2nd European Fluid Dynamics Conference, August 27th, 2025, Dublin
Session 6, Biological/Biomedical Fluid Mechanics

Flow in a 23-generation model of human airways: laminar but not steady!

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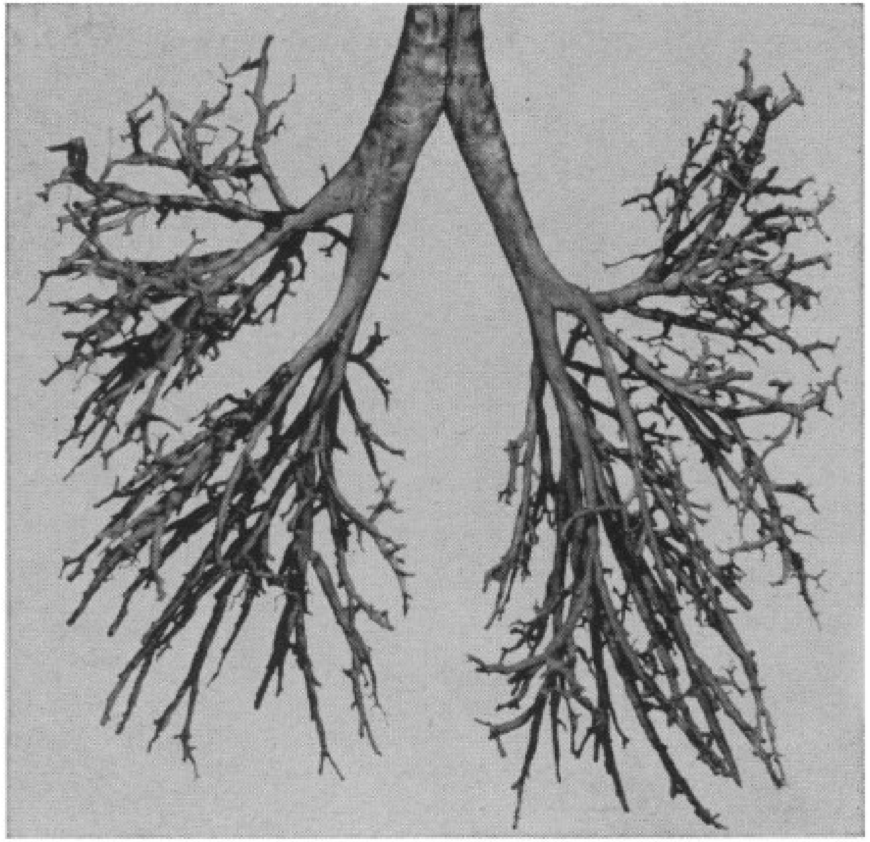
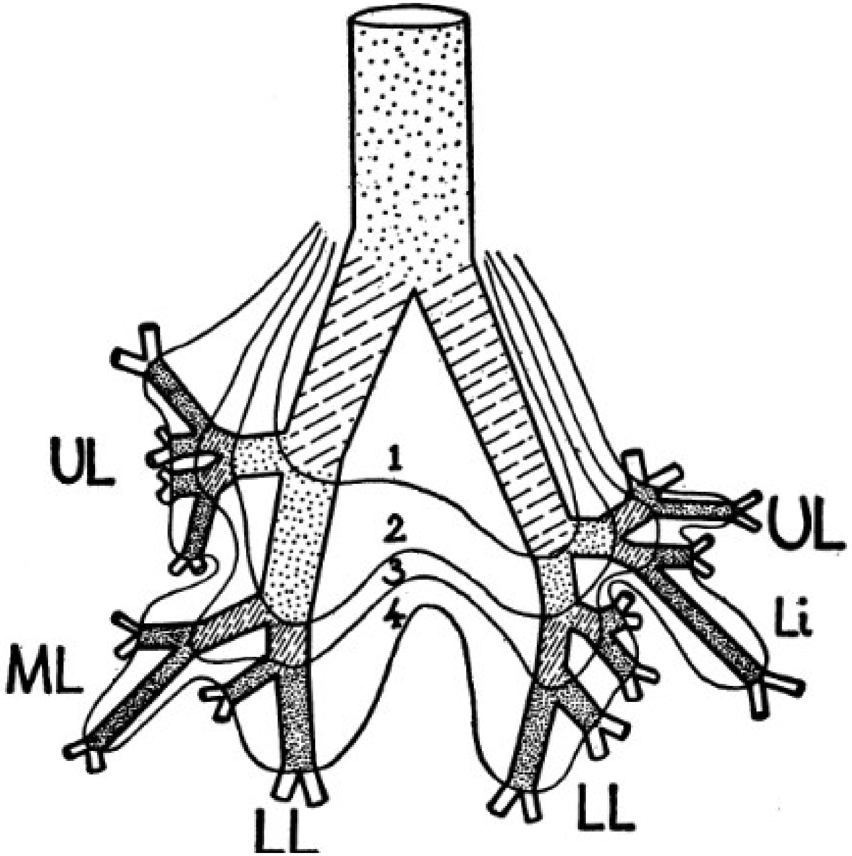
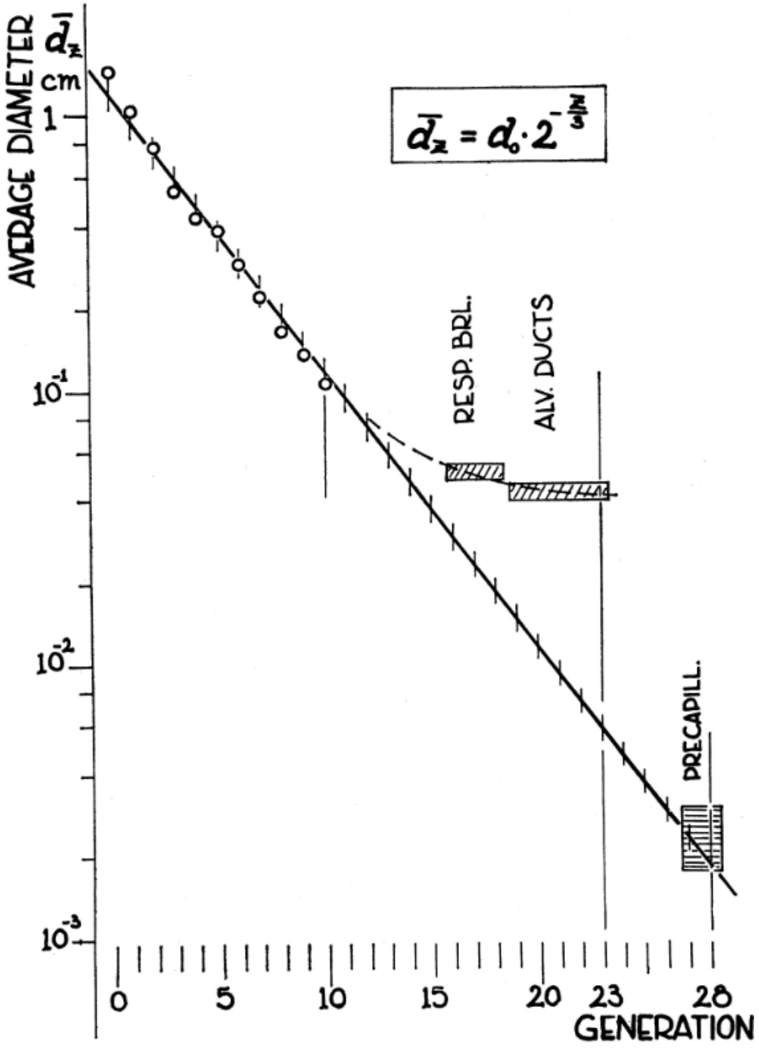
What are we talking about?







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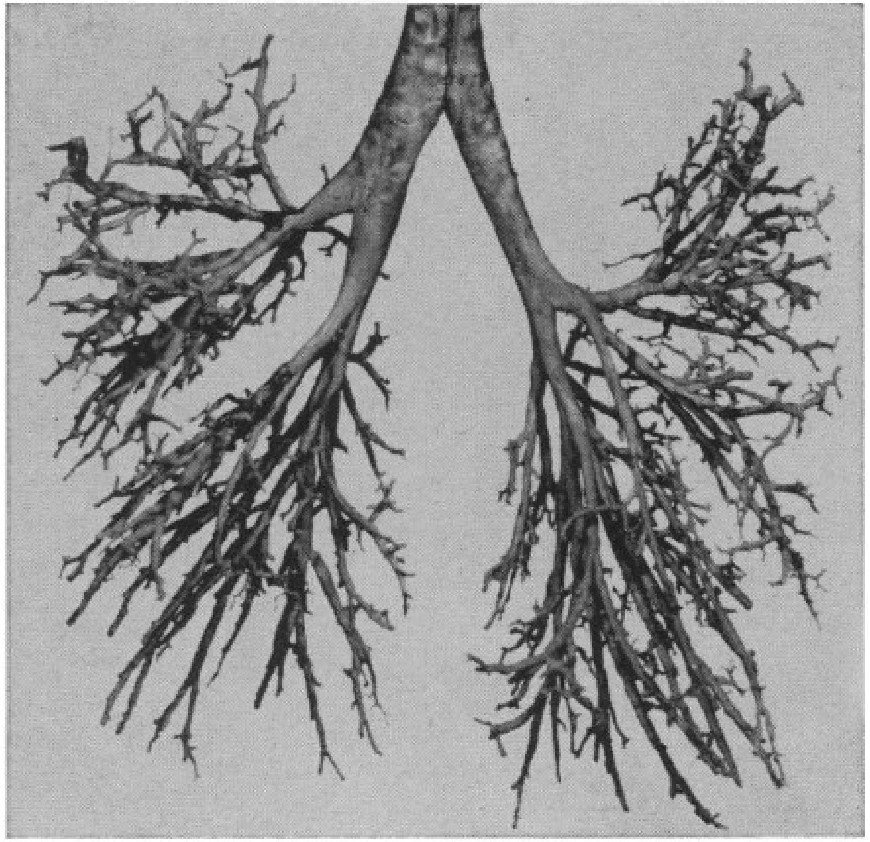
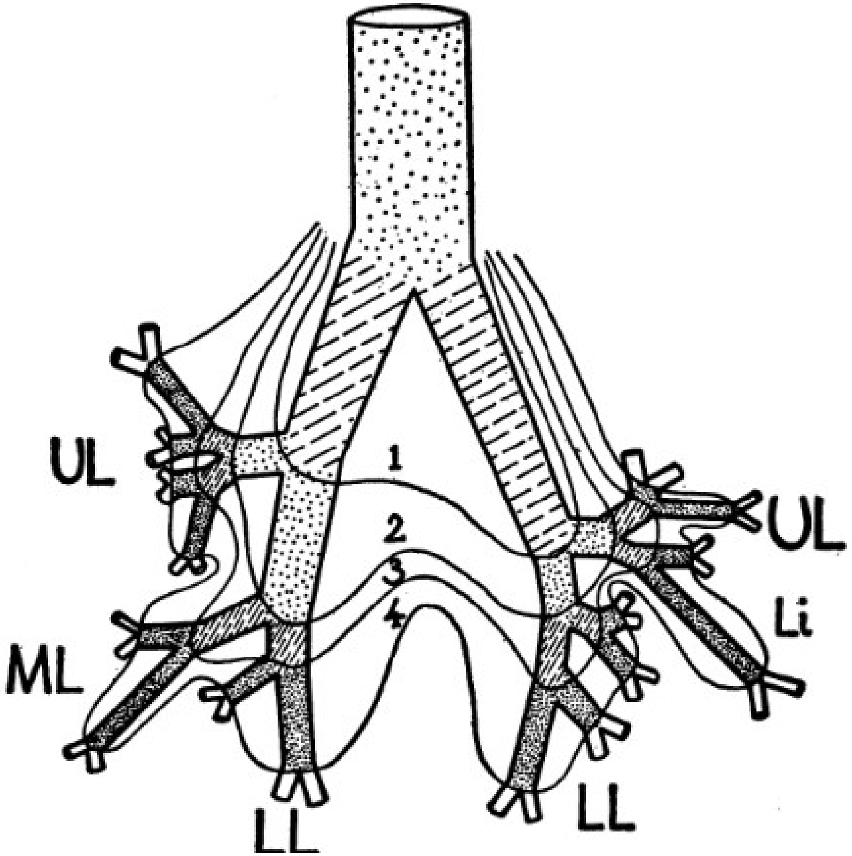
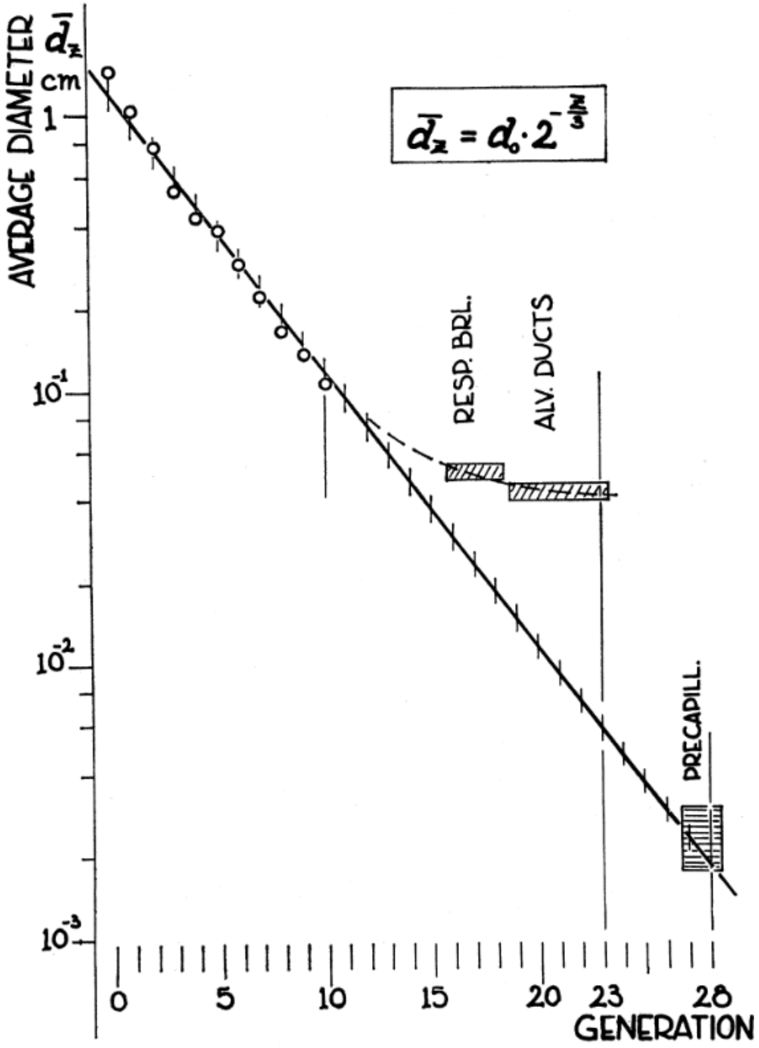


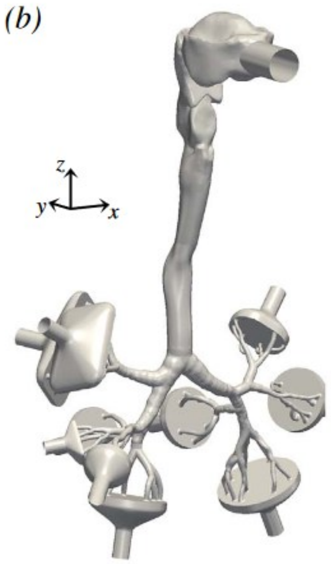




But difficult to describe in-vivo tissue at very low scales!

Weibel and Gomez, "Architecture of the Human Lung: Use of quantitative methods..." *Science* **137**, 577—585 (1962)

How do we study it now?



LES & experiments
(often with constant flow rates)

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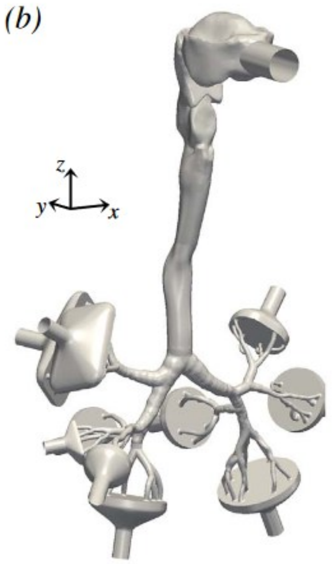

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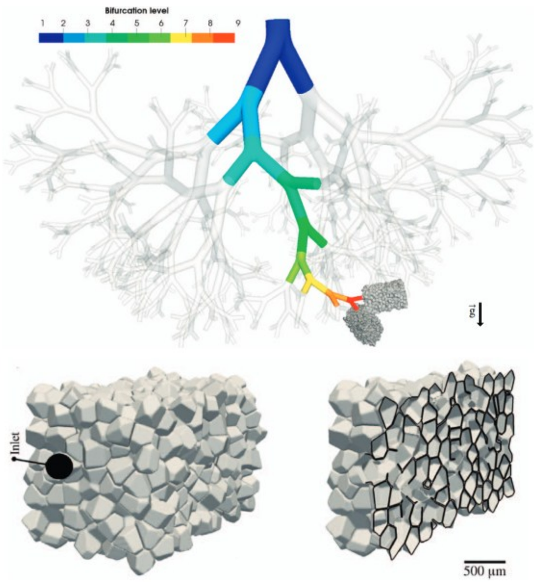

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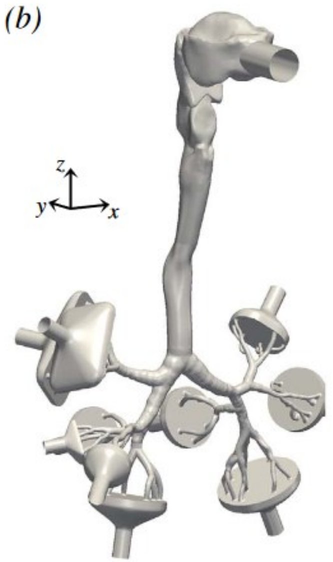

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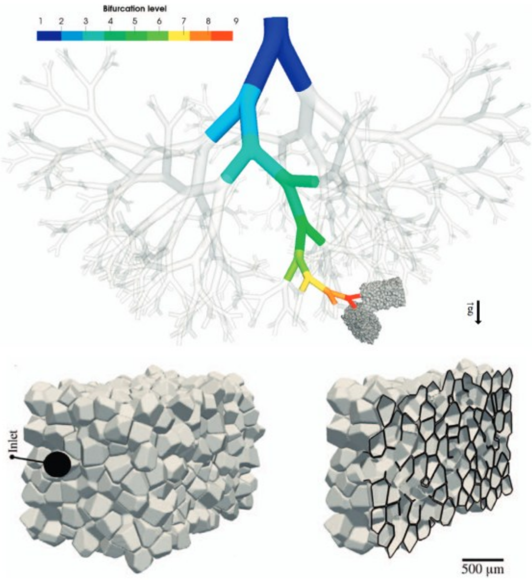

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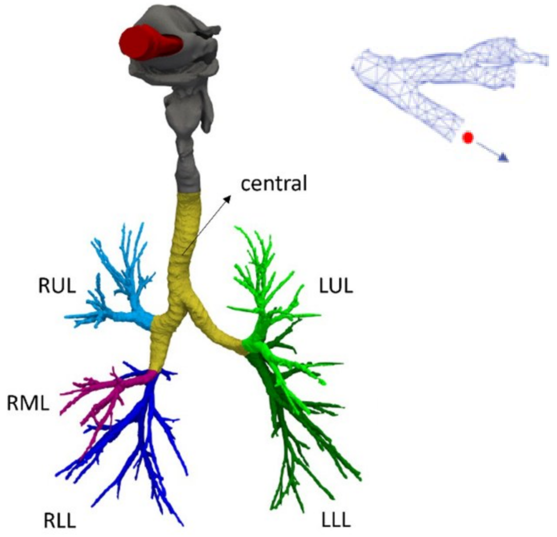
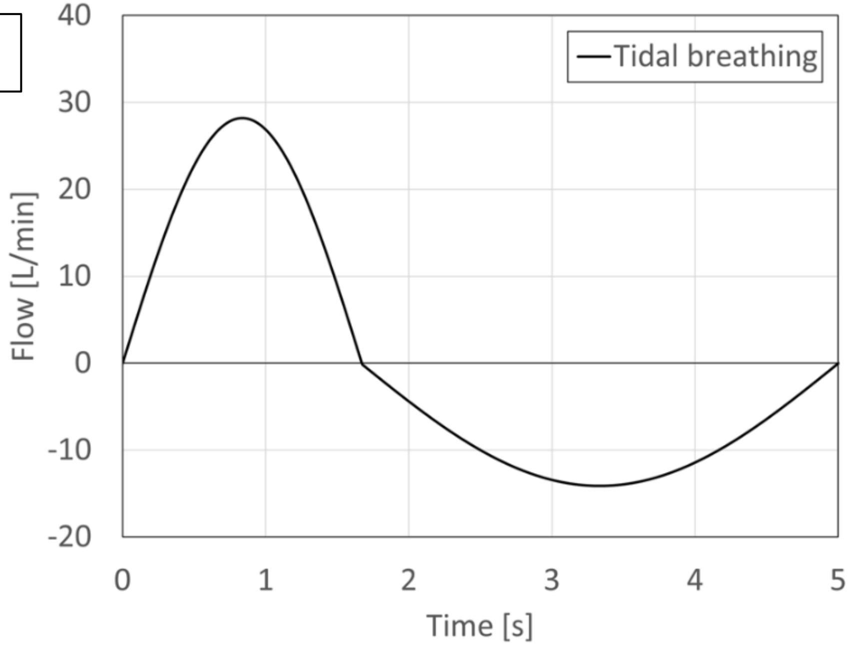
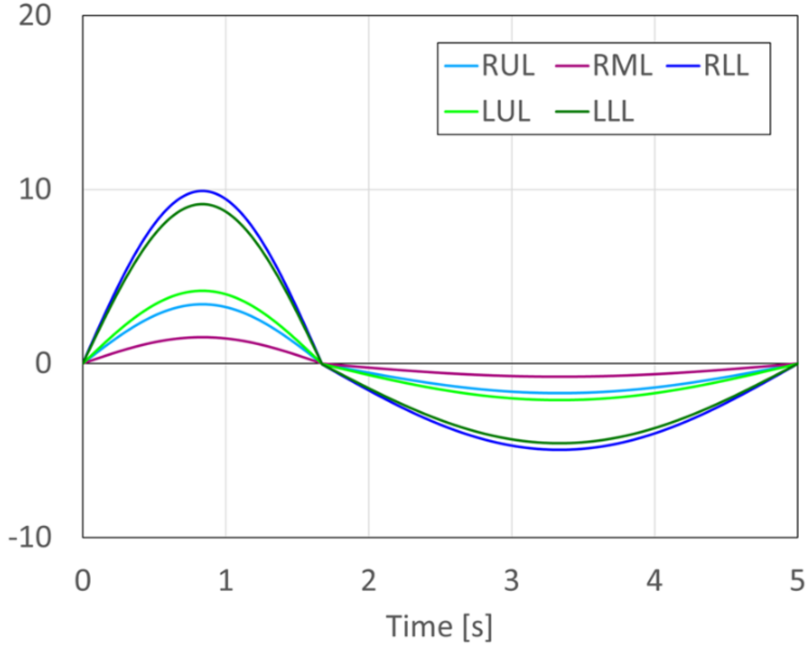
URANS + deep lung model







Sadafi, P. et al. Validation of computational fluid dynamics model airways deposition with SPECT data... *Sci. Rep.* **14**, 5492 (2024)

Our point of view:

Can we do something without modelling (i.e. DNS)?

If we pick the simplest possible case…

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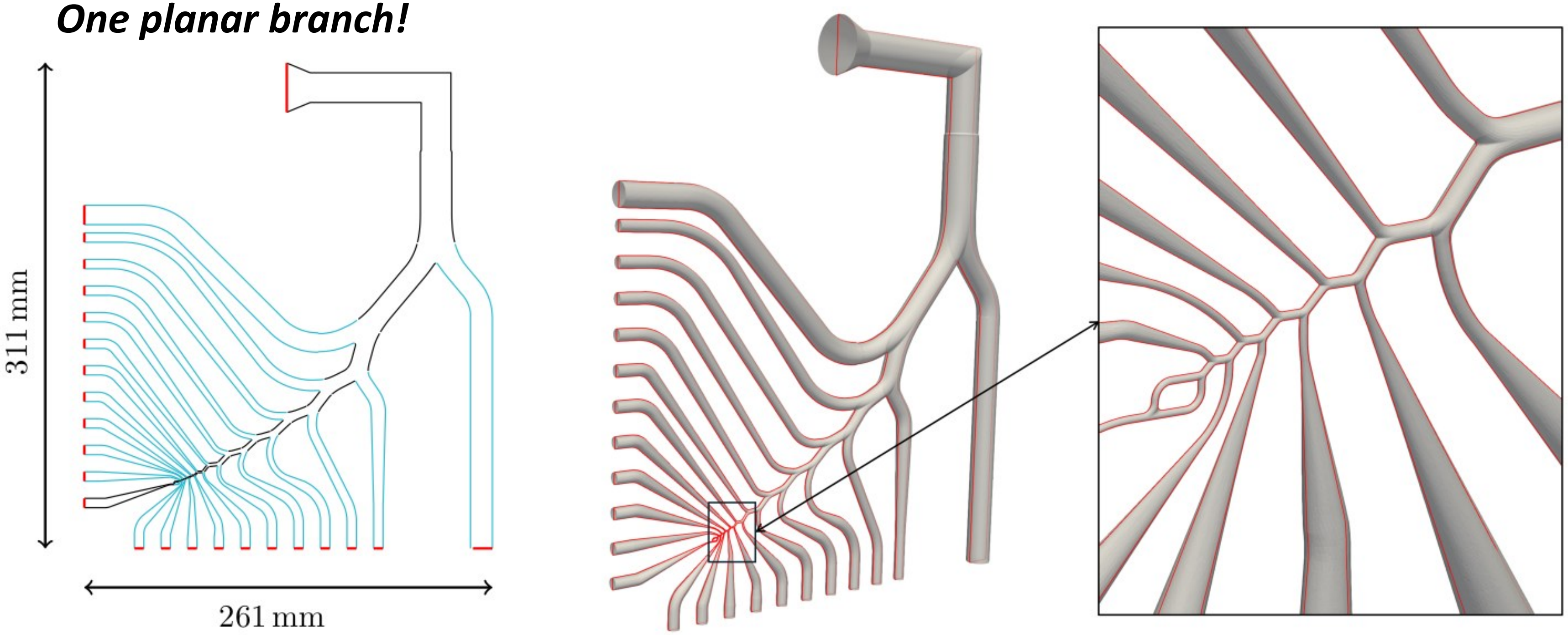
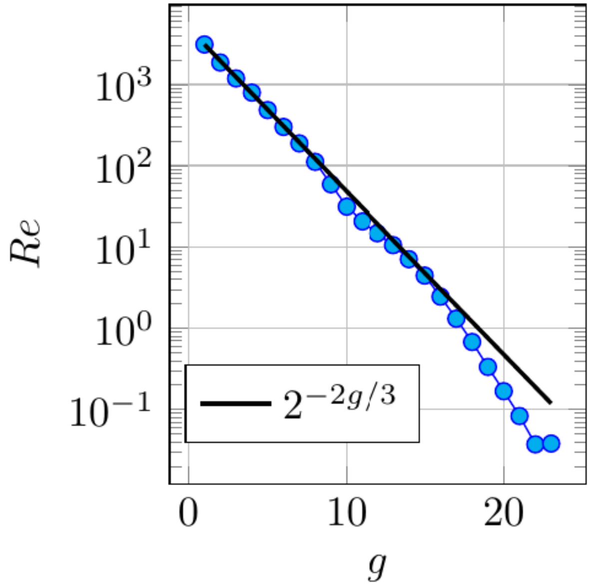
One planar branch!



For $Q_0 = 60\ \mathrm{L/min} = \ 10^{-3}\mathrm{m}^3/\mathrm{s}$



Möller et al., Transparent 23-generation airway model for experimental investigation of aerosol flow… *J. Aerosol Sci.*, **156**, 105782 (2021)

Case study: numerical experiment with as little control on flow rate as possible…

Step 1, Calibration:
Neumann-type BC velocity +
Flow-rate control for pressure values

↓

Step 2, Run:
Neumann-type BC velocity +
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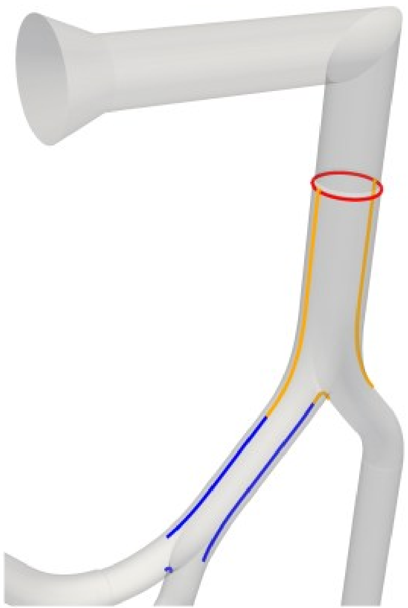

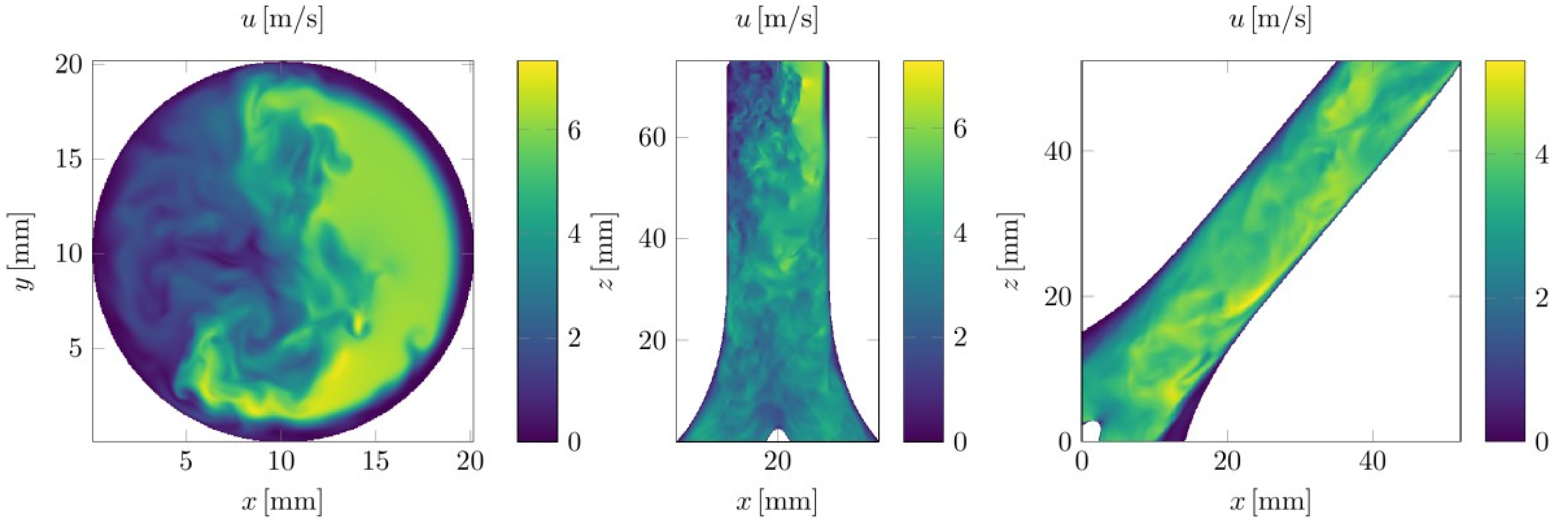

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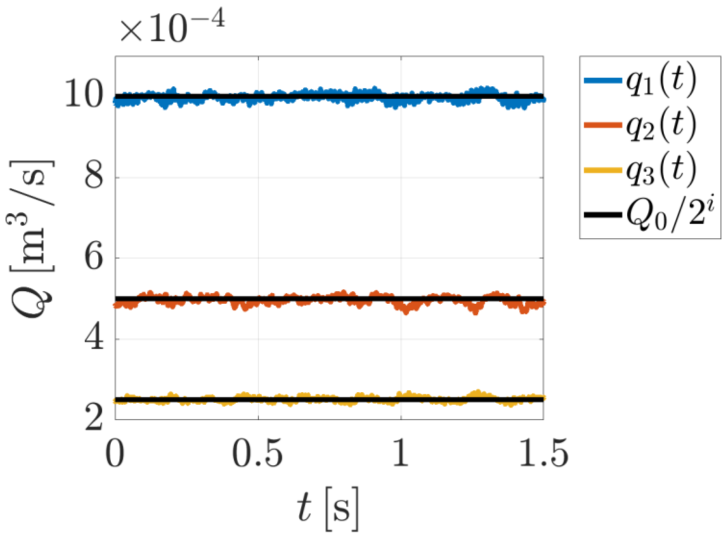
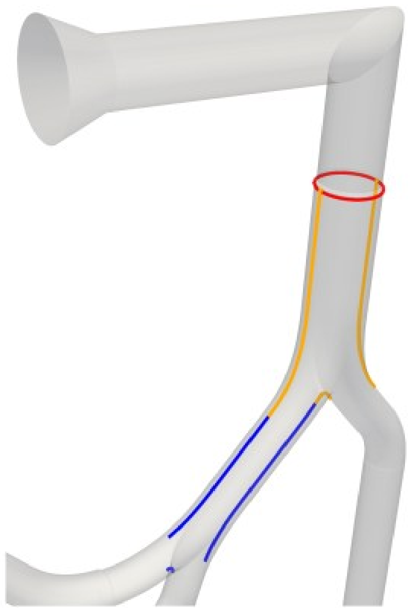
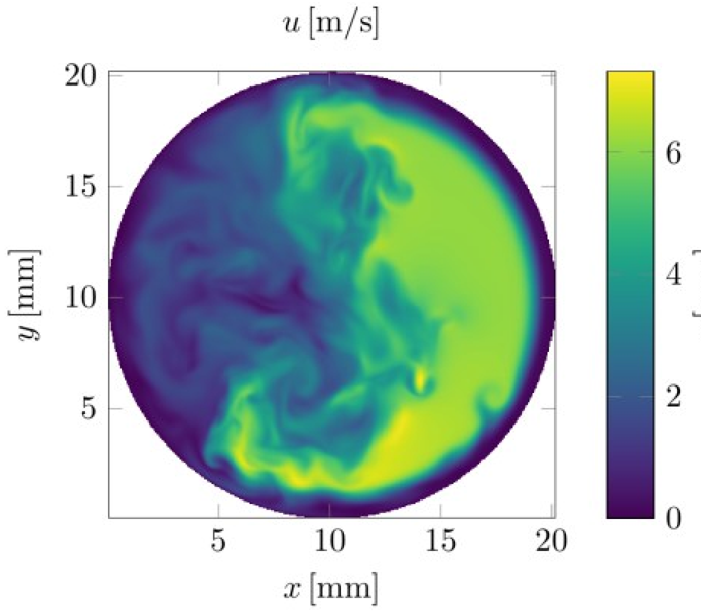
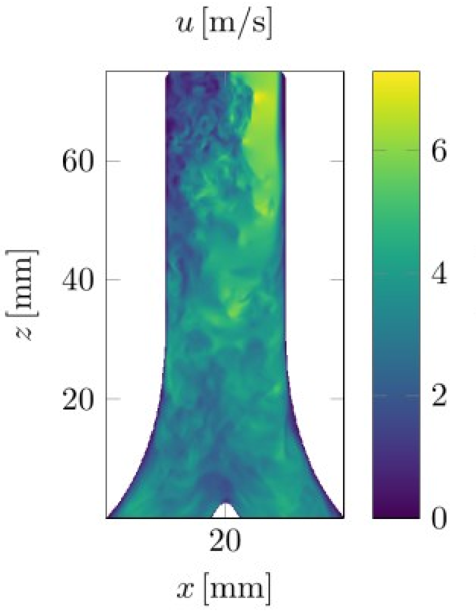
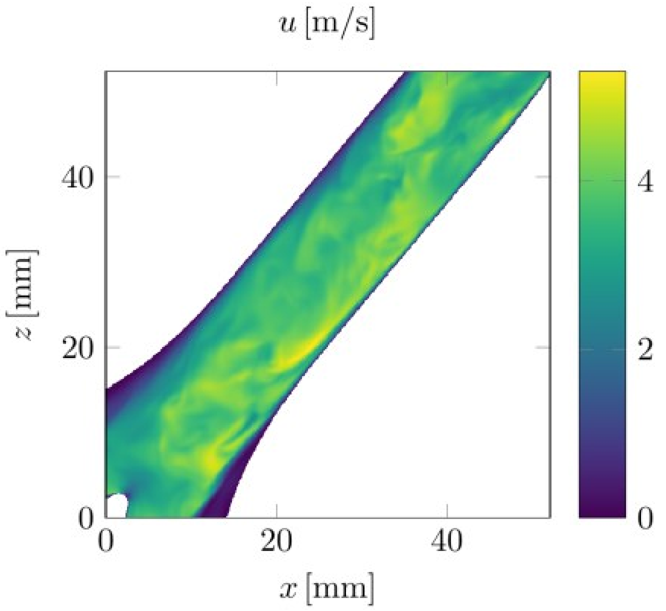


g	$Q\,[\mathrm{m}^3/\mathrm{s}]$	Q_g/Q_{g-1}
0	$9.97 \cdot 10^{-4}$	–
1	$4.95 \cdot 10^{-4}$	0.497
2	$2.51 \cdot 10^{-4}$	0.507
3	$1.25 \cdot 10^{-4}$	0.497
…	…	…
21	$4.69 \cdot 10^{-10}$	0.500
22	$2.46 \cdot 10^{-10}$	0.524
23	$1.93 \cdot 10^{-10}$	0.784



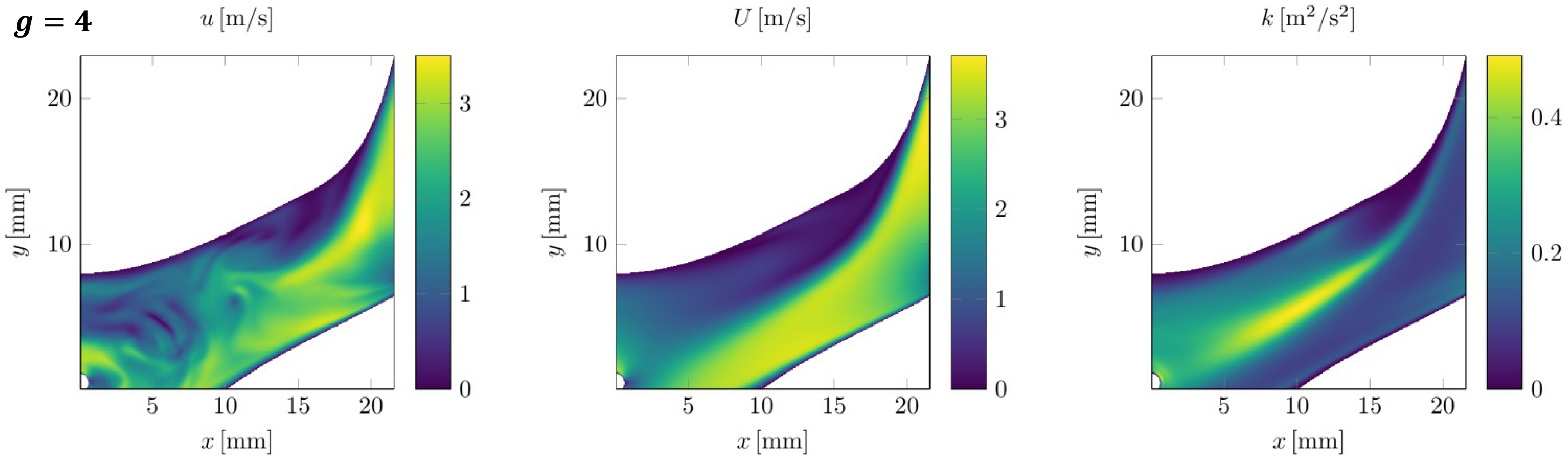






Overview

$g = 4$



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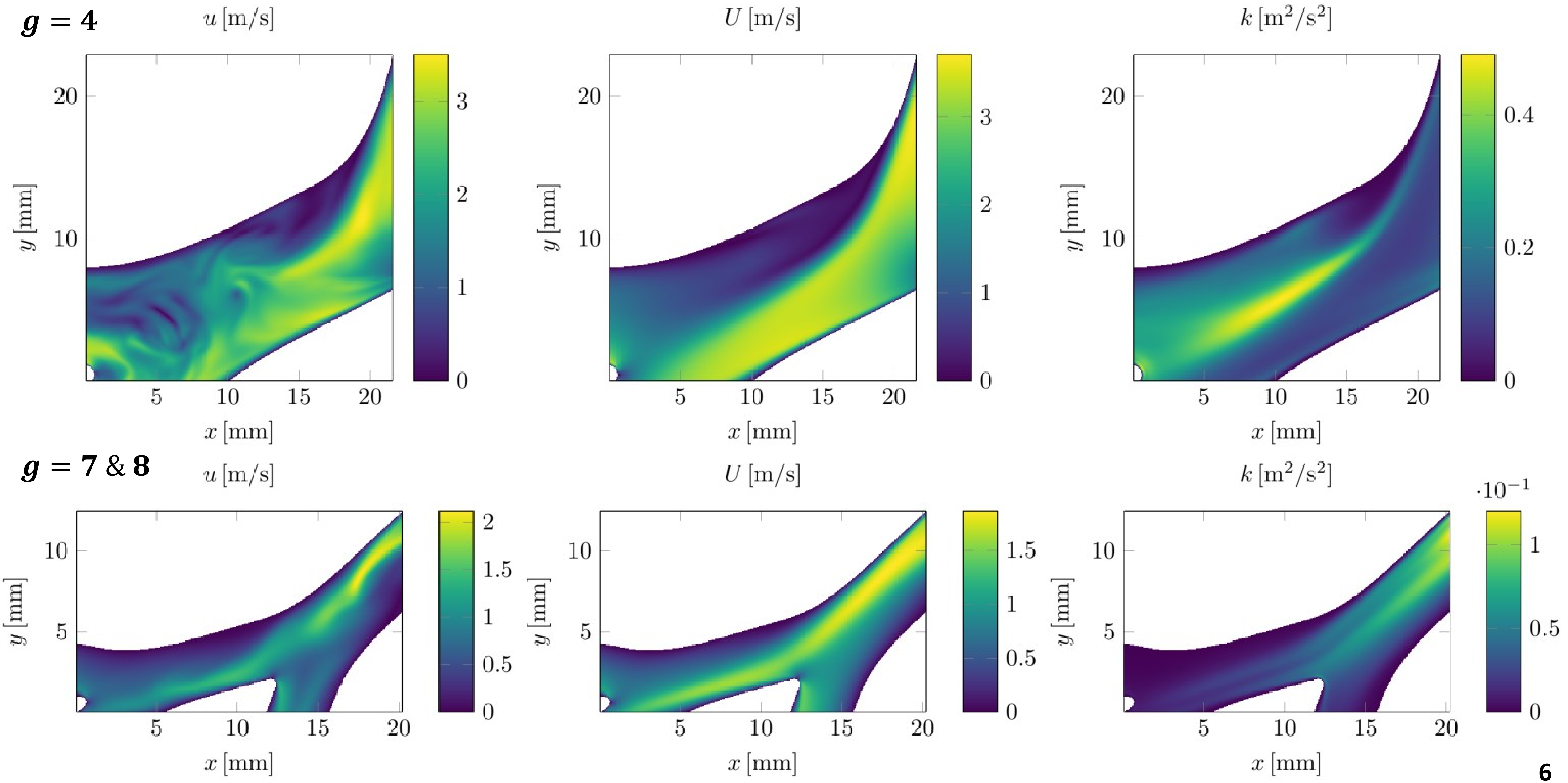
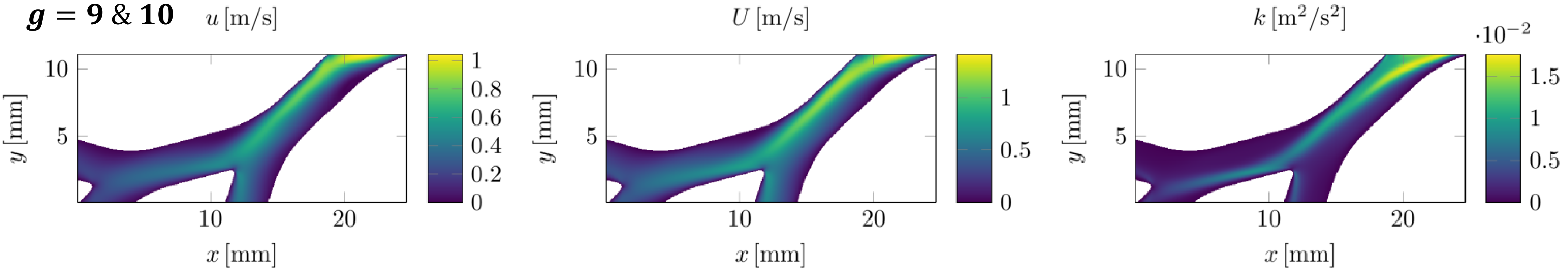


$g = 4$
u [m/s]
U [m/s]
k [m^2/s^2]
y [mm]
x [mm]
5
10
15
20
0
1
2
3
0.2
0.4
$g = 7$ & 8
u [m/s]
U [m/s]
k [m^2/s^2]
$\cdot 10^{-1}$
0.5
1.5

Overview

$g = 9$ & 10



Overview

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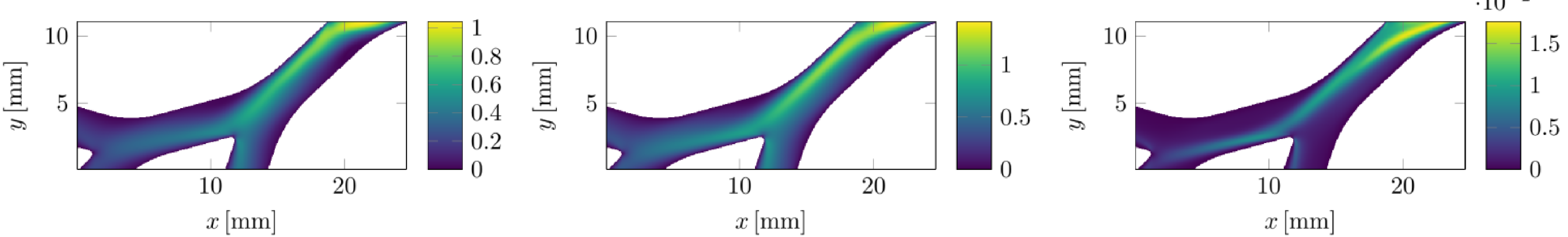
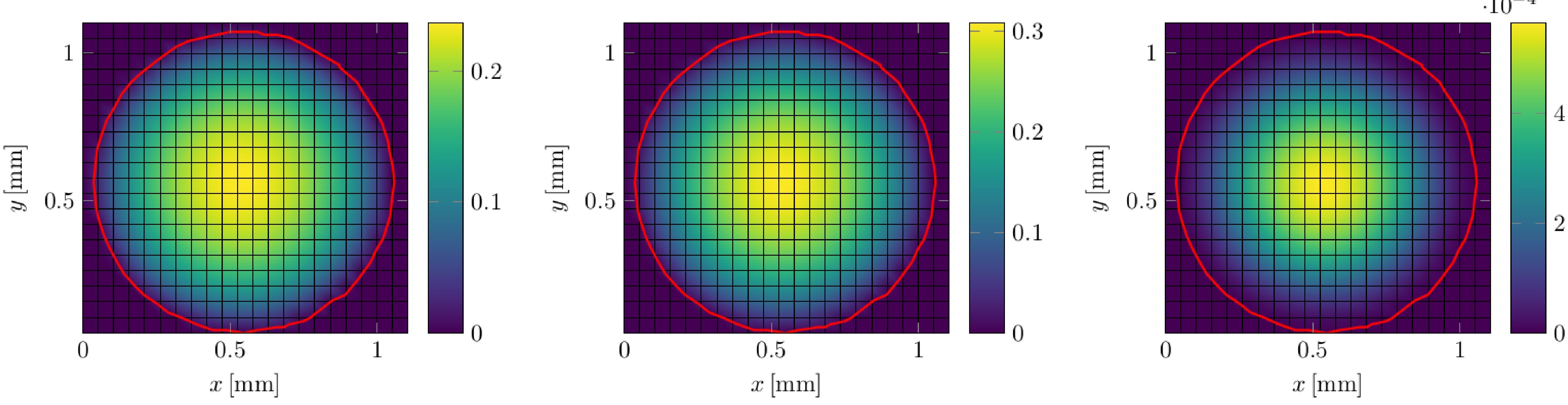


g = 13

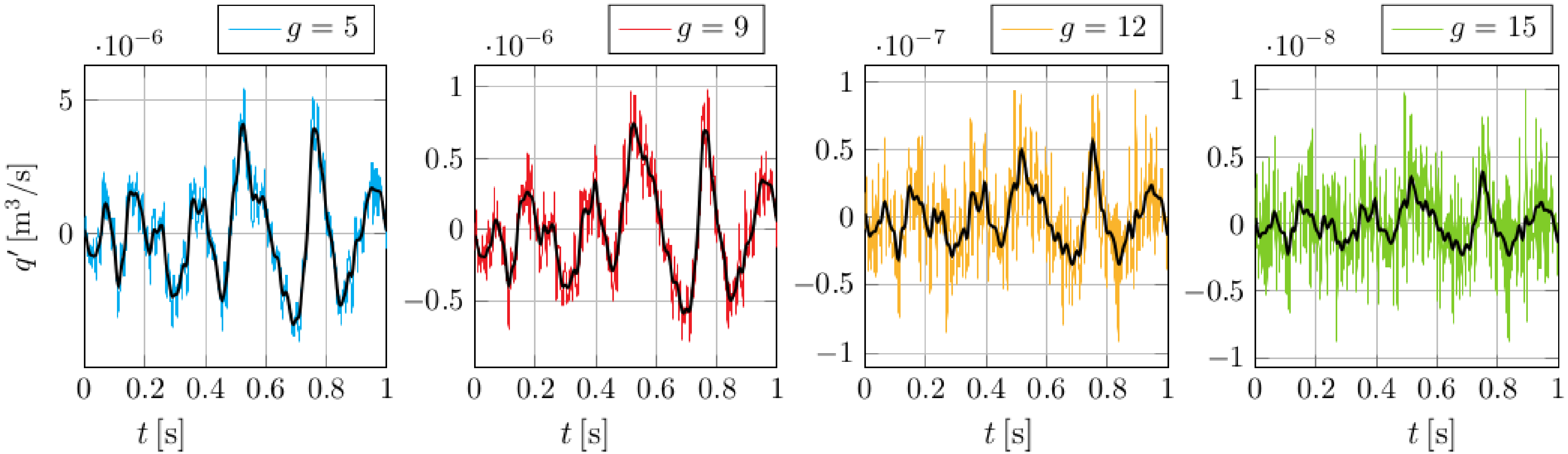


Active time scales

Filtered signal:

$$\tilde{q}(t) = \int_0^T q(\tau)G(t-\tau)\,dt$$

$$f_0 = 5\ Hz$$



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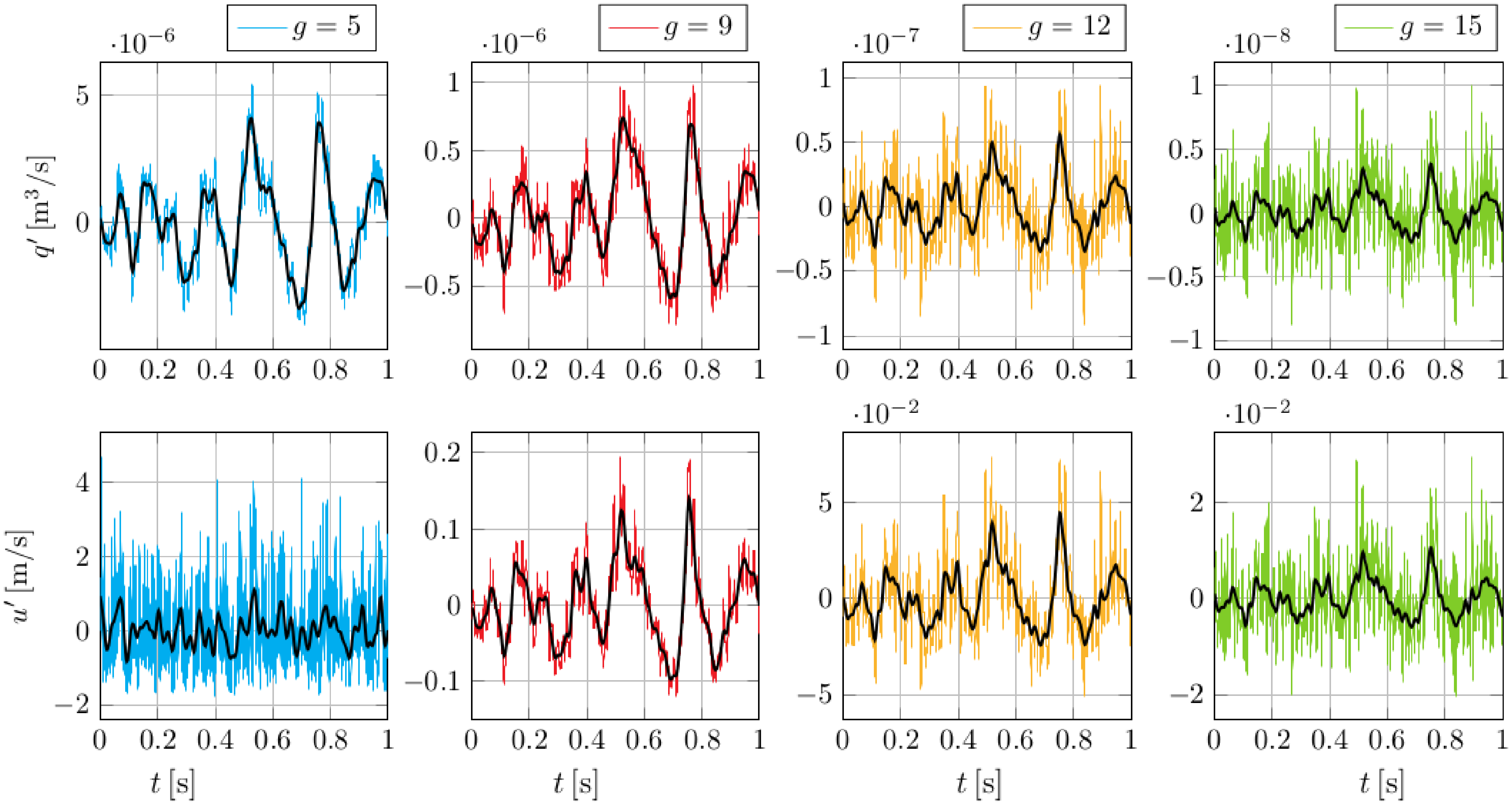

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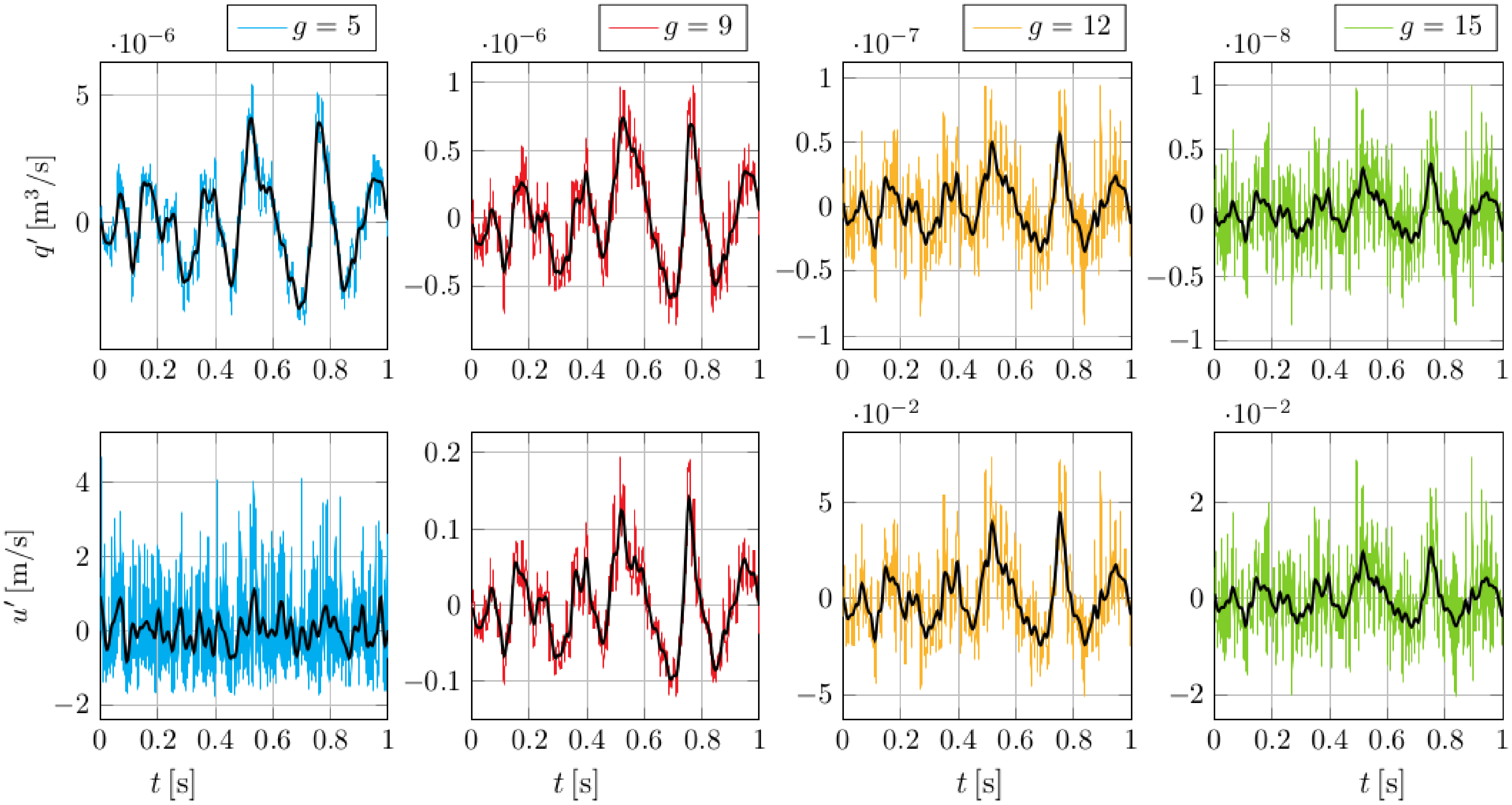

More on active frequencies in: Atzori, M. *et al.* Direct numerical simulations of inhalation in a 23-generation lung model. *Submitted* (2025), arXiv.2506.14729

What can we say about expected flow rate fluctuations? (I)

On average, we have: $\frac{Q_{g+1}}{Q_g} \approx \frac{1}{2}$

Splitting coefficients as random variables:

$$q_{g+1}(t) = s_g(t) q_g(t)$$

$$s(t) = S + s'(t)$$

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Case 2: unsteady flow rate, fixed splitting ($\boldsymbol{q(t), s(t) = S}$):

$$q_{g+1}(t) = S_g q_g(t) \quad \rightarrow \quad \begin{cases} Q_{g+1} = S_q Q_q \\ \mathrm{Var}[q_{g+1}] = S_g^2 \mathrm{Var}[q_g] \end{cases}$$

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Case 3: variable splitting with small fluctuations ($q(t), s(t), s'(t) \ll S$) :

$$\left.\begin{aligned} q_{g+1} &\approx S_g Q_g + Q_g(s_g - S_g) + S_g(q_g - Q_g) \\ \mathrm{Var}[q_{g+1}] &\approx \mathrm{Var}[S_g Q_g + Q_g(s_g - S_g) + S_g(q_g - Q_g)] \\ &\approx \mathrm{Var}[Q_g s_g + S_g q_g] \\ &\approx Q_g^2 \mathrm{Var}[s_g] + S_g^2 \mathrm{Var}[q_g] + 2 Q_g S_g \mathrm{Cov}[s_g, q_g] \end{aligned}\right\} \rightarrow \begin{cases} Q_{g+1} \approx S_g Q_g \\ \mathrm{Var}[q_{g+1}] \approx Q_g^2 \mathrm{Var}[s_g] + S_g^2 \mathrm{Var}[q_g] + 2 Q_g S_g \mathrm{Cov}[s_g, q_g] \end{cases}$$

What can we say about fluctuation intensity?

So far, only "exact" equations, without assumption other than small fluctuation intensities.

Case 3 ($q(t), s(t), s'(t) \ll S$) + educated guess:

$$S_g = \frac{Q_{g+1}}{Q_g} \approx \frac{1}{2} \qquad Q_g \approx \frac{Q_0}{2^g} \qquad \mathrm{Var}[s_q] \equiv A \approx 1\% \qquad \mathrm{Cov}[s_g, q_g] = 0$$

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After substitution, we get a recursive formula:

$$\mathrm{Var}[q_{g+1}] = \frac{Q_0^2 A}{4^g} + \frac{\mathrm{Var}[q_g]}{4}$$

Negligible for high g

The only term for Case 2
($s(t) = S$, $A = 0$)

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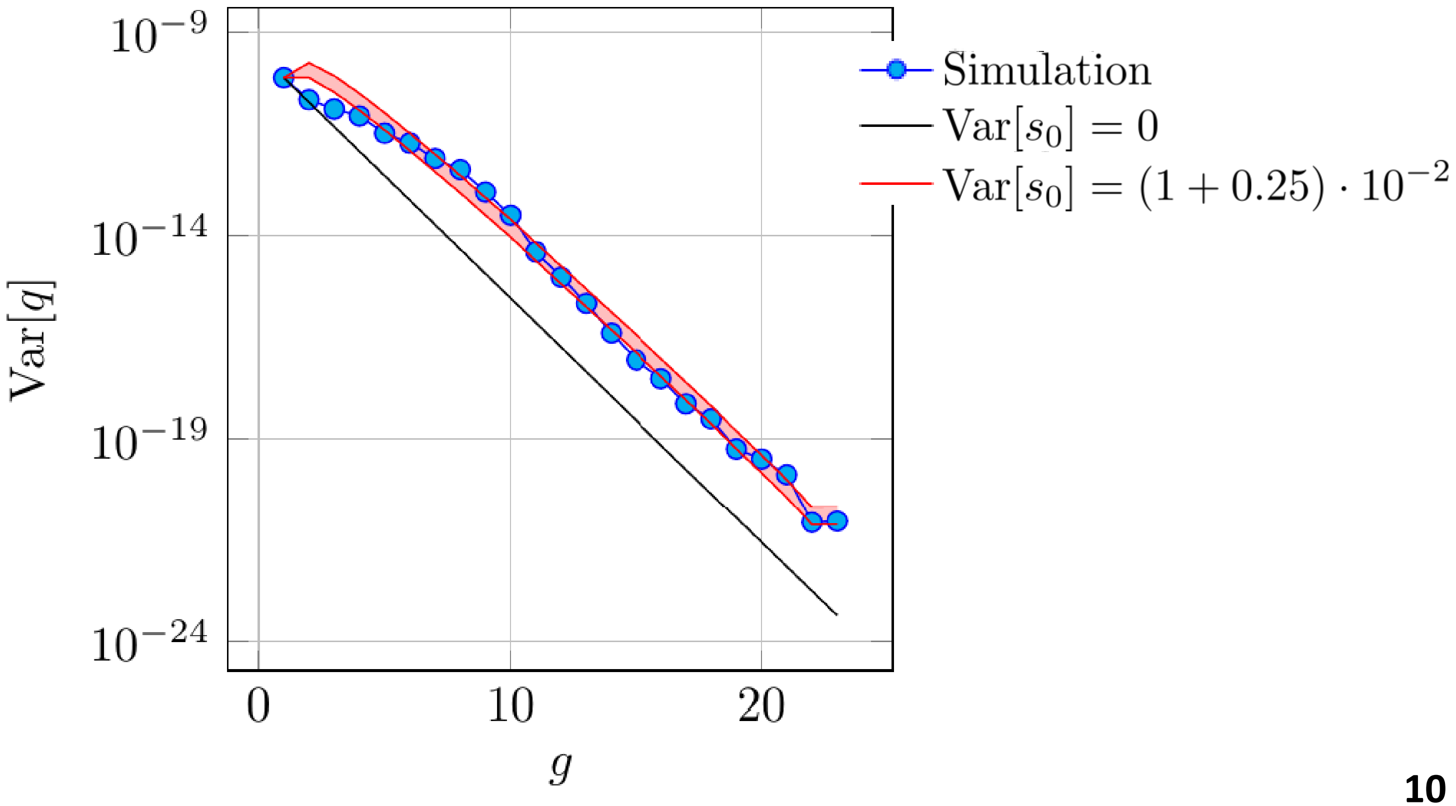

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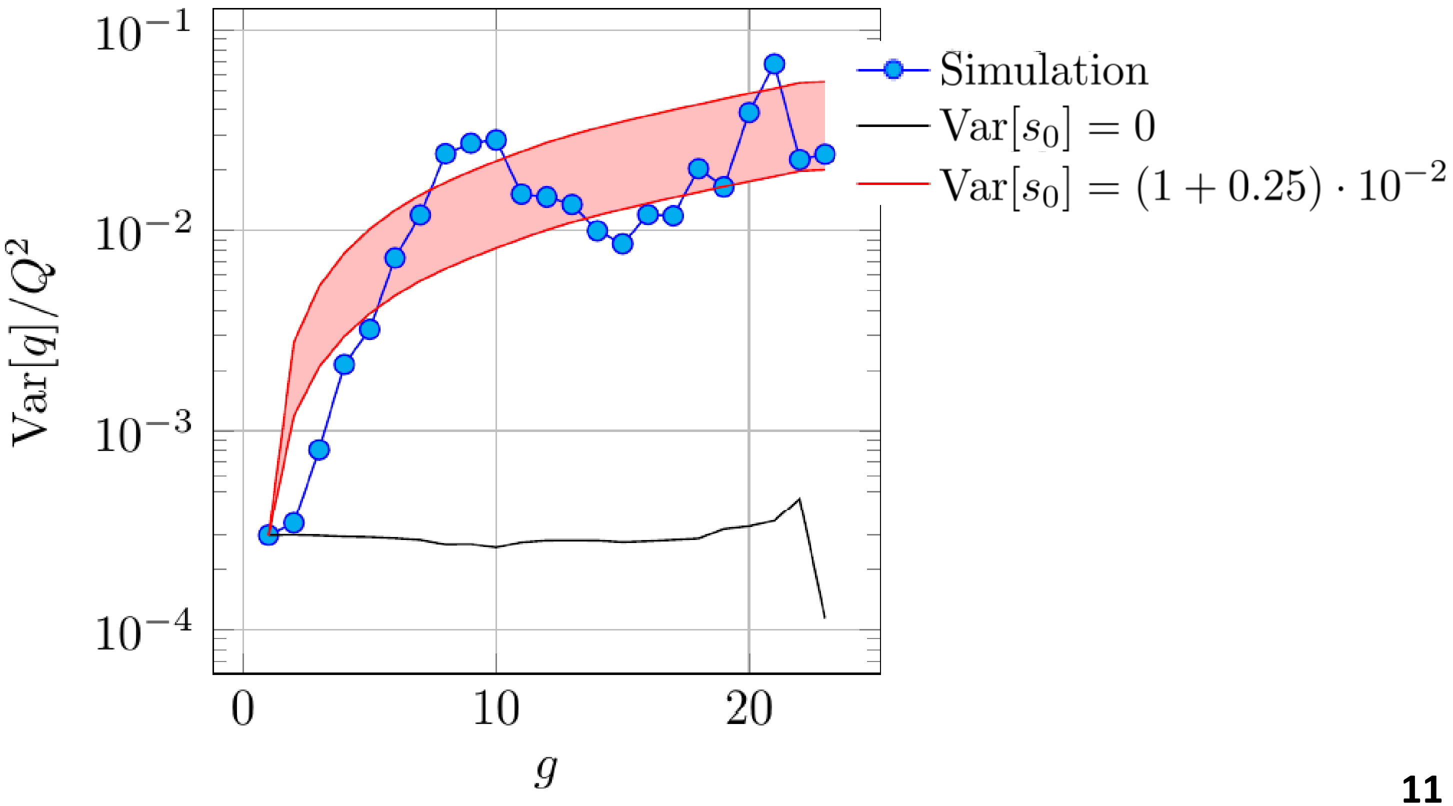
And, for the relative fluctuation intensity:

$$\frac{\mathrm{Var}[q_{g+1}]}{Q_{g+1}^2} = 4A + \frac{\mathrm{Var}[q_g]}{4^{g+2} Q_0^2}$$



Conclusions and Outlook

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What about transient conditions?

What about wall deformations?