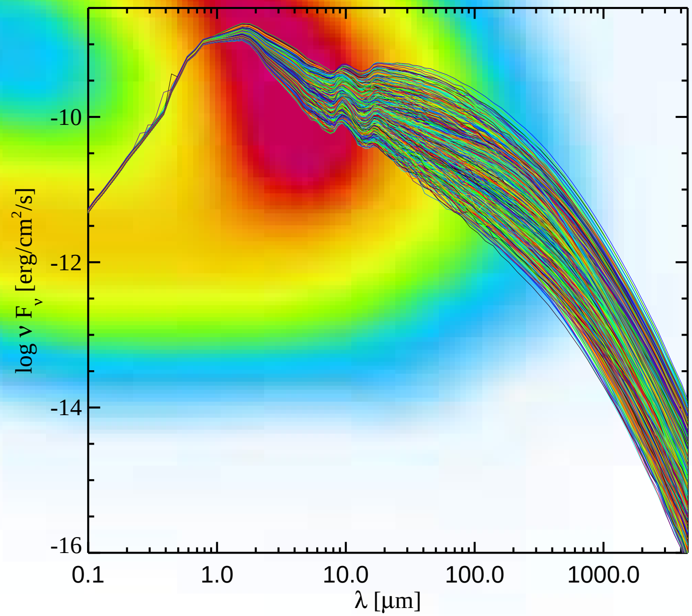
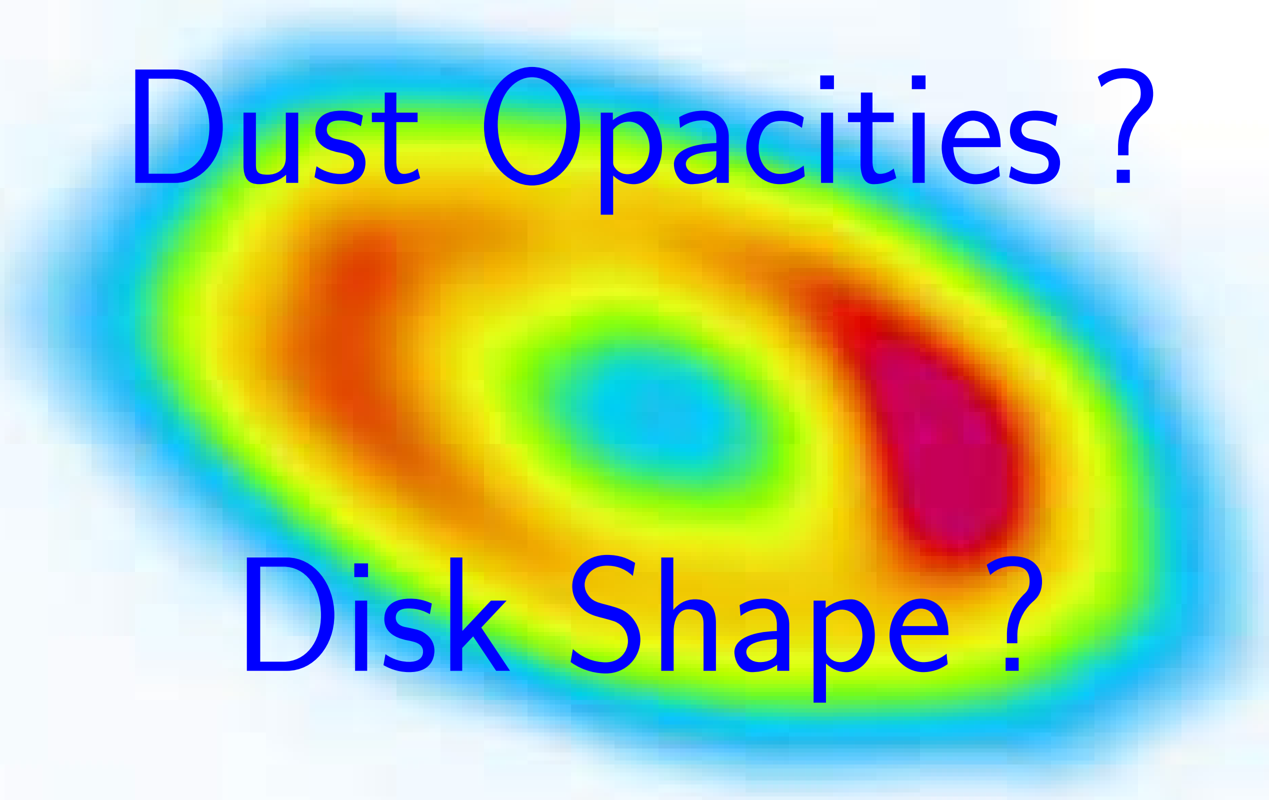
What determines the SED mm-slope of protoplanetary discs?

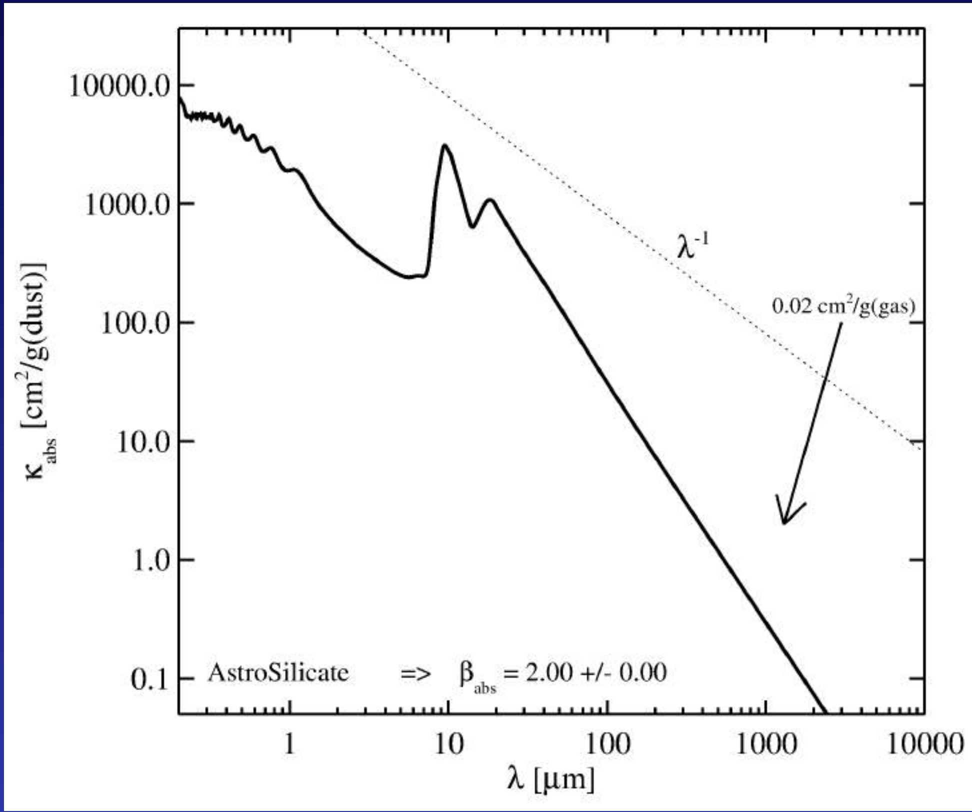
Peter Woitke & Michiel Min

St. Andrews University (UK)   University of Amsterdam (NL)




Dust Opacities ?
Disk Shape ?

1. Dust Opacities

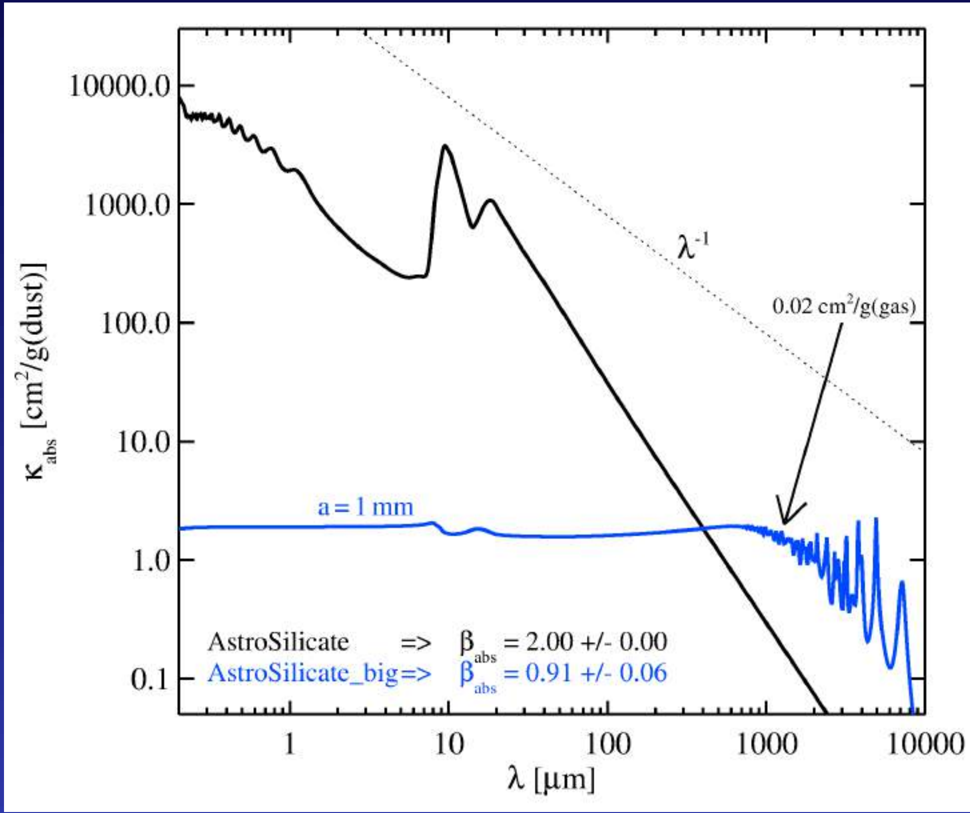


AstroSilicate: mono-sized ($a = 0.3\,\mu$m), perfect spheres, Mie-theory astronomical silicate (Draine & Lee 1984)

$$\beta_{\rm abs} = -\frac{d\log\kappa_{\rm abs}}{d\log\lambda}$$

(here measured between $\lambda = 850\,\mu$m and 3.5 mm)

1. Dust Opacities



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$$\beta_{\rm abs} = -\frac{d\log\kappa_{\rm abs}}{d\log\lambda}$$

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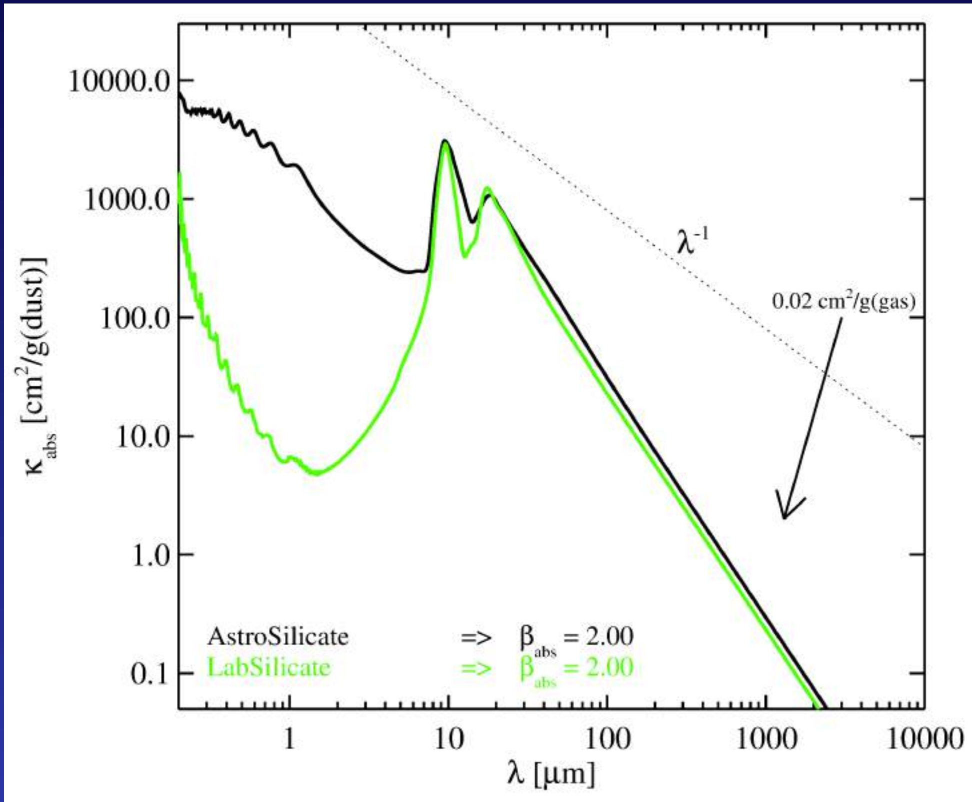
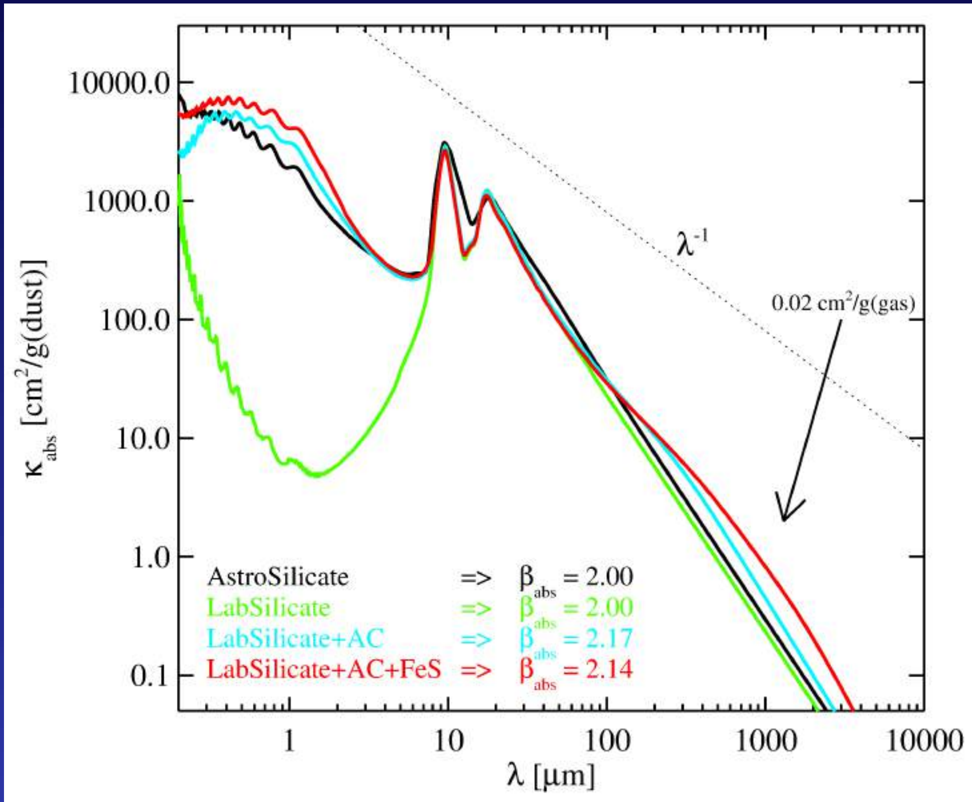
Laboratory Silicate, AC, and FeS



all:	mono-sized ($a = 0.3\,\mu$m), perfect spheres, Mie-theory
AstroSilicate:	astronomical silicate (Draine & Lee 1984)
LabSilicate:	60% Mg_2SiO_4 + 40% $MgSiO_3$, Jena-database, Bruggeman (1935) mixing
+AC:	add 5% amorphous carbon (Jaeger et al. 1998 – cel800)
+FeS:	add 5% troilite (http://www.mpia-hd.mpg.de/homes/henning/Dust_opacities/Opacities/RI/new_ri.html)

Laboratory Silicate, AC, and FeS



all: mono-sized ($a = 0.3\,\mu$m), perfect spheres, Mie-theory

AstroSilicate: astronomical silicate (Draine & Lee 1984)

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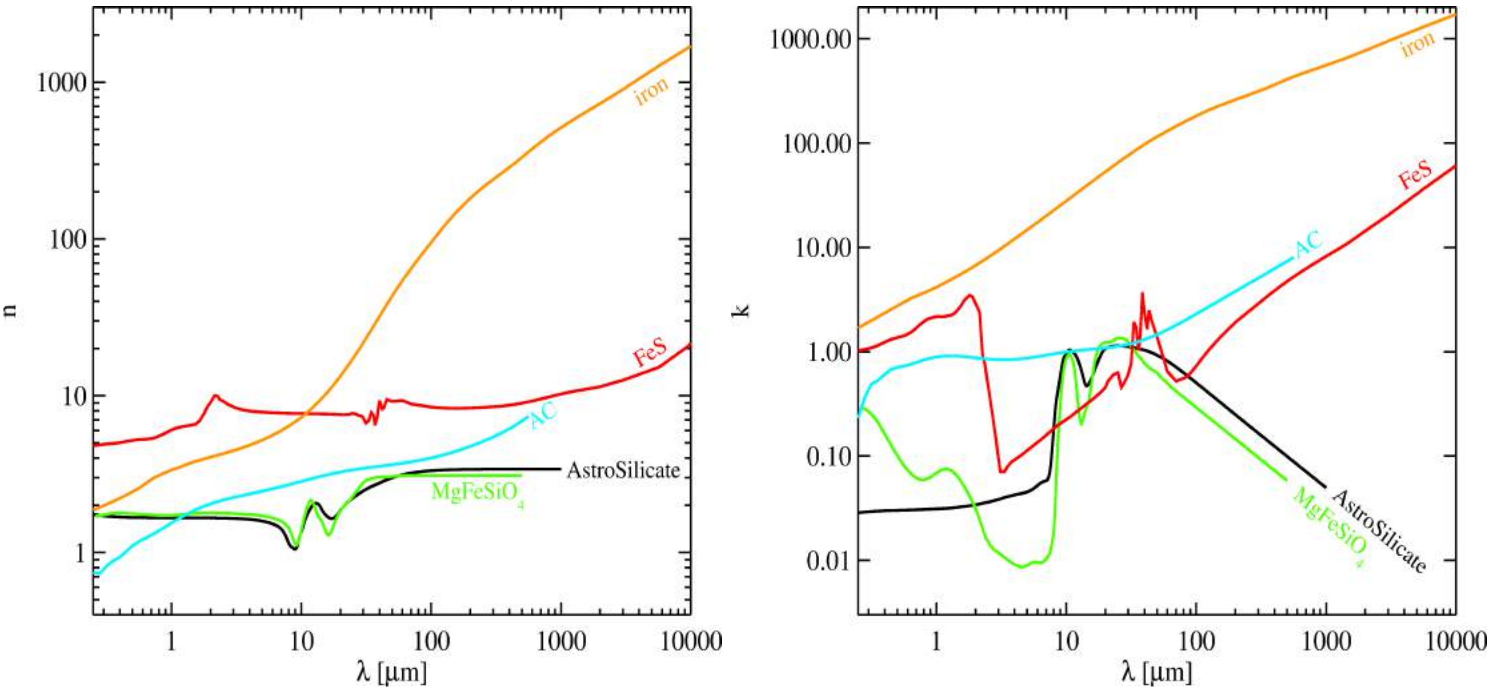
The Effect of Conducting Impurities

real part of refractory index n complex part k



iron: metallic iron (http://www.mpia-hd.mpg.de/homes/henning/Dust_opacities/Opacities/RI/new_ri.html)

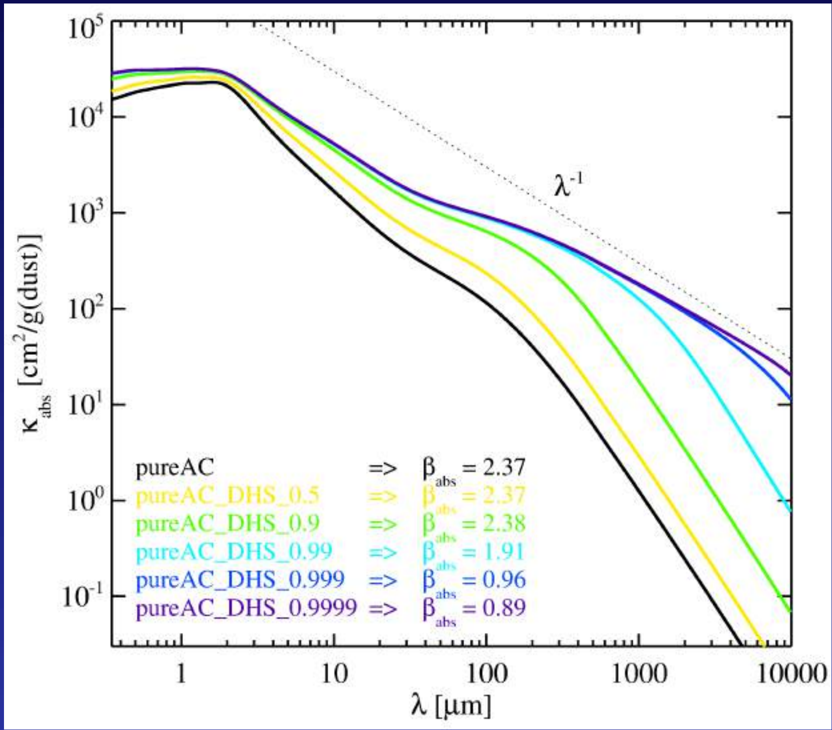
FeS: troilite (http://www.mpia-hd.mpg.de/homes/henning/Dust_opacities/Opacities/RI/new_ri.html)

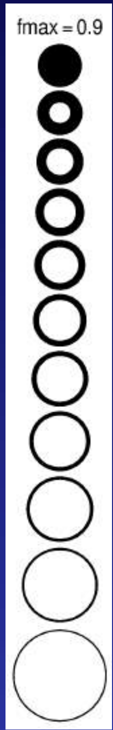
AC: amorphous carbon (Jaeger et al. 1998 – cel800)

AstroSilicate: astronomical silicate (Draine & Lee 1984)

$MgFeSiO_4$: amorphous olivine (Dorschner et al. 1995)

Shape Irregularities and DHS





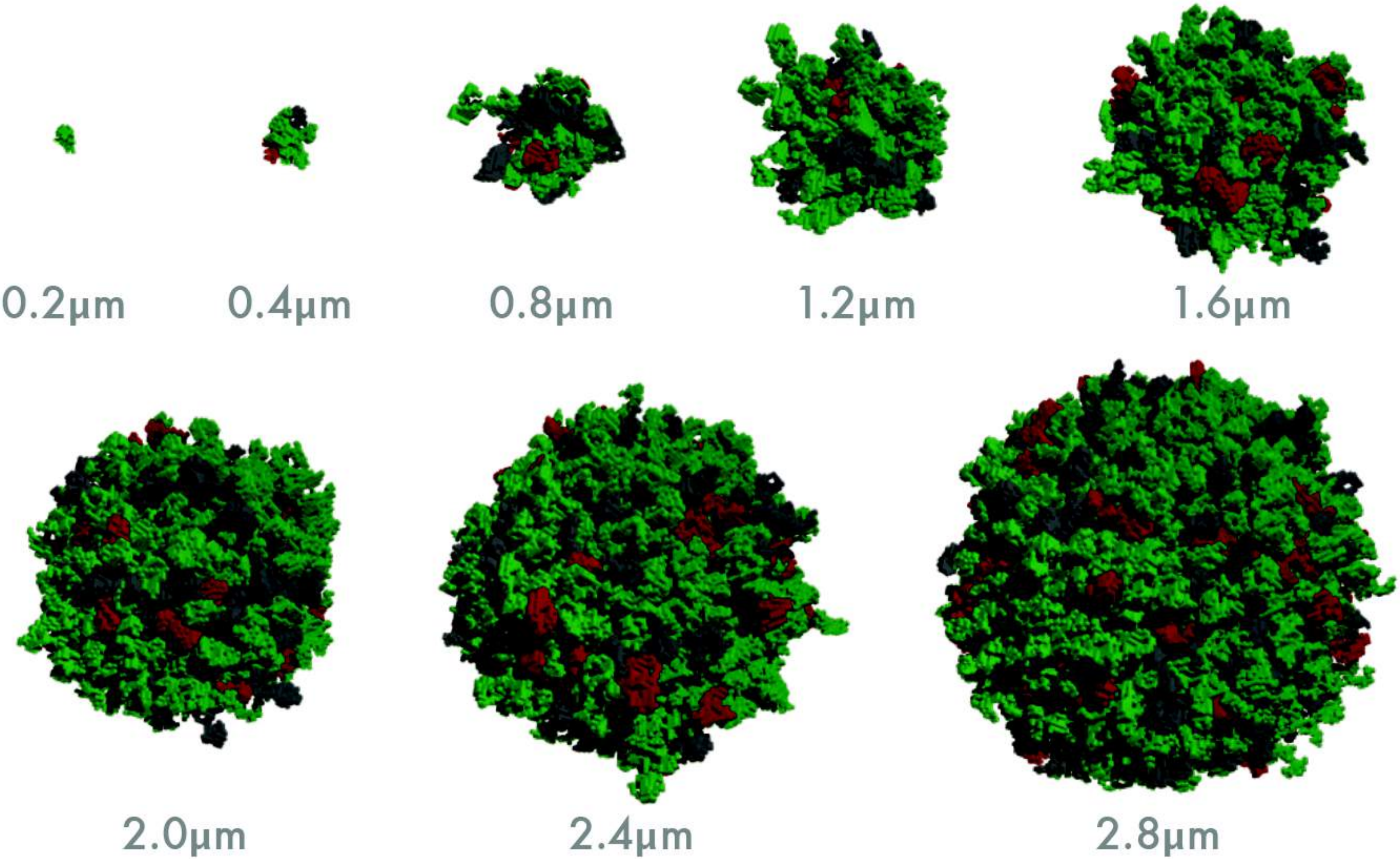
pureAC: $a = 0.3\,\mu$m, amorphous carbon (Jaeger et al. 1998 – cel800)

DHS: distribution of hollow spheres (Min et al. 2005),

e.g. **0.9**: maximum hollow sphere volume ratio $f_{\rm max} = V_{\rm core}/V$

- hollow sphere's radius and shell thickness provide two different spatial scales to model shape irregularities ("antennas", "iron needles", etc.)
- these are sub-μm particles! Also applies to impurities in big grains!

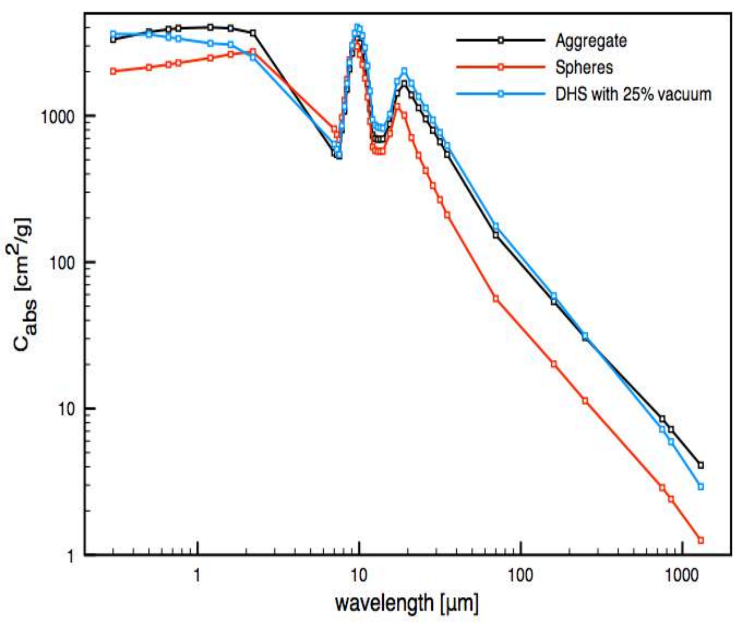
Irregular Particles (Aggregates)



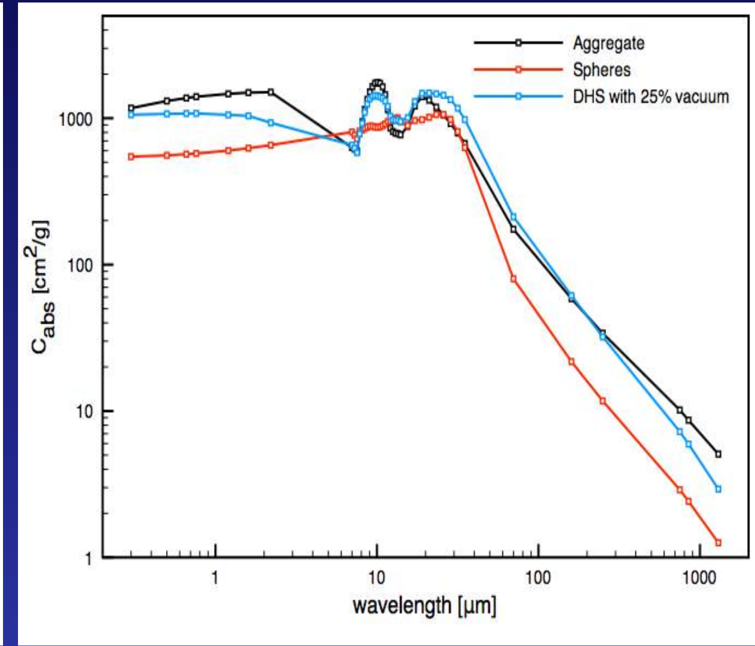
M. Min et al. (2013, in prep.)

Aggregate Particles (DDA)

a = 1.2 μm



a = 4 μm



Aggregate (DDA): composite, irregular particles (discrete dipole approximation) 75% $MgSiO_3$, 10% FeS, 15% AC

Spheres: same Bruggeman (1935)-mix, Mie theory

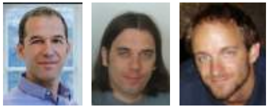
DHS: same mix, but with 25% porosity & DHS

Min et al. (2013, in prep.): check simple methods against detailed DDA computations recommend opacity standards for multi-λ disk models

DiscAnalysis DIANA

FP7-SPACE 2011 collaboration

Analysis and Modelling of Multi-wavelength Observational Data from Protoplanetary Discs

St Andrews	Vienna	Amsterdam	Grenoble	Groningen
				
P. Woitke	*M. Güdel*	*R. Waters*	*F. Ménard*	*I. Kamp*
				
Greaves Ilee Rigon	*Dionatos Rab Liebhart*	*Min Dominik*	*Thi Pinte Carmona Anthonioz*	*Antonellini*
sub-mm to cm	**X-rays**	**near-mid IR**	**near-far IR**	**near IR - mm**
coordination JCMT, eMERLIN astrobiology	obs./mod. XMM, Herschel high energy	mod./obs. VLT, JWST dust mod.	obs./mod. HST, Herschel interferometry	mod./obs. Herschel, JWST gas mod.

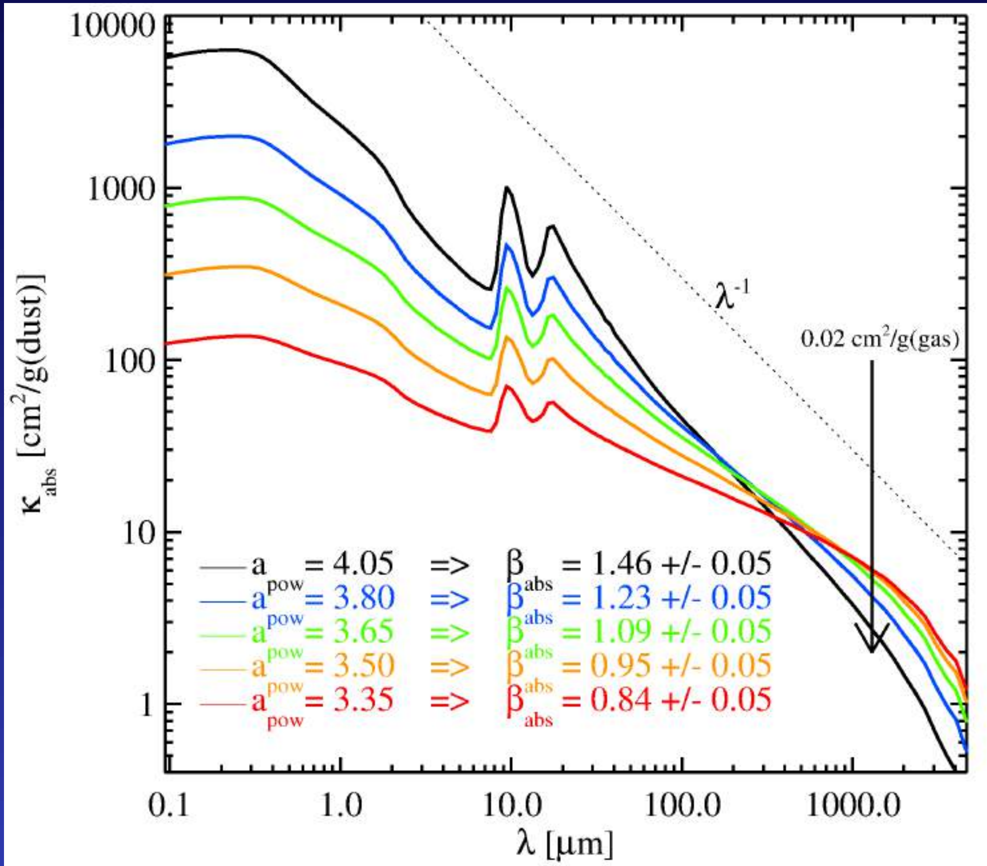
multi-λ data collection X-ray to cm (archival and proprietary)

coherent, detailed modelling of gas & dust throughout the disc

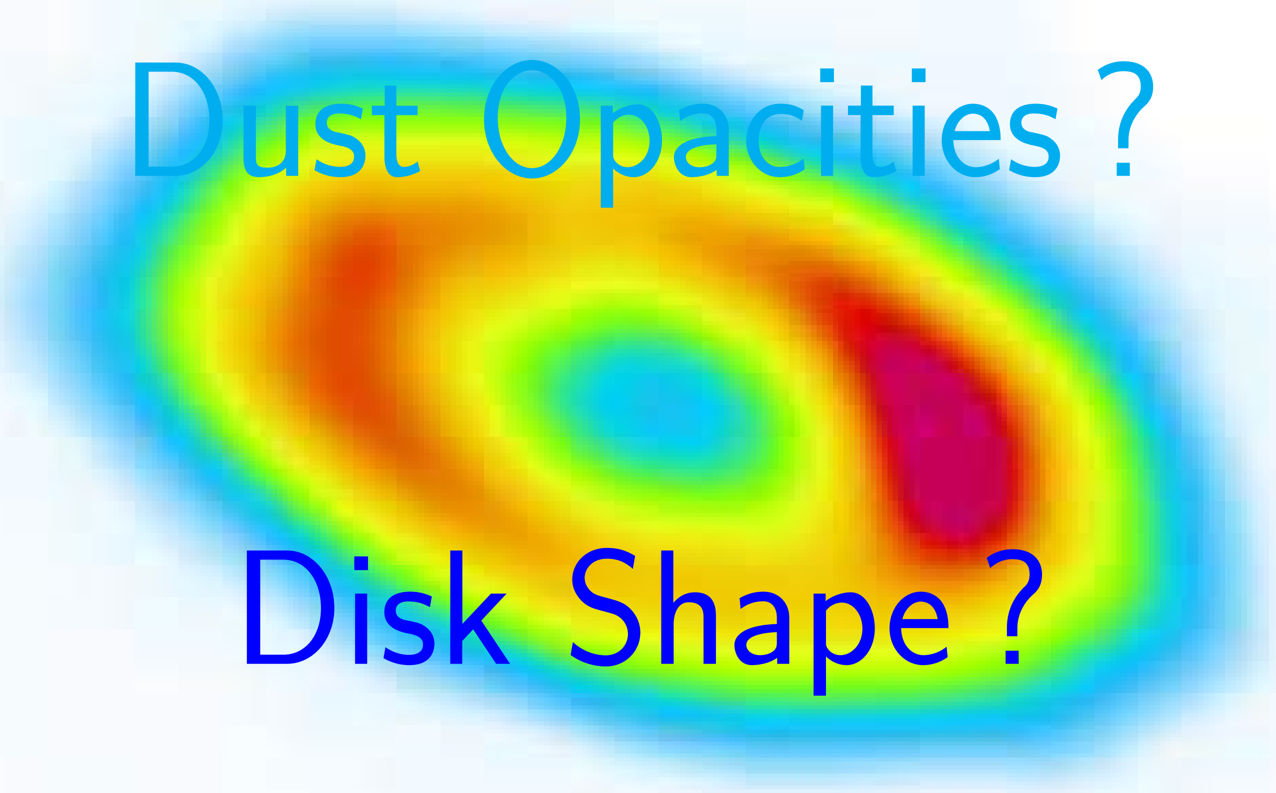
using disk modelling software ProDiMo, MCMax, MCFOST

aim: disc shape, temperatures, dust properties, chemistry in the birth-places of exoplanets

size distribution and mm-slope



- size distribution $f(a) \propto a^{-a_{pow}}$ from $a_{\rm min} = 0.05\,\mu$m to $a_{\rm max} = 1$ mm,
- 50% $MgFeSiO_4$ + 30% $Mg_{0.5}Fe_{0.5}SiO_3$ + 10% AC + 10% FeS
- no porosity, no DHS, no irregularities


Dust Opacities ?
Disk Shape ?

Parameters of the betaGRID

stellar parameter

fixed: T Tauri (K7), $T_{\rm eff} = 4000\,$K, $L_\star = 1\,L_\odot$, $M_\star = 0.7\,M_\odot$, $L_{\rm UV}/L_\star = 0.01$, $L_X = 10^{30}\,L_\odot$

disk shape parameter

1.	$M_{\rm dust}$	disk mass $[M_\odot]$	0.001, 0.003, 0.01, 0.03, 0.1
2.	$R_{\rm out}$	outer disk radius $[AU]$	100, 200, 400
3.	ϵ	column density power index using $\Sigma(r) \propto r^{-\epsilon} \exp\big(-r/R_{\rm tap}\big)$	0.5, 0.75, 1.0, 1.25, 1.5
4.	H_0	scale height [AU] at $R_0 = 3\,$AU	0.1, 0.14, 0.2, 0.28, 0.4
5.	β	flaring power $H(r) = H_0\big(\frac{r}{R_0}\big)^\beta$	1.04, 1.08, 1.12, 1.16, 1.2

fixed: gas/dust $= 100$, $R_{\rm in} = 0.07\,$AU, $R_{\rm tap} = R_{\rm out}/4$

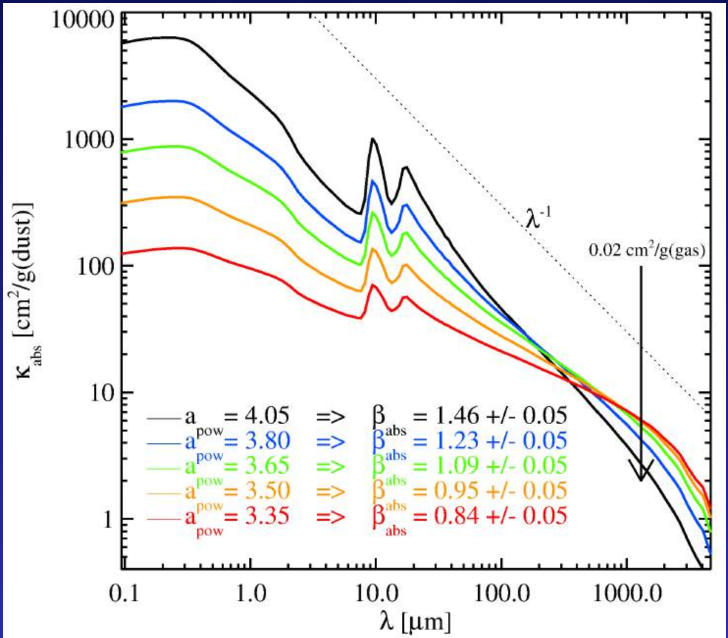
dust parameter

6.	$a_{\rm pow}$	size power index $f(a) \propto a^{-a_{\rm pow}}$	3.35, 3.5, 3.65, 3.8, 4.05
7.	α	turbulent mixing for settling	10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}

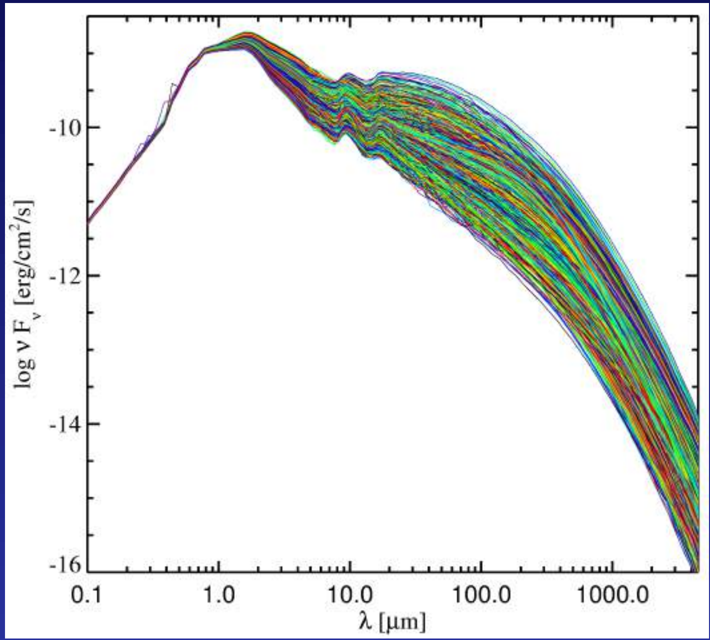
fixed: $a_{\rm min} = 0.05\,\mu$m, $a_{\rm max} = 1\,$mm, Dubrulle(1995)-settling (45% $MgFeSiO_4$, 35% $Mg_{0.5}Fe_{0.5}SiO_3$, 15% AC, 5% FeS)

- 1000 disk models, $T_{\rm dust}(r,z)$ & SEDs computed with MCMax (Min et al. 2009)
- $T_{\rm gas}(r,z)$, chemistry & emission lines computed with ProDiMo (Woitke et al. 2009)

2. Does the opacity-slope determine the SED mm-slope ?



? $\Leftrightarrow$



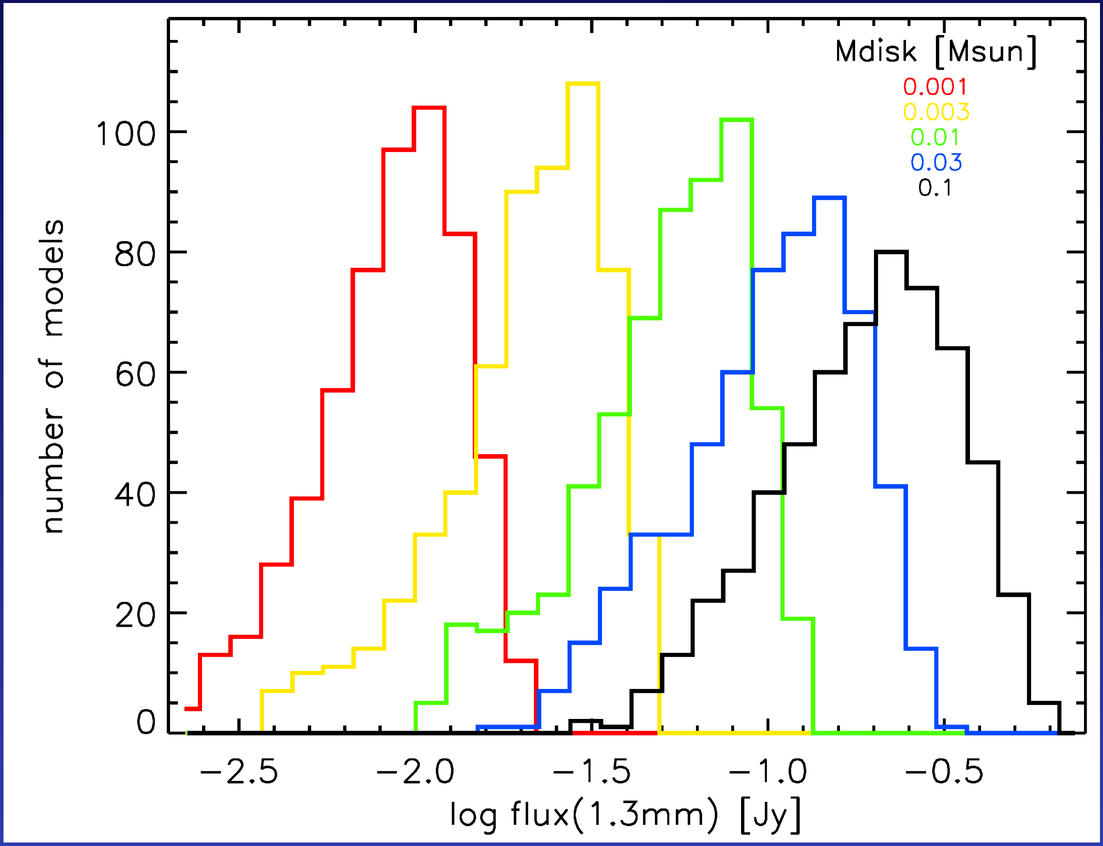
Beckwith et al. (1990): $\alpha_{\rm SED} = 2 + \frac{\beta_{\rm abs}}{1+\Delta}$

with $\Delta = \Delta(M_{\rm disk}, p, q, R_{\rm in}, R_{\rm out})$ being a correction for optical depths effects,

analytically derived from $\Sigma(r) \propto r^{-p}$, $T_{\rm dust}(r) \propto r^{-q}$, $\kappa_{\rm abs}(\lambda) \propto \lambda^{-\beta_{\rm abs}}$

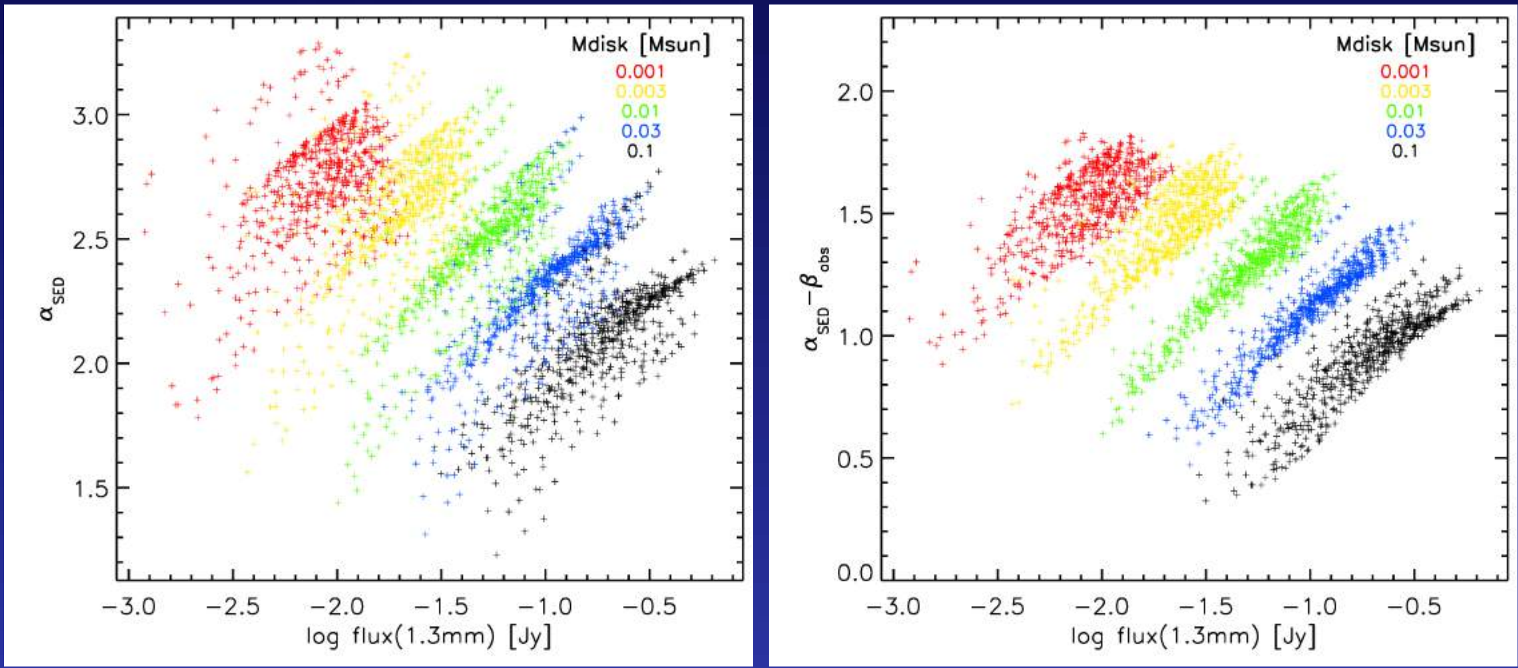
$\rightarrow$ *Is this valid ?*

Dust Mass Determination via $F_\nu(1.3\,\mathrm{mm})$



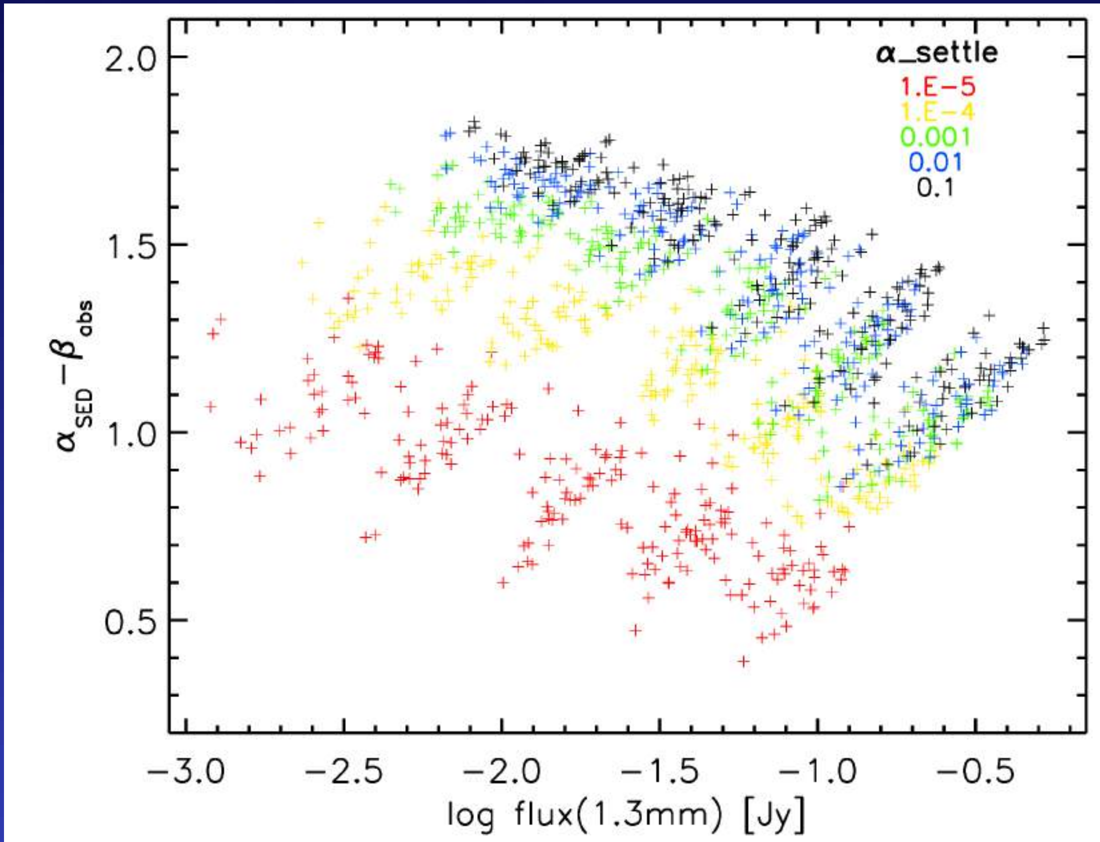
- **optical depths effects** limit flux-increase for $M_{\rm disk} \gtrsim 0.01\,M_\odot$, as expected
- **FWHM** of single-$M_{\rm disk}$ flux-distribution is about 0.6 dex (!)

An Improved Dust Mass Determination Method?



- the **SED-slope** $\alpha_{\rm SED}$ can help to disentangle $M_{\rm disk} = M_{\rm disk}(F_{1.3\,\rm mm})$
- if the **opacity slope** $\beta_{\rm abs}$ is known, the correlation becomes very tight $M_{\rm disk} = M_{\rm disk}(F_{1.3\,\rm mm}\,,\ \alpha_{\rm SED} - \beta_{\rm abs})$

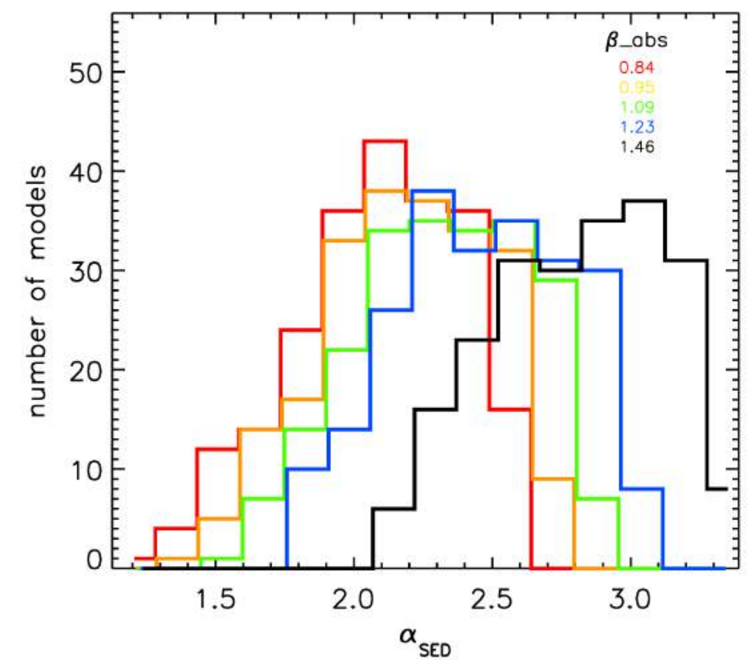
Why still 1 order of mag diversity?



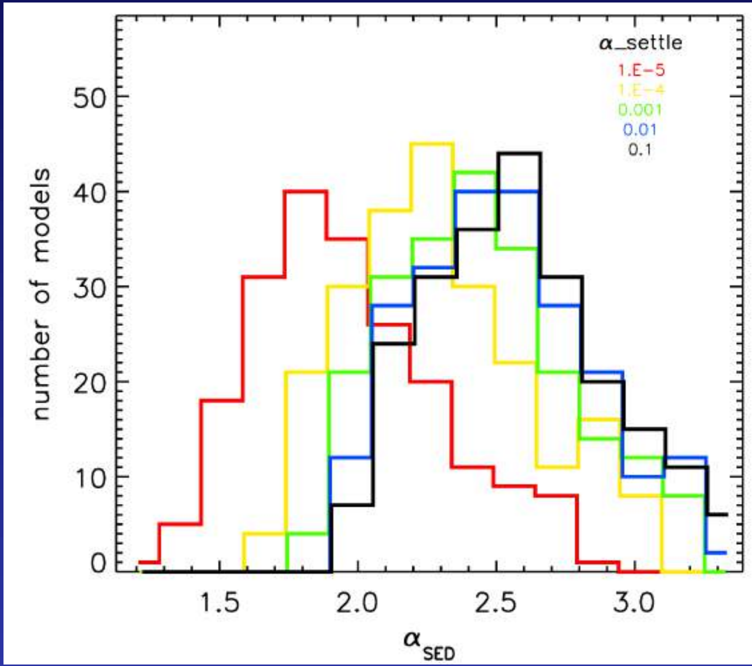
- one parameter sticks out: **dust settling**!

What is more important for SED mm-slope?

dependence on opacity-slope



dependence on dust settling

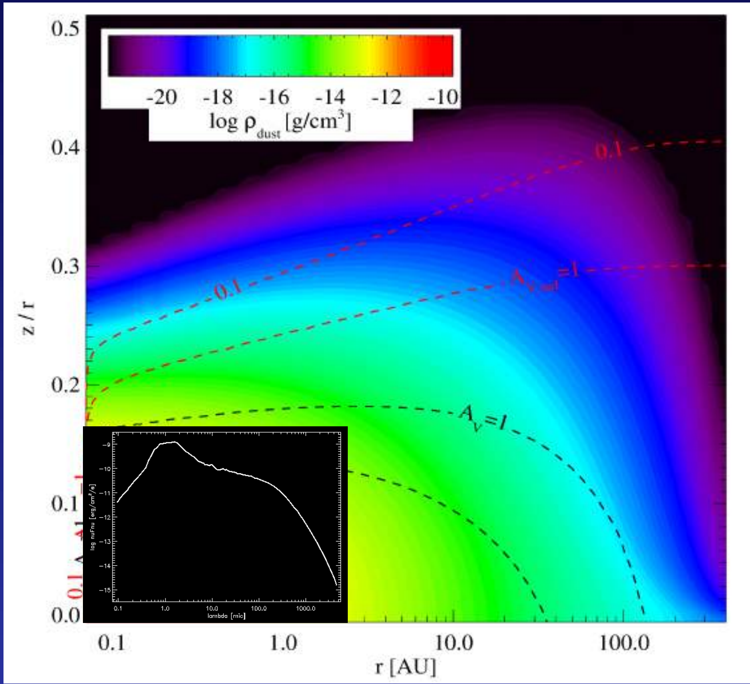


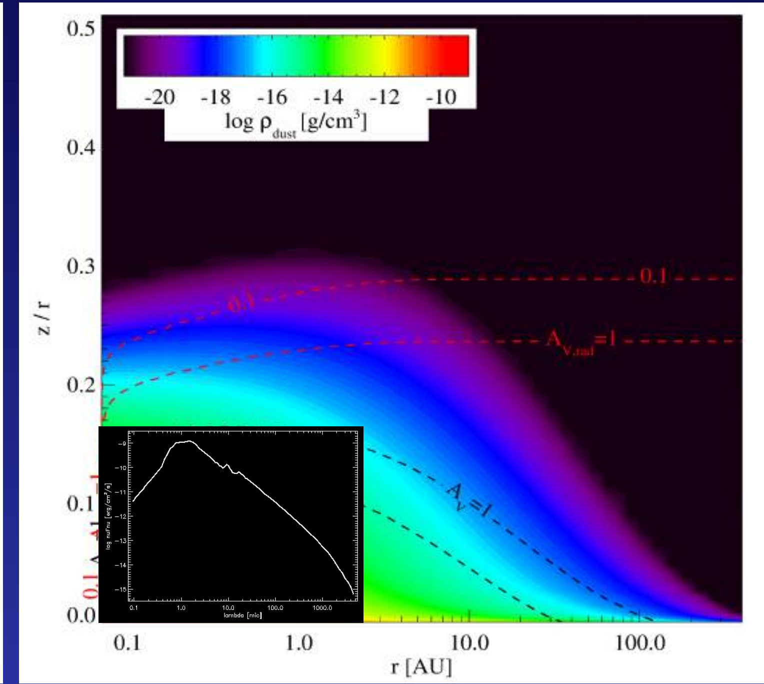
- dust settling alone is as important as the opacity-slope
- other disk properties ($R_{\rm out}$, scale height, flaring, ϵ, ...) play a role, too

⇒ **together, disk shape & settling seem more important (!)**

Why can settling make an order-of-mag difference?

well-mixed ($\alpha = 0.1$) **strong settling ($\alpha = 10^{-5}$)**





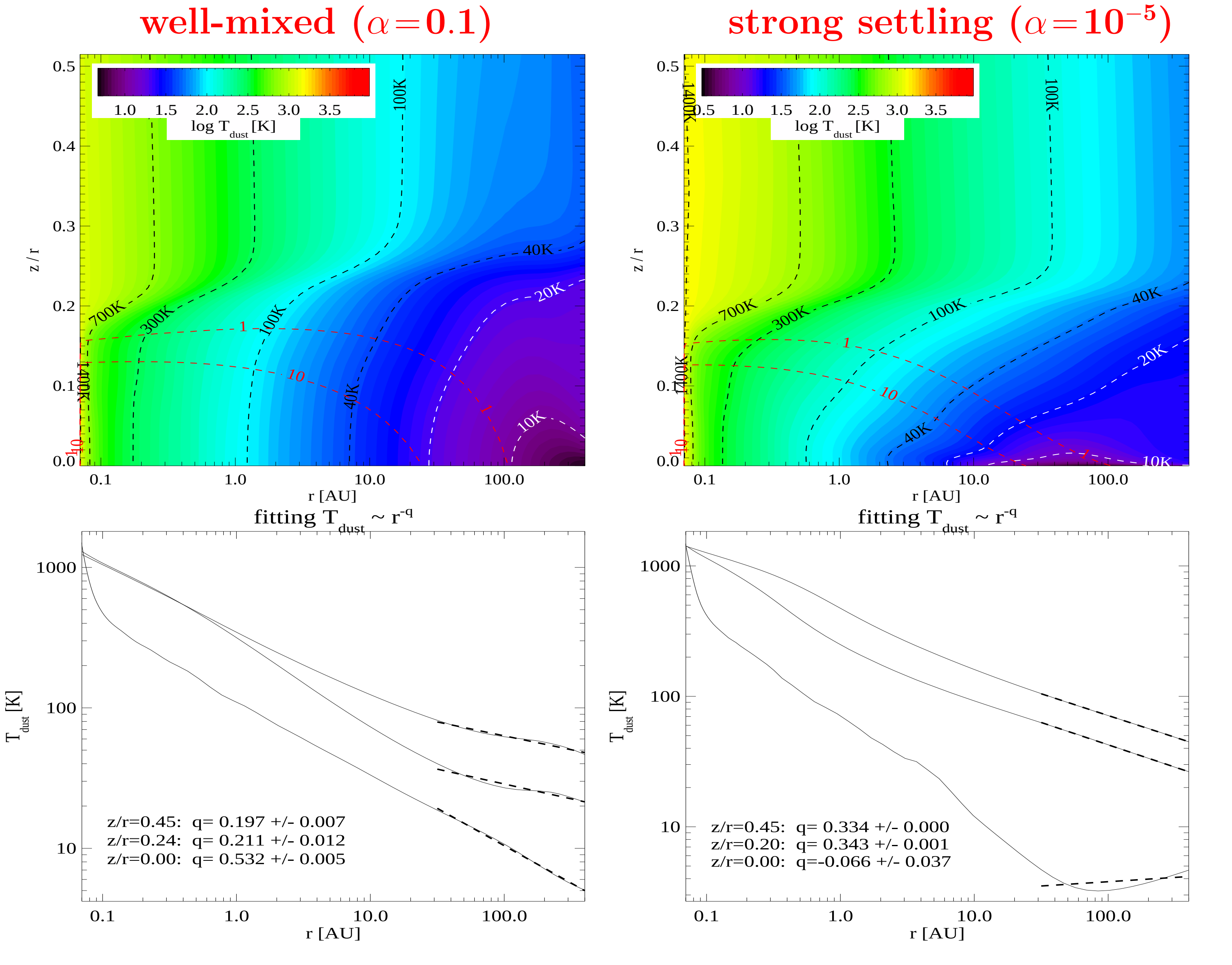
(otherwise identical model parameters $M_{\rm disk} = 0.01\, M_\odot$, $R_{\rm out} = 400\, AU$, $\epsilon = 1$, $H_0 = 0.2\, AU$, $\beta = 1.12$, $a_{\rm pow} = 3.5$)

$\mathbf{F_{1.3\,mm} = 0.096\,Jy}$, $\alpha_{\rm SED} = \mathbf{2.50}$ $\mathbf{F_{1.3\,mm} = 0.014\,Jy}$, $\alpha_{\rm SED} = \mathbf{1.65}$

- **dust settling** moves the grains to the cold midplane, where almost no photons are going
- **dust settling** enhances the shadowing effect, and vertical $T_{\rm dust}$-contrast
- **dust settling** changes the fraction between small and large grain emission

Summary

- mm-sized particles: A size distribution up to mm-sized particles is the most obvious explanation for a flat mm-opacity slope.
- conducting materials: Dust emission at (sub-mm) wavelengths is dominated by impurities of conducting materials.
- irregular shape: If these impurities have strongly irregular shapes, the mm-opacity is flat and very strong, even for small particles
- Disk shape (in particular dust settling, also flaring) is at least as important for the SED mm-slope as the dust opacity-slope
- Strongly settled disks are cold & faint, with a flat SED mm-slope
- dust mass: Observing the mm-flux in combination with the SED mm-slope can improve $M_{\rm dust}$-determination



well-mixed (α=0.1)
strong settling (α=10^{-5})
log T_{dust} [K]
z / r
r [AU]
700K
300K
100K
40K
20K
10K
1400K
fitting T_{dust} ~ r^{-q}
T_{dust} [K]
z/r=0.45: q= 0.197 +/- 0.007
z/r=0.24: q= 0.211 +/- 0.012
z/r=0.00: q= 0.532 +/- 0.005
z/r=0.45: q= 0.334 +/- 0.000
z/r=0.20: q= 0.343 +/- 0.001
z/r=0.00: q=-0.066 +/- 0.037