Making Earths from Interstellar Grains:
Evidence of Grain Processing in Proto-Planetary Disks

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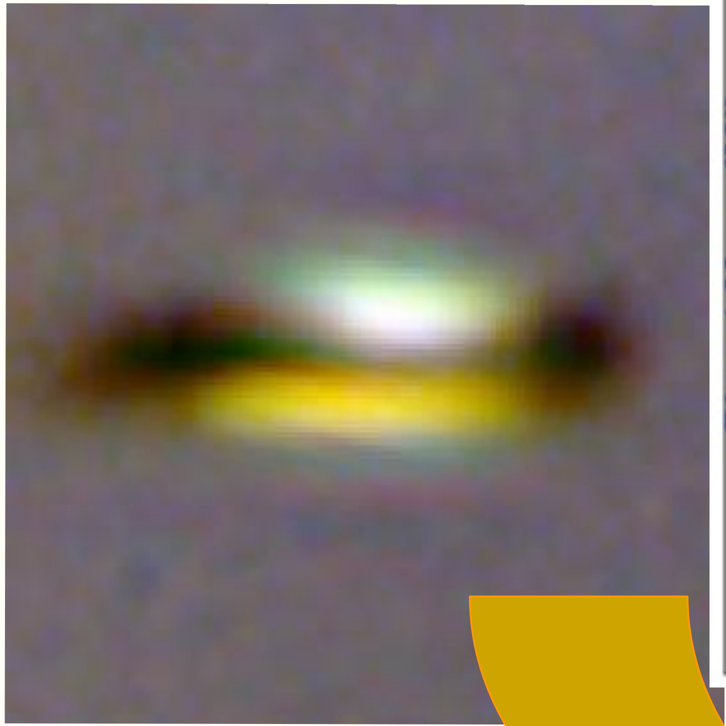
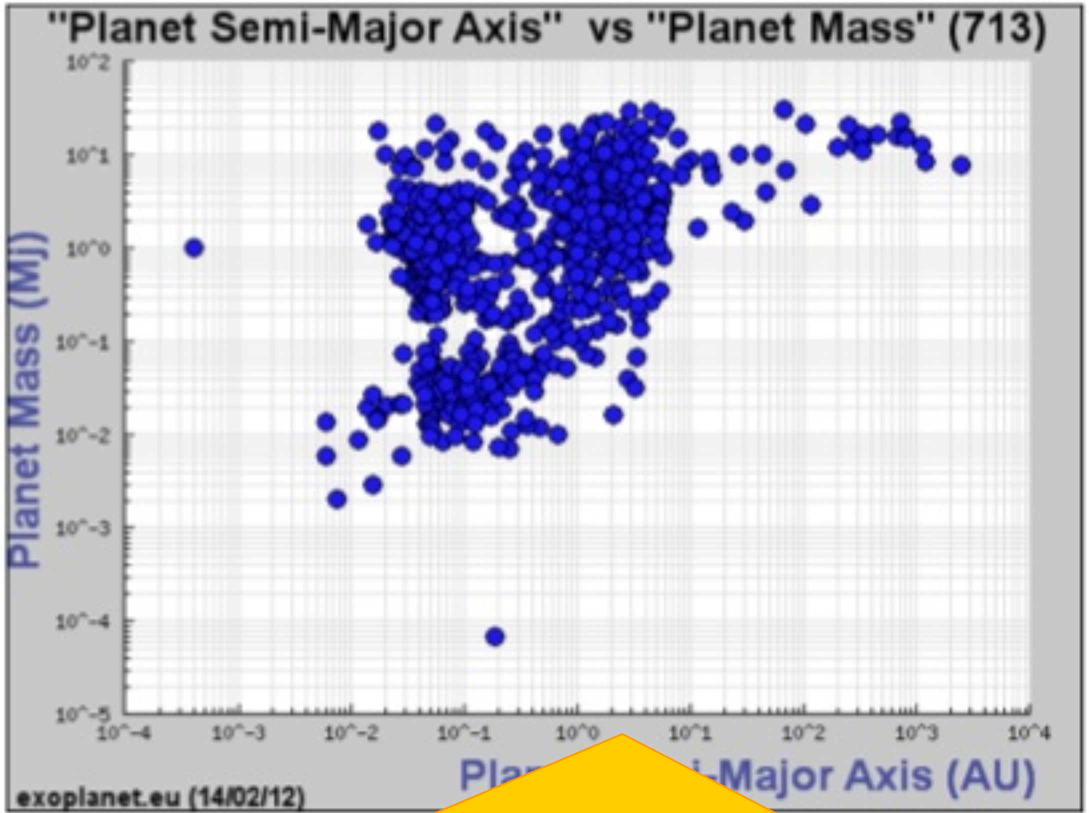
Abstract:

Earth-like planets and the solid cores of gaseous planets like Jupiter are formed in circumstellar disks by the coalescence of solids (grains) that were originally mixed with gas in the parental molecular cloud. This process involves growth over 13 order of magnitude in size and more than 40 orders of magnitude in mass, from the sub-micron grains in the interstellar medium to Earth.
The physical and chemical processes that occur at different times in this path are complex and not well understood.

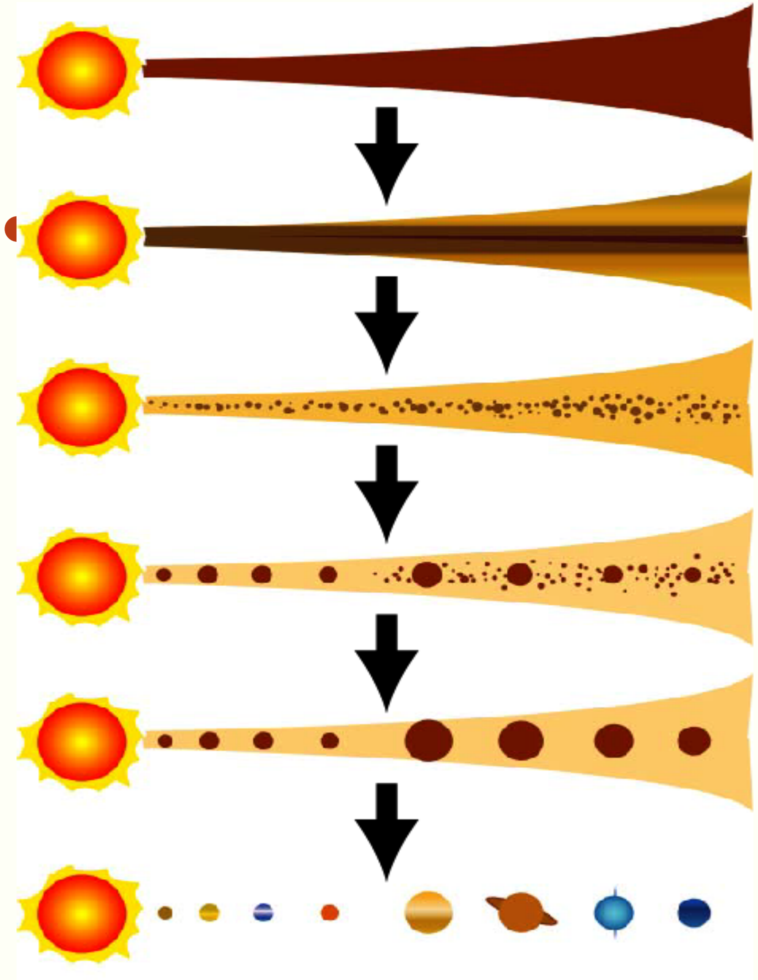
In this talk, I will review the more important processes that take place in circumstellar disks, including grain settling, coalescence and fragmentation. I will then discuss the observational evidence we have of grain growth in disks, and the challenge it poses to the planet formation theories.

From disks to planetary systems





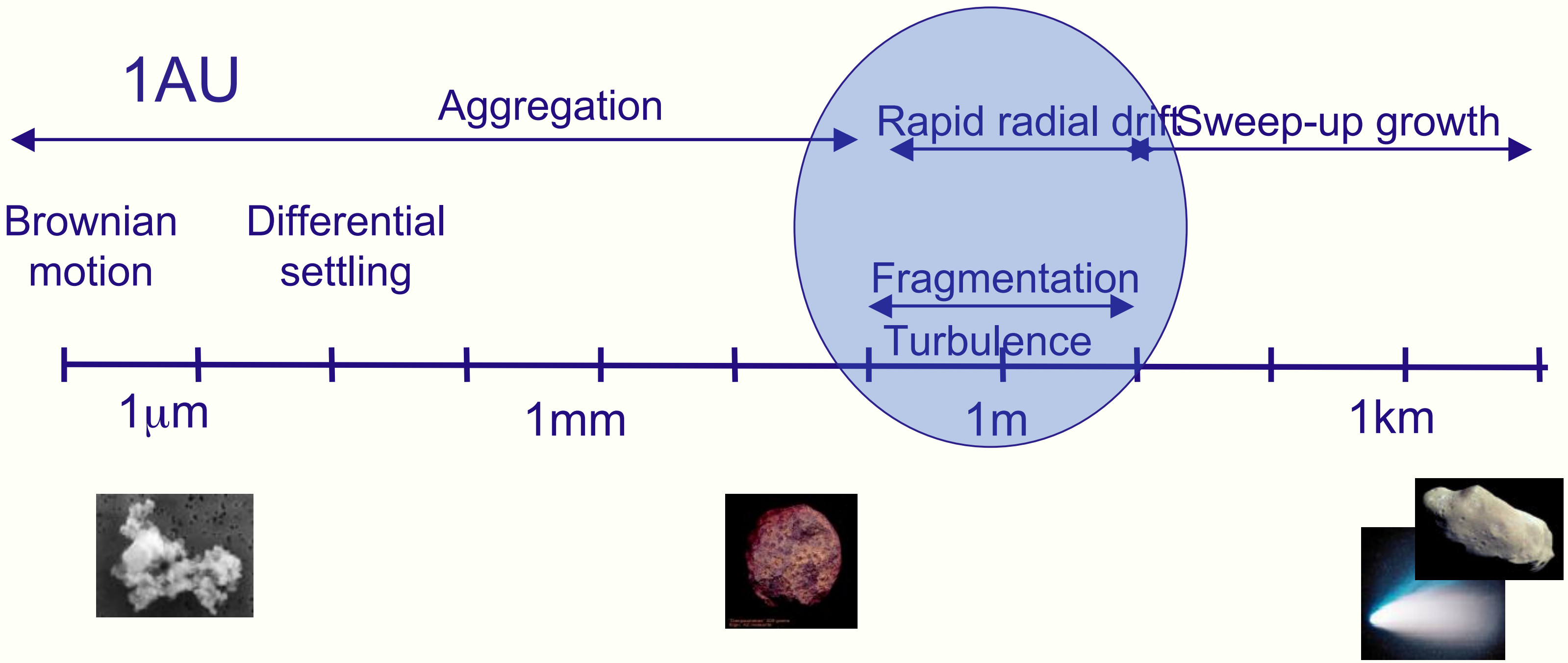
Two possible routes



- Dust particles collide and stick together
- Aggregates continue to grow until gravity becomes important (planetesimals)
- Planetesimals agglomerate via gravitational interactions and form rocky planet
- Two ways from here:
  - Stay a rocky planet (like Earth)
  - Accrete gas and become Jupiter-like planet

From ISM grains to planetesimals:

11 orders of magnitude in size (from sub-micron to km)



Theoretical prediction:

- at any given distance from the star, grains larger than a critical size cannot exist:

- Critical grain size :
- meters @ 1AU in the solar nebula
- millimeters @ 50AU in a TTS disk

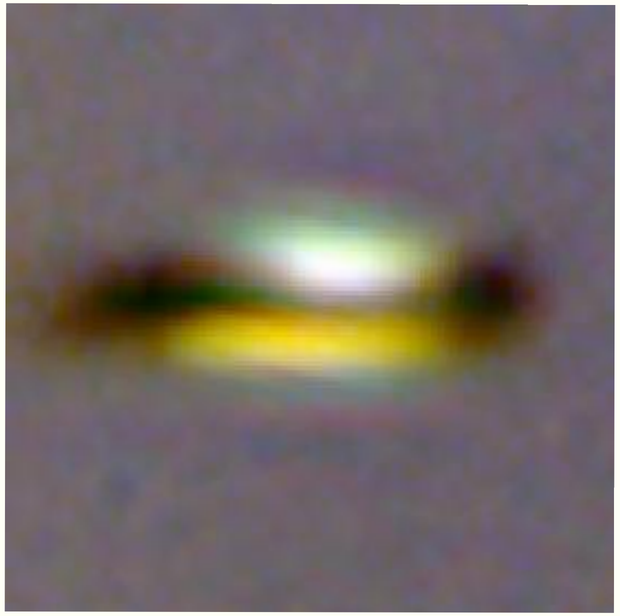
Observable!

A nice collaboration:

- The observers: L.Ricci, L. Testi, A. Natta, M. Benisty, A. Isella

- The theoreticians: K. Dullemond, T. Birnstiel, P. Pinilla, C. Dominik, etc. (the Heidelberg group)

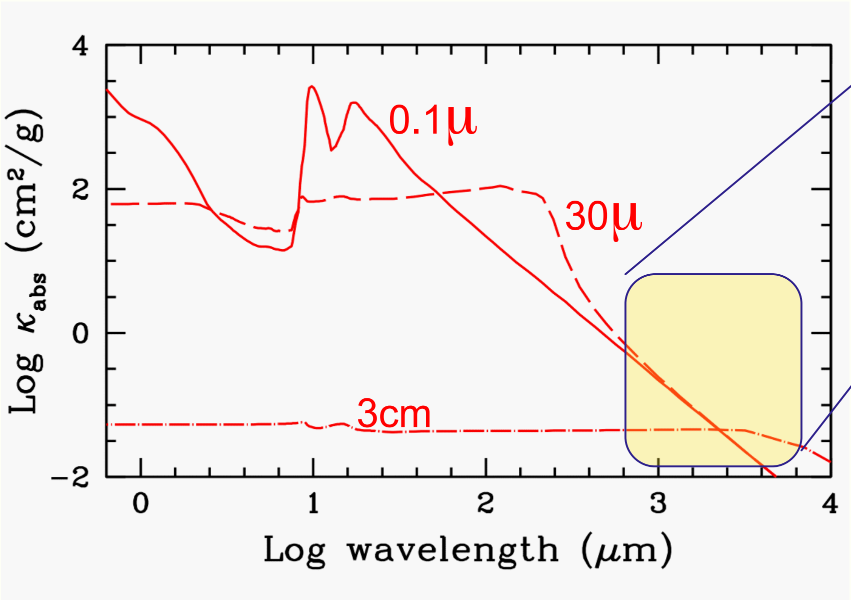
Circumstellar disks



- Gas and dust (initially, ~1% in mass)
- Mass: few % of Mstar
- Dense, cold and neutral
- Lifetime: few million years
- Large range of properties
  - Mass (only dust)
  - Radius
  - Mass accretion rate
  - Stellar properties

How do we “measure” grain sizes?

- By measuring the dependence of the opacity on wavelength



size=0.1μ : $\kappa_{mm} \sim \nu^{2.0}$

size=30μ : $\kappa_{mm} \sim \nu^{2.0}$

size= 3cm : $\kappa_{mm} \sim \nu^{0.3}$

Flat opacity $\longrightarrow$ grains >> wavelength

Radiation transfer in a nutshell

$$F_\nu \sim (1\text{-}e^{-\tau})\, B_\nu(T_{dust})\ \text{Area}$$

$$(\ \kappa_\nu \sim \nu^\beta\ )$$

Optically thin emission

$$\begin{cases} F_\nu \sim \nu^\alpha \sim \nu^{\beta+2} \\ \alpha = \beta + 2 \end{cases}$$

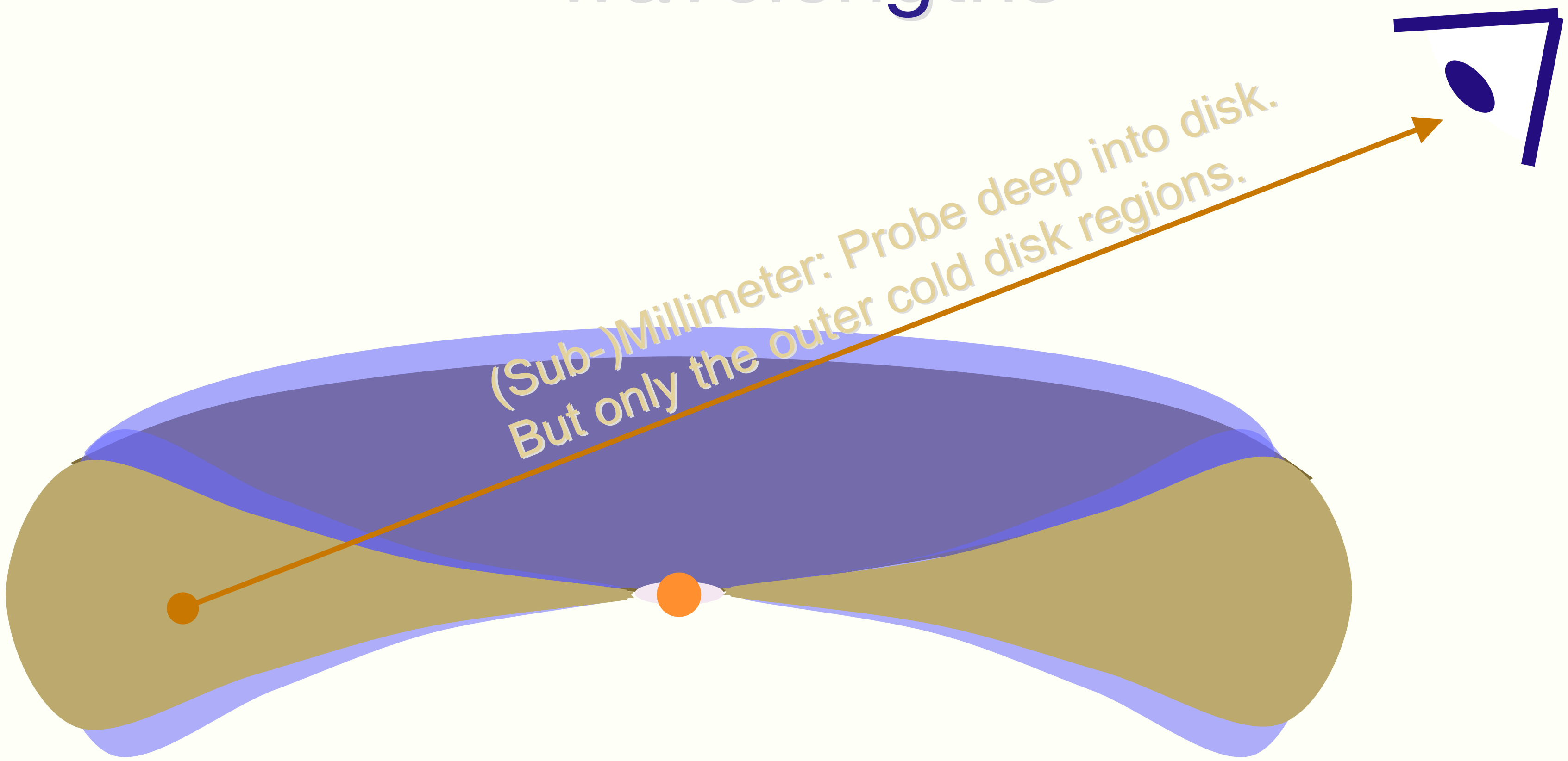
From the spectral index α one can derive the opacity index β

Optically thick emission

$$F_\nu \sim B_\nu\,(T_{dust})\text{Area} \sim \nu^2$$

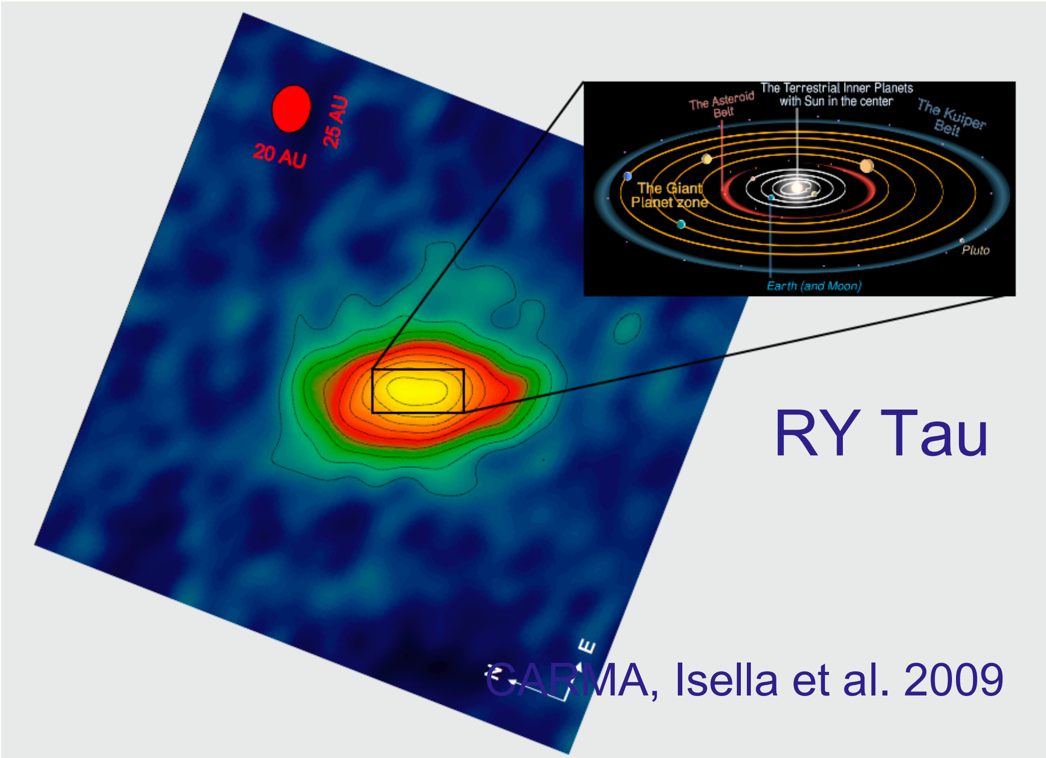
No access to the dust properties

Disks are optically thin only at mm wavelengths



- Flat spectral distribution (α ~ 2): grains >1mm at R~50 AU
- Critical size for growth models !

Many years of observations using mm interferometers



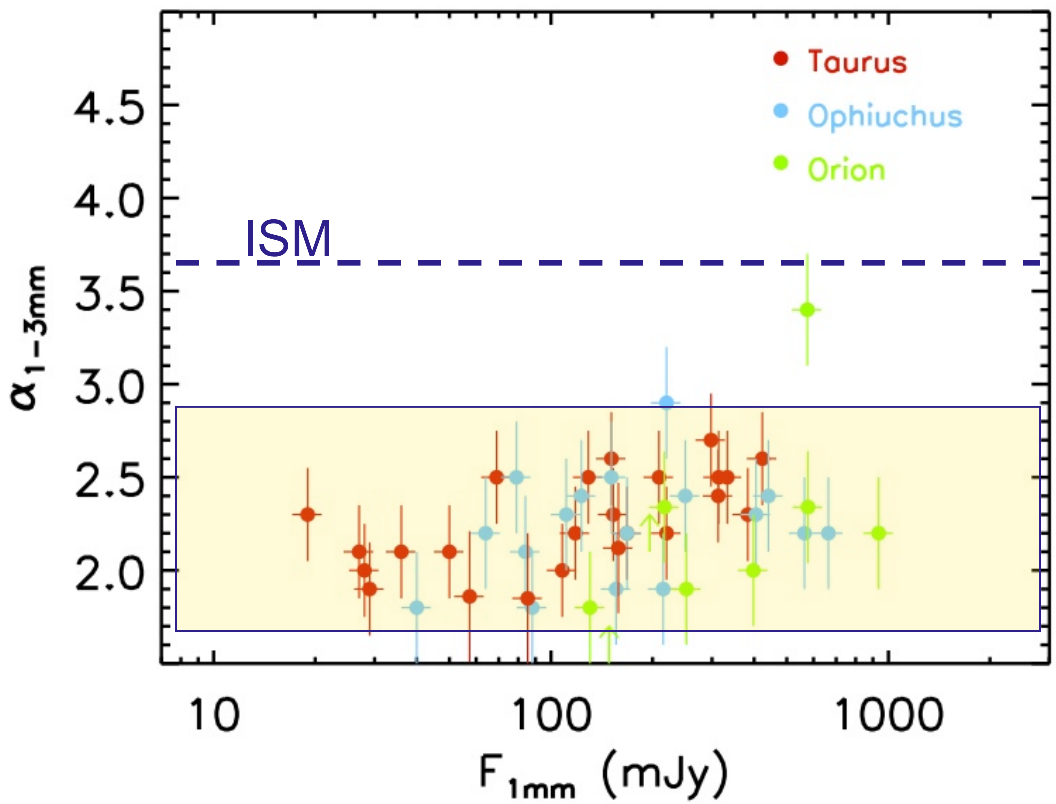
- Disks are large and optically thin at mm wavelengths
- Most disks have flat spectra ($\alpha<2.5$): no dependence on flux, stellar mass, age, environment, etc.

Beckwith and Sargent 1995
Testi, Natta et al. 2001, 2003, etc.
And many othe

Flat spectrum ⇒flat opacity ⇒mm-cm size grains

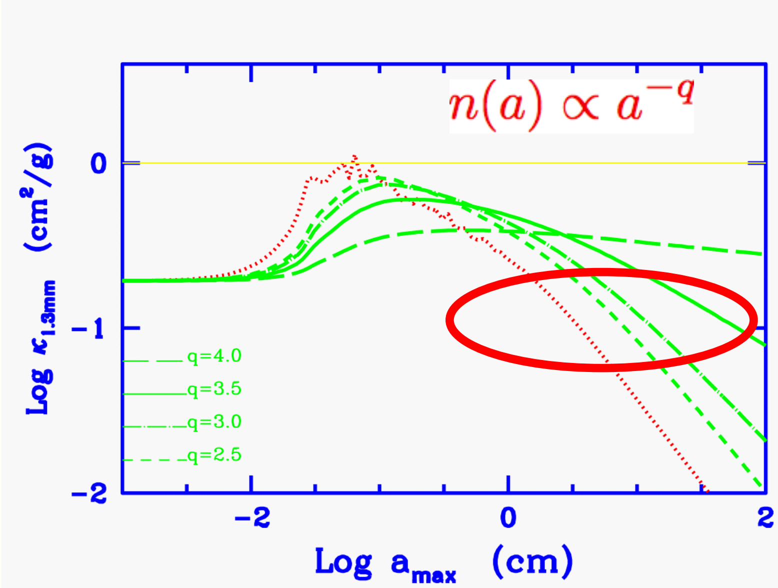
T Tauri disks in Taurus, Ophiuchus, Orion (age ~ 1-3 My)

Ricci et al. 2009, 2010, 2011



- ✓ All TTS have very large grains in their outer disk
- ✓ These grains contain a very large solid mass

Masses



$F_\nu \sim (1\text{-}e^{-\tau})\, B_\nu(T_{dust})$ Area

$\sim B_\nu(T_{dust})\, \kappa_\nu\, M_{dust}$

100 mJy @ 1mm $\Rightarrow \kappa_\nu\, M_{dus}$

$\kappa_{1mm} < 1$ cm^2/g

$M_{dust} > 3\ 10^{-4}\ M_{sun} \Rightarrow M_{disk} > 0.03\ M_{sun}$

$M_{disk}/M_{star} > 0.06$

Only 5 times less than the maximum mass

(30% M_{star})

We have convincing evidence that mm-cm grains dominate @ 50AU in most TTS

The mm barrier at 50 AU is broken!

Grain Growth

- Coalescence
- Fragmentation
- Radial drift & gas drag

$\Longrightarrow$ Controlled by gas density and motions:

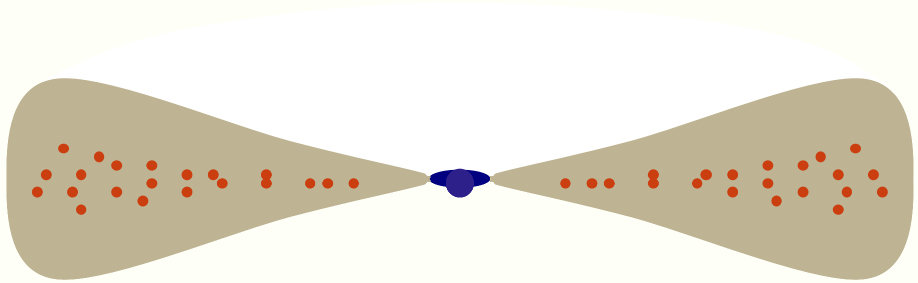
turbulence

radial inward motion (accretion)

Disk structure and dynamics

Sedimentation and coalescence

- Grains are pulled toward the midplane by the vertical component of the stellar gravity
- But kept at high z by coupling with gas
  - (gas is not collapsed in the midplane because of thermal pressure and turbulence)
- The coupling depends on grain size: larger grains drift more easily toward the midplane and grow even larger in the process



Dullemond and Dominik 2005

Too fast! Disks would disappear in 1000 years

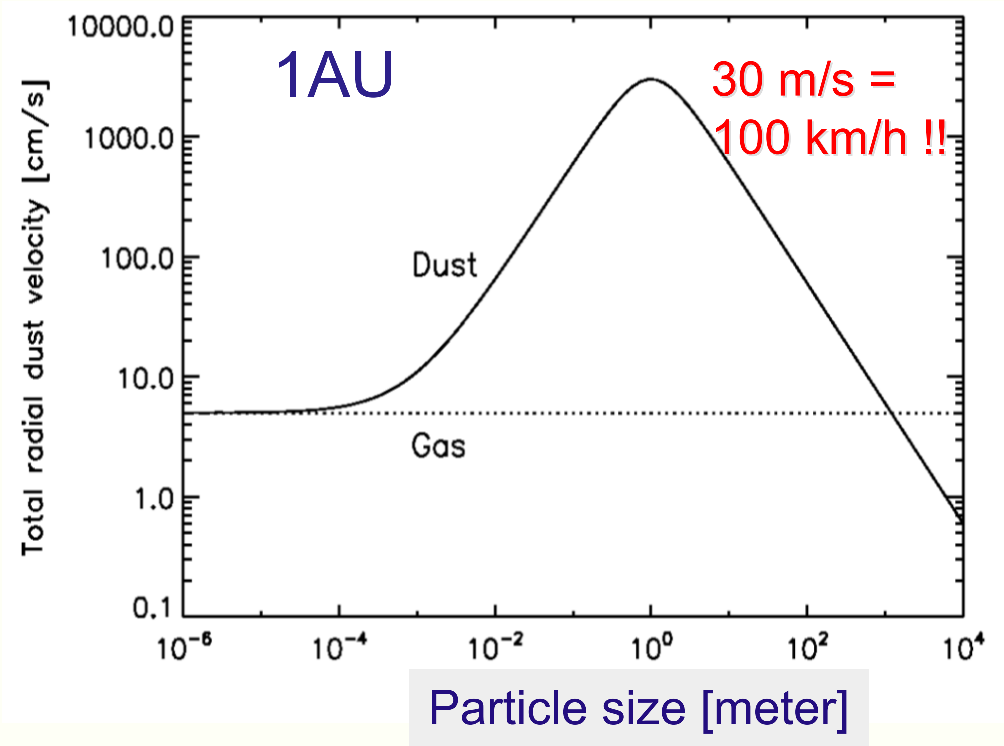
Fragmentation

- Grain collisions may lead to sticking but also to fragmentation
  - critical velocity $u_f \sim$ 1-10 m/s
- What kind of fragments? Laboratory experiments

Coalescence+ settling+fragmentation:
Not bad, but …

The enemy: radial inward drift

The pressure-supported gas moves at sub-keplerian velocity

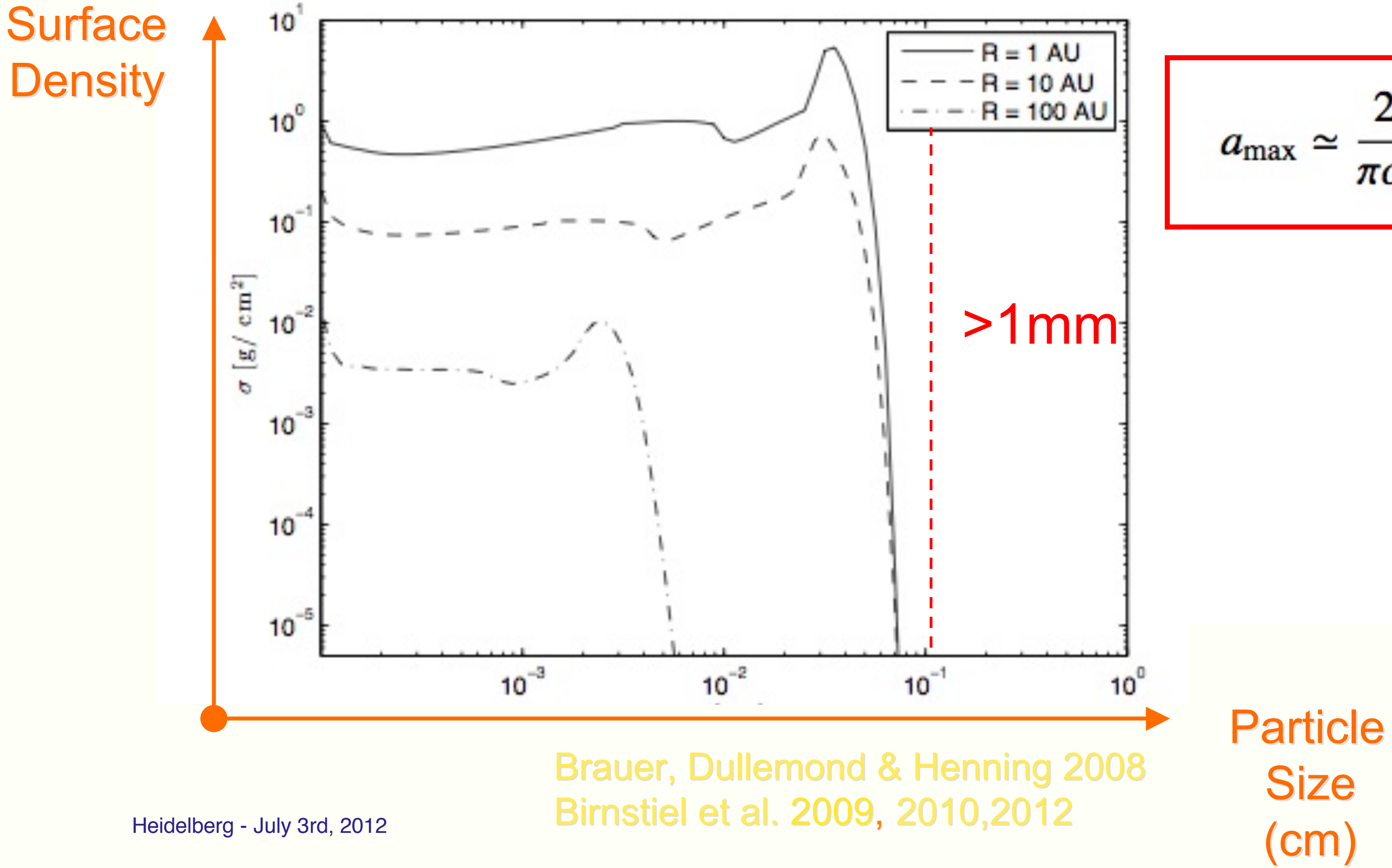


Drift velocity is size-selective, peak depends on gas density + dynamics

Full 2-D dust evolution models

Includes: growth, fragmentation, drift and mixing

1 My, Mdisk~50M_J

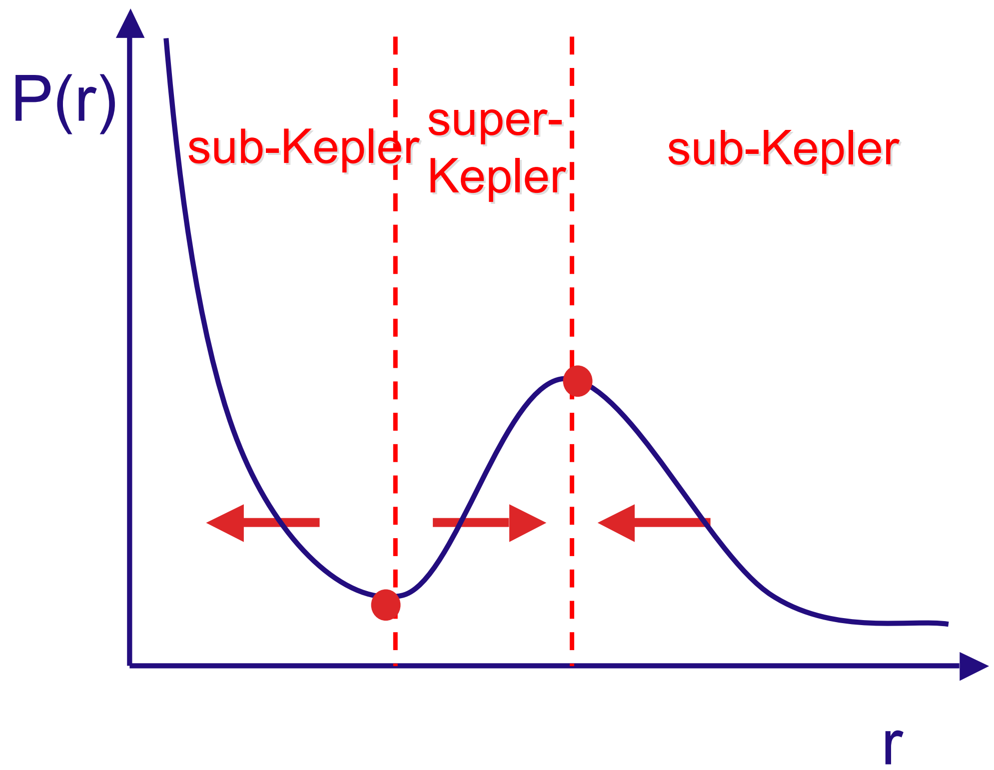


$$a_{\max} \simeq \frac{2\Sigma_g}{\pi \alpha_t \rho_s} \cdot \frac{u_f^2}{c_s^2},$$

Brauer, Dullemond & Henning 2008
Birnstiel et al. 2009, 2010,2012

Trapping dust in pressure maxima?

- Spiral waves
- MRI (dead zones)
- Gap edges
- Etc.



Introducing strong inhomogeneities in the gas density profile

Pinilla et al. 2012

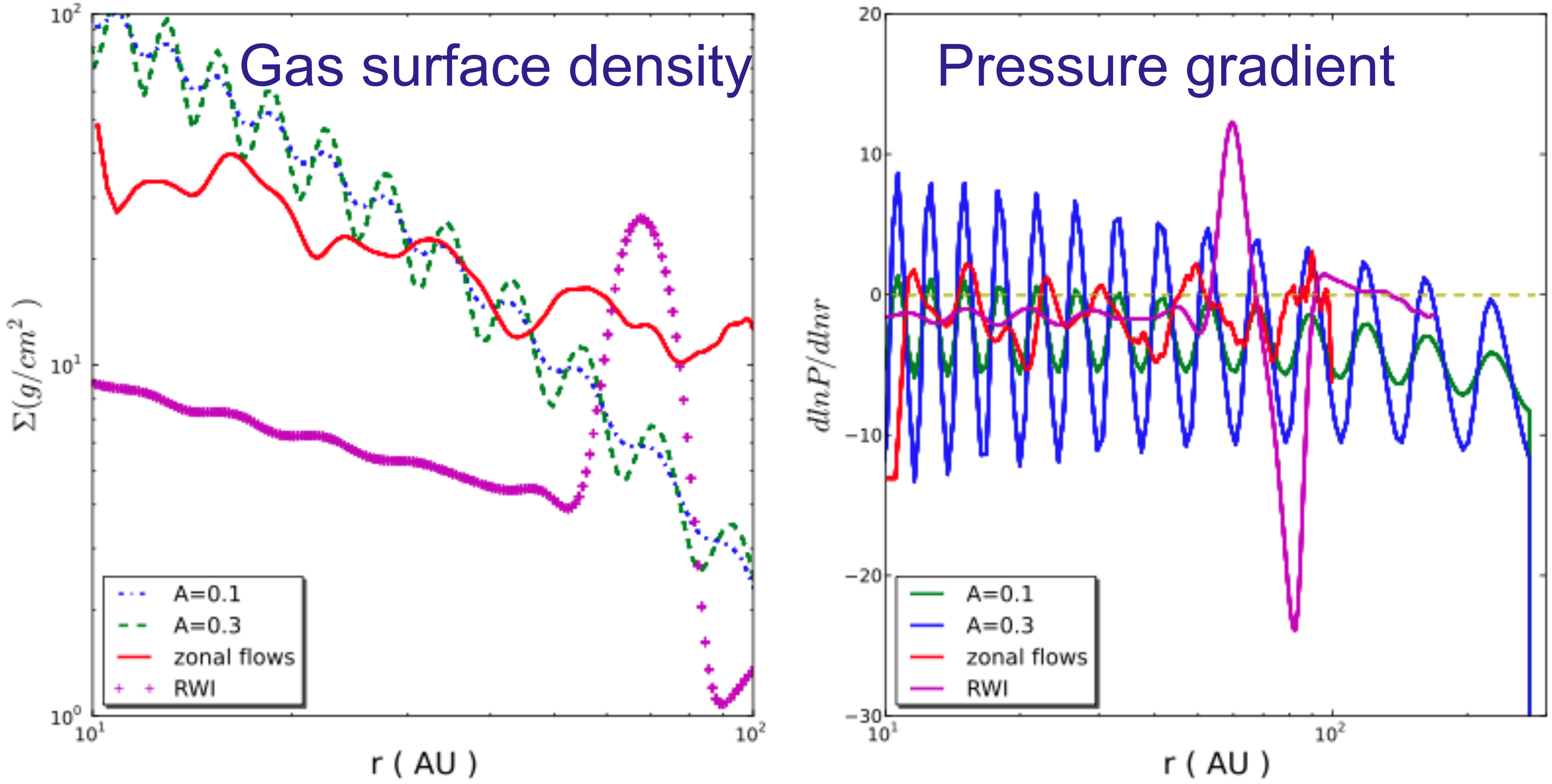


Fig. 1. Comparison between: The gas surface density (left plot) taken in this work (Eq. 1) for two different values of the amplitude and constant width (dashed and dot-dashed lines). The Rossby wave instability (Regaly et al. 2011), and the presence of zonal flows due to MHD instabilities (Uribe et al. 2011). Right plot shows the pressure gradient for each of the gas surface density profiles.

Global models of grain growth

Disk physical model + grain physics

↓ Dust coagulation+fragmentation+dynamics

Dust size distribution function

↓ Dust opacity model for each grain size

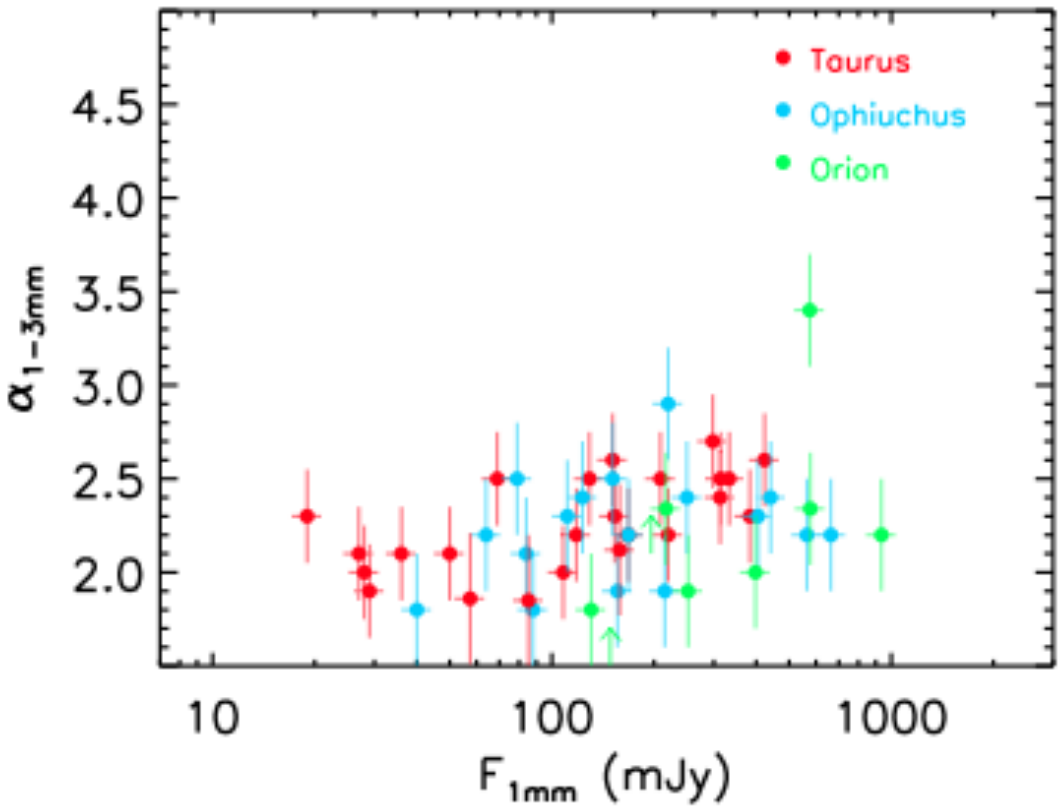
Opacity κ_ν (β-index)

↓ Disk & radiative transfer model

Model F_ν (α-index)

(Birnstiel et al. 2010; Pinilla et al. 2012)

Larger grains



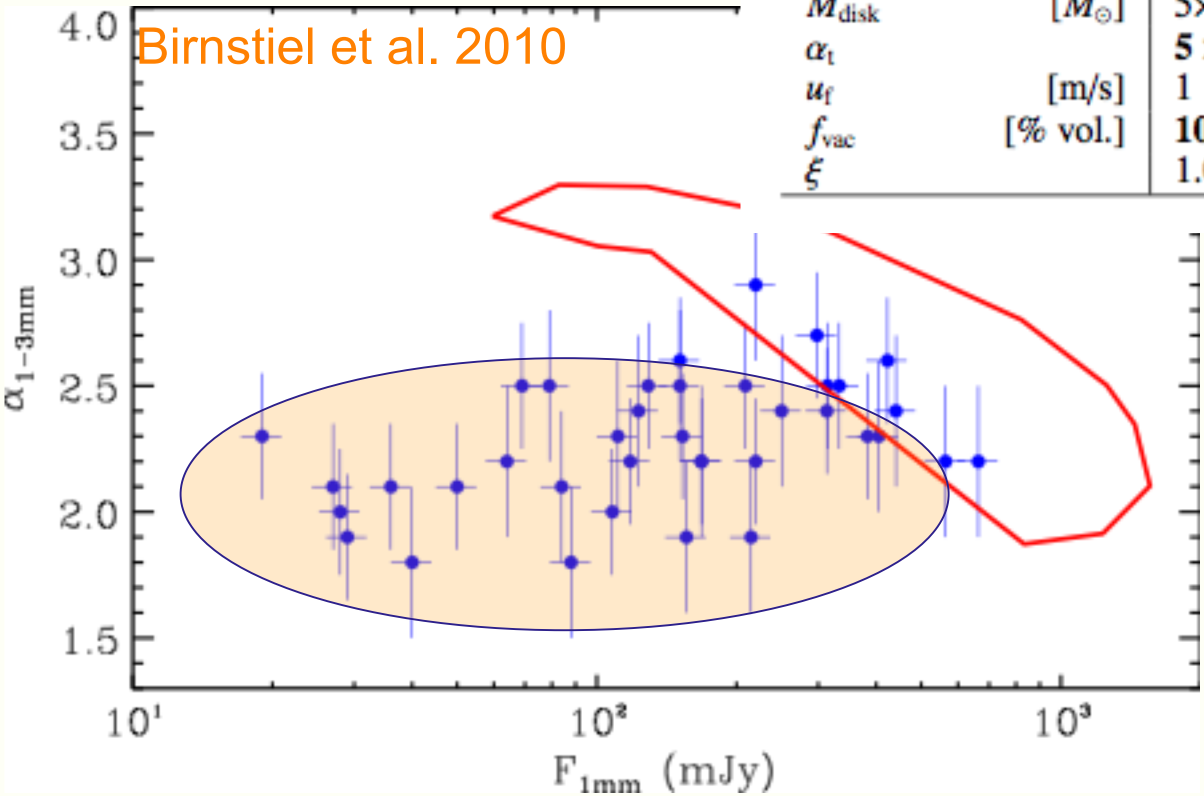
Smaller dust mass

Models of TTS disks with drift suppressed

Coagulation+sedimentation+fragmentation

parameter		values			
M_{disk}	$[M_\odot]$	5×10^{-3}	$\mathbf{1\times10^{-2}}$	5×10^{-2}	1×10^{-1}
α_t		$\mathbf{5\times10^{-4}}$	1×10^{-3}	5×10^{-3}	-
u_f	[m/s]	1	**3**	10	-
f_{vac}	[% vol.]	**10**	30	50	-
ξ		1.0	**1.5**	1.8	-

Birnstiel et al. 2010

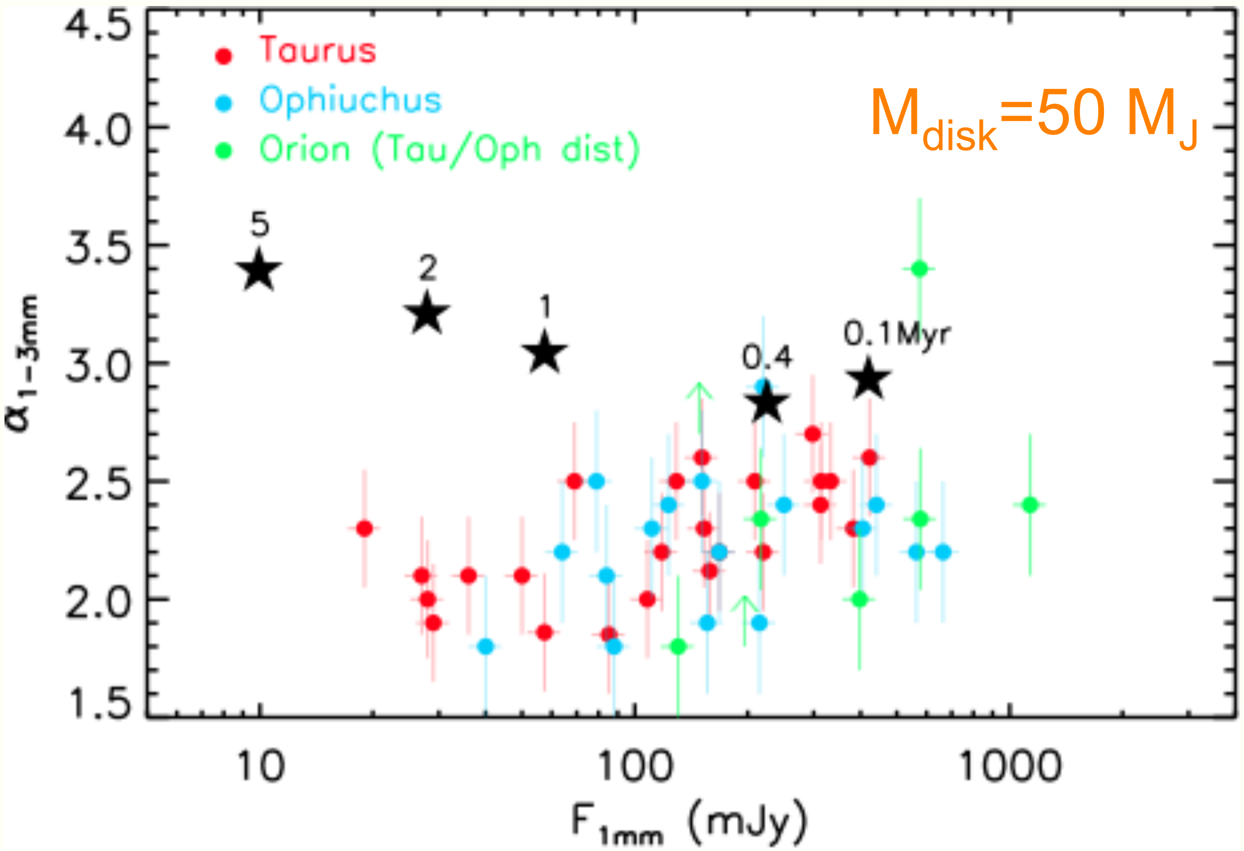


Grain sizes ok in massive disks, but the dust mass is too large

Steady-state is reached in <1My

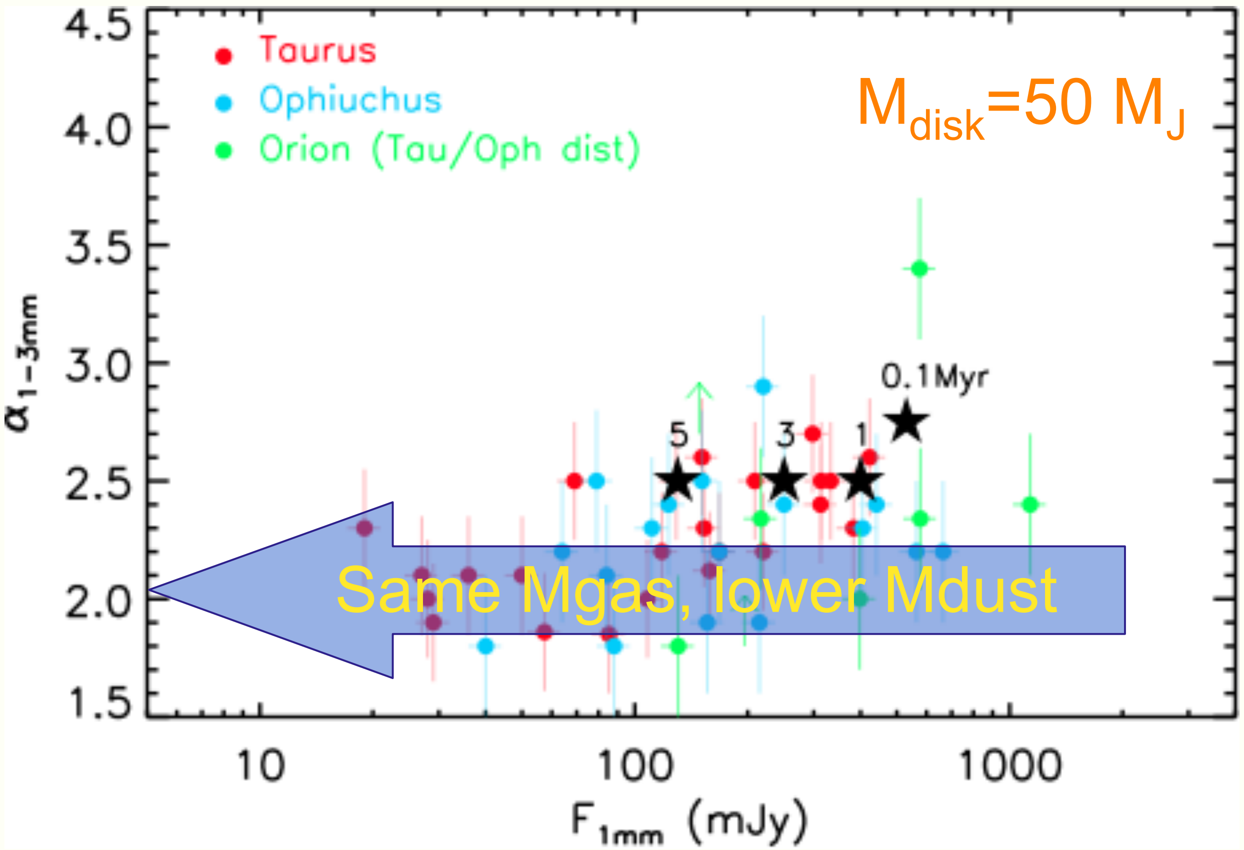
Models with drift: no way!

Pinilla et al. 2012



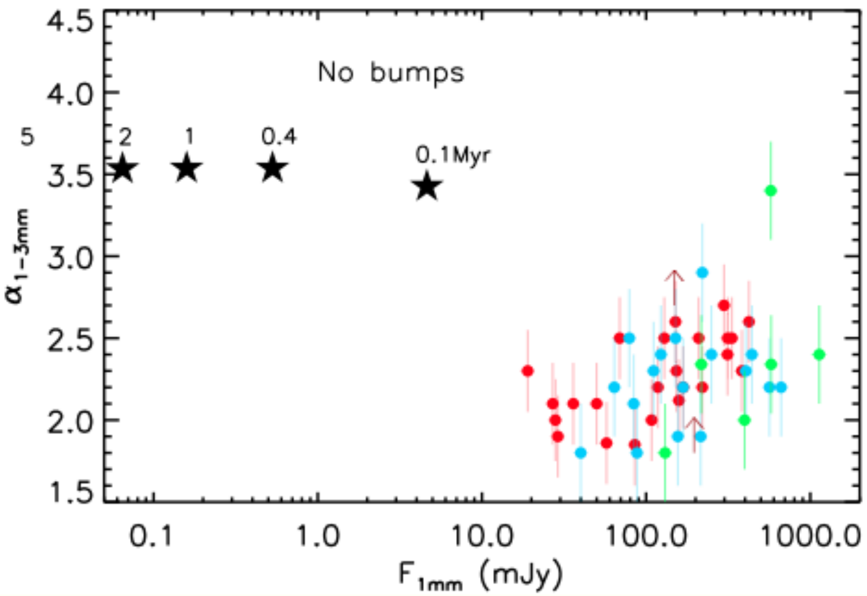
Models with pressure bumps (reduced drift efficiency)

Pinilla et al. 2012

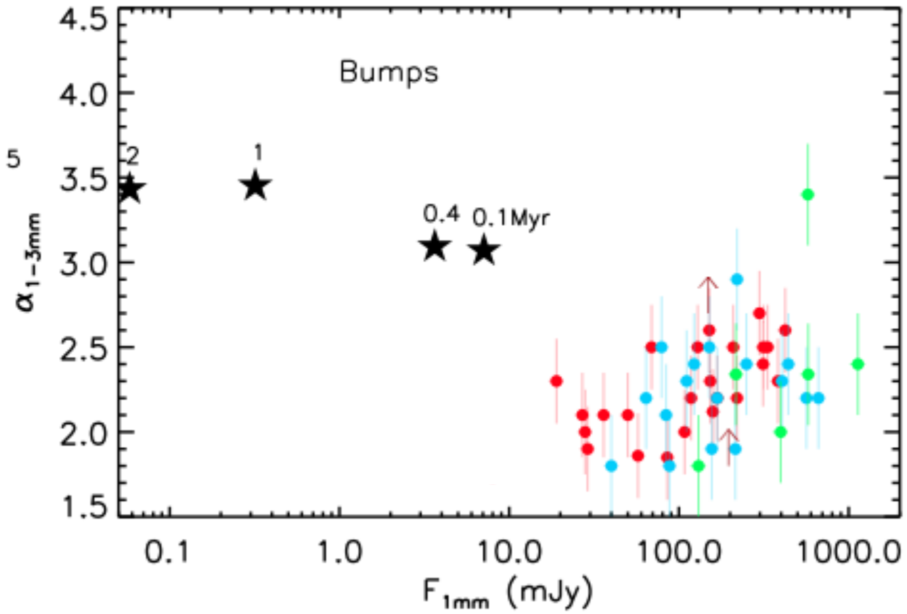


Gas masses are difficult to measure. But ….

Brown dwarf disks must have low gas mass (M_{disk}/M_{star} <0.3)

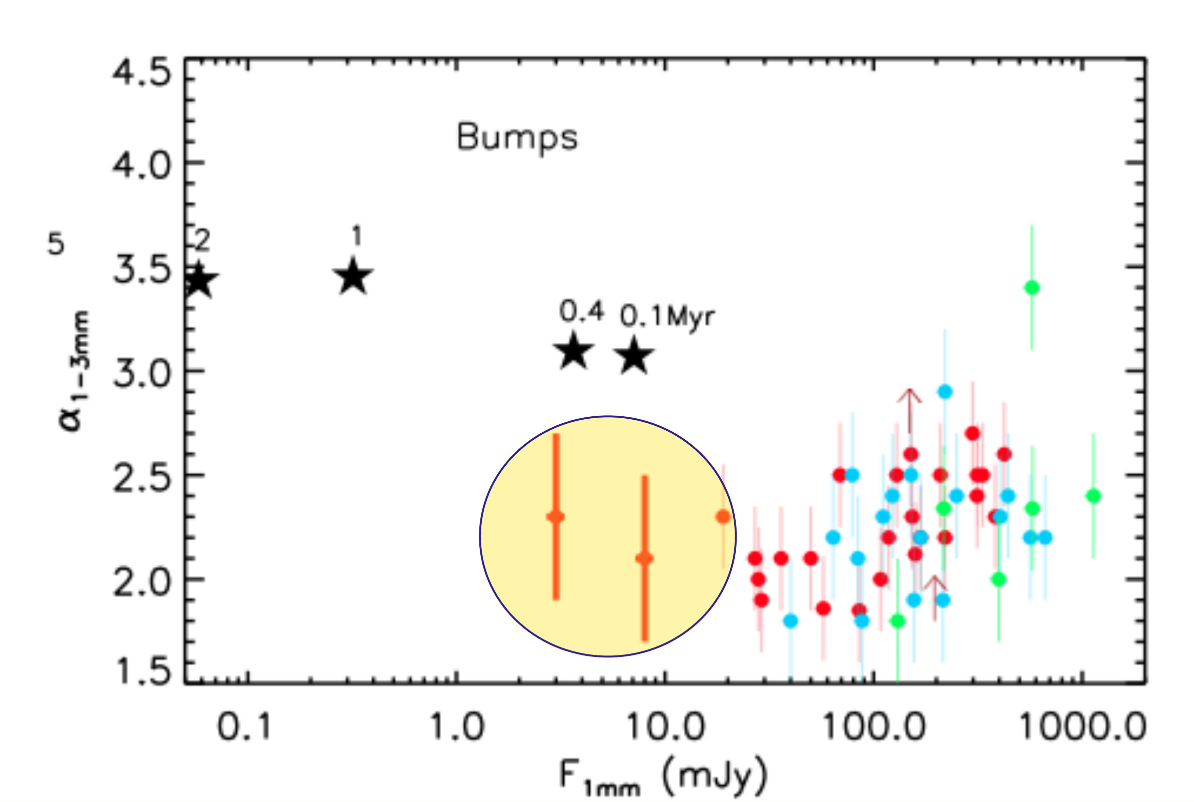


M_{disk}=1 M_J: no growth



Thanks to Pinilla, Birnstel, Ricci etc.

Grains grow equally in disks of all masses



How?

Summary

- In order to form planetesimals and planets, grains have to grow by many order of magnitudes
- Models of growth in proto-planetary disks predict that there is a maximum size (1m at 1AU, 1mm at 50 AU), which is a barrier for further growth
- The 1mm barrier at 50 AU can be tested via mm-interferometric observations: at age of ~1My, the mm barrier is broken in all kind of disks, around stars and brown dwarfs
- How?
  - Pressure bumps (I.e., disk inhomogeneities) are certainly required
  - Ices?
  - Maybe our view of disk structures and dynamic is wrong (turbulence?)
- We need more and better observations (gas/dust ratios, alpha vs. R, etc. etc.)