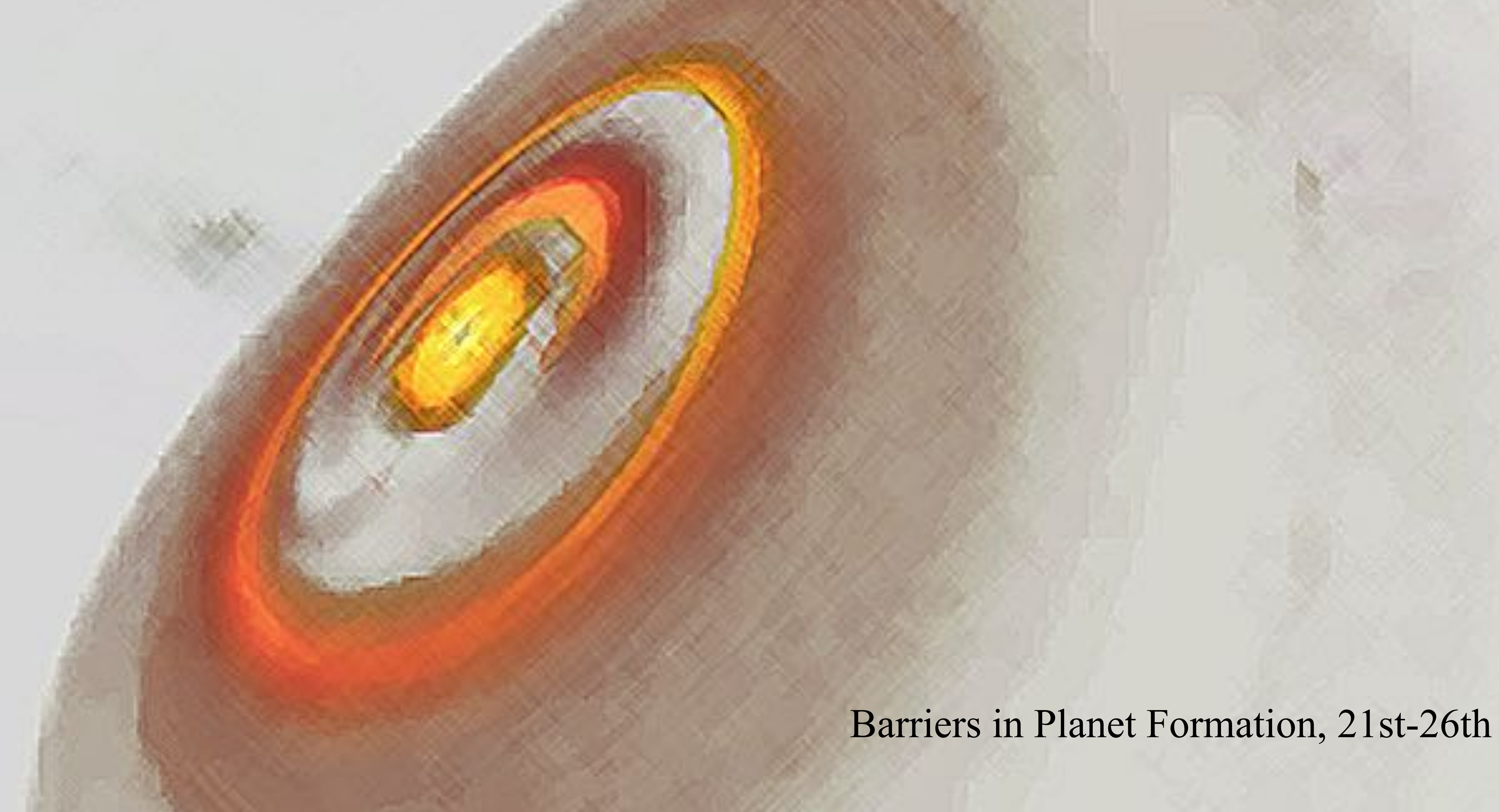
Substructures and **Dust Scattering** for Our Understanding of Planet Formation

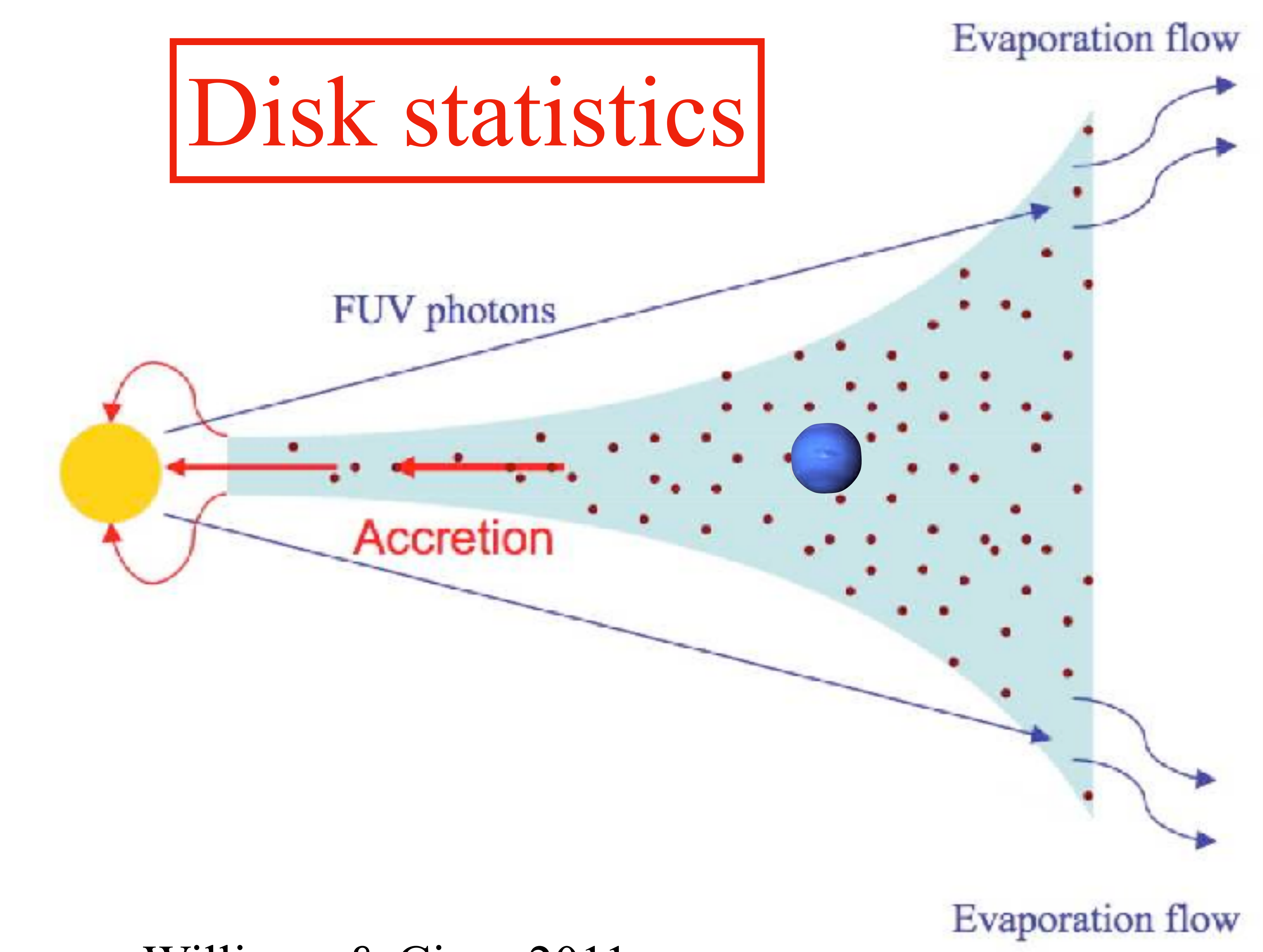
Zhaohuan Zhu
University of Nevada, Las Vegas



Barriers in Planet Formation, 21st-26th July, 2019

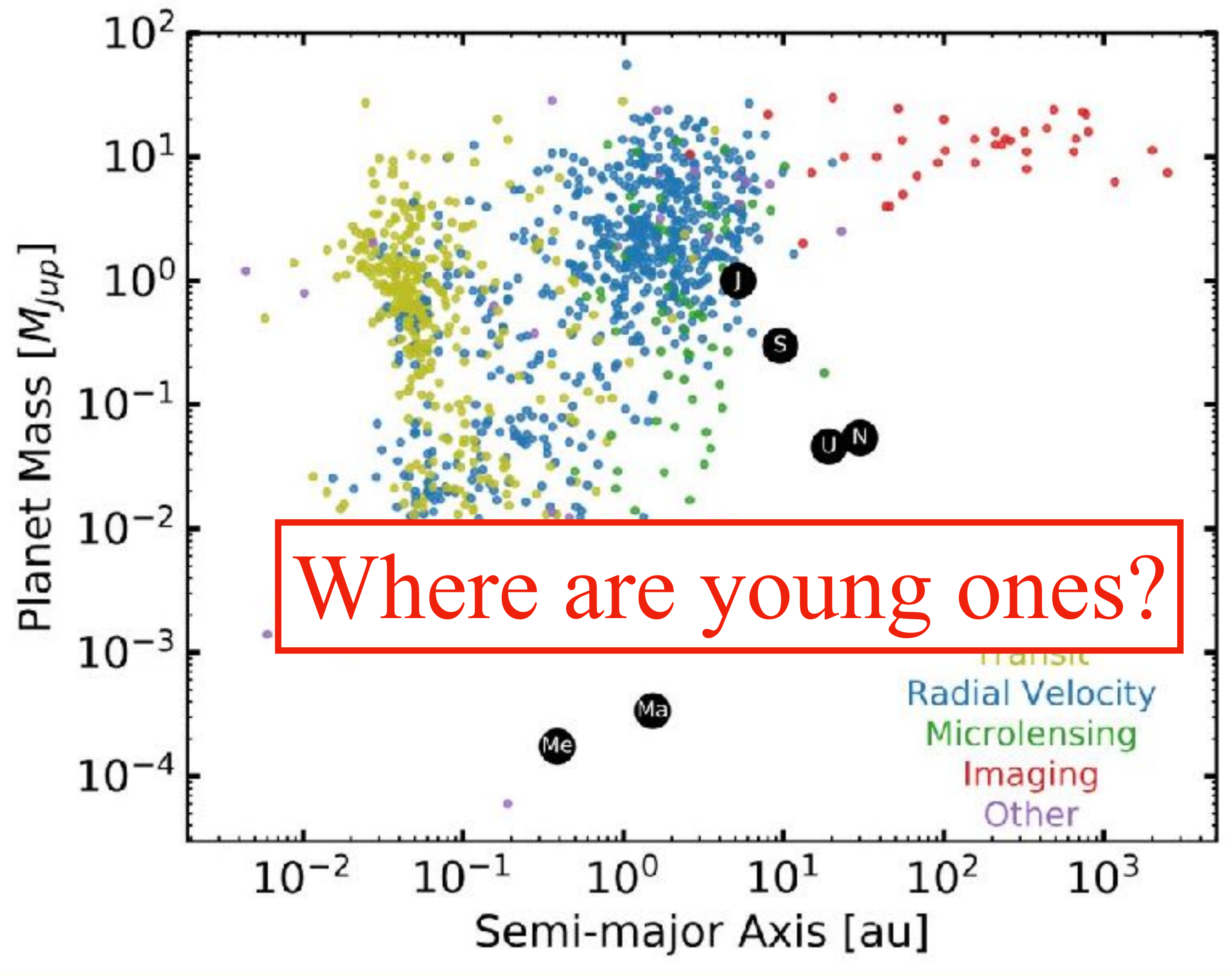
How do protoplanetary disks evolve to such diverse exoplanets?

1. Study disk structures and young planet population (High resolution)
2. Understand the demographics of protoplanetary disks (High sensitivity)



Williams & Cieza 2011

?



Two new barriers:

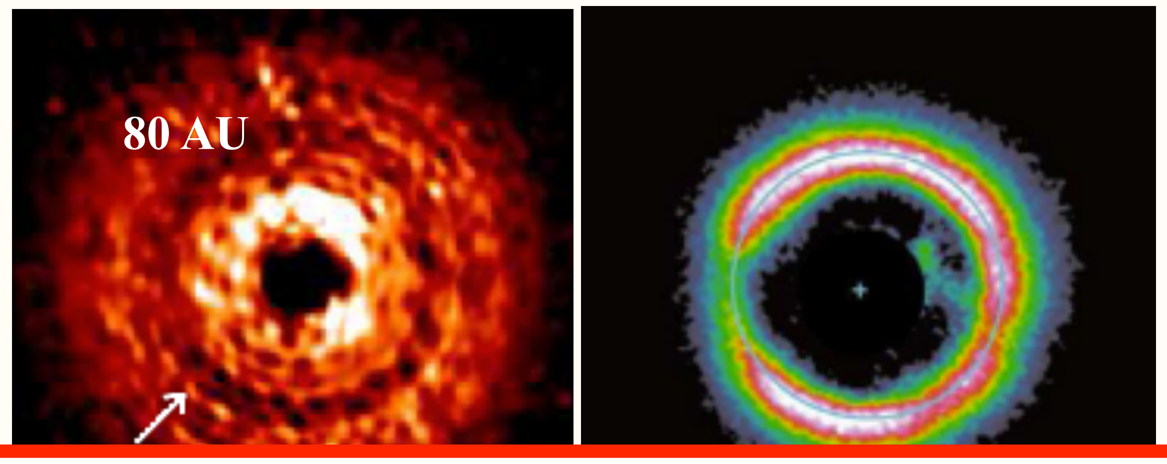
1. Disk substructures (young planets)
    - Planet-disk interaction
    - Young planet population from DSHARP
2. Dust scattering (demographics of protoplanetary disks)
    - Mass budget problem
    - One solution: dust scattering

Diverse disk structure

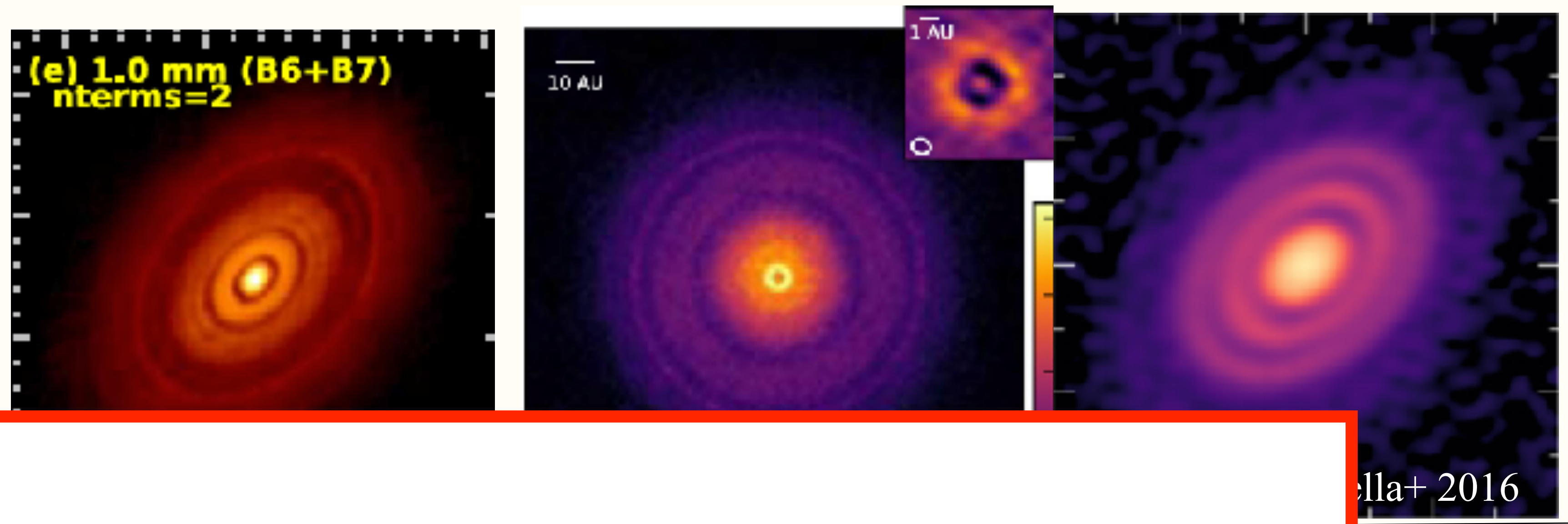
Axisymmetric

Rings/gaps

Optical/Near-IR

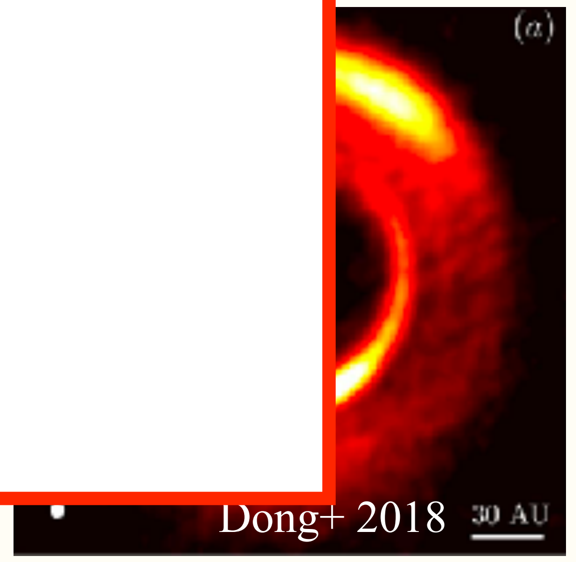


Radio

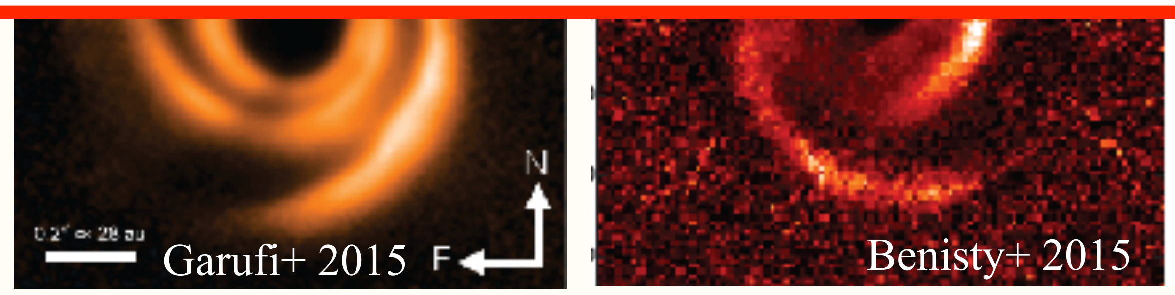


nonaxisymmetric

Blobs

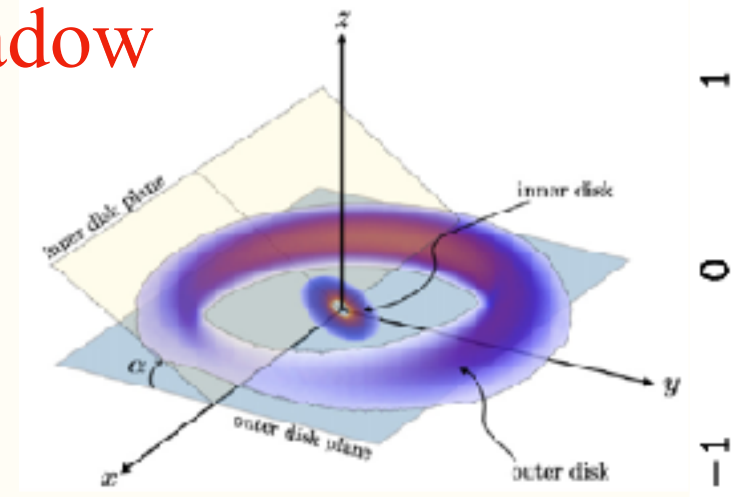


Spirals

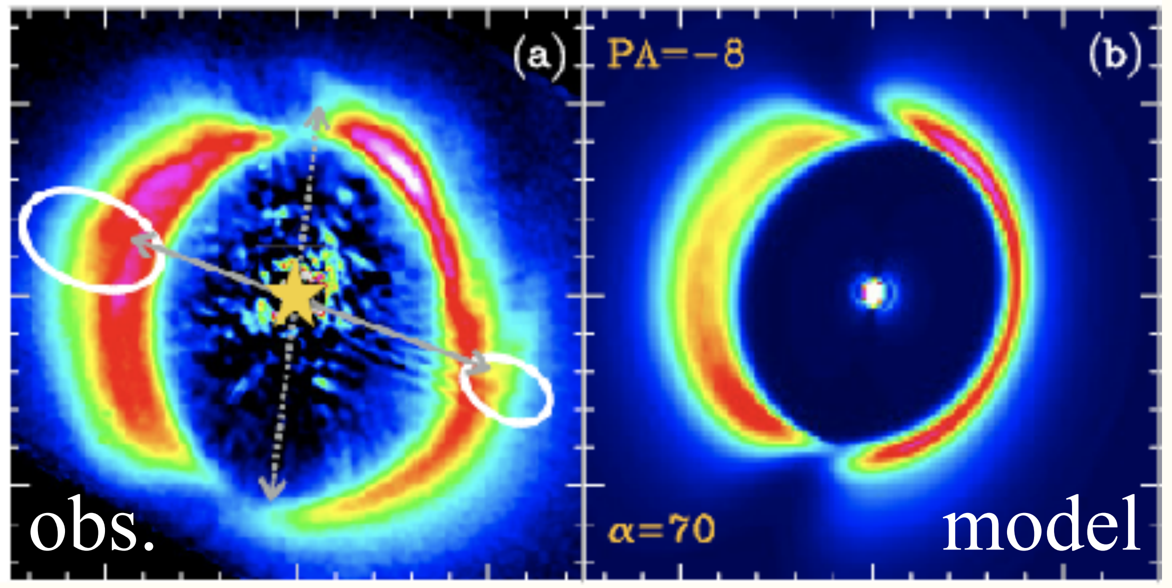


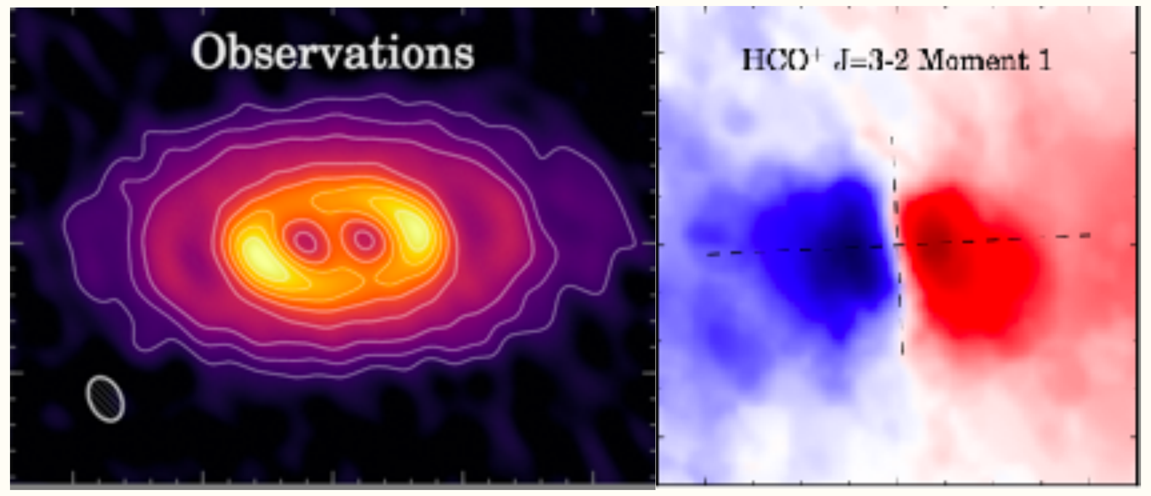
1. What causes these structures ?
2. If these structures are caused by…, what can we learn? Does that make sense?

Disk Shadow



Marino et al. 2015





Loomis et al. 2017

Features due to coplanar young planets

Direct Signatures:

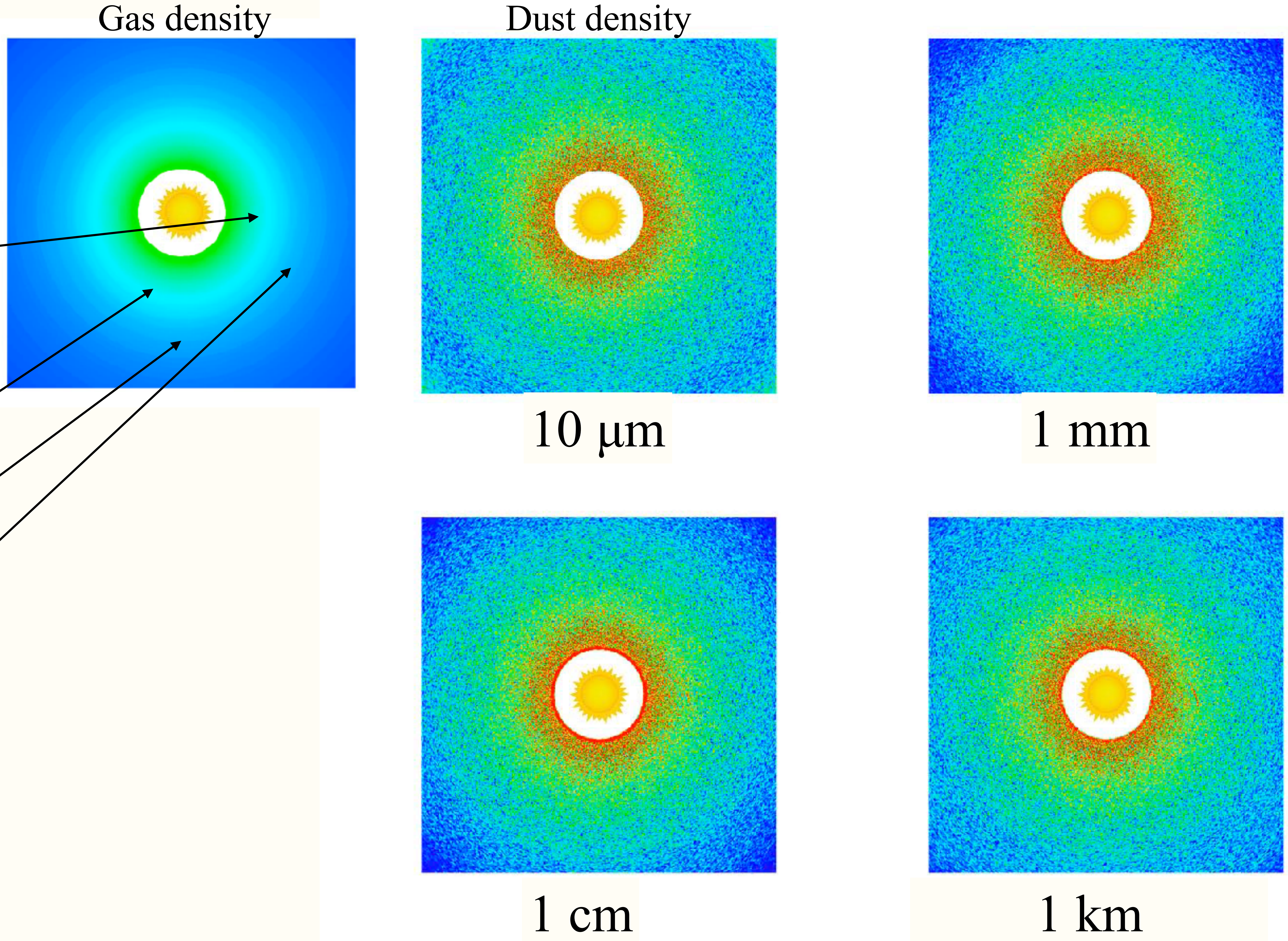
The Planet and
Circumplanetary Disk

Indirect Signatures:

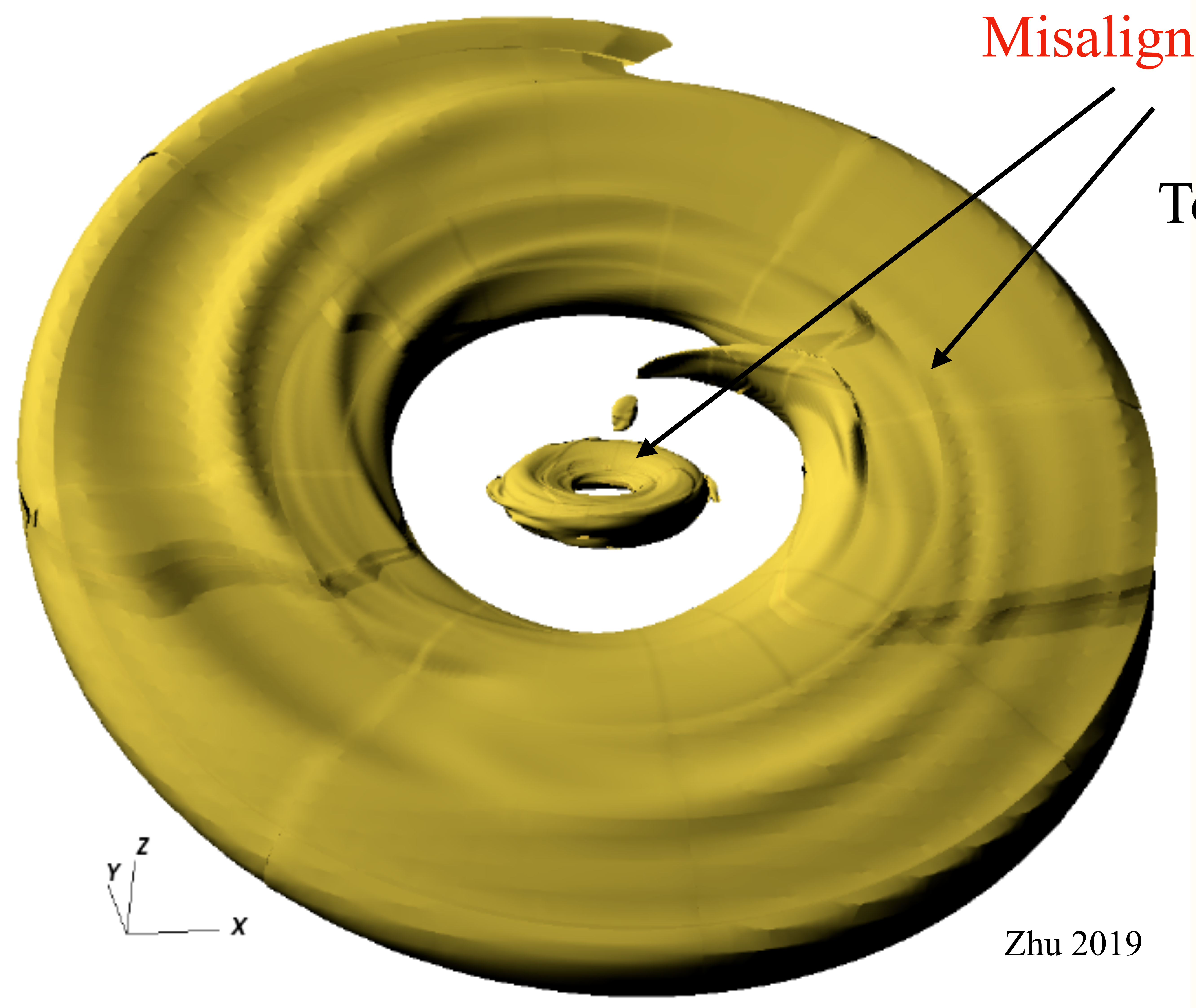
Gaps

Spirals

Blobs



Features due to misaligned planets



Zhu 2019

Misaligned inner and outer disks

To break the disk, the planet mass needs:

$$q > \sqrt{20/3}\alpha^{1/4}h^{7/4}$$

$\alpha=10^{-4}$, $h=0.05$, $q>0.0014$

Massive Planet!

(See R Nealon's talk)

Constraining planet properties using different methods

Direct:		Optical/IR	Radio	Planets Properties(~50 au)
Planets		Near-IR		Hot start: 2 M_J Cold start: >10 M_J Fortney+ 2008
CPDs	*I*	Hα, Mid-IR (L',M)	dust thermal /gas lines	$M\dot{M}$<5x10^{-8} M_J^2/yr Jean-Baptiste+ 2018
	V	spectro-		M_J Perez+ 2015, Pinte+ 2018
Indirect:	*I*	Y		ptune mass Zhang+ 2018
Gaps	*V*		azimuthally averaged V	ΔV~5% V_K >Saturn mass Teague+ 2018 Zhang+ 2018
Spirals		Yes	Yes	>3 M_J Dong+ 2015
Vortices		Hard to tell	Yes	α<10^{-3}
Shadow		Yes	Yes	Circumbinary Planet > M_J Facchini+ 2014,Price+ 2018 Zhu 2019

How to test these theories?

PDS 70: testbed for all previous predictions

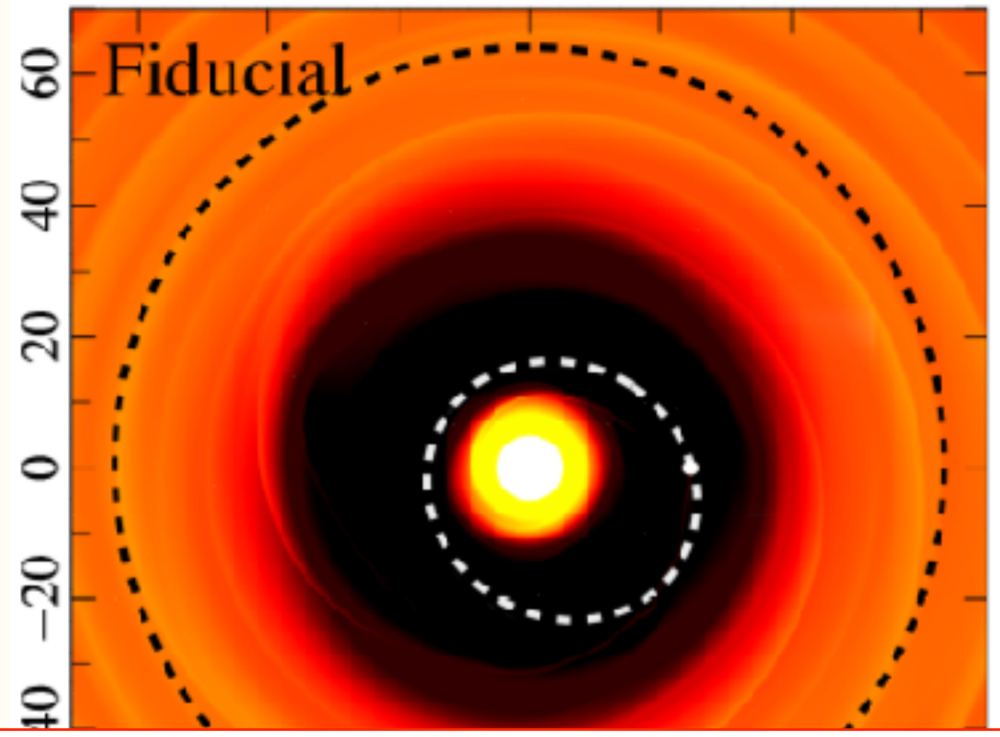
weak line T Tauri star
(See M. Benisty's talk)

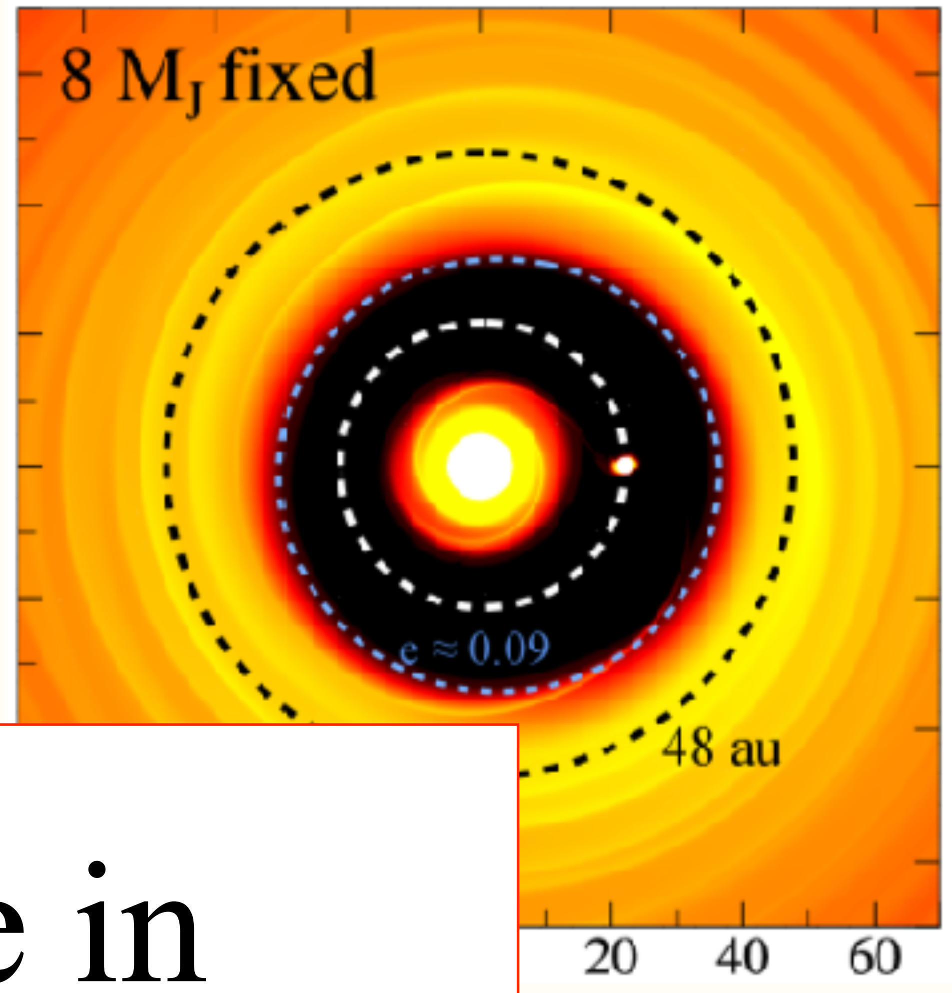
How can a 22 au planet open a 40-70 au gap?

Single planet

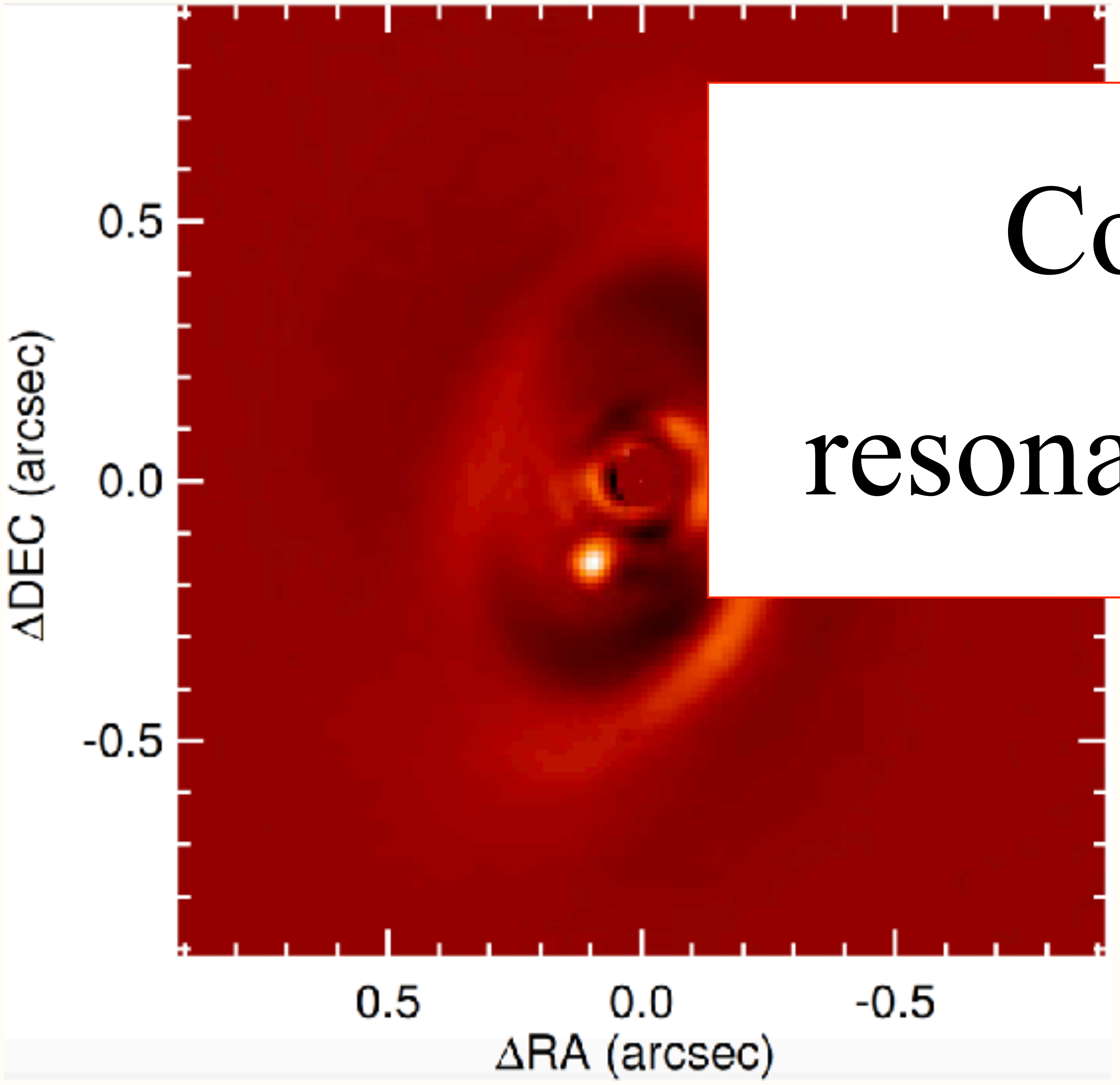
e>0.2

Requires the planet to accrete





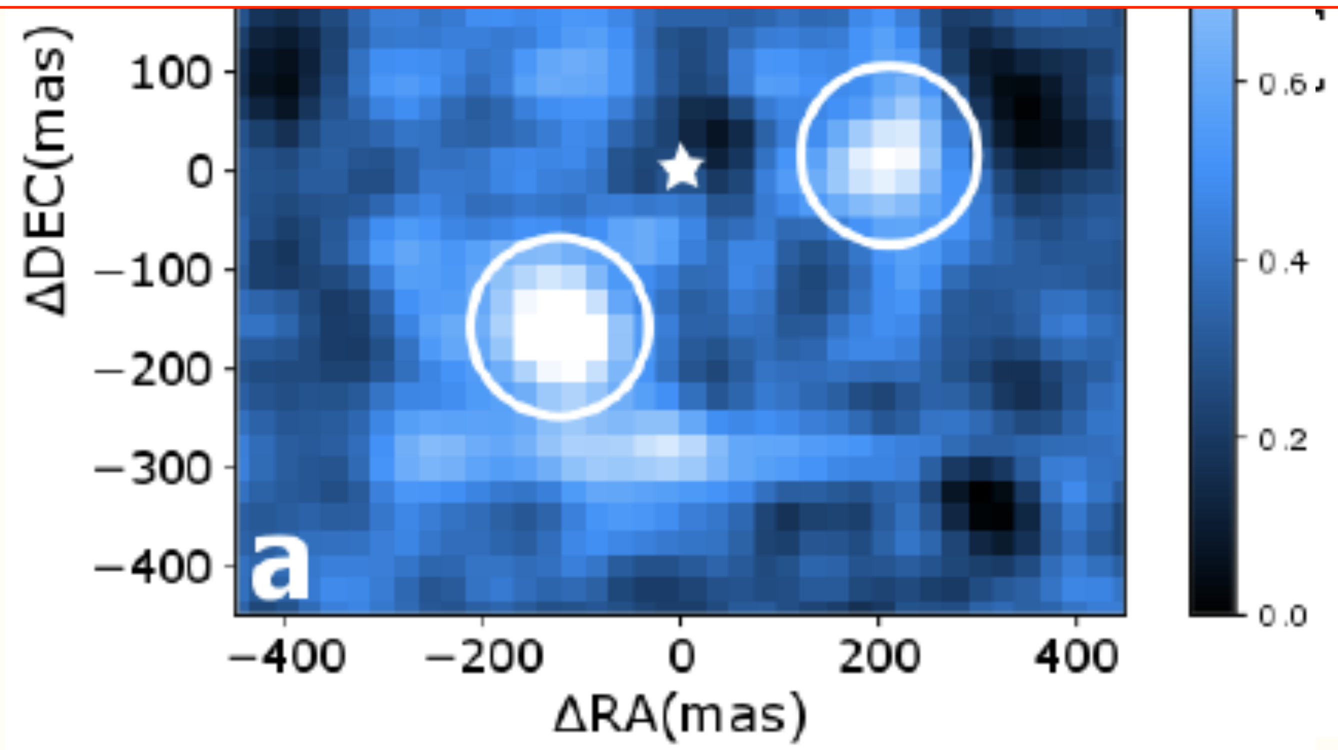
Van der Marel 2019



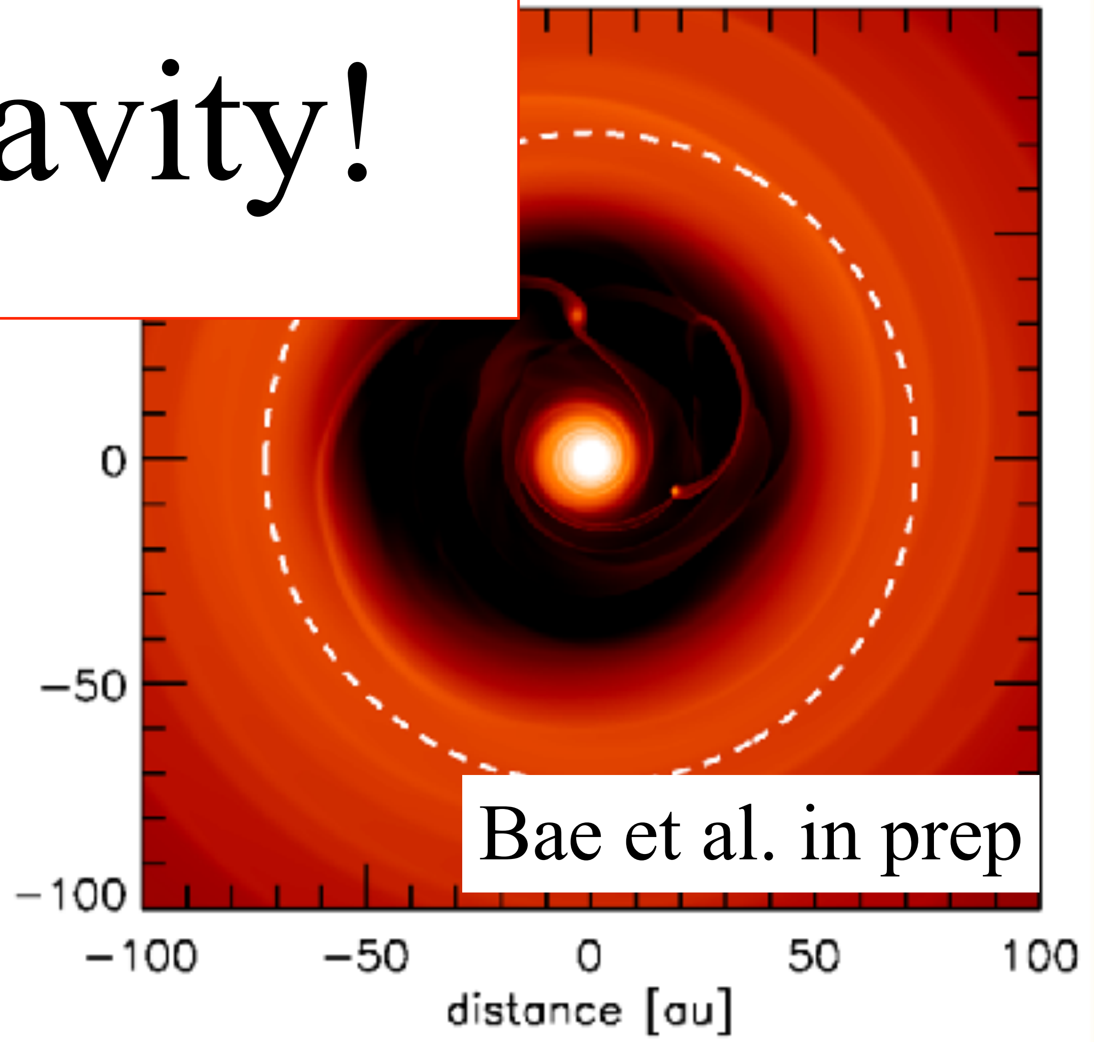
Keppler et al. 2018,
Muller et al. 2018

Confirm that multi-planets are in resonances and open a common cavity!

PDS 70c ~35 AU
2:1 mean motion resonance with b



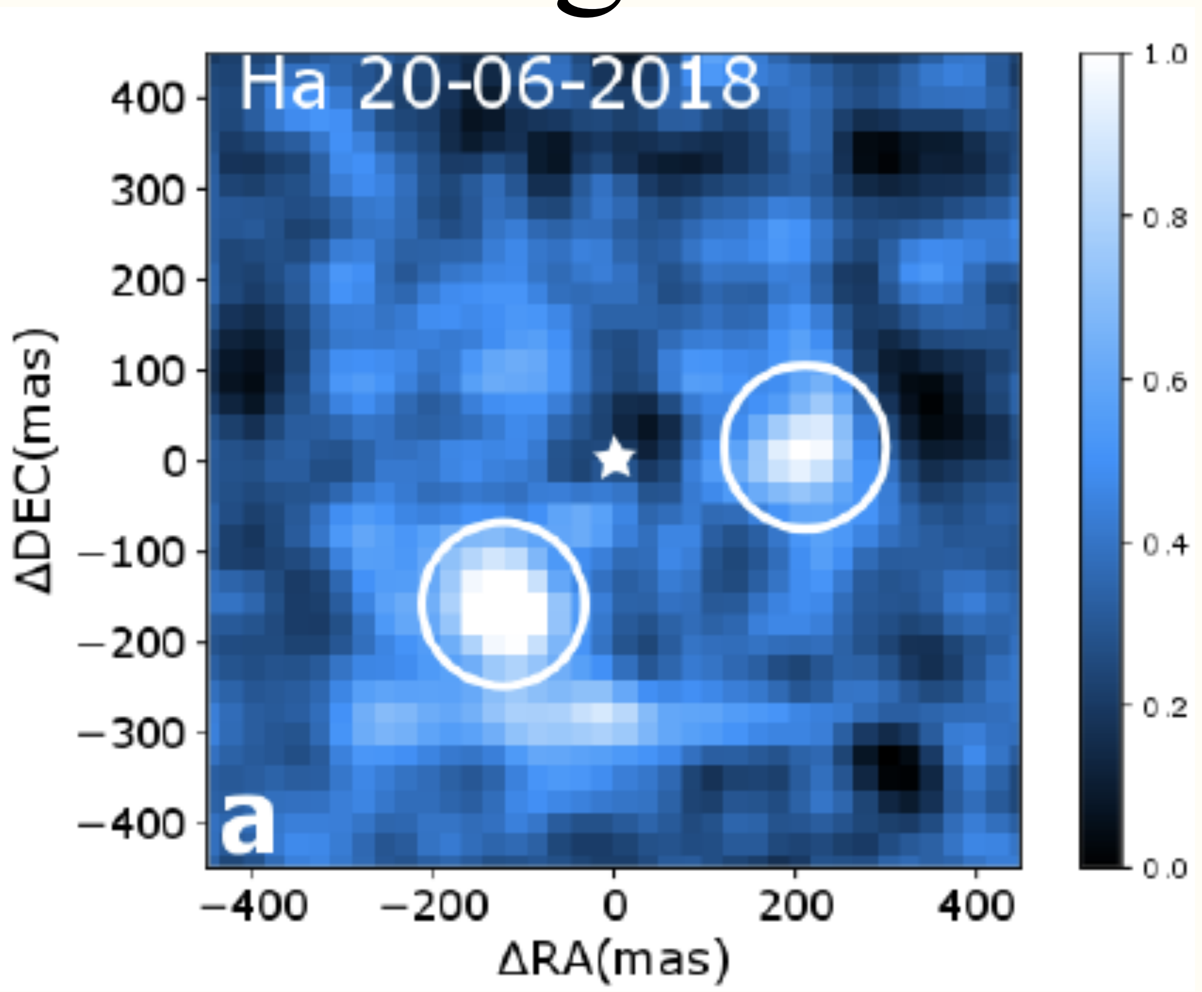
Haffert et al. 2019



Zhu et al. 2011
Dodson-Robinson & Salyk 2011

PDS 70: test for circumplanetary disks

First sign: Hα line



Haffert et al. 2019, Wagner+ 2018

Hα line flux of $2\times10^{-6}\ L_{\odot}$,
10% line width ~200 km/s
=> $\dot{M}_p \sim 10^{-8}\ M_J/yr$

Magnetospherical Accretion:

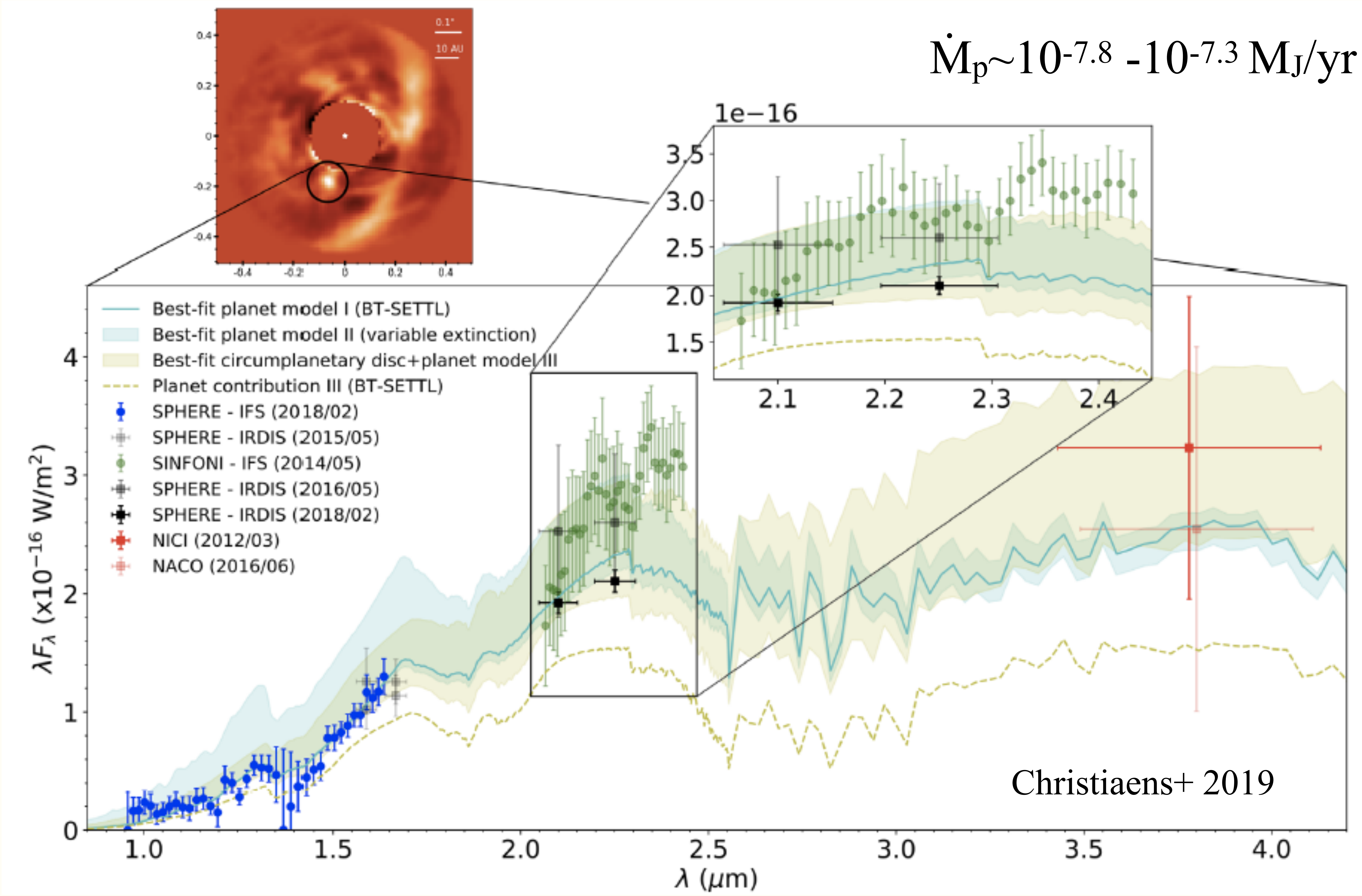
$$V_S \sim 59\,\mathrm{km\,s^{-1}} \left(\frac{M_p}{M_J}\right)^{1/2} \left(\frac{R_p}{R_J}\right)^{-1/2} \zeta^{1/2}$$

$$L_{H_\alpha} < 4.7\times10^{-6}\ L_{\odot} \left(\frac{R_T}{R_J}\right)^{2} \left(\frac{v_s}{59\,\mathrm{km\,s^{-1}}}\right)$$

Zhu 2015

Second sign: near-IR excess

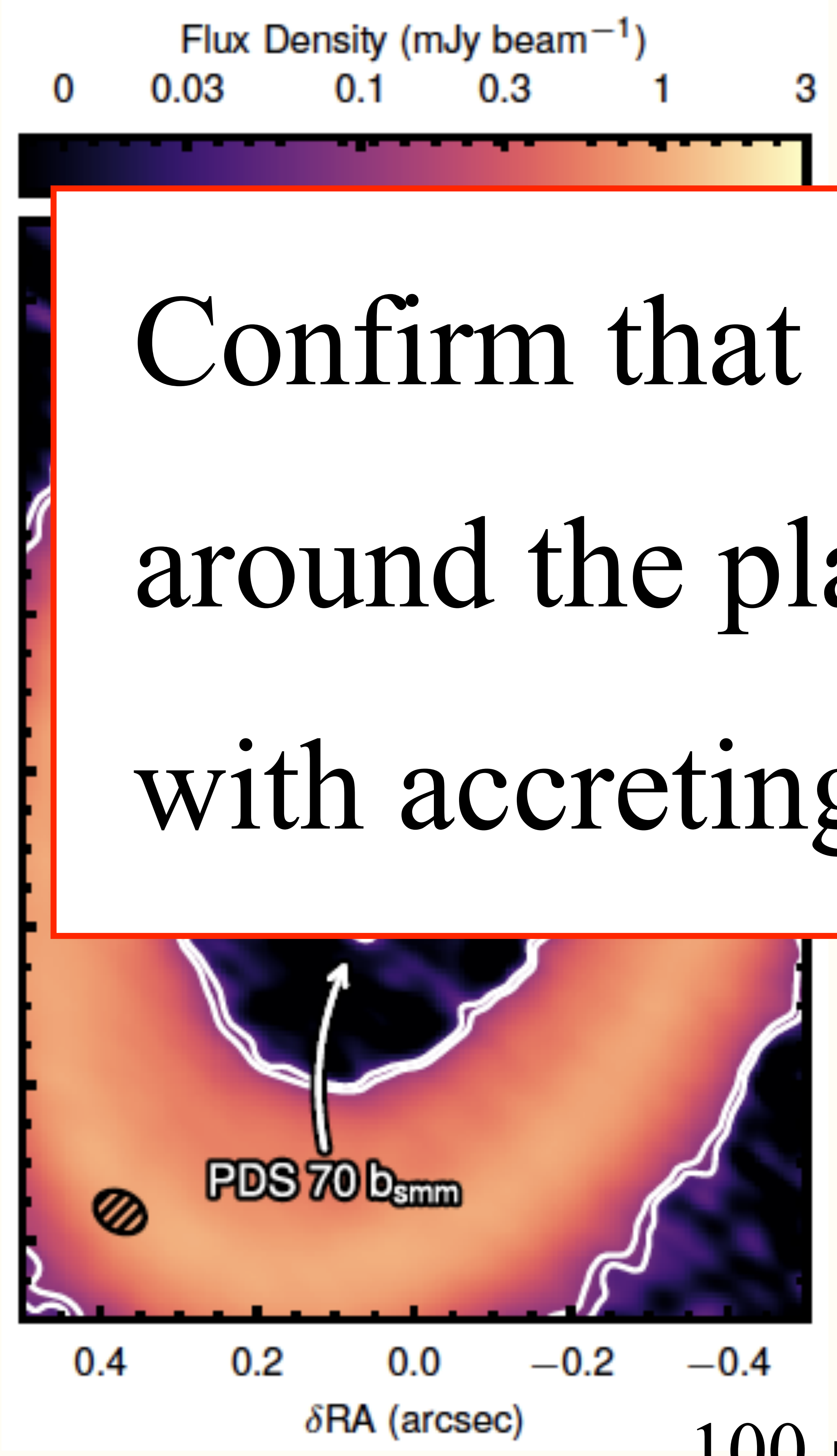
$\dot{M}_p \sim 10^{-7.8}$ - $10^{-7.3}\ M_J/yr$



Christiaens+ 2019

PDS 70: test for circumplanetary disks

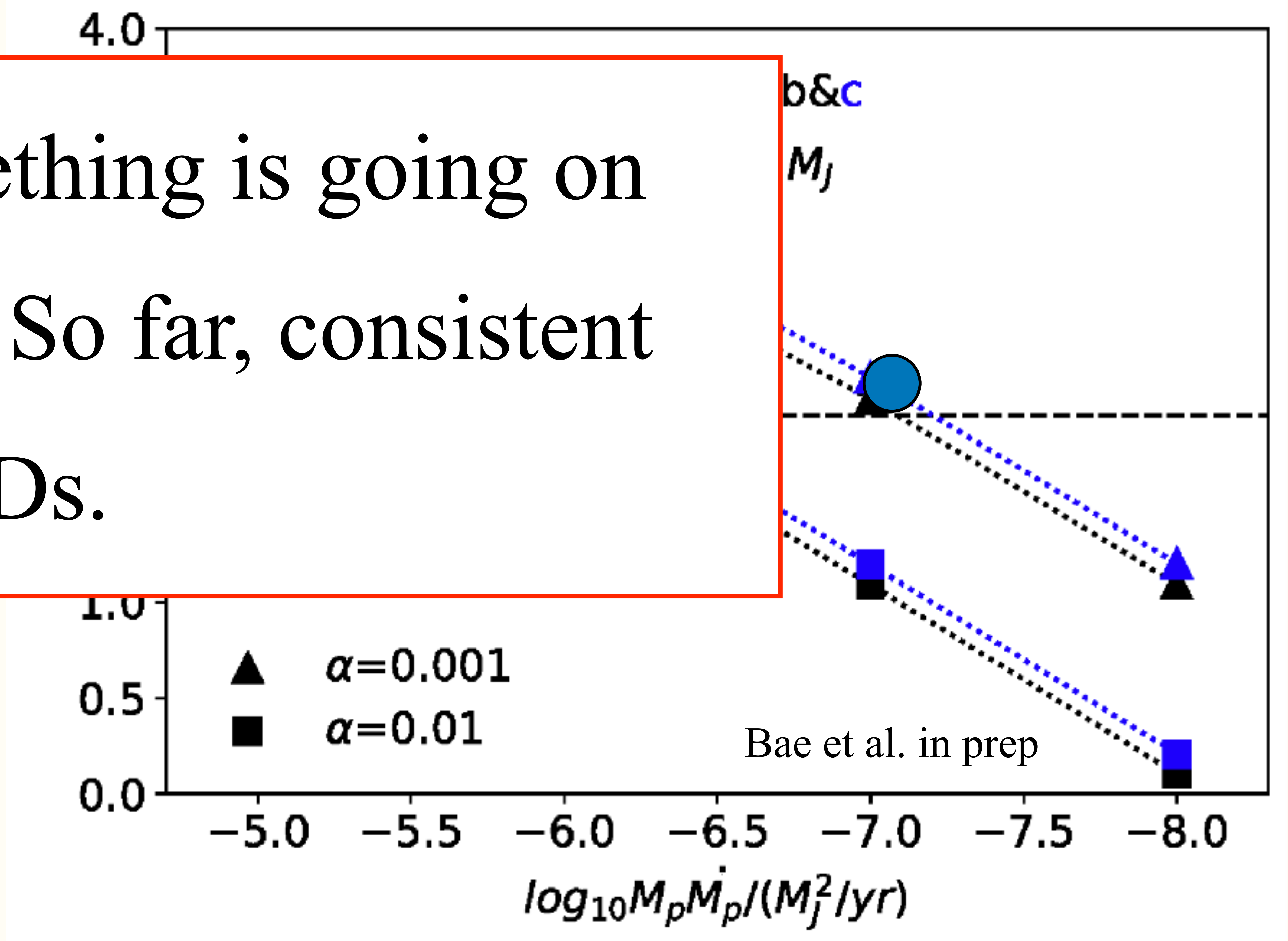
Third sign: submm source



100 μJy/beam

Isella+ 2019

Assuming dust/gas mass ratio 1:100

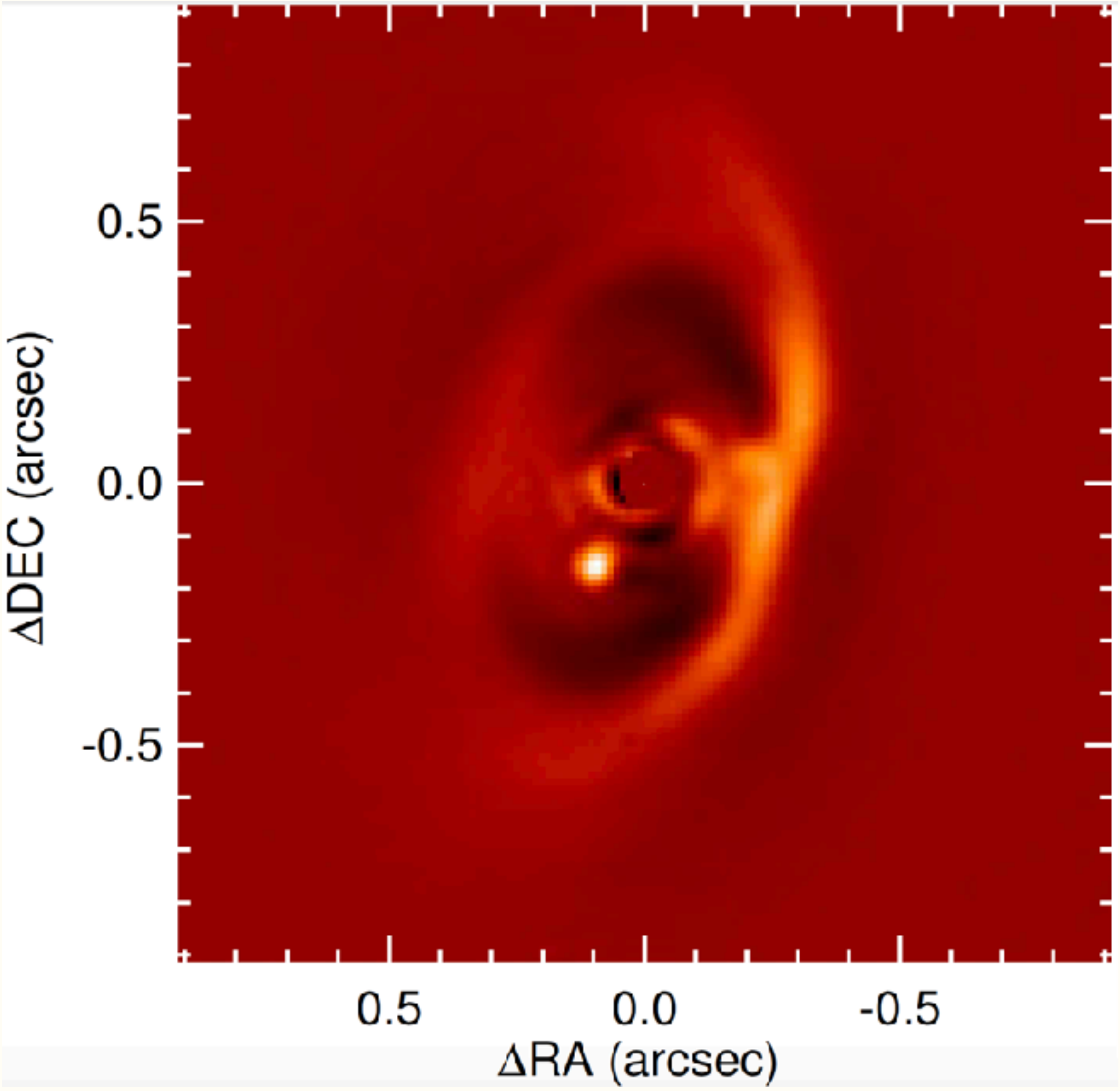


Confirm that something is going on around the planet. So far, consistent with accreting CPDs.

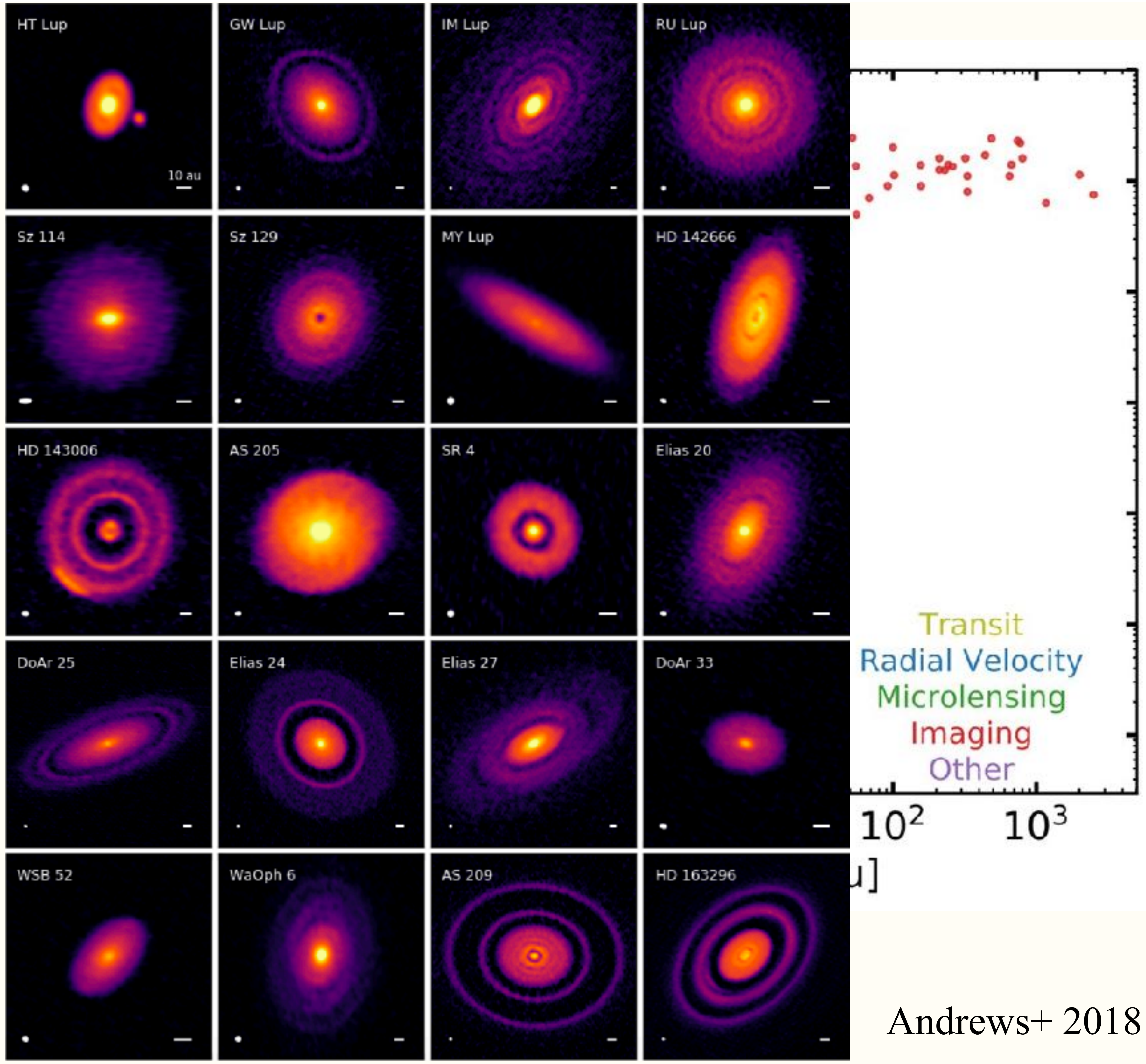
Zhu, Andrews & Isella, 2018
Isella et al. 2014
Szulagyi et al. 2019

Young Planet Population

A single case



What about the young planet population?



Andrews+ 2018

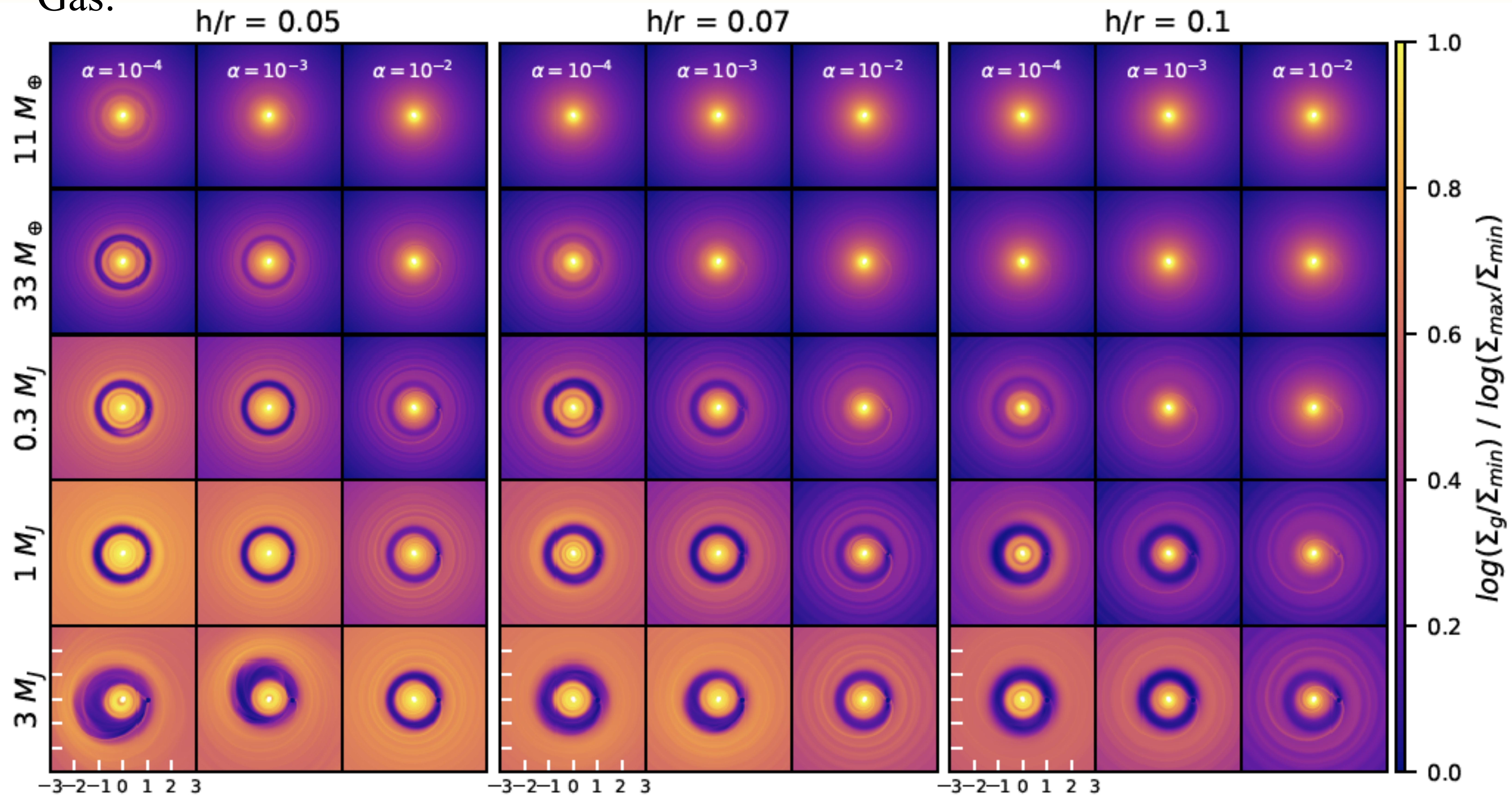
Young Planet Population (DSHARP VII, Zhang, Zhu+2018)

We did a full parameter study for simulations.

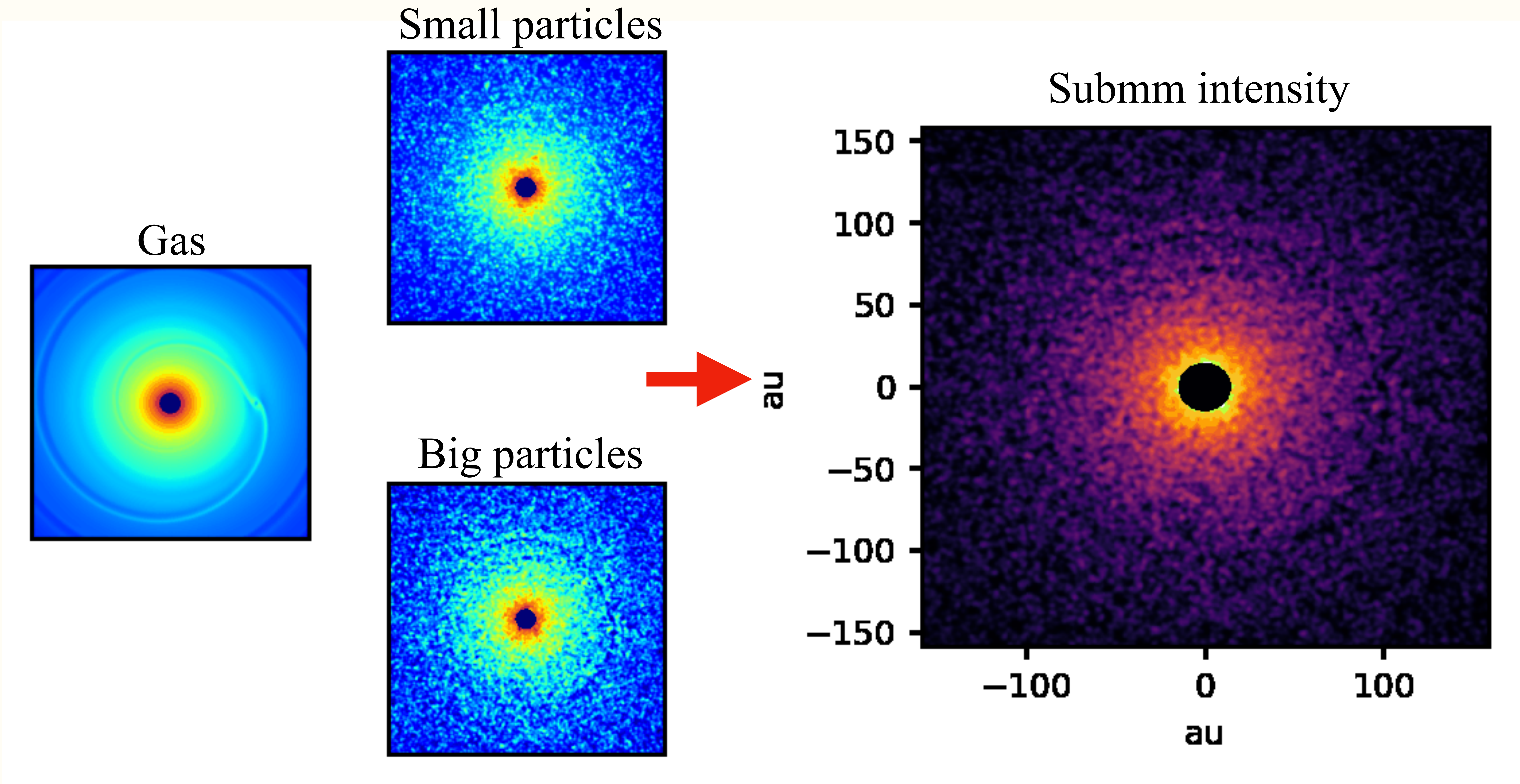
Code: Dusty FARGO-ADSG (Masset 2000, Baruteau & Masset 2008, Baruteau & Zhu 2016)

5 Planet masses, 3 turbulent level (α), 3 disk scale height (h/r)

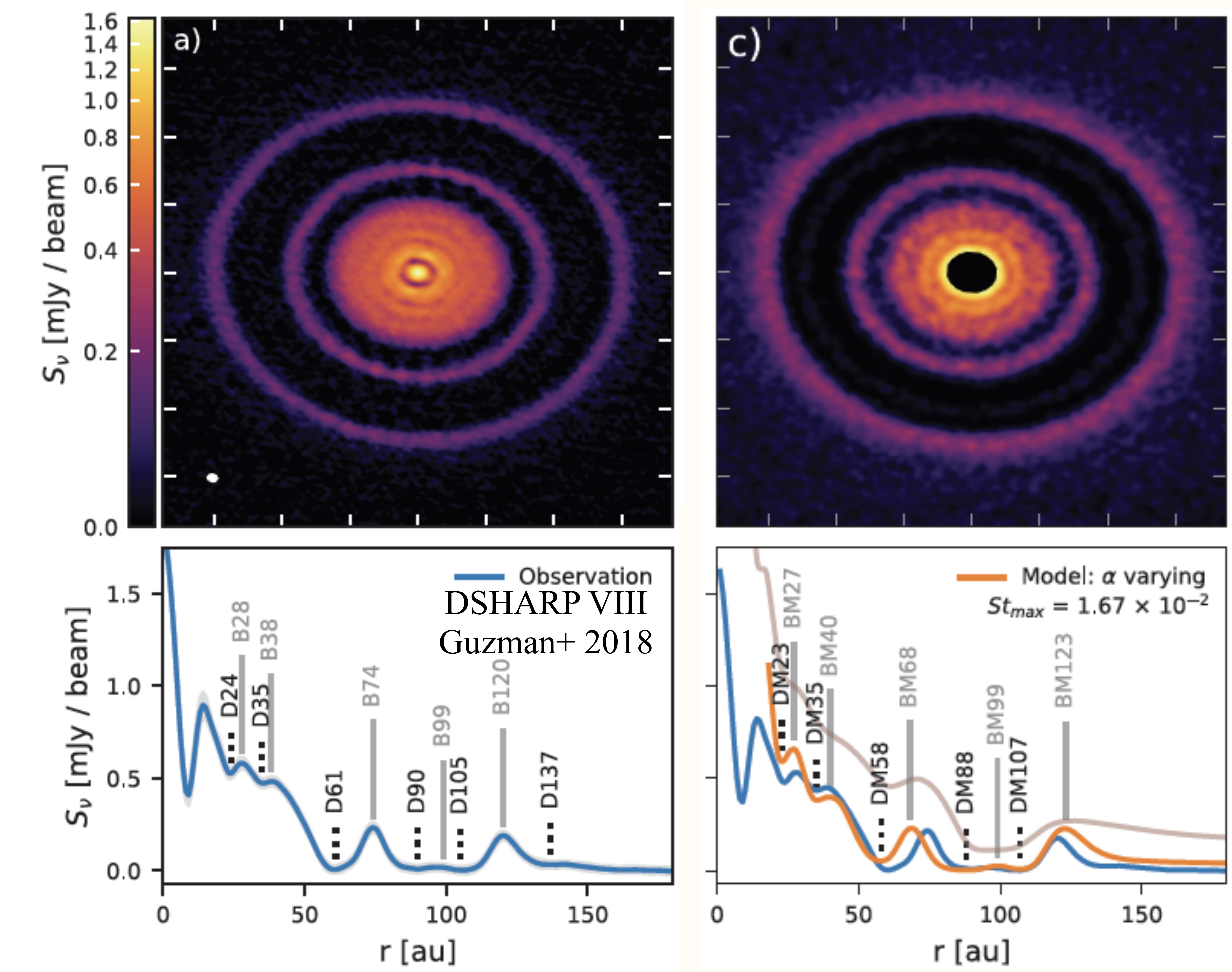
Gas:



Synthetic Images



AS 209

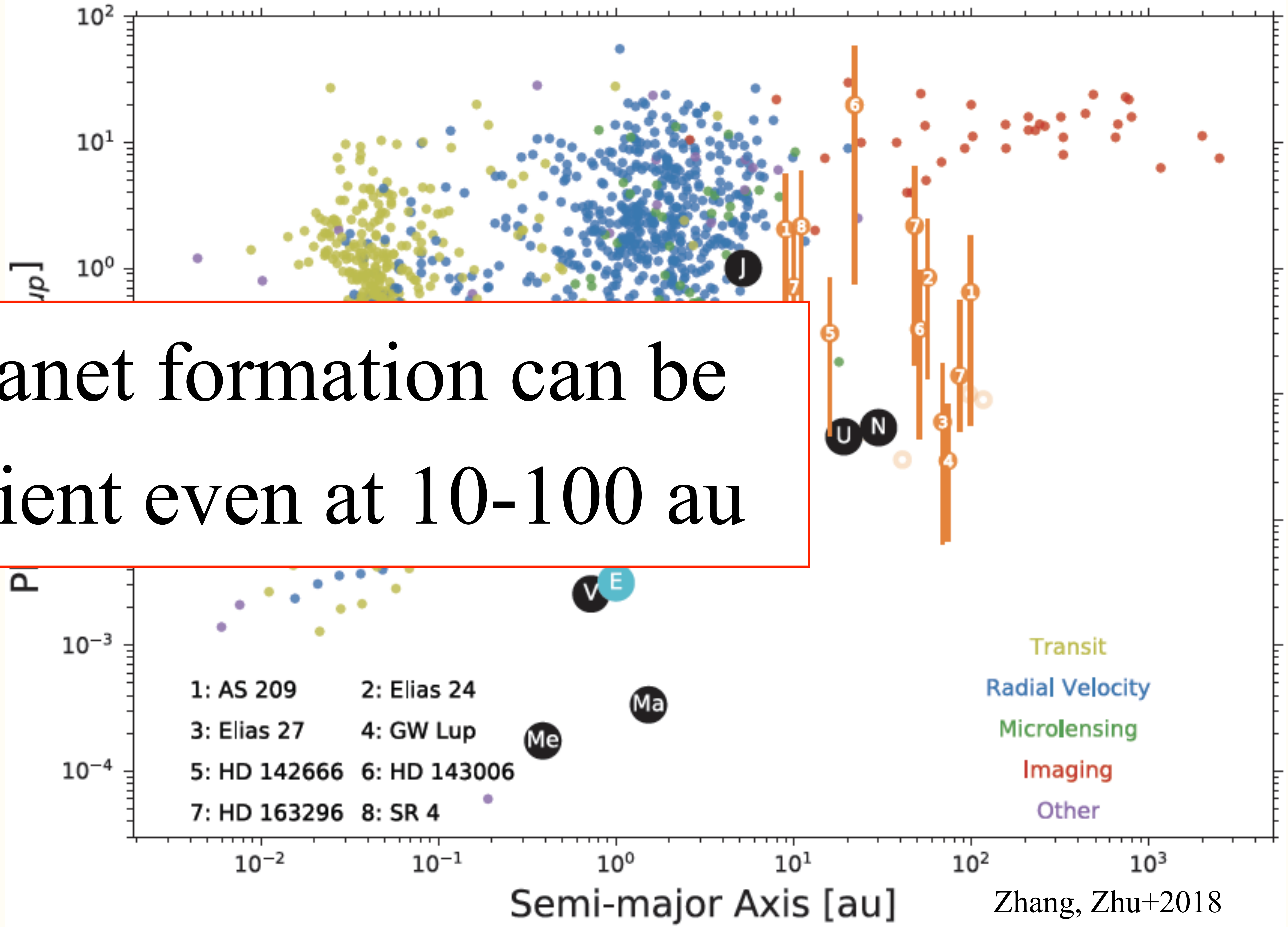


M_p=0.3 M_{saturn}

Young Planet Population

1. The occurrence rate for $M_p > 5\ M_J$ beyond 5-10 au is 6% (consistent with direct imaging results)

2. A large population of Neptune to Jupiter mass planets beyond 5-10 au. (occurrence rate



Zhang, Zhu+2018

Planet formation can be efficient even at 10-100 au

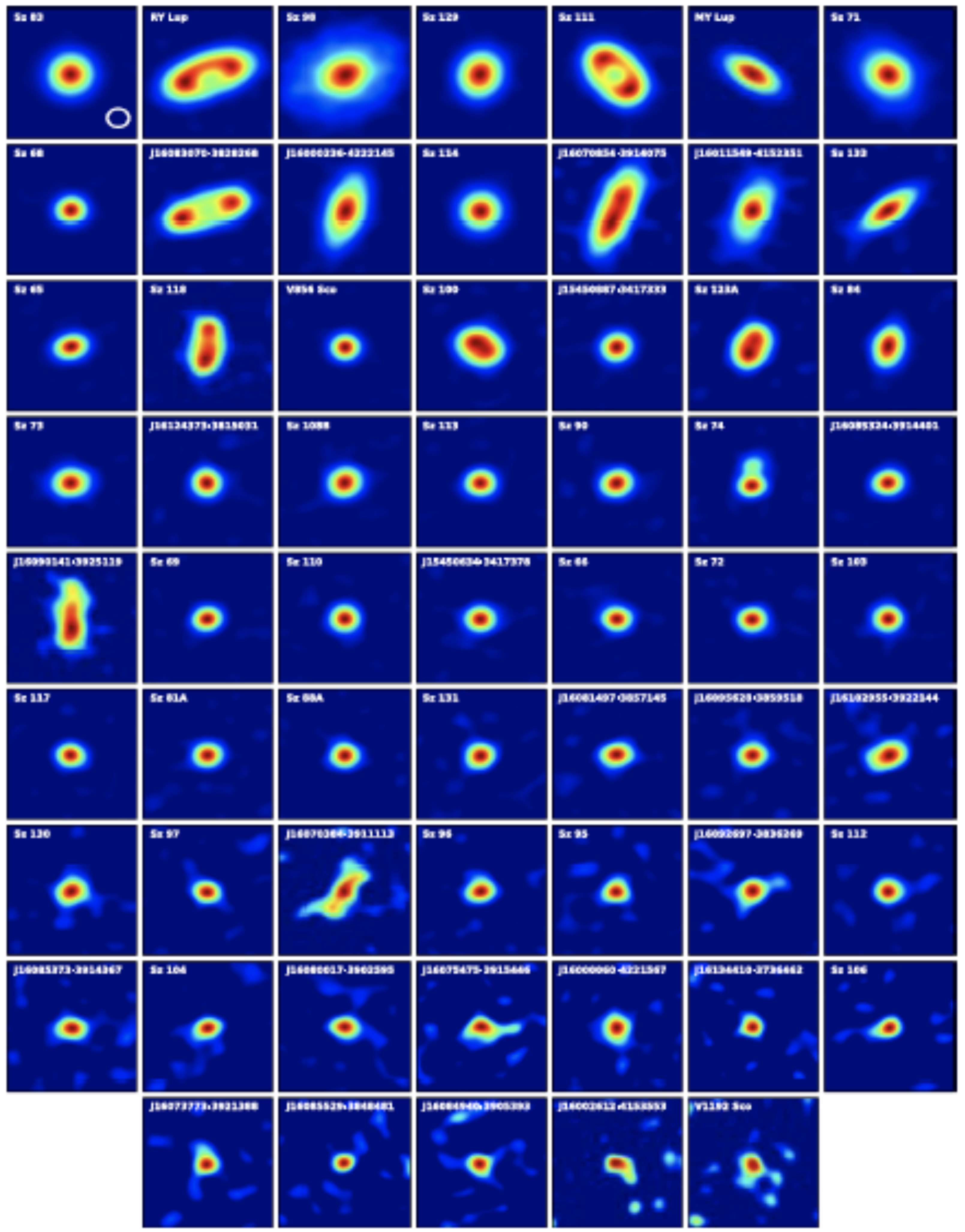
What are the consequences?

e.g. Lodato+ 2019

Outline:

1. Observational Signatures of Young Planets
    - Planet-disk interaction (gap opening)
    - Planet population from DSHARP
2. Understand demographics of protoplanetary disks
    - Mass budget problem
    - One solution: dust scattering

ALMA disk survey: Mass Budget Problem



Lupus ALMA cycle 2 Survey

Ansdell et al. 2016

$$I_\nu(r) = B_\nu(T_{mid}(r))(1 - e^{-\tau_\nu(r)})$$

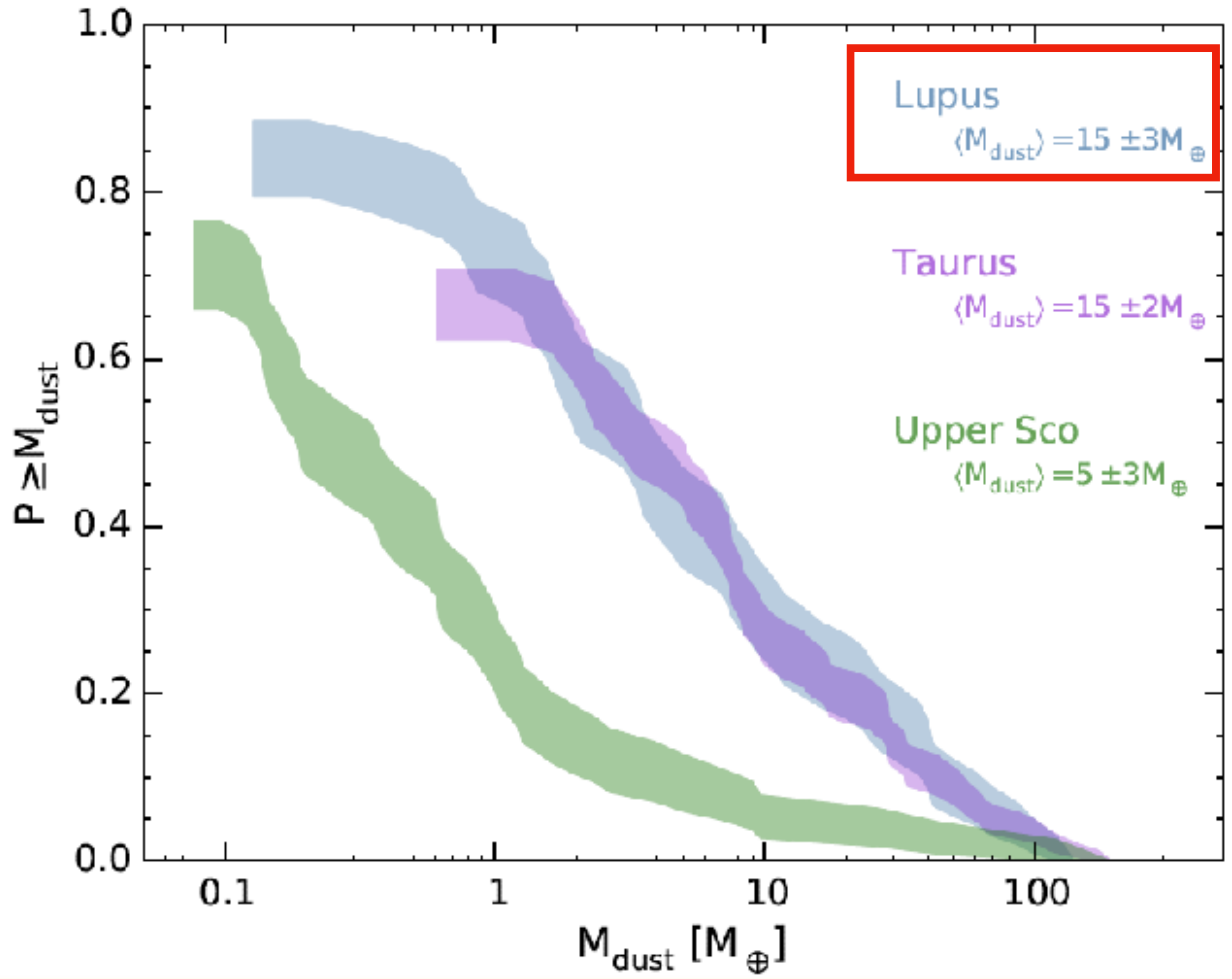
Beckwith et al. (1990)

When the disk is optically thin:

$$M_{\rm dust} = \frac{F_\nu d^2}{\kappa_\nu B_\nu(T_{\rm dust})}$$

Hildebrand (1983)

Assume T_{dust}=20 K, and opacity κ =3 cm²/g at 1 mm

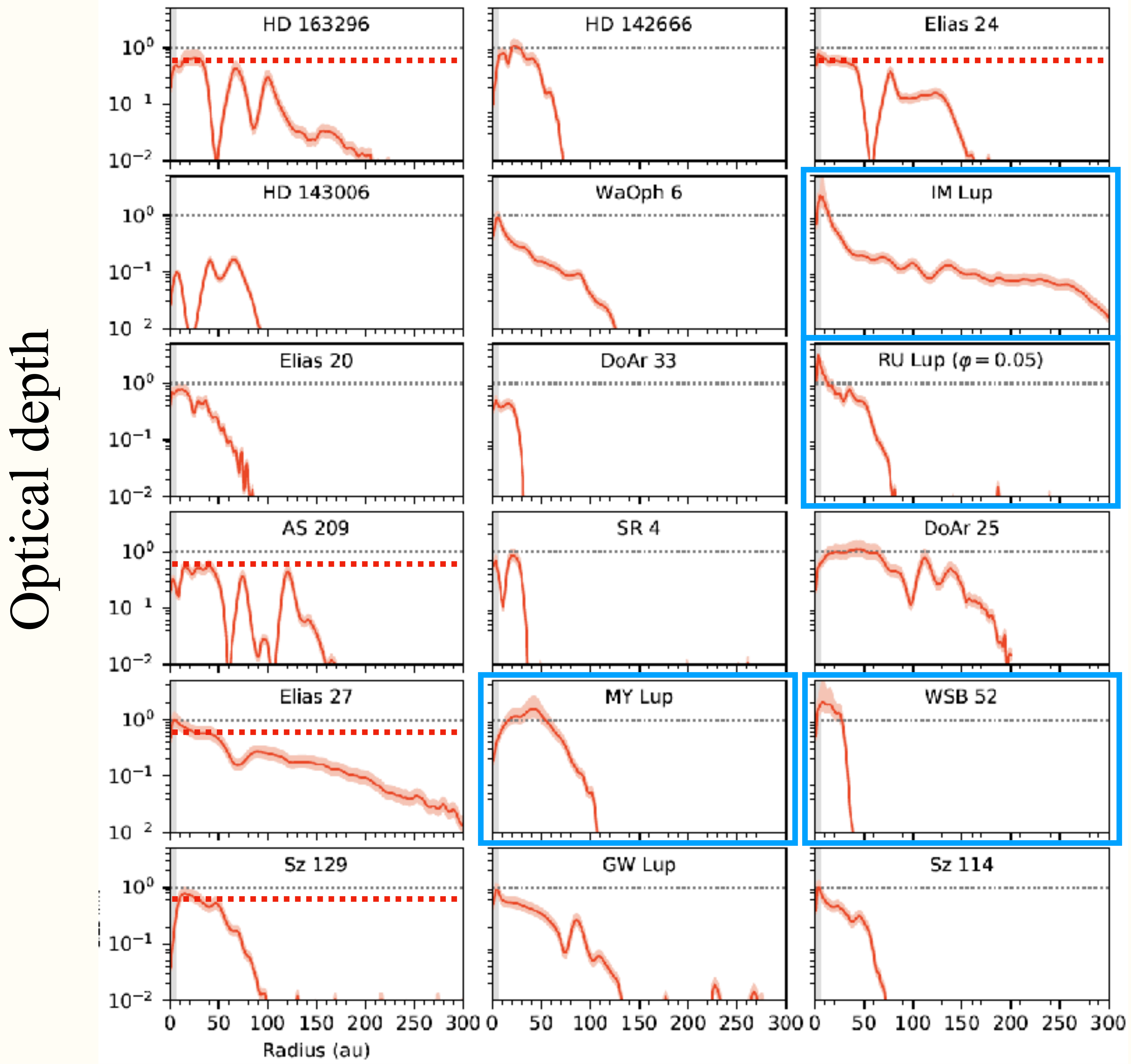


Ansdell et al. 2016, Andrews et al. 2013, Cieza et al. 2019

There appears to be a **mass budget problem** (Najita & Kenyon 2014)

Solutions:

1. Dust growth starts early (e.g. HL Tau) (Najita & Kenyon 2014)
2. Protoplanetary disks are optically thick, more dust than observed



$$I_\nu(r) = B_\nu(T_{mid}(r))(1 - e^{-\tau_\nu(r)})$$

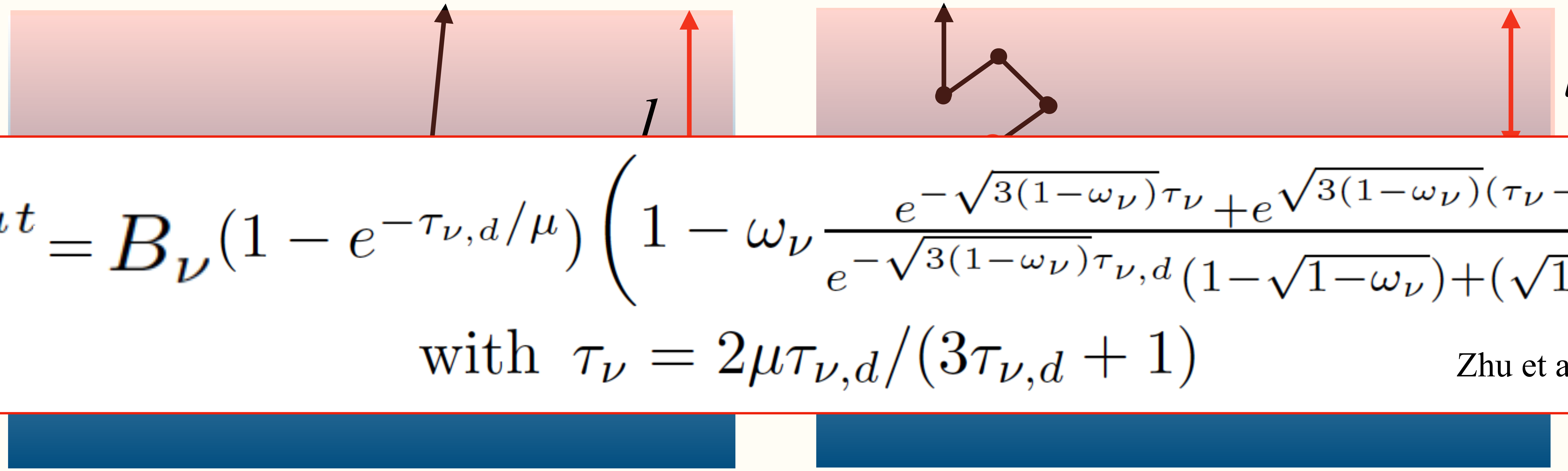
- Only 4 disks are optically thick. Even these 4 disks have $\tau \lesssim 3$
- A lot of disks have the maximum $\tau \sim 0.6$

Dullemond et al. 2018

Optically thick disk scenario is not preferred

DSHARP II
Huang et al. 2018

But $I_\nu(r) = B_\nu(T_{mid}(r))(1-e^{-\tau_\nu(r)})$ only stands if there is no scattering!



$$I_\nu^{out} = B_\nu(1-e^{-\tau_{\nu,d}/\mu})\left(1-\omega_\nu\frac{e^{-\sqrt{3(1-\omega_\nu)}\tau_\nu}+e^{\sqrt{3(1-\omega_\nu)}(\tau_\nu-\tau_{\nu,d})}}{e^{-\sqrt{3(1-\omega_\nu)}\tau_{\nu,d}}(1-\sqrt{1-\omega_\nu})+(\sqrt{1-\omega_\nu}+1)}\right)$$

with $\tau_\nu = 2\mu\tau_{\nu,d}/(3\tau_{\nu,d}+1)$

Zhu et al. (2019)

$I \sim$ … $(\sigma_a + \sigma_s)$

…ing absorbed

…bsorption is

Scattering makes optically-thick disks look fainter!

This effect have b…

Miyake & Nakagawa (1…

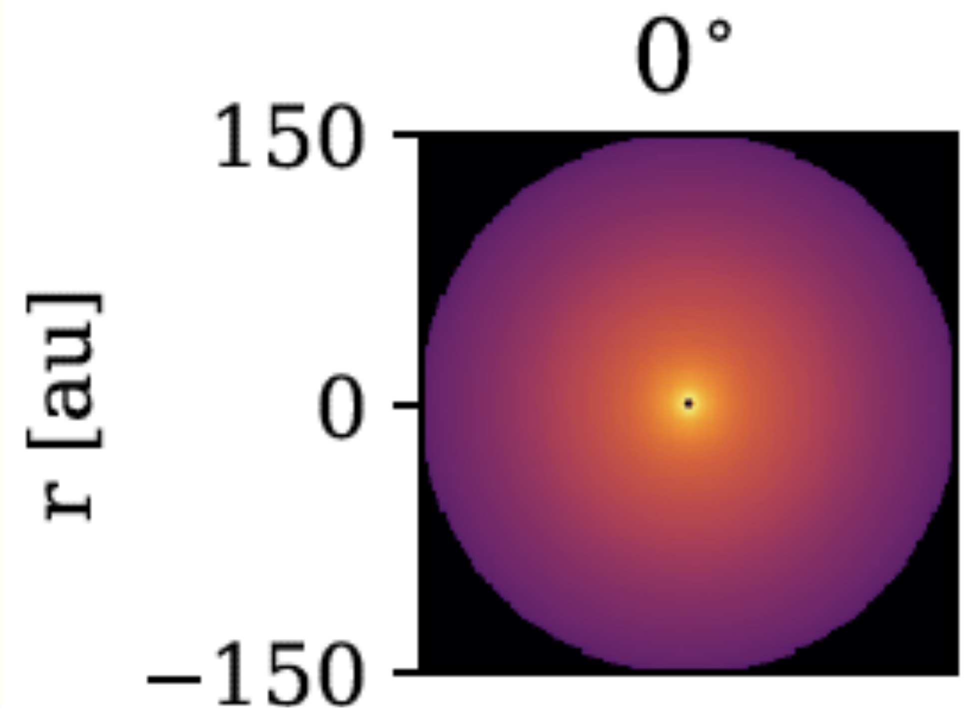
Sierra et al. (2017), Bir…

But its effect on disk mass measurement has been ignored!

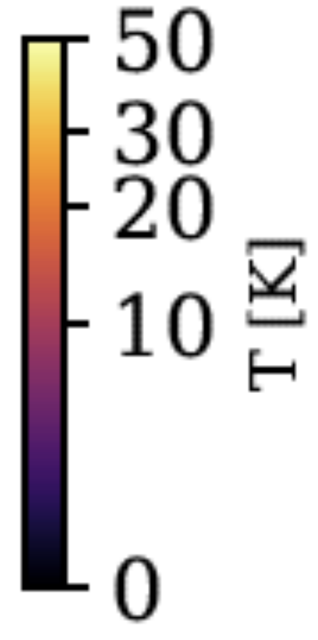
$$I \sim j \times l_{eff} = \sigma_a B l_{eff} = B(1-\omega)^{1/2}$$

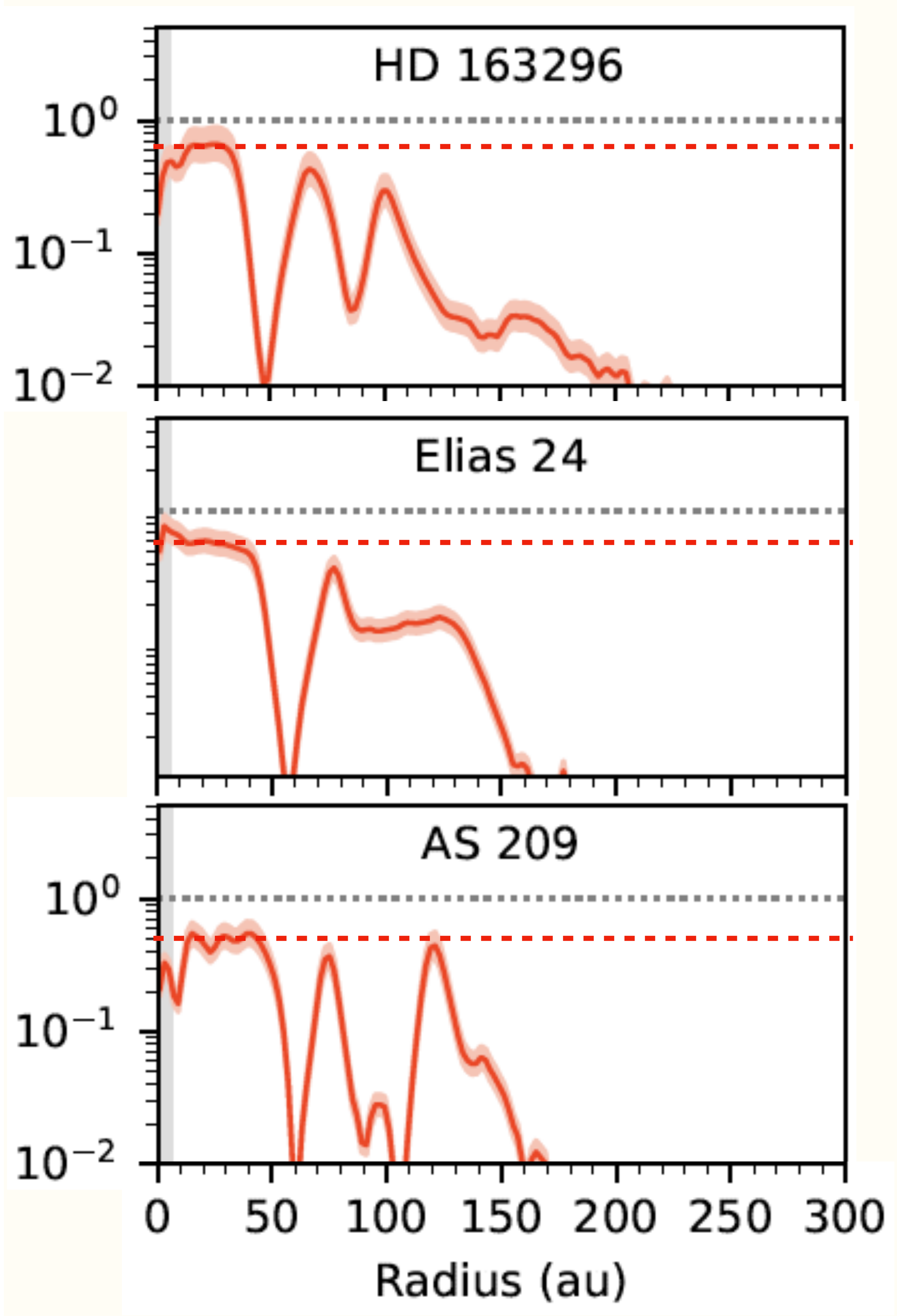
Zhu et al. (2019)

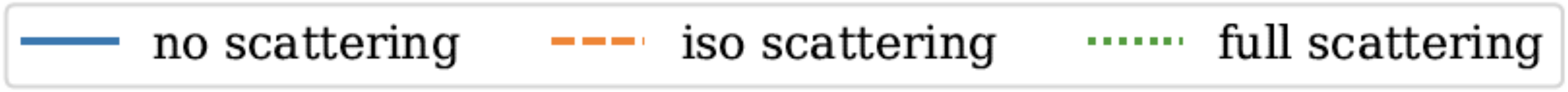
Underestimate the optical depth significantly (MCRT)



Q=1 massive disk
DSHARP opacity
with a_{max}=1 mm

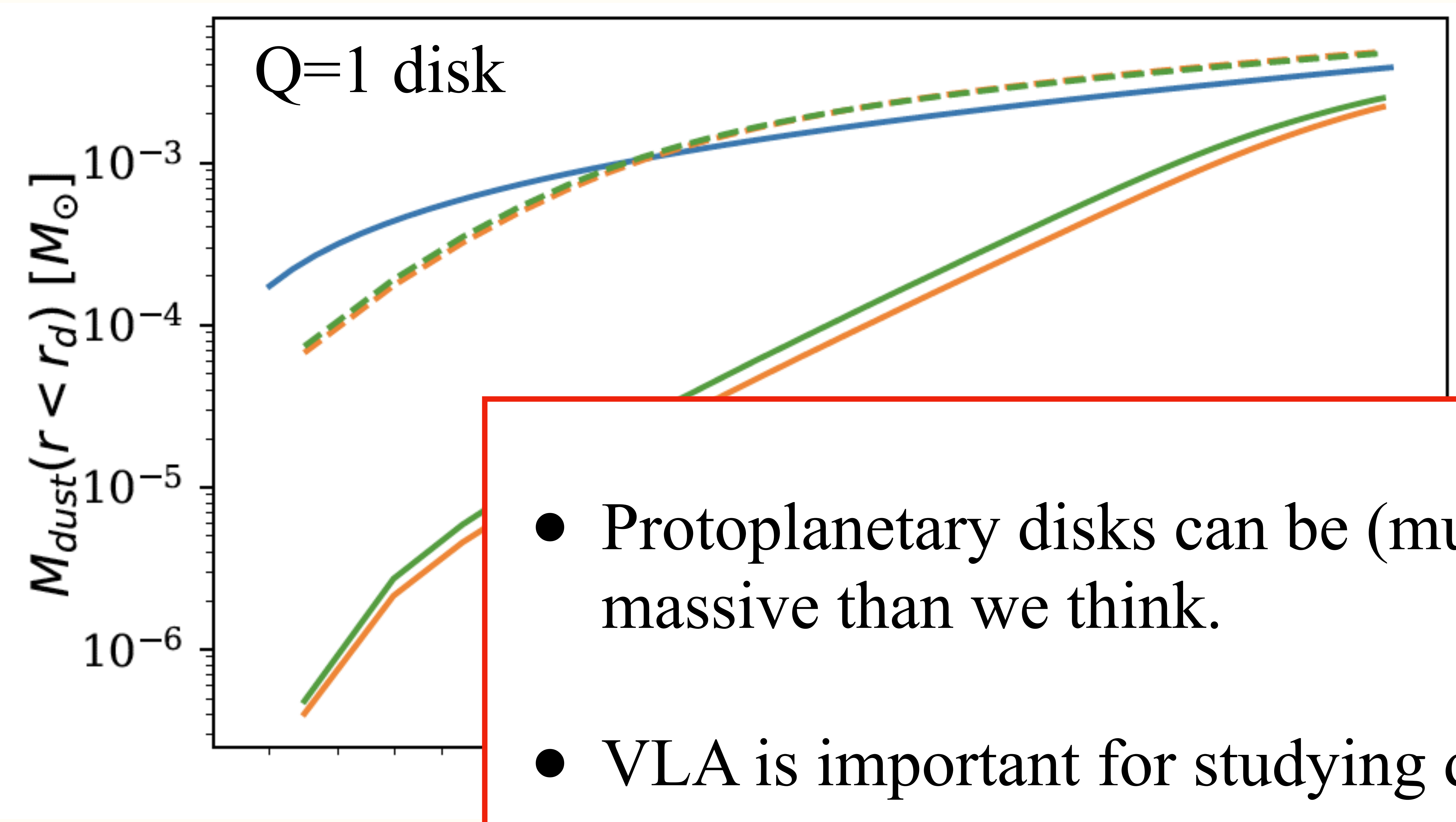




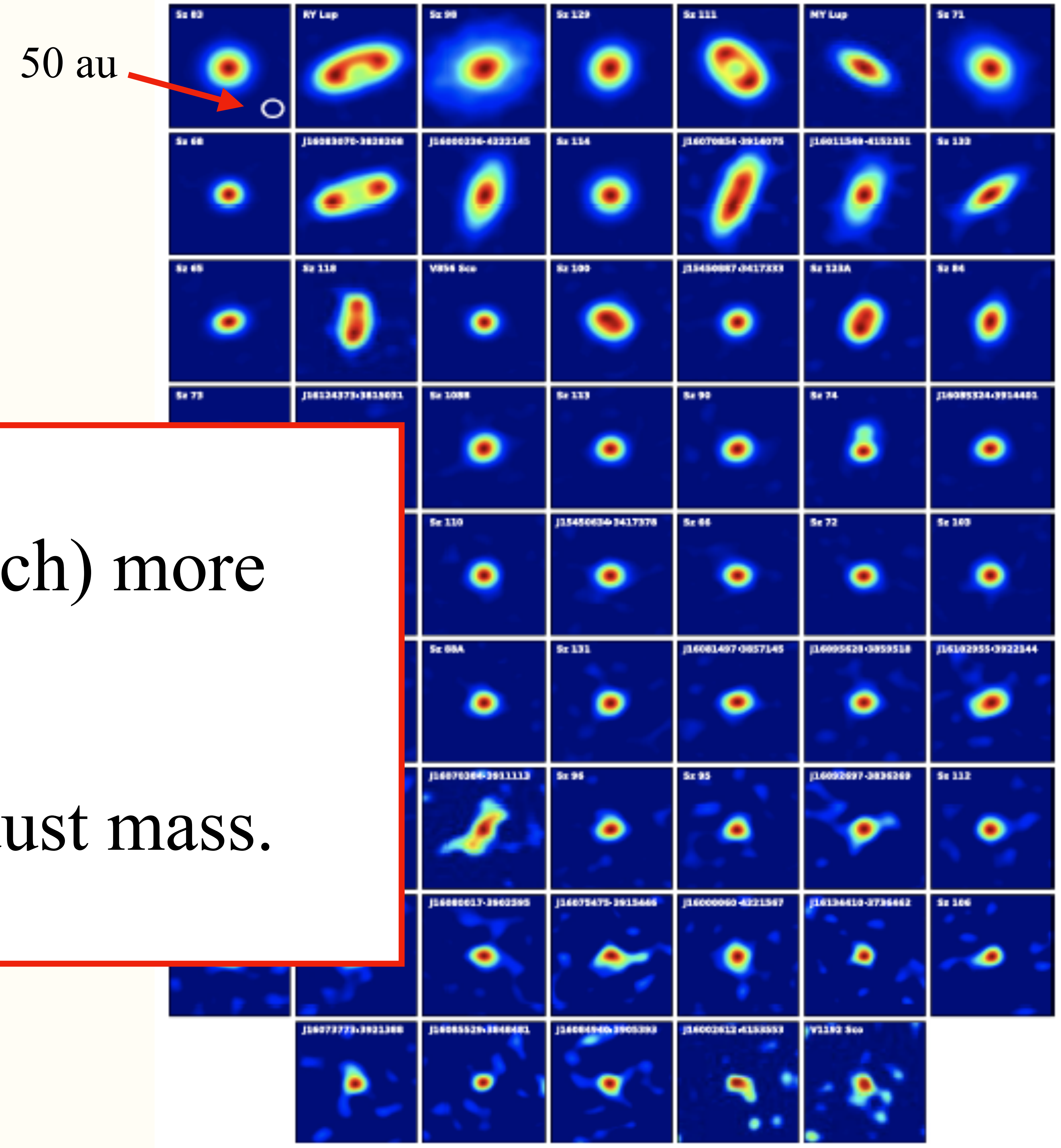


Zhu et al. (2019)

Underestimate the disk mass significantly!



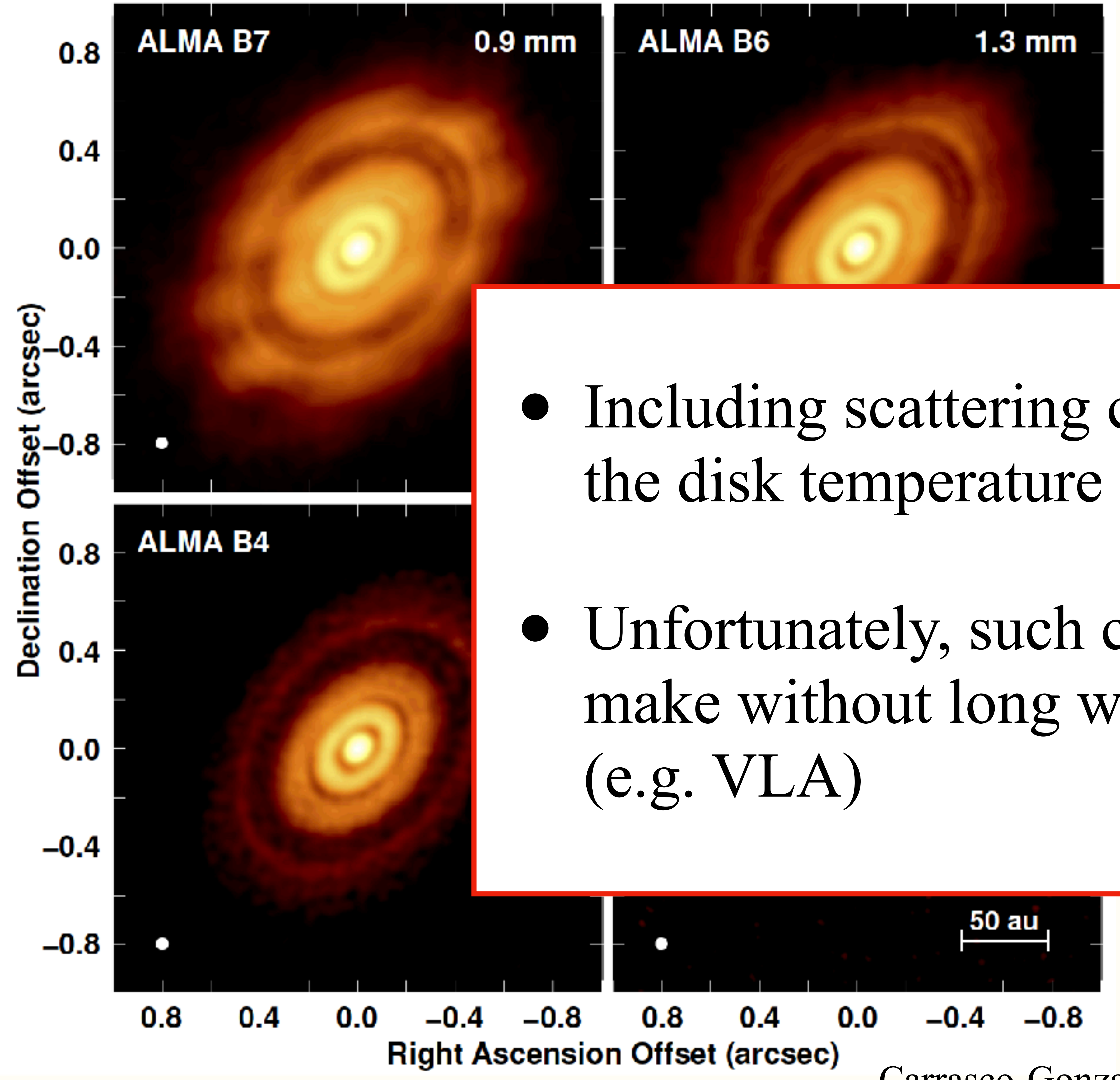
- Protoplanetary disks can be (much) more massive than we think.
- VLA is important for studying dust mass.

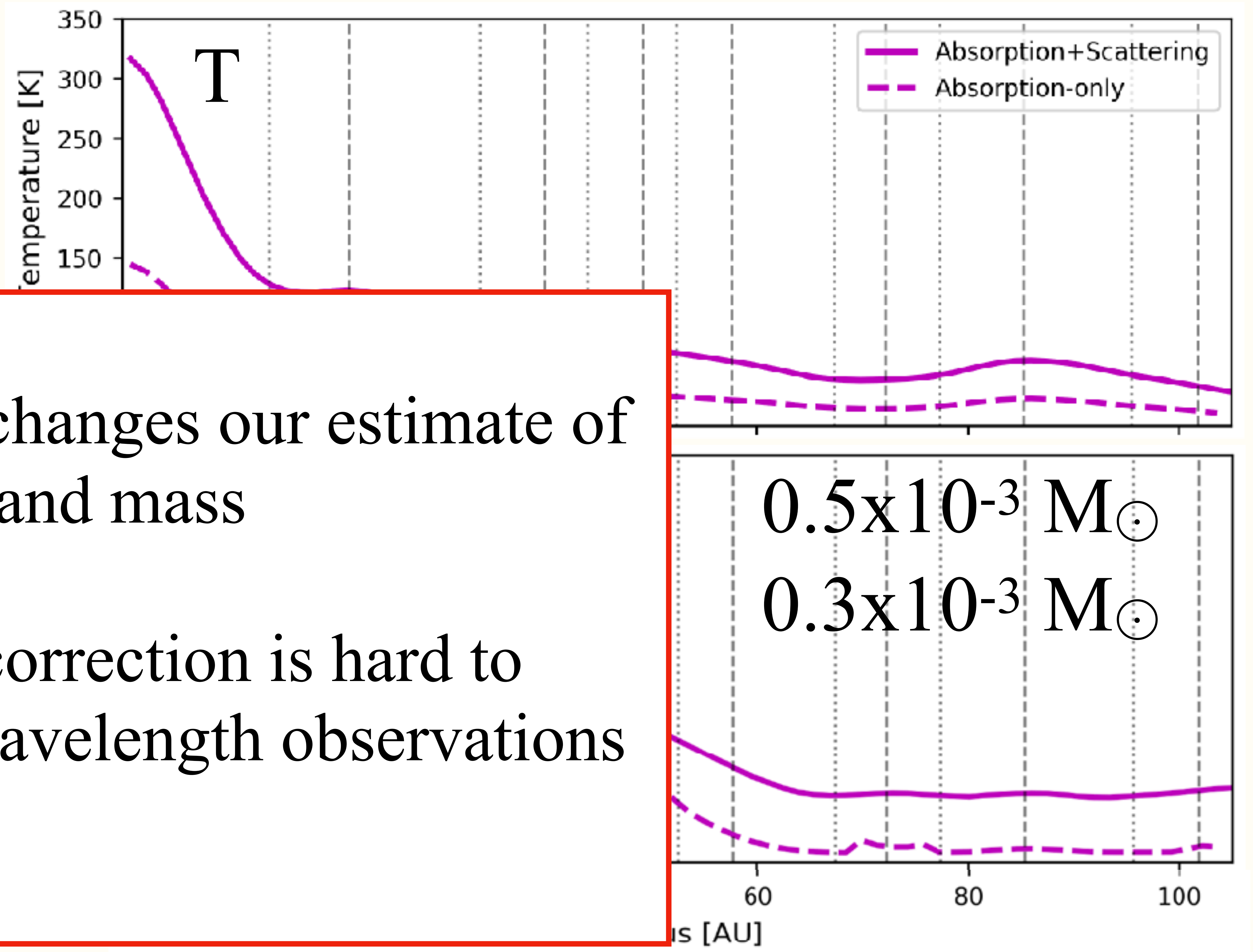


Ansdell et al. 2016

At 1 mm, easily underestimate the dust mass by a factor of >10 for compact disks with r_d<30 au

One example: HL Tau





- Including scattering changes our estimate of the disk temperature and mass
- Unfortunately, such correction is hard to make without long wavelength observations (e.g. VLA)

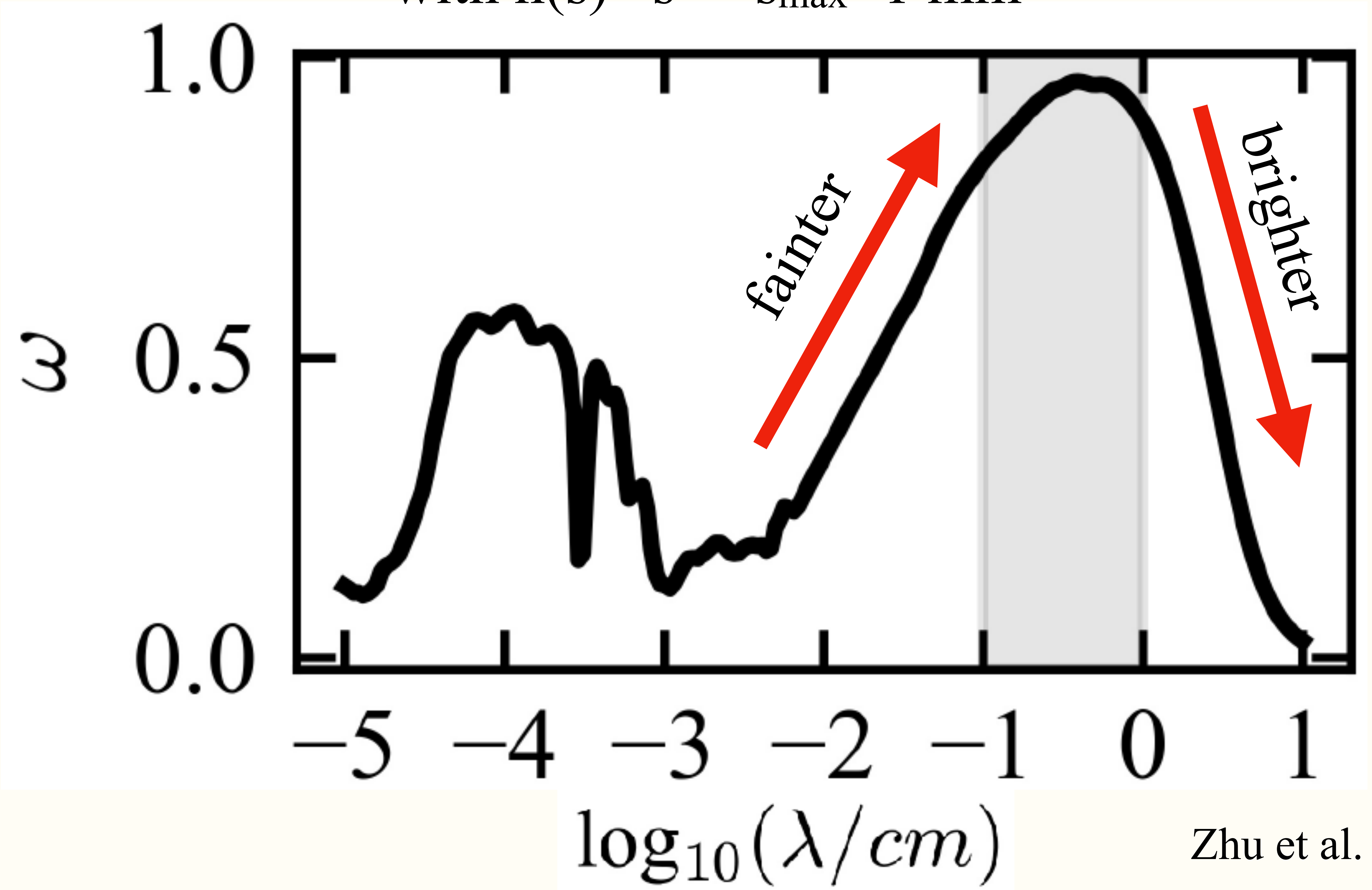
Carrasco-Gonzalez+ submitted

constraining not mass but dust properties

DSHARP $\tau \sim 0.6$

=> Albedo $\omega_{1.25\,mm} \sim 0.9$

DSHARP opacity
with $n(s) \propto s^{-3.5}$ s_{max}=1 mm

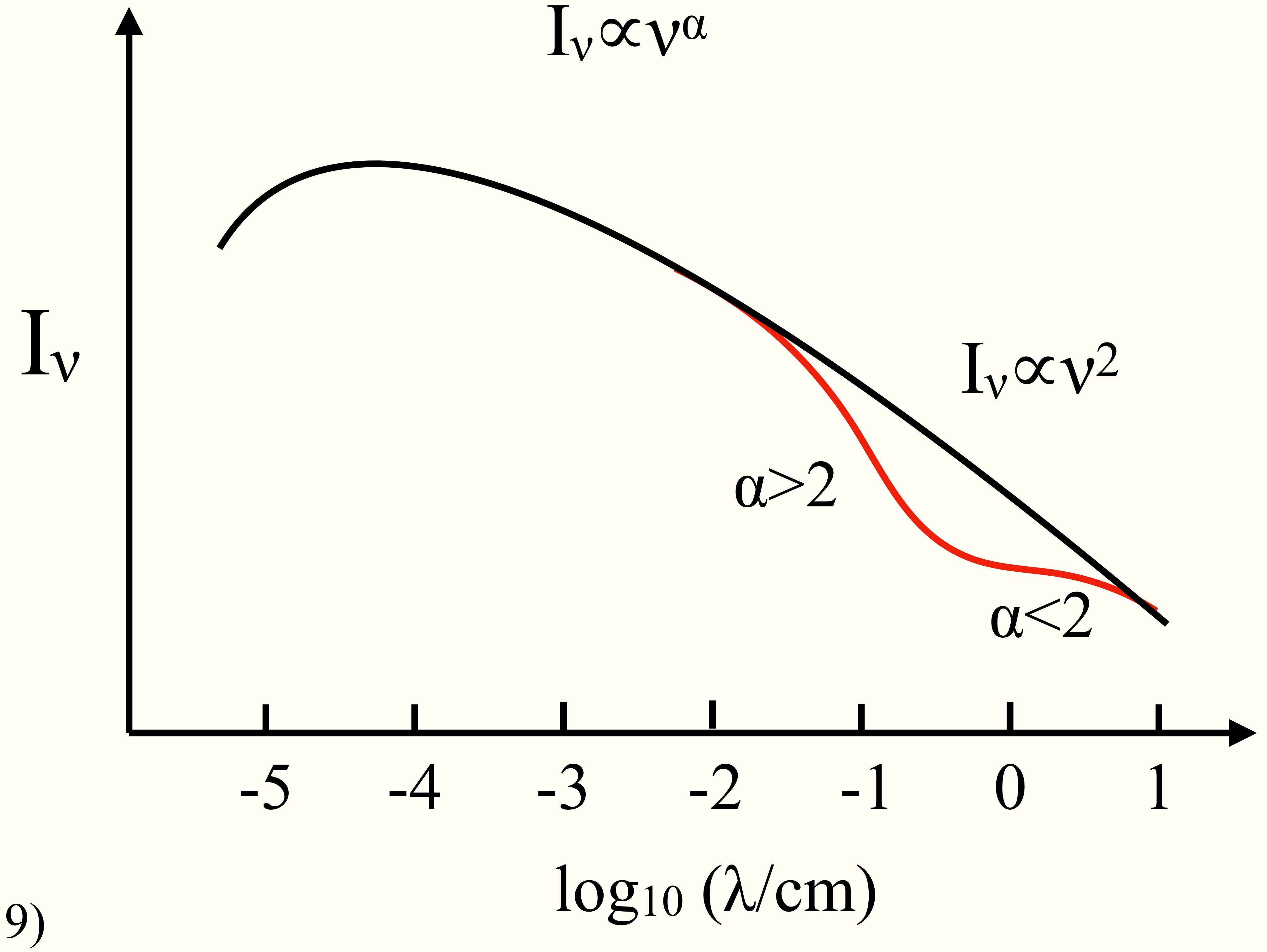


Zhu et al. (2019)

α can be larger or smaller than 2 depending on if ω increases or decreases with wavelength

Also in Liu (2019)

TW Hydrae: α<2 at the inner disk. (Huang et al.2018)



Other applications:

1. Luminosity-size relationship

Andrews et al. 2010, 2018
Tripathi et al. 2017

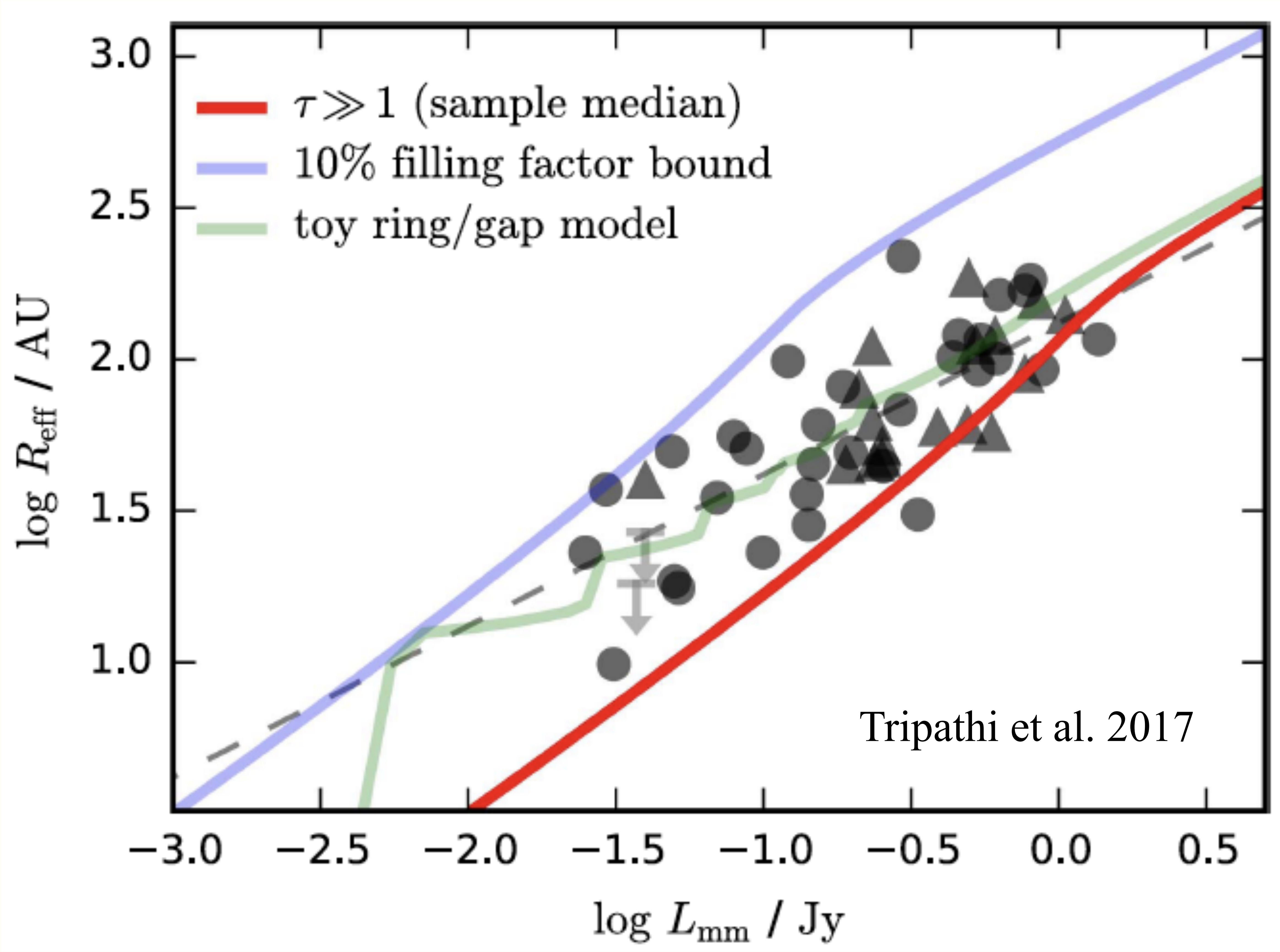
0.3 filling factor
gaps or scattering

2. Polarization measurements

Kataoka et al. 2015, 2016, 2017
Yang et al. 2016ab

3. Pebble accretion

4. Implications for molecules?



Conclusion:

1. Disk structure and young planet population
    - Diverse disk structure. If they are caused by planets, what
    - PDS 70 (explore all other methods)
    - Young planet population (Neptune-Jupiter mass planets are cor
2. Understand demographics of protoplanetary disks
    - Mass budget problem
    - One Solution: optically thick disks with dust scattering
    - Solve many problems (τ~0.6, spectral index, luminosity-ra