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# Millimeter image of the HL Tau disk: gaps opened by planets?

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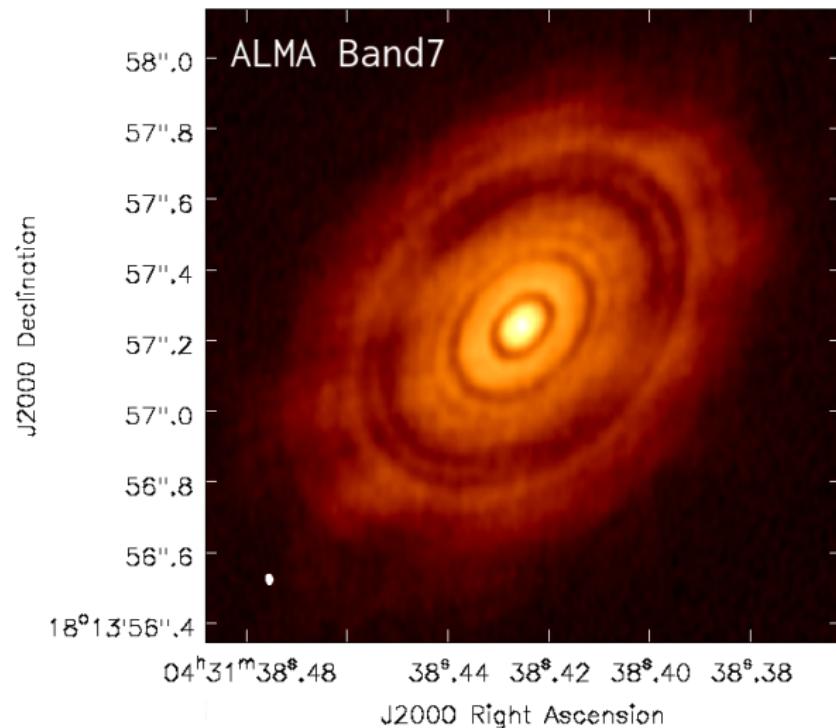
1 Introduction

2 Model

3 Results

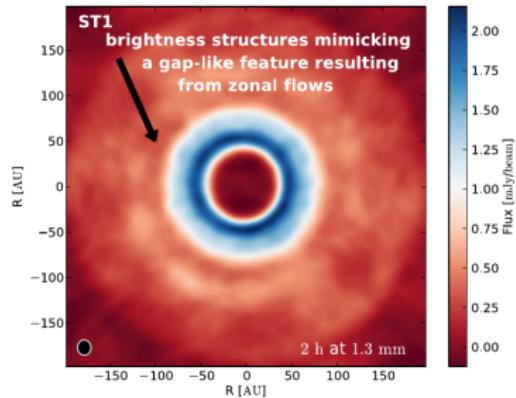
4 Conclusions

# Angular resolution of 0.025 arcsec (3.5 AU)

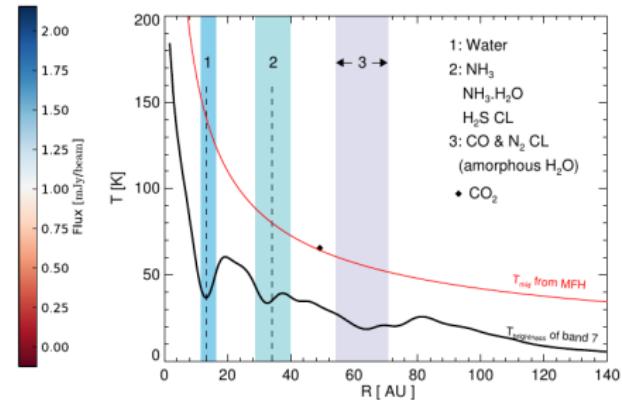


(ALMA Partnership et al. 2015)

# Bright and dark rings: Possible mechanisms



(Ruge et al. 2013)



(Zhang et al. 2015)

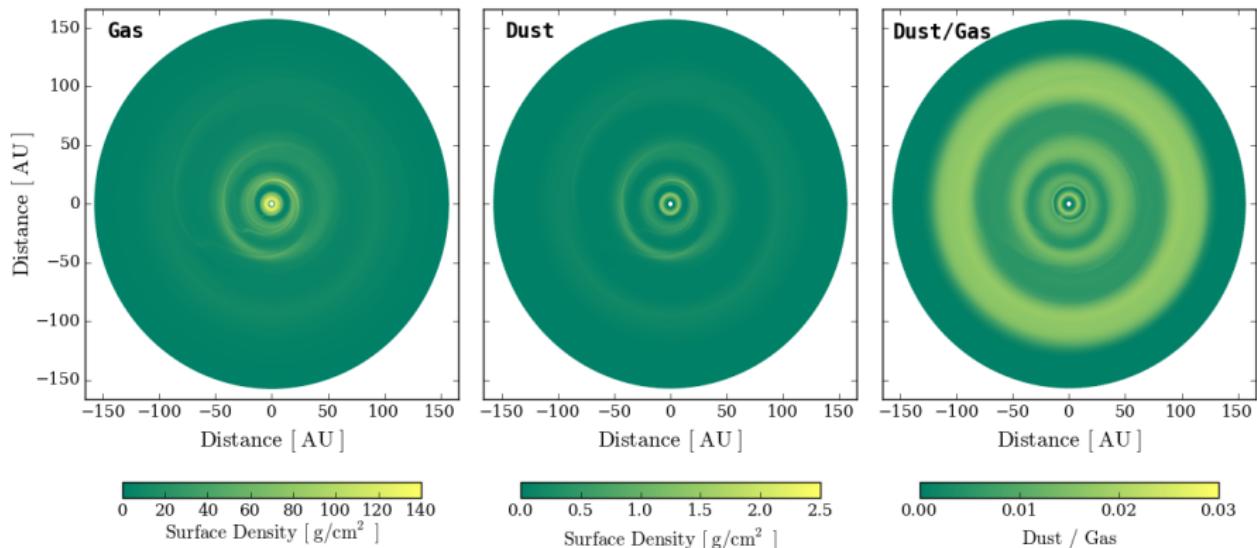
- Zonal flows or Rossby wave instability. (Ruge et al. 2013; Regály et al. 2012; Pinilla et al. 2012)
- Rapid pebble growth around condensation fronts. (Zhang et al. 2015)
- Interaction between planets, gas and dust. (e.g., Dong et al. 2014)

# Observed features that favour planet-induced gaps:

- The spectral index at the location of the dark rings is optical thin. (ALMA Partnership et al. 2015).
- The eccentricities of the rings increase at large orbital radii. (ALMA Partnership et al. 2015)
- The dust size constrained by polarized emission is around  $150 \mu m$ , thus the structure of multiple rings also exists in the gas disk. (Kataoka et al. 2015)
- The depletion of dust at each of the deepest gaps is up to  $40 M_{\oplus}$ , close to the point of runaway gas accretion. (Pinte et al. 2015)

## Our hydro model:

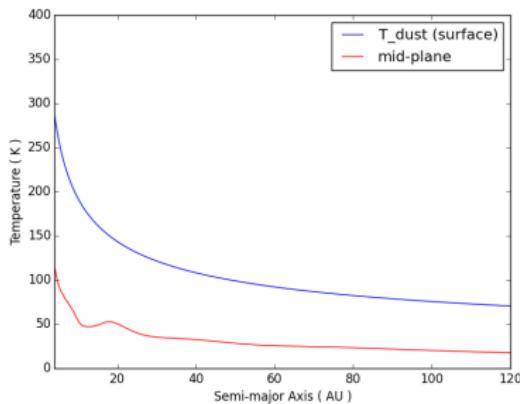
- Two-fluid (gas and dust) simulation that includes the interaction between planets, gas, dust and disk self-gravity, using the LA-COMPASS code.
- Three planets of  $0.35$ ,  $0.17$  and  $0.26 M_{\text{Jup}}$  are fixed at  $13.1$   $33.0$   $68.6$  AU.
- The system evolves for 4000th orbit ( $r = 10$  AU).
- We vary the  $\alpha$ -viscosity and planetary masses, or turn off the disk self-gravity for parameter studies.
- NOTE: planets are fixed at their orbital locations.

Hydro snapshot at 4000th orbit ( $r = 10$  AU)

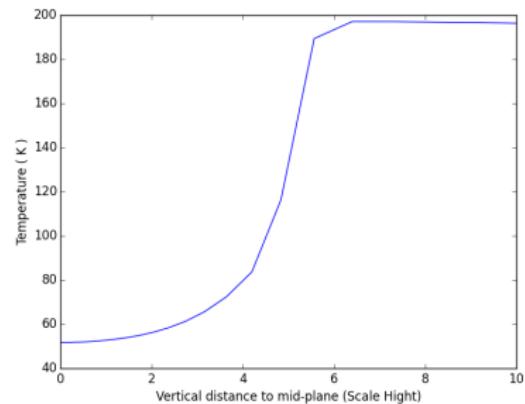
(Jin et al. in prep)

# Radiation transfer model

- The micron-size dust (well-coupled with gas) determine the temperature.
- The observed millimeter flux are mainly from the emission of  $\sim 0.15$  mm dust.



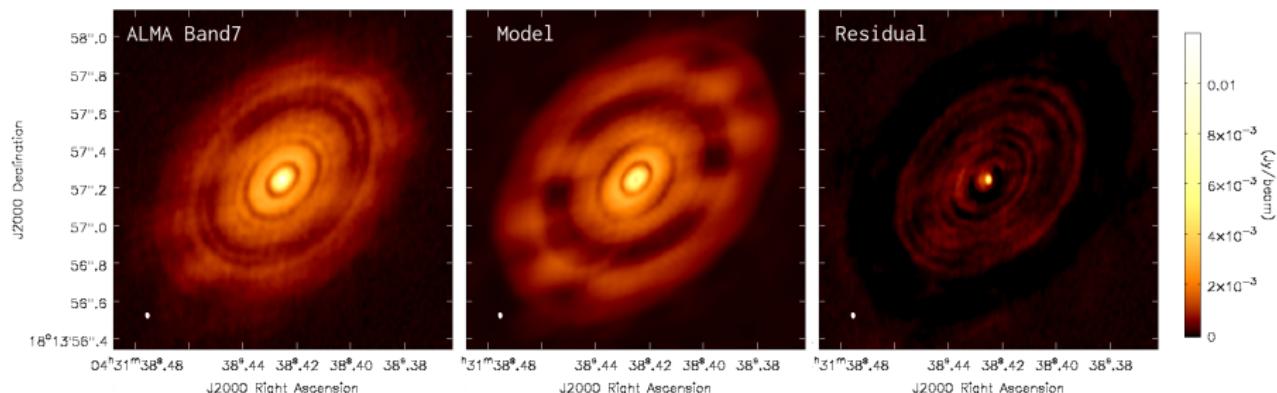
Radial temperature profile



Vertical (10 AU) temperature

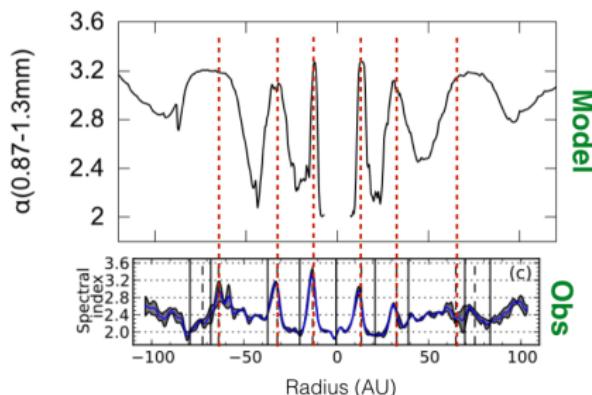
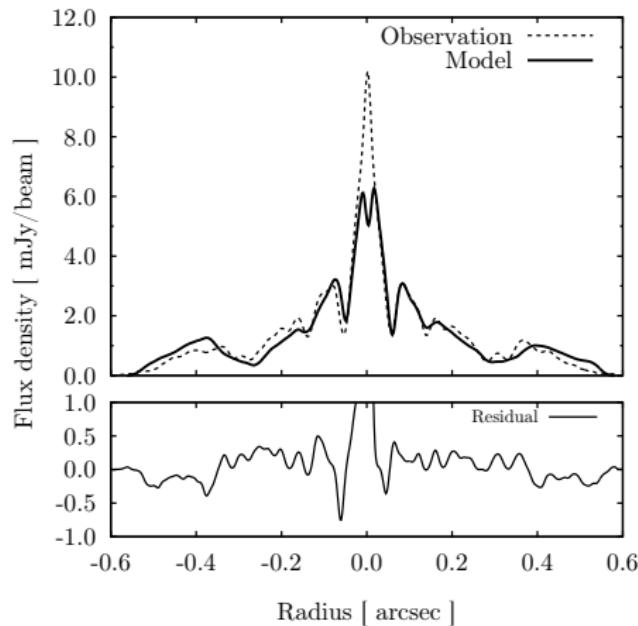
# Observe the model

- For each u,v point in the ALMA data, replace the observed visibility by the Fourier transfer of our model image.
- Observe the new model data using the “clean” algorithm in CASA.



(Jin et al. in prep)

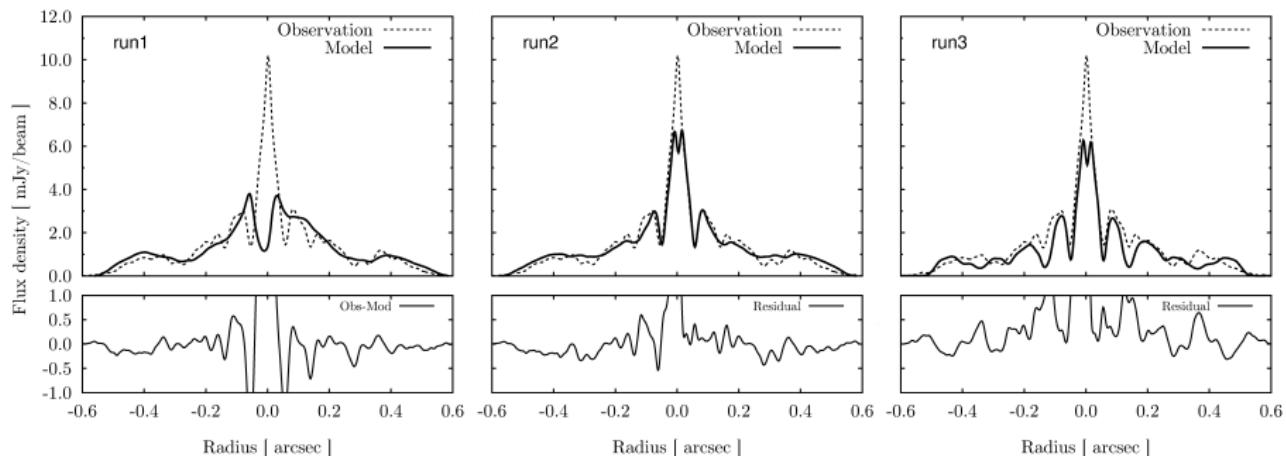
# Radial profiles of flux density and spectral index



(Jin et al. in prep)

# Comparison of parameters

- run1: planetary masses are reduced by half.
- run2: disk self-gravity is not included.
- run3:  $\alpha$ -viscosity is reduced by one-fifth.



(Jin et al. in prep)

# Conclusions

- Interaction between planets, gas, and dust can explain the main features in the ALMA observation.
- The millimeter image of a disk is determined by the dust profile, which in turn is influenced by planetary masses, viscosity, disk self-gravity, etc.
- Models that focus on the complex physics between gas and dust (and planets) are crucial in interpreting the (sub)millimeter images of disks.

Many Thanks!