Can shocks from high-mass planets explain infrared emission in protoplanetary disks?

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Friend of the department

Collaborators

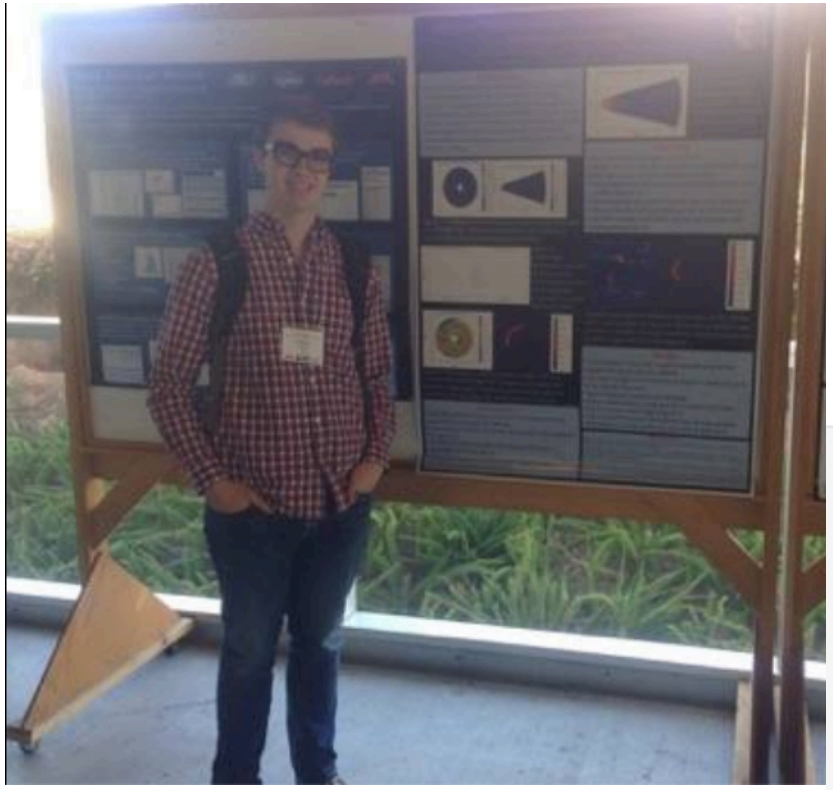
Aaron Boley (Vancouver), Kees Dullemond (Heidelberg), Mario Flock (JPL),
Blake Hord (Dobbs Ferry High School, NY), Anders Johansen (Lund),
Mordecai Mac Low (AMNH), Satoshi Okuzumi (JPL), ***Alex Richert (PSU),*** Neal Turner (JPL).

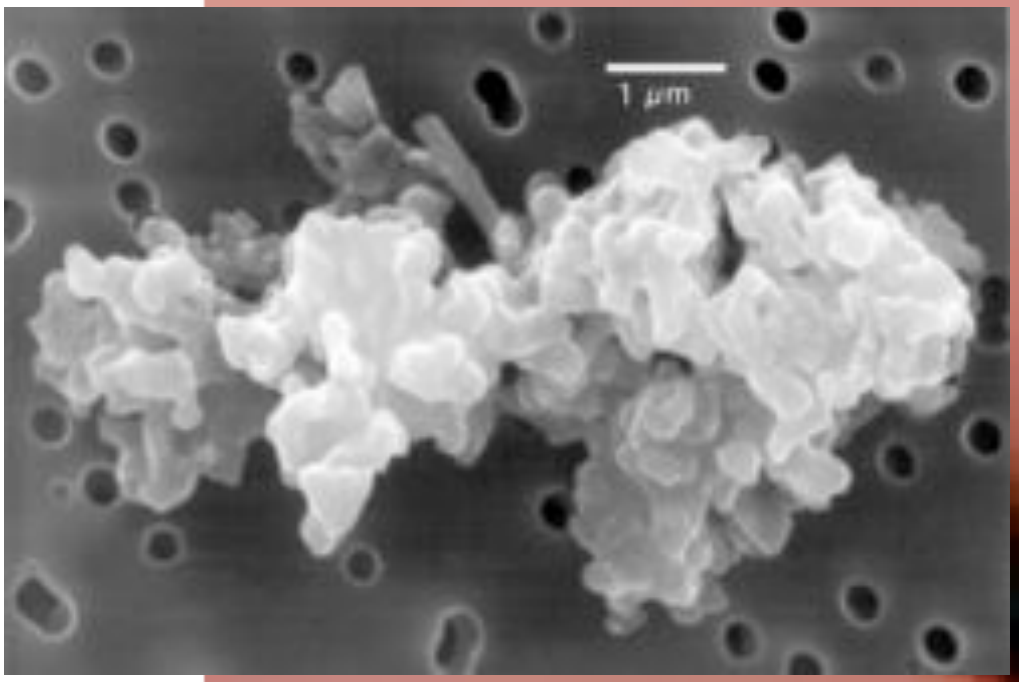
LARIM, Cartagena de Indias, Colombia, Oct 6th, 2016

Alex Richert

I am currently a PhD student in Penn State's Department of Astronomy & Astrophysics, where I work on observations of young star clusters and protoplanetary disks, as well as detailed computer simulations of planet formation. More broadly, I am interested in Big Data-driven science, especially machine learning, as well as high-performance computing. Below is a listing of projects/collaborations past and present (also found under "Research" menu).

Blake Hord *(Dobbs Ferry High School, NY)*




1 µm

Protoplanetary Disks

PP disk fact sheet

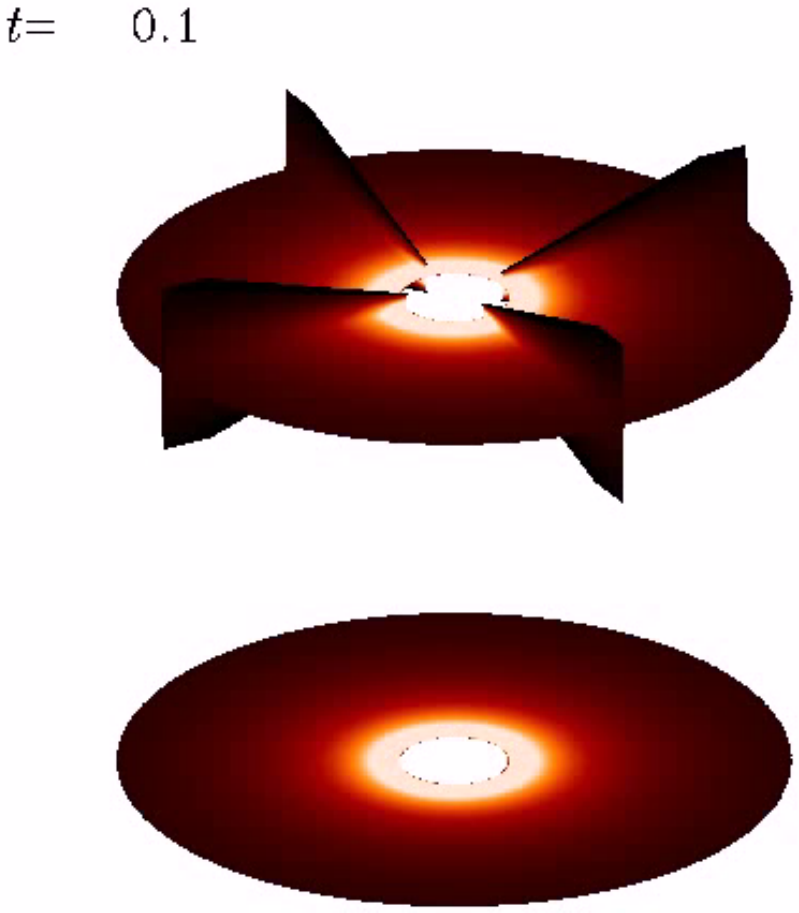
Density: 10^{13} – 10^{15} cm^{-3}
(Air: 10^{21} cm^{-3})

Temperature: 10-1000 K

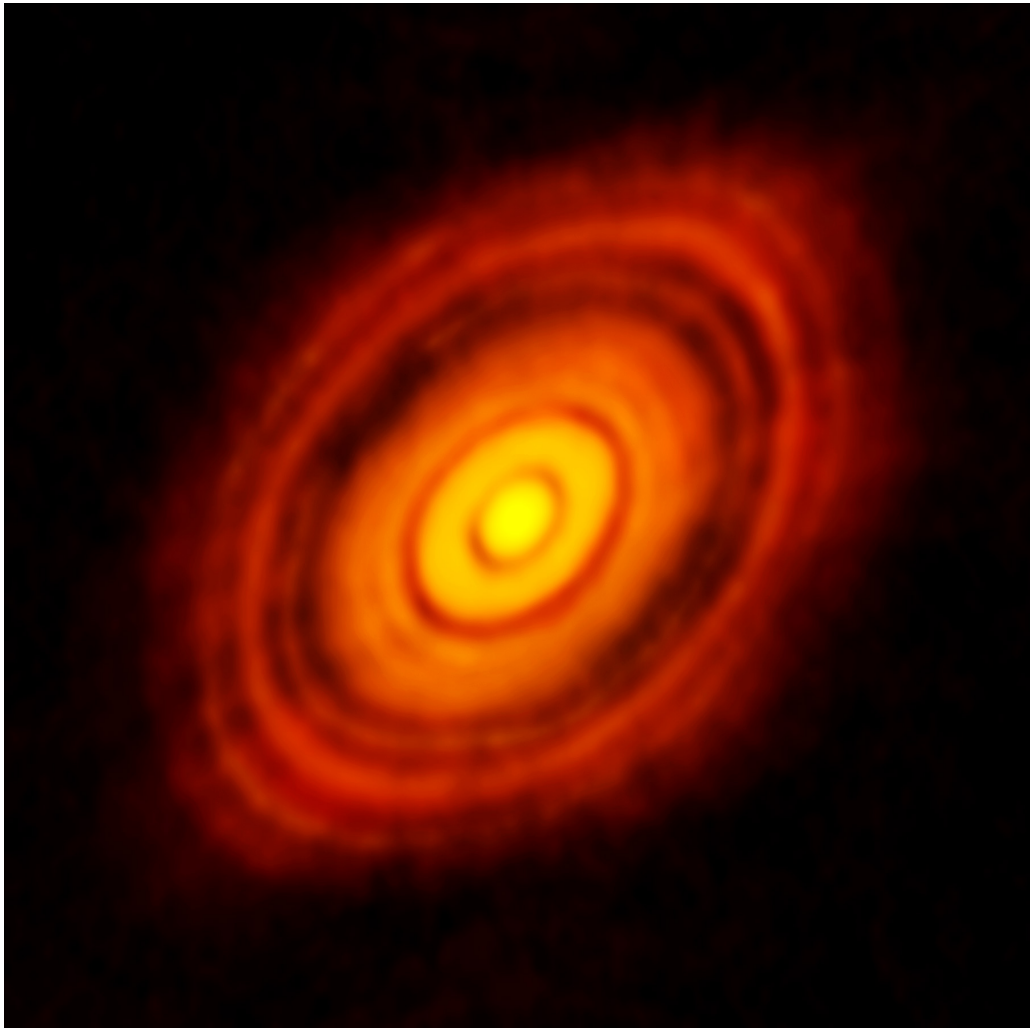
Scale: 0.1-100AU
(1 AU = 1.49 x 10^{13} cm)

Mass: 10^{-3} – 10^{-1} M_{sun}
(1 M_{sun} = 2 x 10^{33} g)

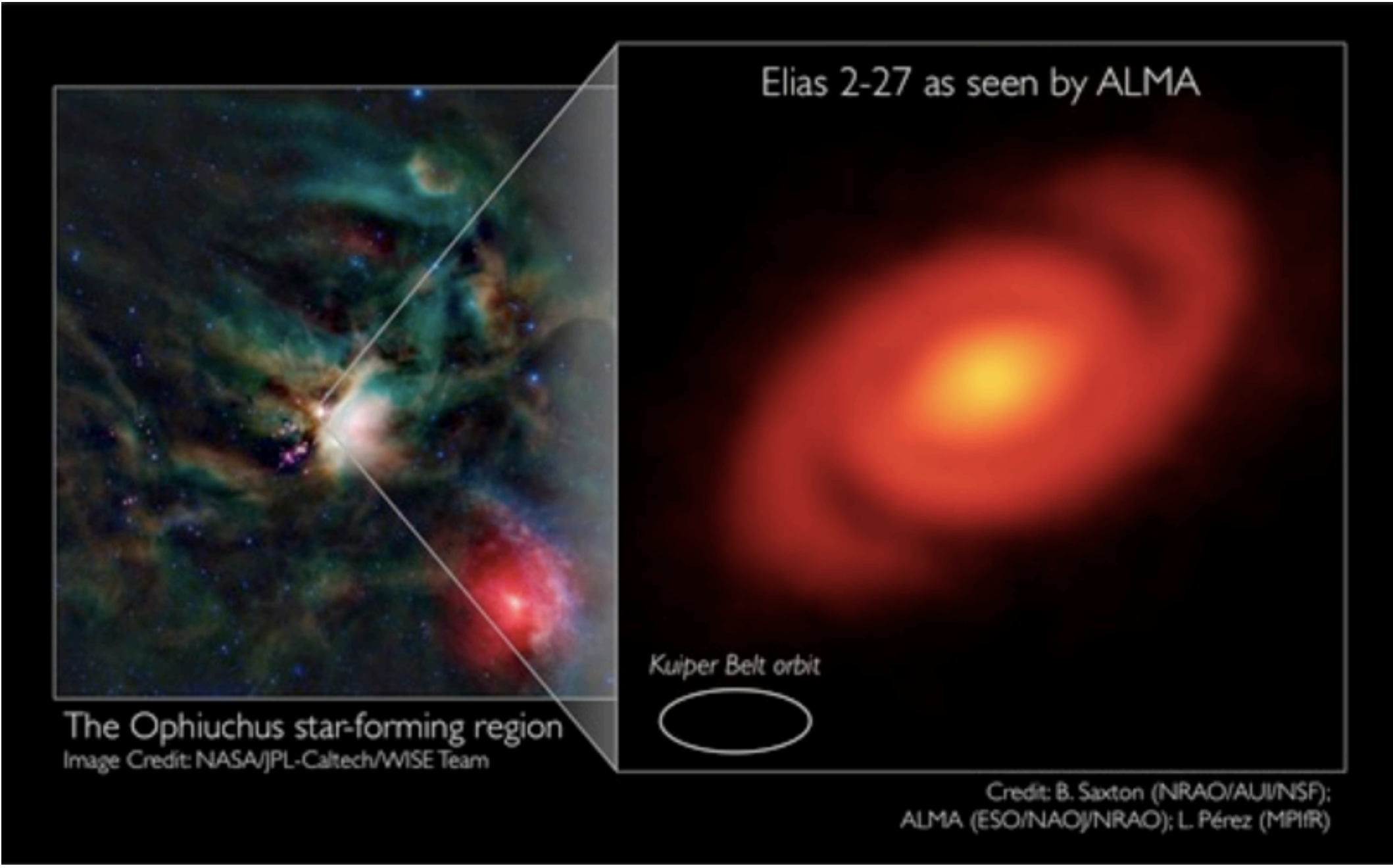
Planet-Disk Interaction



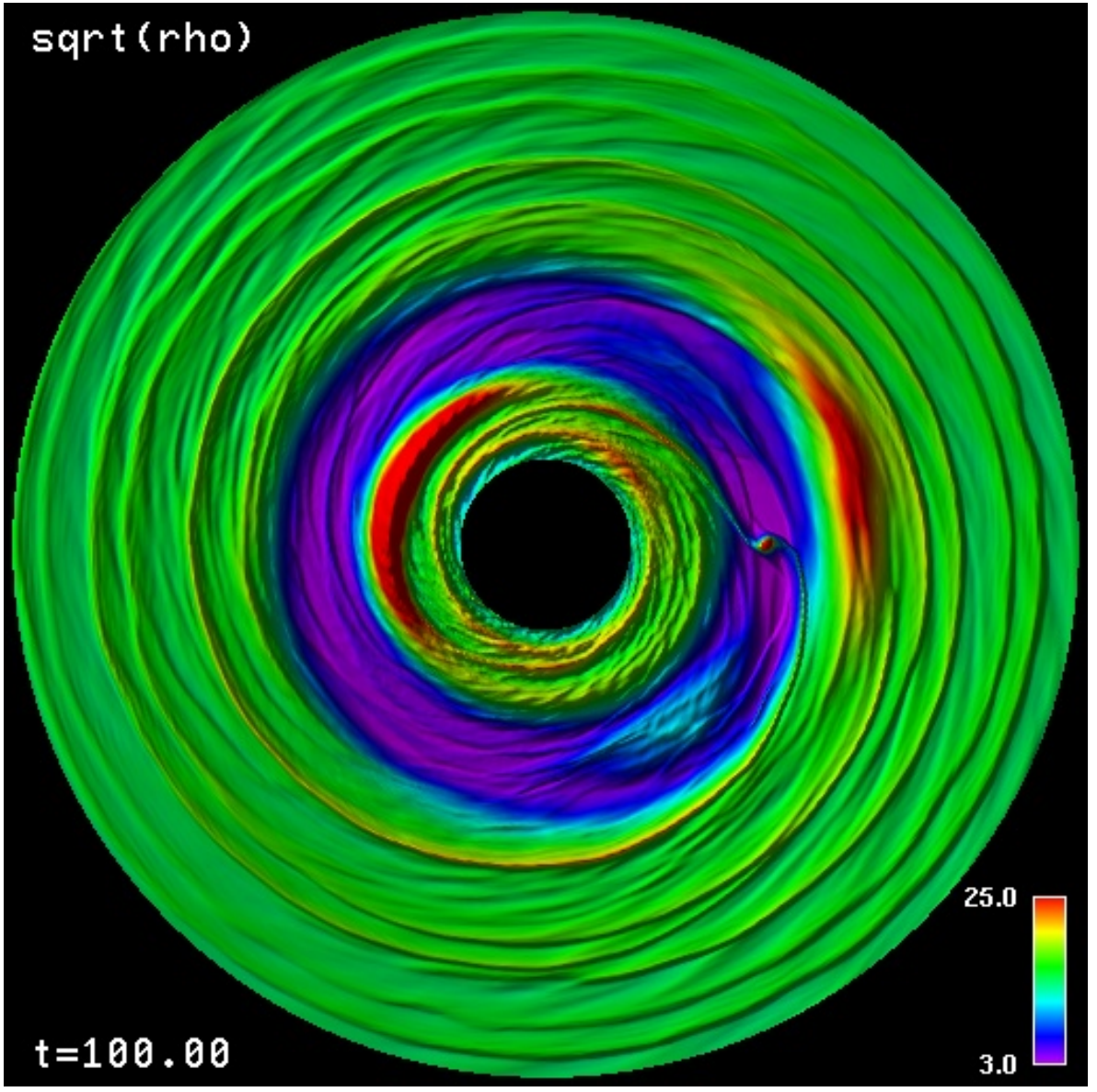
ALMA observation: HL Tau



Elias 2-27

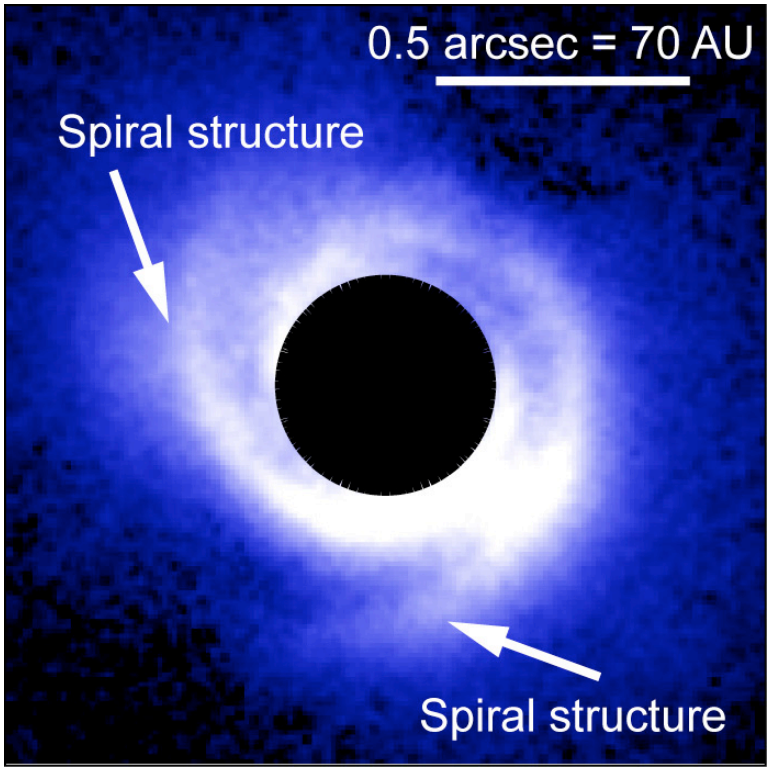

Elias 2-27 as seen by ALMA
Kuiper Belt orbit
The Ophiuchus star-forming region
Image Credit: NASA/JPL-Caltech/WISE Team
Credit: B. Saxton (NRAO/AUI/NSF);
ALMA (ESO/NAOJ/NRAO); L. Pérez (MPIfR)

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



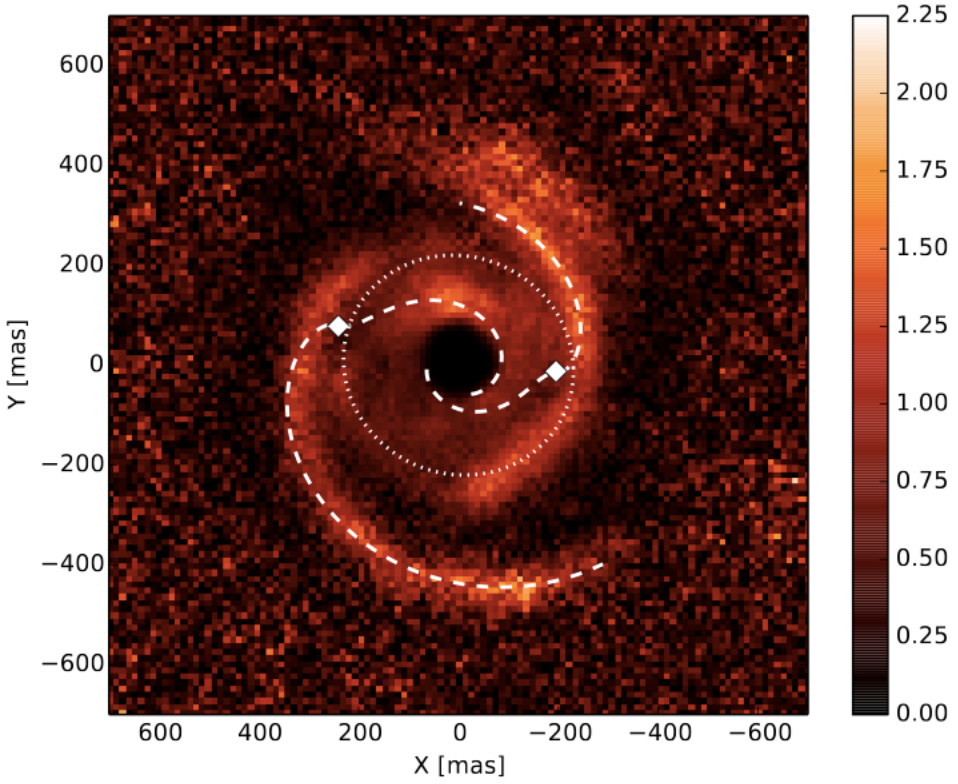
Observational evidence: Spirals

SAO 206462



Muto et al. (2012)

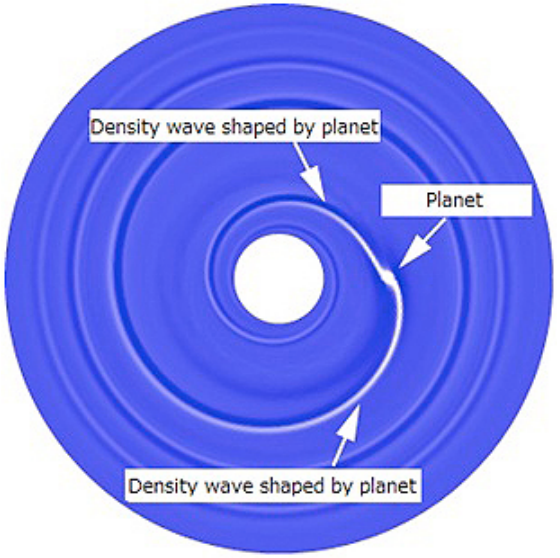
MWC 748



Benisty et al. (2015)

Spiral arm fitting leads to problems

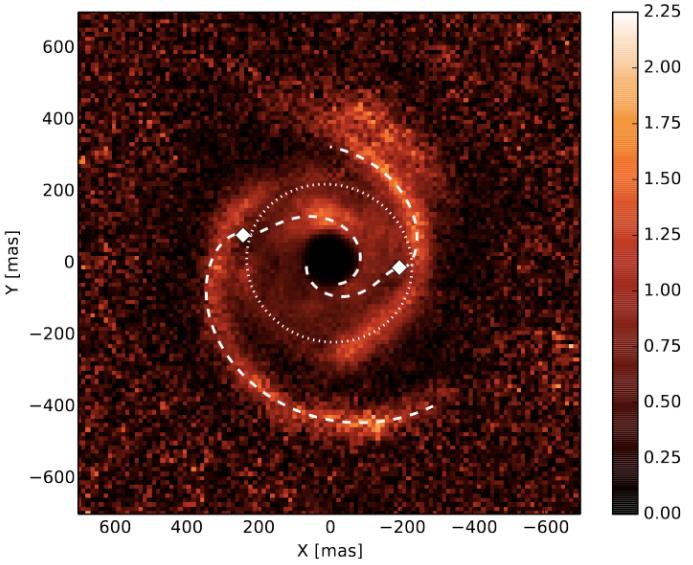
Analytical spiral fit



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

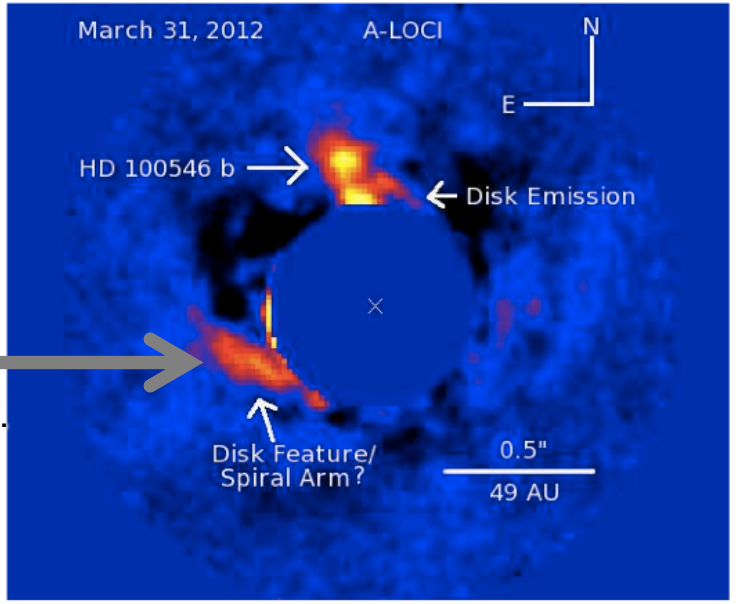
Rafikov (2002)
Muto et al. (2012)

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



Benisty et al. (2015)

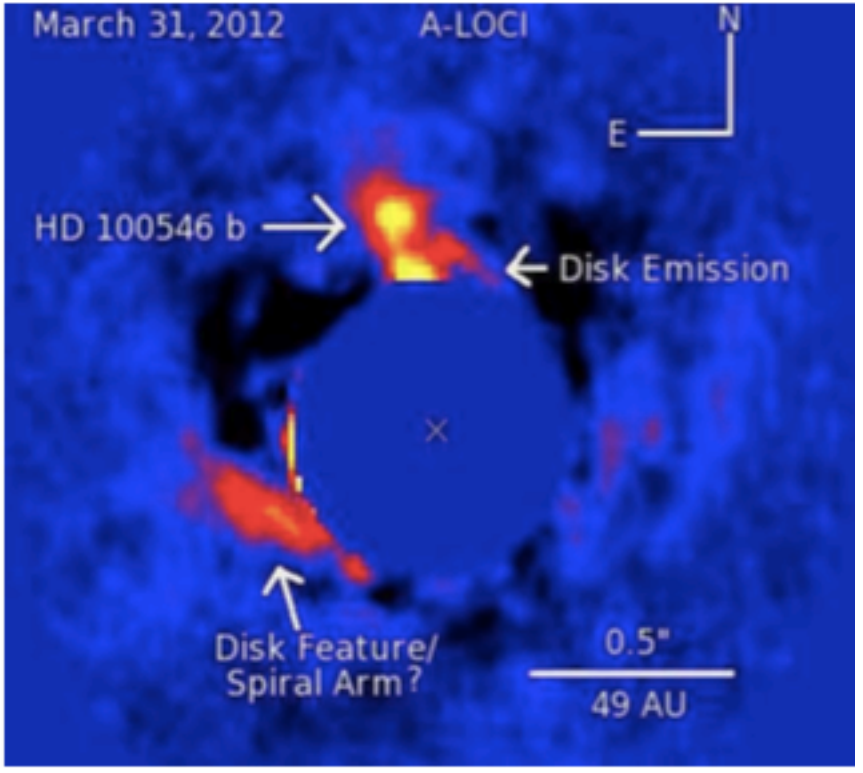
Spiral has little
polarization. Must be
thermal emission at 1000K.



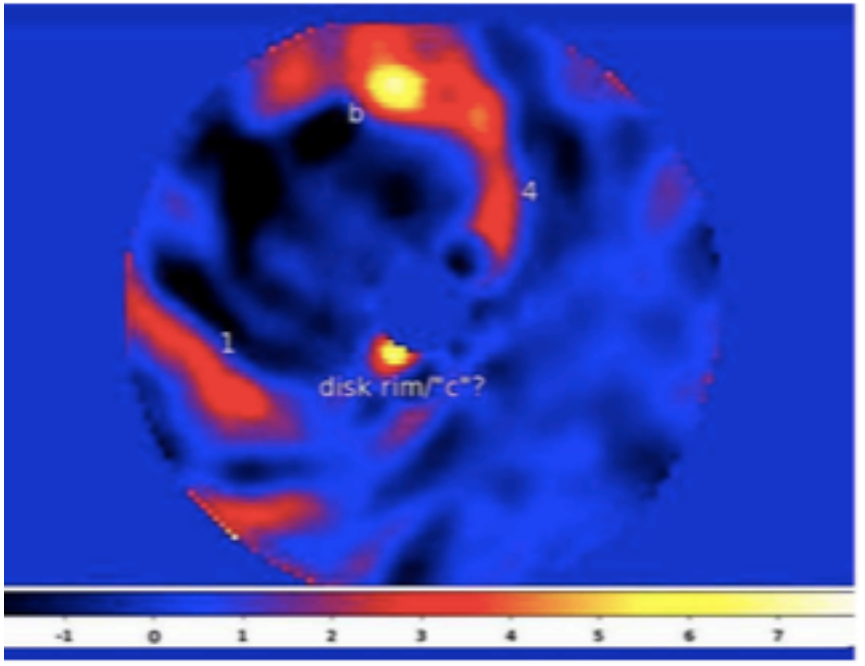
Currie et al. (2014)

The strange case of thermal emission in HD 100546

L band (~3.5 μm)

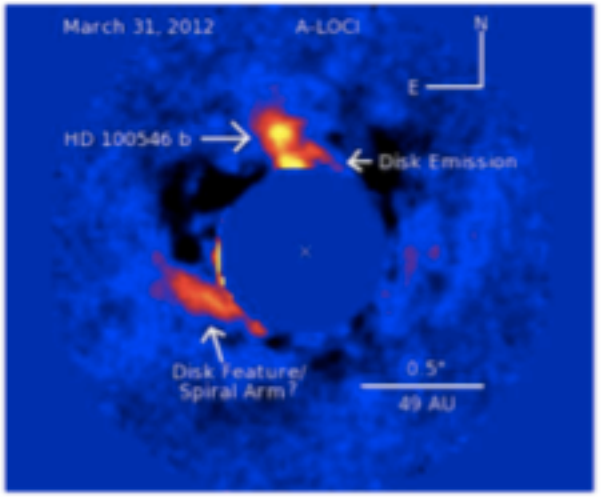


H band (~1.6 μm)

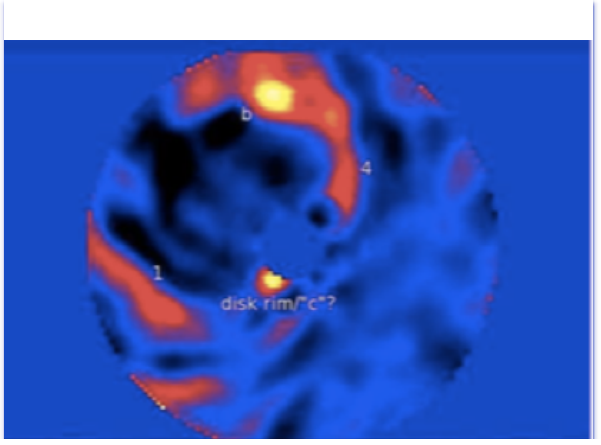


Currie et al. (2014), Currie et al. (2015)

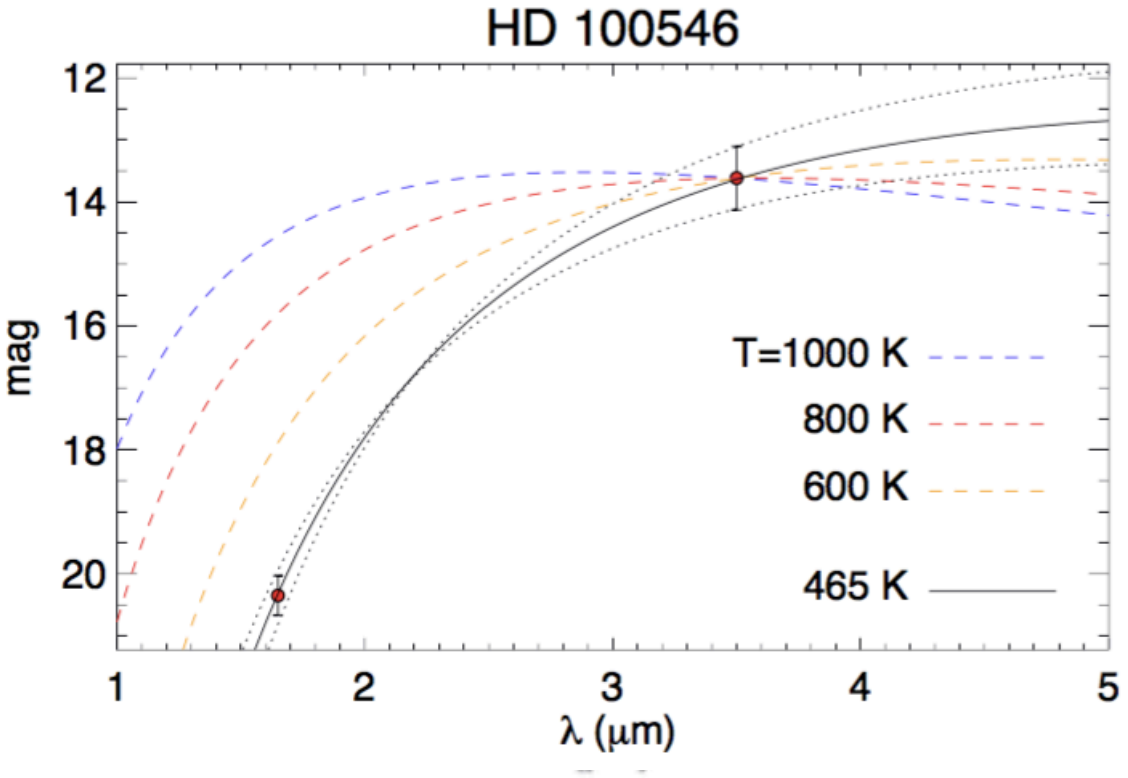
Pinning down the temperature



L band

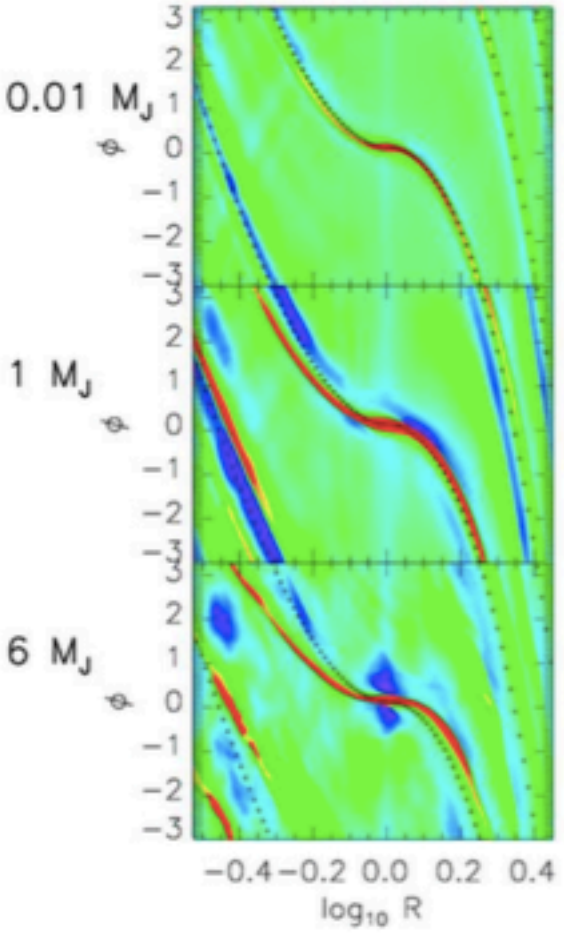


H band



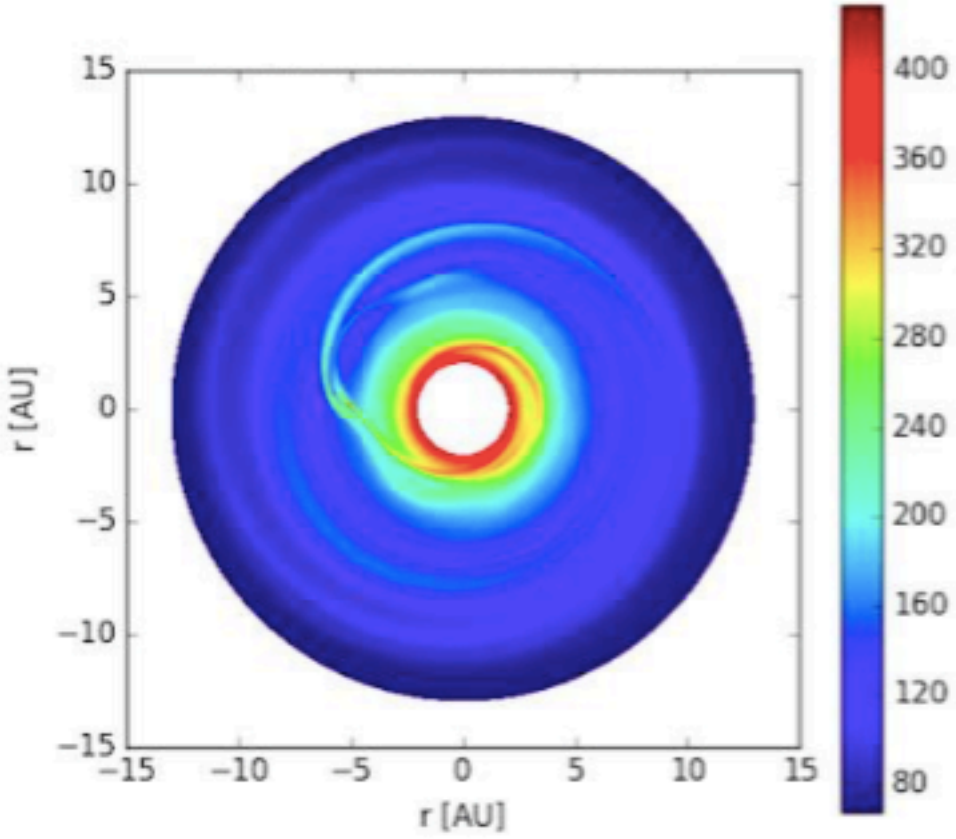
Lyra et al. (2016)

Supersonic Wakes of High Mass Planets



Density

Zhu et al. (2015)

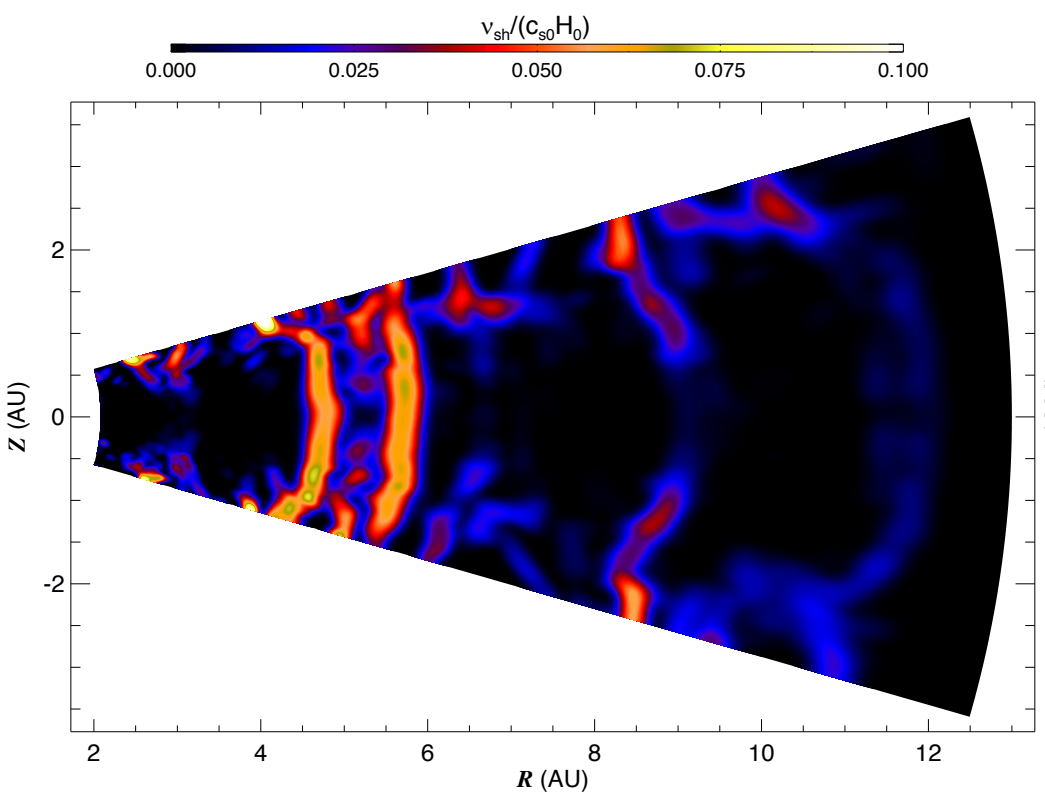


Temperature - 5M_J

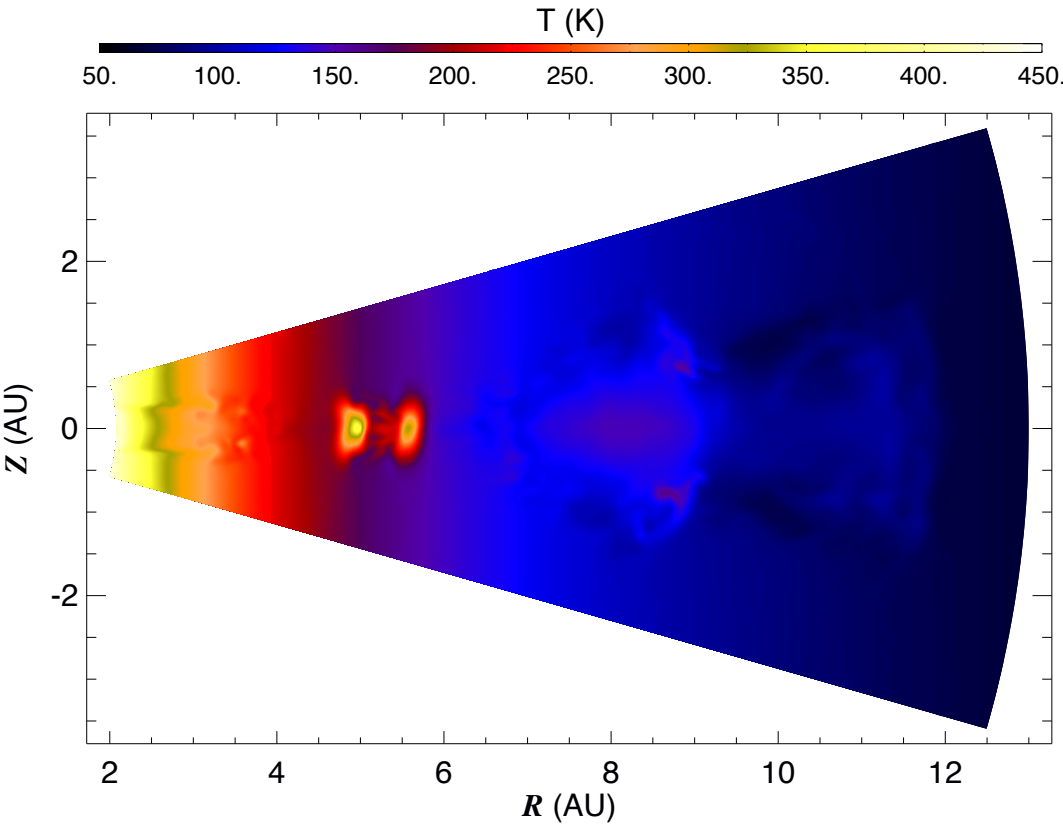
Lyra et al. (2016)

Shock bores

Shocks (velocity convergence)



Temperature



Lyra et al. (2016)

Radiative transfer approximation

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

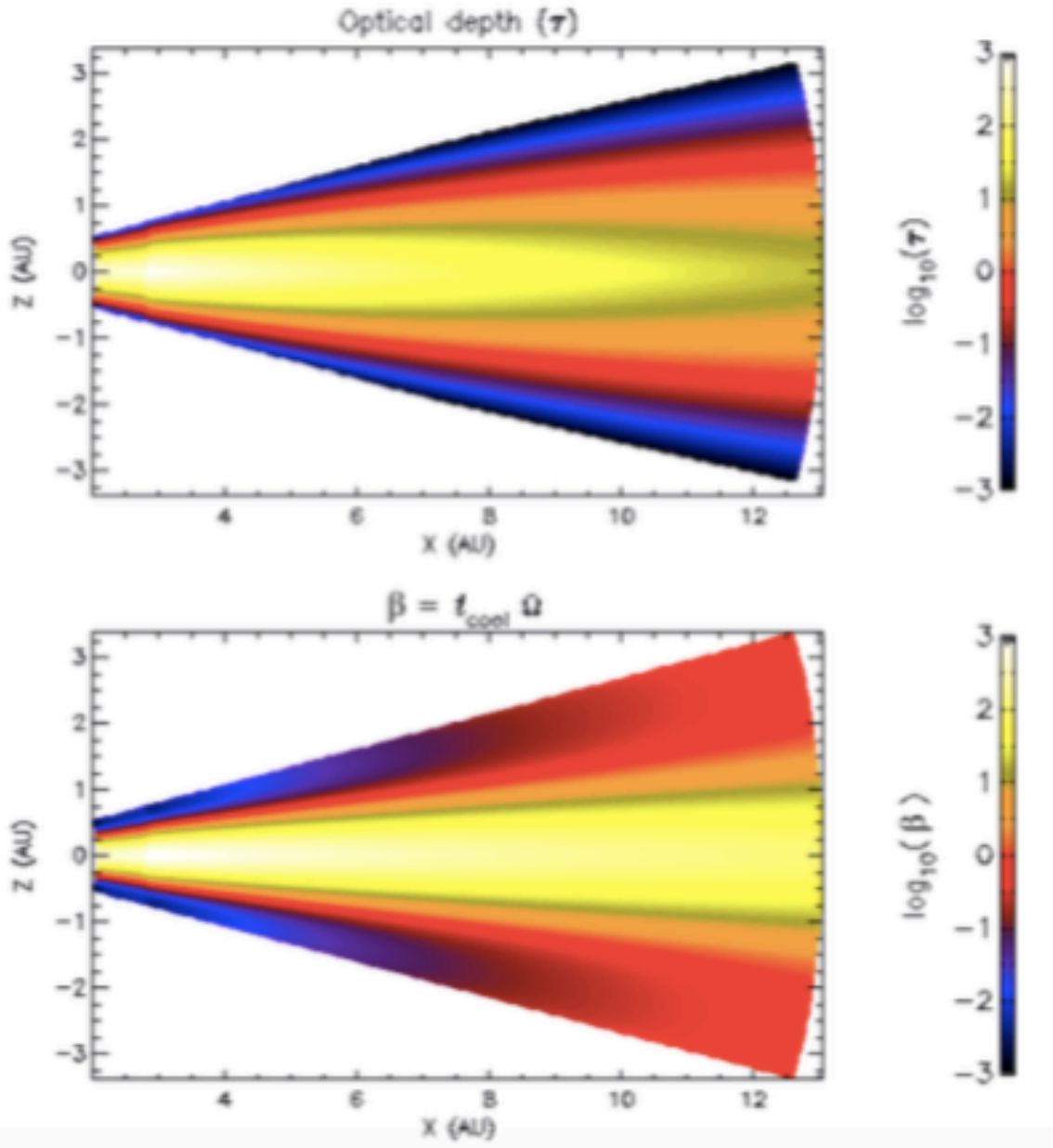
$$t_{\mathrm{rad}} = E/\dot{E}$$

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

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

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

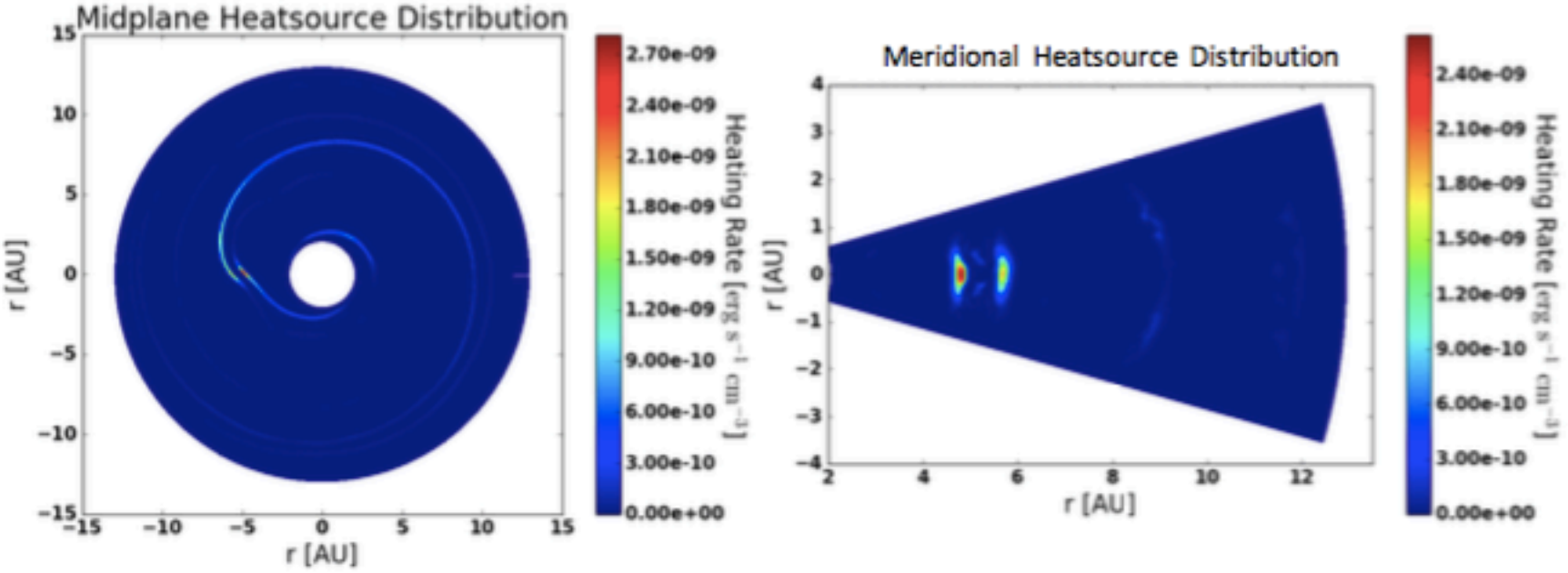
$$\tau_{\mathrm{eff}} = \frac{3\tau}{8} + \frac{\sqrt{3}}{4} + \frac{1}{4\tau}.$$



RADMC-3D

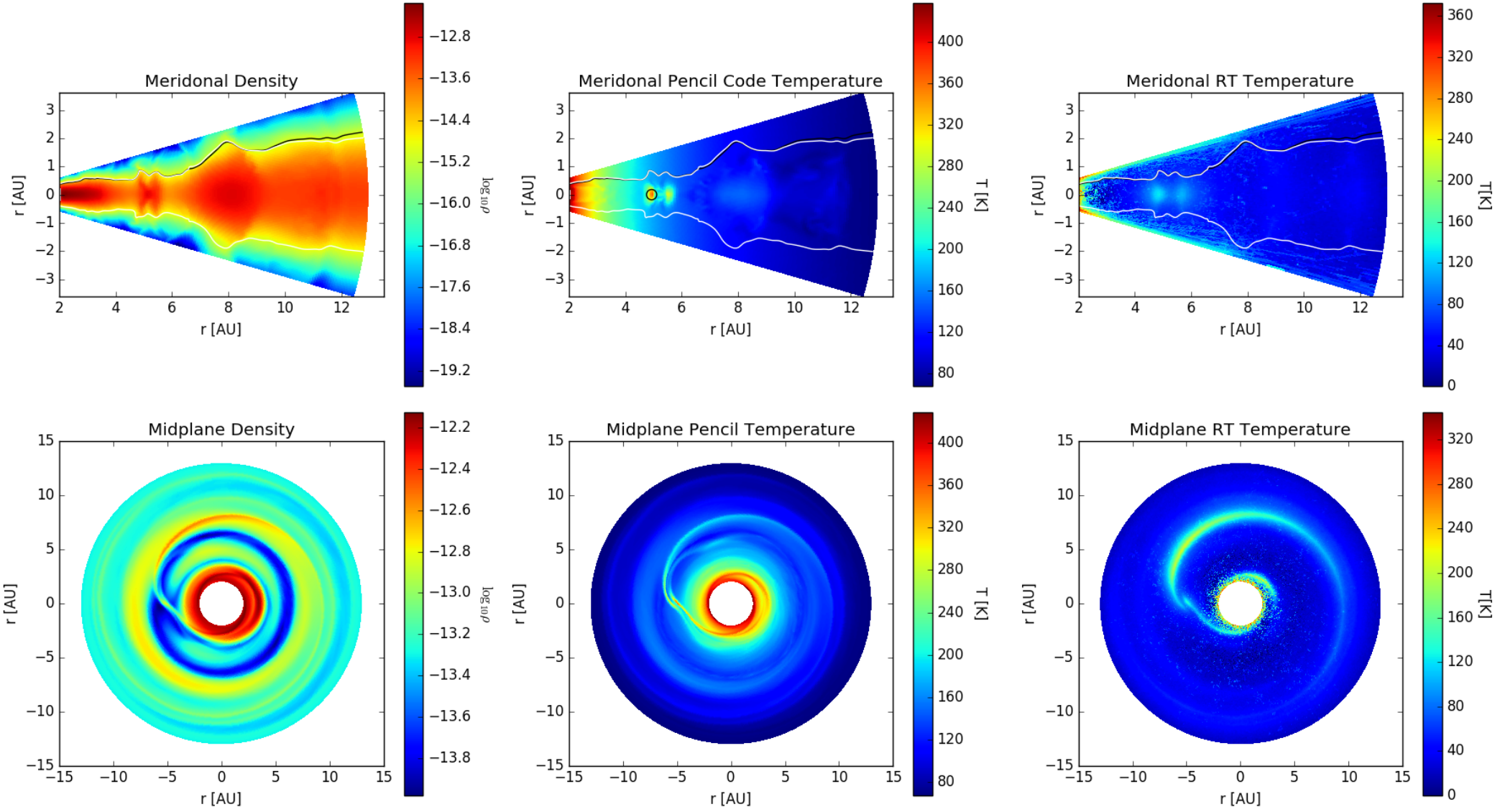
(Dullemond 2012)

Radiative Transfer - **Shock heating**



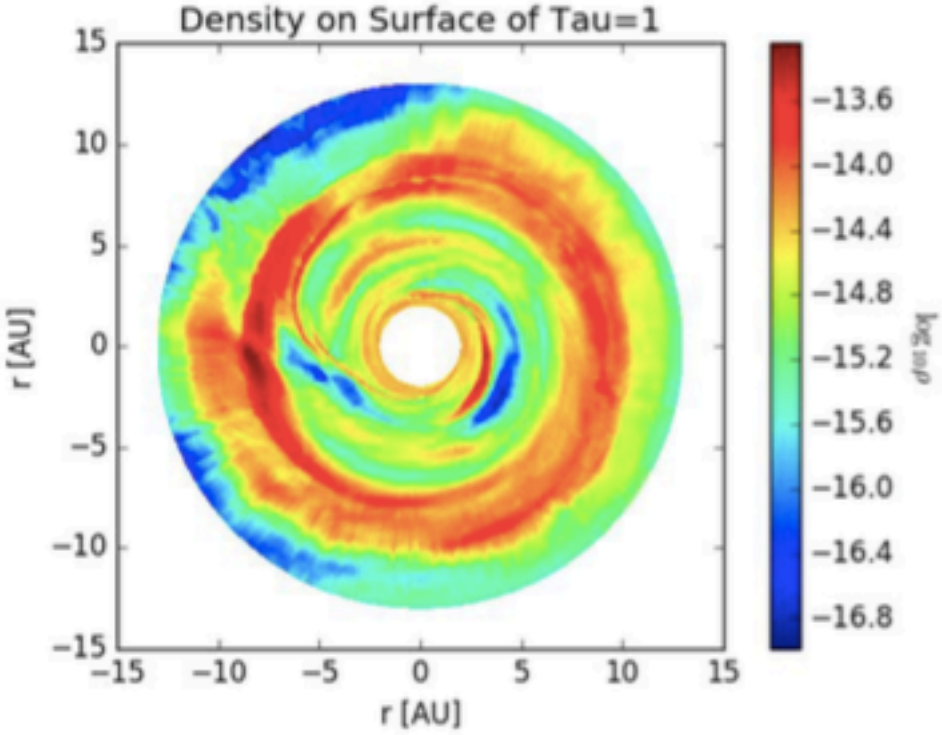
Hord et al. (2016, in prep)

Radiative Transfer post-processing

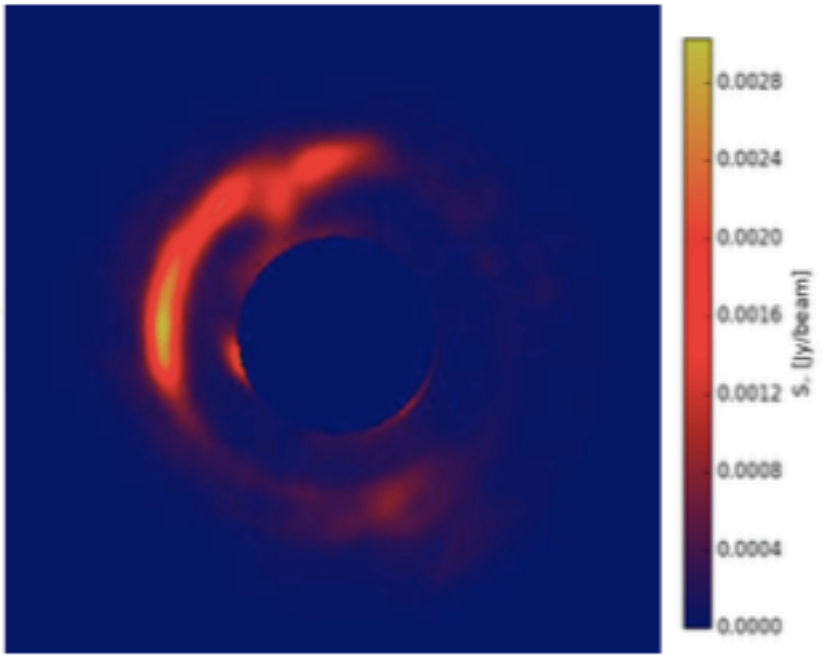


Hord et al. (2016, in prep)

Scattering in Image



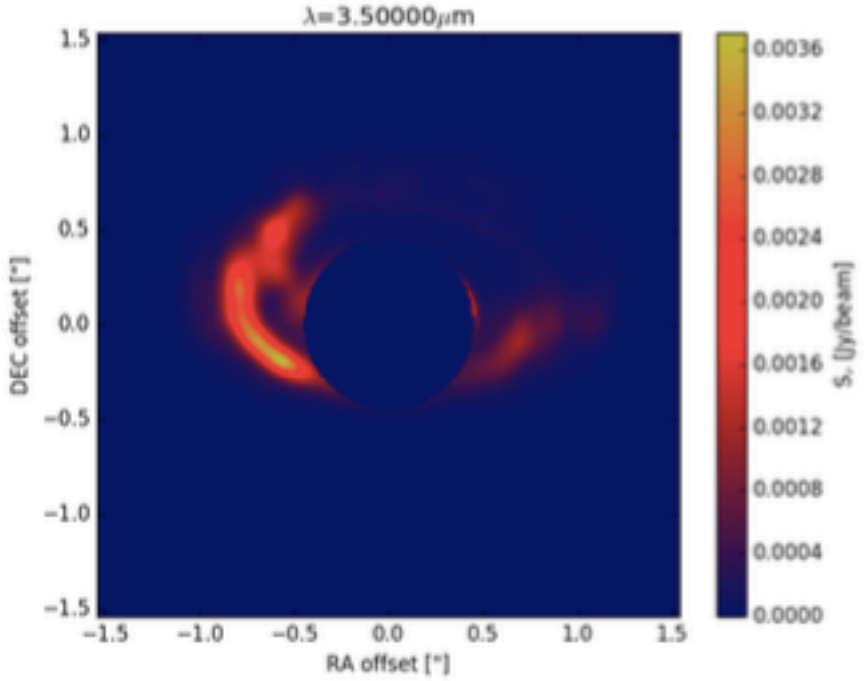
Light scattered off **gap outer edge**

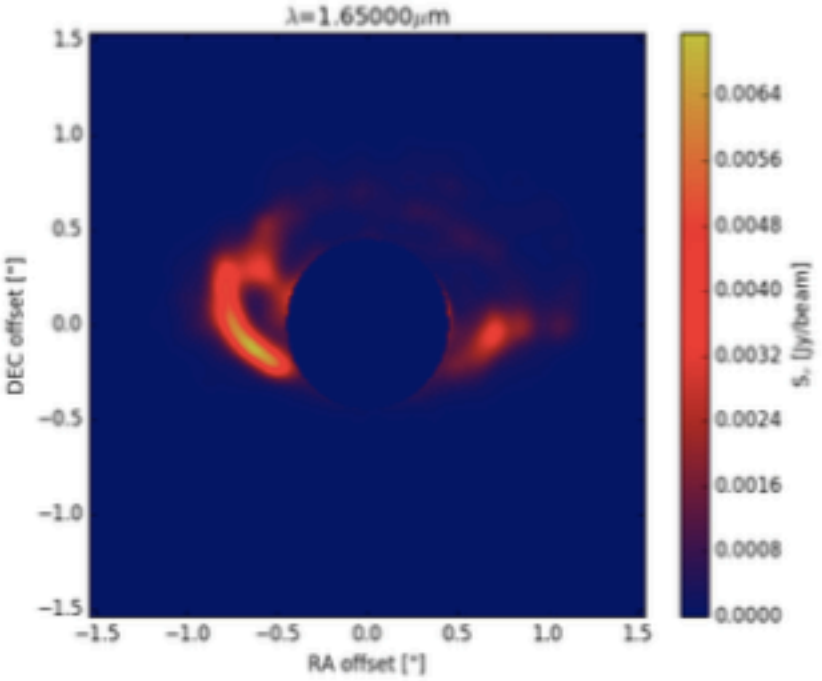


"Bird's eye view"
synthetic image

Hord et al. (2016, in prep)

Synthetic Images





λ = 3.5 microns (**L' Band**)

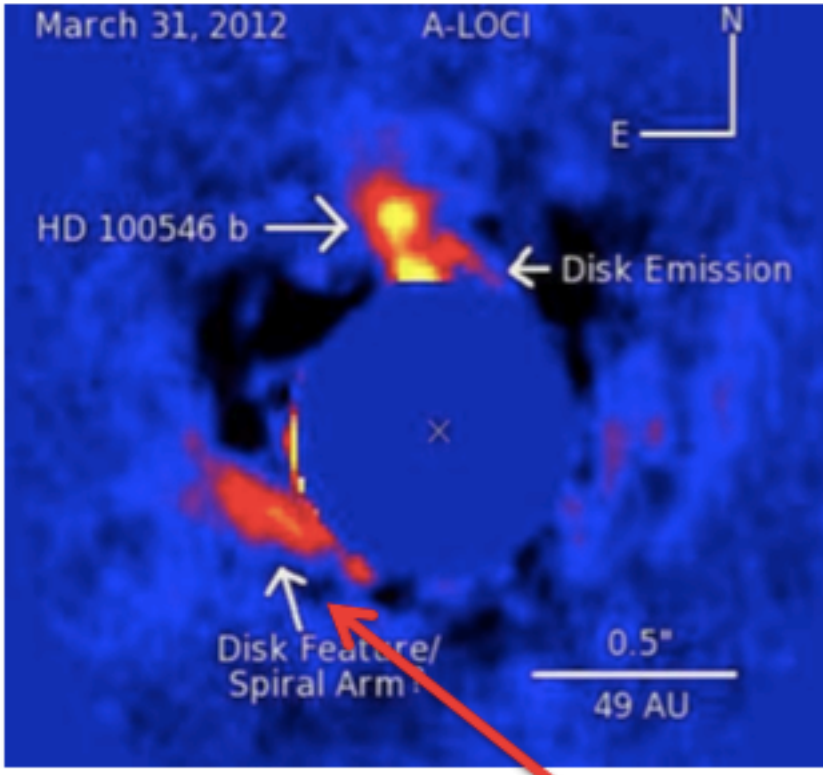
λ = 1.65 microns (**H Band**)

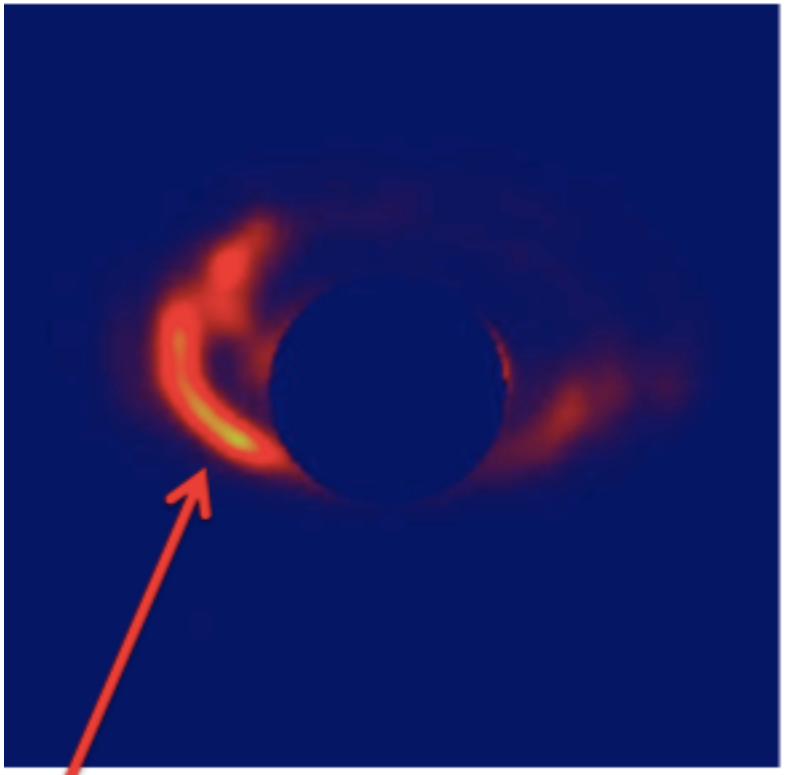
Made with 138 degree position angles and 50 degree inclination angles to match Currie et al. (2014) observations.

Disk scaled by factor of 10 to map T Tauri 5 AU to Herbig Ae 50 AU

Hord et al. (2016, in prep)

Comparison



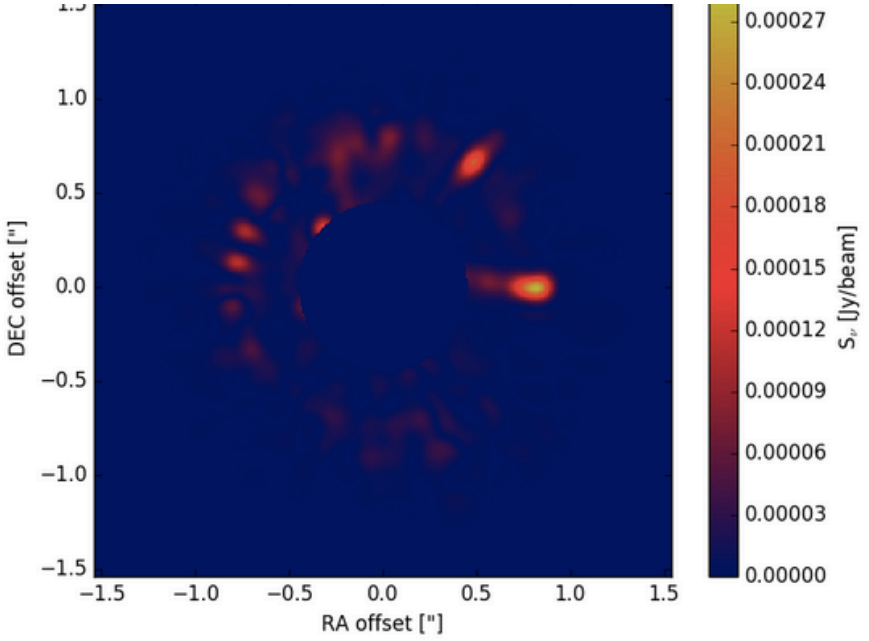


Matching general morphologies

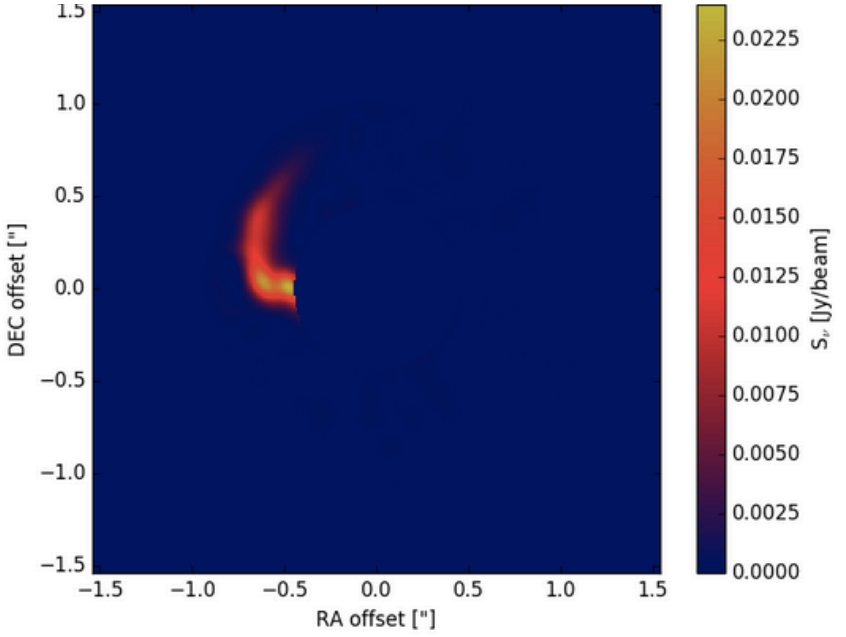
Hord et al. (2016, in prep)

Effect of shocks alone

1 μm

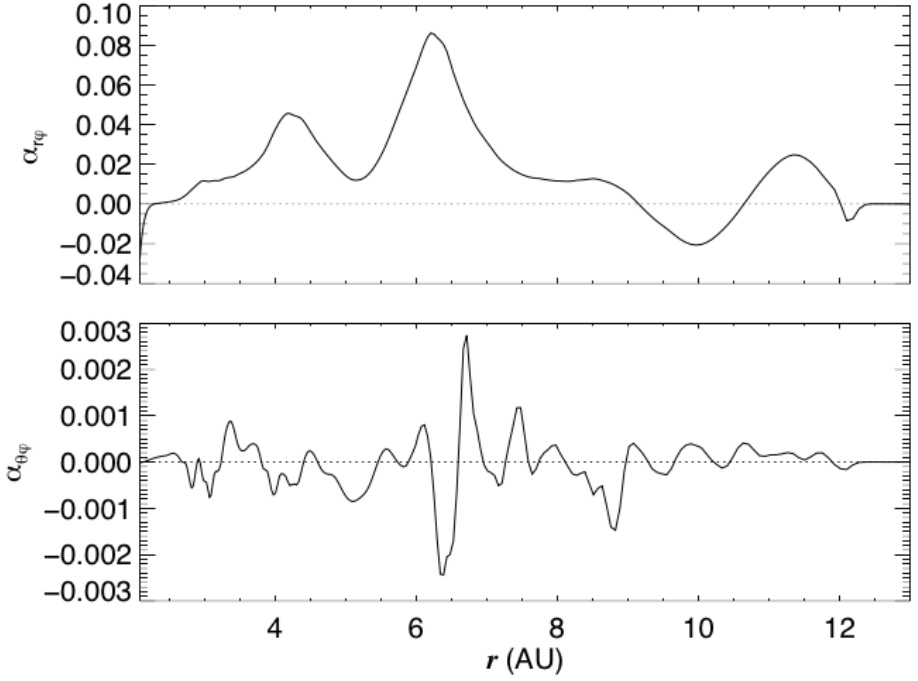


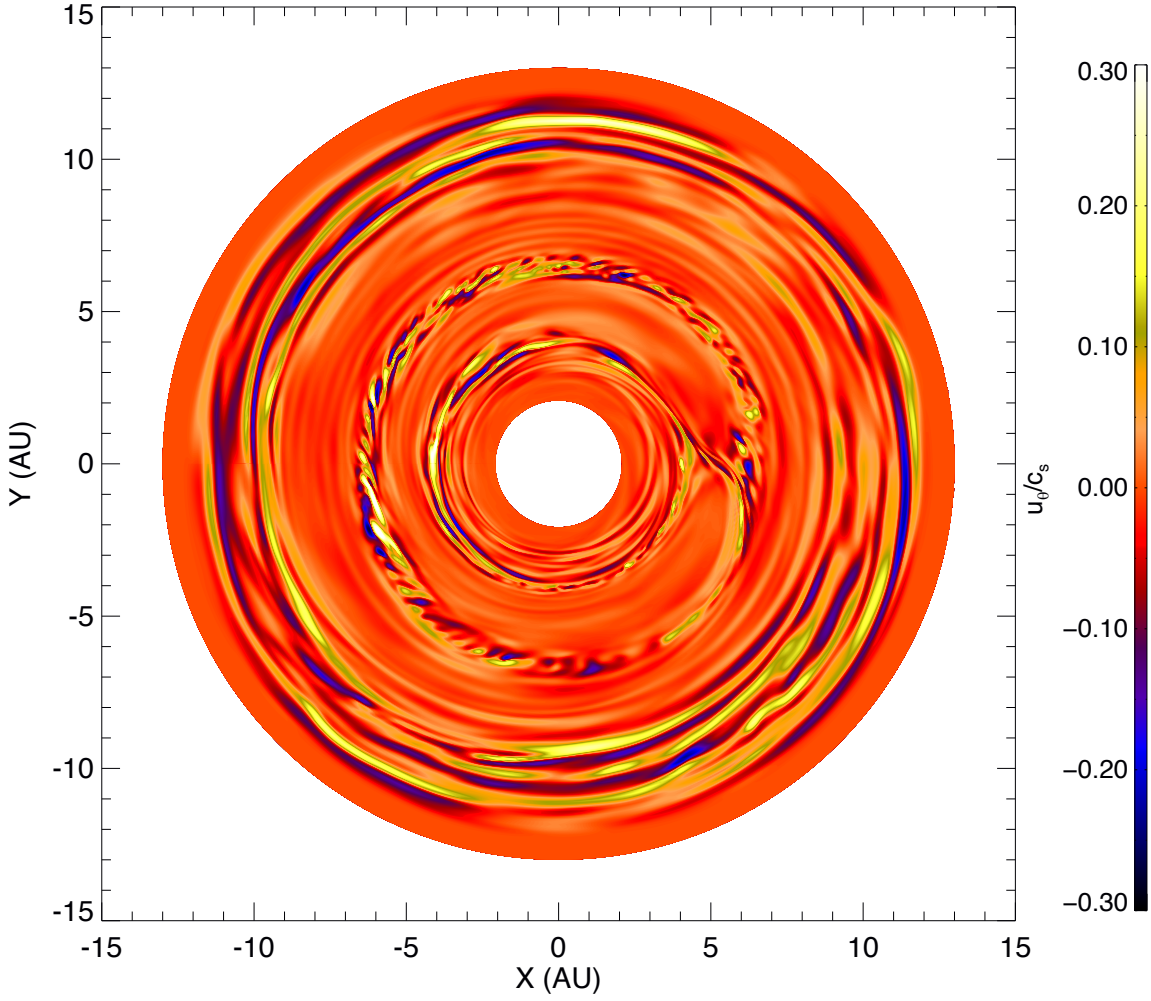
10 μm



Hord et al. (2016, in prep)

Prediction for spectroscopy: Turbulent surf





Lyra et al. (2016)

Conclusions

- Predictions:
  - Hot lobes next to high mass planets at high resolution
  - High(er) turbulence around the orbit of a high-mass planet
- Shocks from high-mass planets (~> 5 Mjup) is a significant source of radiation in disks.
- Shocks due to high mass planets better fits to observed spirals.