

Dust Dynamics - Growth and Destruction of rotating magnetized Aggregates

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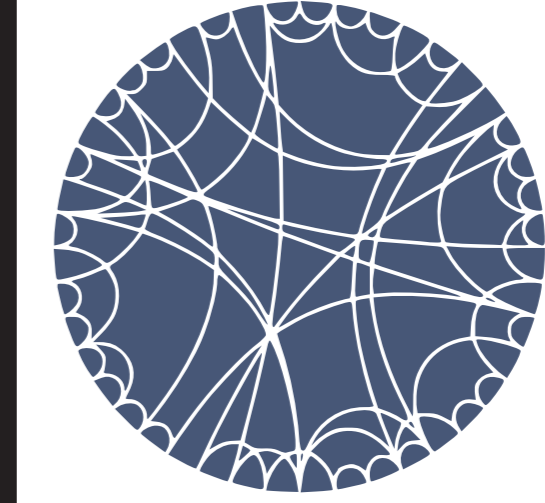
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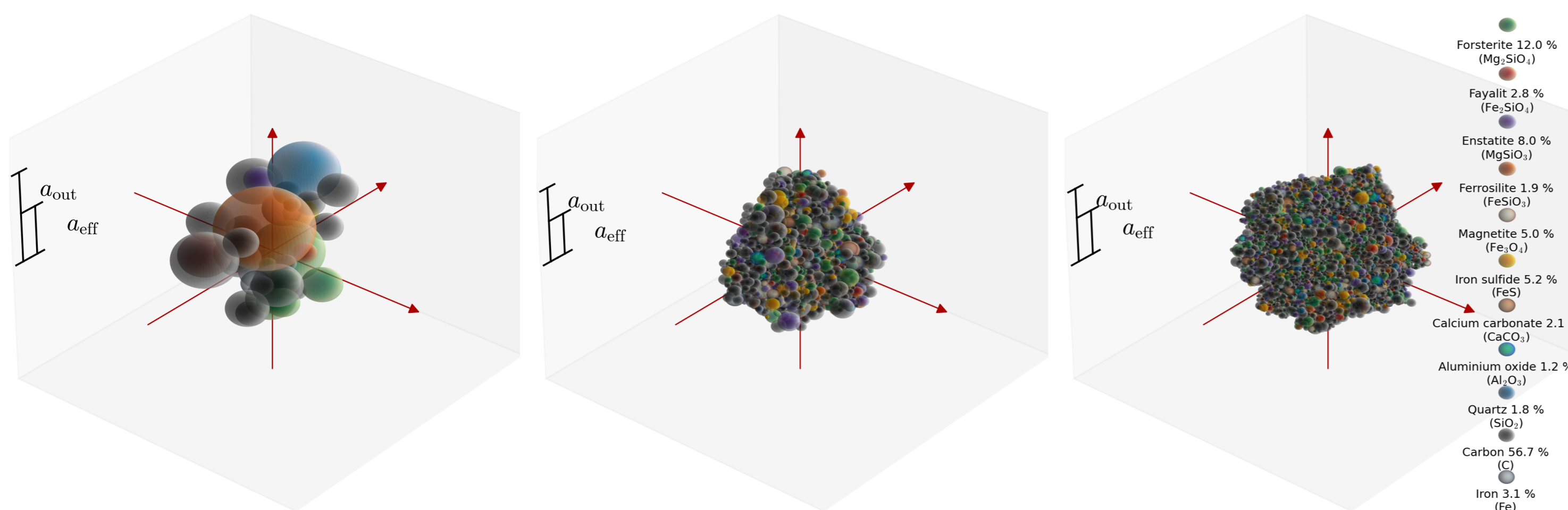
STRUCTURES
CLUSTER OF
EXCELLENCE

Introduction

The initial stages of planet formation may begin concurrently with the aggregation of smaller primary particles (monomers) within a protoplanetary disk. Typically, the dust-to-gas ratio in the disk is on the order of a few percent, but this ratio is highly variable due to various growth and destruction processes that continuously redistribute the grain sizes. When irregular grains are exposed to a directed beam of radiation or a gas-dust drift, they spin up most efficiently. However, rapid grain rotation is a parameter commonly ignored in modeling dust growth and destruction. In this project, we aim to explore, in particular, the two processes of rotational disruption by means of centrifugal forces and the grain growth of magnetized grains in detail, based on ab-initio dust grain modeling (Zürn & Reissl & Klessen in prep.).

Dust Grain Growth

Dust samples collected in our own solar system suggest that dust grains are fractal aggregates of small building blocks (monomers) consisting of carbonaceous and silicate compounds. We mimic the growth of such aggregates through ballistic aggregation and migration (BAM) of monomers with the help of a Monte Carlo (MC)-based algorithm (Reissl & Meehan 2022, Reissl & Nguyen 2024) to account for the various shapes and optical features observed in the interstellar medium (ISM) and protoplanetary disks. The resulting grains are classified based on their volume, average inter-monomer connections, moments of inertia, and (paramagnetic) material properties, as suggested by the ASTRODUST model (Draine & Hensley 2021).



Exemplary BAM grains with an effective volume radius of $a_{\text{eff}} = 100$ nm (left), $a_{\text{eff}} = 400$ nm (middle), and $a_{\text{eff}} = 700$ nm (right), where each monomer consists of a distinct material.

N-body Simulations of rotating Dust

Numerical simulations are performed using the analytical description of the forces and angular velocities according to the JKR model (Johnson+ 1971), which was later reformulated with the help of contact pointer notation and a viscoelastic damping of energy (Wada+ 2007, Seizinger+ 2013, Reissl & Nguyen 2024), more accurately reflecting the actual monomer interactions as observed in the laboratory.

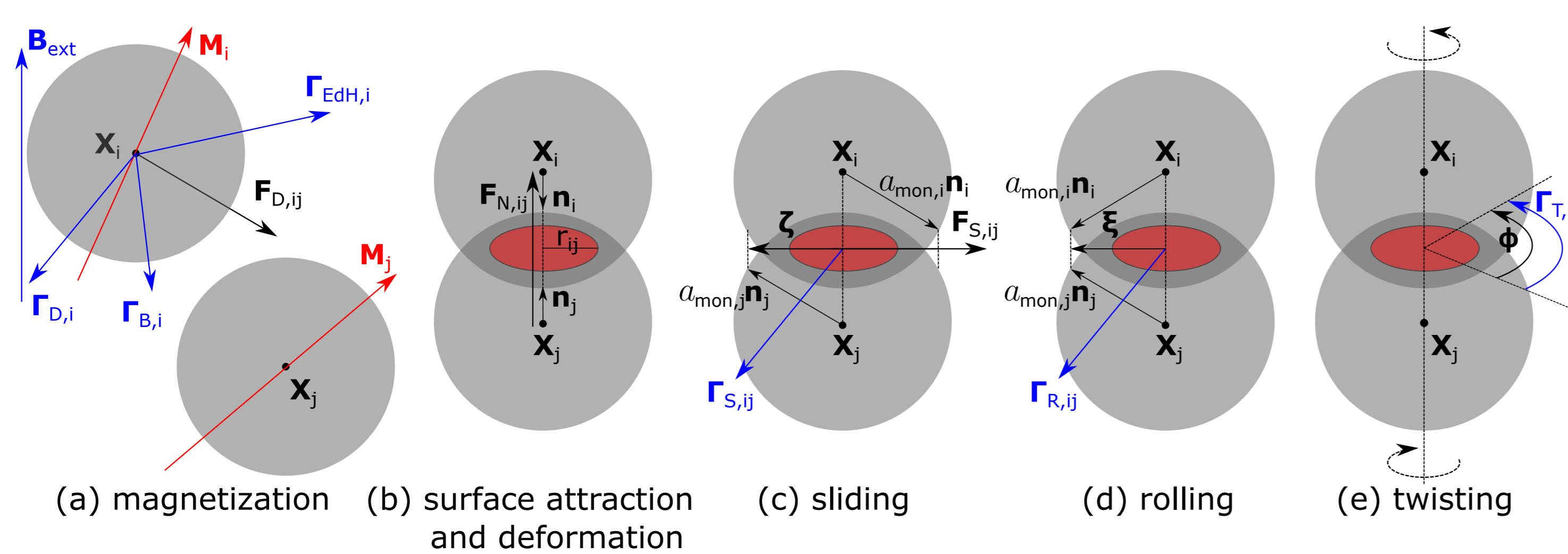
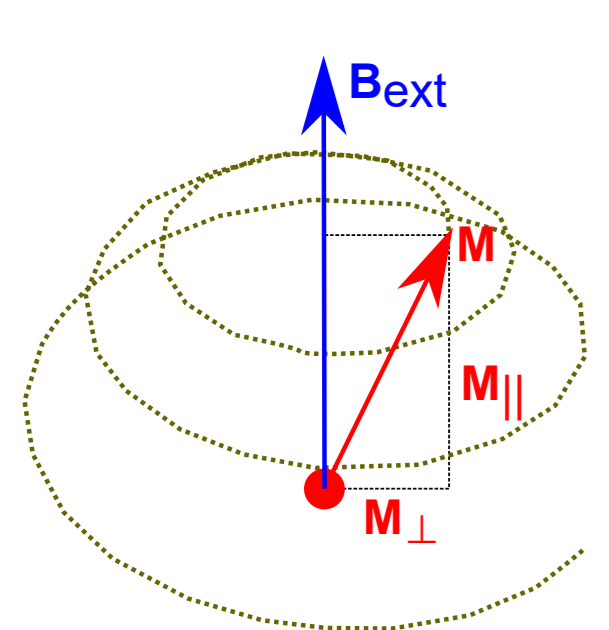


Illustration of the considered inter-monomer contact forces and torques caused by (a) monomer magnetization and rotation ($\vec{F}_{D,ij}$, $\vec{F}_{D,i}$, $\vec{F}_{B,i}$, $\vec{F}_{EdH,i}$), (b) surface attraction ($\vec{F}_{N,ij}$), (c) sliding ($\vec{F}_{S,ij}$, $\vec{F}_{S,i}$), (d) rolling ($\vec{F}_{R,ij}$), and (e) twisting ($\vec{F}_{T,ij}$).

The translational velocity, \vec{v} , of each monomer within the aggregate is given by balancing the forces caused by an external magnetic field and the contact forces acting between neighboring monomers:



$$m_i \frac{d\vec{v}_i}{dt} = \sum_{i \neq j} (\vec{F}_{N,ij} + \vec{F}_{S,ij} + \vec{F}_{D,ij})$$

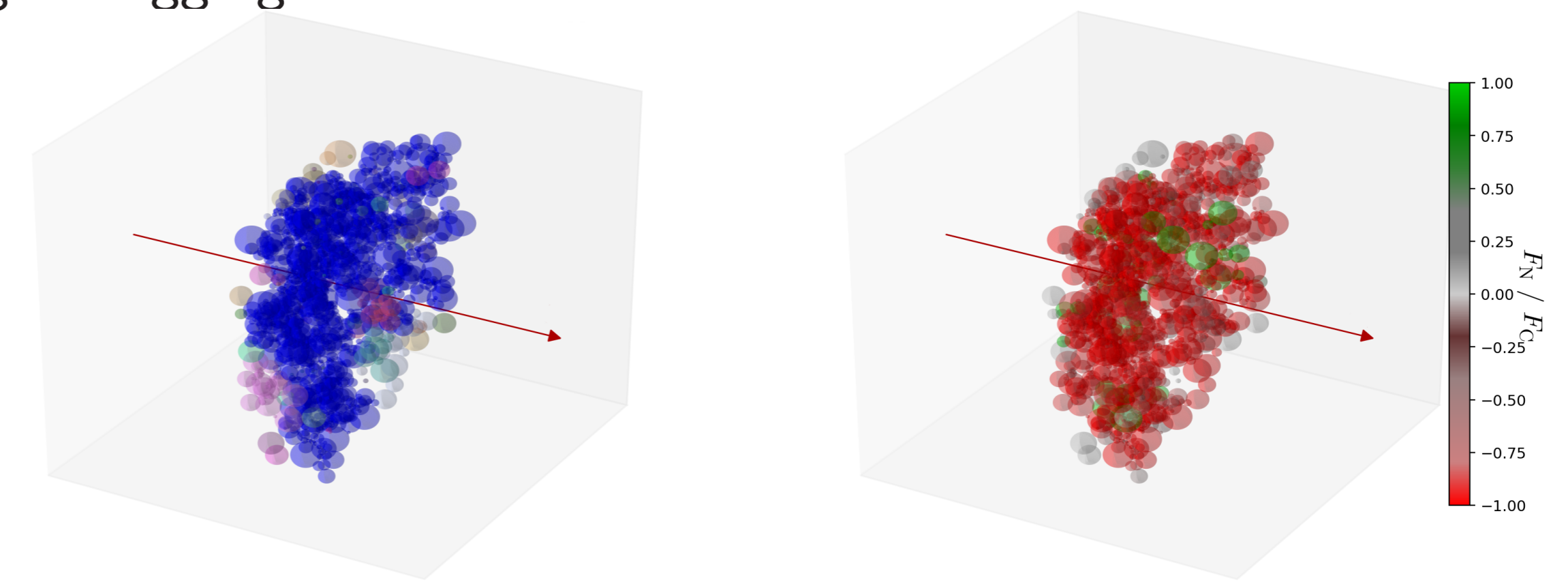
$$I_i \frac{d\vec{\omega}_{rot,i}}{dt} = \vec{F}_{EdH,i} + \vec{F}_{B,i} + \sum_{i \neq j} (\vec{F}_{S,ij} + \vec{F}_{R,ij} + \vec{F}_{T,ij} + \vec{F}_{D,ij})$$

$$\frac{d\vec{M}_i}{dt} = \gamma_e (\vec{M}_i \times \vec{B}_{ext}) - \frac{1}{\tau_{sl}} (\vec{M}_i - \vec{M}_{||}) - \frac{1}{\tau_{ss}} \vec{M}_{\perp}$$

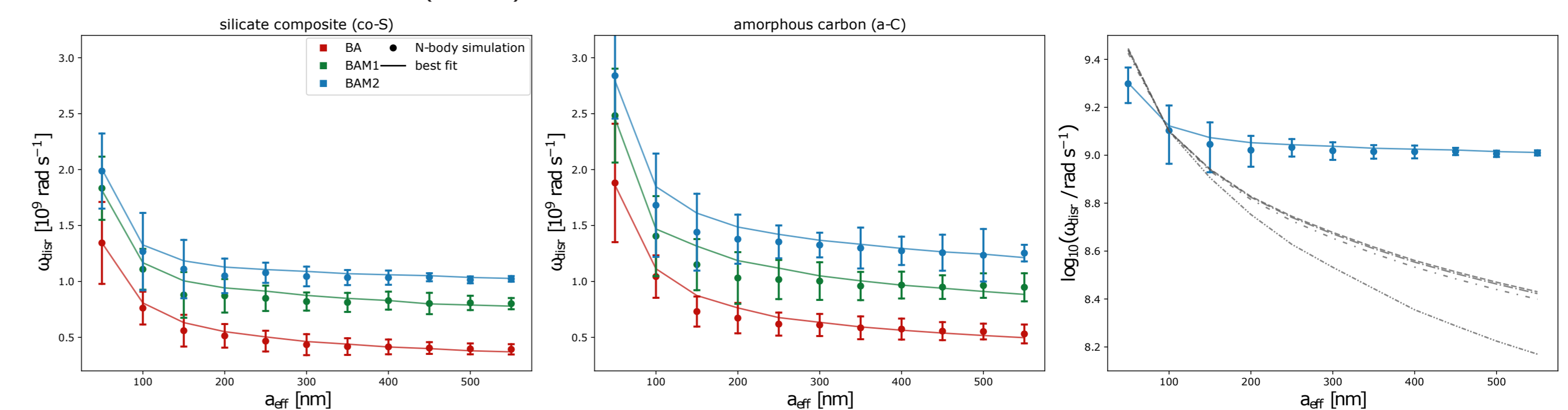
In addition to the contact forces, we consider in our novel approach the monomer magnetization due to induction by an external magnetic field, \vec{B}_{ext} , the Barnett effect (Barnett 1905), as well as the Einstein-de Haas effect (Einstein & de Haas 1915). The time evolution of the (re)magnetization of each monomer is modeled by the Bloch equation (Bloch 1946), accounting for spin-spin (τ_{ss}) and spin-lattice (τ_{sl}) interactions.

Rotational Disruption of Dust Aggregates

Dust disruption simulations are performed by mimicking the grain spin-up processes on a microphysical level, typical for the ISM and protoplanetary disks. We analyze the monomer displacement and fragments to determine the stability criteria of rotating grain aggregates.



An exemplary simulation result for an aggregate rotating at the angular velocity $\omega_{agg} = \omega_{disr}$, where the rotational disruption event sets in. Color-coded are the remaining connected clusters (left) and the inter-monomer forces (right).



The average critical angular velocity ω_{disr} for different effective grain sizes a_{eff} , where the aggregates become rotationally destroyed. Shown are the simulated and best-fit results for an ensemble of silicate grains (left) and carbon grains (middle), considering the different aggregates, as well as the comparison with theoretical models (gray lines, right).

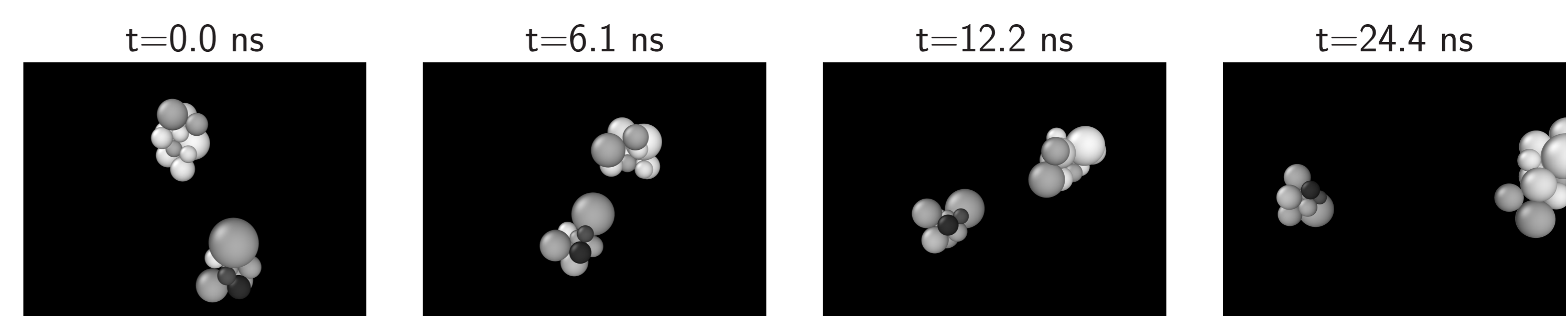
► Our approach allows, for the first time, to link the critical angular velocity of grain disruption:

$$\omega_{disr} = \frac{A}{a_{eff}} \sqrt{\frac{\gamma}{\rho_m \langle a_{mon} \rangle}} (N_{mon} \Phi \langle N_{con} \rangle)^\alpha$$

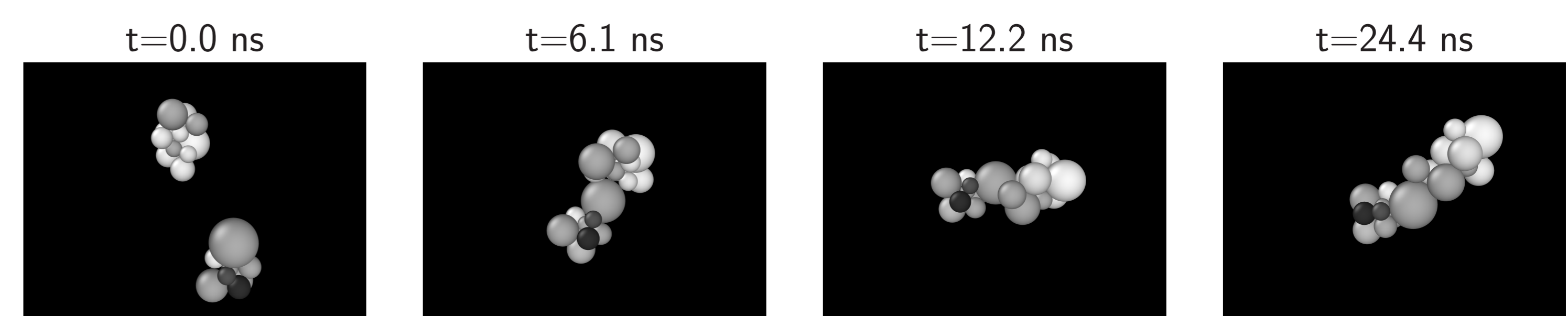
to the particular aggregate parameters of surface energy γ , material density ρ_m , average monomer radius $\langle a_{mon} \rangle$, number of monomers N_{mon} , average number of connections $\langle N_{con} \rangle$, and the volume filling factor Φ , respectively.

Growth of magnetized Dust Aggregates

N-body grain-grain collision simulations are performed, assuming rapidly rotating aggregates, an external magnetic field, and magnetized monomers.



An exemplary simulation at different time steps. The aggregates have an effective radius of $a_{eff} = 150$ nm, collide with a relative velocity of $v = 30$ m s⁻¹, and are rotating with $\omega_{agg} = 10^8$ s⁻¹. The monomers are not magnetized, and the impact parameter is $b > b_{max}$.



The same initial conditions as the simulation above, but with magnetized monomers and an external magnetic field of $\vec{B}_{ext} = 3$ mG.

- Rapid grain rotation only marginally impacts the efficiency of aggregates to stick together and to create larger structures.
- Magnetized grains and an external magnetic field boost grain growth, even though the impact parameter is $b \gg b_{max}$.
- In a forthcoming study, we will explore the impact of magnetic field strength and relative velocity on the growth of magnetized grains systematically (Zürn & Reissl & Klessen in prep.).