Approaching Drag Instabilities in Laboratory Experiments

Niclas Schneider, Gerhard Wurm,
Vincent Carpenter, Hubert Klahr

Great Barriers in Planet Formation 2019

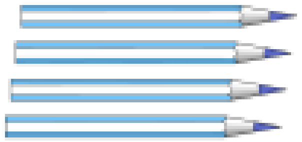
Motivation

Investigation of particle–gas interactions at low ambient pressure

Further insights in collective particle motion

Support Hydrodynamic Simulations

→ Vincent Carpenter & Hubert Klahr



Experimental Setup

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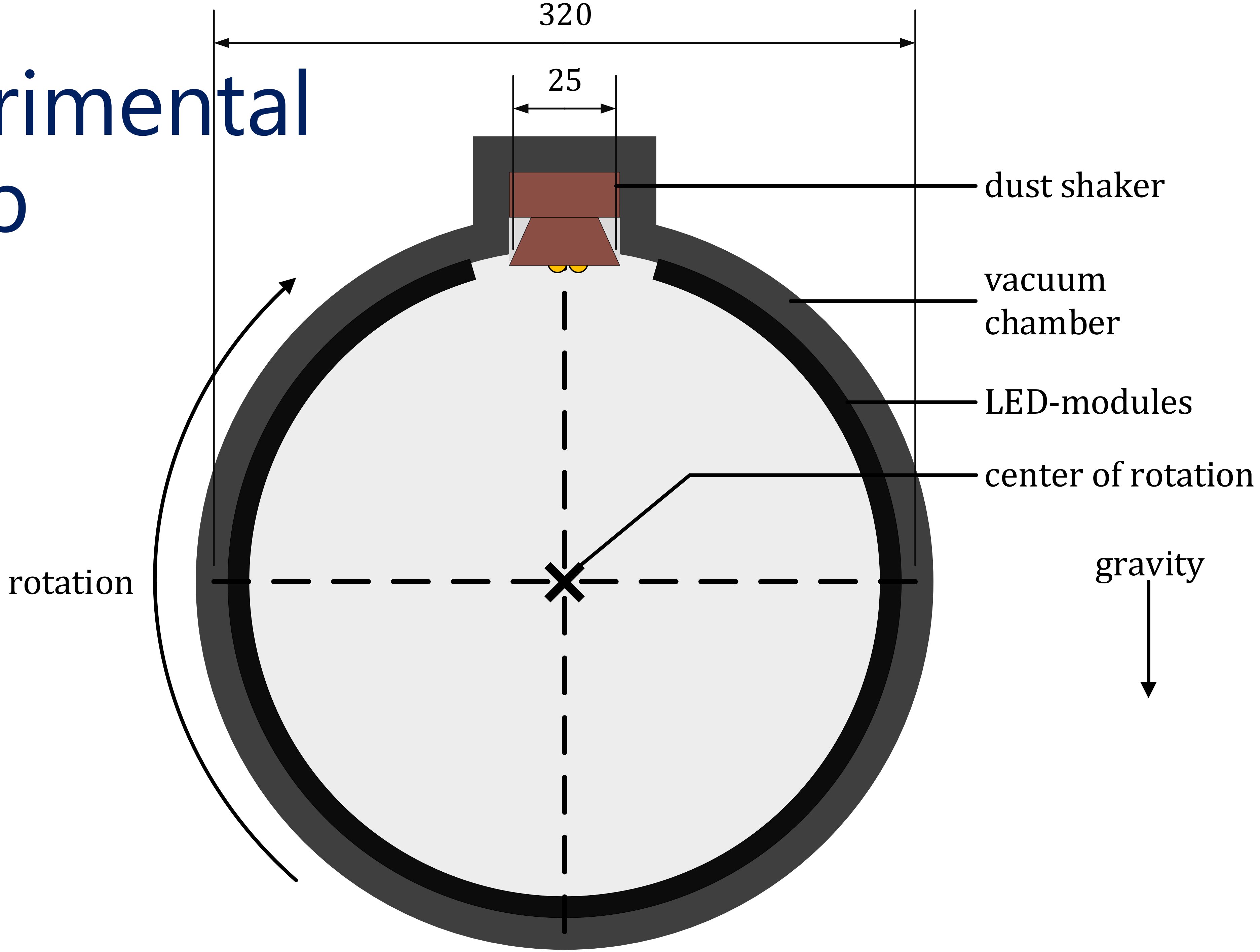
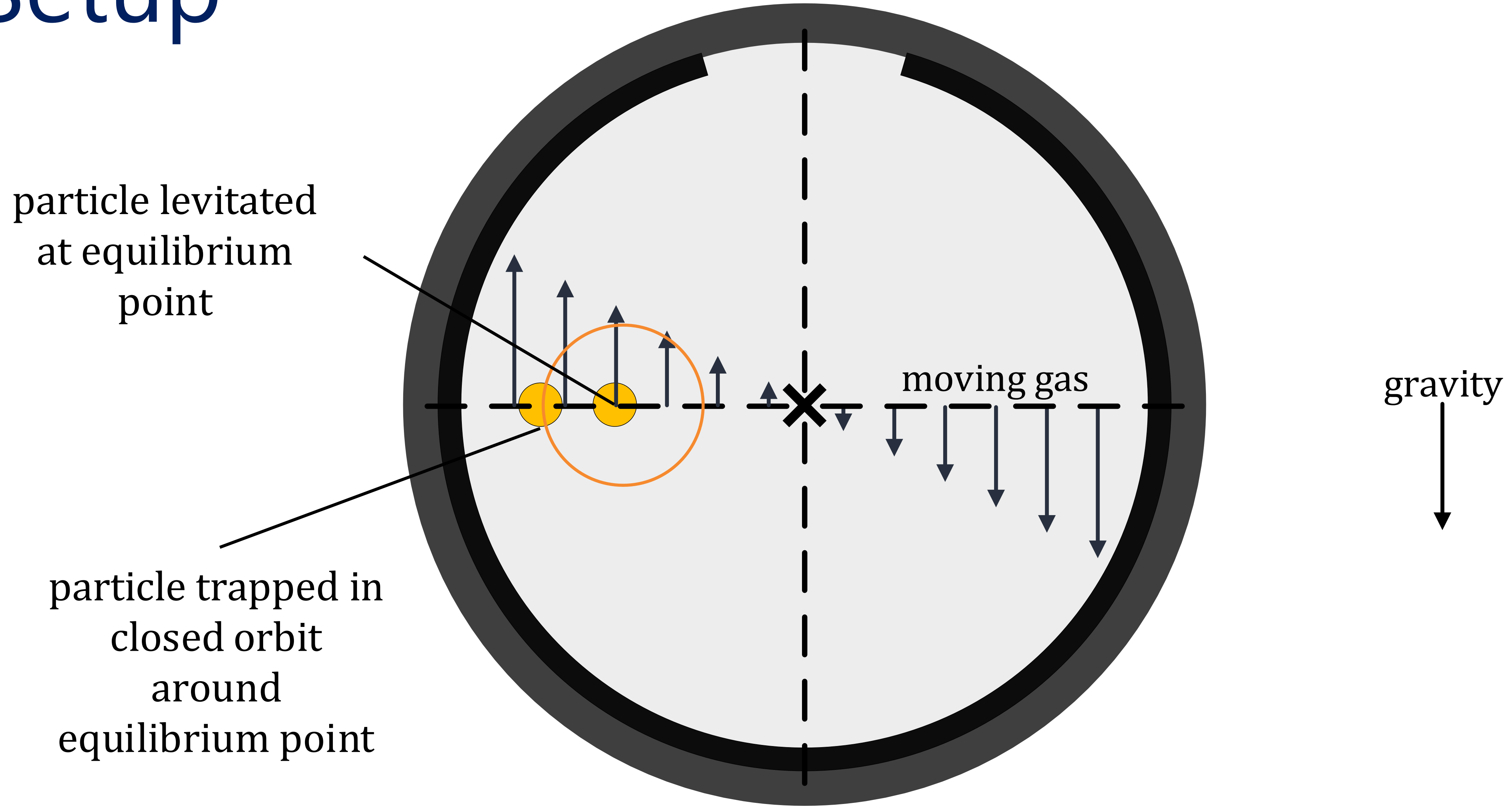


Experimental Setup



Experimental Parameters

Particle Size s

Particle Density ρ_{particle}

Gas pressure p

Rotation Frequency f_{Rot}

Stopping Time $\tau_{\text{particle}} = \frac{v_{\text{rel},0}}{g}$

Average solid-to-gas ratio

$$\epsilon = \frac{\frac{N \cdot m_{\text{particle}}}{V}}{\rho_{\text{Gas}}} \sim \frac{s^3 \cdot \rho_{\text{particle}}}{p}$$

Volume Filling factor

$$\Phi = \frac{N \cdot V_{\text{particle}}}{V_{\text{Gas}}} \sim s^3$$

Stokes Number

$$\text{St} = \tau \cdot f_{\text{Rot}}$$

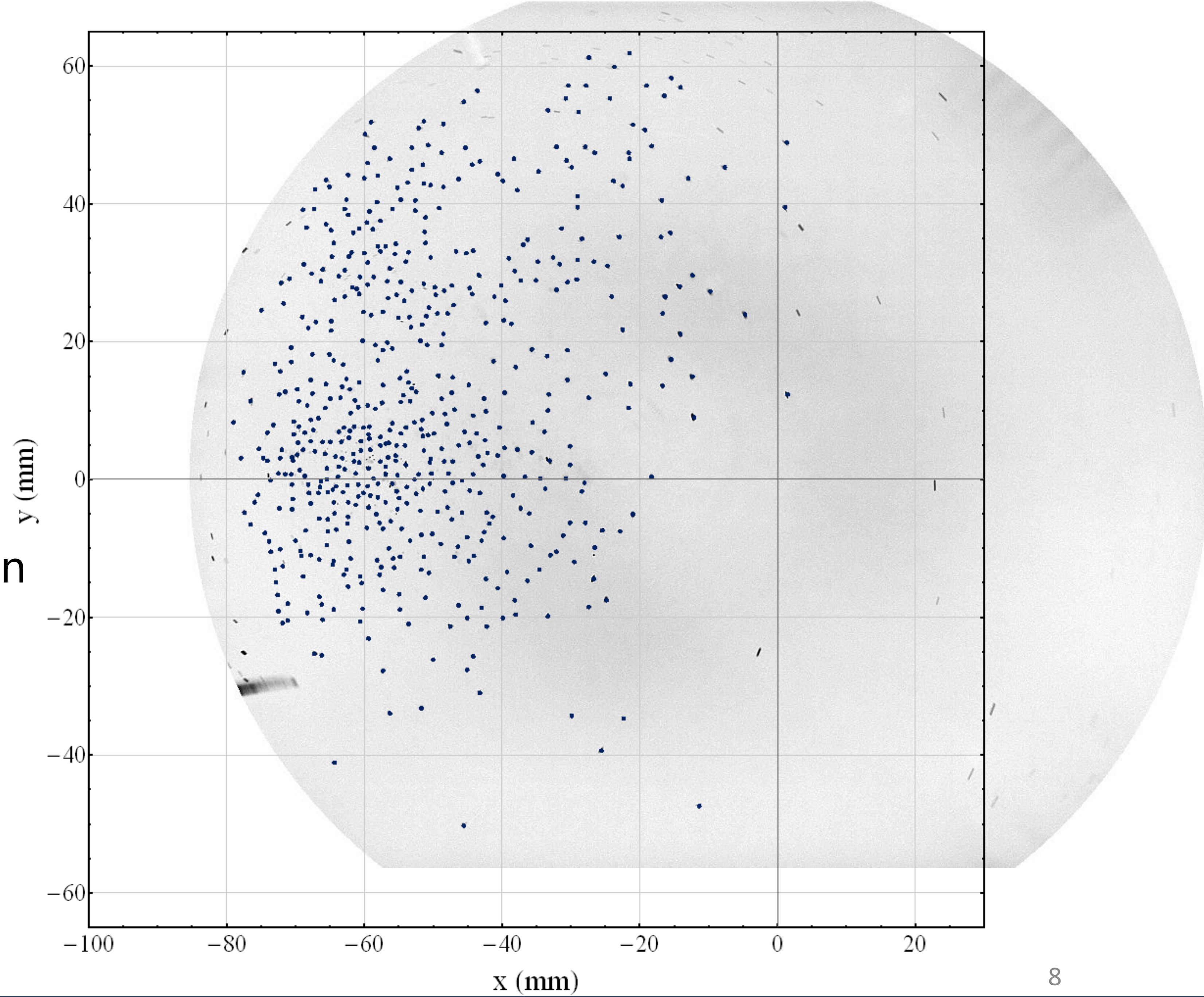
Knudsen Number

$$\text{Kn} = \frac{\lambda}{s} \sim \frac{1}{p \cdot s}$$

Data Analysis

Procedure

1. Particle Detection & Particle Tracking
2. Calculation of the relative velocities normalized on individual sedimentation velocity
3. Closeness of particles



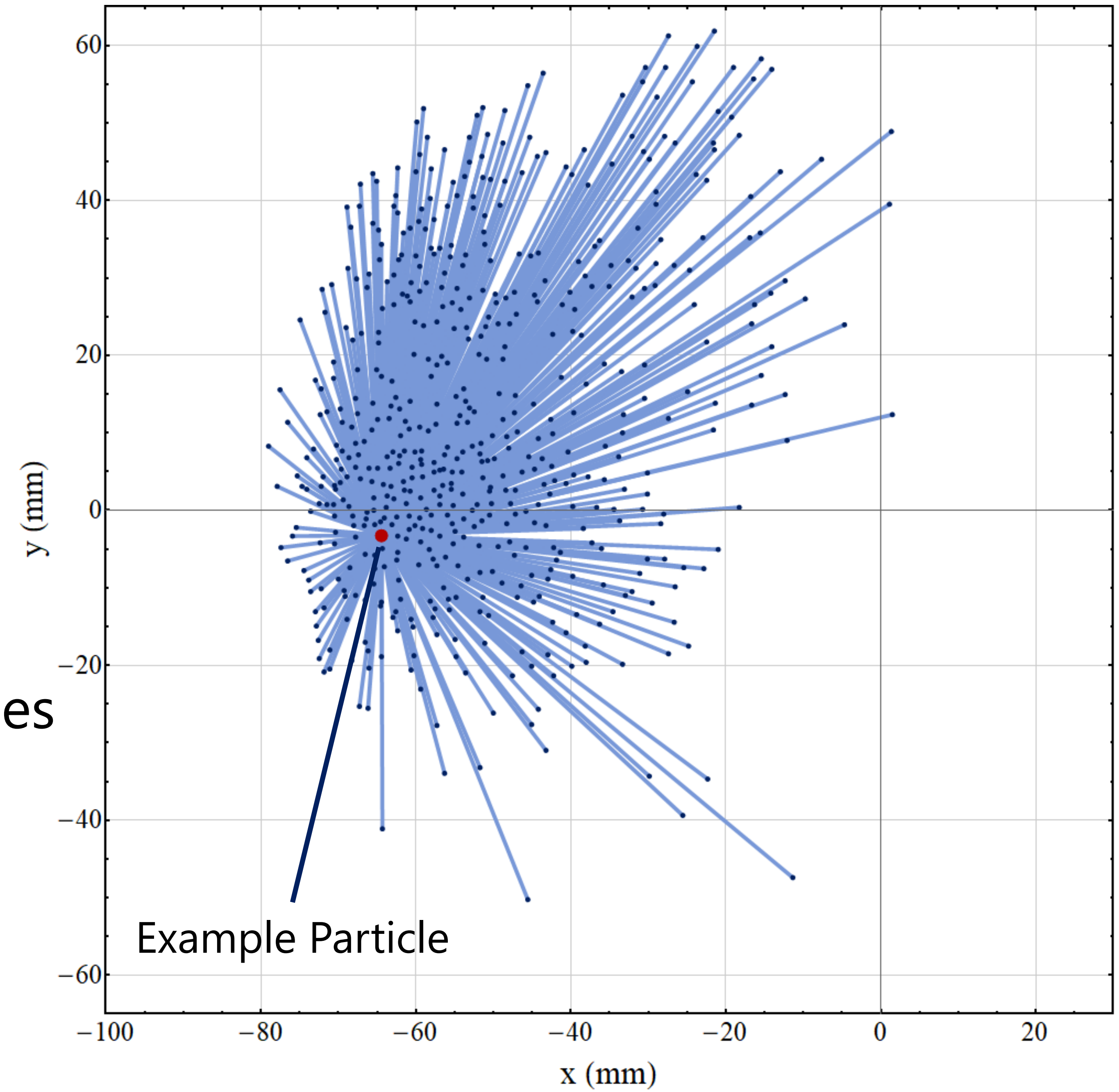
Closeness

Measurement of all interparticle distances in particle size units

Sum of the inverse of all distances

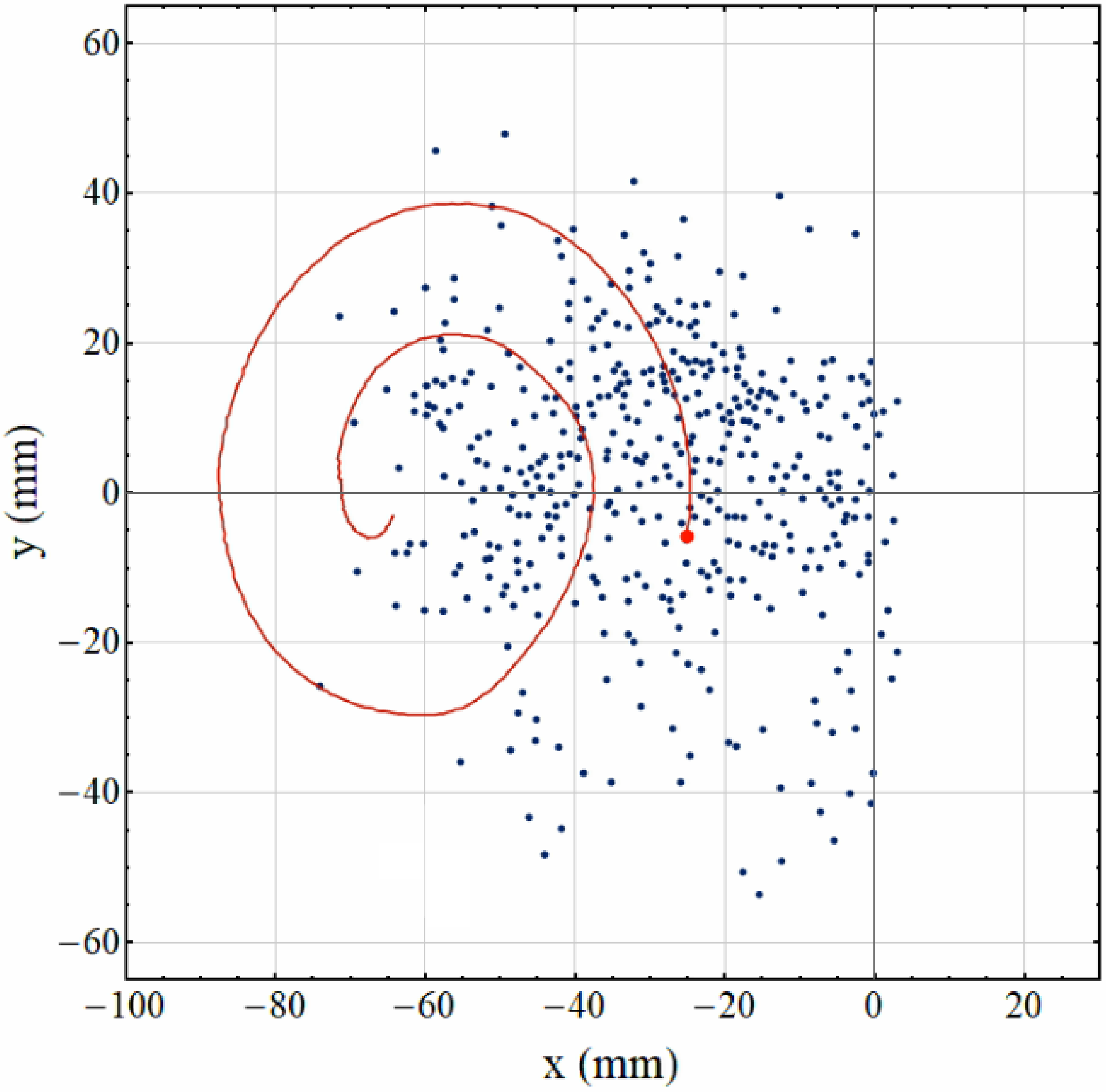
Constructed from distances *and* number of particles

$$C_i = \sum_j^N \frac{s}{d_{i,j}}$$

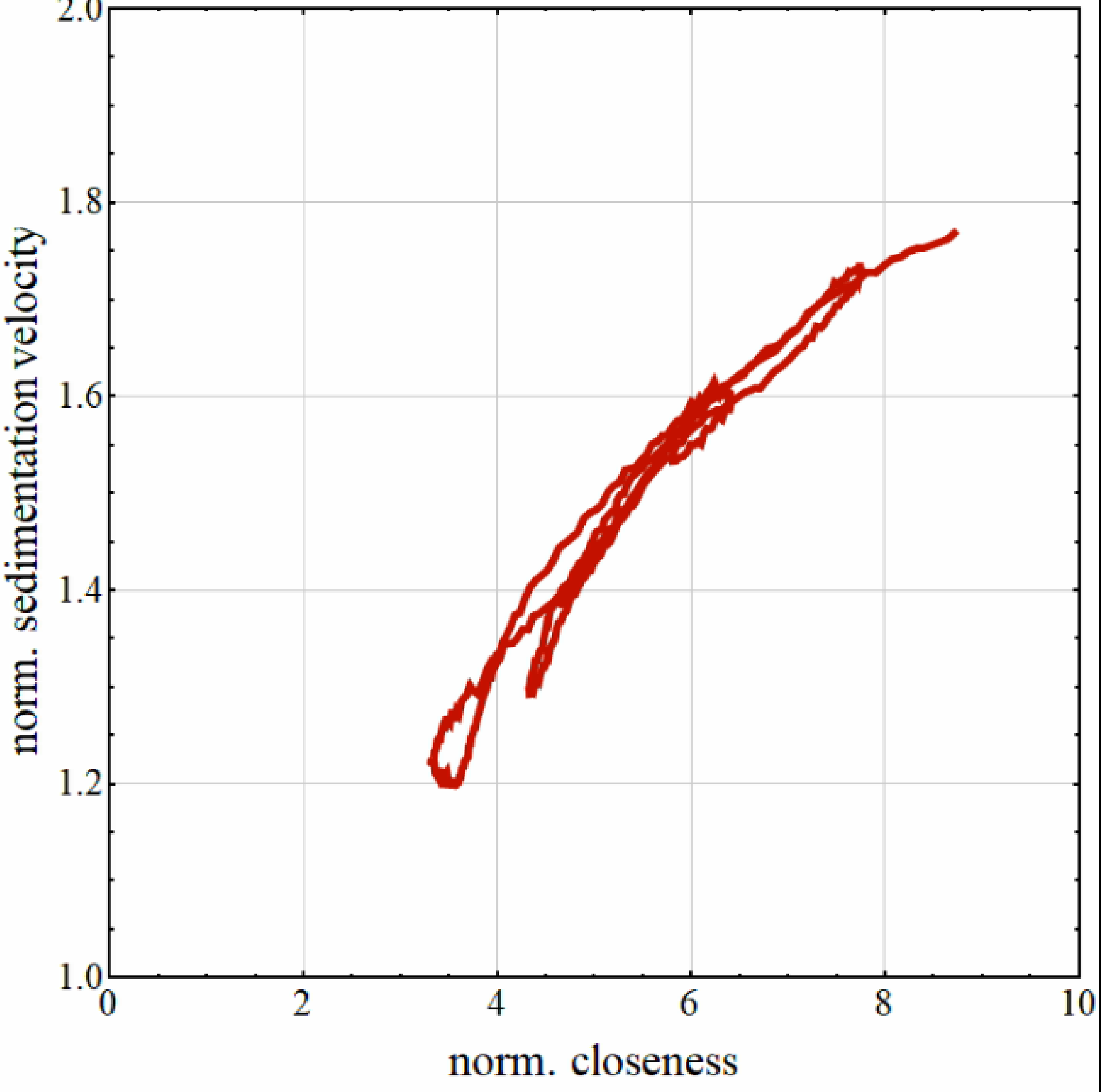


Particle Motion

t = 4.58 s



60
40
20
0
−20
−40
−60
y (mm)
−100
−80
−60
−40
−20
0
20
x (mm)



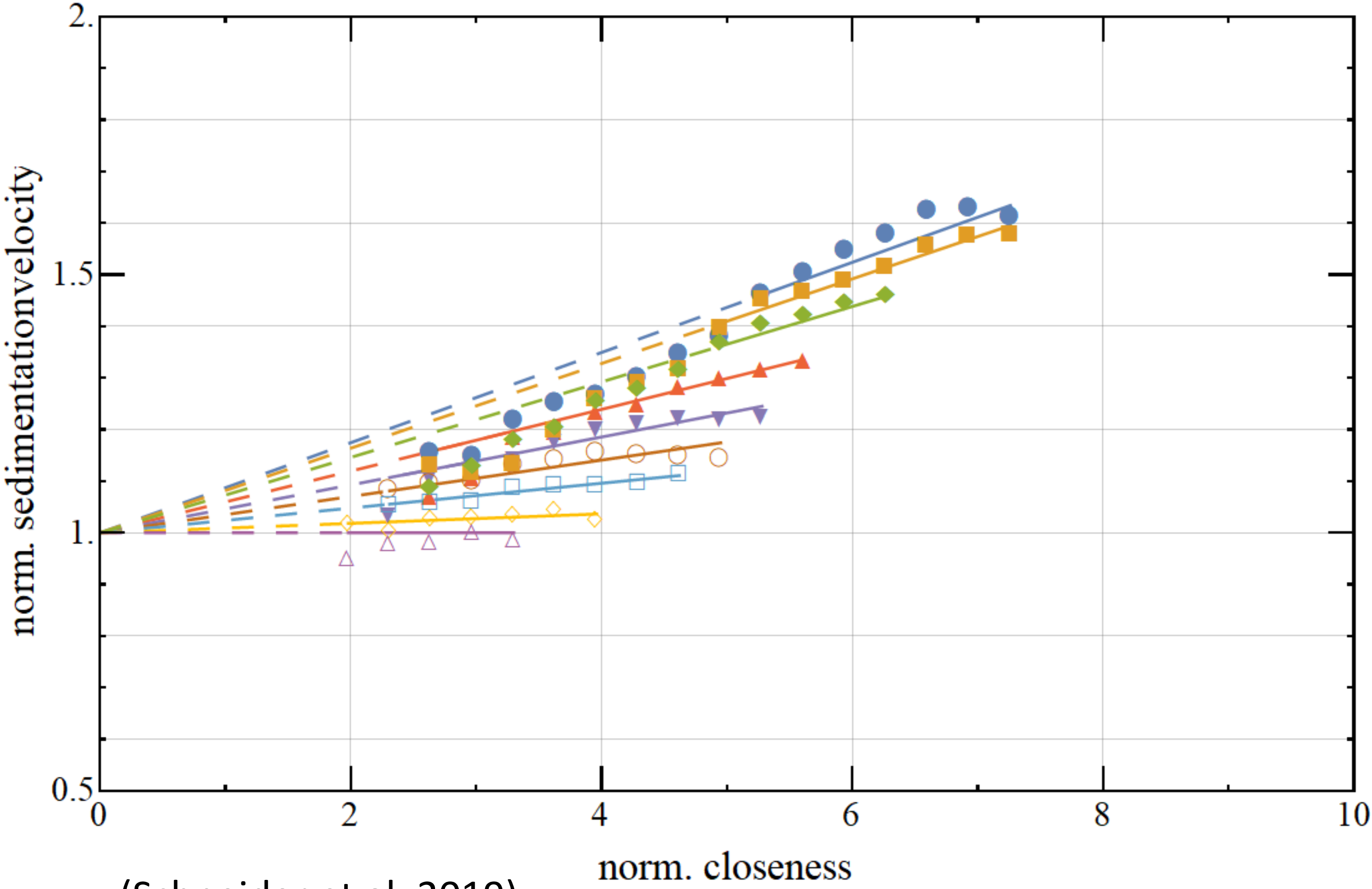
2.0
1.8
1.6
1.4
1.2
1.0
norm. sedimentation velocity
0
2
4
6
8
10
norm. closeness

Velocity – Closeness – Relation

Values are averaged over full revolutions

Values are increasing in time from 3 s (upper curver) to 30 s (lower curve)

$$v_{rel} = v_0 + F_S \cdot C$$



(Schneider et al. 2019)

Collectiveness

Particles sedimentation velocity = individual sedimentation velocity

↓

Back-reaction on the gas does not influence other particles

↓

NO COLLECTIVE BEHAVIOUR

Collectiveness

Particles sedimentation velocity **>** individual sedimentation velocity

↓

Back-reaction on the gas influences other particles

↓

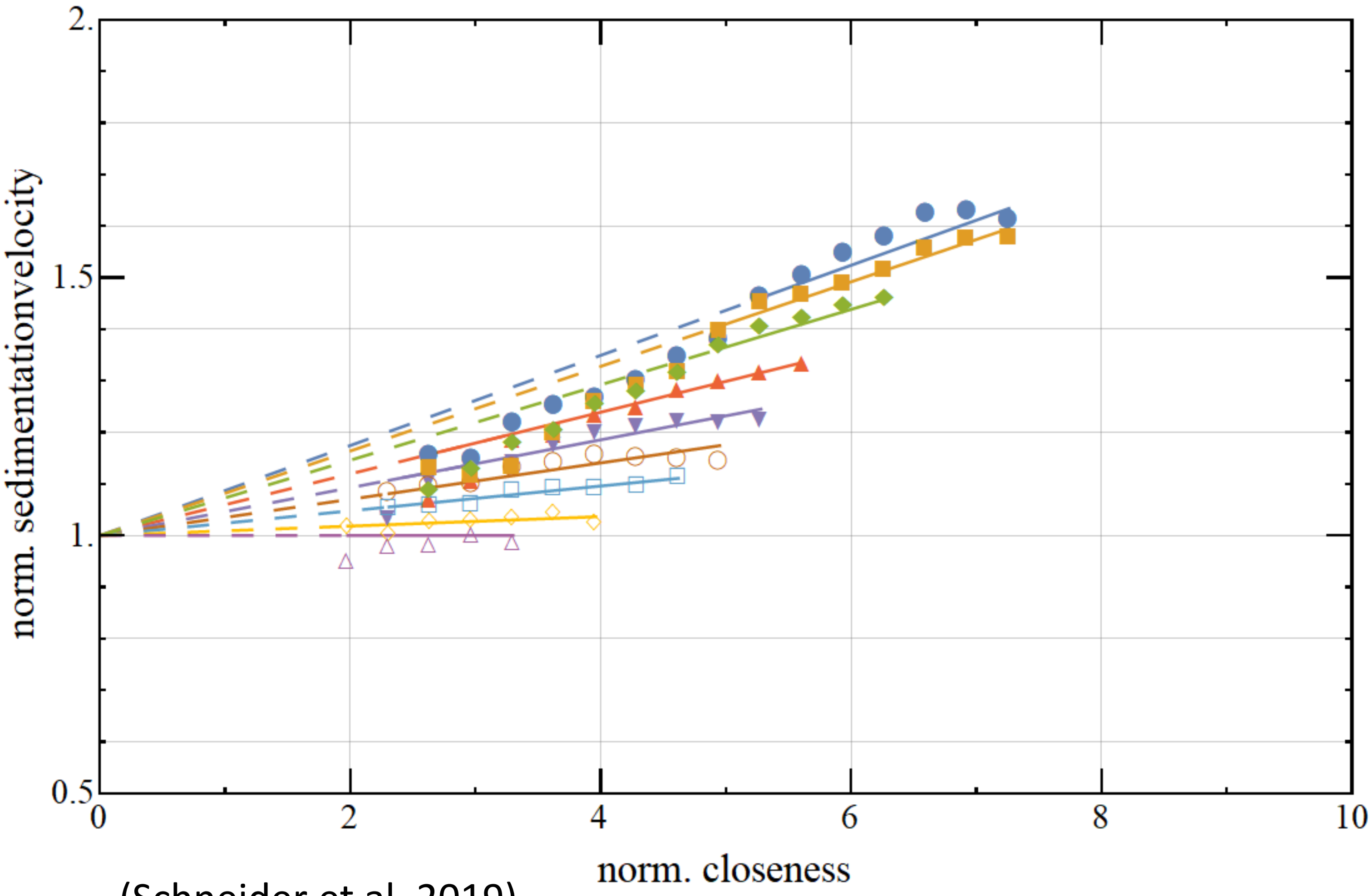
COLLECTIVE BEHAVIOUR

Velocity – Closeness – Relation

Values are averaged over full revolutions

Values are increasing in time from 3 s (upper curver) to 30 s (lower curve)

$$v_{rel} = v_0 + F_S \cdot C$$



(Schneider et al. 2019)

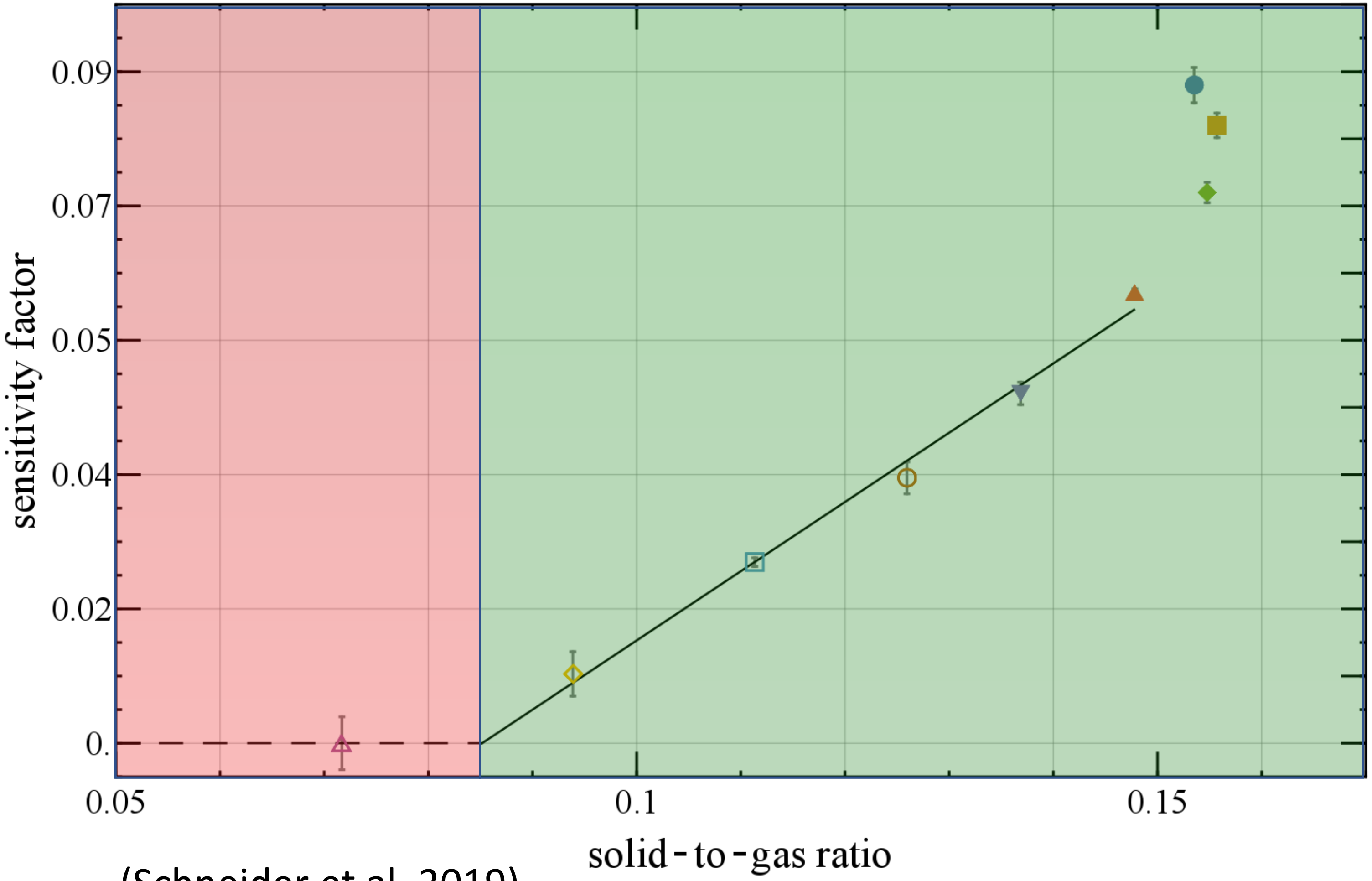
Velocity – Closeness – Relation

Sensitivity factor depends on the solid-to-gas ratio of the system

The system is not collective below an ϵ-threshold

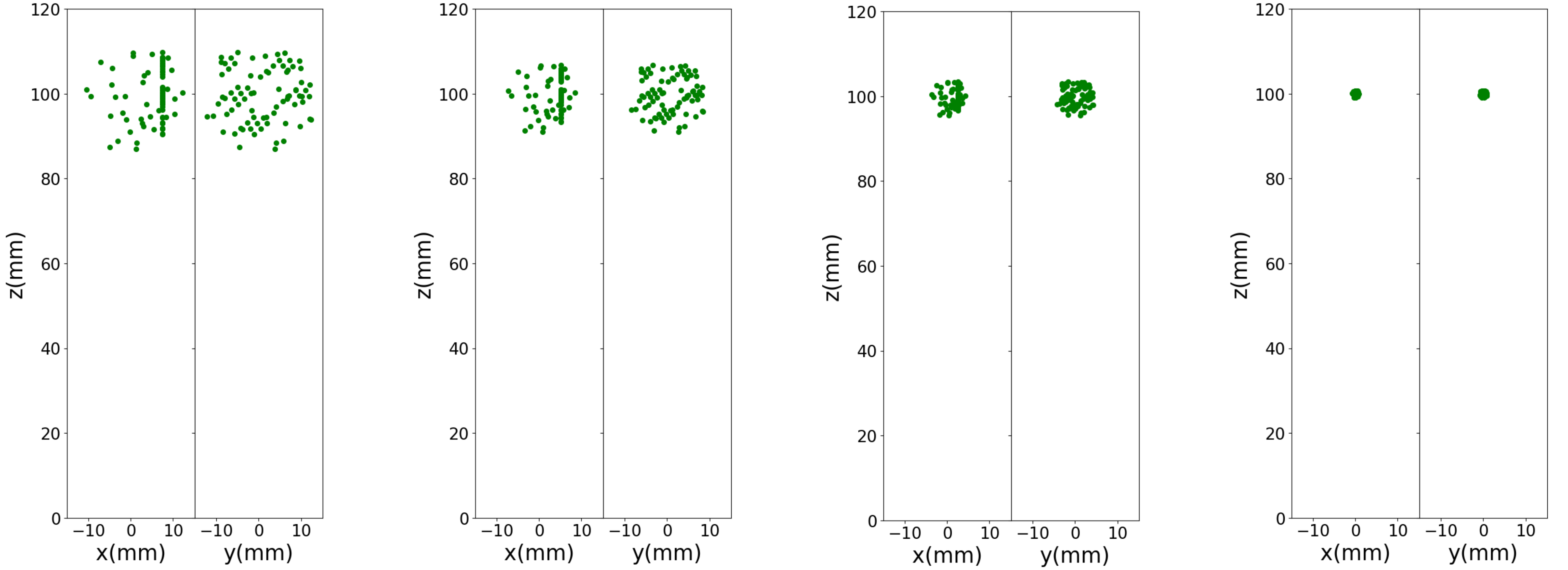
$$v_{\mathrm{rel}} = v_0 + \alpha(\epsilon - \epsilon_{\mathrm{crit}}) \cdot C$$
$$\text{for } \epsilon > \epsilon_{\mathrm{crit}}$$

$$v_{\mathrm{rel}} = v_0$$
$$\text{for } \epsilon < \epsilon_{\mathrm{crit}}$$

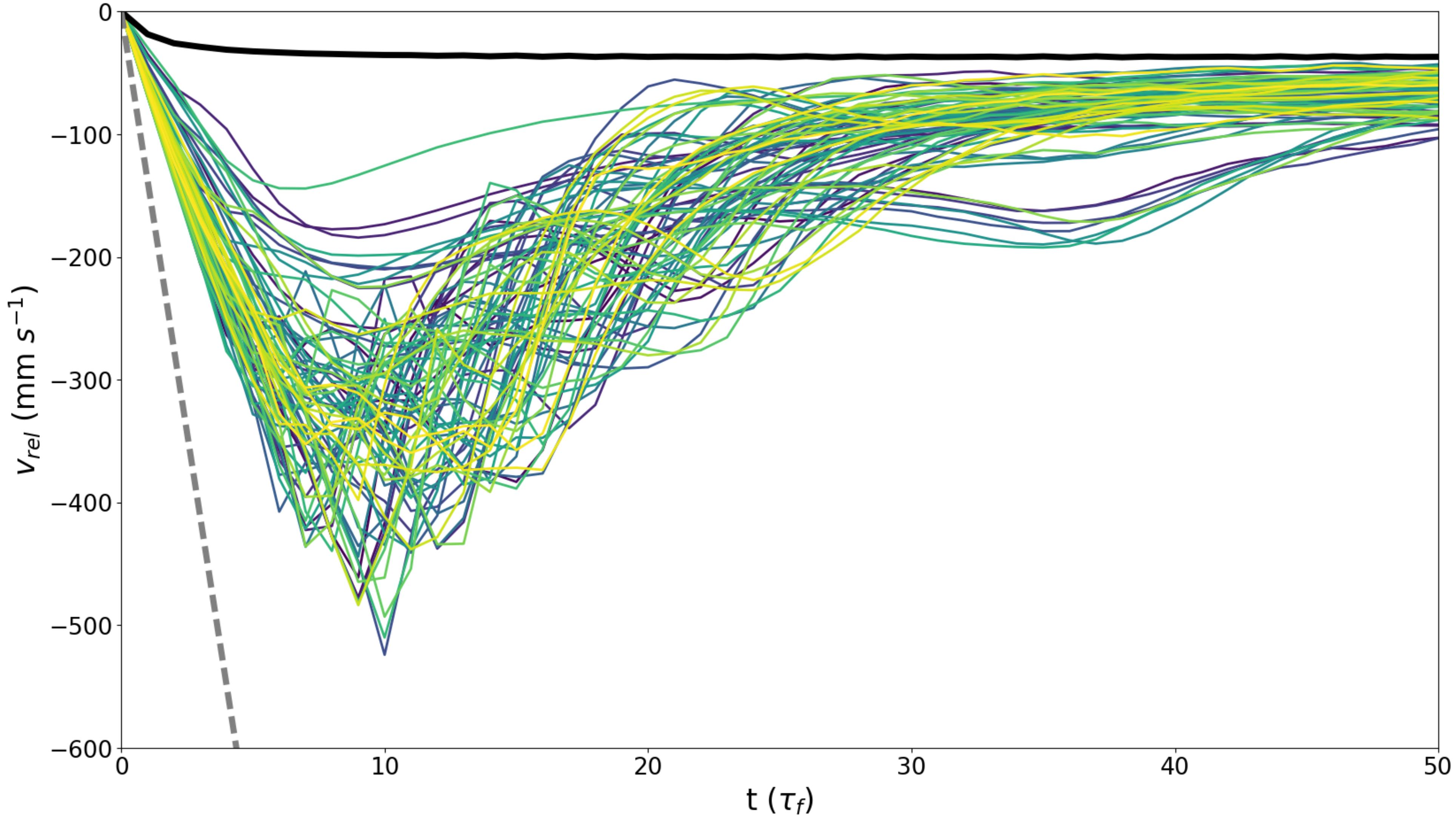


(Schneider et al. 2019)

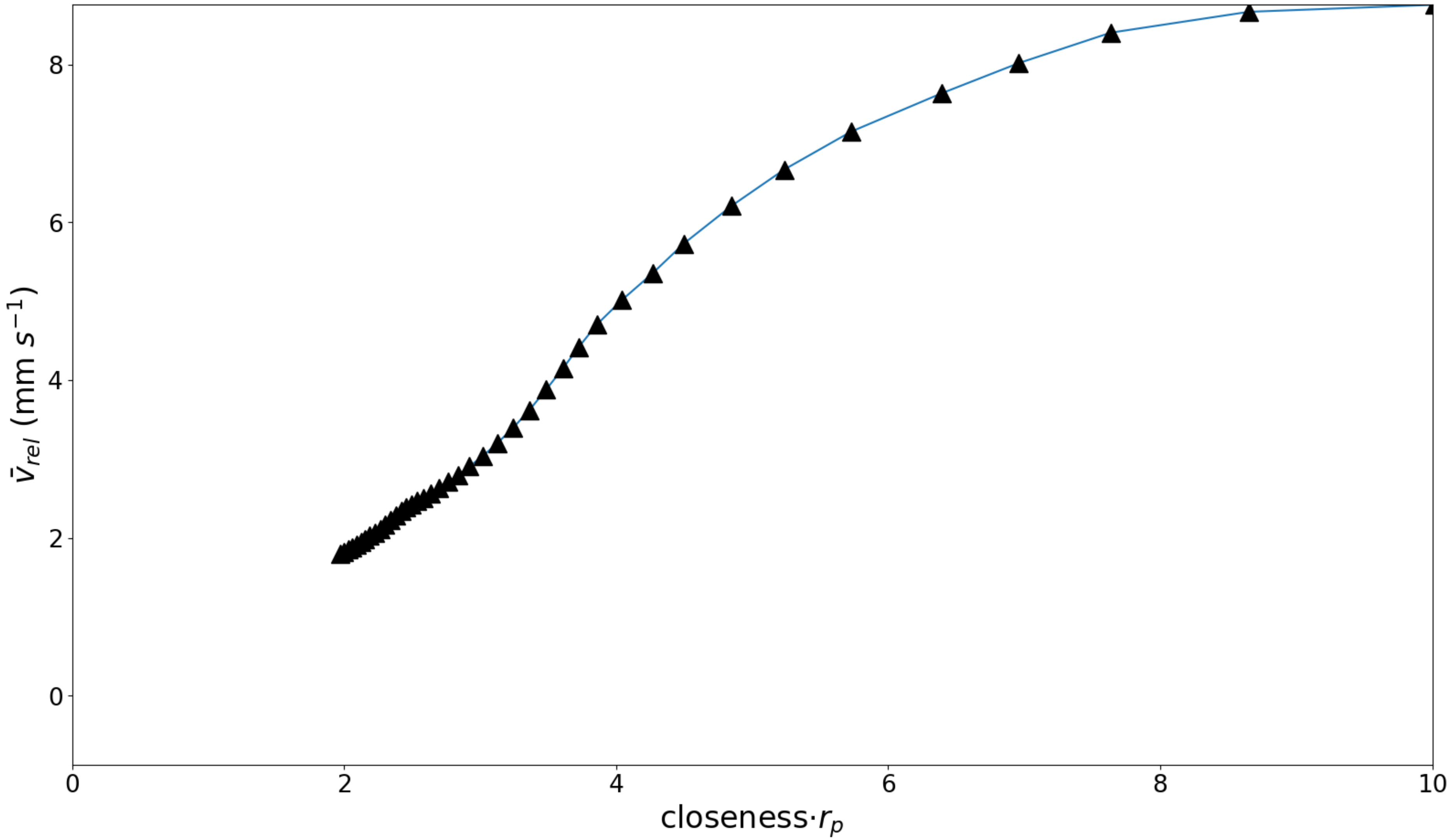
Simulations



Simulations



Velocity – Closeness – Relation



Further Experiments

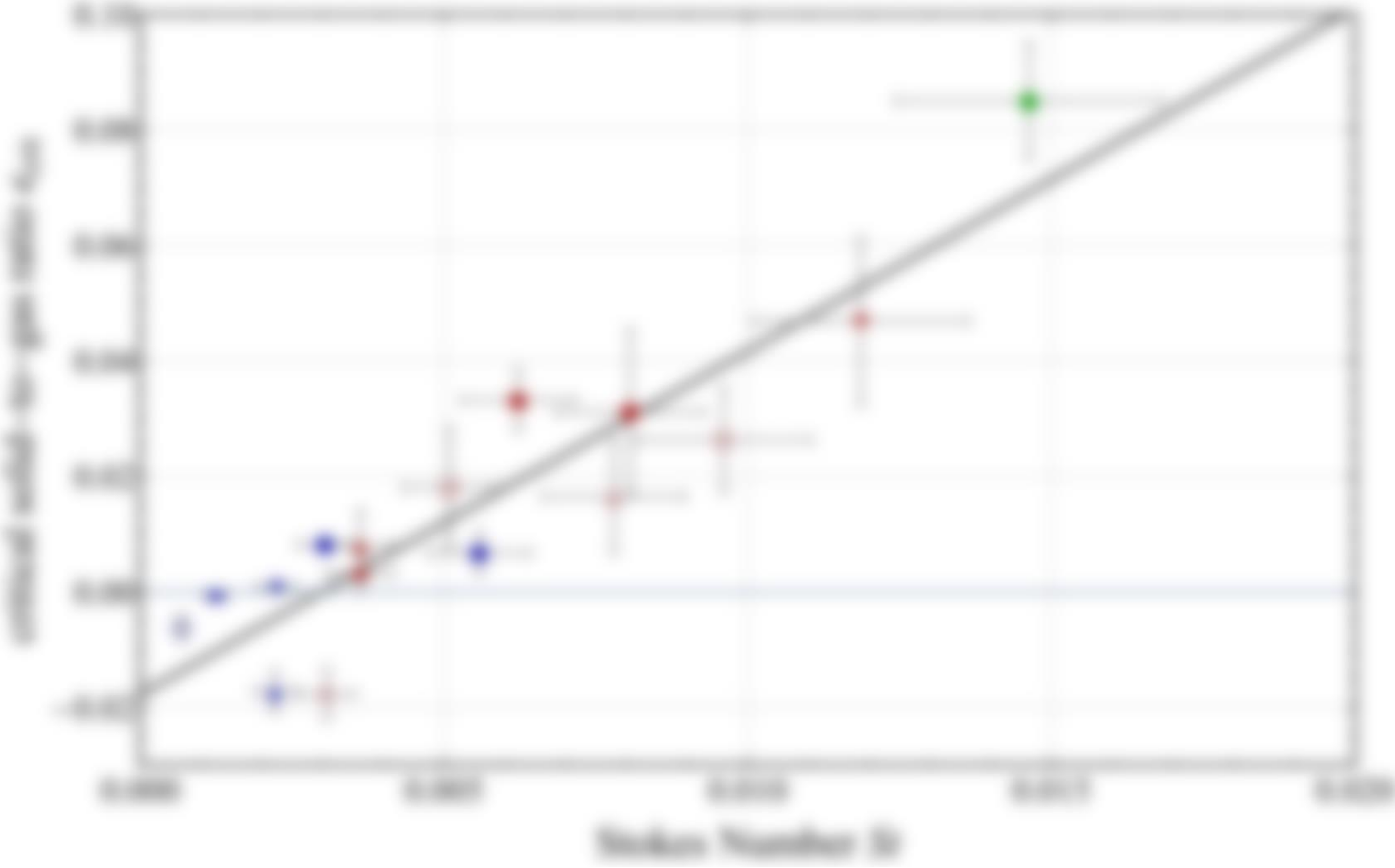
experiment	particle size (μm)	particle density (kg m^{-3})	pressure (mbar)	rotation frequency (Hz)	v_0 (mms^{-1})	Kn	St (10^{-3})	Re (10^{-3})	symbole
Schn19+	165 ± 15	60 ± 6	9.5 ± 1	0.336 ± 0.002	68 ± 7	0.08 ± 0.02	14 ± 2	7 ± 2	●
1	36 ± 9	280 ± 76	8 ± 1	0.216 ± 0.002	22 ± 2	0.46 ± 0.16	3.0 ± 0.5	0.4 ± 0.2	●
2	36 ± 9	280 ± 76	8 ± 1	0.273 ± 0.002	32 ± 3	0.46 ± 0.16	5.6 ± 0.8	0.6 ± 0.25	■
3	36 ± 9	280 ± 76	13.5 ± 1	0.145 ± 0.002	14 ± 1	0.30 ± 0.10	12 ± 0.2	0.4 ± 0.2	◆
4	36 ± 9	280 ± 76	14 ± 1	0.231 ± 0.002	15 ± 2	0.26 ± 0.09	2.2 ± 0.3	0.5 ± 0.2	▲
5	36 ±							0.7 ± 0.3	▼
6	36 ±							0.2 ± 0.1	○
7	132.5 ±							1.4 ± 0.4	●
8	132.5 ±							1.6 ± 0.4	■
9	132.5 ± 8	75 ± 4	4 ± 0.4	0.153 ± 0.002	37 ± 4	0.25 ± 0.04	3.6 ± 0.5	1.3 ± 0.3	◆
10	132.5 ± 8	75 ± 4	4 ± 0.4	0.153 ± 0.002	37 ± 4	0.25 ± 0.04	3.6 ± 0.5	1.3 ± 0.3	▲
11	132.5 ± 8	75 ± 4	8.1 ± 1	0.378 ± 0.002	49 ± 5	0.12 ± 0.02	28 ± 2	3.5 ± 0.9	▼
12	132.5 ± 8	75 ± 4	8.1 ± 1	0.375 ± 0.002	40 ± 5	0.12 ± 0.02	9.6 ± 1	2.8 ± 0.7	○
13	132.5 ± 8	75 ± 4	12 ± 1	0.199 ± 0.002	40 ± 4	0.08 ± 0.01	5.1 ± 0.7	4 ± 1	□
14	132.5 ± 8	75 ± 4	8.1 ± 1	0.160 ± 0.002	30 ± 3	0.12 ± 0.02	3.1 ± 0.5	2.1 ± 0.5	◇
15	132.5 ± 8	75 ± 4	8.1 ± 1	0.297 ± 0.002	41 ± 4	0.12 ± 0.02	8 ± 1	2.9 ± 0.8	△

$$v_{rel} = \boldsymbol{\alpha} \cdot (\epsilon - \boldsymbol{\epsilon}_{\mathbf{crit}}) \cdot C$$

Further Experiments

ϵ_{crit} increases for increasing St – Number particles

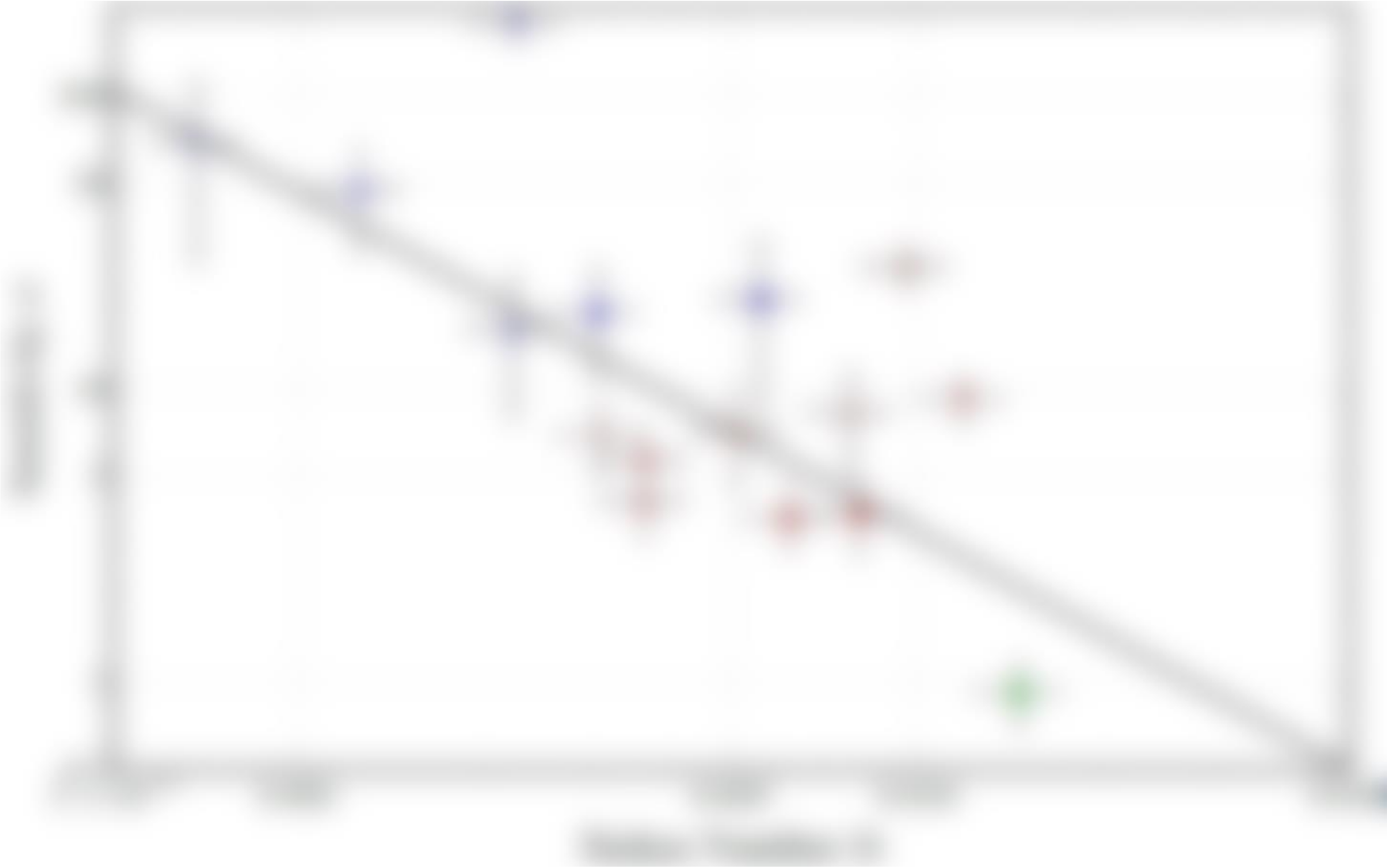
Particles with $\text{St} < 0.003$ always behave collectively



Further Experiments

Small St–number particles have higher impact on the gas flow than large St – number particles for the same ϵ

$$v_{\mathrm{rel}} = v_0 + \alpha \cdot (\epsilon - \epsilon_{\mathrm{crit}}) \cdot C$$
$$\text{for } \epsilon > \epsilon_{\mathrm{crit}}$$



Conclusions

- Below a critical solid-to-gas ratio ϵ_{crit} particles do not show collective behaviour
- Above this threshold particle velocities depend on closeness and on the average solid-to-gas ratio

- ϵ_{crit} increases with St
- Sensitivity on closeness and solid-to-gas ratio decreases with St