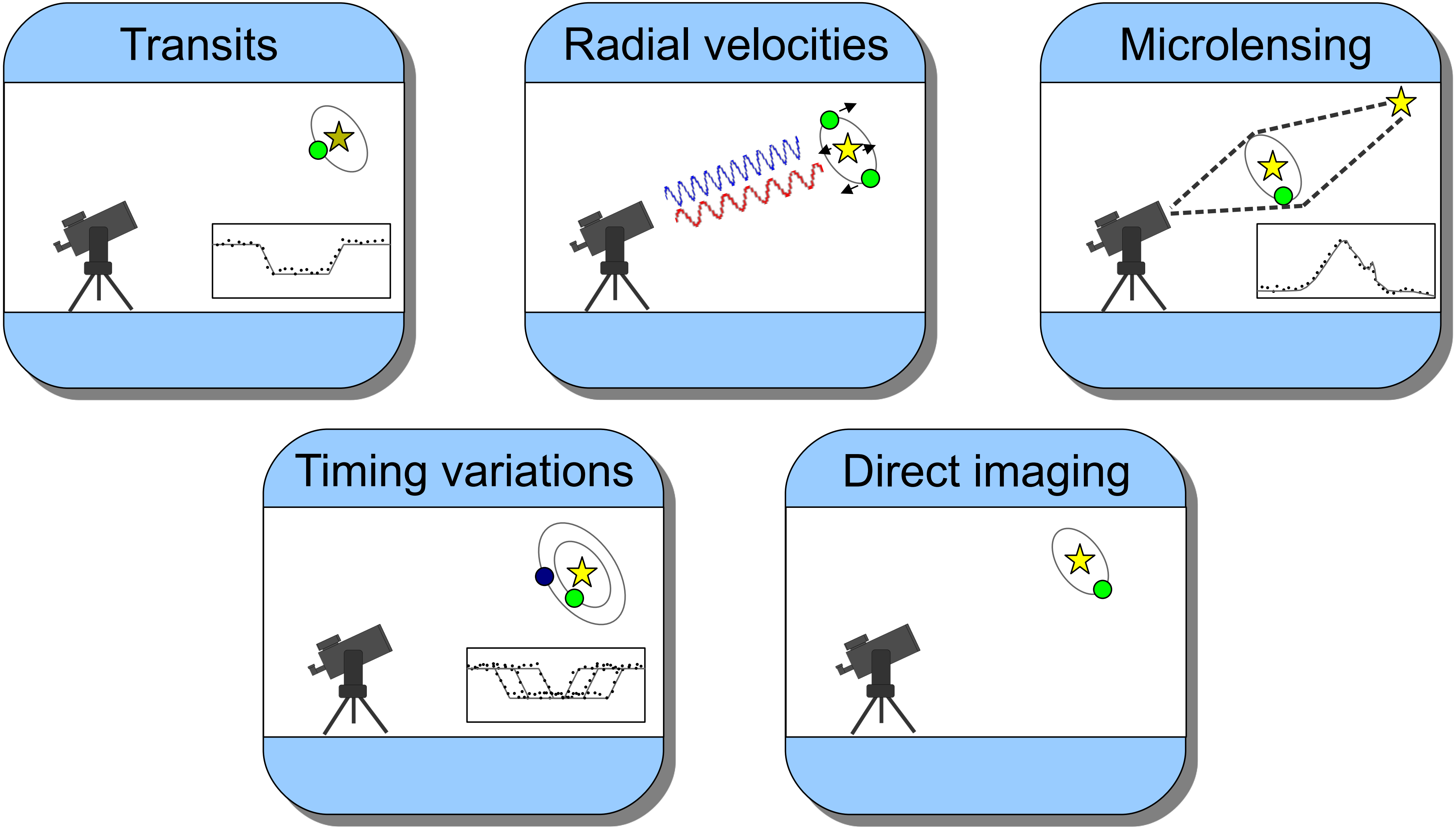
Planet Signatures in Transition Disks

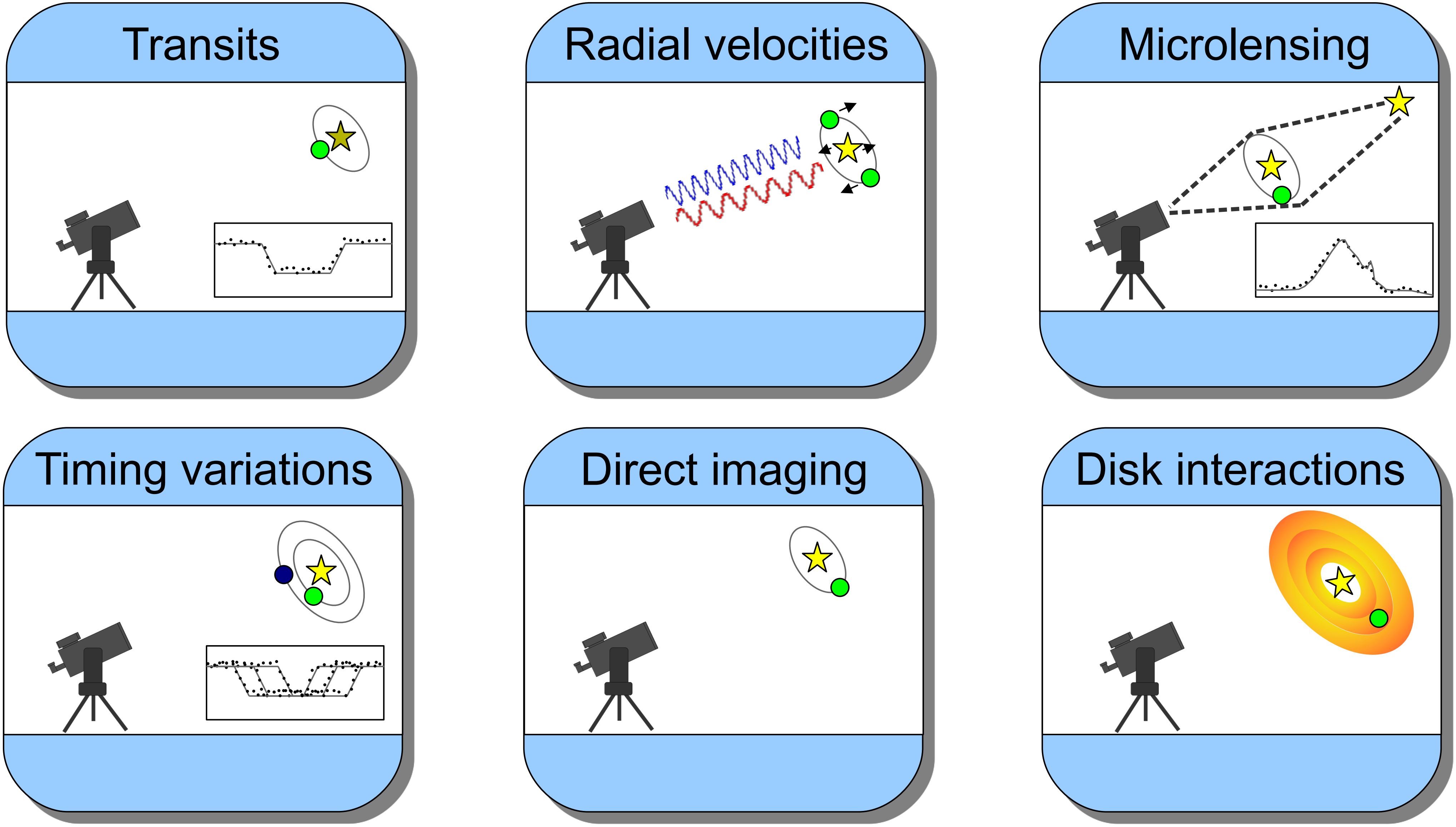
Wladimir Lyra

California State University, Northridge

Sagan Fellows Symposium, Nov 8th, 2018

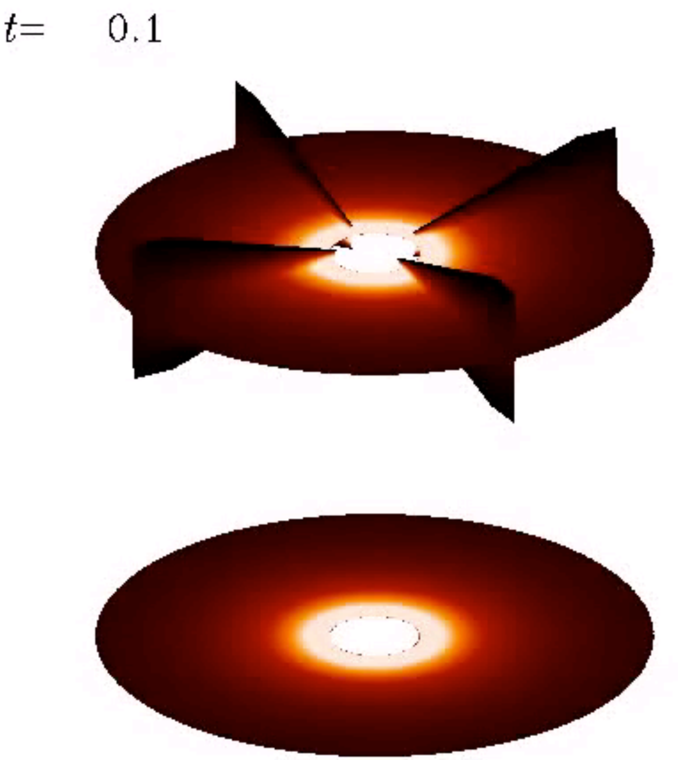


Slide by A. Richert



Slide by A. Richert

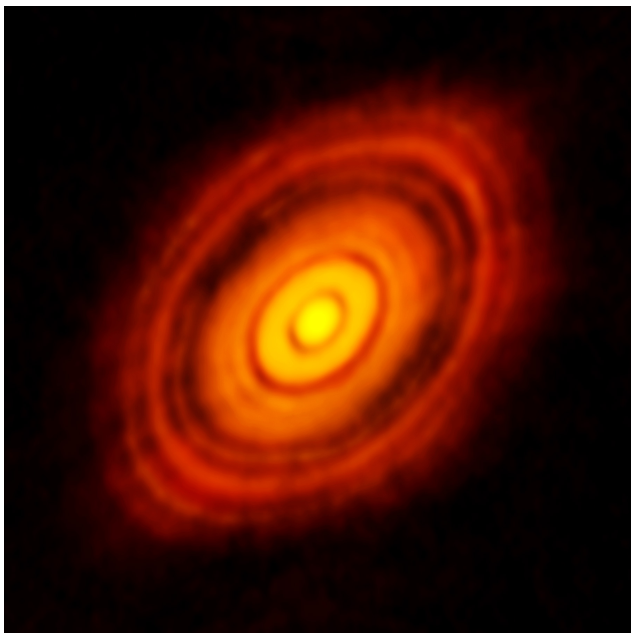
Planet-disk interaction model predictions: gaps, spirals, and vortices.



(Lyra et al. 2009b)

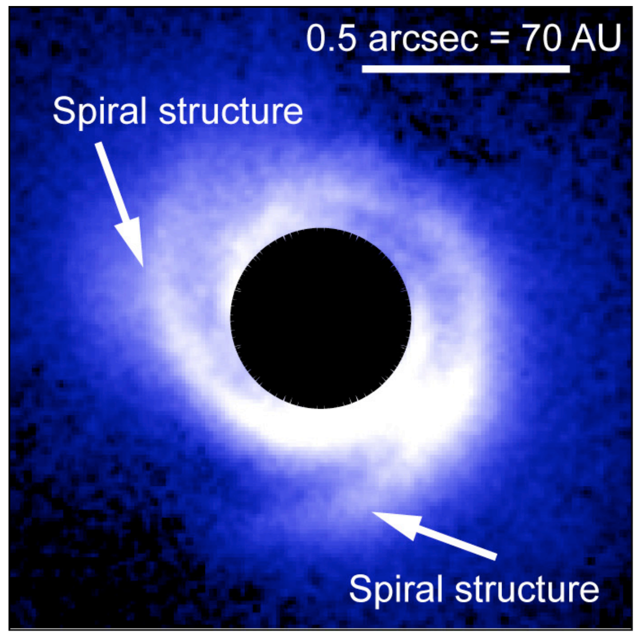
Observational evidence: gaps, spirals, and vortices

HL Tau



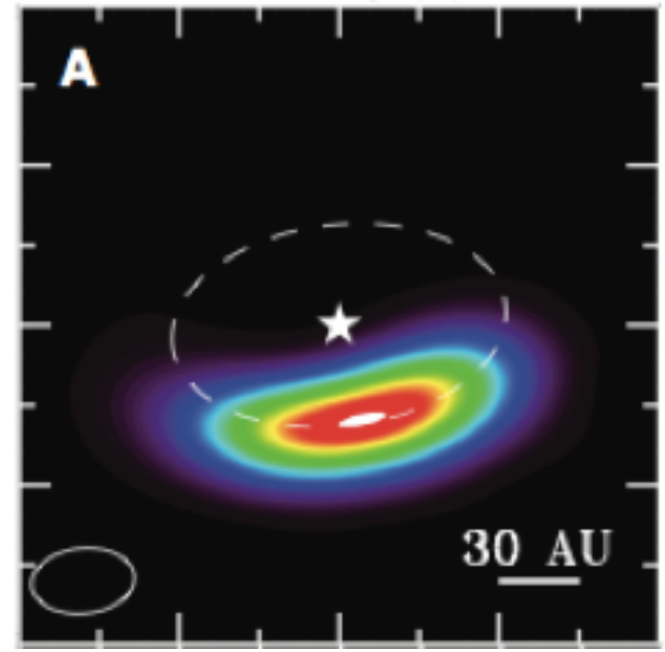
The ALMA Partnership et al. (2015)

SAO 206462



Muto et al. (2012)

Oph IRS 48



van der Marel et al. (2013)

Planet formation in protostellar disks through vortices in layered accretion flows

Wladimir Lyra

The field of planet formation and extrasolar planets, one of the most fascinating topics of contemporary astronomy, is intimately related to the problem of accretion and star formation. Early mathematical considerations by Laplace (1796) applied Newton's theory of universal gravitation and laws of motion to a slowly rotating spherical cloud, implying that it should collapse under its own weight. Due to conservation of angular momentum, the gas settles into a flat disk orbiting the condensing proto-sun in the center, in which planet formation occurs. However, as interstellar clouds are huge in size, even the slightest initial rotation means far too much angular momentum. Even a formed disk stores in its innermost astronomical unit two orders of magnitude more angular momentum than a star can accommodate before achieving break-up velocities. In order to accrete, the gas must somehow get rid of its angular momentum. Even more difficult is to explain the leap of 14 orders of magnitude in size from micron-sized interstellar grains to giant planets such as Jupiter.

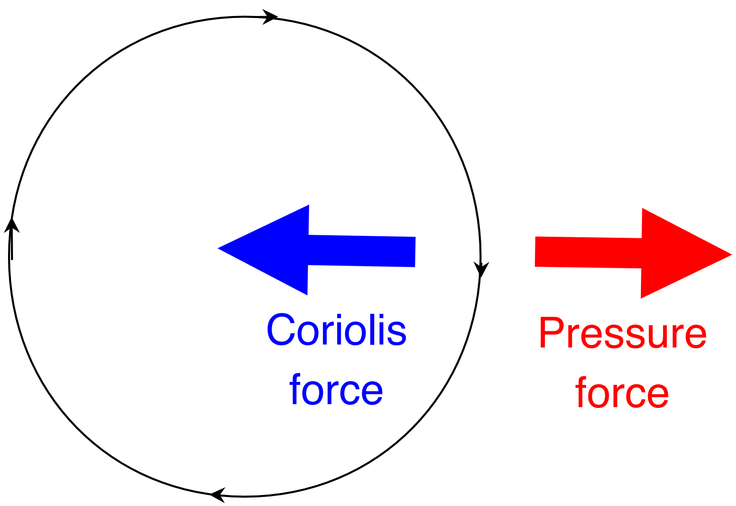
The modern paradigm requires the presence of turbulence in the disk in order to provide the anomalous viscosity necessary for star formation. Turbulence can also assist the trapping of solids needed to quickly aggregate the dust into progressively larger bodies, leading to planet formation. The most-favored mechanism for this turbulence is the magnetorotational instability (MRI; Balbus & Hawley 1998, and references therein), in which the combination of a weak (subthermal) magnetic field and the shear present in the Keplerian rotation of the gas destabilizes the flow.

The MRI, as the name suggests, depends on the coupling between the gas and the magnetic field, which in turn only occurs in the presence of sufficient ionization. In the inner disk this condition is met, since the high temperatures provide enough free electrons. In the outer regions the gas is cold but the column density of gas is thin enough for cosmic rays to penetrate all the way to the disk's midplane and provide ionization throughout. Through most of the disk, however, the gas is too cold and too dense to be ionized in either way. The result is that, when threaded by a weak magnetic field, the disk displays MRI-active regions in the ionized surface layers, and an MRI-dead zone in the neutral parts around the midplane (Gammie 1996; Turner & Drake 2009). We seek here to examine whether there are instabilities at work within the dead zone, that would lead to a steady-state accretion through it.

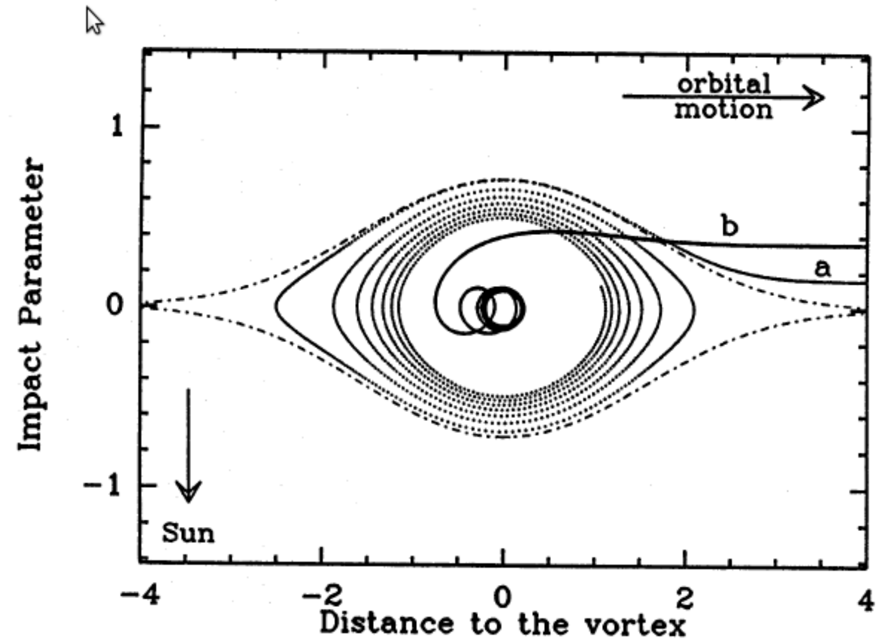
A promising yet largely unexplored possibility is the development of baroclinic instabilities in the dead zone. A baroclinic flow is one where the pressure depends on both density and temperature, as opposed to a barotropic flow where the pressure only depends on density. In a baroclinic flow, the misalignment between surfaces of constant density ρ (isopycnals) and surfaces of constant pressure p (isobars) generates vorticity. This mechanism has long been known in

Vortex Trapping

Geostrophic balance:



Vortex streamline



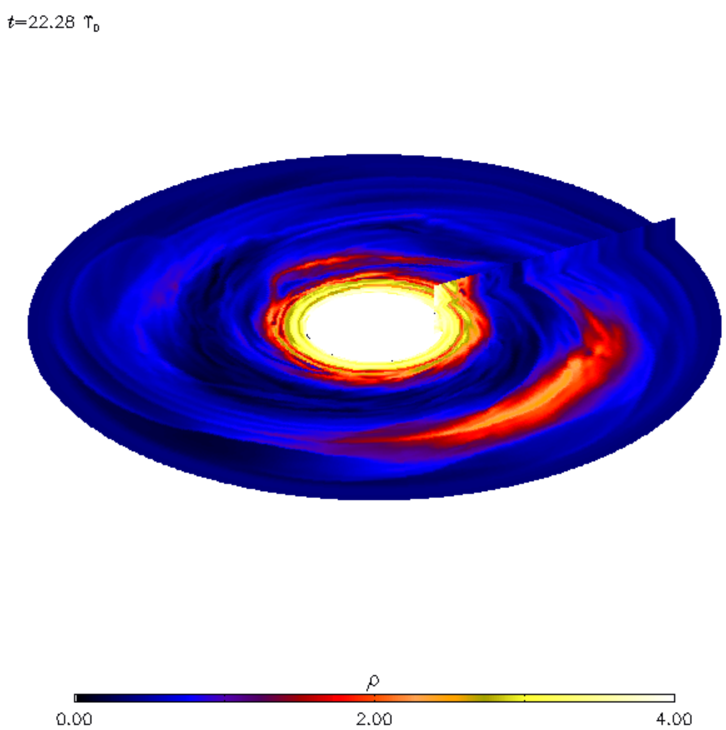
Barge & Sommeria (1995)

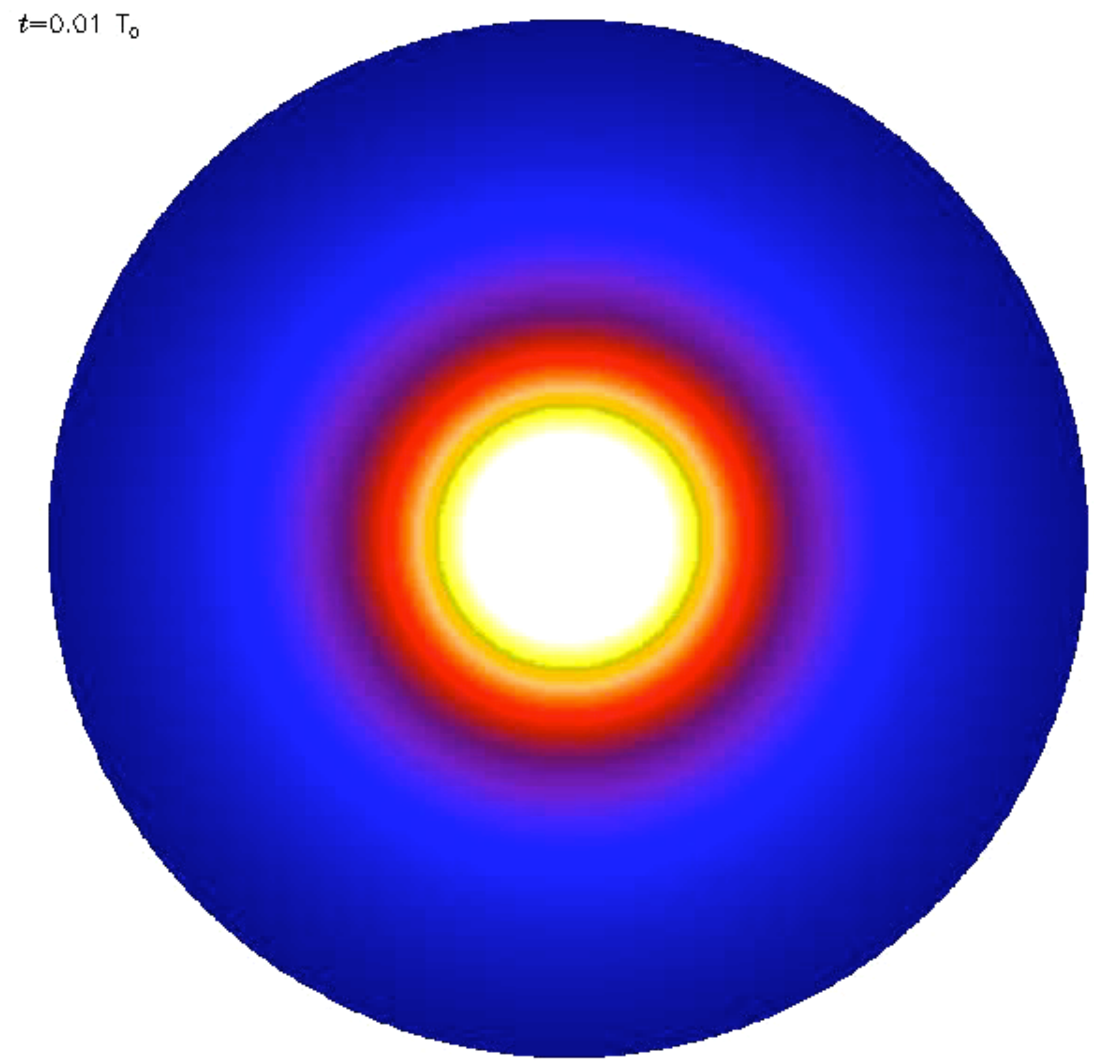
Grains do not feel the pressure gradient.
They sink towards the center, where they accumulate.

Aid to planet formation
(Barge & Sommeria 1995, Tanga et al. 1996, Barranco & Marcus 2005)

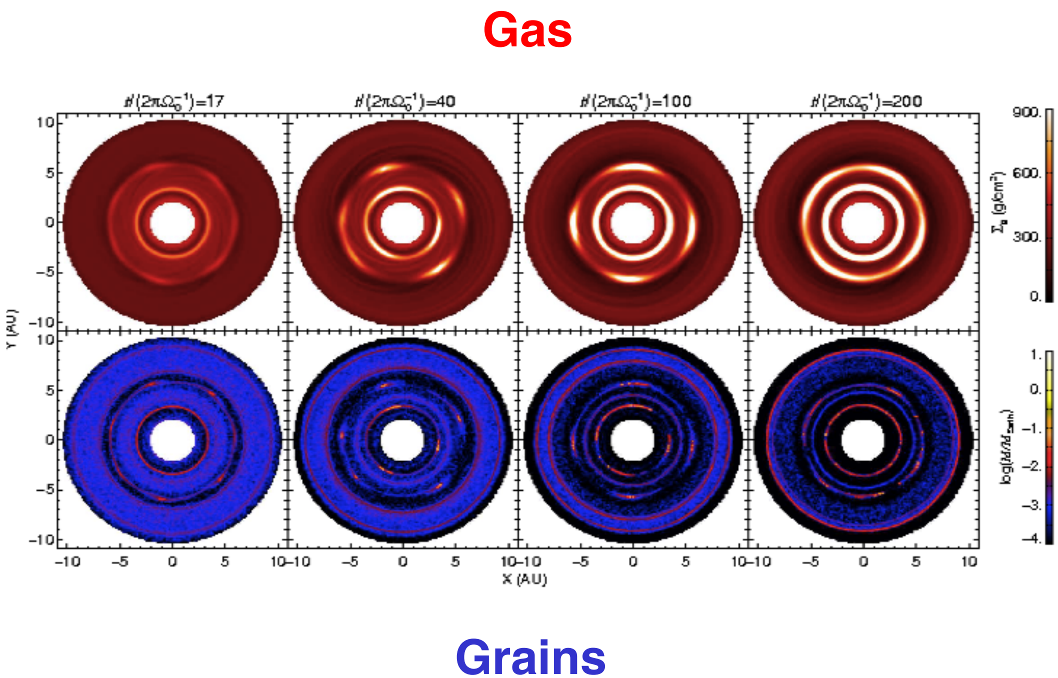
Speed up planet formation enormously
(Lyra et al. 2008b, 2009ab, Raettig et al. 2012)

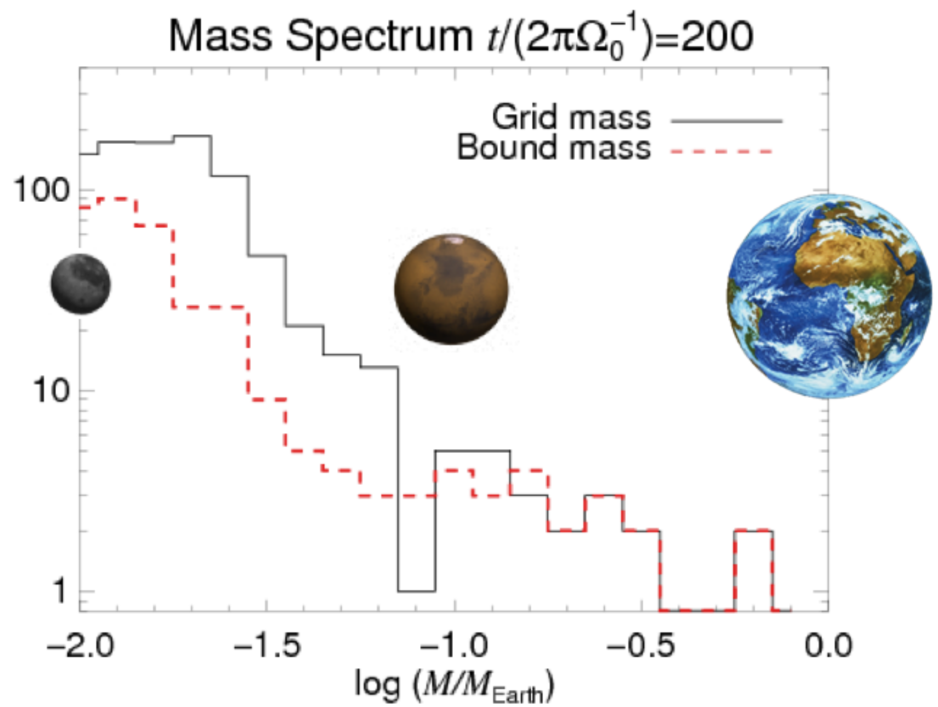
Vortex at turbulent/non-turbulent transitions





Vortices and Planet Formation





Collapse into Mars mass objects

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

Oph IRS 48

A Major Asymmetric Dust Trap in a Transition Disk

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

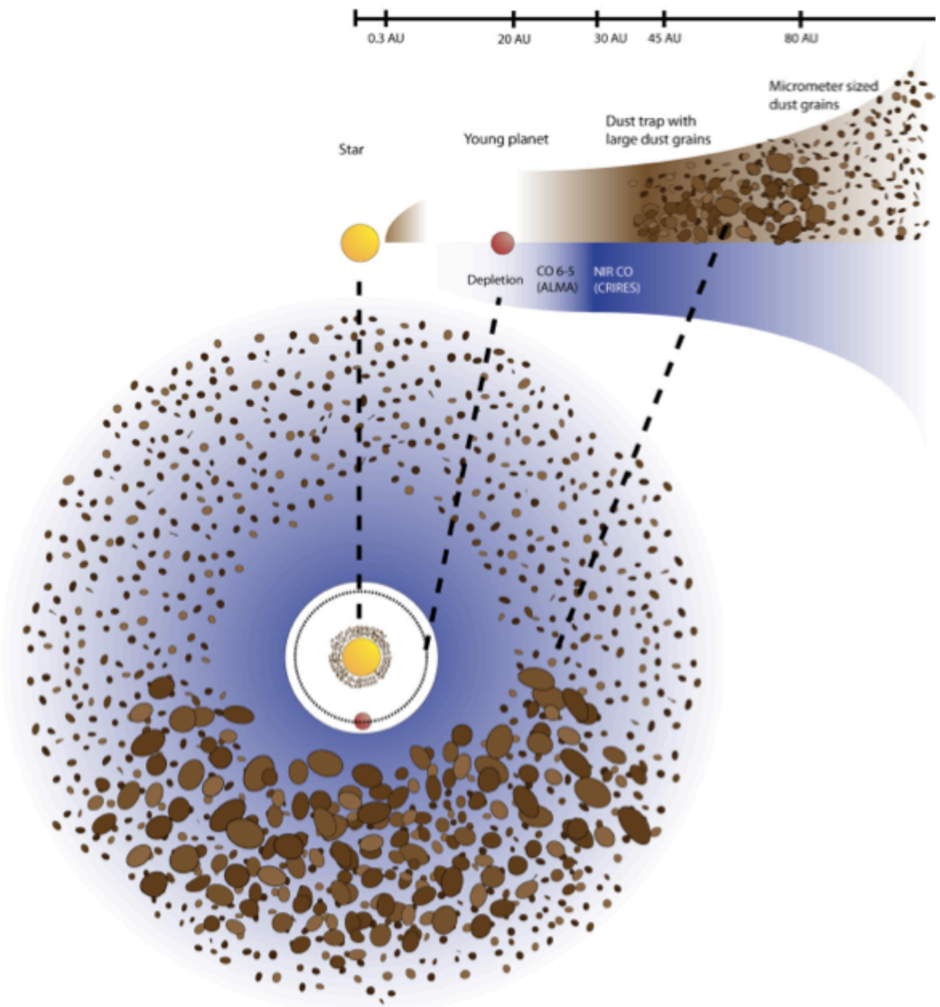
The statistics of discovered exoplanets suggest that planets form efficiently. However, there are fundamental unsolved problems, such as excessive inward drift of particles in protoplanetary disks during planet formation. Recent theories invoke dust traps to overcome this problem. We report the detection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

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

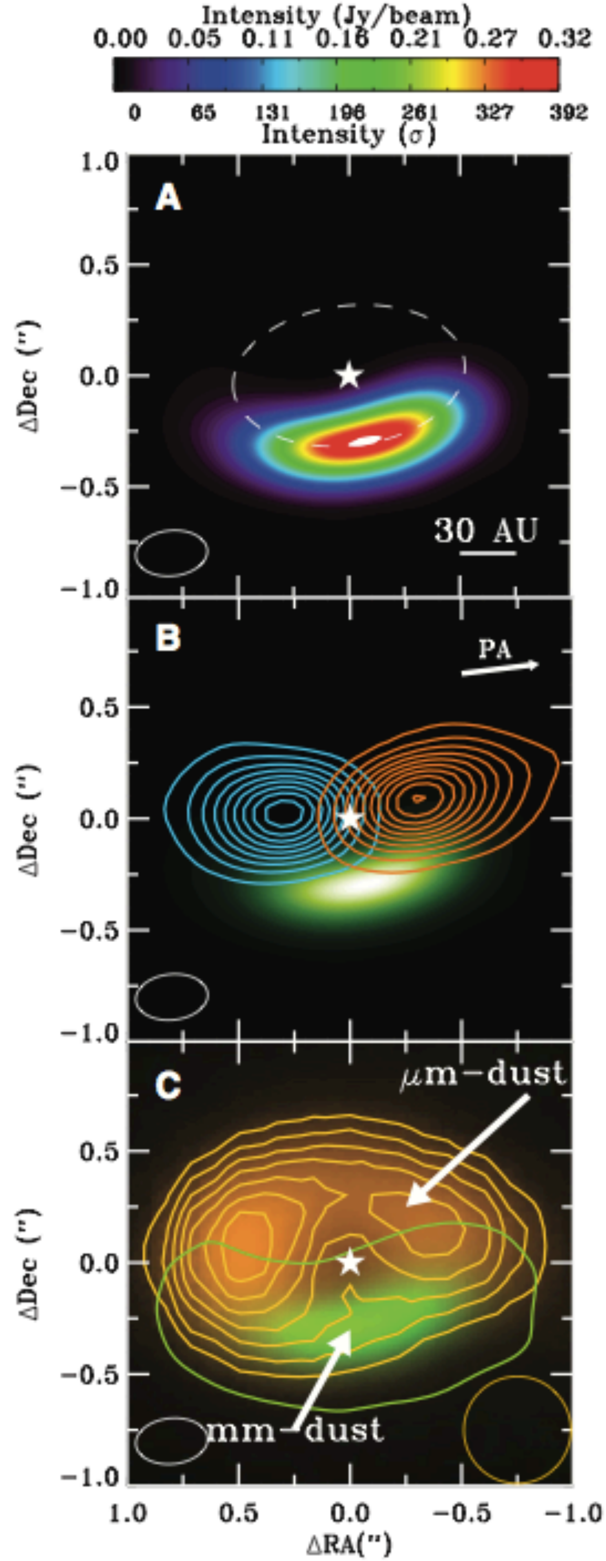
van der Marel et al. 2013

A huge vortex observed with ALMA

The Oph IRS 48 “dust trap”



van der Marel et al. (2013)

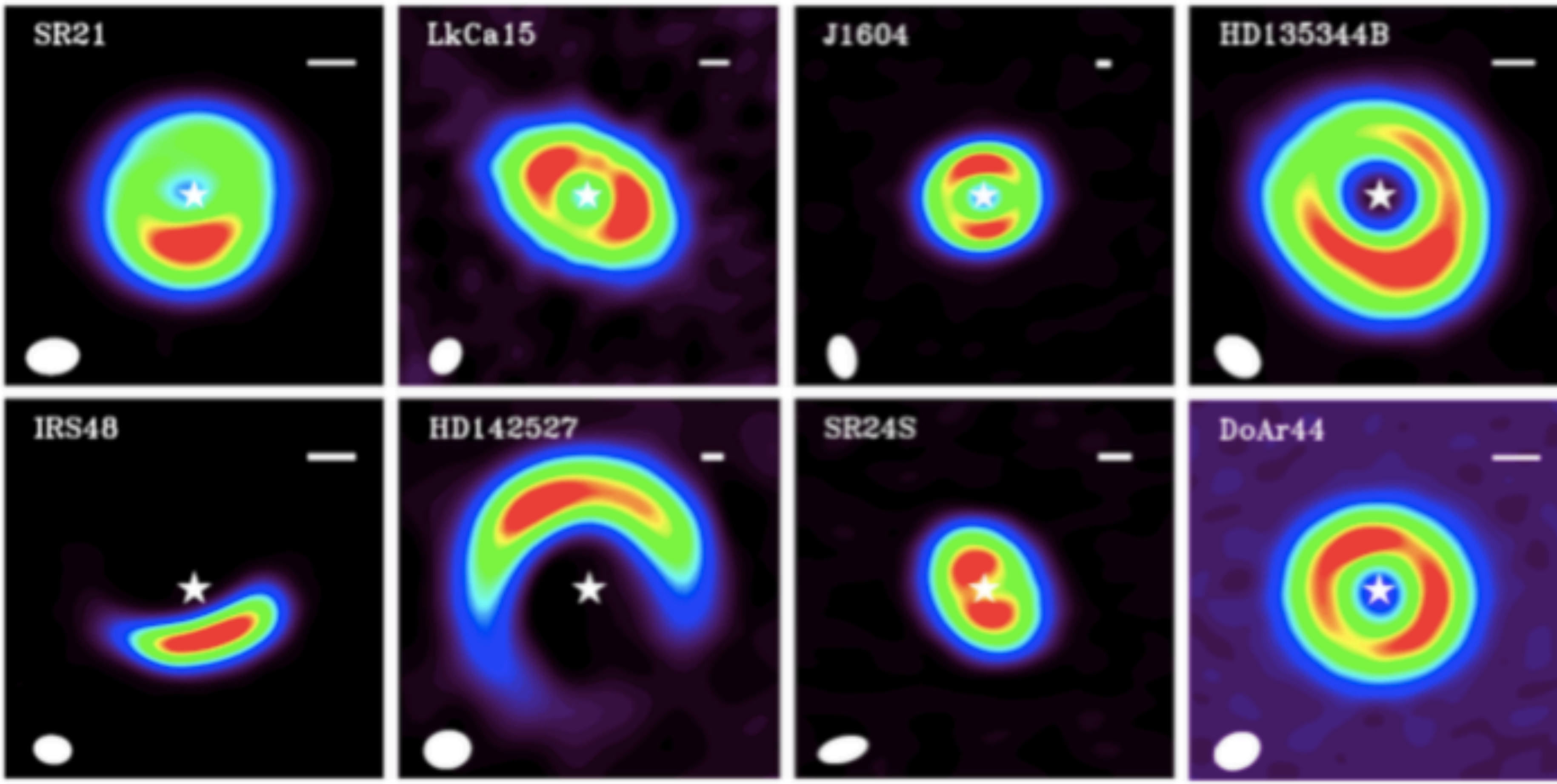


asymmetric mm dust at 63 AU

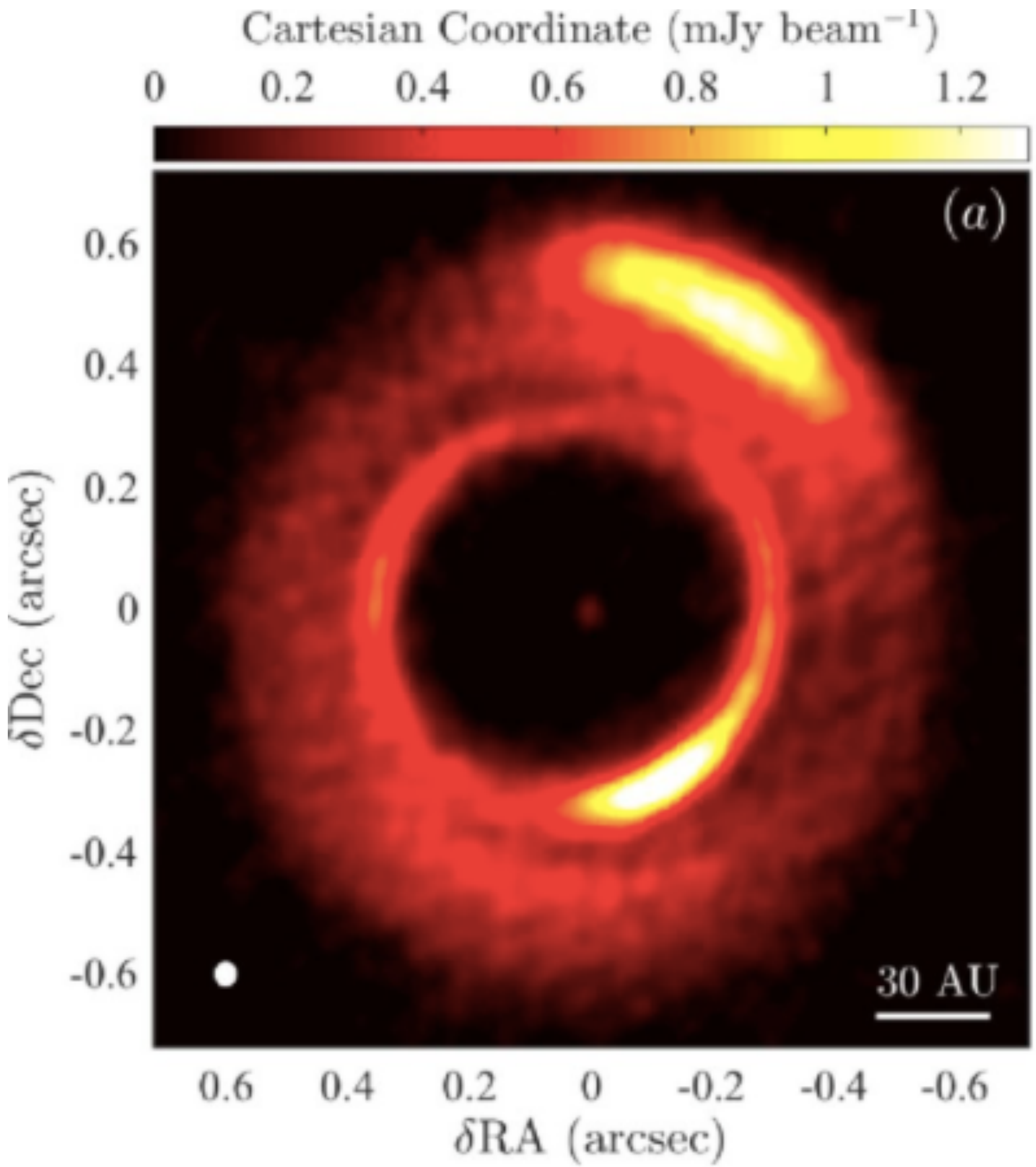
Gas detection: Keplerian rotation

Micron-sized dust follows gas

Vortices everywhere!



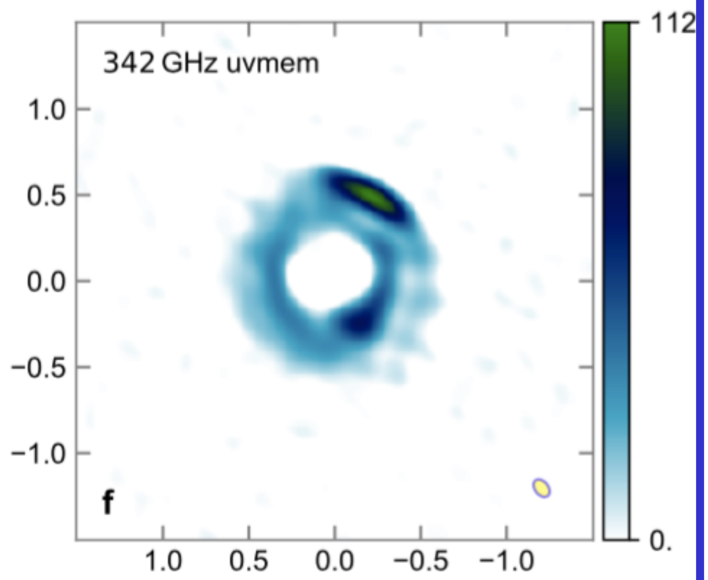
MWC 758



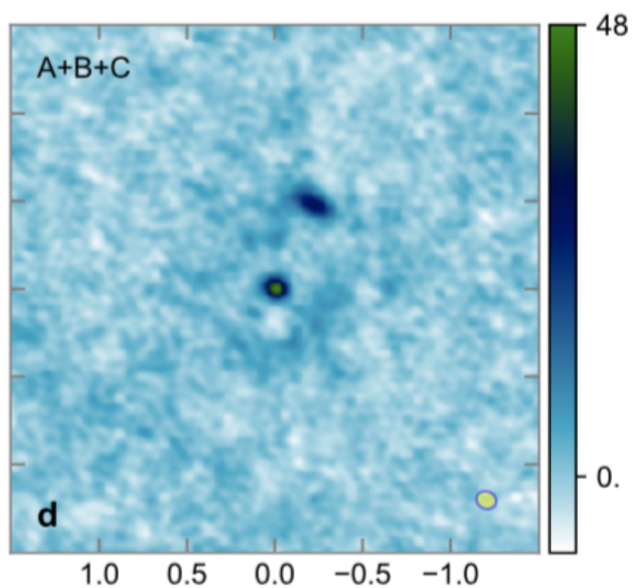
Cartesian Coordinate (mJy beam^{-1})
0
0.2
0.4
0.6
0.8
1
1.2
(a)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
δDec (arcsec)
30 AU
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
δRA (arcsec)

Pebble trapping

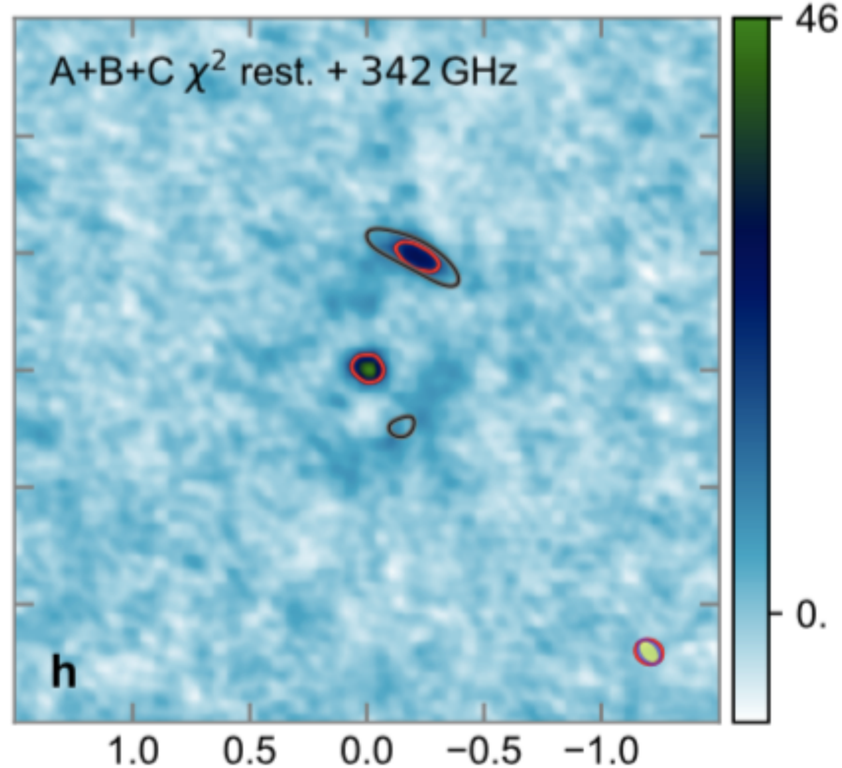
ALMA (mm)



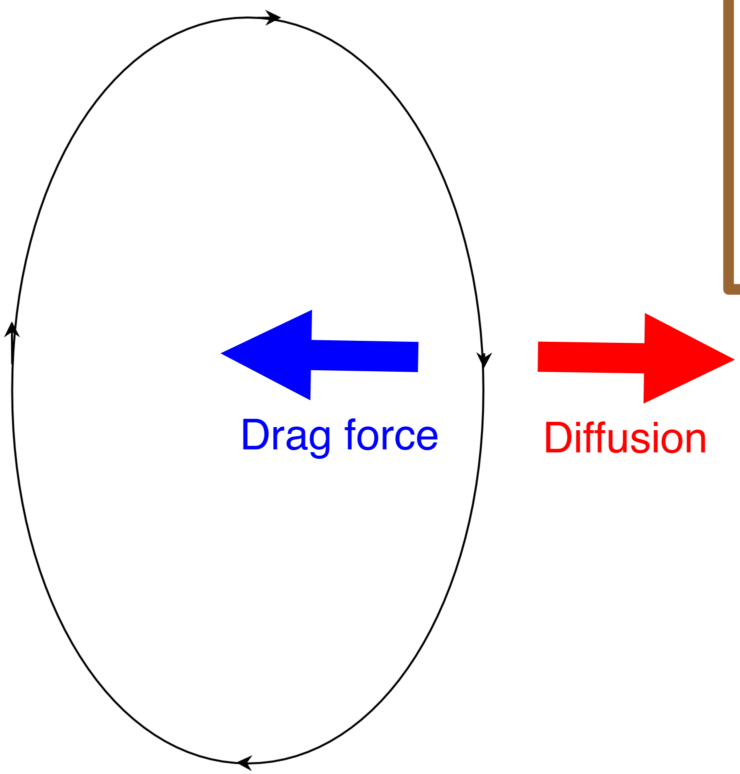
VLA (cm-m)



Overlay



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)

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

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

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

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

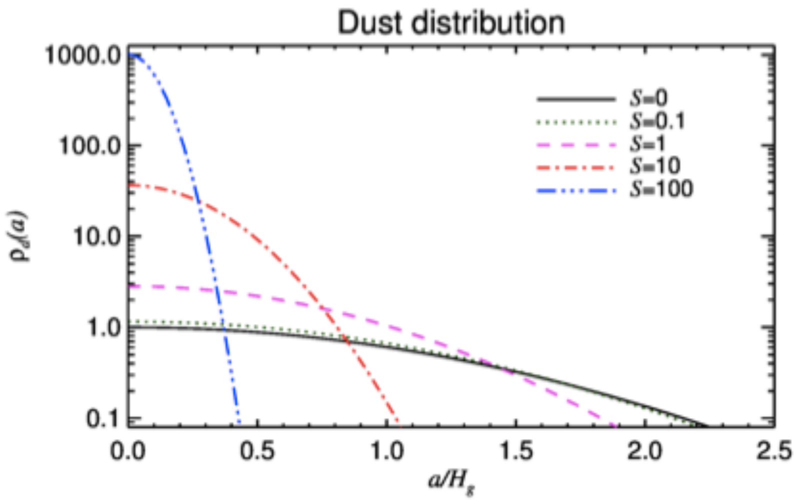
$$\int \rho_d(a,z)dV = (2\pi)^{3/2}\,\varepsilon\rho_0\,\chi H H_g^2$$

Vortex size

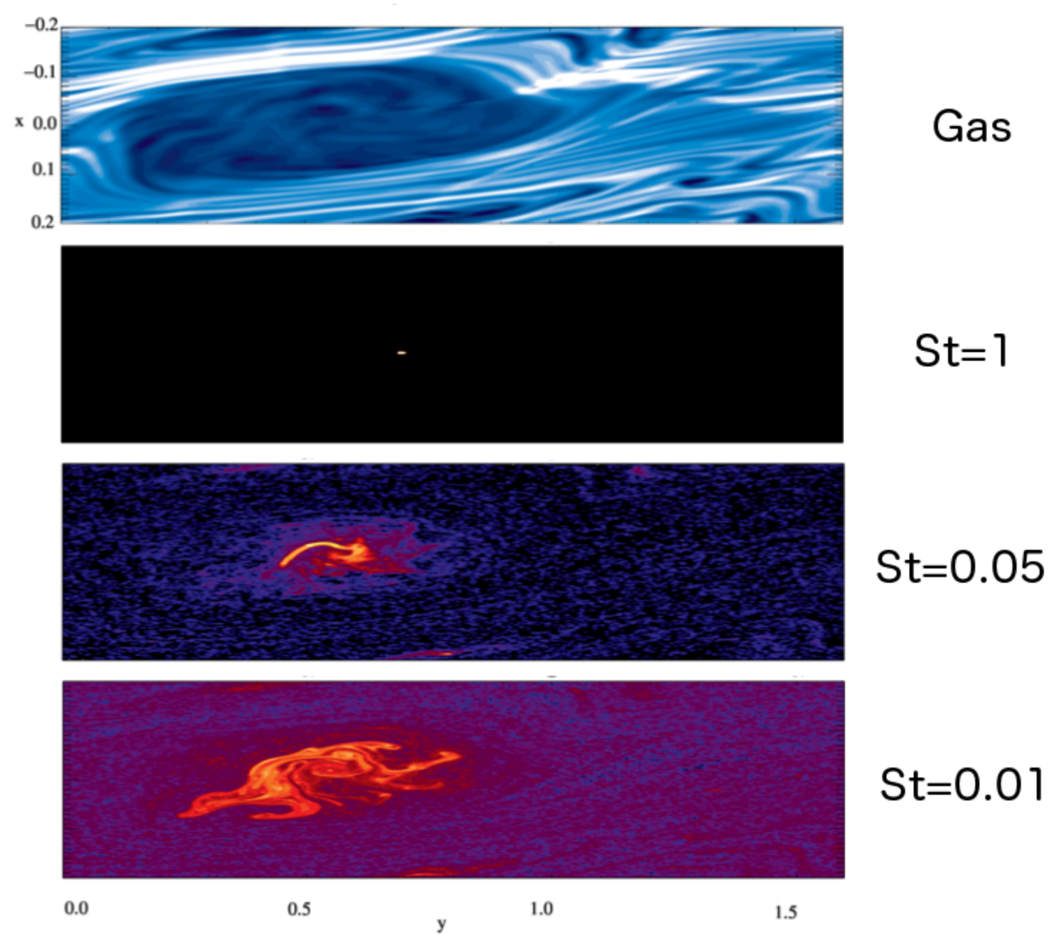
$$a_s = H(\chi\omega_V)^{-1}$$

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

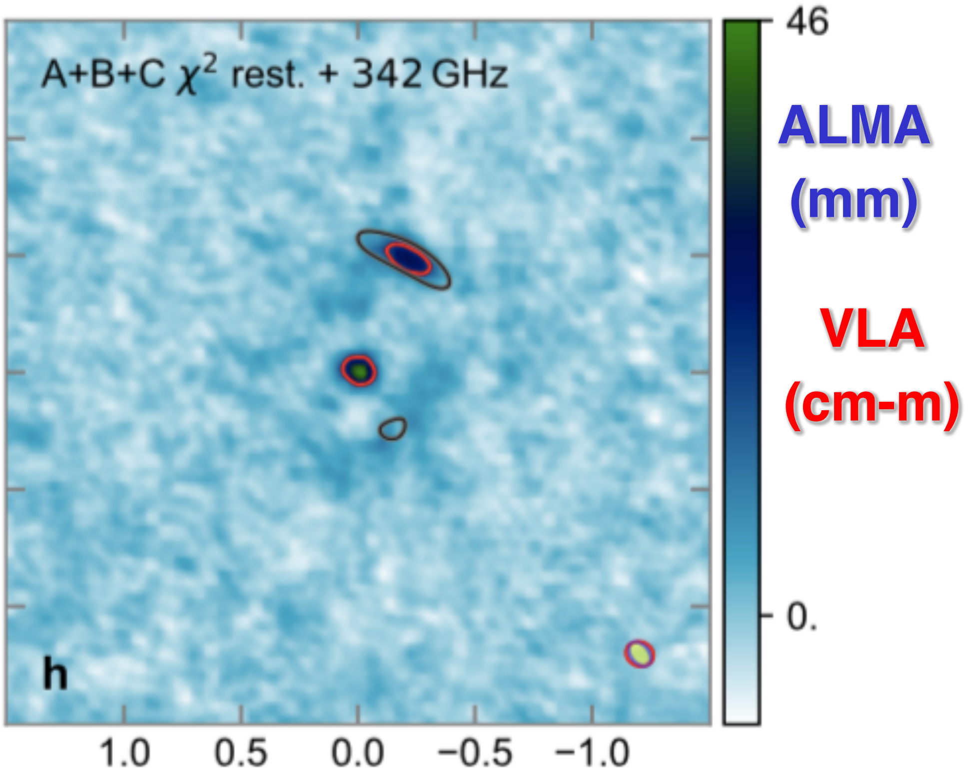
Analytical vs Numerical vs Observational



Lyra & Lin (2013)

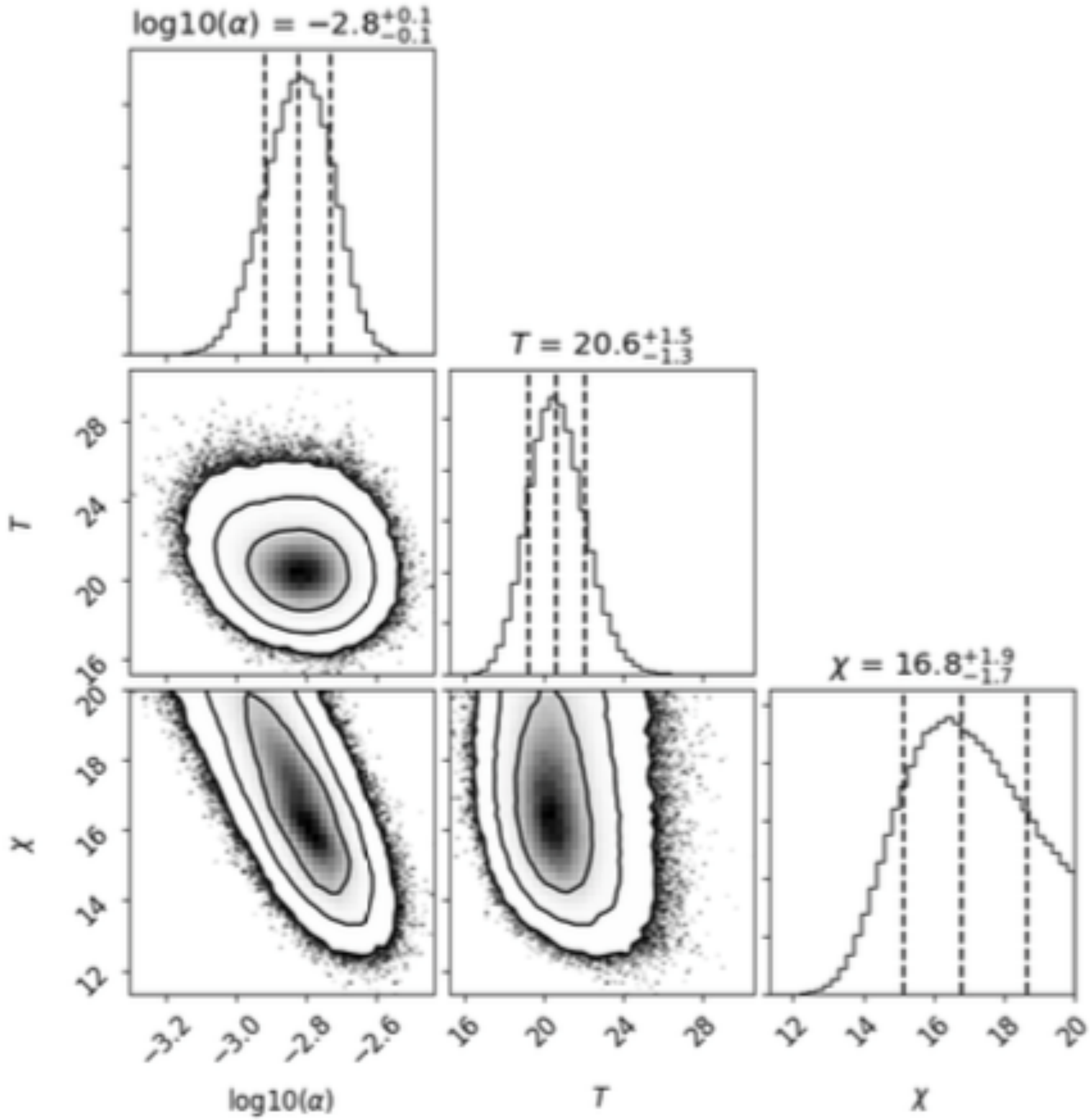


Raettig, Lyra , & Klahr et al (2015)



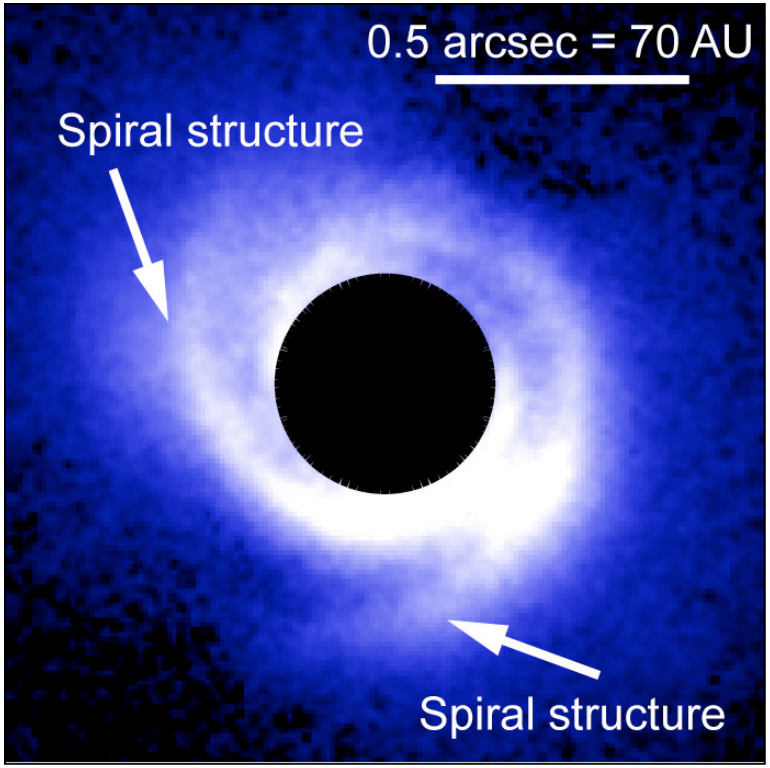
Casassus, Marino, Lyra et al. (2018)

Observational vs Analytical



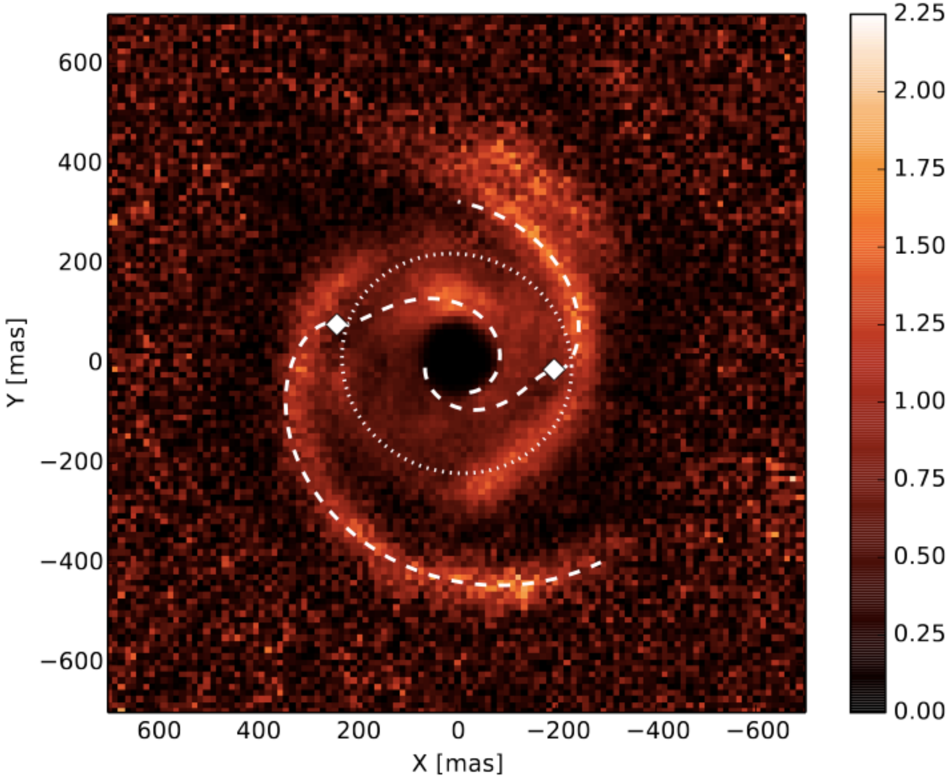
Observational Evidence: Spirals

SAO 206462



Muto et al. (2012)

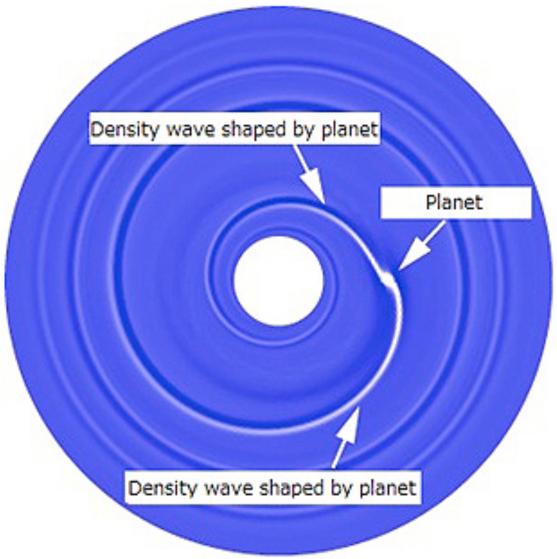
MWC 758



Benisty et al. (2015)

Spiral arm fitting leads to problems

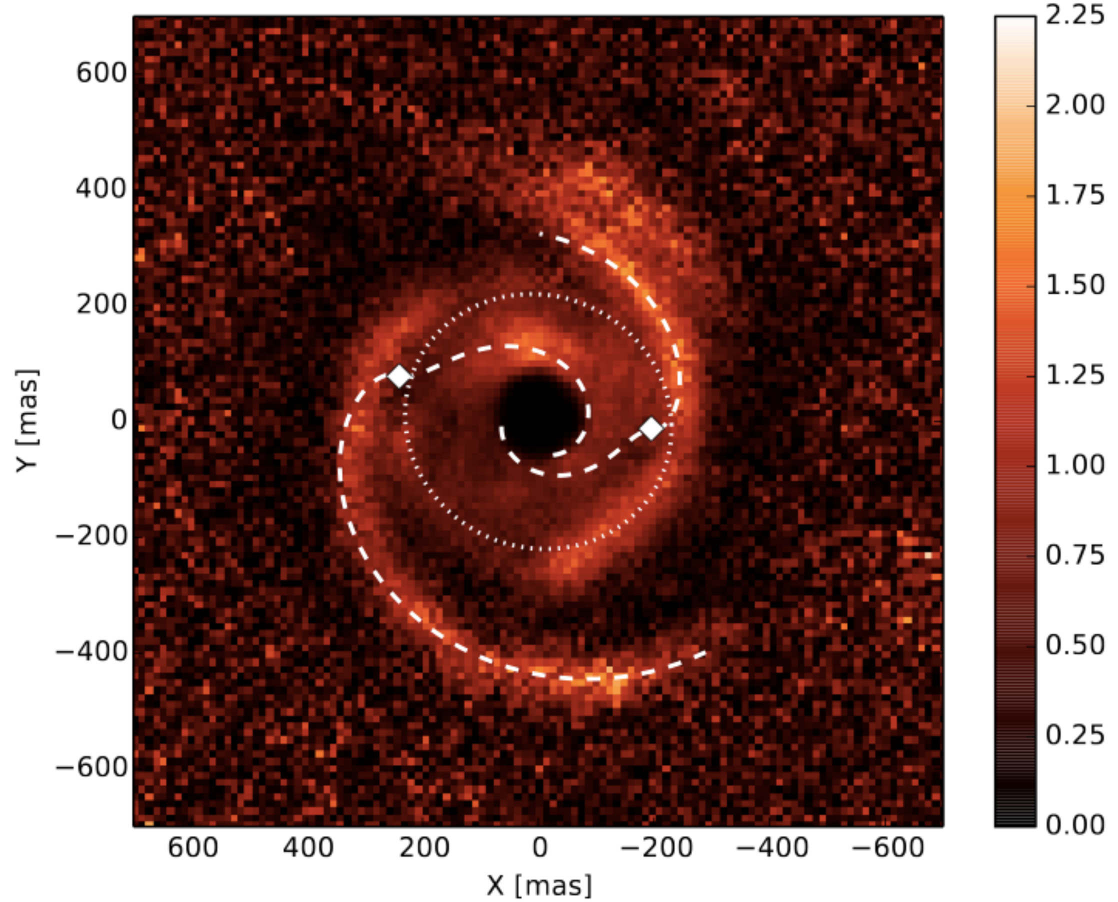
Analytical spiral fit



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

Rafikov (2002)
Muto et al. (2012)

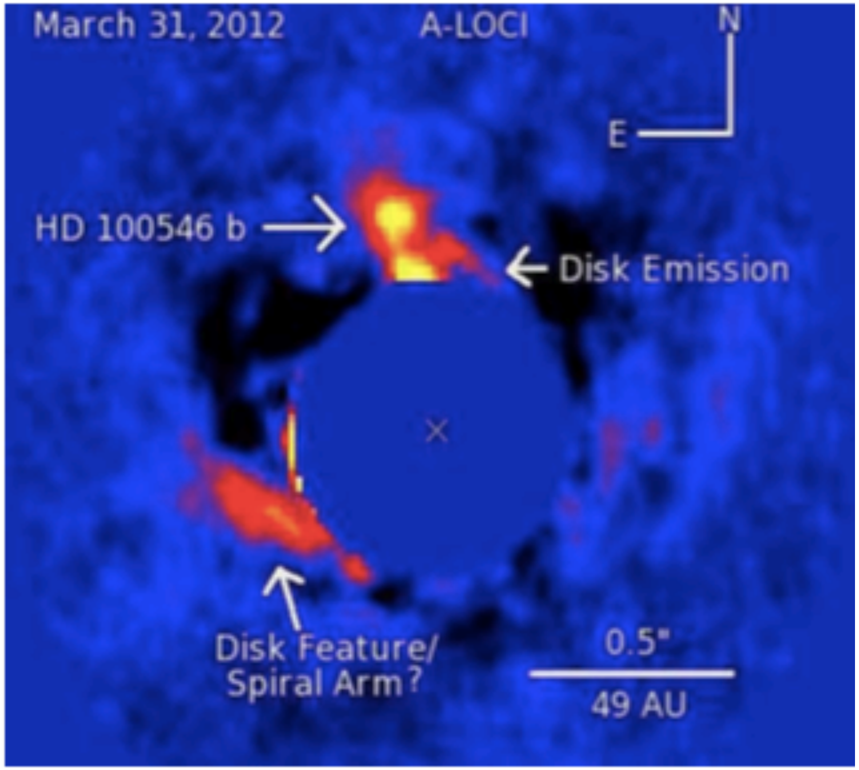
Spirals are **too wide**,
hotter (300K) than ambient gas (50K).



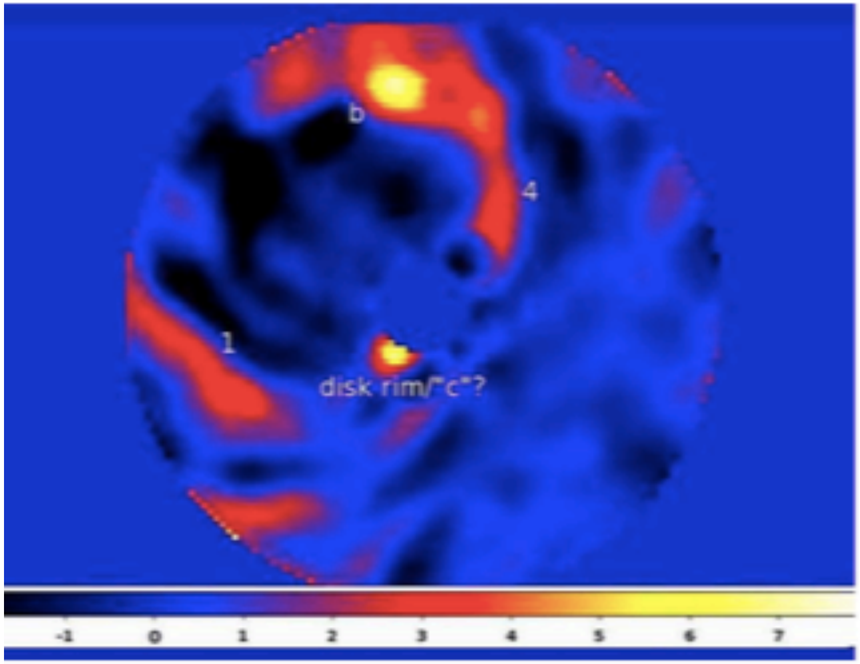
Benisty et al. (2015)

HD 100546

L band (~3.5 μm)

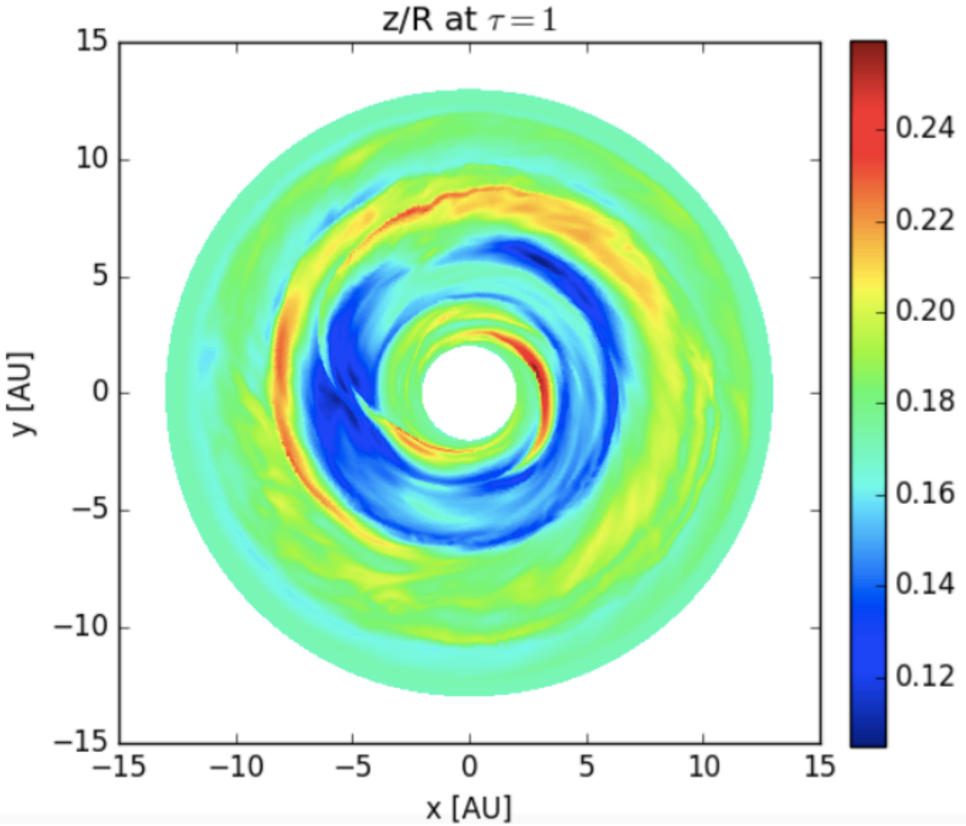


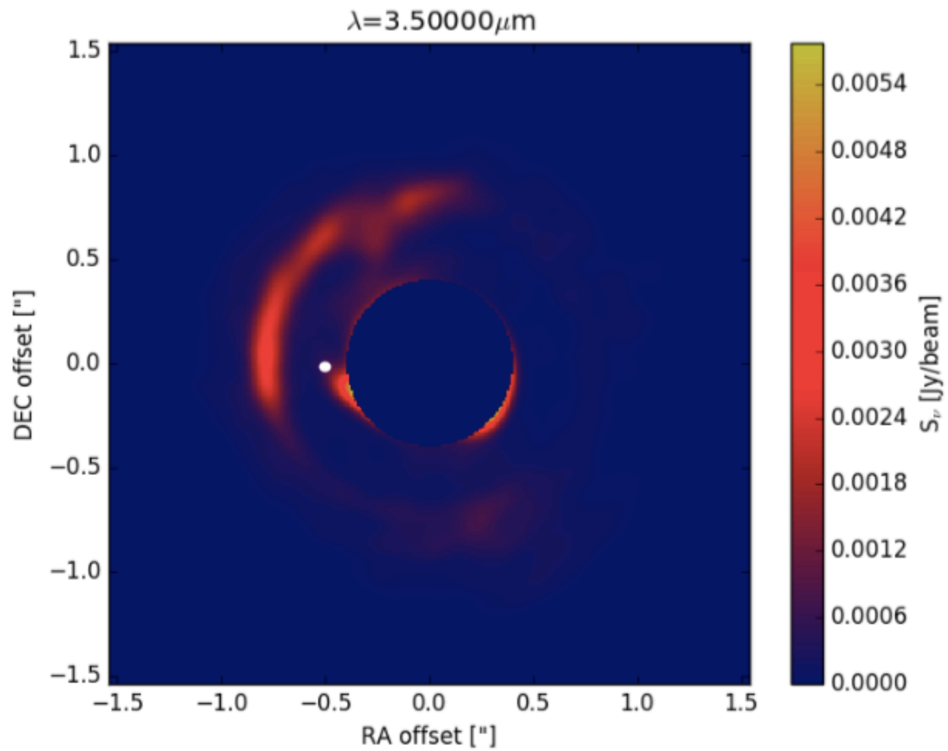
H band (~1.6 μm)



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

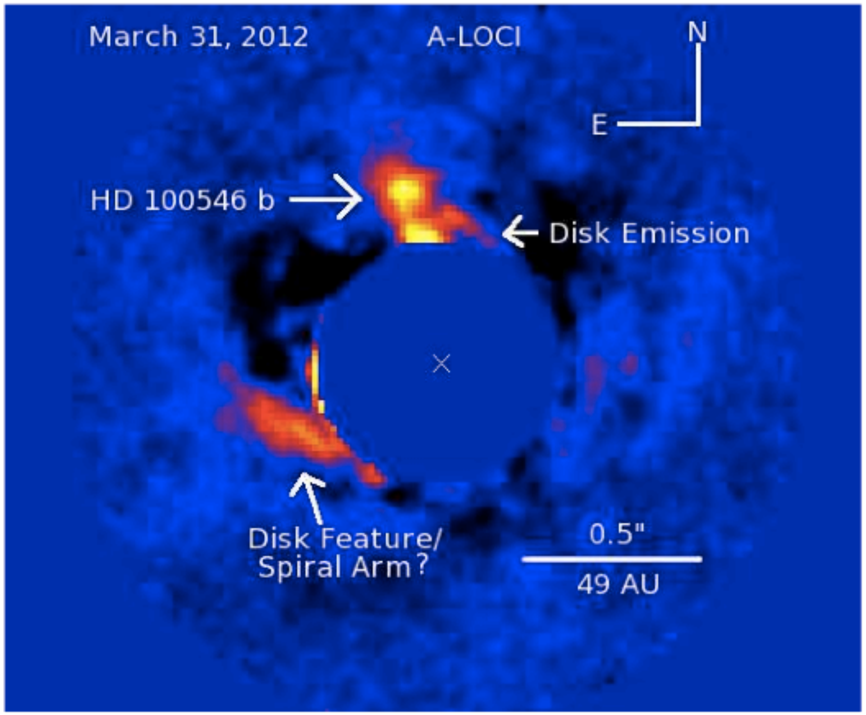
Scattering

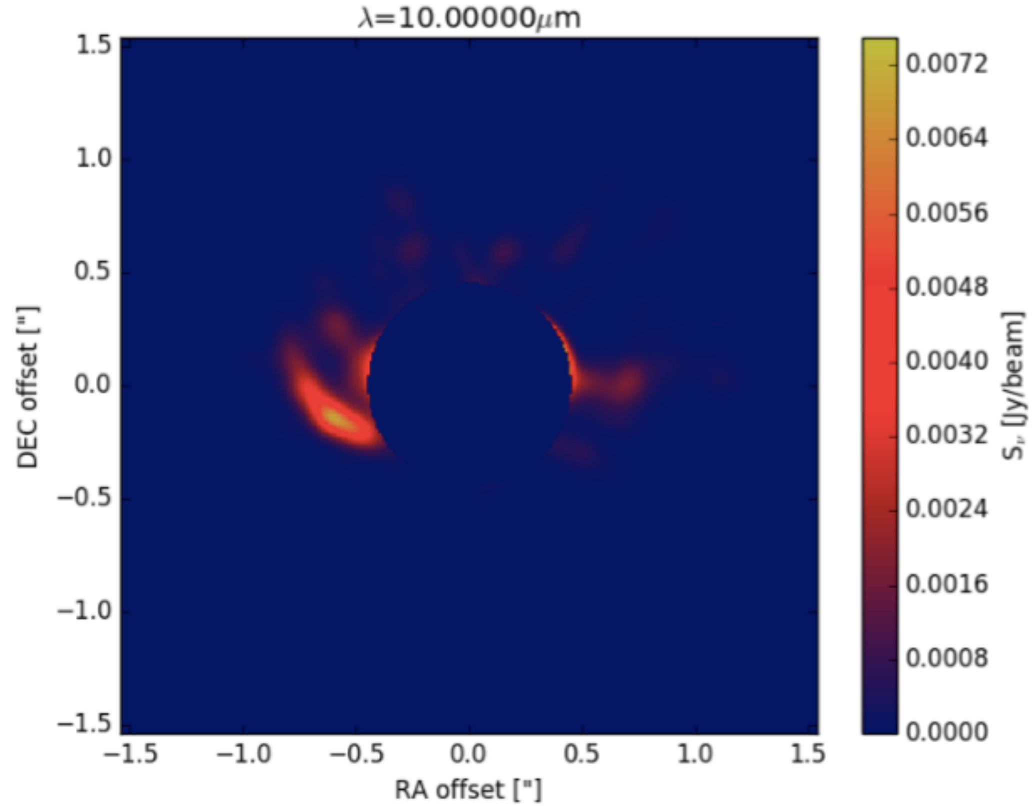




Hord et al. (2017)

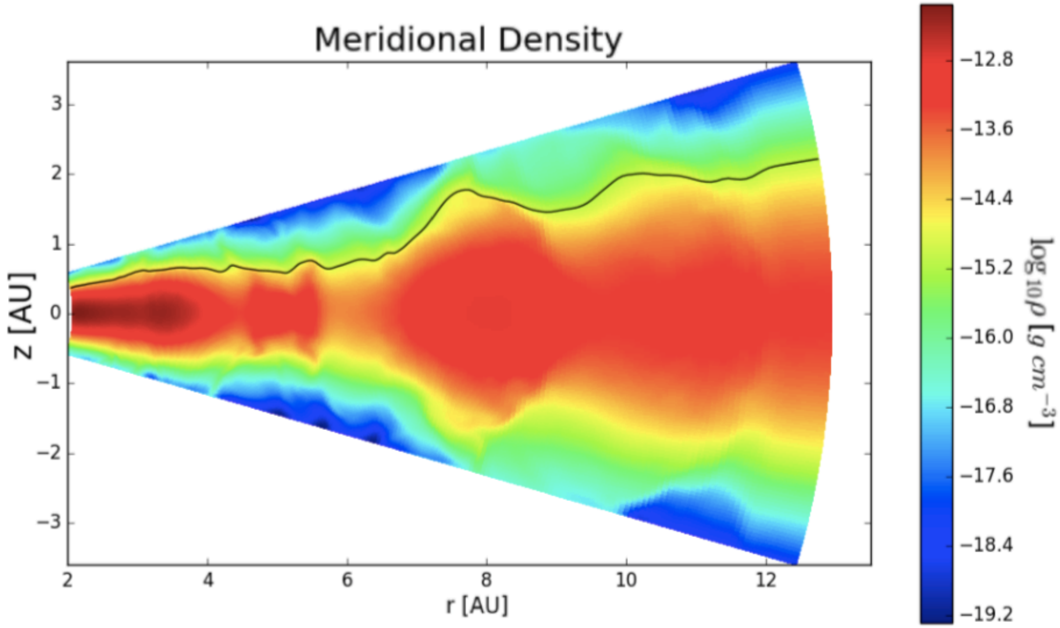
Observation vs Synthetic Image

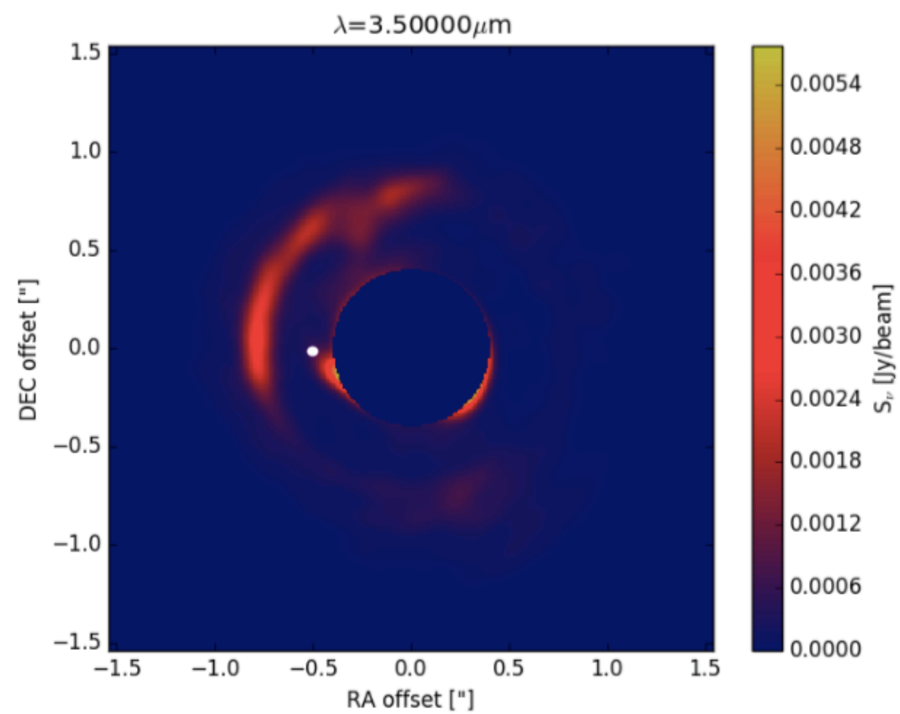




Hord et al. (2017)

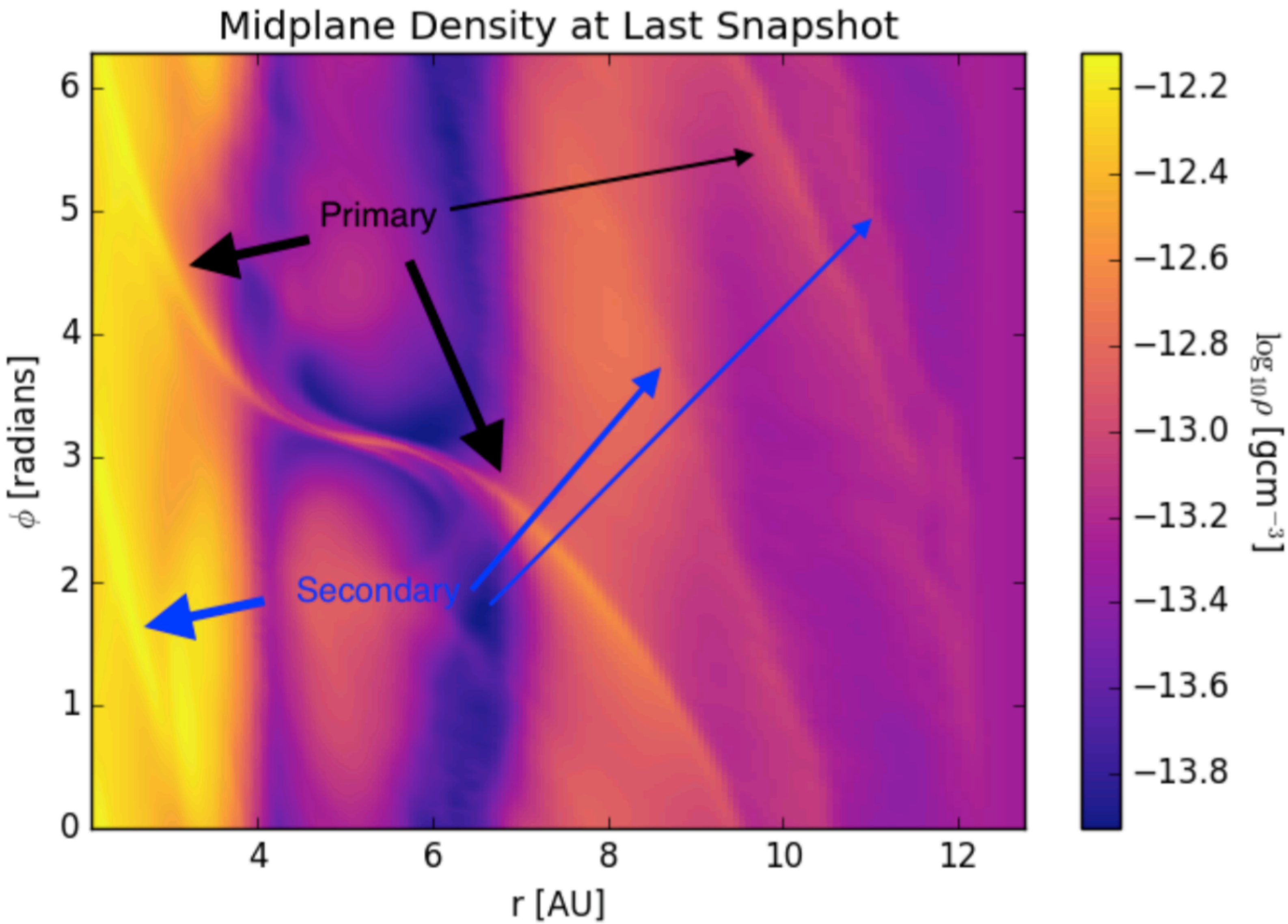
Scattering – A puffed up outer gap





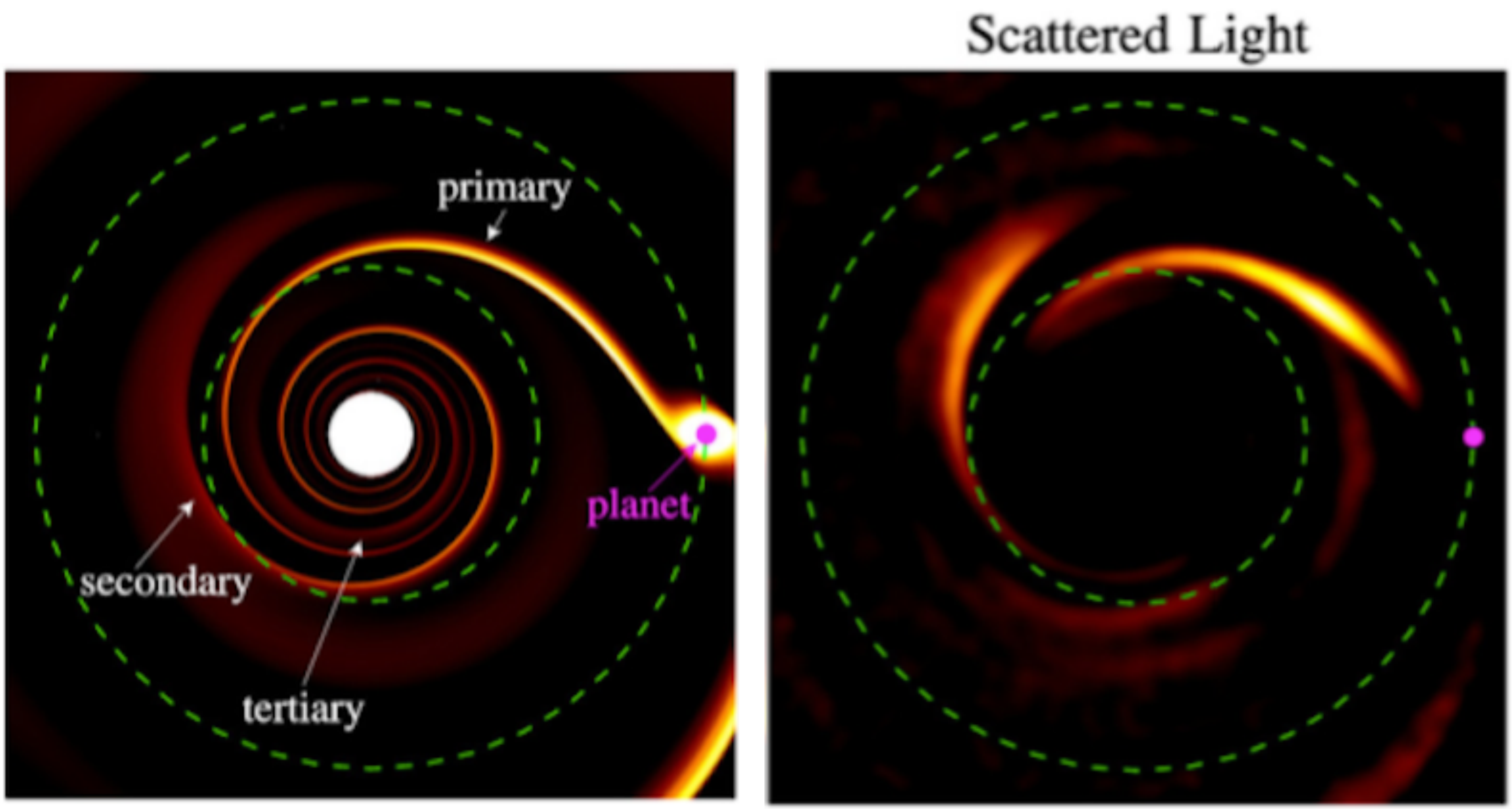
Hord et al. (2017)

Primary and Secondary spiral arms



Hord et al. (2017)

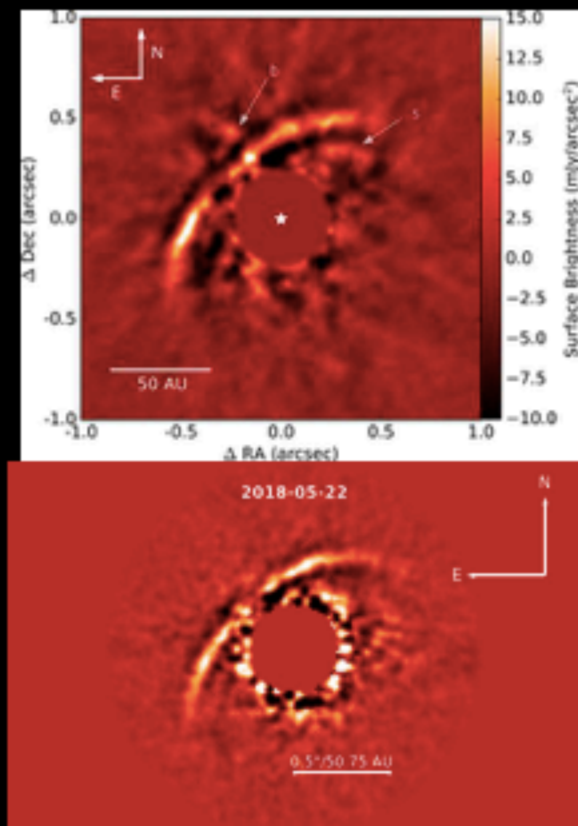
Primary and Secondary spiral arms



Fung & Dong (2015)

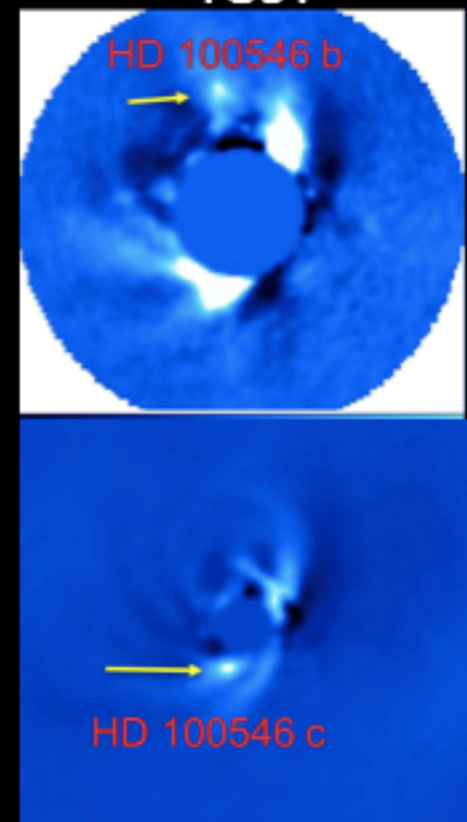
Planets in Transitional Disks?
HD 163296 and HD 100546

No?



Candidate planet not recovered
(Rich et al. in prep)

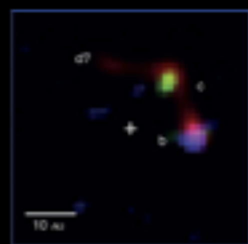
Yes?



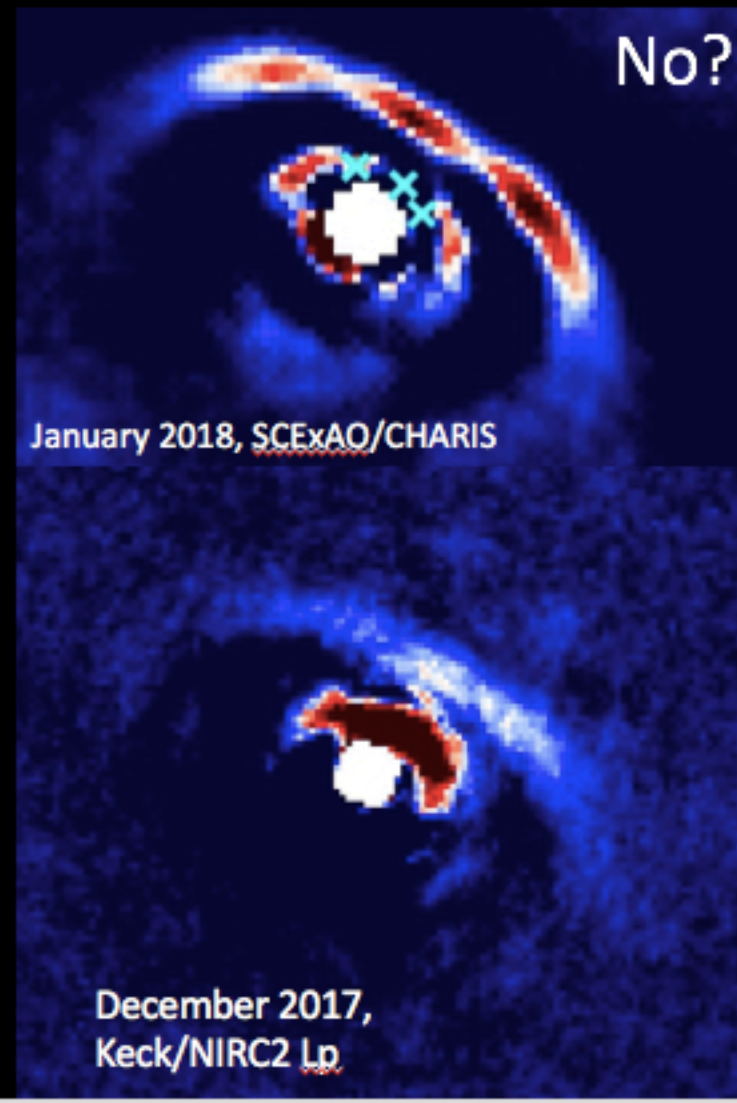
Likely 2nd epoch recovery of HD 100546 b and c; orbital motion (T. Currie, in prog.)

Slide by T. Currie

Planets in Transitional Disks? LkCa 15



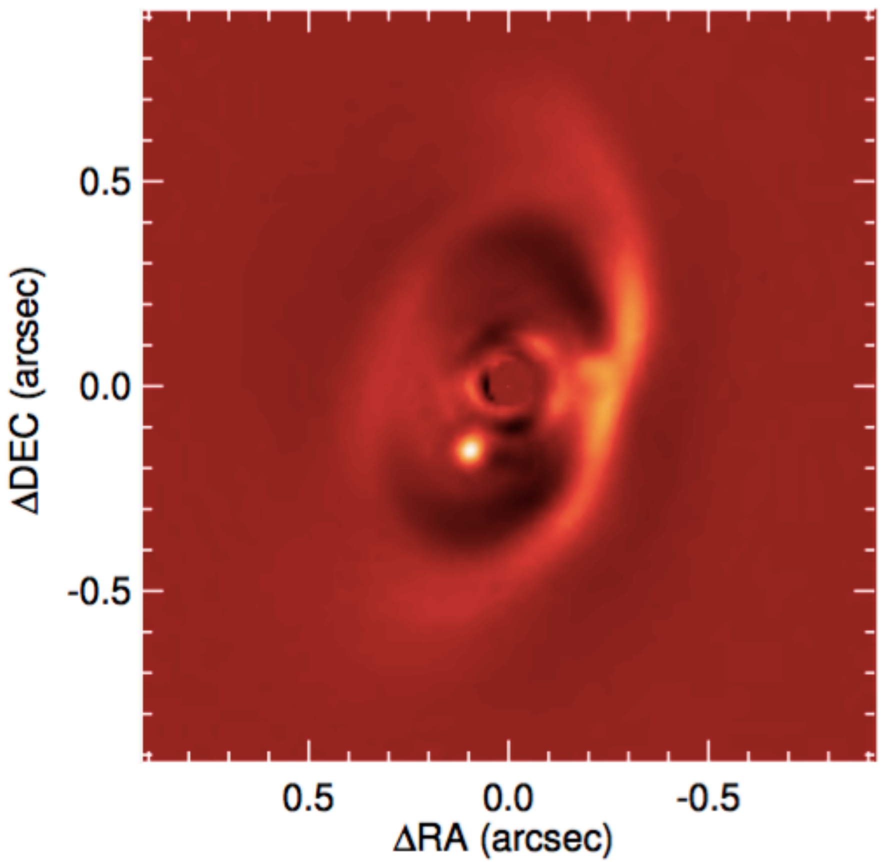
"LkCa 15 bcd": trace the outer edge of a bright extended inner disk

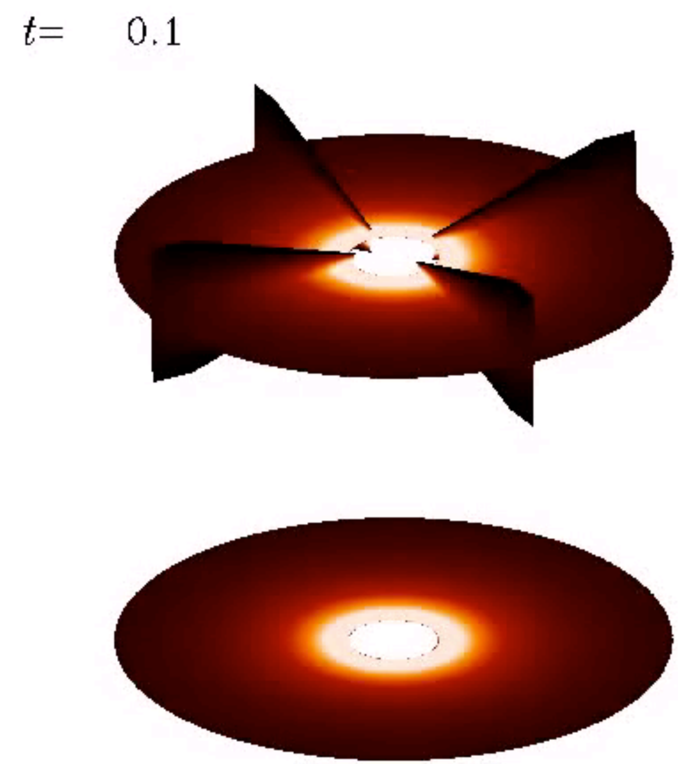


Currie, Marois, Cieza et al. in prep

Slide by T. Currie

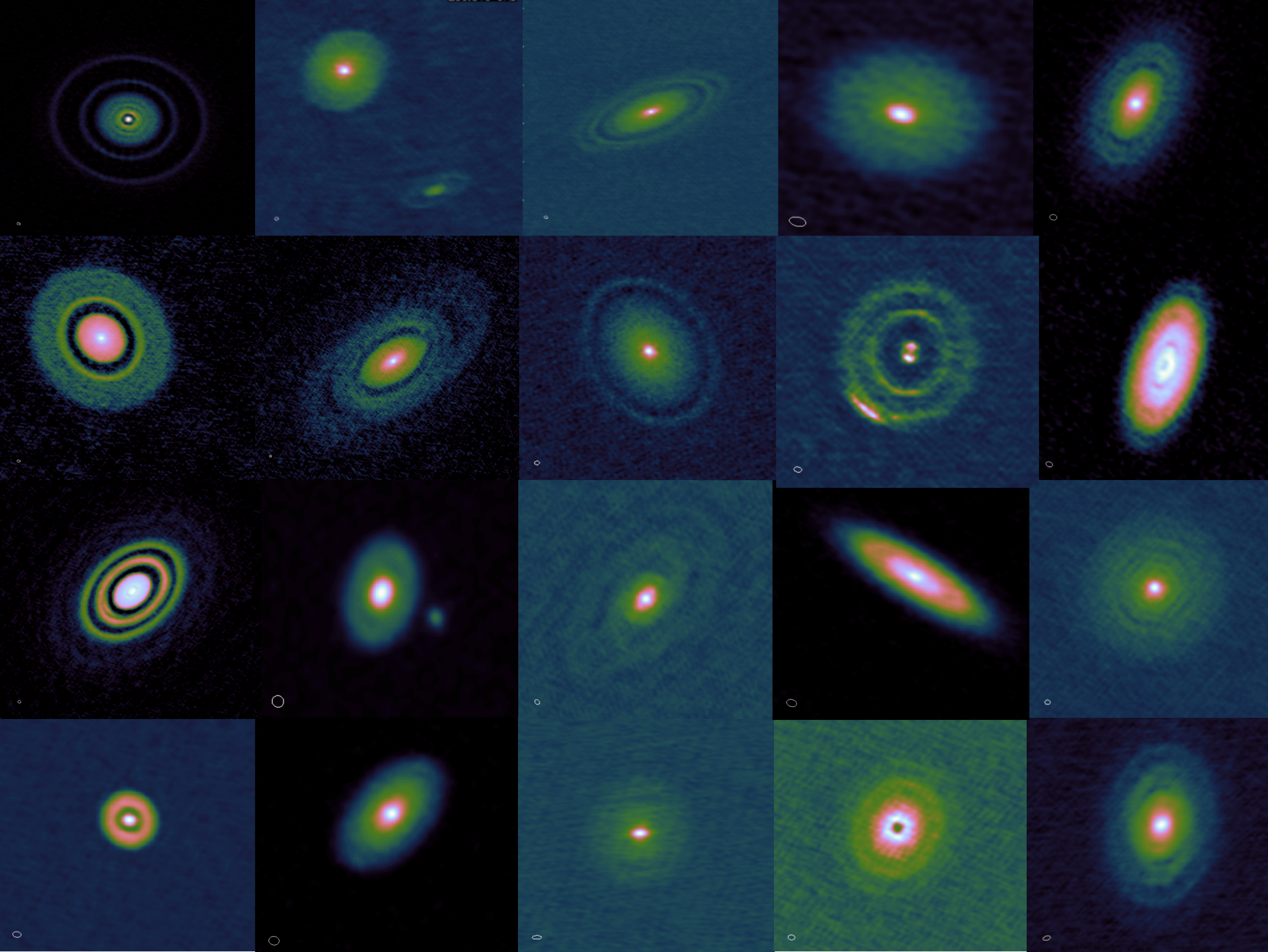
PDS 70



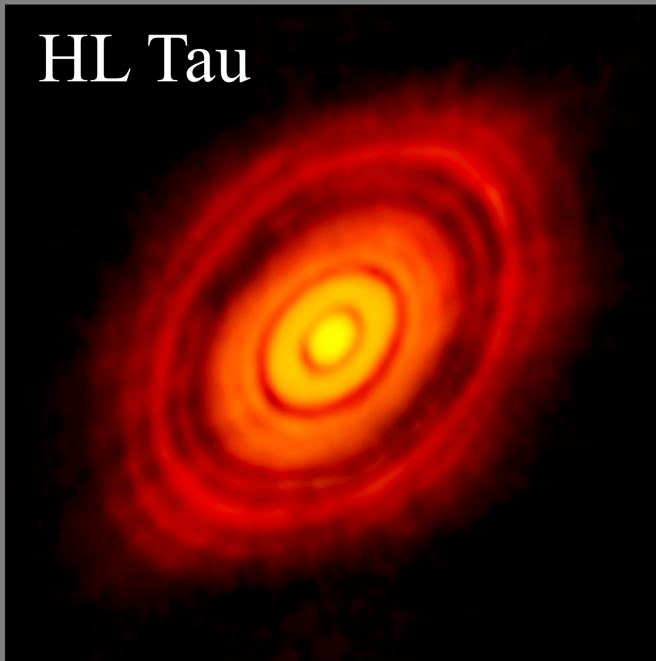


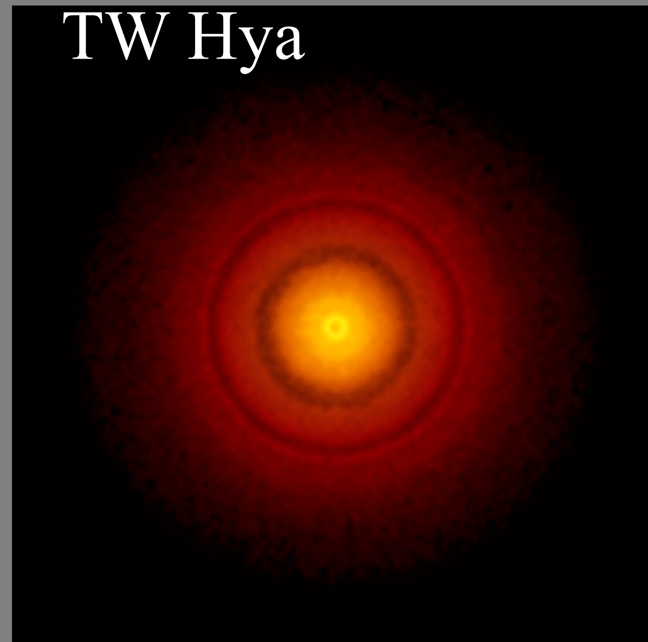
Conclusions

- Vortex-trapped dust in drag-diffusion equilibrium explains the observations
- Pending: Are observed vortices caused by planets?
- 3D radiation-hydro models needed to explain spirals and extended features
- 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

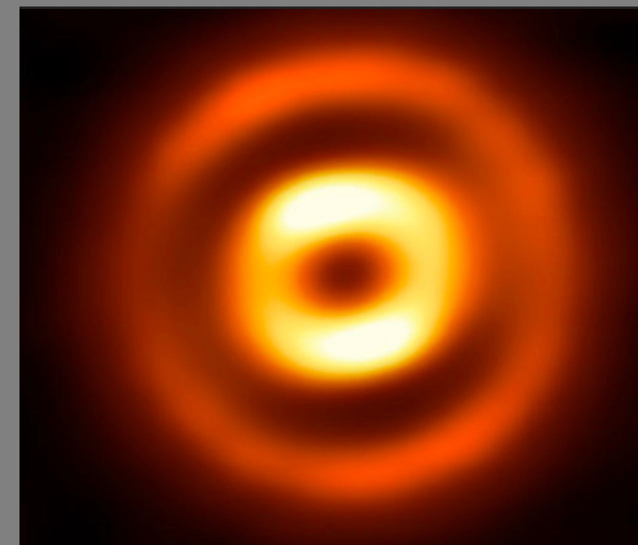


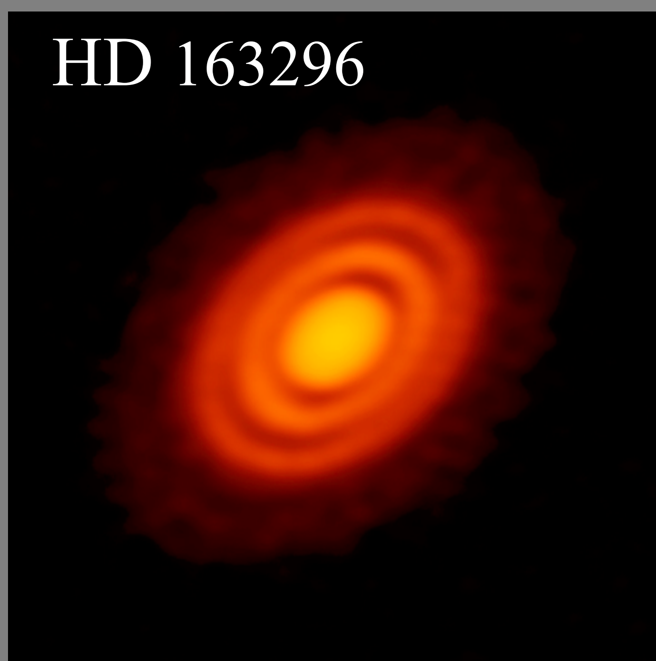
Rings and gaps





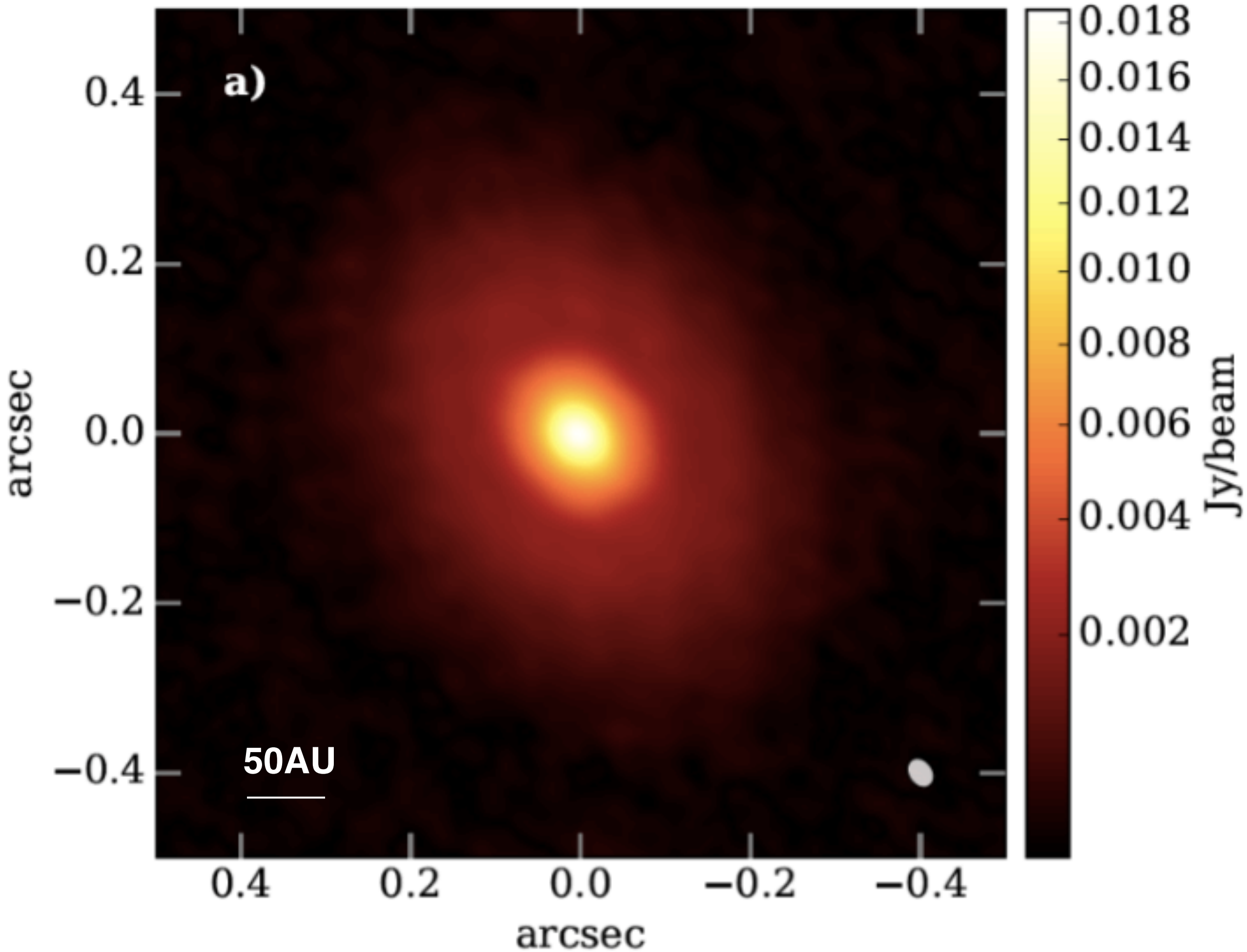
HD 169142





ALMA Partnership+ 15, Andrews, Ricci+ 16, Isella, Ricci+ 16, Cieza+ 16, Fedele+ 17

V883Ori

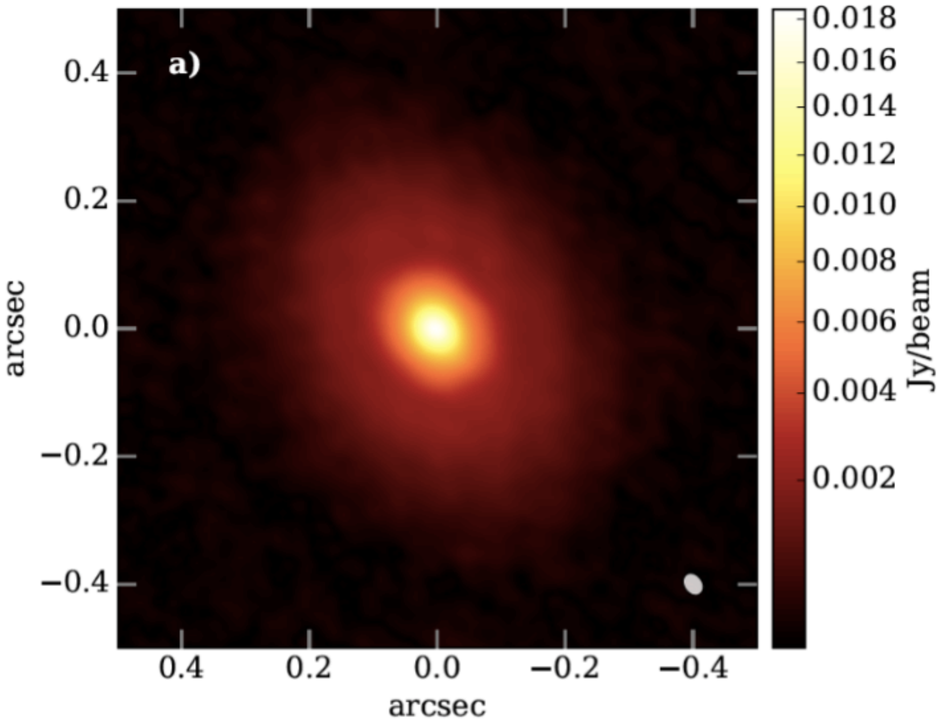


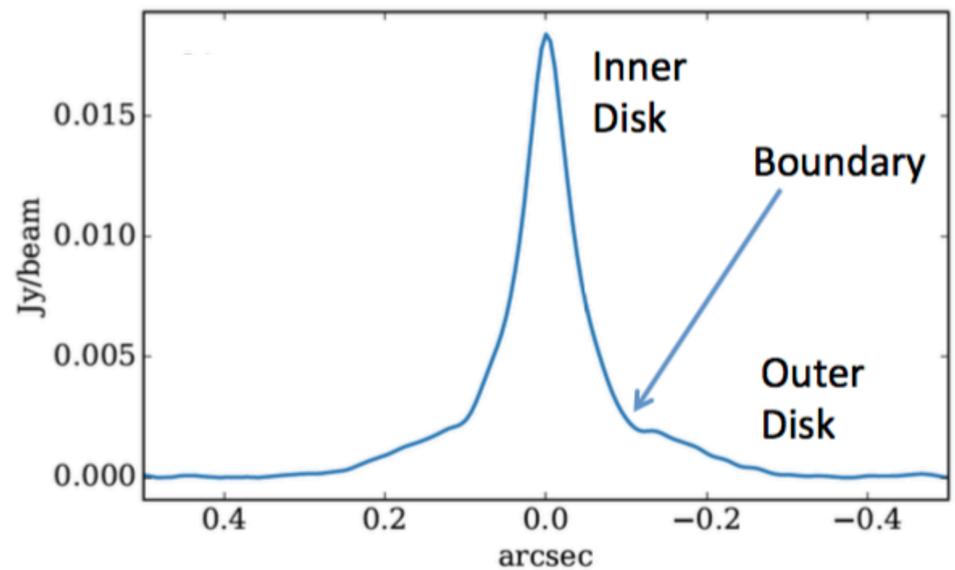
Class I protostar
(Age ~0.5 Myr)
(L_* ~ 6 L_{sun})

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)

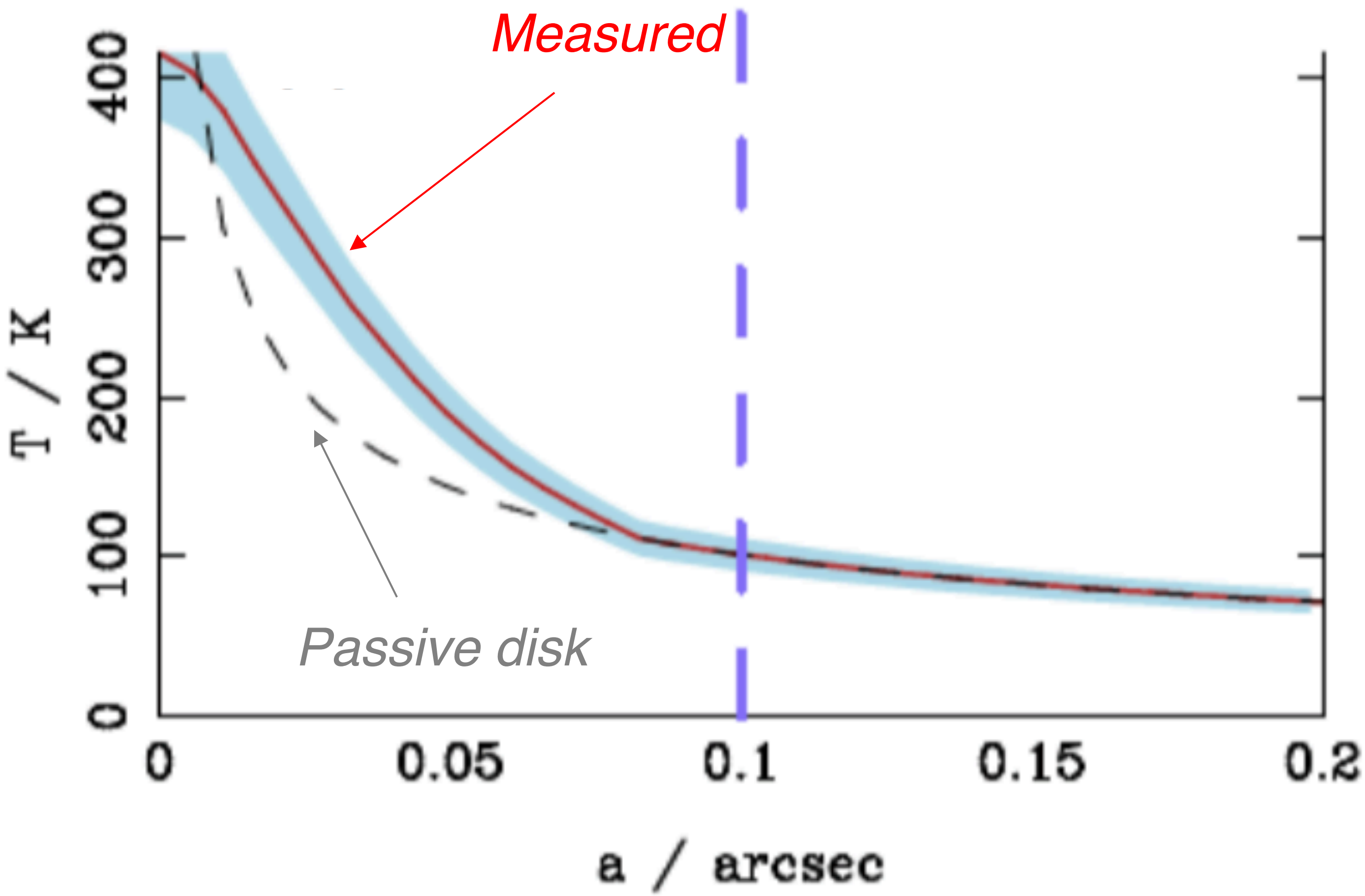
V883Ori





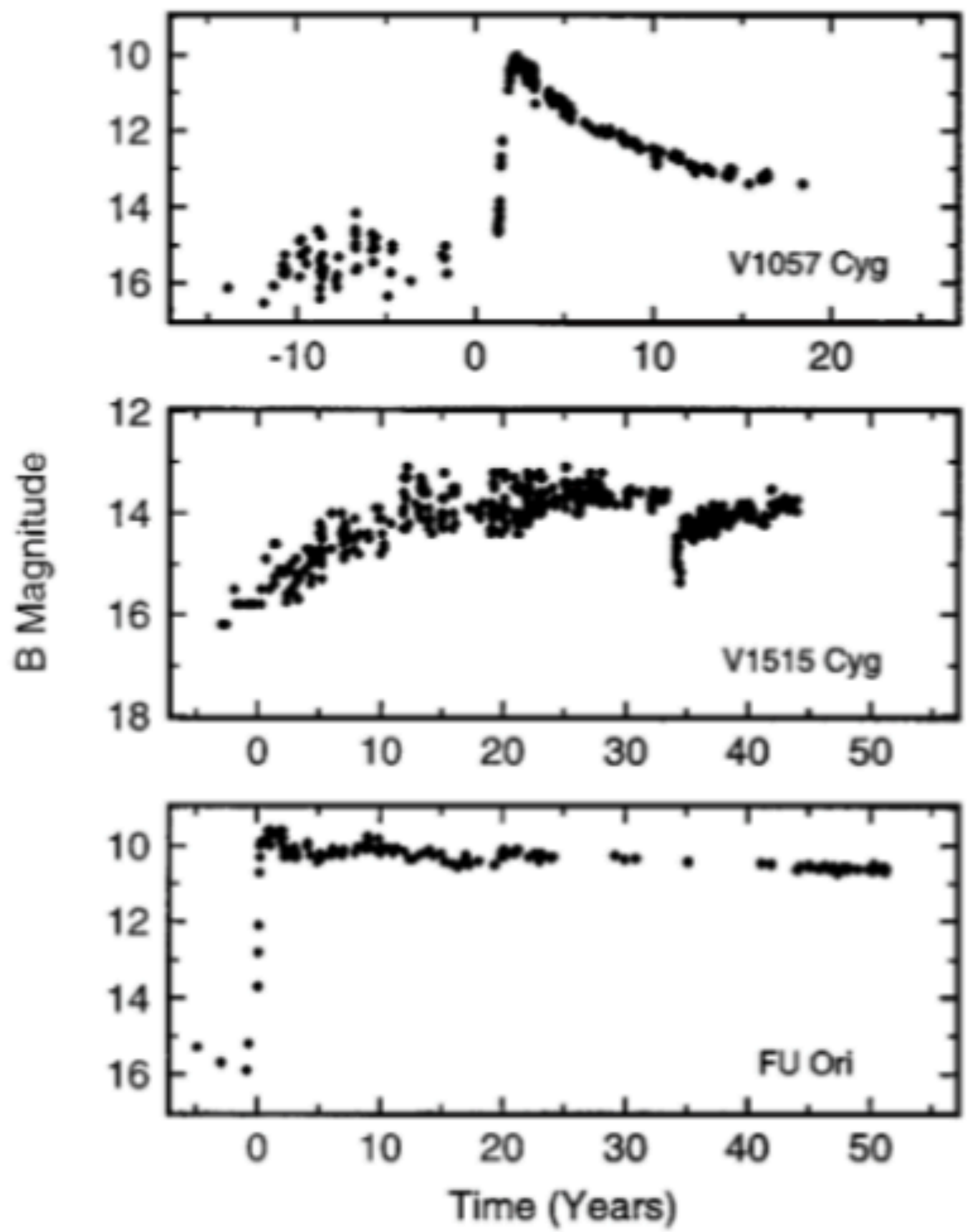
Cieza et al. (2016)

Extra source of heating needed

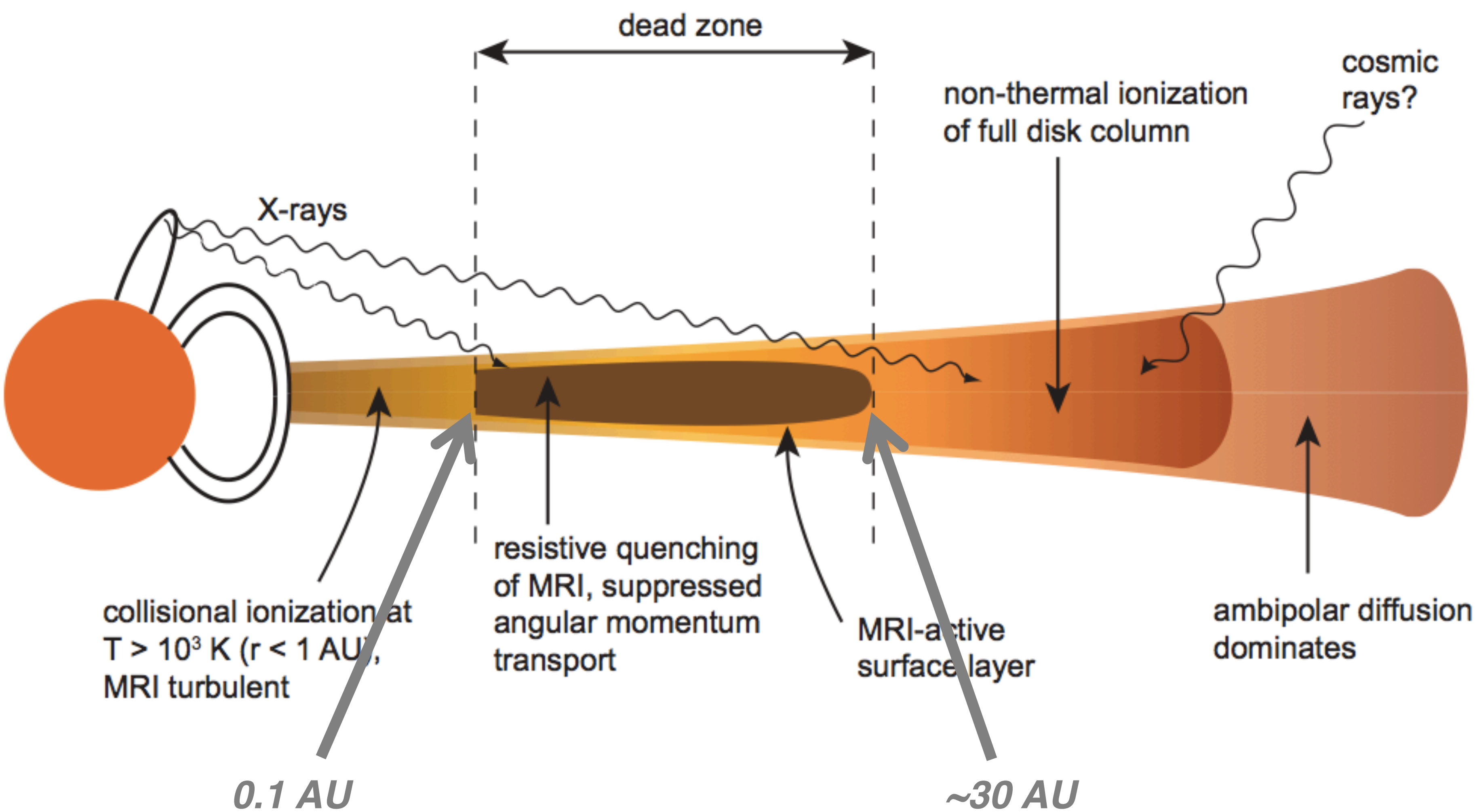


Cieza et al. (2016)

V883 Orionis is an FU Orionis star

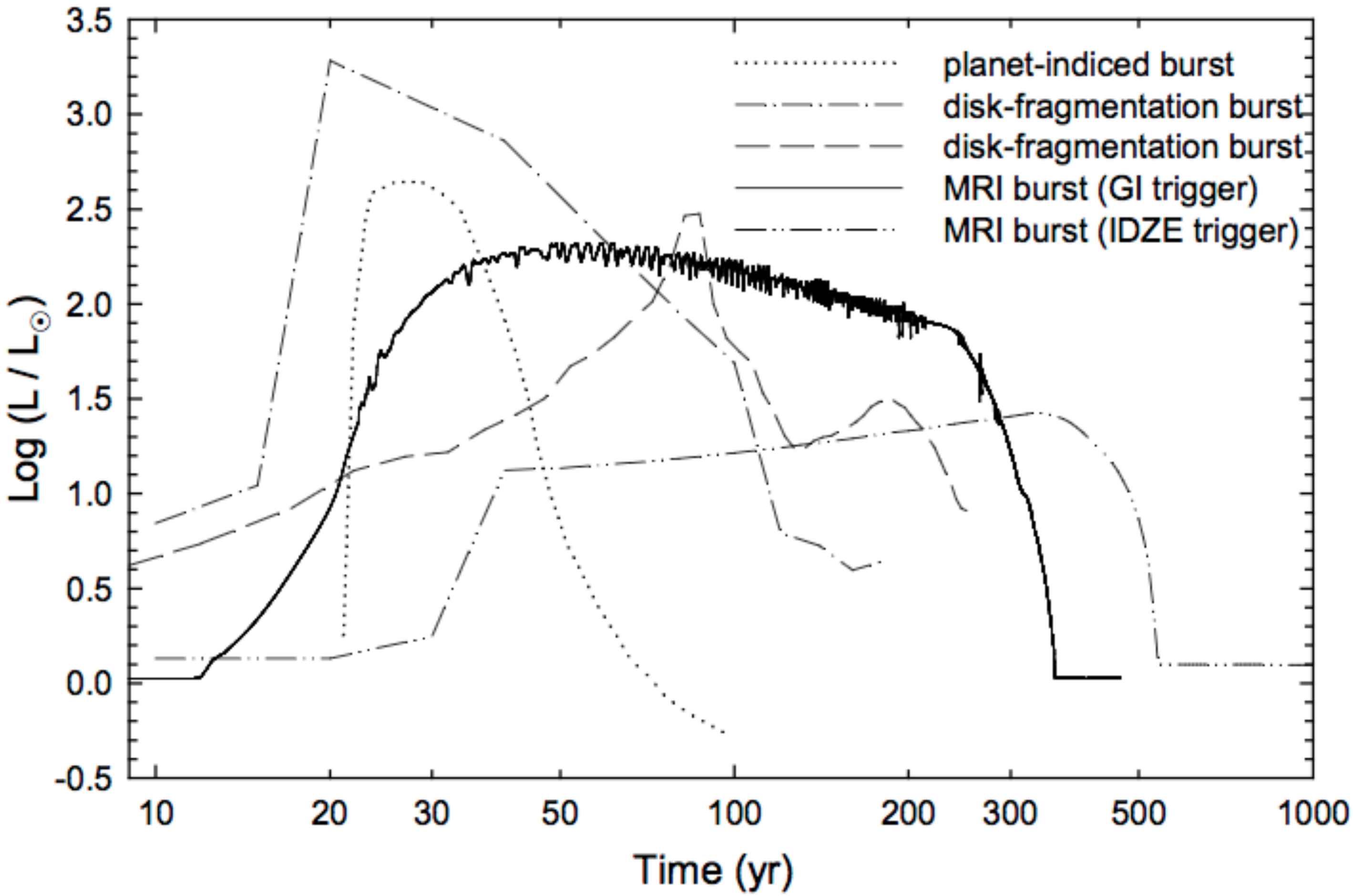


Episodic Accretion – Loading a dead zone



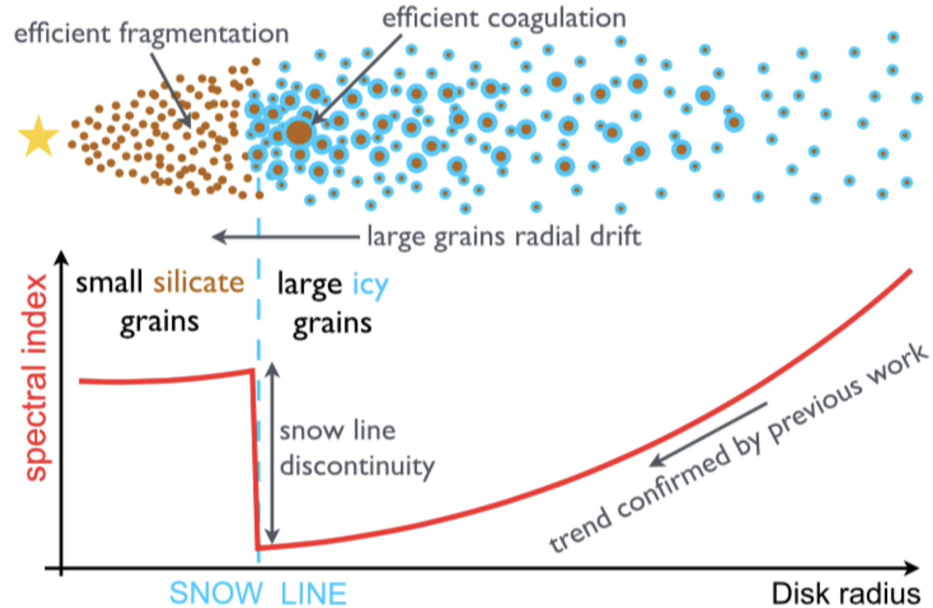
There should be a **magnetized, active zone**
and a **non-magnetic, dead zone**

Possible FU Ori triggers



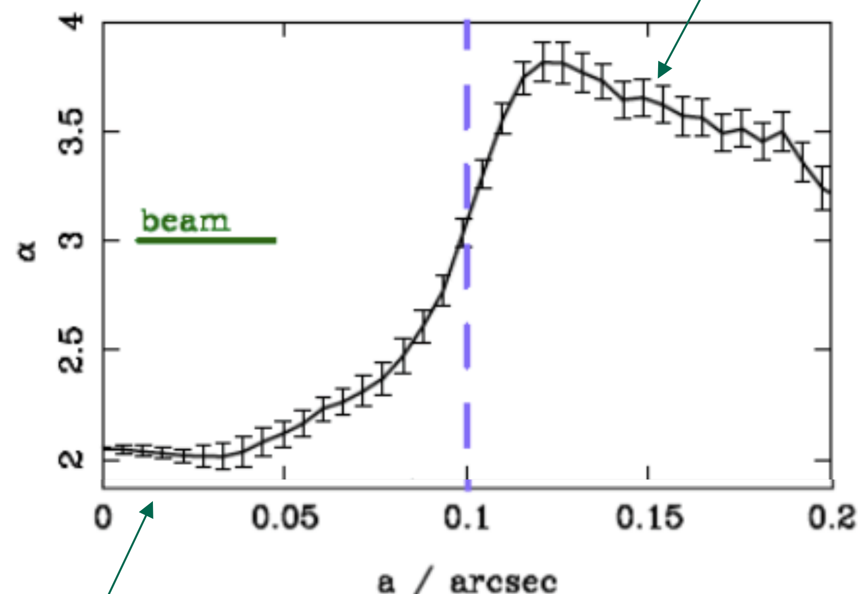
Audard et al. (2014)

Signature of a snowline: Spectral index



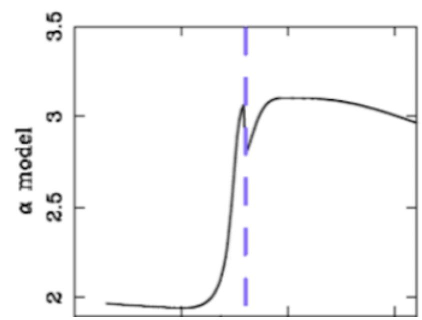
Banzatti et al. (2014)

Optically thin ISM-ilke values

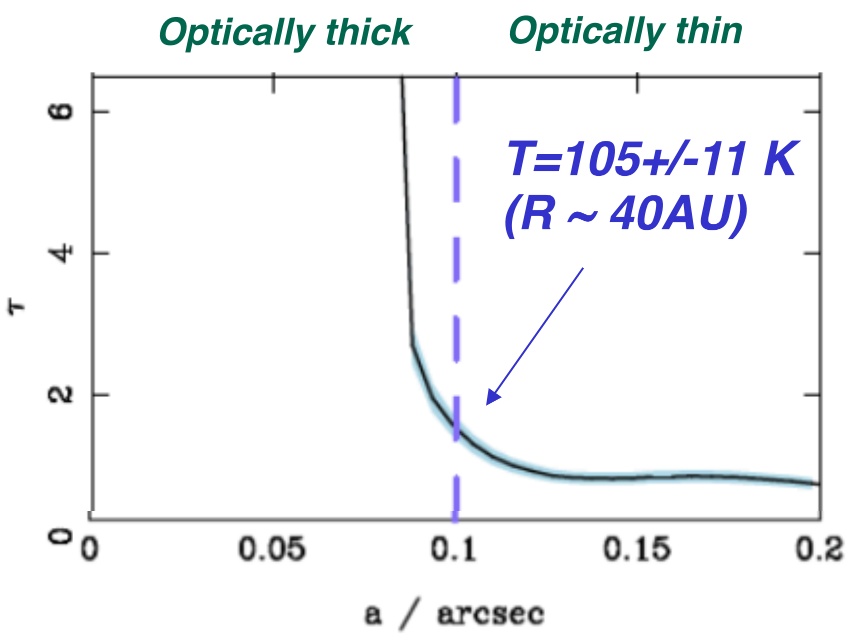


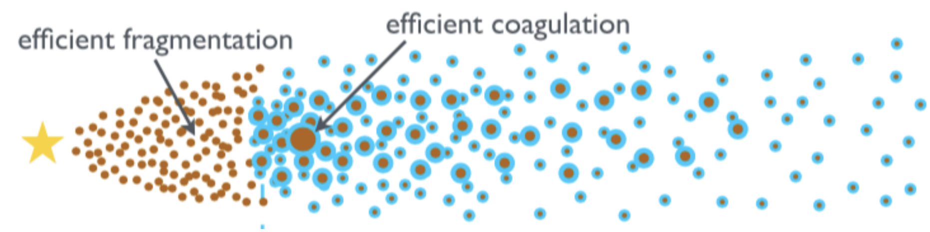
Optically thick blackbody emission

Cieza et al. (2016)



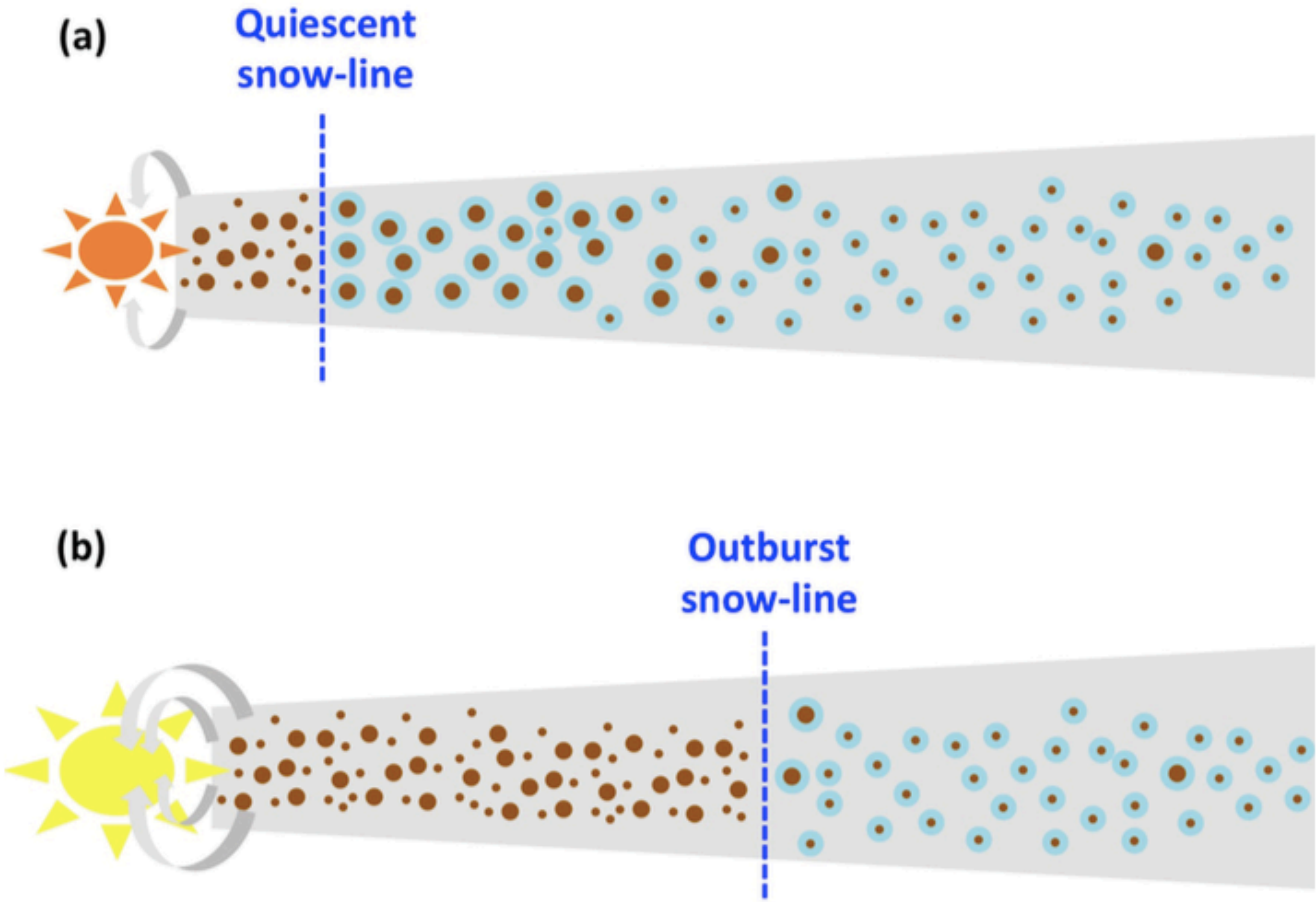
Signature of a snowline: Optical depth





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

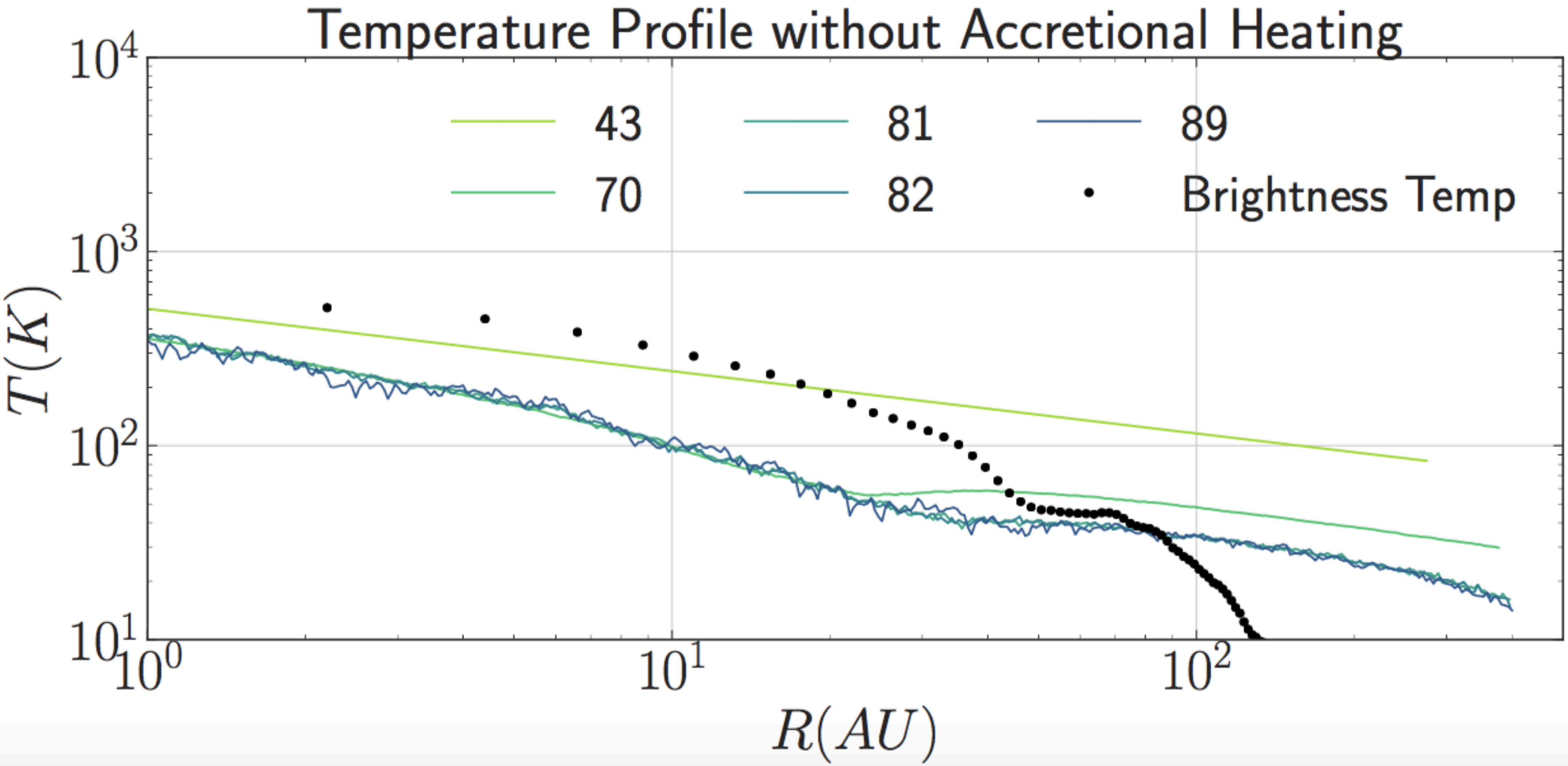
$$T_{\rm eff}^4 = T_{\rm irr}^4 + T_{\rm acc}^4$$

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

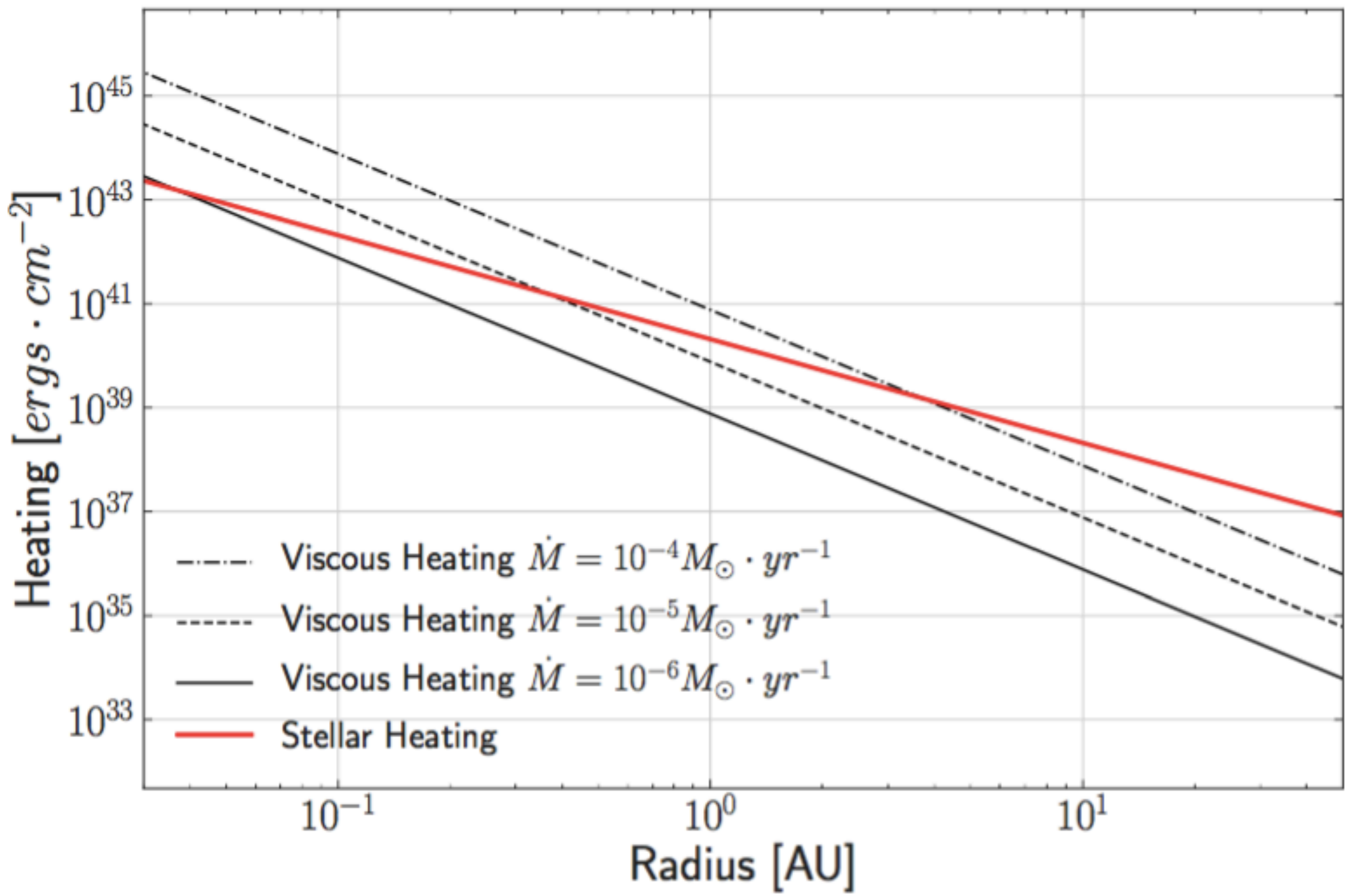
Chiang et al. (2001), Alarcon et al. (in prep)



Alarcon et al. (in prep)

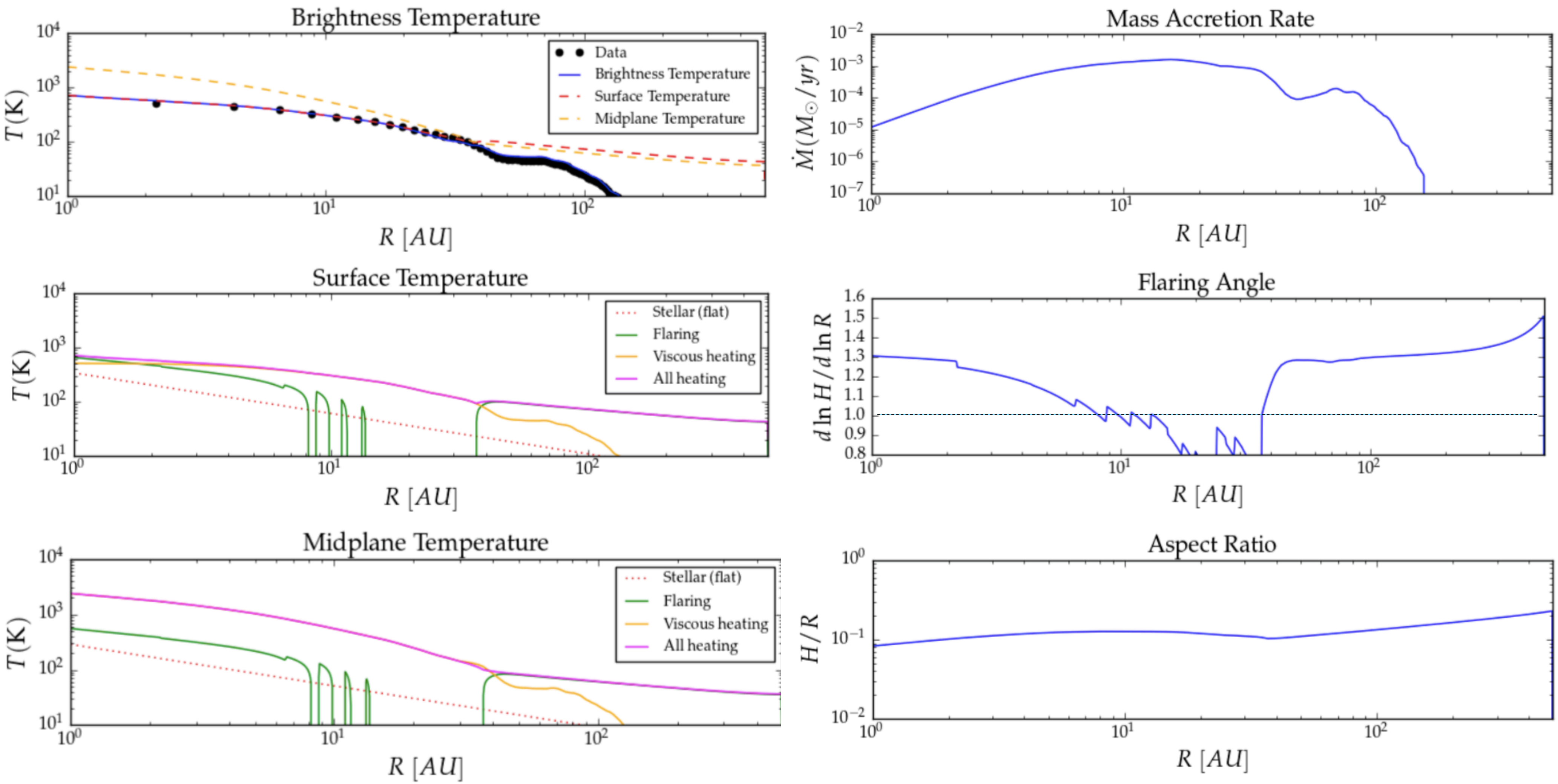
Viscous heating

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



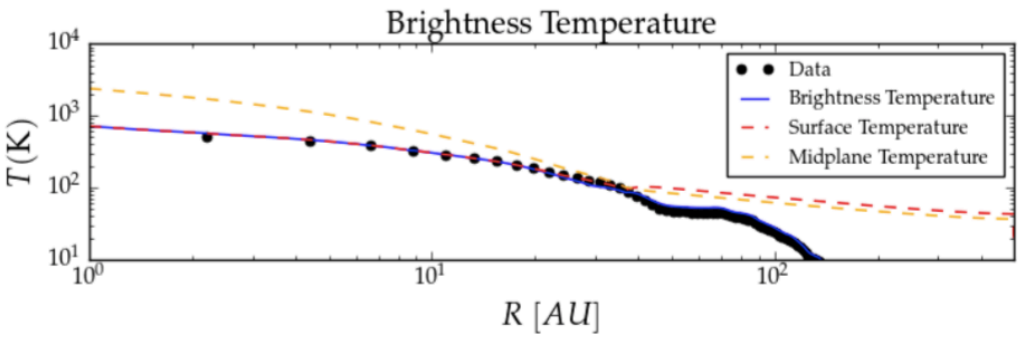
Alarcon et al. (in prep)

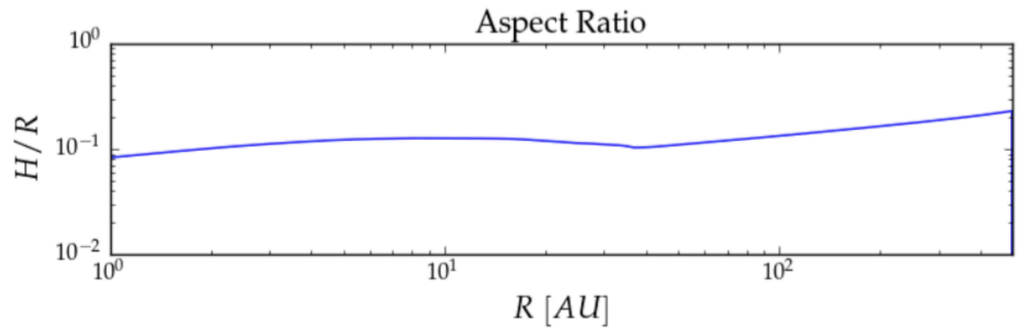
Best fit

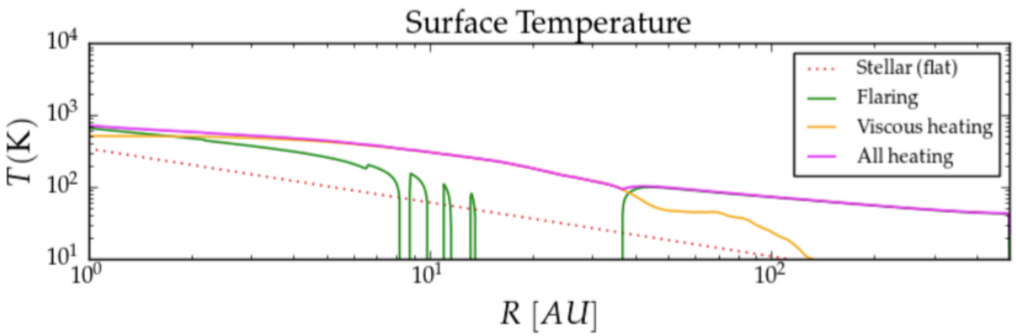


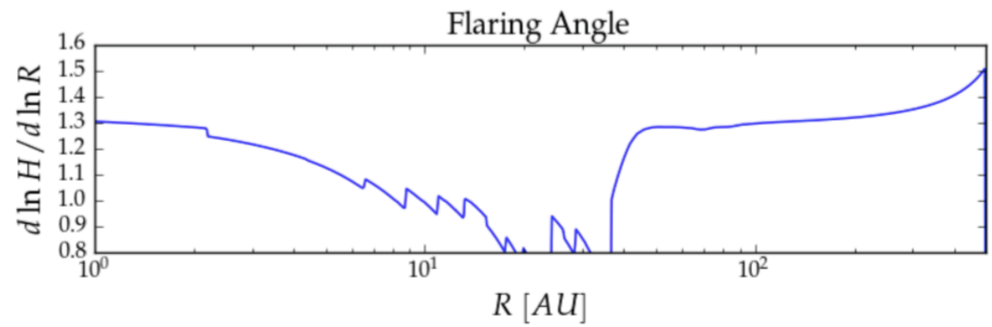
Alarcon et al. (in prep)

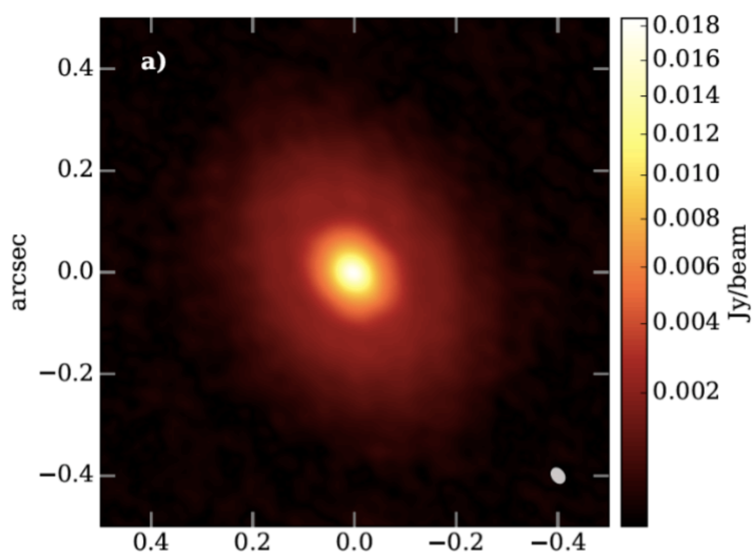
Self-shadowing

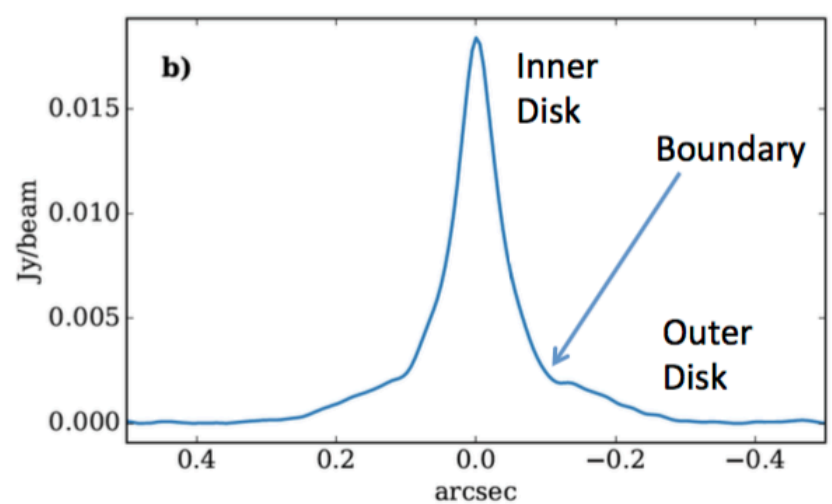












Cieza et al. (2016), Alarcon et al. (in prep)

Conclusions

- 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?*