

# Clusters of heavy particles in 2D Keplerian turbulence

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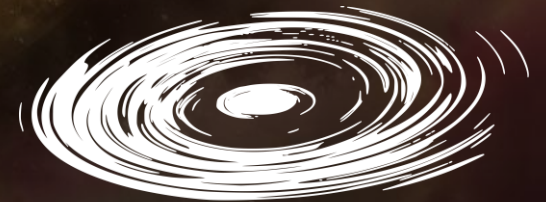
Jérémie Bec

7 February 2023

**Complex Day**

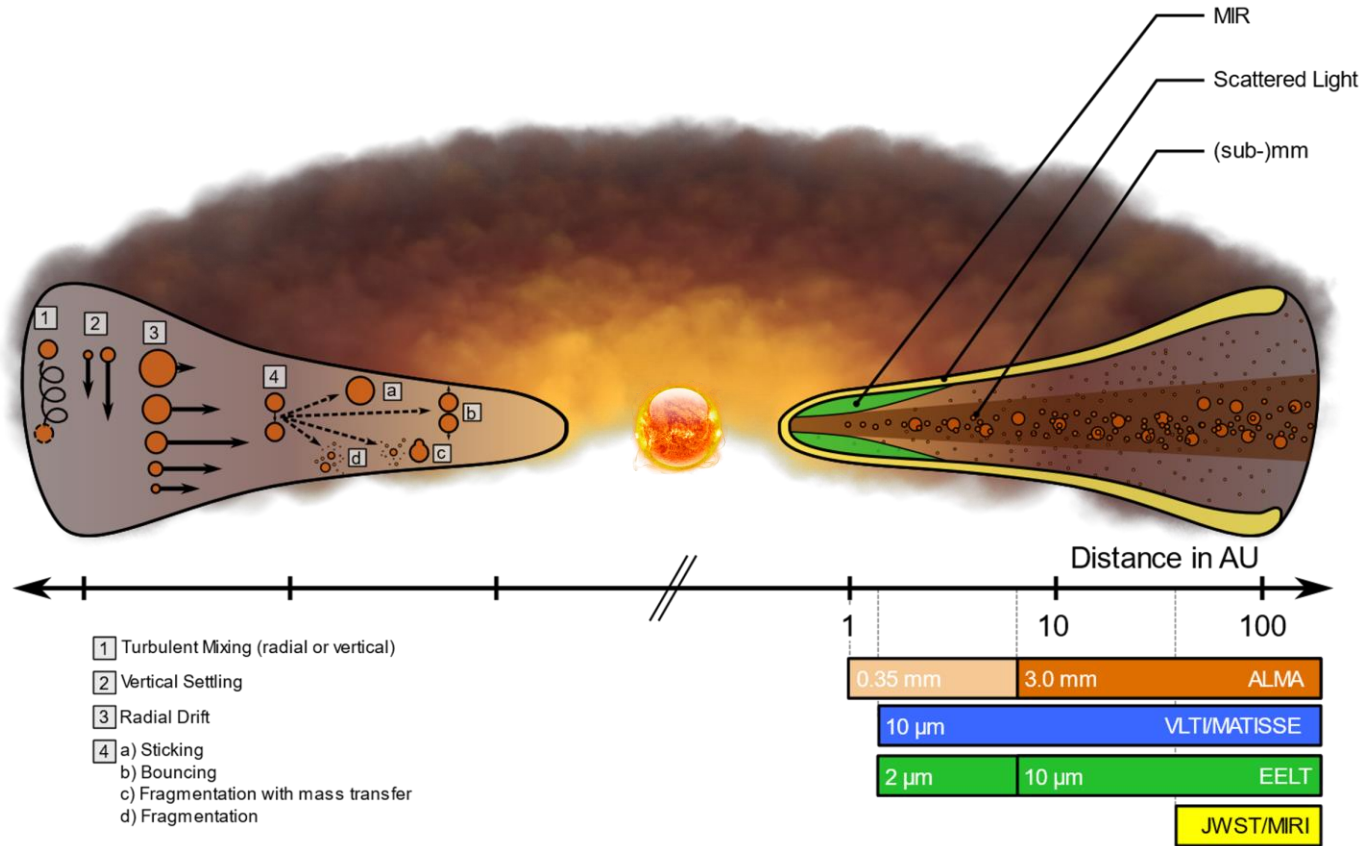


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# Introduction



## PROTOPLANETARY DISKS

- In rotation around young stars
- 99% gas and 1% dust
- Regions of planet formation
- Complex dynamics

Credits: Testi et al., 2014



Credits: Daria Dall'Olio

Dust  
↕  
μm-sized

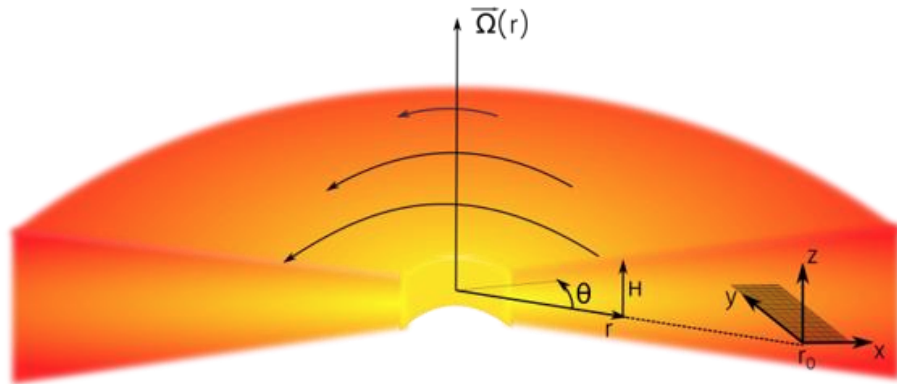
Pebbles

Planetesimals  
↕  
km-sized

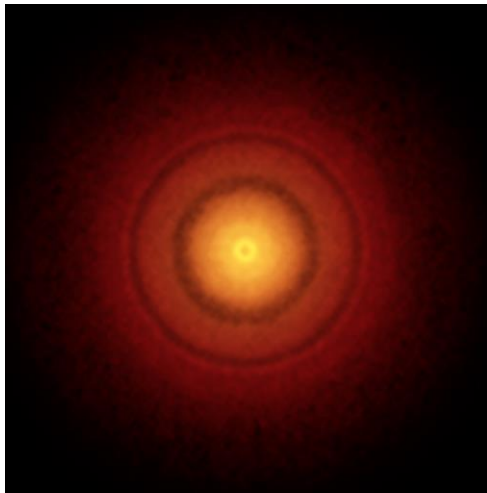
## PLANETESIMALS

- Formation: open question
- Turbulence for particles concentration?

# Method



Gerosa et al., 2023



Credits: Andrews et al., 2016

## 2D DIRECT NUMERICAL SIMULATIONS

- Shearing box approach
- Incompressible Navier–Stokes equation with stochastic forcing and linear friction
- Eulerian approach for the gas
- Lagrangian approach for the dust
- Parameters: rotation frequency  $\Omega$  and solid response time  $\tau_p$
- Tools borrowed from the study of dynamical systems

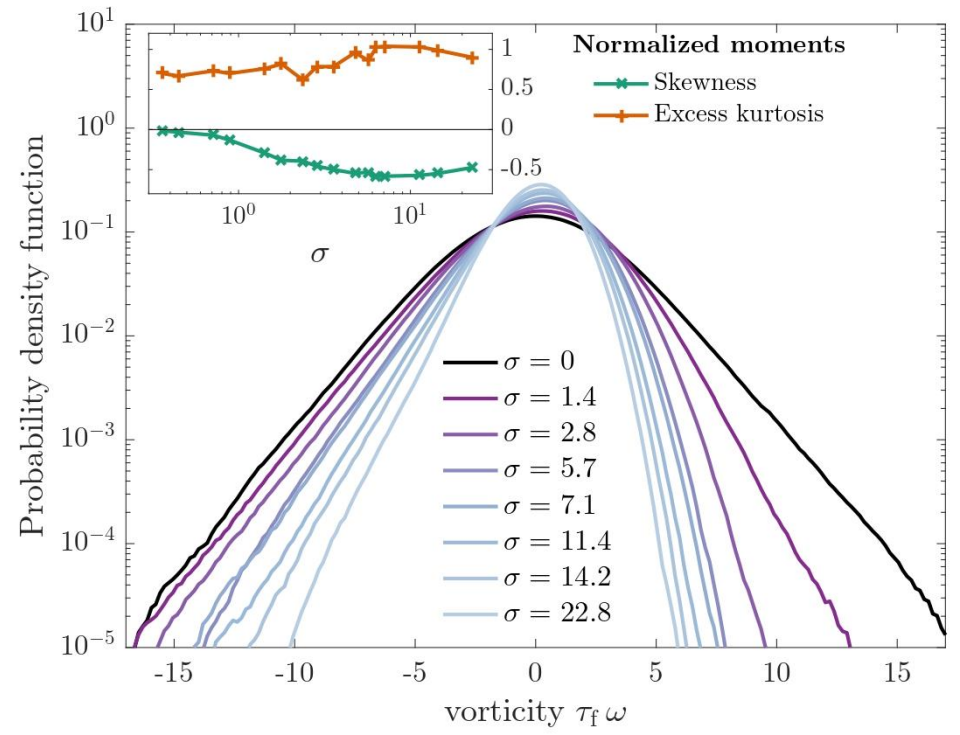
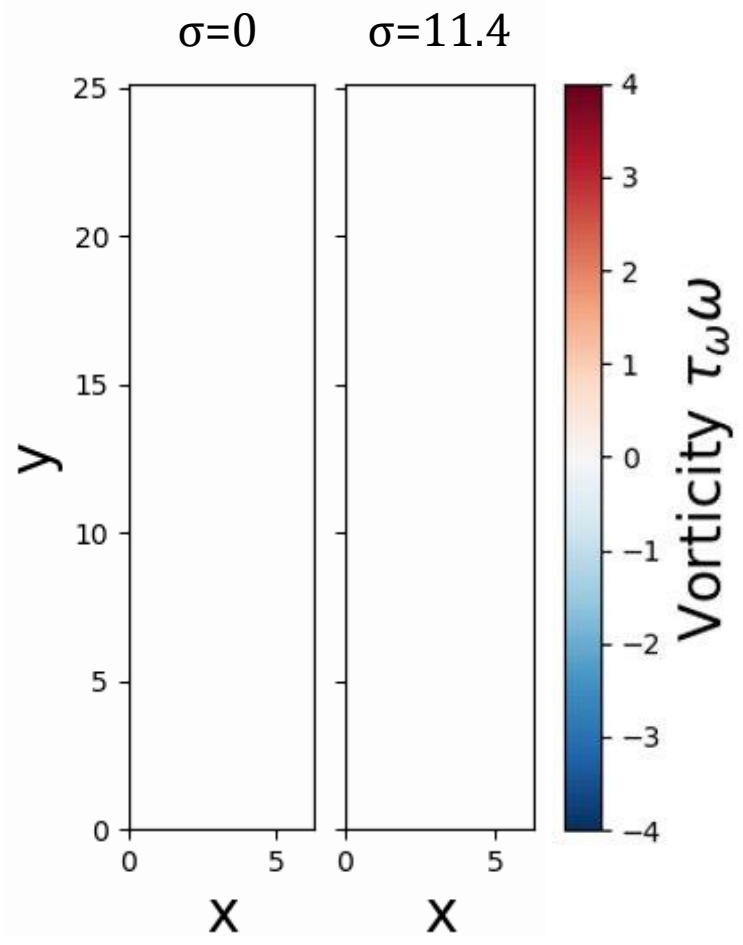
# Results

## TURBULENT GAS

Main effects:

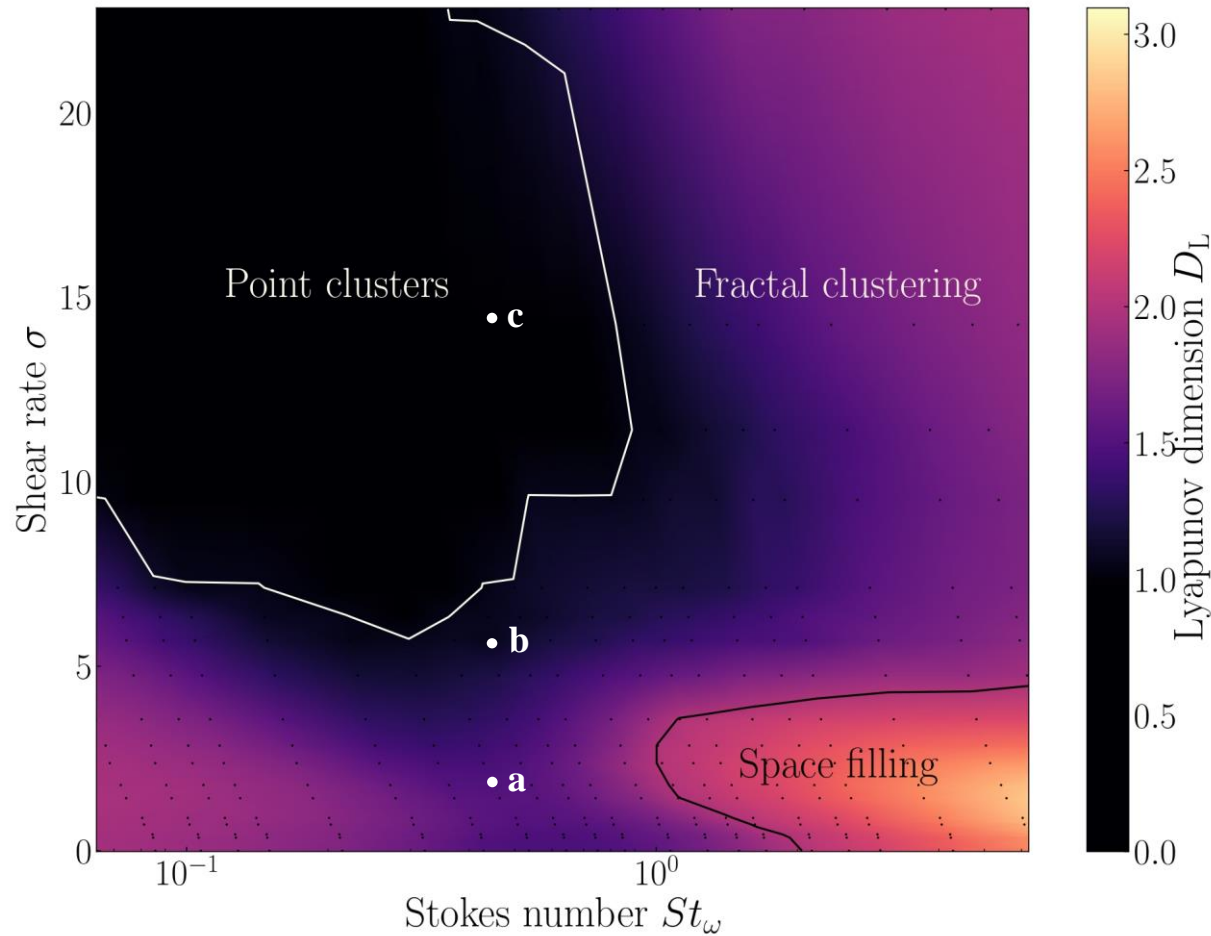
- Vortexes get stretched
- Shear destroys cyclones

$$\tau_f = \eta_I^{-1/3}$$
$$\sigma = (3/2)\Omega\tau_f$$
$$\tau_\omega = \langle \omega^2 \rangle^{-1/2}$$



Gerosa et al., 2023

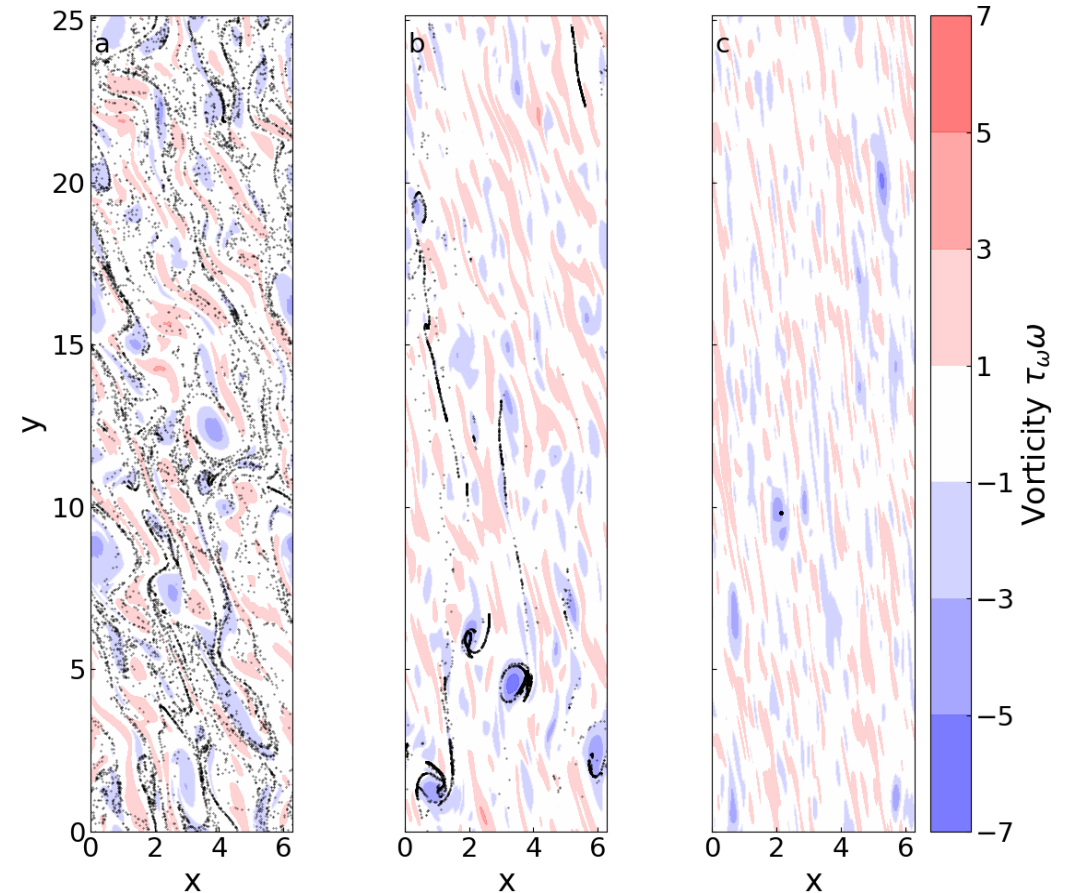
# CONCENTRATION OF DUST



$$St_\omega = \tau_p / \tau_\omega$$

Three behaviours:

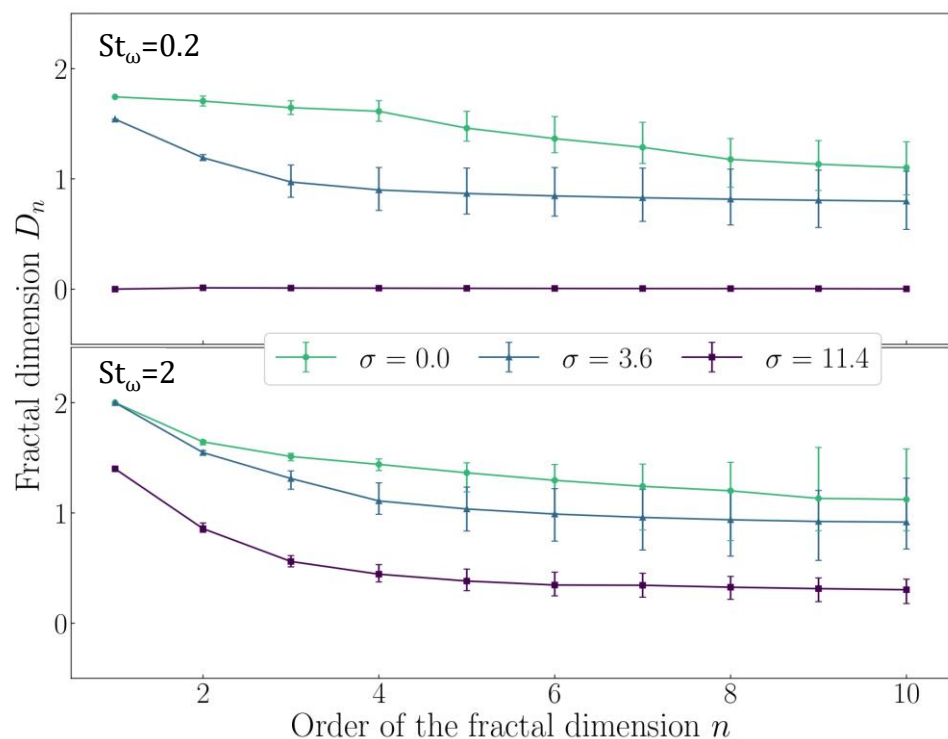
- Lines between the eddies
- Points inside the anticyclones
- Space filling



Gerosa et al., 2023

# FRACTAL CLUSTERING

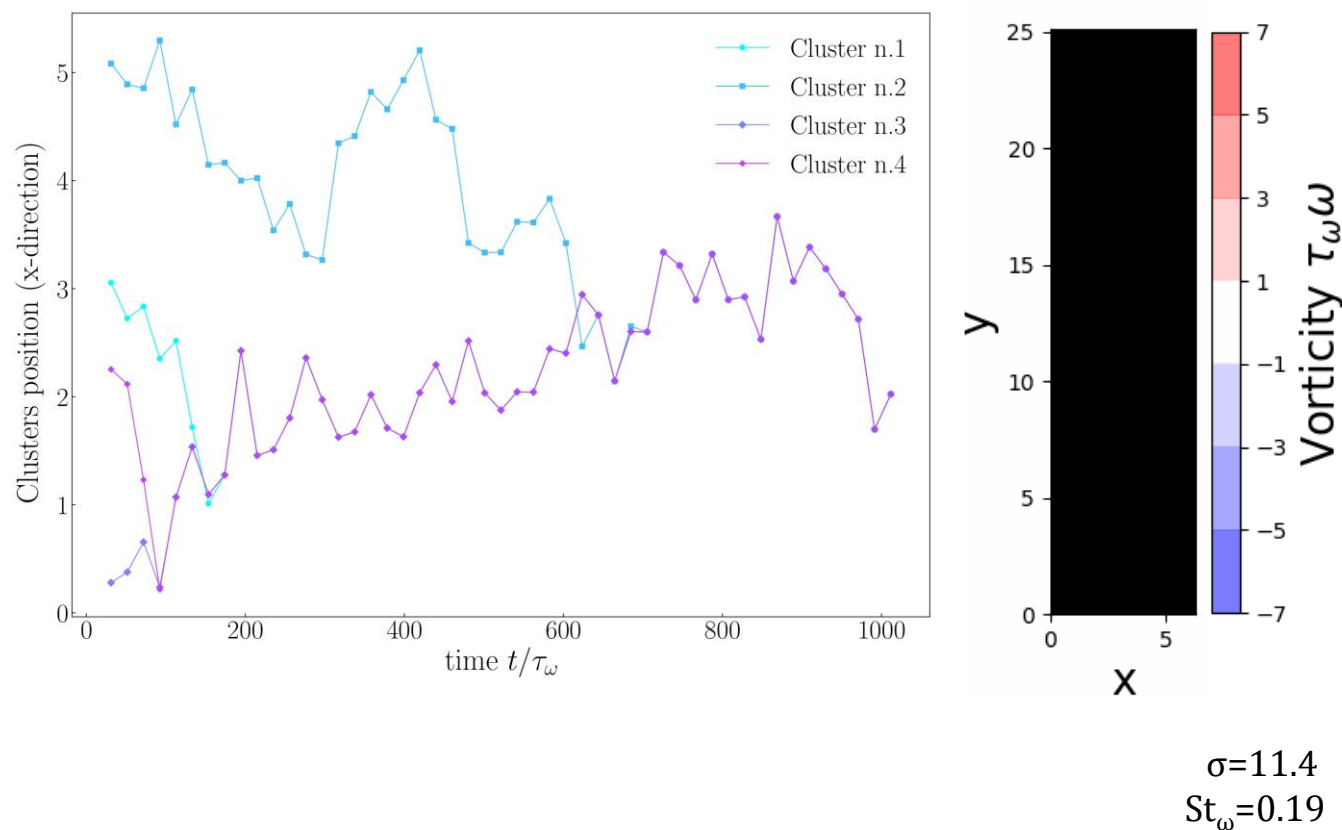
Concentration strength increases for larger sets of particles



Gerosa et al., 2023

# STRONG CLUSTERING

Clusters form inside anticyclones and merge with time



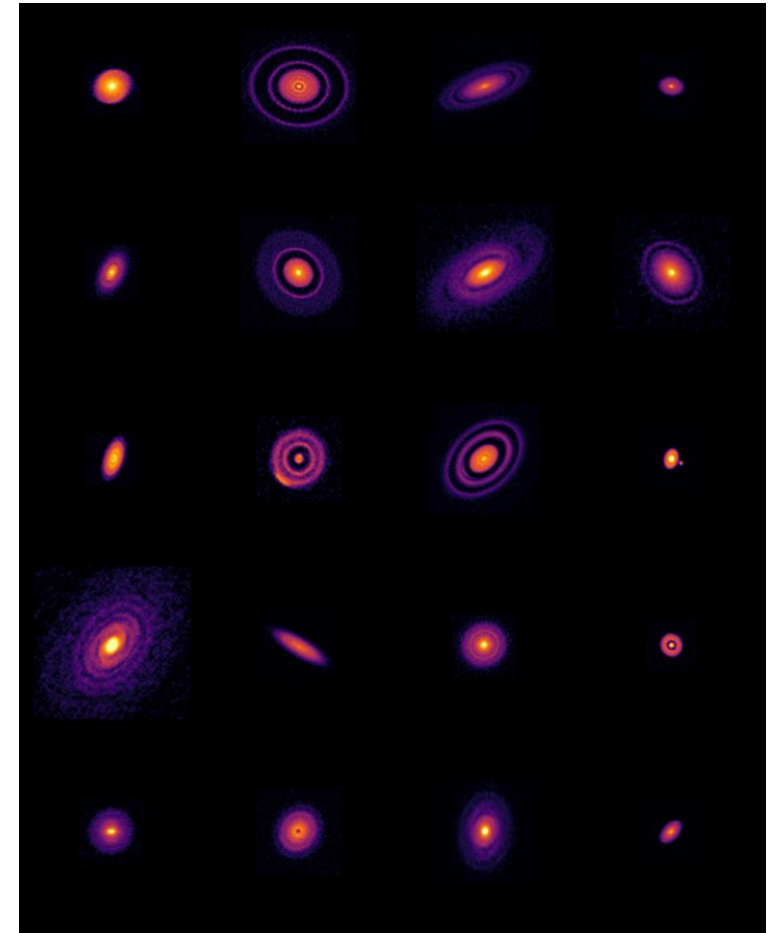
$\sigma = 11.4$   
 $St_\omega = 0.19$

# Conclusions

- Impact of Keplerian rotation on turbulence properties
- Dependency of dust clustering on shear rate and stokes number
- Formation of dust clumps
- Promising results for the formation of planetesimals

**Gerosa et al., 2023**

[10.1140/epjp/s13360-022-03585-8](https://doi.org/10.1140/epjp/s13360-022-03585-8)



Credits: Andrews et al., 2018





**Thank you!**

$$\mathbf{v} = \mathbf{u} + (3/2)\Omega_0 y \mathbf{e}_x$$

$$\partial_t \mathbf{u} + (\mathbf{u} \cdot \nabla) \mathbf{u} = \frac{3}{2} \Omega_0 y \partial_x \mathbf{u} + 2\Omega_0 + \frac{3}{2} \Omega_0 u_y \hat{\mathbf{e}}_x - \frac{1}{\rho} \nabla P + \nu \nabla^2 \mathbf{u}$$

$$\nabla \cdot \mathbf{u} = 0$$

$$\omega = \nabla \times \mathbf{u} \equiv \partial_x u_y - \partial_y u_x$$

$$\partial_t \omega + \mathbf{v} \cdot \nabla \omega = \underbrace{\nu \nabla^2 \omega}_{\text{Linear friction}} + \underbrace{f_\omega}_{\text{Stochastic forcing}}$$

Linear friction    Stochastic forcing

$$\frac{d\mathbf{V}_P}{dt} = \underbrace{-\frac{1}{\tau} (\mathbf{V}_P - \mathbf{v})}_{\text{Drag force}} - \underbrace{2\boldsymbol{\Omega}_g \times \mathbf{V}_P}_{\text{Coriolis force}} - \underbrace{(\Omega_g^2 - \Omega_K^2) r_0 \mathbf{e}_y}_{\text{Gravitational + centrifugal forces}} + \underbrace{(\Omega_g^2 + 2\Omega_K^2) y_p \mathbf{e}_y}_{\text{Gravitational + centrifugal forces}}$$

$$\tau = \frac{2}{9} \frac{\rho_p a^2}{\rho_f \nu}$$

GAS:  
Eulerian  
approach

DUST:  
Lagrangian  
approach

