Planet signatures in transition disks

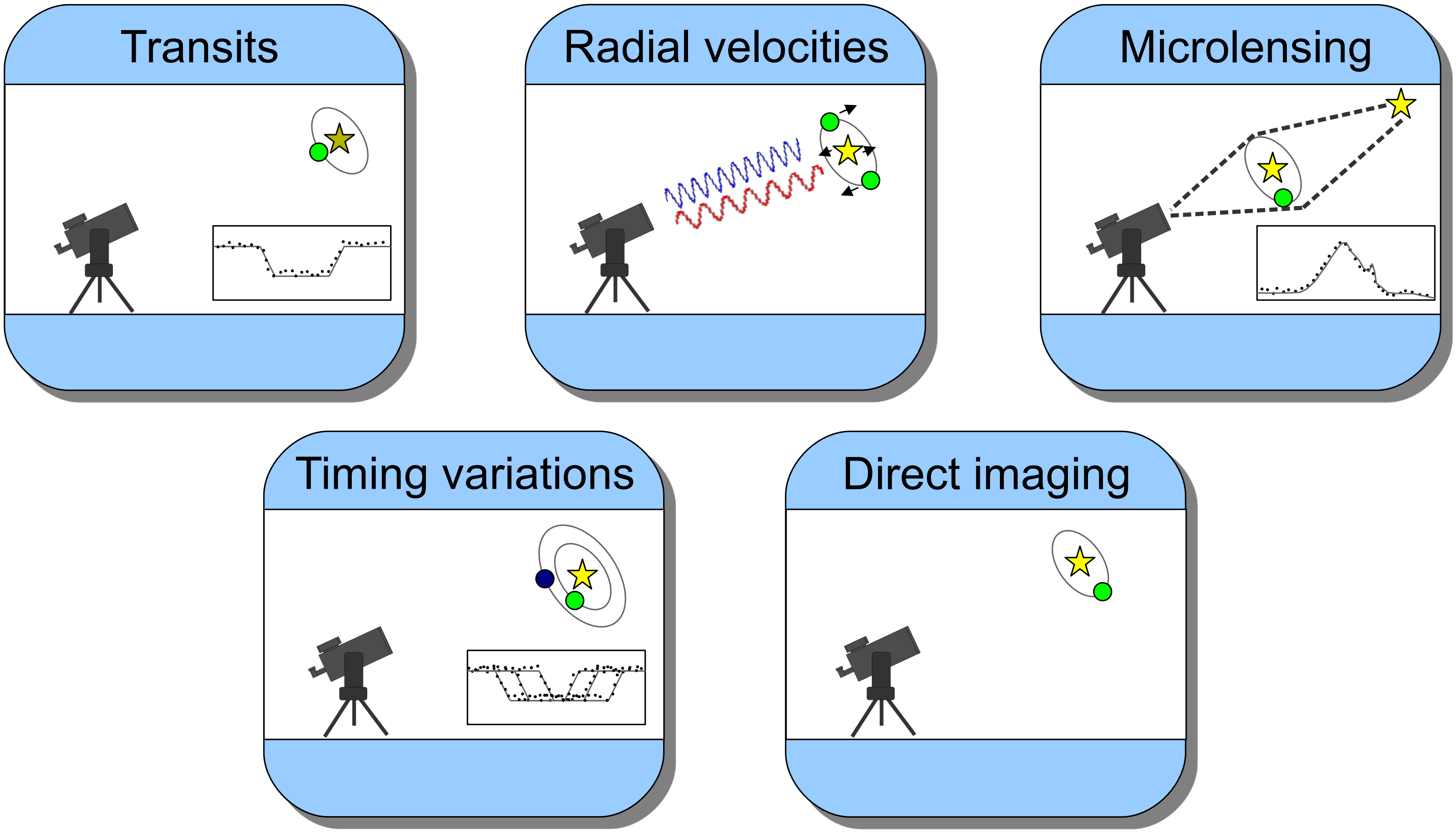
Wladimir Lyra

California State University
Jet Propulsion Laboratory

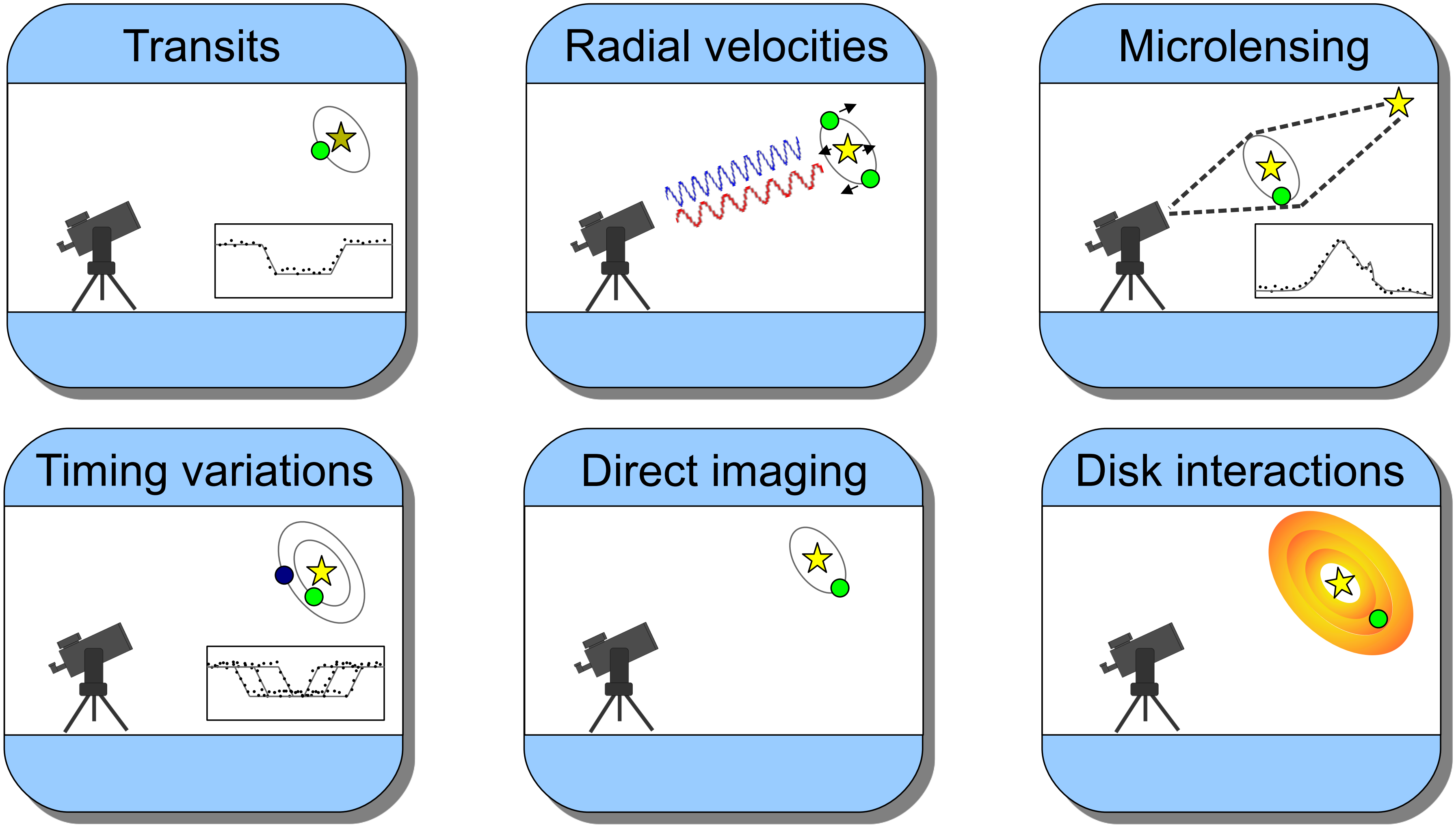
Collaborators

Aaron Boley (Vancouver), Axel Brandenburg (Stockholm), Simon Casassus (Chile), Thayne Currie (NASA Ames), Kees Dullemond (Heidelberg), Mario Flock (Heildeberg), Blake Hord (Stanford), Anders Johansen (Lund), Tobias Heinemann (Copenhagen), Hubert Klahr (Heidelberg), Marc Kuchner (Goddard), Michiel Lambrechts (Lund), Min-Kai Lin (ASIAA), Mordecai-Mark Mac Low (AMNH), Frederic Masset (Mexico), Colin McNally (London), Krzysztof Mizerski (Warsaw), Richard Nelson (London) Satoshi Okuzumi (Tokyo), Sijme-Jan Paardekooper (London), Sebastian Perez (Chile), Nikolai Piskunov (Uppsala), Natalie Raettig (Heidelberg), Alex Richert (PSU), Zsolt Sandor (Budapest), Neal Turner (JPL), Orkan Umurhan (NASA Ames), Nienke van der Marel (Victoria), Chao-Chin Yang (UNLV).

Caltech, Dec 7th, 2018

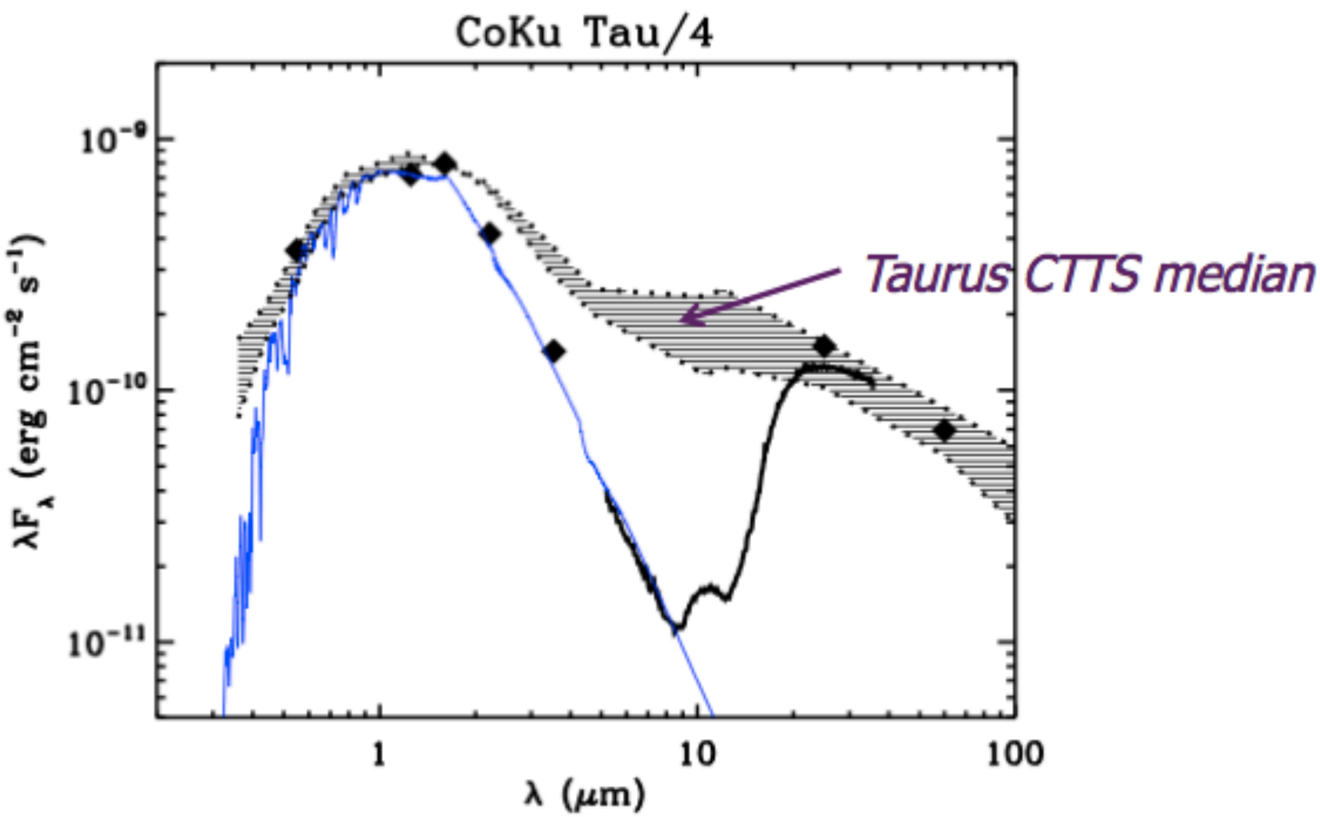


Slide by A. Richert

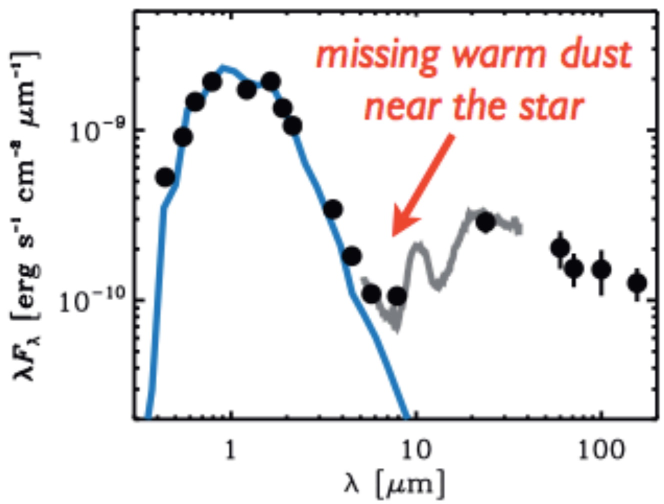


Slide by A. Richert

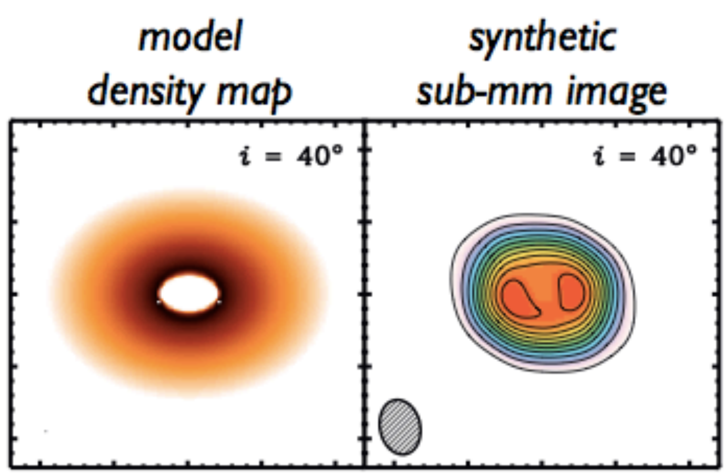
Transition Disks: Disks with missing hot dust.



Transition Disks: Disks with missing hot dust.

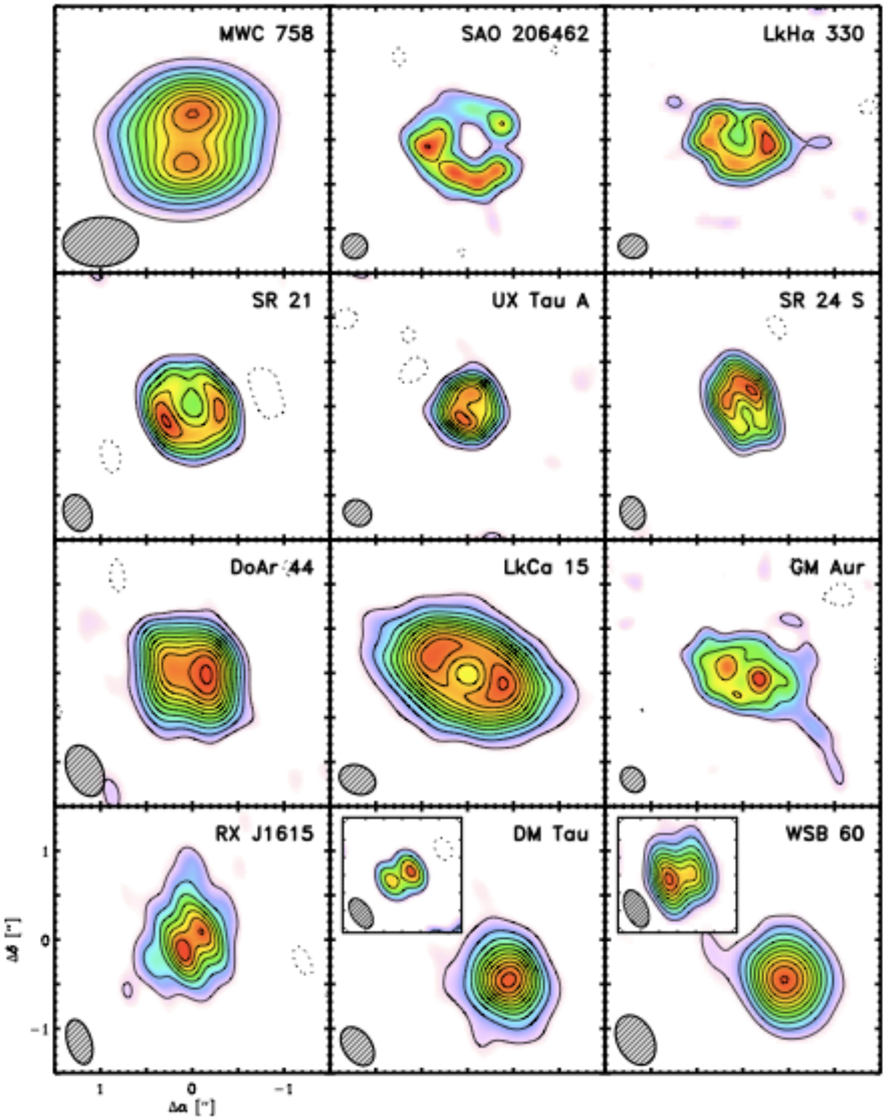


[e.g., Furlan et al. 2009]

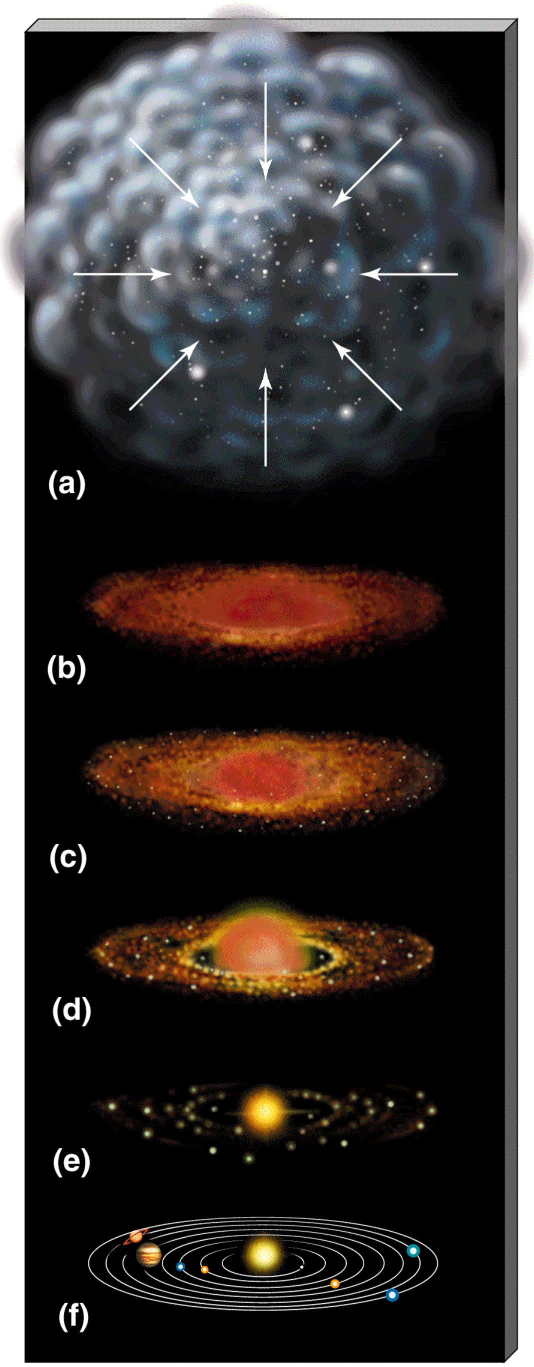


a disk with a large reduction
in optical depth near the star
(i.e., a “cavity” or “hole”)

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



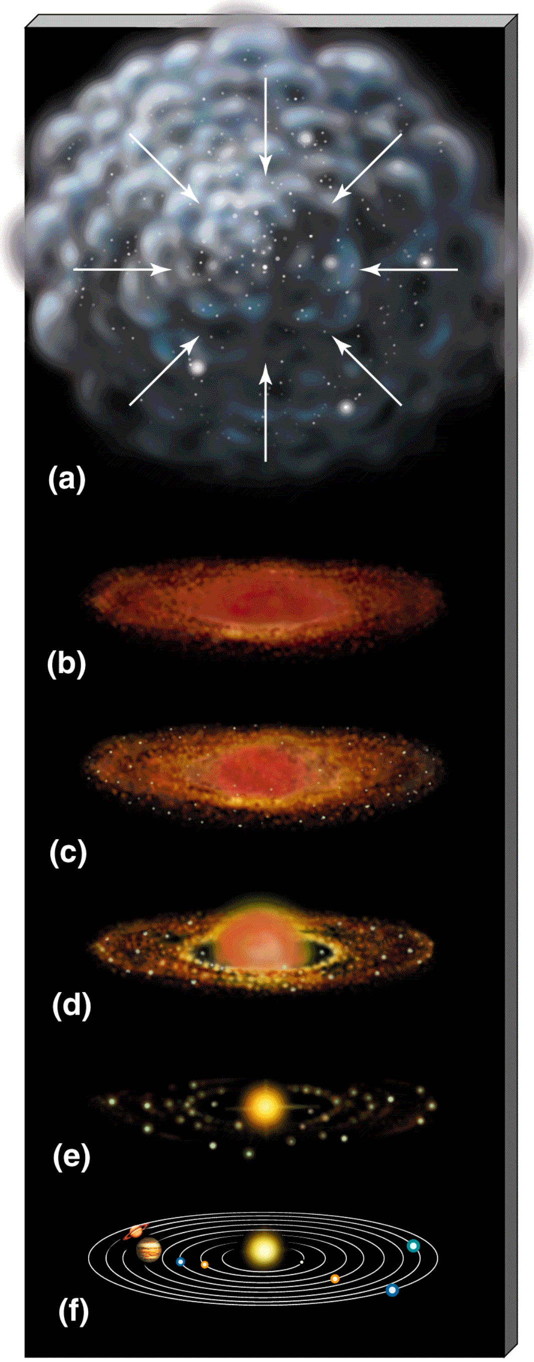
0.85mm
0.3'' ~ 20 AU resolution



Are transitional disks related to disk evolution?

Gas-rich phase (< 10 Myr)
Primordial Disks

Gas-poor phase (>10 Myr)
Debris Disks



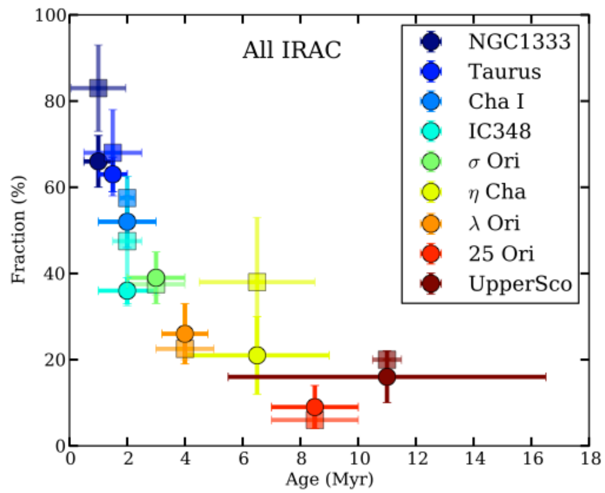
Are transitional disks related to disk evolution?

Gas-rich phase (< 10 Myr)
Primordial Disks

Conjecture:
Thinning phase (~10 Myr)
Transitional Disks

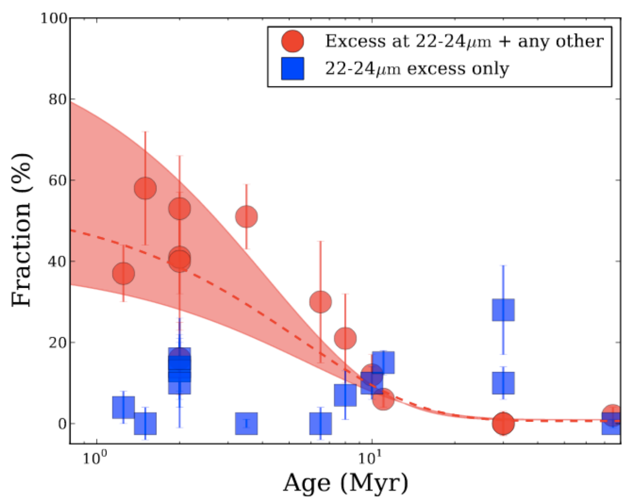
Gas-poor phase (>10 Myr)
Debris Disks

Transition disks and disk evolution



(Ribas et al. 2014)

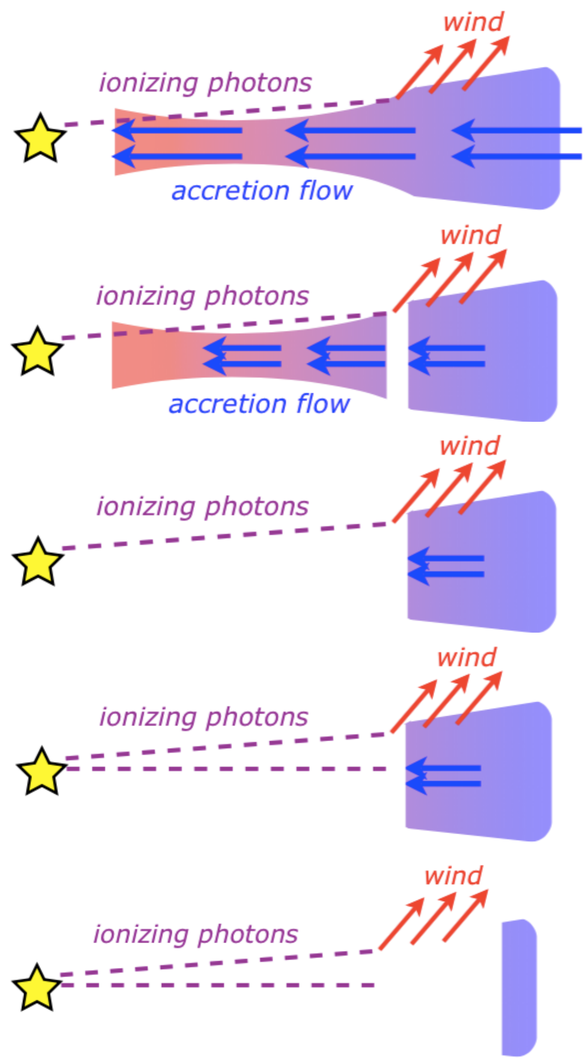
"Total" disk fraction



(Ribas et al. 2014)

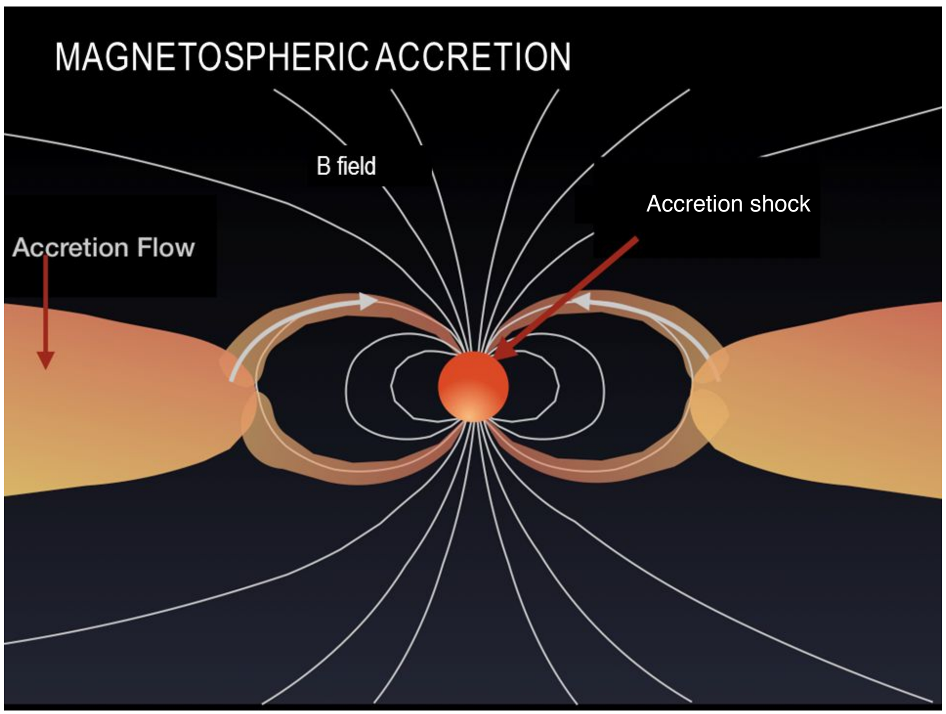
Transition disk fraction

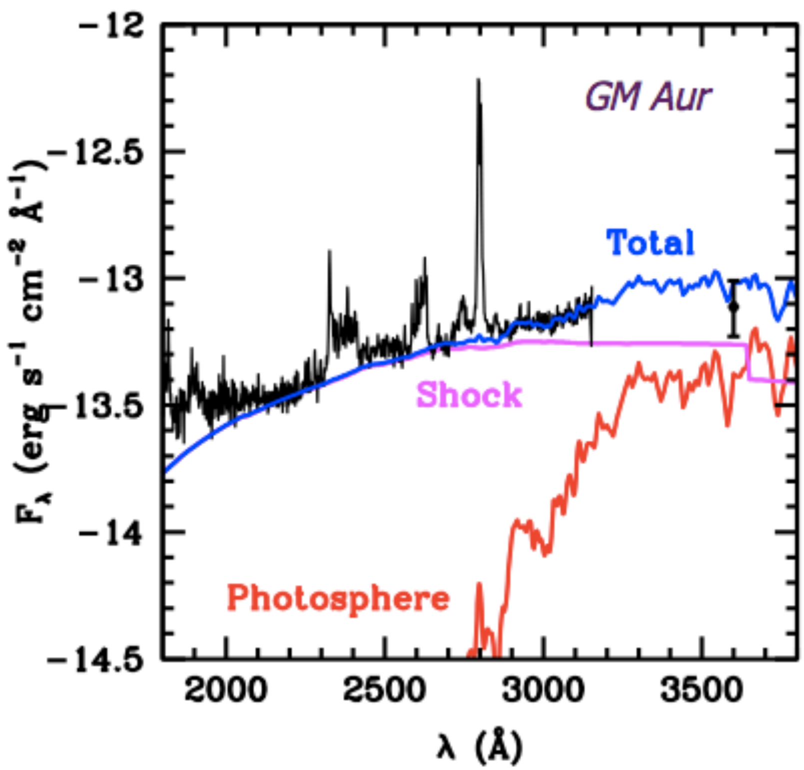
Photoevaporation



UV excess

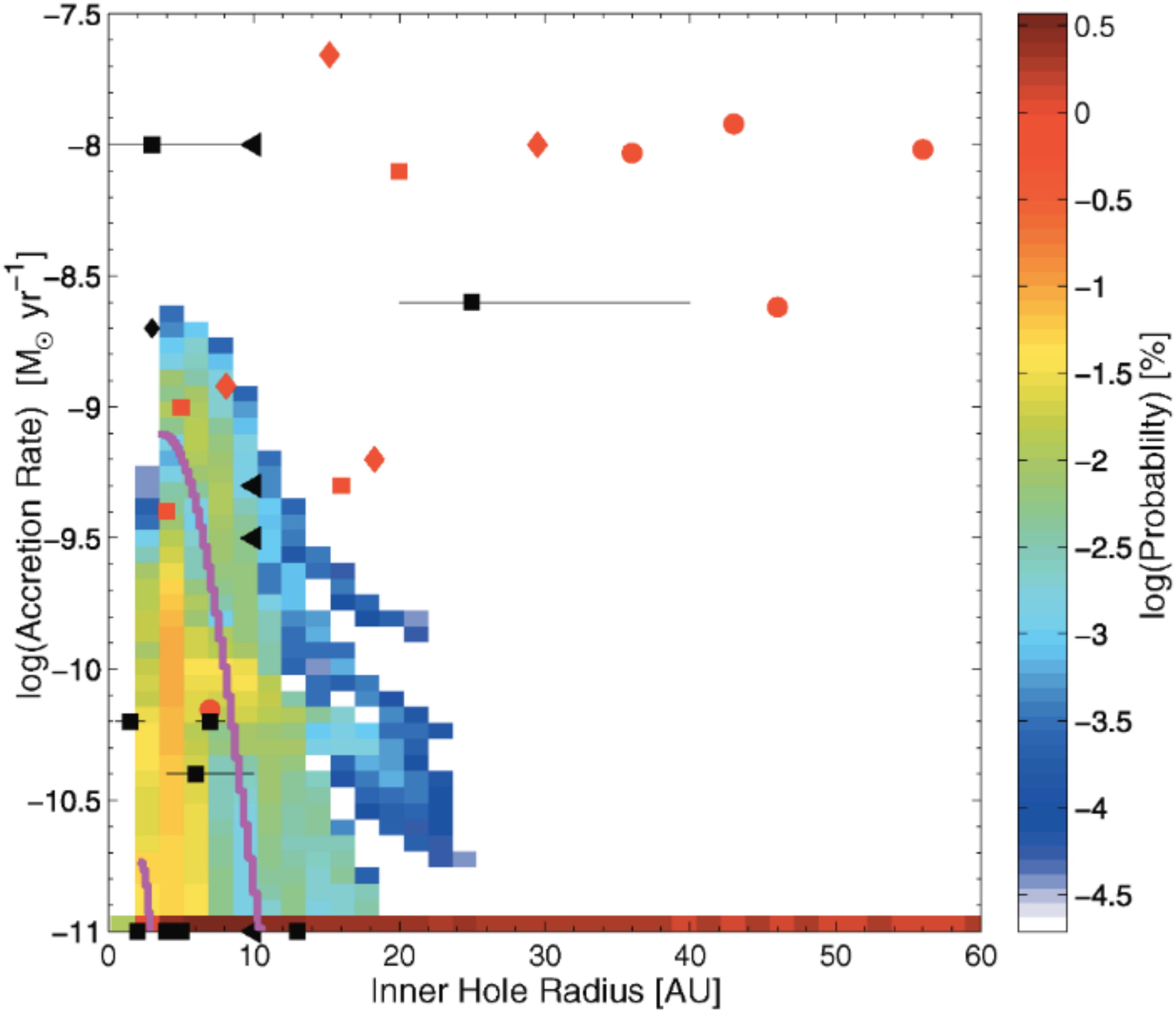
Many transitional disks show signs of accretion,
at the level of primordial (classical T-Tauri) disks.





(Ingleby et al. 2011)

Bimodal distribution of transition disks

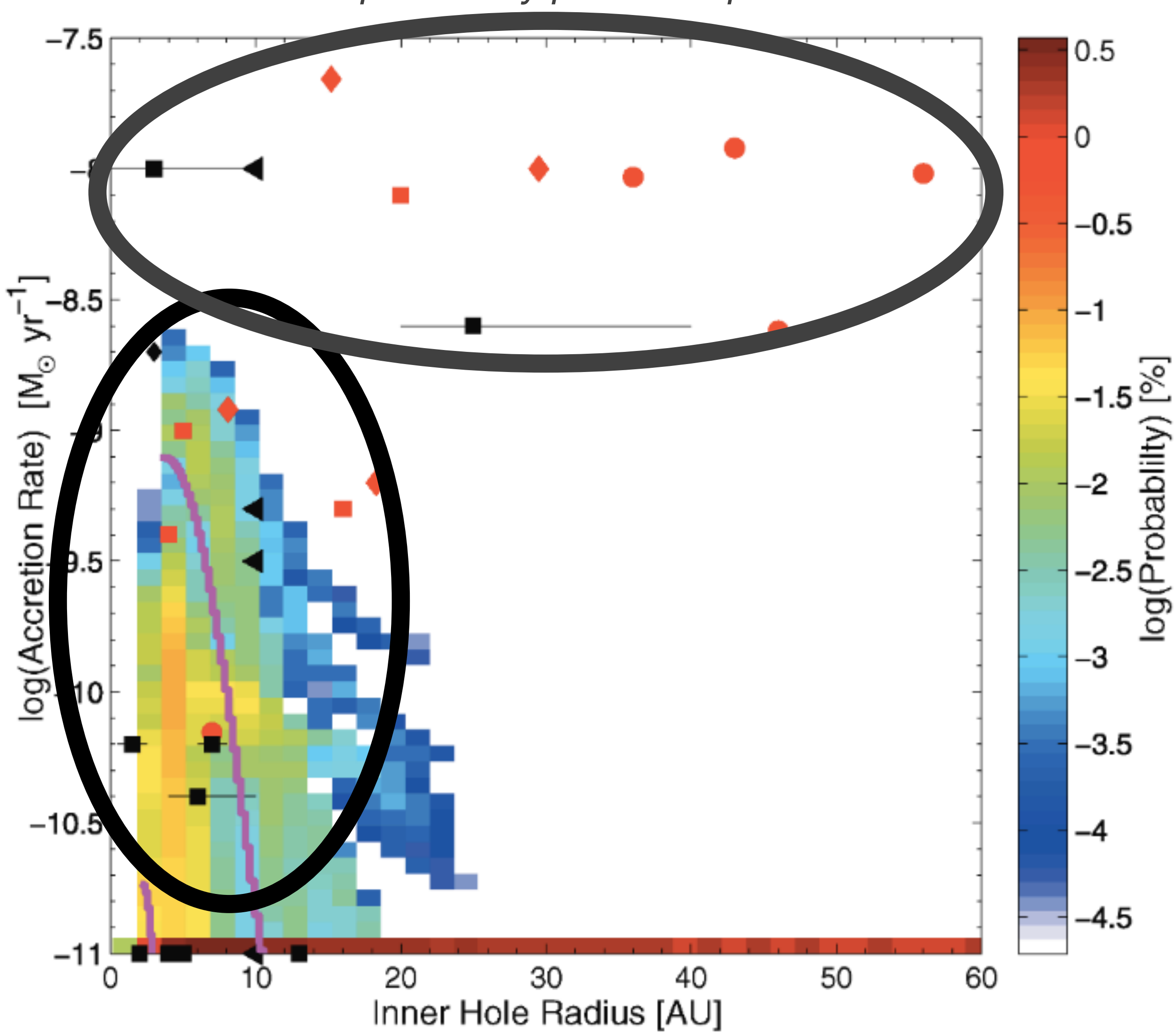


(Owen et al. 2011)

Bimodal distribution of transition disks

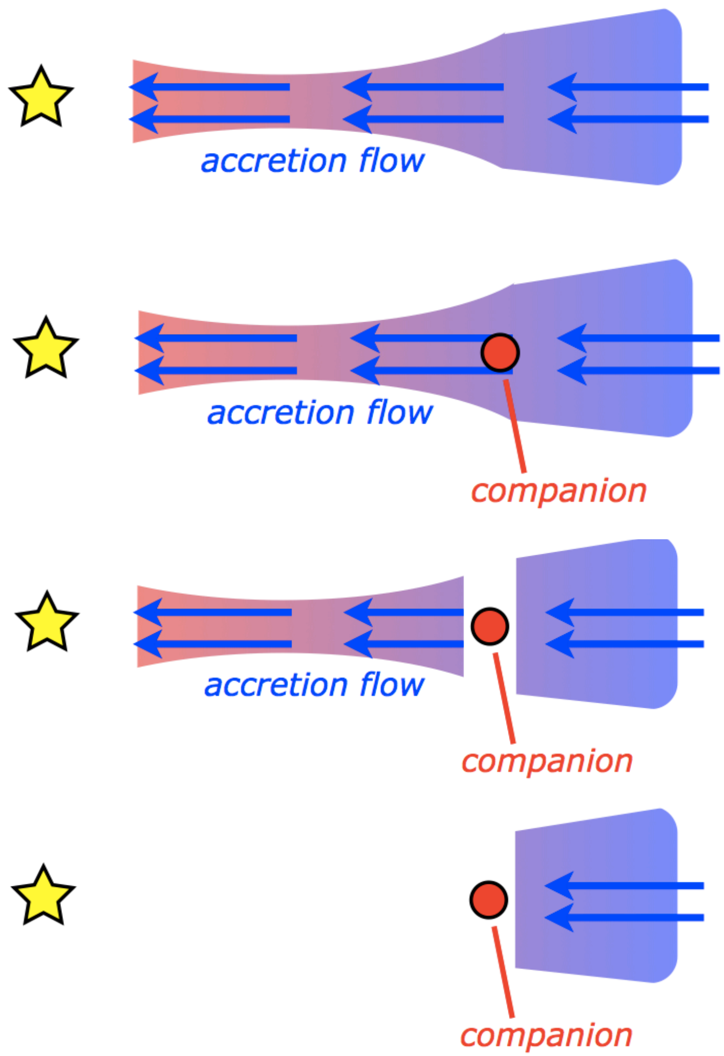
Not explained by photo-evaporation

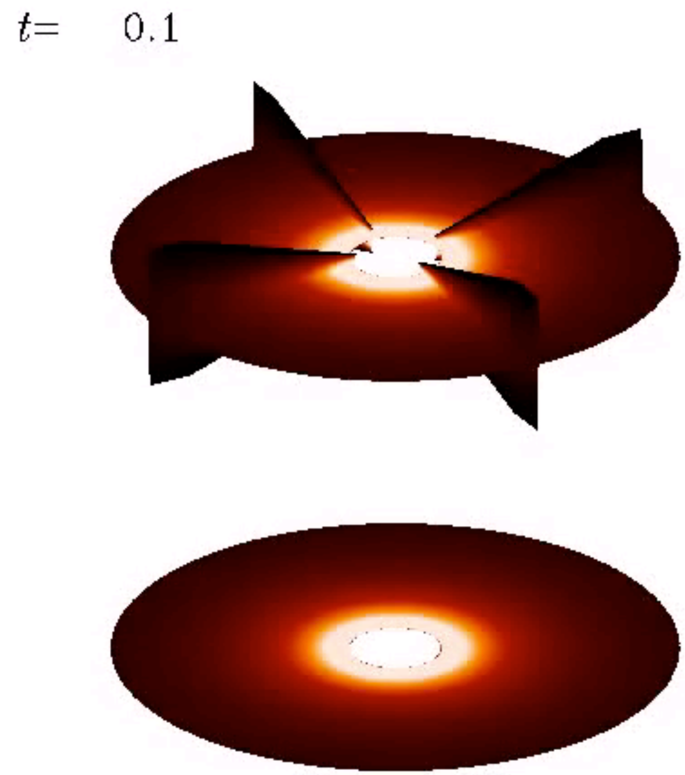
Explained by Photo-evaporation



(Owen et al. 2011)

Planetary companion

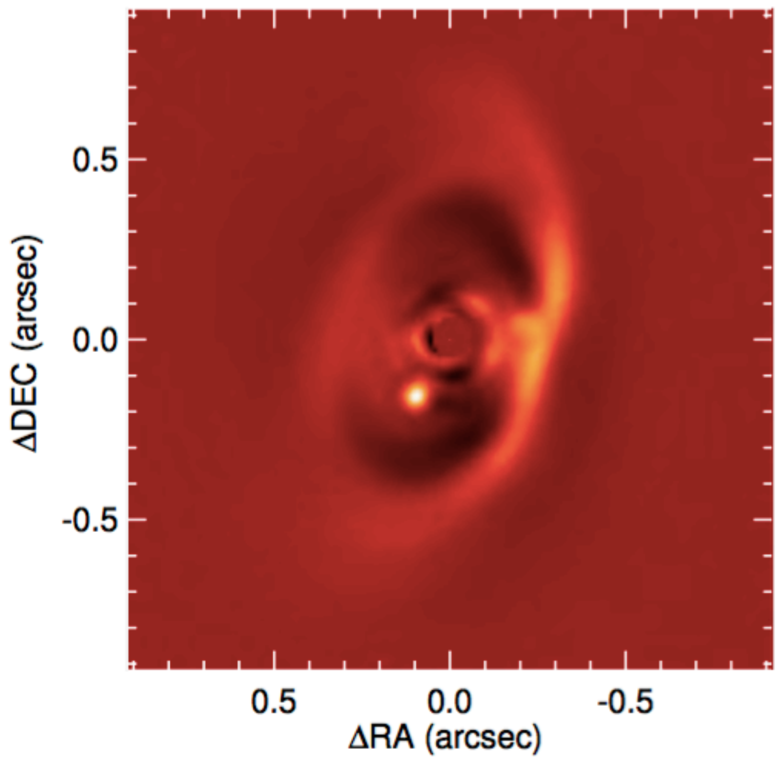




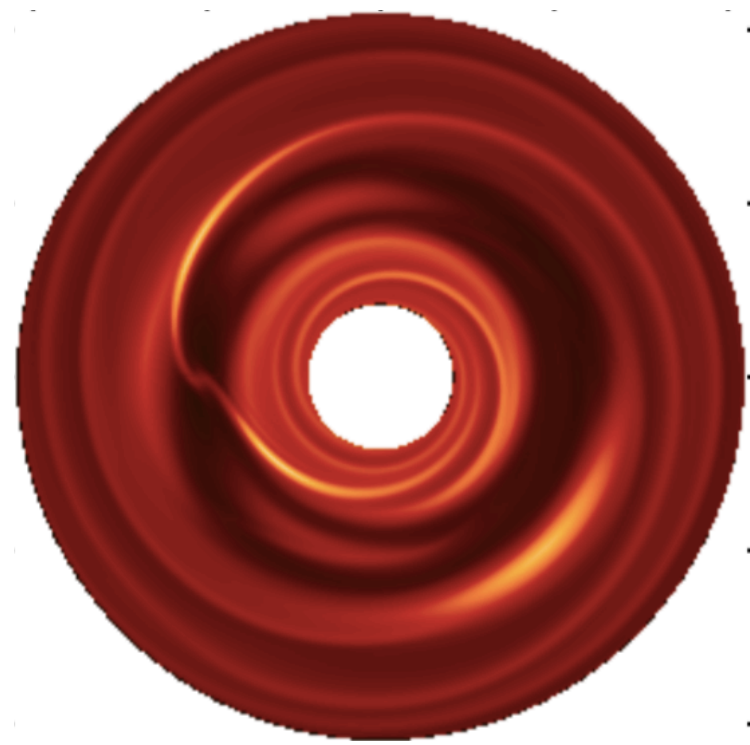
(Lyra 2009)

These cavities may be the telltale signature of forming planets

PDS 70 and PDS 70b



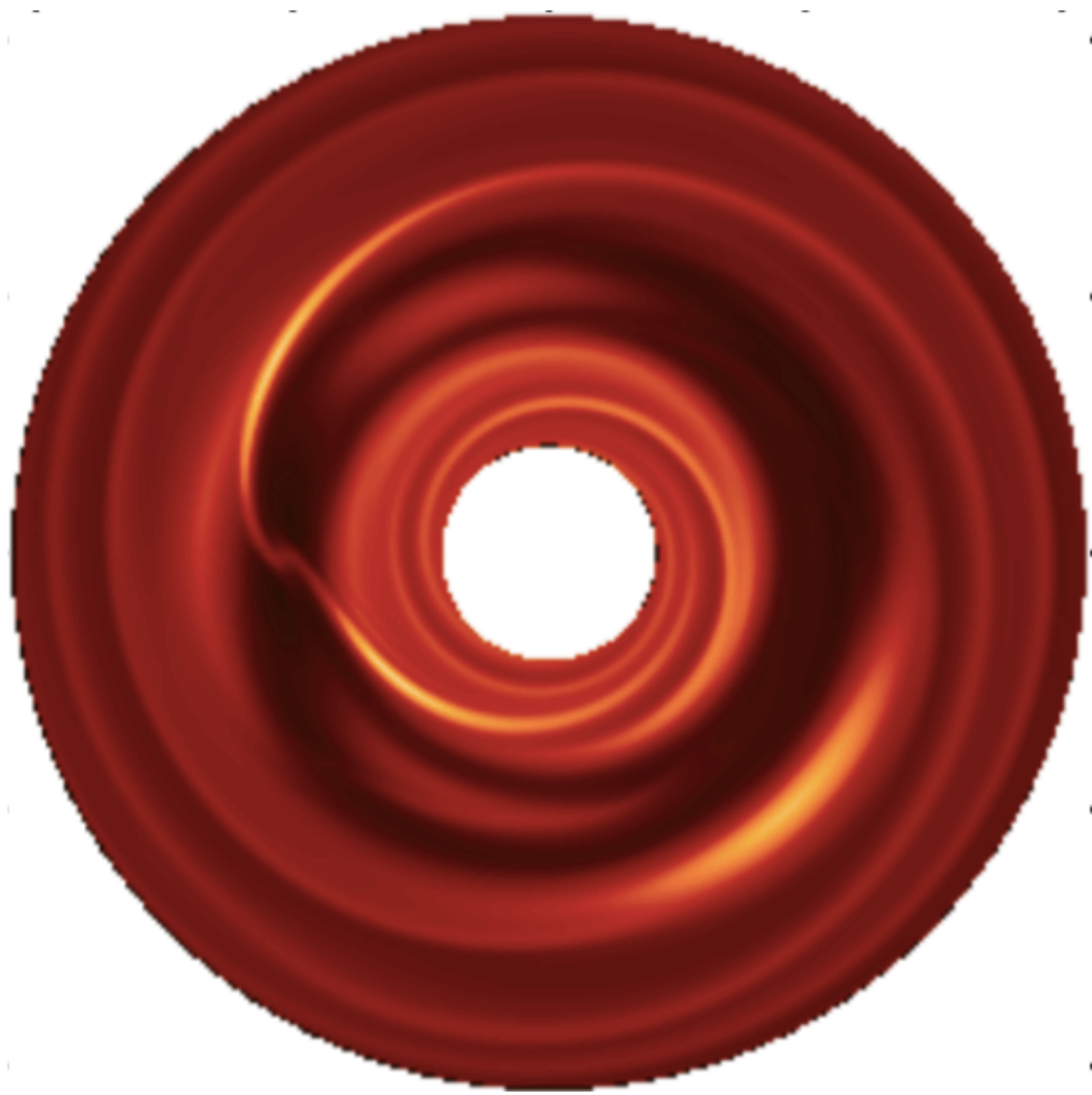
(Muller et al. 2018)



(Lyra et al. 2009b)

A way to directly study planet-disk interaction

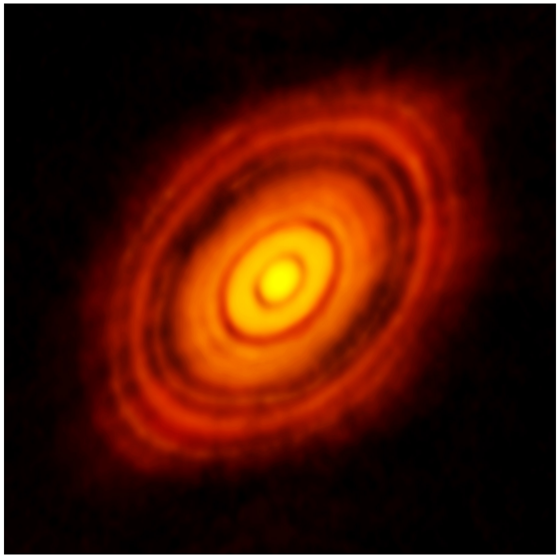
Planet-disk interaction: gaps, spirals, and vortices.



(Lyra et al. 2009b)

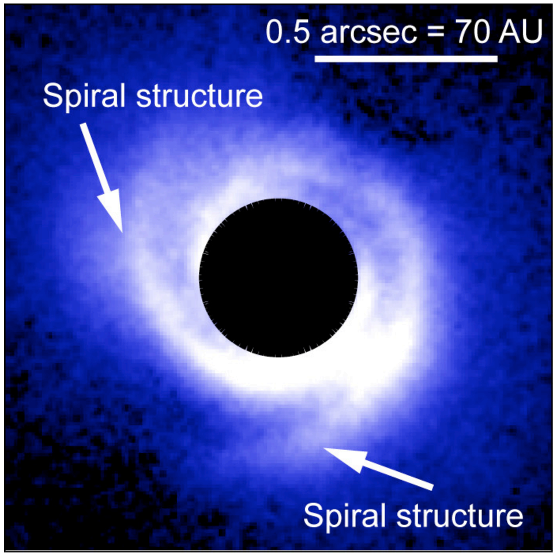
Observational evidence: gaps, spirals, and vortices

HL Tau



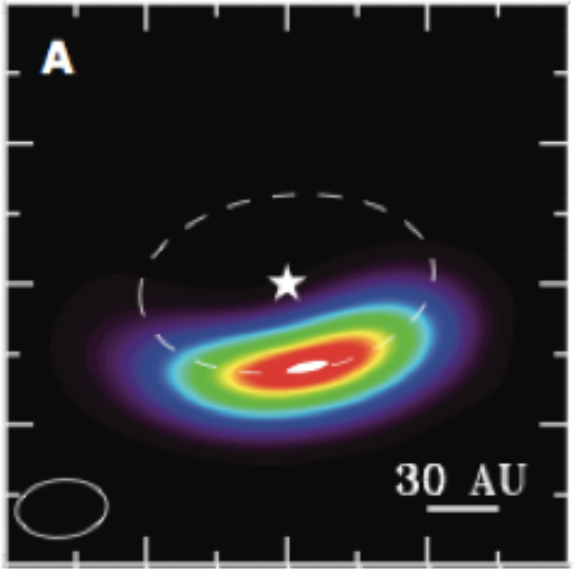
The ALMA Partnership et al. (2015)

SAO 206462



Muto et al. (2012)

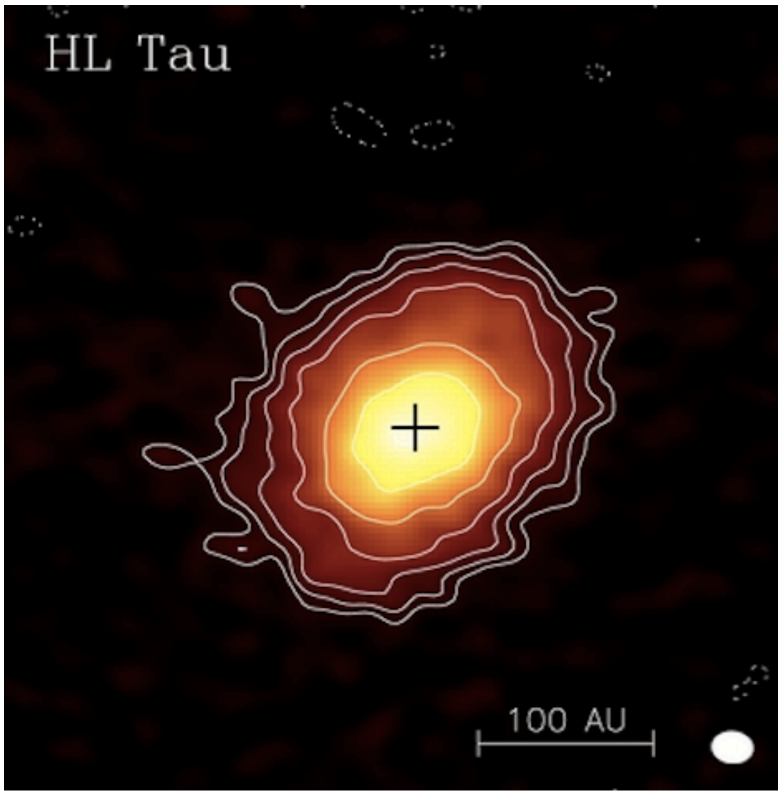
Oph IRS 48



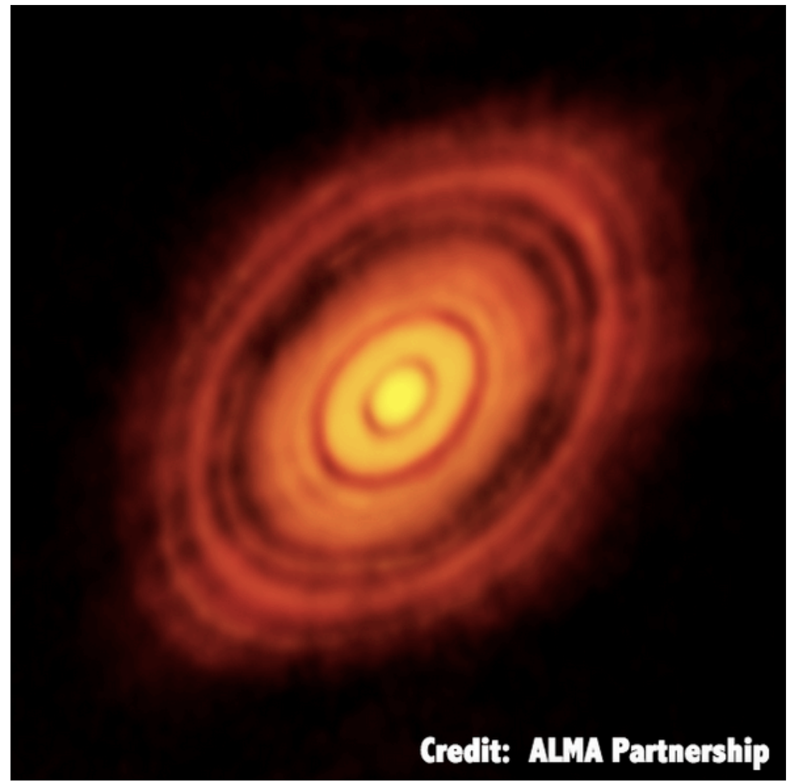
van der Marel et al. (2013)

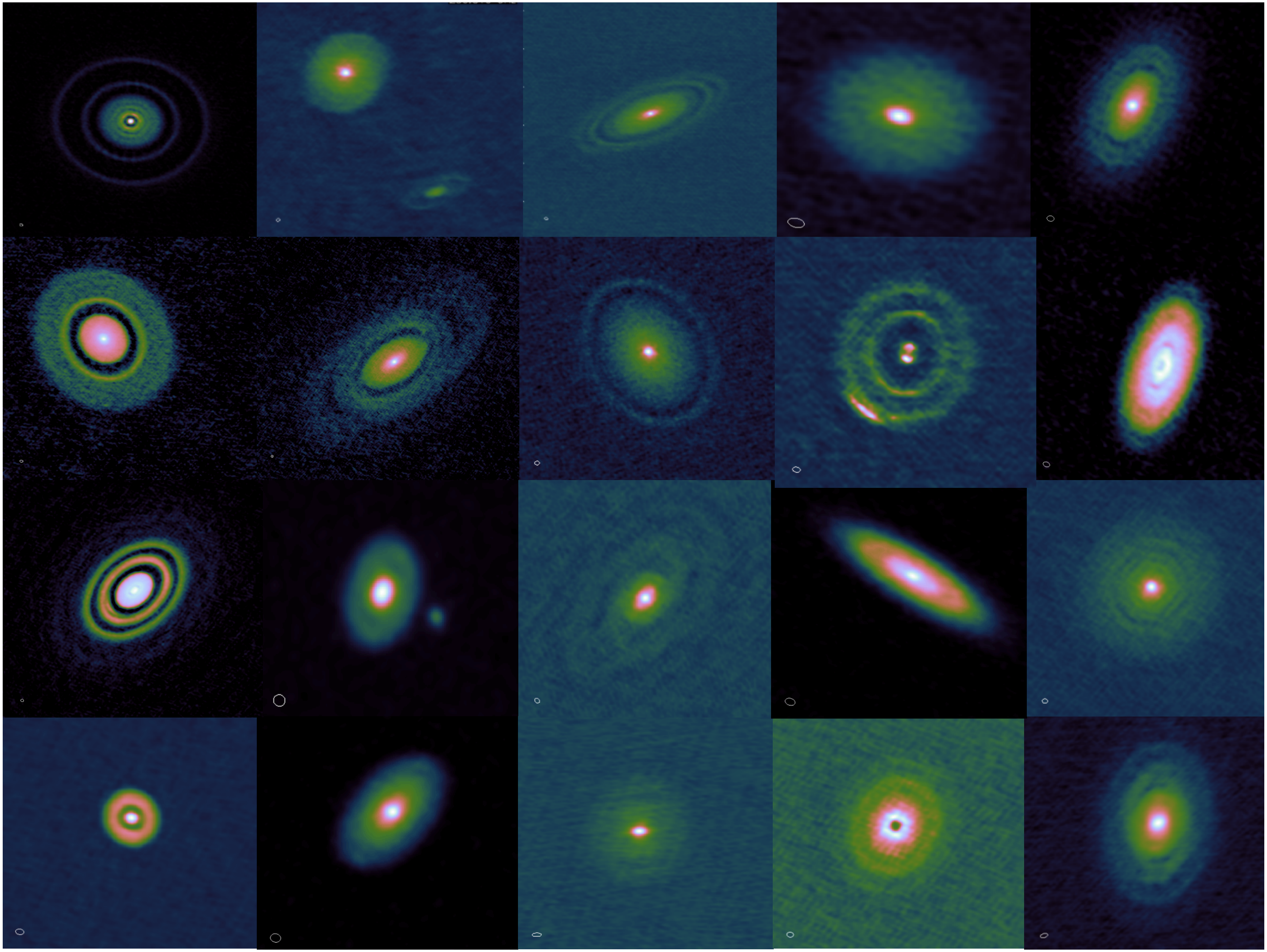
The Atacama Large Millimeter Array (ALMA)

Before ALMA

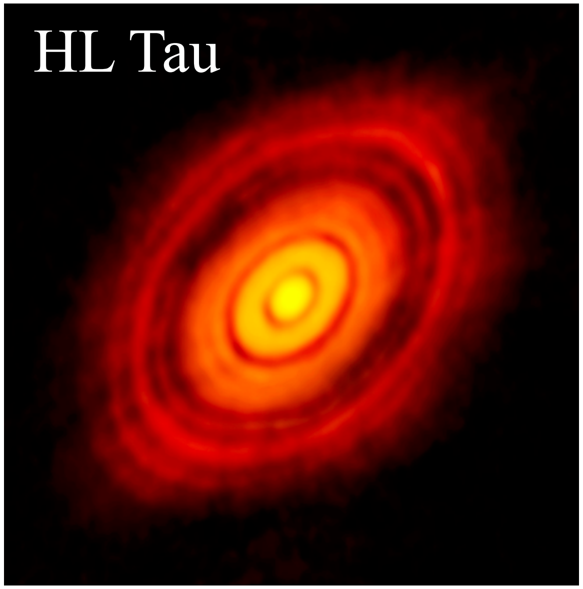


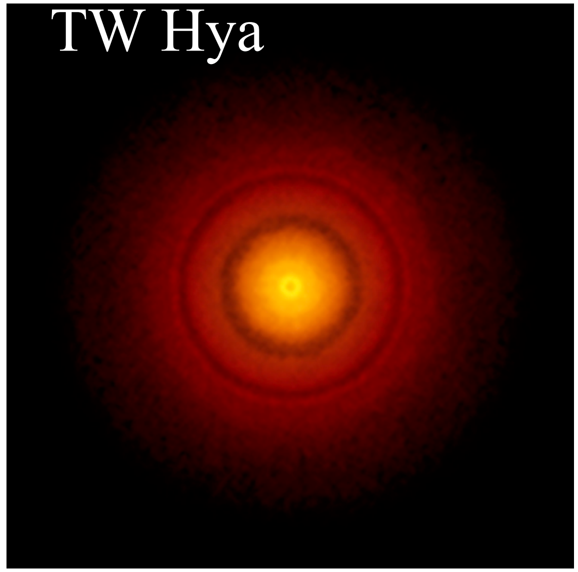
ALMA

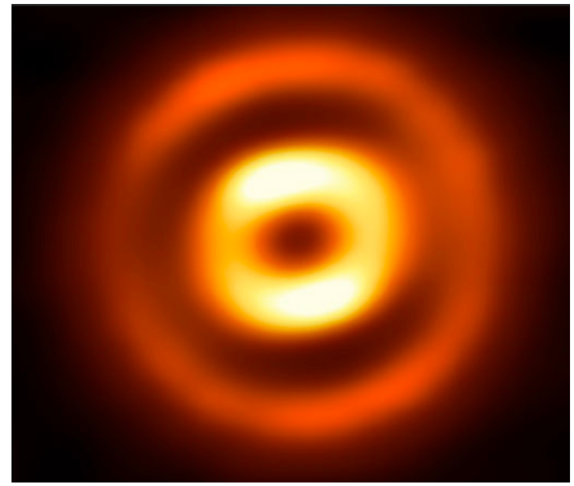


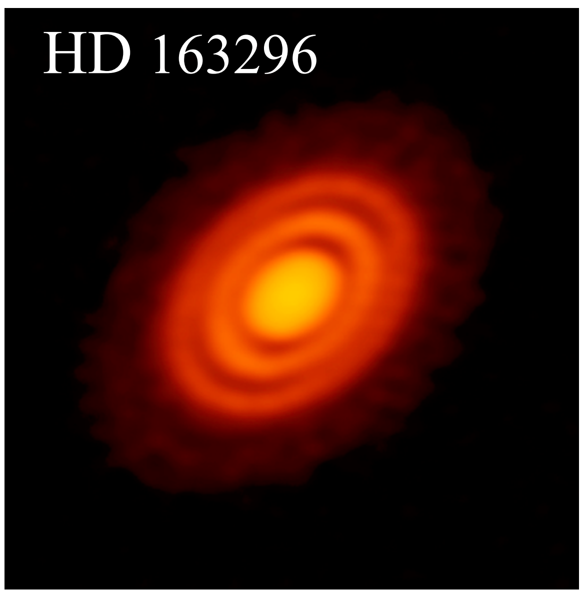


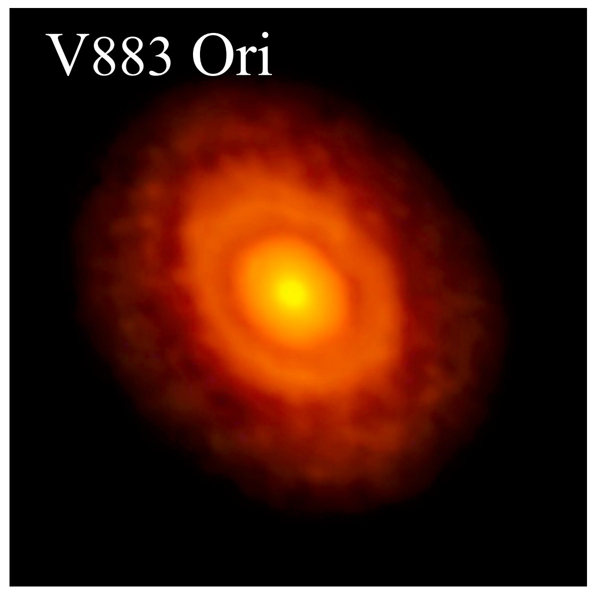
Rings and gaps











Oph IRS 48

A Major Asymmetric Dust Trap in a Transition Disk

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

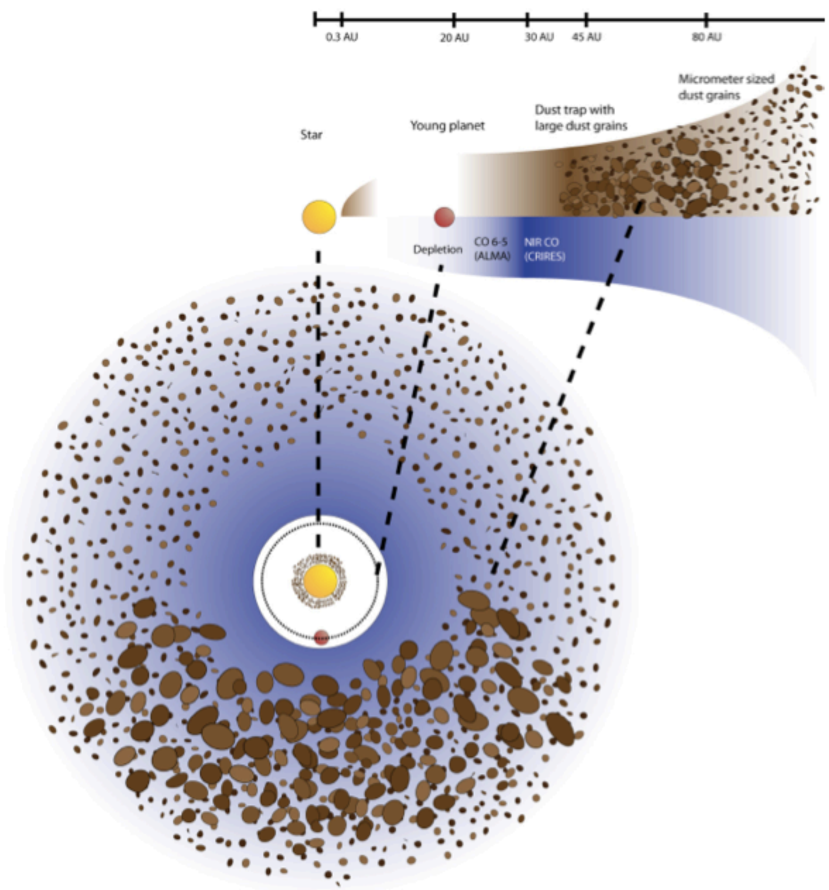
The statistics of discovered exoplanets suggest that planets form efficiently. However, there are fundamental unsolved problems, such as excessive inward drift of particles in protoplanetary disks during planet formation. Recent theories invoke dust traps to overcome this problem. We report the detection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

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

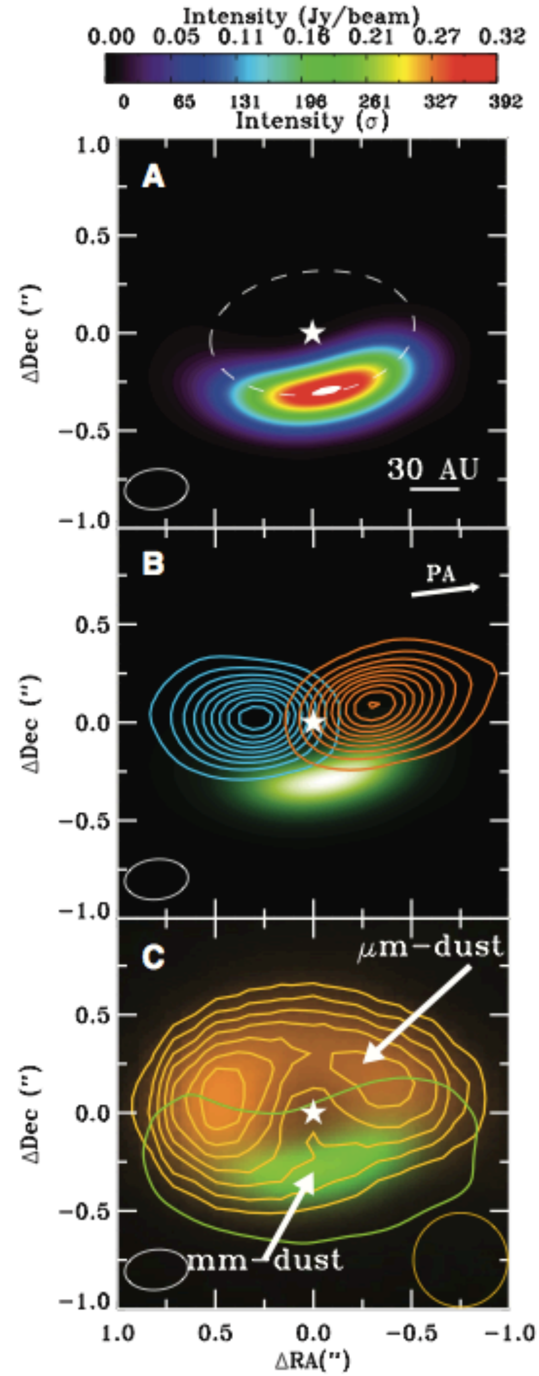
van der Marel et al. 2013

A huge vortex observed with ALMA

The Oph IRS 48 "comet formation factory"



van der Marel et al. (2013)

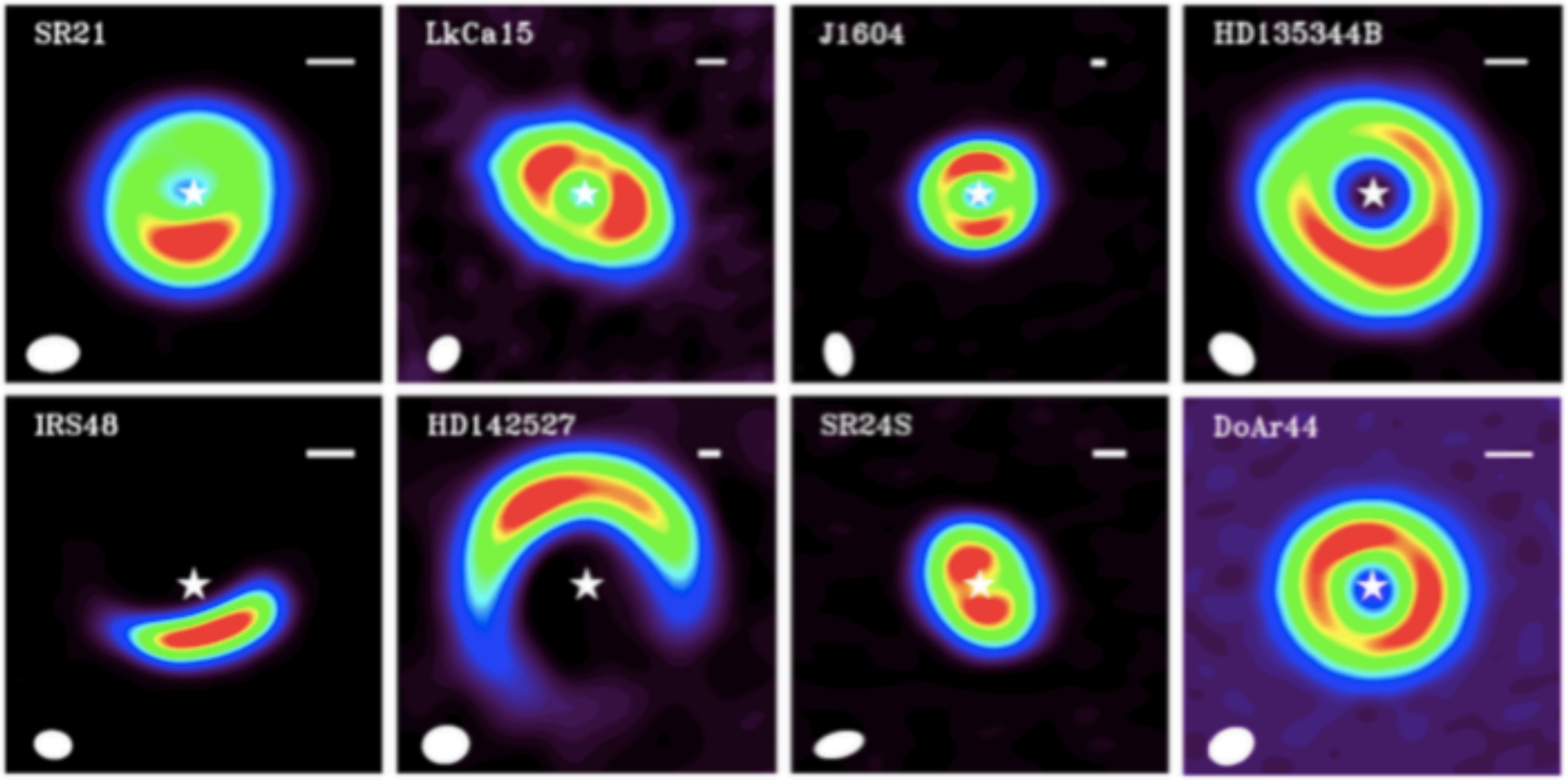


asymmetric mm dust at 63 AU

Gas detection: Keplerian rotation

Micron-sized dust follows gas

Asymmetries everywhere!

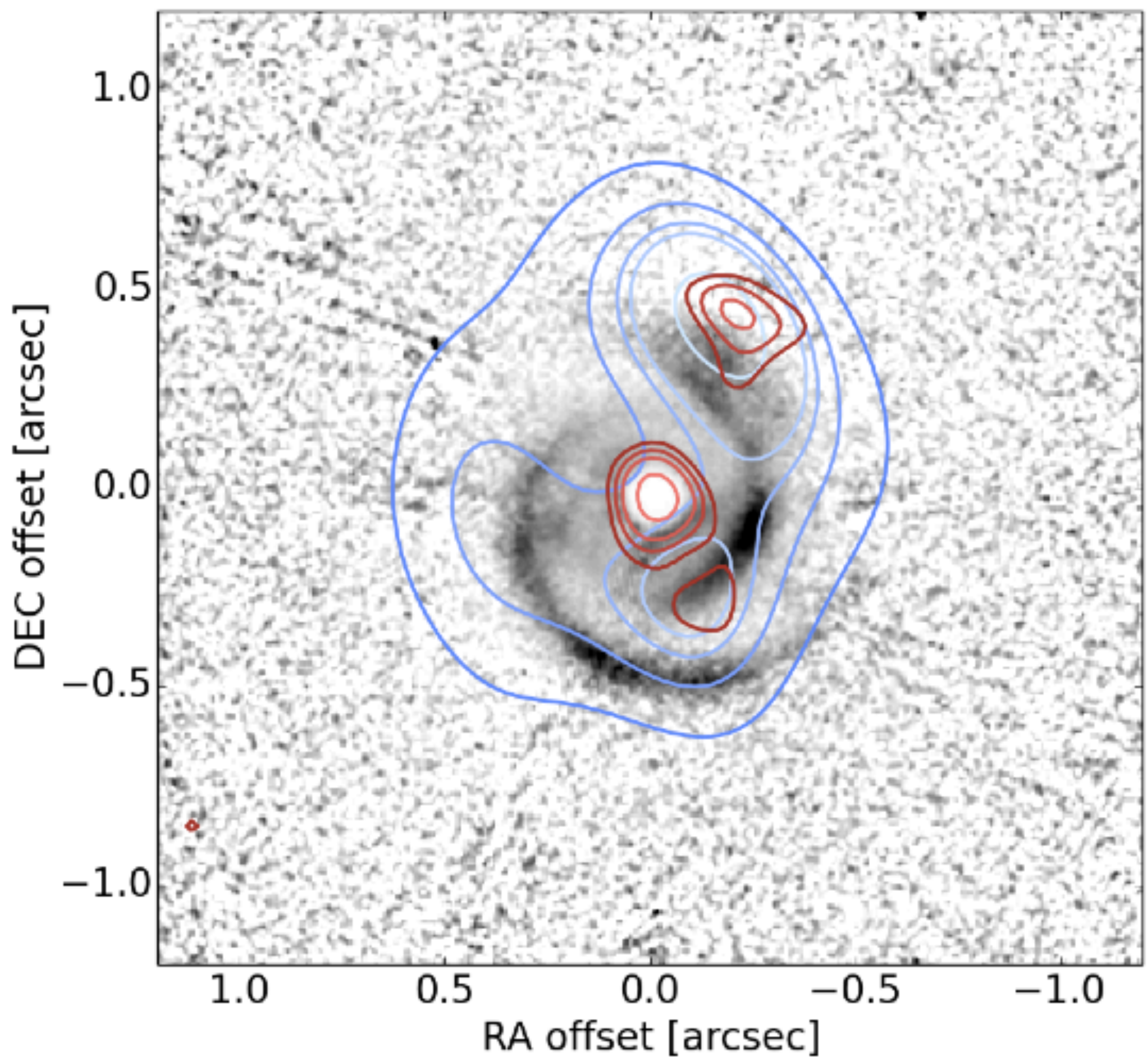


SPHERE-ALMA-VLA overlay of MWC 758

SPHERE (μm)

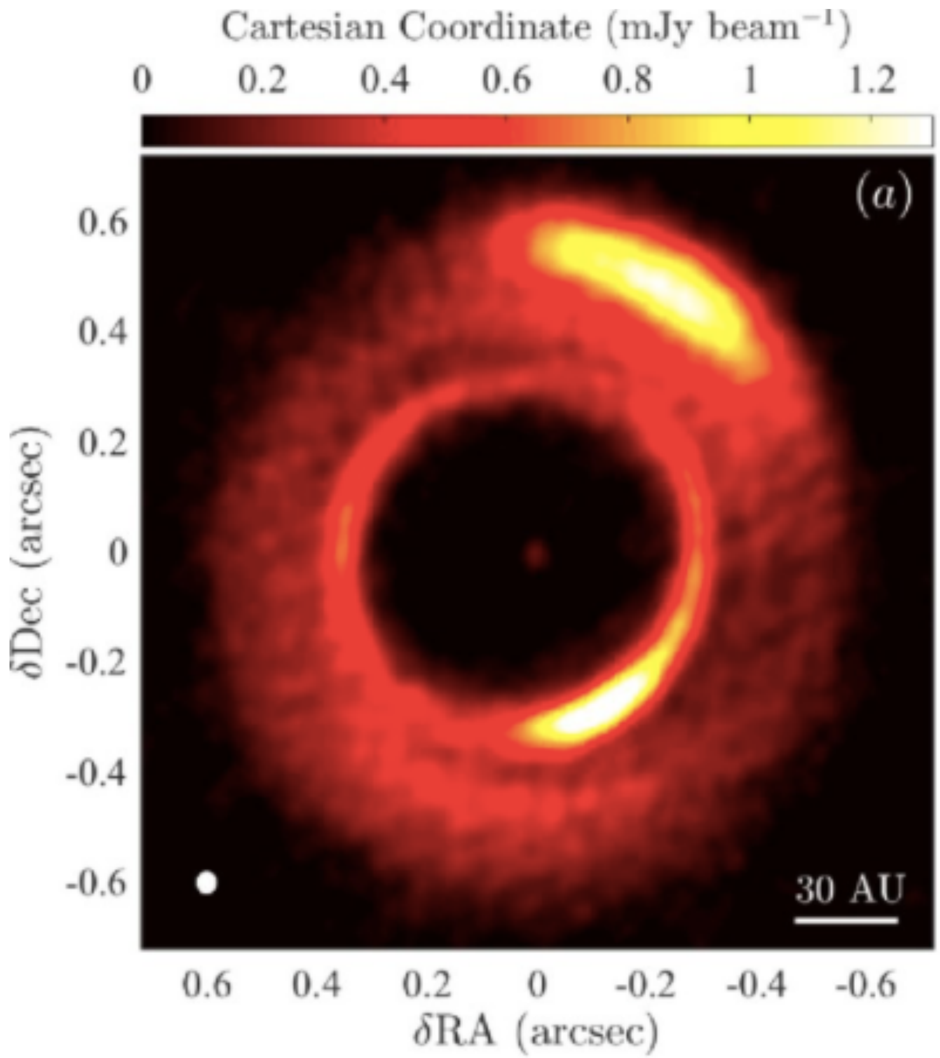
ALMA (~ mm)

VLA (cm-m)



Marino et al. (2015)

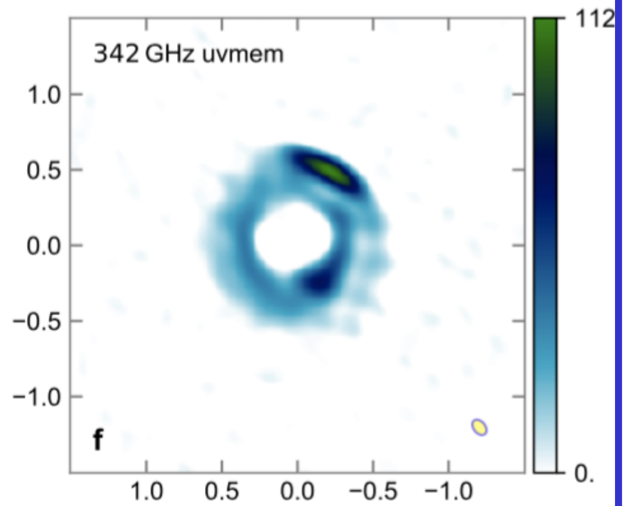
MWC 758



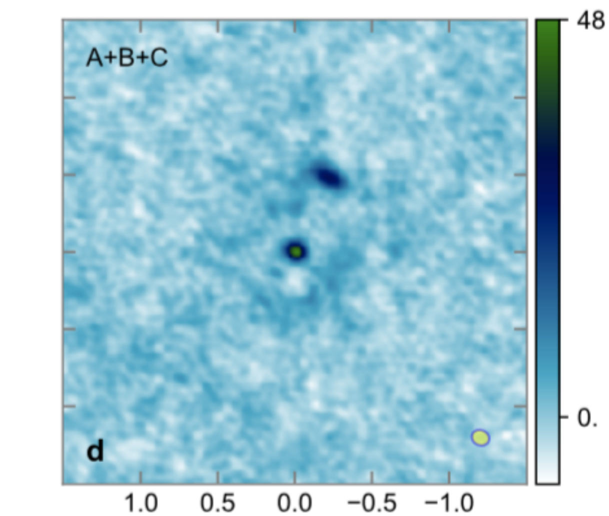
Dong et al. (2018)

Pebble trapping

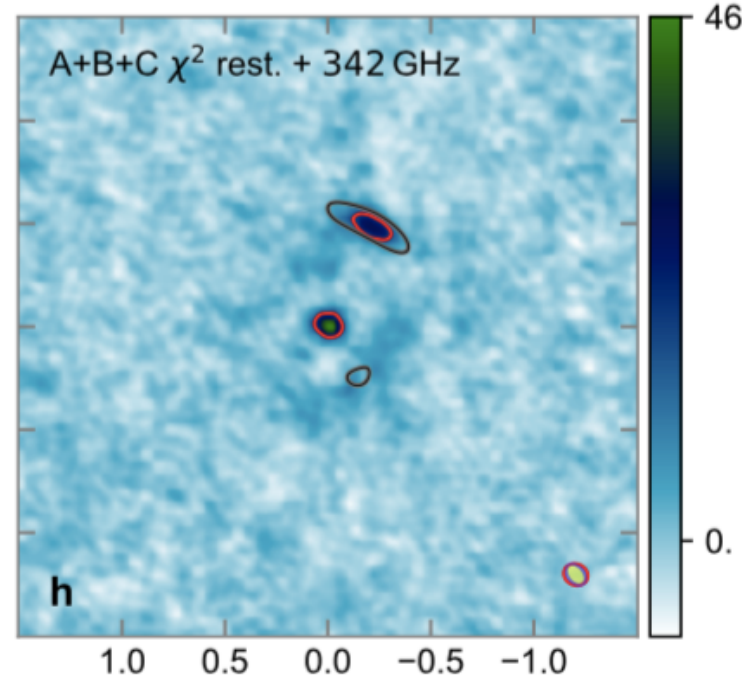
ALMA
(mm)



VLA
(cm-m)



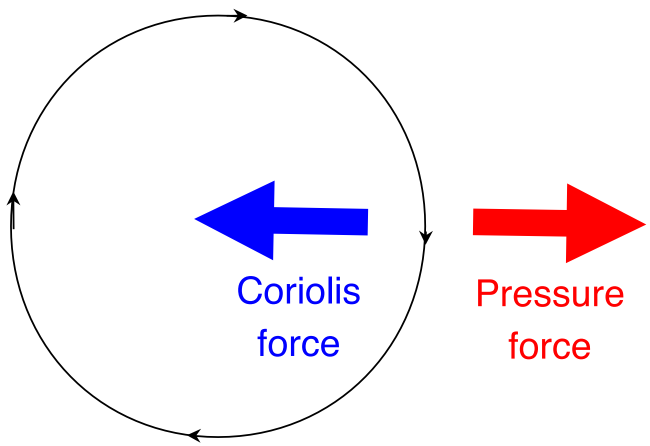
Overlay



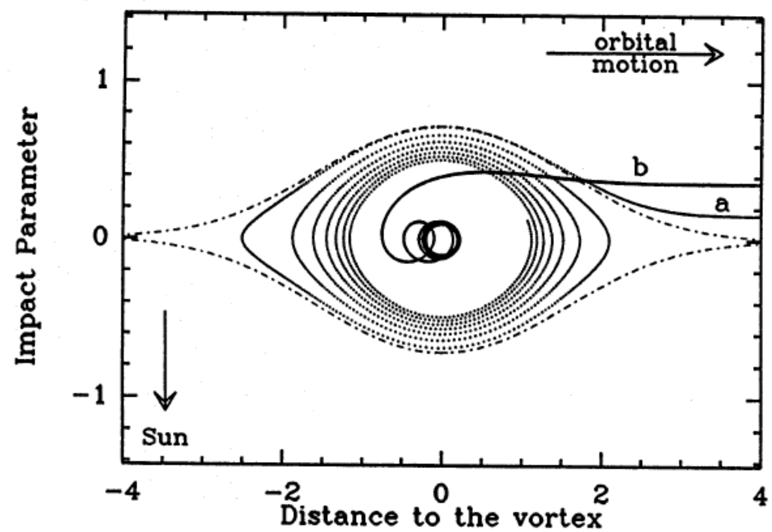
Casassus et al. (2018)

Vortex Trapping

Geostrophic balance:



Vortex
streamline



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)

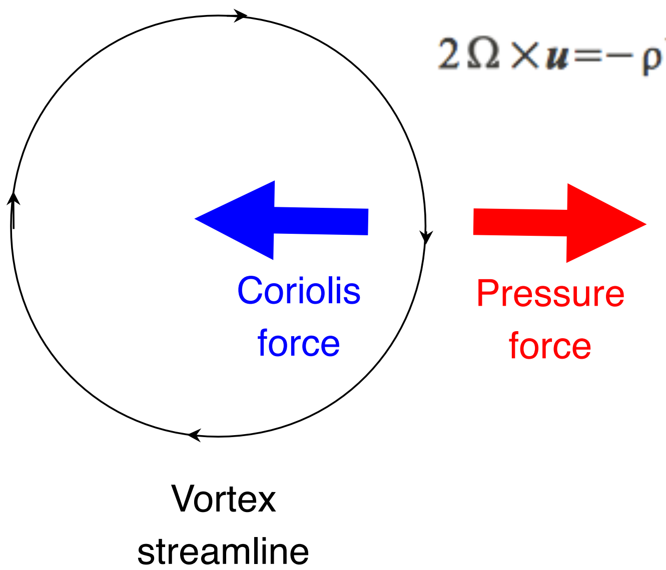
Speed up planet formation enormously

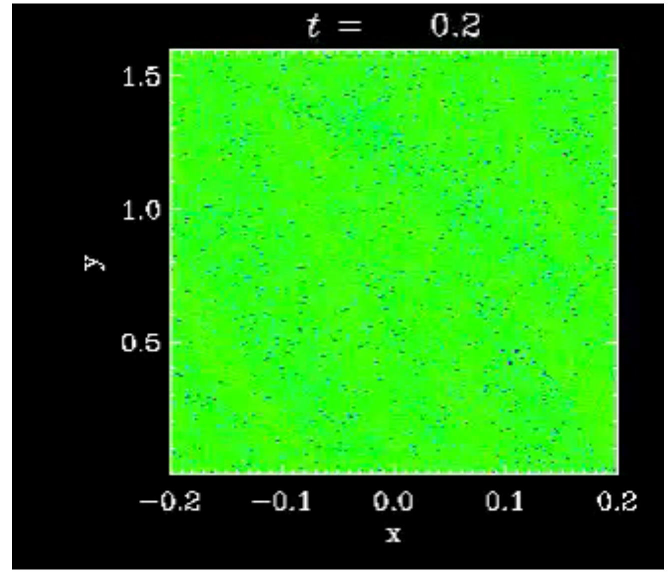
(Lyra et al. 2008b, 2009ab, Raettig et al. 2012)

Vortex Trapping

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.

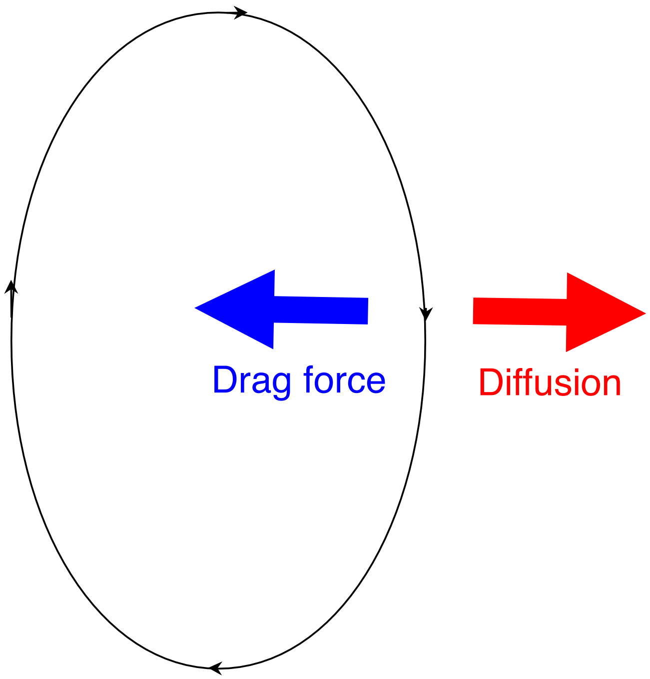
Aid to planet formation

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

Speed up planet formation enormously

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

Drag-Diffusion Equilibrium



Trapped particle

Dust continuity equation

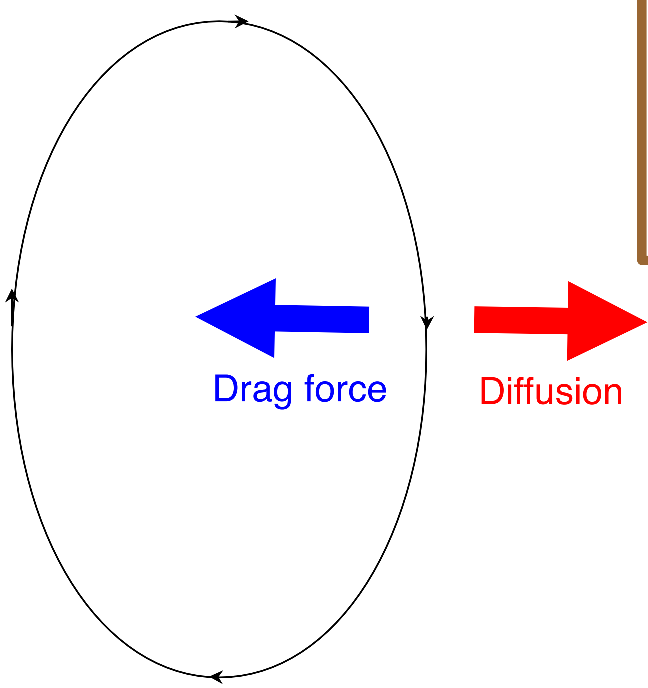
$$\frac{\partial \rho_d}{\partial t} = -(\boldsymbol{v} \cdot \boldsymbol{\nabla})\rho_d - \rho_d \boldsymbol{\nabla} \cdot \boldsymbol{v} + D\nabla^2 \rho_d,$$

advection

compression

diffusion

Drag-Diffusion Equilibrium



Trapped particle

Steady-state solution

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

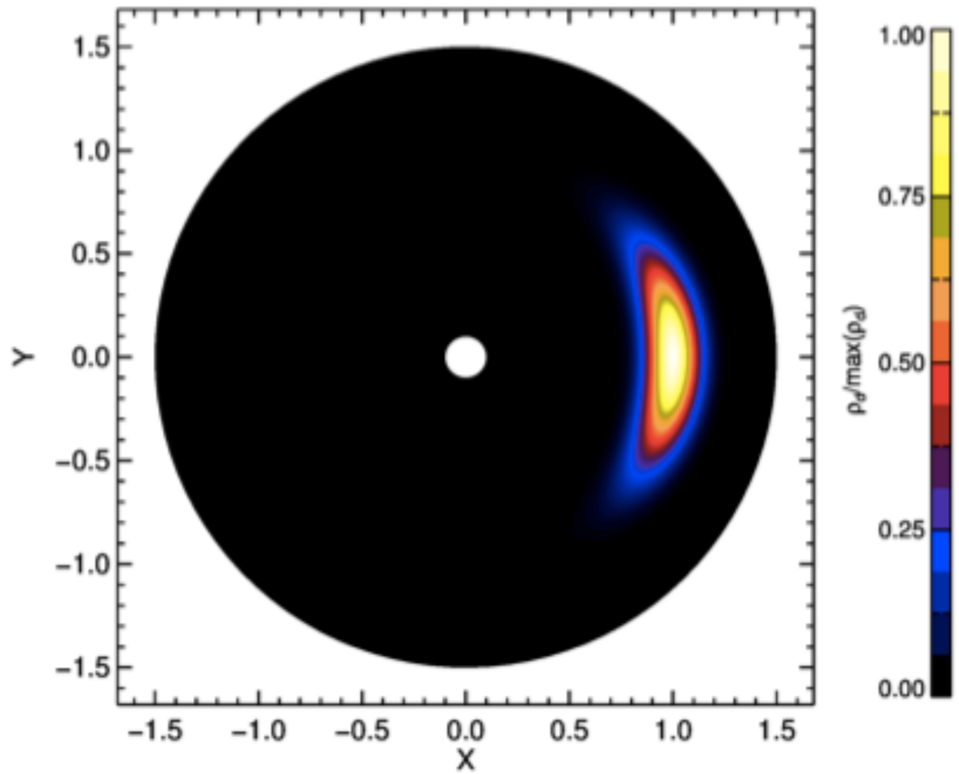
Lyra & Lin (2013)

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

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

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 in drag-diffusion equilibrium



Solution for

H/r=0.1 χ*=4* *S*=1

Solution

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

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

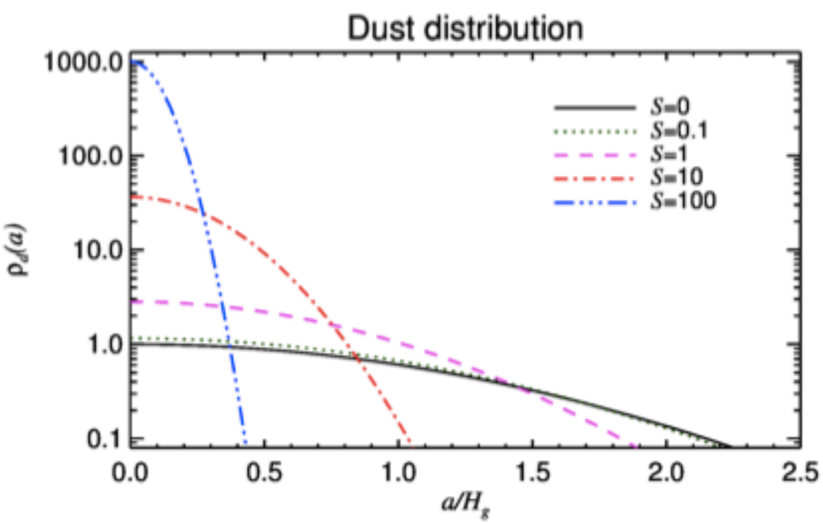
$$S = \frac{St}{\delta}$$

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

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

Lyra & Lin (2013)

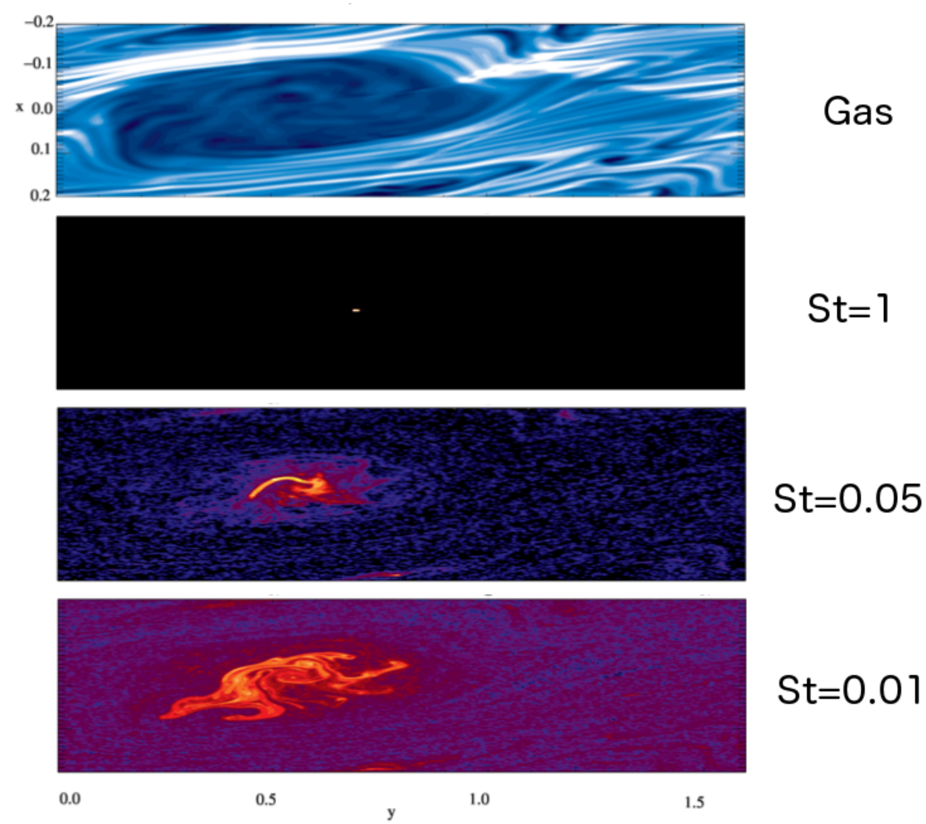
Analytical vs Numerical



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

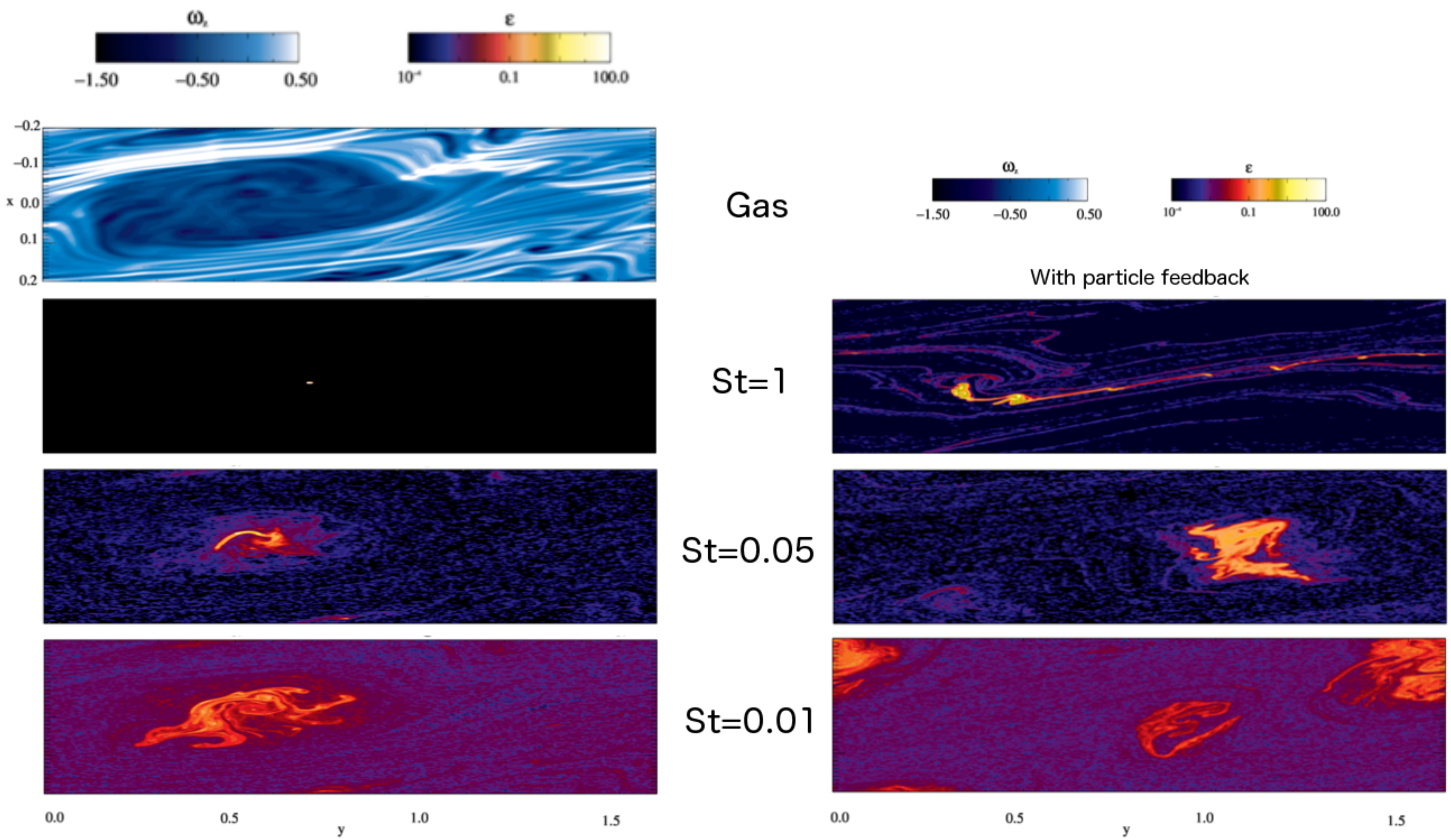
$$\delta = v_{\rm rms}^2 / c_s^2,$$

Lyra & Lin (2013)

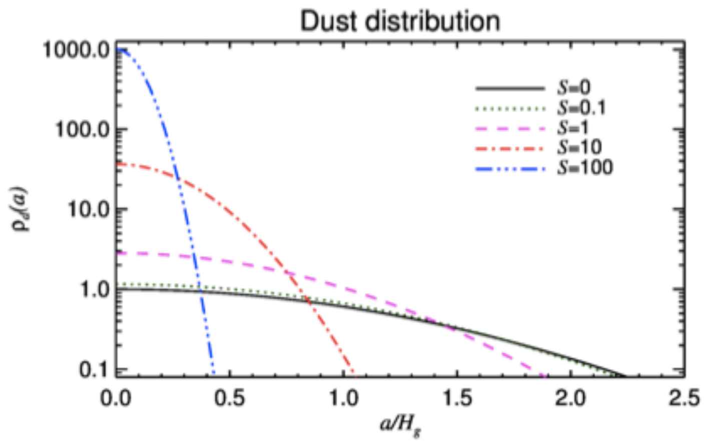


Raettig et al (2015)

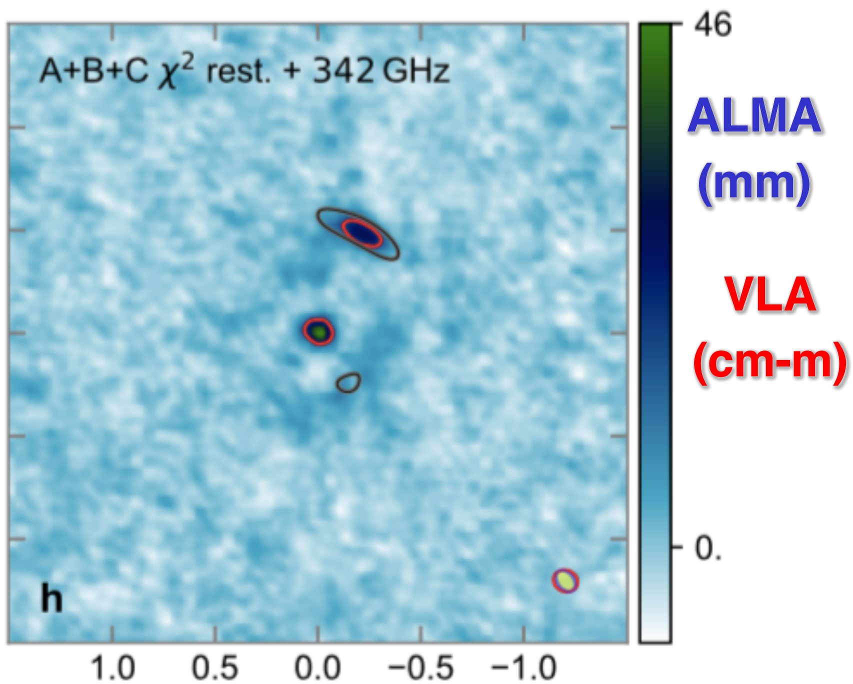
Analytical vs Numerical



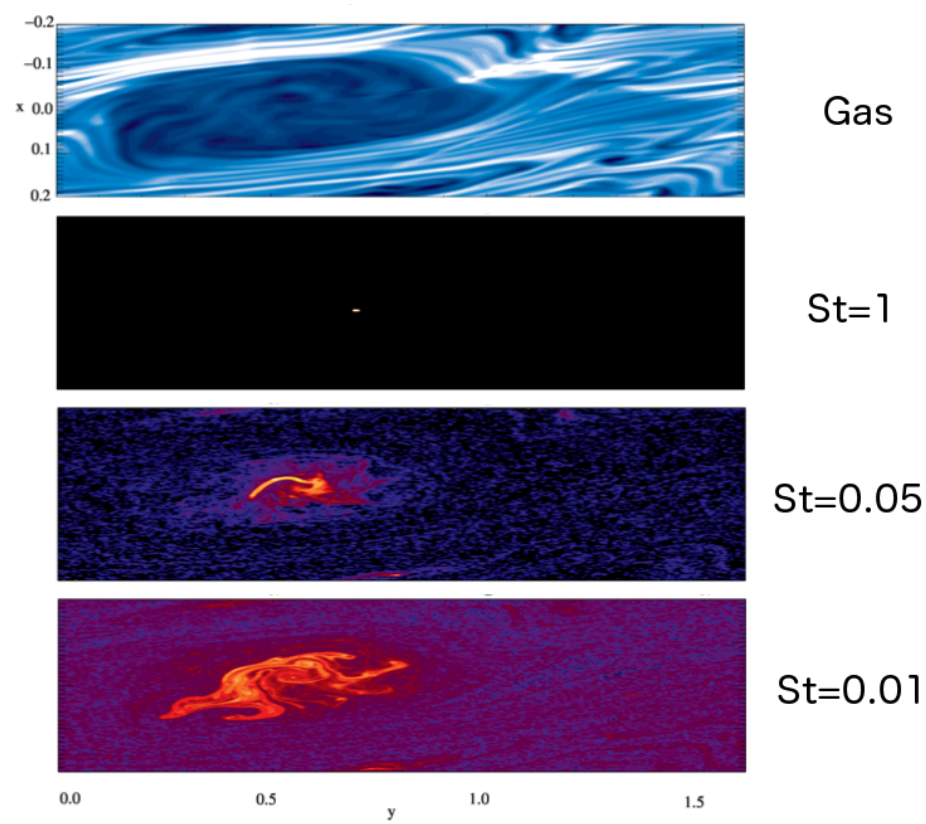
Analytical vs Numerical vs Observational



Lyra & Lin (2013)

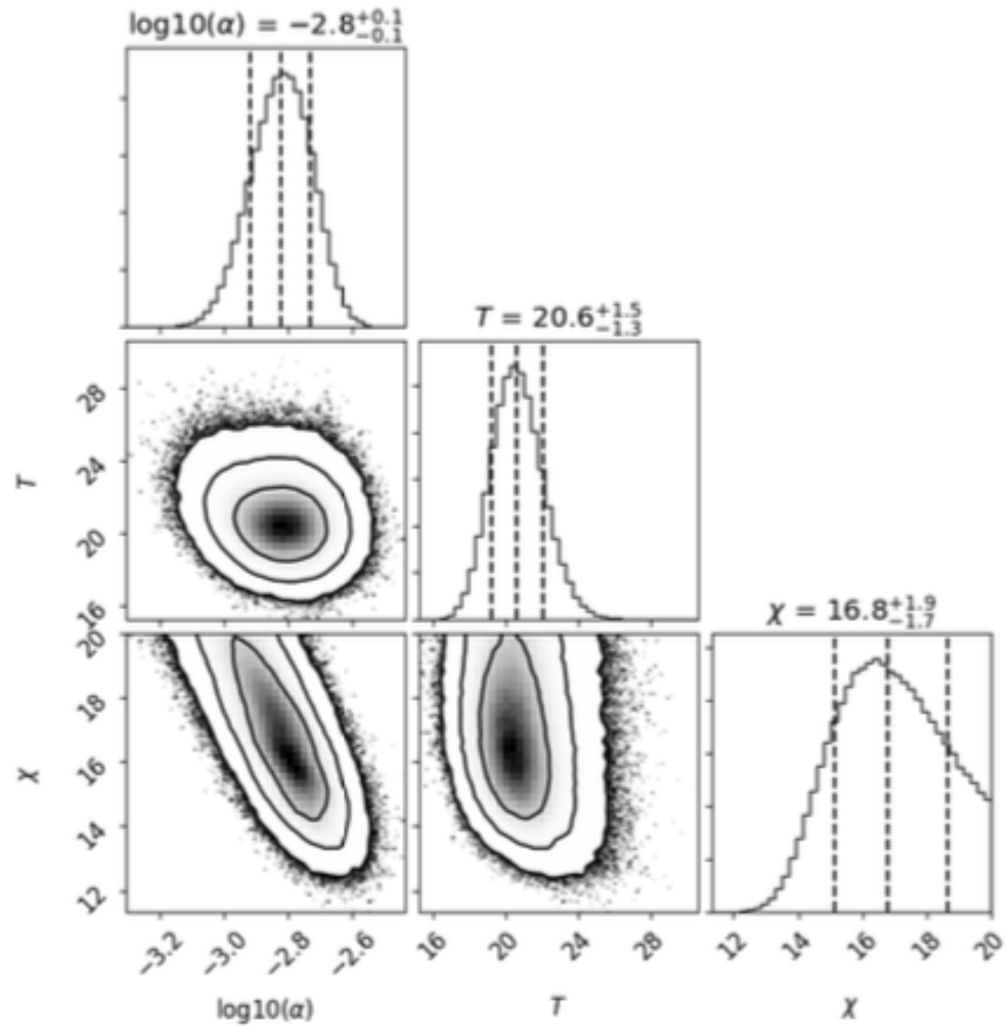


Casassus, Marino, Lyra et al. (2018)



Raettig, Lyra , & Klahr et al (2015)

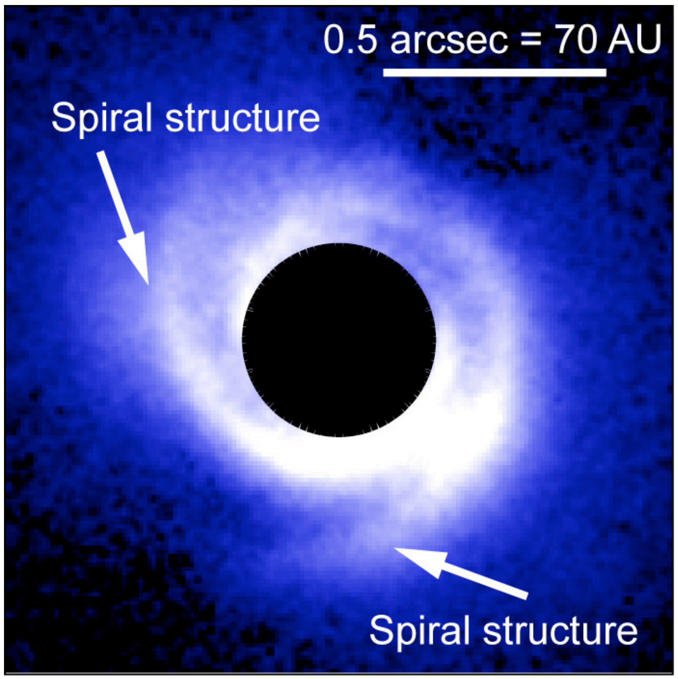
Observational vs Analytical
(Monte Carlo Markov Chain)



Casassus et al. (2018)

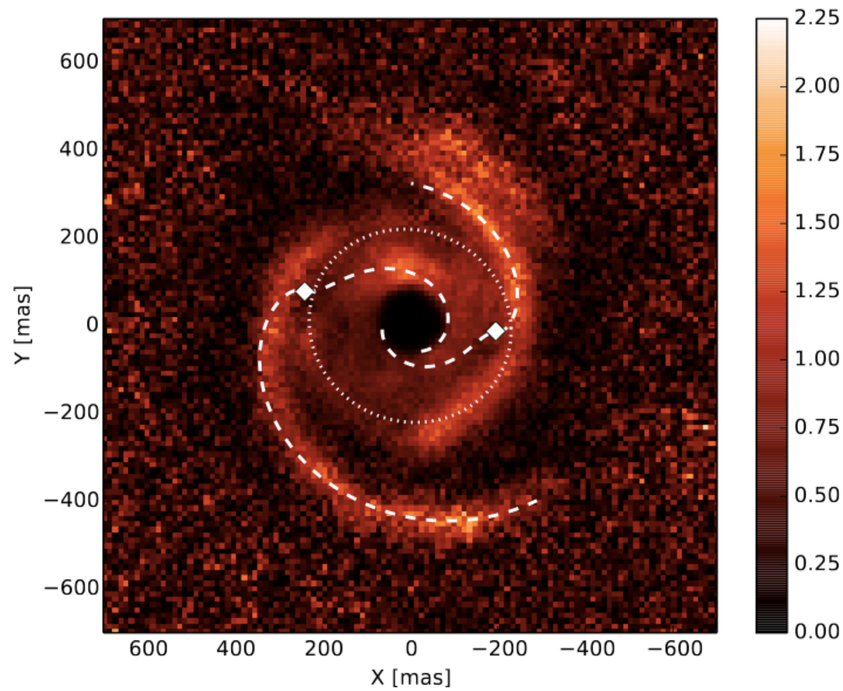
Observational Evidence: Spirals

SAO 206462



Muto et al. (2012)

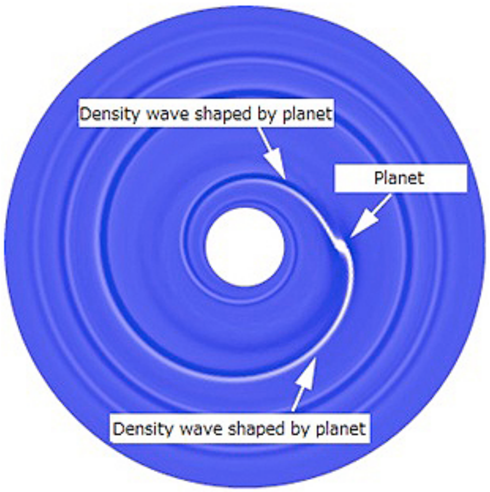
MWC 758



Benisty et al. (2015)

Spiral arm fitting leads to problems

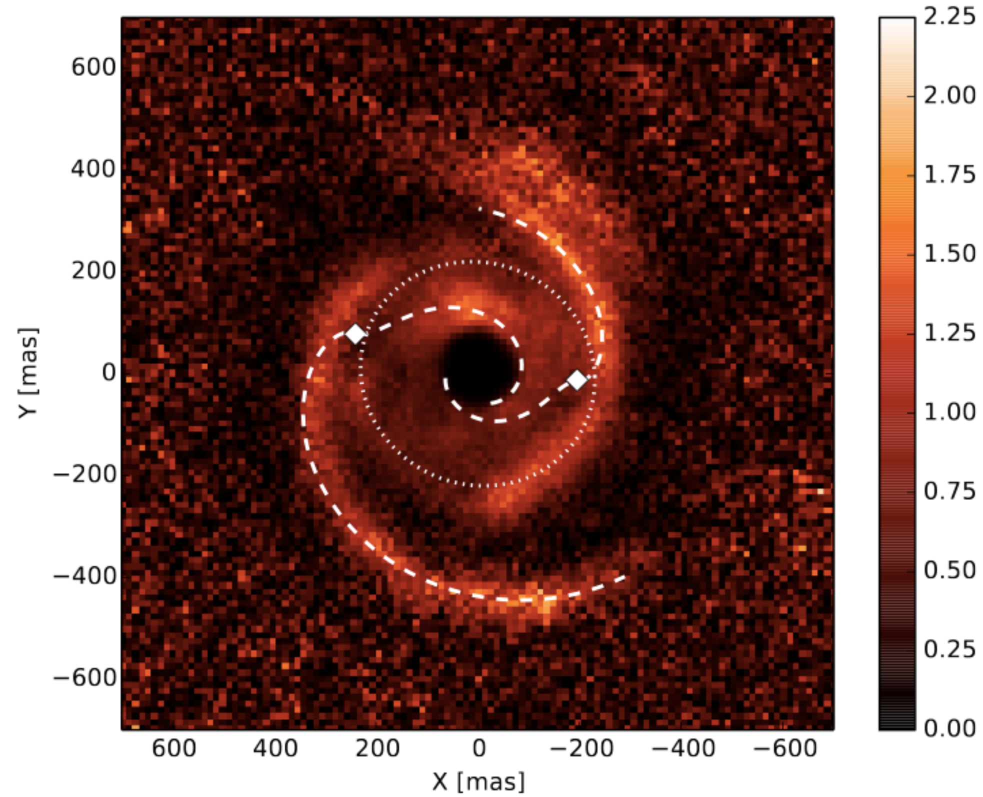
Analytical spiral fit



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

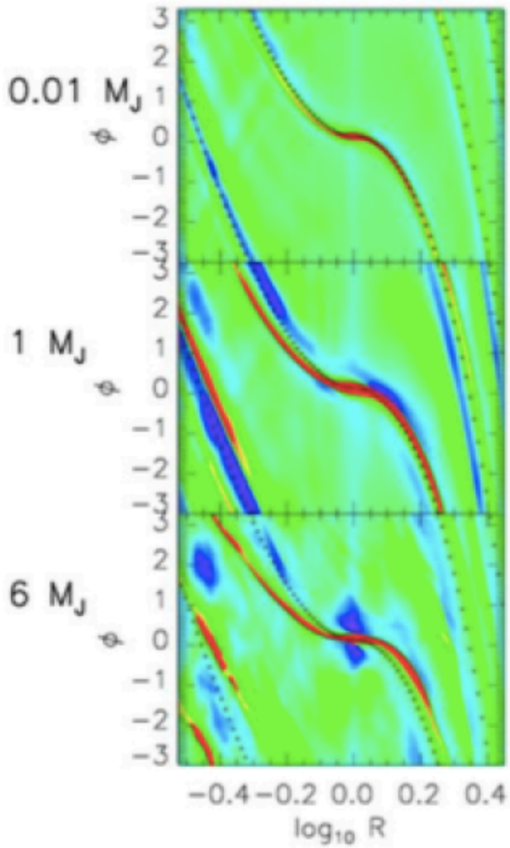
Rafikov (2002)
Muto et al. (2012)

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



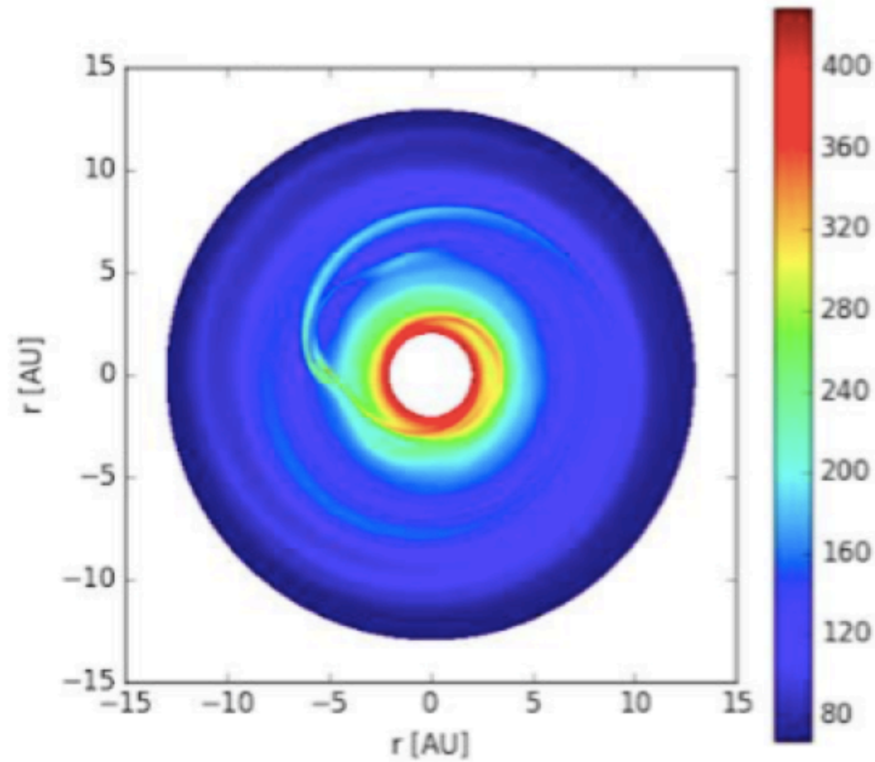
Benisty et al. (2015)

Supersonic wake of high mass planets does not follow the linear prediction



Density

Zhu et al. (2015)

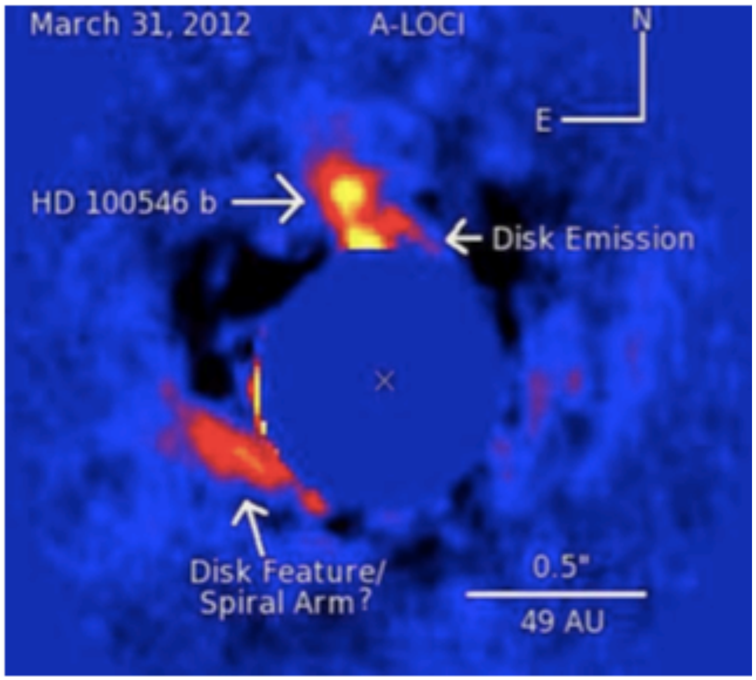


Temperature - **5M$_J$**

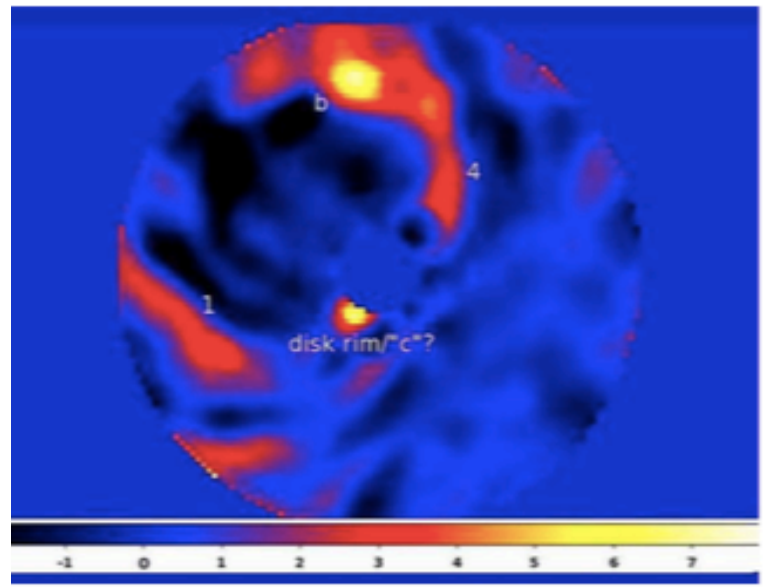
Lyra et al. (2016)

The strange case of thermal emission in HD 100546

L band (~3.5 μm)

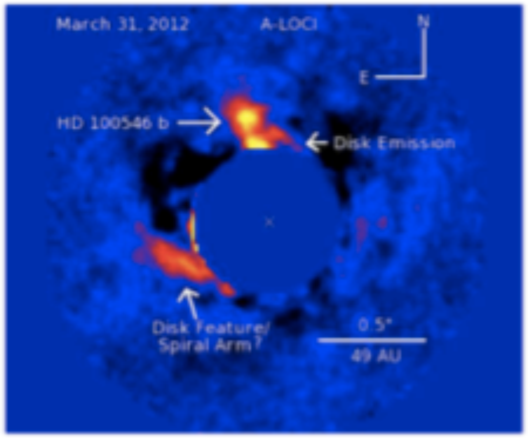


H band (~1.6 μm)

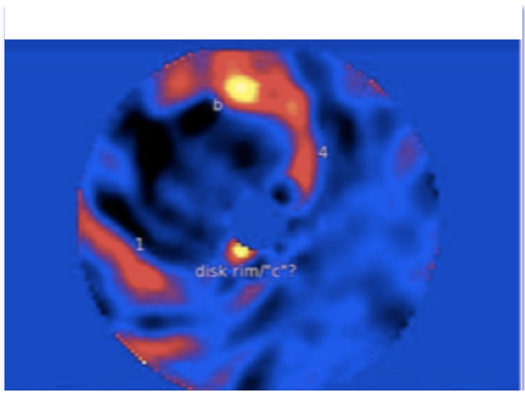


Currie et al. (2014), Currie et al. (2015)

Pinning down the temperature

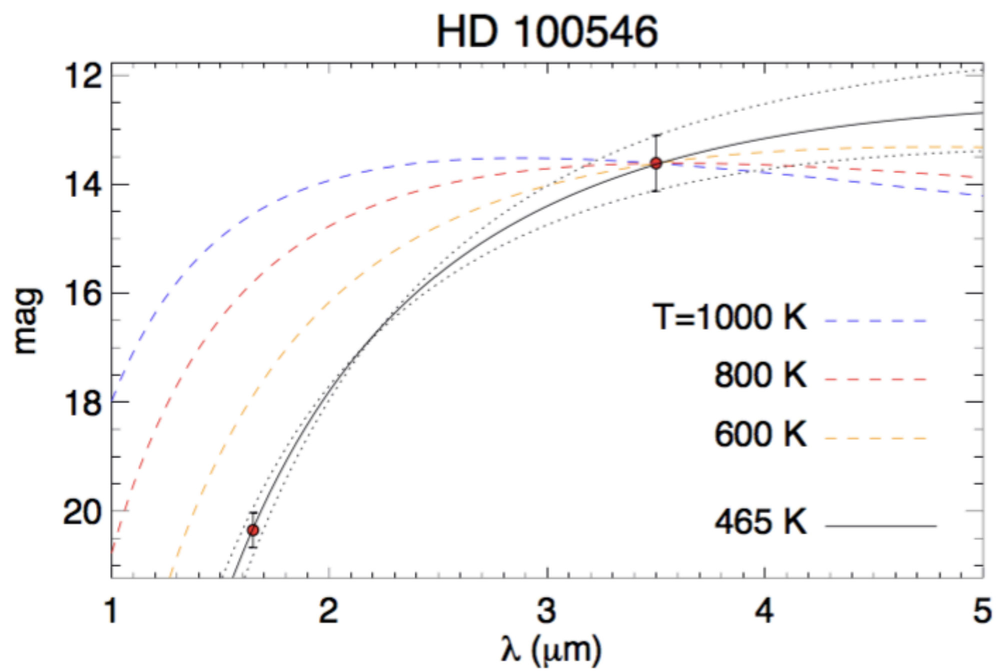


L band



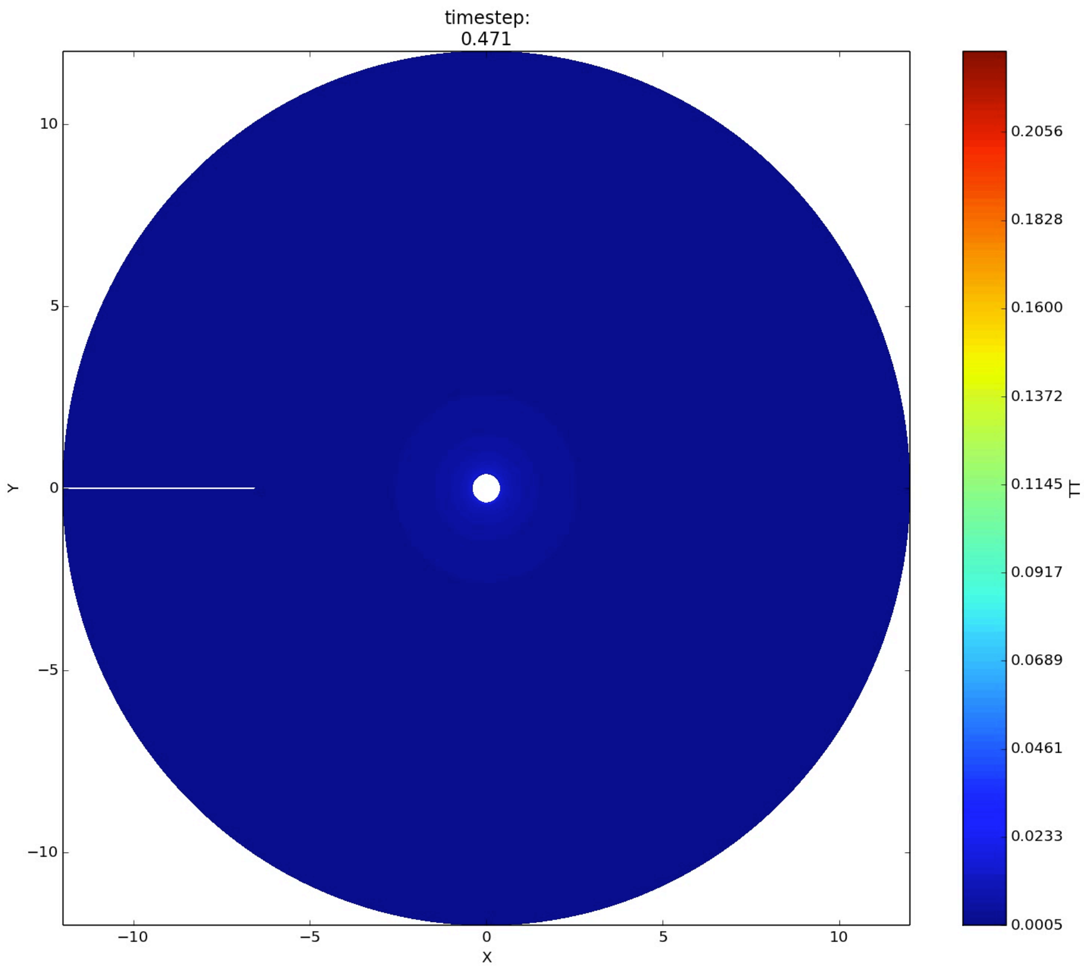
H band

Curries et al. (2014, 2015)



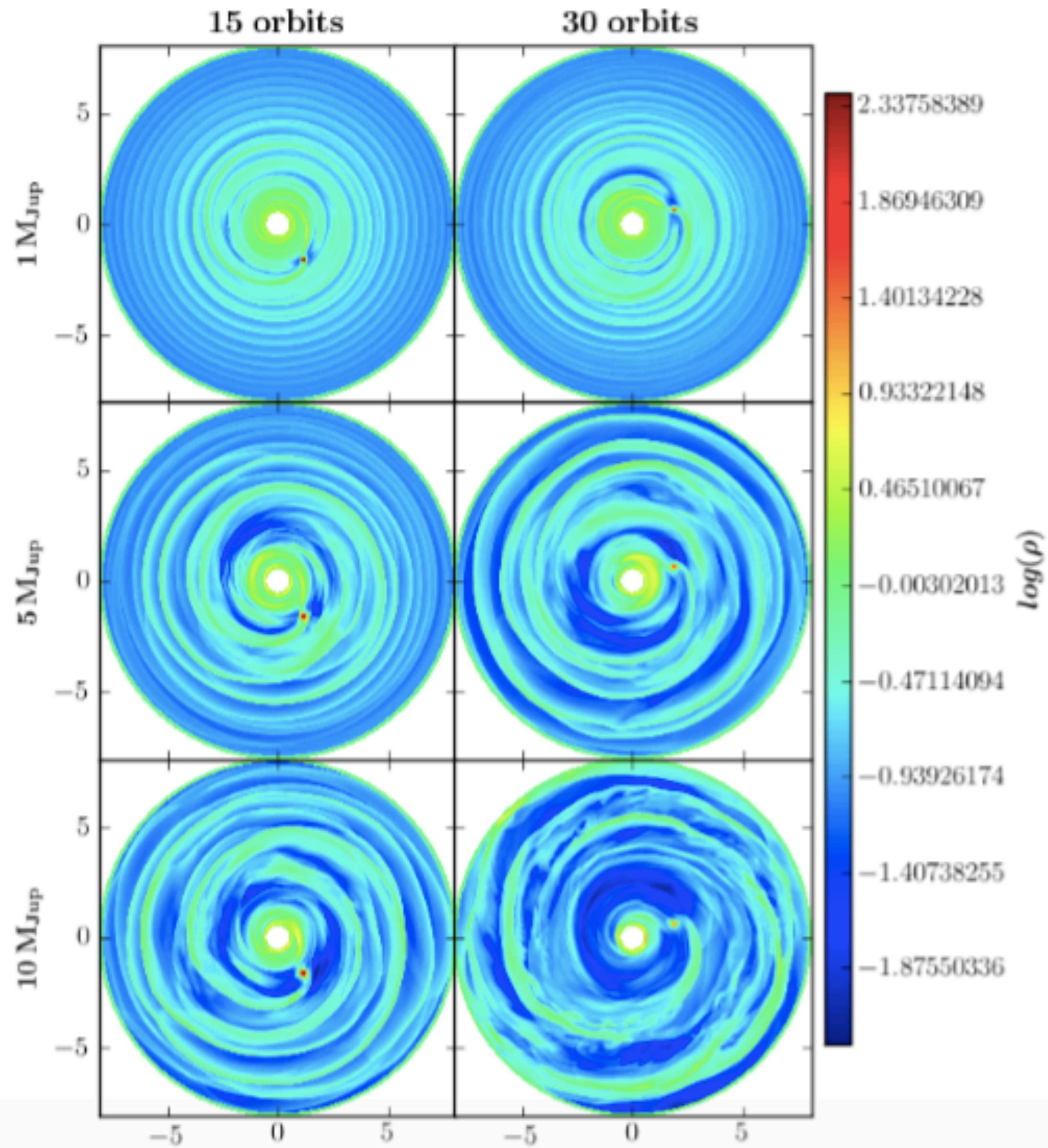
Lyra et al. (2016)

Planet-driven turbulence

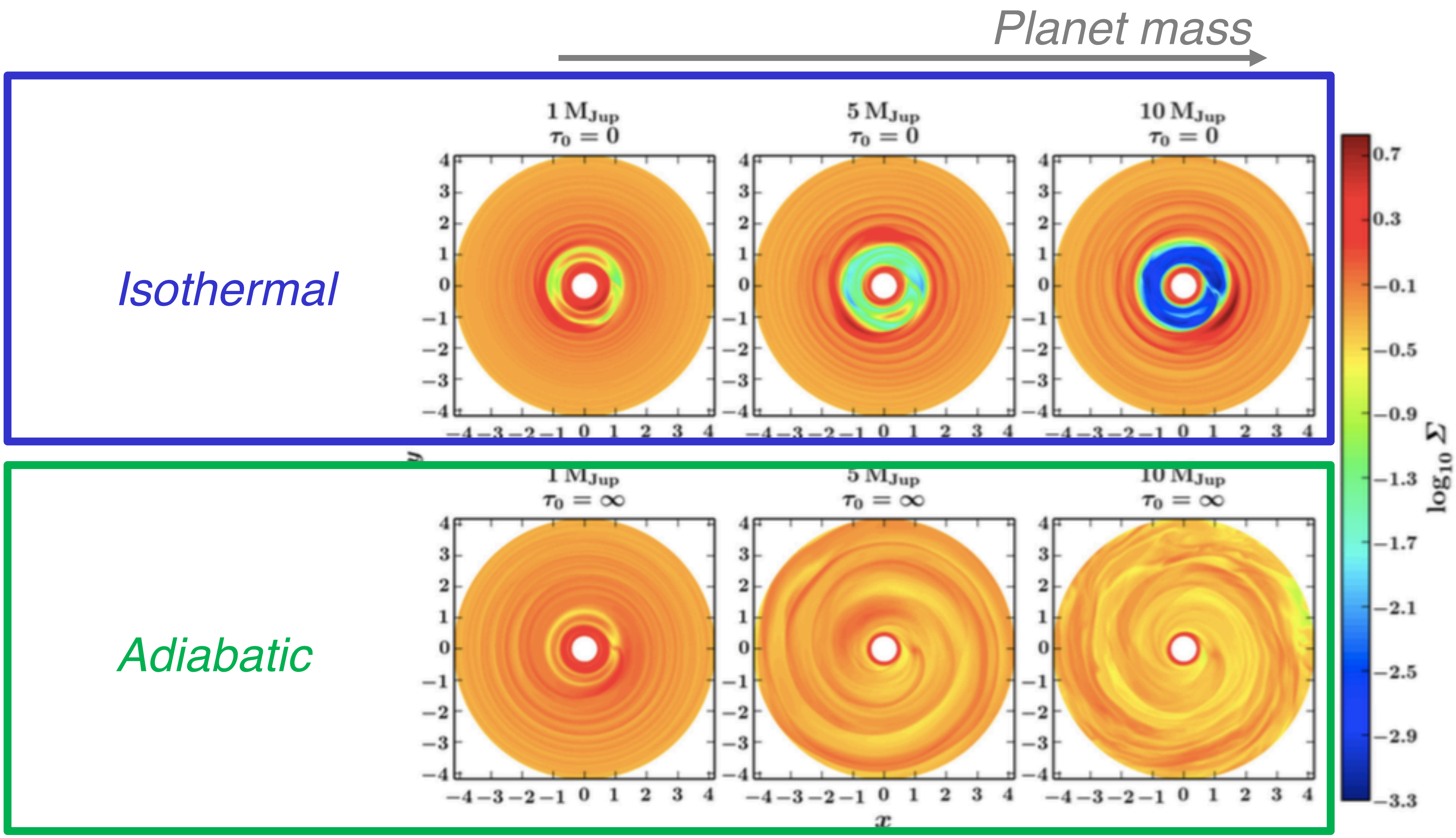


Richert et al. (2015)

Some crazy turbulence showing up at high planet mass….

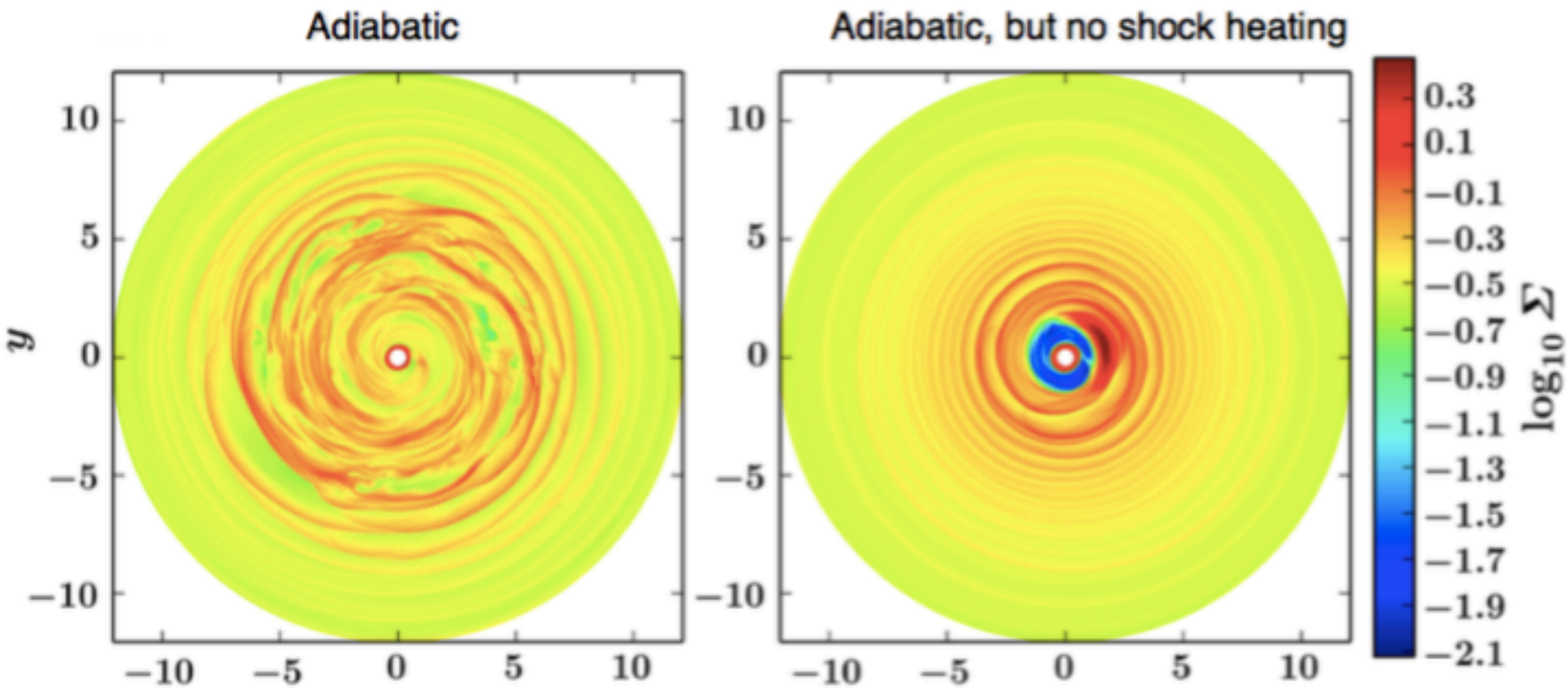


Turbulence in high-mass planets in adiabatic disks



Richert et al. (2015)

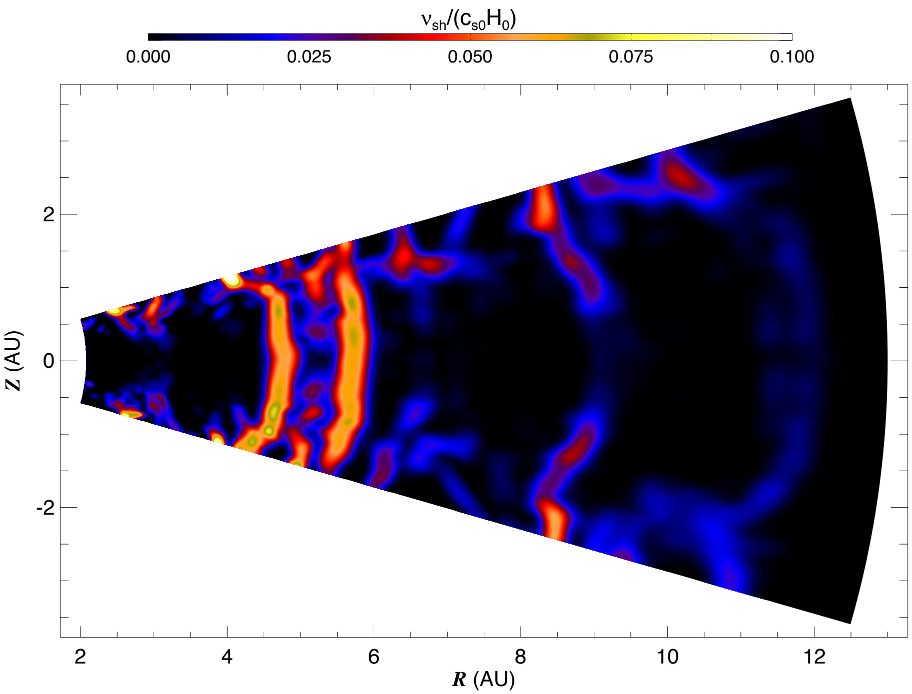
The energy source: shock heating!



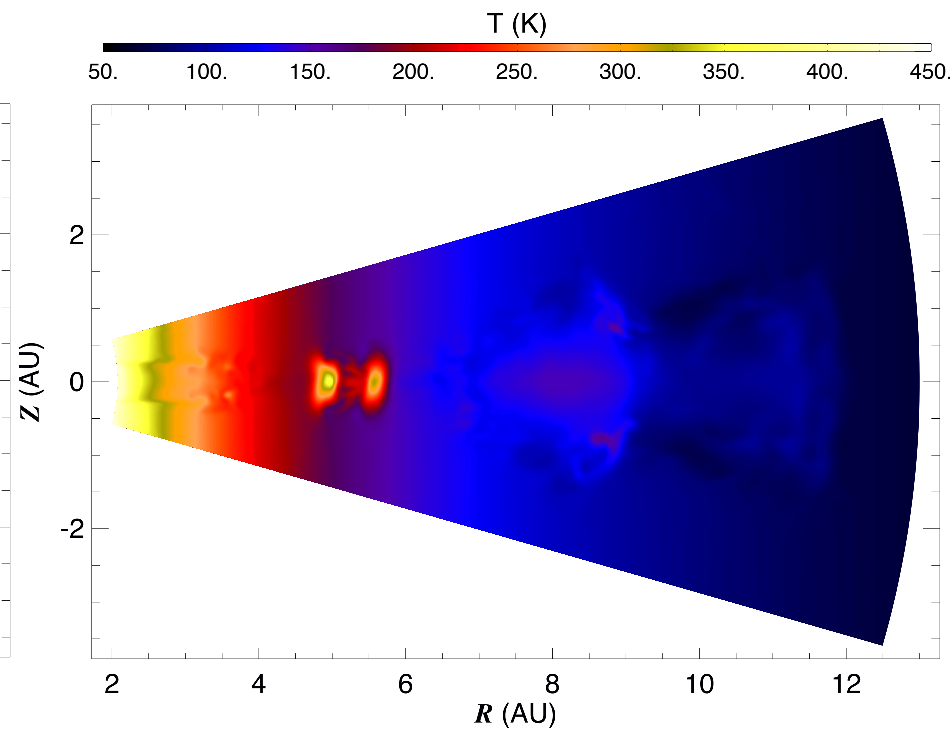
Richert et al. (2015)

3D: Shock bores

Shocks (velocity convergence)

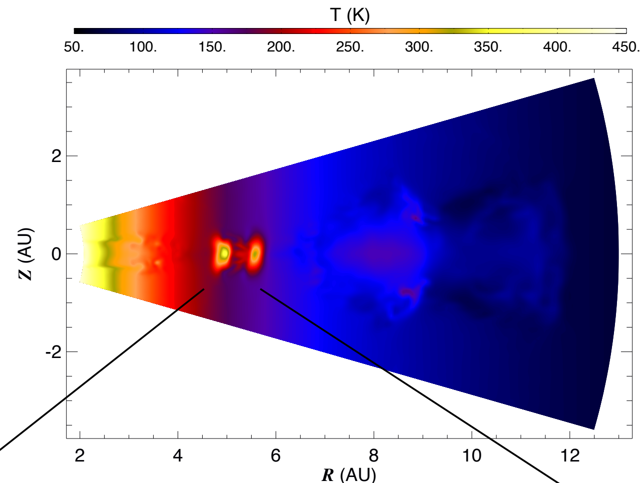


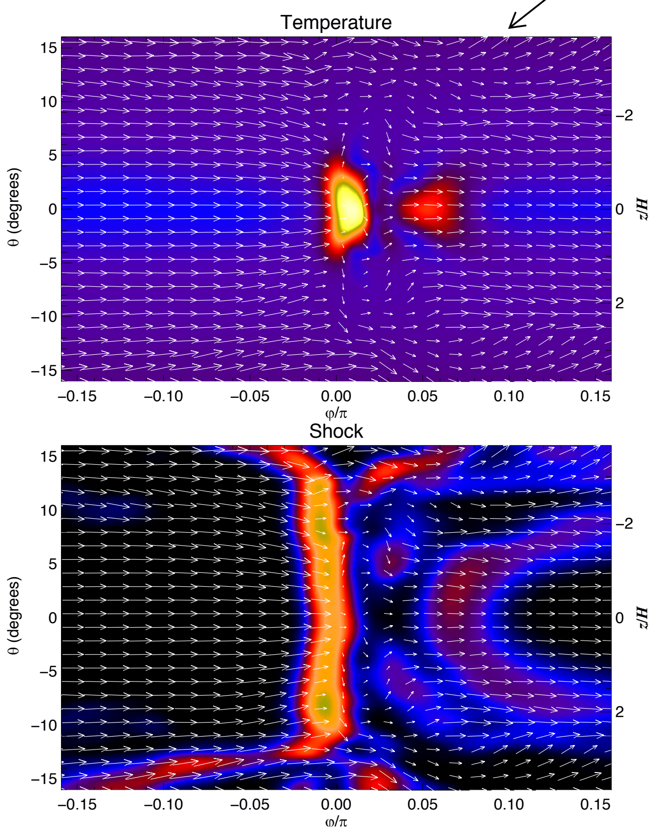
Temperature



Lyra et al. (2016)

3D shocks: bores and breaking waves

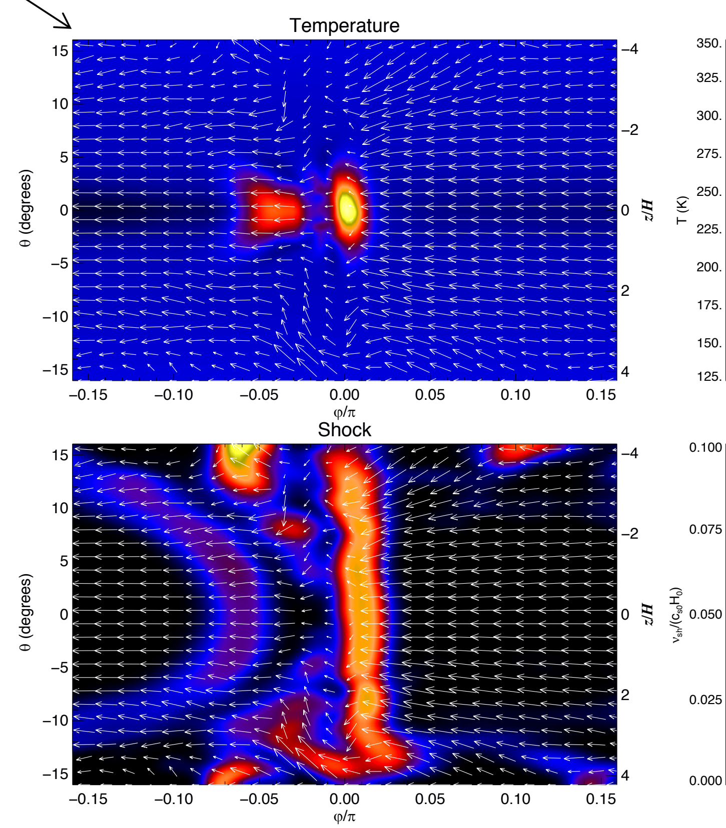




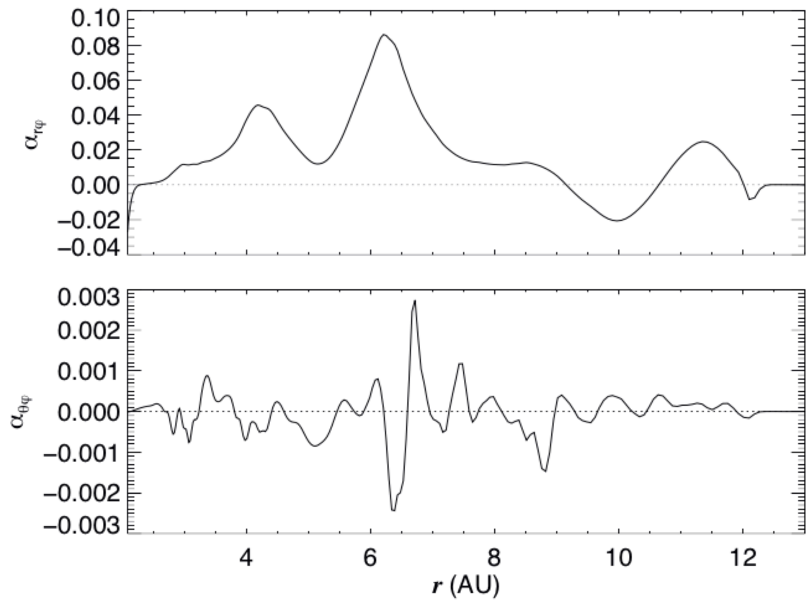
Temperature

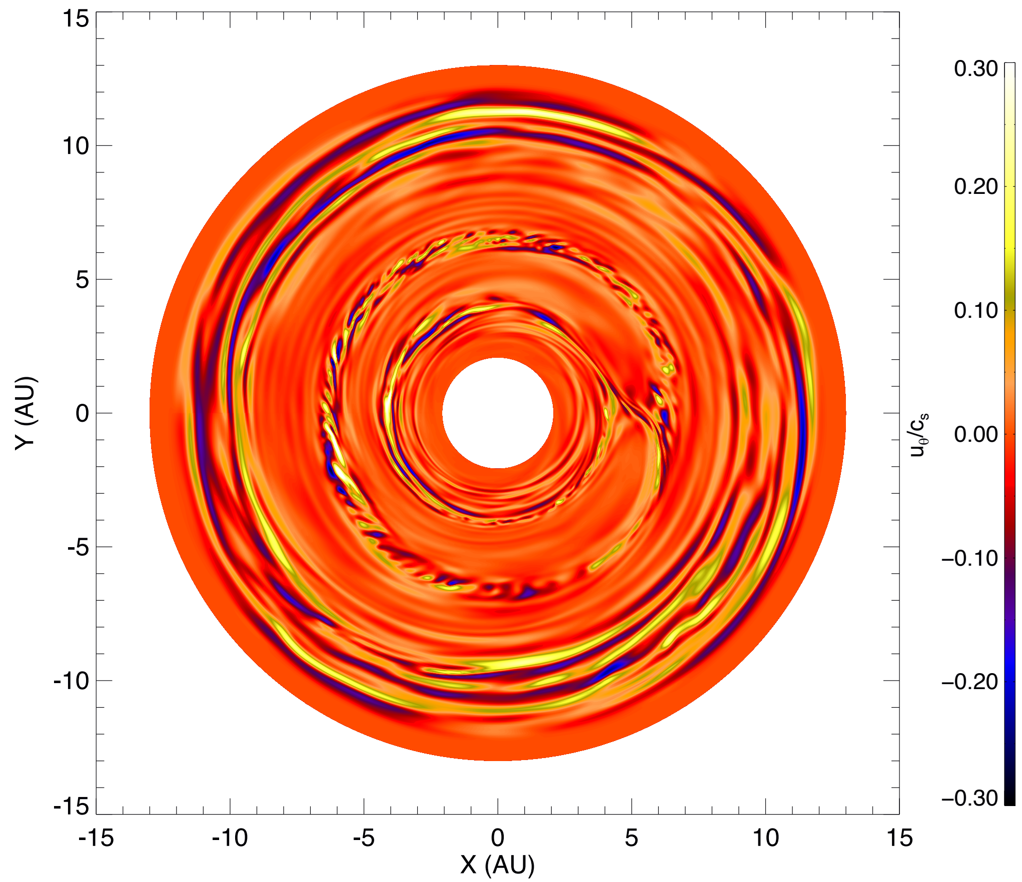
Div u
(shock)

Lyra et al. (2016)



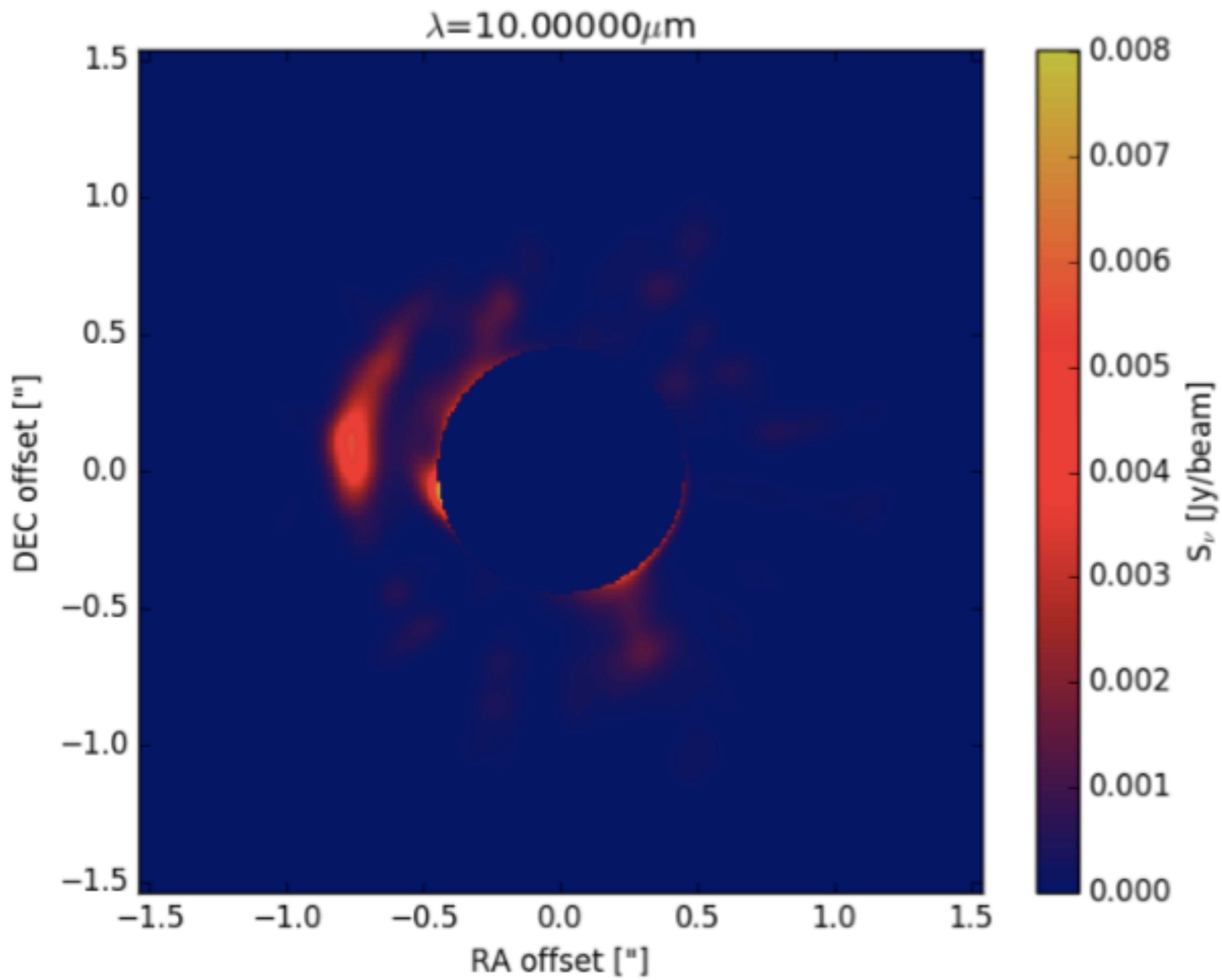
Prediction for spectroscopy: Turbulent surf





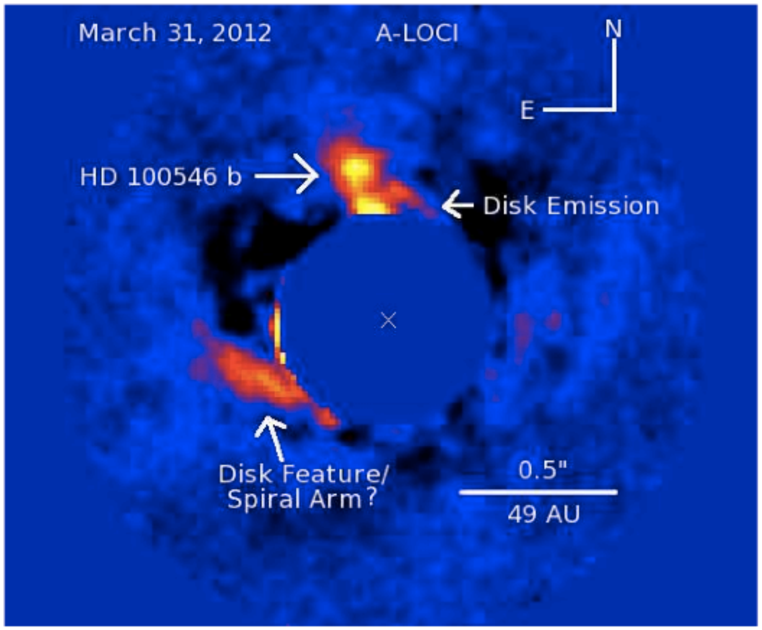
Lyra et al. (2016)

Synthetic image by RADMC3D and shock heating

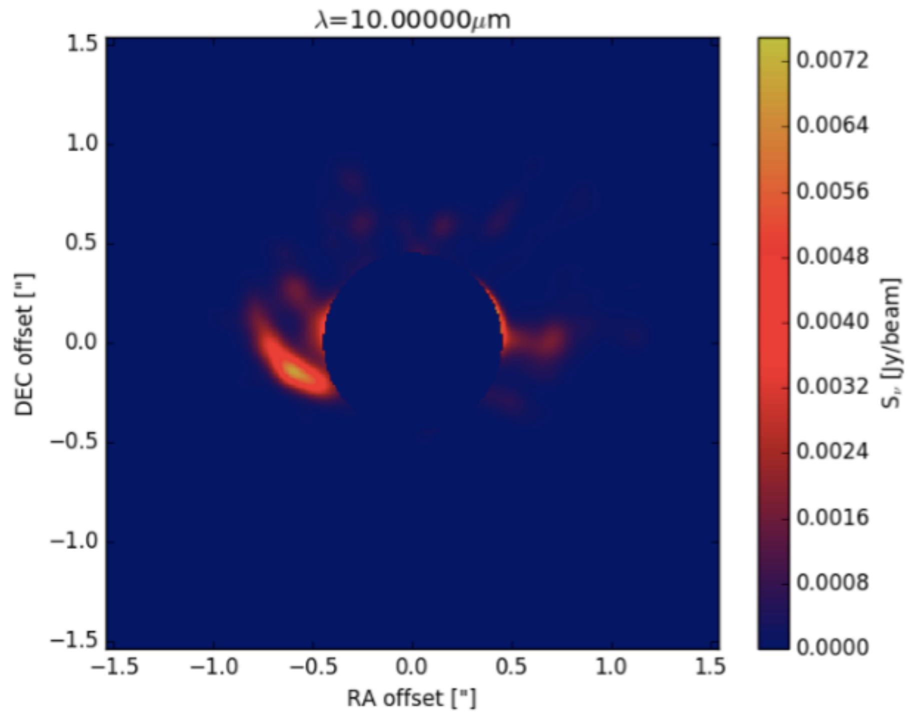


Hord et al. (2017)

Observation vs Synthetic Image

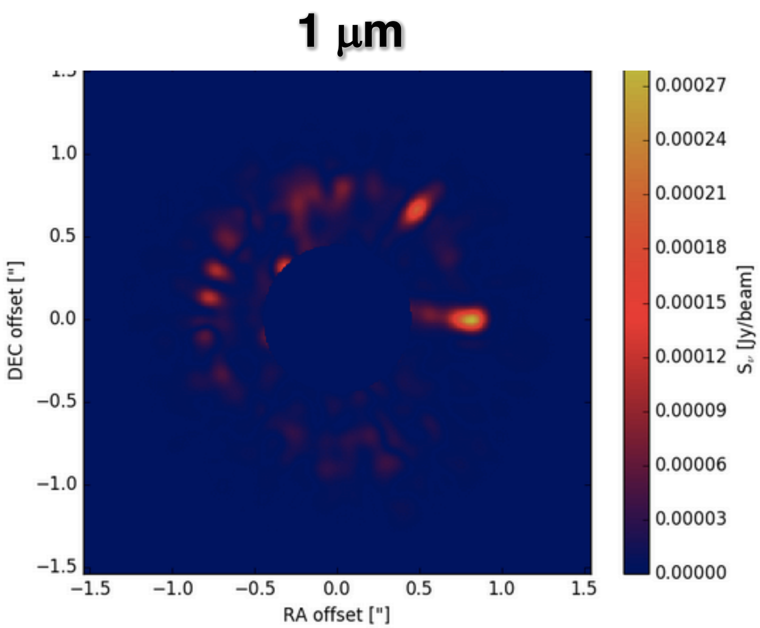


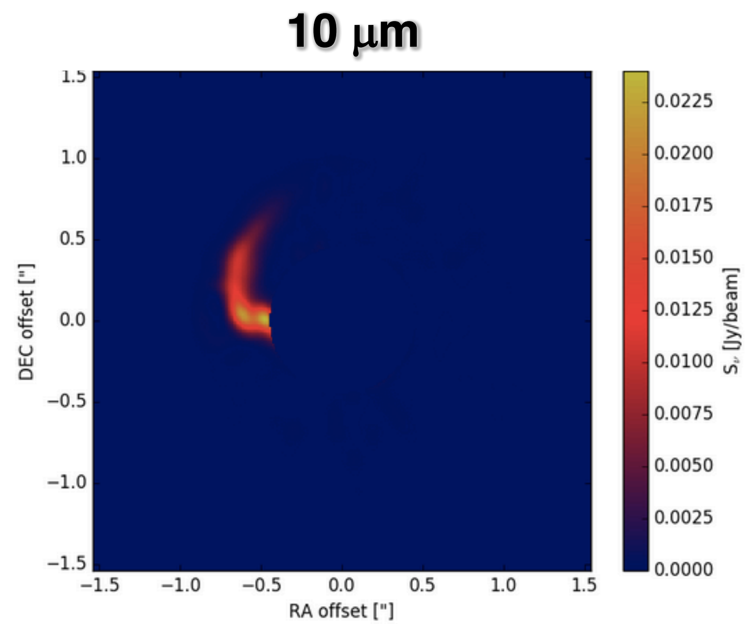
Currie et al. (2015)



Hord et al. (2017)

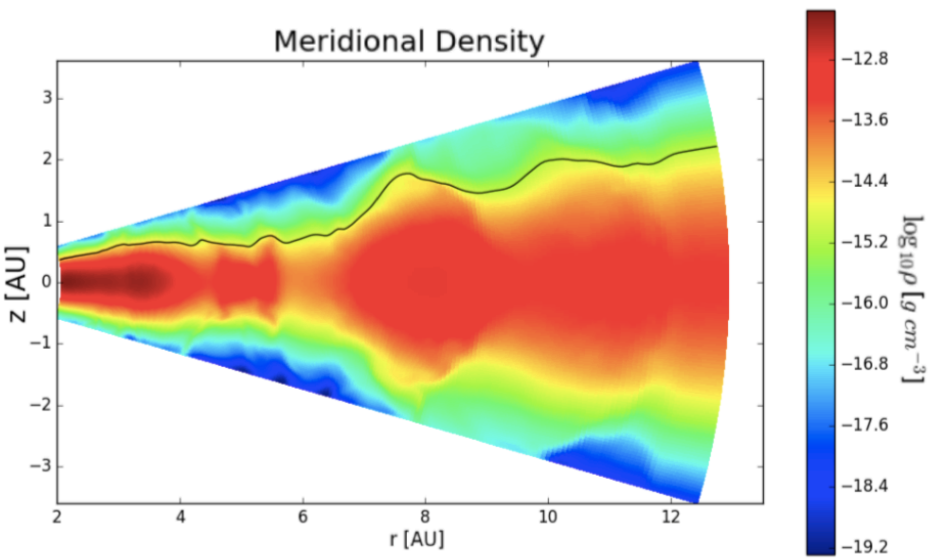
Effect of shocks alone

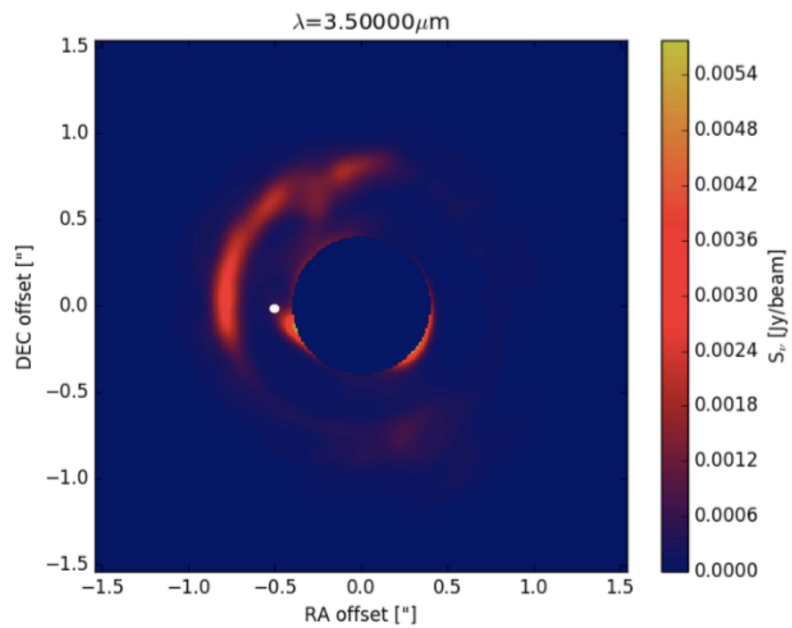




Hord et al. (2017)

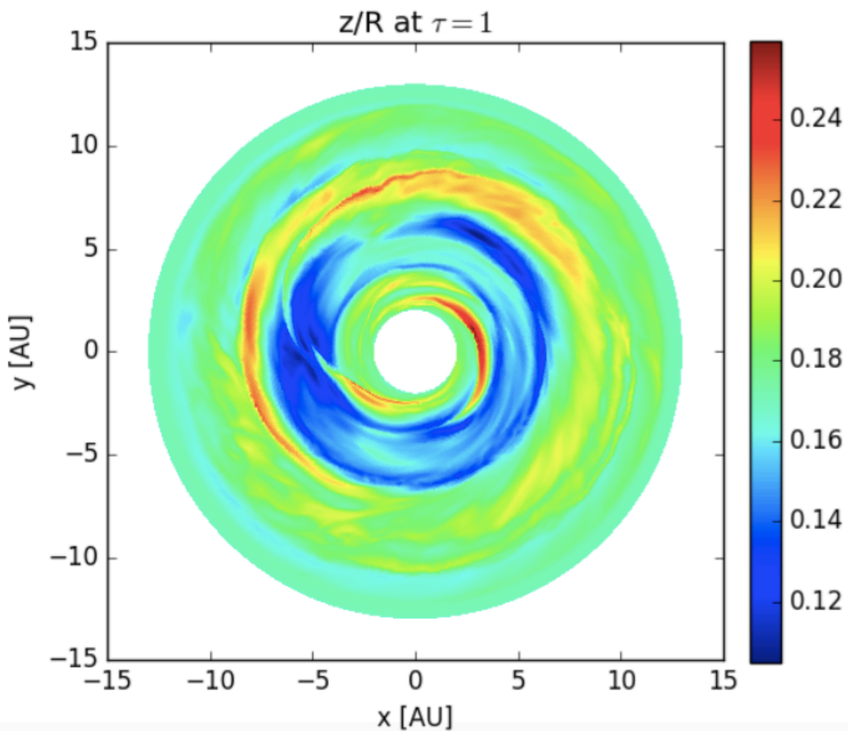
Scattering – A puffed up outer gap

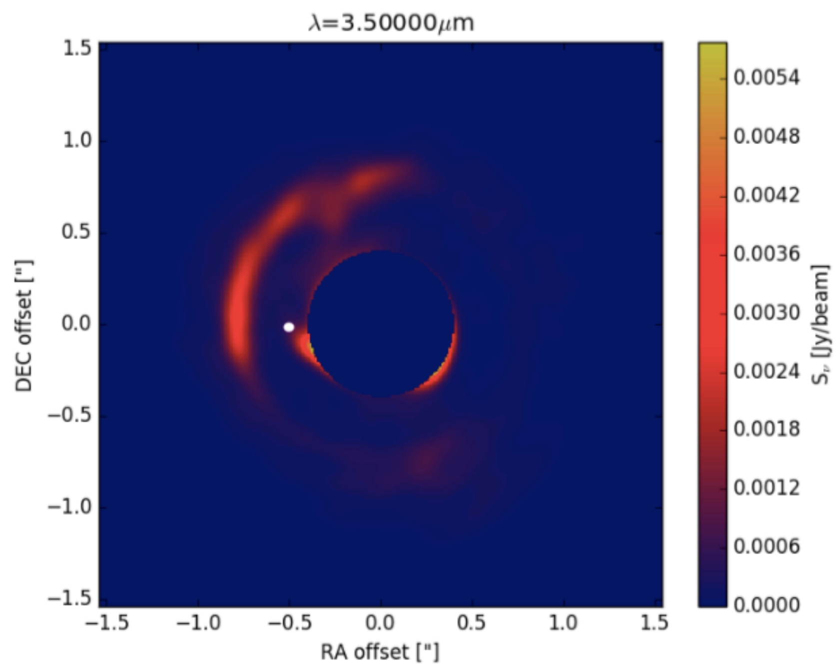




Hord et al. (2017)

Scattering



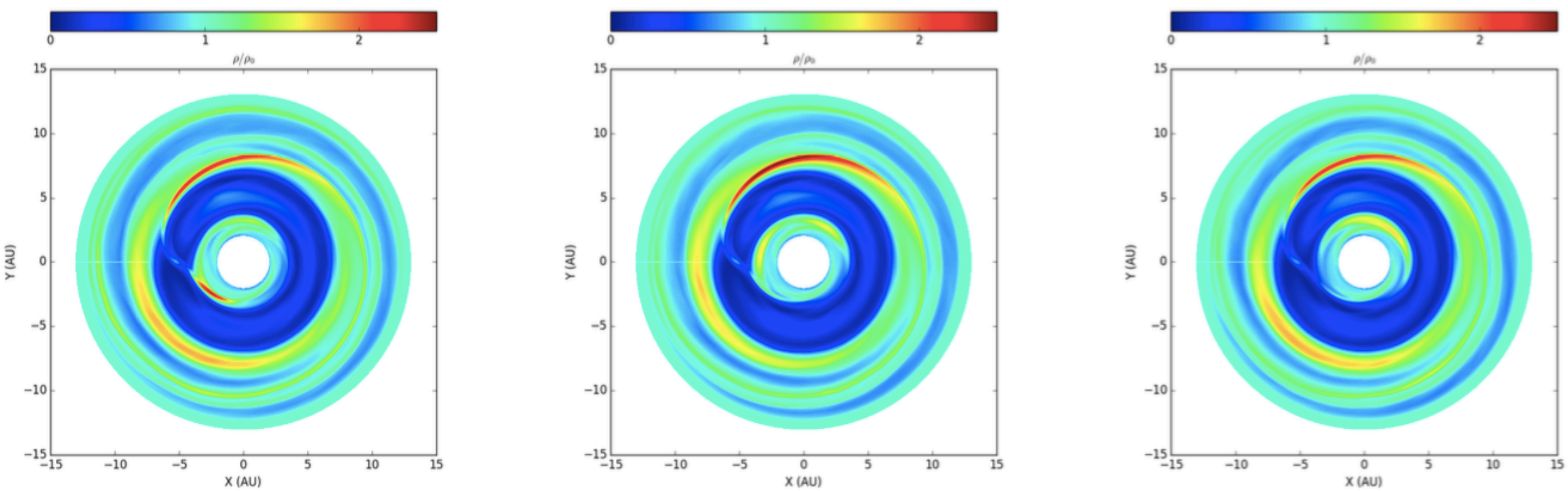


Hord et al. (2017)

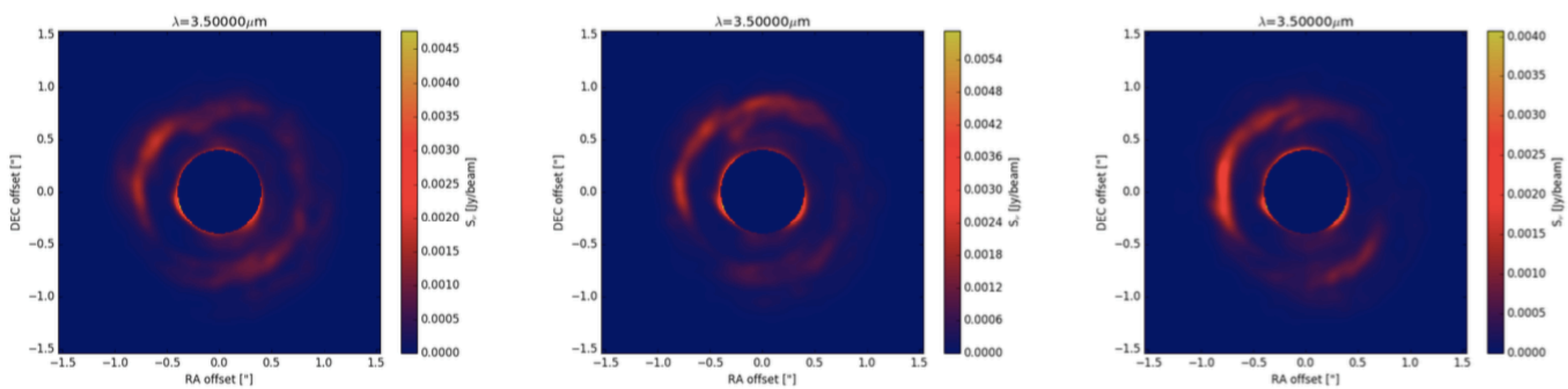
The pattern is stationary

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

Density

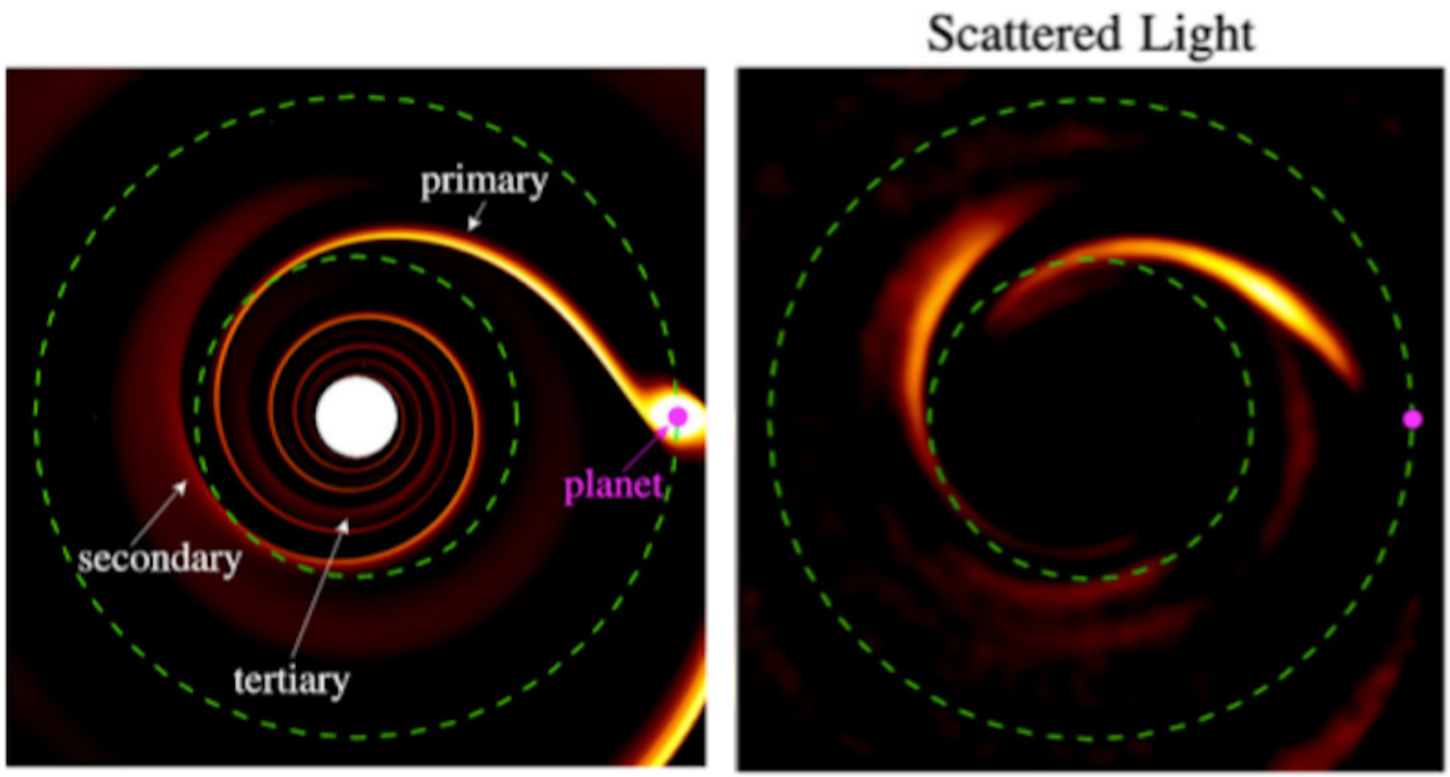


Intensity



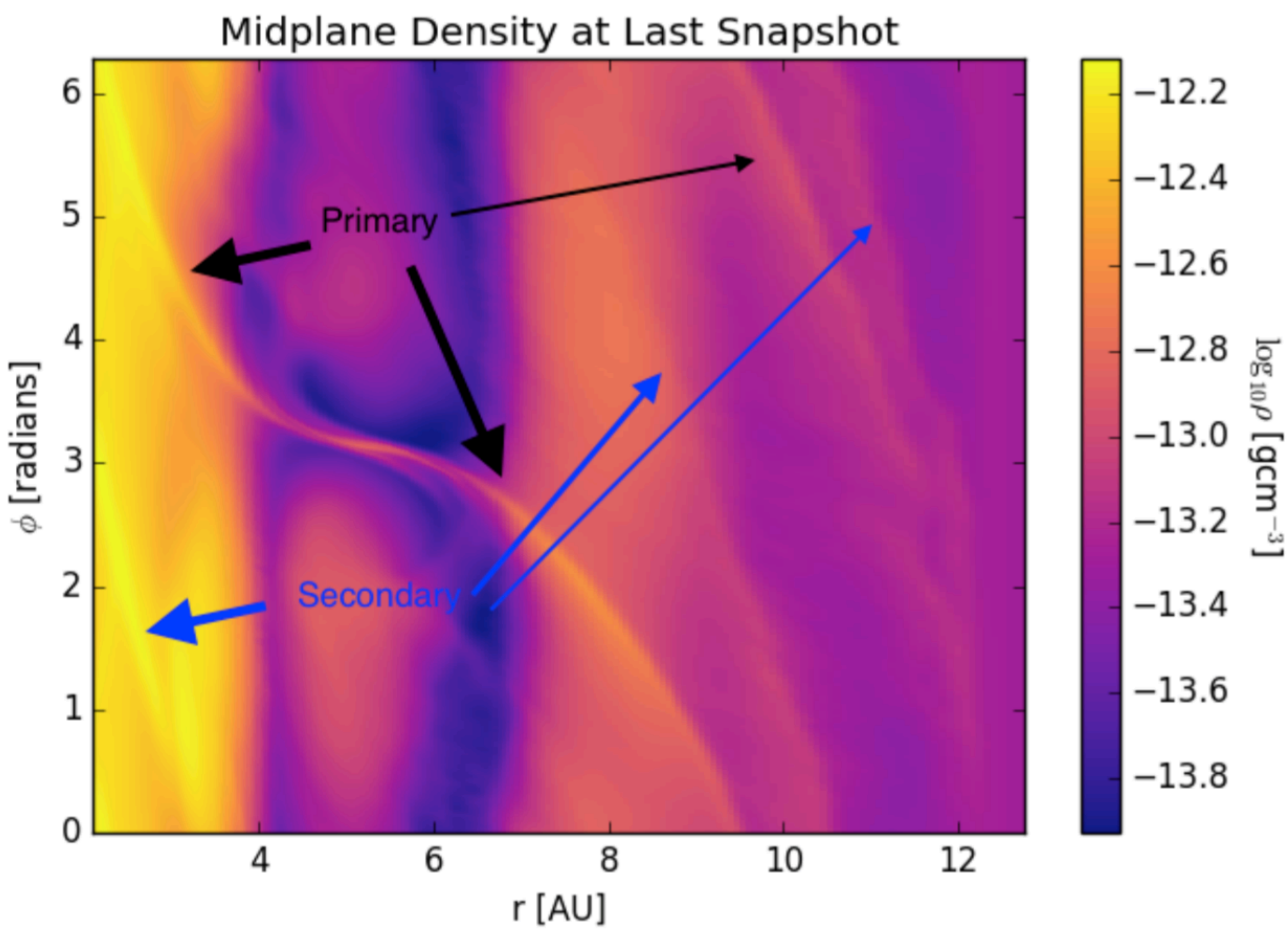
Hord et al. (2017)

Primary and Secondary spiral arms



Fung and Dong (2015)

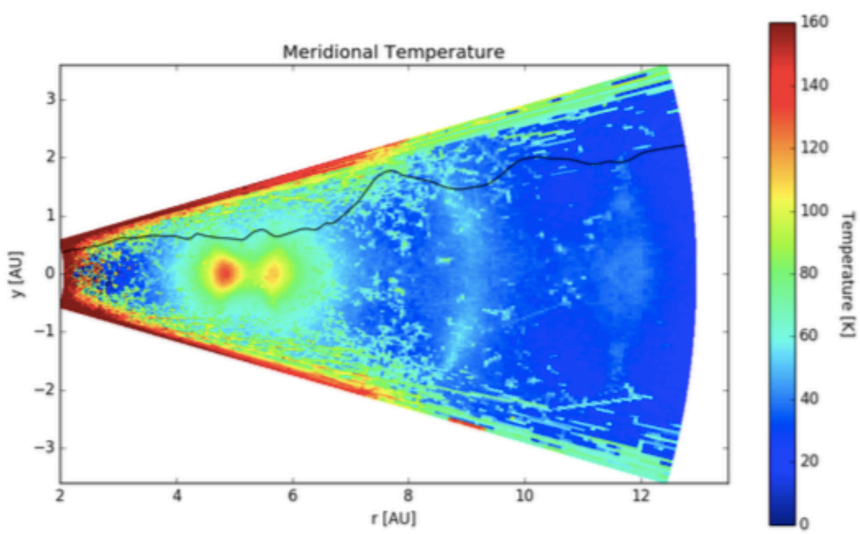
Primary and Secondary spiral arms

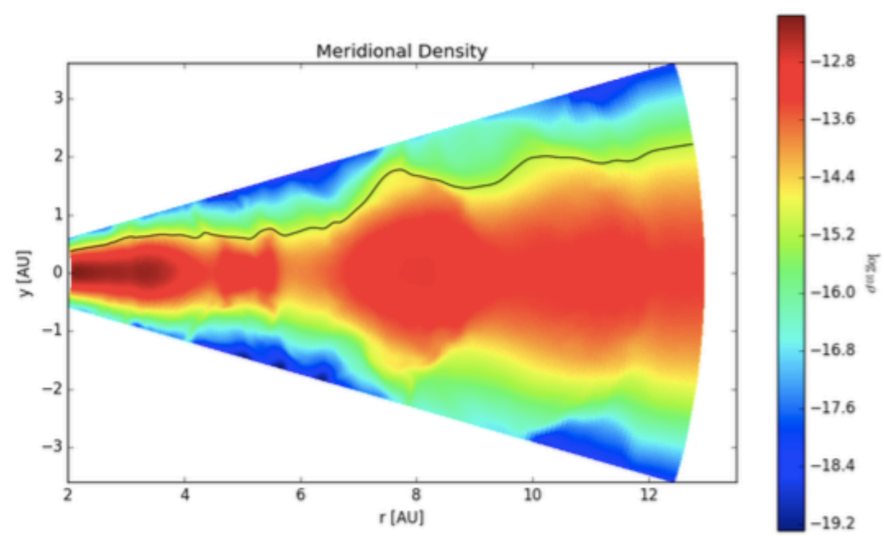


Hord et al. (2017)

Conclusions

- 3D radiation-hydro models give results widely different than 2D isothermal
- Planet-induced shocks modify disk structure
- Hot lobes near high-mass planets in high resolution
- Planets puff up their outer gaps – visible in scattered light





Conclusions

- 3D radiation-hydro models give results widely different than 2D isothermal
- Planet-induced shocks modify disk structure
- Hot lobes near high-mass planets in high resolution
- Planets puff up their outer gaps – visible in scattered light