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Title: Millimeter image of the HL Tau Disk: gaps opened by planets?

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

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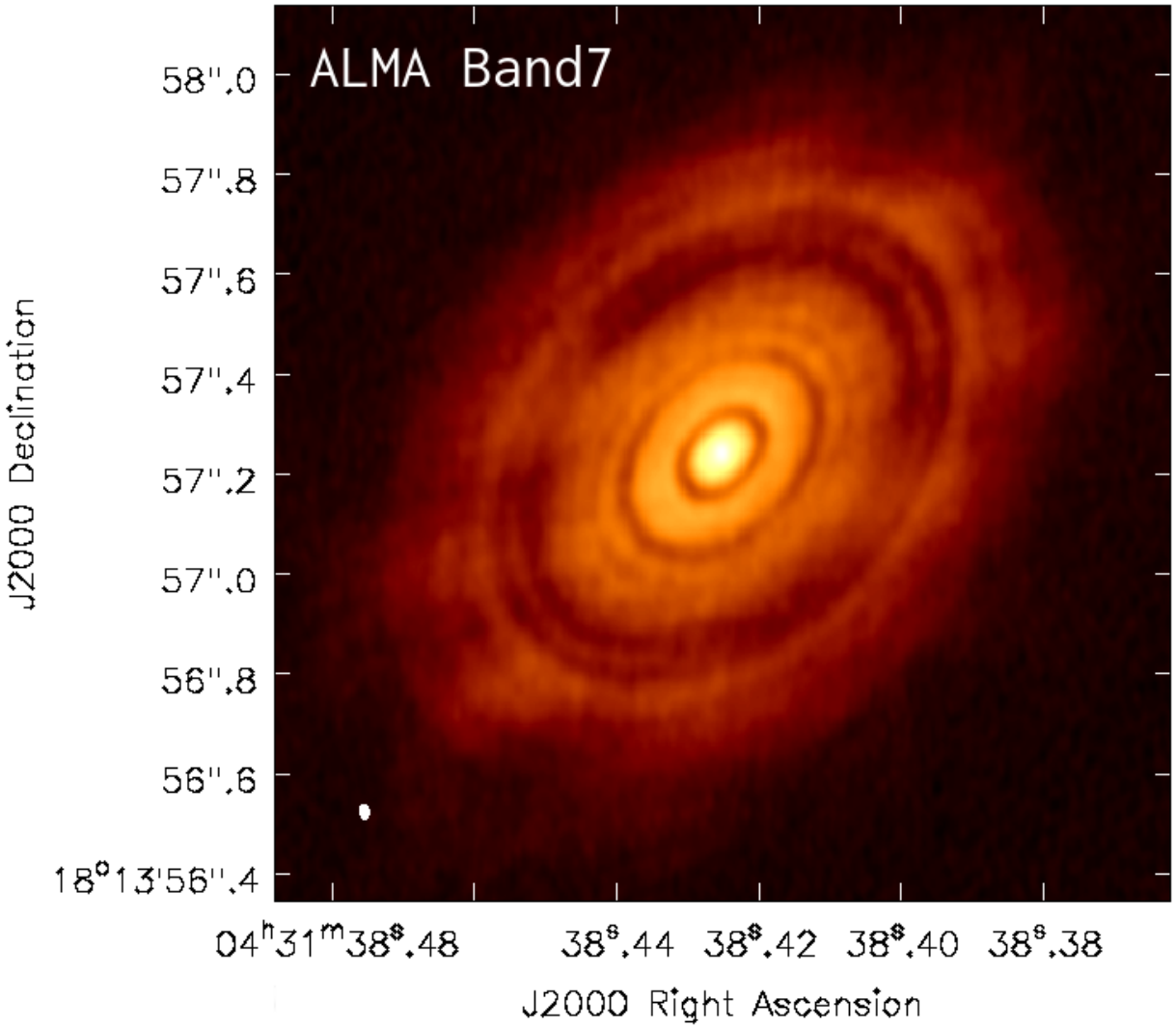
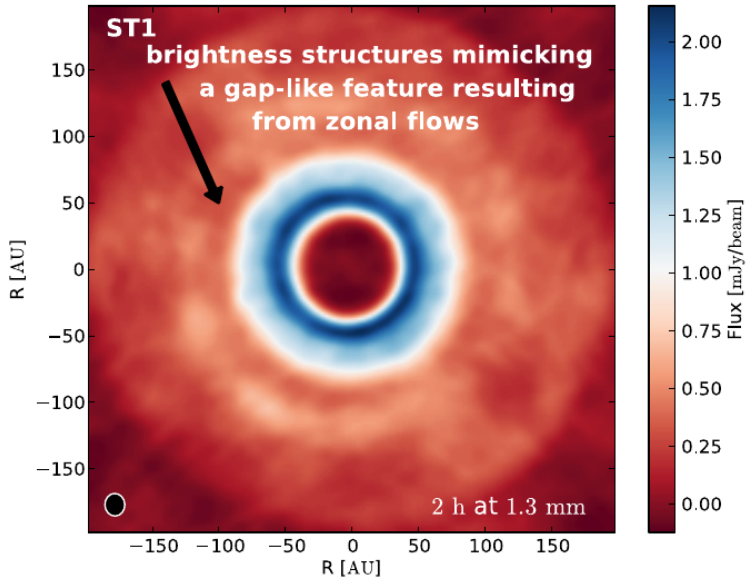
Angular resolution of 0.025 arcsec (3.5 AU)

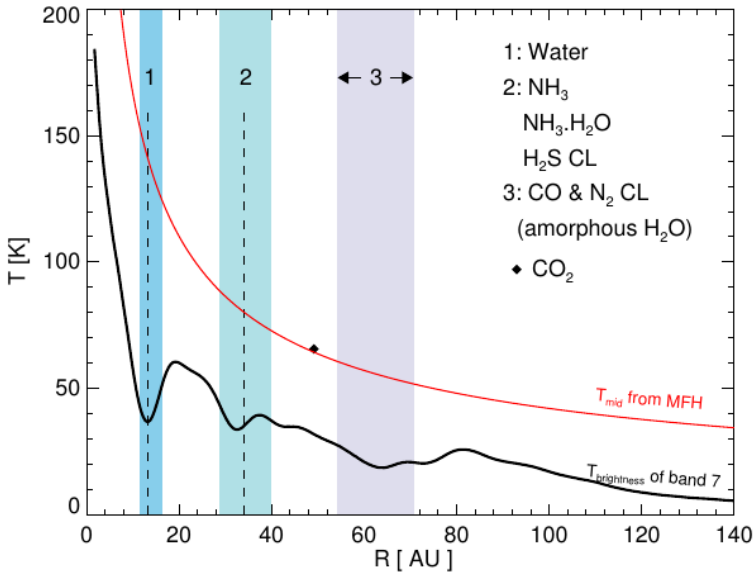


(ALMA Partnership et al. 2015)

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)

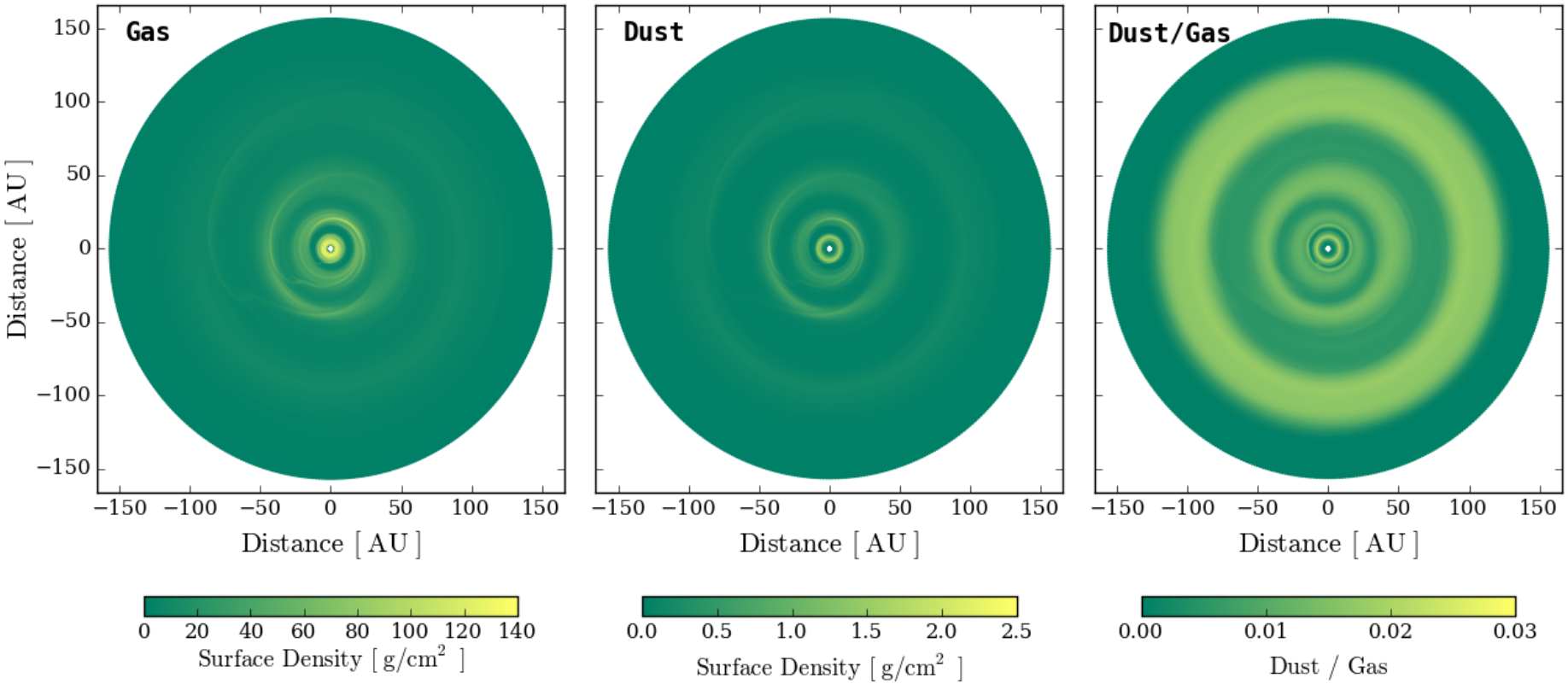
Observed features that favour planet-induced gaps:

- The spectral indexex 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 μm, 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 $M_{\rm Jup}$ are fixed at 13.1 33.0 68.6 AU.
- The system evolves for 4000th orbit (r $=$ 10 AU).
- We vary the α-viscosity and planetary masses, or turn off the disk self-gravity for parameter studies.
- NOTE: planets are fixed at their orbital locations.

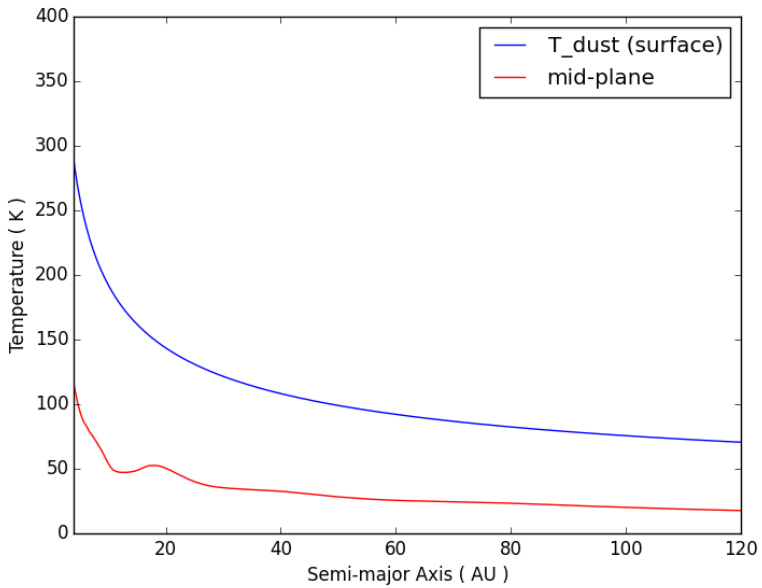
Hydro snapshot at 4000th orbit ($r = 10$ AU)



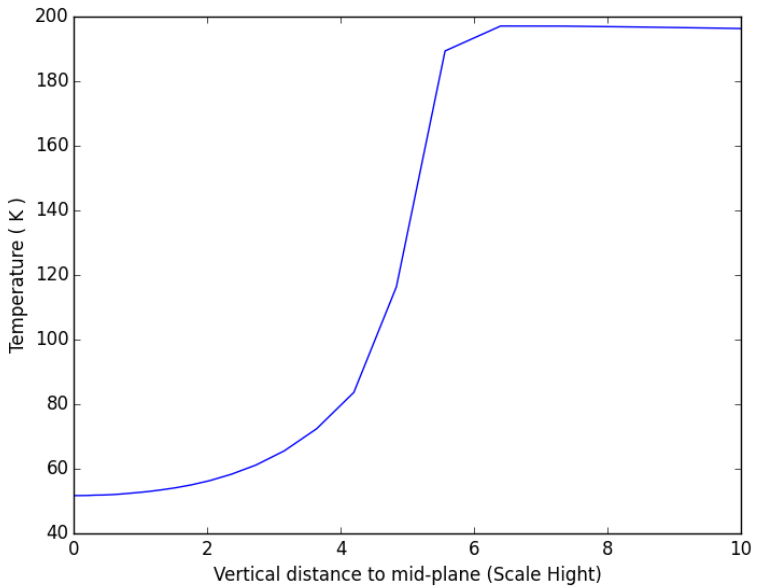
(Jin et al. in prep)

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.



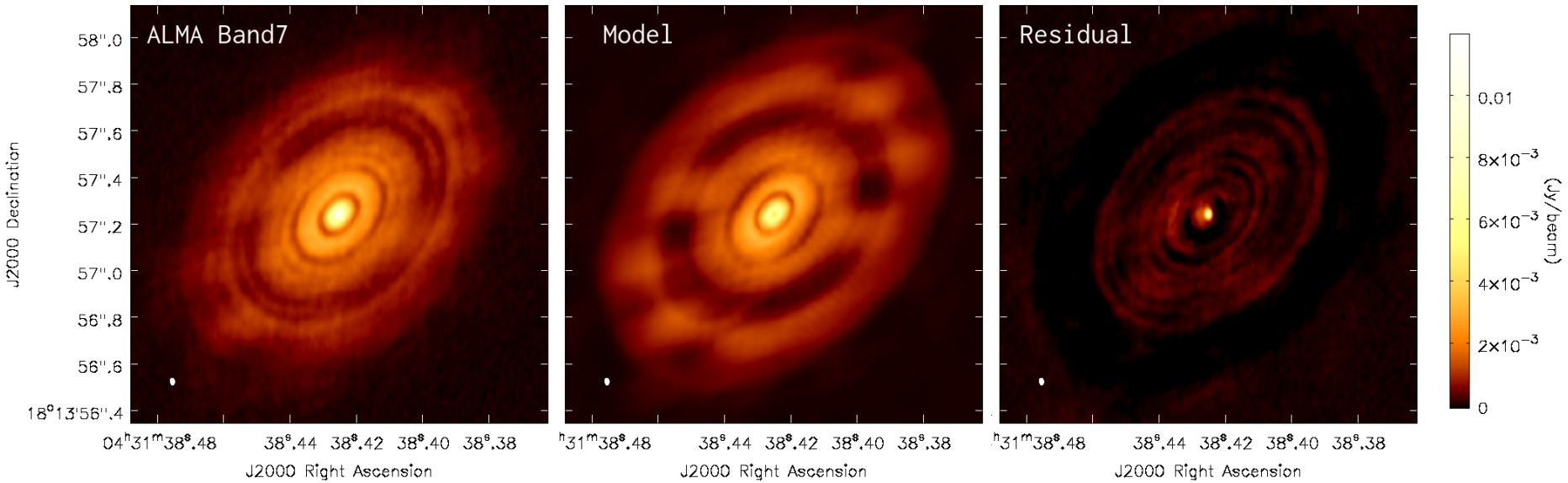
Radial temperature profile



Vertical (10 AU) temperature

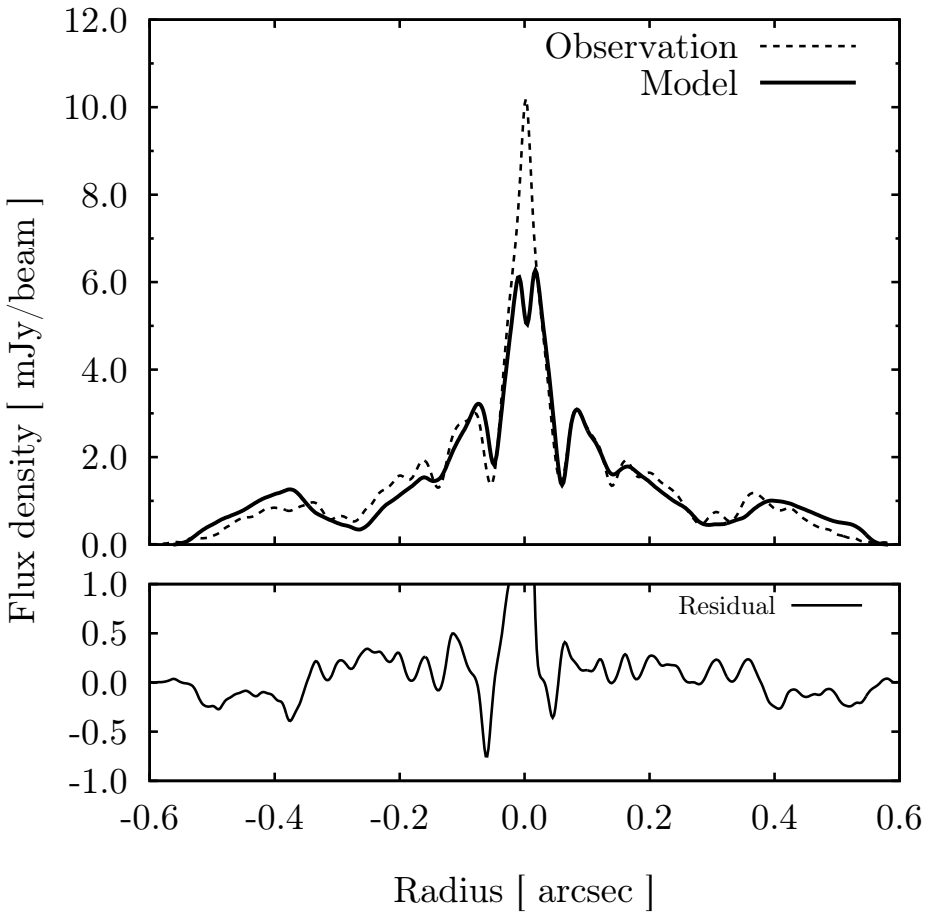
Observe the model

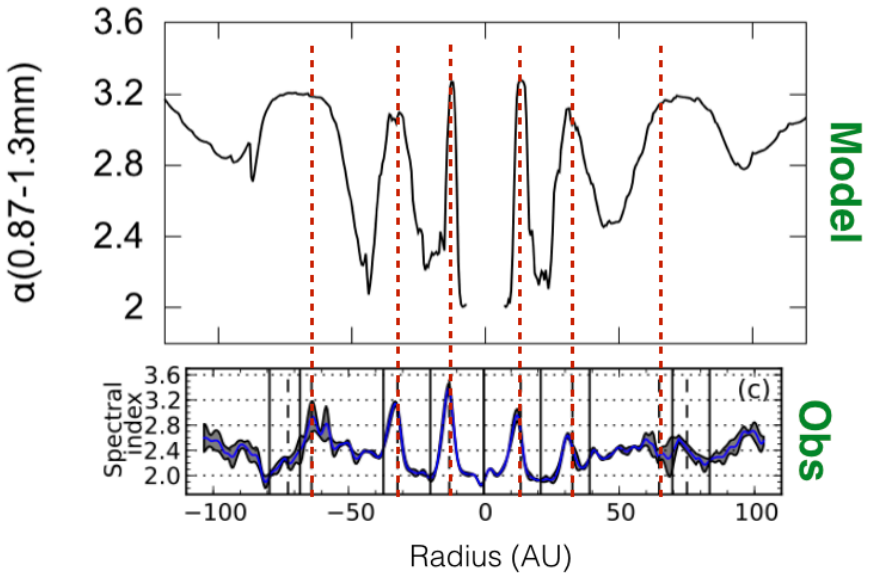
- For each u,v point in the ALMA data, replace the observed visibility by the Fourier transfer of our model image.
- Observe the new model data using the "clean" algorithm in CASA.



(Jin et al. in prep)

Radial profiles of flux density and spectral index

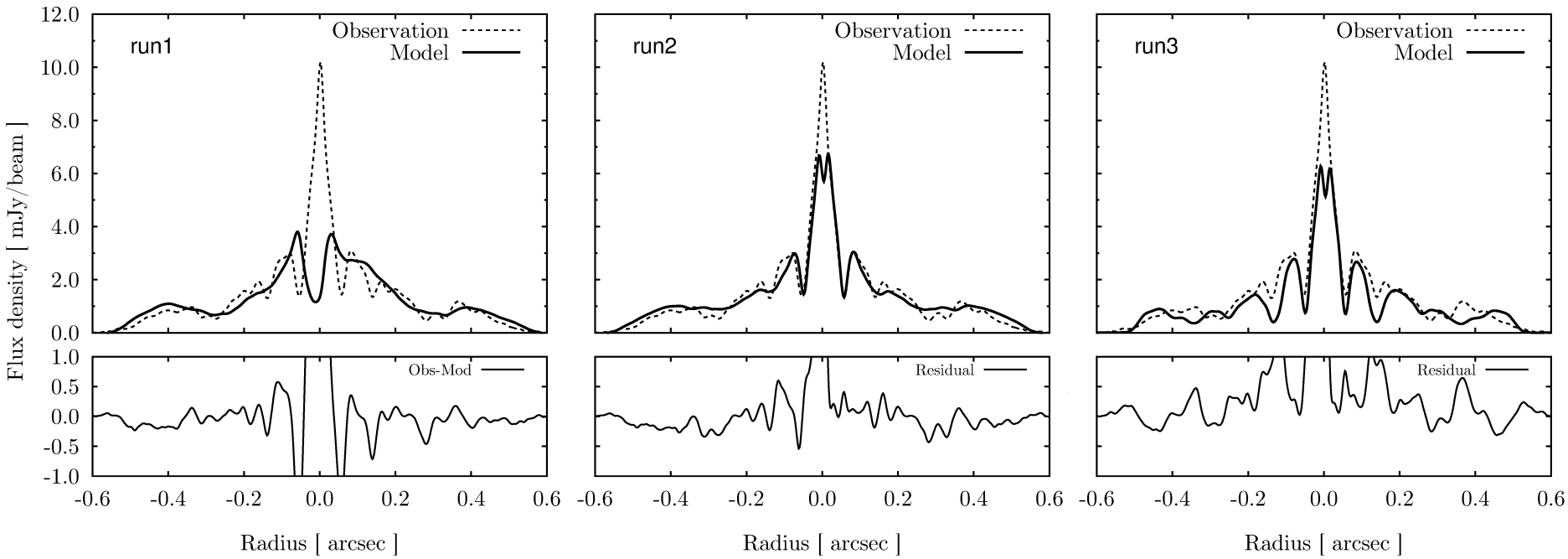




(Jin et al. in prep)

Comparison of parameters

- run1: planetary masses are reduced by half.
- run2: disk self-gravity is not included.
- run3: α-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 planteray 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!