Planet Signatures in Transition Disks

Wladimir Lyra

California State University

Jet Propulsion Laboratory

Collaborators

Aaron Boley (Vancouver), Axel Brandenburg (Stockholm), Kees Dullemond (Heidelberg), Mario Flock (JPL), Anders Johansen (Lund), Tobias Heinemann (KITP), Hubert Klahr (Heidelberg), Min-Kai Lin (ASU), Mordecai-Mark Mac Low (AMNH), Colin McNally (Copenhagen), Krzysztof Mizerski (Warsaw), Satoshi Okuzumi (JPL), Sijme-Jan Paardekooper (London), Nikolai Piskunov (Uppsala), Natalie Raettig (Heidelberg), Alex Richert (PSU), Neal Turner (JPL), Miguel de Val-Borro (Princeton), Andras Zsom (MIT).

University of Delaware, Apr 11th, 2017

Protoplanetary Disks

PP disk fact sheet

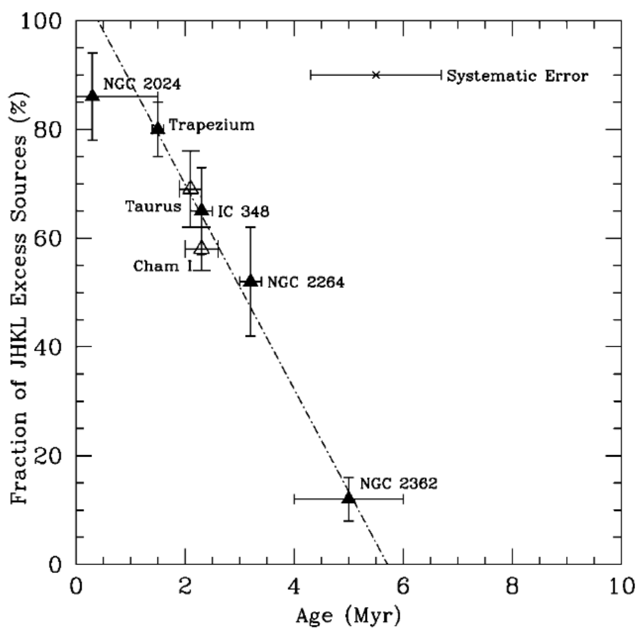
Density: $10^{13} – 10^{15}$ cm^{-3}
(Air: 10^{21} cm^{-3})

Temperature: 10-1000 K

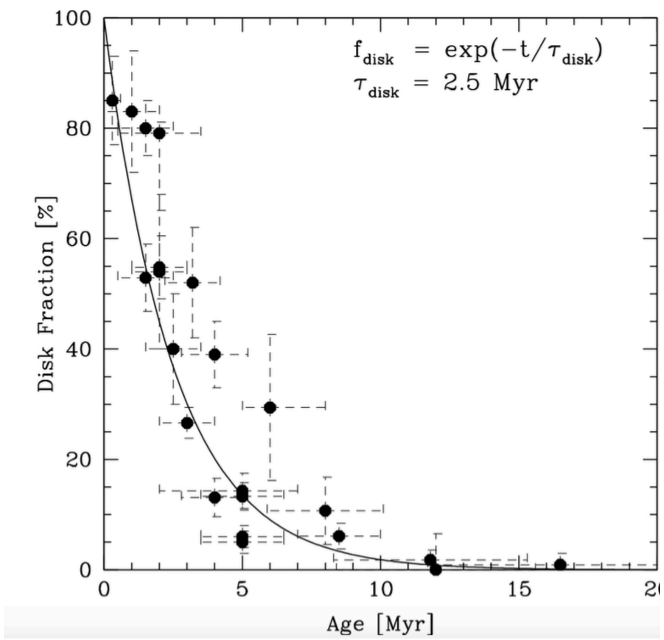
Scale: 0.1-100AU

Mass: $10^{-3} – 10^{-1}$ M_{sun}

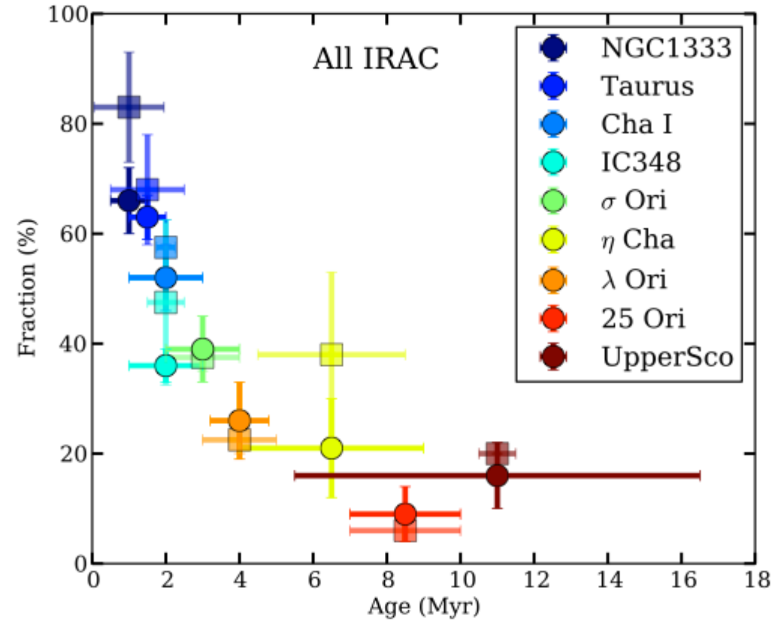
Disk lifetime



(Haisch et al. 2001)



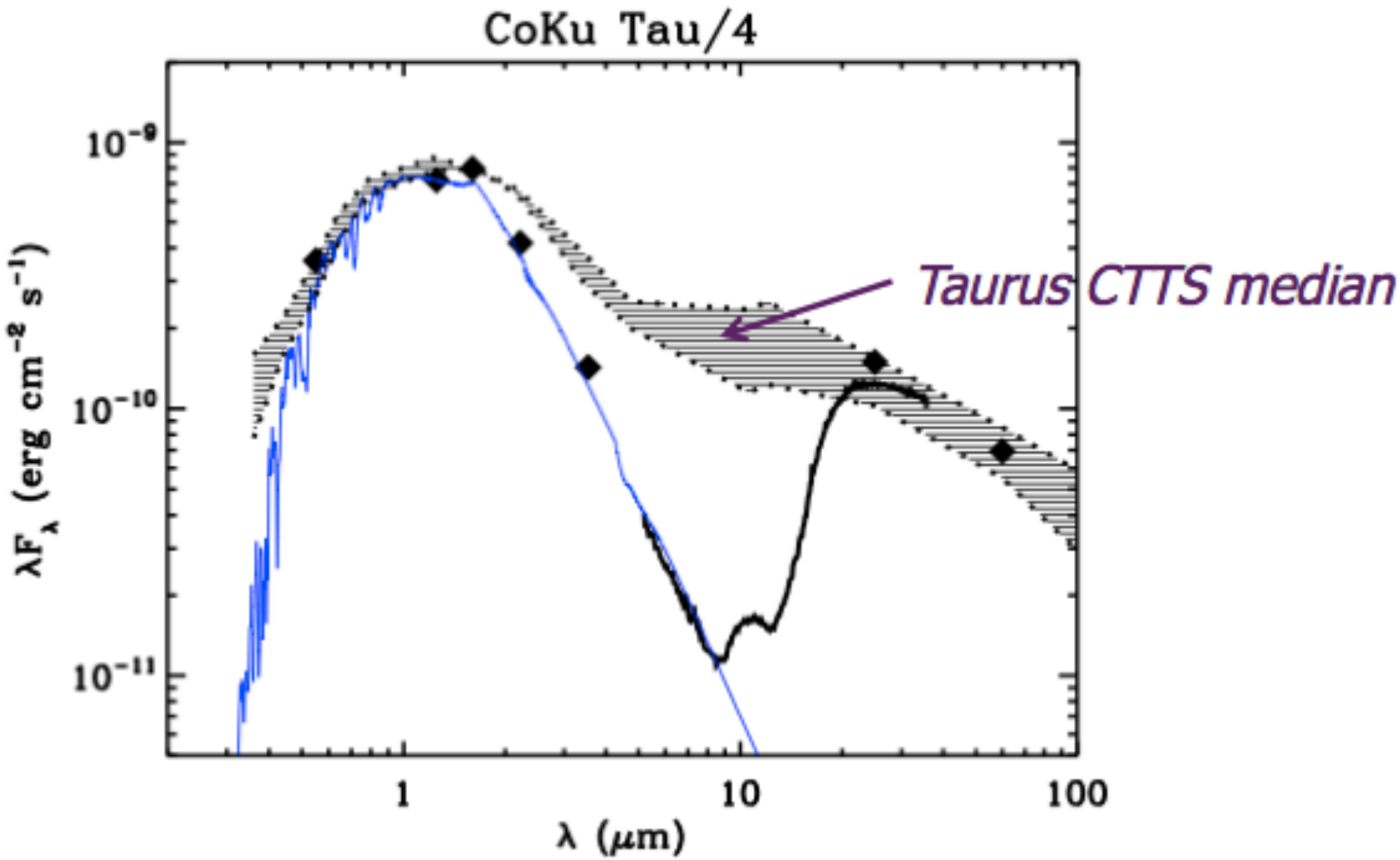
(Mamajek et al. 2009)



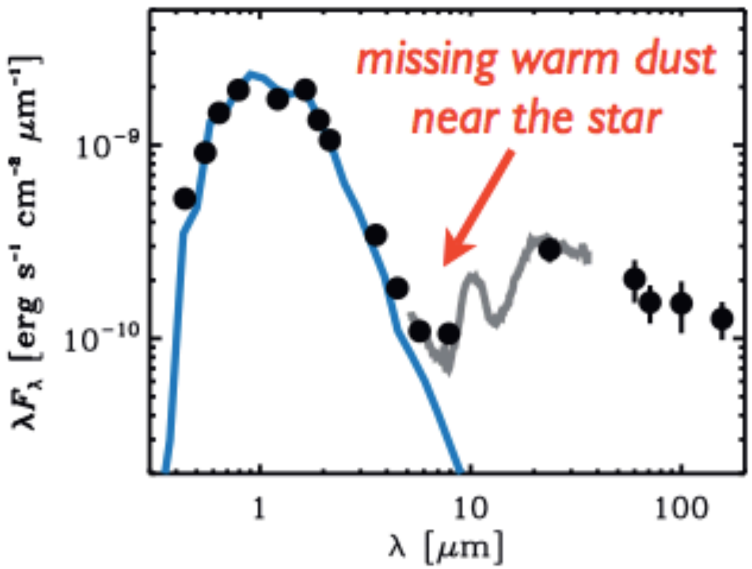
(Ribas et al. 2014)

Disks dissipate with an e-folding time of 2.5 Myr

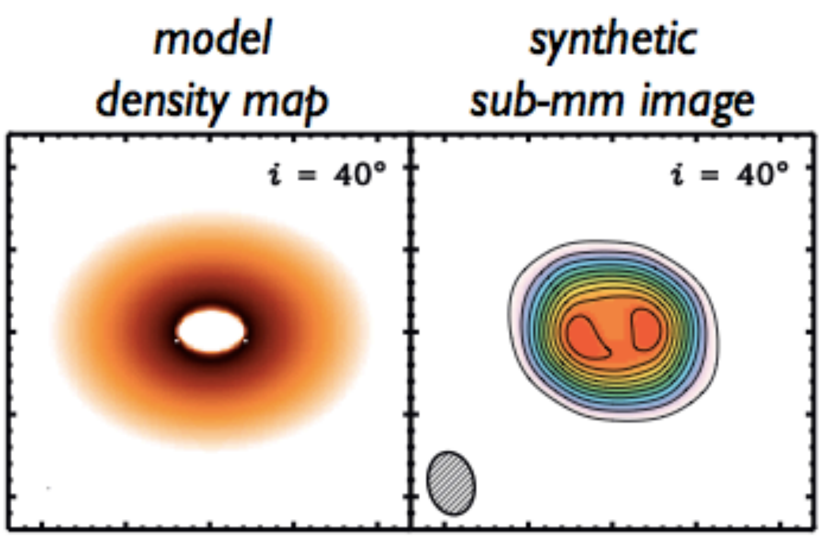
Transition Disks: Disks with missing hot dust.



Transition Disks: Disks with missing hot dust.

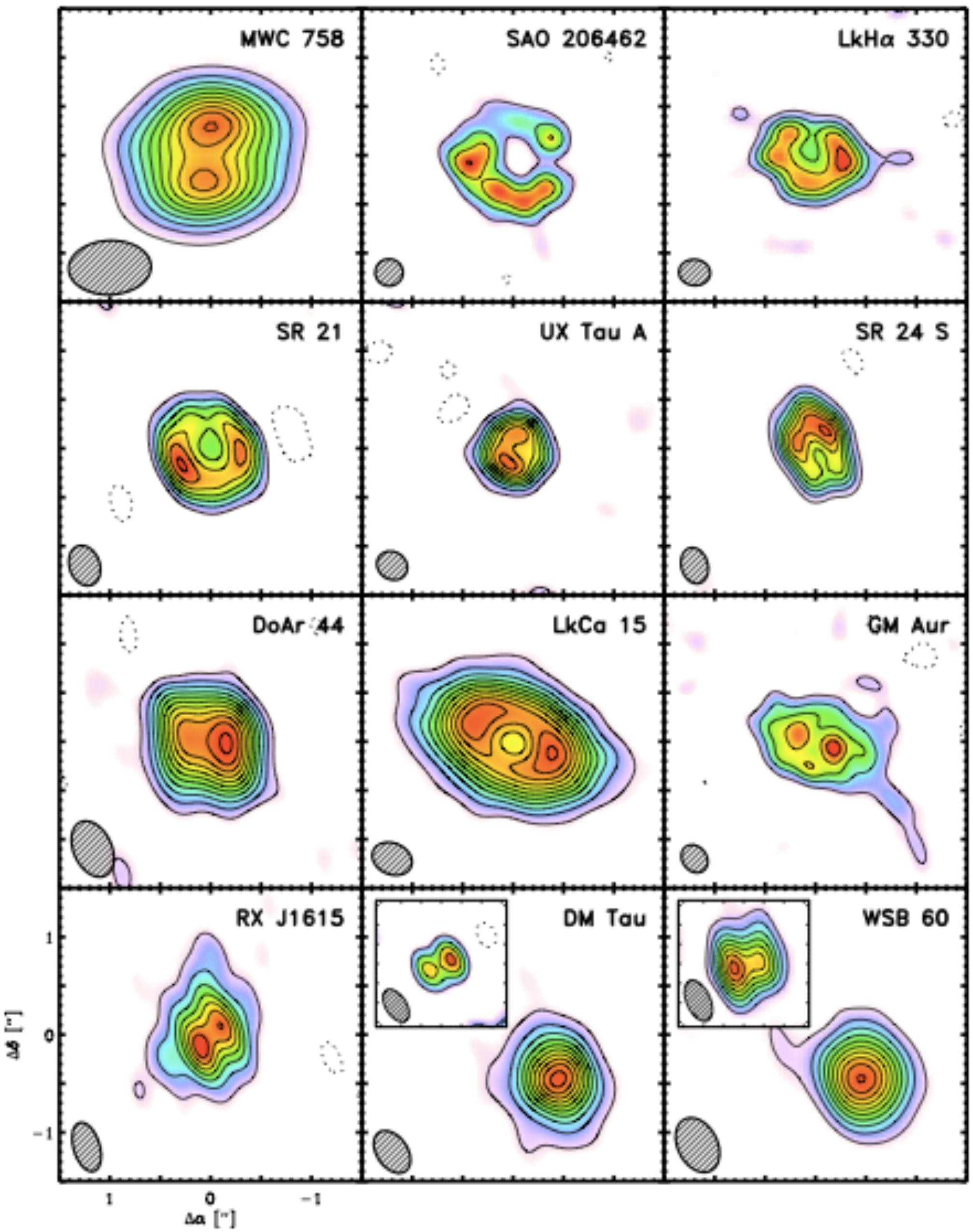


[e.g., Furlan et al. 2009]

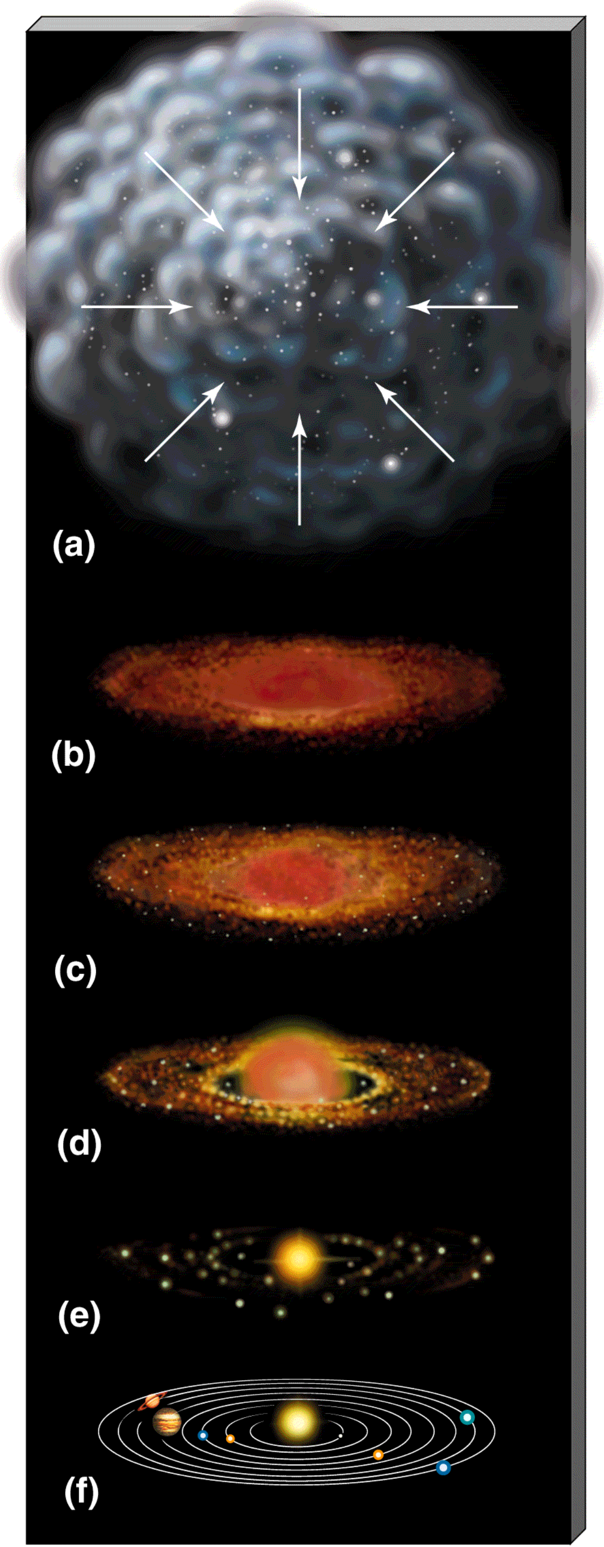


a disk with a large reduction
in optical depth near the star
(i.e., a “cavity” or “hole”)

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



0.85mm
0.3" ~ 20 AU resolution



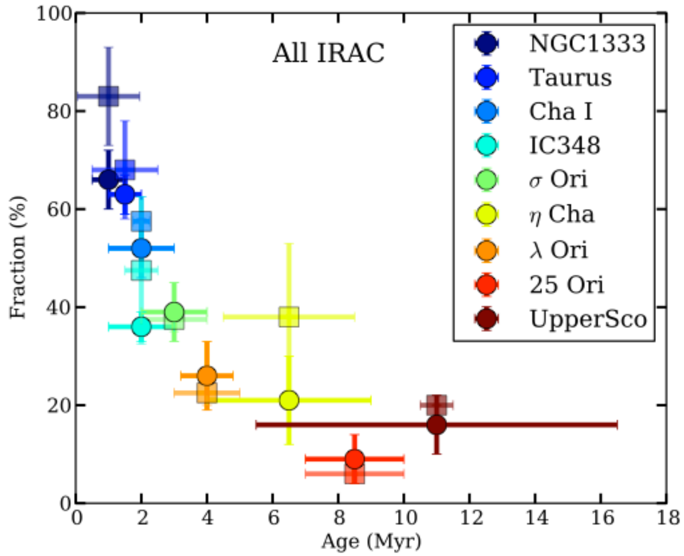
Are transitional disks
related to disk evolution?

Gas-rich phase (< 10 Myr)
Primordial Disks

Conjecture:
Thinning phase (~10 Myr)
Transitional Disks

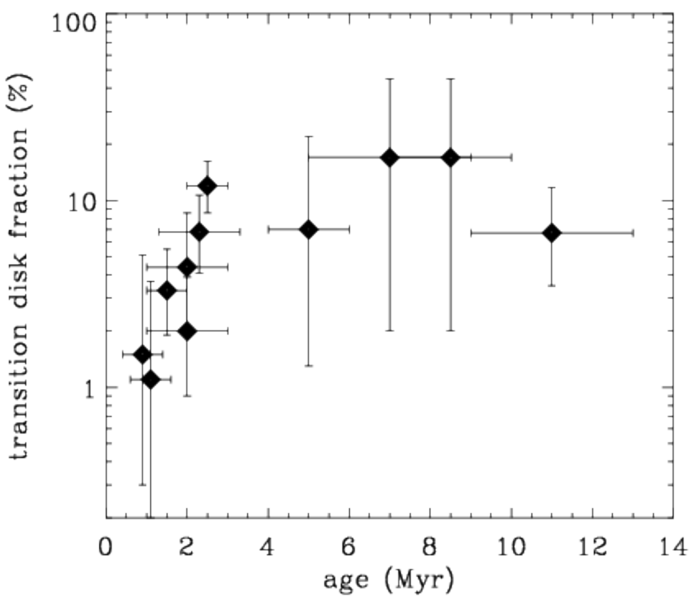
Gas-poor phase (>10 Myr)
Debris Disks

Transition disks and disk evolution



(Ribas et al. 2014)

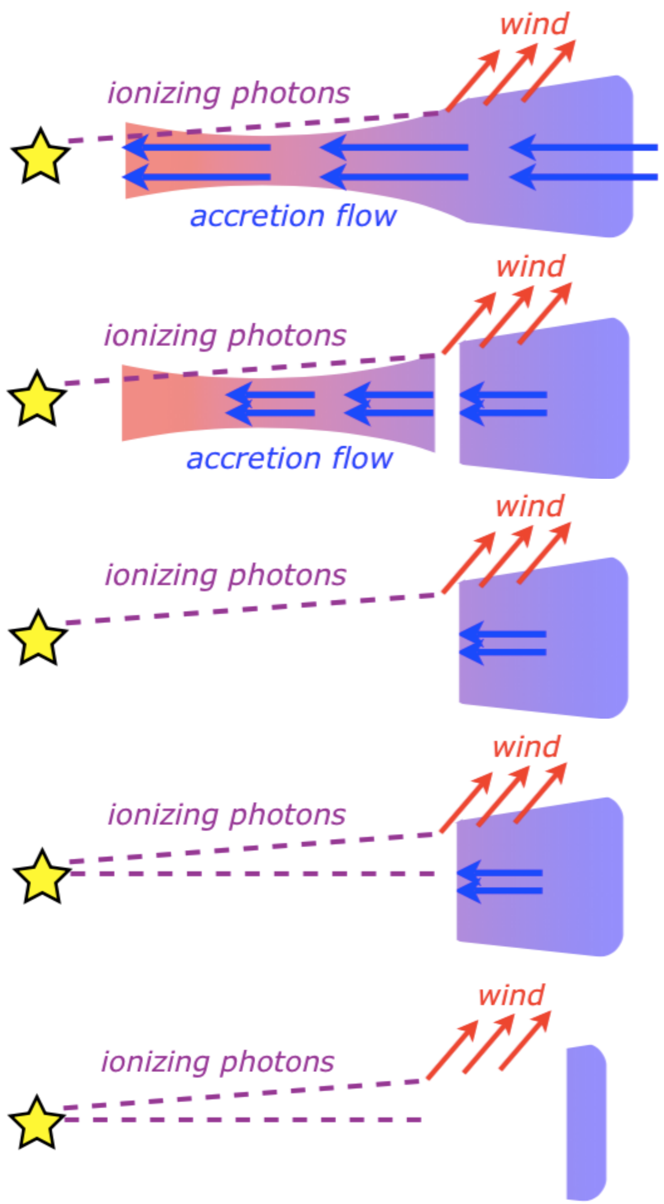
"Total" disk fraction



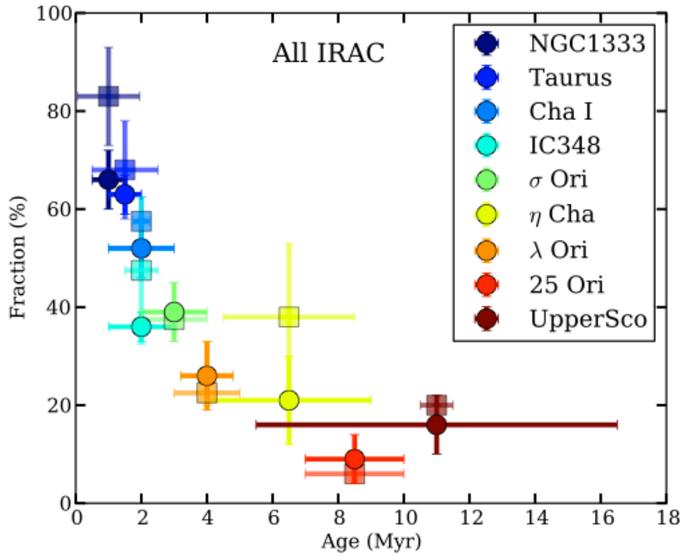
(Espaillat et al. 2014)

Transition disk fraction

Photoevaporation

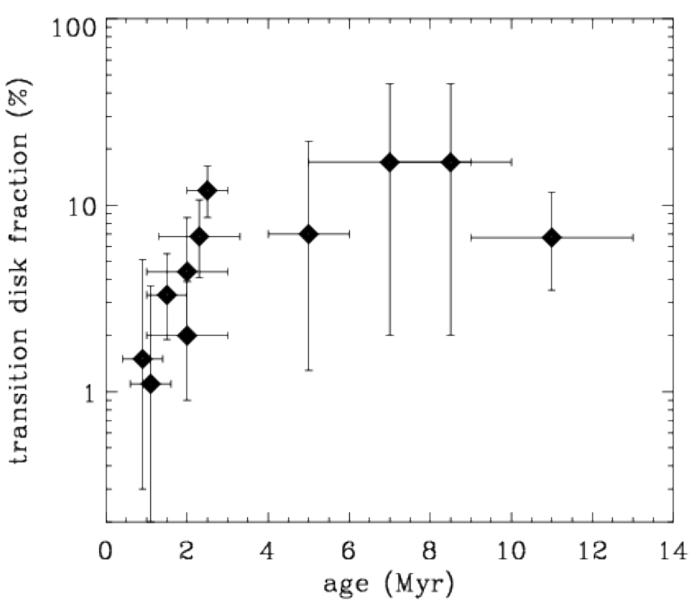


Look again…



(Ribas et al. 2014)

“Total” disk fraction

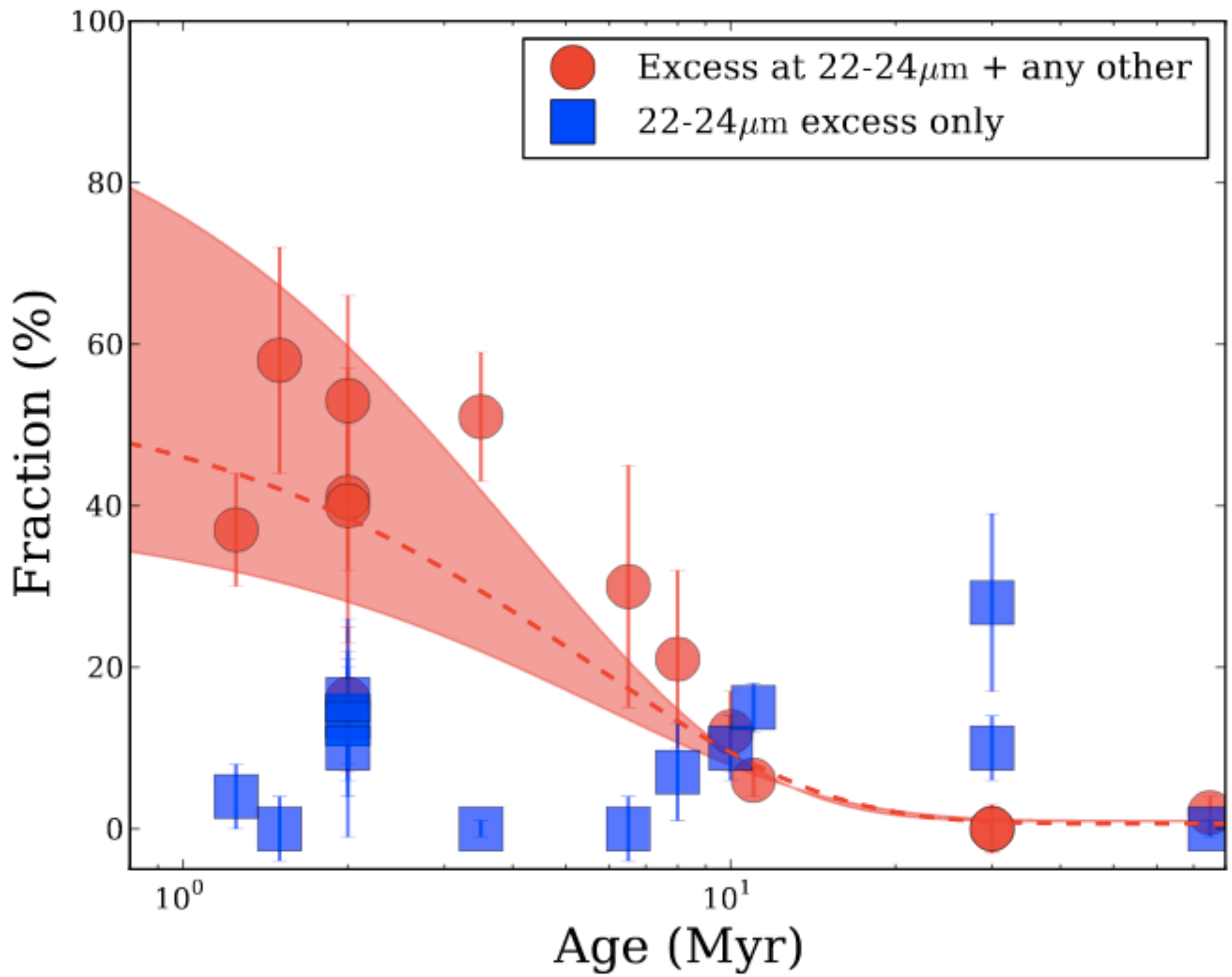


(Espaillat et al. 2014)

Transition disk fraction

Transition disks linked to disk evolution?

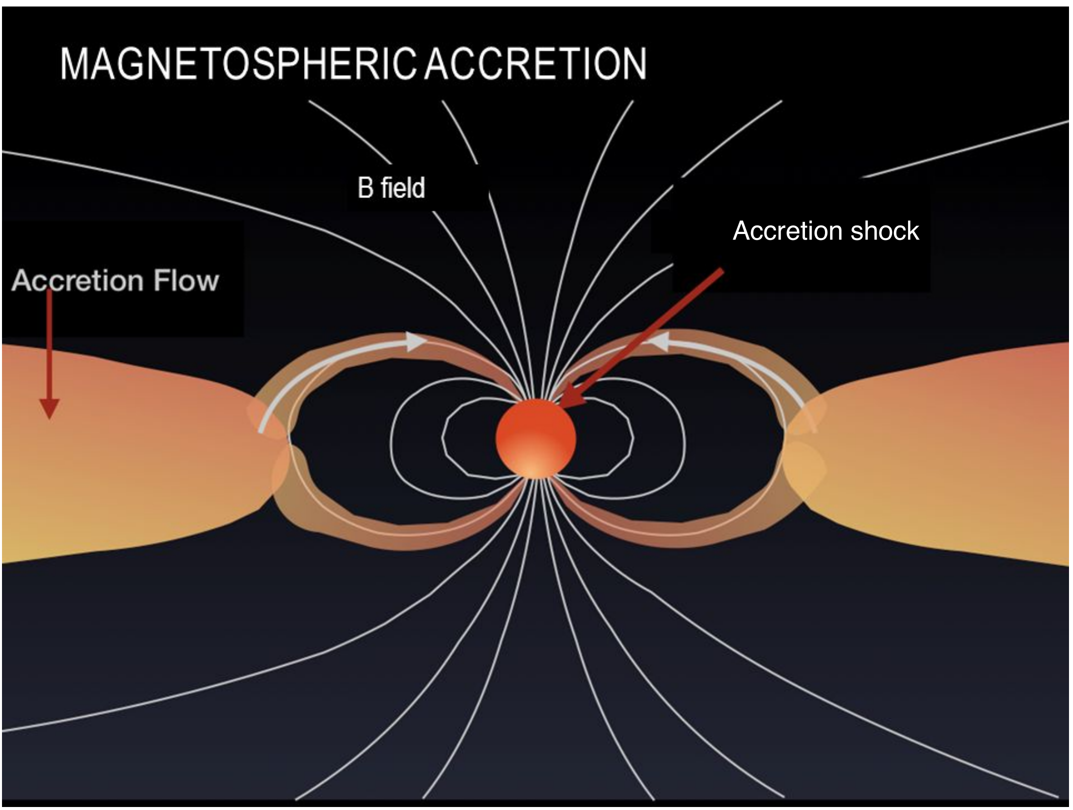
The distribution in age is consistent with a uniform distribution.

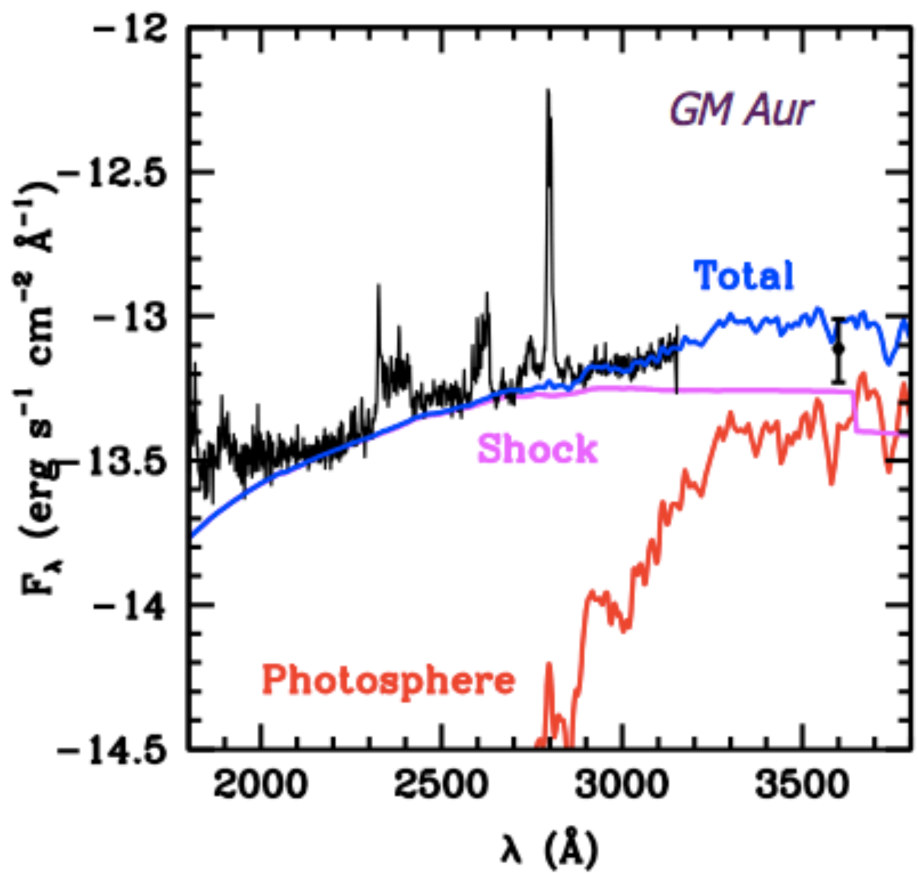


(Ribas et al. 2014)

UV excess

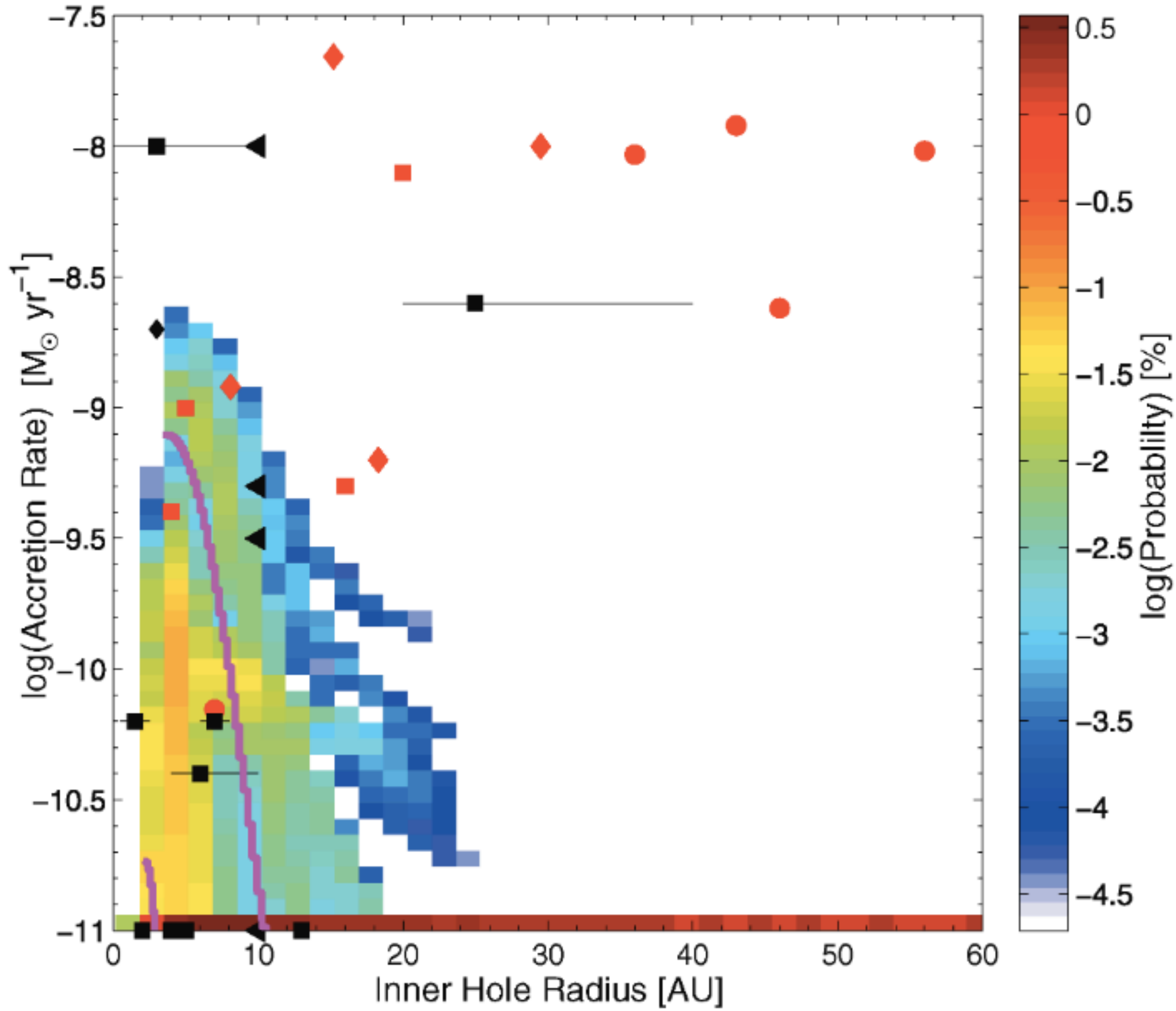
Many transitional disks show signs of accretion,
at the level of primordial (classical T-Tauri) disks.





(Ingleby et al. 2011)

Bimodal distribution of transition disks

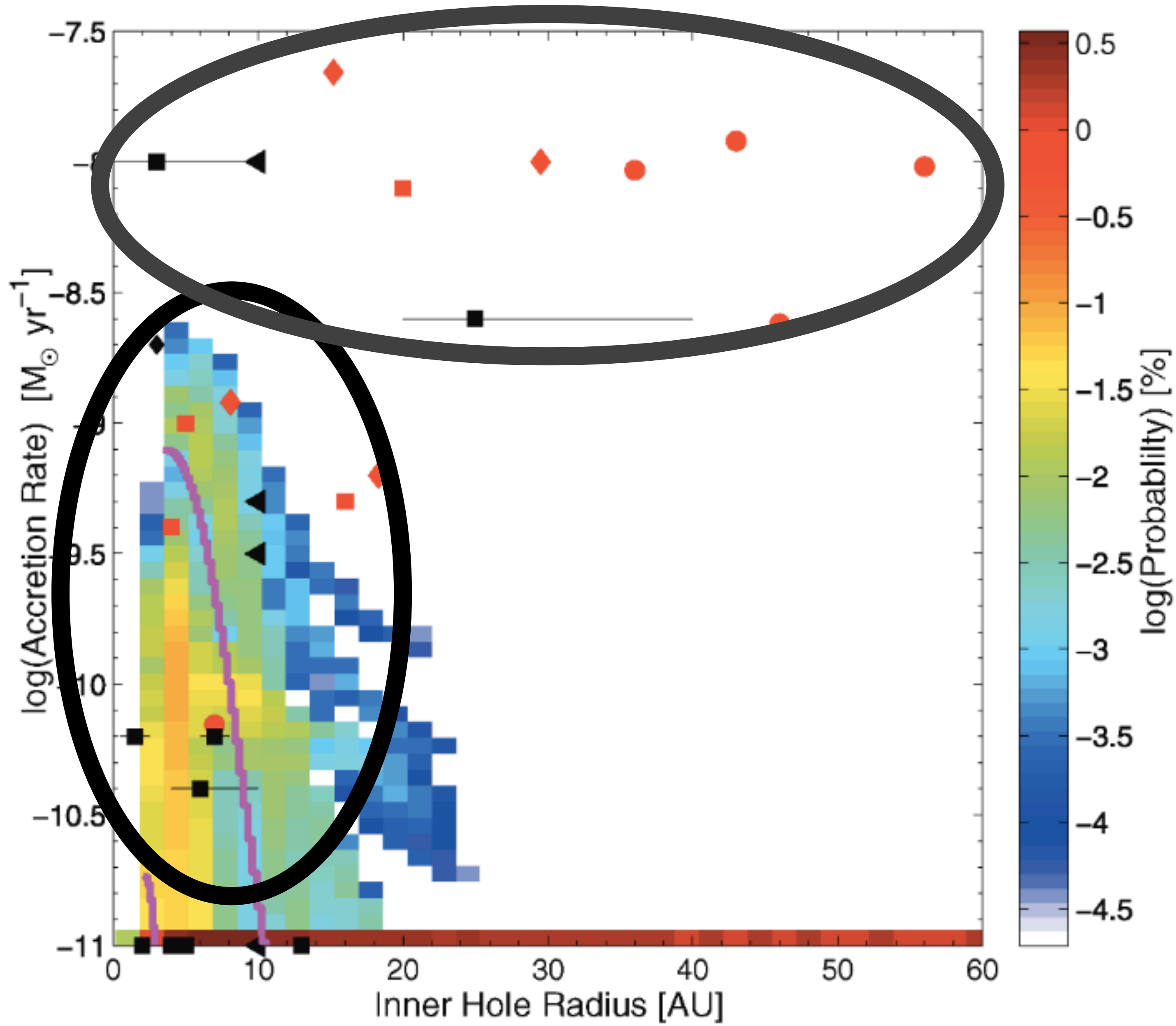


(Owen et al. 2011)

Bimodal distribution of transition disks

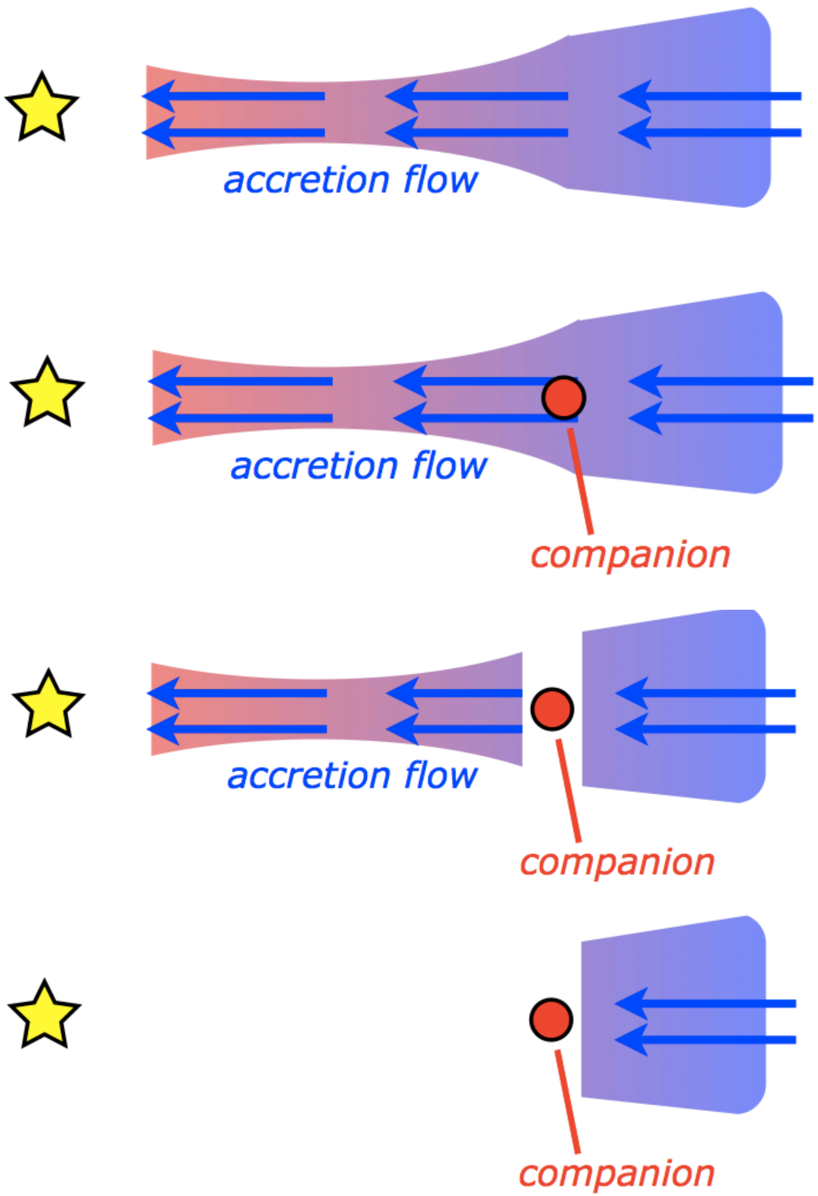
Not explained by photo-evaporation

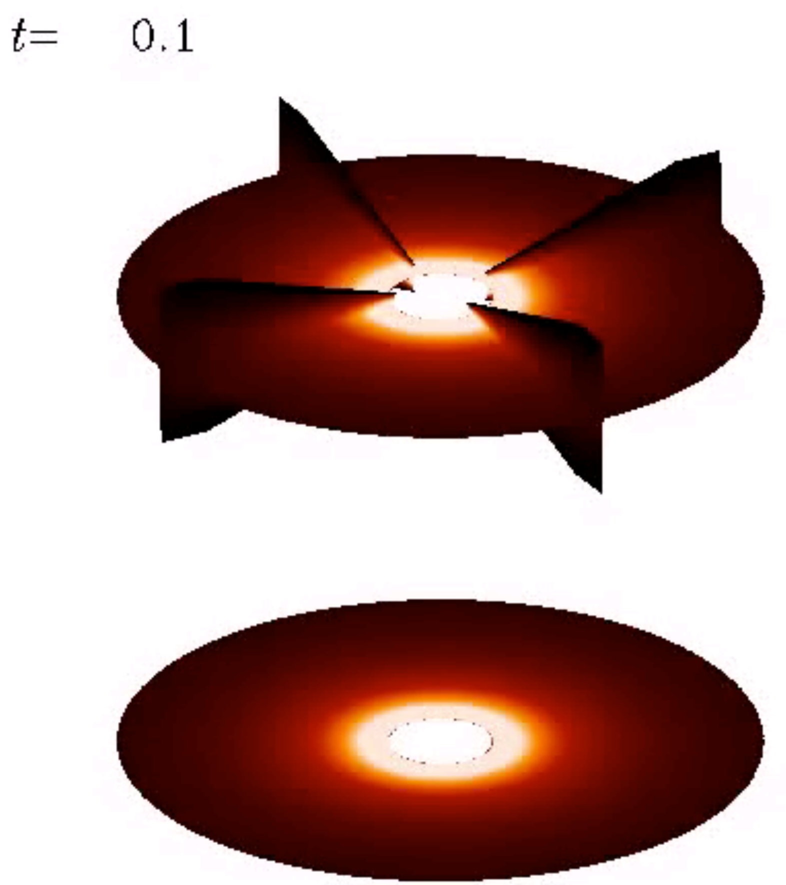
Explained by Photo-evaporation



(Owen et al. 2011)

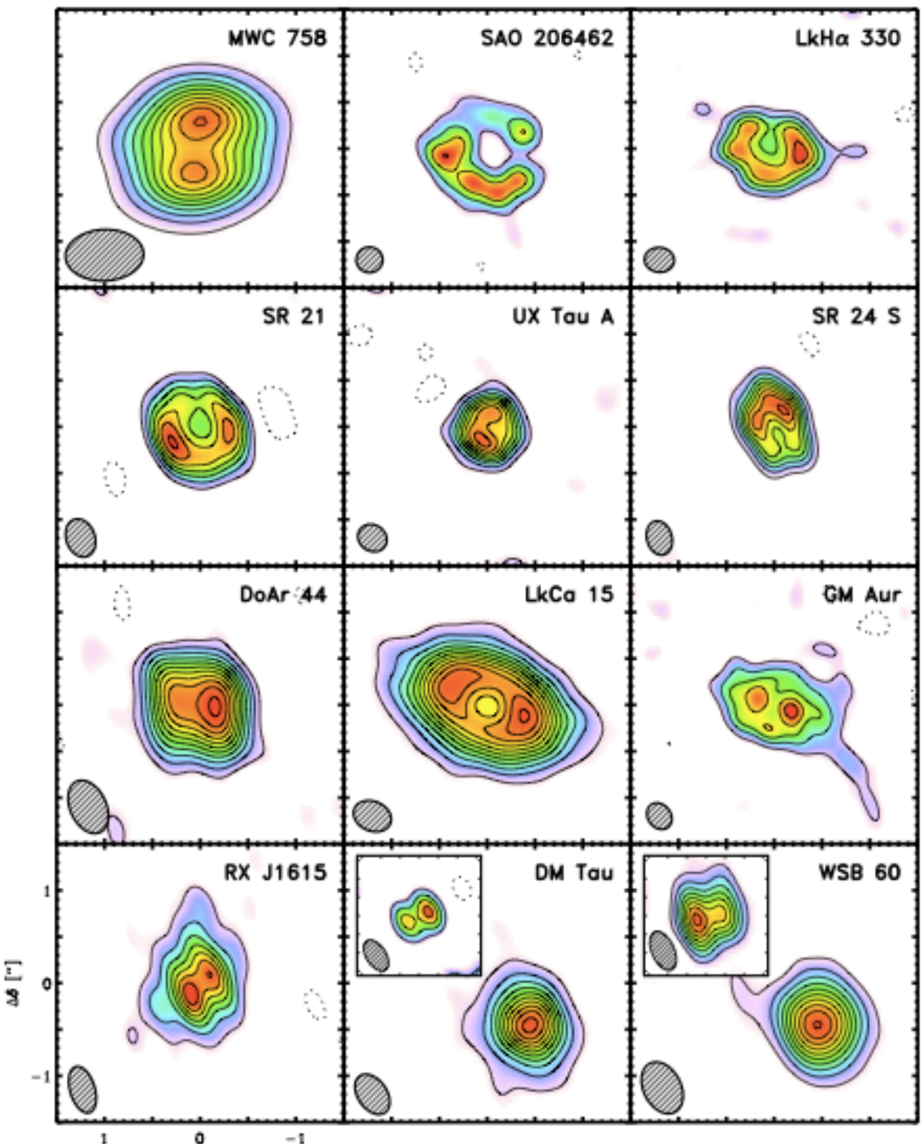
Planetary companion

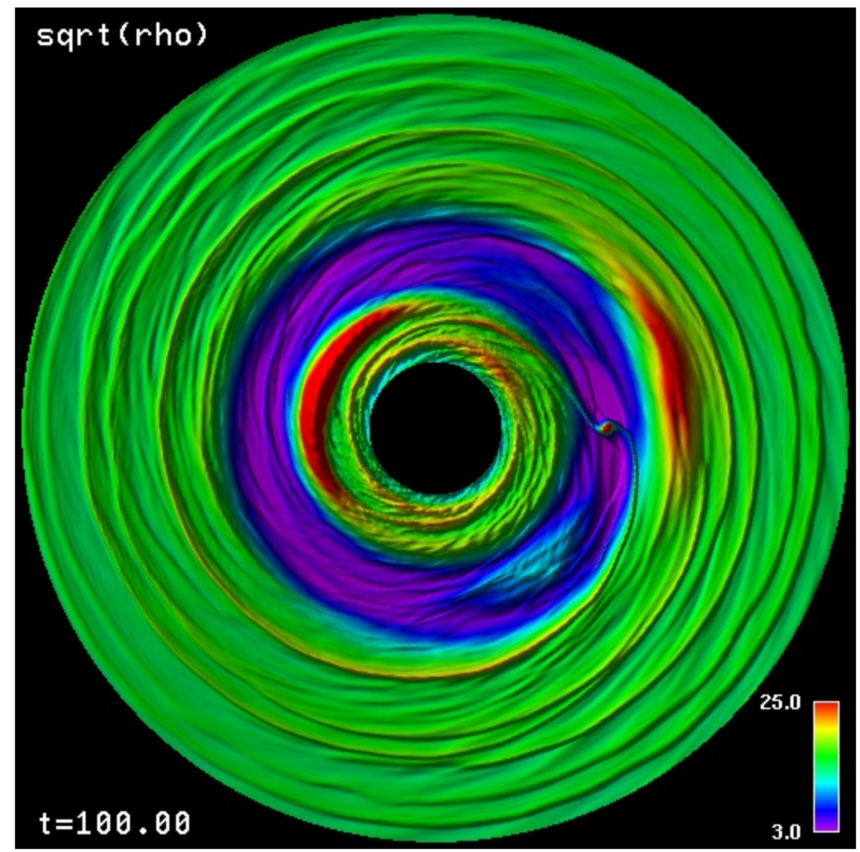




(Lyra 2009)

These cavities may be the telltale signature of forming planets

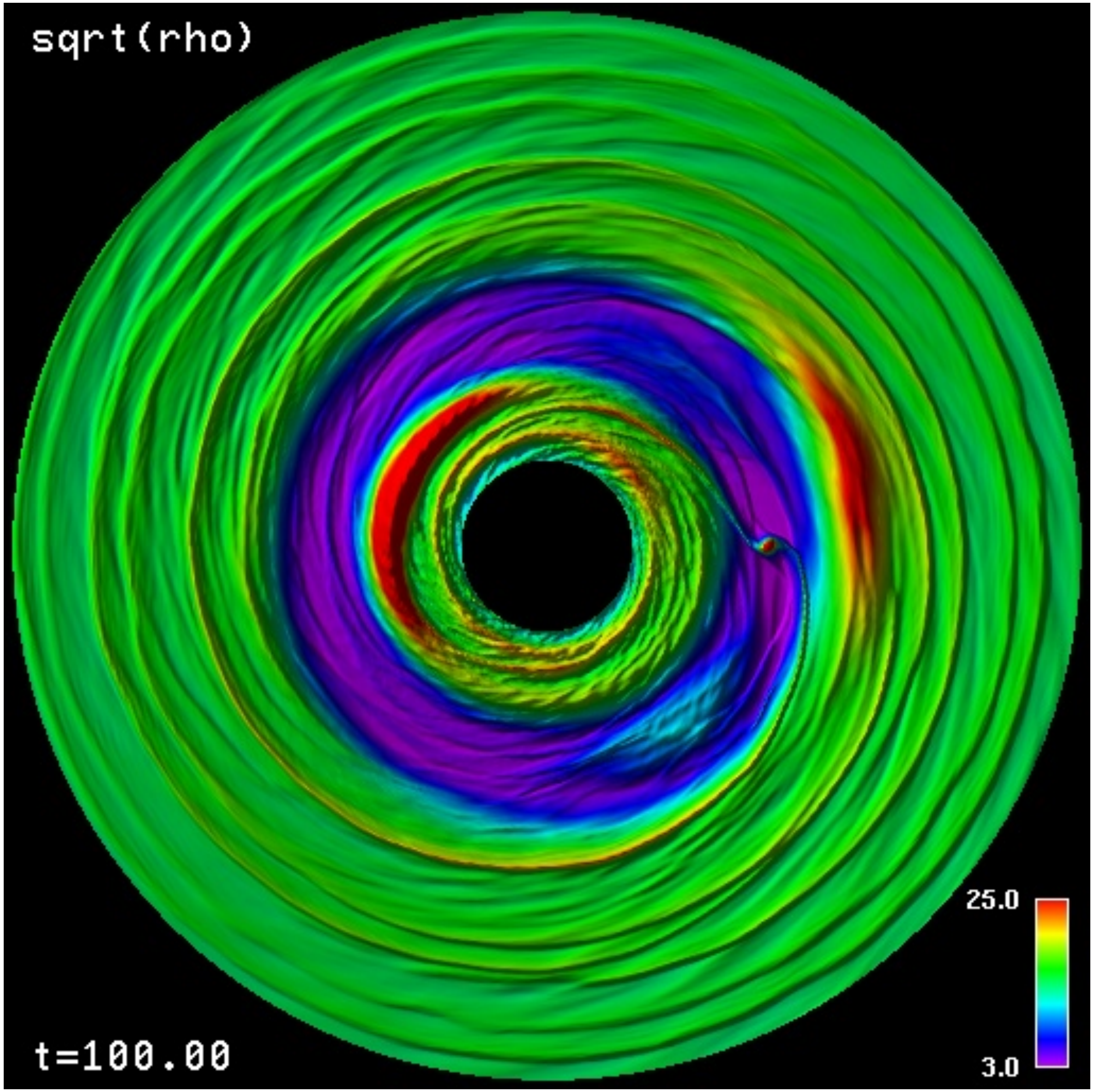




(Bryden et al. 1999)

A way to directly study planet-disk interaction

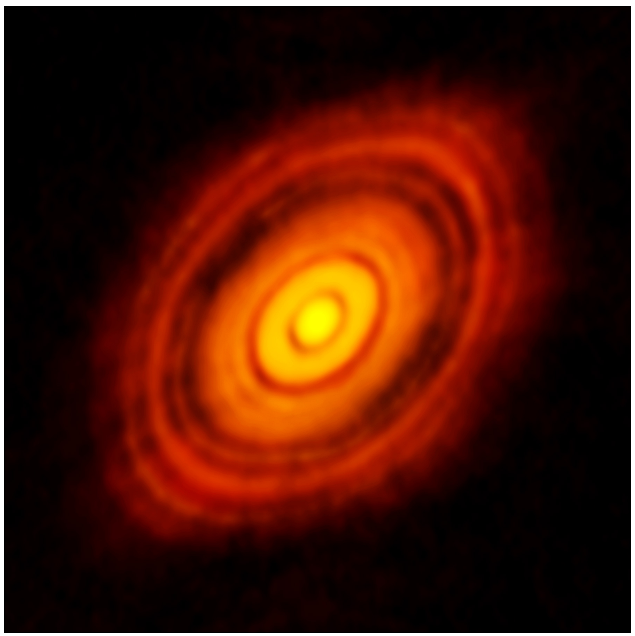
Planet-disk interaction: gaps, spirals, and vortices.



(Bryden et al. 1999)

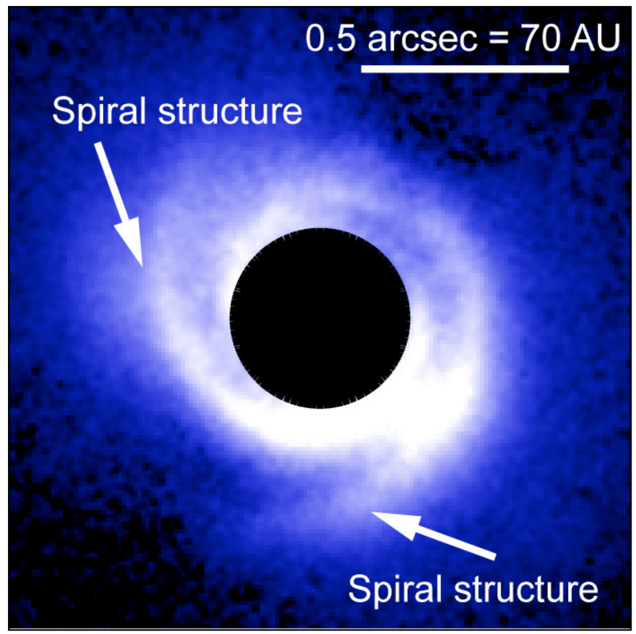
Observational evidence: gaps, spirals, and vortices

HL Tau



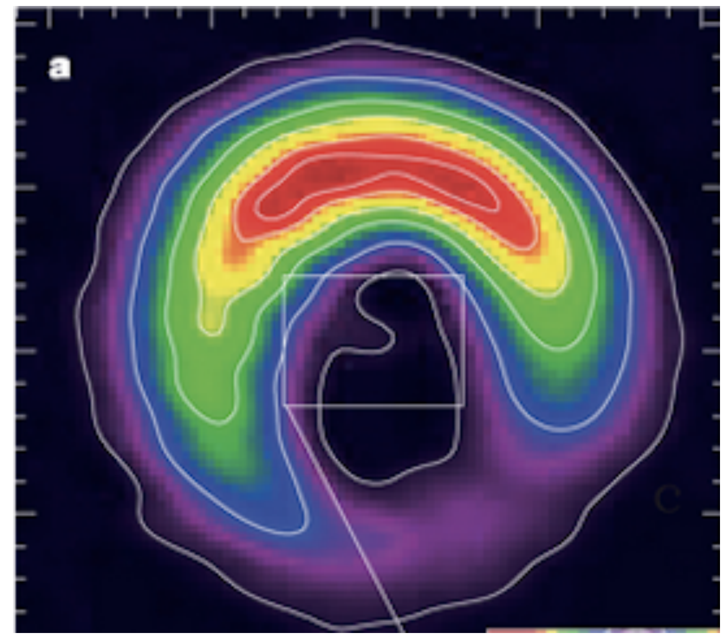
The ALMA Partnership et al. (2015)

SAO 206462



Muto et al. (2012)

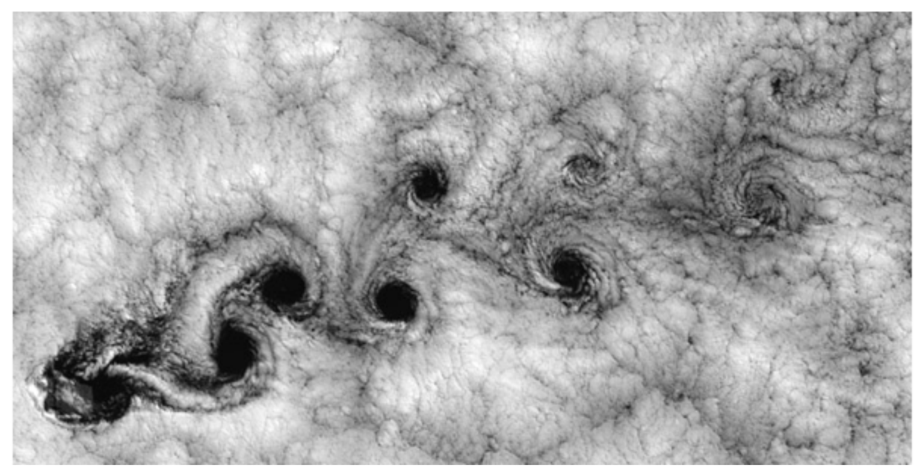
HD 142527



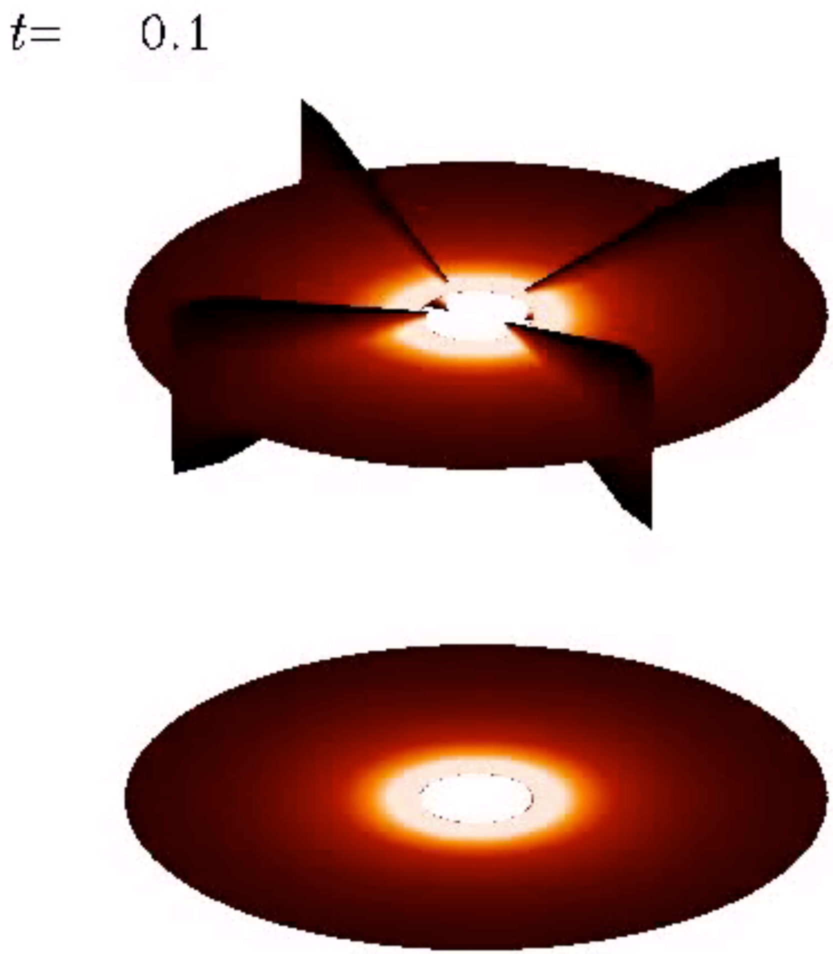
Casassus et al. (2013)

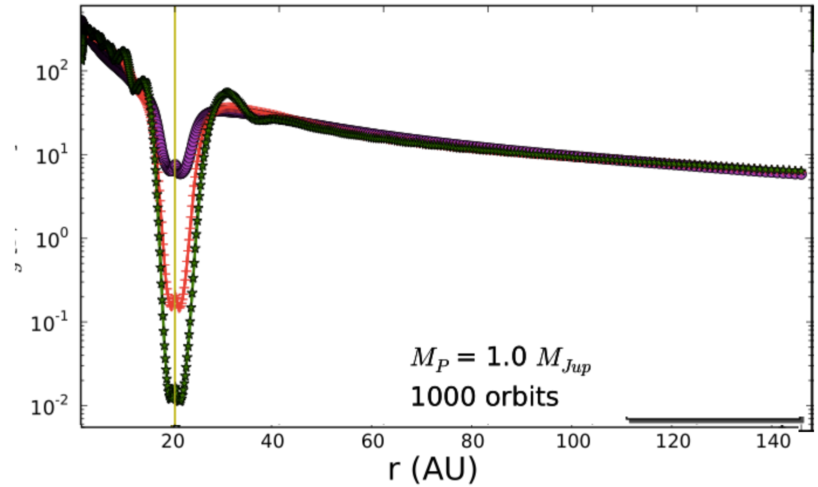
Vortices – an ubiquitous fluid mechanics phenomenon

Von Kármán *vortex street*



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



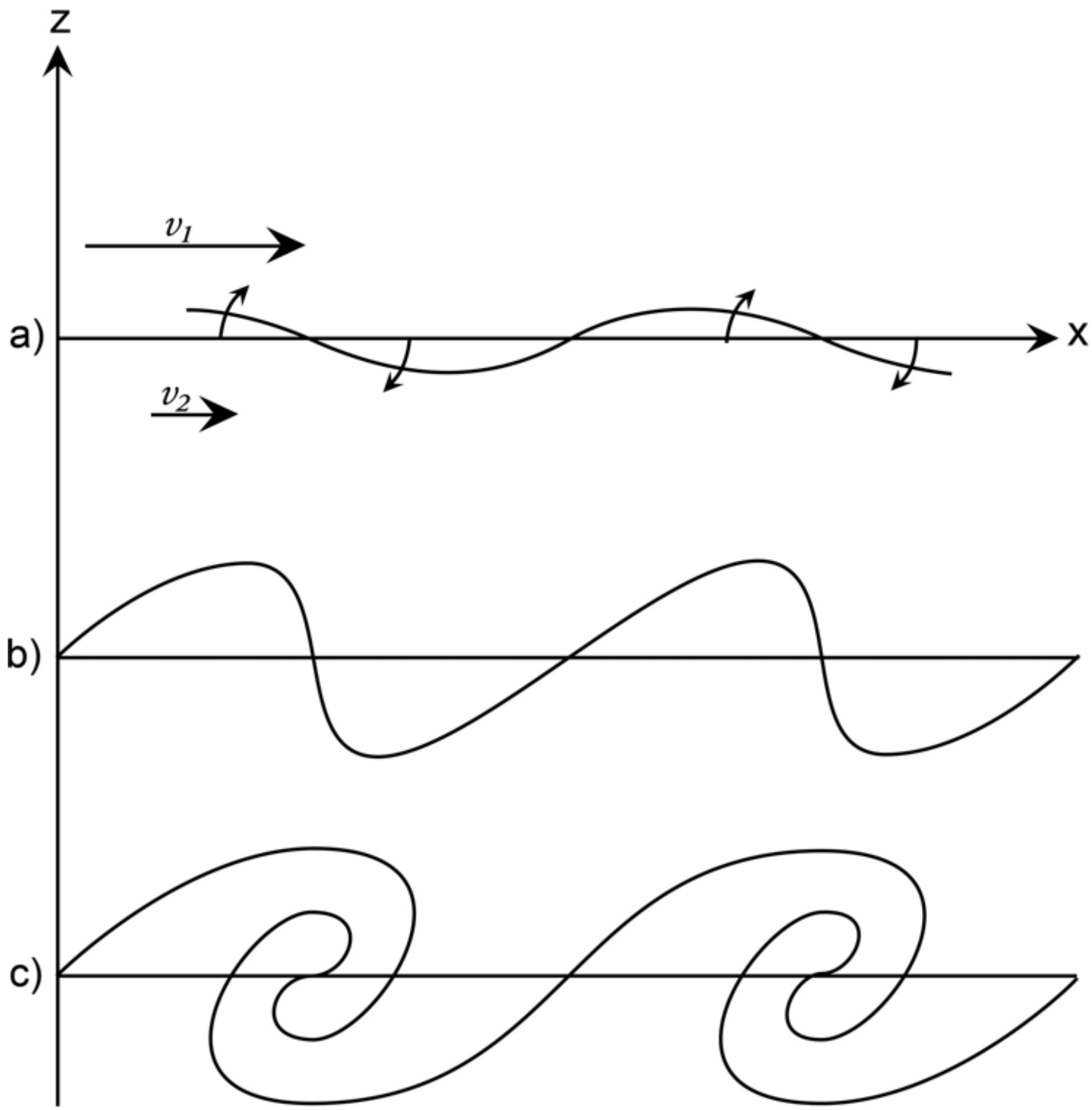


Planet tides carve gap

Gap walls are unstable to Kelvin-Helmholtz instability

Lyra (2009)

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



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

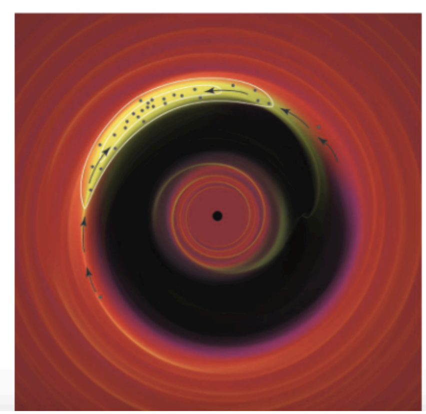
ASTRONOMY

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-



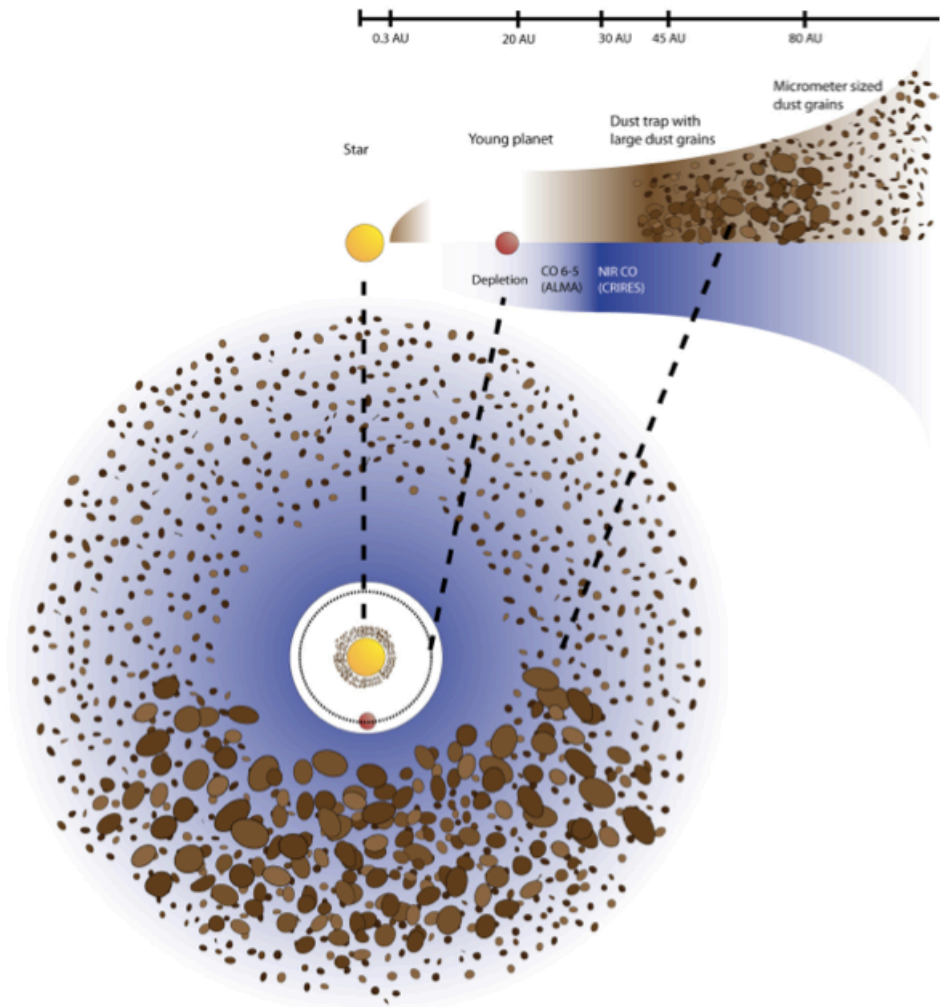
From dust to planet. Illustration of the proposed mechanism that creates a dust trap in the disk of IRS 48. A massive planet (plus symbol) creates an annular gap in the gas disk, whose surface density is shown as a color map. A high-pressure vortex (contours) forms at the gap edge, collecting and trapping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

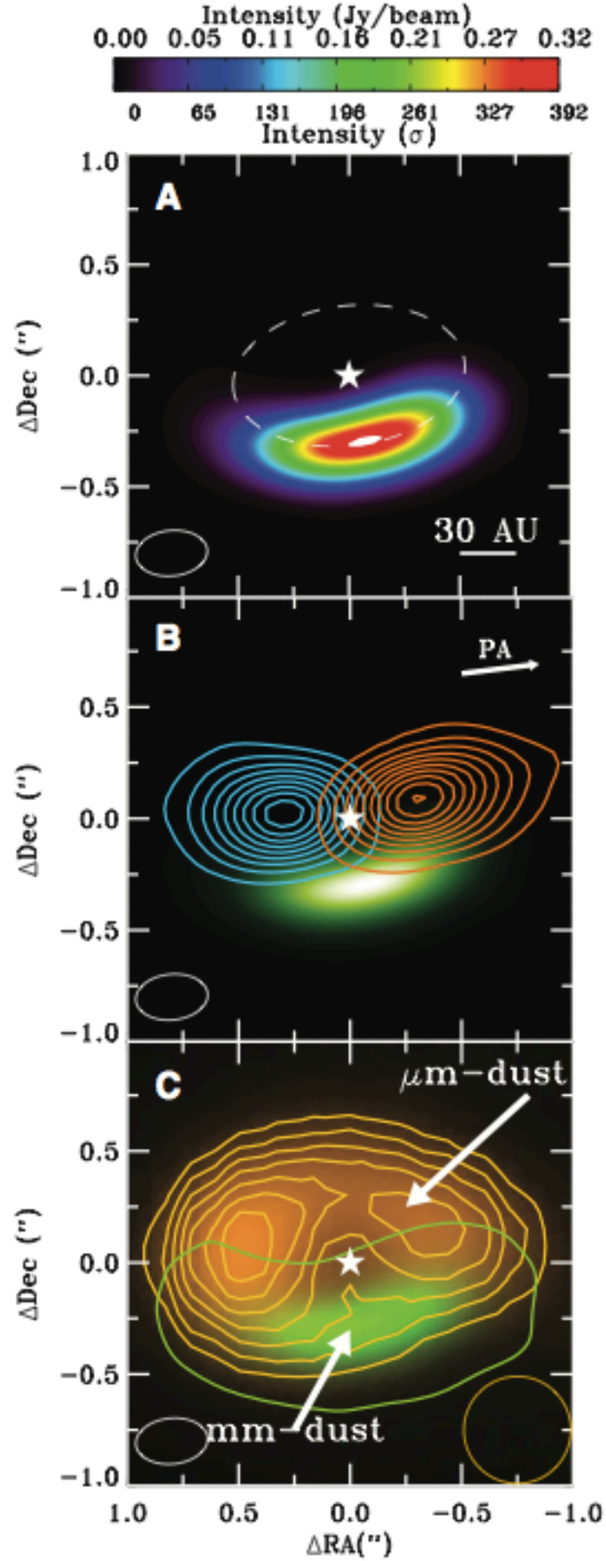
van der Marel et al. 2013

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

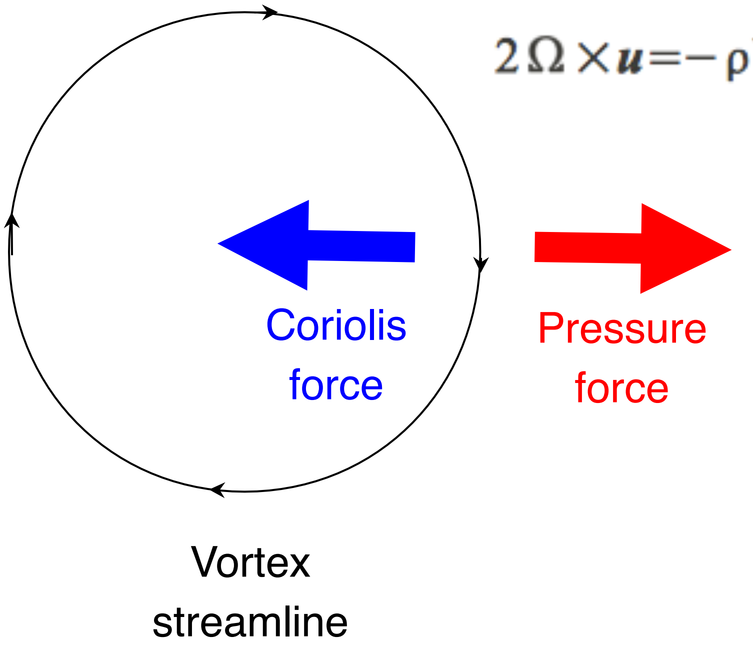
Gas detection: Keplerian rotation

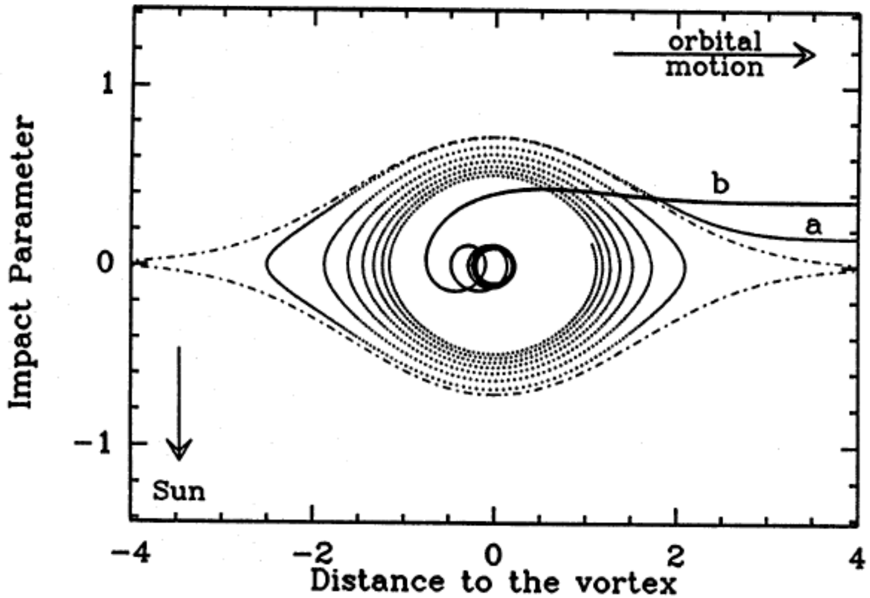
Micron-sized dust follows gas

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)

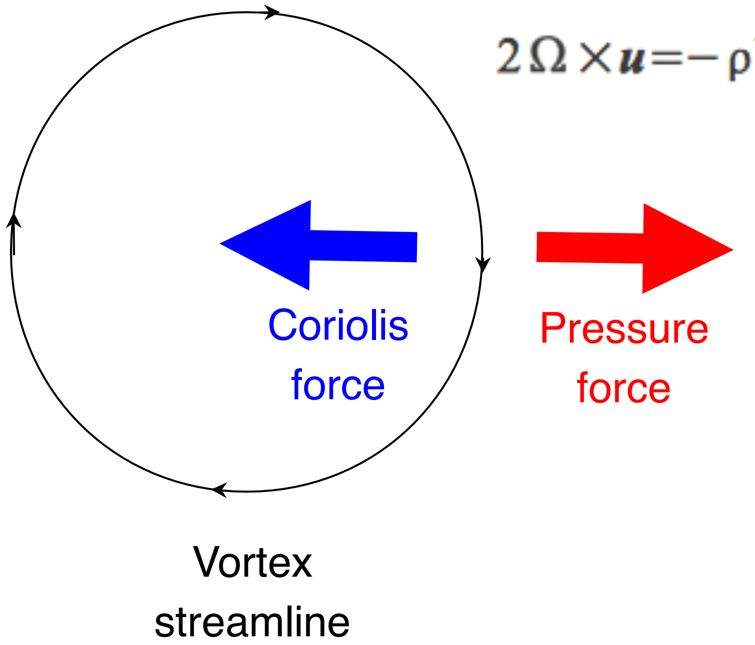
Speed up planet formation enormously

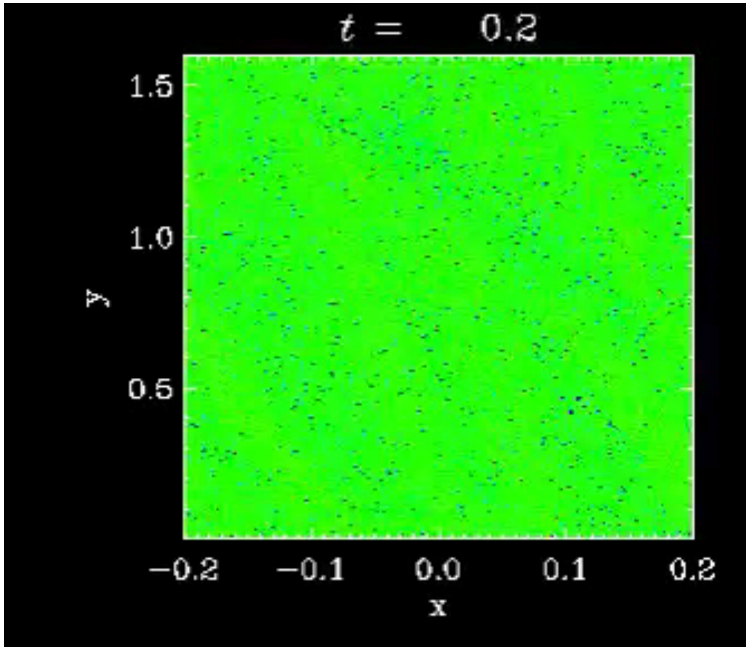
(Lyra et al. 2008b, 2009ab, Raettig et al. 2012)

The Tea-Leaf effect

Geostrophic balance:

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





Raettig, Lyra, & Klahr (2013)

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

Aid to planet formation

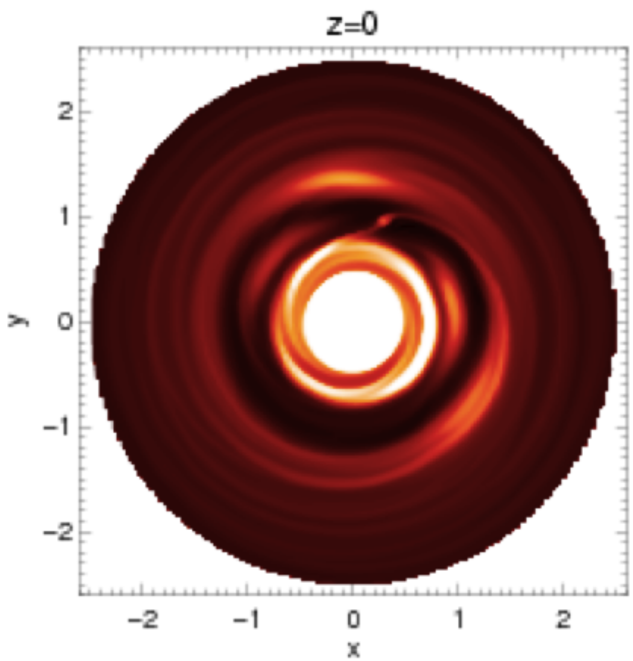
(Barge & Sommeria 1995, Tanga et al. 1996, Barranco & Marcus 2005)

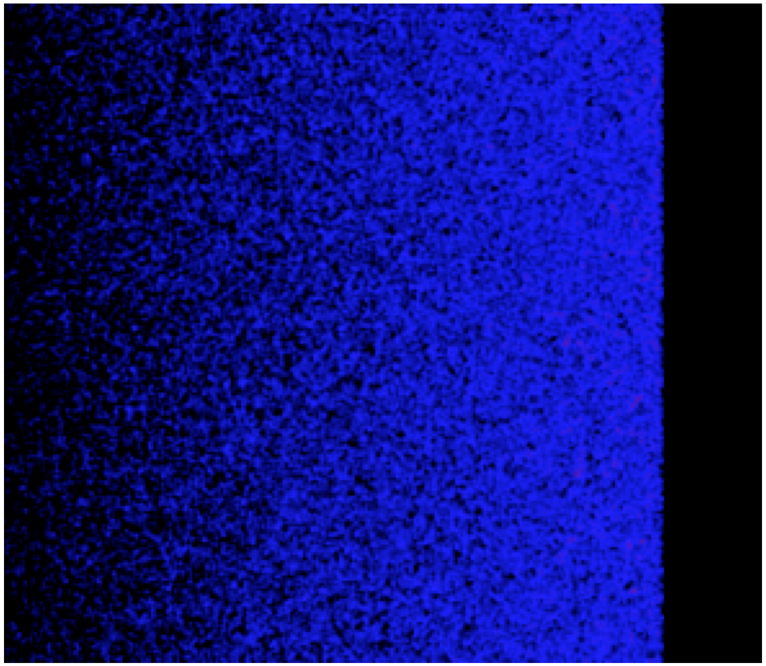
Speed up planet formation enormously

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

Planet Formation in gap edge vortices

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

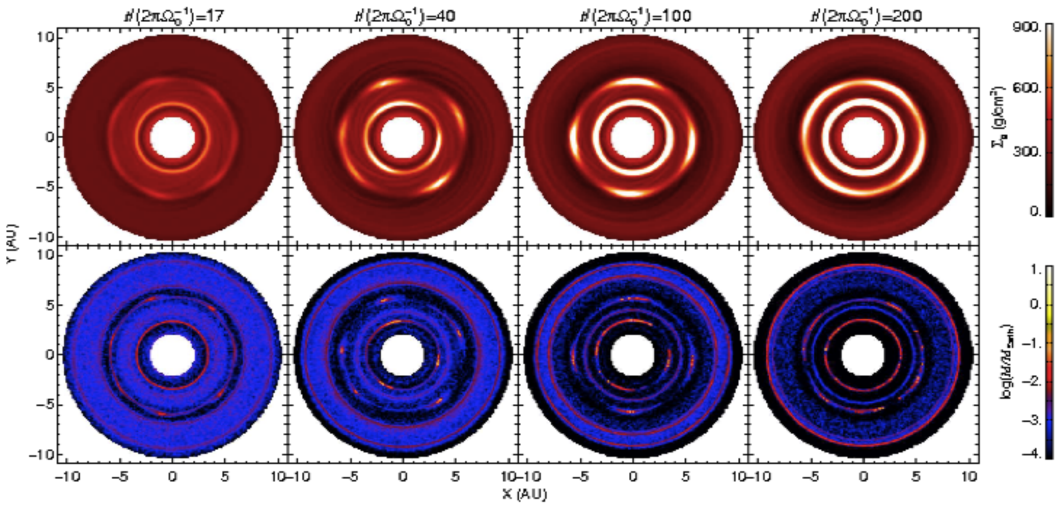




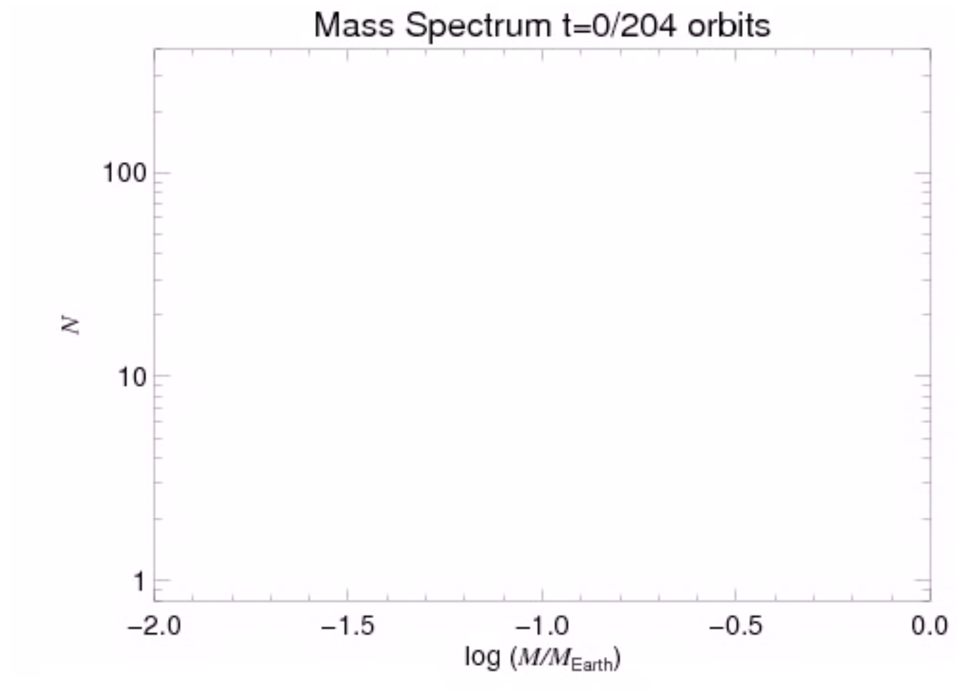
Burst of formation in gap vortices

Vortices and Planet Formation

Gas



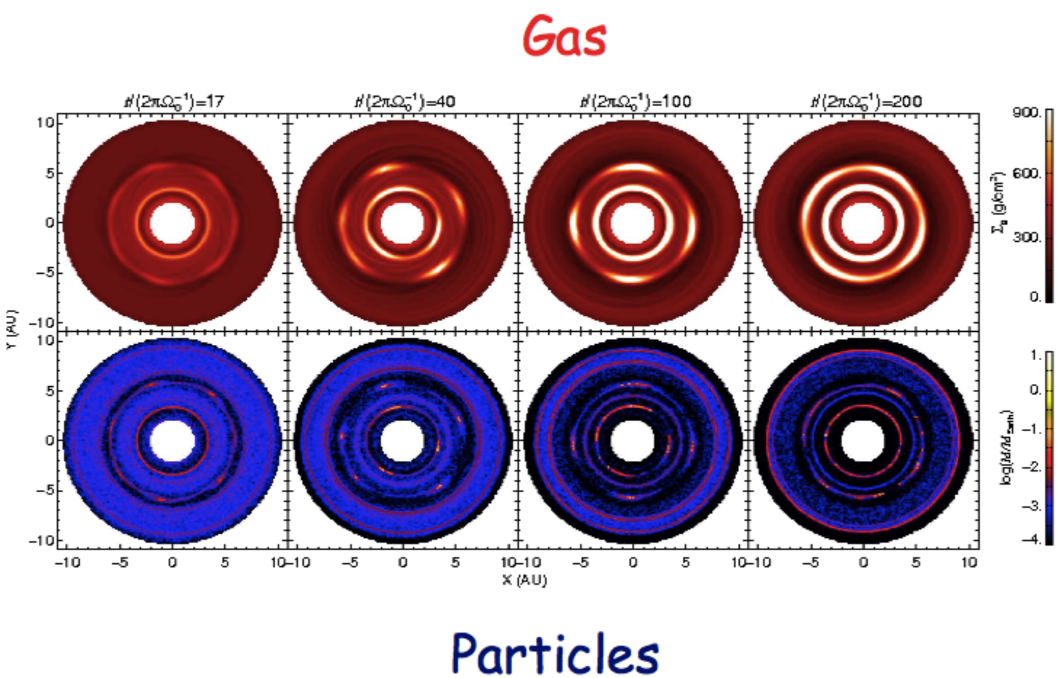
Grains

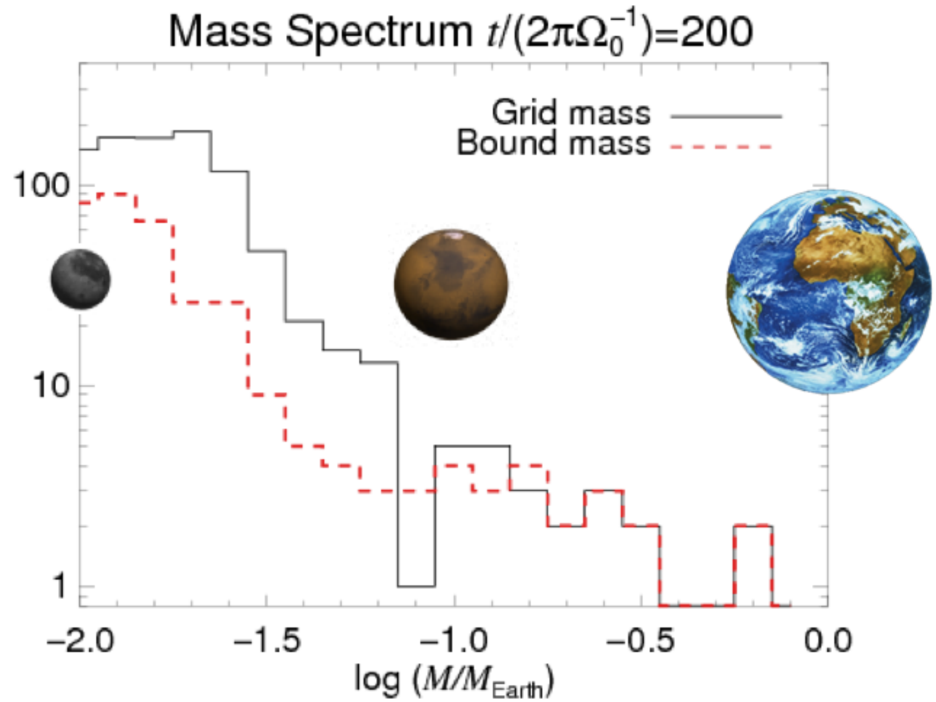


Collapse into Mars mass objects

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

Vortices and Planet Formation

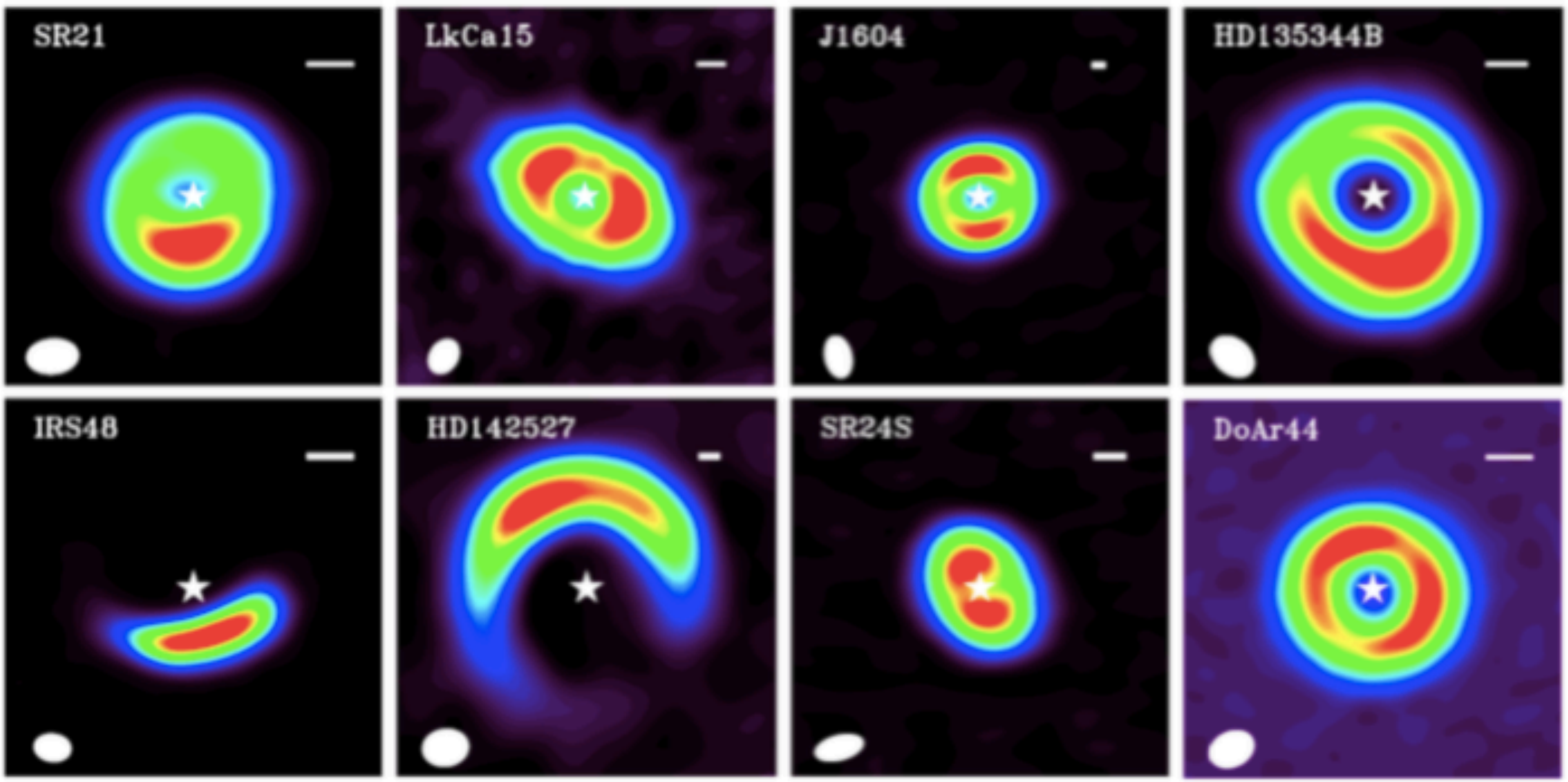




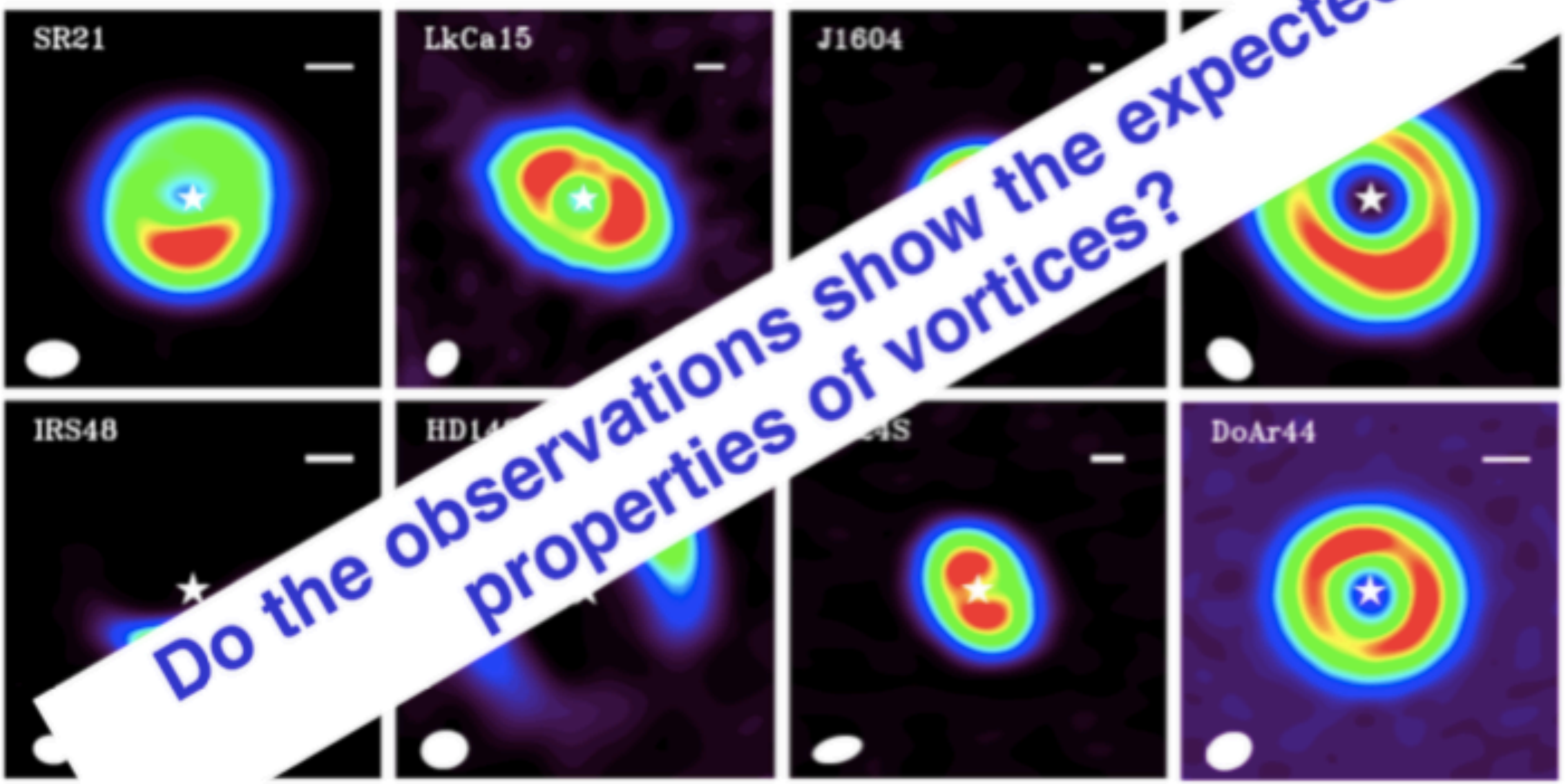
Collapse into Mars mass objects

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

“Asymmetries” everywhere

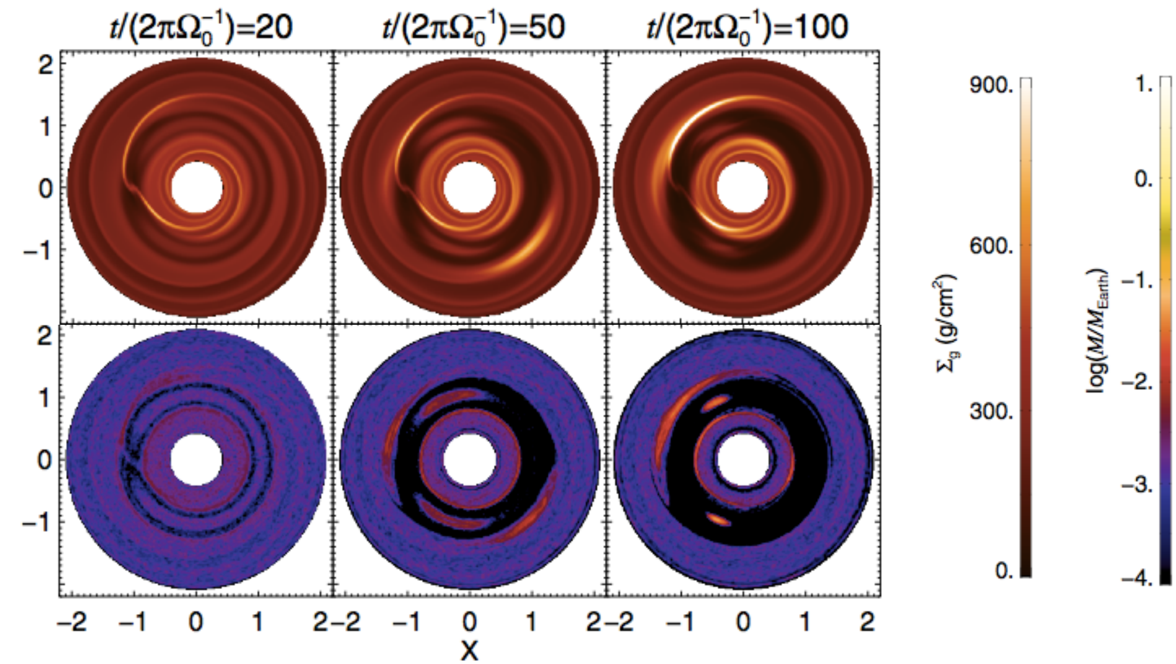


"Asymmetries" everywhere



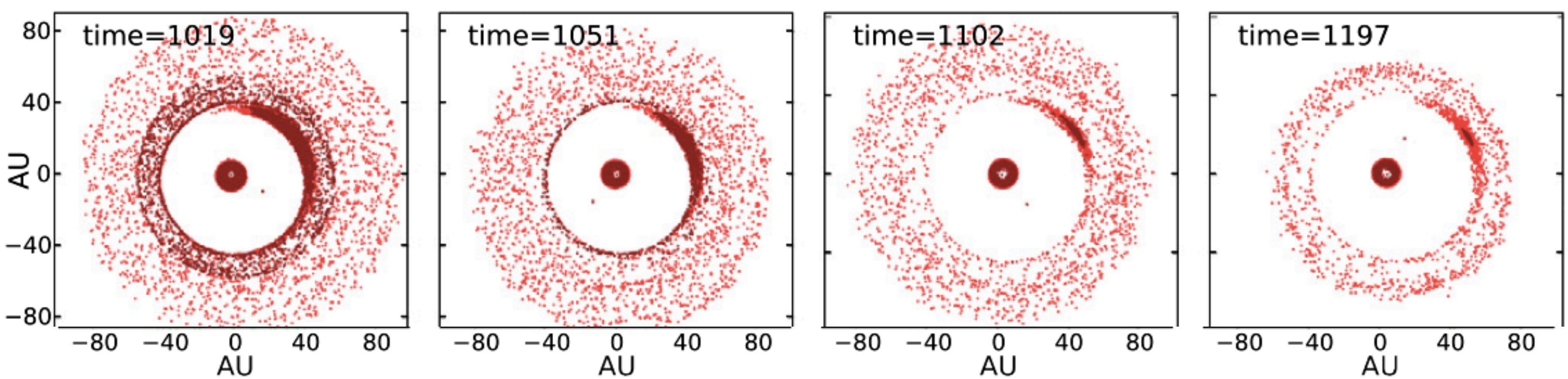
Do the observations show the expected properties of vortices?

Dust Trapping



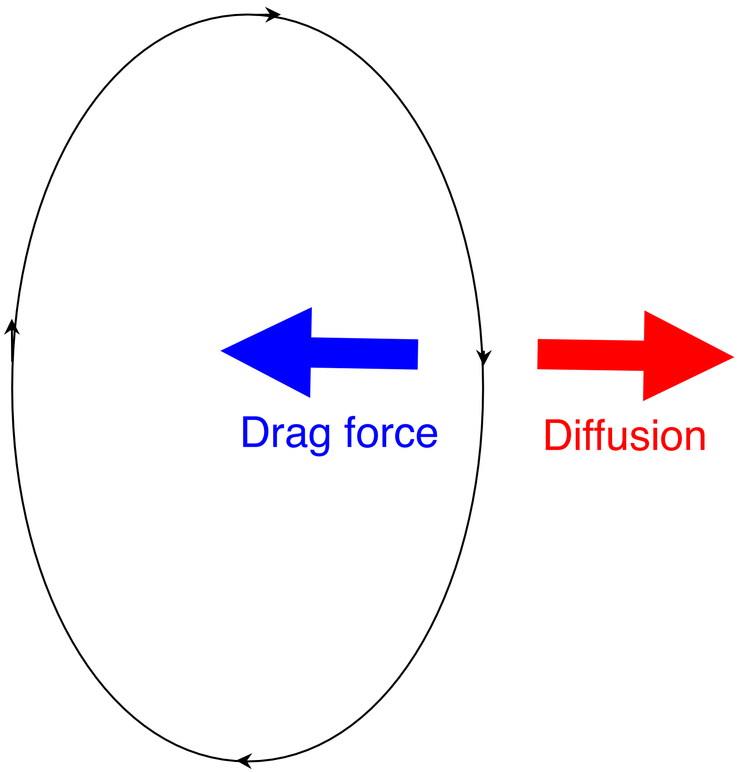
Lyra et al (2009b)

Turbulent "kicks" lead to steady state



Ataiee et al. (2013)

Drag-Diffusion Equilibrium



Trapped particle

Dust continuity equation

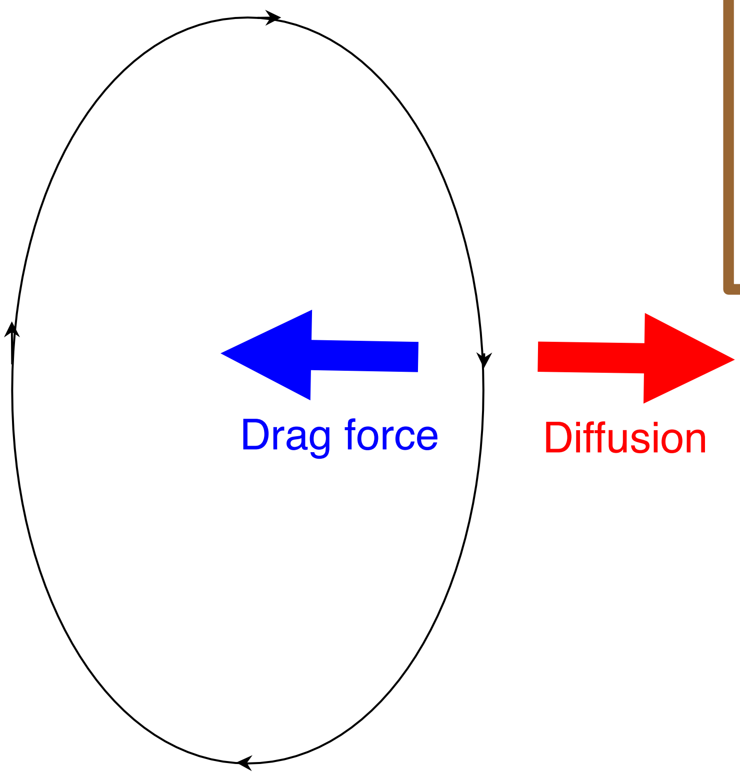
$$\frac{\partial \rho_d}{\partial t} = -(\boldsymbol{v} \cdot \boldsymbol{\nabla})\rho_d - \rho_d \boldsymbol{\nabla} \cdot \boldsymbol{v} + D\nabla^2 \rho_d,$$

advection — $-(\boldsymbol{v} \cdot \boldsymbol{\nabla})\rho_d$

compression — $-\rho_d \boldsymbol{\nabla} \cdot \boldsymbol{v}$

diffusion — $D\nabla^2 \rho_d$

Drag-Diffusion Equilibrium



Trapped particle

Steady-state solution

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

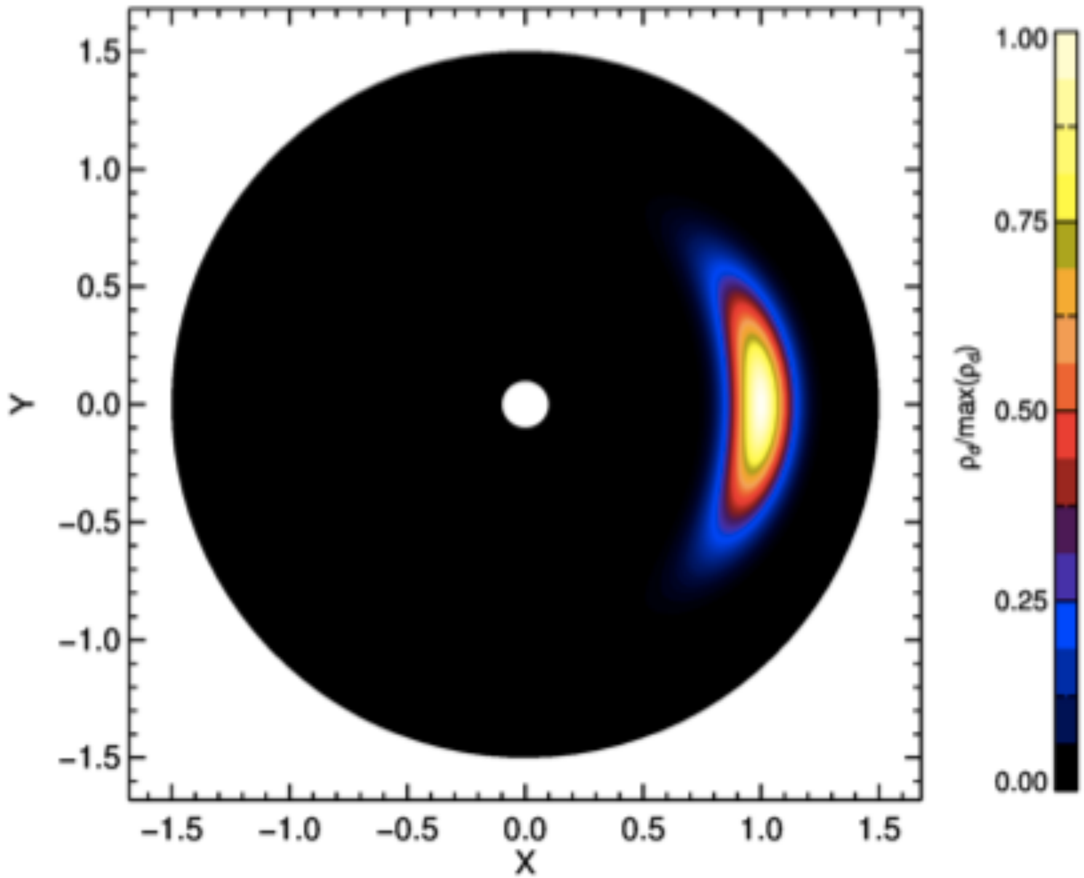
Lyra & Lin (2013)

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

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

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 for

H/r=0.1 χ*=4* *S*=1

Solution

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

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

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

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

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

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}

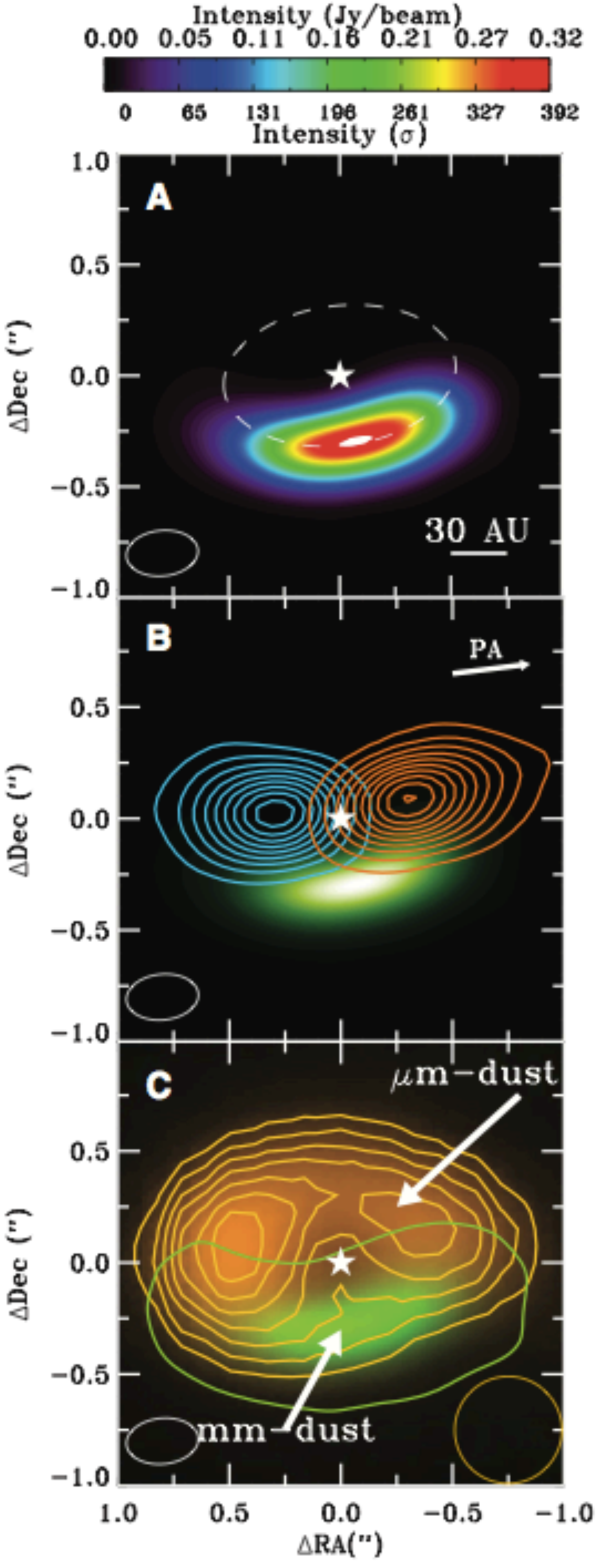
Derived parameters

S=4.8

Stokes number, St=0.008

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

Trapped mass: 11 M_{Earth}



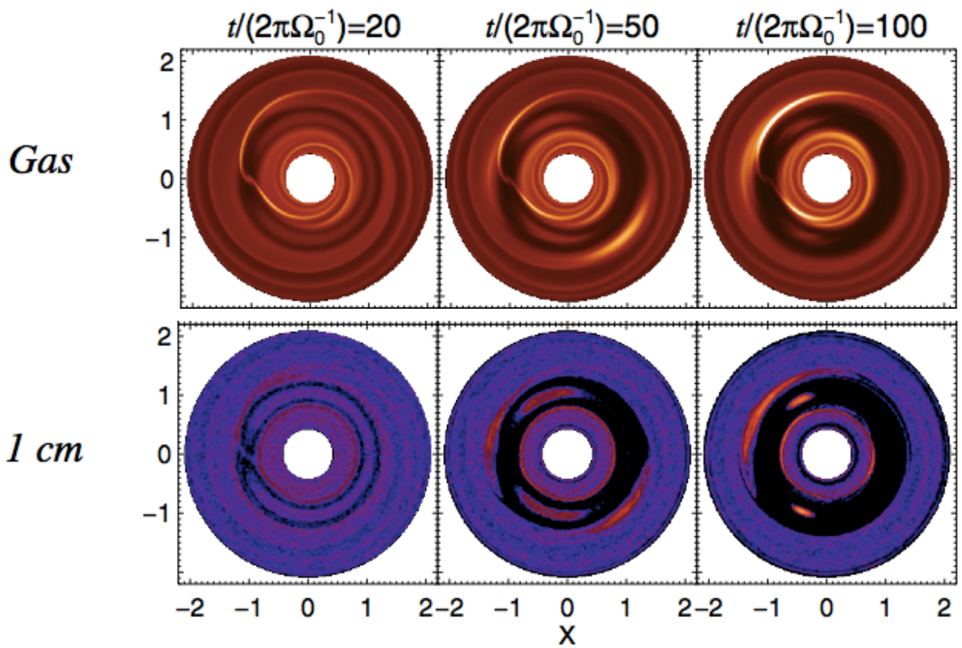
asymmetric mm dust at 63 AU

Gas detection: Keplerian rotation

Micron-sized dust follows gas

Lyra & Lin (2013)

Planetary gap vortices: Chicken or the Egg problem



Lyra et al (2009b)

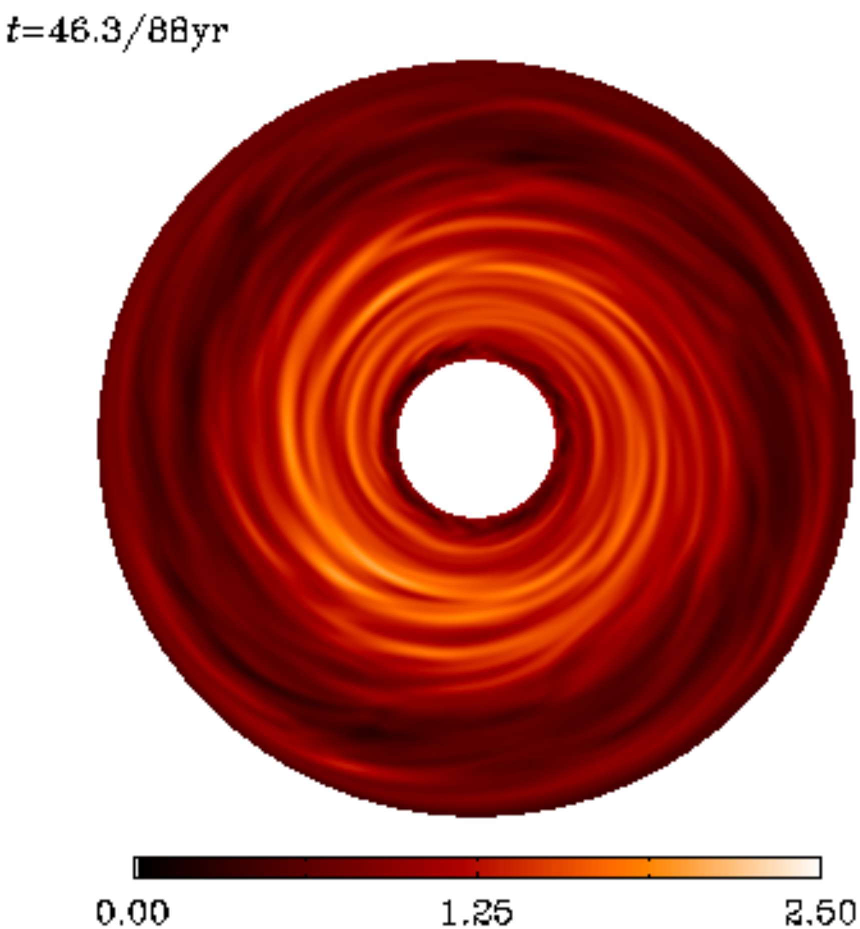
Does the observational detection of a particle trap in IRS 48 imply that traps are the answer to surmounting the radial drift barrier and allowing planet formation? Not immediately. Particle traps solve theoretical problems in planet formation that exist at millimeter to meter scales, and they are no 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

Magneto-Rotational Instability

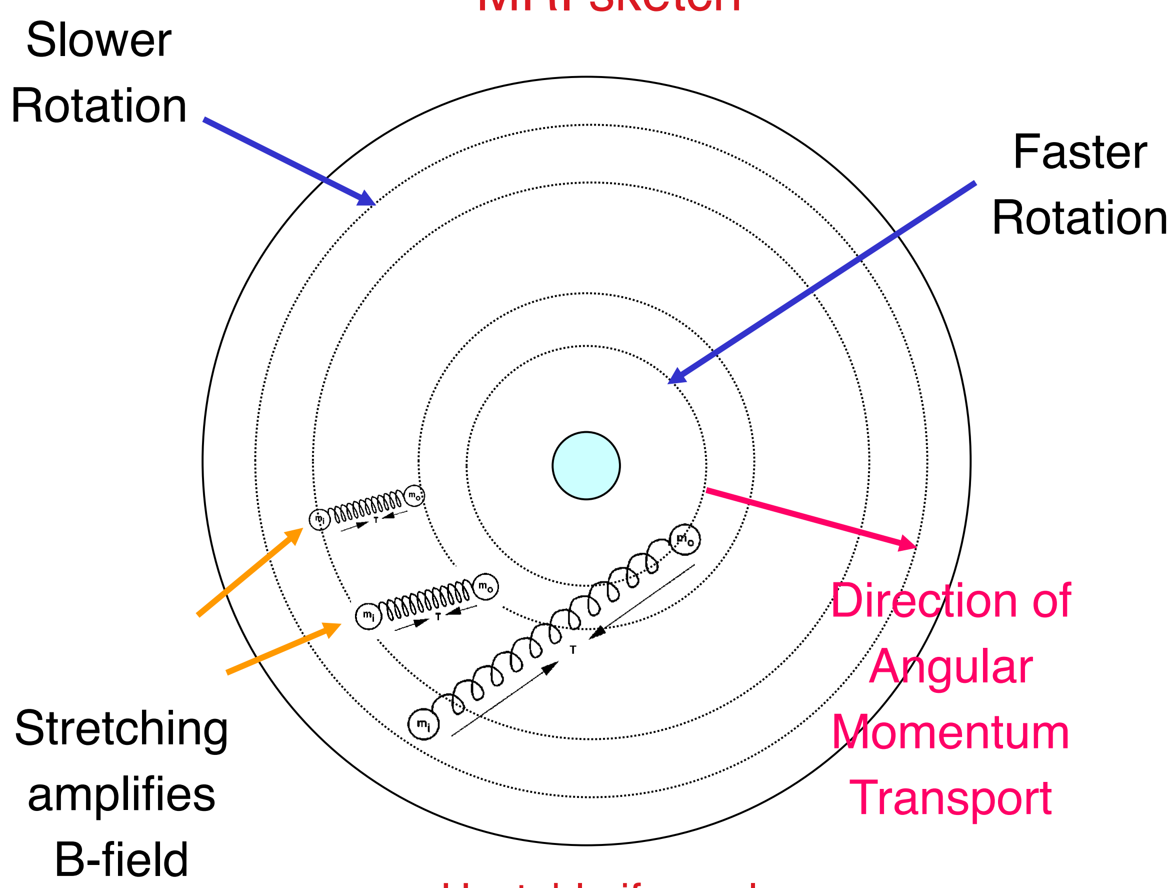
Turbulence in disks is enabled by the
Magneto-Rotational Instability (Balbus & Hawley, 1991)



Magnetized disk

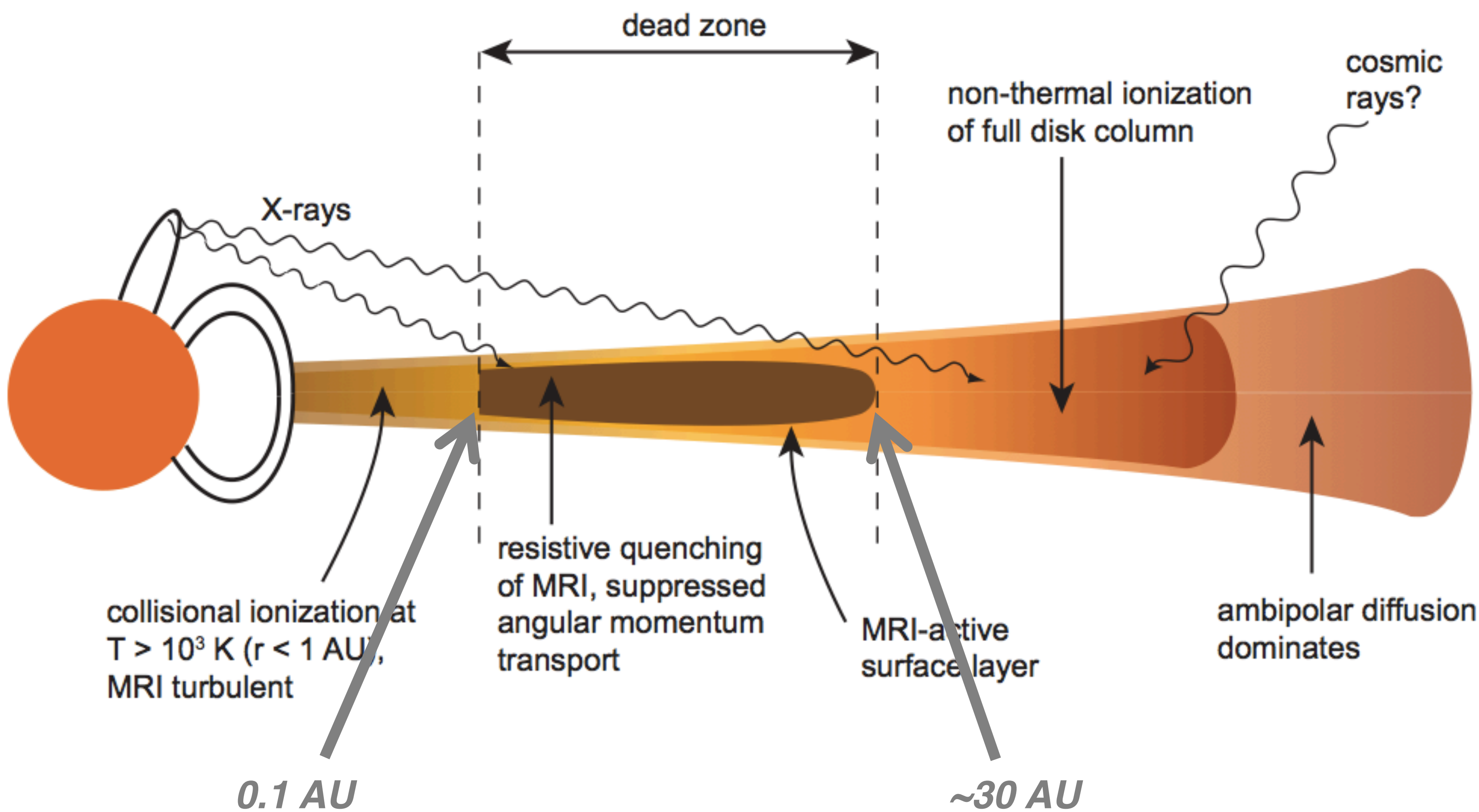
Lyra et al. (2008a)

MRI sketch



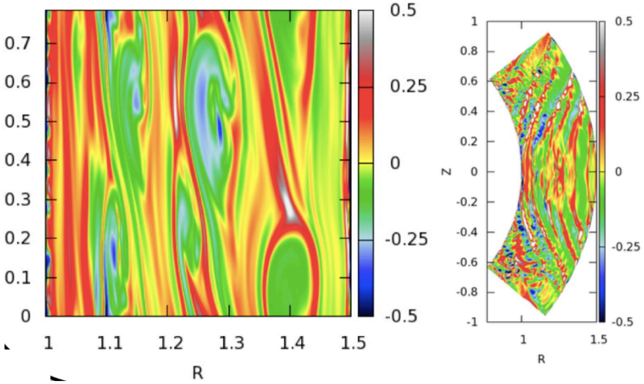
Unstable if angular velocity decreases outward

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

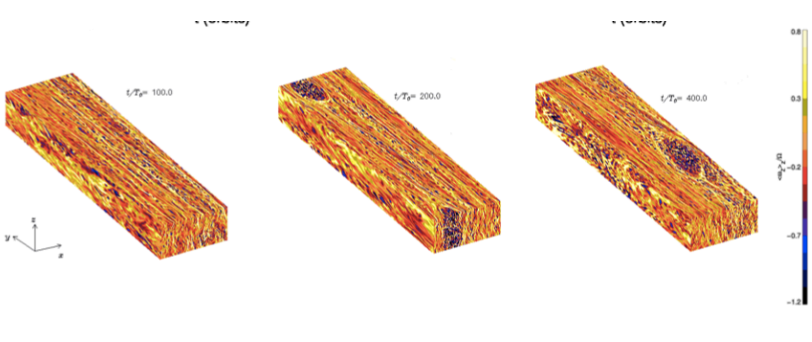
Thermal Instabilities

Vertical Shear Instability



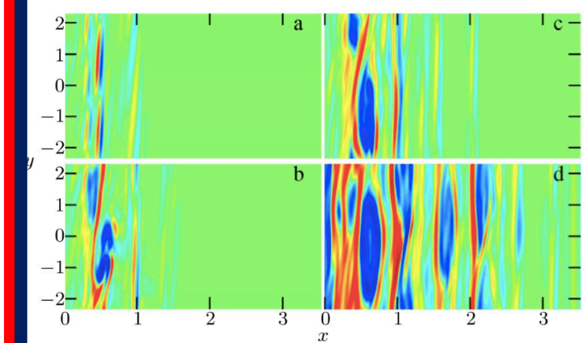
Nelson et al. 2013, Lin & Youdin 2015, Umurhan et al. 2016

Convective Overstability



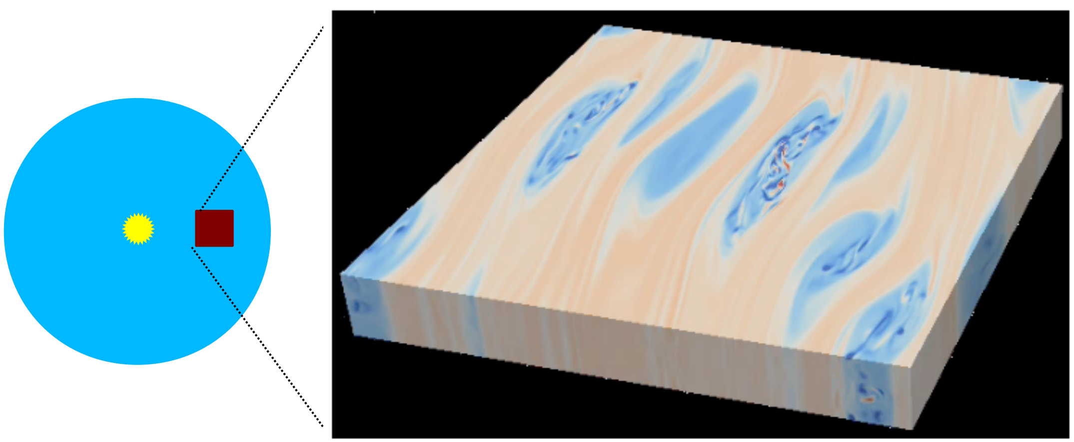
Klahr 2003, Lesur & Papaloizou 2010, Lyra & Klahr 2011, Lyra 2014

Zombie Vortex Instability



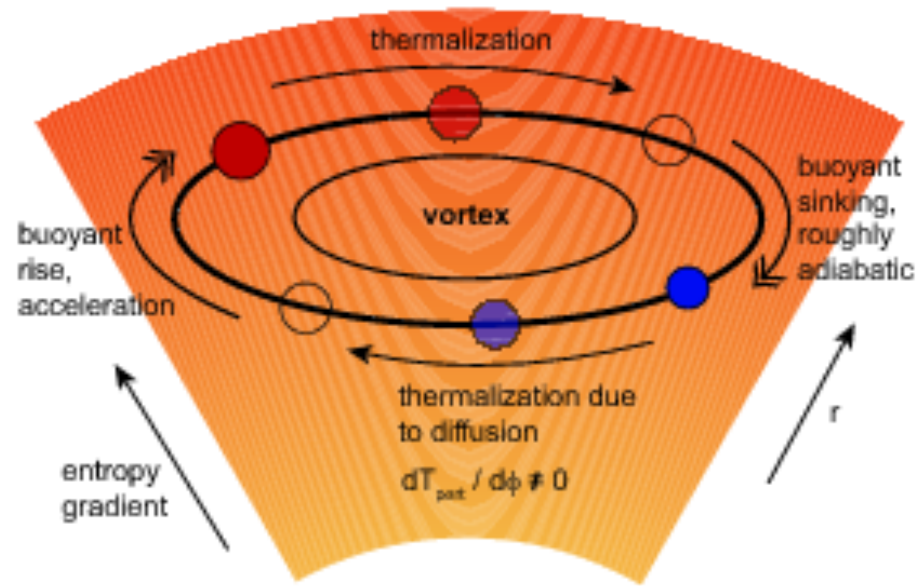
Marcus et al. 2012, 2013, 2015, 2016
Umurhan et al 2016, Lesur & Latter 2016

Convective Overstability (née "Subcritic Baroclinic Instability")



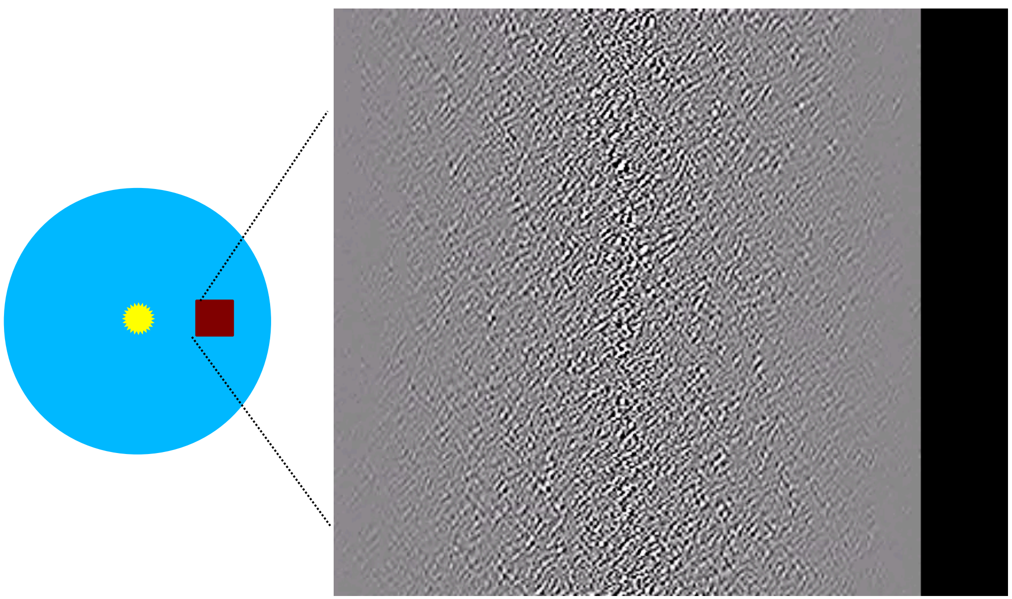
Lesur & Papaloizou (2010)

Sketch of the
Subcritic Baroclinic Instability



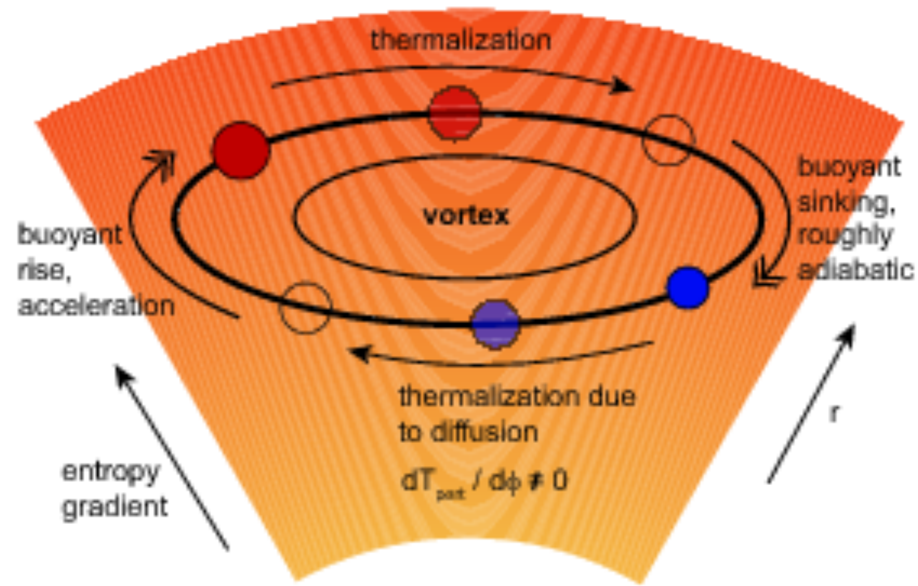
Armitage (2010)

Convective Overstability (née "Subcritic Baroclinic Instability")



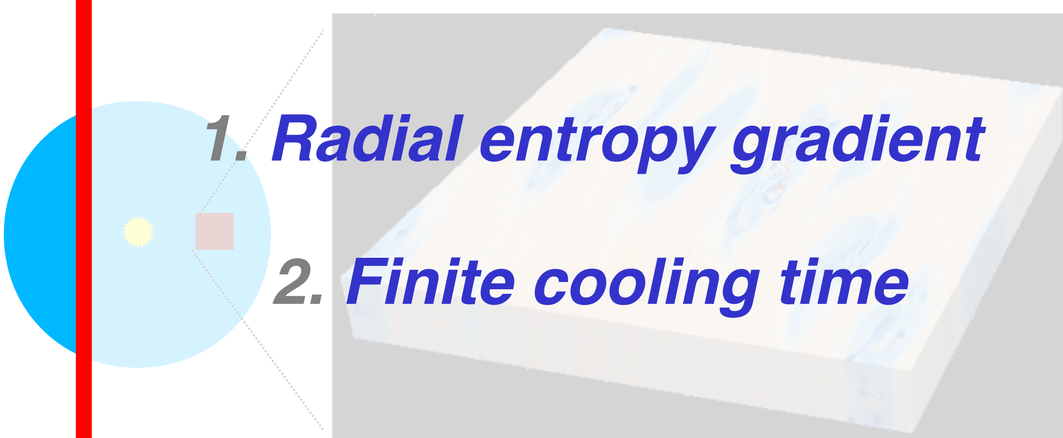
Lyra & Klahr (2011)

Sketch of the
Subcritic Baroclinic Instability



Armitage (2010)

Convective Overstability (née “Subcritic Baroclinic Instability”)

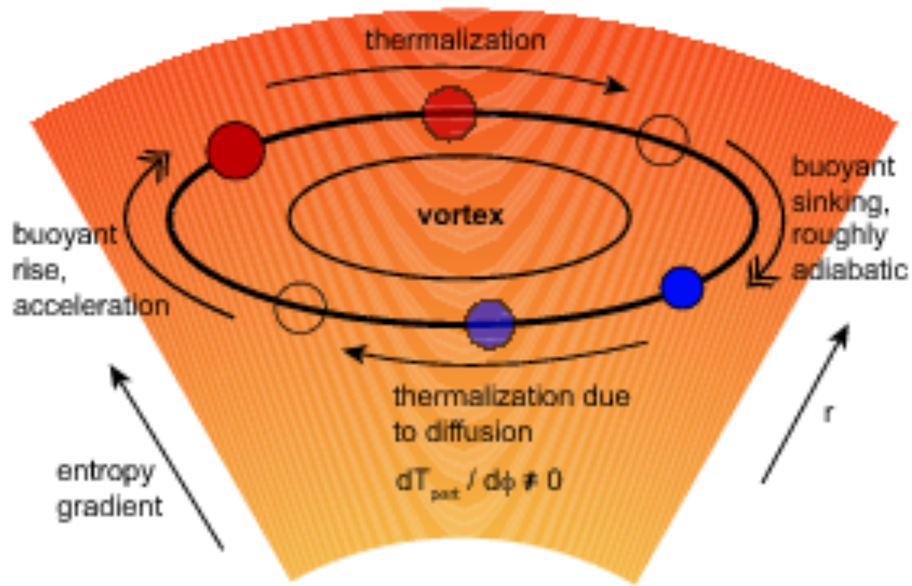


1. ***Radial entropy gradient***

2. ***Finite cooling time***

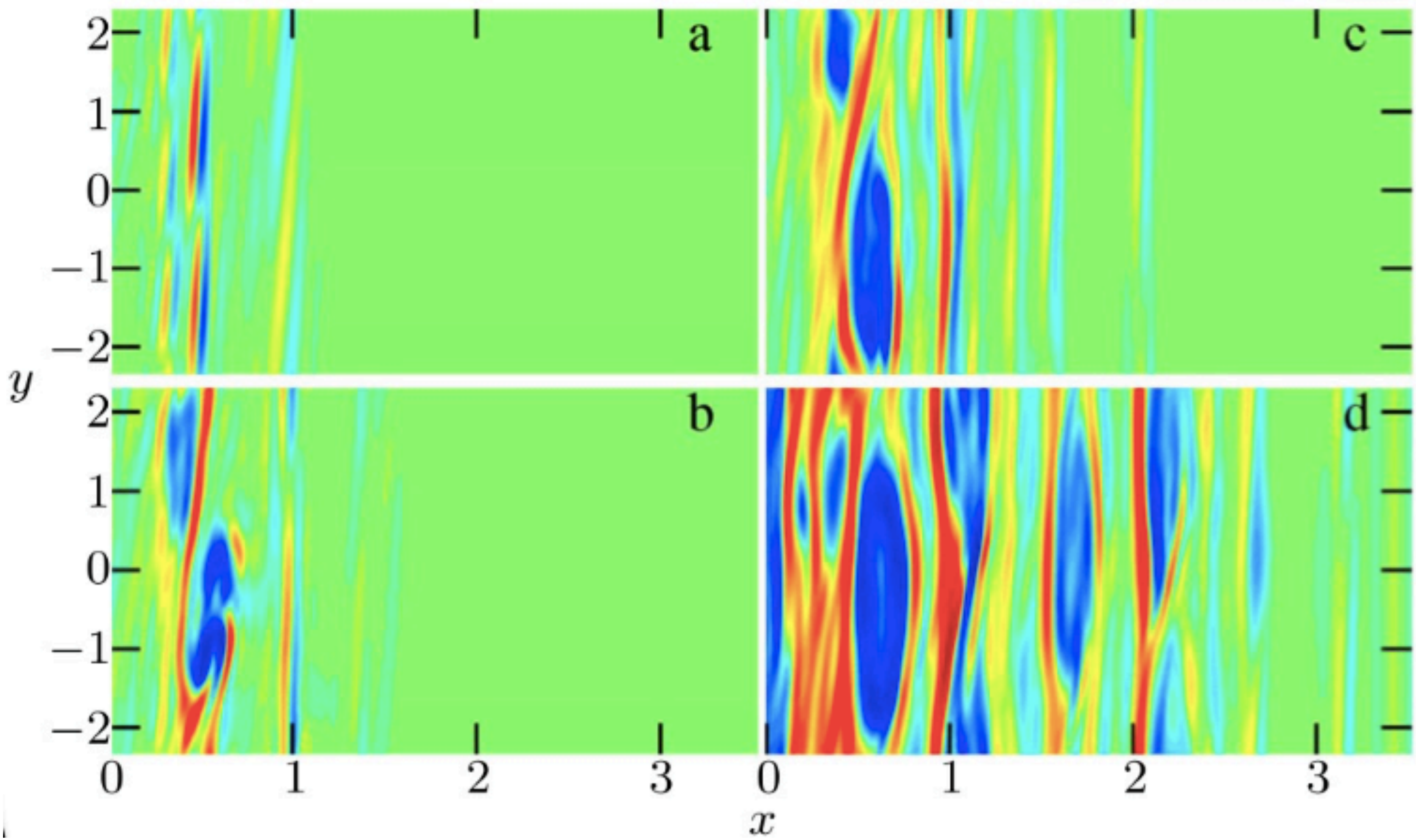
Lesur & Papaloizou (2010)

Sketch of the
Subcritic Baroclinic Instability



Armitage (2010)

Zombie Vortex Instability



Cascade of baroclinic critical layers

Marcus et al. (2015, 2016)

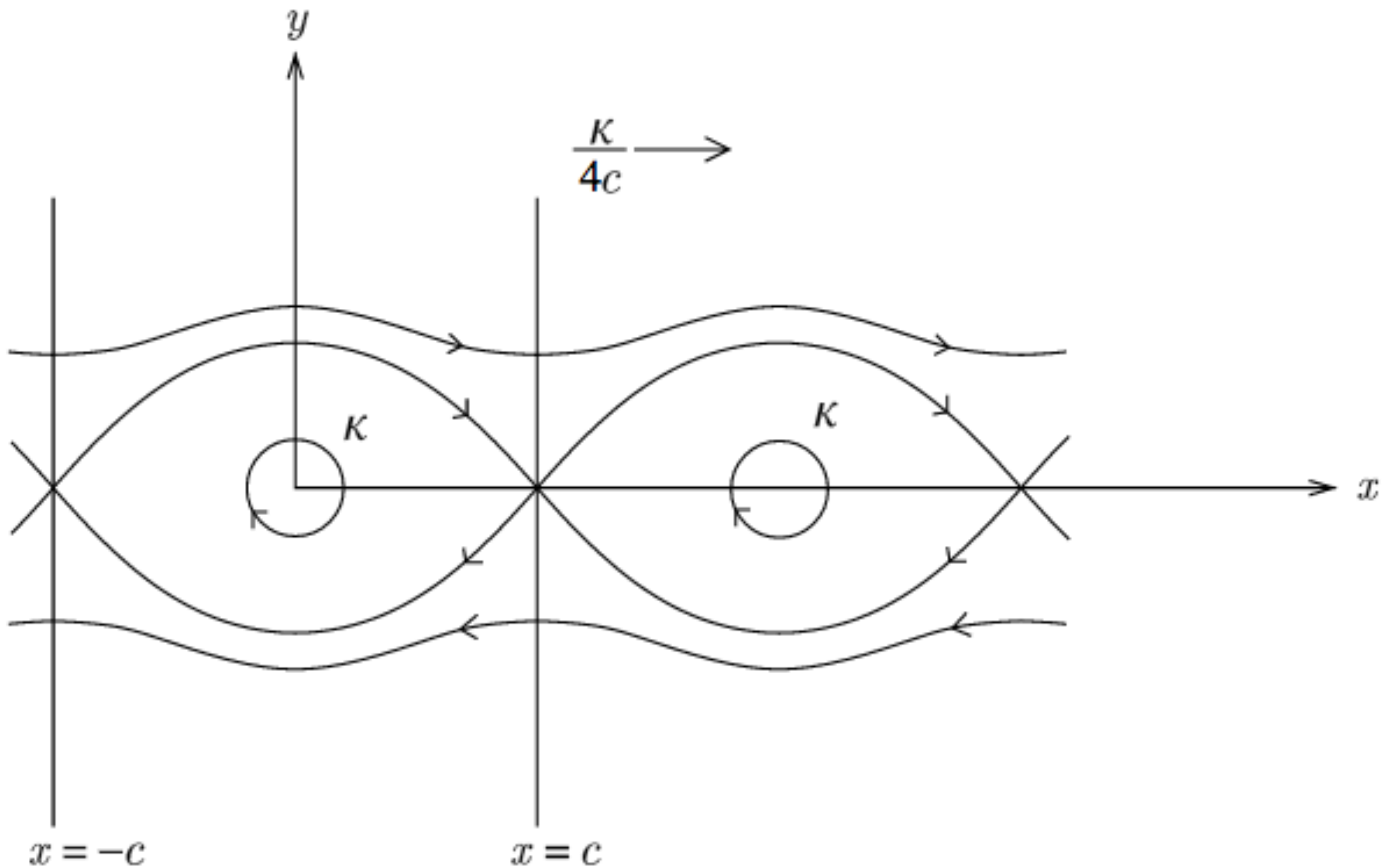


Figure 1. Notation and cat's-eye streamlines.

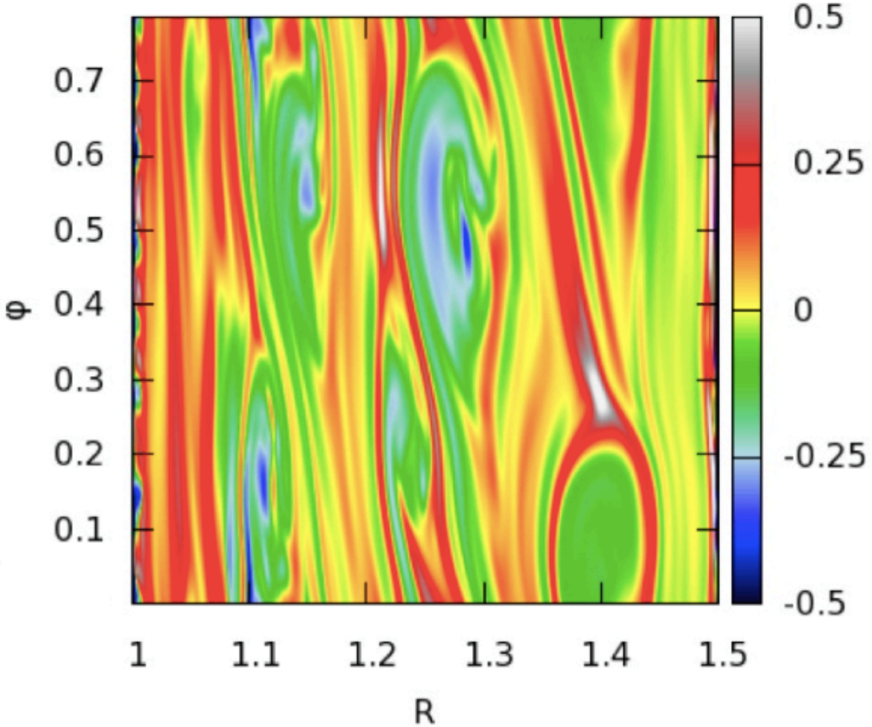
Vertical shear instability

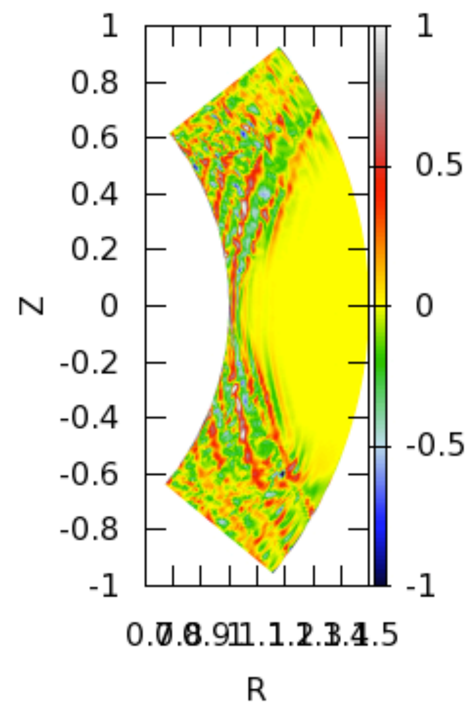
$$\rho_{\mathrm{mid}} = \rho_0 \left(\frac{R}{R_0}\right)^p ,$$

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

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

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





Nelson et al. (2013)

Vertical shear instability

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

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

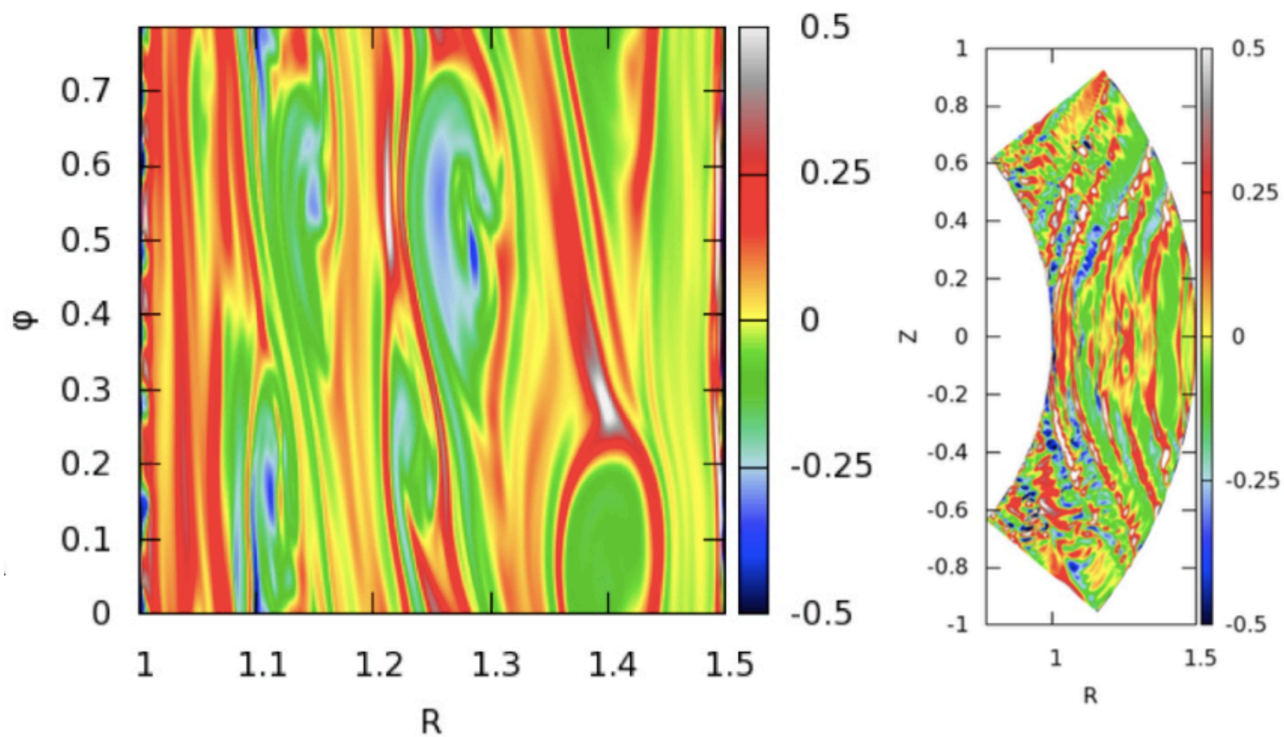
→

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

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

Solberg-Hoiland stability criterion

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



Nelson et al. (2013)

Vertical shear instability

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

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

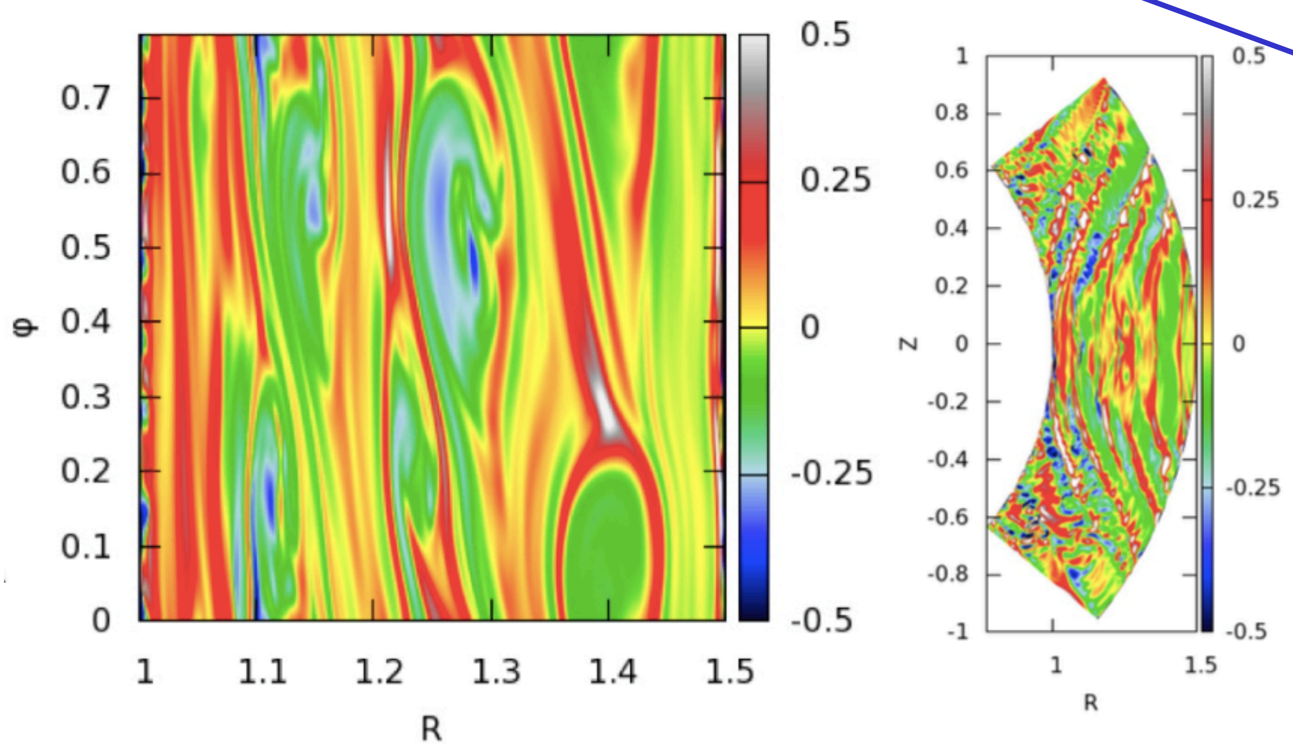
$$\Omega = \Omega_K \left[1 + \frac{1}{2}\left(\frac{H}{R}\right)^2 \left(p + q + \frac{q}{2}\frac{Z^2}{H^2}\right)\right]$$

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

Solberg-Hoiland stability criterion

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

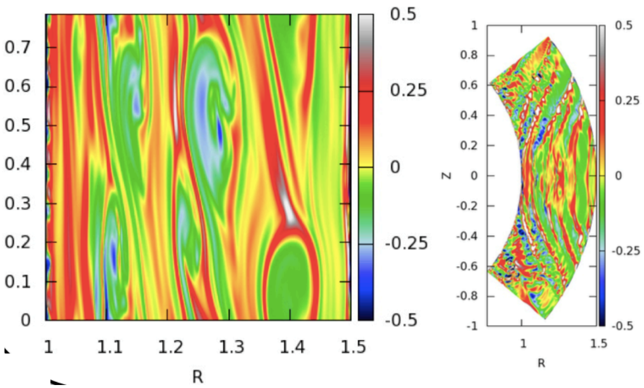
Buoyancy stabilizes!



Nelson et al. (2013)

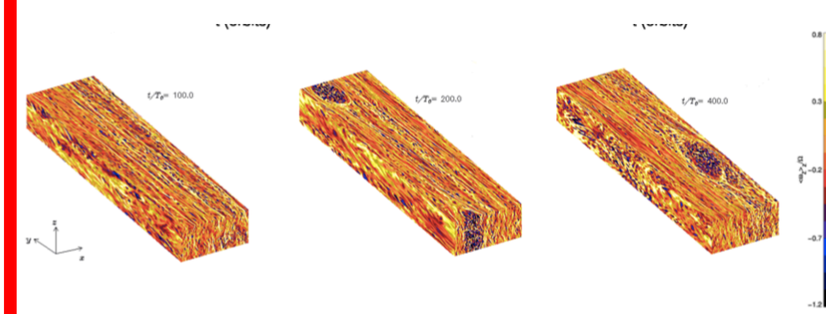
Thermal Instabilities

Vertical Shear Instability



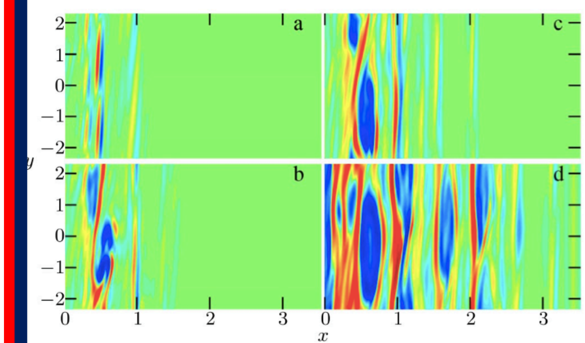
Nelson et al. 2013, Lin & Youdin 2015, Umurhan et al. 2016

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

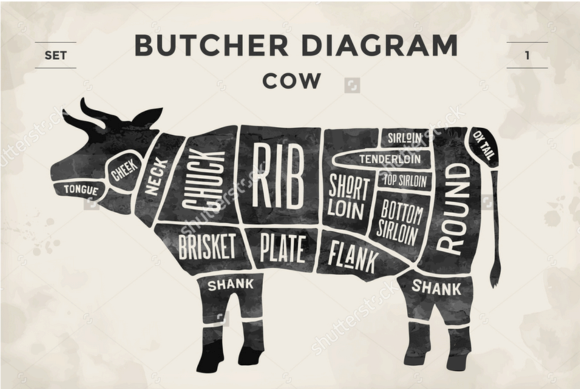
$\Omega\tau \ll 1$
($\kappa < 1$ cm^2/g)

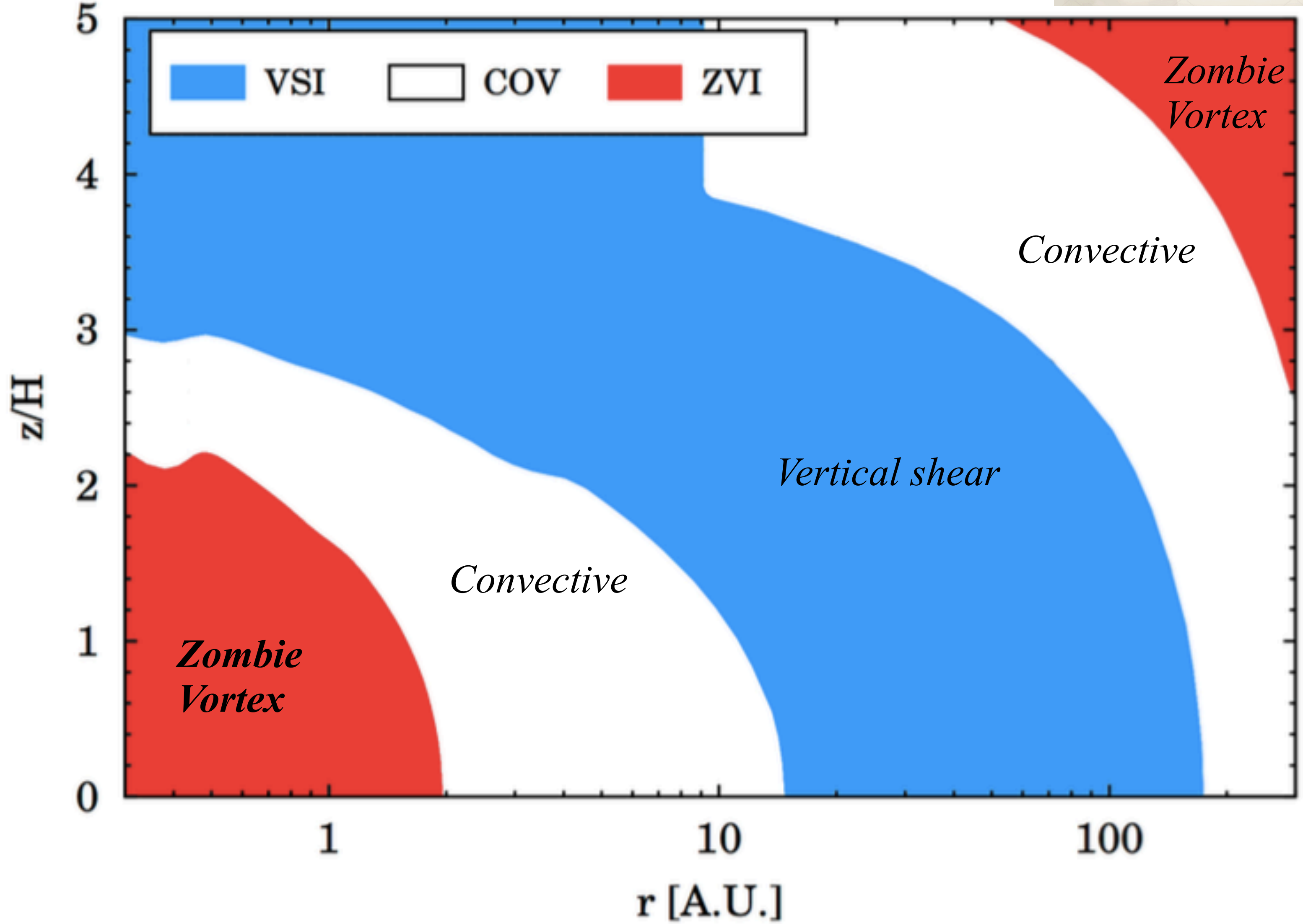
$\Omega\tau \sim 1$
($\kappa \sim 1$–50 cm^2/g)

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

Synthesis

A "butcher diagram" for hydro instabilities.

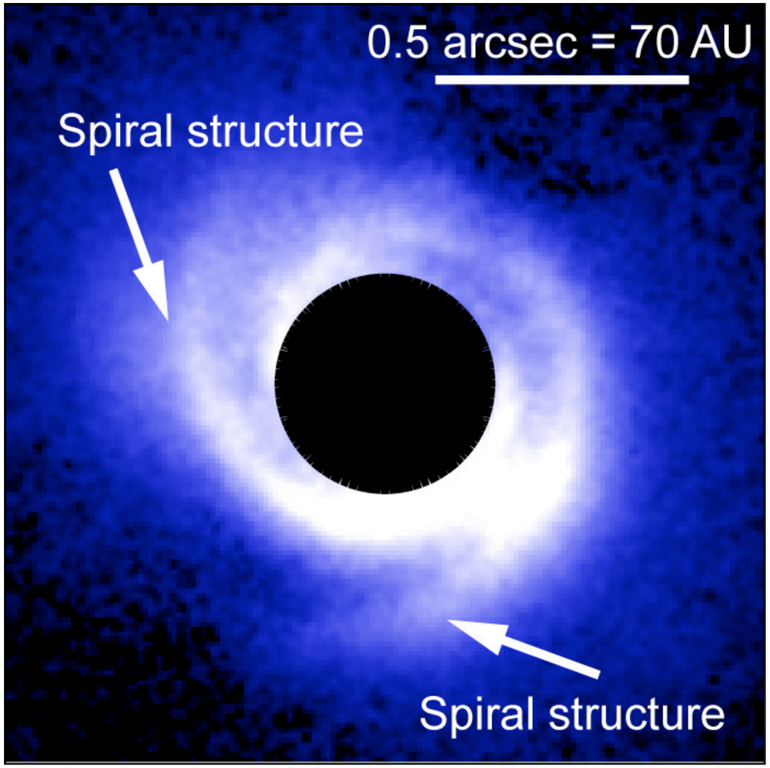




Malygin 2016

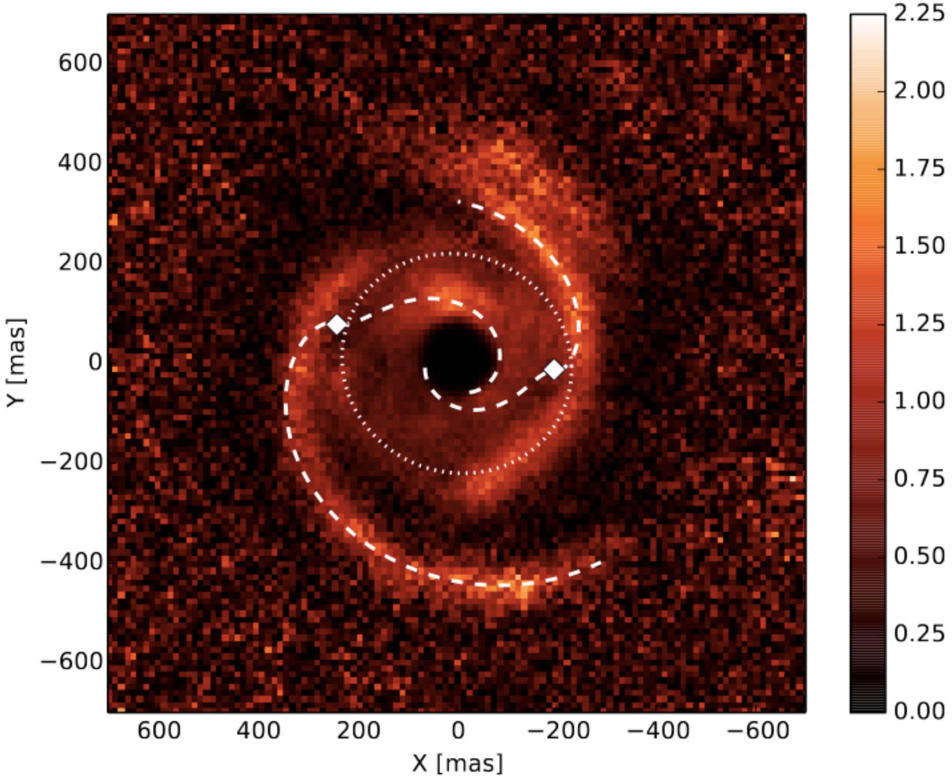
Observational Evidence: Spirals

SAO 206462



Muto et al. (2012)

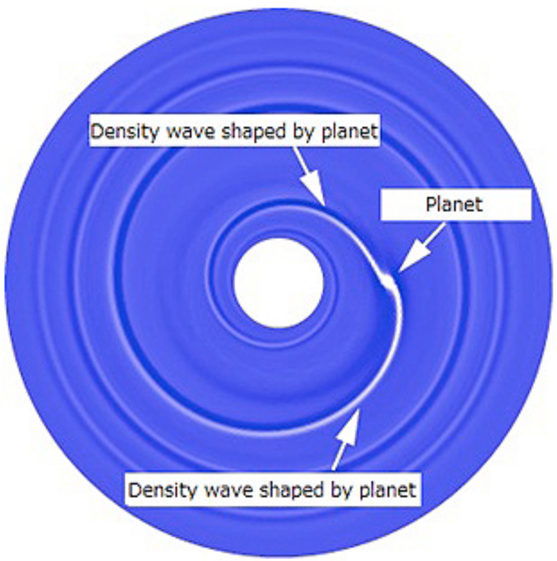
MWC 748



Benisty et al. (2015)

Spiral arm fitting leads to problems

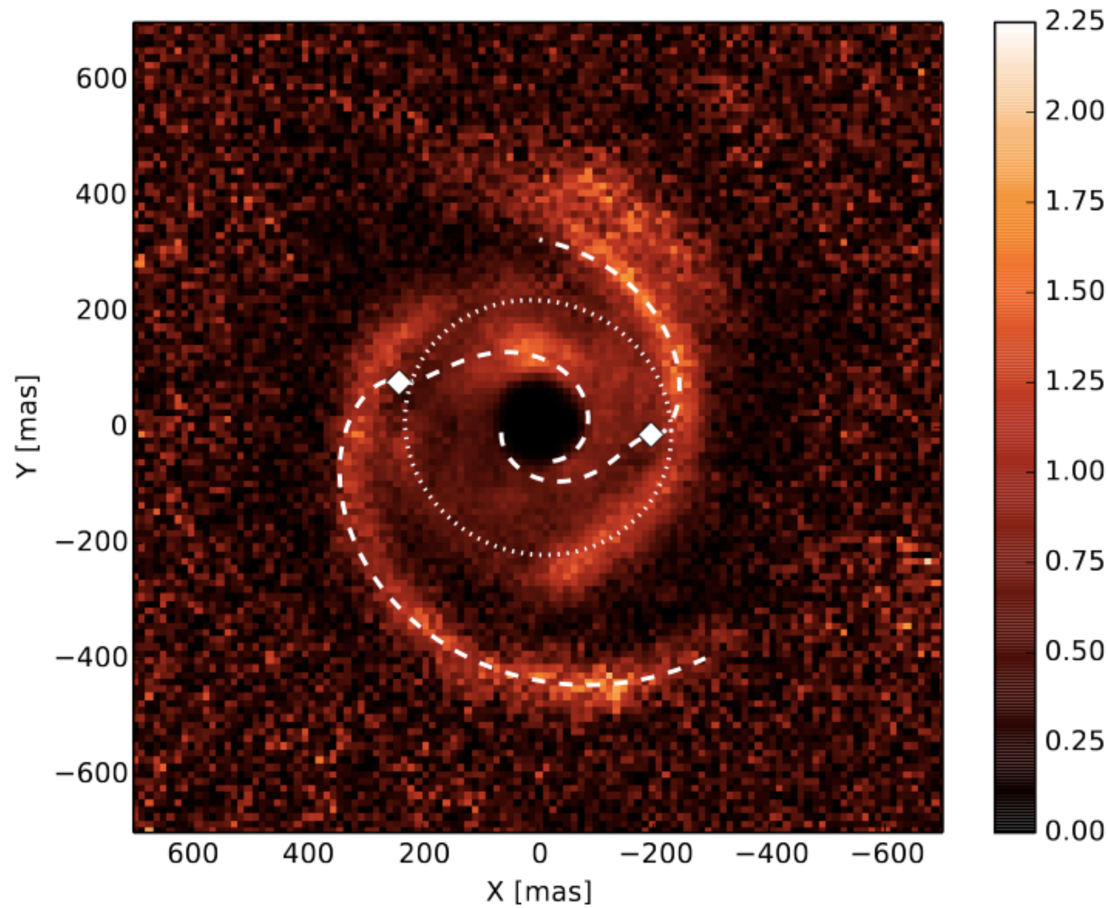
Analytical spiral fit



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

Rafikov (2002)
Muto et al. (2012)

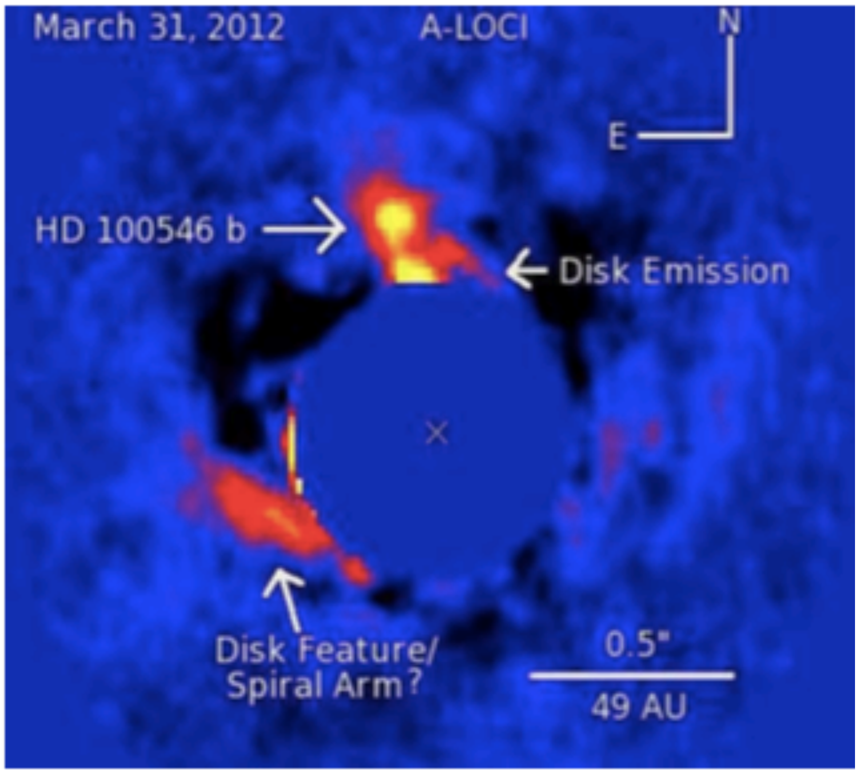
Spirals are **too wide**,
hotter (300K) than ambient gas (50K).



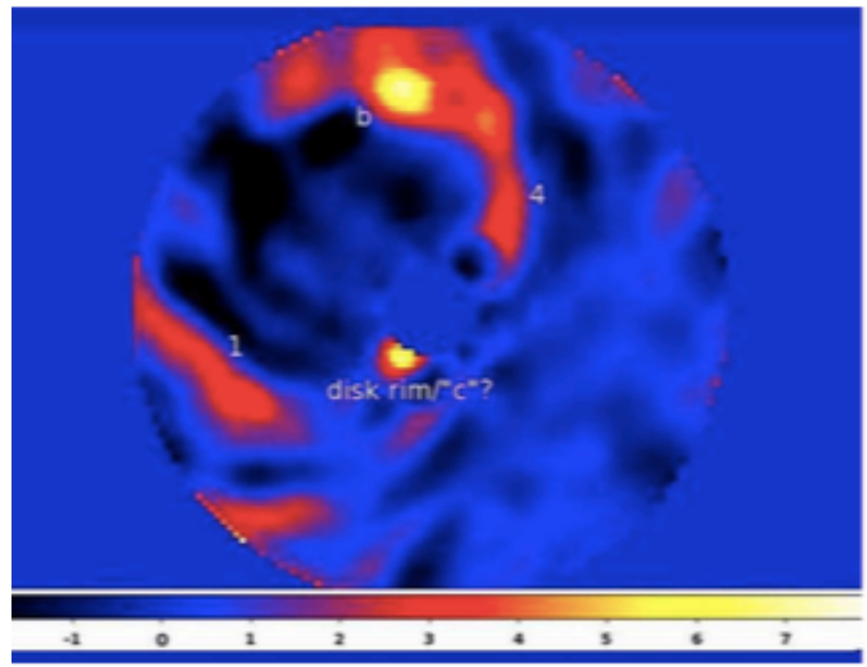
Benisty et al. (2015)

The strange case of thermal emission in HD 100546

L band (~3.5 μm)

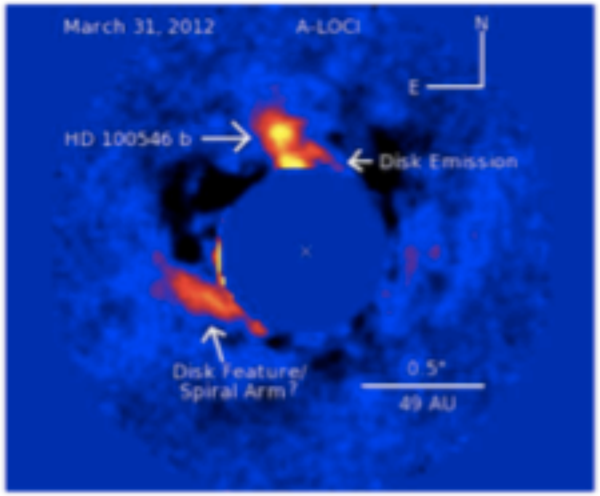


H band (~1.6 μm)

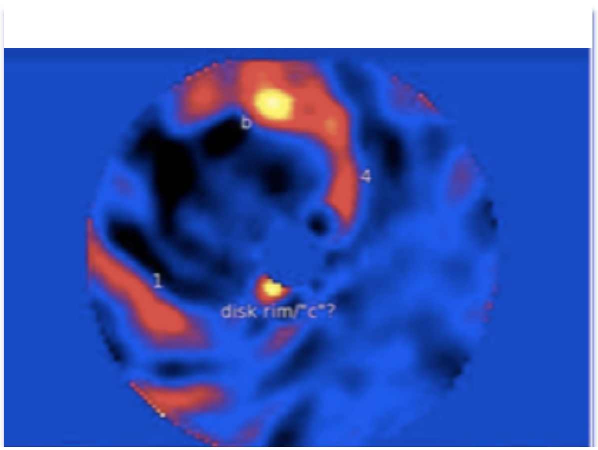


Currie et al. (2014), Currie et al. (2015)

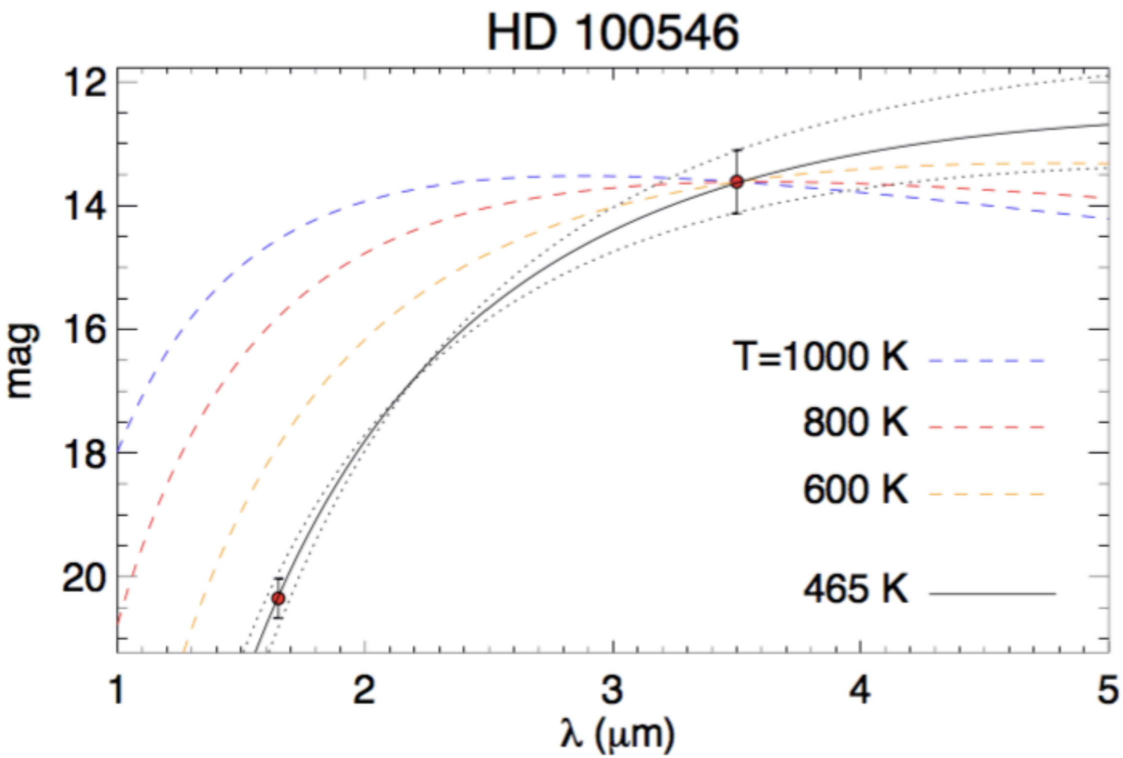
Pinning down the temperature



L band

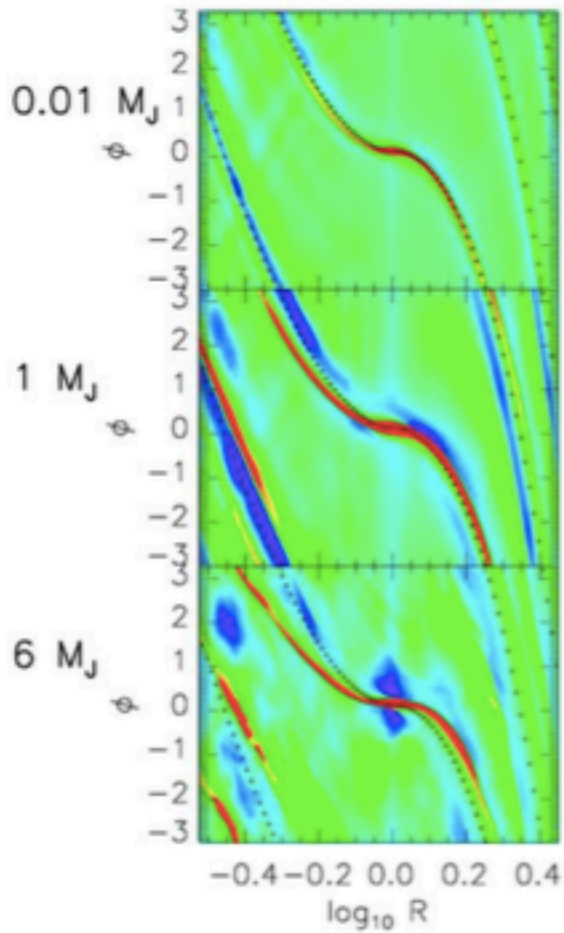


H band



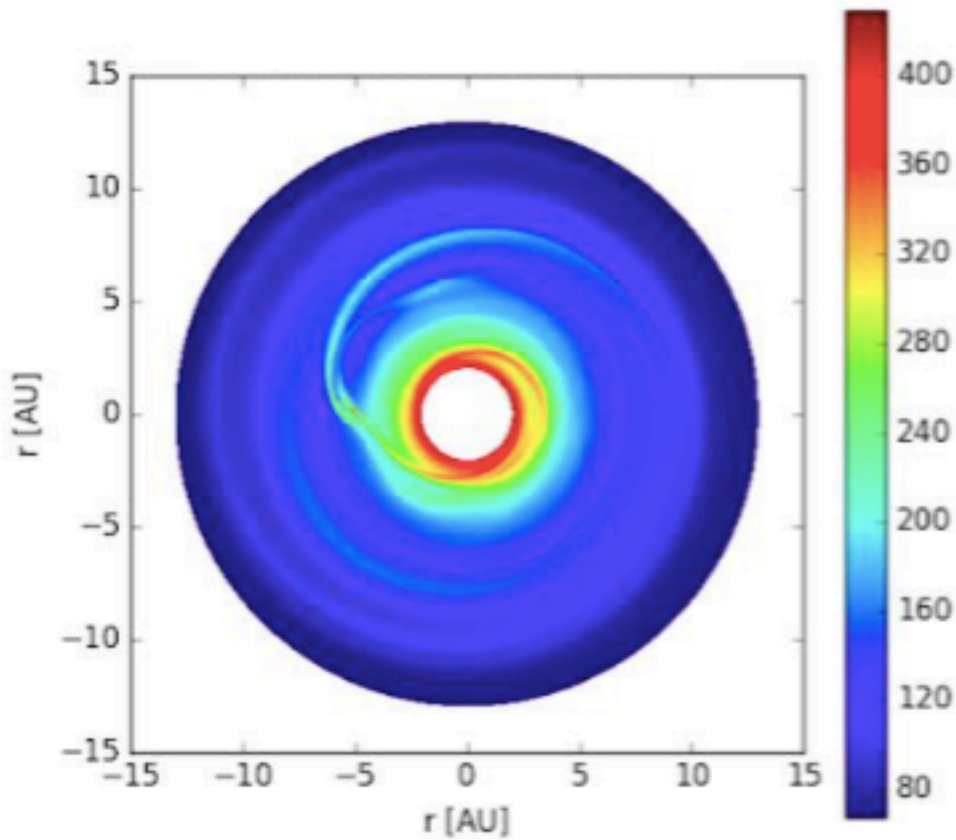
Lyra et al. (2016)

Supersonic Wakes of High Mass Planets



Density

Zhu et al. (2015)

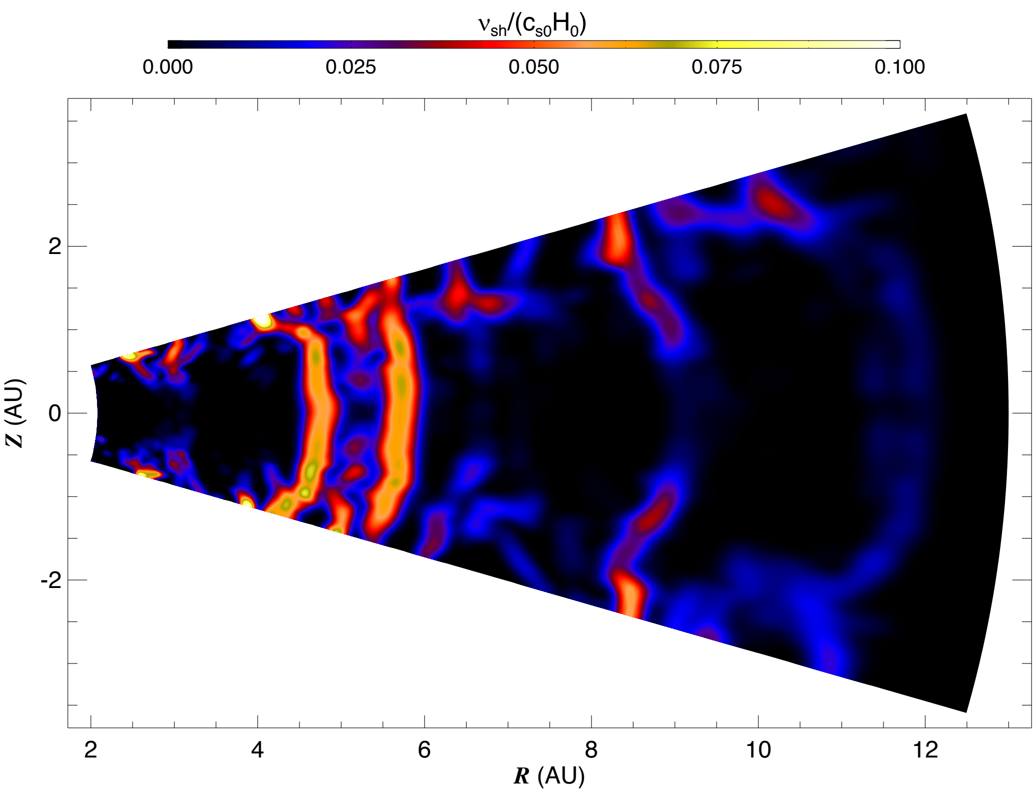


Temperature - **5M$_J$**

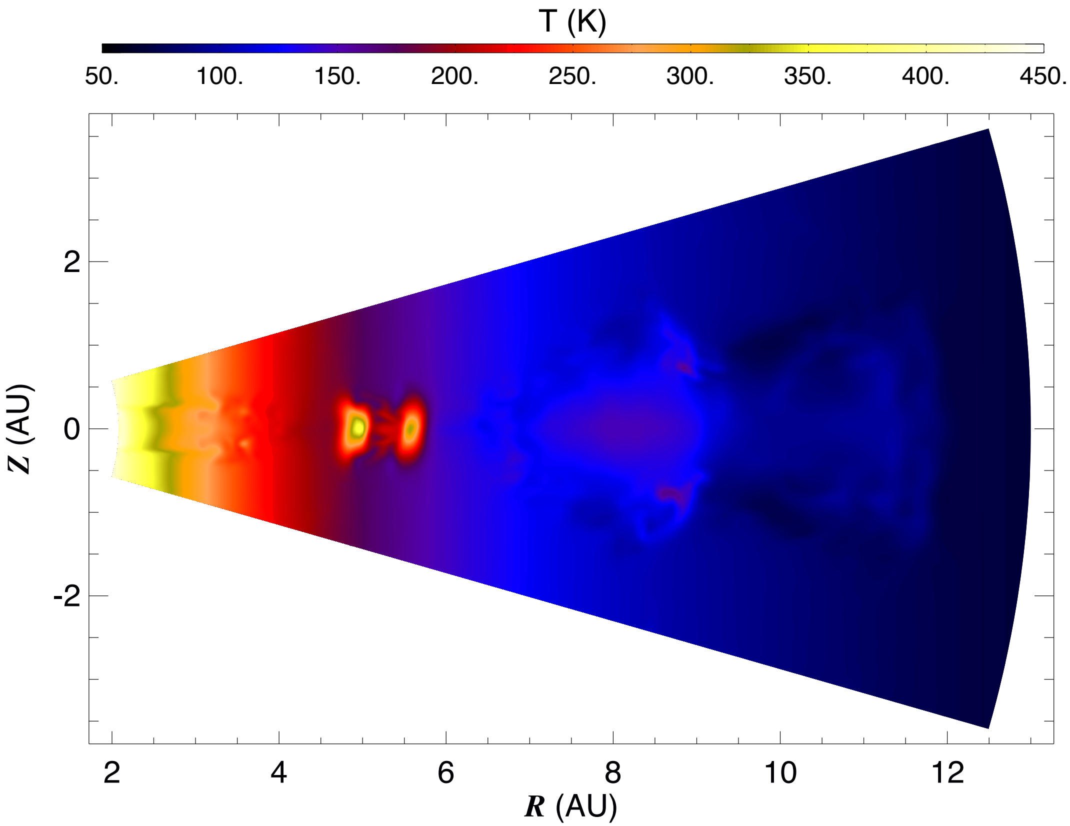
Lyra et al. (2016)

Shock bores

Shocks (velocity convergence)

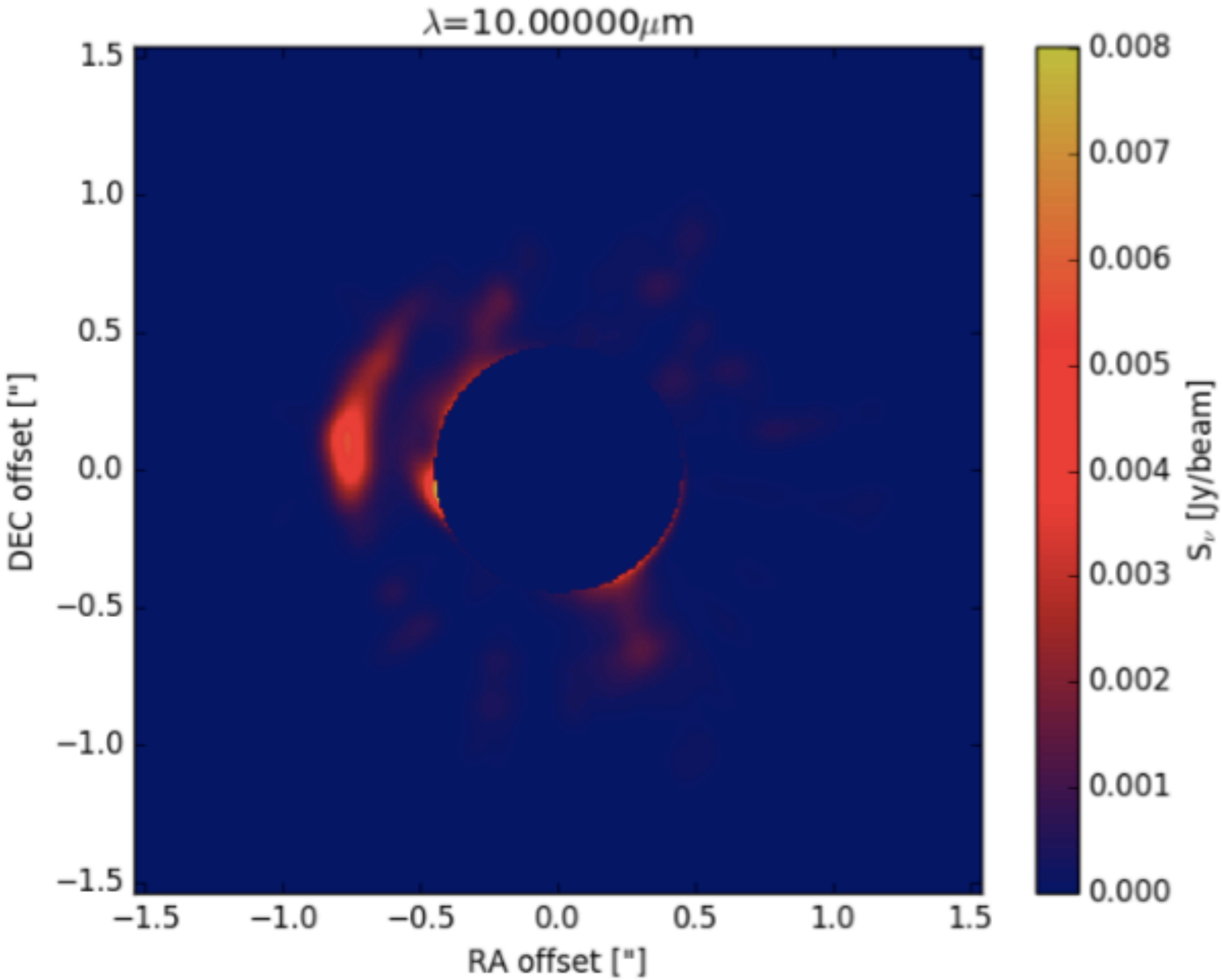


Temperature



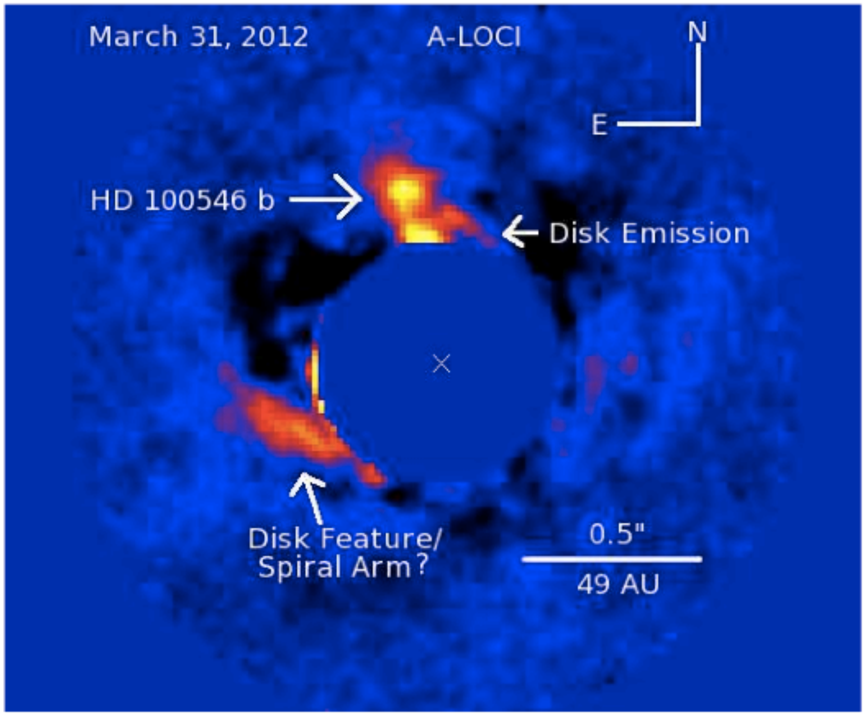
Lyra et al. (2016)

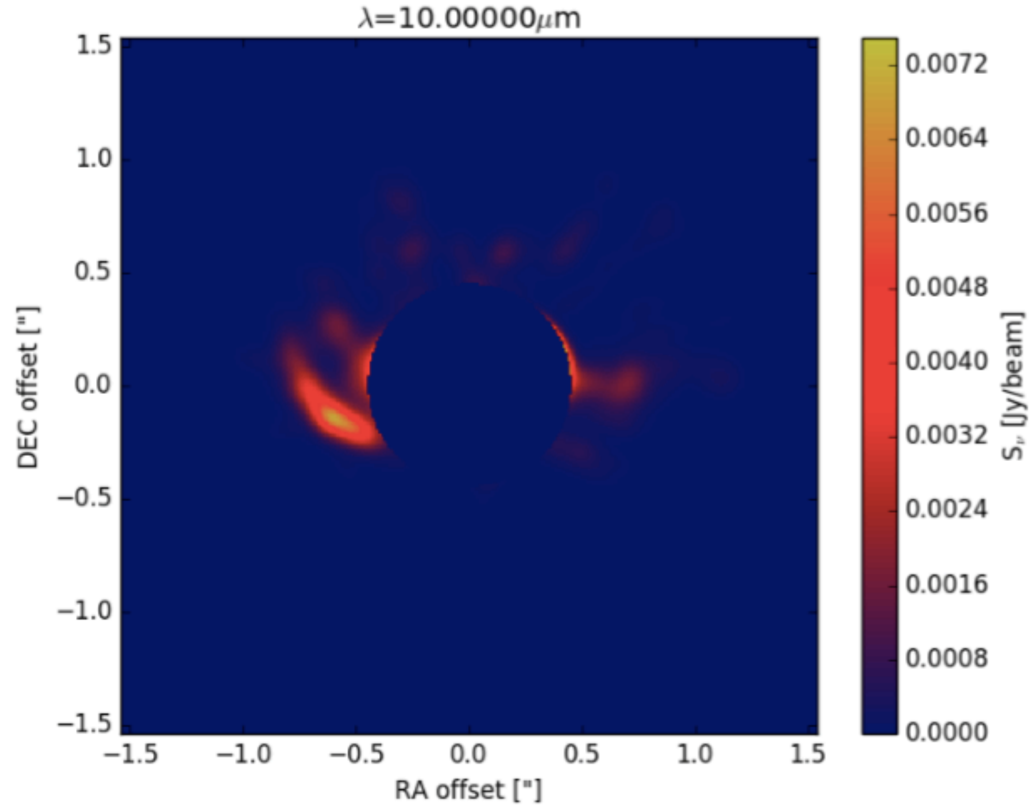
Synthetic image



Hord et al. (2017)

Observation vs Synthetic Image

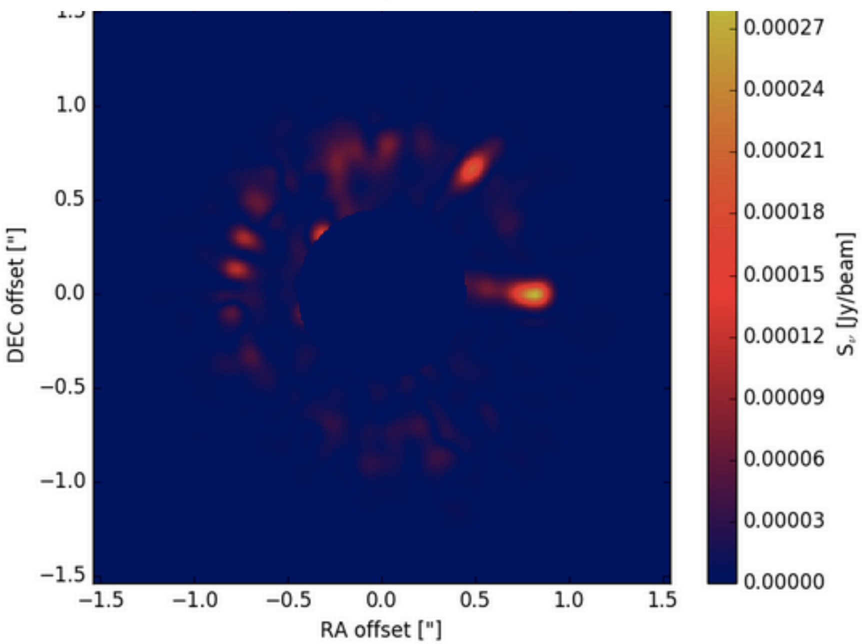




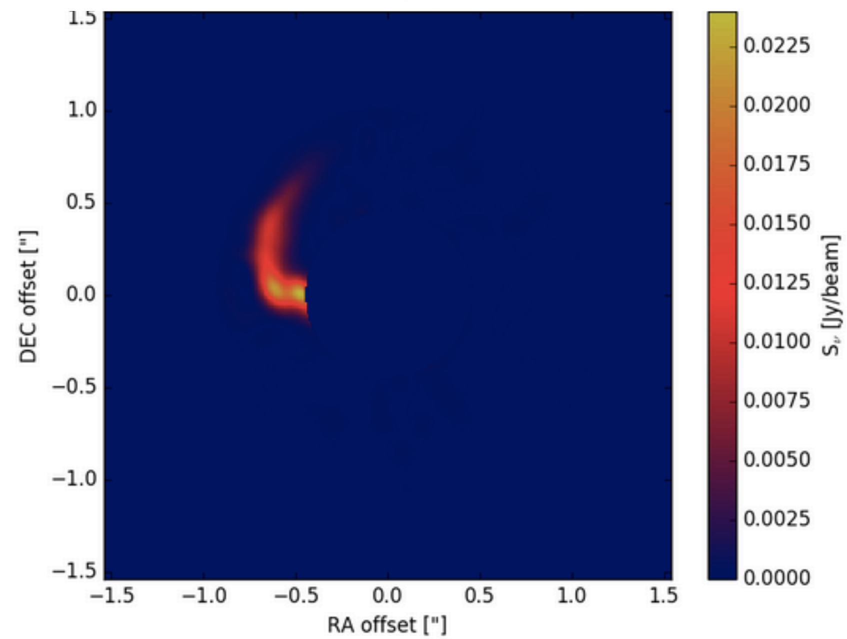
Hord et al. (2017)

Effect of shocks alone

1 μm

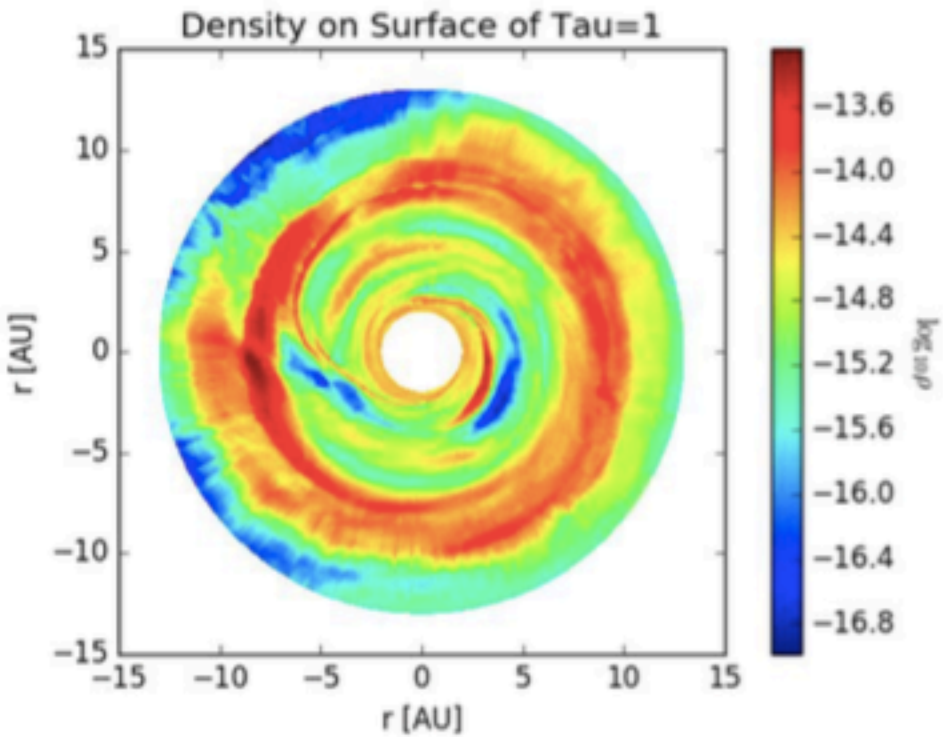


10 μm

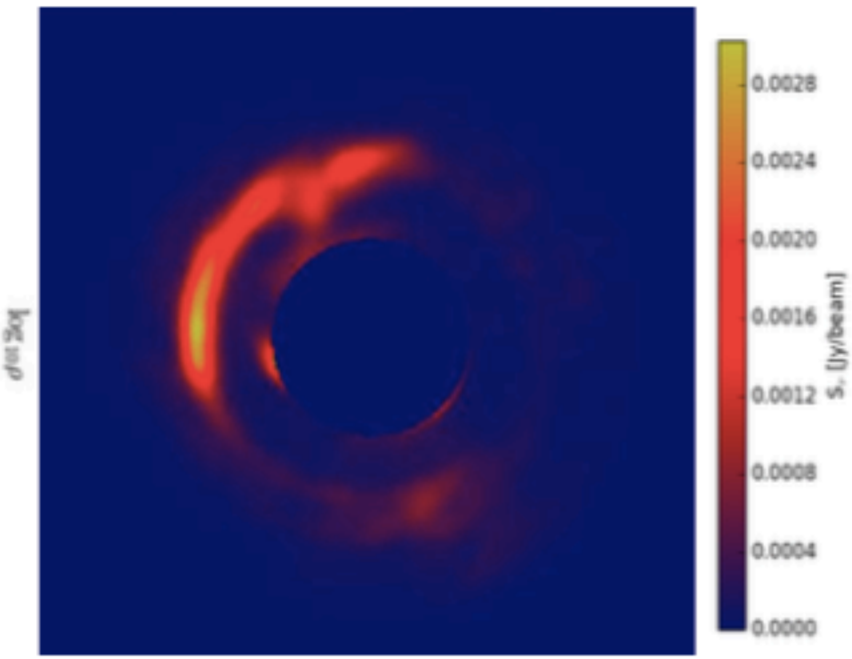


Hord et al. (2017)

Scattering in Image



Light scattered off **gap outer edge**



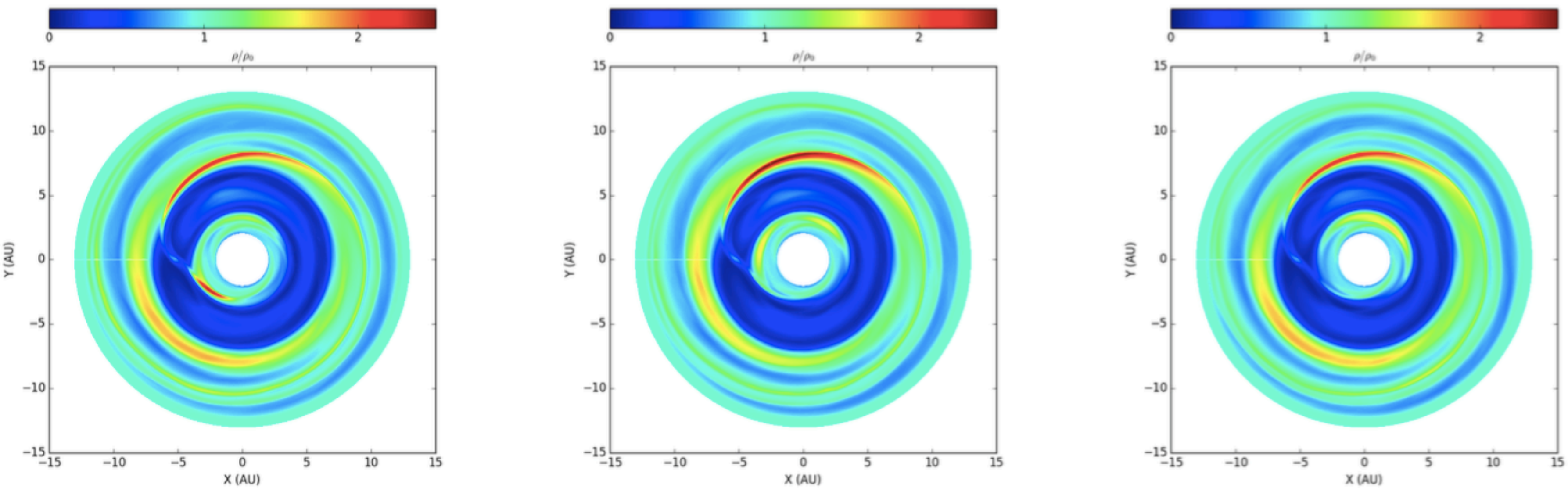
"Bird's eye view"
synthetic image

Hord et al. (2017)

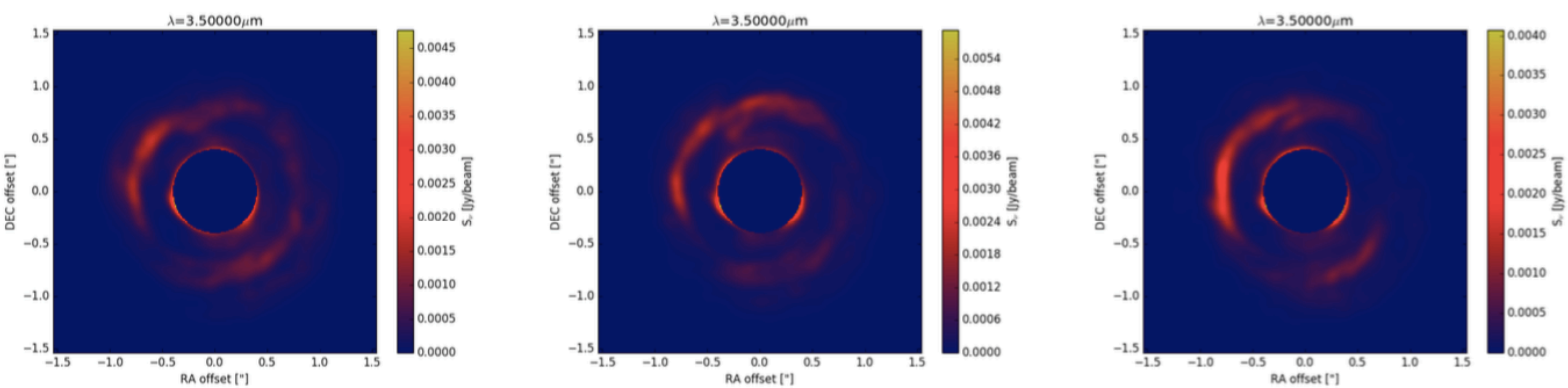
The vortex raises the scale height

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

Density

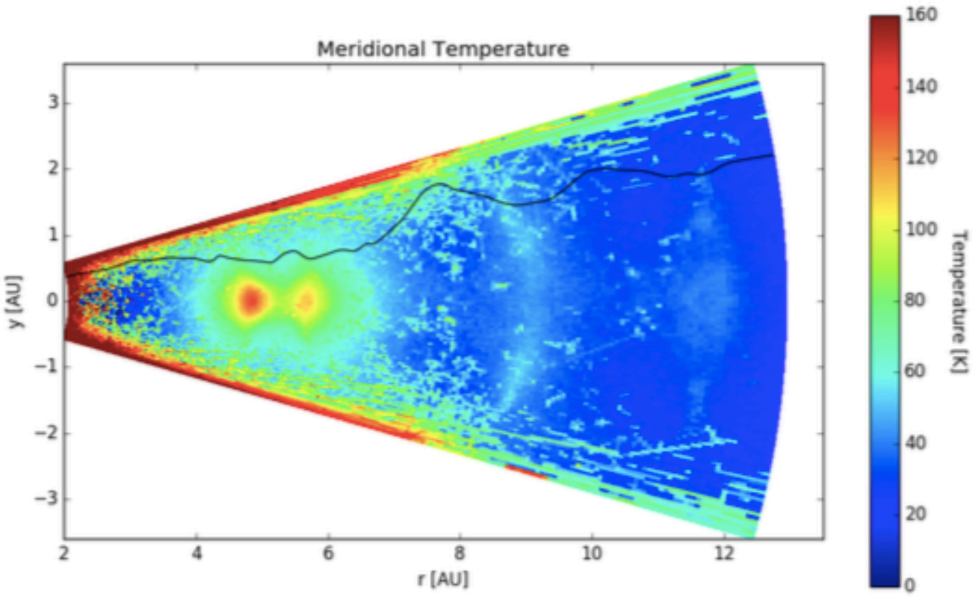


Intensity

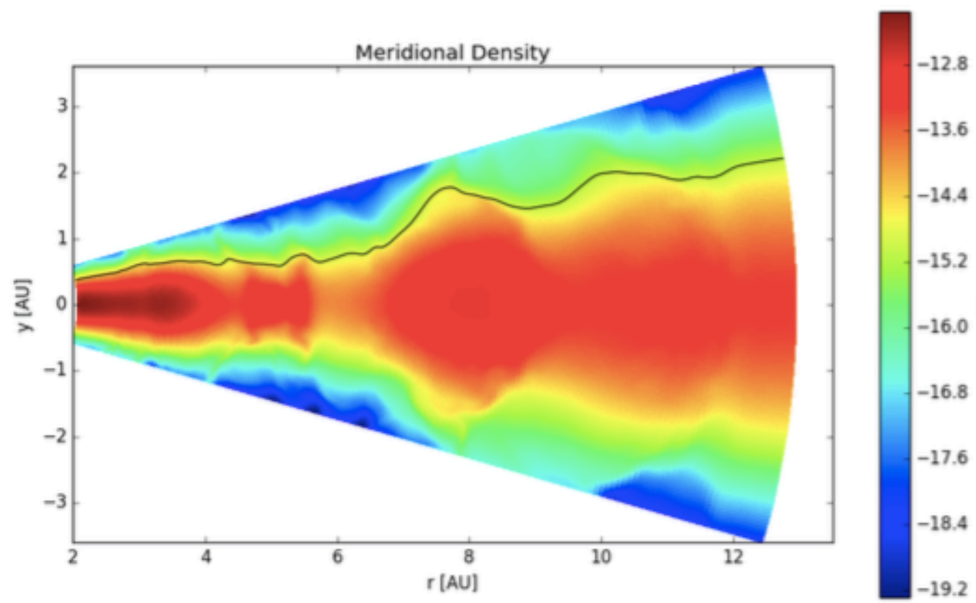


A puffed-up outer gap

Temperature

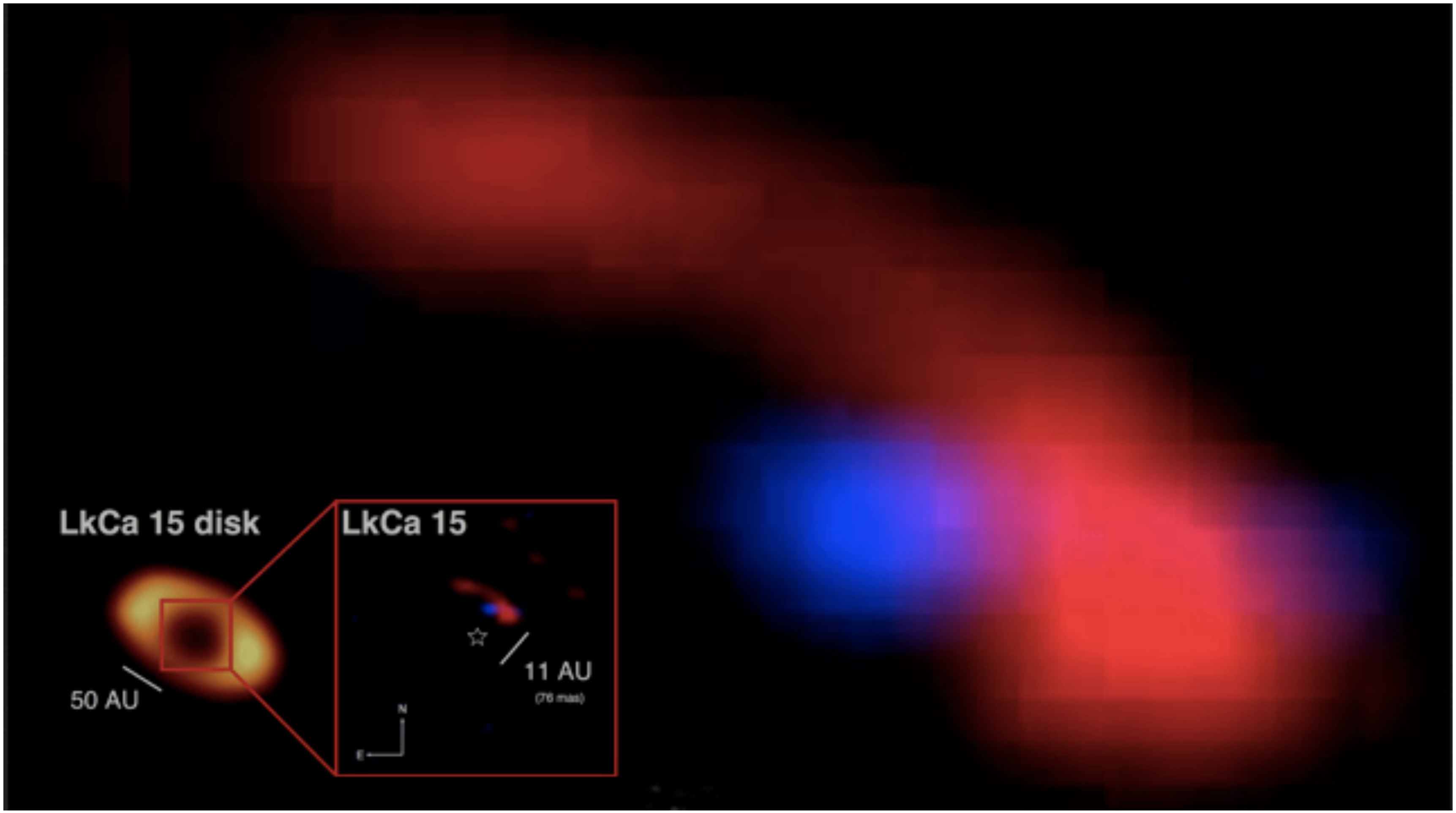


Density



Hord et al. (2017)

LkCa 15



Conclusions

- Disk vortices are a prime location for planet formation
    - Tea leaf effect

- Dust trapped in drag-diffusion equilibrium explains the observations

- Hydrodynamical instabilities vs planet excitation mechanism:
    - Vertical Shear Instability
        - *Vertical violation of Solberg-Hoiland criterion*
    - Convective Overstability
        - *Amplification of epicyclic motion by buoyancy*
    - Zombie Vortex Instability
        - *Resonance between epicyclic and buyoancy frequency*

- Hot lobes next to high mass planets at high resolution

- Planets puff up their outer gap edges – visible in scattered light

Conclusions

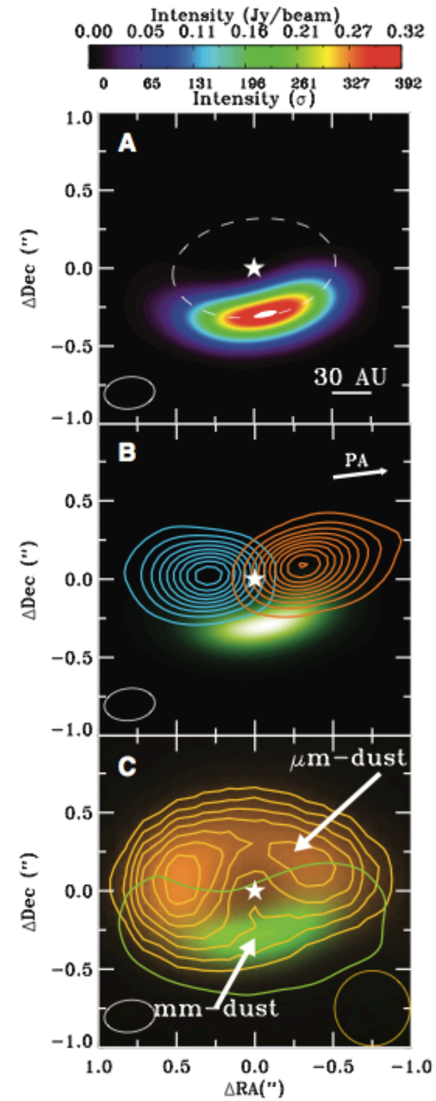
- Disk vortices are a prime location for planet formation
  - Tea leaf effect

- 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

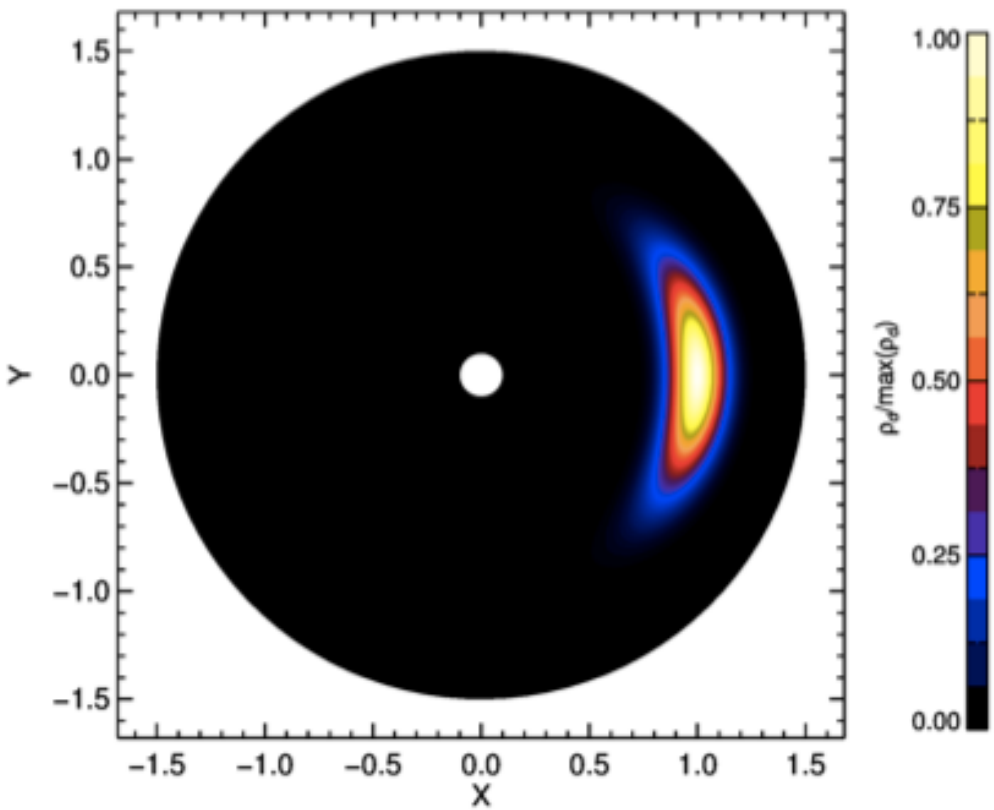
- Planets puff up their outer gap edges – visible



Conclusions

- Disk vortices are a prime location for planet formation
  - Tea leaf effect

- Dust trapped in drag-diffusion equilibrium explains the observations



xcitation mechanism:

criterion

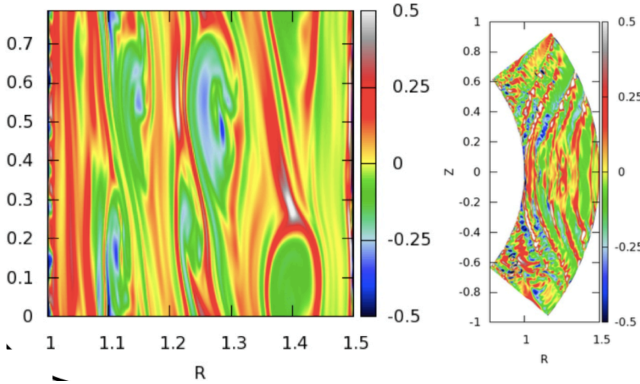
uoyancy

oancy frequency

gh resolution

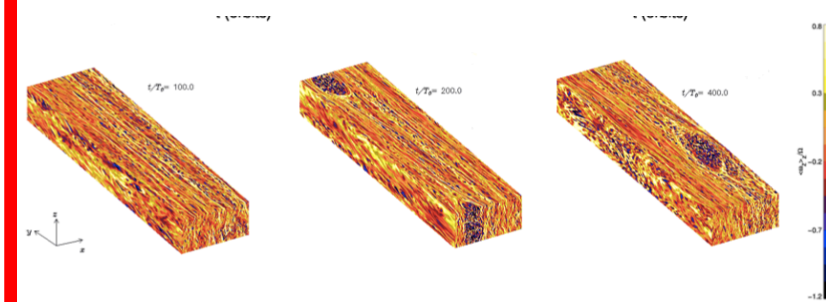
sible in scattered light

Vertical Shear Instability



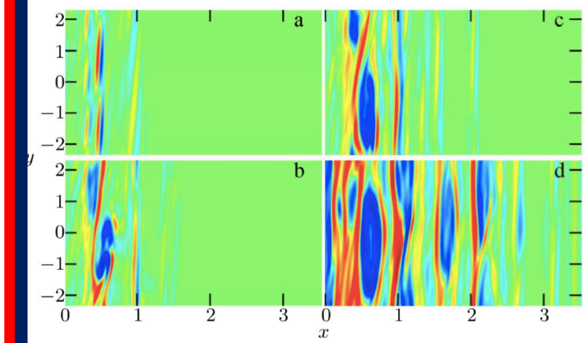
Nelson et al. 2013, Lin & Youdin 2015, Umurhan et al. 2016

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

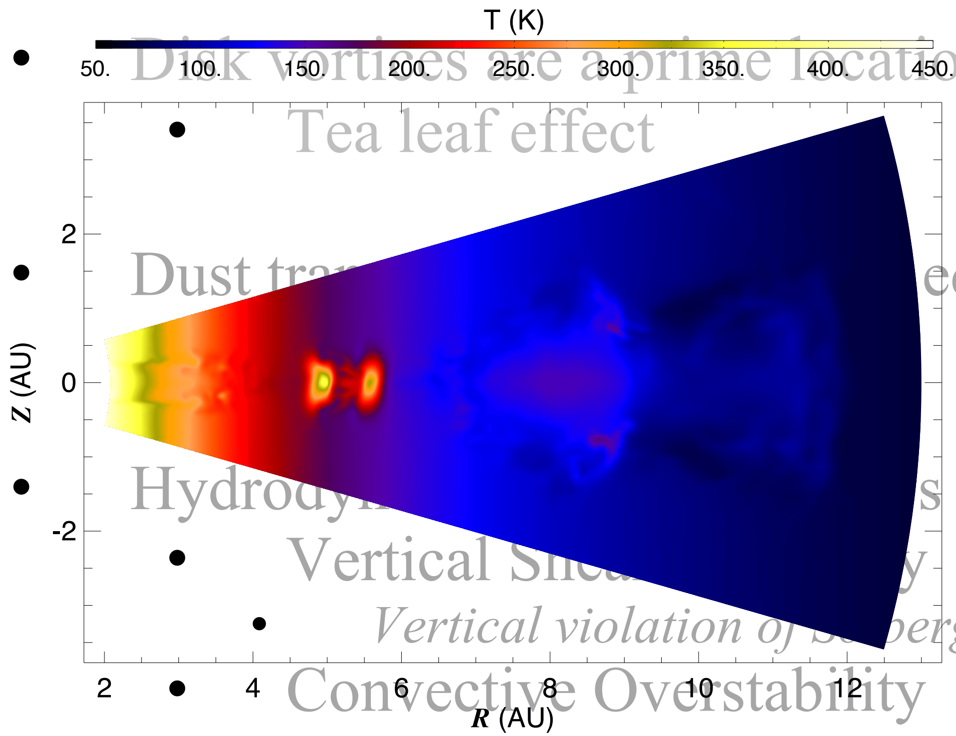
- Hydrodynamical instabilities vs planet excitation mechanism:
  - Vertical Shear Instability
    - *Vertical violation of Solberg-Hoiland criterion*
  - Convective Overstability
    - *Amplification of epicyclic motion by buoyancy*
  - Zombie Vortex Instability
    - *Resonance between epicyclic and buyoancy frequency*

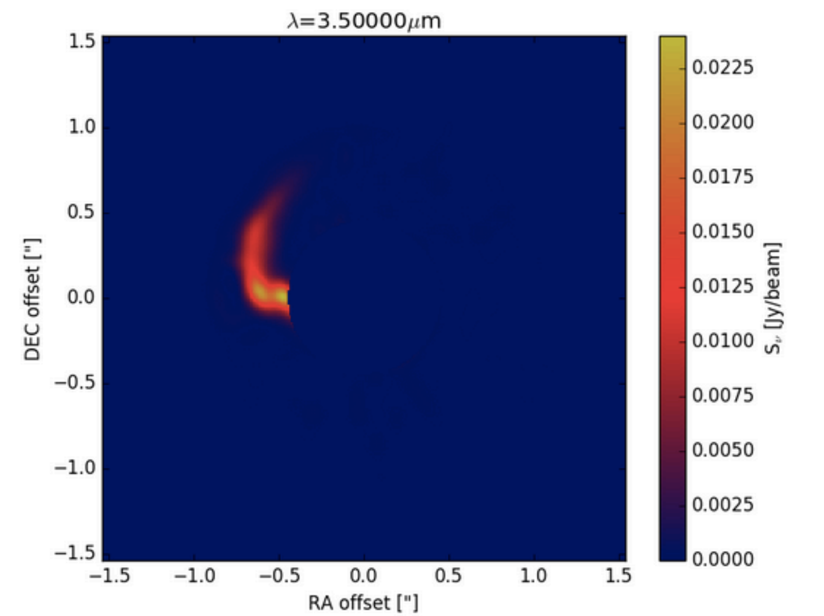
- Hot lobes next to high mass planets at high resolution

- Planets puff up their outer gap edges – visible in scattered light

Conclusions

- Disk vortices are a prime location for planet formation
  - Tea leaf effect
- Dust tra... equilib...
- Hydrody... s planet
  - Vertical Shea... y
    - *Vertical violation of S... berg-Hoila...*
  - Convective Overstability
    - *Amplification of epicyclic motion by buoyancy*
  - Zombie Vortex Instability
    - *Resonance between epicyclic and buyoancy frequency*



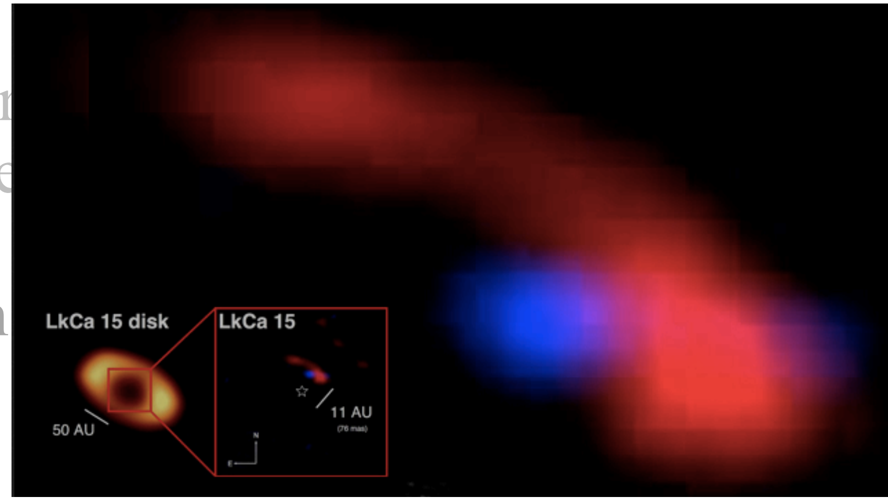


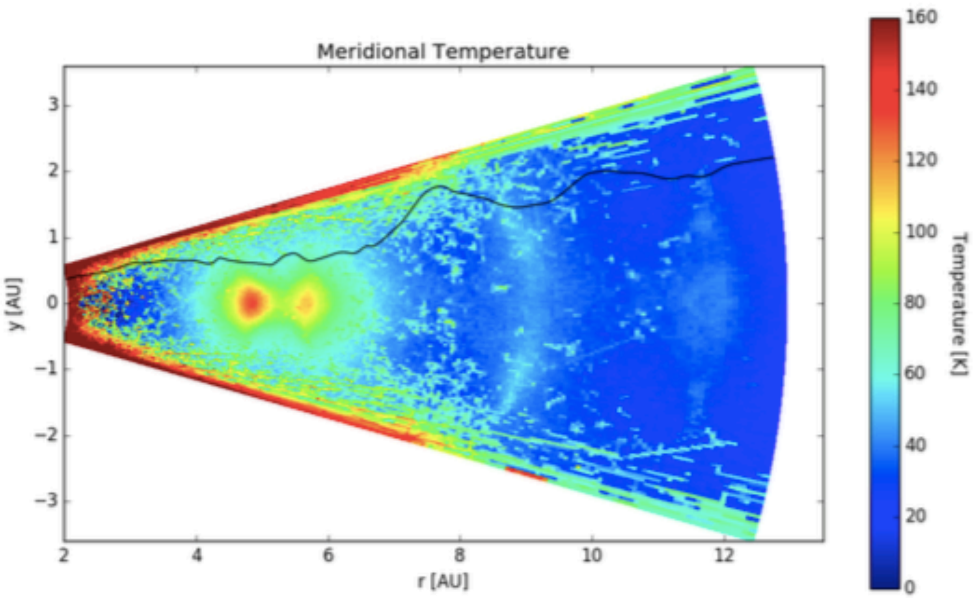
- Hot lobes next to high mass planets at high resolution

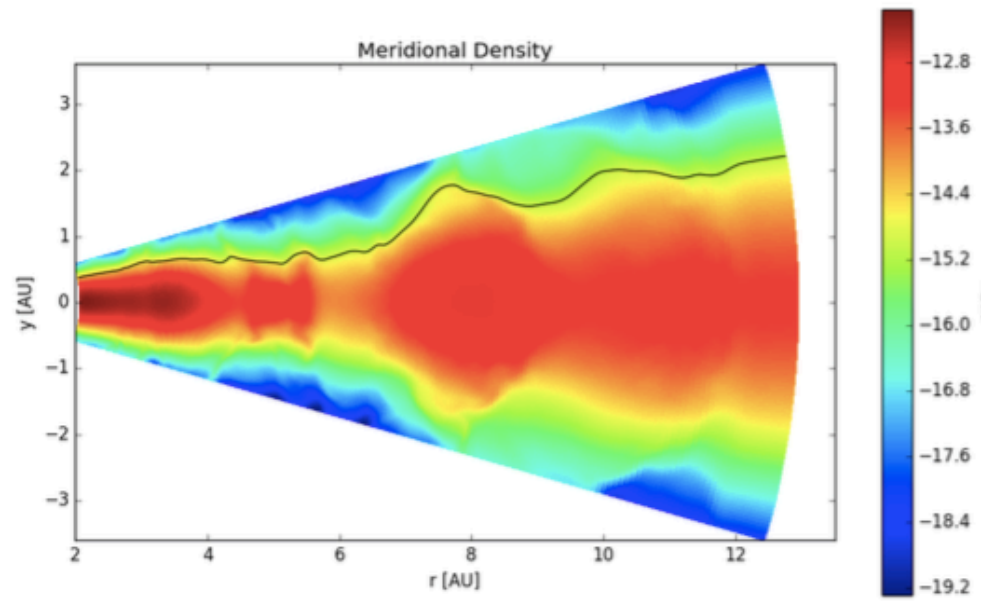
- Planets puff up their outer gap edges – visible in scattered light

Conclusions

- Disk vortices ar ... ation
  - Tea leaf e
- Dust trapped in ... s the observations

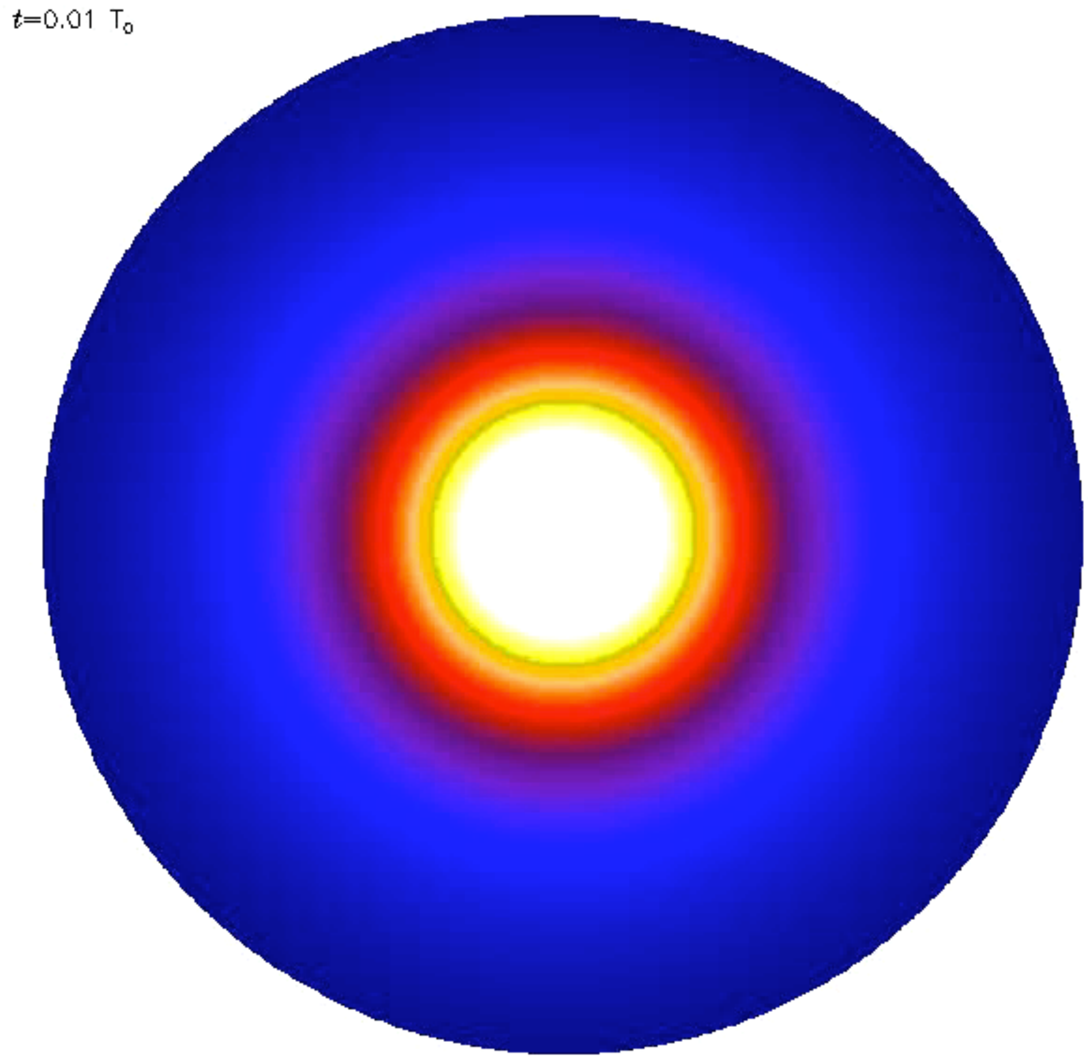






- Planets puff up their outer gap edges – visible in scattered light

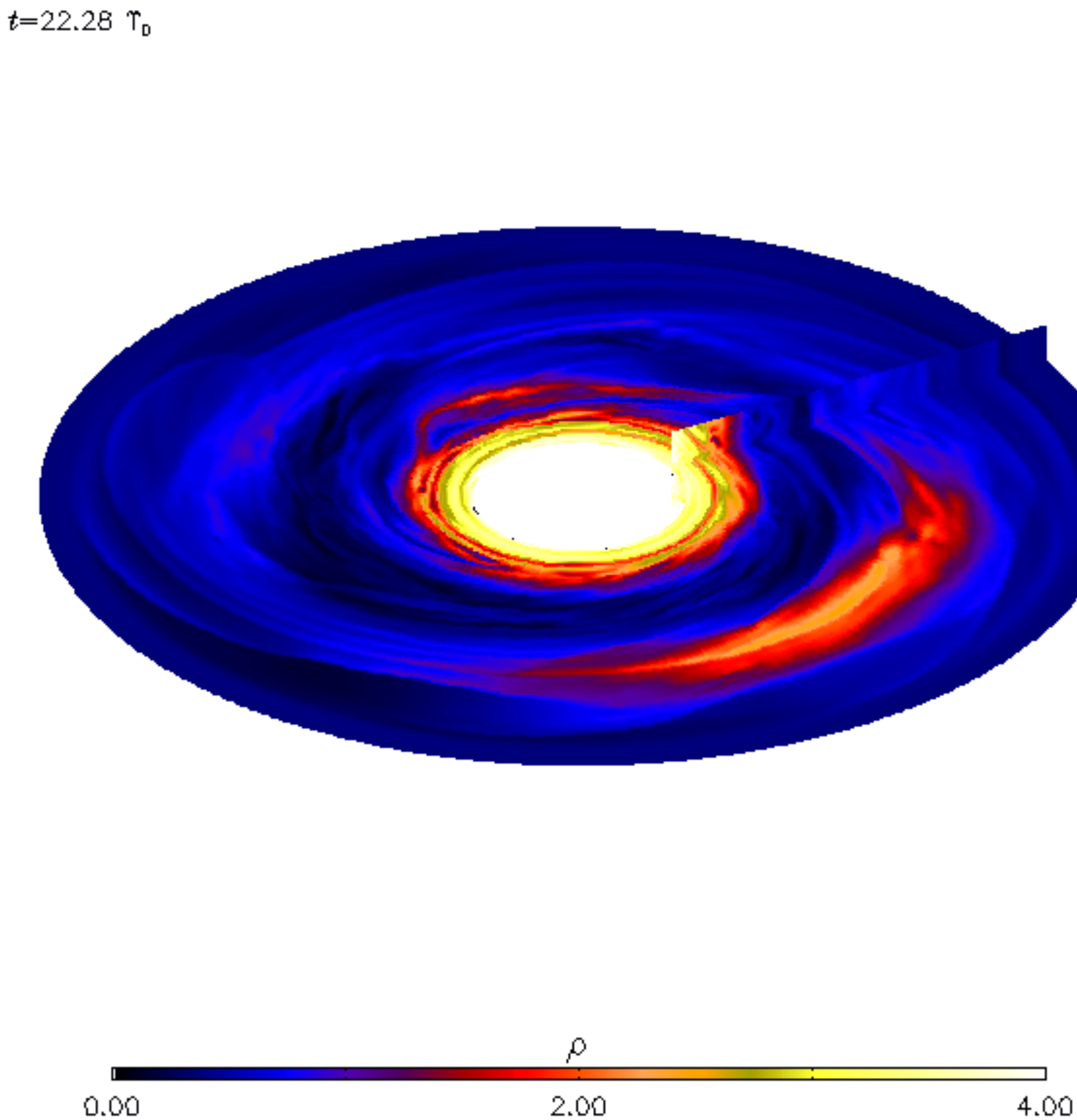
Inner (0.1 AU) active/dead zone boundary

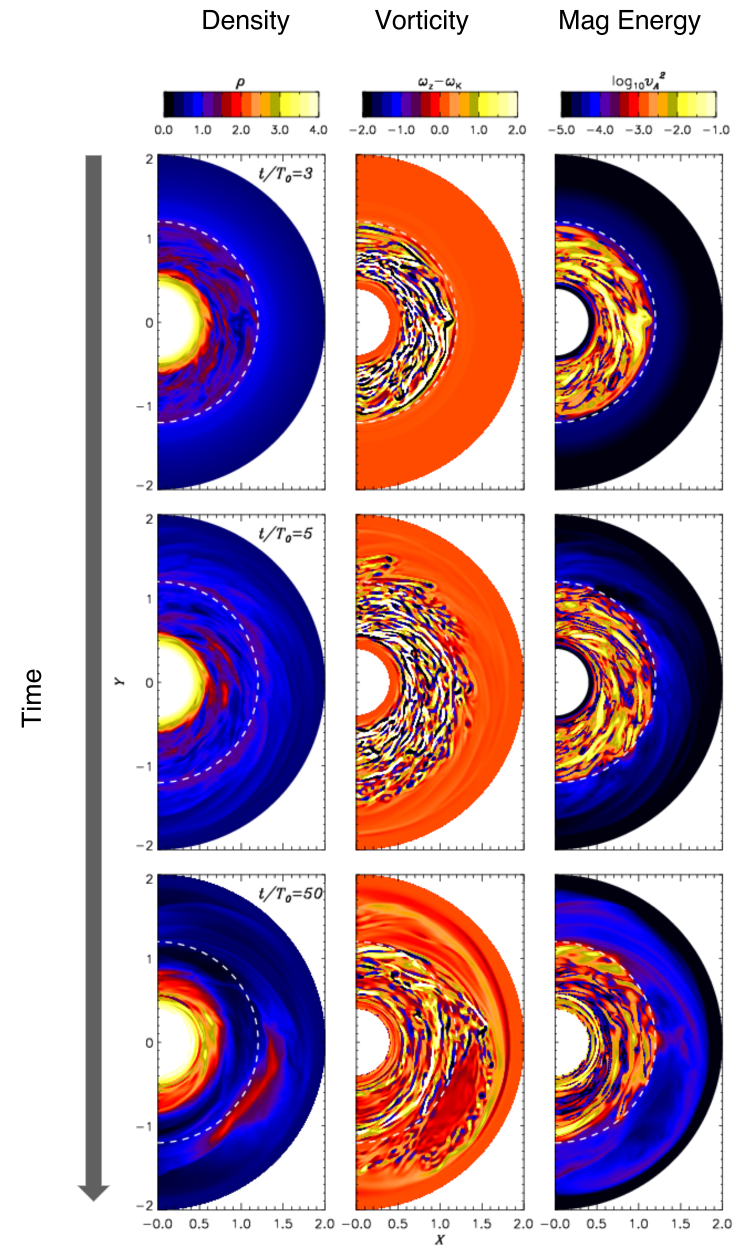


Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Inner (0.1AU) active/dead zone boundary

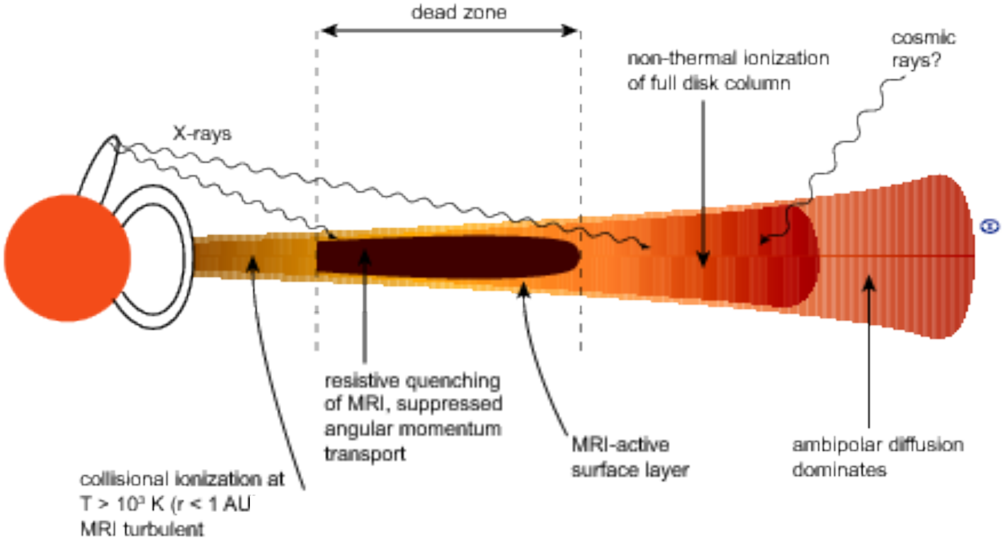




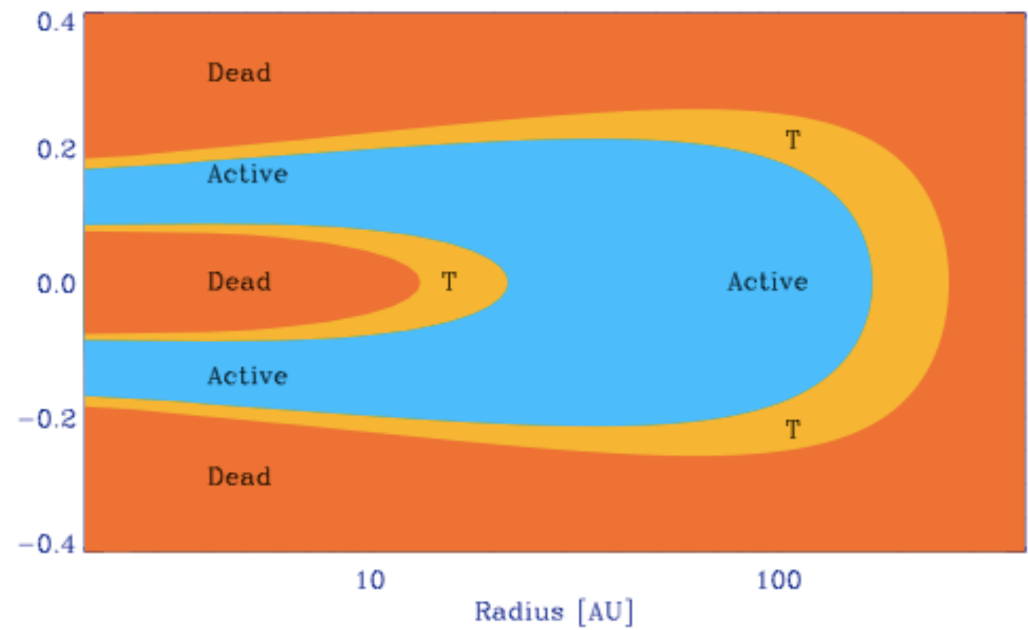
Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Outer Dead/Active zone transition KHI



Armitage (2010)



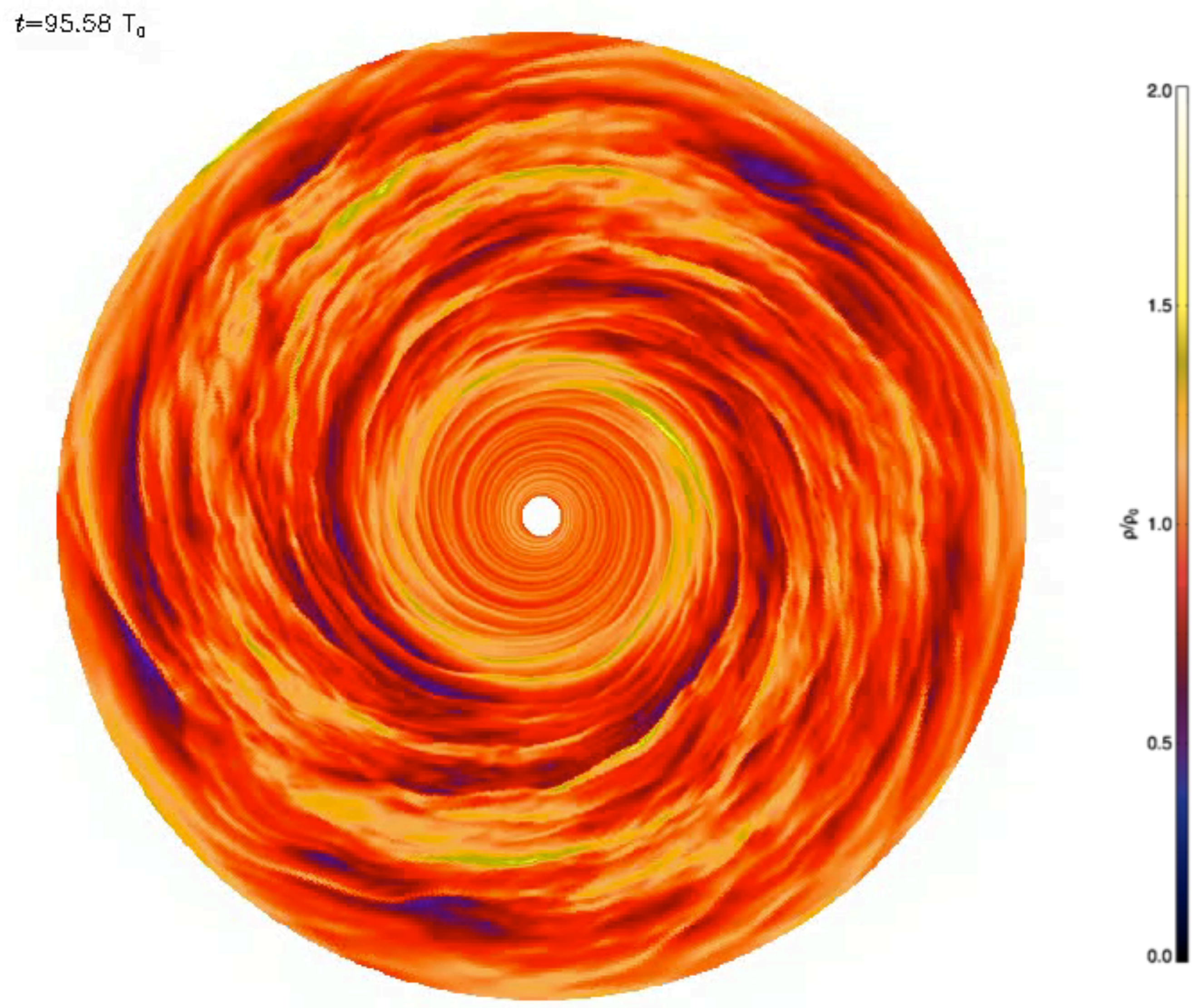
Dzyurkevitch et al (2013)

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

TOO SMOOTH

to generate an KH-unstable bump.

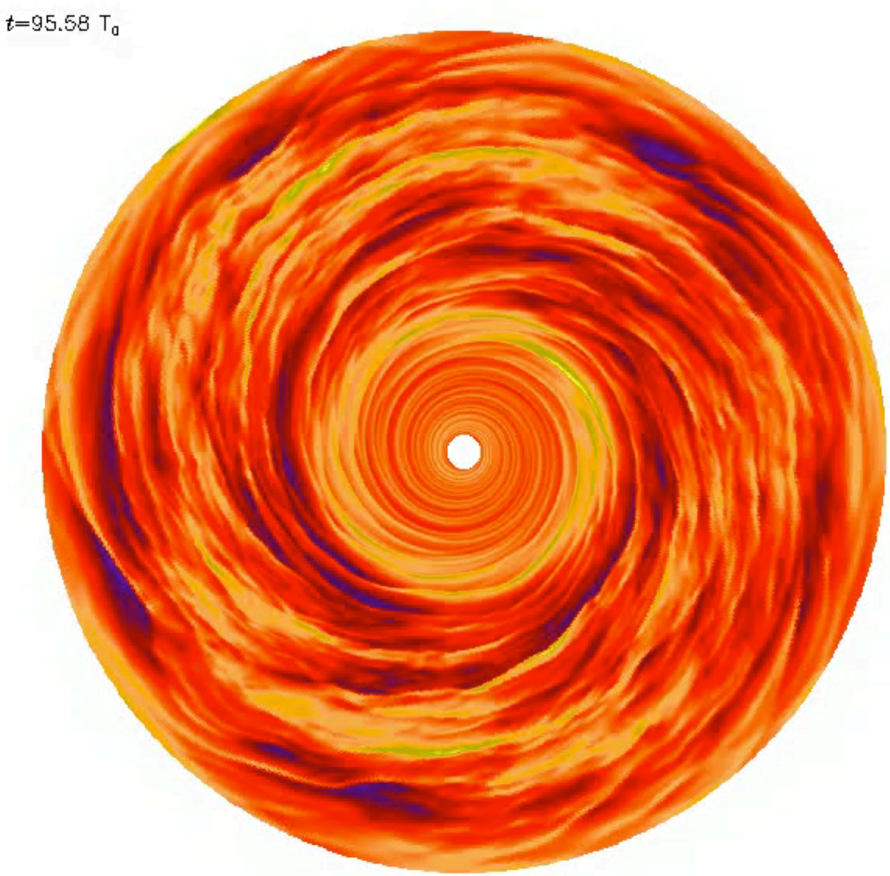
Outer Dead/Active zone transition: 3D MHD

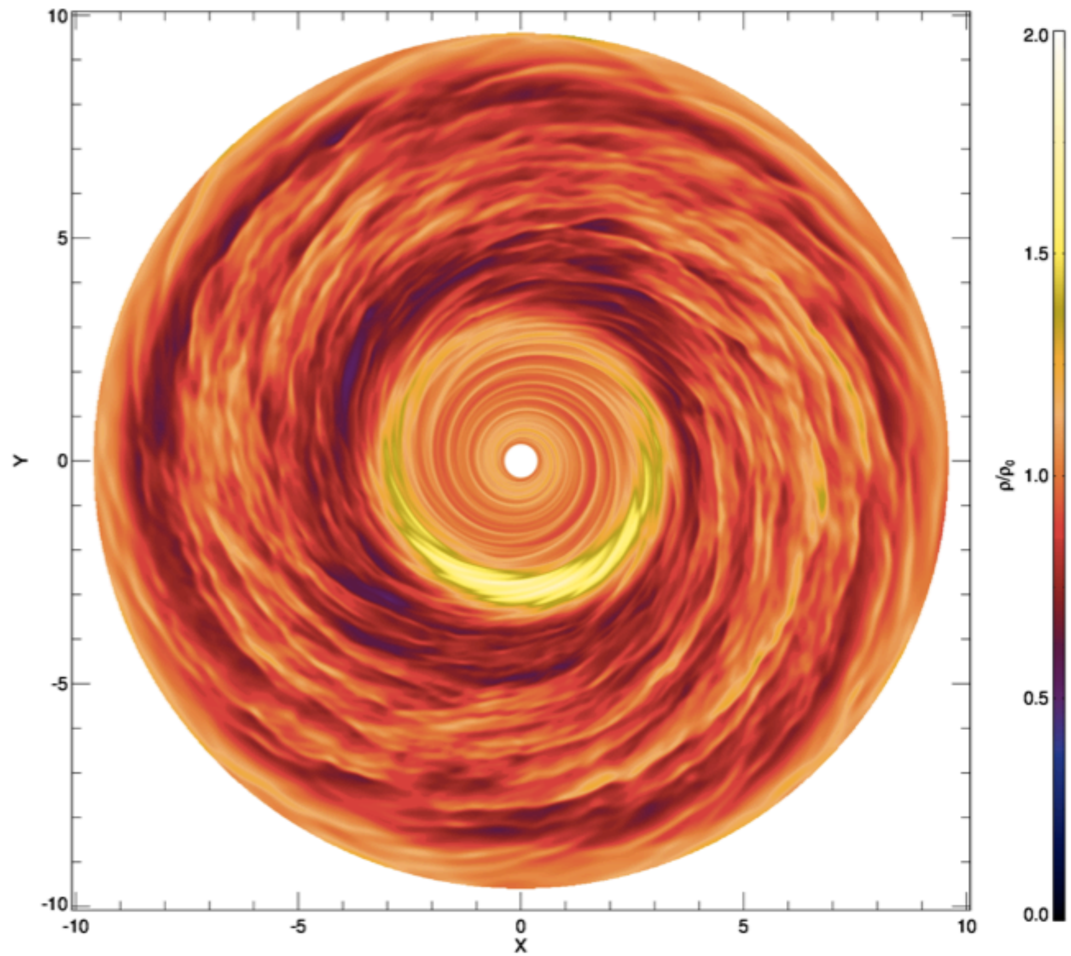


Resistive inner disk + magnetized outer disk

Lyra et al (2015)

Outer Dead/Active zone transition KHI

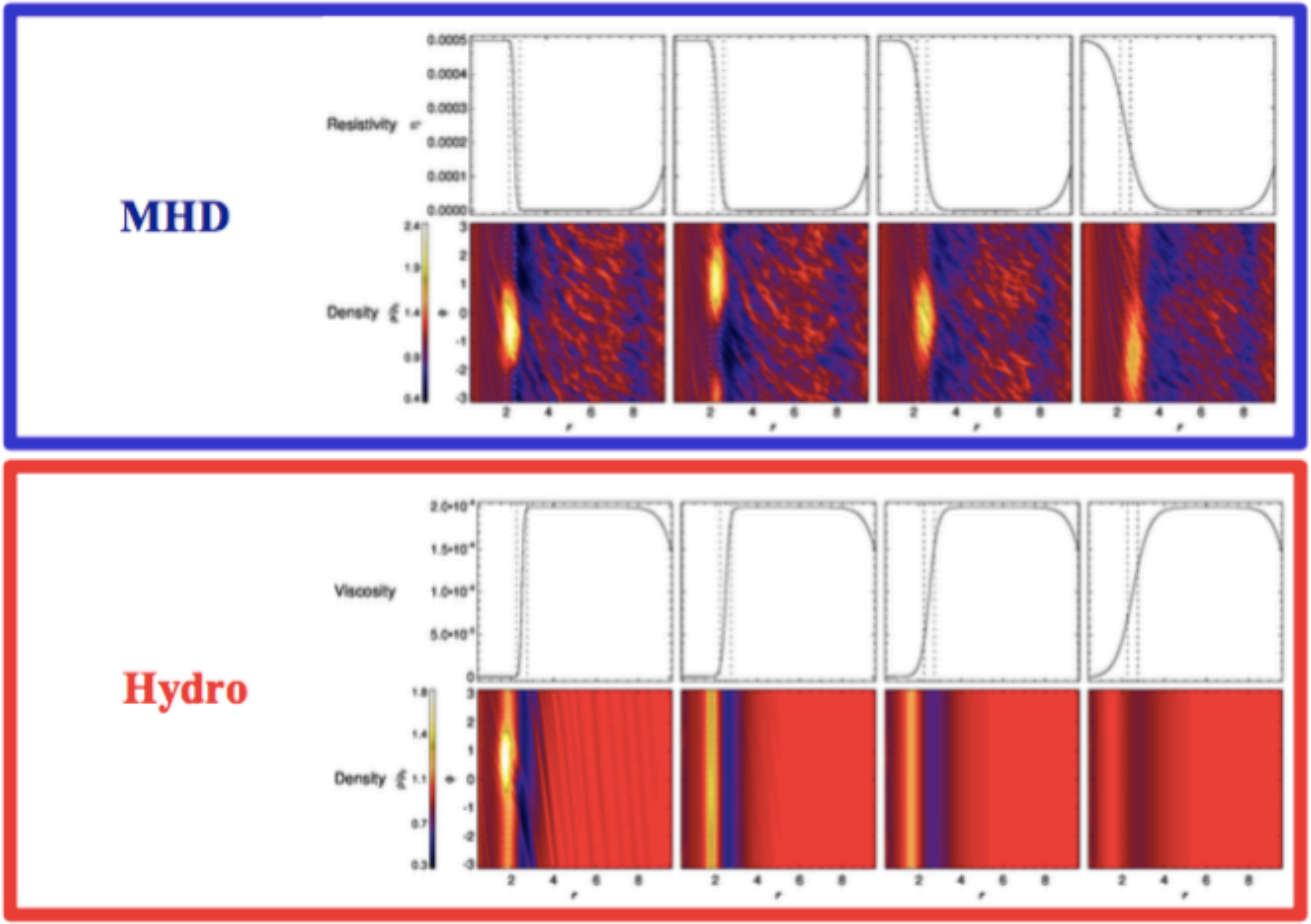




Resistive inner disk + magnetized outer disk

Lyra, Turner, & McNally (2015)

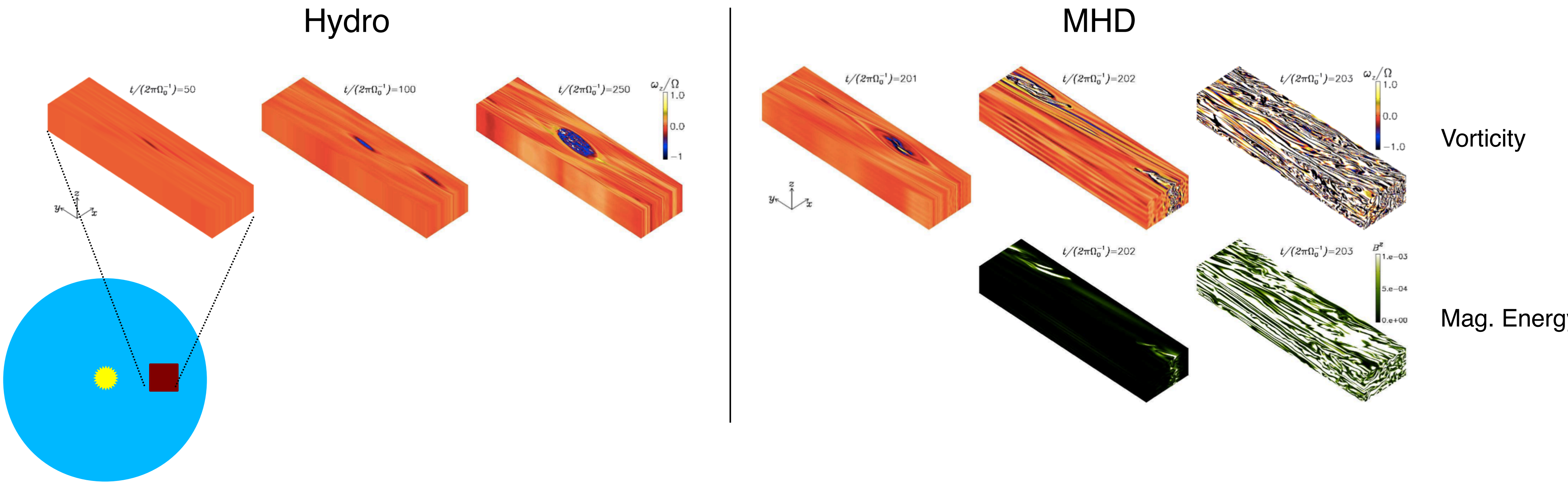
Outer Dead/Active zone transition RWI



Lyra, Turner, & McNally (2015)

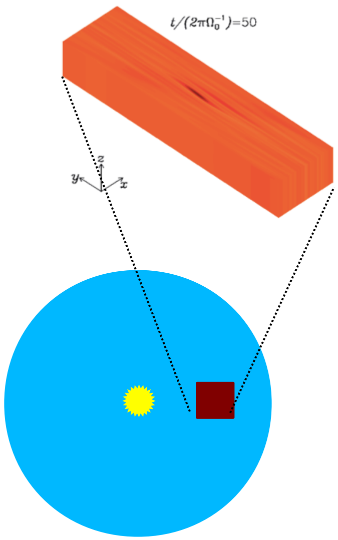
COV/SBI and MRI

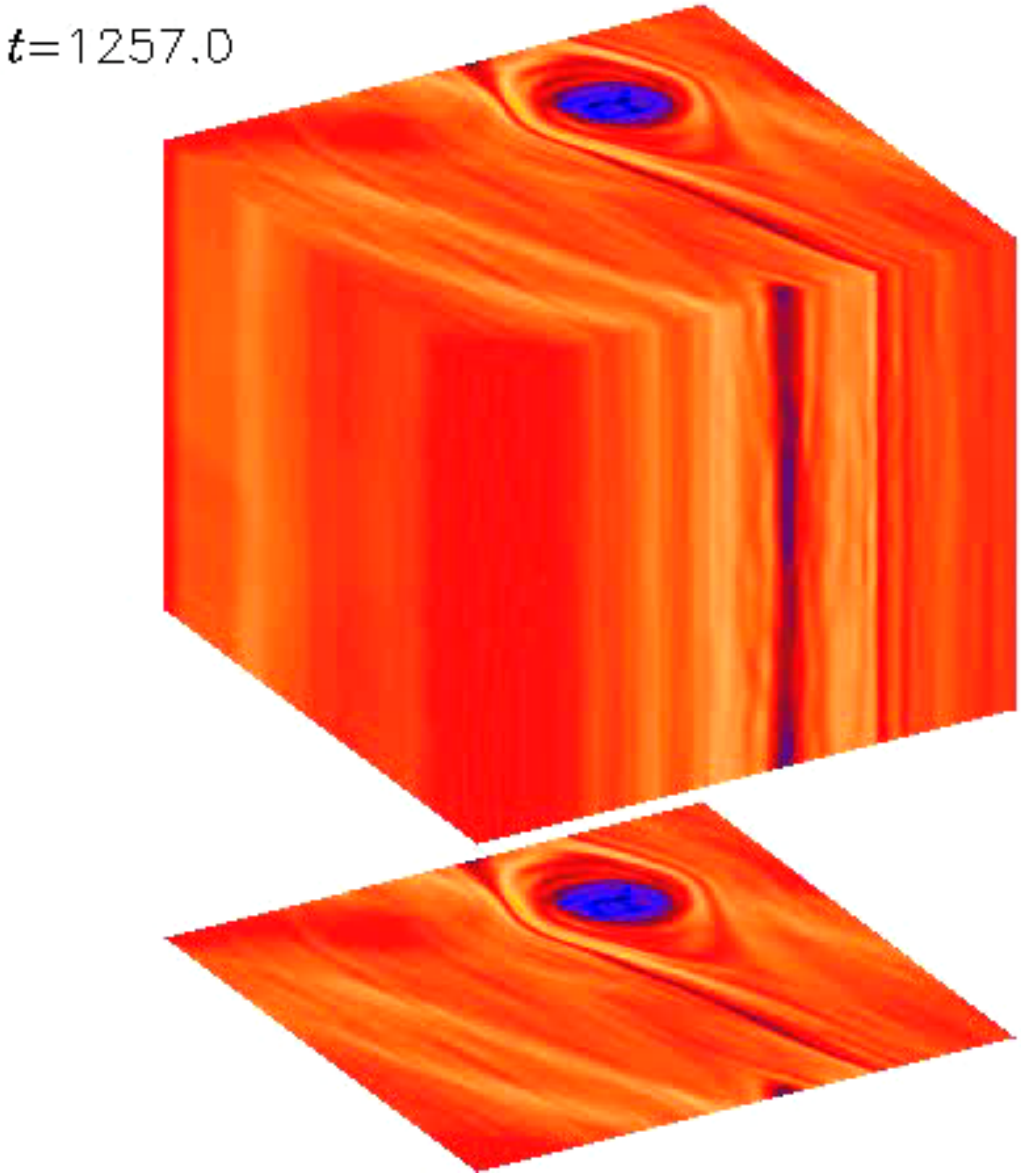
What happens when the disk is magnetized?

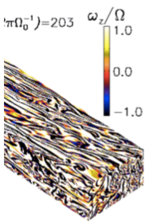


Lyra & Klahr (2011)

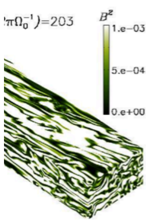
COV/SBI and MRI







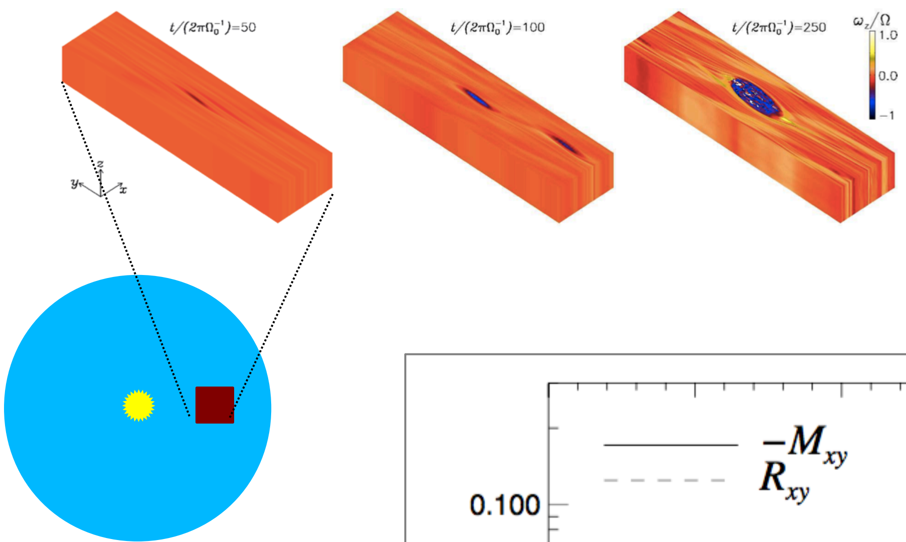
Vorticity



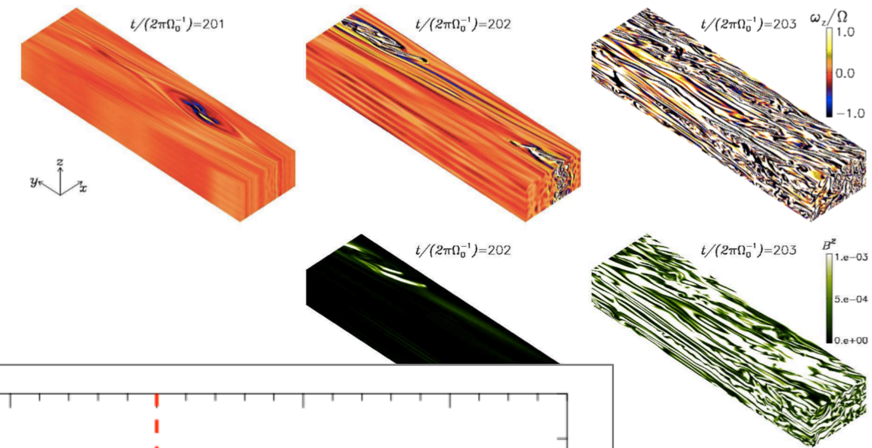
Mag. Energy

COV/SBI and MRI

Hydro

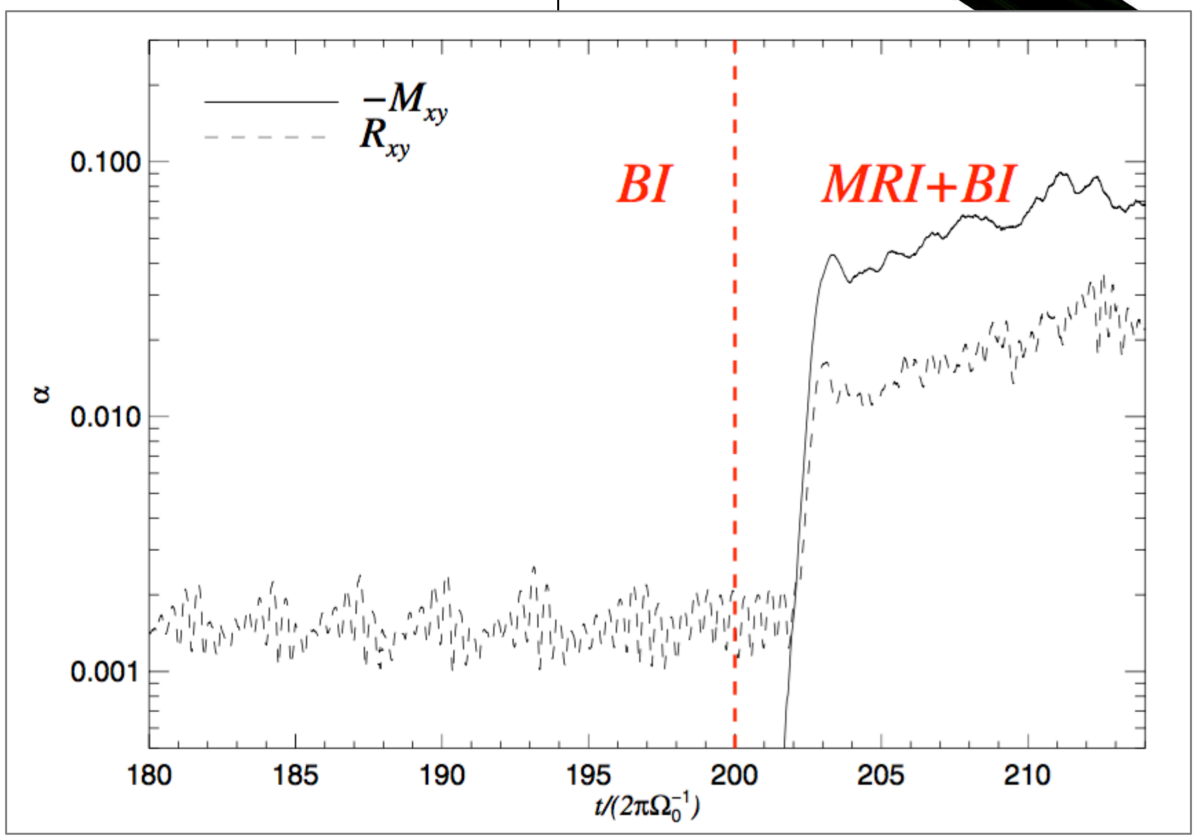


MHD



Vorticity

Mag. Energy



Lyra & Klahr (2011)