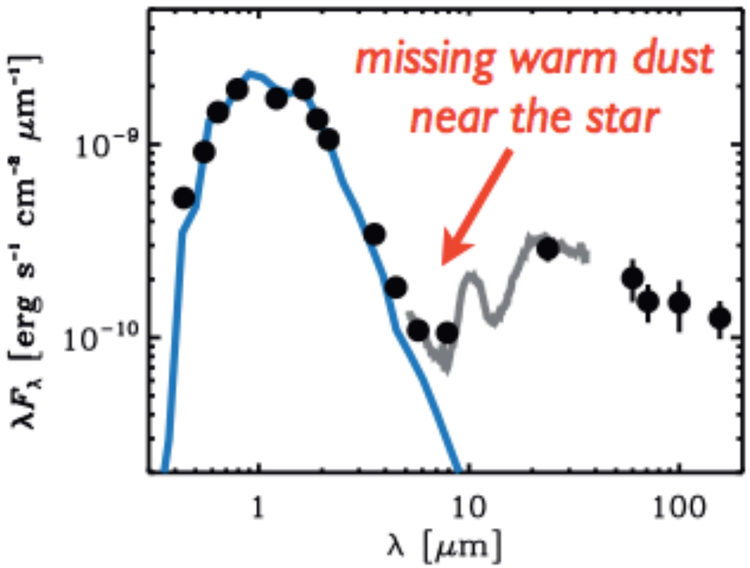
(Ribas et al. 2014)

Disks dissipate with an e-folding time of 2.5 Myr

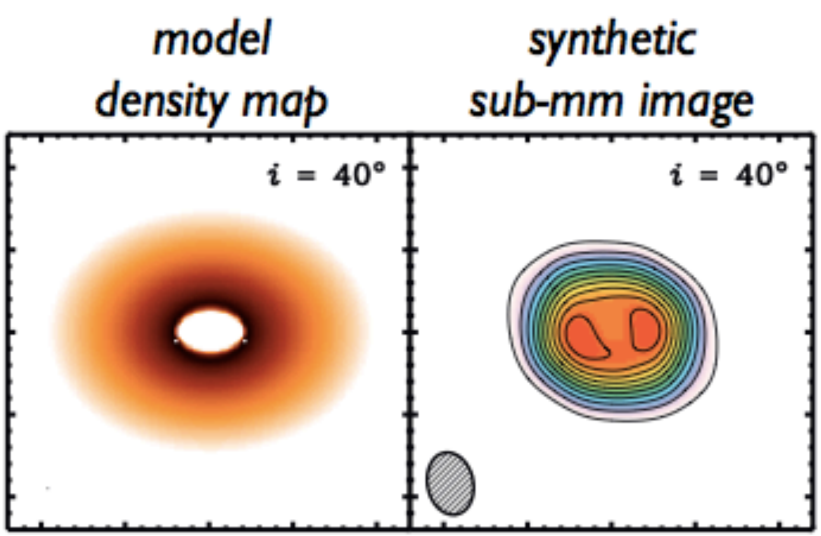
Transition Disks: Disks with missing hot dust.



Transition Disks: Disks with missing hot dust.

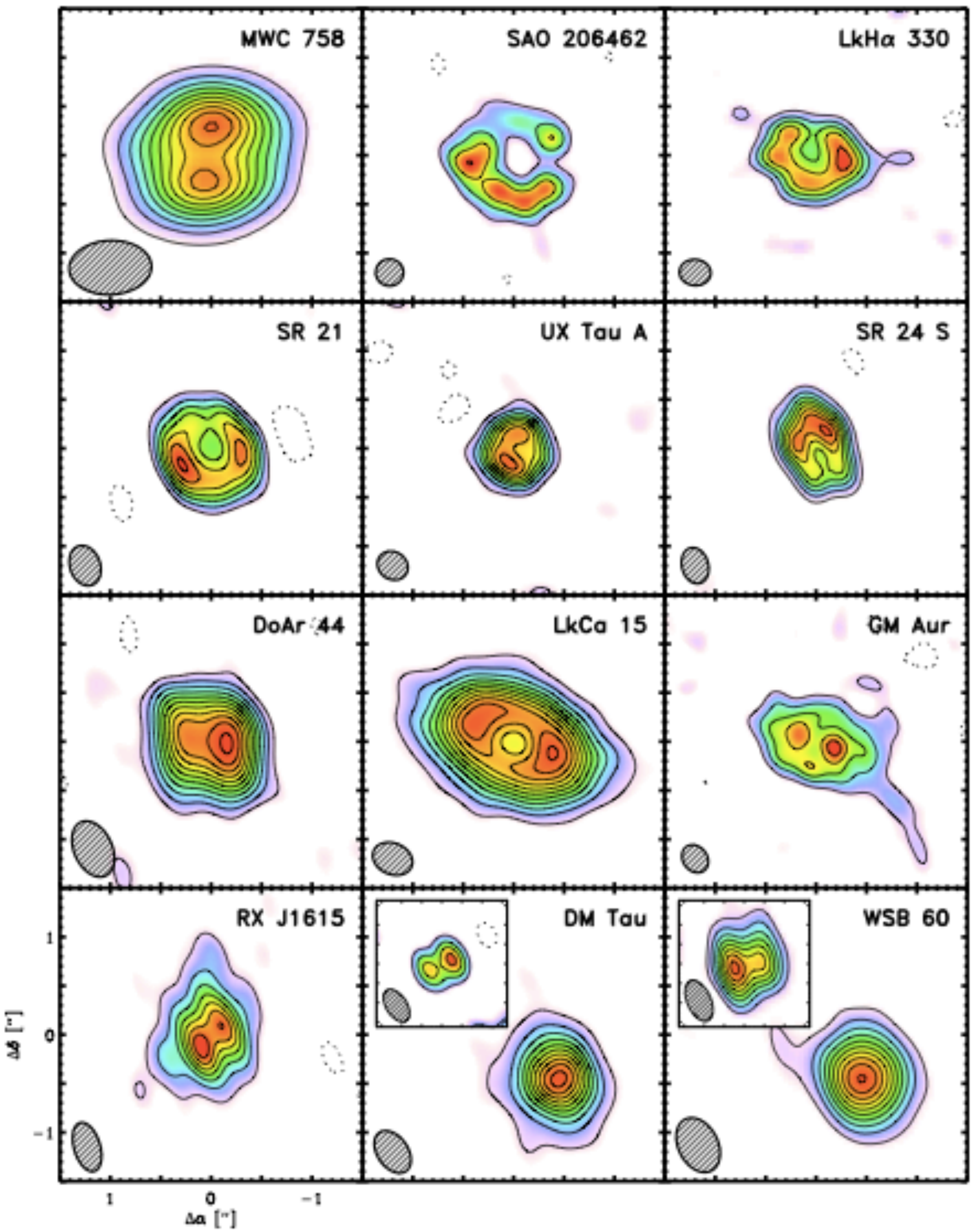


[e.g., Furlan et al. 2009]

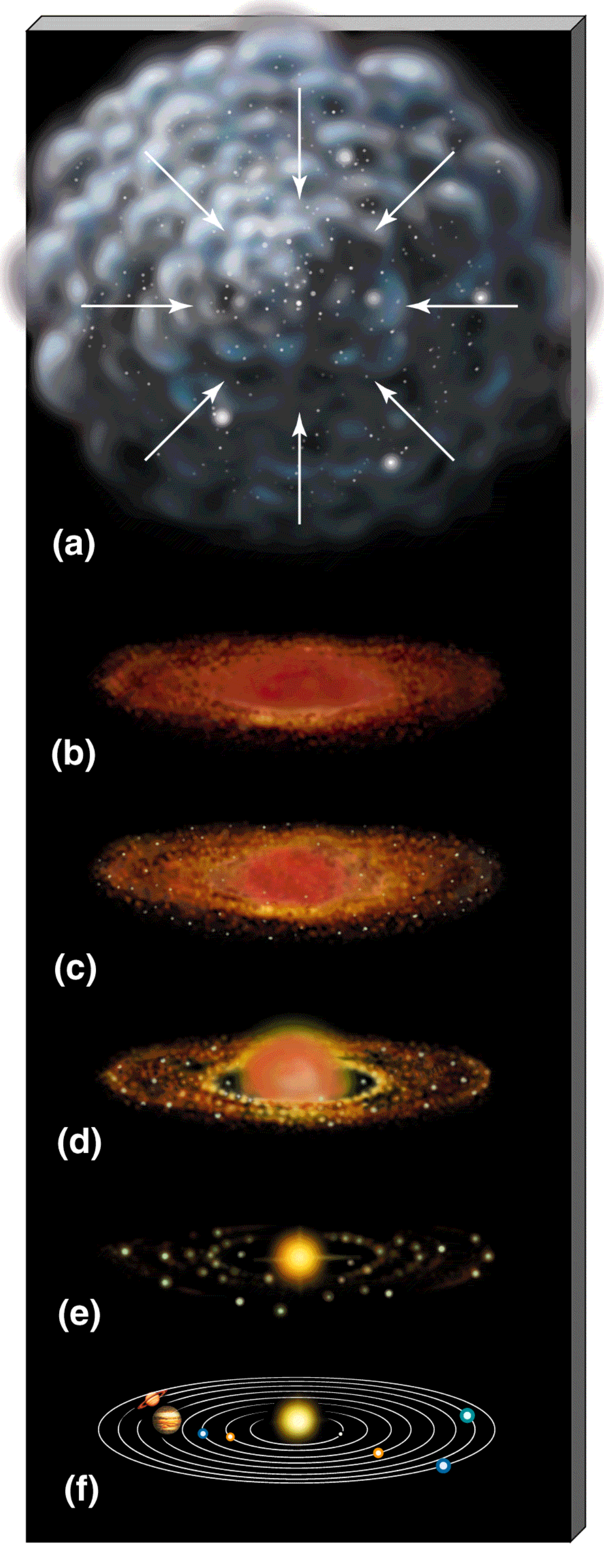


a disk with a large reduction in optical depth near the star (i.e., a “cavity” or “hole”)

Resolved transition disks with the Sub-millimeter Array (SMA)



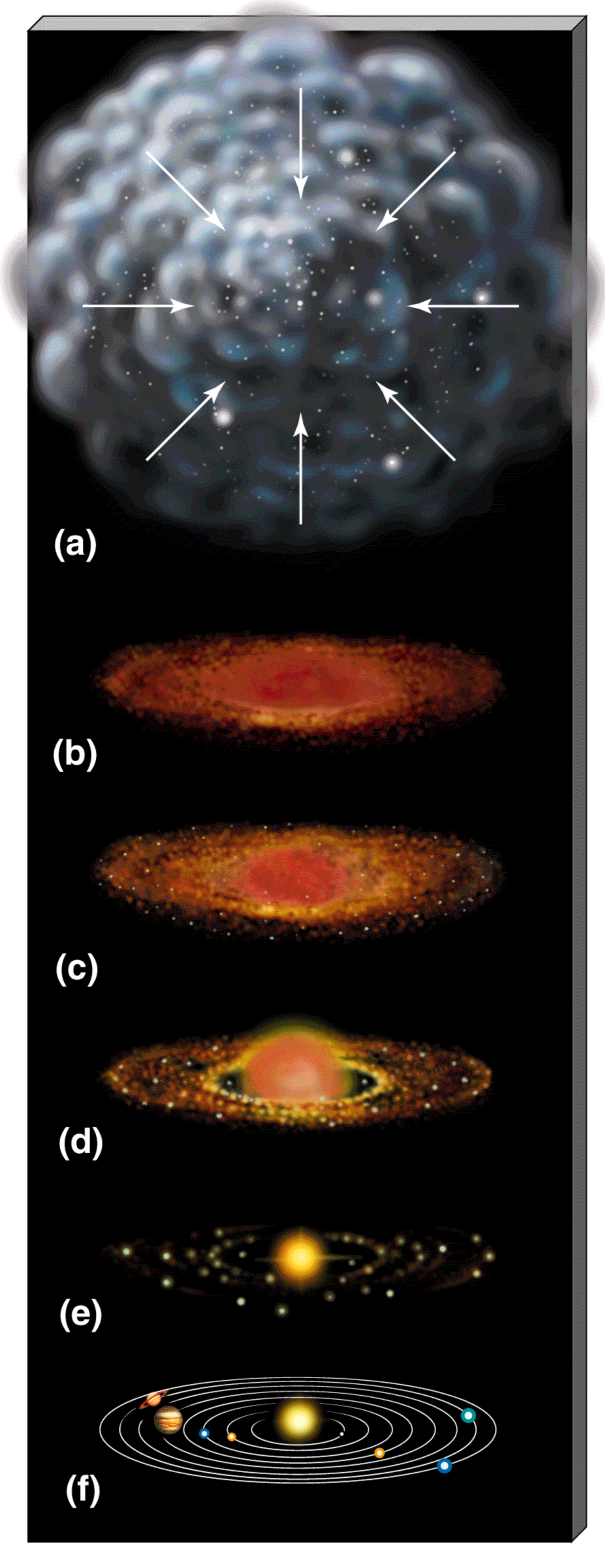
0.85mm
0.3” ~ 20 AU resolution



Are transitional disks related to disk evolution?

Gas-rich phase (< 10 Myr)
Primordial Disks

Gas-poor phase (>10 Myr)
Debris Disks



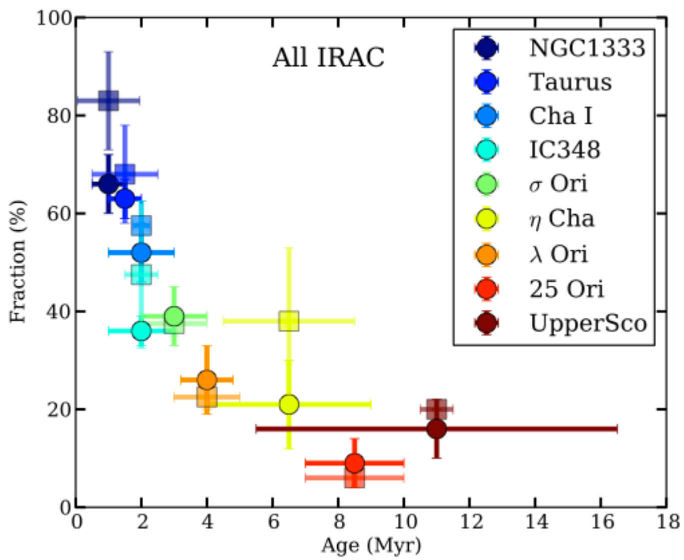
Are transitional disks related to disk evolution?

Gas-rich phase (< 10 Myr)
Primordial Disks

Conjecture:
Thinning phase (~10 Myr)
Transitional Disks

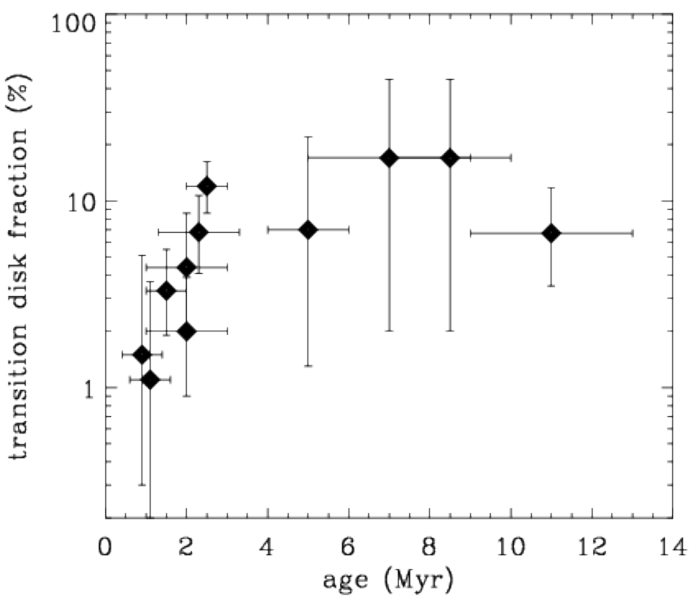
Gas-poor phase (>10 Myr)
Debris Disks

Transition disks and disk evolution



(Ribas et al. 2014)

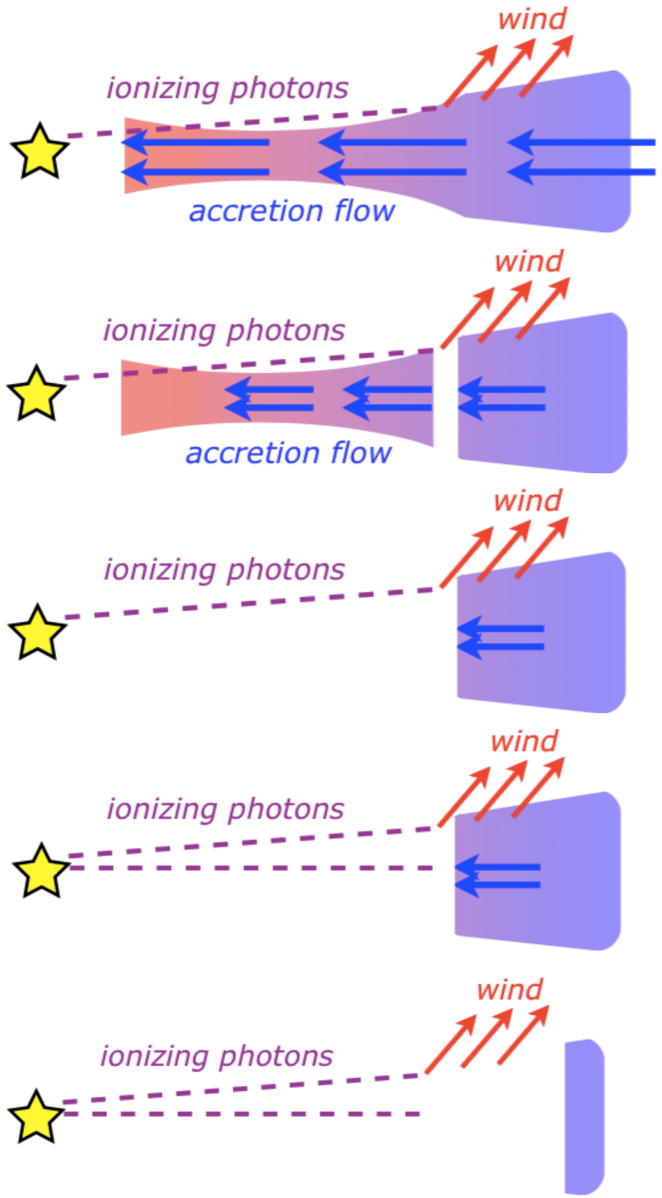
"Total" disk fraction



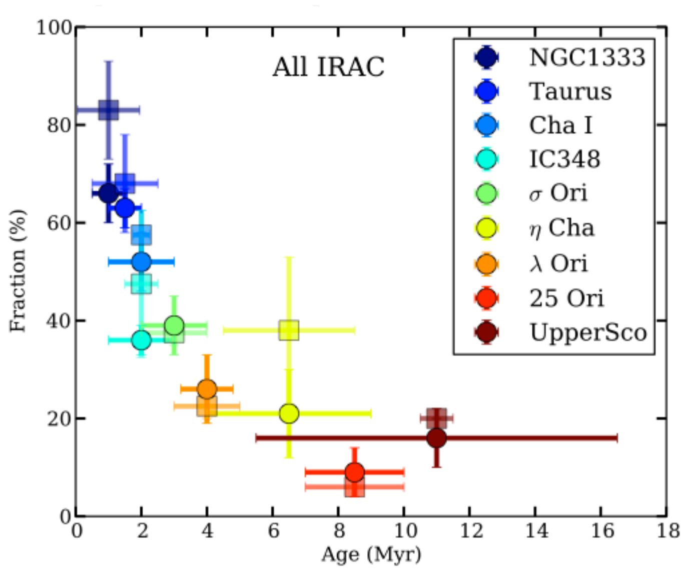
(Espaillat et al. 2014)

Transition disk fraction

Photoevaporation

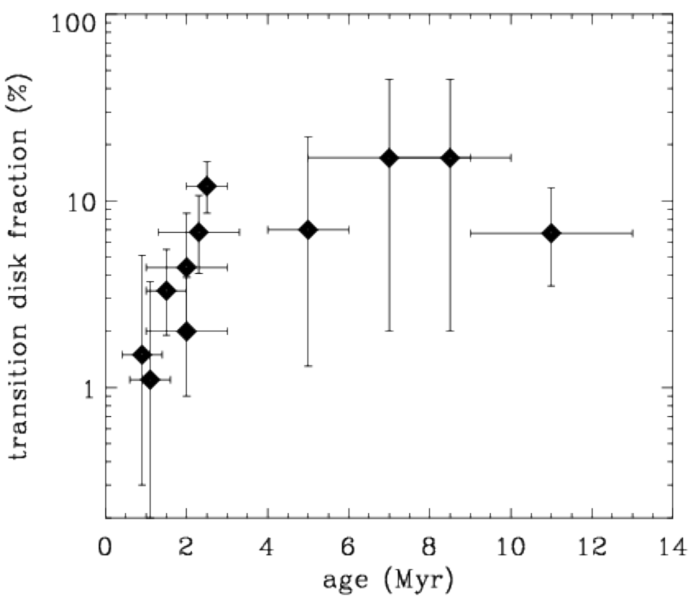


Look again…



(Ribas et al. 2014)

“Total” disk fraction

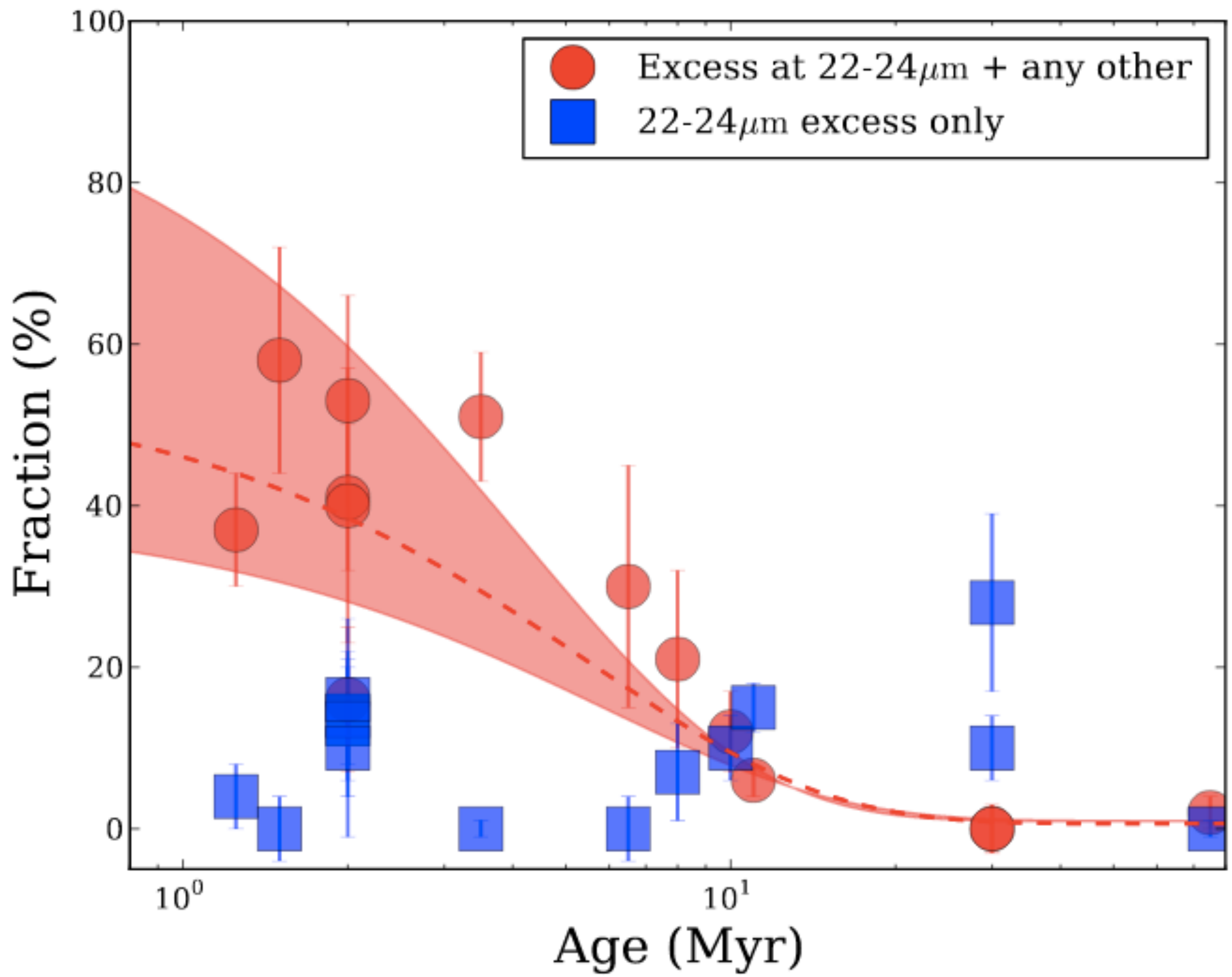


(Espaillat et al. 2014)

Transition disk fraction

Transition disks linked to disk evolution?

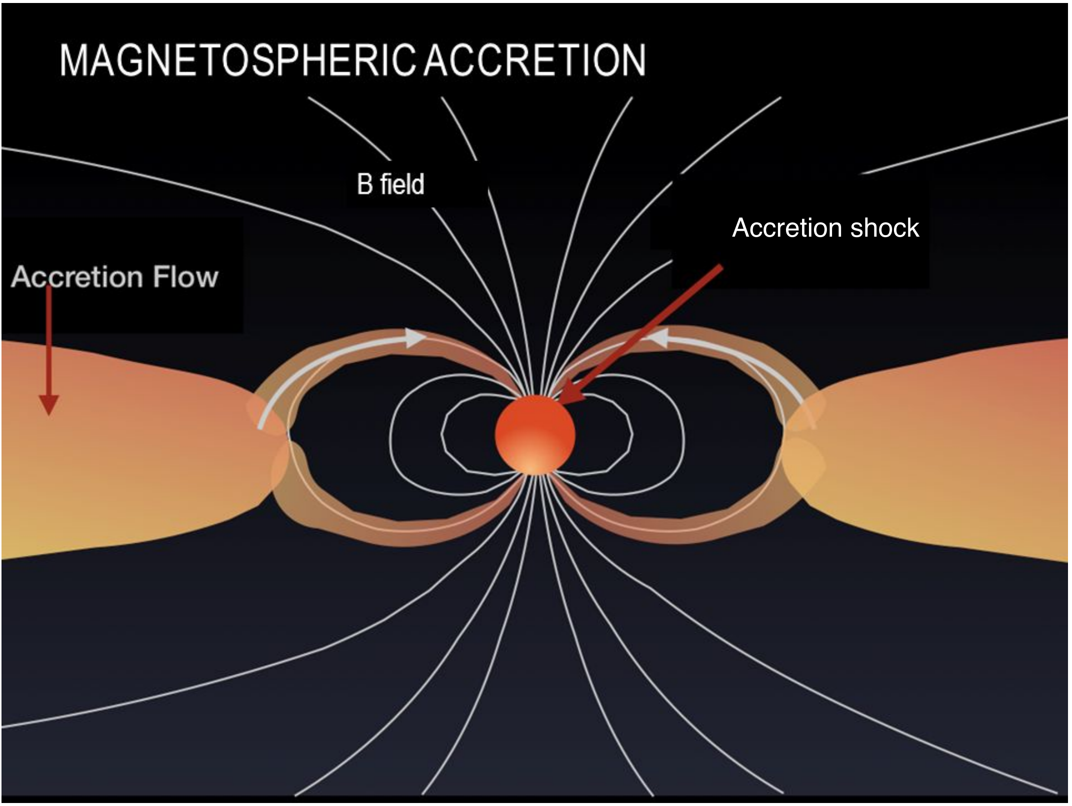
The distribution in age is consistent with a uniform distribution.

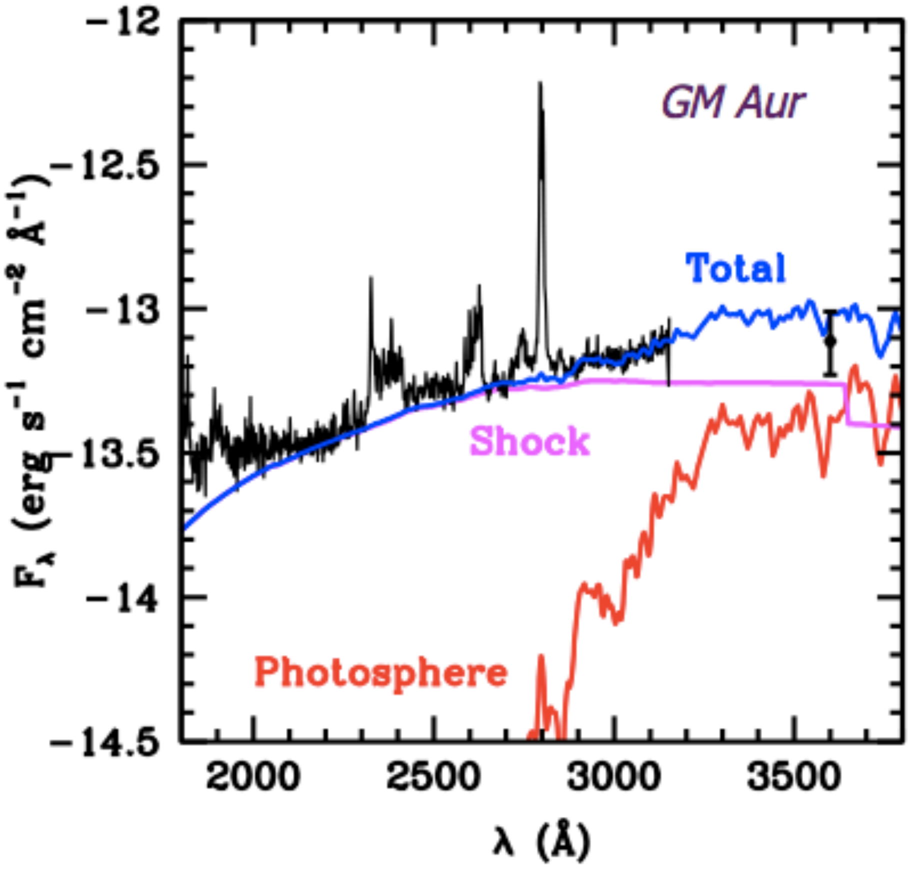


(Ribas et al. 2014)

UV excess

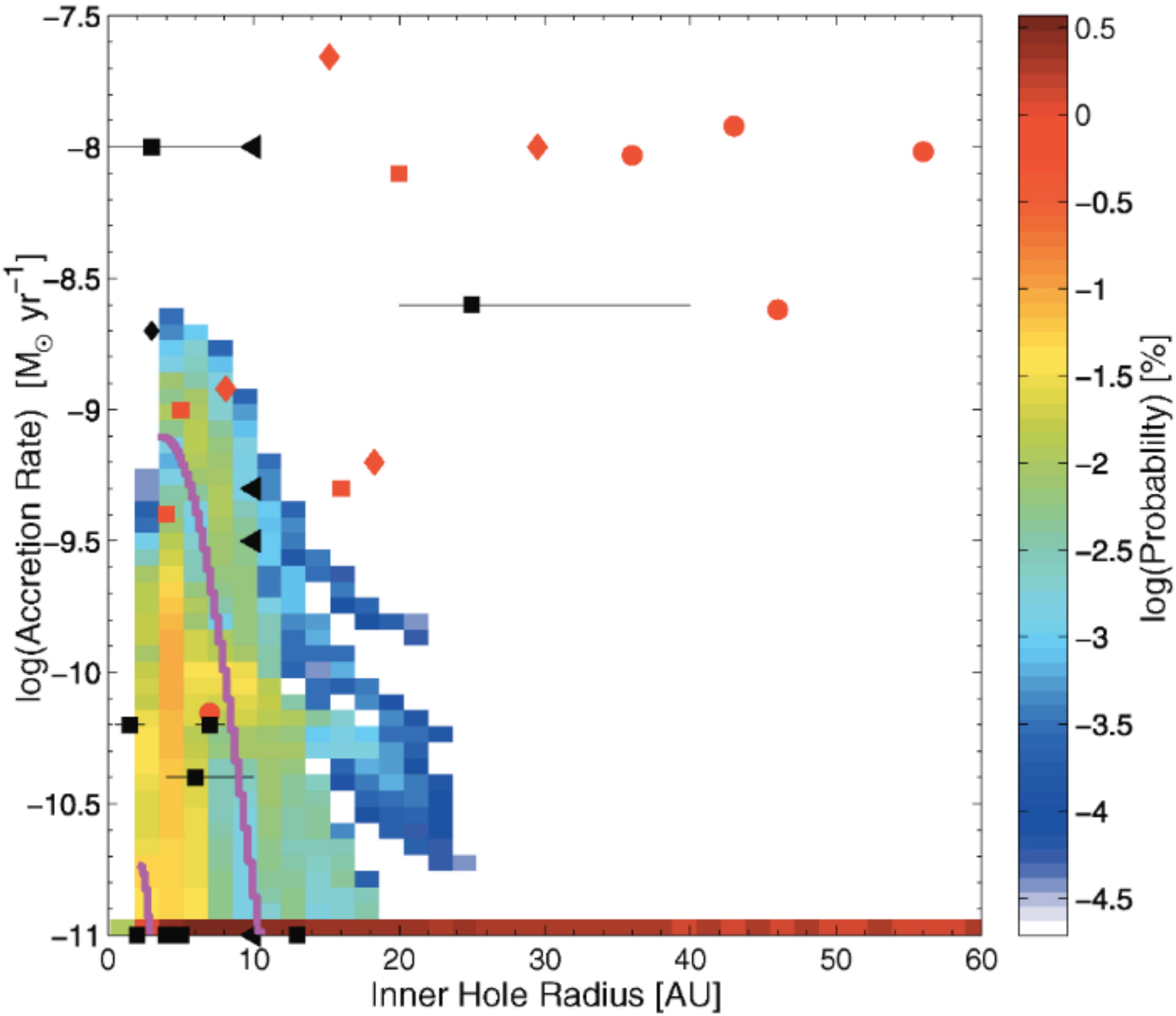
Many transitional disks show signs of accretion,
at the level of primordial (classical T-Tauri) disks.





(Ingleby et al. 2011)

Bimodal distribution of transition disks

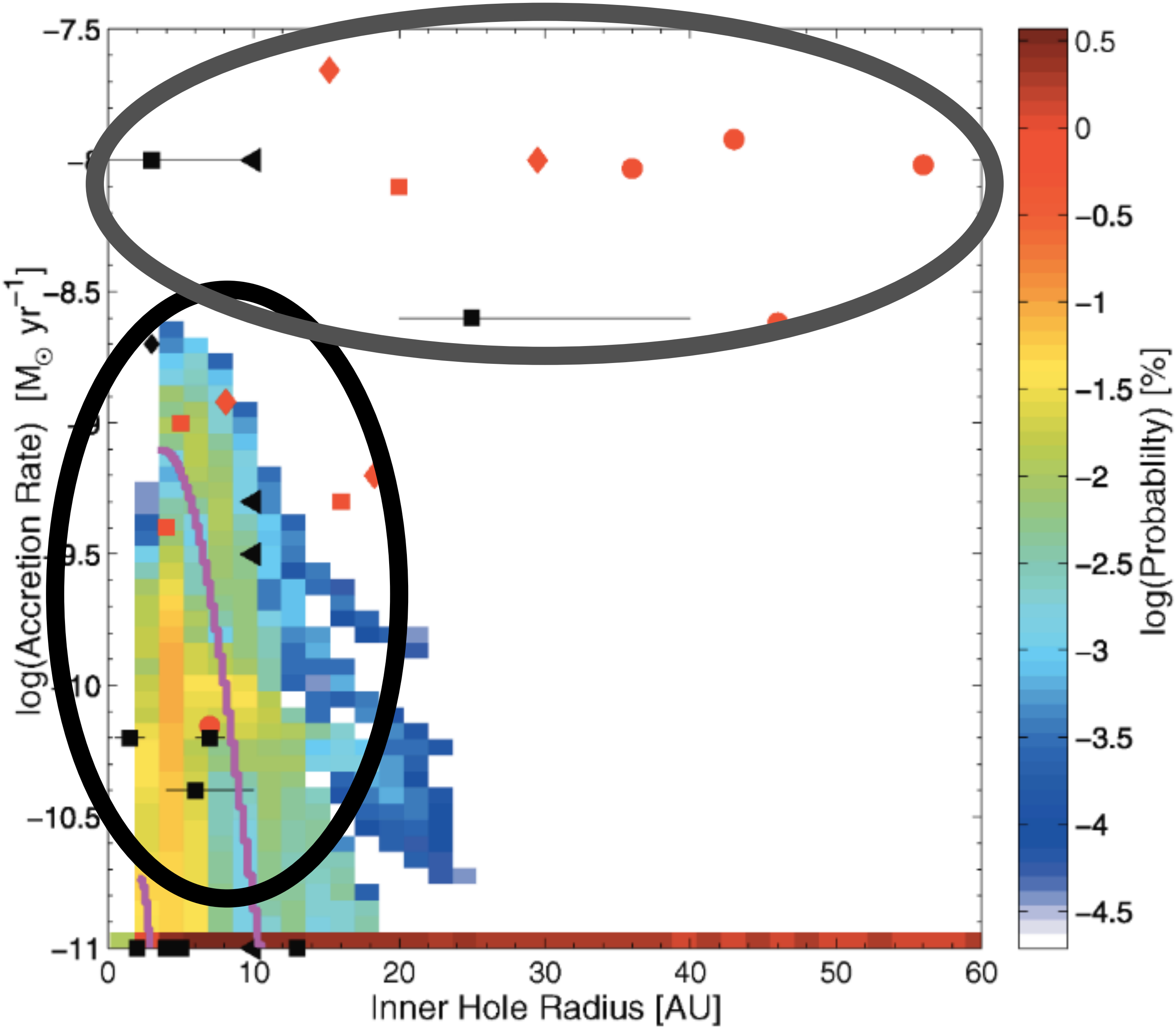


(Owen et al. 2011)

Bimodal distribution of transition disks

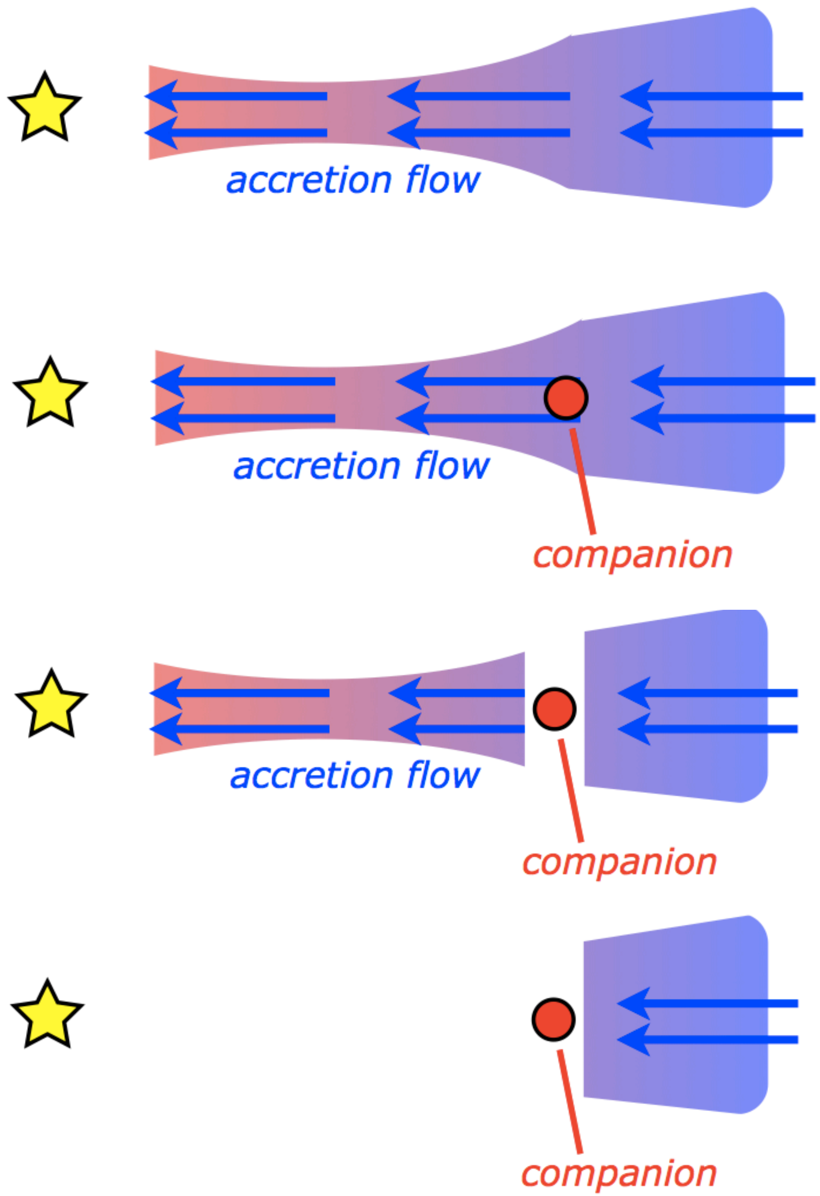
Not explained by photo-evaporation

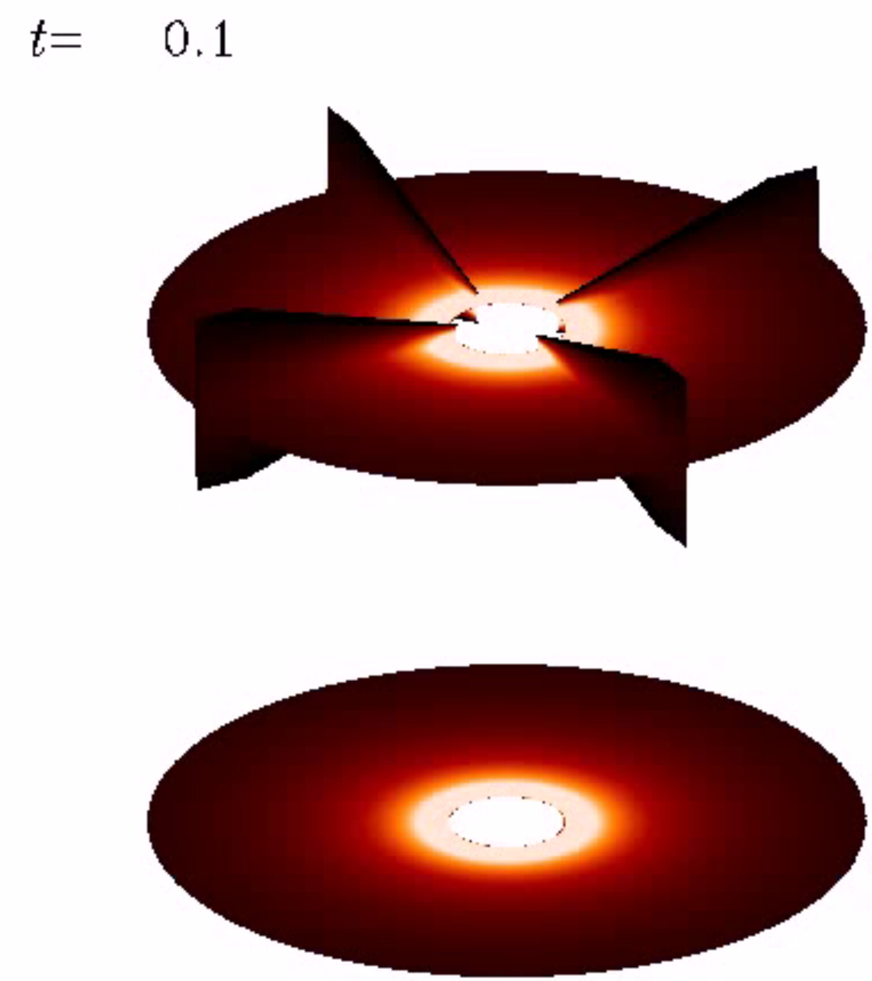
Explained by Photo-evaporation



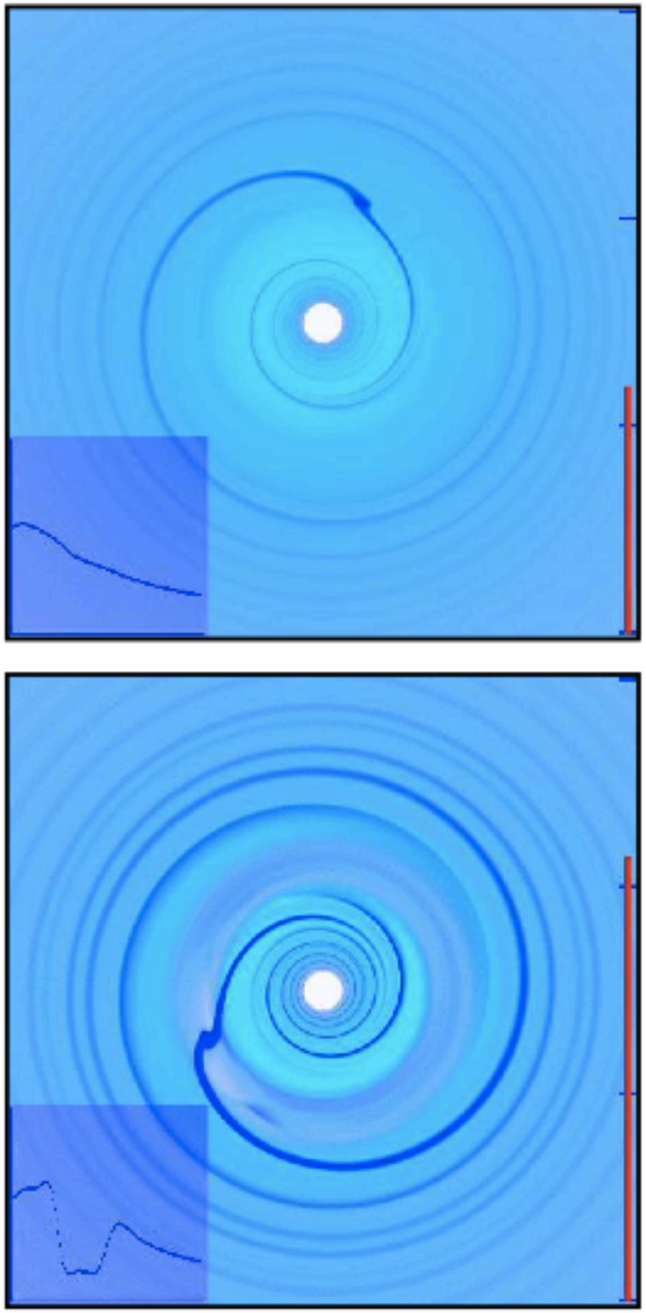
(Owen et al. 2011)

Planetary companion





the "transition" disks (and why you should care)



[Rice et al. 2008]

these cavities might be the telltale signatures of extremely young (~1 Myr) giant exoplanets

if so, they are our best bet for studying disk-planet interactions...

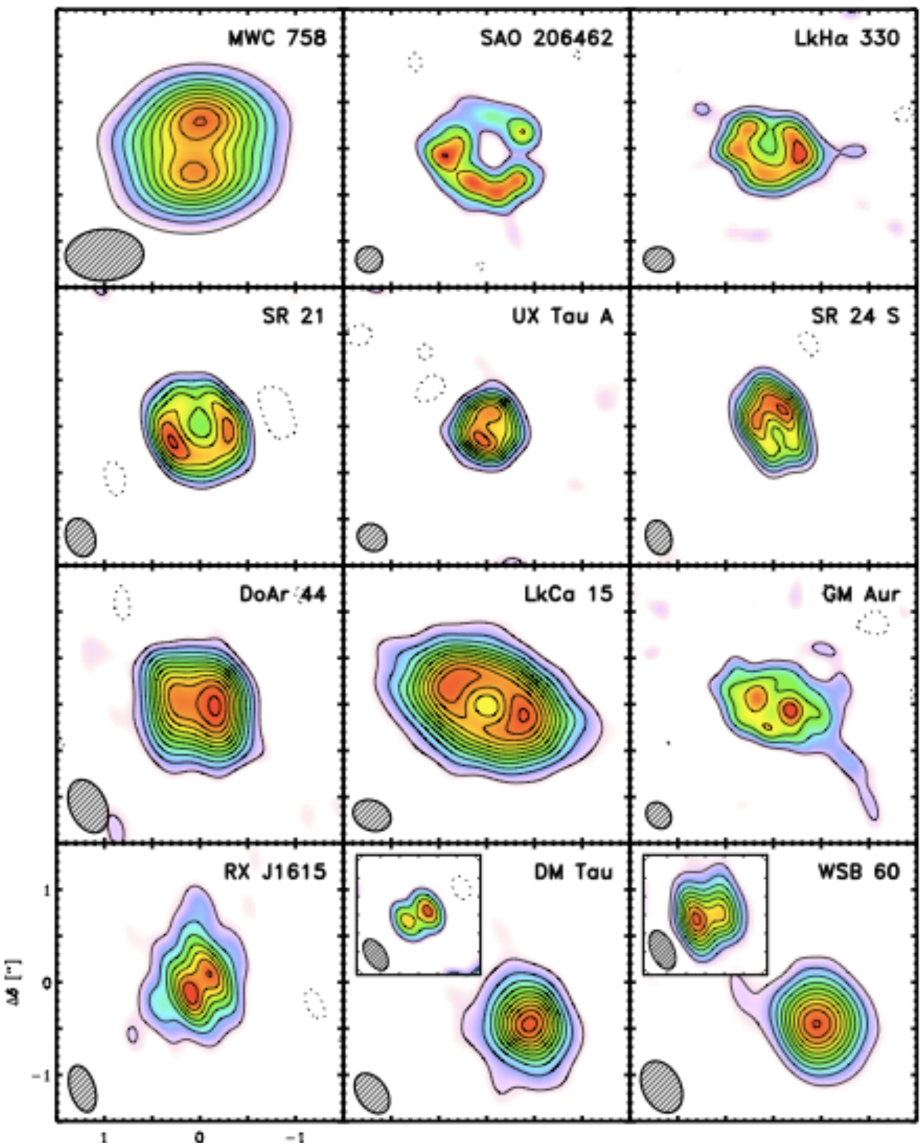
- accretion in the feeding zone
- migration, disk dissipation

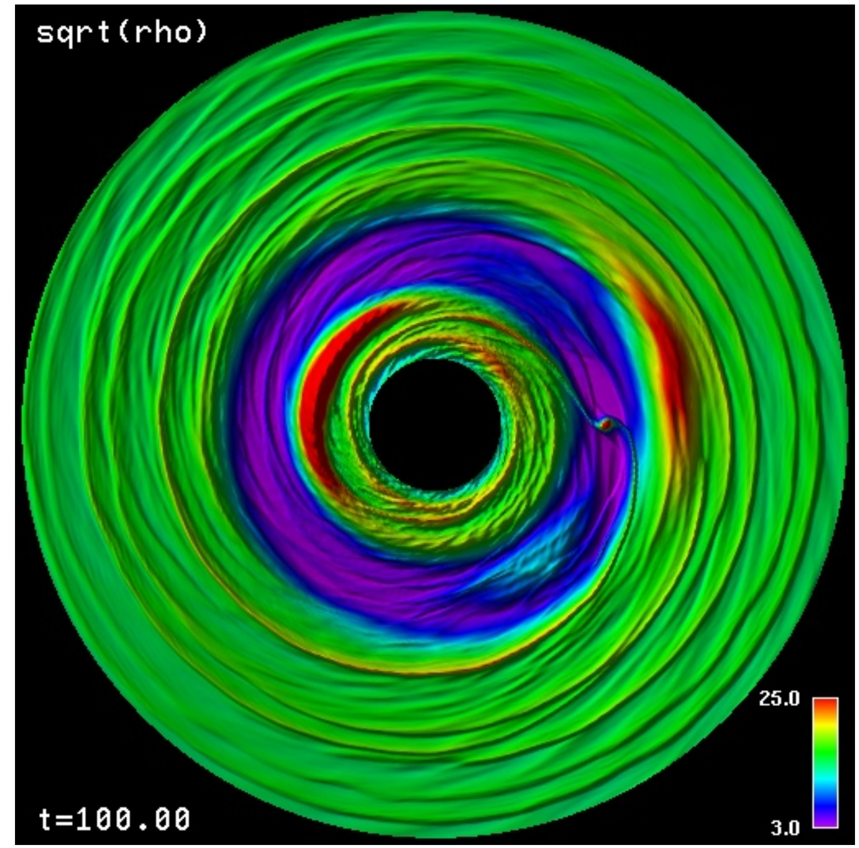
and may be a novel way of indirectly finding long-period exoplanets

- cavity size ~ semimajor axis
- mass in cavity ~ mass of planet

such interactions are among the most important factors that shape exoplanet properties (orbits, masses, composition, etc)

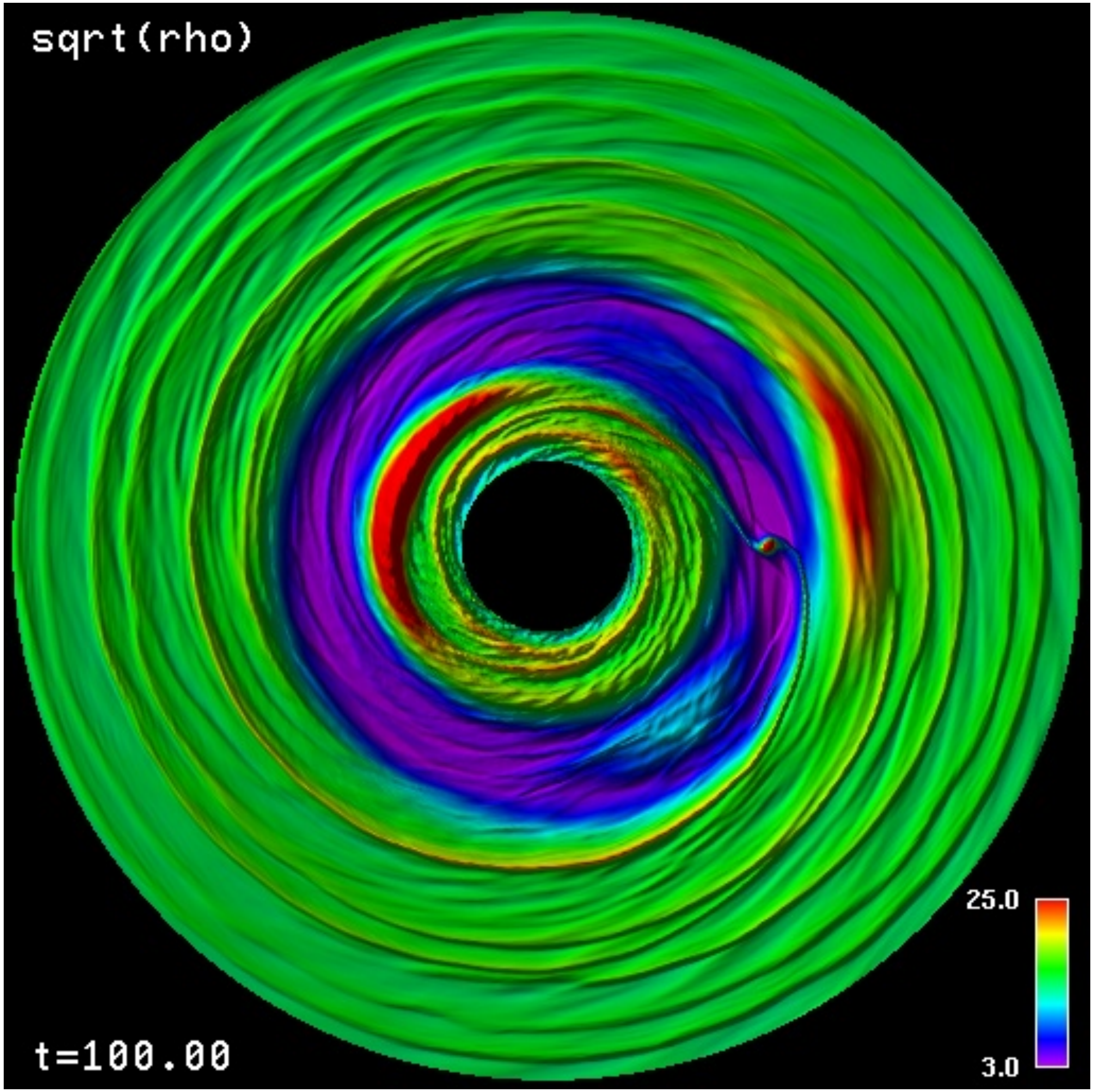
These cavities may be the telltale signature of forming planets





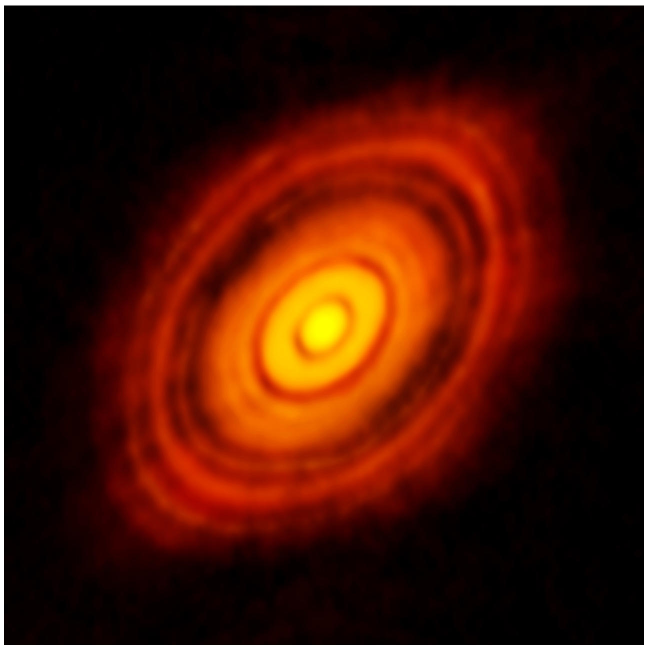
A way to directly study planet-disk interaction

Planet-disk interaction: gaps, spirals, and vortices.

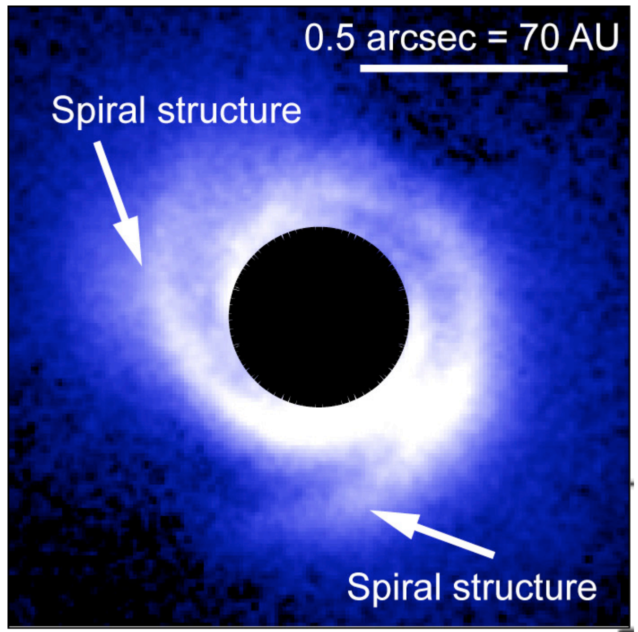


Observational evidence: gaps, spirals, and vortices

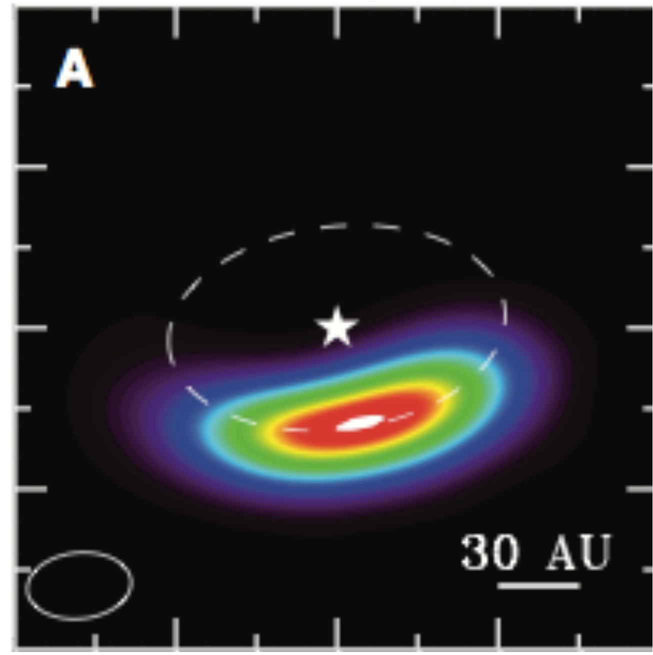
HL Tau



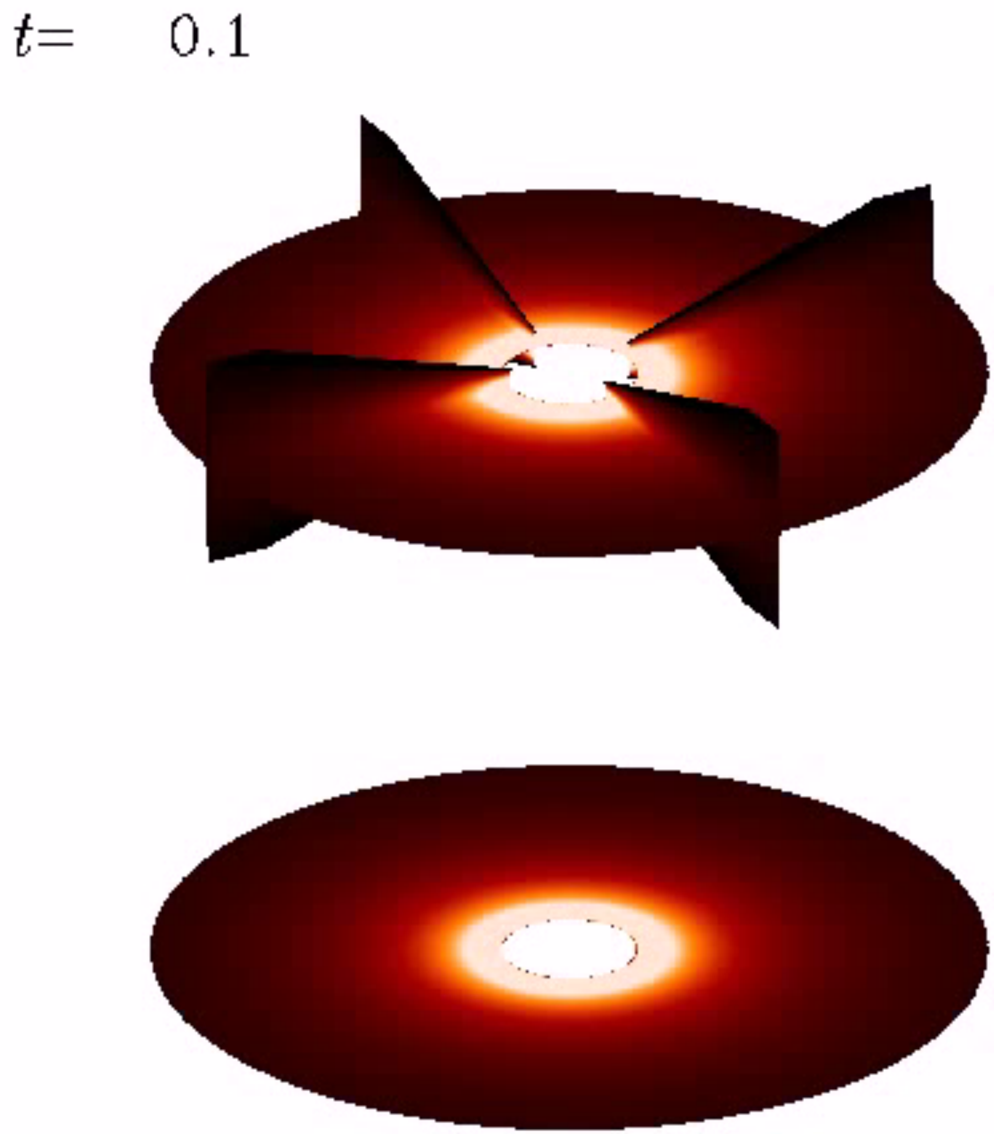
SAO 206462



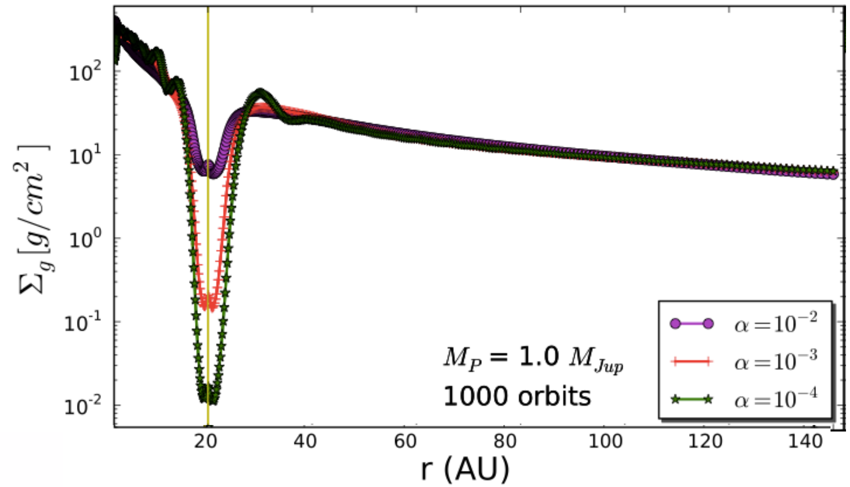
Oph IRS 48



Planet-disk interaction: gaps, spirals, and vortices.



Lyra (2009)

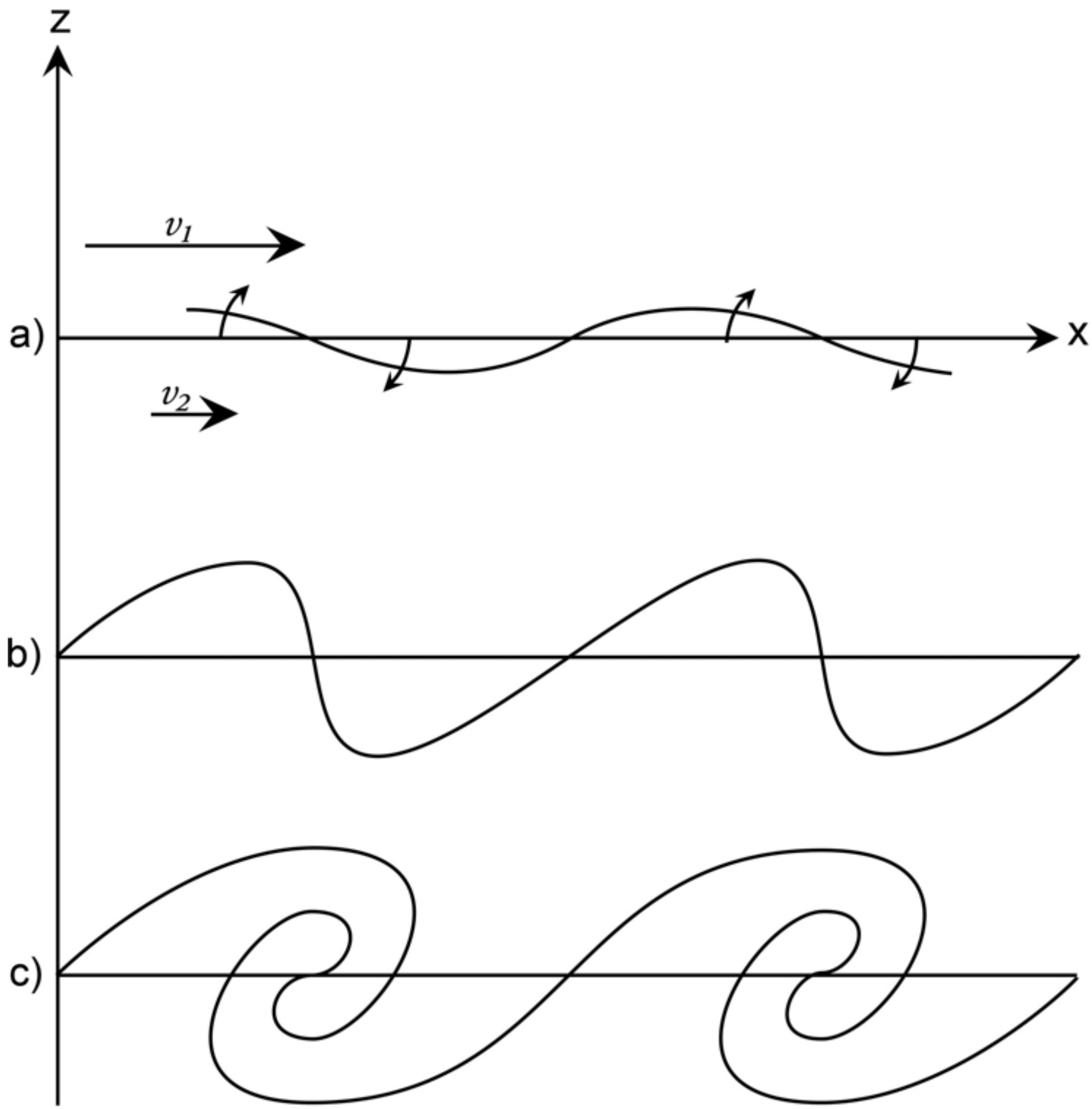


Pinilla et al. (2012)

Planet tides carve gap

Gap walls are unstable to Kelvin-Helmholtz instability

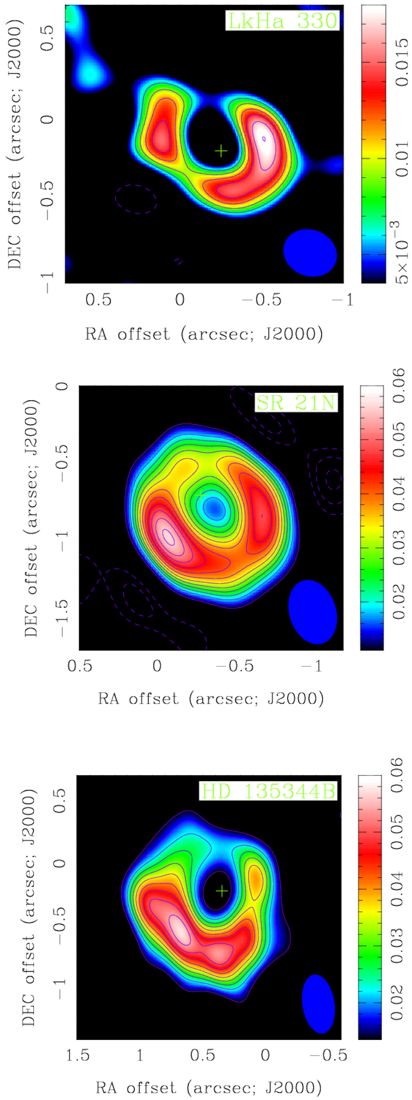
Rossby wave instability
(or Kelvin-Helmholtz instability in differentially rotating gas)

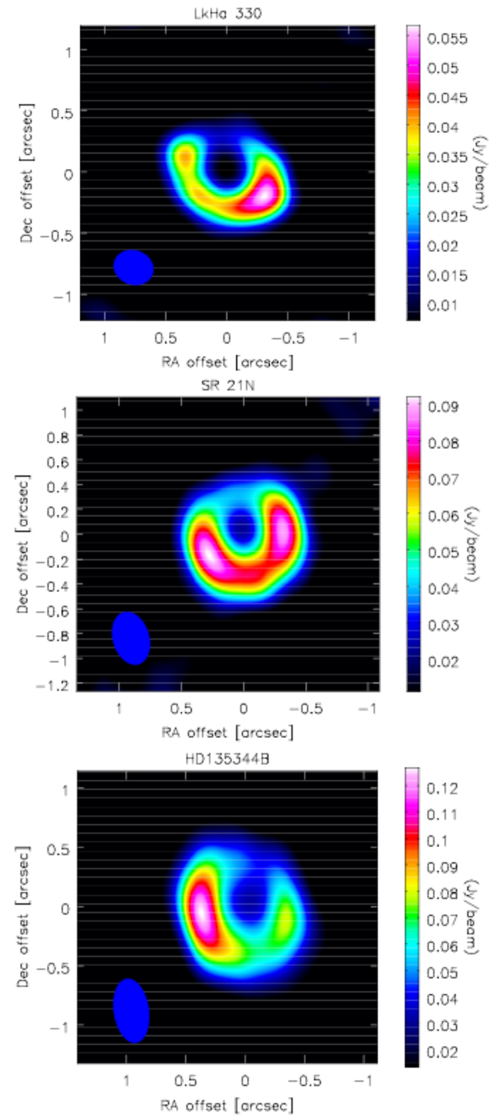


A possible detection?

Observations

Brown et al. (2009)





Models

Simulated observations

Regaly et al. (2012)

Oph IRS 48

A Major Asymmetric Dust Trap in a Transition Disk

Nienke van der Marel,[1]* Ewine F. van Dishoeck,[1,2] Simon Bruderer,[2] Til Birnstiel,[3] Paola Pinilla,[4] Cornelis P. Dullemond,[4] Tim A. van Kempen,[1,5] Markus Schmalzl,[1] Joanna M. Brown,[3] Gregory J. Herczeg,[6] Geoffrey S. Mathews,[1] Vincent Geers[7]

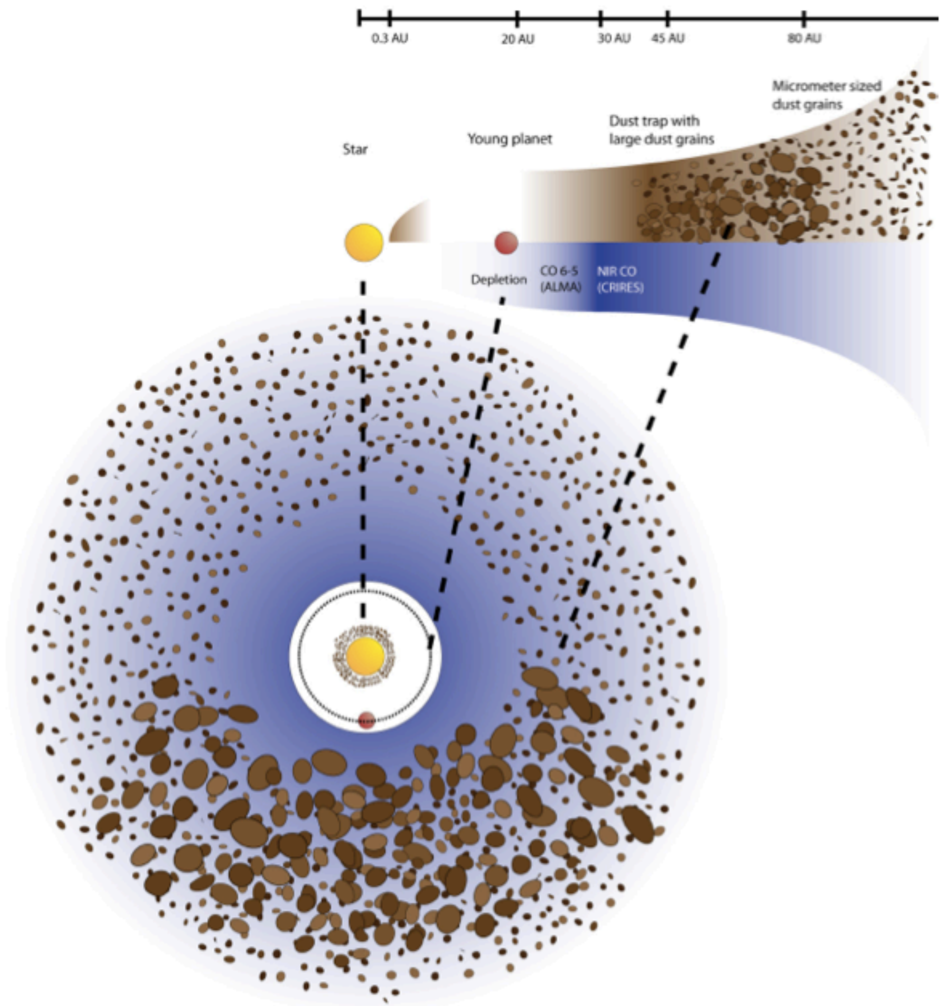
The statistics of discovered exoplanets suggest that planets form efficiently. However, there are fundamental unsolved problems, such as excessive inward drift of particles in protoplanetary disks during planet formation. Recent theories invoke dust traps to overcome this problem. We report the detection of a dust trap in the disk around the star Oph IRS 48 using observations from the Atacama Large Millimeter/submillimeter Array (ALMA). The 0.44-millimeter–wavelength continuum map shows high-contrast crescent-shaped emission on one side of the star, originating from millimeter-sized grains, whereas both the mid-infrared image (micrometer-sized dust) and the gas traced by the carbon monoxide 6-5 rotational line suggest rings centered on the star. The difference in distribution of big grains versus small grains/gas can be modeled with a vortex-shaped dust trap triggered by a companion.

Although the ubiquity of planets is confirmed almost daily by detections of new exoplanets (*1*), the exact formation mechanism of planetary systems in disks of gas and dust around young stars remains a long-standing problem in astrophysics (*2*). In

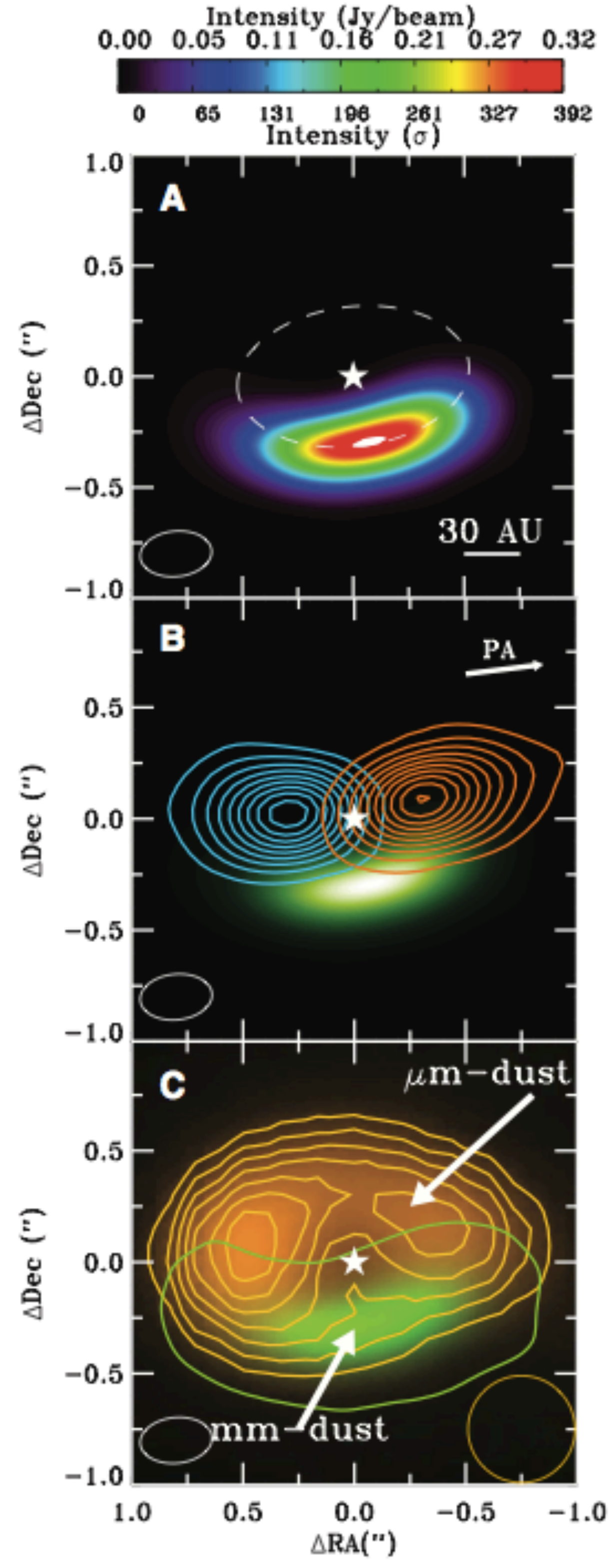
van der Marel et al. 2013

A possible huge vortex observed with ALMA

The Oph IRS 48 "dust trap"



van der Marel et al. (2013)



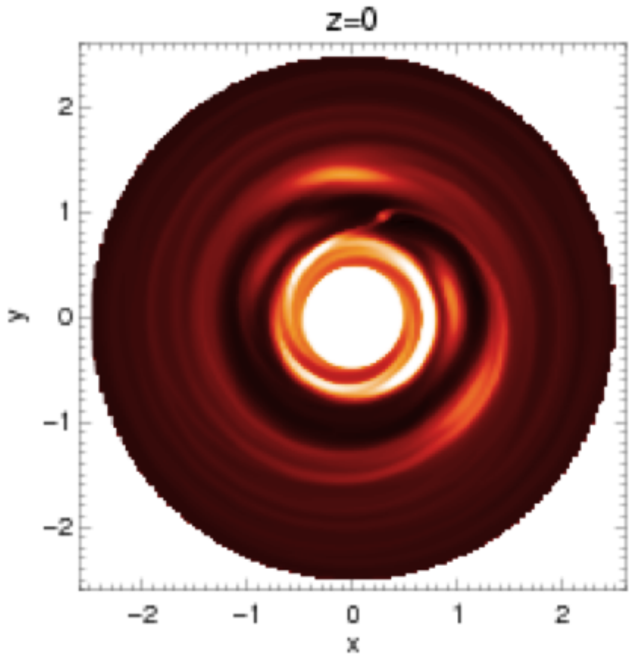
asymmetric mm dust at 63 AU

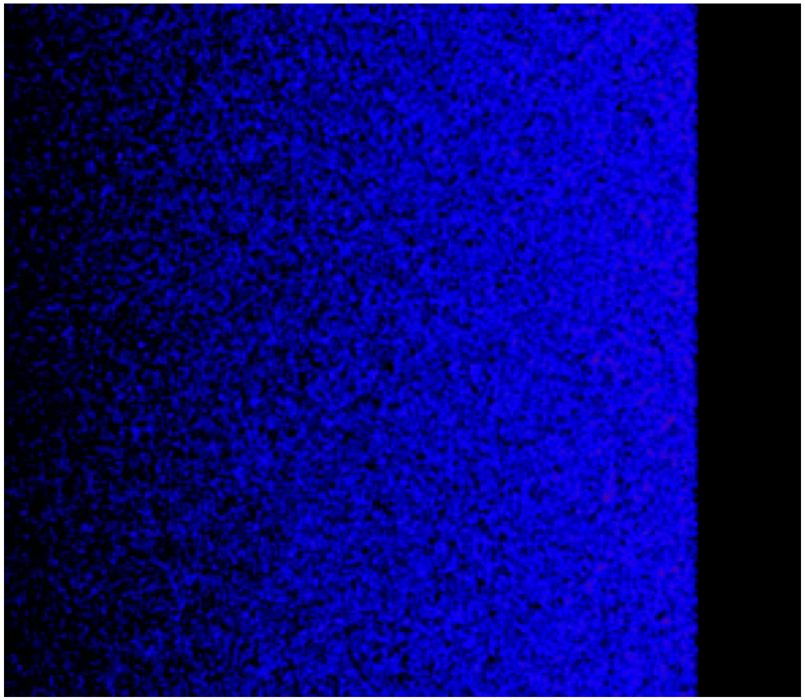
Gas detection: Keplerian rotation

Micron-sized dust follows gas

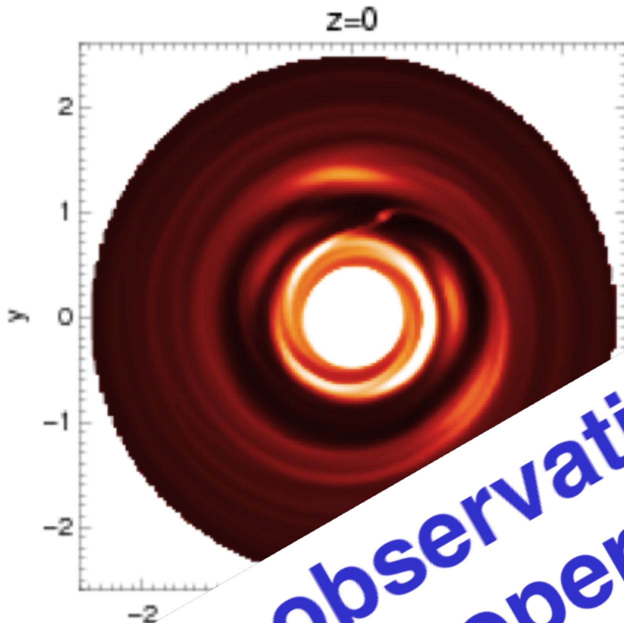
Planet Formation in gap edge vortices

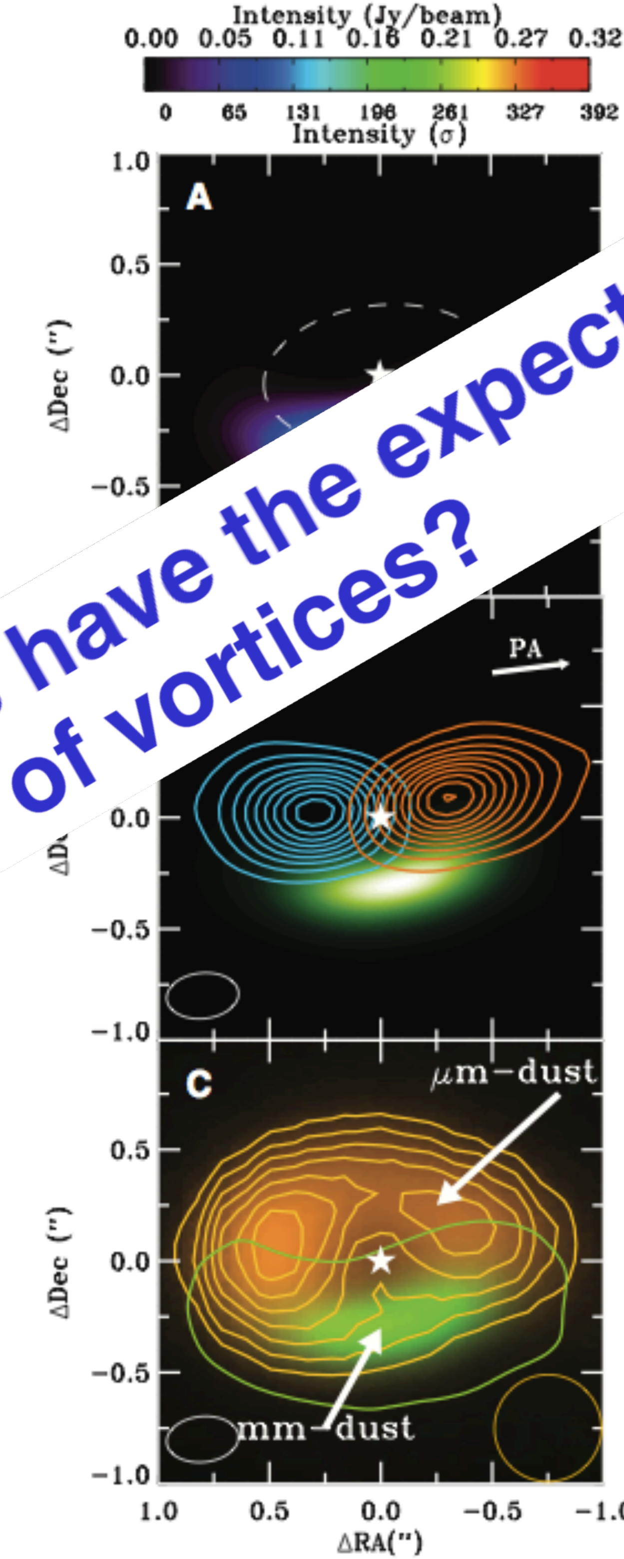
Lyra et al. (2009b),
see also de Val-Borro et al. (2007)





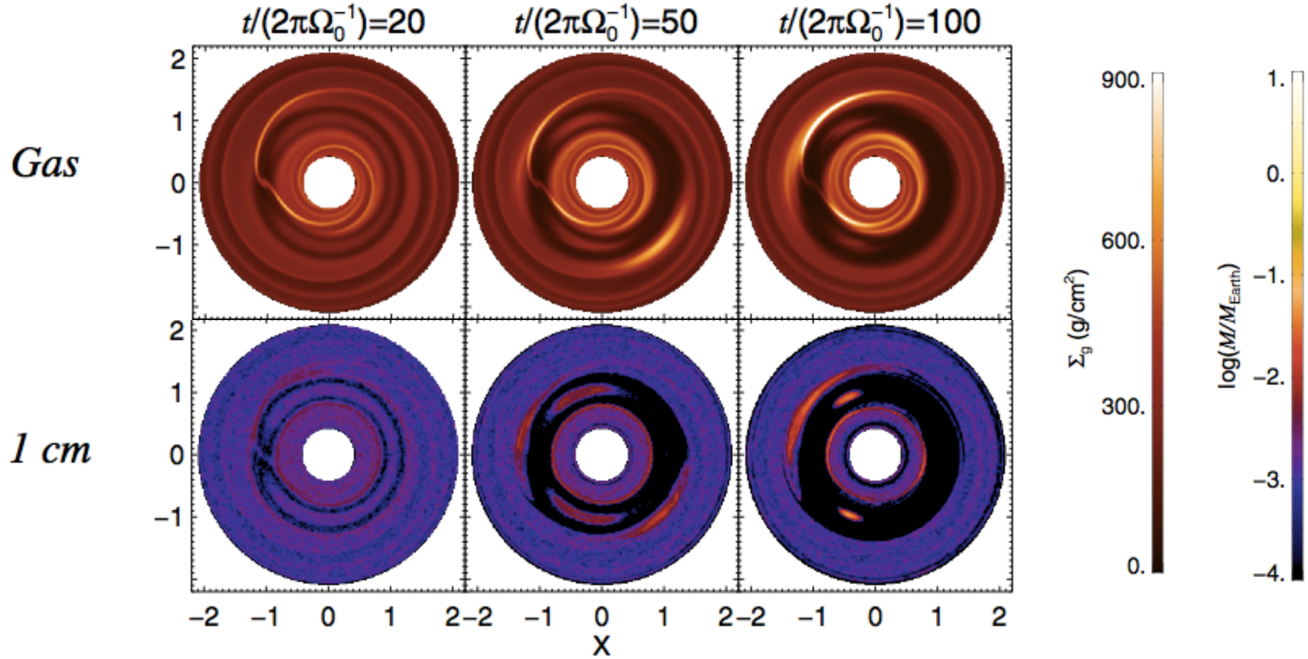
Burst of formation in gap vortices





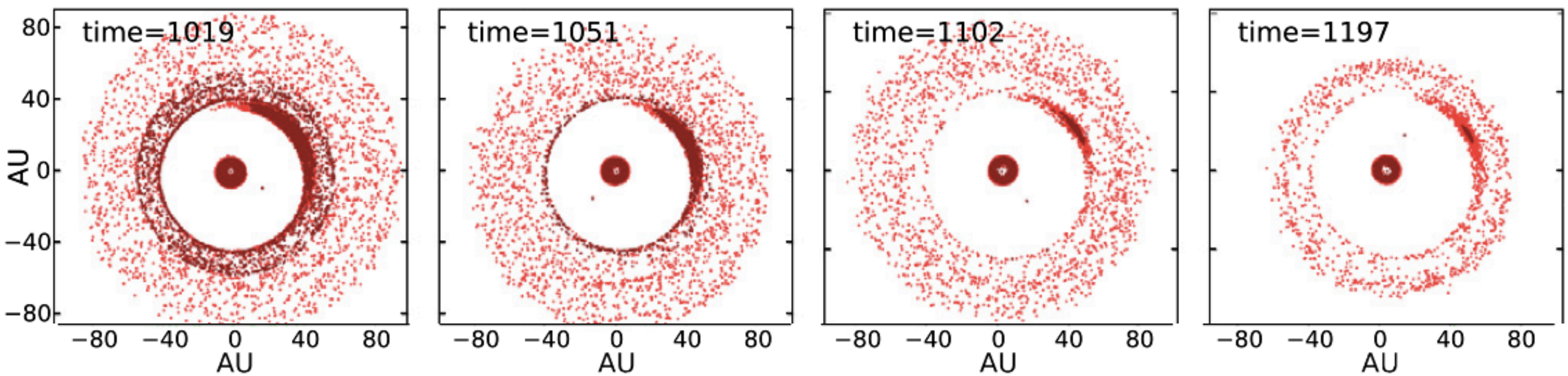
Do the observations have the expected properties of vortices?

Dust Trapping



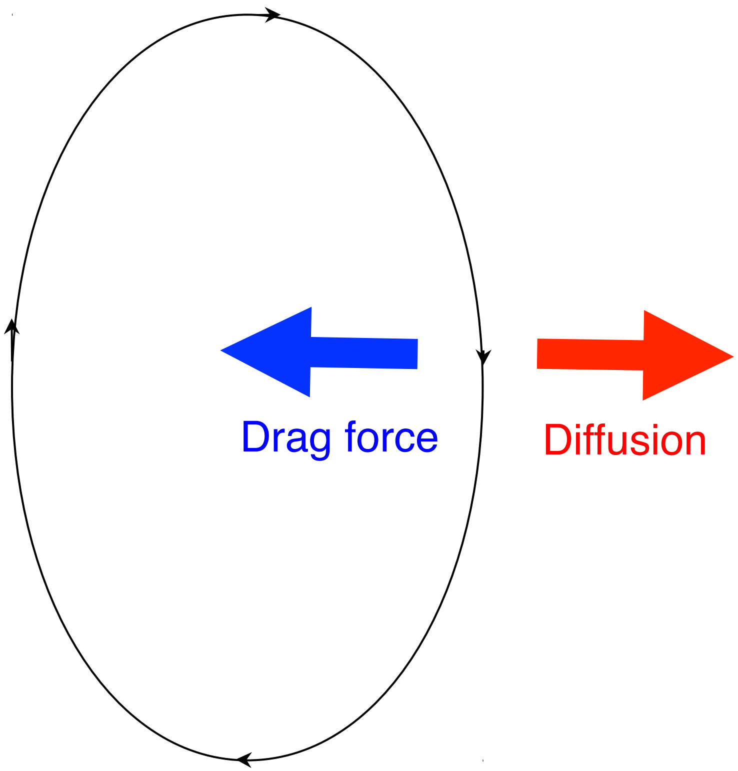
Lyra et al (2009b)

Turbulent "kicks" lead to steady state



Ataiee et al. (2013)

Drag-Diffusion Equilibrium

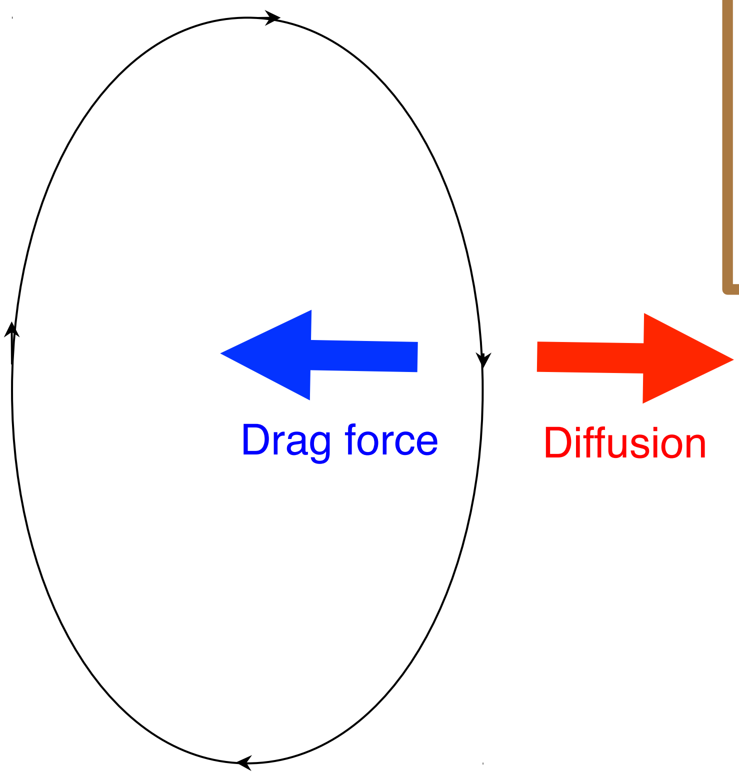


Trapped particle

Dust continuity equation

$$\frac{\partial \rho_d}{\partial t} = \underbrace{-(\boldsymbol{v} \cdot \boldsymbol{\nabla})\rho_d}_{\text{advection}} \underbrace{- \rho_d \boldsymbol{\nabla} \cdot \boldsymbol{v}}_{\text{compression}} + \underbrace{D\nabla^2 \rho_d}_{\text{diffusion}},$$

Drag-Diffusion Equilibrium



Trapped particle

Steady-state solution

$$\rho_d(a,z) = \varepsilon\rho_0\,(S+1)^{3/2}\,\exp\left\{-\frac{[a^2 f^2(\chi)+z^2]}{2H^2}(S+1)\right\}$$

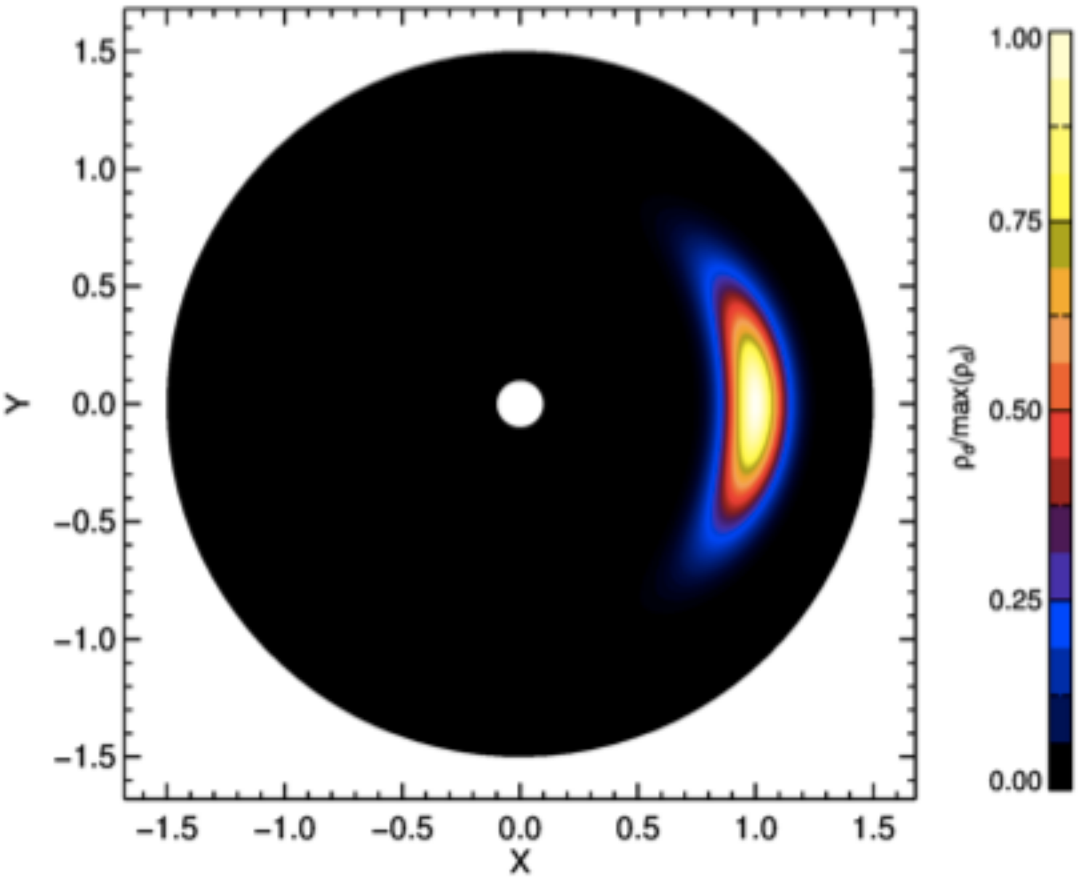
Lyra & Lin (2013)

$$S = \frac{St}{\delta}$$

$$\delta = v_{\rm rms}^2/c_s^2,$$

a	= vortex semi-minor axis
H	= disk scale height (temperature)
χ	= vortex aspect ratio
δ	= diffusion parameter
St	= Stokes number (particle size)
$f(\chi)$	= model-dependent scale function

Analytical solution for dust trapping



Solution

$$\rho_d(a) = \rho_{d\,\max} \exp\left(-\frac{a^2}{2H_V^2}\right),$$

$$H_V = \frac{H}{f(\chi)}\sqrt{\frac{1}{S+1}}$$

$$S = \frac{St}{\delta}$$

$$\delta = v_{\rm rms}^2 / c_s^2,$$

a = vortex semi-minor axis
H = disk scale height (temperature)
χ = vortex aspect ratio
δ = diffusion parameter
St = Stokes number (particle size)
$f(\chi)$ = model-dependent scale function

Solution for

$H/r=0.1$ $\chi=4$ $S=1$

Lyra & Lin (2013)

Derived quantities

$$\rho_d(a,z) = \varepsilon \rho_0 (S+1)^{3/2} \exp\left\{-\frac{[a^2 f^2(\chi) + z^2]}{2H^2}(S+1)\right\}$$

Lyra & Lin (2013)

Gas distribution

$$\rho_g(a) = \rho_{g\max} \exp\left(-\frac{a^2}{2H_g^2}\right),$$

Maximum dust density

$$\rho_{d\max} = \varepsilon\, \rho_0\, (S+1)^{3/2}$$

Gas contrast

$$\frac{\rho_{g\max}}{\rho_{g\min}} = \exp\left[\frac{f^2(\chi)}{2\chi^2\omega_V^2}\right],$$

Dust contrast

$$\frac{\rho_{d\max}}{\rho_{d\min}} = \frac{\rho_{g\max}}{\rho_{g\min}} \exp(S),$$

Total trapped mass

$$\int \rho_d(a,z)dV = (2\pi)^{3/2}\, \varepsilon \rho_0\, \chi H H_g^2$$

Vortex size

$$a_s = H(\chi\omega_V)^{-1}$$

H = disk scale height (temperature)
χ = vortex aspect ratio
δ = diffusion parameter
St = Stokes number (particle size)
$f(\chi)$ = model-dependent scale function
ε = dust-to-gas ratio

Applying the model to Oph IRS 48

Observed parameters

Aspect ratio: 3.1

Dust contrast: 130

Temperature: 60K

Trapped mass: 9 M_{Earth}

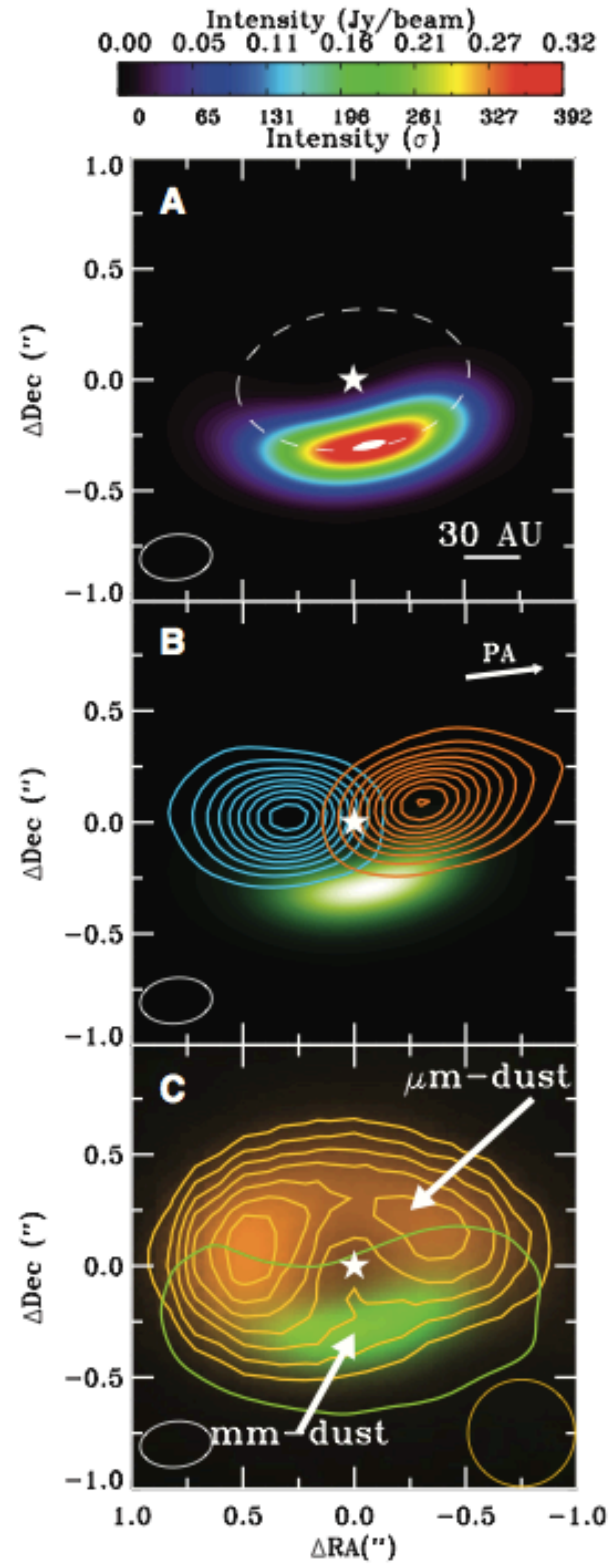
Derived parameters

S=4.8

Stokes number, St=0.008

$\delta = 0.005$, v_{rms} = 4% c_s

Trapped mass: 11 M_{Earth}



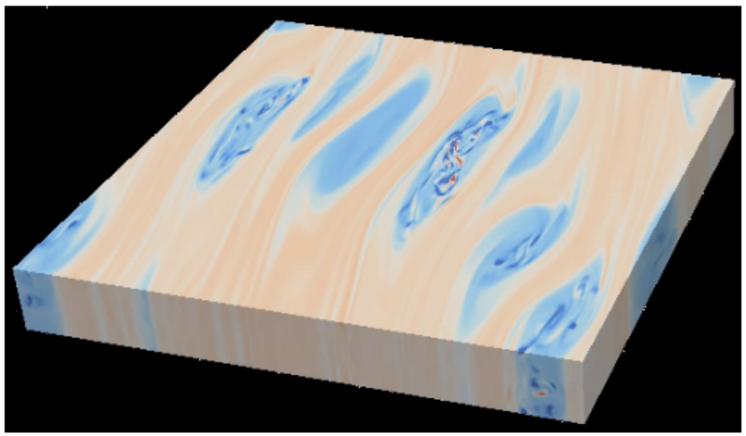
asymmetric mm dust at 63 AU

Gas detection: Keplerian rotation

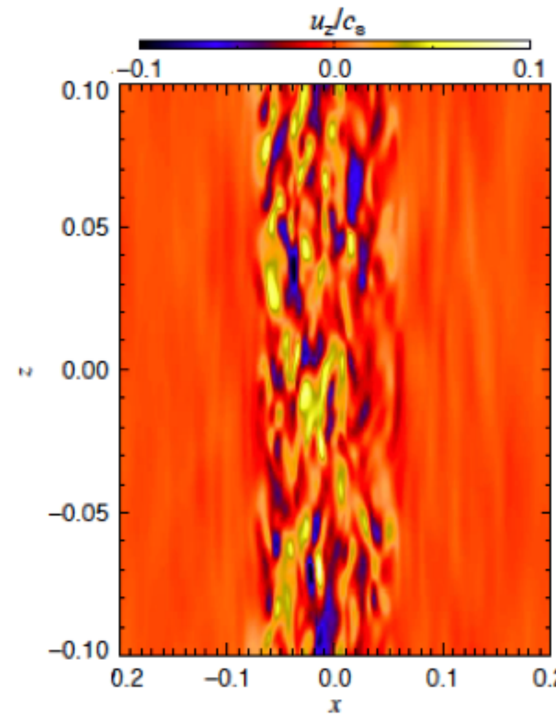
Micron-sized dust follows gas

Lyra & Lin (2013)

Turbulence in vortex cores



Lesur & Papaloizou (2010)

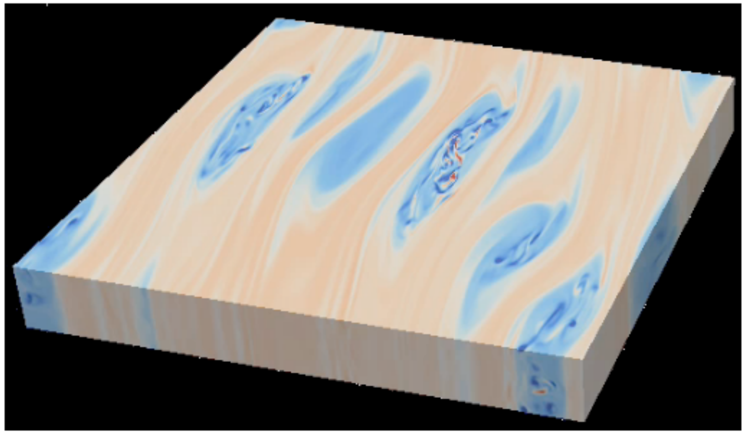


Lyra & Klahr (2011)

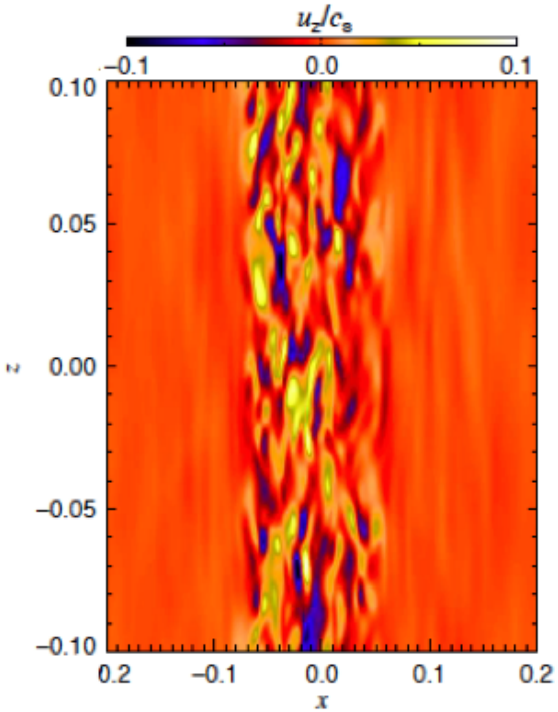
Turbulence in vortex cores:

max at ~10% of sound speed
rms at ~3% of sound speed

Who needs a planet?



Lesur & Papaloizou (2010)



Lyra & Klahr (2011)

Convective Overstability (née "Baroclinic Instability")

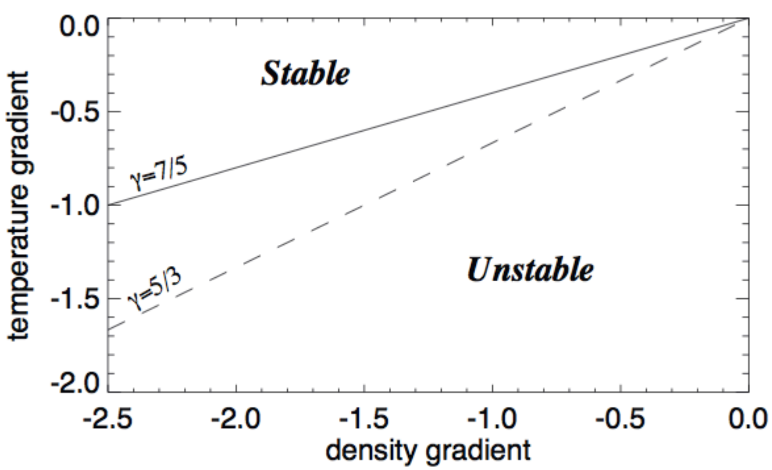
Klahr & Hubbard (2014), Lyra (2014), Latter (2015)

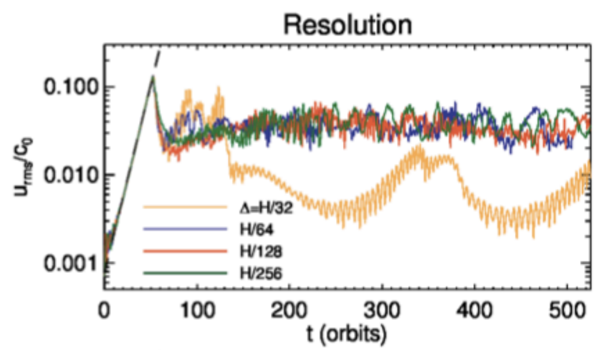
$$\frac{\partial \rho}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\,\rho = -\rho\boldsymbol{\nabla}\cdot\boldsymbol{u},$$
$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\,\boldsymbol{u} = -\frac{1}{\rho}\boldsymbol{\nabla} p + \boldsymbol{g},$$
$$\frac{\partial p}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\,p = -\gamma p\boldsymbol{\nabla}\cdot\boldsymbol{u} - \frac{p}{T}\frac{(T-T_0)}{\tau},$$

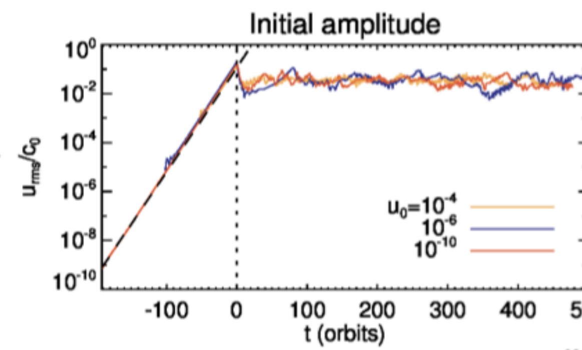
$$\bar{\omega}^3 + i\varsigma\bar{\omega}^2 - \bar{\omega}\mu^2(\kappa^2+N^2) - i\varsigma\kappa^2\mu^2 = 0,$$

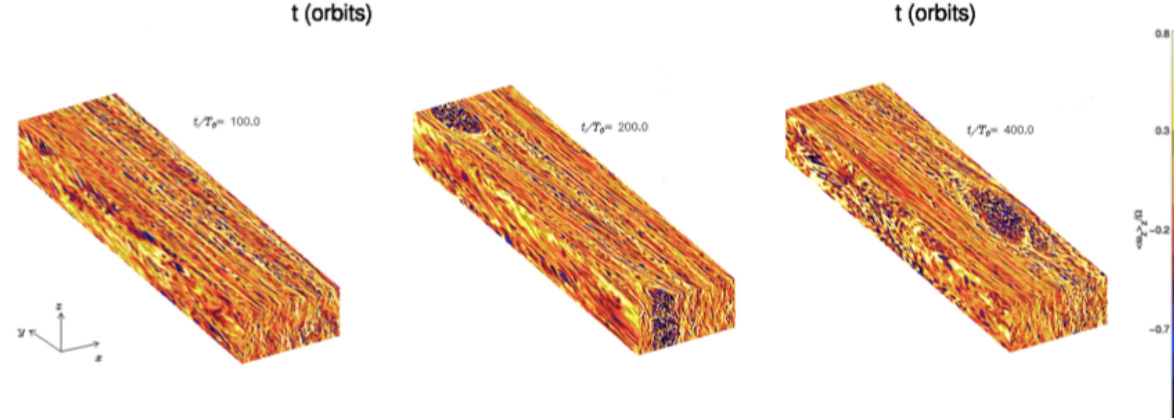
$$\varsigma = 1/\gamma\tau \qquad \mu^2 = k_z^2/k^2.$$

$$\tau_{\max} = \frac{1}{\gamma}\left|\frac{k}{k_z}\right|\frac{1}{\sqrt{\kappa^2+N^2}} \qquad \sigma_{\max} = -\frac{1}{4}\left|\frac{k_z}{k}\right|\frac{N^2}{\sqrt{\kappa^2+N^2}}$$



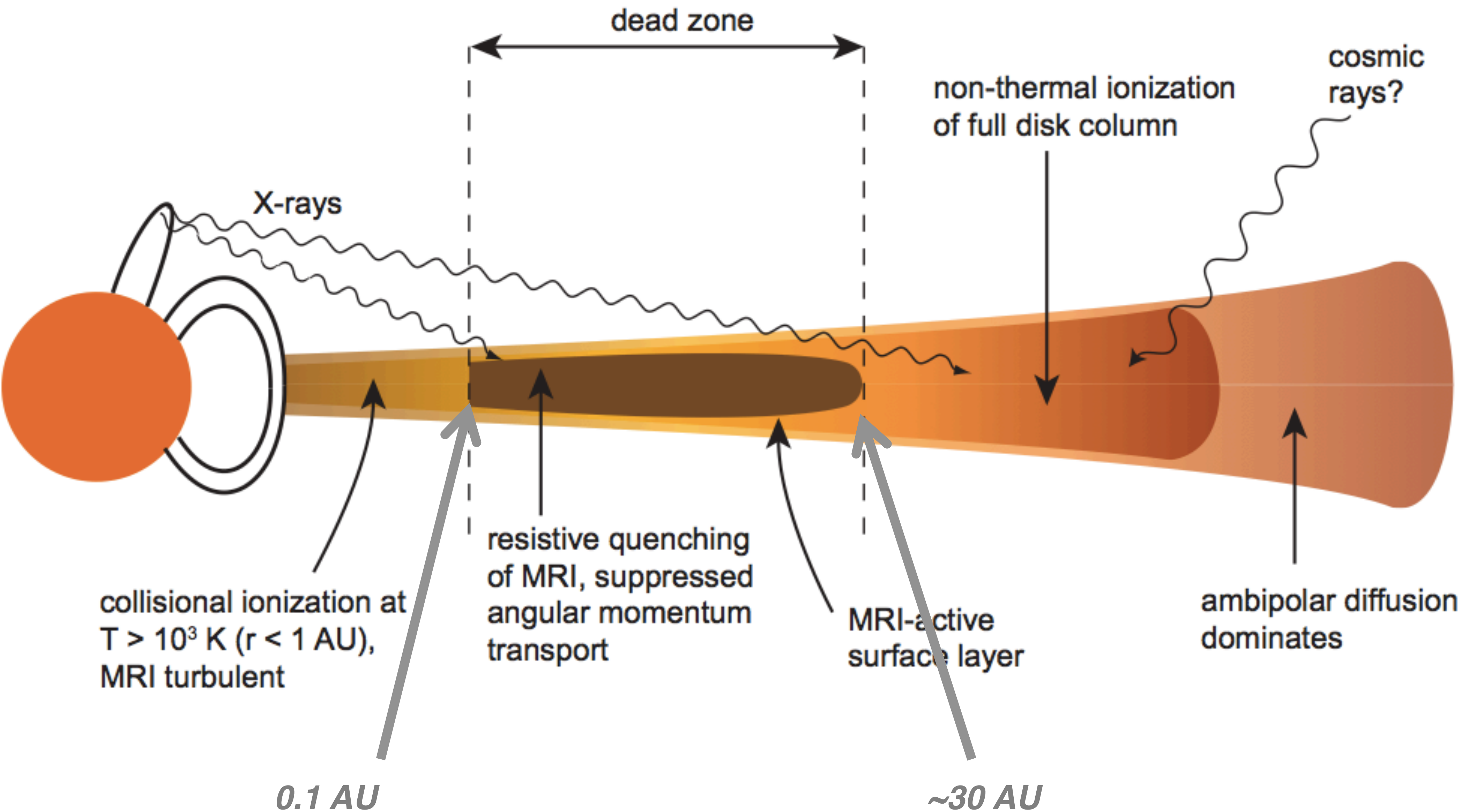






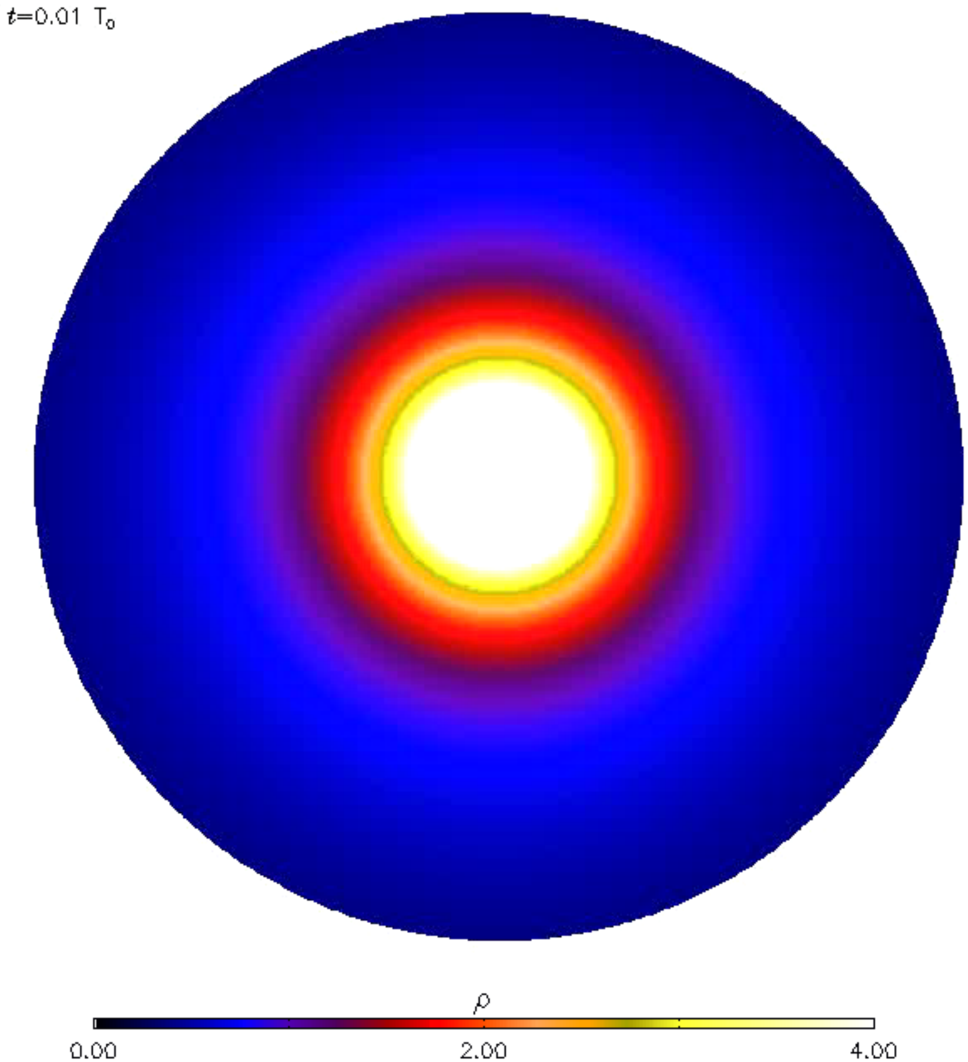
Lyra (2014)

Dead zones



dead zone
cosmic rays?
non-thermal ionization of full disk column
X-rays
resistive quenching of MRI, suppressed angular momentum transport
collisional ionization at T > 10³ K (r < 1 AU), MRI turbulent
MRI-active surface layer
ambipolar diffusion dominates
0.1 AU
~30 AU

Inner Active/Dead zone boundary



Unstratified isothermal MHD
with static Ohmic resistivity jumps.

$$\frac{\partial \rho}{\partial t} = -(\boldsymbol{u}\cdot\boldsymbol{\nabla})\,\rho - \rho\boldsymbol{\nabla}\cdot\boldsymbol{u},$$

$$\frac{\partial \boldsymbol{u}}{\partial t} = -(\boldsymbol{u}\cdot\boldsymbol{\nabla})\,\boldsymbol{u} - \frac{1}{\rho}\boldsymbol{\nabla}p - \boldsymbol{\nabla}\Phi + \frac{\boldsymbol{J}\times\boldsymbol{B}}{\rho},$$

$$\frac{\partial \boldsymbol{A}}{\partial t} = \boldsymbol{u}\times\boldsymbol{B} - \eta\mu_0\boldsymbol{J}$$

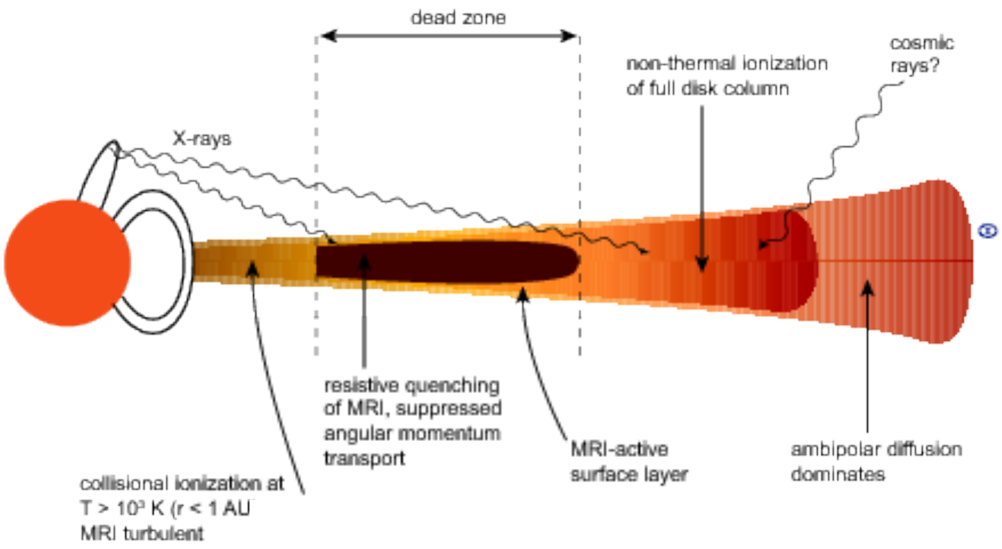
$$p = \rho c_s^2.$$

$$\eta(r) = \eta_0 - \frac{\eta_0}{2}\left[\tanh\left(\frac{r-r_1}{h_1}\right) - \tanh\left(\frac{r-r_2}{h_2}\right)\right]$$

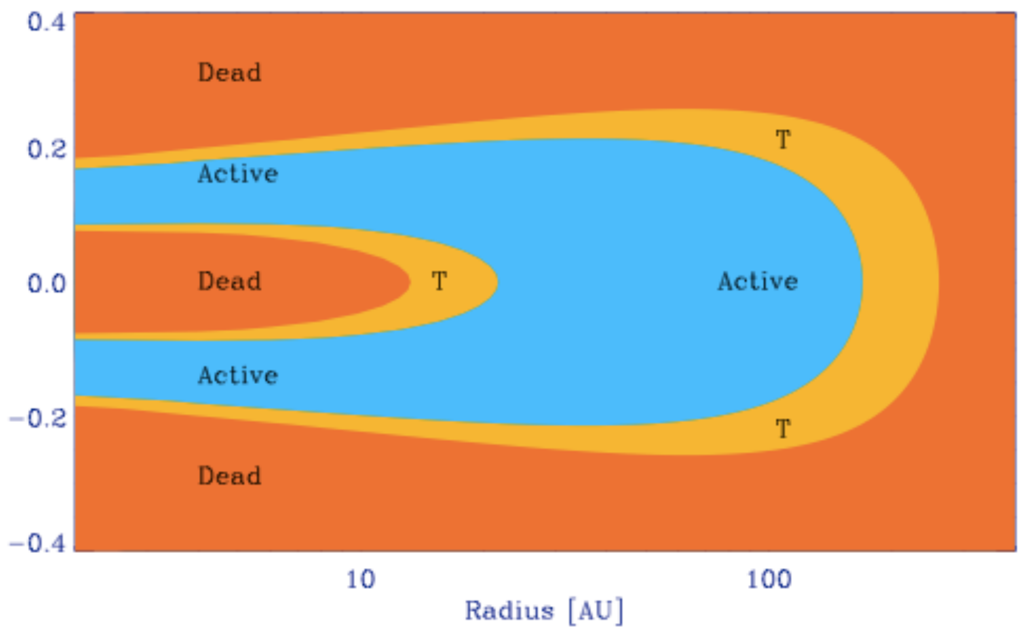
Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012);
see also Faure et al. (2015)

Outer Dead/Active zone transition KHI



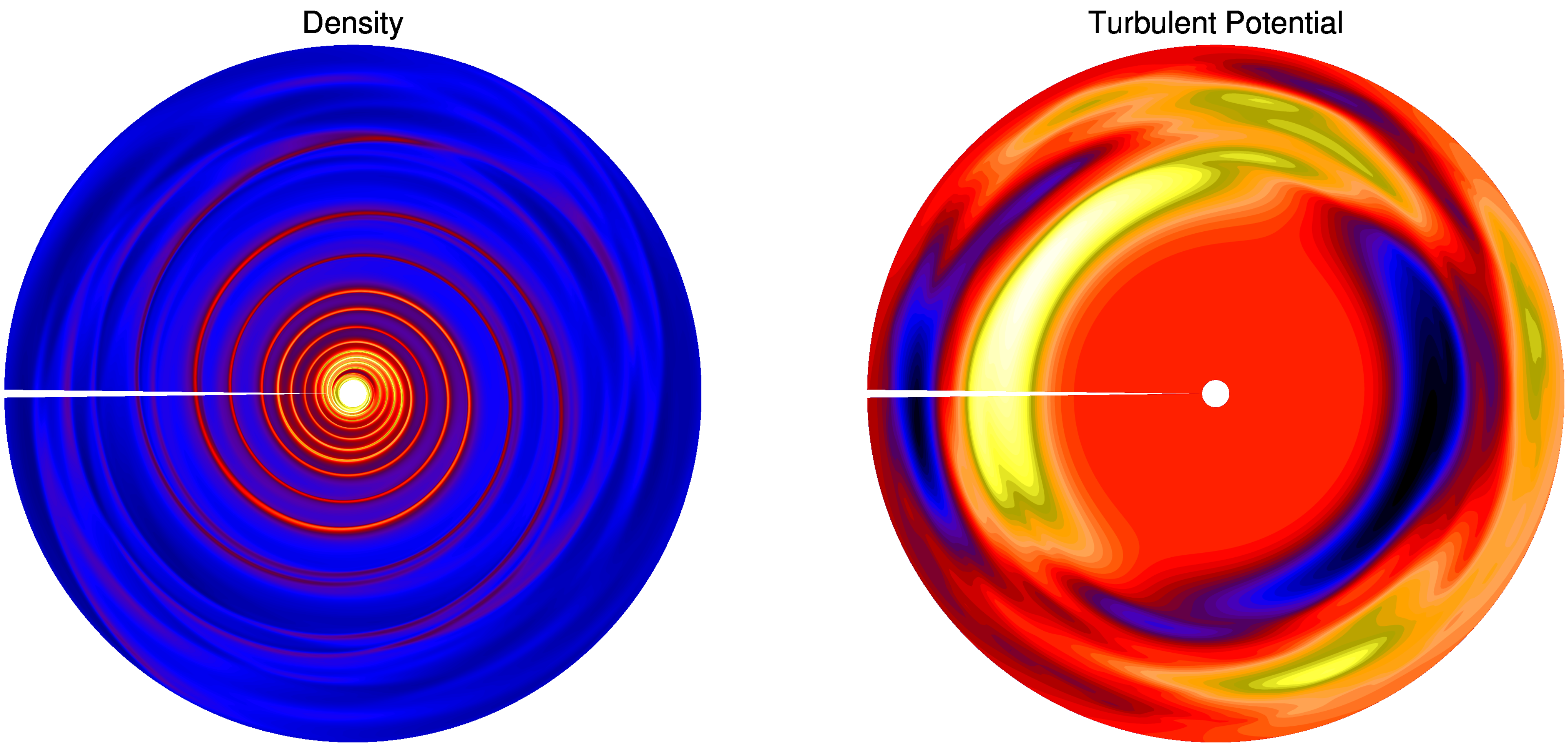
Armitage (2010)



Dzyurkevitch et al (2013)

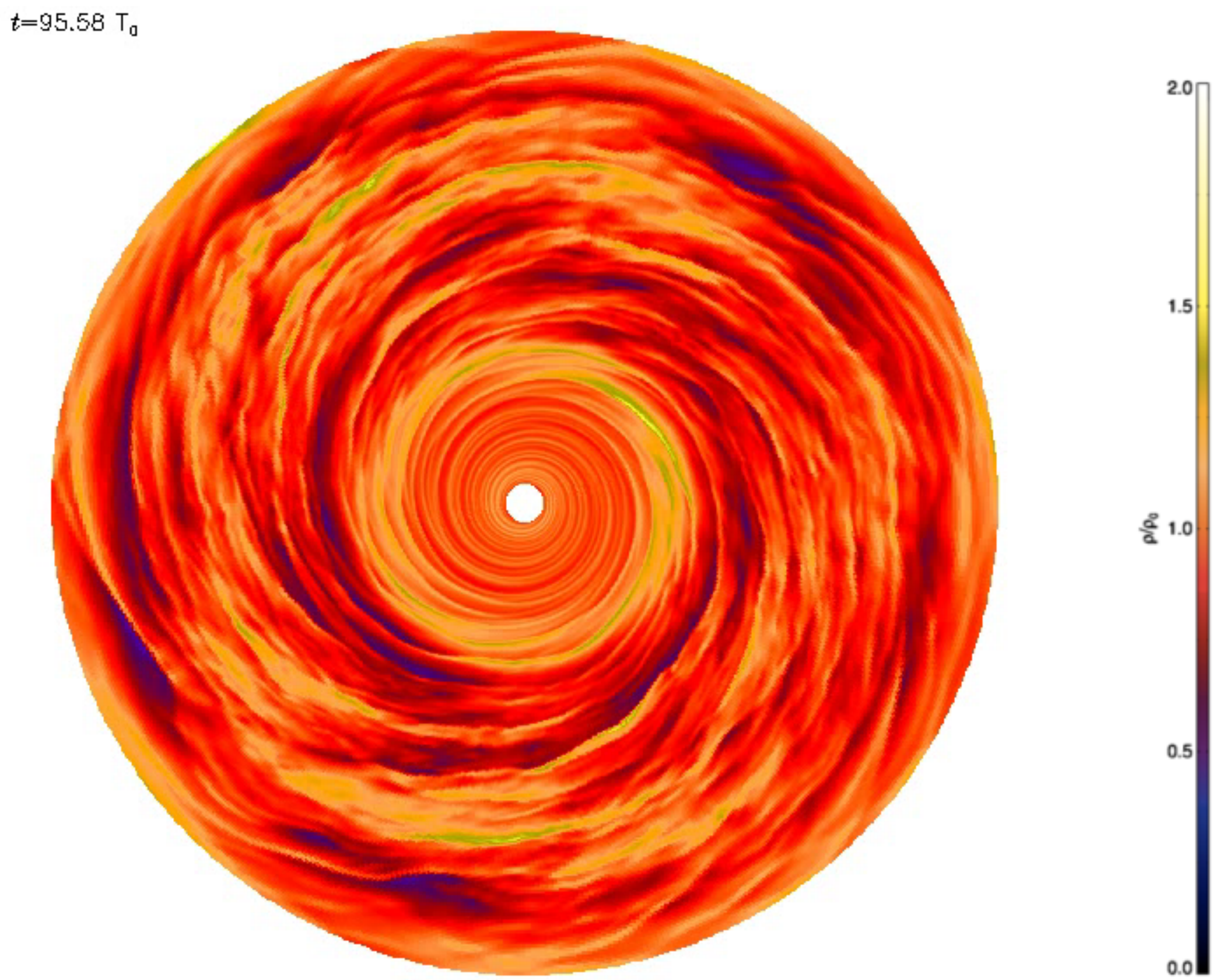
The **outer** dead zone transition in ionization supposed
TOO SMOOTH
to generate an KH-unstable bump.

Outer Dead/Active zone transition: Spirals without planets



Waves launched at the active zone propagate into the dead zone as a coherent spiral.

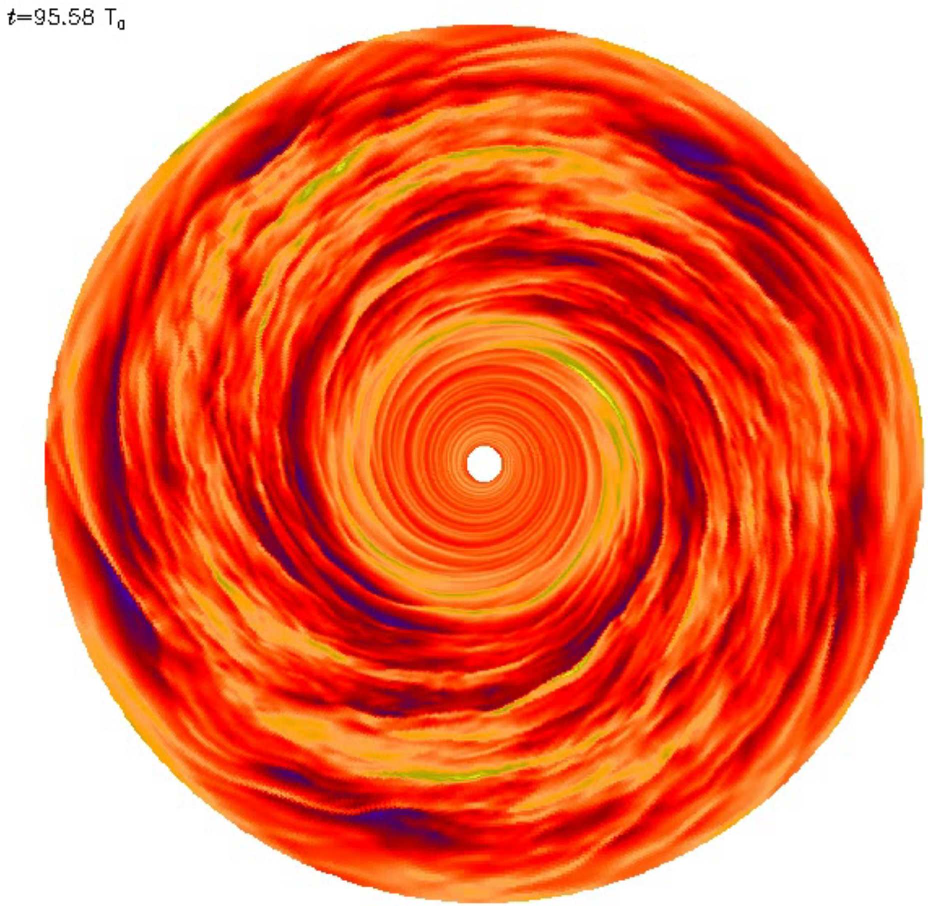
Outer Dead/Active zone transition: 3D MHD

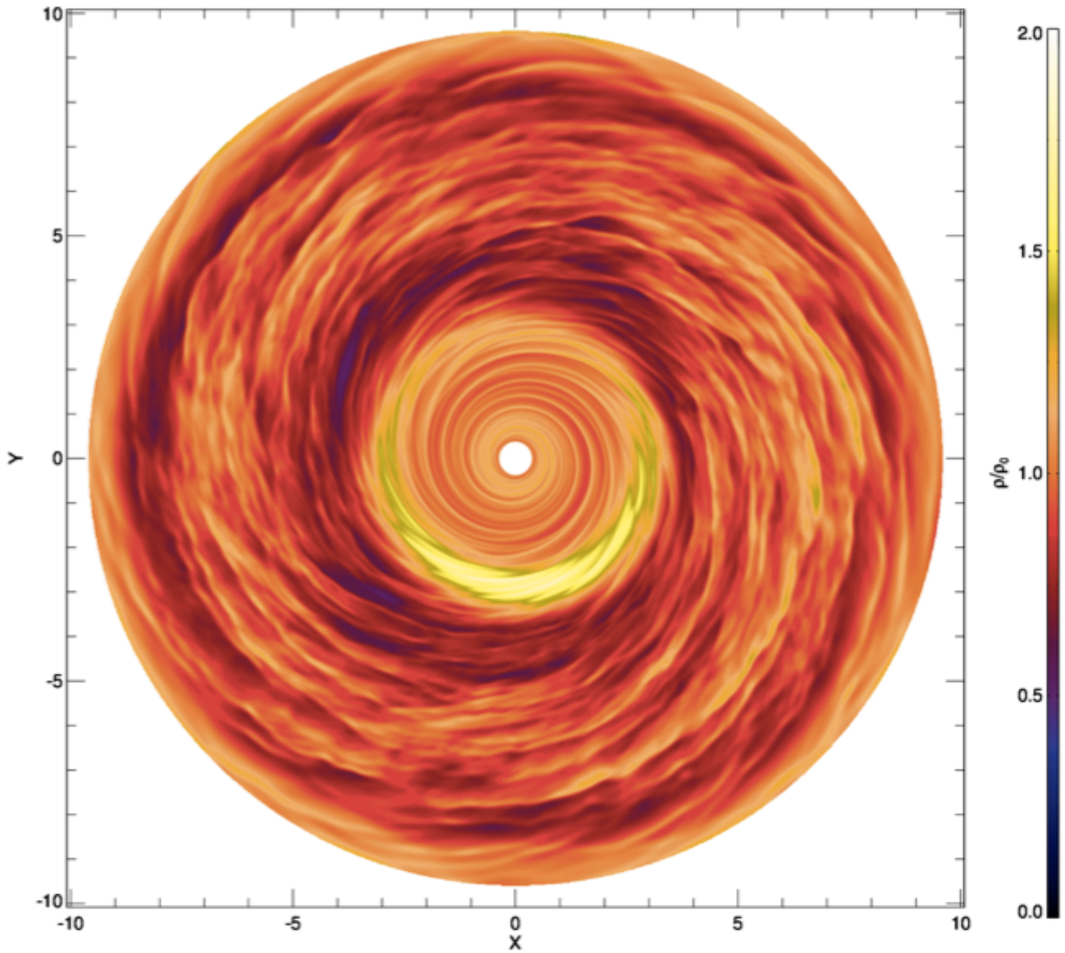


Resistive inner disk + magnetized outer disk

Lyra et al (2015)

Outer Dead/Active zone transition KHI

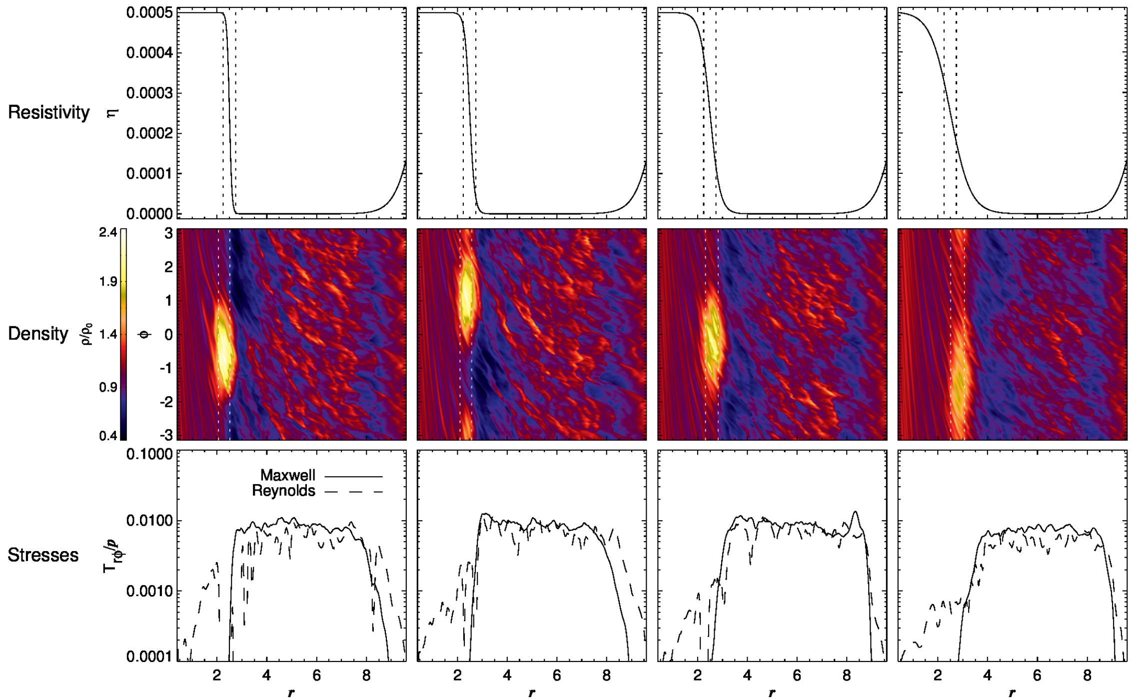




Resistive inner disk + magnetized outer disk

Lyra, Turner, & McNally (2015)

Outer Dead/Active zone transition RWI



Lyra, Turner, & McNally (2015)

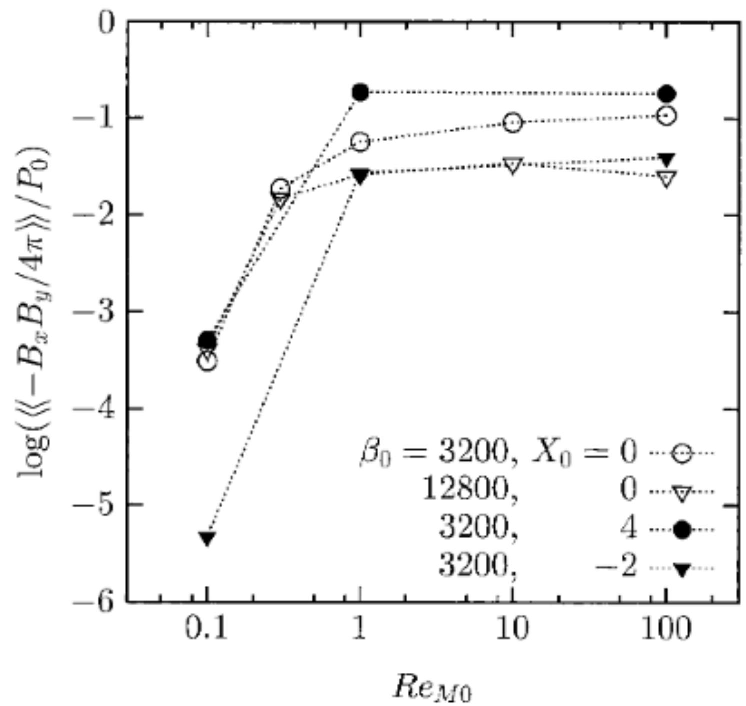
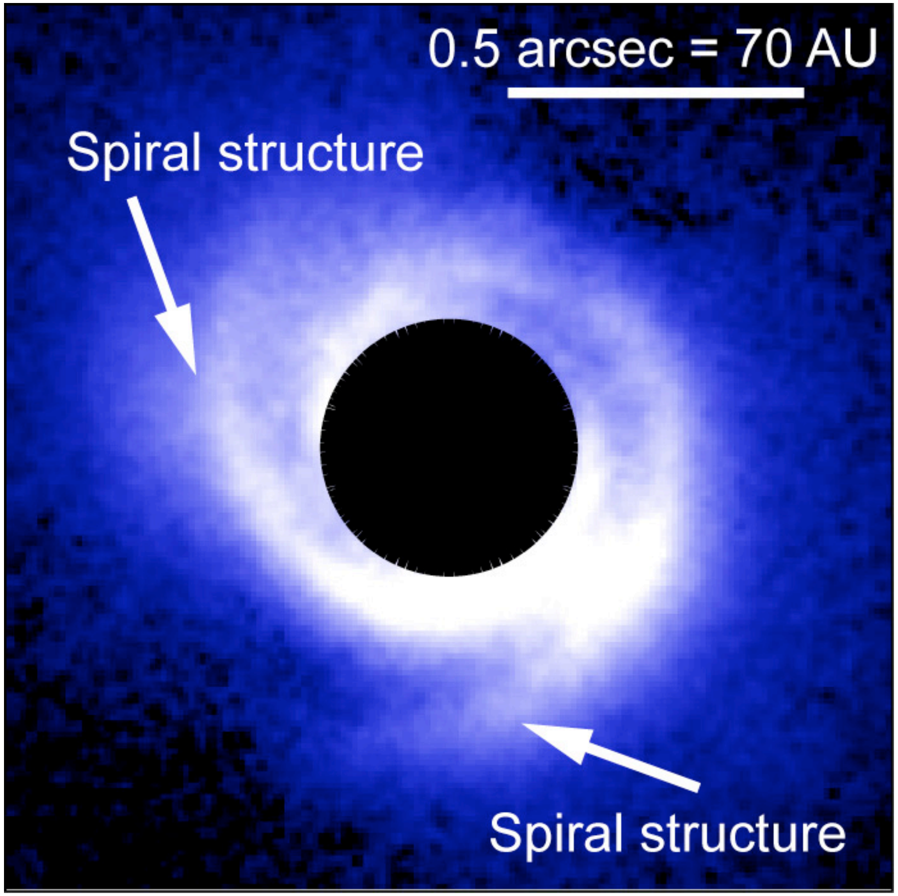
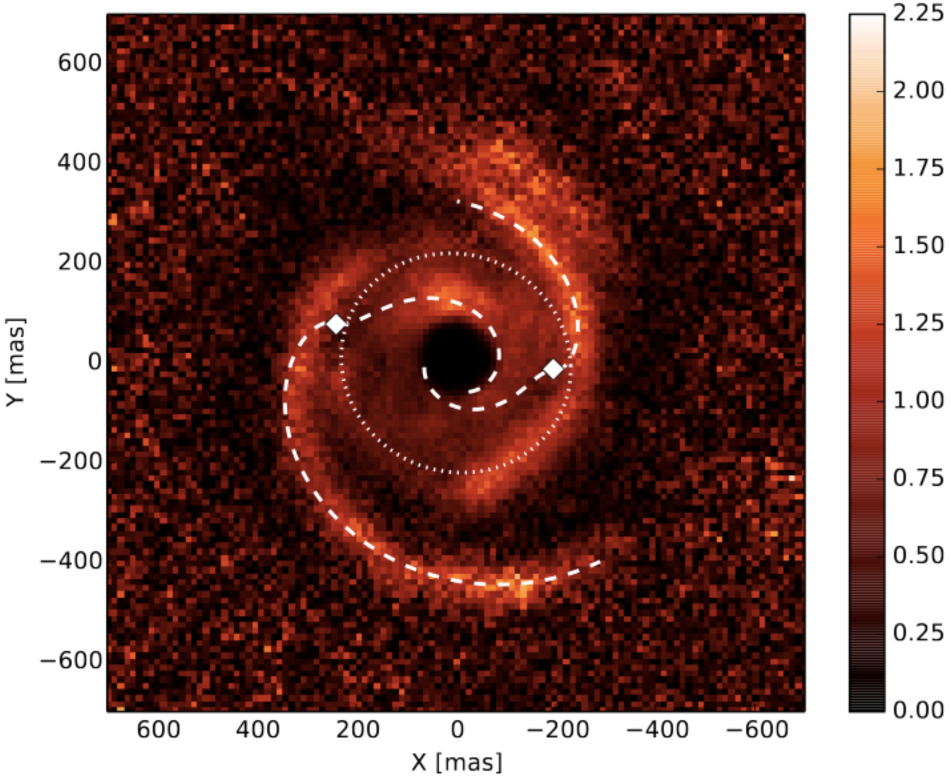


FIG. 9.—Saturation level of the Maxwell stress as a function of the magnetic Reynolds number Re_{M0}. Open circles and triangles denote the models without Hall term ($X_0 = 0$) for $\beta_0 = 3200$ and 12,800, respectively. The models including the Hall term are shown by filled circles ($X_0 = 4$) and triangles ($X_0 = -2$).

Sano and Stone (2002)

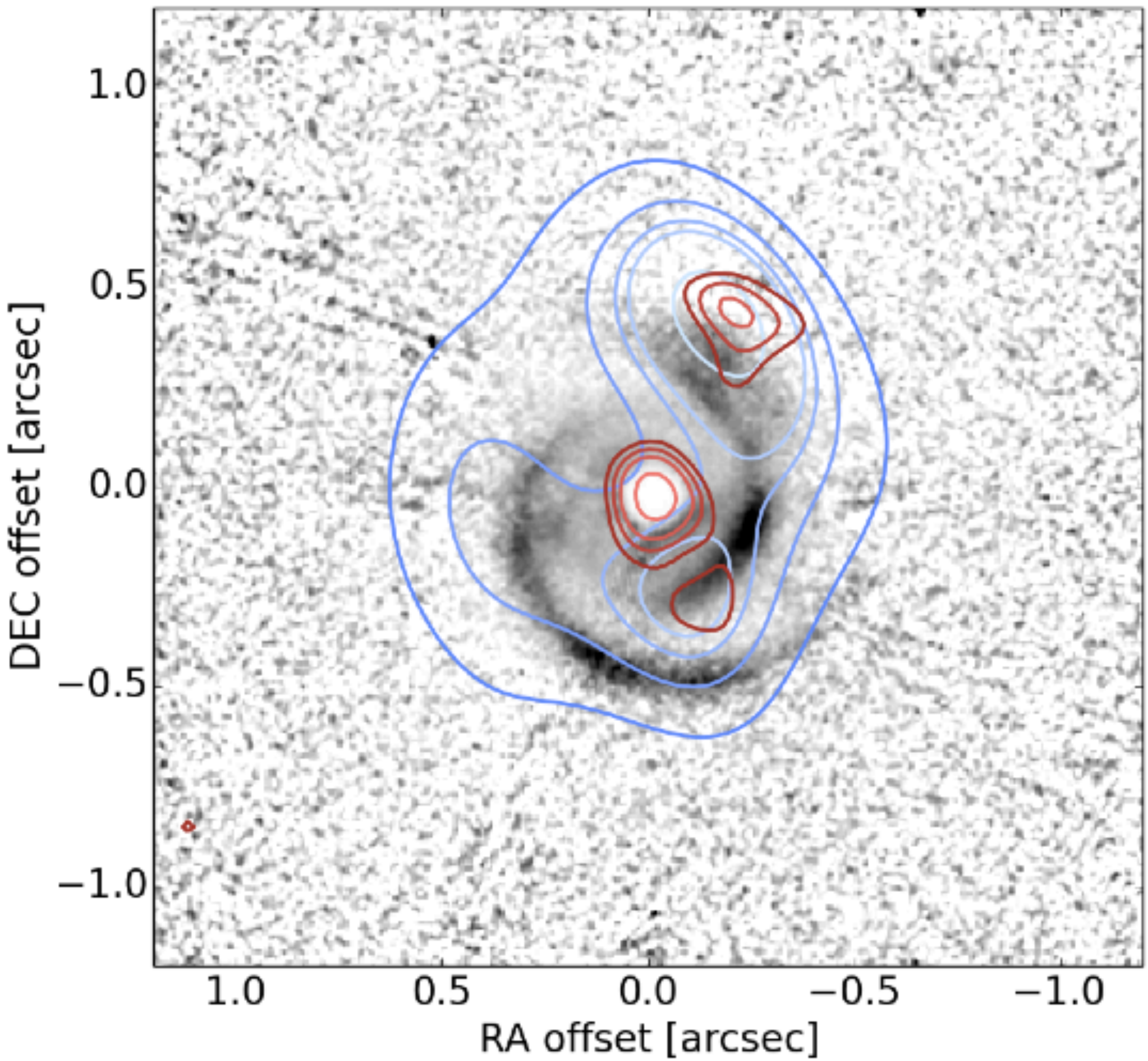
Observational evidence: Spirals





SPHERE-ALMA-VLA overlay of MWC 758

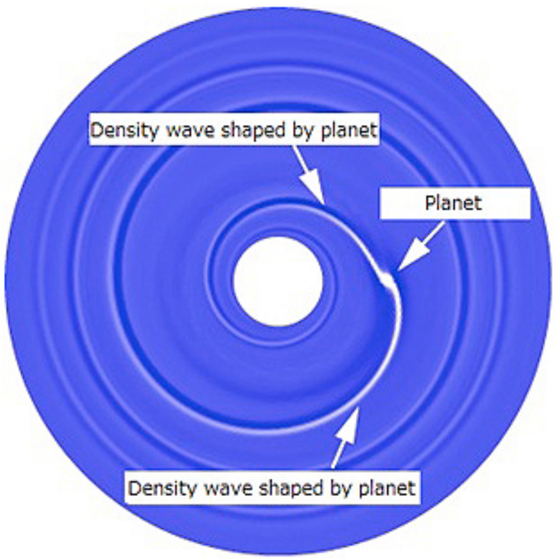
SPHERE
ALMA
VLA



Marino et al., (2015, accepted)

Spiral arm fitting leads to problems

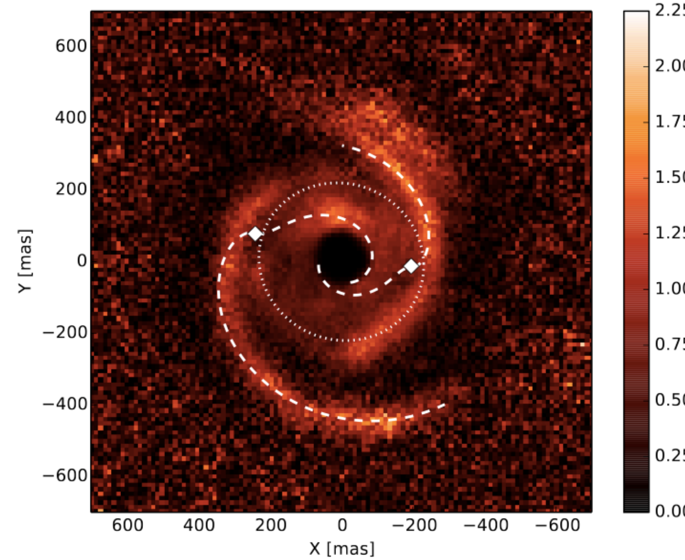
Analytical spiral fit



$$\theta(r) = \theta_c + \frac{\mathrm{sgn}(r - r_c)}{h_c} \times \left\{ \left(\frac{r}{r_c}\right)^{1+\beta} \left[\frac{1}{1+\beta} - \frac{1}{1-\alpha+\beta} \left(\frac{r}{r_c}\right)^{-\alpha} \right] - \left(\frac{1}{1+\beta} - \frac{1}{1-\alpha+\beta} \right) \right\},$$

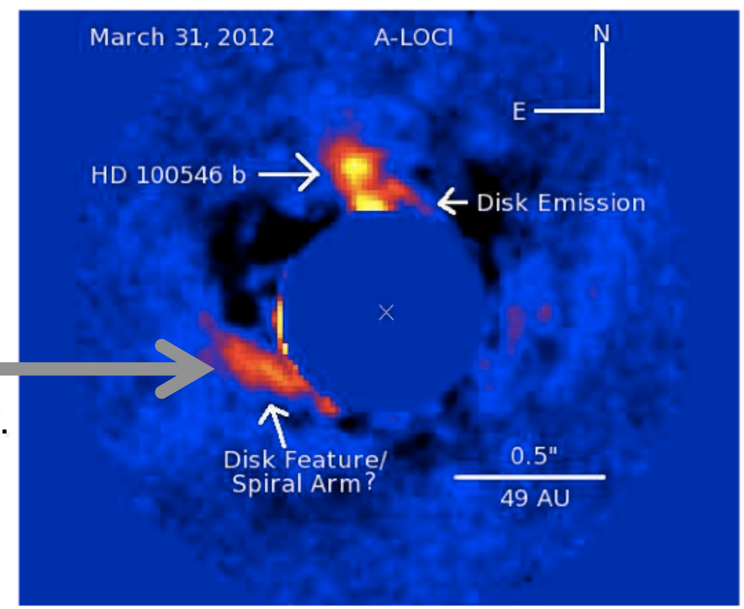
Rafikov (2002)
Muto et al. (2012)

Spirals are too wide hotter (300K) than ambient gas (50K).



Benisty et al. (2015)

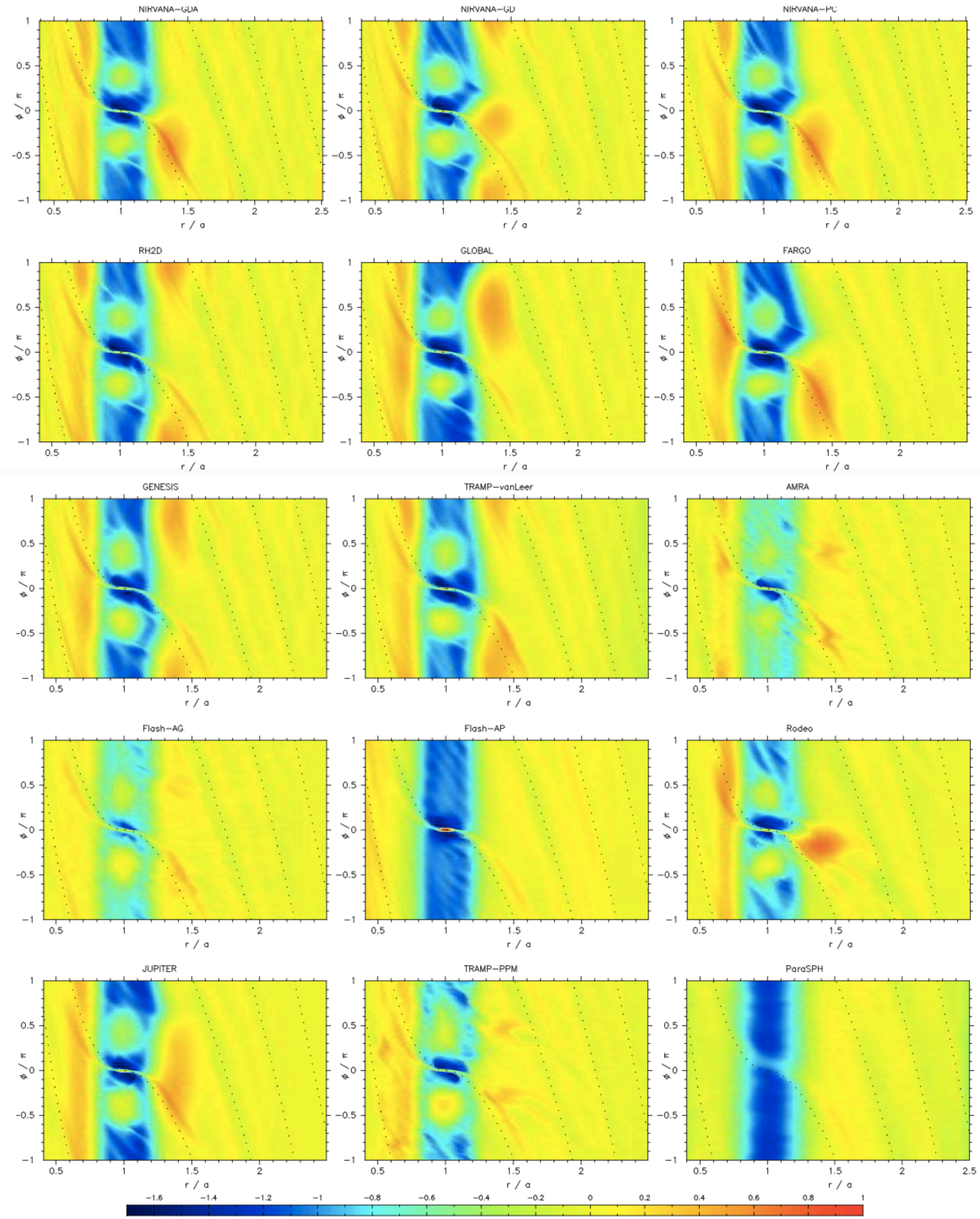
Spiral has little polarization. Must be thermal emission at 1000K.



Currie et al. (2014)

The code comparison project of 2006 (de Val-Borro et al. 2006)

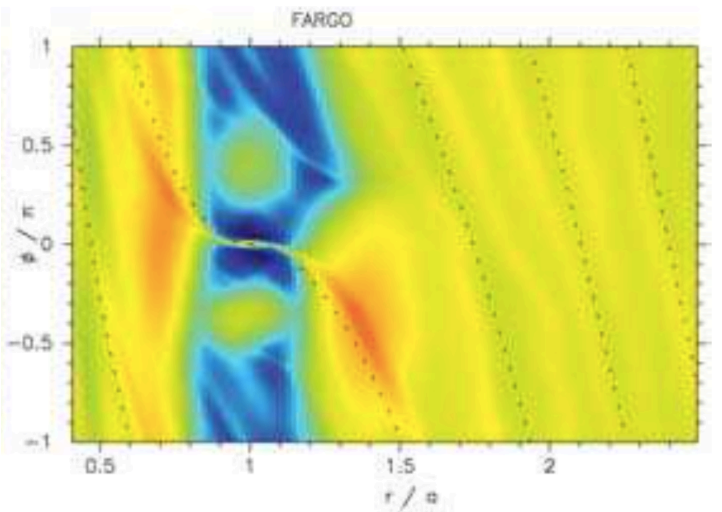
Problem of choice:
2D ‘vanilla’ planet-disk interaction.



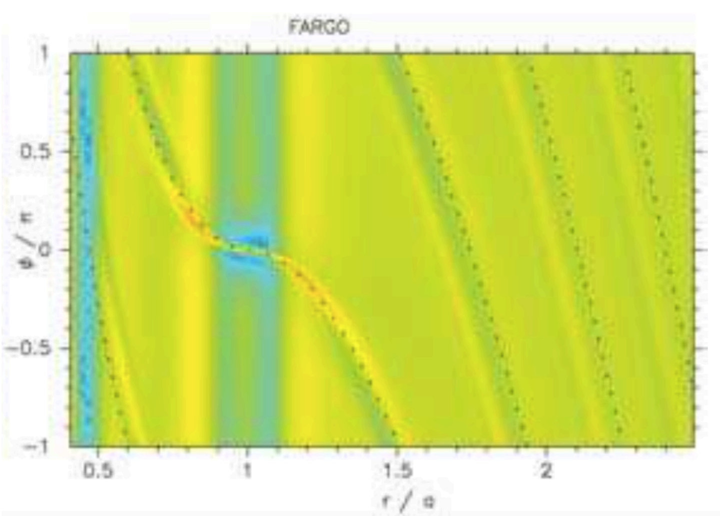
The “hot spiral problem” has never been a problem

Wakes of high-mass planets are not sonic, but *supersonic*.

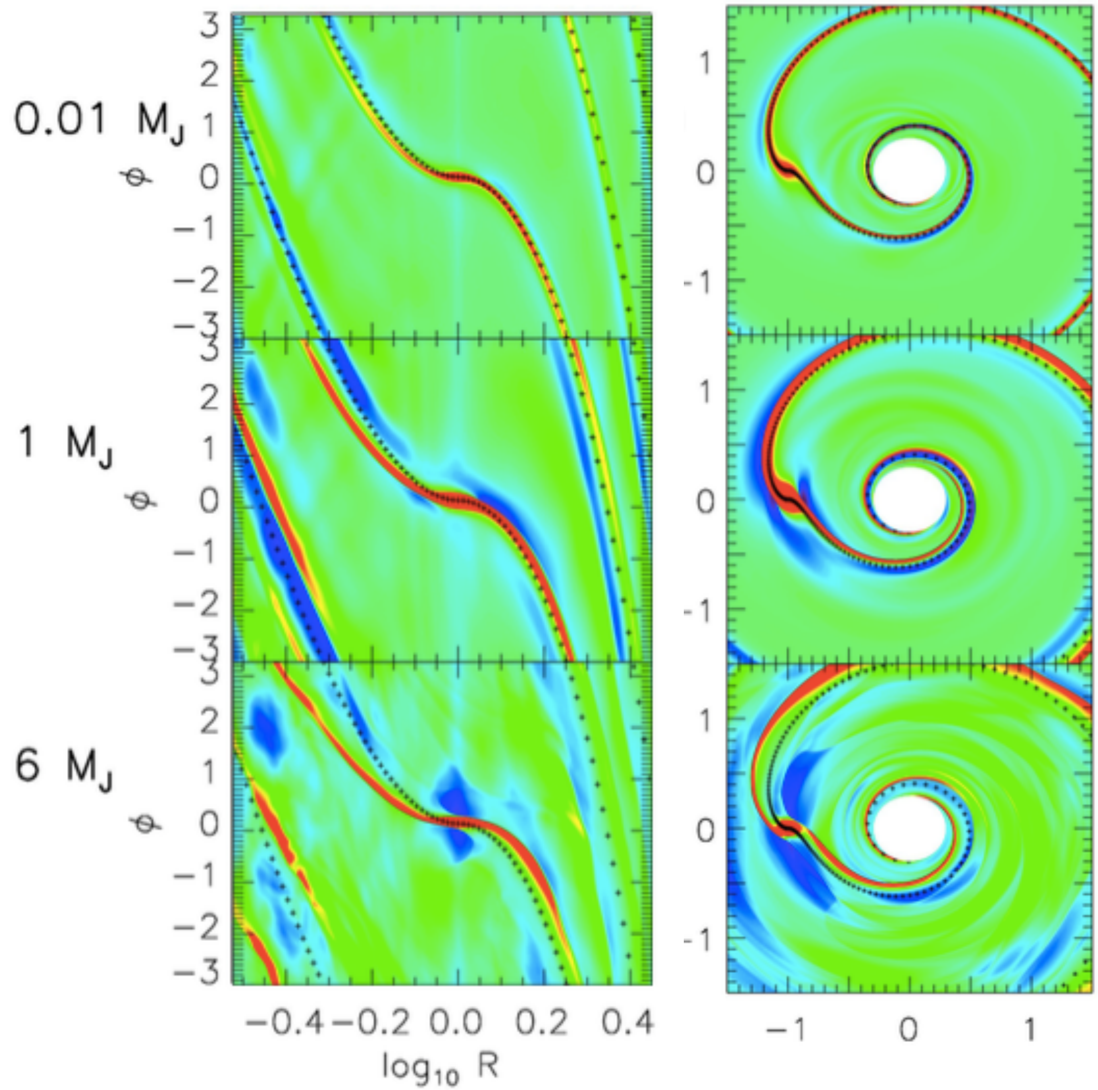
Jupiter-mass (non-linear)



Neptune-mass (linear)

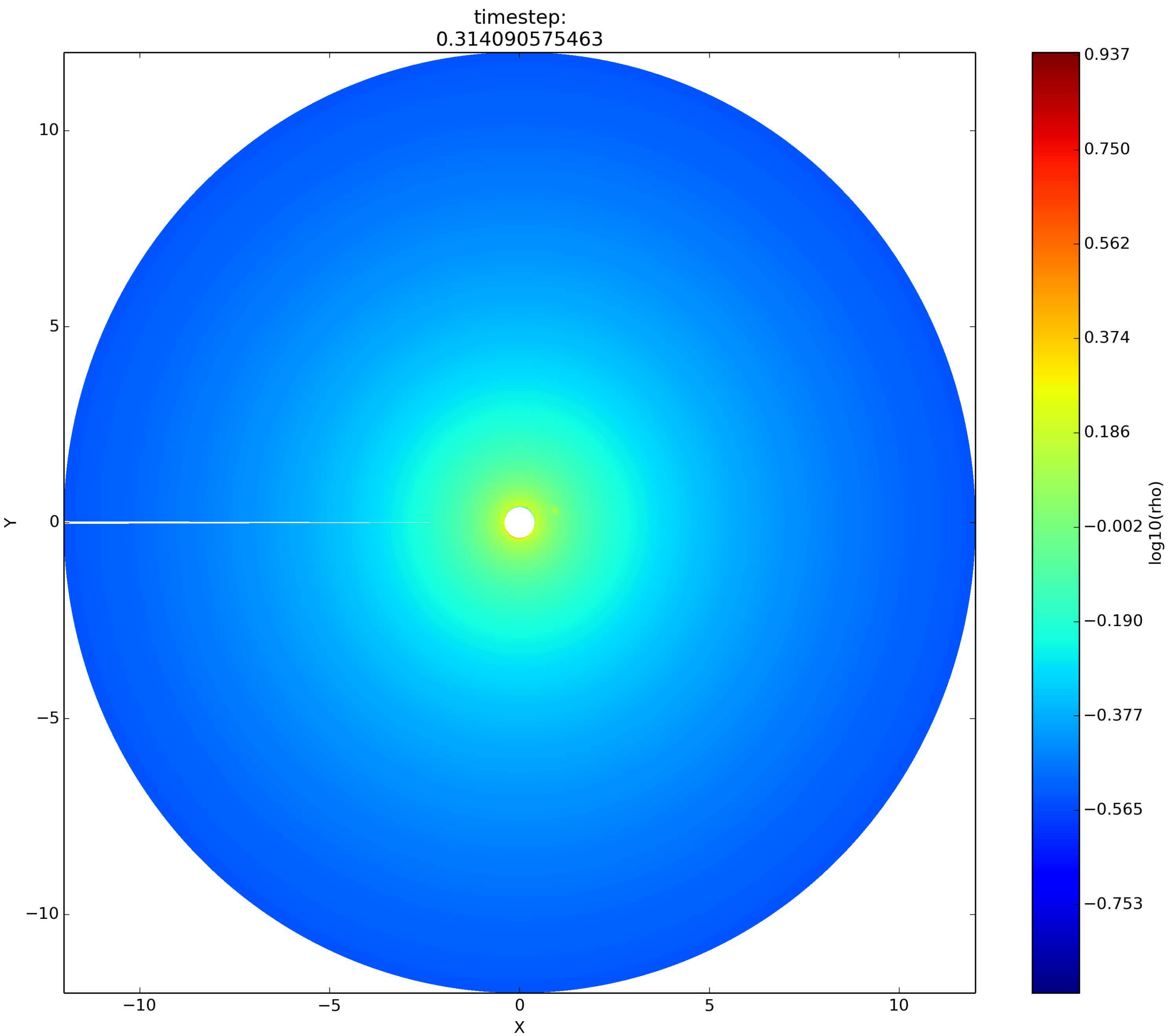


de Val-Borro al. (2006)



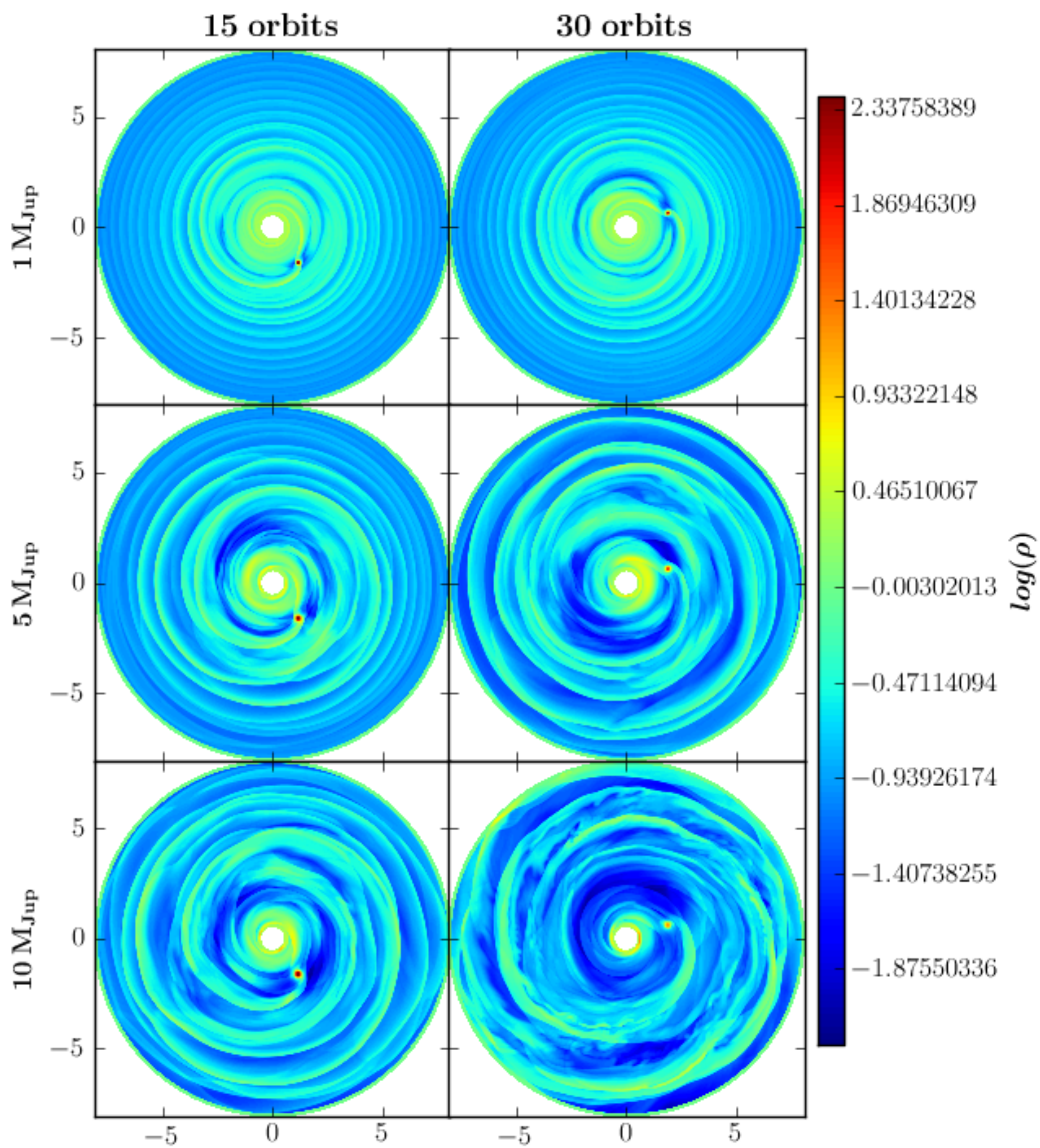
Zhu et al. (2015)

Spiral wake of high-mass planets in non-isothermal disks

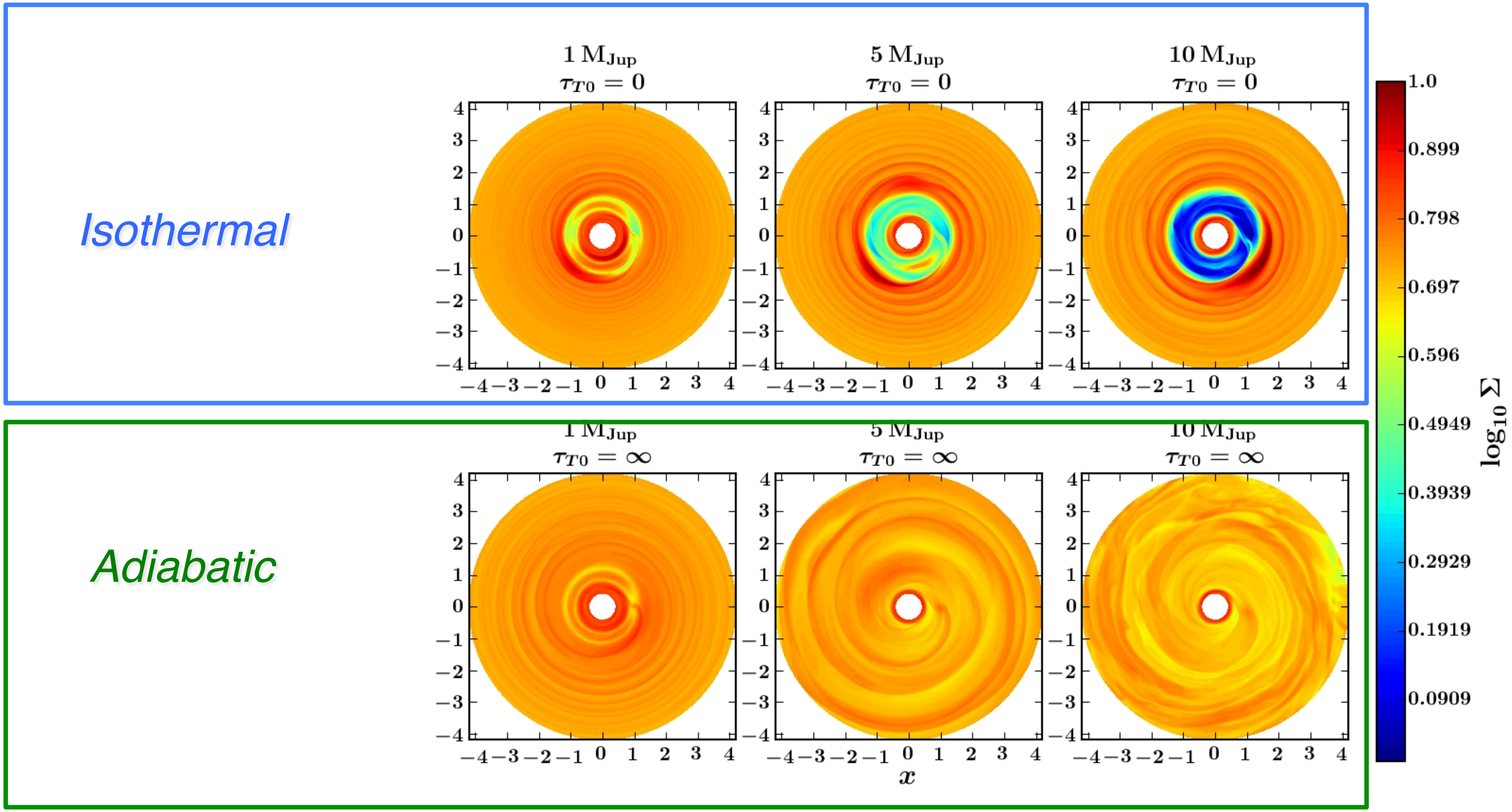


Richert et al. (2015)

Some crazy turbulence showing up at high planet mass….

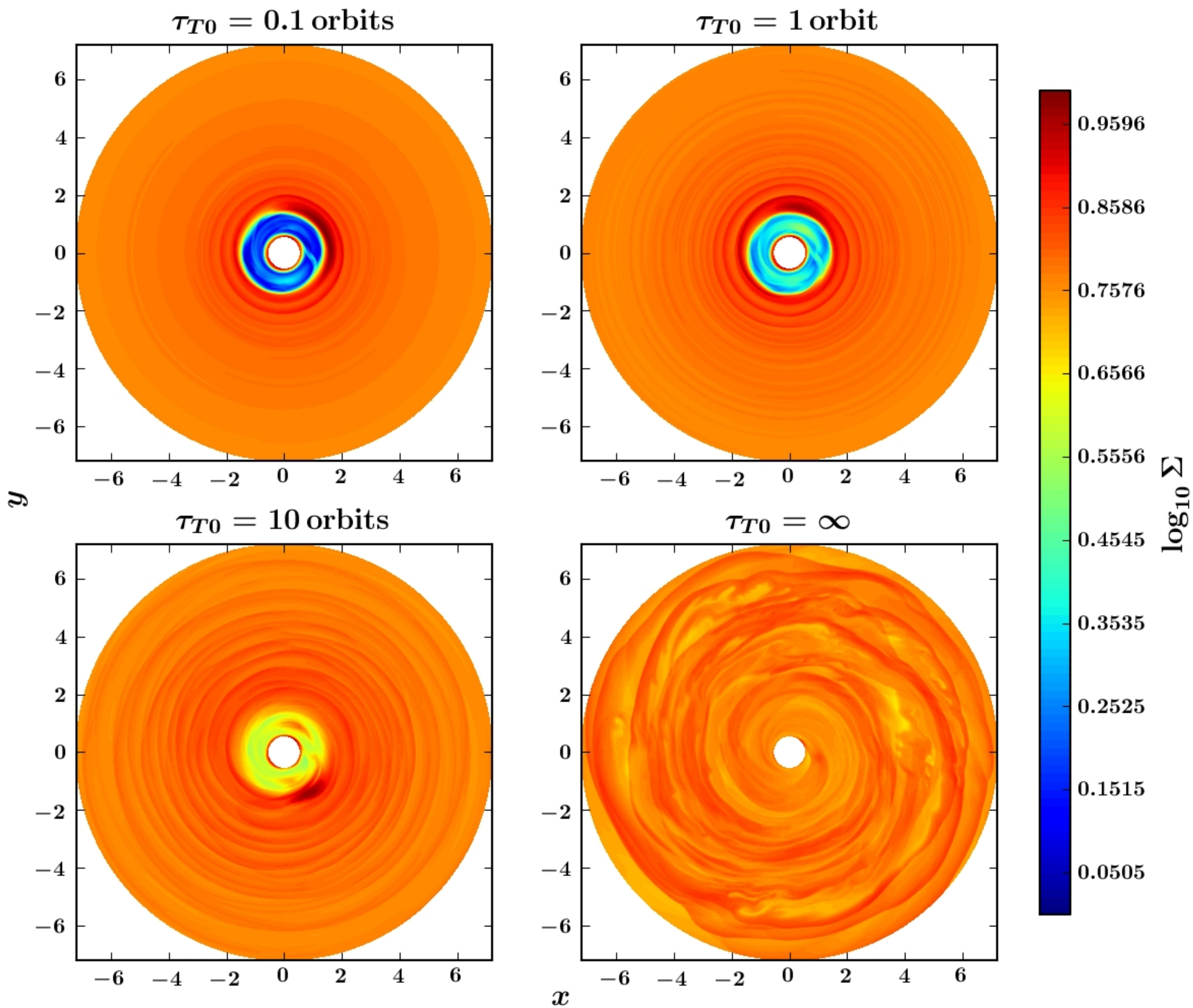


Shows up for high-mass planets in adiabatic disks

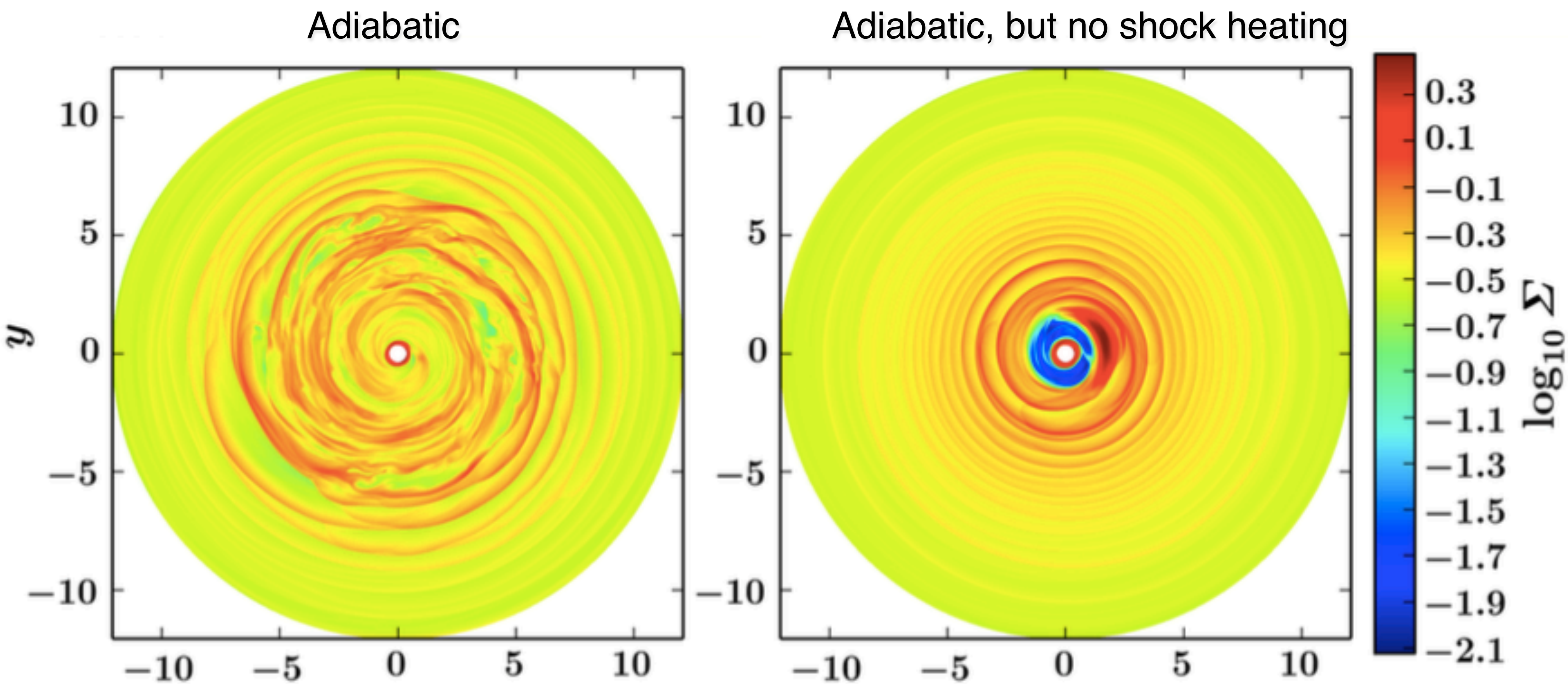


Richert et al. (2015)

Shows up for long cooling times….

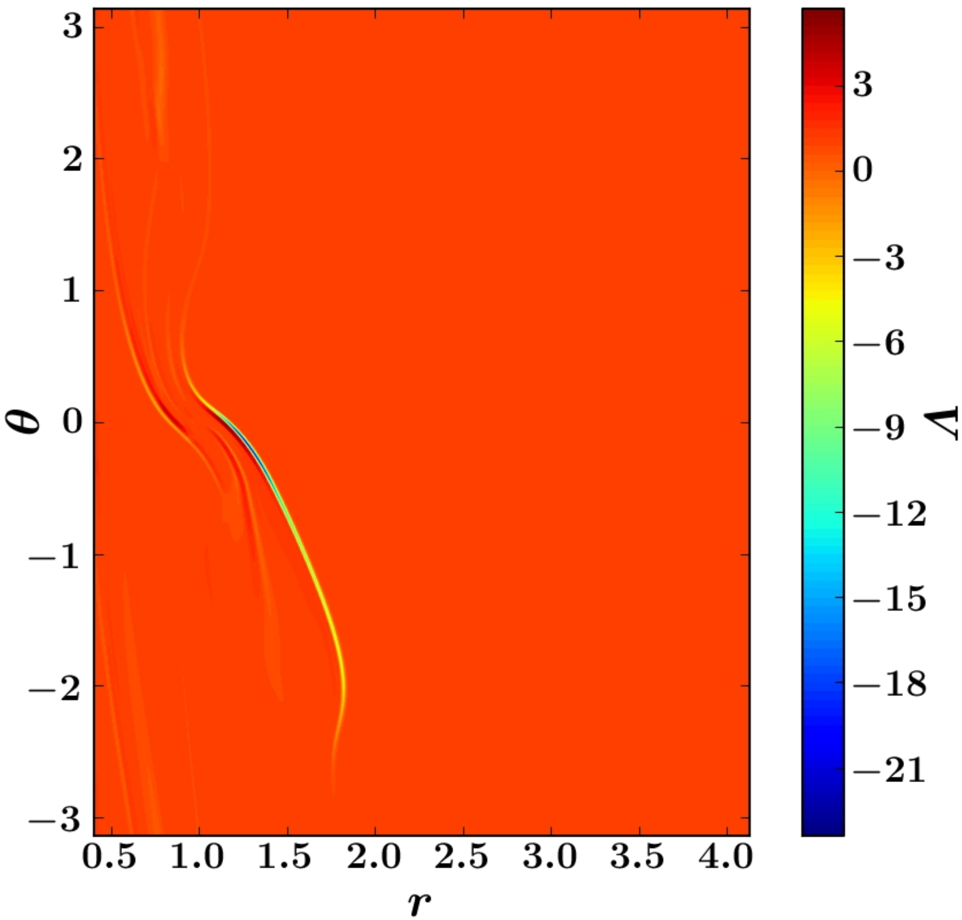


The energy source: shock heating!

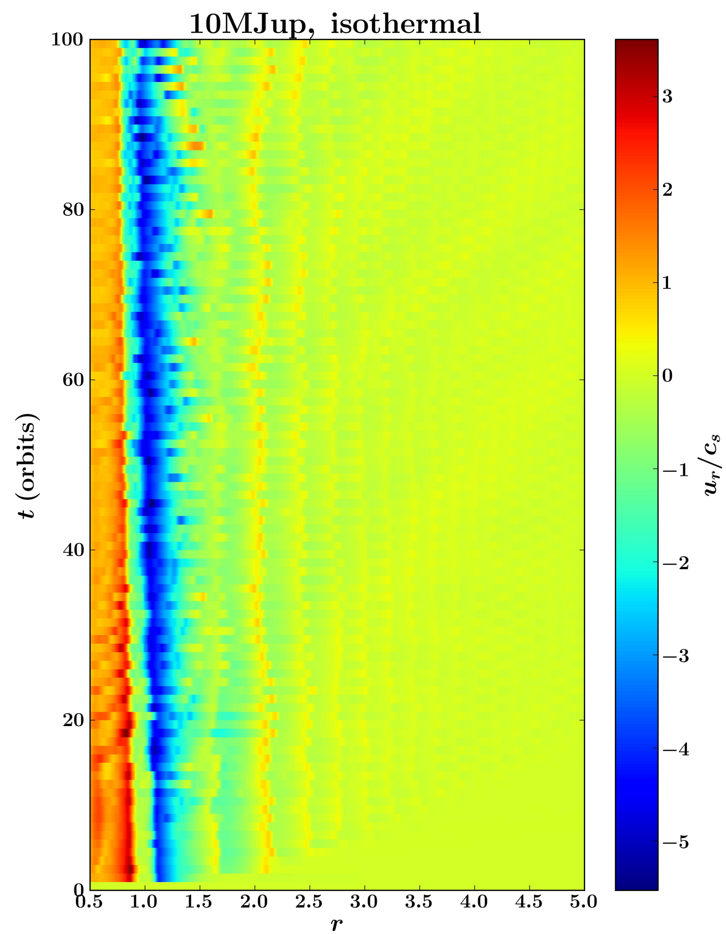


Richert et al. (2015)

The spiral is buoyantly unstable



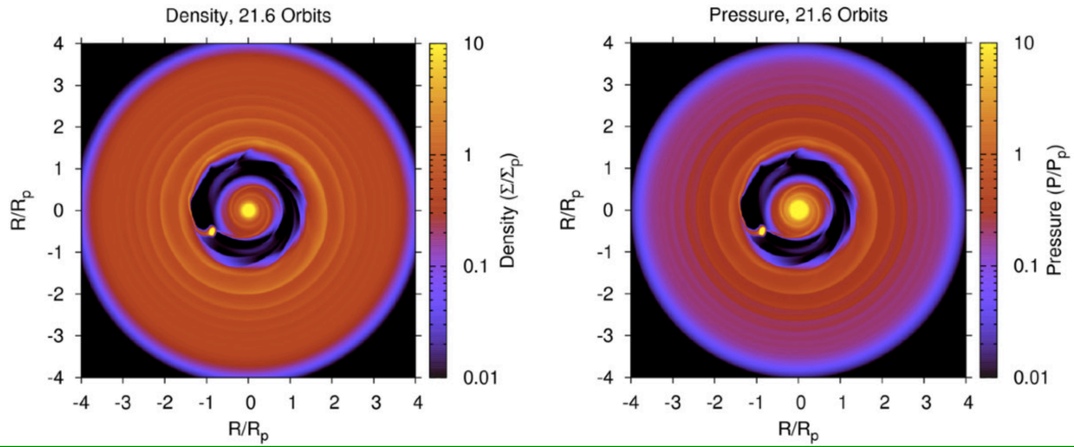
The spiral has Ma >~ 1



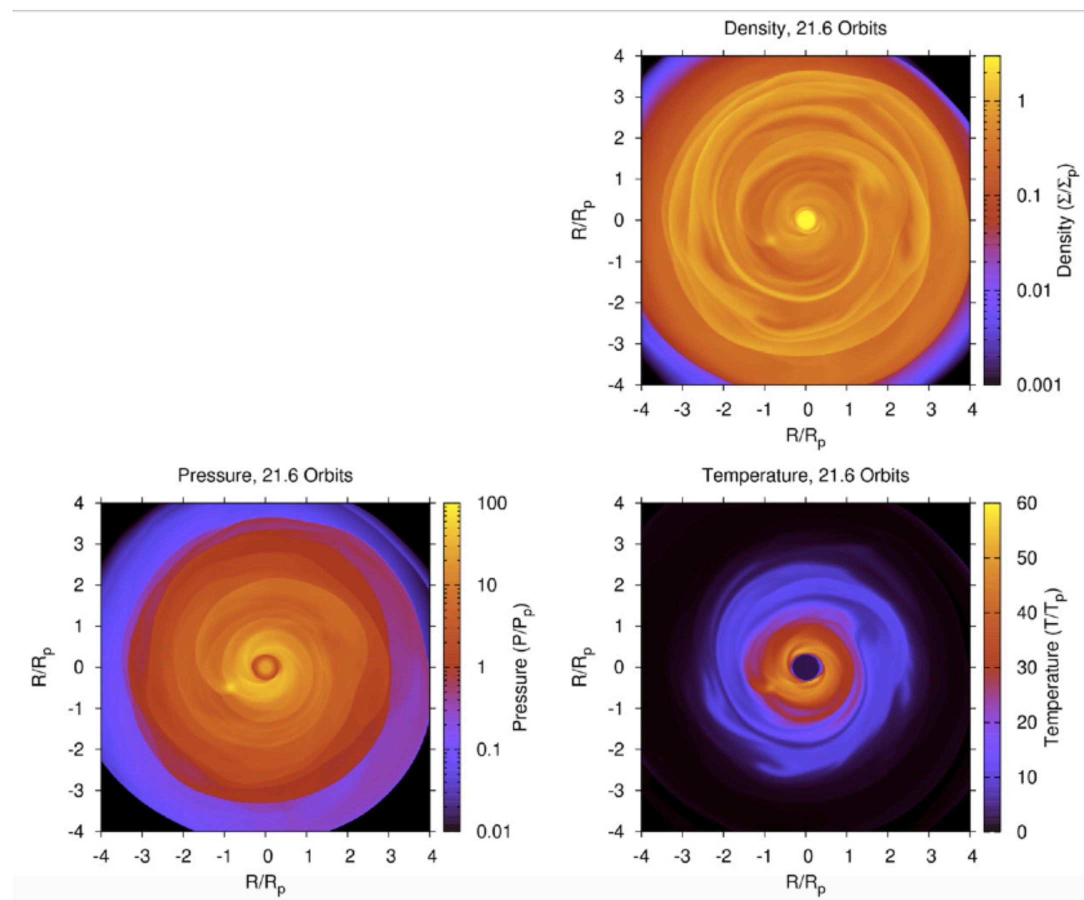
Richert et al. (2015)

Independent code

Isothermal control run



Adiabatic



3D shocks: ascending bores and breaking waves

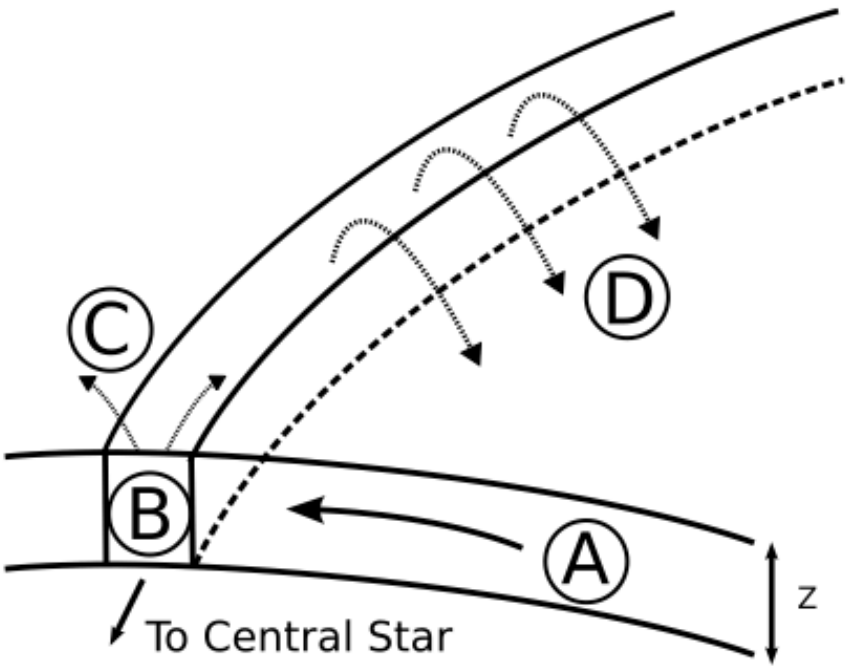
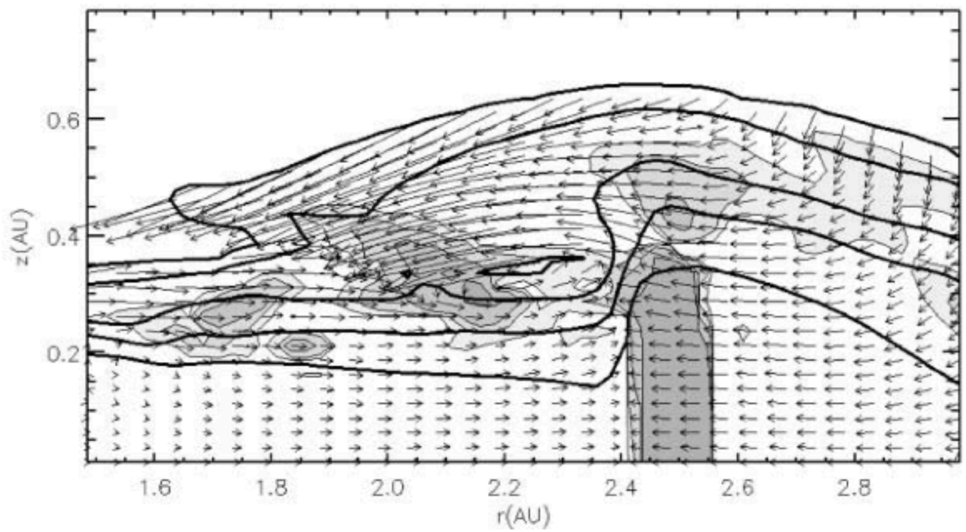
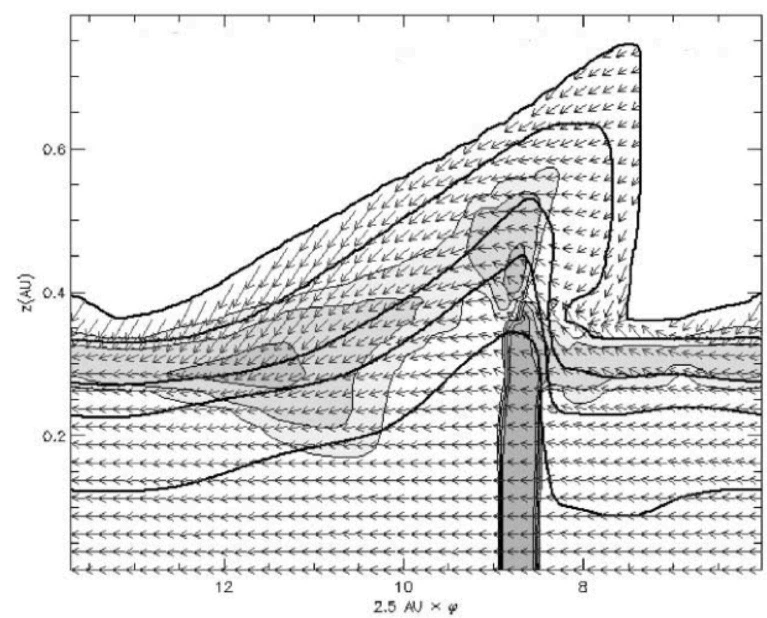


FIG. 2.—Cartoon depicting the gas flow in a shock bore in the frame of the spiral shock inside corotation. The gas in the preshock region flows into the spiral shock (A). The shock (B) causes the material to be out of vertical force balance and a rapid expansion results (C). Due to spiral streaming and the loss of pressure confinement, some of the gas will flow back over the spiral wave and break onto the disk in the preshock region at a radius inward from where it originated (D).





Boley & Durisen (2006)

Radiative transfer approximation

$$T\frac{Ds}{Dt} = -c_V\frac{(T - T_{\rm ref})}{t_{\rm cool}} + \Gamma_{\rm sh},$$

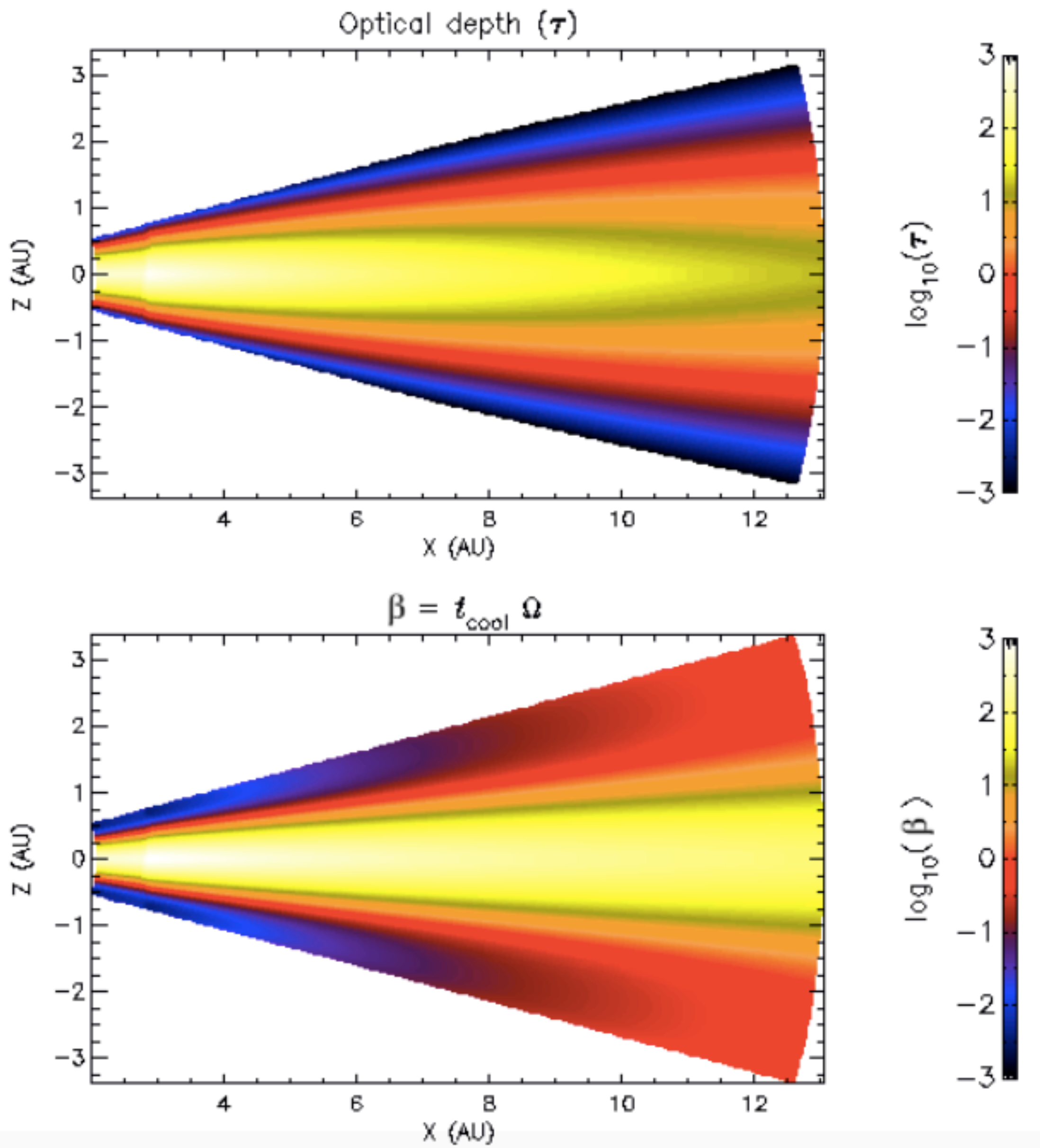
$$t_{\rm rad} = E/\dot{E}$$

$$\dot{E} = \nabla \cdot \boldsymbol{F}$$

$$t_{\rm cool} \equiv \frac{\int E dV}{\int F\hat{\boldsymbol{n}} \cdot d\boldsymbol{A}}.$$

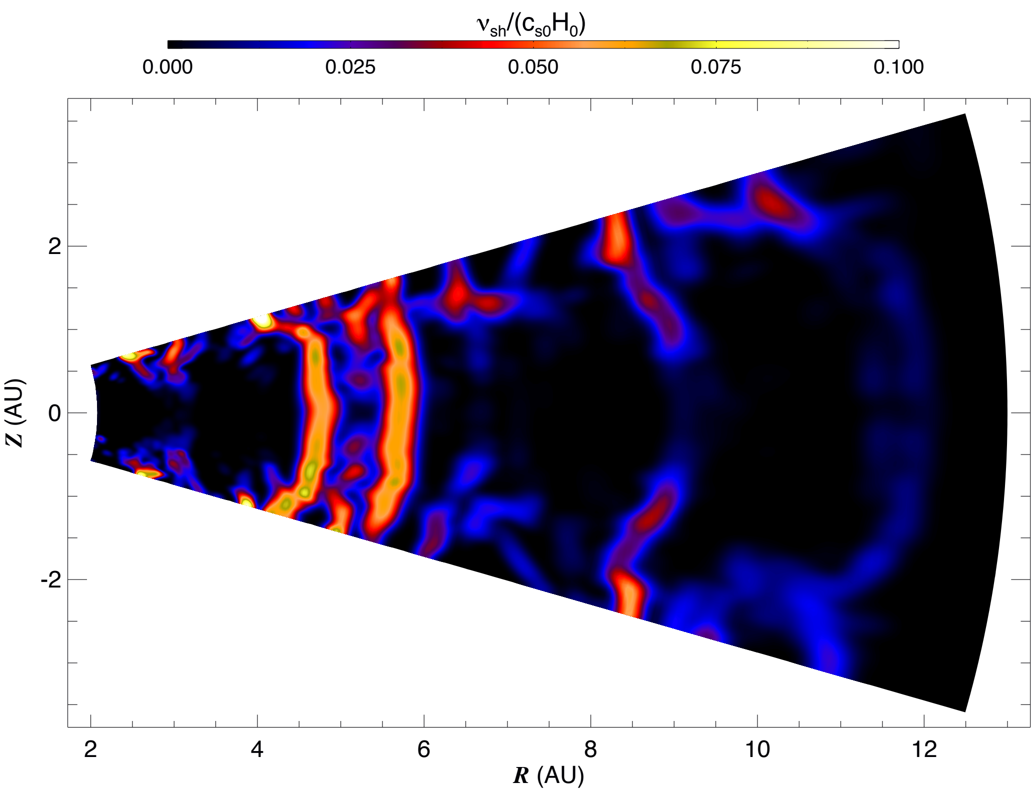
$$t_{\rm cool} = \frac{c_V \rho H \tau_{\rm eff}}{3\sigma T^3}.$$

$$\tau_{\rm eff} = \frac{3\tau}{8} + \frac{\sqrt{3}}{4} + \frac{1}{4\tau}.$$

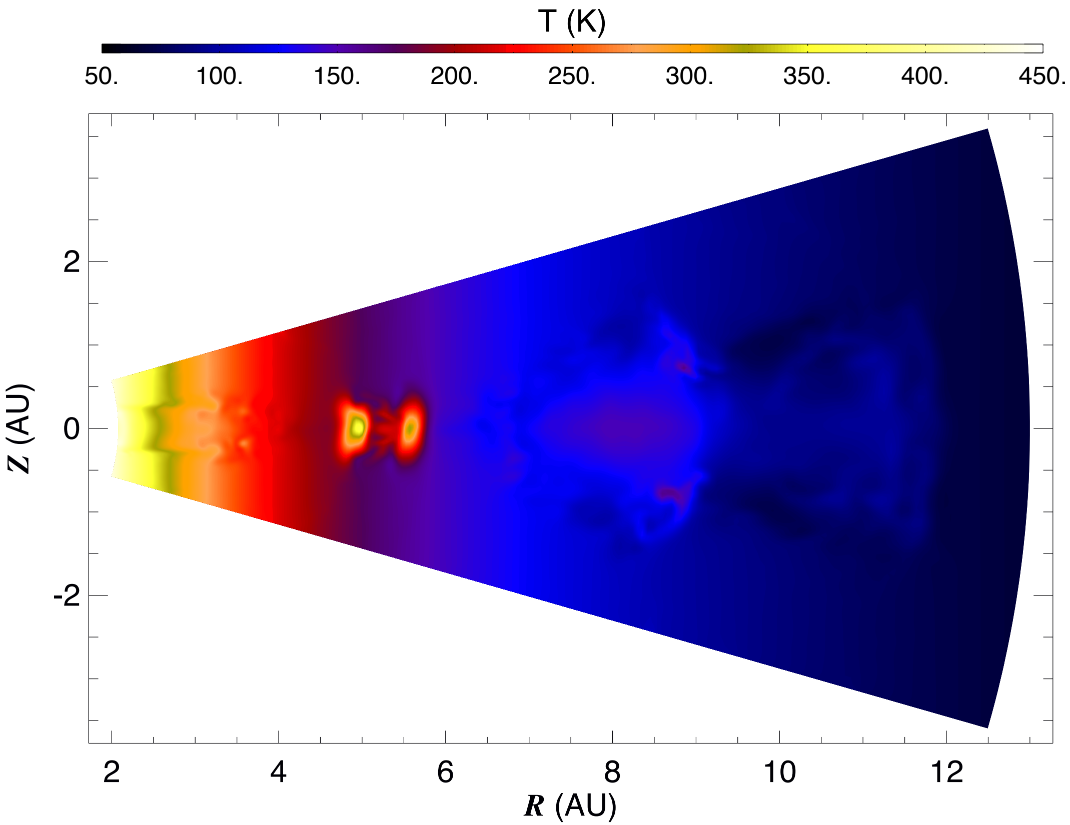


Shock bores

Velocity convergence

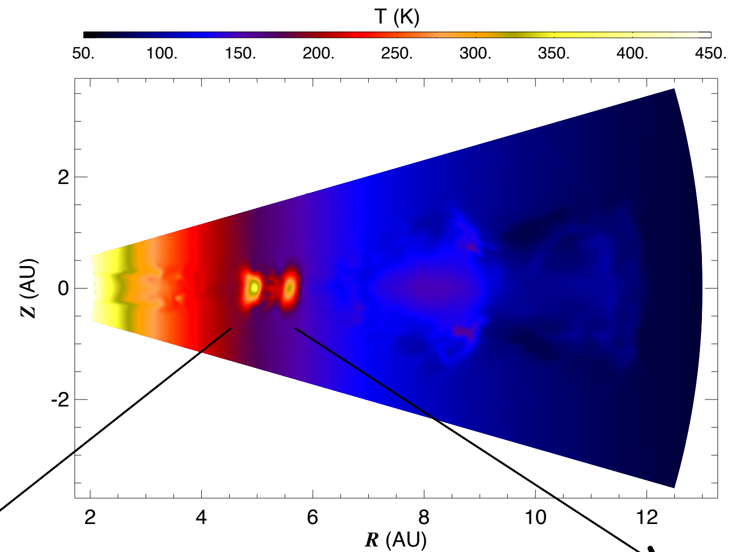


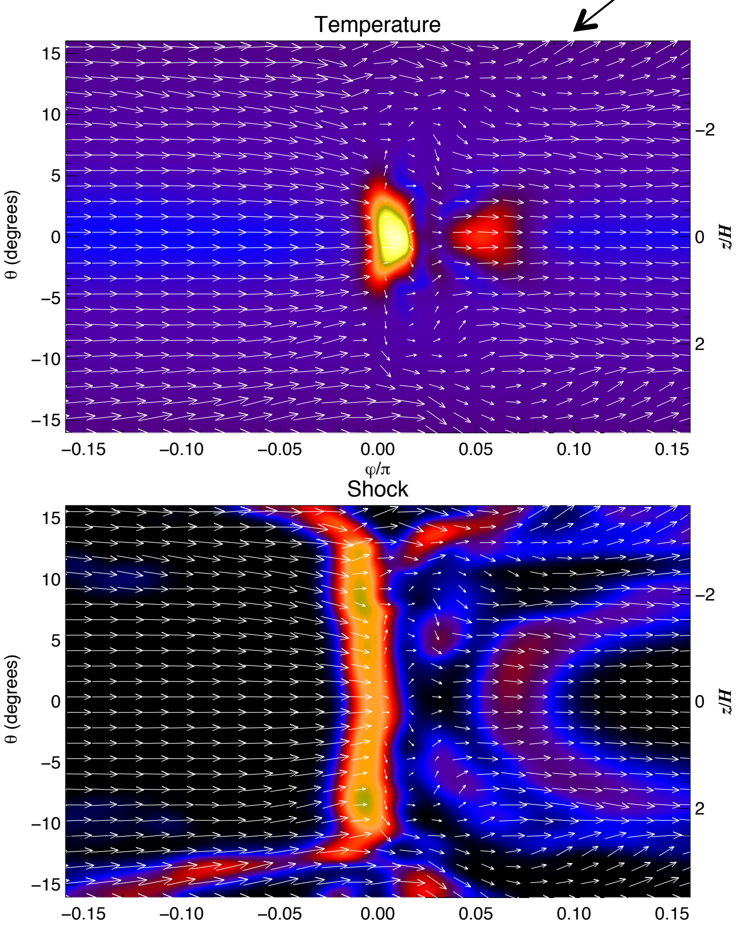
Temperature



Lyra et al. (2015b, submitted)

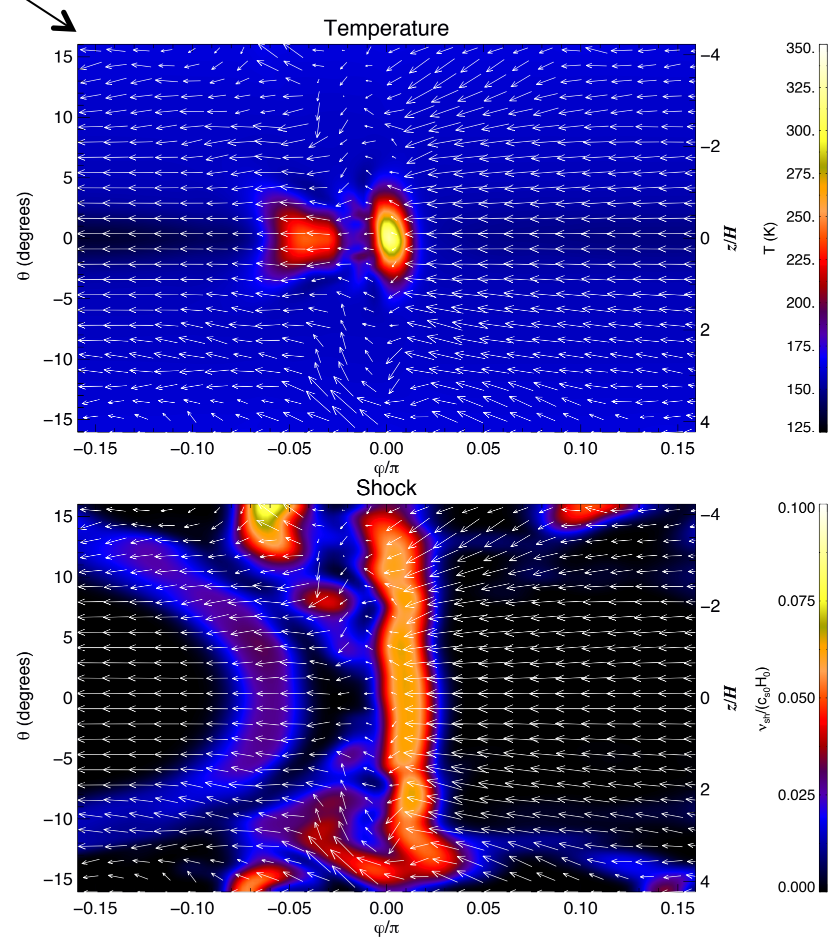
3D shocks: bores and breaking waves





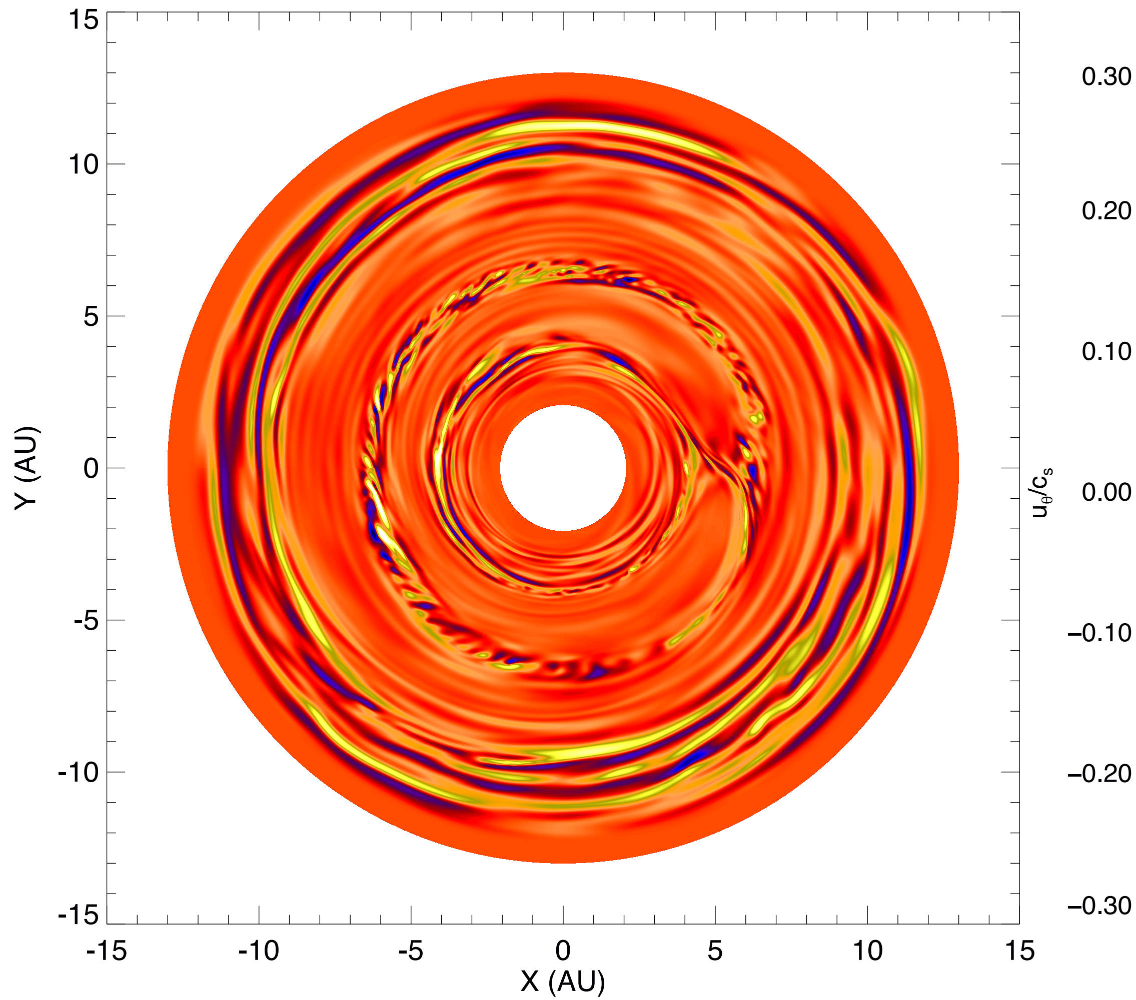
Temperature

Div u
(shock)



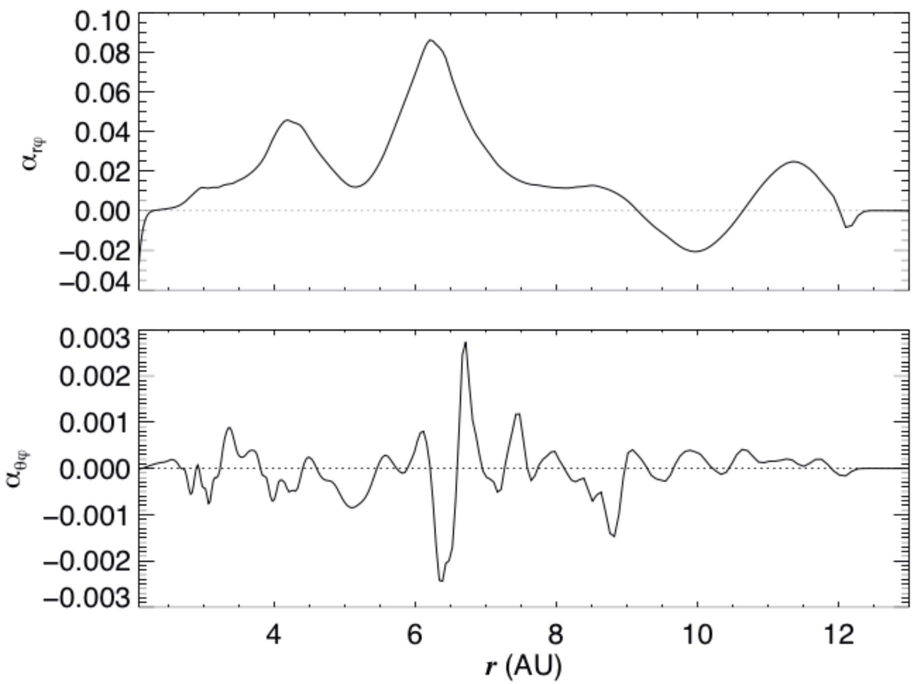
Lyra et al. (2015b, submitted)

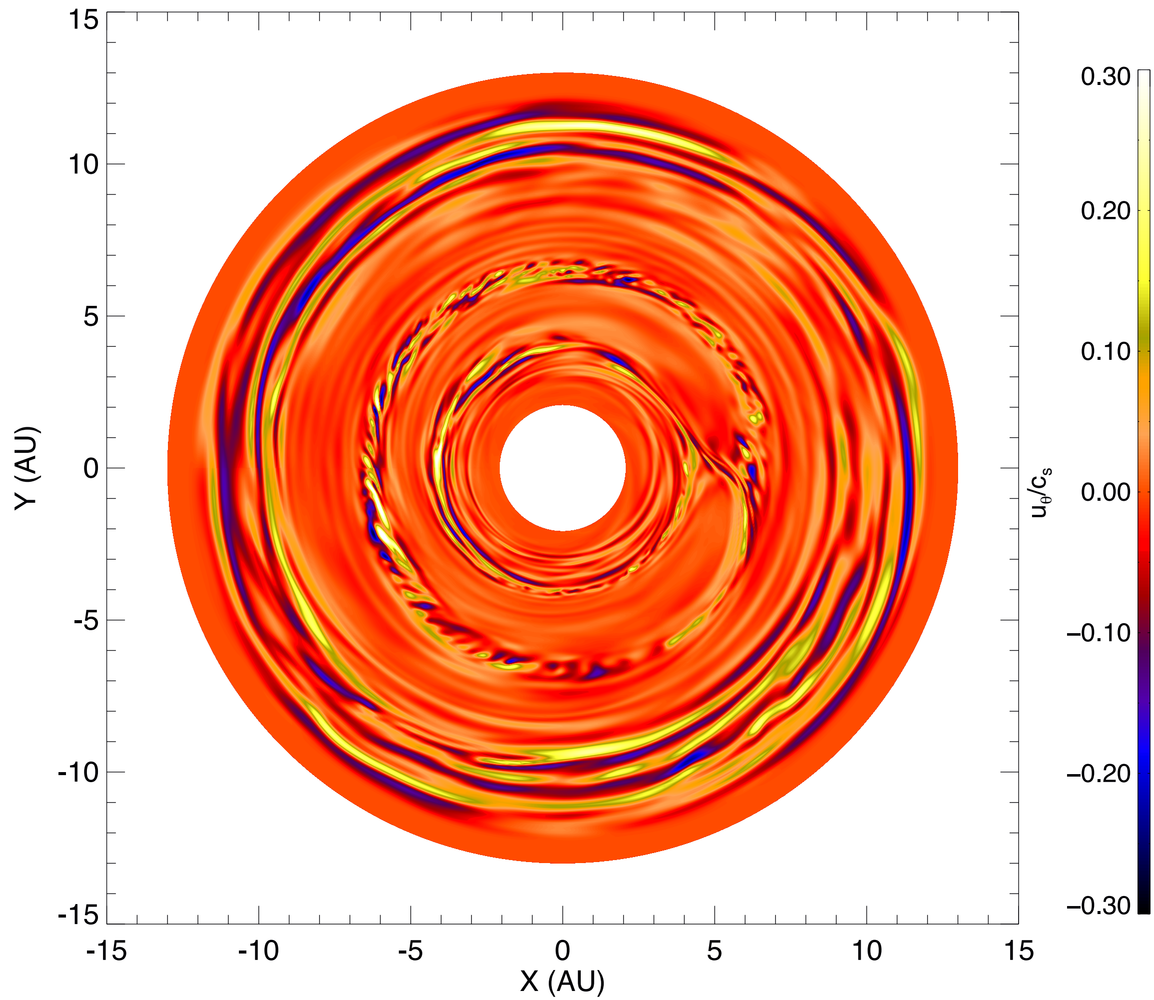
Turbulent surf



Lyra et al. (2015b, submitted)

Turbulent surf

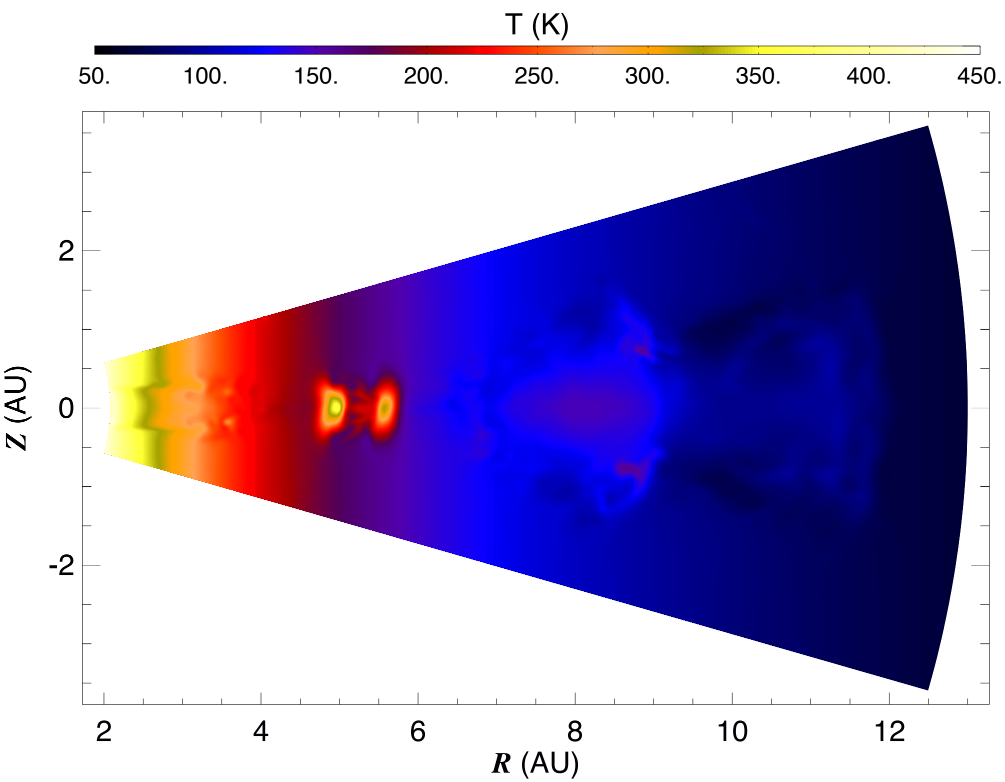




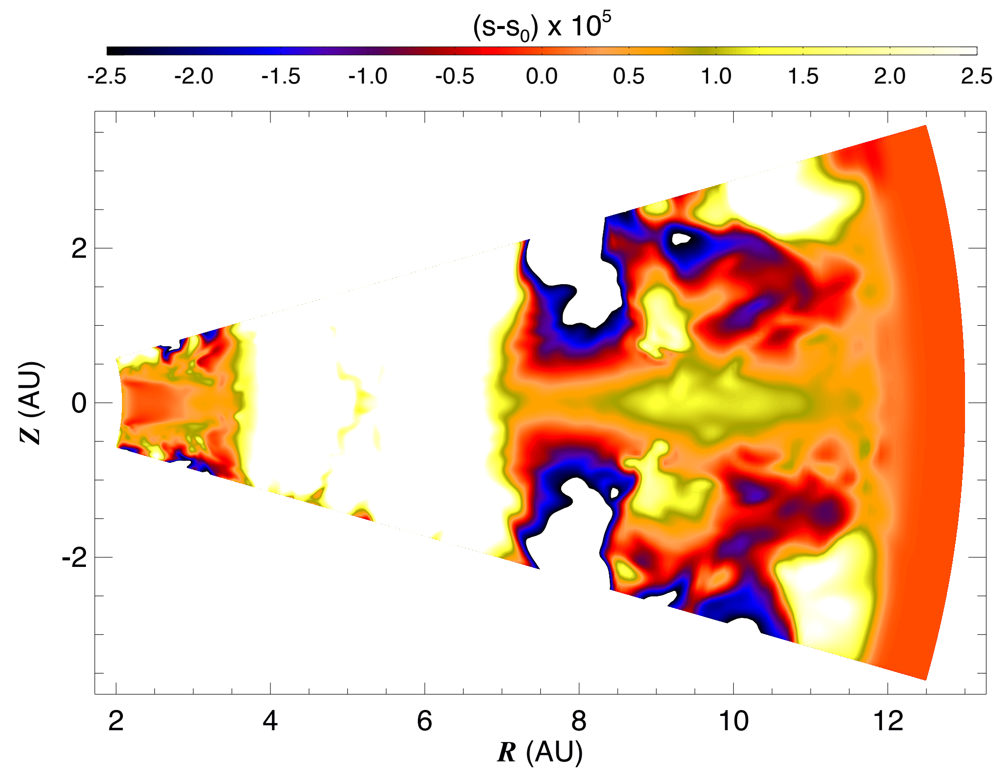
Lyra et al. (2015b, submitted)

Convection

Temperature

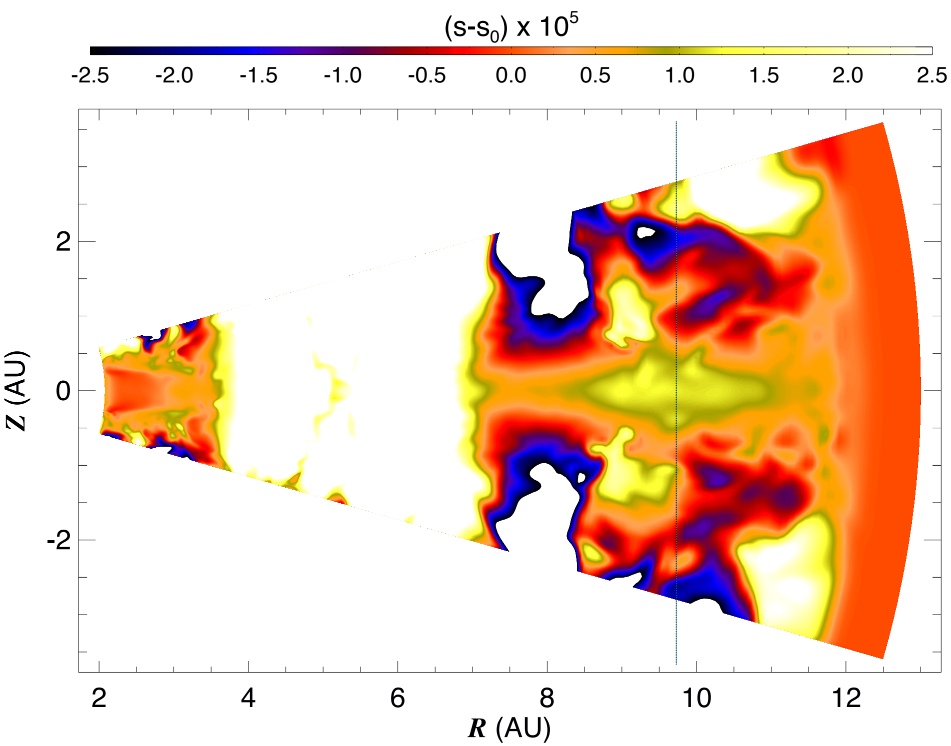


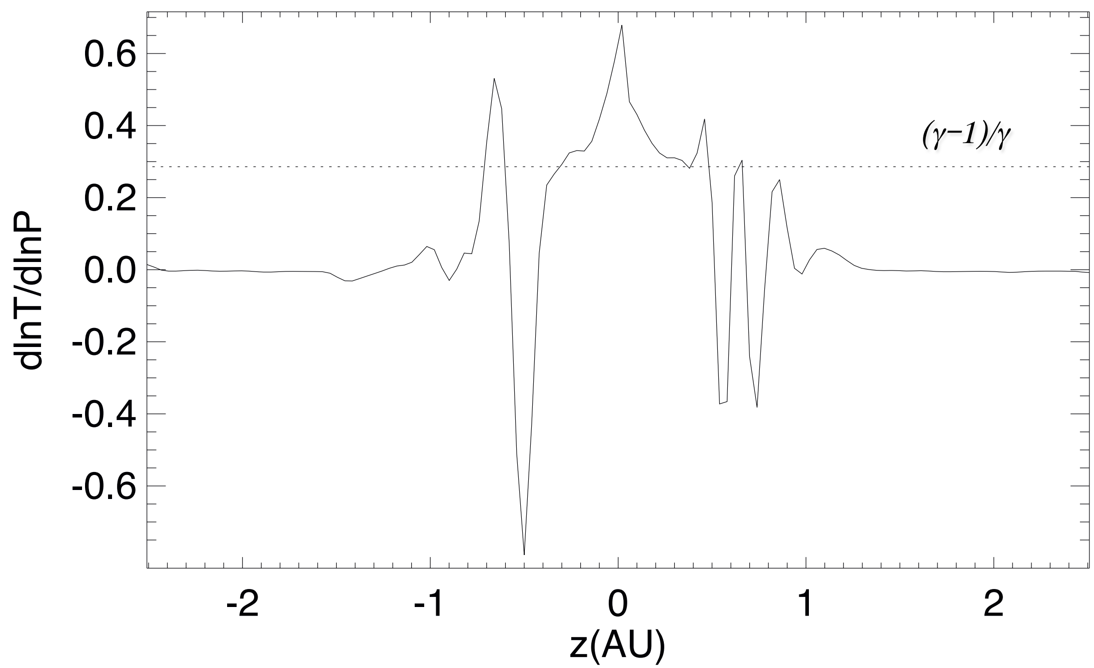
Entropy



Lyra et al. (2015b, submitted)

Convection

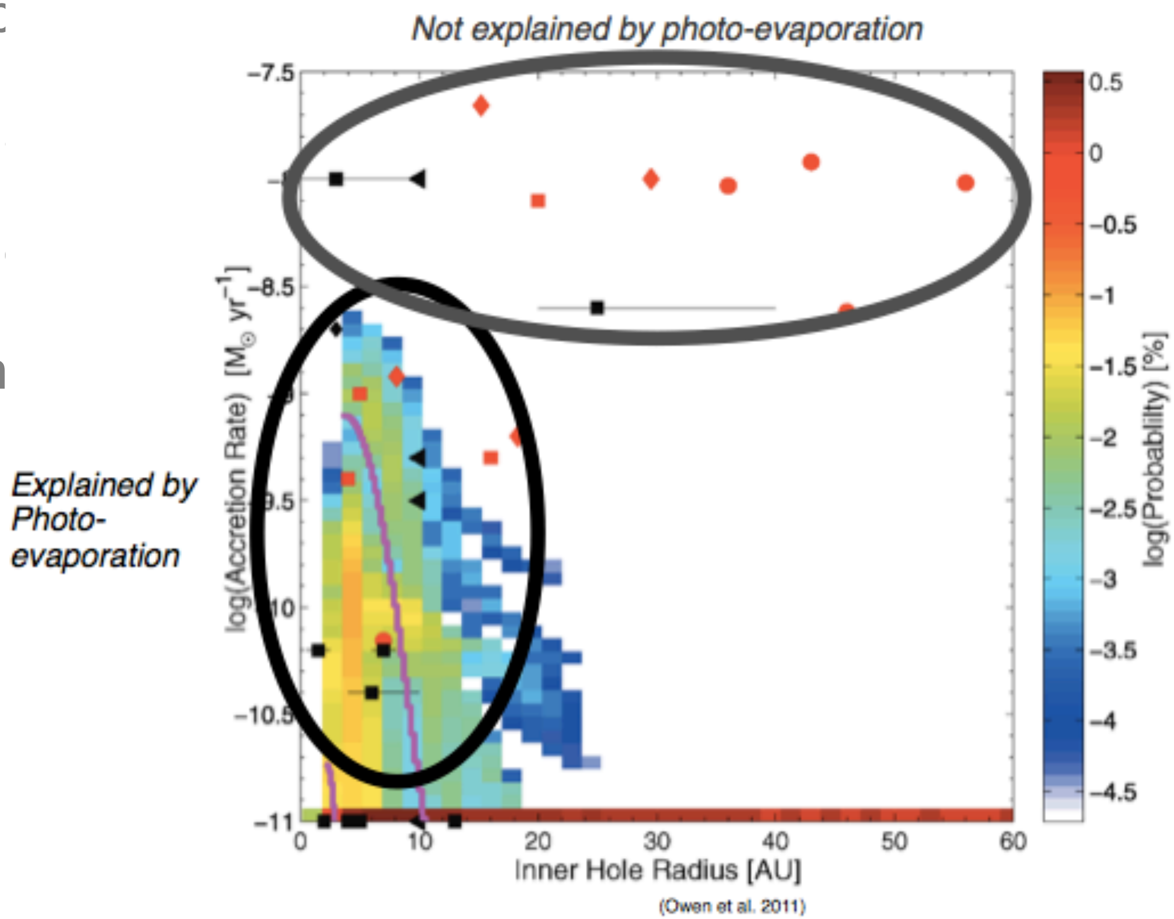




Lyra et al. (2015b, submitted)

Summary and Conclusions

- Evidence for two populations of transition disks, one due to planet-disk interaction.
- Vortex-trap … bservations.
- Vortices m … on transitions.
- Shocks du … d spirals.
- We're in th … odel predictions!

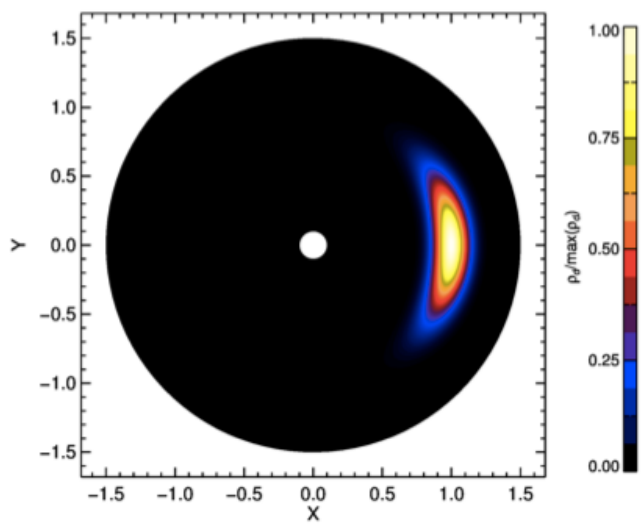


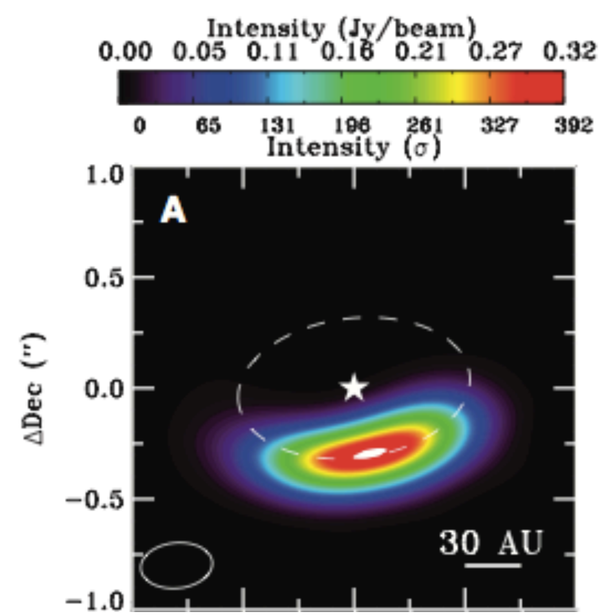
Summary and Conclusions

- Evidence for two populations of transition disks, one due to planet-disk interaction.
- Vortex-trapped dust in drag-diffusion equilibrium explains the observations.
- Vortices may ... transitions.
- Shocks due t... pirals.
- We're in the ... predictions!

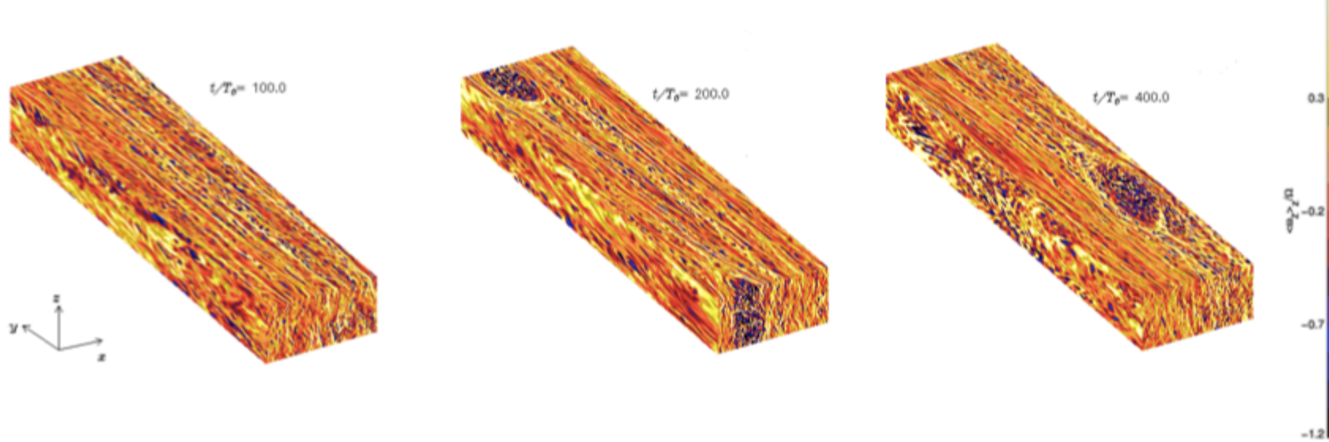
$$\rho_d(a,z) = \varepsilon\rho_0 (S+1)^{3/2} \exp\left\{-\frac{[a^2 f^2(\chi)+z^2]}{2H^2}(S+1)\right\}$$

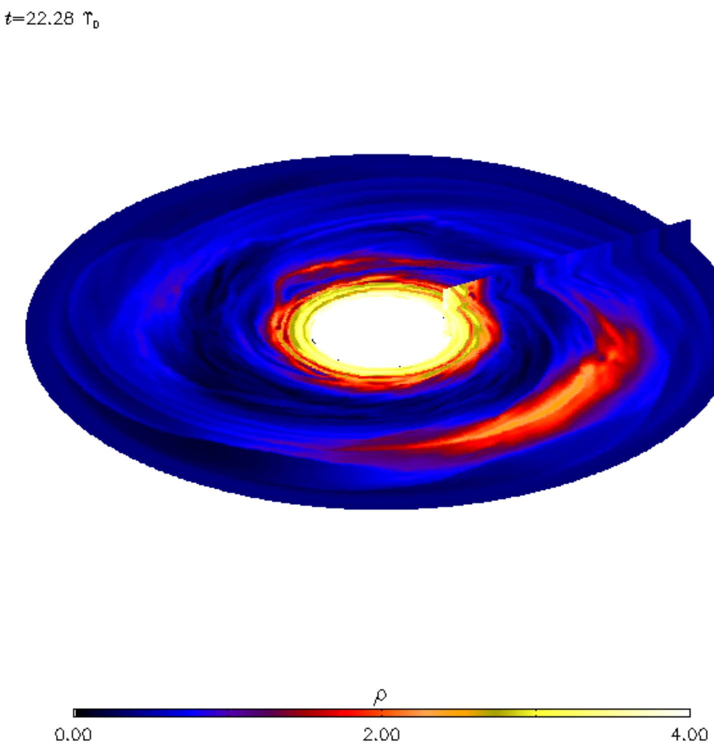
Lyra & Lin (2013)

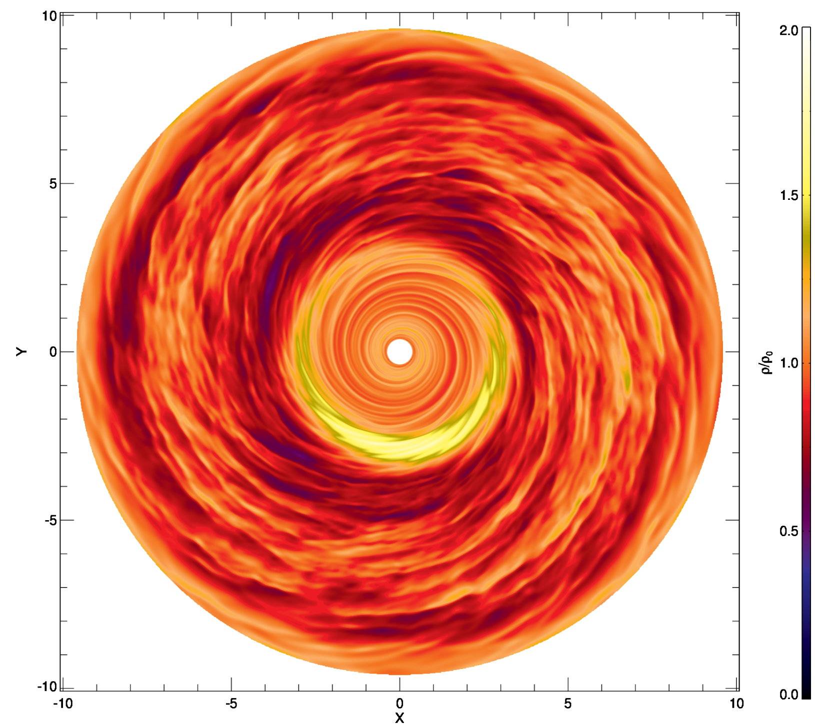




- Evidenc … isk interaction.
- Vortex-t … ations.
- Vortices may be either due to planet-disk interaction or hydro instabilities.
- … s may
- … testin … ions!

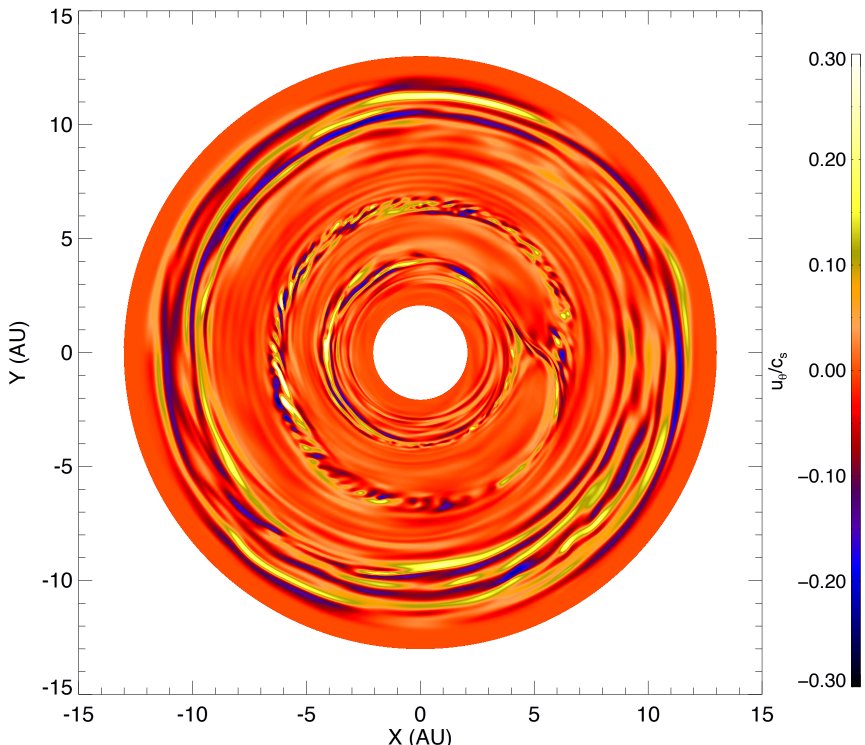


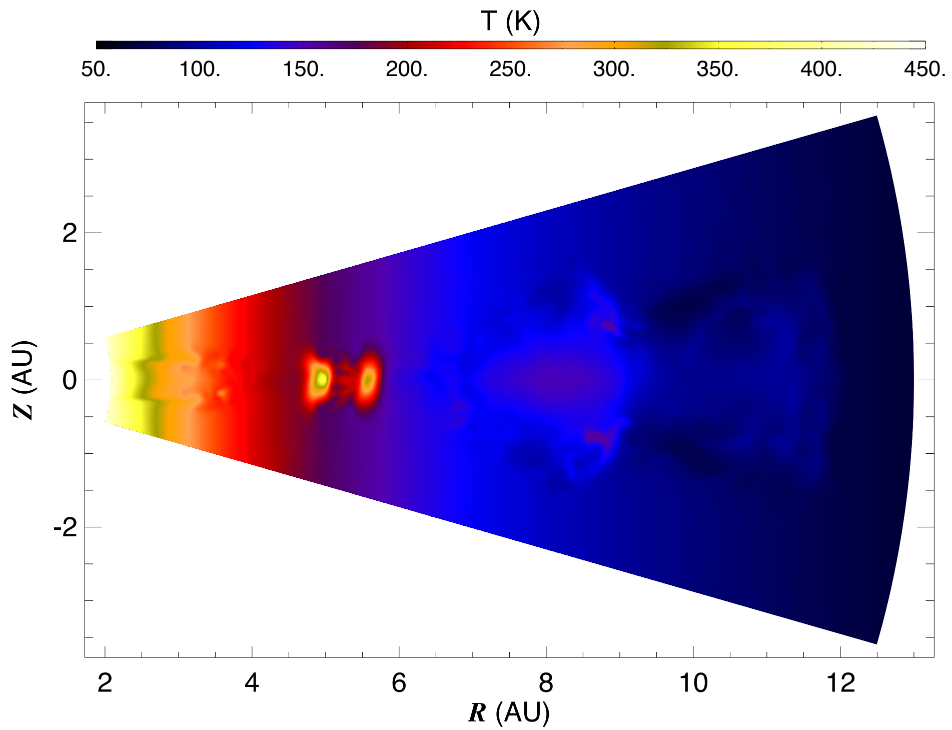




Summary and Conclusions

- Evidence for two populations of transition disks, one due to planet-disk interaction.
- Vortex-trapped dust in drag-diffusion equilibrium explains the observations.
- Vortices may be either due to planet-disk interaction or ionization transitions.
- Shocks due to high mass planets may be better fits to observed spirals.
    - In addition to **supersonic pitch angles**, we predict:
        - **high-temperature lobes** and **turbulent surf** near the planet
        - **convection** far from the planet's orbit





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- Vortices may be either due to planet-disk interaction or ionization transitions.
- Shocks due to high mass planets may be better fits to observed spirals.
- We're in the era of observational testing/confirmation of our model predictions!