# CIRCUMPLANETARY DISK SIMULATIONS AND OBSERVATION EFFORTS

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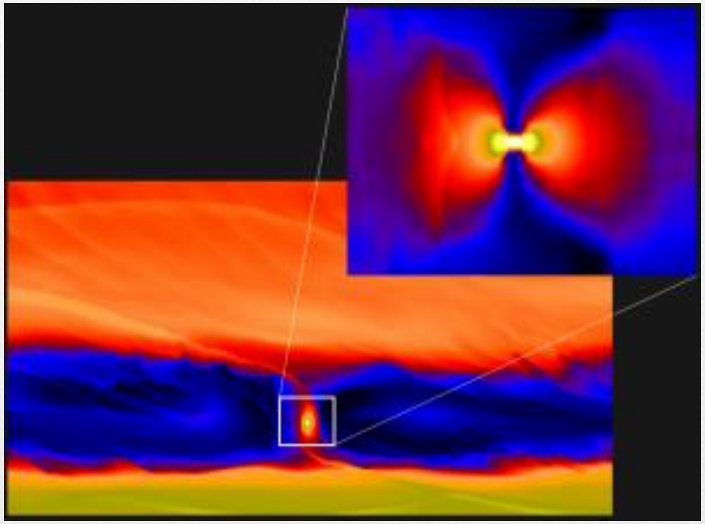
# Why we care about circumplanetary disks?



- Regulate the late accretion to the giant planet
- Birthplace of satellites
- No observations yet, but we want to detect them

# Outline

I. Planetary temperature effects on the circumplanetary gas
II. Entropy of the circumplanetary disk
III. Distinguishing between core accretion and disk instability formation mechanisms via observations
IV. ALMA Data
V. Wavelength Specific Radiative Transfer

# I. PLANETARY TEMPERATURE

Szulagyi 2016b submitted

# Planetary Temperature Matters!

Evolutional Temperature sequence of

10000 K

8000 K

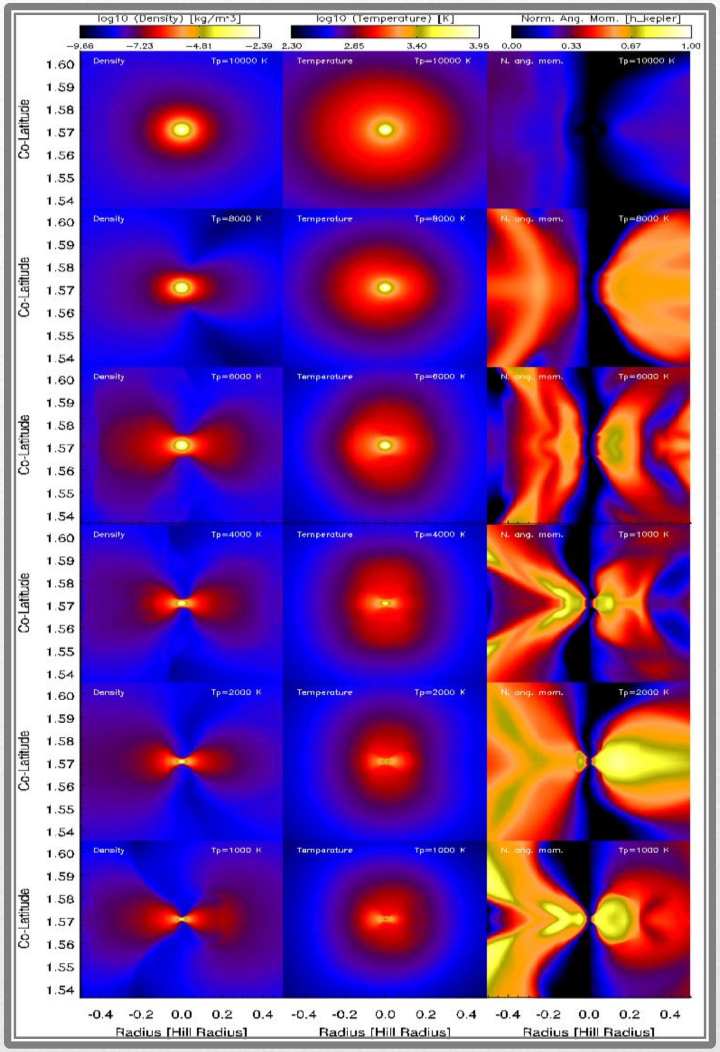
6000 K

4000 K

2000 K

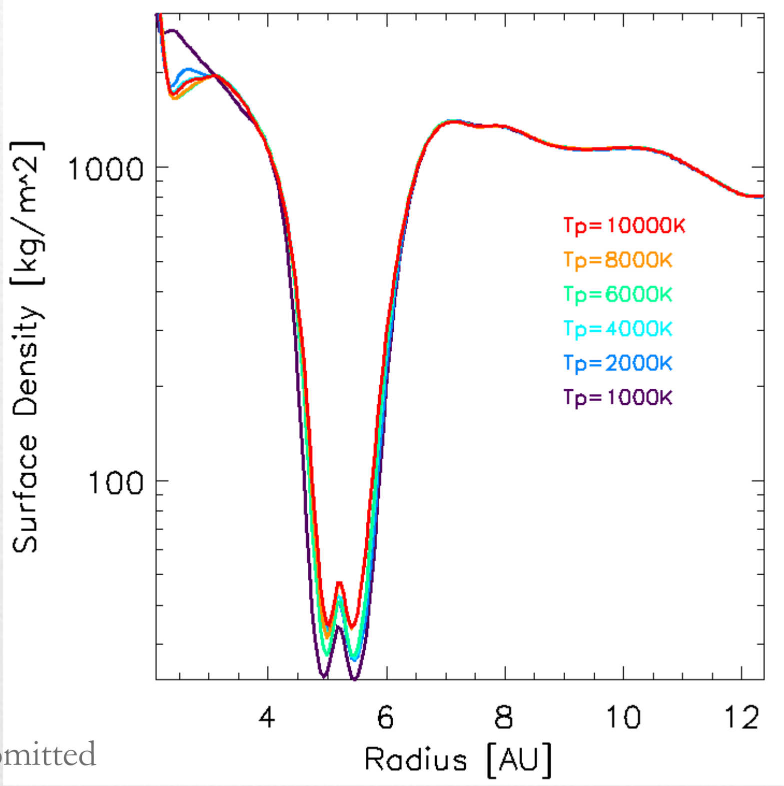
1000 K

Mordasini et al. in prep. 2016, Guillot et al. 1995




Szulagyi 2016b submitted

# Gap Profile based on $T_{planet}$

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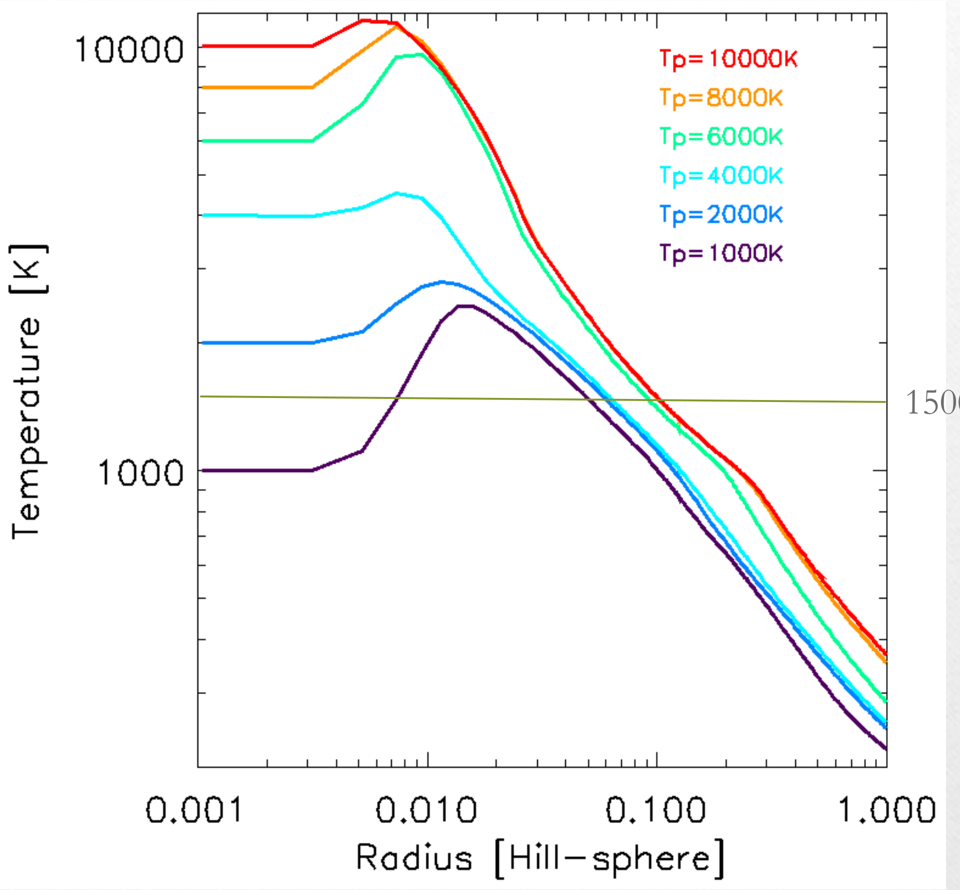



1500 K – silicate sublimation point

Szulagyi 2016b submitted

# Consequences

- Satellites form late
  - Bulk temperature of the circumplanetary disk < 1500 K (dust can exist)
  - Disky state needed

# II. ENTROPY

Szulagyi & Mordasini 2016 submitted

# SHOCKINGLY HOT NEWS ON THE CIRCUMPLANETARY DISKS

Szulagyi & Mordasini 2016 submitted

# Review

Marley+07, Marleau & Cumming14, Mordasini+ 12,13

## Hot-Start Scenario

- High luminosity & entropy (>9.5 kB/baryon)
- (((Gravitational Instability)))
- No shock
- Big core planets

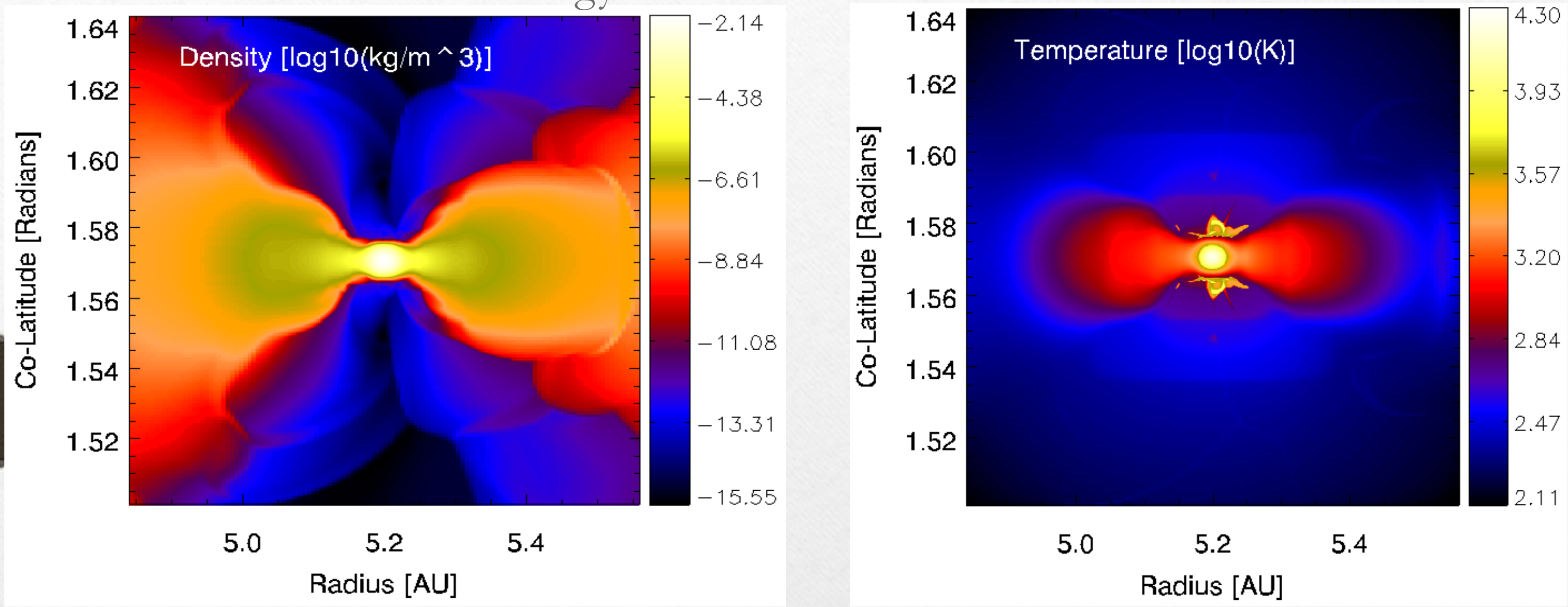
## Cold-Start Scenario

- Low luminosity & entropy (<9.5 kB/baryon)
- (((Core-Accretion)))
- Shock-accretion

# Observational Motivations

*All directly imaged planets* consistent with
hot-start scenario (high luminosity and entropy)
but most of them could not form via GI

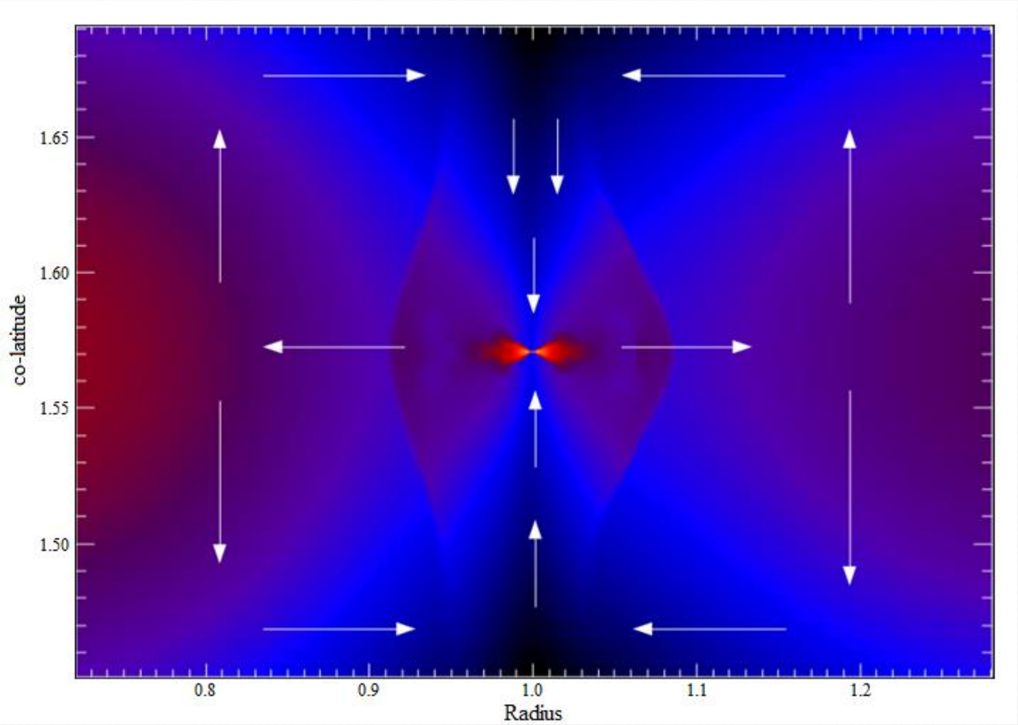
Szulagyi & Mordasini 2016 subm



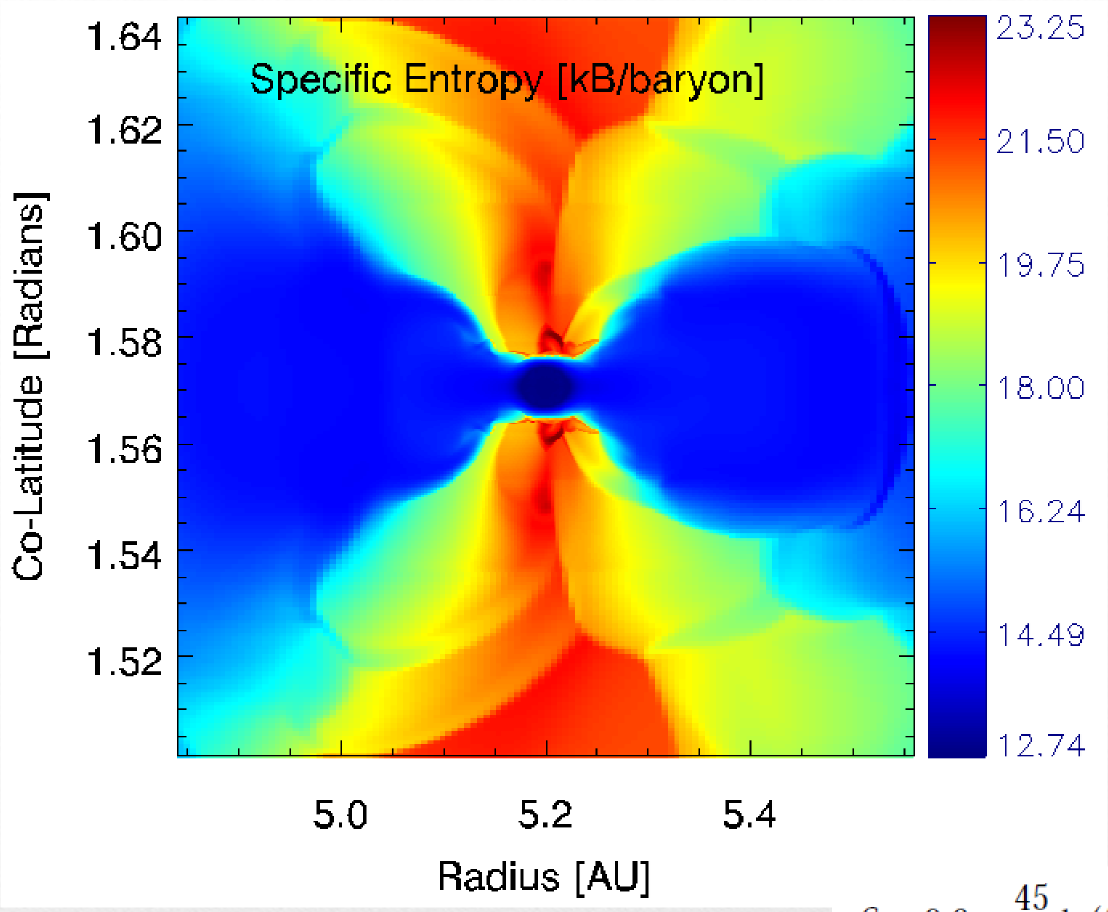

Vertical influx, Meridional circulation,
Szulagyi+14, Morbidelli+14

Hot Shock Surface on the top of the circumplanetary disk!!

# Meridional Circulation, Vertical Influx




Szulagyi+14, Morbidelli+14, Szulagyi PhD thesis




Szulagyi & Mordasini 2016 subm

$$S = 9.6 + \frac{45}{32}\ln(T/1600\ \mathrm{K}) - \frac{7}{16}\ln(P/3\ \mathrm{bar})$$

# Equation of States

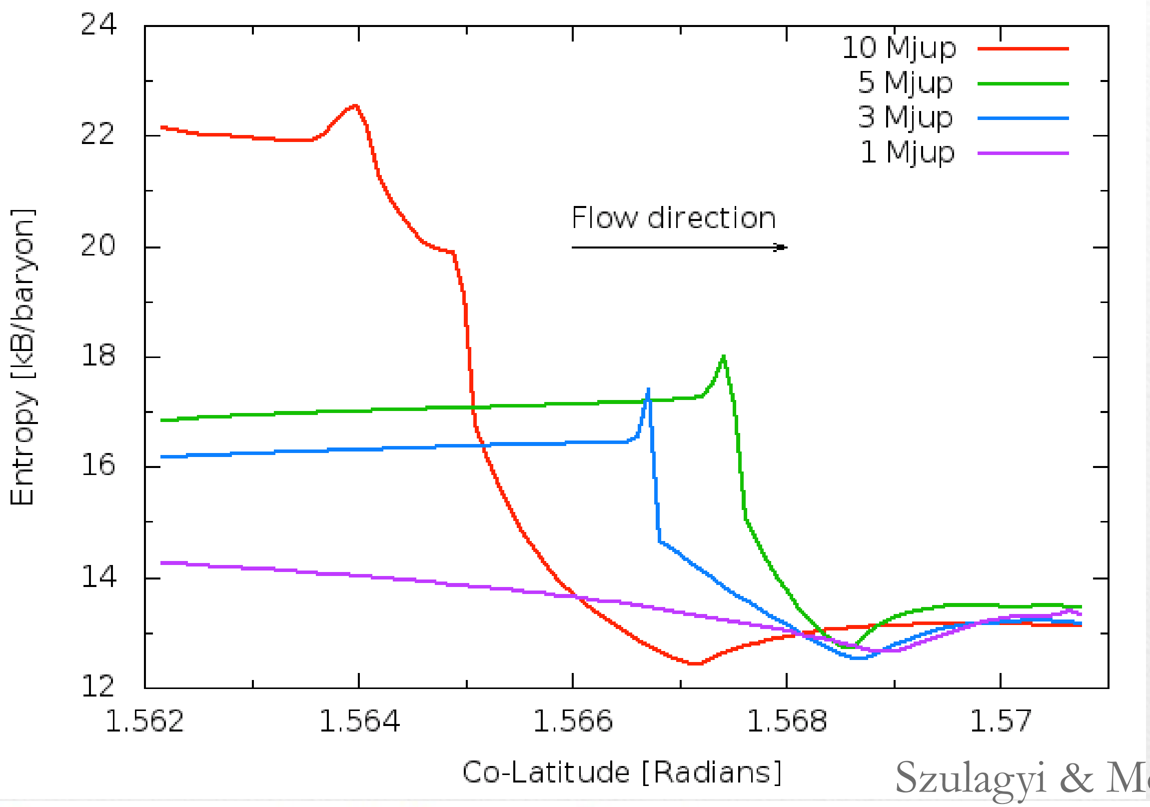
No Ionization

- Sackur-Tetrode expression
- NASA Chemical Equilibrium Code

Ionization Included

- Saumon-Chaubrier EOS (planet interiors)
- NASA Chemical Equilibrium Code

See in Saumon et al. 1995, Marleau & Cumming14




Szulagyi & Mordasini 2016 subm

**Table 1.** Temperatures, post-shock, and shock entropy for different planet masses

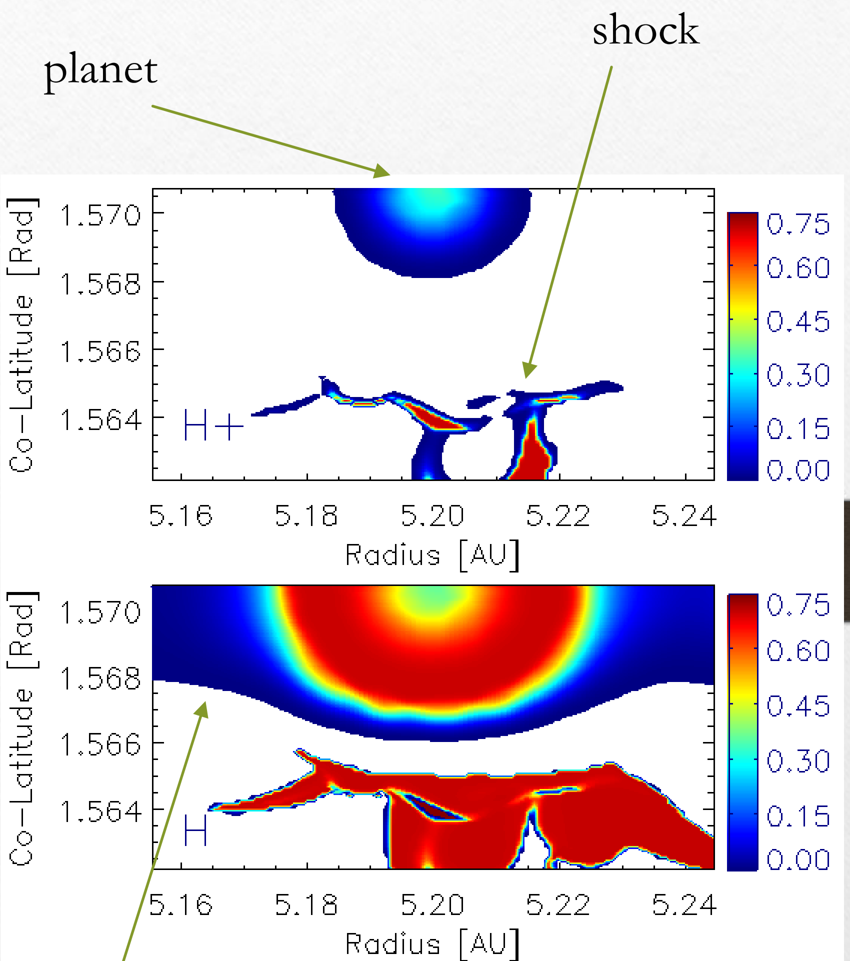
| Planet mass [$M_{\jupiter}$] | $T_{peak}$ in the shock front [K] | S (ST)[a] | S (SCvH)[a] | S (CEA-ion)[a] | S (CEA-neutral)[a] | $S_{shock}$ (CEA-ion) | $S_{shock}$ (CEA-neutral) |
|---|---|---|---|---|---|---|---|
| 3.0 | 3923 | 15.39 | 14.73 | 14.66 | 14.66 | 28.39 | 17.40 |
| 5.0 | 3667 | 15.74 | 15.14 | 15.05 | 15.05 | 29.33 | 18.00 |
| 10.0 | 8868 | 17.51 | 16.85 | 16.77 | 16.77 | 62.69 | 22.53 |

[a] The entropies $S$ were measured immediately after the Zeldovich spike, and $S_{shock}$ in the spike. ST denotes the Sackur-Tetrode expression, SCvH the Saumon-Chabrier-van Horn EOS, CEA-ion and CEA-neutral is the Chemical Equilibrium Code with ionization and dissociation and without. Entropies are in $k_B$/baryon.

## Mass-fractions of

- H (dissociation)
- H+ (ionization) →

**H-alpha emission**




Szulagyi & Mordasini 2016 subm

Observation: H-alpha from LkCa15 (Sallum+15)

# Take Home Messages

- Hot, luminous **shock surface** on the top of the circumplanetary disk
  - → Alter the **observational appearance** of circumplanetary disk (looking like hot-start)
  - → Alter the **entropy budget** of the planet (shock surface lowers the entropy)
  - → Conceal the planet entropy/luminosity below (optically thick surface on certain wavelengths)

# III. CORE ACCRETION OR DISK INSTABILITY?

Szulagyi, Mayer, & Quinn 2016d submitted

# Motivation

- Observing the circumplanetary disk mass with ALMA, can we distinguish between the two major formation mechanisms?
- Our ALMA data from 2015, J. Pineda et al. in prep. (see later)

# Circumplanetary Disk Mass

## Core Accretion

- $10^{-3} – 10^{-4}$ of $M_{planet}$

Gressel+ 2013, Ayliffe & Bate2009, D'Angelo+ 2003, Szulagyi+ 2014, Szulagyi+16

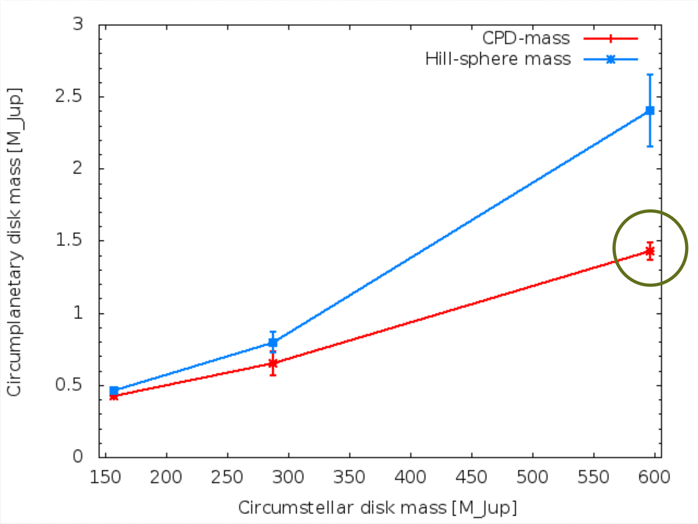
Orders of magnitude difference

## Disk Instability

- 0.25-0.5 of the planet mass

Shabram & Boley 2013, Galvagni et al. 2012

# Correllation between Circumplanetary Disk Mass and Protoplanetary Disk Mass

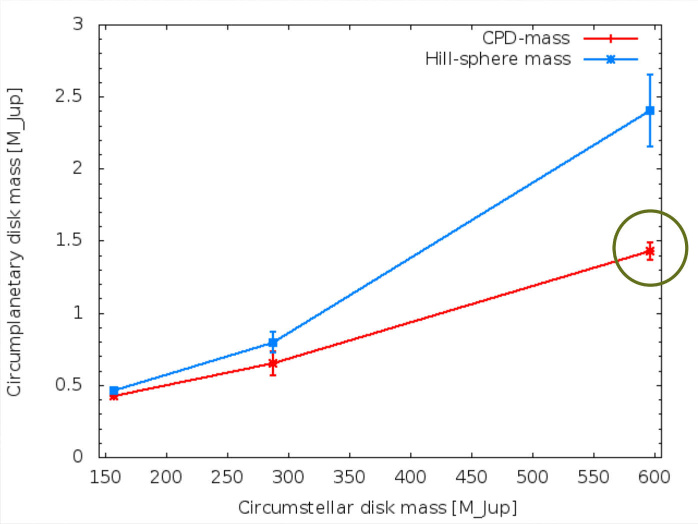



0.12 $M_{planet}$

Szulagyi et al 2016d subm

# Correllation between Circumplanetary Disk Mass and Protoplanetary Disk Mass

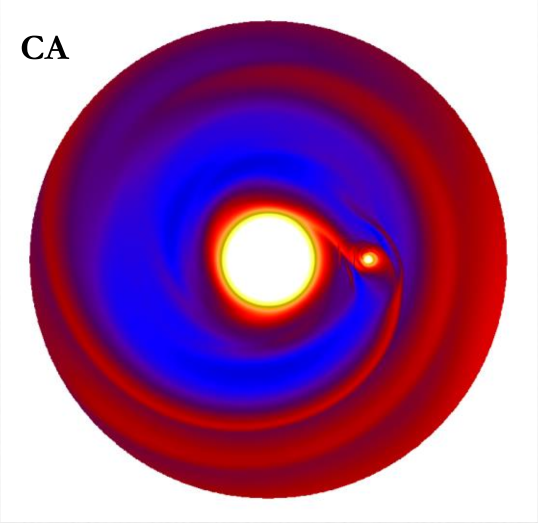
Not the different formation scenarios lead to different circumplanetary disk mass, simply the mass of the circumstellar disk!

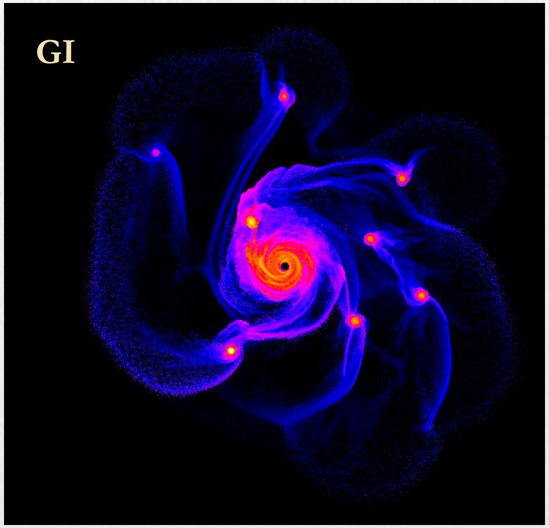



$0.12\ M_{planet}$

Szulagyi et al 2016d subm

# Similar Initial Parameters for the two types of simulations!



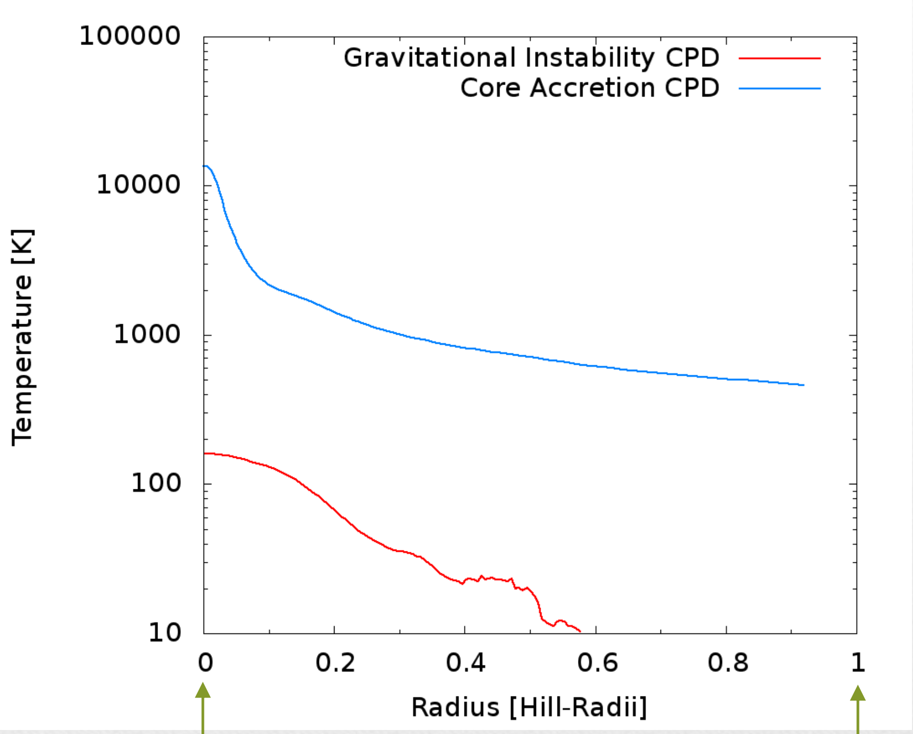




Szulagyi et al 2016d subm

Szulagyi et al 2016d subm

# Temperature on the midplane

Order of magnitude difference! ← observability!

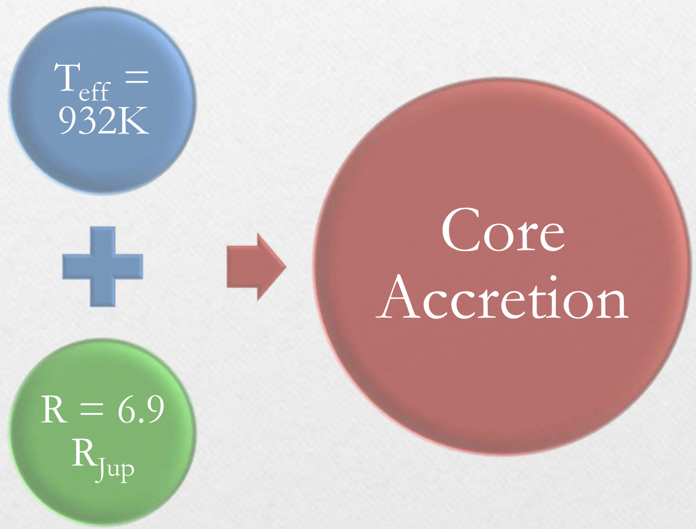



Planet

Hill-sphere

# Review - Observations

HD 100546 b
Quanz et al. 2015



# Conclusions

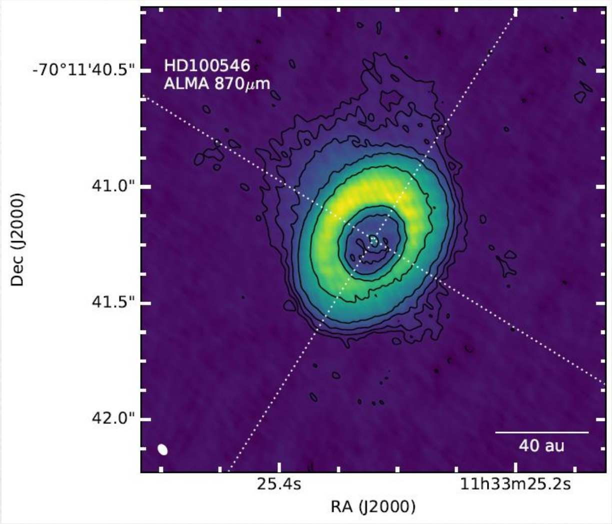
- Mass difference a factor of ~8 (more massive GI)
- Temperature difference 50 K (GI) vs 800 K (CA)

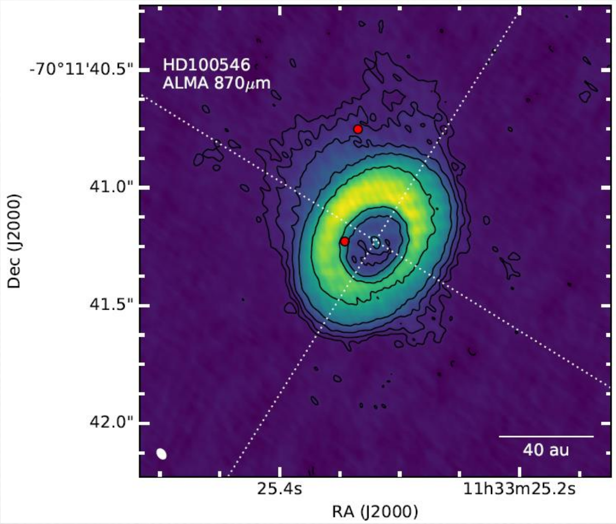
Observationally temperature-wise would be easier to distinguish

# IV. ALMA DATA

Pineda et al. 2016 in prep.

# Dust Continuum – HD100546




Pineda et al. in prep.

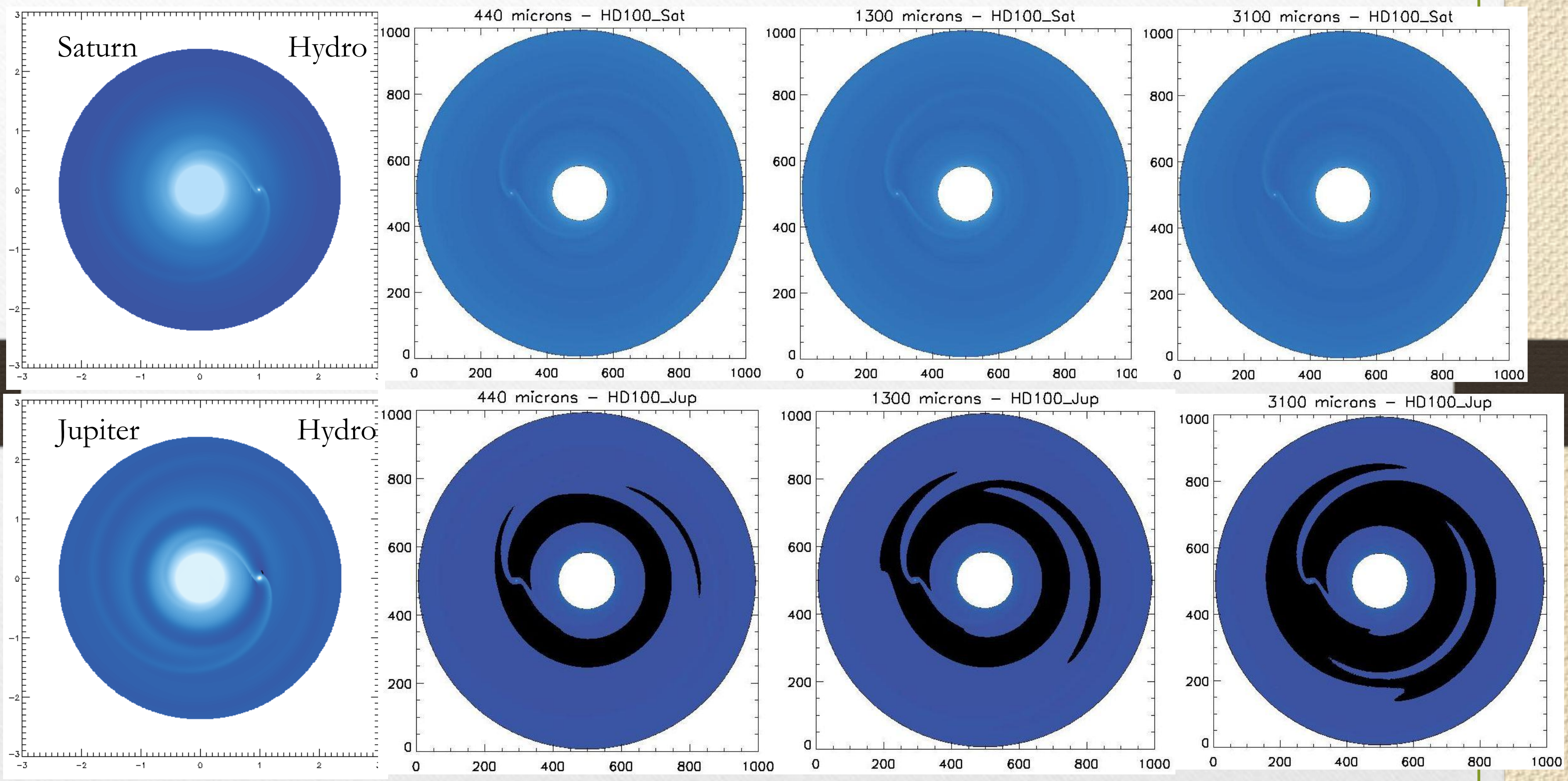
# V. RADIATIVE TRANSFER

Szulagyi et al. 2016 e & f in prep.

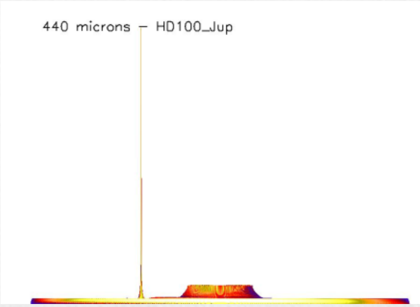
# Hydro + RADMC3D

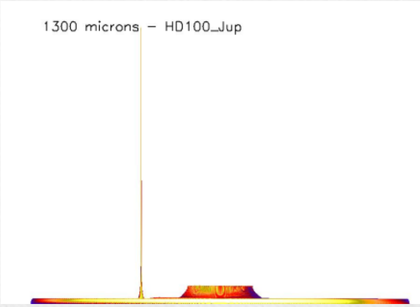
- Spectral Energy Distributions (SEDs) for the circumstellar and for the circumplanetary disks
- Synthetic images for ALMA and for other instruments (e.g. ESO NACO)
- Luminosities of circumplanetary disks → revise planetary masses from direct imaging observations

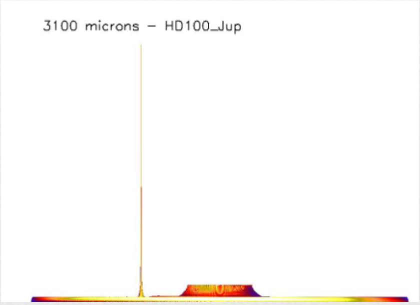
- Case study for HD100546


Saturn
Hydro
440 microns – HD100_Sat
1300 microns – HD100_Sat
3100 microns – HD100_Sat
Jupiter
Hydro
440 microns – HD100_Jup
1300 microns – HD100_Jup
3100 microns – HD100_Jup

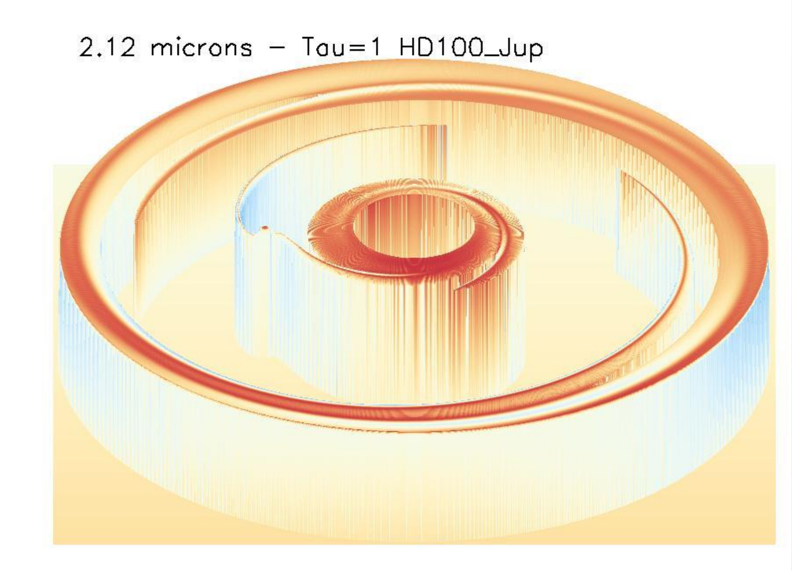
# Intensity maps a bit differently

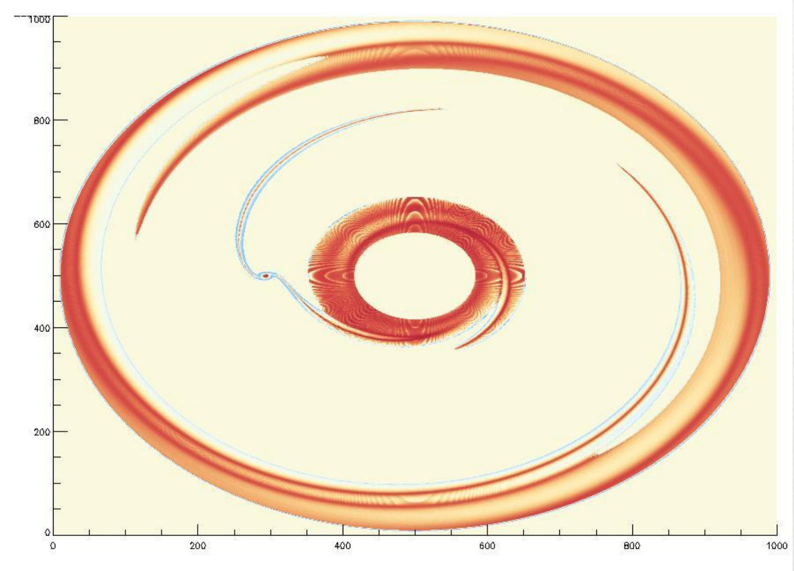


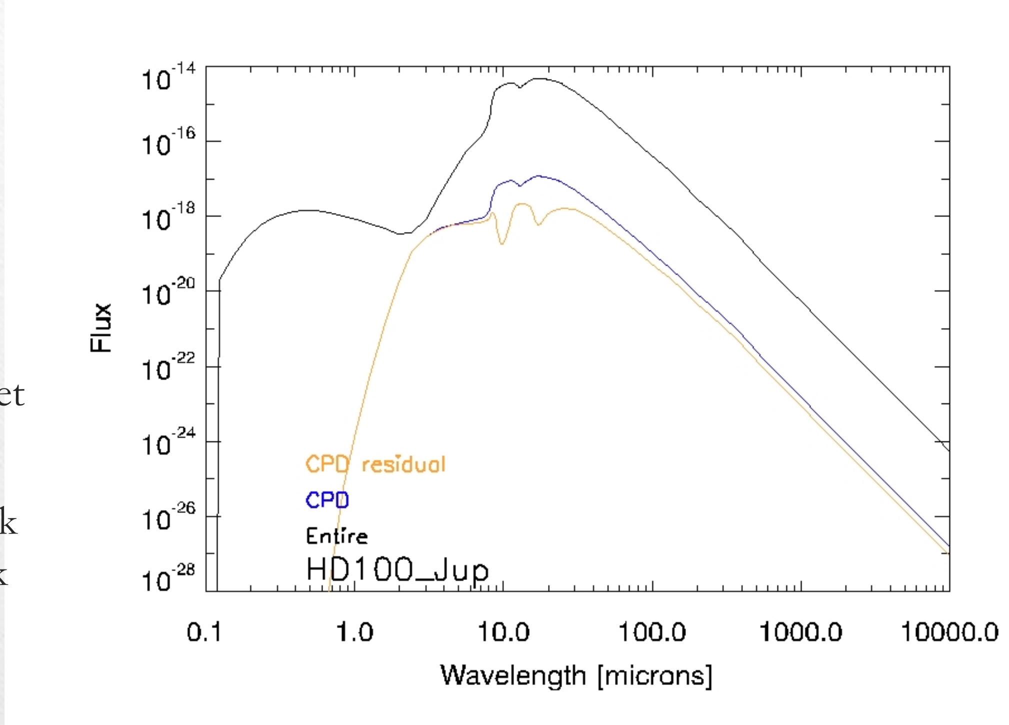
# Optical depth = 1.0 maps



# Spectral Energy Distributions

- Entire system (star+circumstellar disk+ planet + circumplanetary disk)
- Box SED: circumplanetary disk + underlying circumstellar disk
- Box SED 2: residual of circumplanetary disk - underlying circumstellar disk




Szulagyi et al. 2016 e,f in prep

# Conclusions

- Planetary temperature matters whether we get envelope or a disk around the planet – satellite formation happens late
- Shock front on the surface of the circumplanetary disk that alters the observational appearance, changes the planet entropy budget
- GI ↔ CA: circumplanetary disk temperature, not mass can distinguish; mass scales with circumstellar disk mass
- Circumplanetary disk luminosity contribution leads to overestimation of planetary mass