Global gravitoviscous protoplanetary discs with dust evolution: disc sizes and opacity gaps

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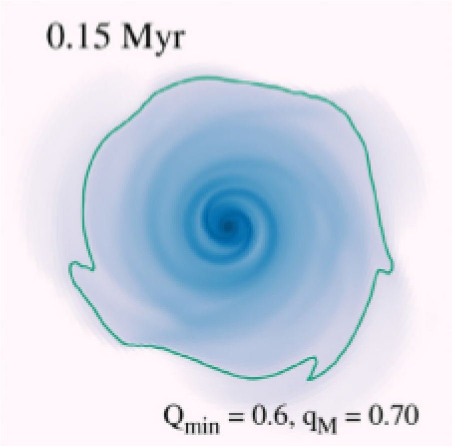
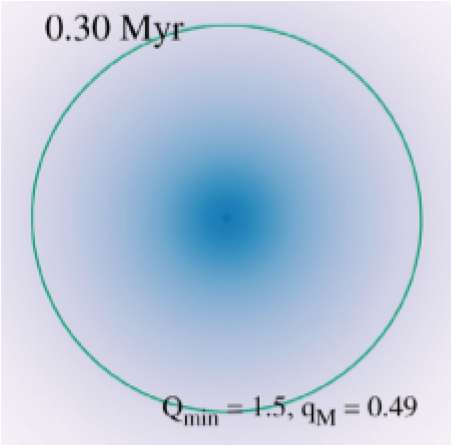
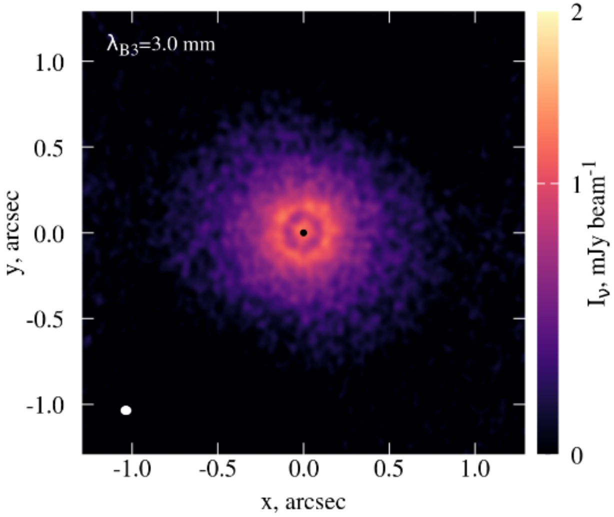






«Dynamical and chemical evolution of protoplanetary disks»
04 March 2021, Russian PPD workshop

Barriers Against Dust Growth

1μm

1mm

grain size

Coulomb repulsion

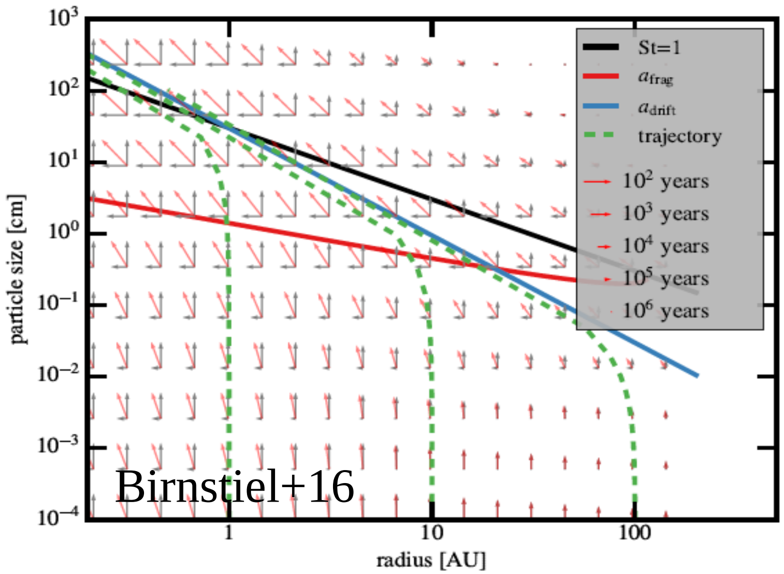
Bouncing

Fragmentation

Radial drift

- *Micron-size dust*: **electrostatic** barrier (Okuzumi+09, Akimkin+20)

- *Macroscopic dust*: **radial drift** barrier (Whipple 72), **bouncing** barrier (Zsom+10), **fragmentation** barrier (Dullemond & Dominik 2005, Brauer+08, Birsnstiel+09)



Birnstiel+16

Dust evolution models

- **Monodisperse model**

$$\frac{da_g}{dt} = \frac{\rho_d v_{rel}}{\rho_s}$$

Stepinski & Valageas 1997

- **Bidisperse model**

$$a_{sm} = \text{const}, \quad \frac{da_{gr}}{dt} = \frac{\rho_d v_{rel}}{\rho_s}$$

a) $\frac{\rho_{gr}}{\rho_d} = \begin{cases} 0.75 & \text{fragm. limited} \\ 0.97 & \text{drift limited} \end{cases}$

Birnstiel+2012

b) power-law with $a_{max}=a_{gr}$

Vorobyov+2018

c) separate equation on mass transfer

Akimkin+2020

- **Multidisperse model**

Smoluchowski equation or Monte-Carlo simulations

Brauer+2008,
Zsom+2010,
Drążkowska+2019,
...

FEOSAD code

– thin disk 2D hydrodynamics with self-gravity and realistic cooling/heating (Vorobyov & Basu 2009);

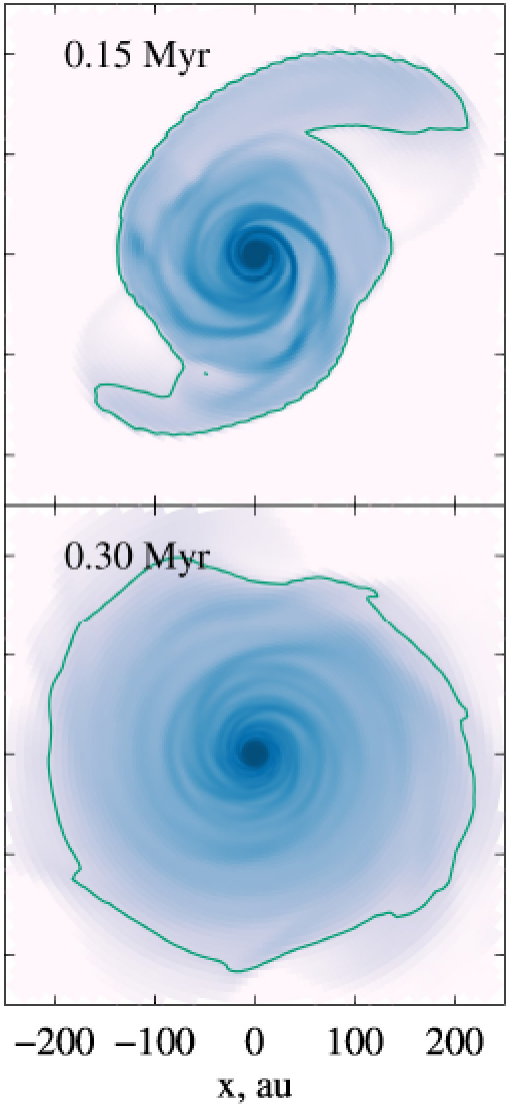
– initial conditions: flattened protostellar core;

– evolving star (stellar evolution code, feedback to the disk via accretion bursts);

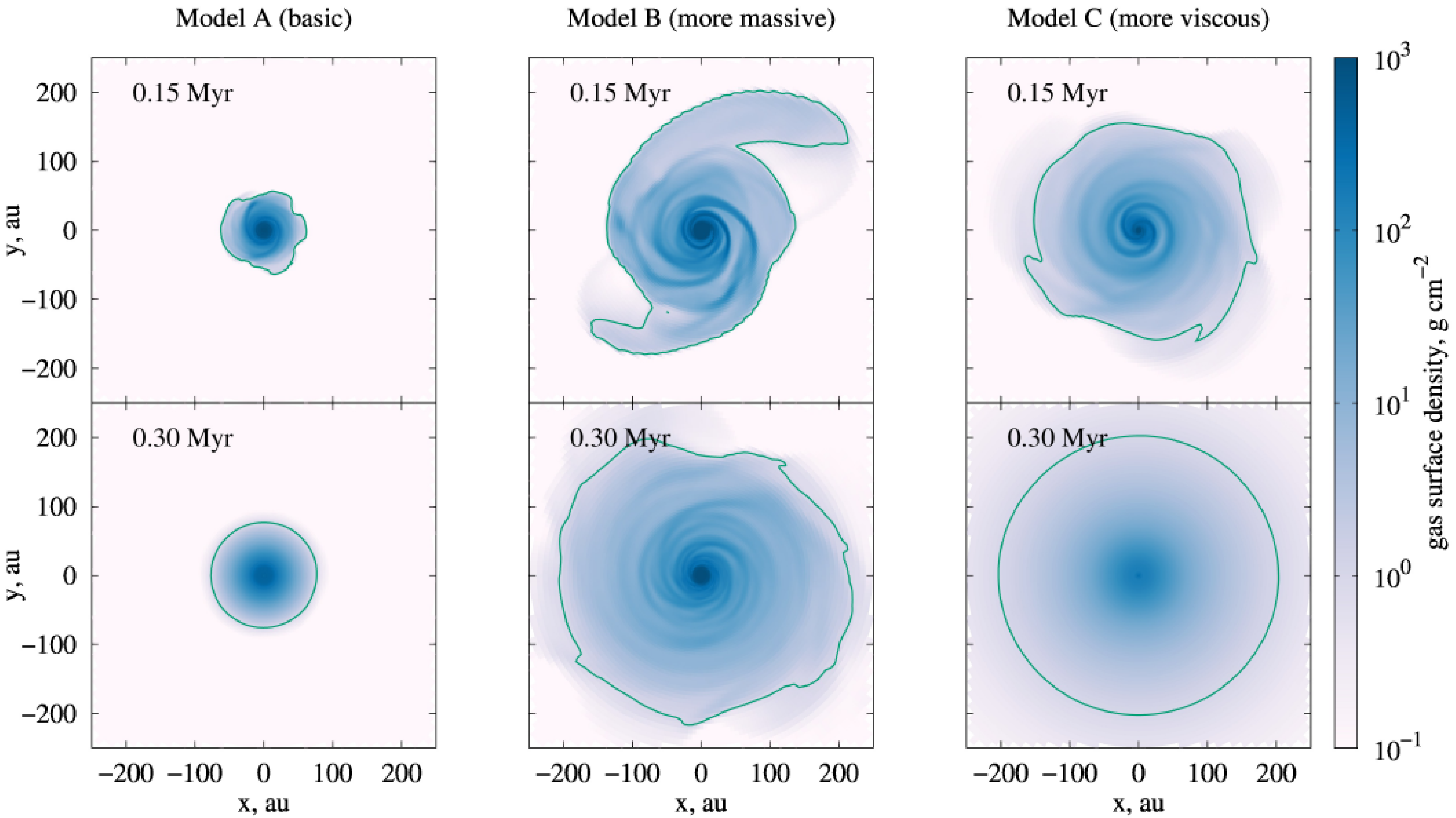
– global (from 1 to 3000 au) and long-term simulations (up to several Myr);

– three components: gas and two dust populations (Epstein, Stokes and Newton drag; Stoyanovskaya+18,20);

– evolving dust (coagulation, fragmentation, and drift);

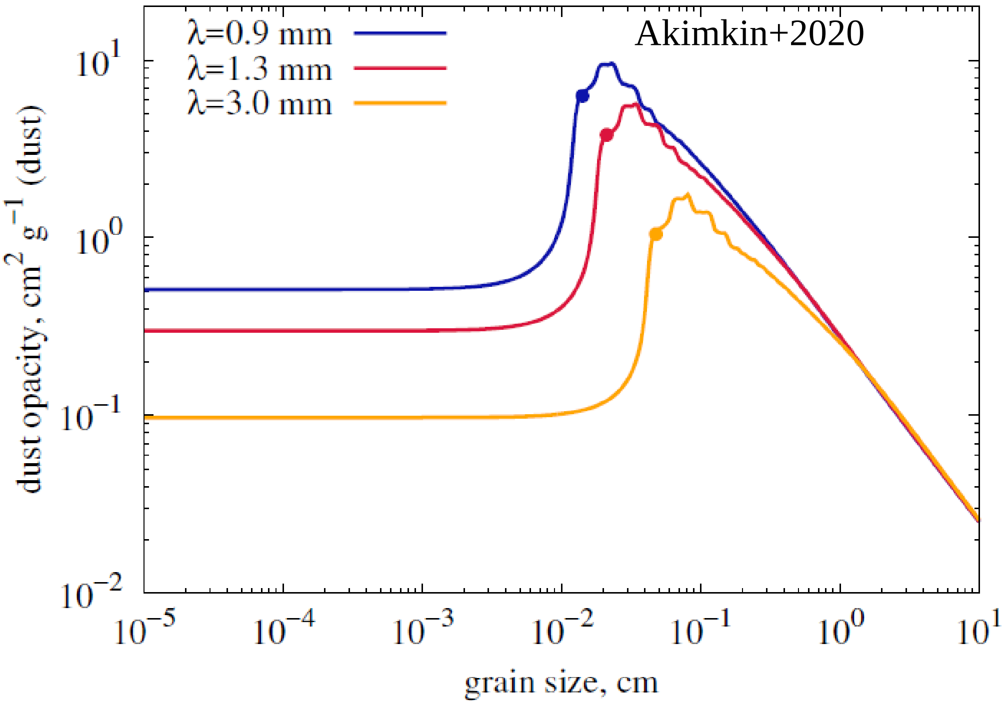


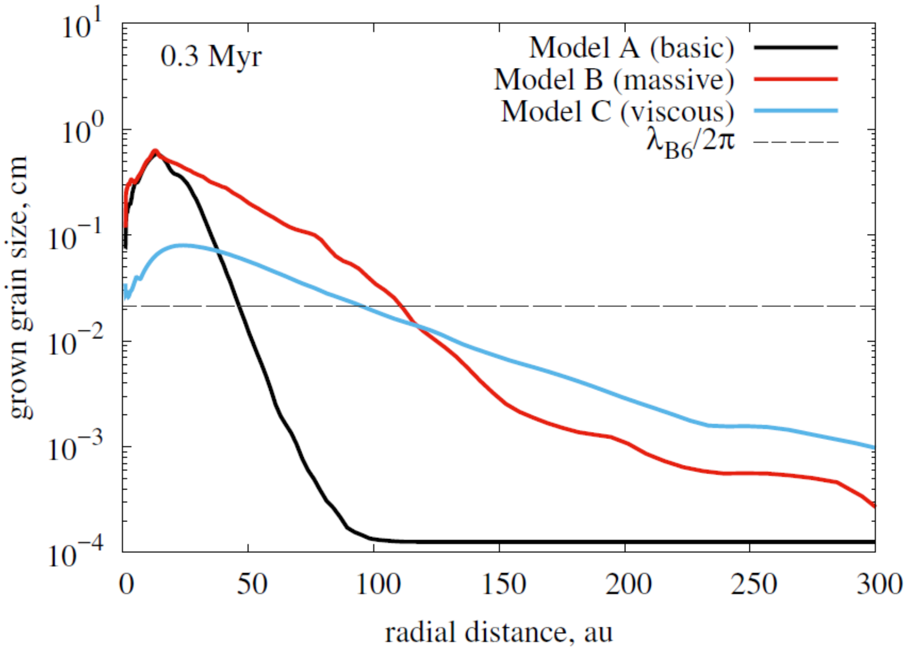
Disk physical structure



	$M_{\rm core}$, $M_\odot$	$E_{\rm rot}/E_{\rm grav}$	α
Model A (basic)	0.53	0.13%	10^{-3}
Model B (massive)	1.03	0.24%	10^{-3}
Model C (viscous)	0.53	0.13%	10^{-2}

Dust opacity





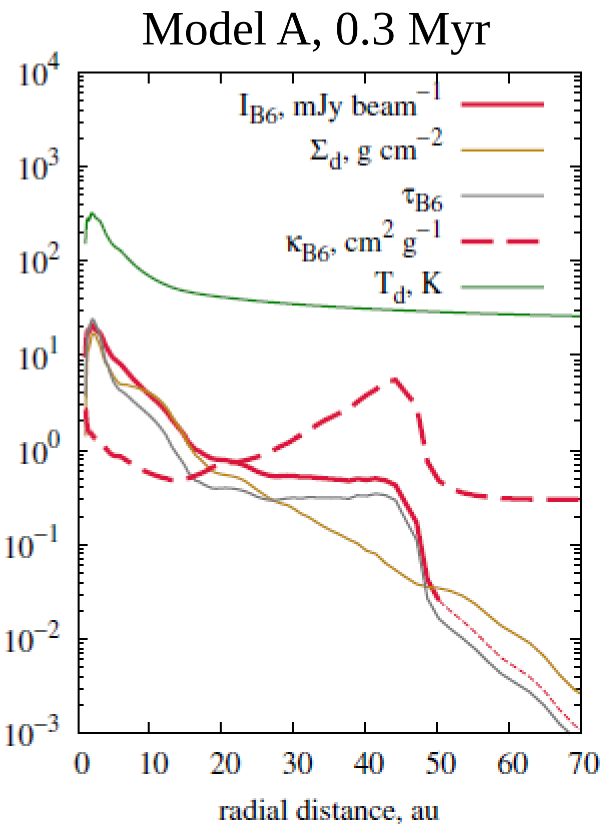
10 – 100x opacity change for grain sizes within 0.1 – 10mm

$$I_\nu \propto T_\mathrm{d} \Sigma_\mathrm{d} \varkappa_\nu$$

see also Woitke+15, Birnstiel+18, Rosotti+19, ...

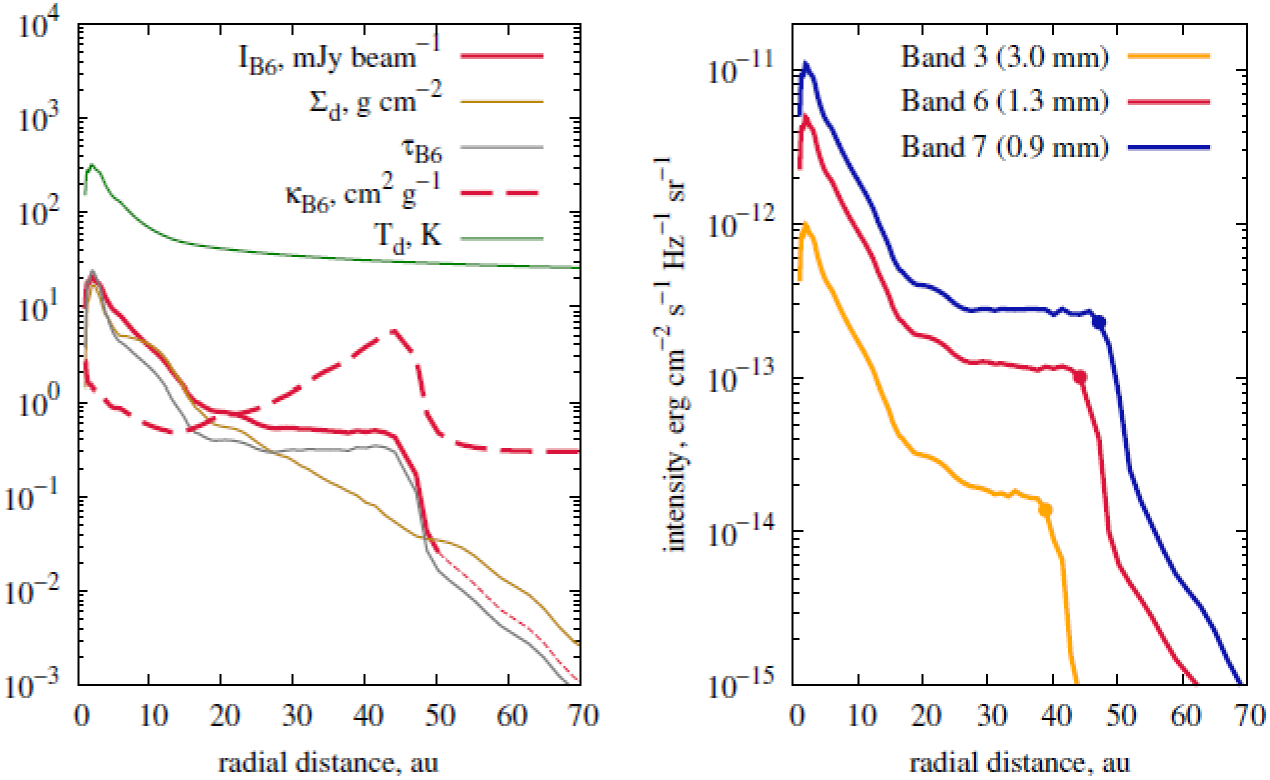
Dust continuum emission

$$I_\nu \propto T_\mathrm{d} \Sigma_\mathrm{d} \varkappa_\nu$$


Model A, 0.3 Myr

See also: Birnstiel & Andrews 2014, Powell+19, Rosotti+2019

Dust continuum emission



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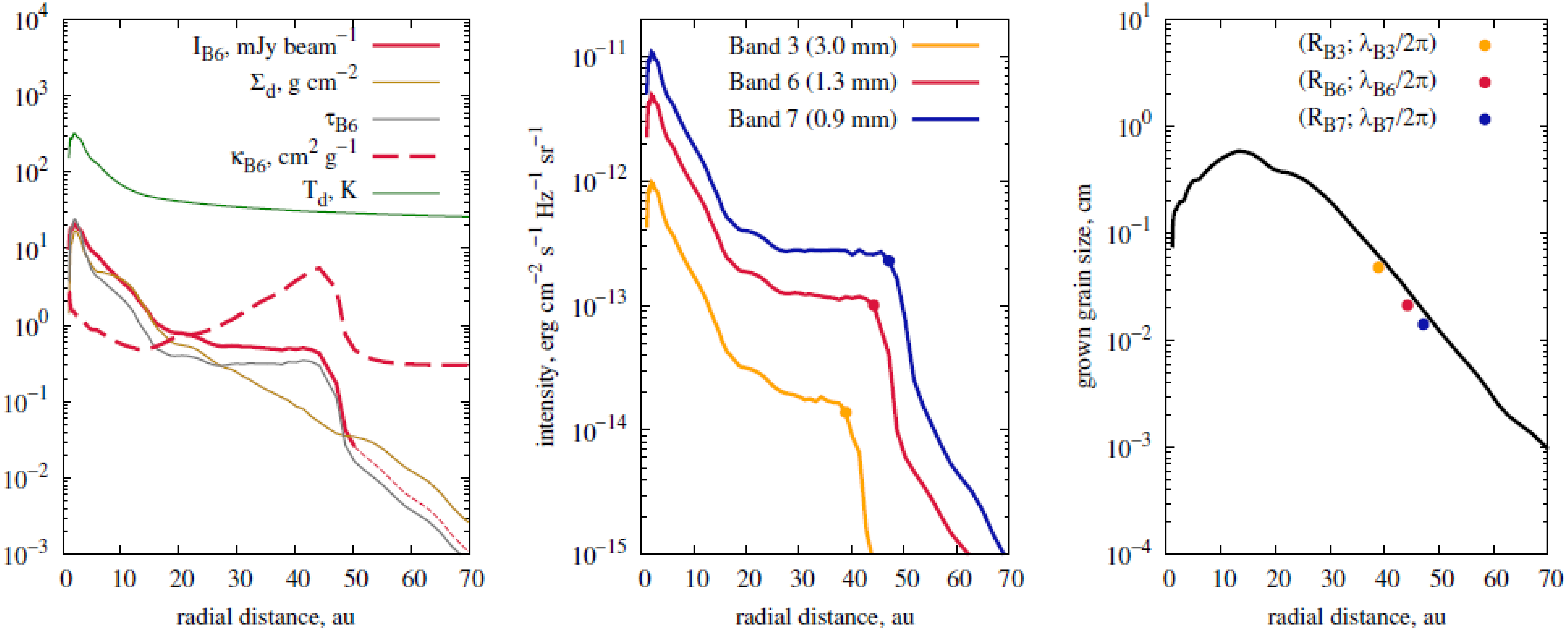
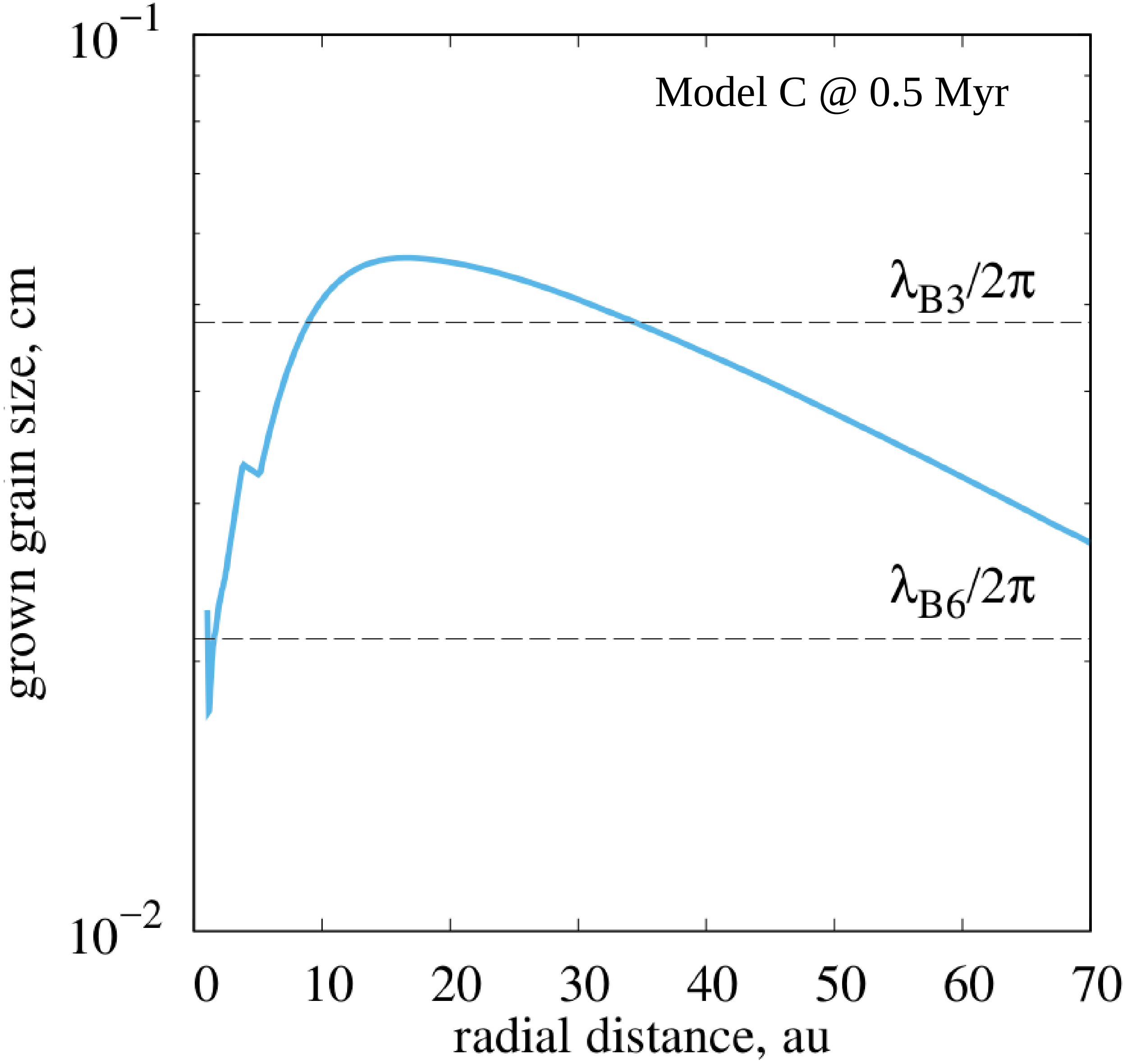
Dust continuum emission

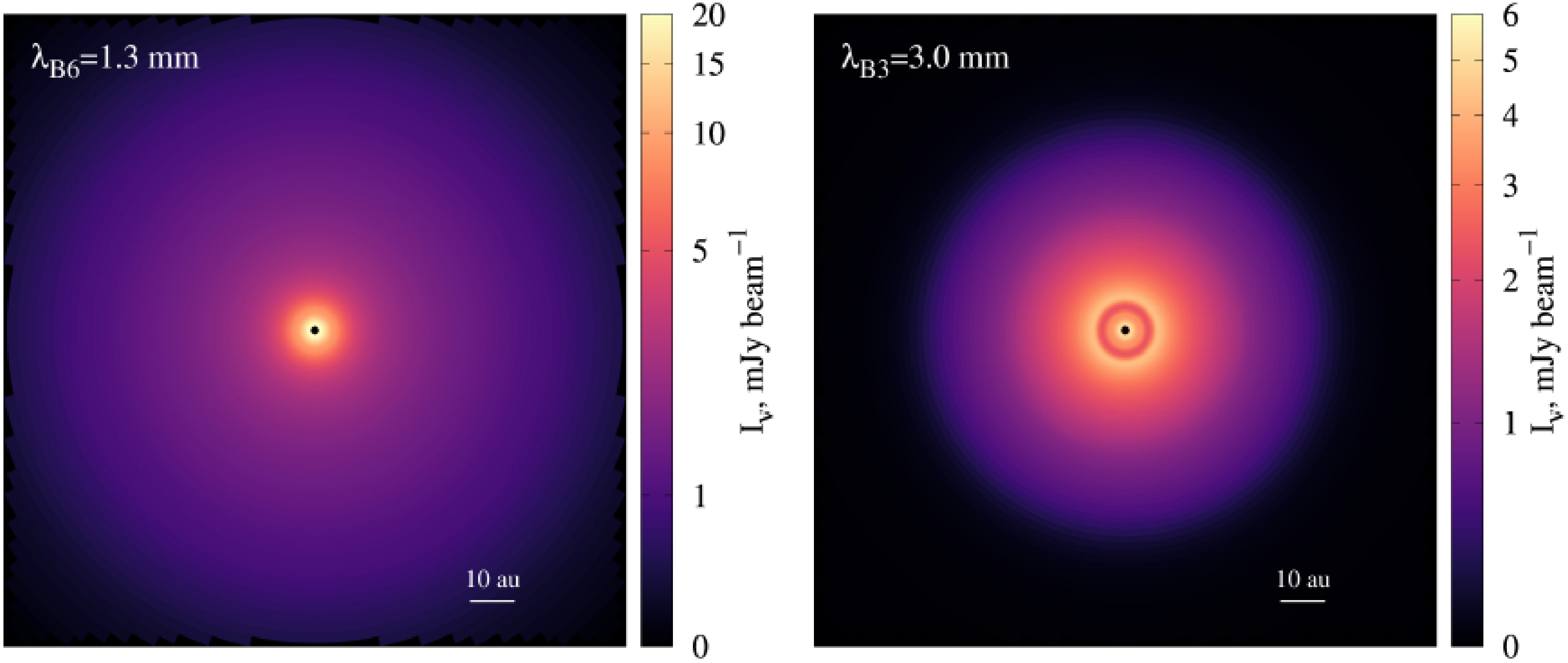


See also: Birnstiel & Andrews 2014, Powell+19, Rosotti+2019

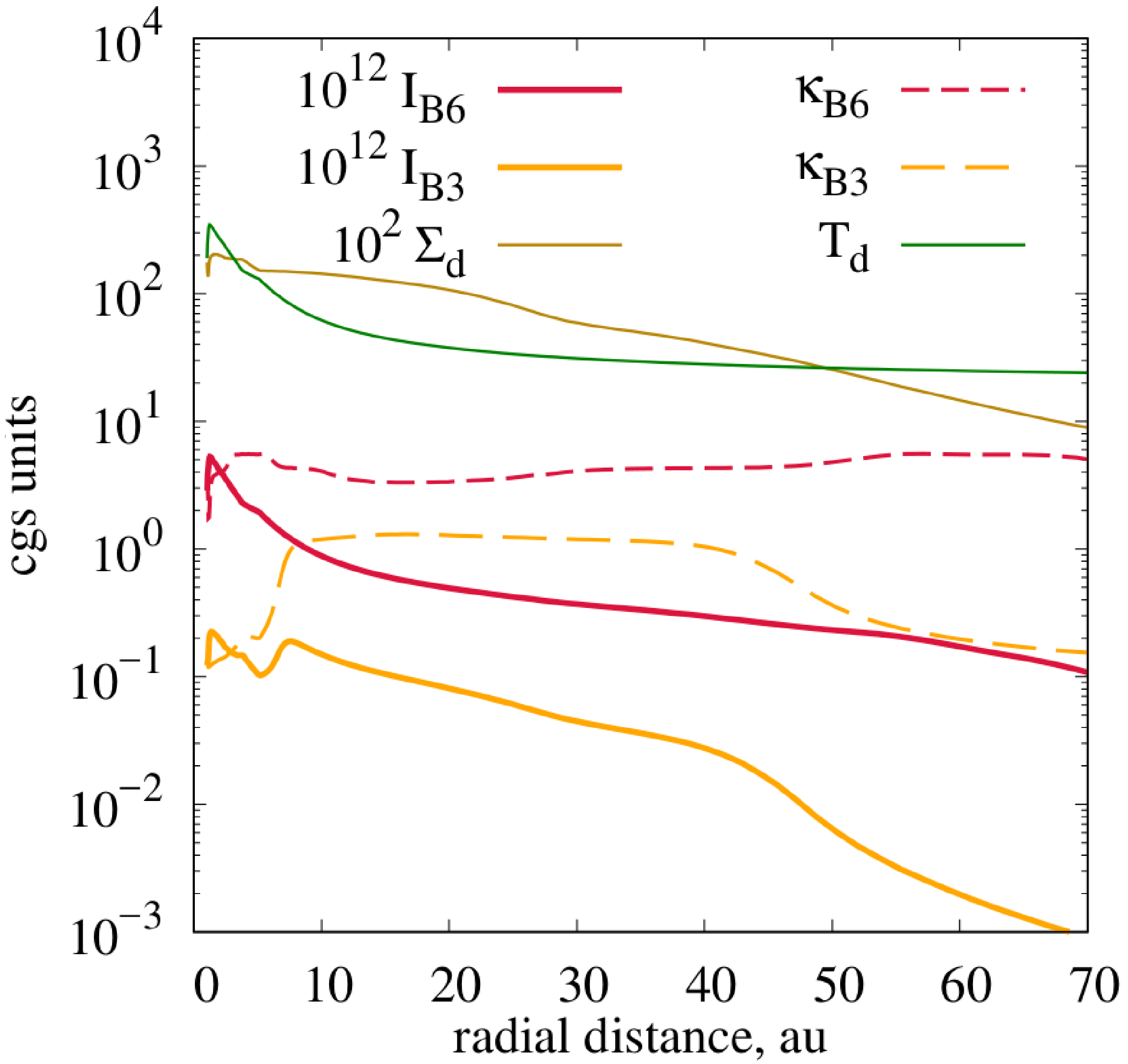
Peculiar case



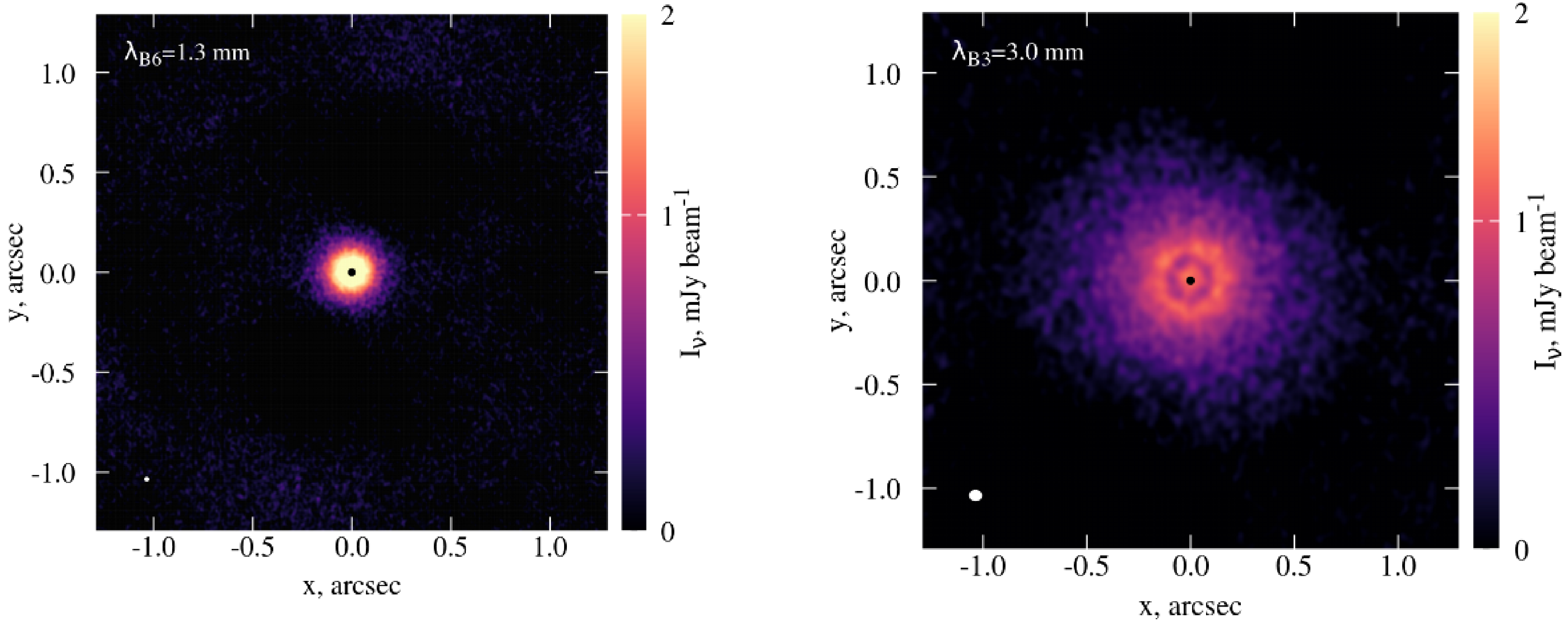
Peculiar case:
same disk, different wavelengths



Peculiar case: explanation

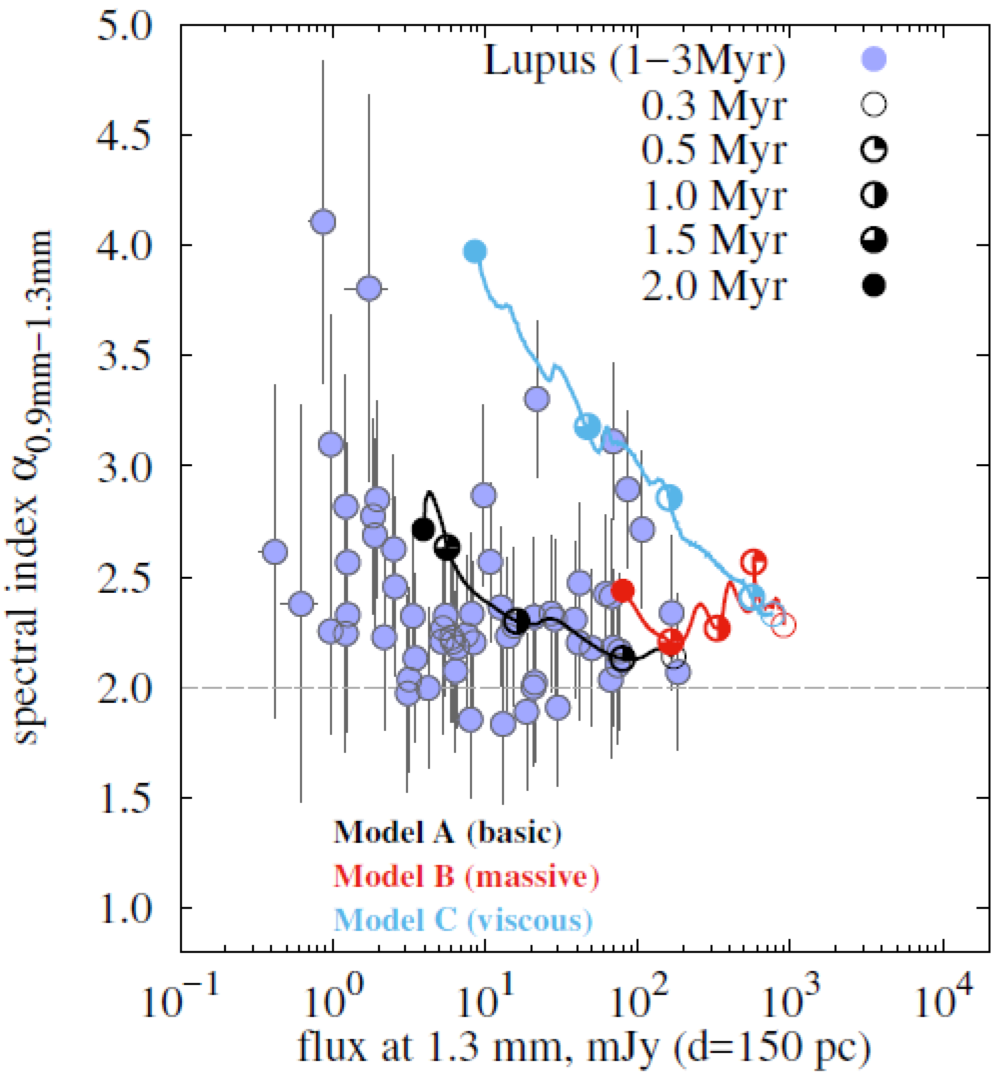


Peculiar case: ALMA simulations



54 pc, 16 km baseline, 6h observation

Comparison with observations



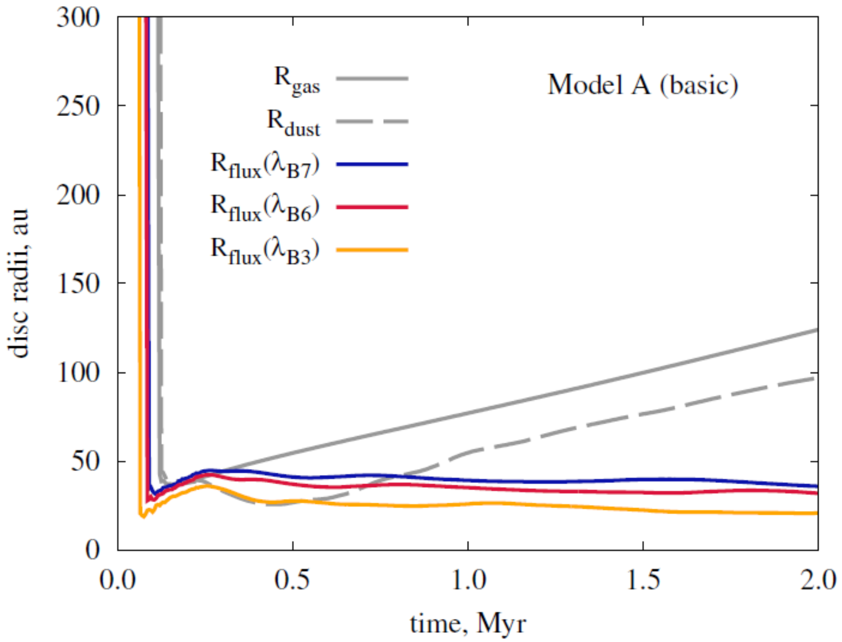
$$I_\nu(r,\phi) = B_\nu(T_\mathrm{d})(1 - e^{-\tau_\nu}),$$

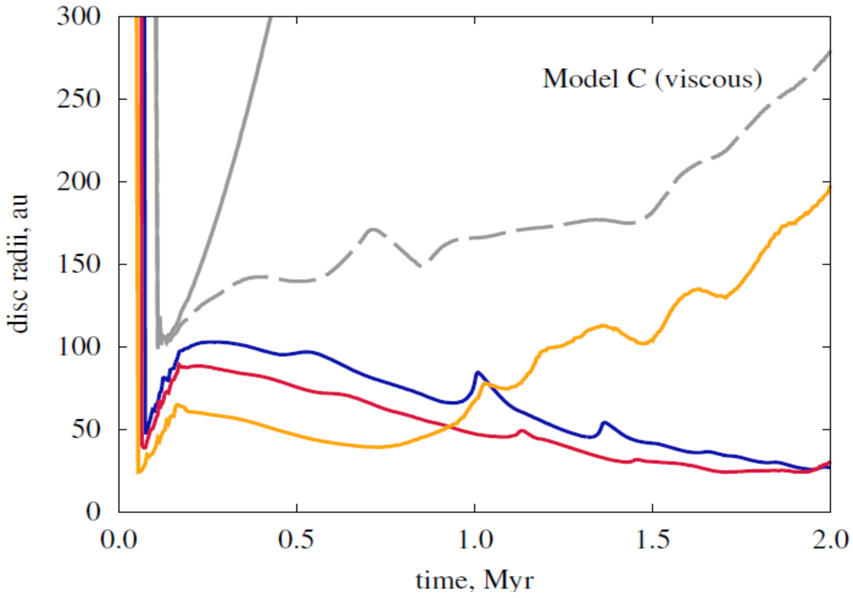
$$F_\nu = \frac{1}{d^2}\int\limits_0^{2\pi}\int\limits_0^{\infty} I_\nu(r,\phi) r \mathrm{d}\phi \mathrm{d}r,$$

$$\alpha = \frac{\mathrm{d}\lg F}{\mathrm{d}\lg \nu},$$

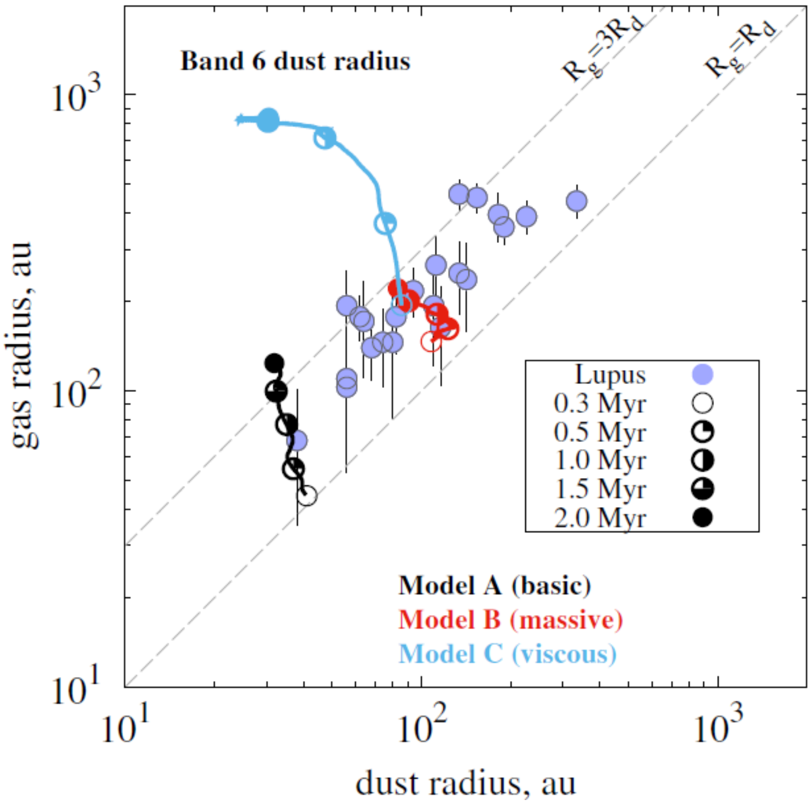
Dots: Lupus discs (Ansdell+2016,2018)
Lines: FEOSAD simulations (Akimkin+2020)

Disk radii





- **Physical radius** – contains 90% of the gas or dust mass (see Rosotti+19)
- **Visible radius** – contains 90% of emission (depends on the wavelength!)



Conclusions

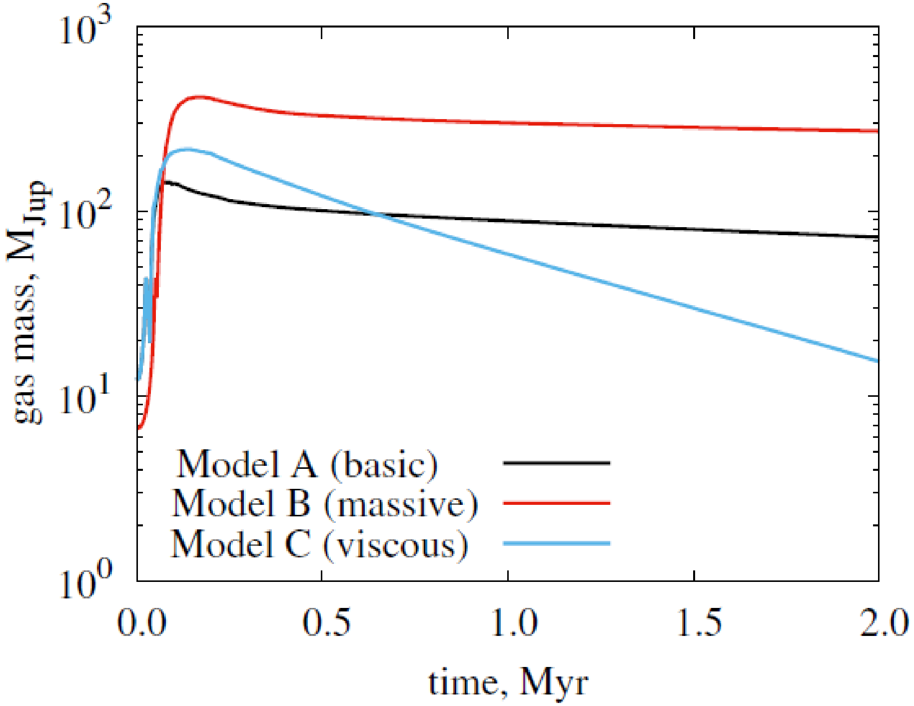
– most of dust growth happens at the early stage protostellar stage (<300 kyr), when compact and dense disk is forming;

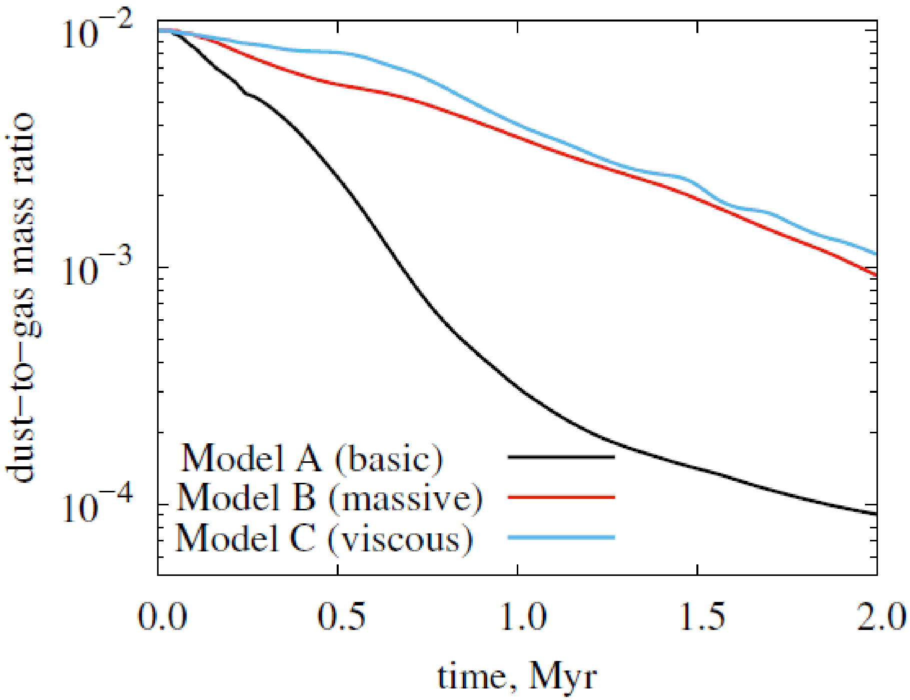
– sharp outer edge can be seen due to drop in dust opacity, but not in surface density. The edge is wavelength-dependent;

– non-monotonic radial variations of grain size can produce an opacity gap, which is not accompanied by a physical gap and shift with the wavelength.

More details: arxiv.org/abs/2010.06566

Disk mass





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$$\mathrm{St} = \frac{a\,\rho_{\rm s}}{\Sigma_{\rm g}}\frac{\pi}{2}$$

$$a_{\rm drift} \simeq 0.35\frac{\Sigma_{\rm d}}{\rho_{\rm s}\gamma}\left(\frac{H_{\rm g}}{r}\right)^{-2}$$

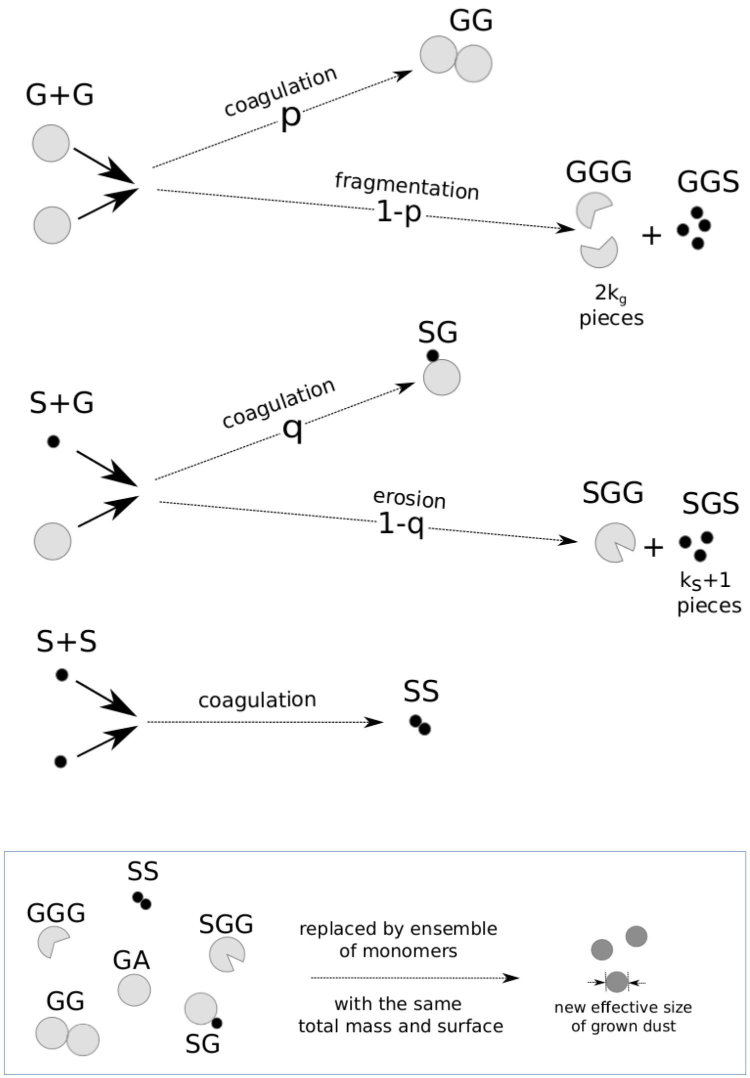
$$a_{\rm frag} \simeq 0.08\,\frac{\Sigma_{\rm g}}{\rho_{\rm s}\,\alpha}\left(\frac{v_{\rm frag}}{c_{\rm s}}\right)^2$$

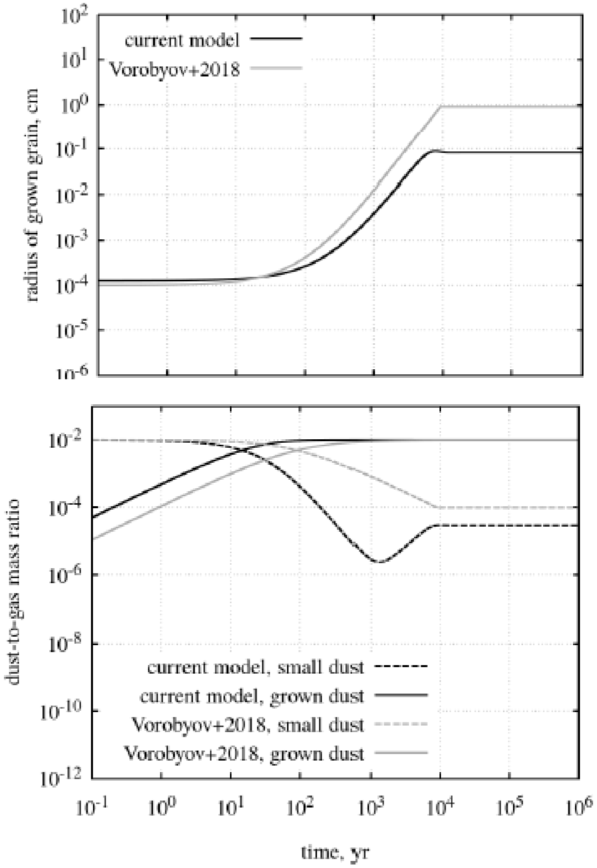
Birnstiel et al., 2016

Dust evolution model in FEOSAD

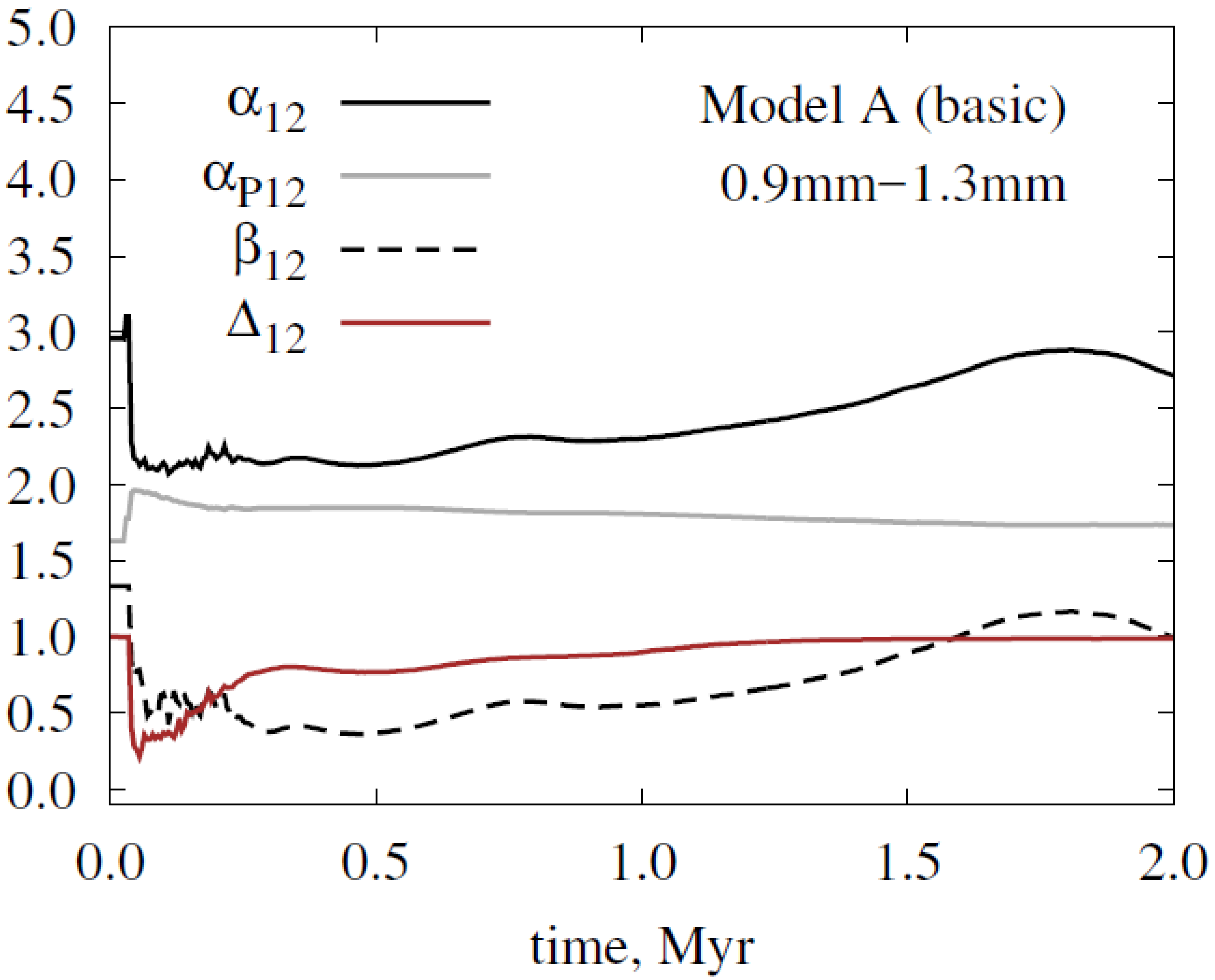
1) Small dust (S): fixed size (1 um), coupled to the gas
2) Grown dust (G): size depends on time, radial and azimuthal position

$$
\begin{aligned}
\frac{da_{\mathrm{g}}}{dt} =& \frac{n_{\mathrm{s}}^2}{n_{\mathrm{g}}} a_{\mathrm{s}}^2 a_{\mathrm{g}} \left(C_1 \left(\frac{a_{\mathrm{s}}}{a_{\mathrm{g}}} \right)^D - C_2 \left(\frac{a_{\mathrm{s}}}{a_{\mathrm{g}}} \right)^2 \right) \\
&+ n_{\mathrm{s}} (a_{\mathrm{s}} + a_{\mathrm{g}})^2 a_{\mathrm{g}} C_3 \times \\
&\times \left(1 - \xi\delta - q(\delta + 1)^{2/D} - (1-q)(1 - k_{\mathrm{s}}\delta)^{2/D} \right) \\
&+ C_4 a_{\mathrm{g}}^3 n_{\mathrm{g}},
\end{aligned}
$$





Decomposition of the spectral index



$$\alpha_{12} = \alpha_{P12} + \beta_{12}\Delta_{12}$$