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).

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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 fi
mass planets in an isothermal gas. In this work, we describe two-
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)

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doi:10.3847/0004-637X/817/2/102

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

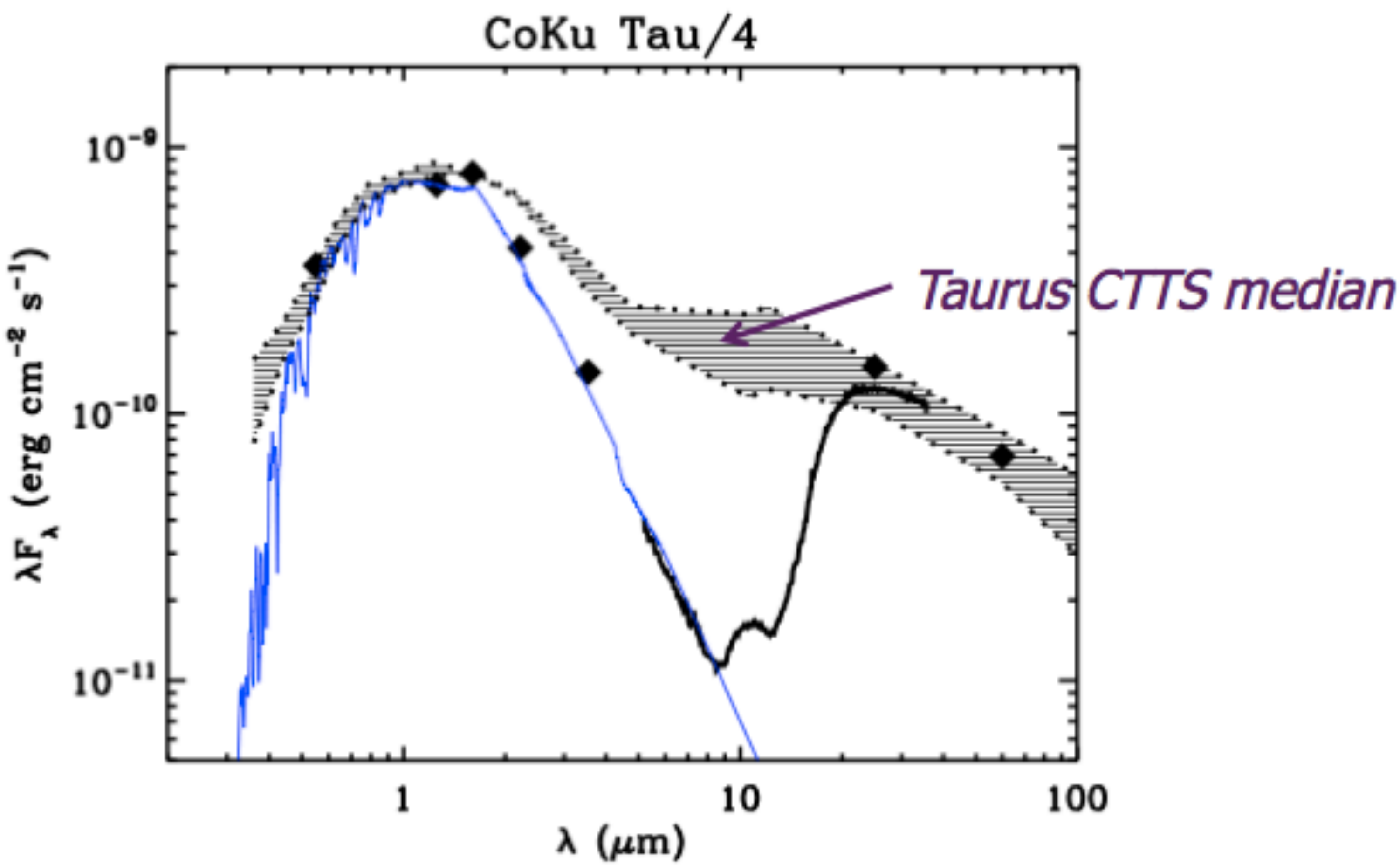
Blake Hord[1,2,3], Wladimir Lyra[2,3], Mario Flock[3], Neal J. Turner[3]
(Dated: Received ; Accepted)
Draft version

ABSTRACT

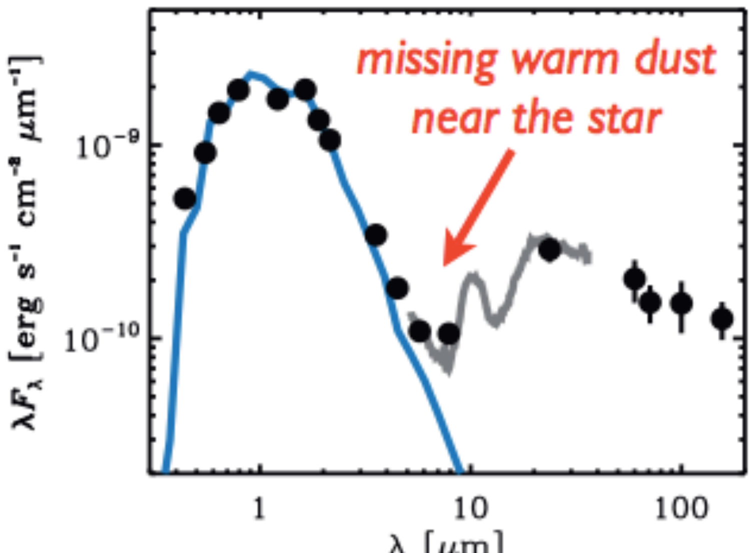
Recent observations of the protoplanetary disk around the Herbig Be star HD 100546 show two bright features in infrared (bands H and L') at about 50 AU. While one appears at the location of a confirmed exoplanet, the other has not been explained. A recent hydrodynamic model of the effects of shocks induced 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)

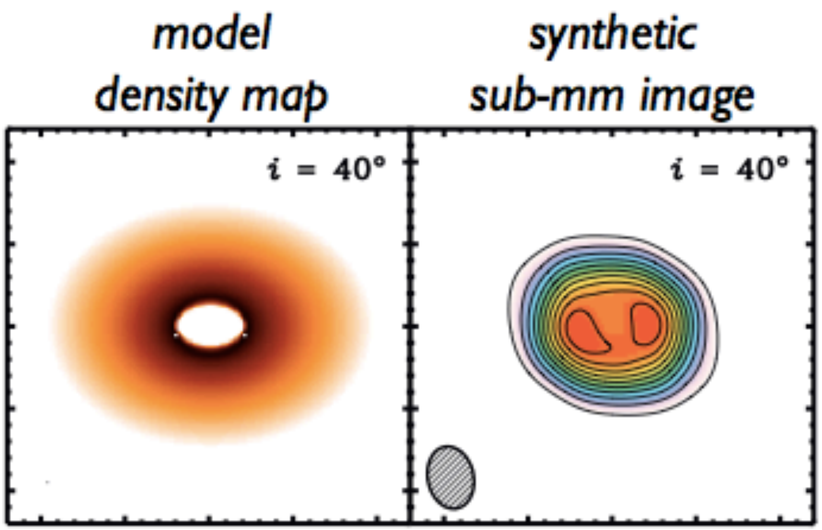
Transition Disks: Disks with missing hot dust.



Transition Disks: Disks with missing hot dust.

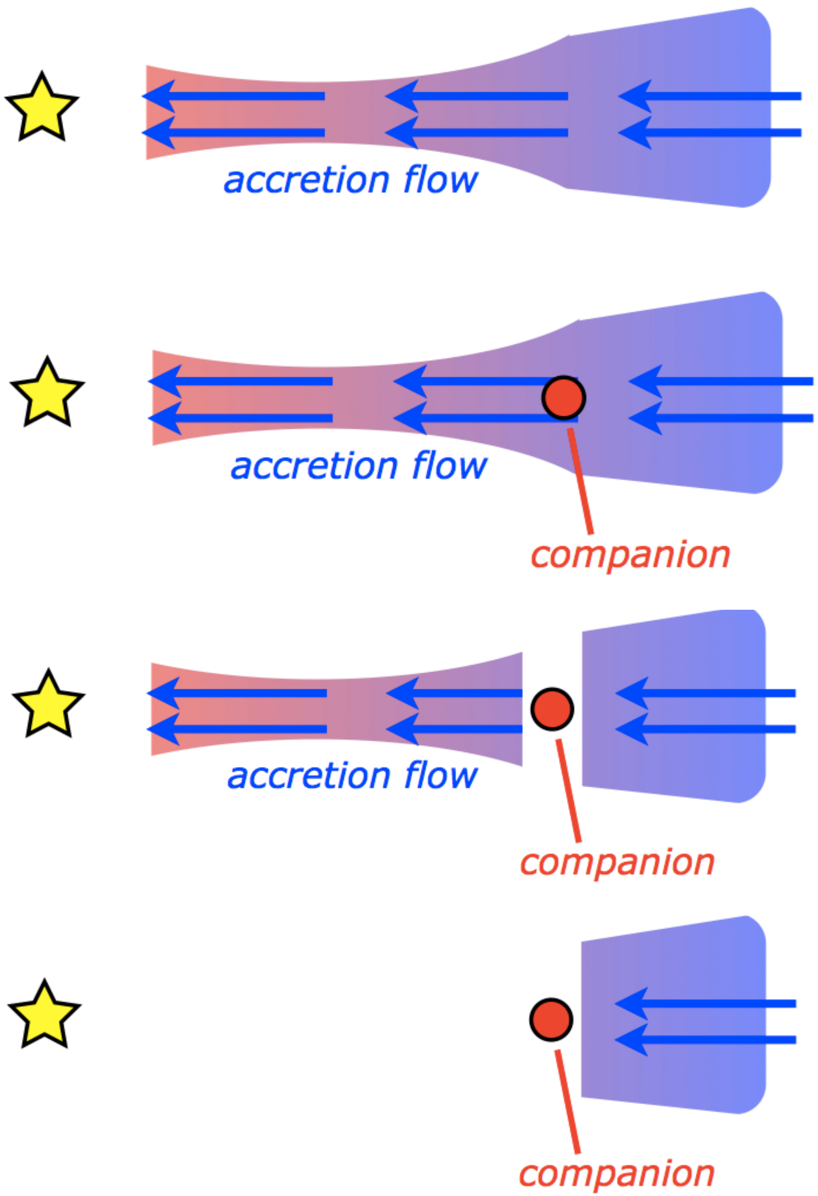


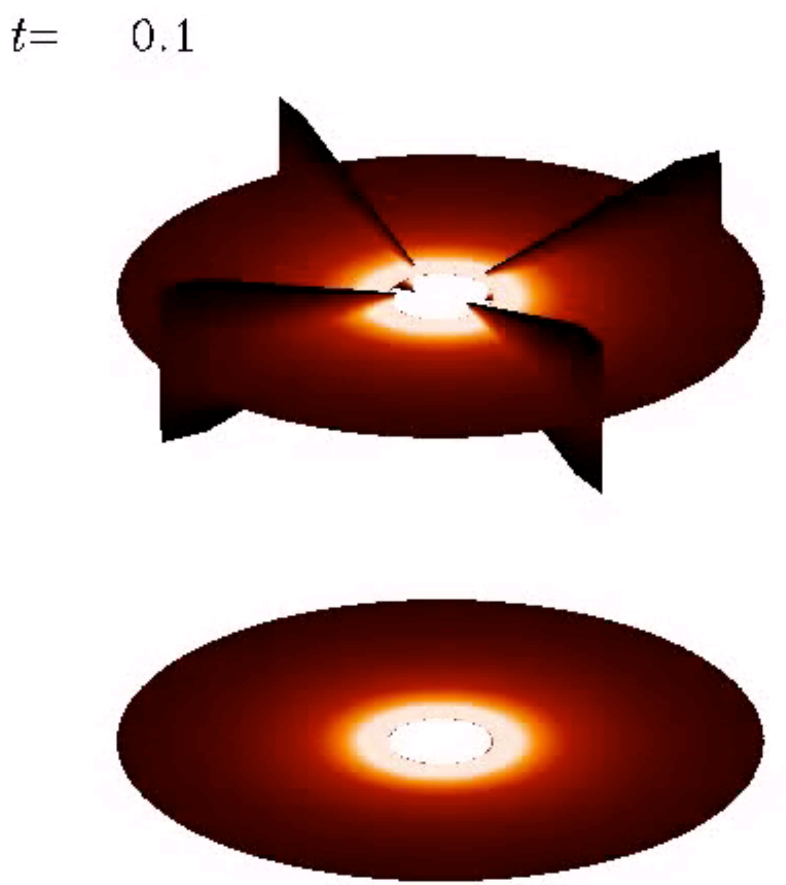
[e.g., Furlan et al. 2009]



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

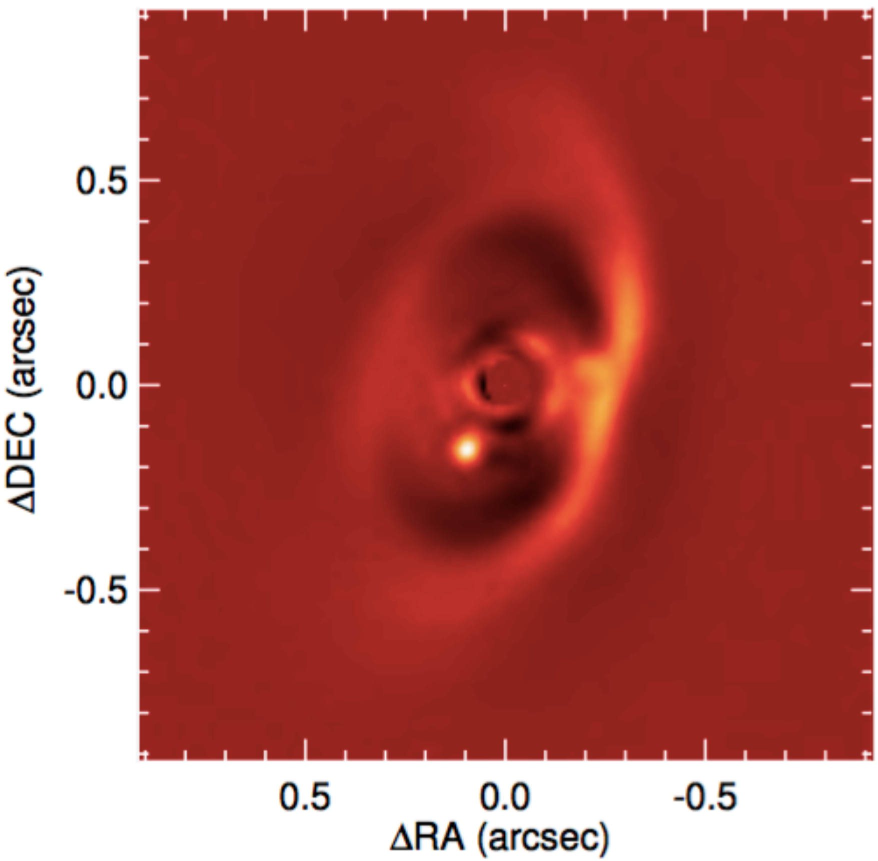
Planetary companion





(Lyra 2009)

These cavities may be the telltale signature of forming planets



(Lyra et al. 2009b)

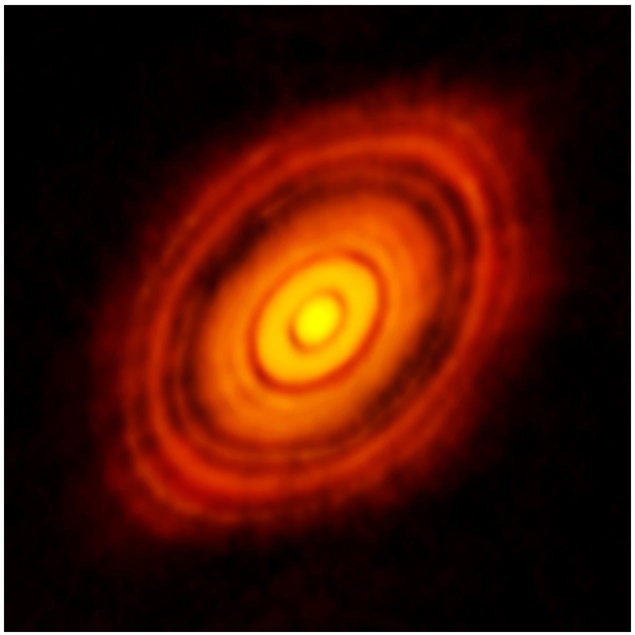
A way to directly study planet-disk interaction

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

(Lyra et al. 2009b)

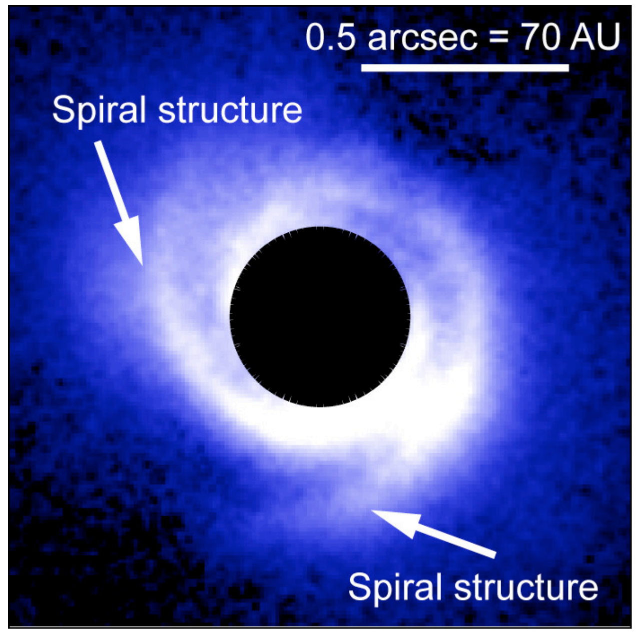
Observational evidence: gaps, spirals, and vortices

HL Tau



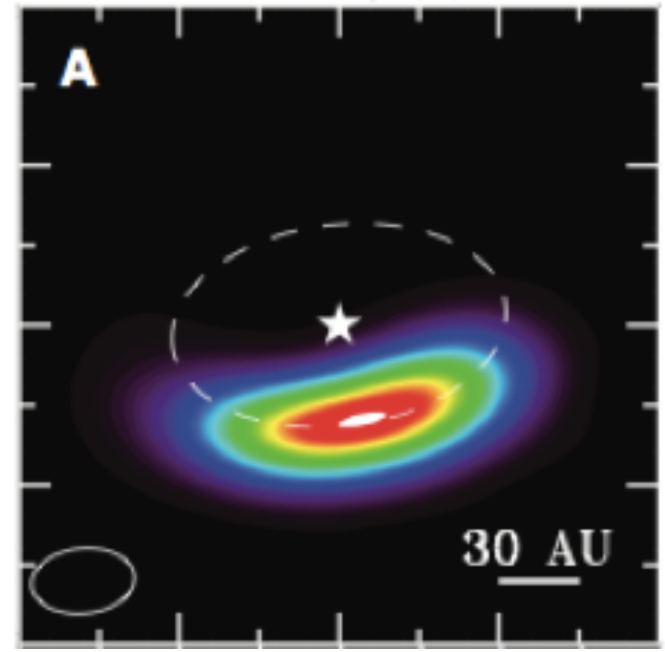
The ALMA Partnership et al. (2015)

SAO 206462



Muto et al. (2012)

Oph IRS 48



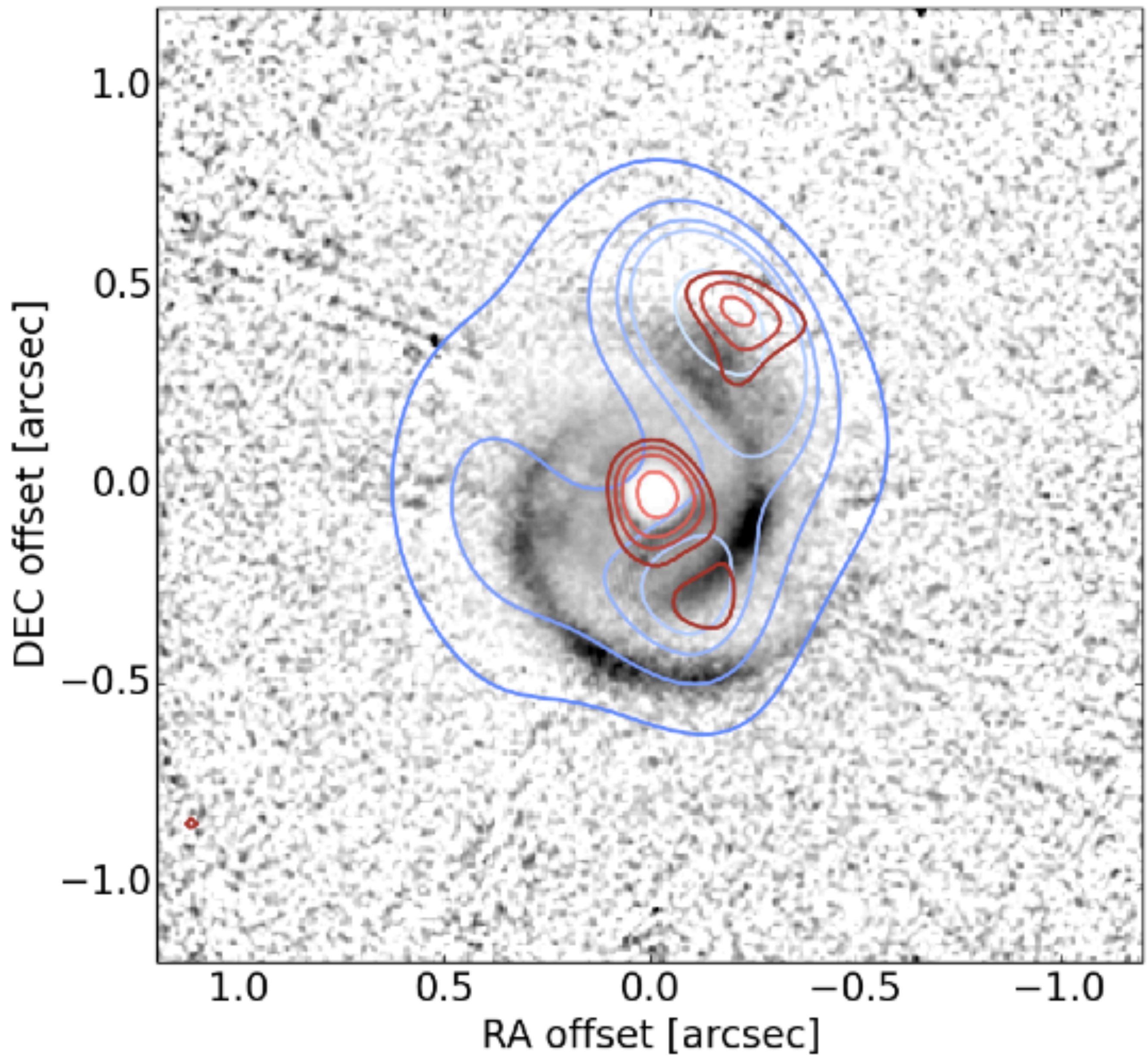
van der Marel et al. (2013)

SPHERE-ALMA-VLA overlay of MWC 758

SPHERE (μm)

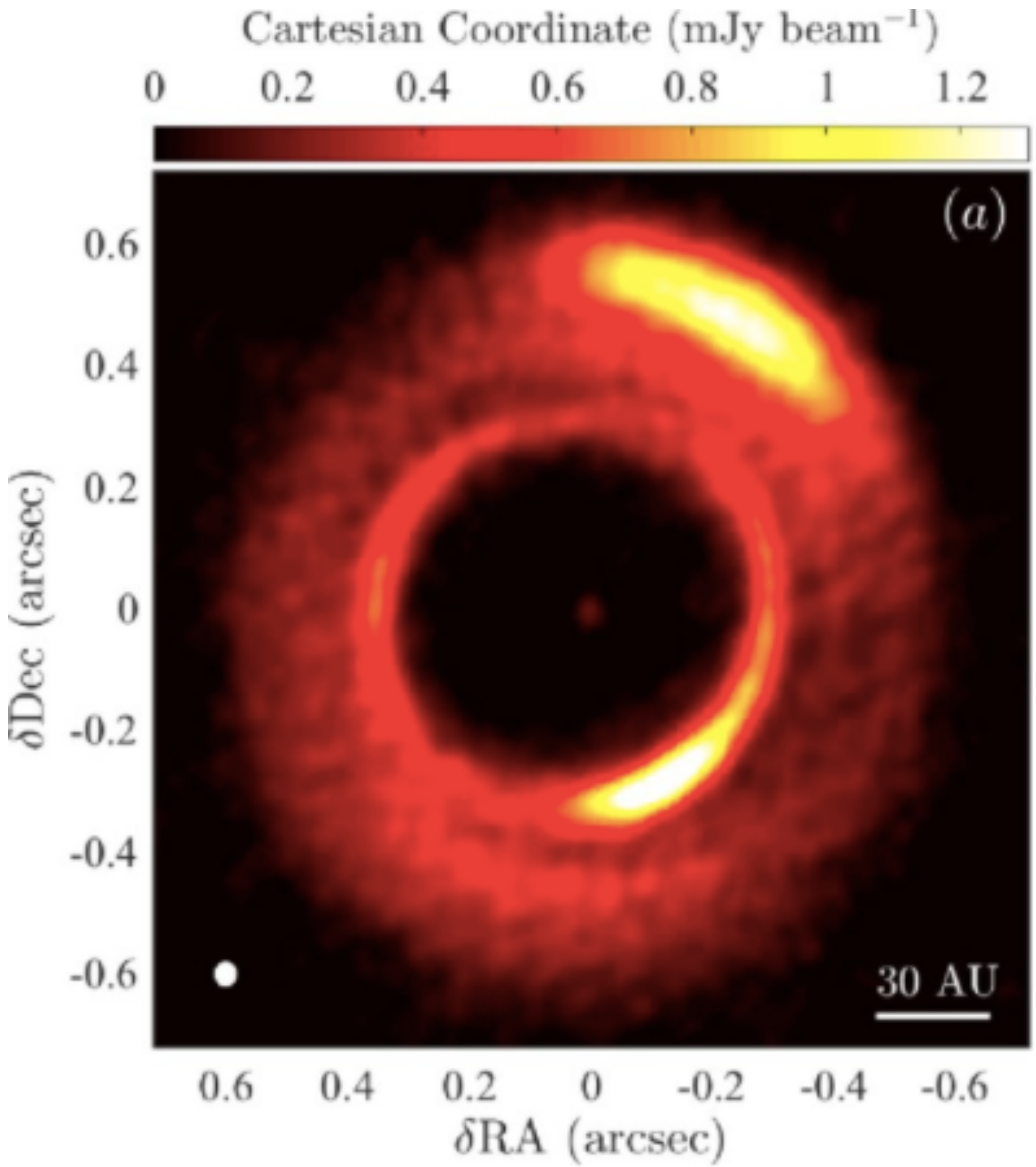
ALMA (~ mm)

VLA (cm-m)



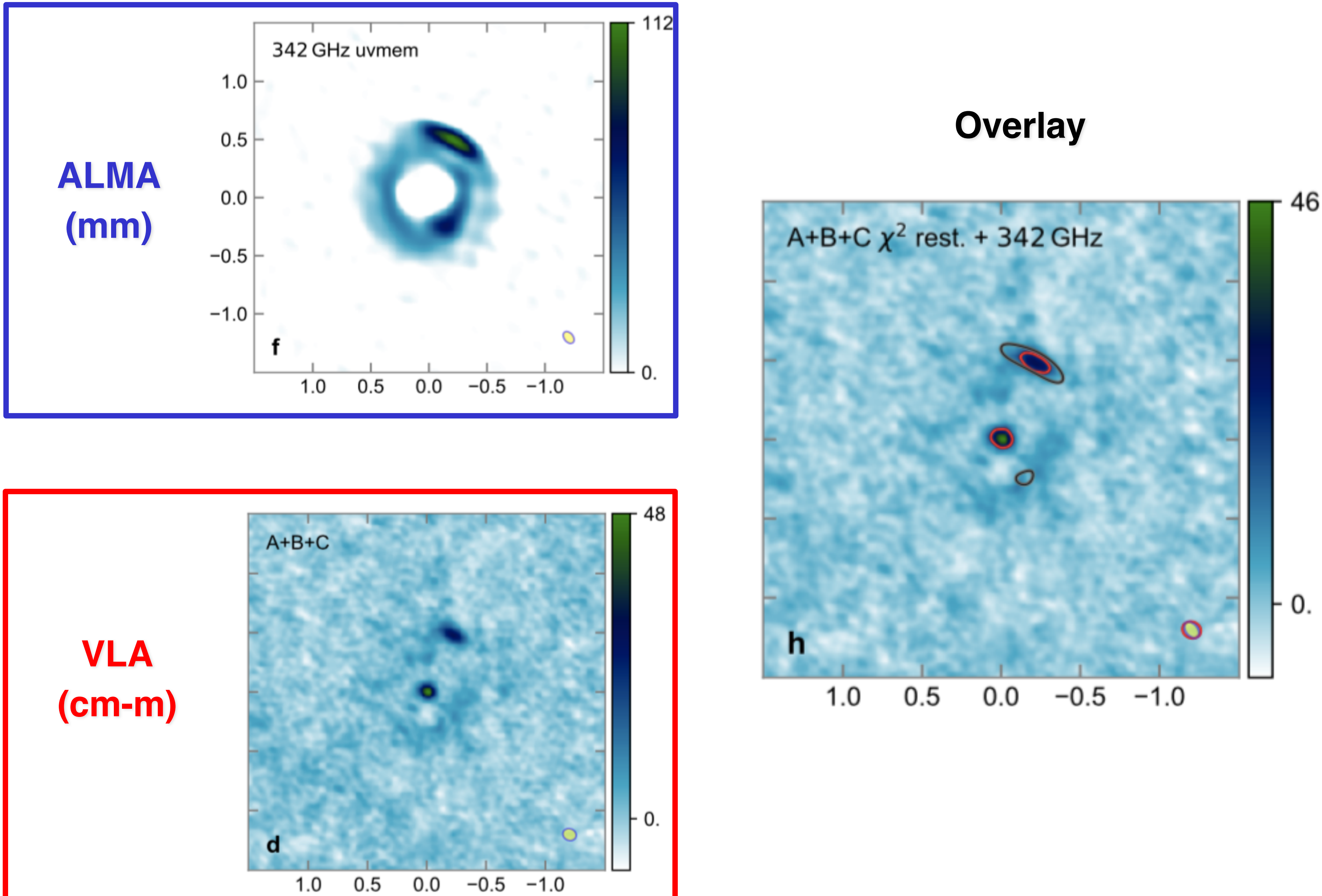
Marino et al. (2015)

MWC 758

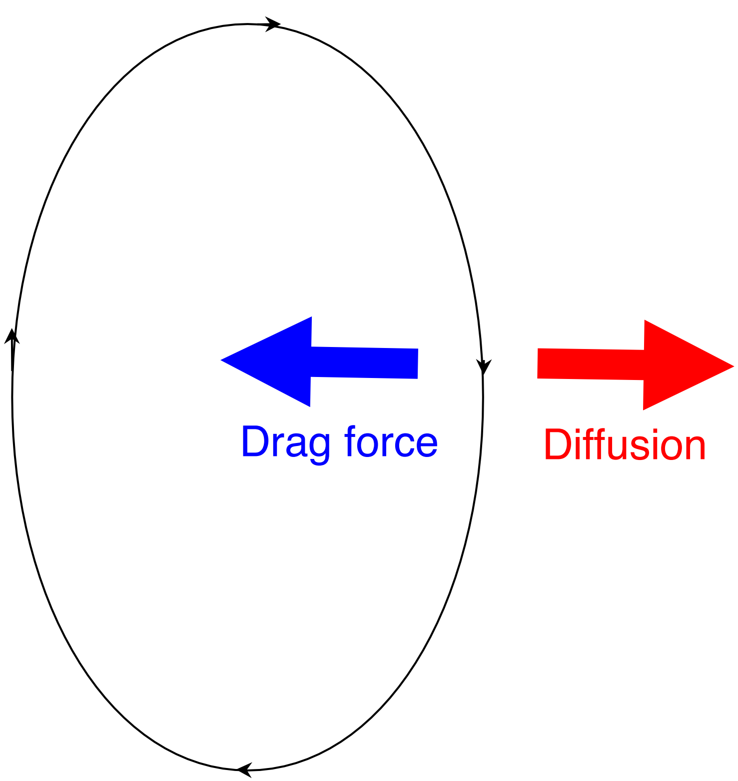


Cartesian Coordinate (mJy beam^{-1})
0
0.2
0.4
0.6
0.8
1
1.2
(a)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
δDec (arcsec)
30 AU
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
δRA (arcsec)

Pebble trapping



Drag-Diffusion Equilibrium



Trapped particle

Dust continuity equation

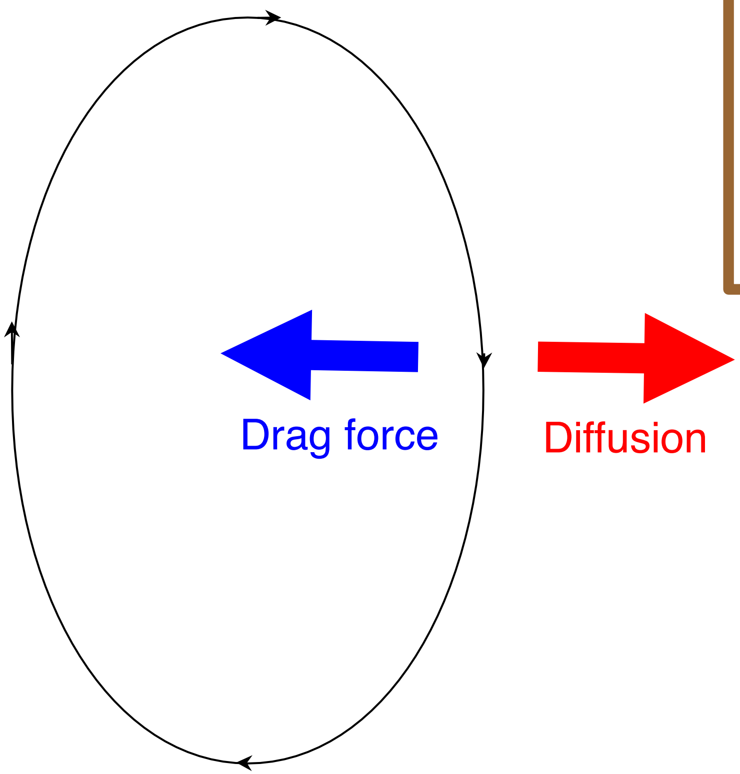
$$\frac{\partial \rho_d}{\partial t} = -(\boldsymbol{v} \cdot \boldsymbol{\nabla})\rho_d - \rho_d \boldsymbol{\nabla} \cdot \boldsymbol{v} + D\nabla^2 \rho_d,$$

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

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

diffusion — $D\nabla^2 \rho_d$

Drag-Diffusion Equilibrium



Trapped particle

Steady-state solution

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

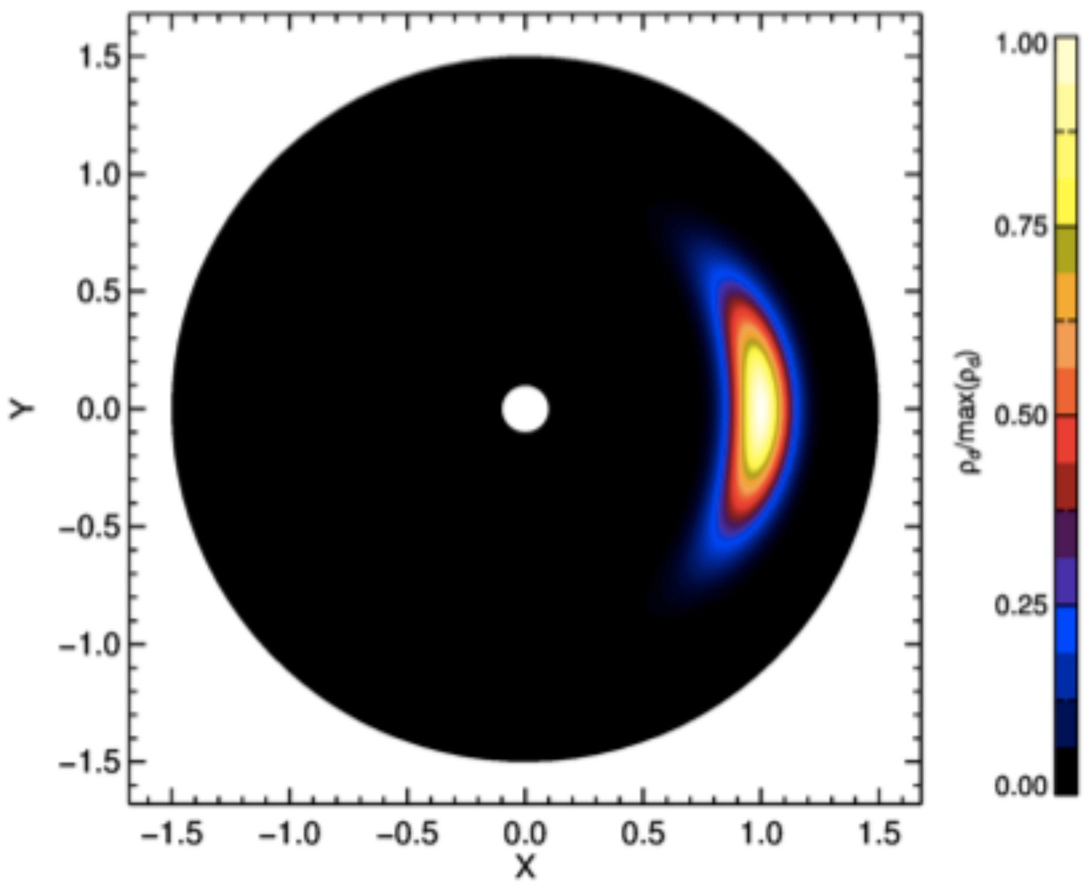
Lyra & Lin (2013)

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

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

a	= vortex semi-minor axis
H	= disk scale height (temperature)
χ	= vortex aspect ratio
δ	= diffusion parameter
St	= Stokes number (particle size)
$f(\chi)$	= model-dependent scale function

Analytical solution for dust in drag-diffusion equilibrium



Solution

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

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

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

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

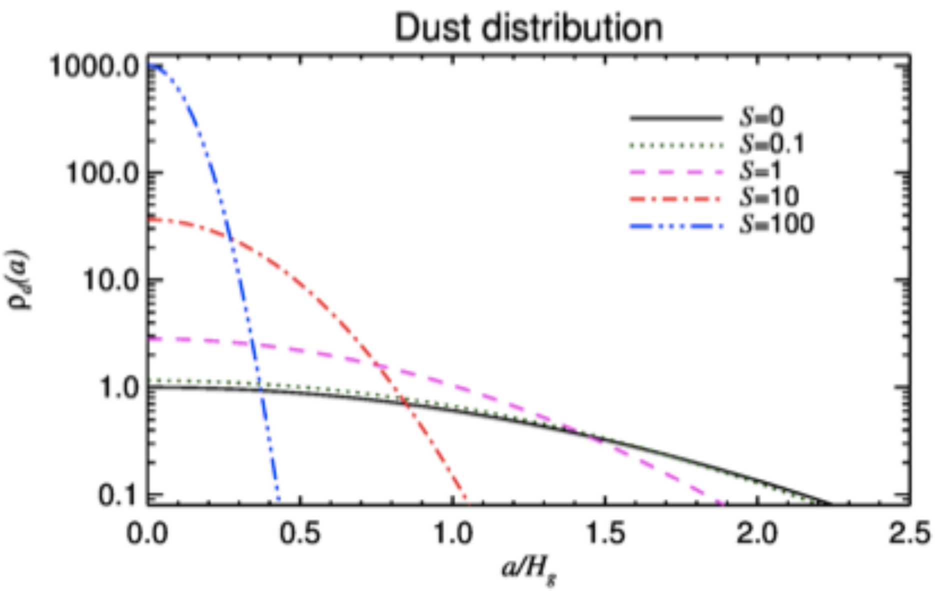
- a = distance to vortex center
- H = disk scale height (temperature)
- χ = vortex aspect ratio
- δ = diffusion parameter
- St = Stokes number (grain size)
- $f(\chi)$ = model-dependent scale function

Solution for

$H/r=0.1$ $\chi=4$ $S=1$

Lyra & Lin (2013)

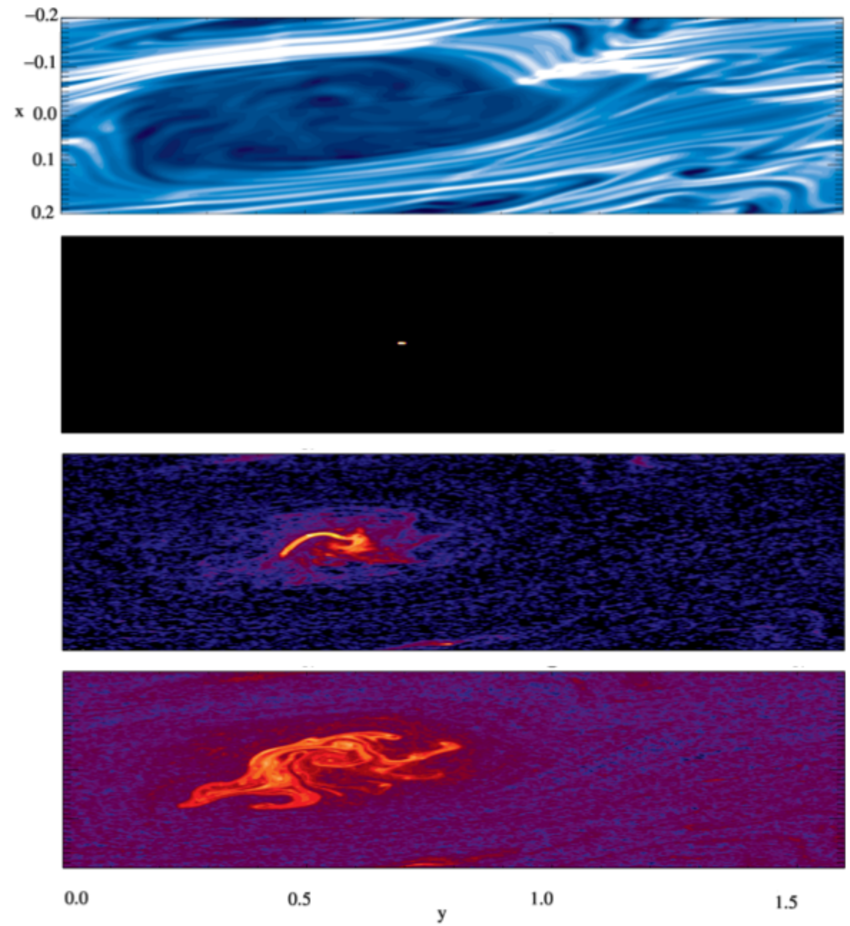
Analytical vs Numerical



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

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

Lyra & Lin (2013)



Gas

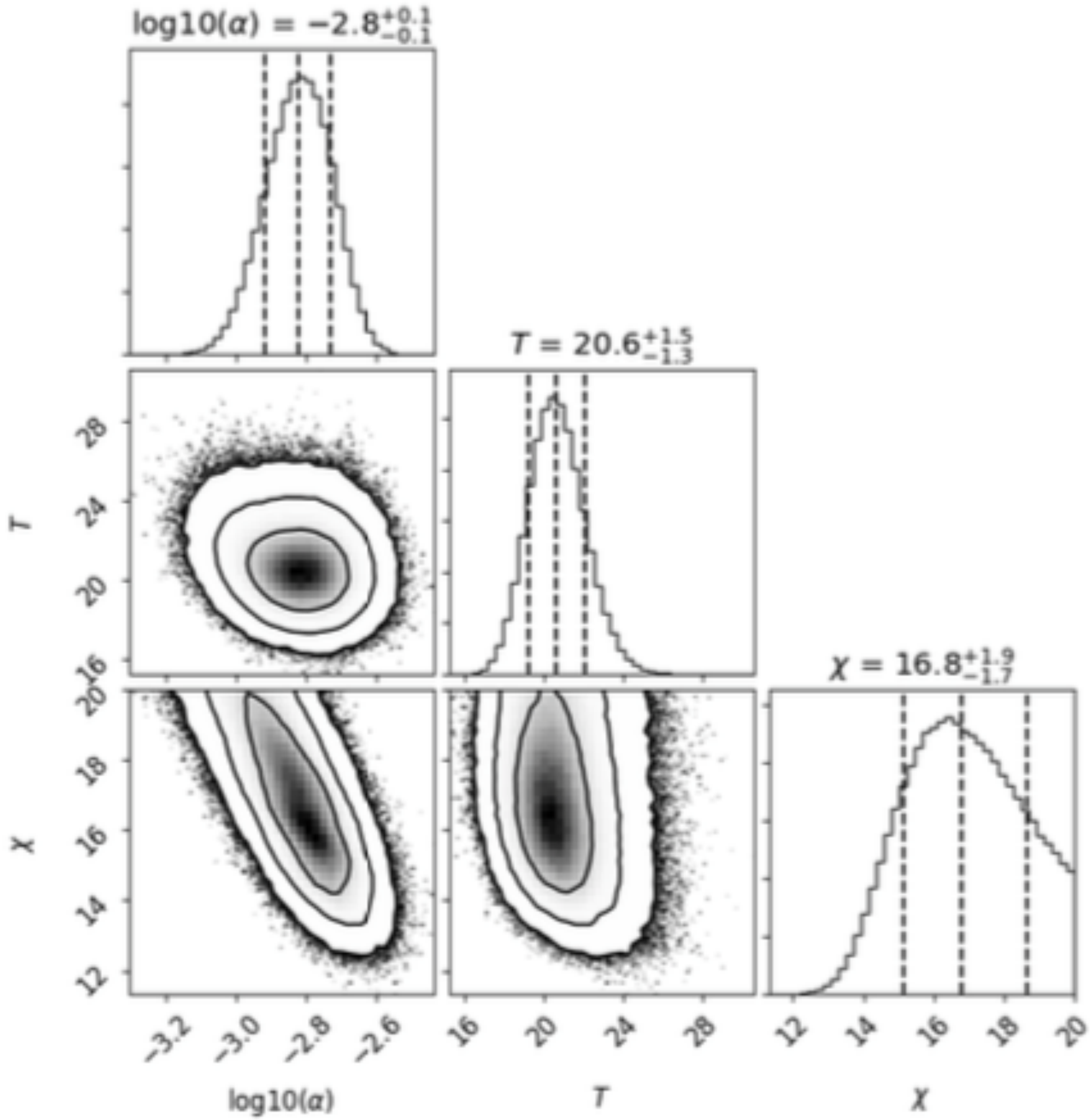
St=1

St=0.05

St=0.01

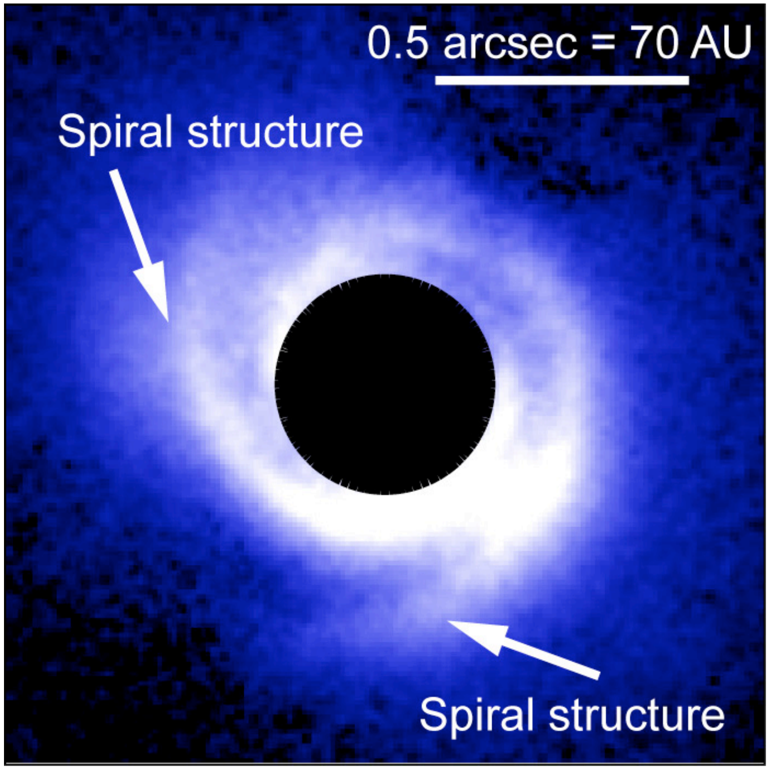
Raettig et al (2015)

Observational vs Analytical



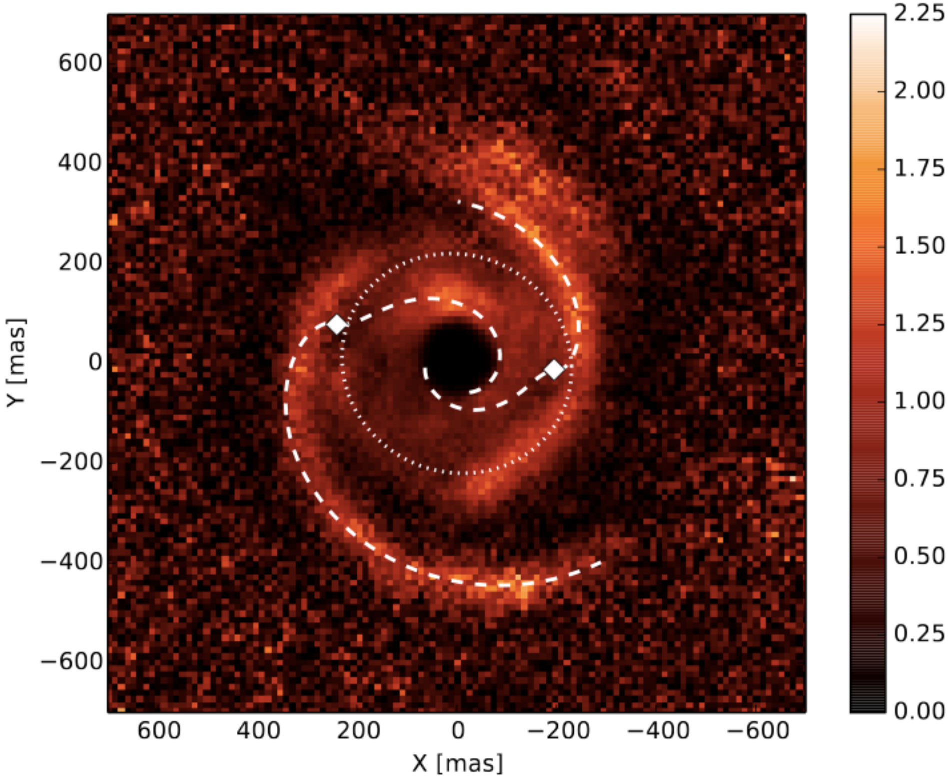
Observational Evidence: Spirals

SAO 206462



Muto et al. (2012)

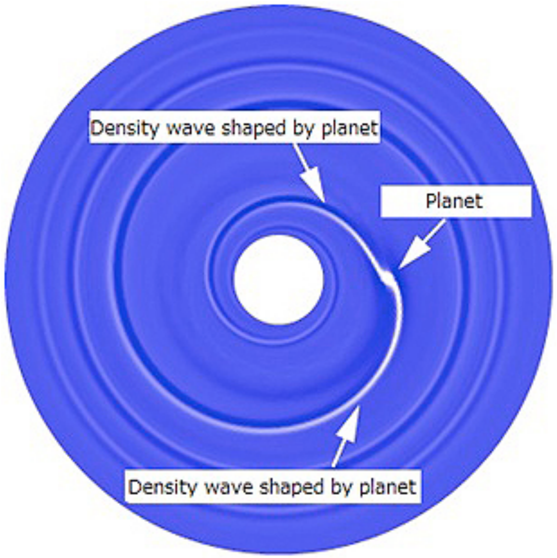
MWC 758



Benisty et al. (2015)

Spiral arm fitting leads to problems

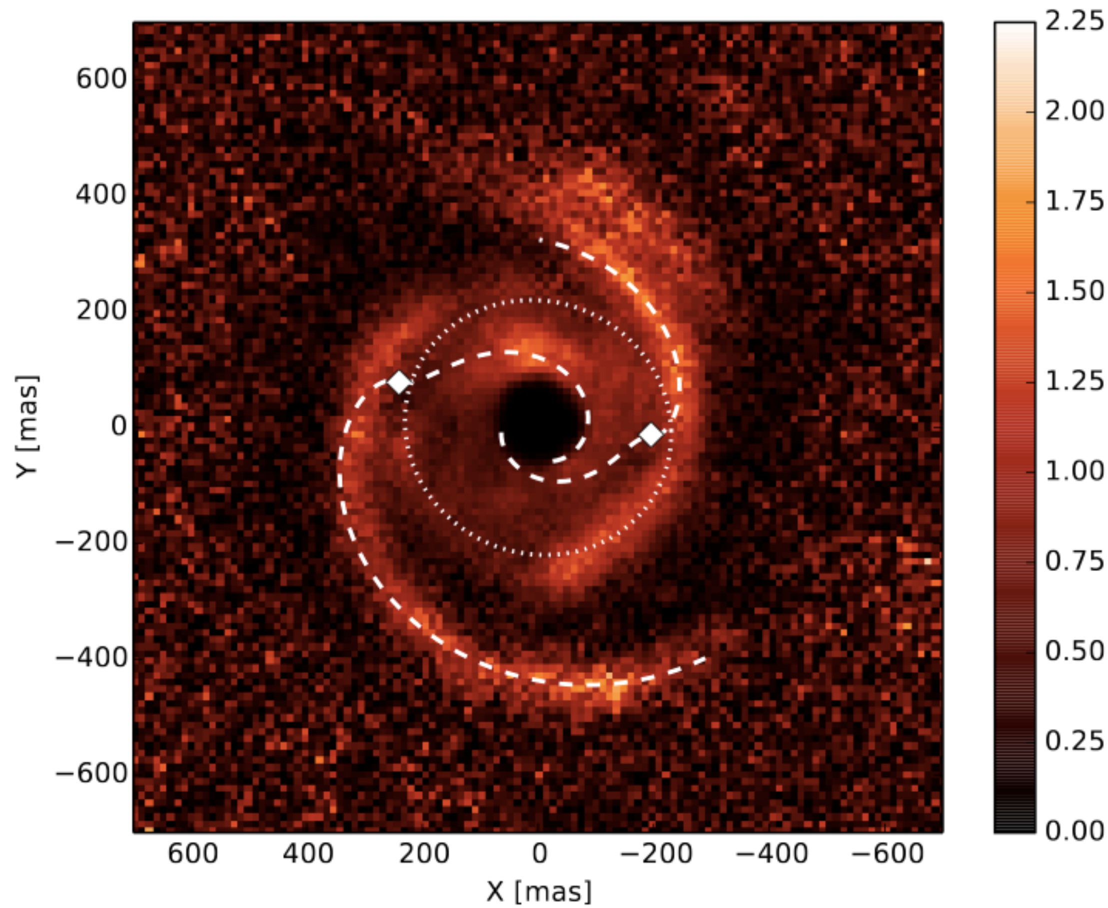
Analytical spiral fit



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

Rafikov (2002)
Muto et al. (2012)

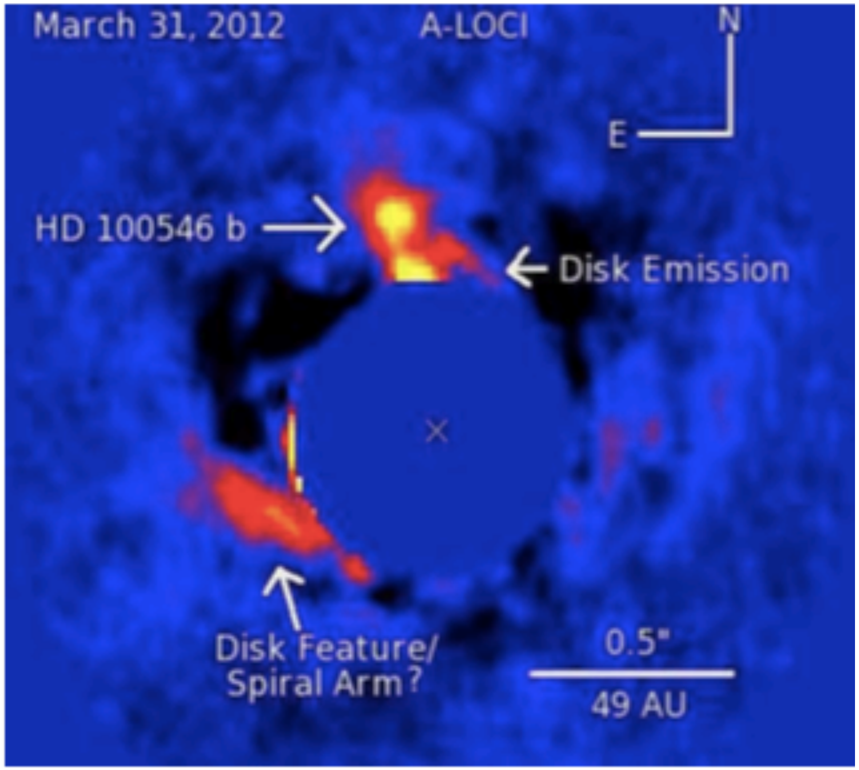
Spirals are **too wide**,
hotter (300K) than ambient gas (50K).



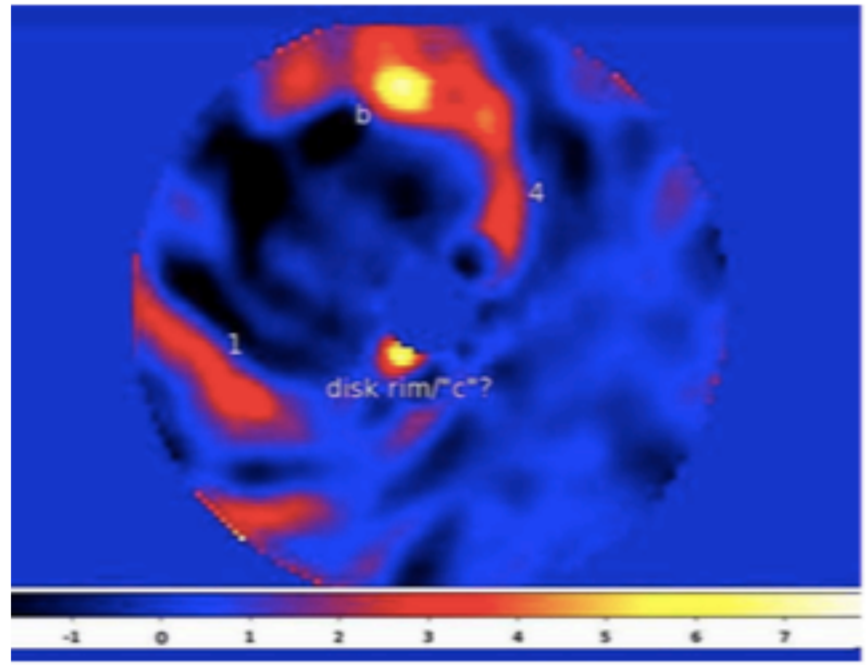
Benisty et al. (2015)

The strange case of thermal emission in HD 100546

L band (~3.5 μm)

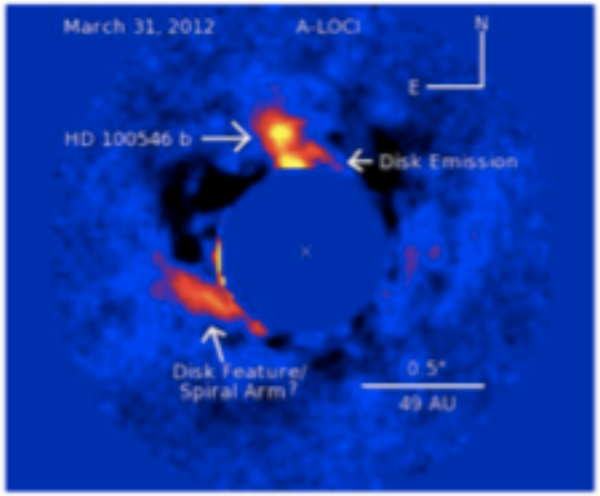


H band (~1.6 μm)

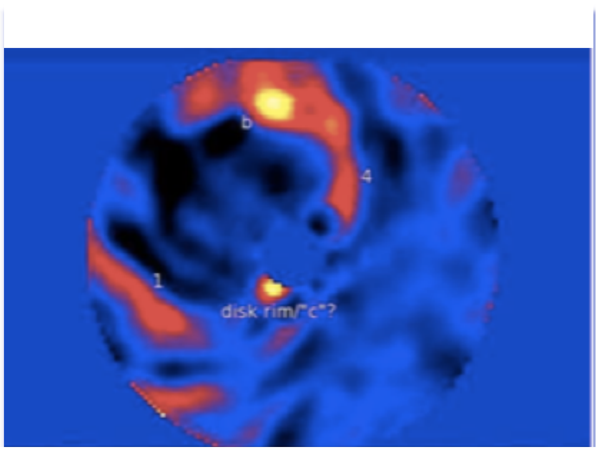


Currie et al. (2014), Currie et al. (2015)

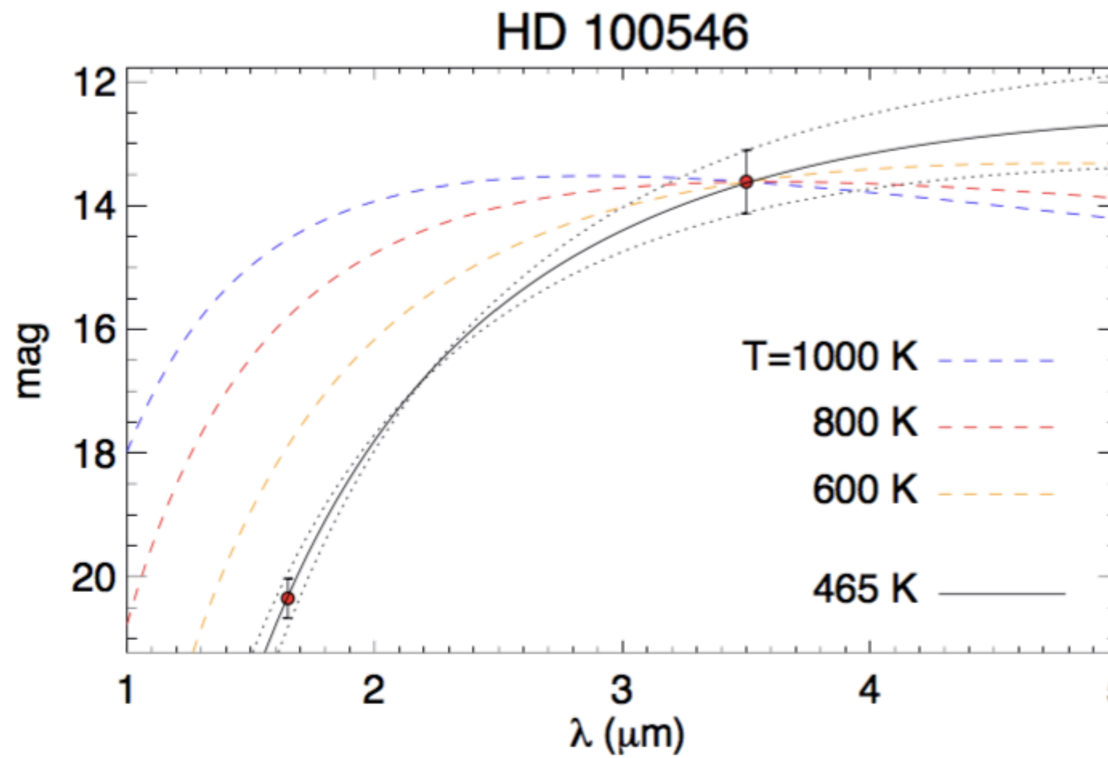
Pinning down the temperature



L band

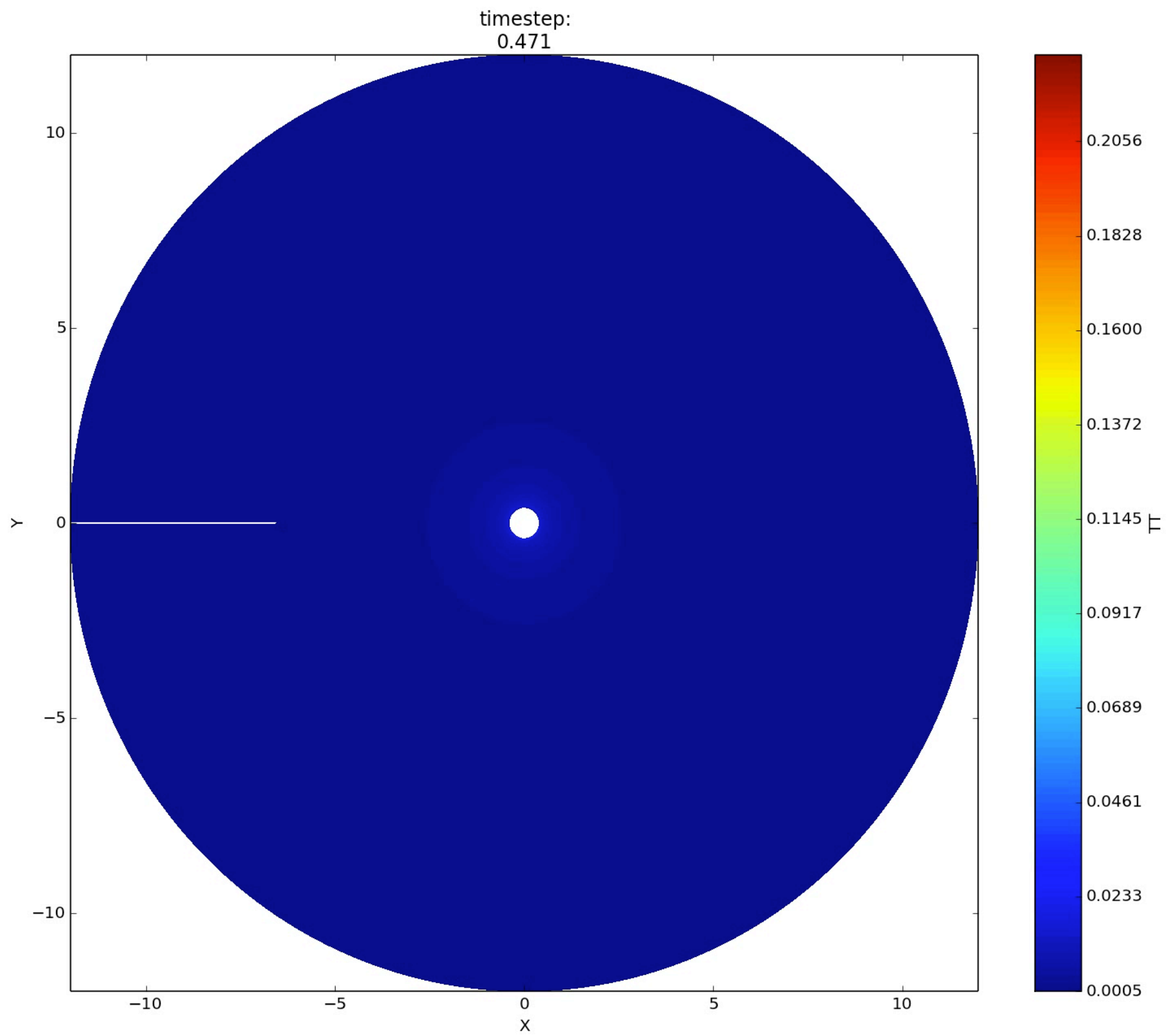


H band



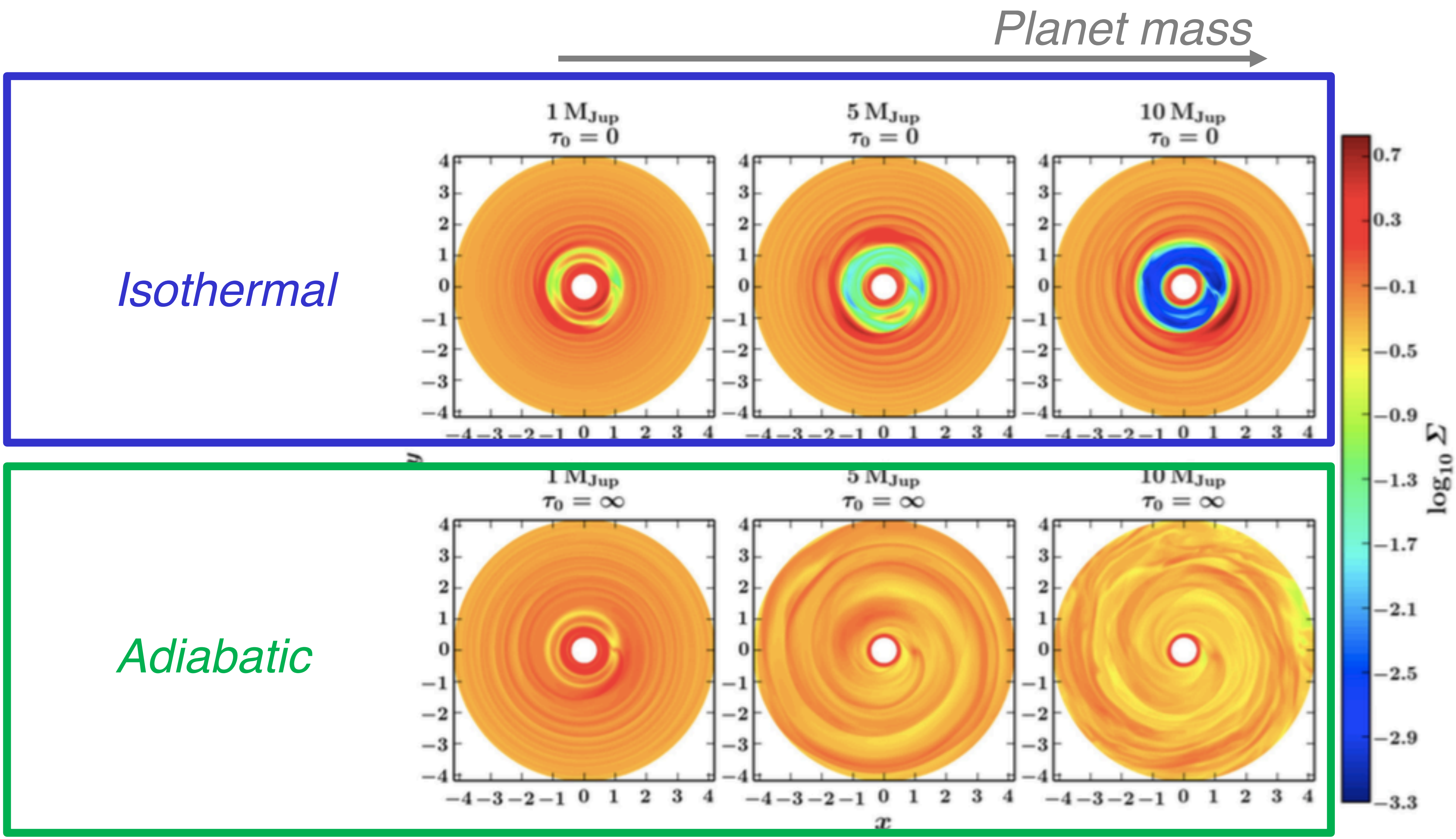
Lyra et al. (2016)

Planet-driven turbulence



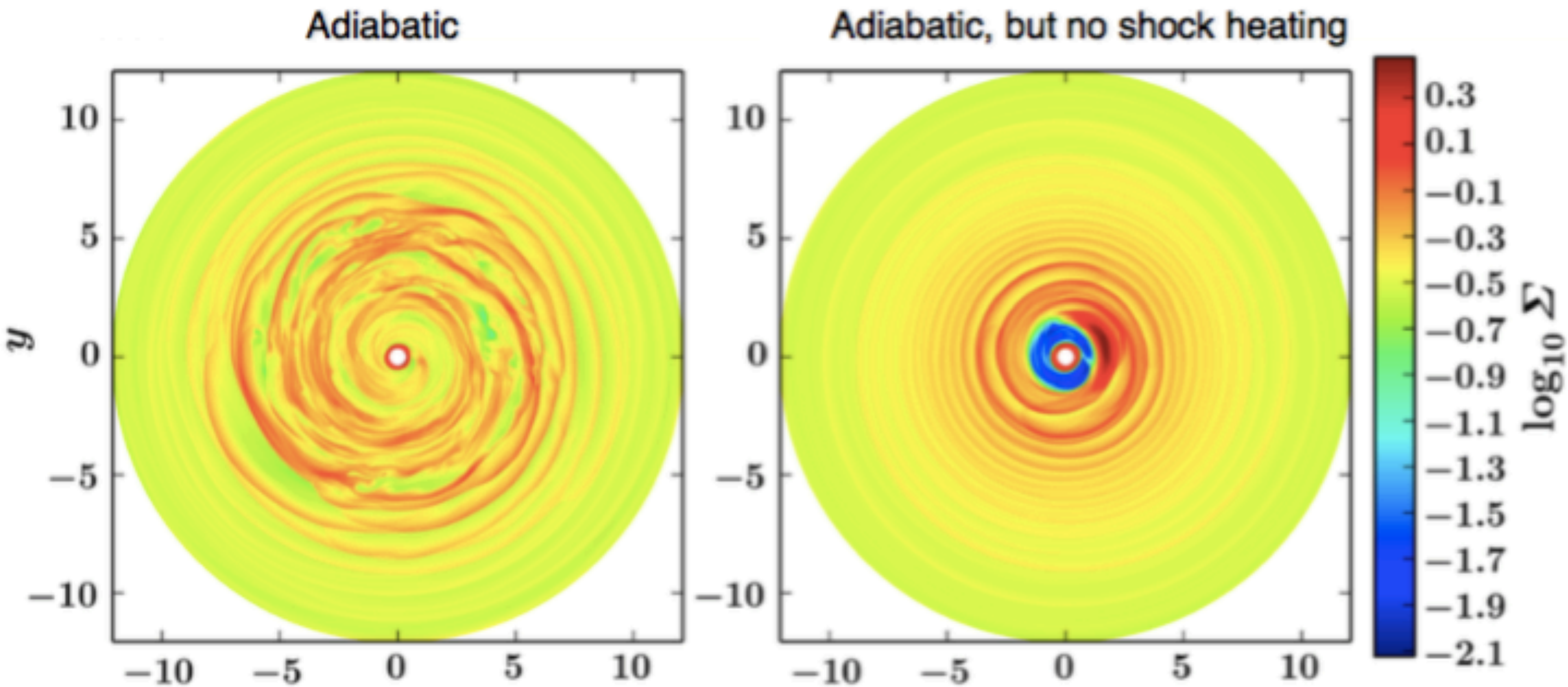
Richert et al. (2015)

Turbulence in high-mass planets in adiabatic disks



Richert et al. (2015)

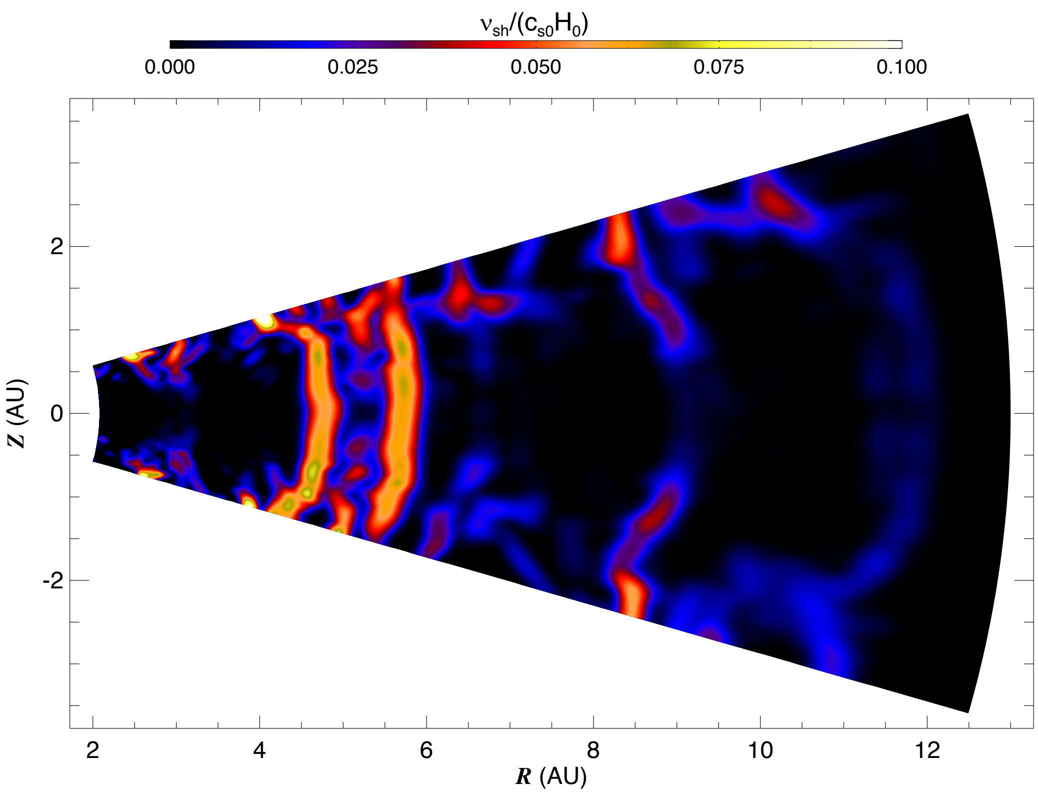
The energy source: shock heating!



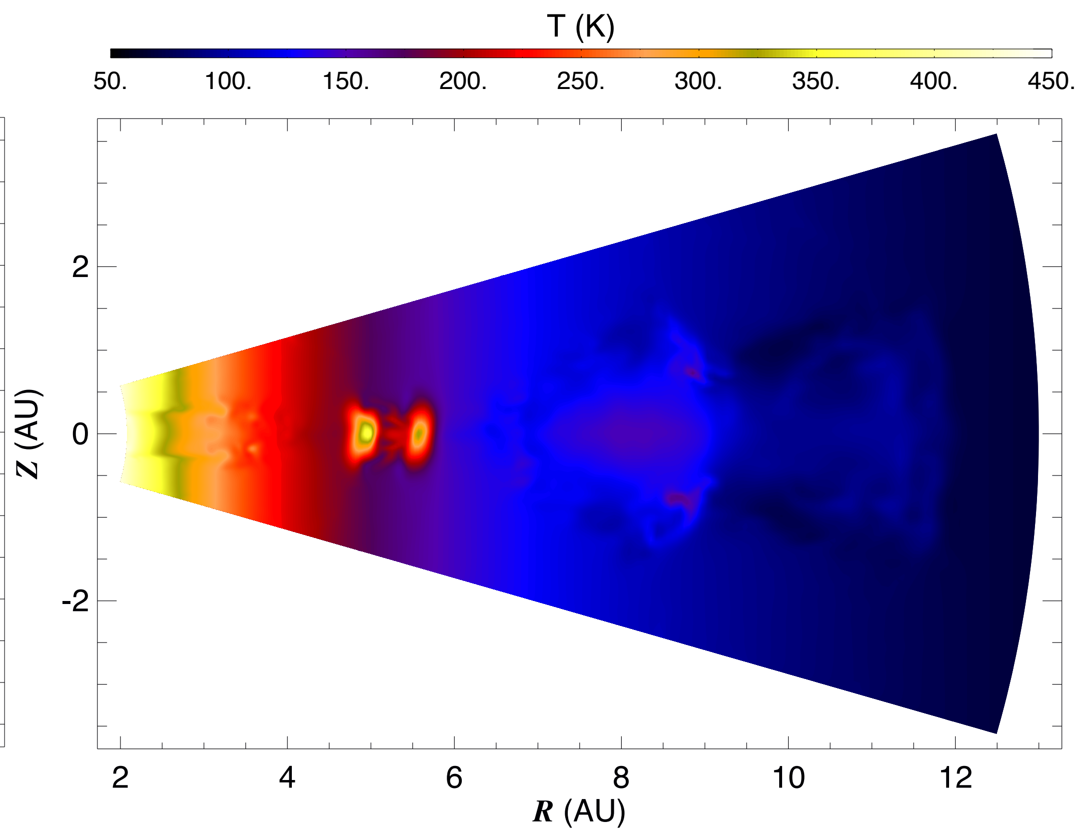
Richert et al. (2015)

3D: Shock bores

Shocks (velocity convergence)

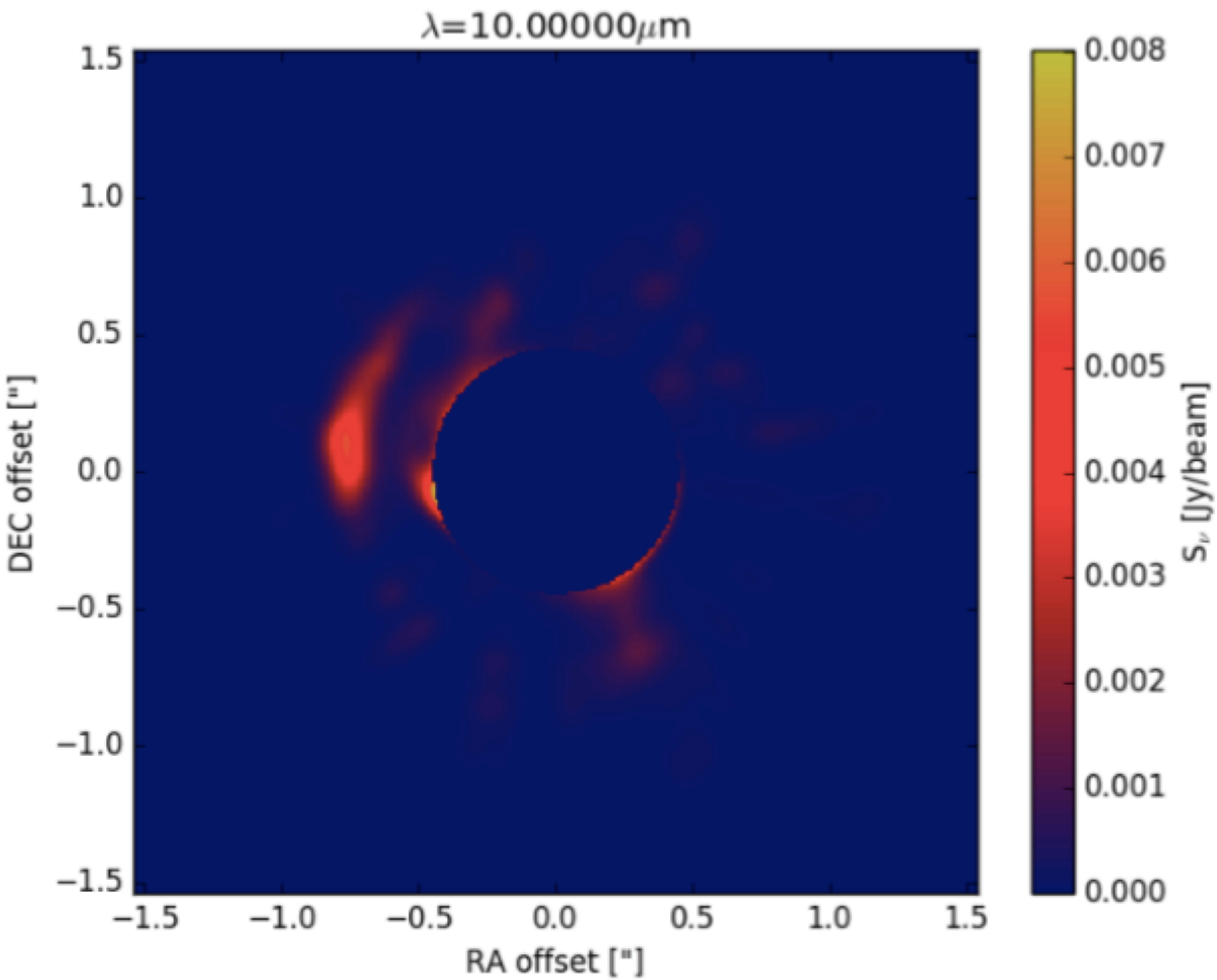


Temperature



Lyra et al. (2016)

Synthetic image by RADMC3D and shock heating

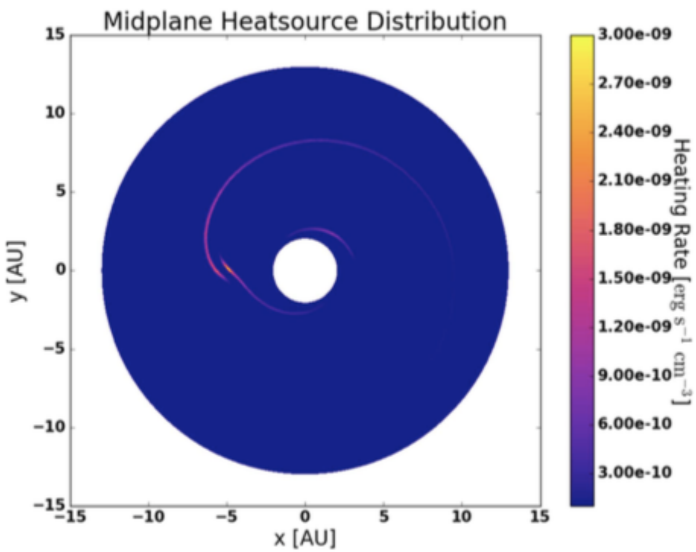


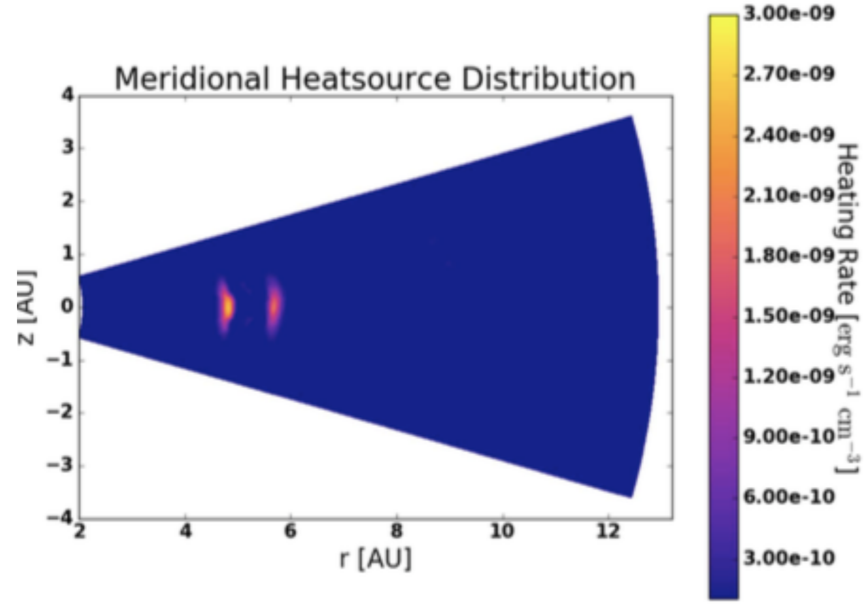
Hord et al. (2017)

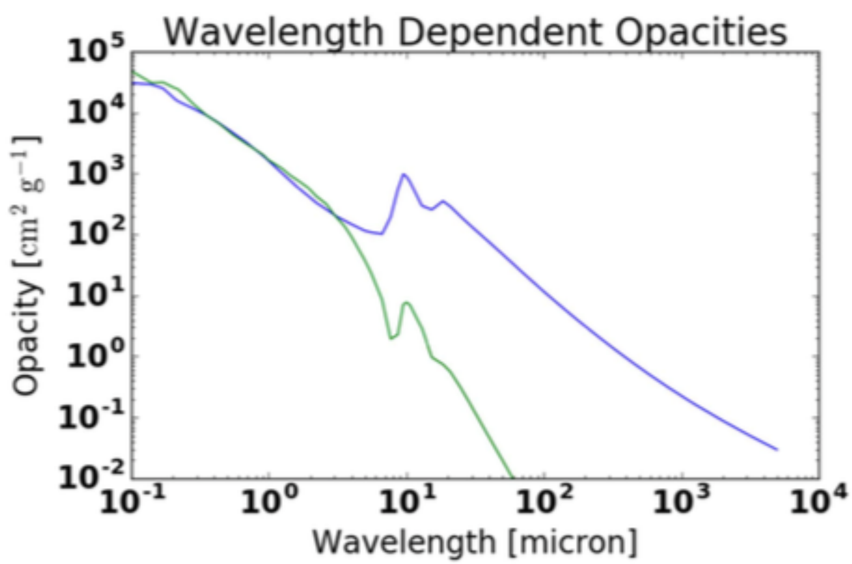
Shock heating and opacities

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

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







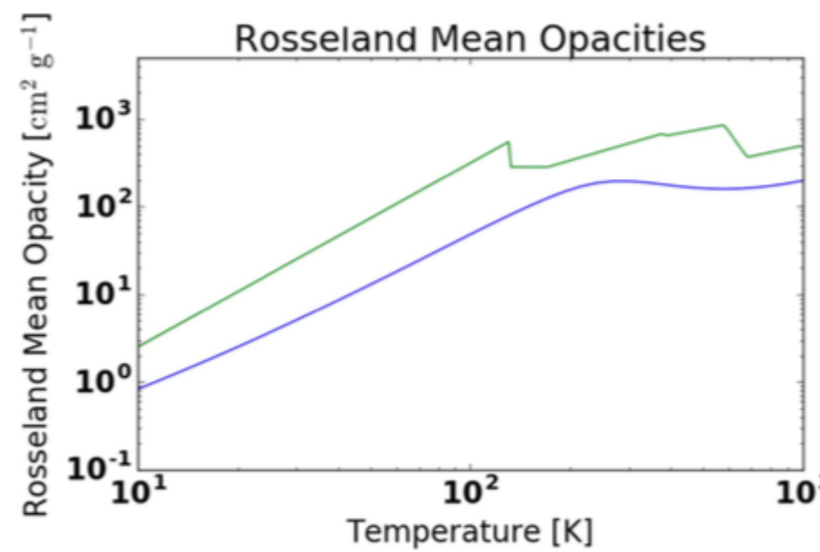
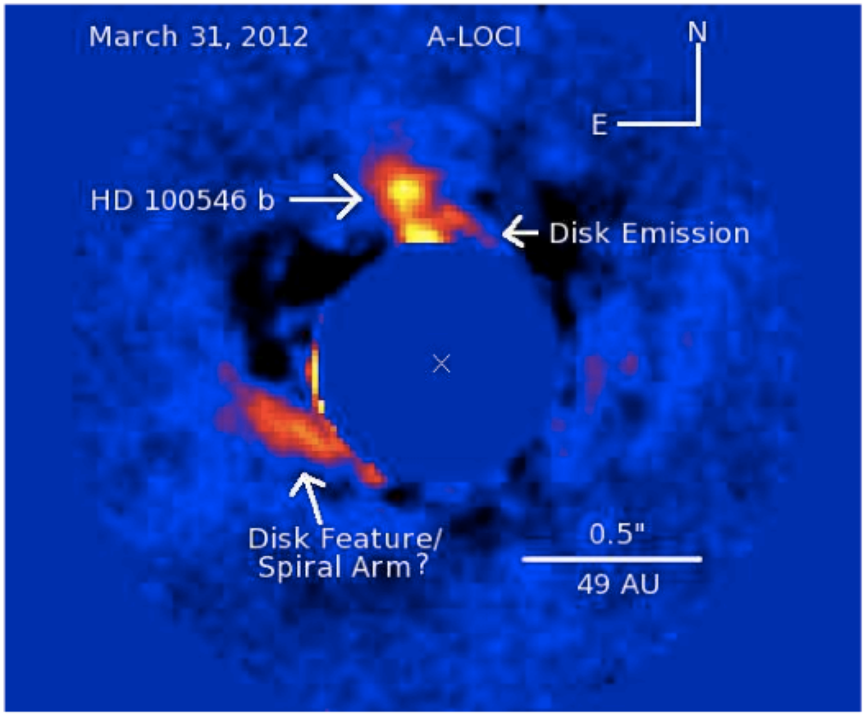
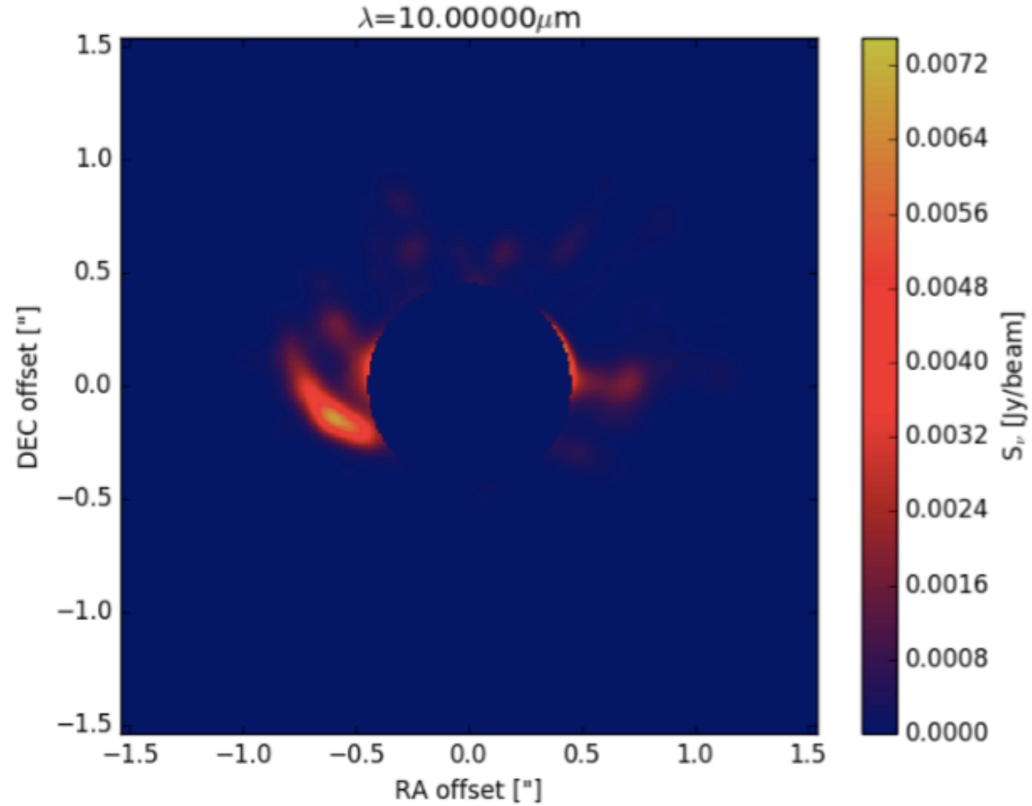


Figure 1. Wavelength-dependent opacities from Preibisch et al. (1993), including the absorption (top, blue) and scattering (top, green) opacities, input into RADMC-3D. The calculated Rosseland mean opacities (bottom, blue) match the Rosseland mean of Bell et al. (1997). The piece-wise Rosseland Mean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

Observation vs Synthetic Image

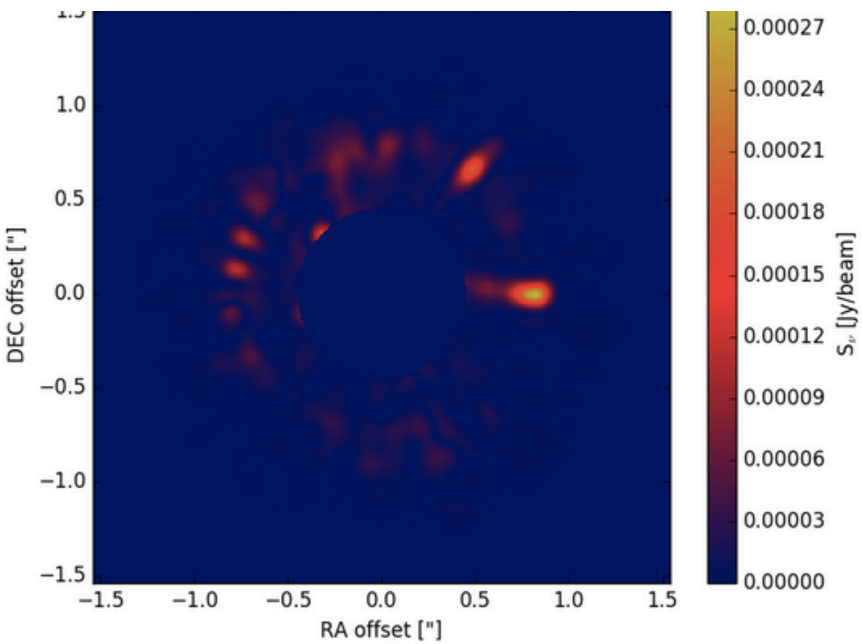




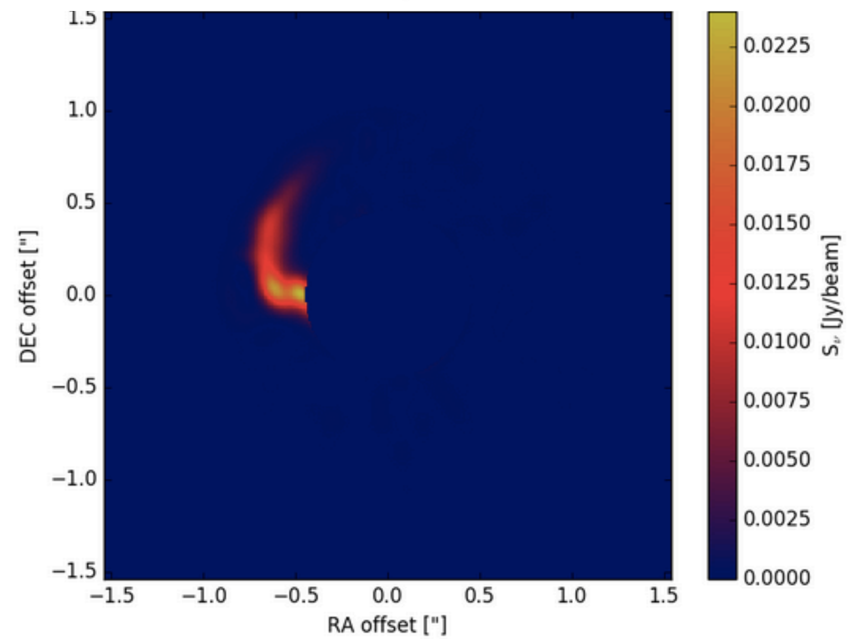
Hord et al. (2017)

Effect of shocks alone

1 μm

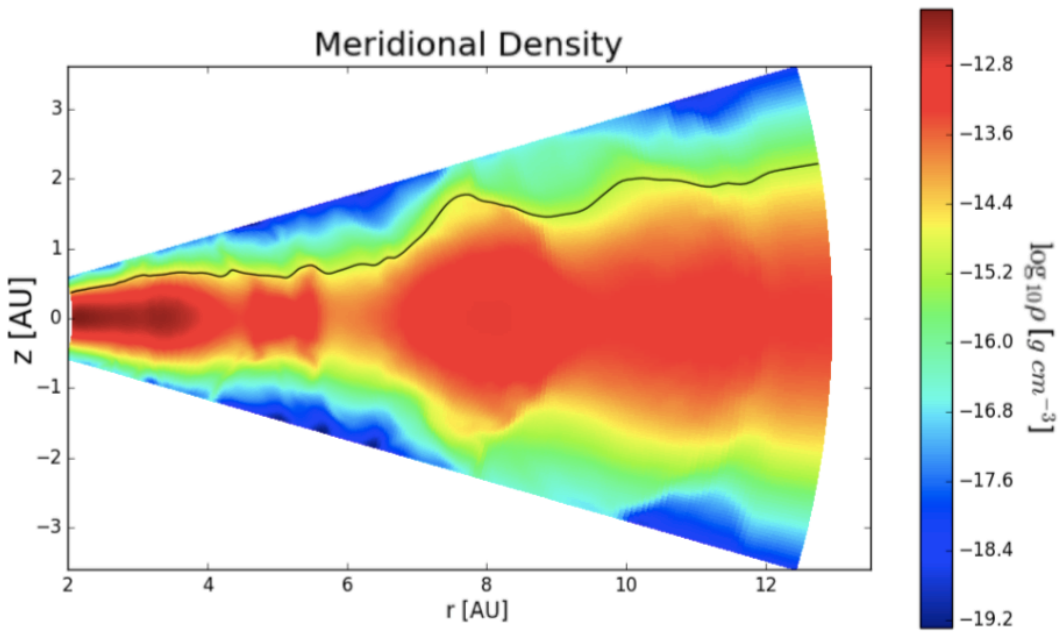


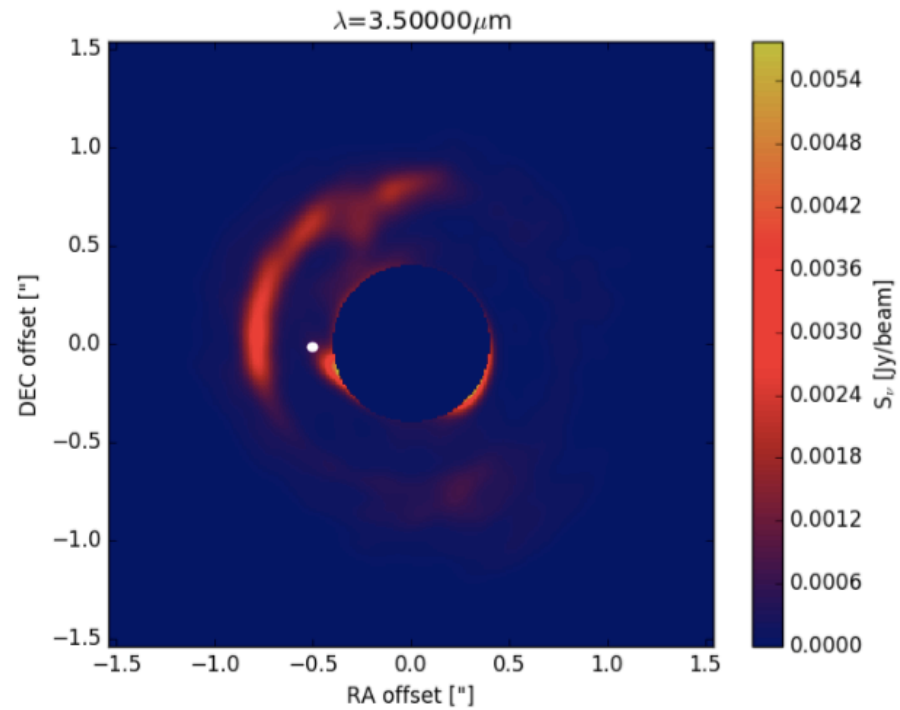
10 μm



Hord et al. (2017)

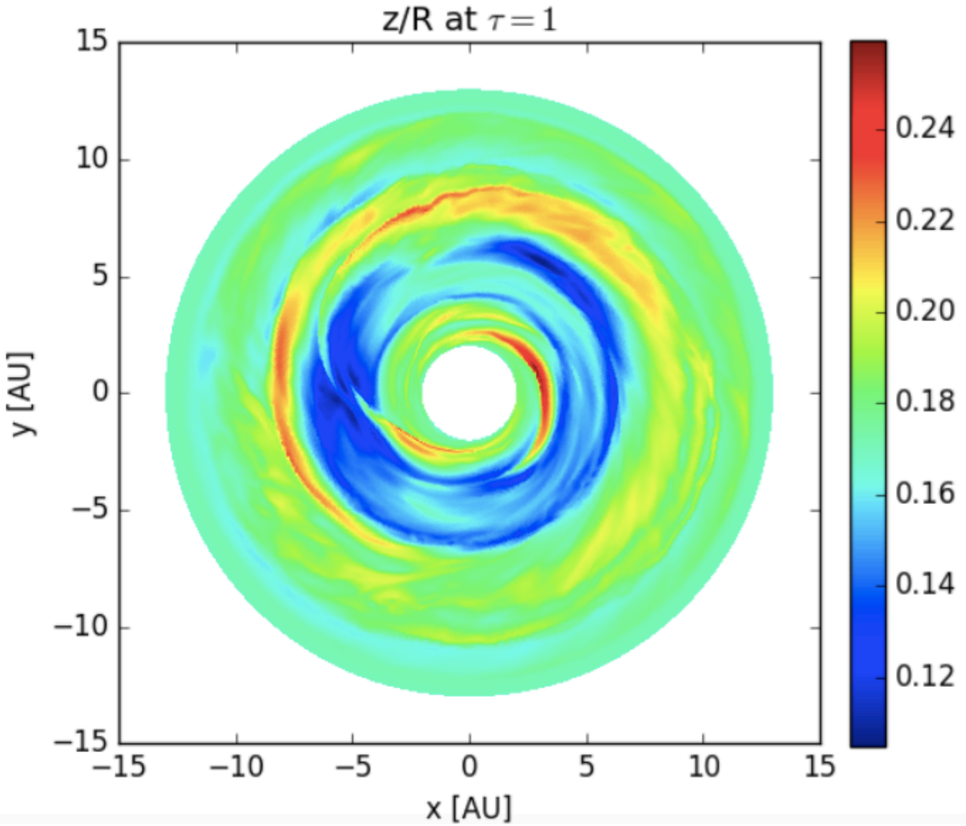
Scattering – A puffed up outer gap

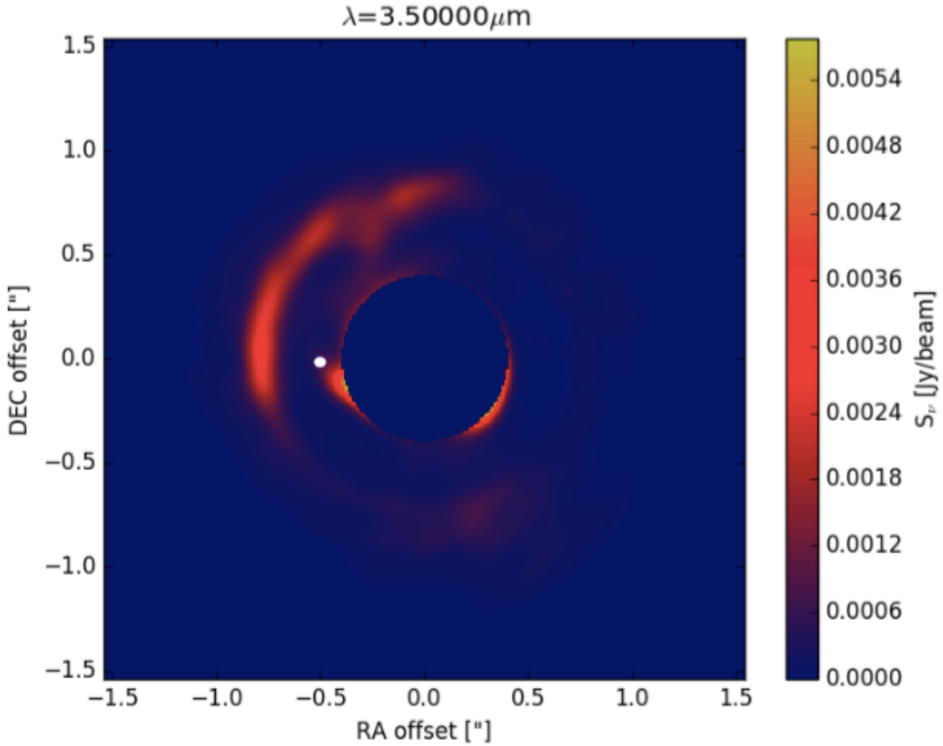




Hord et al. (2017)

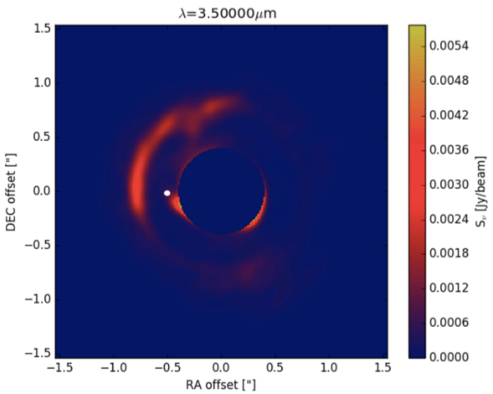
Scattering

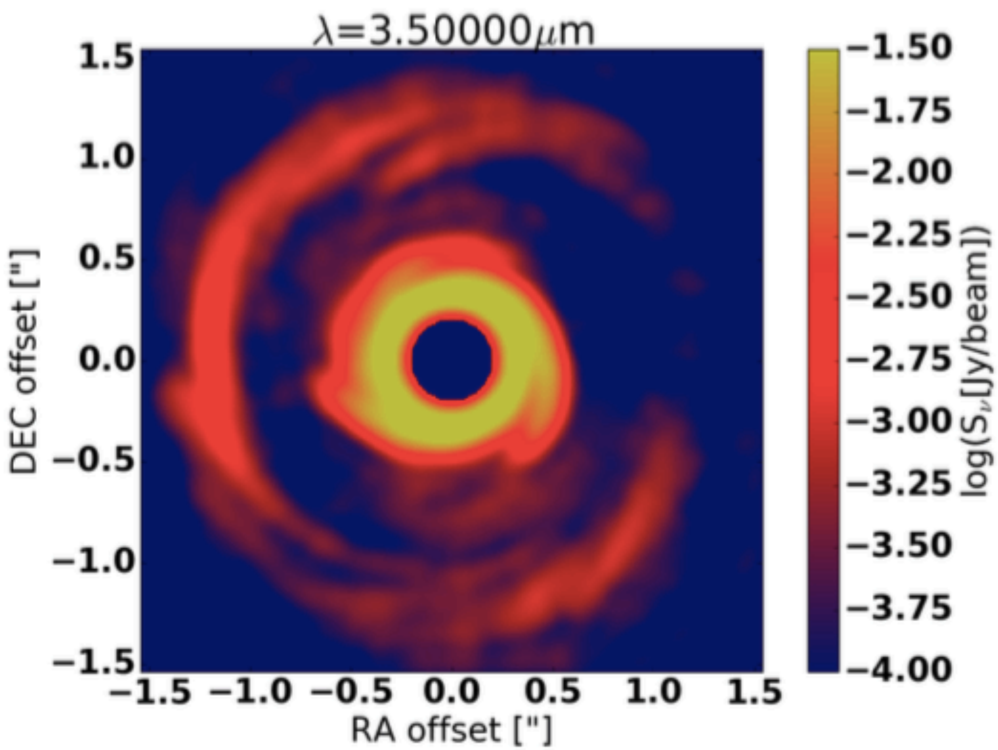


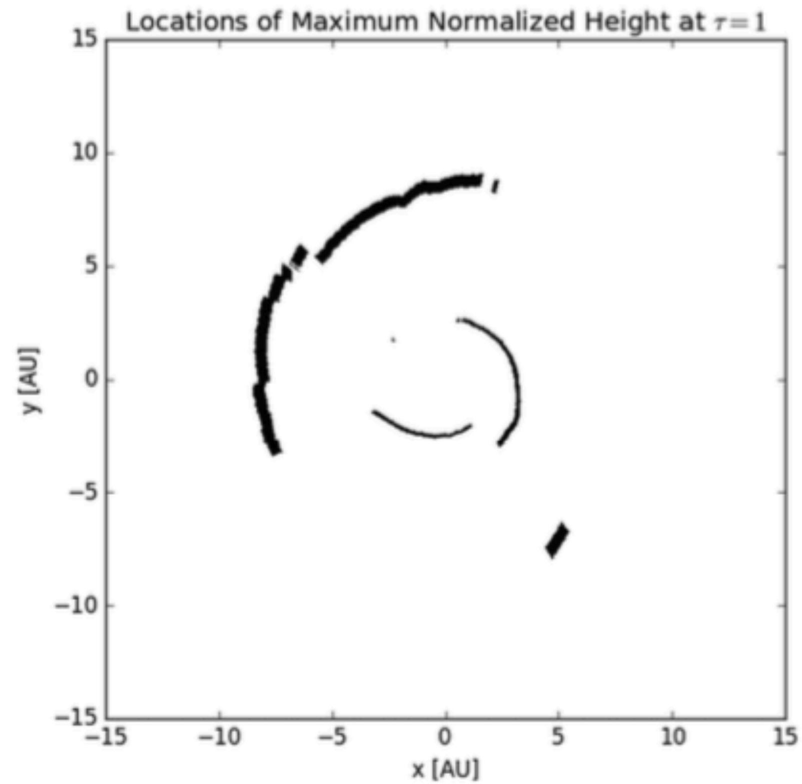


Hord et al. (2017)

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





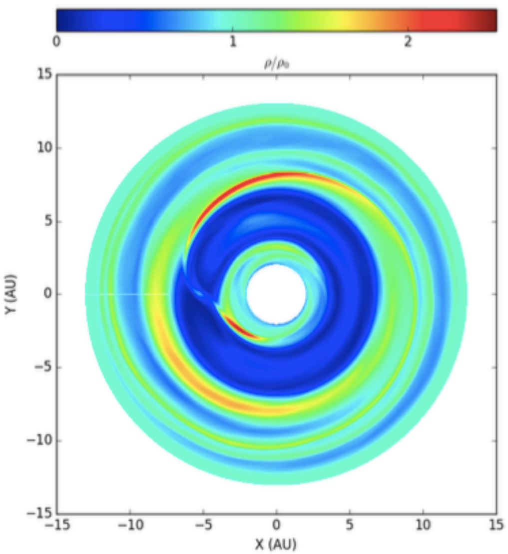


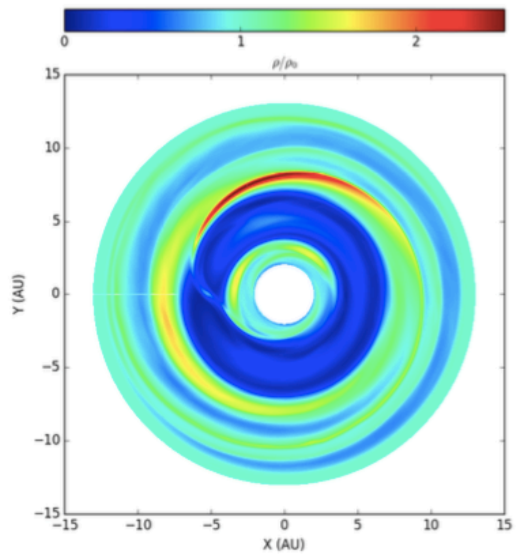
Hord et al. (2017)

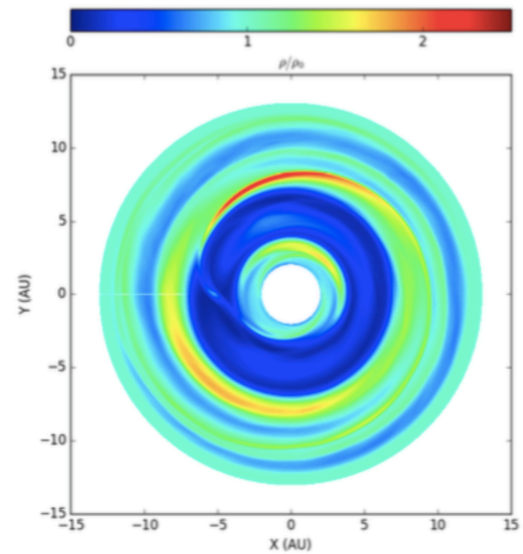
The pattern is stationary

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

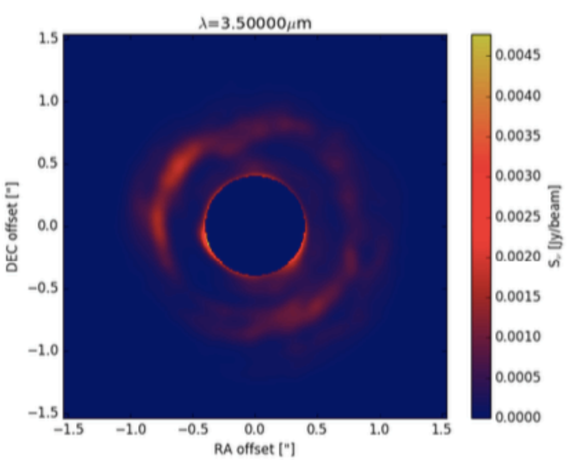
Density

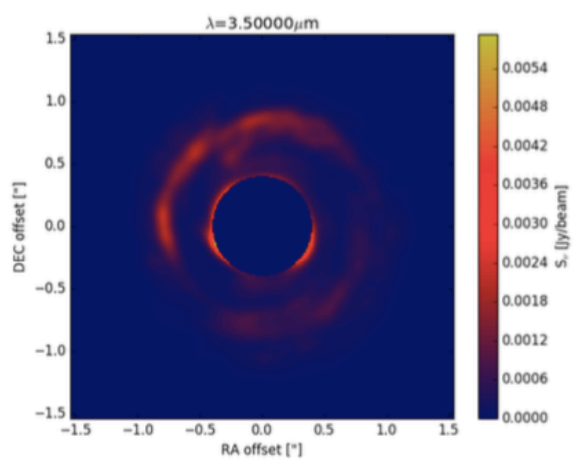


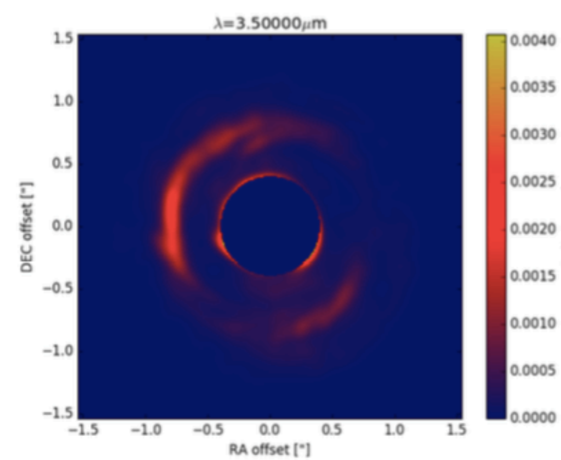




Intensity

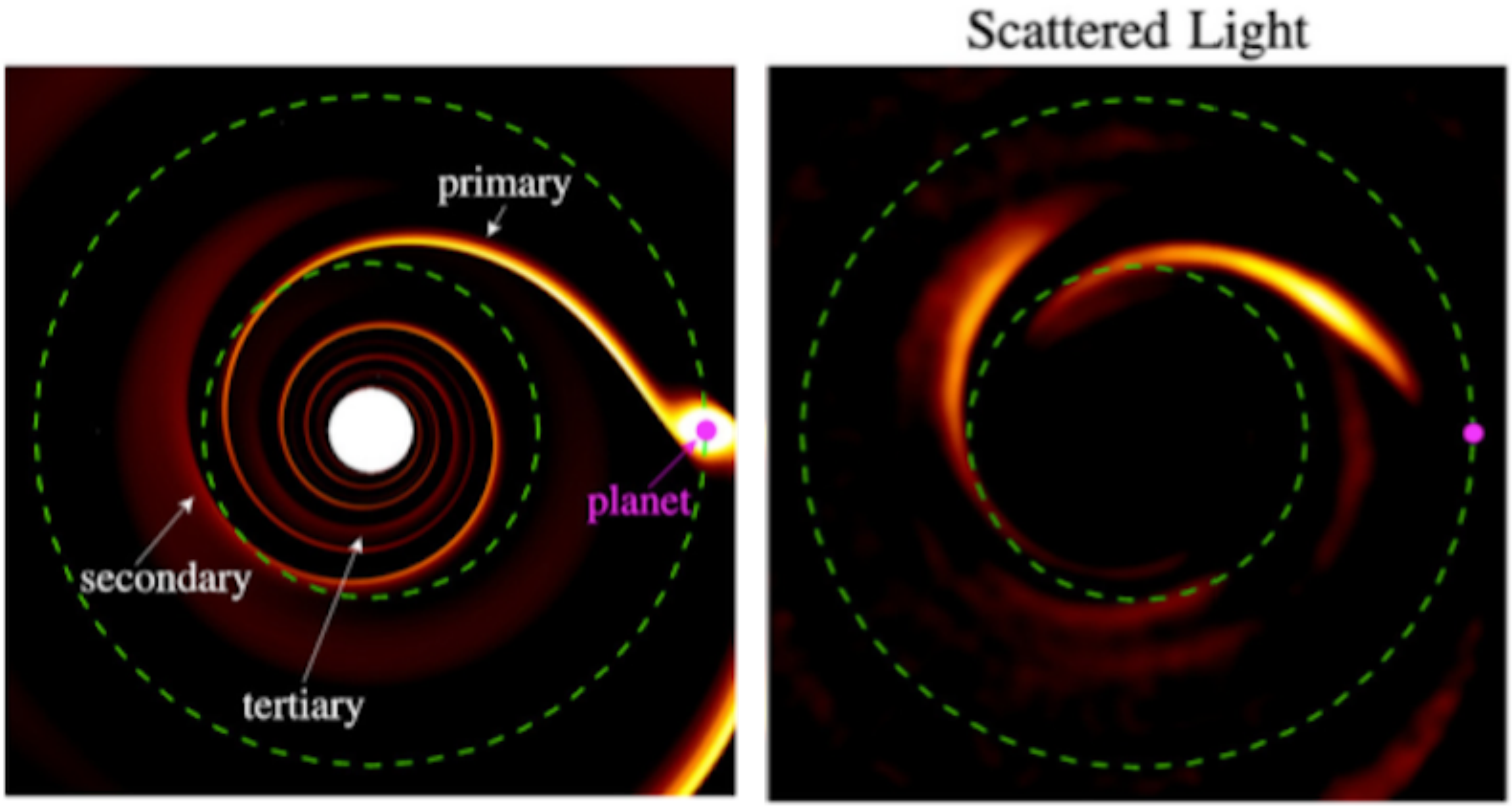






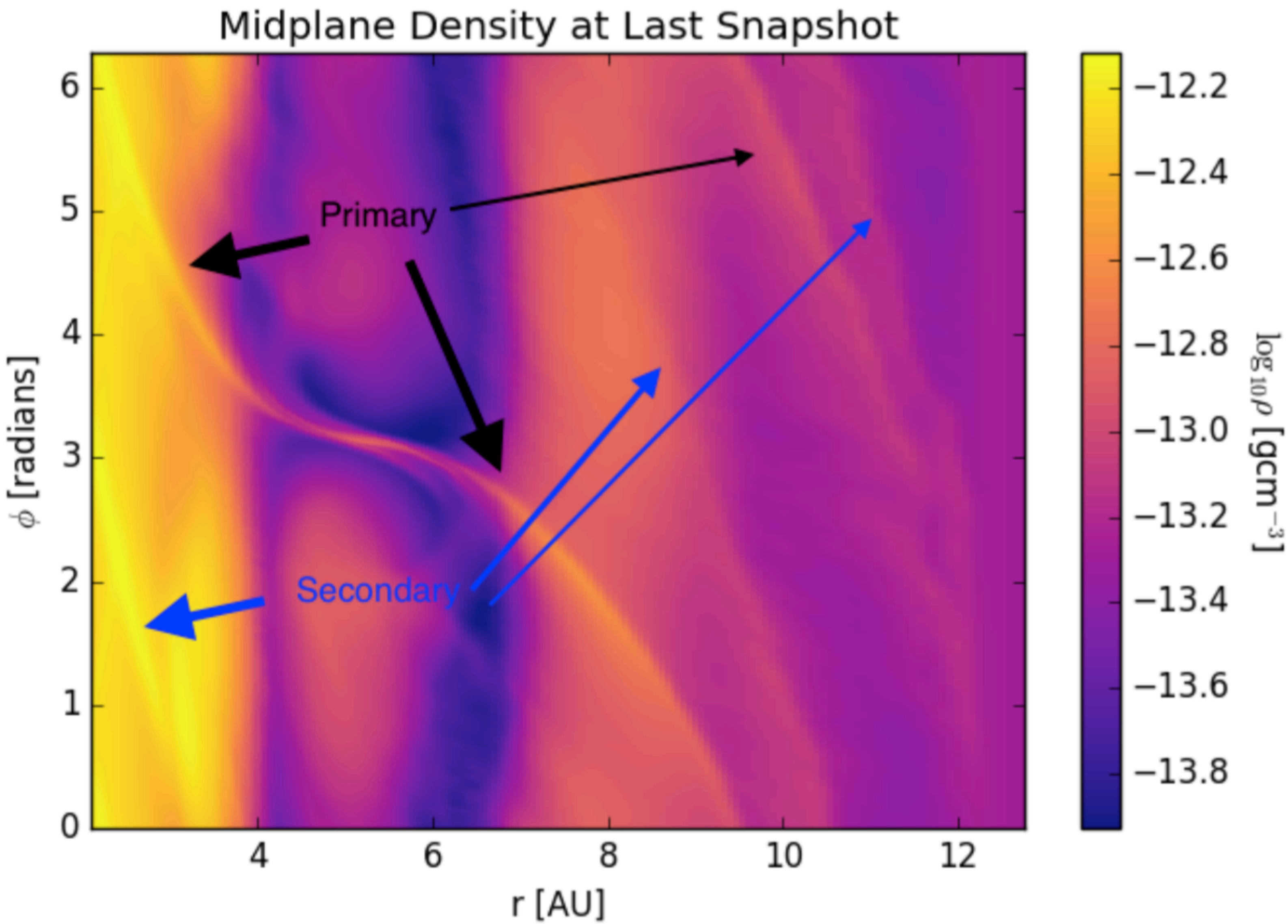
Hord et al. (2017)

Primary and Secondary spiral arms



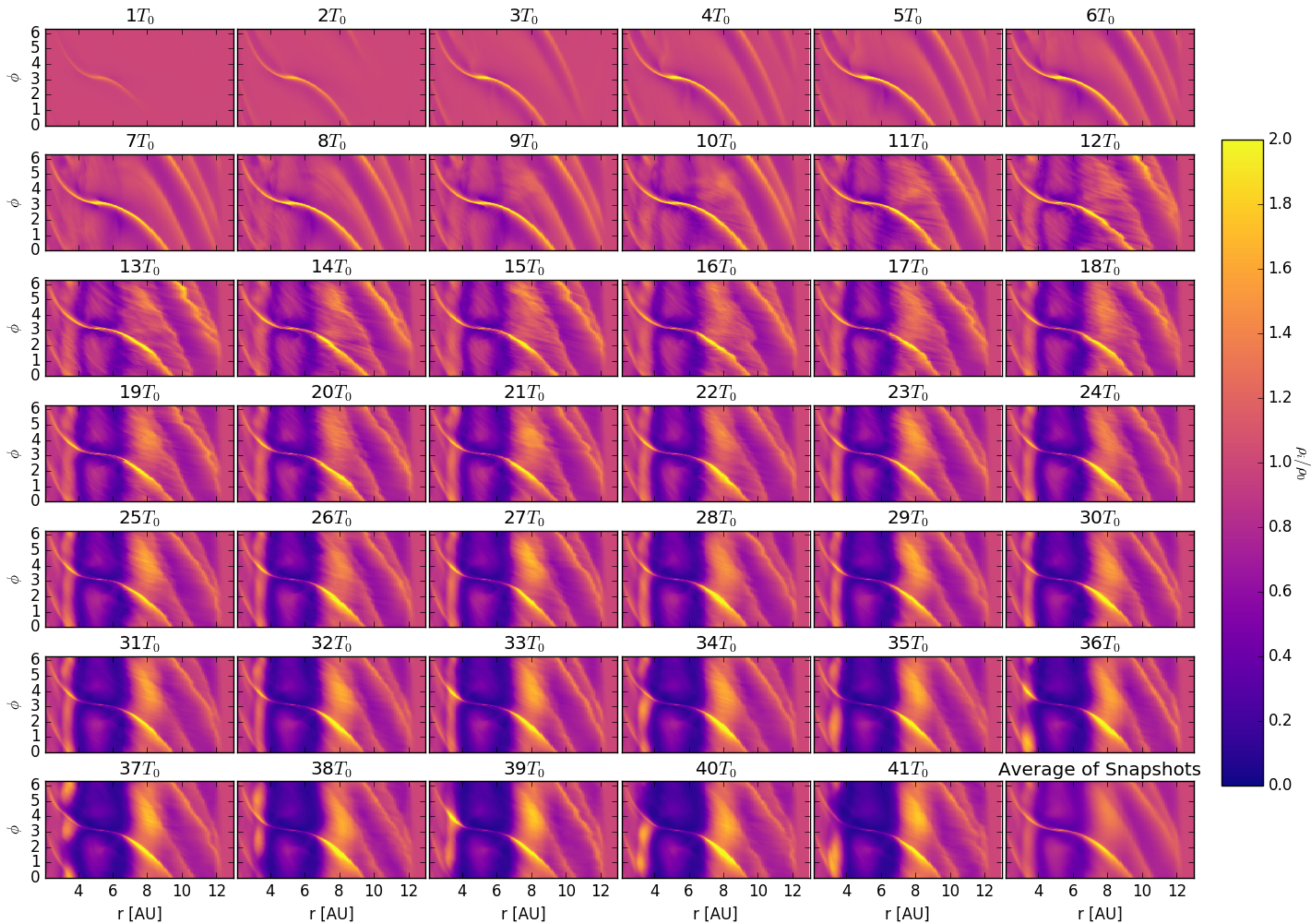
Dong et al. (2015)

Primary and Secondary spiral arms



Hord et al. (2017)

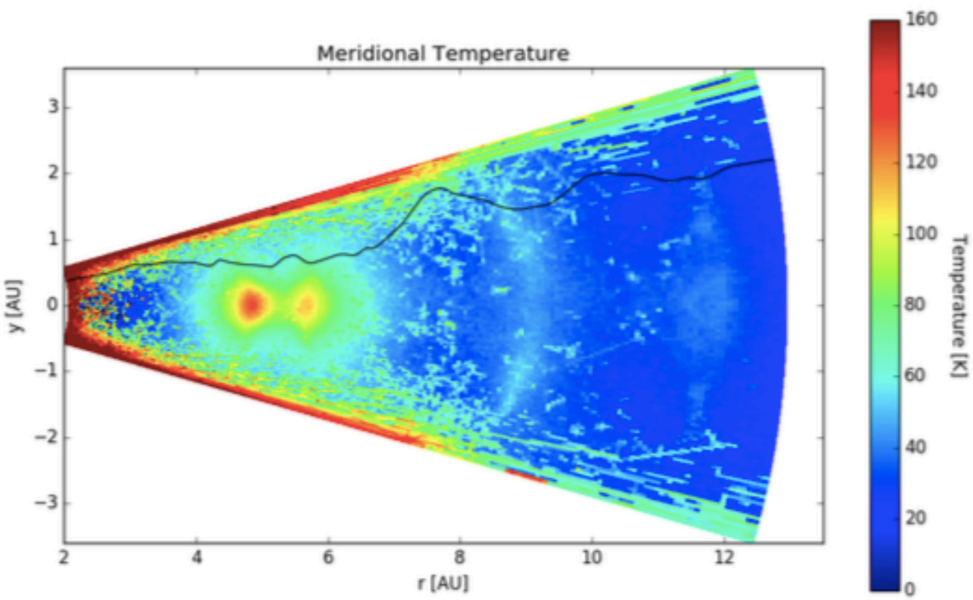
The raised feature has its origins in a secondary spiral arm

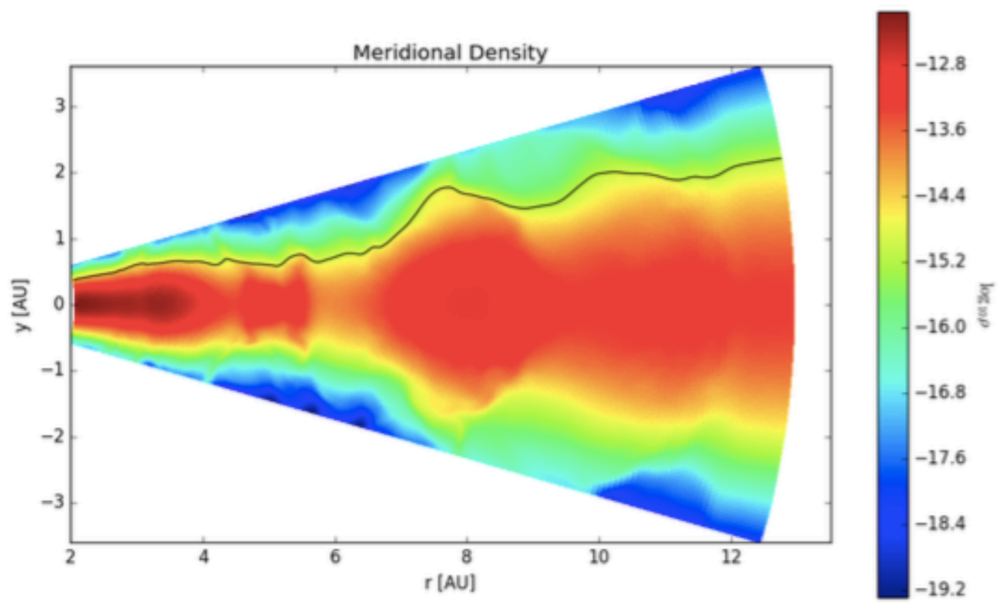


Hord et al. (2017)

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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