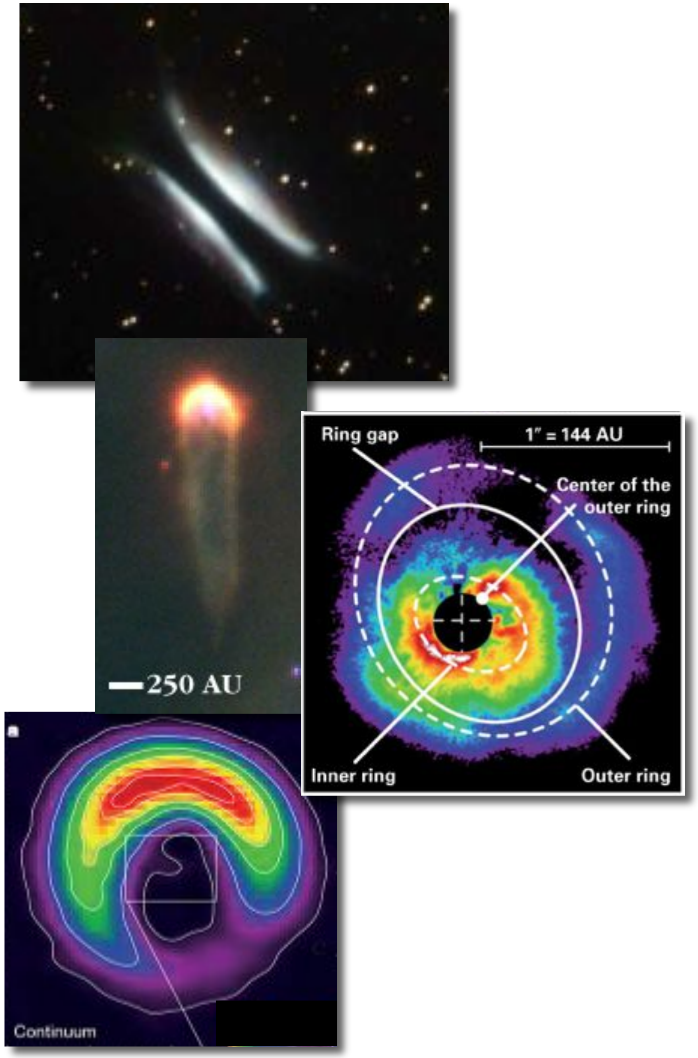
university of groningen / faculty of mathematics and natural sciences / kapteyn astronomical institute

Protoplanetary disks and planet formation

A single pathway to making planets?

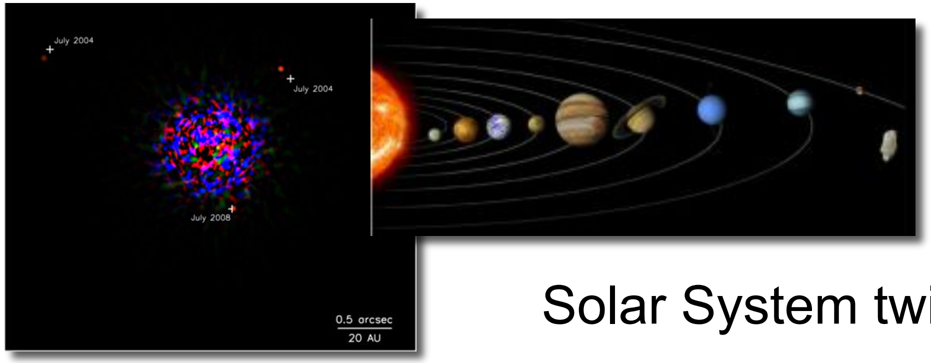
Inga Kamp

Disks evolve into planetary systems

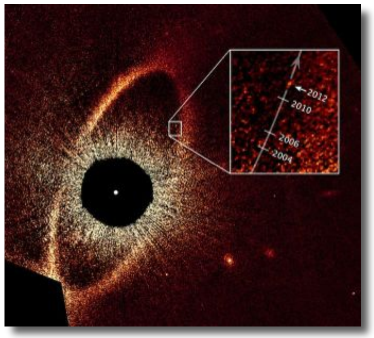


?

Hot Jupiters

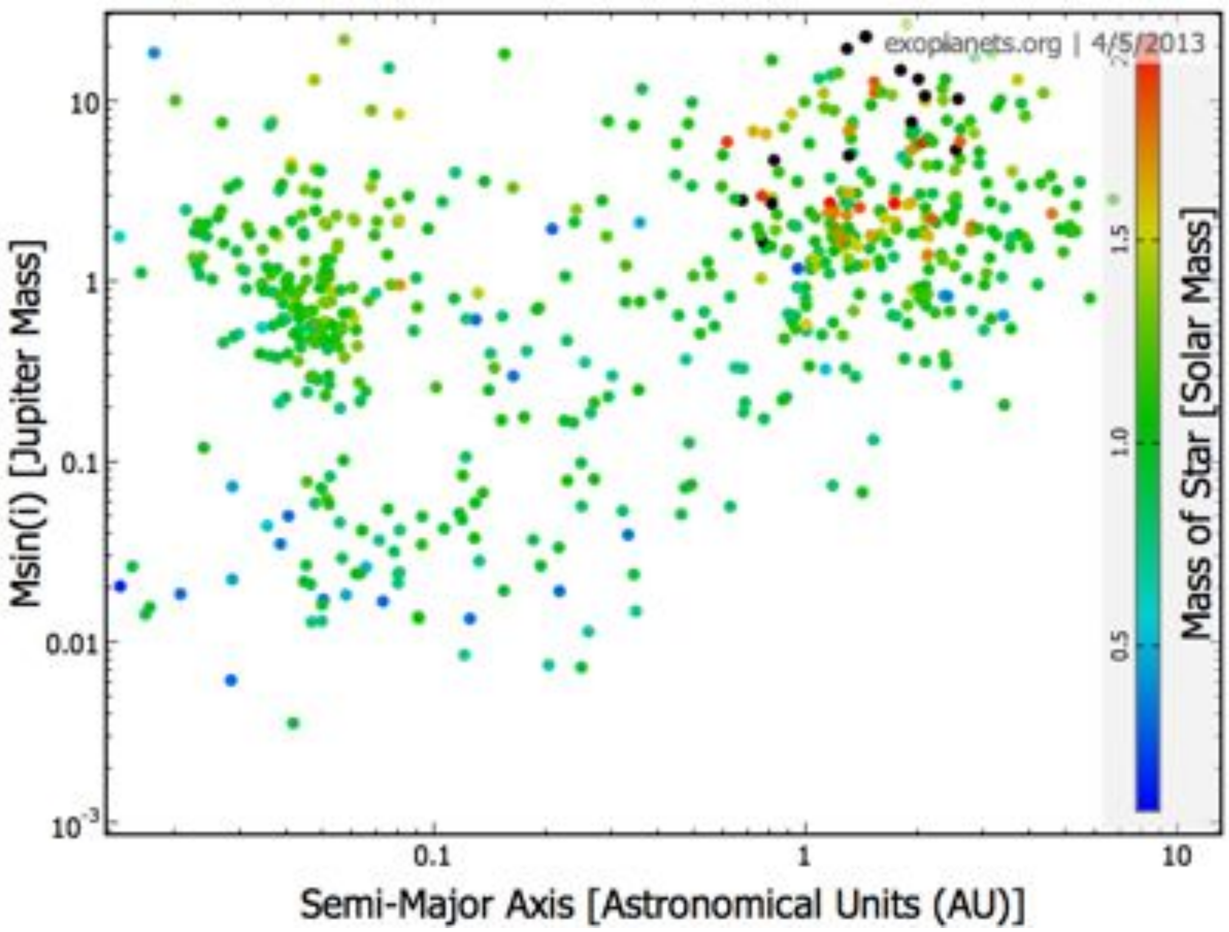


Solar System twins



Giant planets @ 100s AU

Disks evolve into planetary systems



Is there a dependence in planetary system architecture on spectral type?

possibly more massive and longer orbital periods around A/F-type stars

[Doellinger, Hatzes et al. 2011]

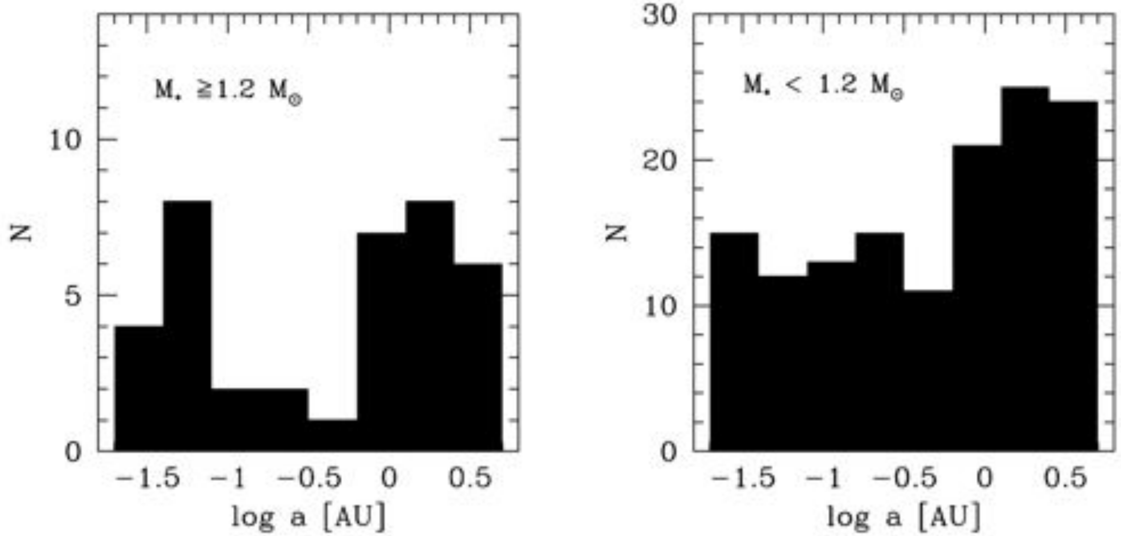
no difference in giant planet occurence around M dwarfs

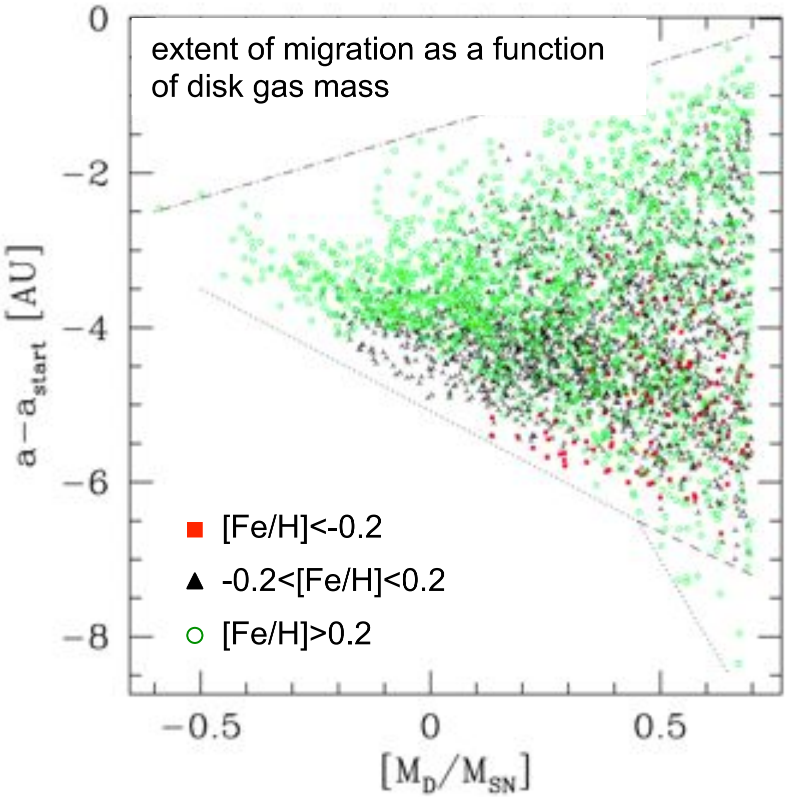
[Neves et al. 2013]

detection biases?

Disks evolve into planetary systems

[Burkert & Ida 2007]





Feature	Values
Type I migration reduction factor f_I	0.001
Viscous parameter α	7×10^{-3}
Initial exponent gas disk $\Sigma(a, t = 0)$	–3/2
Rockline included	no
Iceline included	yes
Outer radius of the computational disk	30
Inner radius of the computational disk	0.1
$f_{D/G,\odot}$	0.04

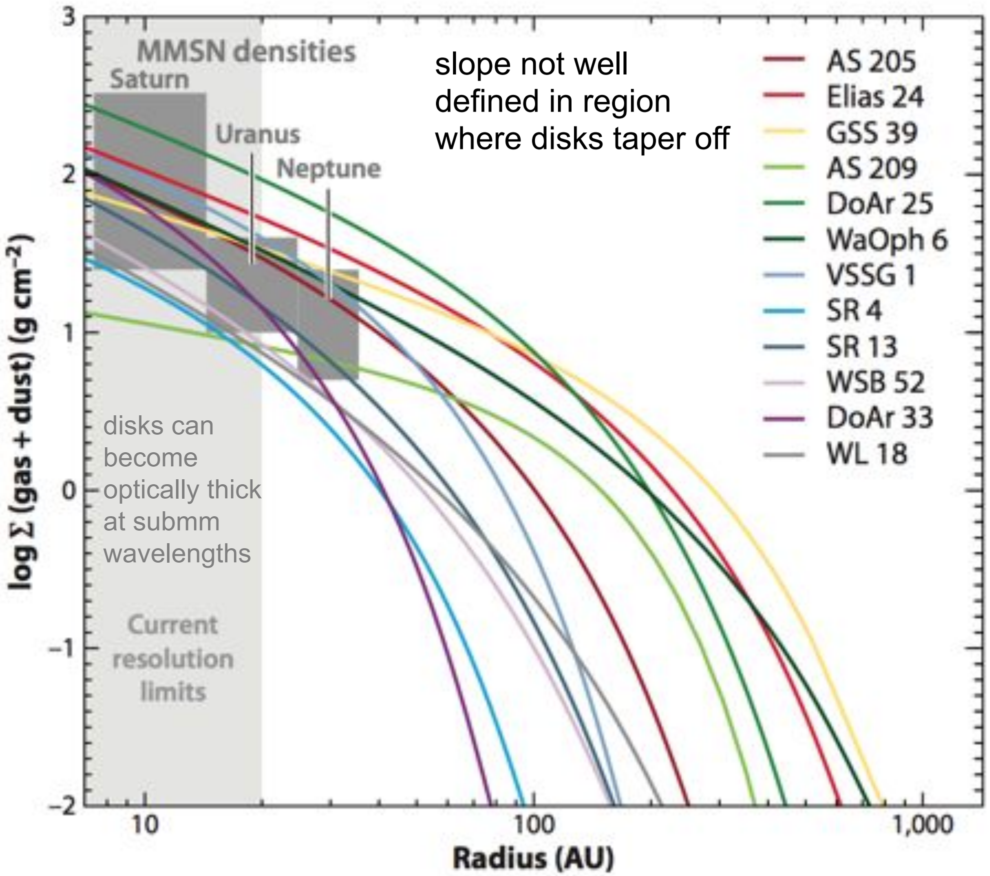
$$M_{\rm disk} \propto M_{\rm star}^{\alpha_D}$$

growth of single embryo in disk

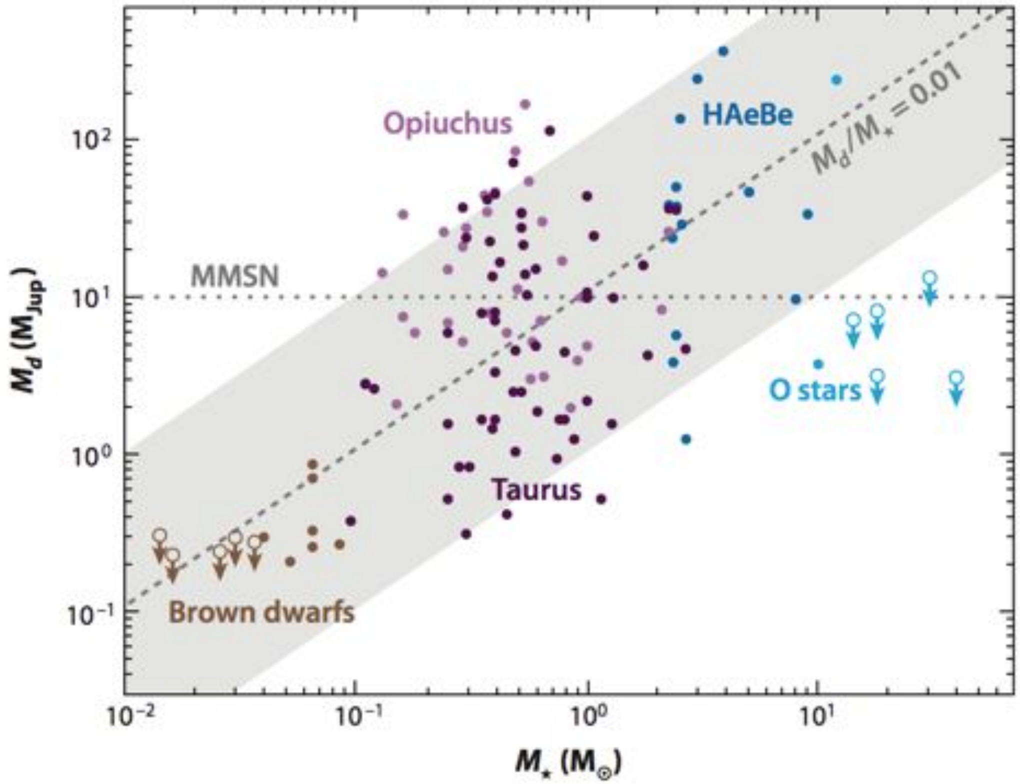
[Mordasini et al. 2009ab, Alibert et al. 2011, Mordasini et al. 2012]

Linking disk properties to planetary systems

planet population synthesis models start with very narrow range of disk parameters



However, do all disks start equal?



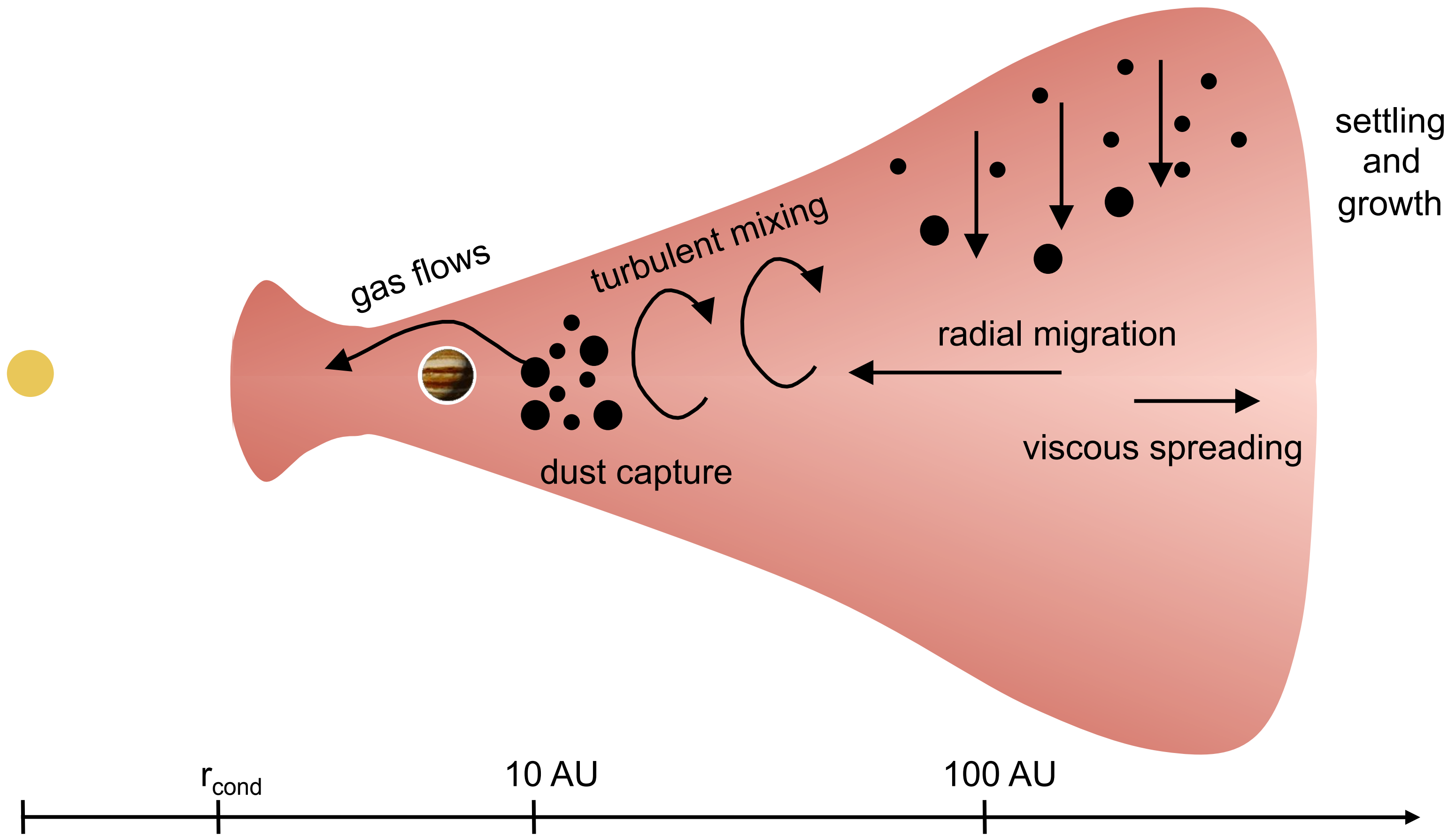
[Williams & Cieza 2011, Andrews et al. 2009, 2010]

Outline

- Processes that play a role when disks evolve into planets
    - dust grain growth and trapping
    - dust settling
    - viscous gas radial spreading and dust radial migration
    - gas dispersal
- More questions than answers… Can space interferometry help?

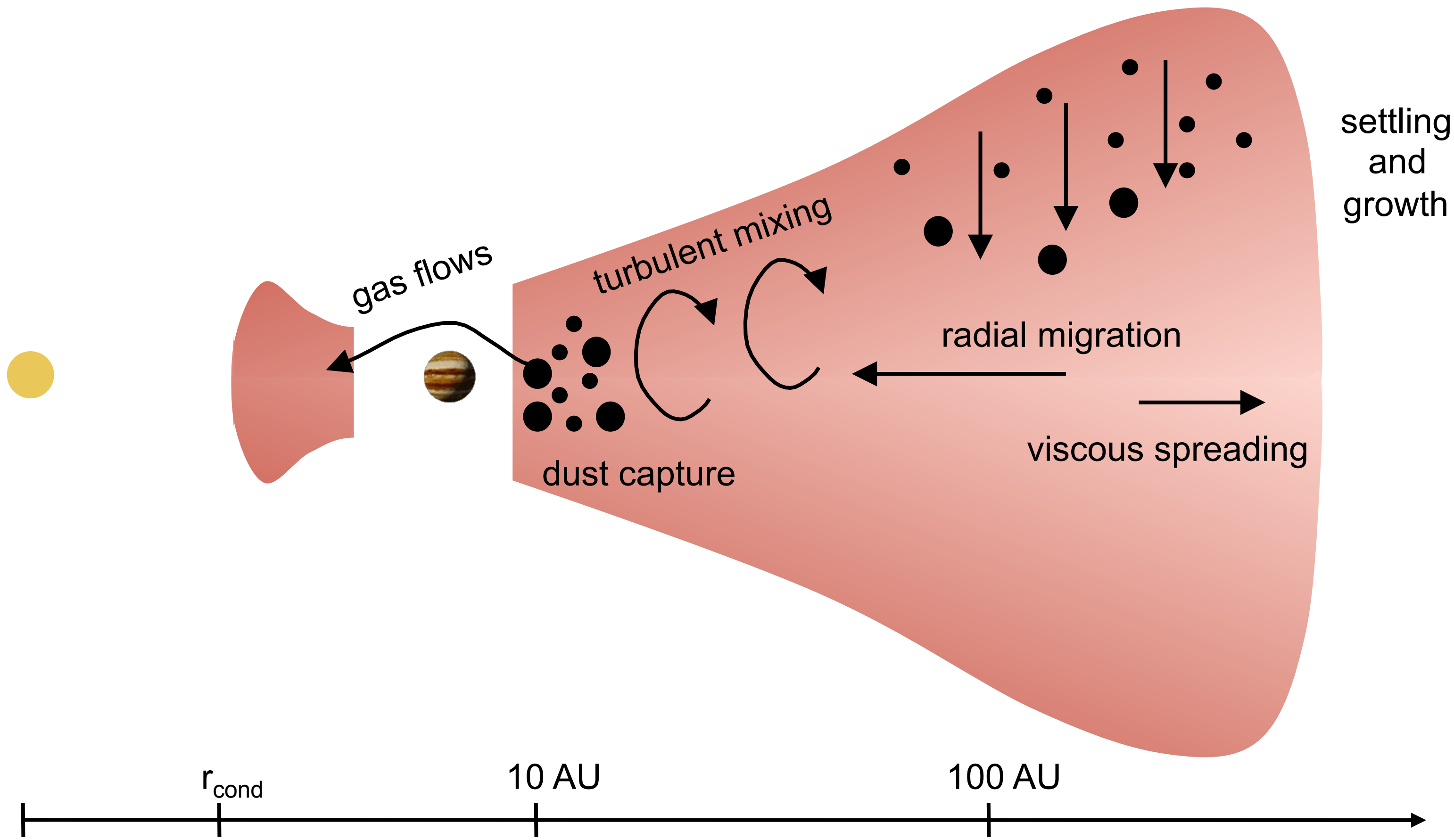
Disk evolution

Can we observe the disk evolution connected to planet formation?



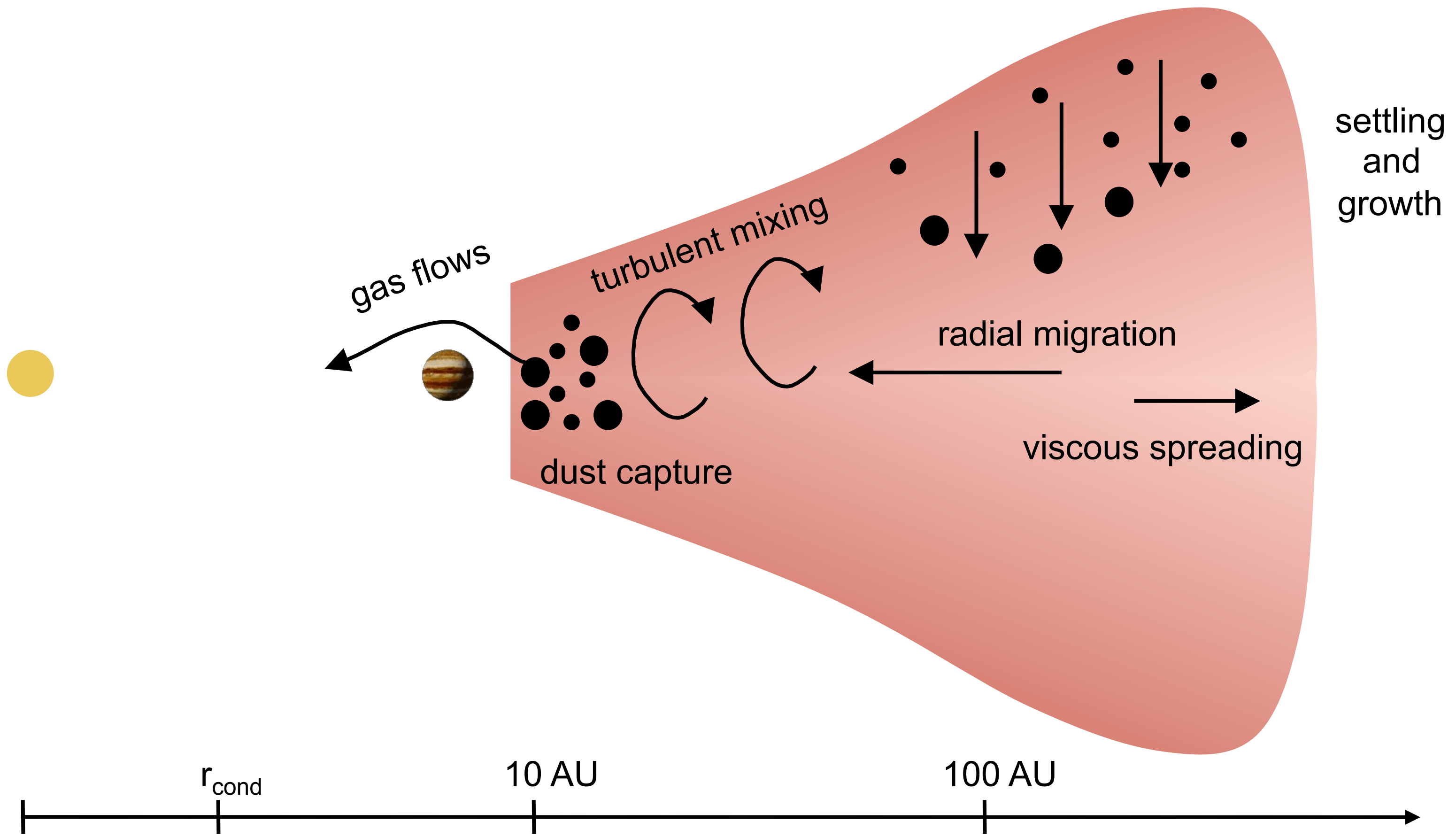
Disk evolution

Can we observe the disk evolution connected to planet formation?

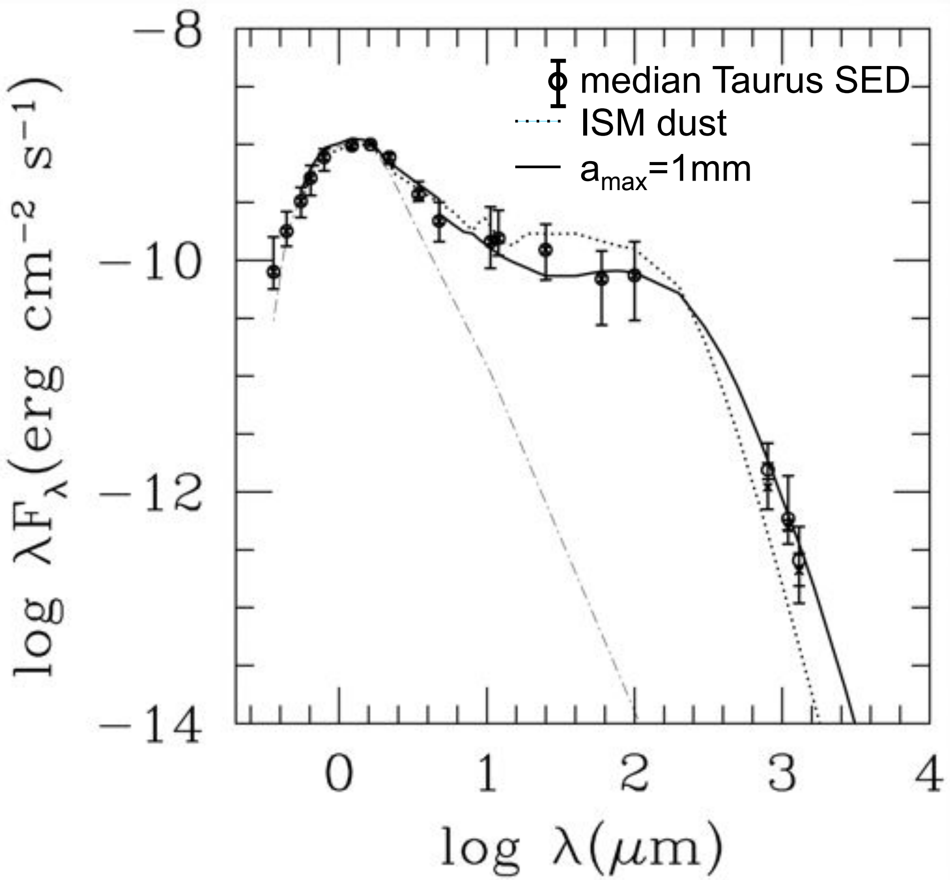


Disk evolution

Can we observe the disk evolution connected to planet formation?

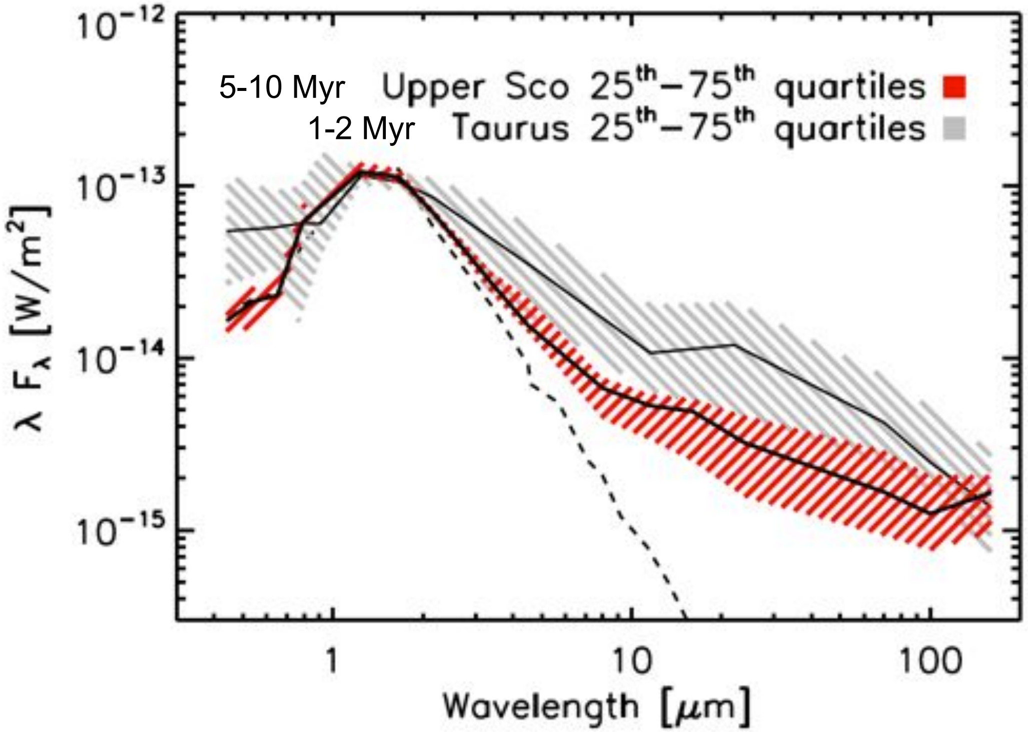


Dust grain growth



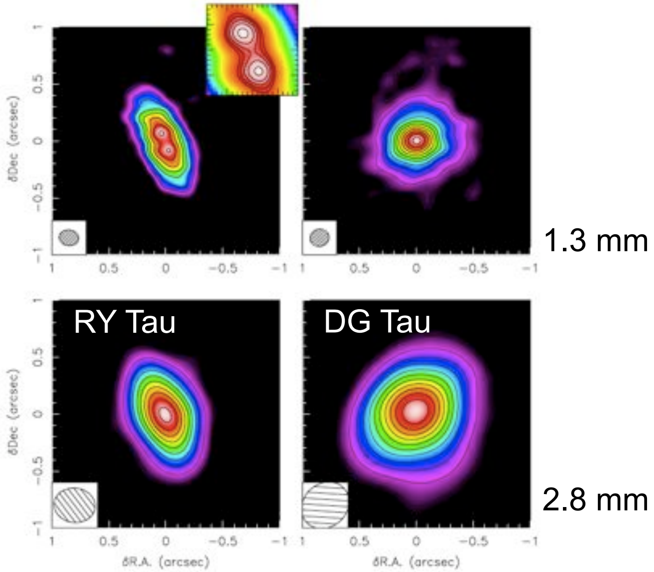
[D'Alessio, Calvet, Hartmann 2001]

new Herschel results from GASPS KP



[Howard et al. 2013, Matthews et al. 2013]

Dust grain growth

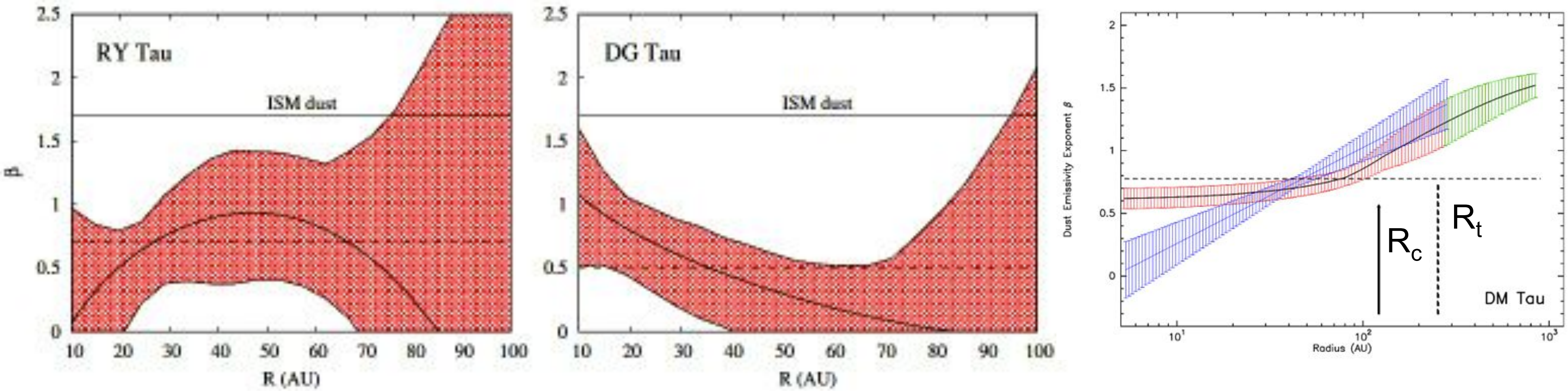


- dust largely different than ISM dust
- β inside R~50 AU smaller than in outer disk

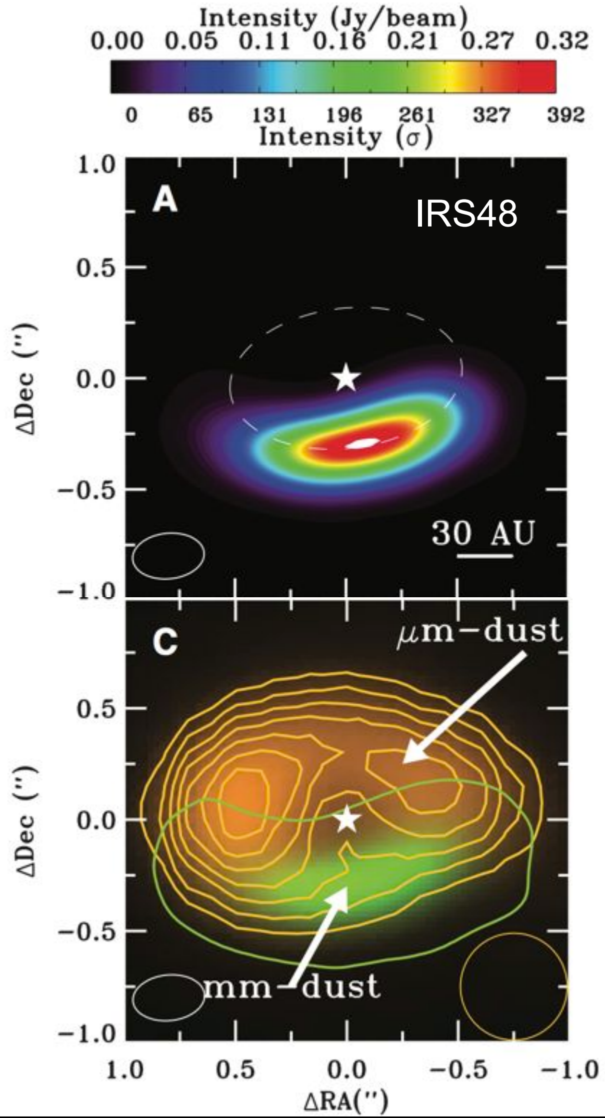
…but what does it mean? $\kappa_\nu(r) \sim (\nu/\nu_0)^{\beta(r)}$

=> grain growth timescales?
=> migration of large grains?

[Ricci et al. 2010, Isella et al. 2010, Guilloteau et al. 2011]



Dust grain growth … and trapping

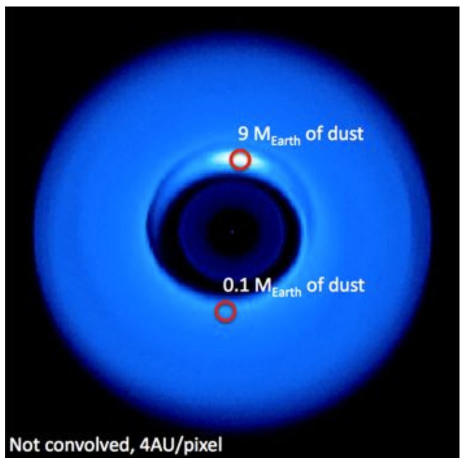


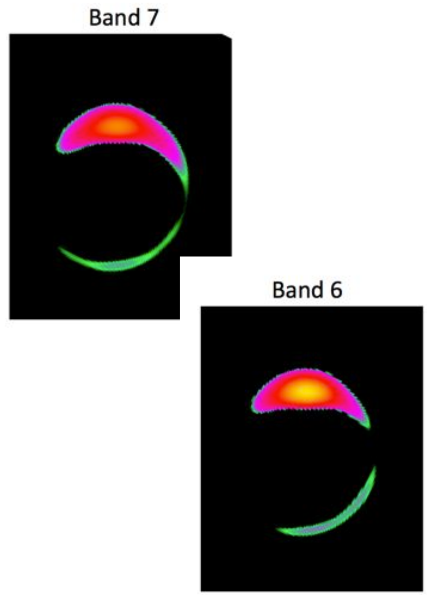
traps for mm-sized in disks:

- disk gas instabilities (Rossby Wave Instability)
- trapping of grains

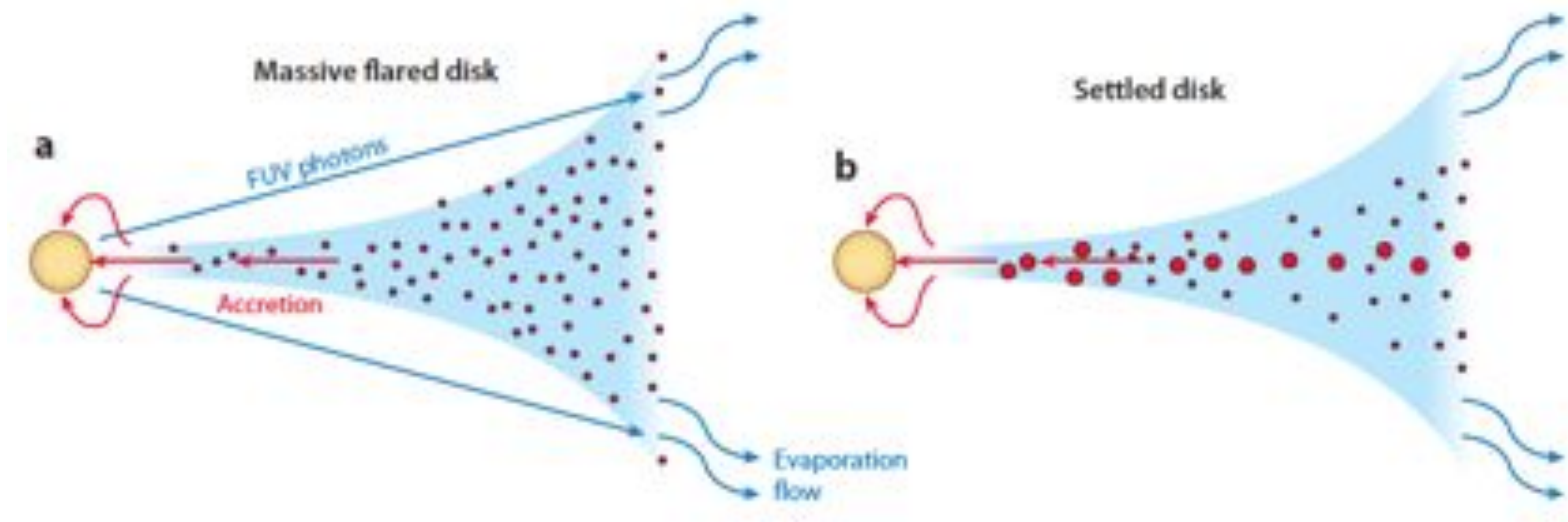
[Casassus et al. 2012, 2013, Pinilla et al. 2012, van der Marel et al. 2013, Menard in prep.]

Casassus et al. (2012, 2013)



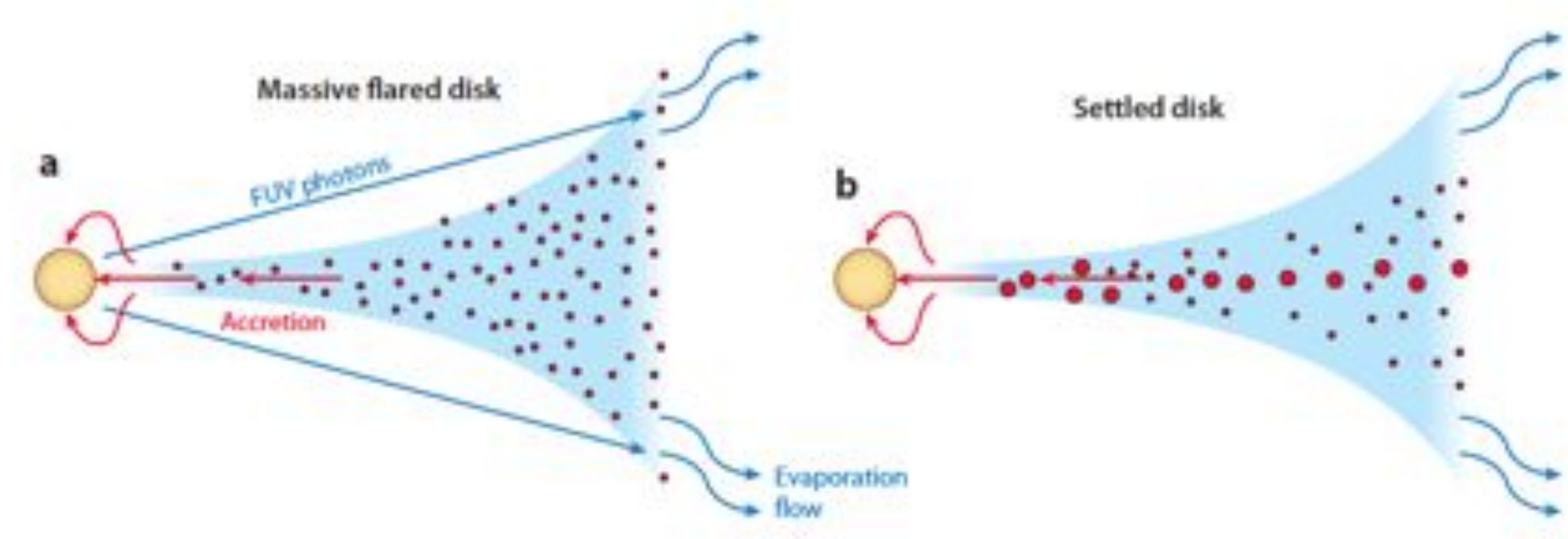


Dust settling



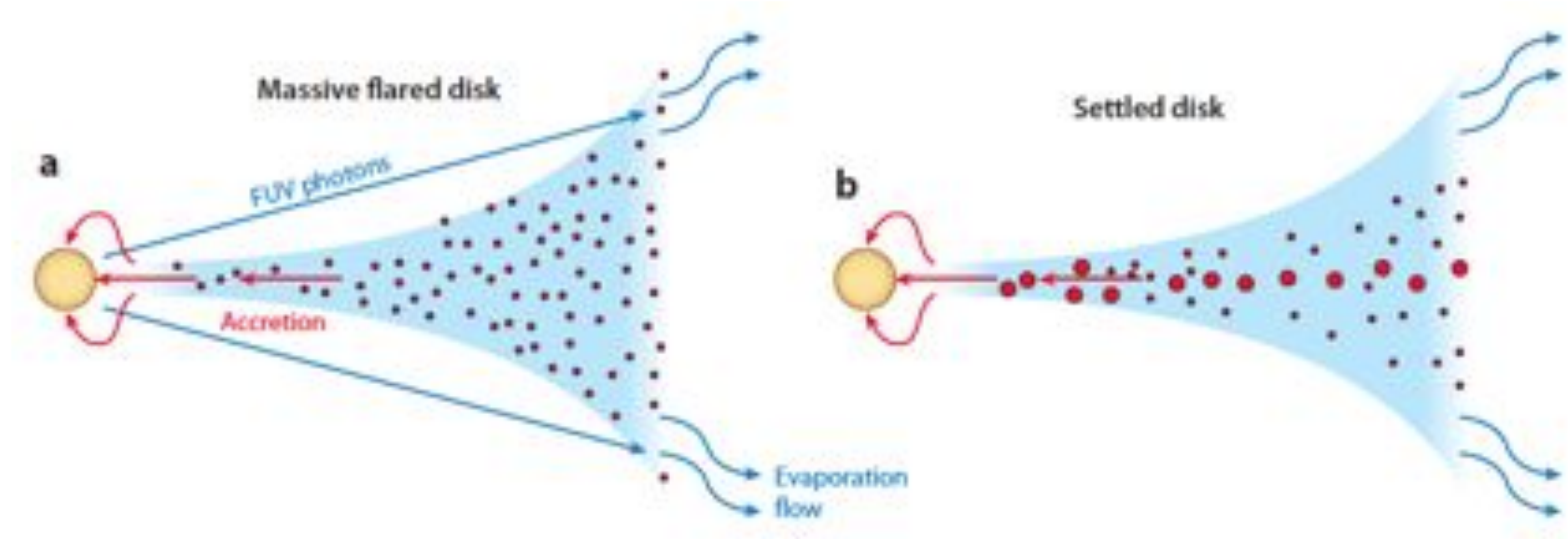
[Williams & Cieza 2011]

Dust settling



[Williams & Cieza 2011]

Dust settling



[Williams & Cieza 2011]

Dust settling

Indirectly:

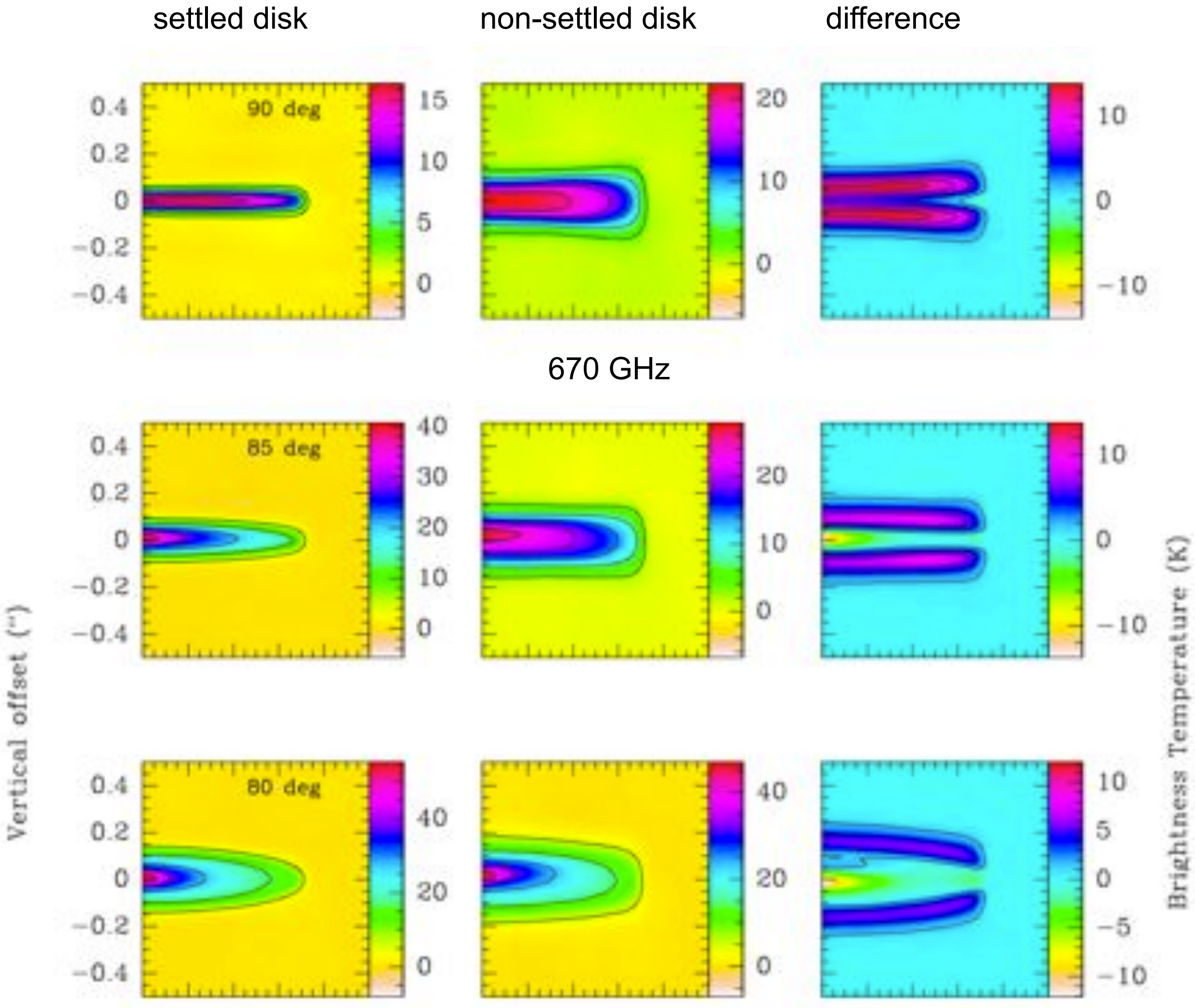
from the shape of SEDs in the 5-30 μm range

[e.g. Furlan et al. 2006]

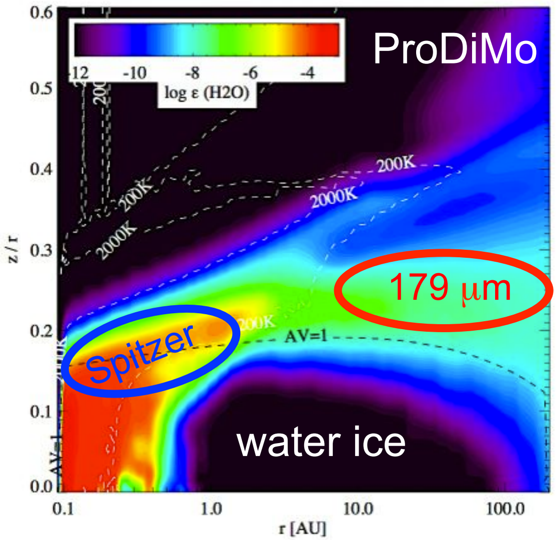
=> degeneracies?

eventually from imaging at longer wavelengths

[Sauter & Wolf 2011, Boehler et al. 2013]



Dust settling from gas lines…

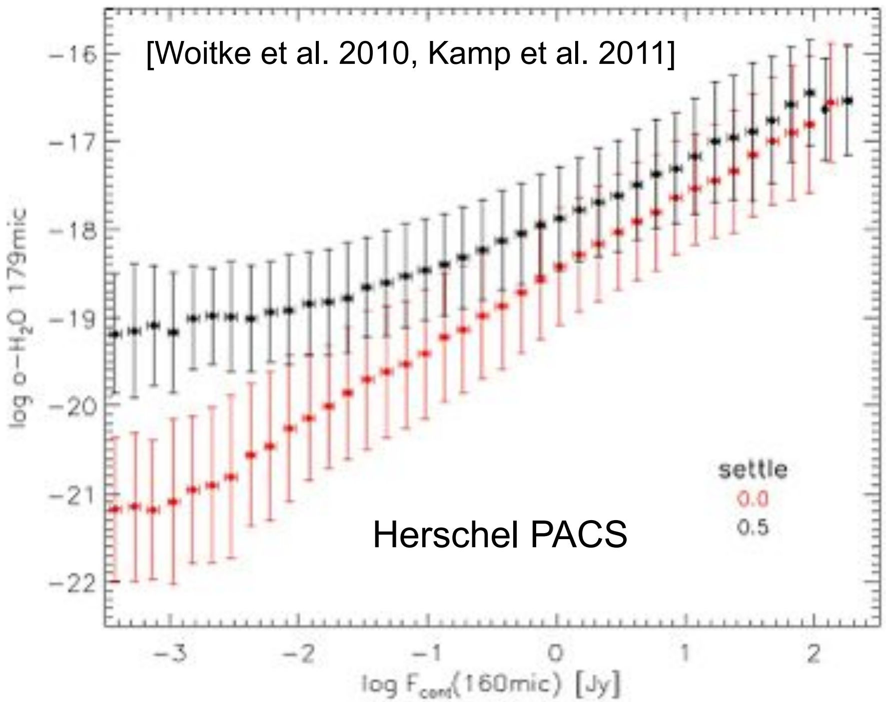


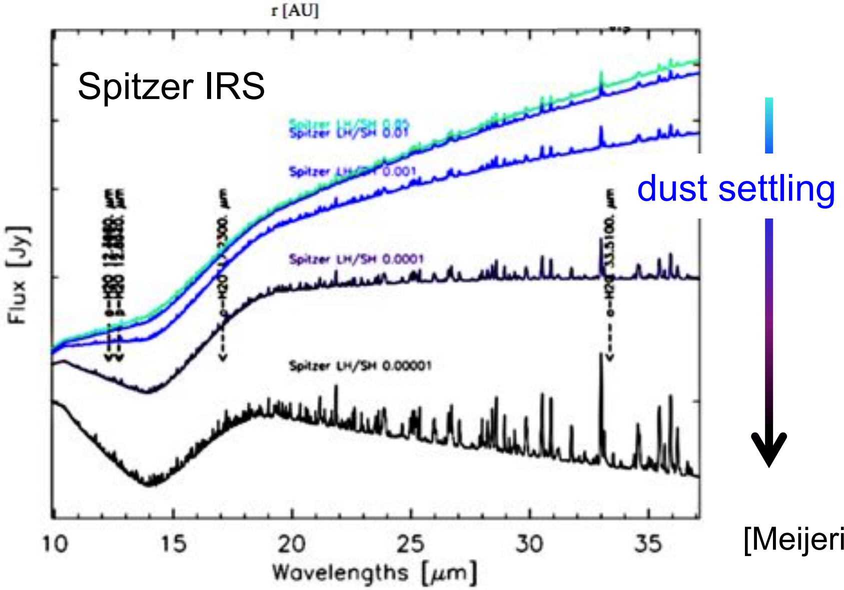
gas likely remains flaring in settled disks (co-spatial with small dust grains)

=> stronger water lines
but not unique !

DENT grid of 300000 disk models

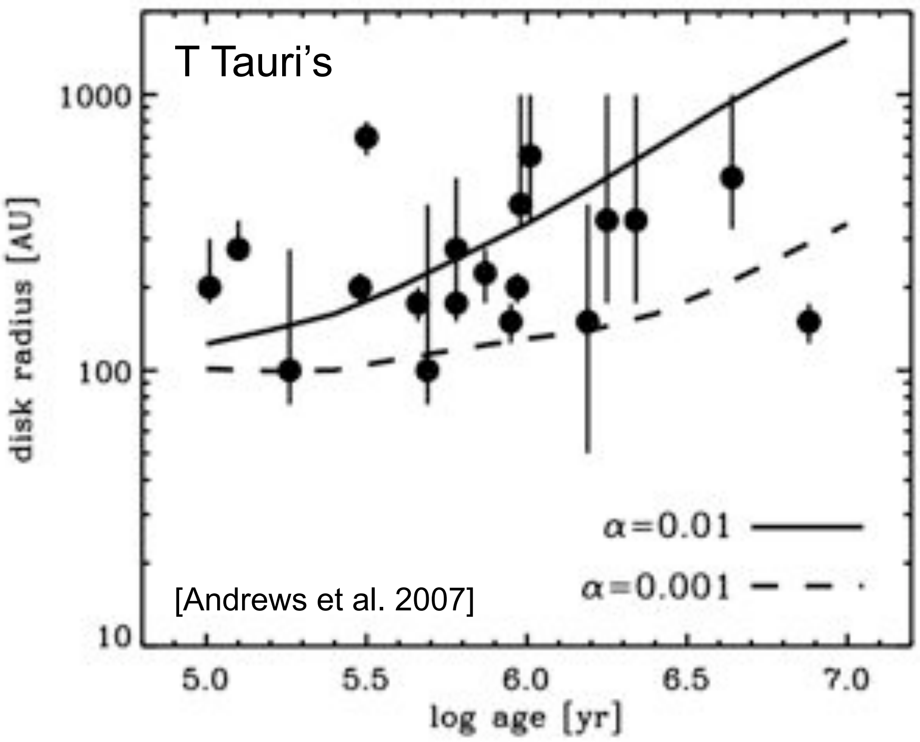
change in water chemistry in strongly settled disks

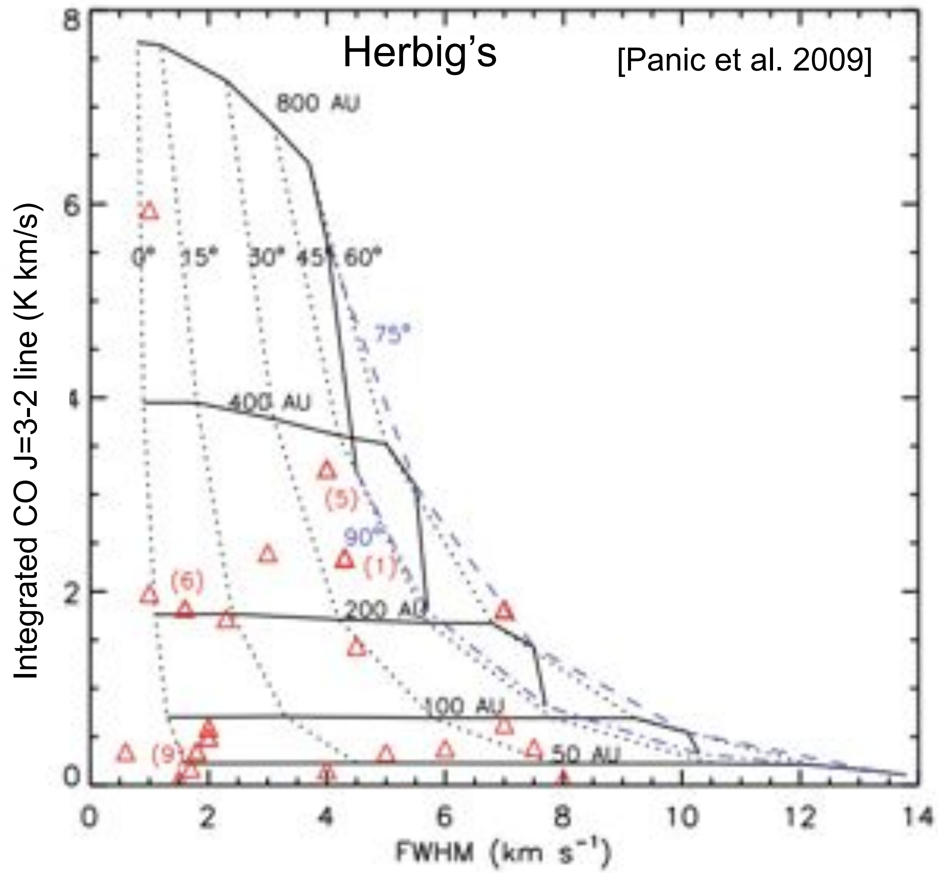




[Meijerink et al. 2009, Antonellini in prep]

Viscous radial spreading



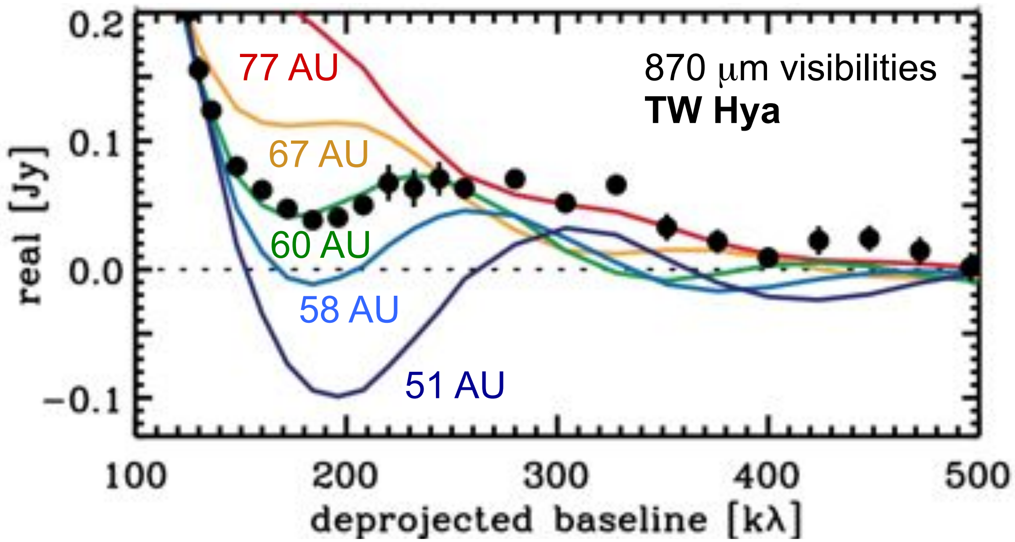


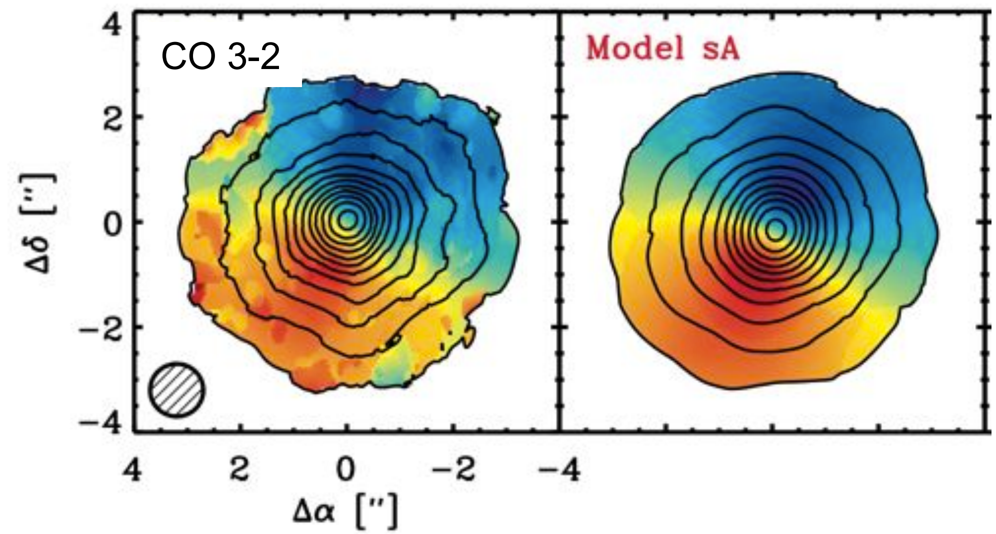
disk radii R_d impacted by sensitivity limit

gas and dust outer radii not necessarily the same, also different dust populations can have different outer radii

[Hughes et al. 2008, Qi et al. 2011, Andrews et al. 2012]

Dust radial migration





[Andrews et al. 2012]

sharp edge of mm dust grains at 60 AU

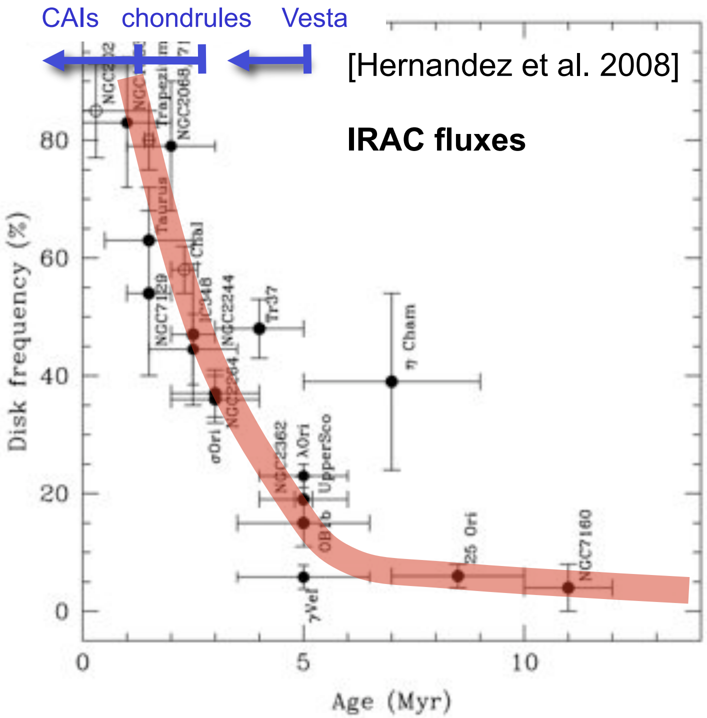
different dust populations could have different radial distribution

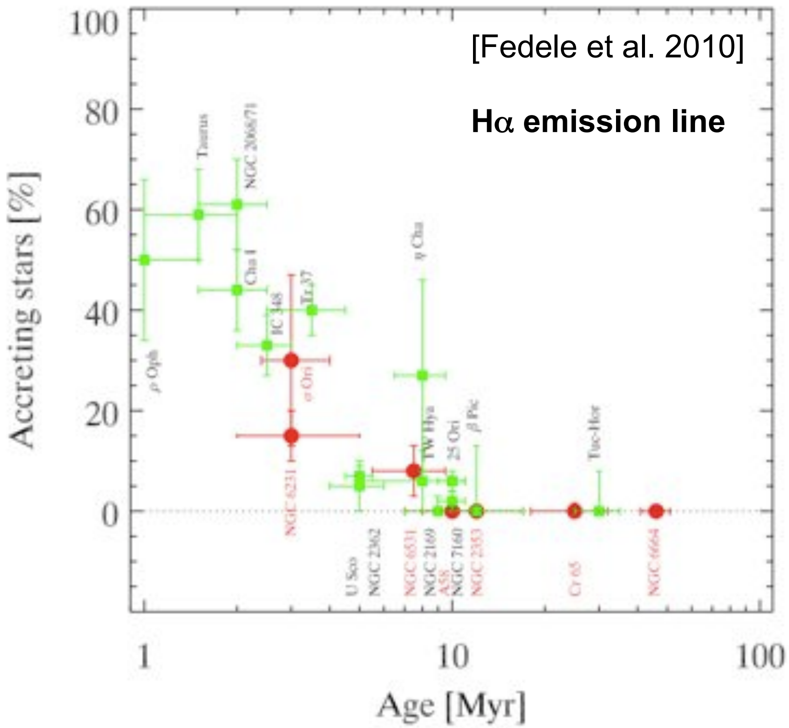
power law gas model extending to 215 AU

gas is radially more extended compared to mm dust grains

Dispersal of inner warm disk

~ 99% of initial mass in disks is gas, but it is notoriously difficult to assess
Gas evolution timescale impacts planet formation and dust dynamics/evolution

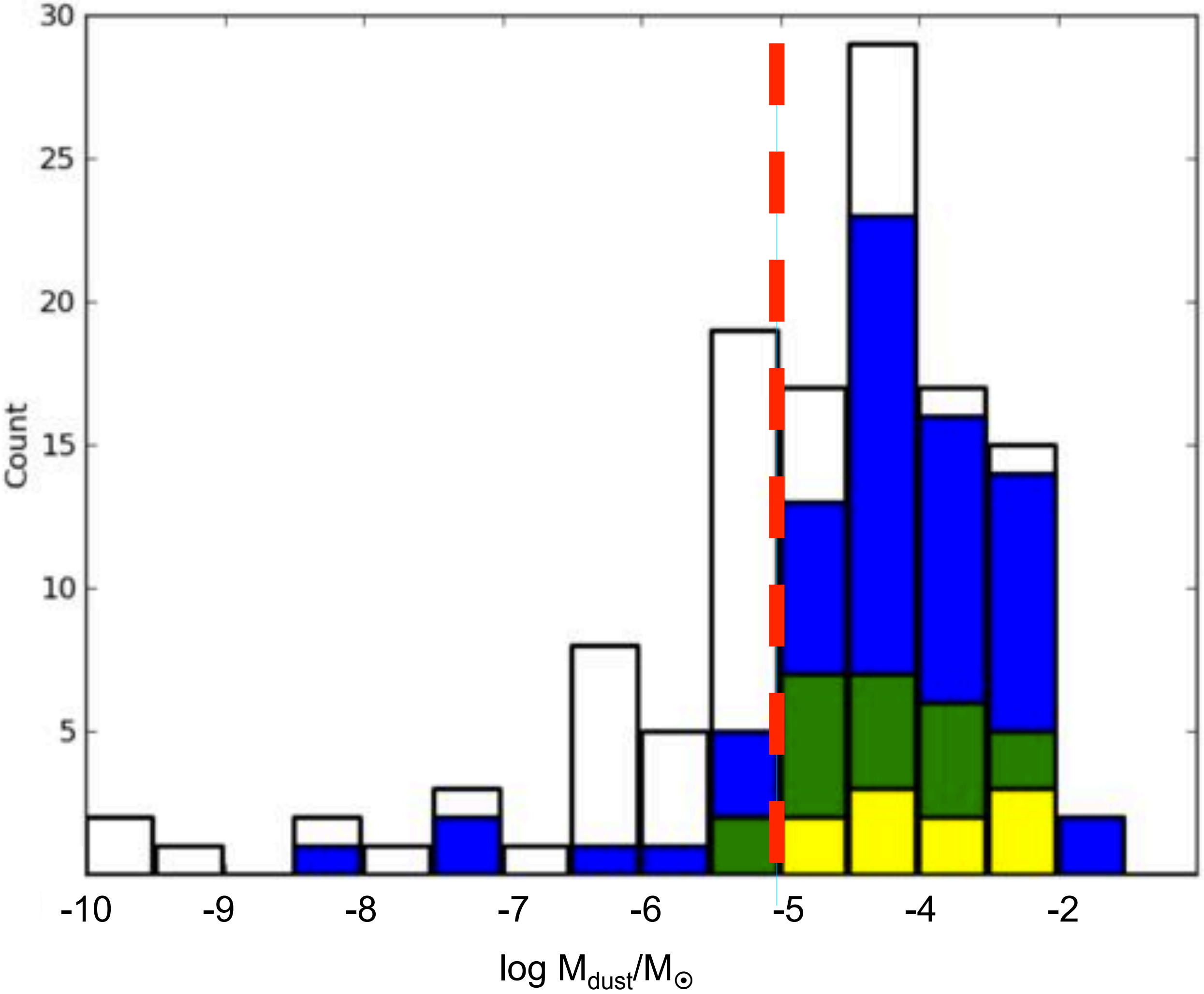




[e.g. Evans et al. 2003 - c2d, Meyer et al. 2008 - FEPS, Andrews & Williams 2007]

[e.g. Dent et al. 1995, Pascucci et al. 2009, Schaefer et al. 2009, Dent et al. 2013 - GASPS]

Gas dispersal



GASPS KP (PI: Dent)

~250 targets in Taurus, Cha II,
η Cha, TW Hya, Upp Sco,
β Pic, Tuc Hor associations

[OI]63 μm brightest line
detected in 100% of HAeBe's
43% of T Tauris

above dust mass $M_{dust}=10^{-5}\ M_{\odot}$
85% of disks detected in [OI]

at very low M_{dust} few unusual objects

[Dent et al. 2013]

Gas dispersal

Detailed multi-wavelengths disk modeling of 10 targets (GASPS team)

MCFOST, ProDiMo [Pinte et al. 2006, 2009, Woitke et al. 2009, Kamp et al. 2010]

target	type	gas-to-dust	reference
HD169142	Herbig	20-50	Meeus et al. (2010)
HD100546	Herbig (inner gap)	4-8	Thi et al. (2011)
HD163296	Herbig	~100	Tilling et al. (2012)
HD135344	Herbig (inner gap)	35 (outer)	Carmona et al. submitted
HD141569	Herbig (inner gap)	95-230	Thi et al. (2014)
T Tau N	T Tauri class I/II	~100	Podio et al. (2014)
DG Tau	T Tauri class II	~100	Podio et al. (2013)
FT Tau	T Tauri class II	20-50	Garufi et al. submitted
TW Hya	T Tauri class II	~100-2.6 (inner/outer)	Thi et al. (2010), Kamp et al. (2013)
ET Cha	T Tauri (R_{out}~5 AU)	>>100	Woitke et al. (2011)

Is there something like a canonical gas-to-dust mass ratio of 100?

Gas dispersal

Detailed multi-wavelengths disk modeling of 10 targets (GASPS team)

MCFOST, ProDiMo [Pinte et al. 2006, 2009, Woitke et al. 2009, Kamp et al. 2010]

target	type	gas-to-dust	reference
HD169142	Herbig	20-50	Meeus et al. (2010)
HD100546	Herbig (inner gap)	4-8	Thi et al. (2011)
HD163296	Herbig	~100	Tilling et al. (2012)
HD135344	Herbig (inner gap)	35 (outer)	Carmona et al. submitted
HD141569	Herbig (inner gap)	95-230	Thi et al. (2014)
T Tau N	T Tauri class I/II	~100	Podio et al. (2014)
DG Tau	T Tauri class II	~100	Podio et al. (2013)
FT Tau	T Tauri class II	20-50	Garufi et al. submitted
TW Hya	T Tauri class II	~100-2.6 (inner/outer)	Thi et al. (2010), Kamp et al. (2013)
ET Cha	T Tauri (R_{out}~5 AU)	>>100	Woitke et al. (2011)

How does the gas-to-dust mass ratio change radially?

DiscAnalysis DIANA

Open questions

- Do all disks start equal?
- How does the gas-to-dust ratio change radially in a disk and with time?
- Does disk evolution depend on the initial state and/or on stellar properties?
- What causes the wide spread in disk properties at any given age?
- How far into the planet formation process are class II disks?
- How is the spread in disk properties linked to the variety in planetary systems observed?

Open questions

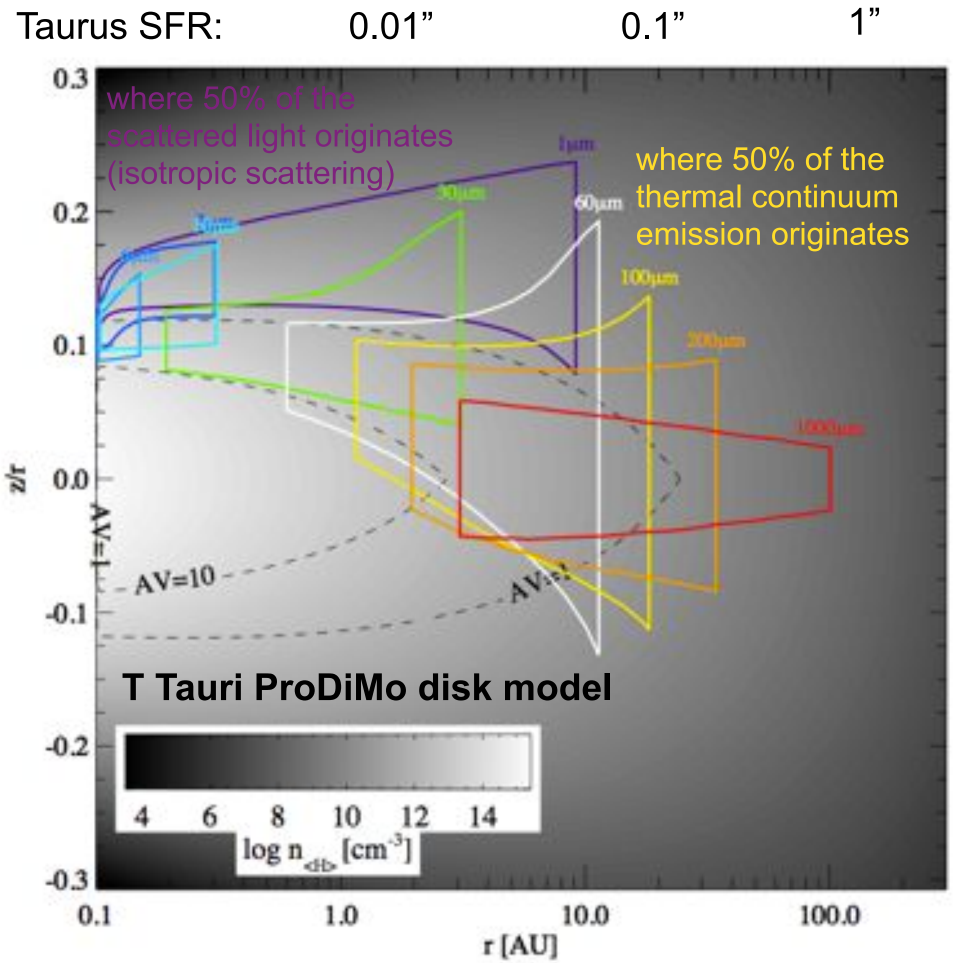
- Do all disks start equal?
- How does the gas-to-dust ratio change radially in a disk and with time?
- Does disk evolution depend on the initial state and/or on stellar properties?
- What causes the wide spread in disk properties at any given age?
- How far into the planet formation process are class II disks?
- How is the spread in disk properties linked to the variety in planetary systems observed?

Disks are smaller than a few arcsec at distances of the nearest SRFs

=> SPICA, JWST/MIRI will not resolve them
=> ELT, ALMA resolve them at optical/near-IR and submm wavelengths

Far-IR sub-arcsec Space Interferometry

spatially resolved spectra, no image reconstruction, R~few 1000, λ>30 μm



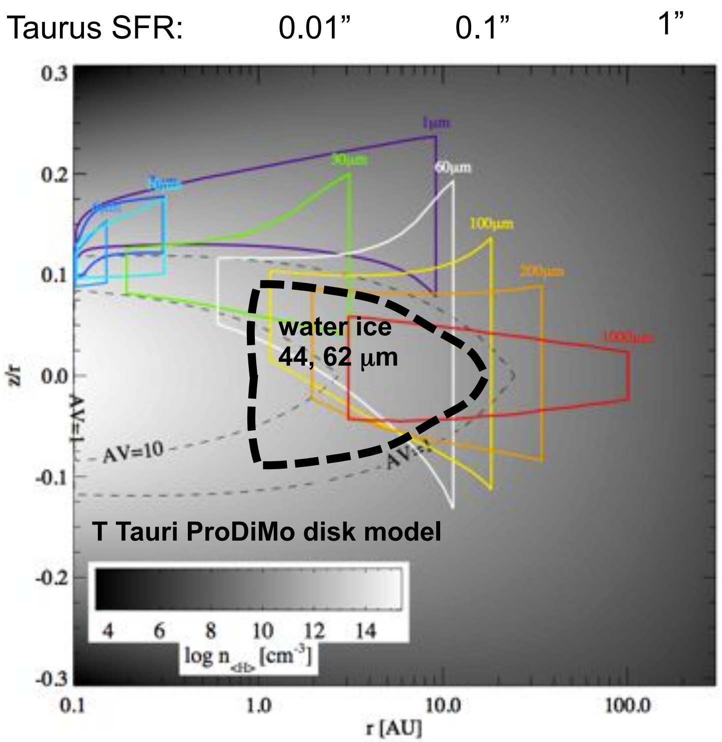
example of unique gas lines which cannot be done from the ground:

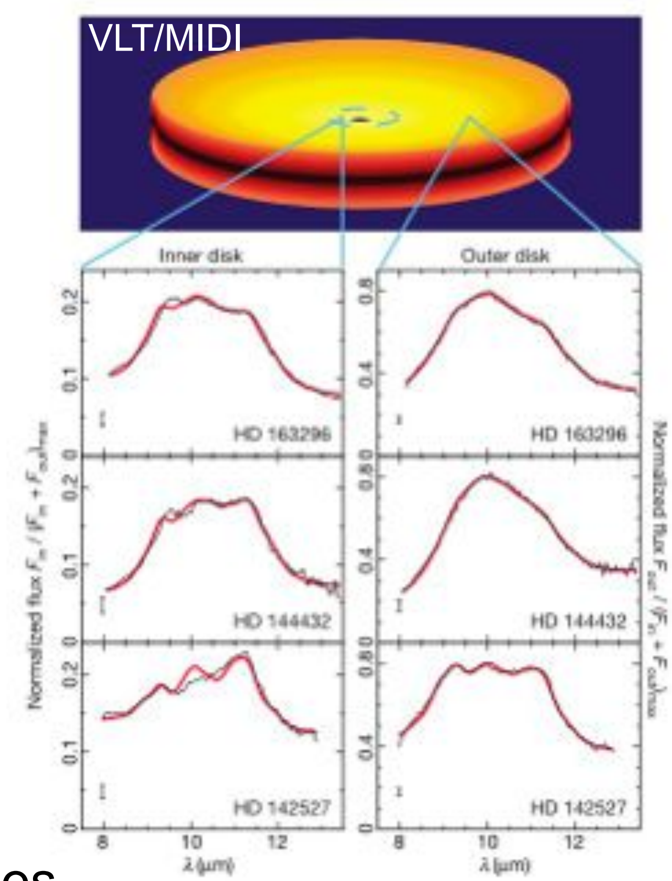
HD – gas mass tracer (56,112 μm)
H_2O – planet formation (many lines)
[OI] – strongest gas cooling lines (63,145 μm)

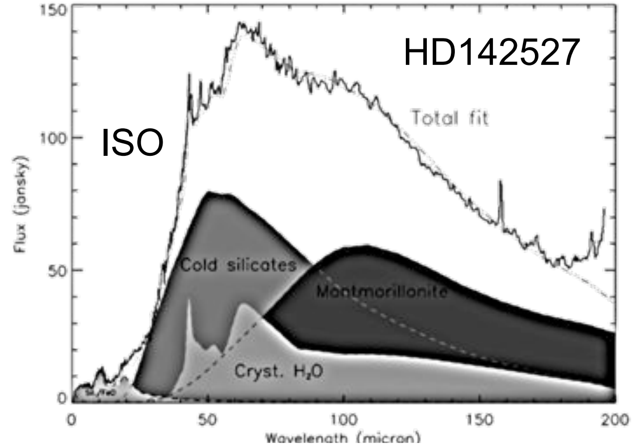
disentangle disks and winds/outflows

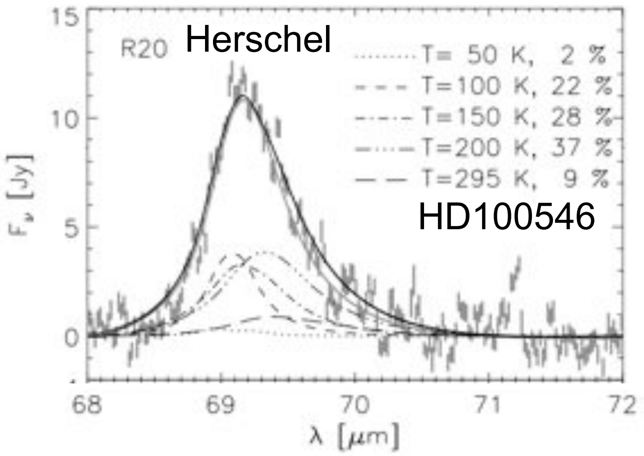
Far-IR sub-arcsec Space Interferometry

spatially resolved spectra, no image reconstruction, R~few 1000, λ>30 μm







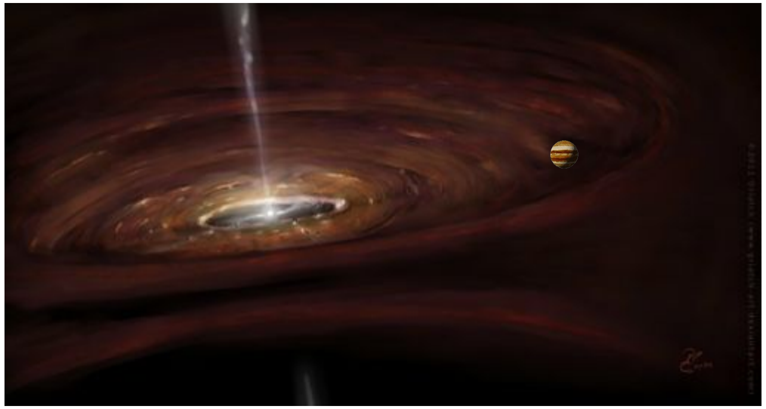


=> how do gas/ice/dust properties
change across the disk

[van Boekel et al. 2004, Malfait et al. 1999, Mulders et al. 2011]

Far-IR sub-arcsec Space Interferometry

image reconstruction, R~few, λ>30 μm

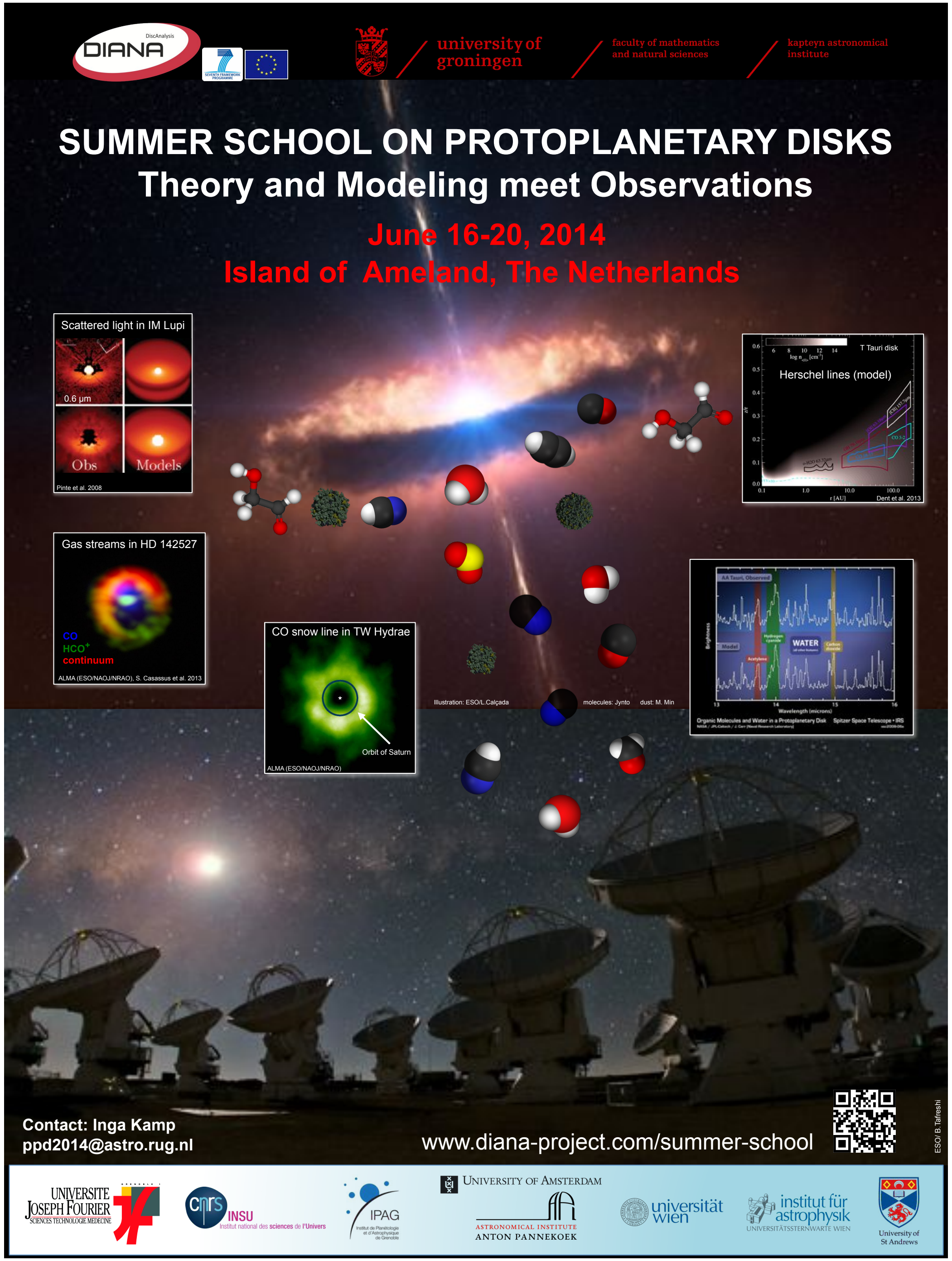


Perturbations from massive planets: spirals, instabilities

traces different dust population compared to ALMA (mm dust) and the ELT (micron sized dust)

Direct detection of warm gas giants accreting from their birth environment:

warm planetary accretion disks



Lectures on:

Disk formation, structure, and evolution
Dust and gas opacities
Radiative transfer and non-LTE
Heating/cooling processes
Disk chemistry (UV, X-rays, CRs, ices …)
Disk observations: dust and gas
Interferometry (mid-IR – ALMA)
Modeling and interpretation: SEDs, images,
gas lines, interferometry