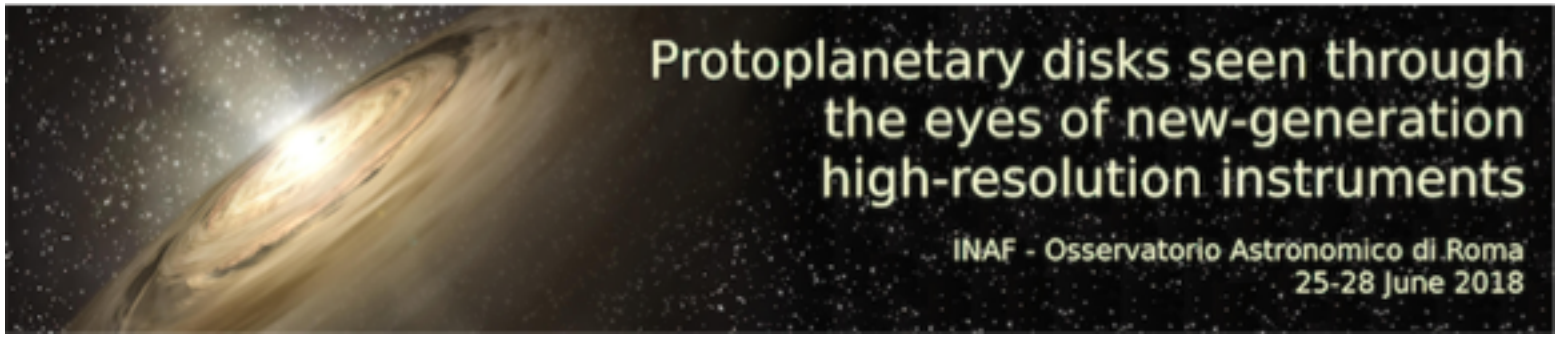

Non-spherical dust dynamics in protoplanetary disks: the effects of particle nonsphericity on the evolution timescales

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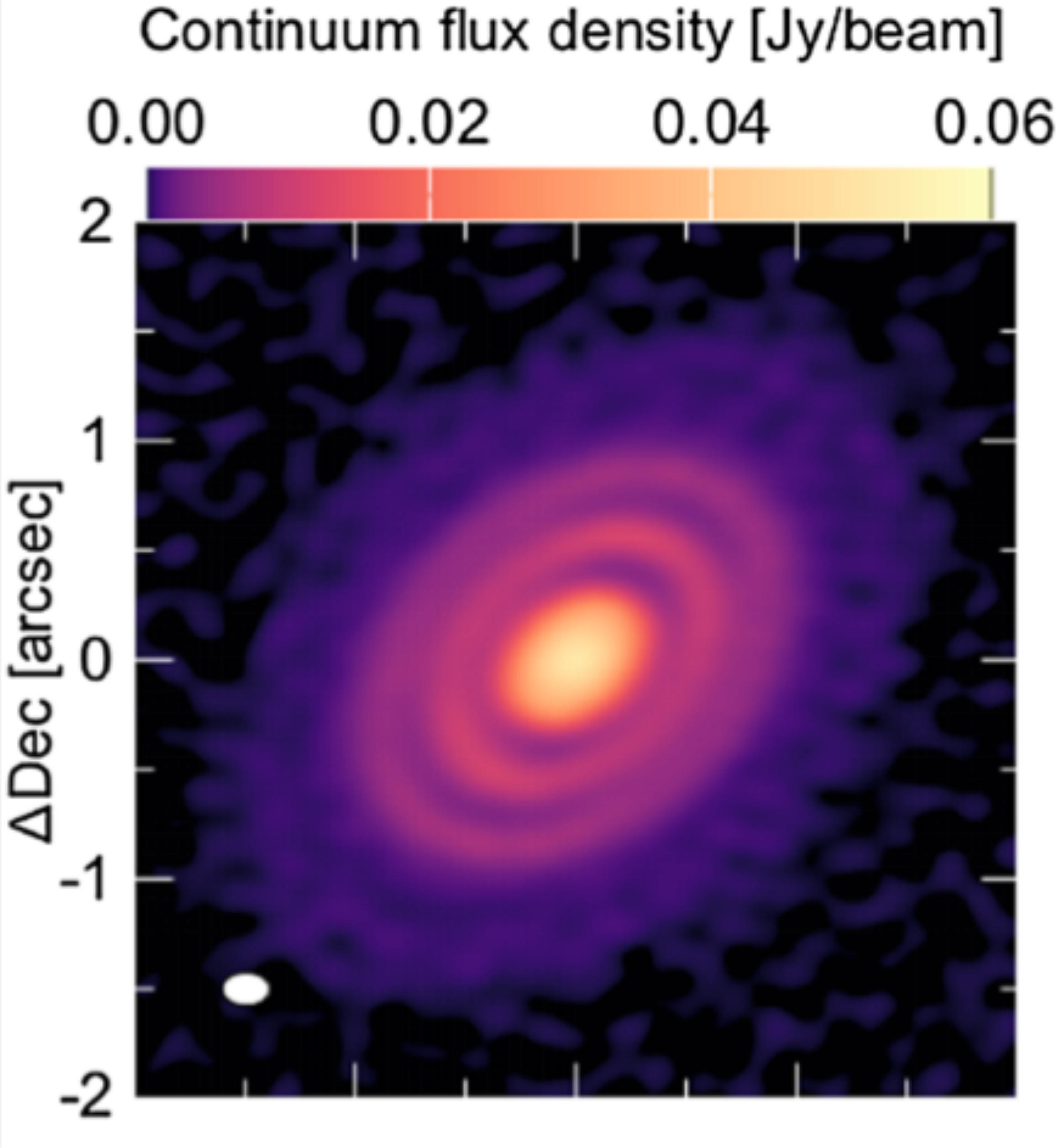
HD163296: A Case Study for Late Disks



5 Myr old circumstellar disk around a star of 2.3 solar masses.

Three identified ***gaps in the dust, two in the gas*** (Isella et al. 2016).

Proposed cause: ***3 giant planets*** of 0.1, 0.3, 0.3 Jovian masses (with large uncertainties) at 60, 100 and 160 au (Isella et al. 2016).

Dust gaps in the circumstellar disc of HD163296 imaged with ALMA (Isella et al. 2016)

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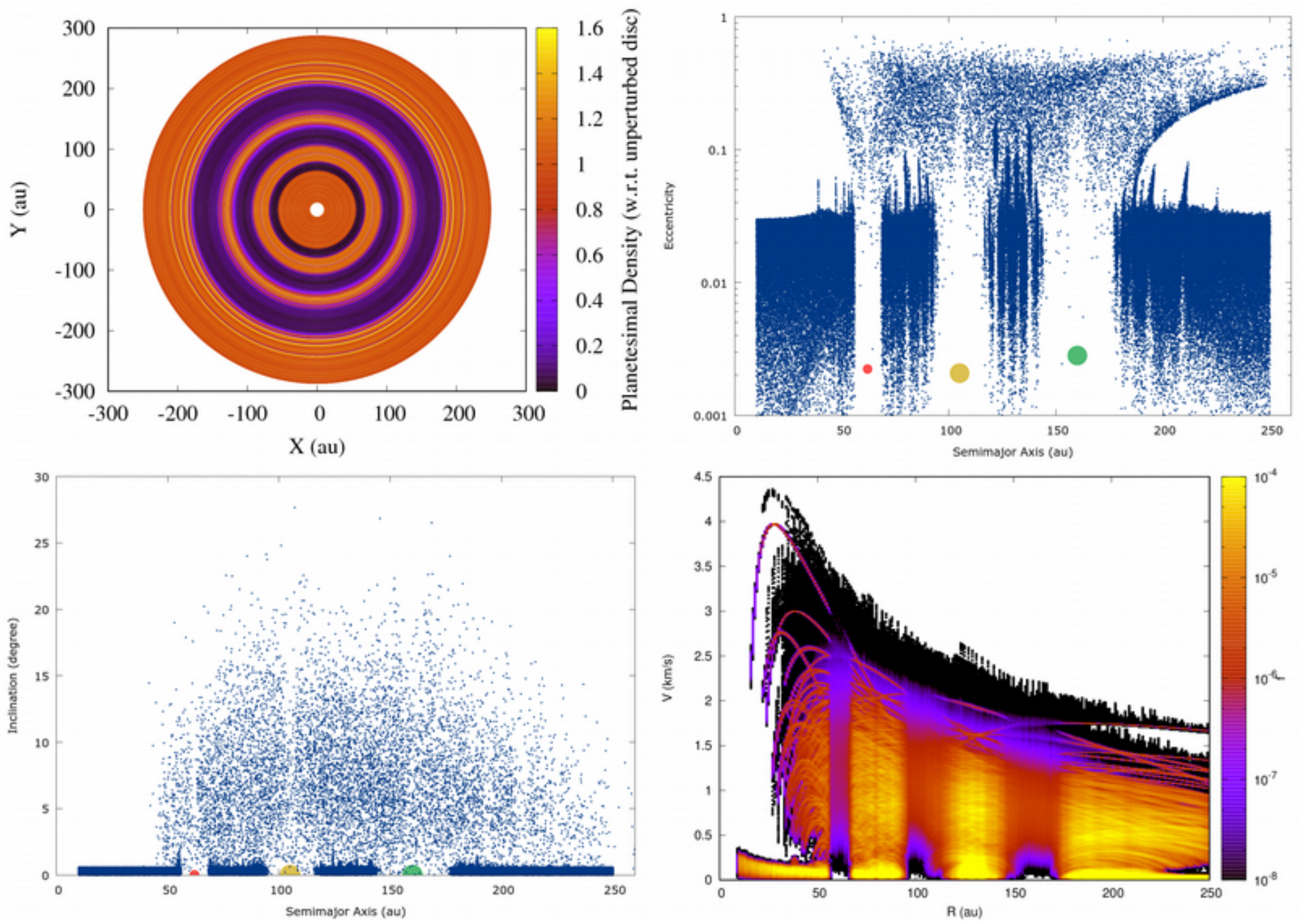
HD163296: Current State?



Dynamical excitation of the planetesimal disk *of HD 163296 caused by the formation of its three giant planets and* ***enhancement of the planetesimal impact velocities****, resulting in* ***collisional regeneration of the dust*** *population (Turrini et al., in prep.) .*

Courtesy: D. Turrini

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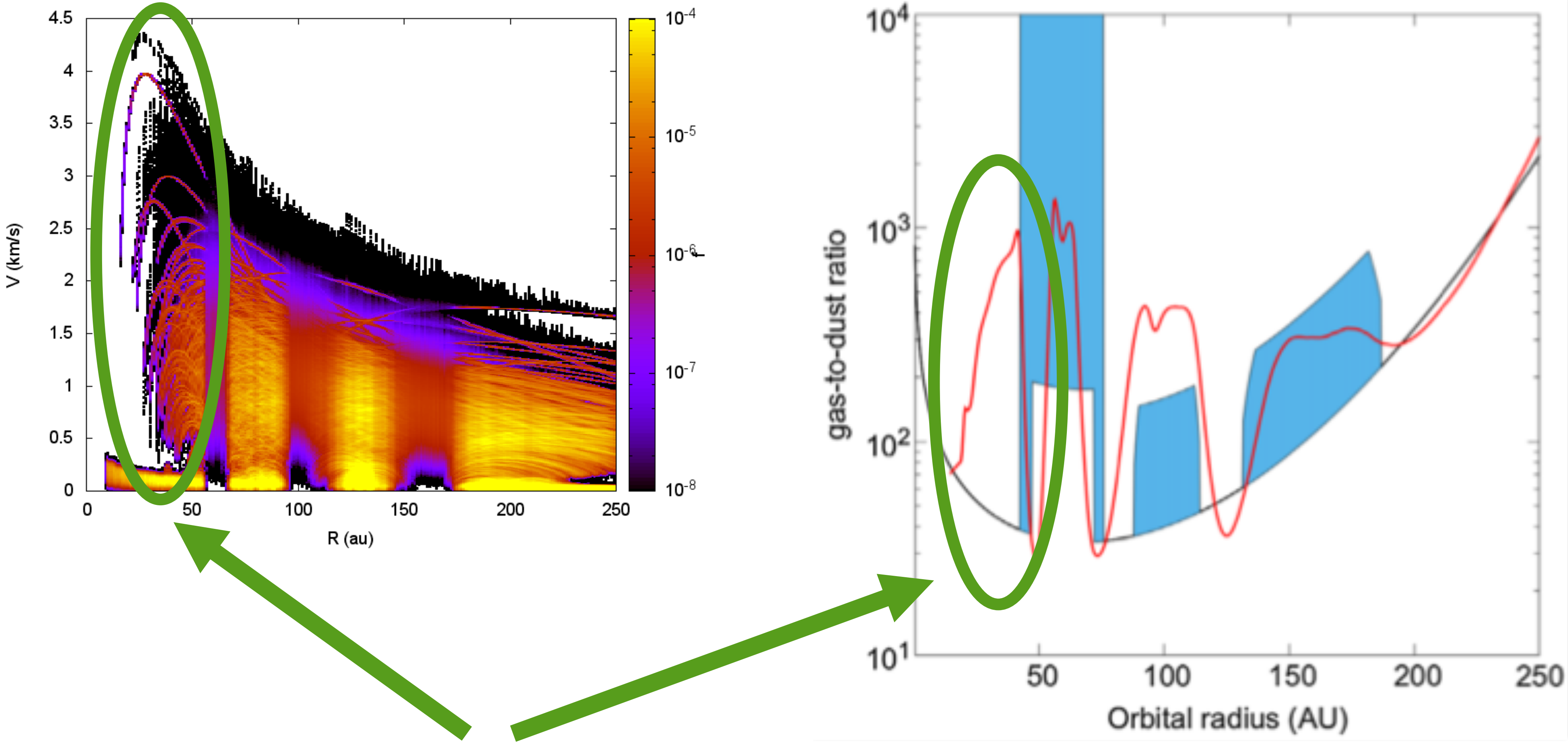
Dynamical Excitation and Planetary Masses

Courtesy: D. Turrini

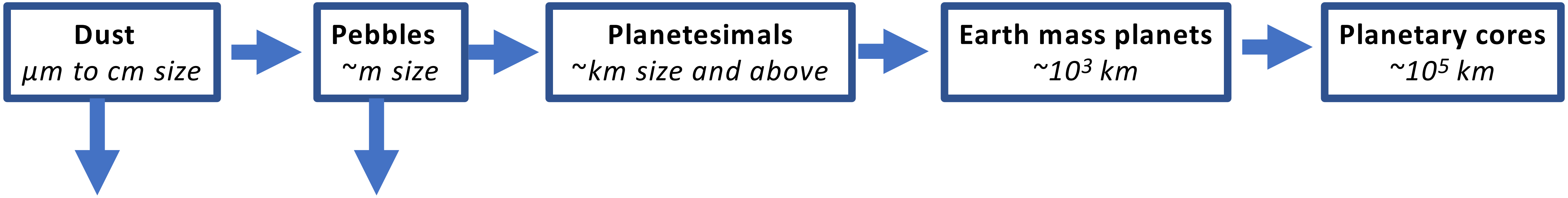


Possible qualitative match between the ***position and size of the region of peak dust production*** due to the excited impact velocities and a ***estimated overabundance of dust*** in HD163296

Reconstructed gas-to-dust ratio in HD163296 and comparison with theoretical expectations (Isella et al. 2016)

Dust evolution in protoplanetary disks

Armitage, P., Lect. Notes, 2017



Dust
μm to cm size

Pebbles
~m size

Planetesimals
~km size and above

Earth mass planets
$\sim 10^3$ km

Planetary cores
$\sim 10^5$ km

SUBSONIC FLOW:

✓ **Epstein Regime of drag**: ***drag due to molecular collisions***
when the size of the particle is less compared to the mean free path of molecules in the gas (i.e. motion in rarefied gas field)

✓ **Stokes Regime of drag**: ***fluid drag via molecular viscosity***
for particles larger than about the mean free path of the gas molecules, a flow structure develops around the dust particle and the drag is governed by continium flow physics.

SUPERSONIC FLOW: **Stokes Regime of drag**

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Aerodynamics of dust particles in protoplanetary disks: spherical (review)

Armitage, P., Lect. Notes, 2017

$$F_D = -\frac{1}{2} C_D \cdot \pi a^2 \cdot \rho v^2$$

Epstein Regime (a<< λmnfp):

$$\boxed{a < \frac{9}{4}\lambda,} \qquad C_D = \frac{8}{3}\frac{\bar{v}}{v}, \qquad \bar{v} = (8/\pi)^{1/2} c_s$$

$$t_{\rm fric} = \frac{mv}{|F_D|}. \qquad \boxed{t_{\rm fric} = \frac{\rho_d}{\rho}\frac{a}{\bar{v}}.}$$

Adopting conditions appropriate to 1 AU within the disk, $\rho = 5 \times 10^{-10}$ g cm^{-3}, $\bar{v} = 2.4 \times 10^5$ cms^{-1} and $\rho_d = 3$ g cm^{-3} we obtain $\boxed{t_{\rm fric} \approx 2.5 \text{ s}}$ Small particles are thus very tightly coupled to the gas.

Stokes Regime (a>> λmnfp):

$$\mathrm{Re} = \frac{2av}{\nu}$$

$$\begin{aligned} C_D &= 24\mathrm{Re}^{-1} & \mathrm{Re} &< 1 \\ C_D &= 24\mathrm{Re}^{-0.6} & 1 < \mathrm{Re} &< 800 \\ C_D &= 0.44 & \mathrm{Re} &> 800. \end{aligned}$$

Define dimensionless stopping time, and for MMSN disk at midplane:

$$\boxed{\tau_s \equiv \Omega t_{\rm stop}} = \max\left[\underbrace{4.4 \times 10^{-3} a_{\rm cm} r_{\rm AU}^{3/2}}_{\text{Epstein}},\ \underbrace{1.4 \times 10^{-3} a_{\rm cm}^2 r_{\rm AU}^{-5/4}}_{\text{Stokes}}\right]$$

For mm size particles: $\tau_s \sim 10^{-3}$ at 1AU; $\tau_s \sim 0.1$ at 30 AU.

Bai, X., Lect. Notes, 2014

Key point message: The stopping(friction) time depends not only on the size but also of the dust grain shape and composition in Epstein regime.

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Testi+2014

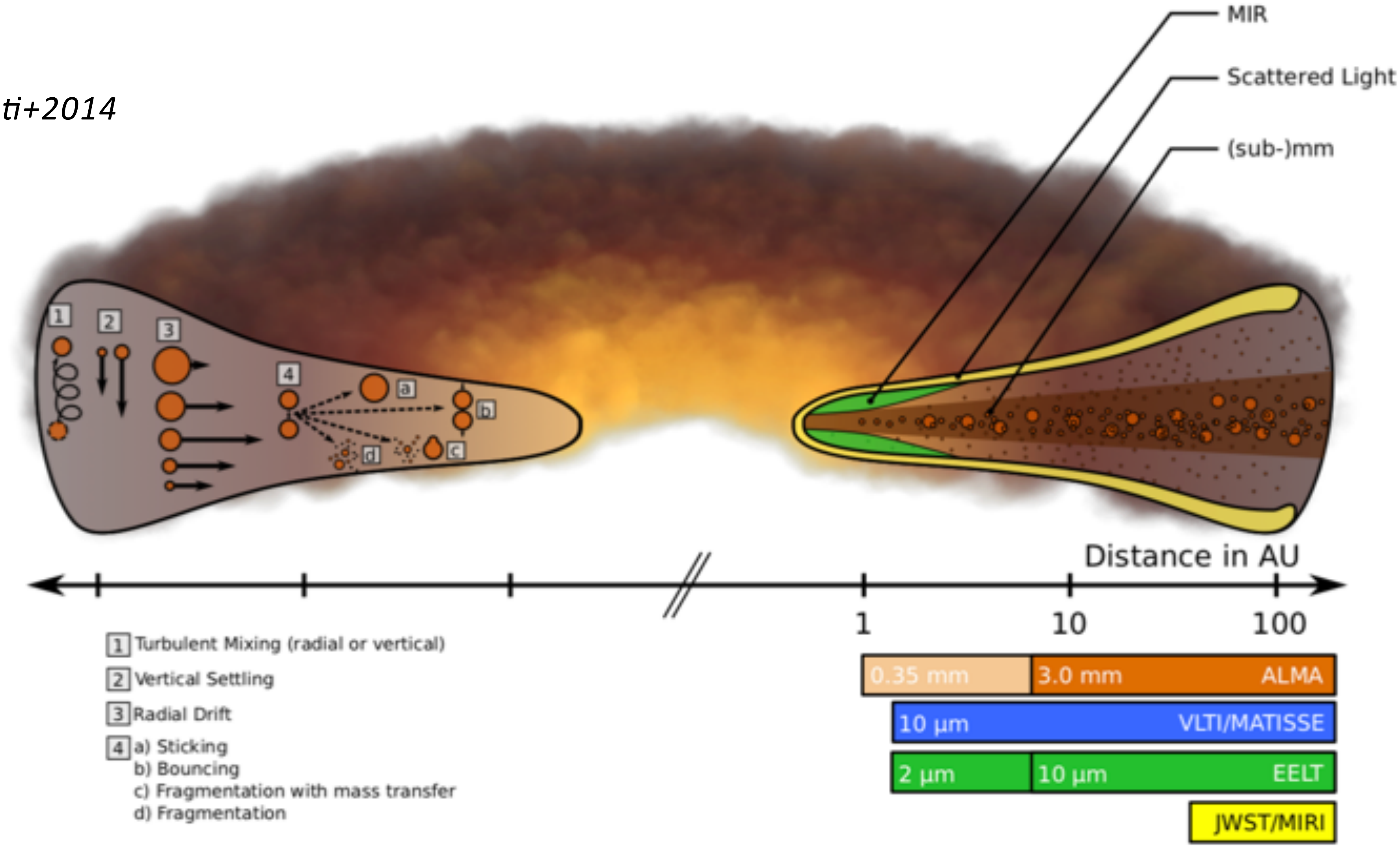
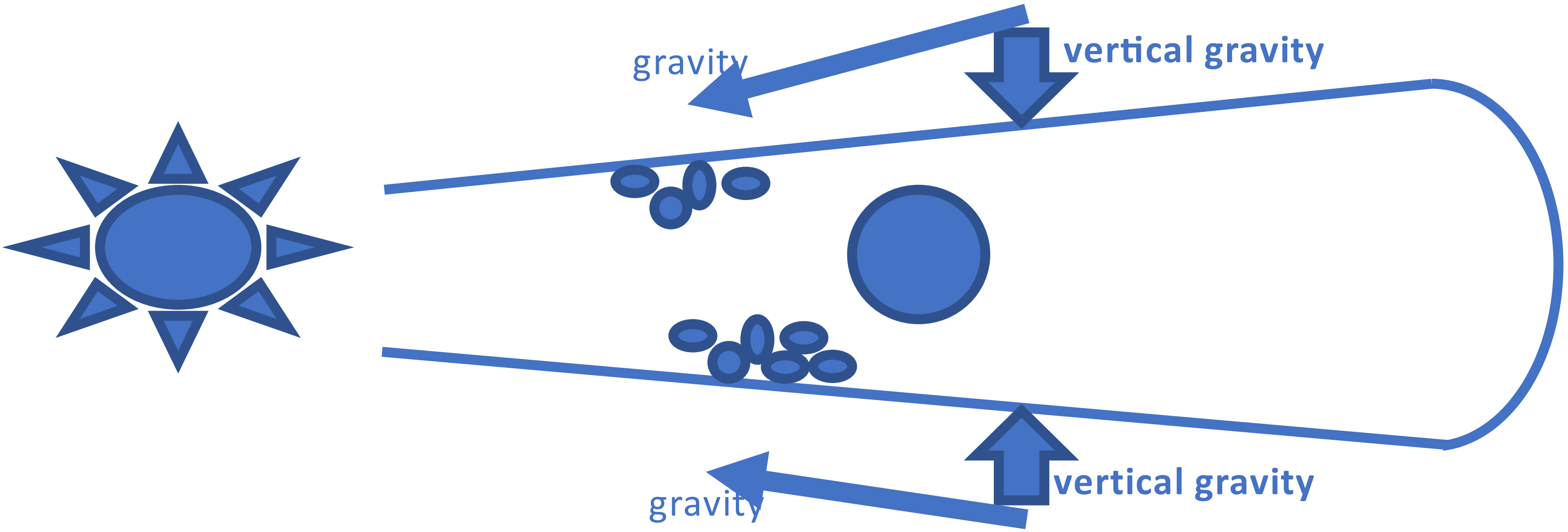


Fig. 1.— Illustration of the structure, grain evolution processes and observational constraints for protoplanetary disks. On the left side we show the main grain transport and collision mechanism properties. The different lengths of the arrows illustrate the different velocities of the different grains. On the right hand side, we show the areas of the disk that can be probed by the various techniques. The axis shows the logarithmic radial distance from the central star. The horizontal bars show the highest angular resolutions (left edge of the bars) that can be achieved with a set of upcoming facilities and instruments for at the typical distance of the nearest star forming regions.

Vertical dust settlement



Armitage, P., Lect. Notes, 2017

$$|F_{\rm grav}| = m\Omega_K^2 z$$
$$|F_D| = \frac{4}{3}\pi a^2 \bar{v}\rho v.$$

$$v_{\rm settle} = \left(\frac{\Omega_K^2}{\bar{v}}\right)\frac{\rho_d}{\rho}az.$$

$$t_{\rm fric} = \frac{\rho_d}{\rho}\frac{a}{\bar{v}}.$$

Active forces: stellar gravity and gas drag , no gas pressure

$\tau_s \equiv \Omega_k t_{fric}$

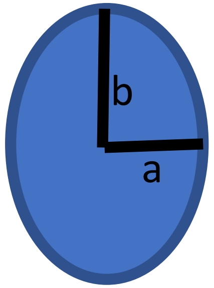
Large grains [m]: vertical damped oscillations **settling timescale τ_s**

Small grains [µm to cm]: terminal velocity v_{settle} **settling timescale ~$1/\tau_s$**

Key point message:

Spherical grain timescale	Spheroid(NON SPHERICAL) grain timescale
τ_s	$k.\tau_s$

k=a/b is the aspect ratio of the spheroid



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Gravity in vertical dust settlement

From the equation of vertical hydrostatic equilibrium and Keplerian angular velocity

Armitage, P., Lect. Notes, 2017

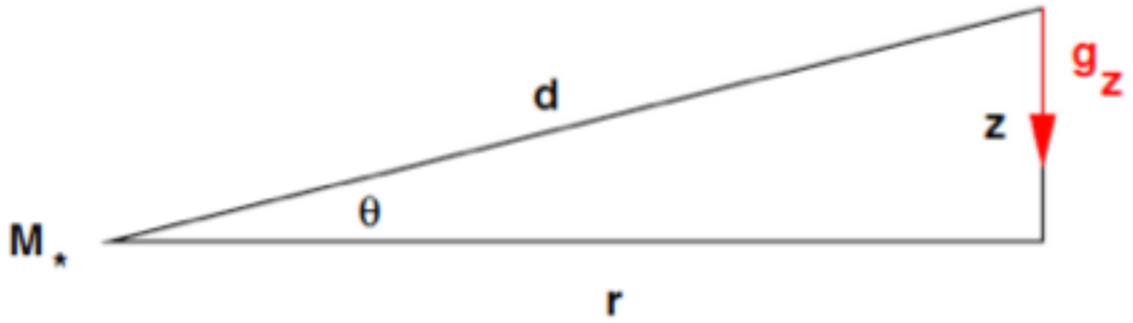

FIG. 10 Geometry for calculation of the vertical hydrostatic equilibrium of a circumstellar disk.

$$|F_{\mathrm{grav}}| = m\Omega_K^2 z$$

$$|F_D| = \frac{4}{3}\pi a^2 \bar{v}\rho v.$$

Gravity

$$F_{grav} = m\frac{GM_{small\_body}}{d^2} \qquad F_{grav\_disk} = m\frac{GM_{star}}{r^3}\,\mathrm{d} \qquad \mathrm{d} = \mathrm{z} = \tan\Theta\,\mathrm{r}$$

Note: The effects of turbulence are ignored and the disk is assumed to be entirely quiescent.

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Dust dynamics in cometary environment and how this knowledge can be utilized in protoplanetary disks

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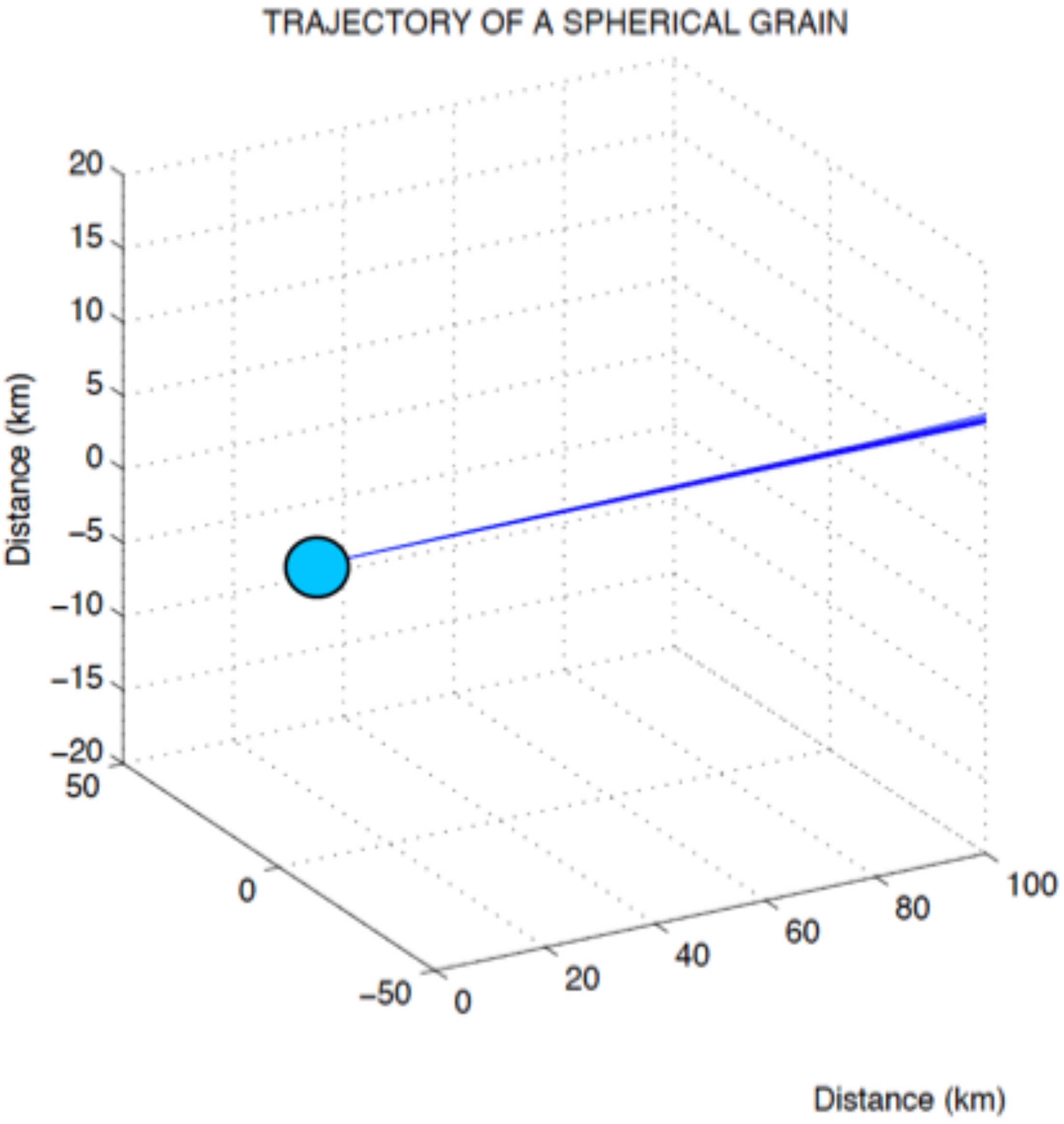
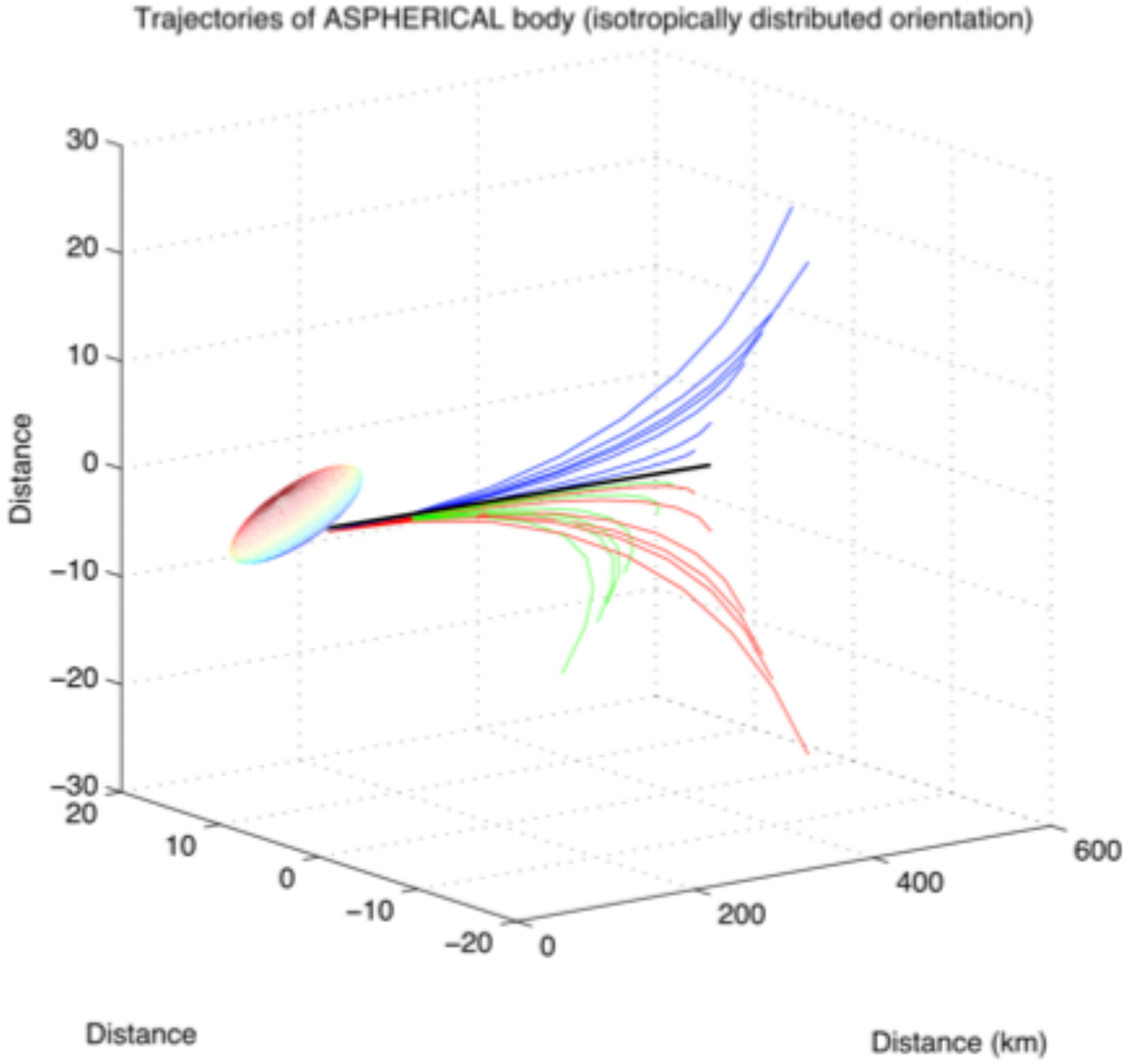
The first non-spherical dust dynamical code in cometary science

Ivanovski + 2017 (Icarus, 282, 333-350)





The model and the radial gas flow approximation

Ivanovski + 2017 (Icarus, 282, 333-350)

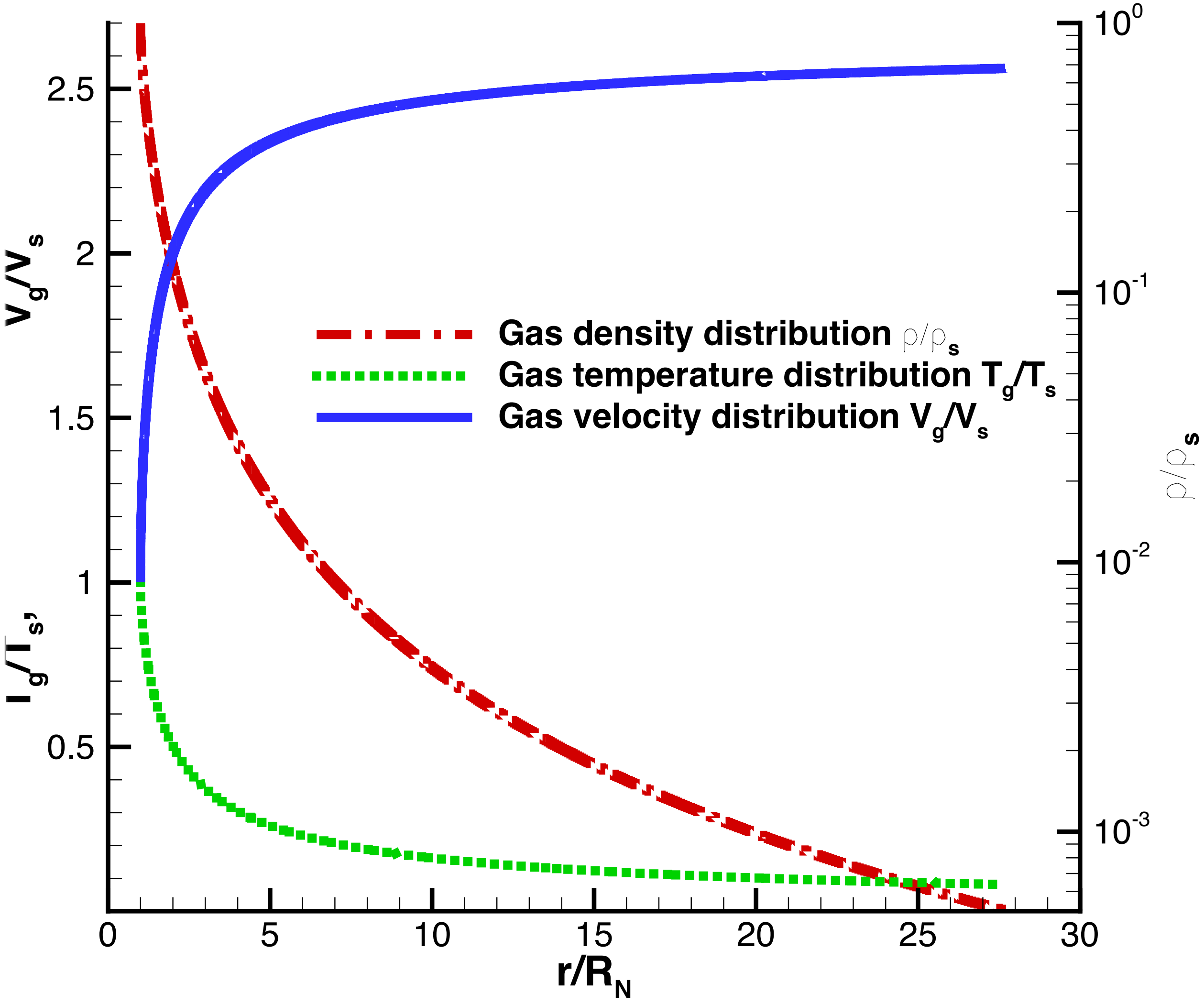
The motion of the center of mass of dust grain is given by:

$$m_{\mathrm{d}} \frac{\mathrm{d}^2 \boldsymbol{r}}{\mathrm{d}t^2} = m_{\mathrm{d}} \frac{\mathrm{d}\boldsymbol{v}_{\mathrm{c}}}{\mathrm{d}t} = \boldsymbol{R}$$

If we assume the motion of the dust under aerodynamic and gravitational forces, for the resulting vector and the torque of external forces acting on the nonsublimating grain we obtain

$$\begin{aligned}\boldsymbol{R} &= \boldsymbol{F}_{\mathrm{g}} + \boldsymbol{F}_{\mathrm{a}} \\ &\equiv -G\frac{M_{\mathrm{N}} m_{\mathrm{d}}}{r^3}\boldsymbol{r} - \int \left(p\boldsymbol{n} + \tau\left[(\boldsymbol{v}_{\mathrm{r}} \times \boldsymbol{n}) \times \boldsymbol{n}\right]/|v_{\mathrm{r}}|\right)\mathrm{d}s,\end{aligned}$$

$$\begin{aligned}\boldsymbol{M}_c &= \boldsymbol{M}_{\mathrm{g}} + \boldsymbol{M}_{\mathrm{a}} \\ &\equiv -GM_{\mathrm{N}}\,\rho_{\mathrm{d}}\int\frac{\boldsymbol{l}\times\boldsymbol{r}}{r^3}\mathrm{d}v - \int \boldsymbol{l}\times\left(p\boldsymbol{n}+\tau\left[(\boldsymbol{v}_{\mathrm{r}} \times \boldsymbol{n}) \times \boldsymbol{n}\right]/|v_{\mathrm{r}}|\right)\mathrm{d}s\end{aligned}$$



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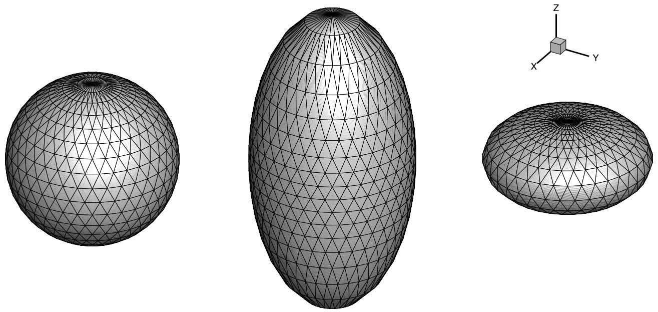
The model : different velocities due to the grain shape

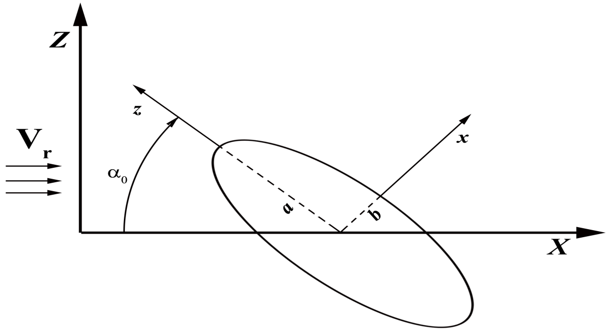


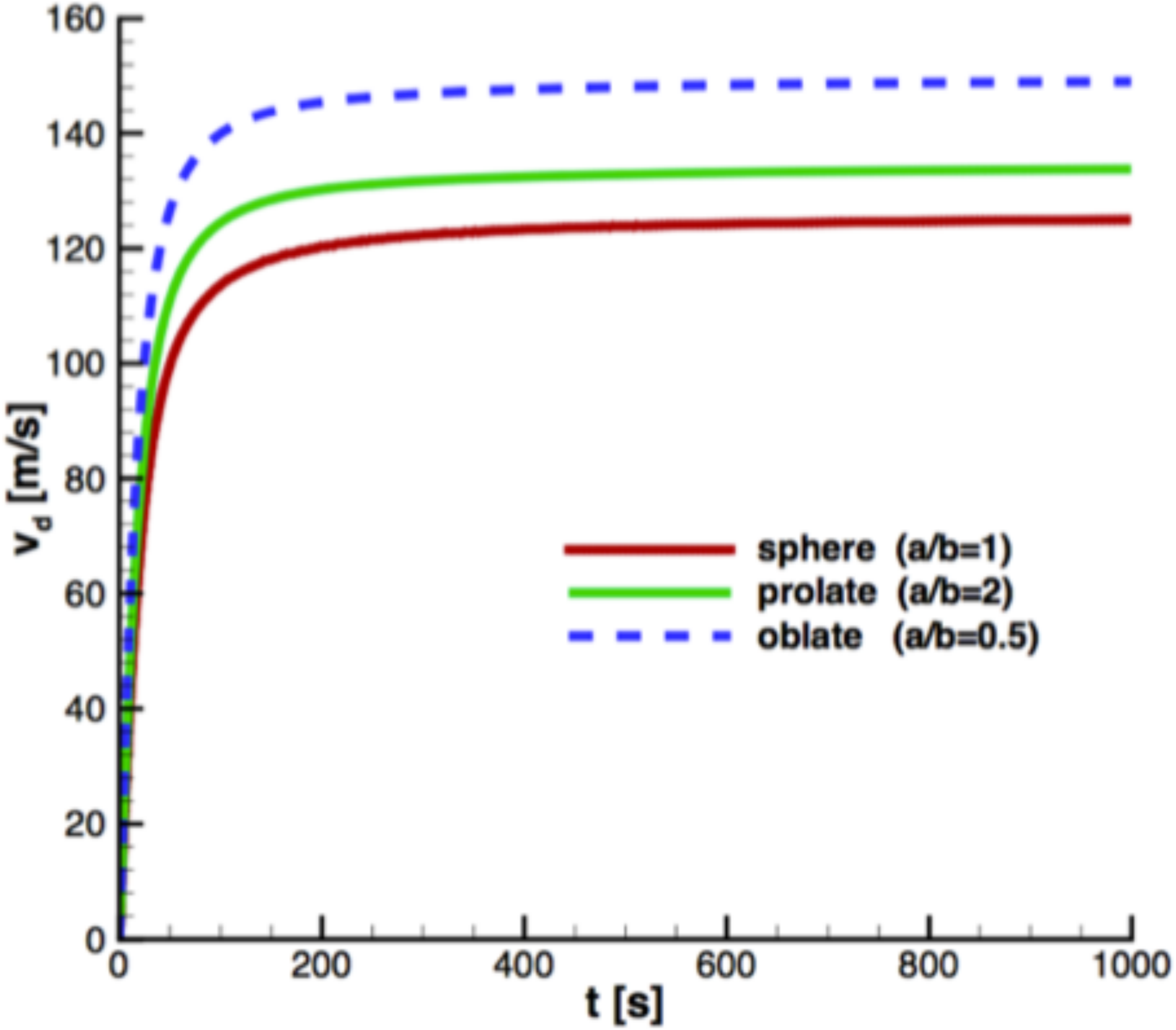
The mass and the principal moments of inertia for an ellipsoid of revolution are:

$$m_d = \frac{4}{3}\pi a b^2 \tilde{\rho} \tag{2}$$

$$I_{zz} = \frac{2}{5} m_d b^2 \;\; ; \;\; I_{xx} = I_{yy} = \frac{1}{5} m_d (a^2 + b^2) \tag{3}$$

where $\tilde{\rho}$ is the dust specific mass [kg/m^3] and z is the axis of revolution of the ellipsoid.





Ivanovski + 2017 (Icarus, 282, 333-350)

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Aerodynamics of dust particles in protoplanetary disks: non-spherical (review)

For non-spherical grain:

- **drag force D** (the aerodynamic force component parallel to the gas velocity relative to the grain) but also
- **lift force L** (the transverse aerodynamic force component)
- **torque**

Dimensionless aerodynamic coefficients – the drag C_D and lift C_L:

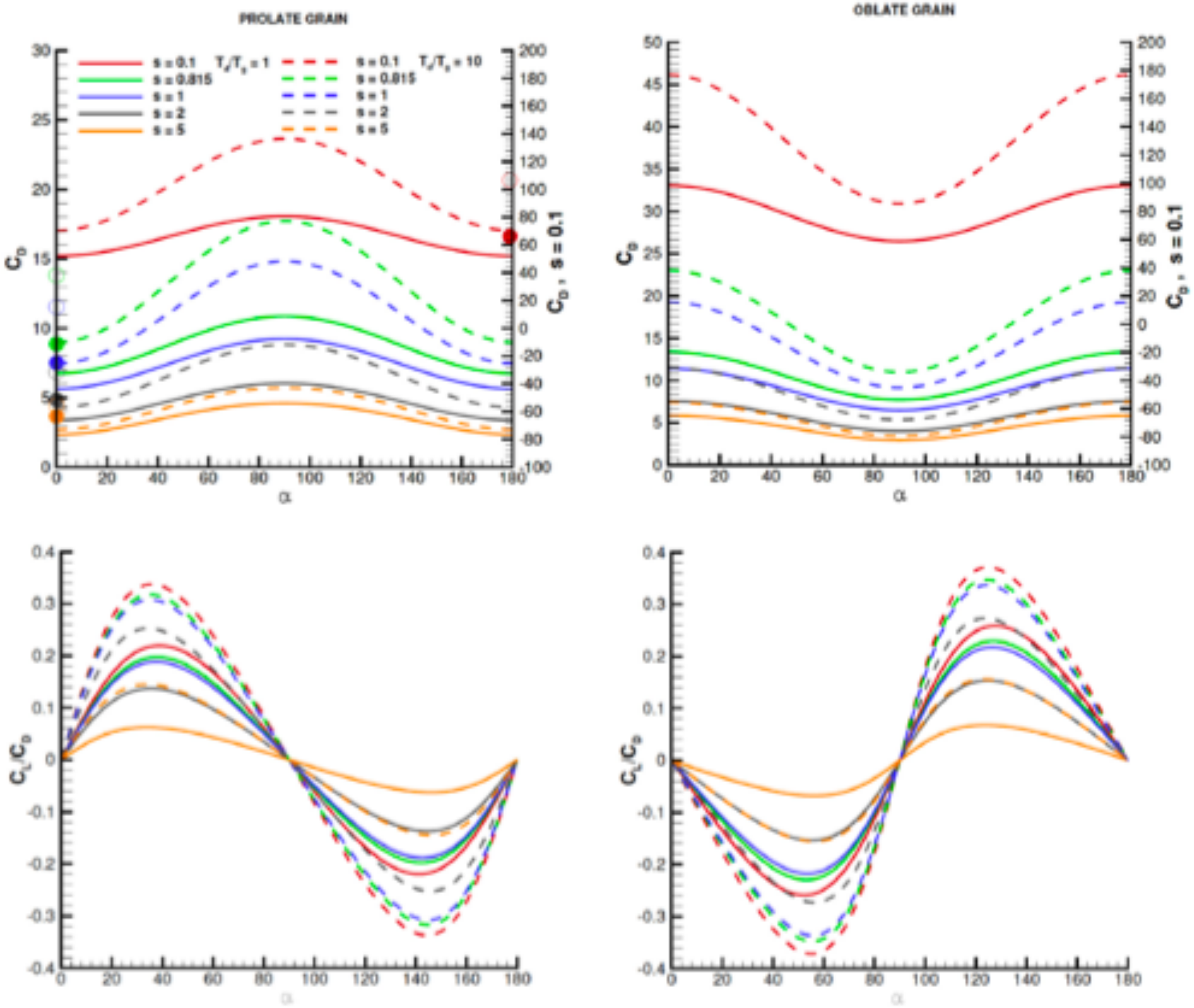
$$C_D = \frac{D}{1/2\rho V_r^2 S} \quad ; \quad C_L = \frac{L}{1/2\rho V_r^2 S}$$

where $V_r = V_g - V_d$ is the gas-grain (center of mass) relative velociity vector, ρ is the gas mass density, $\rho V_r^2/2$ is the dynamic pressure, and S is a shape-dependent characteristic cross-section.

For the torque M_a - the dimensionless aerodynamic torque coefficient C_M

$$C_M = \frac{M_a}{1/2\rho V_r^2 SA}$$

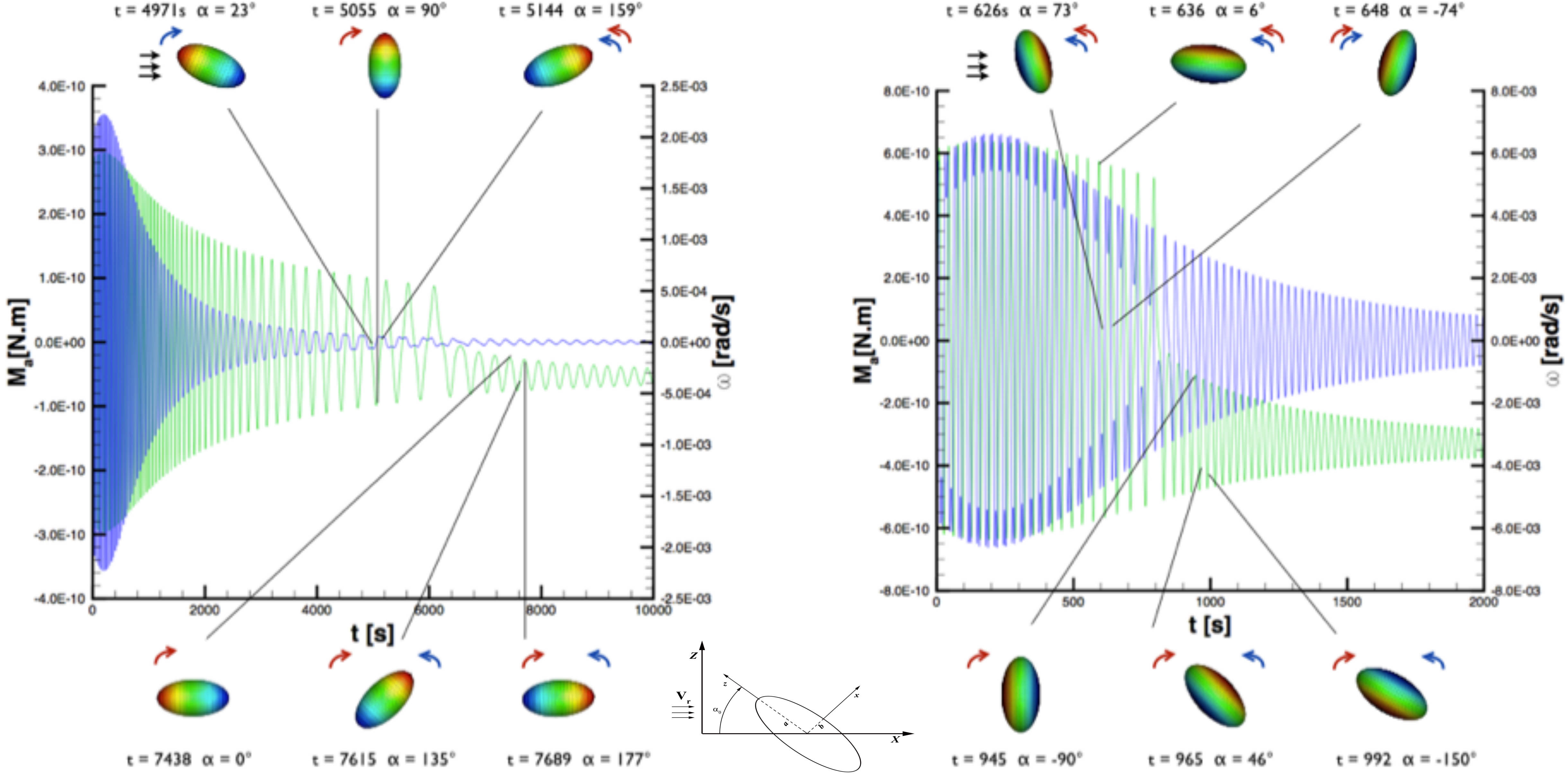
where A is a shape-dependent characteristic linear dimension of the grain.



Ivanovski + 2017 (Icarus, 282, 333-350)

Rotational motion in cometary atmosphere

Ivanovski + 2017 Icarus, Ivanovski + 2017 MNRAS



Terminal speeds of spherical and non spherical particles

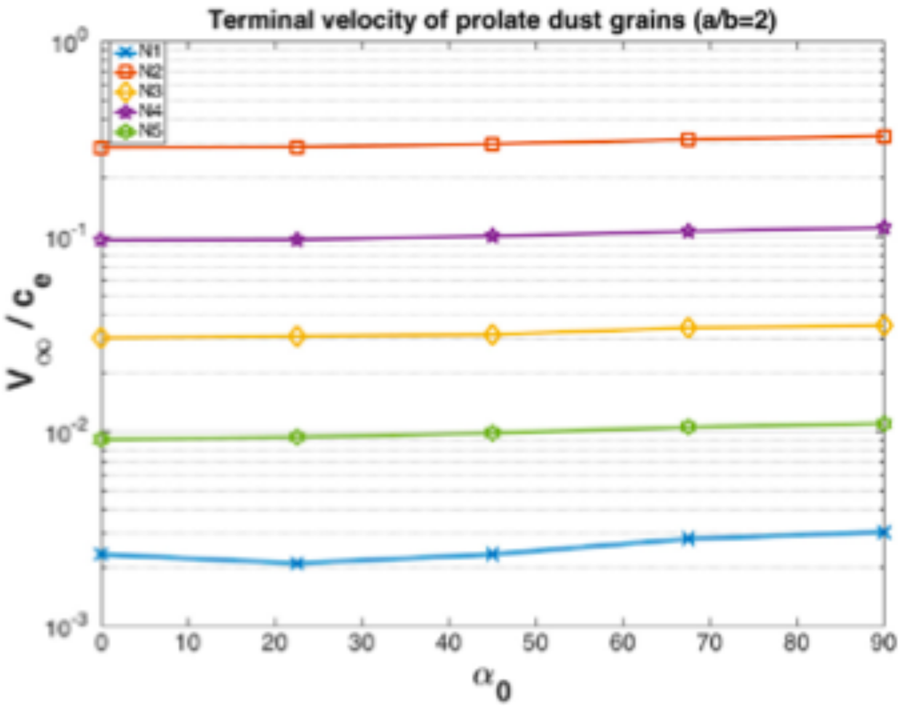
- ✓ Spheroids with aspect ratio k will change the t_{fric} k times. Therefore the coupling of the mm-sized particles can occur in timescales strongly dependent of the grain shape.
- ✓ For HD163296: of μm sized ~cm/s, still on-going checks and running simulations for mm – sized particles.

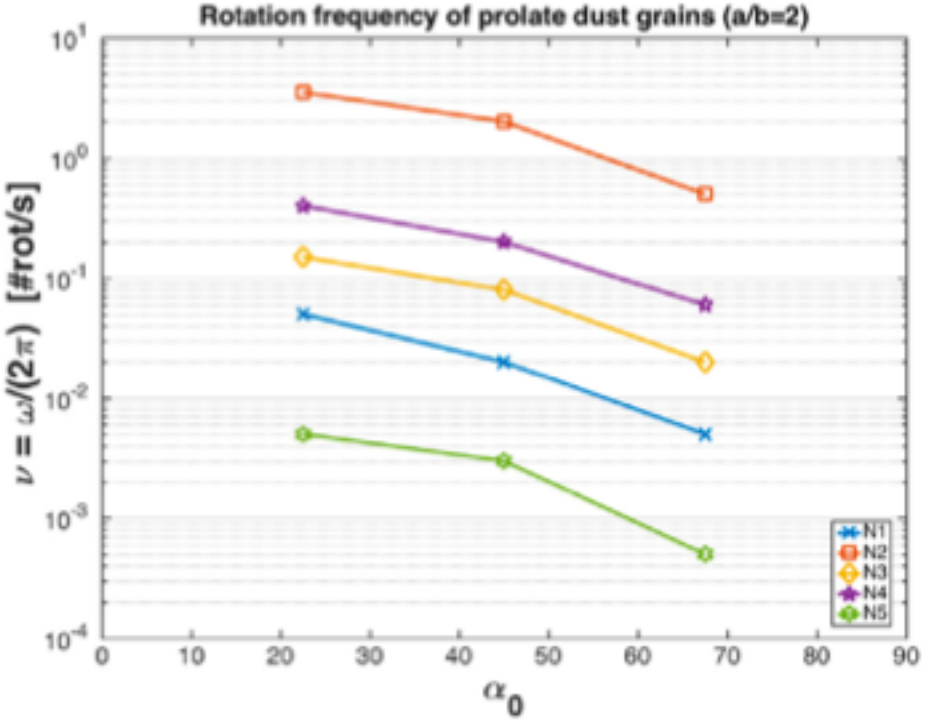
Scaling laws -> from comets to protoplanetary disks

$$\sqrt{\frac{Q_g}{b\tilde{\rho}}} = const$$

while for rotational motion is:

$$\frac{Q_g}{\sqrt{b^5\tilde{\rho}}} = const.$$





Ivanovski et al. 2017 (Icarus, 282, 333-350)

Summary

- ✓ Revise the timescales of the dimensionless stopping time and the settling timescale in the vertical settling phenomena in disks in terms of non spherical particles.

- ✓ A non-spherical cometary dust model can be used to simulate the dust motion in protoplanetary disks.

- ✓ The model is capable to identify particle rotation and to compute the rotational frequencies of the particles.

- ✓ The model determines the bias that the spherical approximation could introduce in simulations of protoplanetary disk.

Some Future Work

- ✓ Parametric study on the dynamical properties of the second generated dust in ***HD163296*** when assuming the 3 giant planets masses. The influence of different dust sizes and initial dust speeds.

- ✓ Time of accumulation and fluence of trace-back particles in the gaps of the disk.