New experiments on the growth of dust aggregates in young protoplanetary disks

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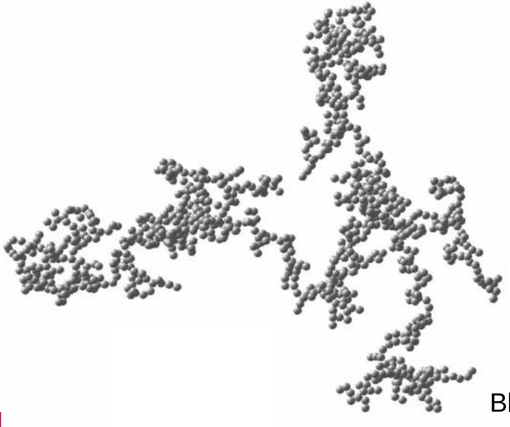
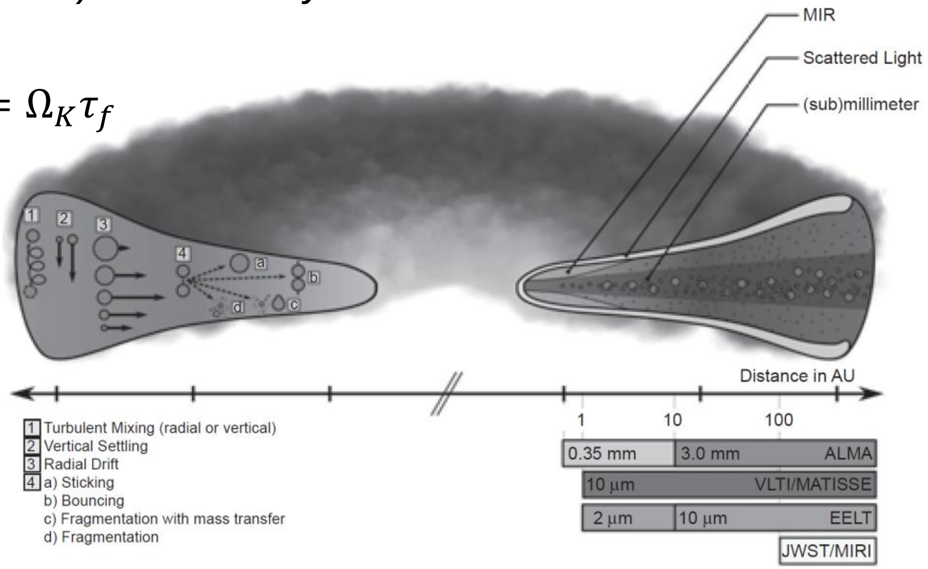
Introduction: dust during the Brownian motion and drift phase in PPDs

- Planet formation:
  dust → *sticking collisions* → pebbles → *SI* → planetesimals → *pebble accretion* → planets
- The initial stage (dust → *sticking collisions* → pebbles) still not fully understood
- Dust growth dominated by radial drift;
  radial drift velocity $v_r \approx 2\,\Delta v\, St$, $\Delta v \approx 50\ \mathrm{m/s}$, $St = \Omega_K \tau_f$
- Experiments indicate fractal growth in this regime



Blum 2006

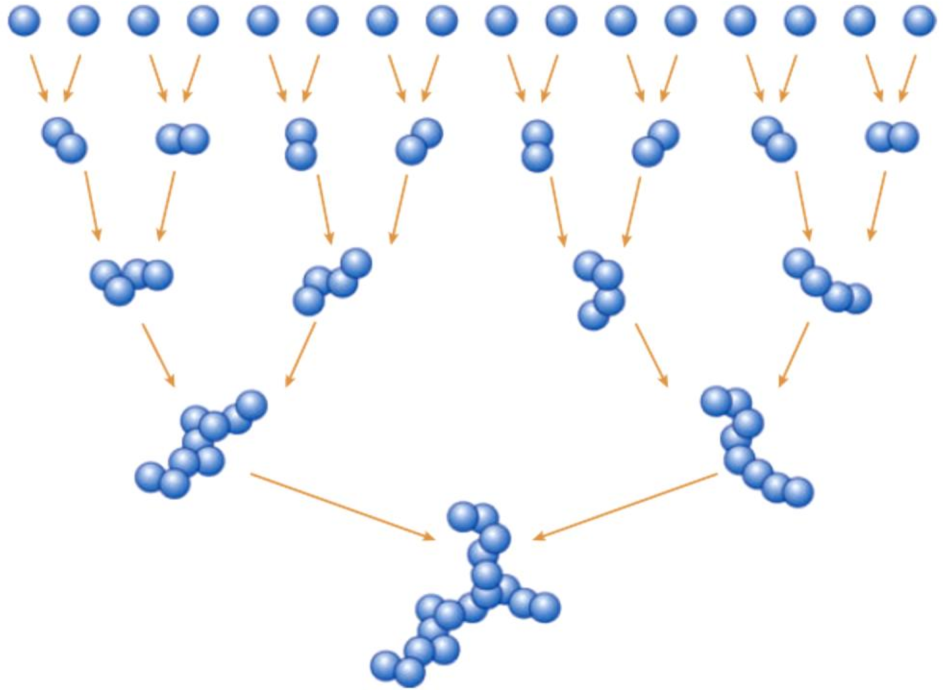


Testi et al. 2014

Model for fractal aggregate growth in the Brownian motion and drift phase

- Discrete particle masses
- Fractal aggregates $(d_f < 2)$
- Low collision speed
- High sticking probability
- Quasi-monodisperse growth
- Single-size Smoluchowski equation
- Mass conservation
- Mass-growth equation

Blum & Wurm 2008



Model for fractal aggregate growth in the Brownian motion and drift phase

Mass-growth equation $$\frac{\partial N(t)}{\partial t} = v_0 \sigma_0 \mu_0 N(t)^{1+\alpha}$$

- Case I: Brownian motion $v(N) \approx v_0 N^{\alpha}; \alpha = -1/2$

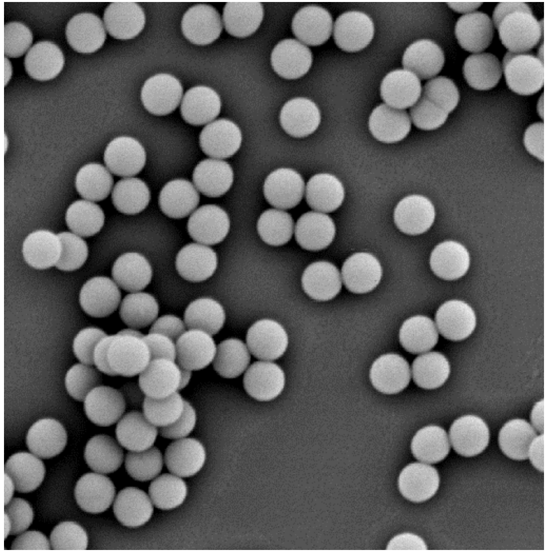
  Solution I: power-law growth $$\boxed{N(t) = \left(\frac{1}{2}\frac{t}{\tau_c} + N_0^{1/2}\right)^2}$$ $$\boxed{\tau_c = \frac{1}{v_0 \sigma_0 \mu_0}}$$ (collision timescale)

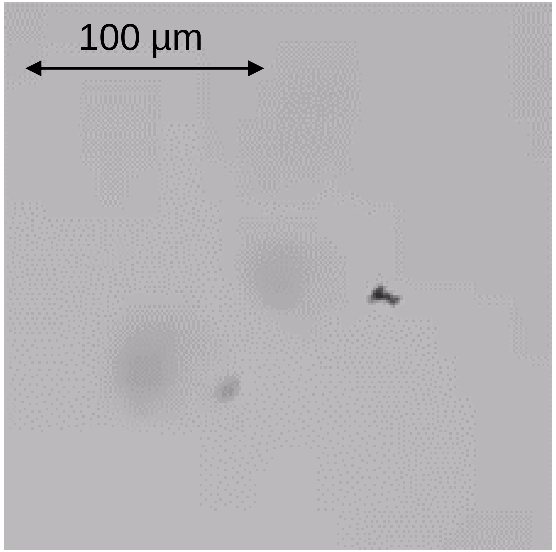
- Case II: drift motion $v(N) \approx v_0 N^{\alpha}; \alpha \approx 0$

  Solution II: exponential growth up to the restructuring limit $$\boxed{N(t) = N_0 e^{t/\tau_c}}$$ $$\boxed{\tau_c = \frac{1}{v_0 \sigma_0 \mu_0}}$$ (collision timescale)

The experiments: I. Brownian motion (project ICAPS)

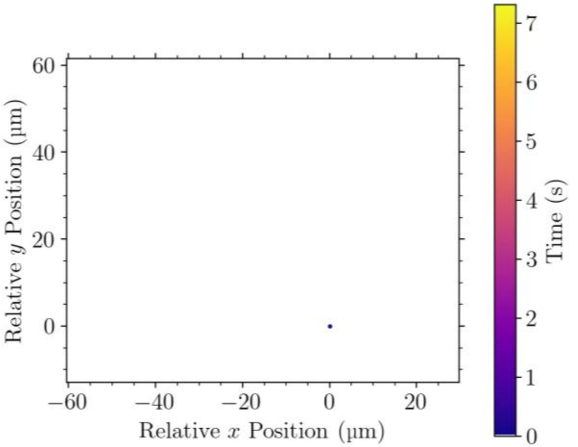
- Six minutes of microgravity time in each of the two sounding-rocket flights (Nov. 2019, Apr. 2023)
- Two injections of dust clouds (1.5 µm SiO_2 spheres) per flight
- Microgravity time usable for Brownian motion analysis: ~180 s (~180k LDM images) per flight
- Temporal and spatial resolution in Brownian motion analysis: $\Delta t \approx 1$ ms and $\Delta x \approx 1$ µm

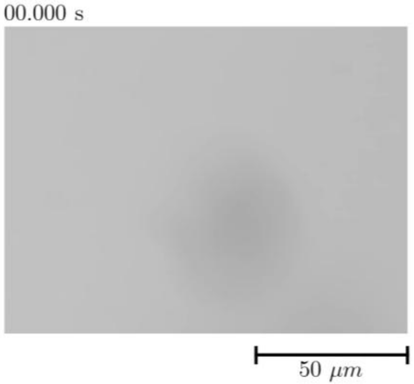


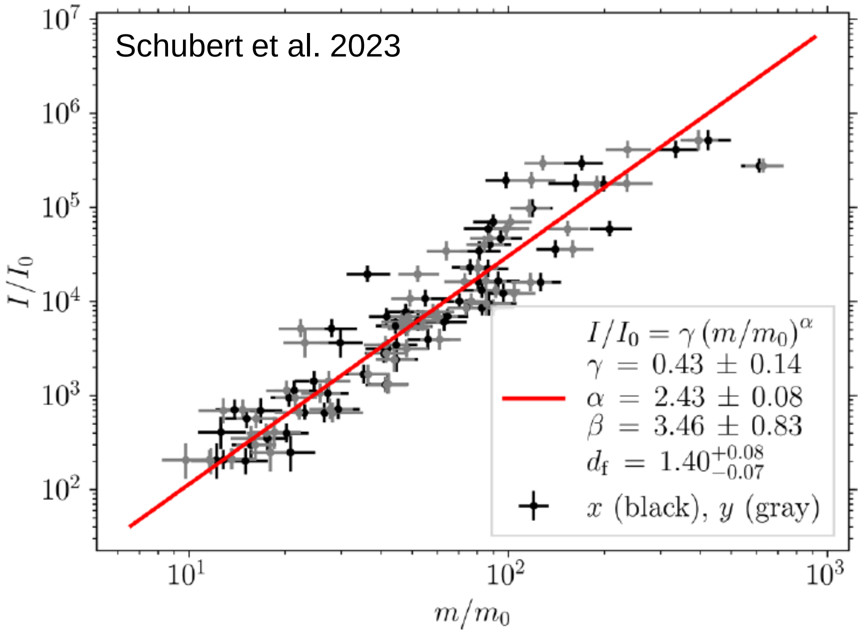


Zoom-in LDM example from ICAPS (slow motion)

The experiments: I. Brownian motion (project ICAPS)







<u>Brownian translation</u>

→ <u>mass</u>: $m \propto r_{\mathrm{gyr}}^{d_f}$

\+

<u>Brownian rotation</u>

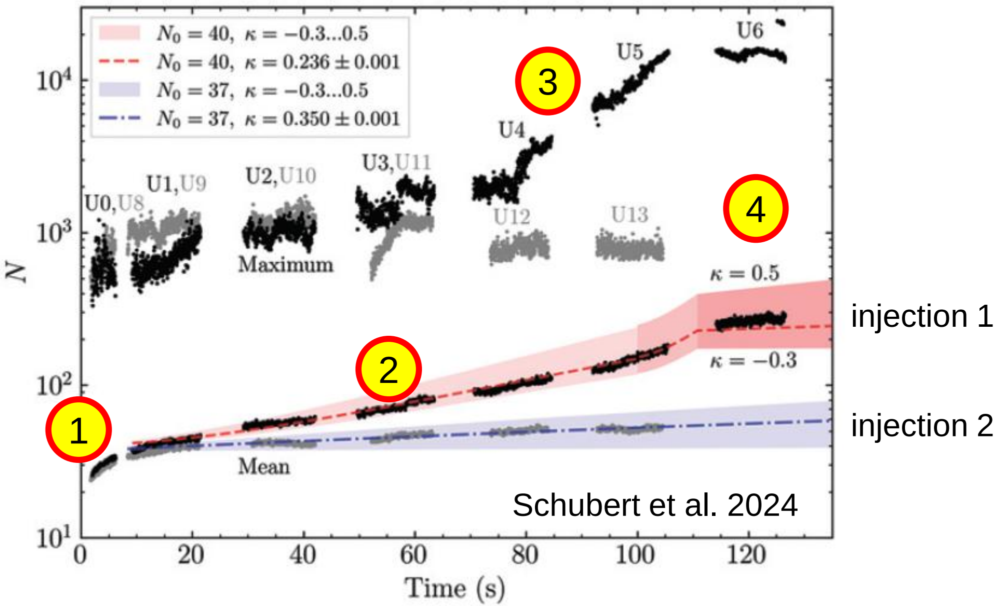
→ <u>moment of inertia</u>: $I = m\, r_{\mathrm{gyr}}^2$

→ $I \propto m^{\left(1+\frac{2}{d_f}\right)} = m^{\alpha}$

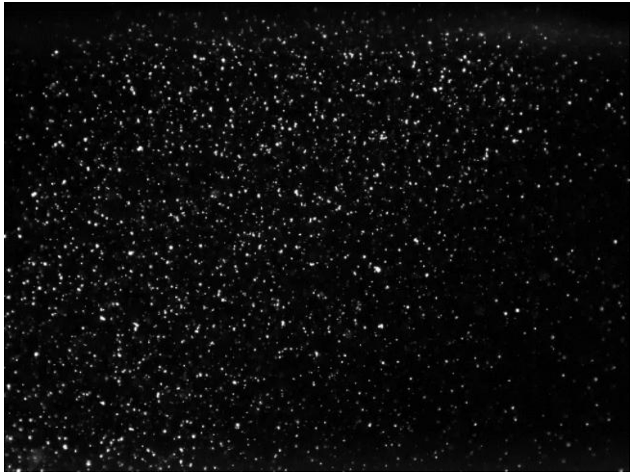
→ <u>fractal dimension</u> d_f

r_{gyr}: Radius of Gyration

The experiments: I. Brownian motion (project ICAPS)



OOS time-lapse movie of cloud evolution



OOS: FOV ~ 12 x 9 mm^2

1. Rapid agglomeration during the first ~5 s (unresolved) due to charge-enhanced collision cross section
2. Rapid agglomeration between ~5 s and ~90 s due to Brownian motion and strong number-density increase
3. Runaway agglomeration after ~90 s
4. Slowed down agglomeration after ~110 s due to stopping of the dust-concentration process

The experiments: I. Brownian motion (outlook: project Laplace)

- Up to 1 hour experiment time
- Up to 100 single experiments
- Launch to the ISS currently foreseen in April 2026

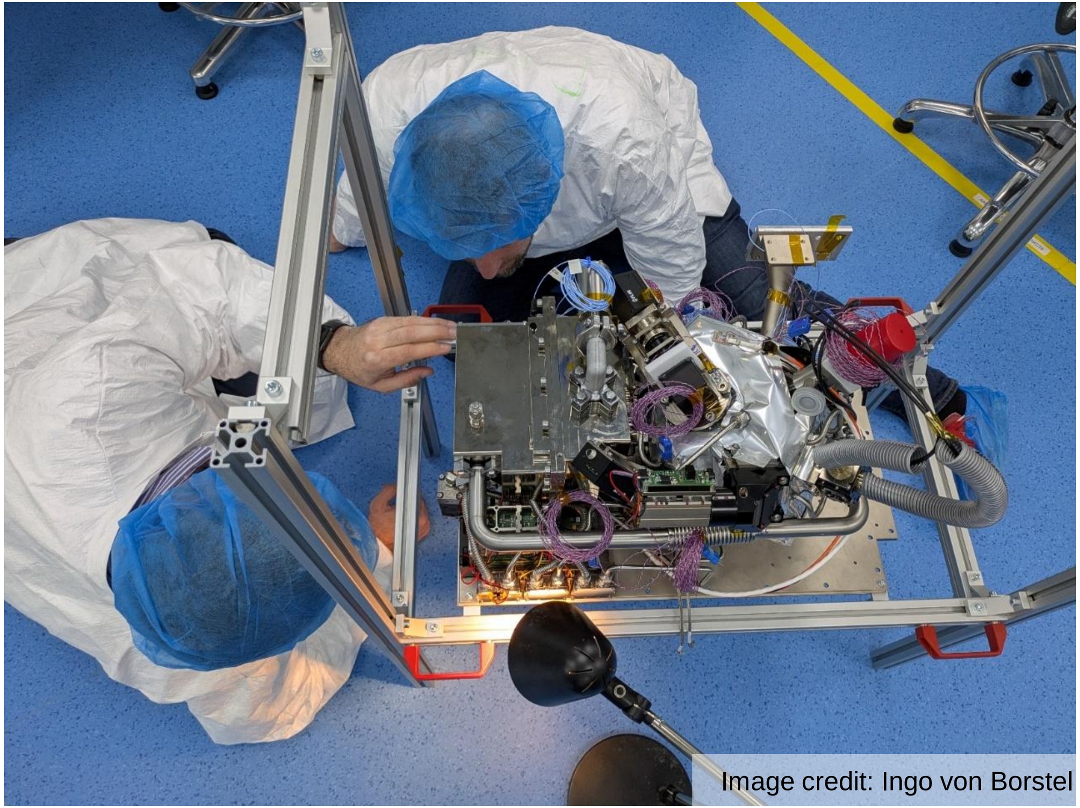
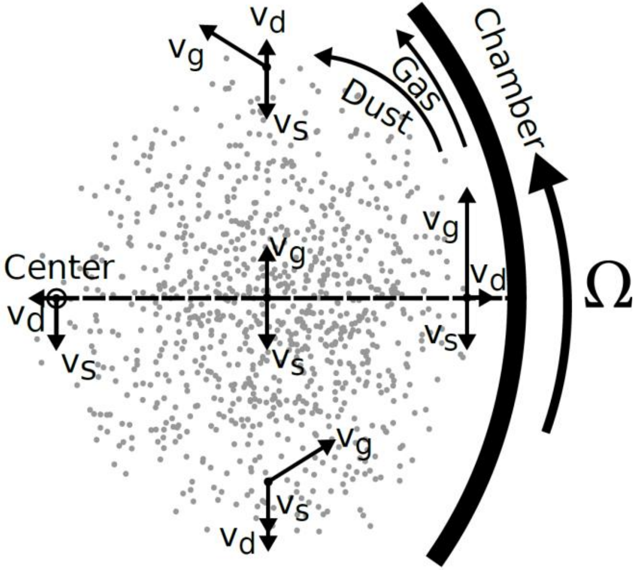


Image credit: Ingo von Borstel

The experiments: II. drift motion (experimental concept)

Rarefied gas + cloud of µm-sized dust grains + gravity

- Sedimentation at a speed proportional to τ_f (mass-to-surface ratio)
- For fractal particles with $d_f < 2$, τ_f is basically independent of aggregate mass
- Collision speed determined by intrinsic differences in τ_f; for µm-sized SiO_2 and $p_{\mathrm{gas}} = 100\ \mathrm{Pa}$, the sedimentation (and typical collision) speed is on the order of 1 cm/s
- Collision speeds very similar to PPDs
- Gas rotation is stiff for rarefied gas
- Experiment duration only limited by centrifugal drift timescale τ_d



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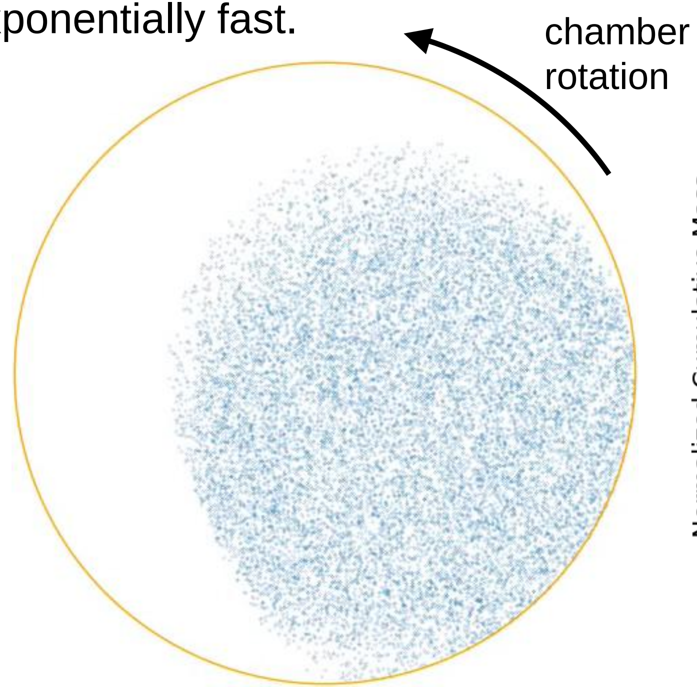
The experiments: II. drift motion (Monte Carlo simulations)

Taking chamber rotation, gas friction and gravity into account, fractal agglomerates ($d_f = 1.9$) grow exponentially fast.



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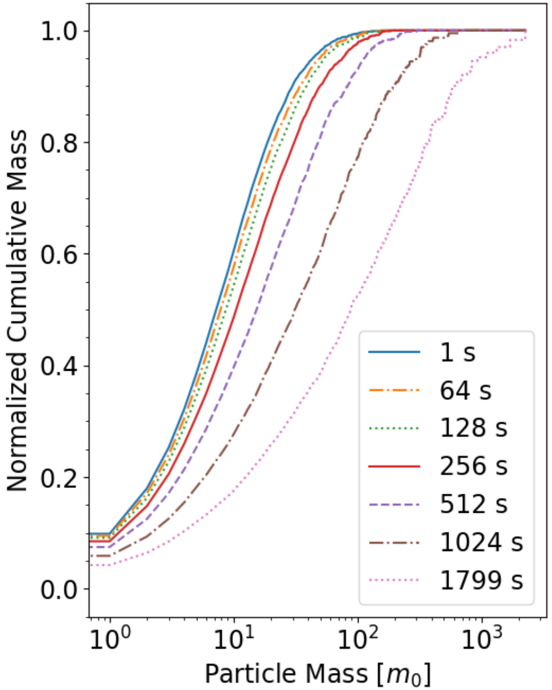
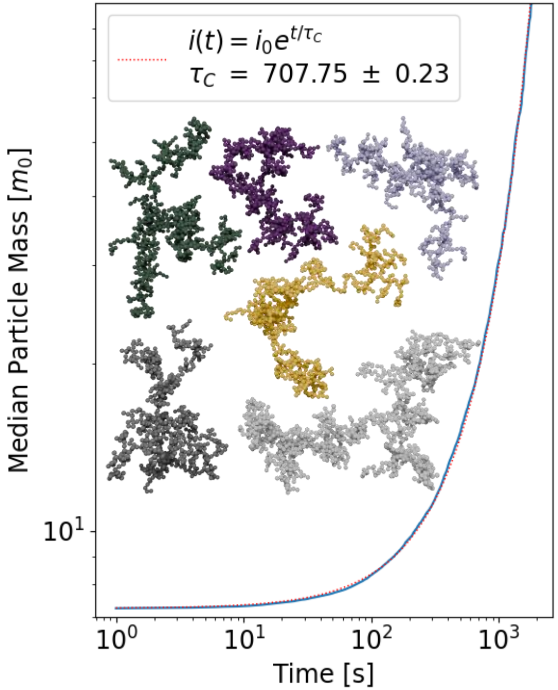
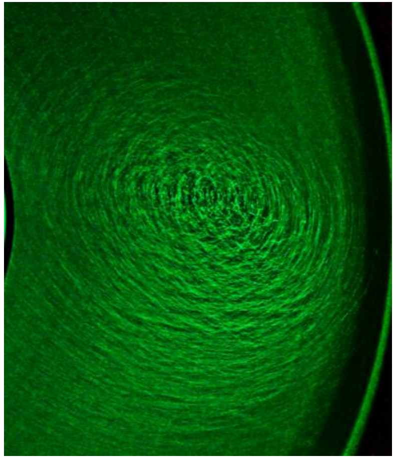


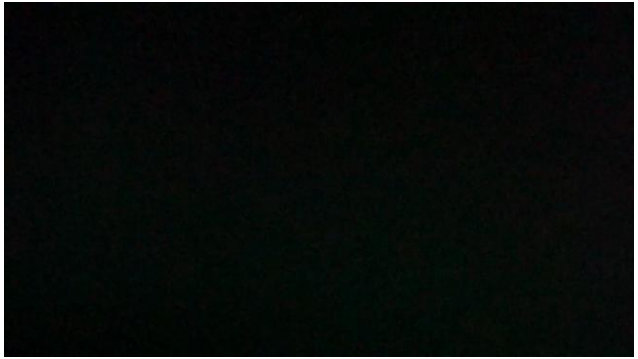


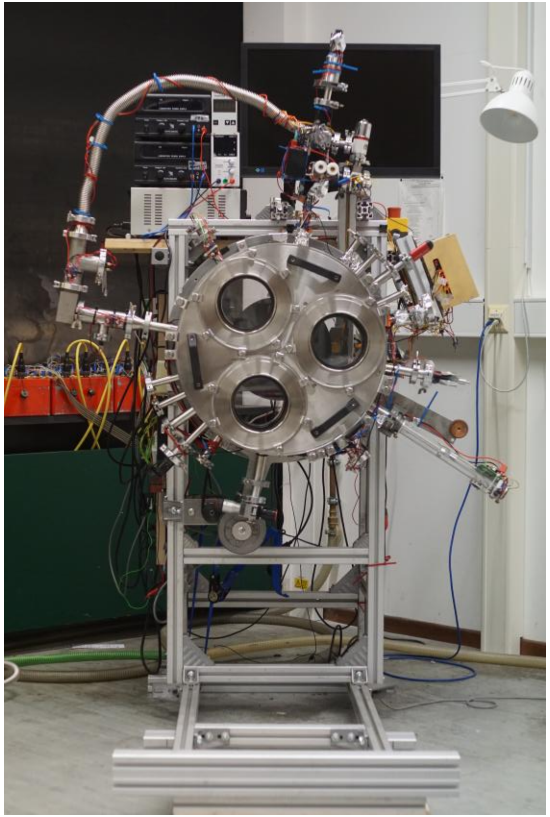
The experiments: II. drift motion (test setup)

PhD Thesis C. Aktas (in prep.)

- Vacuum chamber with 50 cm diameter
- Gas pressure ~100 Pa
- SiO_2 particles with 0.75 µm radius



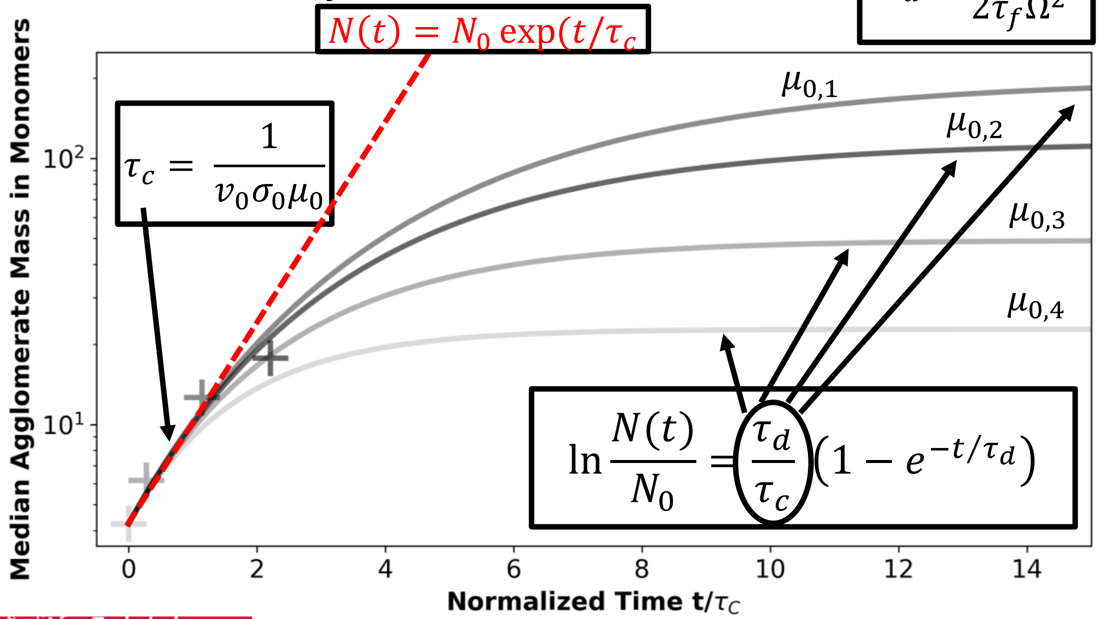




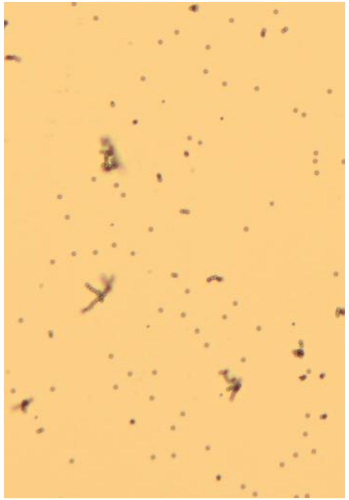
The experiments: II. drift motion (first results)

- Growth of fractal agglomerates
- Growth rate in agreement with model
- Growth limited by small chamber size

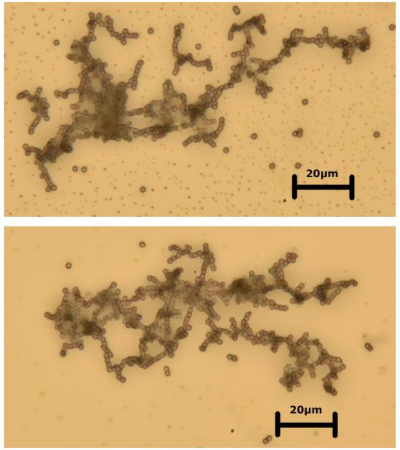
$$\tau_d = \frac{1}{2\tau_f \Omega^2}$$



Sampling of agglomerates after stopping the rotation



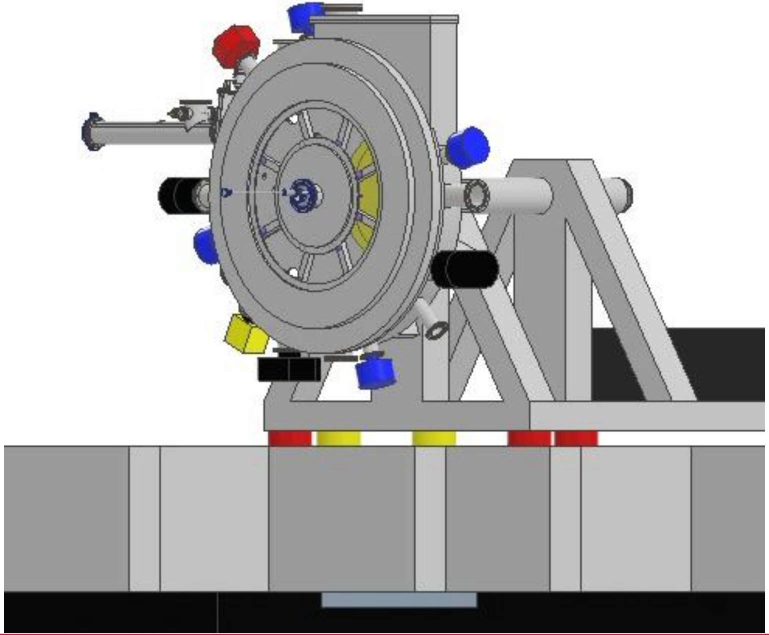
Examples of the fractal agglomerates



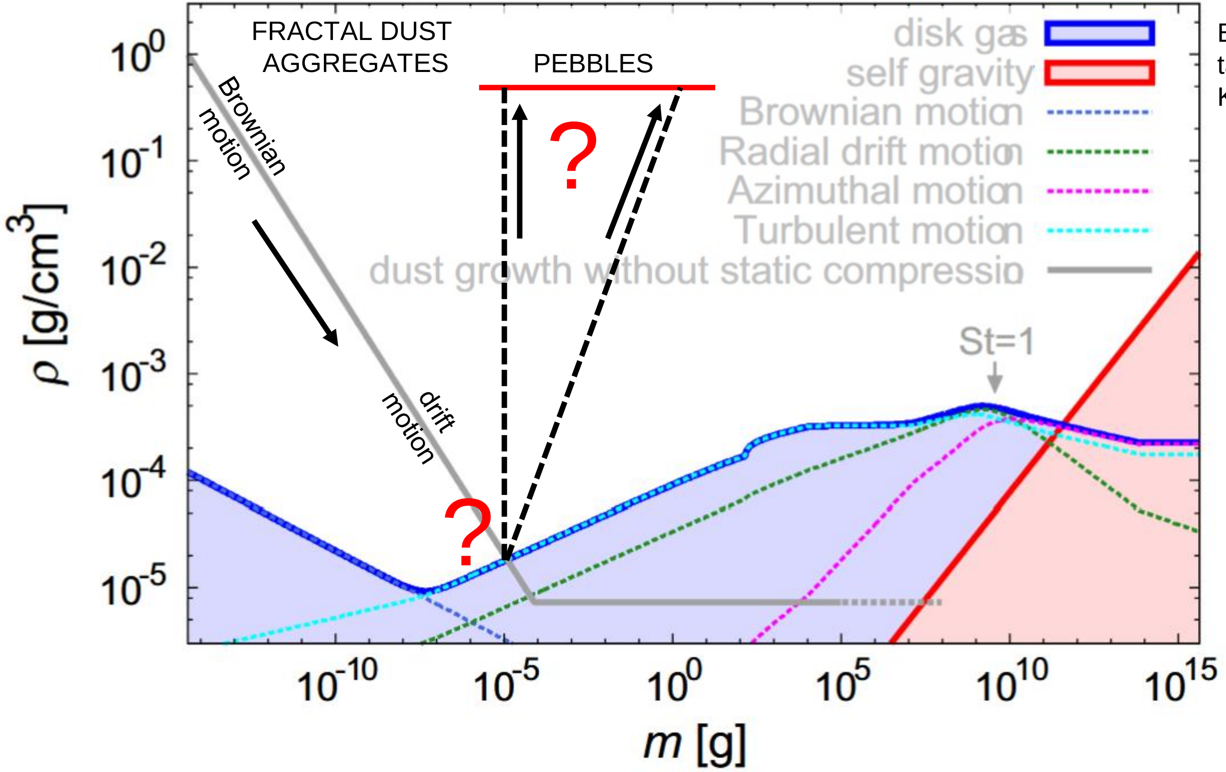
MSc Thesis A. Bodenstein 2023

The experiments: II. drift motion (overcoming the centrifugal limit)

- ERC Advanced Grant (C. Dominik, J. Blum), Oct. 2025 – Sep. 2030
- New rotating vacuum chamber with 2 m inner diameter
- Fractal growth only limited by collisional compaction
  → determines the pebble size
- Diagnostics:
  → Cameras
  → Extinction sensor
  → Polarizing light-scattering unit
  → MIR spectroscopy
  → Sampling
- Active experiment: UV-induced grain charging
- Expectation: growth of cm-dm-sized fractal
  dust agglomerates within a few hours → stay tuned!



Conclusion and outlook

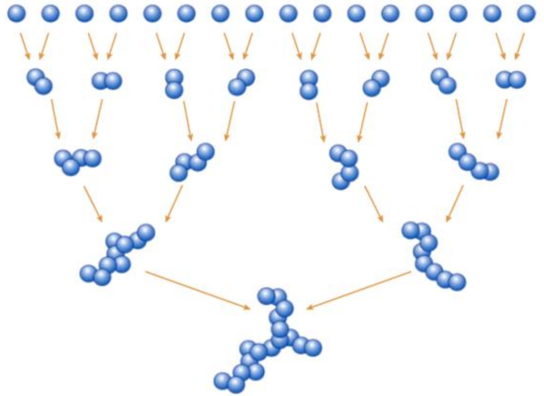


Background graph taken from Kataoka et al. 2013

Extra slides

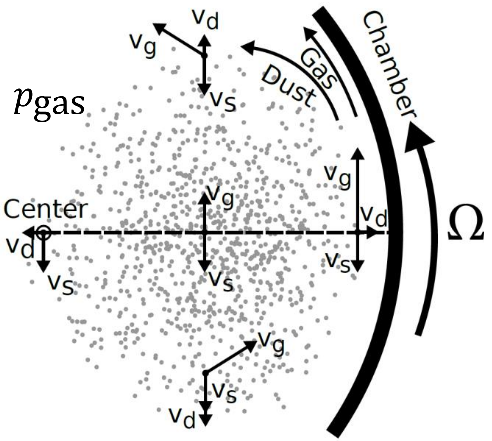
Model for fractal aggregate growth in the Brownian motion and drift phase

Blum & Wurm 2008



- Discrete particle masses $N = \frac{m}{m_0}$ (number of monomer grains in an aggregate)
- Fractal aggregates $(d_f < 2)$ $\sigma(N) \approx \sigma_0 \, N$ (collision cross section)
- Low collision speed $v(N) \approx v_0 N^{\alpha}$
- High sticking probability $\beta(N) = 1$
- Quasi-monodisperse growth $n(N,t)\, N(t) = \mu_0$ (total monomer-grain concentration)
- Single-size Smoluchowski equation $\frac{\partial n(N,t)}{\partial t} = -\beta(N) v(N) \sigma(N)\, n^2(N,t) \approx -v_0 \sigma_0 \, N^{1+\alpha}\, n^2(N,t) \approx -v_0 \sigma_0 \mu_0 N^{\alpha} n(N,t)$
- Mass conservation $N(t)\, n(N,t) = \text{const}$ $\rightarrow$ $N(t) \frac{\partial n(N,t)}{\partial t} + n(N,t) \frac{\partial N(t)}{\partial t} = 0$
- Mass-growth equation $\frac{\partial N(t)}{\partial t} = v_0 \sigma_0 \mu_0 N(t)^{1+\alpha}$

The experiments: II. drift motion (overcoming the centrifugal limit)



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- Mass loss due to centrifugal drift
- Single-size Smoluchowski equation with mass loss
- Fractal aggregates $(d_f < 2)$
- Mass-growth equation
- Solution: initially exponential growth up to the centrifugal-drift limit
- Growth limit for $t \to \infty$
- Maximize $\frac{\tau_d}{\tau_c}$!

$$n(t)N(t) = \mu(t) = \mu_0\, e^{-\frac{t}{\tau_d}}$$

$$\boxed{\tau_d = \frac{1}{2\tau_f \Omega^2}}$$

$$\frac{\partial n(N,t)}{\partial t} = -K\, n^2(N,t) - \frac{n(N,t)}{\tau_d}$$

$$K = \beta(N) v(N) \sigma(N) \approx v_0 \sigma_0\, N$$

$$\boxed{\tau_c = \frac{1}{v_0 \sigma_0 \mu_0}}$$

$$\frac{\partial N(t)}{\partial t} = \frac{N(t)}{\tau_c}\, e^{-t/\tau_d}$$

$$\boxed{\ln \frac{N(t)}{N_0} = \frac{\tau_d}{\tau_c}\left(1 - e^{-t/\tau_d}\right)}$$

$$\boxed{\ln \frac{N_{\max}}{N_0} \approx \frac{\tau_d}{\tau_c} \text{ for } t \gg \tau_c}$$

Sedimentation speed
$v_S = g\tau_f = \Omega R_{sp}$

$$\boxed{\frac{\tau_d}{\tau_c} = \frac{v_0 \sigma_0 \mu_0}{2\tau_f \Omega^2}}$$

→ Highest possible gas pressure (within Epstein drag regime)

→ Largest possible experiment chamber