Dust Dynamics - On the Origin of Dust Polarization in protoplanetary Disks

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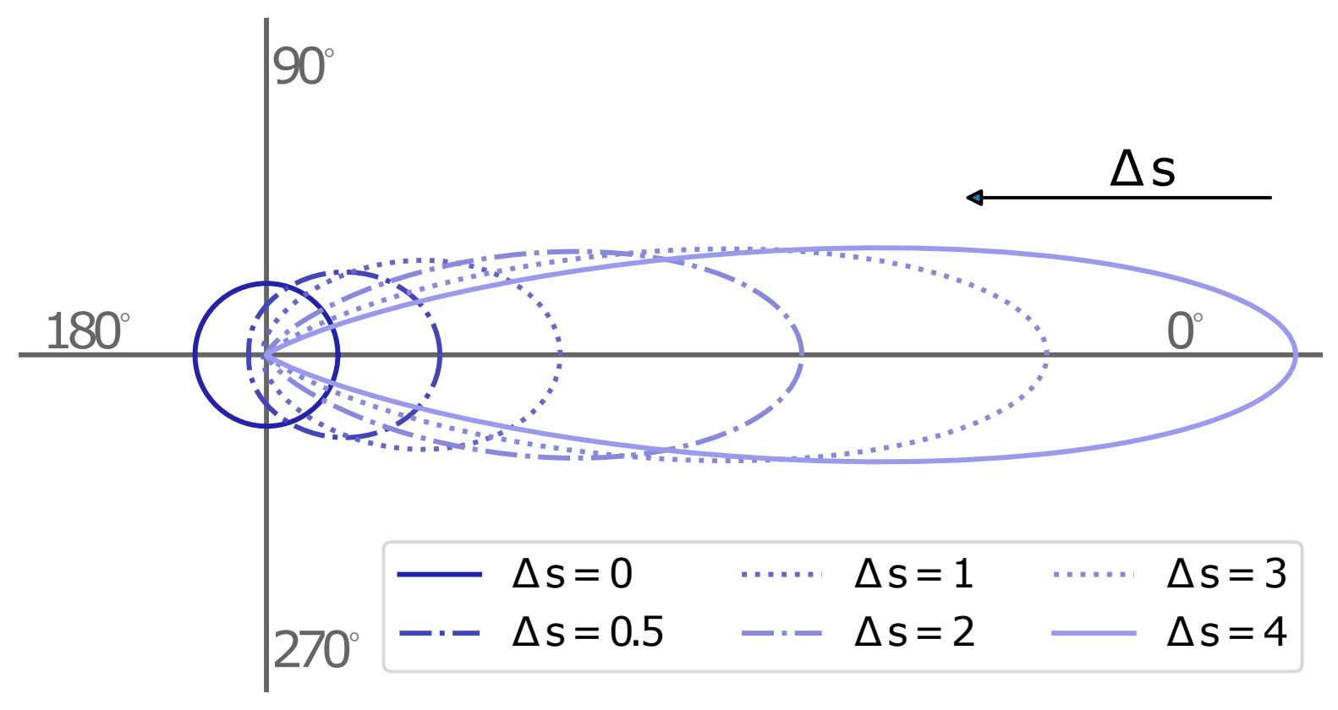
Introduction

Magnetic fields impact the time evolution in protoplanetary disks by driving turbulence and angular momentum transport, subsequently enabling the accretion of matter onto the central object. Dust polarization observations have become a well-established technique to probe the magnetic field properties in such disks, as rapidly rotating dust grains tend to align their rotation axis along the field direction. However, such observations are often ambiguous because the spin-up processes of dust grains remain poorly constrained to this date. In addition to the field direction, the grains may also align in the direction of the gas-dust drift (mechanical alignment). Moreover, dust polarization not only arises from the emission of aligned grains but also from radiation emitted and scattered by dust grains (self-scattering). The aim of this project is to model the dust polarization processes of mechanical alignment and self-scattering from first principles as a first attempt to separate dust polarization that originates from dust aligned with the magnetic field from contributions that have their origin in other physical processes (Lietzow-Sinjen+ in prep.).

Numerical Simulations of Dust Grain Dynamics

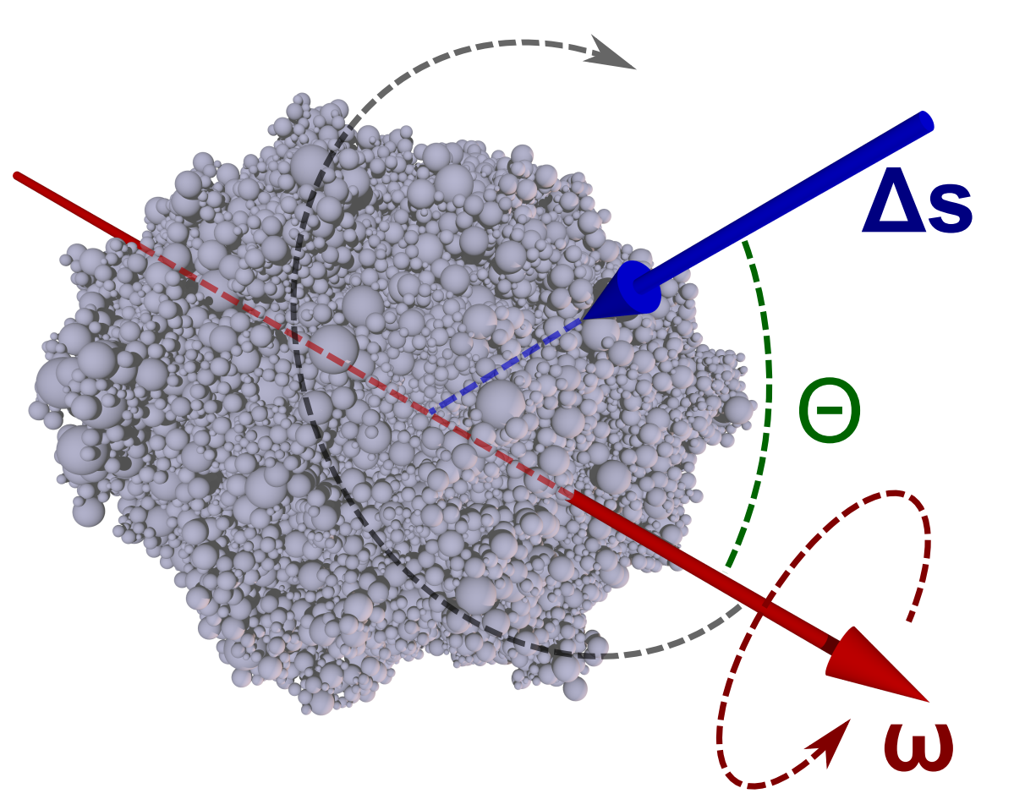
Complex dust grain analogues are prepared by means of ballistic aggregation and migration (BAM) of primary particles (monomers). The resulting aggregates are classified by their size, material, and the connections between monomers. A code was developed for simulations of the complex dynamics of grain spin-up processes and subsequent rotational disruption (Reissl & Meehan 2024). Trajectories of individual gas particles are sampled from a modified Maxwell-Boltzmann distribution via a Monte Carlo (MC) algorithm, where $\Delta s = (v_{\mathrm{gas}} - v_{\mathrm{dust}})/v_{\mathrm{th}}$ is the dimensionless gas-dust drift velocity.



Left: The probability for a gas particle to collide with a dust grain under a certain angle varies with different drift velocities Δs. For $\Delta s \geq 1$, the probability of finding a gas particle approaching the dust grain at an angle of 180° is already virtually zero.

BAM dust aggregates gain net angular momentum through anisotropic gas collisions. We simulate the time evolution of the angular velocity ω, the alignment angle Θ, and the precession at each time step by solving the equation

$$\frac{\mathrm{d}\vec{\omega}}{\mathrm{d}t} = \frac{1}{I_{\mathrm{m}}}\vec{\Gamma}_{\mathrm{MET}}(\Theta) - \frac{\vec{\omega}}{\tau_{\mathrm{drag}}}$$

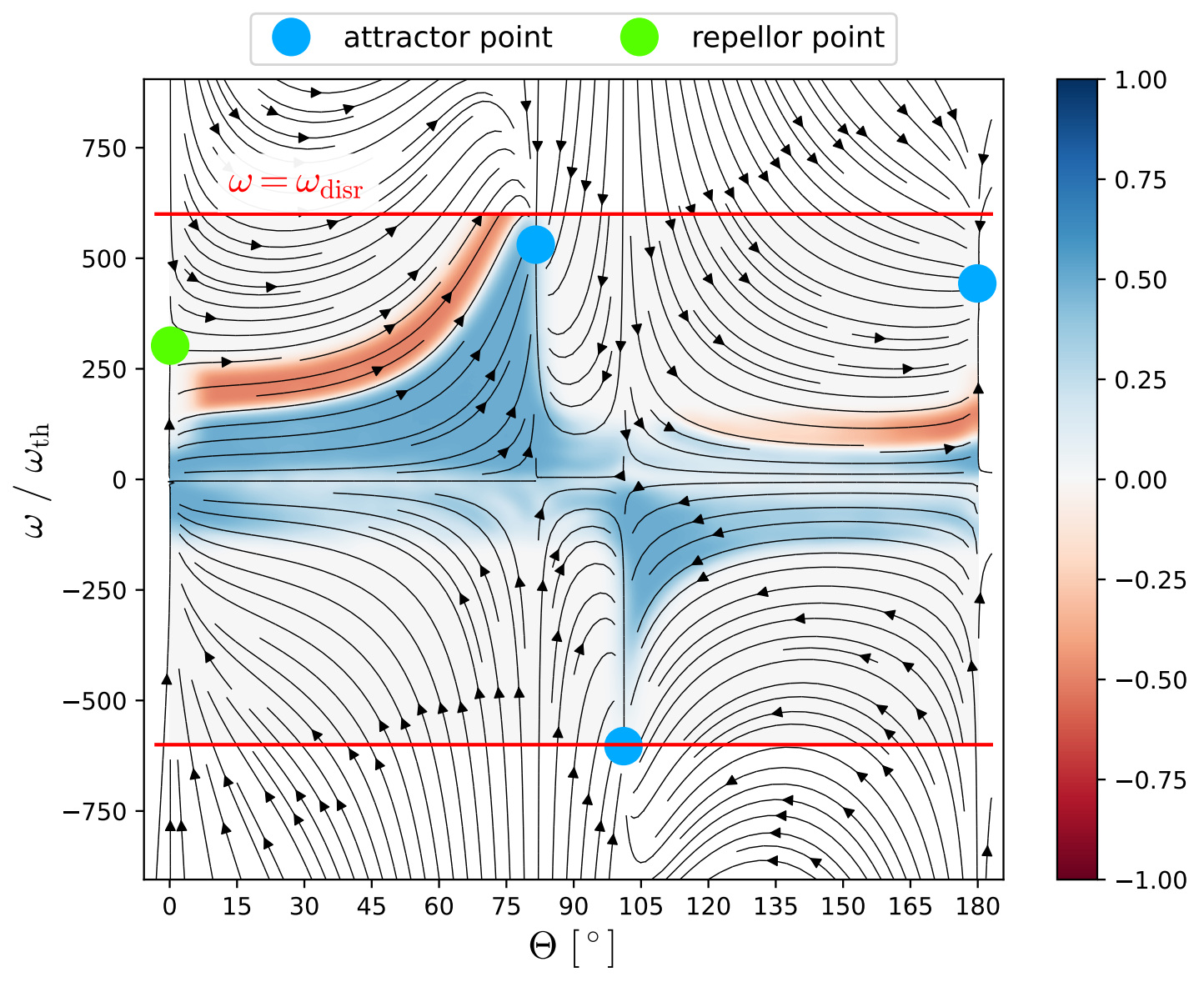


where $\vec{\Gamma}_{\mathrm{MET}}$ is the total mechanical torque (MET) resulting from gas collisions, scattering, and evaporation, whereas τ_{drag} is the characteristic timescale of gas drag and photon drag.

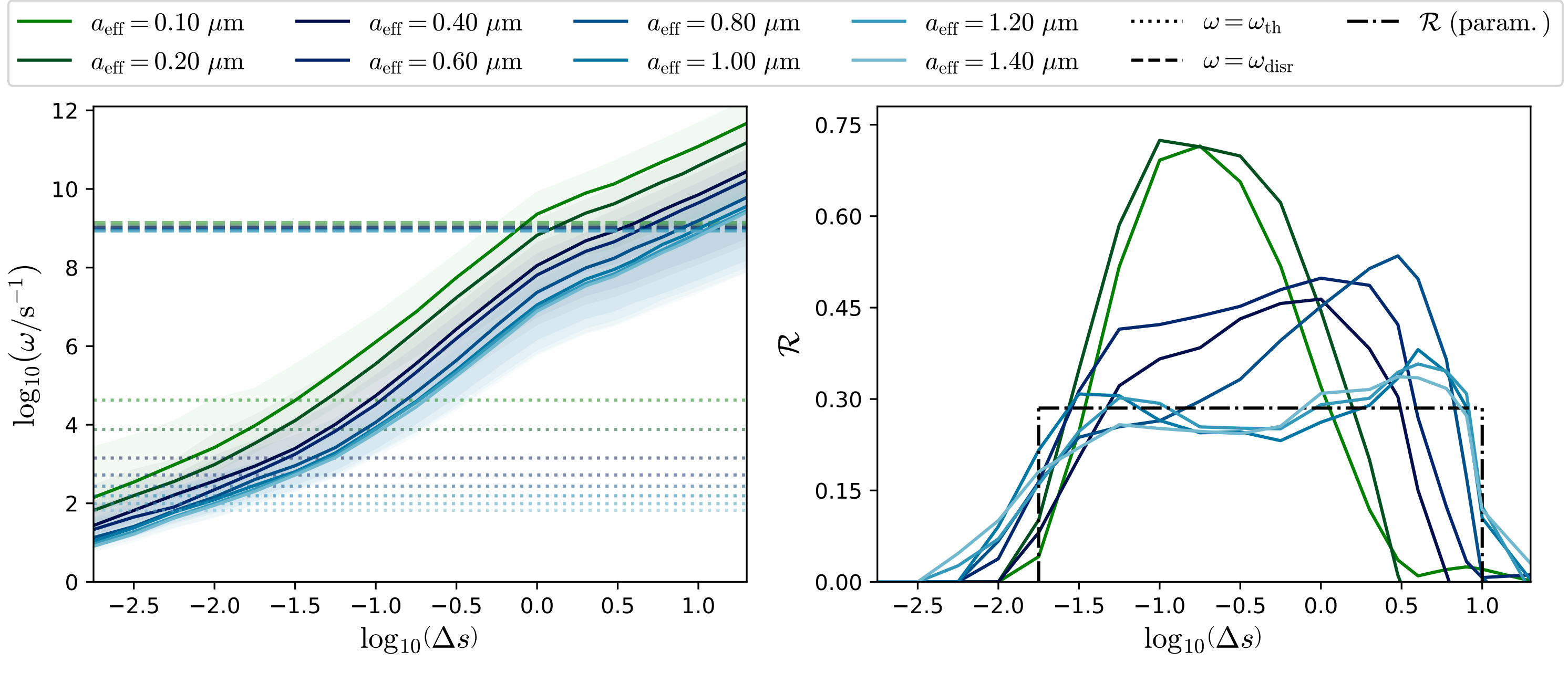
Left: An exemplary BAM aggregate rotates with an angular velocity $\vec{\omega}$. The rotation and precession of the dust aggregate result from gas-dust interactions, where the gas and dust components move with a relative drift Δs through the disk. The quantity Θ is the angle between $\vec{\omega}$ and Δs.

Stable Grain Alignment and Precession

The time evolution of each individual BAM dust aggregate is traced in the ω-Θ phase space to determine the attractors, i.e., the points of long-term stable alignment in the direction Δs.



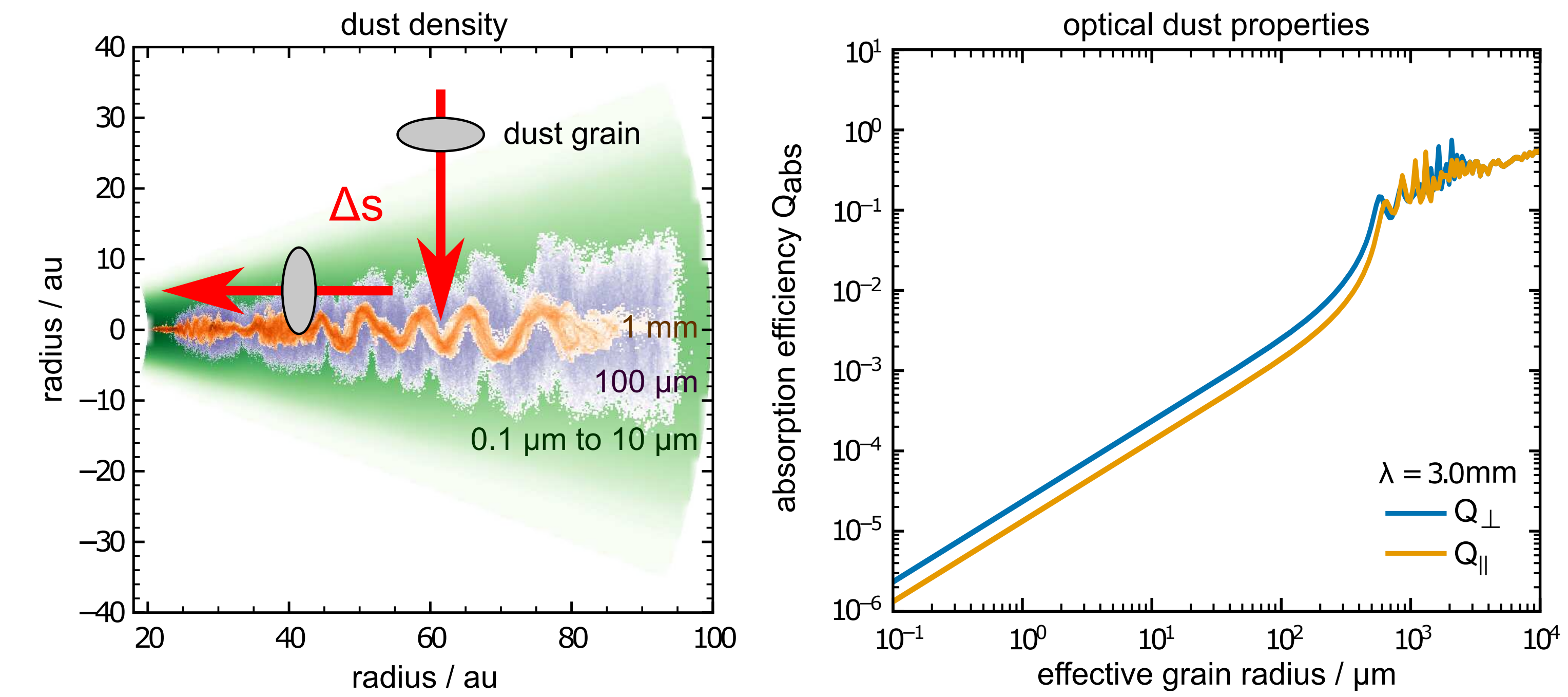
Left: A phase portrait of the evolution of angular velocity ω and alignment angle Θ is presented for an exemplary BAM dust aggregate for different initial conditions. For a trajectory where $\omega > \omega_{\mathrm{disr}}$, the aggregate becomes rotationally disrupted.



Left panel: Angular velocity ω as a function of the drift velocity. The effective grain radii are color-coded. Dotted lines show the lower limit, ω_{th}, for stable alignment, and dashed lines represent the upper limit, ω_{disr}, for rotational disruption. *Right panel*: The corresponding Rayleigh reduction factor $\mathcal{R}$ for dust polarization, where $\mathcal{R} = 1$ indicates perfect alignment.

Protoplanetary Disk and Dust Properties

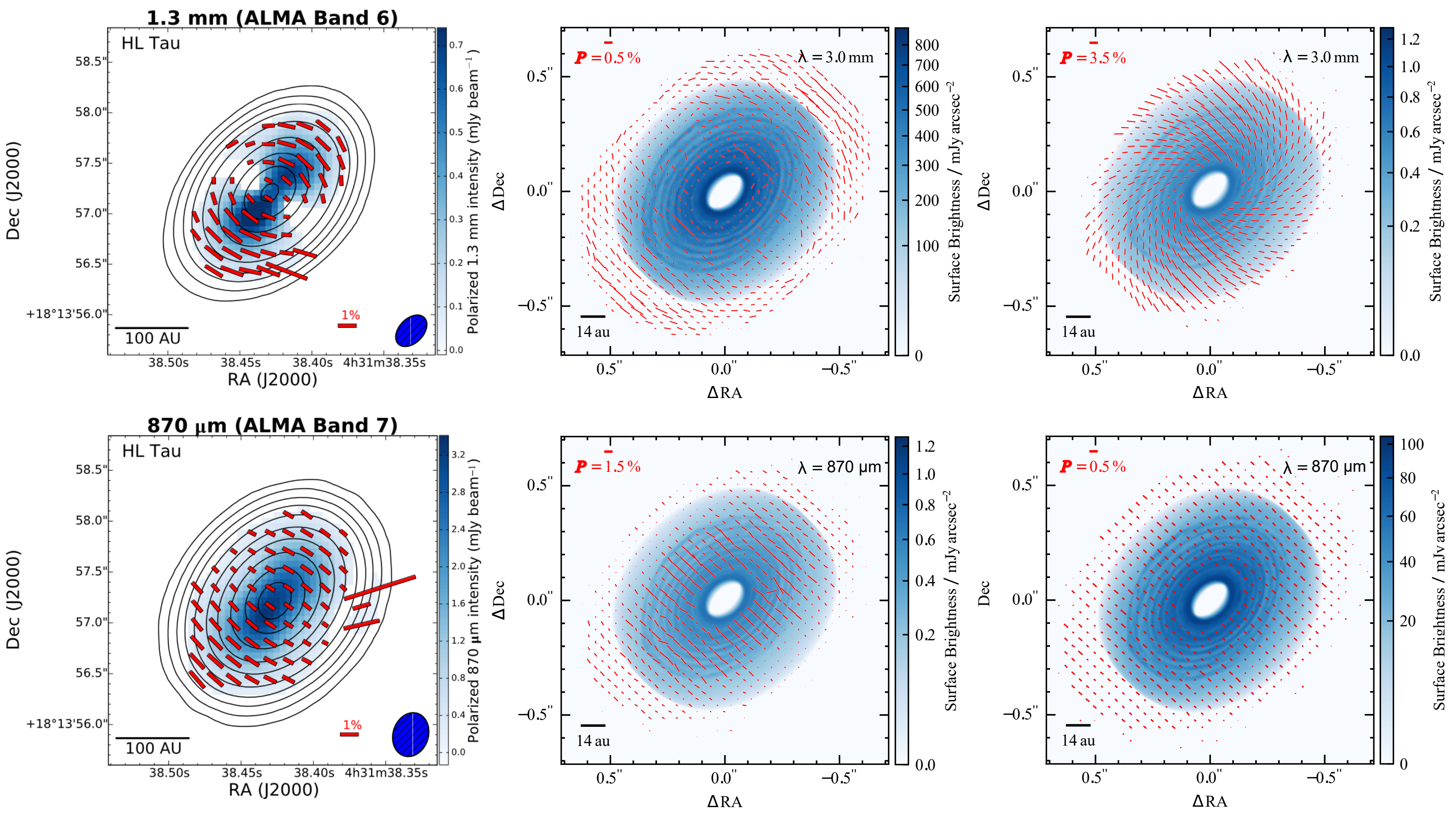
To constrain the orientation of drifting grains under the effect of METs, we utilize radiation hydrodynamical simulation using the PLUTO code (Flock+ 2017, 2020). The simulations provide the gas and dust density distributions as well as the local drift velocity. Optical dust properties are pre-calculated considering the DSHARP dust composition (Wolf & Voshchinnikov 2004, Birnstiel+ 2018), which consists of refractory organics, astronomical silicate, water ice, and troilite.



Left panel: The dust density for grains of different sizes. Red arrows indicate the drift velocity and oblate shapes the preferential grain alignment direction. *Right panel:* The absorption efficiencies, Q_{abs}, over effective grain size for polarized dust emission parallel, $Q_{||}$, and perpendicular, $Q_{\perp}$, to the rotation axis.

Synthetic Dust Polarization Observations

MC dust heating and polarization simulations are performed with the radiative transfer code POLARIS (Reissl+ 2016, 2020), based on the dust and gas parameters of the PLUTO disk simulations. As polarization mechanisms, we consider self-scattering and thermal emission, including the micro-physics model of the mechanical alignment of BAM aggregates (Lietzow-Sinjen+ in prep.).



ALMA dust polarization observations (*left column*, Kataoka+ 2017, Stephens+ 2017) in comparison with synthetic observations of self-scattered radiation (*middle column*) and thermal emission from mechanically aligned grains (*right column*).

- The mechanical spin-up process in protoplanetary disks is most efficient for BAM dust aggregates, requiring only a subsonic gas-dust drift to reach a stable alignment with a Rayleigh reduction factor up to $\mathcal{R} = 0.75$.
- Dust polarization observations heavily depend on the maximum grain sizes, the considered grain alignment physics, and the observed wavelengths.
- Both self-scattered radiation and thermal emission from mechanically aligned grains can account for the observed polarization vectors.
- In a follow-up project, we will also include radiative torques (RATs), i.e., the alignment of grains by the radiation field.

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