Evolution of Circumstellar Disks and Planet Formation

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Rio de Janeiro, Aug 10th, 2017

Protoplanetary Disks

PP disk fact sheet

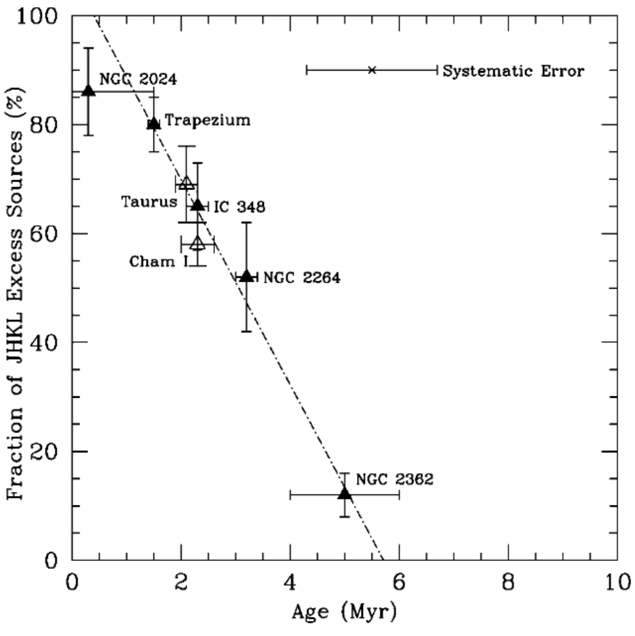
Density: $10^{13} - 10^{15}$ cm^{-3}
(Air: 10^{21} cm^{-3})

Temperature: 10-1000 K

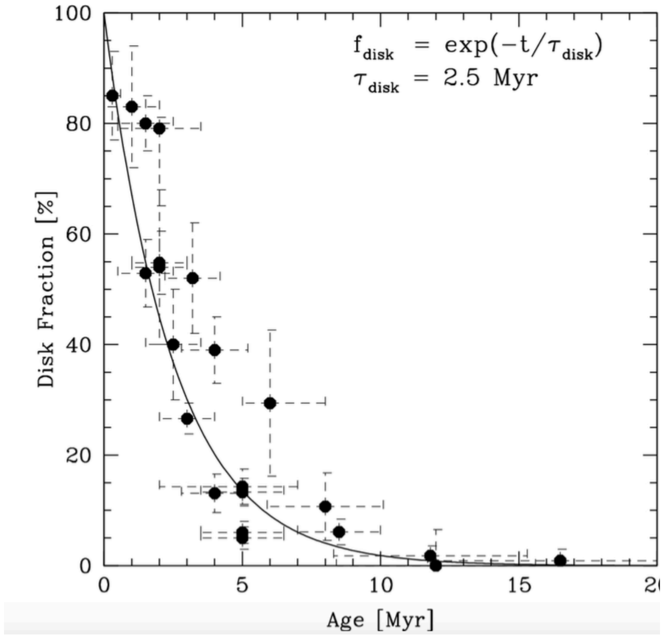
Scale: 0.1-100AU
(1 AU = 1.49×10^{13} cm)

Mass: $10^{-3} - 10^{-1}$ M_{sun}
(1 M_{sun} = 2×10^{33} g)

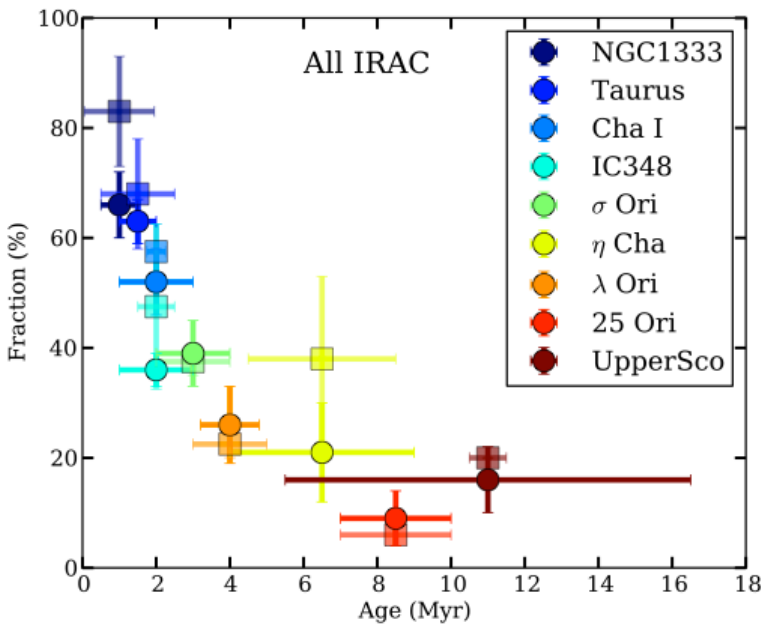
Disk lifetime



(Haisch et al. 2001)



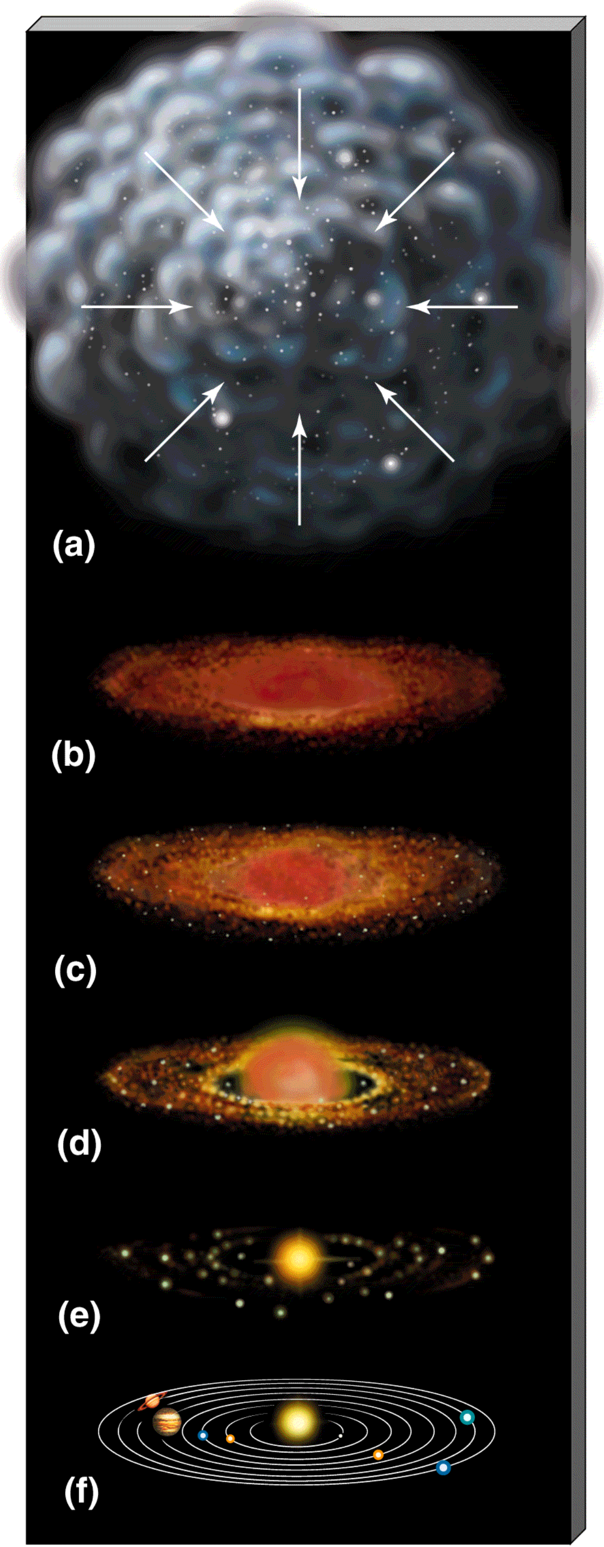
(Mamajek et al. 2009)



(Ribas et al. 2014)

Disks dissipate with an e-folding time of 2.5 Myr

Planet Formation

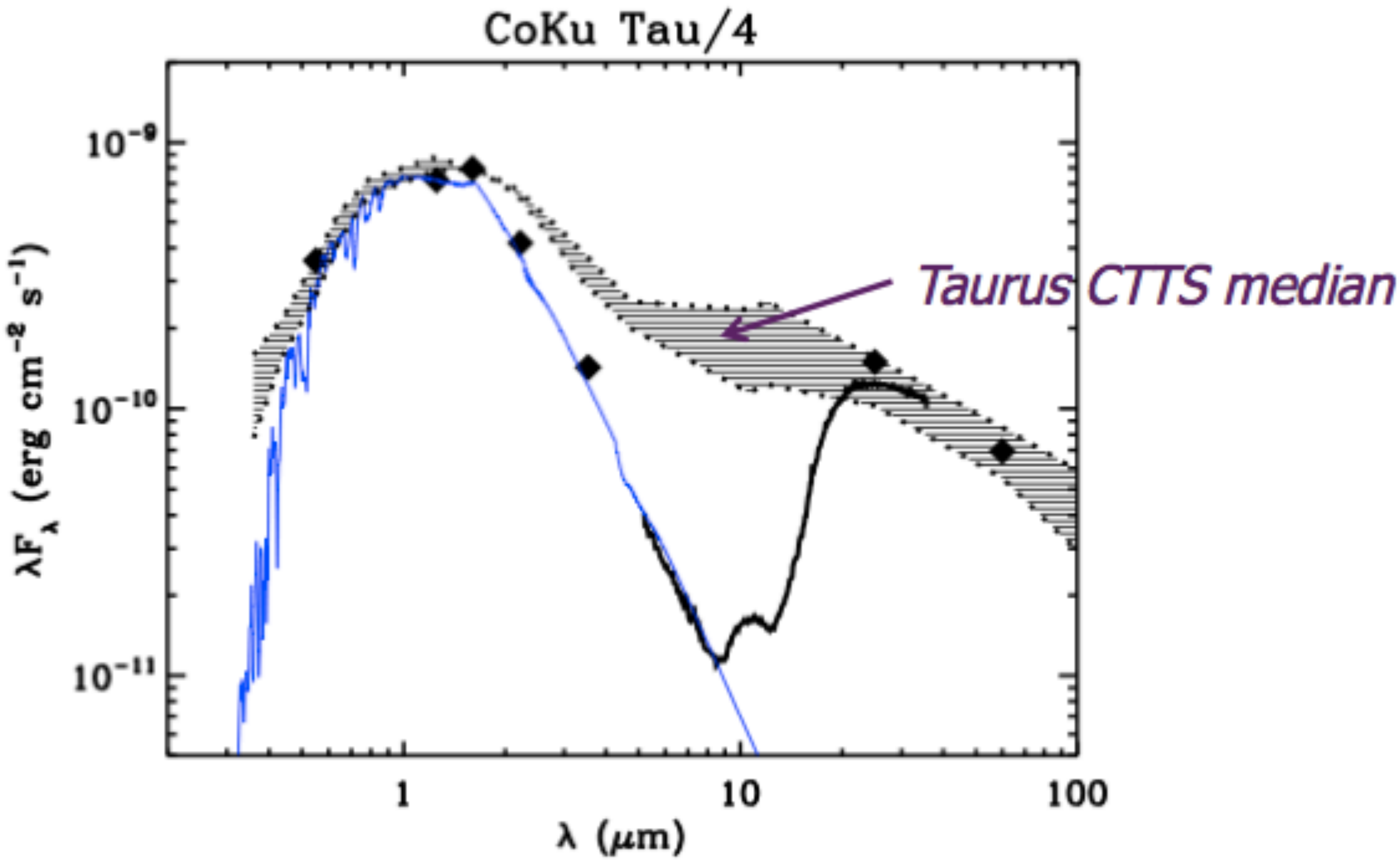


Gas-rich phase (< 10 Myr)
Primordial Disks

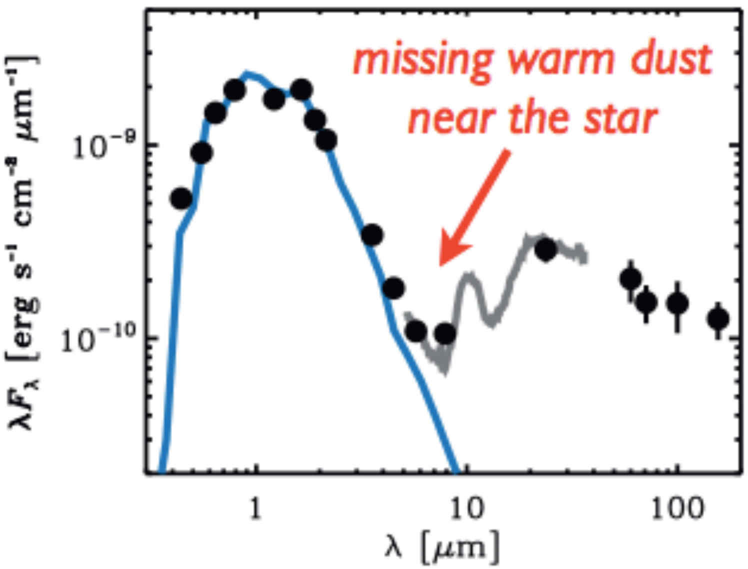
Thinning phase (~10 Myr)
Transition Disks (?)

Gas-poor phase (>10 Myr)
Debris Disks

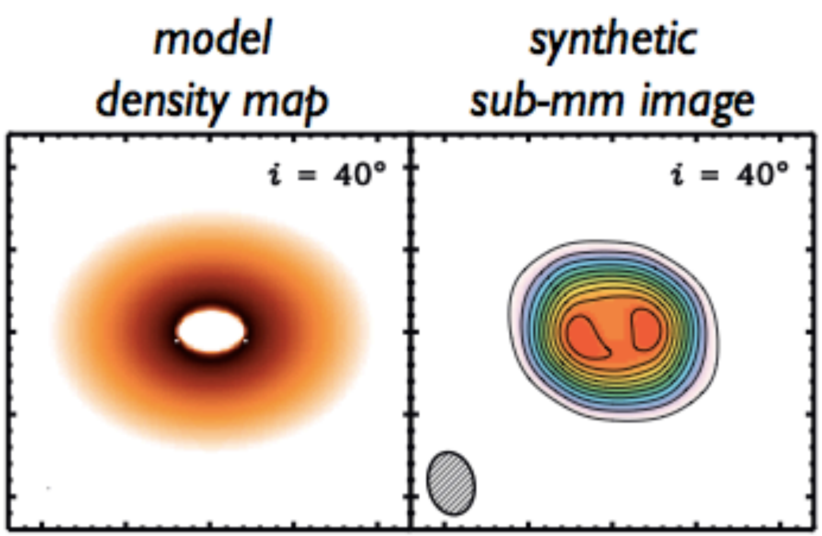
Transition Disks: Disks with missing hot dust.



Transition Disks: Disks with missing hot dust.

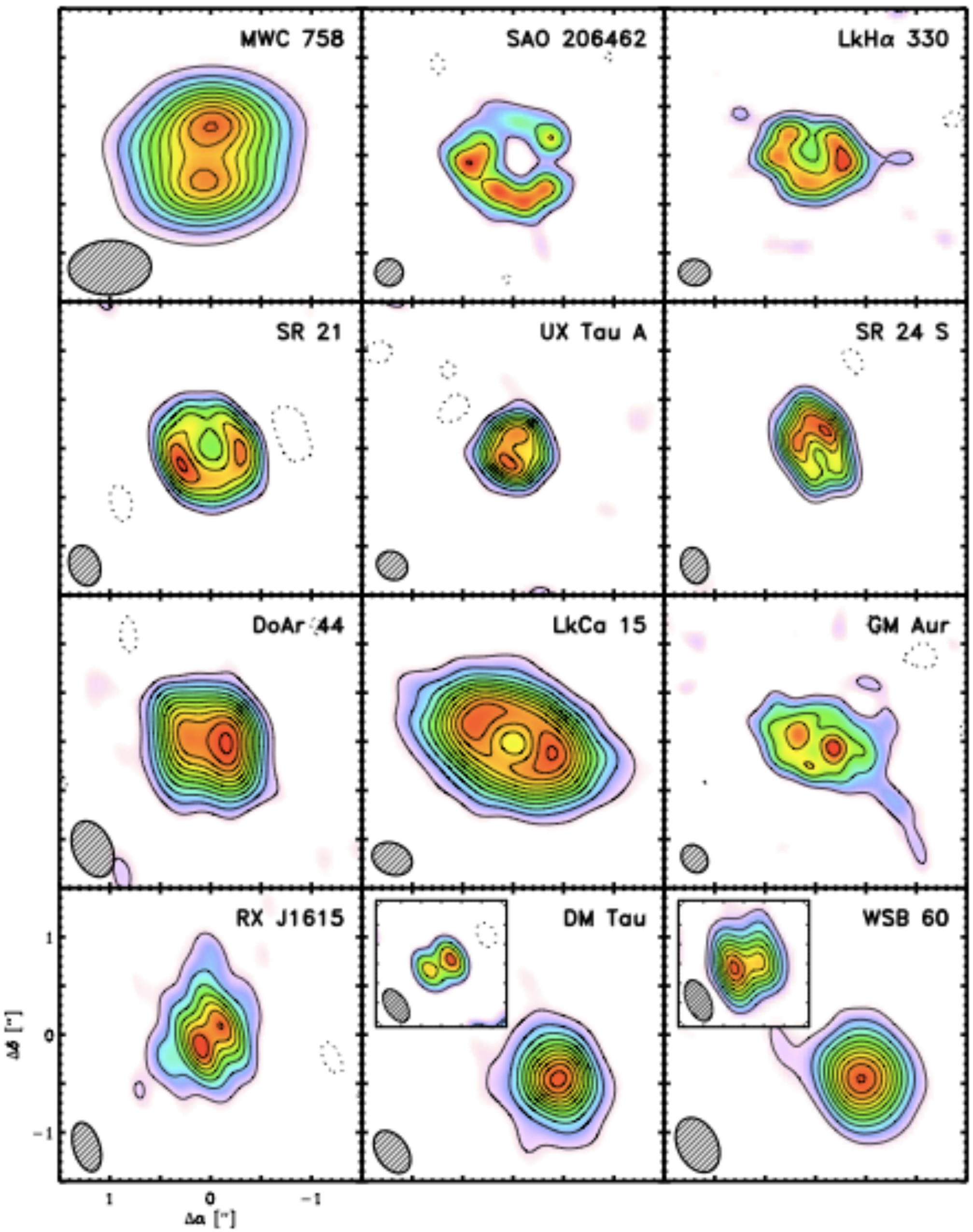


[e.g., Furlan et al. 2009]



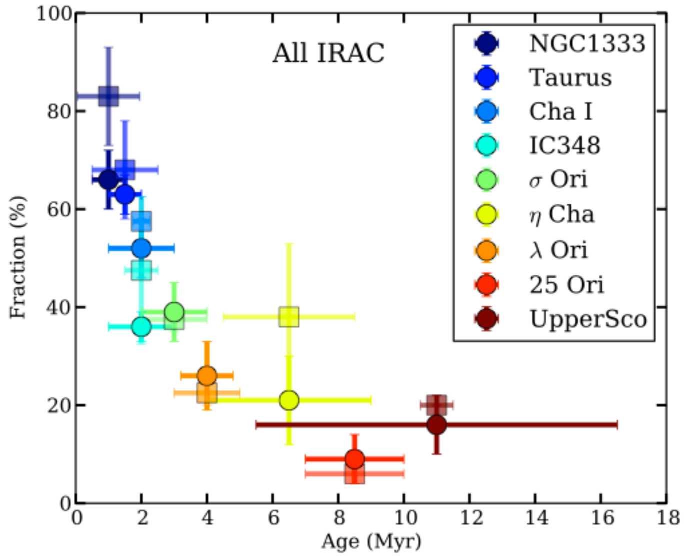
a disk with a large reduction in optical depth near the star (i.e., a "cavity" or "hole")

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



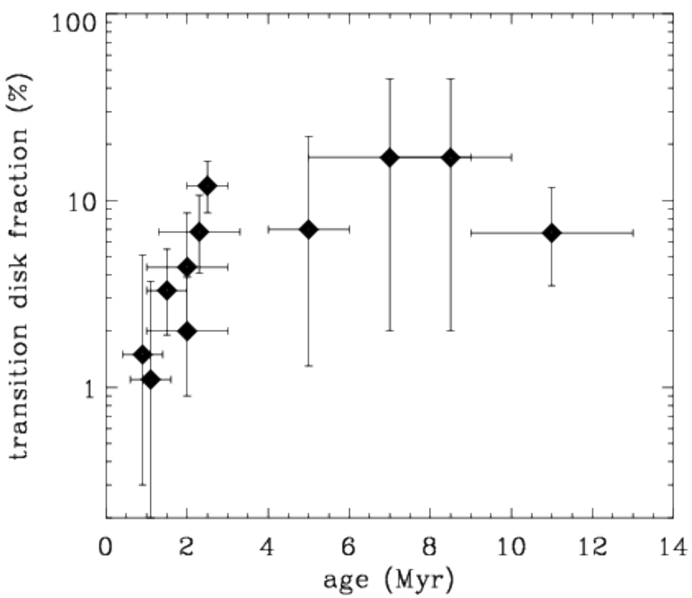
0.85mm
0.3" ~ 20 AU resolution

Are transition disks related to disk evolution?



(Ribas et al. 2014)

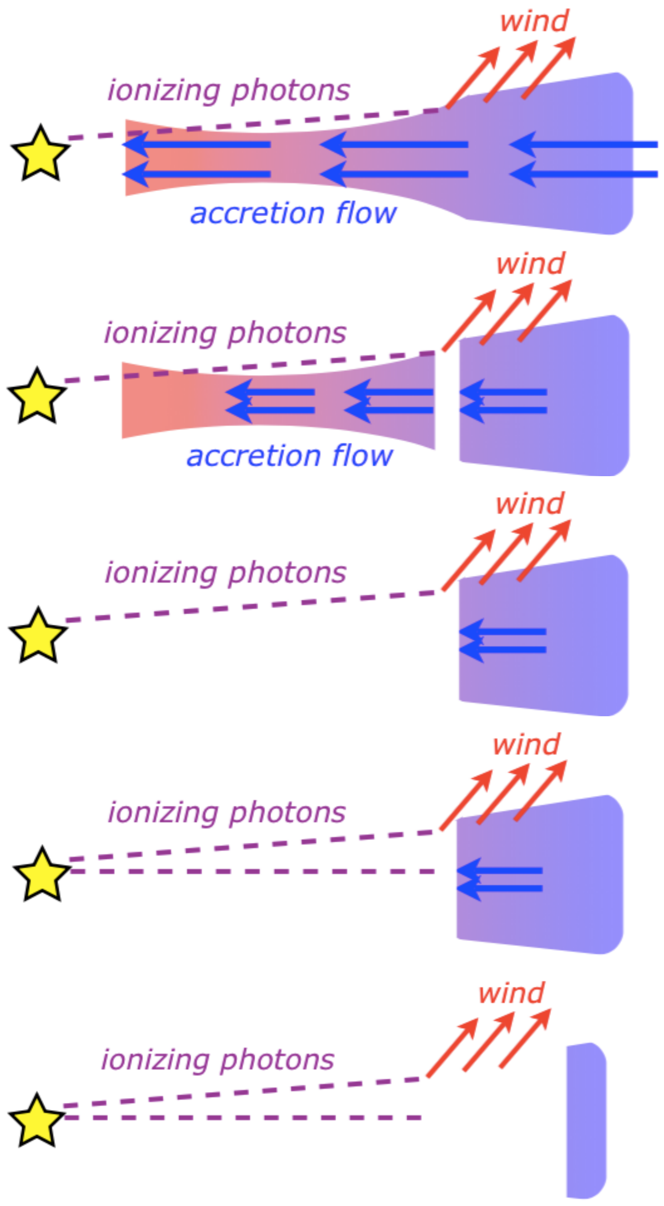
"Total" disk fraction



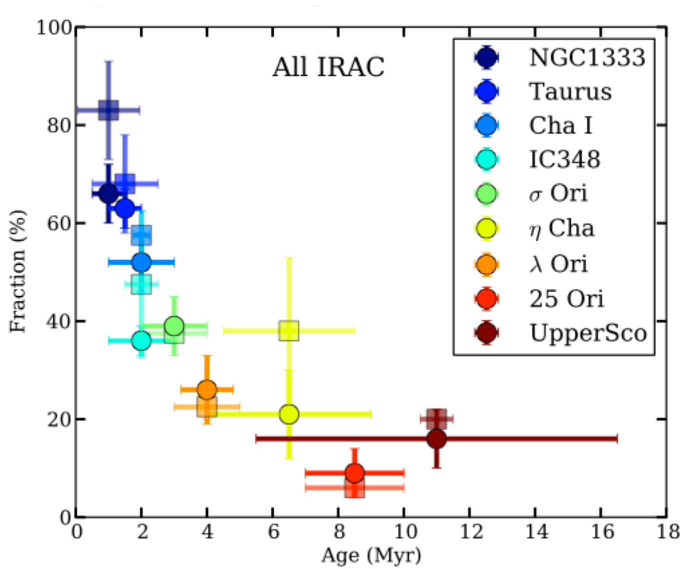
(Espaillat et al. 2014)

Transition disk fraction

Photoevaporation

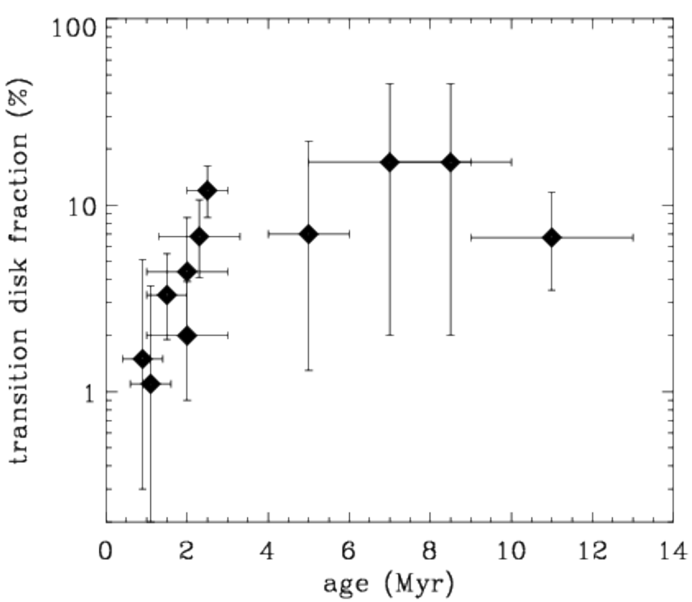


Look again…



(Ribas et al. 2014)

"Total" disk fraction

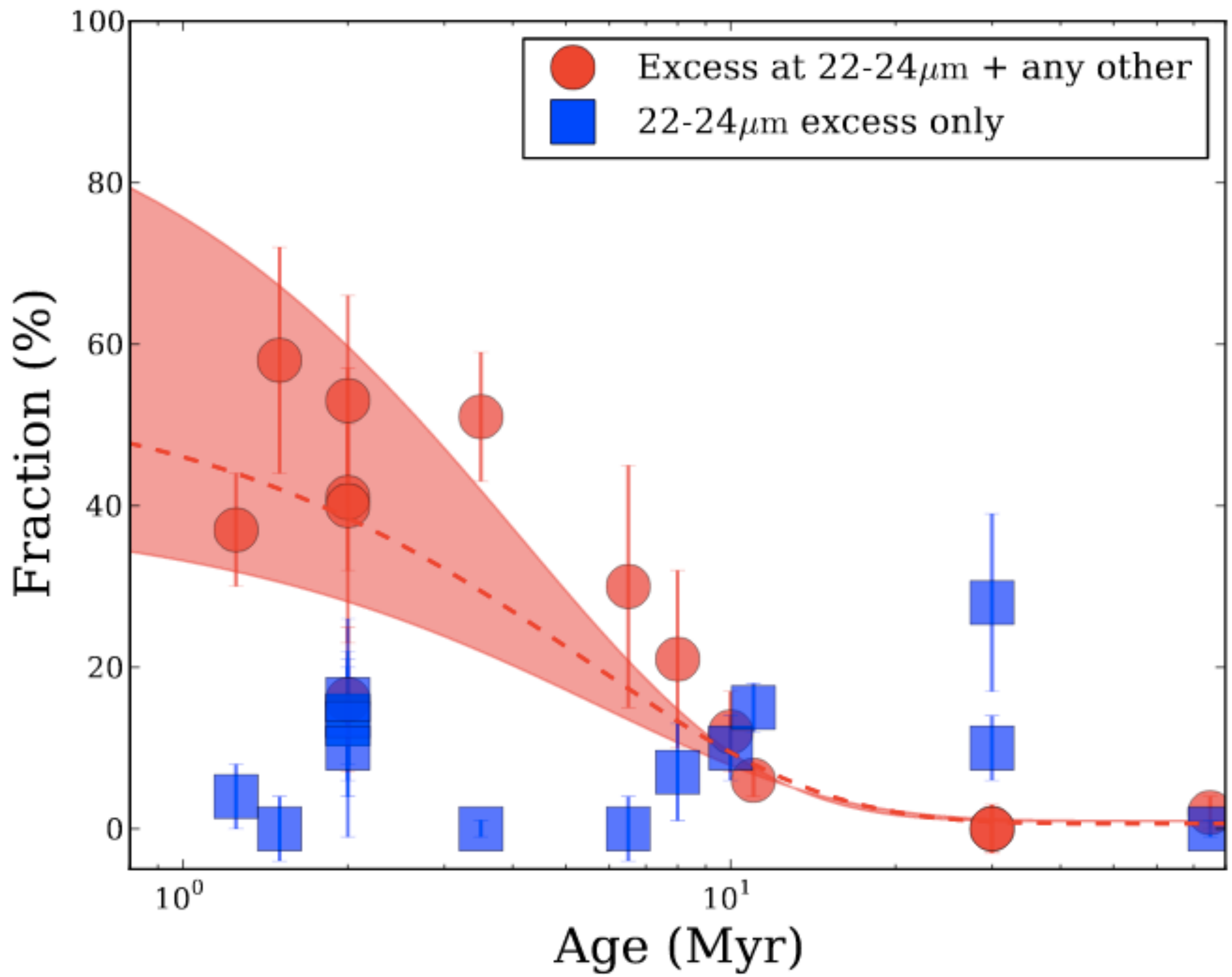


(Espaillat et al. 2014)

Transition disk fraction

Transition disks linked to disk evolution?

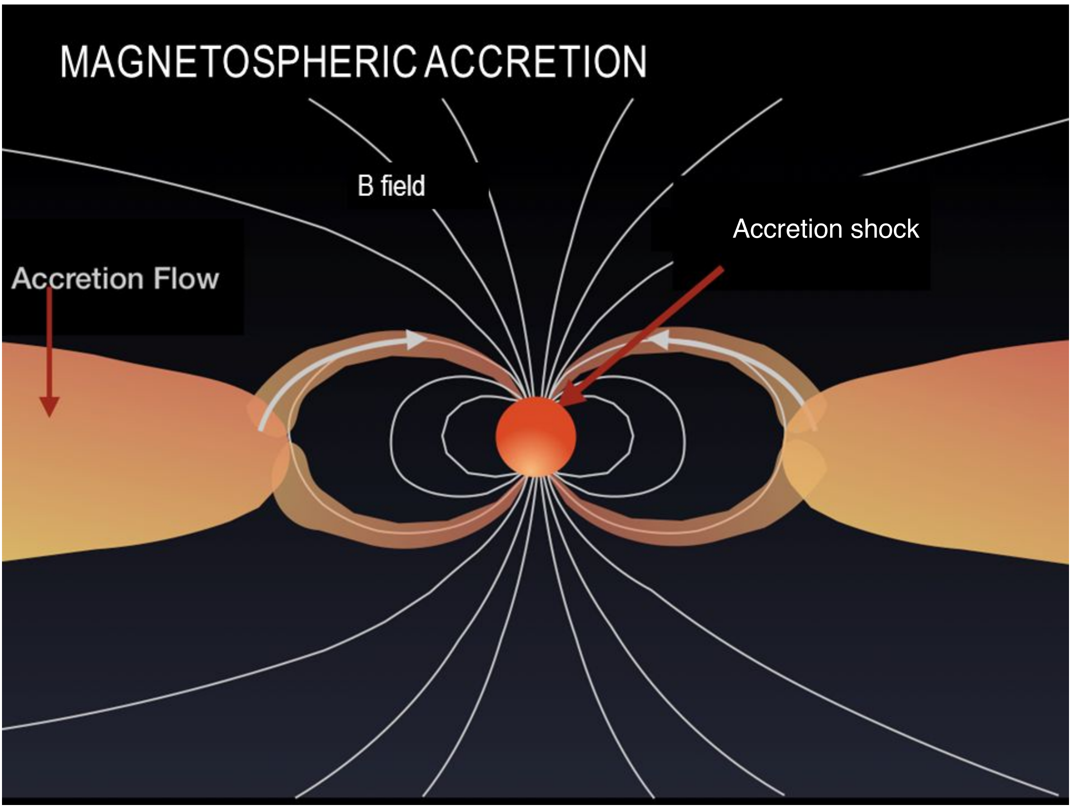
The distribution in age is consistent with a uniform distribution.

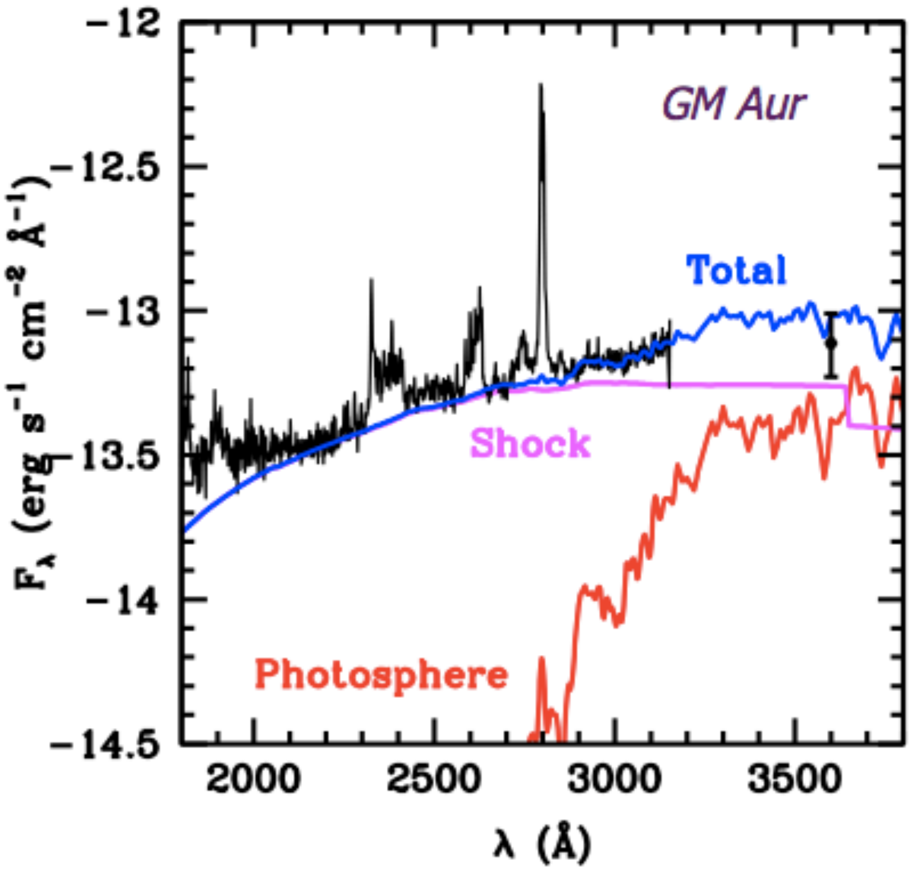


(Ribas et al. 2014)

UV excess

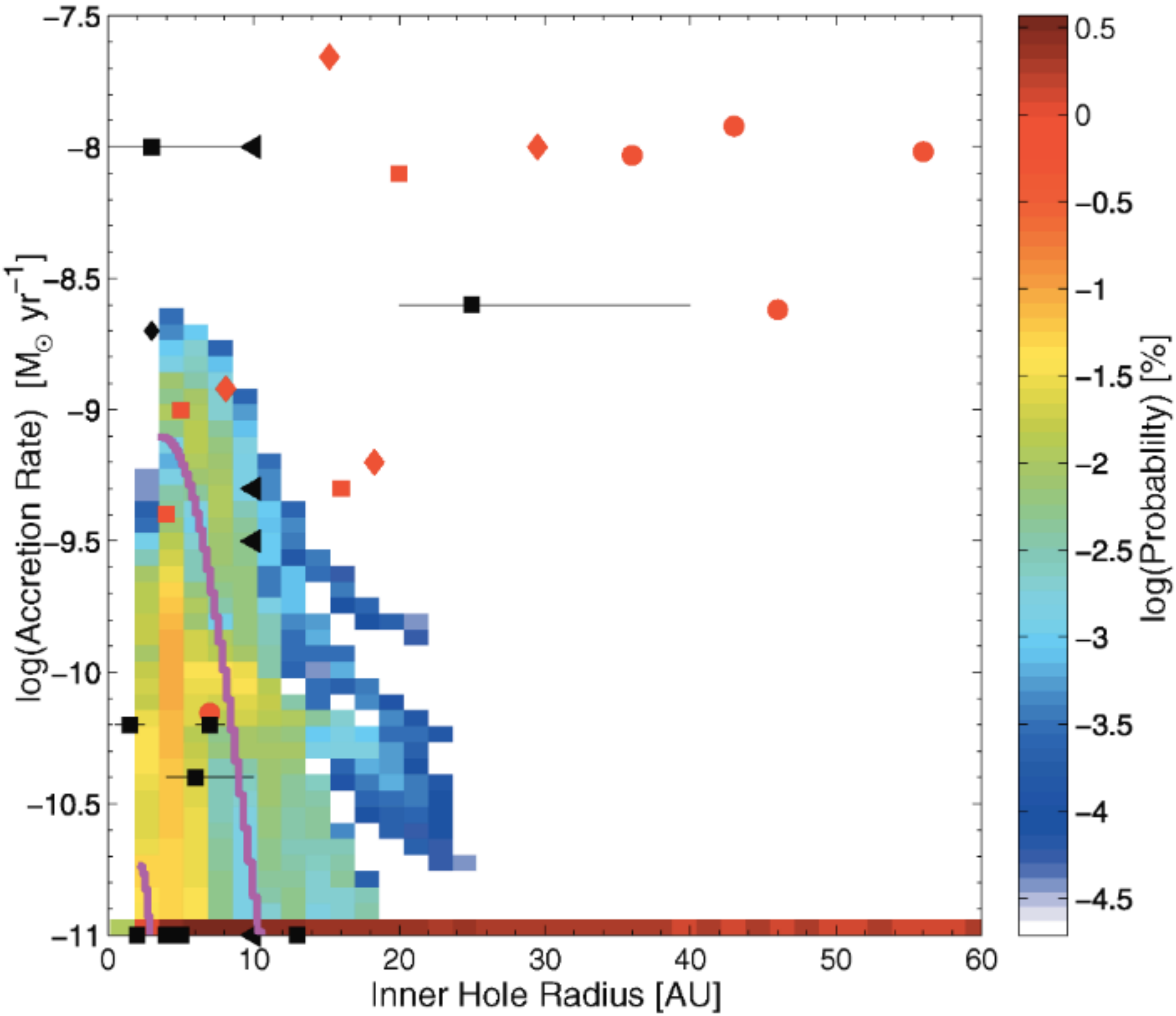
Many transitional disks show signs of accretion,
at the level of primordial (classical T-Tauri) disks.





(Ingleby et al. 2011)

Bimodal distribution of transition disks

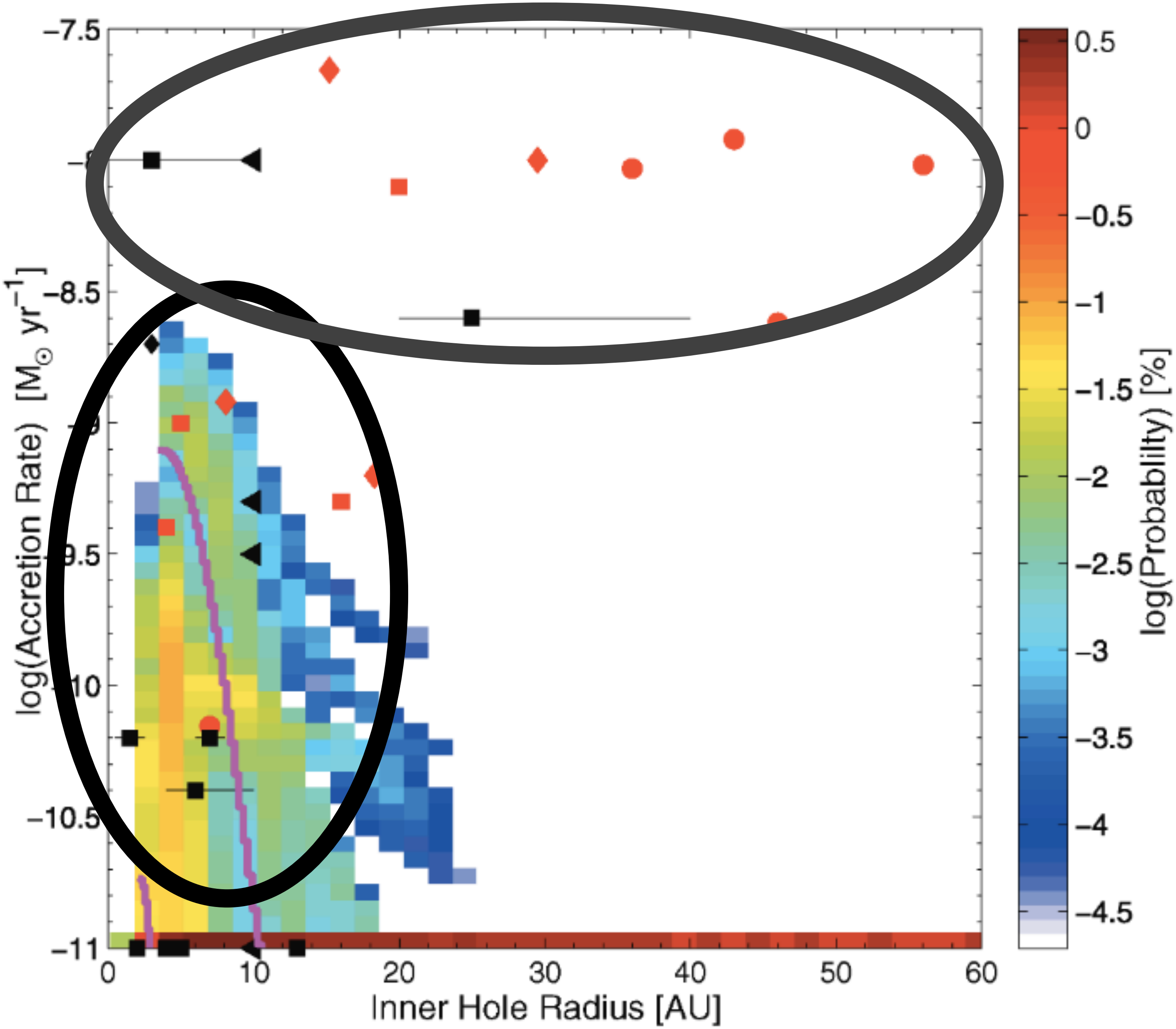


(Owen et al. 2011)

Bimodal distribution of transition disks

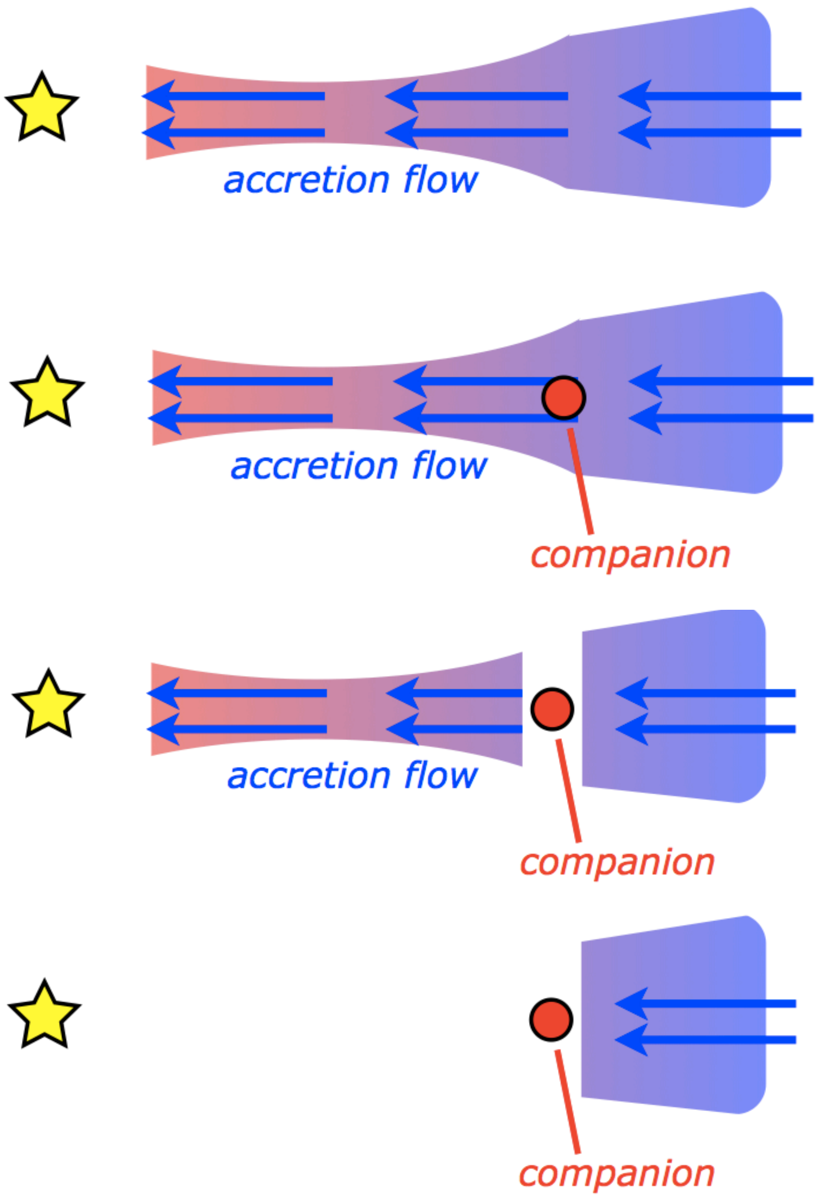
Not explained by photo-evaporation

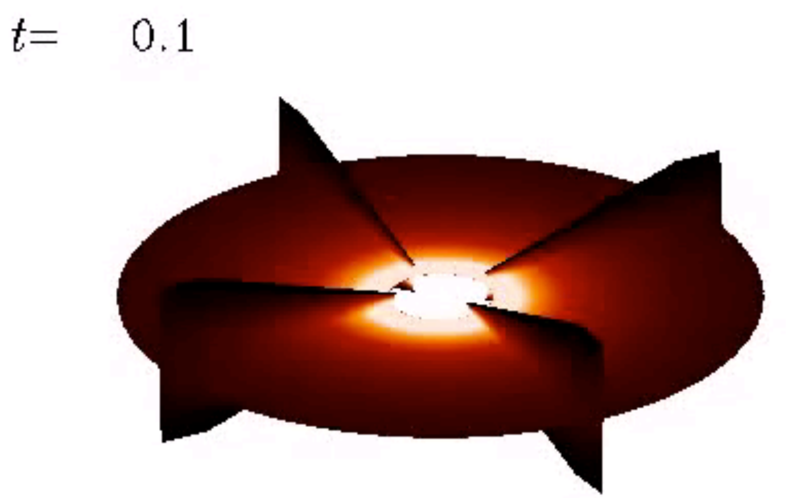
Explained by Photo-evaporation

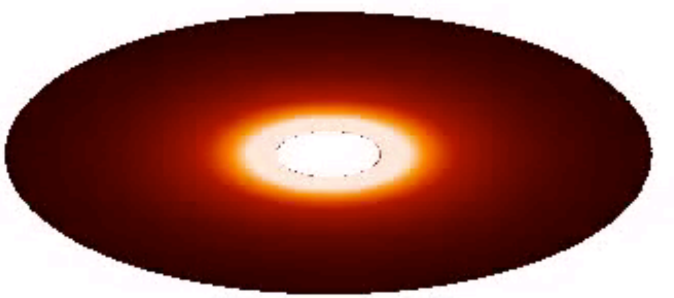


(Owen et al. 2011)

Planetary companion

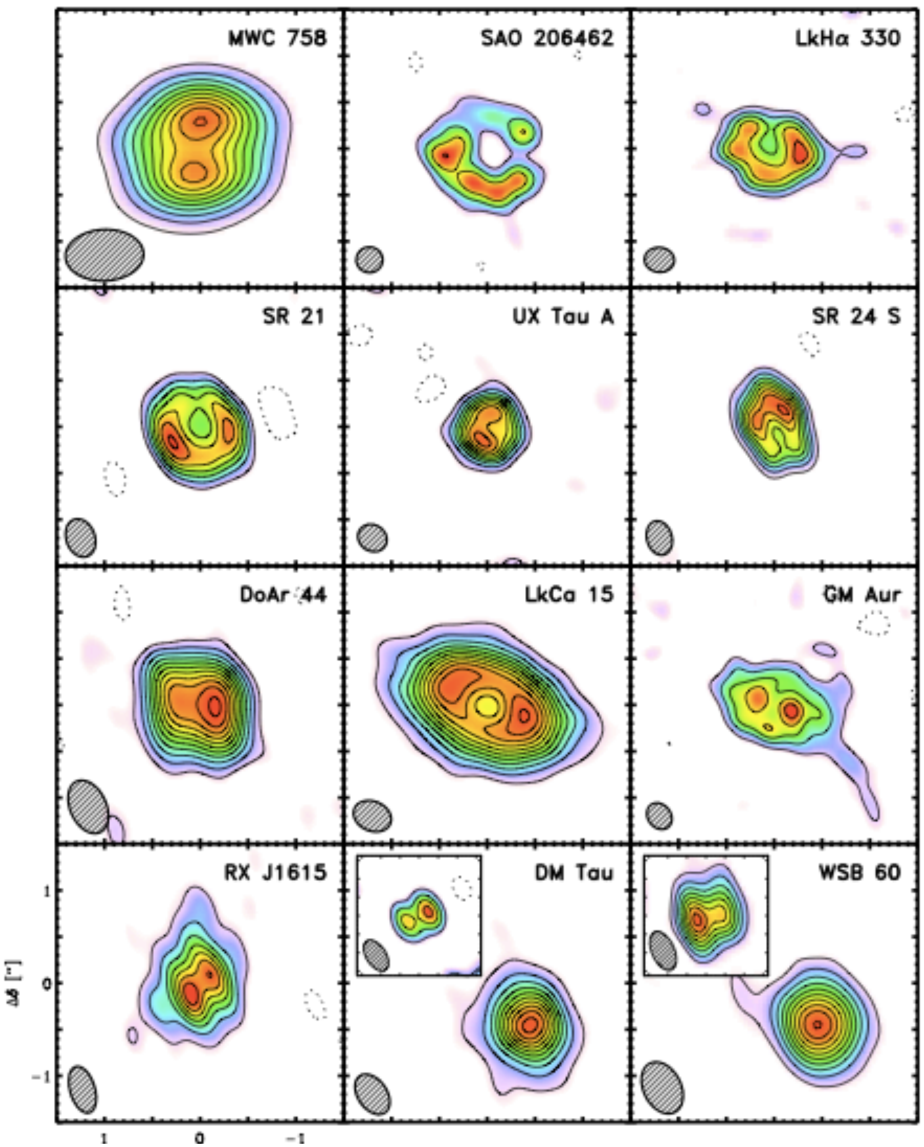


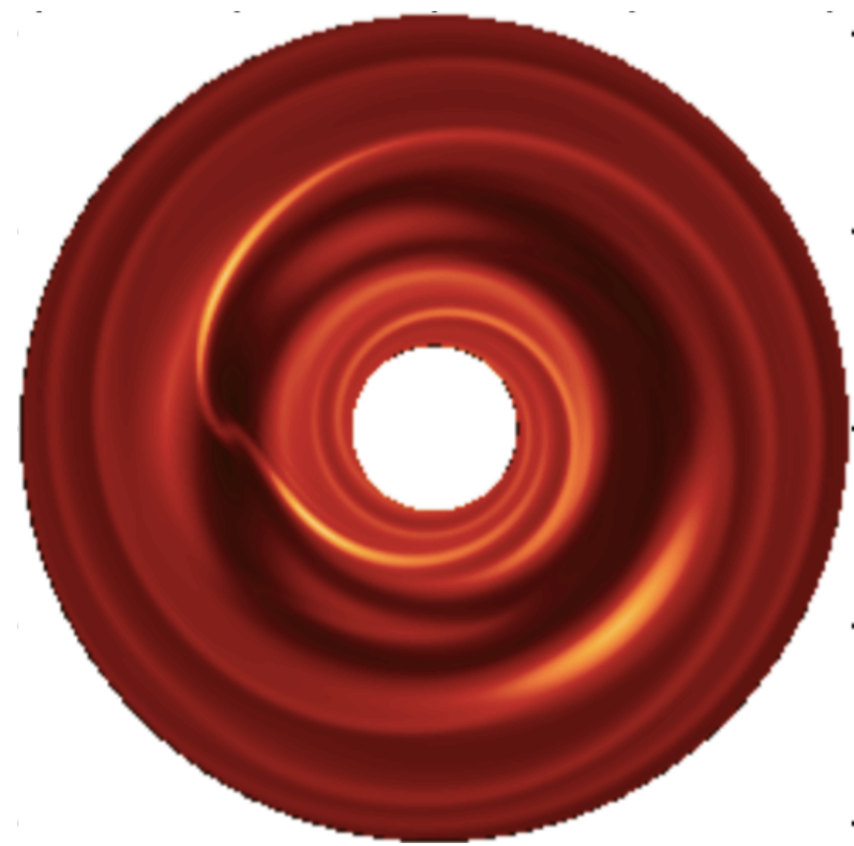




(Lyra 2009)

These cavities may be the telltale signature of forming planets





(Lyra et al. 2009b)

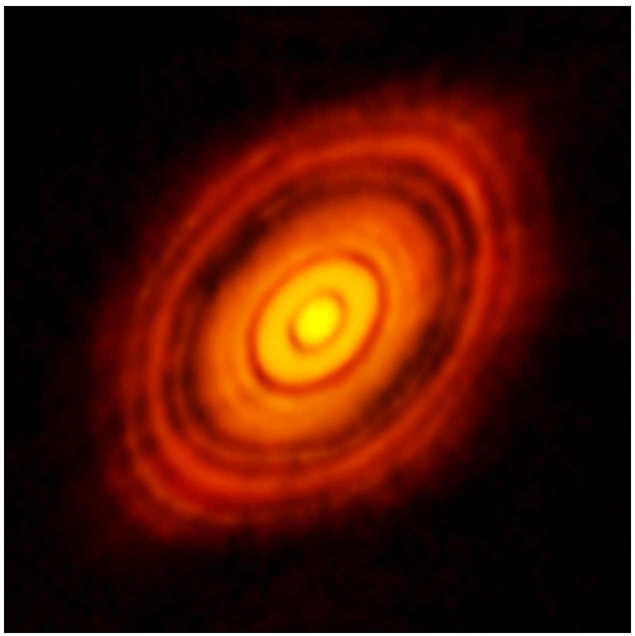
A way to directly study planet-disk interaction

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

(Lyra et al. 2009b)

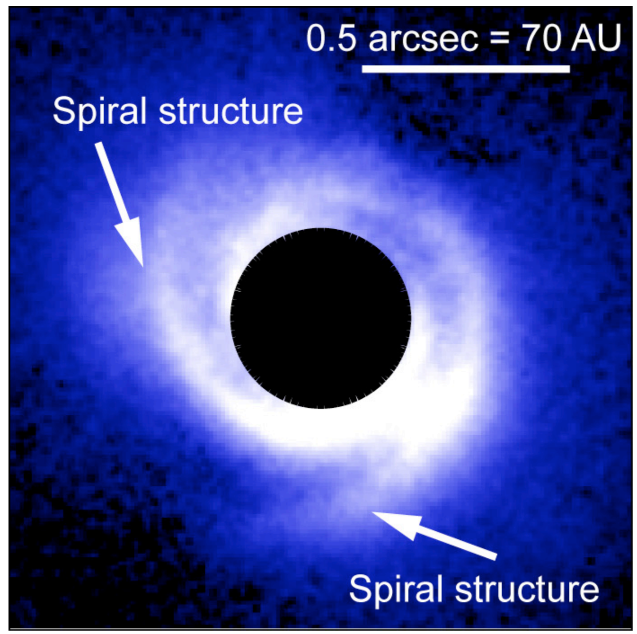
Observational evidence: gaps, spirals, and vortices

HL Tau



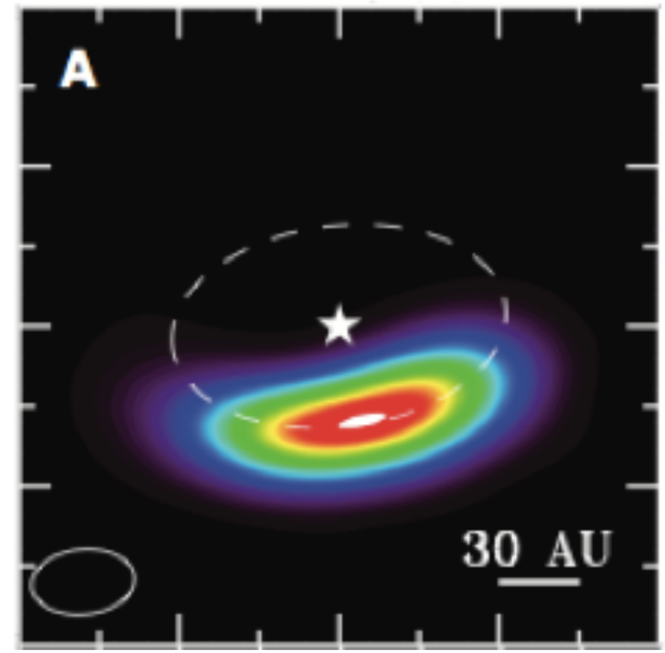
The ALMA Partnership et al. (2015)

SAO 206462



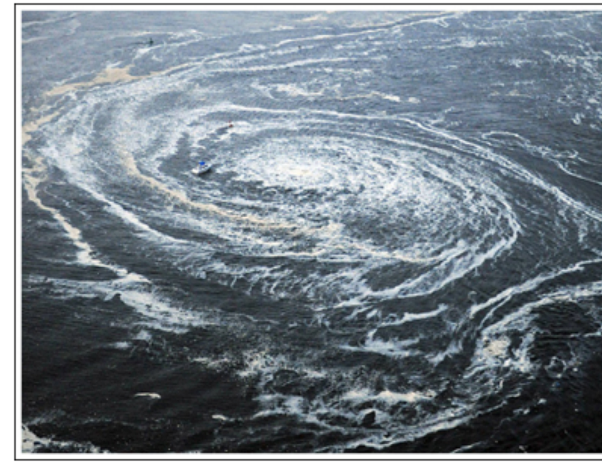
Muto et al. (2012)

Oph IRS 48

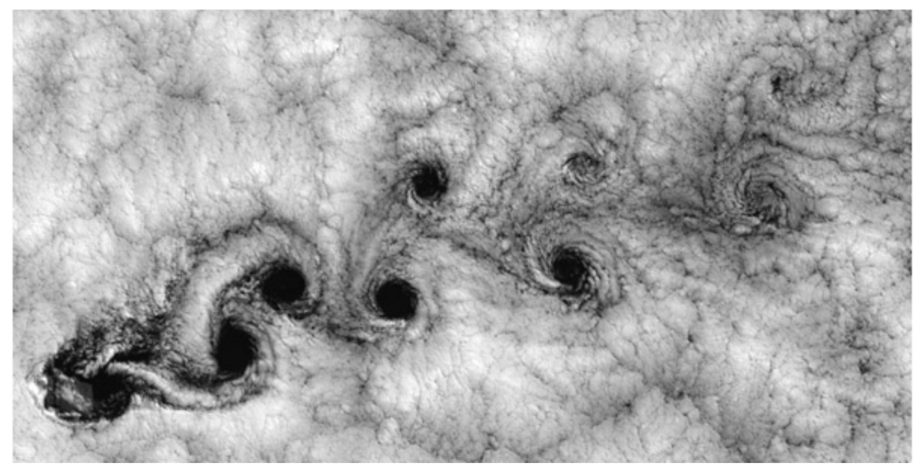


van der Marel et al. (2013)

Vortices – an ubiquitous fluid mechanics phenomenon

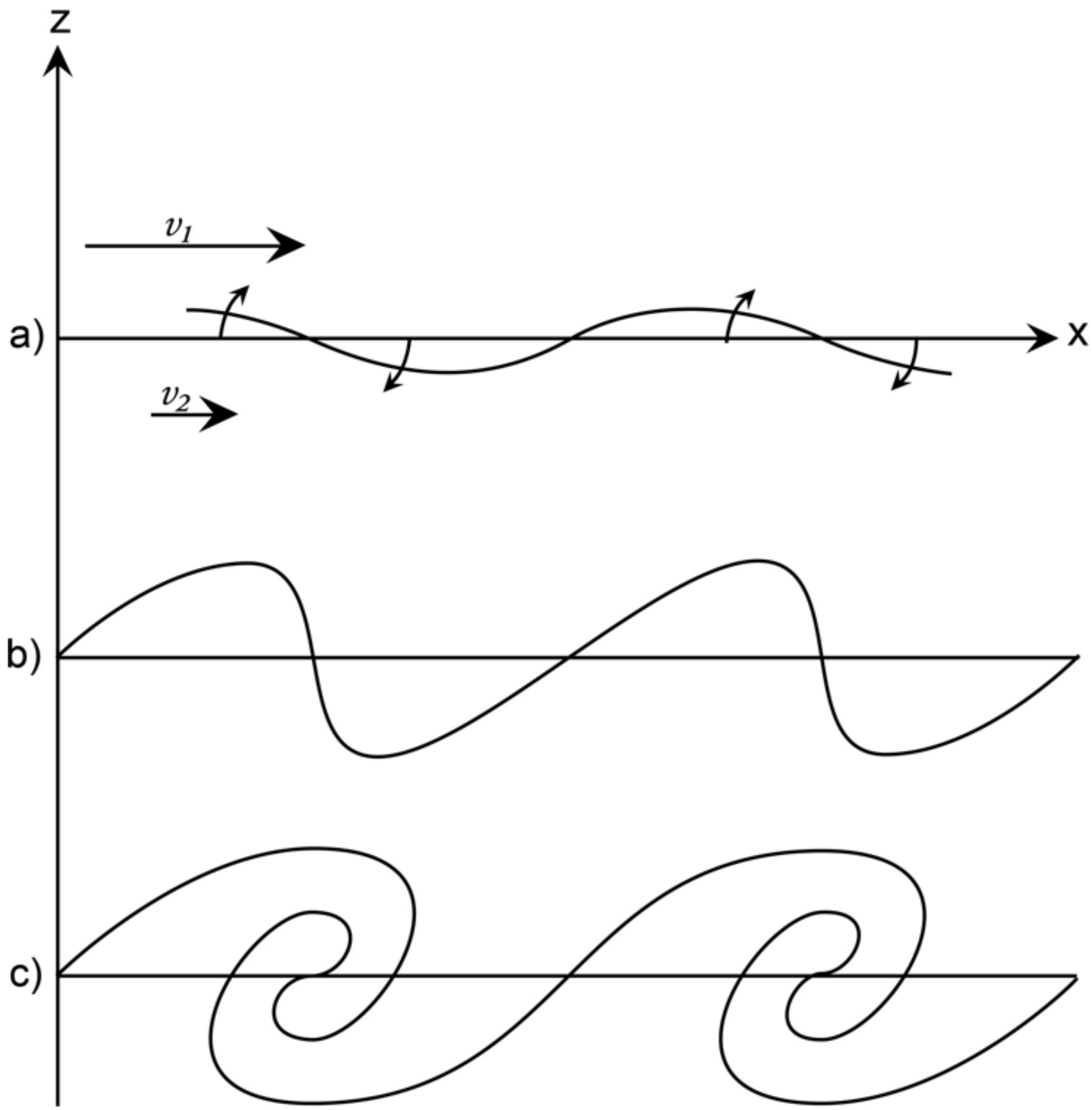


Von Kármán *vortex street*

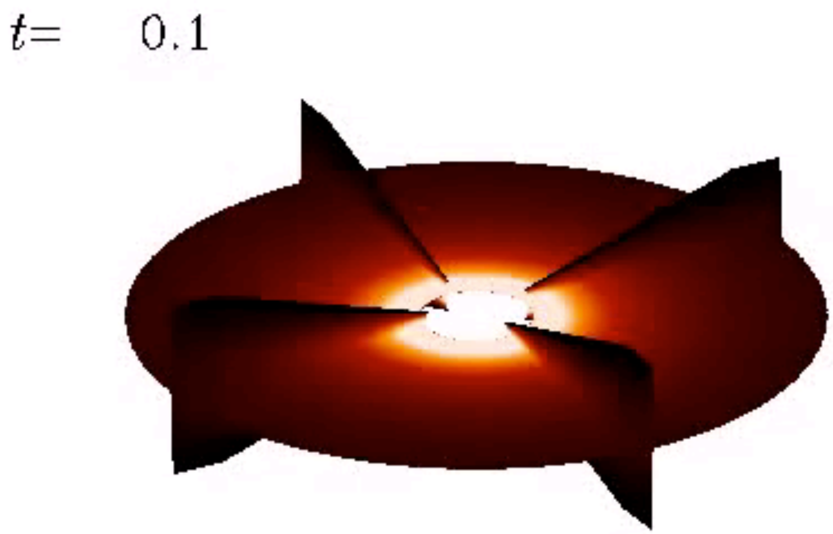


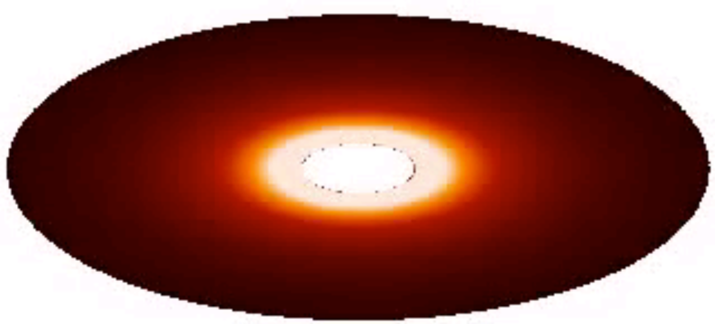
Rossby wave instability

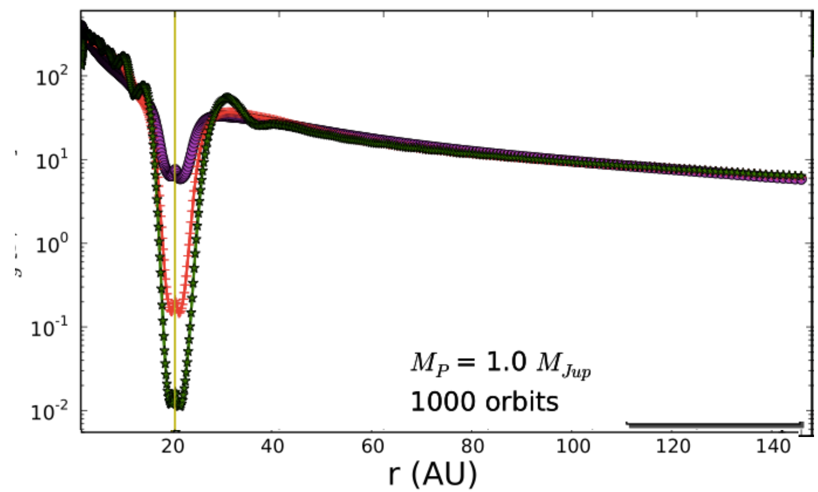
(or **Kelvin-Helmholtz** instability in differentially rotating gas)



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





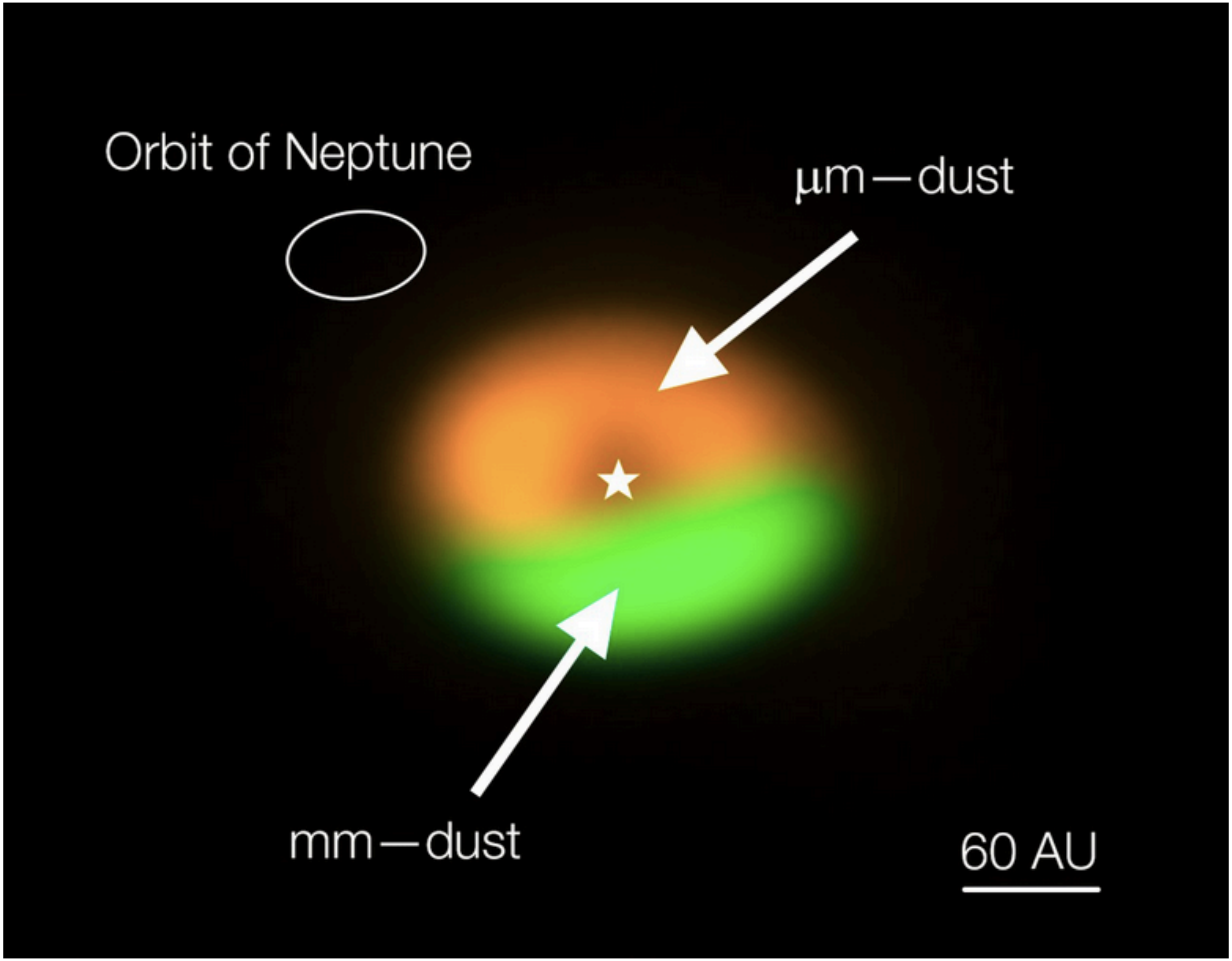


Planet tides carve gap

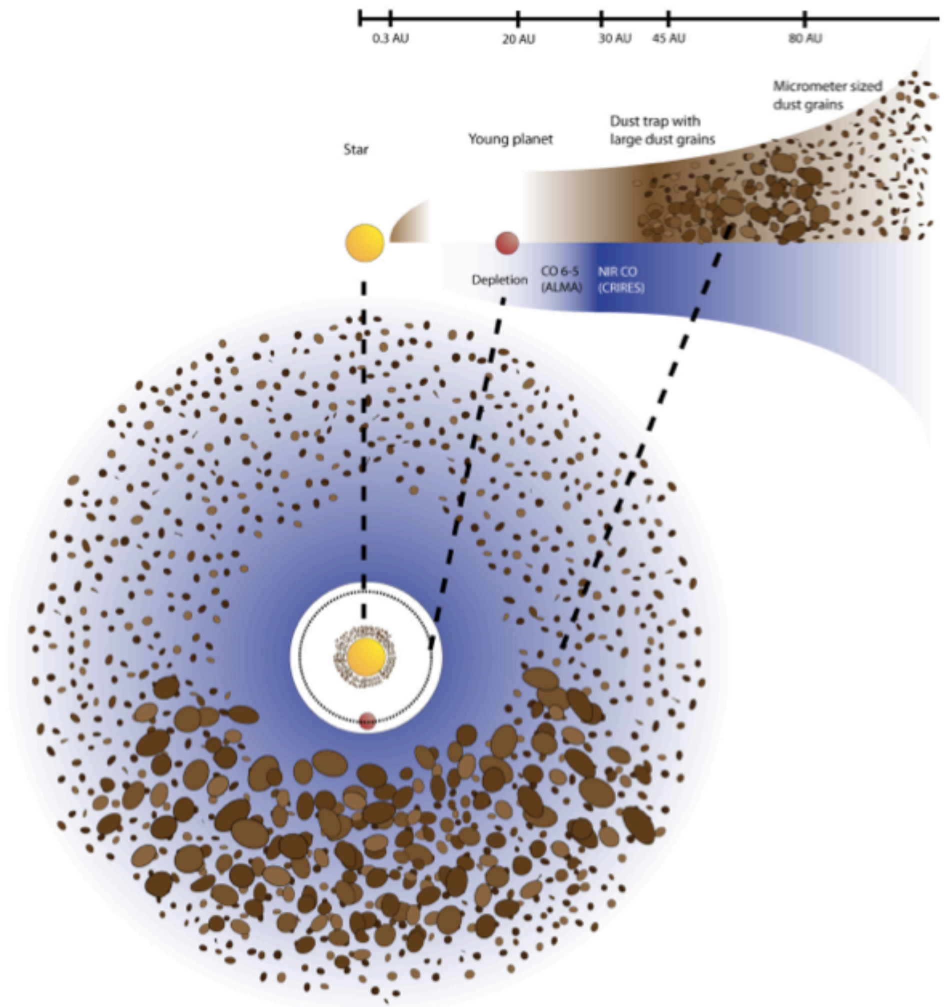
Gap walls are unstable to Rossby wave Instability

Lyra (2009)

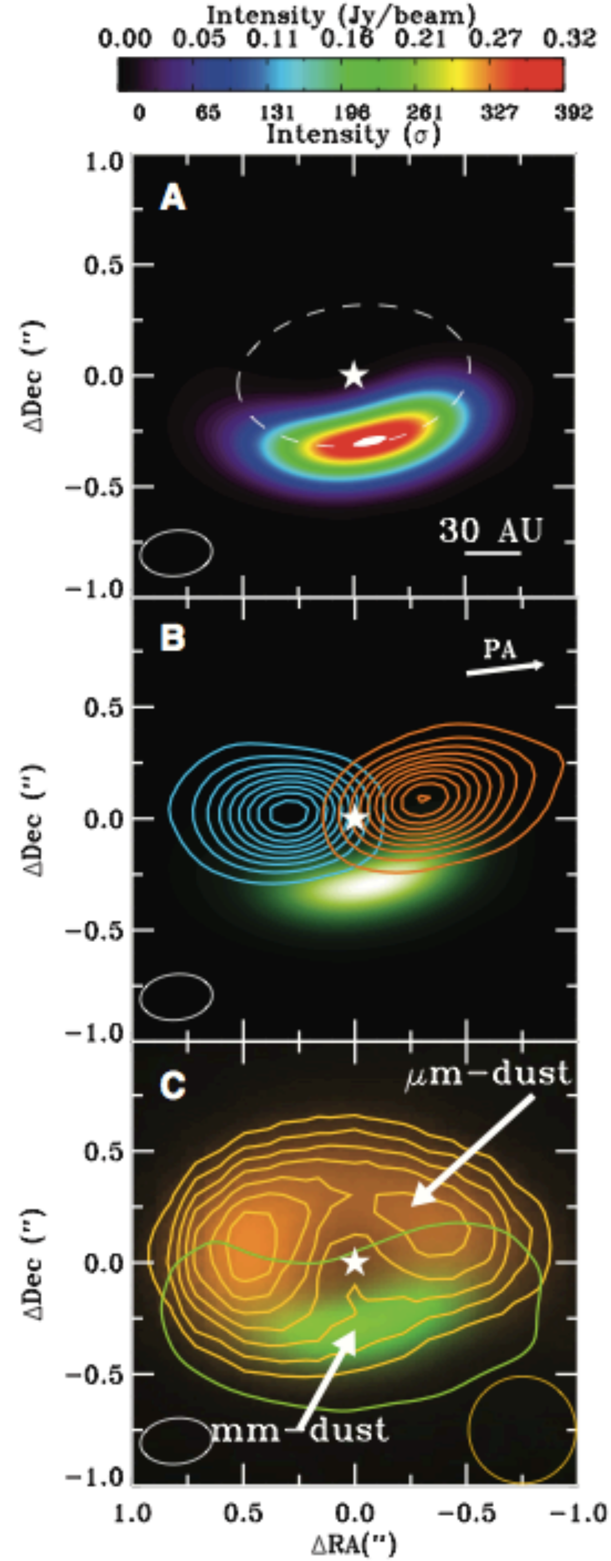
Oph IRS 48



The Oph IRS 48 "dust trap"



van der Marel et al. (2013)



asymmetric mm dust at 63 AU

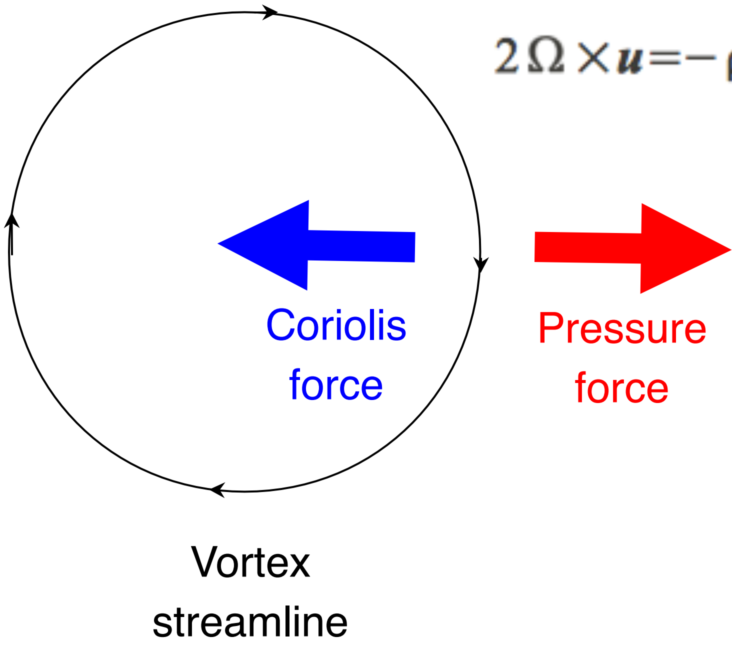
Gas detection: Keplerian rotation

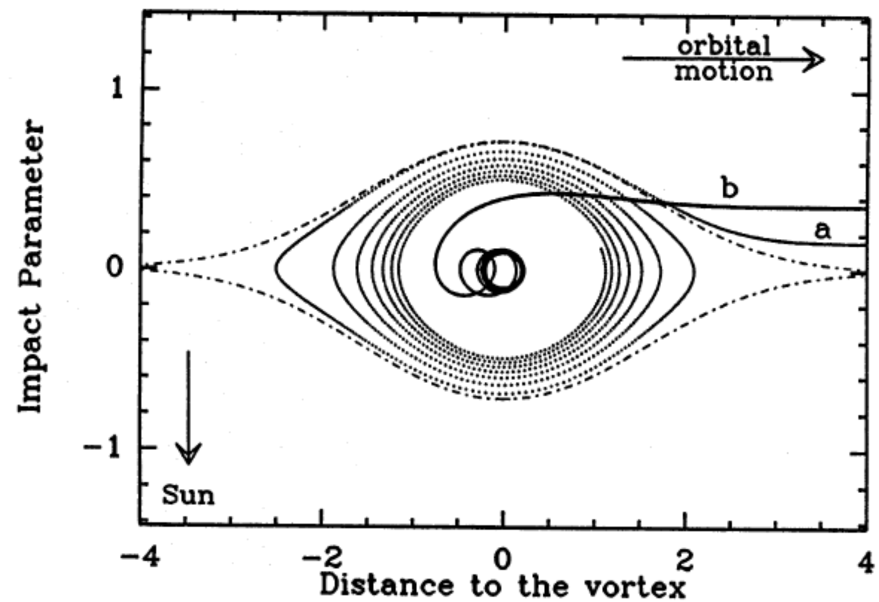
Micron-sized dust follows gas

The Tea-Leaf effect

Geostrophic balance:

$$2\Omega \times \boldsymbol{u} = -\rho^{-1}\nabla p$$





Barge & Sommeria (1995)

Grains do not feel the pressure gradient.
They sink towards the center, where they accumulate.

Aid to planet formation

(Barge & Sommeria 1995, Tanga et al. 1996, Barranco & Marcus 2005)

Speed up planet formation enormously

(Lyra et al. 2008b, 2009ab, Raettig et al. 2012)

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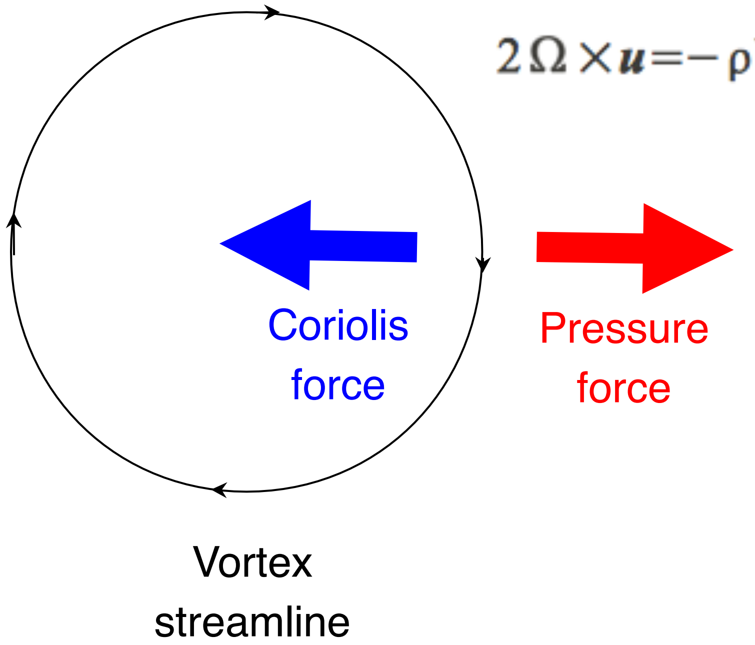

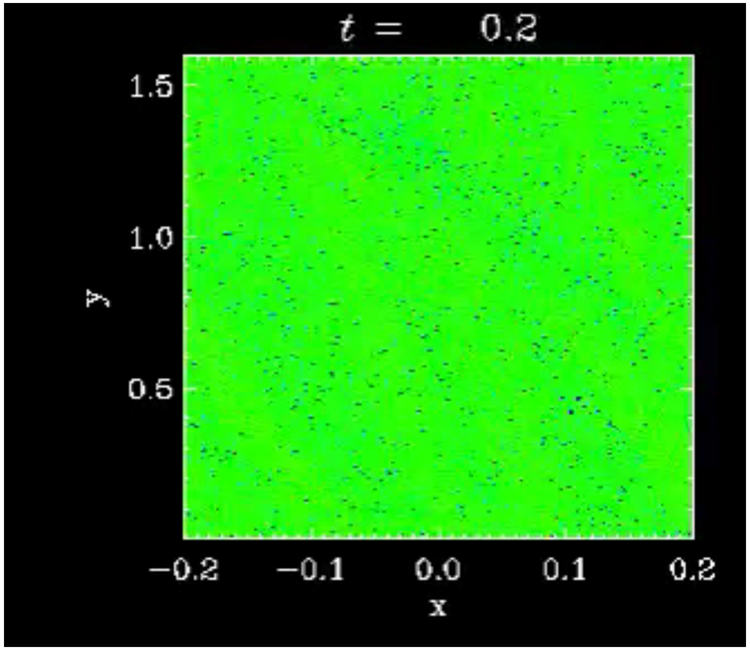

Raettig, Lyra, & Klahr (2013)

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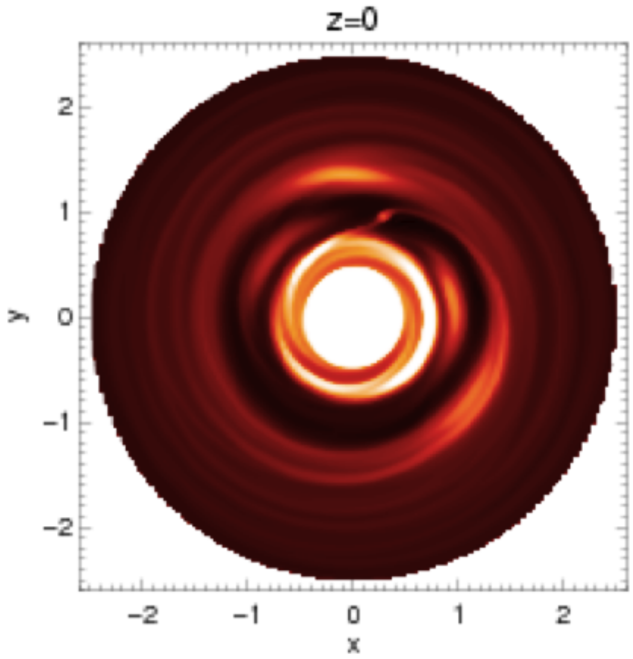
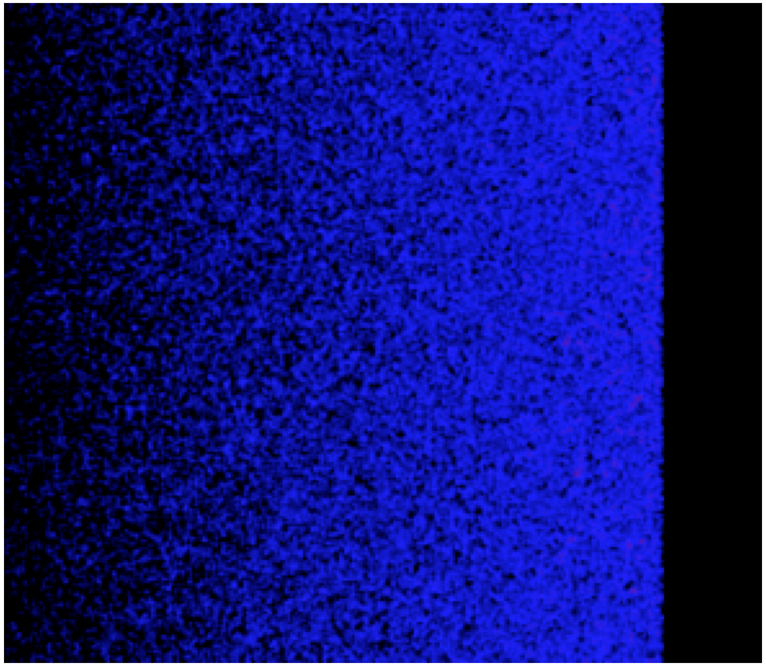
Planet Formation in gap edge vortices

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

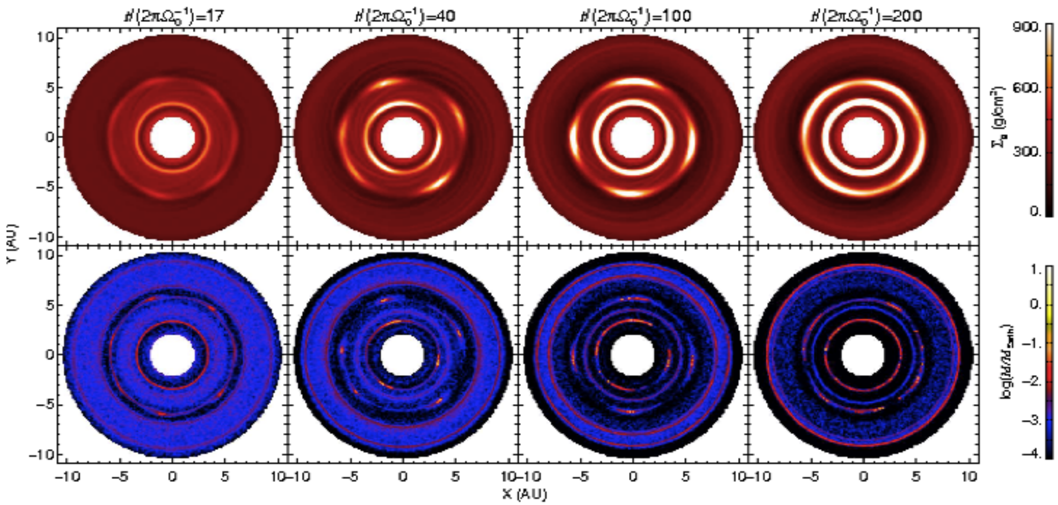




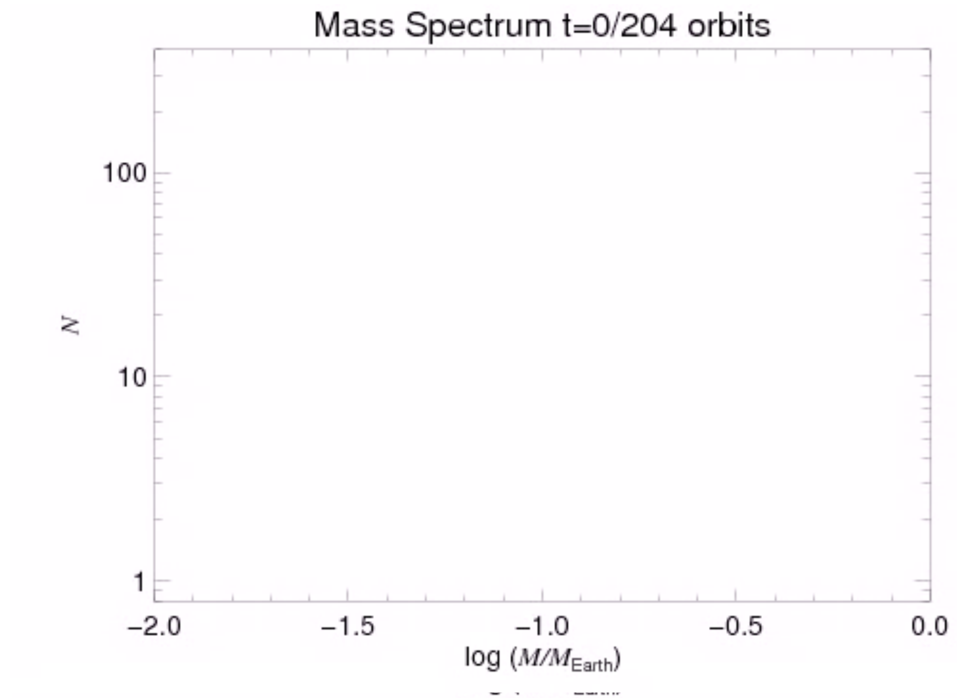
Burst of formation in gap vortices

Vortices and Planet Formation

Gas



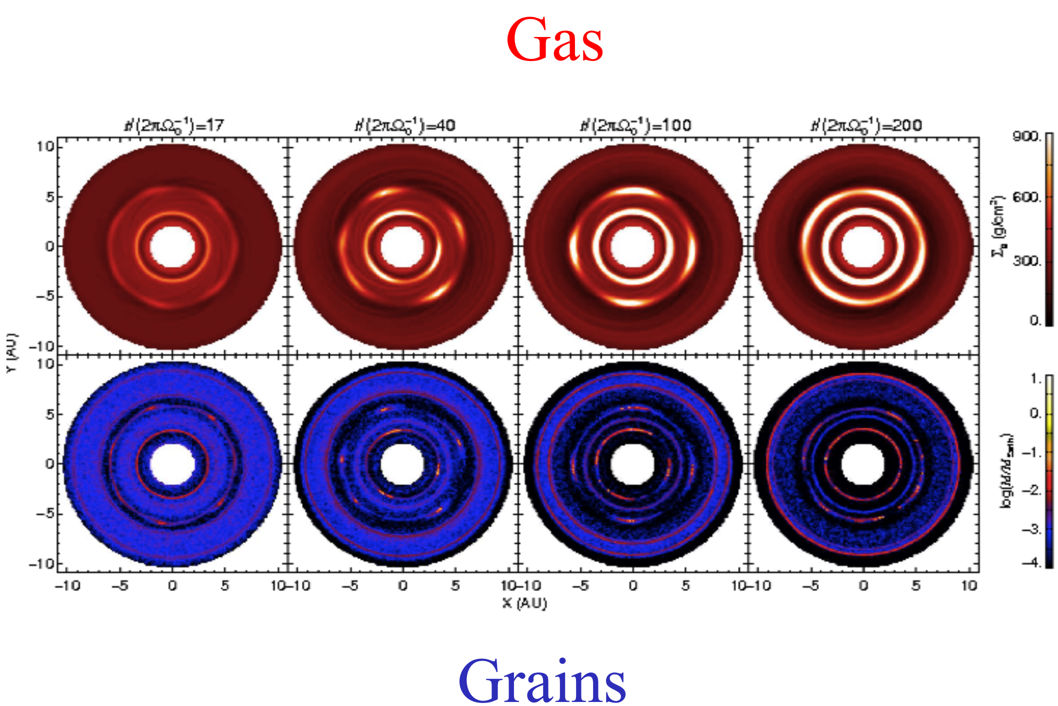
Grains

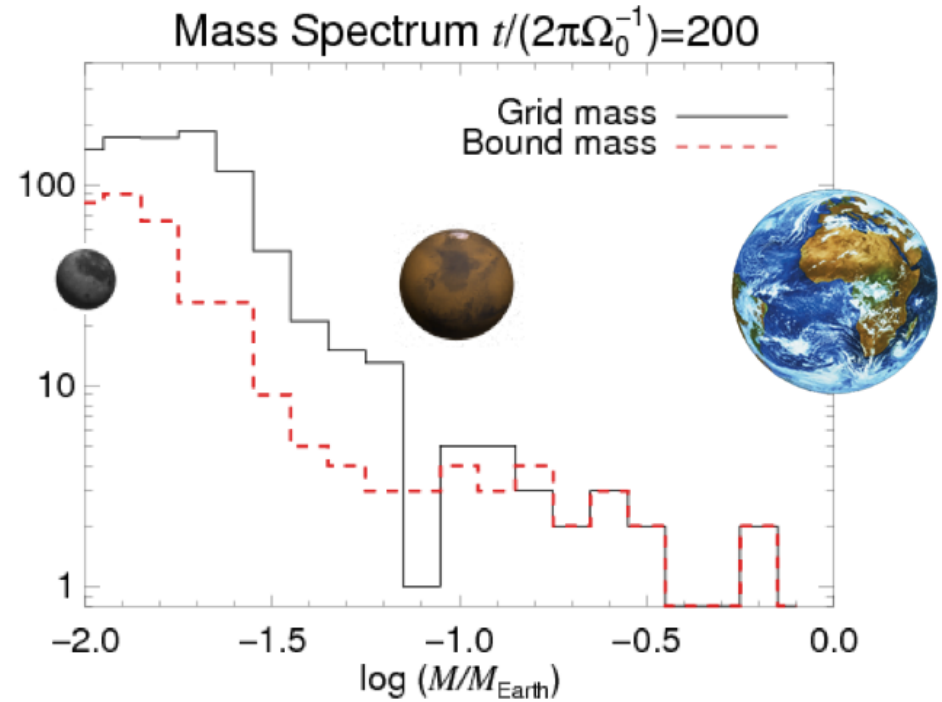


Collapse into Mars mass objects

(Lyra et al. 2008b, 2009a,
Lambrechts & Johansen 2012)

Vortices and Planet Formation





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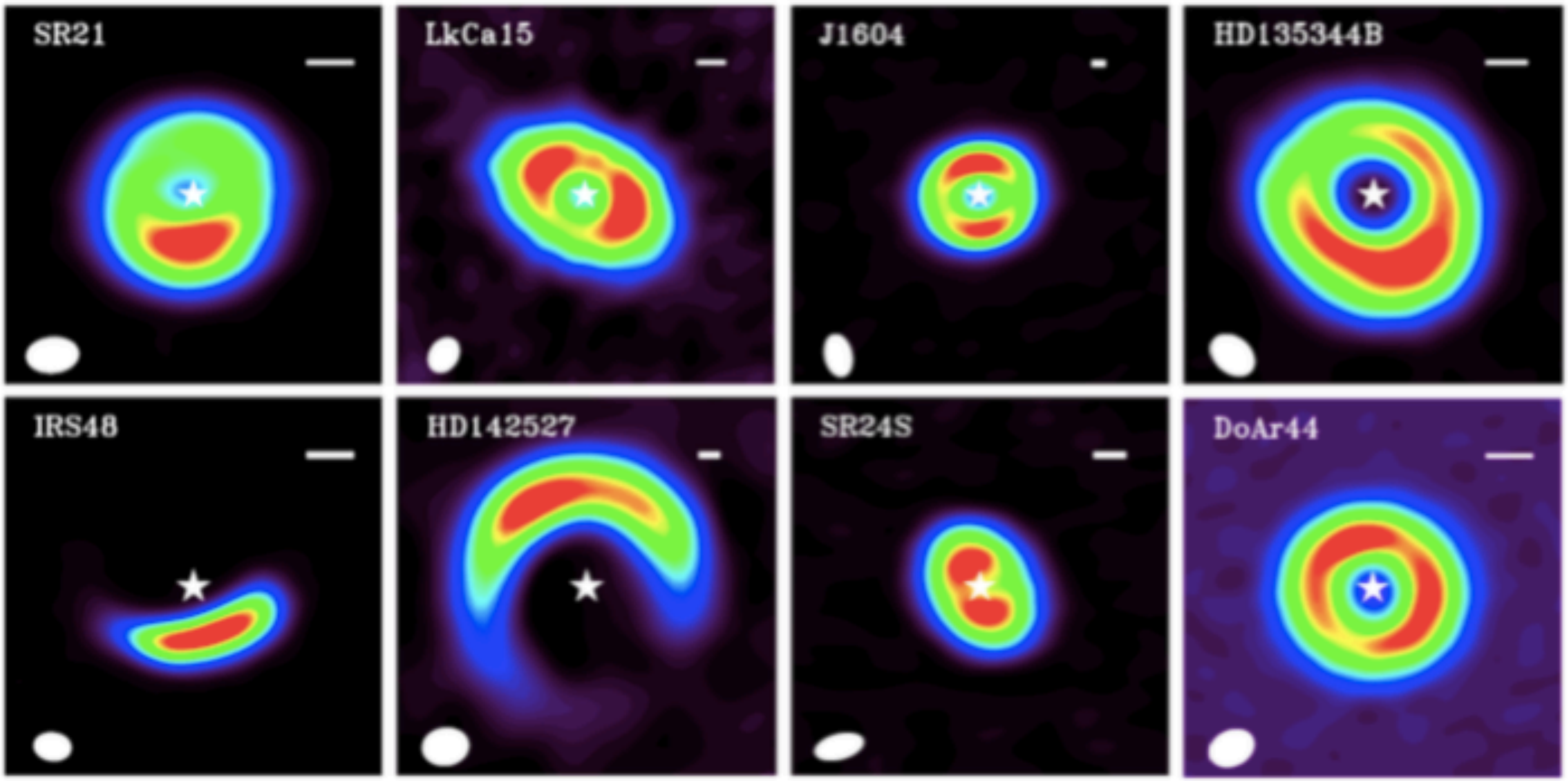
"Asymmetries" everywhere!



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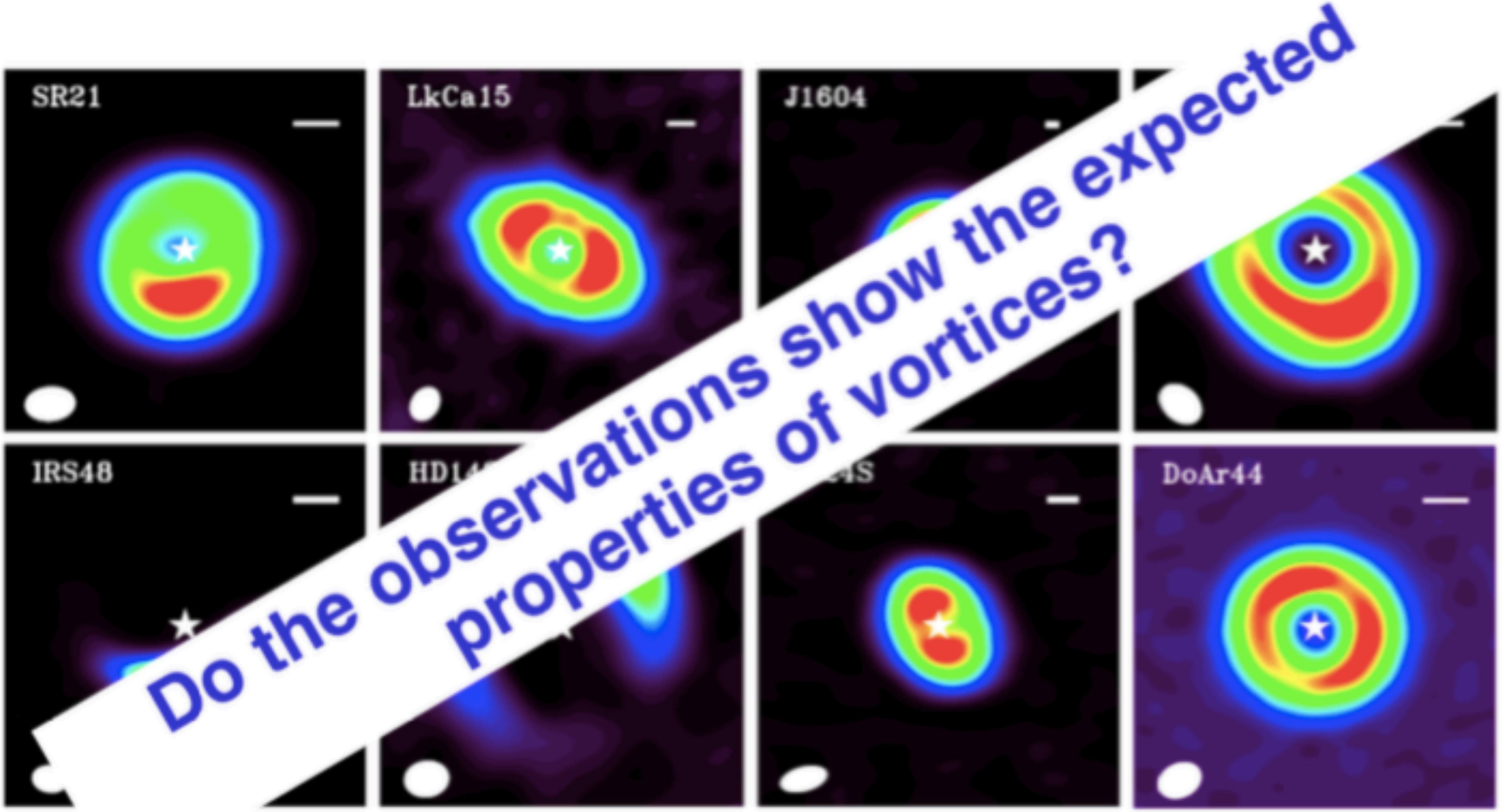
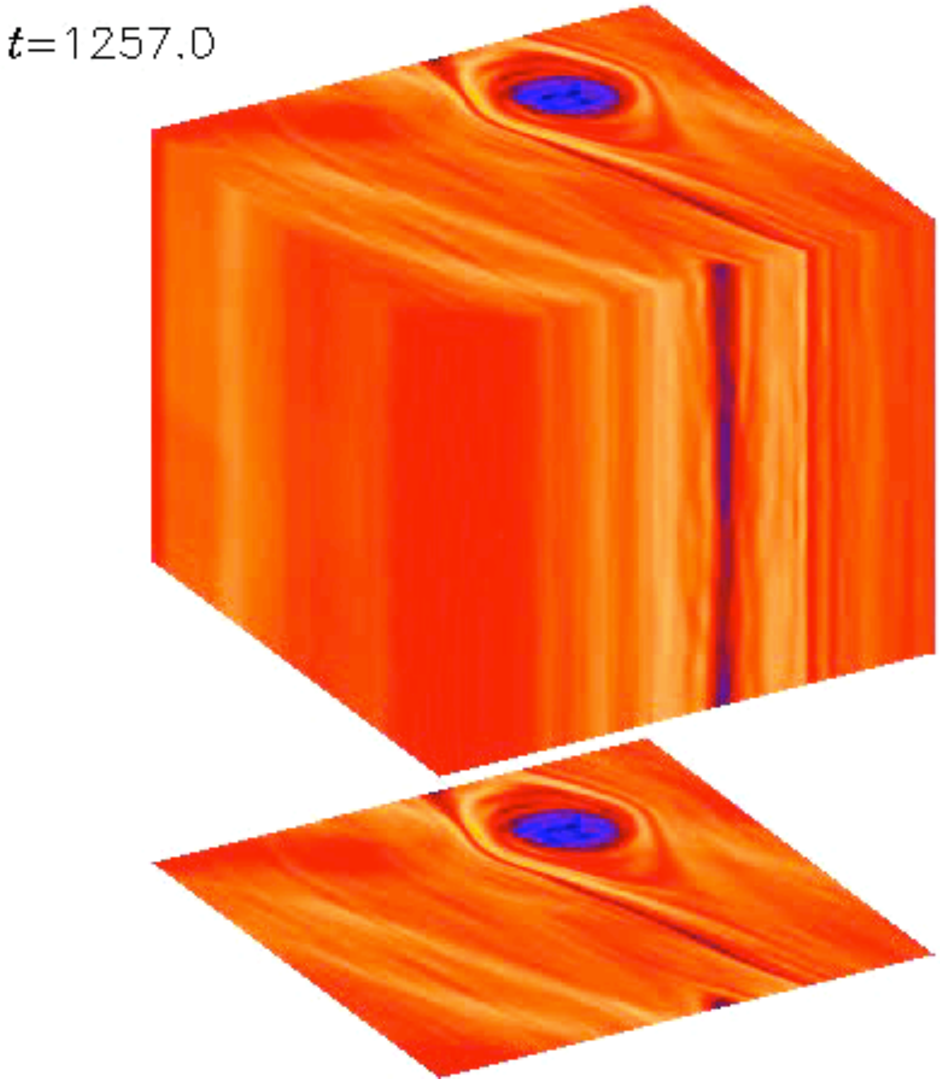
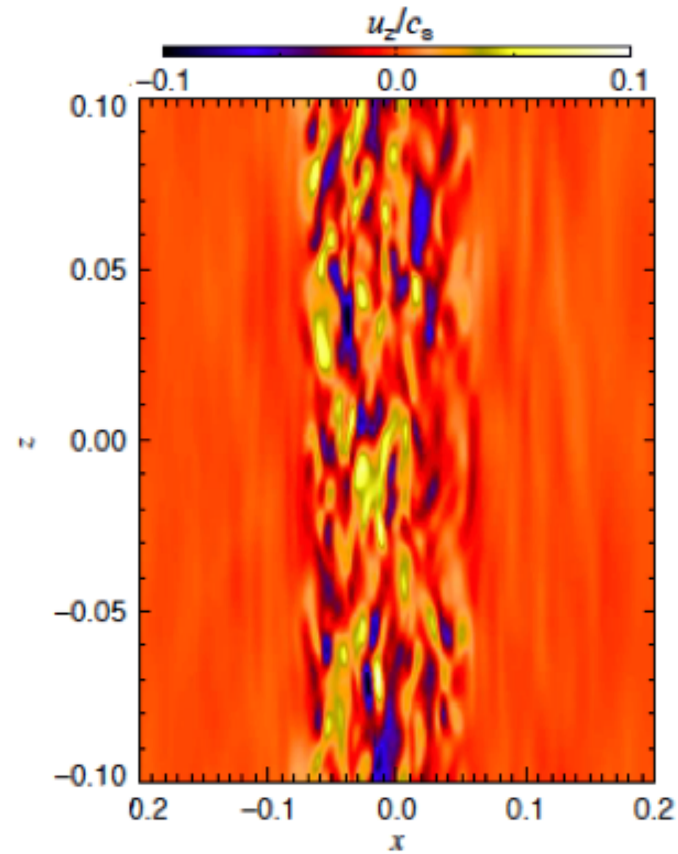


Turbulence in vortex cores

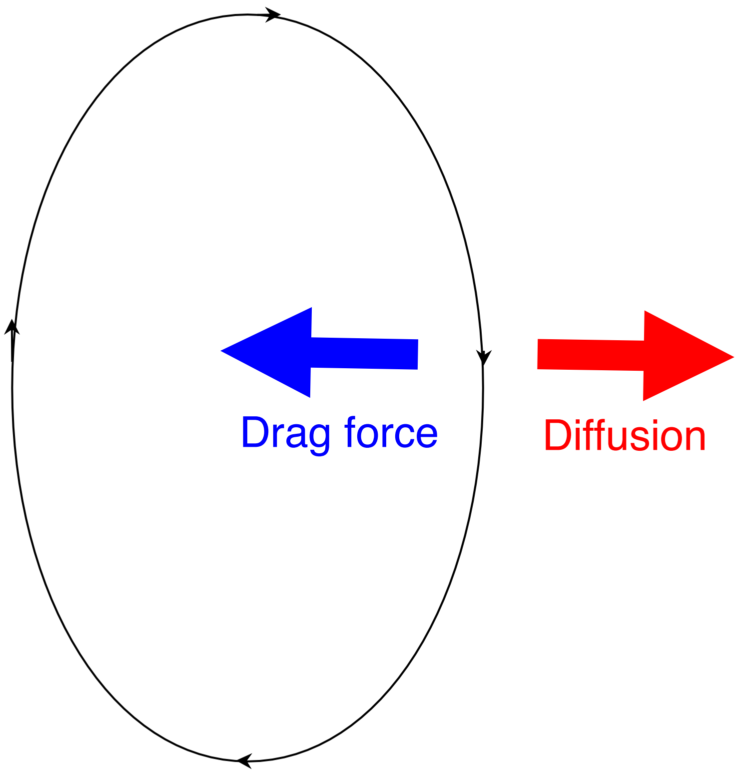




Lyra & Klahr (2011)

V_{max}: ~10% of sound speed
v_{rms}: ~3% of sound speed

Drag-Diffusion Equilibrium

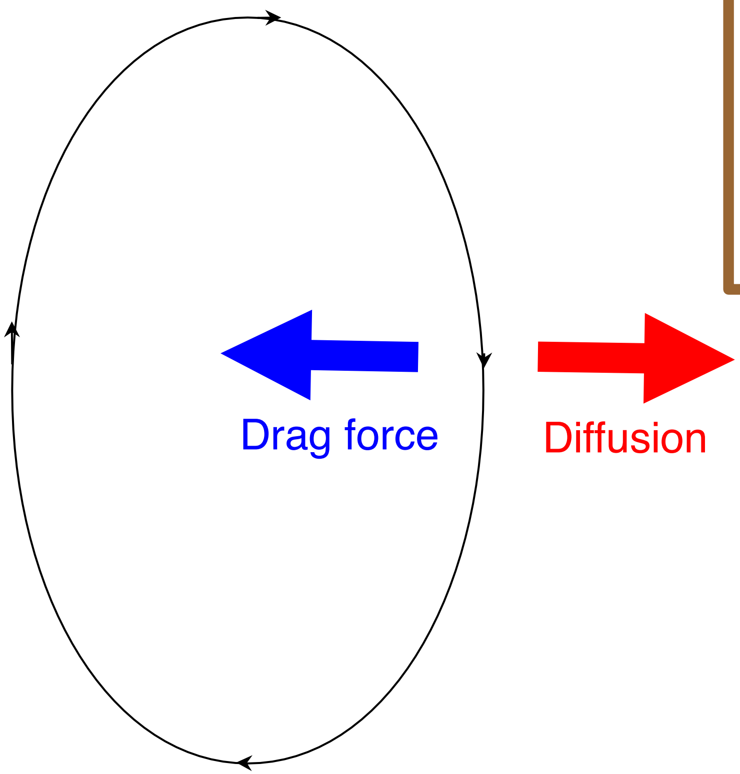


Trapped particle

Dust continuity equation

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

Lyra-Lin solution



Trapped particle

Steady-state solution

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

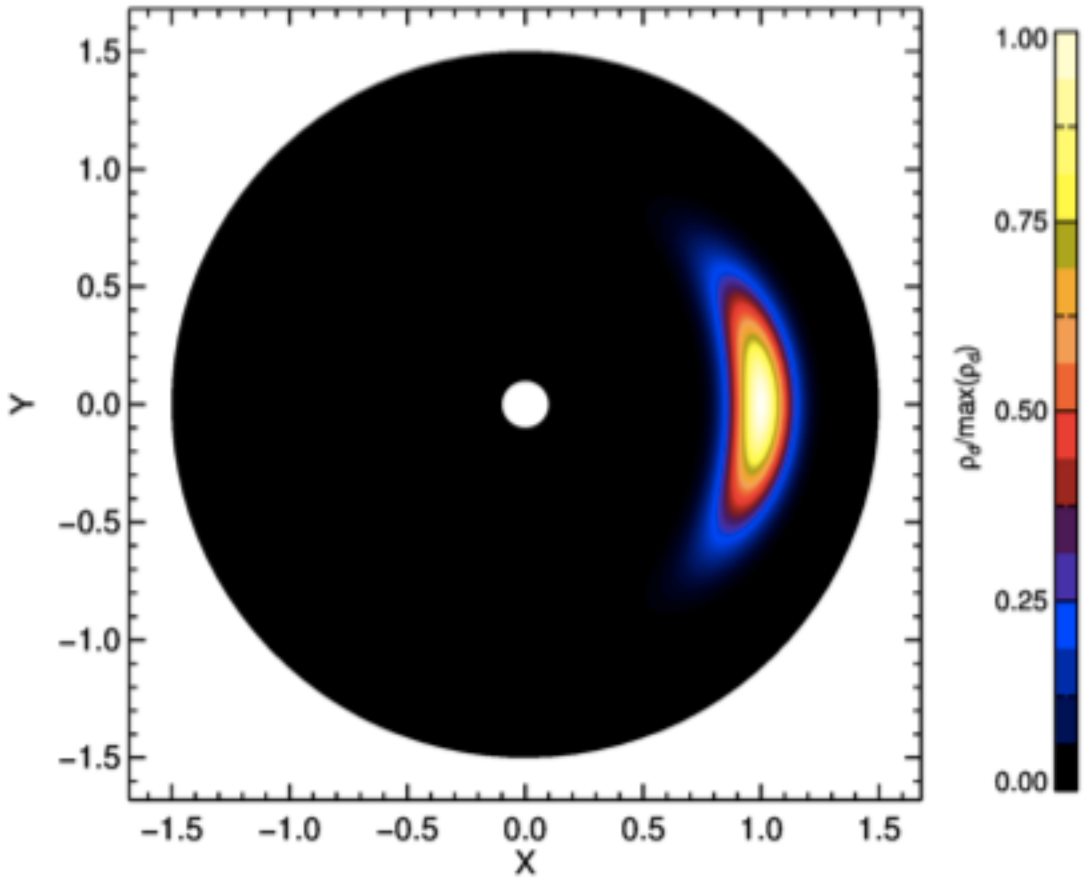
Lyra & Lin (2013)

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

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

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 in drag-diffusion equilibrium



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 = distance to vortex center
H = disk scale height (temperature)
χ = vortex aspect ratio
δ = diffusion parameter
St = Stokes number (grain 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}

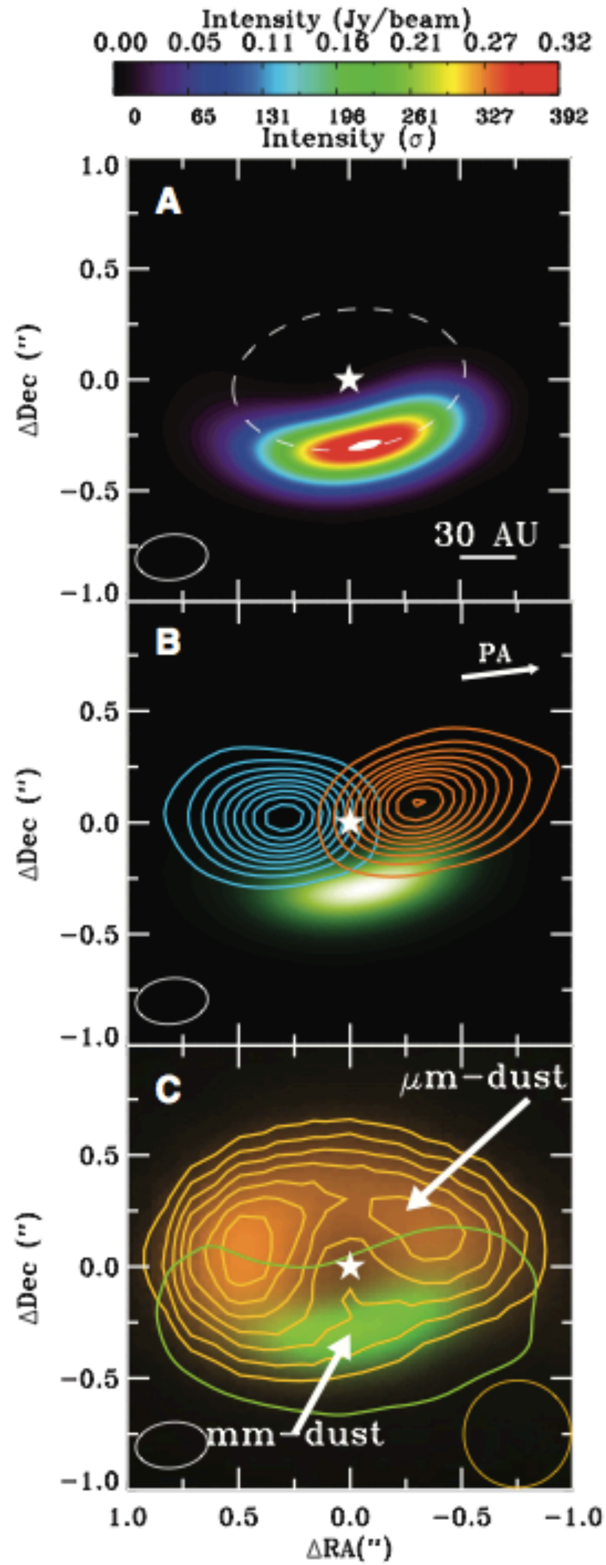
Derived parameters

S=4.8

St=0.008 $\delta = 0.005$

v_{rms} = 4% c_s

Trapped mass: 11 M_{Earth}



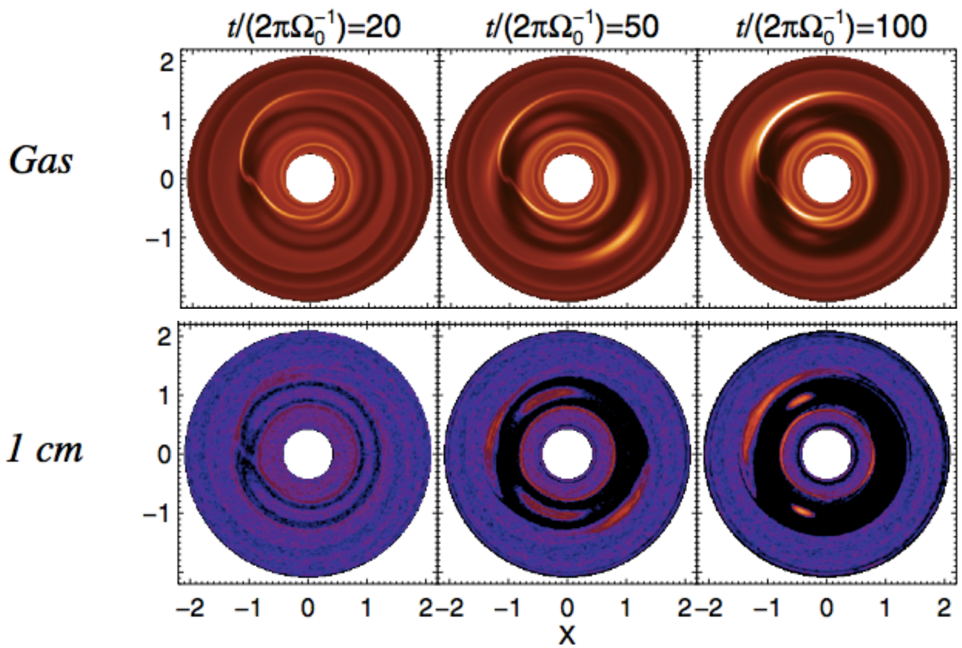
asymmetric mm dust at 63 AU

Gas detection: Keplerian rotation

Micron-sized dust follows gas

Lyra & Lin (2013)

Planetary gap vortices: Chicken or the Egg problem



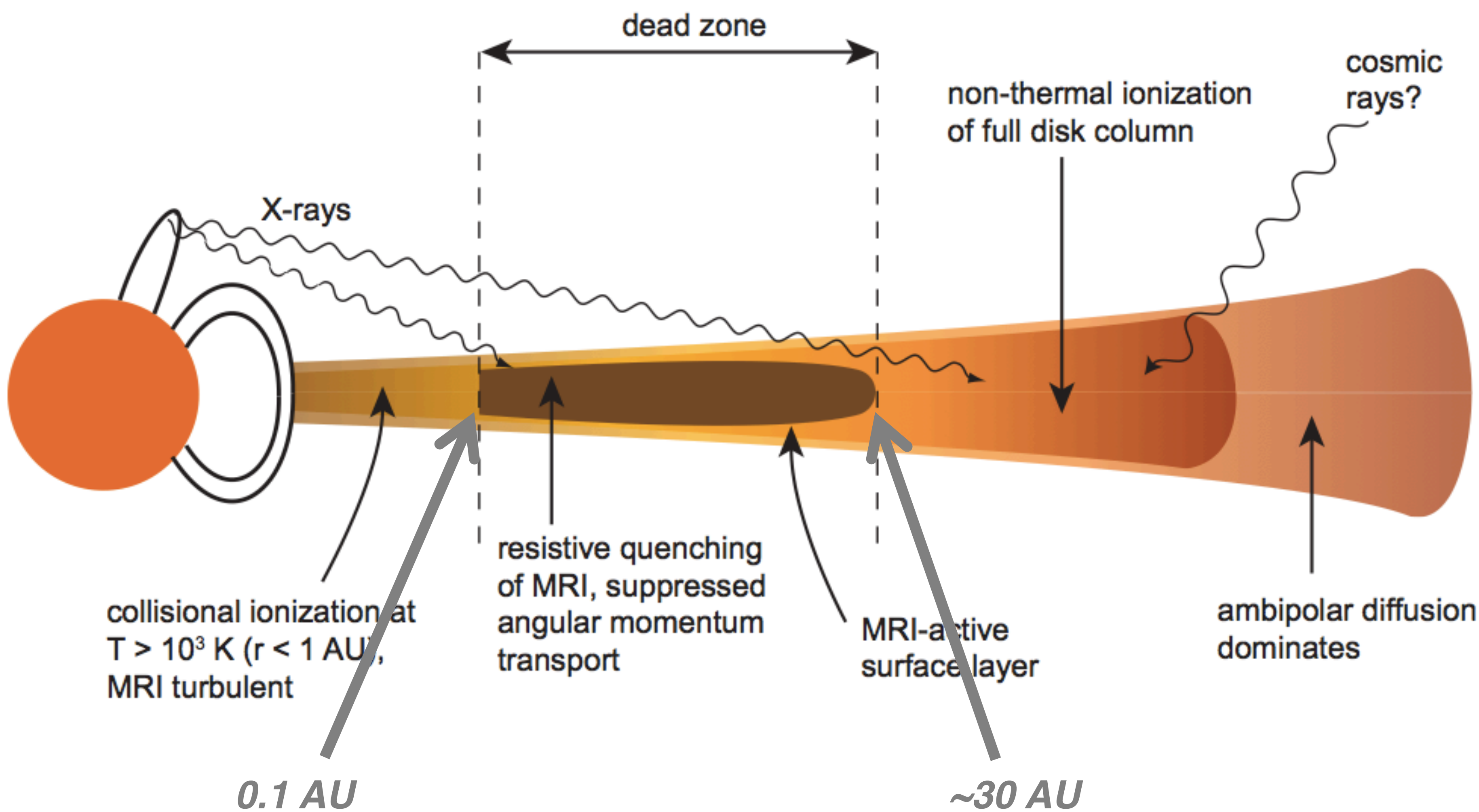
Lyra et al (2009b)

Does the observational detection of a particle trap in IRS 48 imply that traps are the answer to surmounting the radial drift barrier and allowing planet formation? Not immediately. Particle traps solve theoretical problems in planet formation that exist at millimeter to meter scales, and they are no solution at all if the only way to form them requires that gas giant planets already exist. The trap observed in the IRS 48 disk might instead catalyze the formation of additional

Armitage (2013)

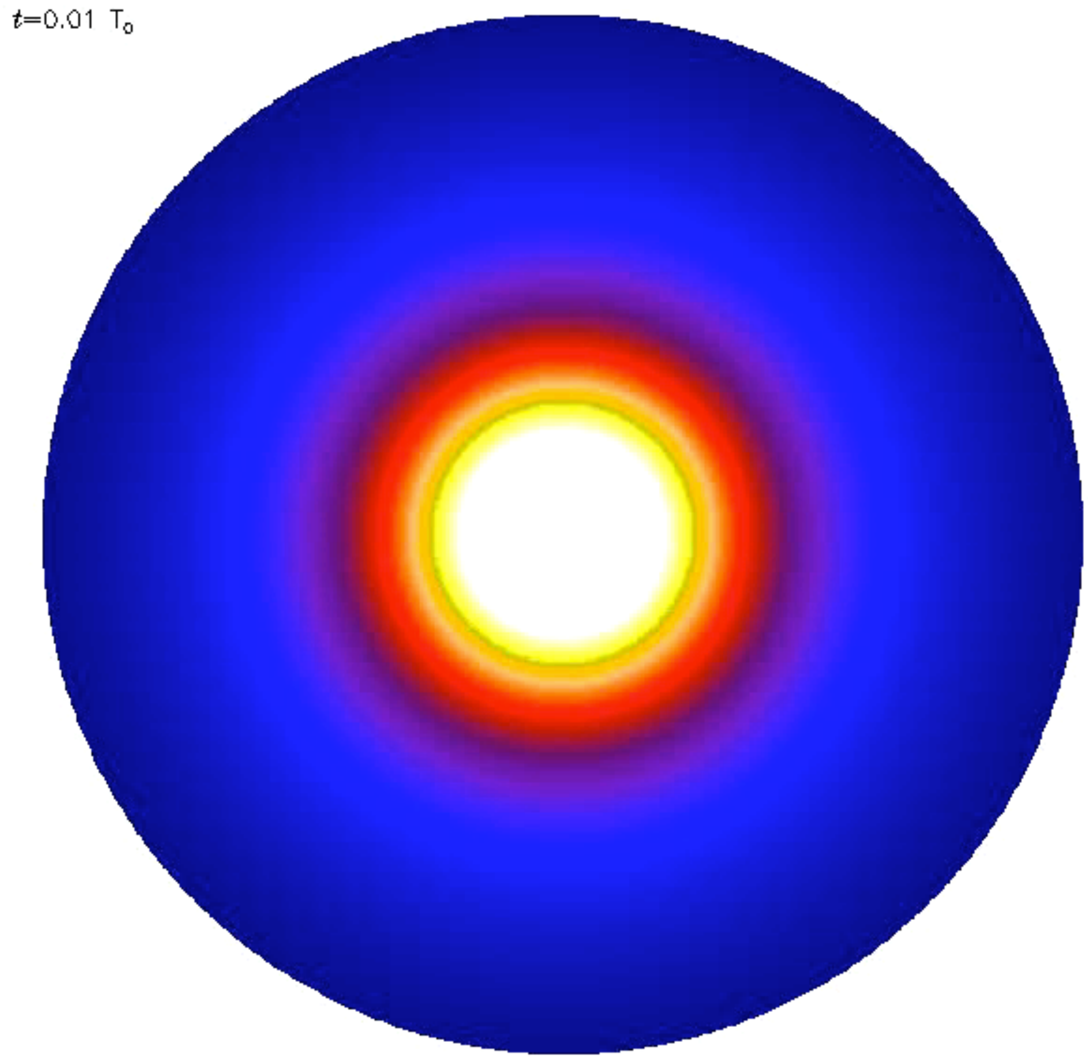
Turbulence and Accretion in 3D Global MHD Simulations of Stratified Protoplanetary Disk

Dead zones



There should be a **magnetized, active zone**
and a **non-magnetic, dead zone**

Inner (0.1 AU) active/dead zone boundary

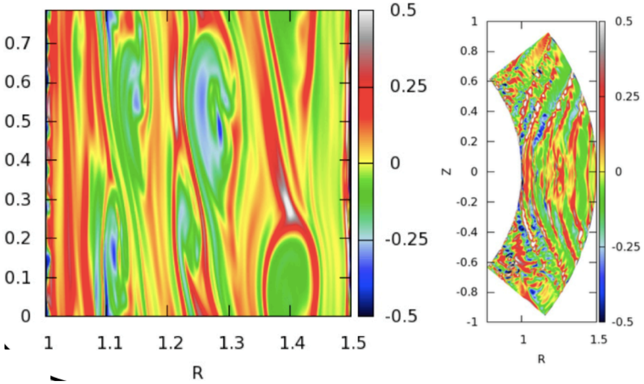


Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

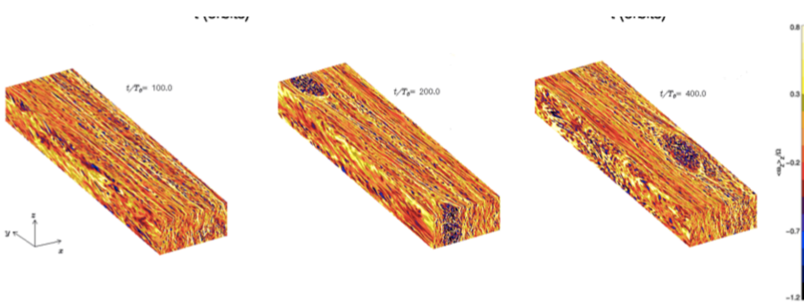
Thermal Instabilities

Vertical Shear Instability



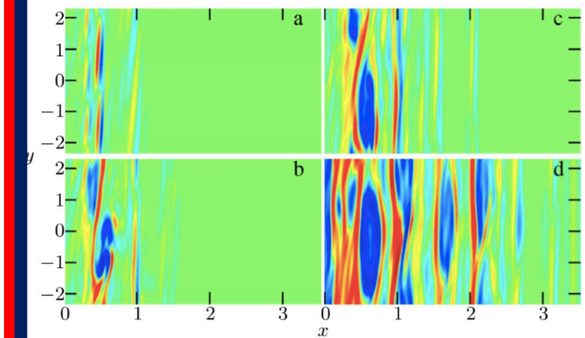
Nelson et al. 2013, Lin & Youdin 2015, Umurhan et al. 2016

Convective Overstability



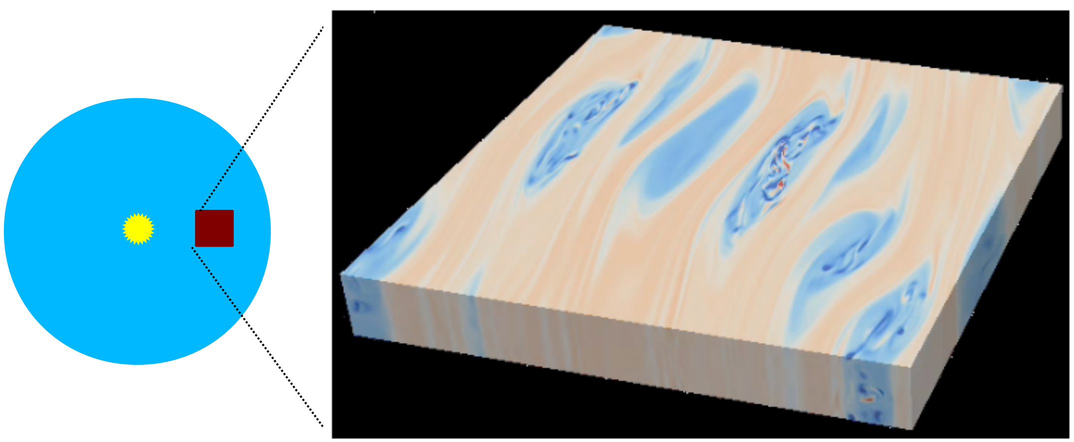
Klahr 2003, Lesur & Papaloizou 2010, Lyra & Klahr 2011, Lyra 2014

Zombie Vortex Instability



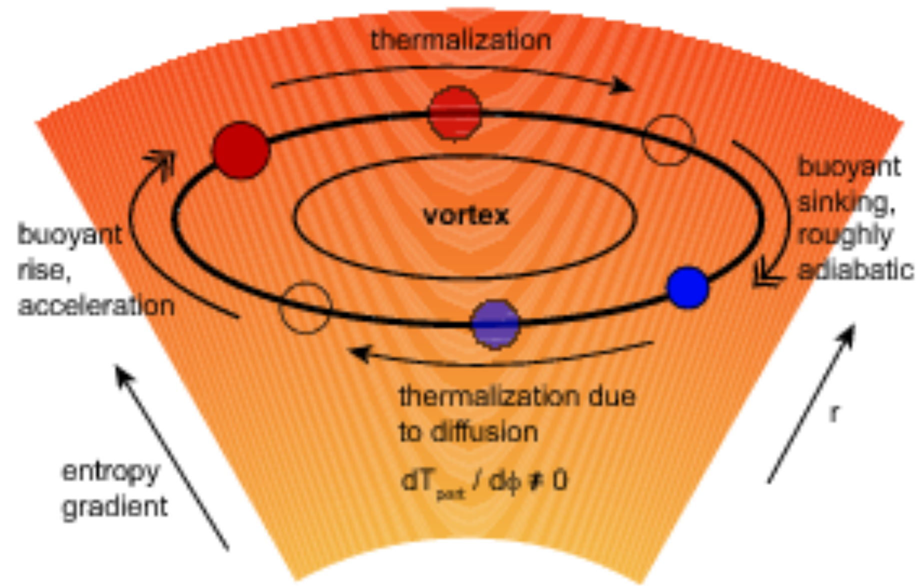
Marcus et al. 2012, 2013, 2015, 2016
Umurhan et al 2016, Lesur & Latter 2016

Convective Overstability



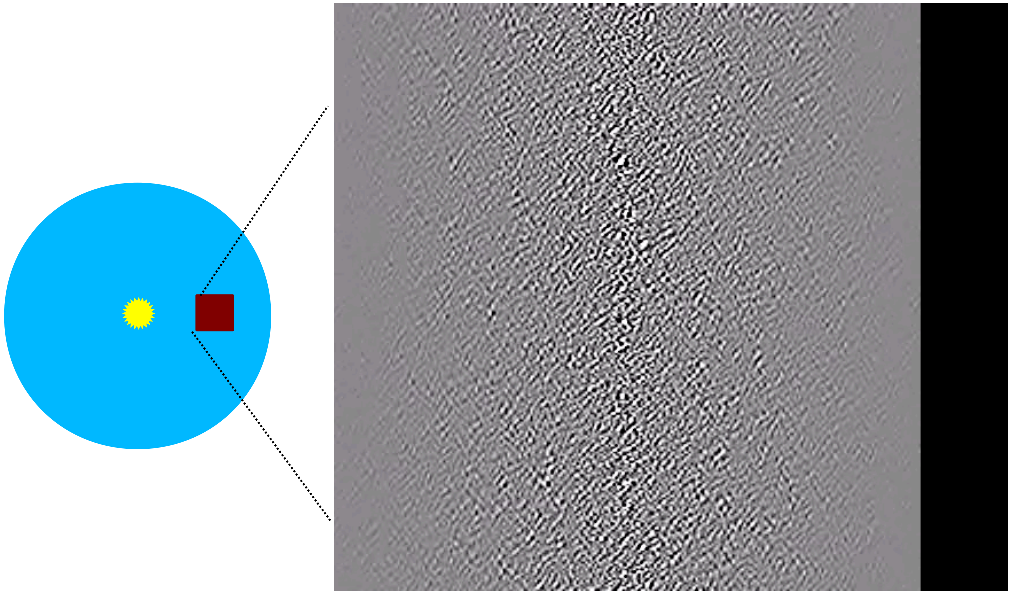
Lesur & Papaloizou (2010)

Sketch of the
Convective Overstability



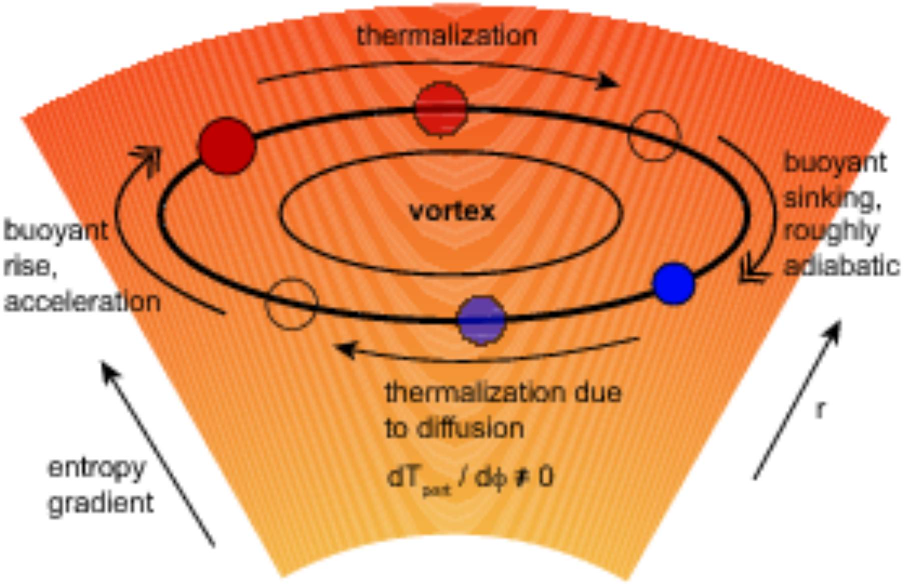
Armitage (2010)

Convective Overstability



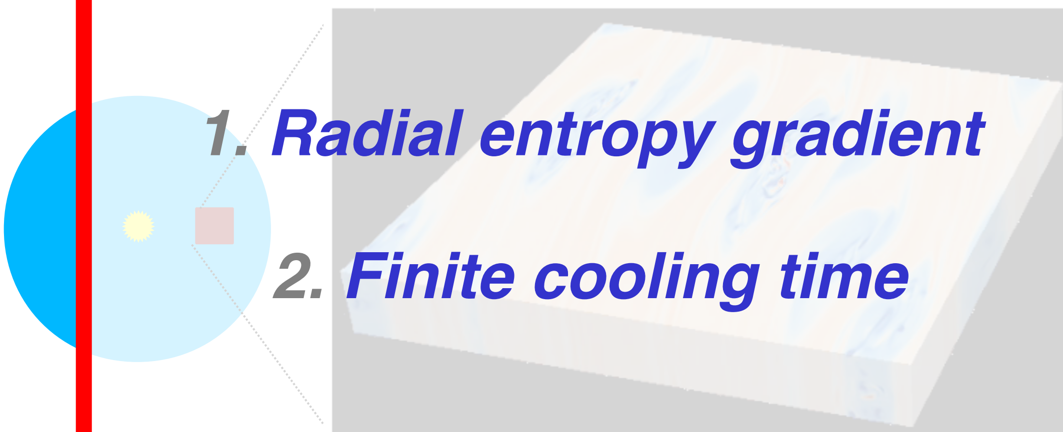
Lyra & Klahr (2011)

Sketch of the
Convective Overstability



Armitage (2010)

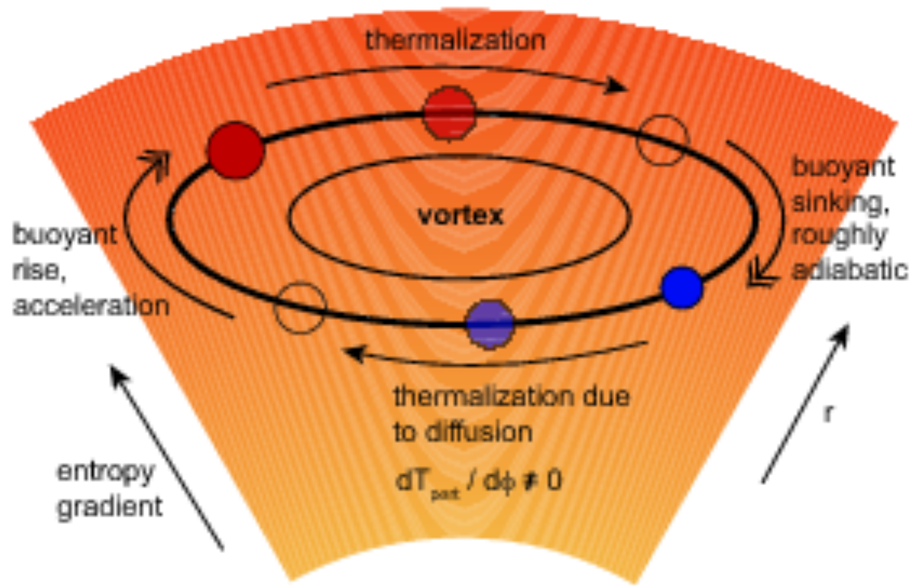
Convective Overstability



1. *Radial entropy gradient*
2. *Finite cooling time*

Lesur & Papaloizou (2010)

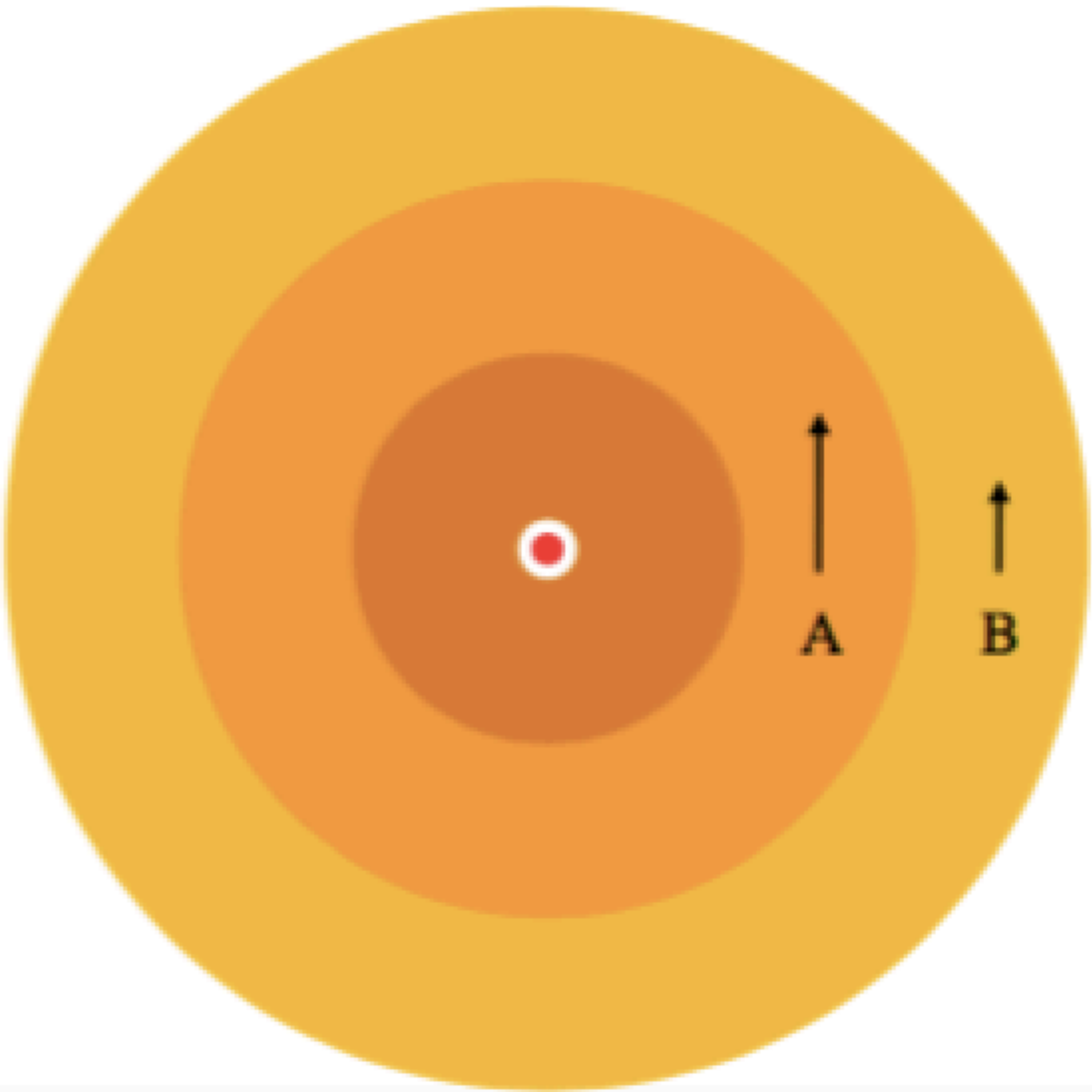
Sketch of the Convective Overstability



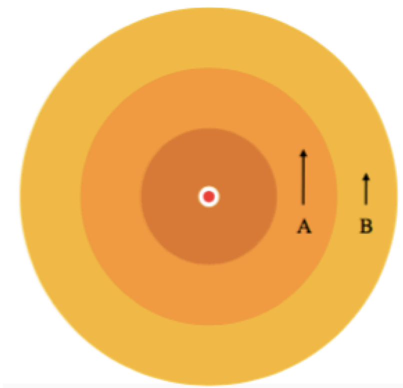
Armitage (2010)

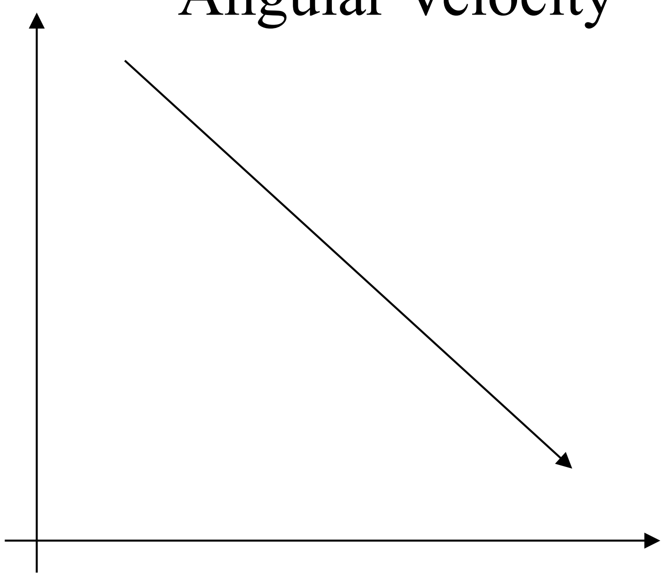
Vertical Shear Instability

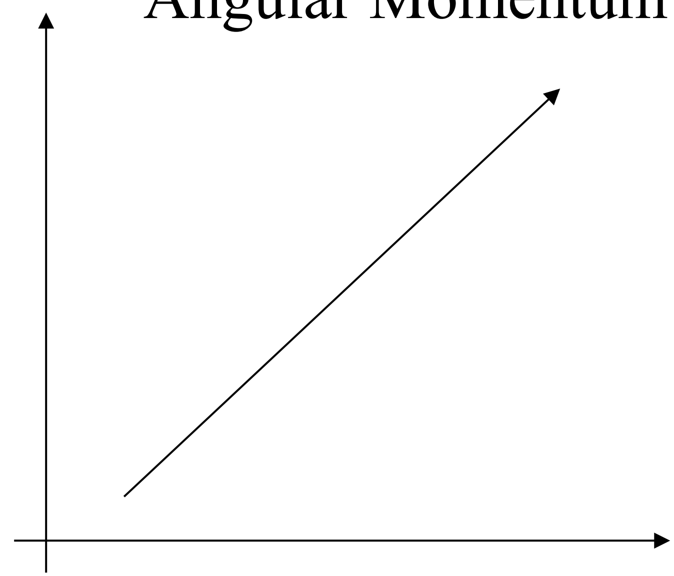
Rayleigh criterion



Stability (Rayleigh criterion)

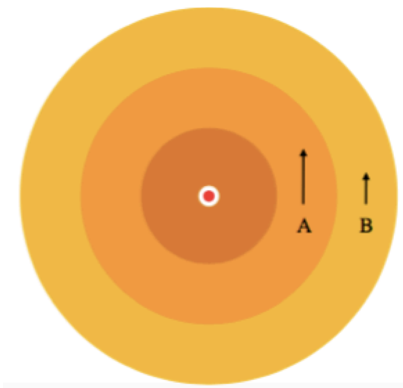




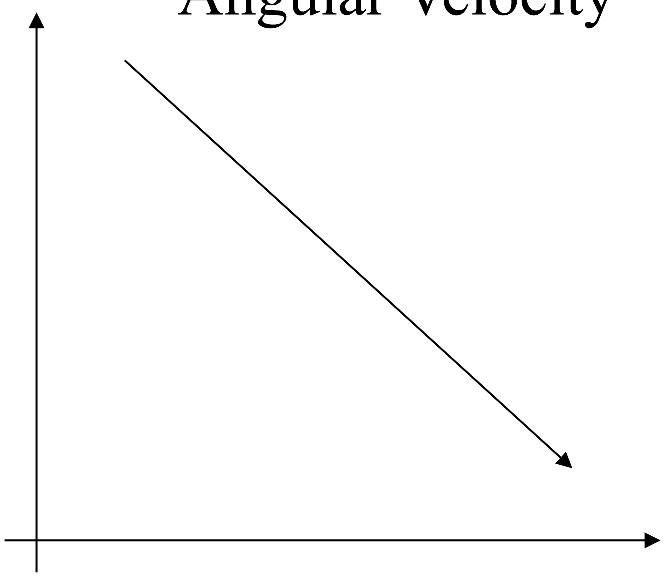


$$|d\ \ln\Omega\ /d\ln r| < 2$$

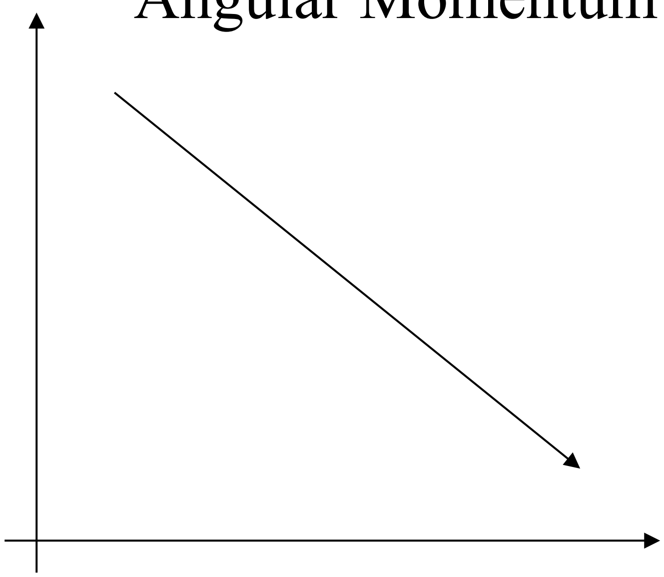
Rayleigh instability



Angular Velocity



Angular Momentum (***r*²*Ω***)



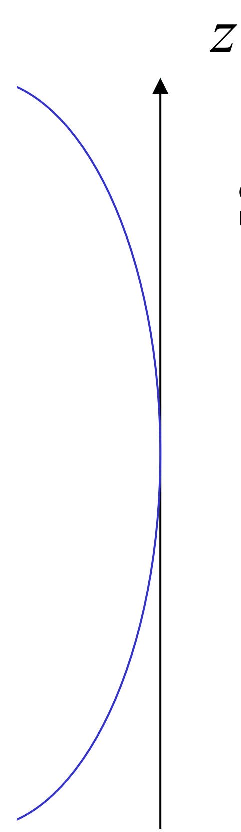
$$|d \ln\Omega / d\ln r| > 2$$

Vertical shear instability

$$\rho_{\rm mid} = \rho_0 \left(\frac{R}{R_0}\right)^p ,$$

$$c_{\rm s}^2 = c_0^2 \left(\frac{R}{R_0}\right)^q ,$$

$$\Omega = \Omega_{\rm K} \left[1 + \frac{1}{2} \left(\frac{H}{R}\right)^2 \left(p + q + \frac{q}{2} \frac{Z^2}{H^2} \right) \right]$$



Unstable $d\Omega / dz < 0$

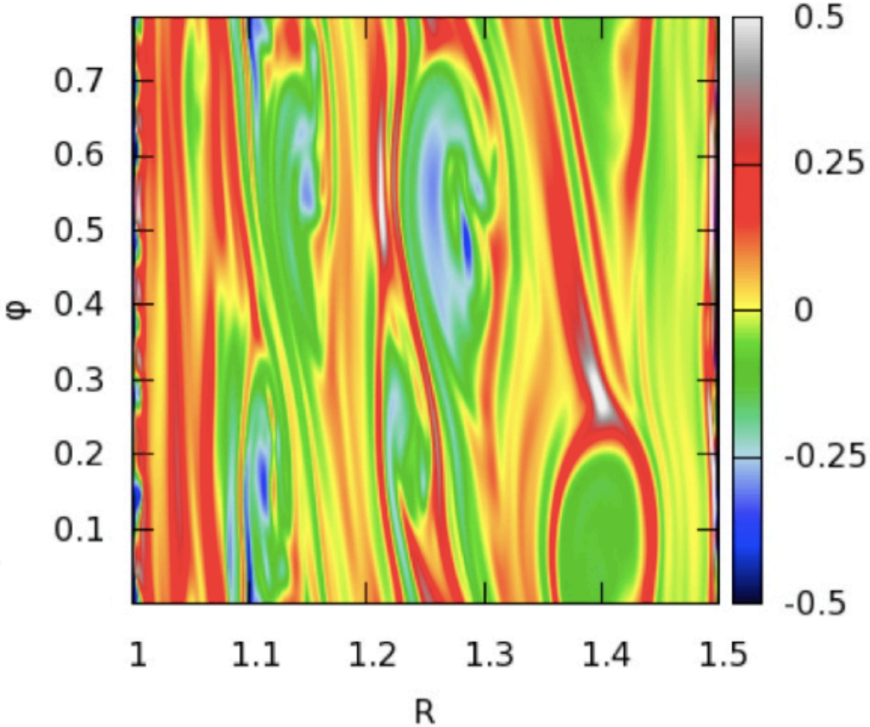
Stable $d\Omega / dz = 0$

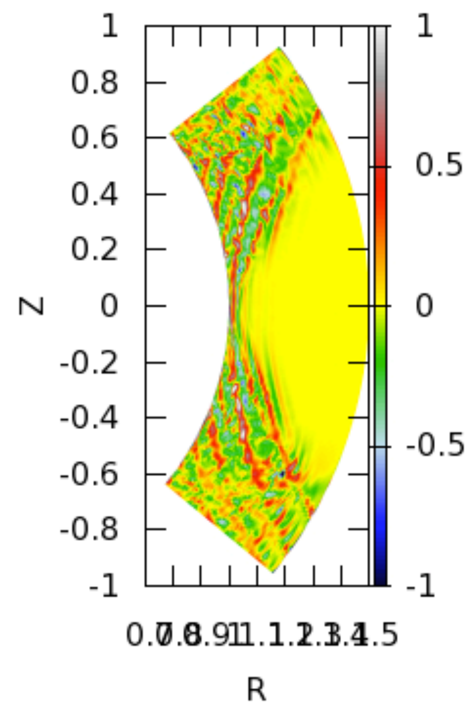
Vertical shear instability

$$\rho_{\rm mid} = \rho_0 \left(\frac{R}{R_0}\right)^p ,$$

$$c_s^2 = c_0^2 \left(\frac{R}{R_0}\right)^q ,$$

$$\Omega = \Omega_K \left[1 + \frac{1}{2}\left(\frac{H}{R}\right)^2 \left(p + q + \frac{q}{2}\frac{Z^2}{H^2}\right)\right]$$





Vertical shear instability

$$\rho_{\rm mid} = \rho_0 \left(\frac{R}{R_0}\right)^p,$$

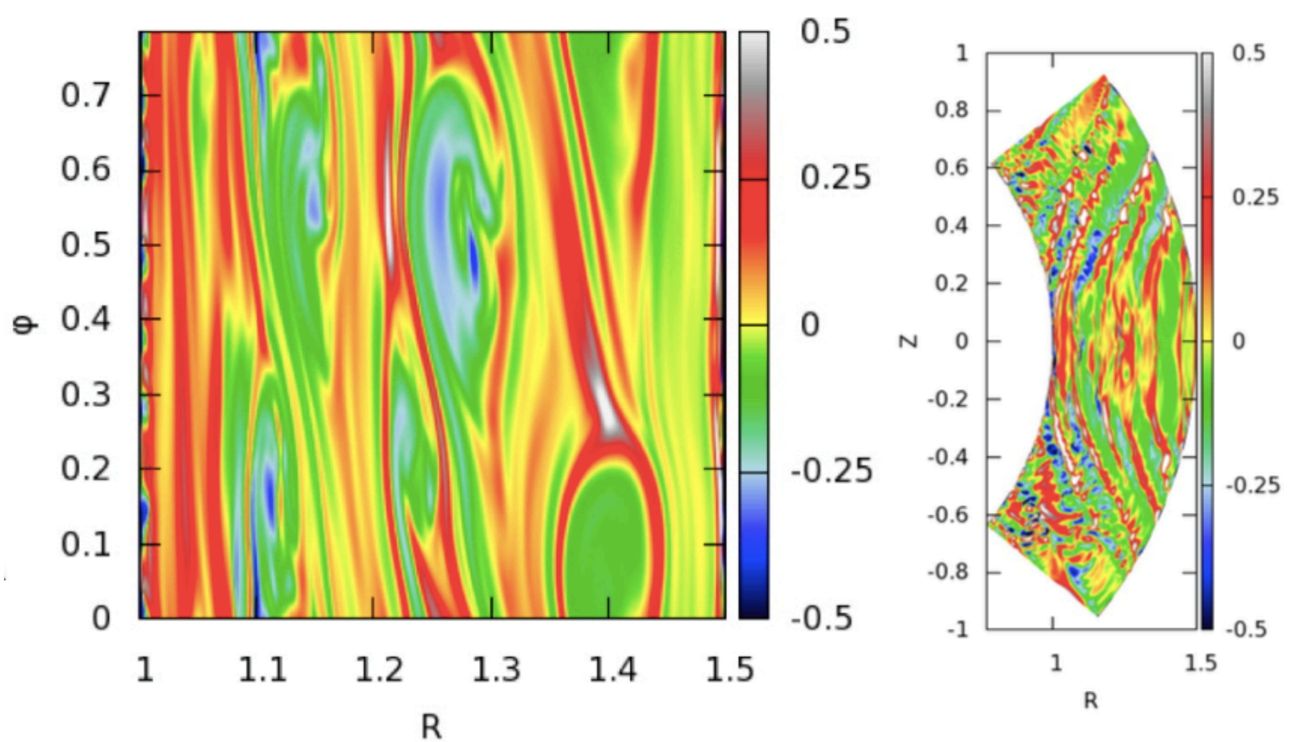
$$c_s^2 = c_0^2 \left(\frac{R}{R_0}\right)^q,$$

$$\Omega = \Omega_K \left[1 + \frac{1}{2}\left(\frac{H}{R}\right)^2 \left(p + q + \frac{q}{2}\frac{Z^2}{H^2}\right)\right]$$

$d\Omega / dz$!= 0 ; $\kappa_z^2 < 0$ => Rayleigh unstable

Solberg-Hoiland stability criterion

$\kappa^2 + N^2 > 0$



Nelson et al. (2013)

Vertical shear instability

$$\rho_{\rm mid} = \rho_0 \left(\frac{R}{R_0}\right)^p,$$

$$c_s^2 = c_0^2 \left(\frac{R}{R_0}\right)^q,$$

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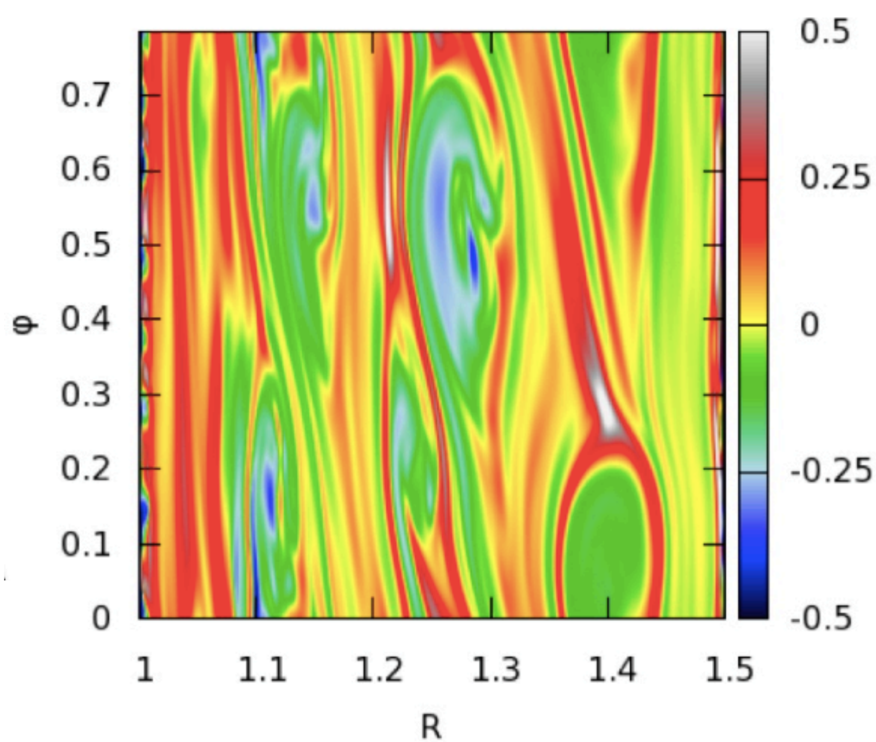
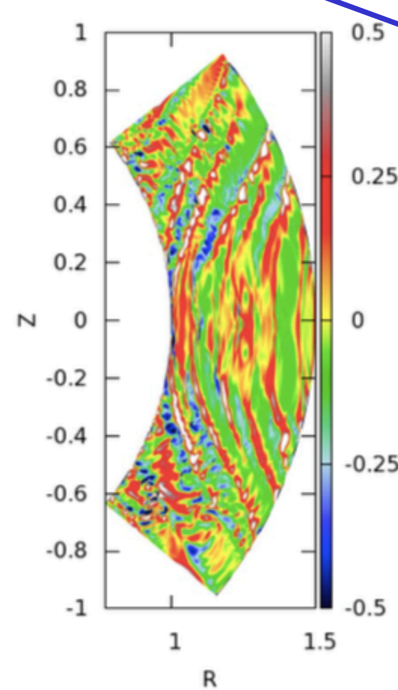
$d\Omega / dz \ != 0\ ;\ \kappa_z^2 < 0$ => Rayleigh unstable

Solberg-Hoiland stability criterion

$\kappa^2 + N^2 > 0$

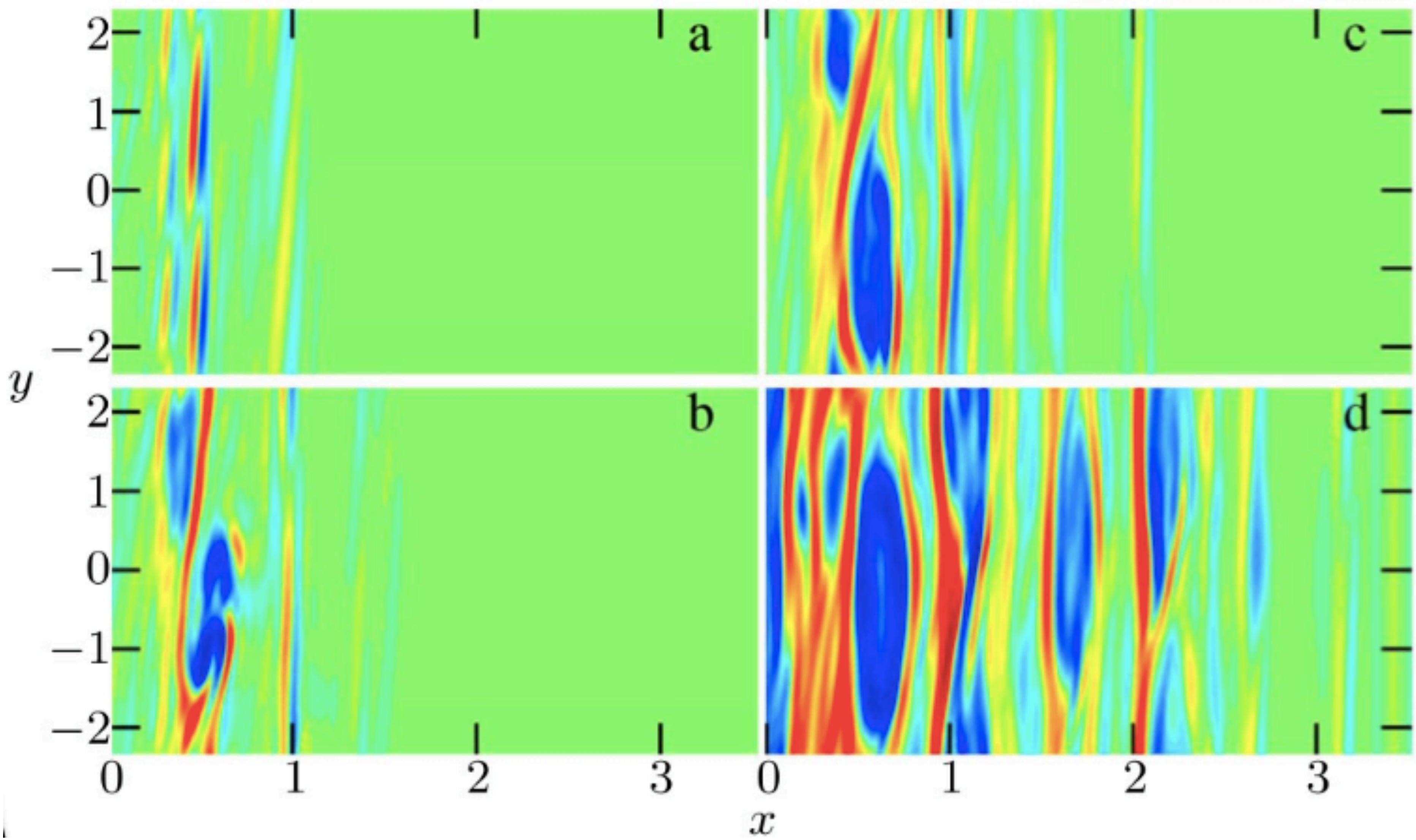
Buoyancy stabilizes!





Nelson et al. (2013)

Zombie Vortex Instability

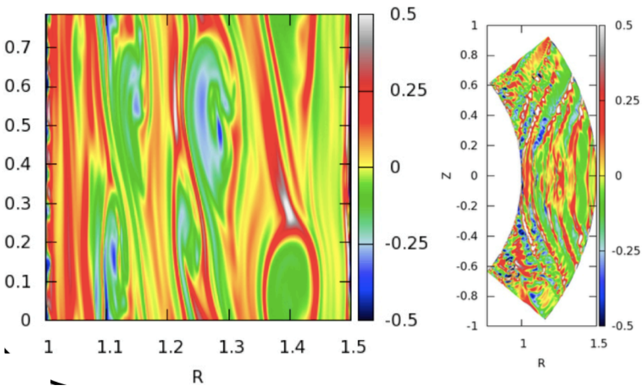


Cascade of baroclinic critical layers

Marcus et al. (2015, 2016)

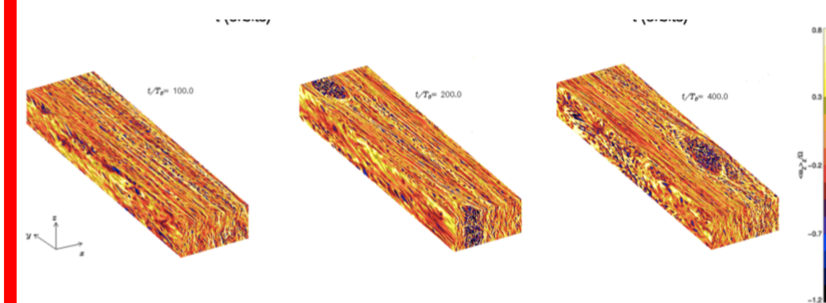
Thermal Instabilities

Vertical Shear Instability



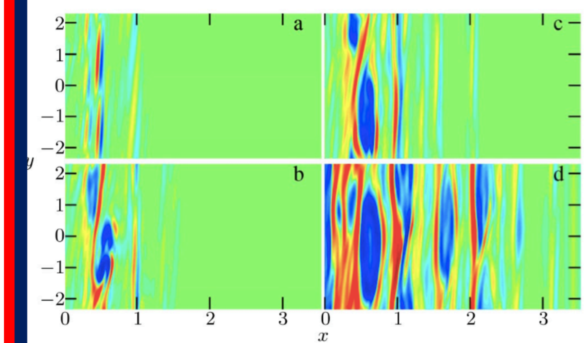
Nelson et al. 2013, Lin & Youdin 2015, Umurhan et al. 2016

Convective Overstability



Klahr 2003, Lesur & Papaloizou 2010, Lyra & Klahr 2011, Lyra 2014

Zombie Vortex Instability



Marcus et al. 2012, 2013, 2015, 2016
Umurhan et al 2016, Lesur & Latter 2016

$\Omega\tau << 1$
($\kappa < 1$ cm^2/g)

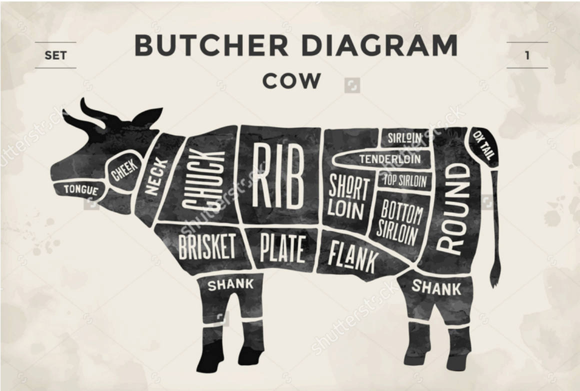
$\Omega\tau \sim 1$
($\kappa \sim 1$–50 cm^2/g)

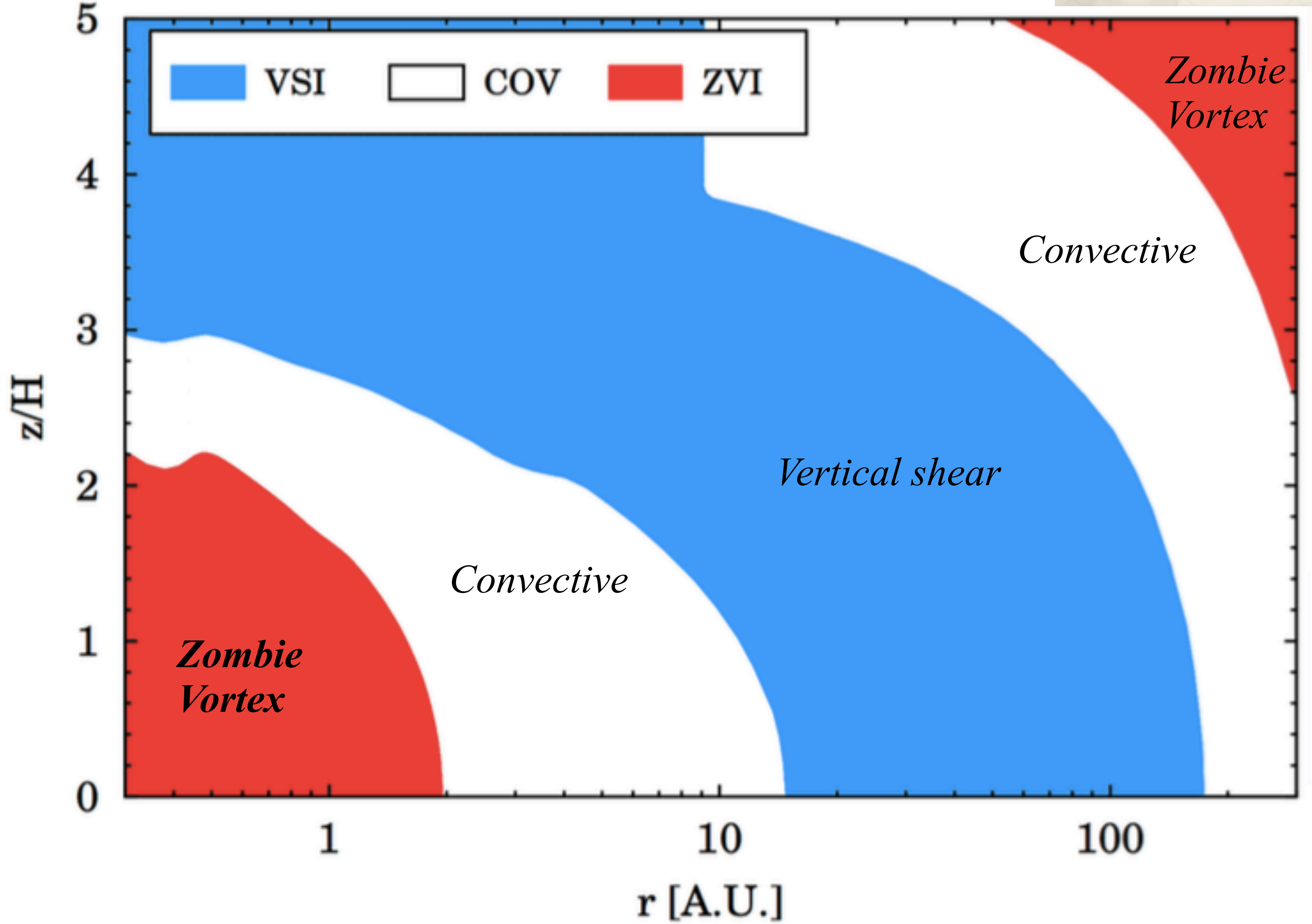
$\Omega\tau >> 1$
($\kappa > 50$ cm^2/g)

Opacity

Synthesis

A “butcher diagram” for hydro instabilities.

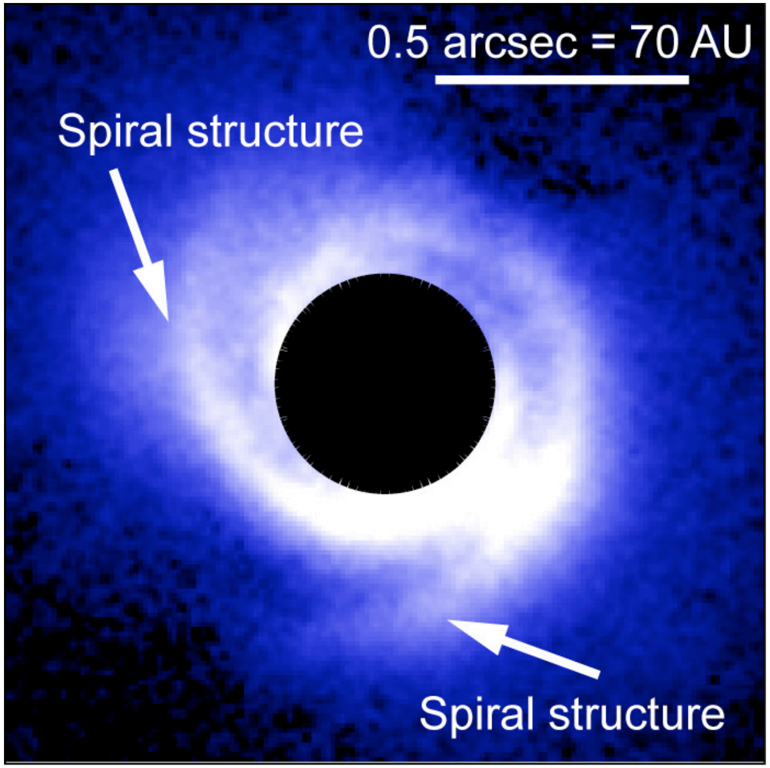




Malygin et al. (2017)

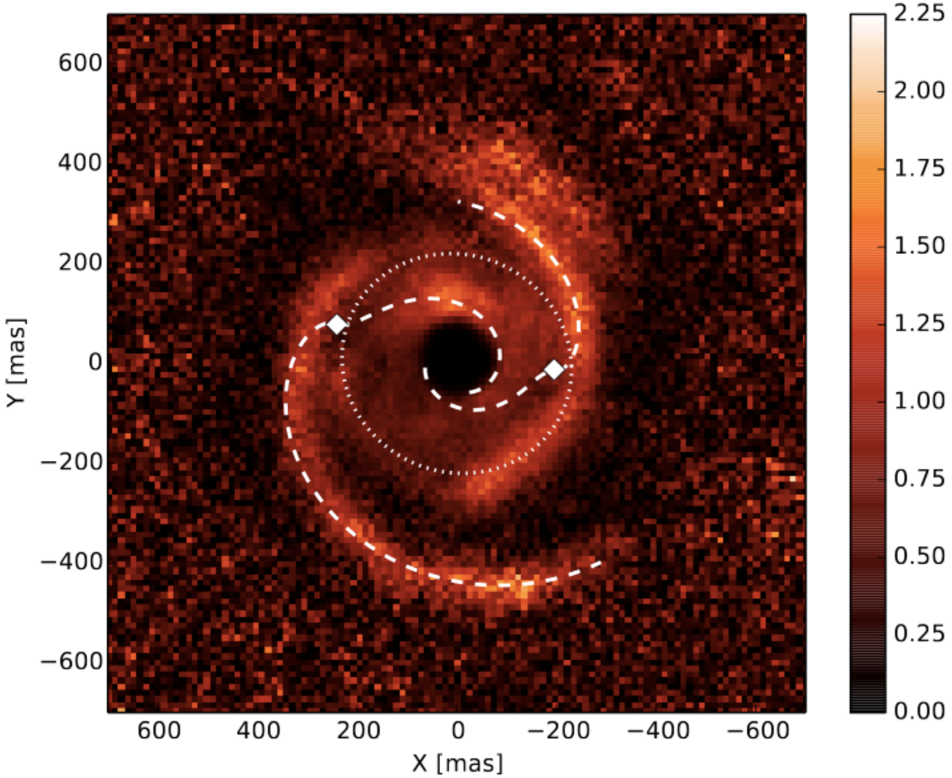
Observational Evidence: Spirals

SAO 206462



Muto et al. (2012)

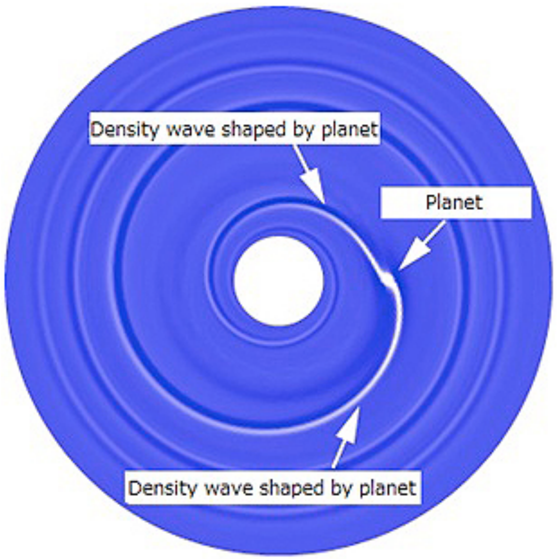
MWC 748



Benisty et al. (2015)

Spiral arm fitting leads to problems

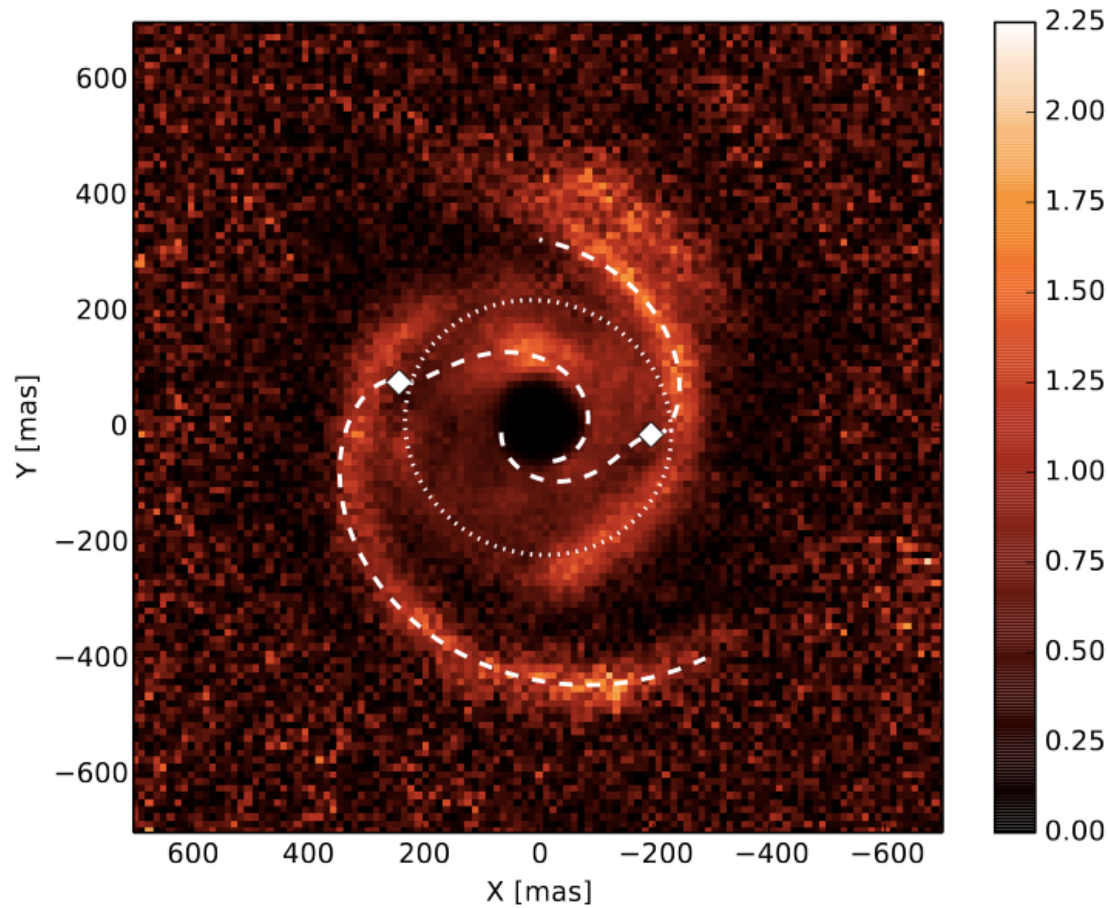
Analytical spiral fit



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

Rafikov (2002)
Muto et al. (2012)

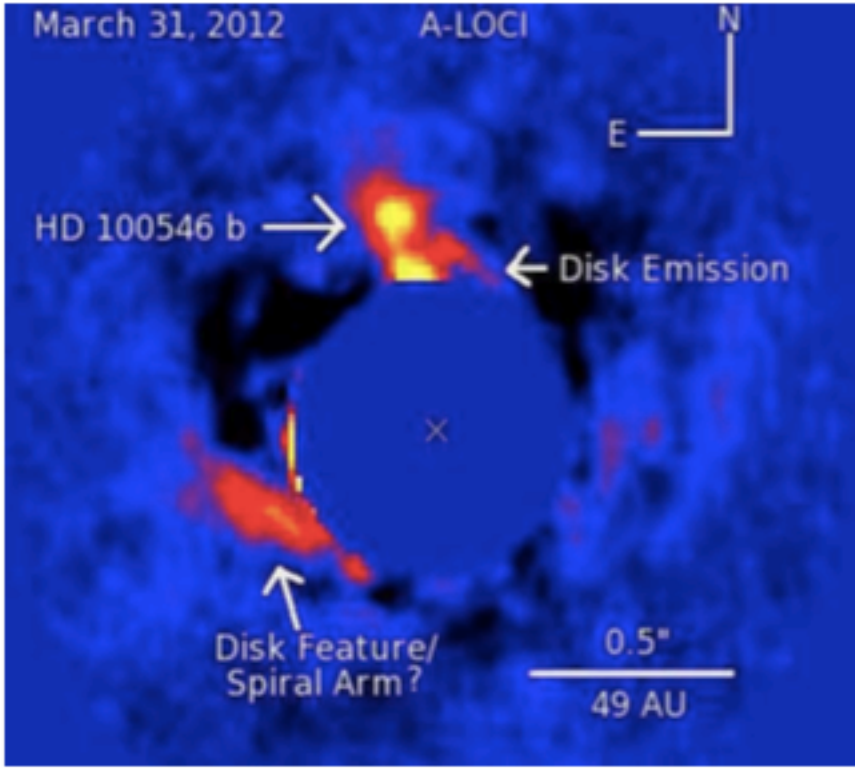
Spirals are **too wide**,
hotter (300K) than ambient gas (50K).



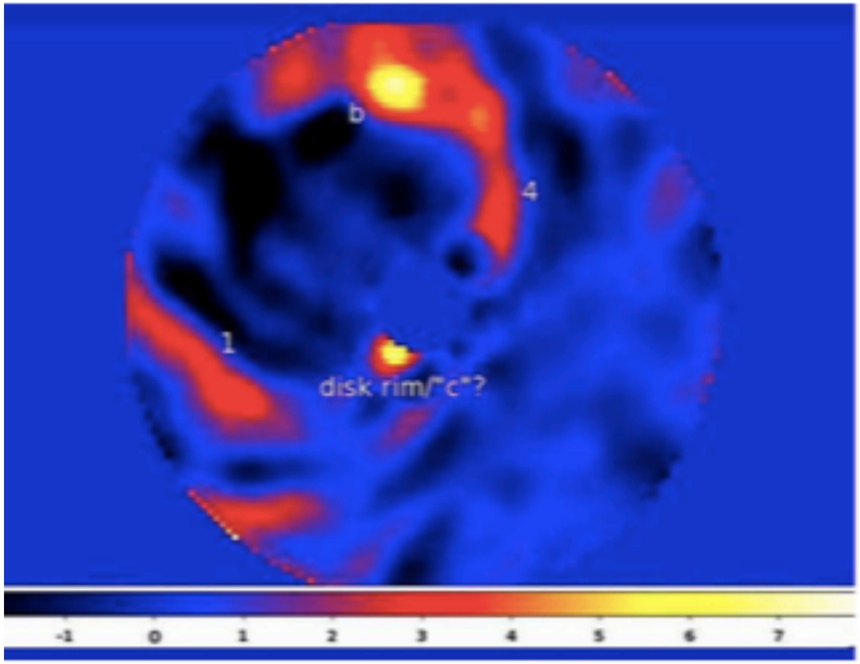
Benisty et al. (2015)

The strange case of thermal emission in HD 100546

L band (~3.5 μm)

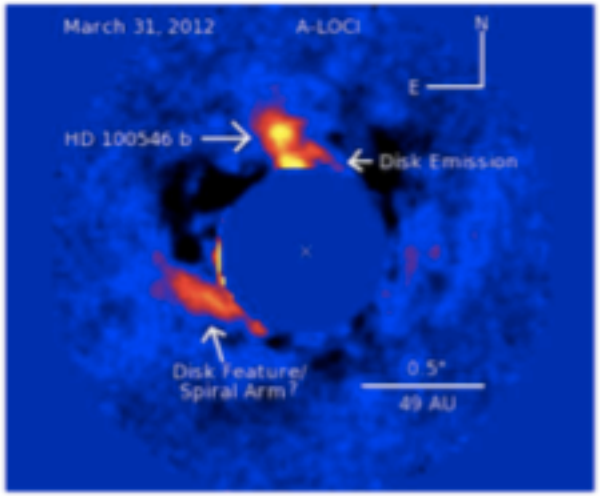


H band (~1.6 μm)

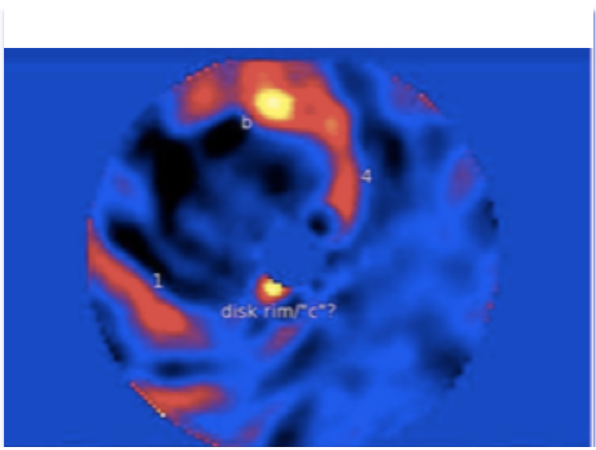


Currie et al. (2014), Currie et al. (2015)

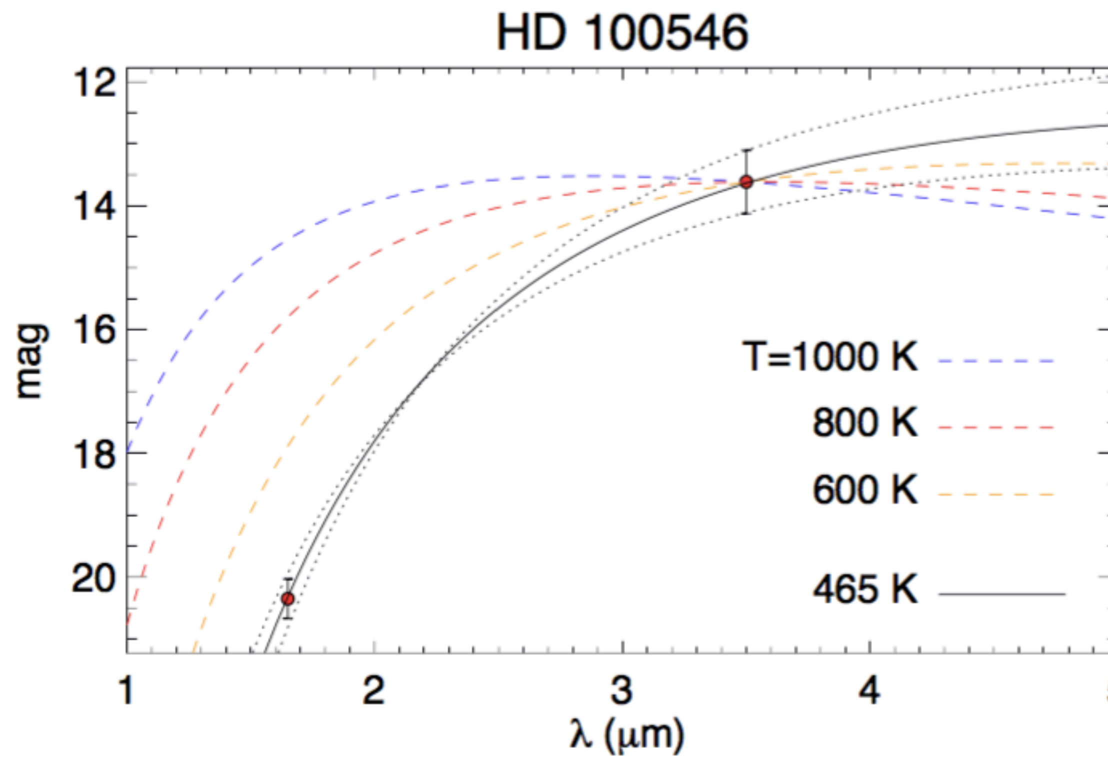
Pinning down the temperature



L band

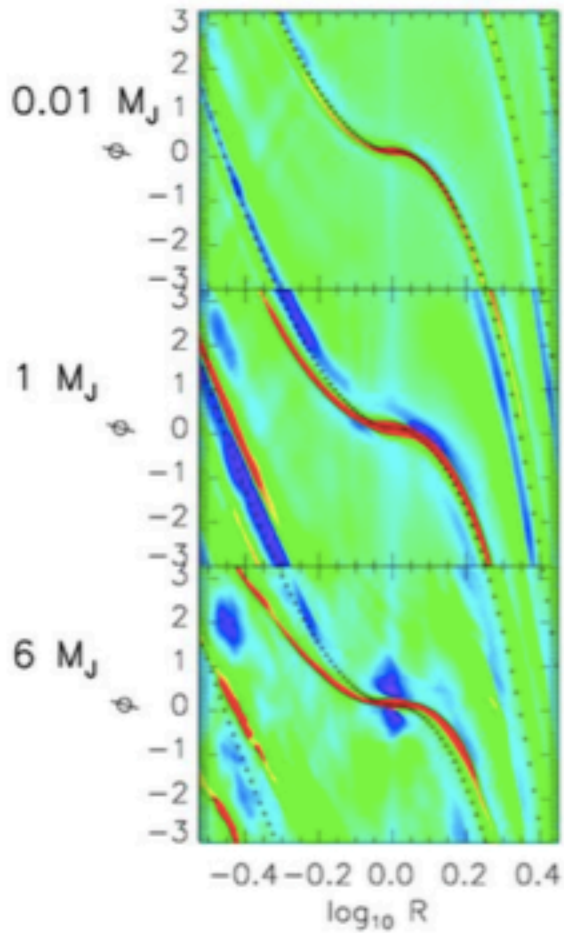


H band



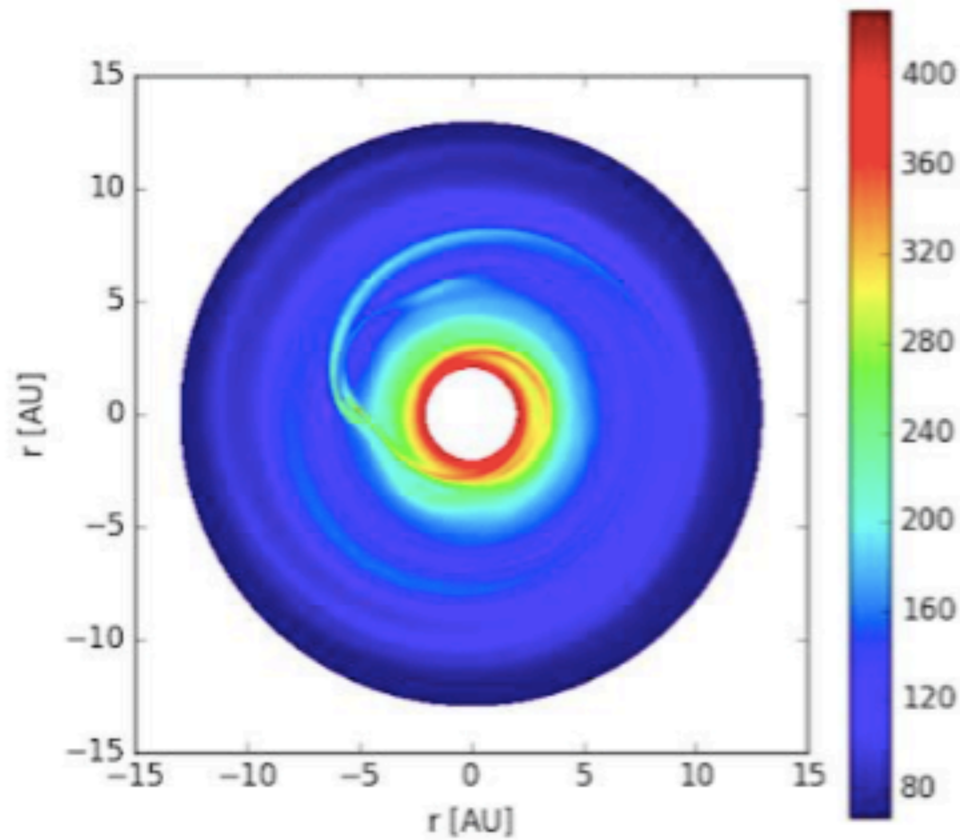
Lyra et al. (2016)

Supersonic Wakes of High Mass Planets



Density

Zhu et al. (2015)

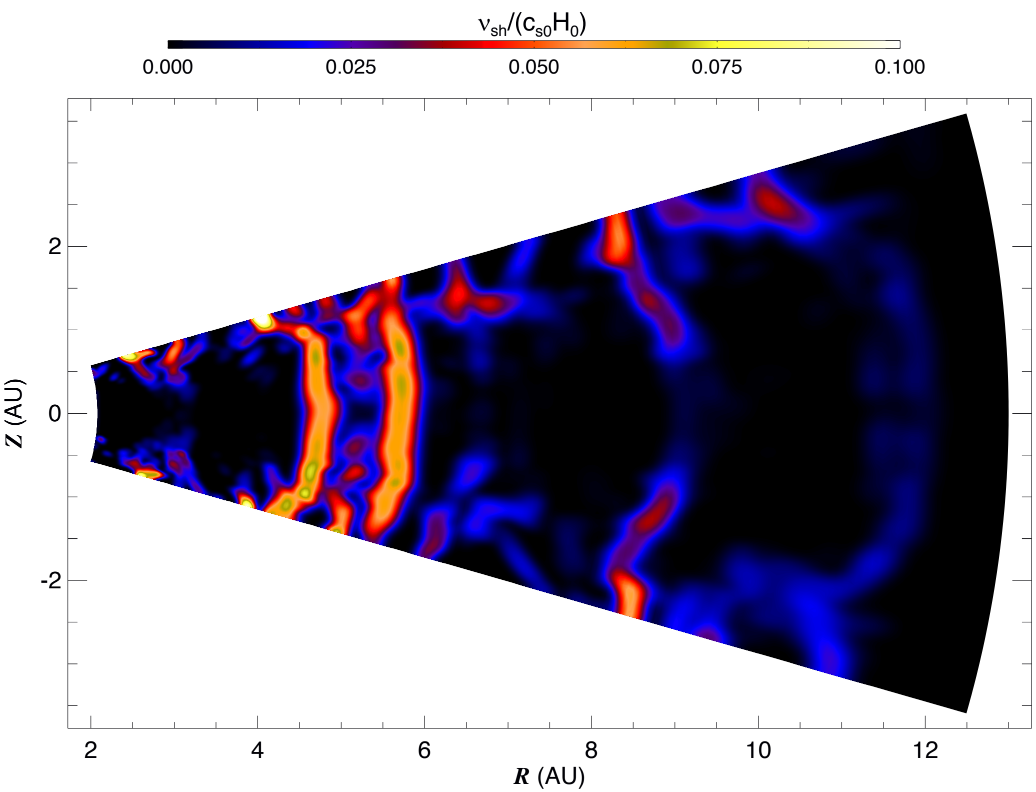


Temperature - **5M$_J$**

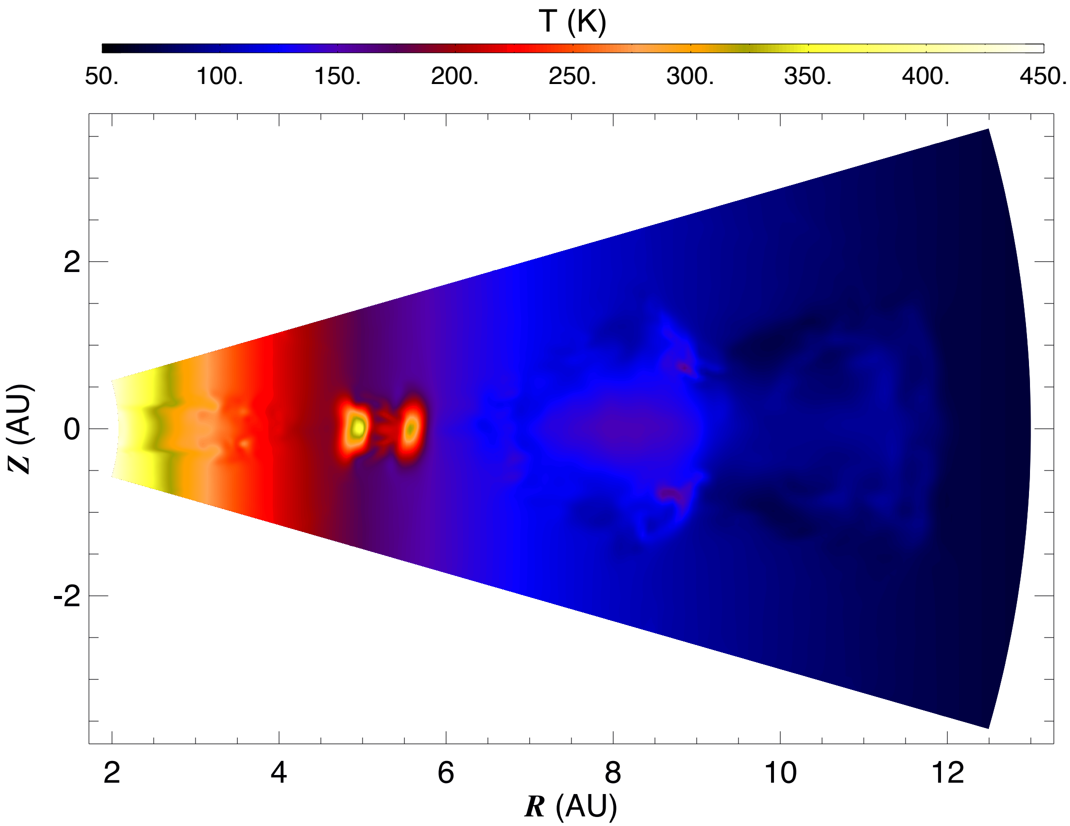
Lyra et al. (2016)

Shock bores

Shocks (velocity convergence)

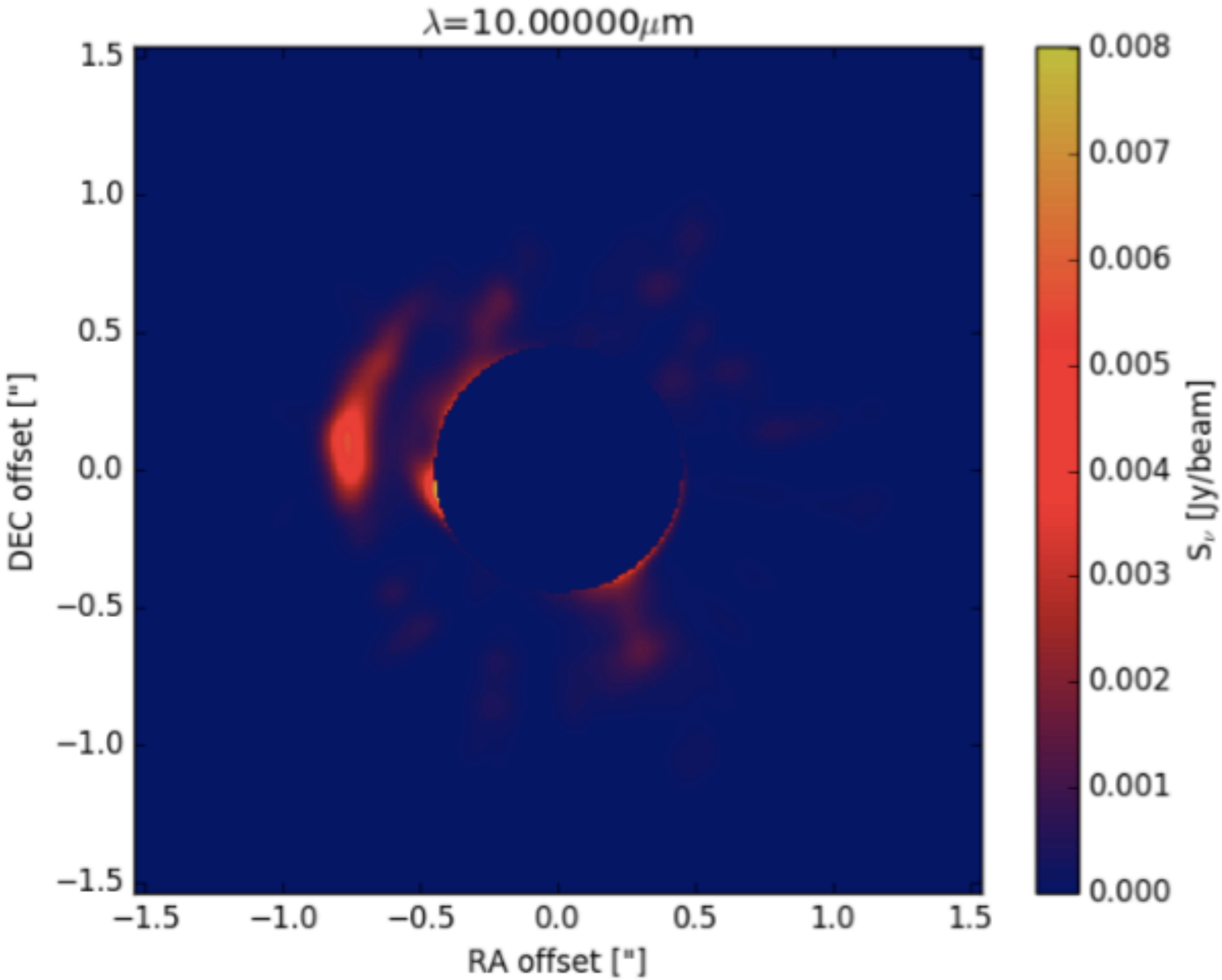


Temperature



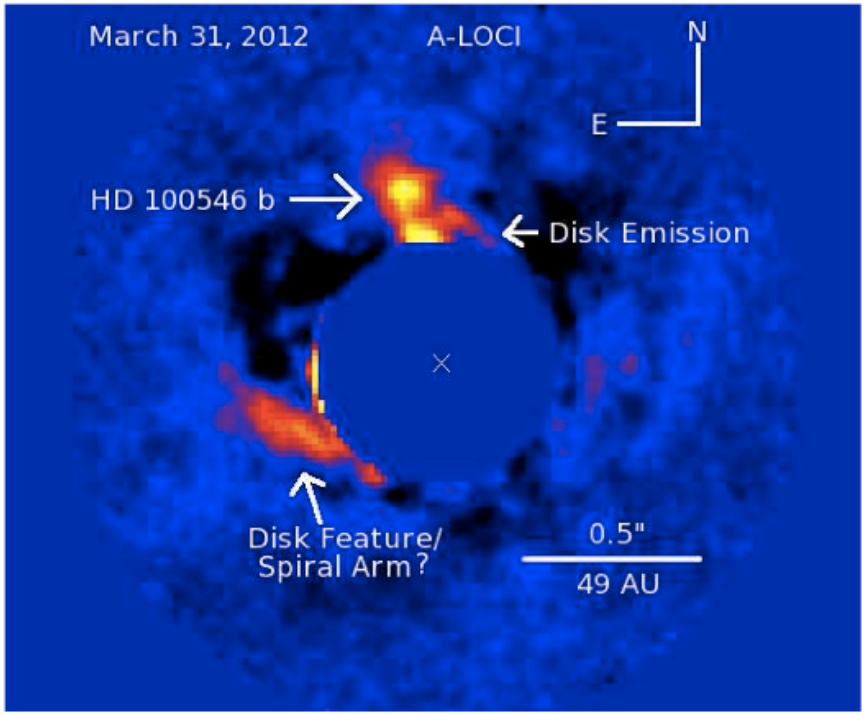
Lyra et al. (2016)

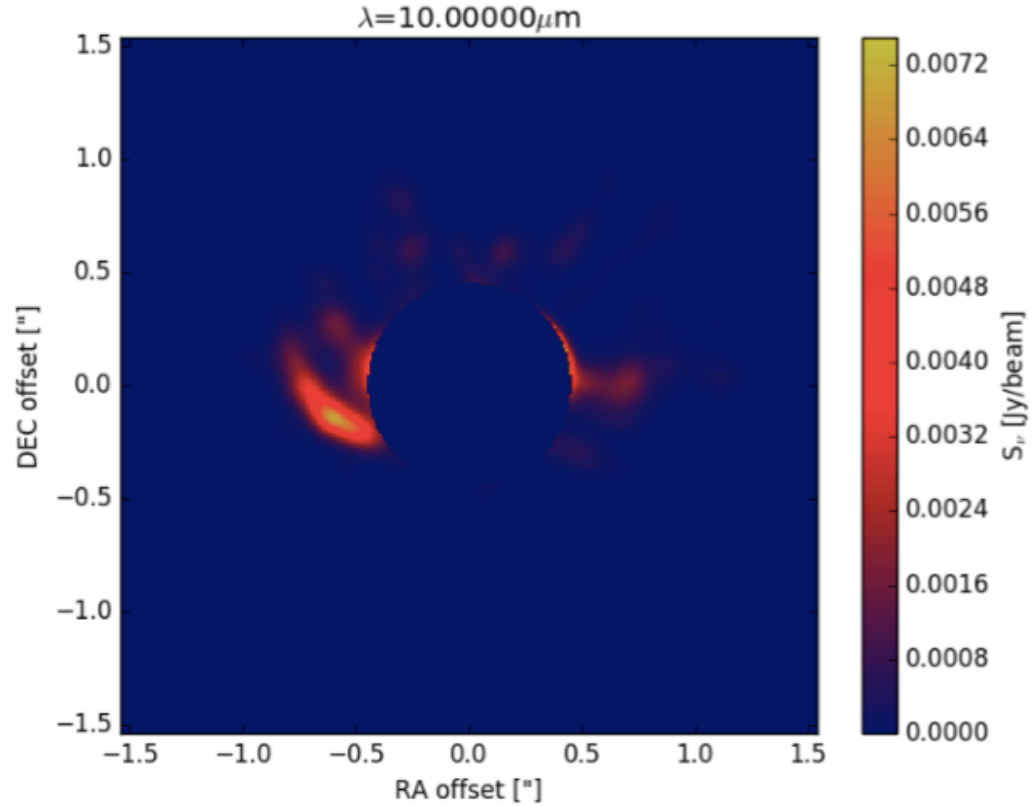
Synthetic image



Hord et al. (2017)

Observation vs Synthetic Image

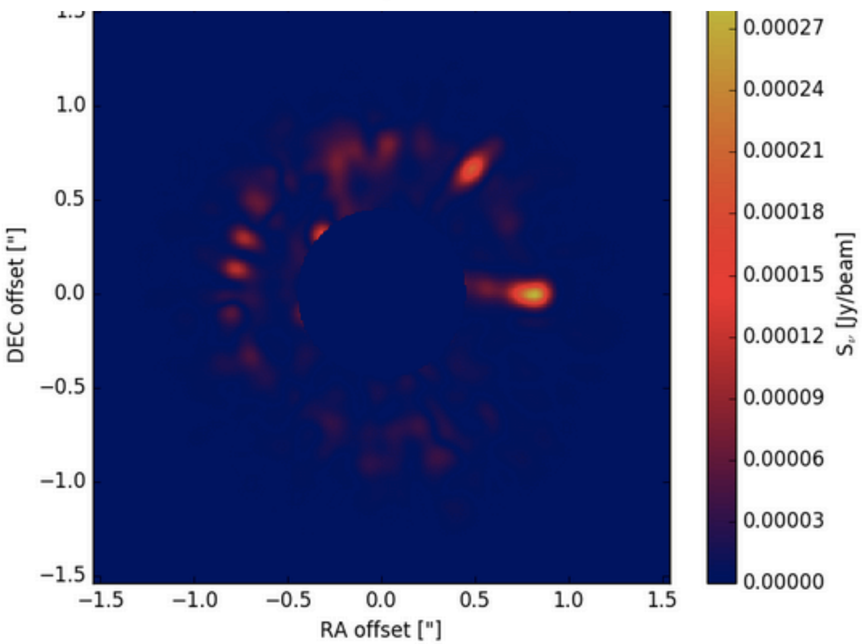




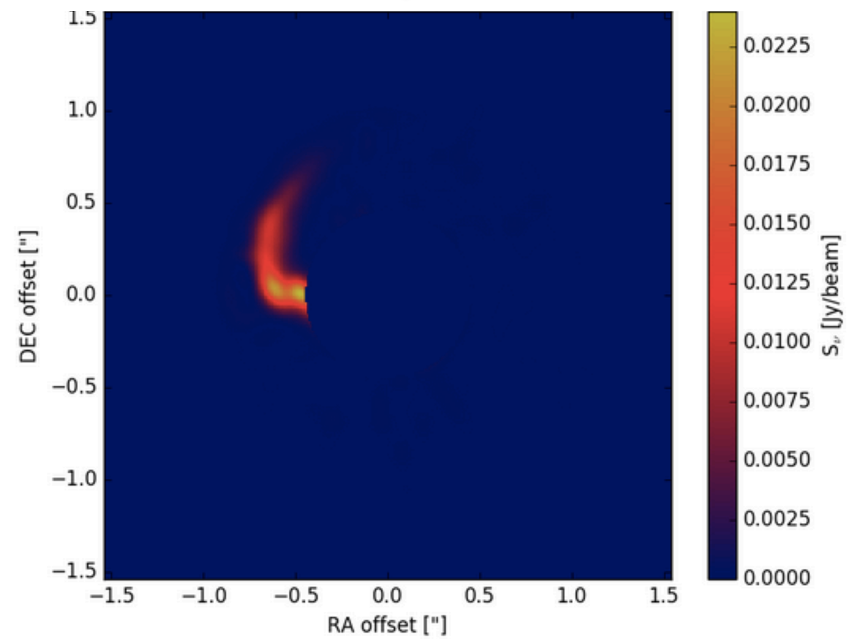
Hord et al. (2017)

Effect of shocks alone

1 μm

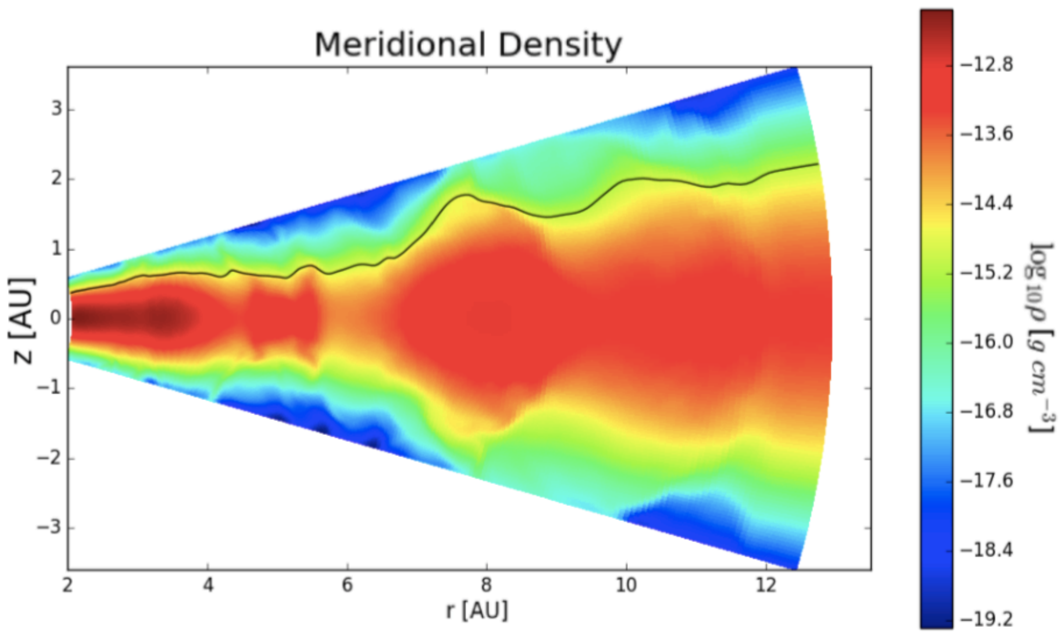


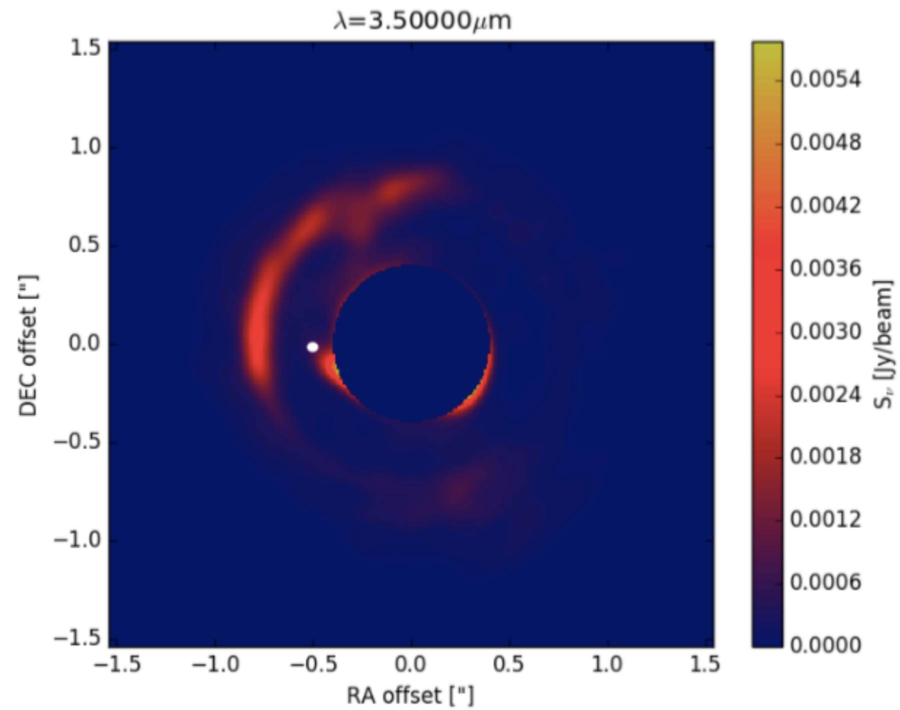
10 μm



Hord et al. (2017)

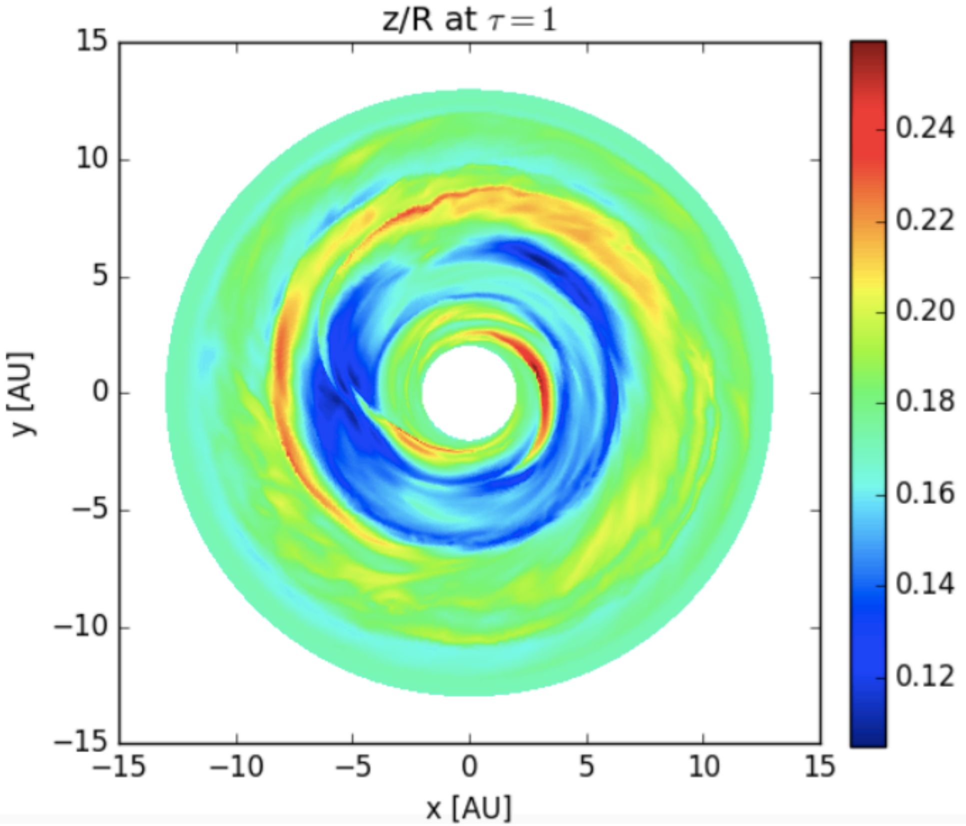
Scattering – A puffed up outer gap

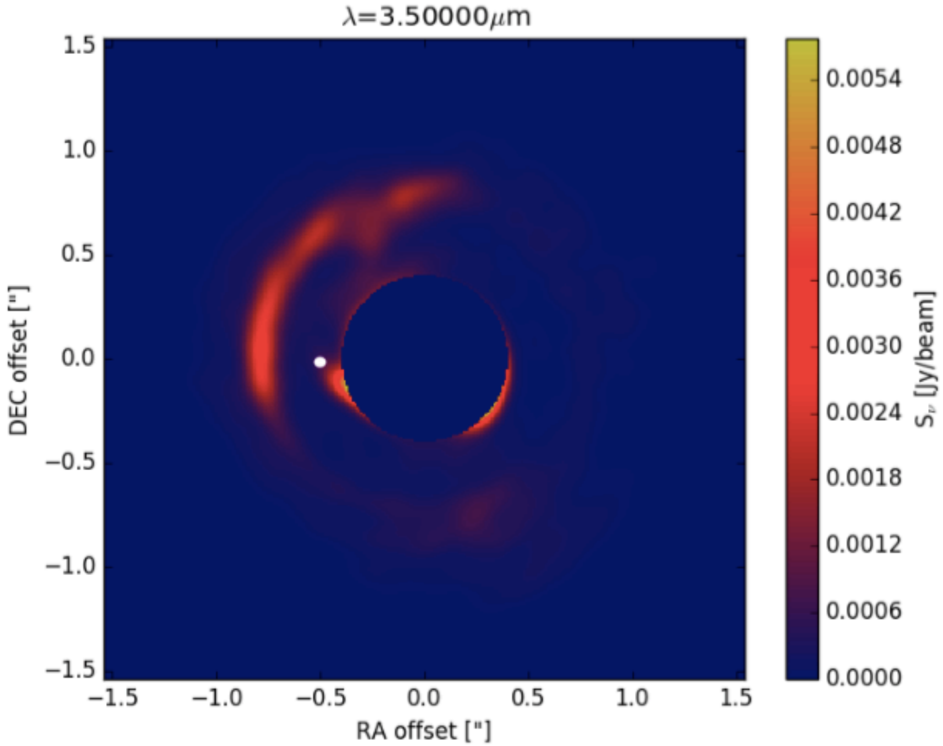




Hord et al. (2017)

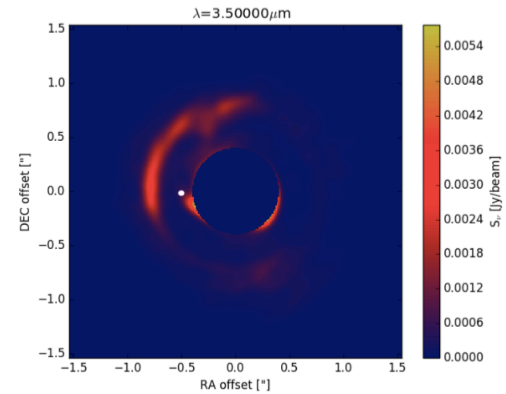
Scattering

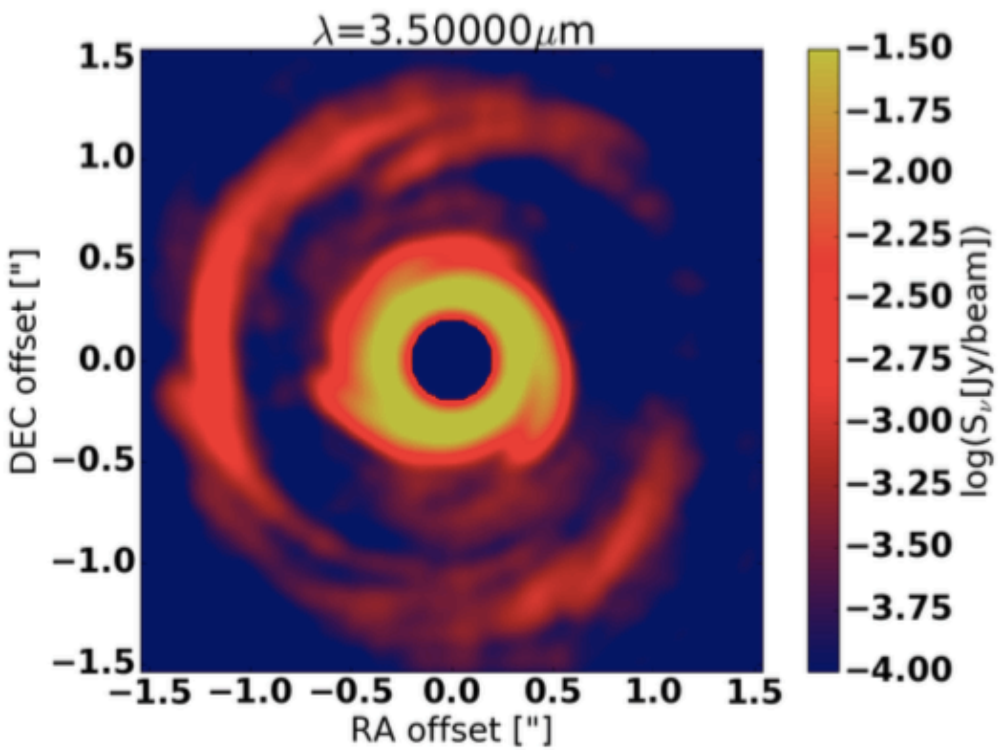


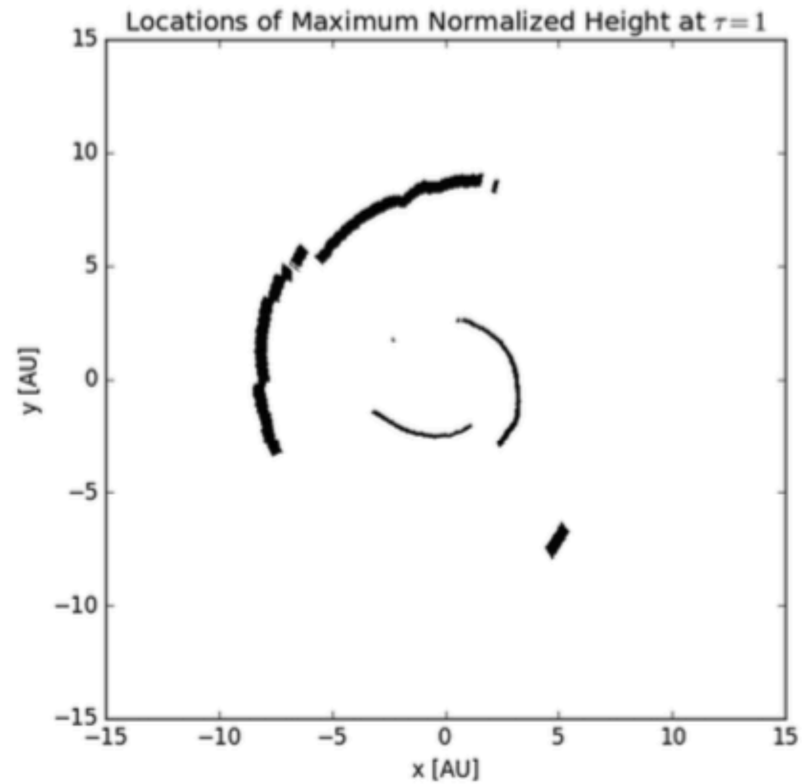


Hord et al. (2017)

We see what is not in the shadow of the inner disk spirals





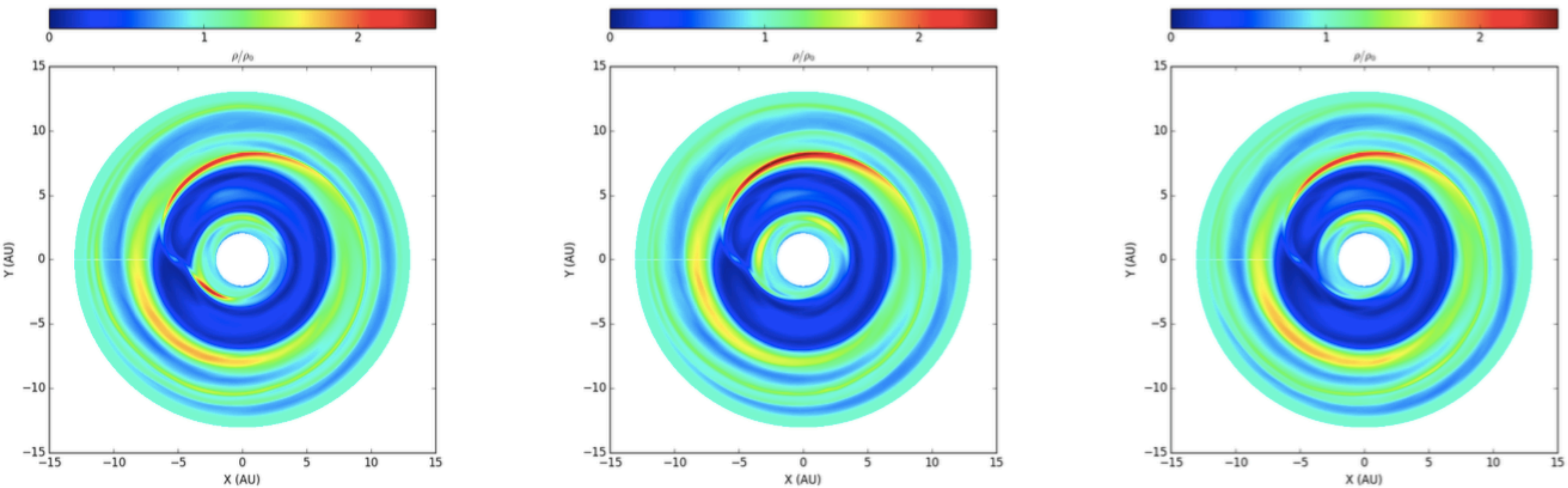


Hord et al. (2017)

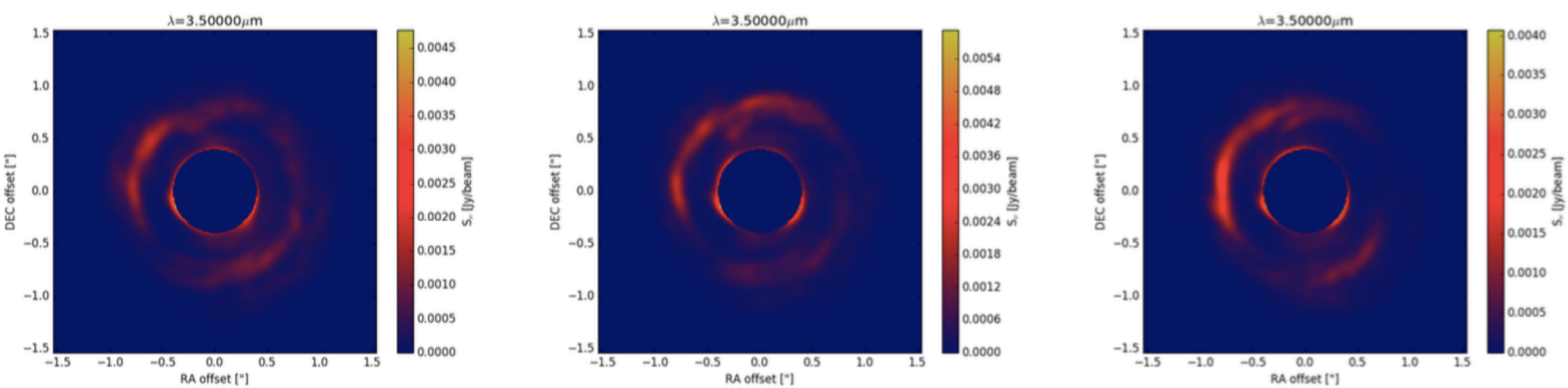
The pattern is stationary

T = 39 orbits | T = 40 orbits | T = 41 orbits

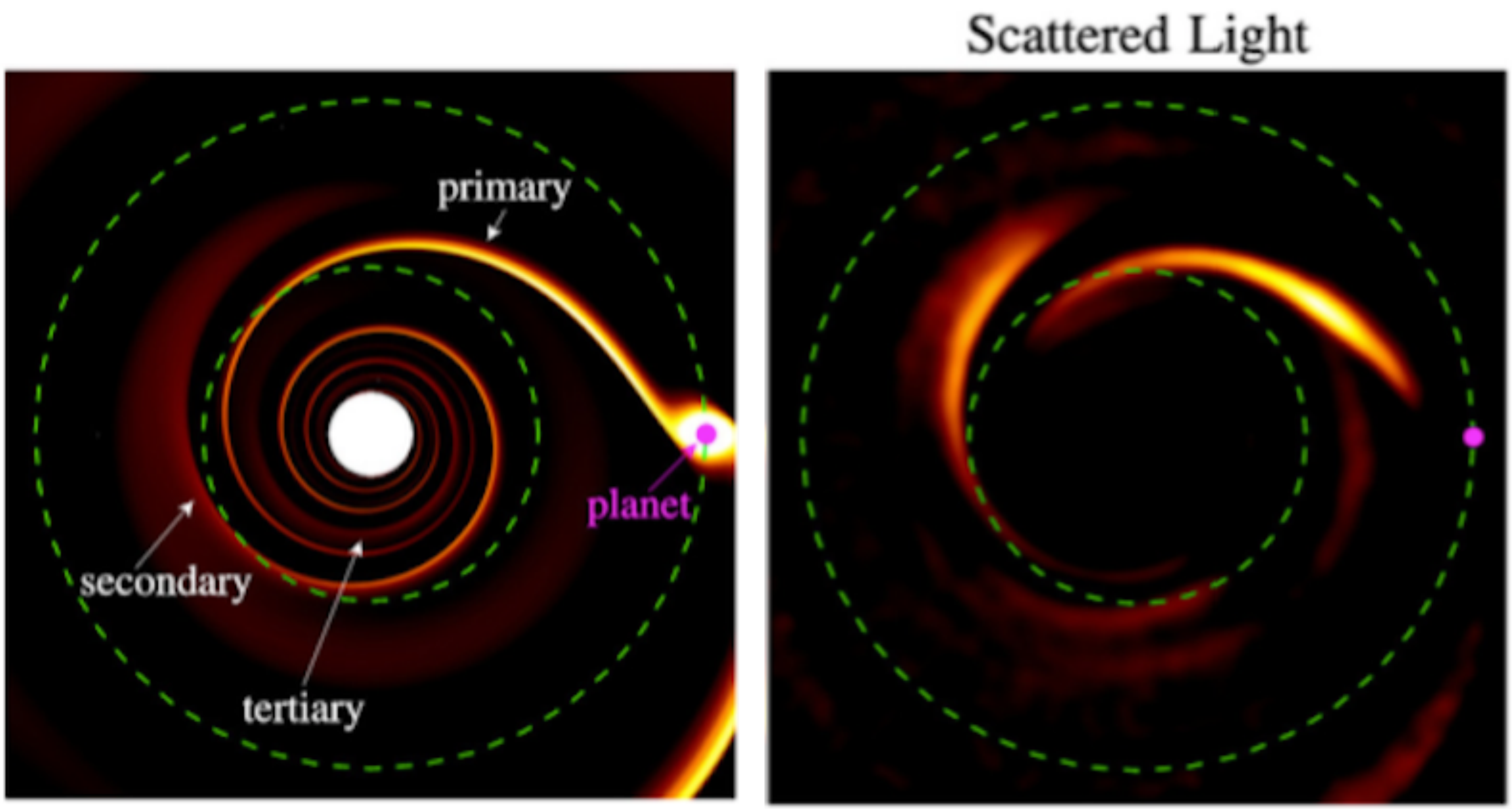
Density



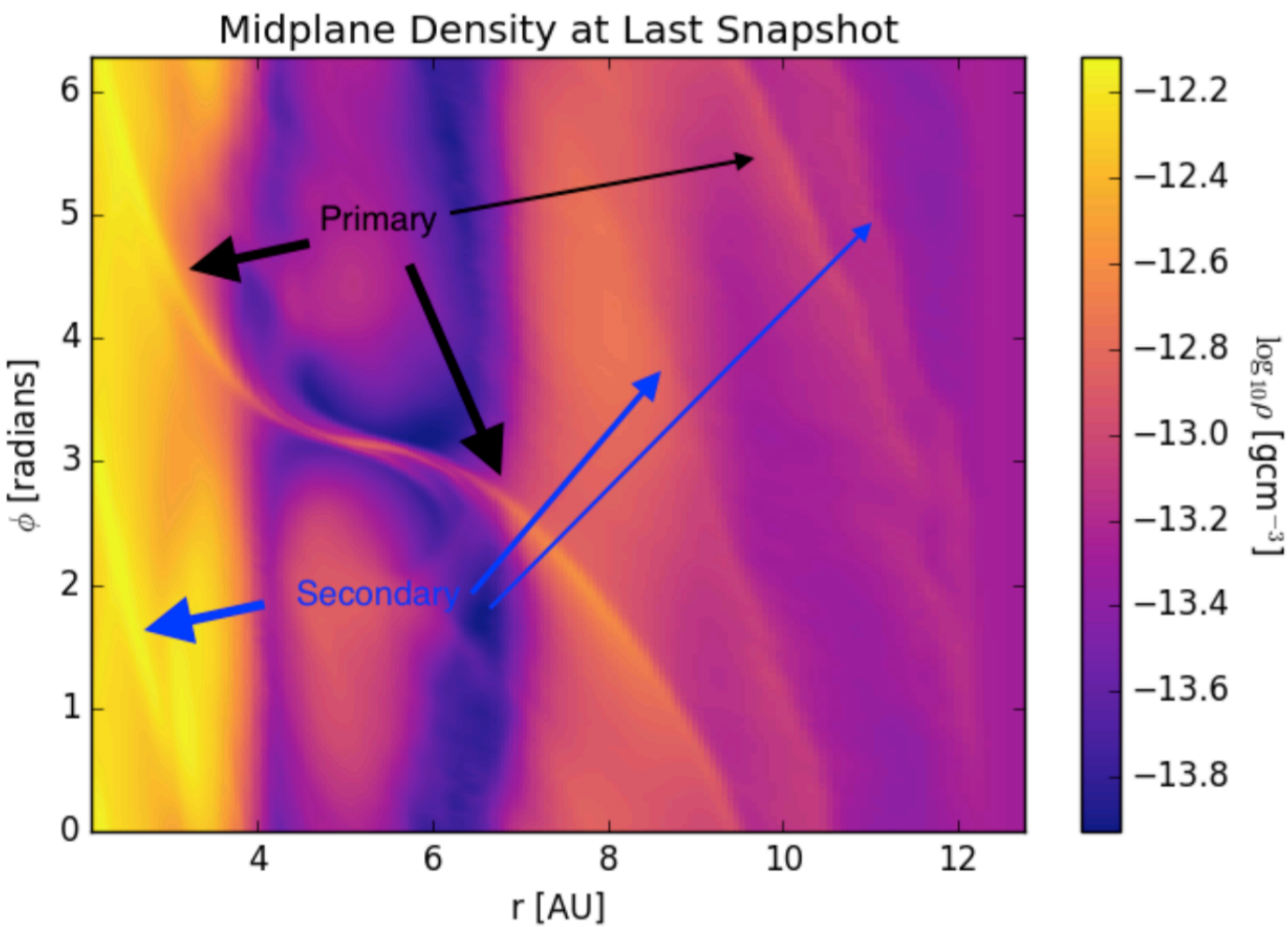
Intensity



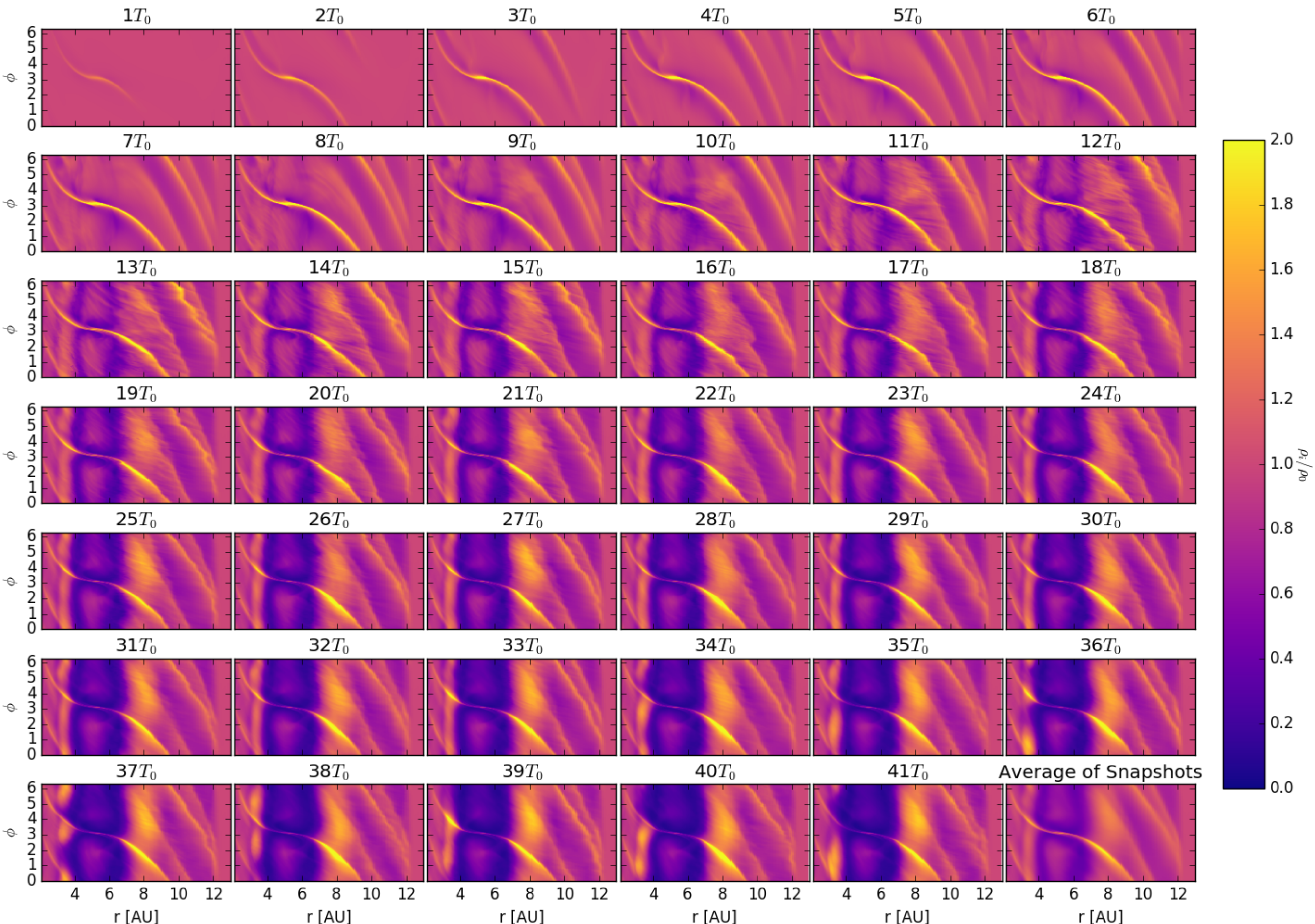
Primary and Secondary spiral arms



Primary and Secondary spiral arms

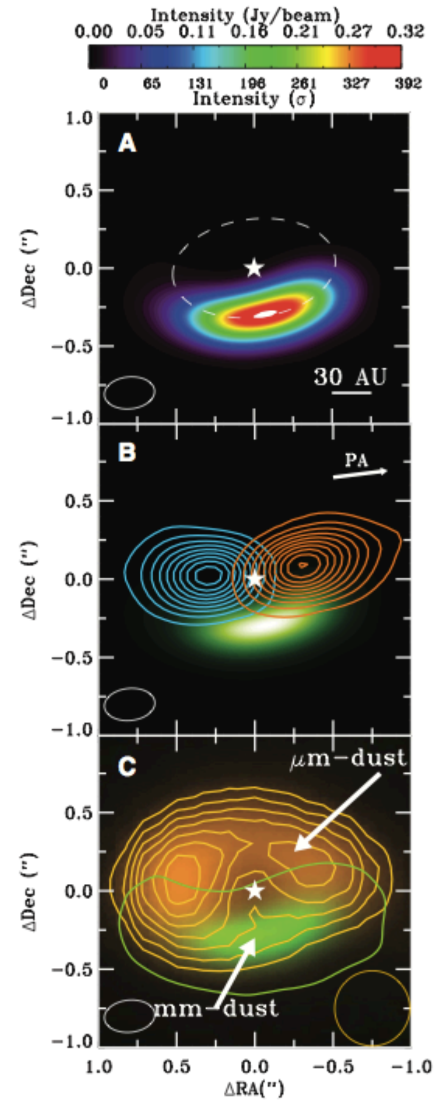


The raised feature has its origins in a secondary spiral arm



Conclusions

- Disk vortices are a prime location for planet formation
  - Tea leaf effect
- Dust trapped in drag-diffusion equilibrium exp observations
- Hydrodynamical instabilities vs planet excitati
  - Vertical Shear Instability
    - *Vertical violation of Solberg-Hoiland criteri*
  - Convective Overstability
    - *Amplification of epicyclic motion by buoyan*
  - Zombie Vortex Instability
    - *Resonance between epicyclic and buyoancy*
- Hot lobes next to high mass planets at high res
- Planets puff up their outer gap edges – visible



Conclusions

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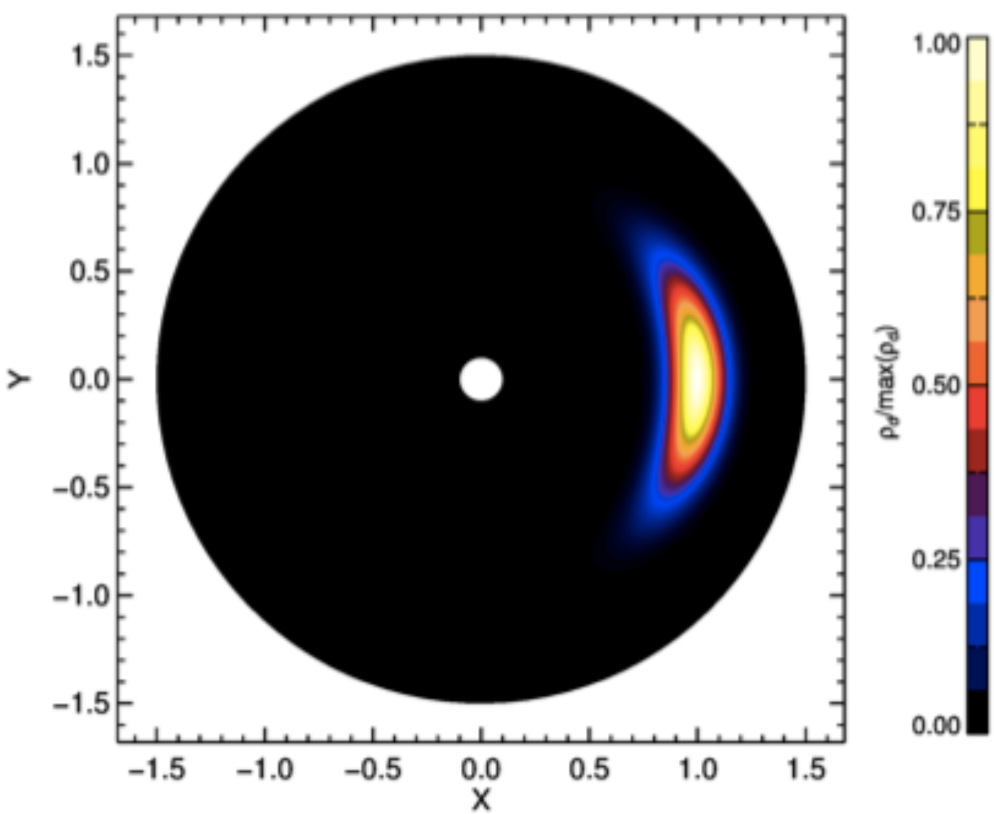
  - Tea leaf effect

- Dust trapped in drag-diffusion equilibrium explains the observations



xcitation mechanism:

criterion

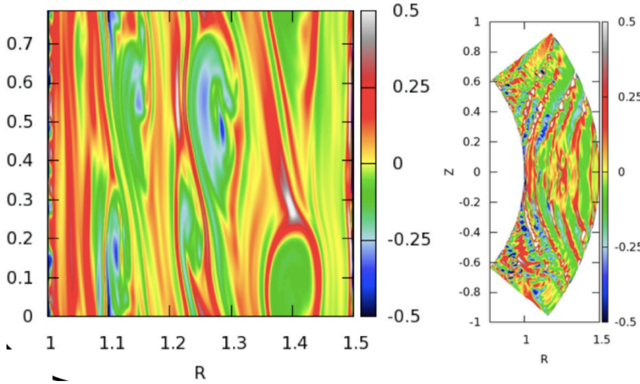
uoyancy

oancy frequency

gh resolution

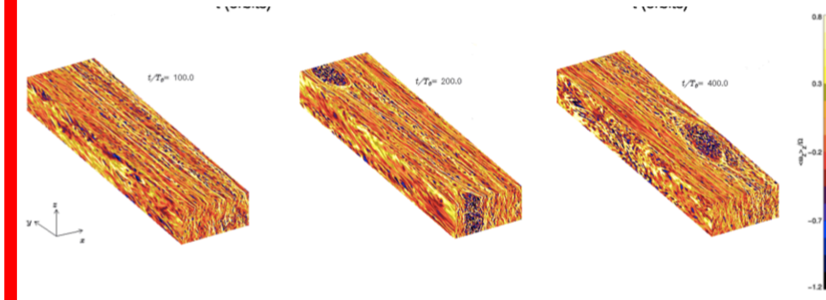
sible in scattered light

Vertical Shear Instability



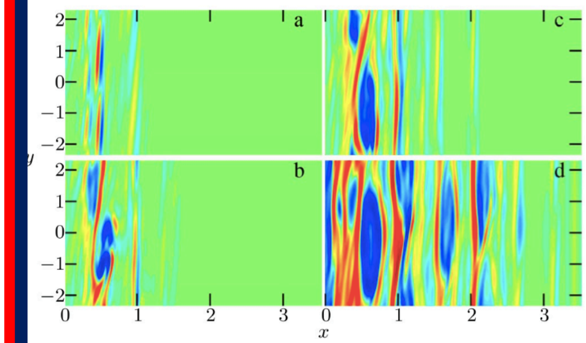
Nelson et al. 2013, Lin & Youdin 2015, Umurhan et al. 2016

Convective Overstability



Klahr 2003, Lesur & Papaloizou 2010, Lyra & Klahr 2011, Lyra 2014

Zombie Vortex Instability



Marcus et al. 2012, 2013, 2015, 2016
Umurhan et al 2016, Lesur & Latter 2016

- Hydrodynamical instabilities vs planet excitation mechanism:
  - Vertical Shear Instability
    - *Vertical violation of Solberg-Hoiland criterion*
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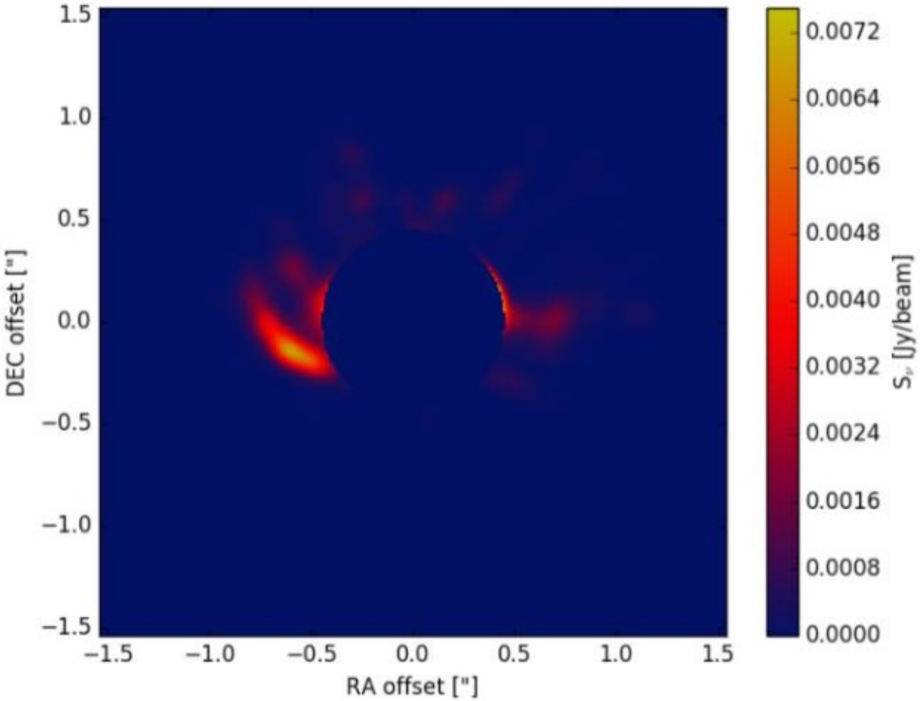

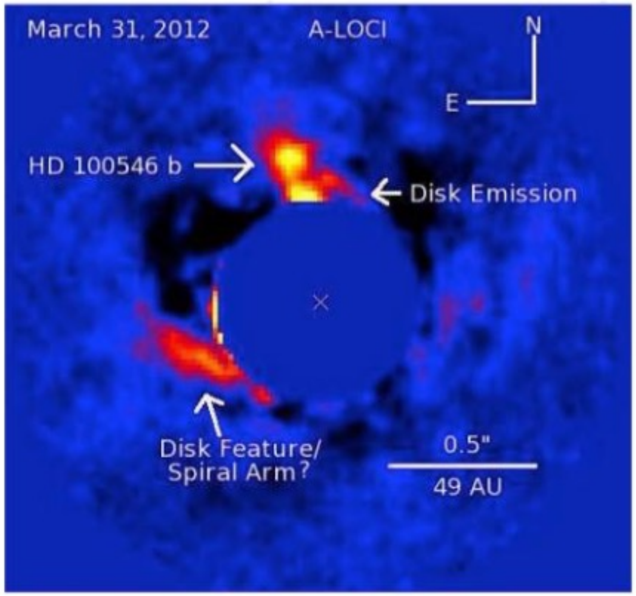

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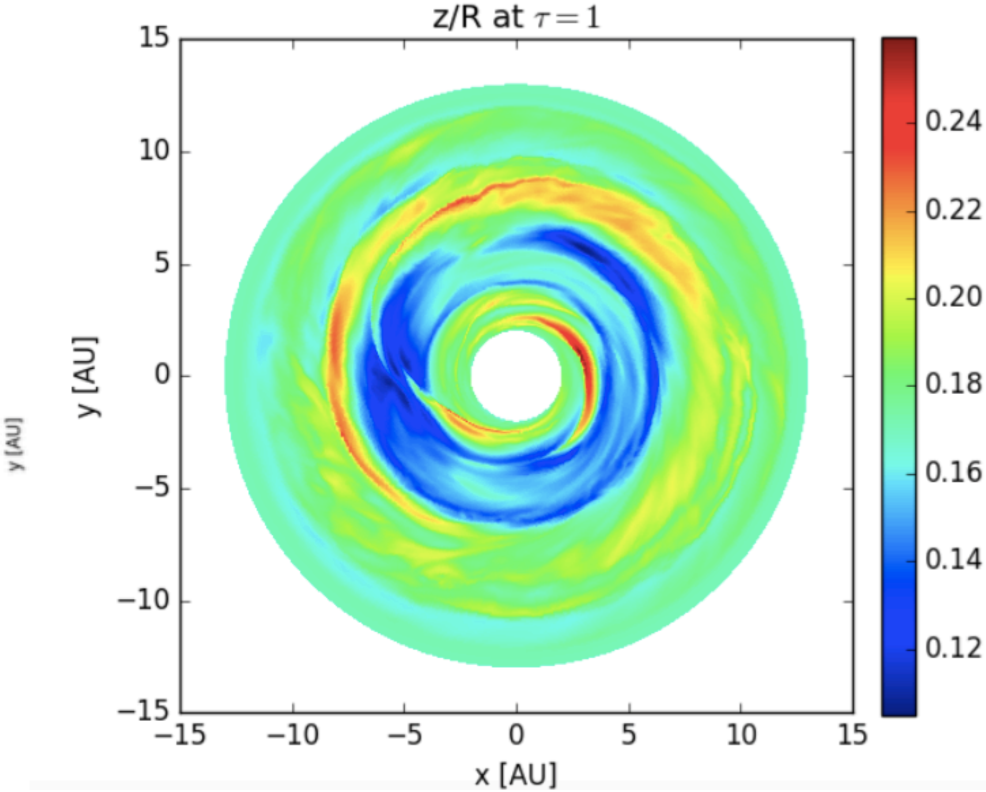

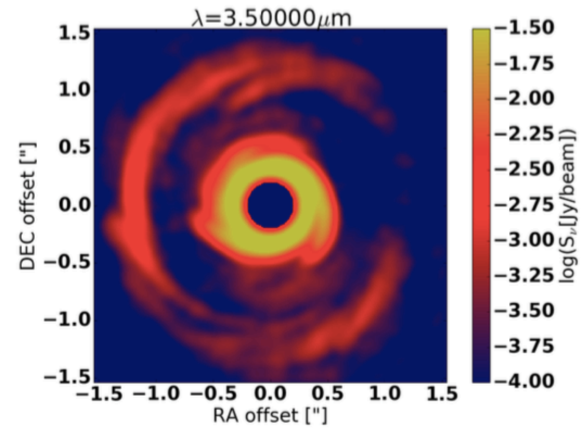

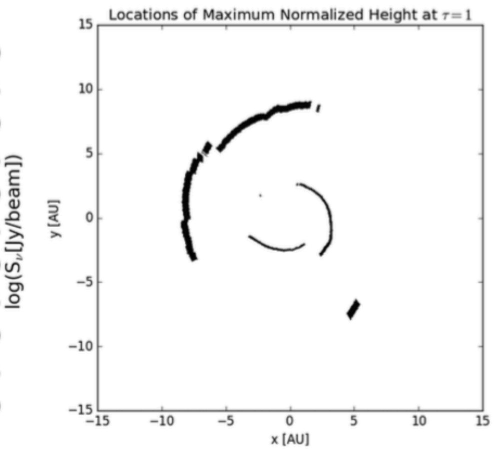

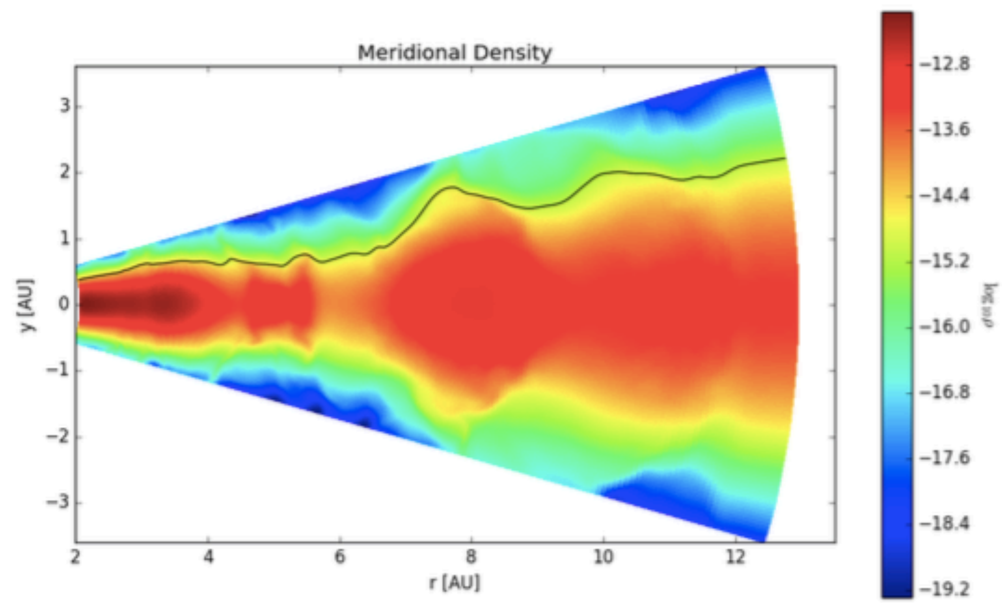

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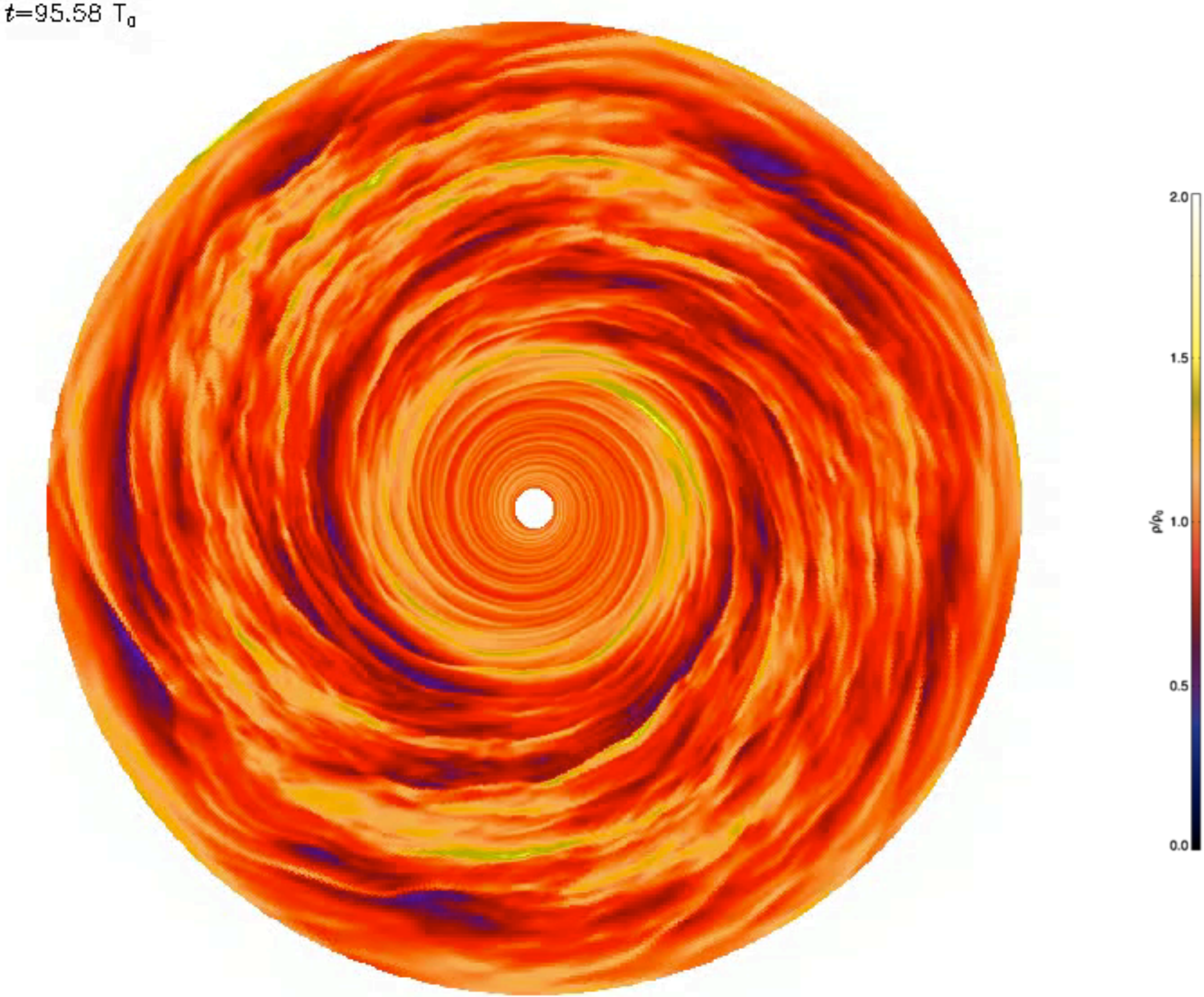
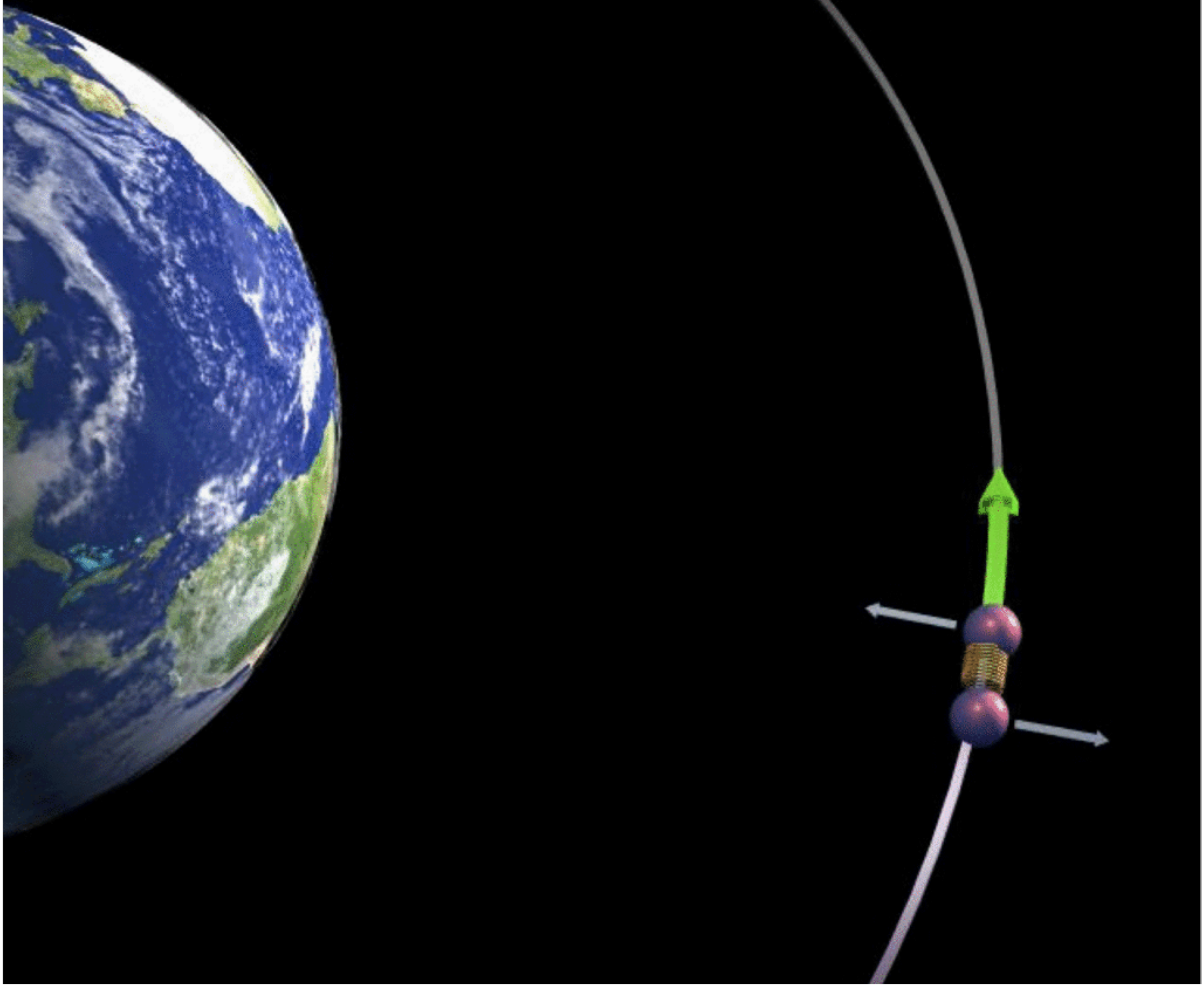
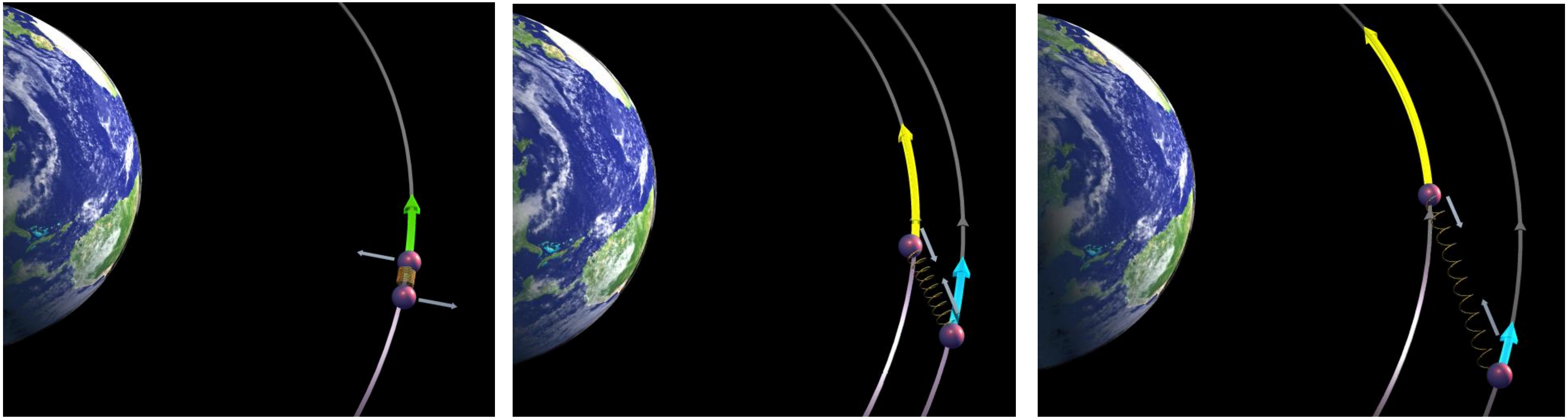

t=95.58 T0
2.0
1.5
1.0
0.5
0.0
ρ/ρ0



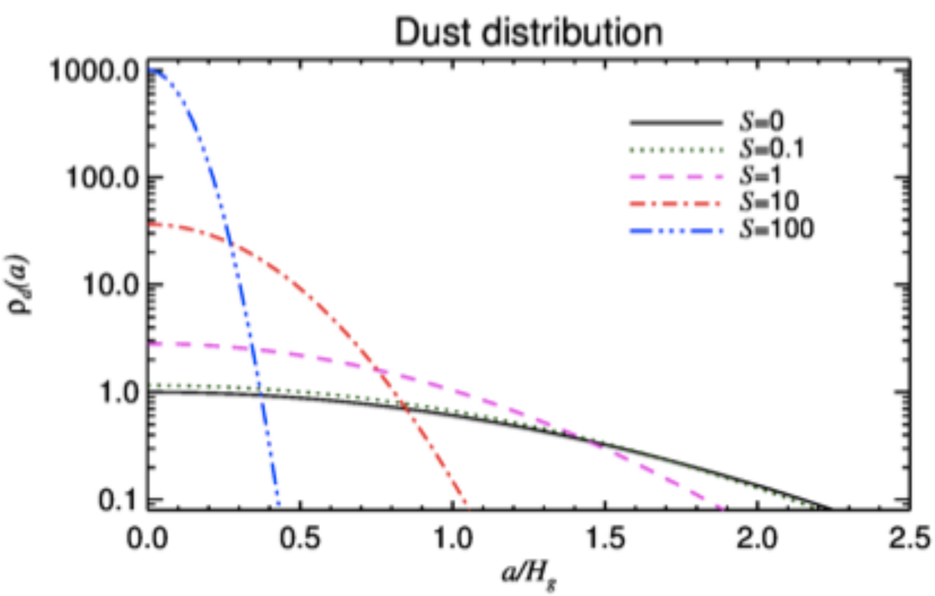
Stretching builds up tension

Tension resists shear



Beads exchange angular momentum

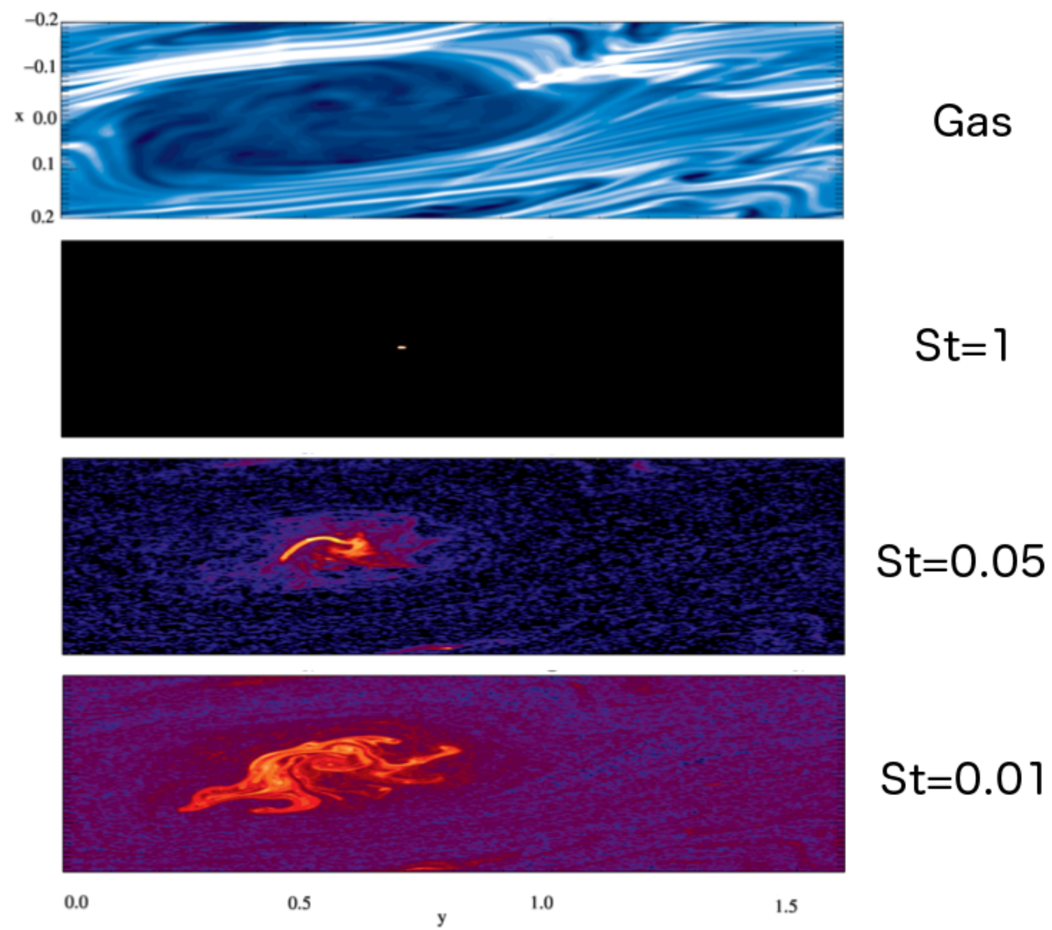
Analytical vs Numerical



$$S = \mathrm{St}/\delta$$

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

Lyra & Lin (2013)



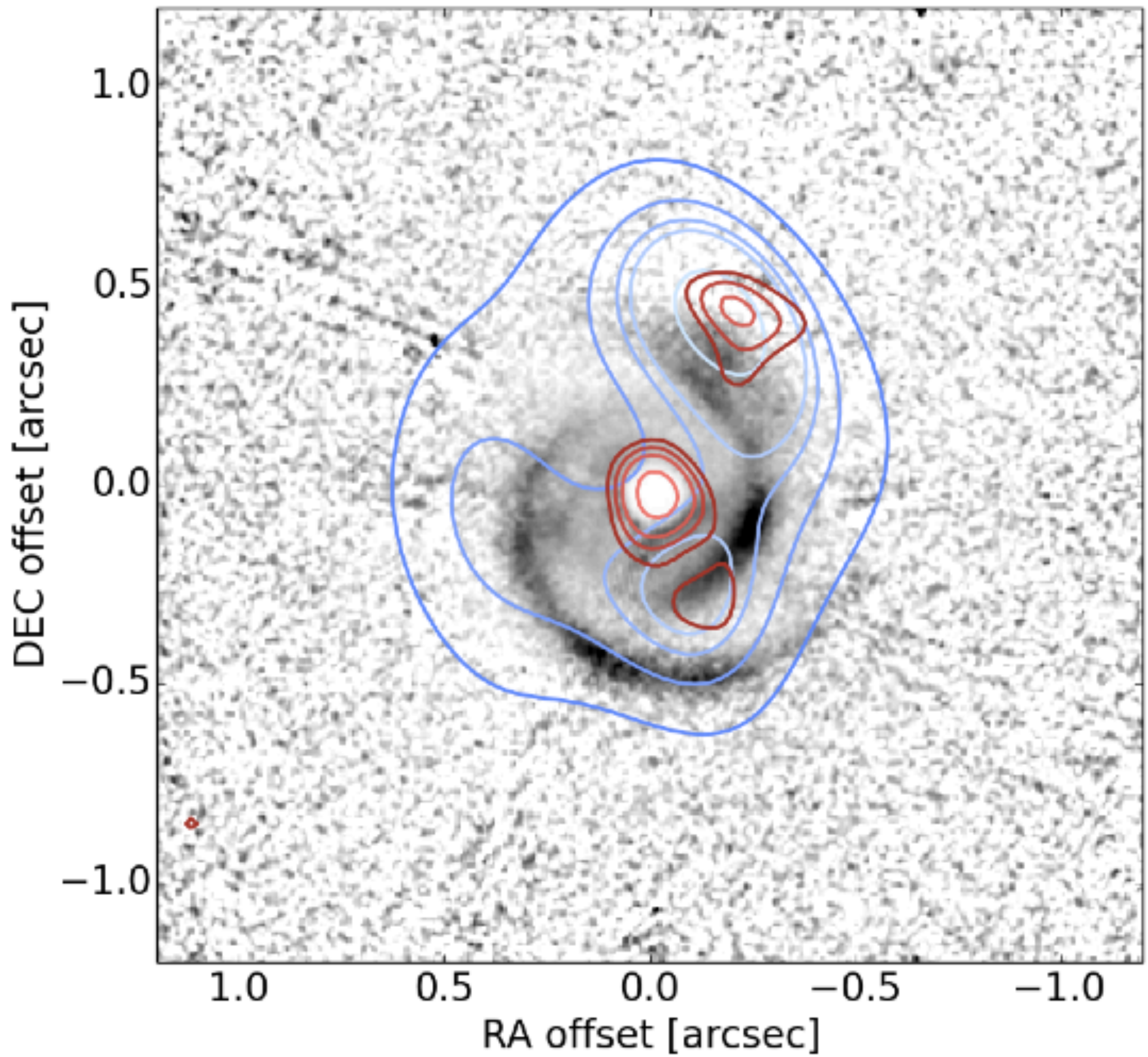
Raettig et al (2015)

SPHERE-ALMA-VLA overlay of MWC 758

SPHERE (μm)

ALMA (~ mm)

VLA (cm-m)



Marino et al. (2015)