Growth of cloud droplets from aerosol In turbulence

2017/11/21

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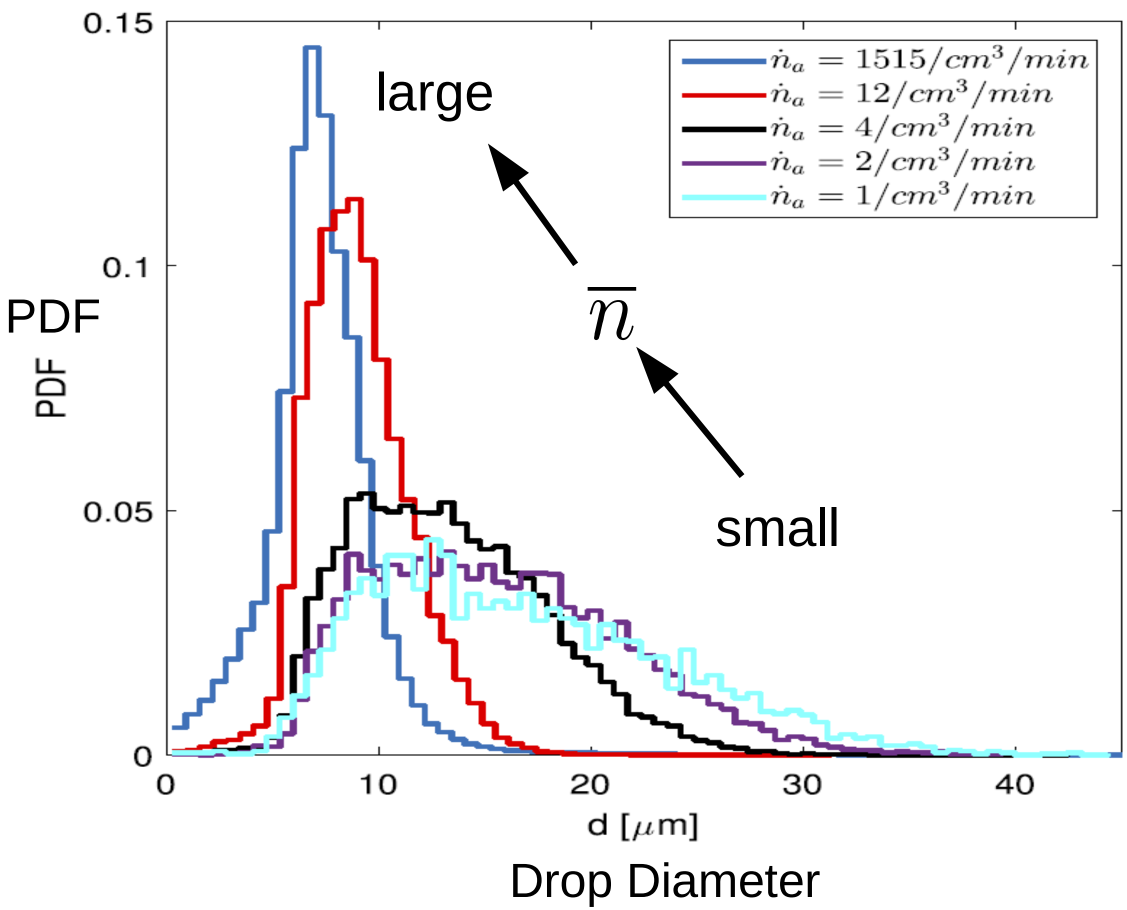
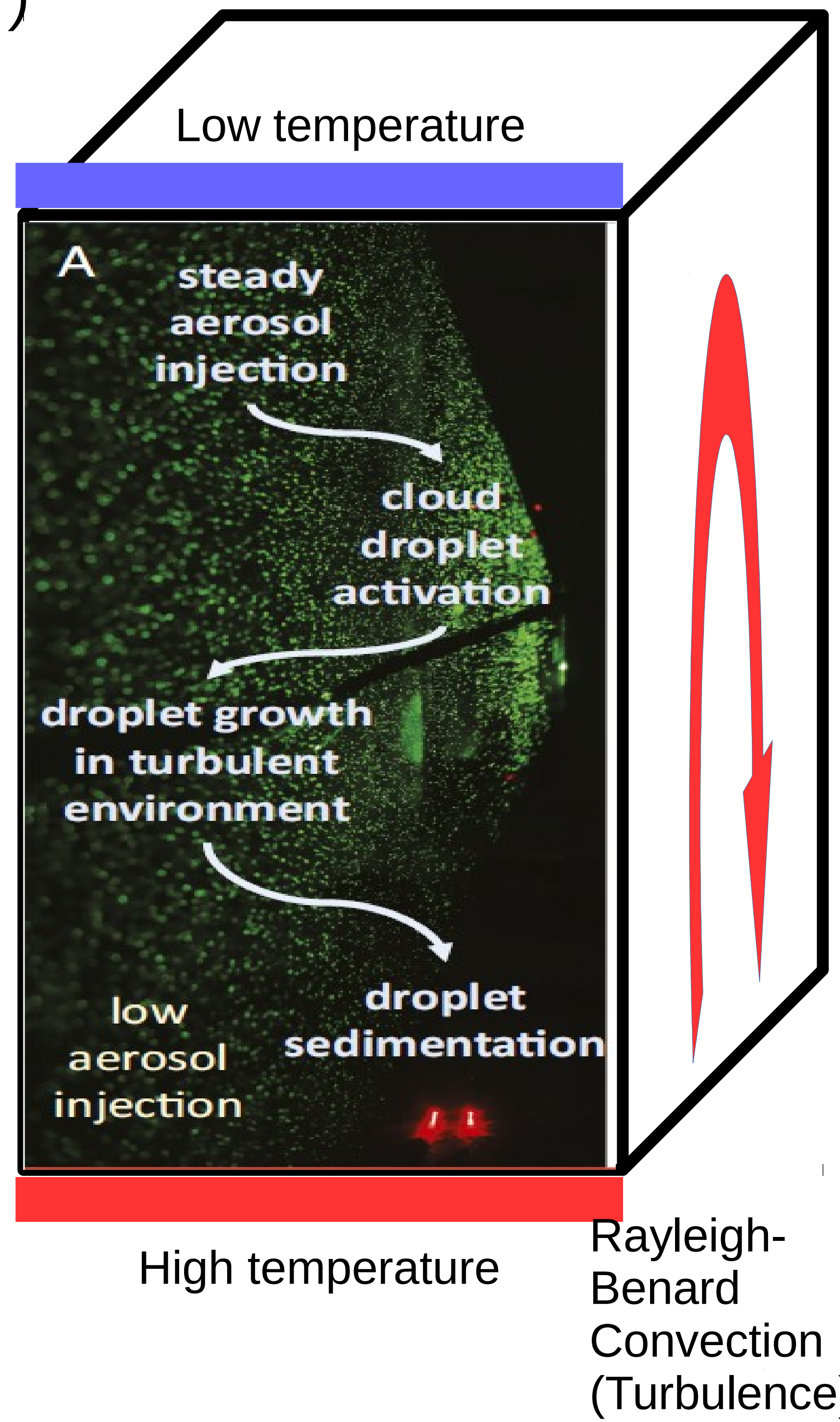
This work is supported by:
KAKENHI: 15H02218
HPCI: hp160085, hp170189
JHPCN: jh170013

70th Annual Meeting of the APS Division of Fluid Dynamics
Sunday–Tuesday, November 19–21, 2017; Denver, Colorado

Chandrakar et al (2016、PNAS)（C16）

- Moist R-B convection（turb.）
- Aerosol injection at const. rate
- Condensation nucleation
  →Condensation growth
  →Removal（⇒steady state）





C16: Statistical theory and experimental results

Langevin Model

$$\frac{dr(t)^2}{dt} = 2KS$$

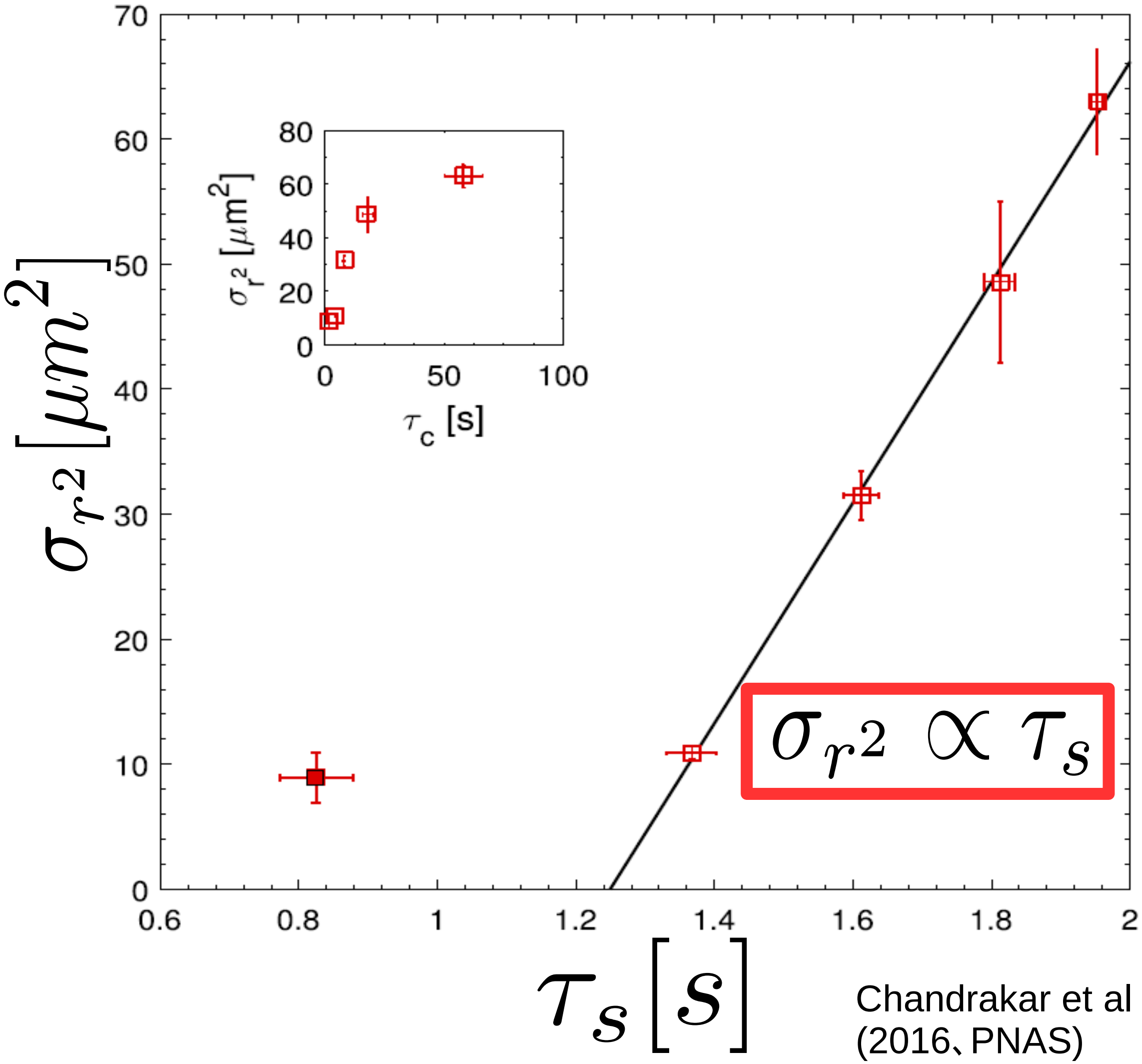
$$dS(t) = S(t+dt) - S(t)$$

$$= \left[\frac{S_{eq} - S}{\tau_t} - \frac{S}{\tau_c}\right] dt$$

$$+ \left(\frac{2\sigma_{s_0}^2 dt}{\tau_t}\right)^{1/2} \eta(t)$$

$$\overline{S'^2} = \left(\frac{\tau_s}{\tau_t}\right) \sigma_{s_0}^2$$

$$\sigma_{r^2}^2 = \frac{8K^2\sigma_{s_0}^2\tau_s^2}{\tau_t}\tau_{\rm res}$$



Chandrakar et al (2016、PNAS)

$$\overline{S'^2} \propto \tau_s$$

$$\sigma_{r^2} \propto \tau_s$$

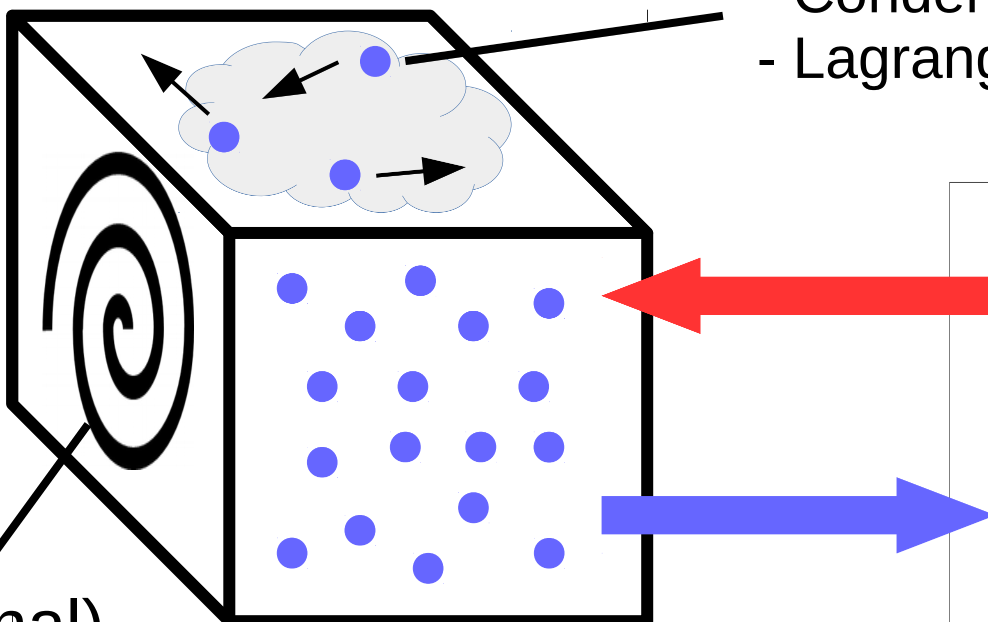
System time scale

$$\left(\tau_s = \frac{\tau_c \tau_t}{\tau_c + \tau_t}\right)$$

phase change

turb.

C16 (Langevin) model



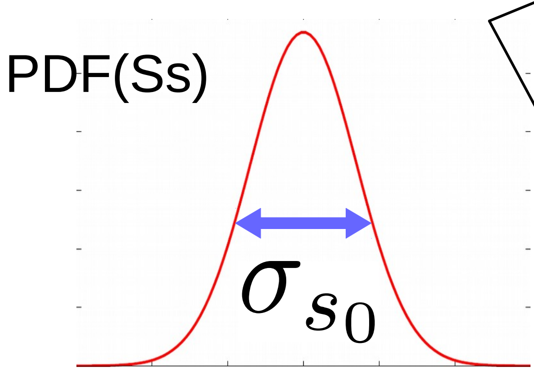
- Condensation growth/decay
- Lagrangian motion

Particle injection at constant rate

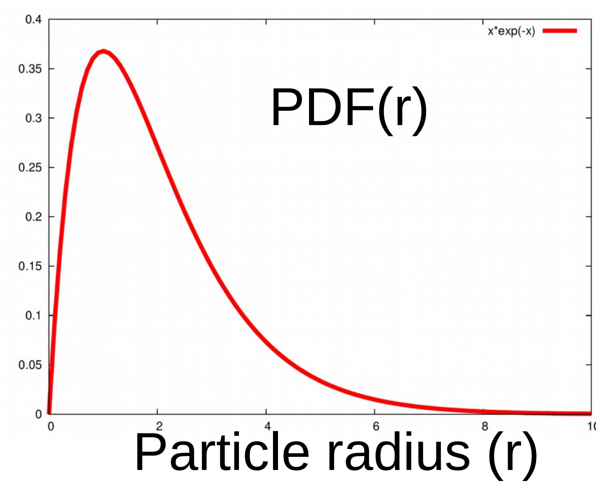
Particle removal with residential time scale $\sim \tau_{\mathrm{res}}$

(External) supersaturation (Ss) fluctuation

⇒ Statistically steady state



Nudging (friction) time scale $\sim \tau_{\mathrm{t}}$ to reference value $Ss = S_{\mathrm{eq}}$



Governing equations for DNS

Fluid

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{\rho_{\mathrm{a}}} \nabla p + \nu_{\mathrm{a}} \nabla^2 \mathbf{u} + \mathbf{f}_1$$

$$\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T = \frac{L_{\mathrm{v}}}{c_{\mathrm{p}}} C_{\mathrm{d}} + \kappa_{\mathrm{T}} \nabla^2 T - \frac{(T - T_{\mathrm{eq}})}{\tau_{\mathrm{t}}}$$

$$\frac{\partial Q}{\partial t} + \mathbf{u} \cdot \nabla Q = -C_{\mathrm{d}} + \kappa_{\mathrm{v}} \nabla^2 Q - \frac{(Q - Q_{\mathrm{eq}})}{\tau_{\mathrm{t}}} + \mathbf{f}_2$$

Nudging to $S_{\mathrm{eq}}(T_{\mathrm{eq}}, Q_{\mathrm{eq}})$

Random force (⇒ Ss fluctuation)

Particle

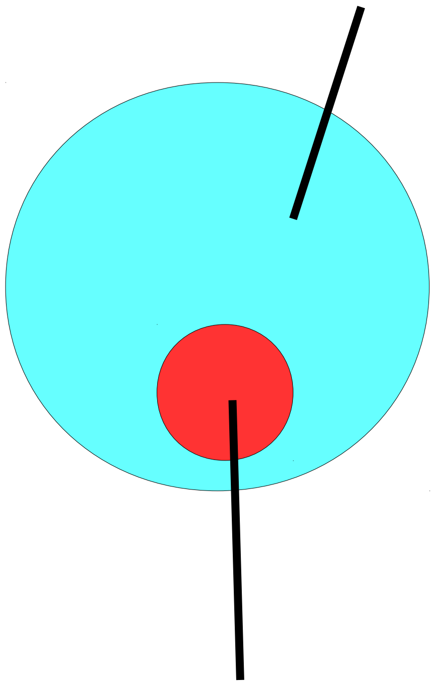
$$\frac{d\mathbf{X}_j(t)}{dt} = \mathbf{V}_j(t)$$

$$\frac{d\mathbf{V}_j(t)}{dt} = \frac{1}{\tau_j(t)} \left(\mathbf{u}(\mathbf{X}_j(t), t) - \mathbf{V}_j(t)\right) - \cancel{g\mathbf{e}_z}$$

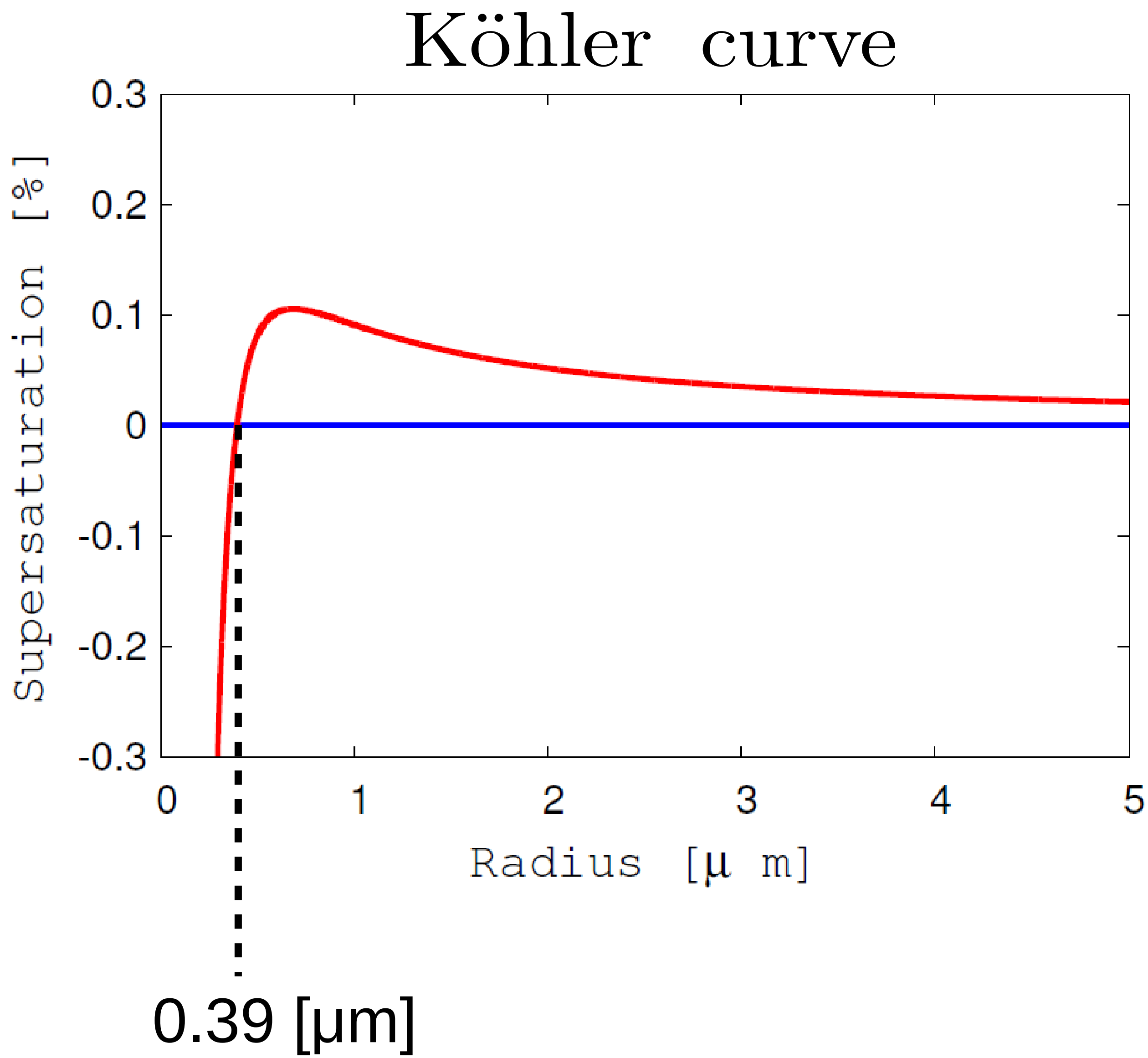
$$\frac{dR_j(t)^2}{dt} = 2K_{\mathrm{s}}(t) S(\mathbf{X}_j(t), t) + (\text{Köhler})$$

Aerosol effect

Injected aerosol particle：NaCl aq



$(m \sim 1.13 \times 10^{-15}$ [g]$)$



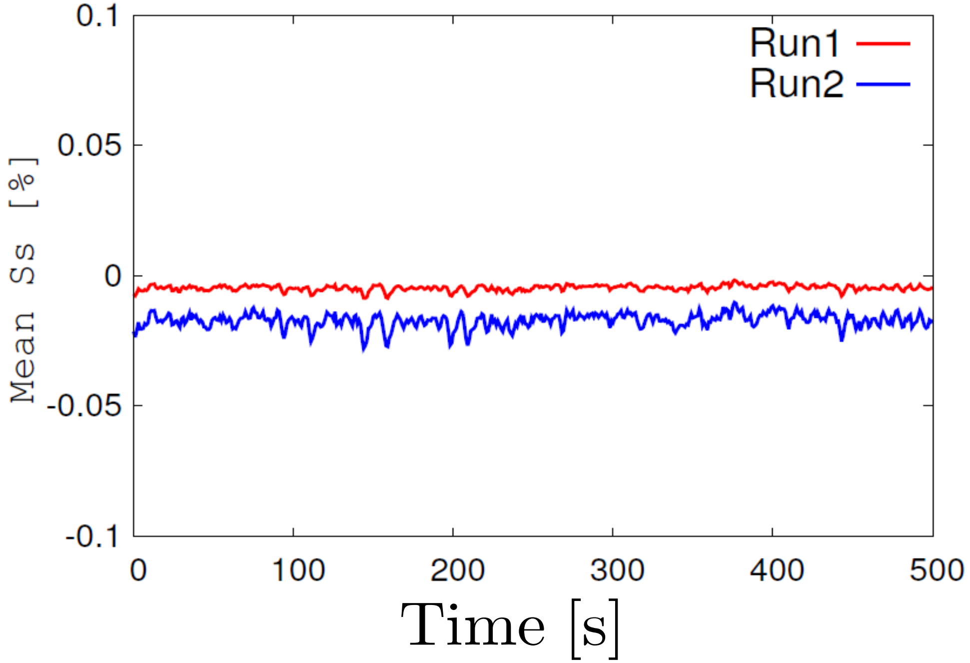
Experimental setups

Residential time scale	τ_{res}	606 [s] ~ 10 [min]
Ss Nudging & fluctuation time scale	τ_{t}	2 [s]
Ss fluctuation without droplets	σ_{s_0}	1.4 [%] (Run1) 2.8 [%] (Run2)
Mean Ss in equilibrium	S_{eq}	0 [%]

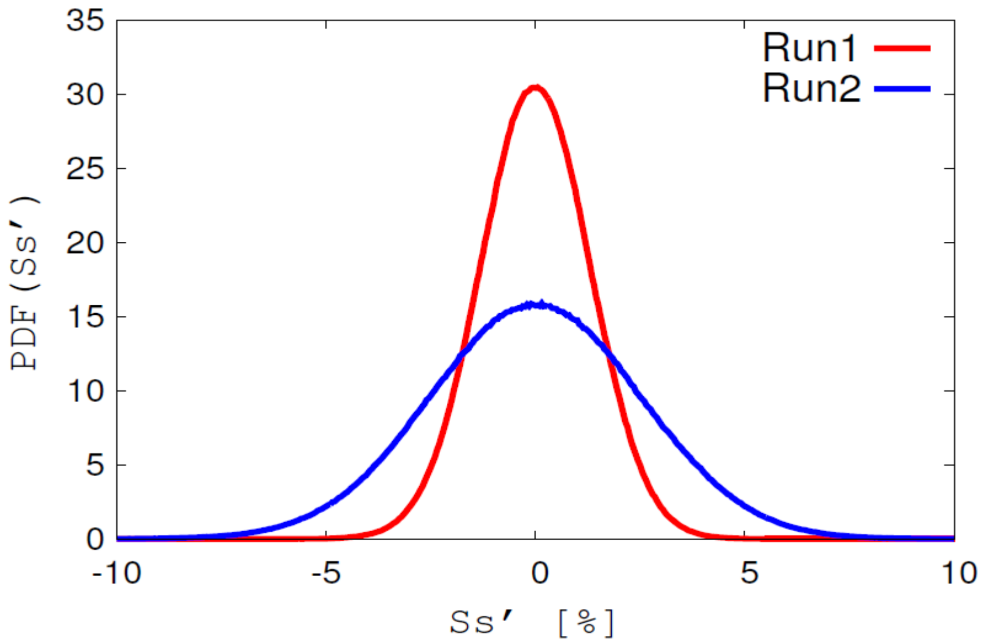
Results

Supersaturation

Volume ave. Ss(t) [%]



PDF of Ss' [%]

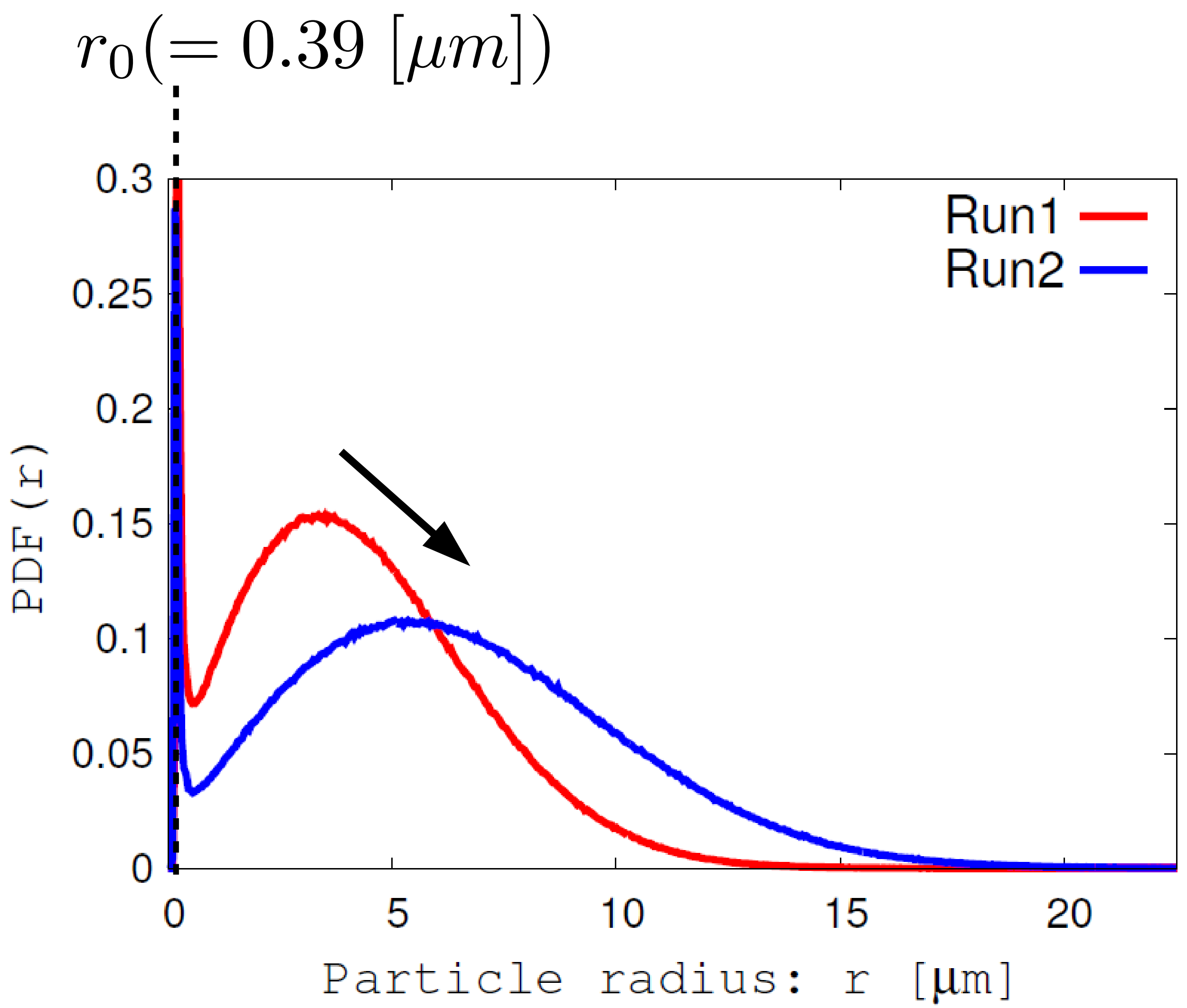


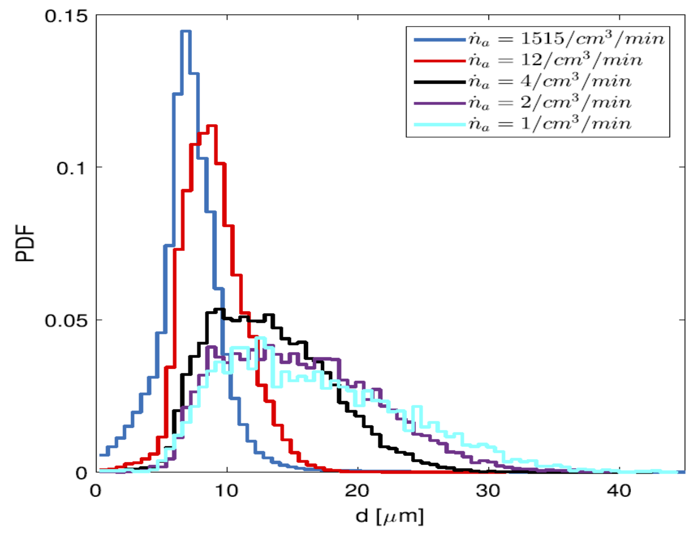
$$\overline{n} \sim 63\ [\mathrm{cm}^{-3}]$$

$$\tau_\mathrm{c} \sim 12.5\ [\mathrm{s}] \qquad \tau_\mathrm{t} = 2\ [\mathrm{s}]$$

$$\tau_\mathrm{s} = \frac{\tau_\mathrm{t}\tau_\mathrm{c}}{\tau_\mathrm{t} + \tau_\mathrm{c}} \sim 1.7\ [\mathrm{s}]$$

Size distribution (steady state)

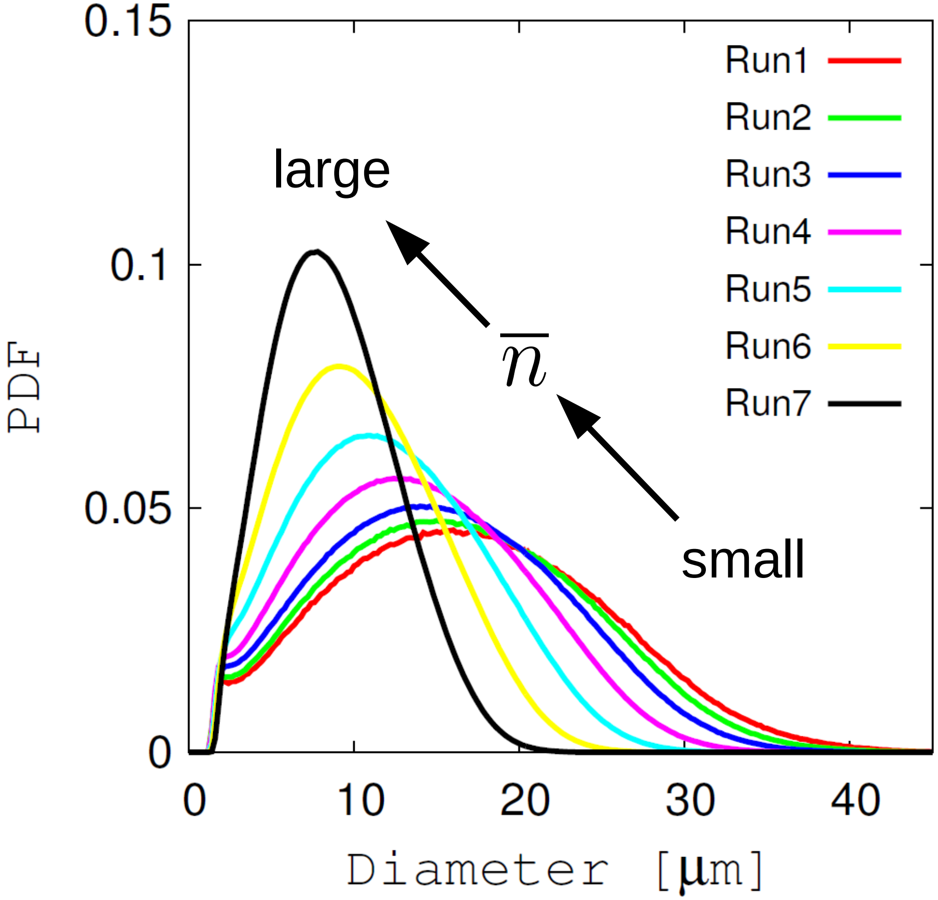




（C16, Fig.2）

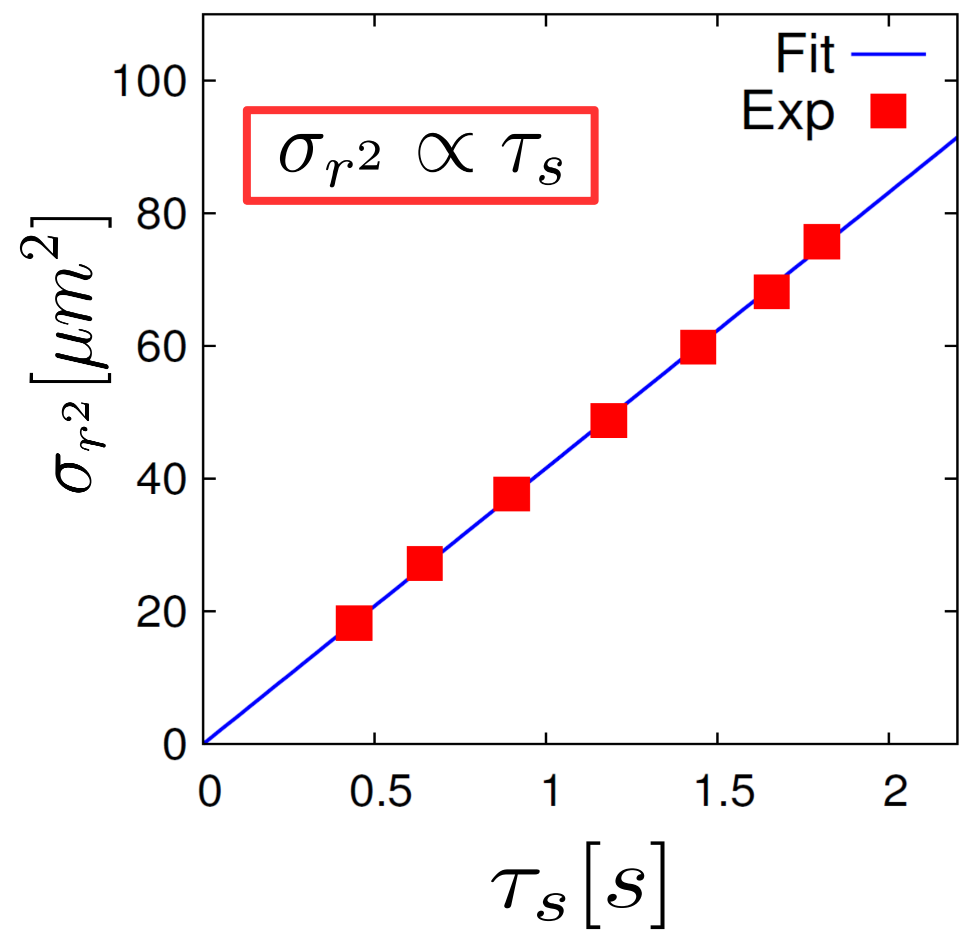
(Results from other experiments)

PDF of droplet diameter

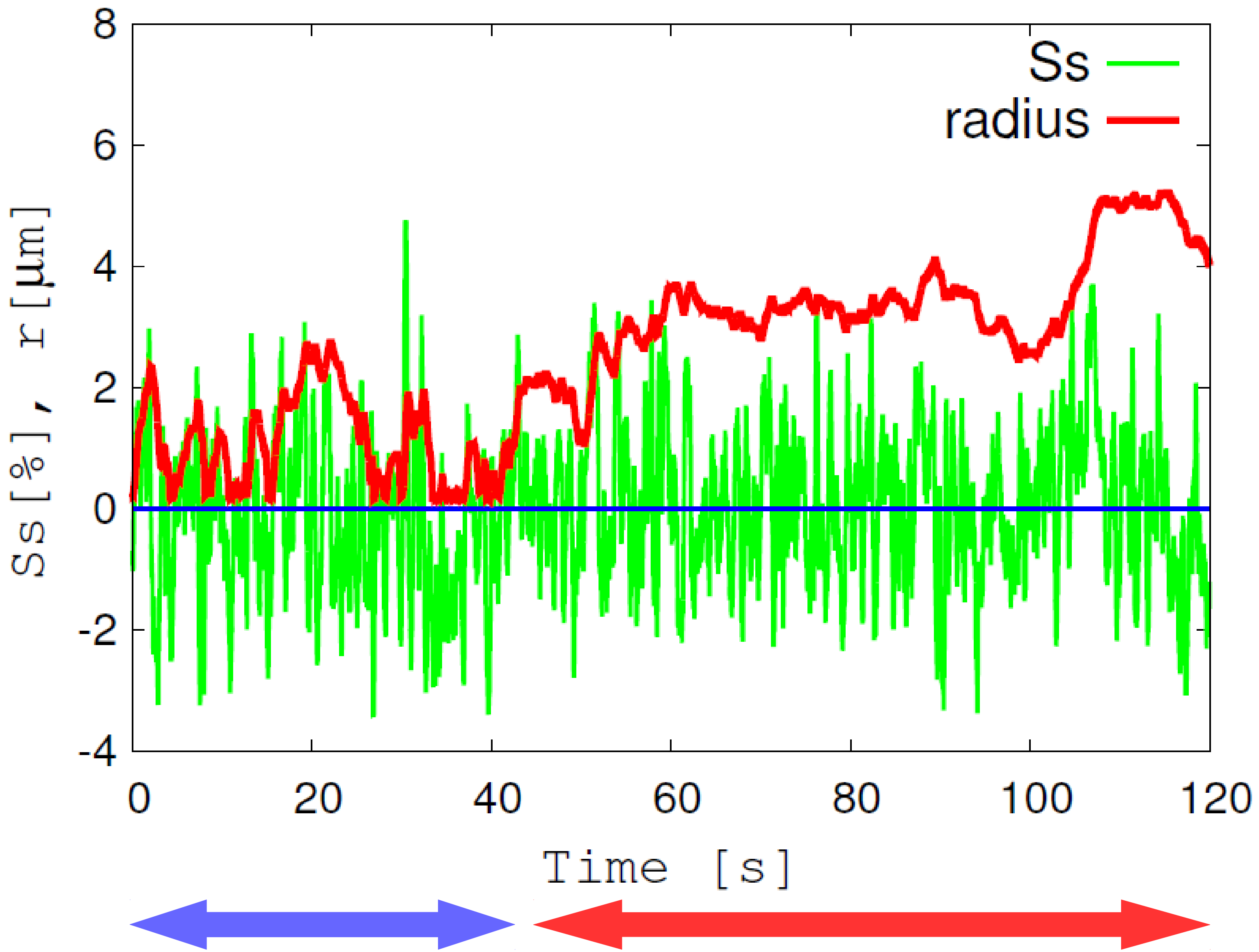


$(S_{\mathrm{eq}} = 0.1\,[\%])$

σ_{r^2} VS τ_s



Run1: Lagrangian tracking, Ex1



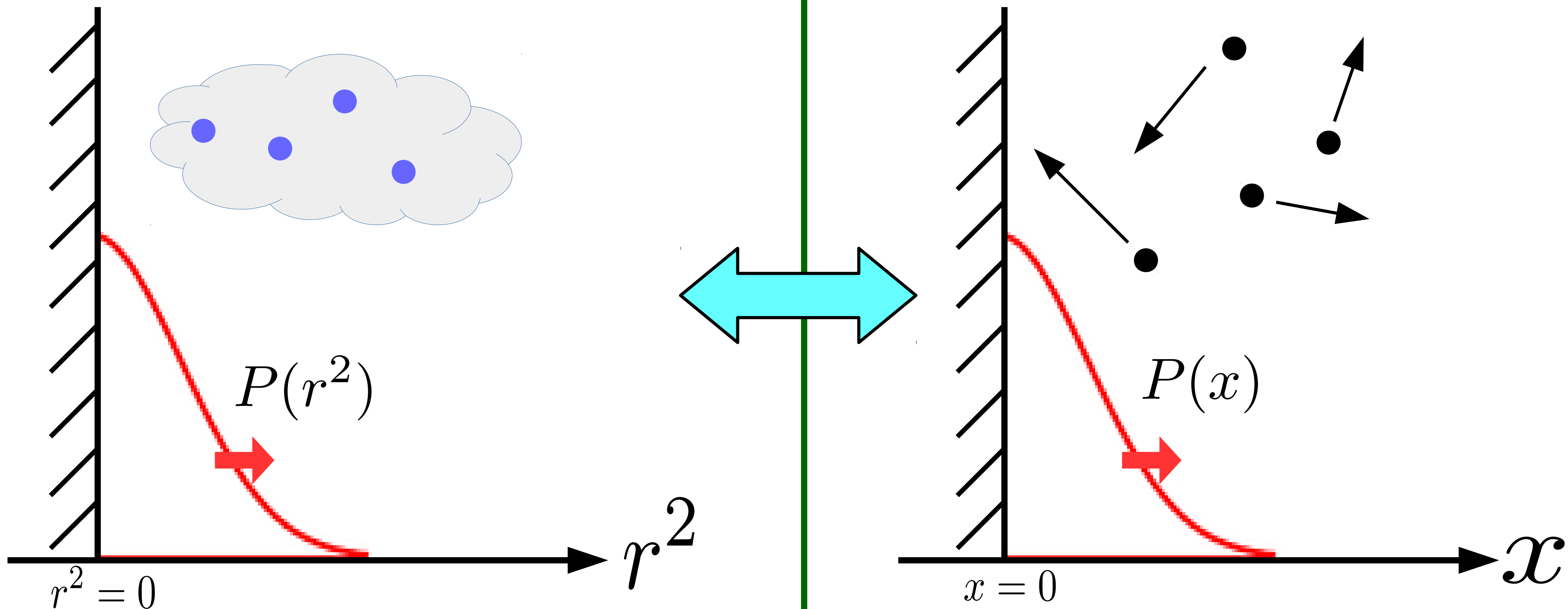
relatively Ss<0
("unlucky")

relatively Ss>0
("lucky")

(Siewert, Bec & Krstulovic, 2017, JFM)

Droplet growth in fluctuating Ss with aerosol effect

Brownian motion with reflecting wall



$$\frac{dr^2}{dt} = 2KS + (\text{Köhler}) \qquad (r^2 > 0)$$

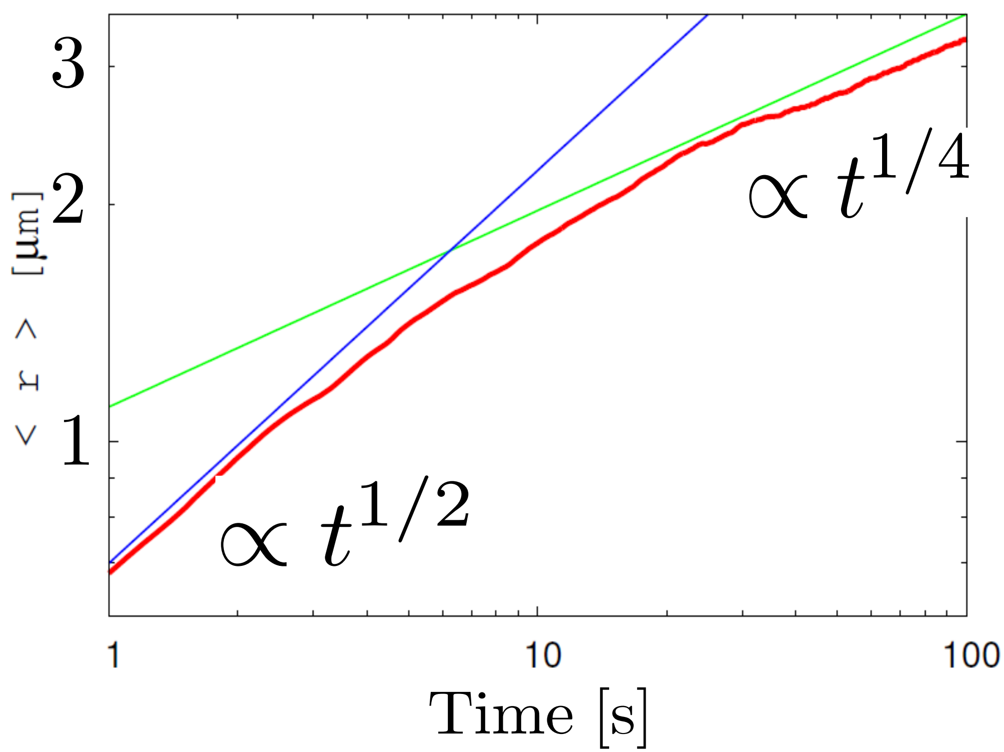
$$\frac{dS}{dt} = -\frac{S}{\tau} + f$$

$$\frac{dx}{dt} = v \qquad (x > 0)$$

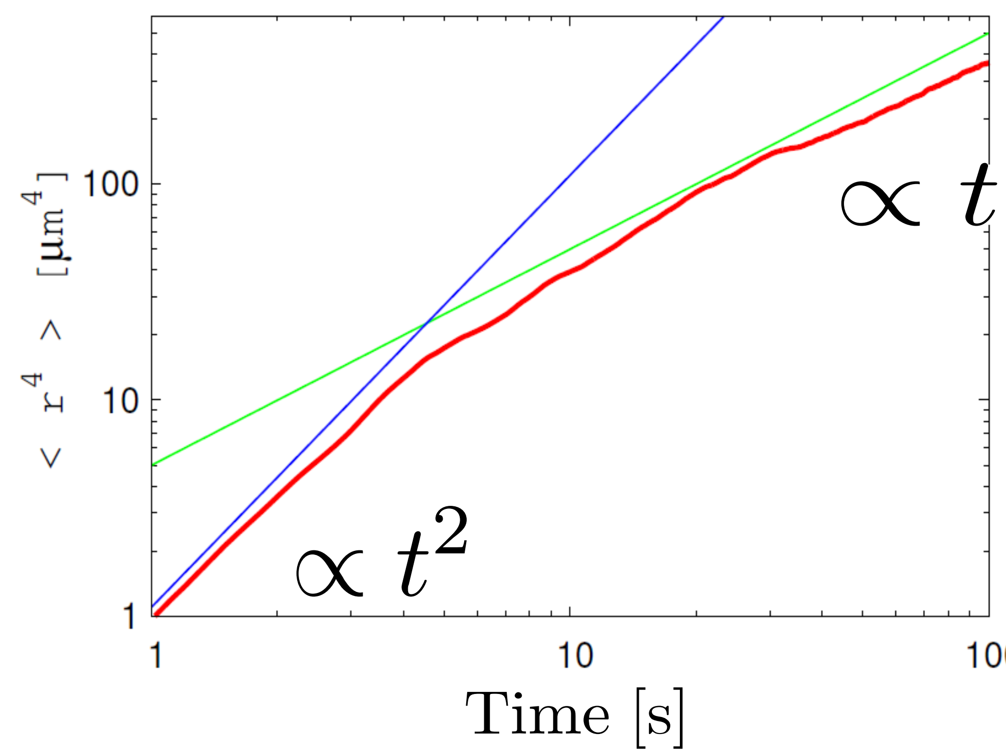
$$\frac{dv}{dt} = -\frac{v}{\tau} + f$$

Droplets	Brownian motion with wall	Scaling
$< r^4 >$	$< x^2 >$	$\sim Dt$ (C16)
$< r >$	$< \sqrt{x} >$	$\sim (Dt)^{1/4}$

$< r >$ (Run1) (Red)



$< r^4 >$ (Run1) (Red)



Summary

- Experimental results by Chandrakar et al (2016) was reproduced well by DNS
- Increase of mean radius due to aerosol effect (= wall effect, Siewert et al, 2017) in experiments with Seq=0 was confirmed
- This mechanism might play important role in C16's chamber experiments, (and possibly in real clouds? where mean Ss is small).

$$(\text{typically } \overline{Ss} \sim 0.1 \ [\%] \text{ in clouds})$$

(Siebert & Shaw, 2017, JAS)