Spray behavior from non-swirling to swirling gas jet in coaxial atomization

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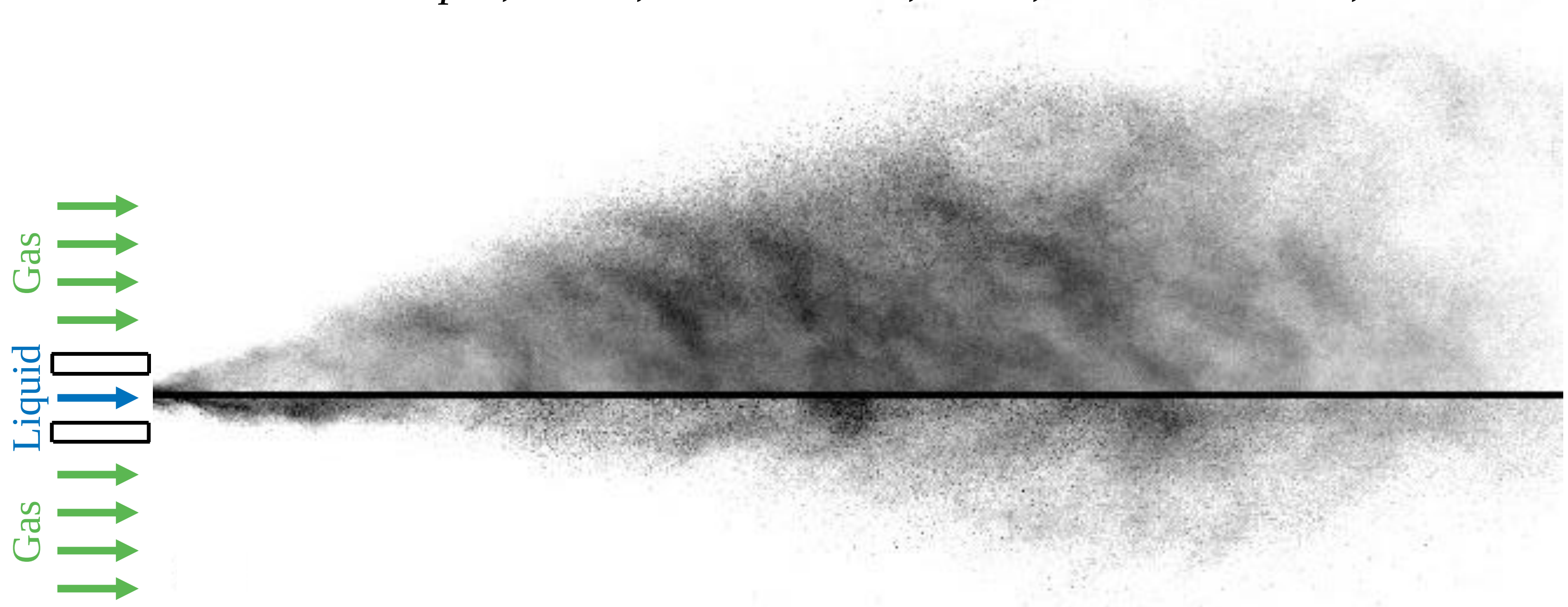
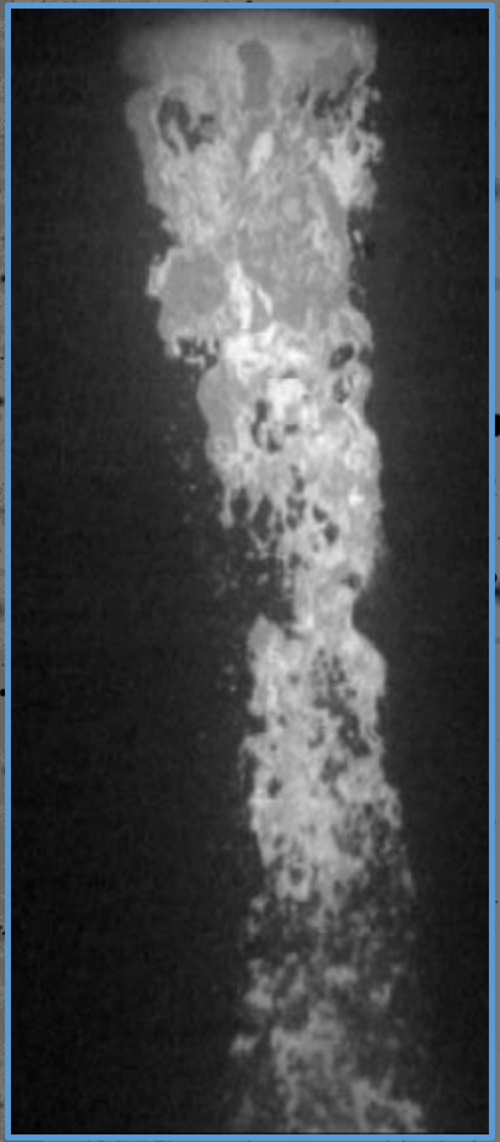


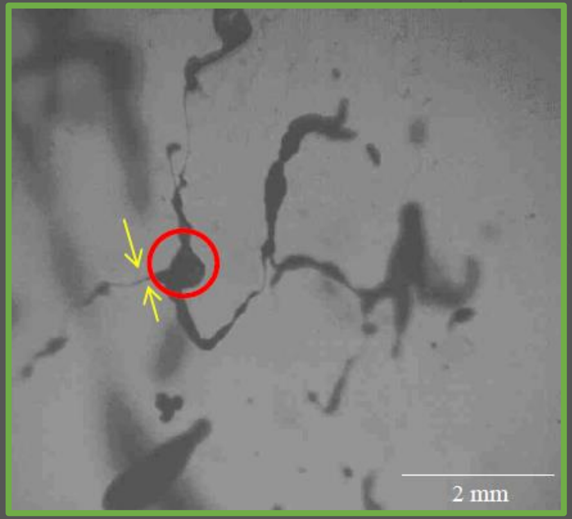
Liquid rocket propulsion

Geiger 2024

Metal powder production



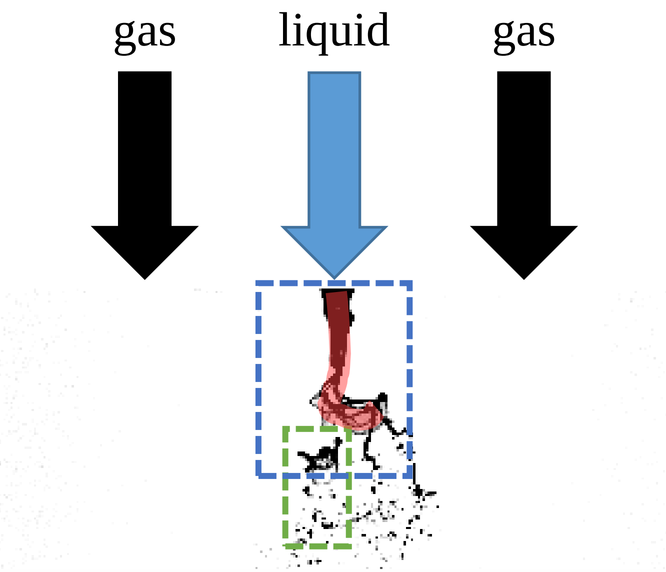
Zerwas et al. 2024



Spray drying

Rozali 2019

Gas-assisted Atomization Phenomena



Near field

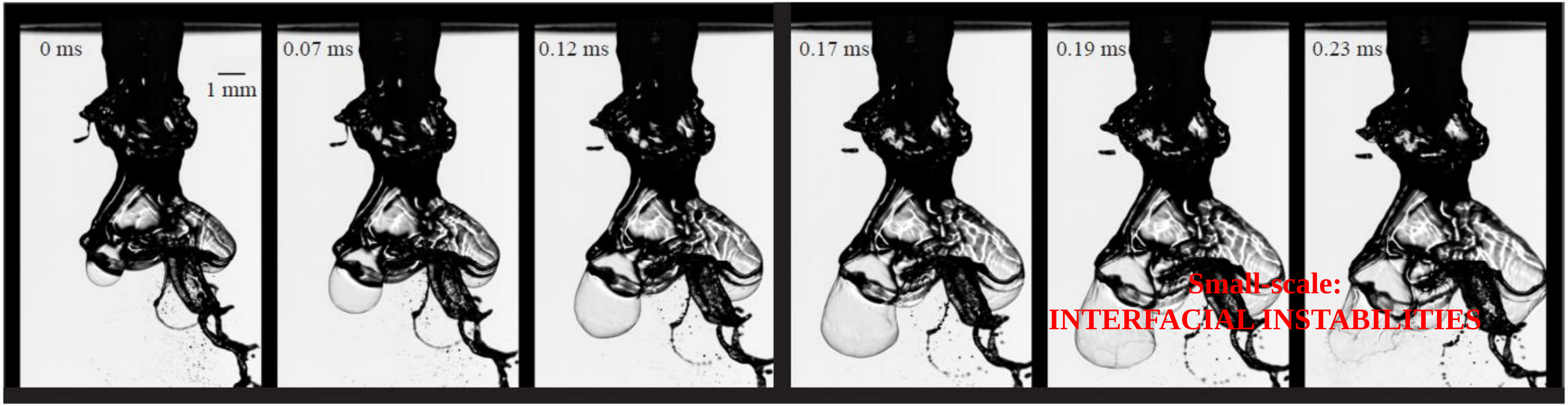
Gas-assisted atomization: breaking of a liquid jet into a spray (droplet cloud) by a gas co-flow

Spray formation:
- Interfacial instabilities
- Primary break-up

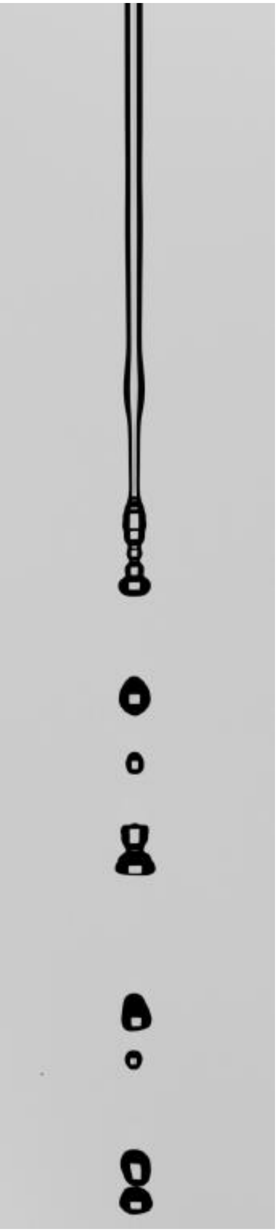
Large-scale: FLAPPING

Farago & Chigier, 1992

Multiscale process



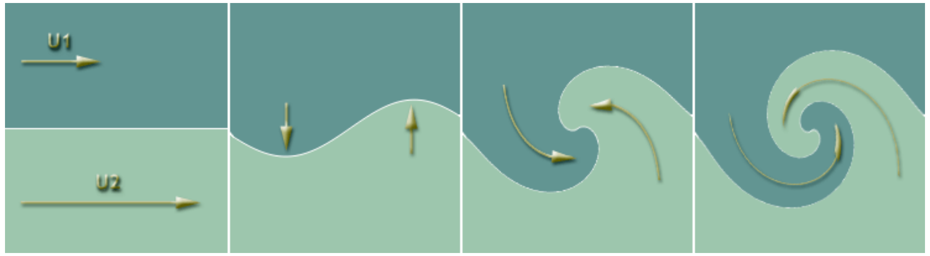
Small-scale: INTERFACIAL INSTABILITIES



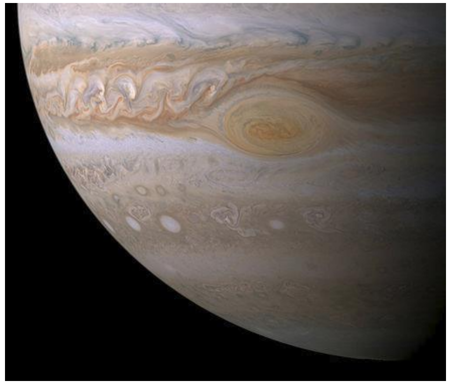
Interface destabilized by surface tension

Rayleigh–Plateau instability

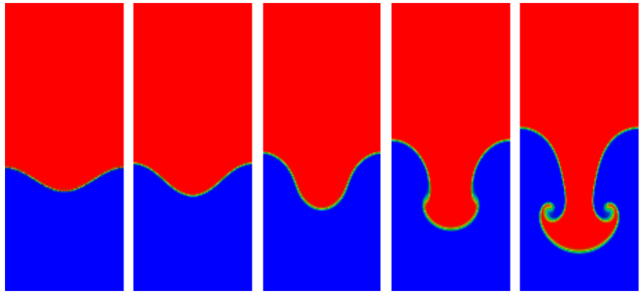
Interface aligned with shear



Kelvin–Helmholtz instability



Accelerated interface (transverse to shear)

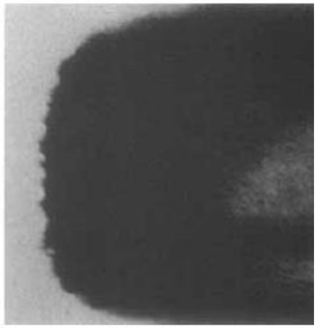


Rayleigh–Taylor instability

Gravity-driven

air

Drop under strong air flow

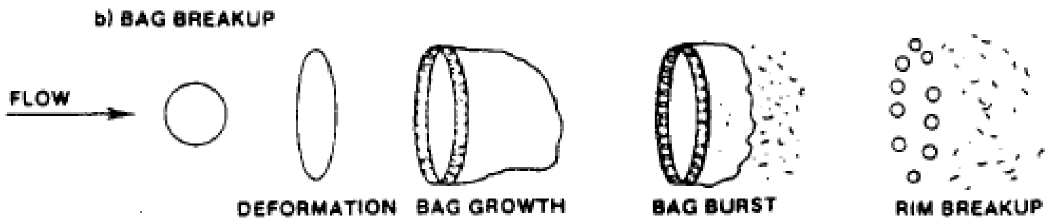


Aero-driven

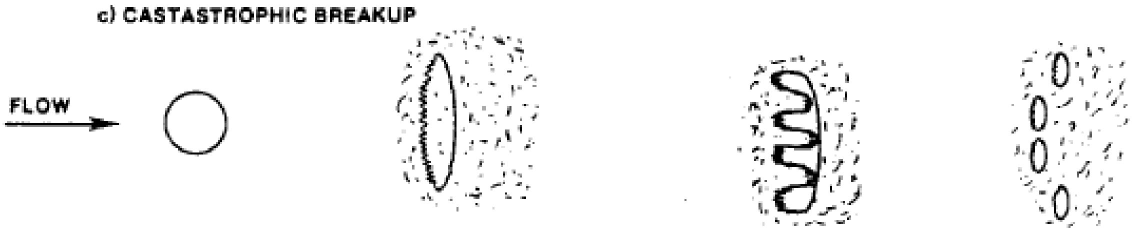
$$We = \frac{\text{gas} - \text{induced stresses}}{\text{surface tension}}$$

$$We = \frac{\rho_g U_g^2 D}{\sigma}$$

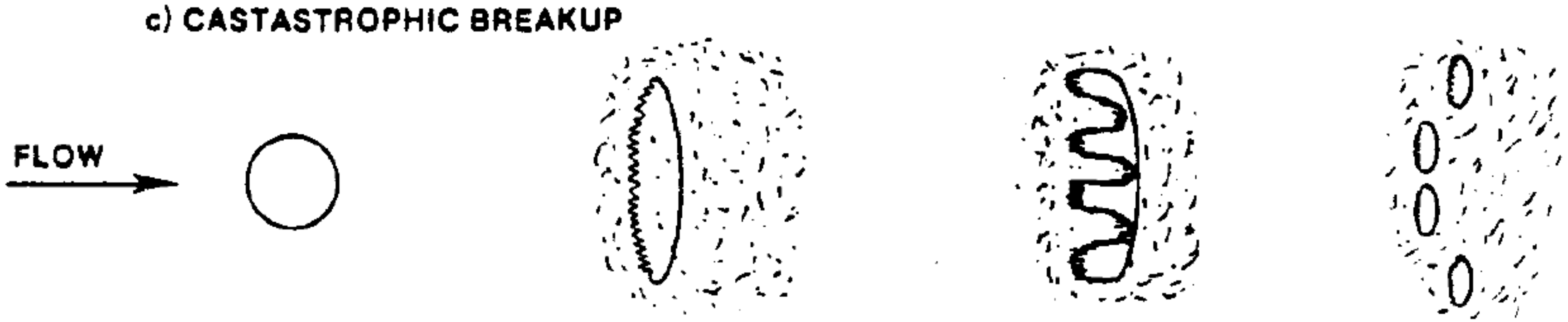
Low to moderate Weber numbers

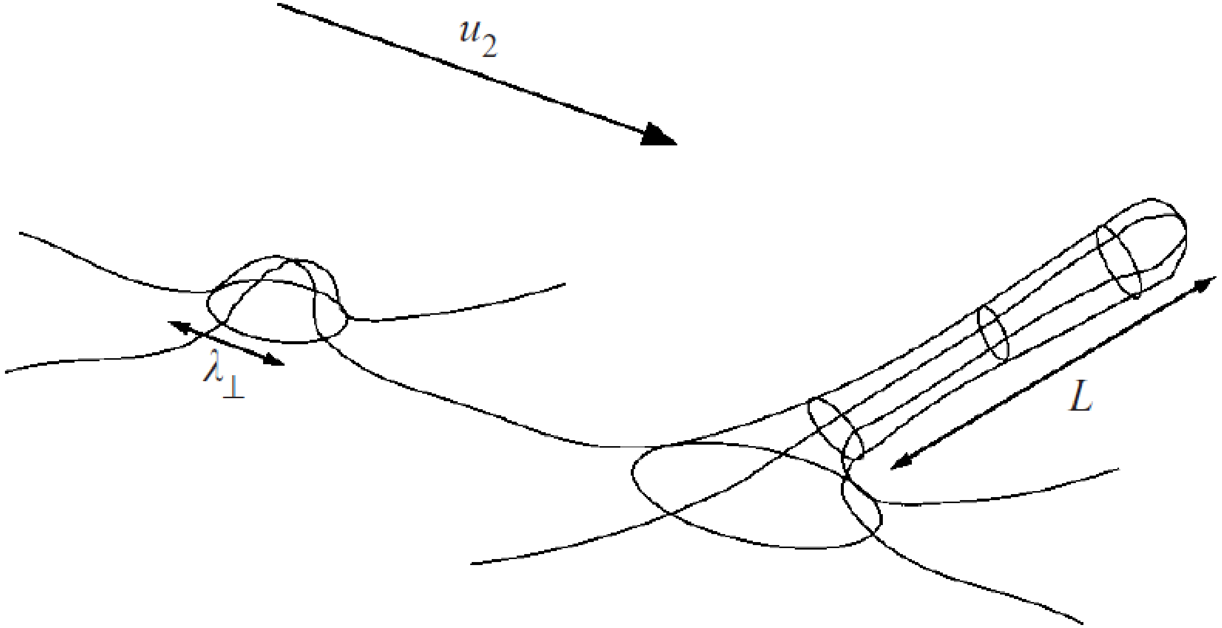


High Weber numbers

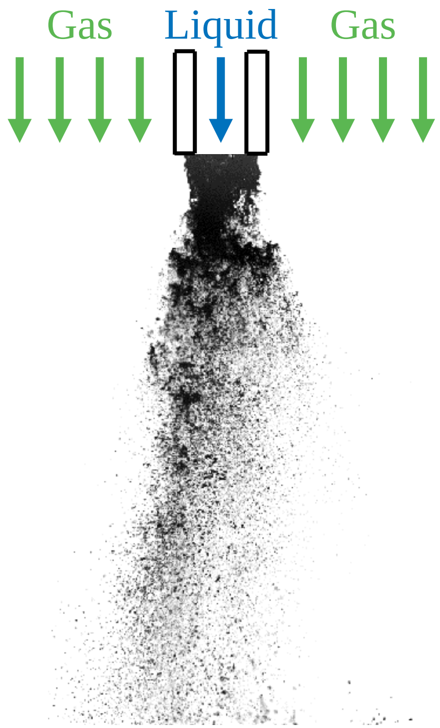


Pilch and Erdman, IJMF 1987

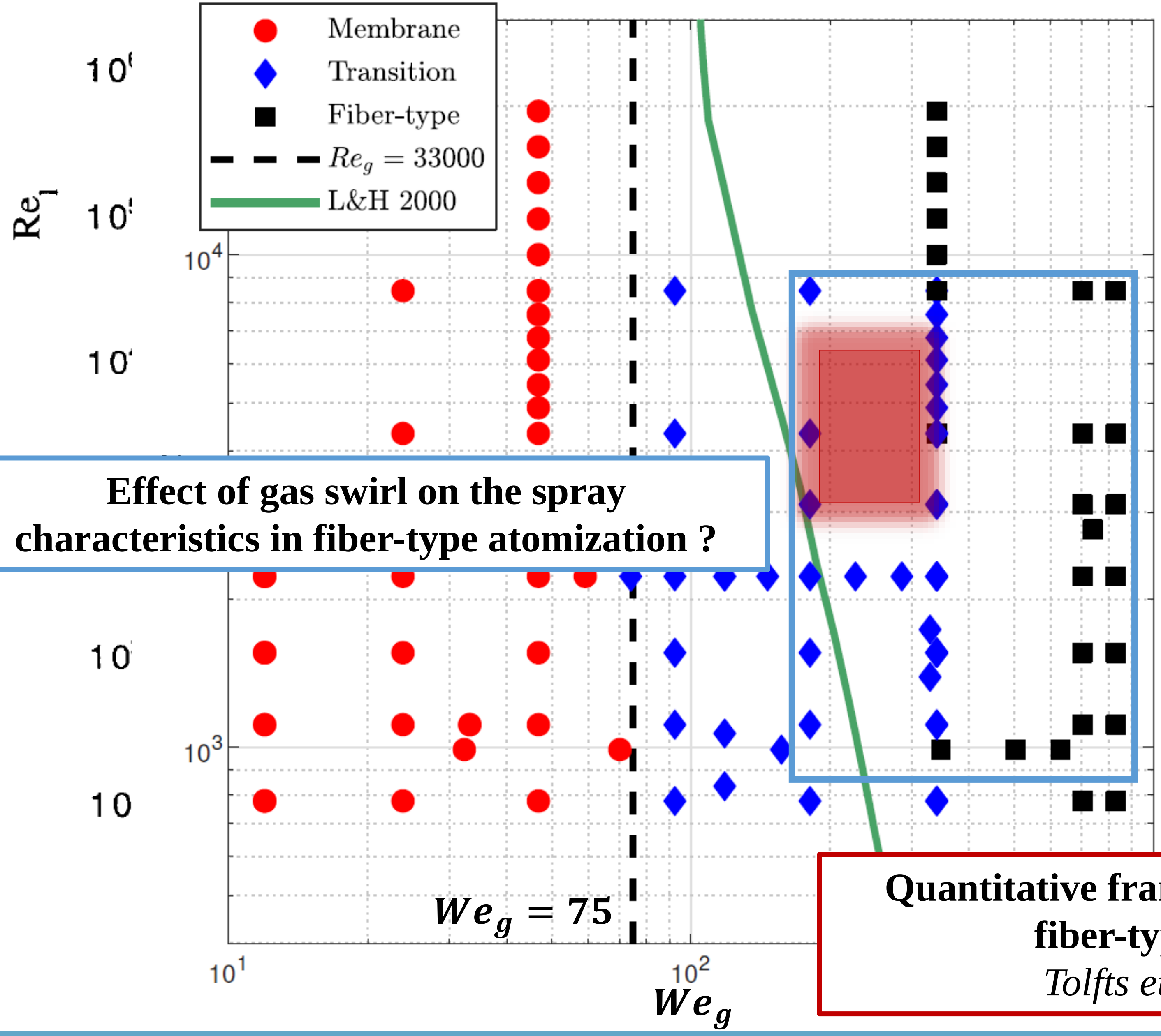




P. Marmottant and E. Villermaux, JFM 2004



Rims produce large drops that contain a large portion of the liquid volume
➔ incomplete combustion/pollutants



Effect of gas swirl on the spray characteristics in fiber-type atomization ?

Quantitative framework for the onset of fiber-type atomization
Tolfts et al., PRF 2023

Experimental set-up

$1100 < Re_l < 8500$

$10^4 < Re_g < 10^5$

By varying the gas and liquid flow rates

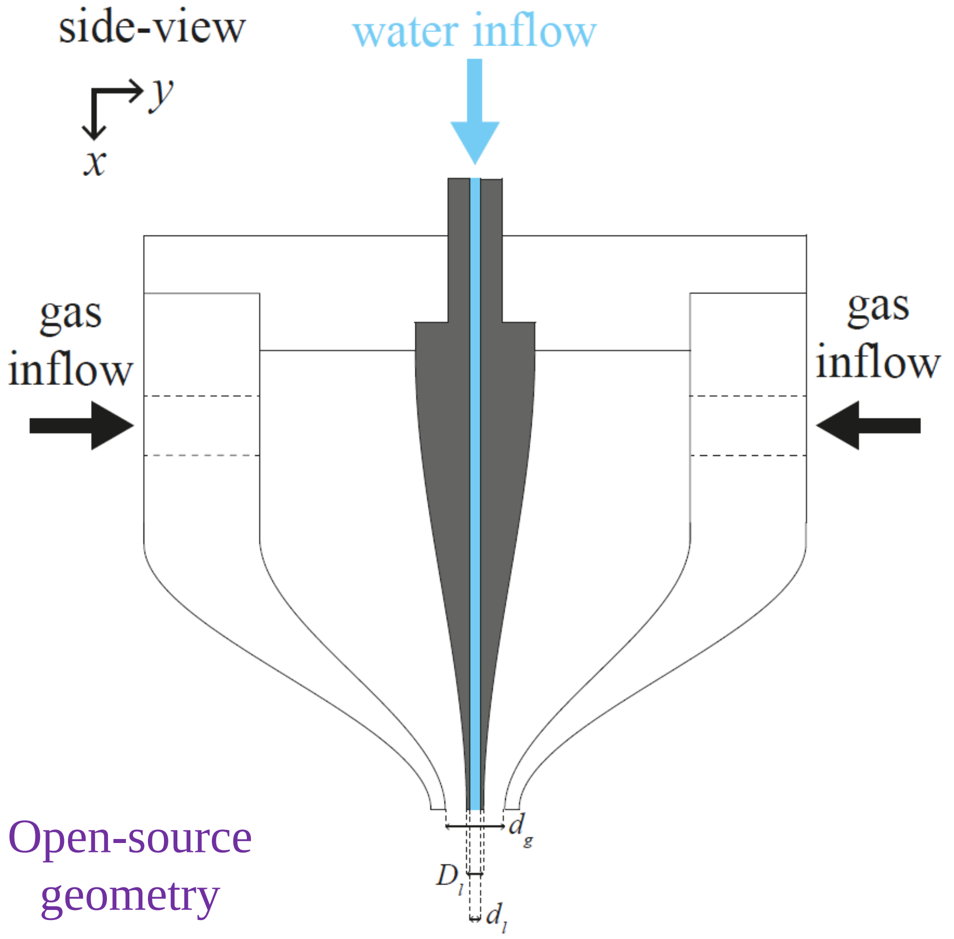
Weber number

$$We_g = \frac{\rho_g {u_g}^2 d_l}{\sigma}$$

Gas-to-liquid dynamic pressure ratio

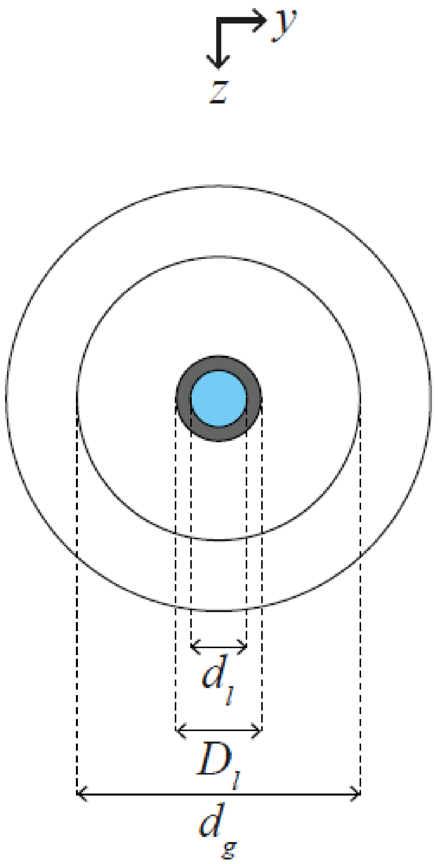
$$M = \frac{\rho_g u_g^2}{\rho_l u_l^2}$$

side-view

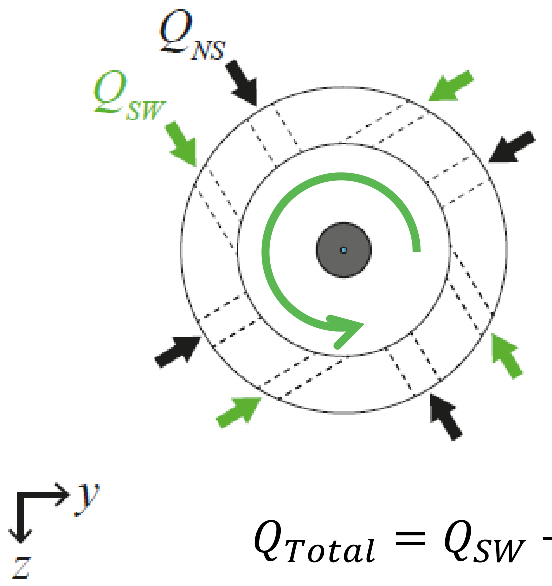


Open-source geometry

exit plane



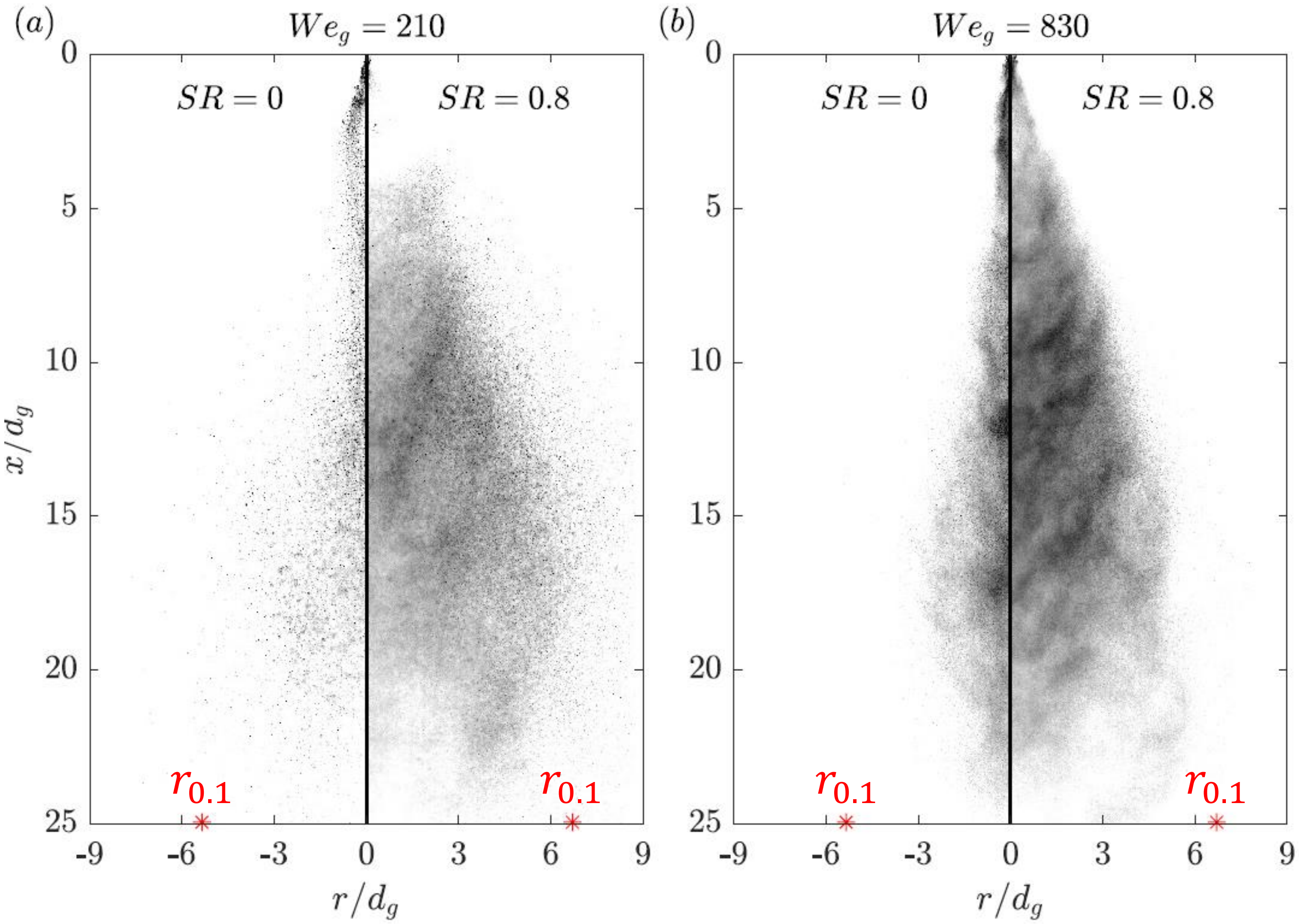
top-view



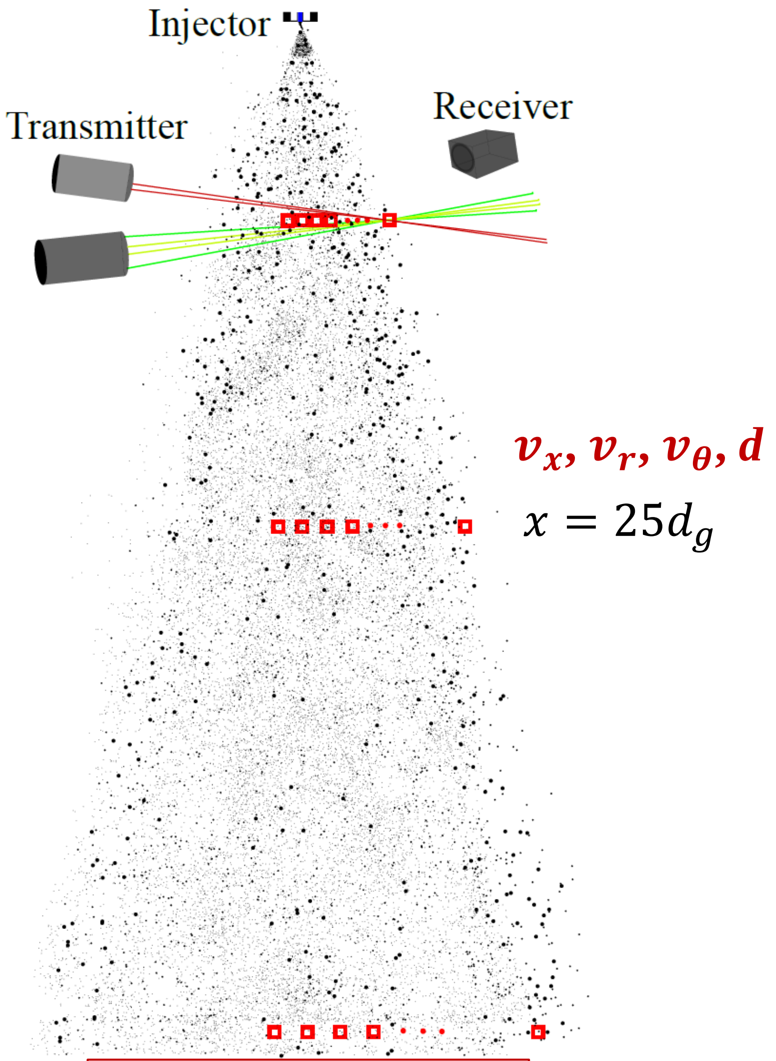
$$Q_{Total} = Q_{SW} + Q_{NS} = cst$$

$$SR = \frac{Q_{swirl}}{Q_{no\ swirl}}$$

Spray characterization



Phase Doppler Interferometry



$1100 \leq Re_l \leq 8500$ $\quad 1 \leq M \leq 140$

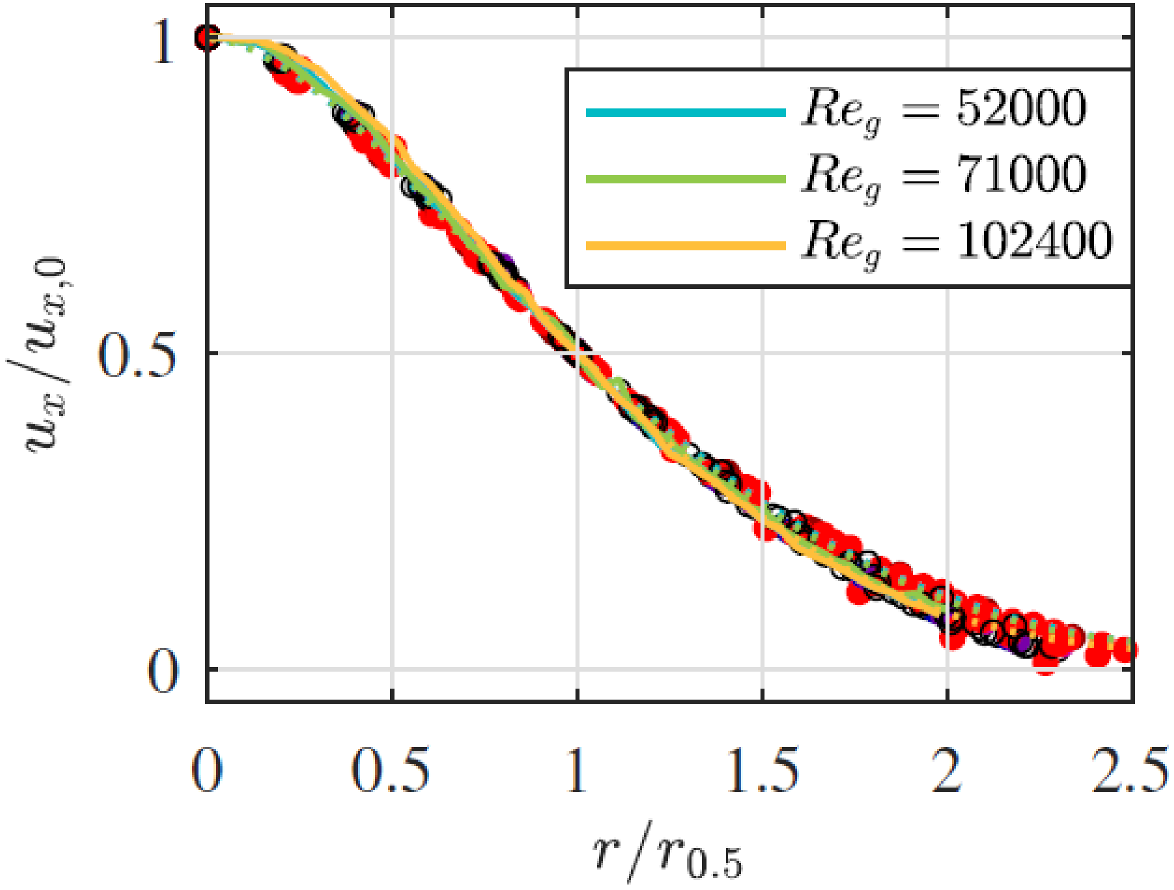
$10^4 \leq Re_g \leq 10^5$ $\quad 200 \leq We_g \leq 1300$

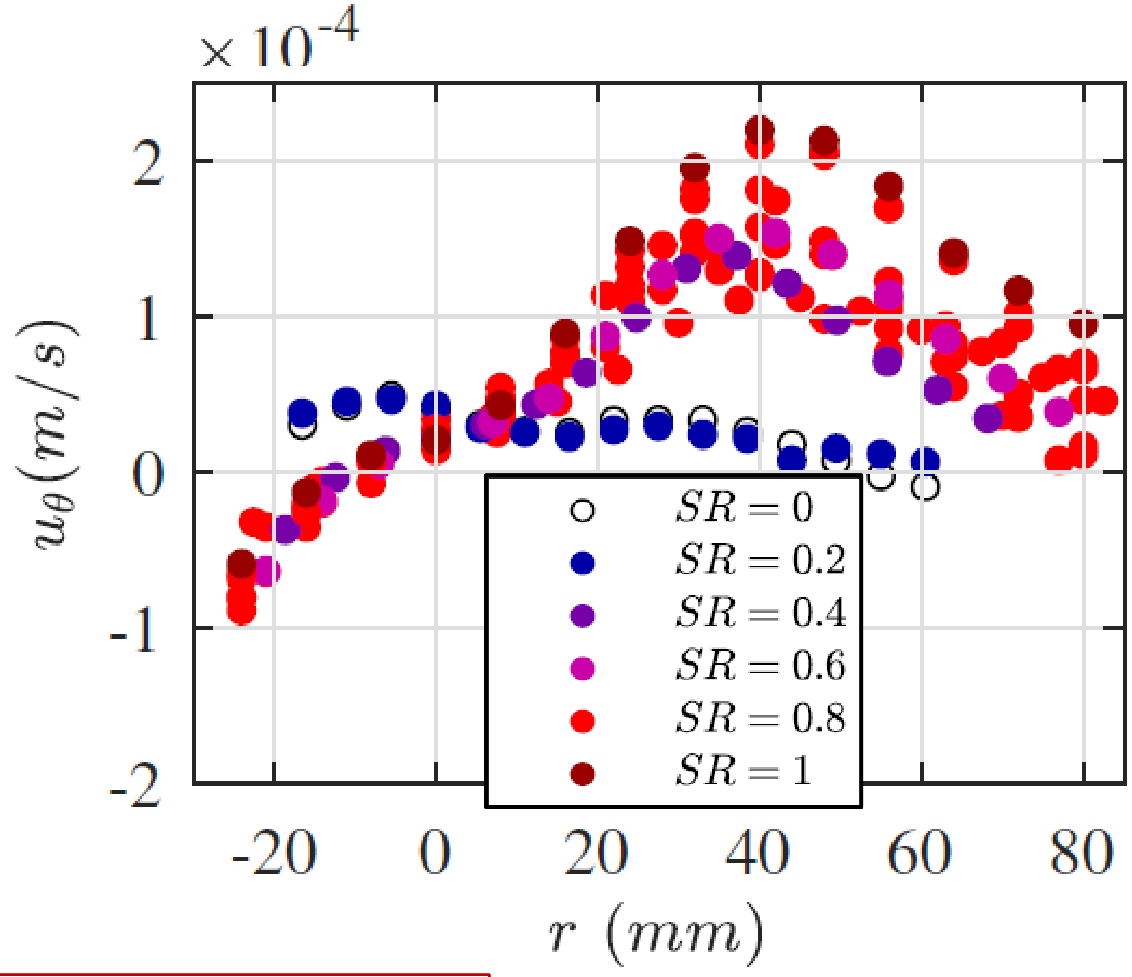
$0 \leq SR \leq 1$

$\mathbf{1 \leq d(\mu m) \leq 100}$

Gas jet radial profiles

$d < 5\ \mu m \rightarrow St_d < 0.002$



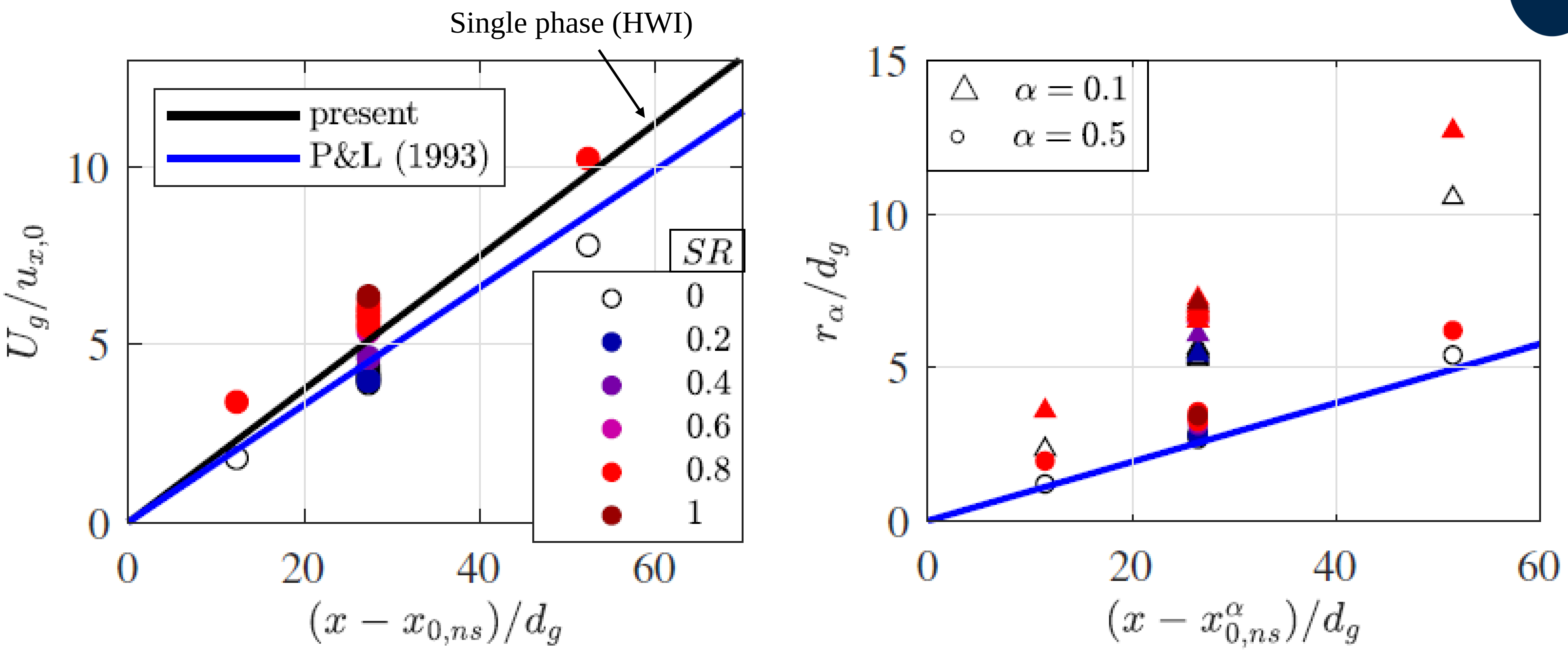


$$St_d = \frac{\tau_p}{d_g/U_g} \qquad \tau_p = \frac{\rho_l d_p^2}{18 \rho_g \nu_g}$$

$$SN = \frac{\int_0^{r_{max}} 2\pi \rho u_x u_\theta r^2 \, \mathrm{d}r}{r_{max} \int_0^{r_{max}} 2\pi \rho u_x^2 r \, \mathrm{d}r}$$

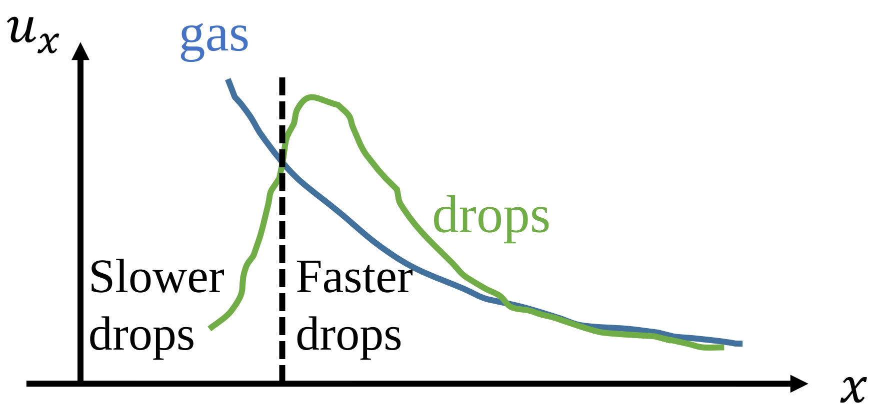
Self-similarity retained with swirl

Axial evolution of the gas jet longitudinal velocity



- Broadening of radial profile with SR
- Properties of the swirled annular jet are those of a round turbulent jet

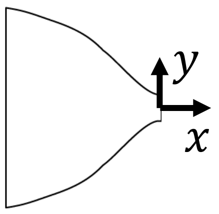
Mean droplet slip velocity



Droplet Stokes number

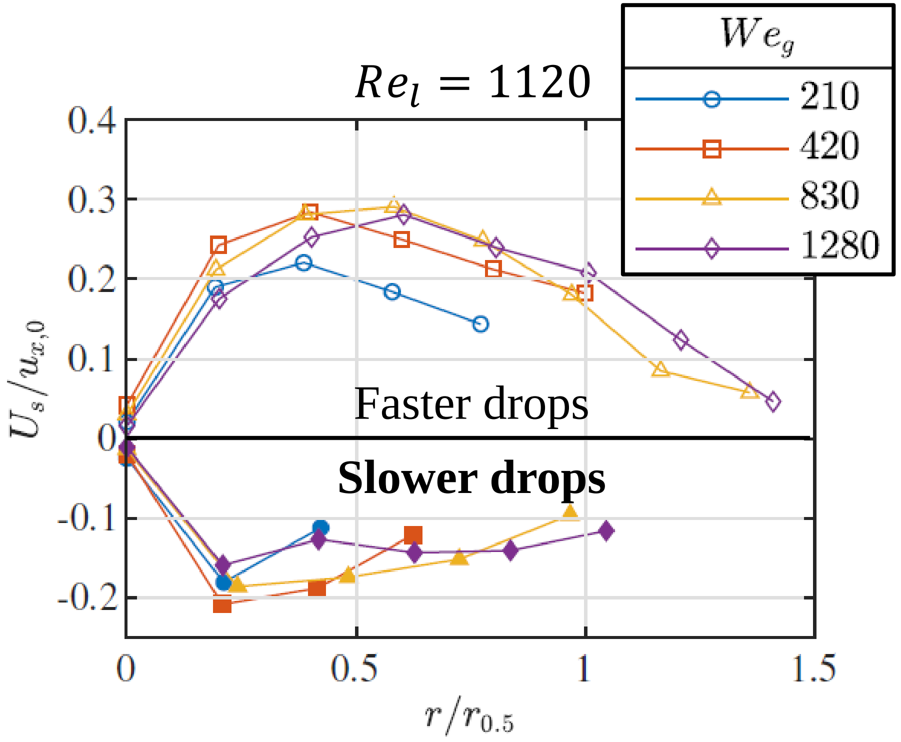
$$St = \frac{\tau_p}{T_E}$$

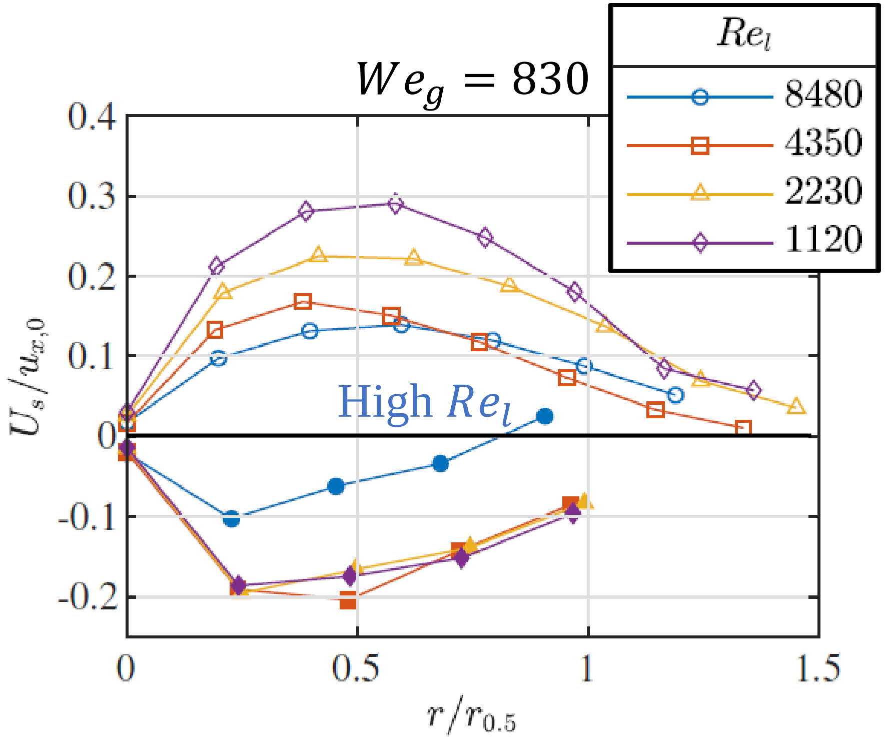
- $\tau_p = \dfrac{\rho_l d_p^2}{18 \rho_g \nu_g}$
- $T_E = \dfrac{u'_x}{r}$



$x = 25 d_g$

$$U_s(r) = \langle v_x^{drop} | St > 0.005 \rangle - \langle u_x^{gas} \rangle$$





○ $SR = 0$ ● $SR = 0.8$

Effect of gas swirl:

- Negative slip velocity overall
- Influence of Re_l is prominent

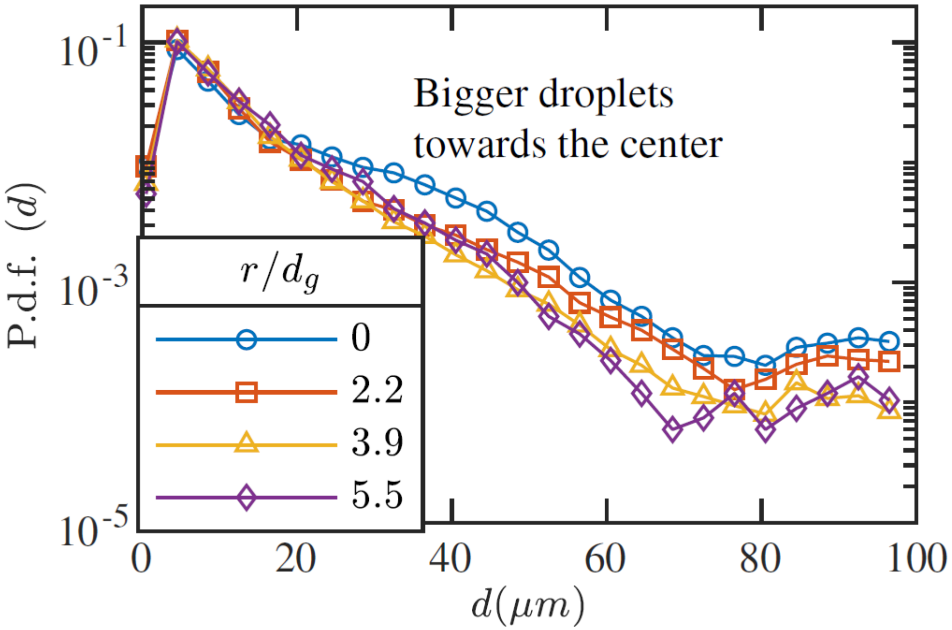
Competing effects:

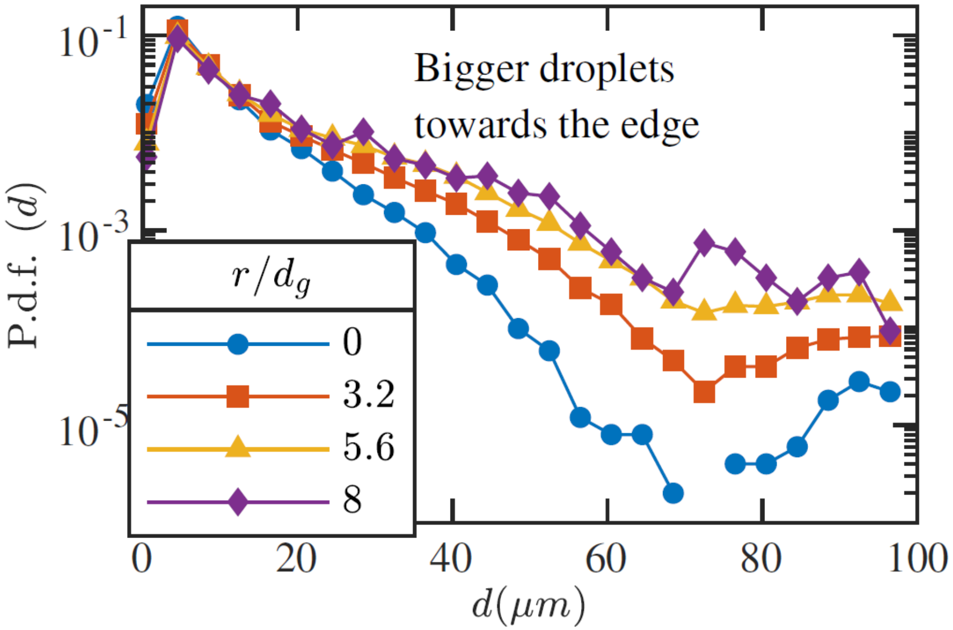
➔ Centrifuged high-momentum drops

➔ Rentrainement of detrained drops (emanating from flapping)

$u_{x.0}$, $r_{0.5}$ centerline axial velocity and half-width of the gas jet

Local droplet size distributions and radial profiles

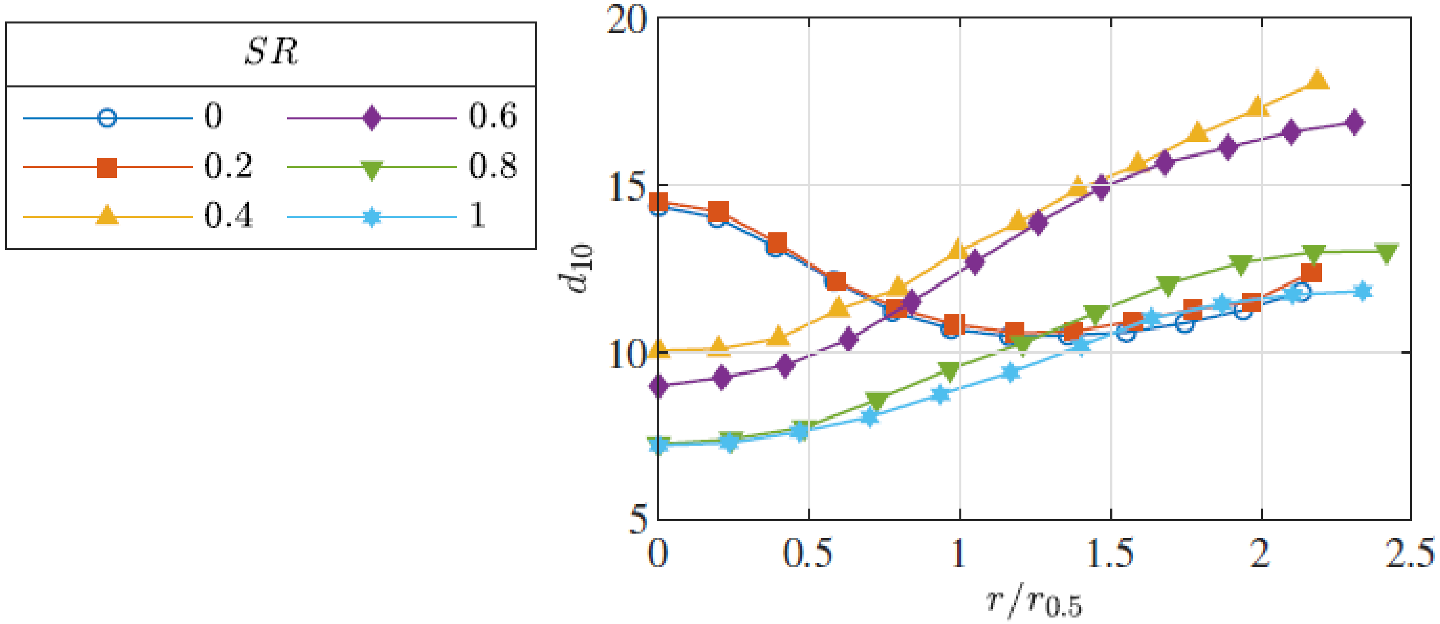




$We_g = 830$
$Re_l = 1120$

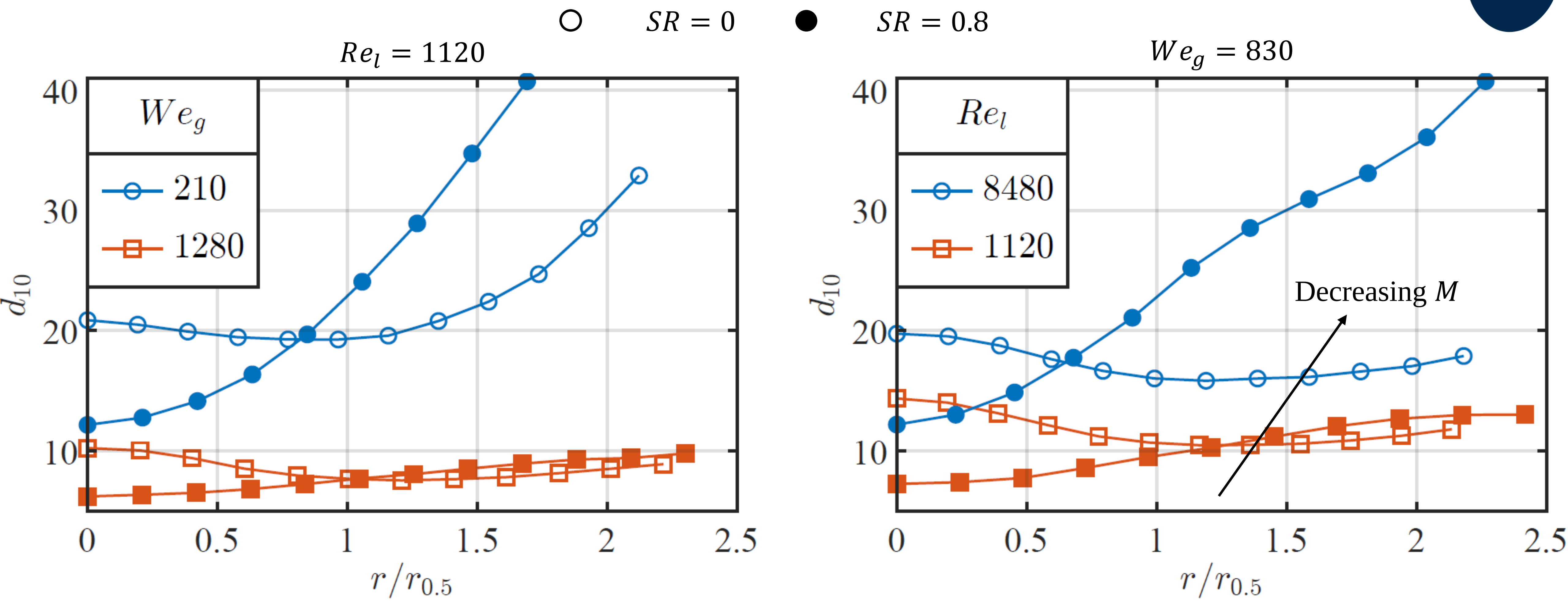
○ $SR = 0$

● $SR = 0.8$



- Swirl leads to rearrangement of the droplets
- Effect of swirl prominent at $SR = 0.4$ and above

Radial profiles of mean droplet size

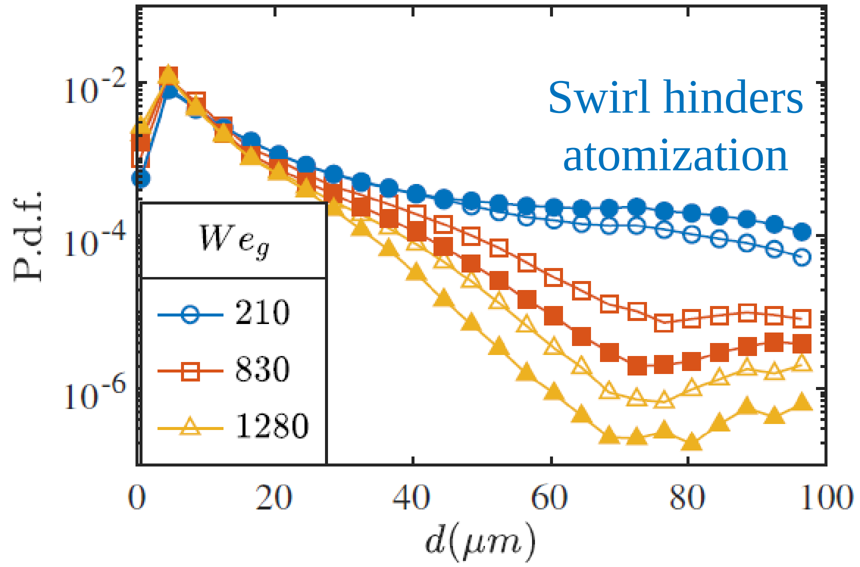


Swirl addition ➔

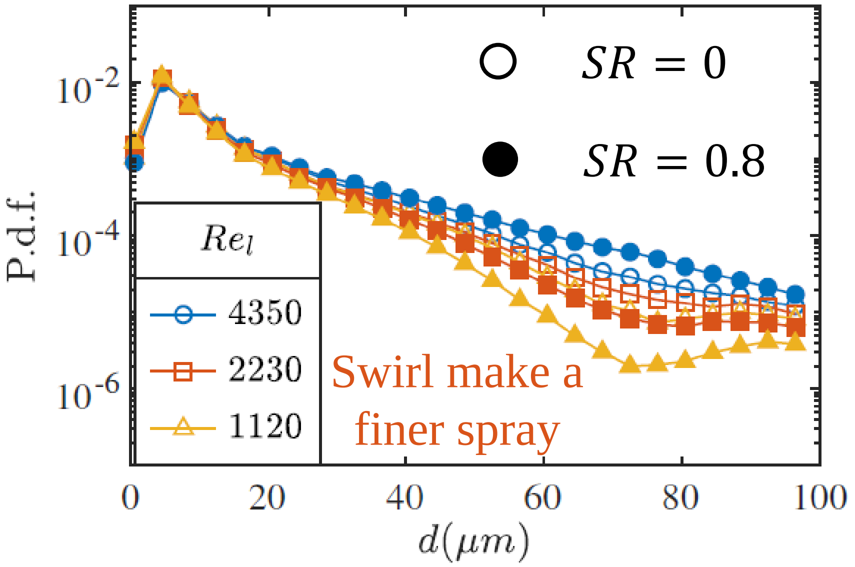
- Spatial rearrangement of the droplet
- Local reduction of mean droplet size at low Re_l and high We_g (high M)

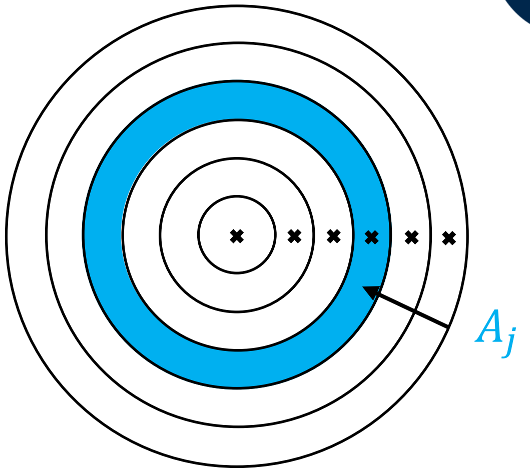
Droplet size statistics – integrated over a transverse plane

$Re_l = 1120$



$We_g = 830$

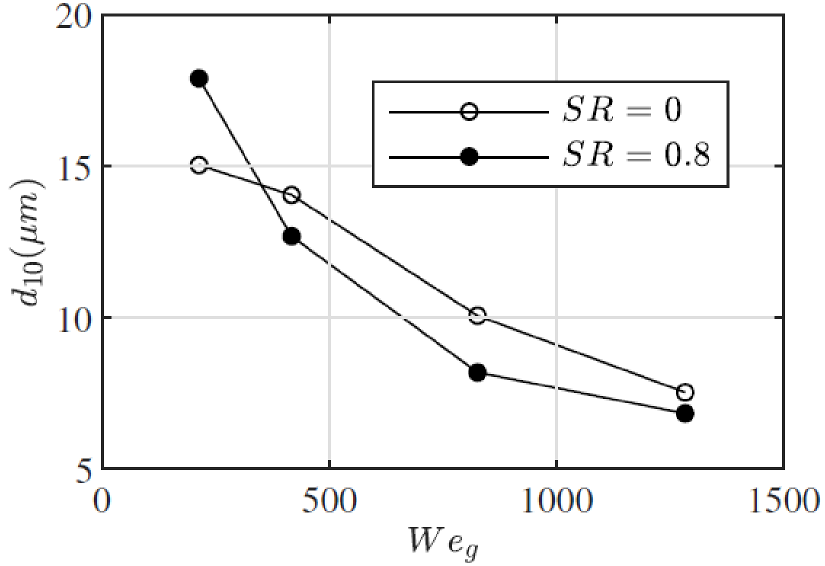


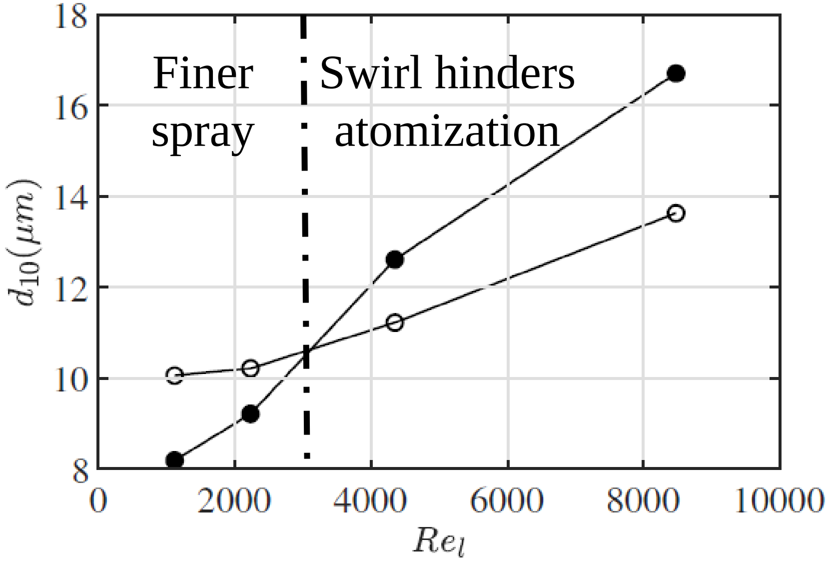


$$p_i = \frac{\sum_j N_{ij} A_j / w_i T_j}{\sum_i \sum_j N_{ij} A_j / w_i T_j}$$

$$d_{nm} = \left(\frac{\sum p_i d_i^n}{\sum p_i d_i^m} \right)^{1/(n-m)}$$

Arithmetic mean diameter





Swirl reduces the drop size beyond $M \left(= \frac{\rho_g U_g^2}{\rho_l U_l^2} \right) \approx 50$

- ➔ All size class
- ➔ Throughout the spray

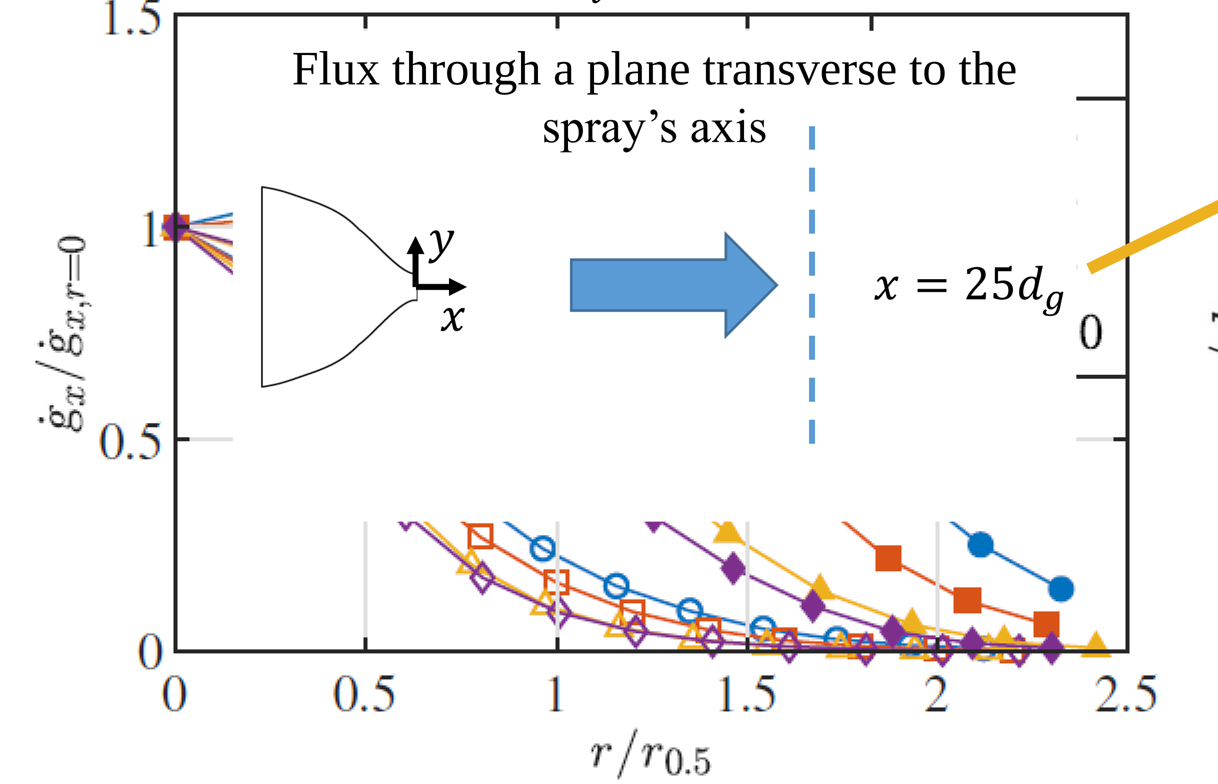
Radial profiles of axial flux

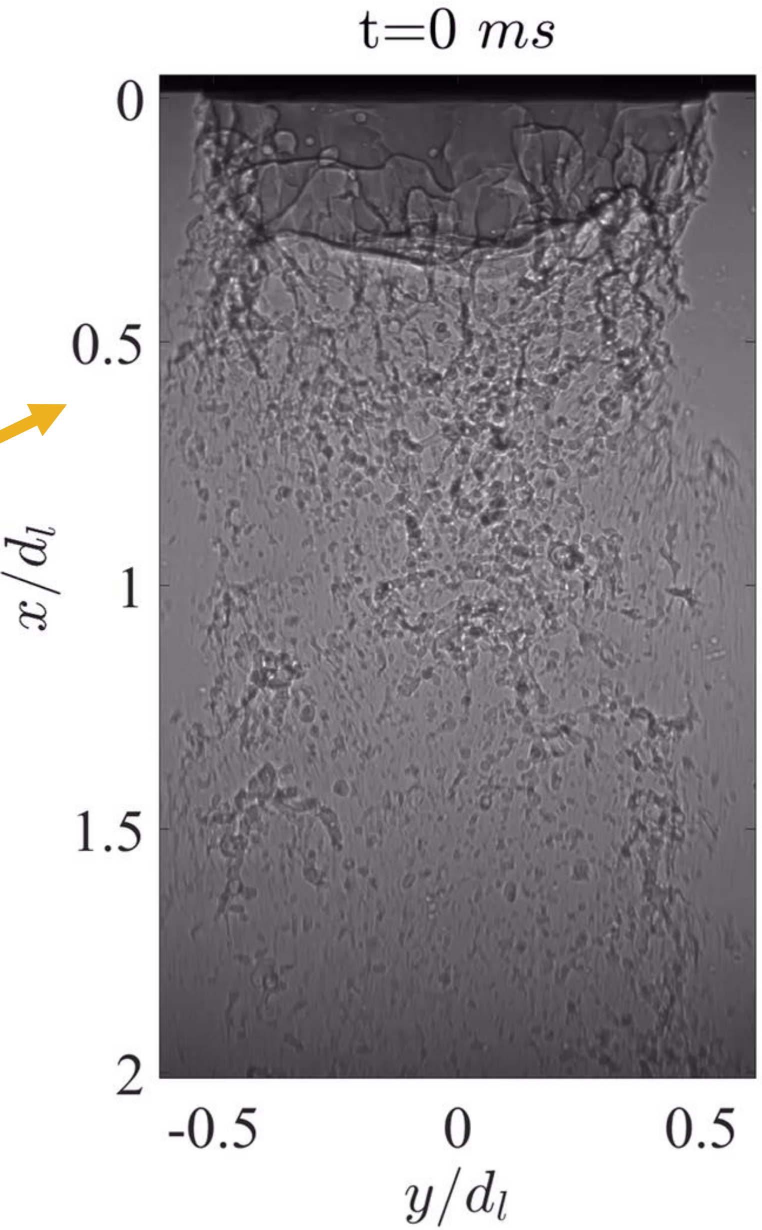
$$\dot{g}_x = \frac{\pi}{6T}\sum_{i=1}^{D}\sum_{j=1}^{N}\frac{d_{j,i}^3 \cos\theta}{S_i}$$

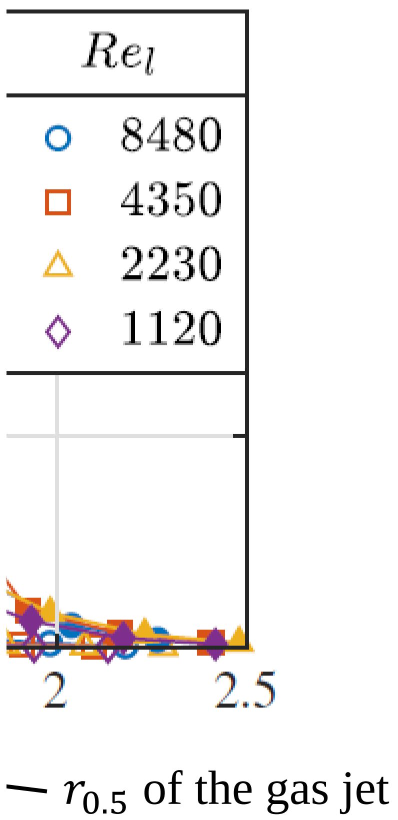
θ velocity angle (u_r
S_i probe volume are
T sampling time

: 0.8 $x = 25d_g$

$Re_l = 1120$







- Swirled low M sprays have off-center maxima of axi
- Axial fluxes show centered maxima for high We_g an

: 0)

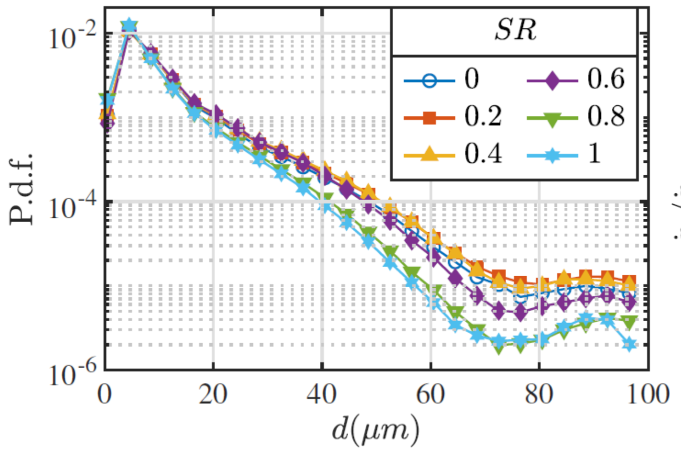
➔ Low M: strong flapping with long liquid jet, brings n

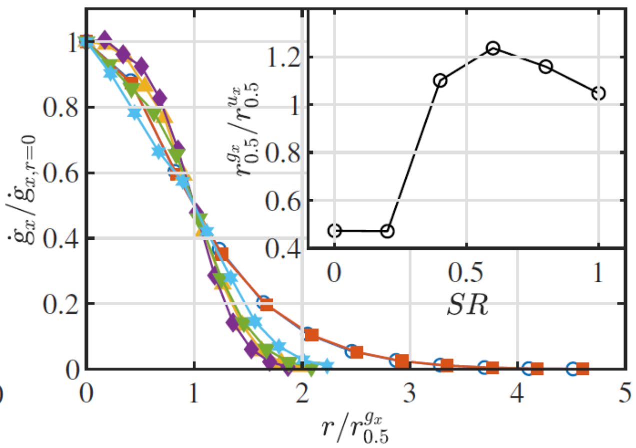
Conclusions & regime map

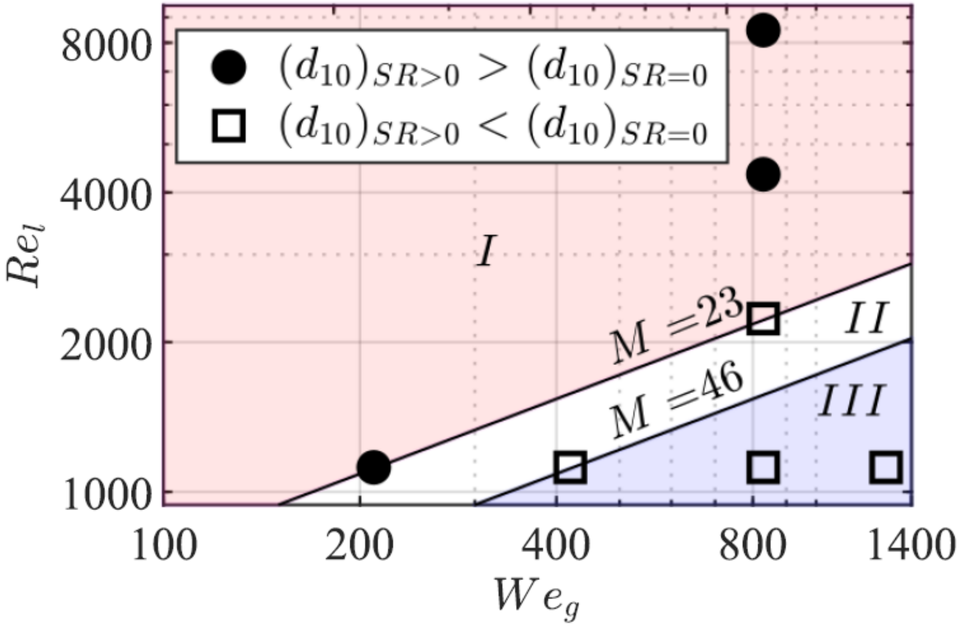
Swirl in the gas flow leads to

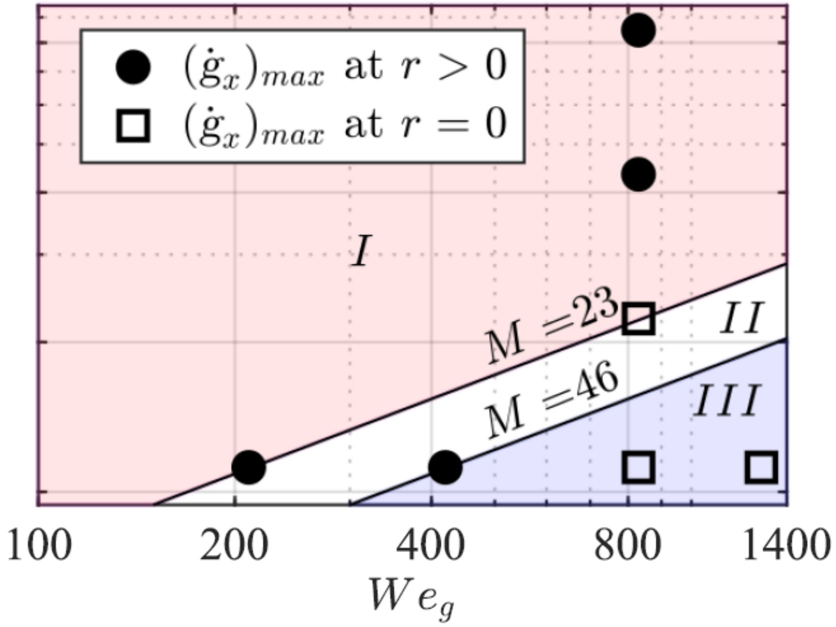
- ➔ Retainment of self-similarity of the gas jet but with different shape factor
- ➔ Prominent effect when $SR \geq 0.6$, with classical broadening of the spray (e. g., $\dot{g}_x$ radial profiles in addition to u_x)
- ➔ For $M > 46$, decrease of drop size everywhere & every size class
- ➔ At low M: swirl hinders atomization
  - Larger drops
  - Off-center maxima for the radial profiles of axial flux
- ➔ $23 \leq M \leq 46$, spray features depend on both Re_l and We_g

$Re_l = 1120, We_g = 830$



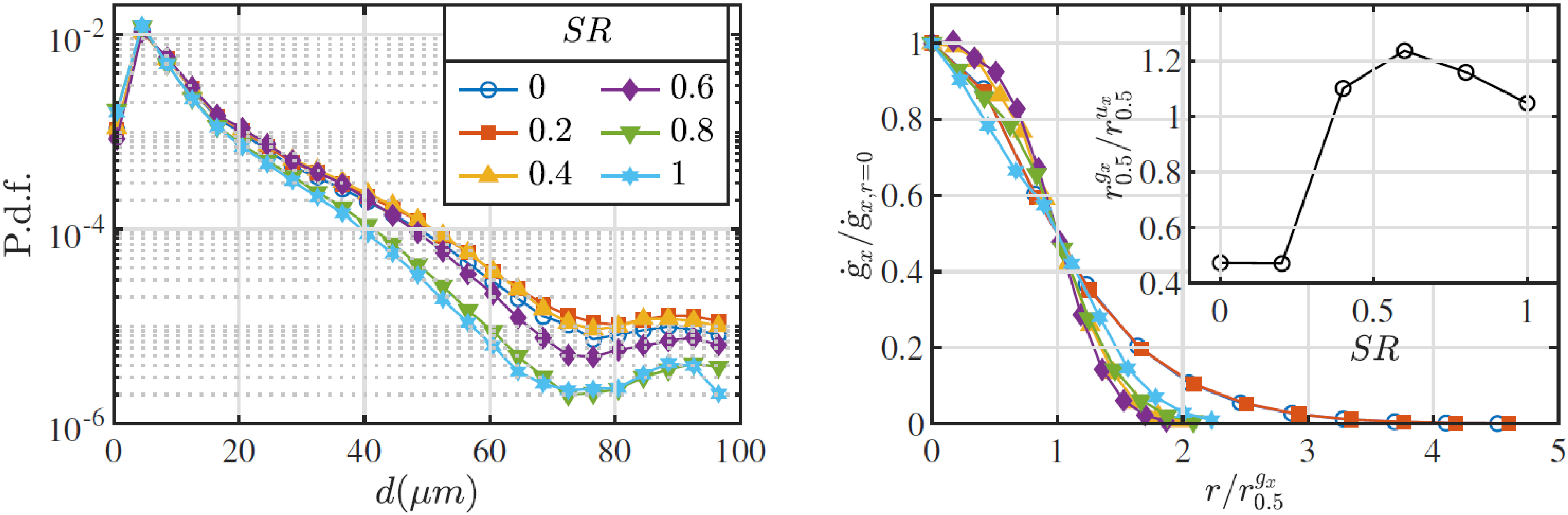




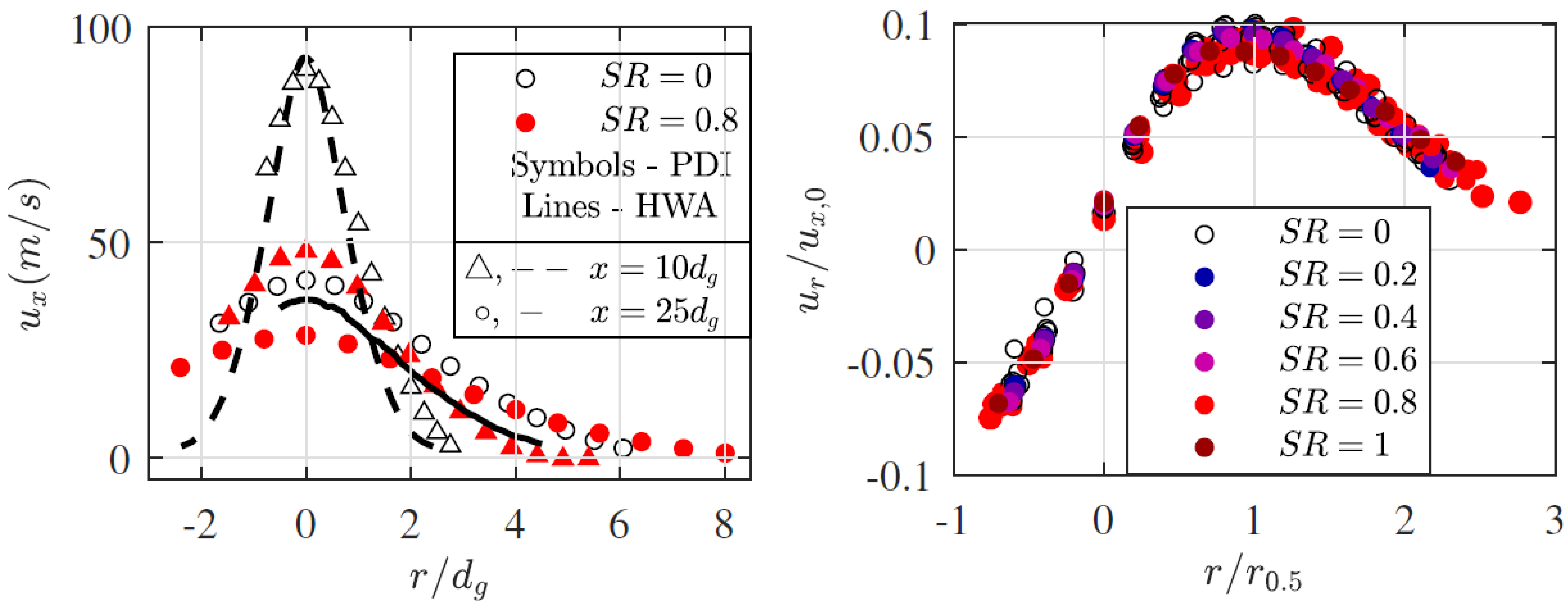


Thank you for your attention

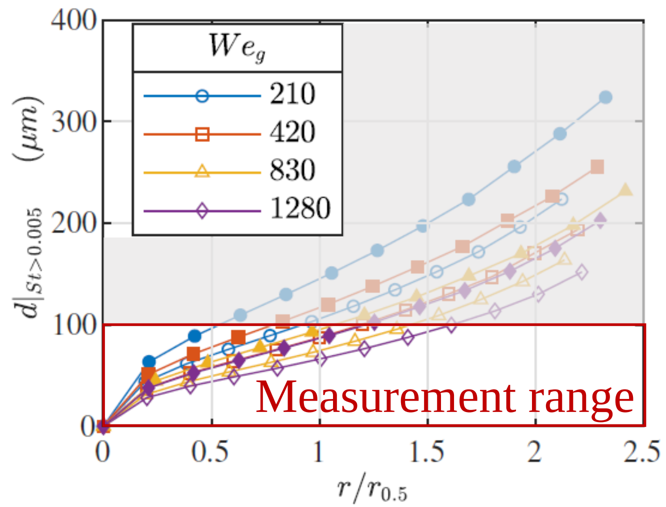
Gradual change of swirl ratio

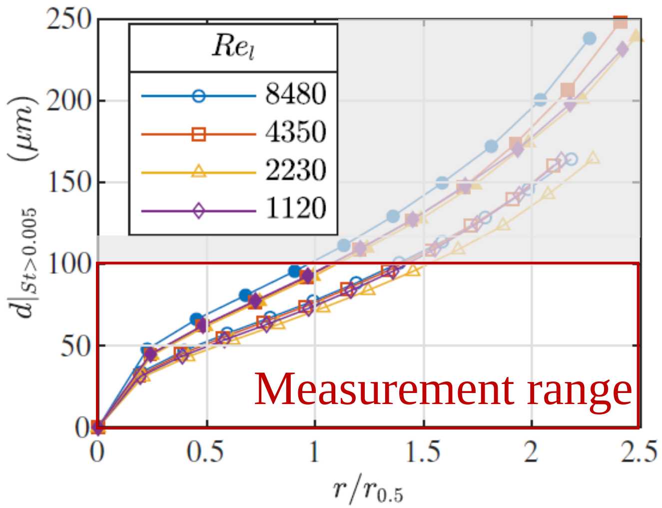


Radial profiles of mean axial and radial velocity



Mean droplet slip velocity

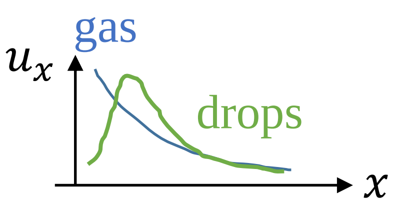




$r_{0.5}$ of the gas jet

○ $SR = 0$

● $SR > 0$



Droplet Stokes number

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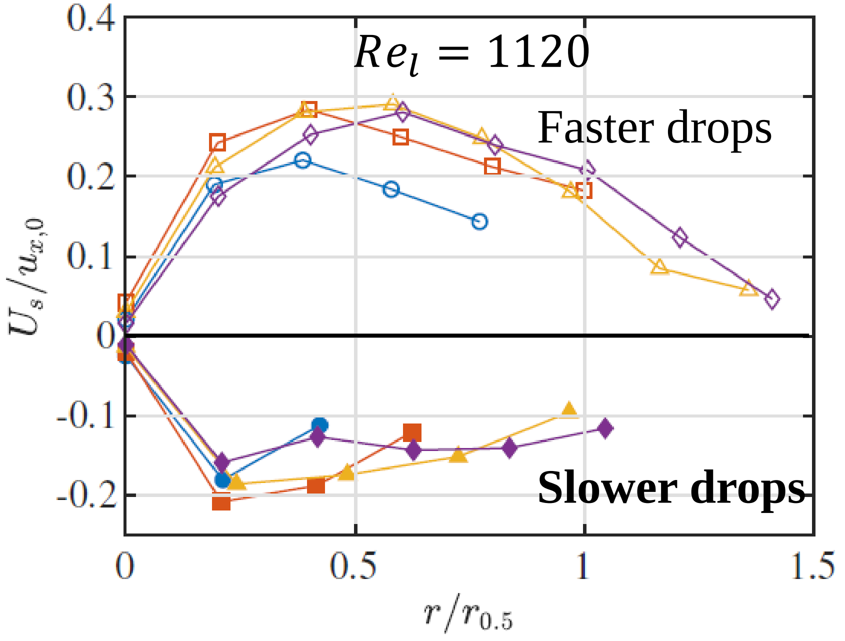
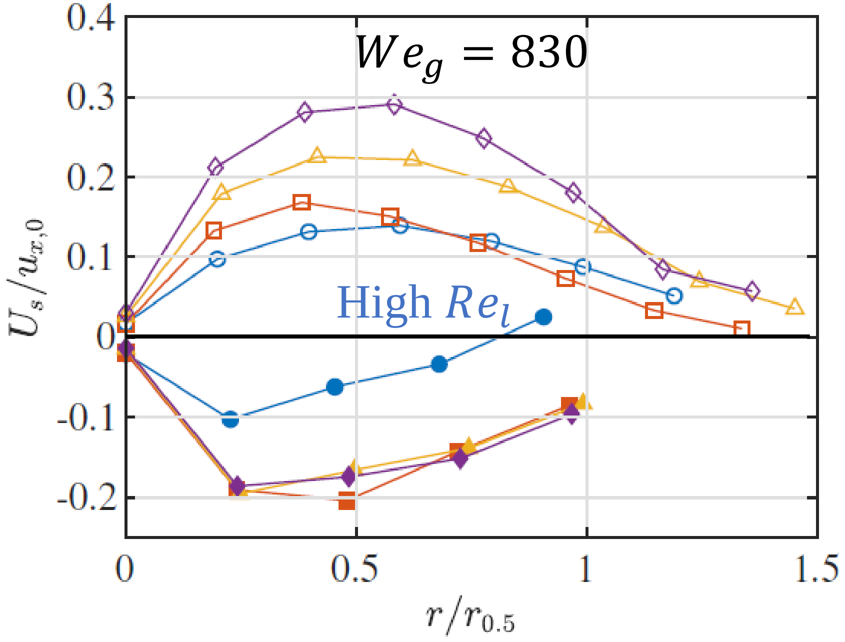
$$U_s(r) = \langle v_x^{drop} | St > 0.005 \rangle - \langle u_x^{gas} \rangle$$





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