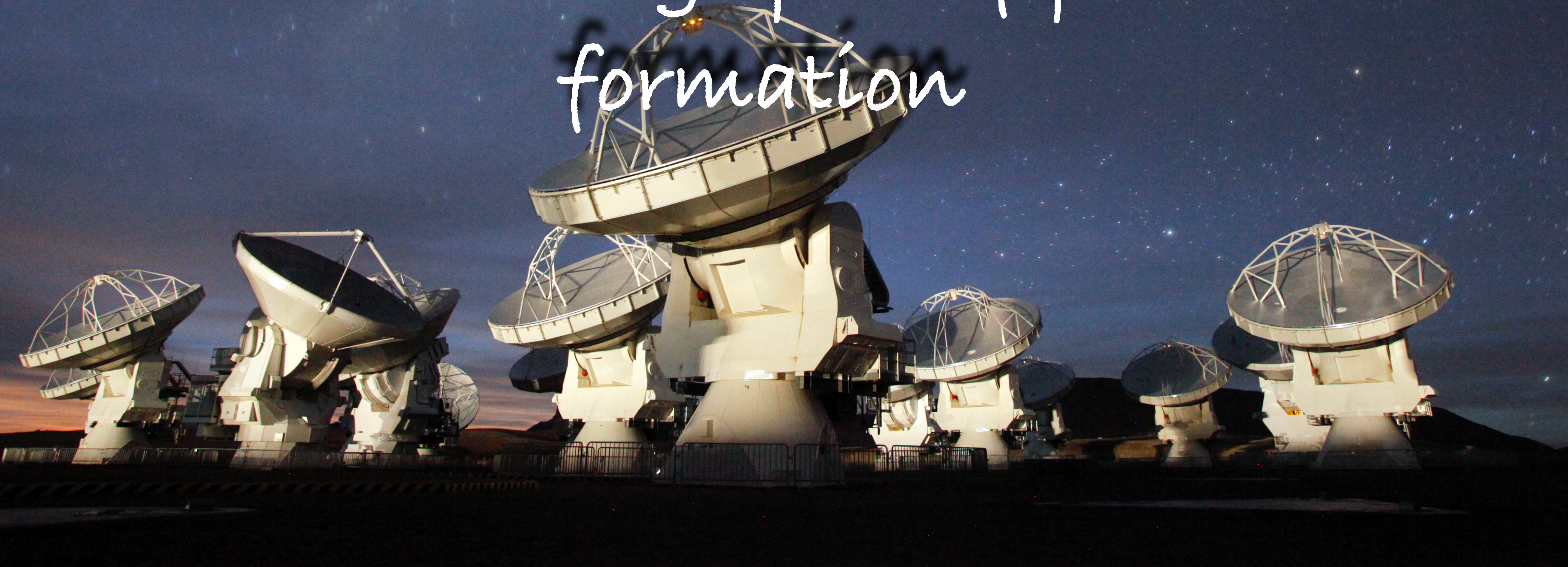
# ESO Cosmic Duolouge
# Structure in Protoplanetary Disks: a signpost of planet formation?

Edwin (Ted) Bergin
University of Michigan

# ESO Cosmic Duolouge
# Structure in Protoplanetary Disks: a signpost of planet formation

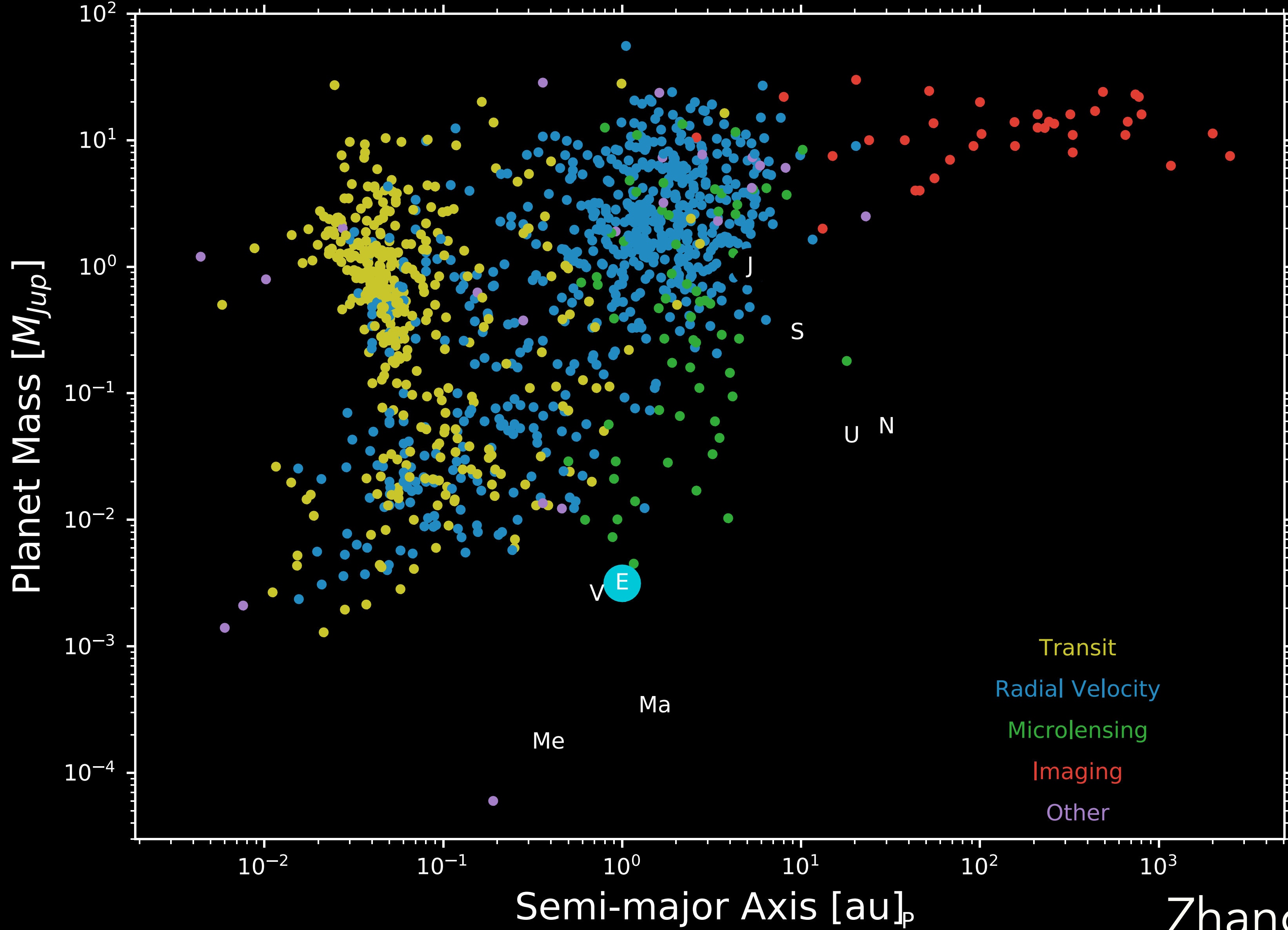


Edwin (Ted) Bergin
University of Michigan

# The Obvious…..

Giant planets form when gas is present.
We are observing the gas-rich stages commensurate with timescales for giant planet assembly - there are some planets here….

# EXOPLANET STATISTICS




Zhang +2018

# Protoplanet Detection

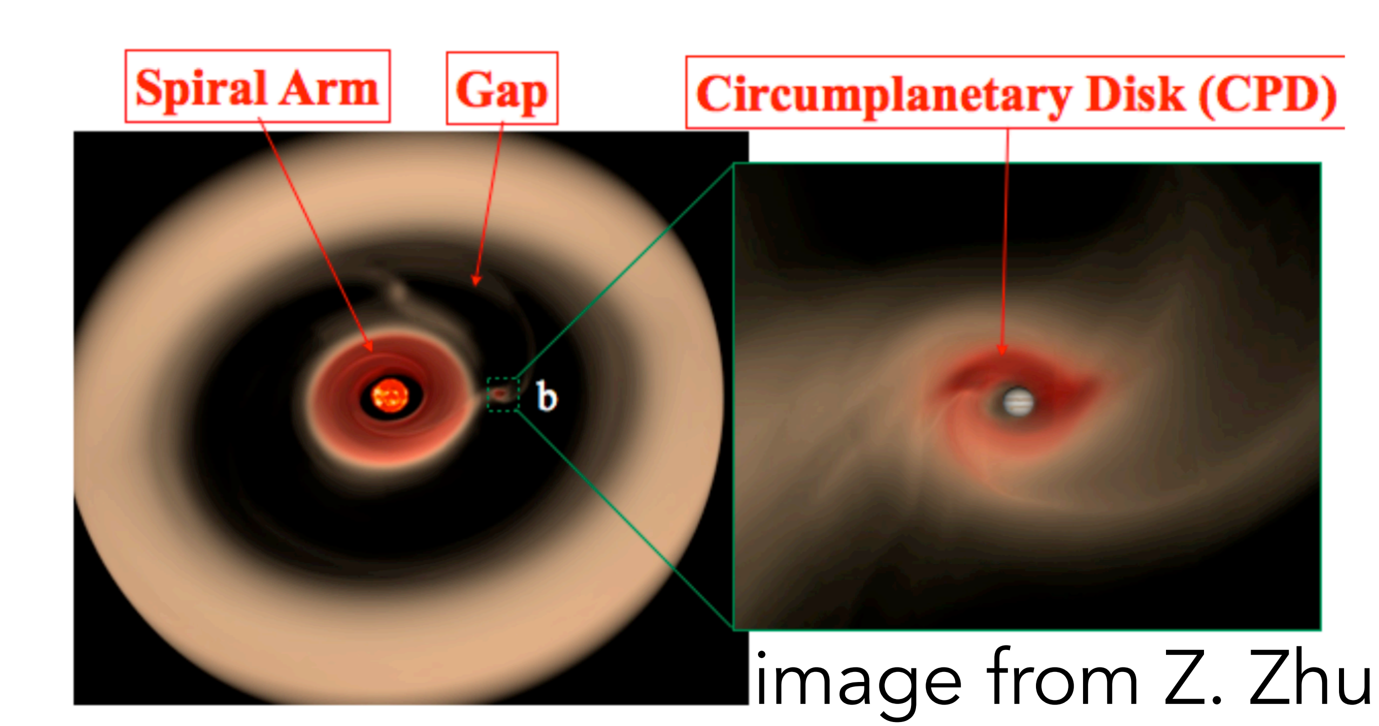
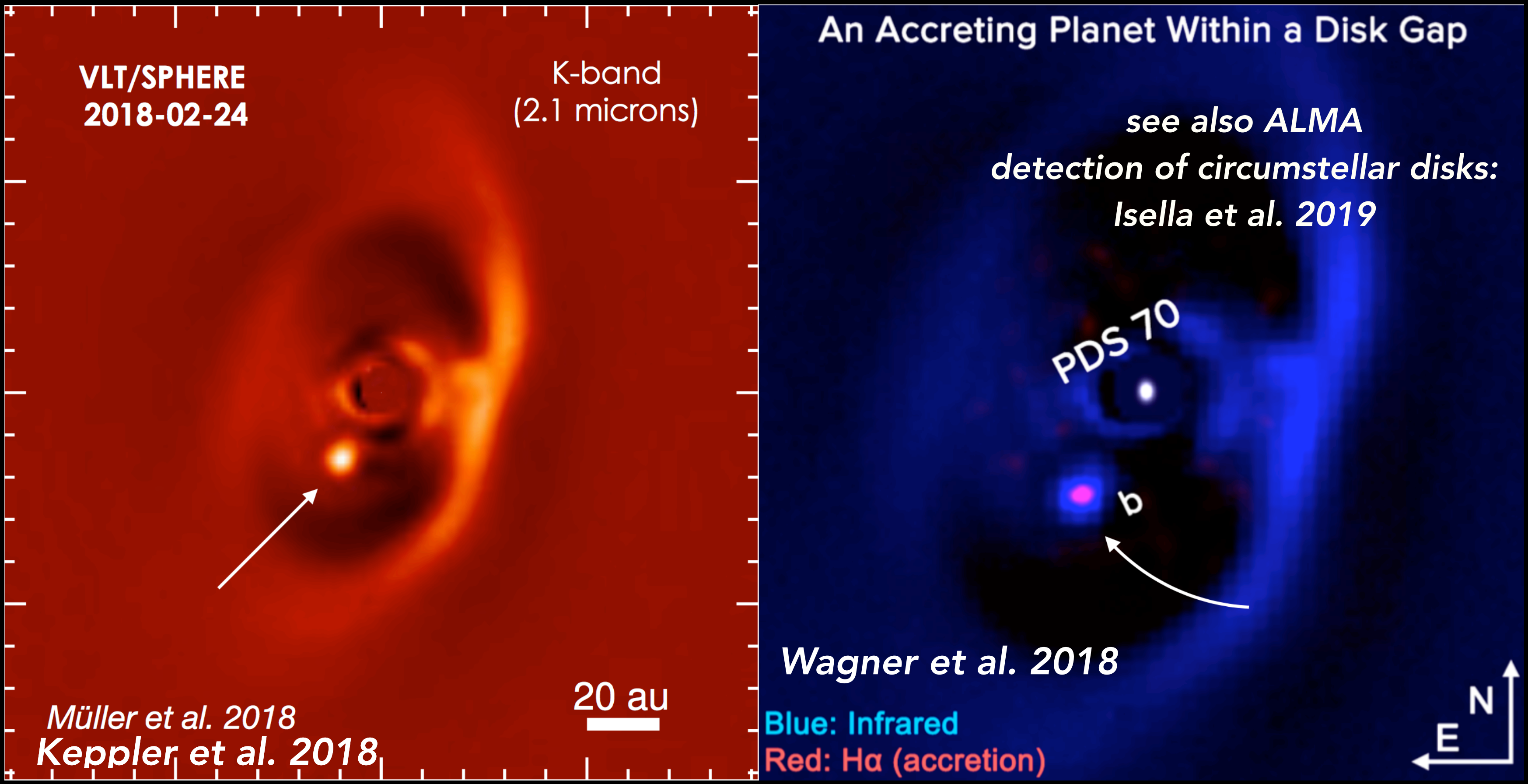


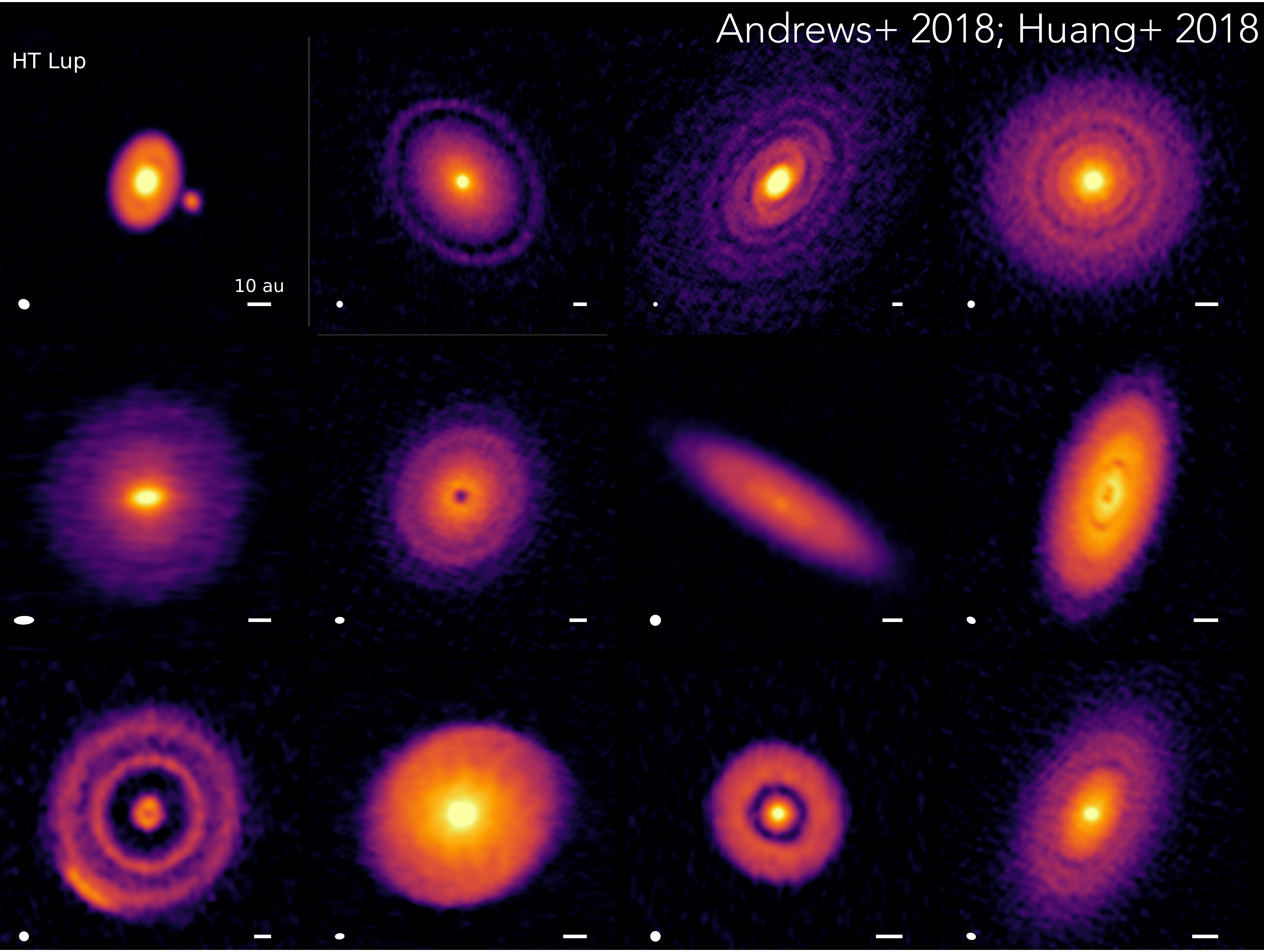
image from Z. Zhu

Will focus on results from ALMA which trace emission from ~mm-sized pebbles in planet-forming midplane of the disk, but....

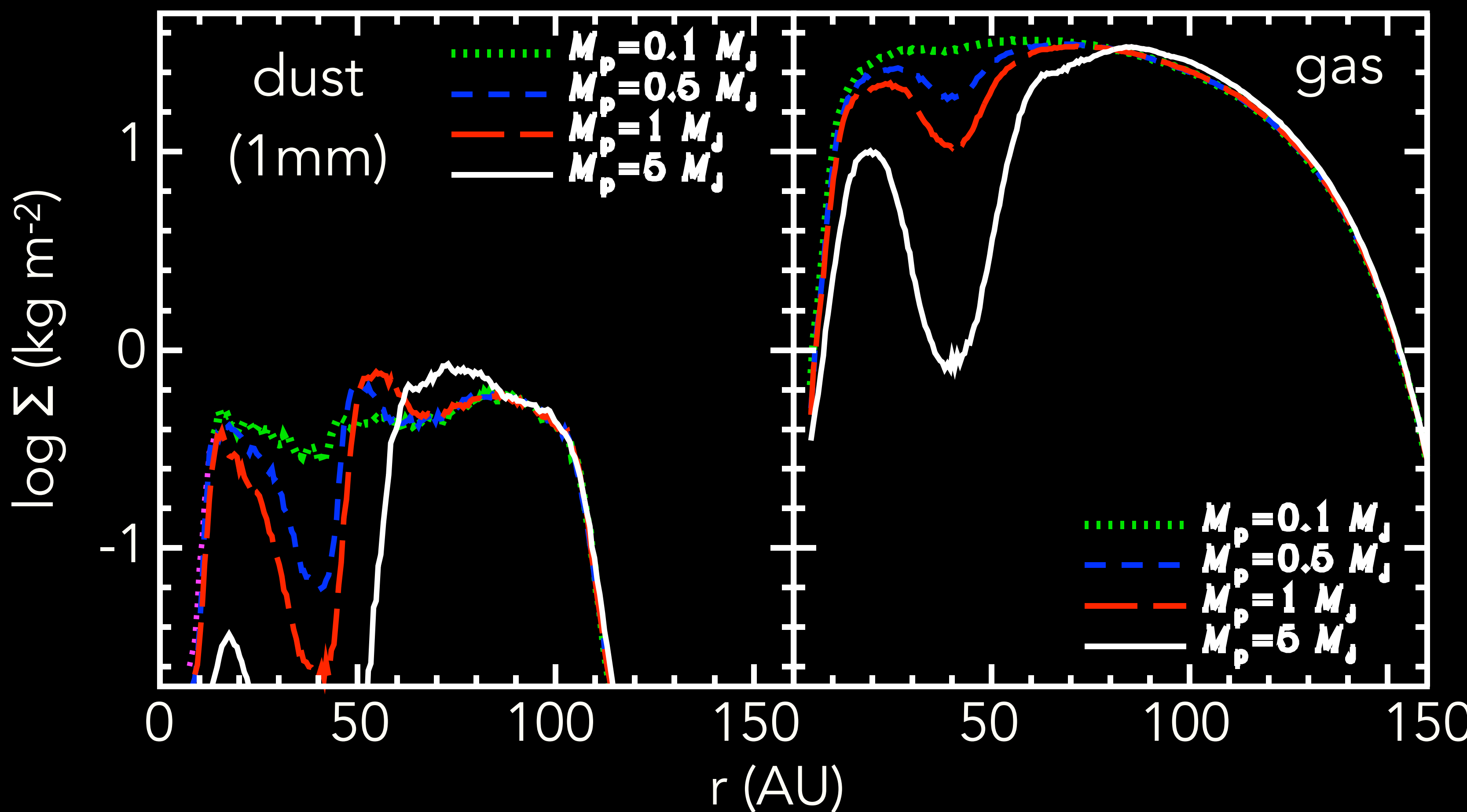
# Protoplanet Direct Emission

- Limitations of direct detection
  - ➡ hot start (Baraffe+2003; Burrows 1997) vs cold start (Marley+2007; Fortney+2008)
  - ➡ episodic accretion (Brittain et al. 2020)
  - ➡ < ice giants remain difficult to detect




Andrews+ 2018; Huang+ 2018
HT Lup
10 au

# Models of Planet-Disk Interaction

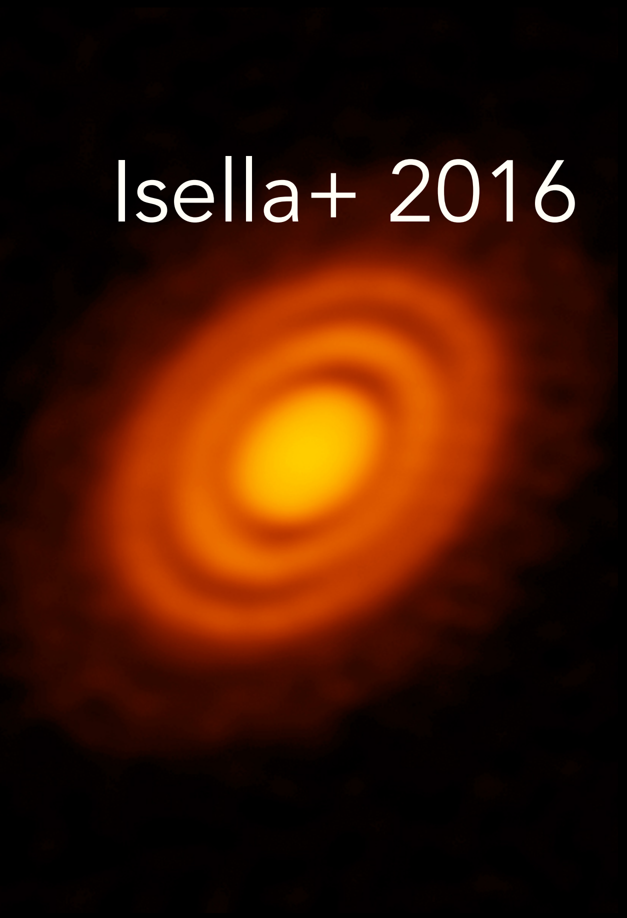


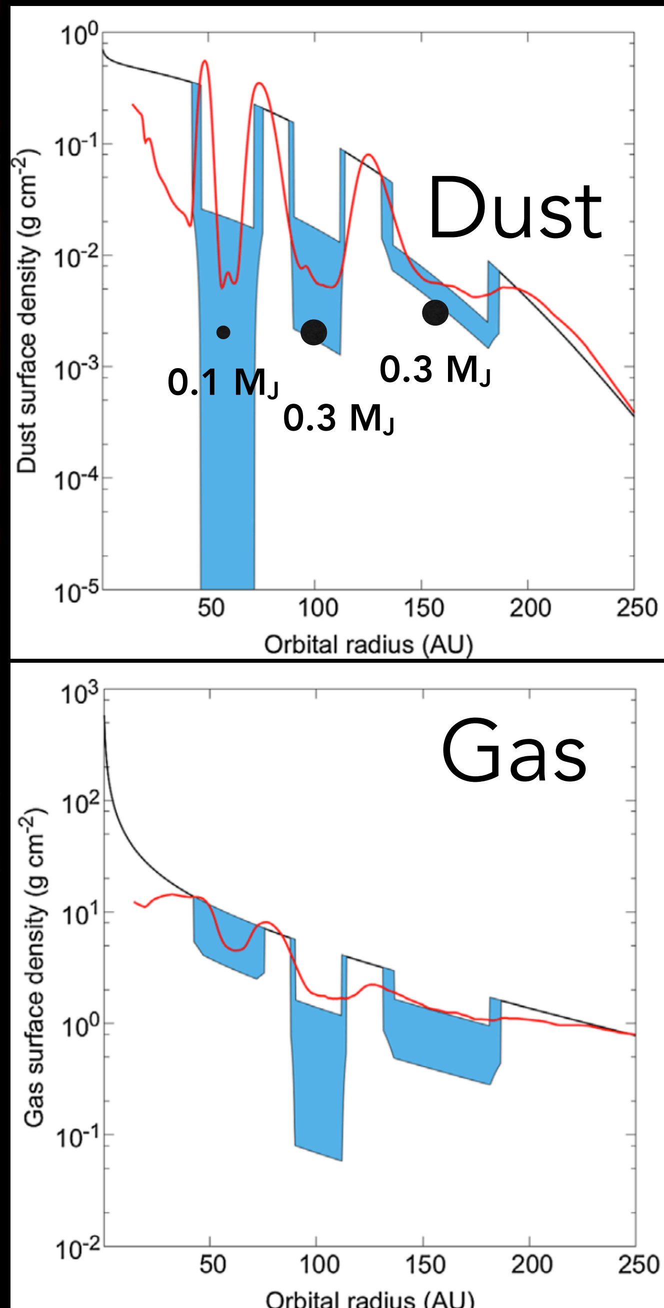

Fouchet+ 2010

- ➡ Gap width appears to depend on planet mass
- ➡ Change in dust surface density larger than gas
- ➡ Note: depends on assumptions regarding disk viscosity parameter (α) and B field - see recent work by Kanagawa et al. 2016; Fung and Chiang 2016; Dipierro and Laibe 2017; Bae et al. 2017; Dong and Fung 2017; Meru et al. 2017; Dipierro et al. 2018; Dong et al. 2018a; Fedele et al. 2018; Forgan et al. 2018; Facchini et al. 2018; Bae et al. 2019

# INFERRING PLANETS WITH ALMA

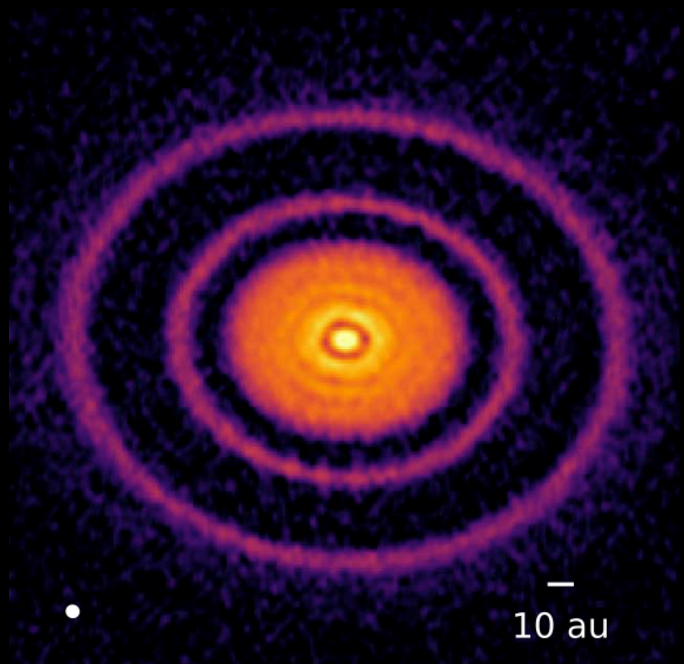
Isella+ 2016

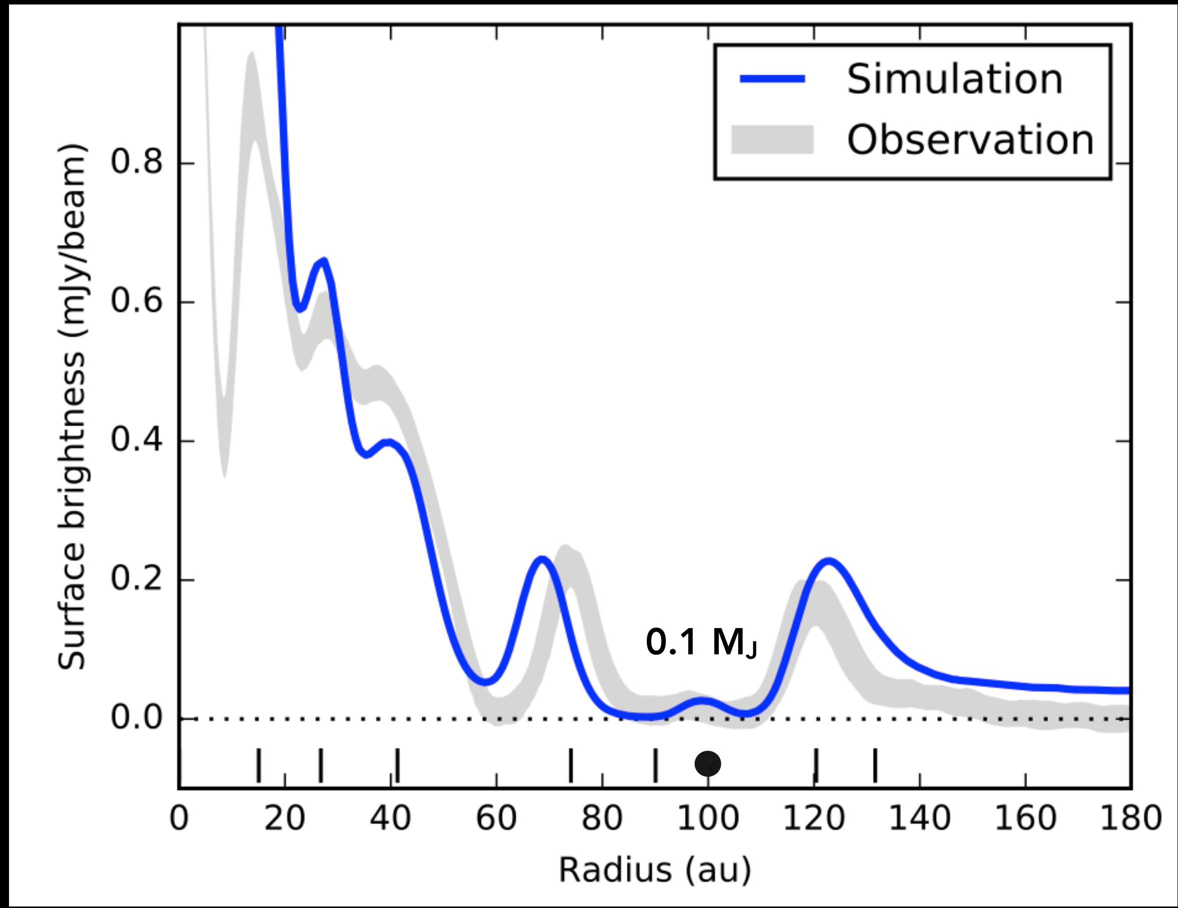




# INFERRING PLANETS WITH ALMA

Guzman+ 2018

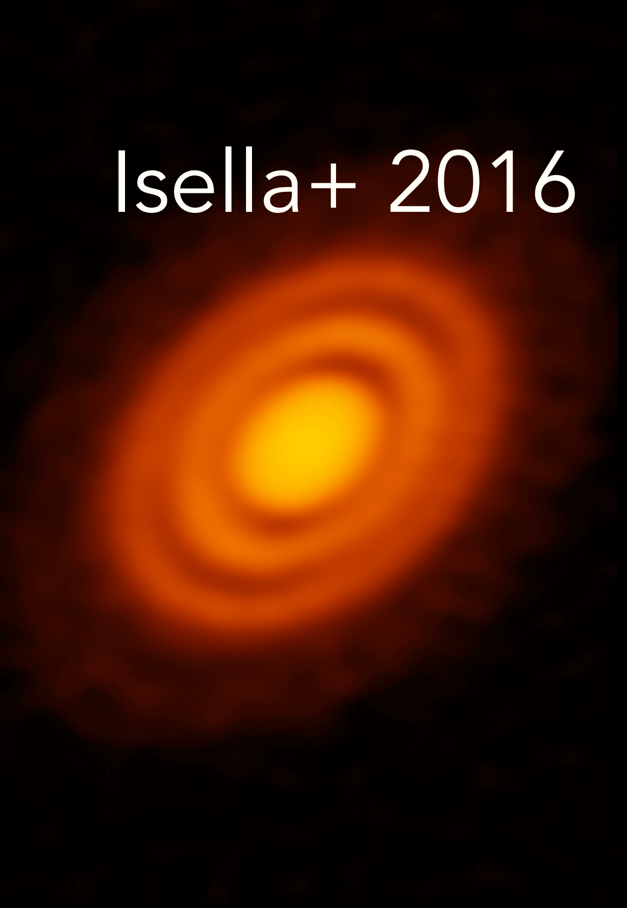


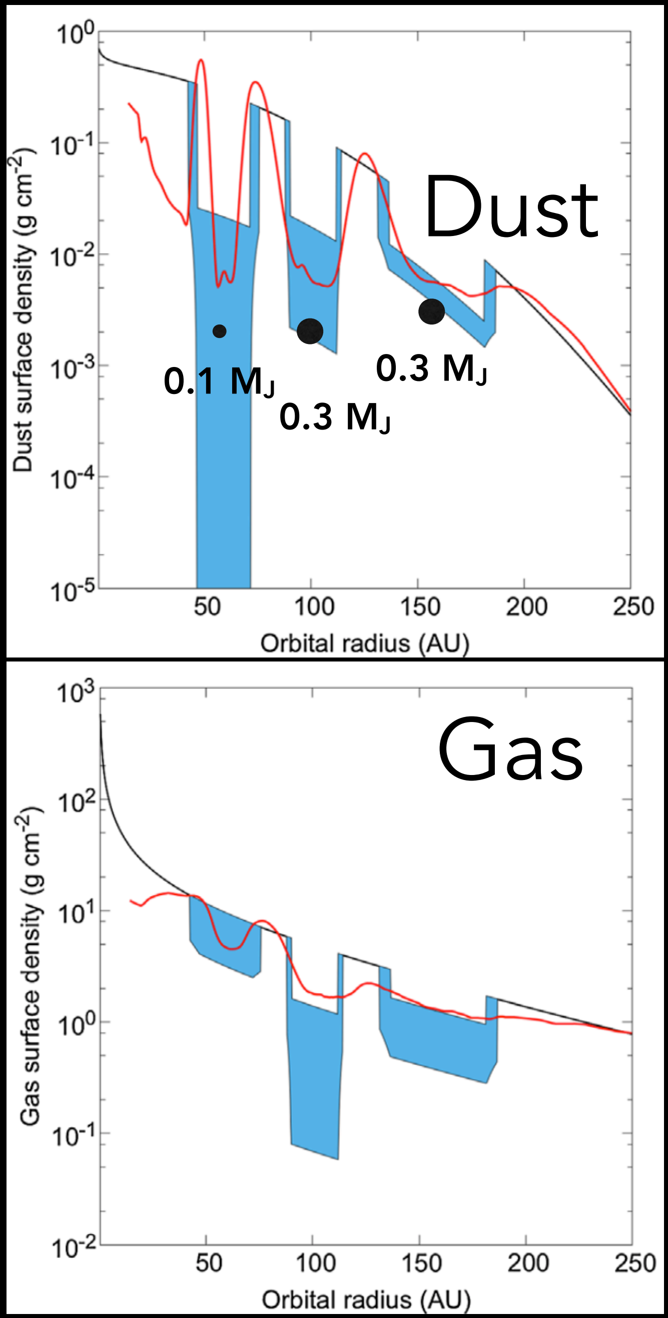




0.1 $M_{Jup}$ planet @100 au in low viscosity disk can also foster gaps at 60 au and 40 au (Zhang+ 18; Dong+18; Bae+ 17)

# INFERRING PLANETS WITH ALMA

Isella+ 2016






Pinilla & Youdin 2017

$\Sigma_{dust}(R) \propto I_\nu(R)/\kappa_\nu$

$\Sigma_{gas} = \Sigma_{CO}(R)/x(CO)$

$\Sigma_{CO}(R) \propto I_\nu(R)$

Aikawa+96

Reboussin+15

Schwarz+ 17,19

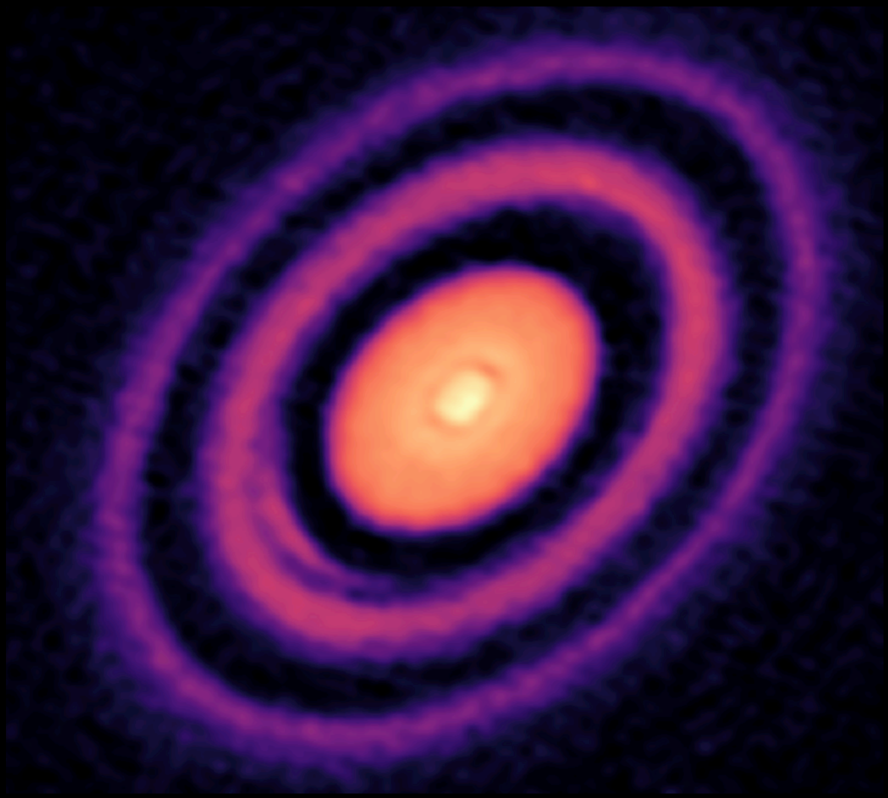
Yu+17

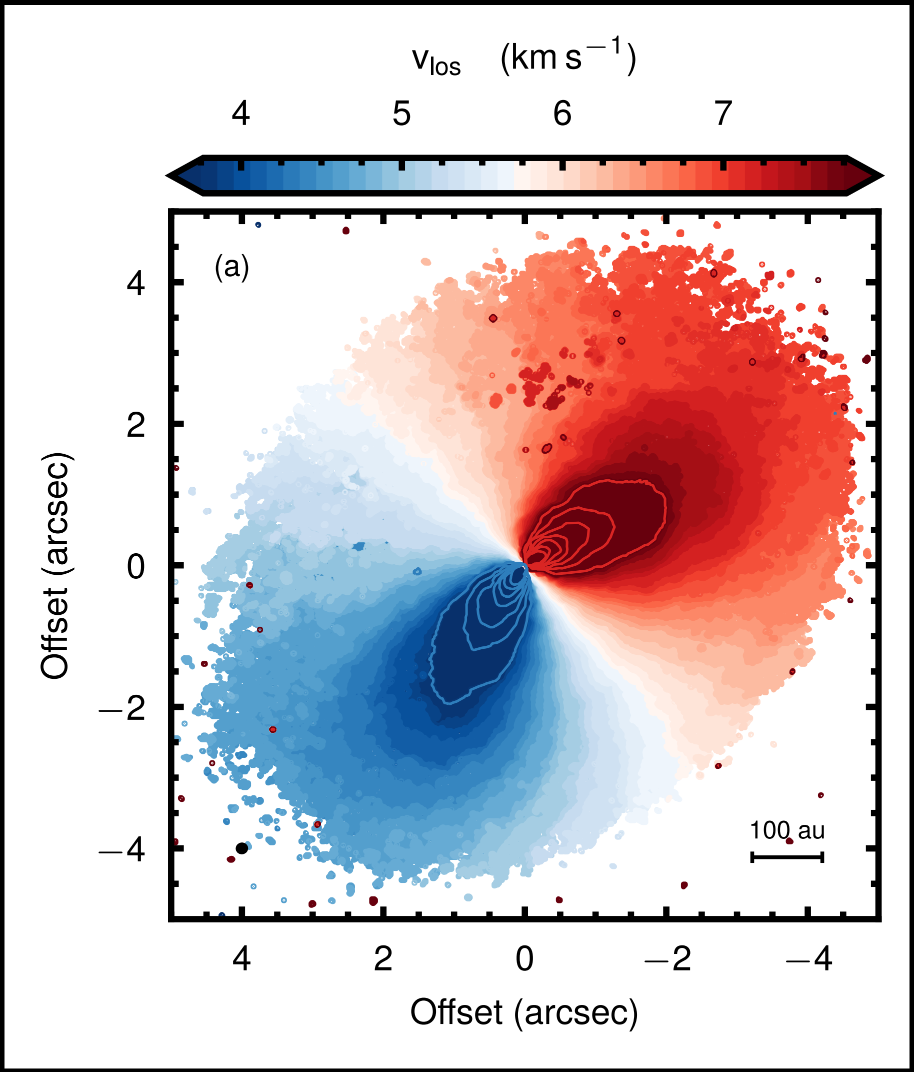
Bosman+18

# DEVIATIONS FROM KEPLERIAN ROTATION

$$\frac{v_{rot}^2}{r} = \frac{GM_* r}{(r^2 + z^2)^{3/2}} + \frac{1}{\rho}\frac{\partial P}{\partial r}$$

image resolution: 3.8 au x 4.8 au



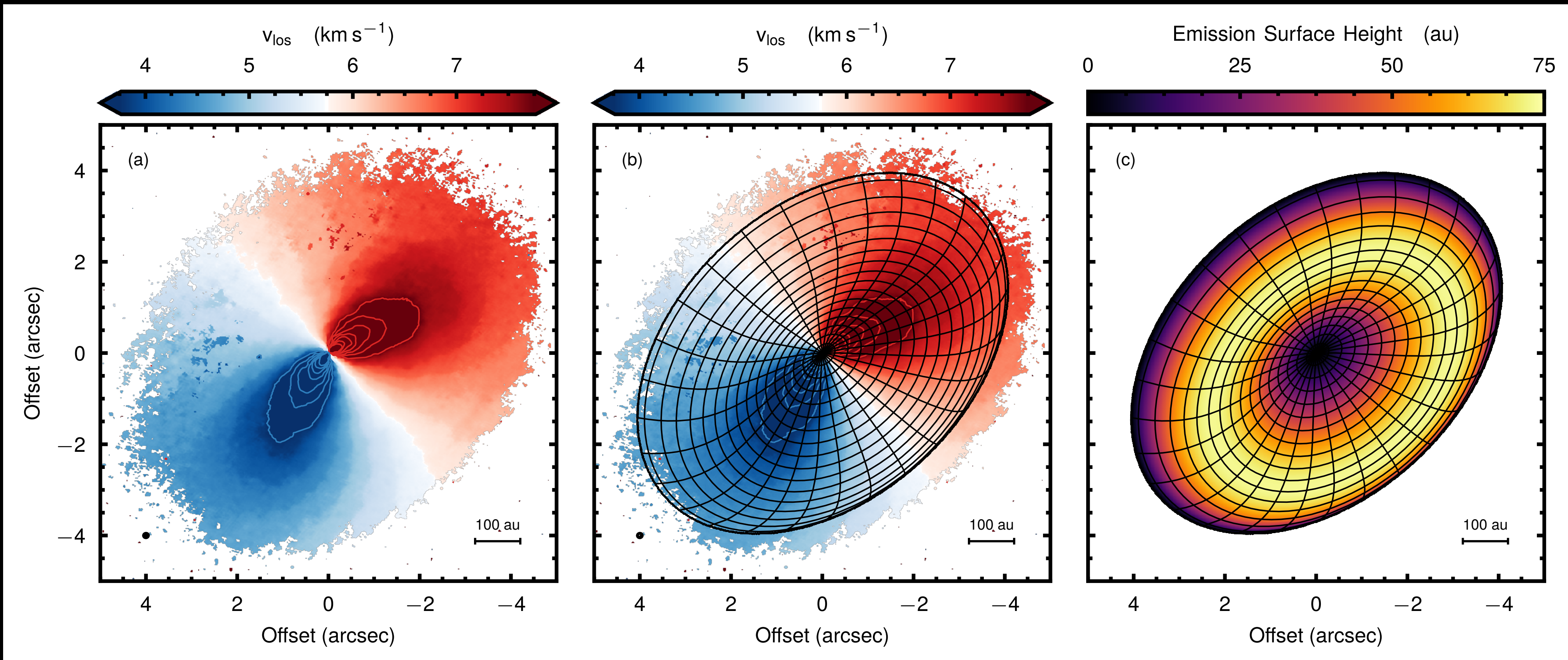



Isella +18

# MEASURING EMISSION SURFACE

$$\frac{v_{rot}^2}{r} = \frac{GM_* r}{(r^2 + z^2)^{3/2}} + \frac{1}{\rho}\frac{\partial P}{\partial r}$$

**image resolution: 3.8 au x 4.8 au**

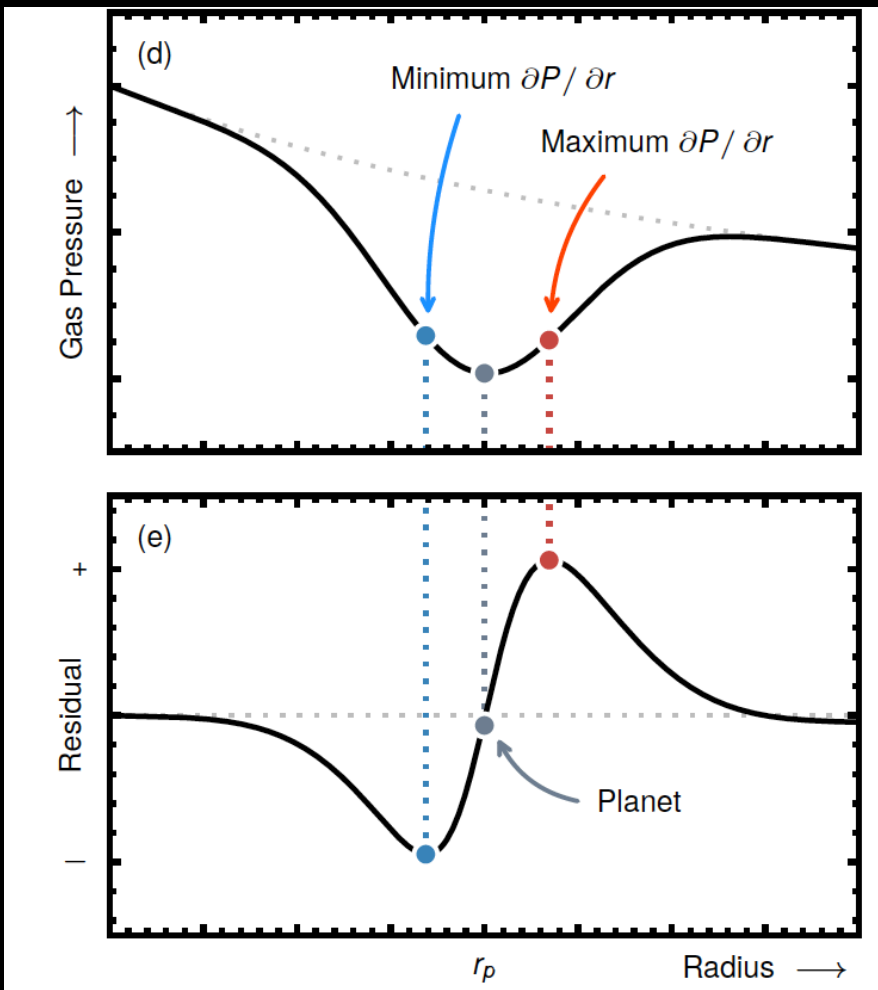



Teague, Bae, and Bergin 2019 (Nature)

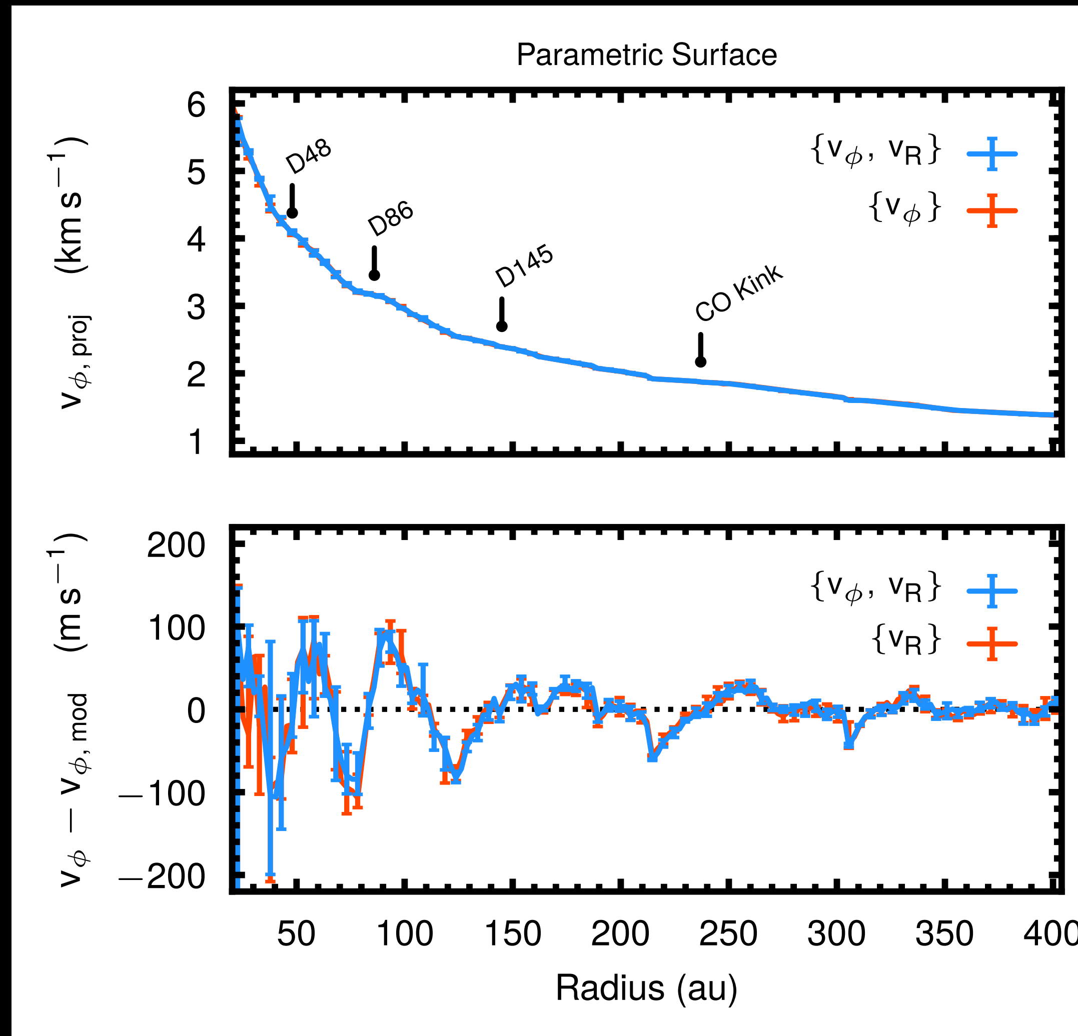
https://github.com/richteague/eddy Teague (2019)

https://github.com/richteague/bettermoments Teague & Foreman-Mackey (2018)

# CONFIRMED $H_2$ GAS PRESSURE GRADIENTS



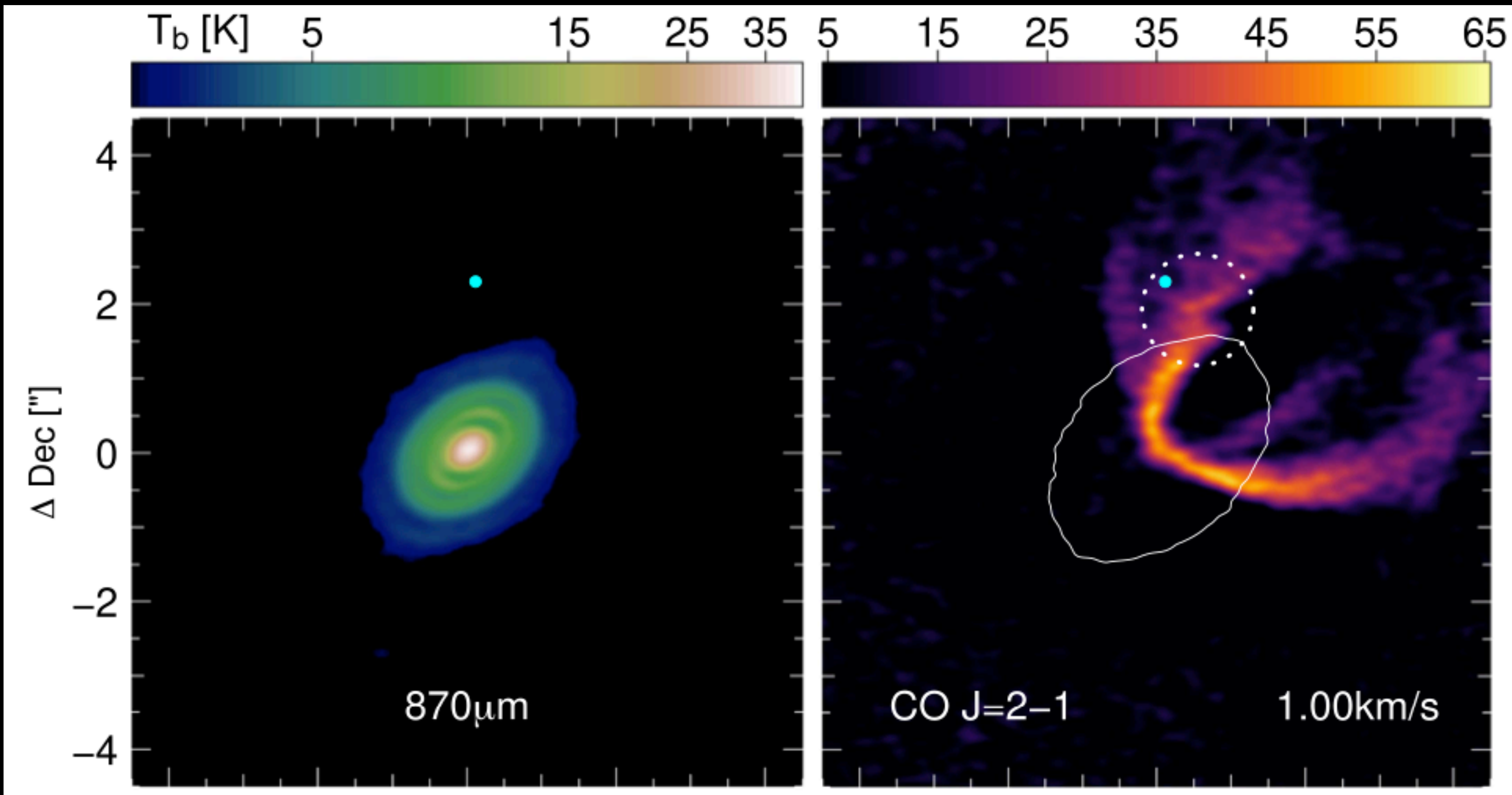

Teague + 2018




Teague + 2018

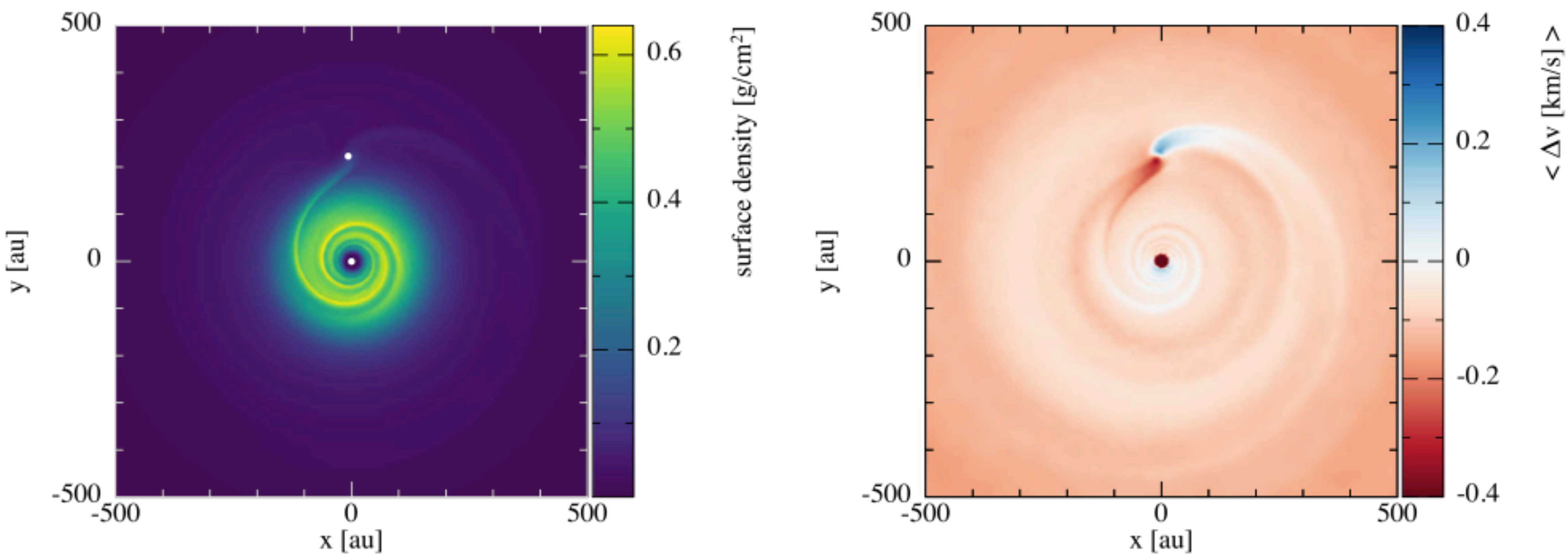
Teague, Bae, and Bergin 2019

# Kinematical Detection




Pinte et al. 2018

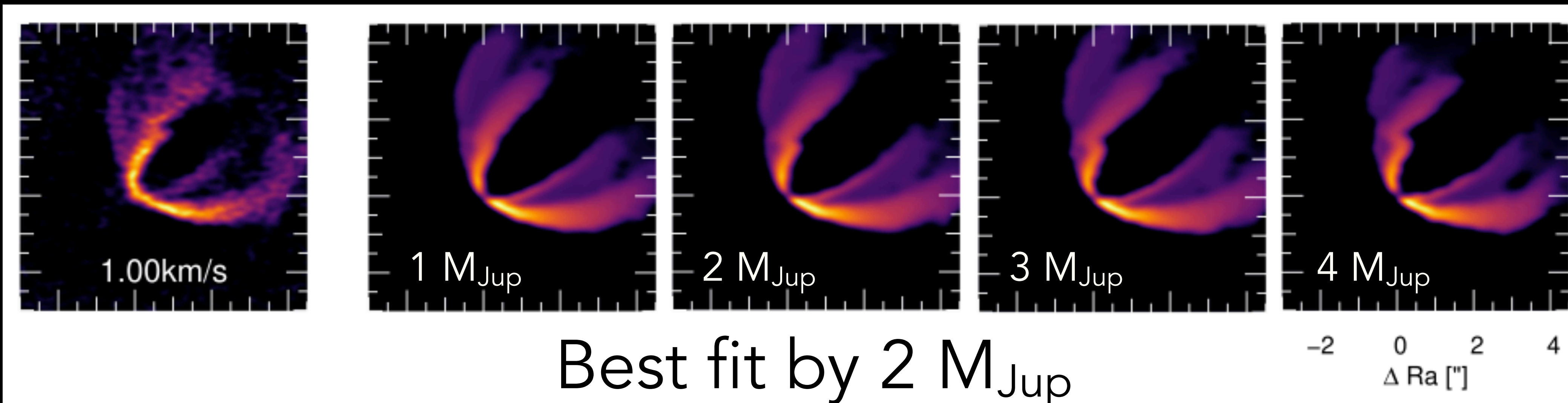
# Kinematical Detection




Pinte et al. 2018

# Kinematical Detection

Data Model Pinte et al. 2018

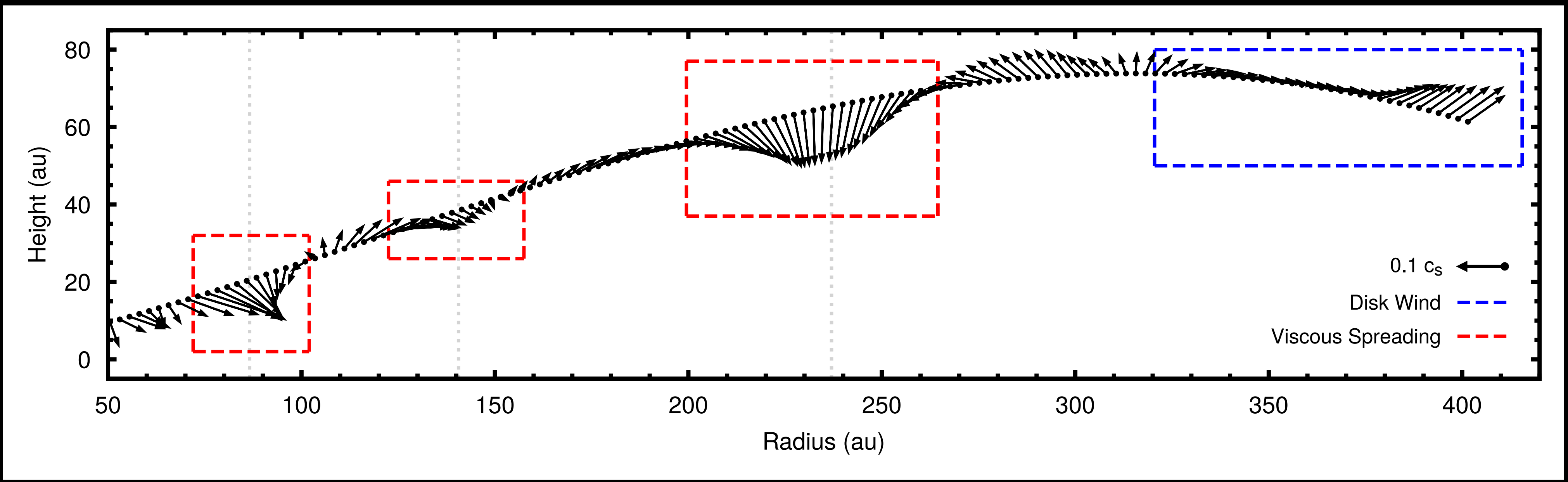



Pinte et al. 2019

- Analysis of DSHARP data finds 9 localized disturbances in velocity structure in 6 systems.
- localized disturbances coincide with gaps.
- see also Casassus & Perez (2019) “doppler flip”

# INFERENCE OF 3D VELOCITIES

the viscous evolution of gas into gaps and a disk wind?

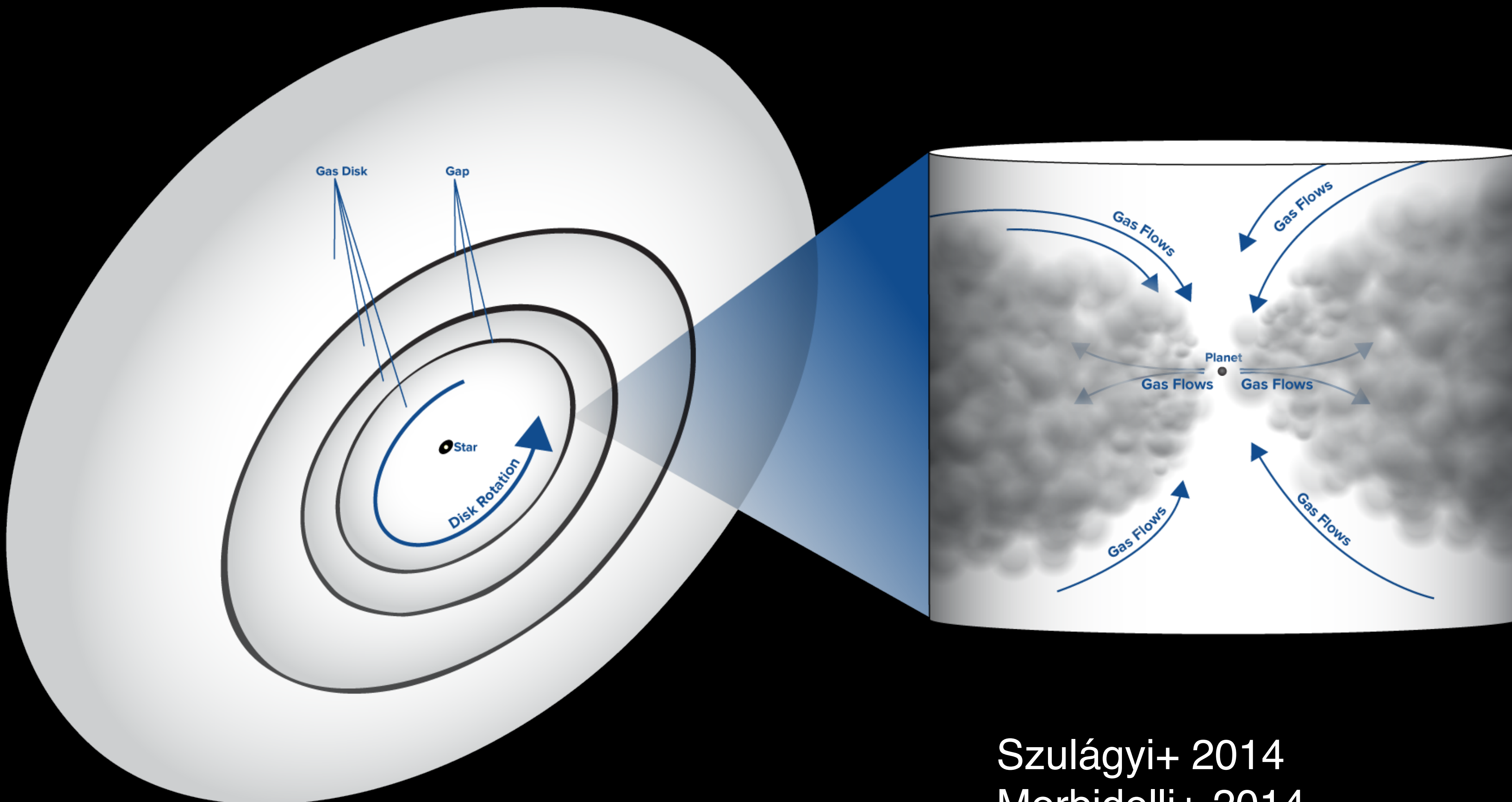



@30 AU $c_s$~600 m/s

@400 AU $c_s$~300 m/s

Teague, Bae, and Bergin 2019 (Nature)

# MERIDIONAL FLOWS




Szulágyi+ 2014
Morbidelli+ 2014
Fung & Chiang 2016
Dong, Liu, & Fung 2019

# ALMA & PLANET FORMATION

Current State:

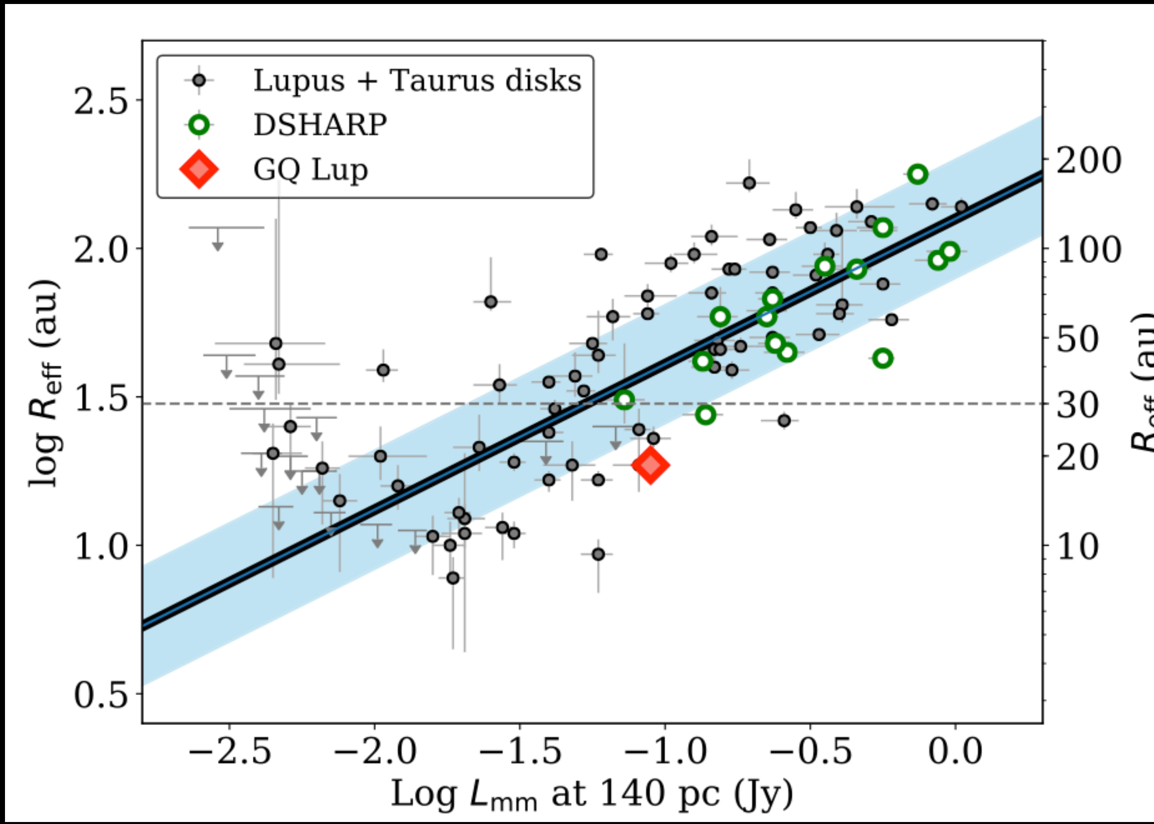
- Case for planets in HD 163296 is strongest
  - ➡ Mismatch between planet mass estimates from surface density structure and from dynamics
  - ➡ Dynamical mass estimates garnered by matching 2D/3D hydro to gas kinematics - gives masses a factor of 3 - 10x higher (Pinte et a. 2018,2019; Teague et al. 2018)

➡ Lodato et al. 2019 - tracks migration of the observed planets.

# ALMA & PLANET FORMATION

Statistics -

DSHARP has 85% occurrence rate of rings and gaps (Huang et al. 2018), but these are the brightest systems.




Long et al. 2020

# ALMA & PLANET FORMATION

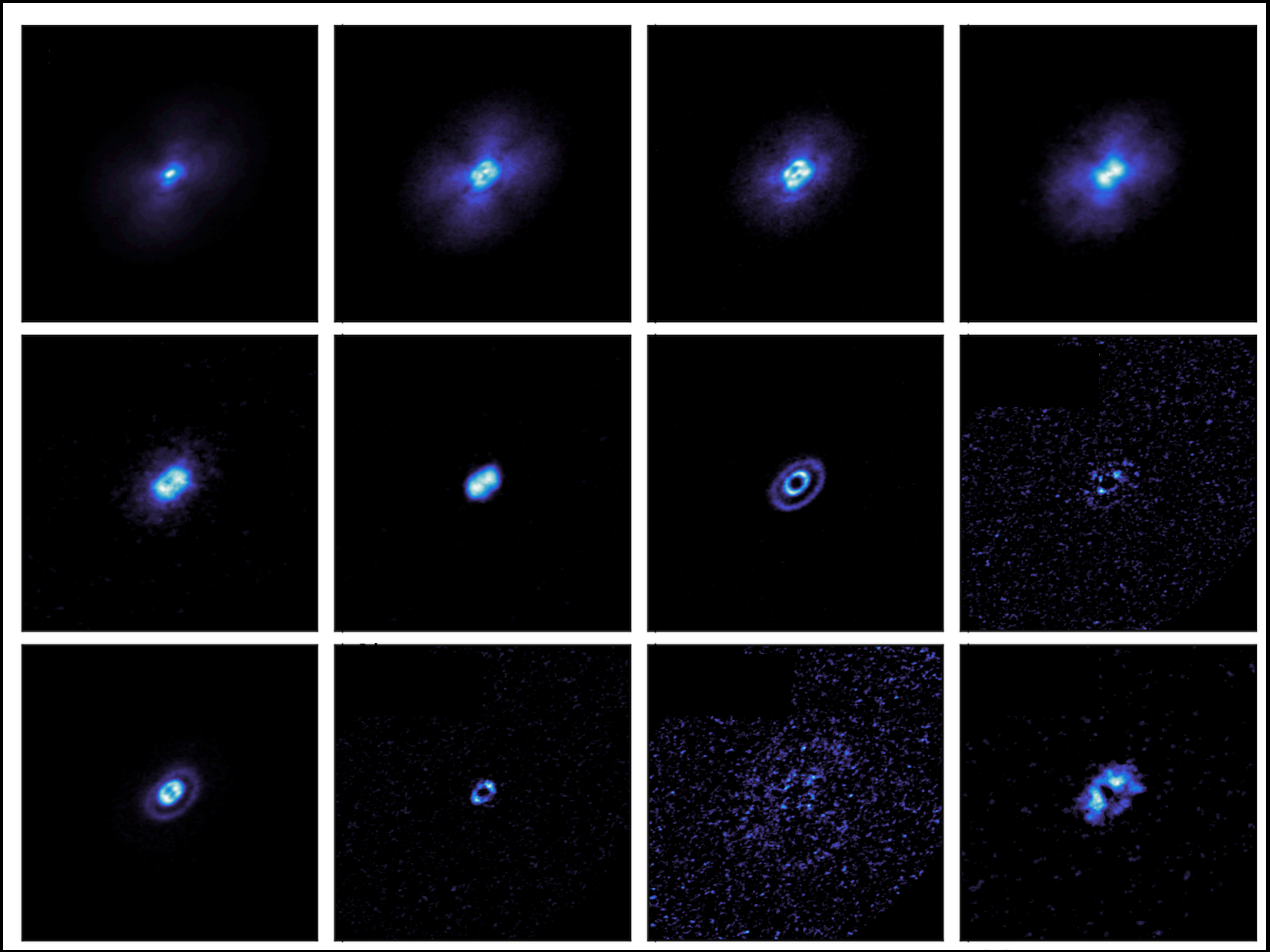
Statistics - Fernandes et al. 2019 (also Lodato et al. 2019)

- Taurus survey (Long et al. 2018) finds 38% occurrence rate.
- Disk frequency is 75% (Luhman et al. 2009) so occurrence rate is ~28%
- Giant Planet occurrence rate from 1 - 100 au and 0.1 - 20 $M_{Jup}$ is 26.6% (Fernandes et al. 2019)
  - ➡ M. Meyer (priv. comm. ) from 0.1 to 1000 au and 1 - 10 $M_{Jup}$ occurrence rate is 21% (higher if down to lower mass).
- Consistent if each source has 1 ring - but, many disks have > 1 ring
  - ➡ single planets can induce multiple rings
  - ➡ need smaller mass planets (< 0.1 $M_{Jup}$) in low viscosity disks to be source of rings (e.g. TW Hya; Mentiplay et al. 2019)
  - ➡ recall tension between dynamical mass estimates and from surface density structure.

# ALMA & PLANET FORMATION

- Current ALMA data sets have been optimized for dust continuum and not gas kinematics (requires many more hours). Urgent need for deep and high resolution kinematic data.
- Need to better characterize dust emission structures in smaller disks (e.g. Long et al. 2020), which requires different techniques (Zhang et al. 2016).
- Have not discussed fantastic results from GPI and SPHERE (see, e.g., Villenave et al. 2019)
- Possibility exists to search for chemical signatures of planets (Cleeves et al. 2015) - and new ALMA large program "The Chemistry of Planet Formation" (PI: Öberg, Aikawa, Guzman, Walsh, Bergin) will search for these signatures and provide better data for kinematic studies.
- Planets are there - we also need to find them by, e.g. direct detection where possible.

# Thank You!



"The Chemistry of Planet Formation" (PI: Öberg, Aikawa, Guzman, Walsh, Bergin)