Моделирование эволюции пыли в протопланетных дисках

Виталий Акимкин
ИНАСАН, Москва

Э.И. Воробьев (ЮФУ)
A. Ivlev, P. Caselli, M. Gong, K. Silsbee (MPE)

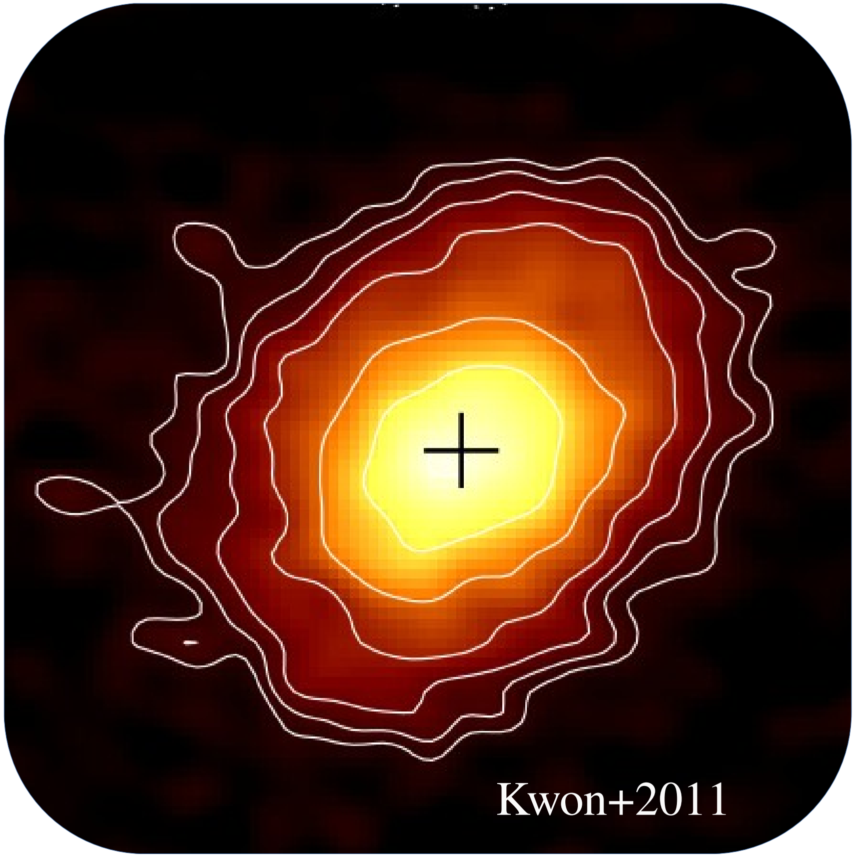
семинар отдела Релятивистской астрофизики ГАИШ МГУ
17 сентября 2024

Protoplanetary Disks at Submillimeter Wavelengths

ALMA Partnership+2015

ALMA; dust emission at λ=1 mm

Protoplanetary Disks at Submillimeter Wavelengths

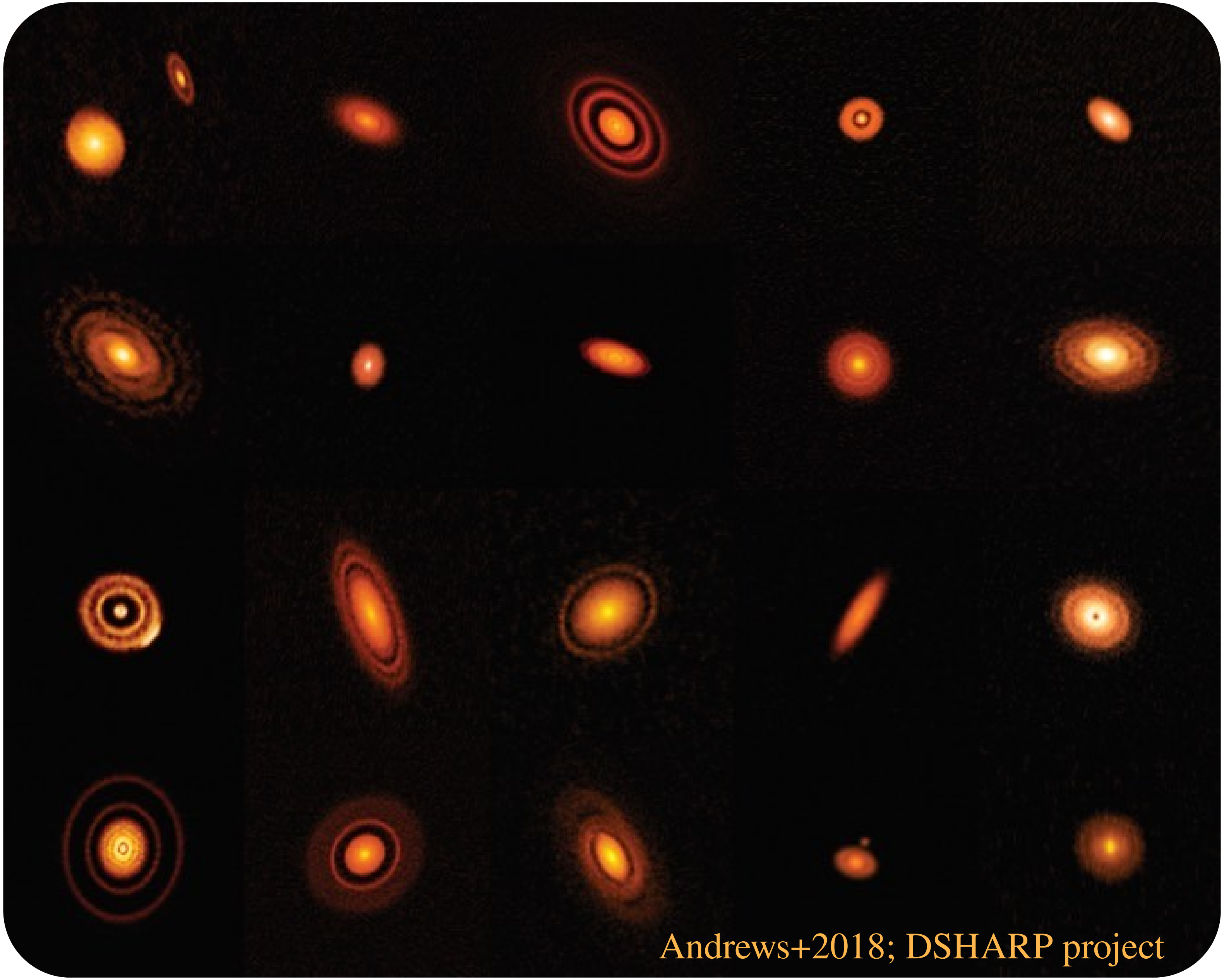

Kwon+2011

→

ALMA Partnership+2015

ALMA; dust emission at λ=1 mm

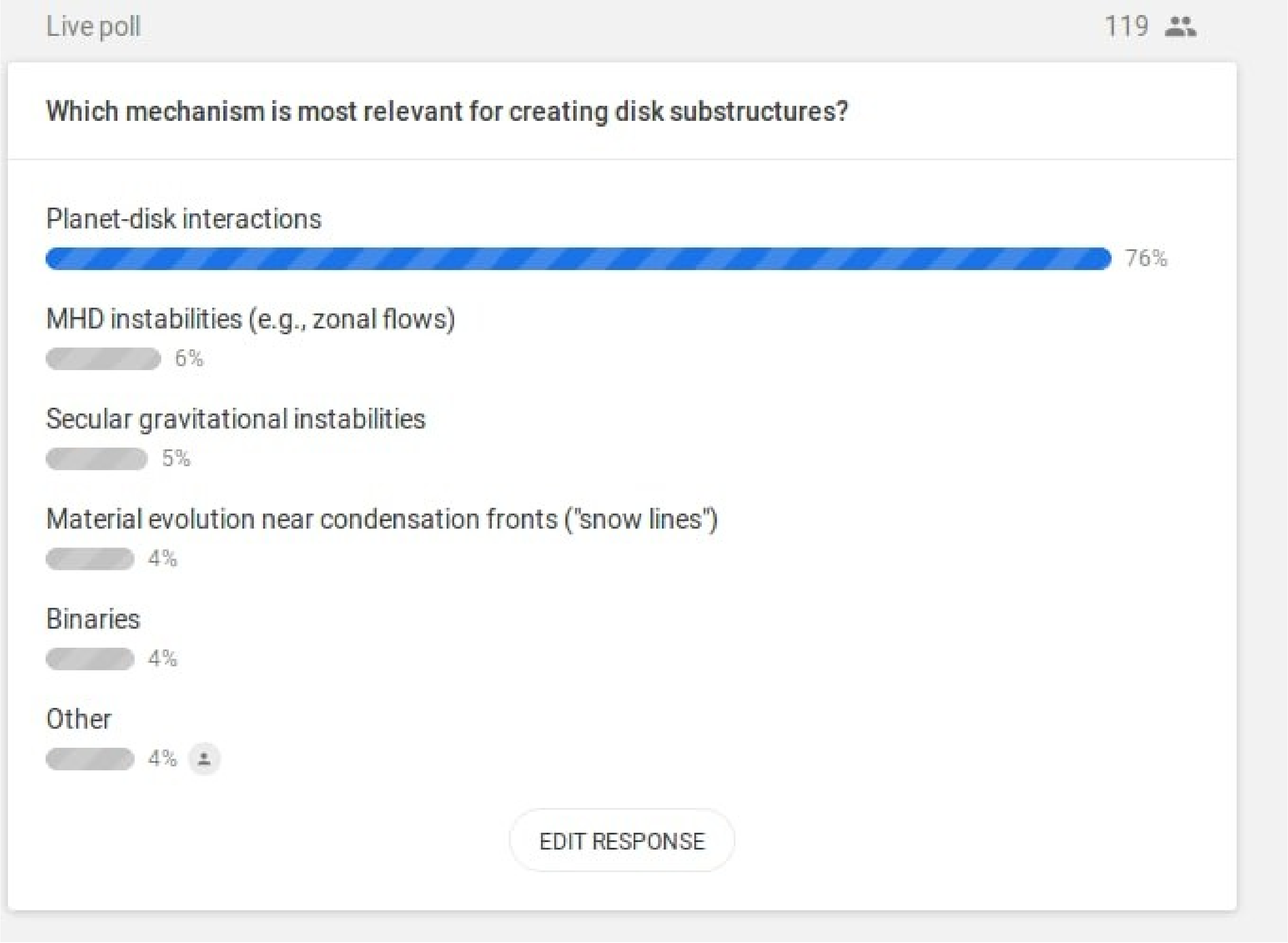
Protoplanetary Disks at Submillimeter Wavelengths



Andrews+2018; DSHARP project

Protoplanetary Disks at Submillimeter Wavelengths

Conference "5 years after HL Tau", Dec 2020



Which mechanism is most relevant for creating disk substructures?

Planet-disk interactions 76%

MHD instabilities (e.g., zonal flows) 6%

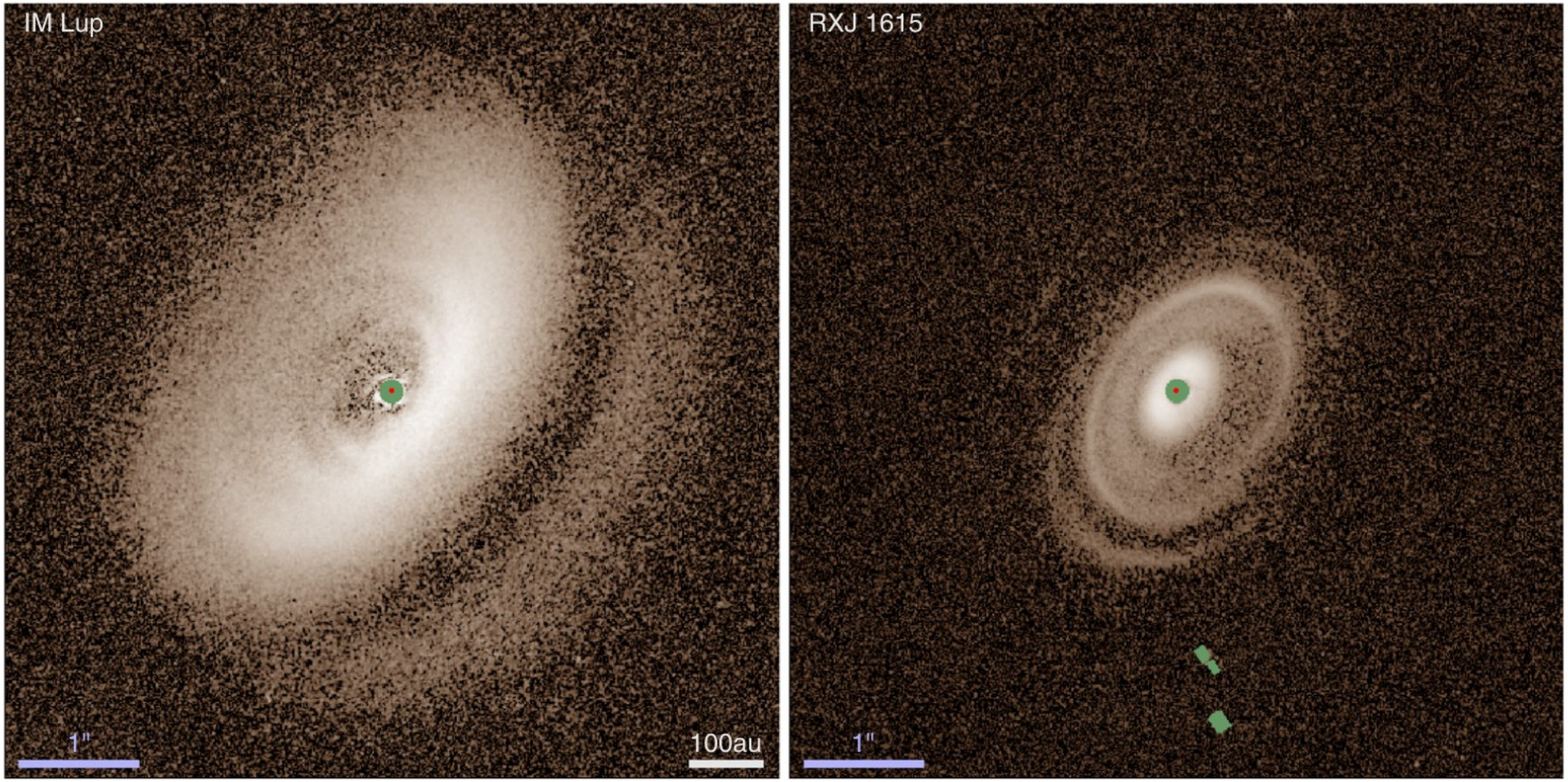
Secular gravitational instabilities 5%

Material evolution near condensation fronts ("snow lines") 4%

Binaries 4%

Other 4%

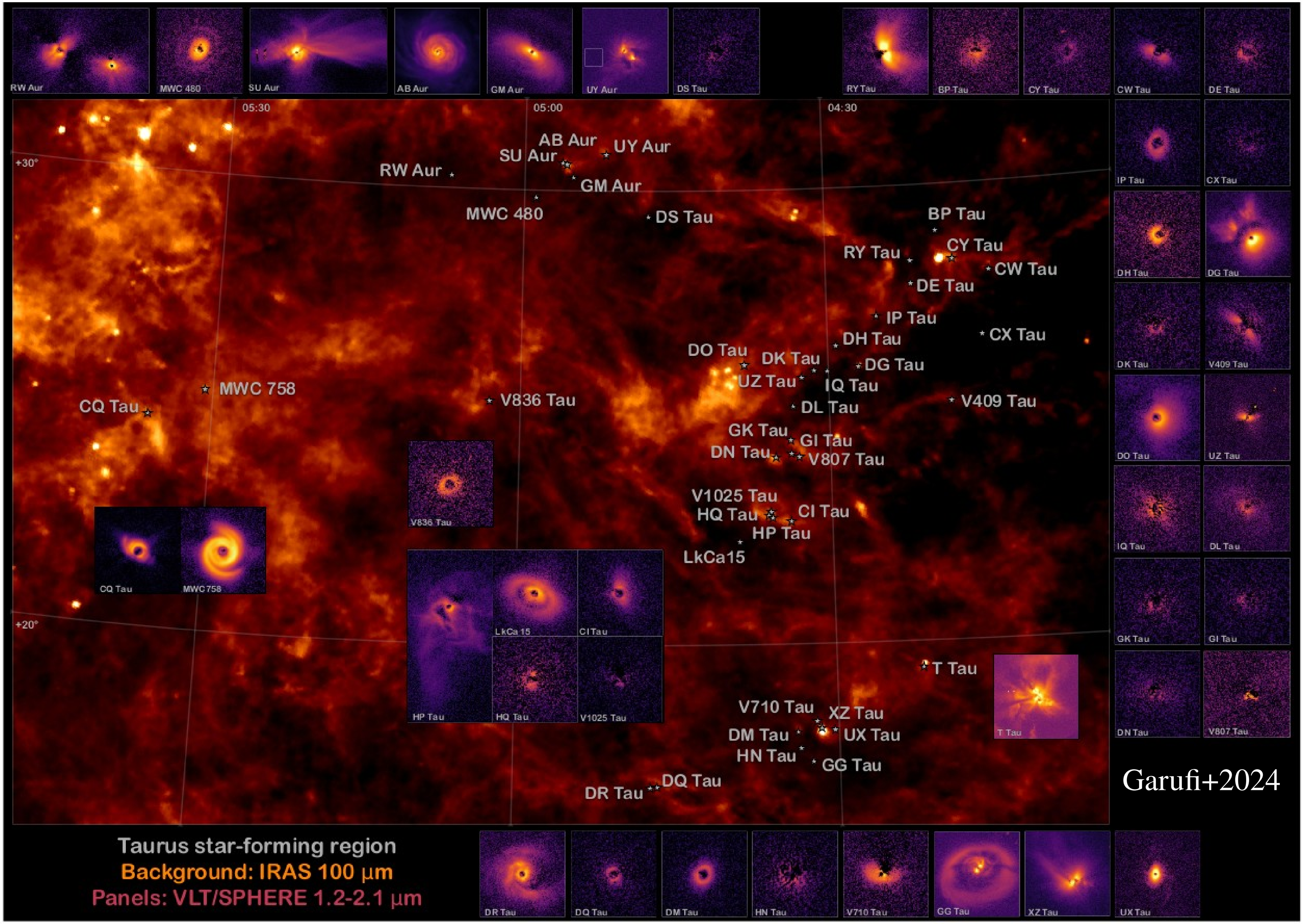
Protoplanetary Disks in Near Infrared



Avenhaus+2018

VLT-SHPERE, dust scattering at $\lambda=1$ μm

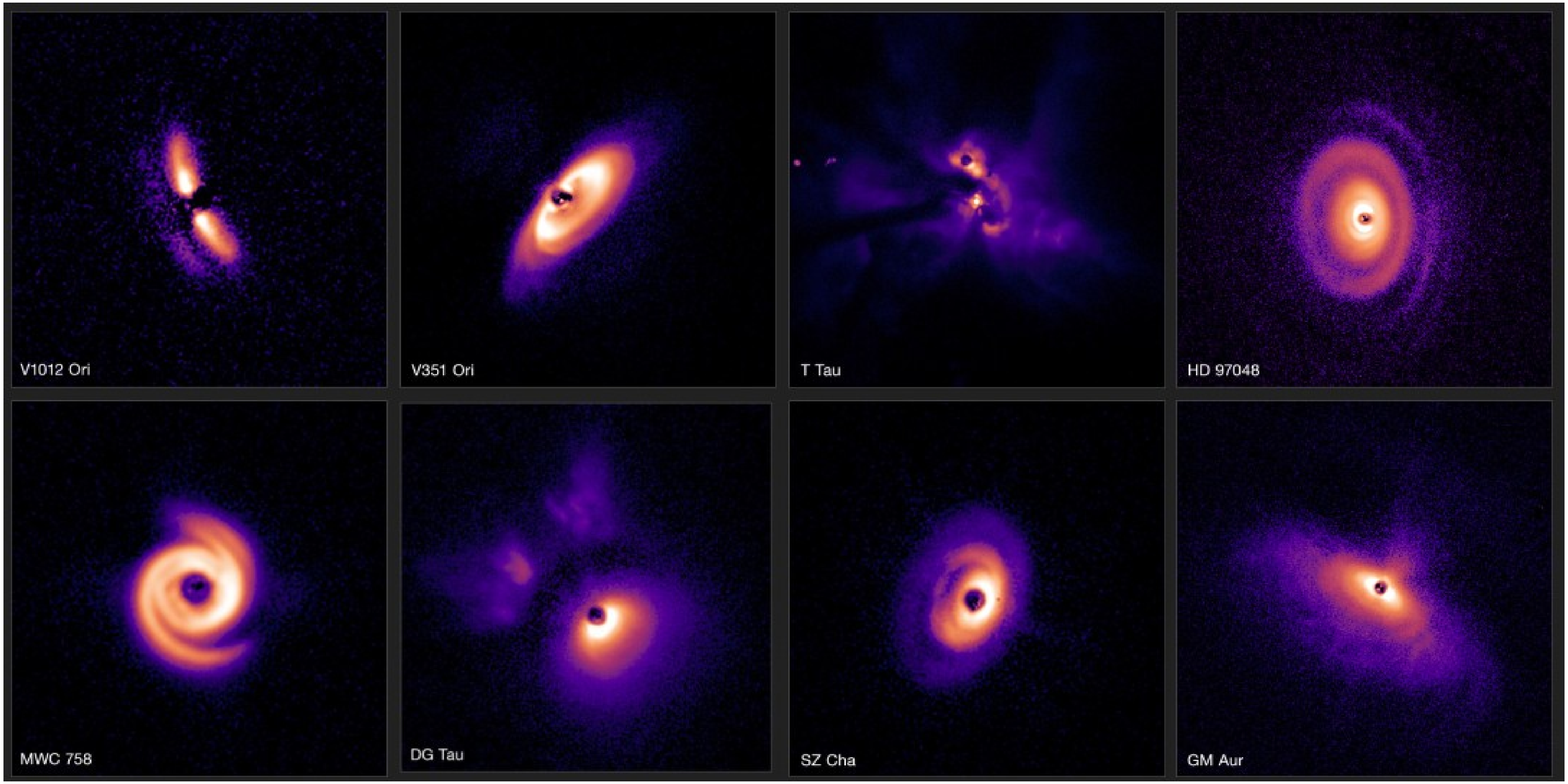
Protoplanetary Disks in Near Infrared



Garufi+2024

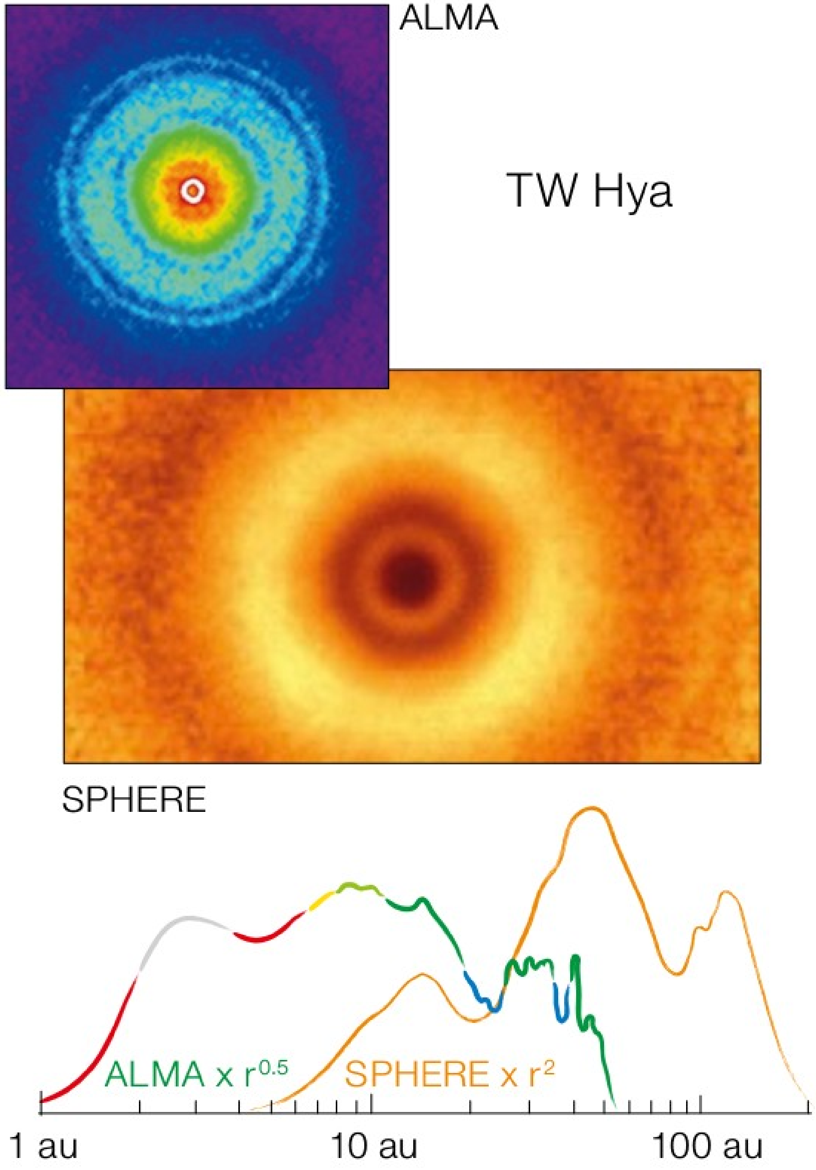
Taurus star-forming region
Background: IRAS 100 µm
Panels: VLT/SPHERE 1.2-2.1 µm

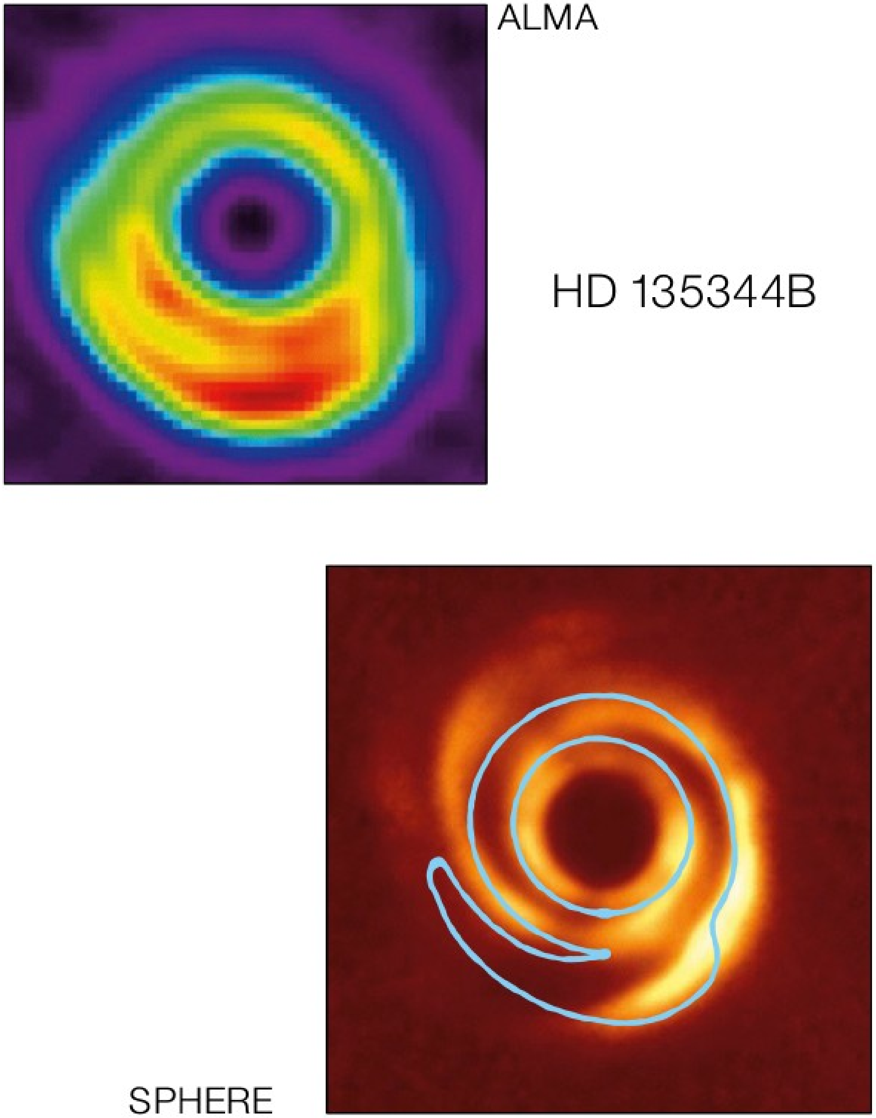
Protoplanetary Disks in Near Infrared



Ginski+2024; Garufi+2024; Valegård+2024

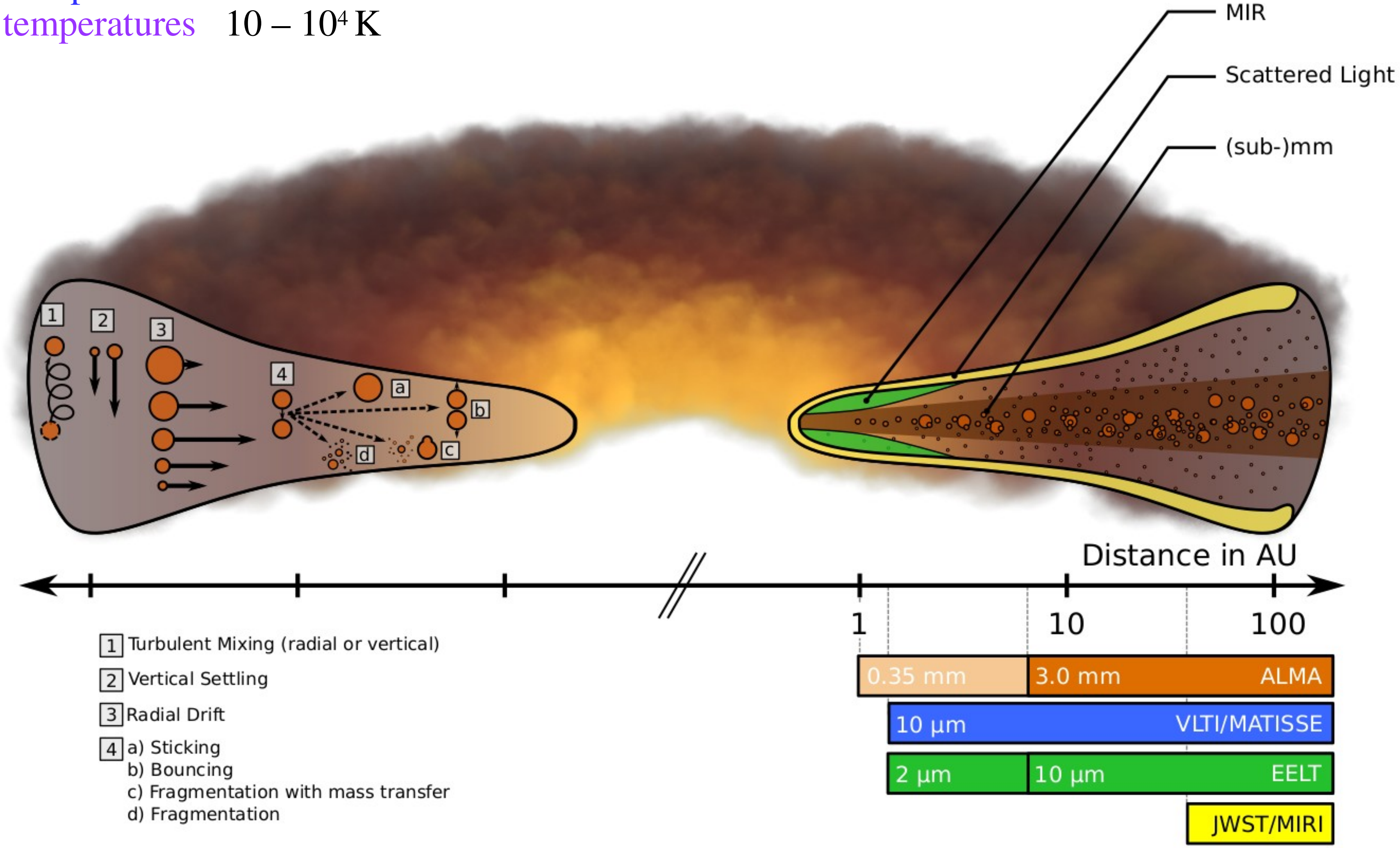
NIR vs FIR





Garufi+2017

Life times	1 – 20 Myr
Masses	0.001 – 0.1 M_{Sun}
Sizes	10 – 500 au
Densities	10^{-12} – 10^{-24} g/cm^3
Dust temperatures	10 – 1 500 K
Gas temperatures	10 – 10^4 K



1 Turbulent Mixing (radial or vertical)

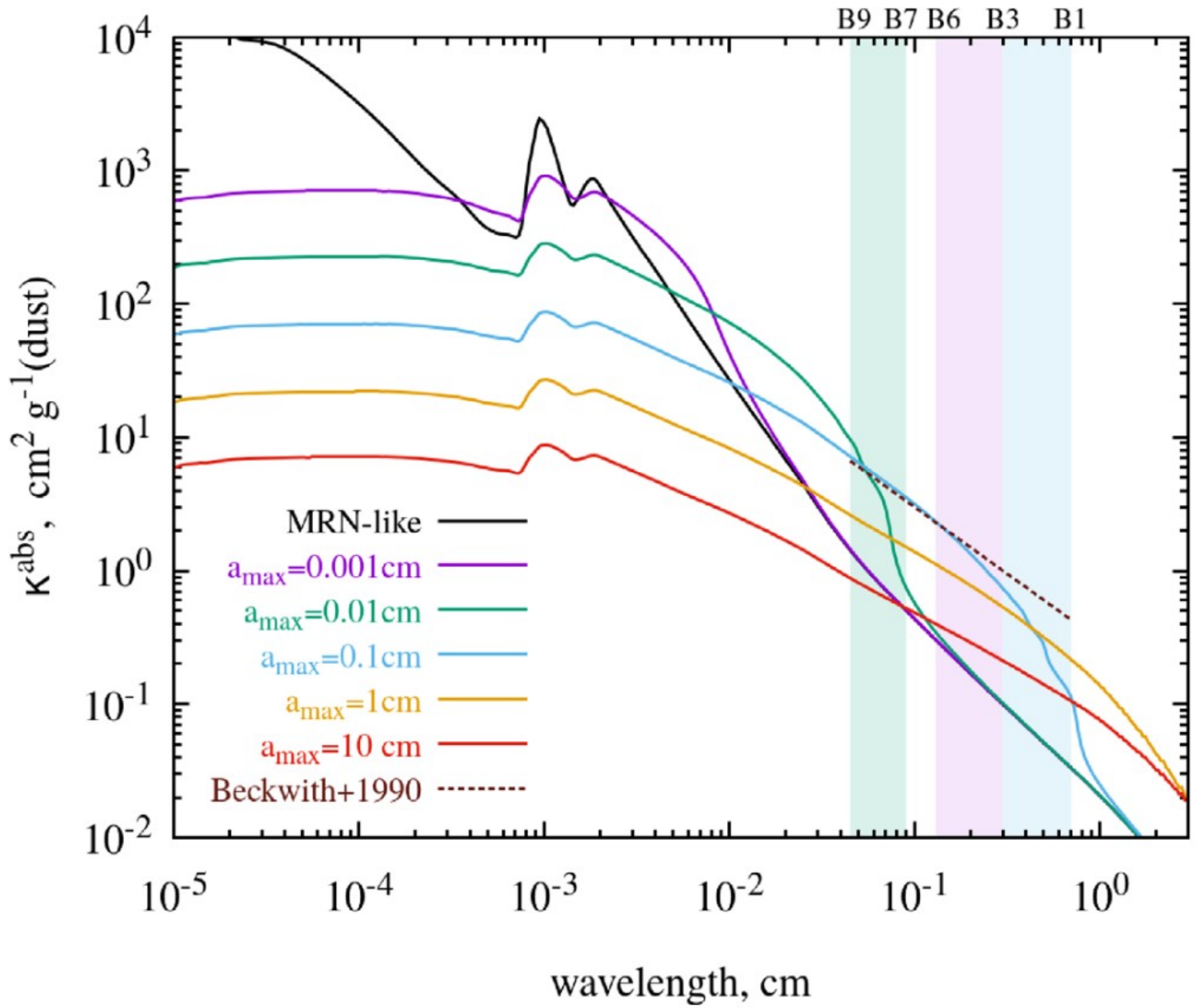
2 Vertical Settling

3 Radial Drift

4 a) Sticking
b) Bouncing
c) Fragmentation with mass transfer
d) Fragmentation

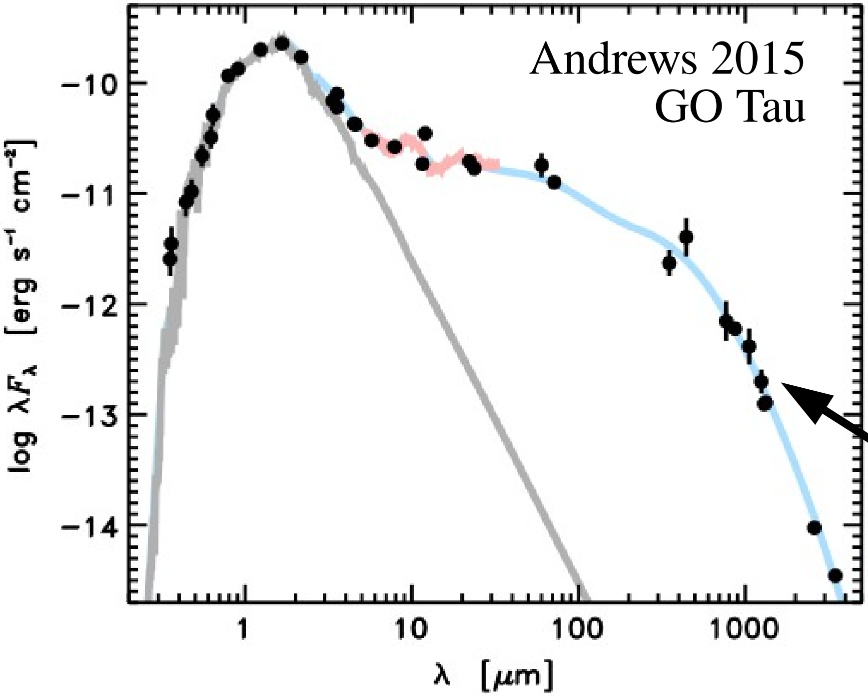
Testi+2014

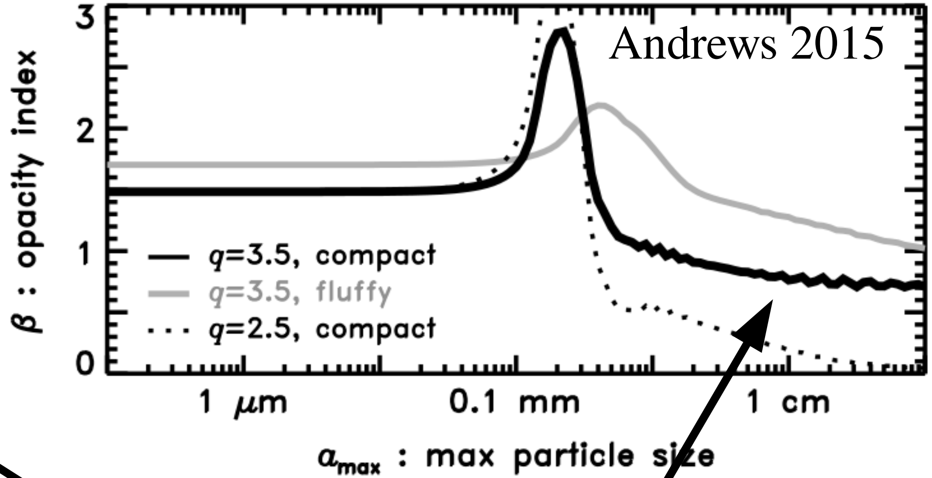
Dust opacities

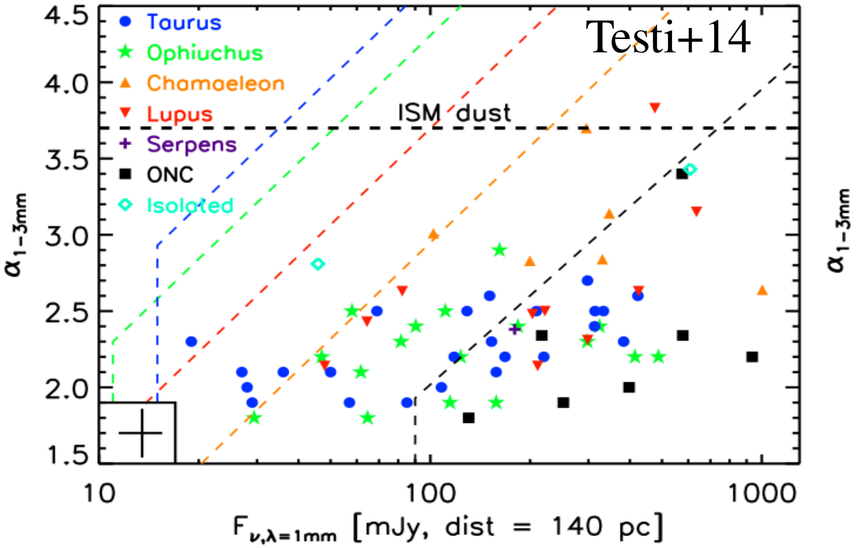


Pavlyuchenkov+2019

A: Evidence of Macroscopic Dust





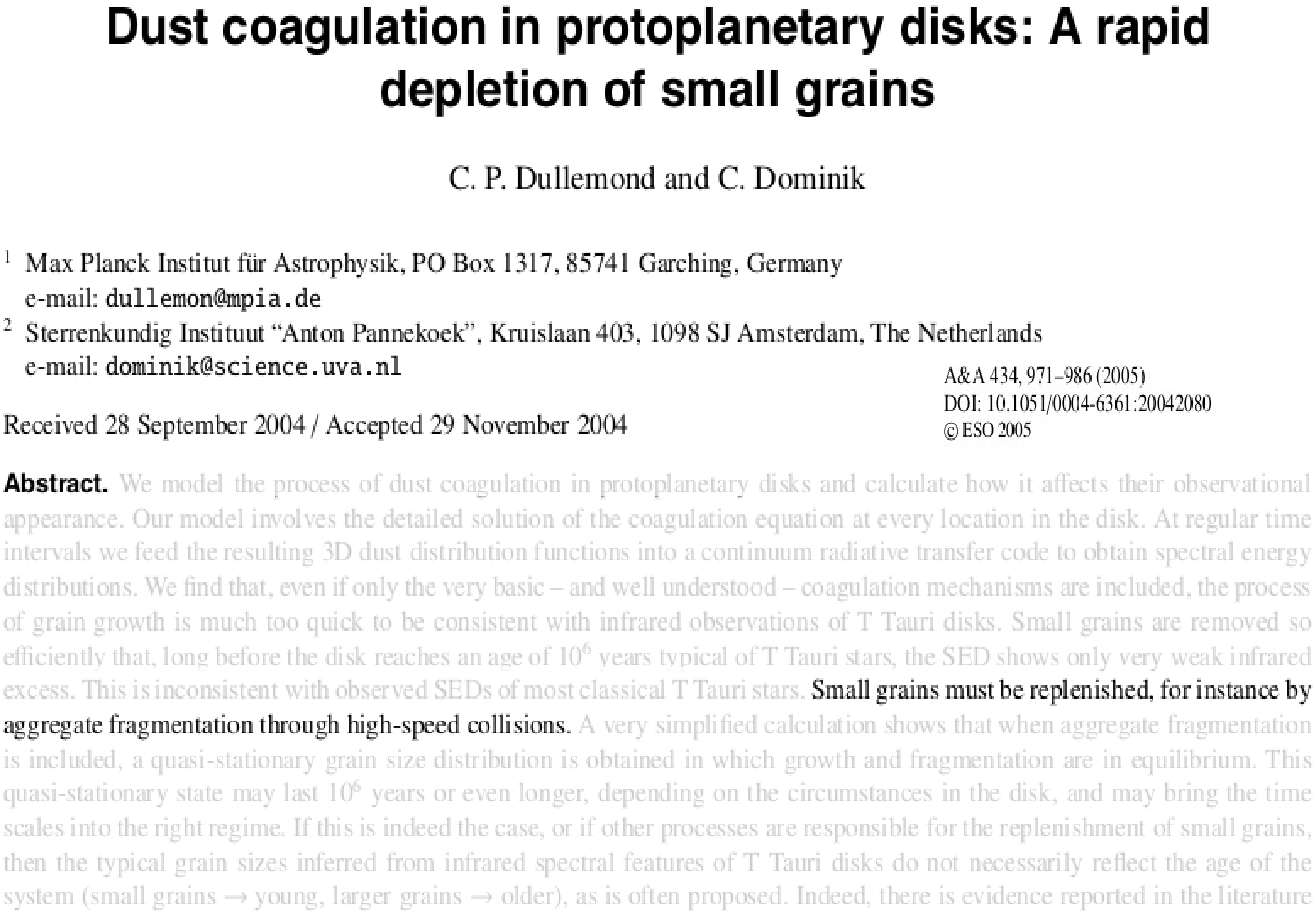


$$\alpha = 2 + \beta$$

→ presence of macroscopic grains

(however, optical depth and temperature gradients may be important)

B: Presence of Micron-size Dust



Dust coagulation in protoplanetary disks: A rapid depletion of small grains

C. P. Dullemond and C. Dominik

[1] Max Planck Institut für Astrophysik, PO Box 1317, 85741 Garching, Germany
e-mail: `dullemon@mpia.de`
[2] Sterrenkundig Instituut "Anton Pannekoek", Kruislaan 403, 1098 SJ Amsterdam, The Netherlands
e-mail: `dominik@science.uva.nl`

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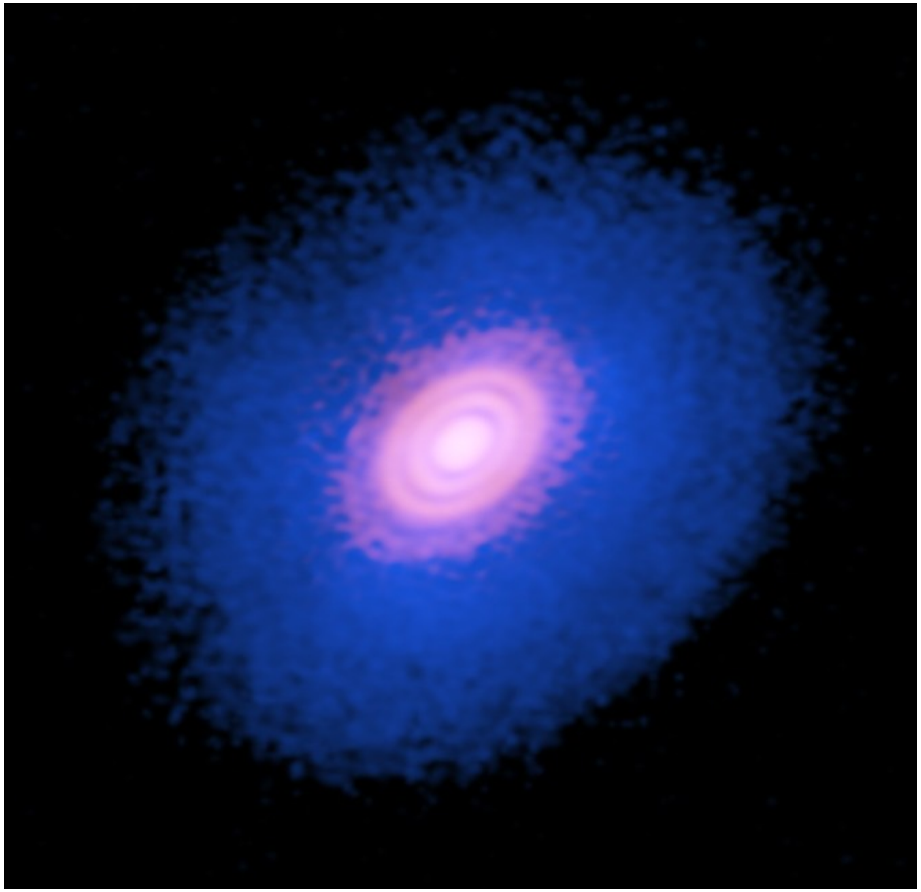
Abstract. We model the process of dust coagulation in protoplanetary disks and calculate how it affects their observational appearance. Our model involves the detailed solution of the coagulation equation at every location in the disk. At regular time intervals we feed the resulting 3D dust distribution functions into a continuum radiative transfer code to obtain spectral energy distributions. We find that, even if only the very basic – and well understood – coagulation mechanisms are included, the process of grain growth is much too quick to be consistent with infrared observations of T Tauri disks. Small grains are removed so efficiently that, long before the disk reaches an age of 10^6 years typical of T Tauri stars, the SED shows only very weak infrared excess. This is inconsistent with observed SEDs of most classical T Tauri stars. Small grains must be replenished, for instance by aggregate fragmentation through high-speed collisions. A very simplified calculation shows that when aggregate fragmentation is included, a quasi-stationary grain size distribution is obtained in which growth and fragmentation are in equilibrium. This quasi-stationary state may last 10^6 years or even longer, depending on the circumstances in the disk, and may bring the time scales into the right regime. If this is indeed the case, or if other processes are responsible for the replenishment of small grains, then the typical grain sizes inferred from infrared spectral features of T Tauri disks do not necessarily reflect the age of the system (small grains → young, larger grains → older), as is often proposed. Indeed, there is evidence reported in the literature

unconstrained dust coagulation is too fast!

C: Signs of Dust Radial Drift



HD 163296, Isella+2016

ABC: Dust Evolution

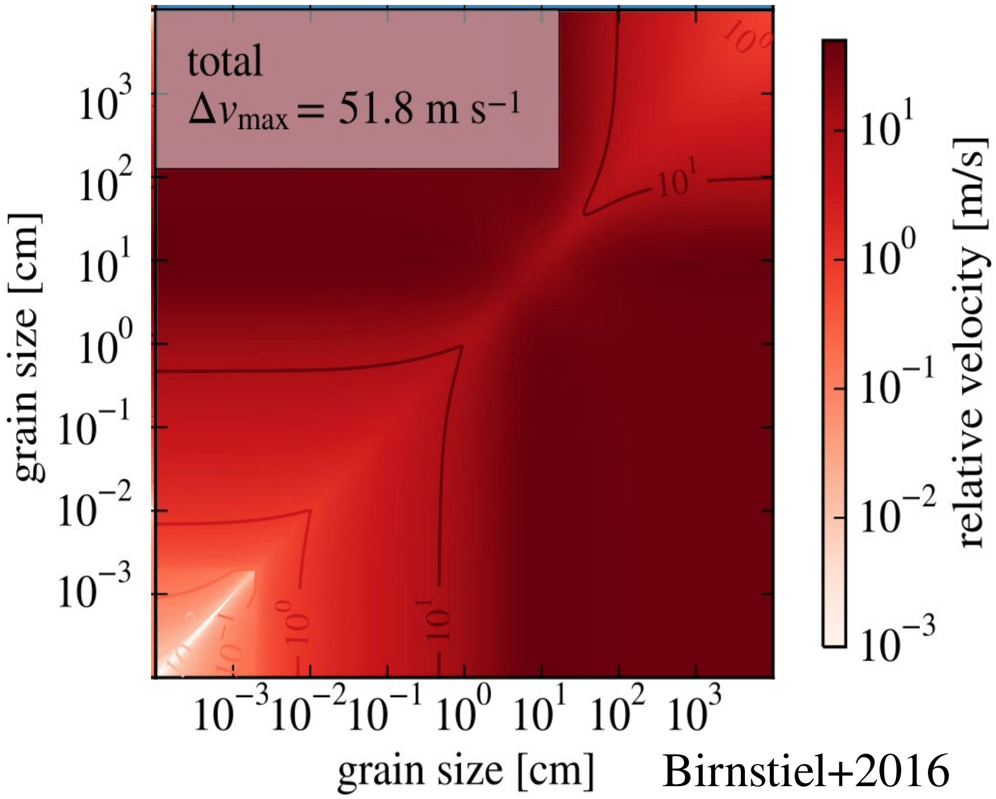
A. Evidence of **Macroscopic** Dust

B. Presence of **Micron-size** Dust

C. Dust Radial **Drift**

Collisional Velocities

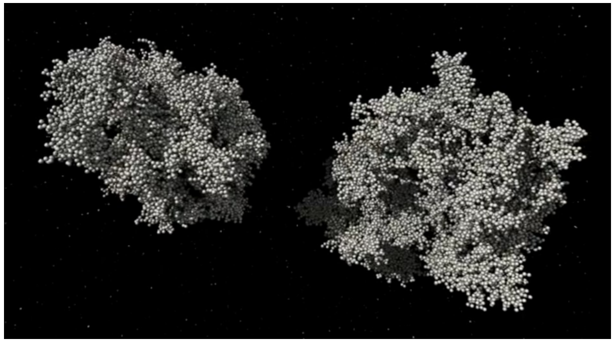
- Brownian motion
- Turbulence-induced velocities
- Size-dependent drift



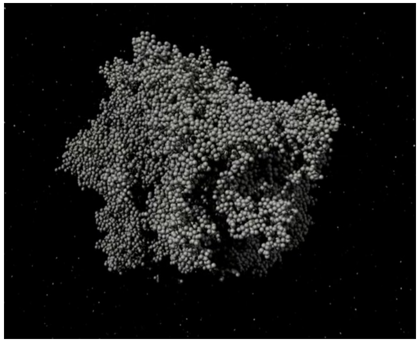
Birnstiel+2016

Collision outcome

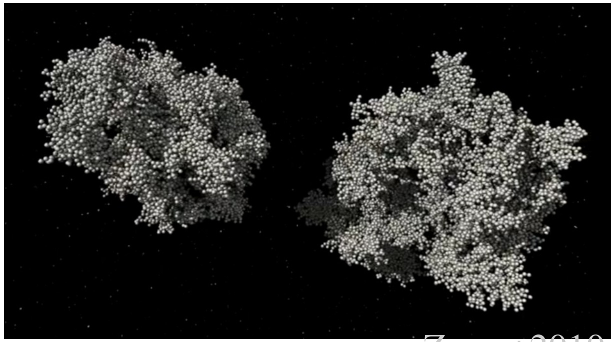
impact velocity



coagulation



bouncing



Zsom+2010

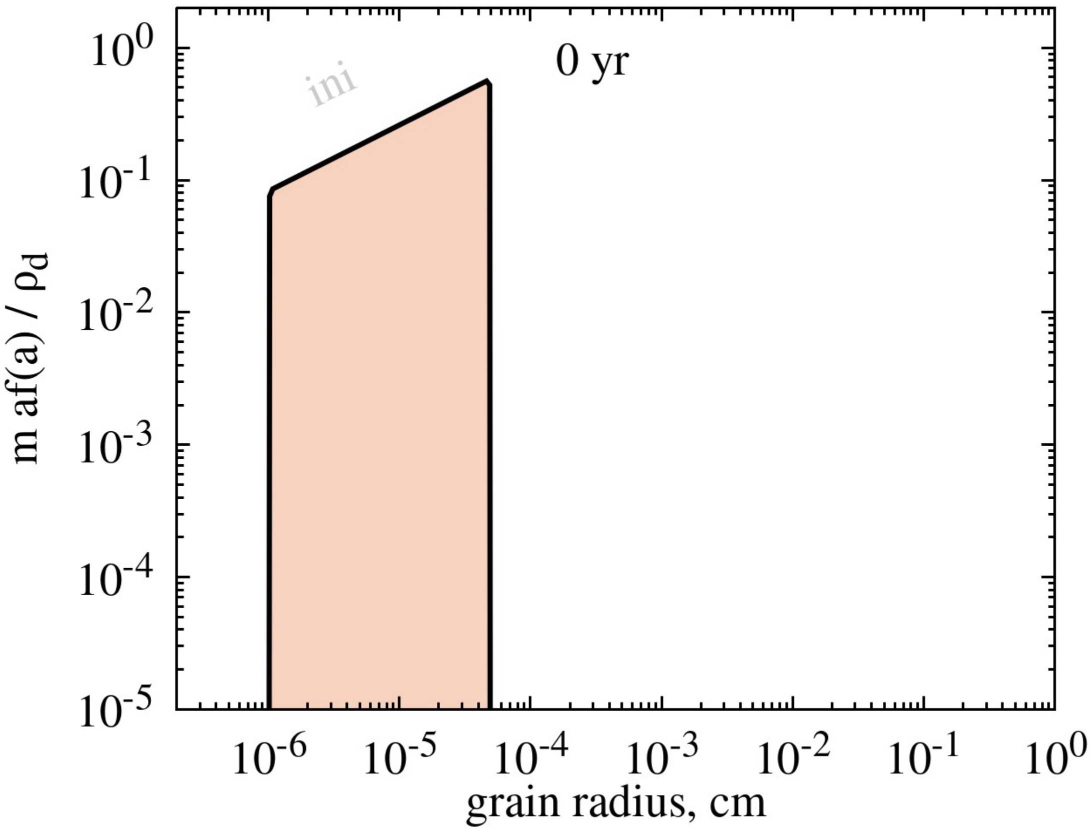
fragmentation

Brauer+2008

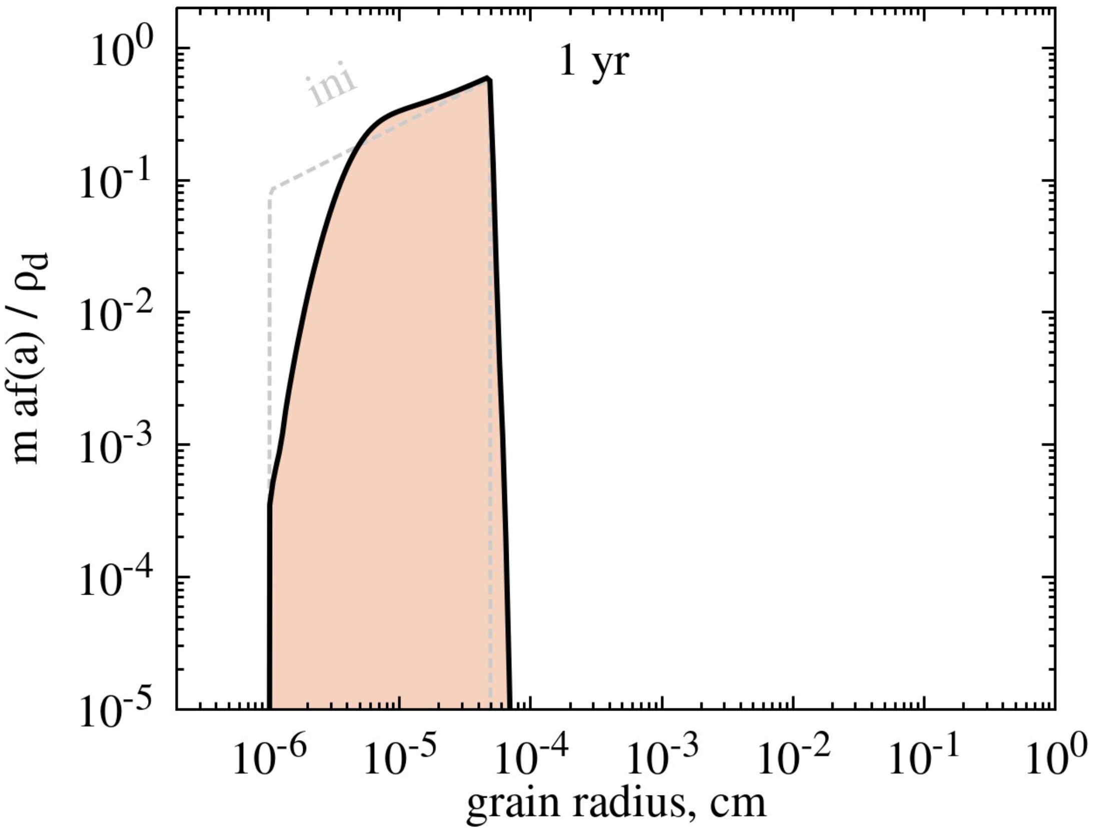
1 – 50 m/s

(c) Alexander Seizinger, University of Tübingen

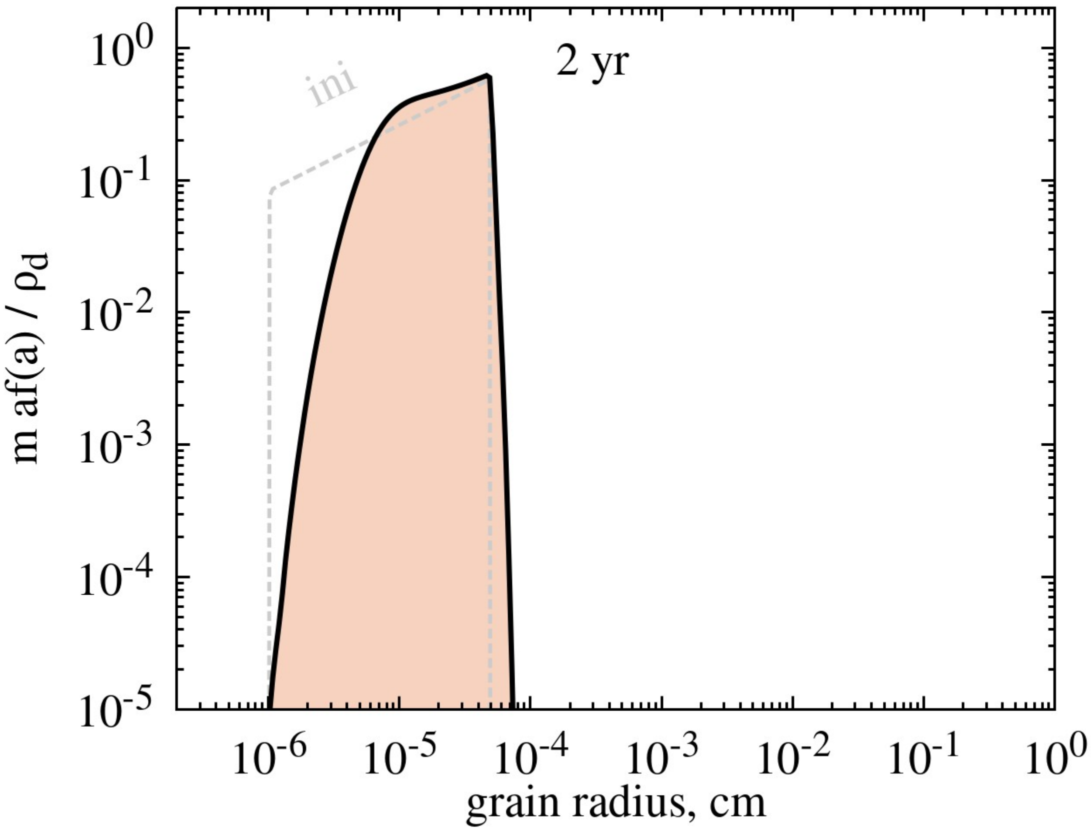
Smoluchowski Equation



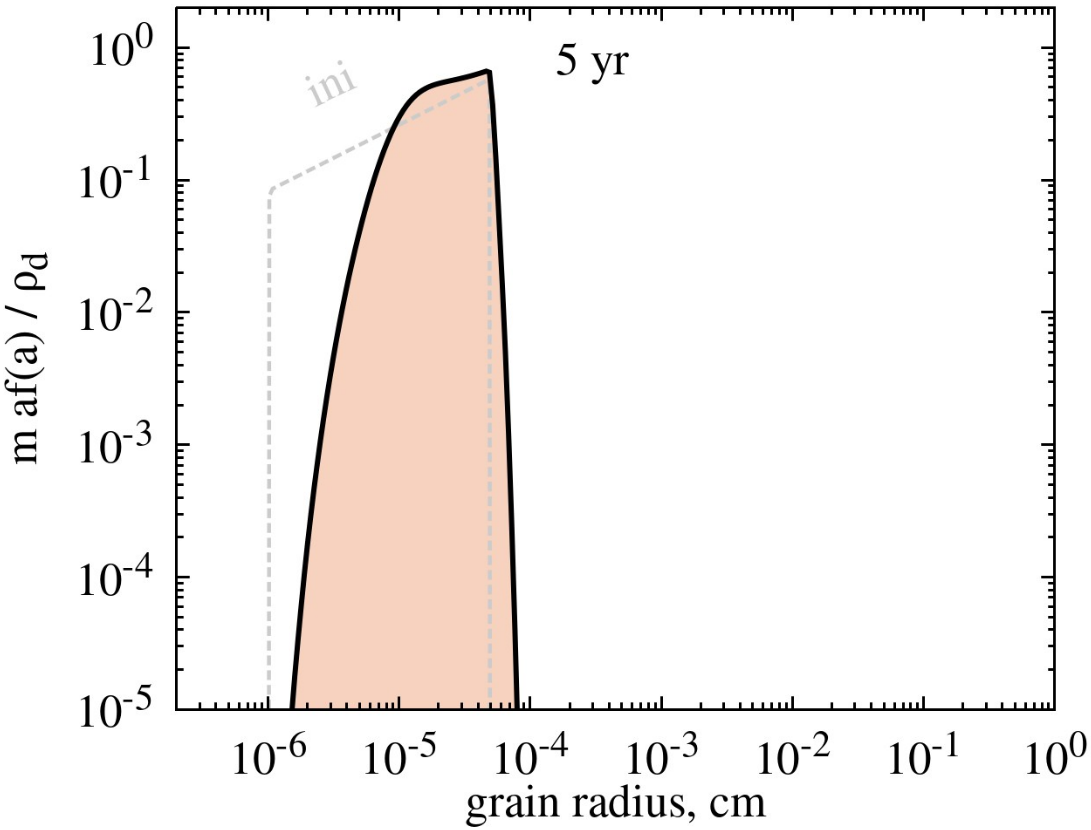
Smoluchowski Equation



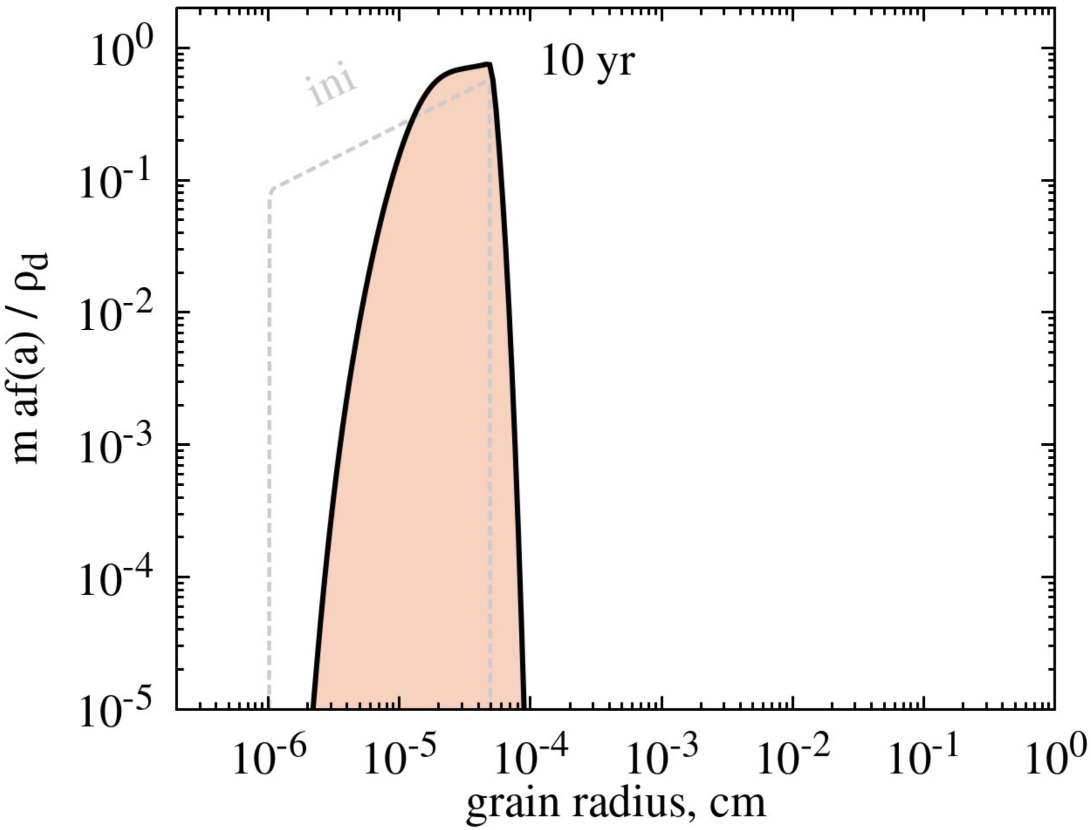
Smoluchowski Equation



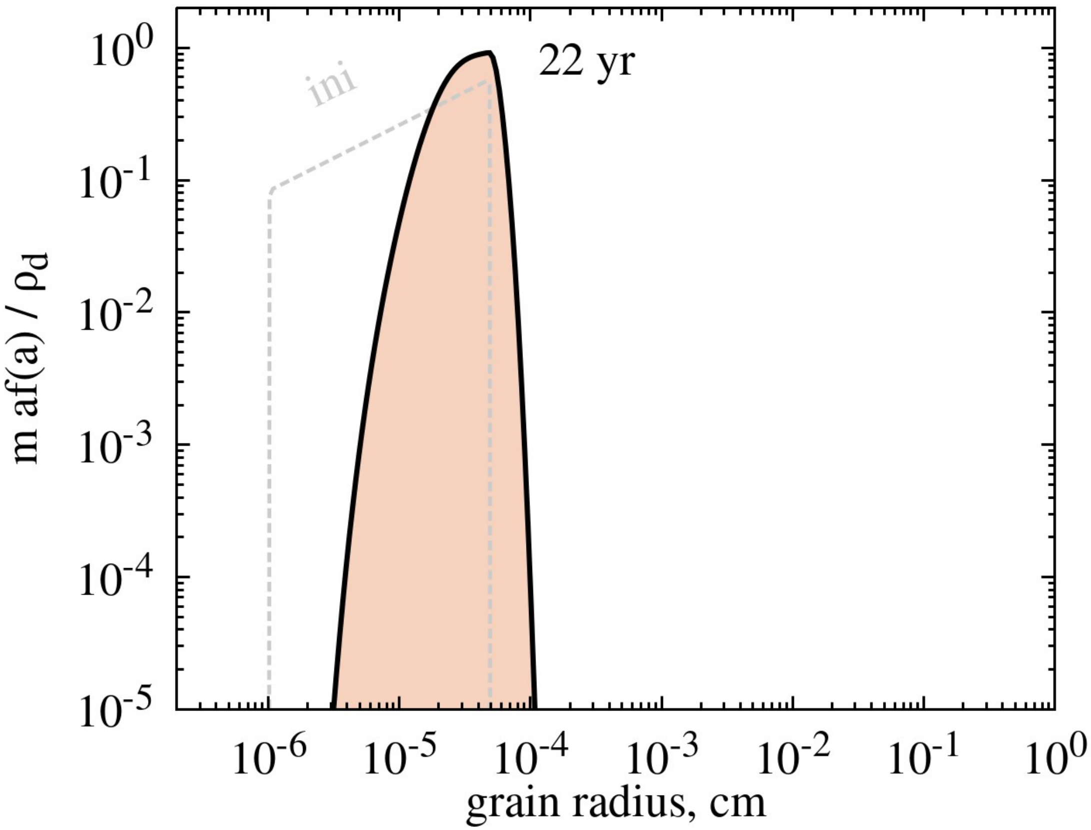
Smoluchowski Equation



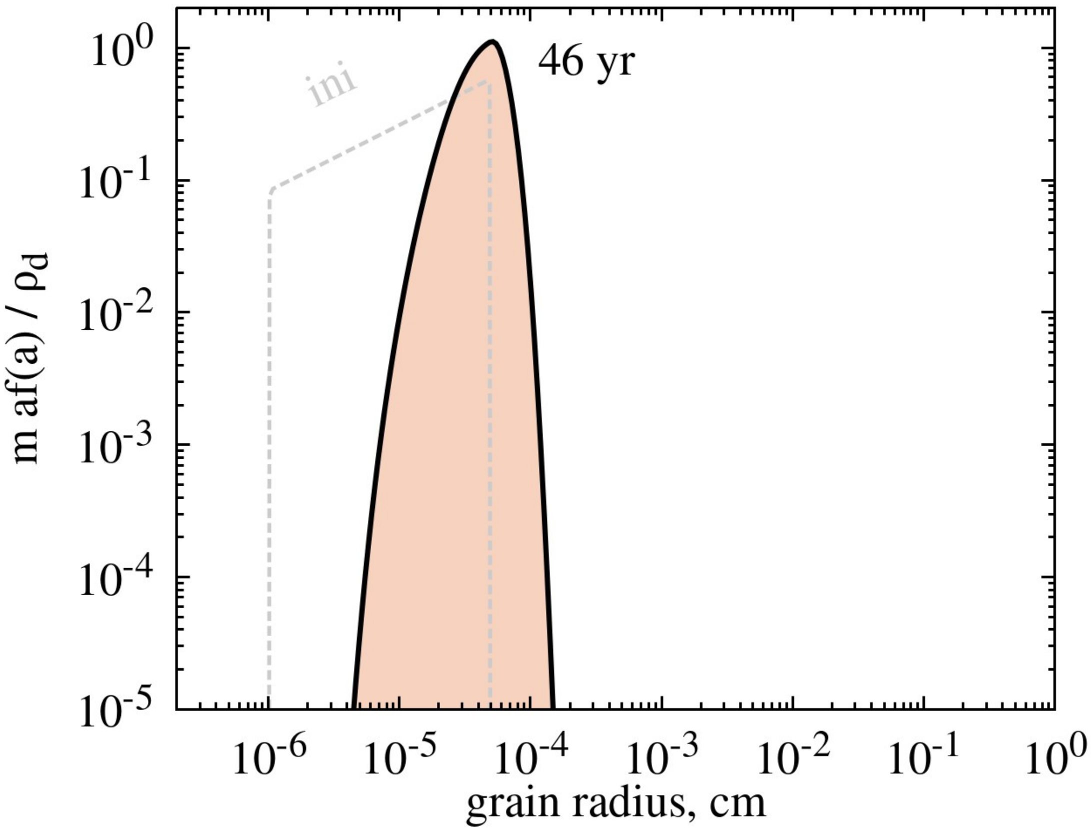
Smoluchowski Equation



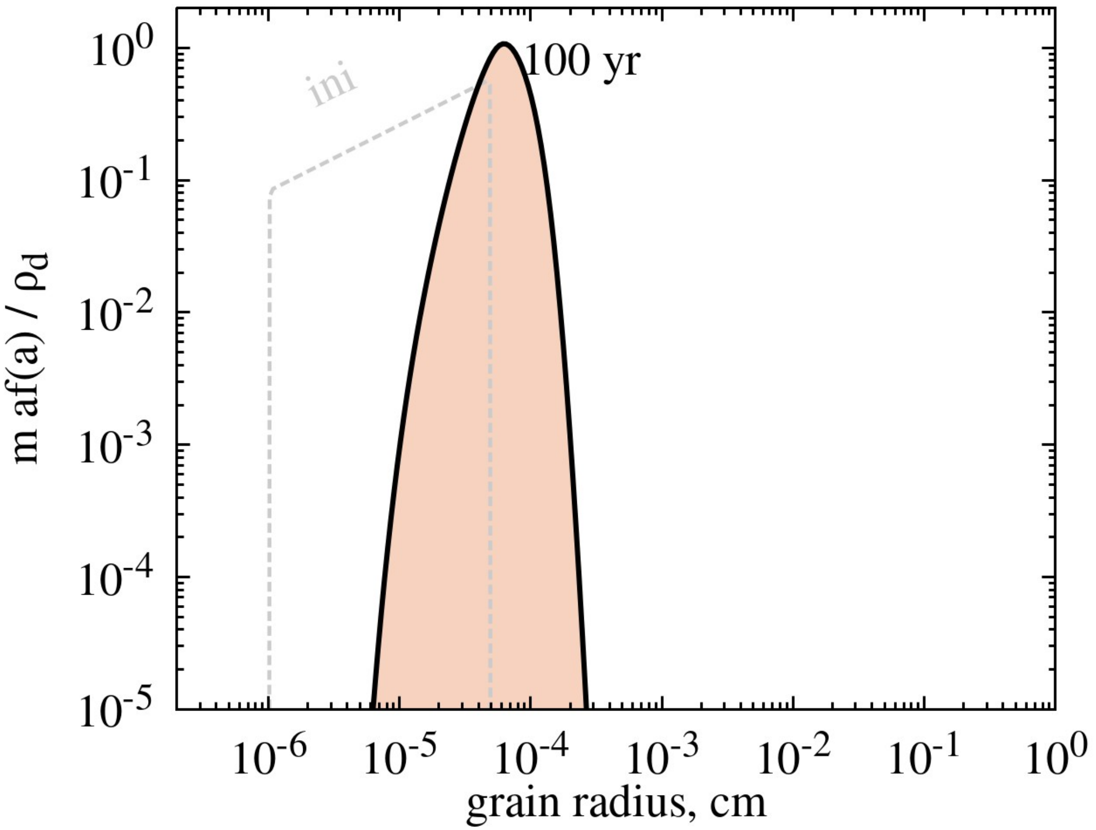
Smoluchowski Equation



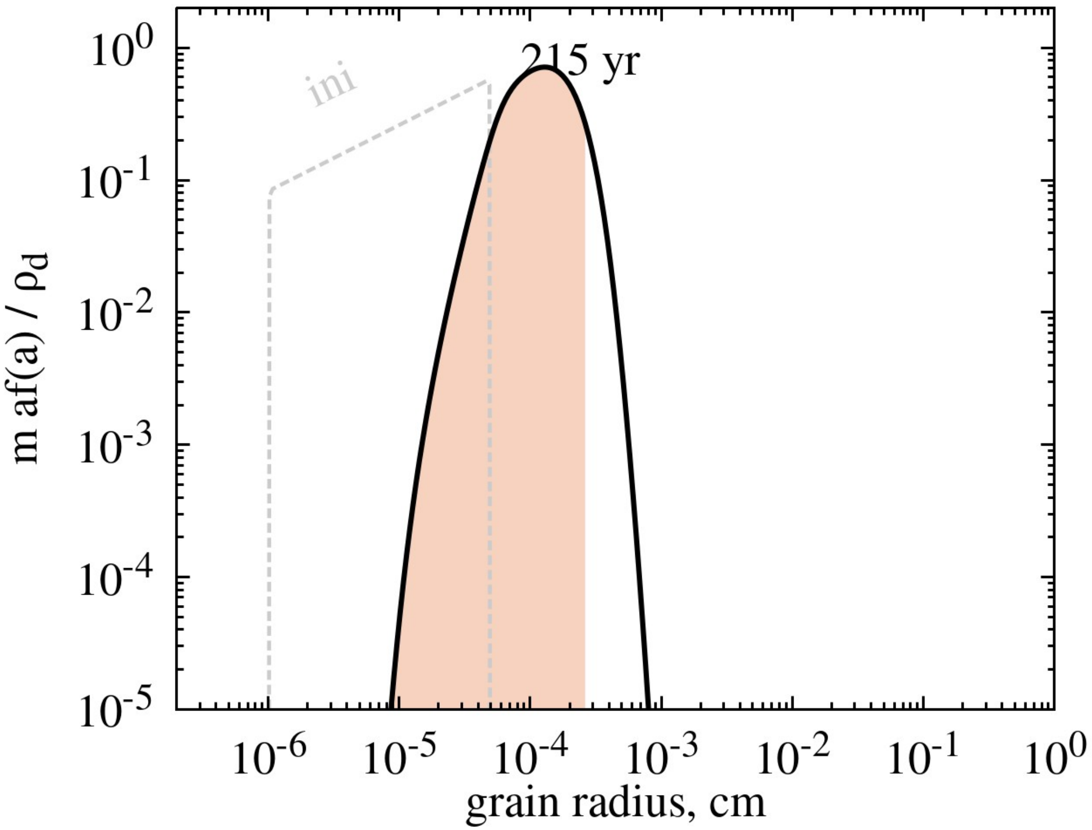
Smoluchowski Equation



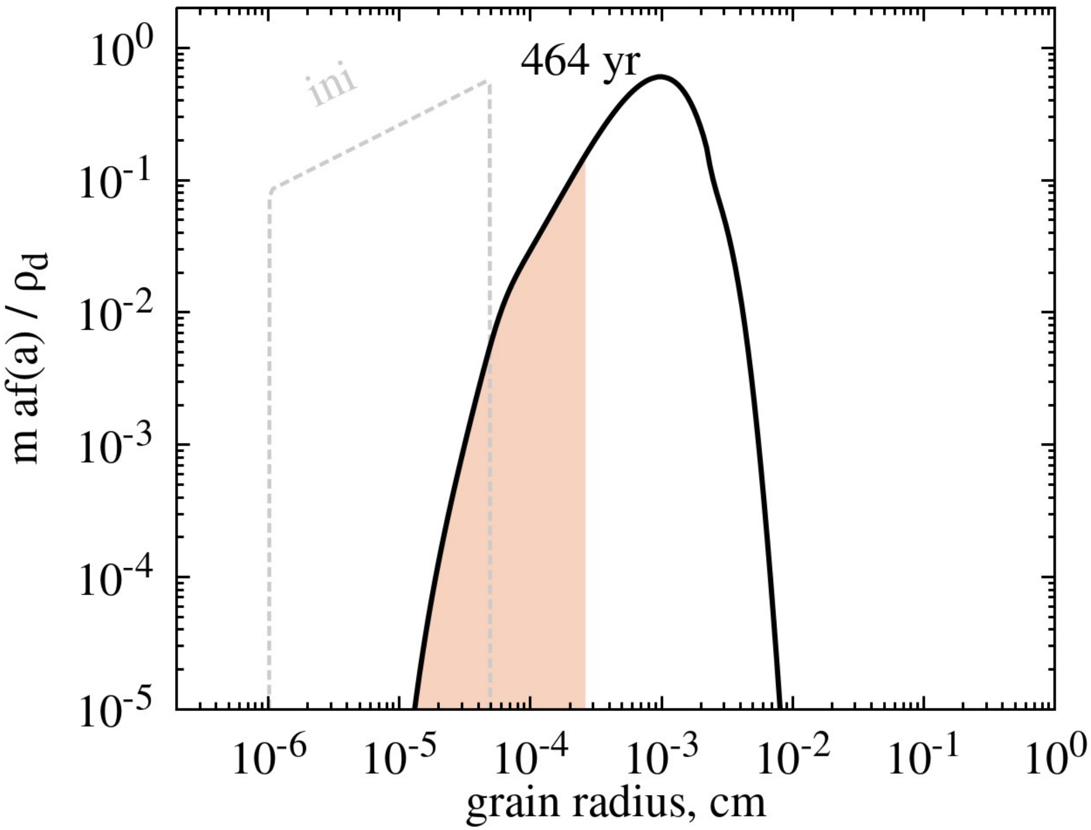
Smoluchowski Equation



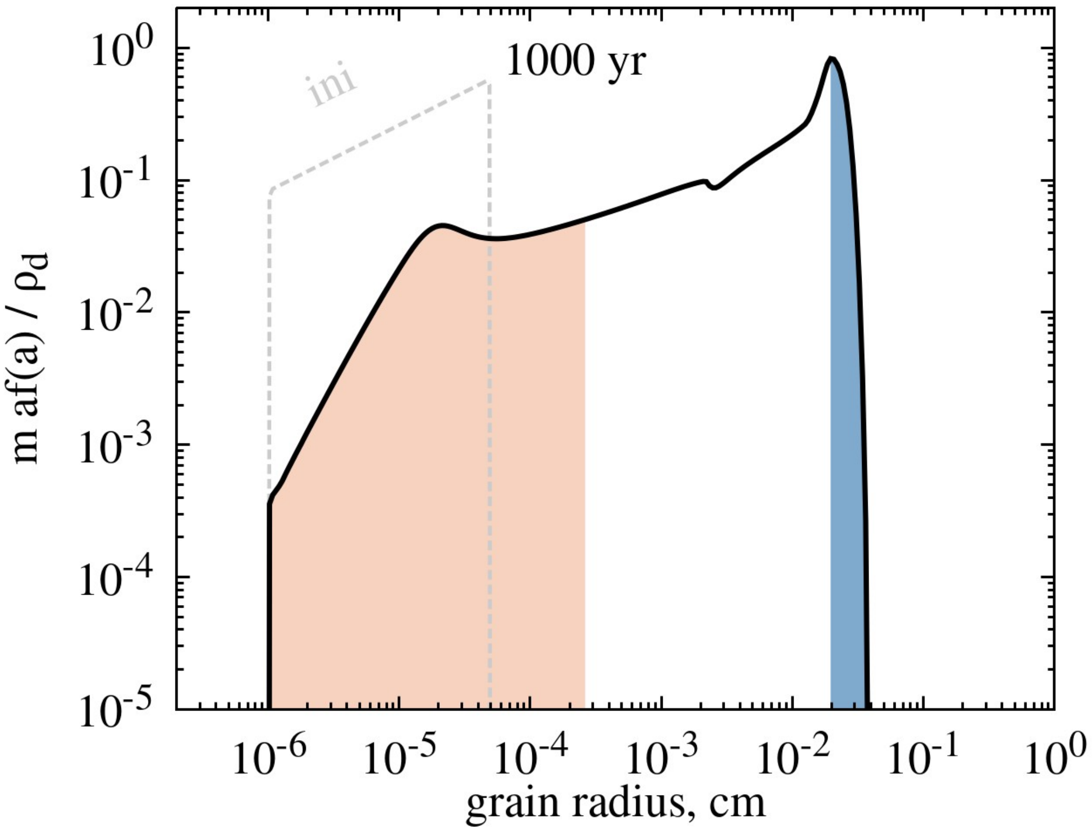
Smoluchowski Equation



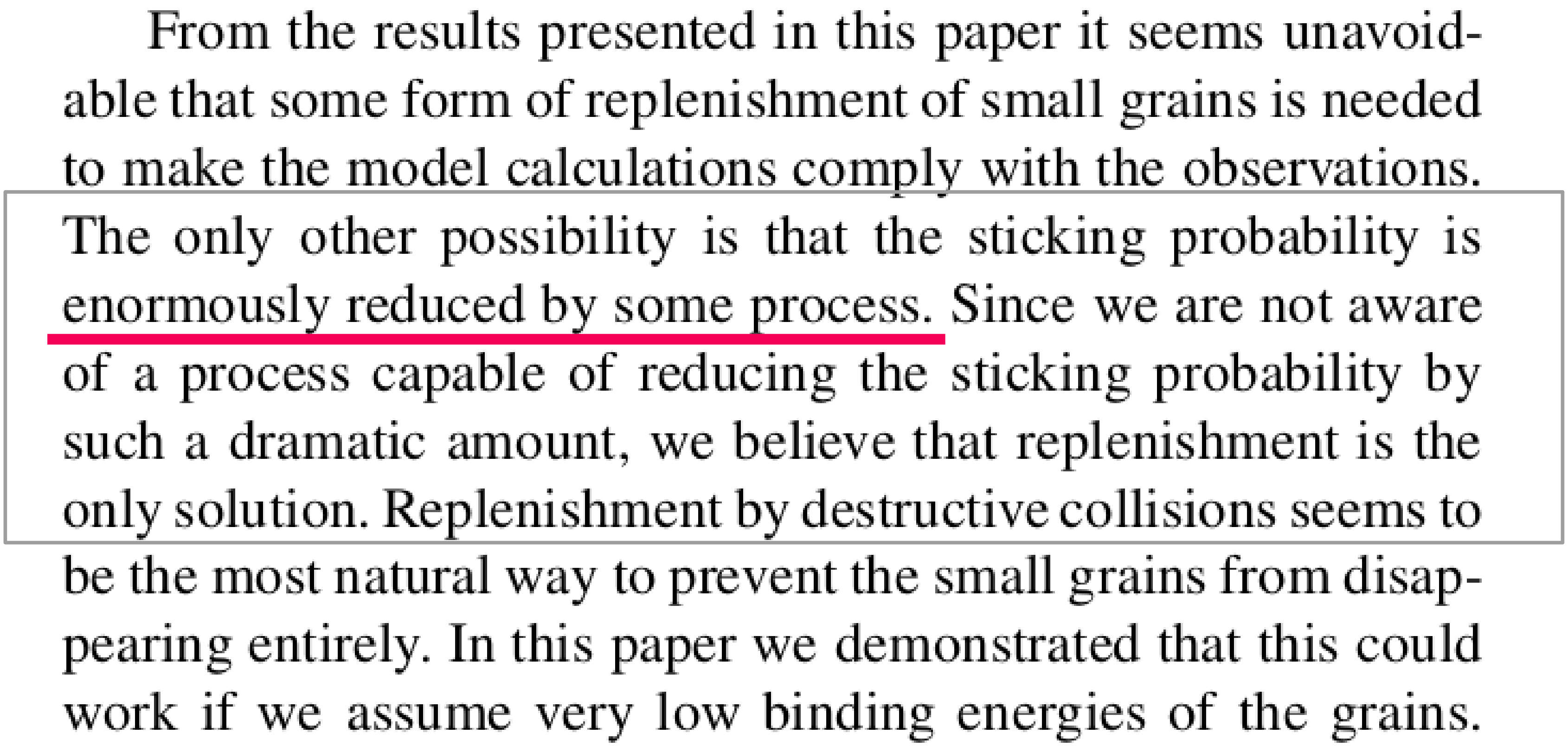
Smoluchowski Equation



Smoluchowski Equation

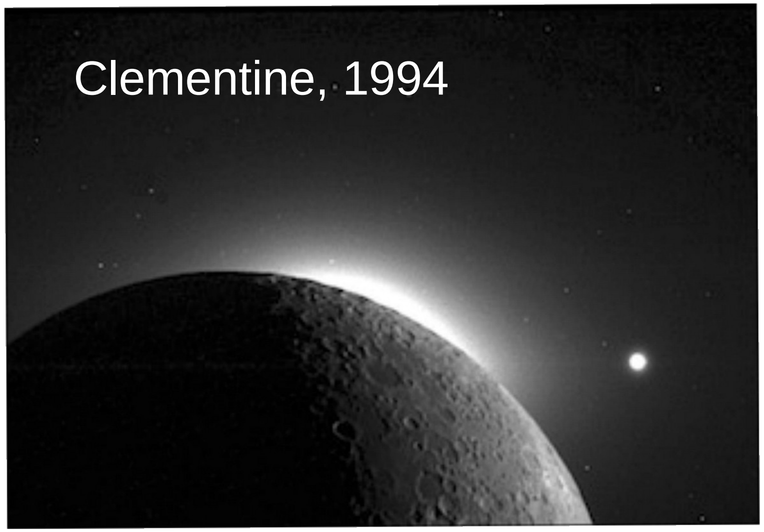


Smoluchowski Equation



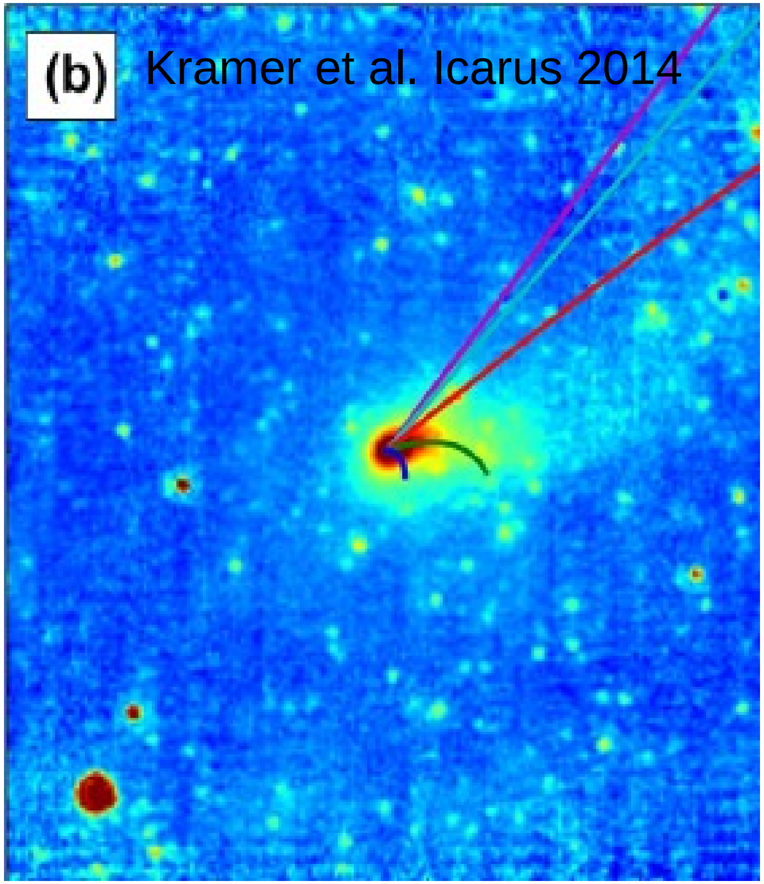
From the results presented in this paper it seems unavoidable that some form of replenishment of small grains is needed to make the model calculations comply with the observations. The only other possibility is that the sticking probability is enormously reduced by some process. Since we are not aware of a process capable of reducing the sticking probability by such a dramatic amount, we believe that replenishment is the only solution. Replenishment by destructive collisions seems to be the most natural way to prevent the small grains from disappearing entirely. In this paper we demonstrated that this could work if we assume very low binding energies of the grains.

Dullemond & Dominik, 2005



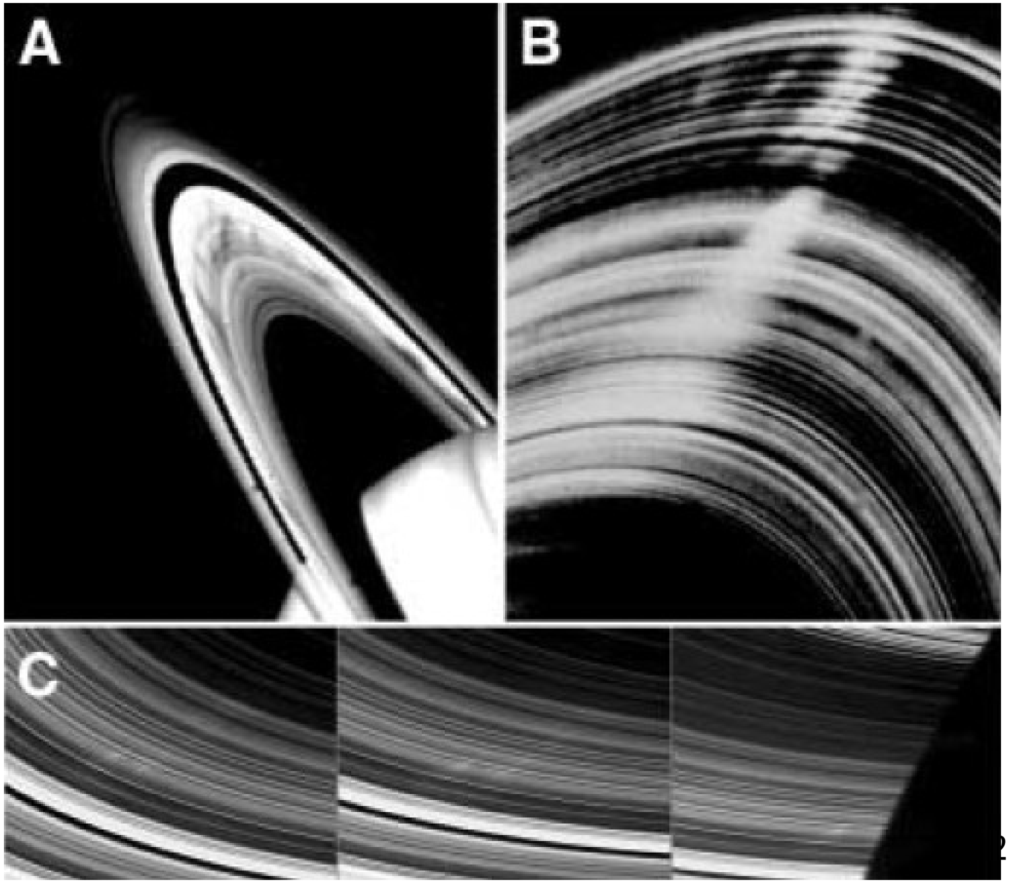
Clementine, 1994

> “A grain in interstellar space in not likely to be electrically neutral”
>
> *Endrik Krügel, “The Physics of Interstellar Dust”*



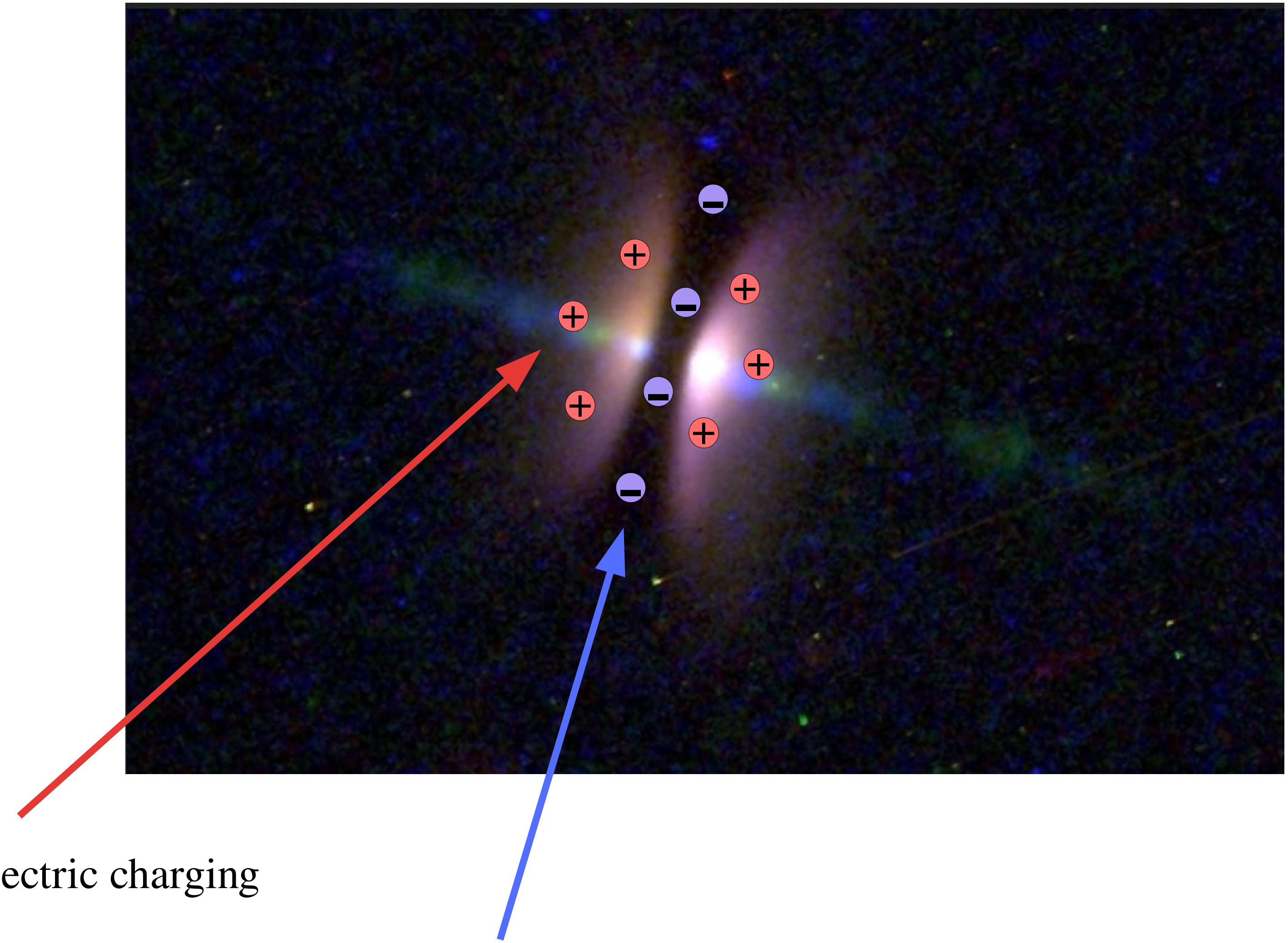
Kramer et al. Icarus 2014

HB, 2005/2008 Spitzer 24 um, 27 AU



Spokes in Saturn rings, Voyagers 2,1, Cassini

Grain Charging in PPDs

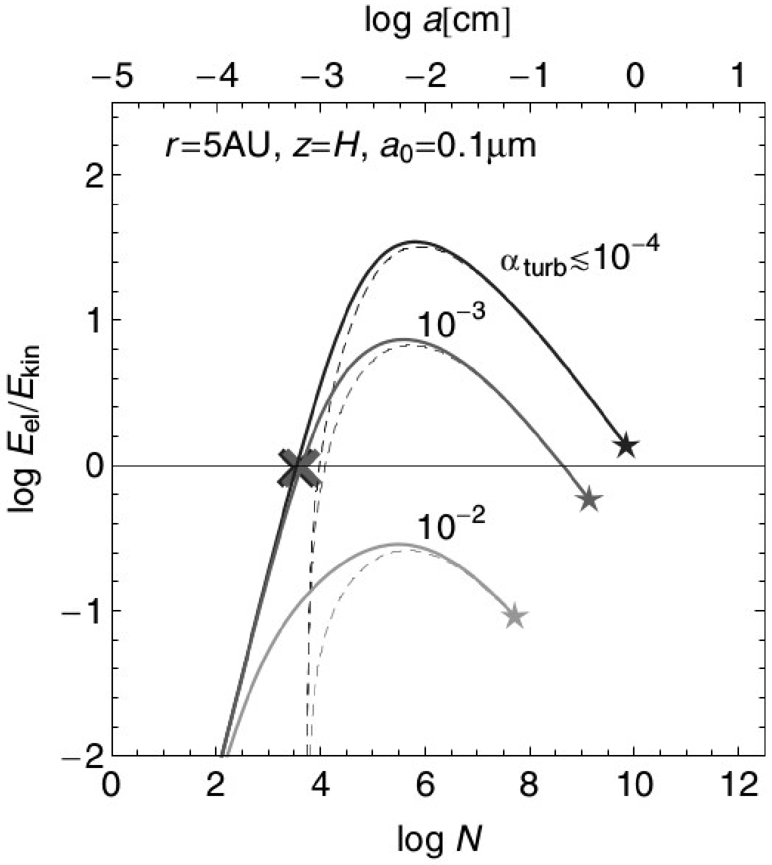


photoelectric charging

plasma charging

Dust Grains are Charged

$$\pi(a_i + a_j)^2 \left[1 - \frac{2Q_iQ_je_p^2}{m_{ij}(a_i + a_j)u_{ij}^2}\right]$$



Okuzumi 2009

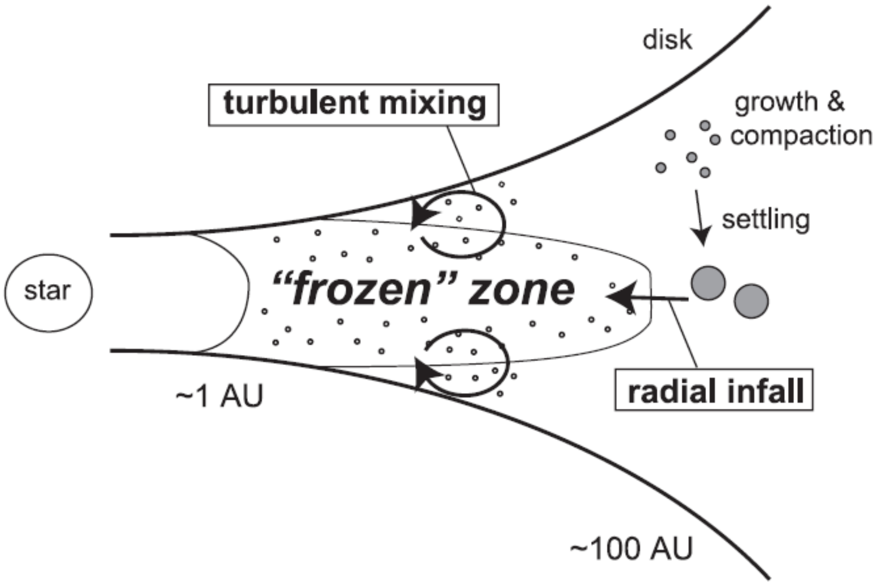
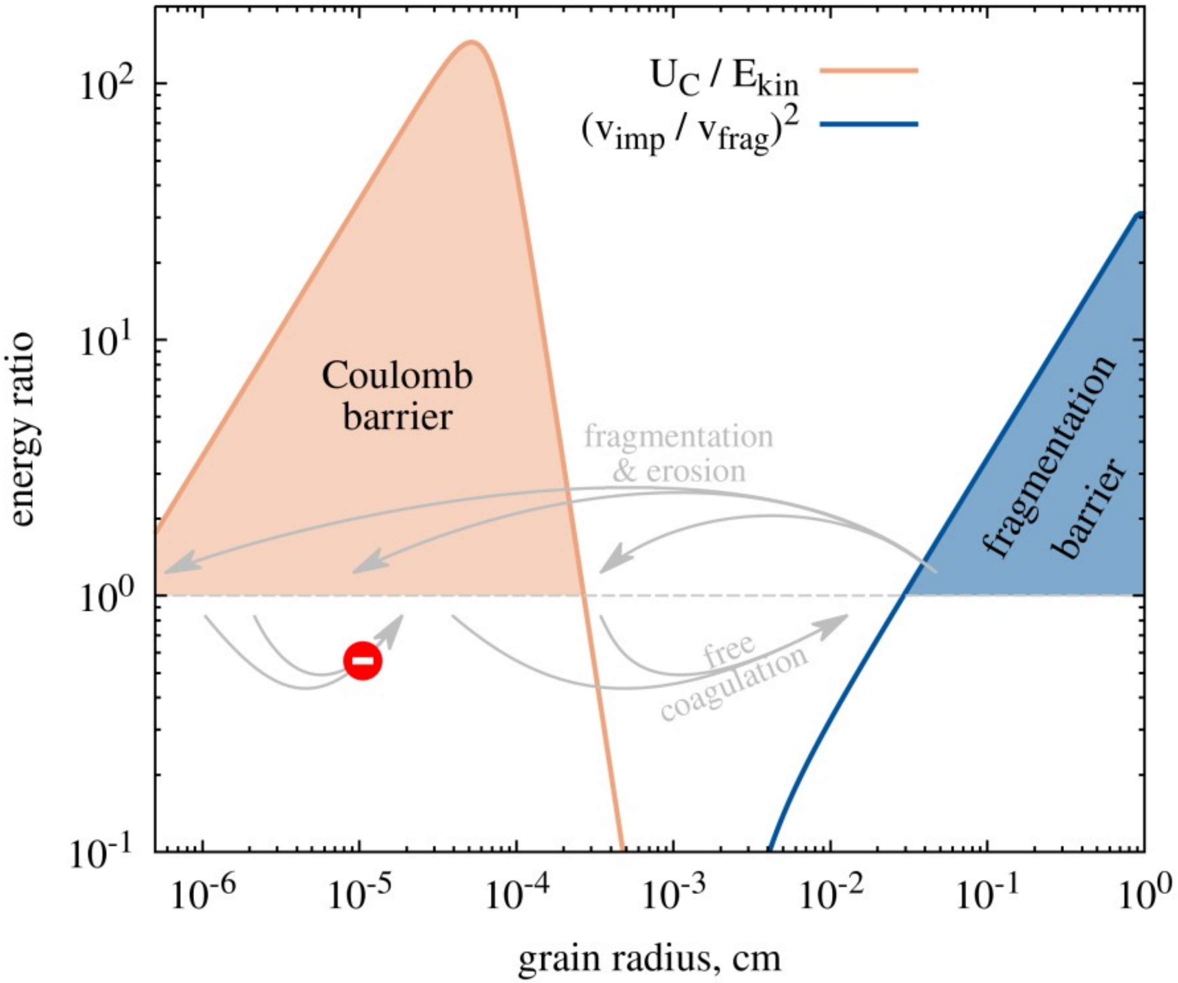


Figure 12. Dust transport mechanisms that could supply large aggregates to the frozen zone (not to scale). Without any transport mechanism, the electrostatic barrier halts dust growth at 1–10 AU $\lesssim r \lesssim$ 100 AU near the midplane (the "frozen" zone). However, vertical mixing due to turbulence could allow the

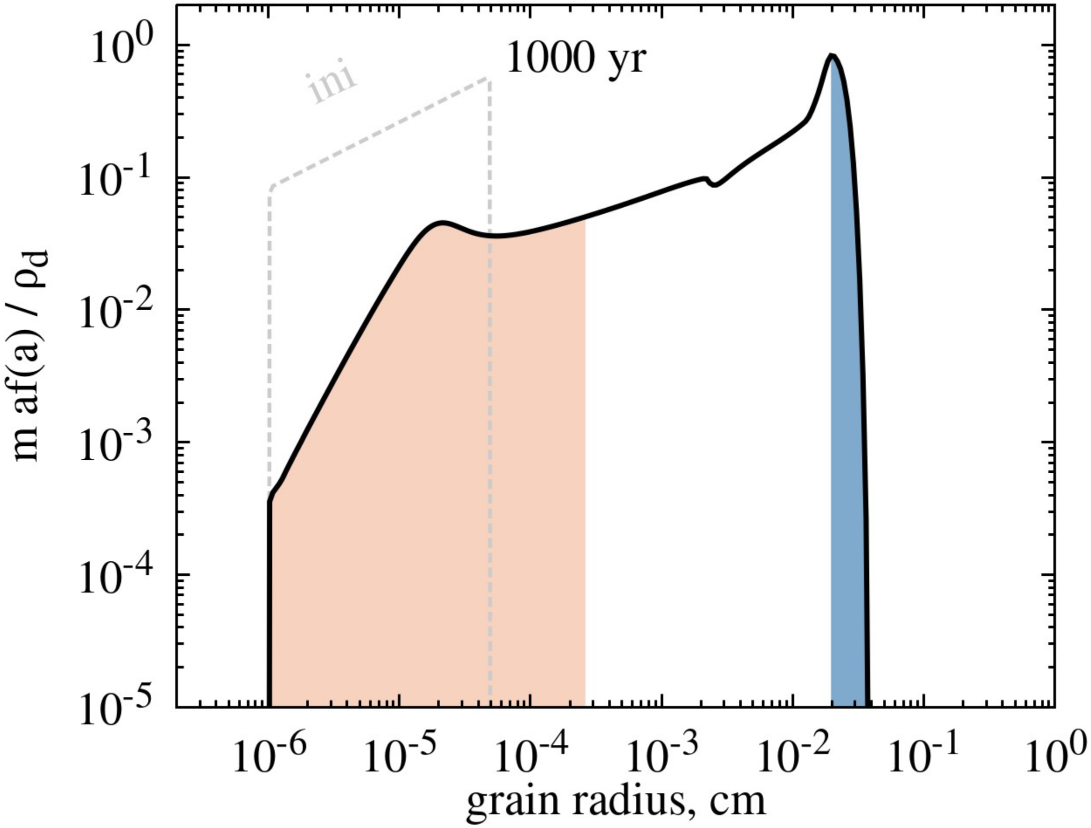
Okuzumi+2011b

Two Barriers Against Dust Growth

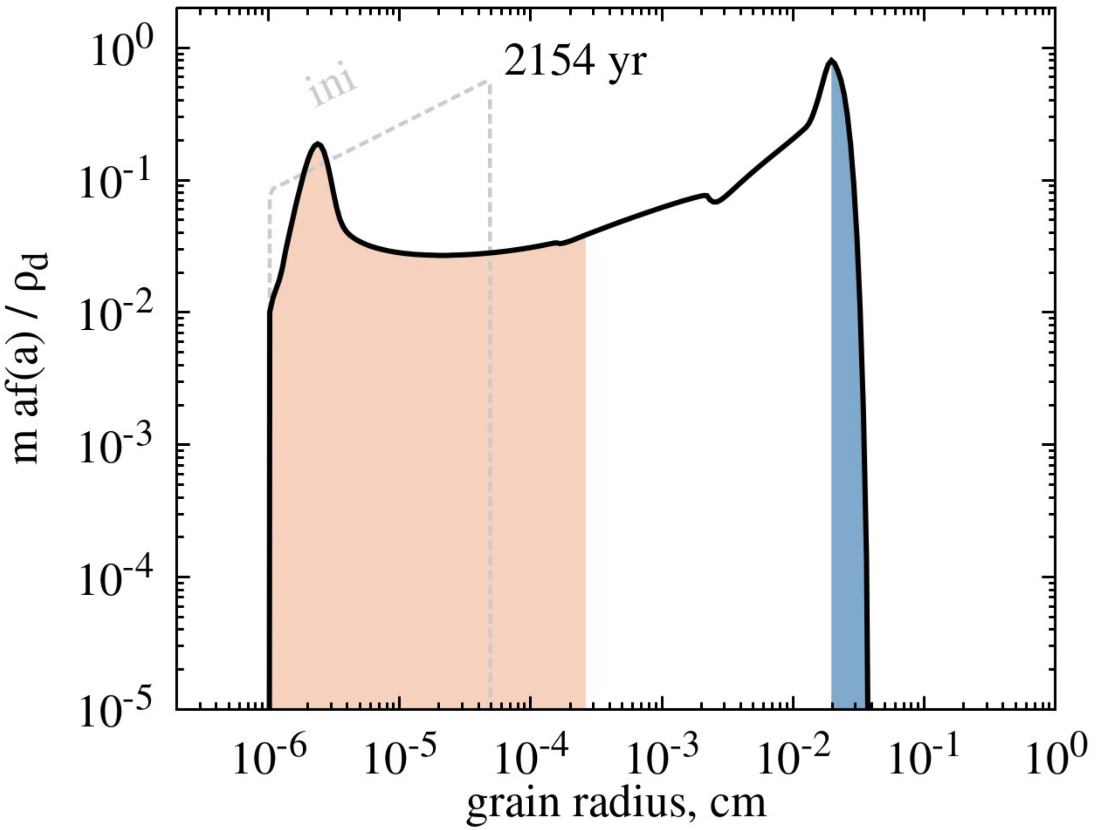


Akimkin+2023

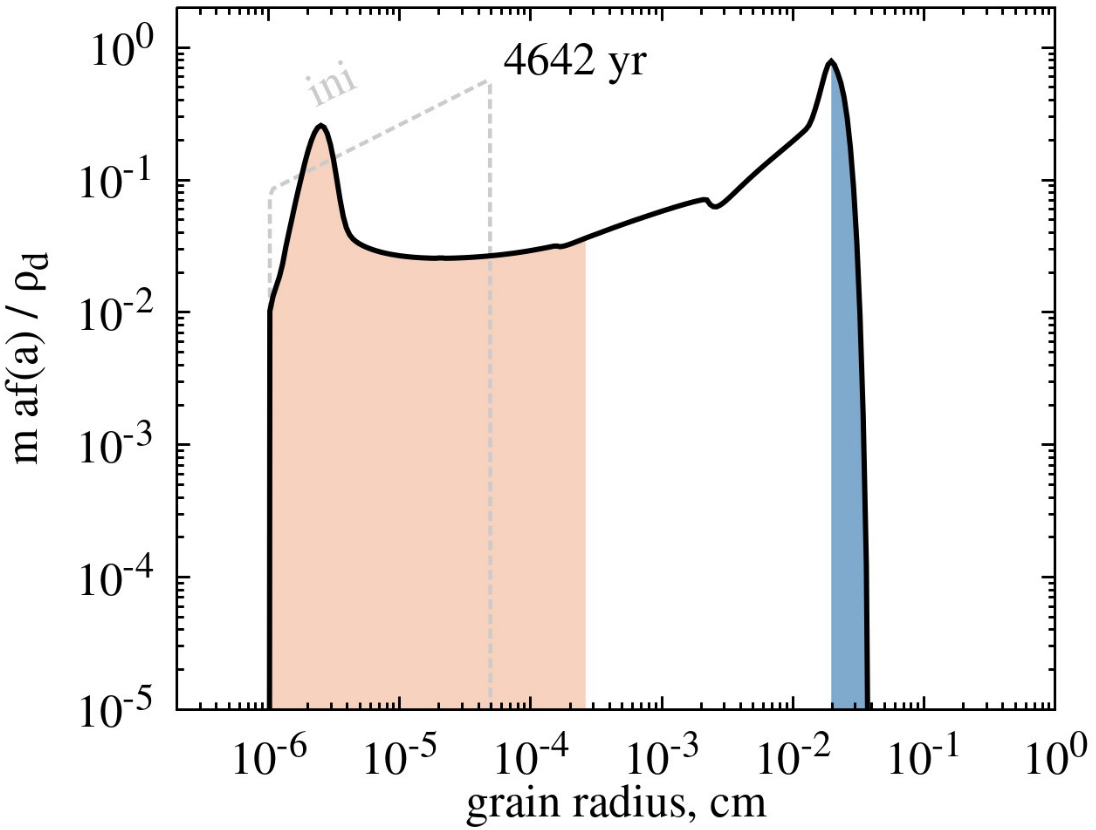
Smoluchowski Equation



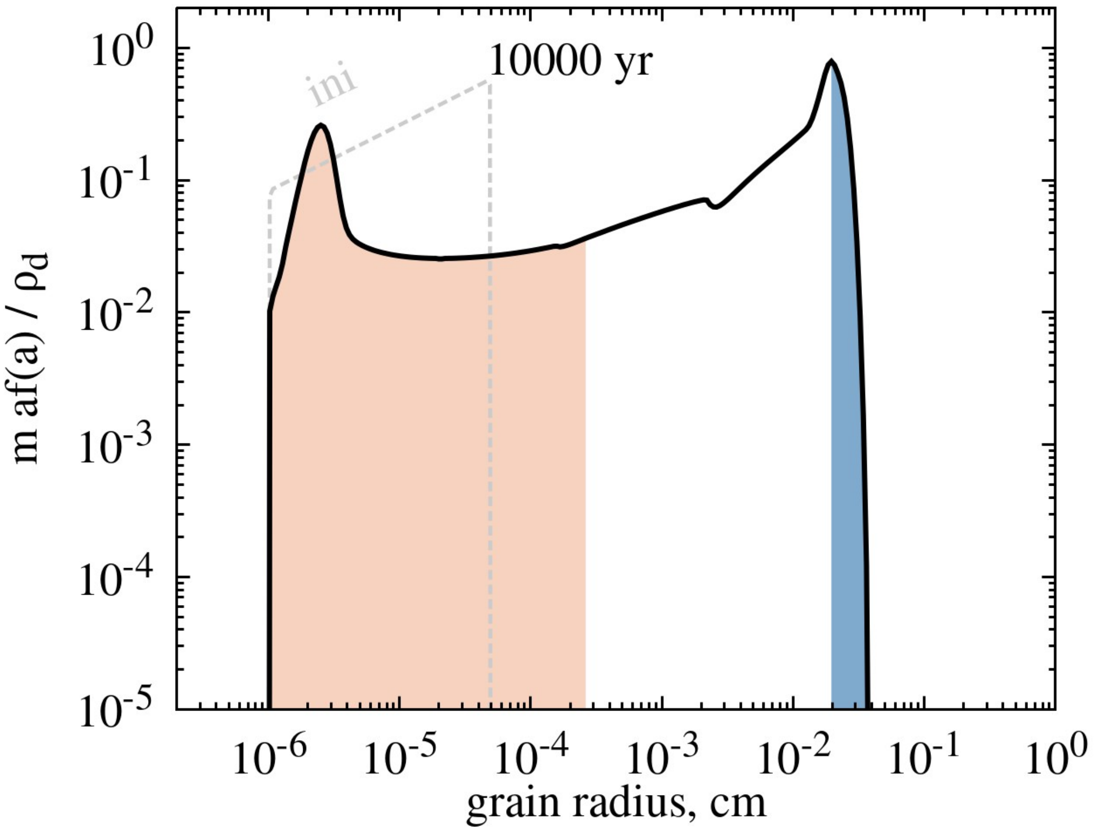
Smoluchowski Equation



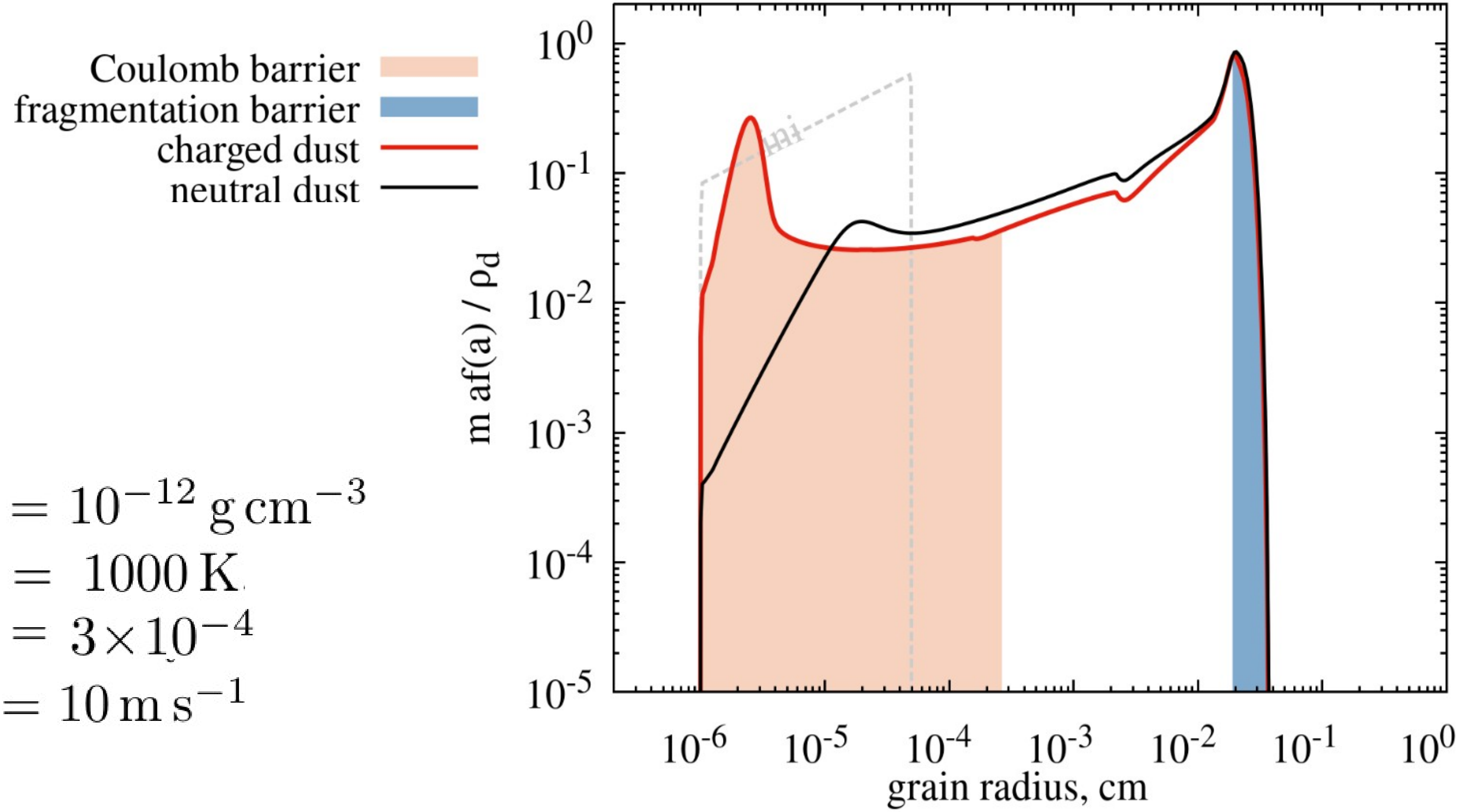
Smoluchowski Equation



Smoluchowski Equation



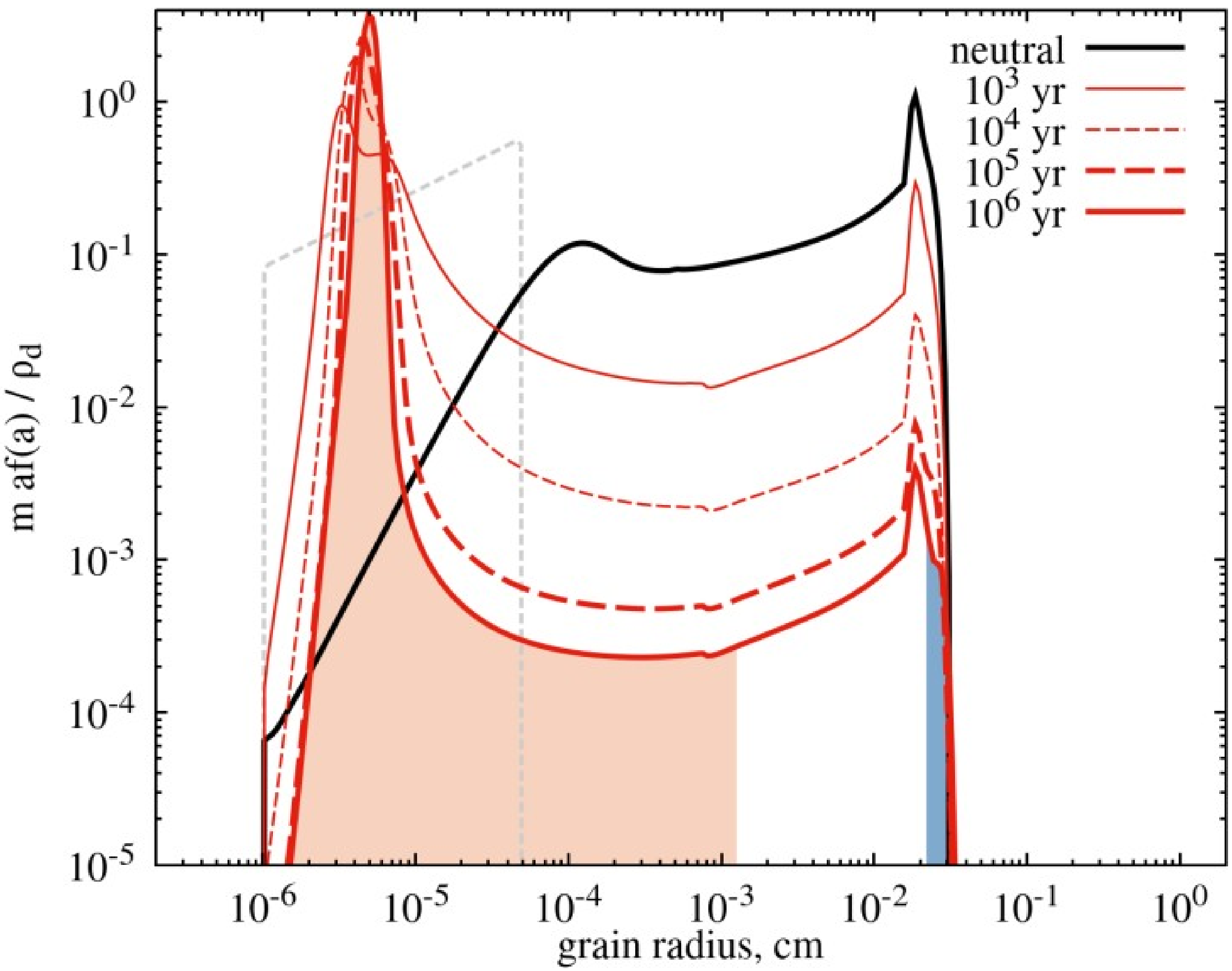
Smoluchowski Equation



$$\rho_{\mathrm{g}} = 10^{-12}\,\mathrm{g\,cm^{-3}}$$
$$T = 1000\,\mathrm{K}$$
$$\alpha_{\mathrm{t}} = 3\times10^{-4}$$
$$v_{\mathrm{frag}} = 10\,\mathrm{m\,s^{-1}}$$

Akimkin+2023

Coagulation-Fragmentation Imbalance



2D Hydrodynamic Modelling with FEOSAD

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

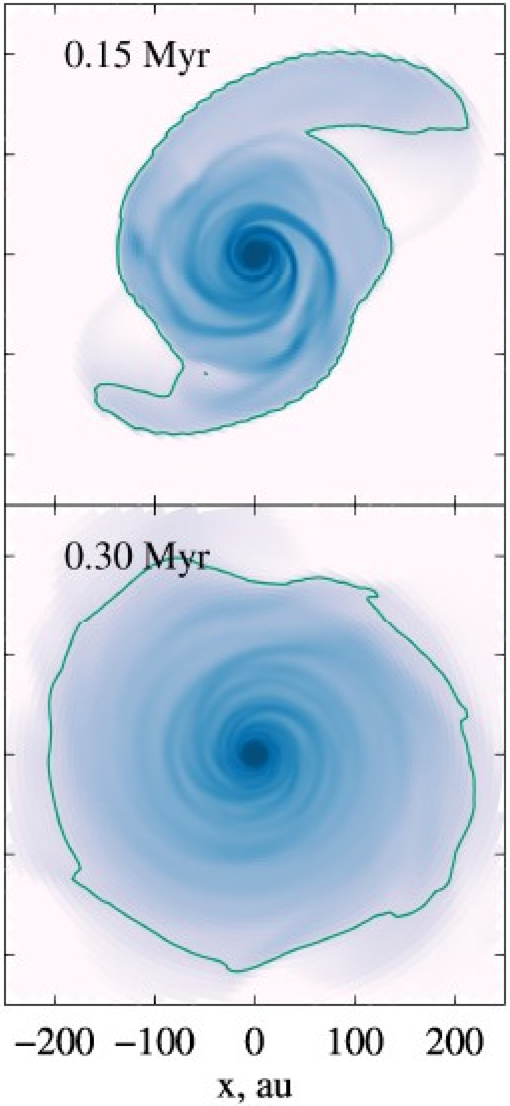
– initial conditions: flattened protostellar core;

– 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);

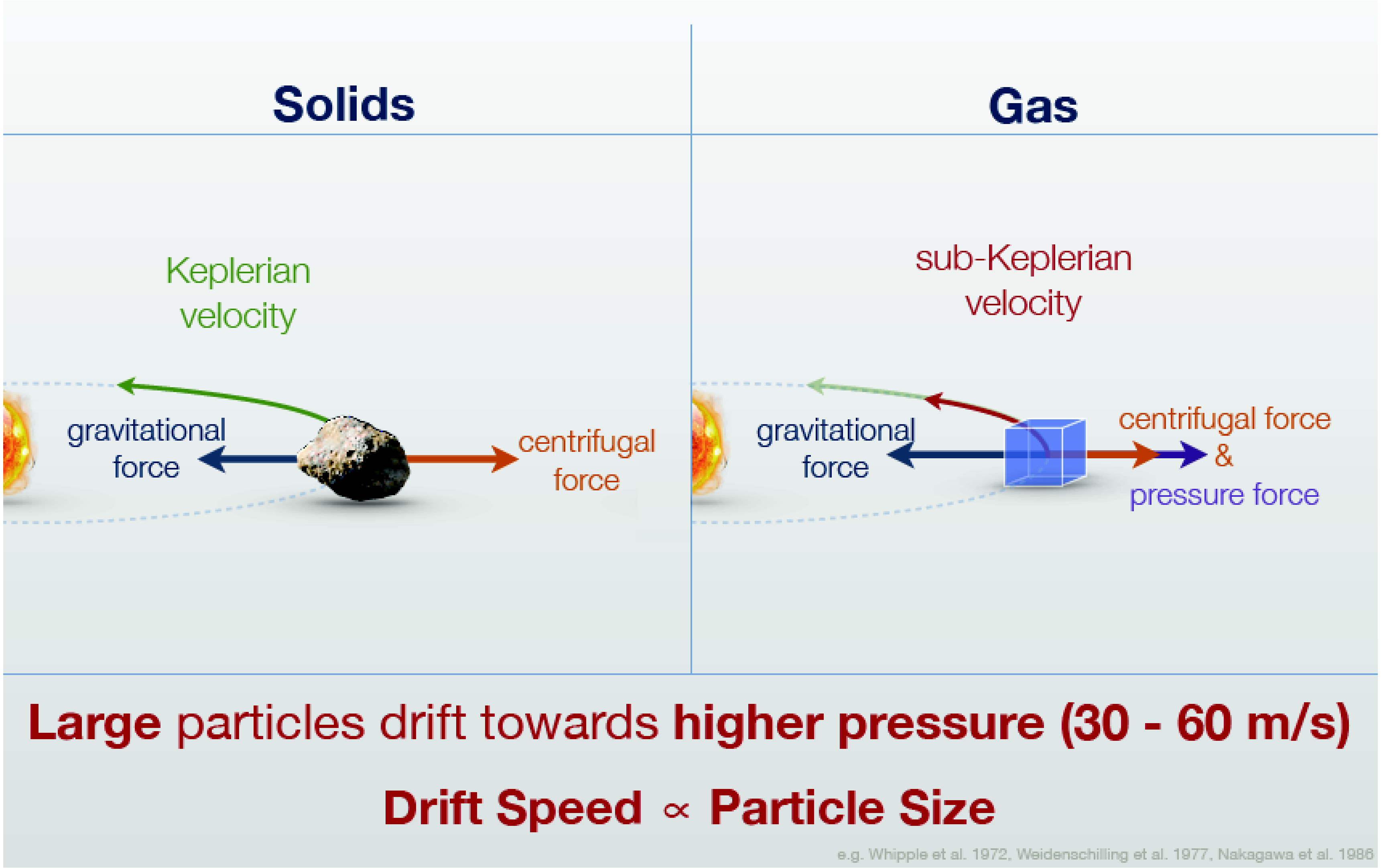
– three components: gas and two dust populations (Epstein, Stokes and Newton drag; Stoyanovskaya+18,20);

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



Vorobyov et al. 2018
Akimkin+2020

Radial Drift



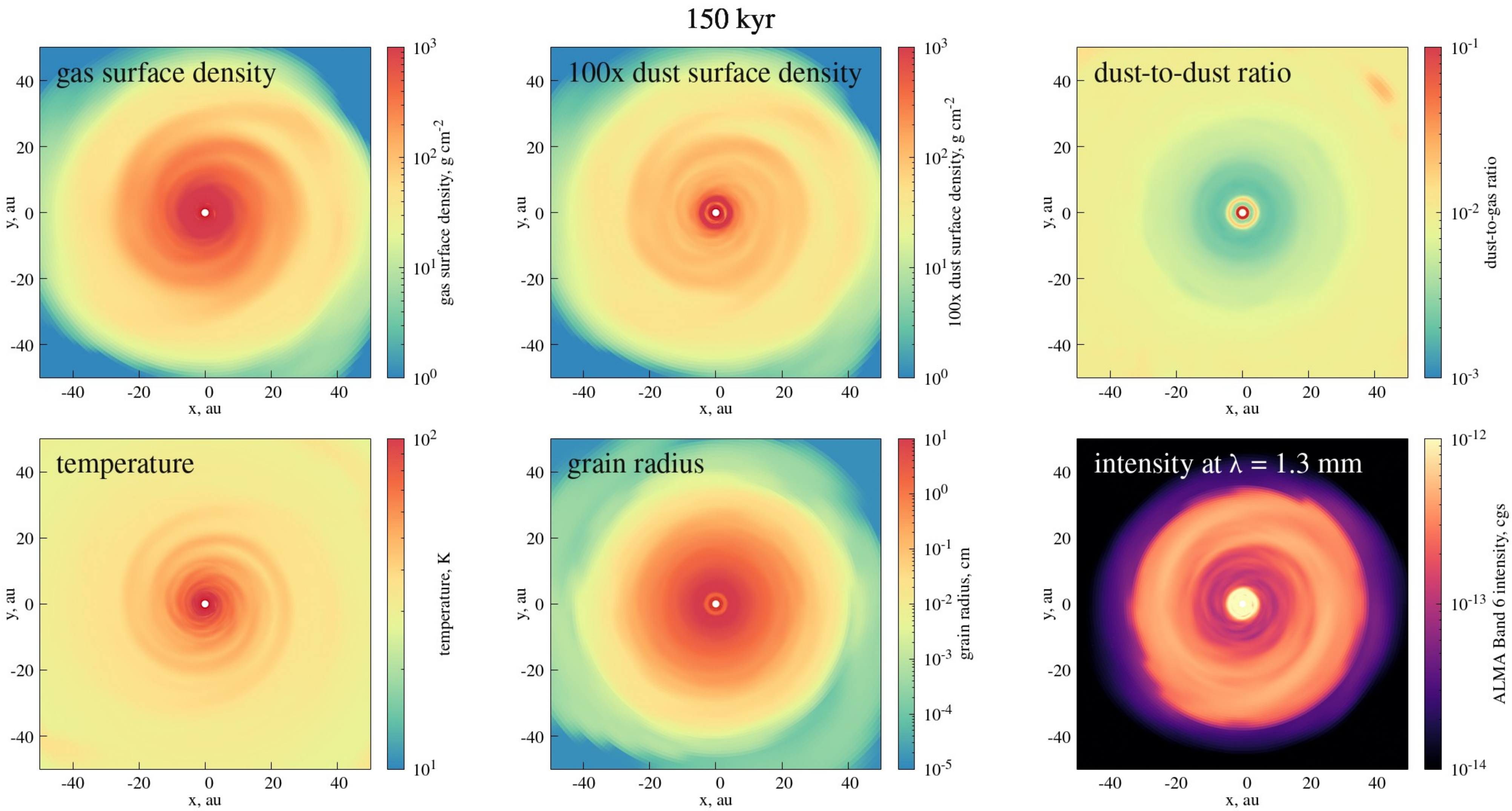
Large particles drift towards **higher pressure (30 - 60 m/s)**

Drift Speed ∝ Particle Size

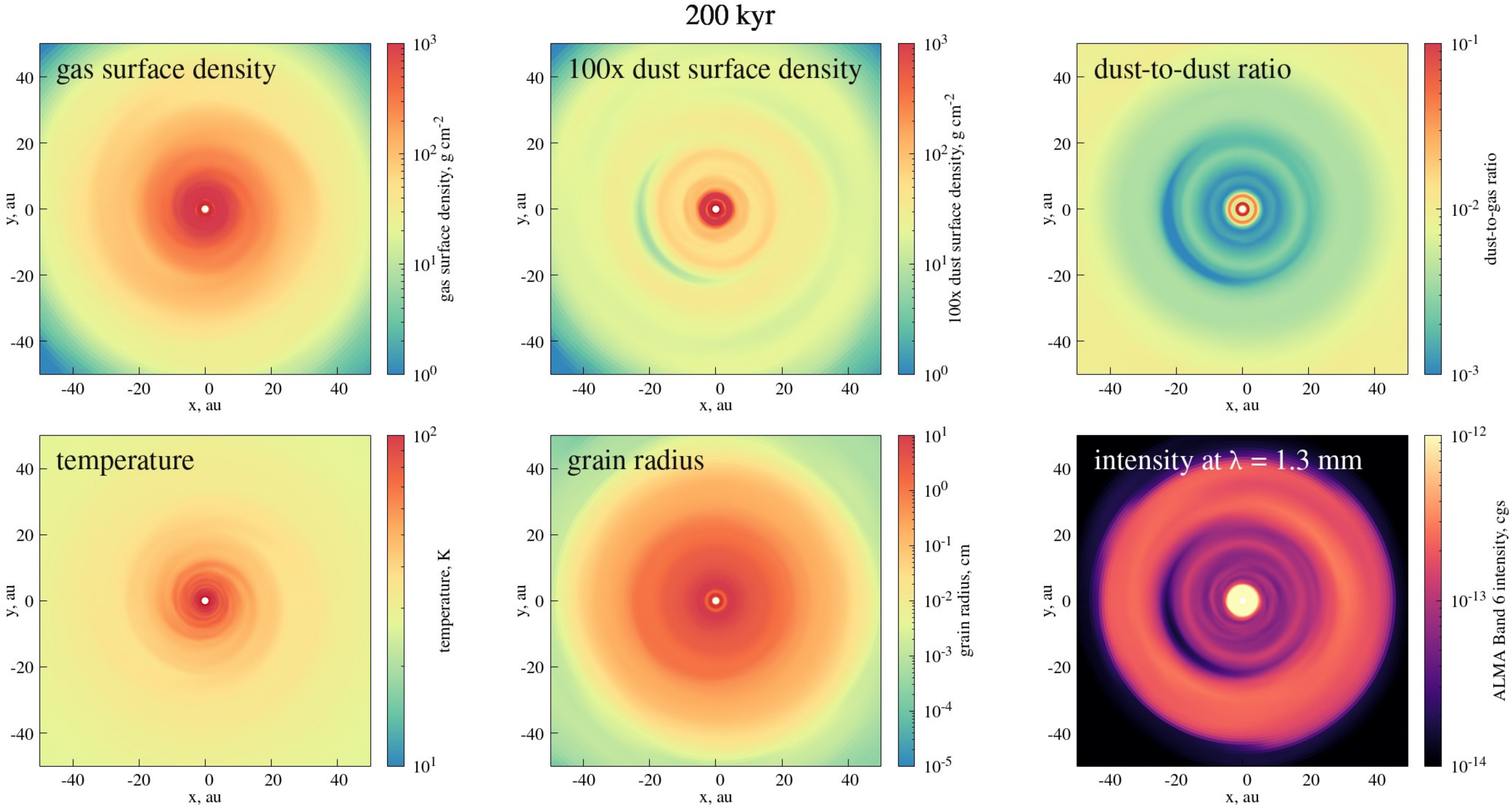
e.g. Whipple et al. 1972, Weidenschilling et al. 1977, Nakagawa et al. 1986

(c) Til Birnstiel

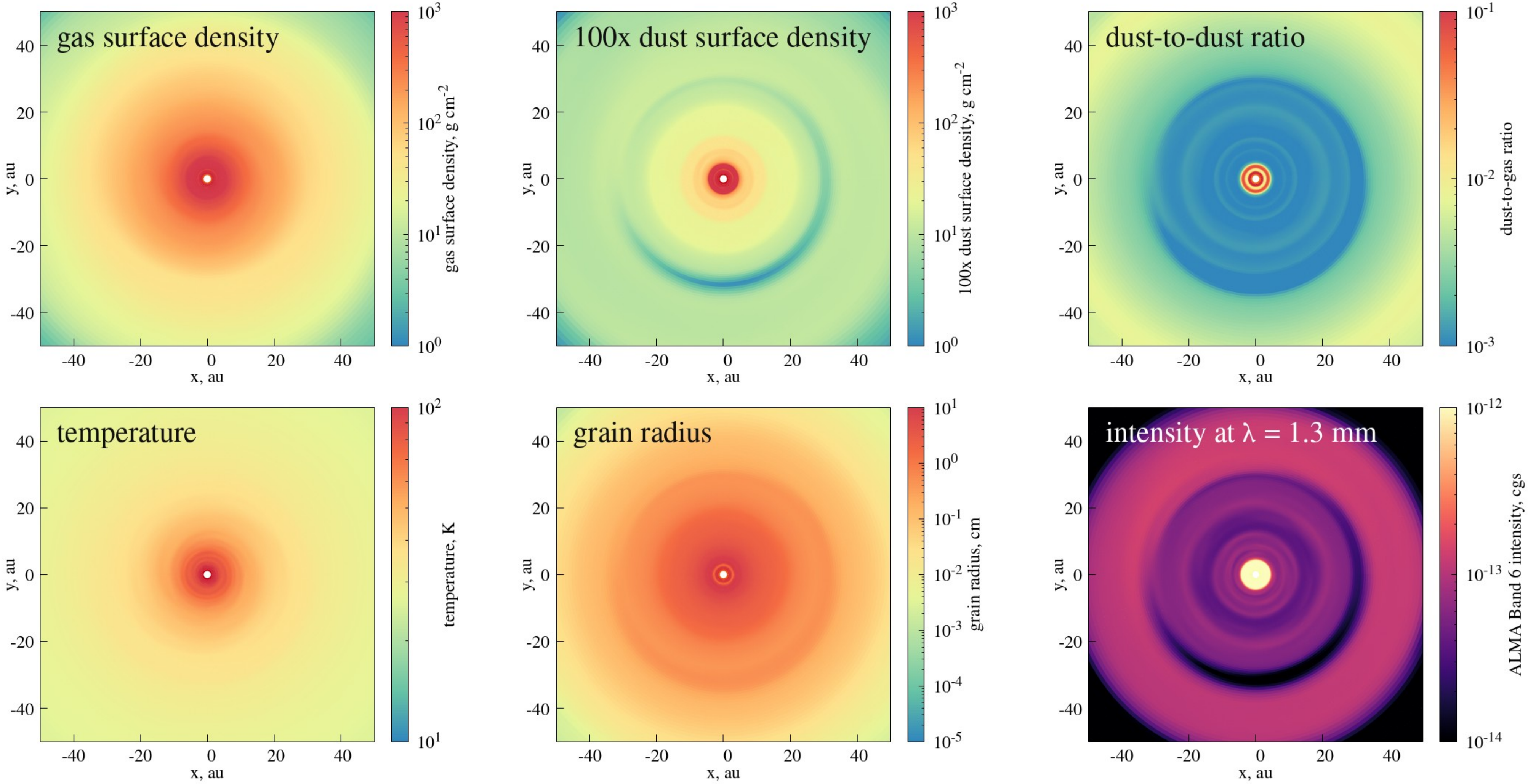
Example: (artificially) neutral dust



Example: (artificially) neutral dust

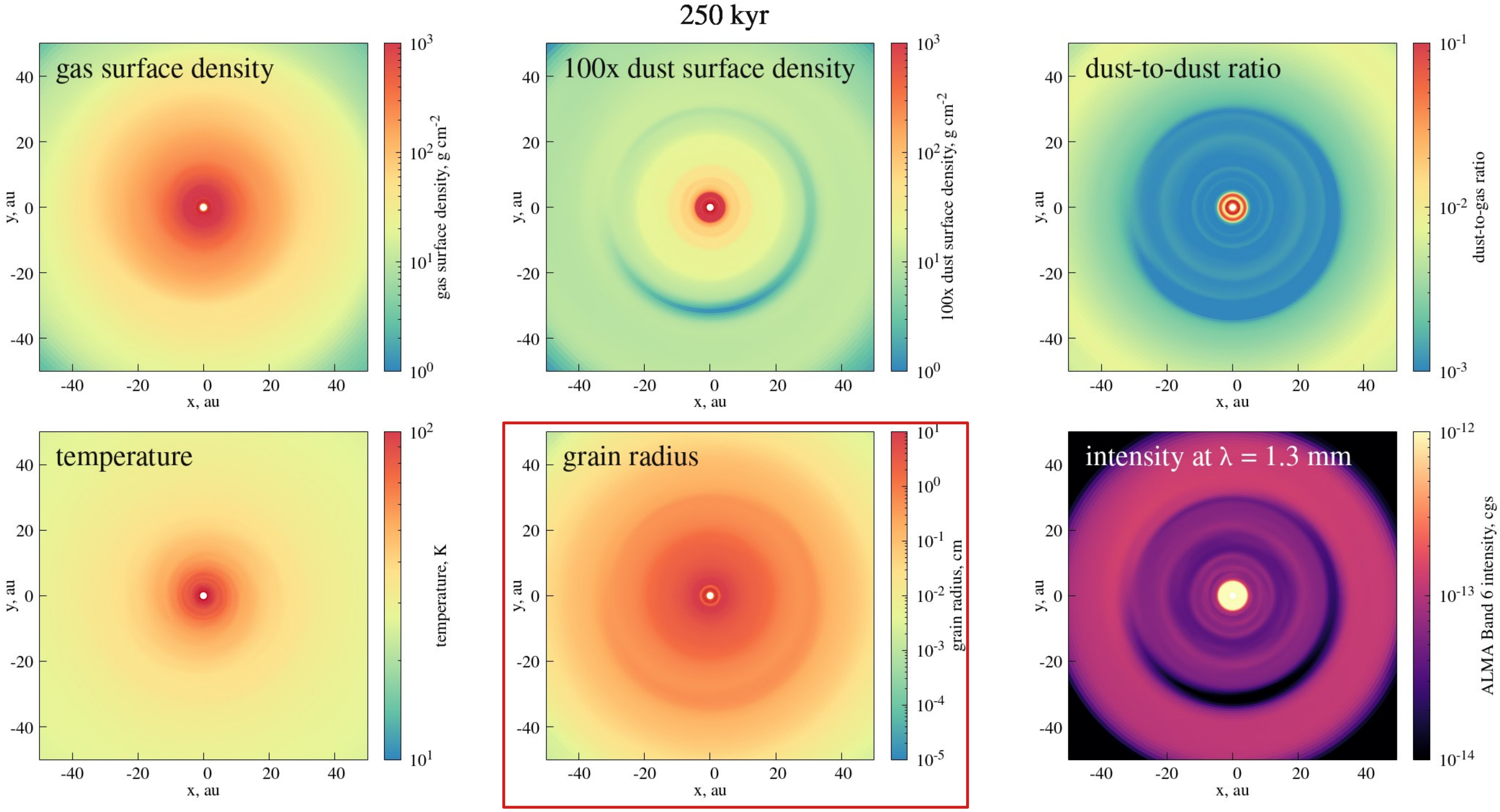


Example: (artificially) neutral dust

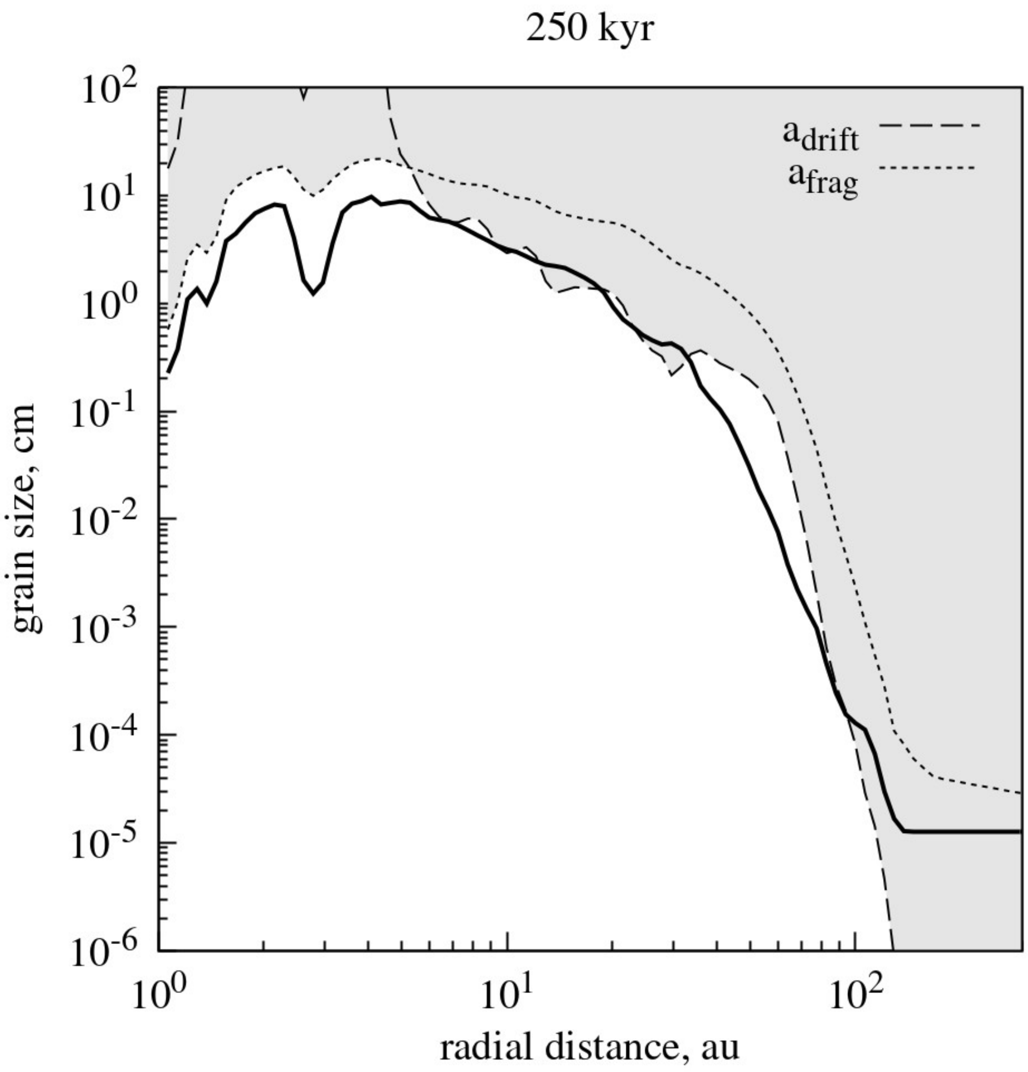


250 kyr

Example: (artificially) neutral dust



Example: (artificially) neutral dust



Drift barrier: $\tau_{\mathrm{coag}} = \tau_{\mathrm{drift}}$

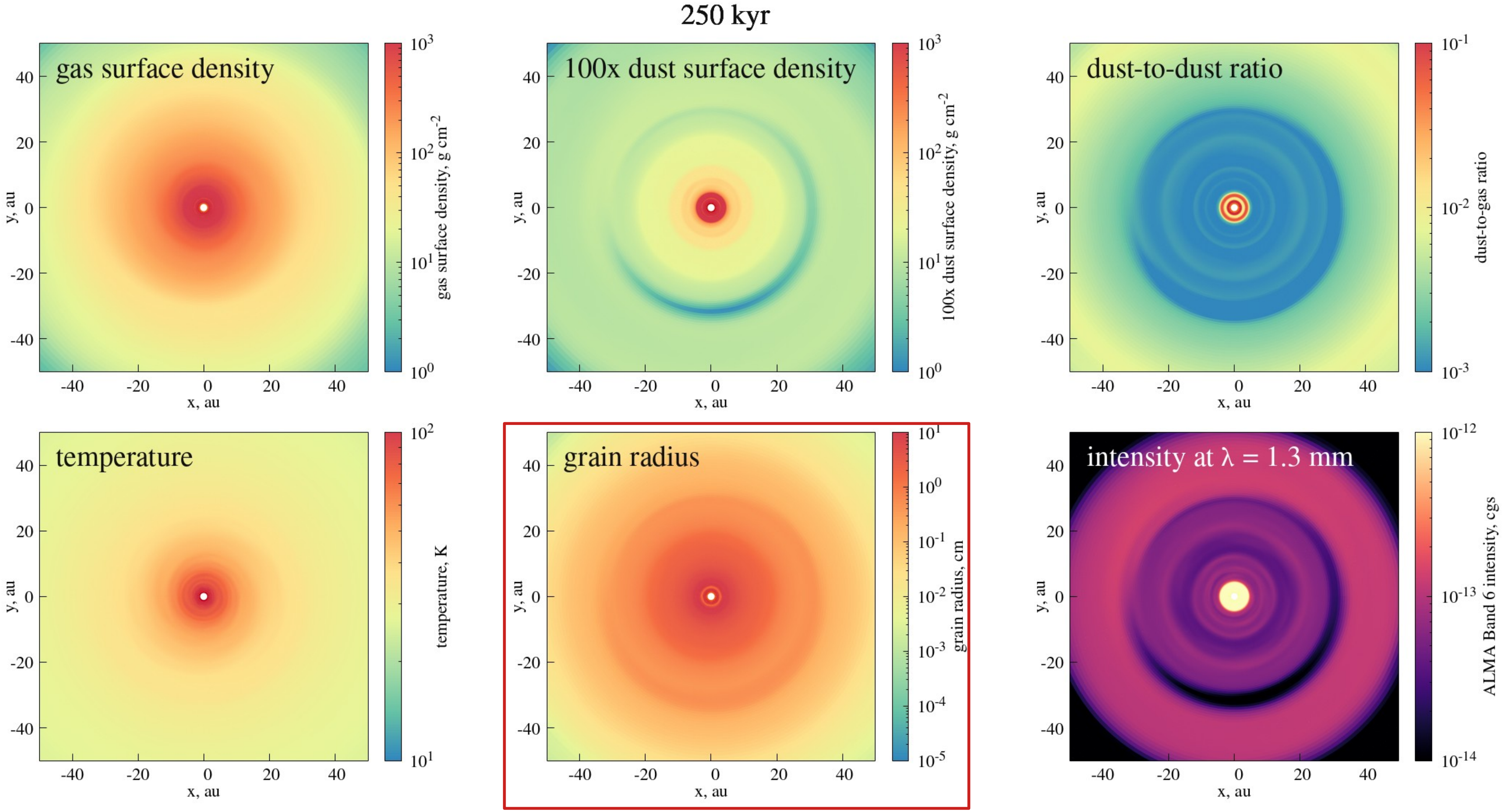
$$a_{\mathrm{drift}} \simeq 0.35 \frac{\Sigma_{\mathrm{d}}}{\rho_{\mathrm{s}}\gamma} \left(\frac{H_{\mathrm{g}}}{r} \right)^{-2}$$

Fragmentation barrier:

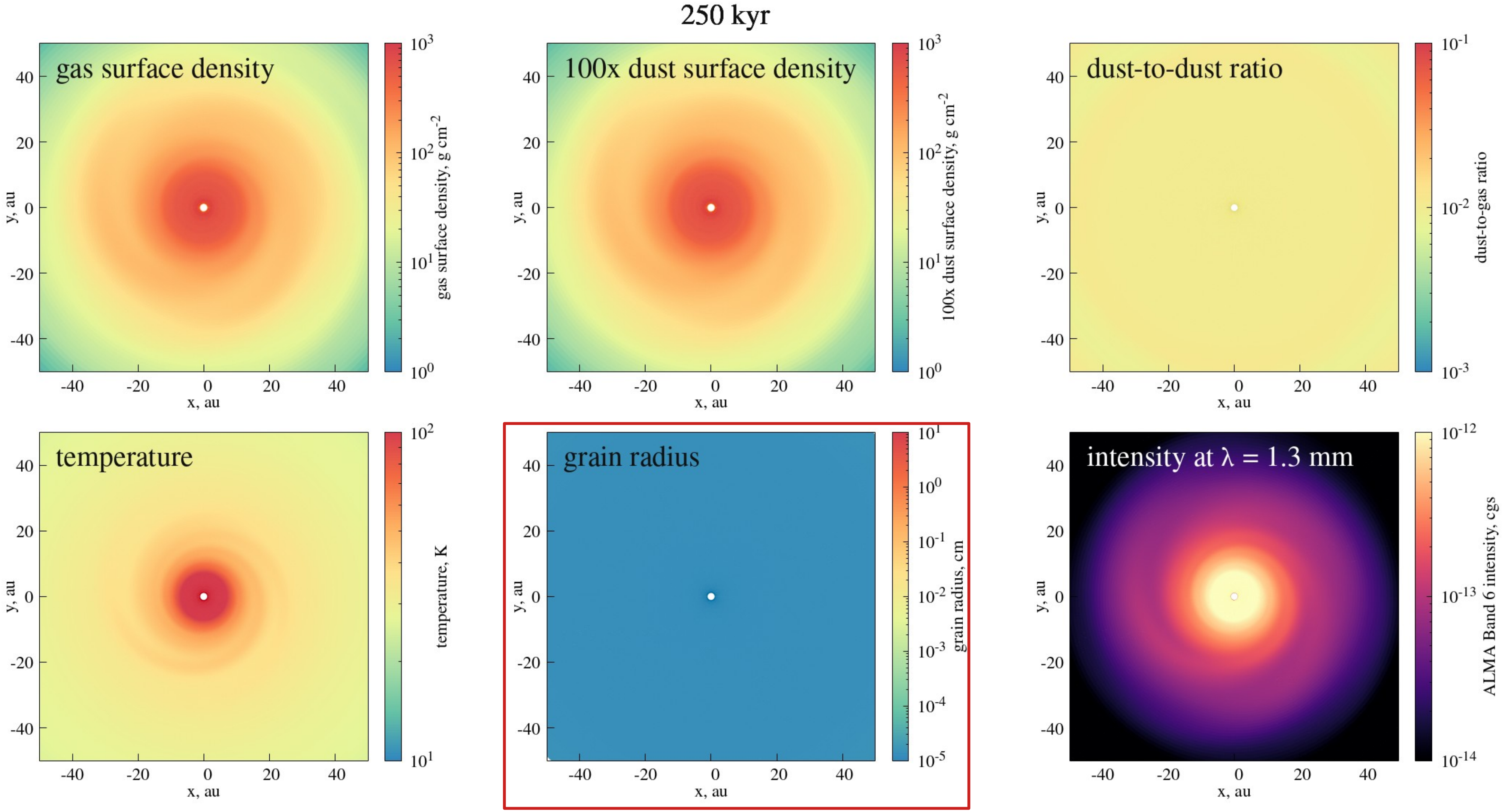
$$v_{\mathrm{coll}} = v_{\mathrm{frag}} \approx 1 - 10\,\mathrm{m/s}$$

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

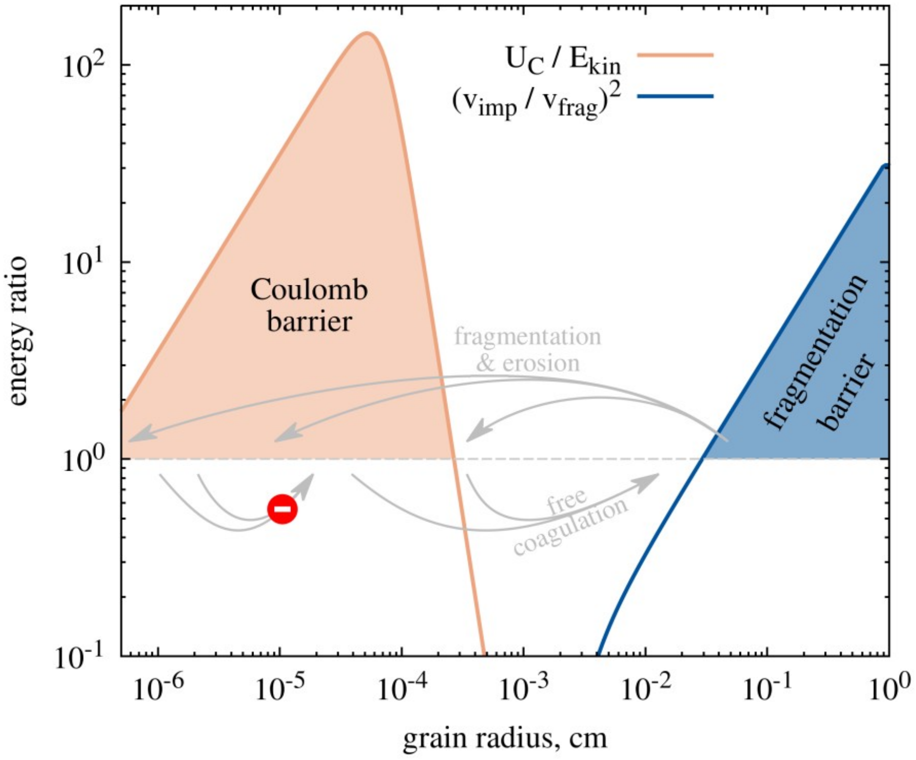
Example: (artificially) neutral dust


250 kyr

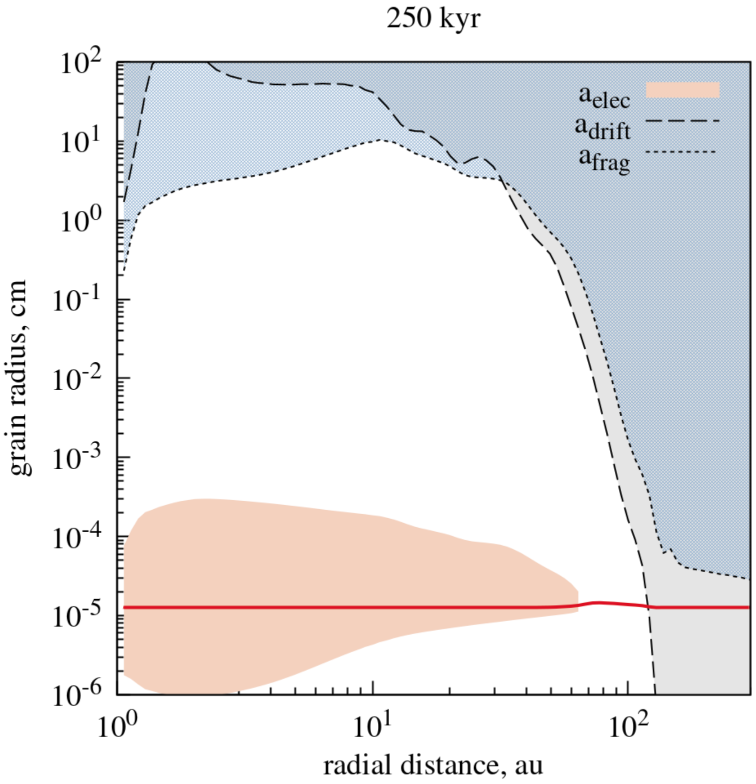
Charged dust



Electrostatic barrier

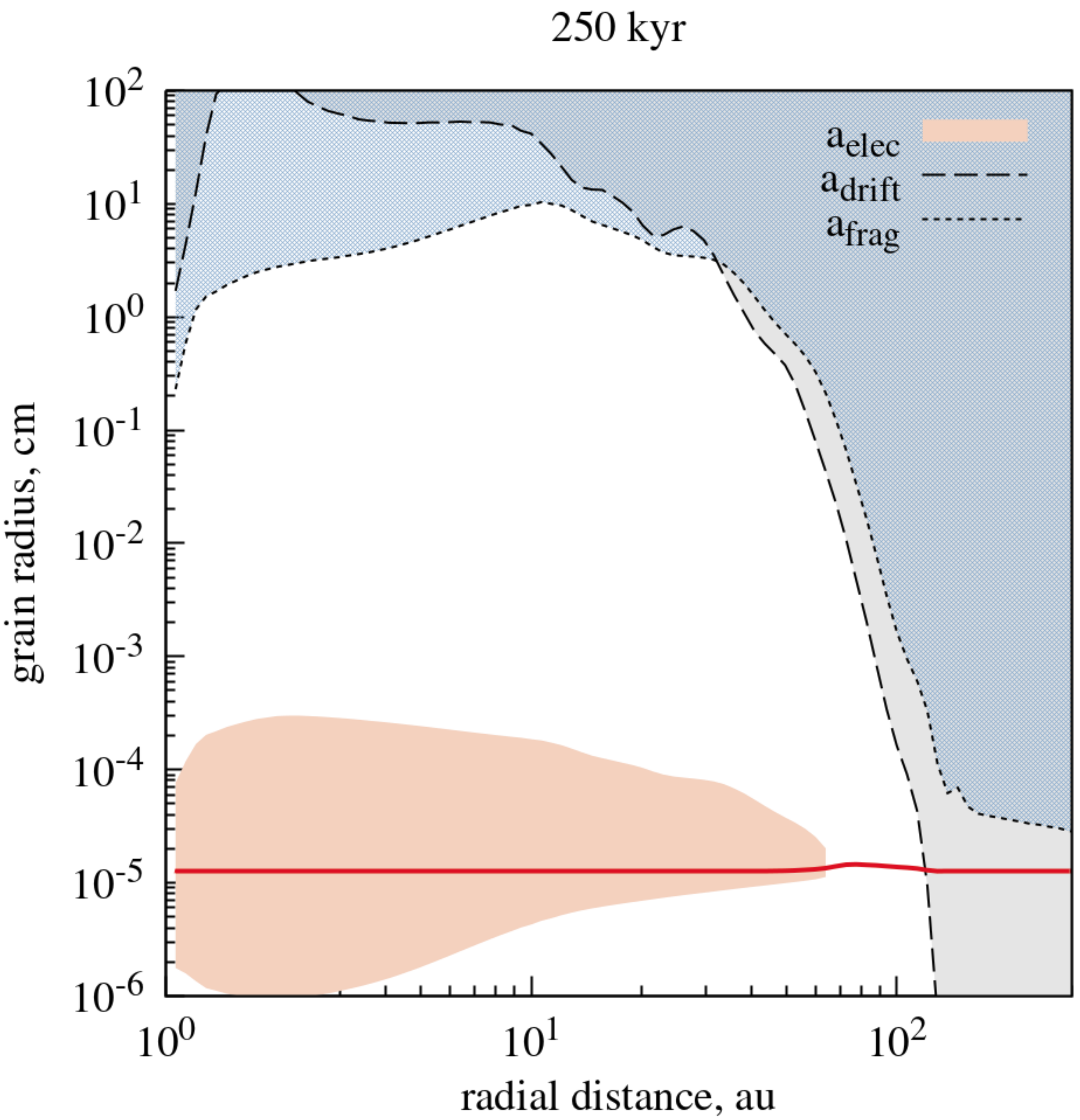


Akimkin et al. 2023

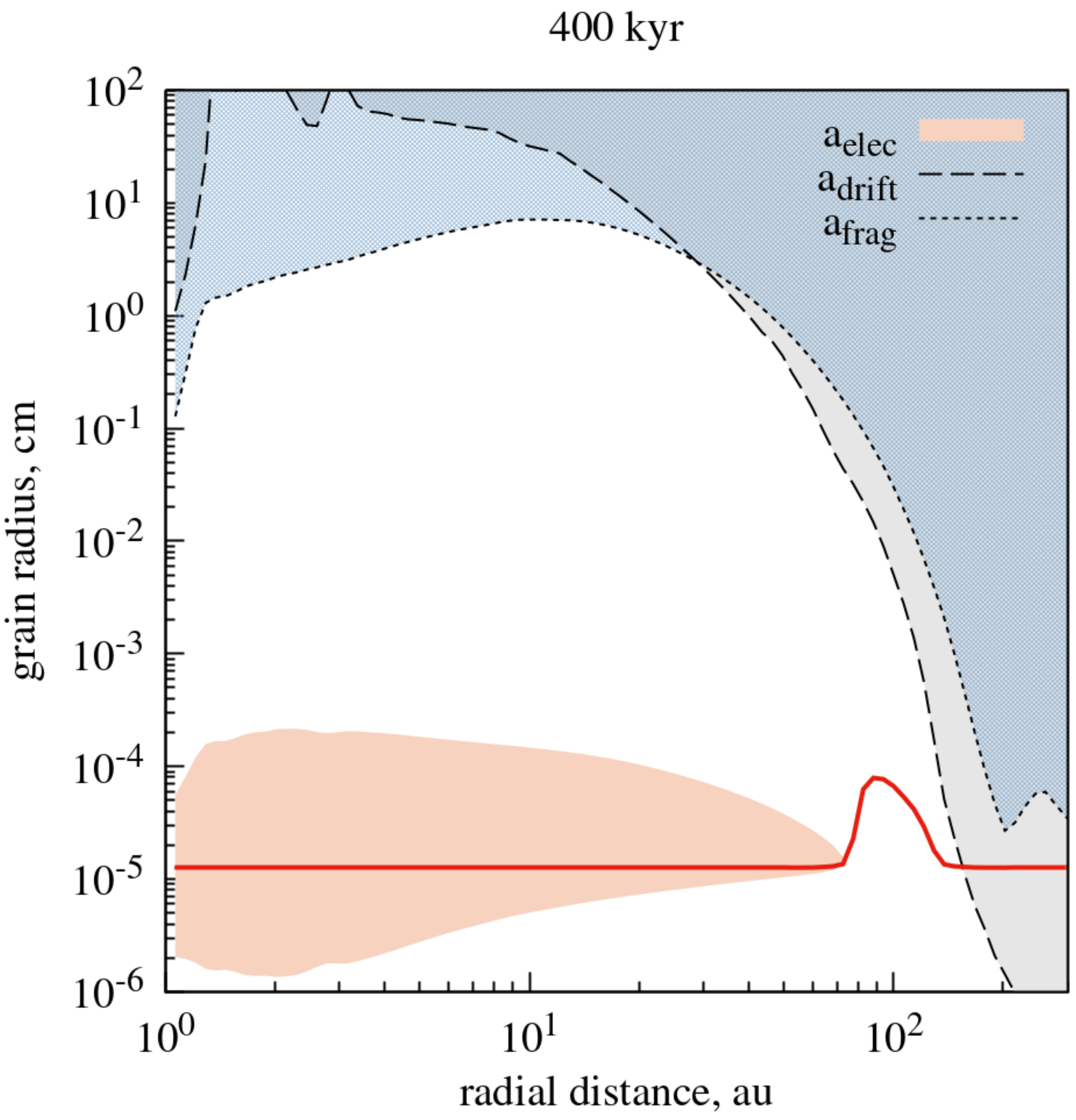


Akimkin et al., in prep.

Electrostatic barrier



Electrostatic barrier



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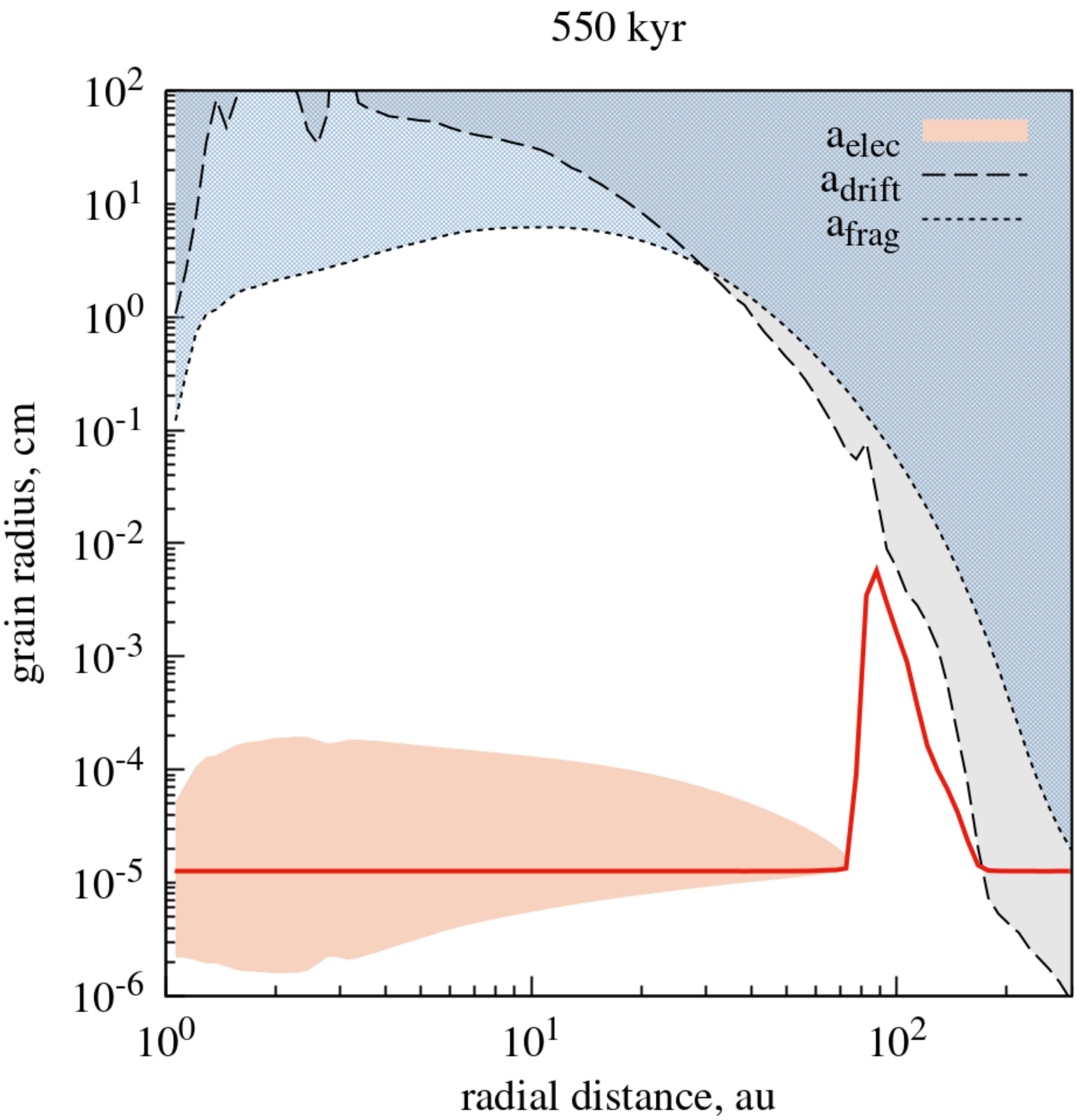

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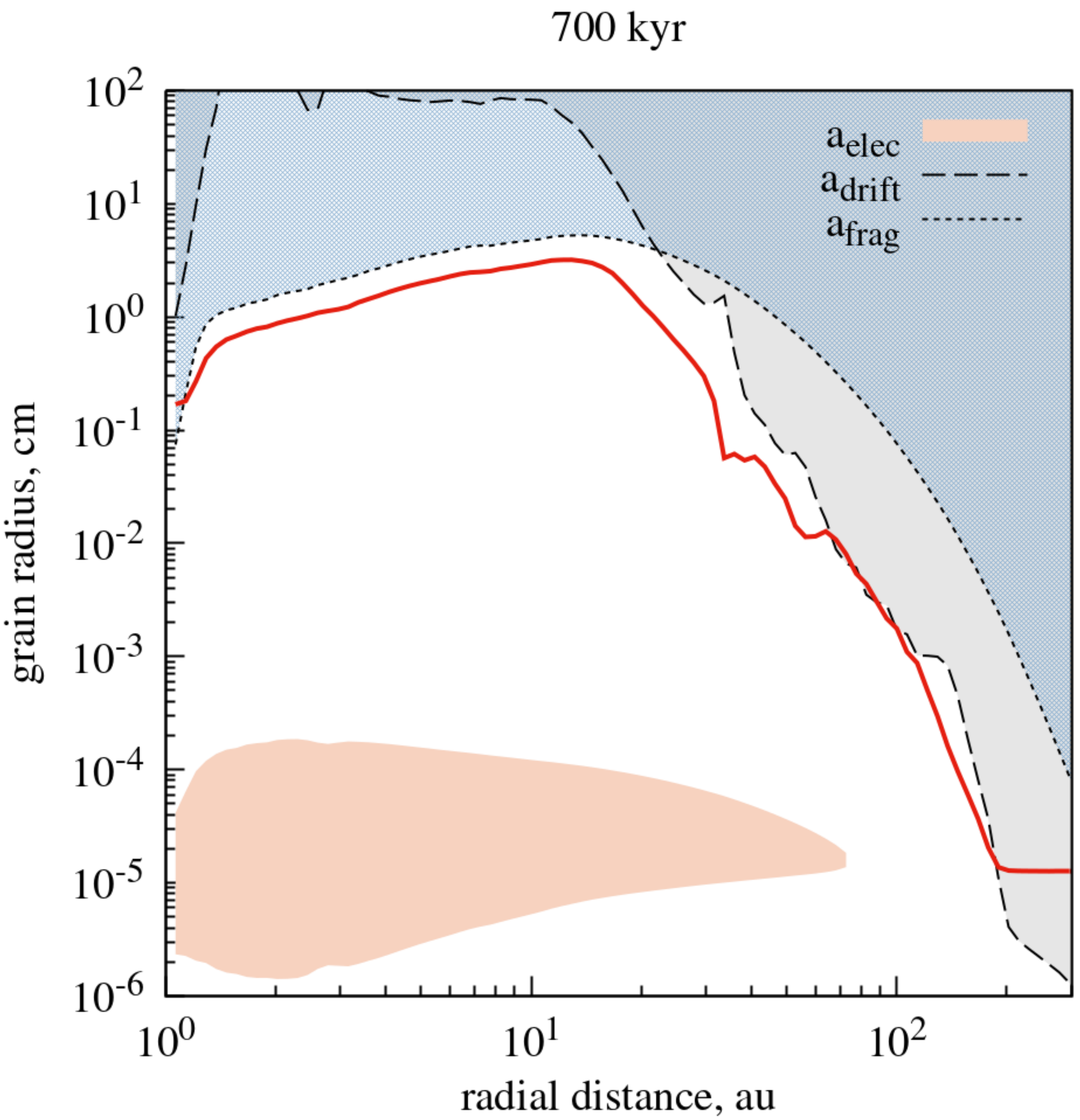

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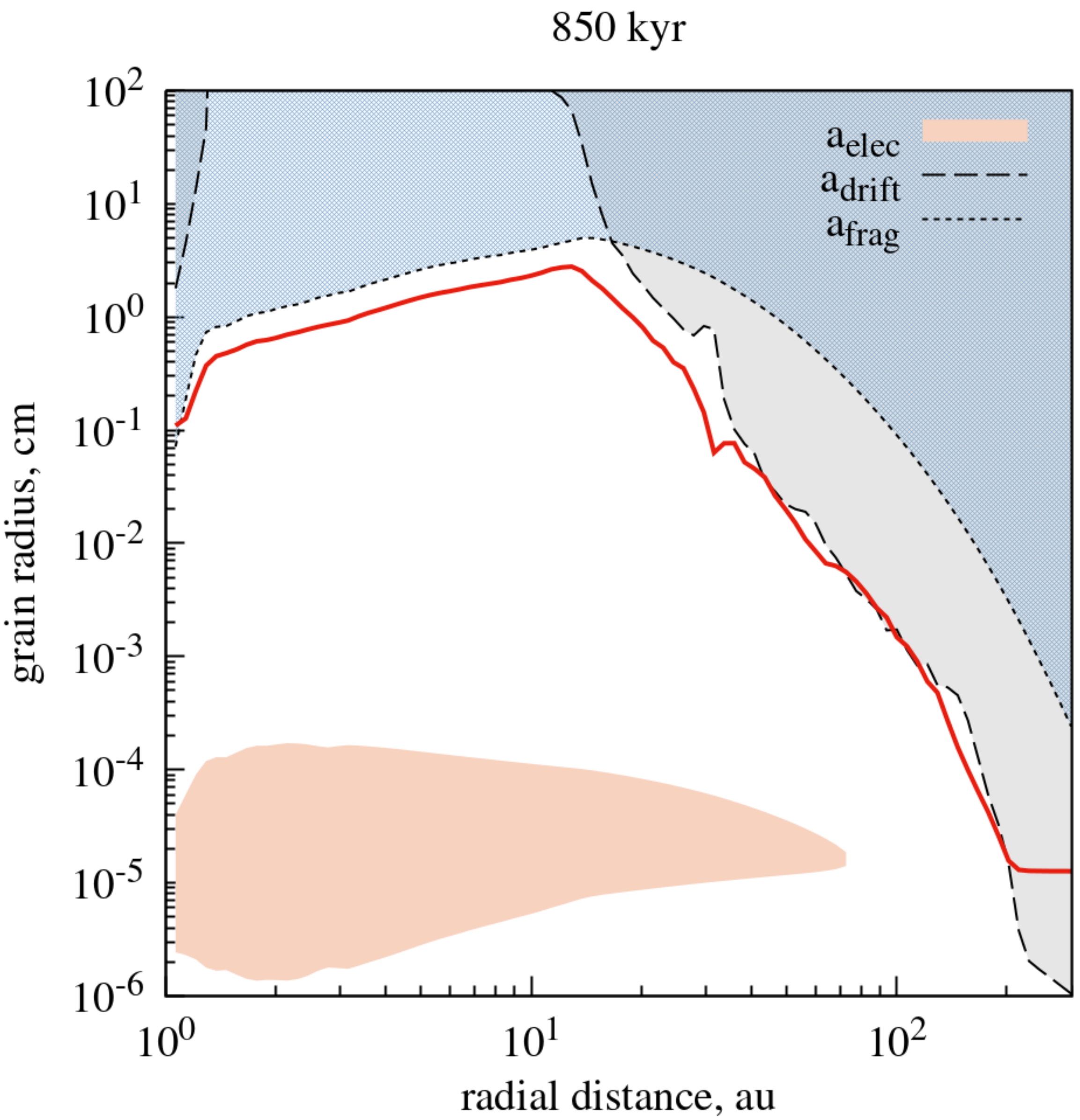
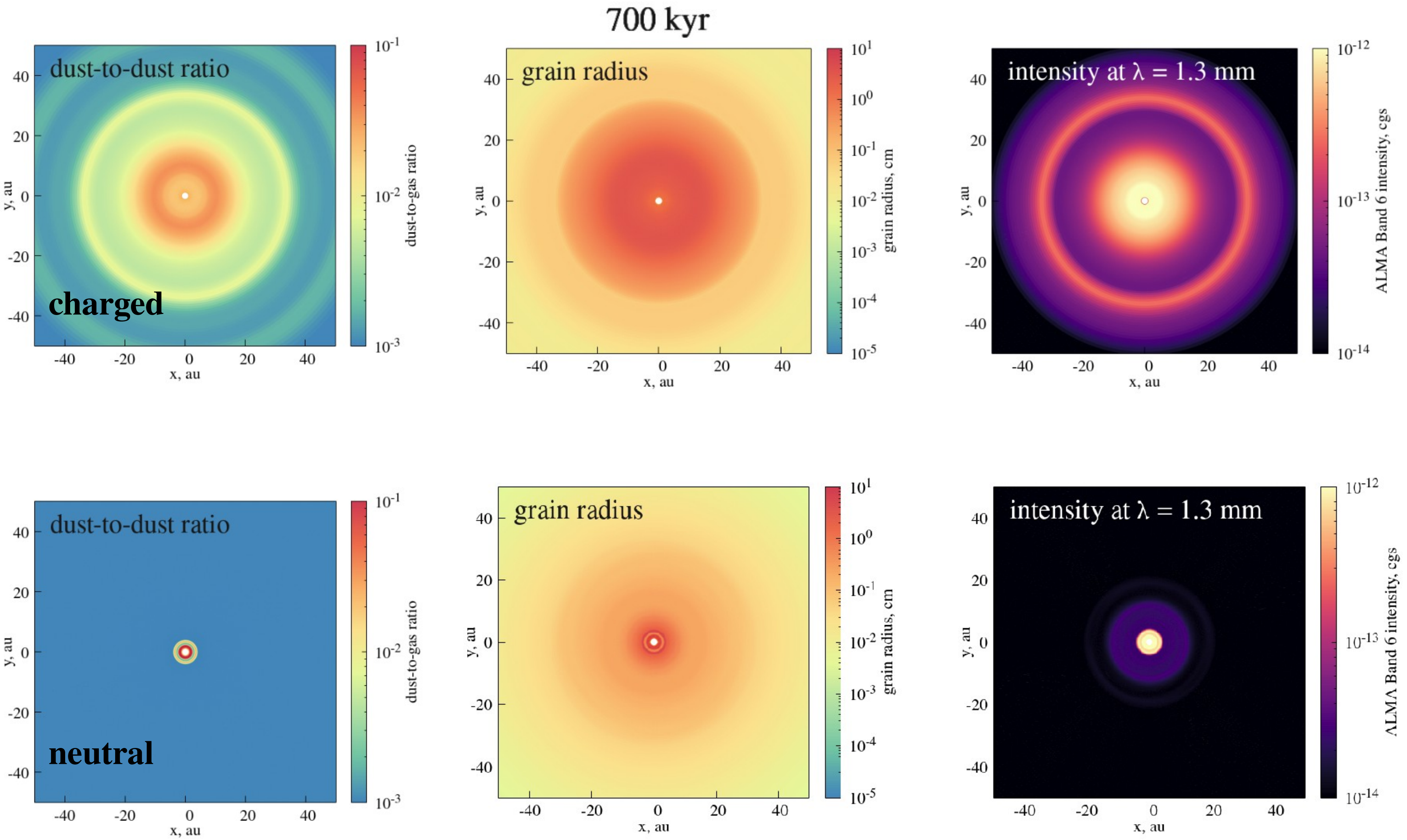


Charged vs Neutral Dust

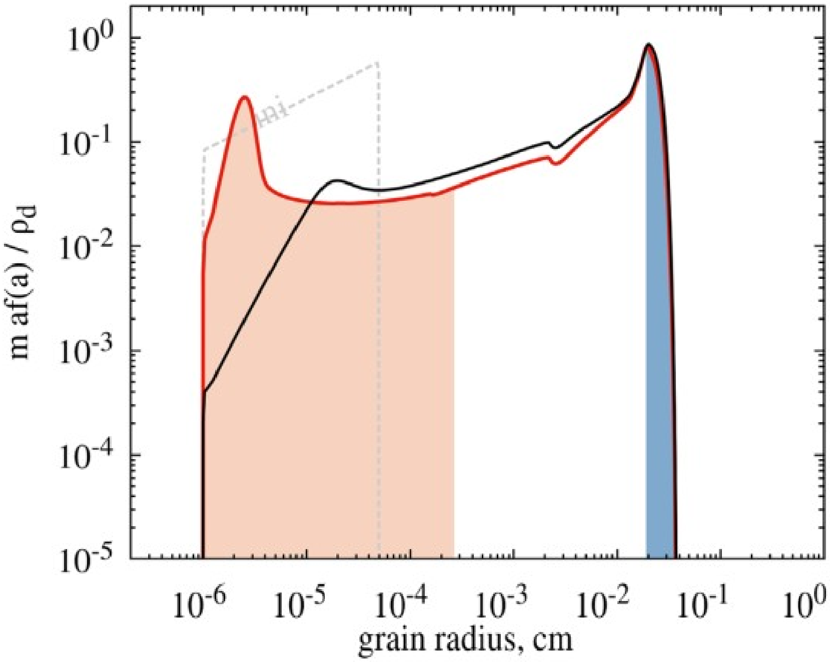


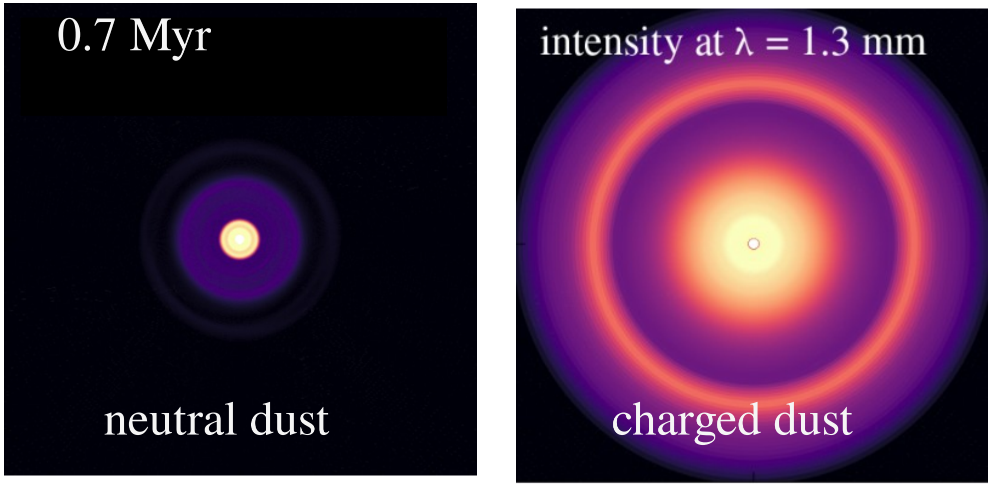
Conclusions

– одновременное действие электростатического и фрагментационного барьеров усугубляет влияние каждого из них на рост пыли;

– электростатический барьер роста пыли блокирует появление макроскопических агрегатов во внутреннем диске (< 50 а.е.) в течение первых ~ 0.5 млн лет. Снятие барьера может произойти из-за радиального дрейфа крупной пыли с периферии диска.

Исследование выполнено за счёт гранта РНФ №22-72-10029





Parameter Space Study