Planet signatures in transition disks

Wladimir Lyra

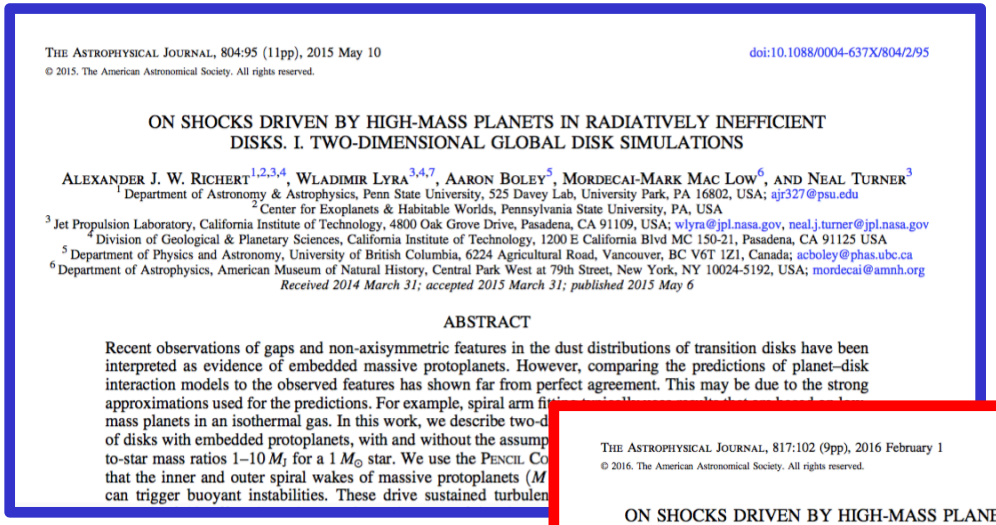
California State University

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).

Lund, Aug 22nd, 2018



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ON SHOCKS DRIVEN BY HIGH-MASS PLANETS IN RADIATIVELY INEFFICIENT DISKS. I. TWO-DIMENSIONAL GLOBAL DISK SIMULATIONS

Alexander J. W. Richert[1,2,3,4], Wladimir Lyra[3,4,7], Aaron Boley[5], Mordecai-Mark Mac Low[6], and Neal Turner[3]
[1] Department of Astronomy & Astrophysics, Penn State University, 525 Davey Lab, University Park, PA 16802, USA; ajr327@psu.edu
[2] Center for Exoplanets & Habitable Worlds, Pennsylvania State University, PA, USA
[3] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA; wlyra@jpl.nasa.gov, neal.j.turner@jpl.nasa.gov
[4] Division of Geological & Planetary Sciences, California Institute of Technology, 1200 E California Blvd MC 150-21, Pasadena, CA 91125 USA
[5] Department of Physics and Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, BC V6T 1Z1, Canada; acboley@phas.ubc.ca
[6] Department of Astrophysics, American Museum of Natural History, Central Park West at 79th Street, New York, NY 10024-5192, USA; mordecai@amnh.org
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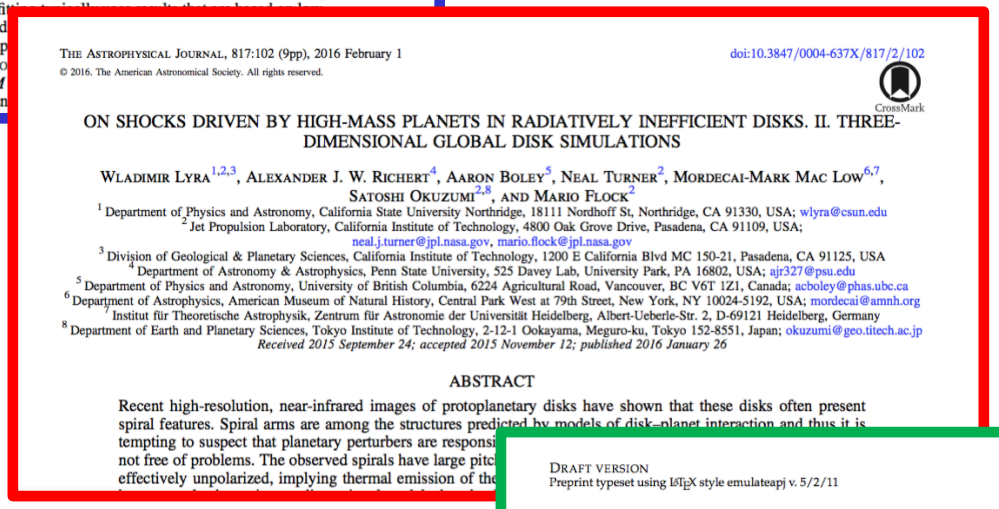
ABSTRACT

Recent observations of gaps and non-axisymmetric features in the dust distributions of transition disks have been interpreted as evidence of embedded massive protoplanets. However, comparing the predictions of planet–disk interaction models to the observed features has shown far from perfect agreement. This may be due to the strong approximations used for the predictions. For example, spiral arm fit
mass planets in an isothermal gas. In this work, we describe two-d
of disks with embedded protoplanets, with and without the assump
to-star mass ratios 1–10 M_J for a 1 $M_\odot$ star. We use the Pencil Co
that the inner and outer spiral wakes of massive protoplanets (M
can trigger buoyant instabilities. These drive sustained turbulen

Richert et al. (2015)



The Astrophysical Journal, 817:102 (9pp), 2016 February 1 doi:10.3847/0004-637X/817/2/102

ON SHOCKS DRIVEN BY HIGH-MASS PLANETS IN RADIATIVELY INEFFICIENT DISKS. II. THREE-DIMENSIONAL GLOBAL DISK SIMULATIONS

Wladimir Lyra[1,2,3], Alexander J. W. Richert[4], Aaron Boley[5], Neal Turner[2], Mordecai-Mark Mac Low[6,7], Satoshi Okuzumi[2,8], and Mario Flock[2]
[1] Department of Physics and Astronomy, California State University Northridge, 18111 Nordhoff St, Northridge, CA 91330, USA; wlyra@csun.edu
[2] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA; neal.j.turner@jpl.nasa.gov, mario.flock@jpl.nasa.gov
[3] Division of Geological & Planetary Sciences, California Institute of Technology, 1200 E California Blvd MC 150-21, Pasadena, CA 91125, USA
[4] Department of Astronomy & Astrophysics, Penn State University, 525 Davey Lab, University Park, PA 16802, USA; ajr327@psu.edu
[5] Department of Physics and Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, BC V6T 1Z1, Canada; acboley@phas.ubc.ca
[6] Department of Astrophysics, American Museum of Natural History, Central Park West at 79th Street, New York, NY 10024-5192, USA; mordecai@amnh.org
[7] Institut für Theoretische Astrophysik, Zentrum für Astronomie der Universität Heidelberg, Albert-Ueberle-Str. 2, D-69121 Heidelberg, Germany
[8] Department of Earth and Planetary Sciences, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan; okuzumi@geo.titech.ac.jp
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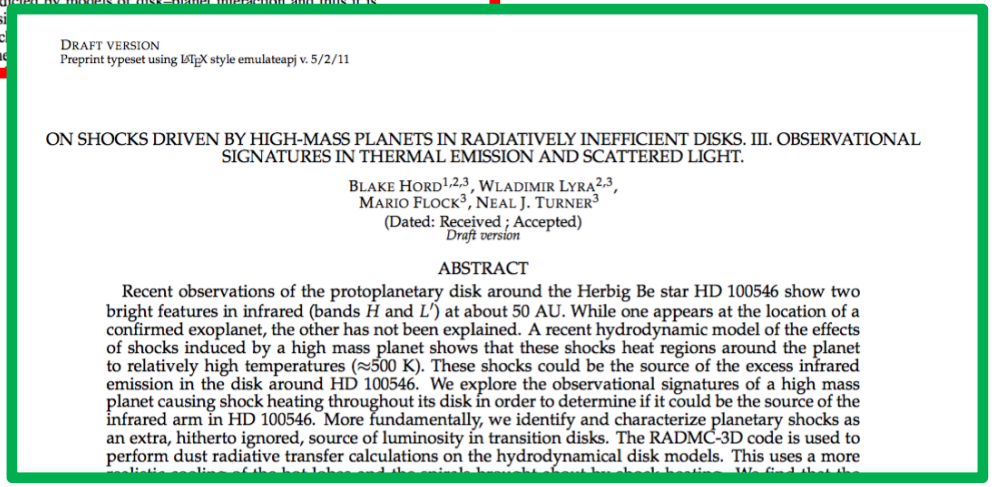
ABSTRACT

Recent high-resolution, near-infrared images of protoplanetary disks have shown that these disks often present spiral features. Spiral arms are among the structures predicted by models of disk–planet interaction and thus it is tempting to suspect that planetary perturbers are responsi
not free of problems. The observed spirals have large pitc
effectively unpolarized, implying thermal emission of the

Lyra et al. (2016)



Draft version
Preprint typeset using LaTeX style emulateapj v. 5/2/11

ON SHOCKS DRIVEN BY HIGH-MASS PLANETS IN RADIATIVELY INEFFICIENT DISKS. III. OBSERVATIONAL SIGNATURES IN THERMAL EMISSION AND SCATTERED LIGHT.

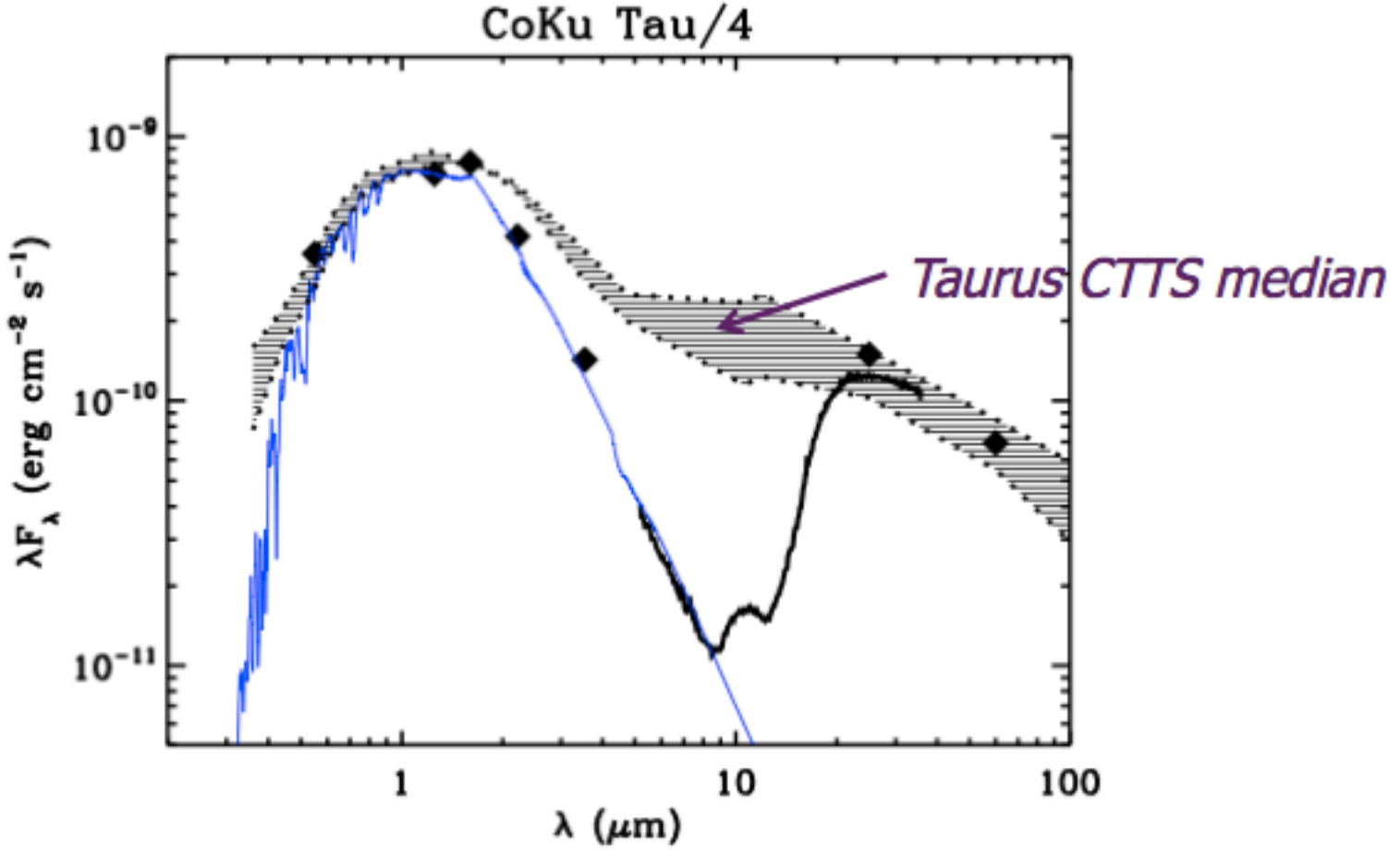
Blake Hord[1,2,3], Wladimir Lyra[2,3],
Mario Flock[3], Neal J. Turner[3]
(Dated: Received ; Accepted)
Draft version

ABSTRACT

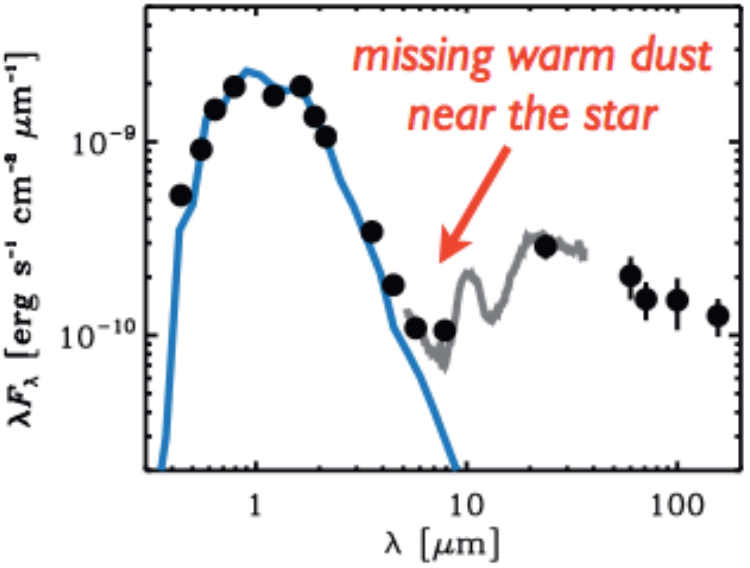
Recent observations of the protoplanetary disk around the Herbig Be star HD 100546 show two bright features in infrared (bands H and L') at about 50 AU. While one appears at the location of a confirmed exoplanet, the other has not been explained. A recent hydrodynamic model of the effects of shocks induced by a high mass planet shows that these shocks heat regions around the planet to relatively high temperatures (≈500 K). These shocks could be the source of the excess infrared emission in the disk around HD 100546. We explore the observational signatures of a high mass planet causing shock heating throughout its disk in order to determine if it could be the source of the infrared arm in HD 100546. More fundamentally, we identify and characterize planetary shocks as an extra, hitherto ignored, source of luminosity in transition disks. The RADMC-3D code is used to perform dust radiative transfer calculations on the hydrodynamical disk models. This uses a more

Hord et al. (2017)

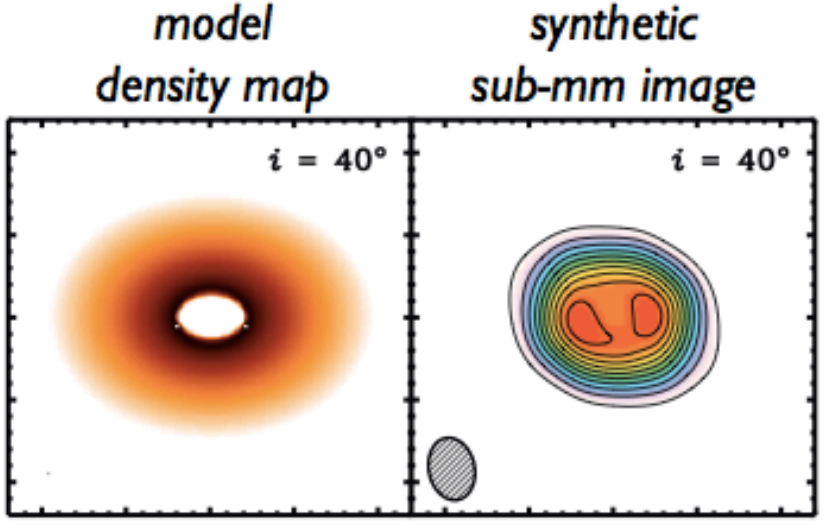
Transition Disks: Disks with missing hot dust.



Transition Disks: Disks with missing hot dust.

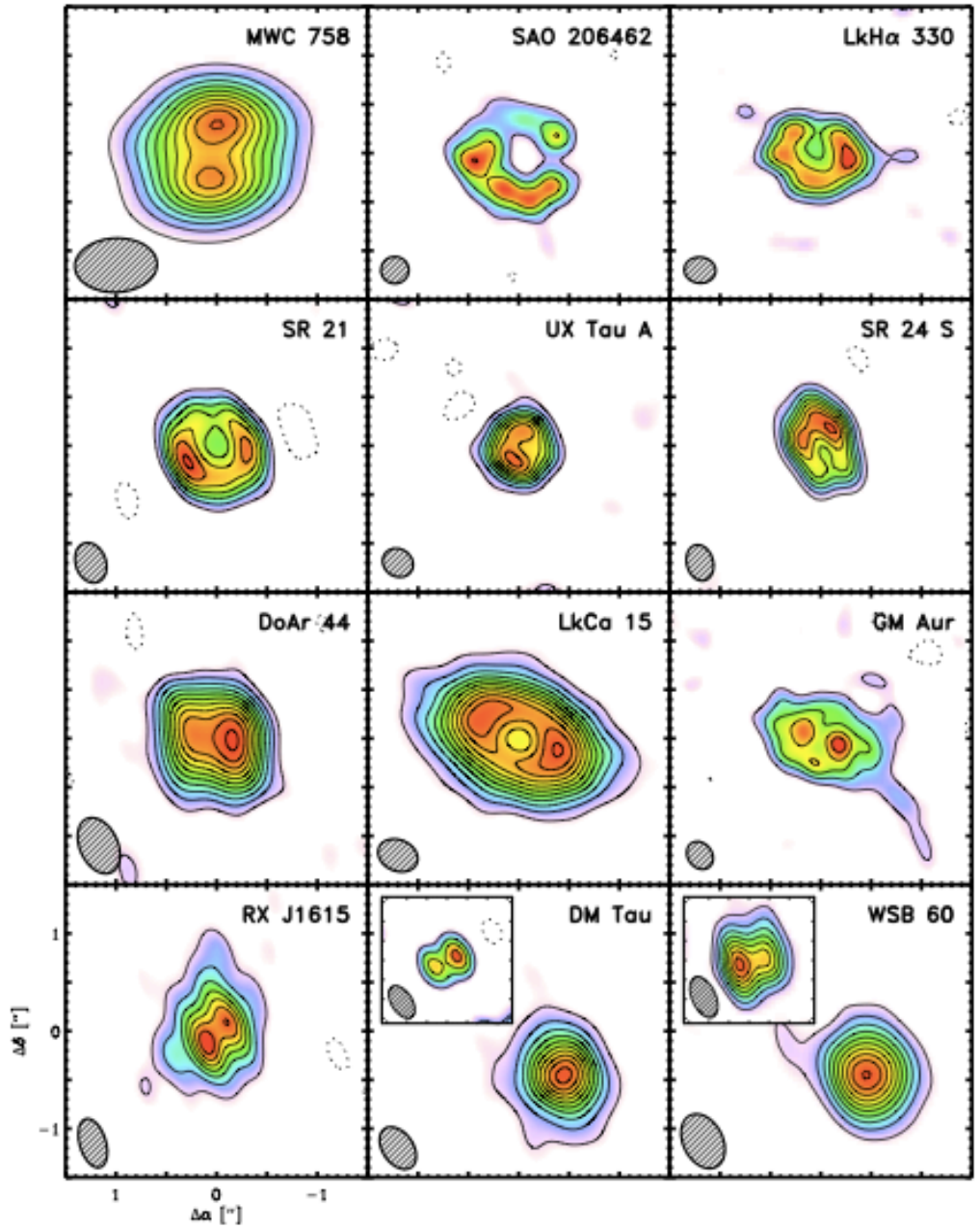


[e.g., Furlan et al. 2009]

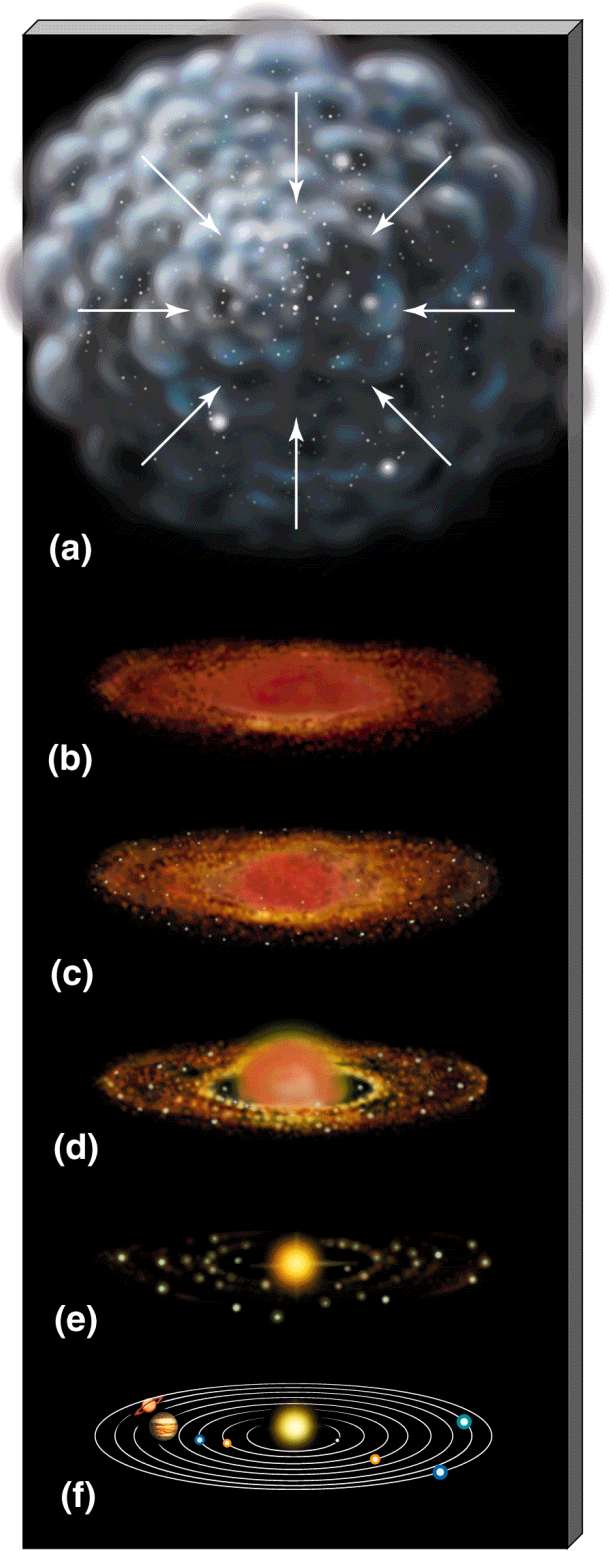


a disk with a large reduction
in optical depth near the star
(i.e., a "cavity" or "hole")

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



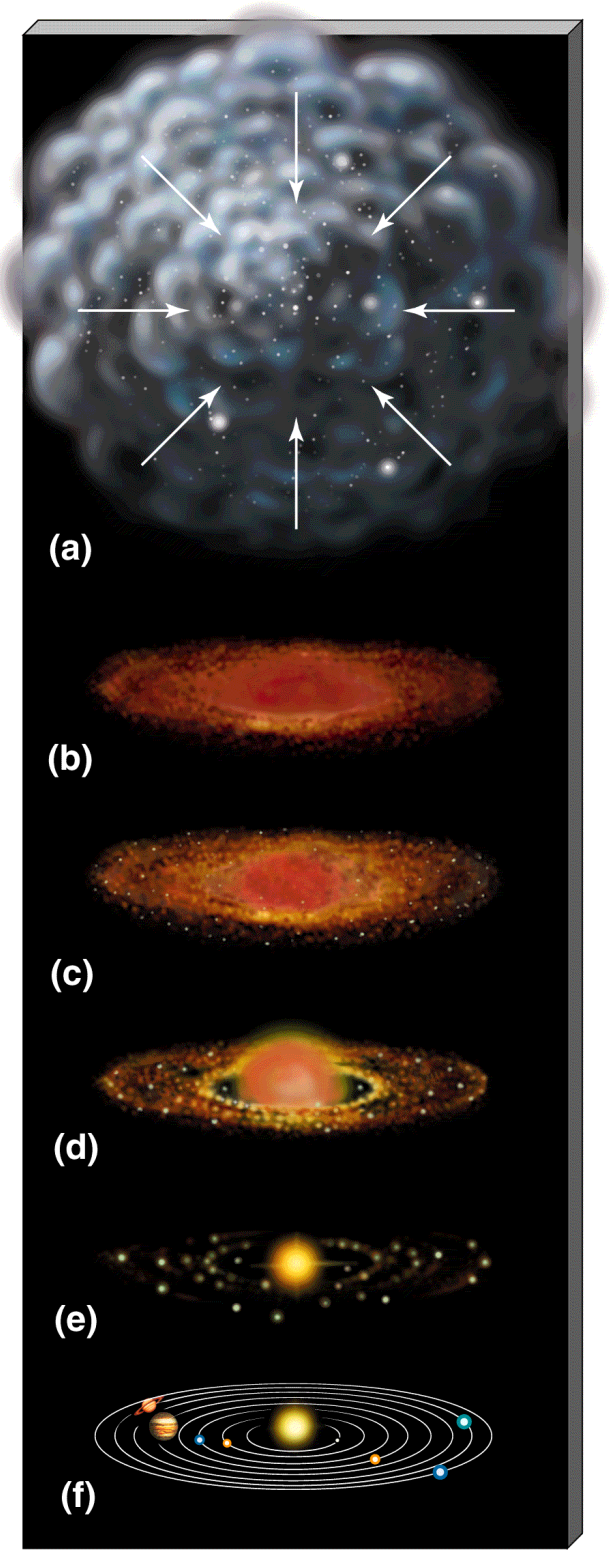
0.85mm
0.3” ~ 20 AU resolution



Are transitional disks
related to disk evolution?

Gas-rich phase (< 10 Myr)
Primordial Disks

Gas-poor phase (>10 Myr)
Debris Disks



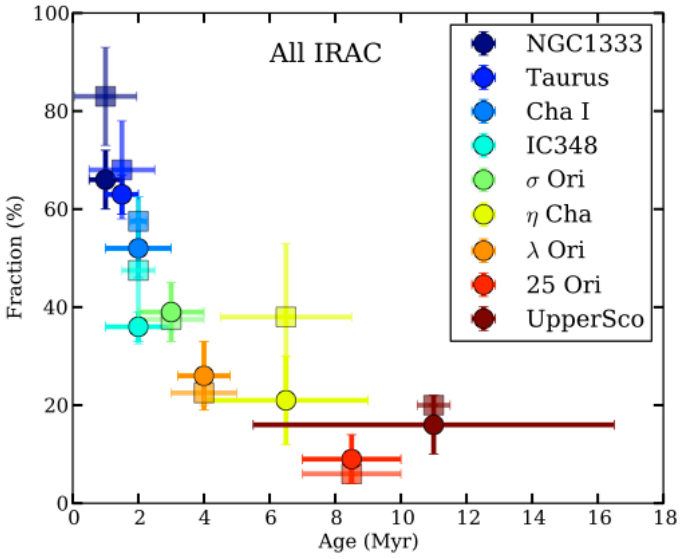
Are transitional disks
related to disk evolution?

Gas-rich phase (< 10 Myr)
Primordial Disks

Conjecture:
Thinning phase (~10 Myr)
Transitional Disks

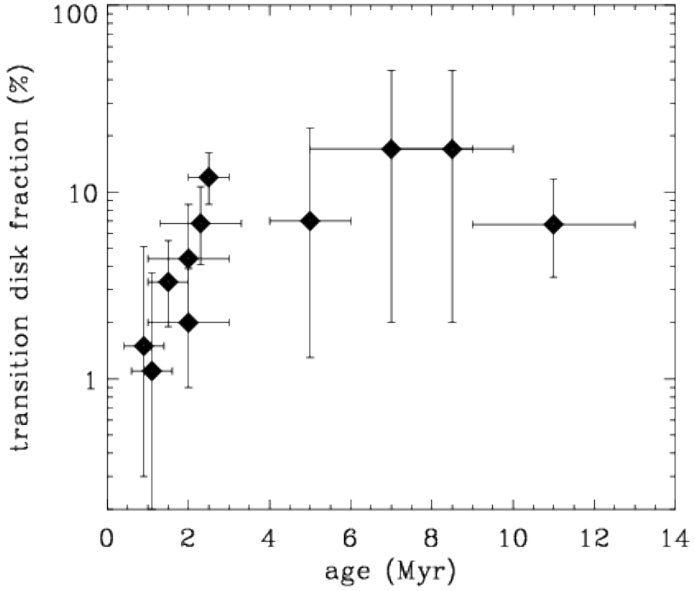
Gas-poor phase (>10 Myr)
Debris Disks

Transition disks and disk evolution



(Ribas et al. 2014)

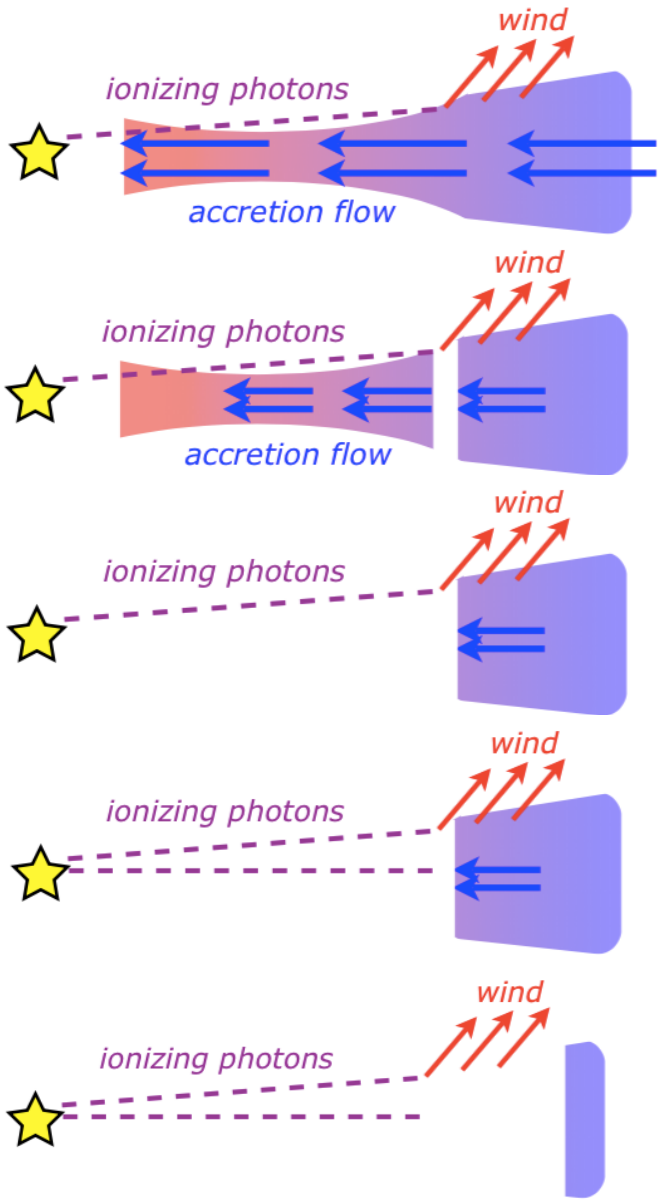
"Total" disk fraction



(Espaillat et al. 2014)

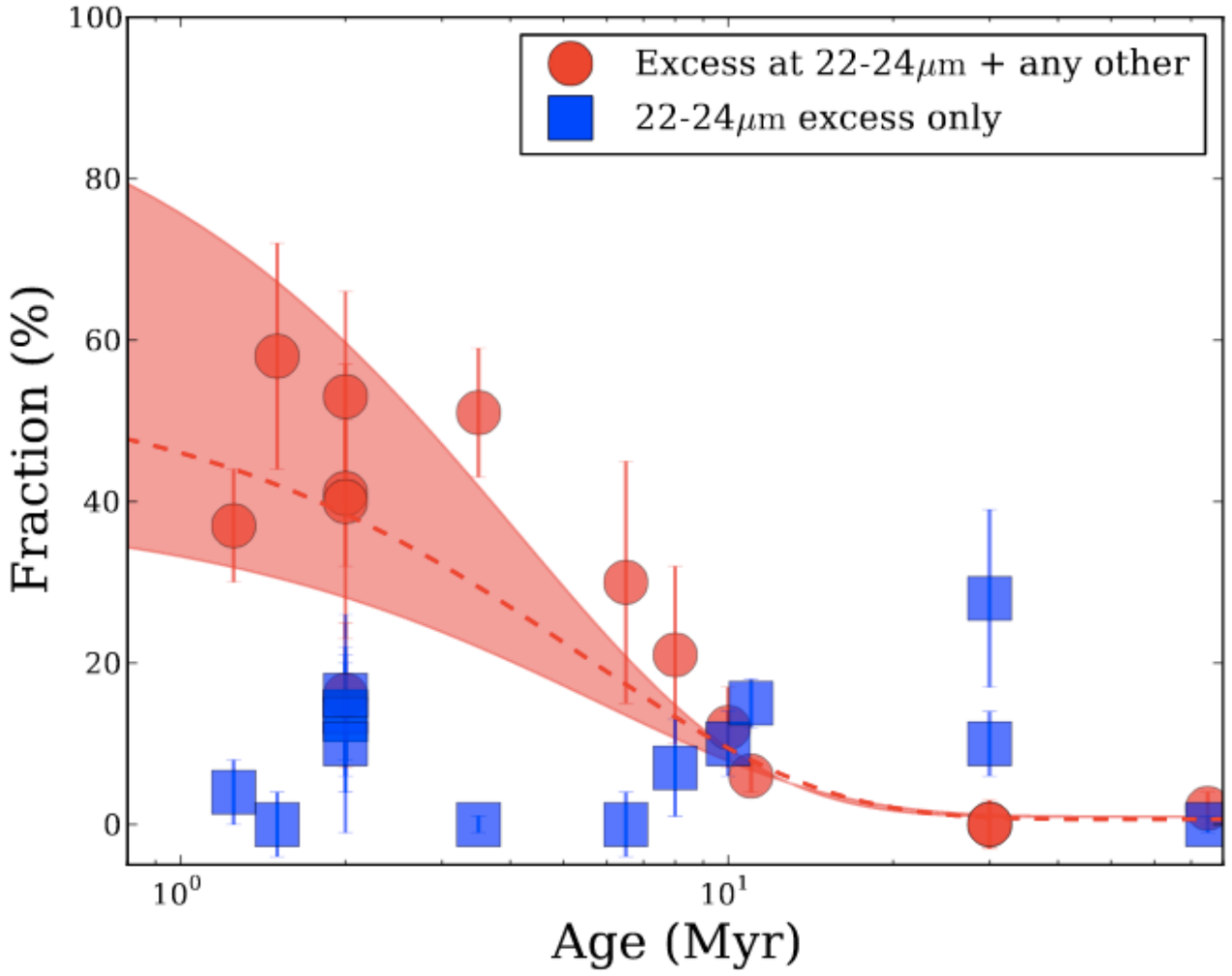
Transition disk fraction

Photoevaporation



Transition disks linked to disk evolution?

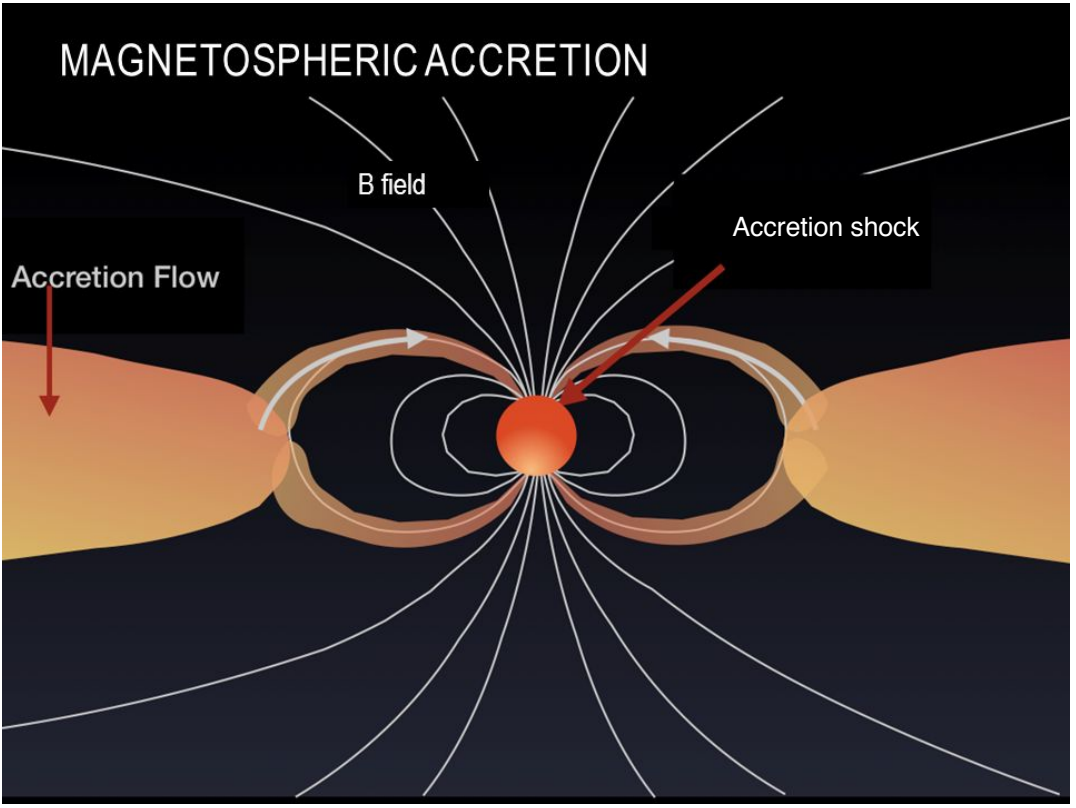
The distribution in age is consistent with a uniform distribution.

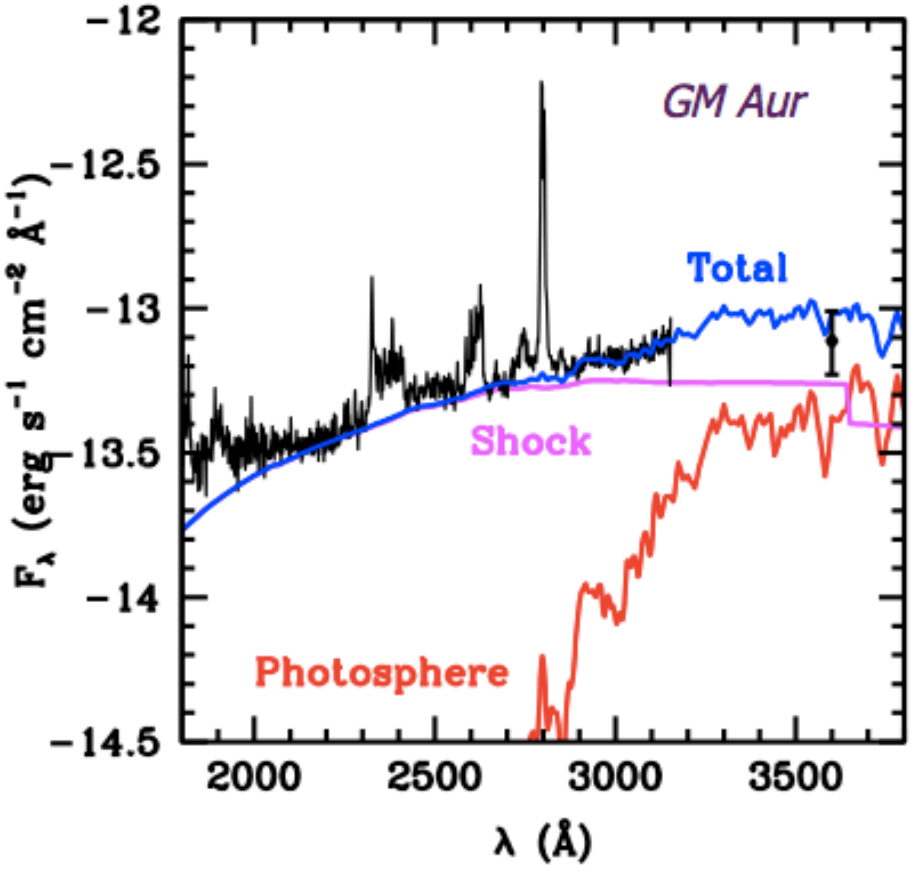


(Ribas et al. 2014)

UV excess

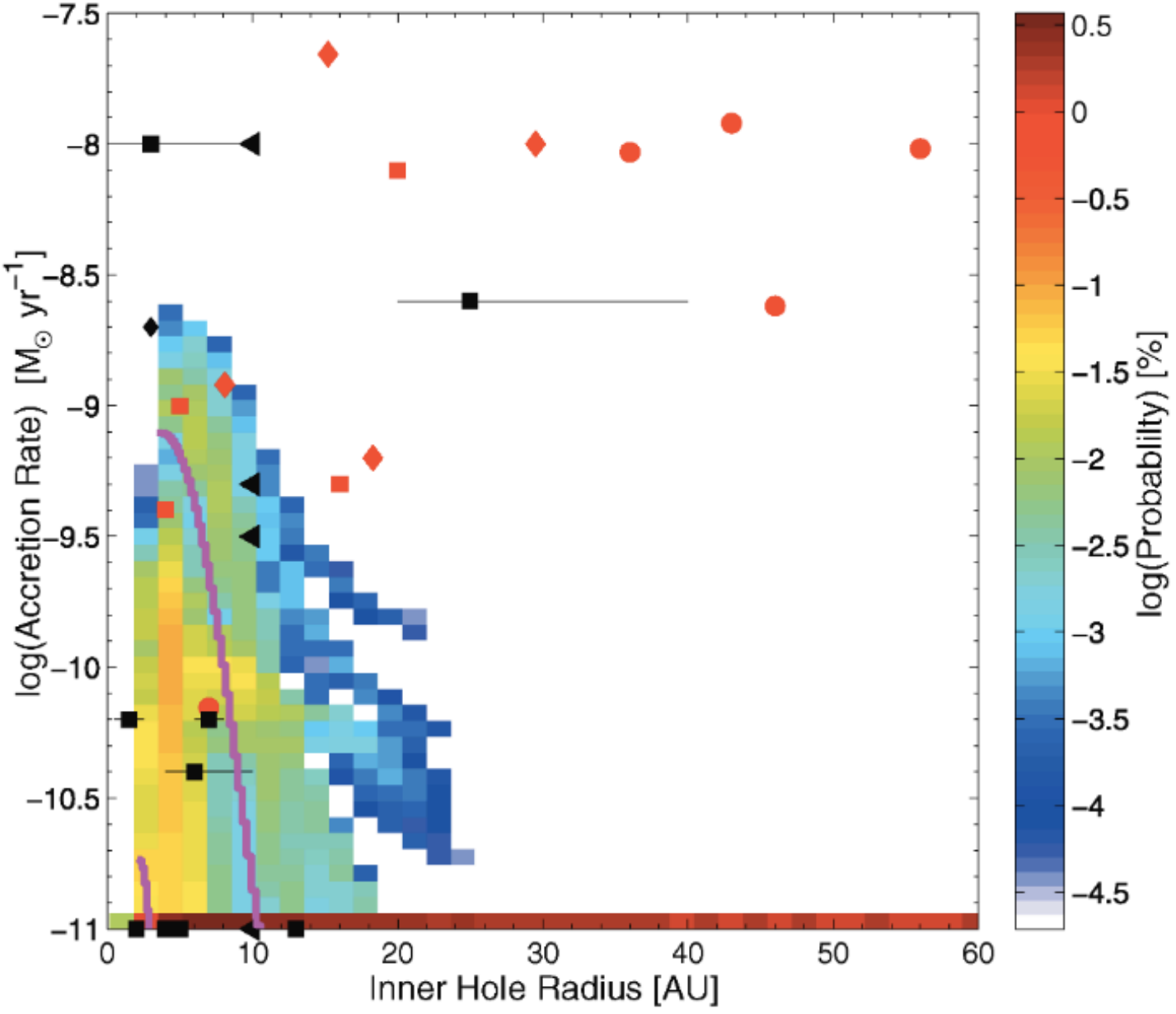
Many transitional disks show signs of accretion,
at the level of primordial (classical T-Tauri) disks.





(Ingleby et al. 2011)

Bimodal distribution of transition disks

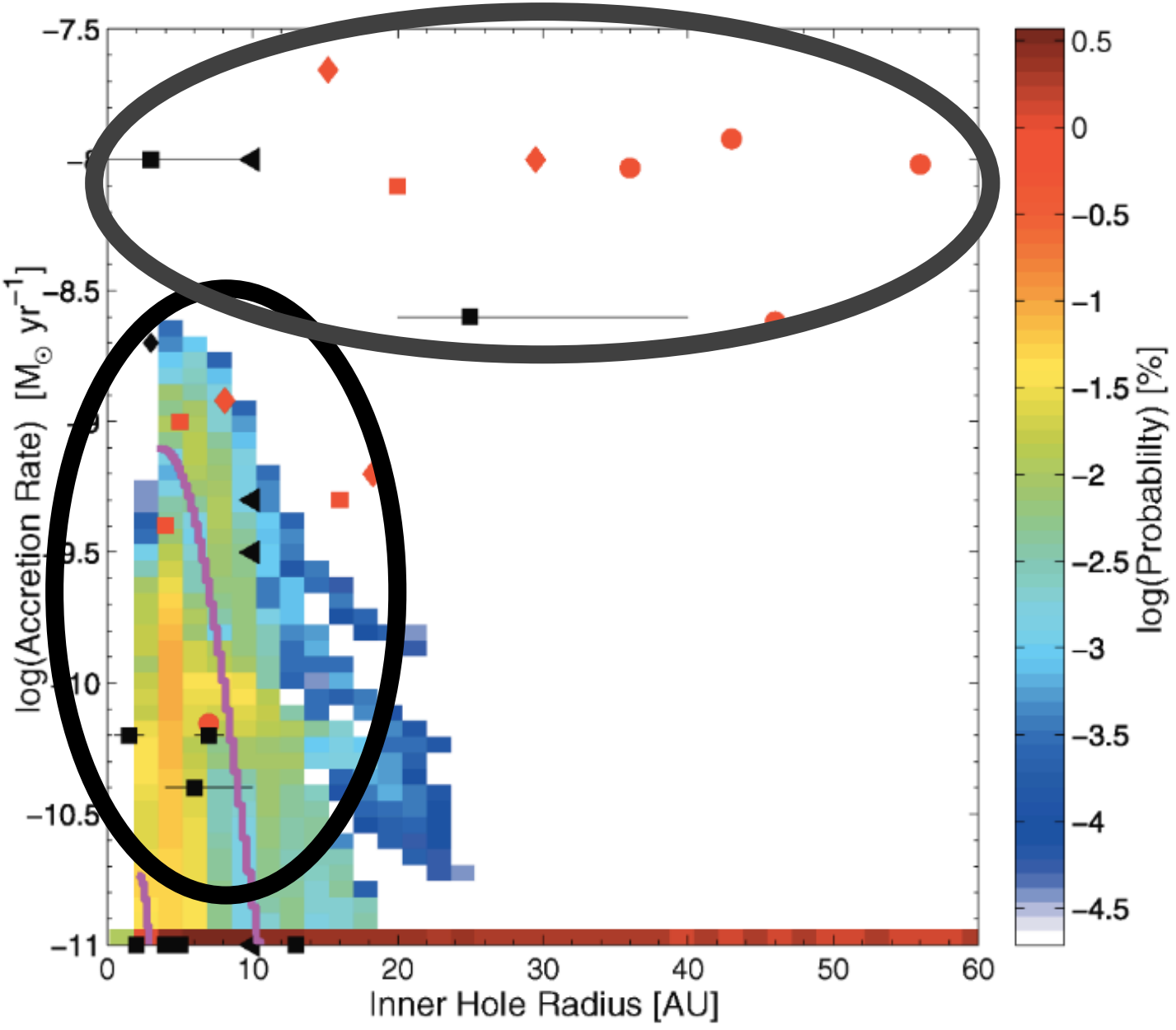


(Owen et al. 2011)

Bimodal distribution of transition disks

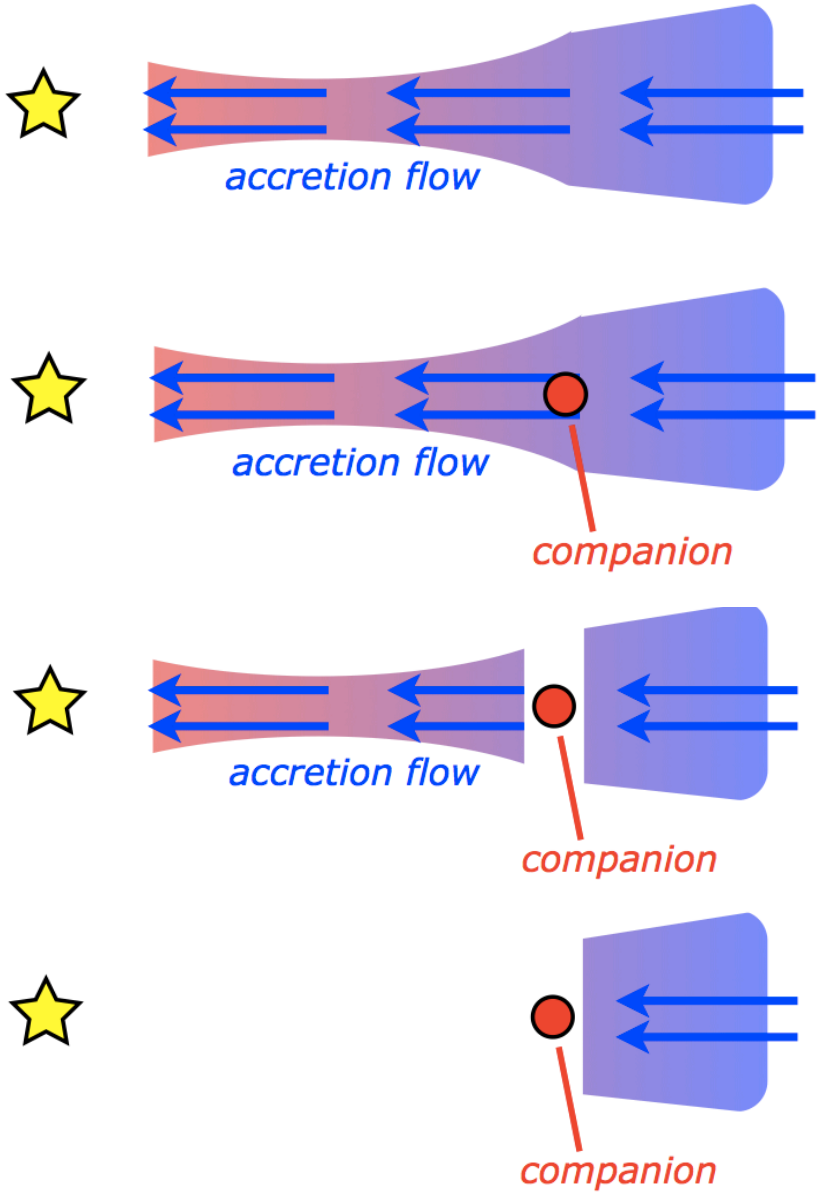
Not explained by photo-evaporation

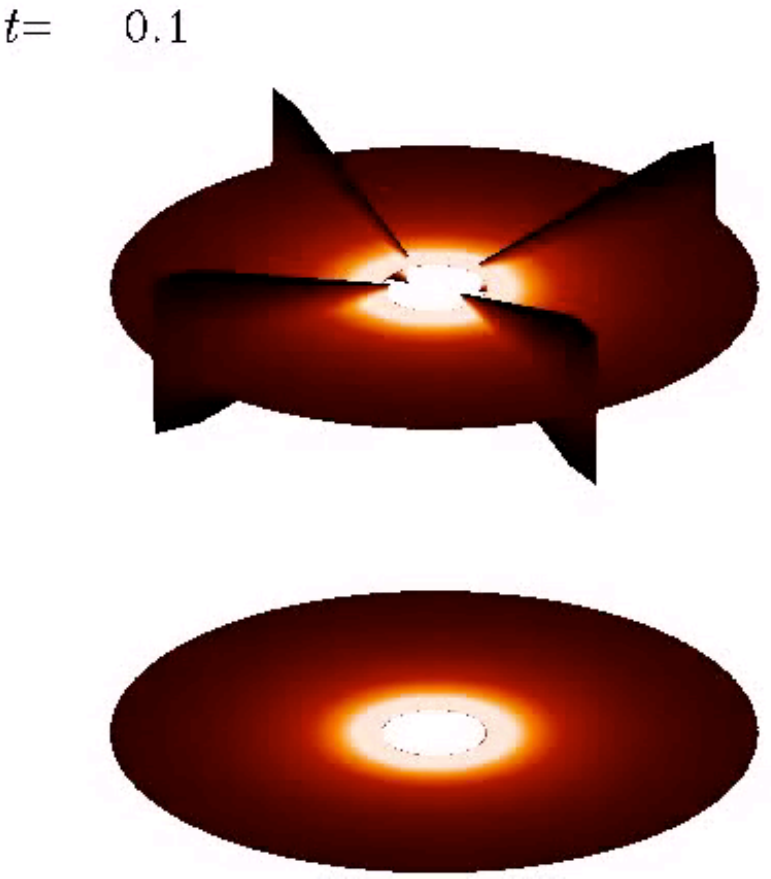
Explained by Photo-evaporation



(Owen et al. 2011)

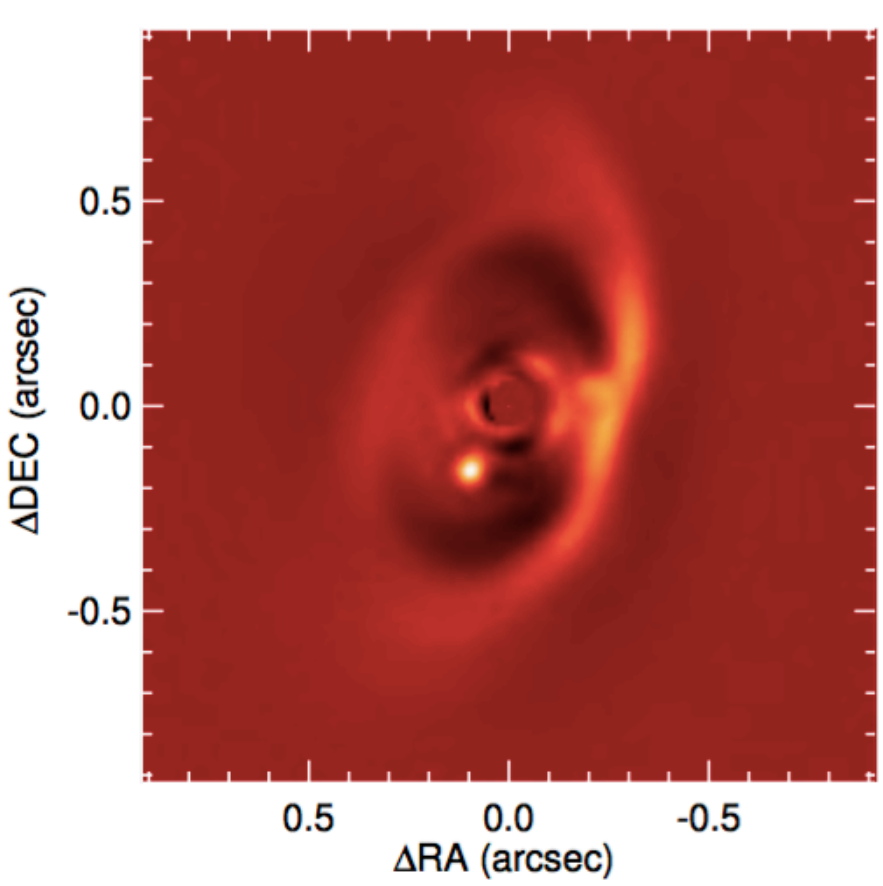
Planetary companion

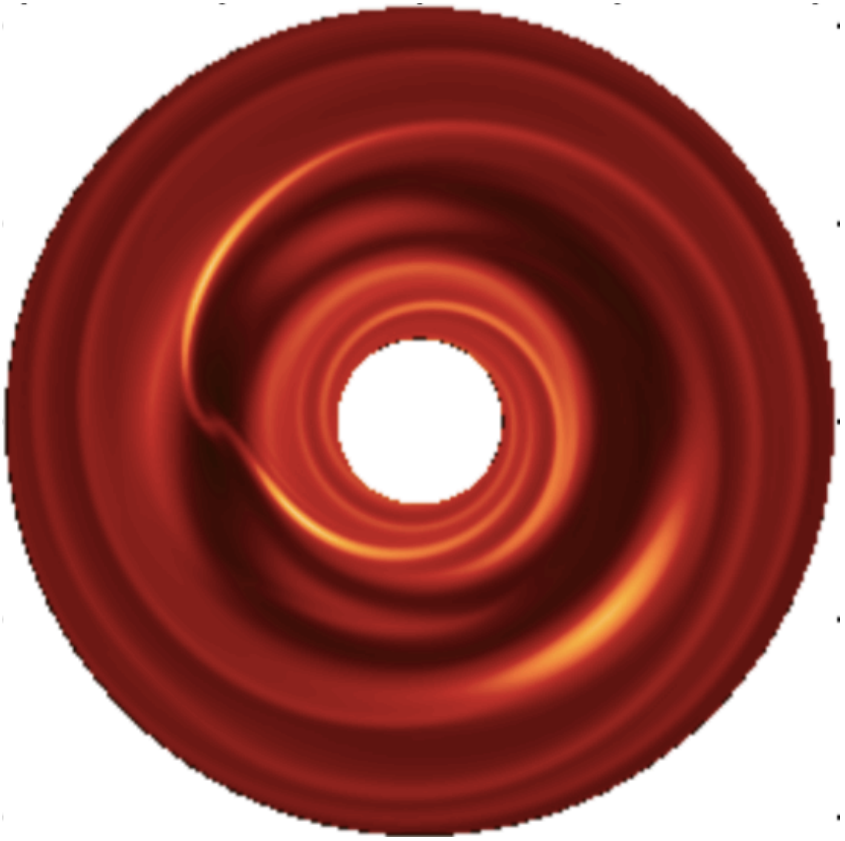




(Lyra 2009)

These cavities may be the telltale signature of forming planets

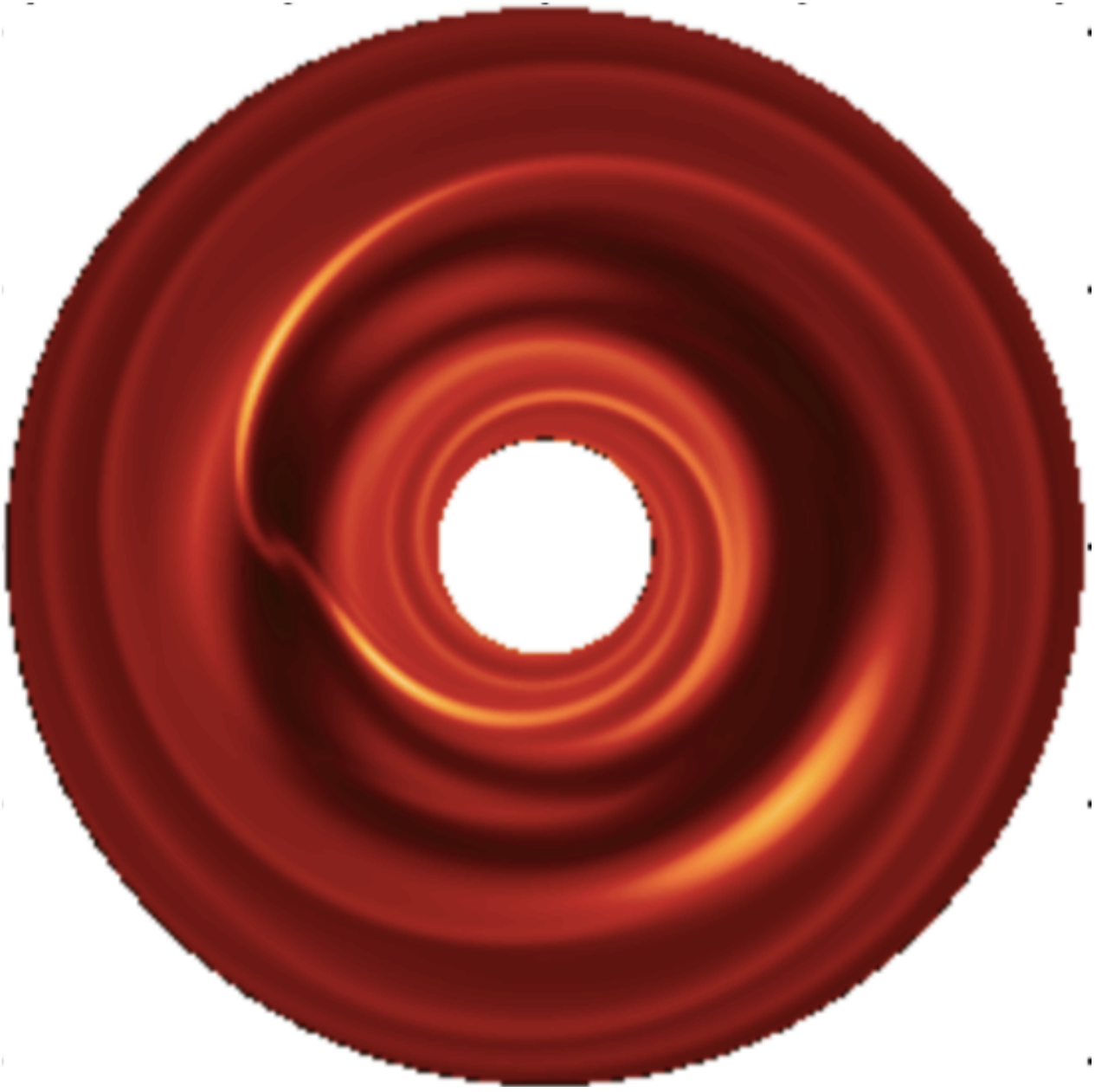




(Lyra et al. 2009b)

A way to directly study planet-disk interaction

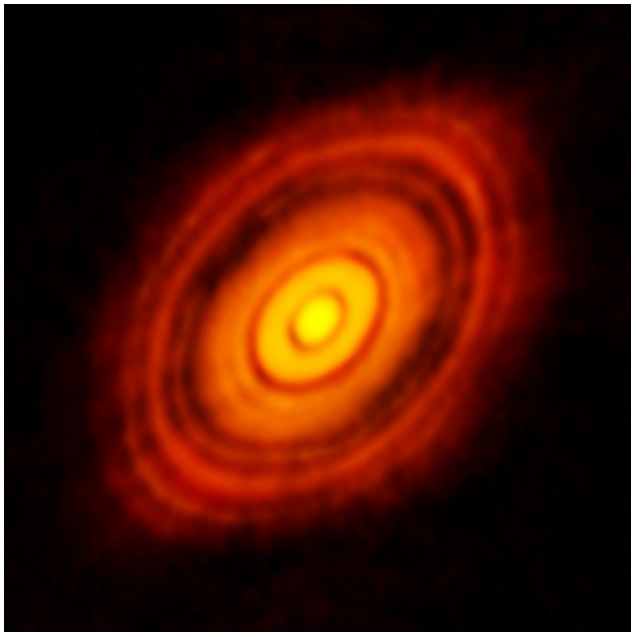
Planet-disk interaction: gaps, spirals, and vortices.



(Lyra et al. 2009b)

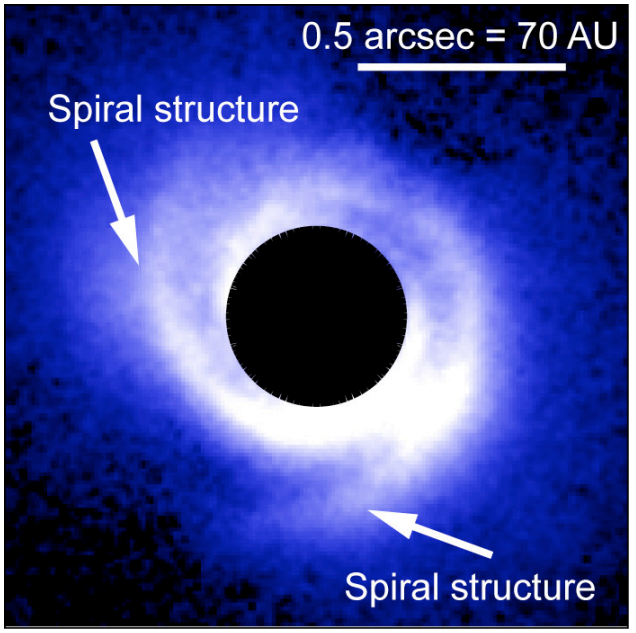
Observational evidence: gaps, spirals, and vortices

HL Tau



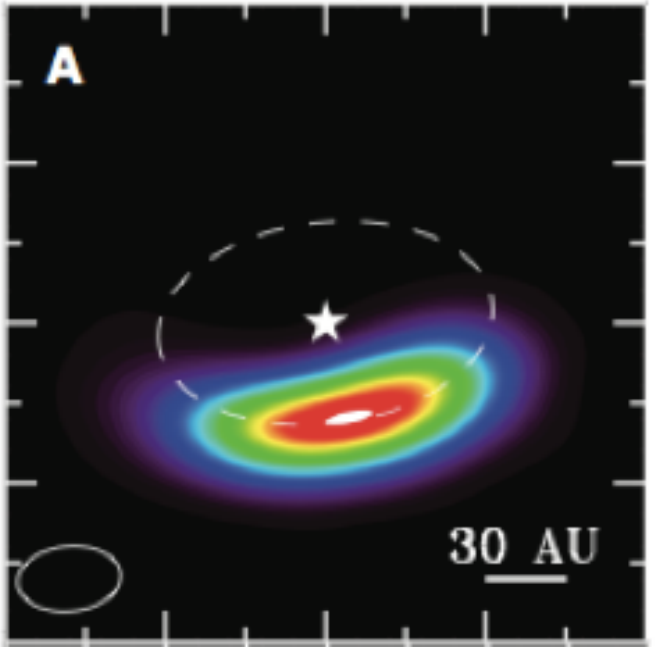
The ALMA Partnership et al. (2015)

SAO 206462



Muto et al. (2012)

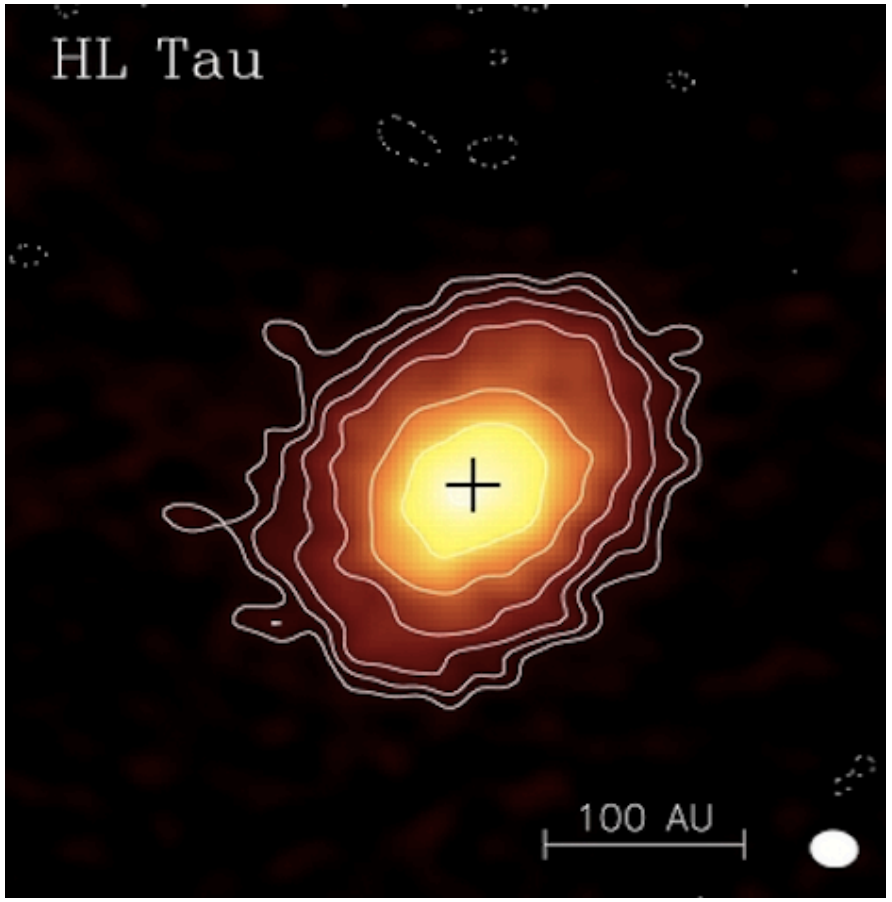
Oph IRS 48



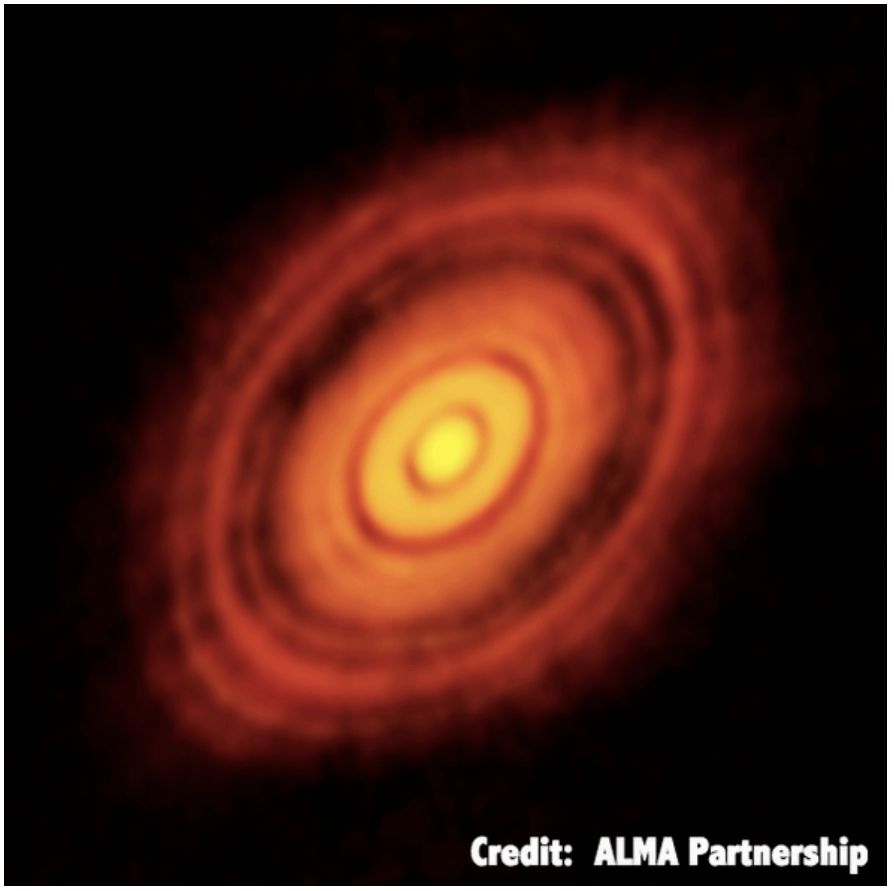
van der Marel et al. (2013)

The Atacama Large Millimeter Array (ALMA)

Before ALMA

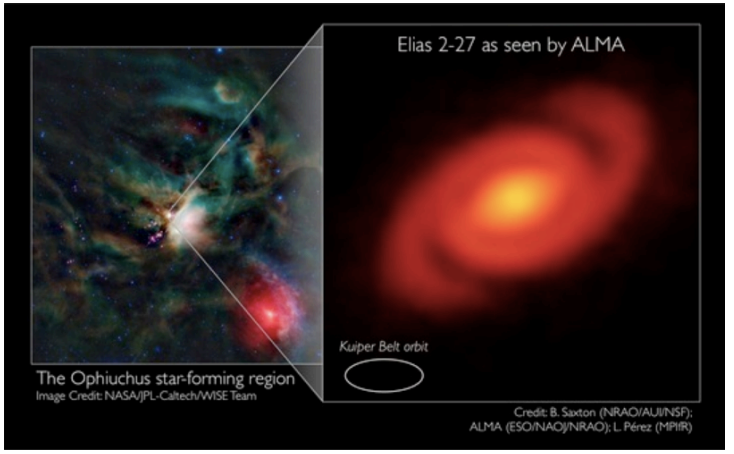


ALMA

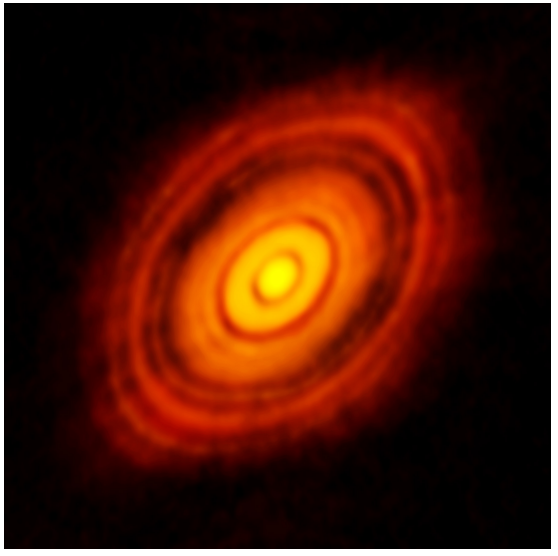


The ALMA view of Protoplanetary Disks

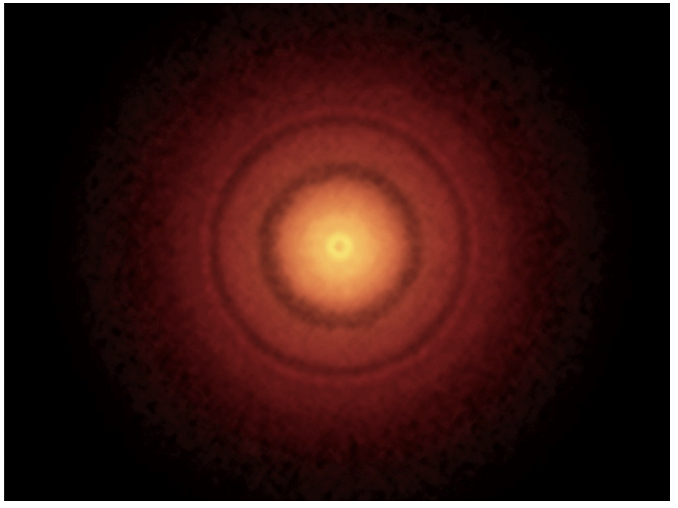
Elias 2-27



HL Tau



TW Hya



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.

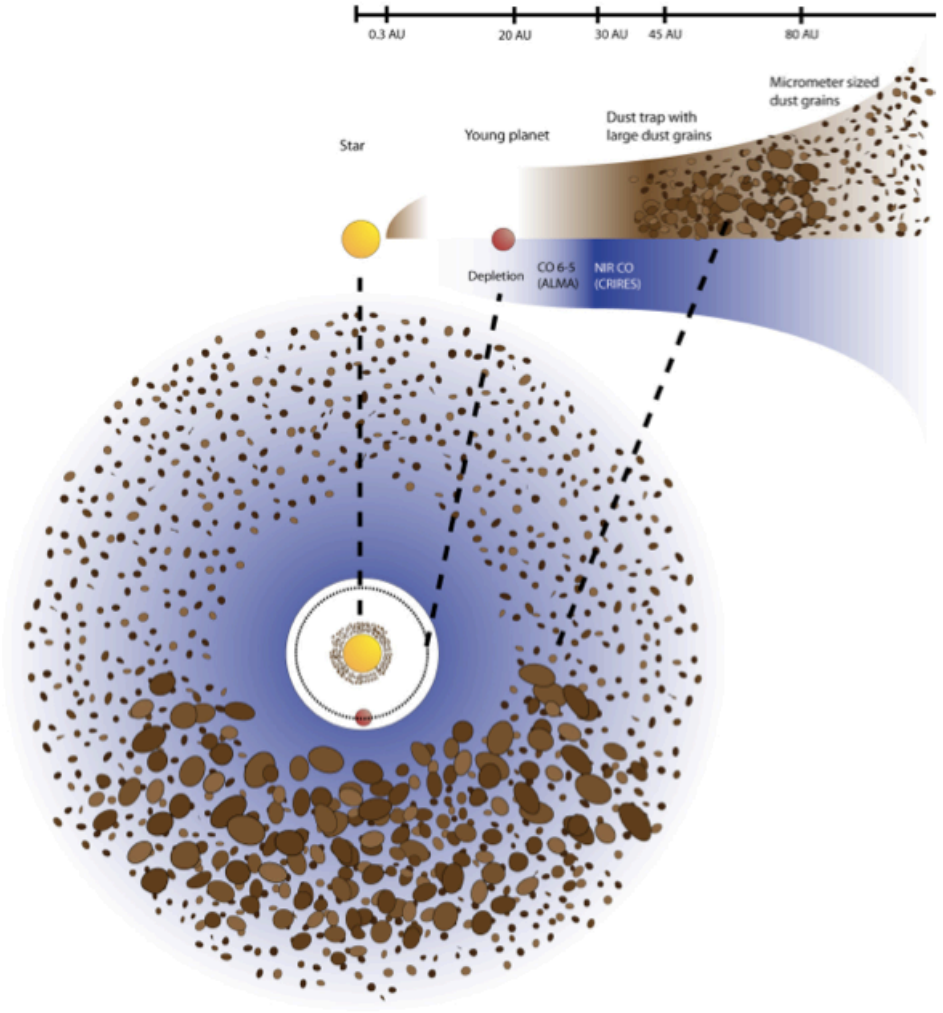
Although the ubiquity of planets is confirmed almost daily by detections of new exoplanets (*1*), the exact formation mechanism of planetary systems in disks of gas and dust around young stars remains a long-standing problem in astrophysics (*2*). In

Down

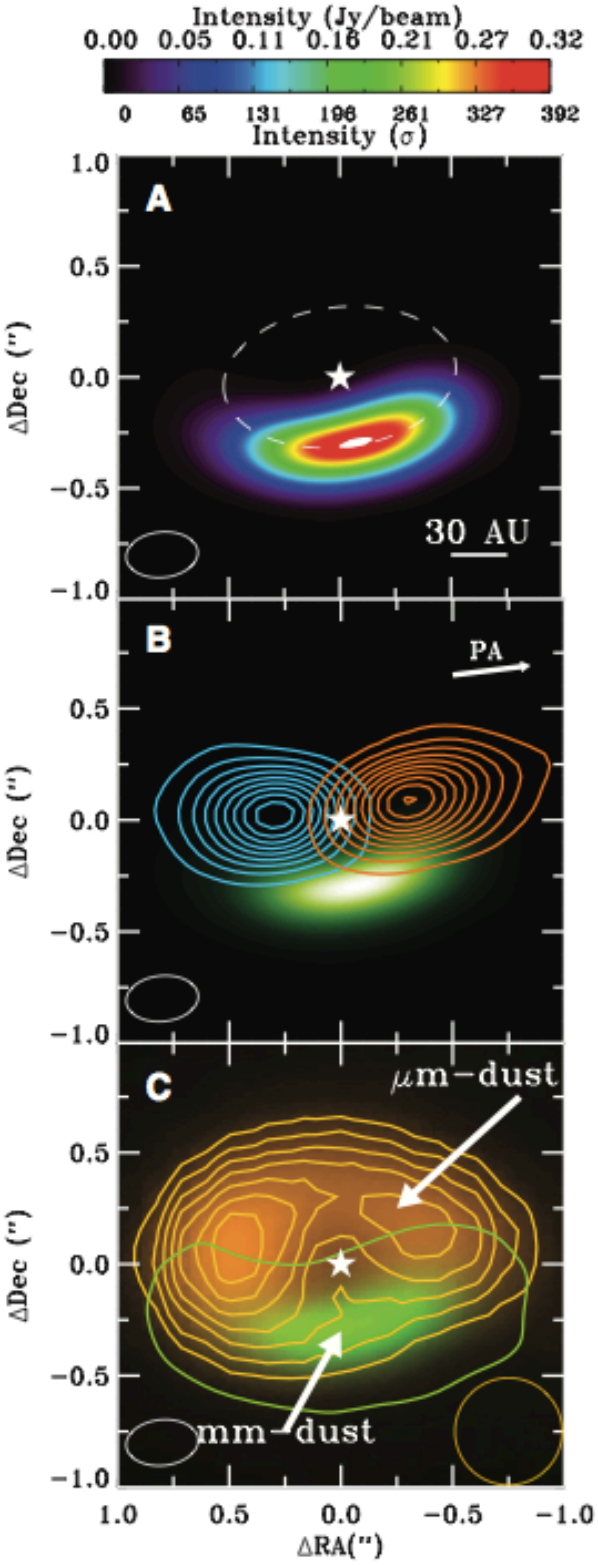
van der Marel et al. 2013

A huge vortex observed with ALMA

The Oph IRS 48 "comet formation factory"



van der Marel et al. (2013)

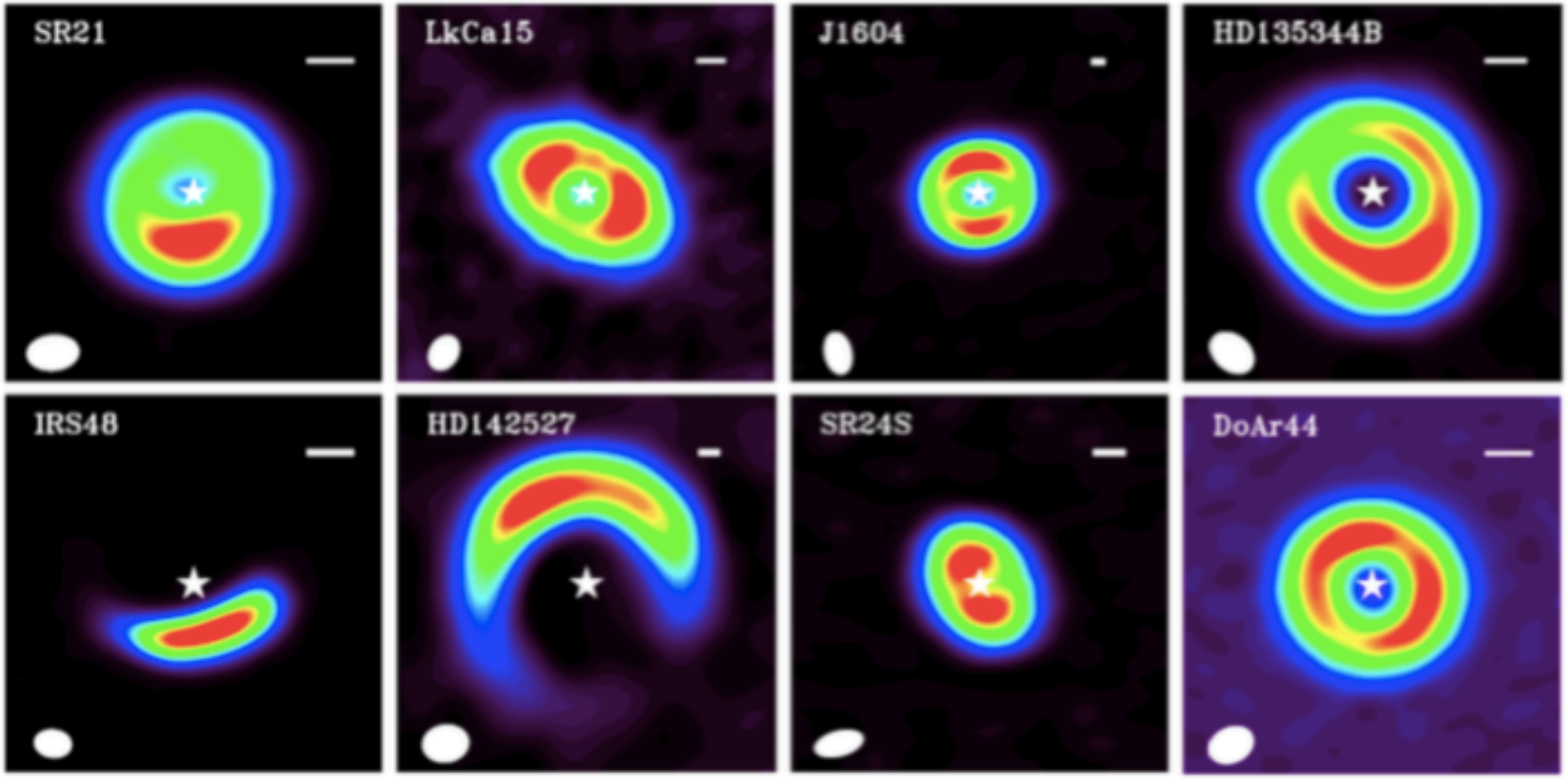


asymmetric mm dust at 63 AU

Gas detection: Keplerian rotation

Micron-sized dust follows gas

Vortices everywhere!
Extrasolar nebulae

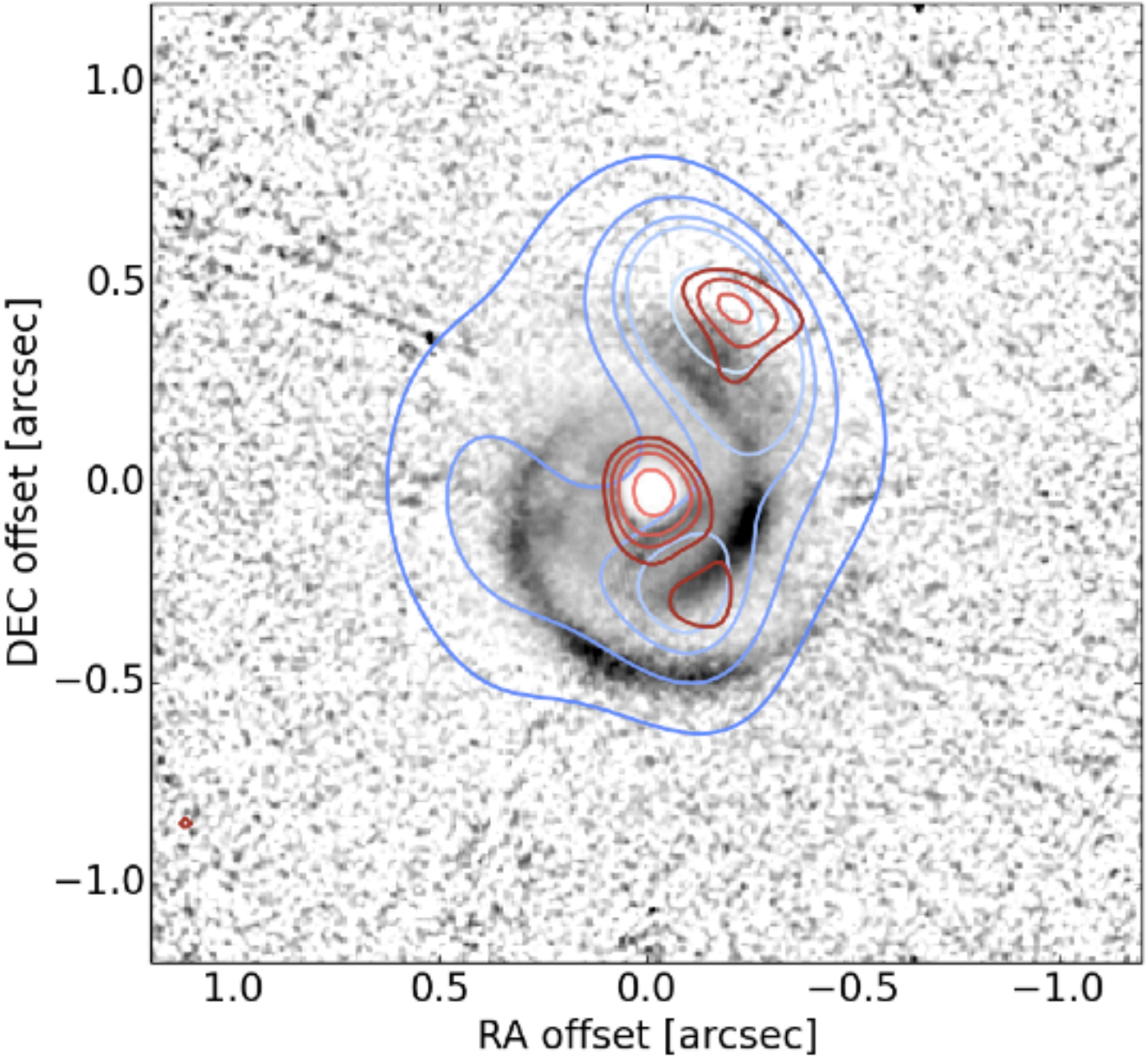


SPHERE-ALMA-VLA overlay of MWC 758

SPHERE (μm)

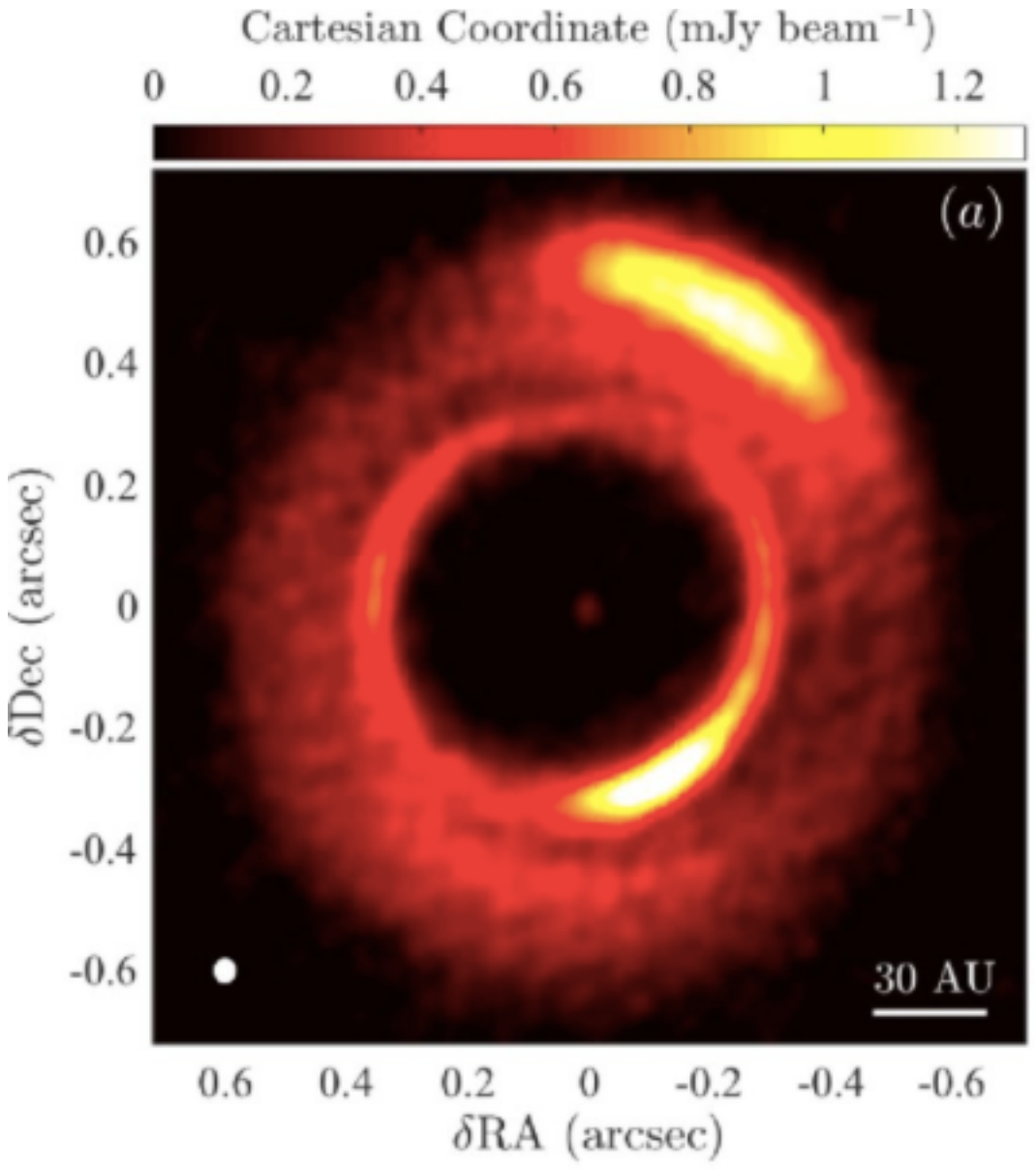
ALMA (~ mm)

VLA (cm-m)



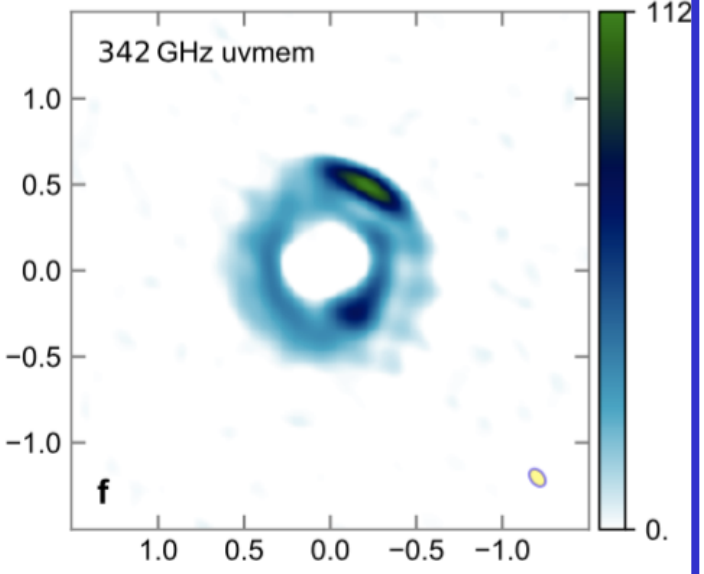
Marino et al. (2015)

MWC 758

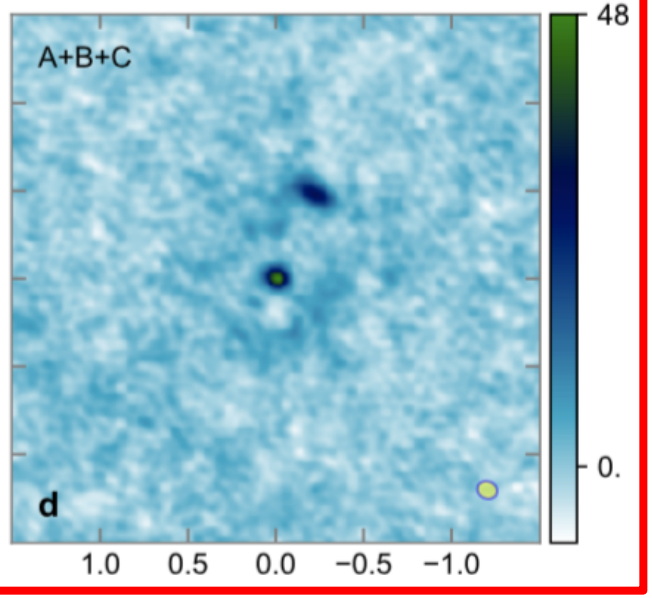

Cartesian Coordinate (mJy beam^{-1})
0
0.2
0.4
0.6
0.8
1
1.2
(a)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
δDec (arcsec)
30 AU
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
δRA (arcsec)

Pebble trapping

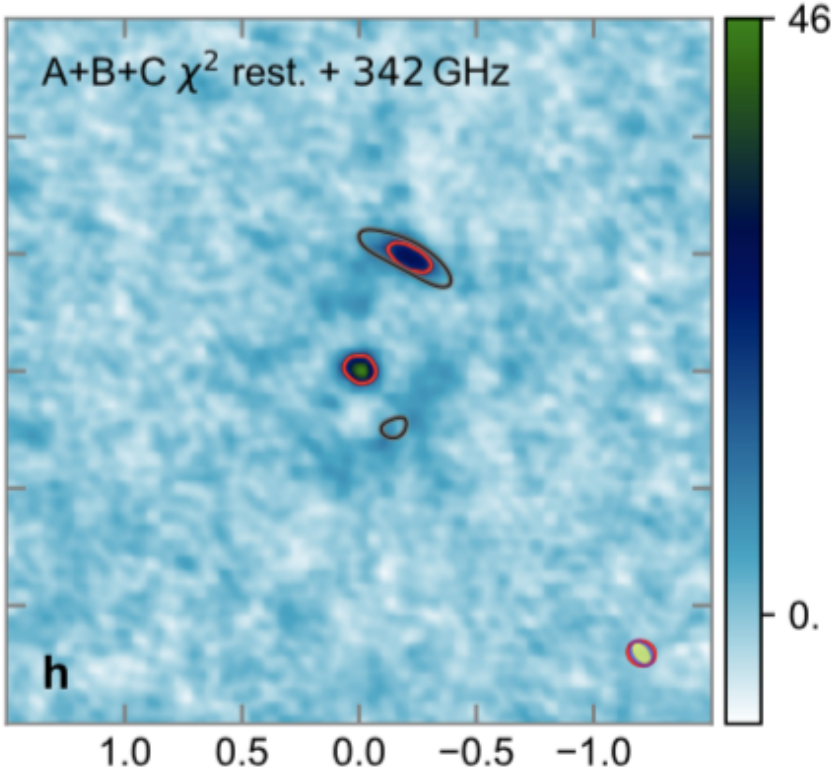
ALMA (mm)



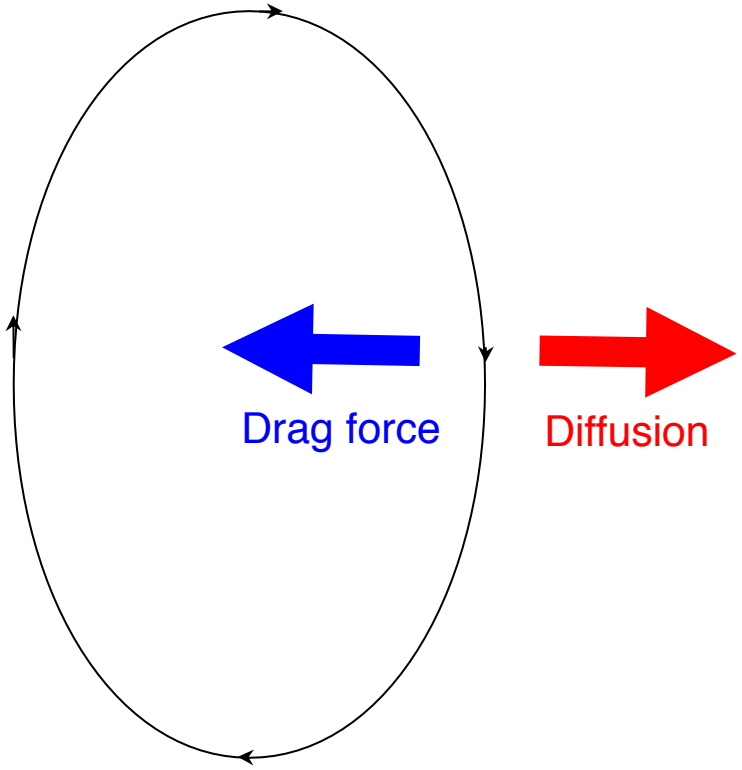
VLA (cm-m)



Overlay



Drag-Diffusion Equilibrium



Trapped particle

Dust continuity equation

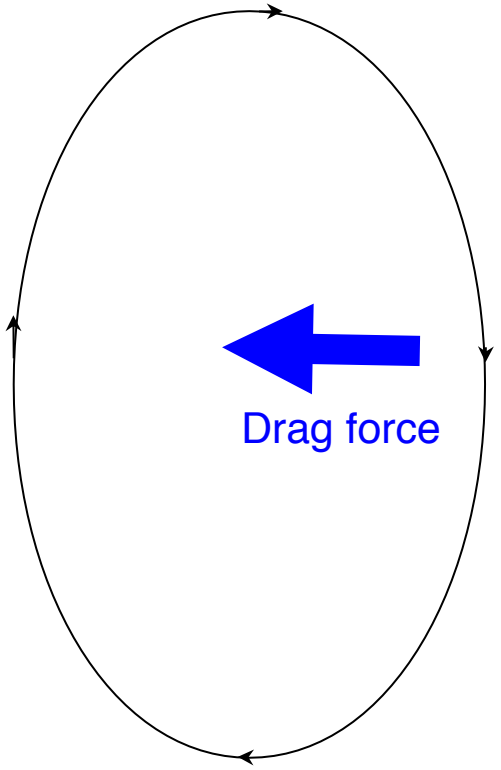
$$\frac{\partial \rho_d}{\partial t} = -(\boldsymbol{v}\cdot\boldsymbol{\nabla})\rho_d - \rho_d \boldsymbol{\nabla}\cdot\boldsymbol{v} + D\nabla^2\rho_d,$$

advection

compression

diffusion

Drag-Diffusion Equilibrium



Trapped particle

Steady-state solution

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

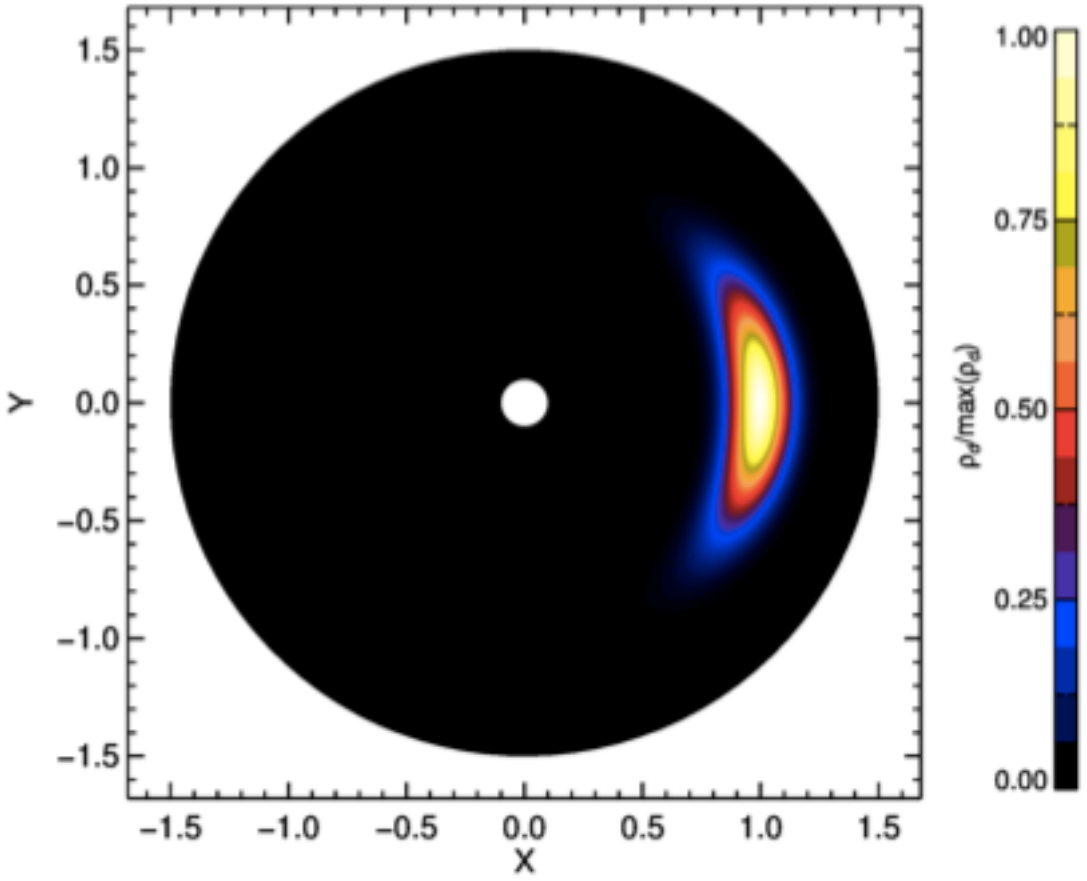
Lyra & Lin (2013)

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

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

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

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

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

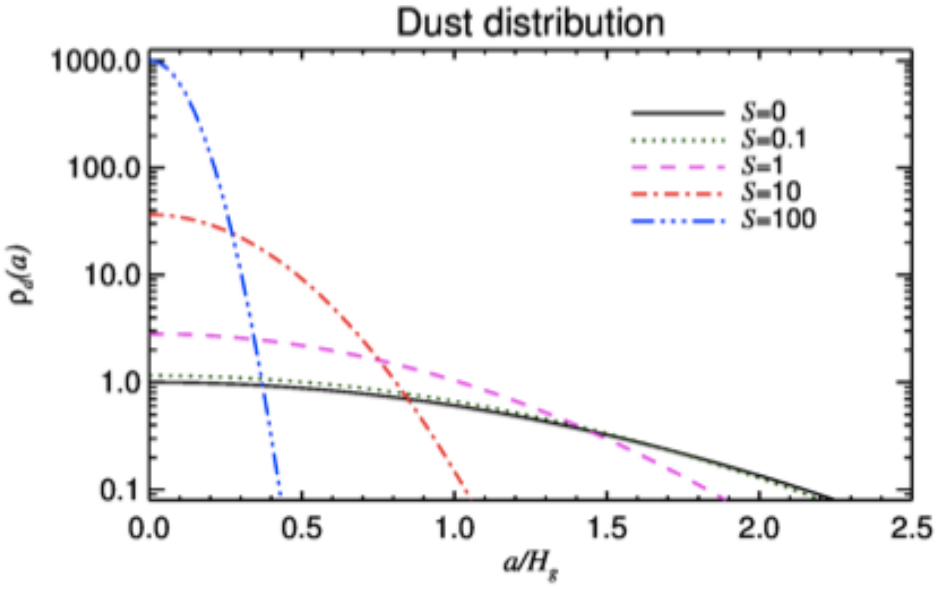
$$S = \frac{St}{\delta}$$

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

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)

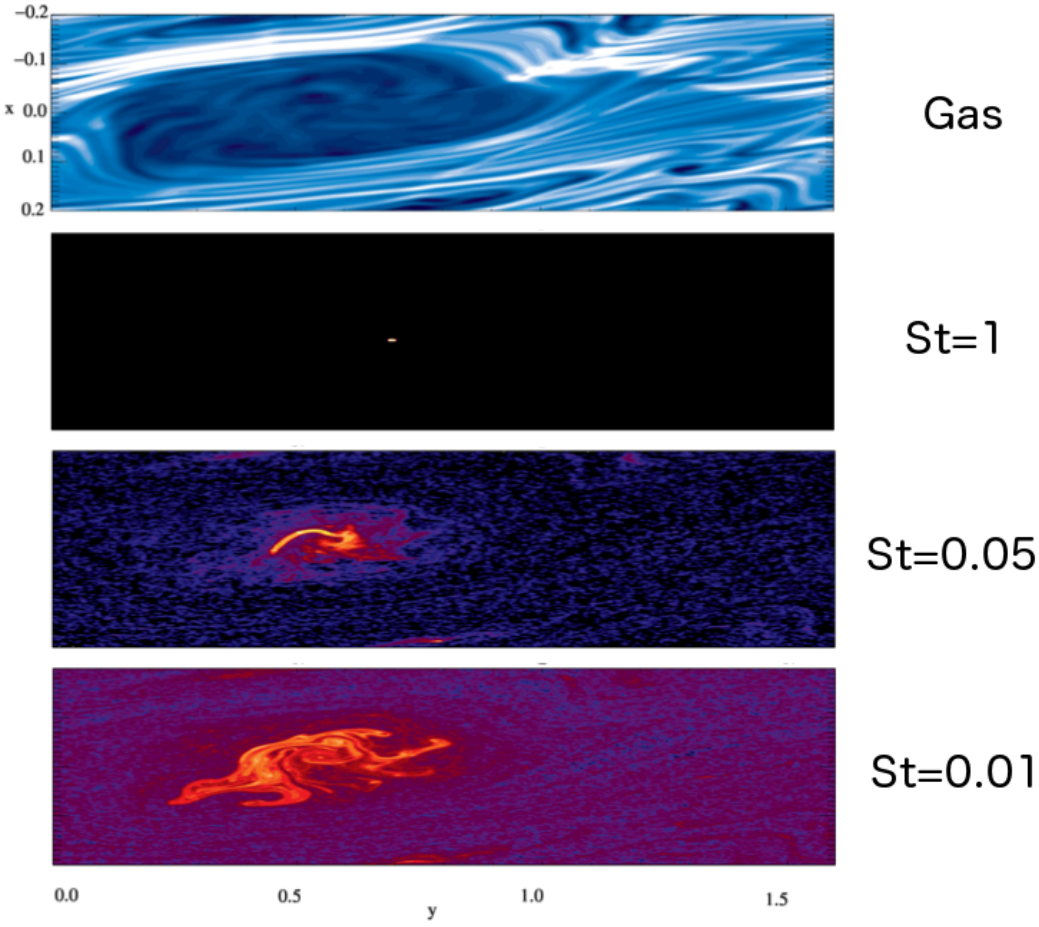
Analytical vs Numerical



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

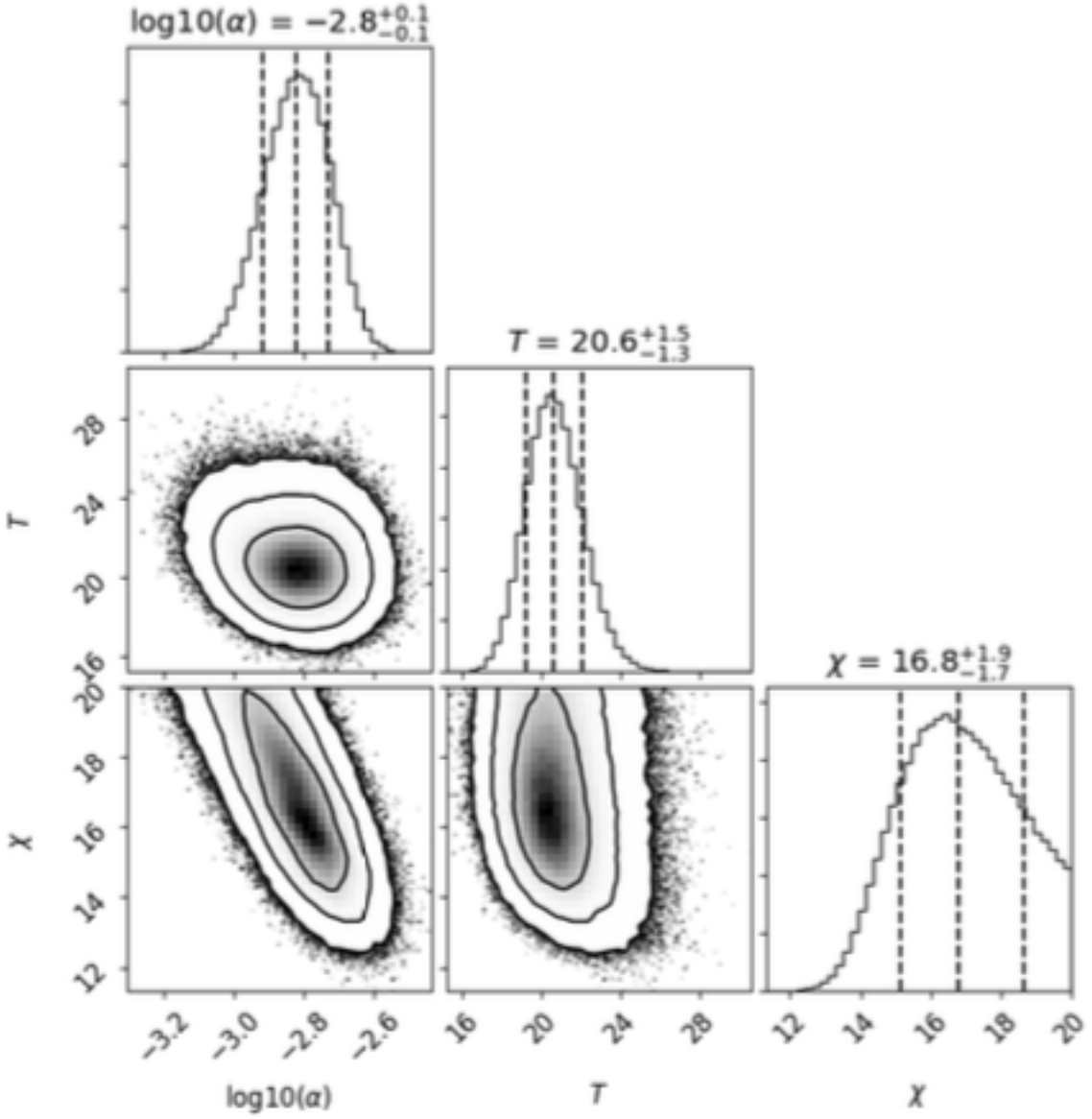
$$\delta = v_{\mathrm{rms}}^2 / c_s^2,$$

Lyra & Lin (2013)



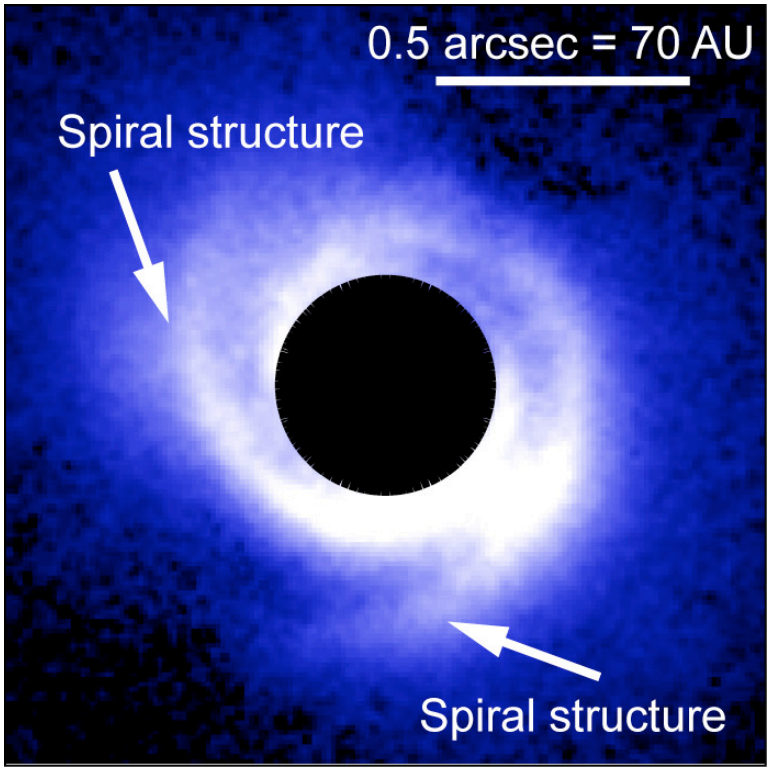
Raettig et al (2015)

Observational vs Analytical



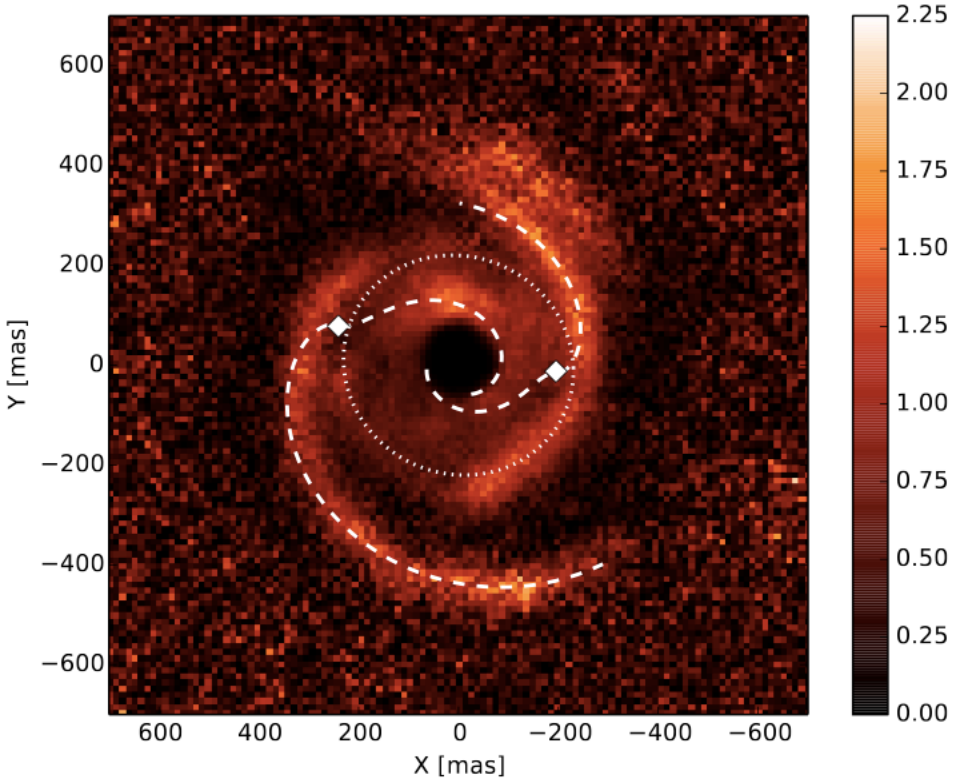
Observational Evidence: Spirals

SAO 206462



Muto et al. (2012)

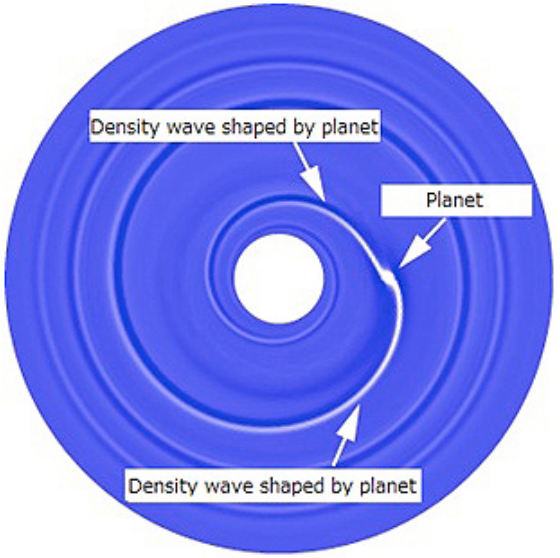
MWC 758



Benisty et al. (2015)

Spiral arm fitting leads to problems

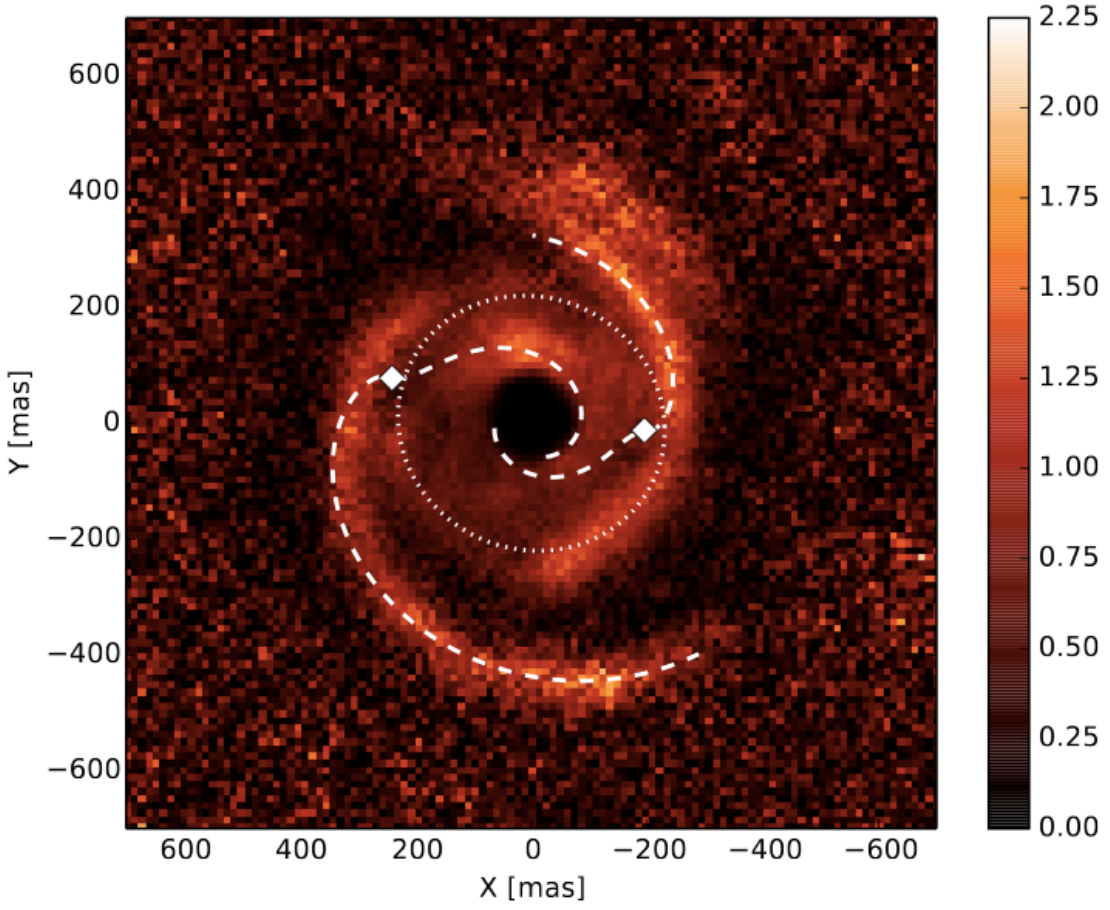
Analytical spiral fit



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

Rafikov (2002)
Muto et al. (2012)

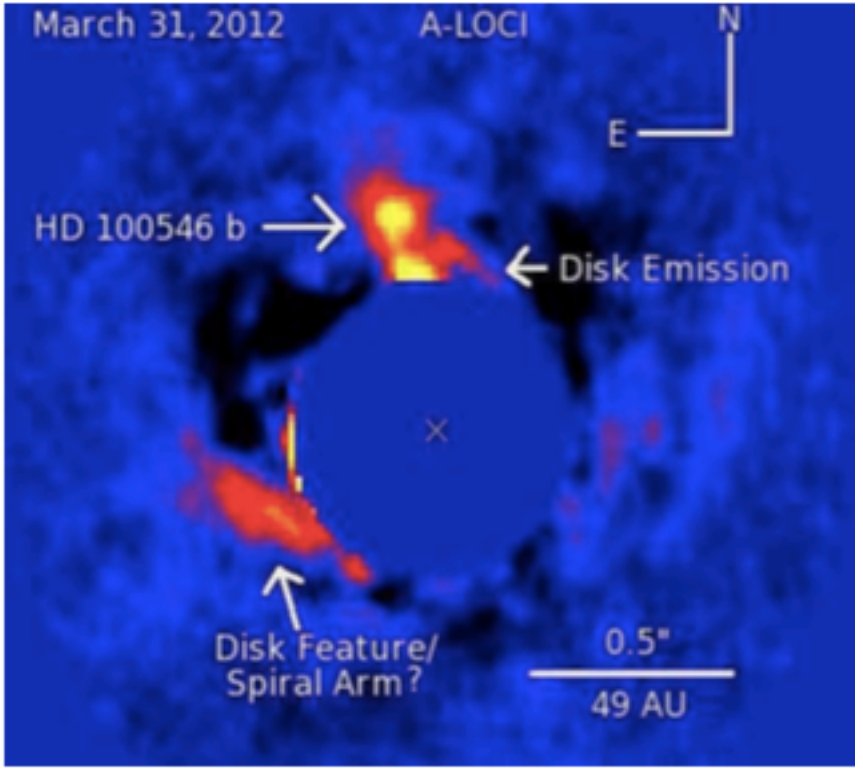
Spirals are **too wide**,
hotter (300K) than ambient gas (50K).



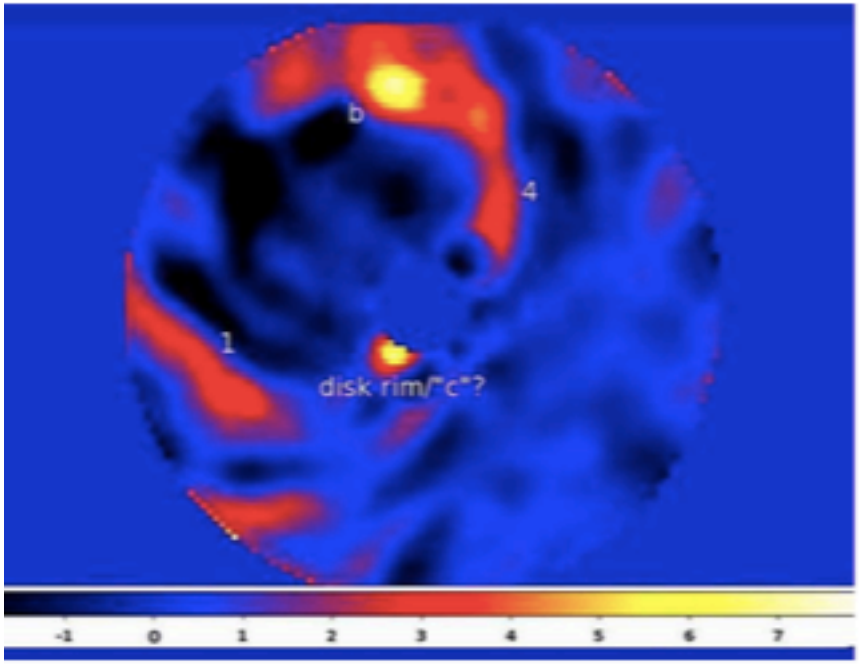
Benisty et al. (2015)

The strange case of thermal emission in HD 100546

L band (~3.5 μm)

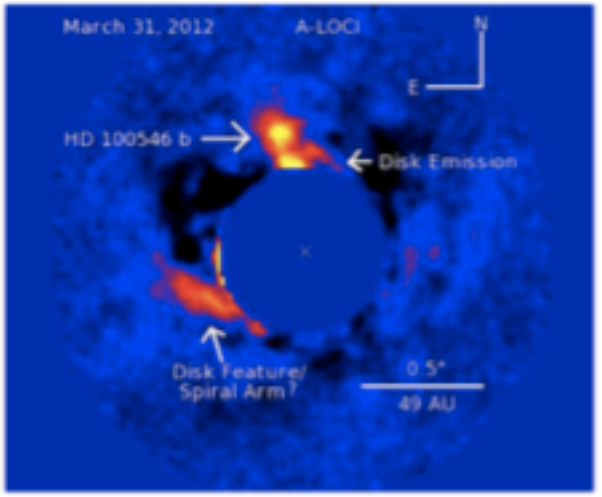


H band (~1.6 μm)

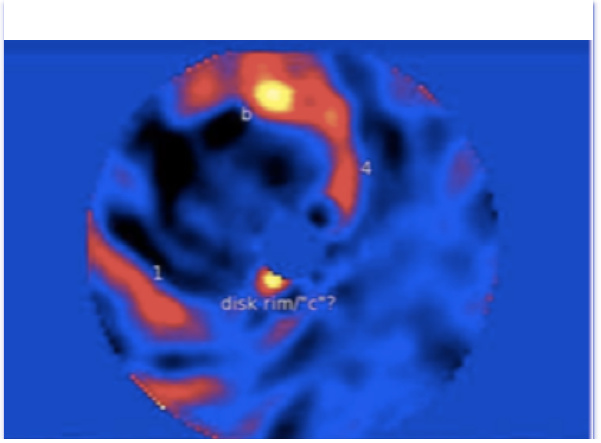


Currie et al. (2014), Currie et al. (2015)

Pinning down the temperature

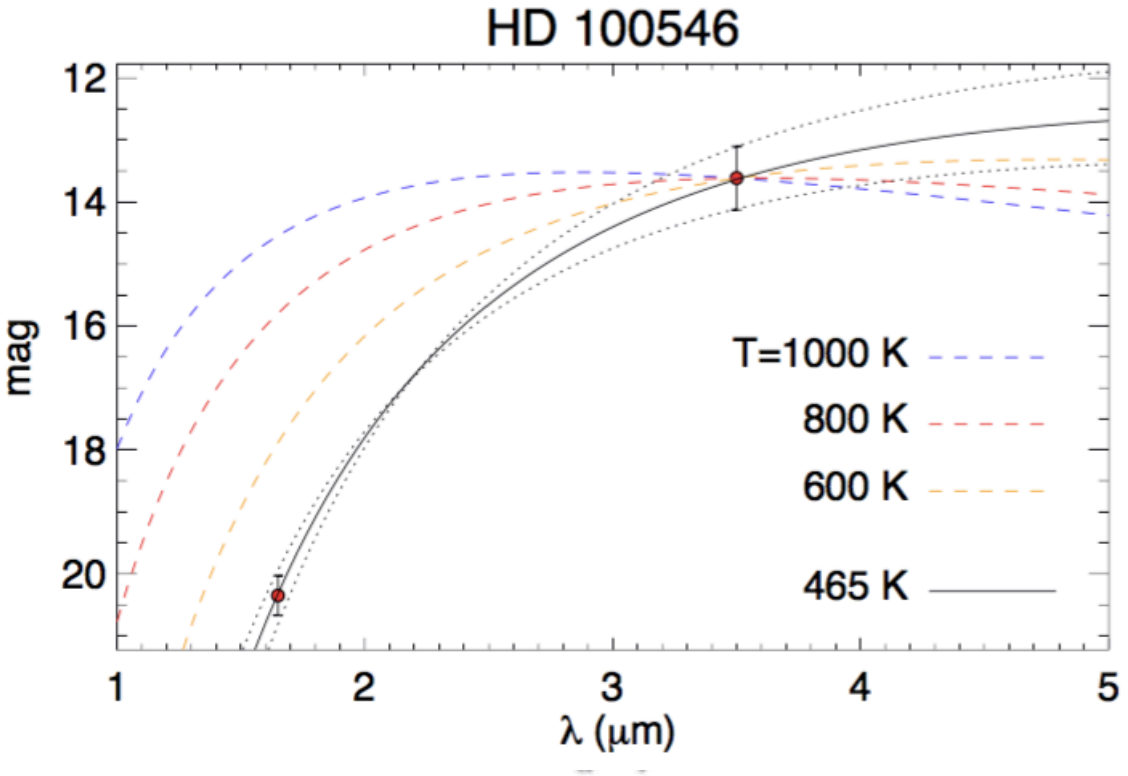


L band



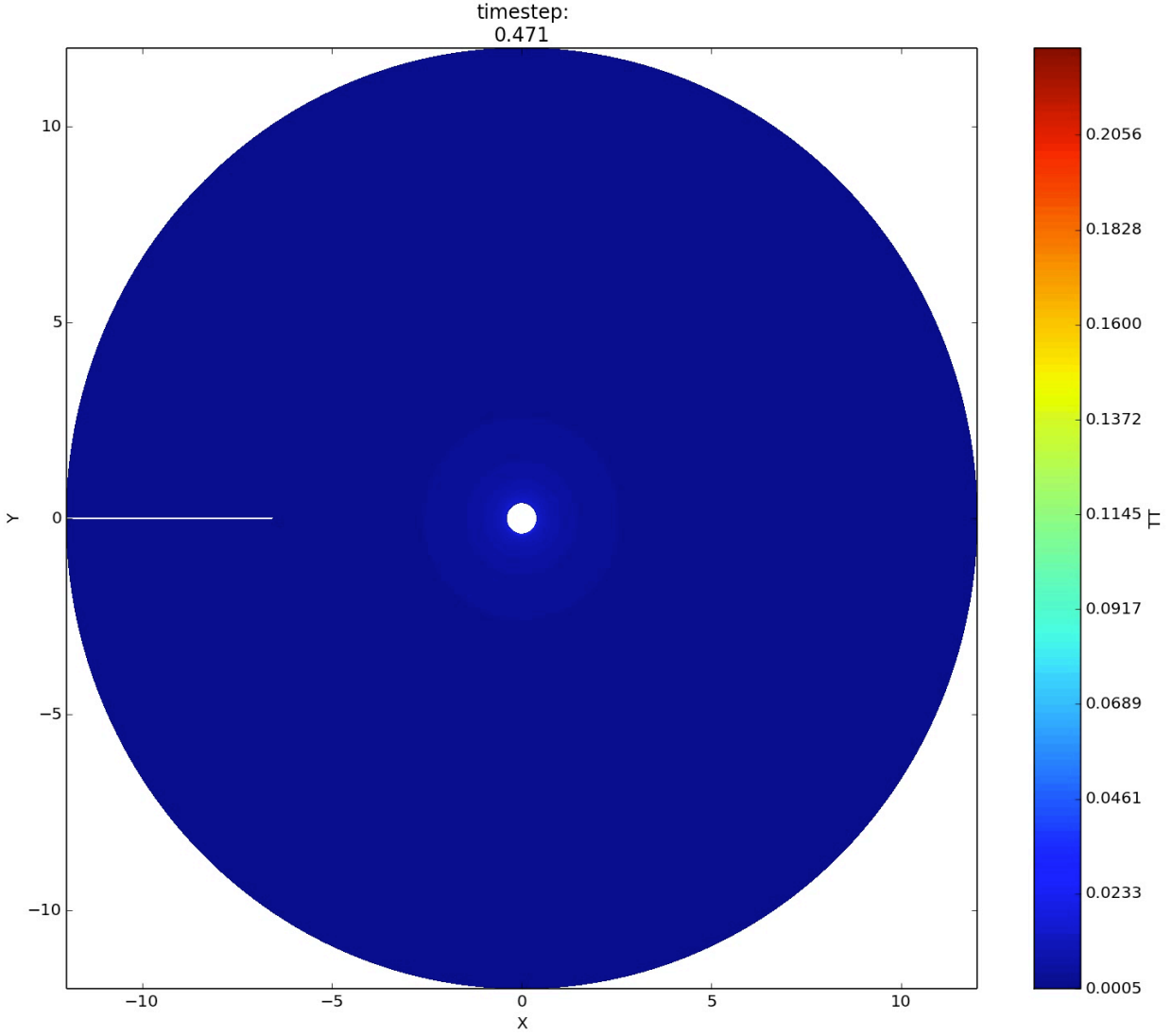
H band

Currie et al. (2014, 2015)



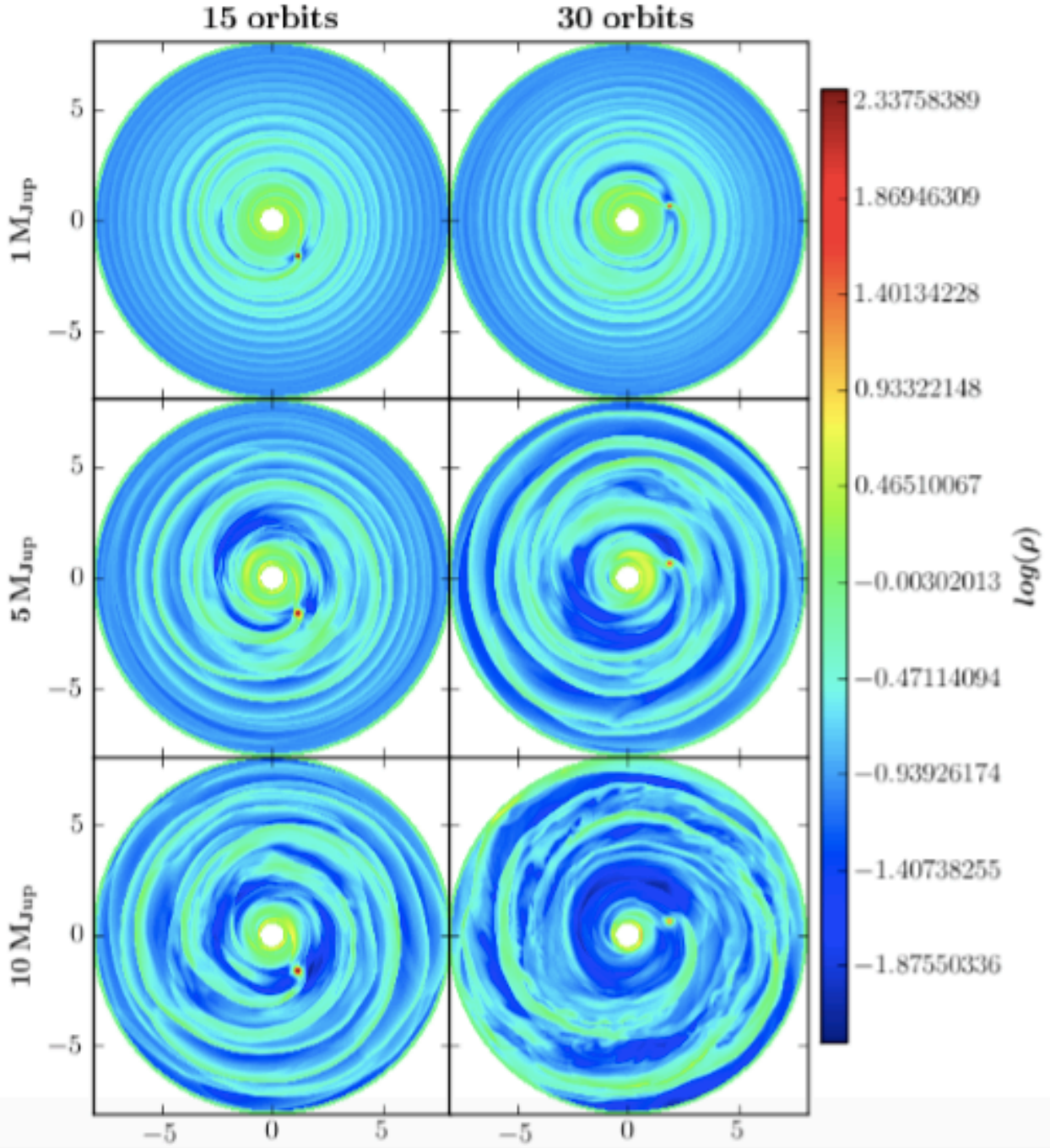
Lyra et al. (2016)

Planet-driven turbulence

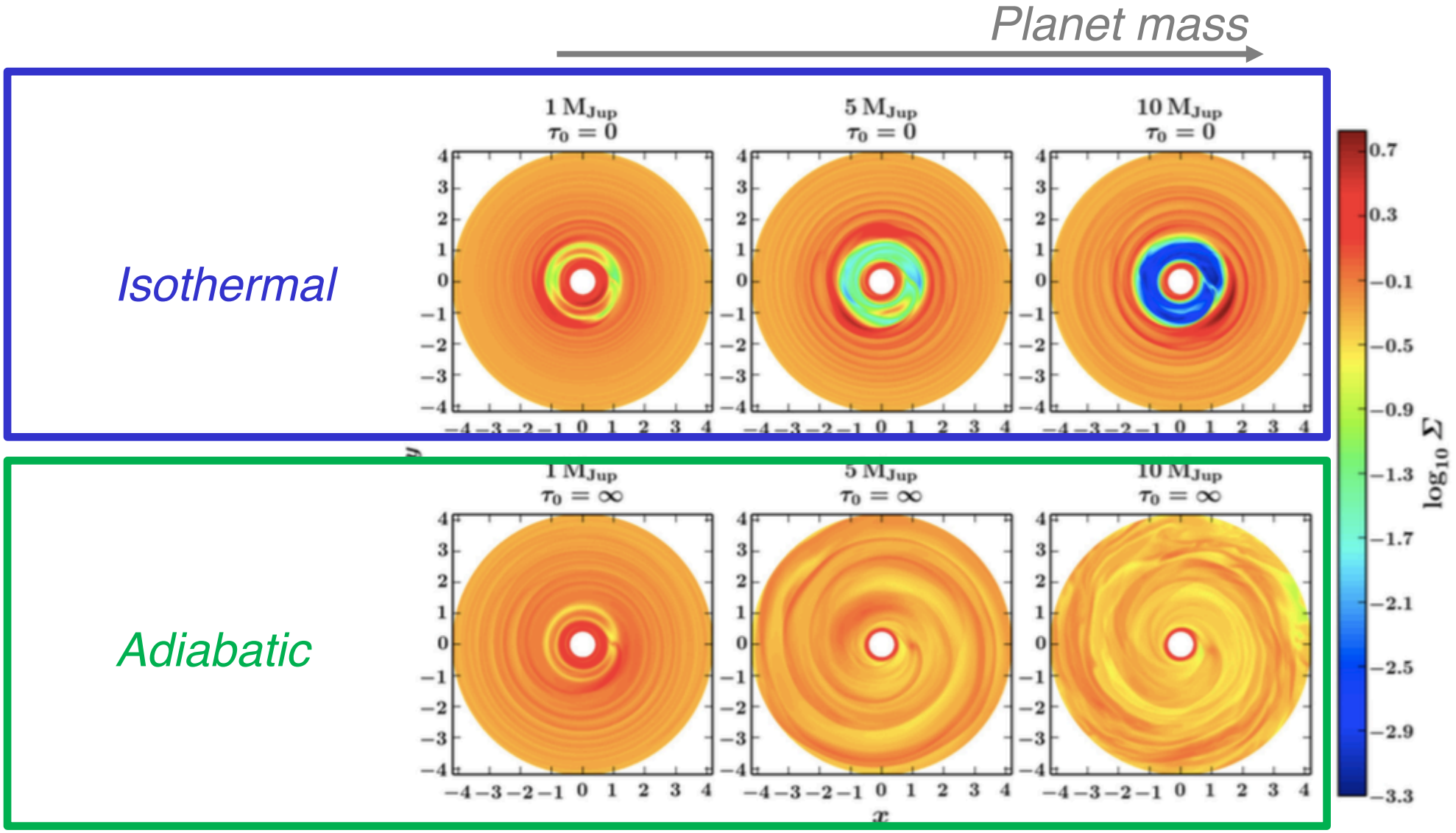


Richert et al. (2015)

Some crazy turbulence showing up at high planet mass….

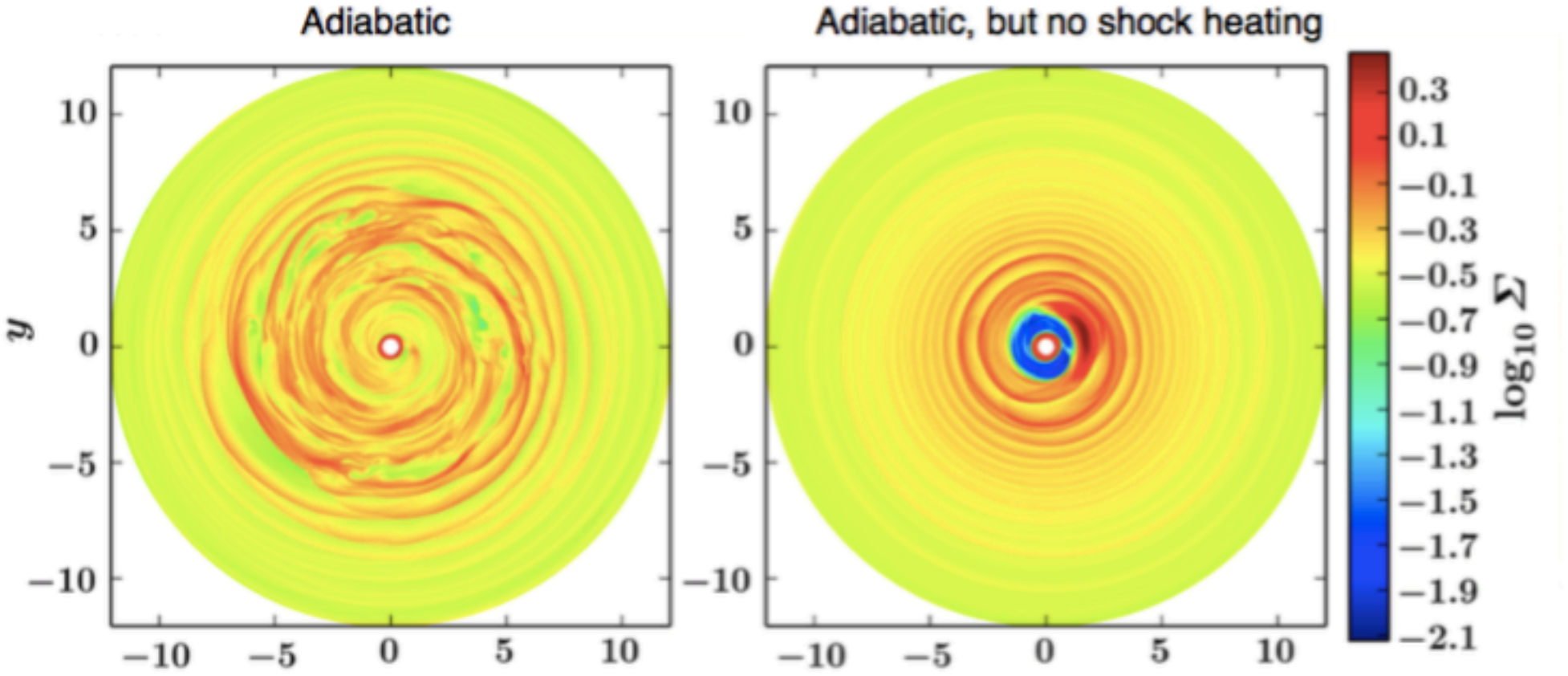


Turbulence in high-mass planets in adiabatic disks



Richert et al. (2015)

The energy source: shock heating!



Richert et al. (2015)

3D shocks: ascending bores and breaking waves

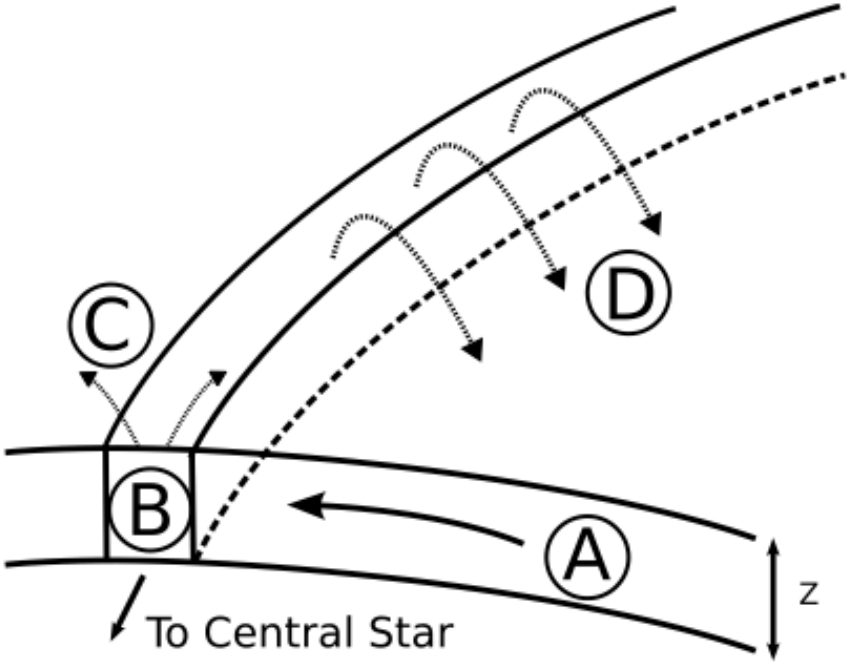
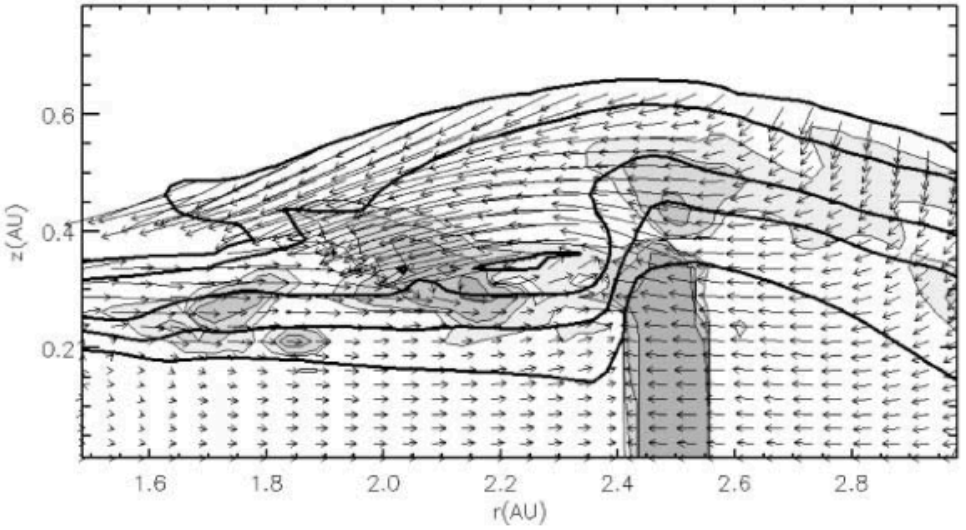
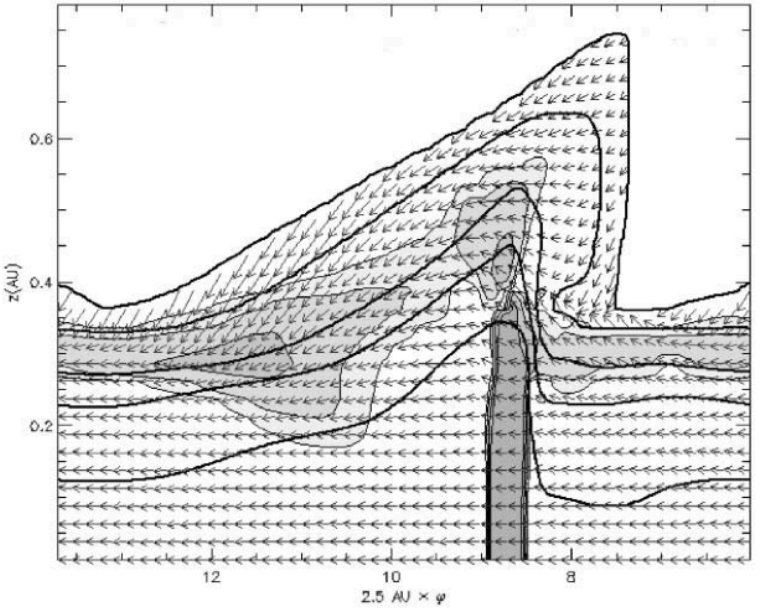


FIG. 2.—Cartoon depicting the gas flow in a shock bore in the frame of the spiral shock inside corotation. The gas in the preshock region flows into the spiral shock (A). The shock (B) causes the material to be out of vertical force balance and a rapid expansion results (C). Due to spiral streaming and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

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

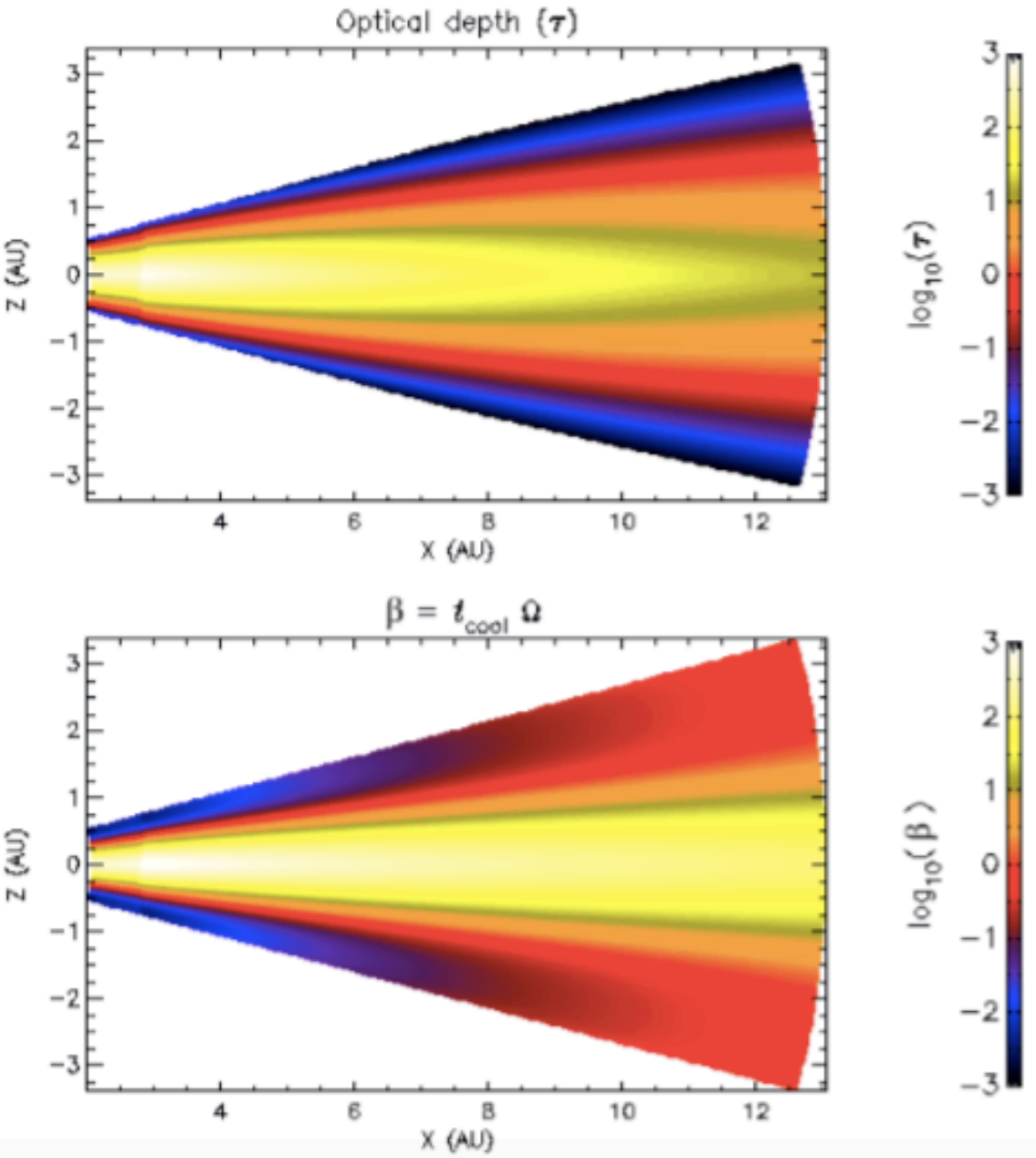
$$t_{\mathrm{rad}} = E/\dot{E}$$

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

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

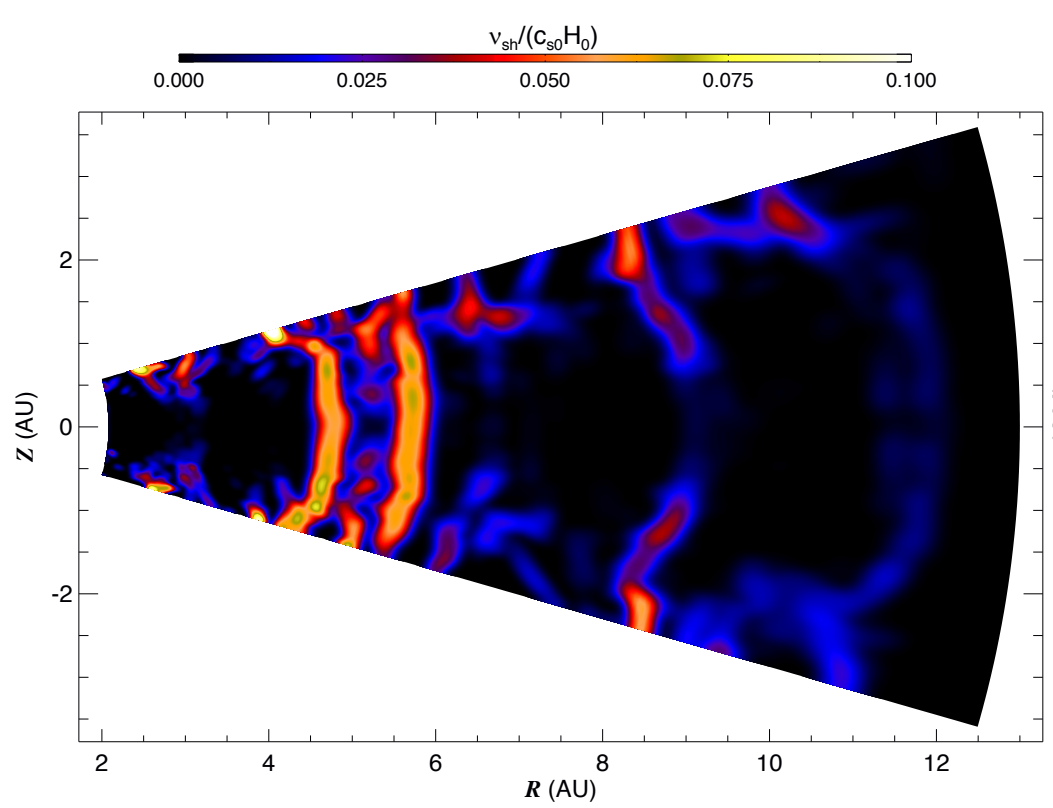
$$t_{\mathrm{cool}} = \frac{c_V \rho H \tau_{\mathrm{eff}}}{3\sigma T^3}.$$

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

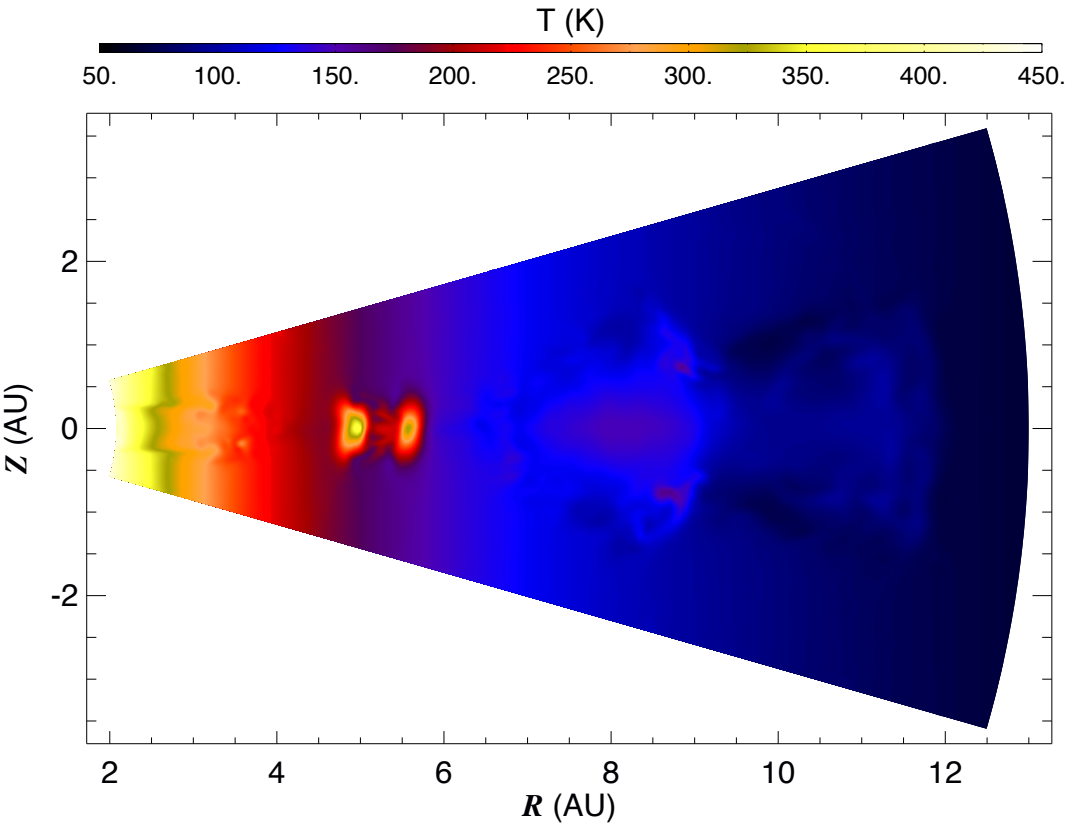


3D: Shock bores

Shocks (velocity convergence)

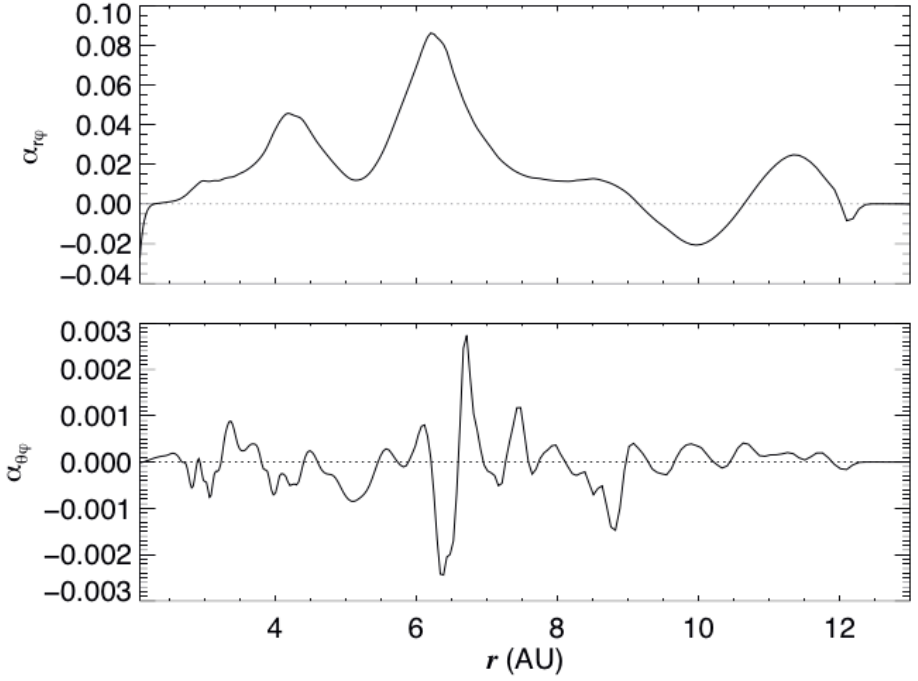


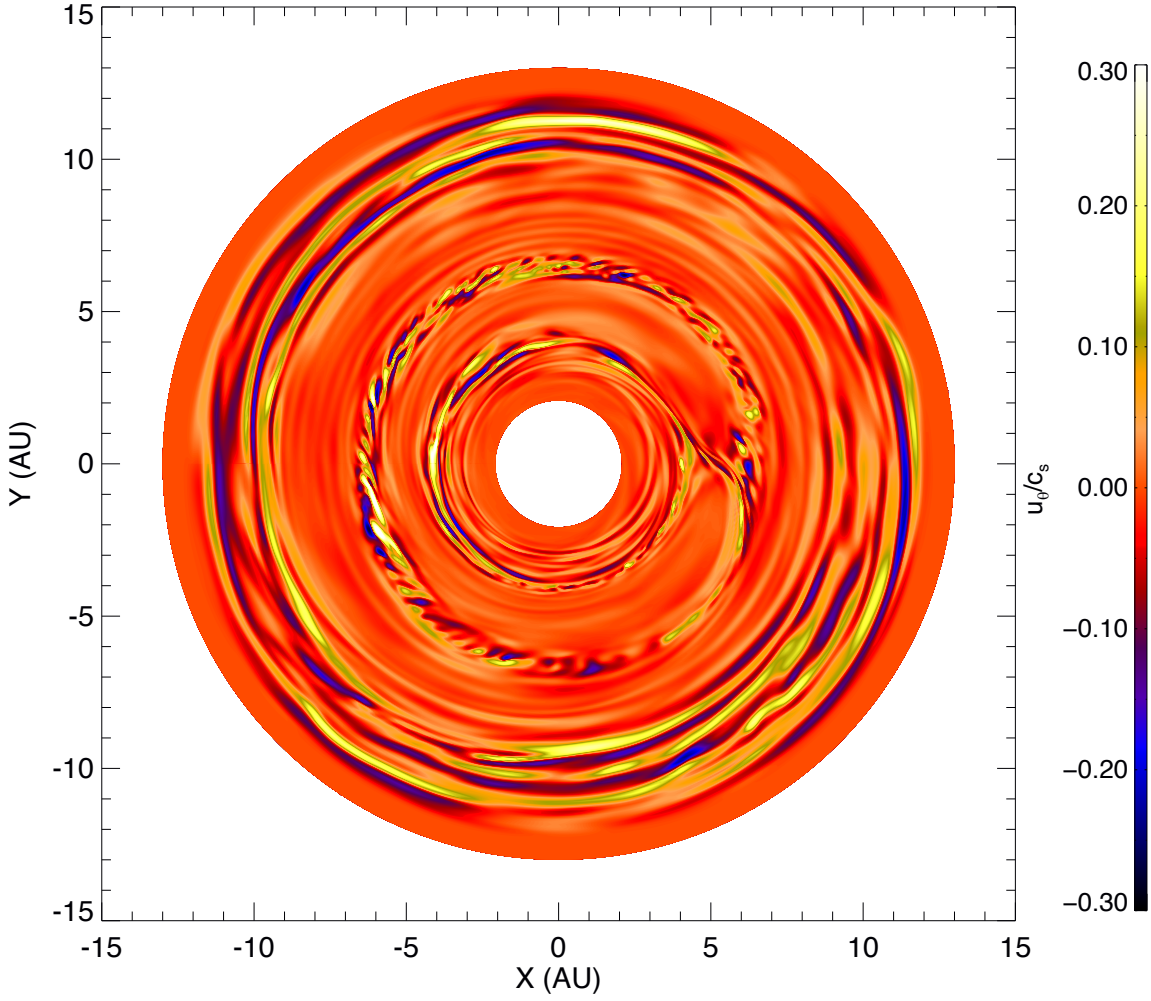
Temperature



Lyra et al. (2016)

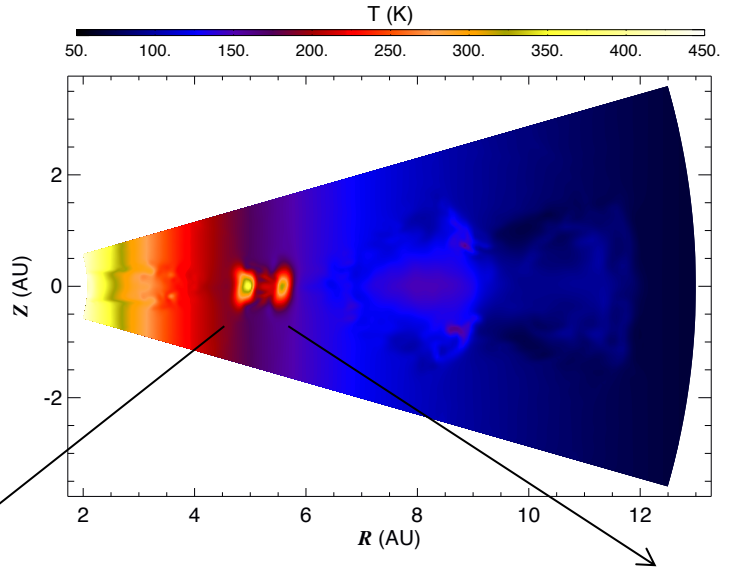
Prediction for spectroscopy: Turbulent surf

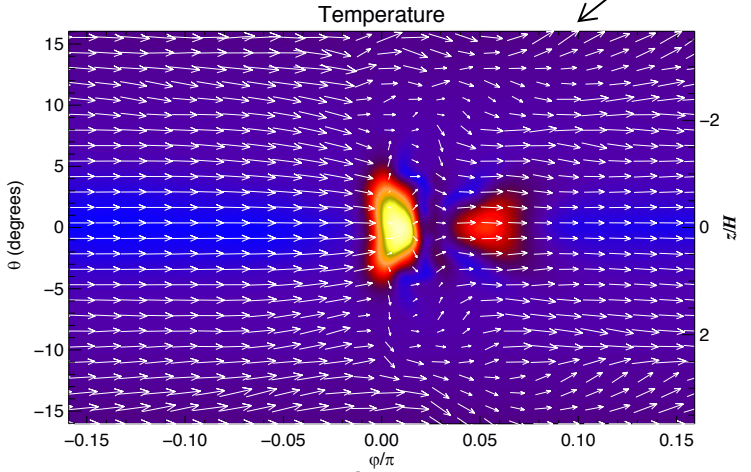


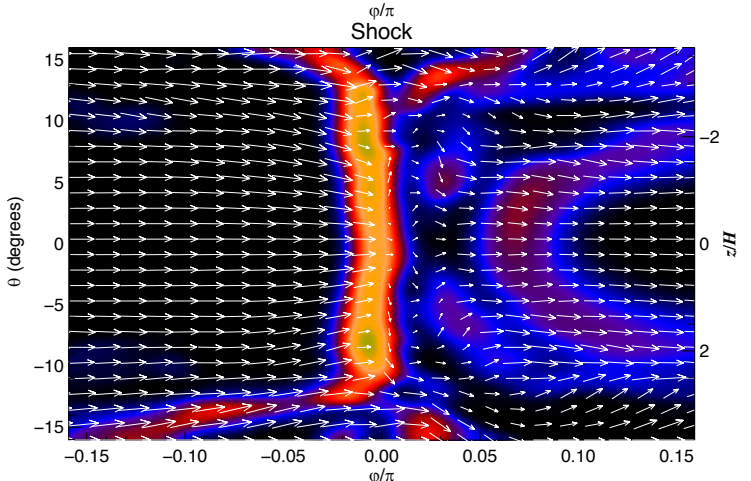


Lyra et al. (2016)

3D shocks: bores and breaking waves

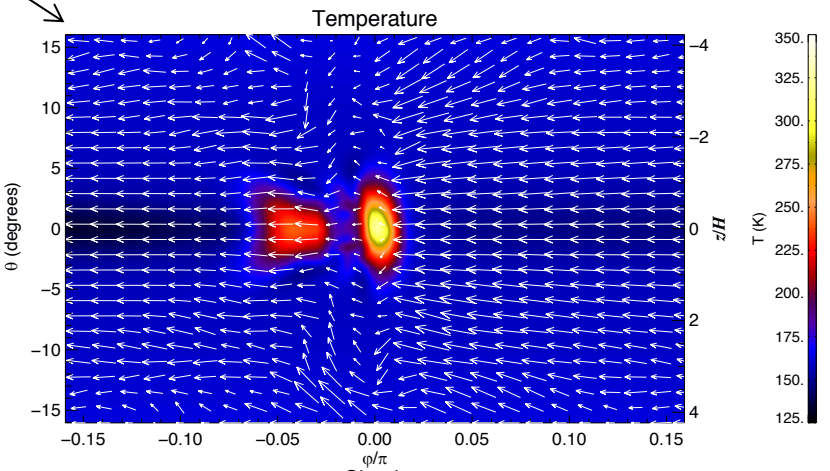


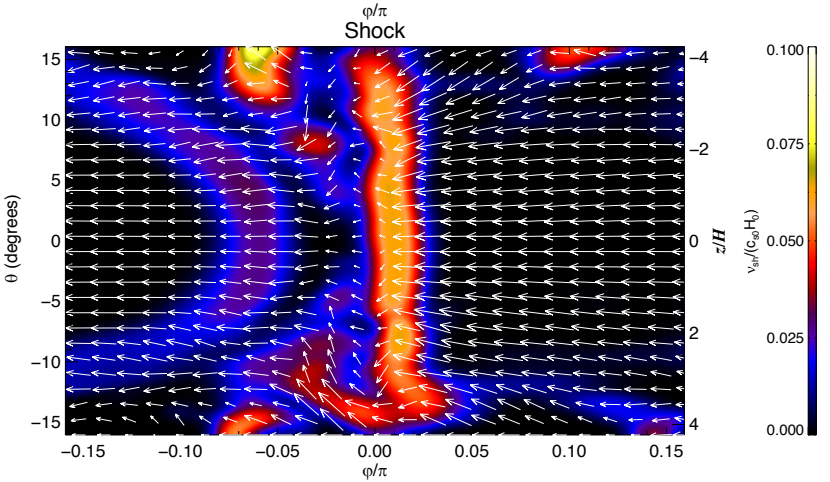




Temperature

Div u
(shock)



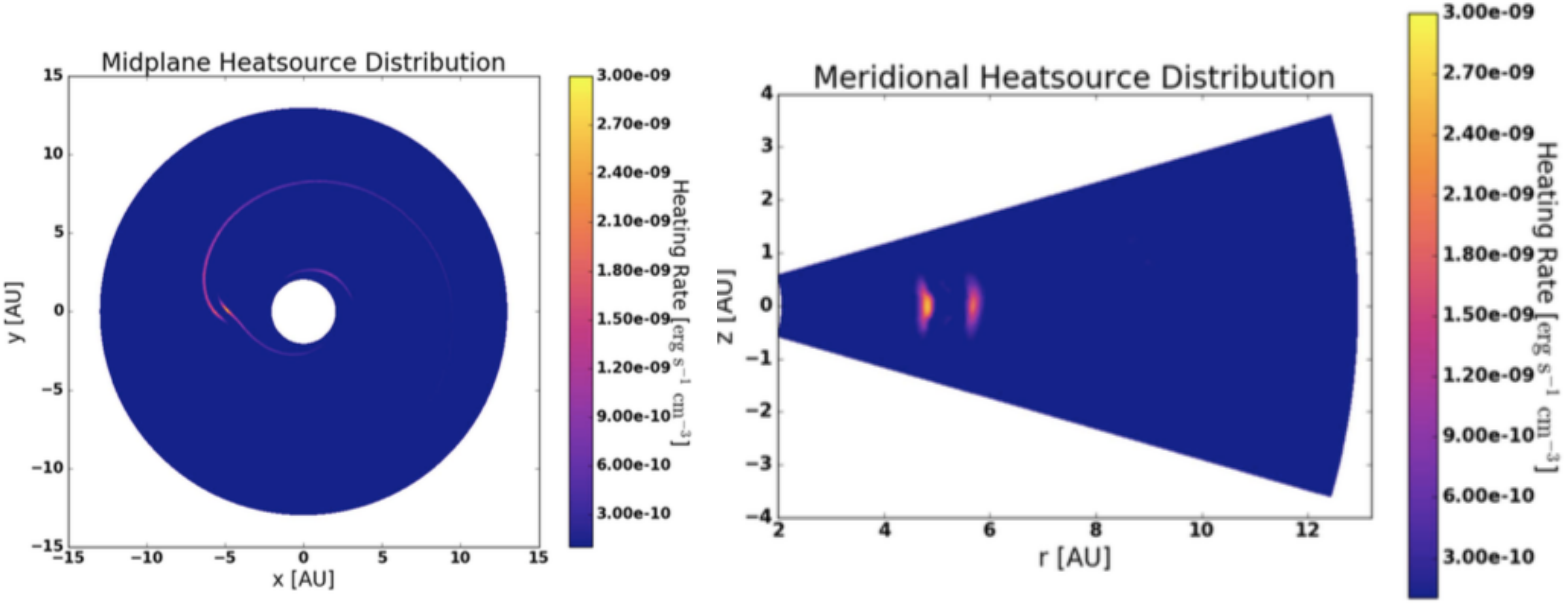


Lyra et al. (2016)

Shock heating and opacities

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

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



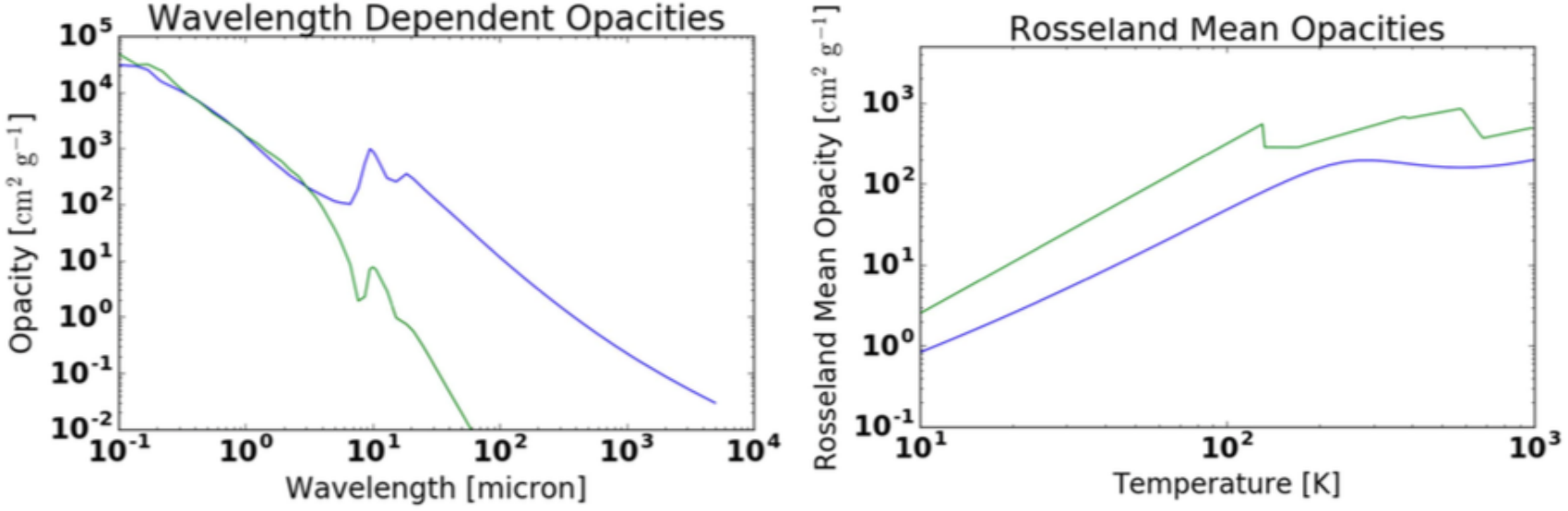
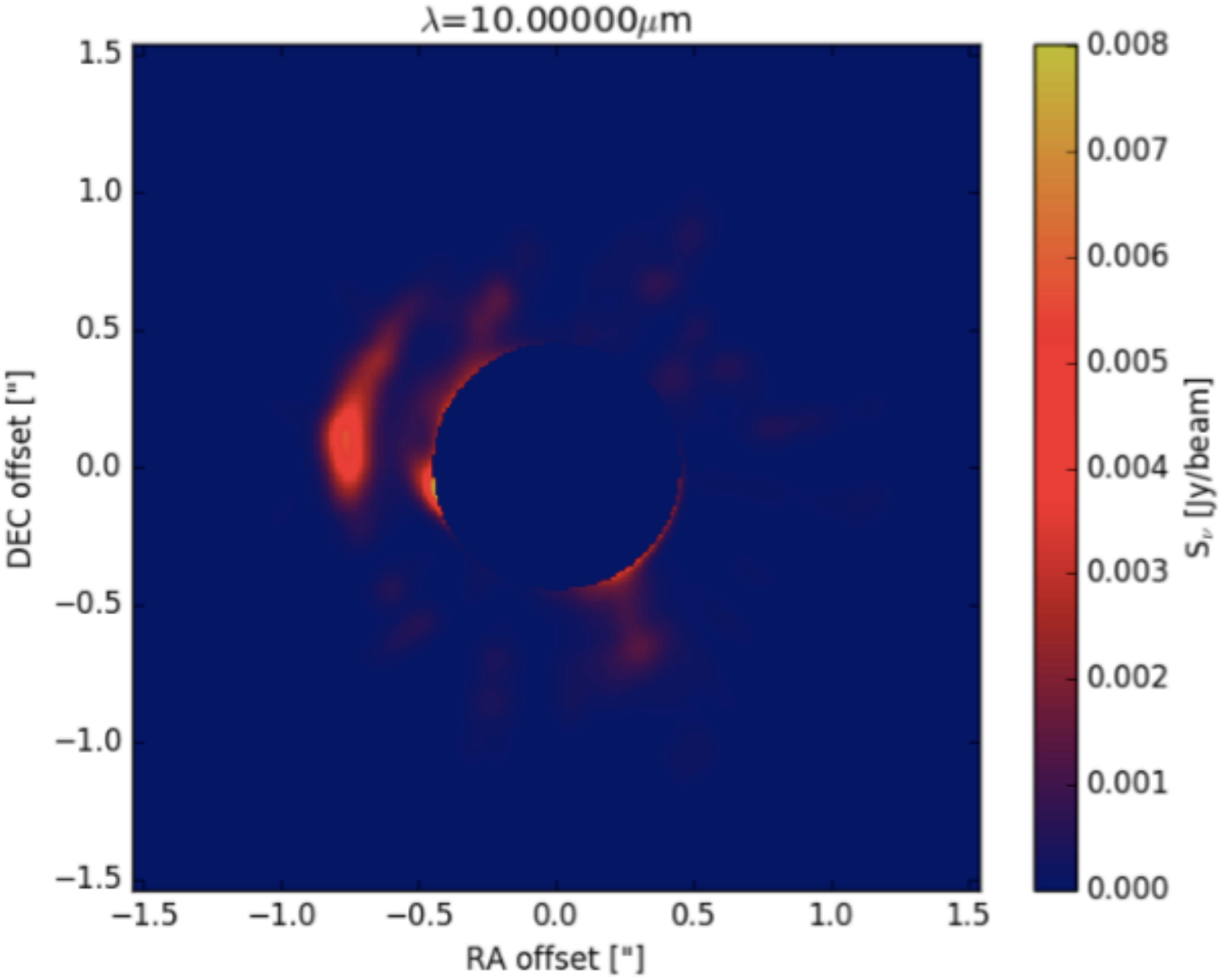


Figure 1. Wavelength-dependent opacities from Preibisch et al. (1993), including the absorption (top, blue) and scattering (top, green) opacities, input into RADMC-3D. The calculated Rosseland mean opacities (bottom, blue) match the Rosseland mean of Bell et al. (1997). The piece-wise Rosseland Mean 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.

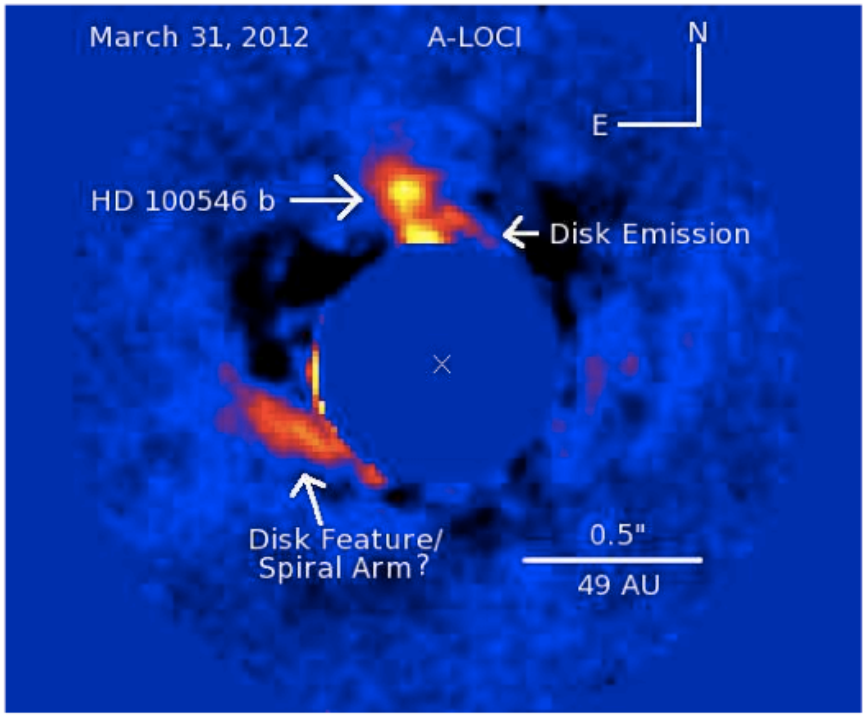
Hord et al. (2017)

Synthetic image by RADMC3D and shock heating

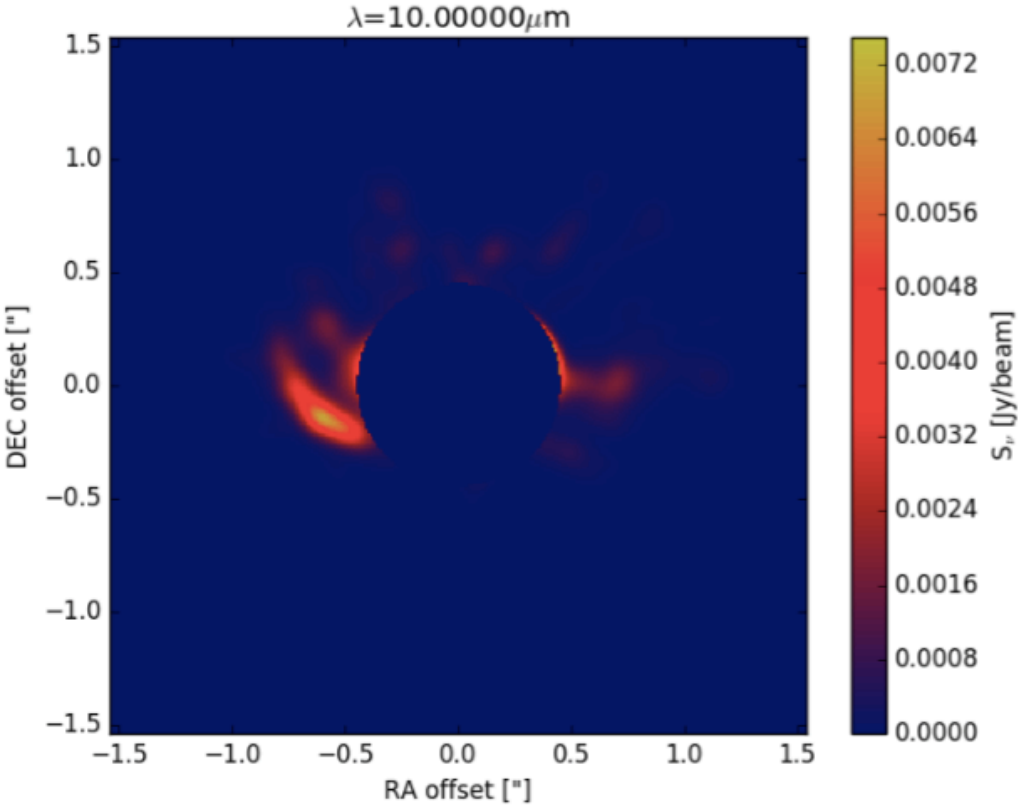


Hord et al. (2017)

Observation vs Synthetic Image



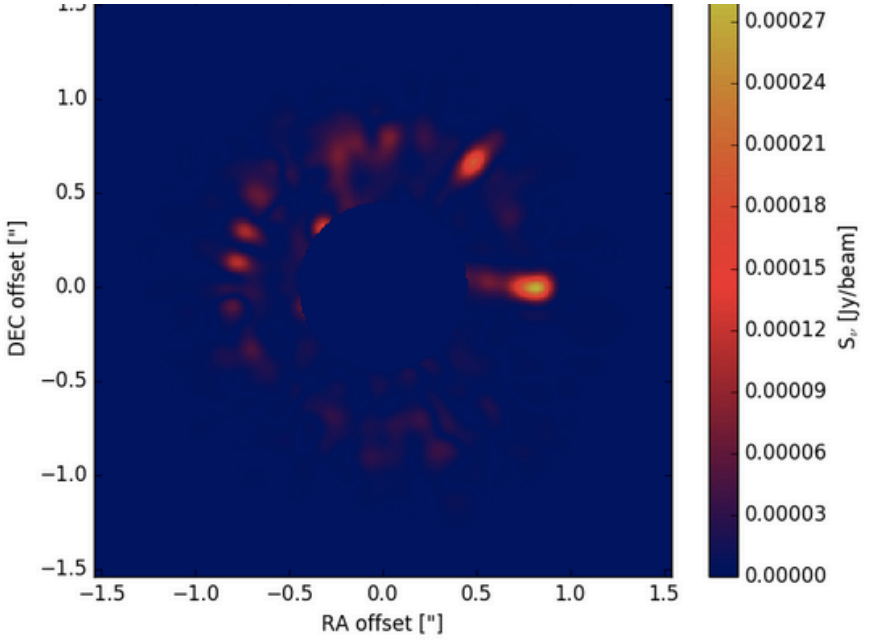
Currie et al. (2015)



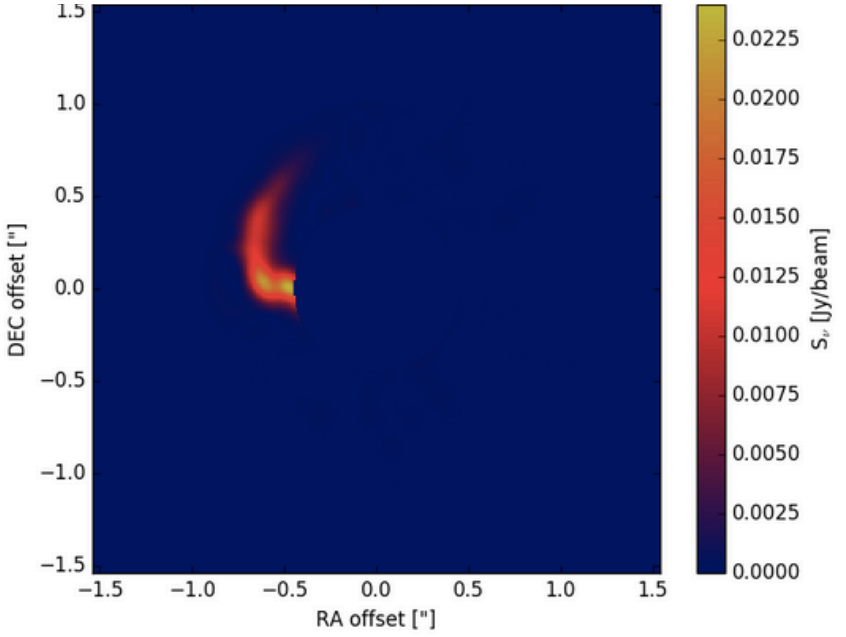
Hord et al. (2017)

Effect of shocks alone

1 μm

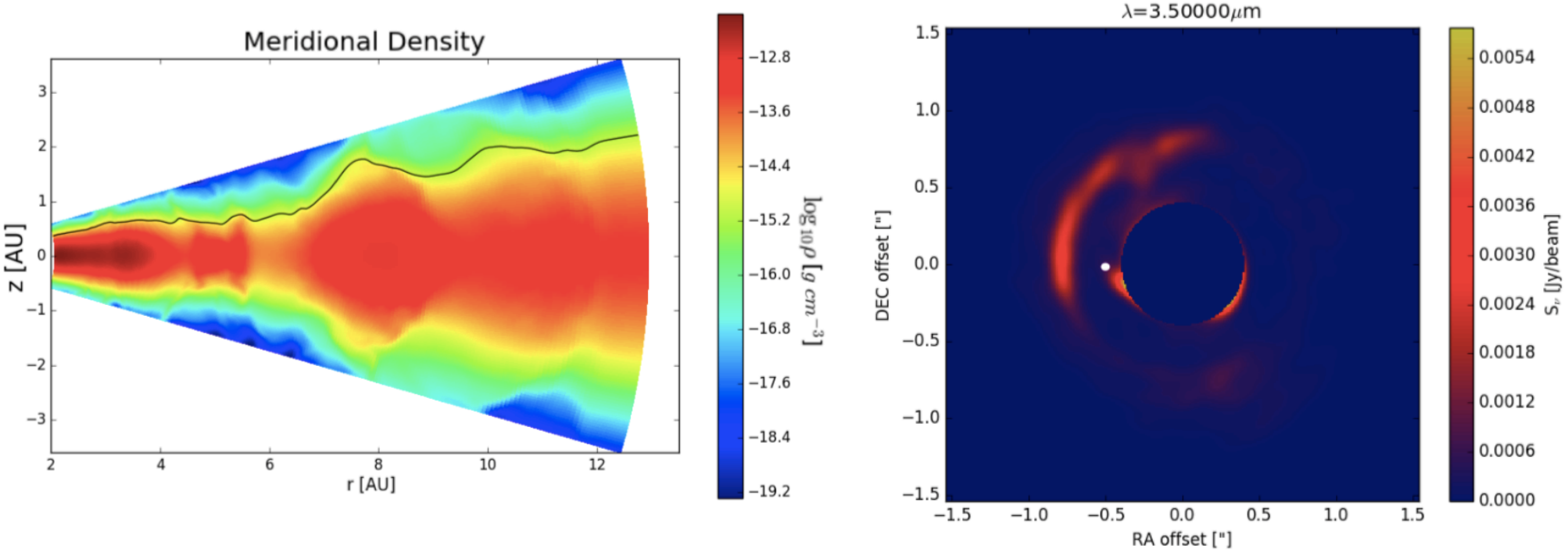


10 μm



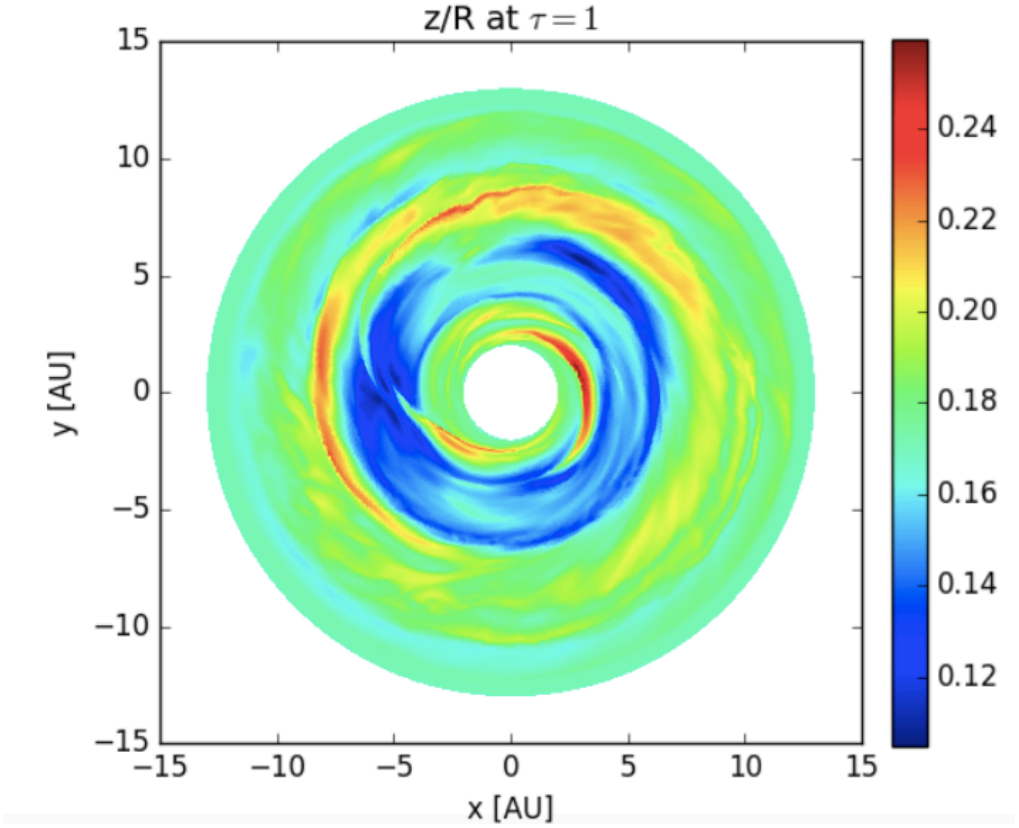
Hord et al. (2017)

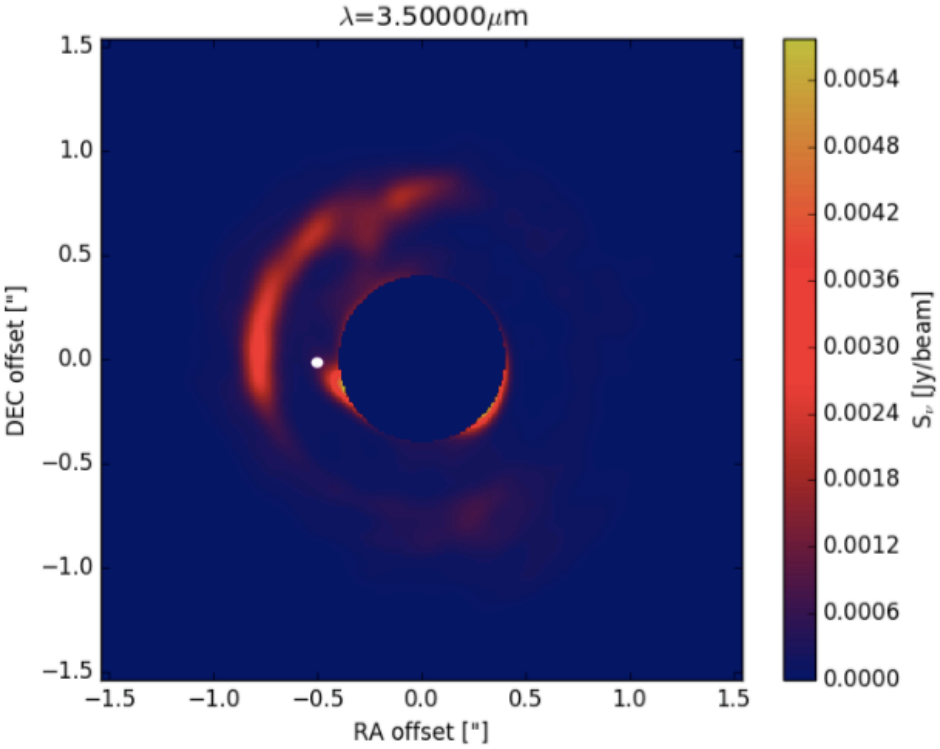
Scattering – A puffed up outer gap



Hord et al. (2017)

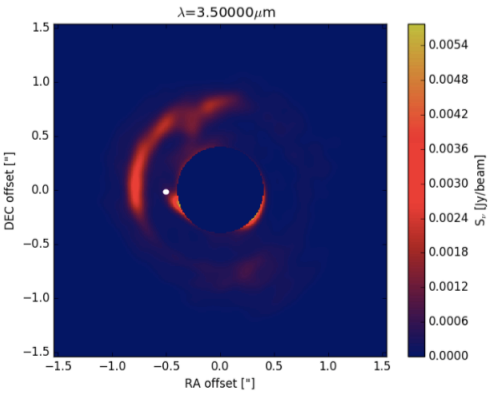
Scattering

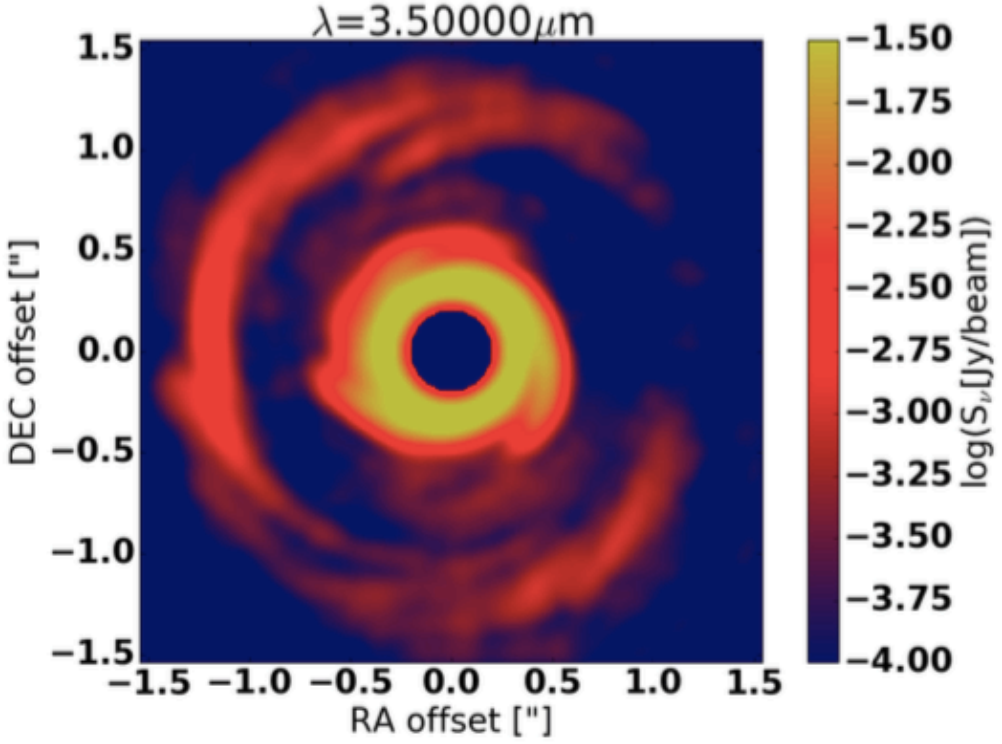


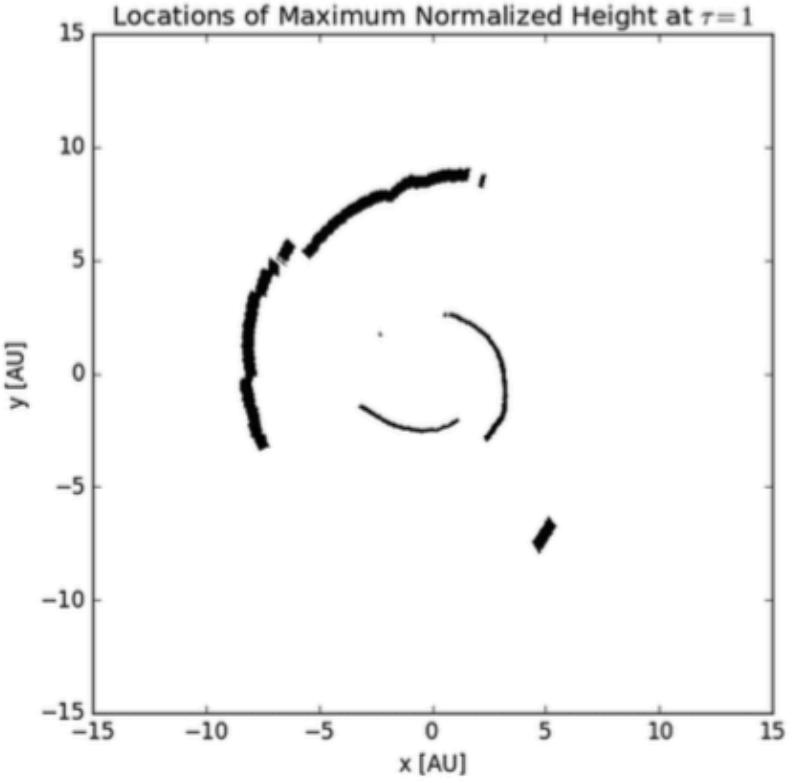


Hord et al. (2017)

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







Hord et al. (2017)

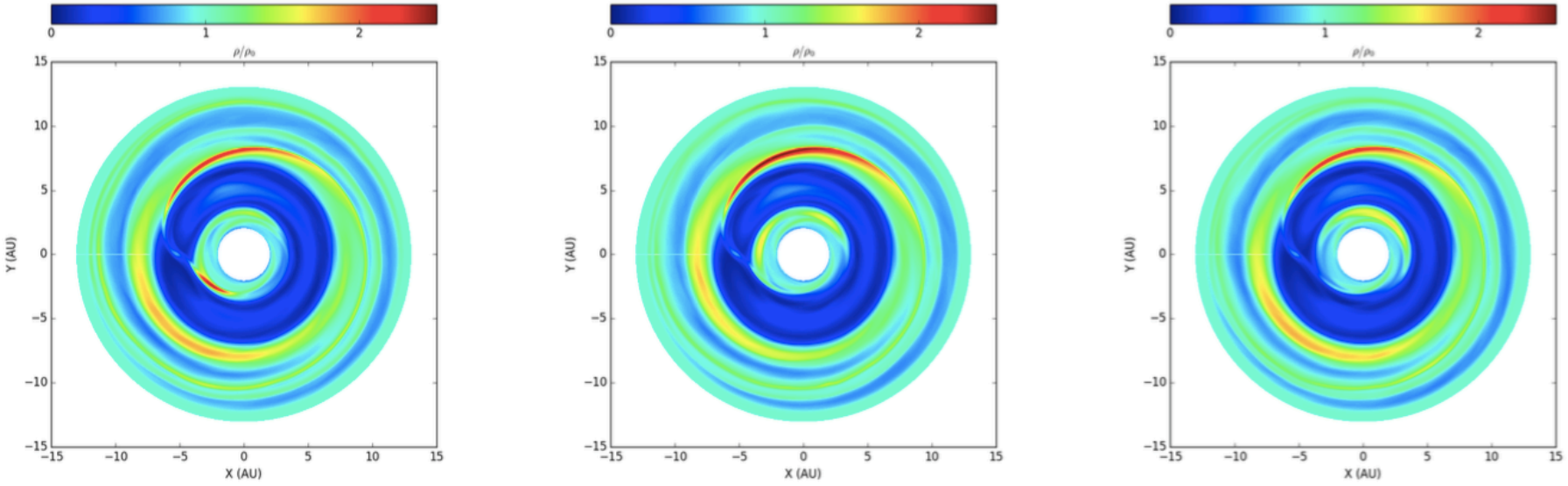
The pattern is stationary

T = 39 orbits

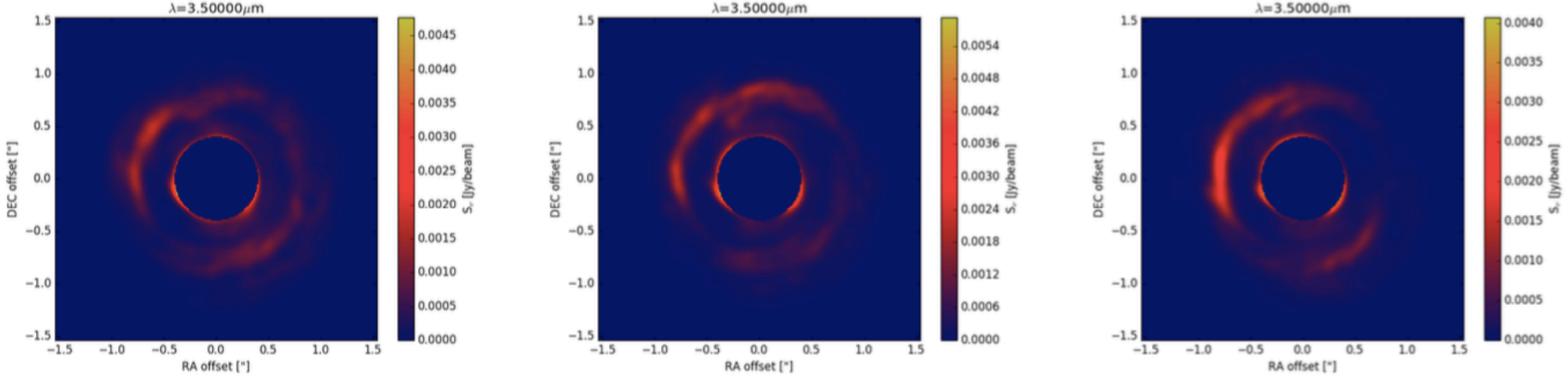
T = 40 orbits

T = 41 orbits

Density

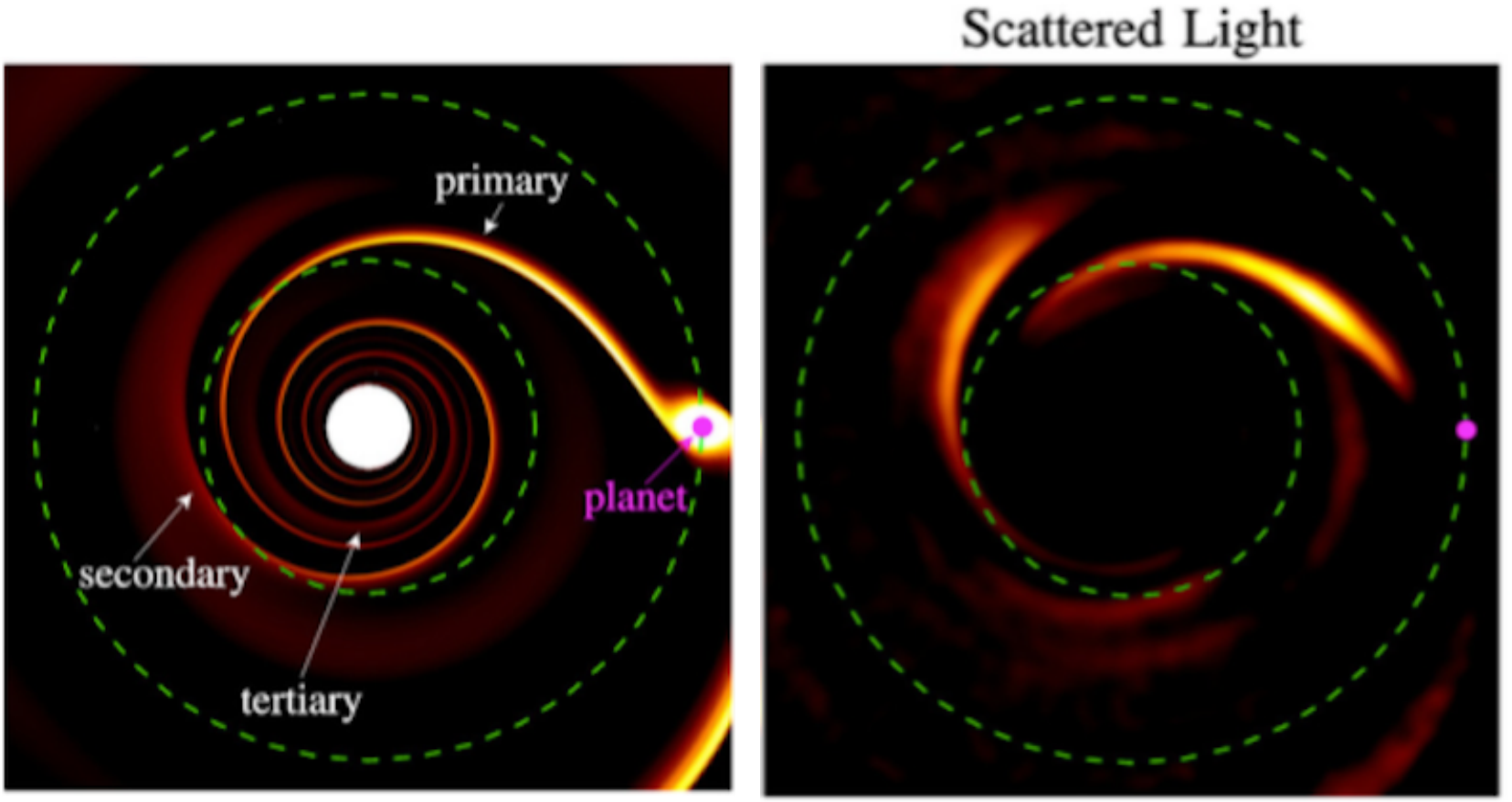


Intensity



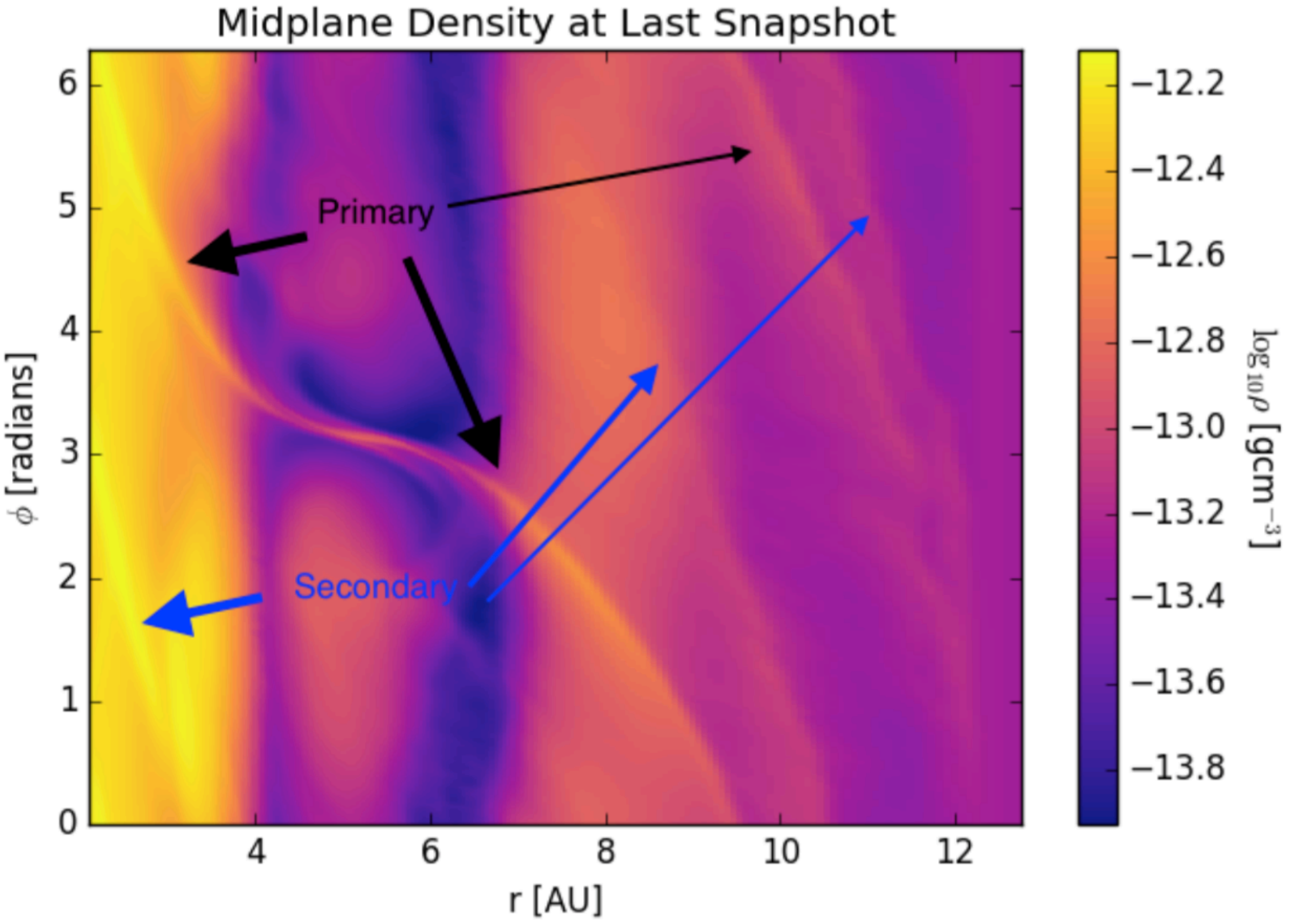
Hord et al. (2017)

Primary and Secondary spiral arms



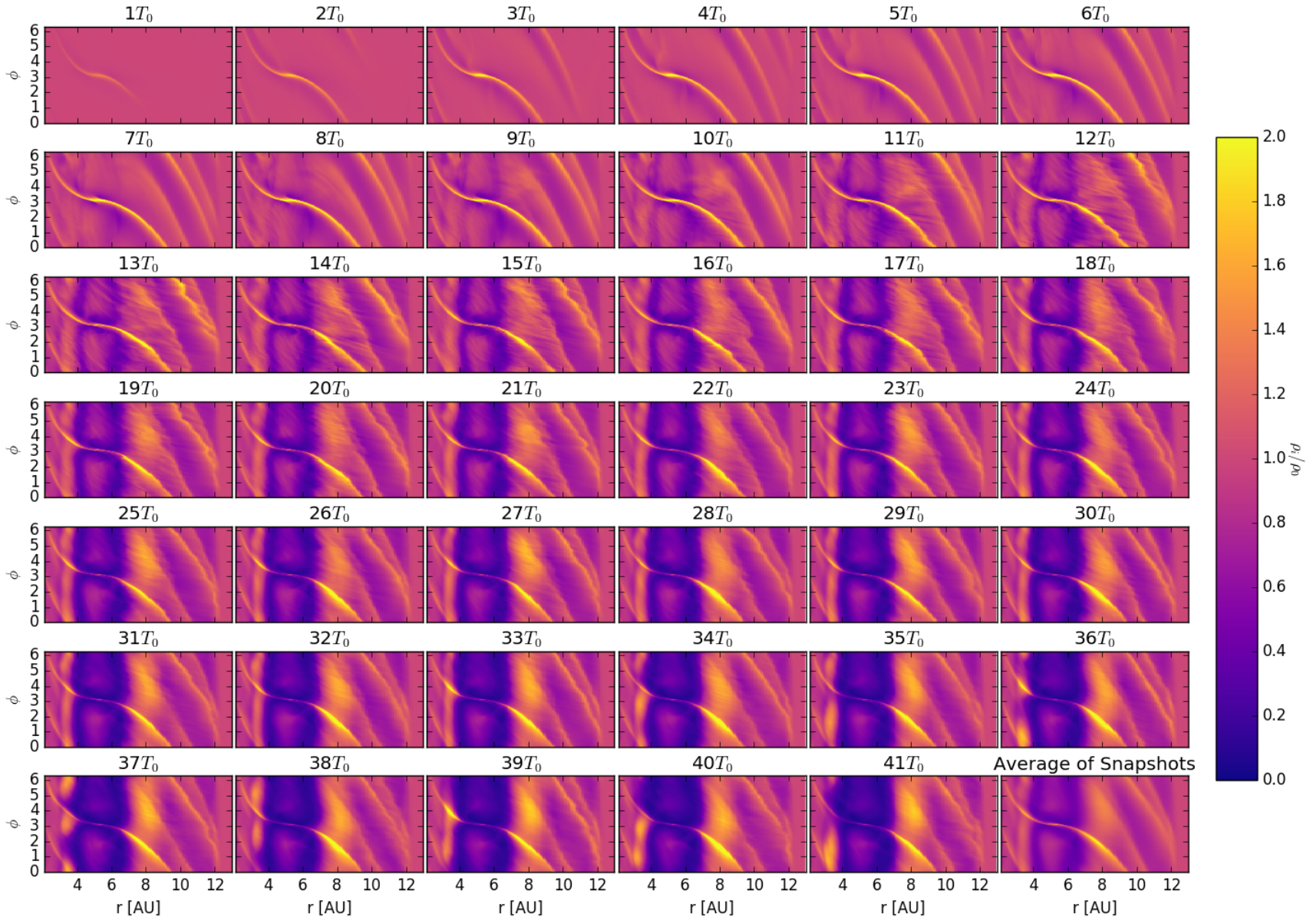
Dong et al. (2015)

Primary and Secondary spiral arms



Hord et al. (2017)

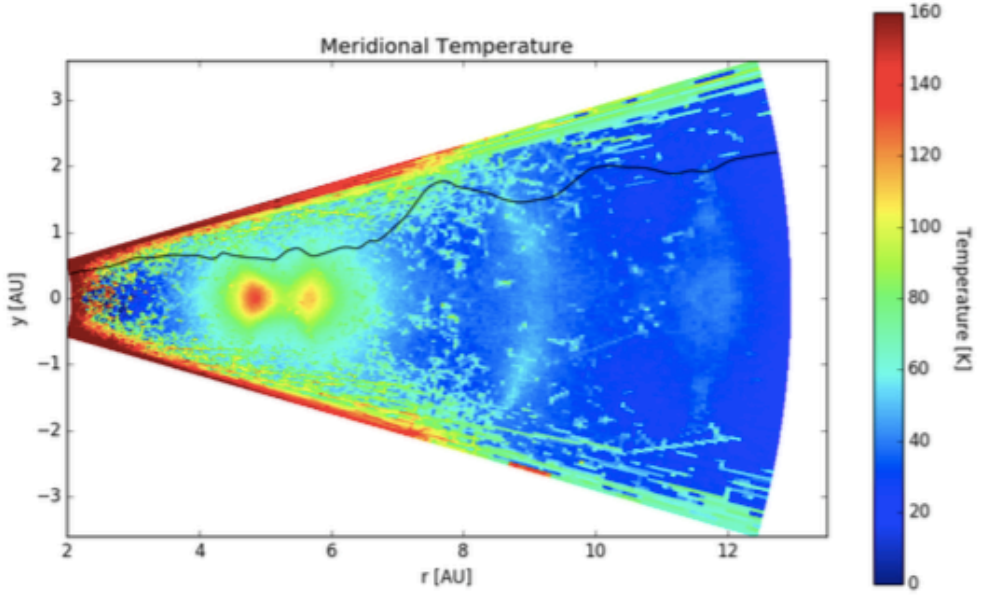
The raised feature has its origins in a secondary spiral arm

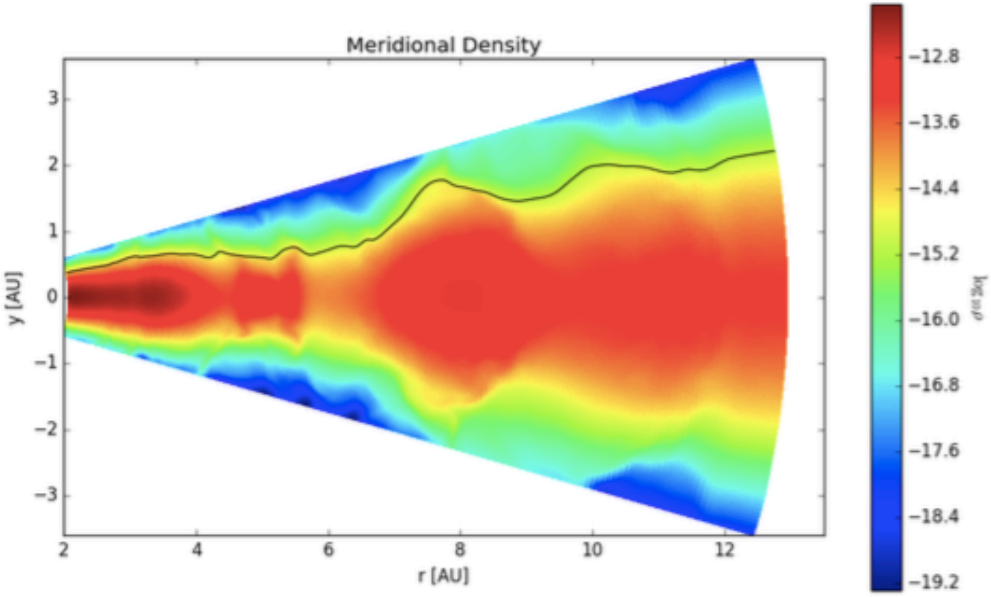


Hord et al. (2017)

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





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