

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), Blake Hord (New York) Anders Johansen (Lund), Tobias Heinemann (KITP), Hubert Klahr (Heidelberg), Marc Kuchner (Goddard), Min-Kai Lin (ASIAA), Mordecai-Mark Mac Low (AMNH), Colin McNally (Copenhagen), Krzysztof Mizerski (Warsaw), Richard Nelson (London) Satoshi Okuzumi (Tokyo), Sijme-Jan Paardekooper (London), Nikolai Piskunov (Uppsala), Natalie Raettig (Heidelberg), b, Zsolt Sandor (Budapest) Neal Turner (NASA JPL), Orkan Umurhan (NASA Ames), Miguel de Val-Borro (NASA Goddard), Nienke van der Marel (IfA Hawaii), Andras Zsom (Brown).

Las Vegas, Nov 30th, 2018









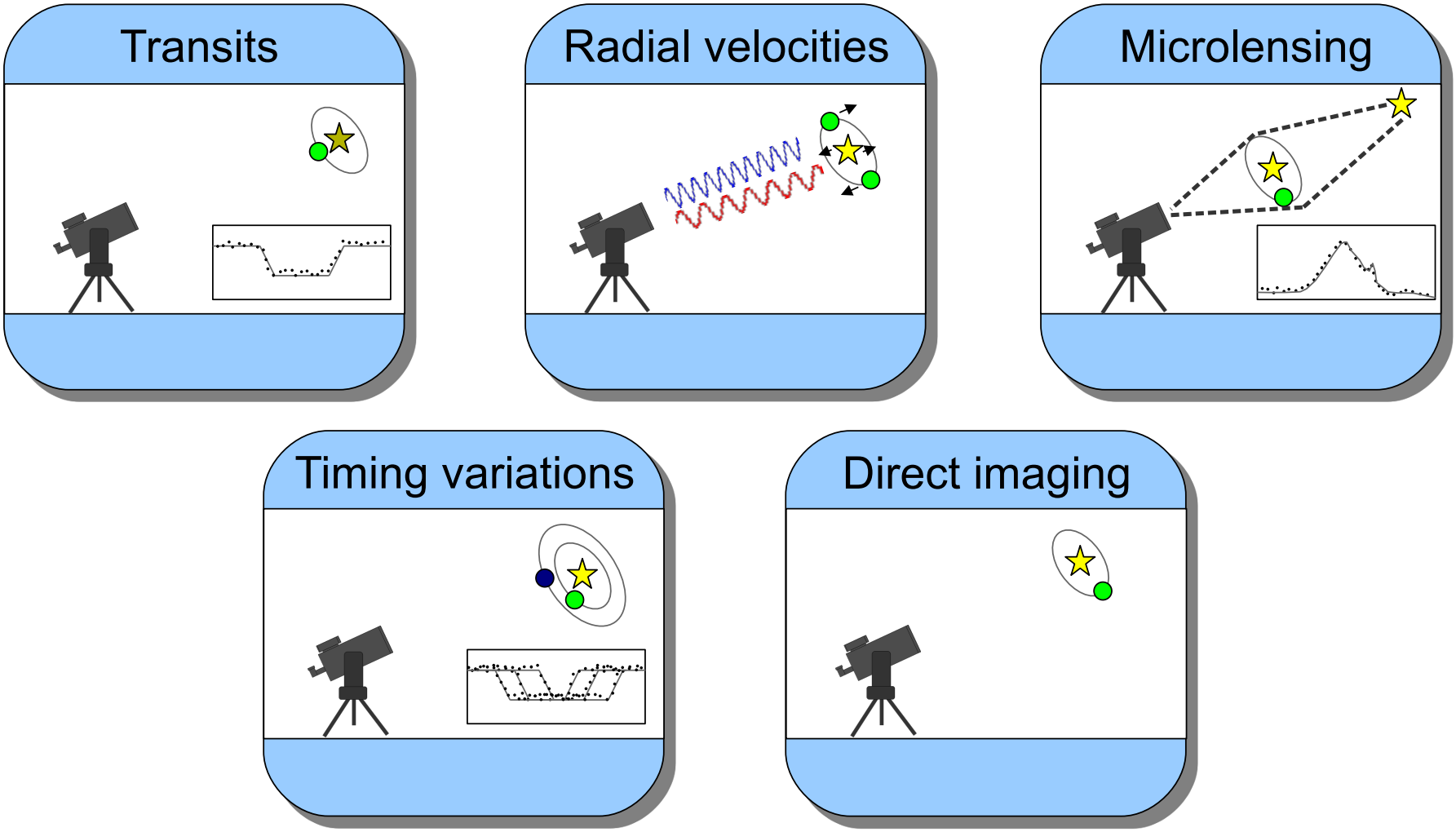




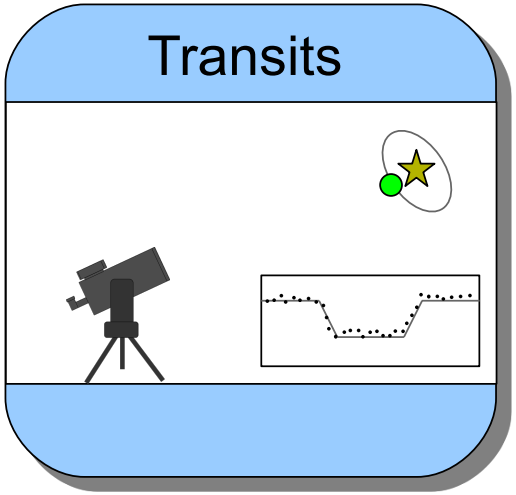


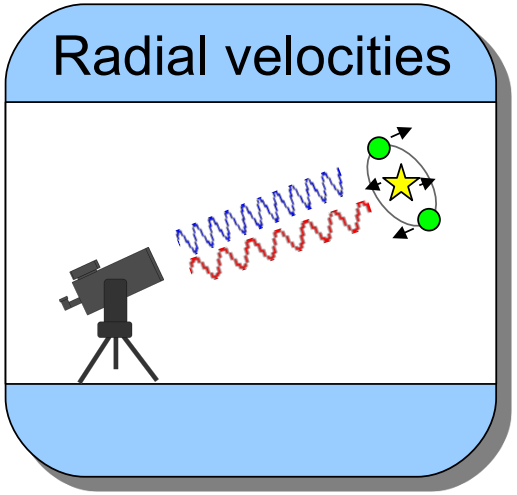


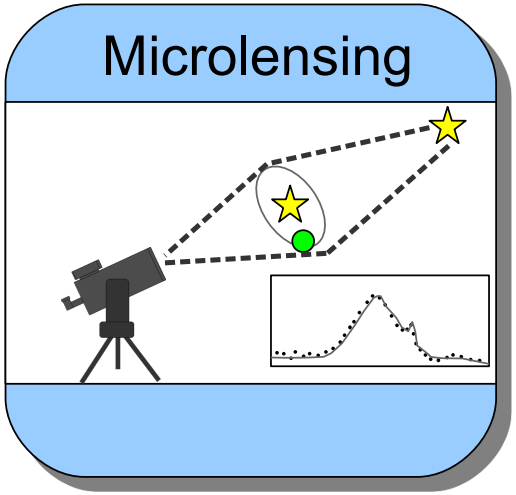


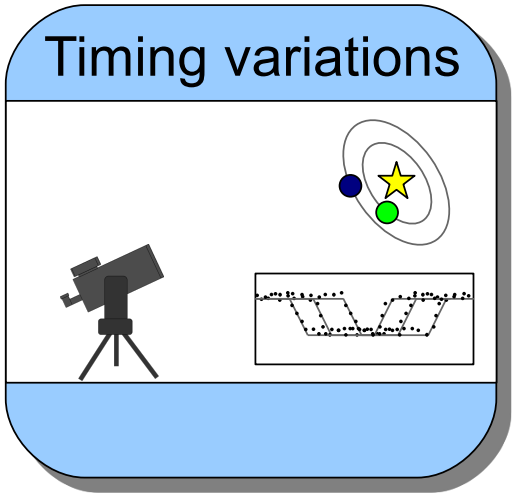


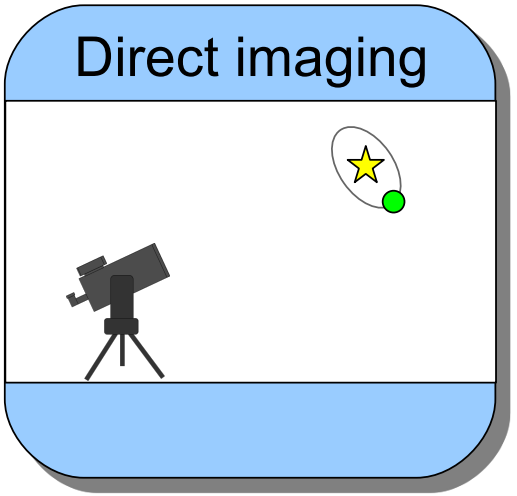
Slide by A. Richert

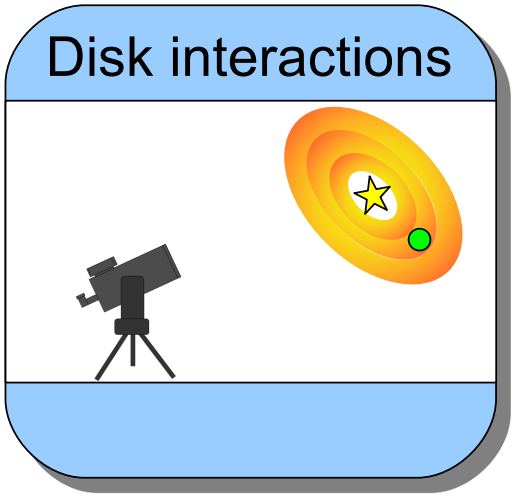






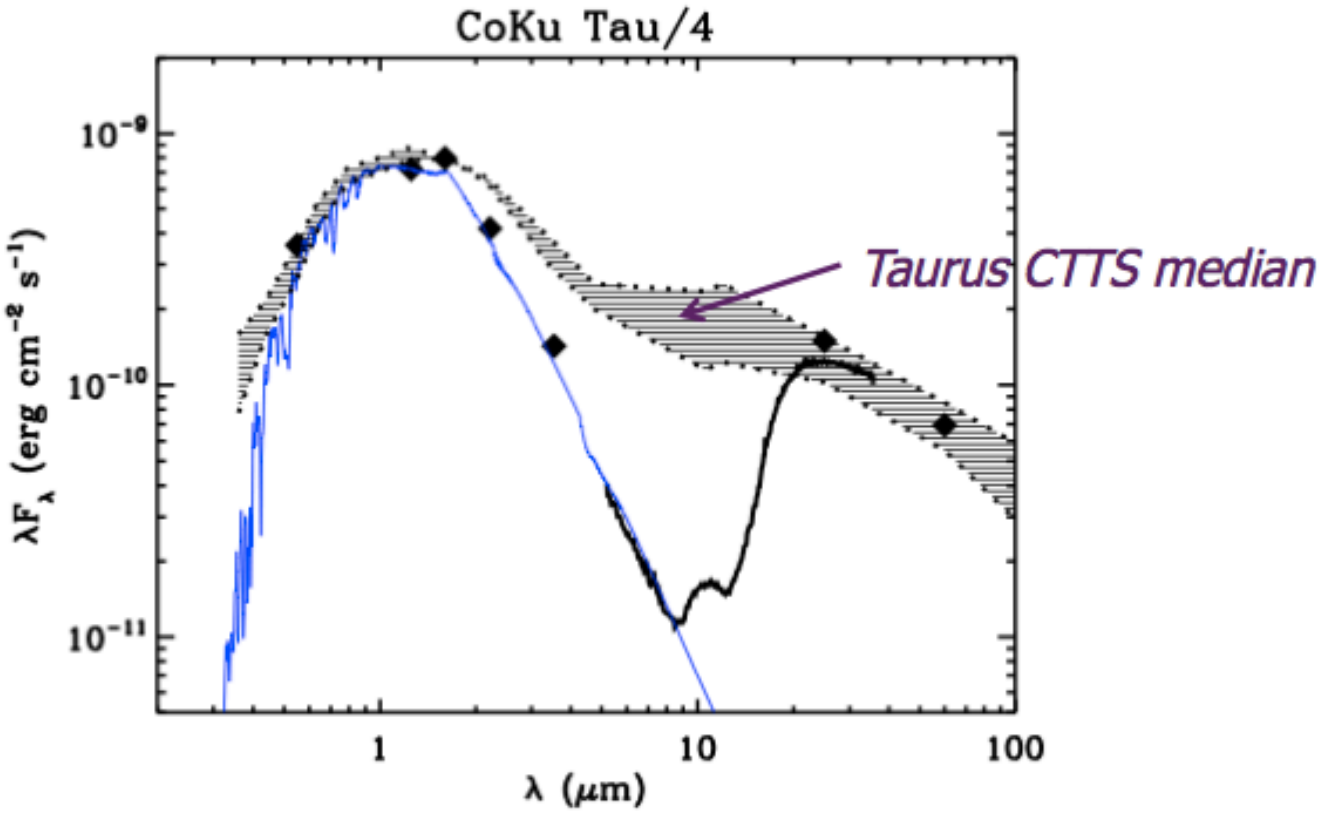




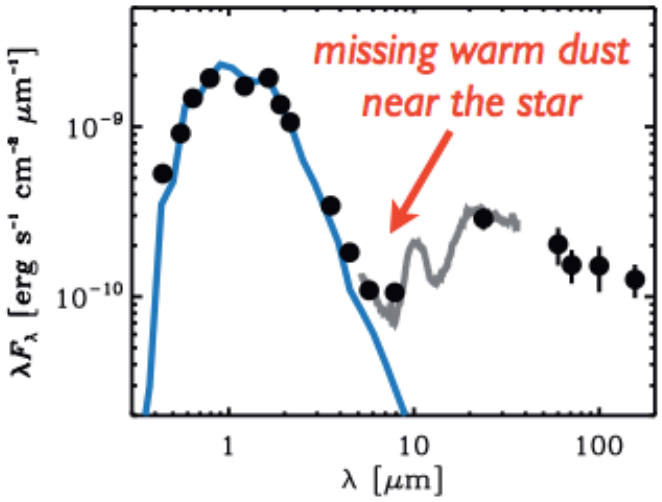


Slide by A. Richert

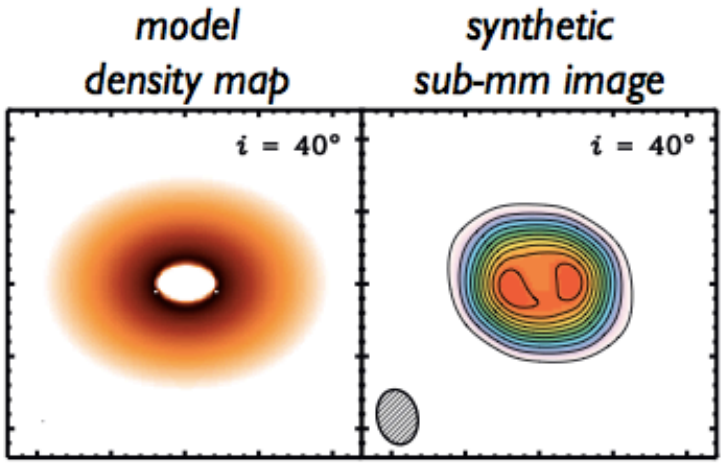
Transition Disks: Disks with missing hot dust.



Transition Disks: Disks with missing hot dust.



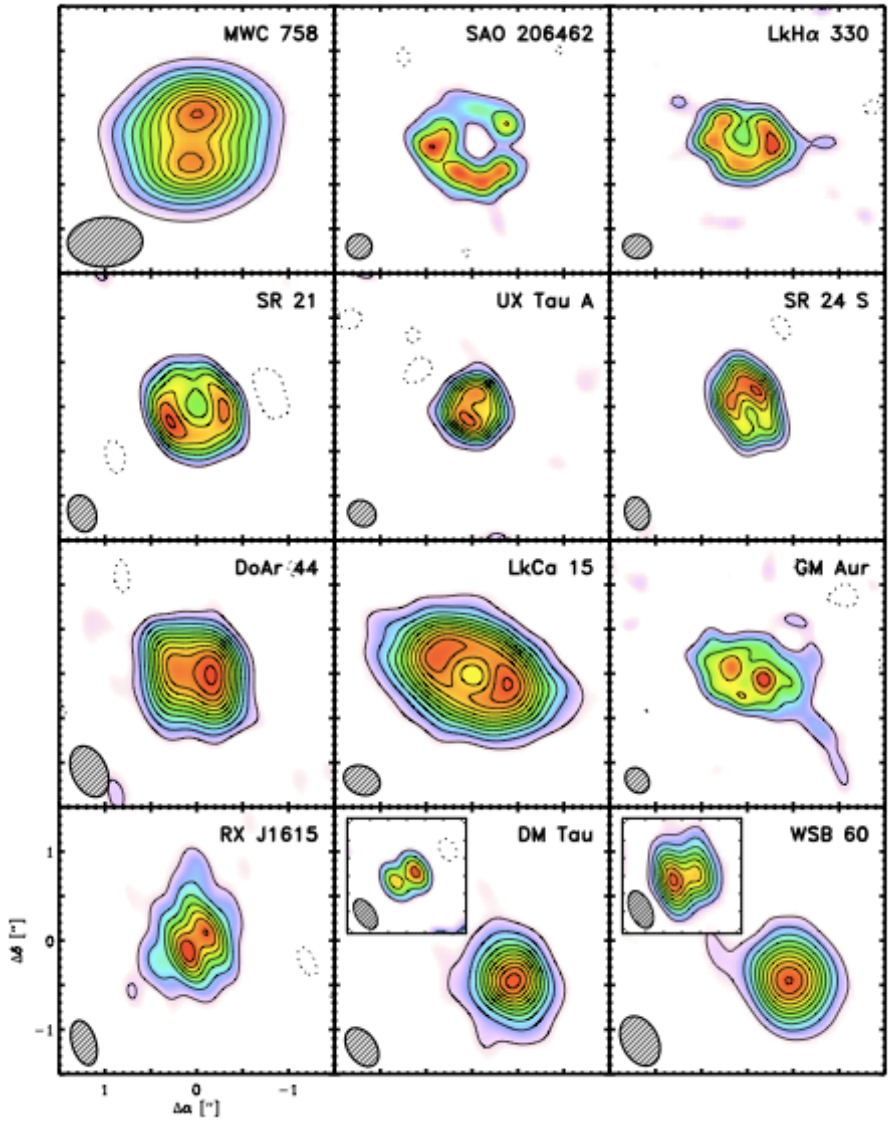
[e.g., Furlan et al. 2009]



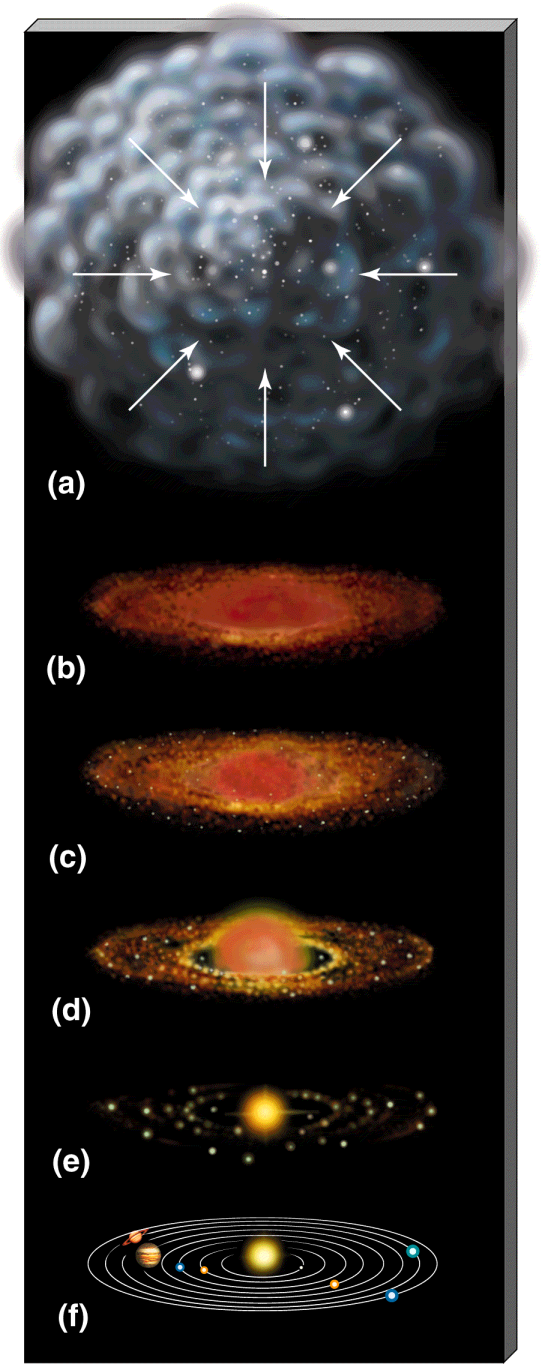
a disk with a large reduction
in optical depth near the star
(i.e., a "cavity" or "hole")



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



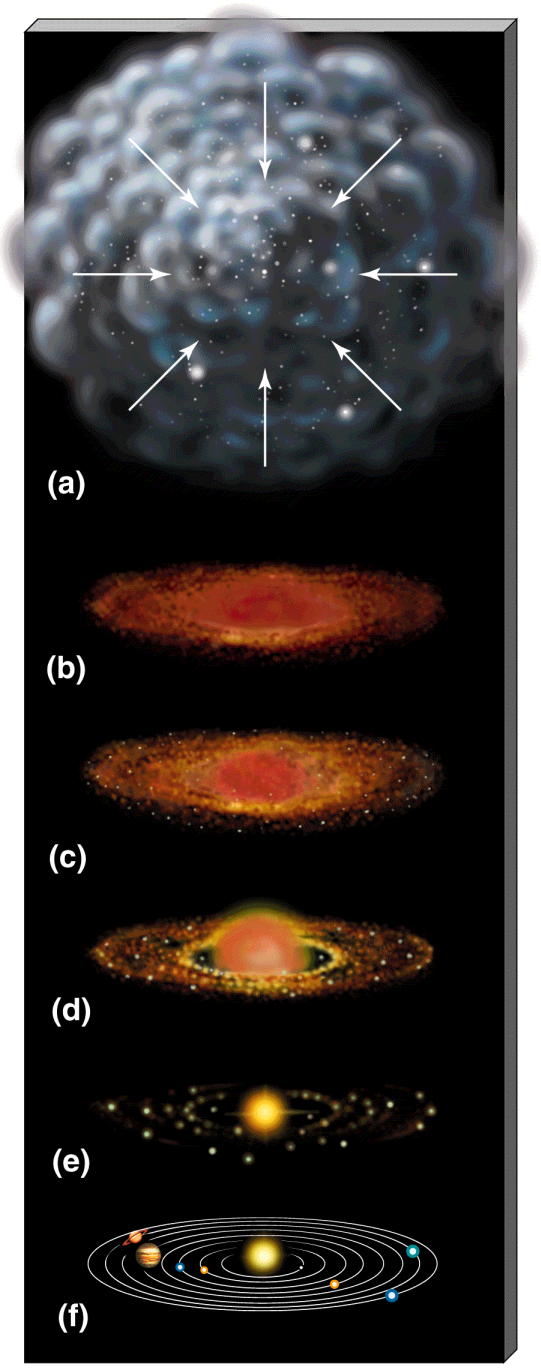
0.85mm
0.3” ~ 20 AU resolution



Are transitional disks
related to disk evolution?

Gas-rich phase (< 10 Myr)
Primordial Disks

Gas-poor phase (>10 Myr)
Debris Disks



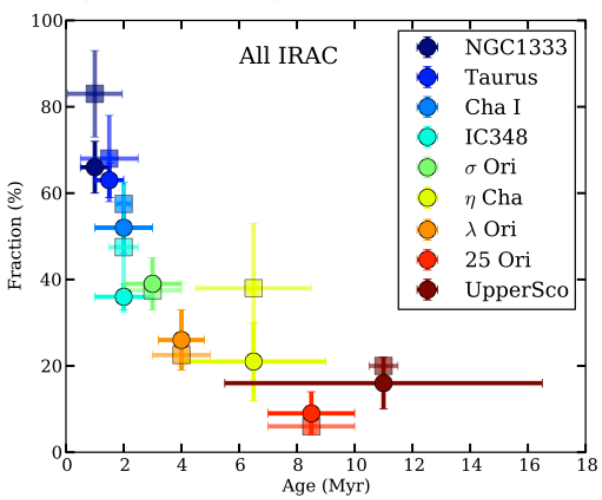
Are transitional disks
related to disk evolution?

Gas-rich phase (< 10 Myr)
Primordial Disks

Conjecture:
Thinning phase (~10 Myr)
Transitional Disks

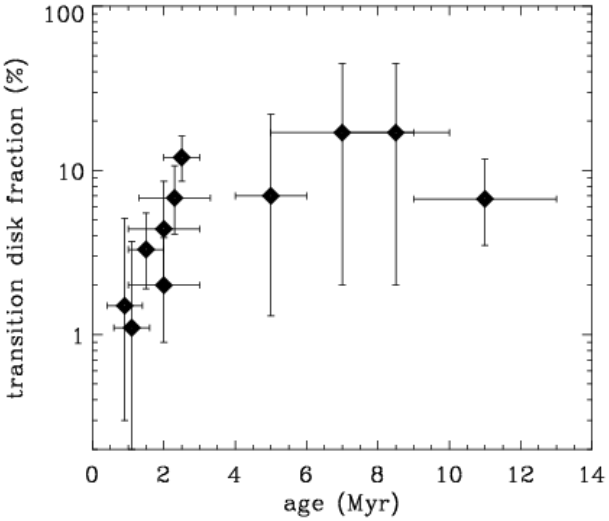
Gas-poor phase (>10 Myr)
Debris Disks

Transition disks and disk evolution



(Ribas et al. 2014)

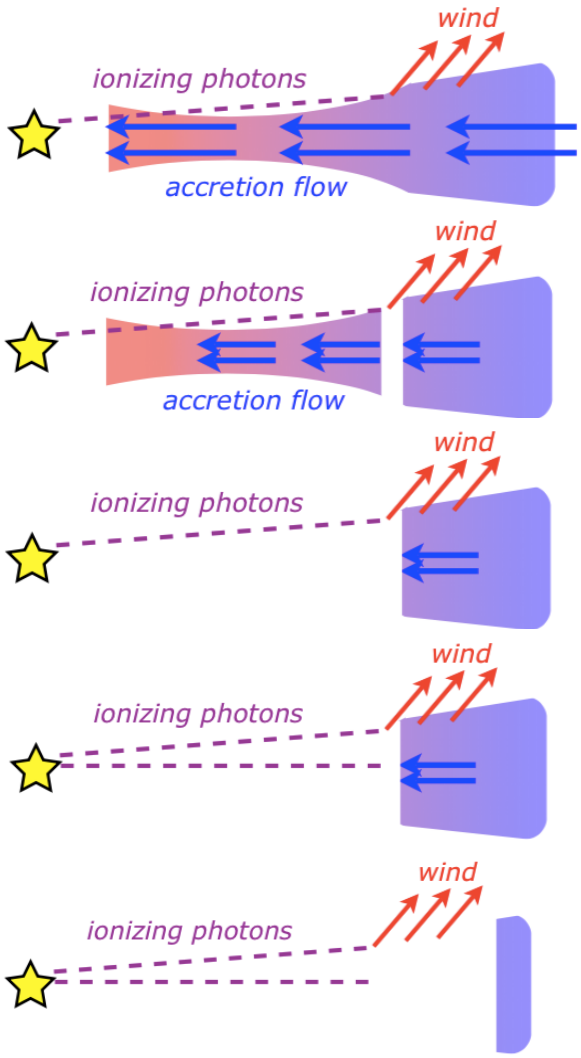
"Total" disk fraction



(Espaillat et al. 2014)

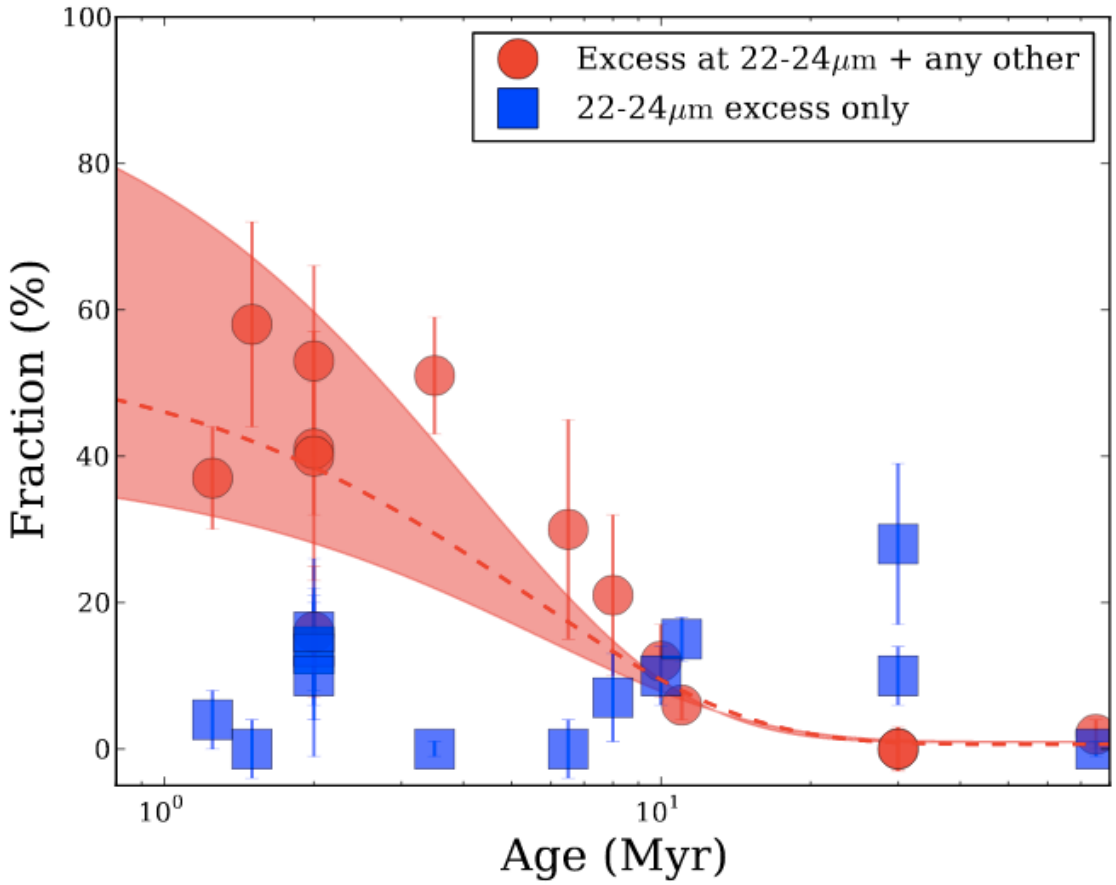
Transition disk fraction

Photoevaporation



Transition disks linked to disk evolution?

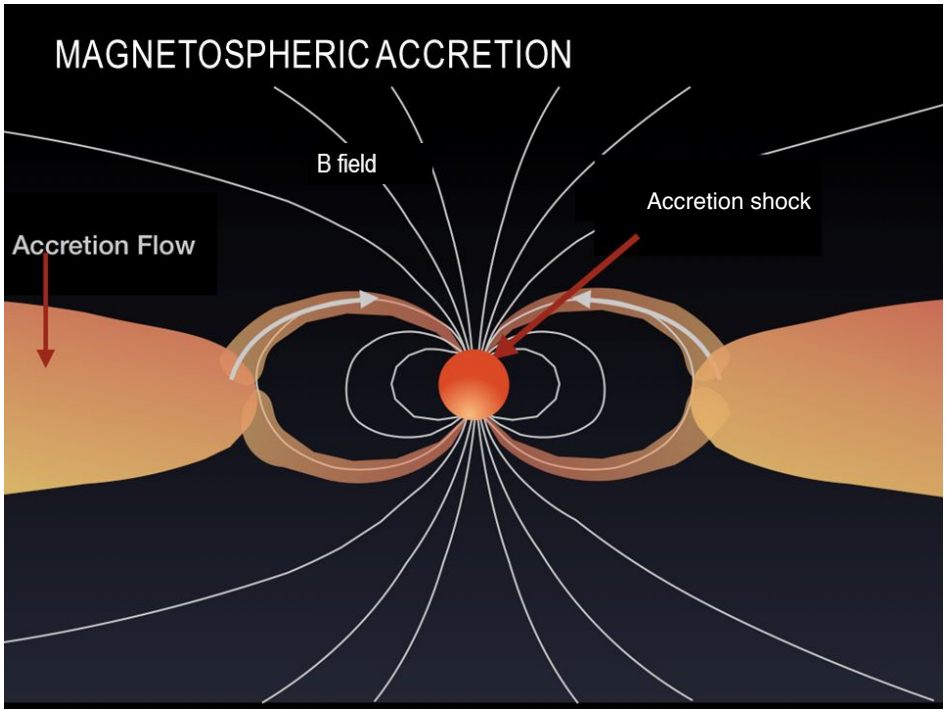
The distribution in age is consistent with a uniform distribution.

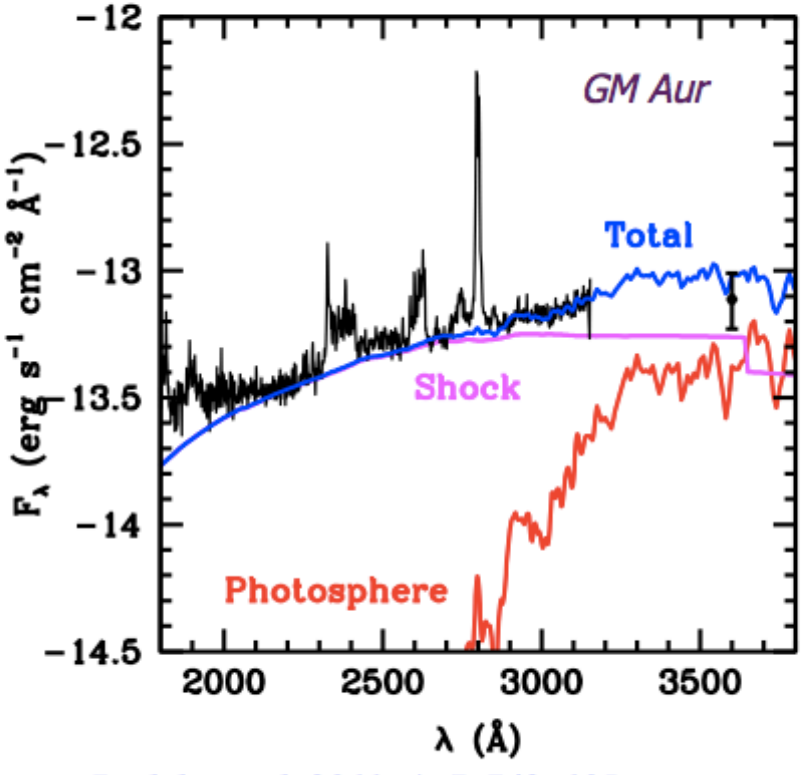


(Ribas et al. 2014)

UV excess

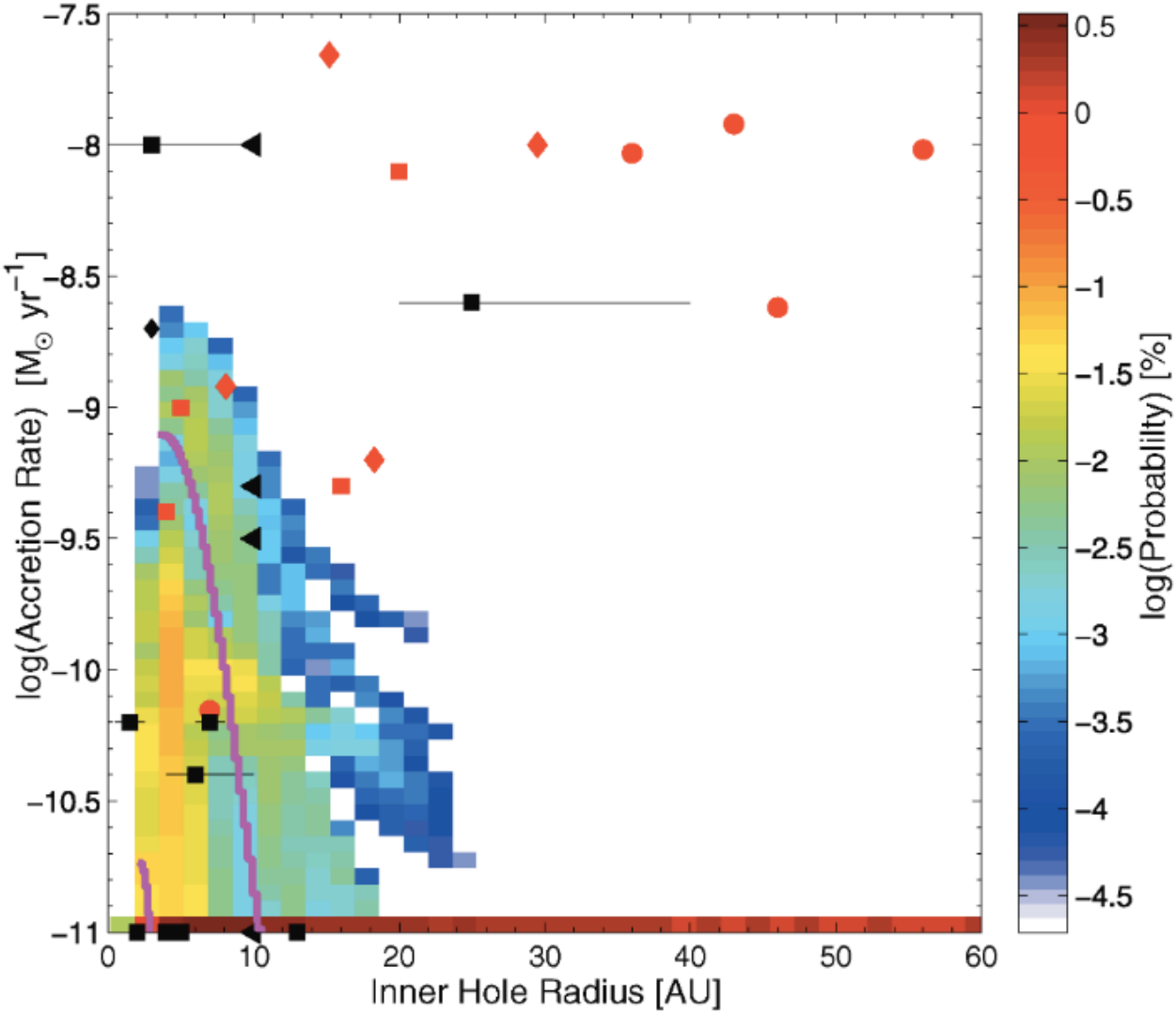
Many transitional disks show signs of accretion,
at the level of primordial (classical T-Tauri) disks.





(Ingleby et al. 2011)

Bimodal distribution of transition disks

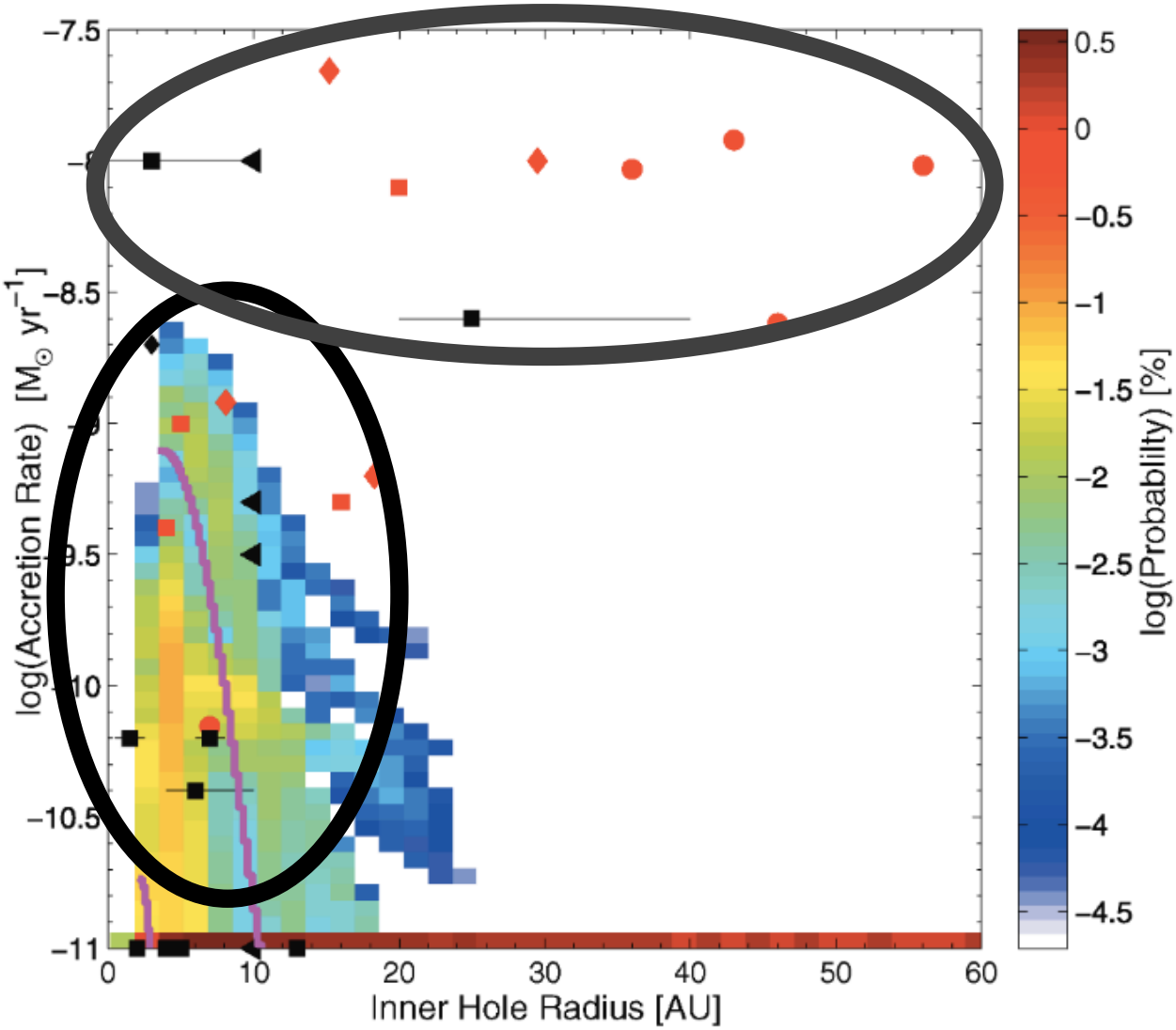


(Owen et al. 2011)

Bimodal distribution of transition disks

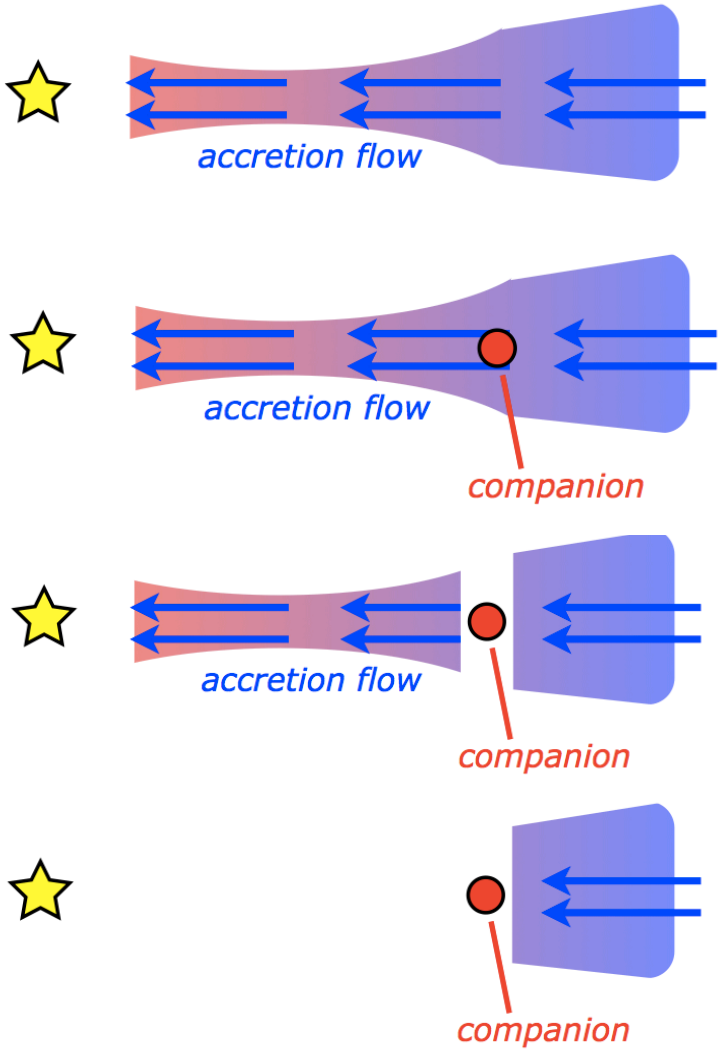
Not explained by photo-evaporation

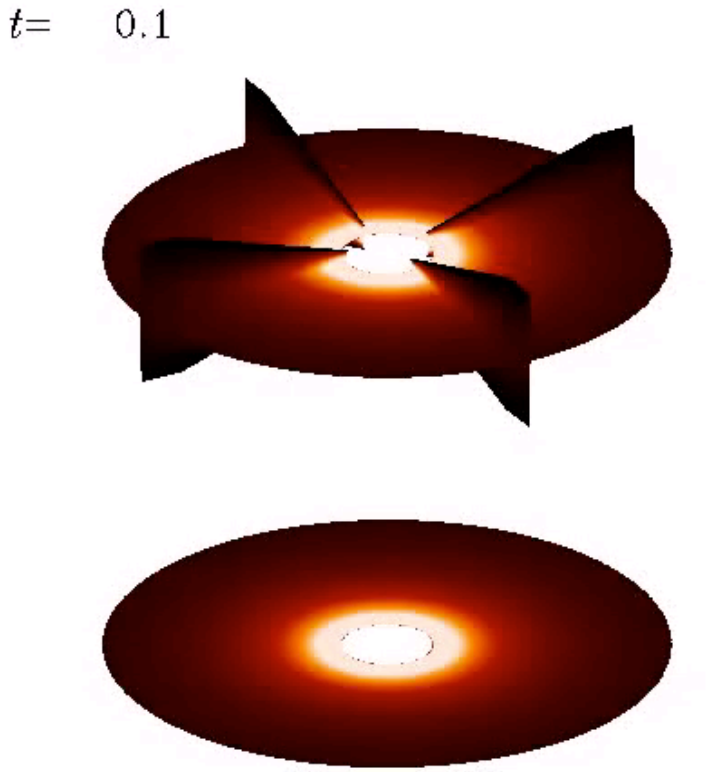
Explained by Photo-evaporation



(Owen et al. 2011)

Planetary companion

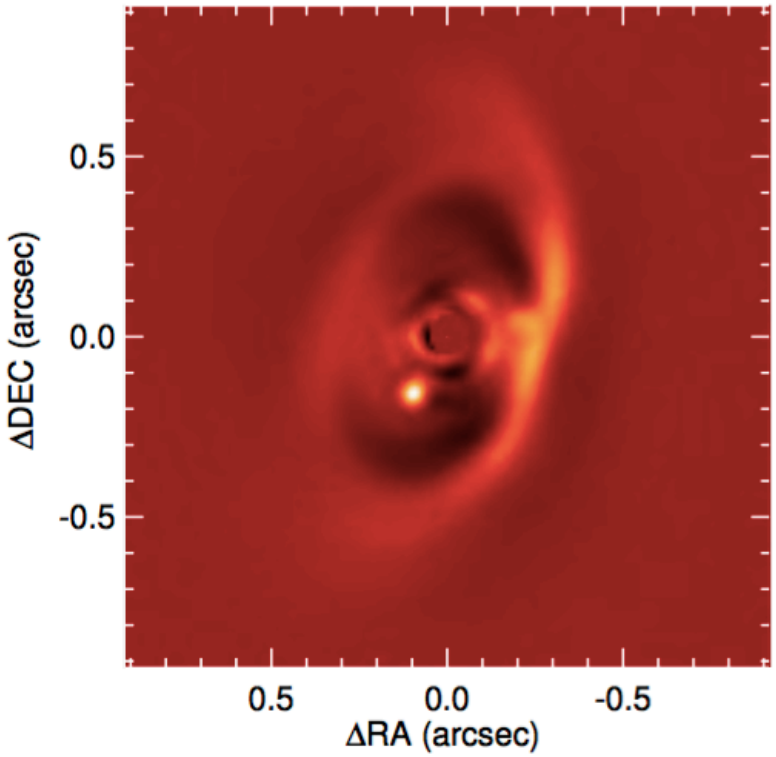




(Lyra 2009)

These cavities may be the telltale signature of forming planets

PDS 70 and PDS 70b



(Muller et al. 2018)



(Lyra et al. 2009b)

A way to directly study planet-disk interaction

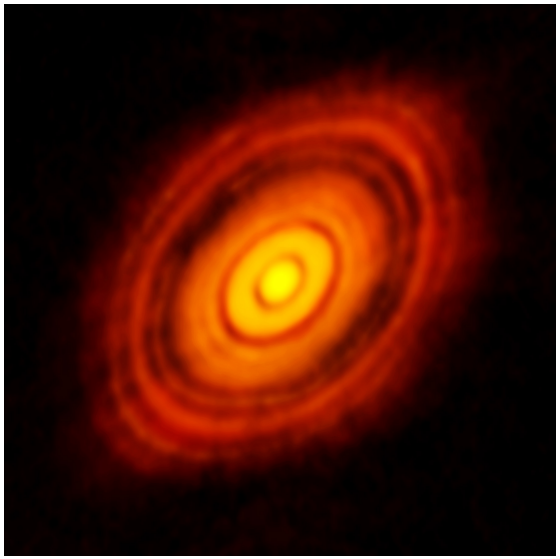
Planet-disk interaction: gaps, spirals, and vortices.



(Lyra et al. 2009b)

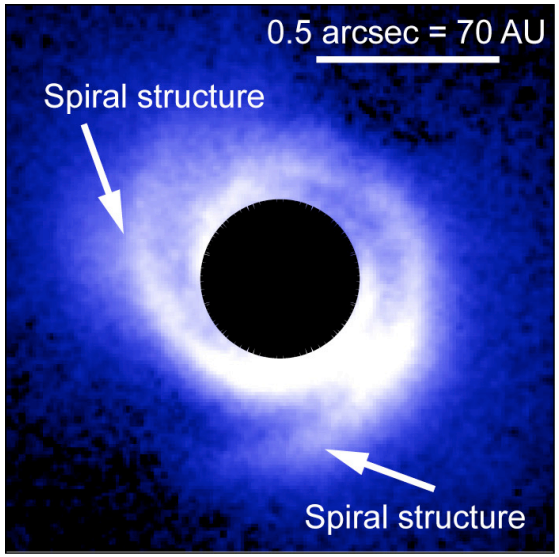
Observational evidence: gaps, spirals, and vortices

HL Tau



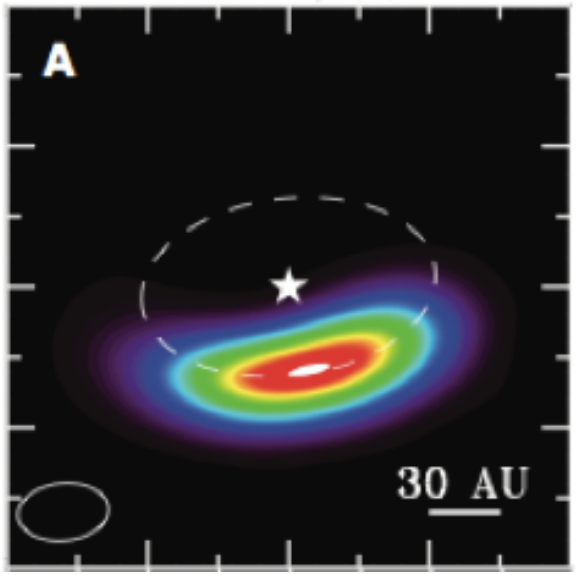
The ALMA Partnership et al. (2015)

SAO 206462



Muto et al. (2012)

Oph IRS 48

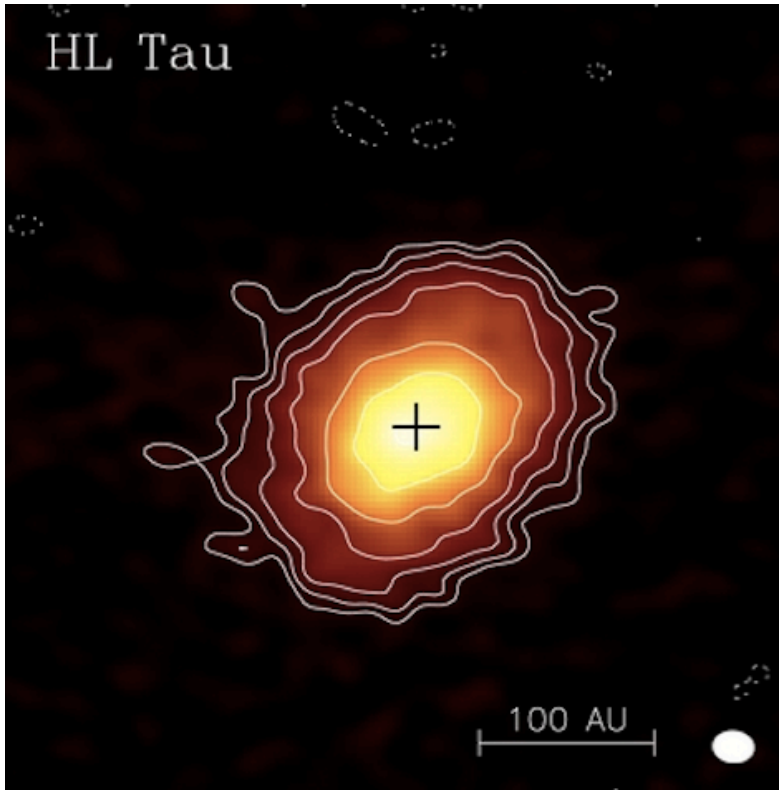


van der Marel et al. (2013)

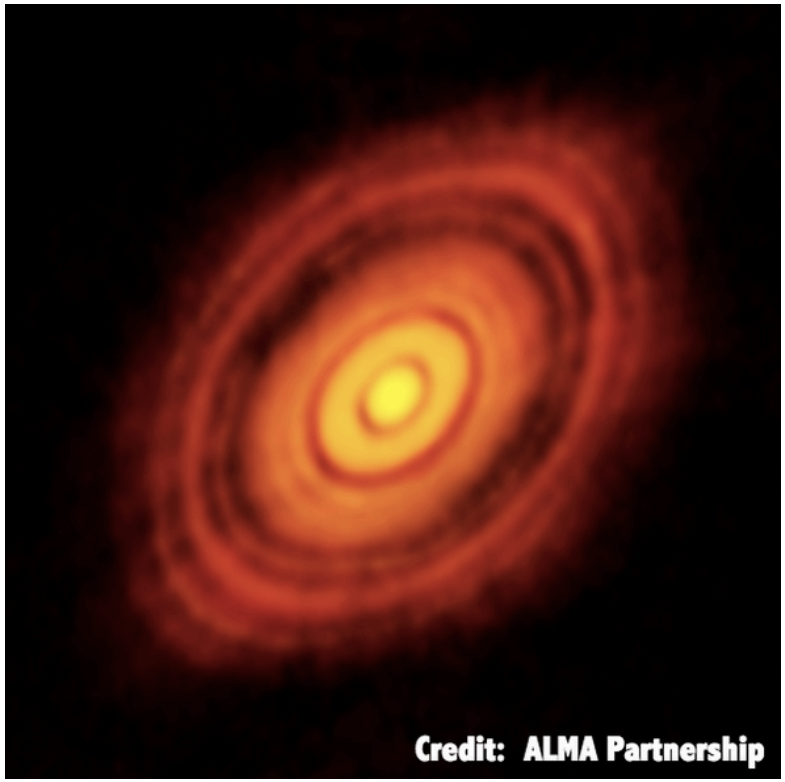
The Atacama Large Millimeter Array (ALMA)

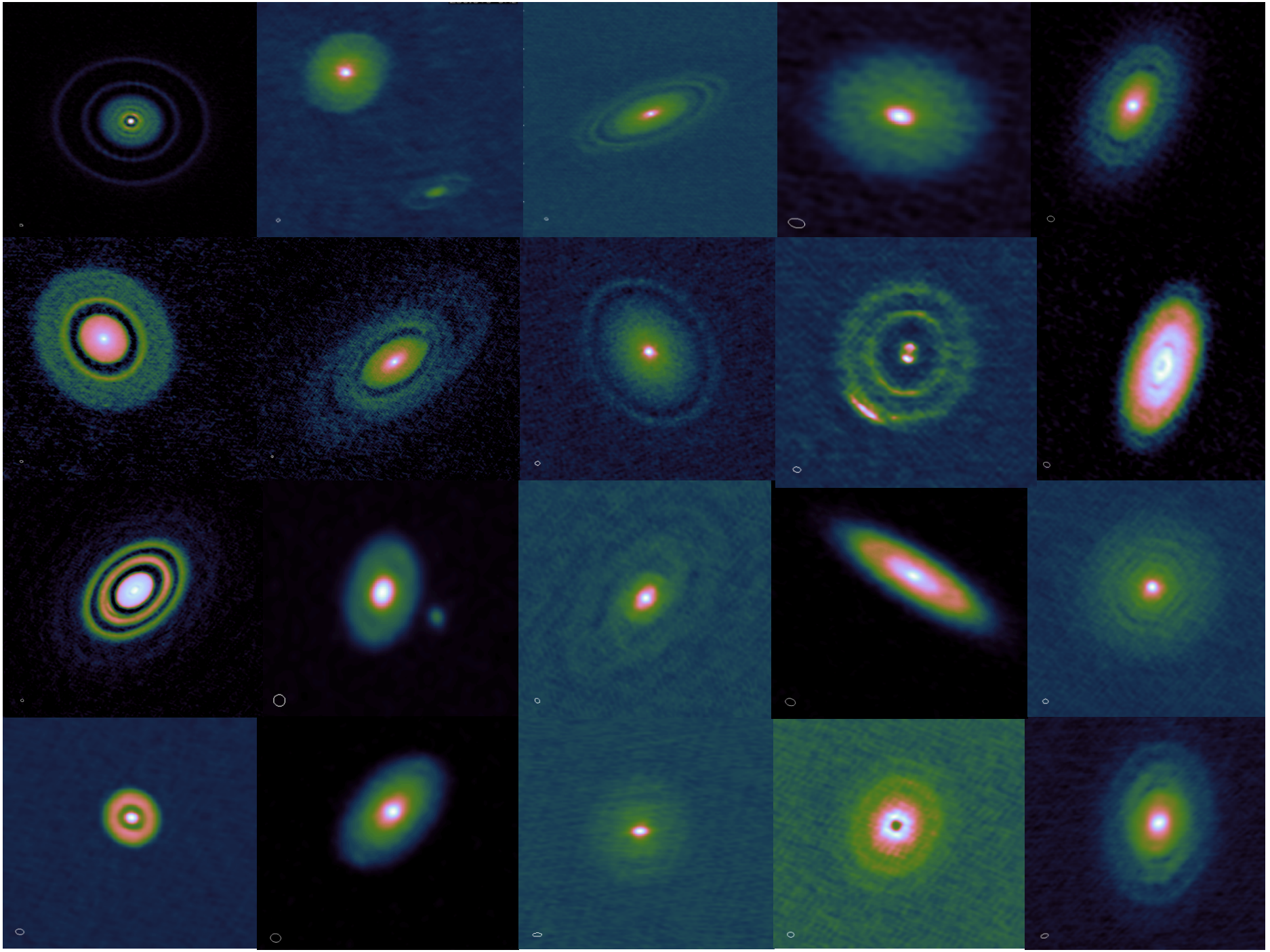


Before ALMA

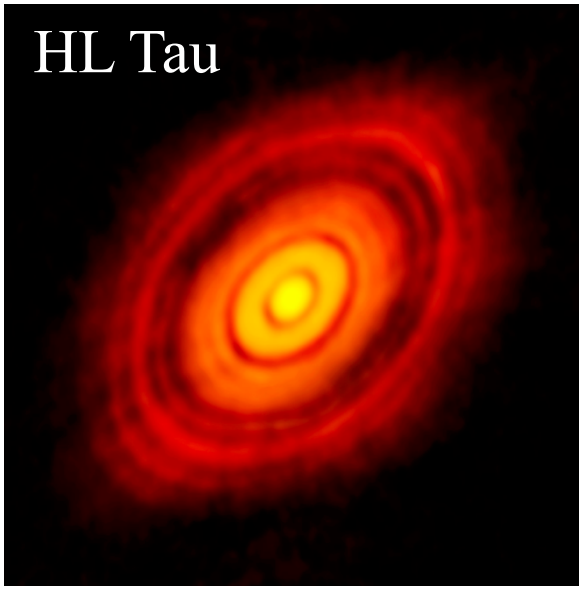


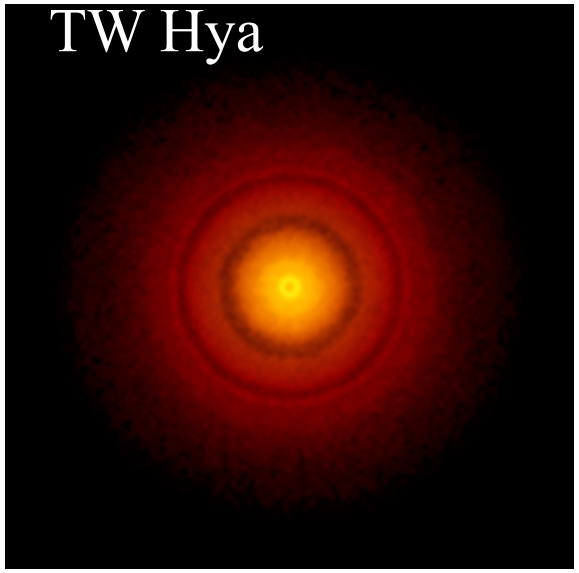
ALMA

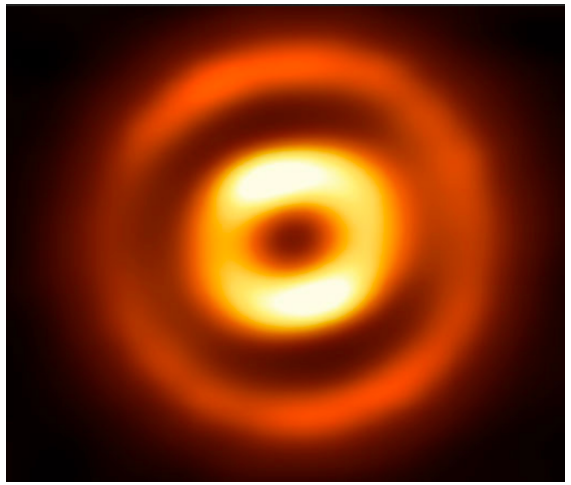


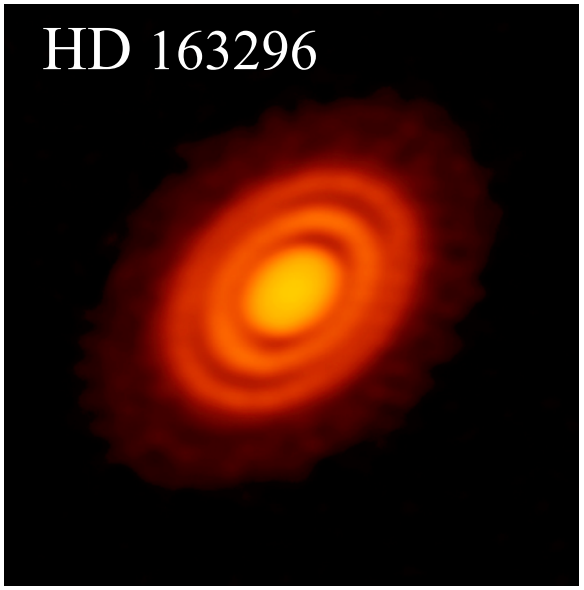


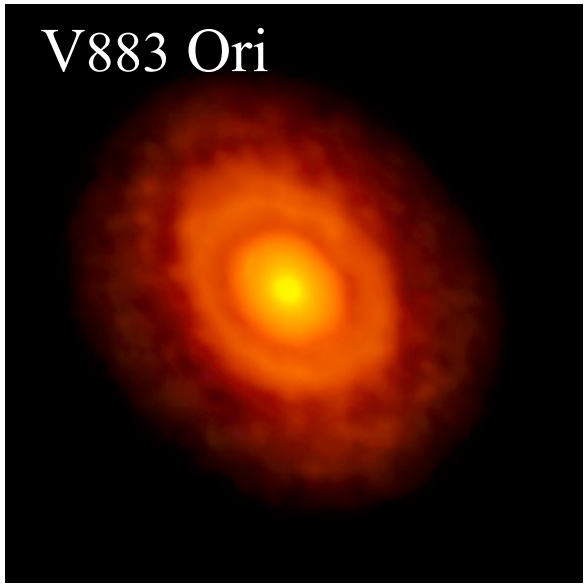
Rings and gaps











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]

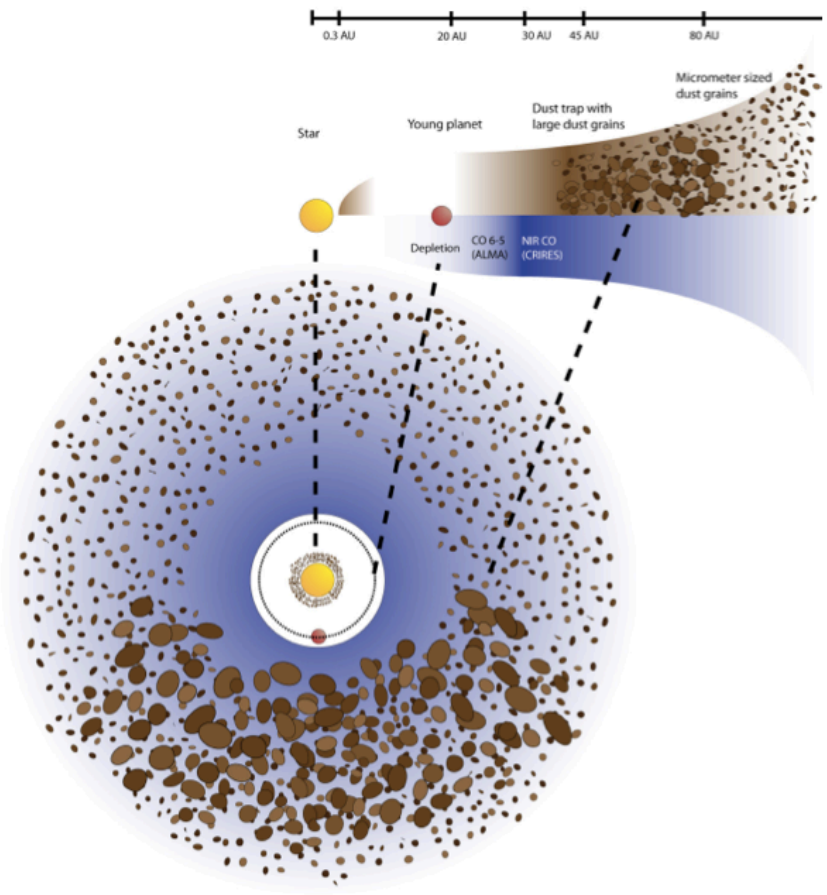
The statistics of discovered exoplanets suggest that planets form efficiently. However, there are fundamental unsolved problems, such as excessive inward drift of particles in protoplanetary disks during planet formation. Recent theories invoke dust traps to overcome this problem. We report the detection 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

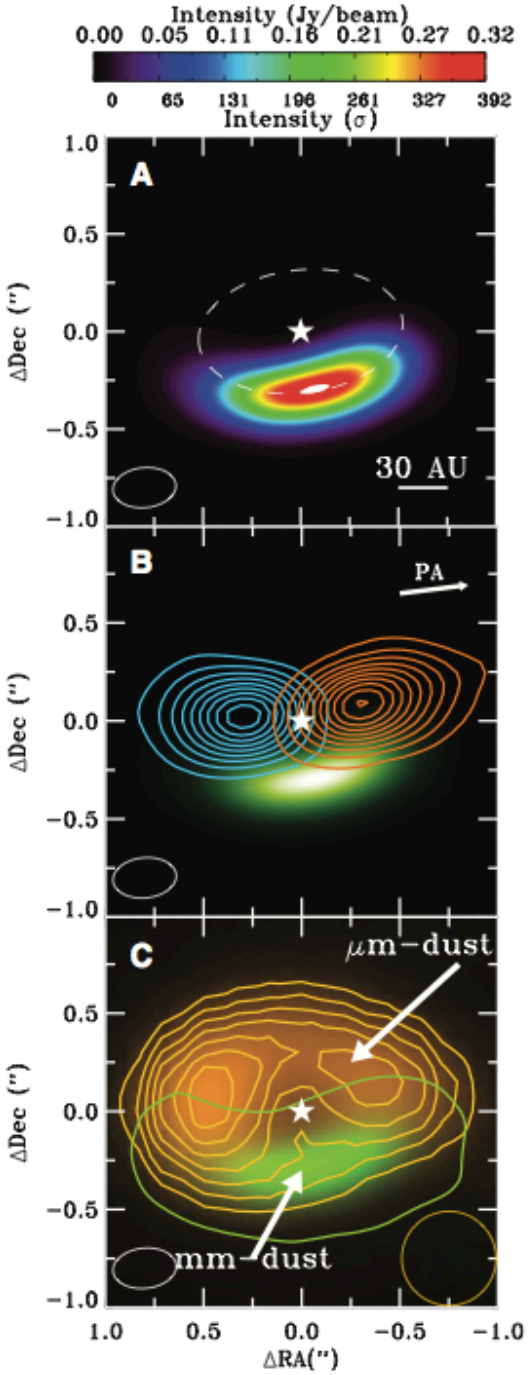
van der Marel et al. 2013

A huge vortex observed with ALMA

The Oph IRS 48 "comet formation factory"



van der Marel et al. (2013)

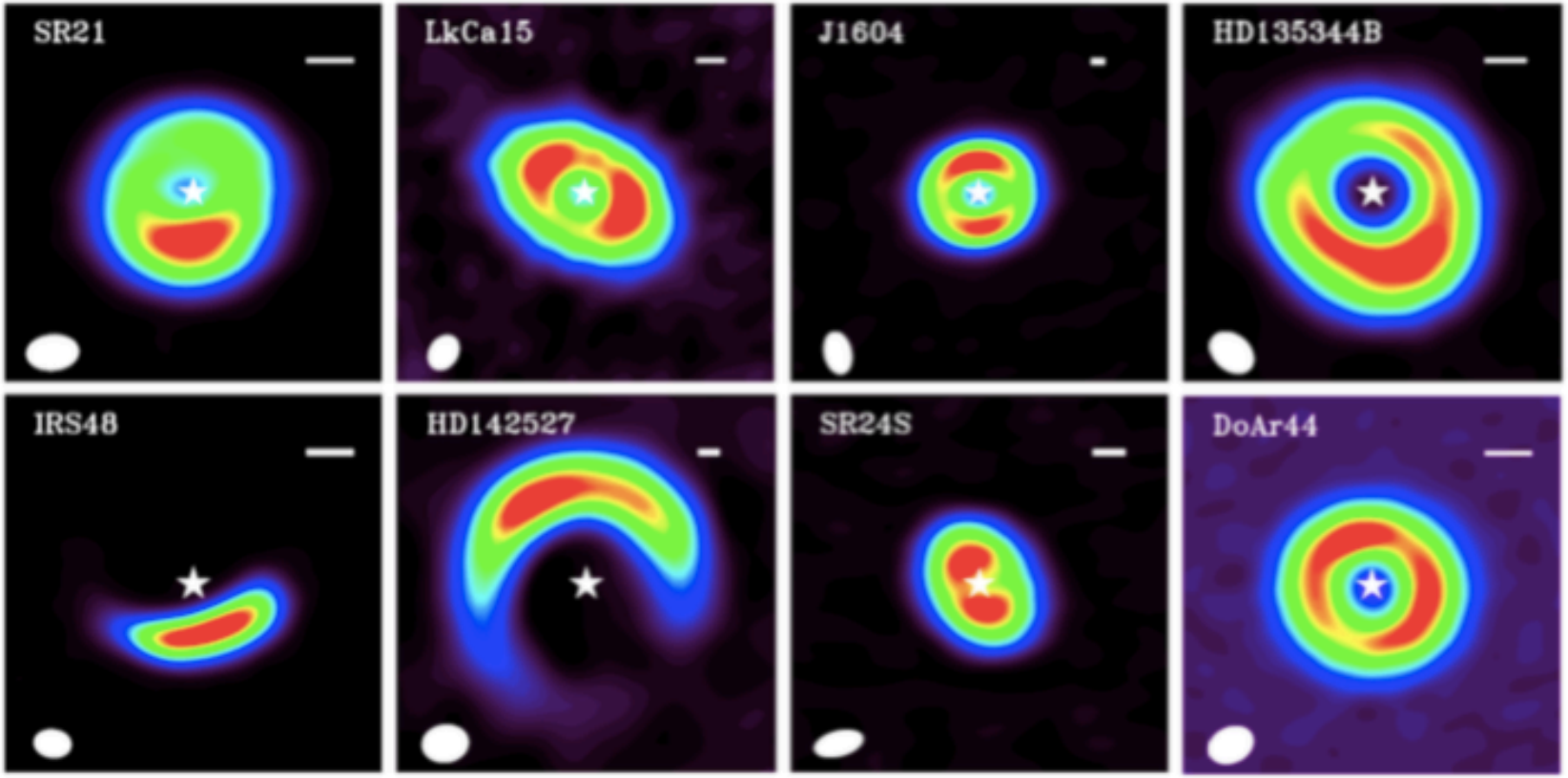


asymmetric mm dust at 63 AU

Gas detection: Keplerian rotation

Micron-sized dust follows gas

Vortices everywhere!
Extrasolar nebulae

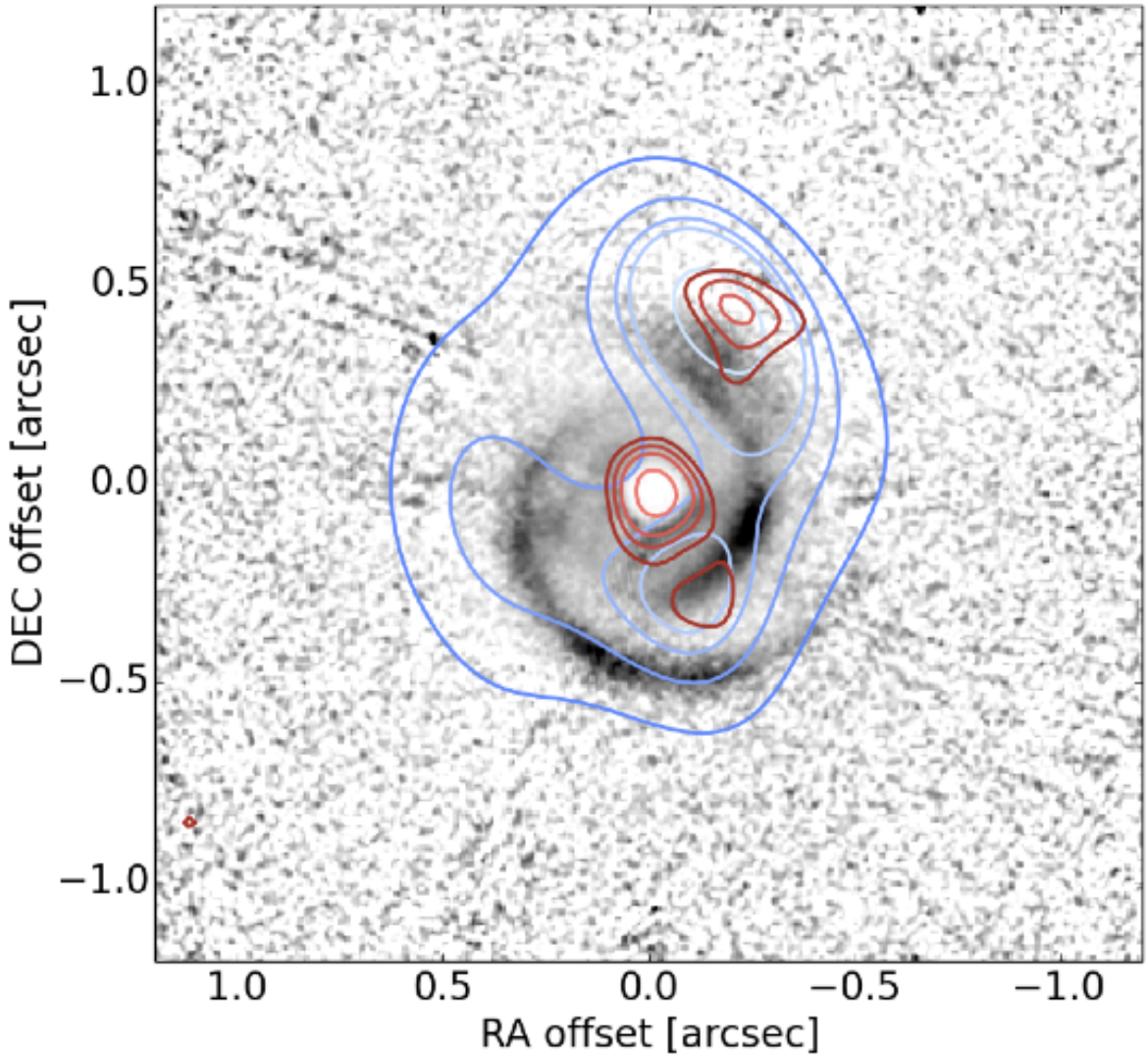


SPHERE-ALMA-VLA overlay of MWC 758

SPHERE (μm)

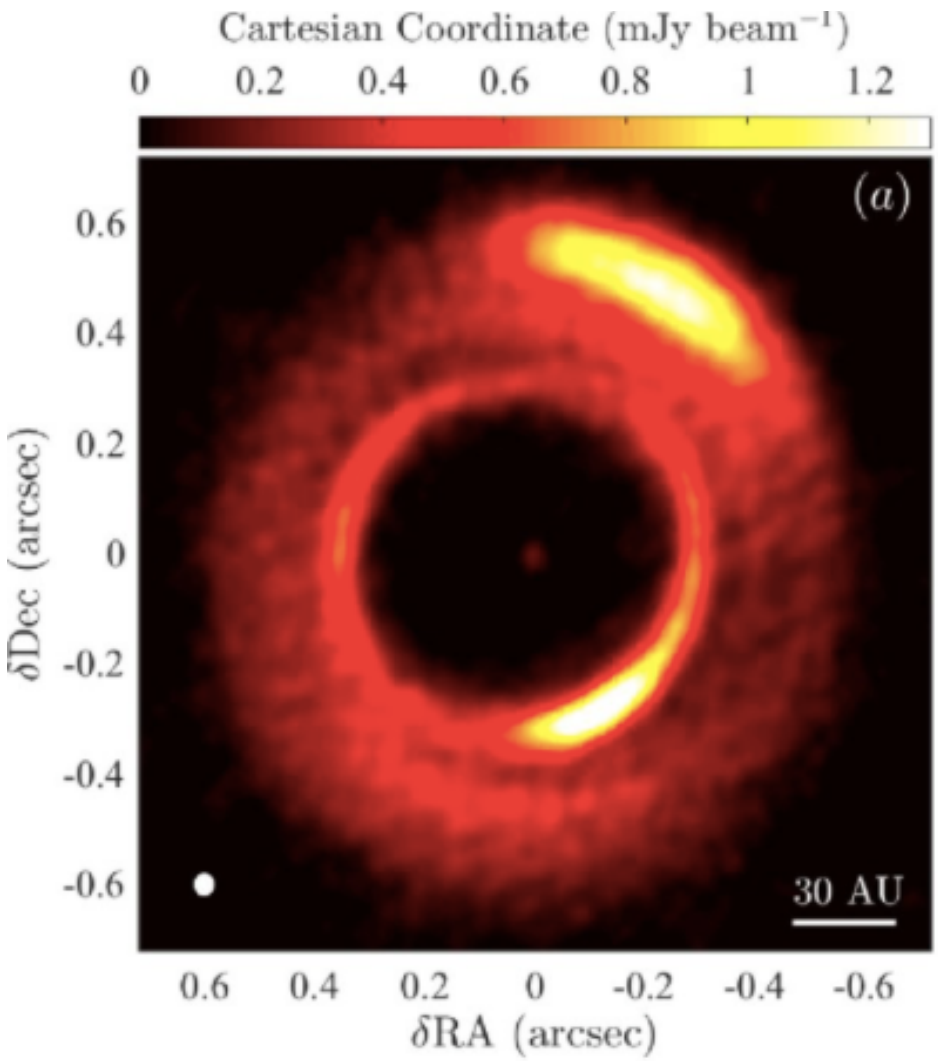
ALMA (~ mm)

VLA (cm-m)



Marino et al. (2015)

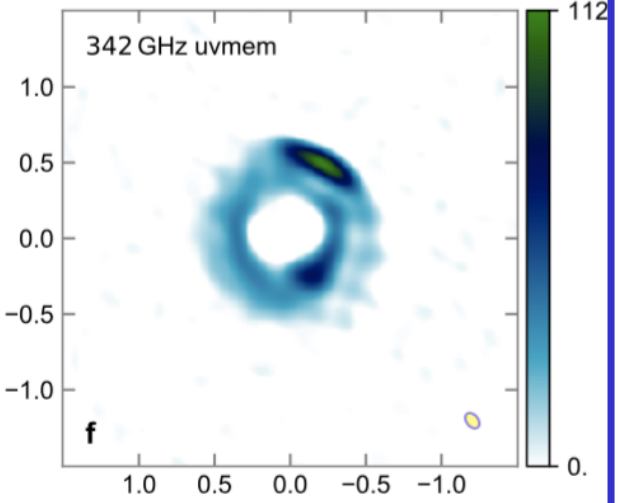
MWC 758



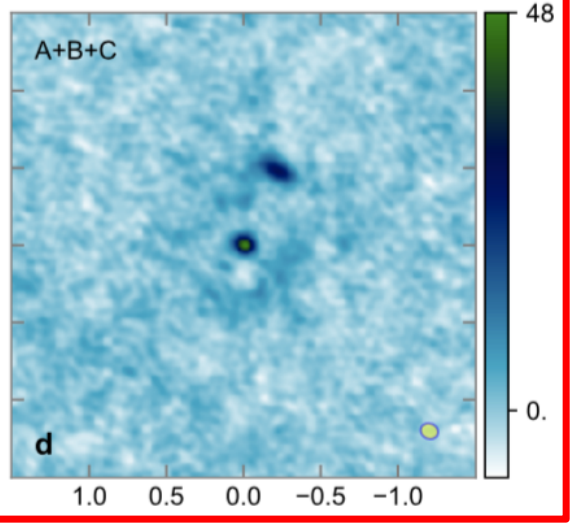
Dong et al. (2018)

Pebble trapping

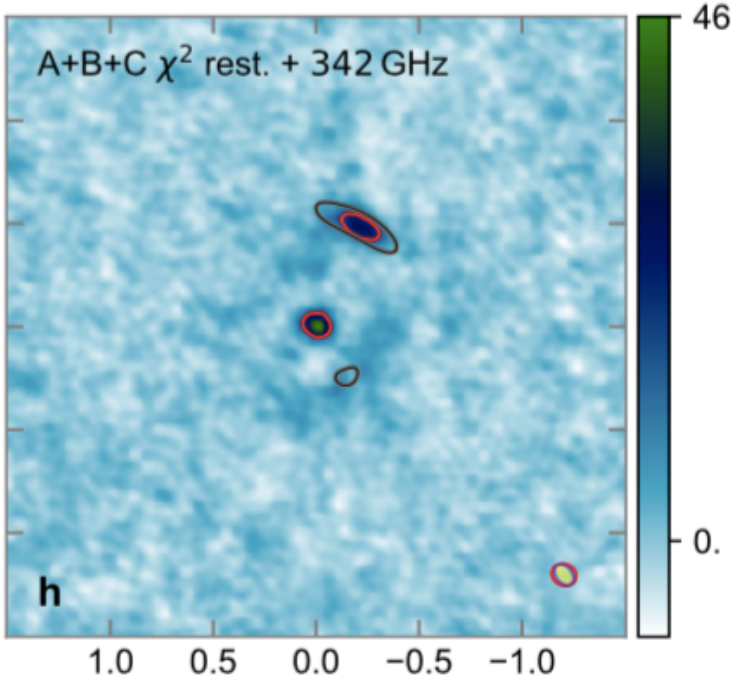
ALMA (mm)



VLA (cm-m)

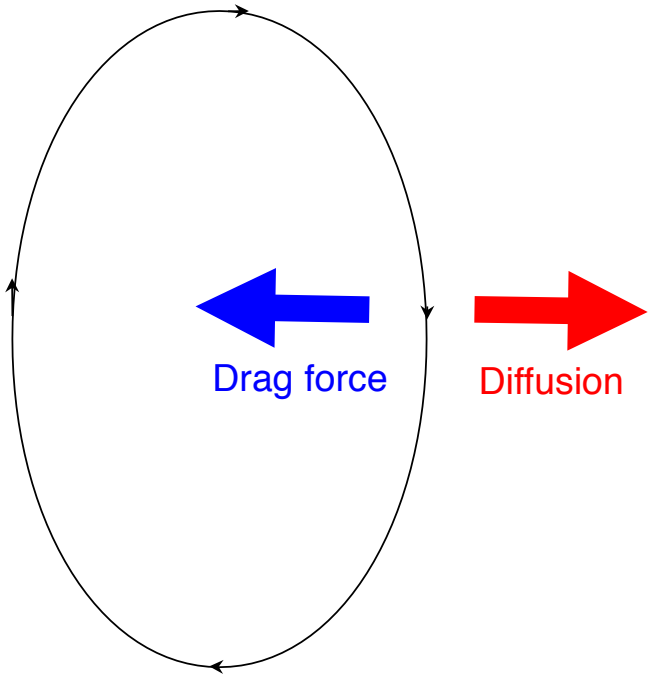


Overlay



Casassus et al. (2018)

Drag-Diffusion Equilibrium



Trapped particle

Dust continuity equation

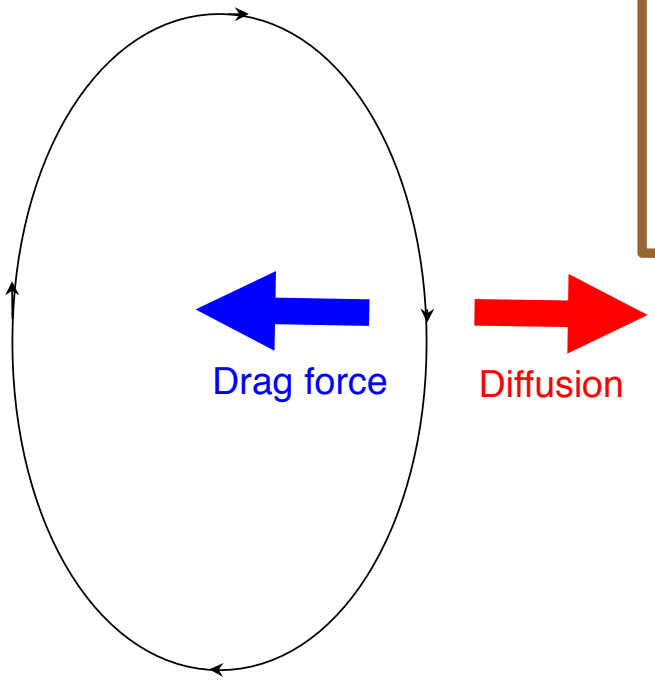
$$\frac{\partial \rho_d}{\partial t} = -(\boldsymbol{v}\cdot\boldsymbol{\nabla})\rho_d - \rho_d \boldsymbol{\nabla}\cdot\boldsymbol{v} + D\nabla^2\rho_d,$$

advection

compression

diffusion

Drag-Diffusion Equilibrium



Trapped particle

Steady-state solution

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

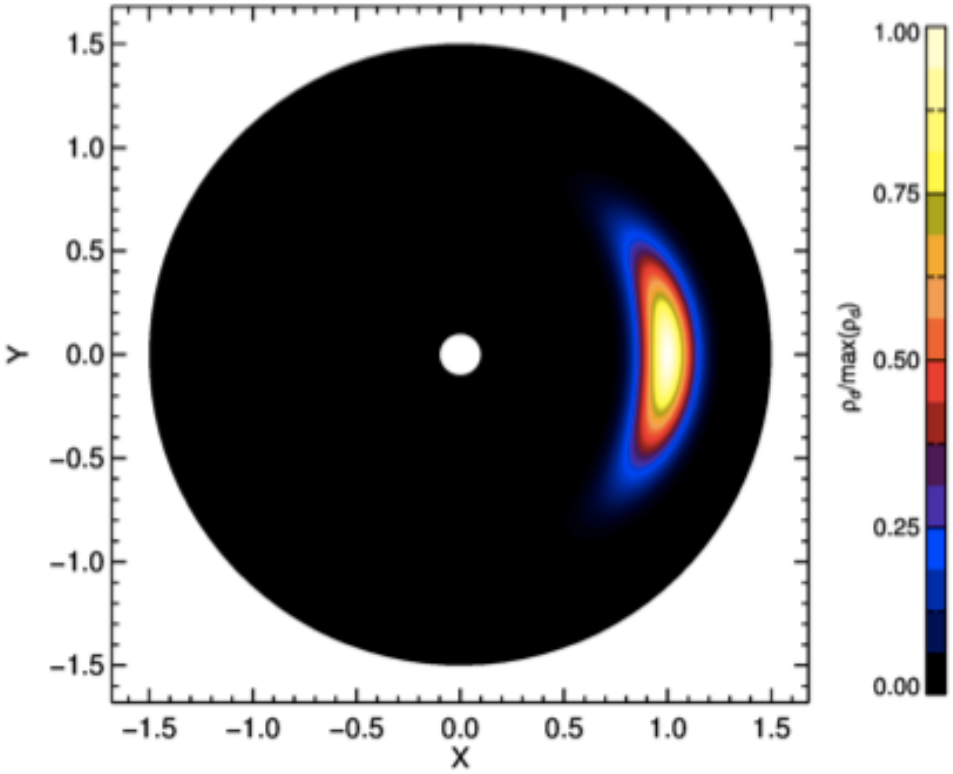
Lyra & Lin (2013)

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

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

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

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

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

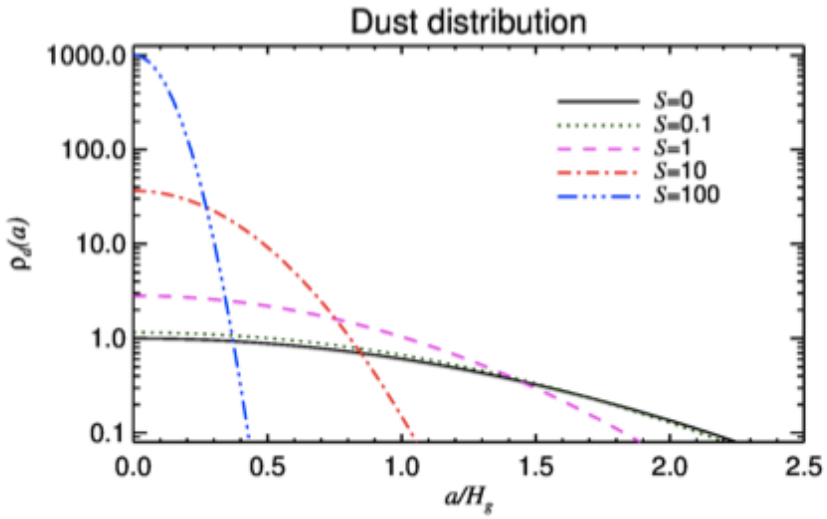
$$S = \frac{St}{\delta}$$

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

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)

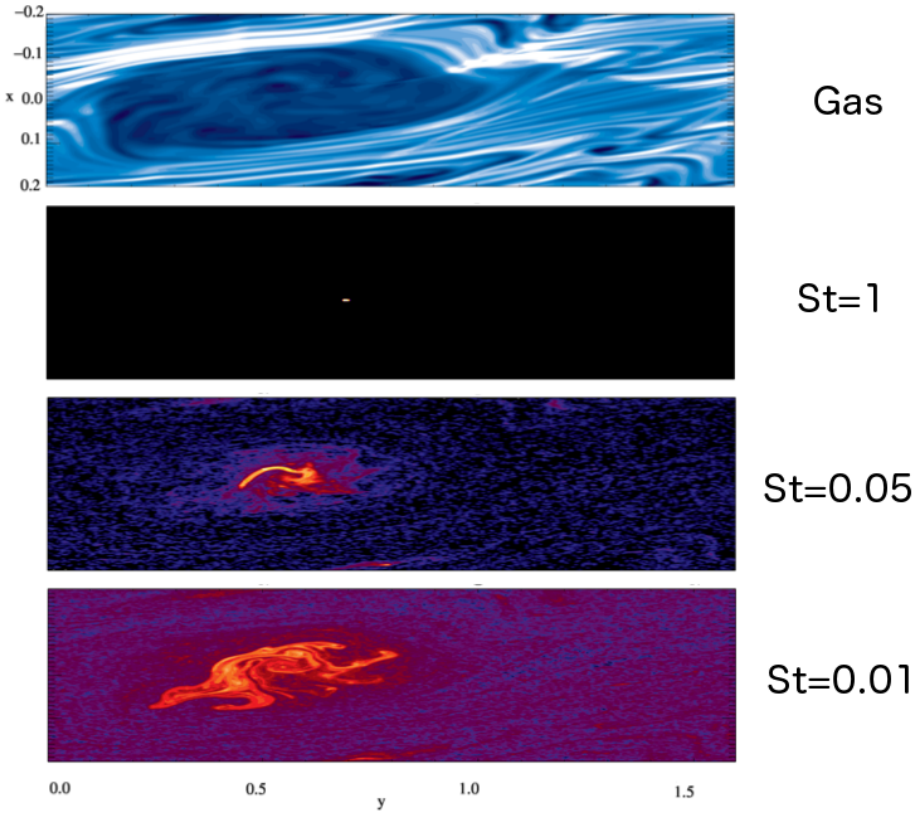
Analytical vs Numerical



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

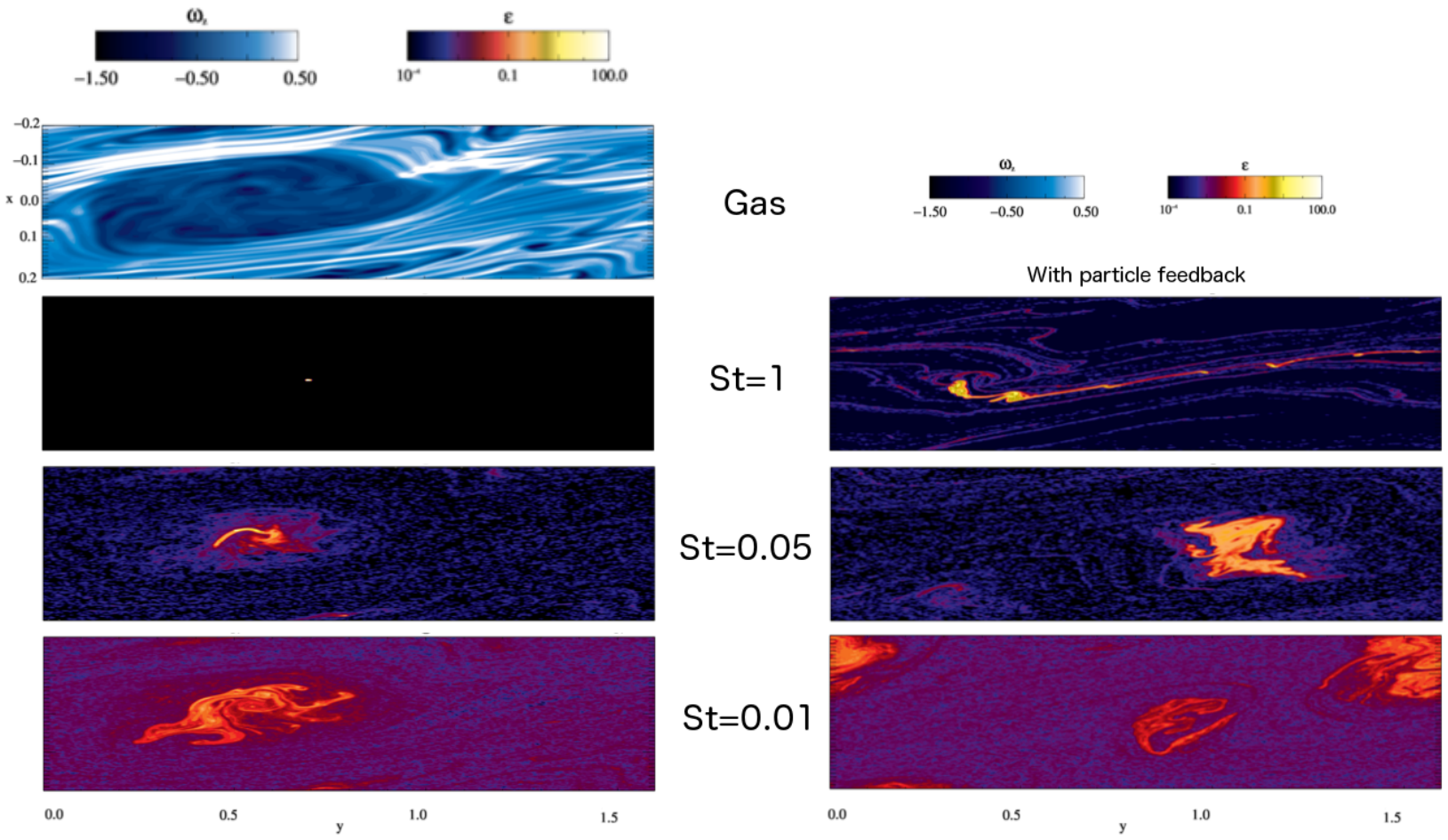
$$\delta = v_{\mathrm{rms}}^2 / c_s^2,$$

Lyra & Lin (2013)

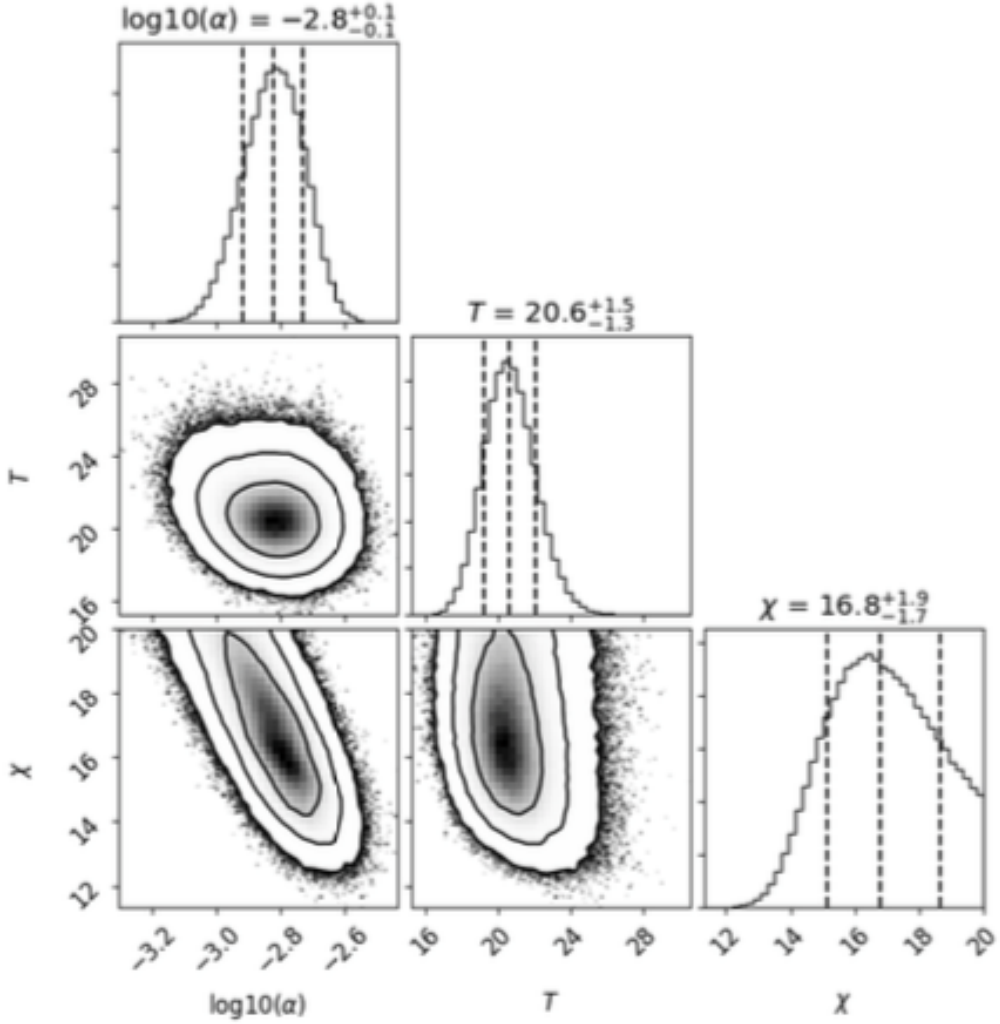


Raettig et al (2015)

Analytical vs Numerical



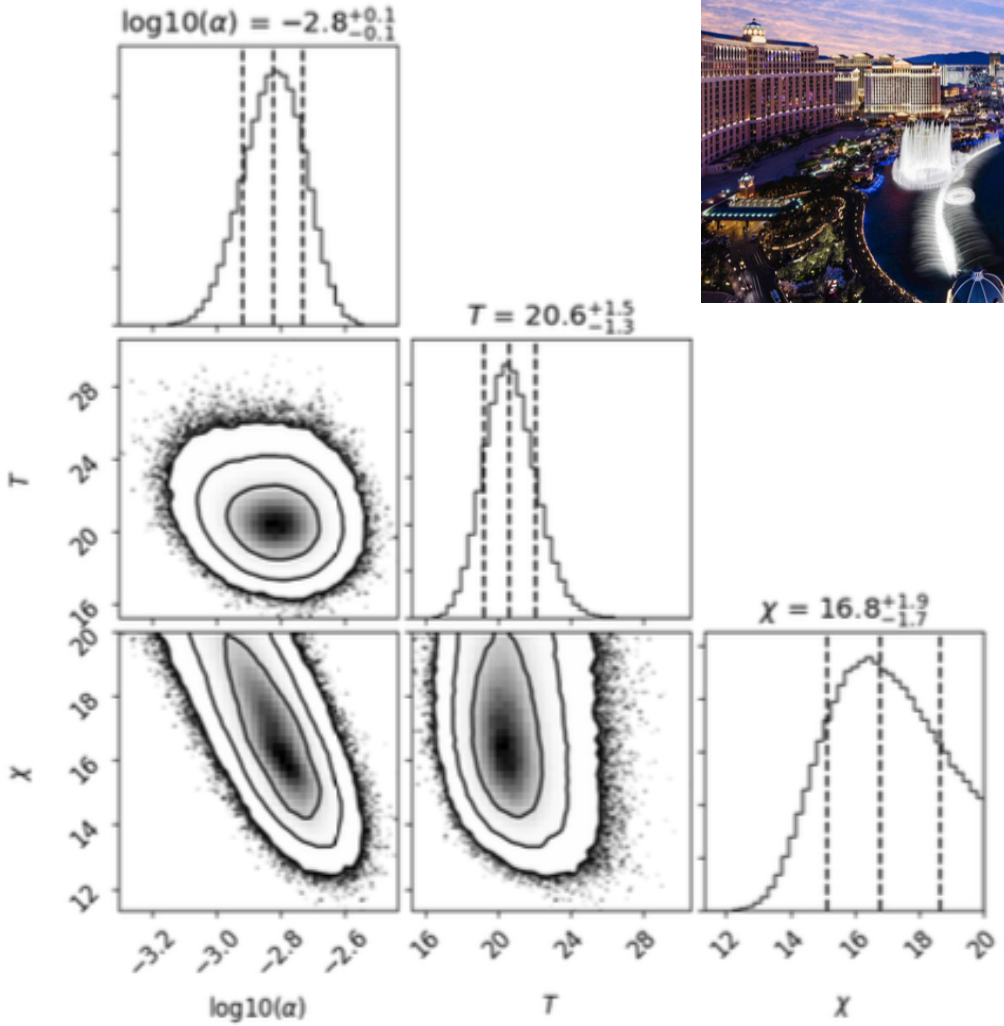
Observational vs Analytical
(Monte Carlo Markov Chain)



Casassus et al. (2018)

Observational vs Analytical
(*Las Vegas* Markov Chain)

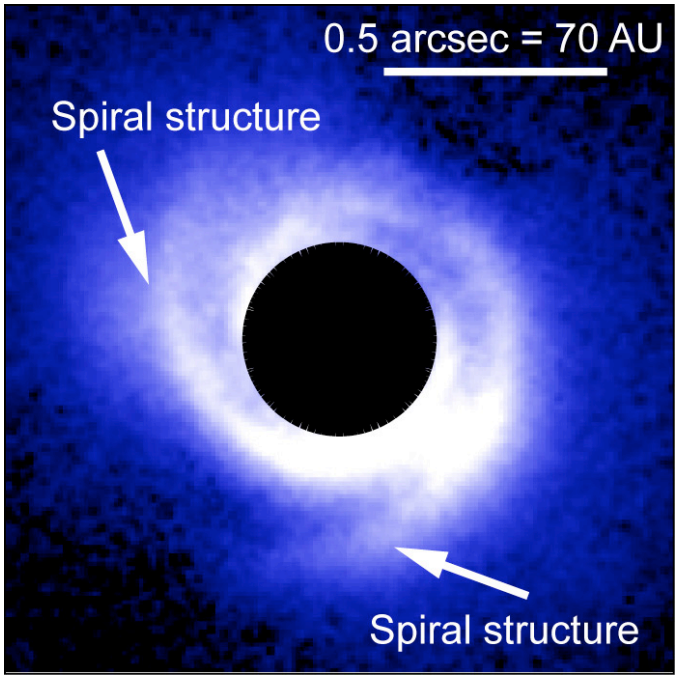




Casassus et al. (2018)

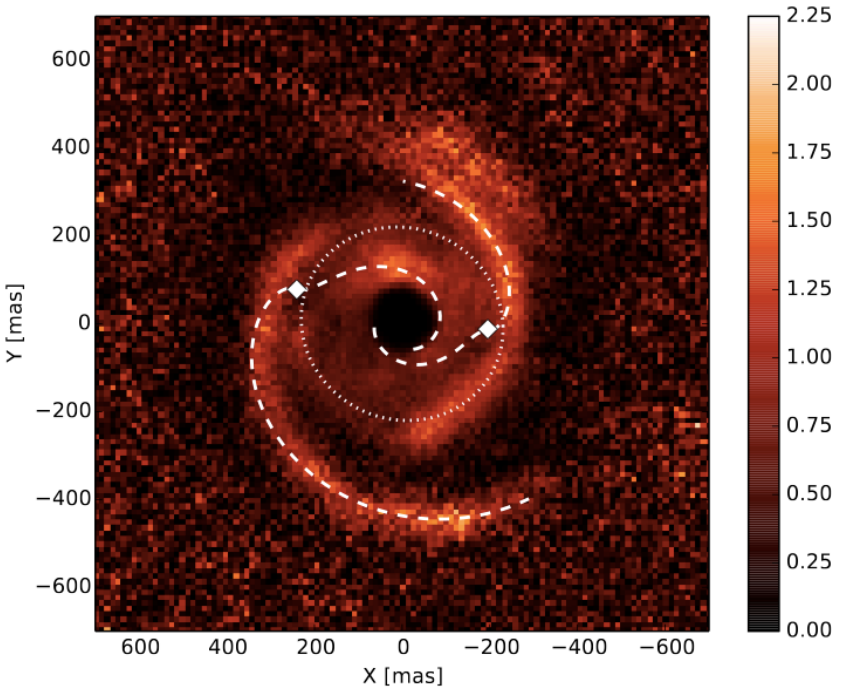
Observational Evidence: Spirals

SAO 206462



Muto et al. (2012)

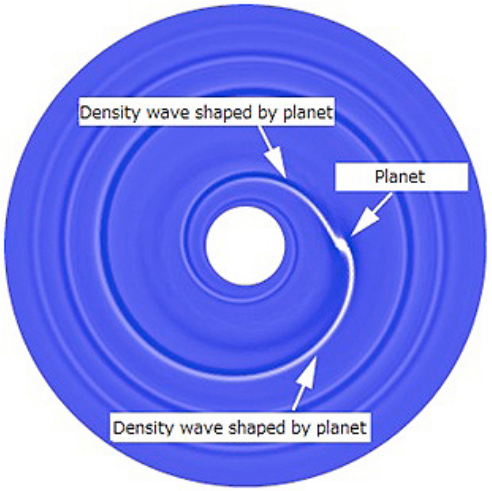
MWC 758



Benisty et al. (2015)

Spiral arm fitting leads to problems

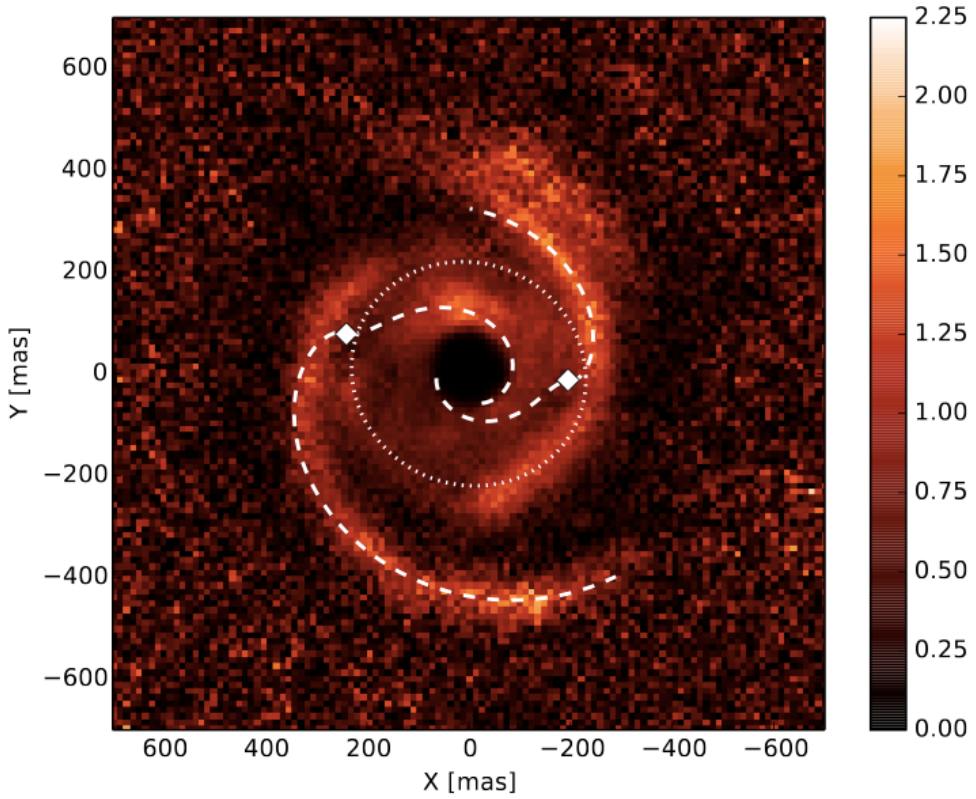
Analytical spiral fit



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

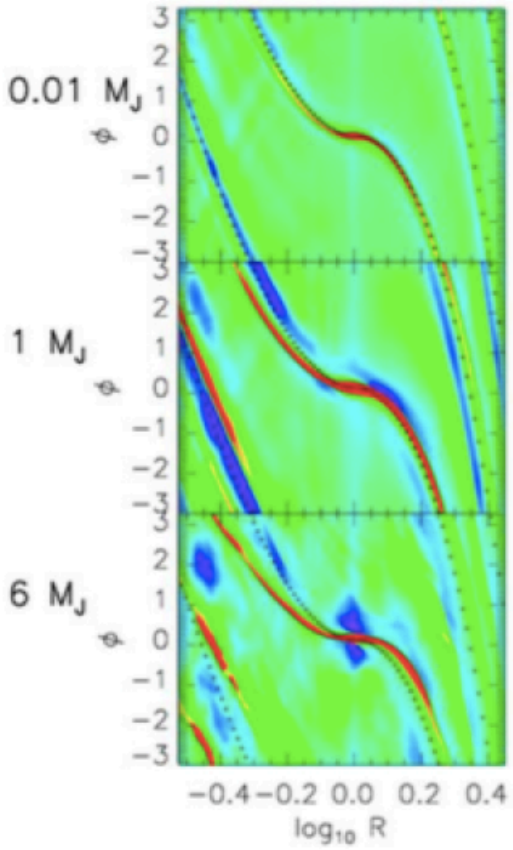
Rafikov (2002)
Muto et al. (2012)

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



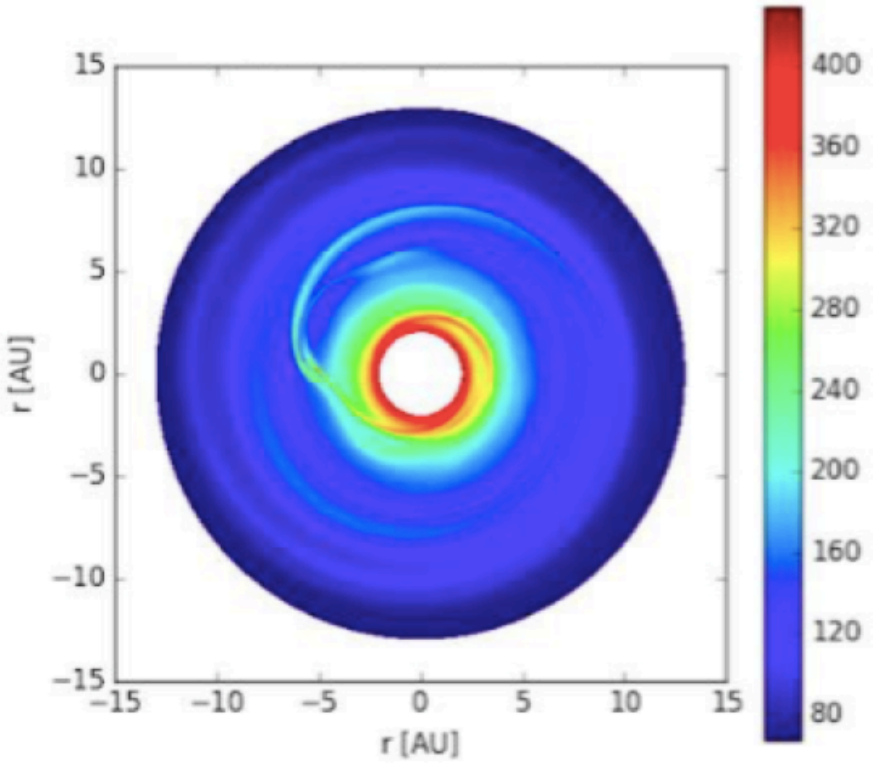
Benisty et al. (2015)

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



Density

Zhu et al. (2015)

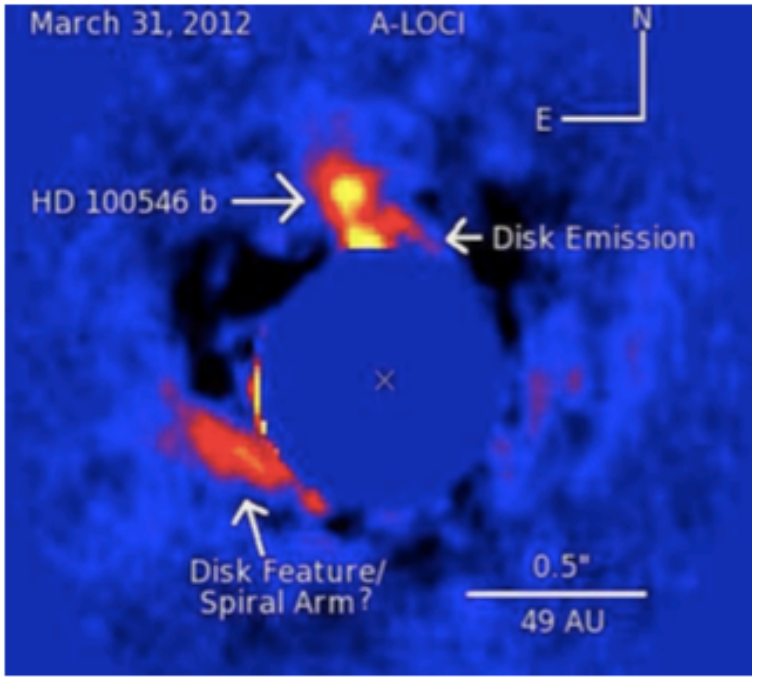


Temperature - **5M_J**

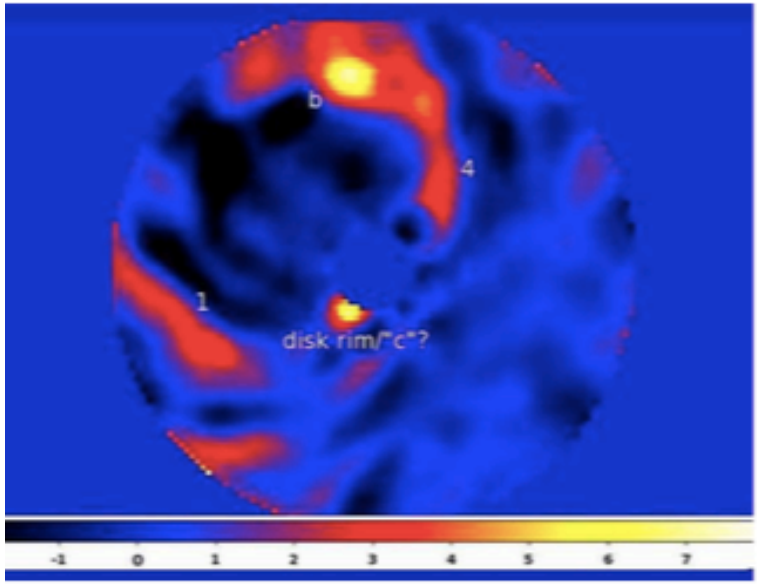
Lyra et al. (2016)

The strange case of thermal emission in HD 100546

L band (~3.5 μm)

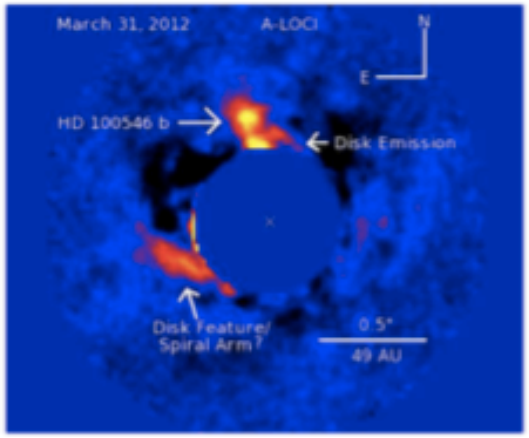


H band (~1.6 μm)

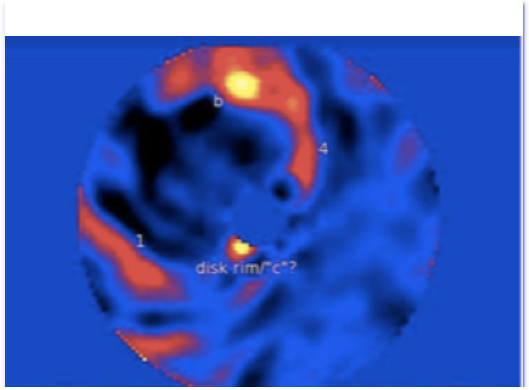


Currie et al. (2014), Currie et al. (2015)

Pinning down the temperature

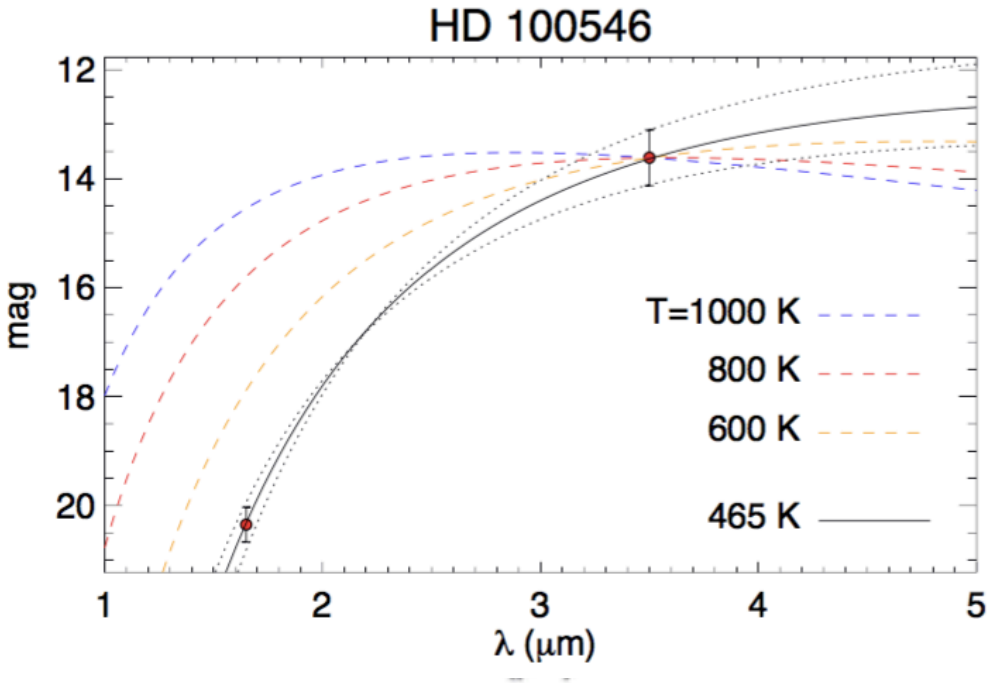


L band



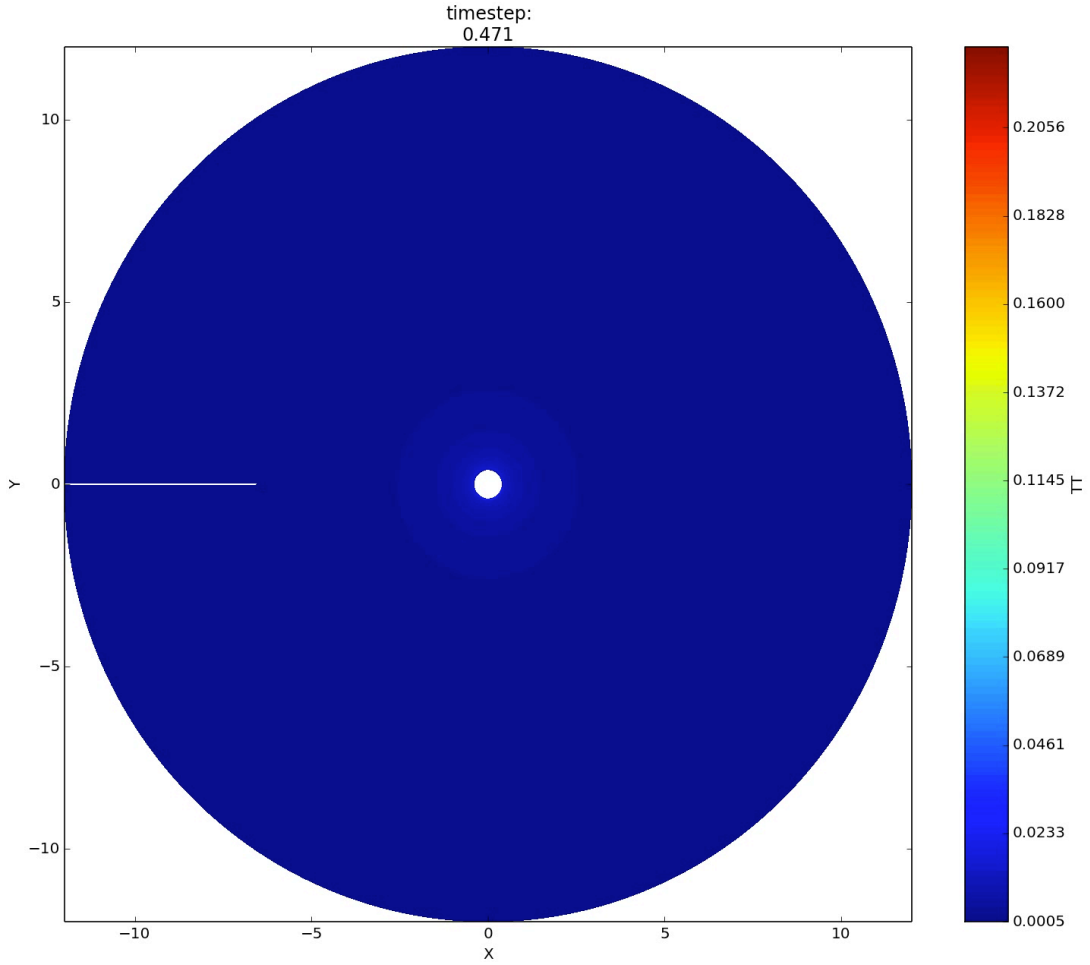
H band

Currie et al. (2014, 2015)



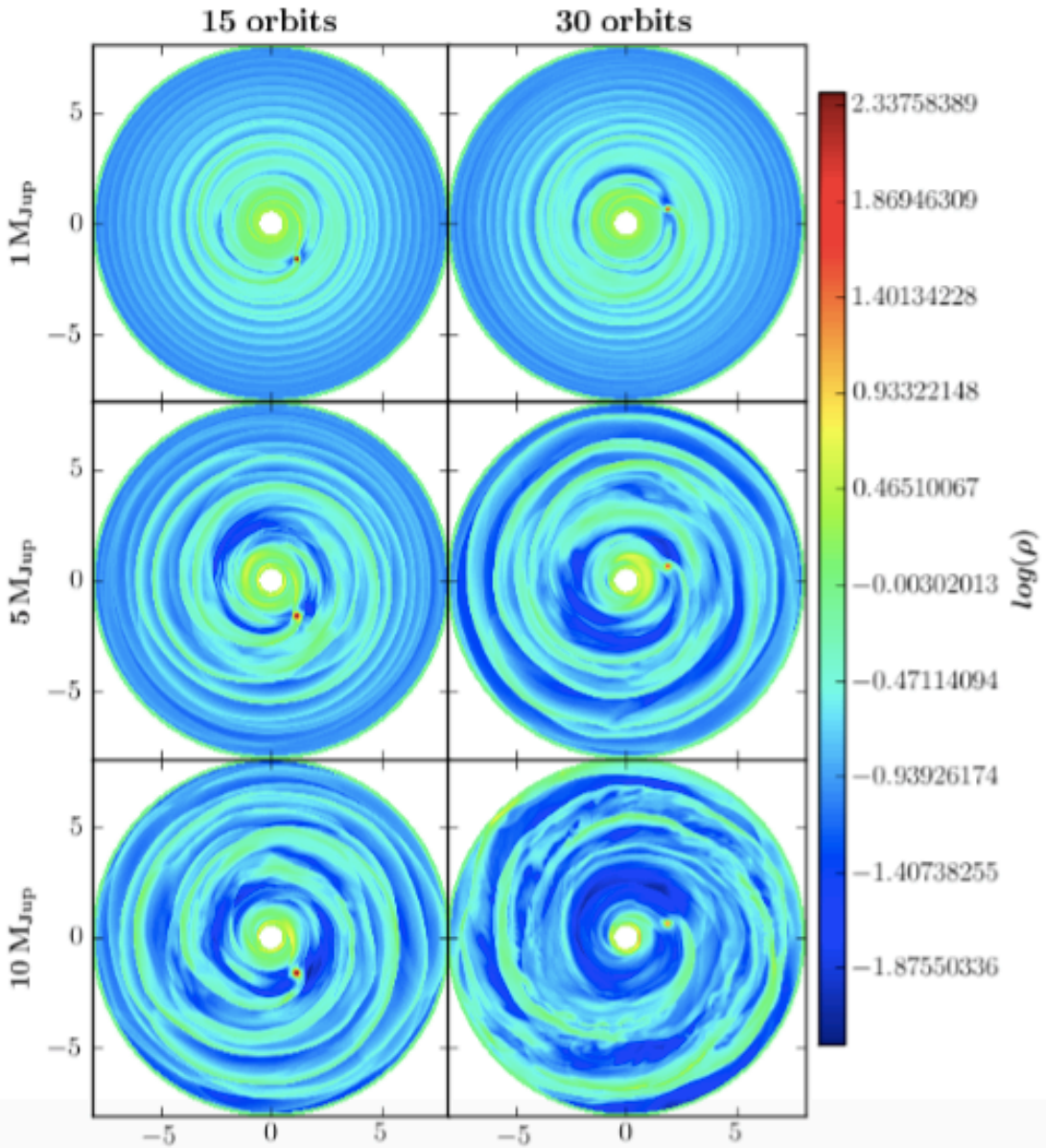
Lyra et al. (2016)

Planet-driven turbulence

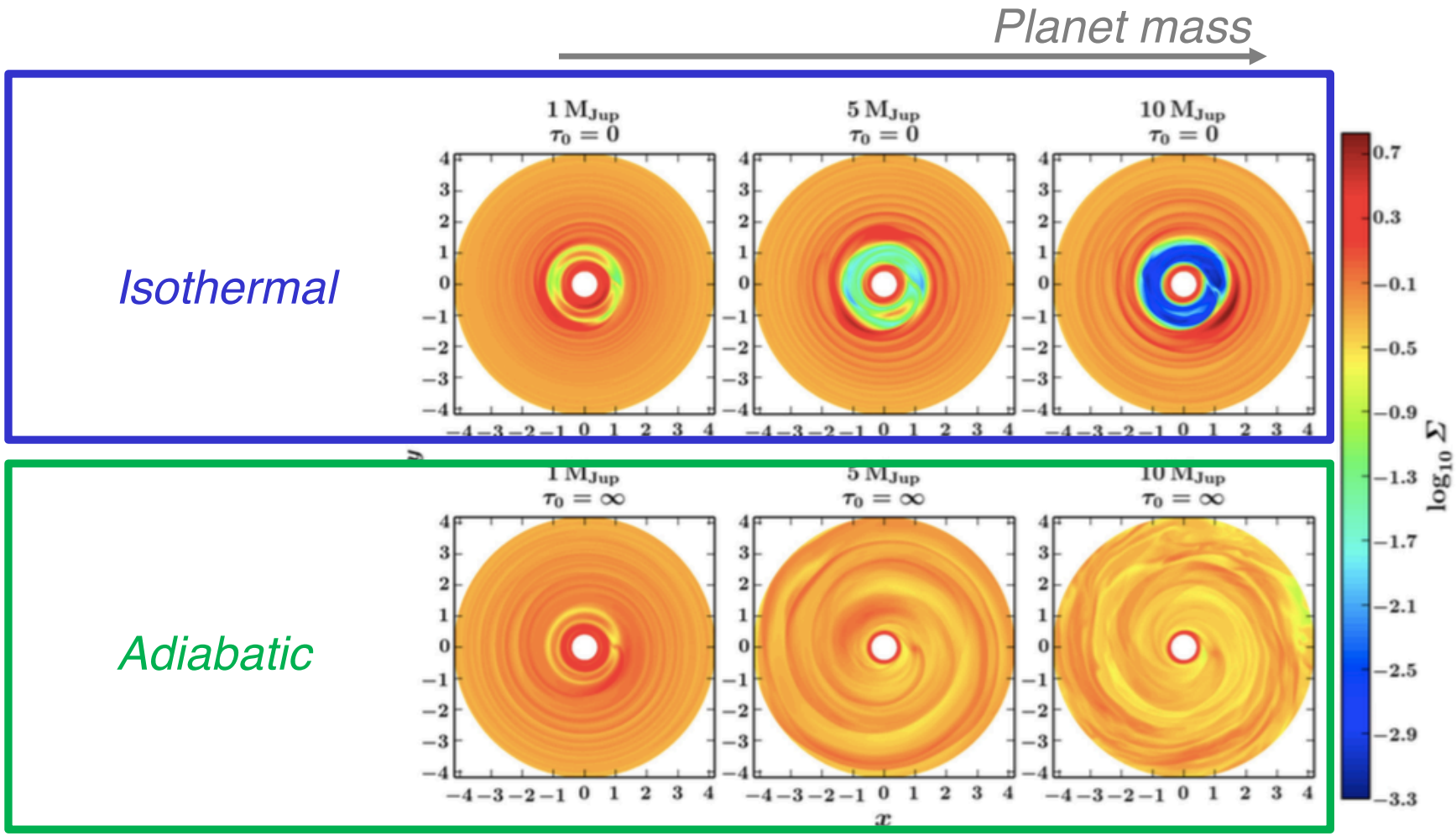


Richert et al. (2015)

Some crazy turbulence showing up at high planet mass….

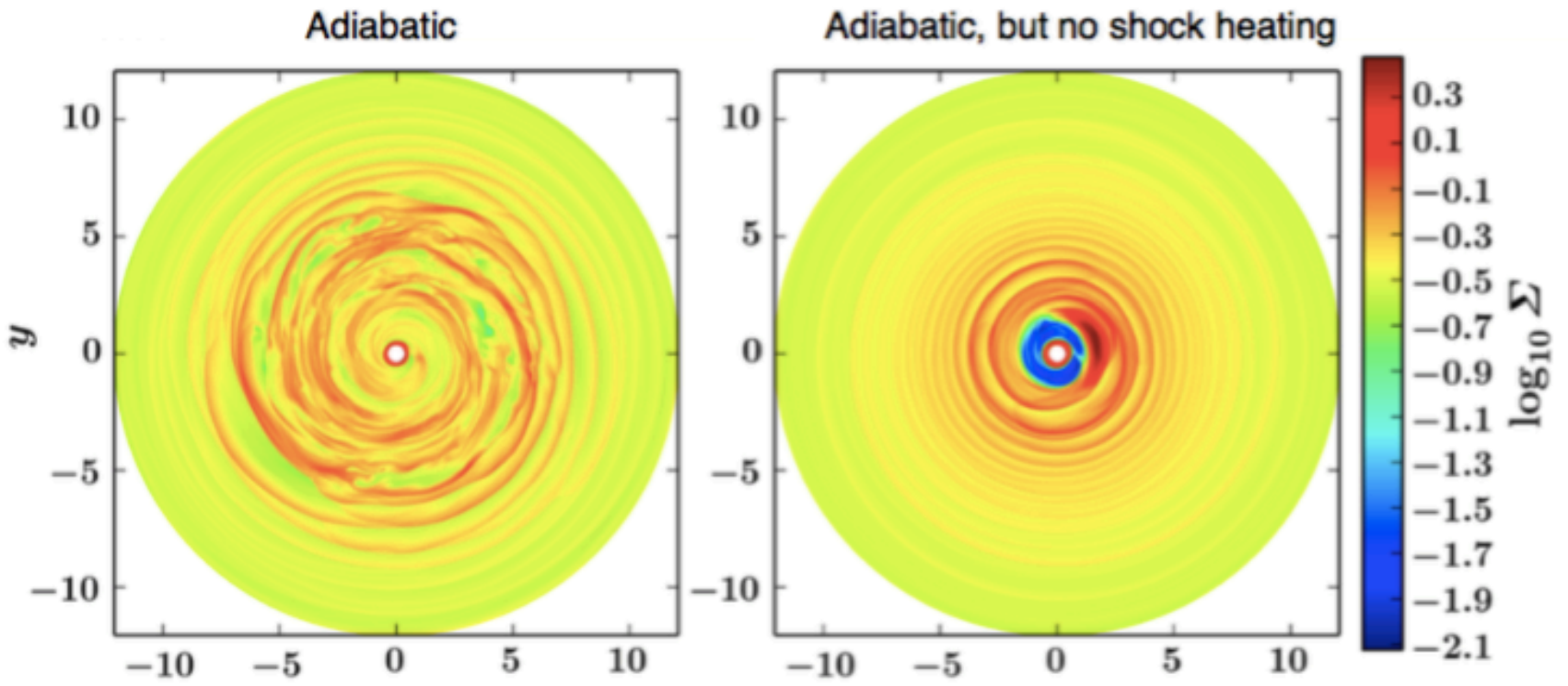


Turbulence in high-mass planets in adiabatic disks



Richert et al. (2015)

The energy source: shock heating!



Richert et al. (2015)

3D shocks: ascending bores and breaking waves

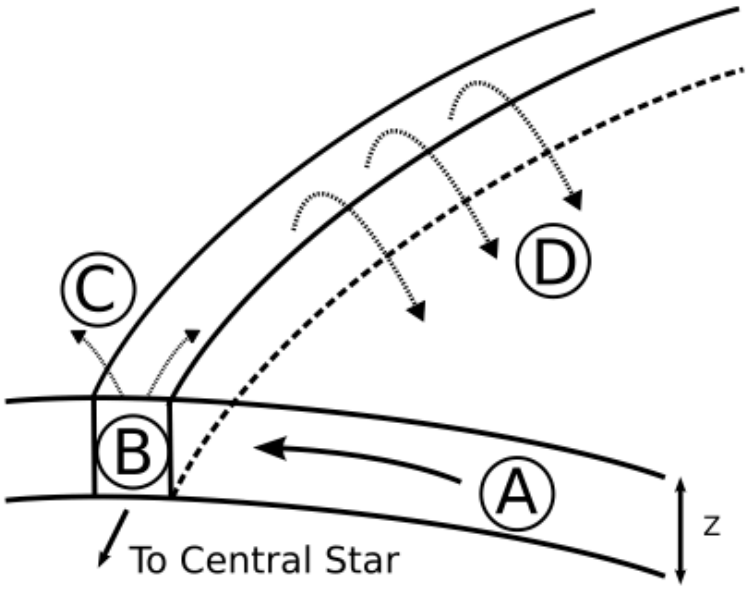
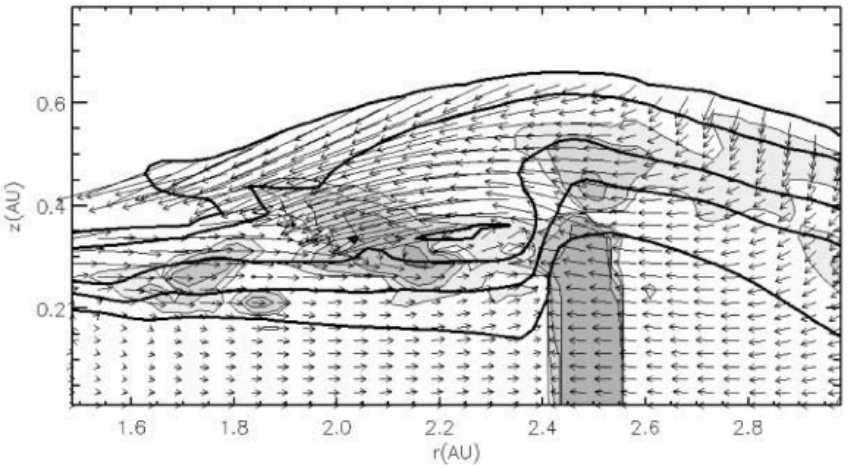
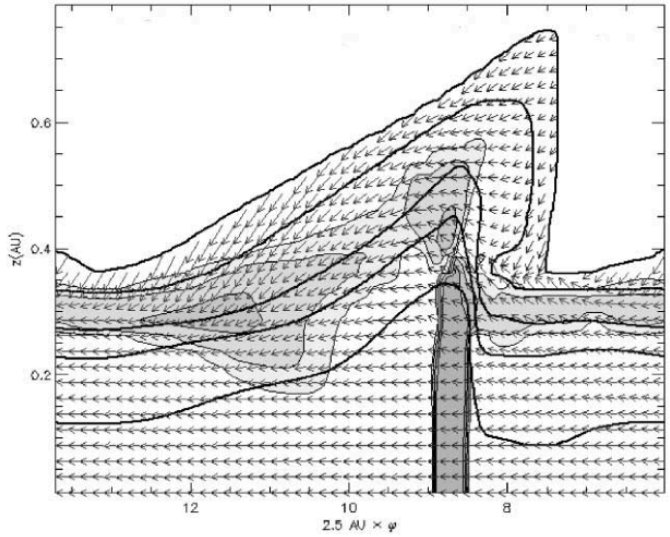


FIG. 2.—Cartoon depicting the gas flow in a shock bore in the frame of the spiral shock inside corotation. The gas in the preshock region flows into the spiral shock (A). The shock (B) causes the material to be out of vertical force balance and a rapid expansion results (C). Due to spiral streaming and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





Boley & Durisen (2006)

Radiative transfer approximation

$$T\frac{\mathrm{D}s}{\mathrm{D}t} = -c_V \frac{(T - T_{\mathrm{ref}})}{t_{\mathrm{cool}}} + \Gamma_{\mathrm{sh}},$$

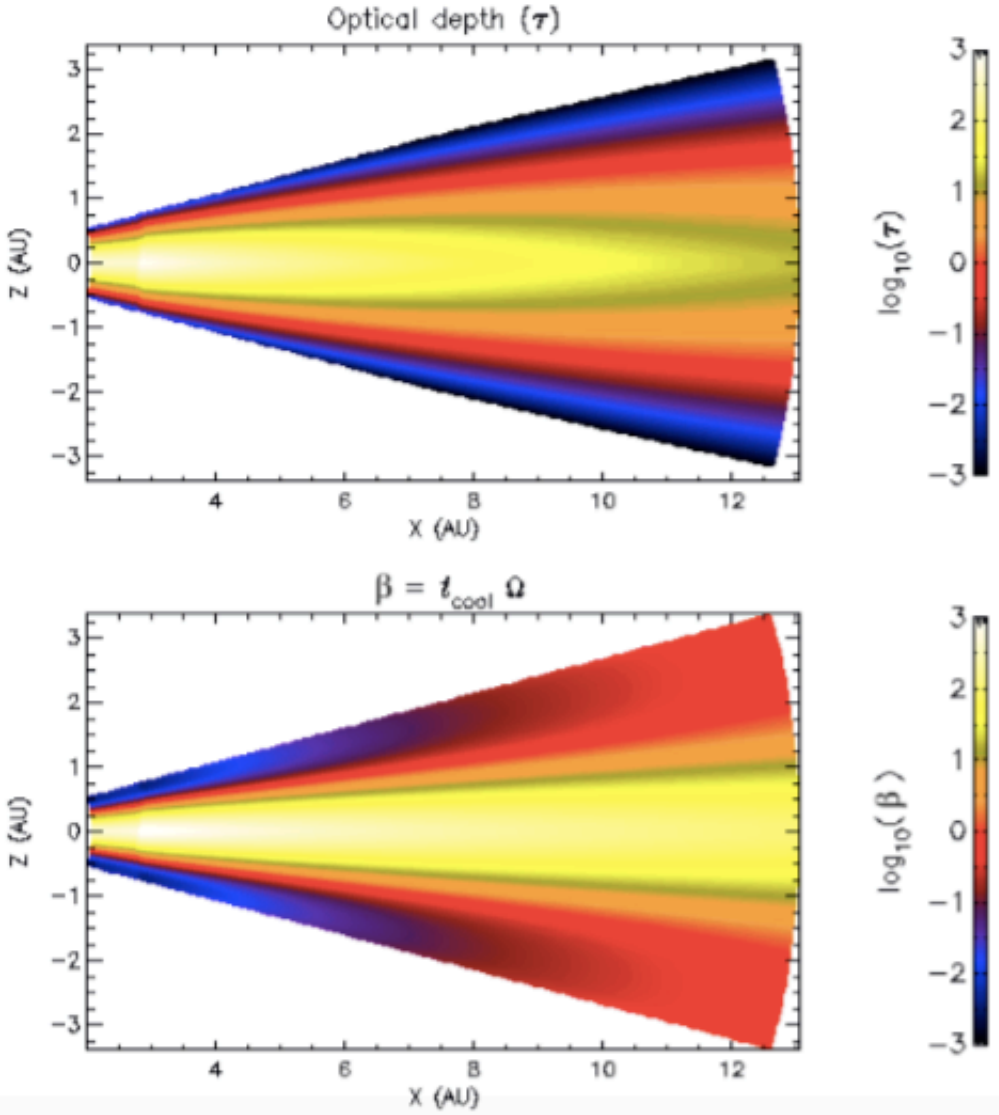
$$t_{\mathrm{rad}} = E/\dot{E}$$

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

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

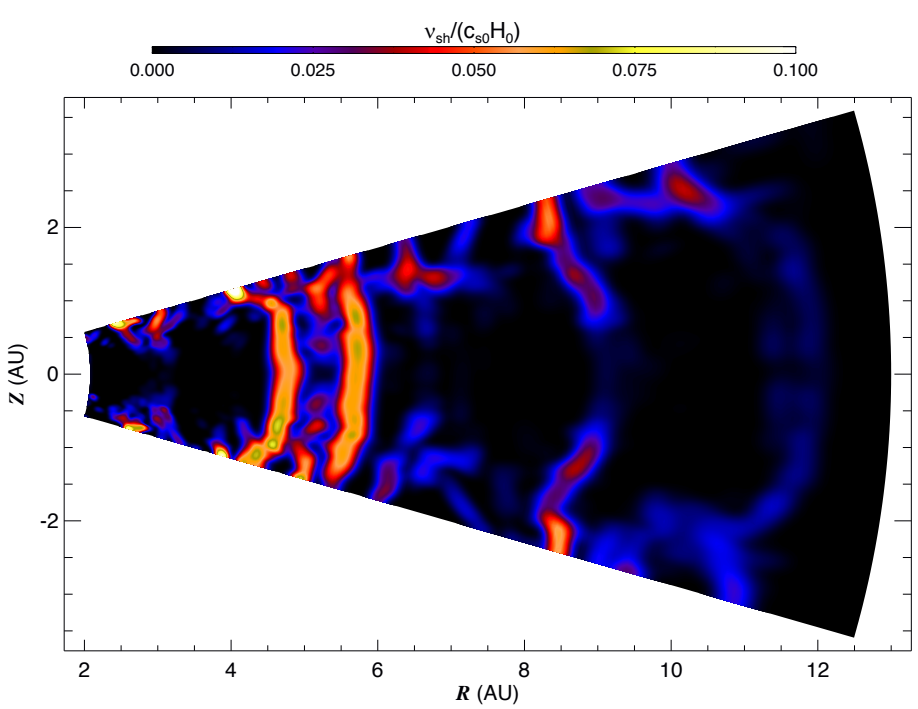
$$t_{\mathrm{cool}} = \frac{c_V \rho H \tau_{\mathrm{eff}}}{3\sigma T^3}.$$

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

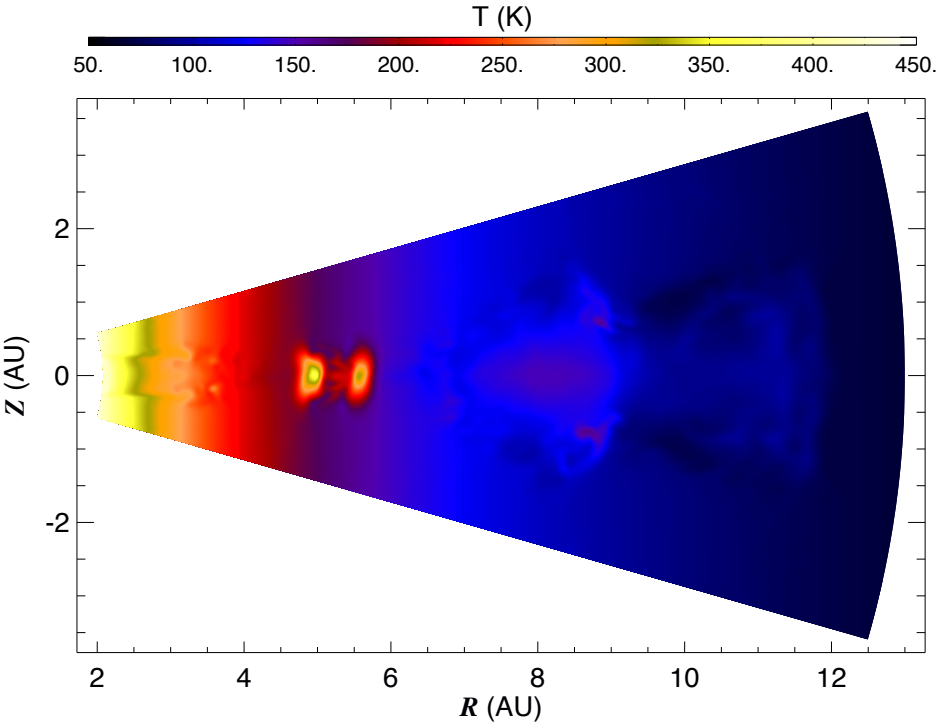


3D: Shock bores

Shocks (velocity convergence)

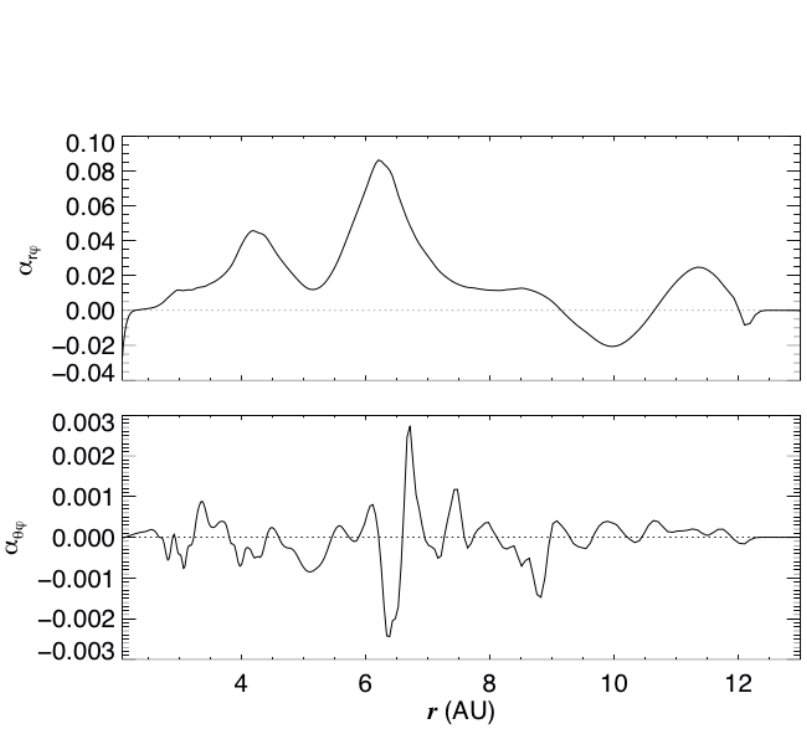


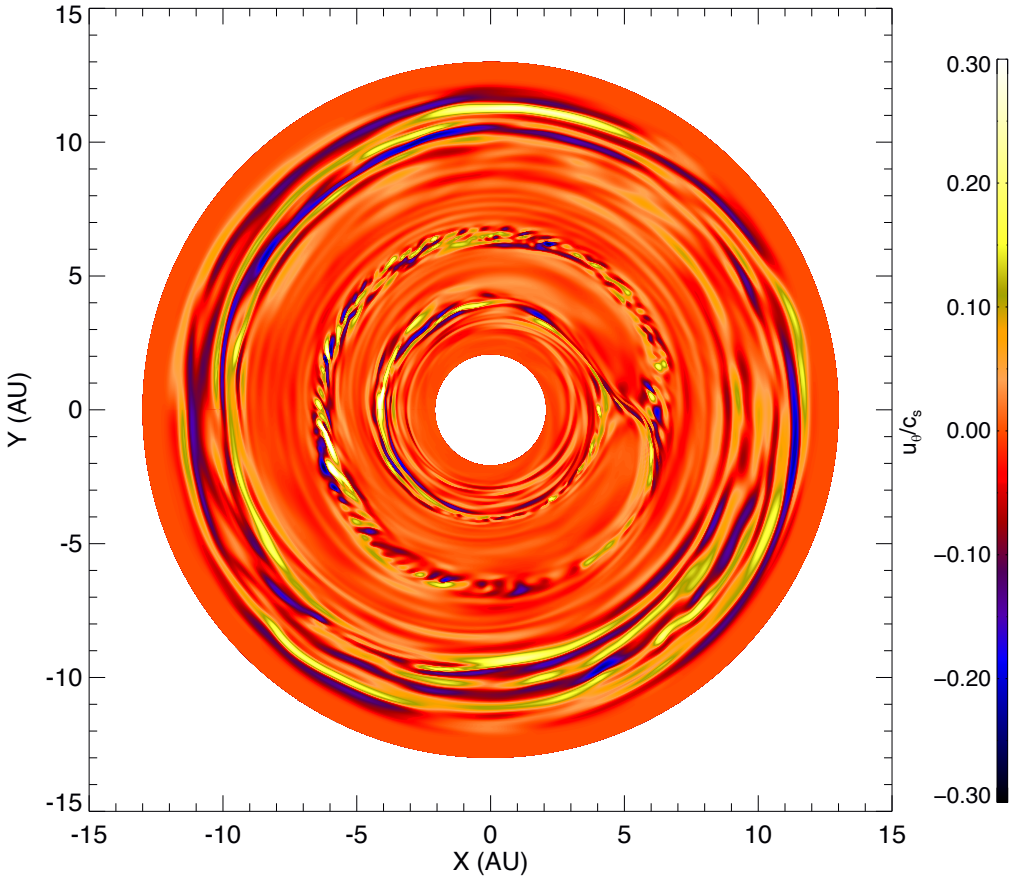
Temperature



Lyra et al. (2016)

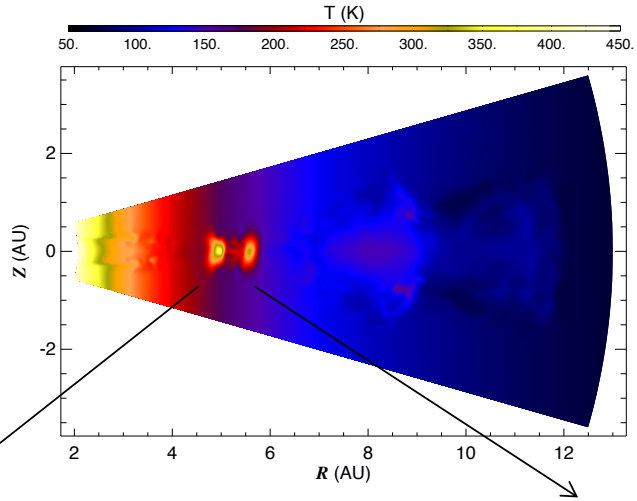
Prediction for spectroscopy: Turbulent surf

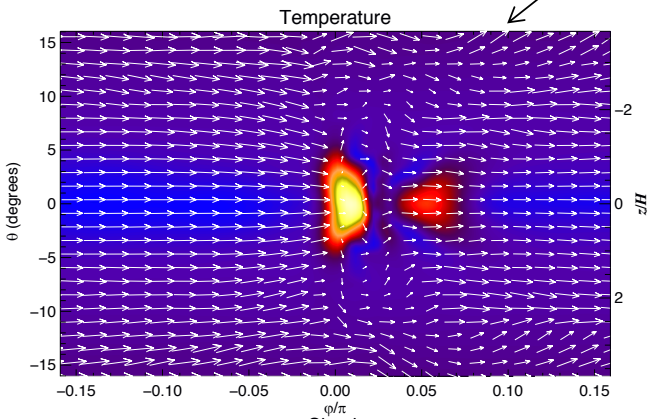




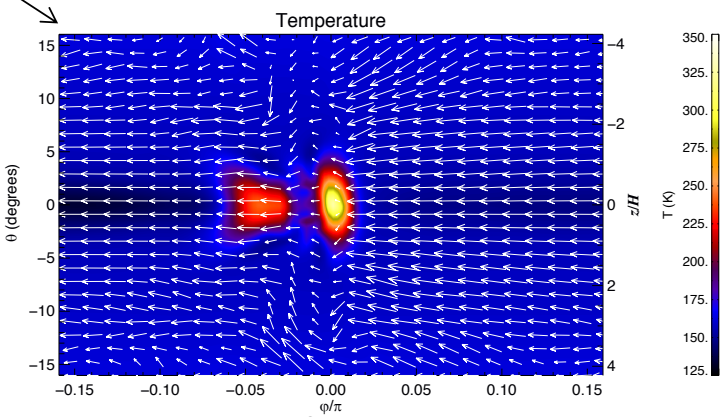
Lyra et al. (2016)

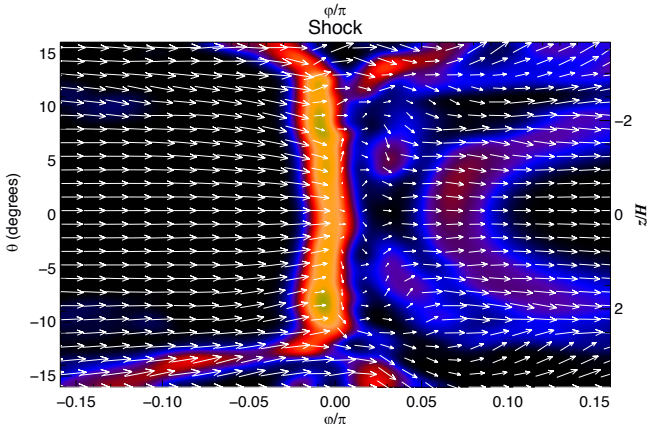
3D shocks: bores and breaking waves





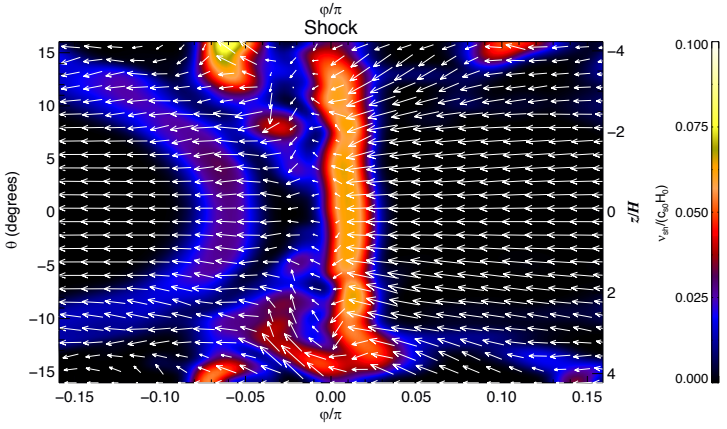
Temperature





Div u
(shock)

Lyra et al. (2016)



Shock heating and opacities

$$\mathcal{H}_{\rm sh} = \rho \nu_{\rm sh} (\boldsymbol{\nabla} \cdot \boldsymbol{u})^2$$

$$\nu_{\rm sh} = c_{\rm sh} \left\langle \max_3 [(-\boldsymbol{\nabla} \cdot \boldsymbol{u})^+] \right\rangle [\min(\Delta x)]^2$$

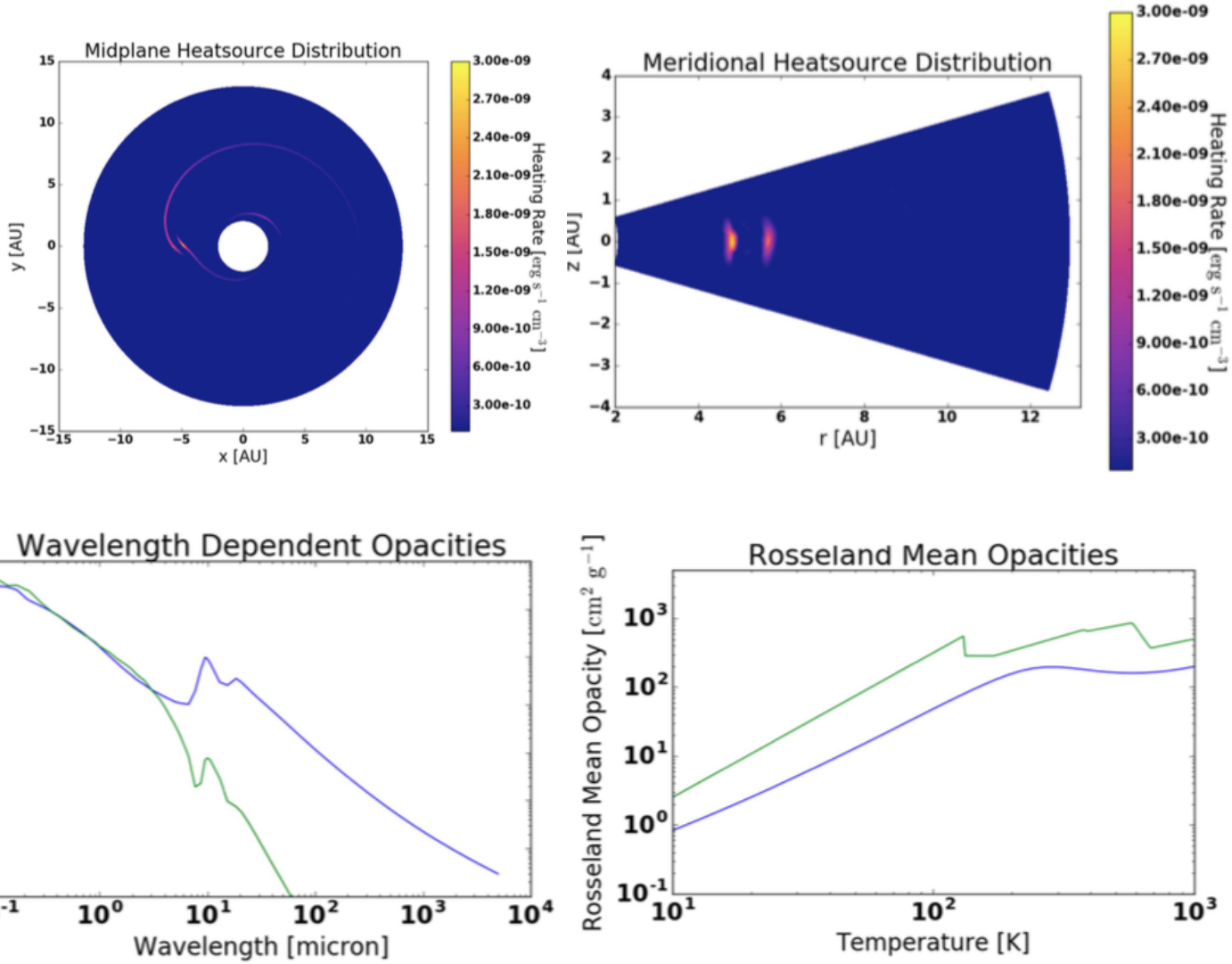
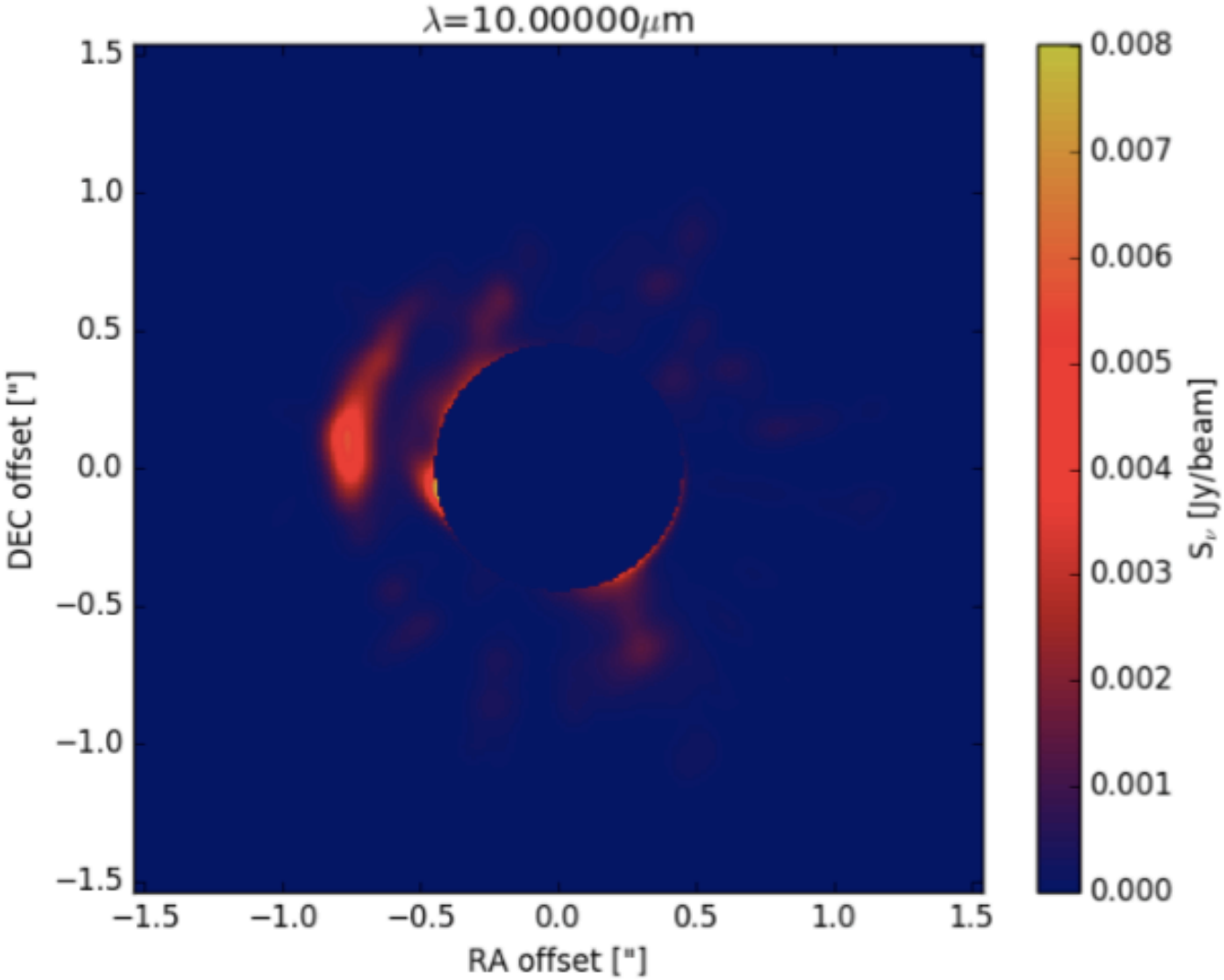


Figure 1. Wavelength-dependent opacities from Preibisch et al. (1993), including the absorption (top, blue) and scattering (top, green) opacities, input into RADMC-3D. The calculated Rosseland mean opacities (bottom, blue) match the Rosseland mean of Bell et al. (1997). The piece-wise Rosseland Mean opacity based on D'Angelo et al. (2003) and implemented in the Pencil Code (bottom, green) only varies by at most a factor of two from the calculation.

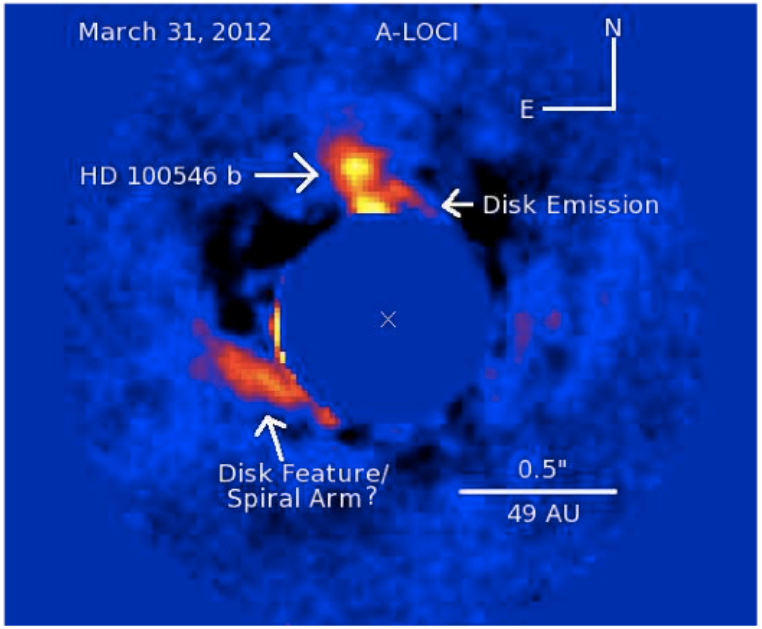
Hord et al. (2017)

Synthetic image by RADMC3D and shock heating

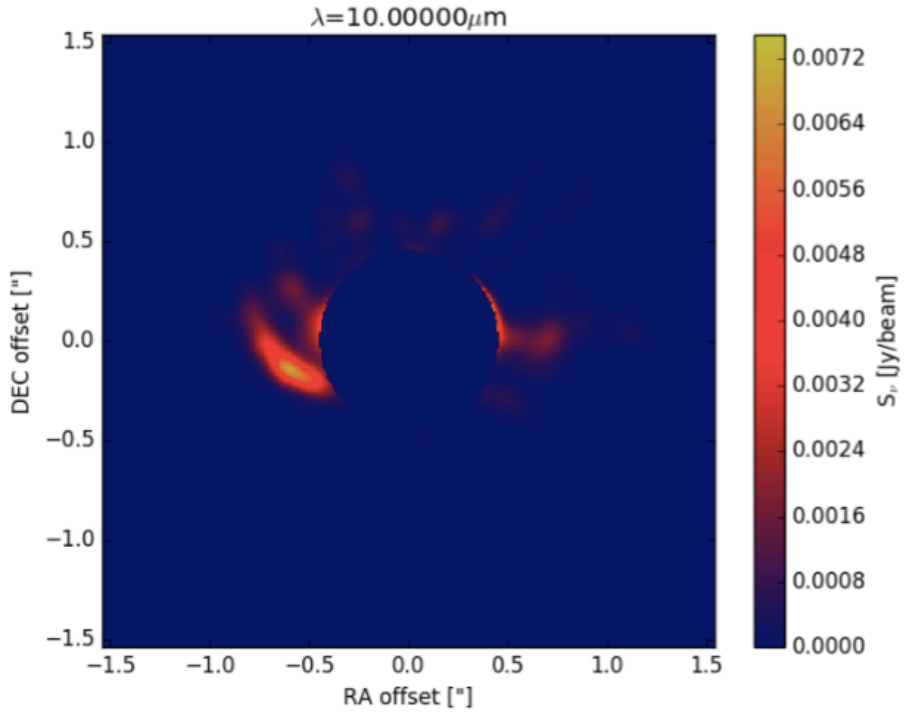


Hord et al. (2017)

Observation vs Synthetic Image



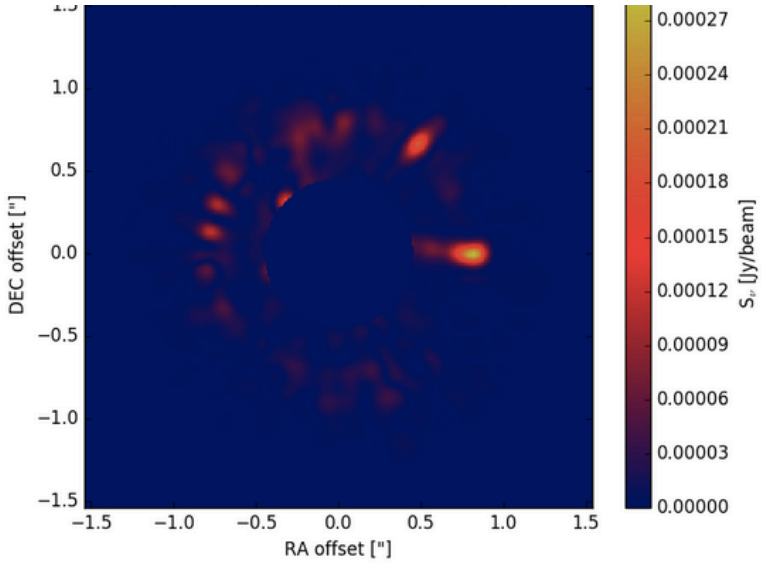
Currie et al. (2015)



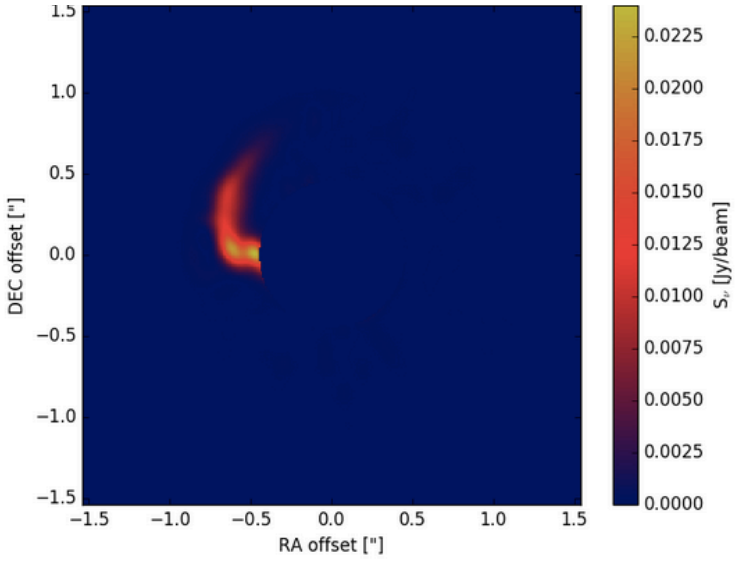
Hord et al. (2017)

Effect of shocks alone

1 μm

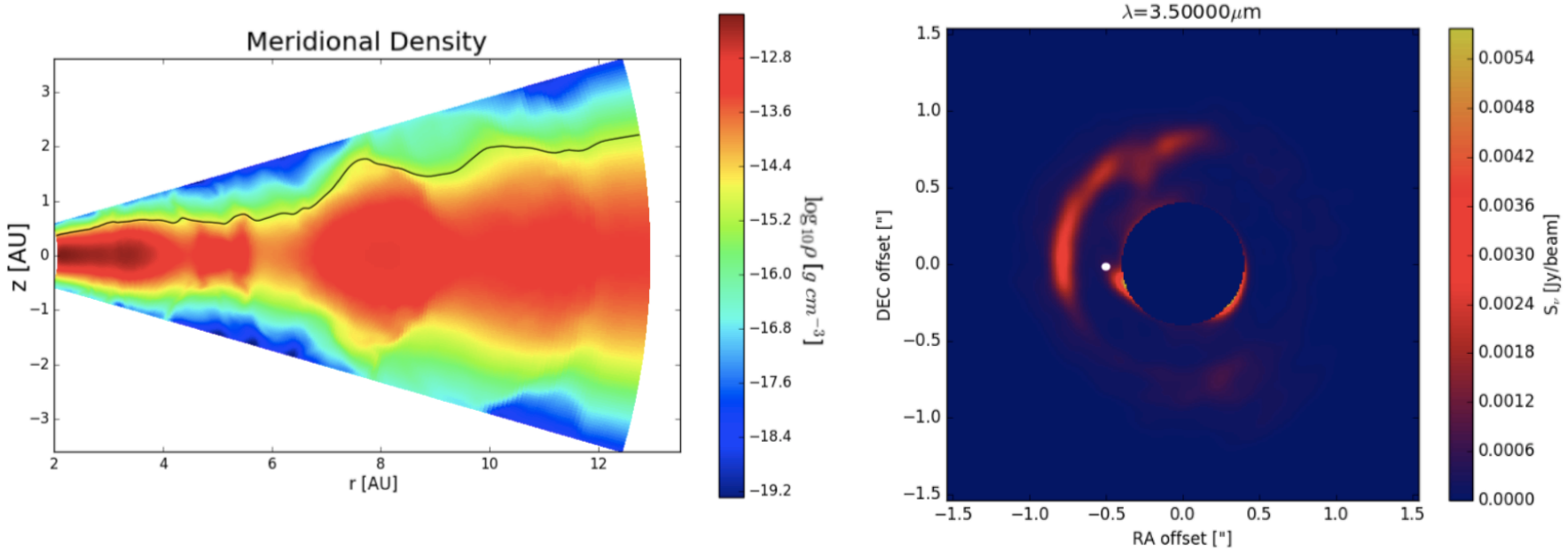


10 μm



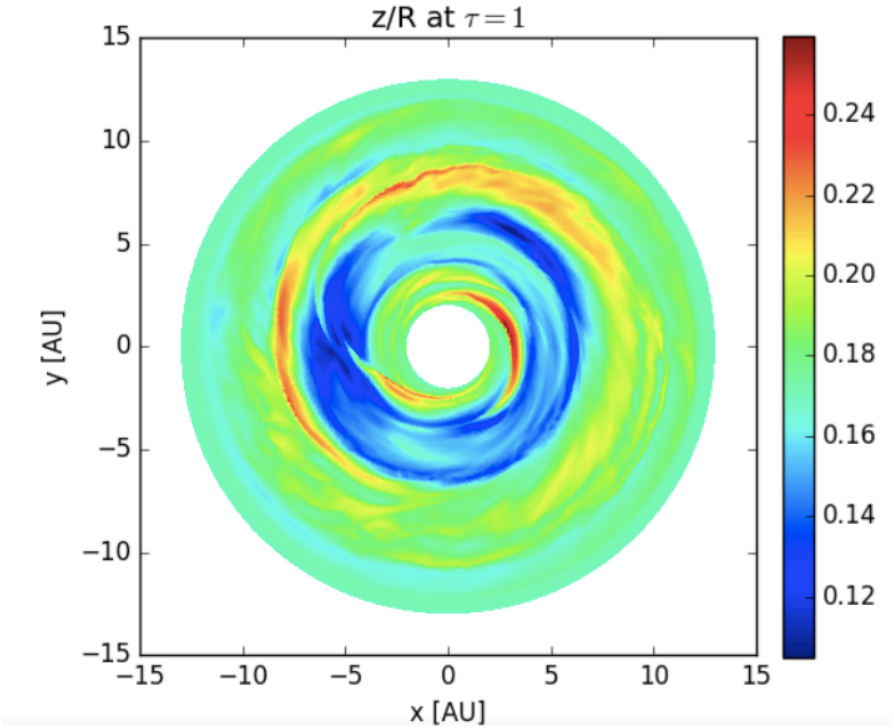
Hord et al. (2017)

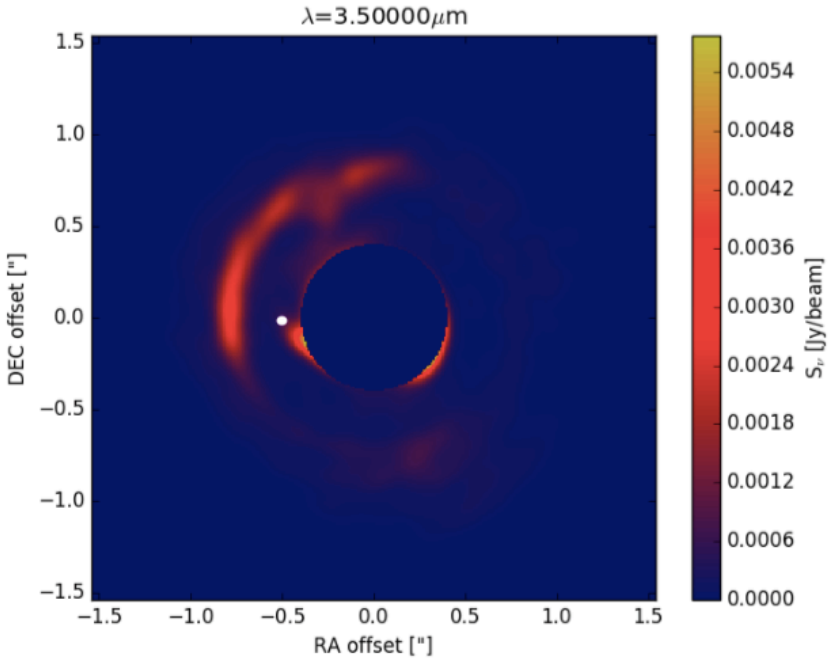
Scattering – A puffed up outer gap



Hord et al. (2017)

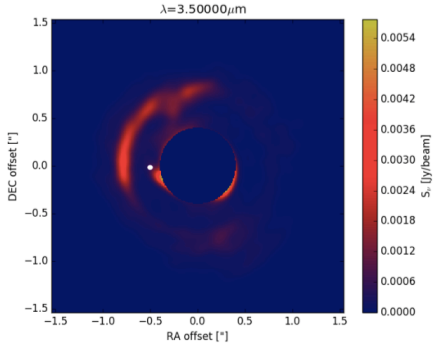
Scattering

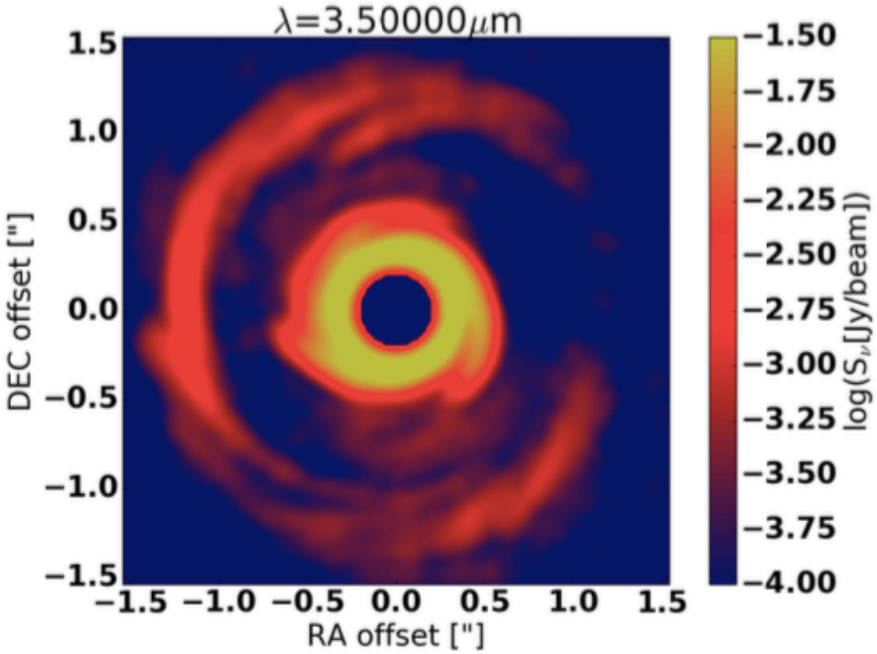


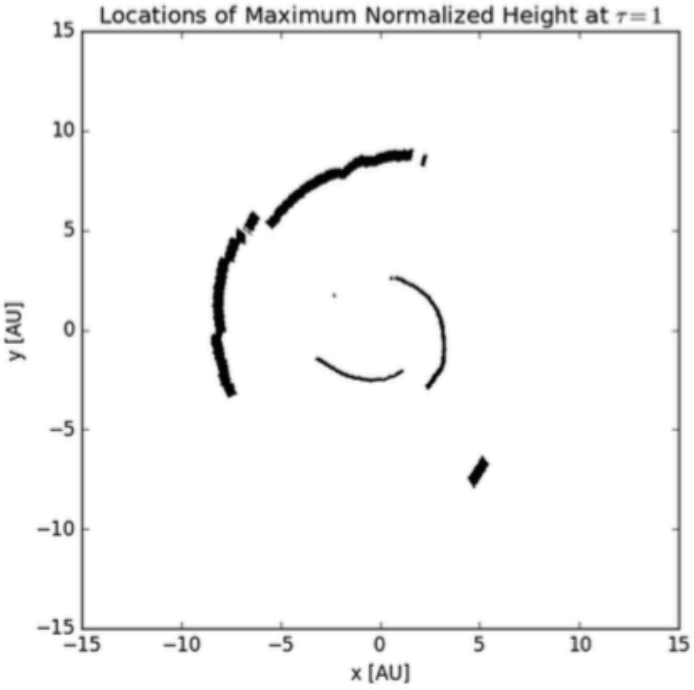


Hord et al. (2017)

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







Hord et al. (2017)

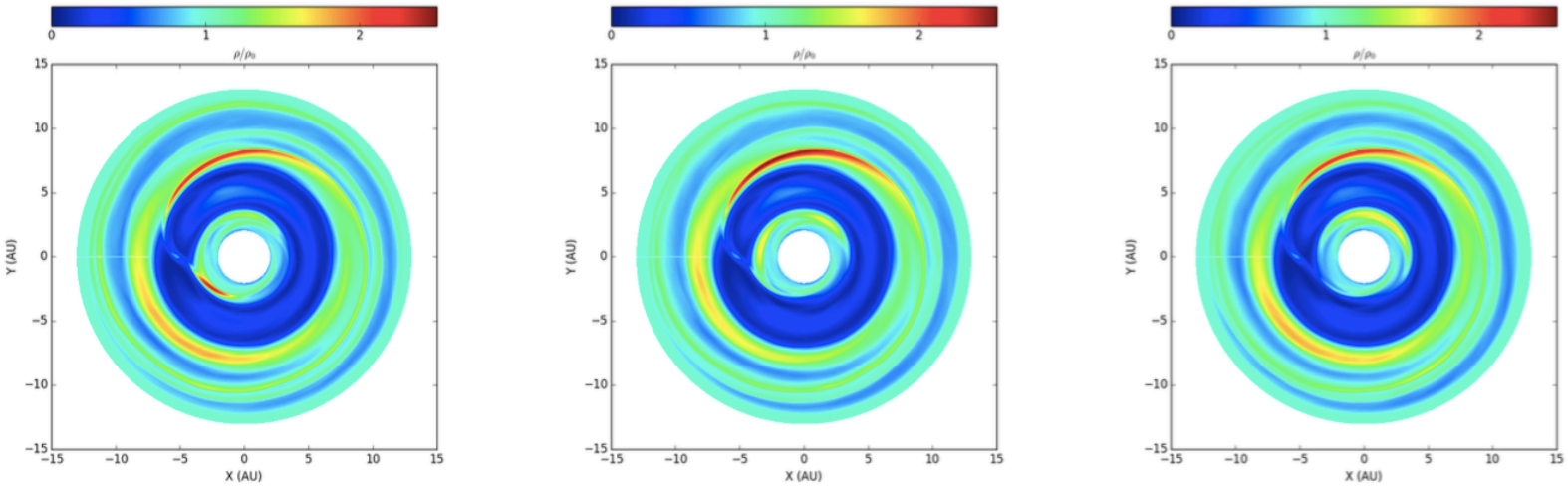
The pattern is stationary

T = 39 orbits

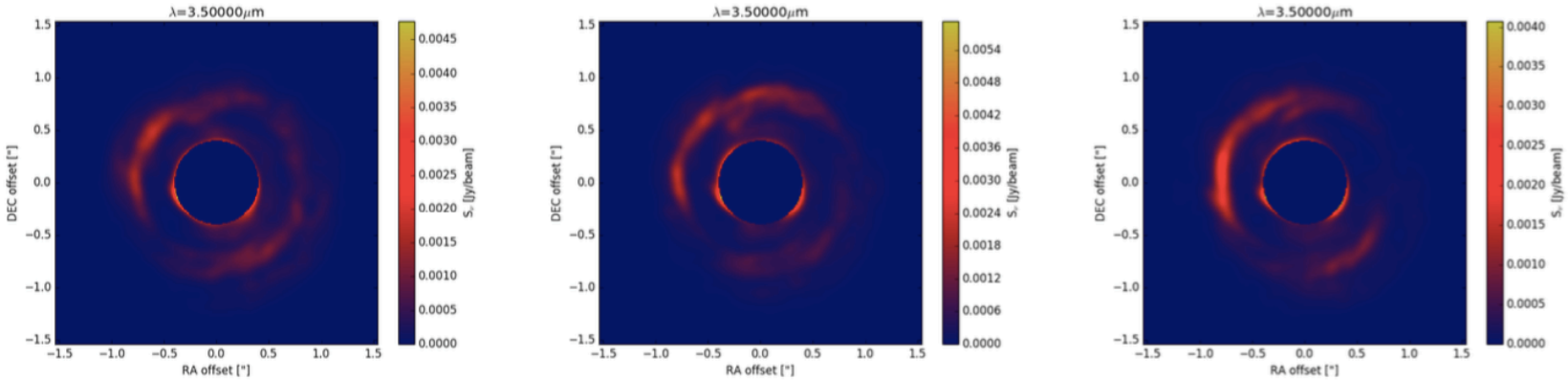
T = 40 orbits

T = 41 orbits

Density

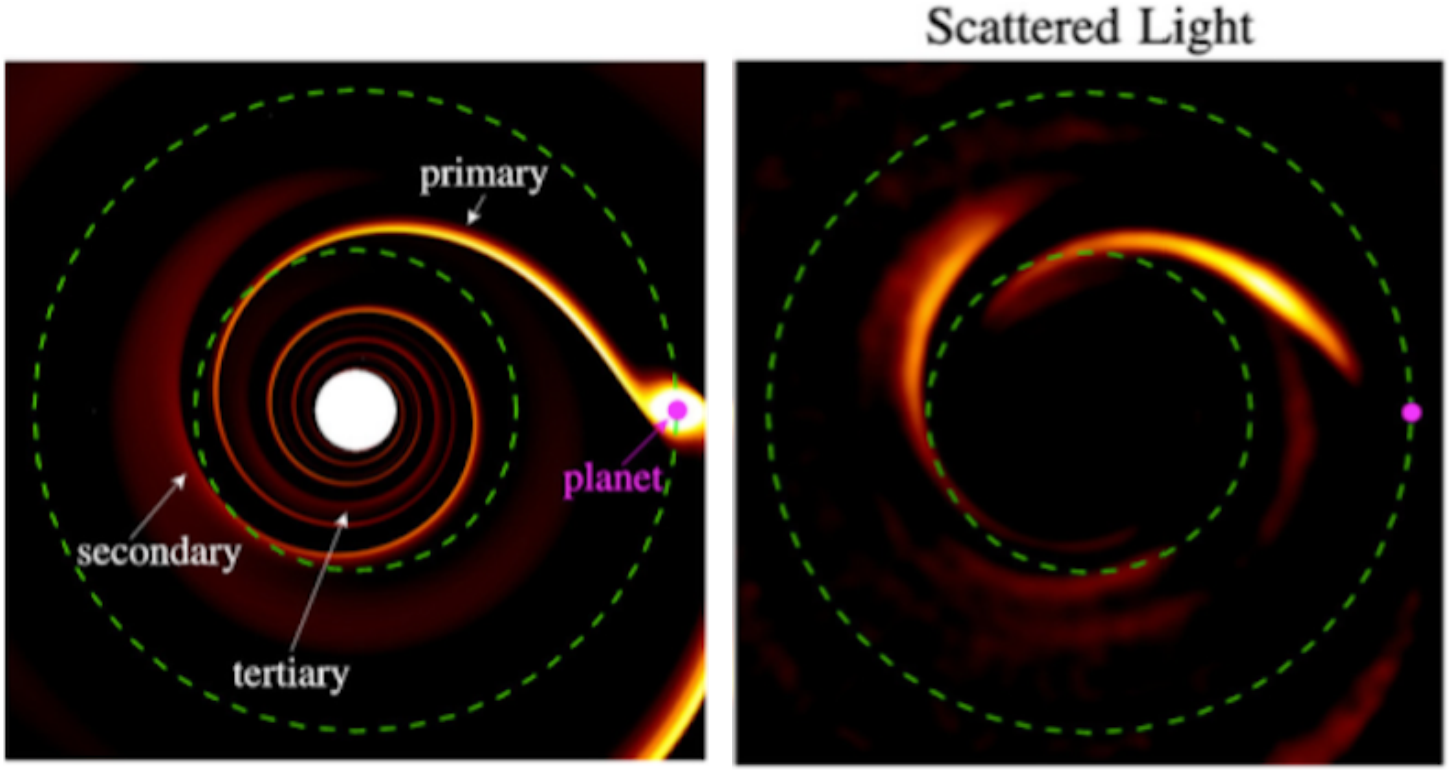


Intensity



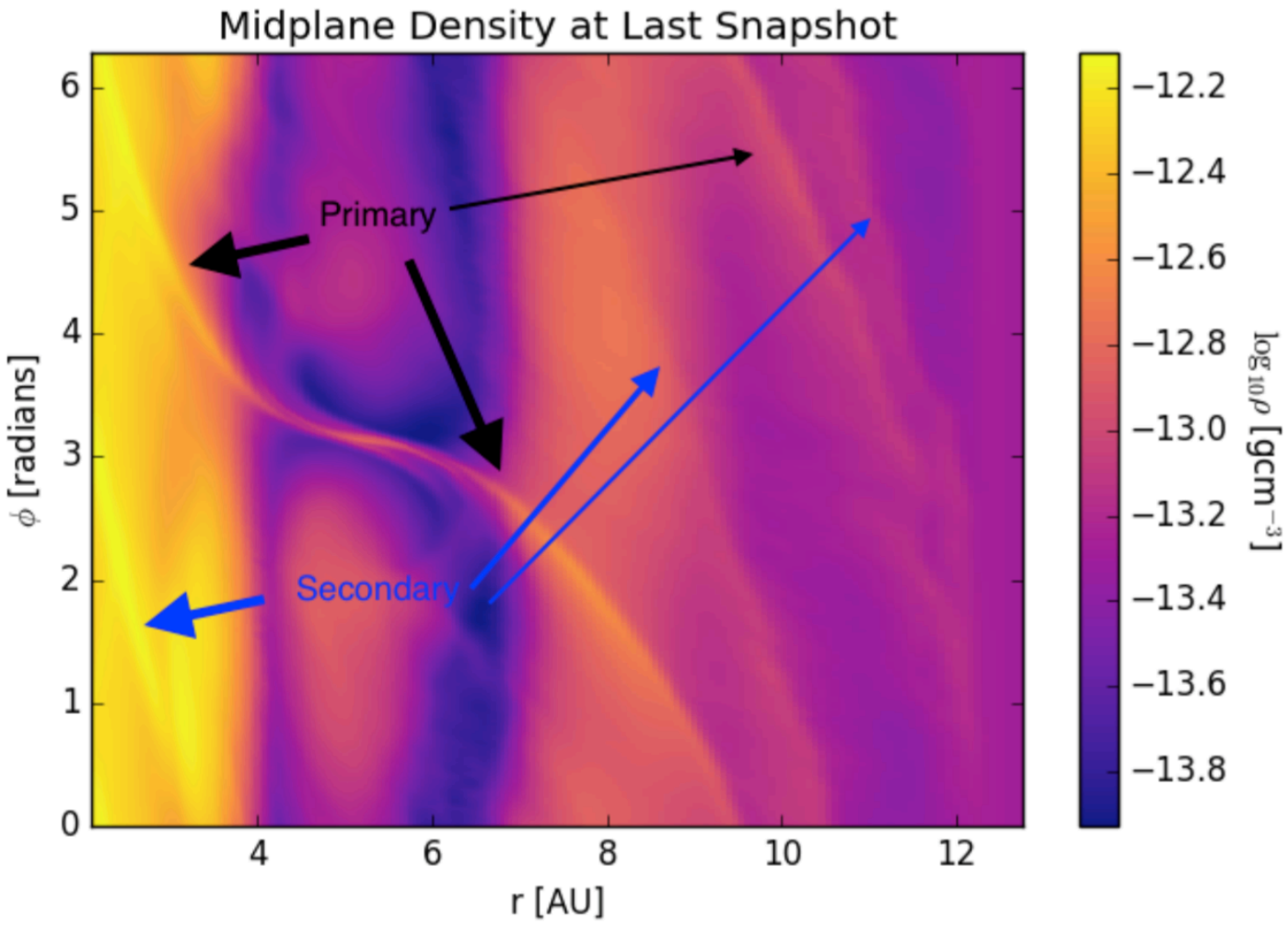
Hord et al. (2017)

Primary and Secondary spiral arms



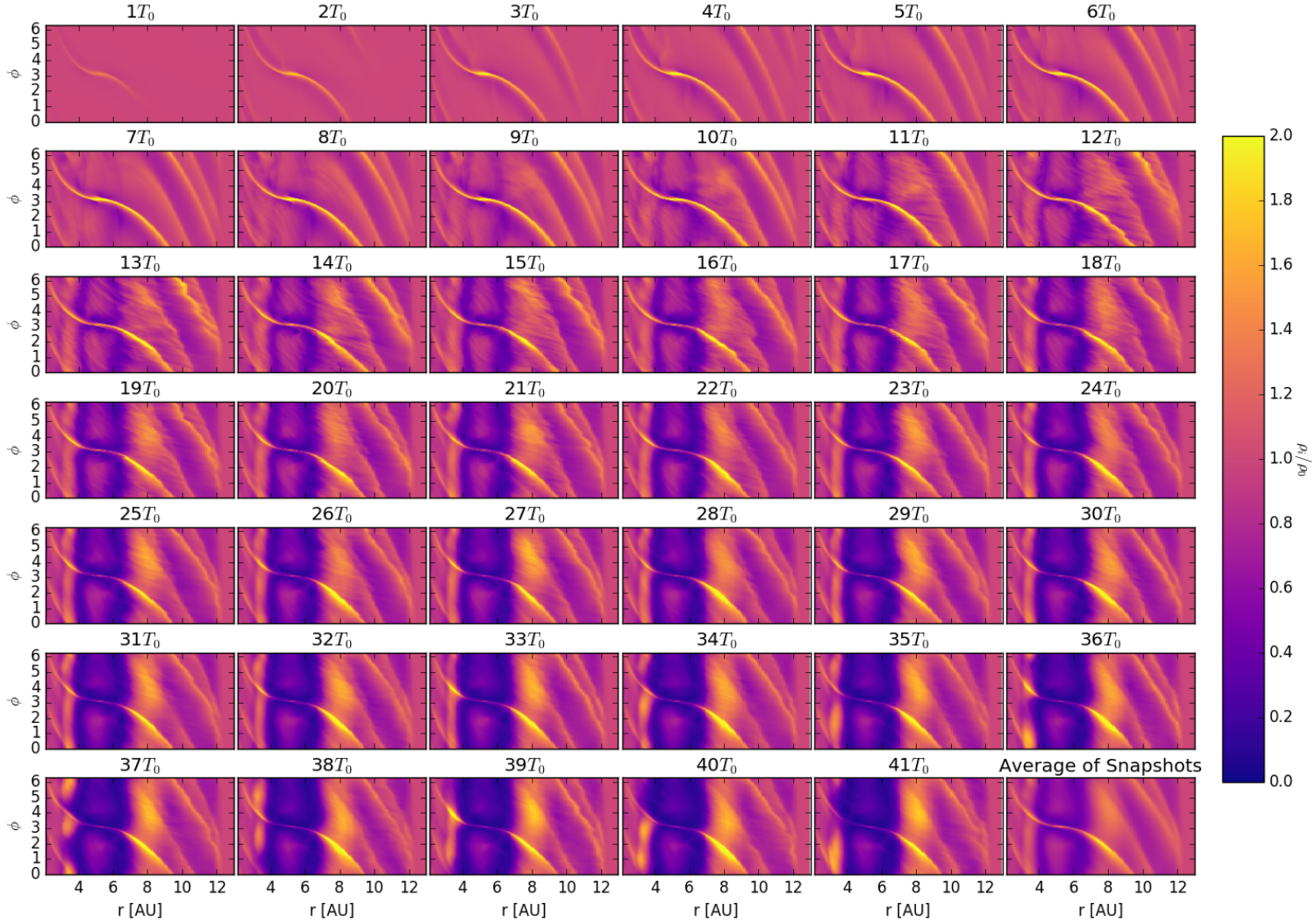
Fung and Dong (2015)

Primary and Secondary spiral arms



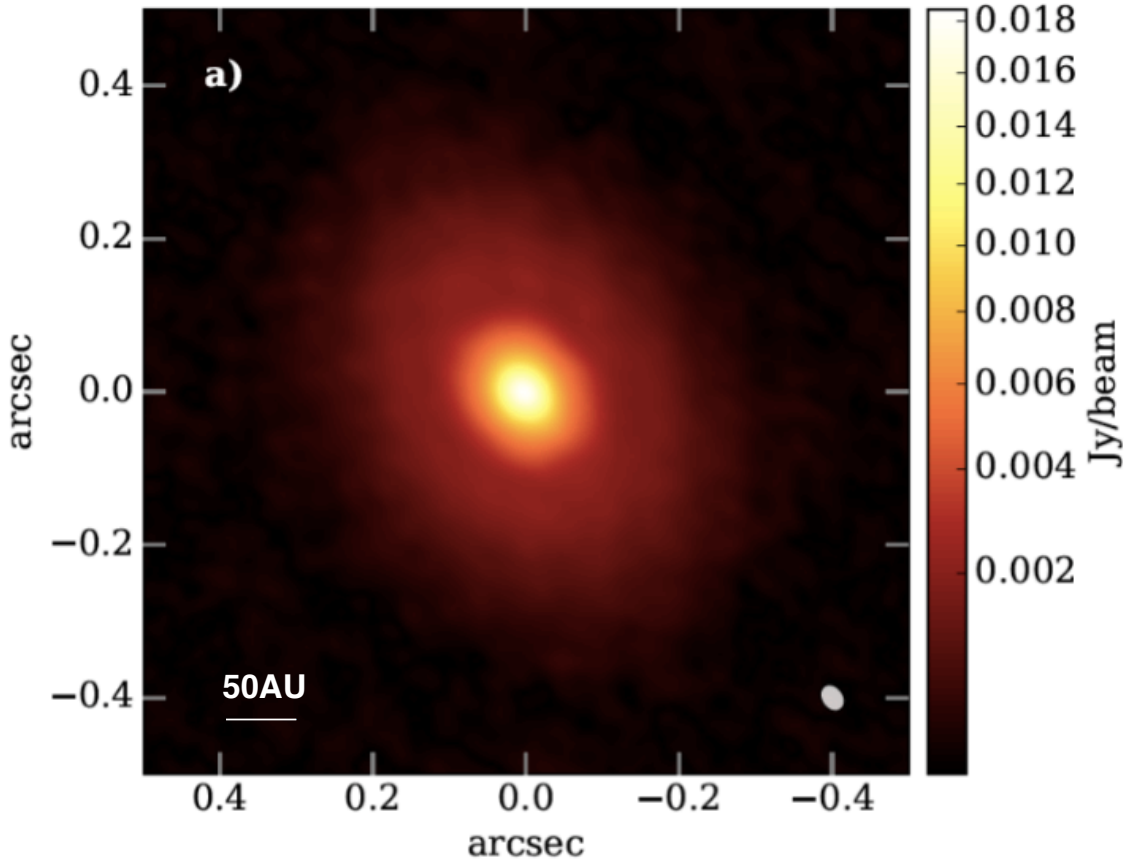
Hord et al. (2017)

The raised feature has its origins in a secondary spiral arm



Hord et al. (2017)

V883Ori

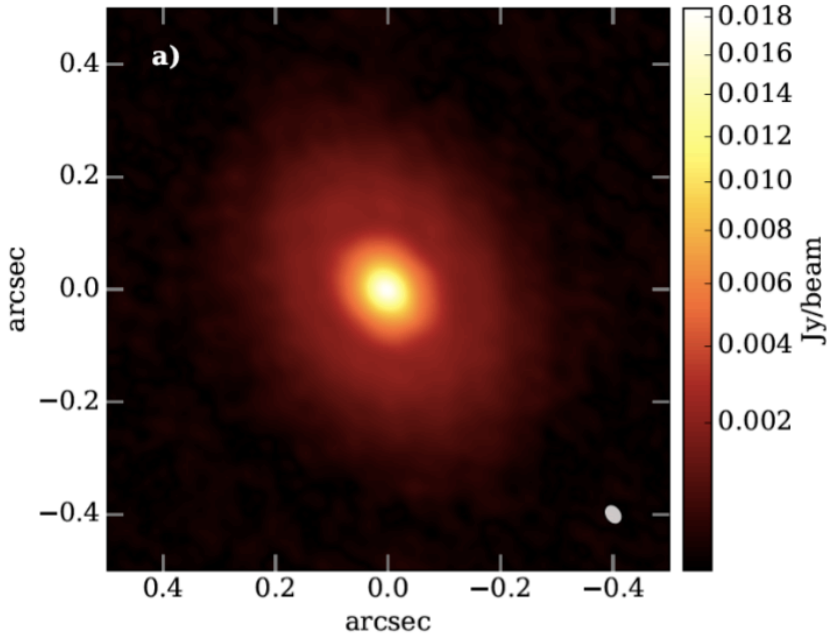


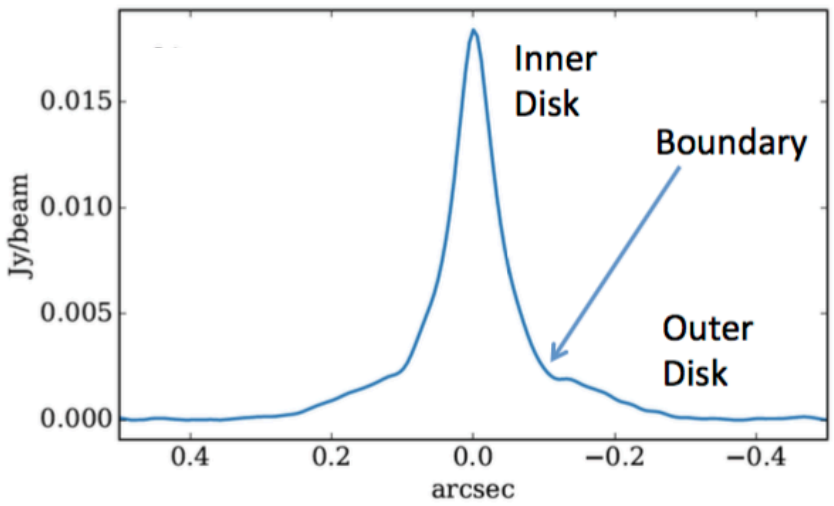
Class I protostar
(Age ~0.5 Myr)
(L_* ~ 6 L_{sun}*)*

M_* = 1.3 +/- 0.1 M_{sun}
M_{disk} ~ 0.3 M_{sun}
d = 414 +/-7 pc
Ldisk = 400 L_{sun}

Cieza et al. (2016)

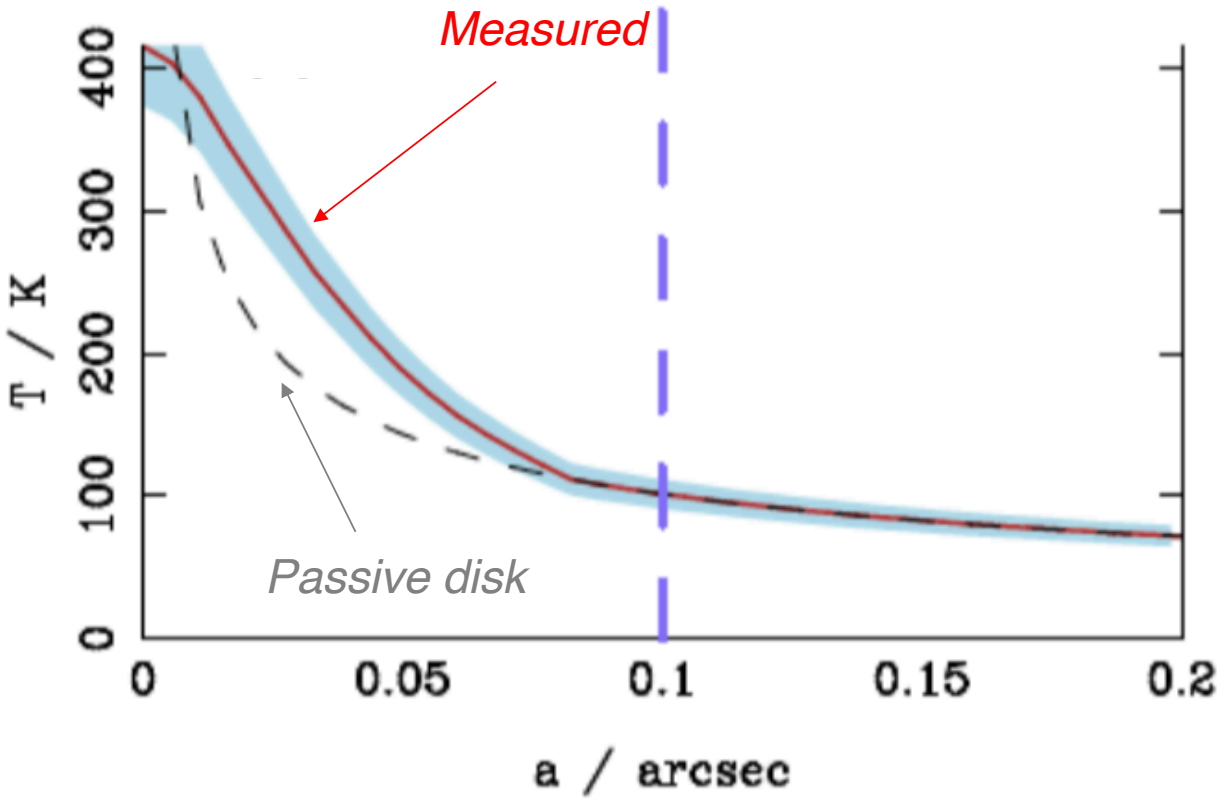
V883Ori





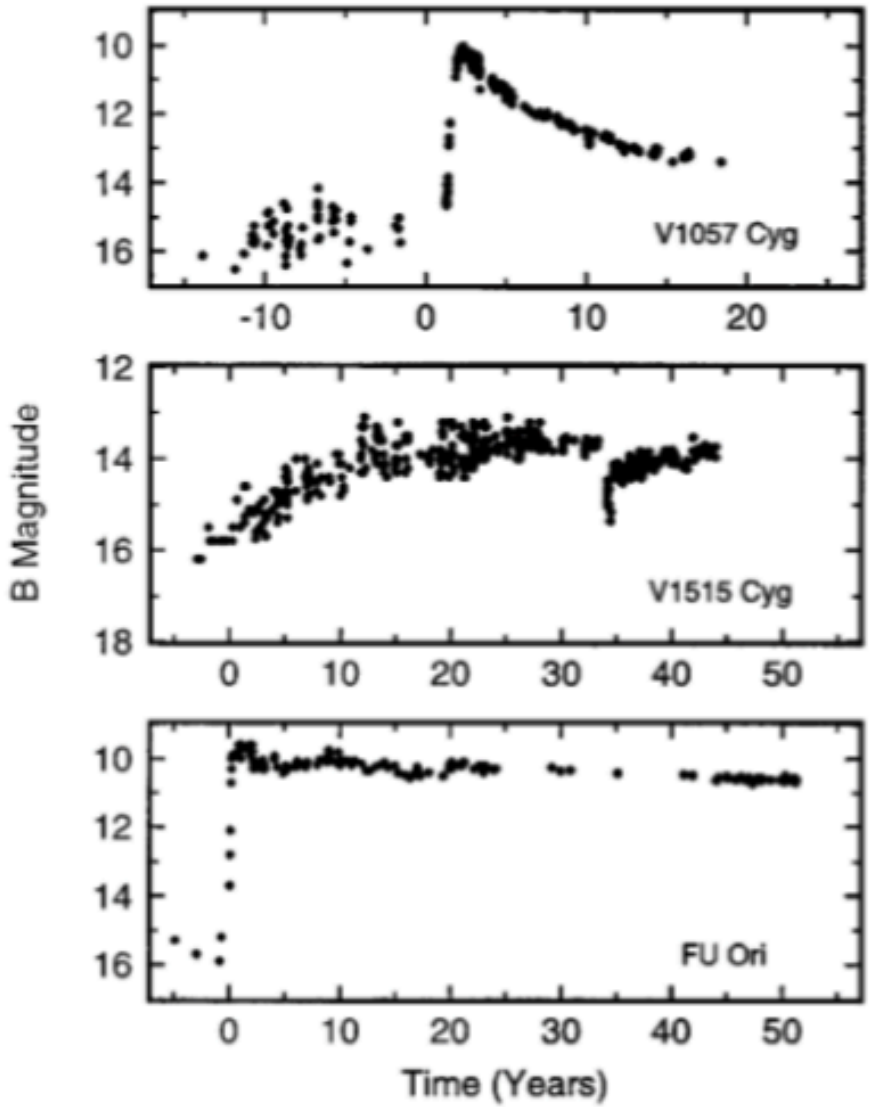
Cieza et al. (2016)

Extra source of heating needed

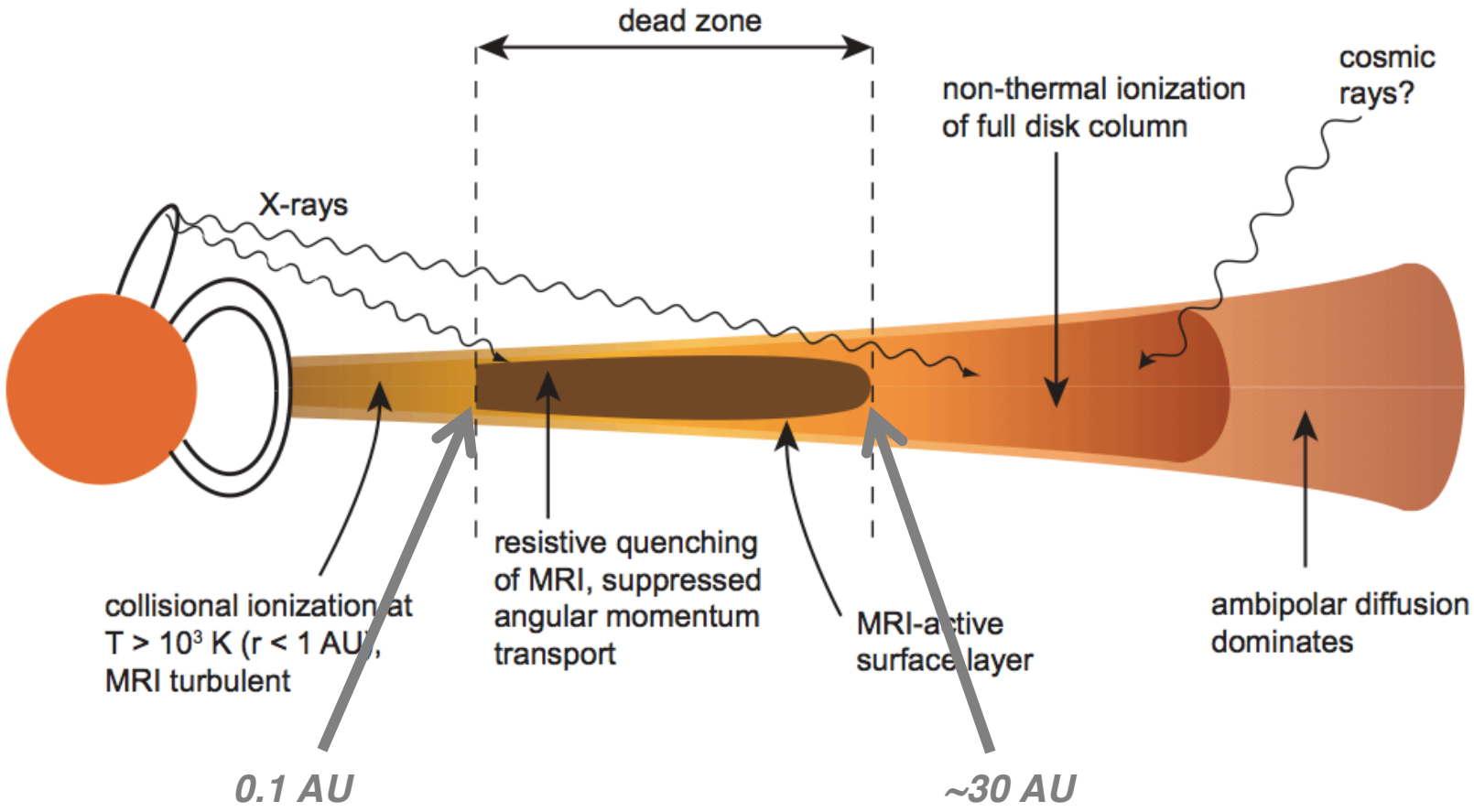


Cieza et al. (2016)

V883 Orionis is an FU Orionis star

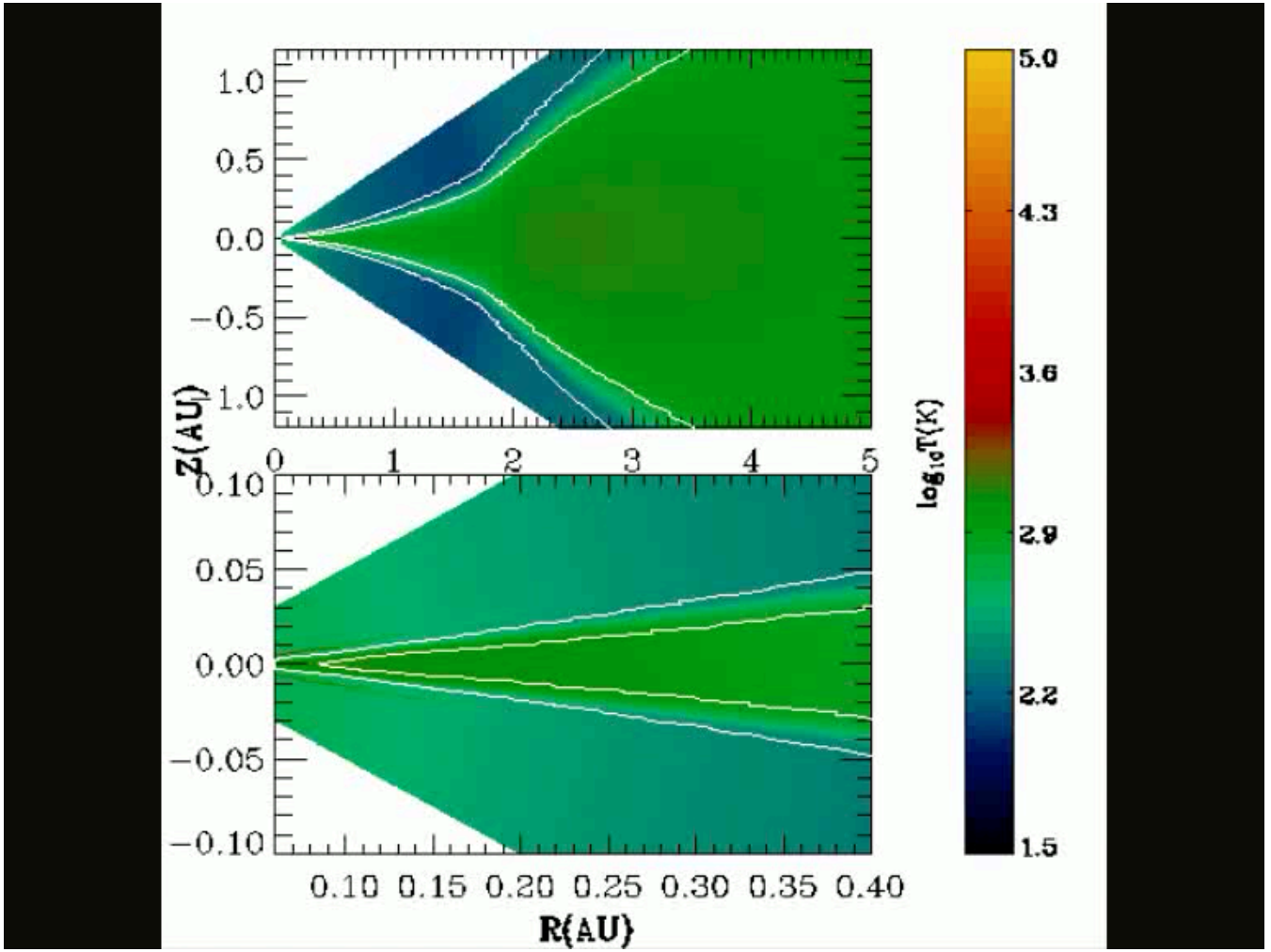


Episodic Accretion – Loading a dead zone



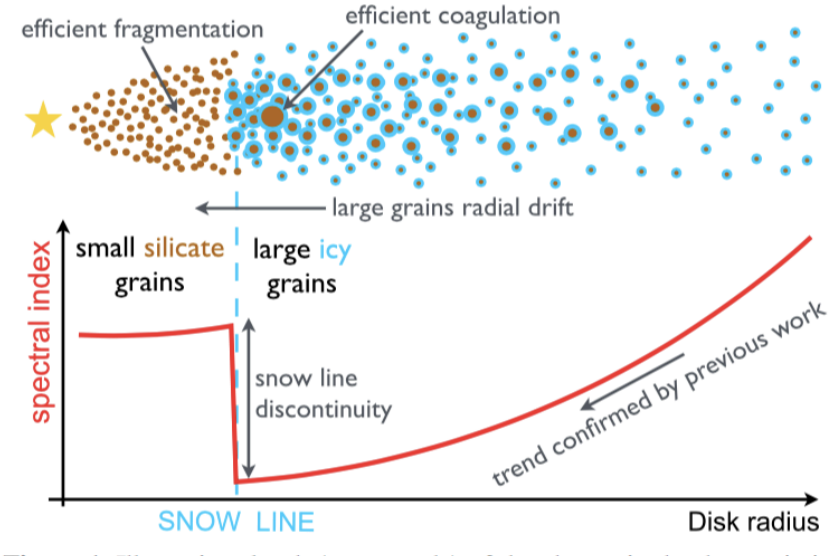
There should be a **magnetized, active zone**
and a **non-magnetic, dead zone**

Episodic Accretion – Loading a dead zone

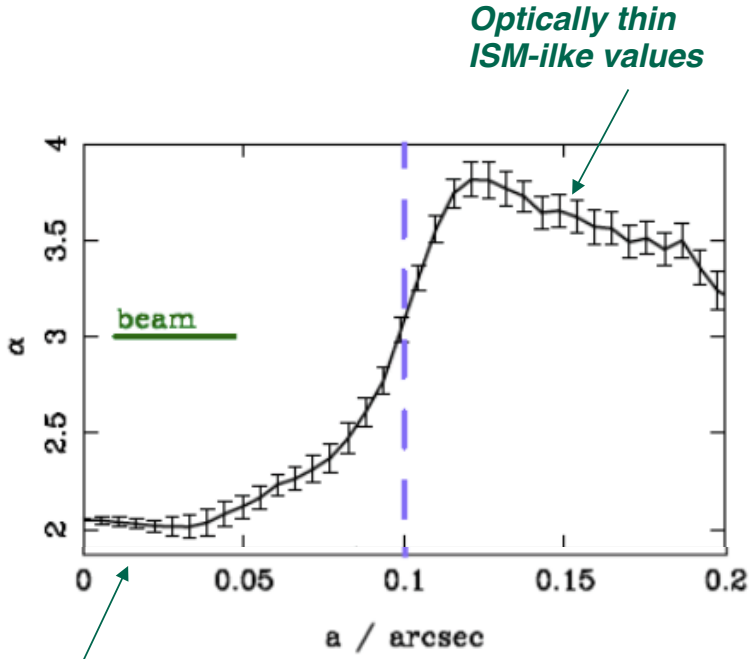


Zhu et al. (2009)

Signature of a snowline: Spectral index

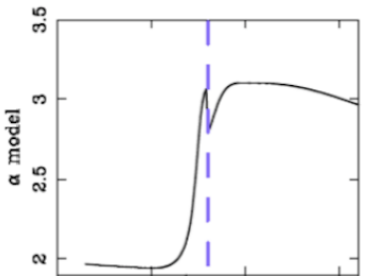


Banzatti et al. (2014)

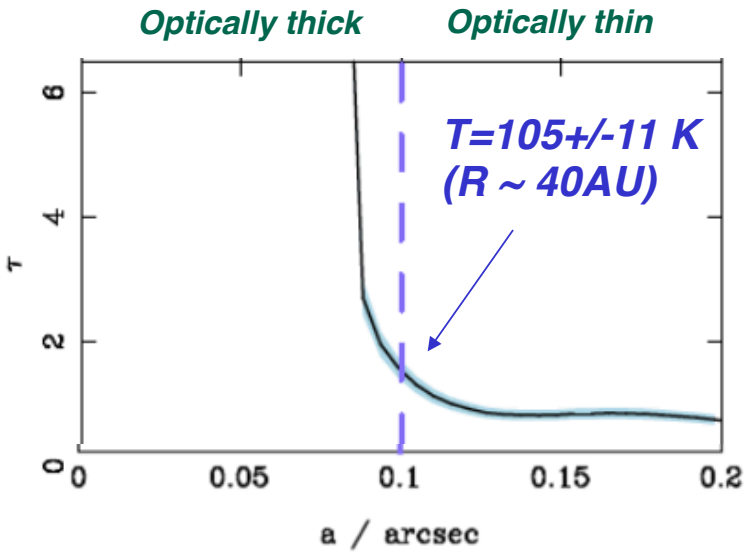


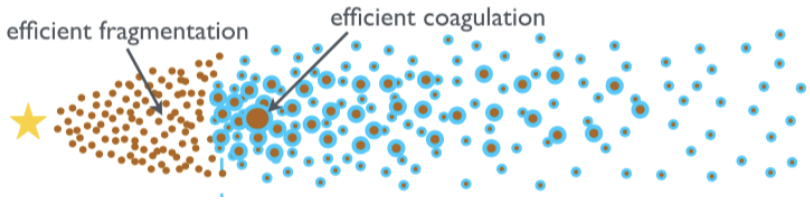
Optically thick blackbody emission

Cieza et al. (2016)



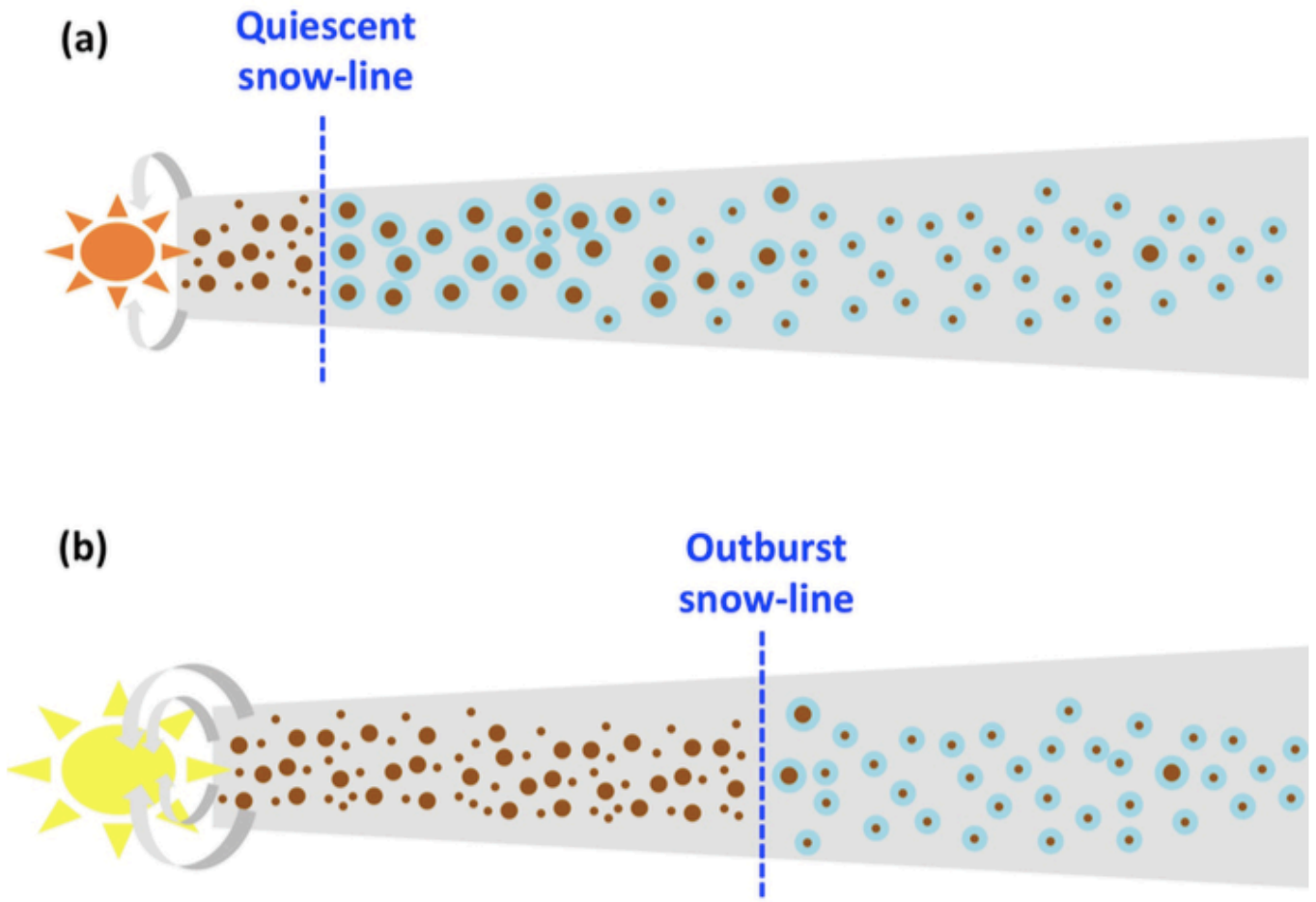
Signature of a snowline: Optical depth





Cieza et al. (2016)

Snowline pushed outward during outburst



Cieza et al. (2016)

The model

$$\Sigma = \Sigma_c \left(\frac{R}{R_c}\right)^{-\gamma} \exp\left[-\left(\frac{R}{R_c}\right)^{2-\gamma}\right]$$

$$q_{\rm irr} = \sigma_{\rm sb} T_{\rm irr}^4 = T_*^4 \left[\left(\frac{R_*}{r}\right)^2 H_h \left(\frac{dH}{dr} - \frac{H}{r}\right) + \frac{2}{3\pi^2}\left(\frac{R_*}{r}\right)^3\right]$$

Stellar heating

$$q_{\rm acc}^+ = \frac{3}{8\pi}\dot{M}\Omega_K^2 = \sigma_{\rm sb} T_{\rm acc}^4$$

$$\nu\Sigma = \frac{\dot{M}}{3\pi}$$

Viscous heating

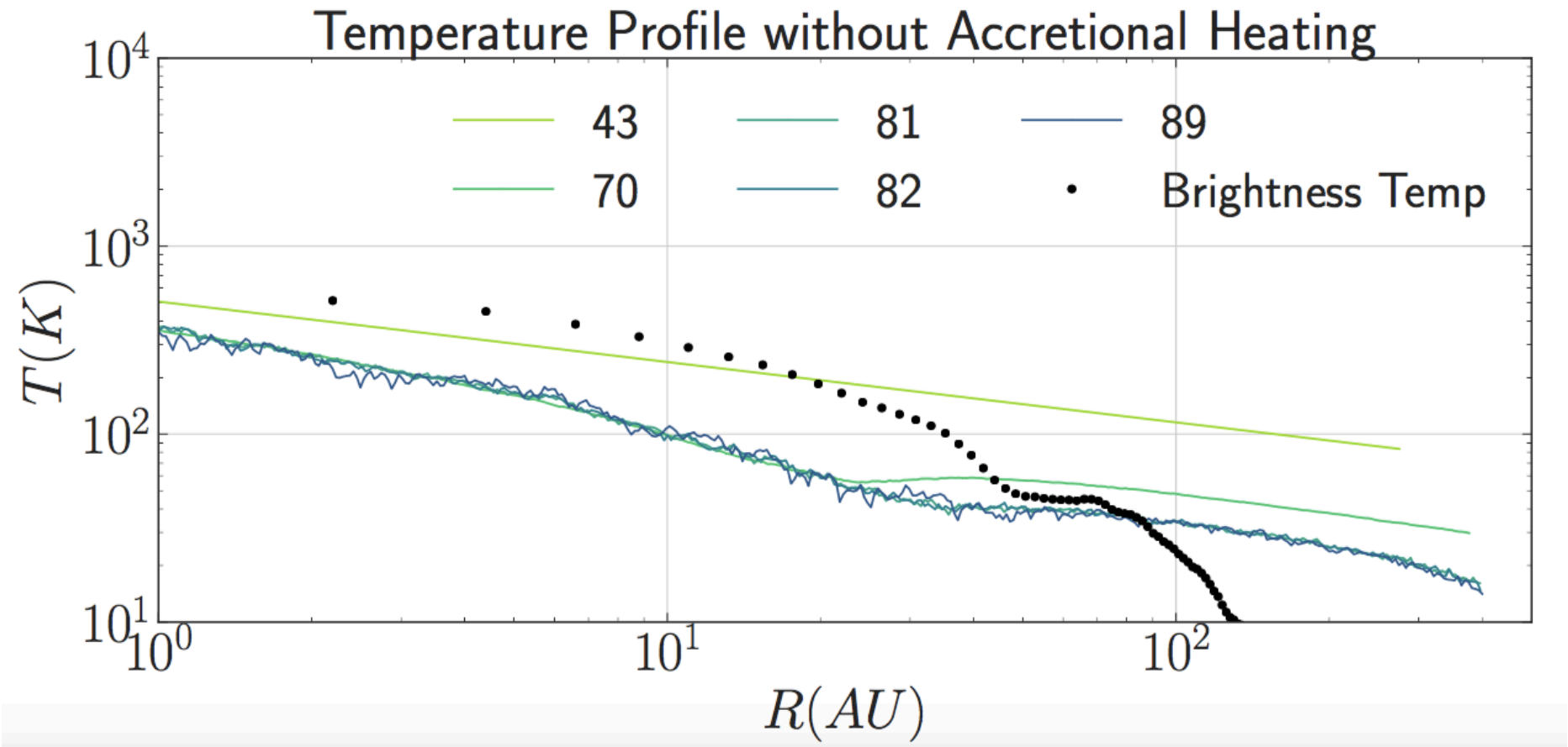
$$T_{\rm eff}^4 = T_{\rm irr}^4 + T_{\rm acc}^4$$

Effective temperature

$$T_{\rm mid}^4 = \frac{3}{4} T_{\rm acc}^4 \left(\tau_{\rm mid} + \frac{2}{3}\right) + \frac{T_{\rm irr}^4}{2}$$

Midplane temperature

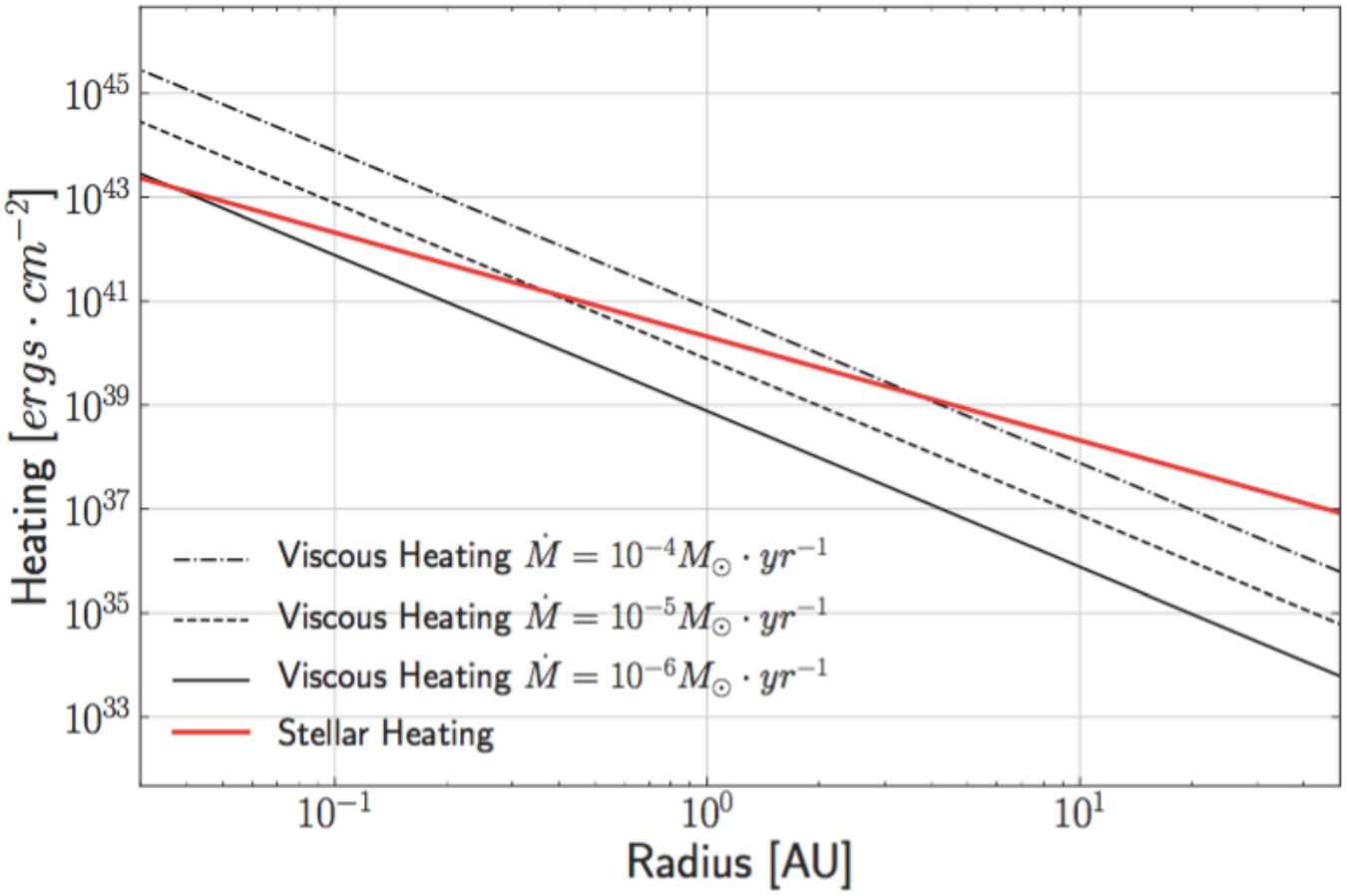
Chiang et al. (2001), Alarcon et al. (in prep)



Alarcon et al. (in prep)

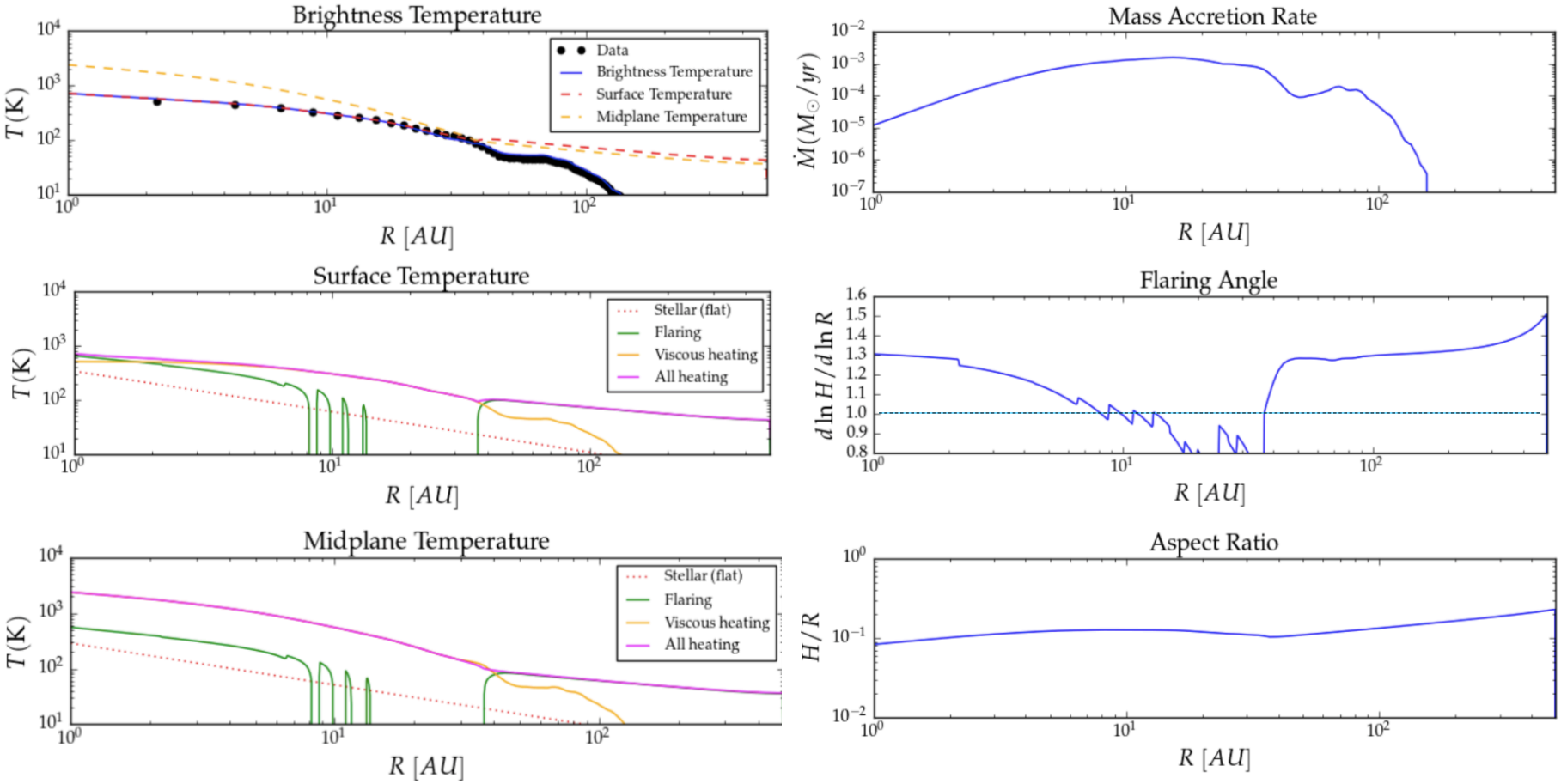
Viscous heating

$$q^{+} = \frac{3}{8\pi}\dot{M}\Omega_K^2$$



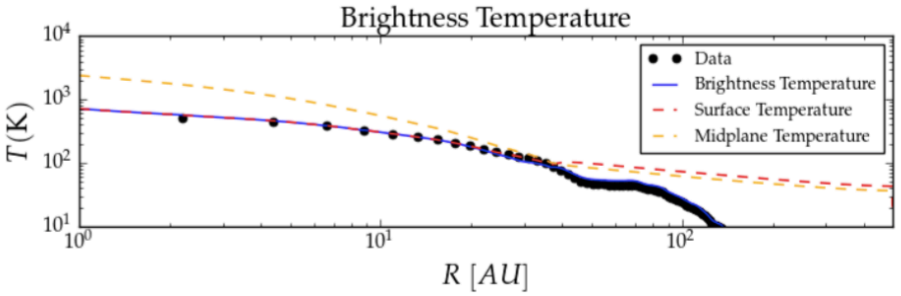
Alarcon et al. (in prep)

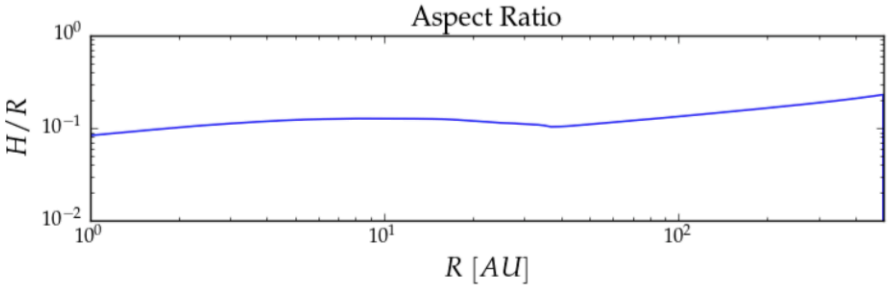
Best fit

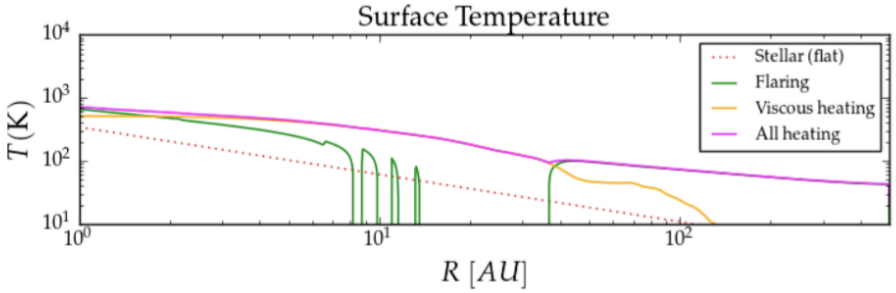


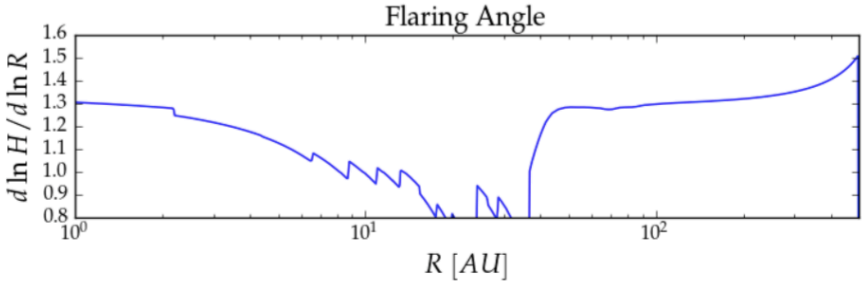
Alarcon et al. (in prep)

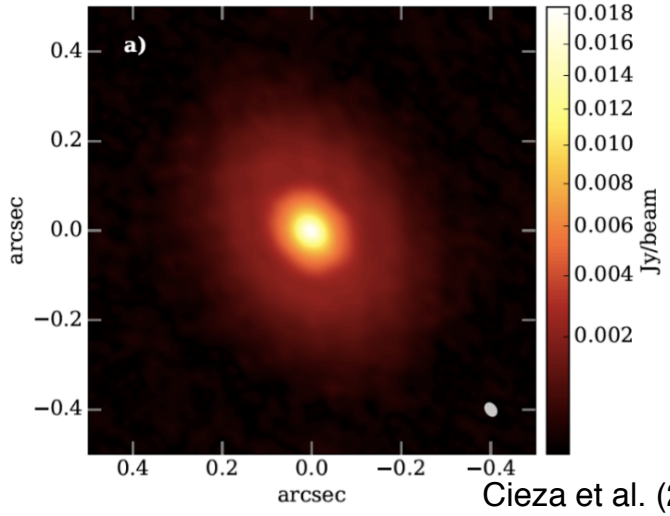
Self-shadowing

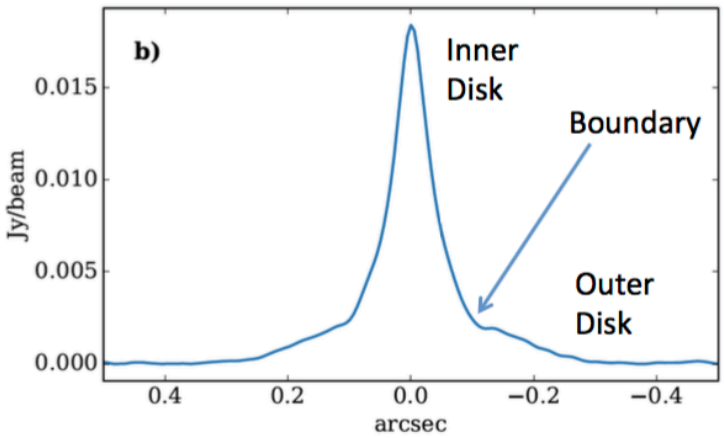












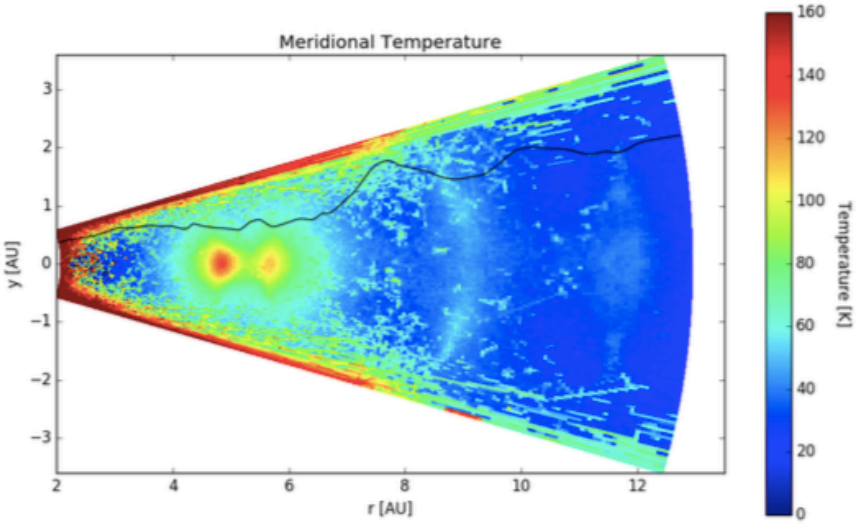
Cieza et al. (2016), Alarcon et al. (in prep)

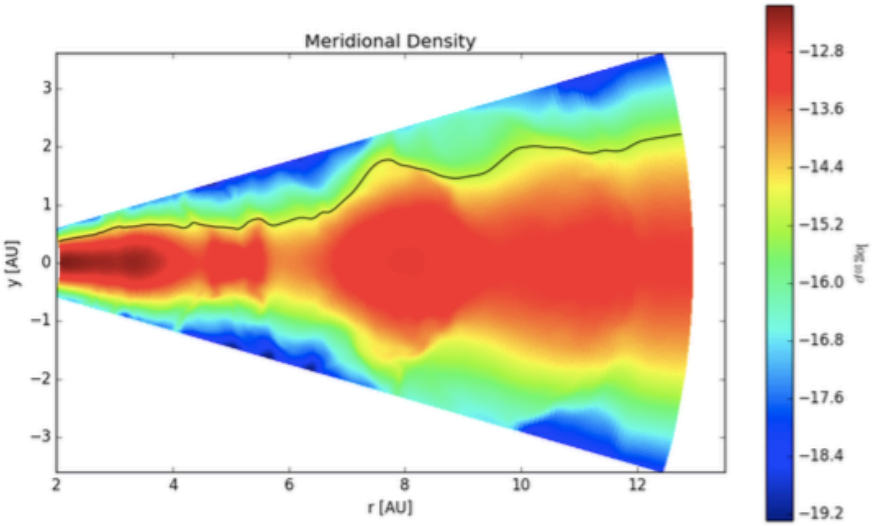
Conclusions

- 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
- First water snowline observed;
- Brightness temperature needs active heating;
- Fit consistent with accretional inner disk, passive outer disk;
- Self-shadowing reproduced;
- Episodic accretion is powering V883 Ori !

Conclusions

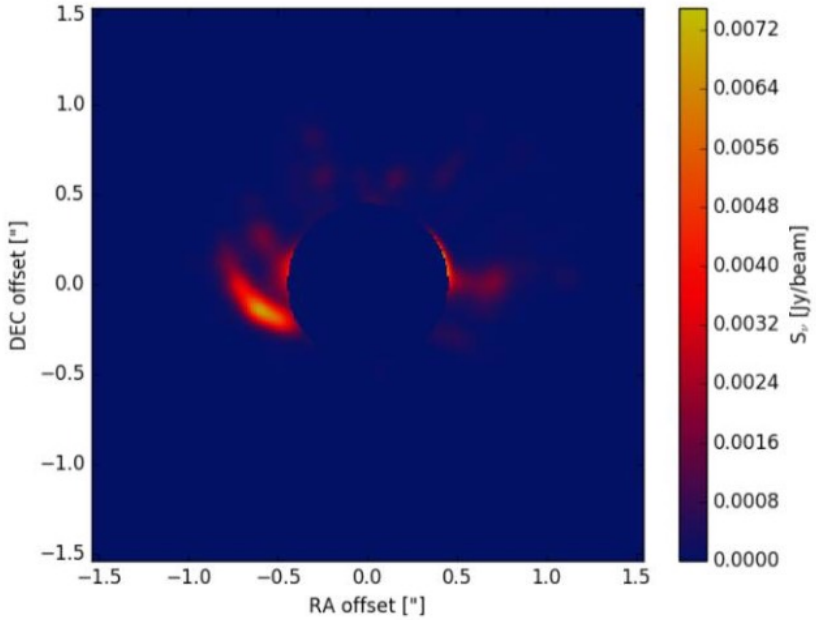
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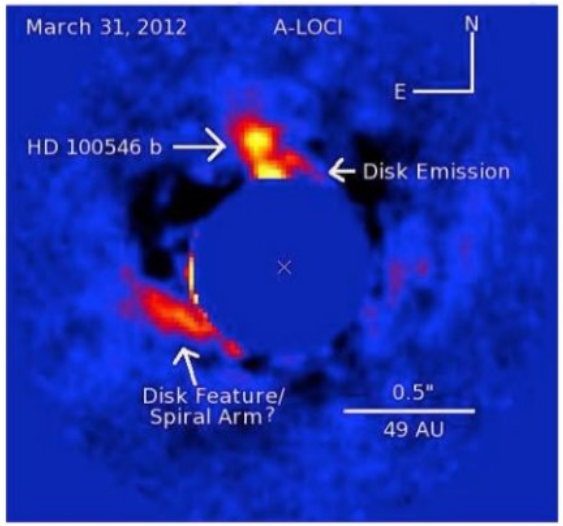




Conclusions

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Conclusions

- First water snowline observed;
- Brightness temperature needs active heating;
- Fit consistent with accretional inner disk, passive outer disk;
- Self-shadowing reproduced;
- Episodic accretion is powering V883 Ori !
    - *What is the mechanism???*
    - *Can we use it to study whatever is causing it?*
        - *Gravitational instability?*
        - *Magnetorotational instability?*
        - *Planet?*
        - *All of the above?*