Planet Signatures in Transition Disks

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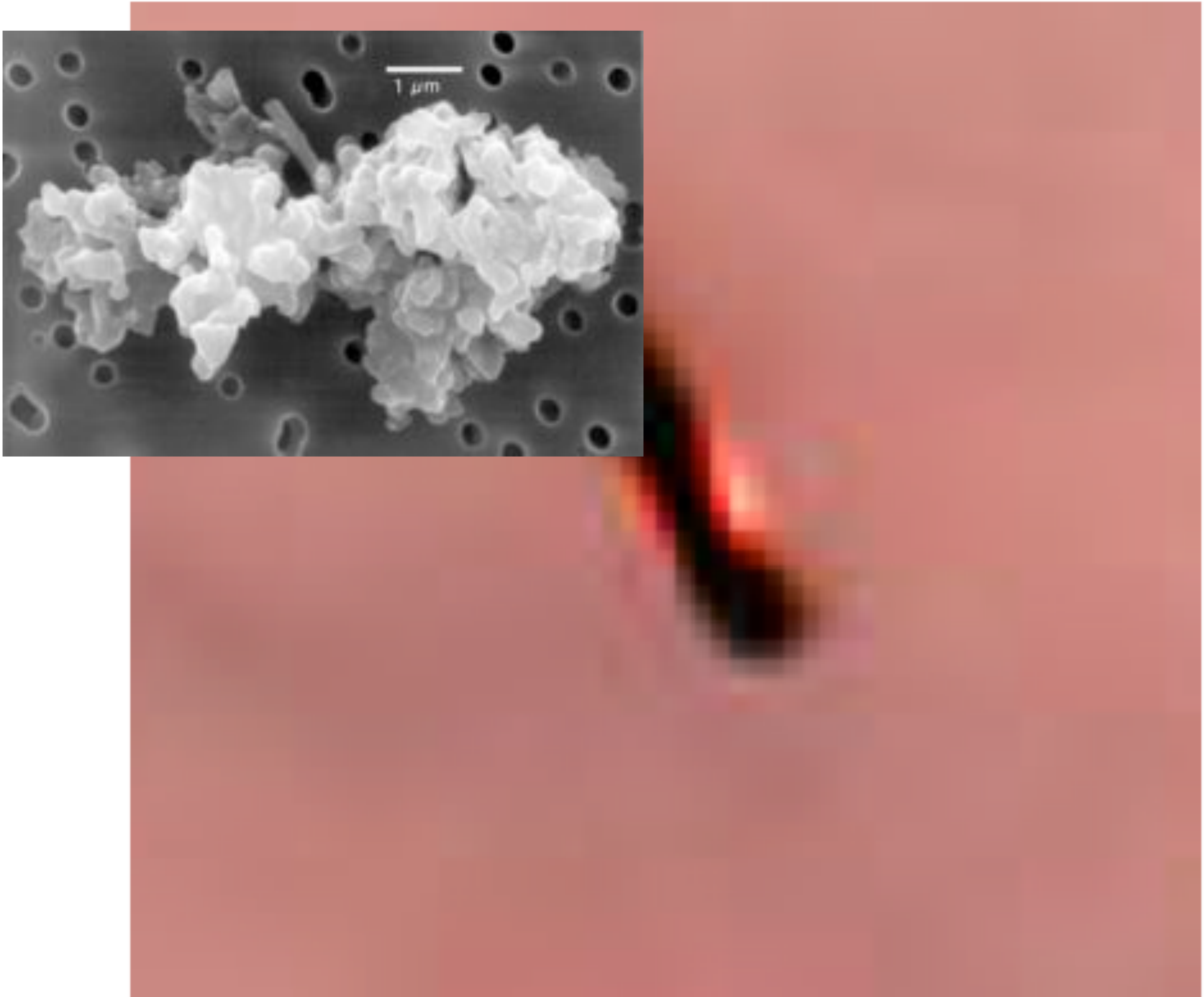
Santiago, Jan 3rd, 2017


1 μm

Protoplanetary Disks

PP disk fact sheet

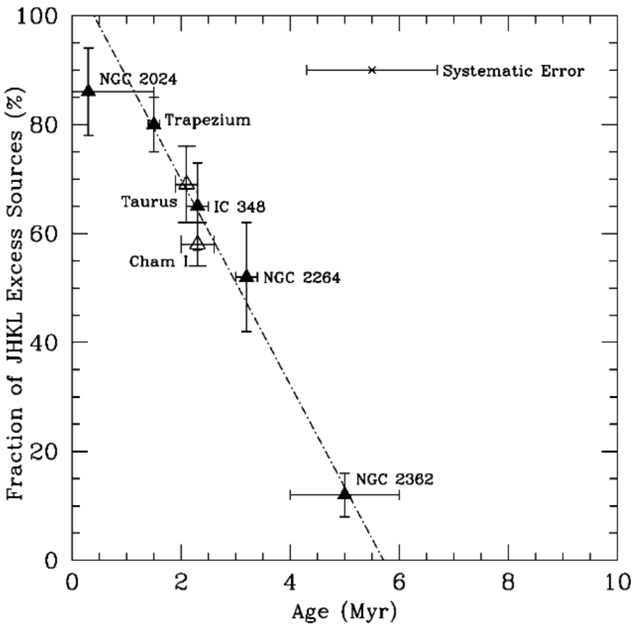
Density: $10^{13} - 10^{15}$ cm^{-3}
(Air: 10^{21} cm^{-3})

Temperature: 10-1000 K

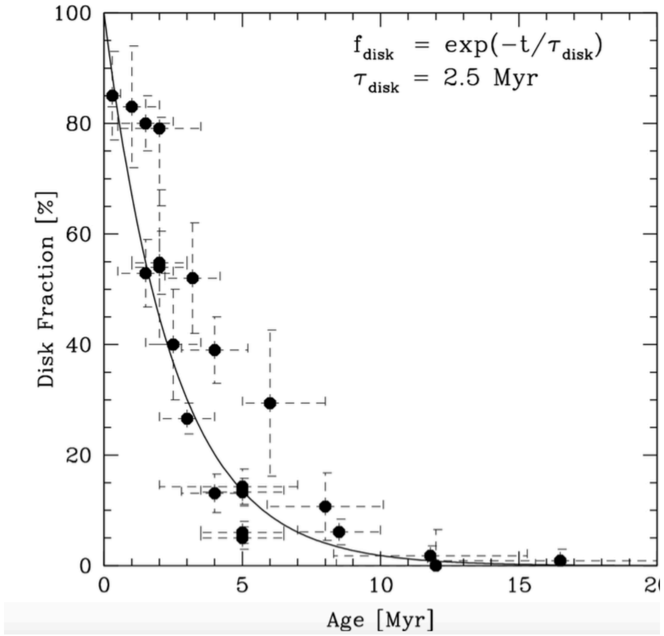
Scale: 0.1-100AU
(1 AU = 1.49×10^{13} cm)

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

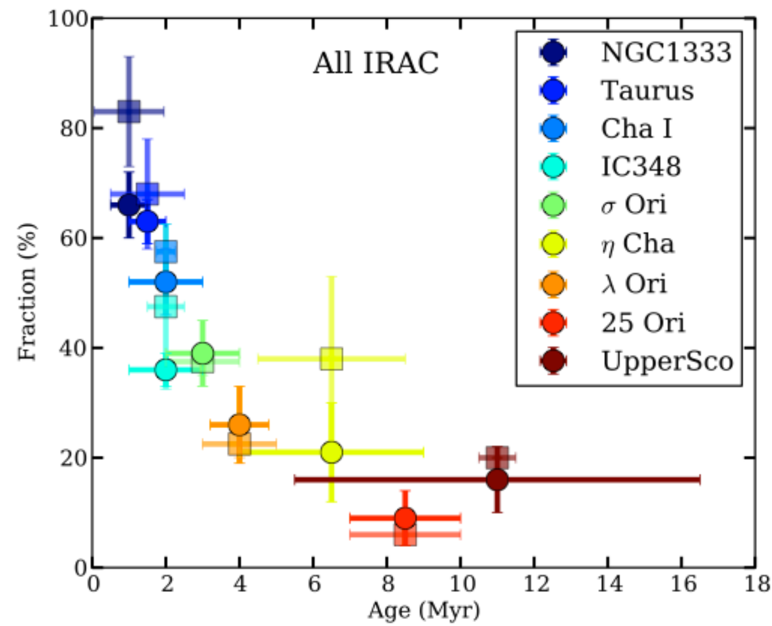
Disk lifetime



(Haisch et al. 2001)



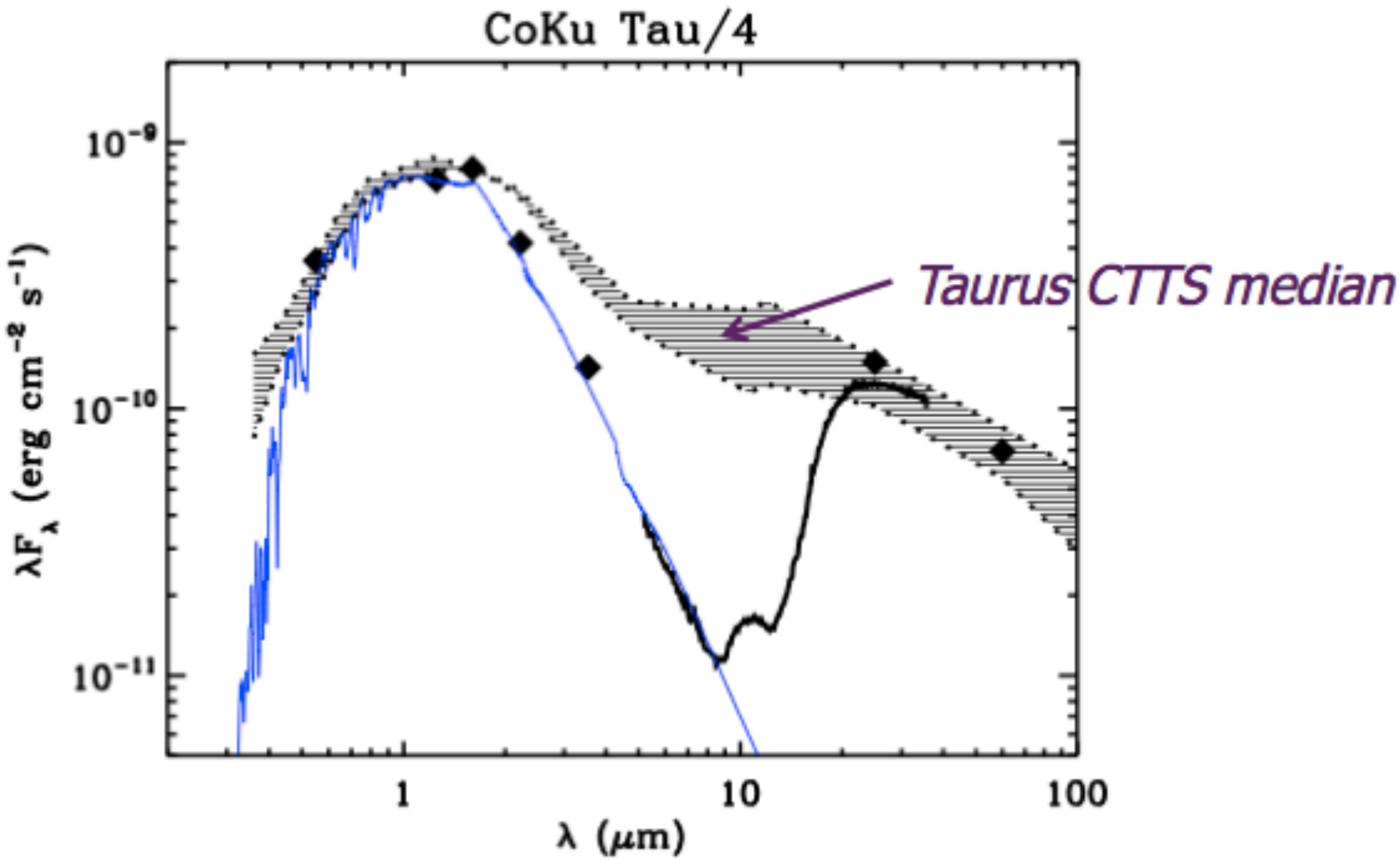
(Mamajek et al. 2009)



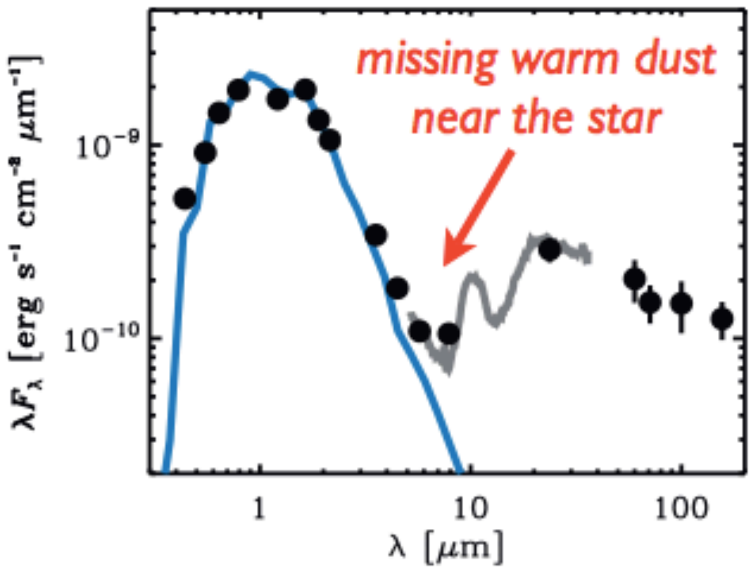
(Ribas et al. 2014)

Disks dissipate with an e-folding time of 2.5 Myr

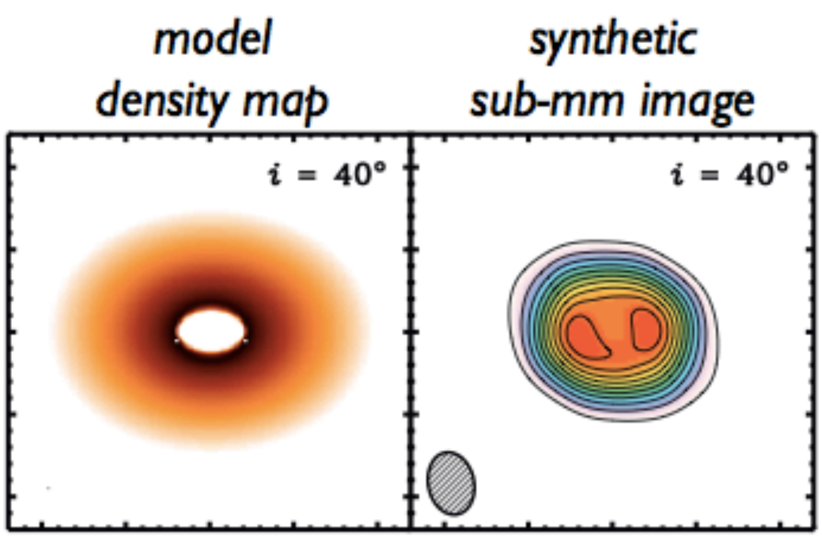
Transition Disks: Disks with missing hot dust.



Transition Disks: Disks with missing hot dust.

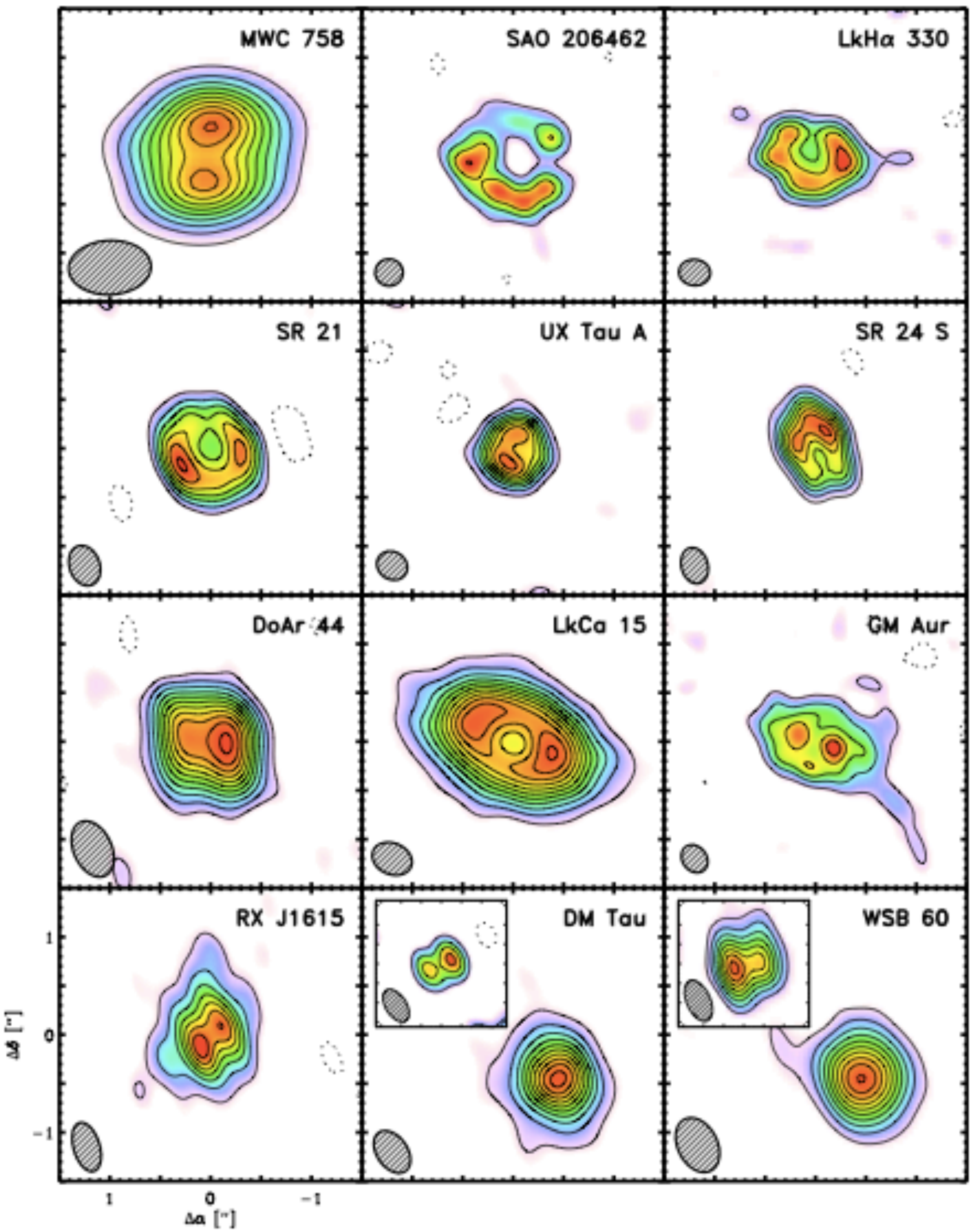


[e.g., Furlan et al. 2009]

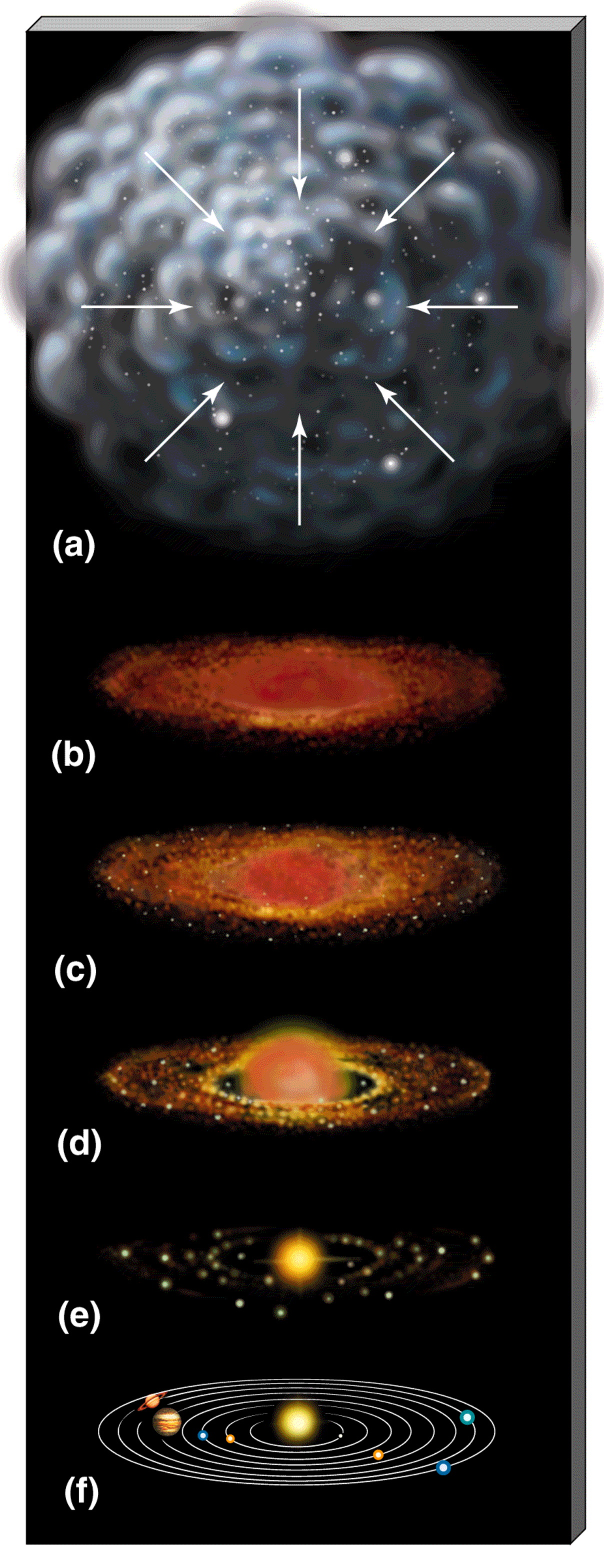


a disk with a large reduction in optical depth near the star (i.e., a "cavity" or "hole")

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



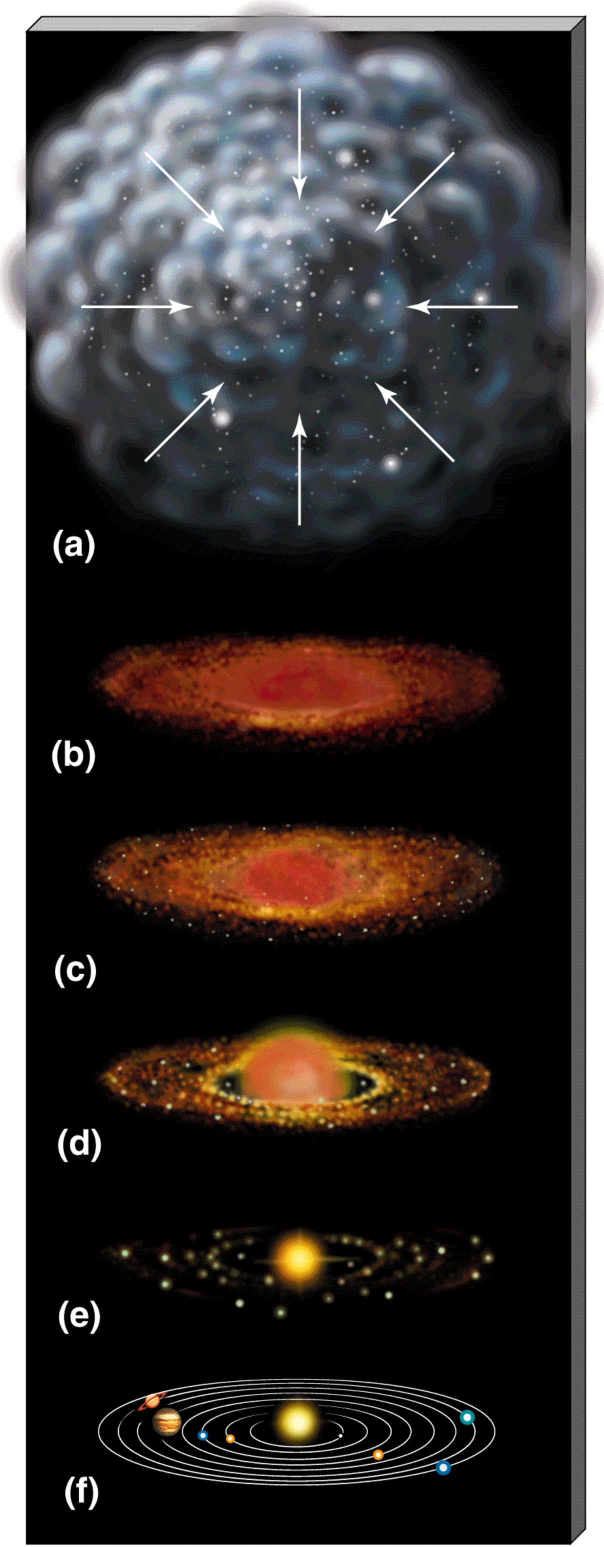
0.85mm
0.3" ~ 20 AU resolution



Are transitional disks related to disk evolution?

Gas-rich phase (< 10 Myr)
Primordial Disks

Gas-poor phase (>10 Myr)
Debris Disks

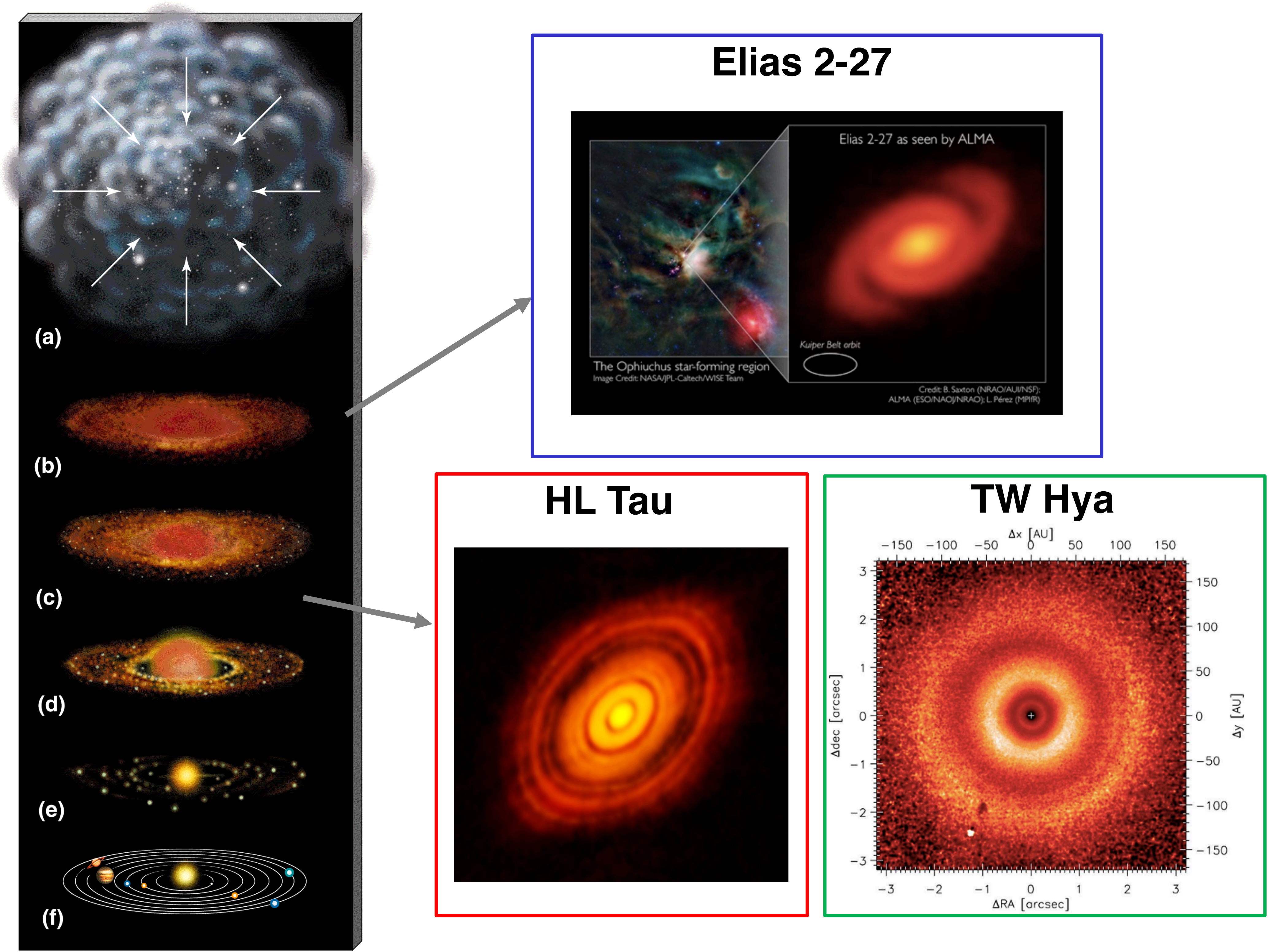


Are transitional disks
related to disk evolution?

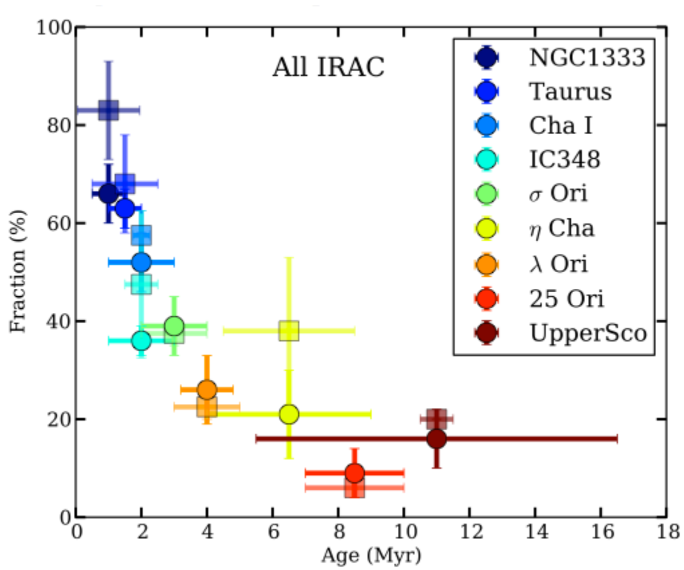
Gas-rich phase (< 10 Myr)
Primordial Disks

Conjecture:
Thinning phase (~10 Myr)
Transitional Disks

Gas-poor phase (>10 Myr)
Debris Disks

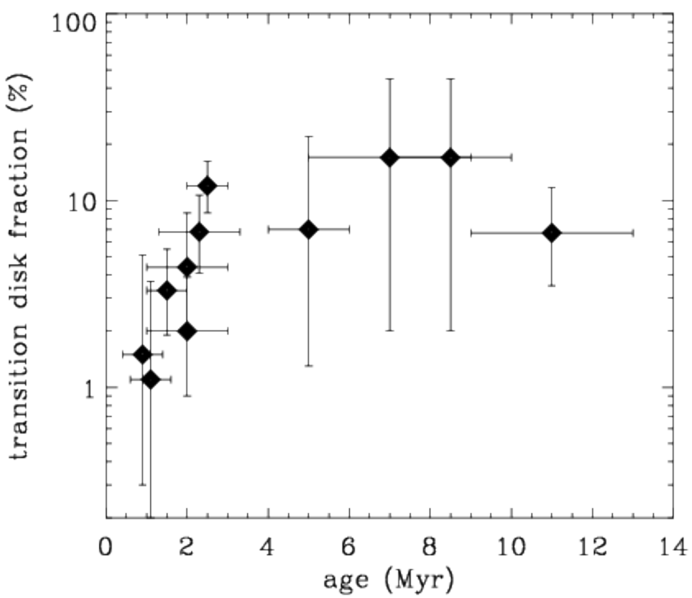

(a)
(b)
(c)
(d)
(e)
(f)
Elias 2-27
Elias 2-27 as seen by ALMA
Kuiper Belt orbit
The Ophiuchus star-forming region
Image Credit: NASA/JPL-Caltech/WISE Team
Credit: B. Saxton (NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO); L. Pérez (MPIfR)
HL Tau
TW Hya
Δx [AU]
−150 −100 −50 0 50 100 150
Δdec [arcsec]
3 2 1 0 −1 −2 −3
Δy [AU]
150 100 50 0 −50 −100 −150
ΔRA [arcsec]
−3 −2 −1 0 1 2 3

Transition disks and disk evolution



(Ribas et al. 2014)

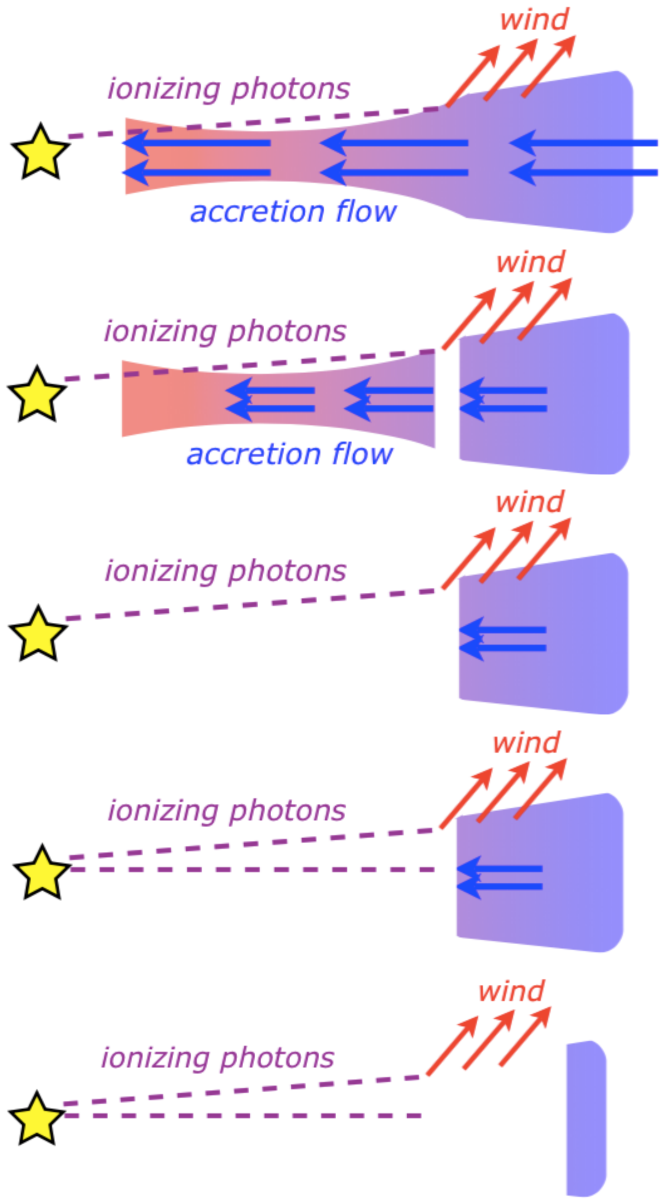
"Total" disk fraction



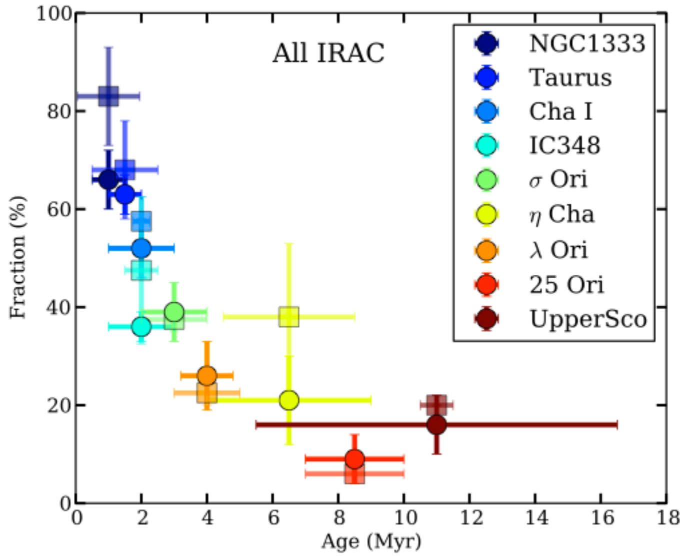
(Espaillat et al. 2014)

Transition disk fraction

Photoevaporation

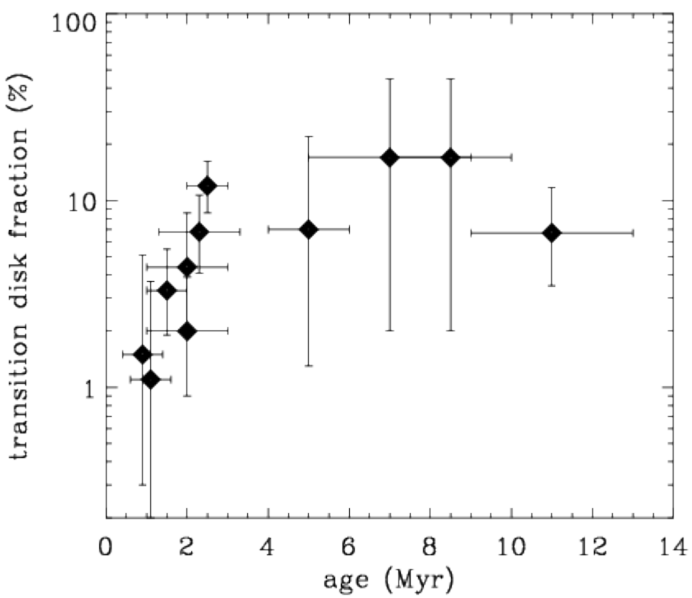


Look again…



(Ribas et al. 2014)

"Total" disk fraction

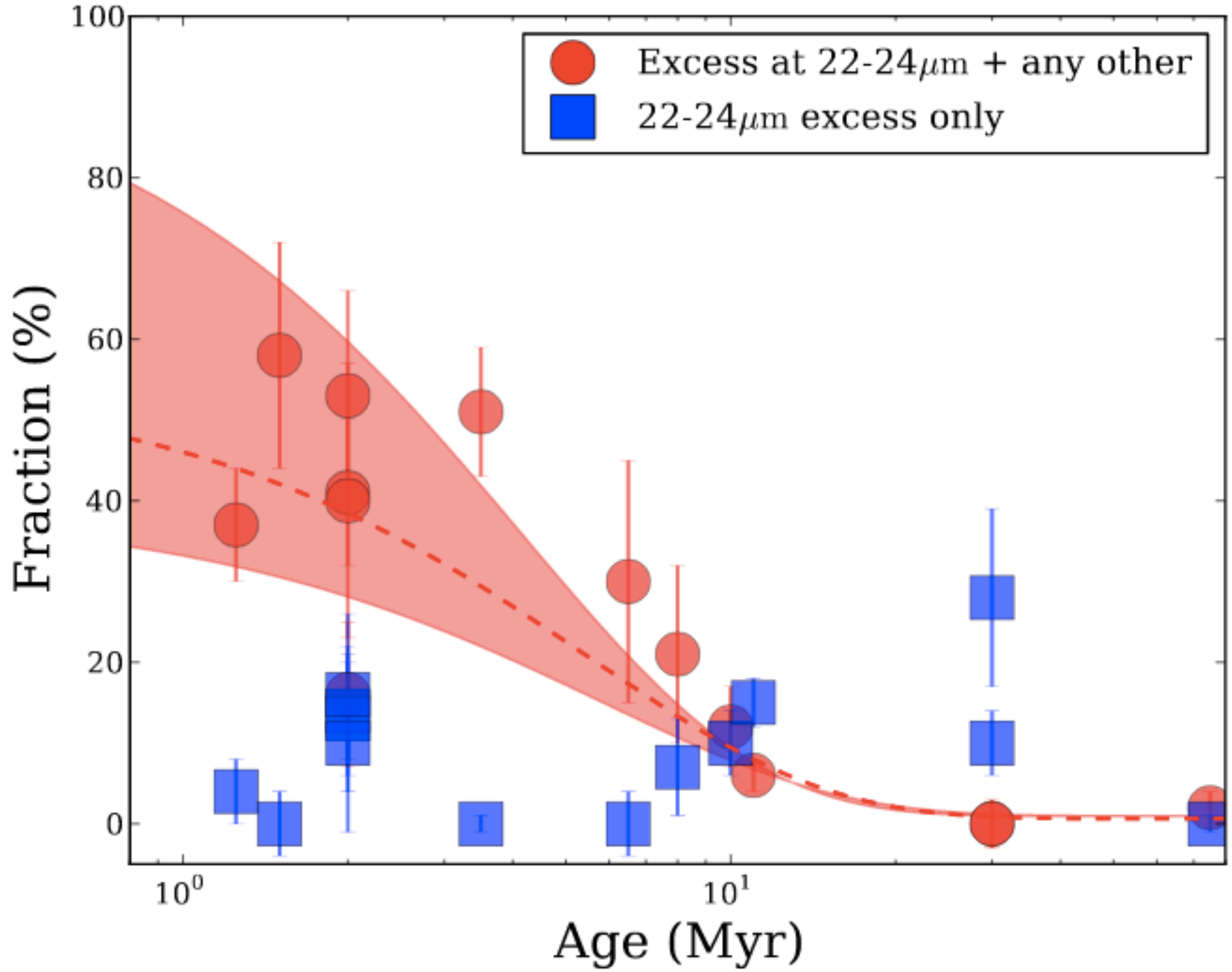


(Espaillat et al. 2014)

Transition disk fraction

Transition disks linked to disk evolution?

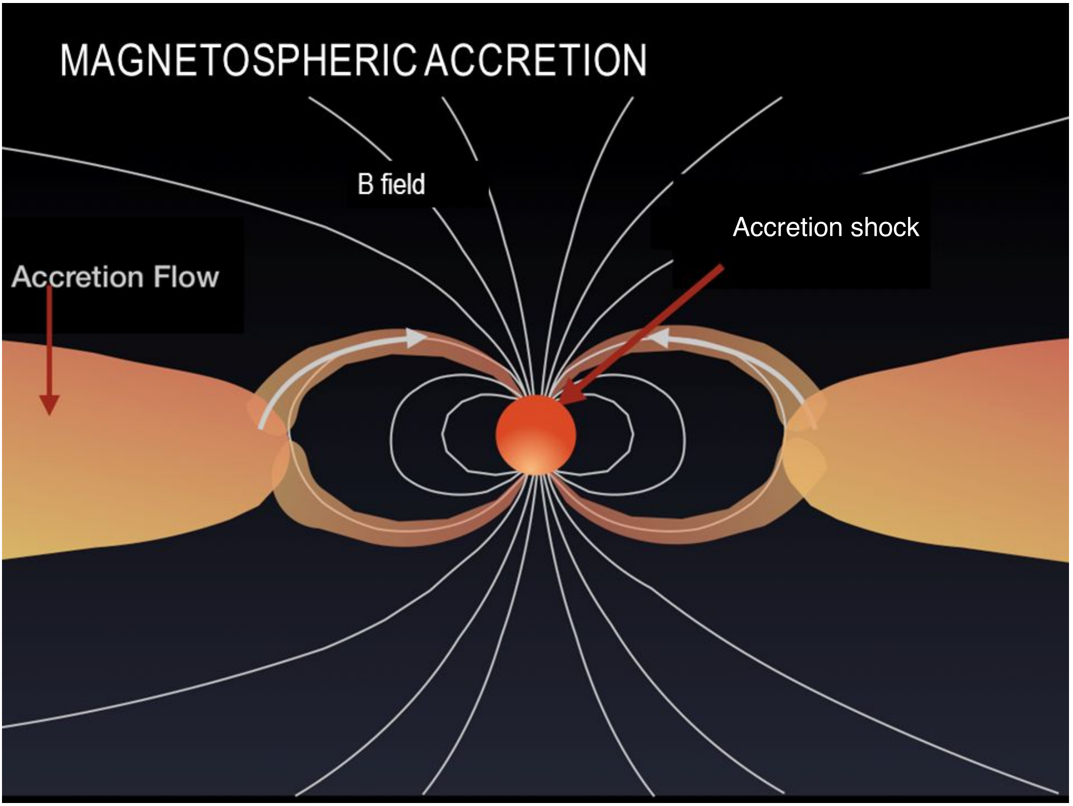
The distribution in age is consistent with a uniform distribution.

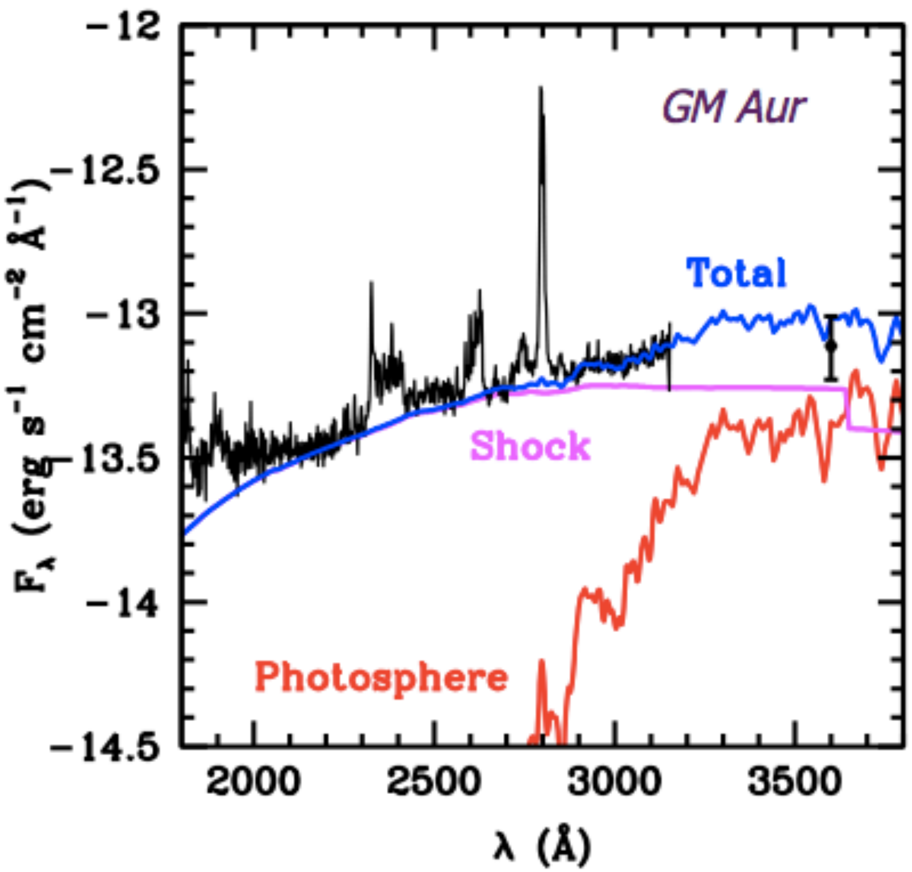


(Ribas et al. 2014)

UV excess

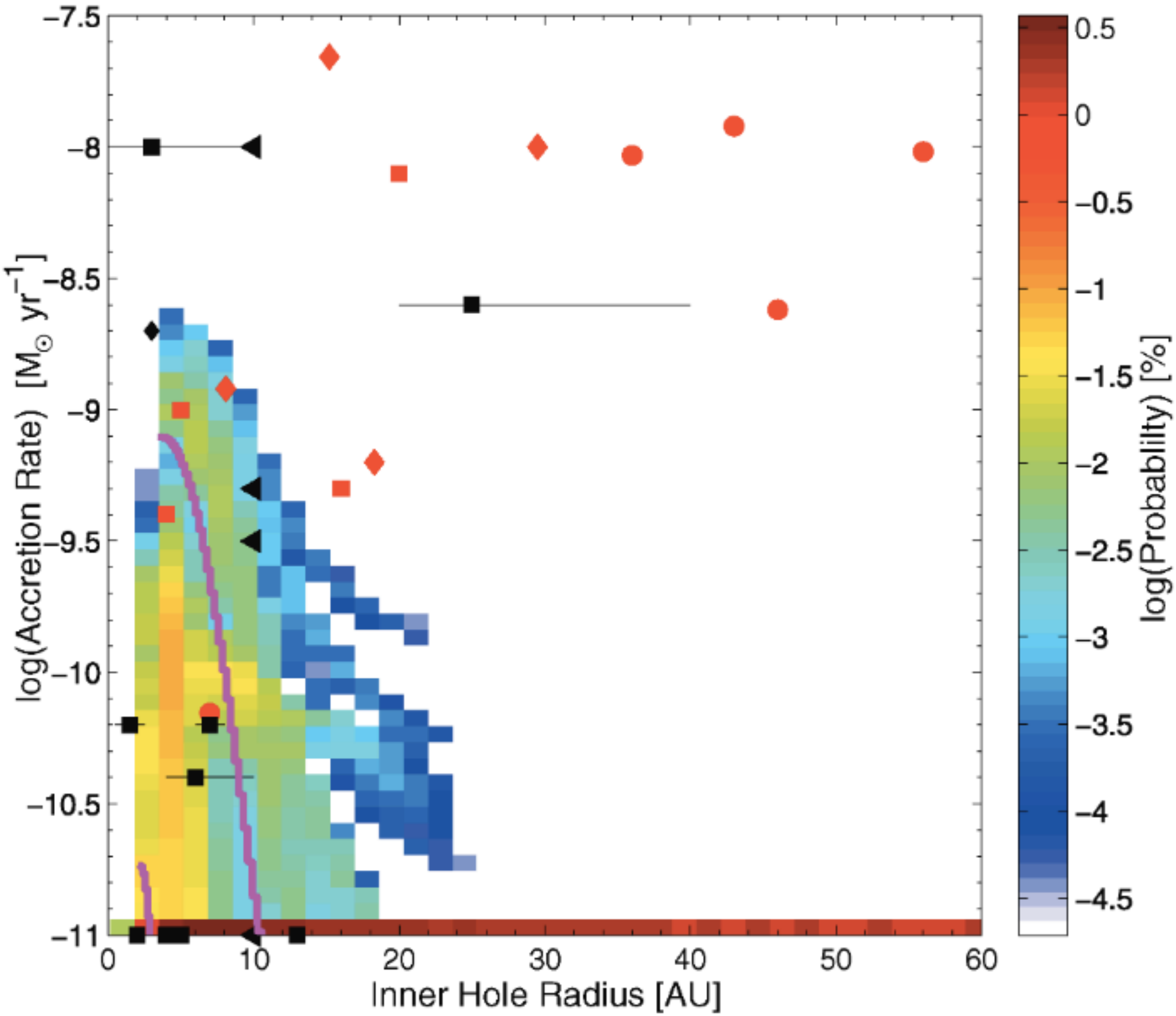
Many transitional disks show signs of accretion,
at the level of primordial (classical T-Tauri) disks.





(Ingleby et al. 2011)

Bimodal distribution of transition disks

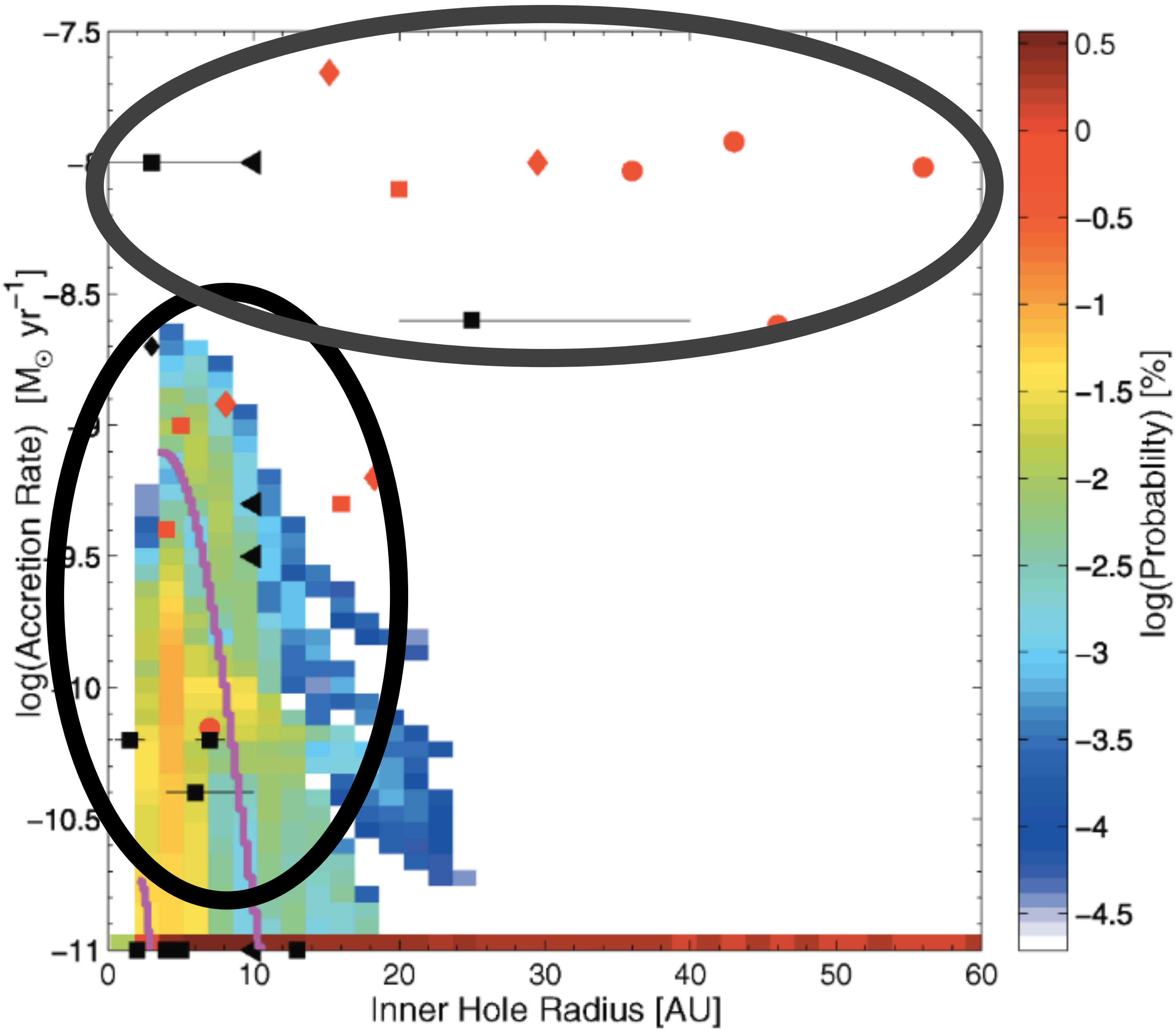


(Owen et al. 2011)

Bimodal distribution of transition disks

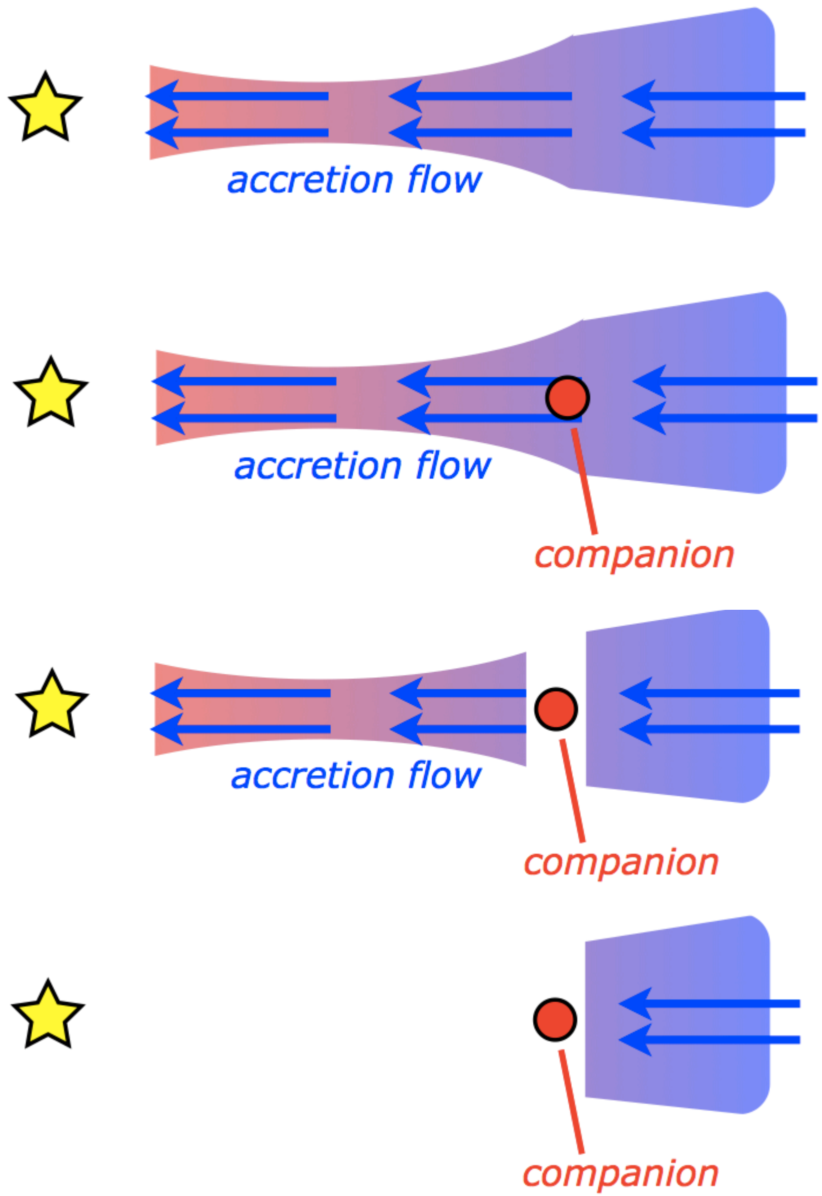
Not explained by photo-evaporation

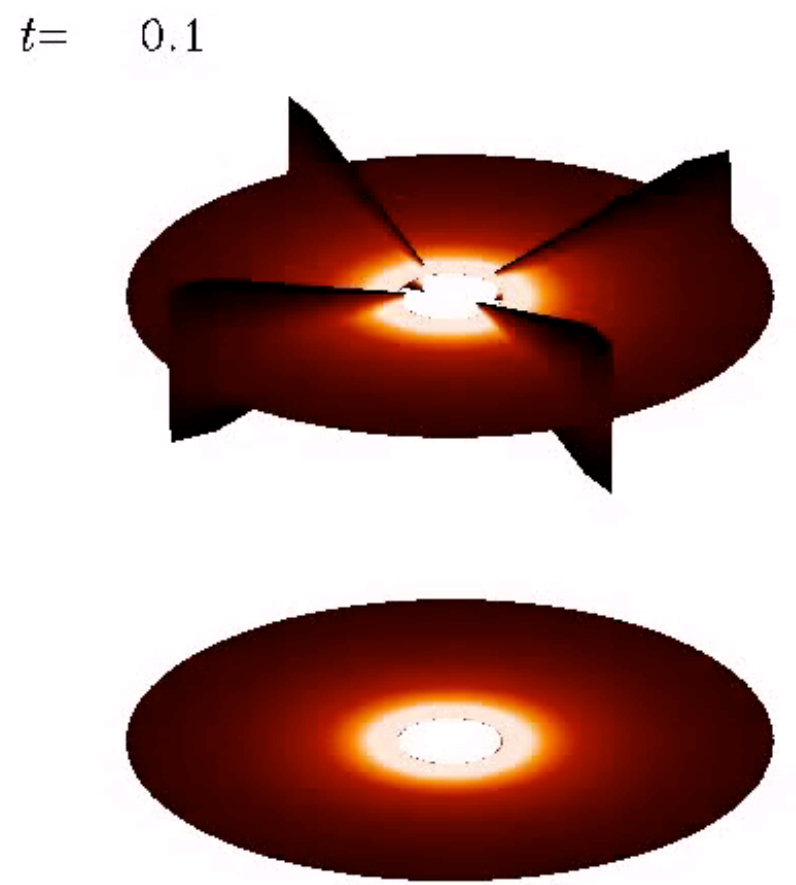
Explained by Photo-evaporation



(Owen et al. 2011)

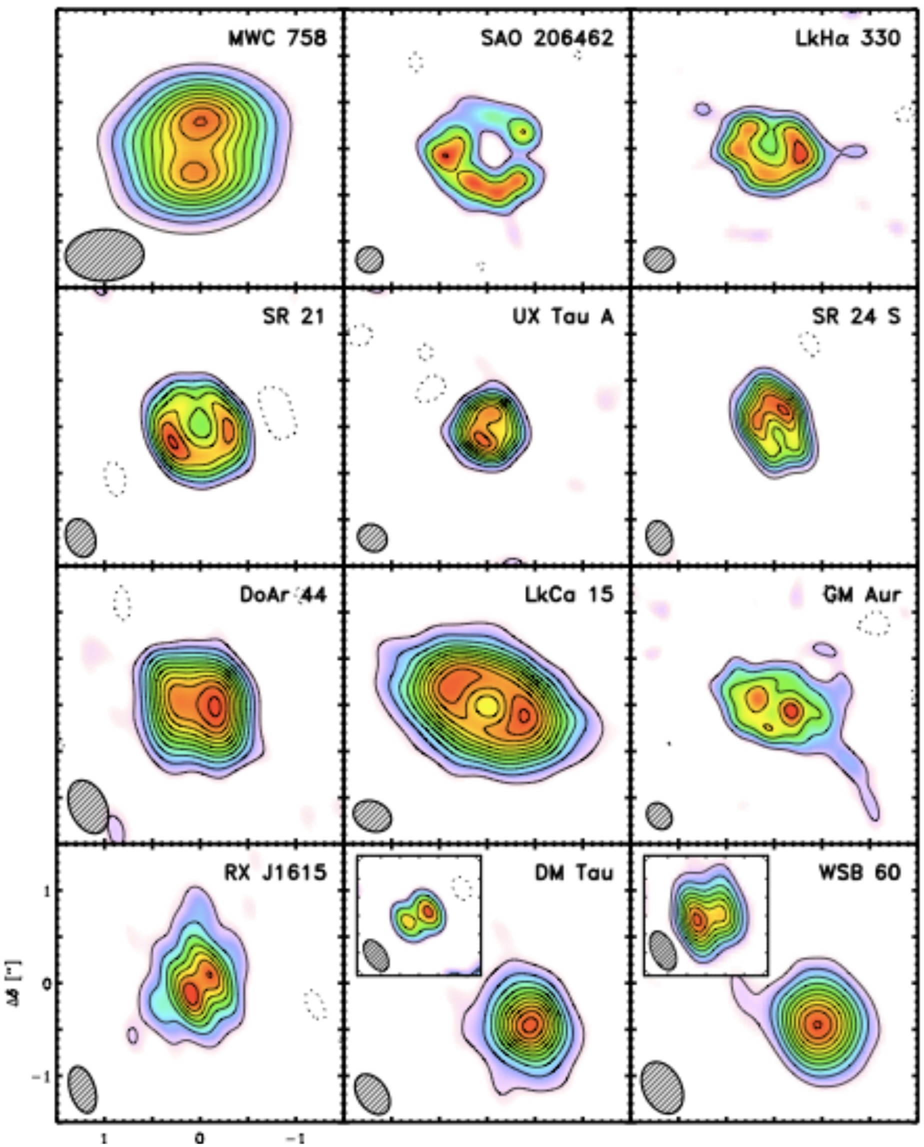
Planetary companion

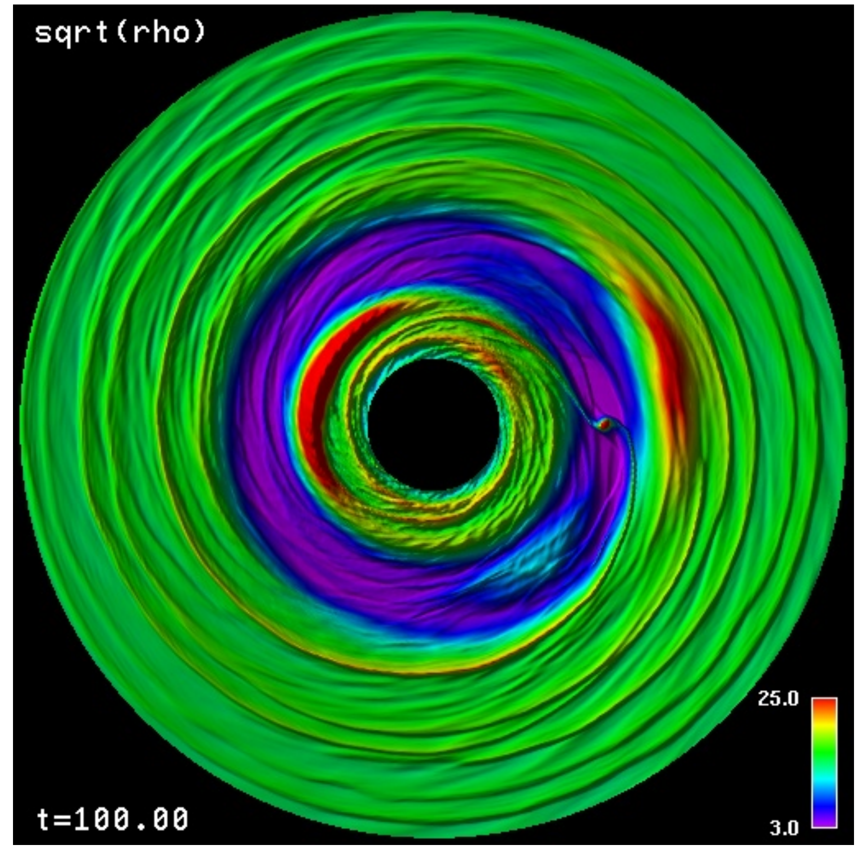




(Lyra 2009)

These cavities may be the telltale signature of forming planets

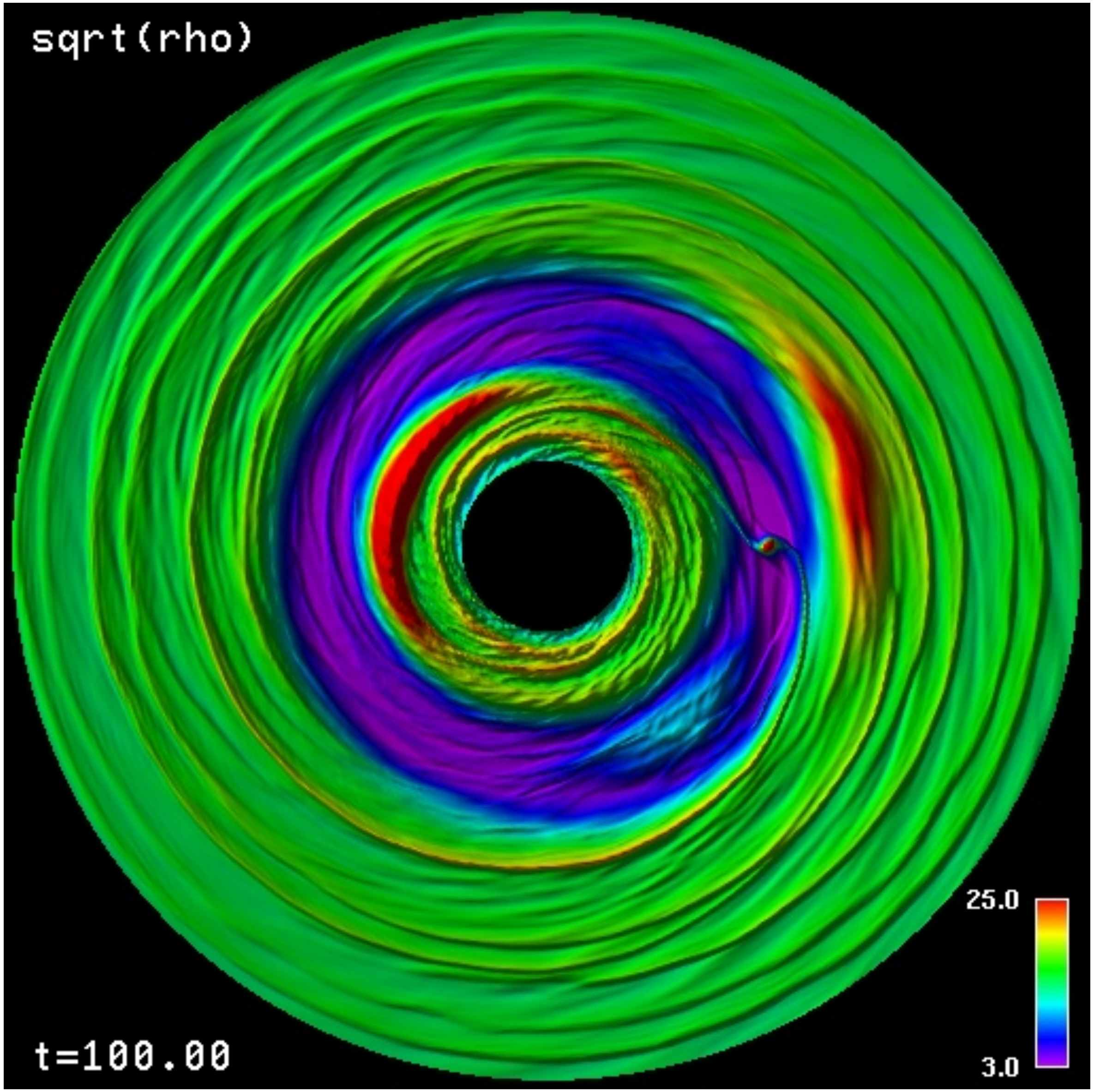




(Bryden et al. 1999)

A way to directly study planet-disk interaction

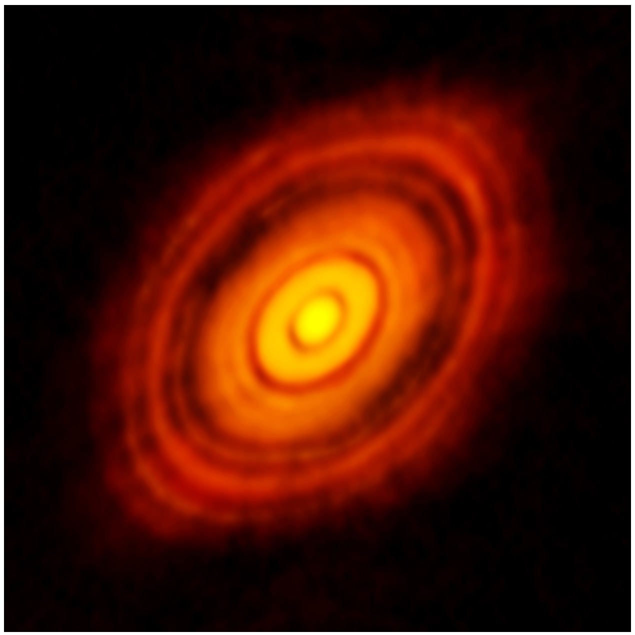
Planet-disk interaction: gaps, spirals, and vortices.



(Bryden et al. 1999)

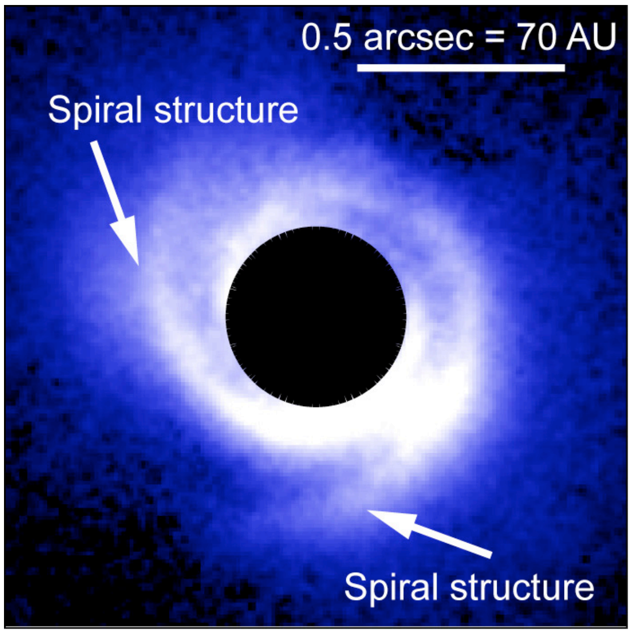
Observational evidence: gaps, spirals, and vortices

HL Tau



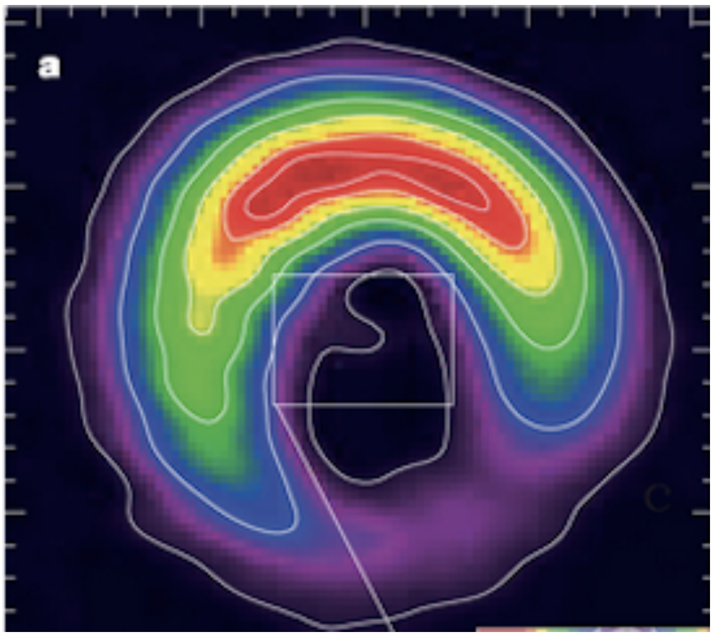
The ALMA Partnership et al. (2015)

SAO 206462



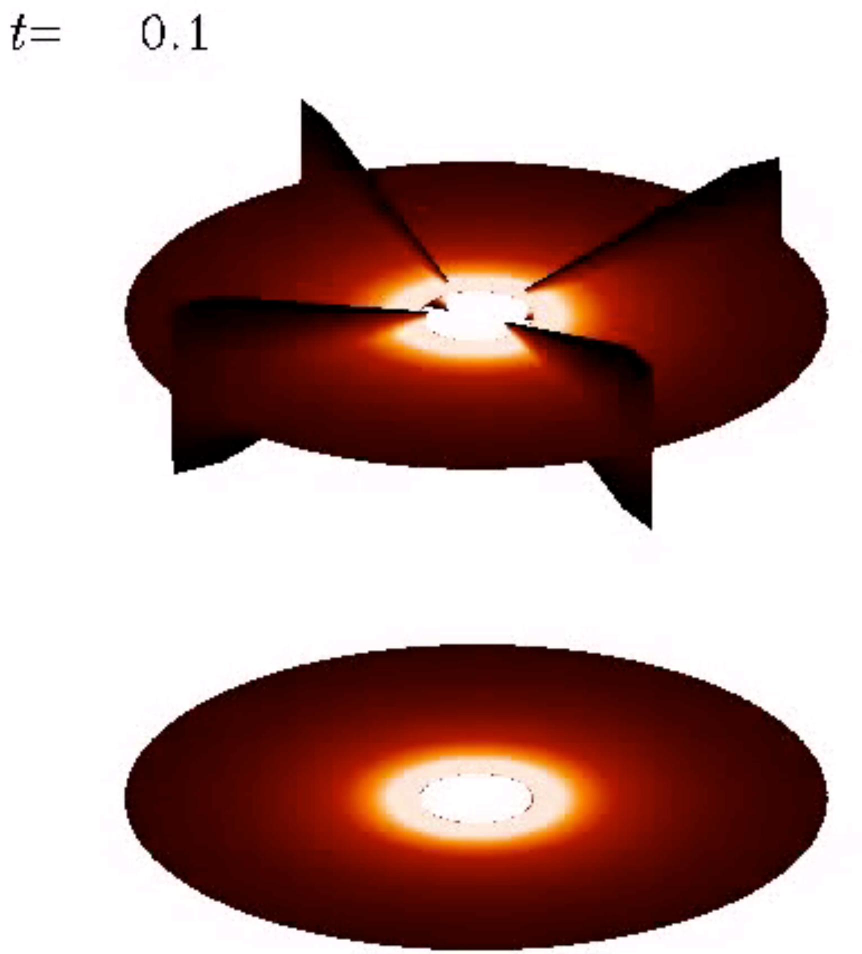
Muto et al. (2012)

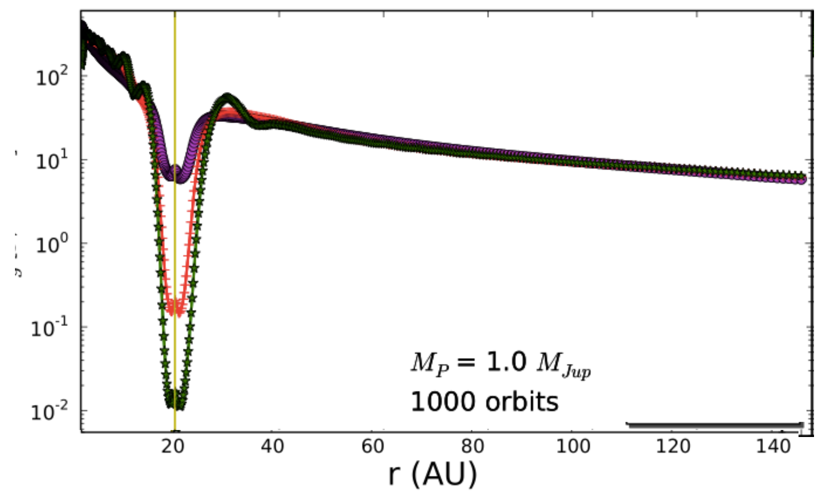
HD 142527



Casassus et al. (2013)

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



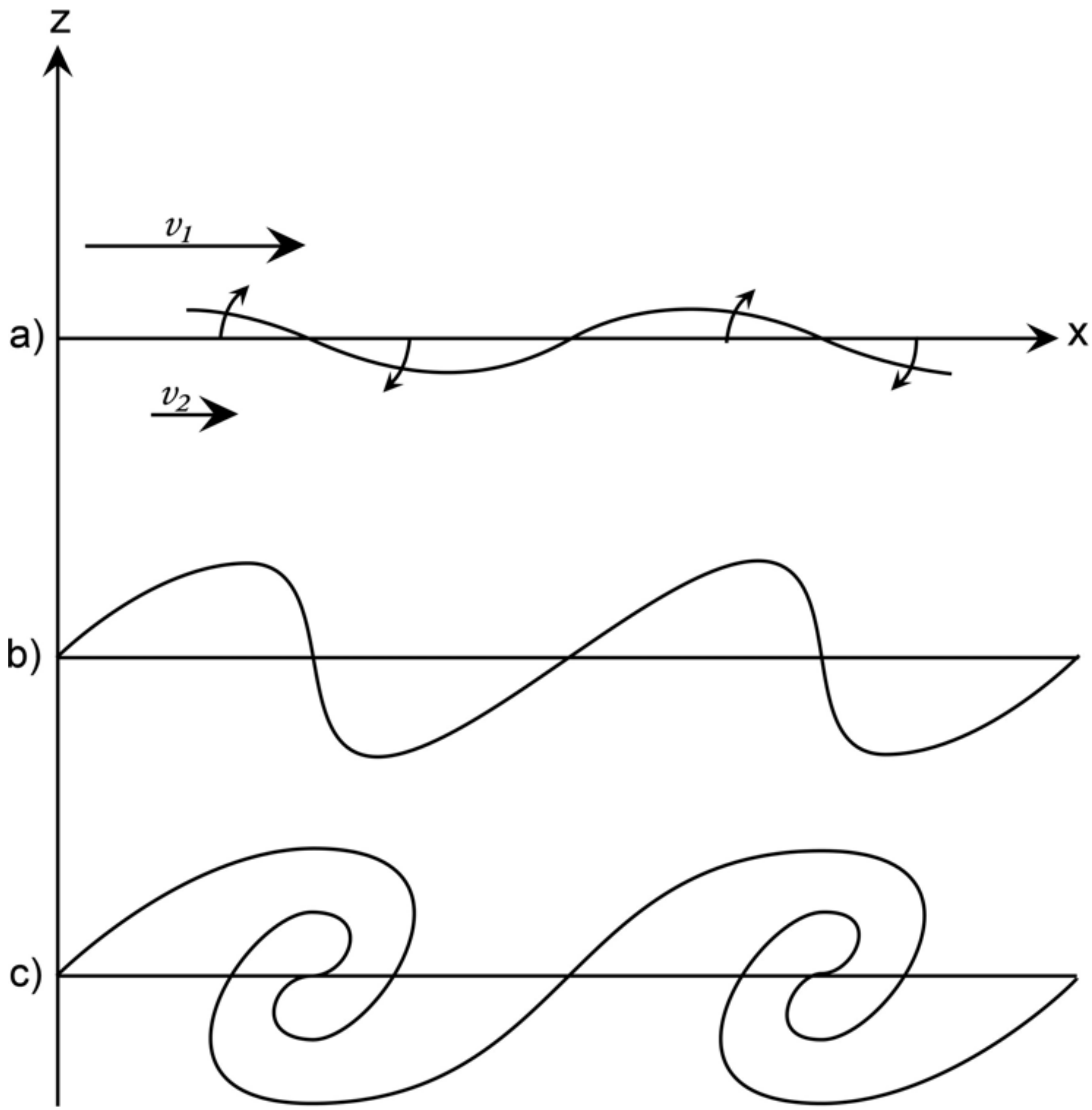


Planet tides carve gap

Gap walls are unstable to Kelvin-Helmholtz instability

Lyra (2009)

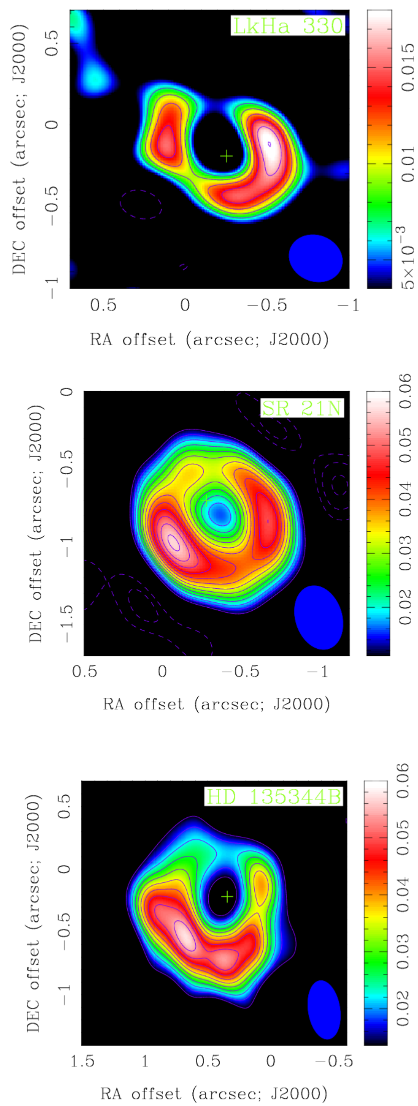
Rossby wave instability
(or Kelvin-Helmholtz instability in differentially rotating gas)

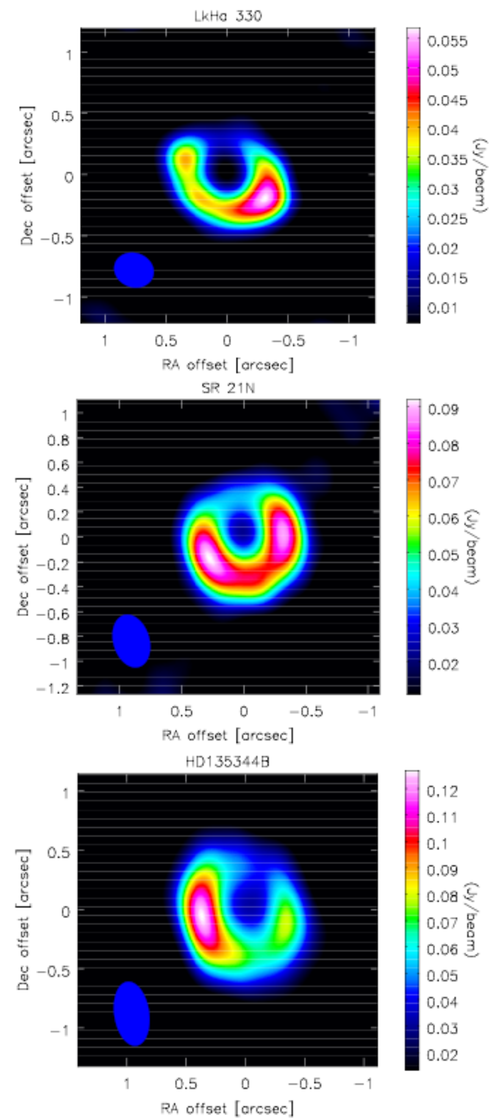


A possible detection?

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

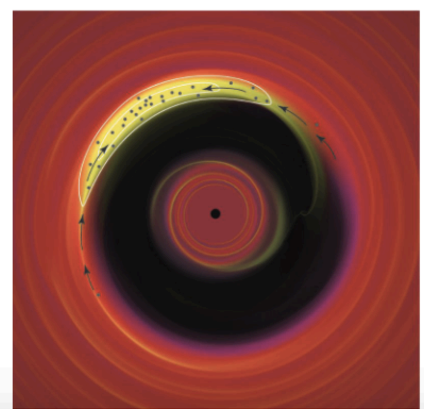
ASTRONOMY

A Trap for Planet Formation

Philip J. Armitage[1,2]

The detection of a pocket of trapped particles may provide a hint to understanding the mechanism of planet formation.

The raw material for forming planets is micrometer to millimeter-sized particles of dust that orbit along with gas in protoplanetary disks around young low-mass stars. These disks are known to be common and to persist for several million years (*1*). The Kepler mission (*2*) showed that mature planetary systems are also common. What is not known, however, is the full sequence of steps that allows the dust within protoplanetary disks to grow into planets. On page 1199 of this issue, van der Marel *et al.* (*3*) report observations from the Atacama Large Millimeter/submillimeter Array (ALMA) that hint at how the most problematic step may be surmounted—millimeter-sized par-



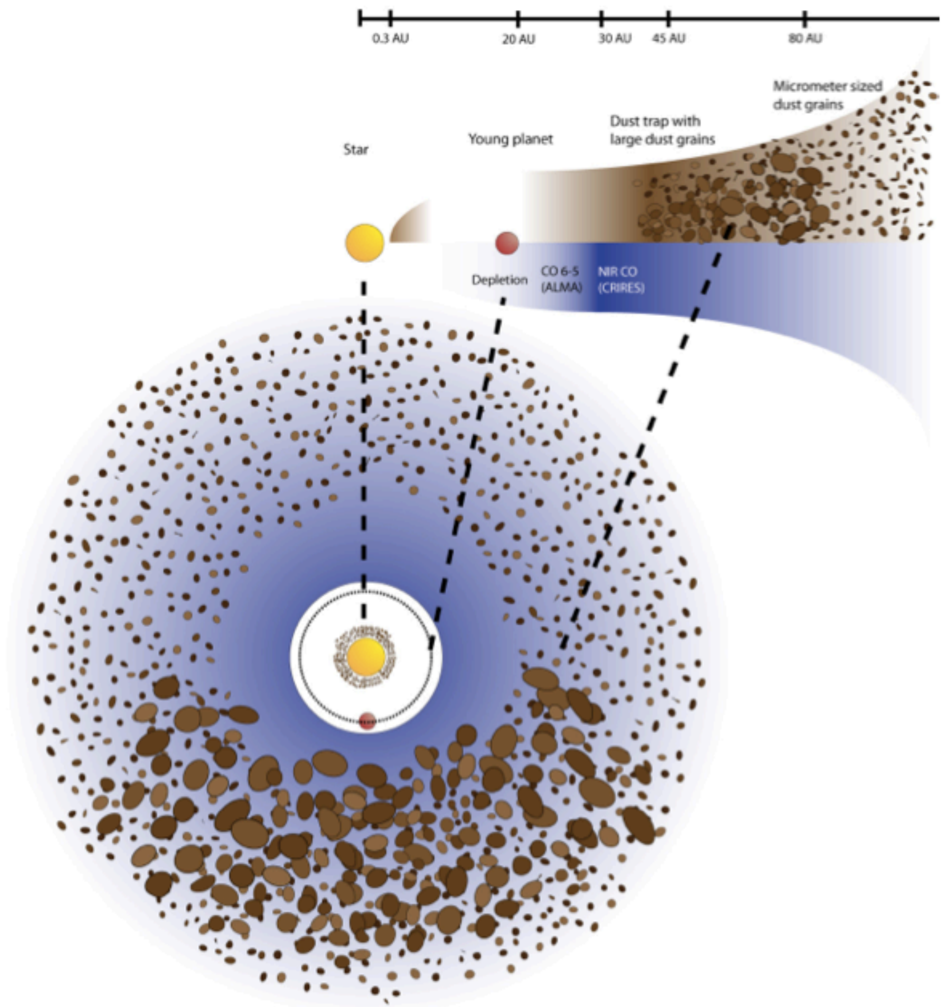
From dust to planet. Illustration of the proposed mechanism that creates a dust trap in the disk of IRS 48. A massive planet (plus symbol) creates an annular gap in the gas disk, whose surface density is shown as a color map. A high-pressure vortex (contours) forms at the gap edge, collecting and trapping millimeter-sized dust particles that would otherwise spiral rapidly inward through the disk.

metric distribution. The emission from smaller dust particles, measured separately at infrared wavelengths, is also distributed uniformly around the orbit (*11*). These observations are consistent with theoretical expectations for a dust trap, in which a modest peak in gas pressure is able to strongly concentrate the millimeter-sized solid particles that

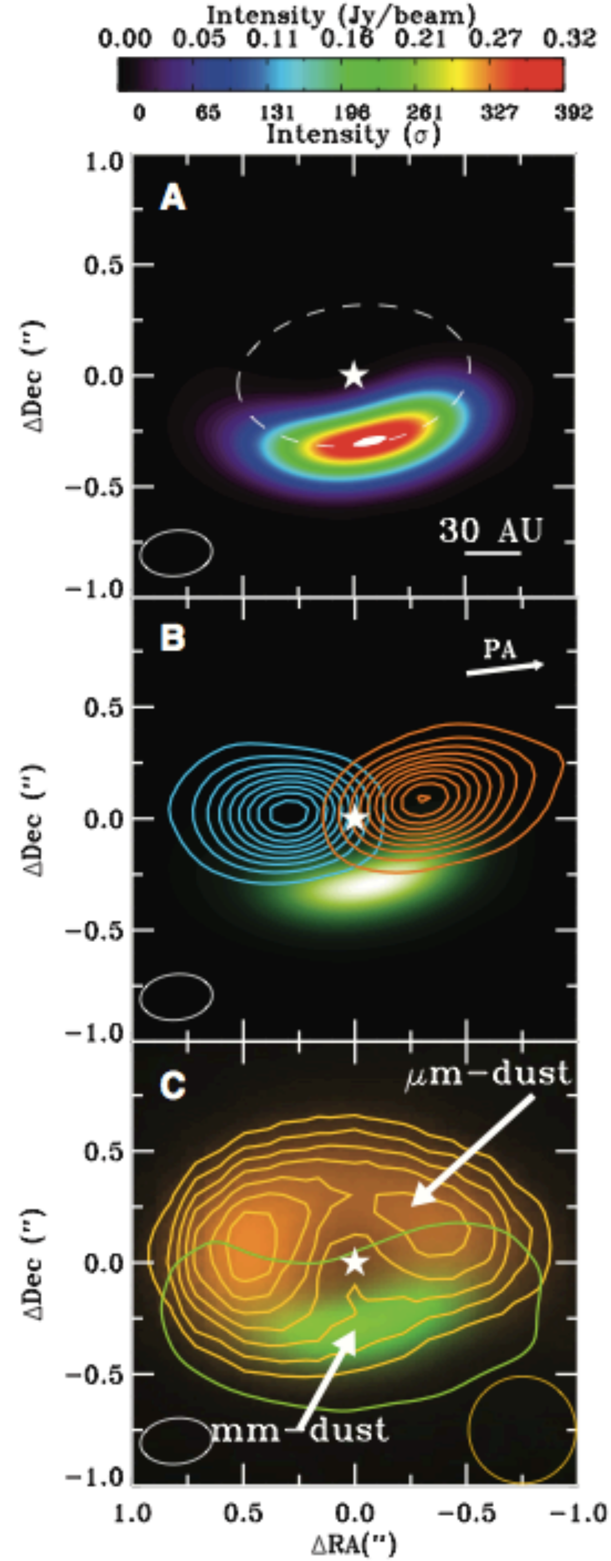
van der Marel et al. 2013

A possible huge vortex observed with ALMA

The Oph IRS 48 “dust trap”



van der Marel et al. (2013)

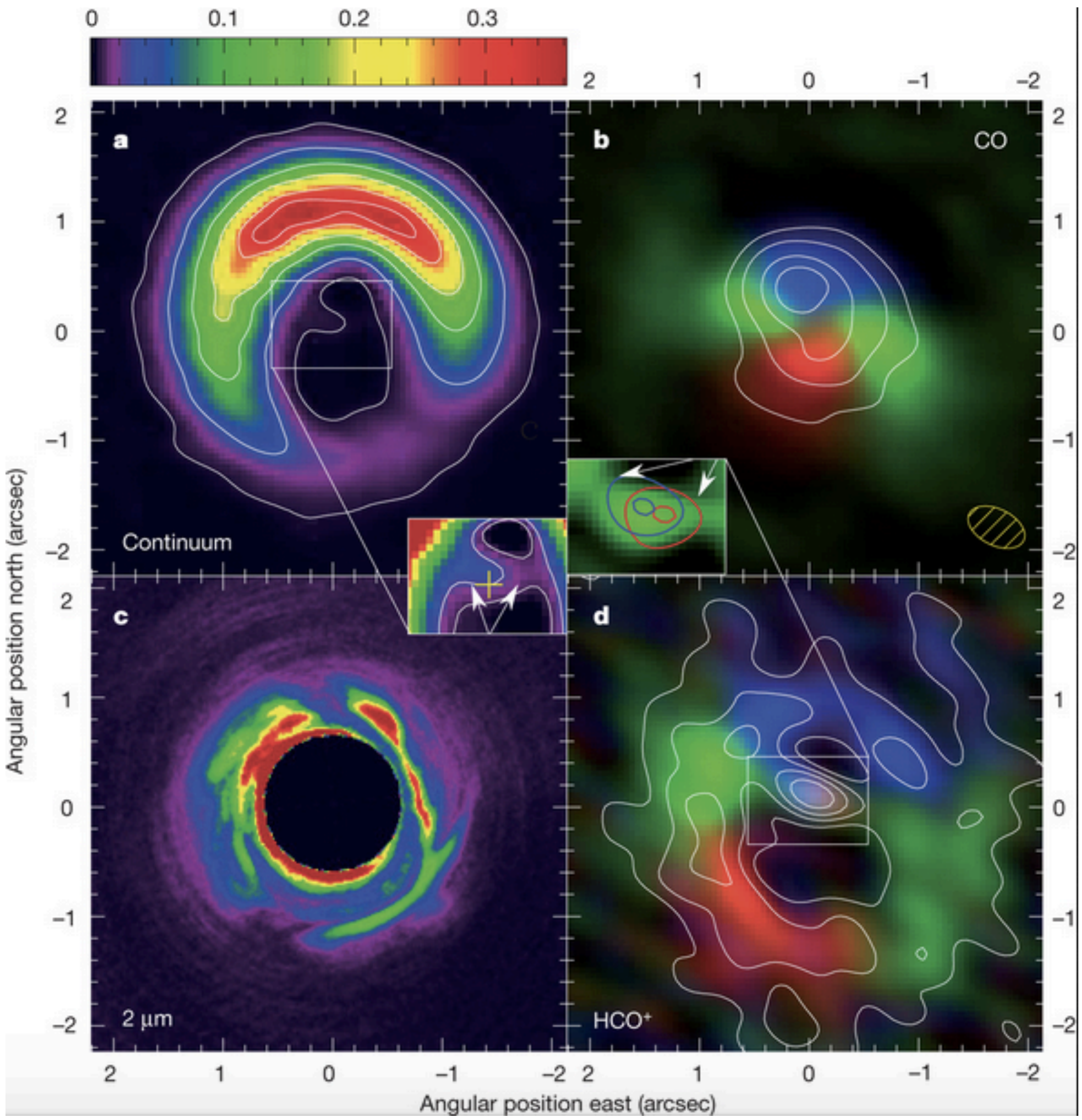


asymmetric
mm dust
at 63 AU

Gas detection:
Keplerian rotation

Micron-sized
dust follows gas

HD 142527

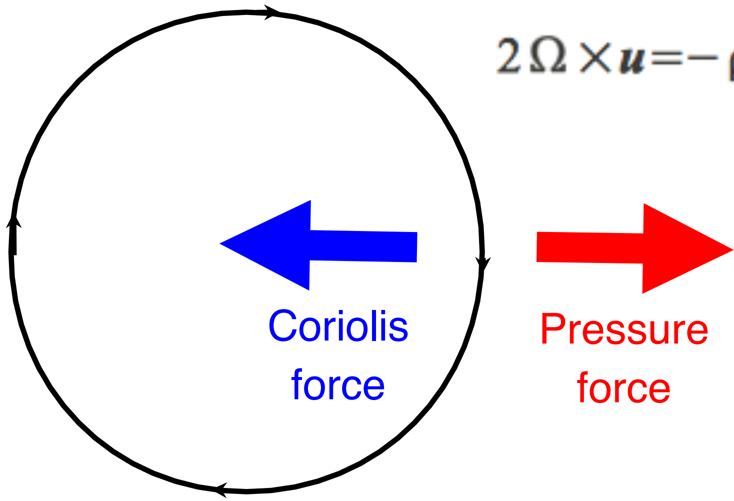


Casassus et al. (2013)

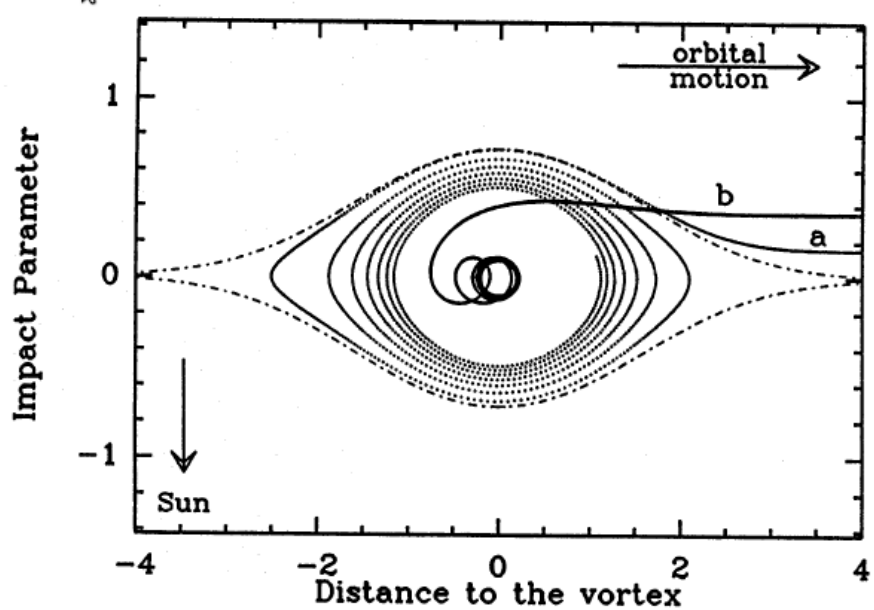
The Tea-Leaf effect

Geostrophic balance:

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



Vortex streamline



Barge & Sommeria (1995)

Particles 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)

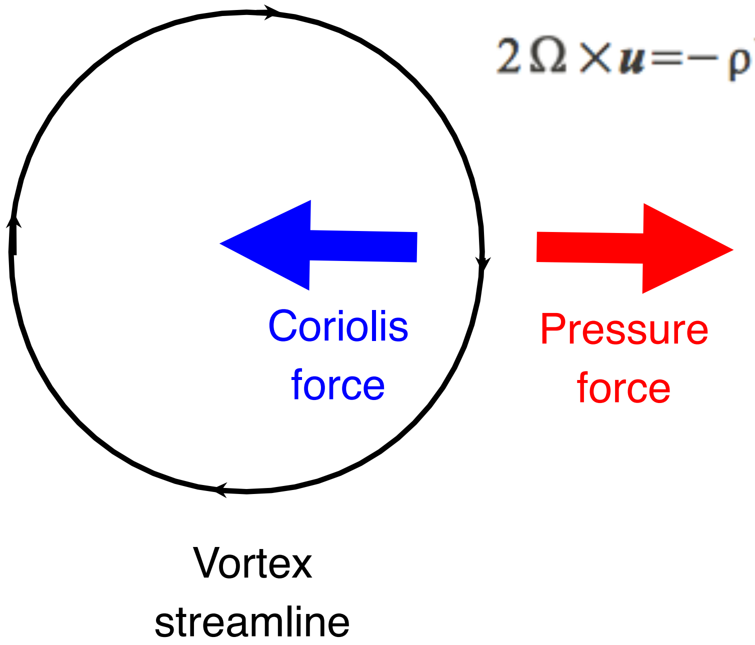
Speed up planet formation enormously

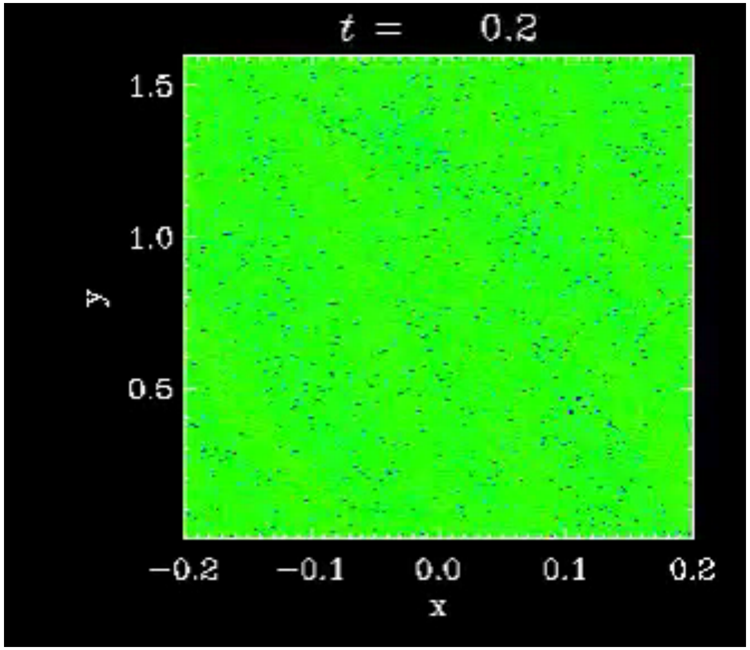
(Lyra et al. 2008b, 2009ab, Raettig et al. 2012)

The Tea-Leaf effect

Geostrophic balance:

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





Raettig, Lyra, & Klahr (2013)

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Aid to planet formation

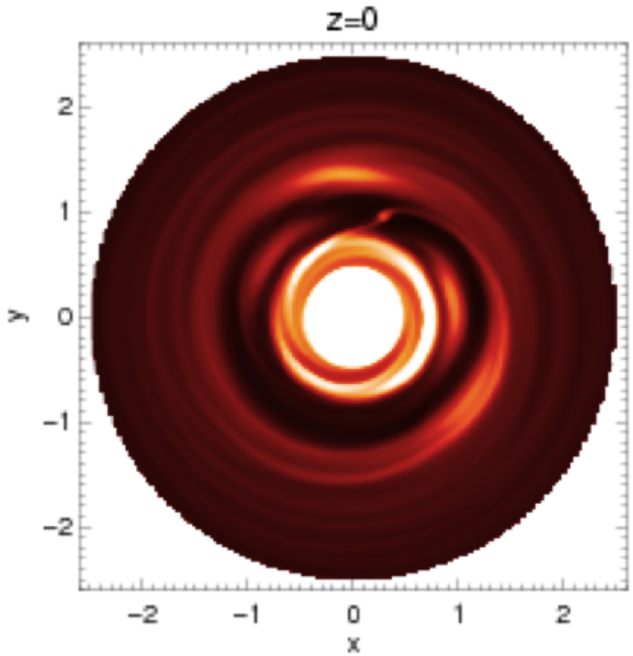
(Barge & Sommeria 1995, Tanga et al. 1996, Barranco & Marcus 2005)

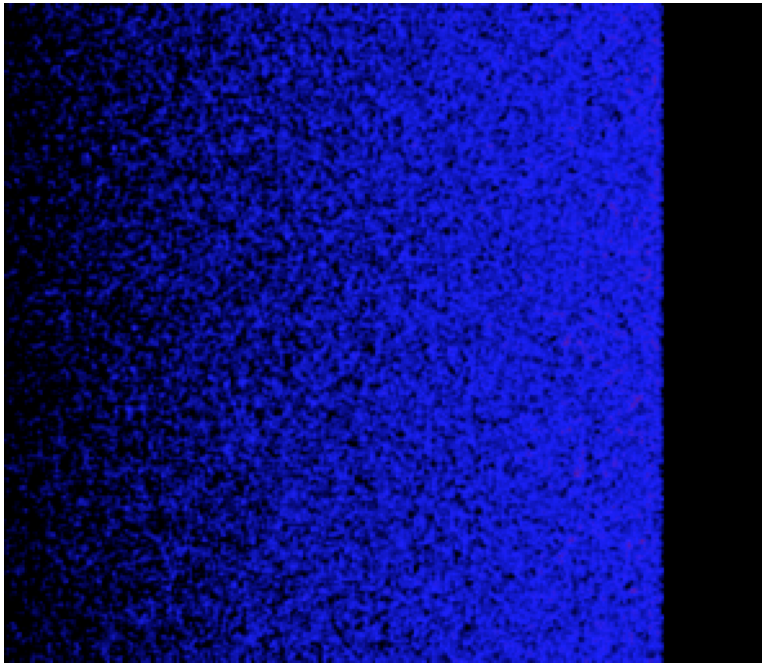
Speed up planet formation enormously

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

Planet Formation in gap edge vortices

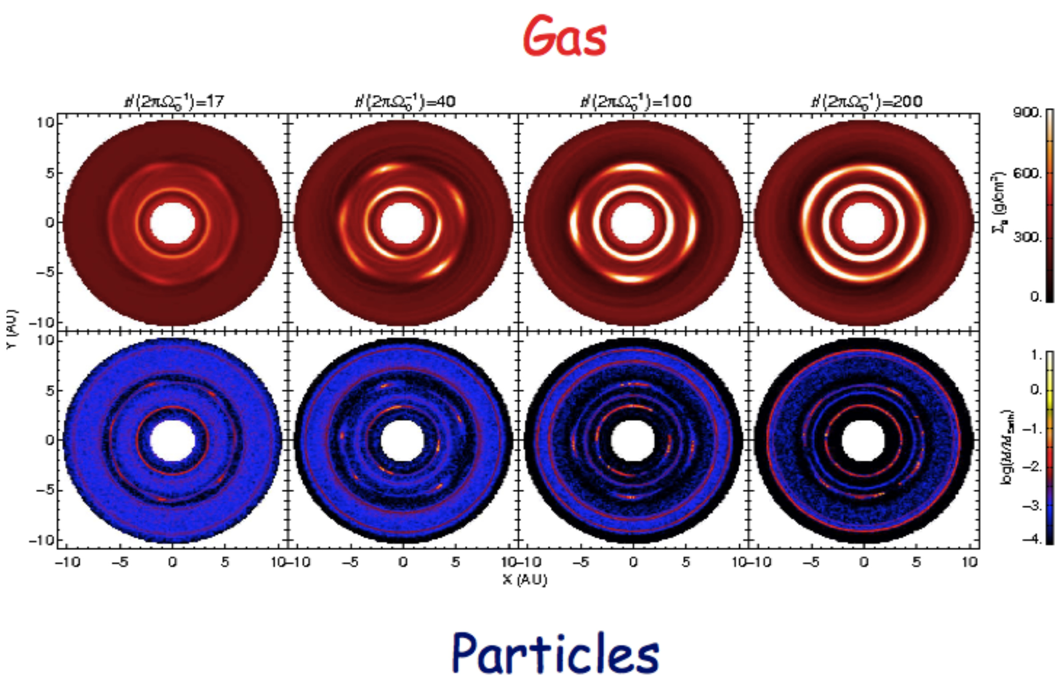
Lyra et al. (2009b),
see also de Val-Borro et al. (2007)

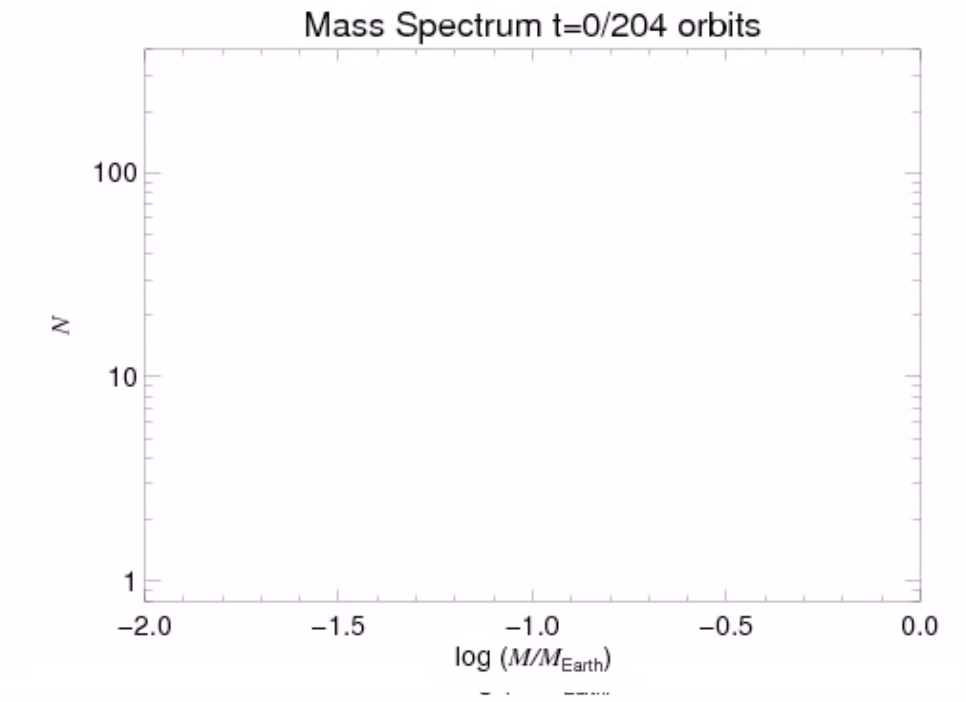




Burst of formation in gap vortices

Vortices and Planet Formation

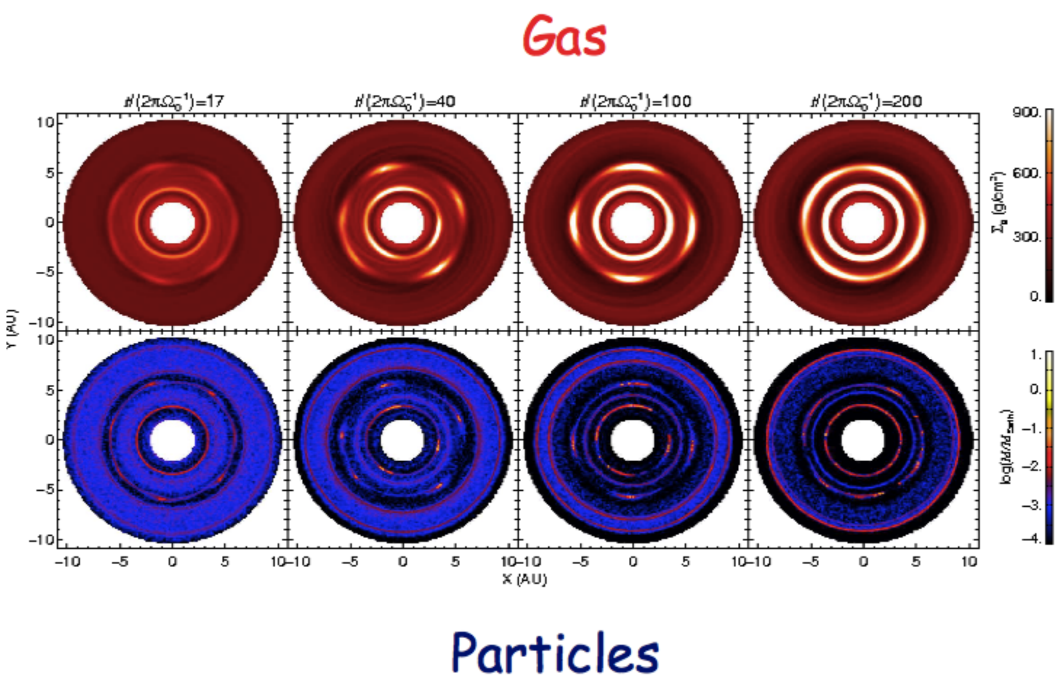


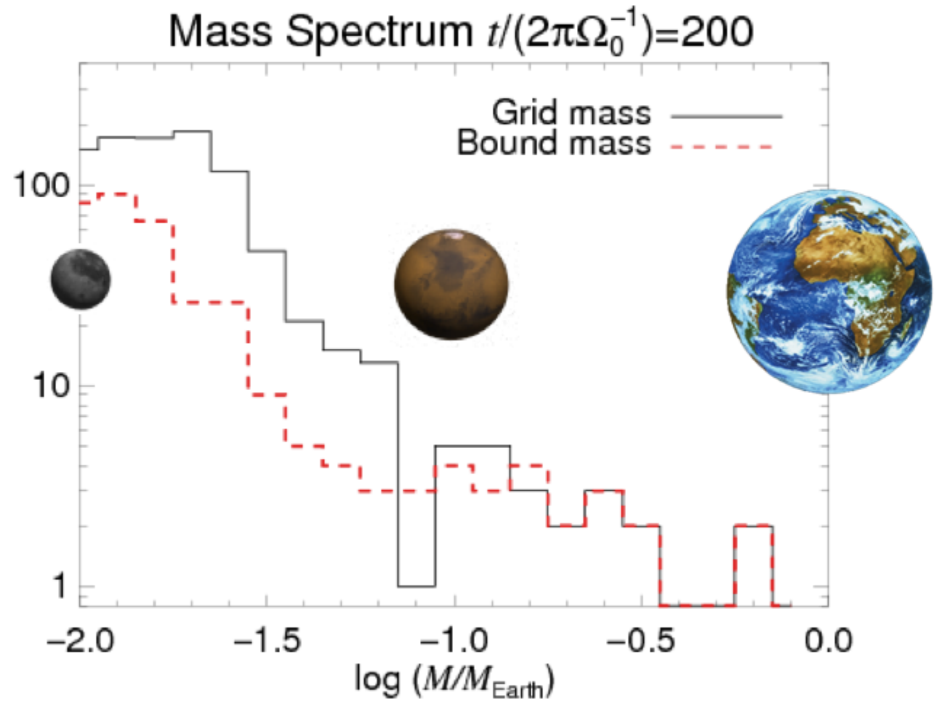


Collapse into Mars mass objects

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

Vortices and Planet Formation

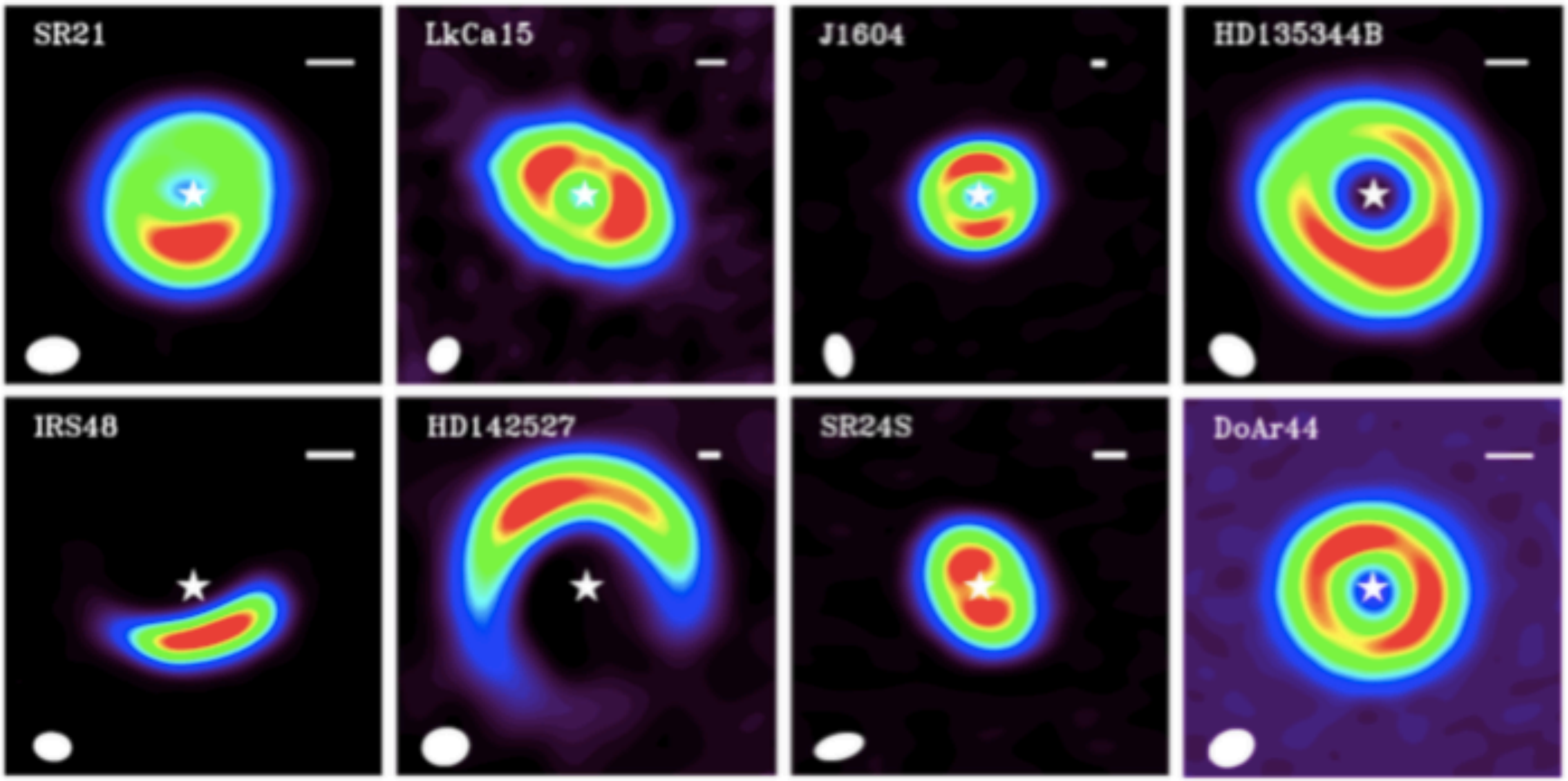




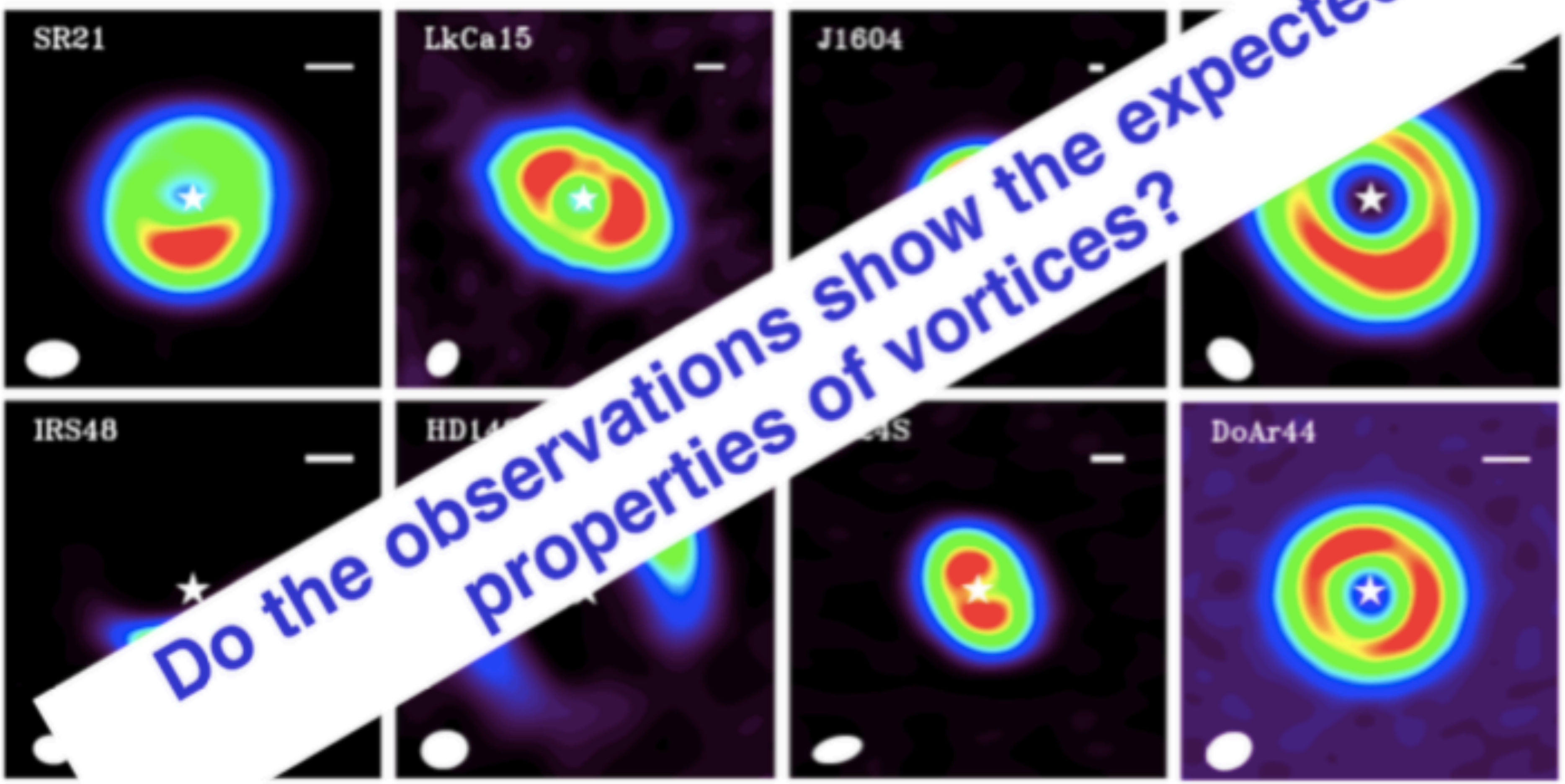
Collapse into Mars mass objects

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

"Asymmetries" everywhere

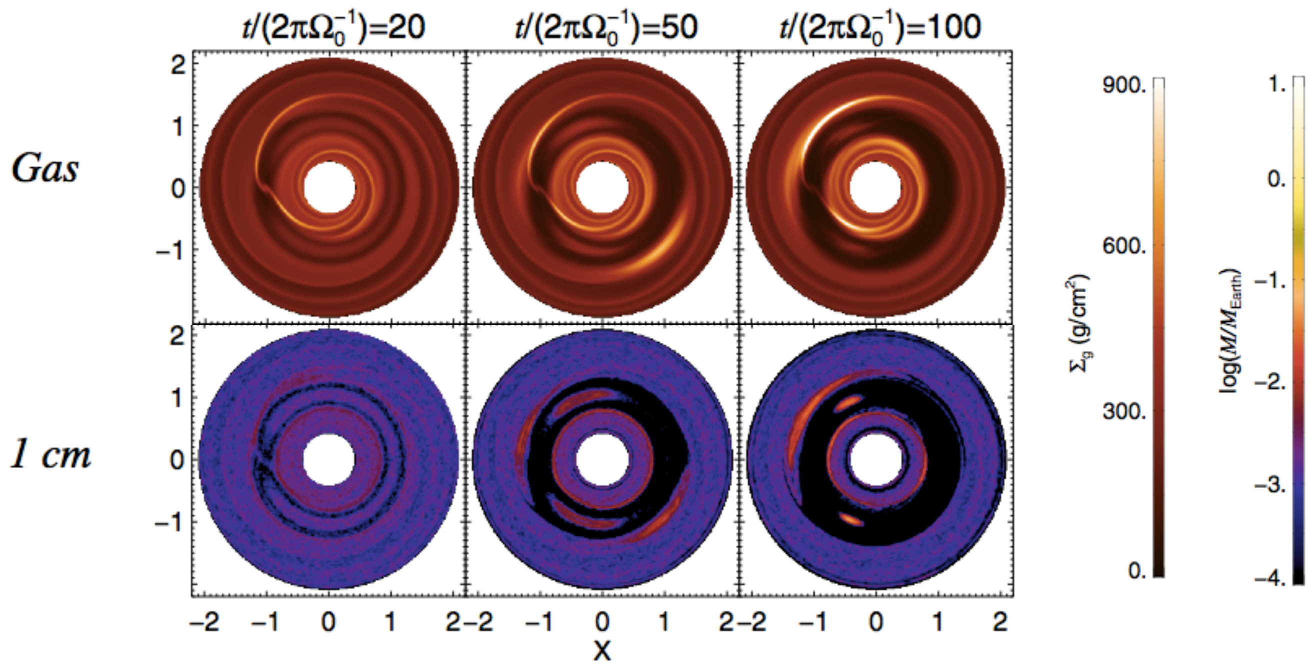


“Asymmetries” everywhere



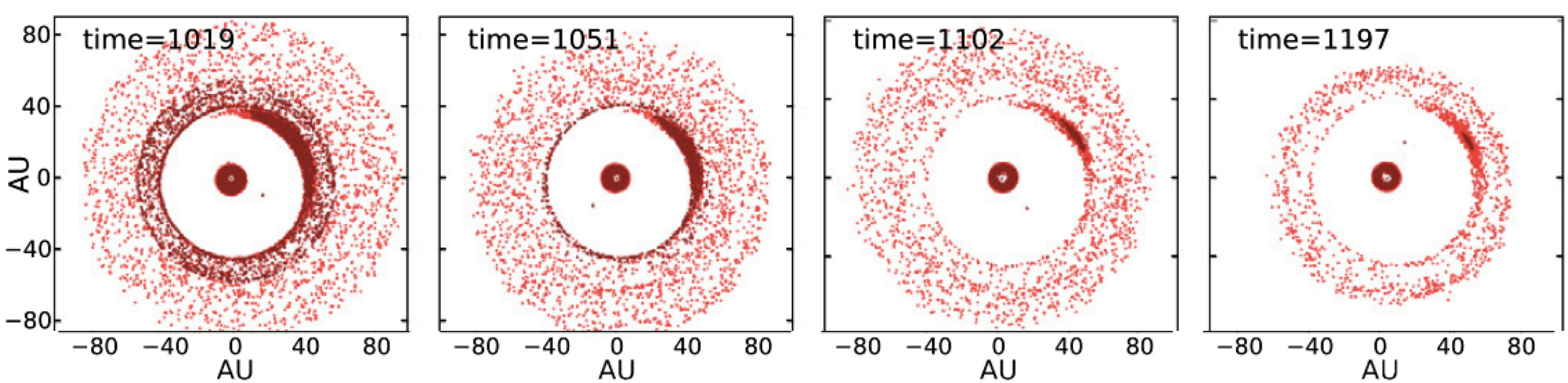
Do the observations show the expected properties of vortices?

Dust Trapping



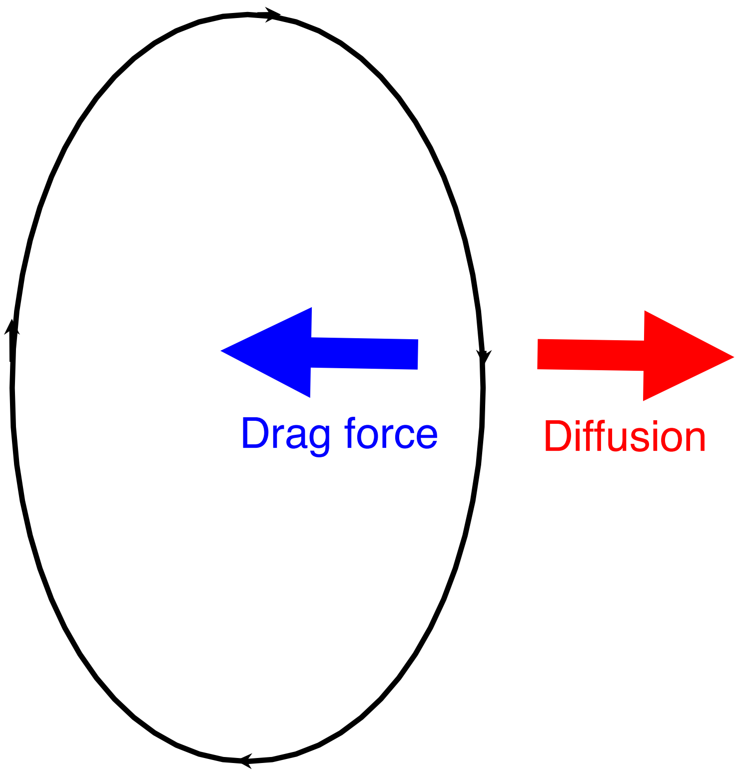
Lyra et al (2009b)

Turbulent “kicks” lead to steady state



Ataiee et al. (2013)

Drag-Diffusion Equilibrium



Trapped particle

Dust continuity equation

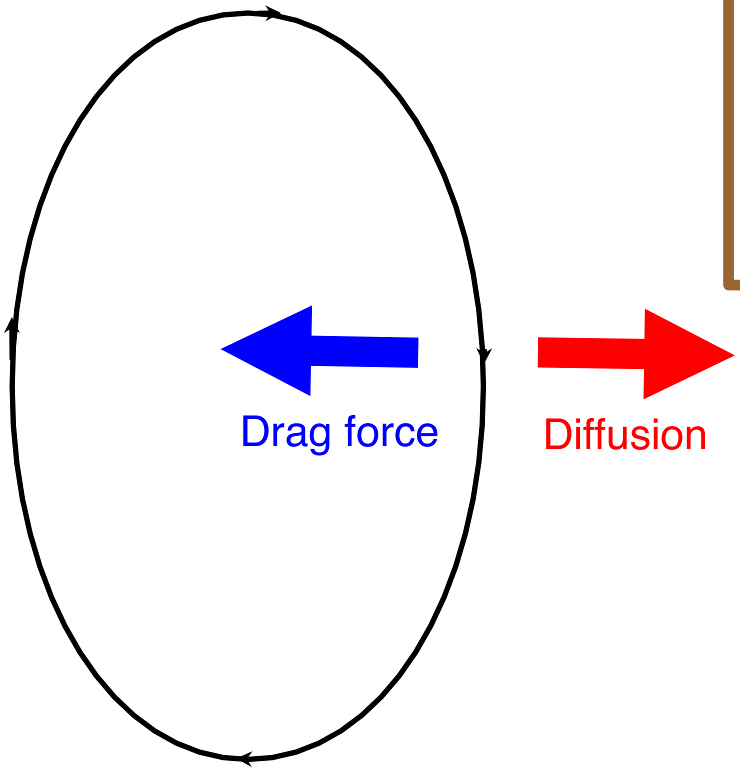
$$\frac{\partial \rho_d}{\partial t} = -(\boldsymbol{v} \cdot \boldsymbol{\nabla})\rho_d - \rho_d \boldsymbol{\nabla} \cdot \boldsymbol{v} + D\nabla^2 \rho_d,$$

compression

advection

diffusion

Drag-Diffusion Equilibrium



Trapped particle

Steady-state solution

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

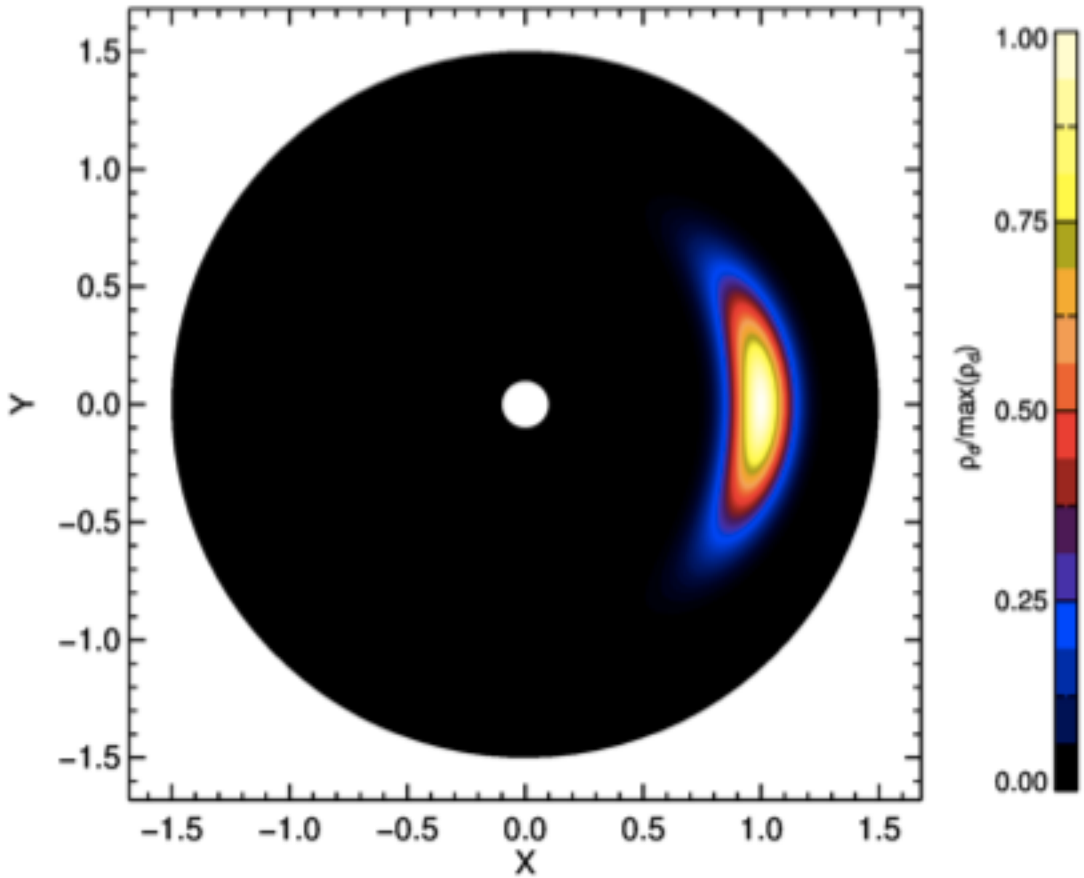
Lyra & Lin (2013)

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

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

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

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

Maximum dust density

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

Gas contrast

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

Dust contrast

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

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}

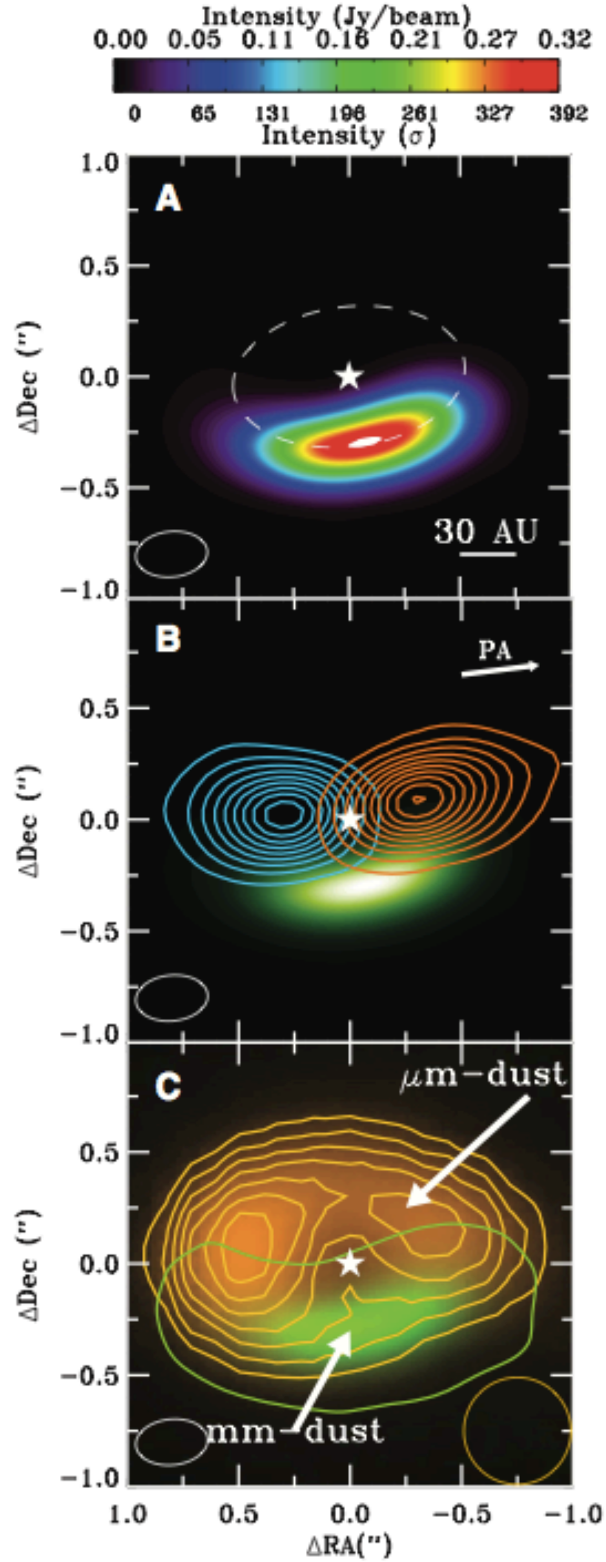
Derived parameters

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)

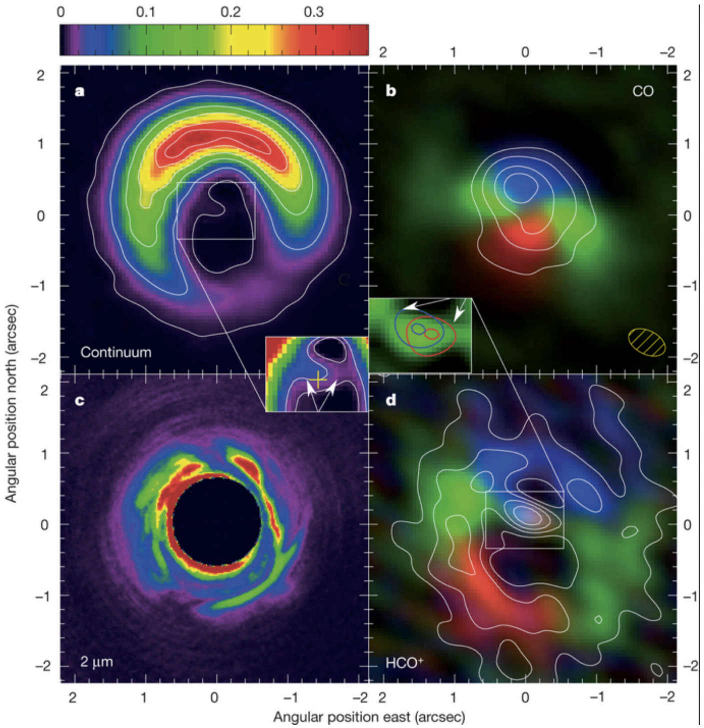
HD 142527

Observed parameters

Aspect ratio: 10

Dust contrast: 30

Temperature: 25K

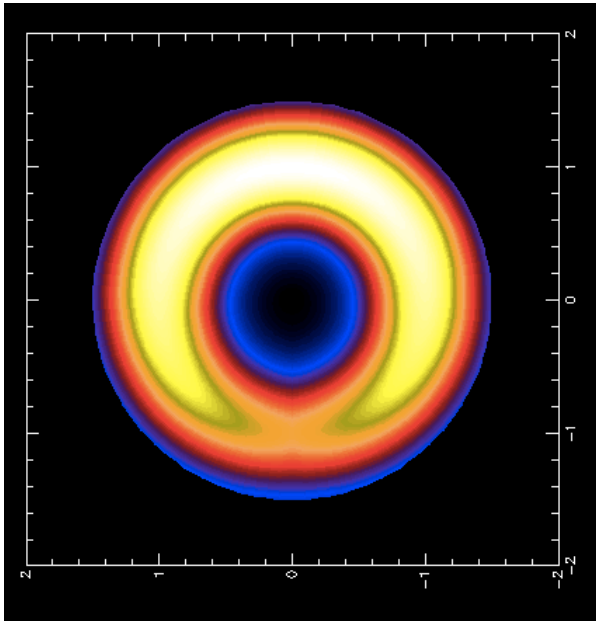


Derived parameters

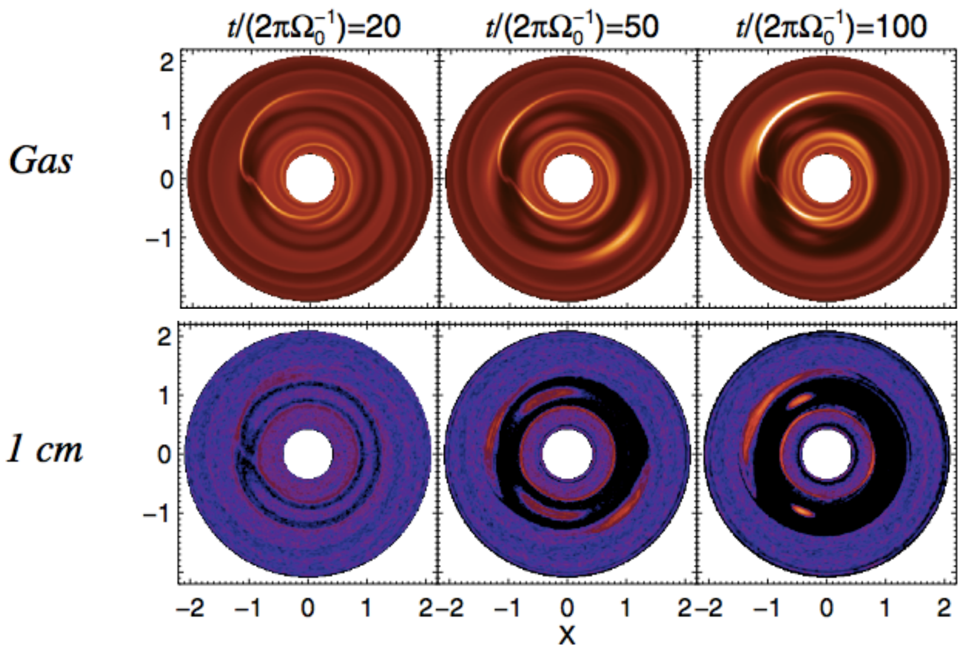
S=3.5

Stokes number, St=0.004

$\delta = 0.001$, $v_{rms} = 4\% \, c_s$



Planetary gap vortices: Chicken or the Egg problem

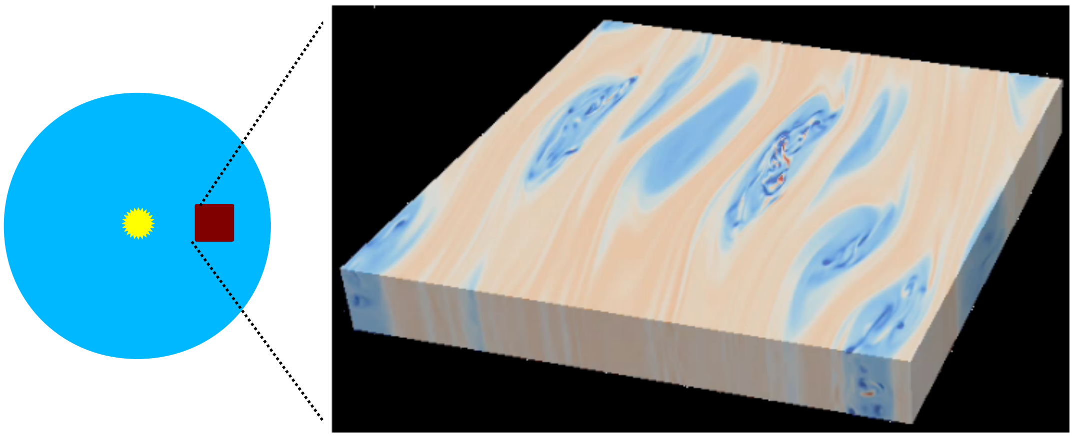


Lyra et al (2009b)

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

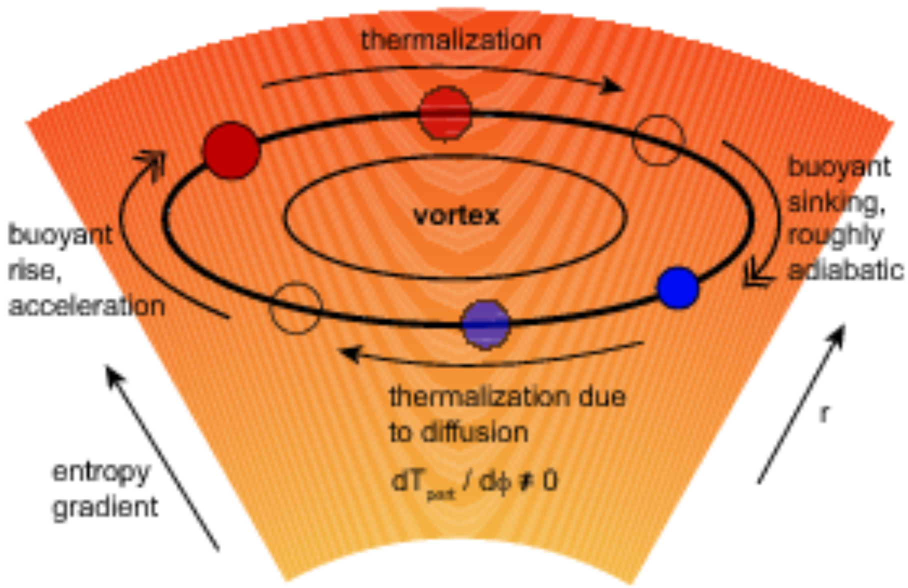
Armitage (2013)

Convective Overstability
Vortices without planets



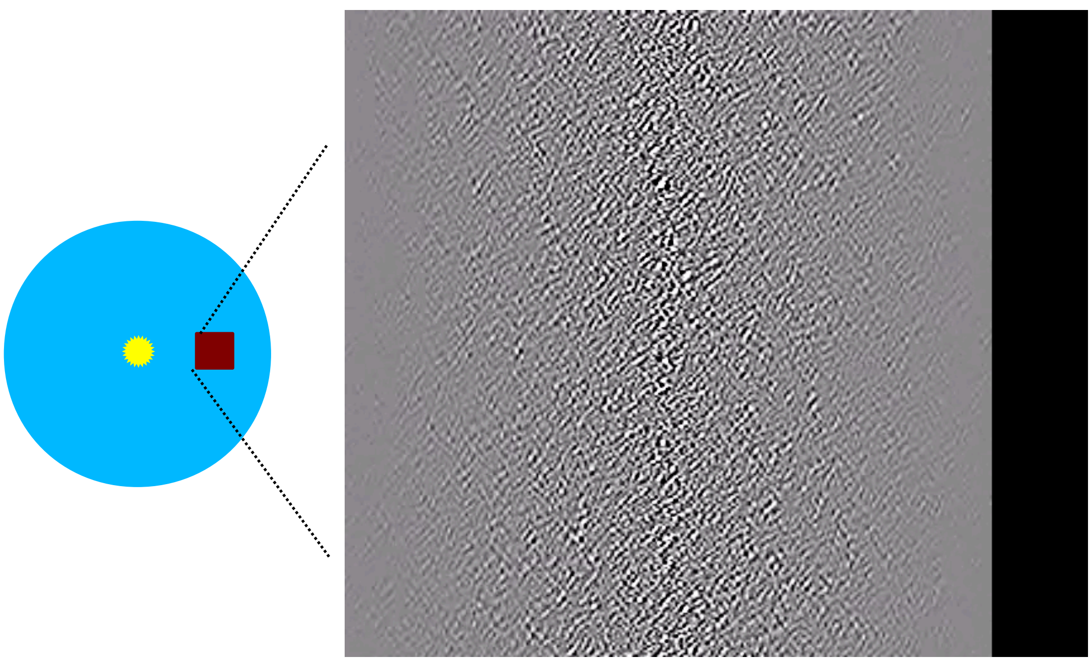
Lesur & Papaloizou (2010)

Sketch of the
Convective Overstability



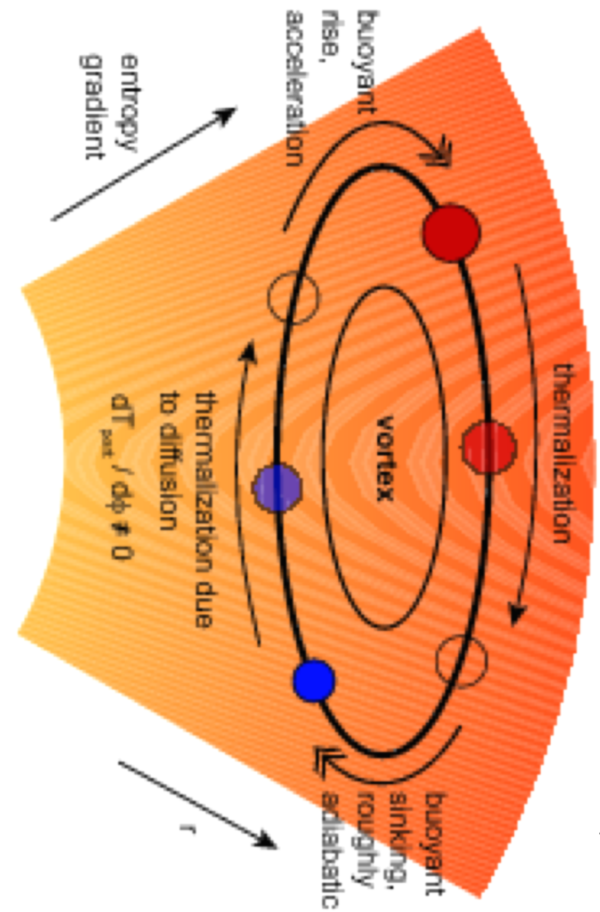
Armitage (2010)

Convective Overstability
Vortices without planets



Lyra & Klahr (2011)

Sketch of the Convective Overstability

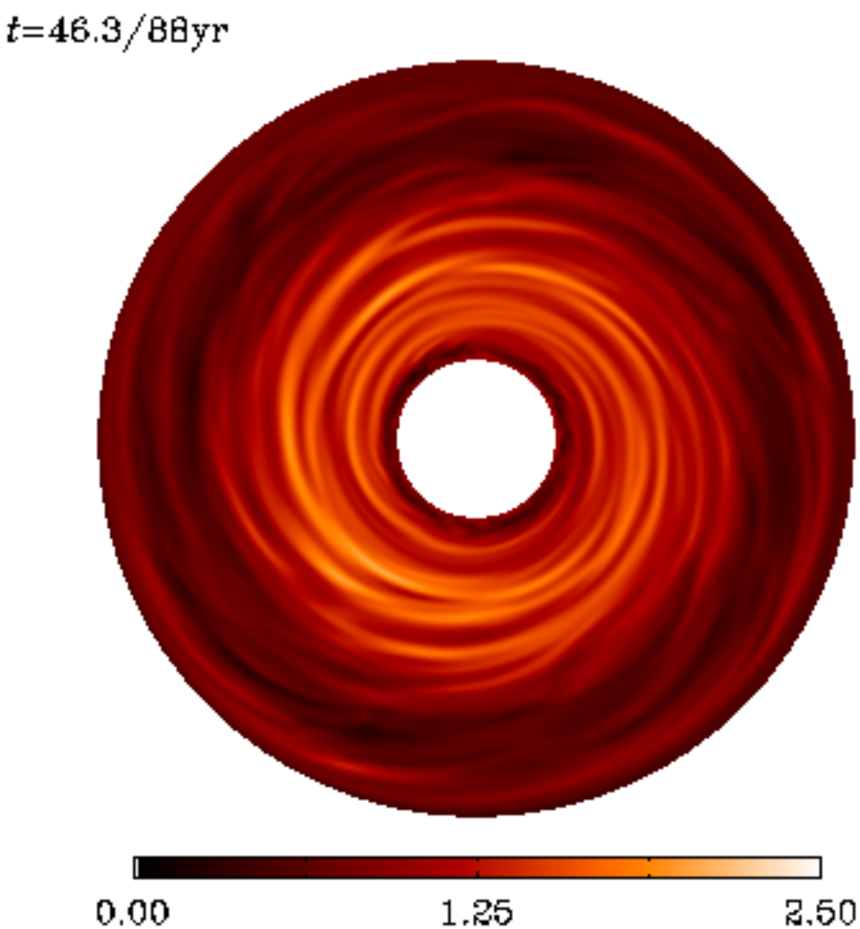


Armitage (2010

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

Magneto-Rotational Instability

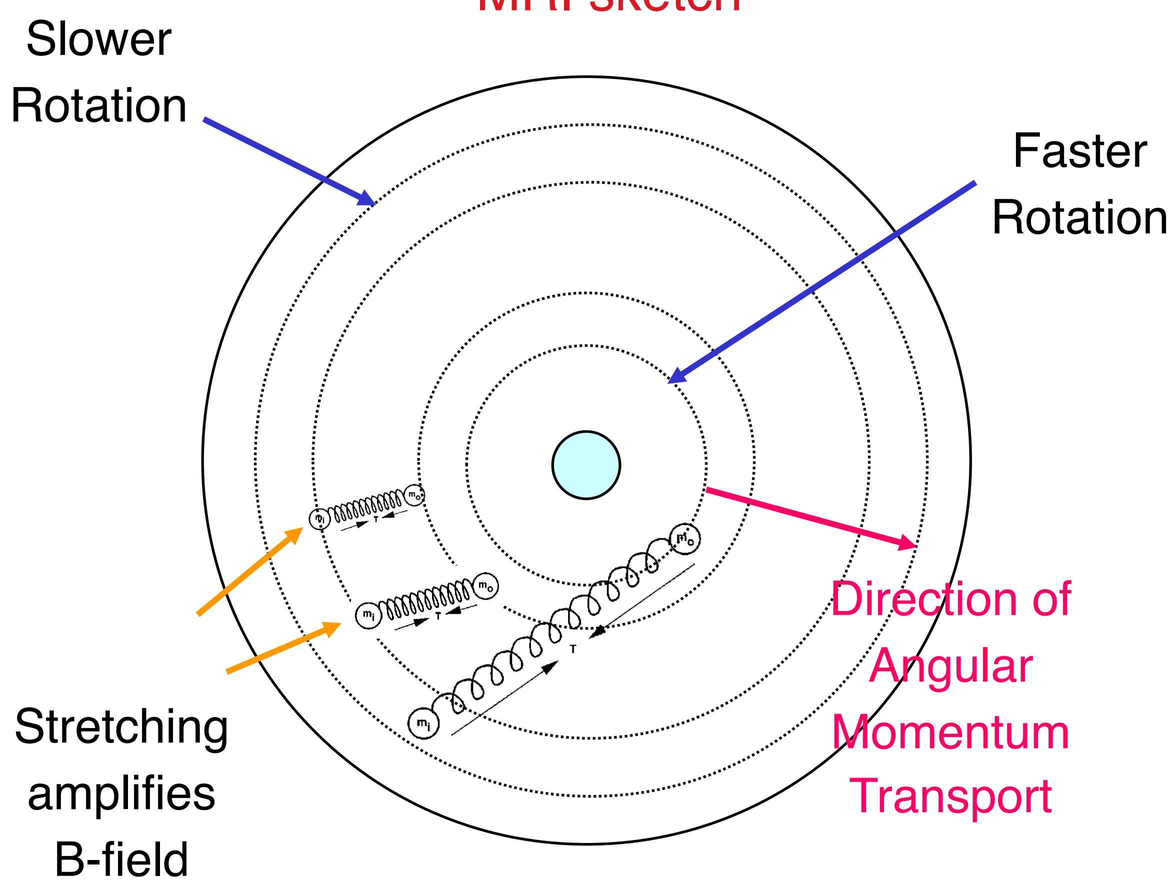
Turbulence in disks is enabled by the
Magneto-Rotational Instability (Balbus & Hawley, 1991)



Magnetized disk

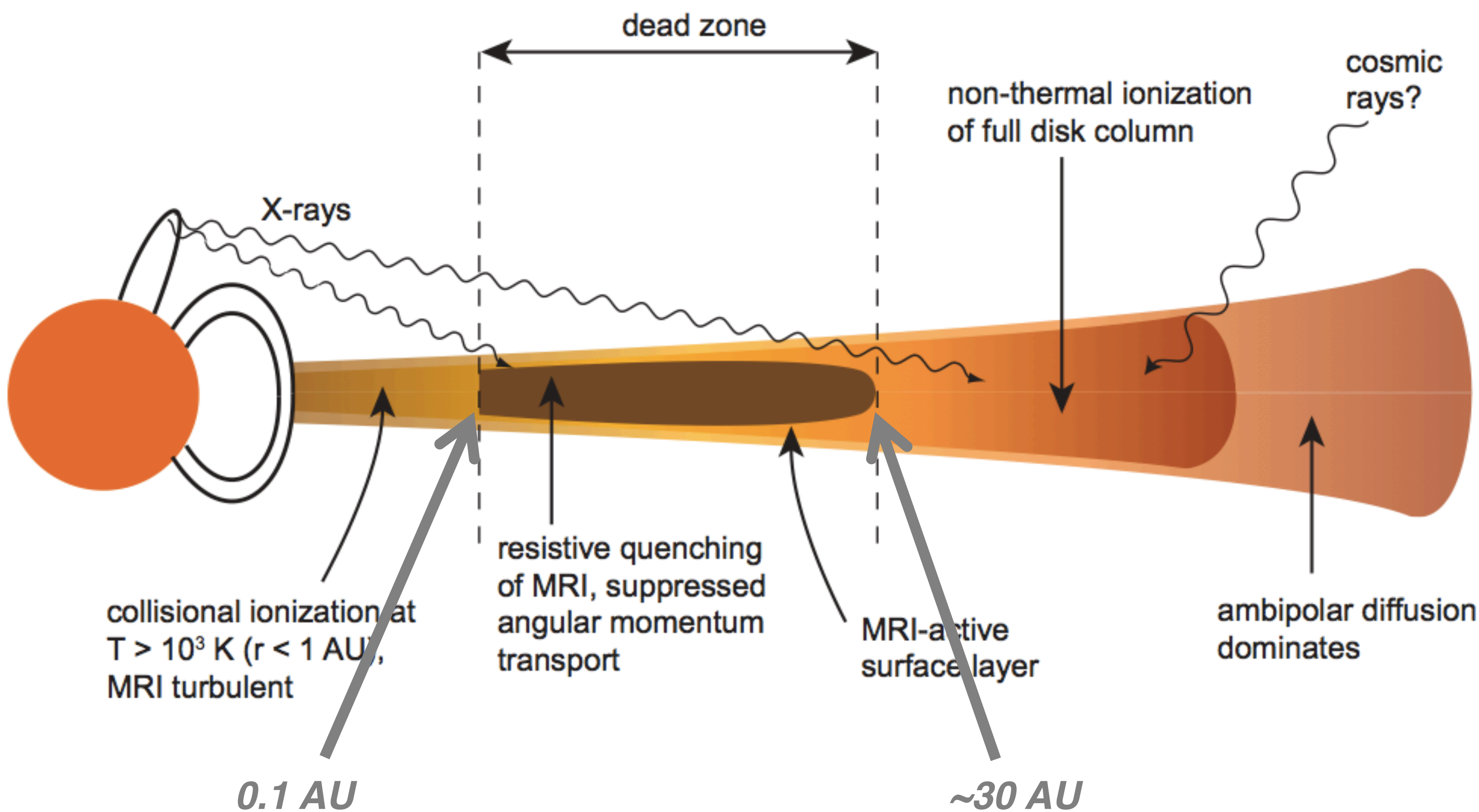
Lyra et al. (2008a)

MRI sketch



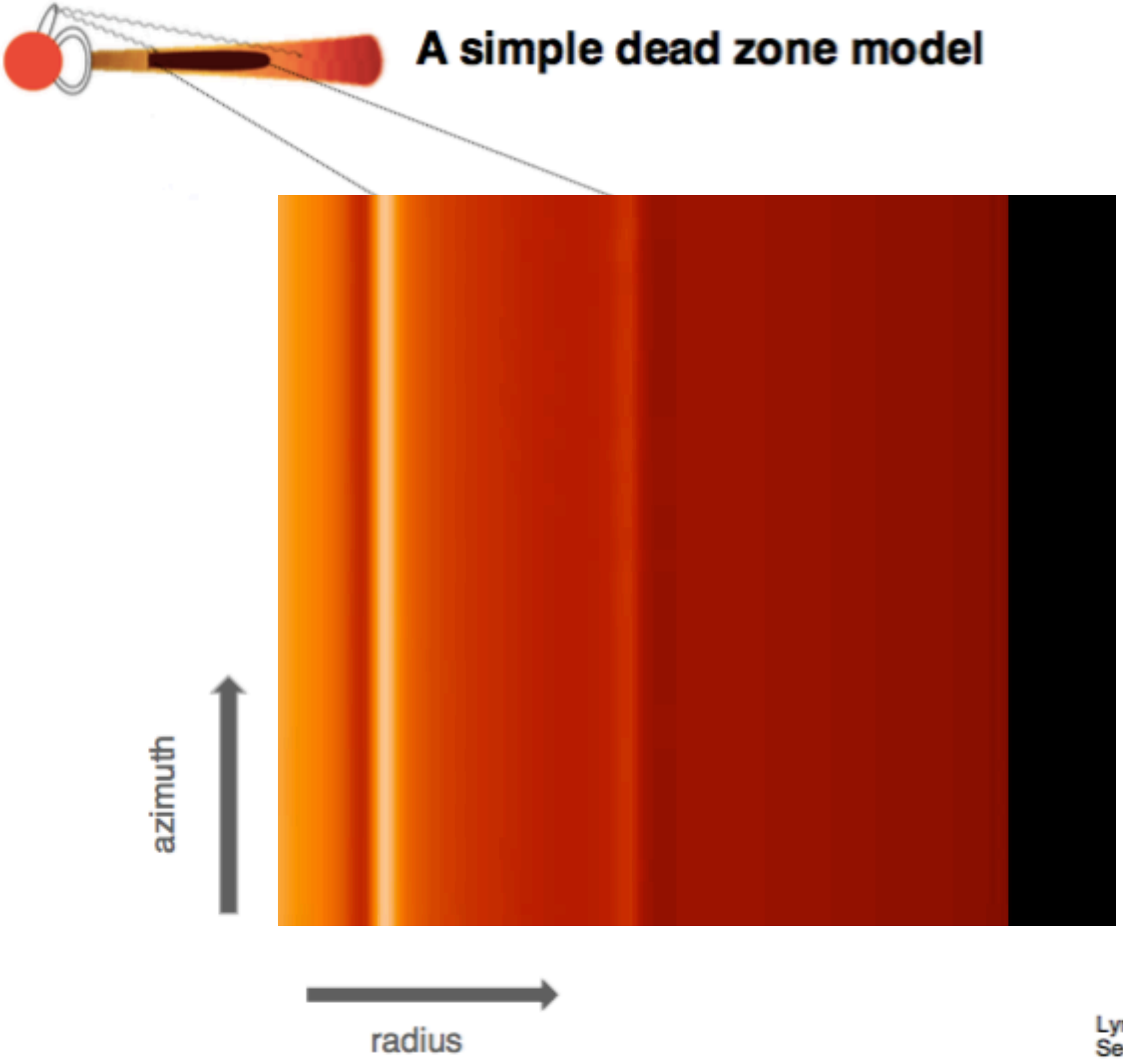
Unstable if angular velocity decreases outward

Dead zones



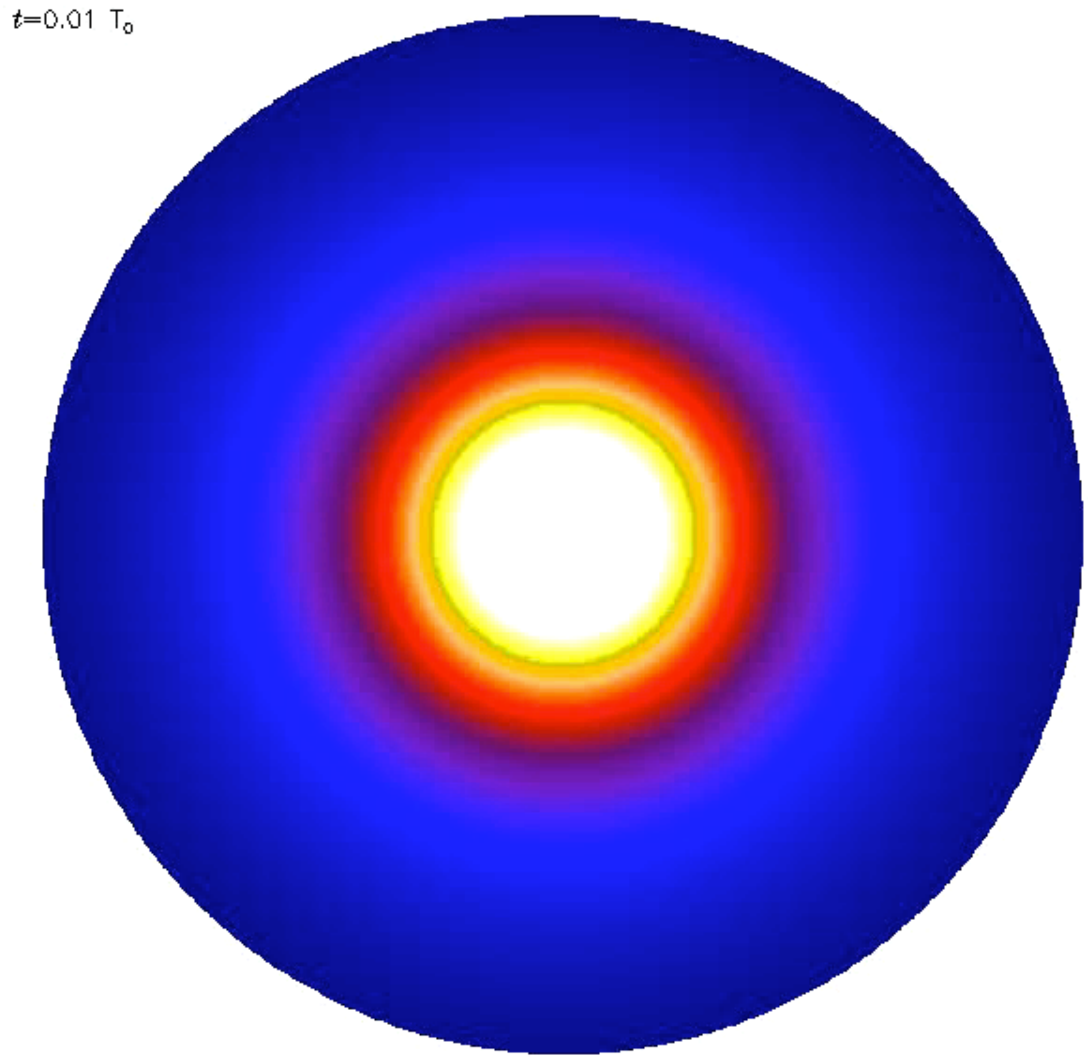
dead zone
non-thermal ionization
of full disk column
cosmic
rays?
X-rays
resistive quenching
of MRI, suppressed
angular momentum
transport
collisional ionization at
T > 10³ K (r < 1 AU),
MRI turbulent
MRI-active
surface layer
ambipolar diffusion
dominates
0.1 AU
~30 AU

A simple dead zone model



Lyra et al. (2008b, 2009a);
See also Varniere & Tagger (2006)

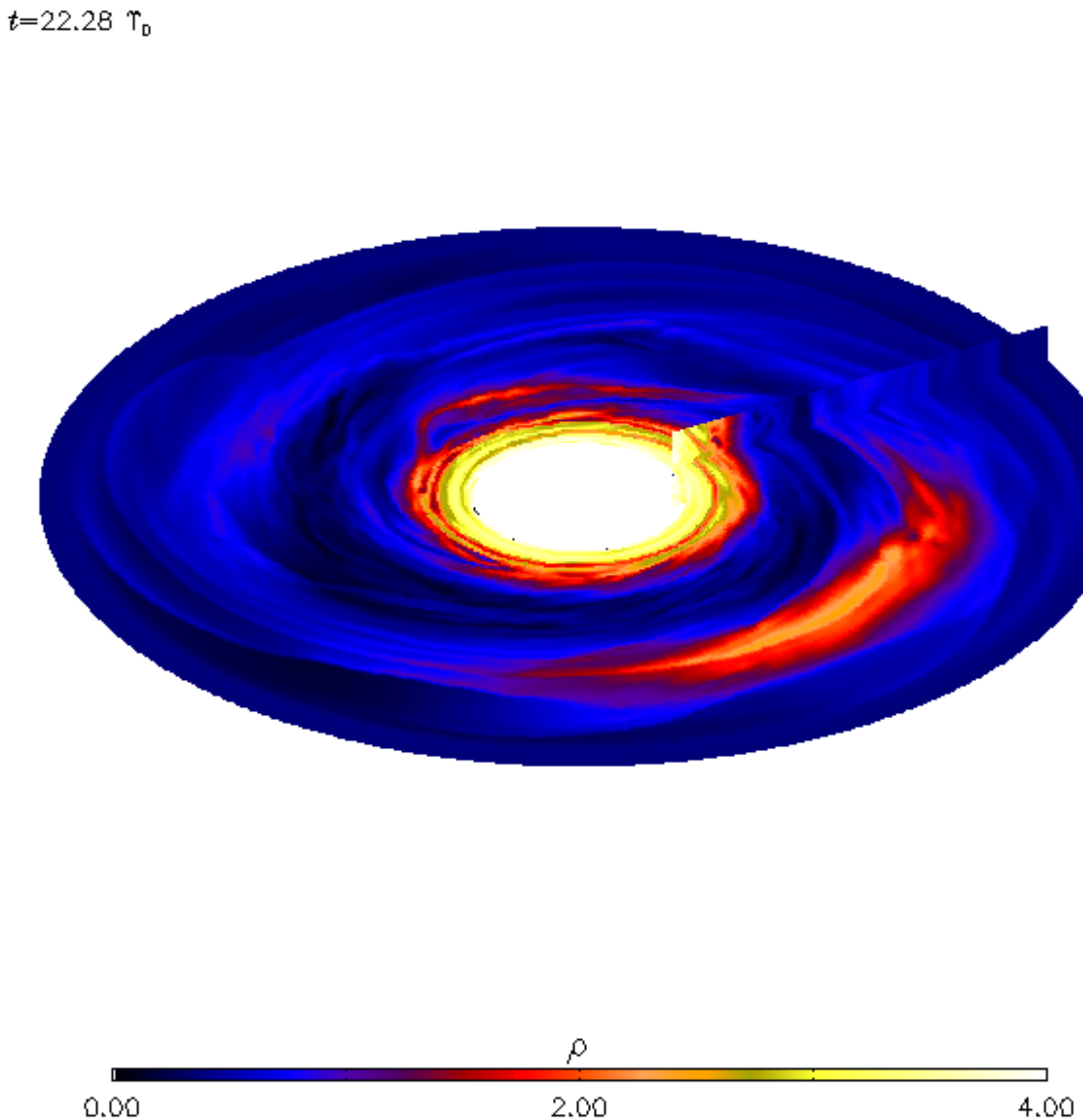
Inner (0.1 AU) active/dead zone boundary

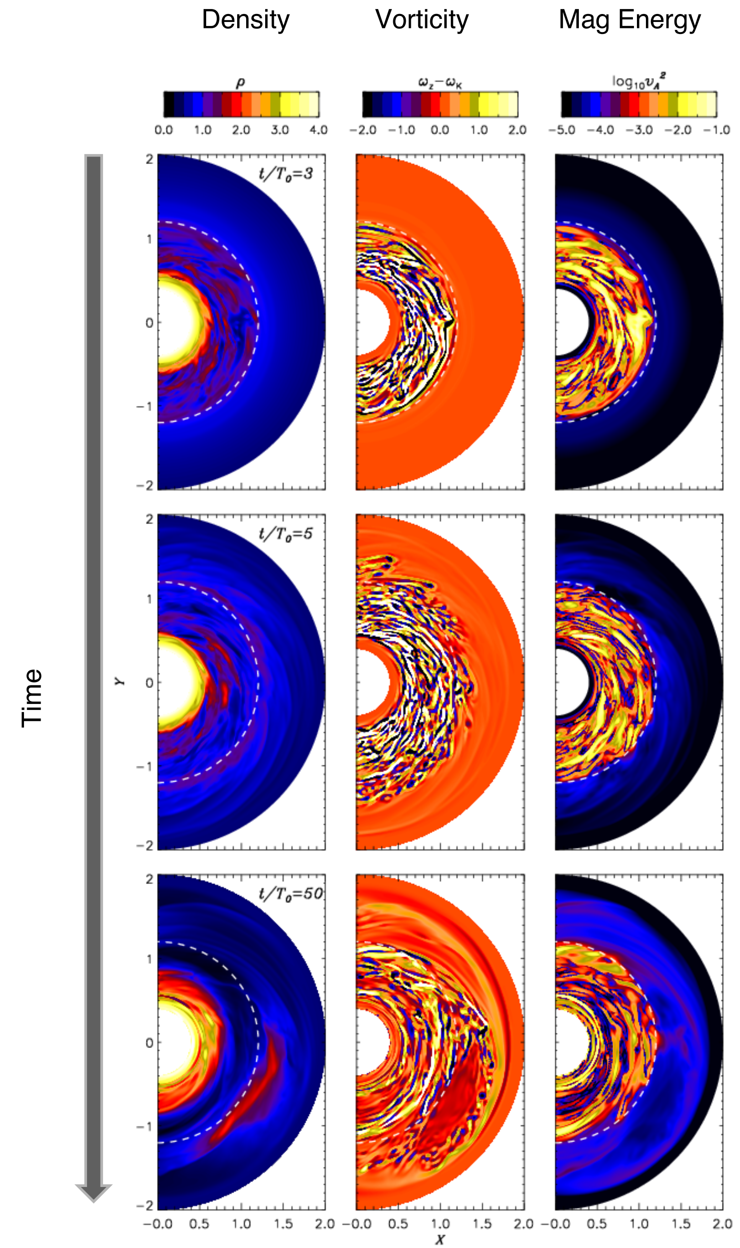


Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Inner (0.1AU) active/dead zone boundary

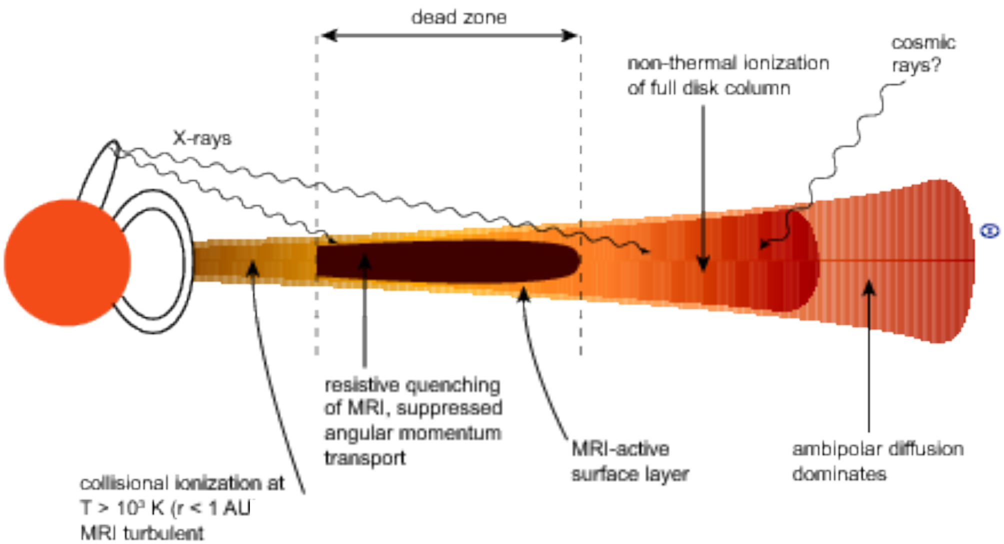




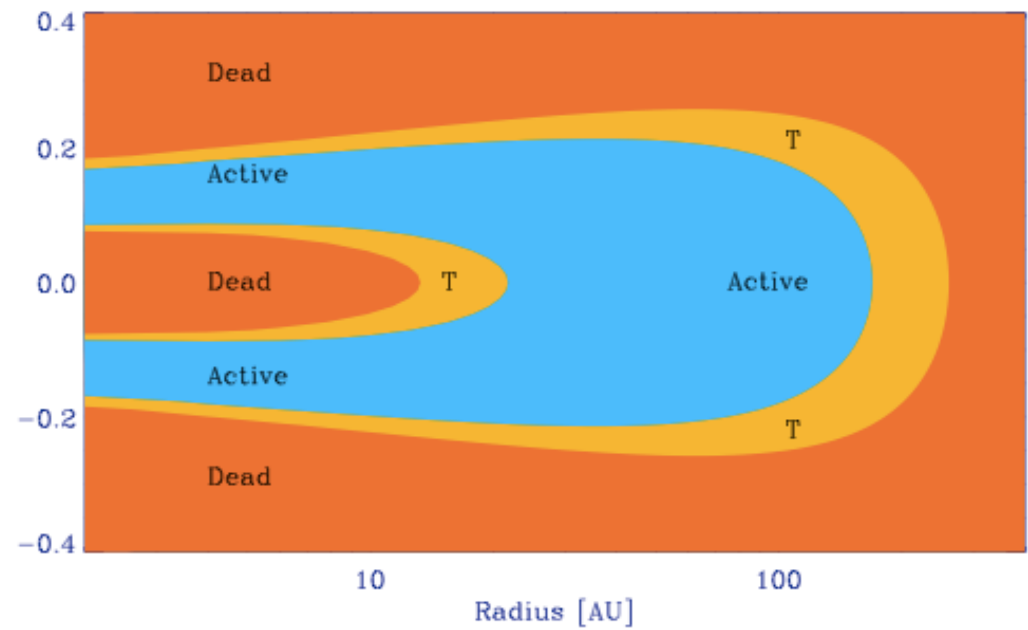
Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Outer Dead/Active zone transition KHI



Armitage (2010)



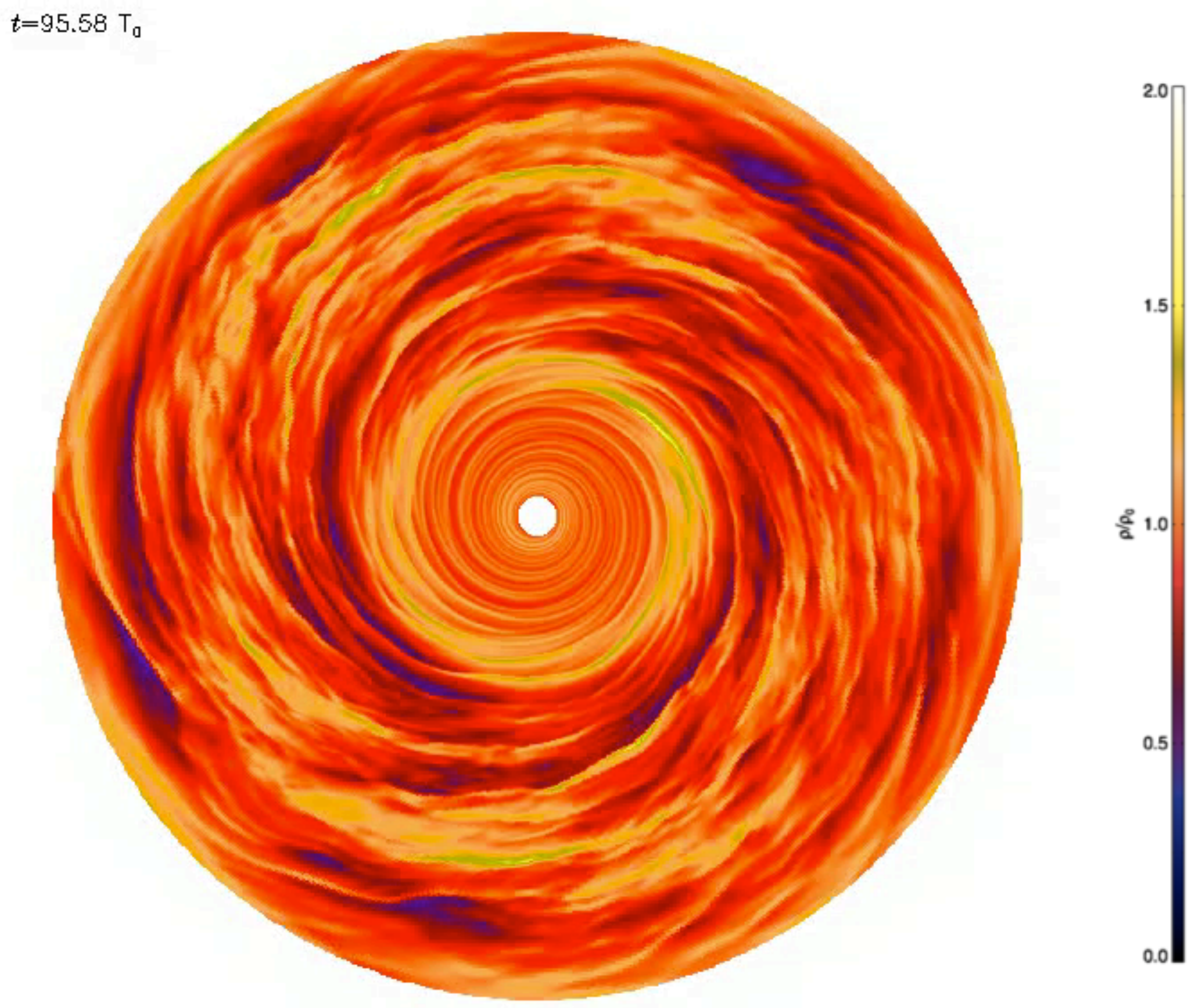
Dzyurkevitch et al (2013)

The **outer** dead zone transition in ionization supposed

TOO SMOOTH

to generate an KH-unstable bump.

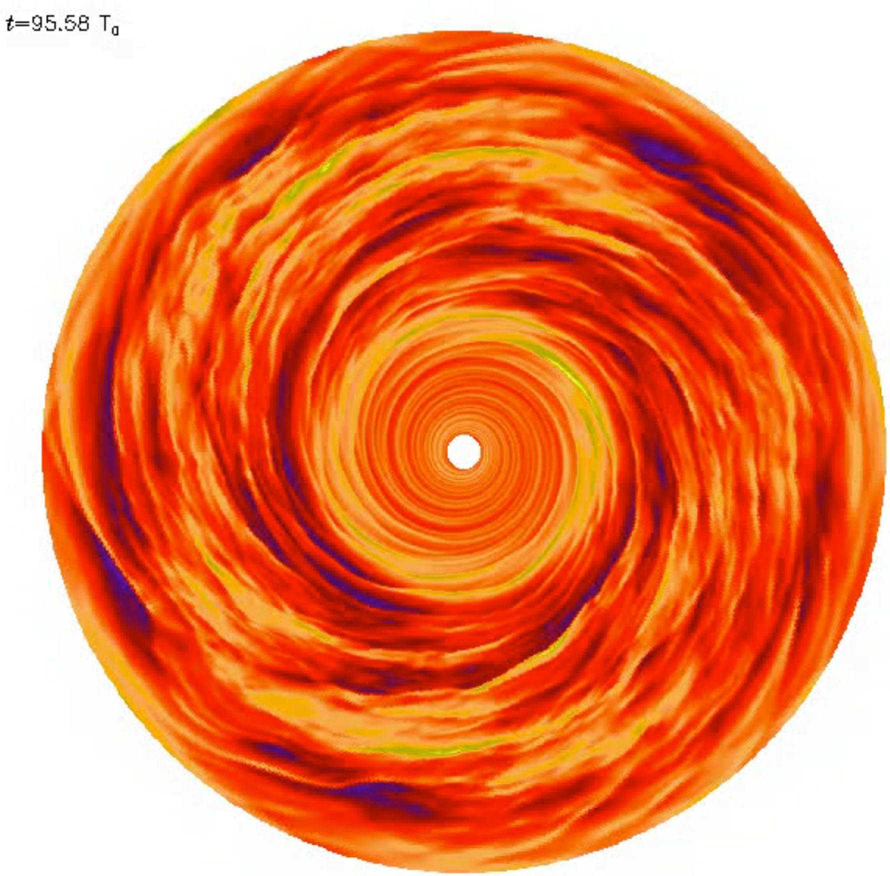
Outer Dead/Active zone transition: 3D MHD

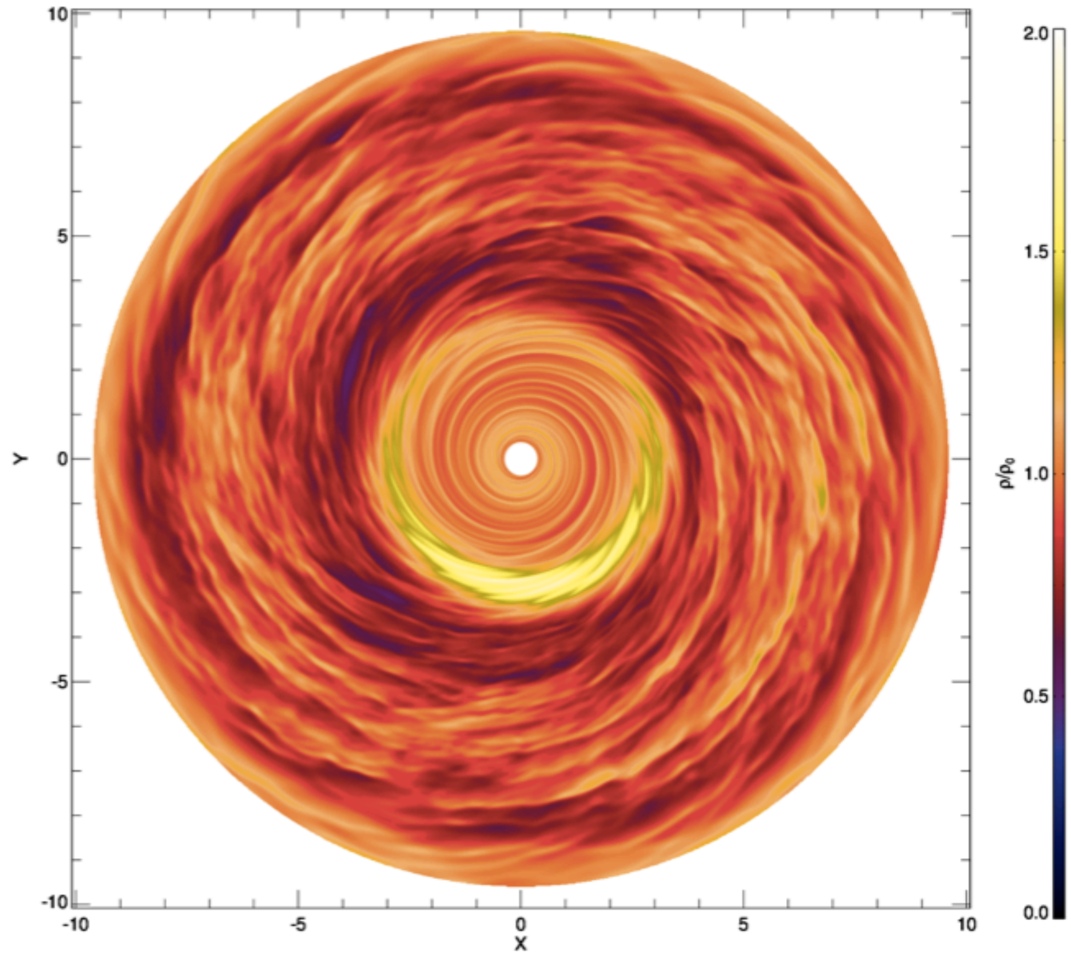


Resistive inner disk + magnetized outer disk

Lyra et al (2015)

Outer Dead/Active zone transition KHI

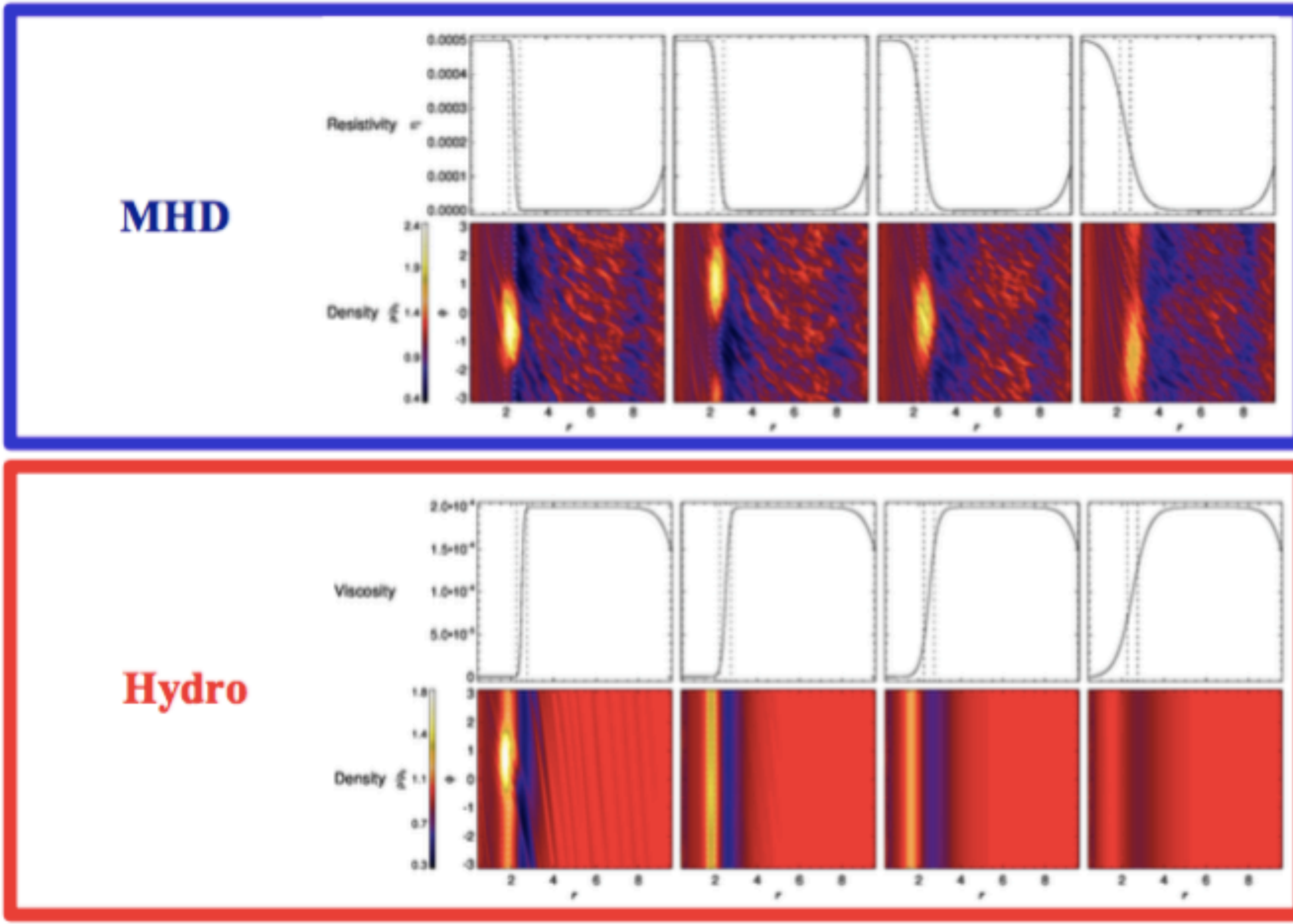




Resistive inner disk + magnetized outer disk

Lyra, Turner, & McNally (2015)

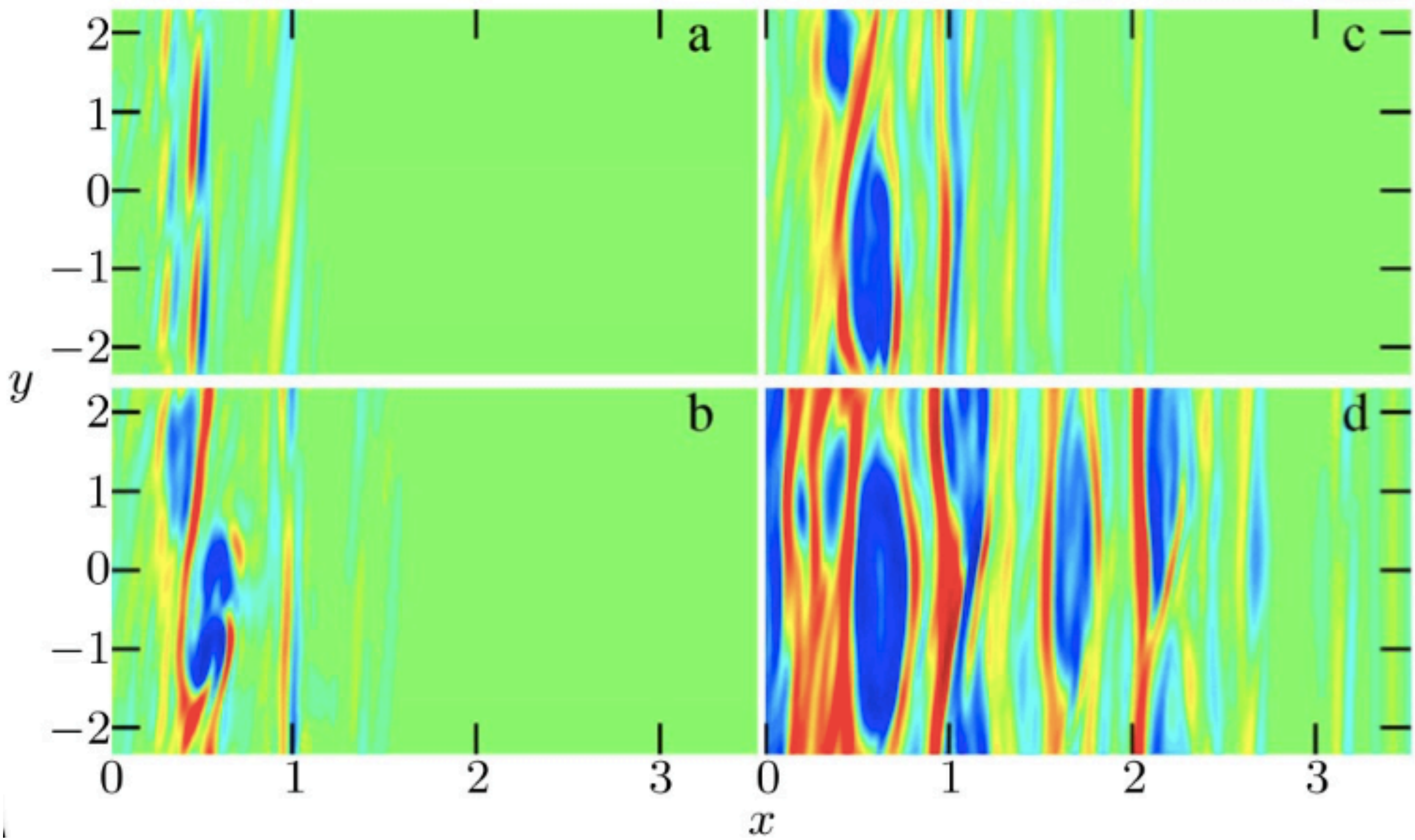
Outer Dead/Active zone transition RWI



Lyra, Turner, & McNally (2015)

Other Dead Zone Instabilities

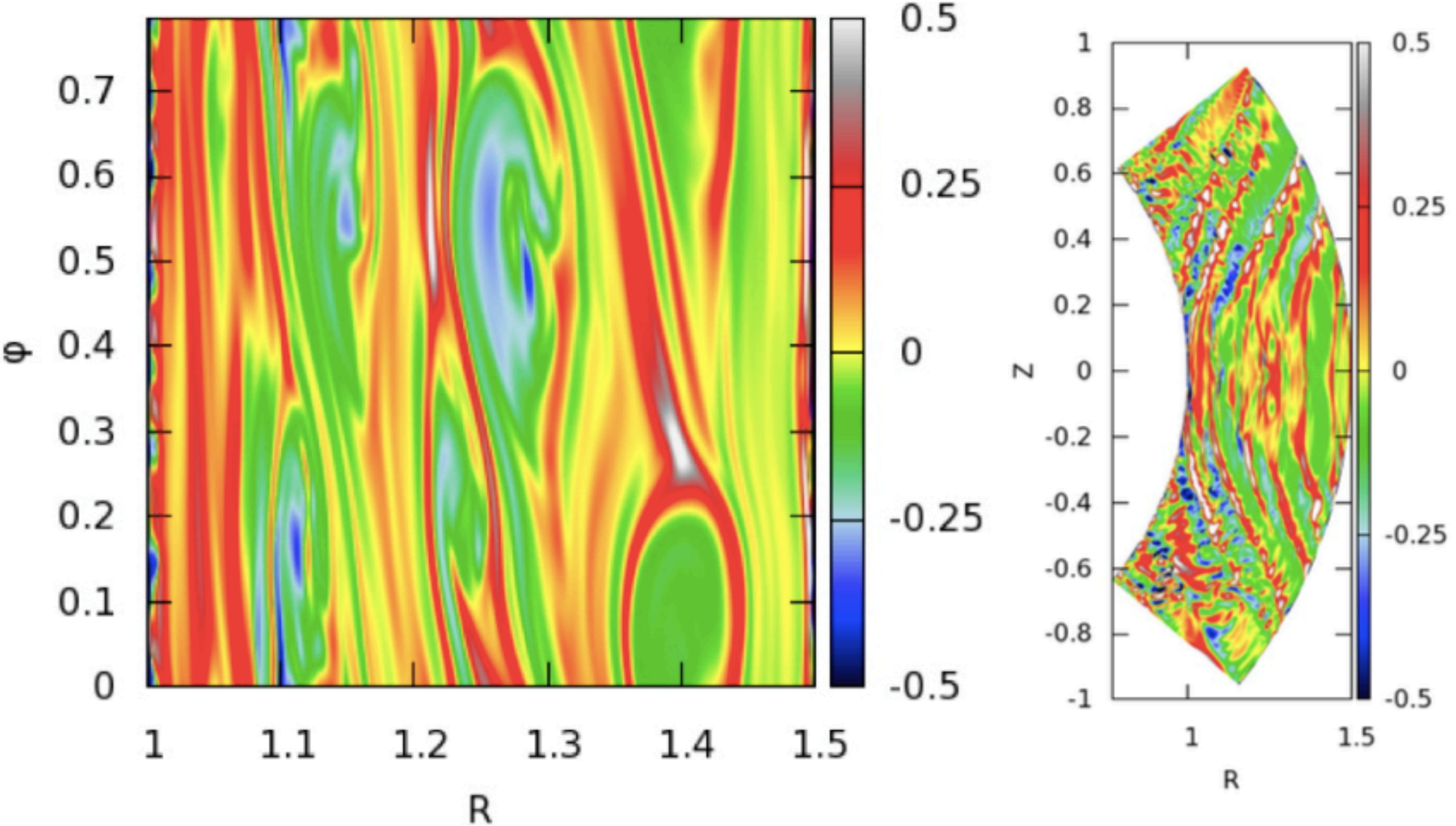
Zombie Vortex Instability



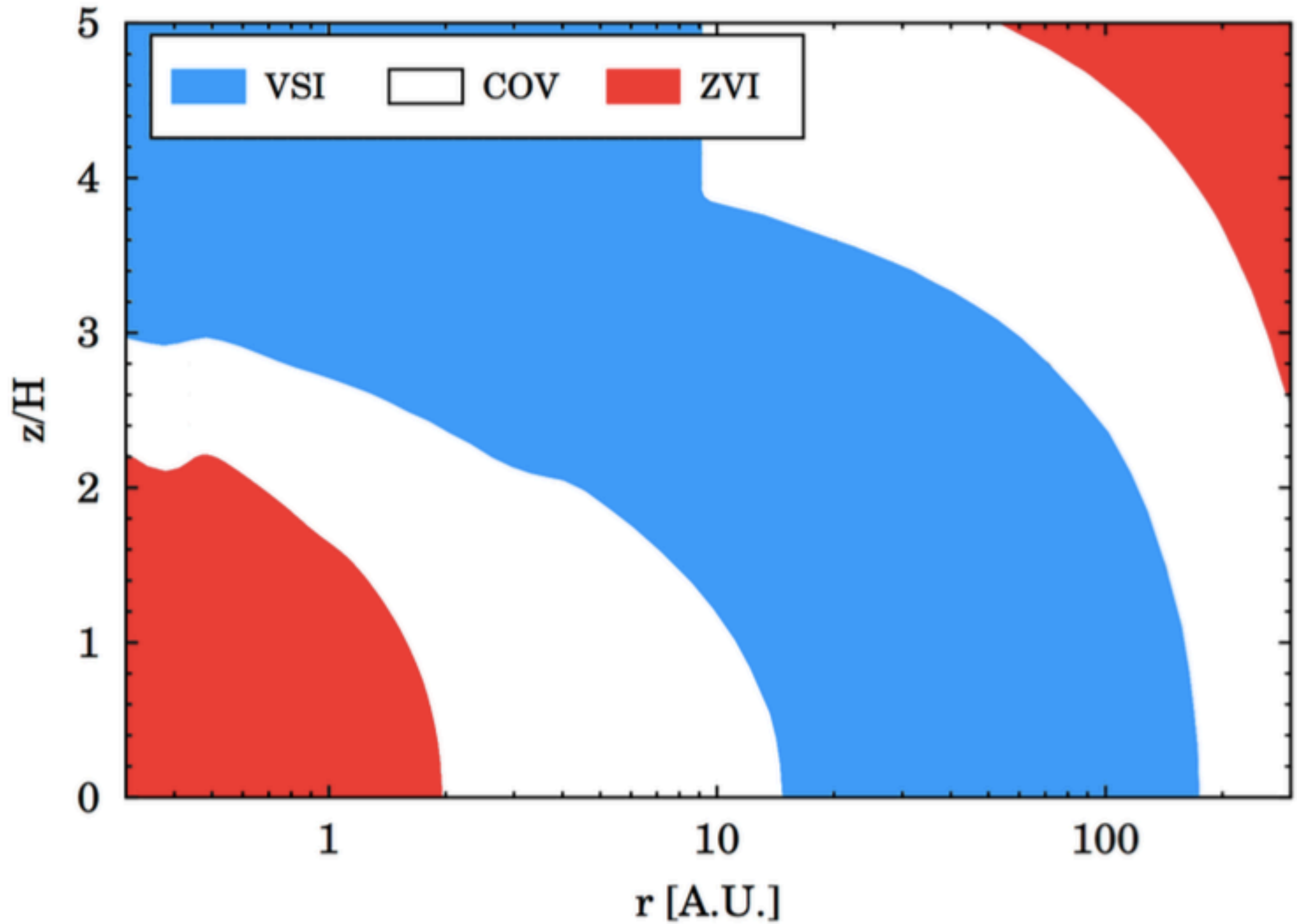
Marcus et al. (2015, 2016)

Other Dead Zone Instabilities

Vertical Shear Instability



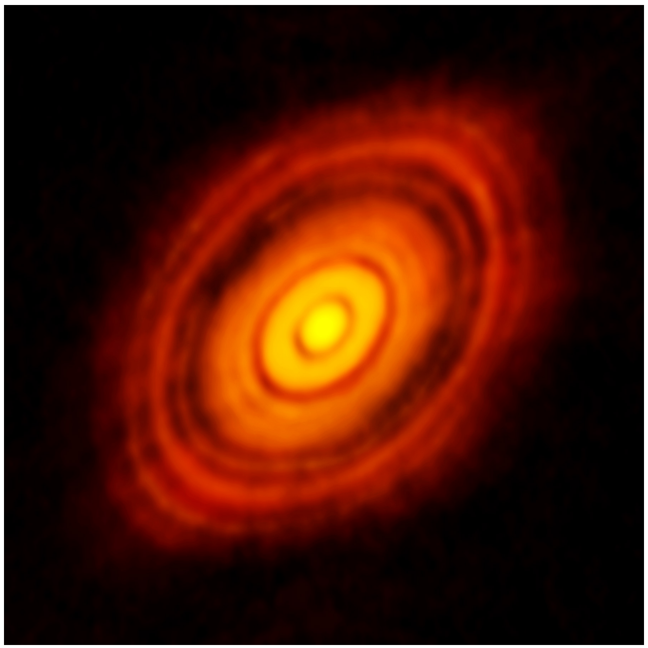
Nelson et al. (2013)



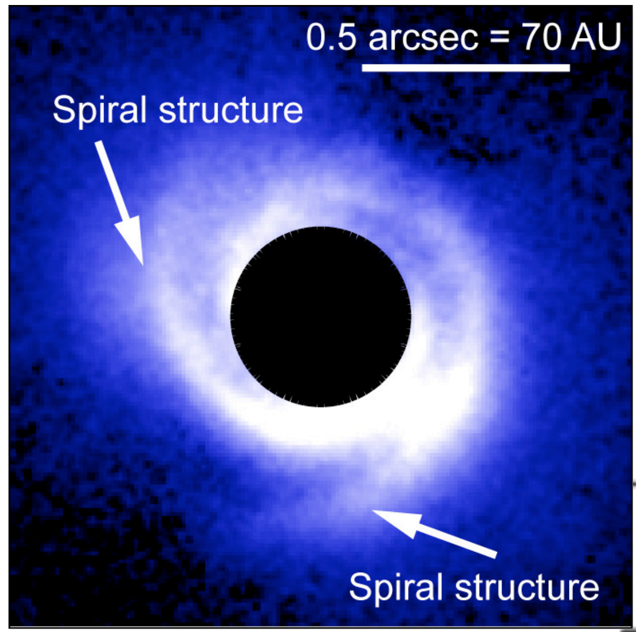
Umurhan (2016), Umurhan & Lyra (2017, in prep)

Observational evidence: gaps, spirals, and vortices

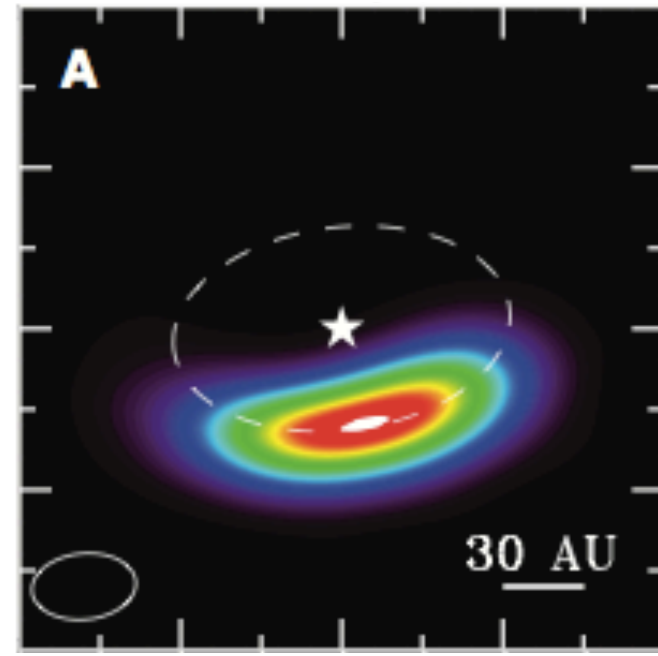
HL Tau



SAO 206462

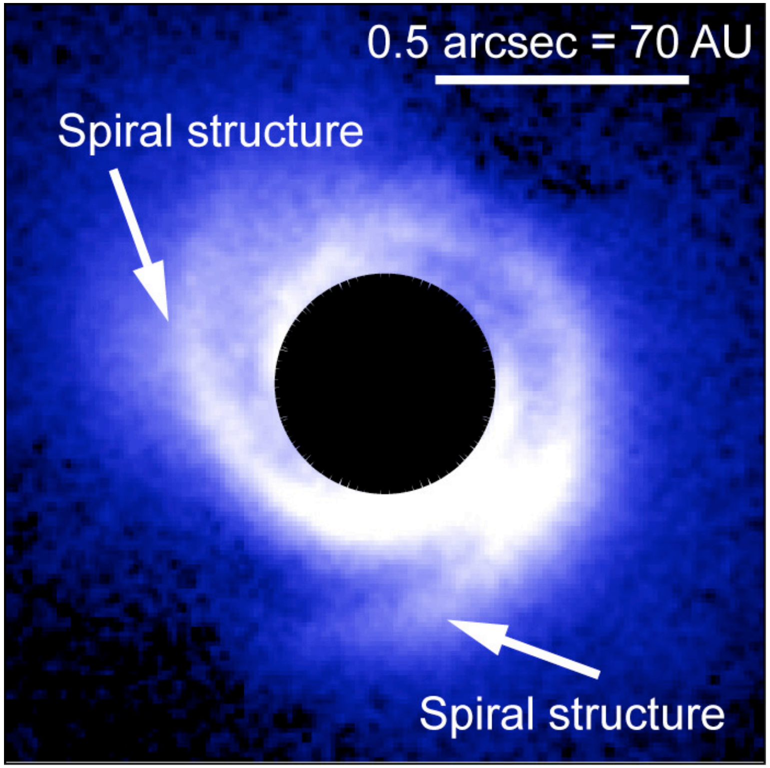


Oph IRS 48



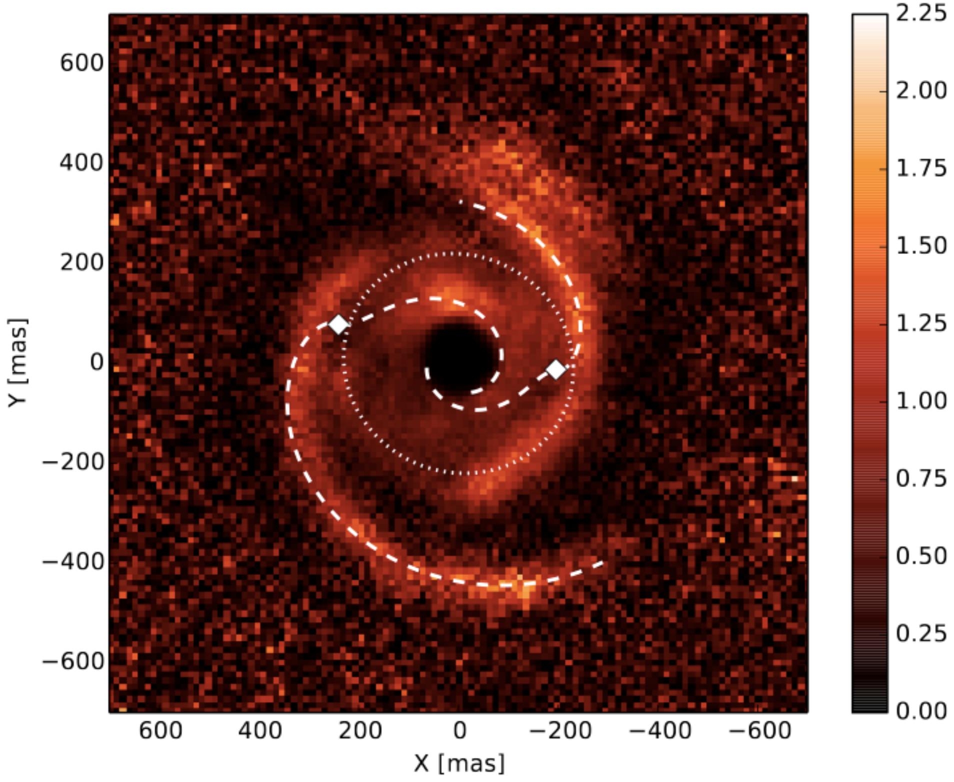
Observational evidence: Spirals

SAO 206462



Muto et al. (2012)

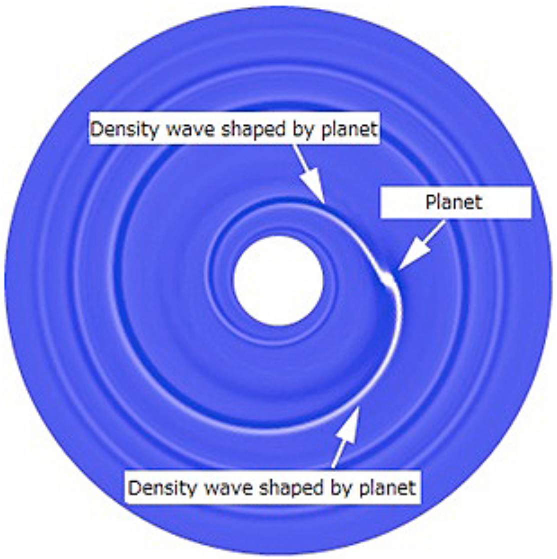
MWC 748



Benisty et al. (2015)

Spiral arm fitting leads to problems

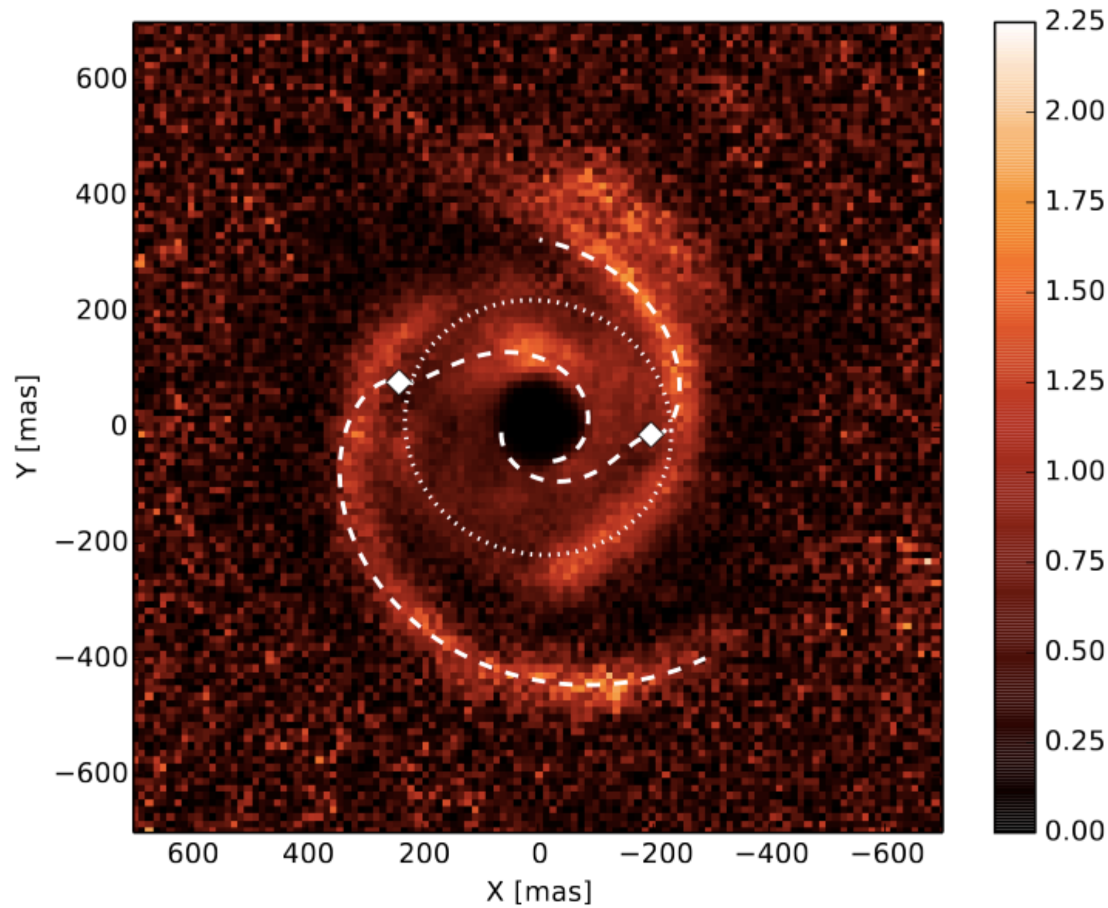
Analytical spiral fit



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

Rafikov (2002)
Muto et al. (2012)

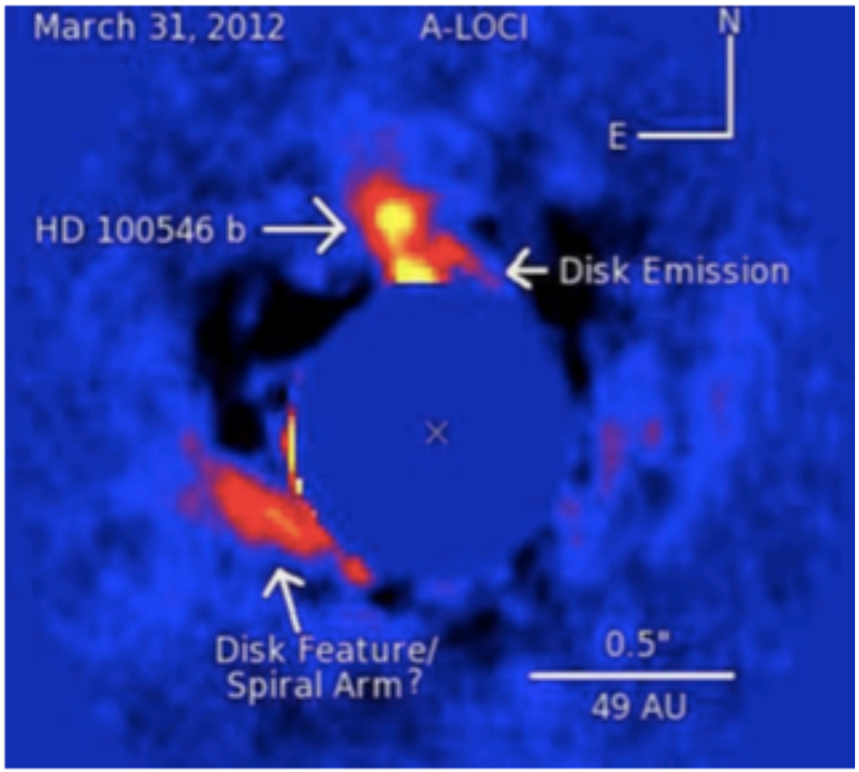
Spirals are **too wide**,
hotter (300K) than ambient gas (50K).



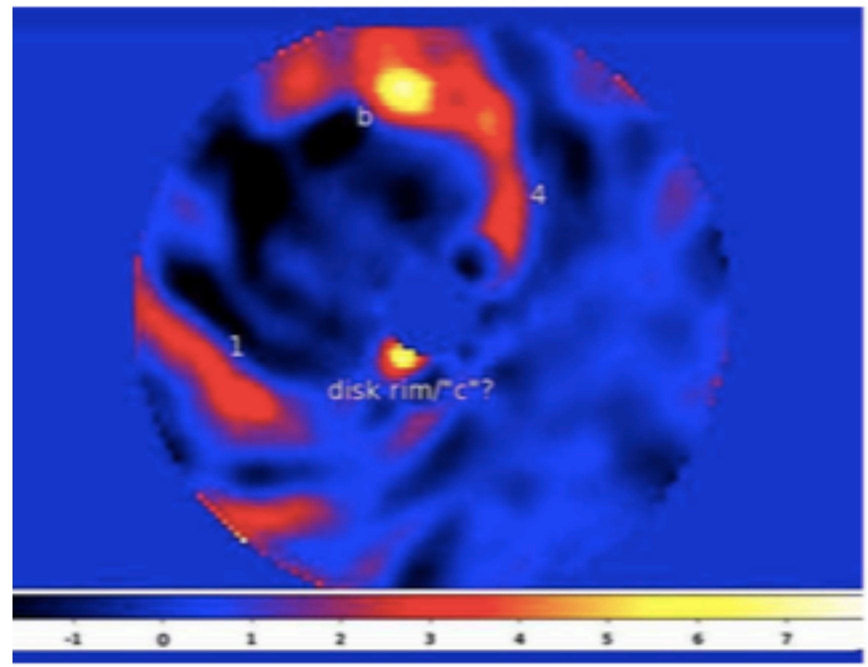
Benisty et al. (2015)

The strange case of thermal emission in HD 100546

L band (~3.5 μm)

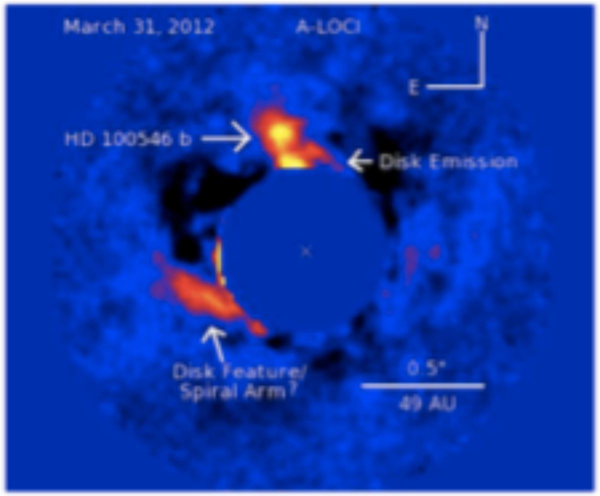


H band (~1.6 μm)

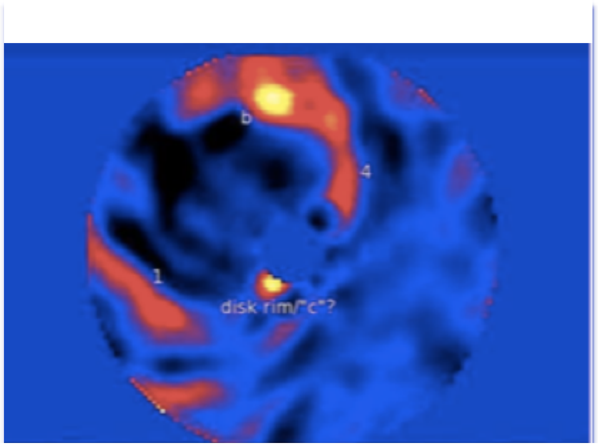


Currie et al. (2014), Currie et al. (2015)

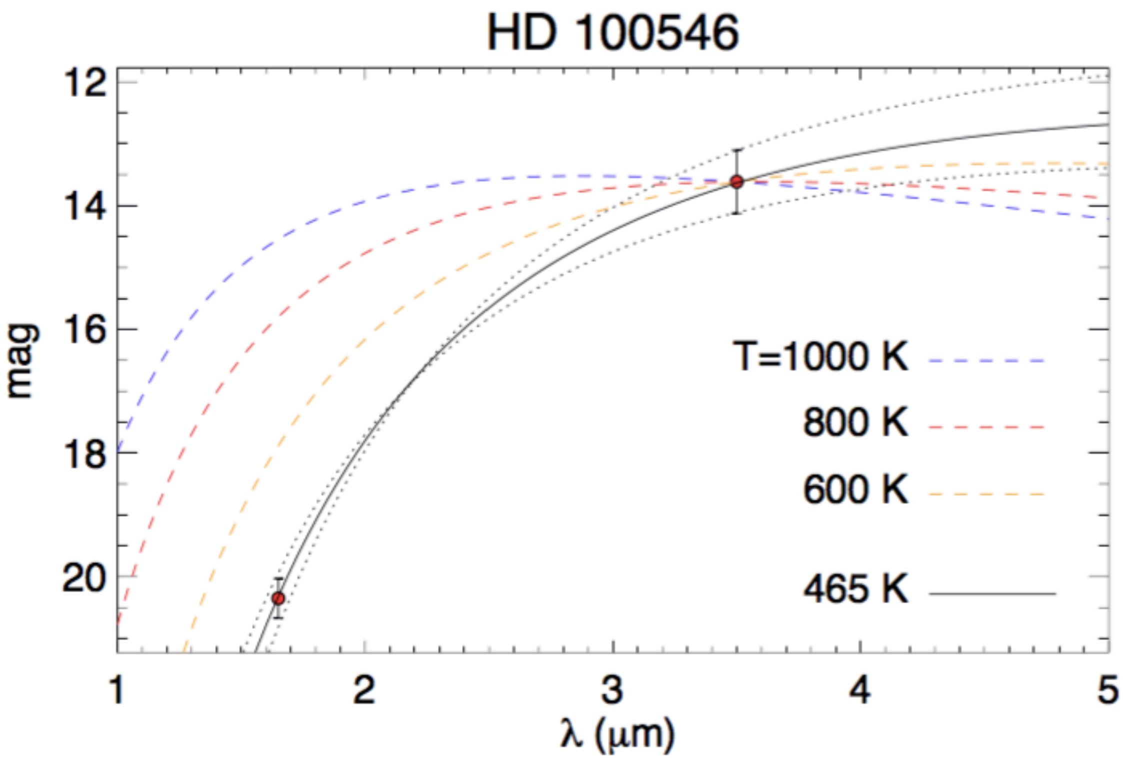
Pinning down the temperature



L band

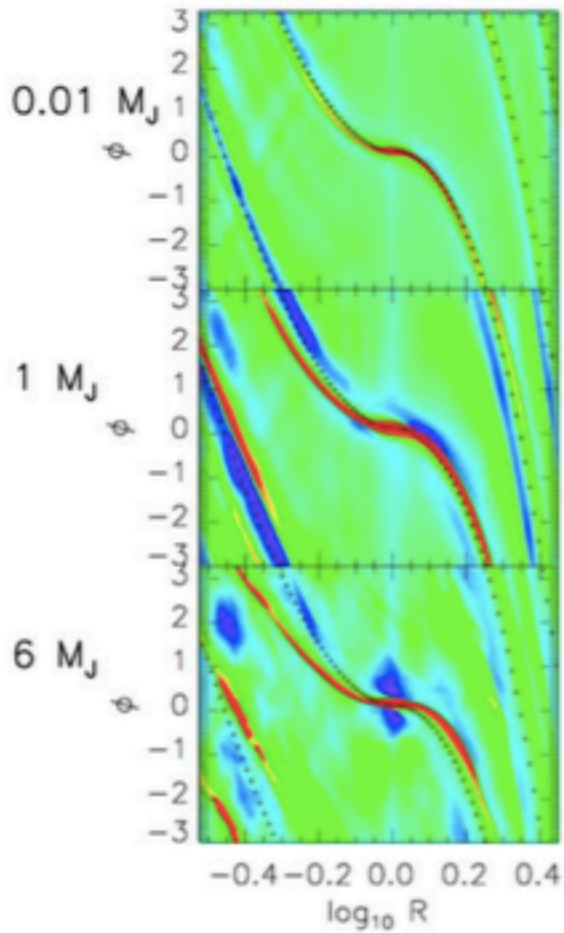


H band



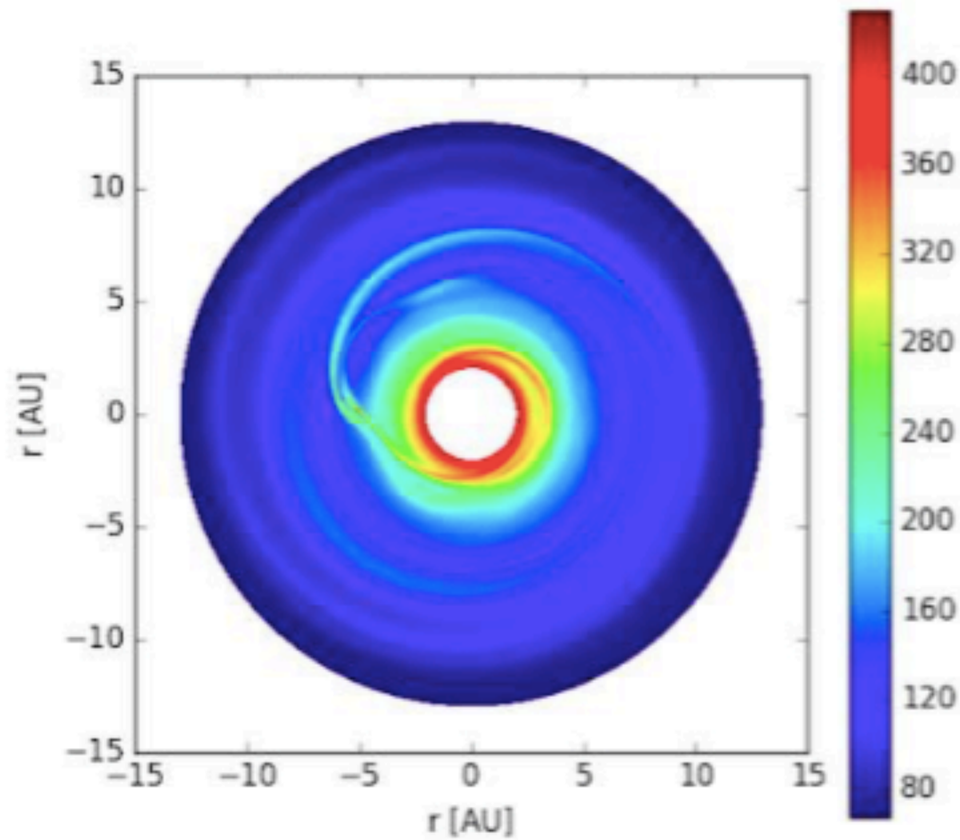
Lyra et al. (2016)

Supersonic Wakes of High Mass Planets



Density

Zhu et al. (2015)

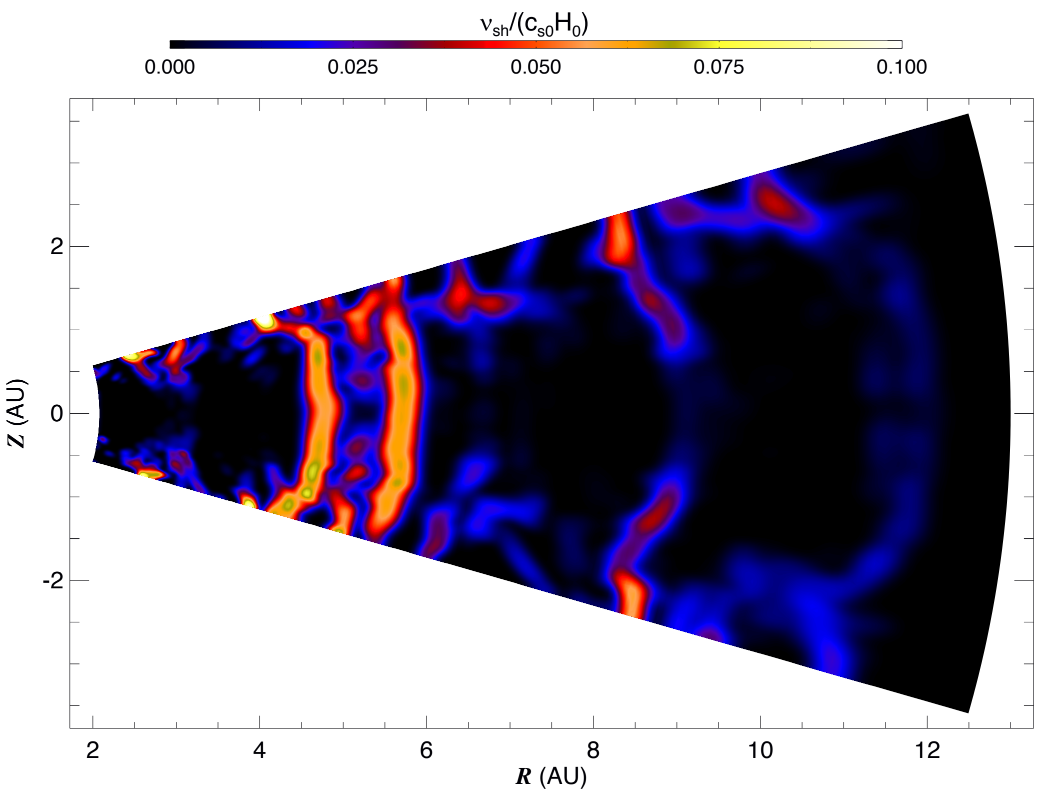


Temperature - **5M_J**

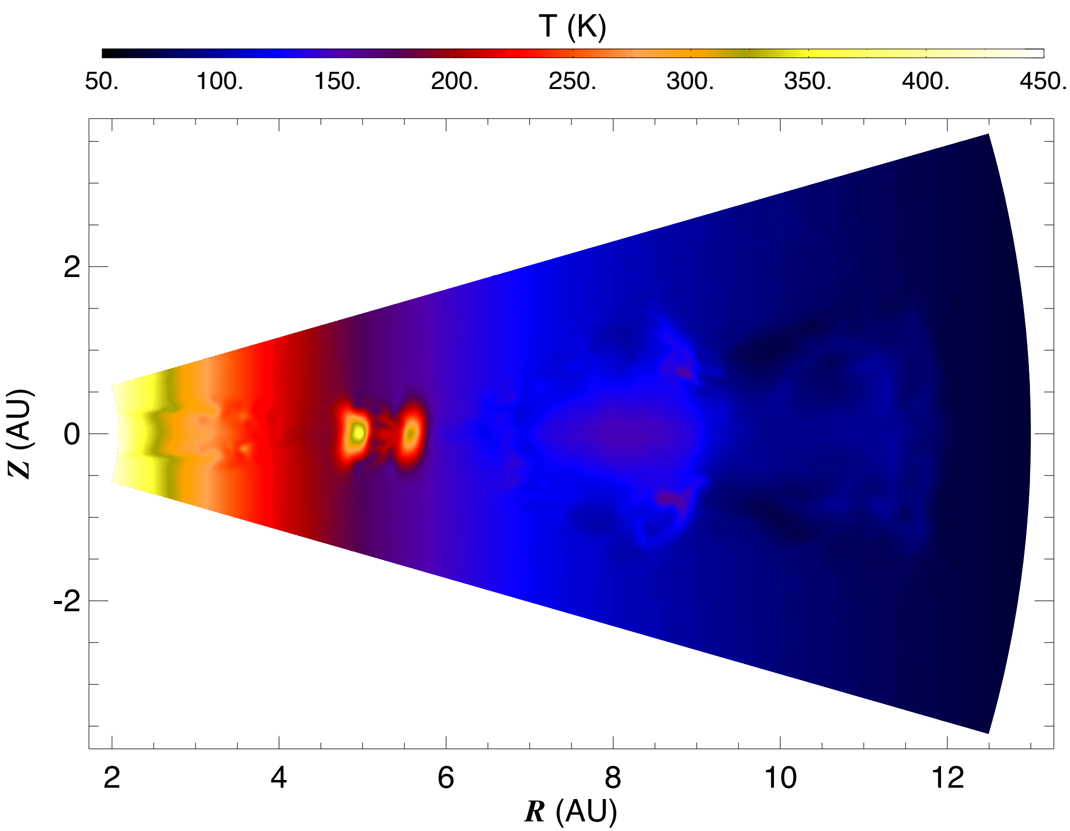
Lyra et al. (2016)

Shock bores

Shocks (velocity convergence)



Temperature



Lyra et al. (2016)

3D shocks: ascending bores and breaking waves

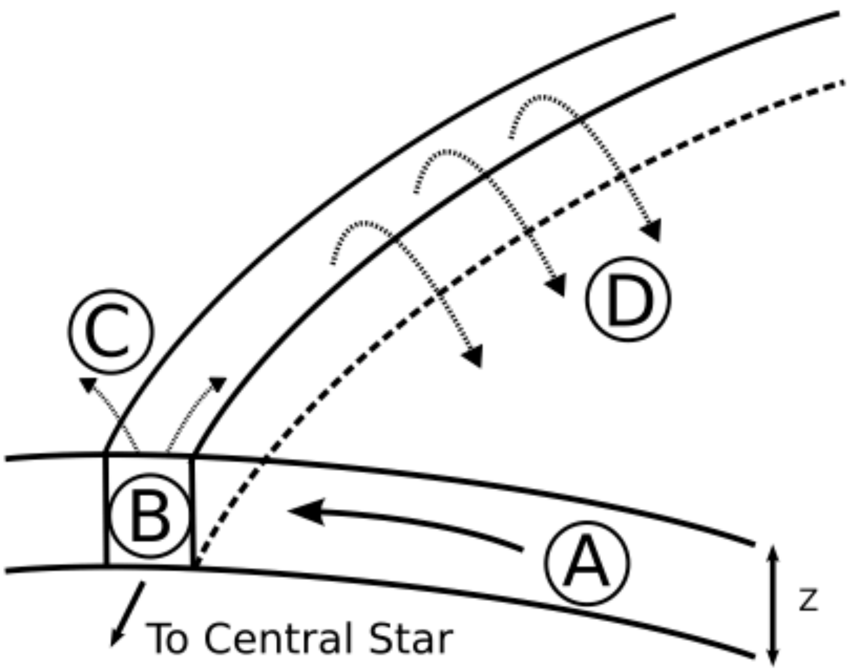
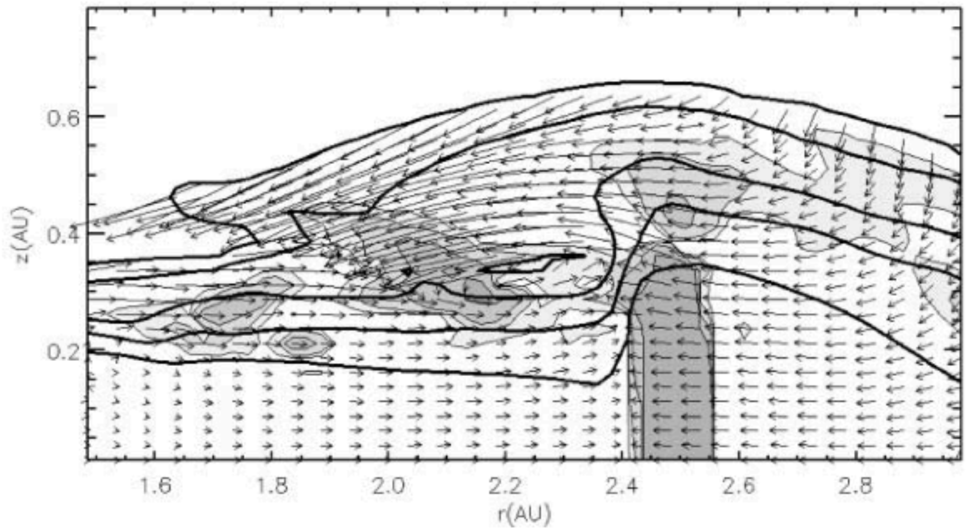
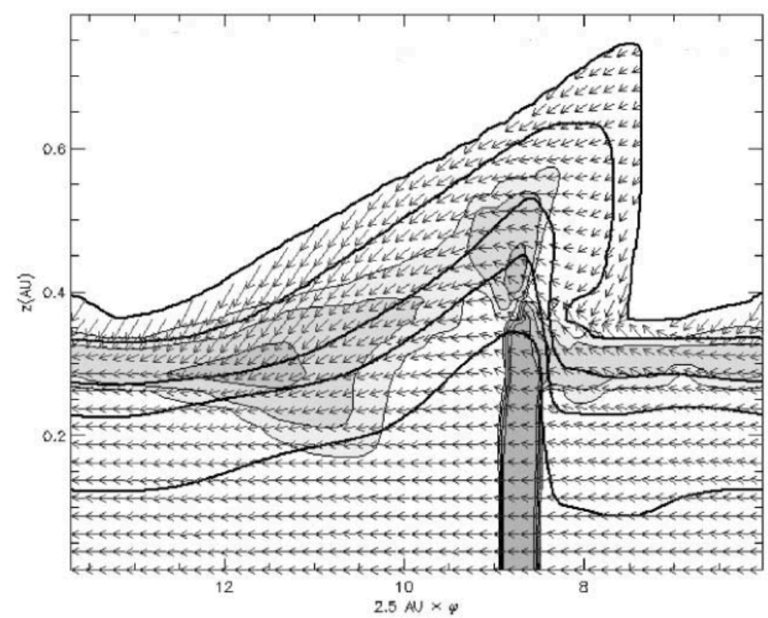


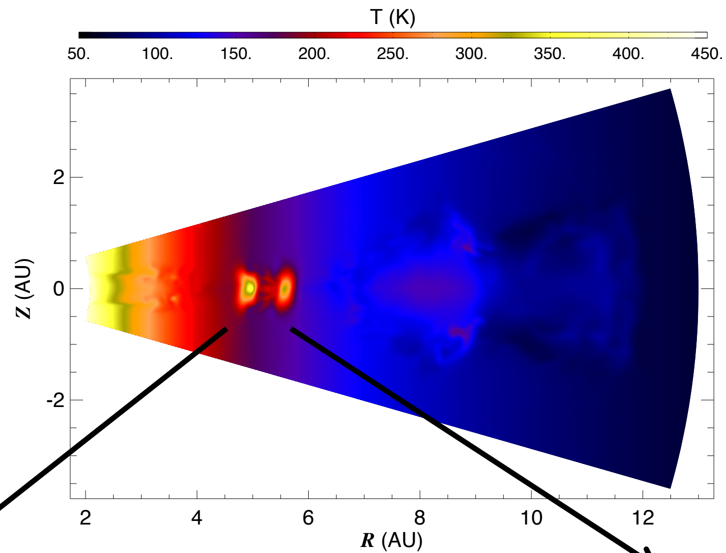
FIG. 2.—Cartoon depicting the gas flow in a shock bore in the frame of the spiral shock inside corotation. The gas in the preshock region flows into the spiral shock (A). The shock (B) causes the material to be out of vertical force balance and a rapid expansion results (C). Due to spiral streaming and 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).

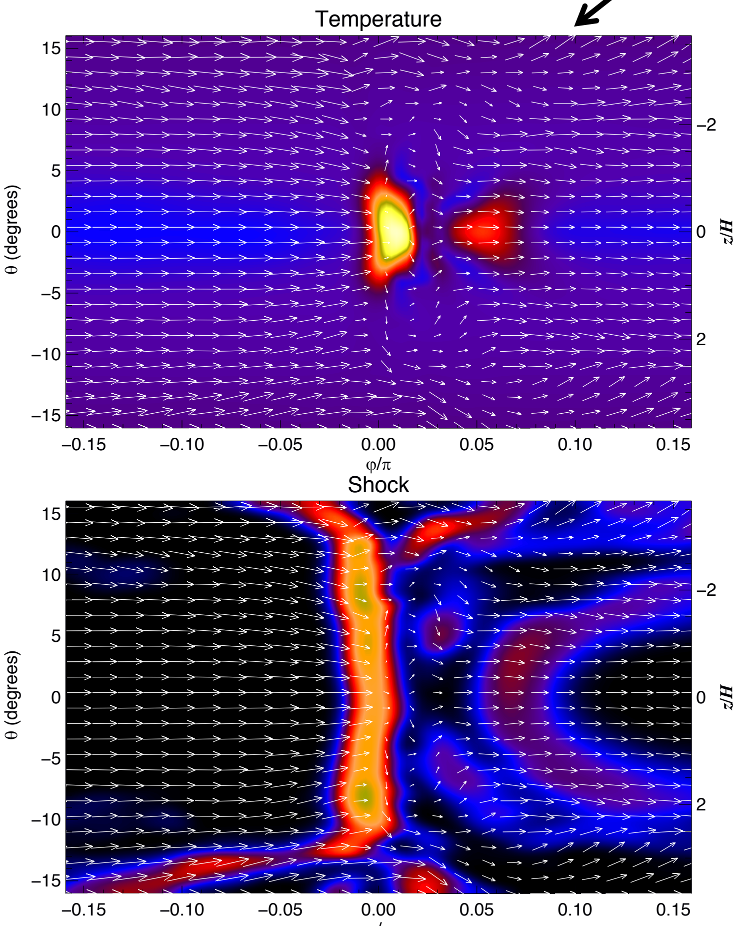




Boley & Durisen (2006)

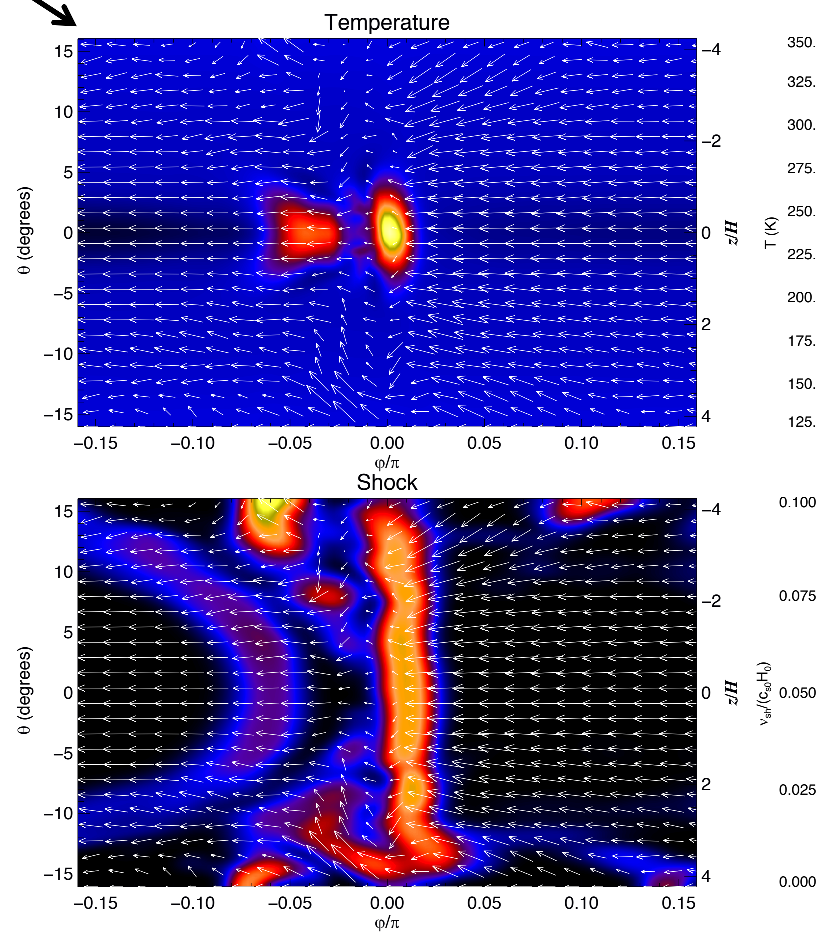
3D shocks: bores and breaking waves





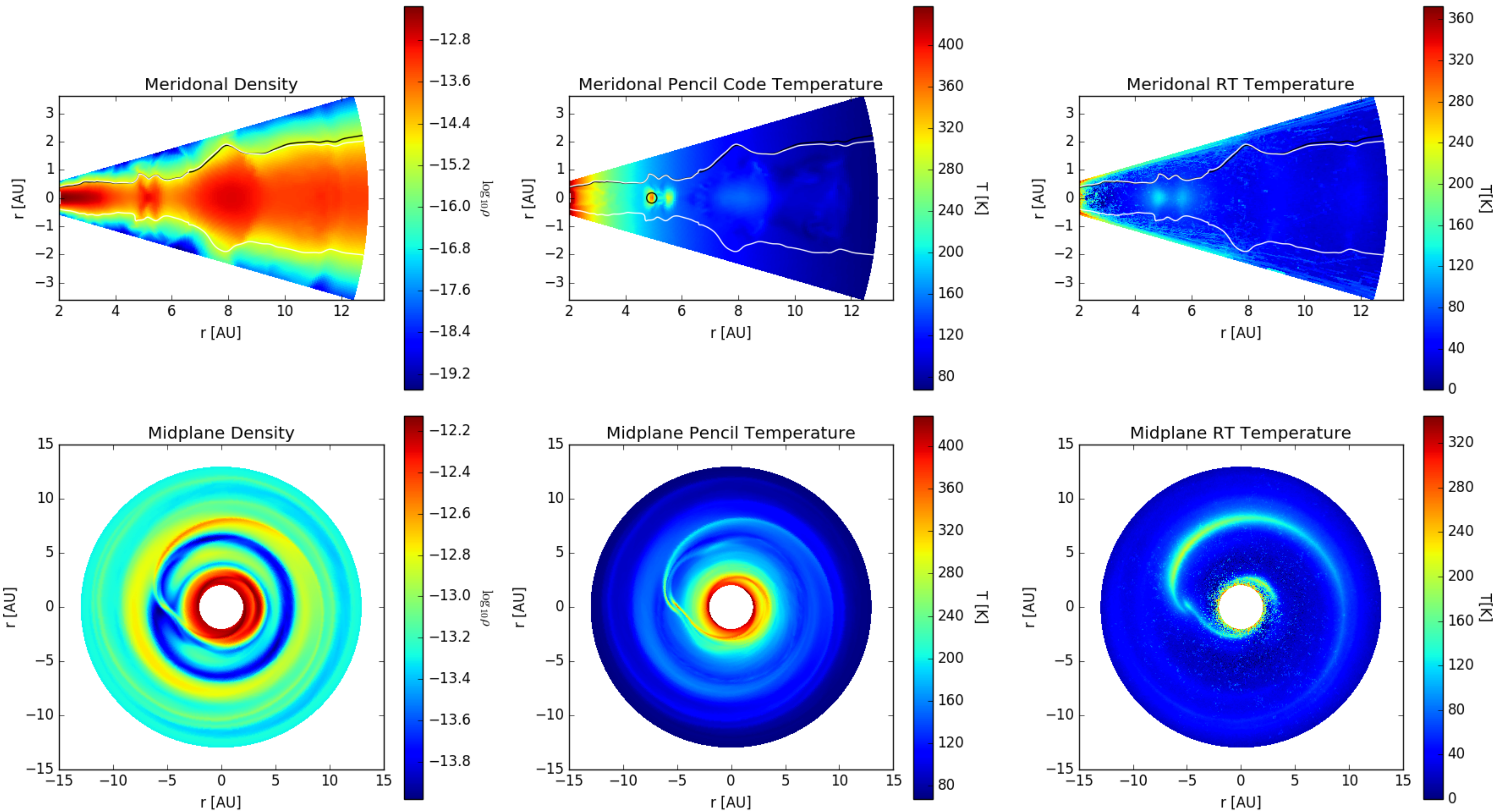
Temperature

Div u
(shock)



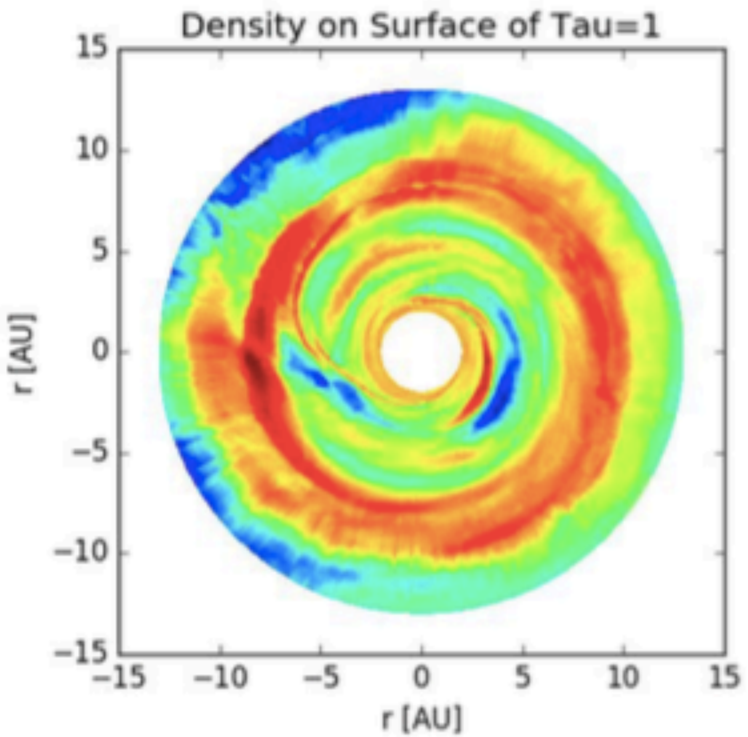
Lyra et al. (2015b, submitted)

Radiative Transfer post-processing

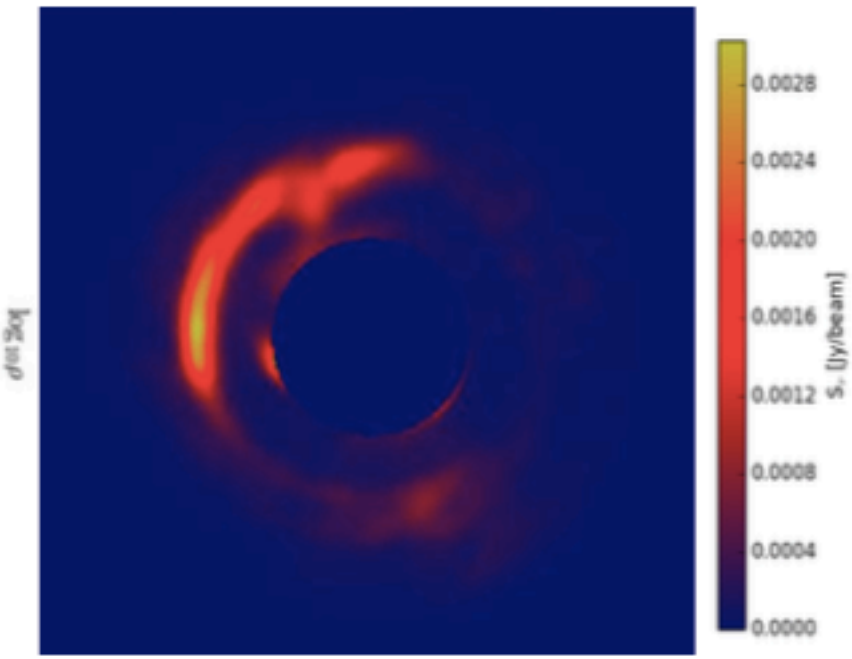


Hord et al. (2016, in prep)

Scattering in Image



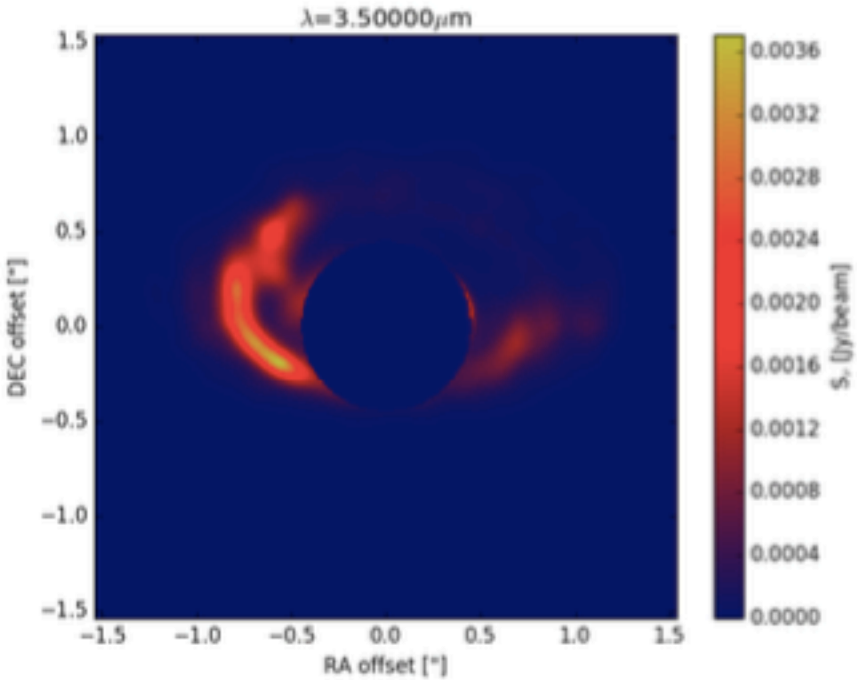
Light scattered off **gap outer edge**

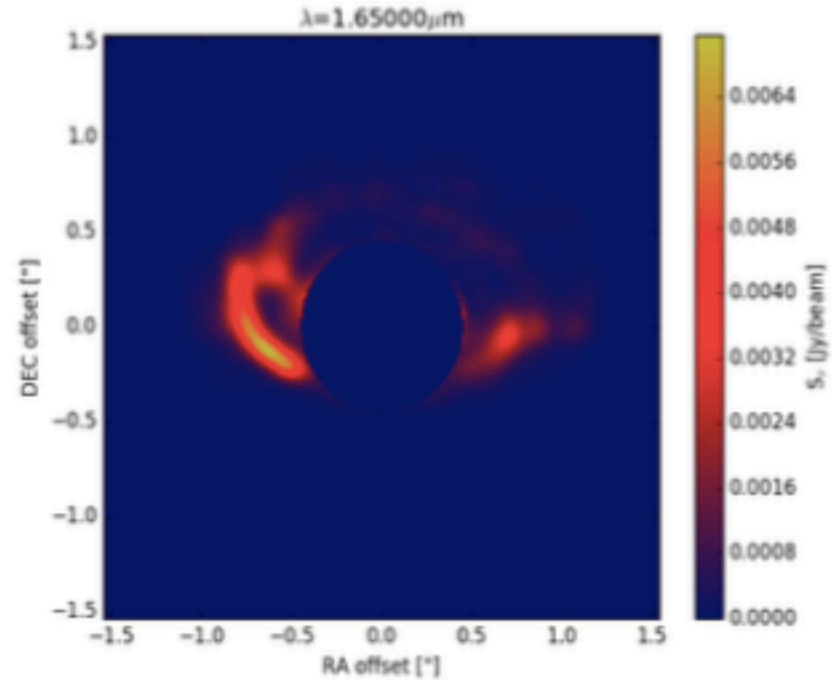


“Bird’s eye view” synthetic image

Hord et al. (2016, in prep)

Synthetic Images





λ = 3.5 microns (**L' Band**)

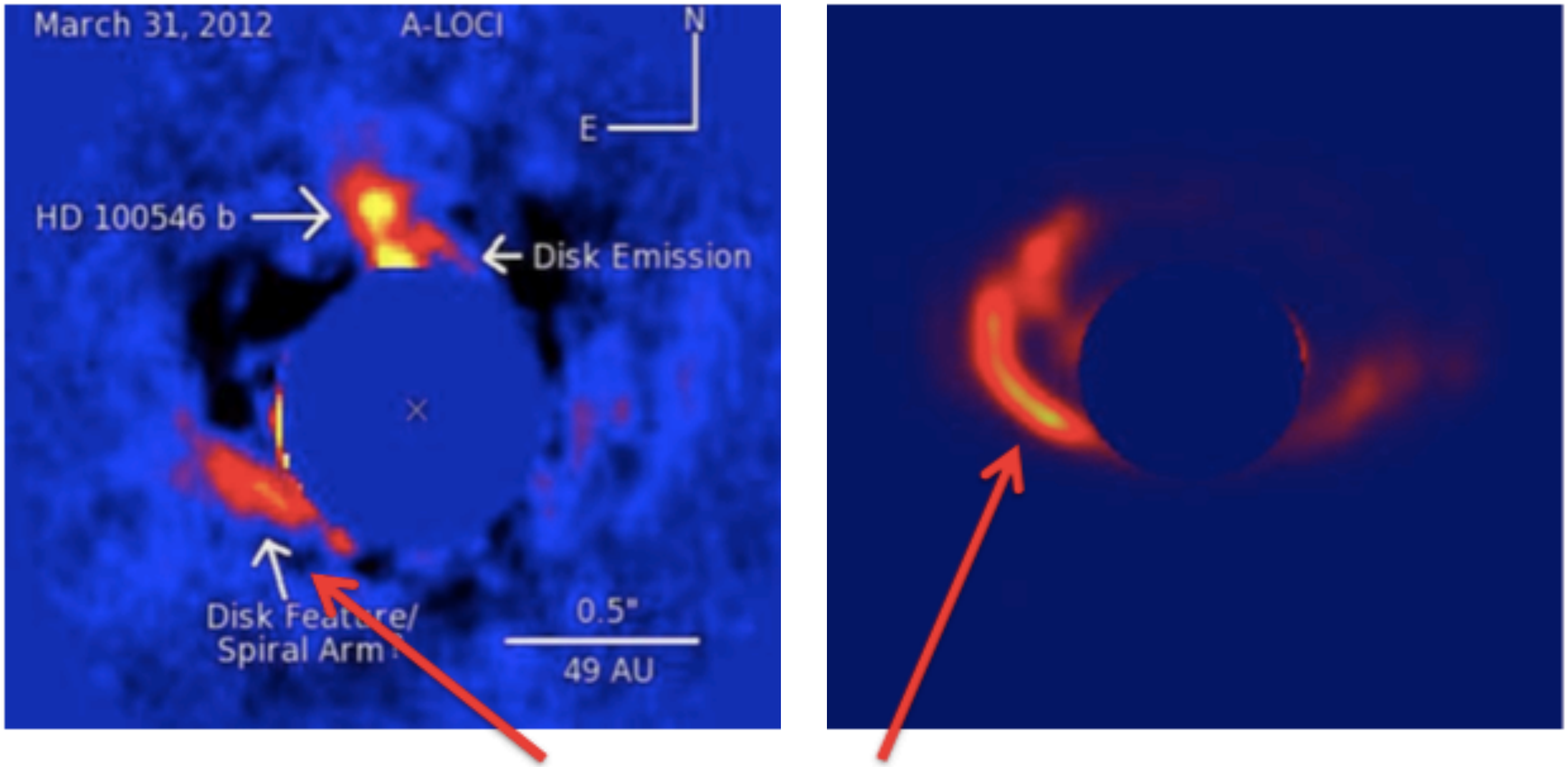
λ = 1.65 microns (**H Band**)

Made with 138 degree position angles and 50 degree inclination angles to match Currie et al. (2014) observations.

Disk scaled by factor of 10 to map T Tauri 5 AU to Herbig Ae 50 AU

Hord et al. (2016, in prep)

Comparison

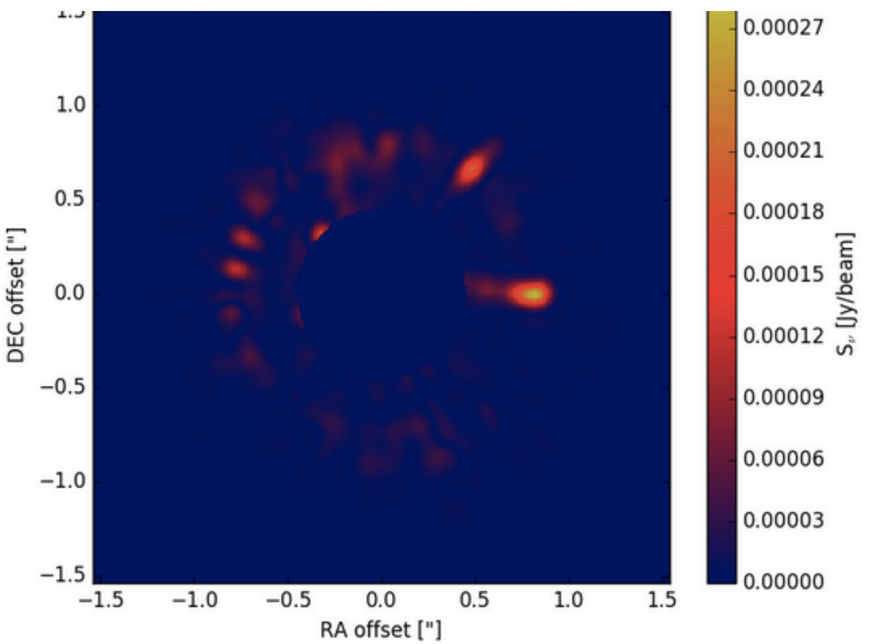


Matching general morphologies

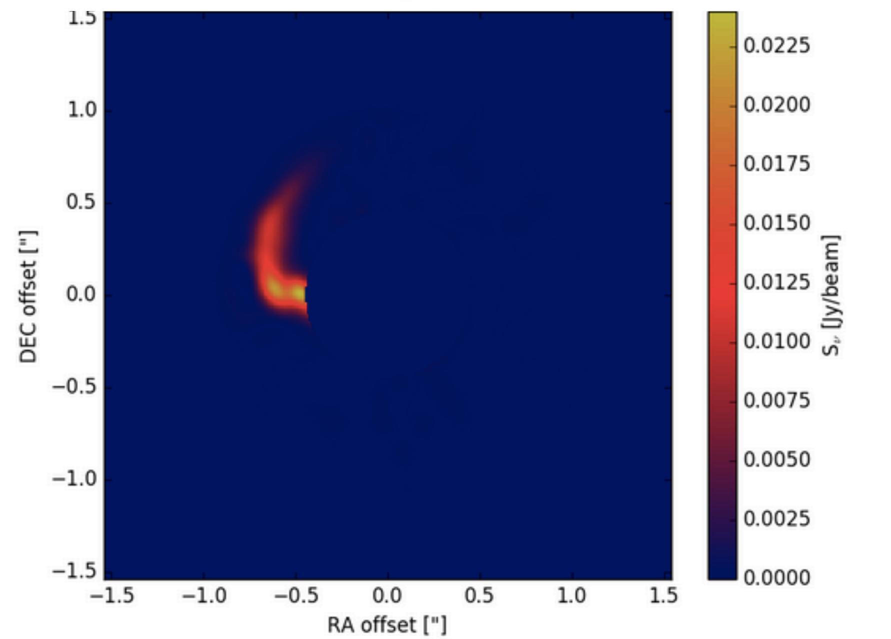
Hord et al. (2016, in prep)

Effect of shocks alone

1 μm

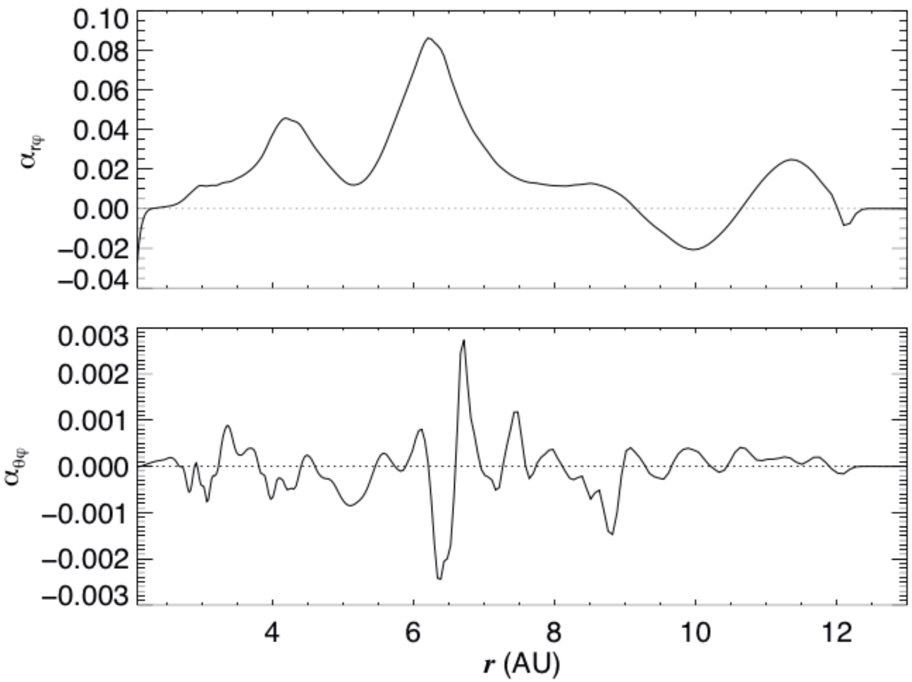


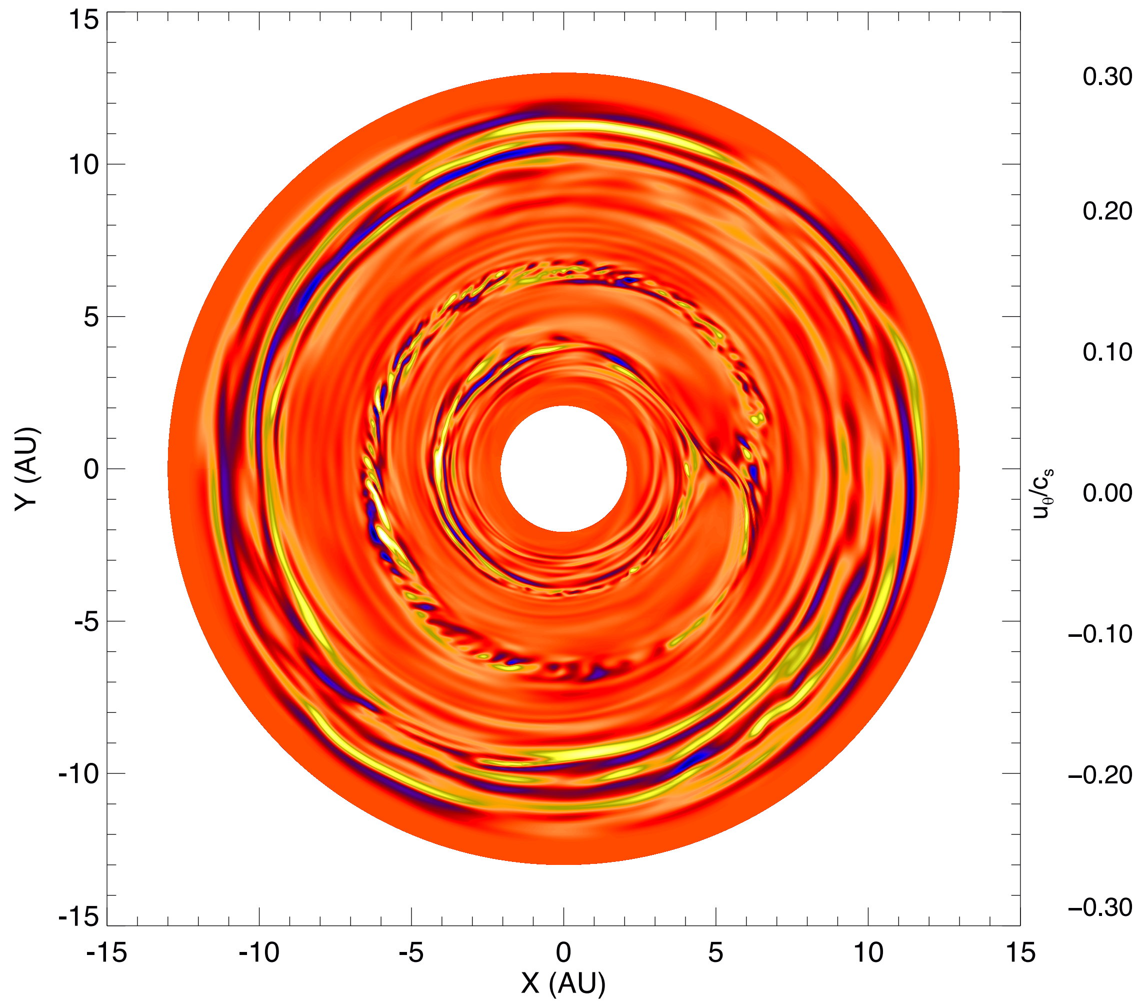
10 μm



Hord et al. (2016, in prep)

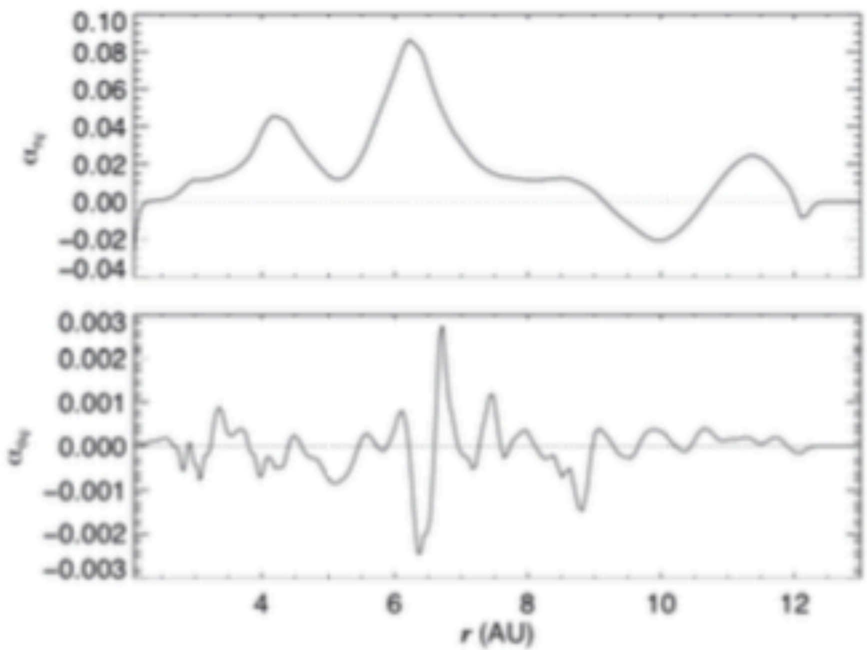
Prediction for spectroscopy: Turbulent surf

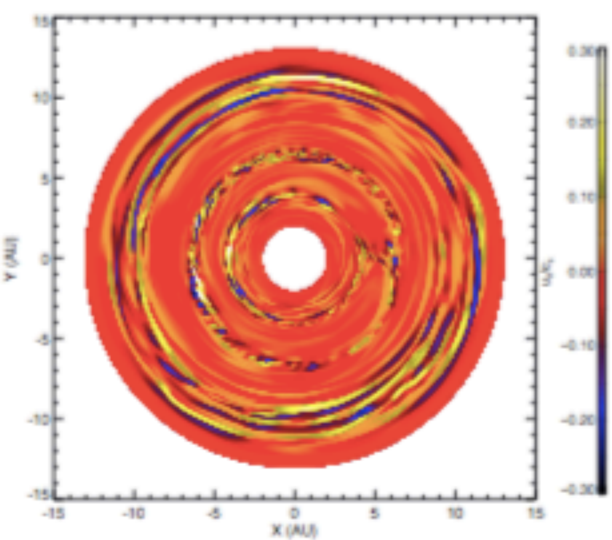


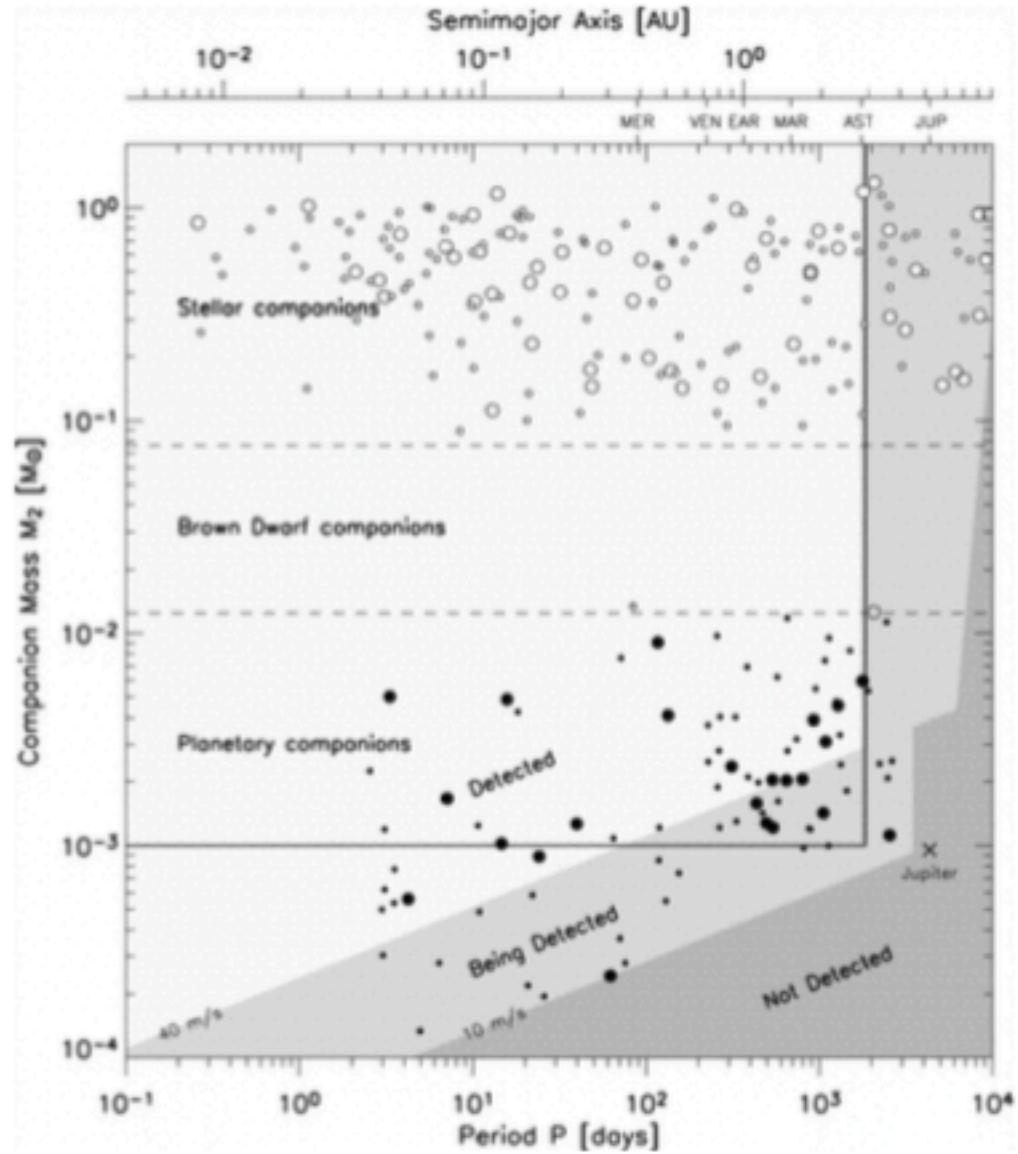


Lyra et al. (2016)

Possible explanation for the brown dwarf desert?





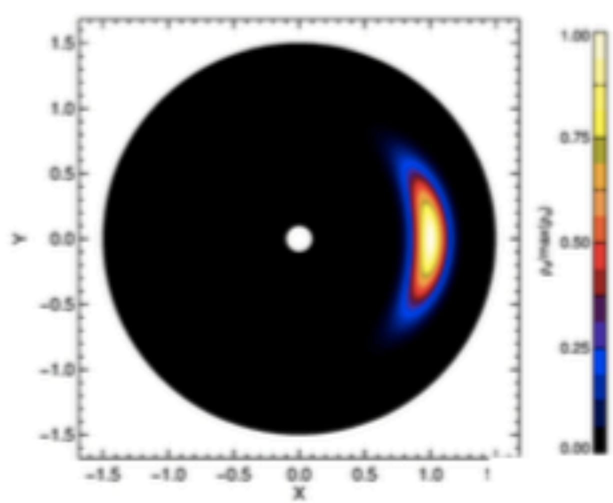


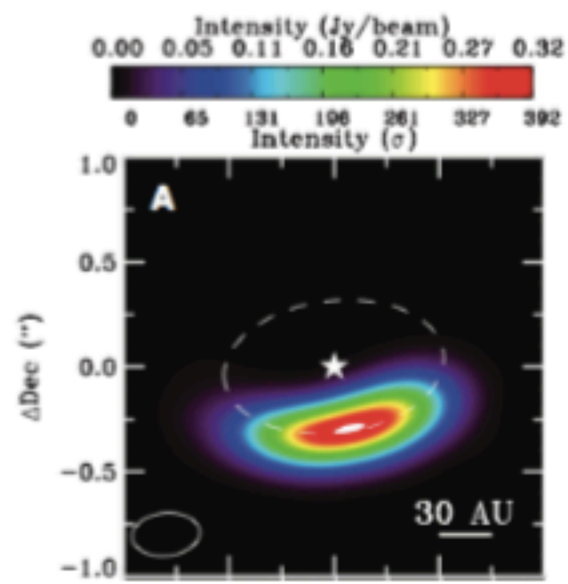
Conclusions

- Two modes of planet formation
- Two sustenance modes: Rossb
- Vortices do not survive magne
- Vortex-assisted and streaming instability are complementary
- Vortex-trapped dust in drag-diffusion equilibrium explains the observations
- Several candidates: RWI/COI/Planets
- Very hig es (BD desert?)

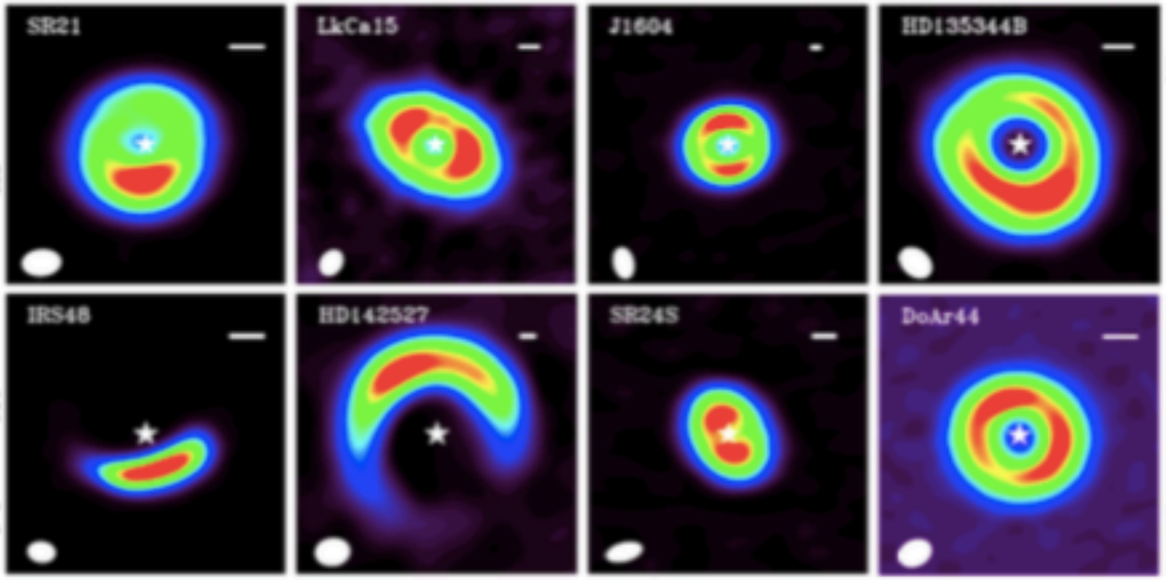
$$\rho_d(a,z) = \varepsilon\rho_0\,(S+1)^{3/2}\,\exp\left\{-\frac{[a^2 f^2(\chi)+z^2]}{2H^2}(S+1)\right\}$$

Lyra & Lin (2013)





Conclusions



- Two modes ... es
- Two sustena ... e Overstability
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- Vortex-assis
- Vortex-trapp ... servations
- Several possible culprits for asymmetries: RWI/COI/Planets
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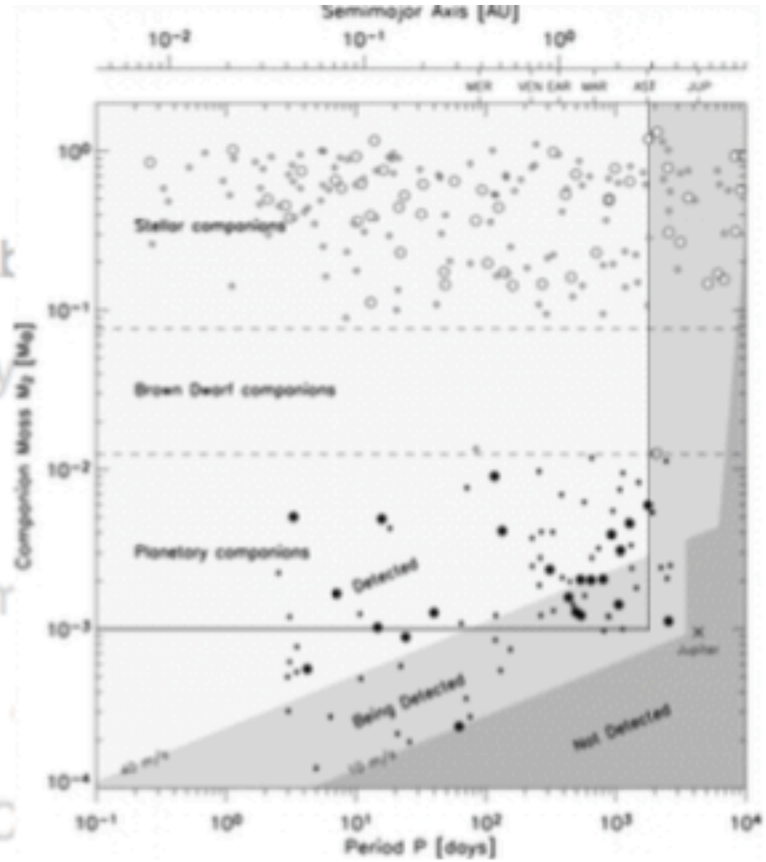
Conclusions



- Two modes of planet formation: Streaming Instal
- Two sustenance modes: Rossby Wave Instability
- Vortices do not survive magnetization
- Vortex-assisted and streaming instability are con
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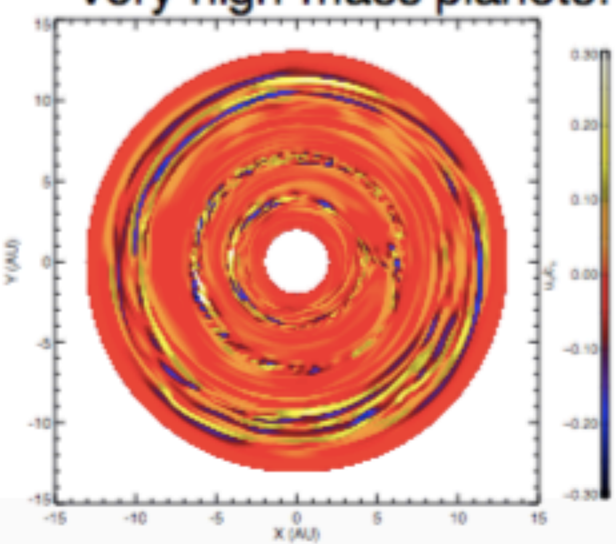

Conclusions

- Predictions:
  - Hot lobes next to high mass planets at high resolution
  - High(er) turbulence around the orbit of a high-mass planet
- Shocks from high-mass planets (~> 5 Mjup) is a significant source of radiation in disks.
- Shocks due to high mass planets better fits to observed spirals.