First Steps of Planet Formation around Very Low Mass Stars

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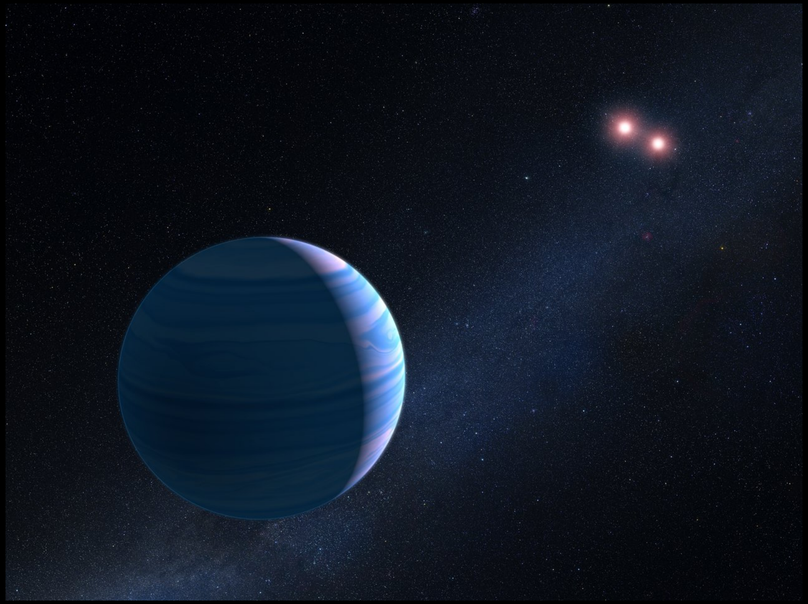
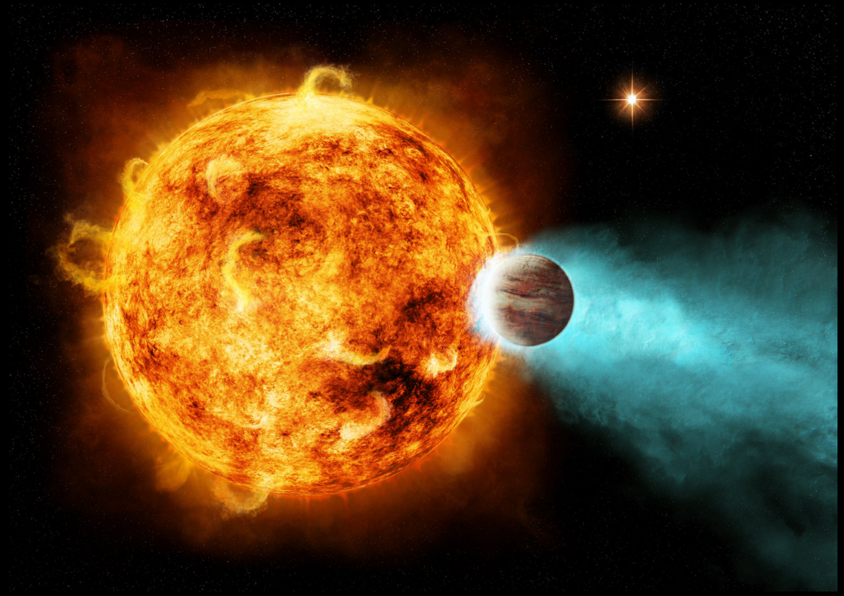
Motivation

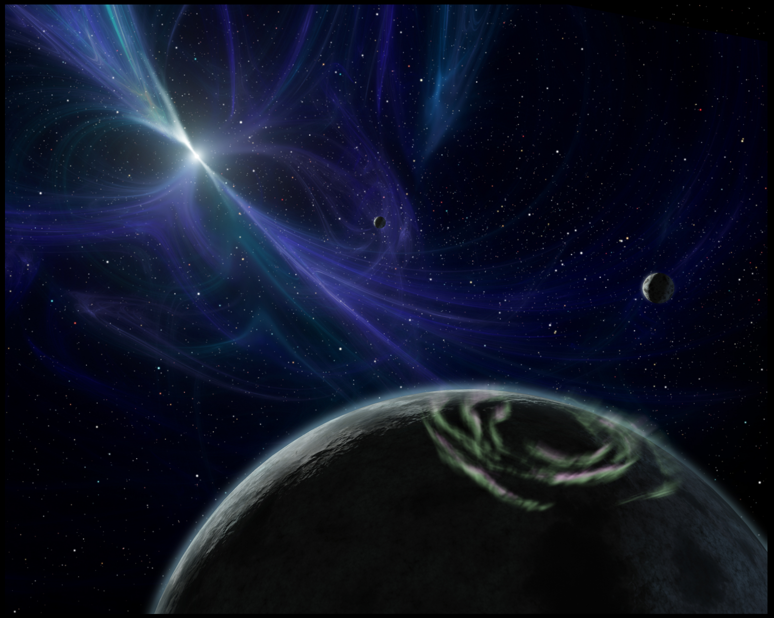
Large Diversity of Exoplanets and their Architectures



Planets around binaries or multiple systems

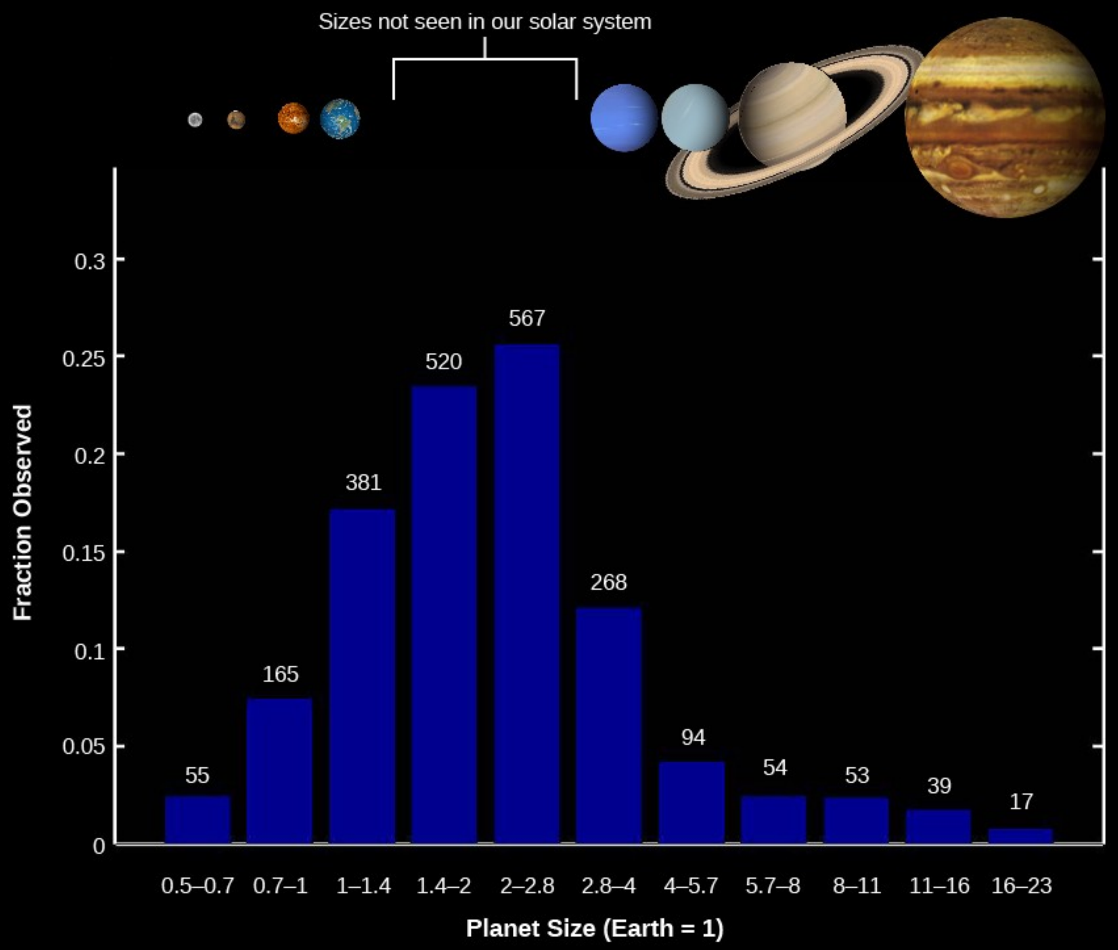


Close-in exoplanets (1-10 days period)

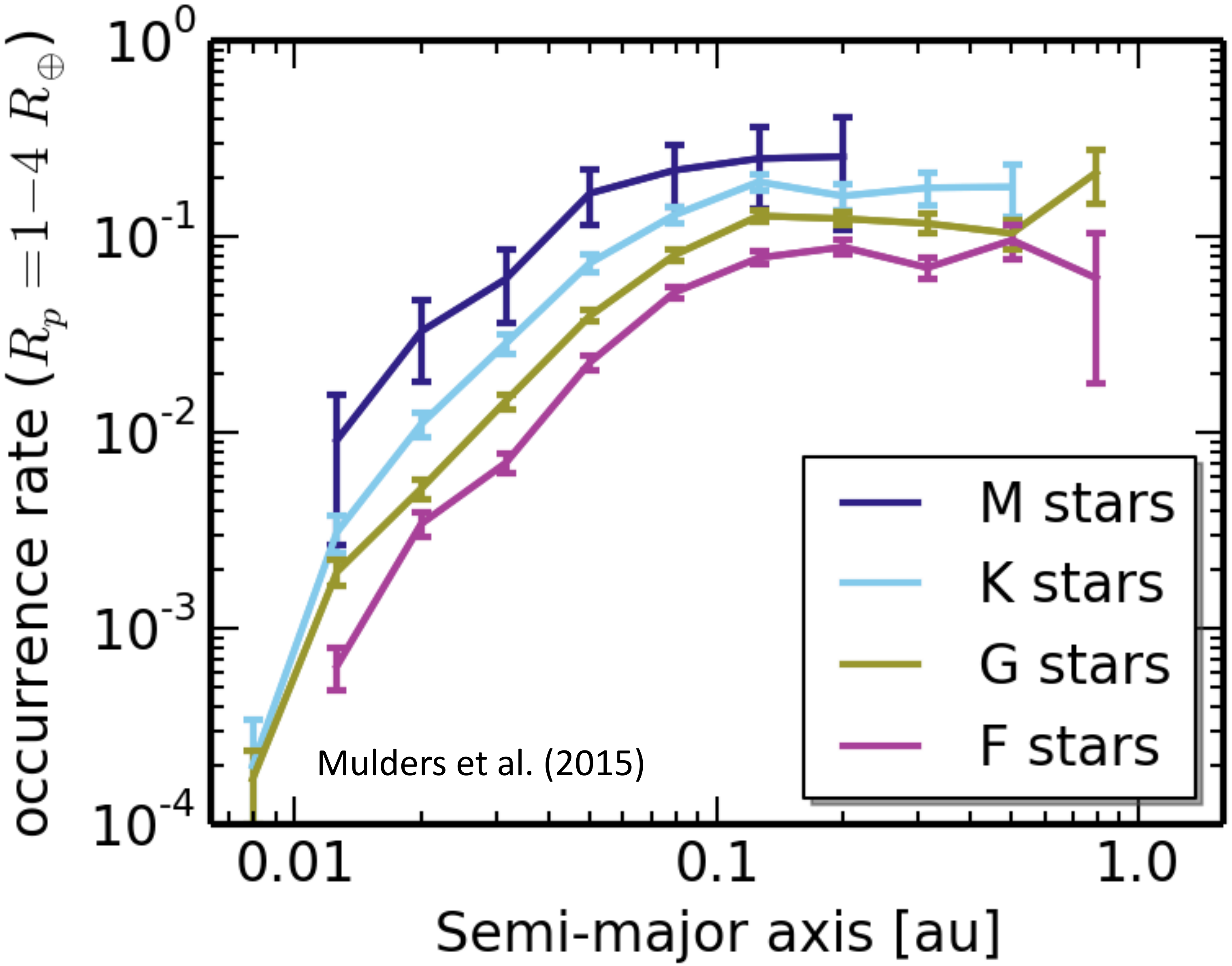


Planets around pulsars

Large Diversity of Exoplanets and their Architectures

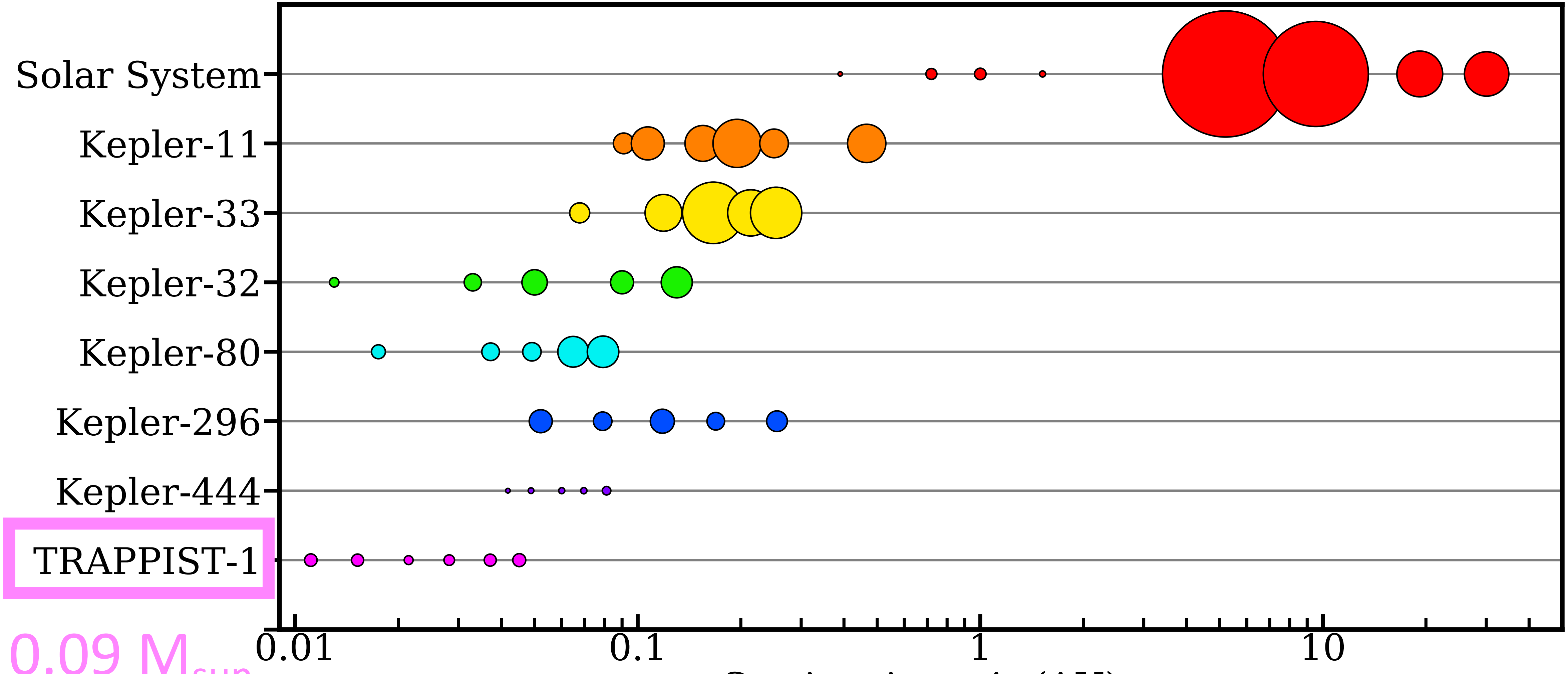


Some Trends with the Stellar Mass



Planetary systems are more compact around low mass stars

Examples of Compact Planetary Systems



$0.09\ M_{sun}$

Figure adapted from Campante et al. (2015)

Stellar Mass may Leave an Imprint on the Properties and Diversity of Exoplanets

Look back in time …

Observational Evidence of Disks around VLM stars and BDs

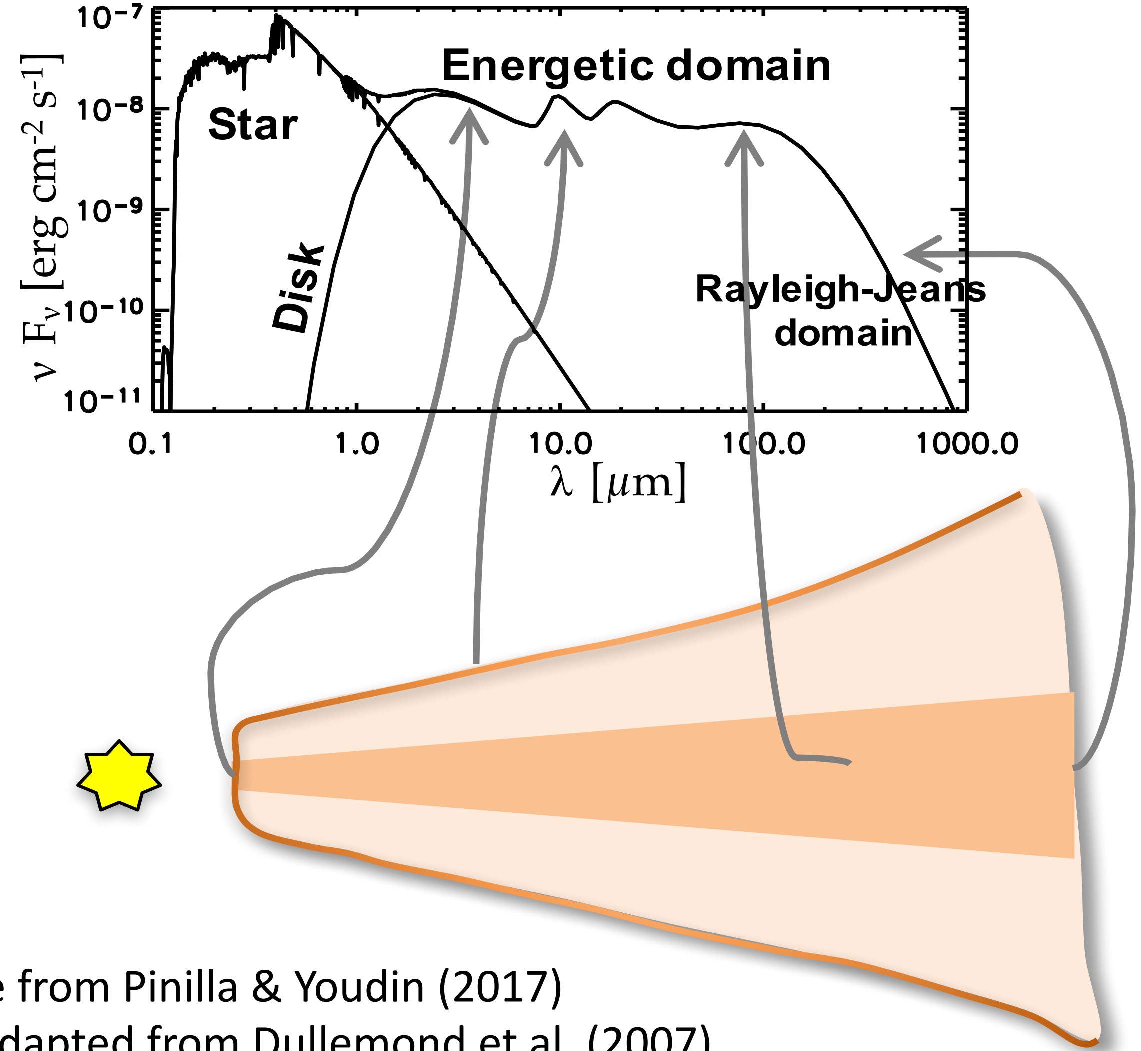
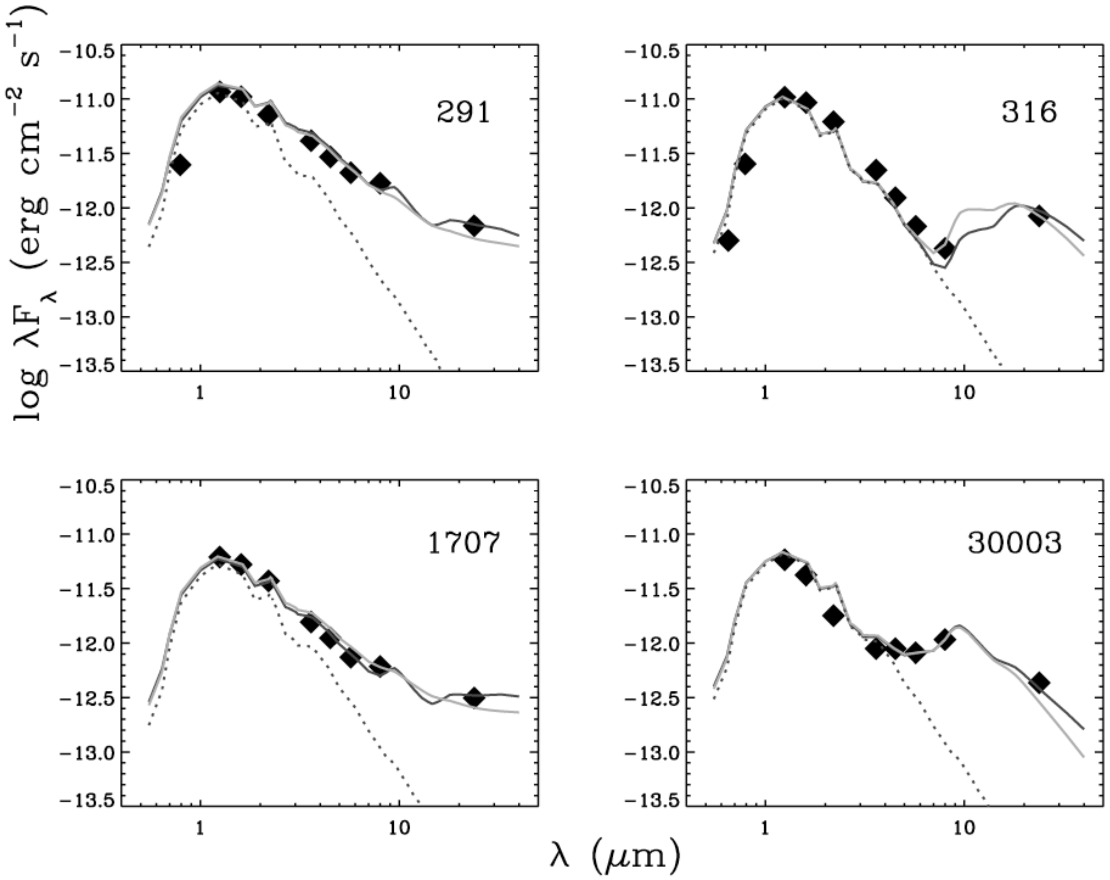
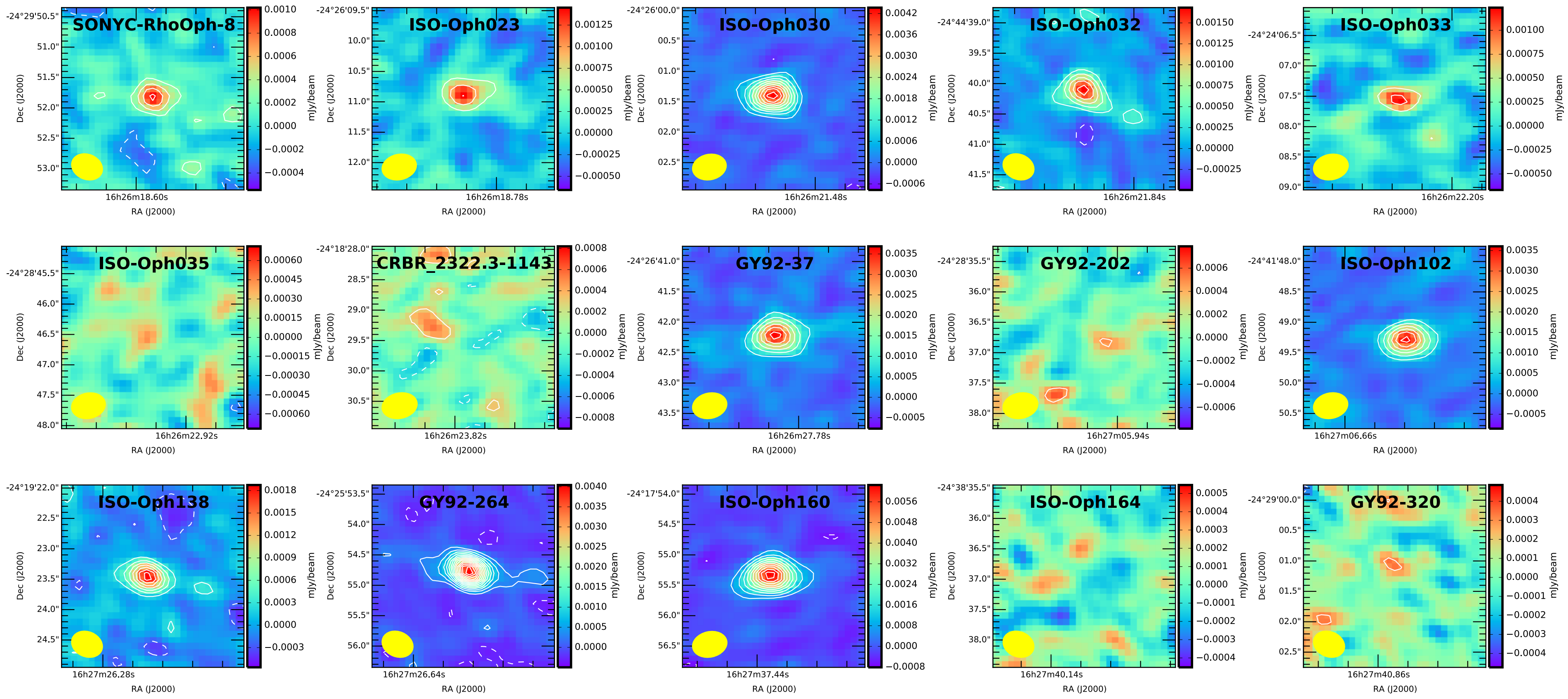


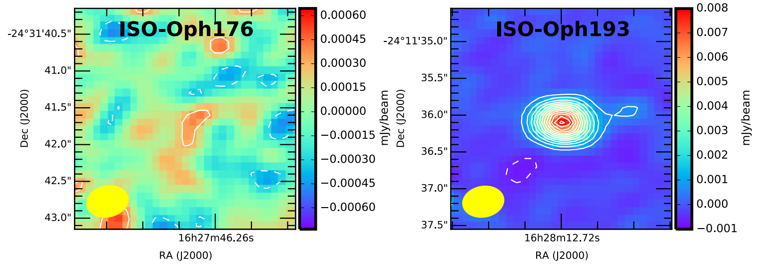
Figure from Pinilla & Youdin (2017)
And adapted from Dullemond et al. (2007)



Observations with *Spitzer* of BDs in the cluster IC 348. Muzerolle et al. (2006)

Recent mm-Observations of Disks around VLM stars and BDs





17 young brown dwarfs were observed at 890 μm

Resolution: 0.''5

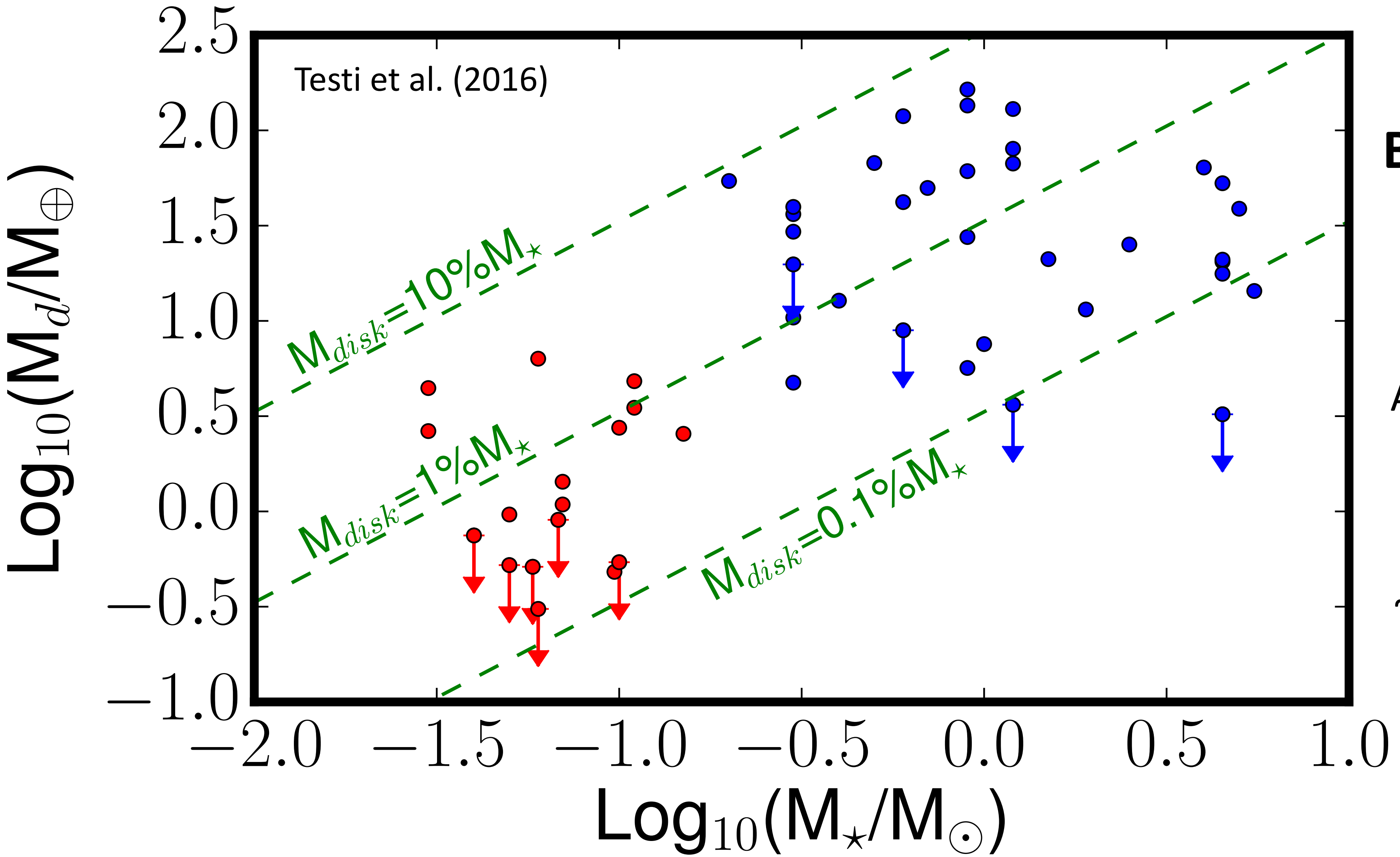
Sensitivity to detect ~0.5 M_{Earth} of dust.

Detection of 11 disks

ALMA first survey of young brown dwarfs in the ρ Oph star-forming region.

Testi et al. (2016)

Disks around VLMS and BDs: excellent laboratories to investigate planet formation in extreme conditions



BD disks are low mass, smaller (how small?) and colder.

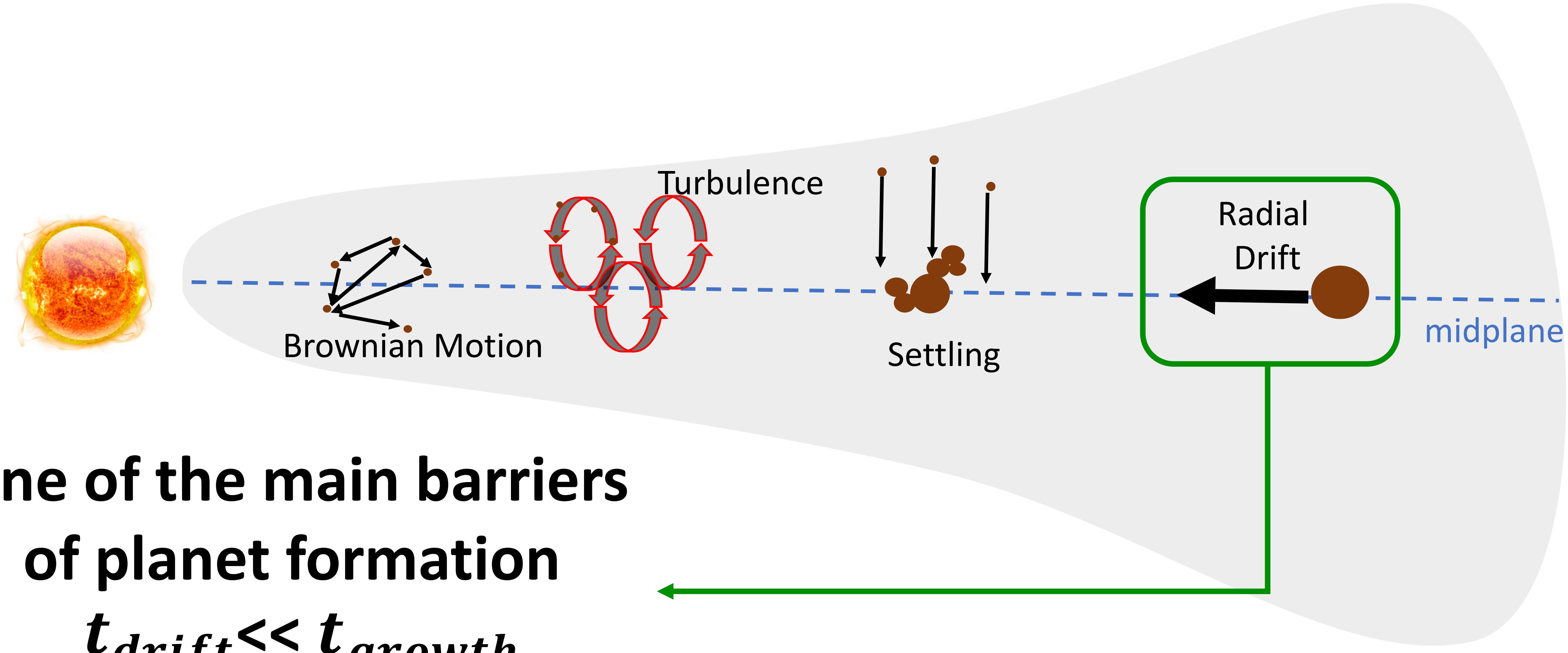
ALMA survey of young brown dwarfs in the ρ-Oph.

Sensitivity to detect ~0.5 M_{Earth} of dust. Detection of 11 disks.

Dust Evolution in Disks around VLM stars and BDs

Dust Evolution

Transport ⟷ **Collisions**



One of the main barriers of planet formation

$$t_{drift} << t_{growth}$$

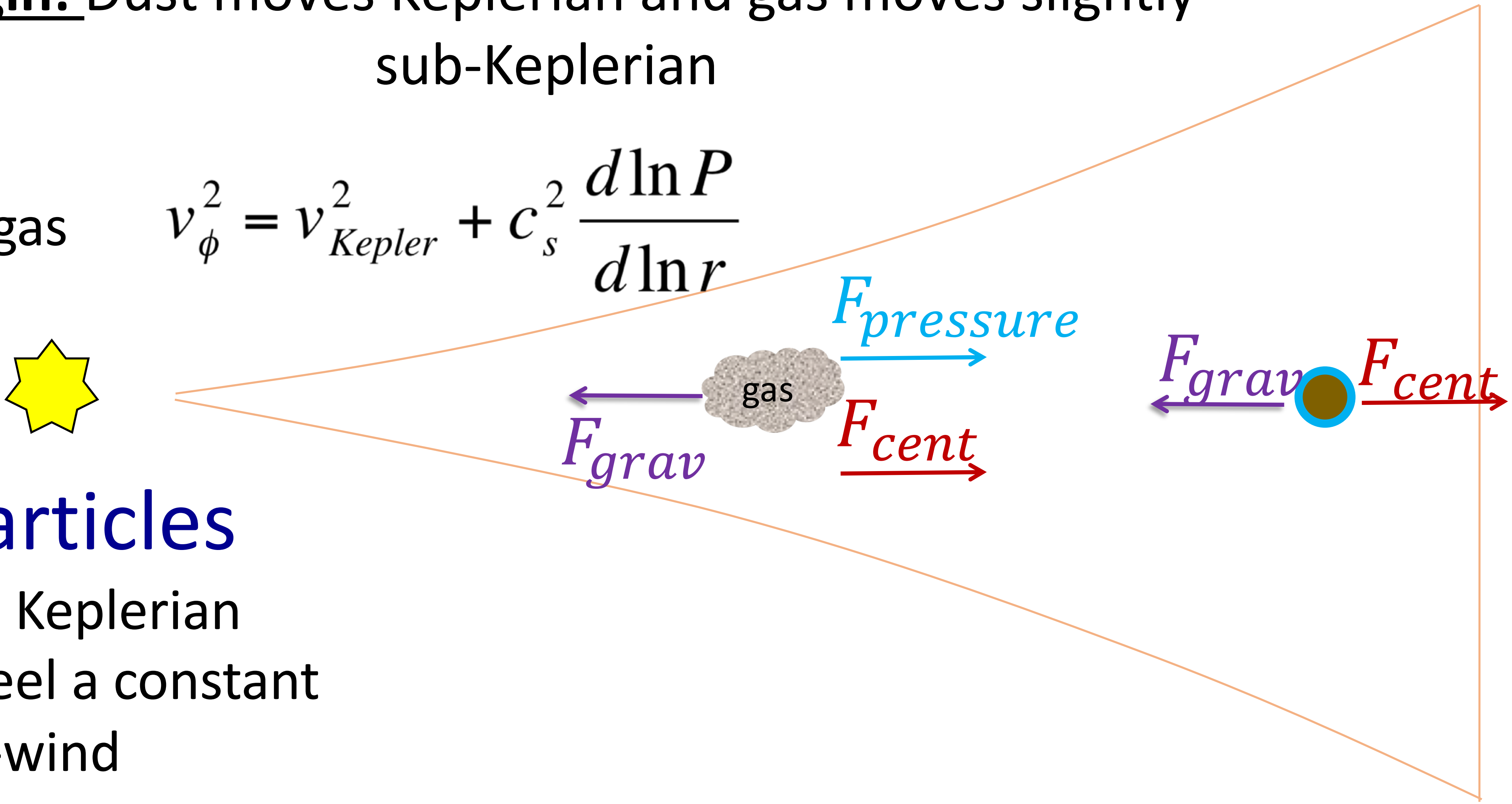
Radial Drift of Particles

Origin: Dust moves Keplerian and gas moves slightly sub-Keplerian

GAS

Supported by gas pressure

$$v_\phi^2 = v_{Kepler}^2 + c_s^2 \frac{d\ln P}{d\ln r}$$



Dust Particles

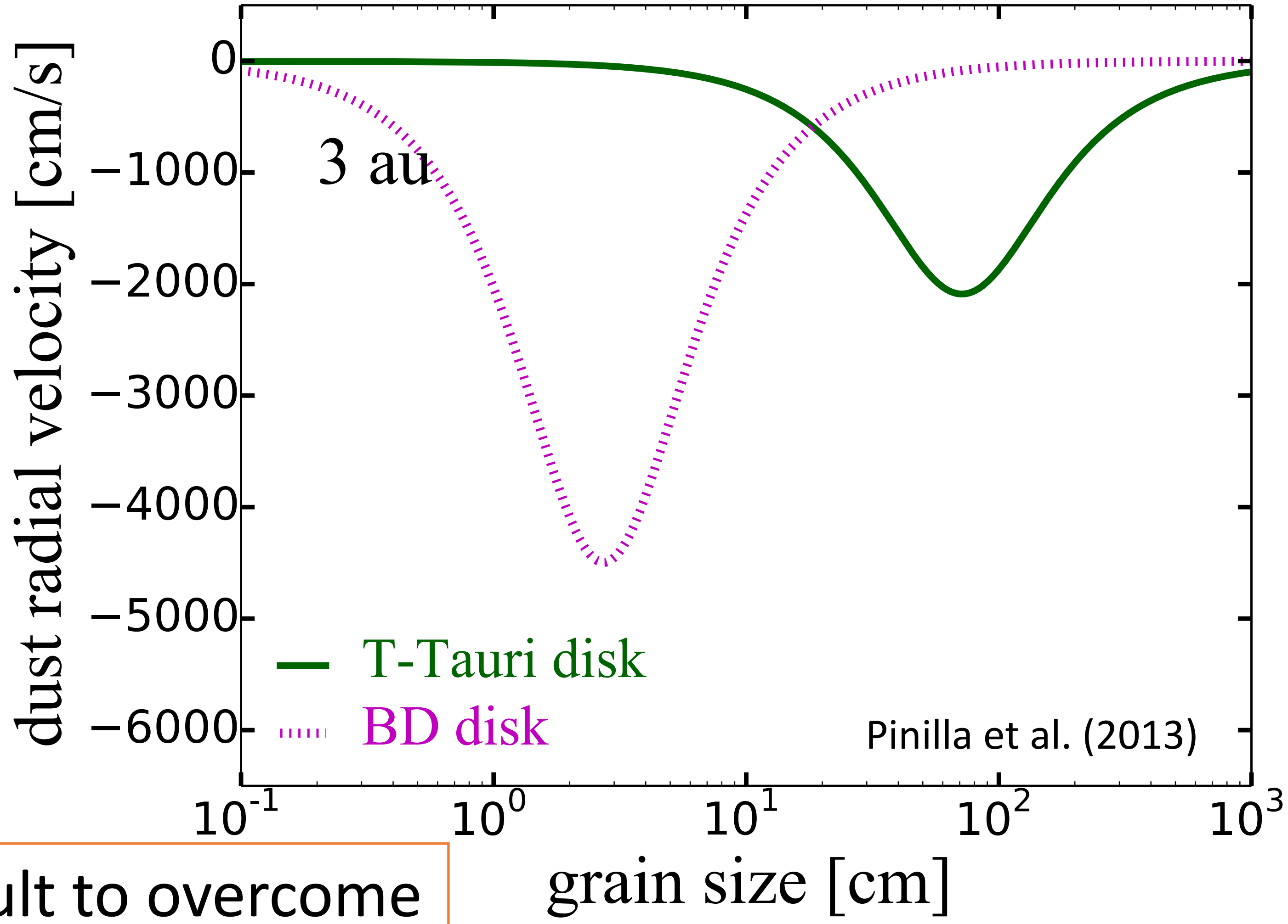
Move with Keplerian velocity and feel a constant head-wind

Radial Drift in VLMS and BD Disks

$$v_{\substack{dust\\drift}} \propto v_{gas} - v_{Kepler}$$

$$v_{gas} - v_{Kepler} \propto \frac{L_*^{1/4}}{\sqrt{M_*}}$$

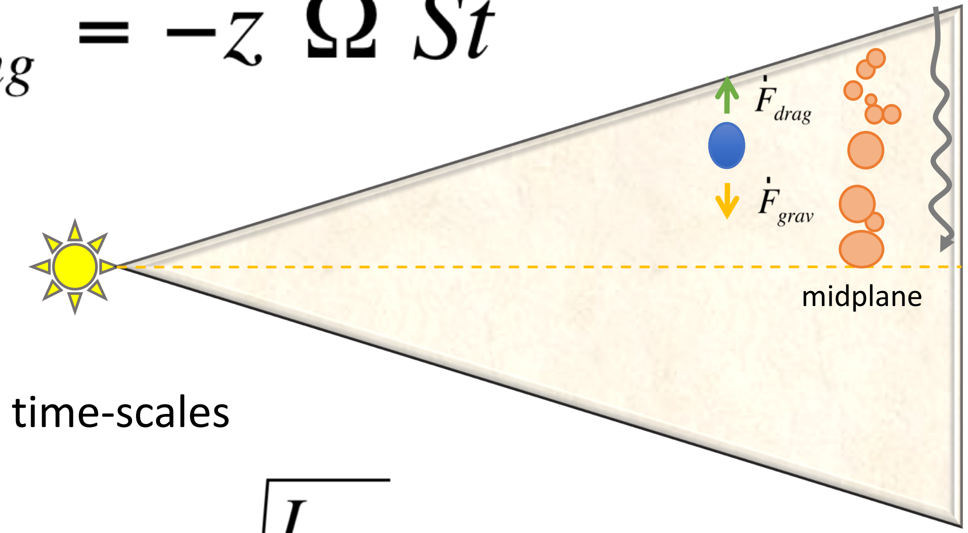
$$v_{\substack{dust\\drift}}^{BD} > v_{\substack{dust\\drift}}^{T-Tauri}$$



The radial-drift barrier is more difficult to overcome for the dust around Brown Dwarfs disks than around typical T-Tauri disks

Settling to the midplane

$$v_{settling} = -z\ \Omega\ St$$



Settling time-scales

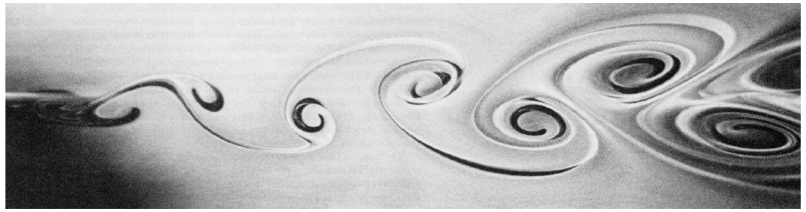
$$t_{sett}^{BD} = t_{sett}^{T-Tauri} \sqrt{\frac{L_{BD}}{L_*}}$$

Mulders & Dominik (2012)

Brown Dwarfs disks are expected to be flatter than T-Tauri disks (15-20% flatter)

Turbulence

Coupling and decoupling to turbulent eddies *(Ormel & Cuzzi 2007)*



$$\Delta v_{turb} \propto \sqrt{\alpha_{turb}}\, c_s$$

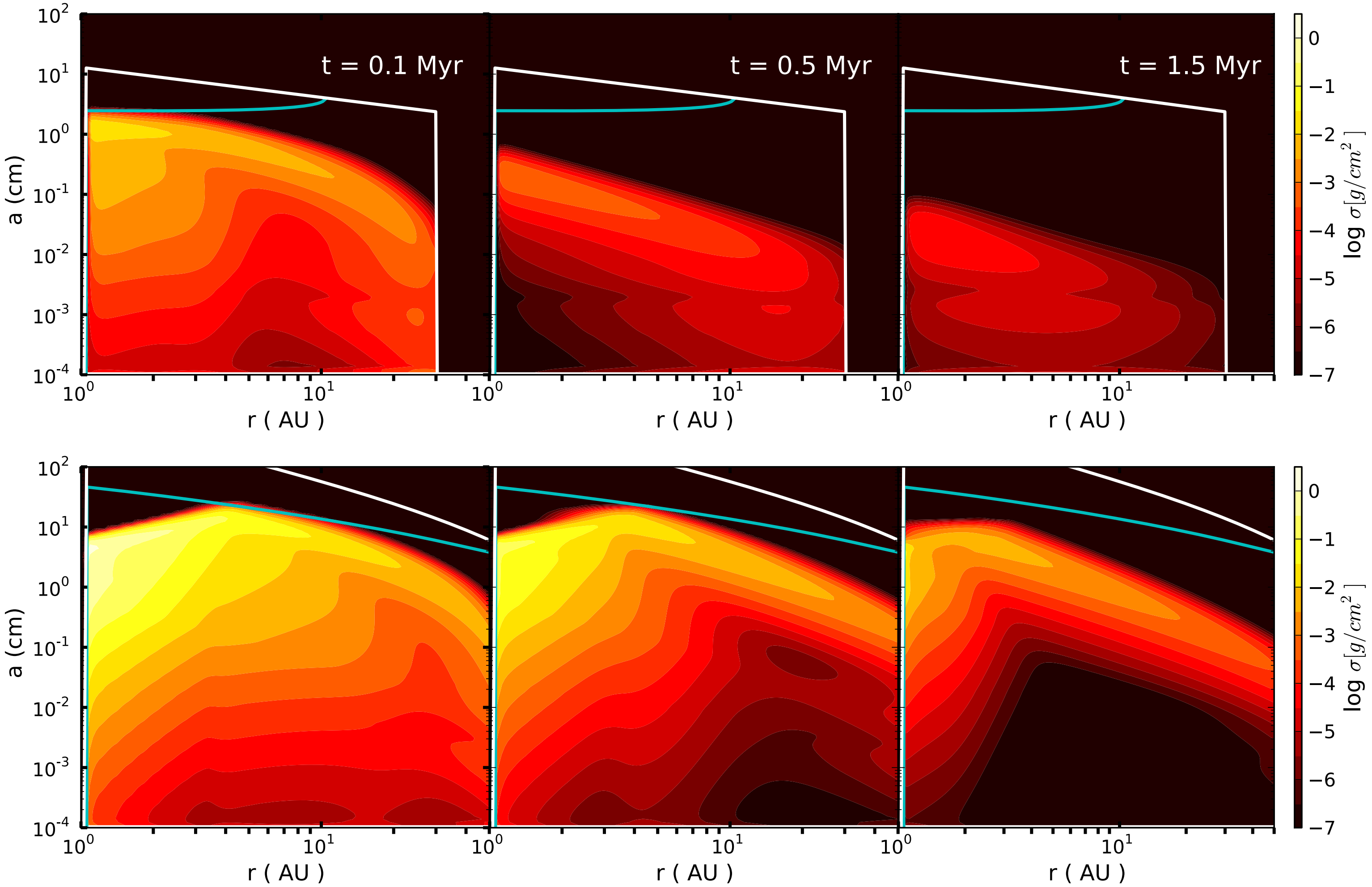
For the same α_{turb}

$$\Delta v_{turb}^{BD} < \Delta v_{turb}^{T-Tauri}$$

Less destructive collisions due to turbulent motion

Dust Evolution Models: T-Tauri vs. VLMS disks

Same dust parameters: intrinsic volume density, fragmentation velocity, etc



Brown Dwarf disk

$$M_{BD} = 0.05 M_{sun}$$

$$L_{BD} = 0.03 L_{sun}$$

$$M_{disk} = 2 M_{Jup}$$

$$T_{BD} = 2880K$$

T-Tauri disk

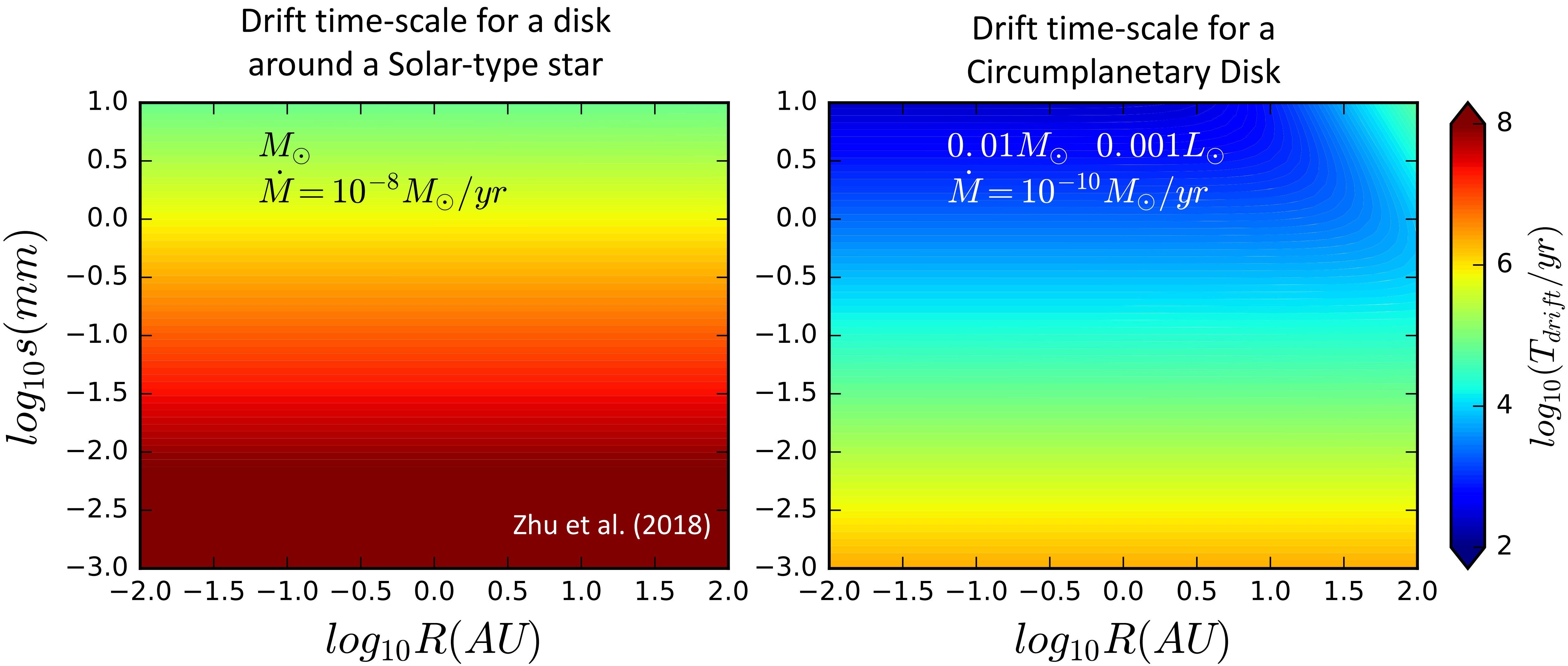
Solar parameters

$$M_{disk} = 50 M_{Jup}$$

Pinilla et al. (2013)

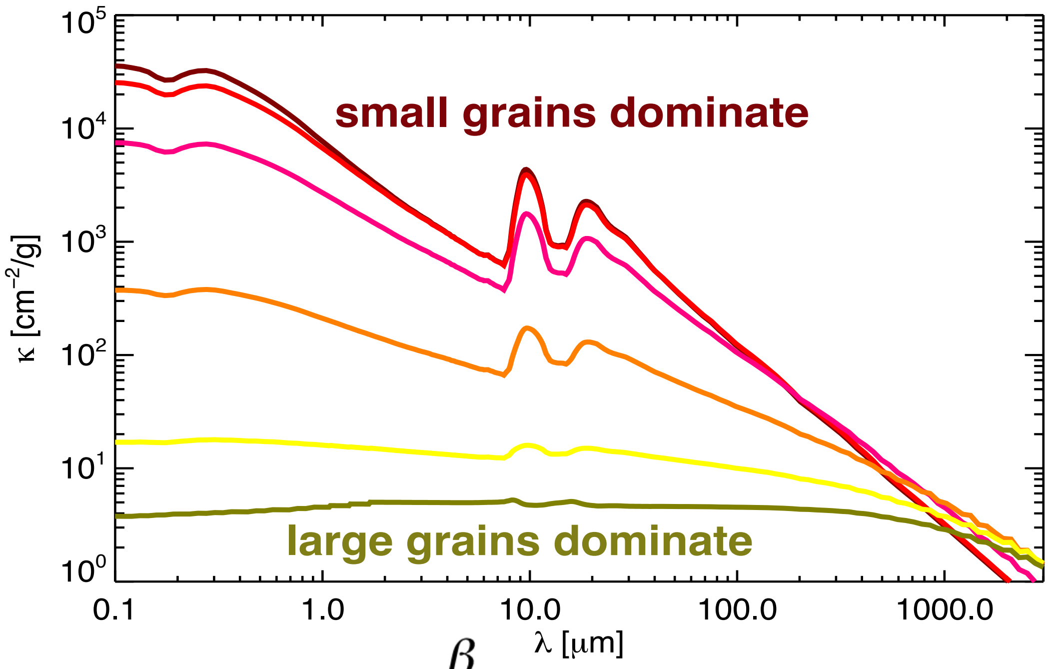
Rapid inward drift is more significant for particles in VLMS and BD disks than in T-Tauri disks

This Radial Drift Problem Applies to CPDs



How Jupiter moons were formed?

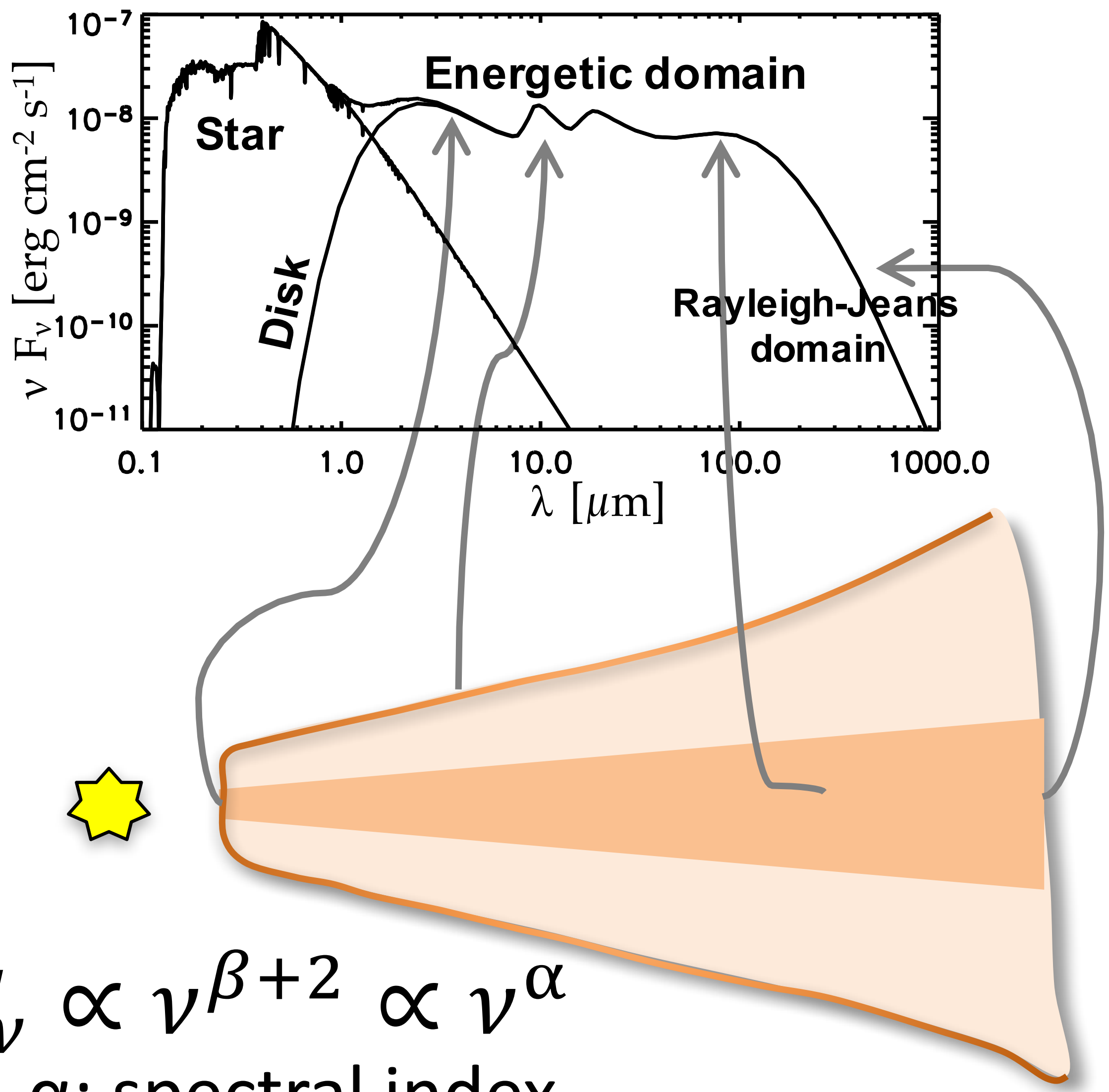
Evidence of mm-grains in PPDs



$$\kappa \propto \nu^{\beta}$$

$$F_{\nu} \propto \nu^{\beta+2} \propto \nu^{\alpha_{mm}}$$

If β≤ 1 (α_{mm}<3), dust grains have grown to millimeter sizes

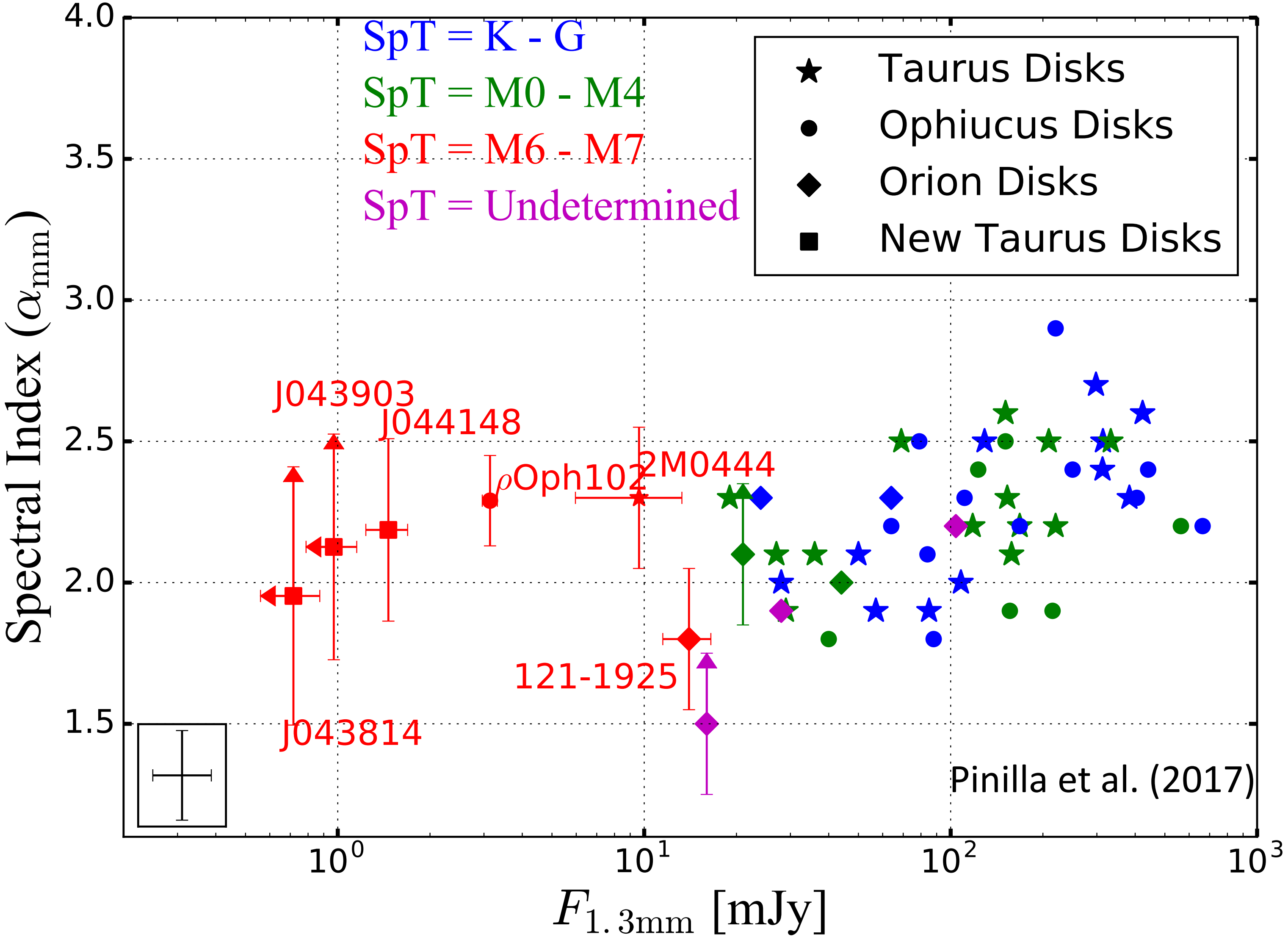


$$F_{\nu} \propto \nu^{\beta+2} \propto \nu^{\alpha}$$

α: spectral index

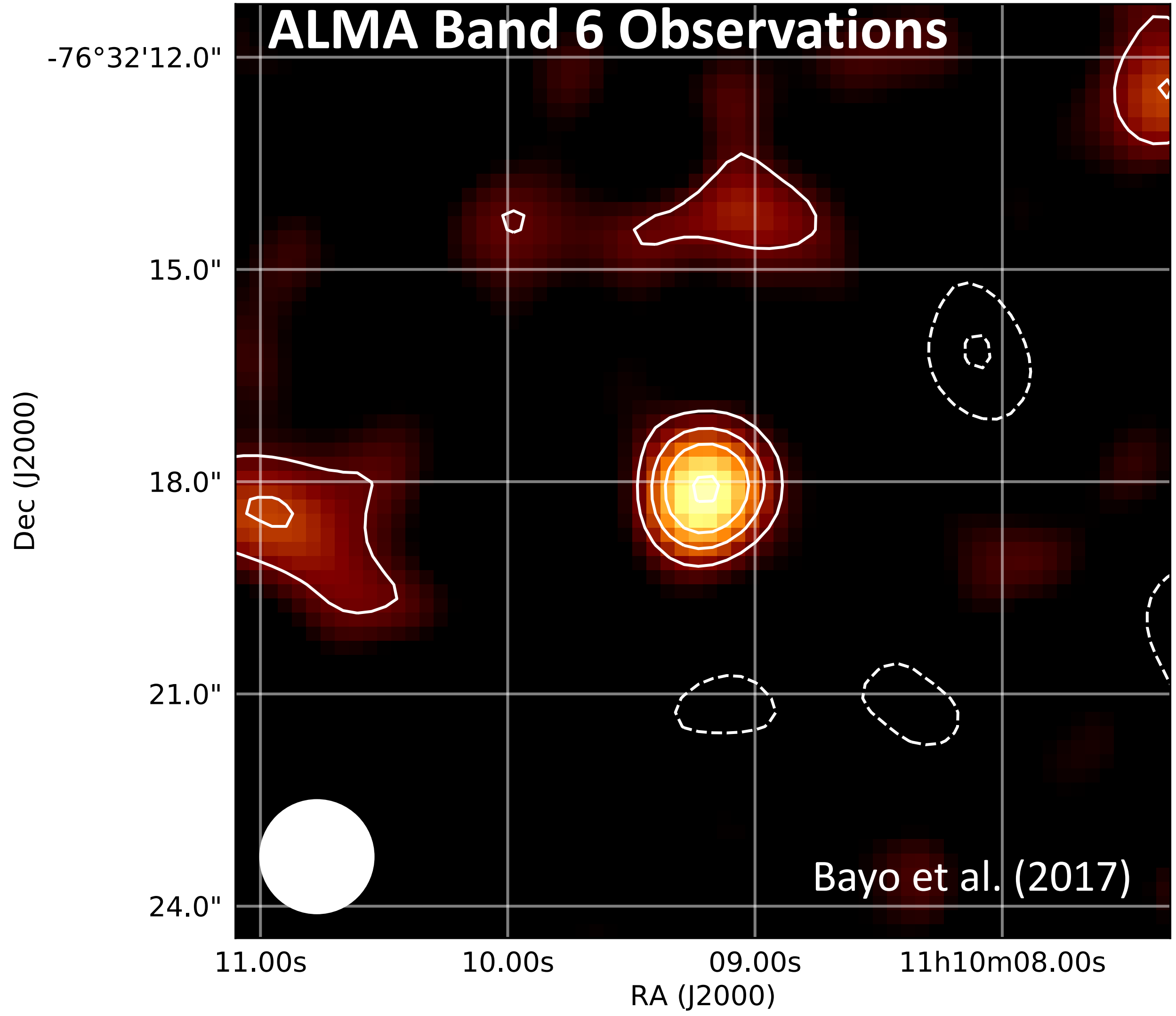
(the slope of the SED at mm-emission)

Spectral Indices in Disks around VLMS and BDs evidence grain growth



How to explain the existence of mm-grains in these disks where radial drift is a more extreme problem?

Millimeter Detection of a Disk around a Isolated Planetary-Mass Object

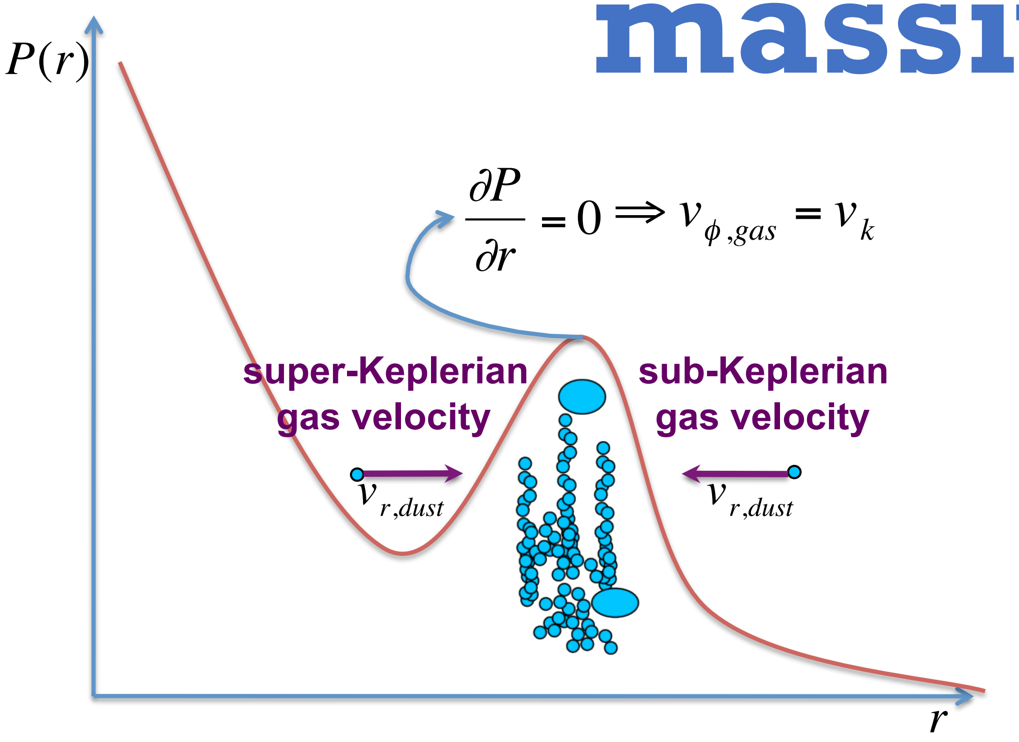


Free-Floating planet
(~12 M_{Jup})

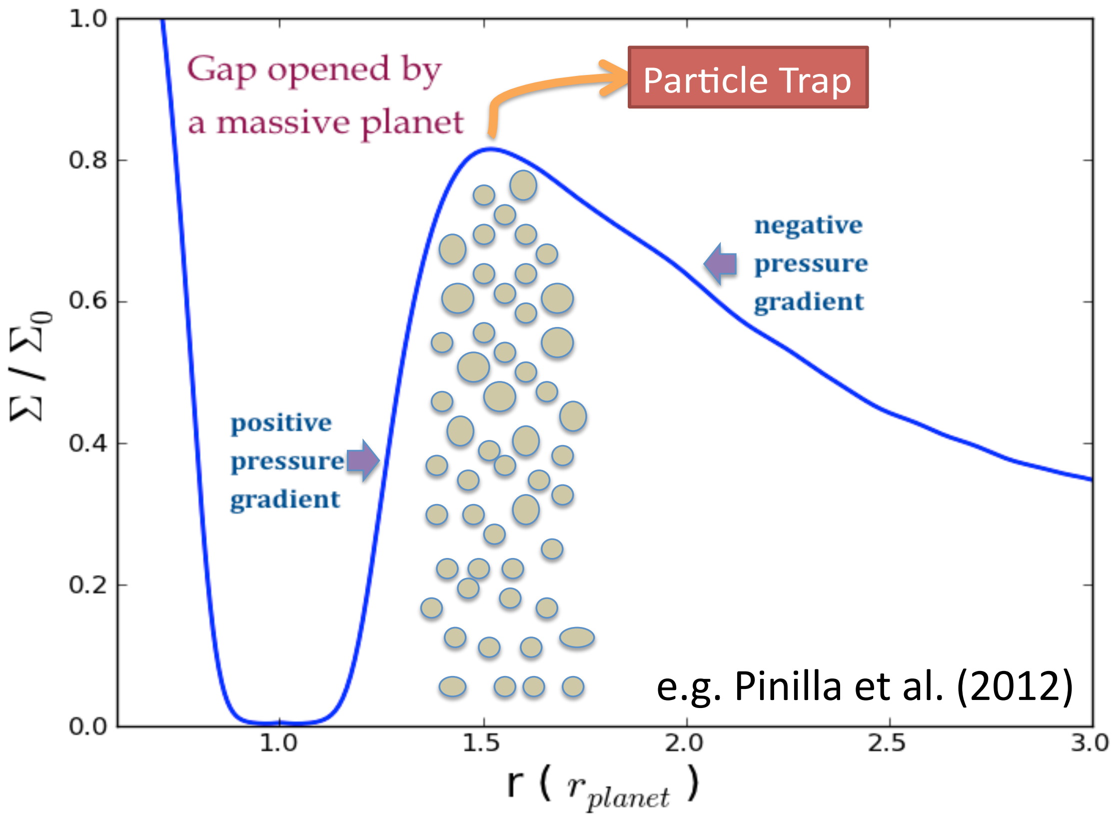
Disk dust mass:
0.07-0.63 M_{Earth}

Accepted ALMA (C6, C7) proposals to measure the spectral index in this disk → grain growth?

Particle Trapping! One possibility: massive planets



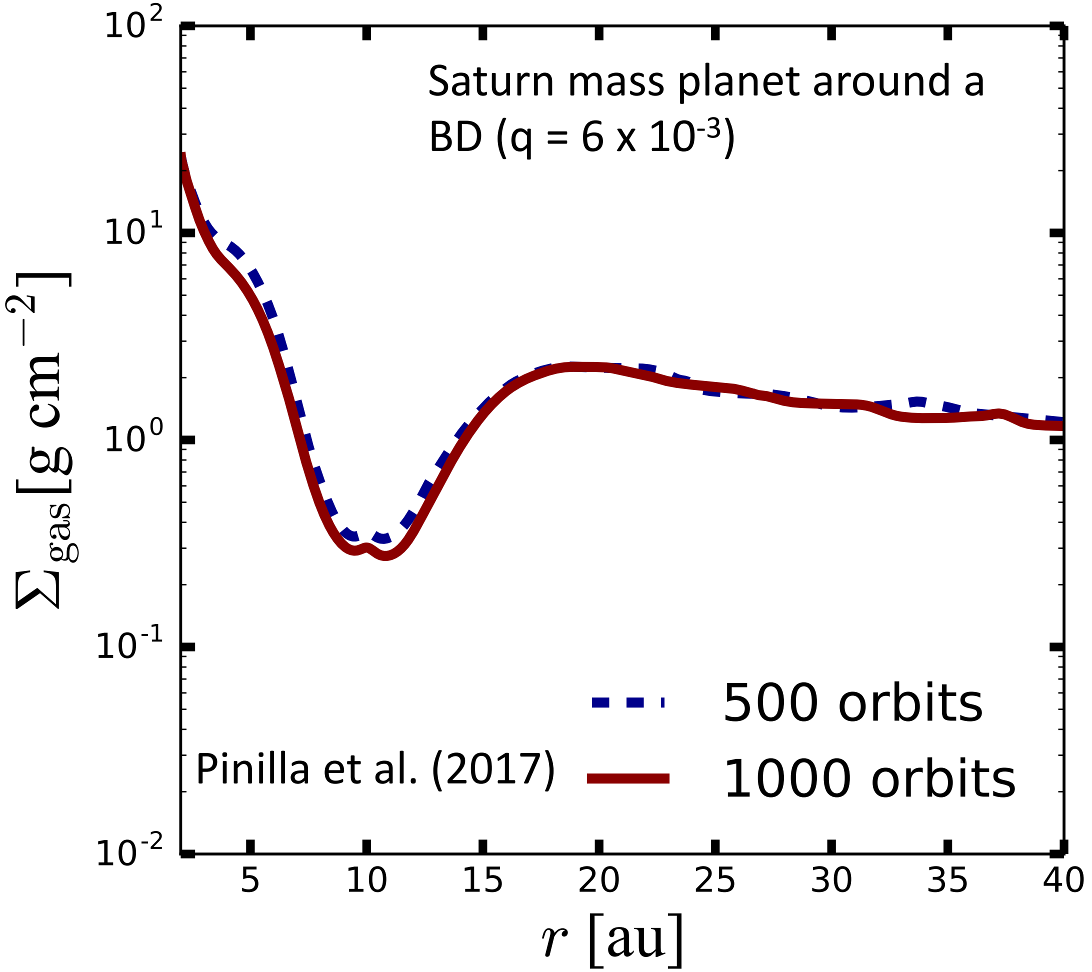
A pressure bump is formed at the outer edge of a gap carved by a massive planet

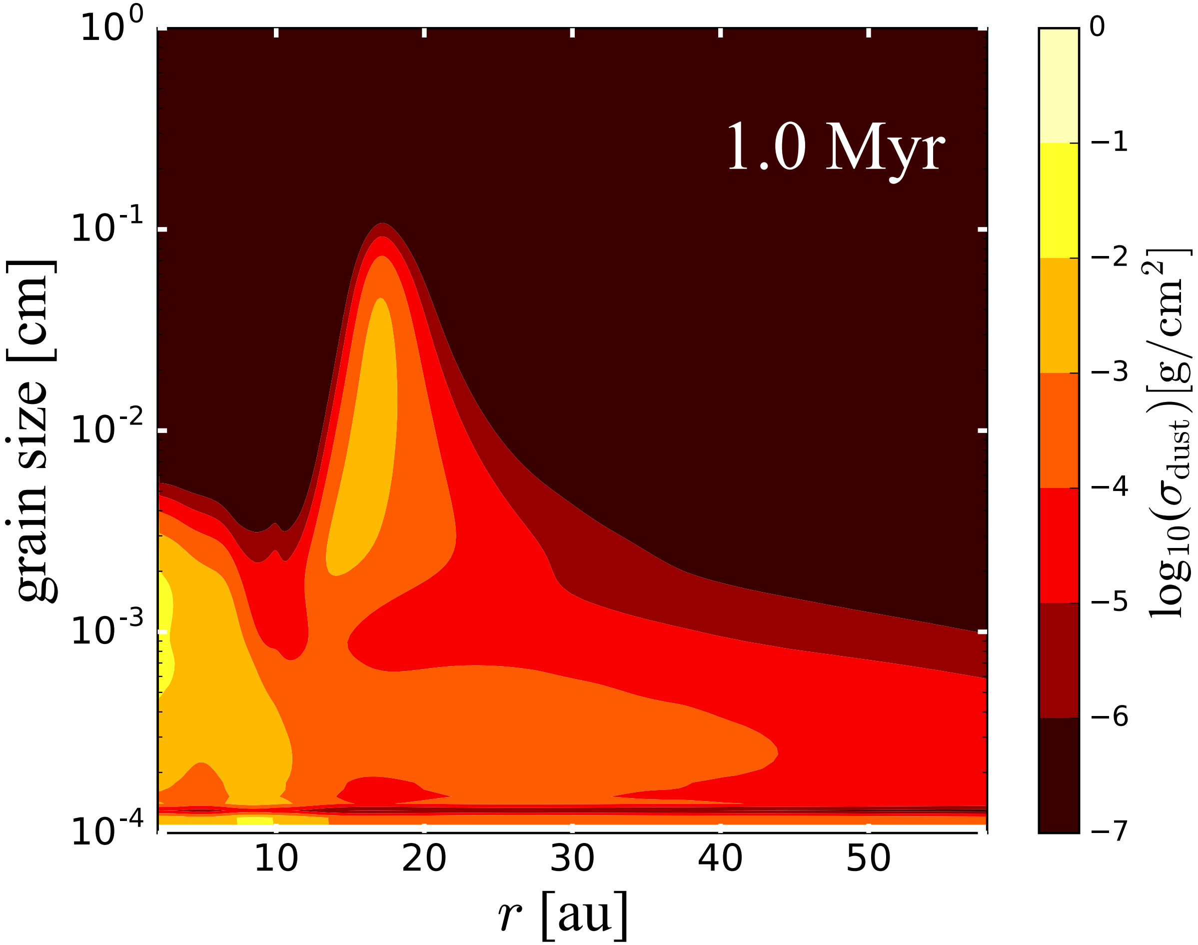


Particle Traps

- Dead Zones
- Vortices
- Planets
- Zonal flows
- Self-gravitating spiral arms

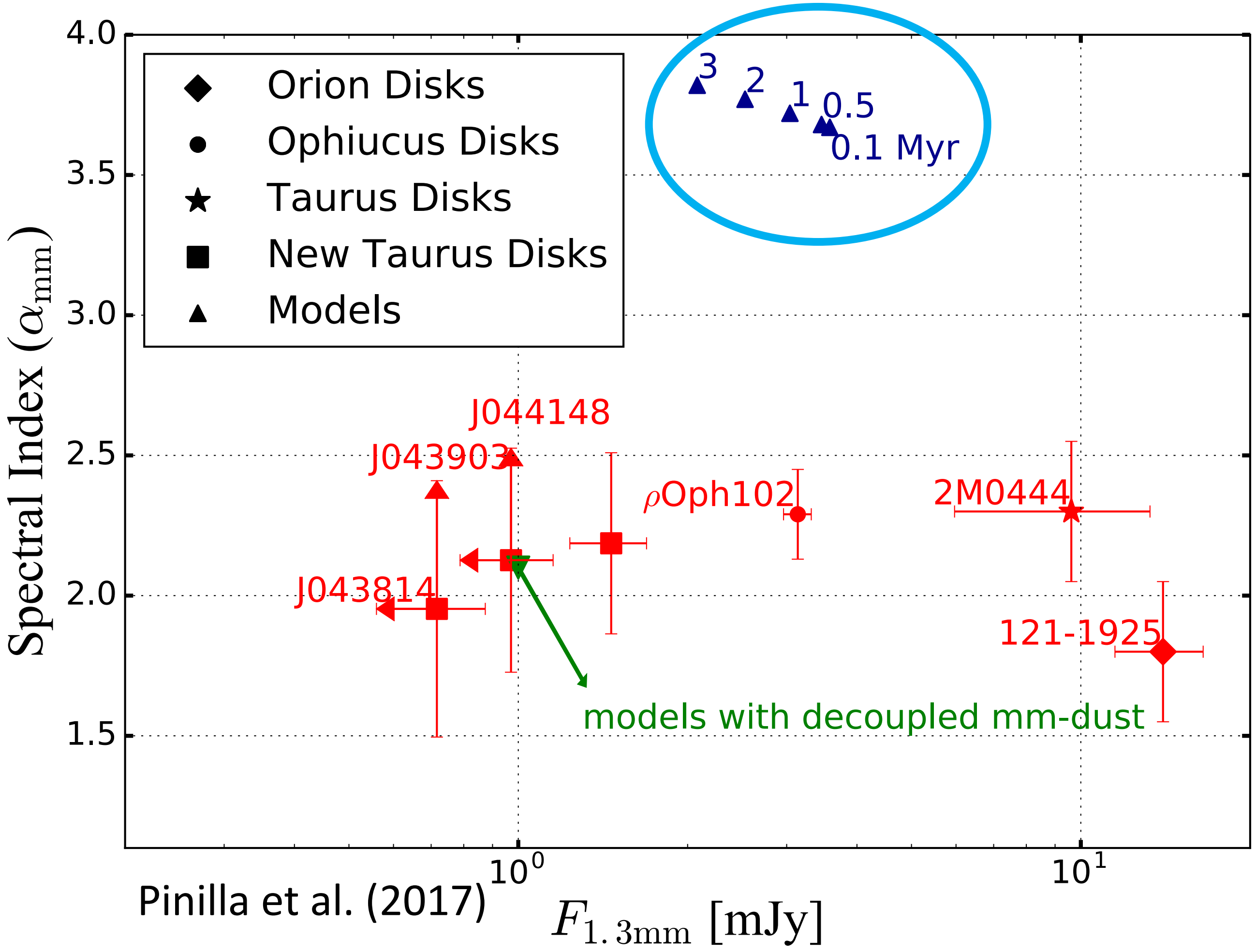
It is More Difficult for a Given Planet to Open a Gap in a BD Disk





The resulting gaps are shallower because the scale height at the planet position is closer to the planet Hill's radius

Expected Spectral Indices when Particles are Trapped at the Outer Edge of the Gap



Pinilla et al. (2017)

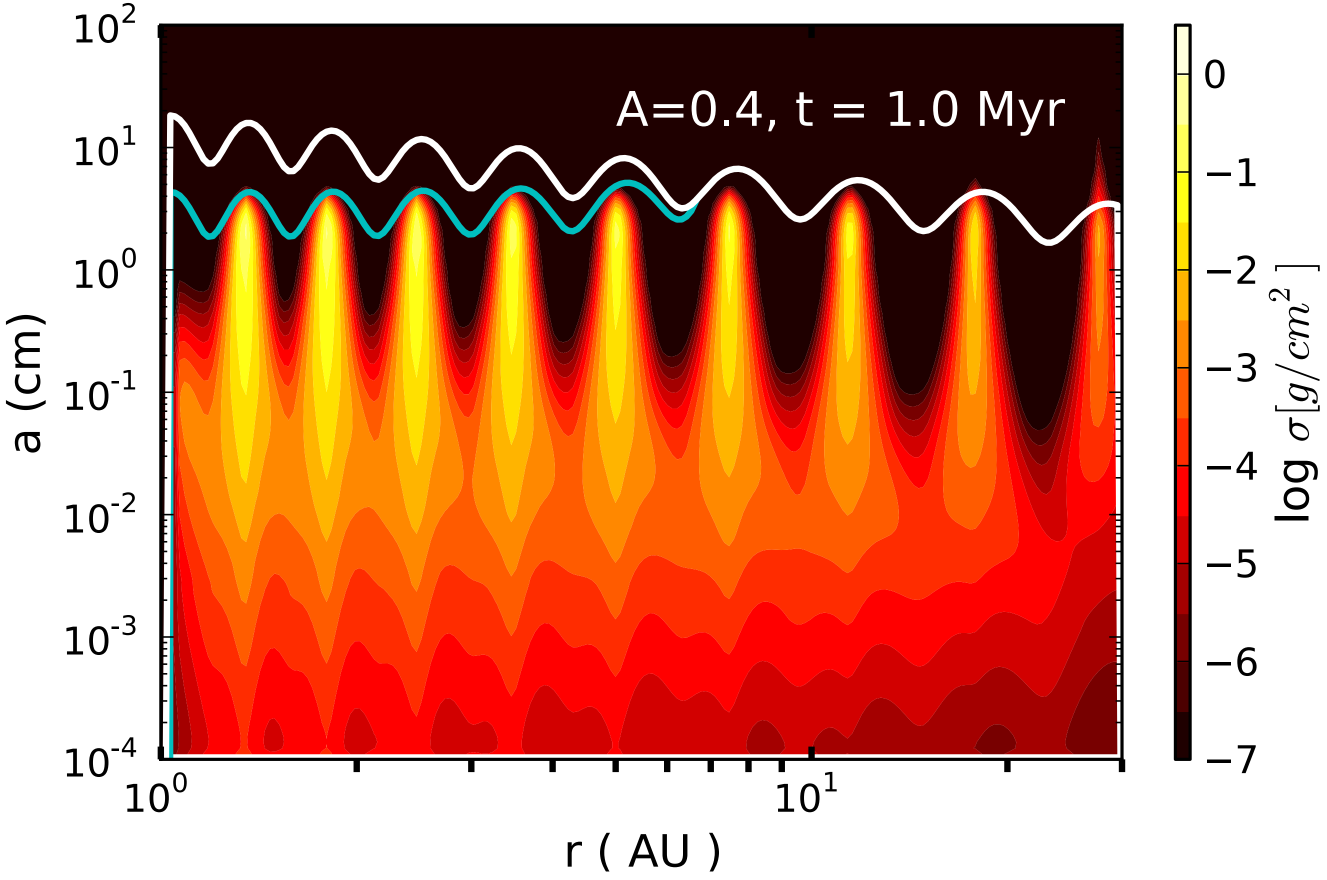
We found that the spectral indices are high, in disagreement with current millimeter-observations of BD disks.

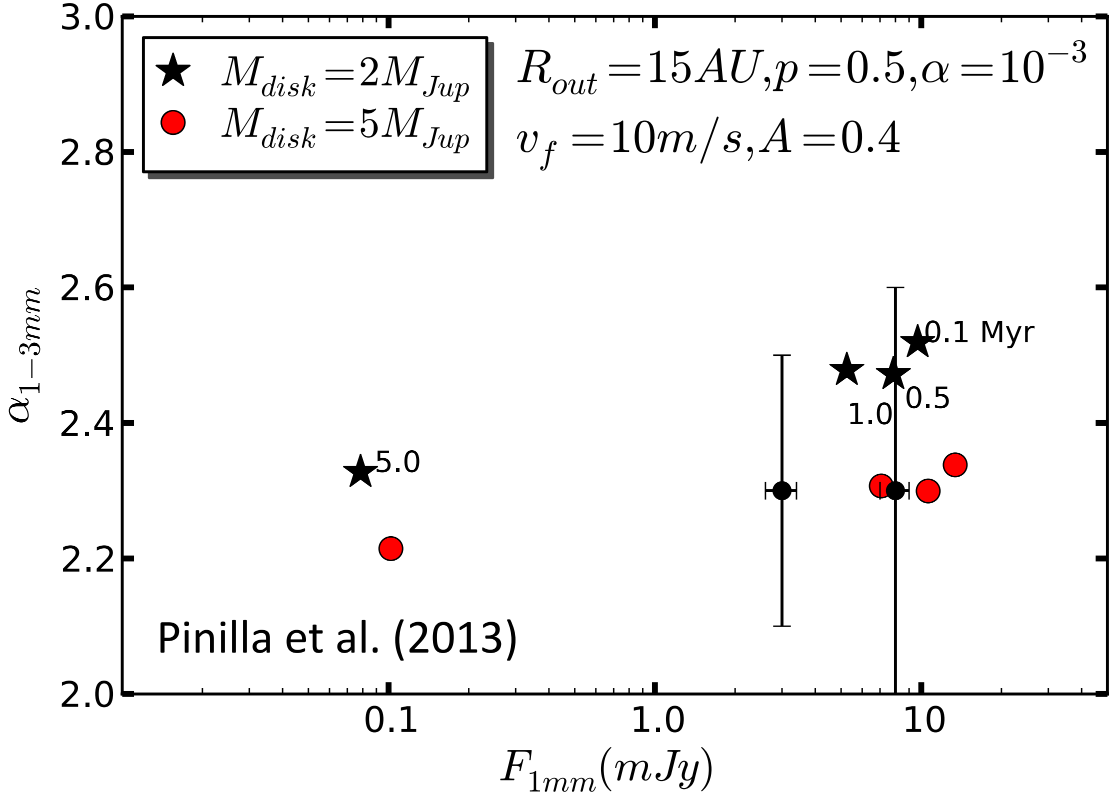
Alternatives

(1) Multiple strong pressure bumps of unknown origin

(2) Gas masses in BD disk are very low such that the millimeter grains are completely decoupled and do not drift

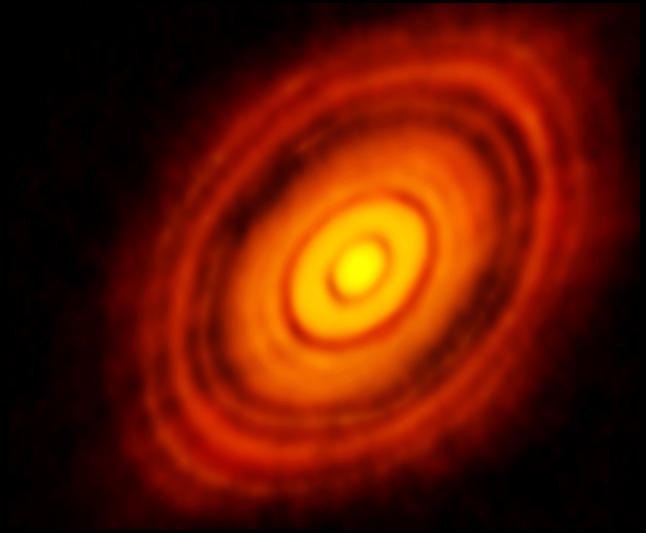
Multiple (very) Strong Pressure Bumps of Unknown Origin



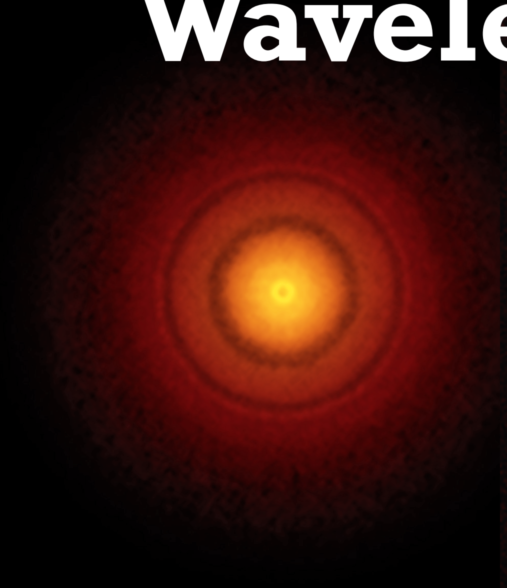


Low spectral indices observed in BD disks may hint to unresolved multi-ring substructures. The pressure bumps need to have stronger amplitude than in more massive and warmer disks

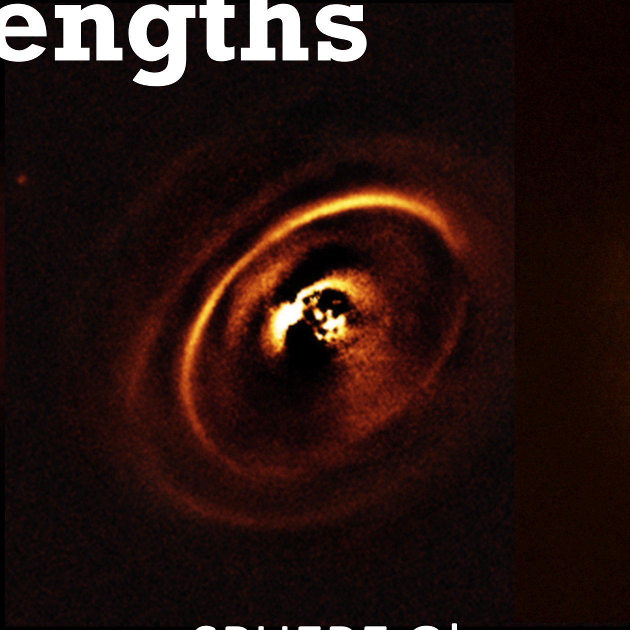
Multiple Rings Observed at Different Wavelengths



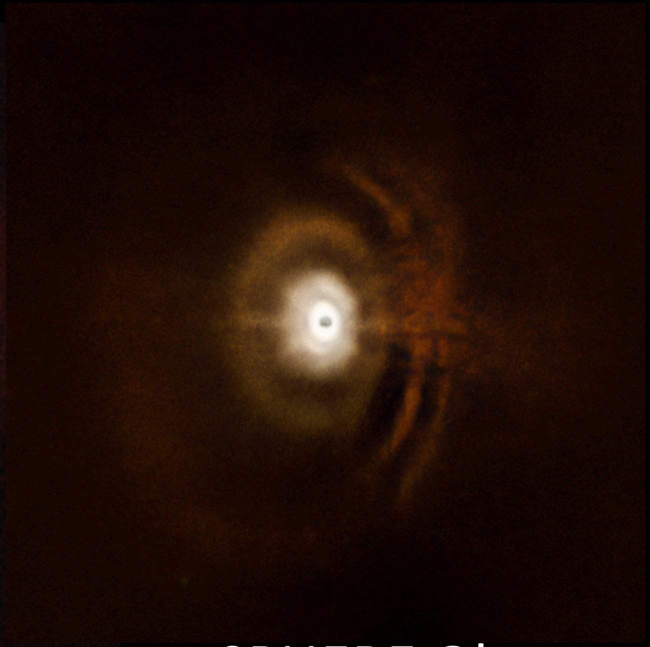
ALMA Obs
HL Tau
ALMA Partnership et al. (2015)



ALMA Obs
TWHya
Andrews et al. (2016)



SPHERE Obs
RX J1615
de Boer et al. (incl. Pinilla, 2016)

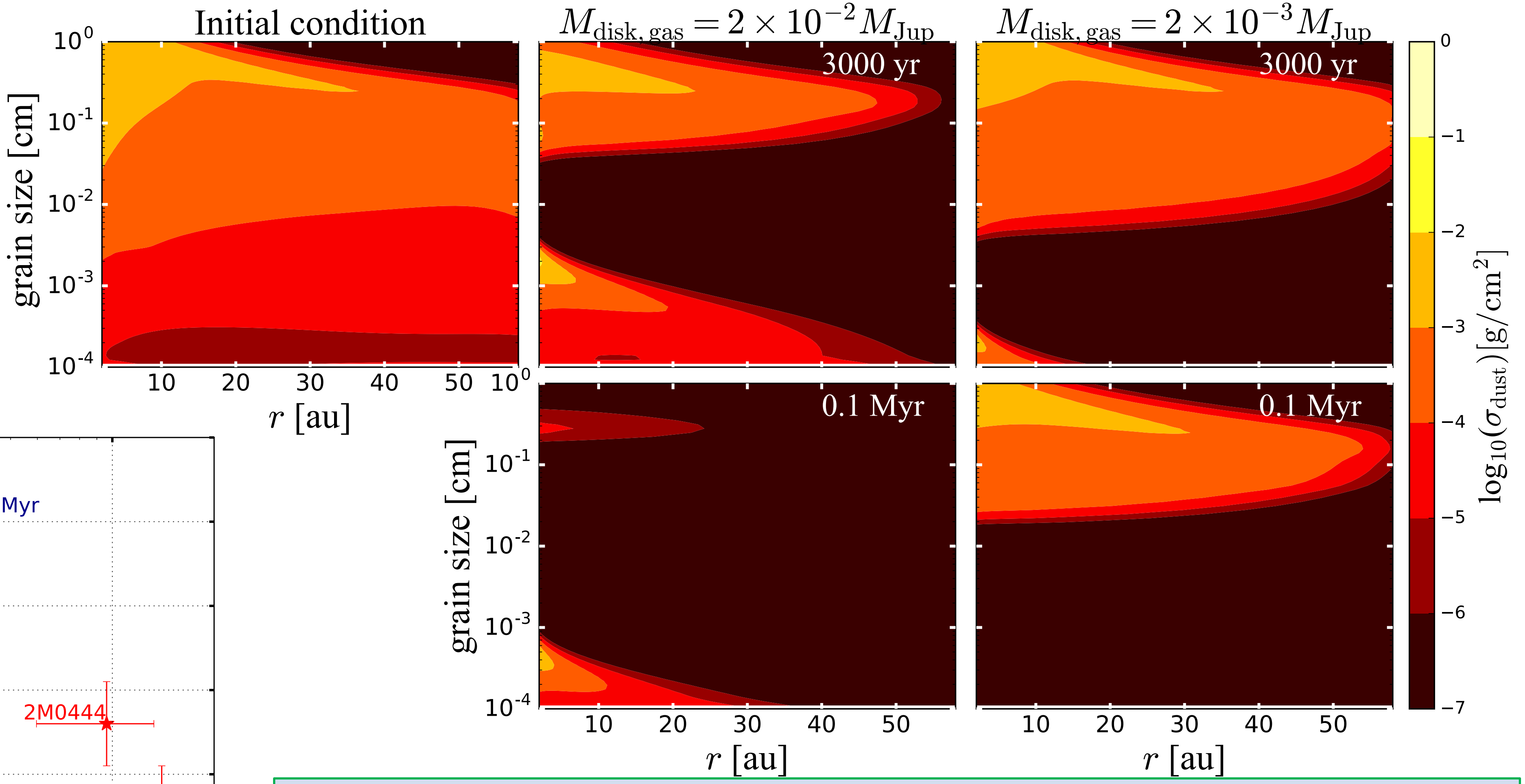


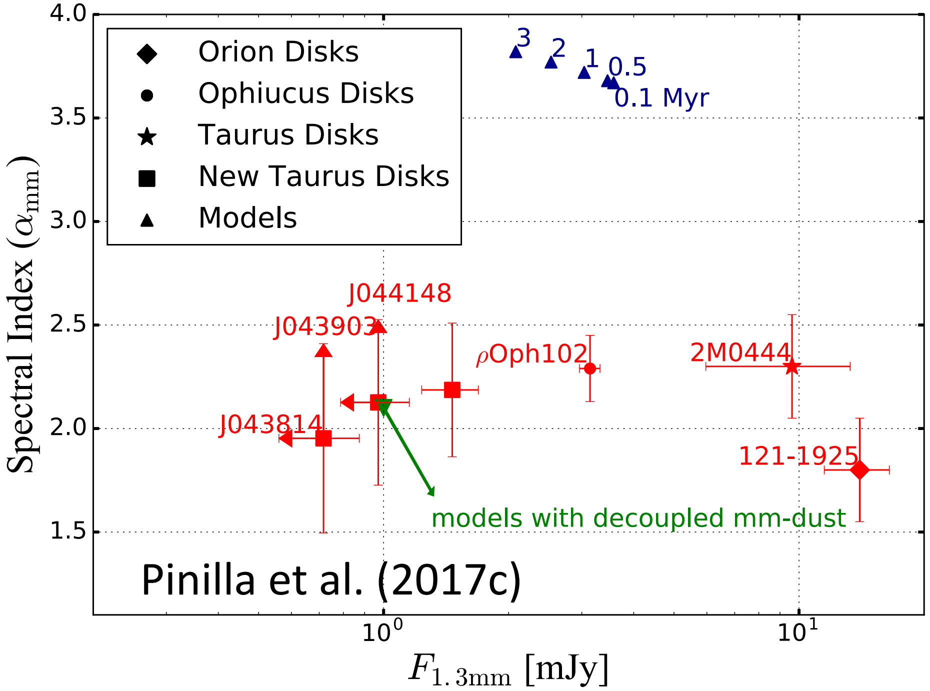
SPHERE Obs
HD 97048
Ginski et al. (incl. Pinilla, 2016)

If we detect structures in disks around low mass stars, we expect that the amplitude of these structures is higher than in disks around more massive objects

Very Low Gas Disk Masses & mm-Grains are Decoupled

Gas mass in BD disks is so low ($\sim 2\times10^{-3}\ M_{Jup}$), such that the millimeter-sized particles are completely decoupled, and preventing them from drifting inwards.

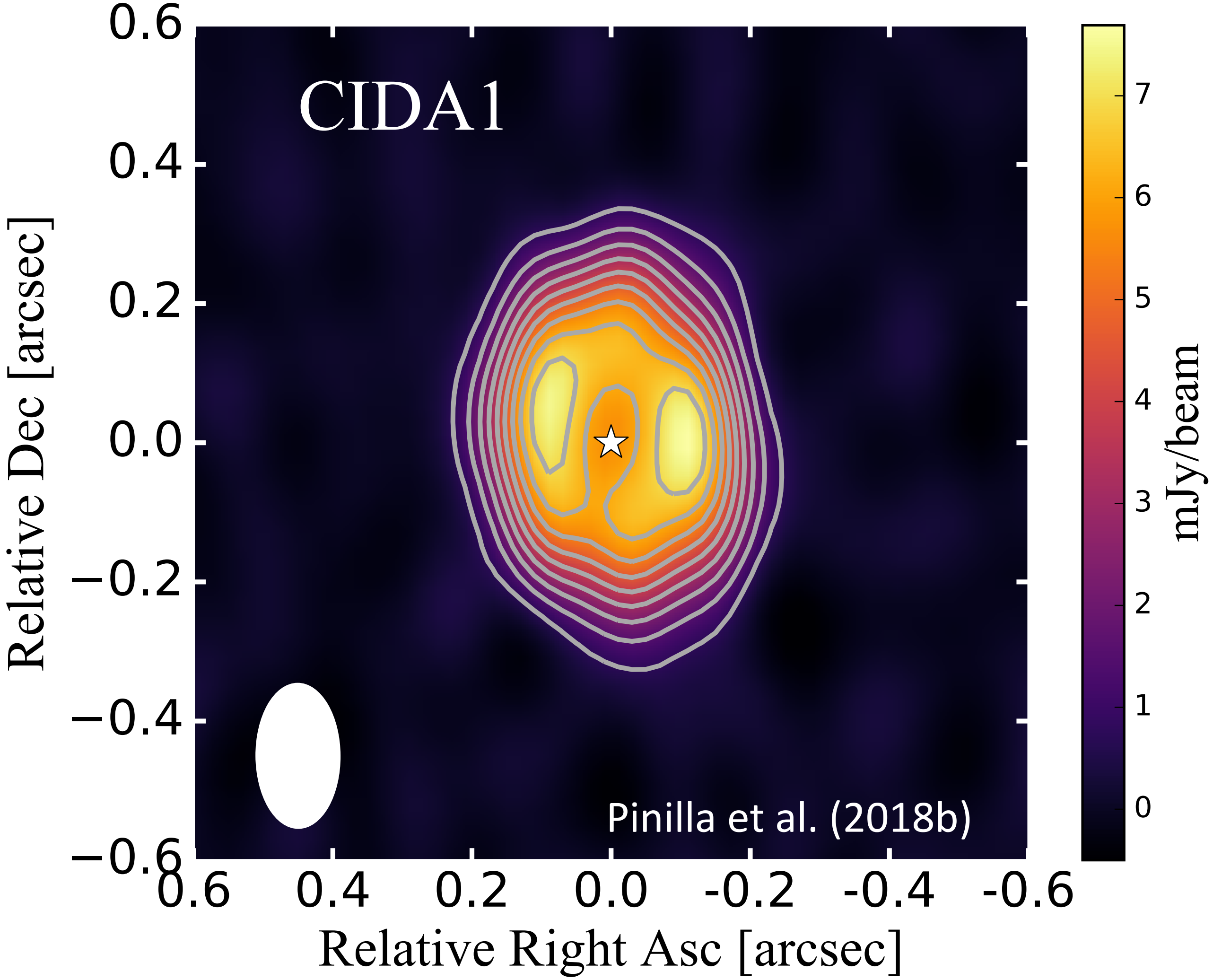




A systematic and sensitive survey with ALMA that provide information of gas distribution/mass, is required to solve this question.


Do we really need an alternative?
We may have already some evidence of massive planets in disks around VLMS

CIDA 1 is the lowest mass star with a resolved large dust cavity (20au) so far



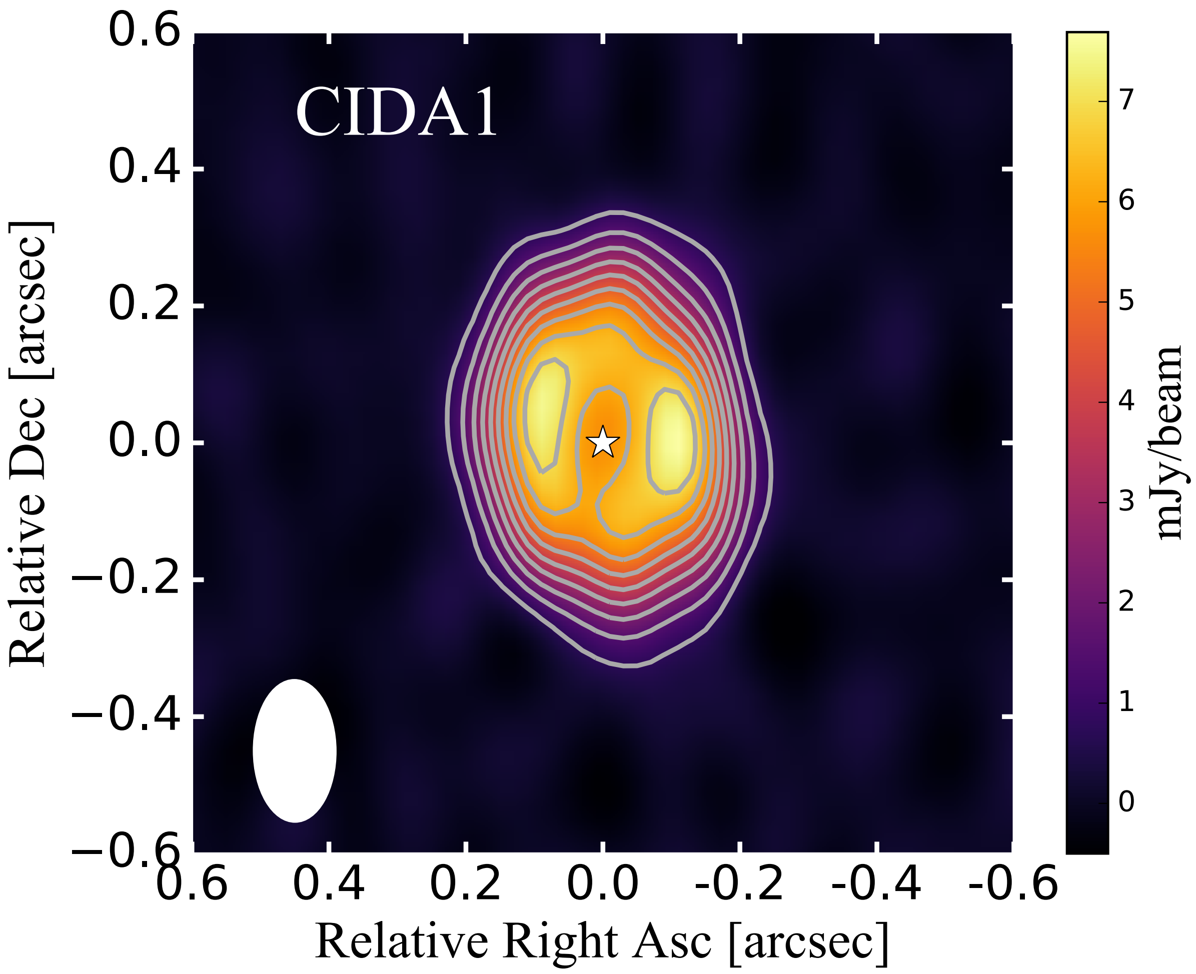
$M_\star$=0.1 Msun

$L_\star$=0.08 Lsun

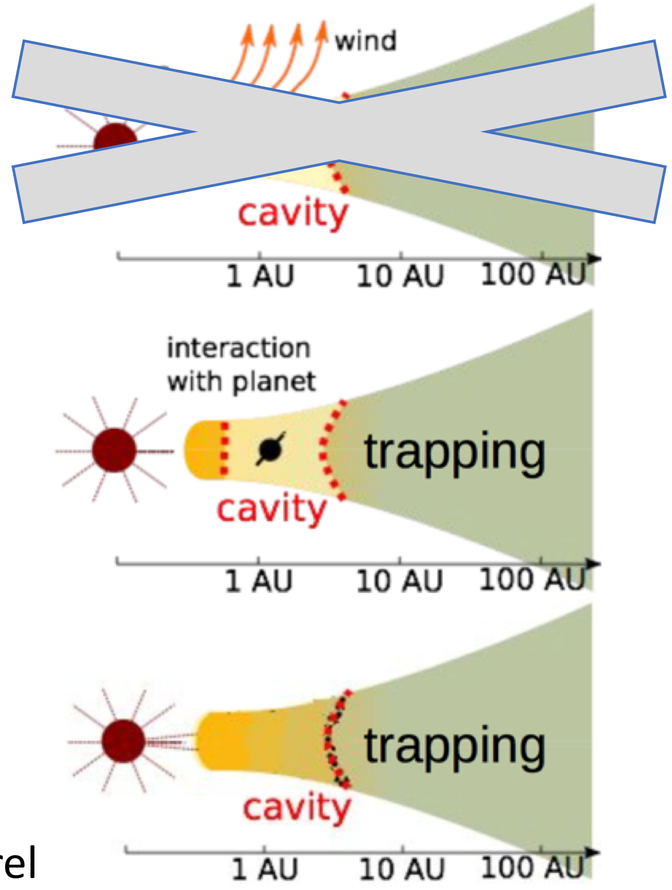
ALMA Observations of CIDA 1 at 887µm

Resolution: 0.21’’ x 0.12’’

Origin of the Cavity in CIDA 1



- Photoevaporation
- Companion
- Dead zones

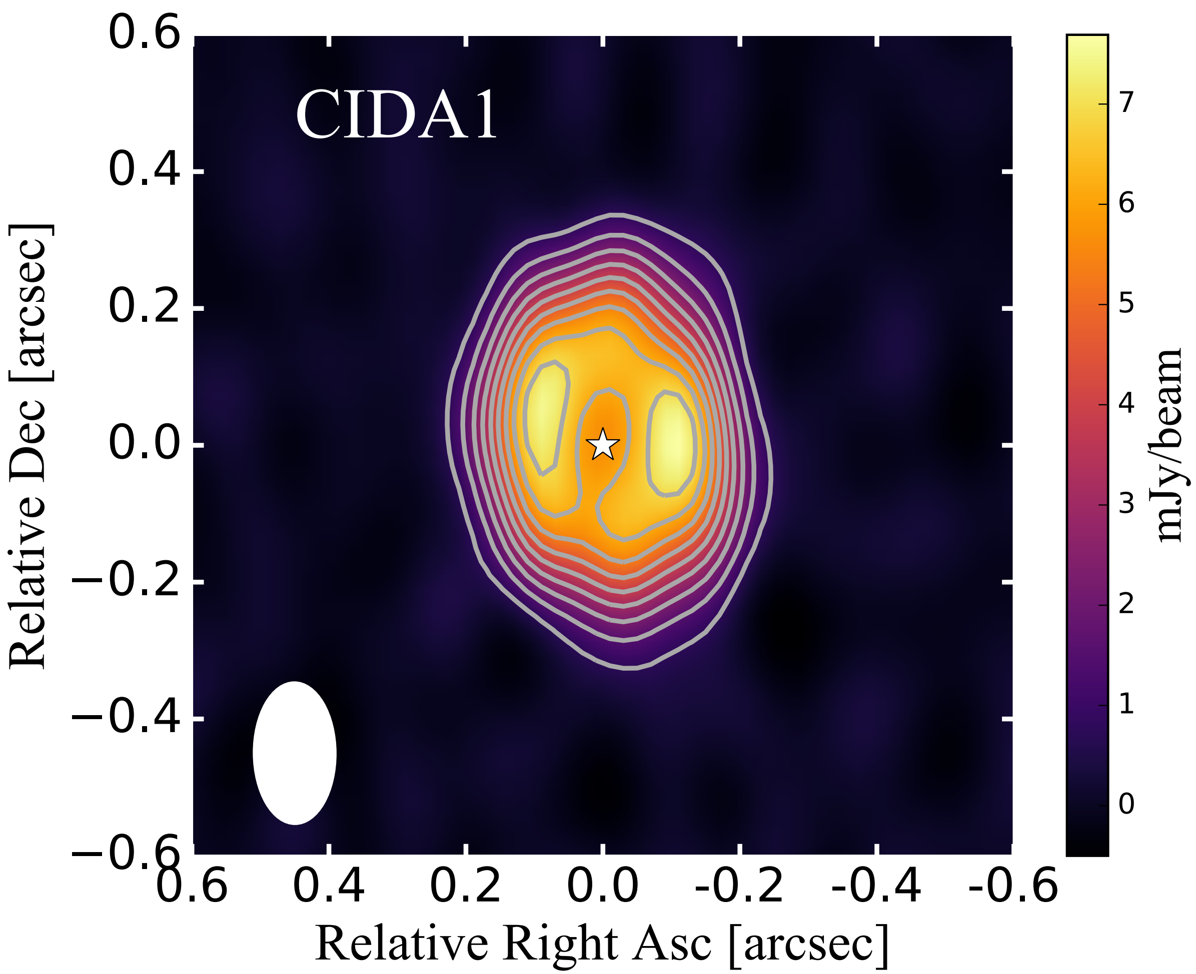


Credit cartoon: N. van der Marel

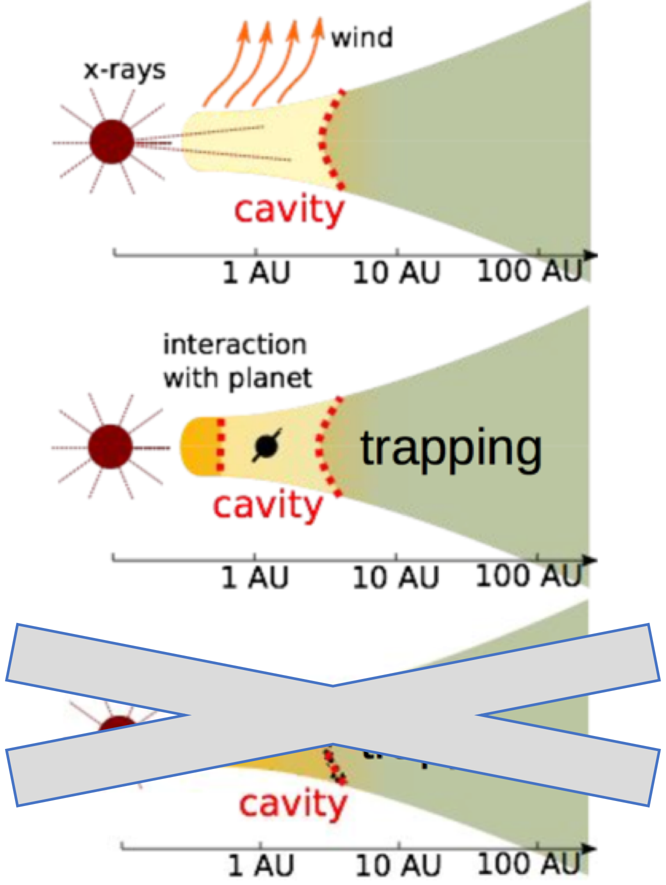
Accretion rate of CIDA 1 is 4×10^{-9} Msun/year

High accretion rate and large cavity size are not expected from photoevaporation

Origin of the Cavity in CIDA 1

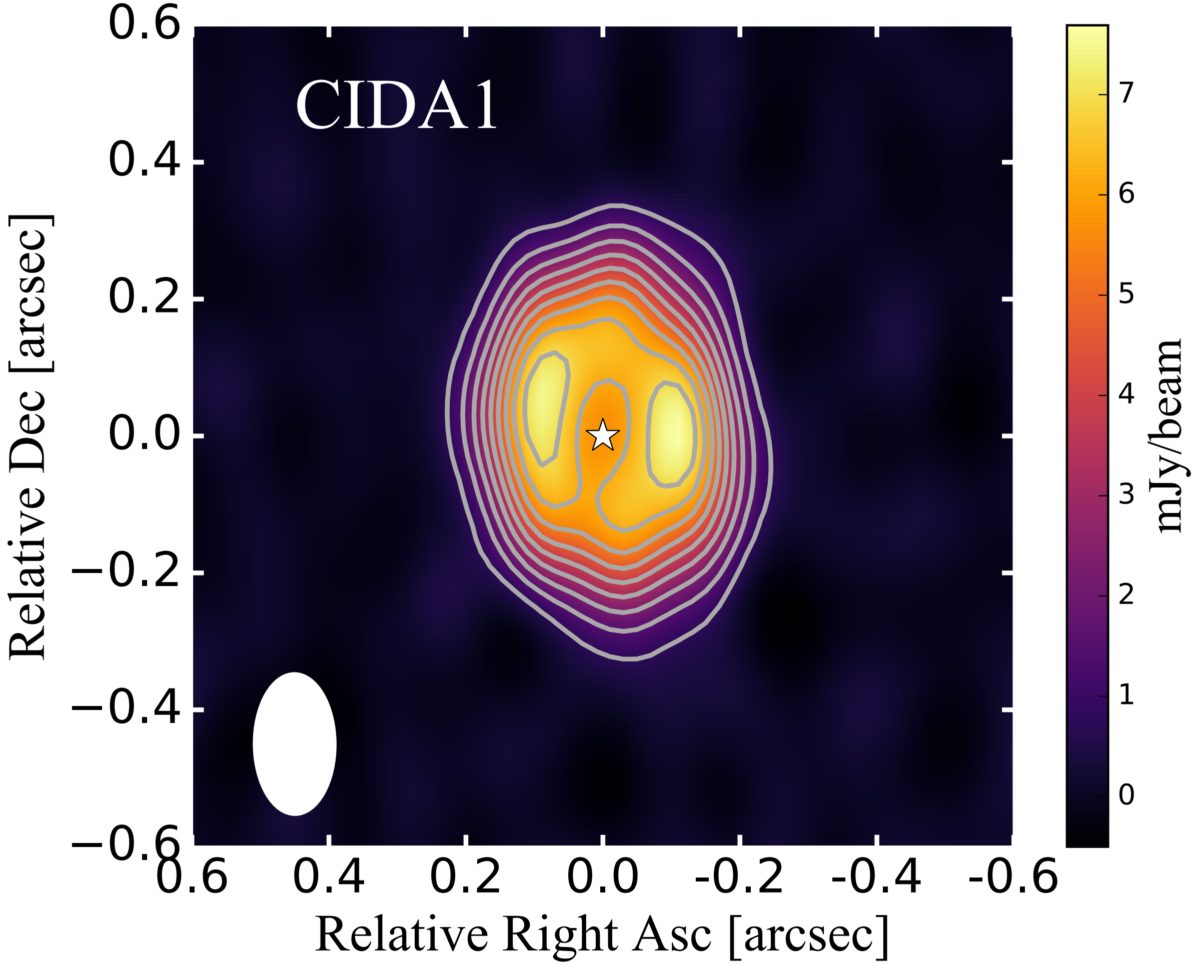


- Photoevaporation
- Companion
- Dead zones

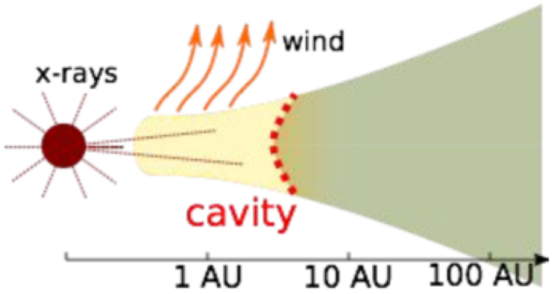


A dead zone in a low mass disk like CIDA1 is not expected to be more than 5au (maybe 10 au) extended

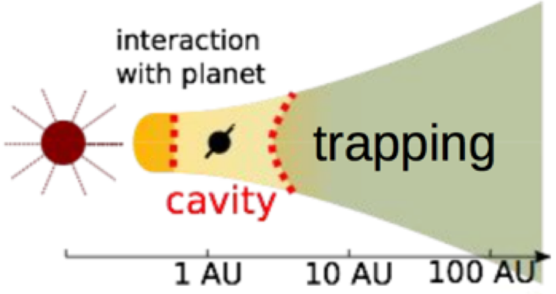
Origin of the Cavity in CIDA 1



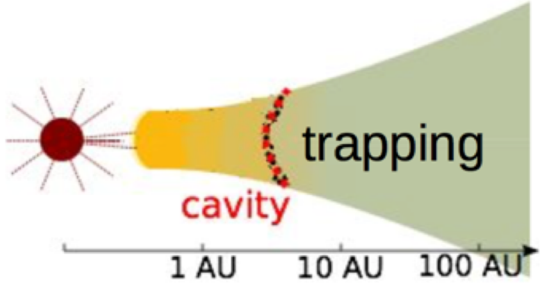
- Photoevaporation



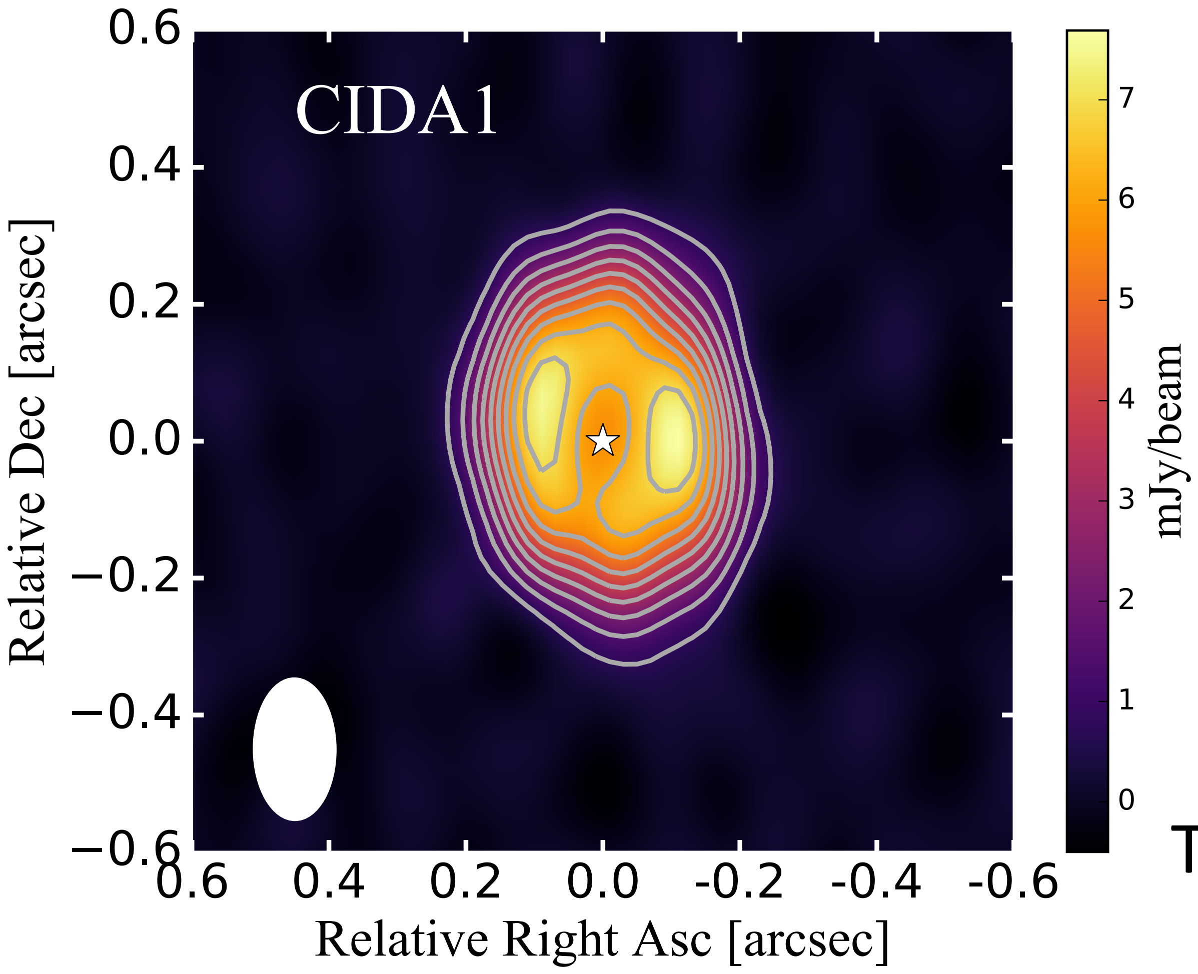
- Companion ?



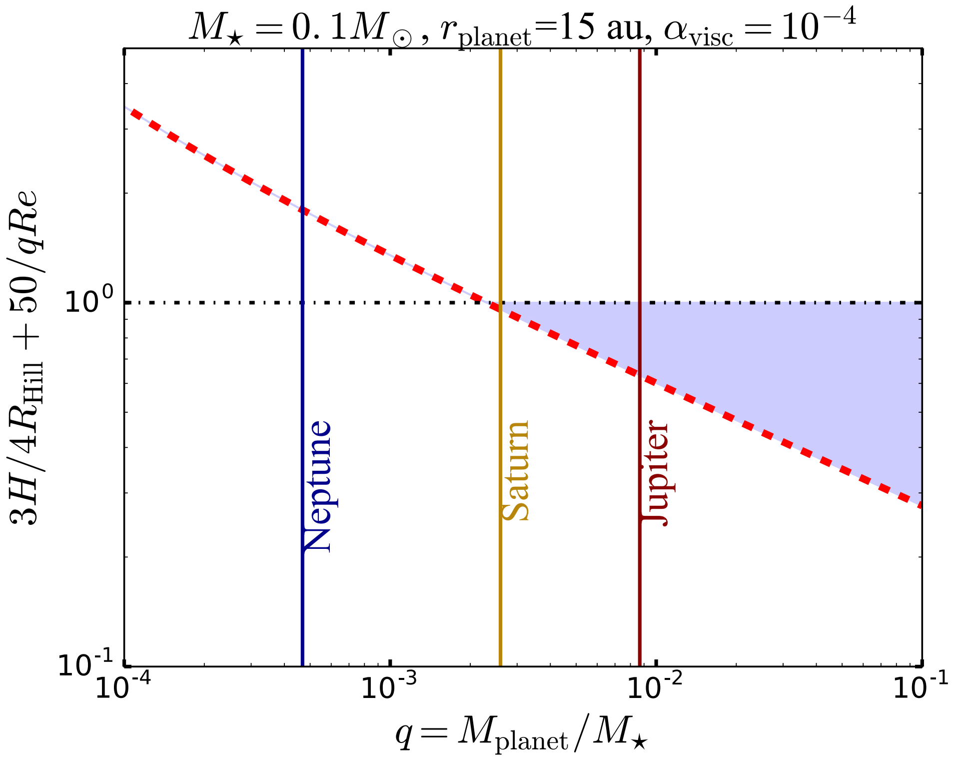
- Dead zones



Origin of the Cavity in CIDA 1



Assuming g/d ratio of 100, disk mass is ~10-18 M_{Saturn}

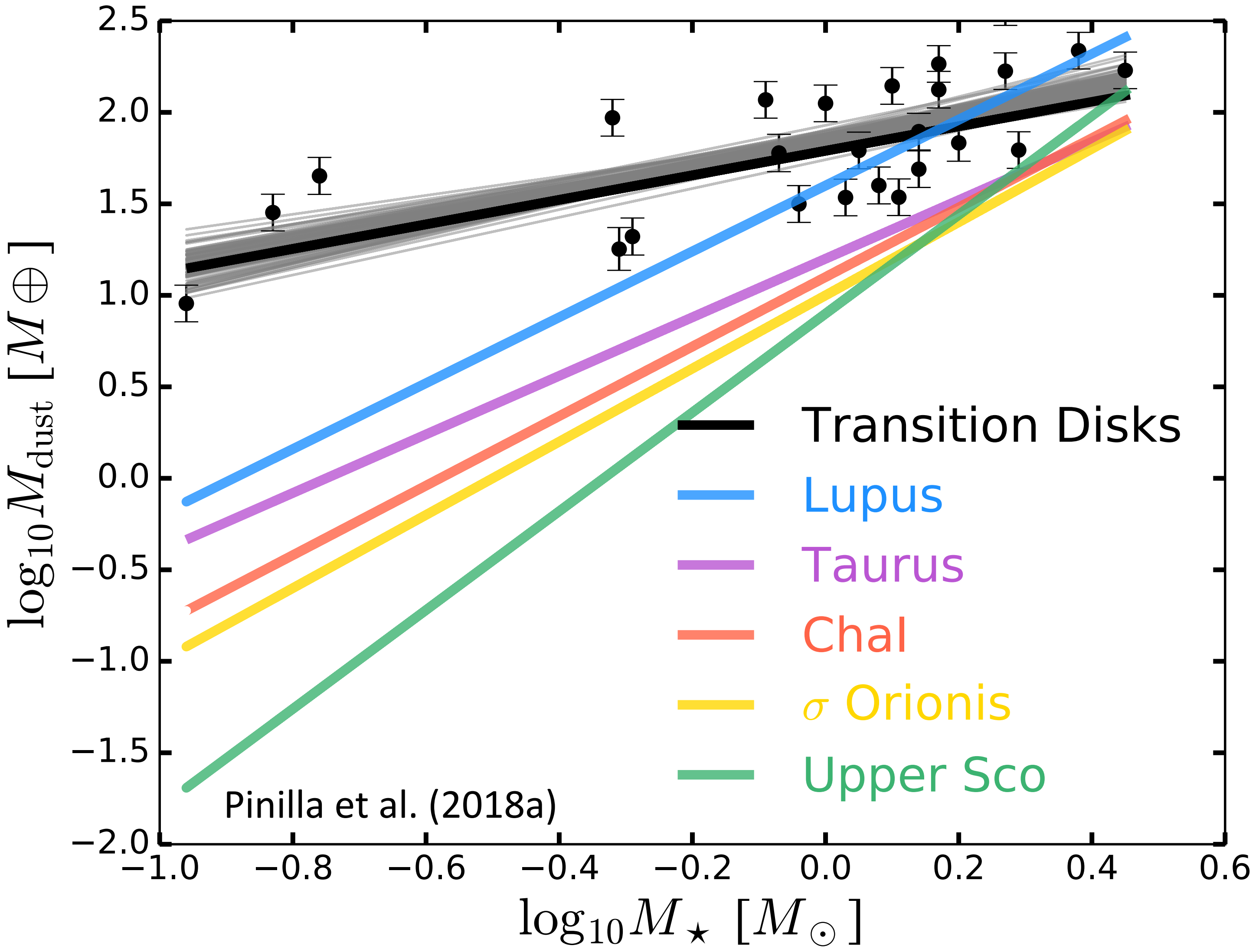


The minimum mass planet to open a gap in a disk like CIDA 1 corresponds to 1 Saturn mass planet when $\alpha = 10^{-4}$ (still possible?)

Future Perspectives

We need more observations !

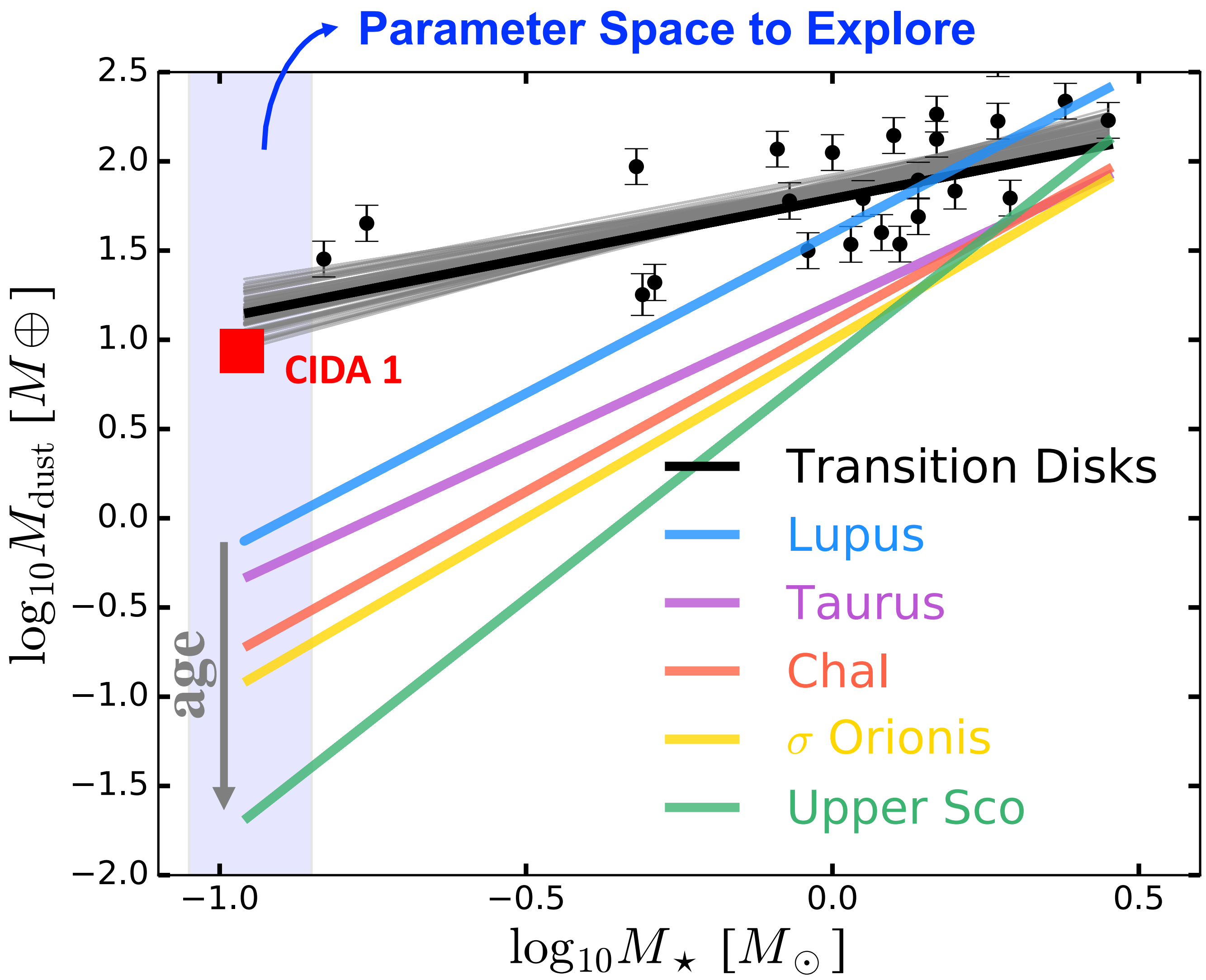
The Slope of Mdust – $M_\star$ Relation Strongly Depends On Very Few Disks Around VLMS



TDs remain massive independent of the stellar mass.

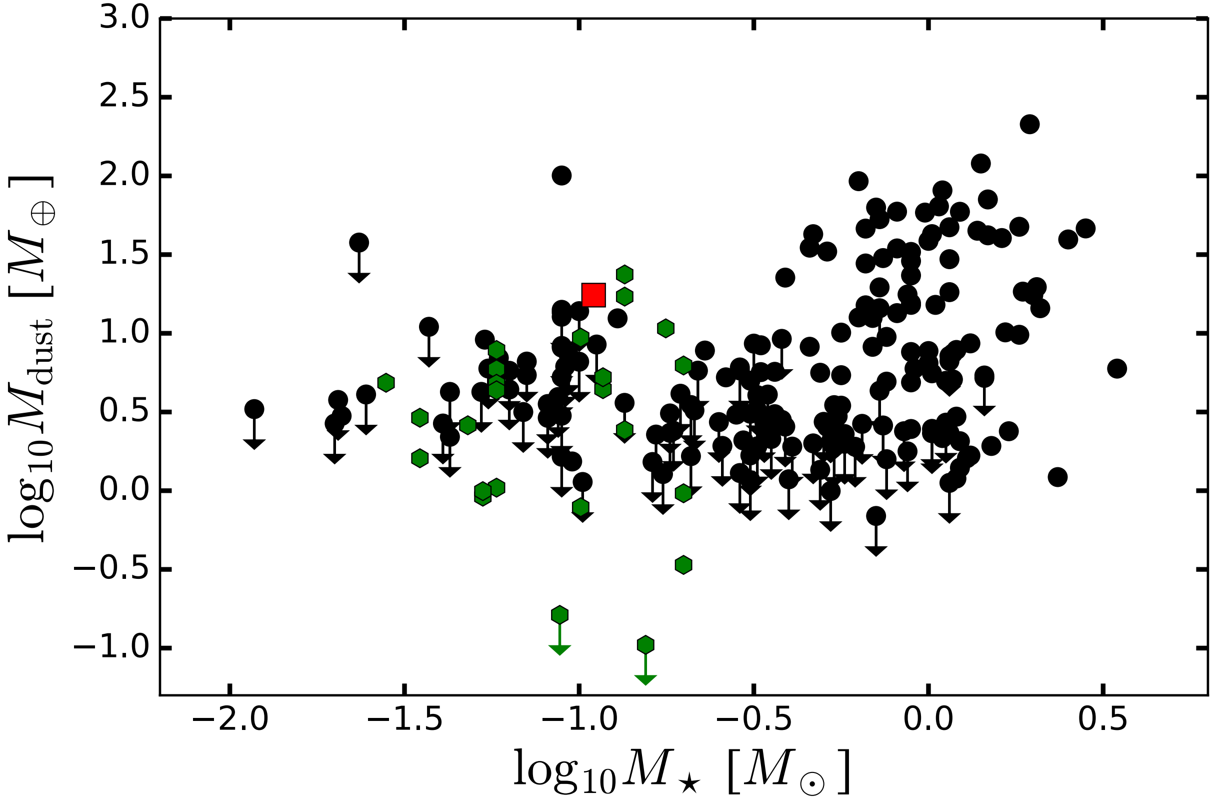
Survey data from Andrews et al. (2013), Ansdell et al. (2016, 2017), Barenfeld (2016), and Pascucci et al. (2016)

What Do we Learn from the TDs around VLMS?

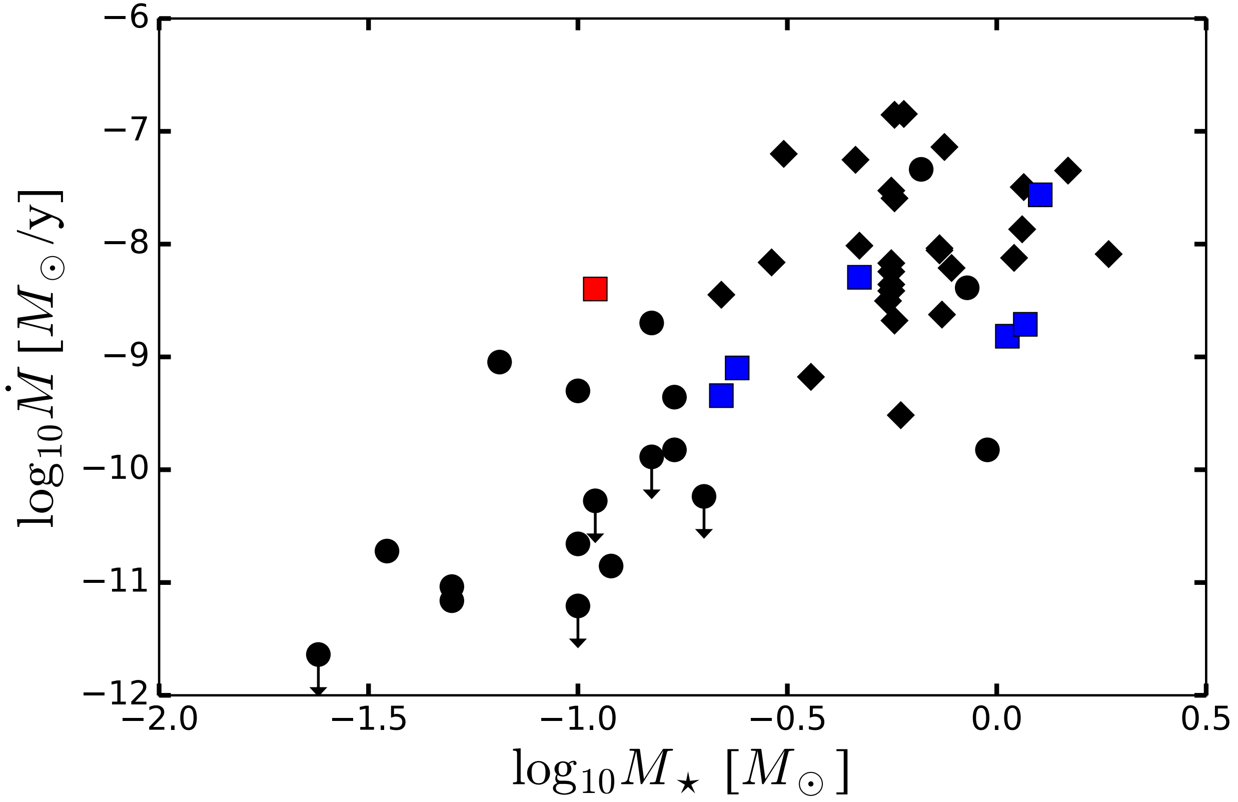


ALMA data coming to hunt for TDs around VLMs. The selection of the targets are based on CIDA 1

CIDA 1 Has a Massive Disk and High Accretion Rate for its Stellar Mass

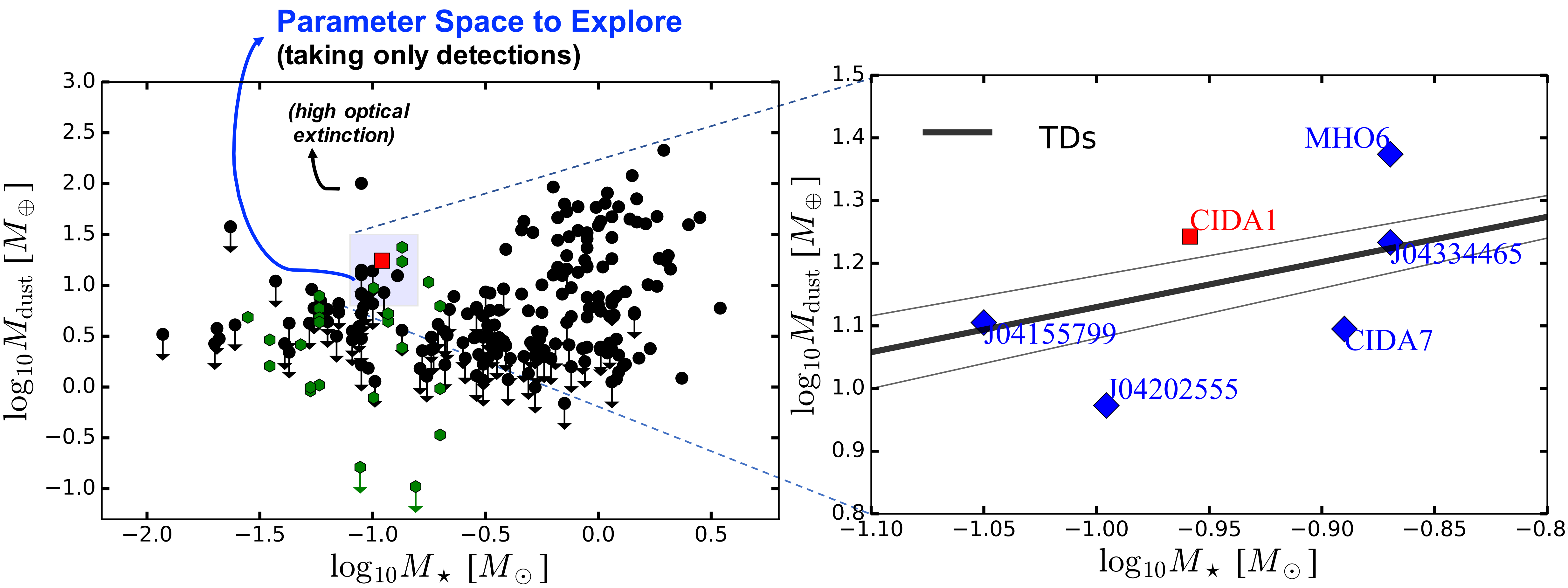


Dots and upper limits from Andrews et al. (2013). Hexagonal points from Ward- Duong et al. (2018)

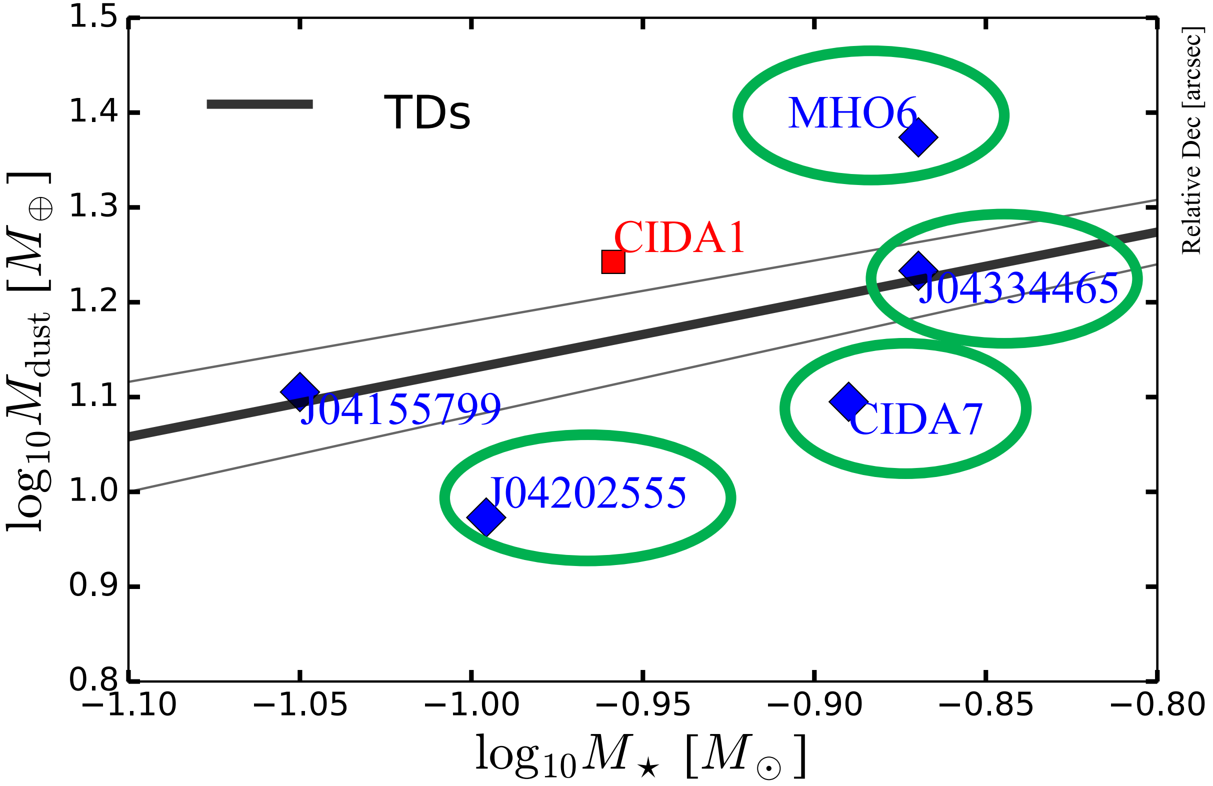


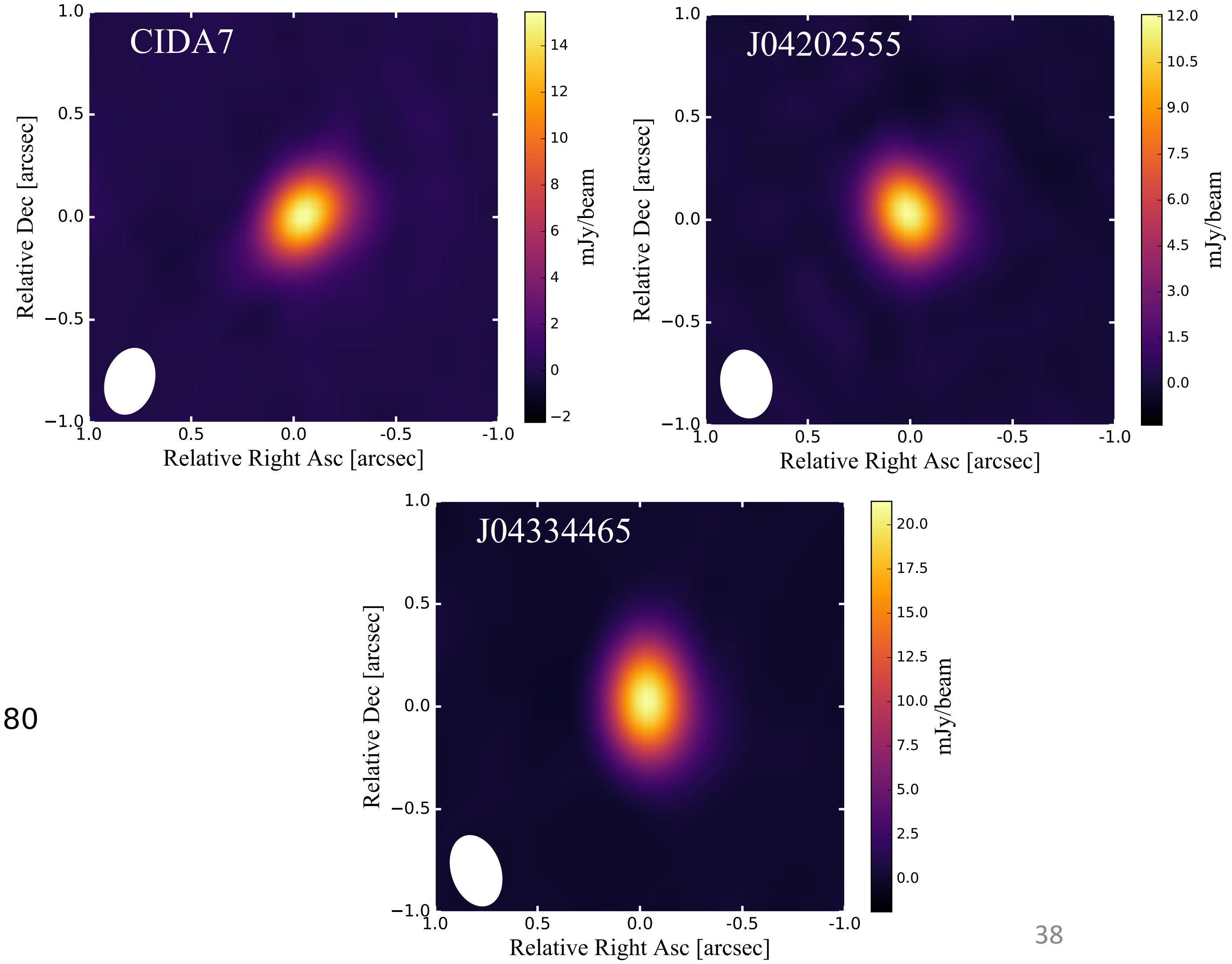
Dots from Herczeg et al. (2008), diamonds from Rigliato et al. (2015) (known TDs are identified by blue squares.). Accretion rate of CIDA 1 is 4 x10^{-9} Msun/year

The Incoming ALMA Data Include Disks with High Mass Relative to their Stellar Masses

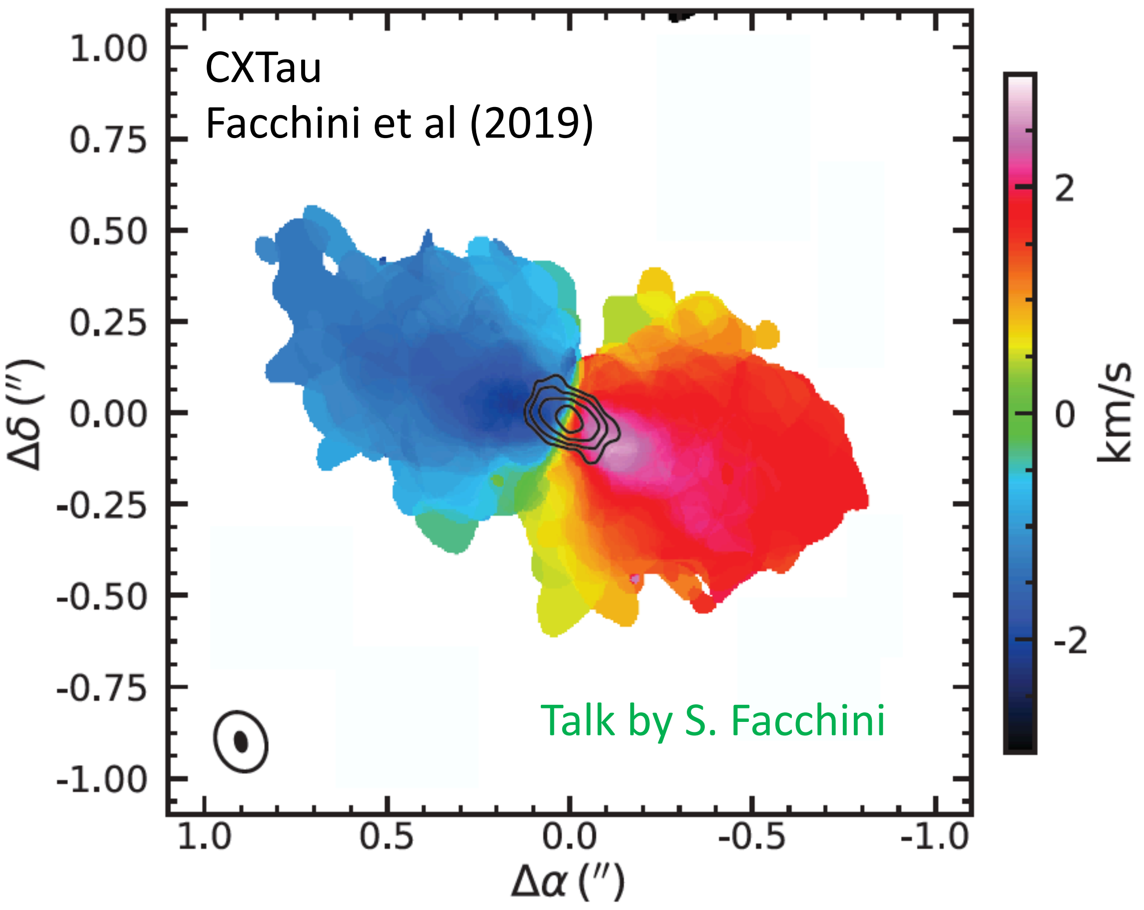


We Obtained so Far Short Baselines Observations of 4 Disks

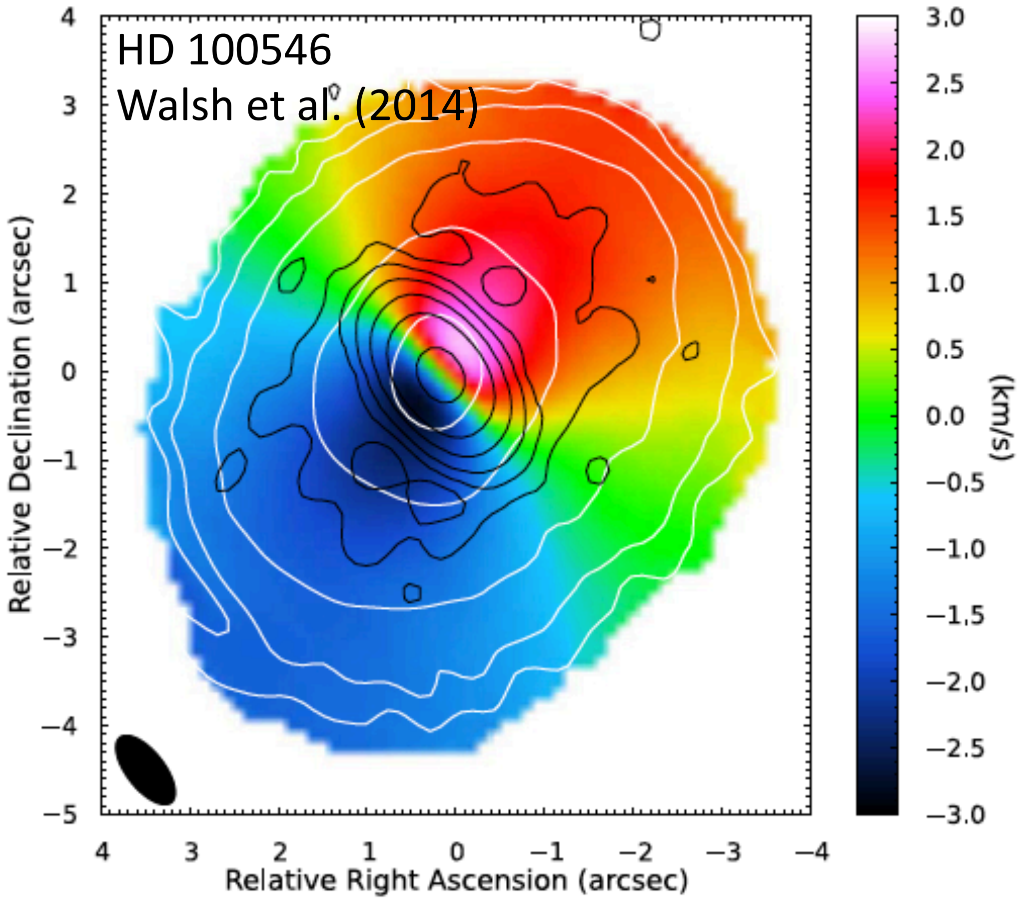




Measuring Rgas/Rdust for Disks around VLMS and BDs



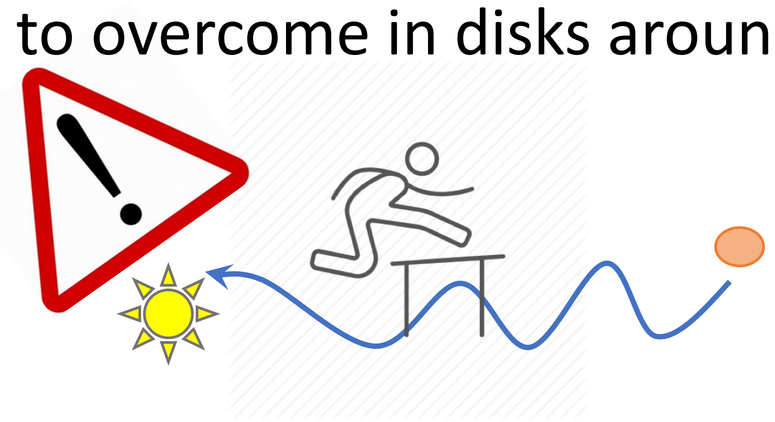
$M_\star$=0.3 Msun

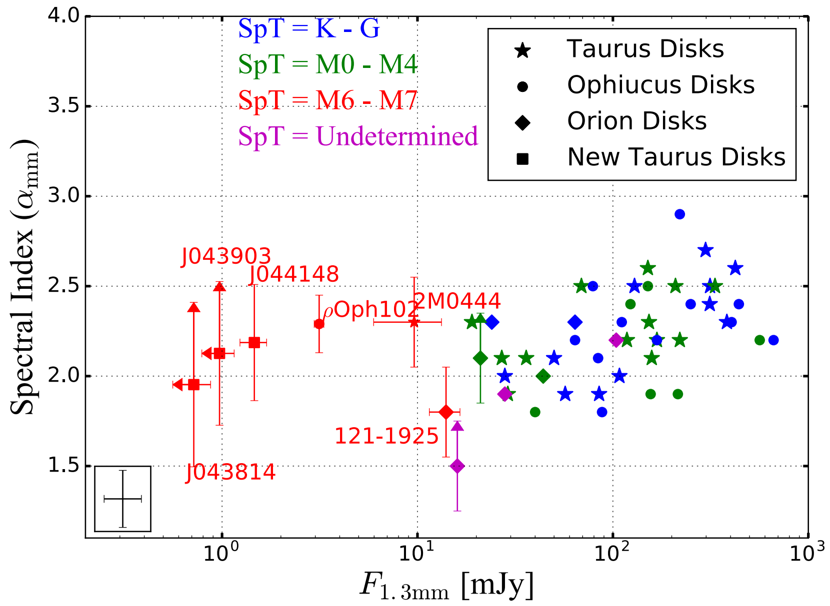


$M_\star$=2.4 Msun

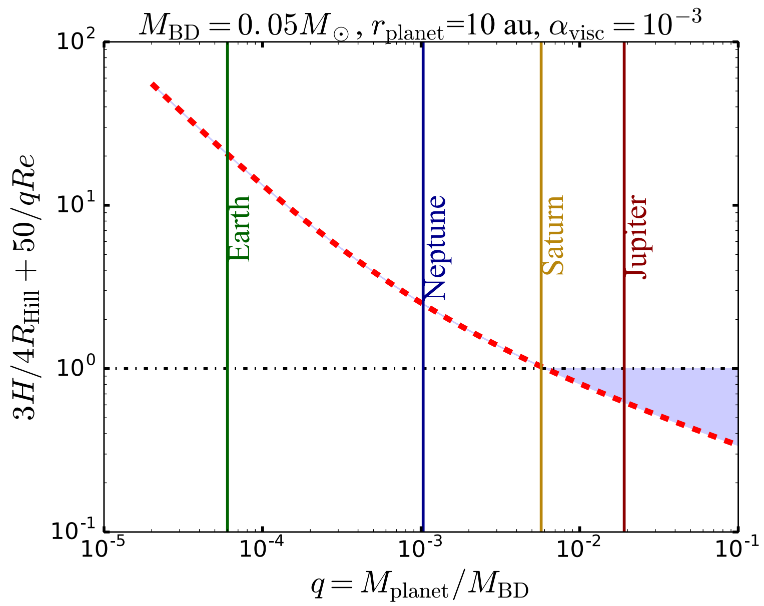
Conclusions

Radial drift is a more difficult barrier to overcome in disks around VLMS and BDs

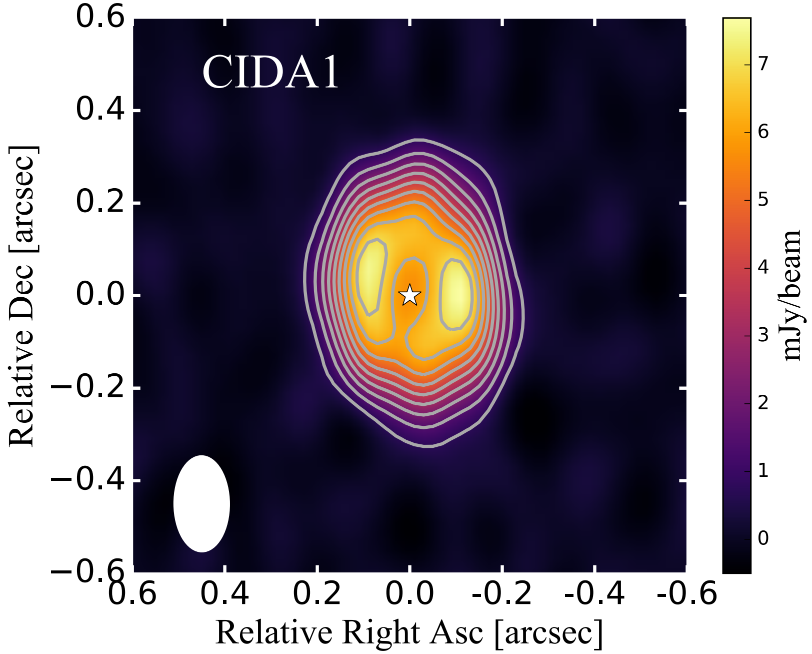




We (may) have observational evidence of mm-sized particles in disks around VLMS and BDs



We need at least a Saturn-mass planet to open a gap and trap particles, but this does not explain α_{mm}



How to explain CIDA 1 and mm-grains in these disks?


Thank you for your attention