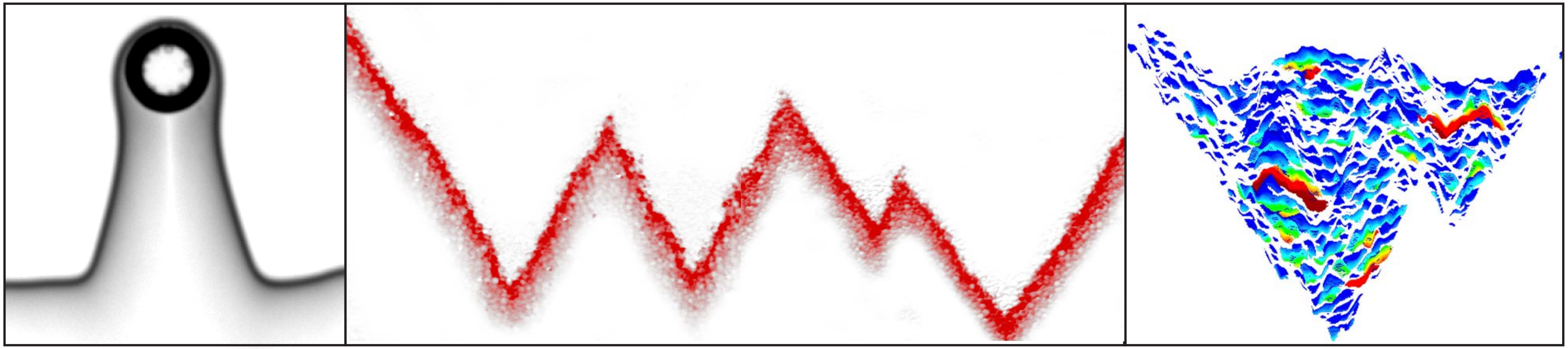
Reaction wave propagation in disordered flow



Séverine Atis

Massachusetts Institute of Technology

Dominique Salin and Laurent Talon

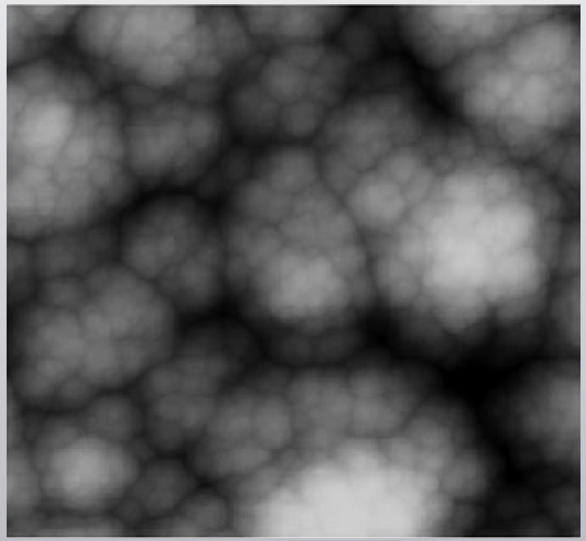
FAST - Université Paris Sud, Orsay

Kay Wiese and Pierre Le Doussal

LPT- Ecole Normale Supérieure, Paris

Growth phenomena and scale invariant structures

Vapor atom deposition



[Castro et al., 2012]

Imbibition fronts

coffee stain on paper

Clouds

Boulder sky, summer 2011

Growth phenomena and scale invariant structures

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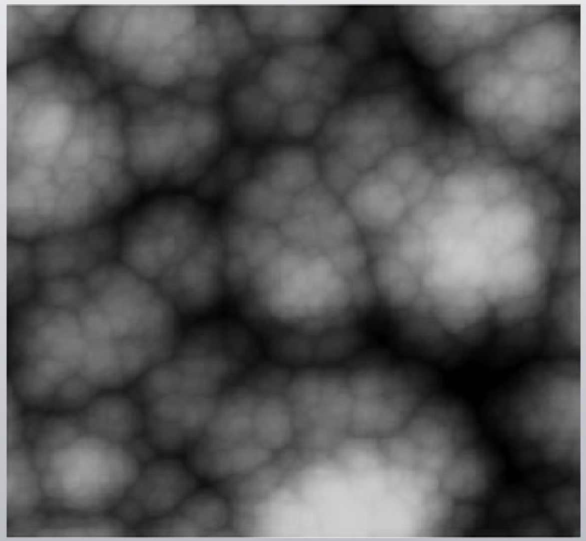

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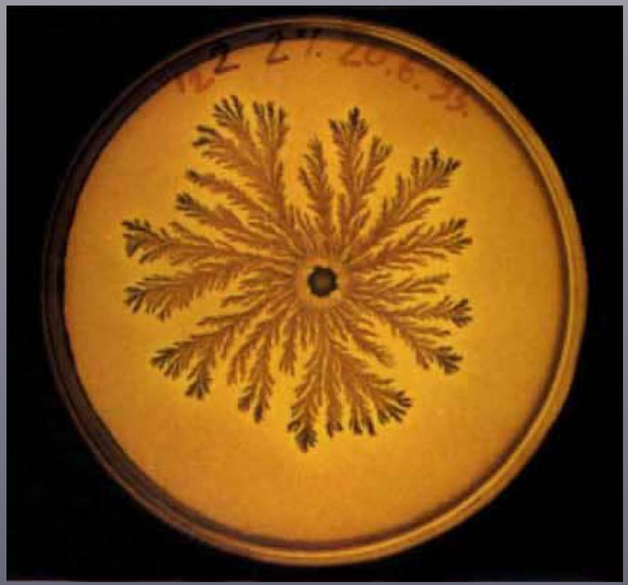
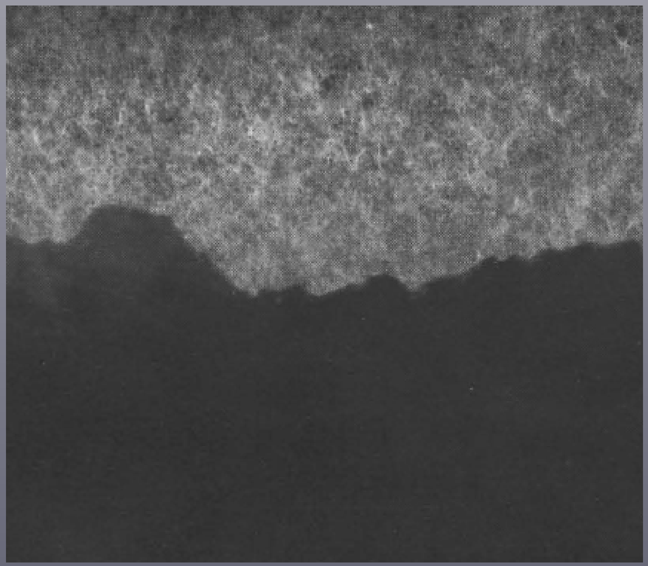
- **Self-sustained systems**

Bacterial colonnies



[Benjacob et al., 1994]

Paper combustion



[Zhang et al., 1992]

Plants growth

Lychen, New Hampshire

Growing interfaces

- Autocatalytic chemical reaction

feedback

model equation: $A + B \longrightarrow 2B + C$

- Self-organization

flame front
[movie Fume FX]

Belousov-Zhabotinsky
oscillations
[movie S. Morris]

reaction wave
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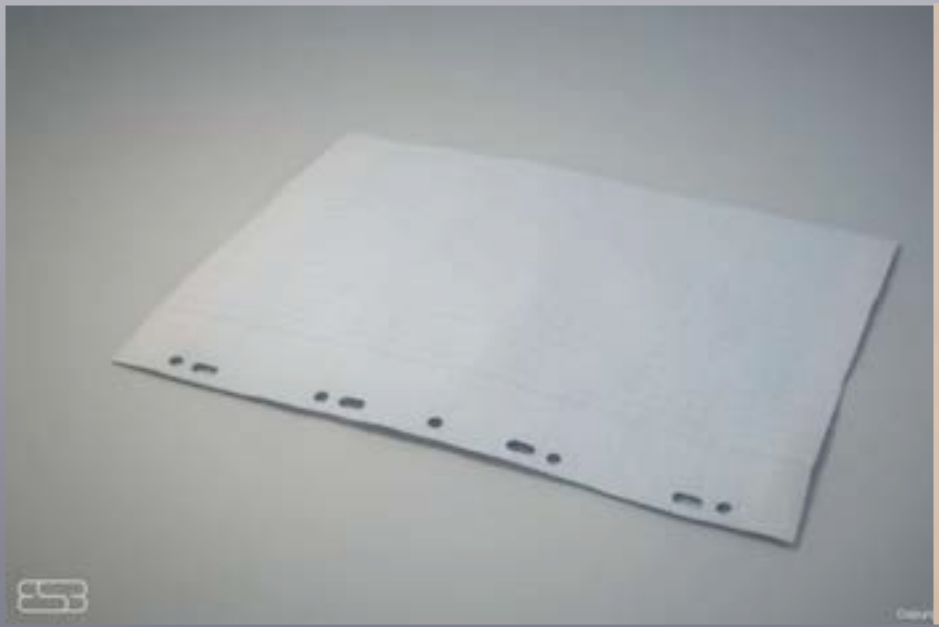

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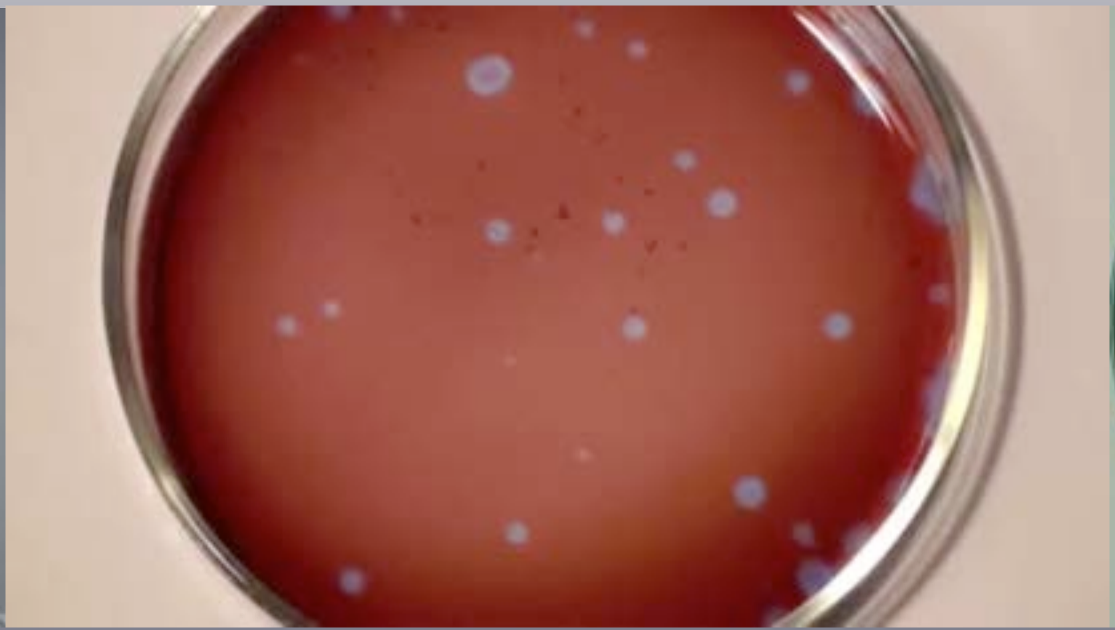

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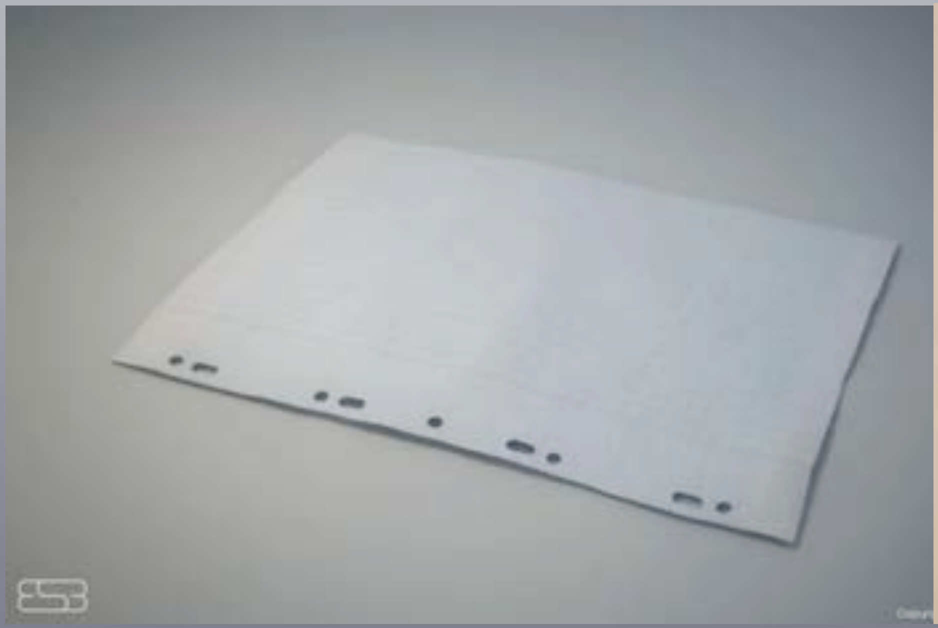

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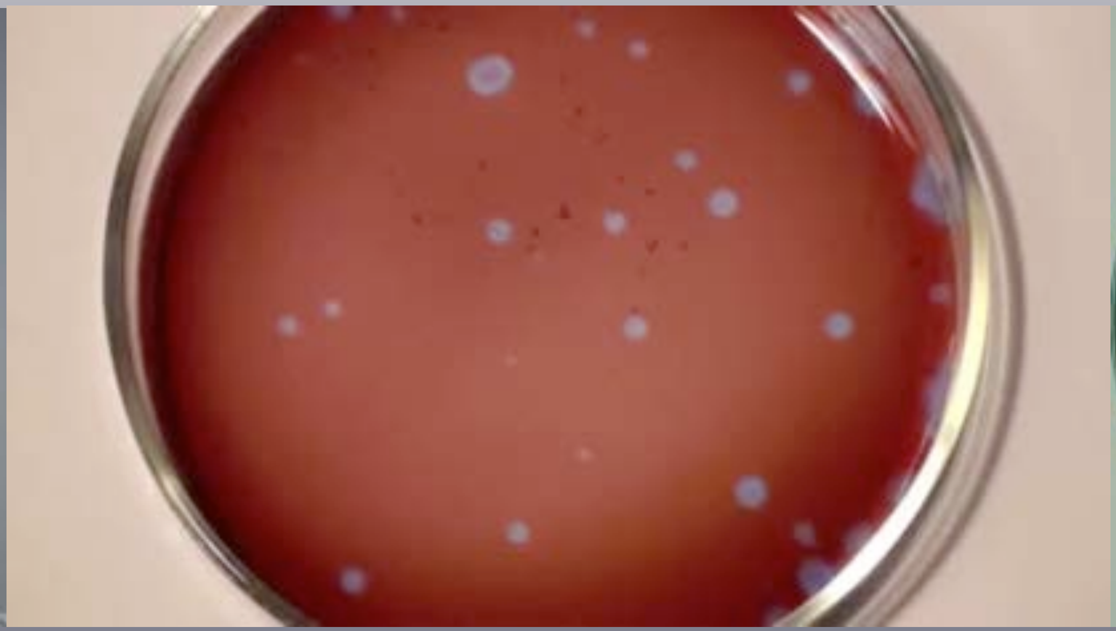

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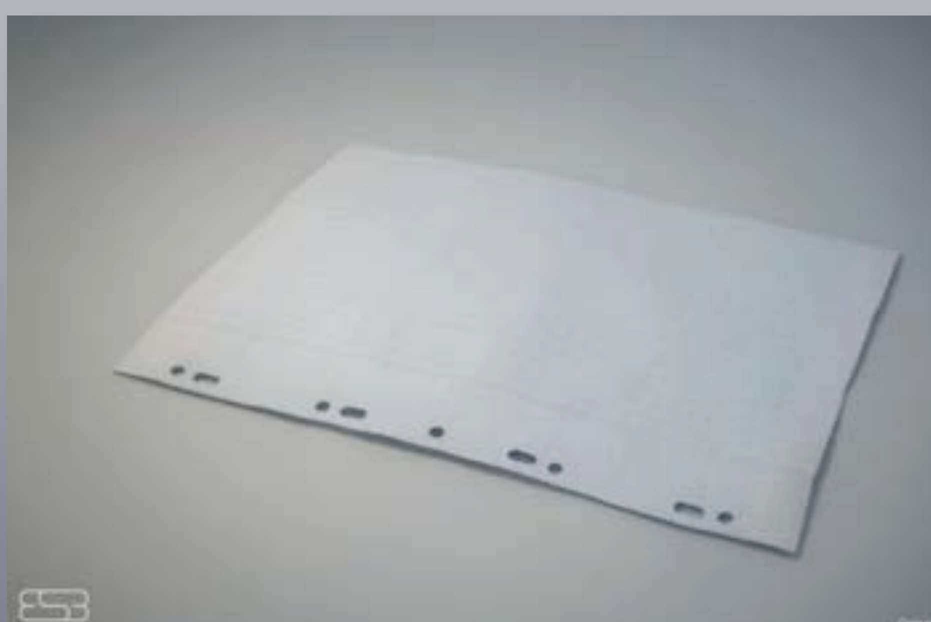

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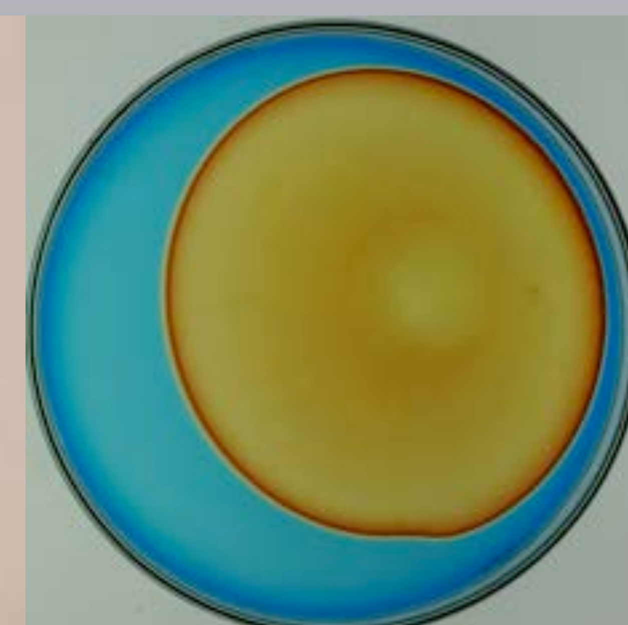

reaction wave
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- Reaction Diffusion equation $$\frac{\partial u}{\partial t} = D\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + f(u)$$

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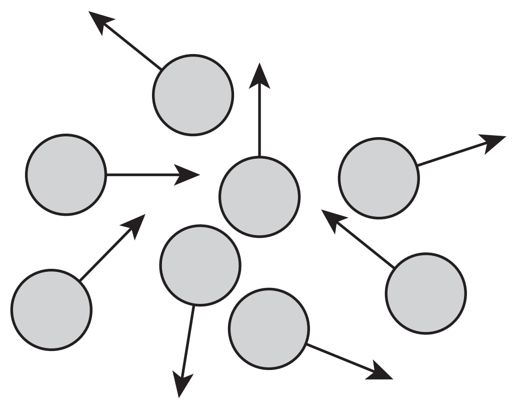

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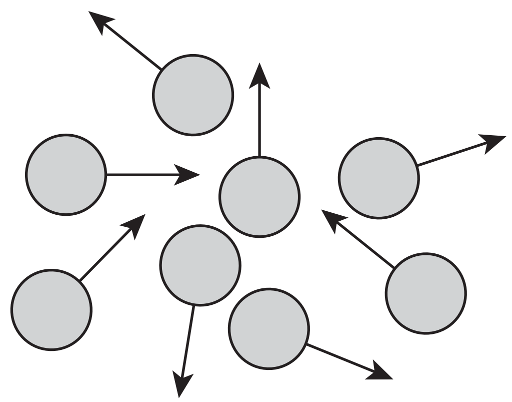

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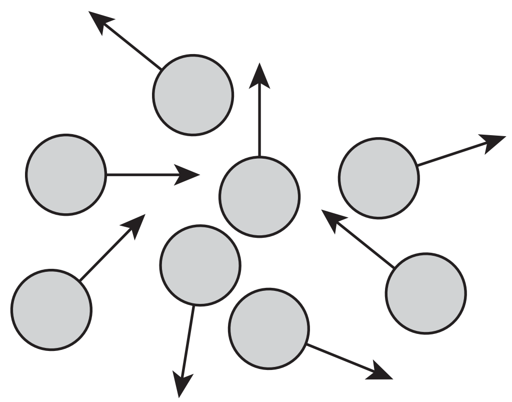
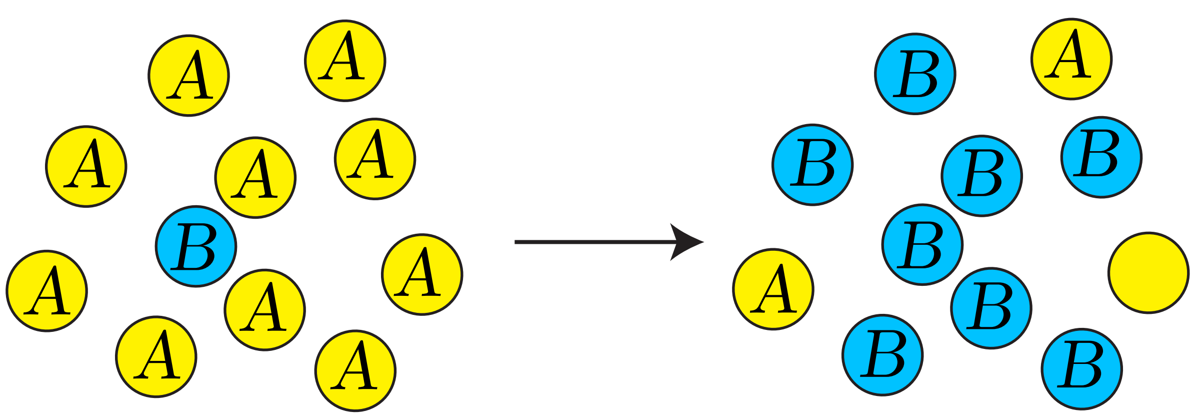


$\longrightarrow$ • $f(u)$ reaction term

autocatalytic process $\longrightarrow$ nonlinearity $f(u) = r\,u(1-u)$



- Fisher-Kolmogorov equation (FKPP model)

[Kolomogorov et al. 1937, R. A. Fisher 1937]

$$\frac{\partial u}{\partial t} = D\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + r\,u(1-u)$$

$$X = x \pm ct \quad \longrightarrow \quad c\frac{\partial u}{\partial X} = D\frac{\partial^2 u}{\partial X^2} + f(u)$$

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$$u(x,t) = u(x \pm c t)$$

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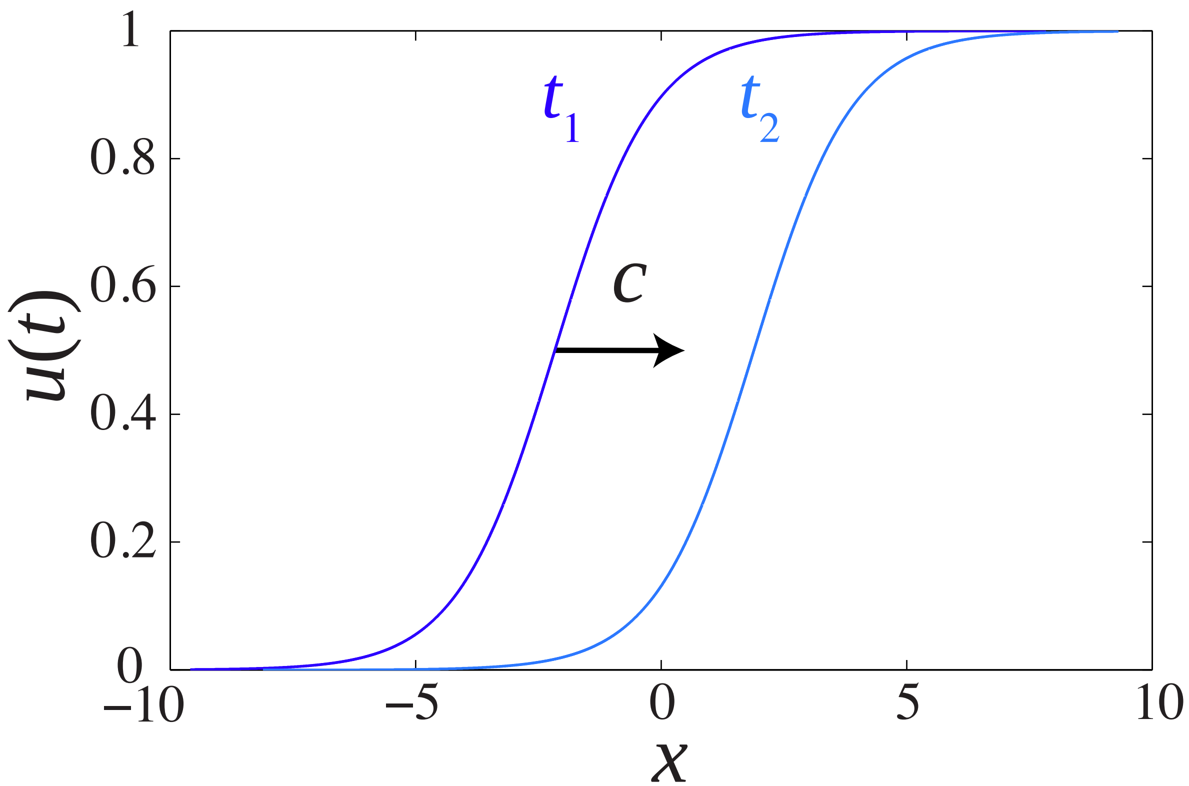

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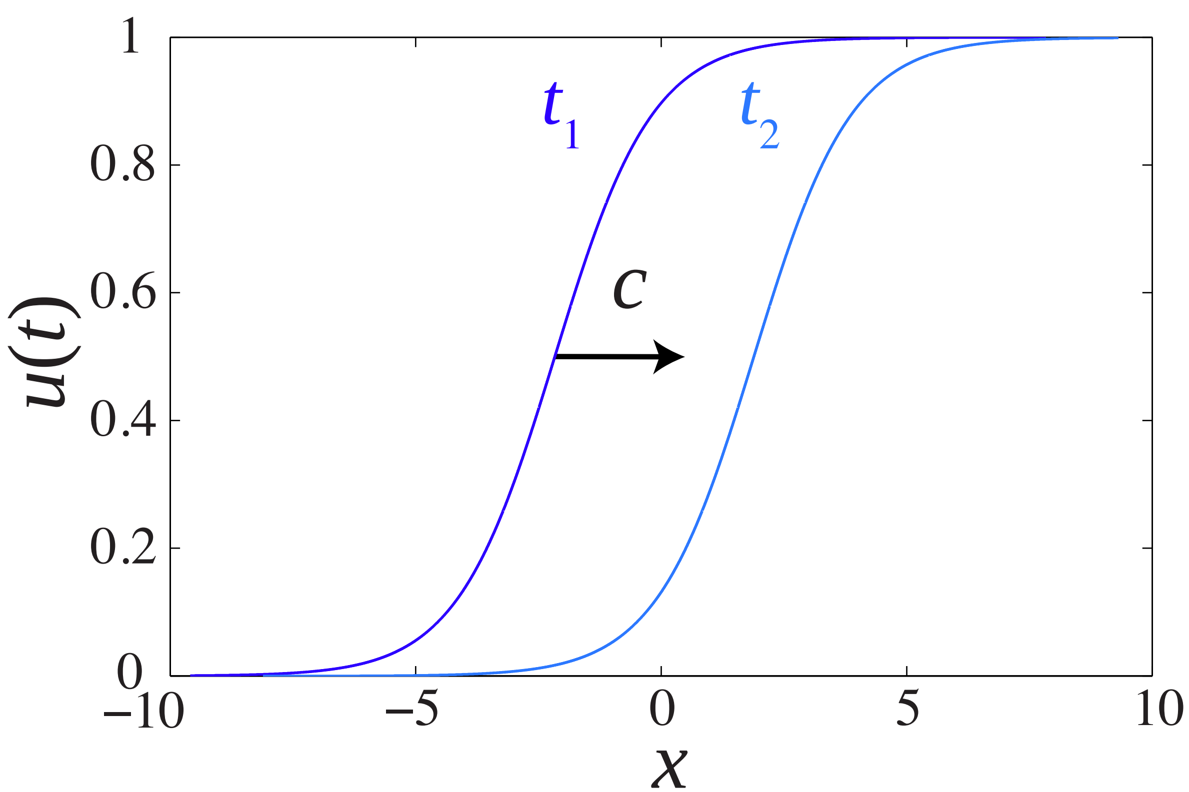
FKPP

$$\longrightarrow c = 2\sqrt{rD}$$



PLAN

1 - Experimental setup

2 - Front dynamics in high flow strength

3 - Pinning process in low flow strength

4 - Transcient dynamics and universality

5 - Conclusion and perpectives

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1 - Experimental setup

- Iodate acid arseneous reaction (IAA)

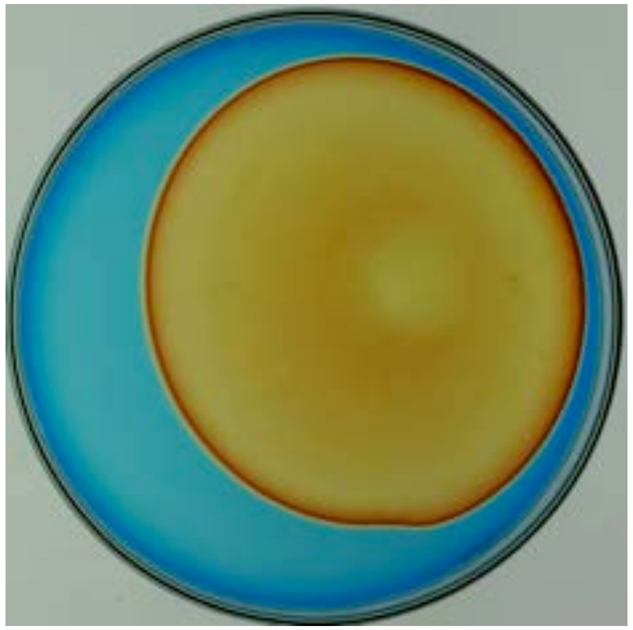
$$IO_3^- + 5I^- + 3H_3AsO_3 \rightarrow 6I^- + 3H_3AsO_4$$

- 3rd order chemical kinetics $f(C) = \alpha C^2(1-C)$

$$\frac{\partial C}{\partial t} = D_m\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2}\right) + \alpha C^2(1-C)$$

C : autocatalists concentration $[I^-]/[IO_3^-]_0$

α : reaction rate



1 - Experimental setup

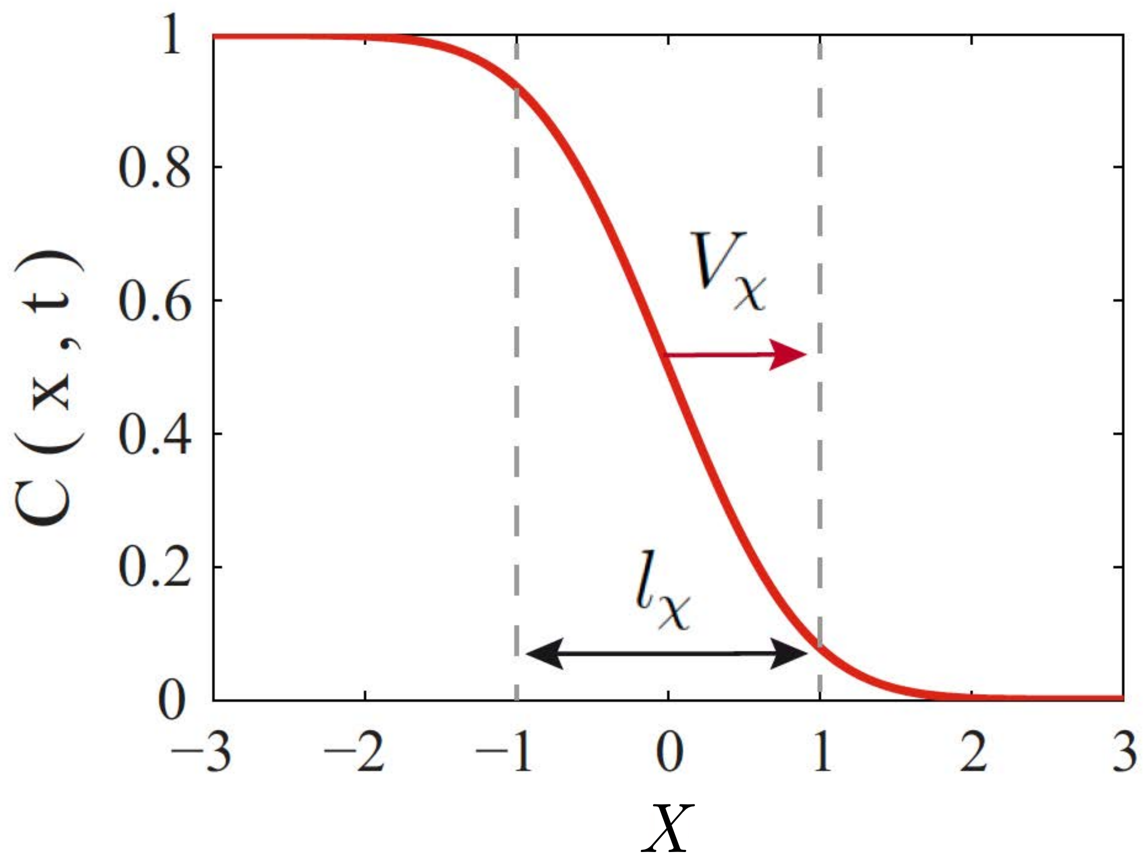
- Stationary solution $$C(x,t) = \frac{1}{1+\exp[(x-V_\chi t)/l_\chi]}$$

$\longrightarrow$ resulting from the balance between diffusion and reaction

reaction front velocity and thickness remain constant

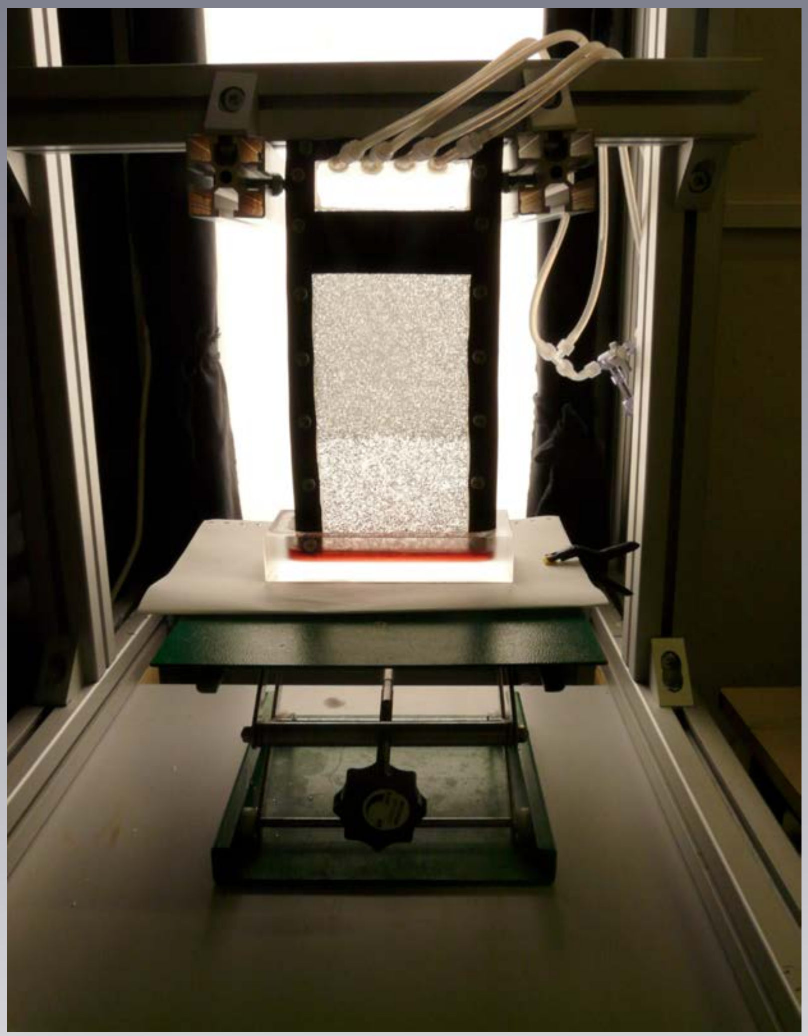
$$\begin{cases} V_\chi = \sqrt{\dfrac{\alpha D_m}{2}} \simeq 10\mu m/s \\ l_\chi = \sqrt{\dfrac{2D_m}{\alpha}} \simeq 100\mu m \end{cases}$$

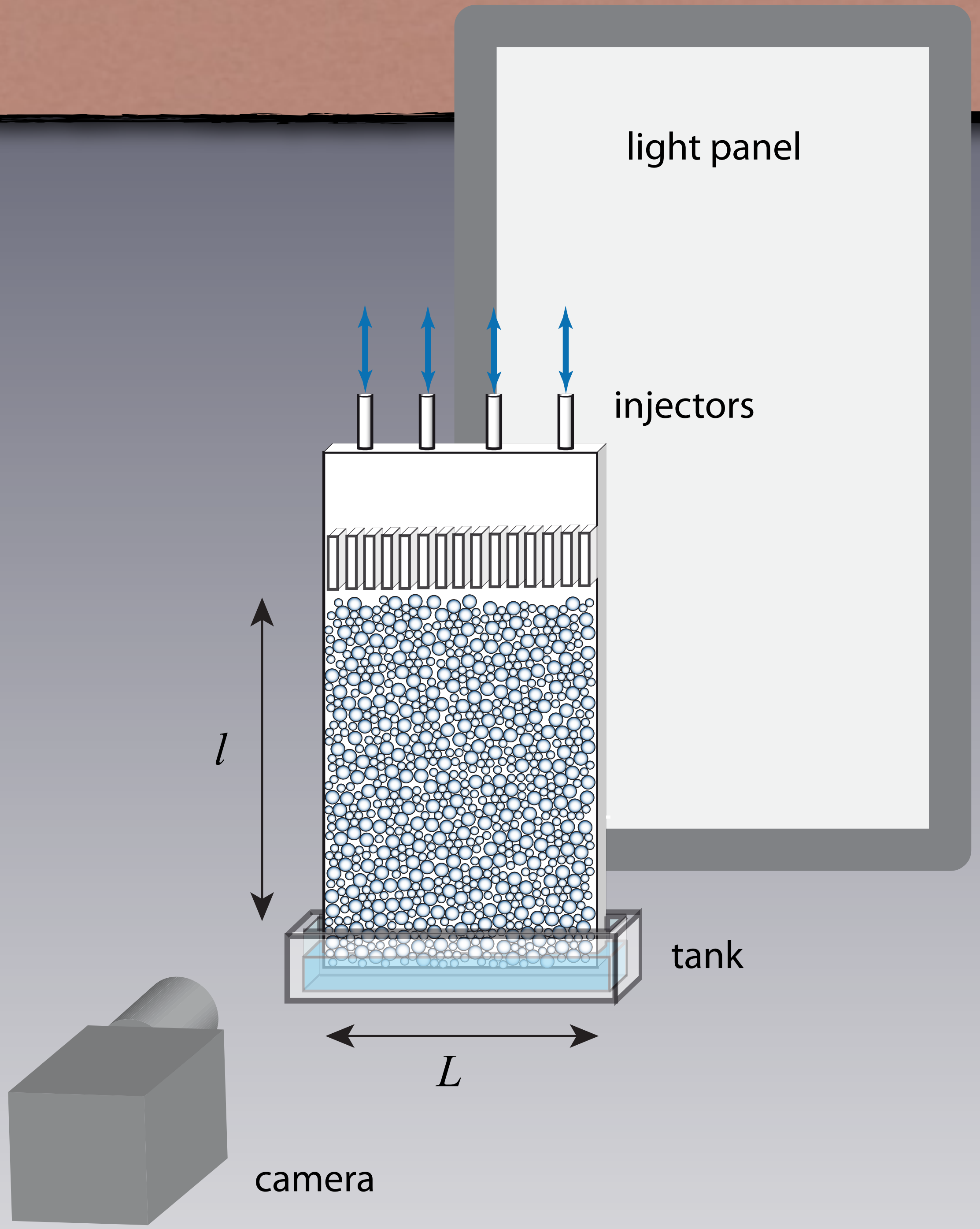
concentration profile of the front



1 - Experimental setup

- Spatially disordered flow





flow through a granular medium

1.5 mm and 2 mm
diameter glass beads

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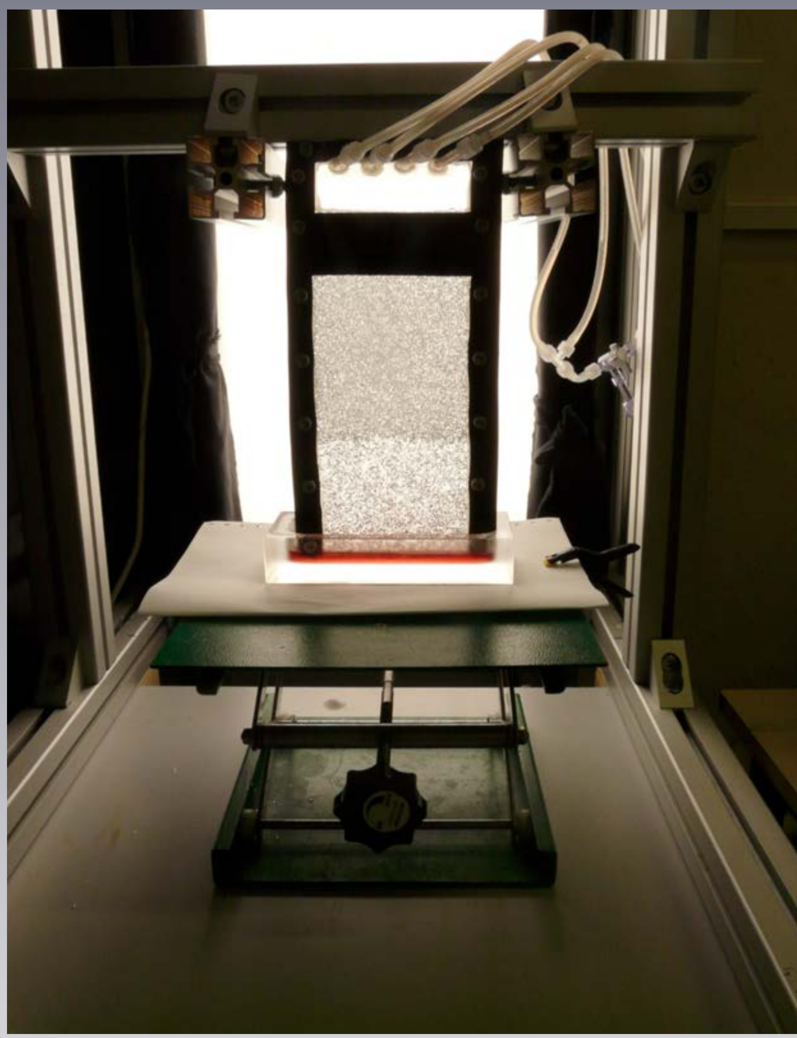

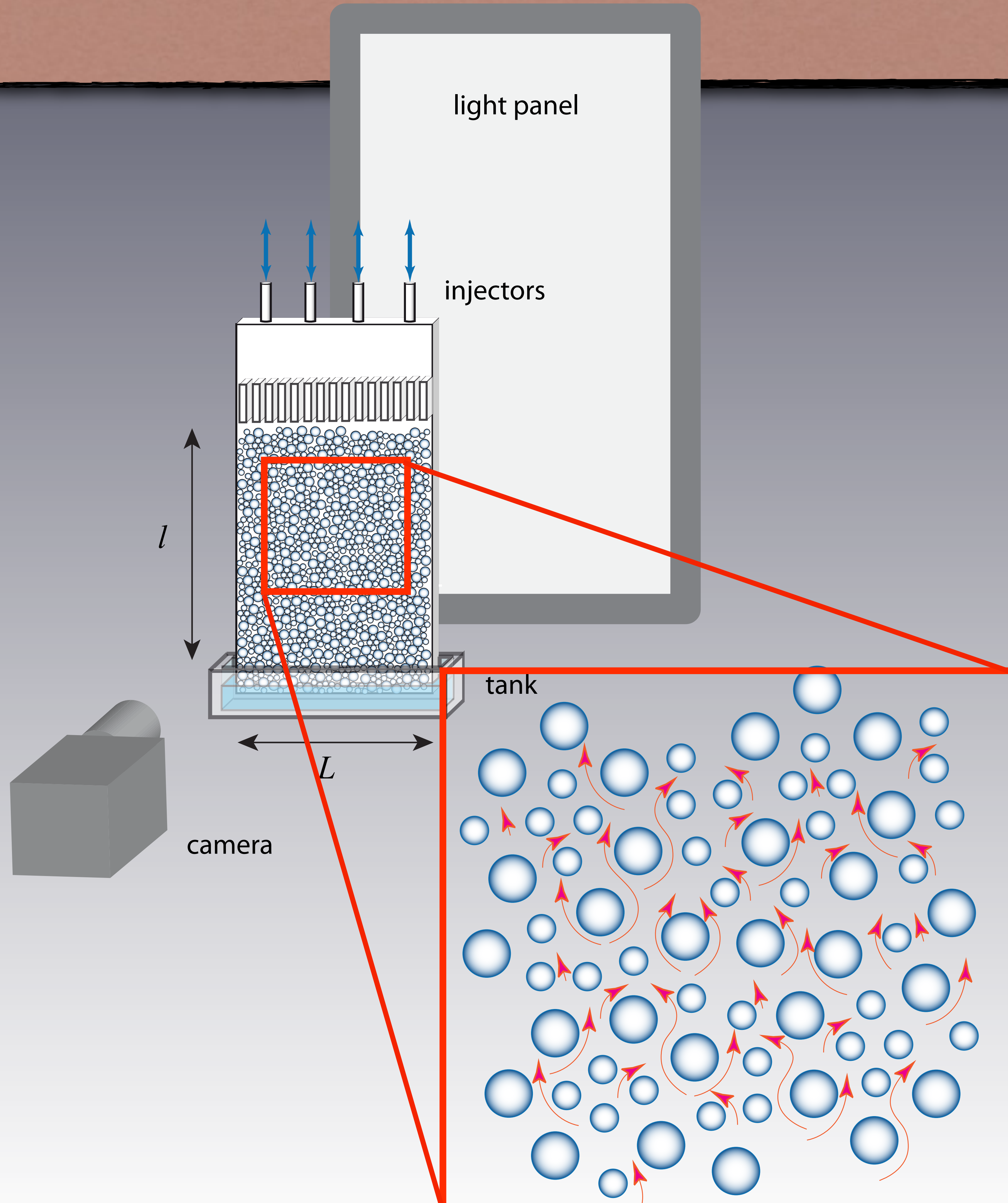

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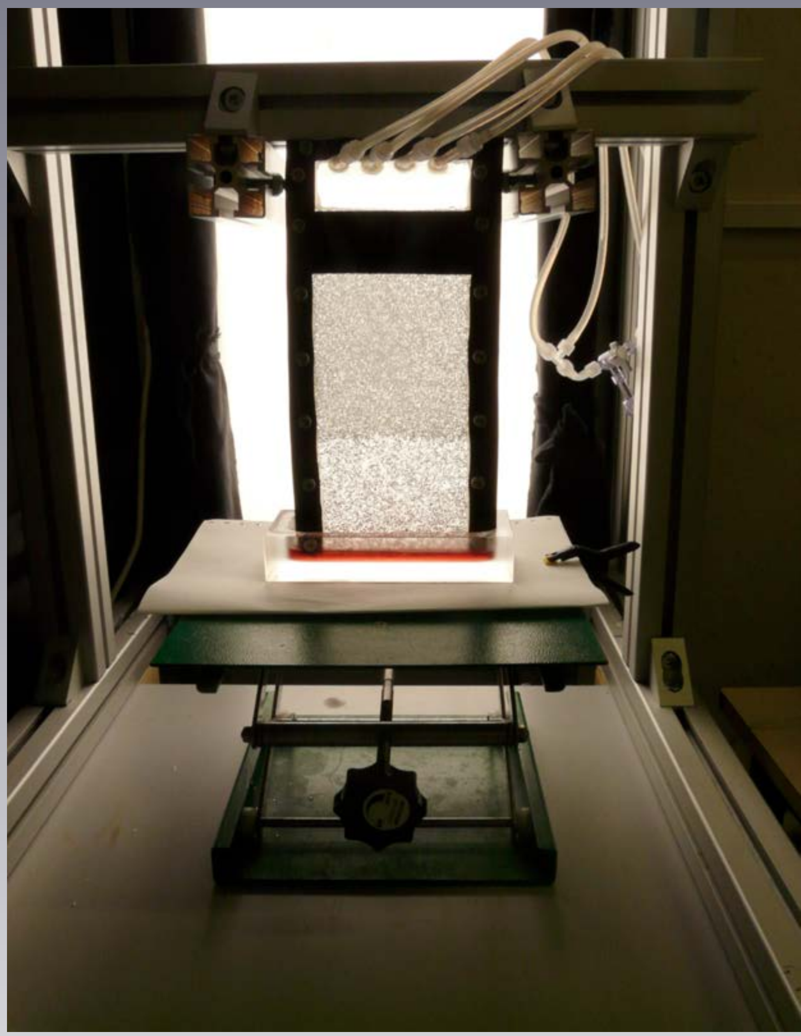

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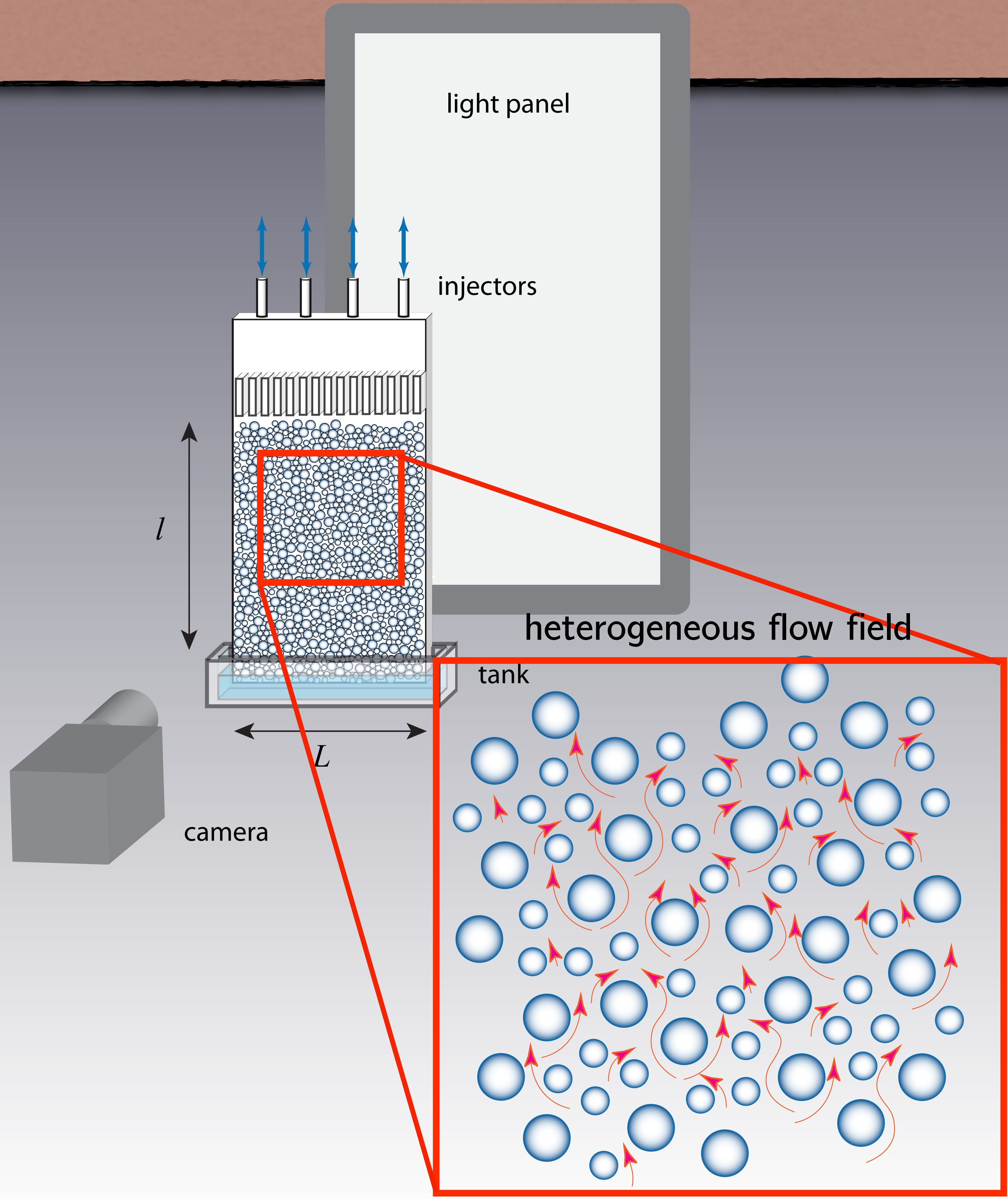
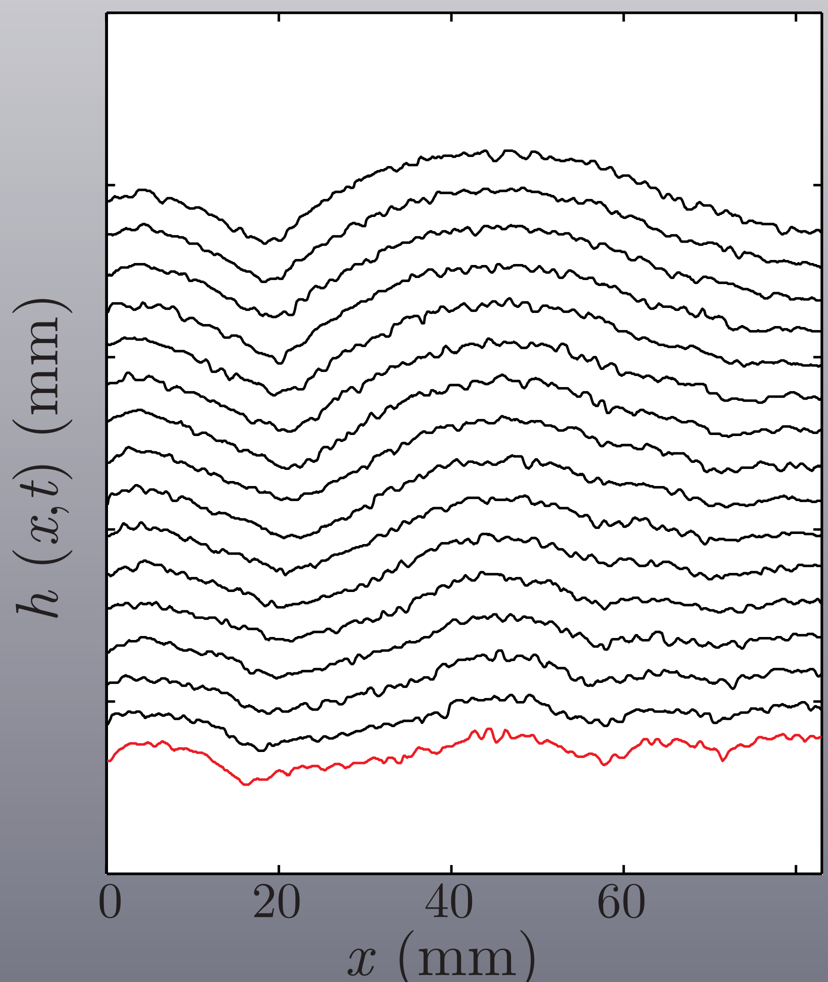
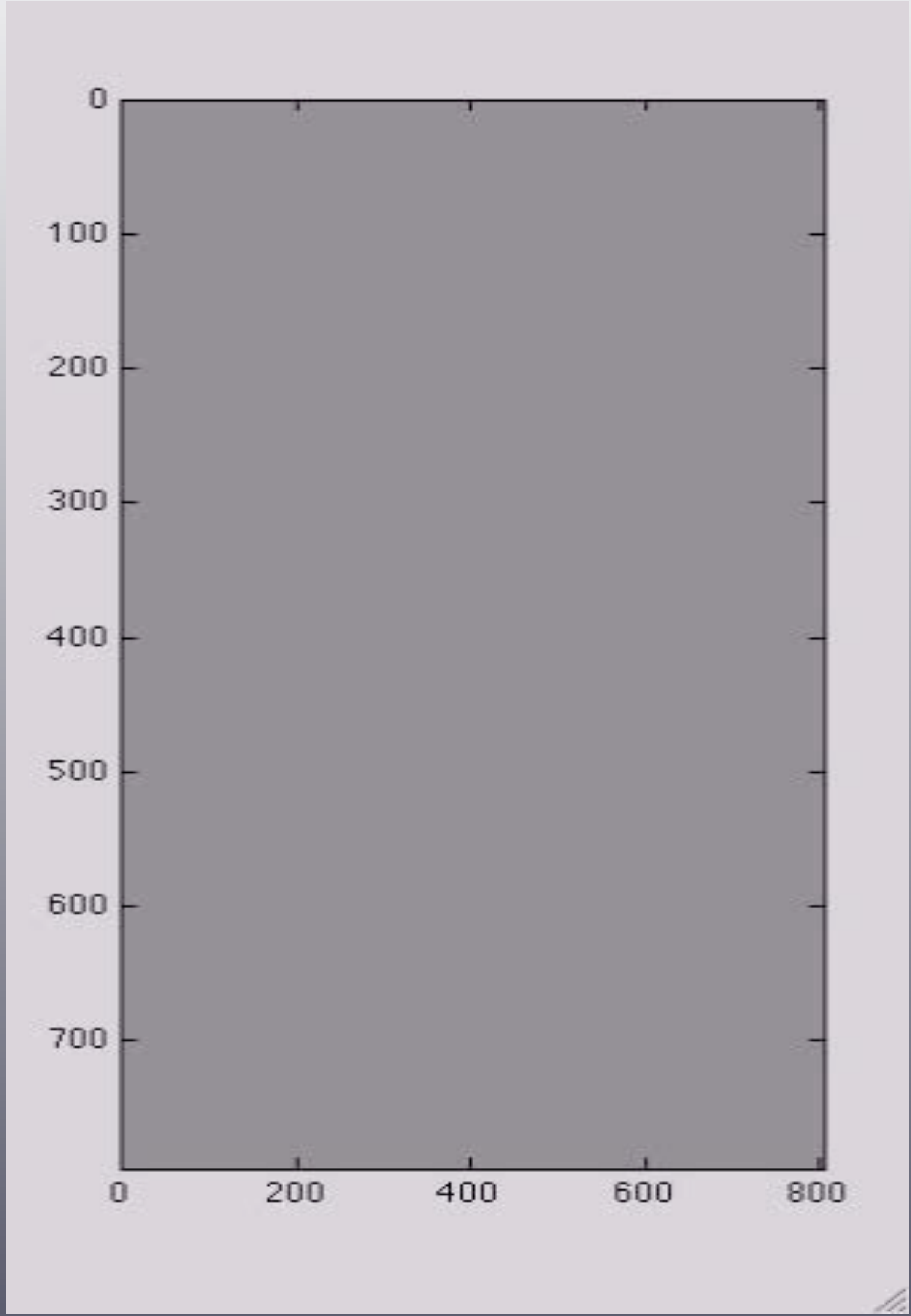


1 - Experimental setup

- Reaction front propagation without disordered flow





1 - Experimental setup

- **Tracers dispersion experiments: measurements of the local flow velocity**

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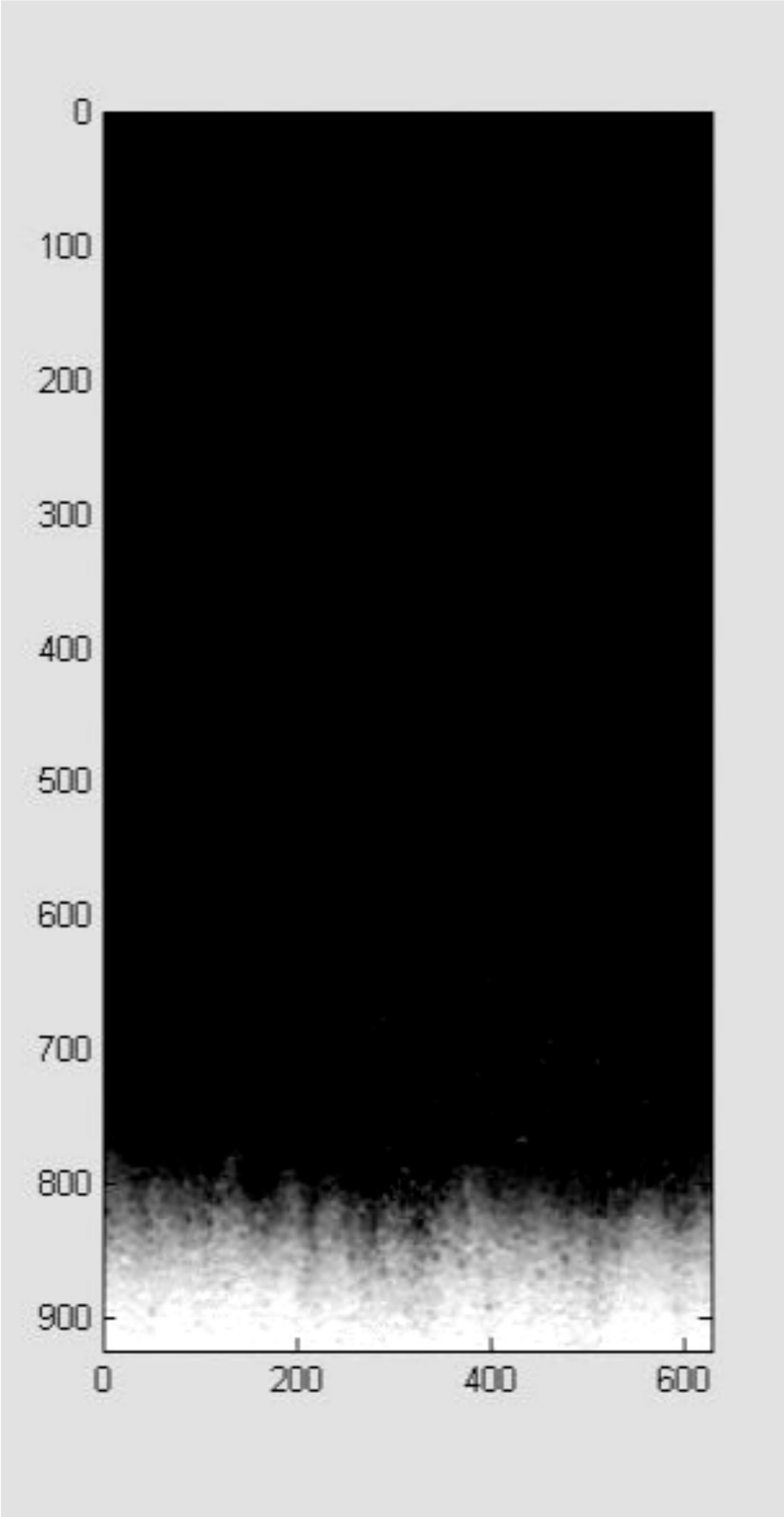

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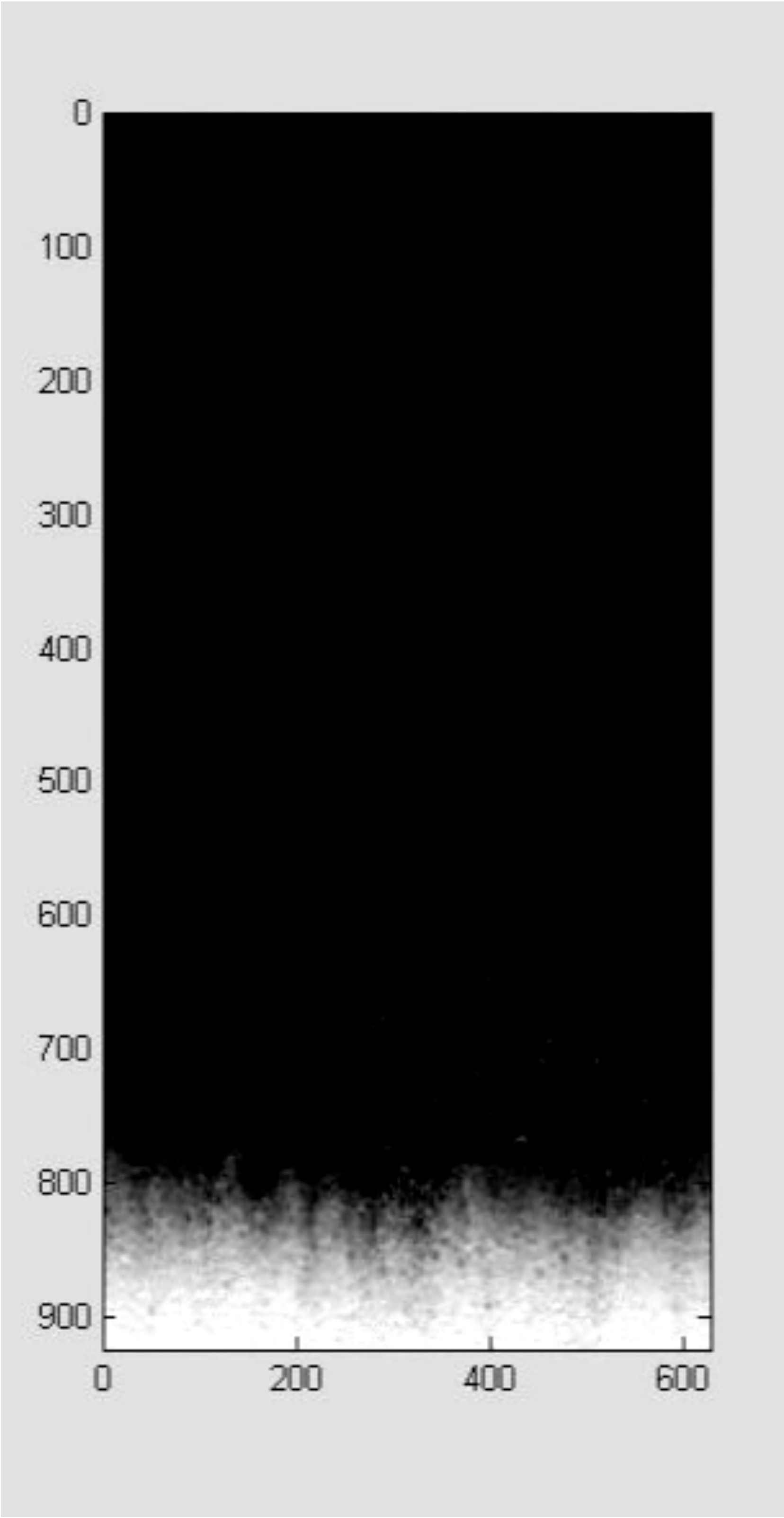

Fluctuations correlation length:

$$d_{\parallel} = 1.8 \pm 0.1\,\mathrm{mm}$$

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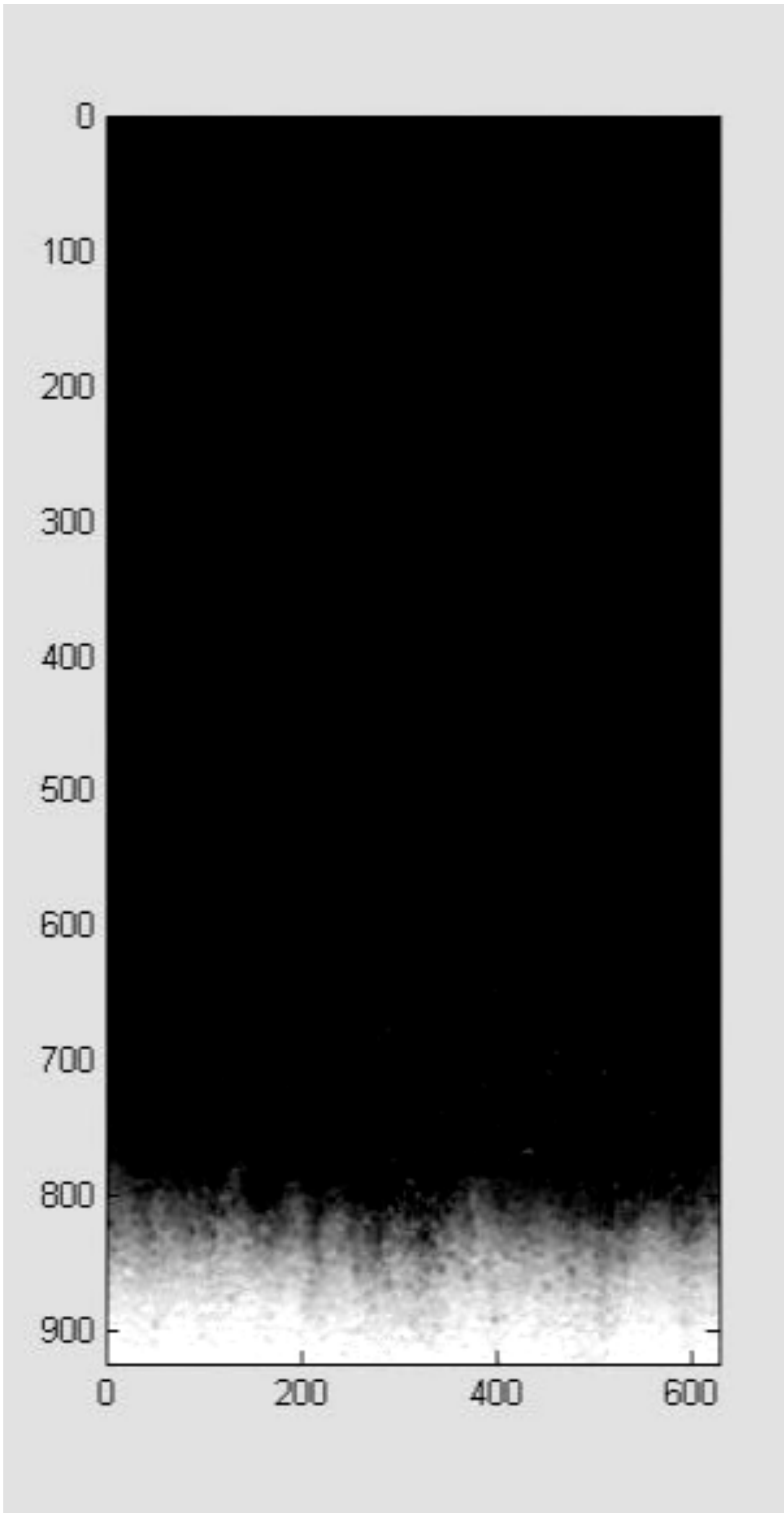

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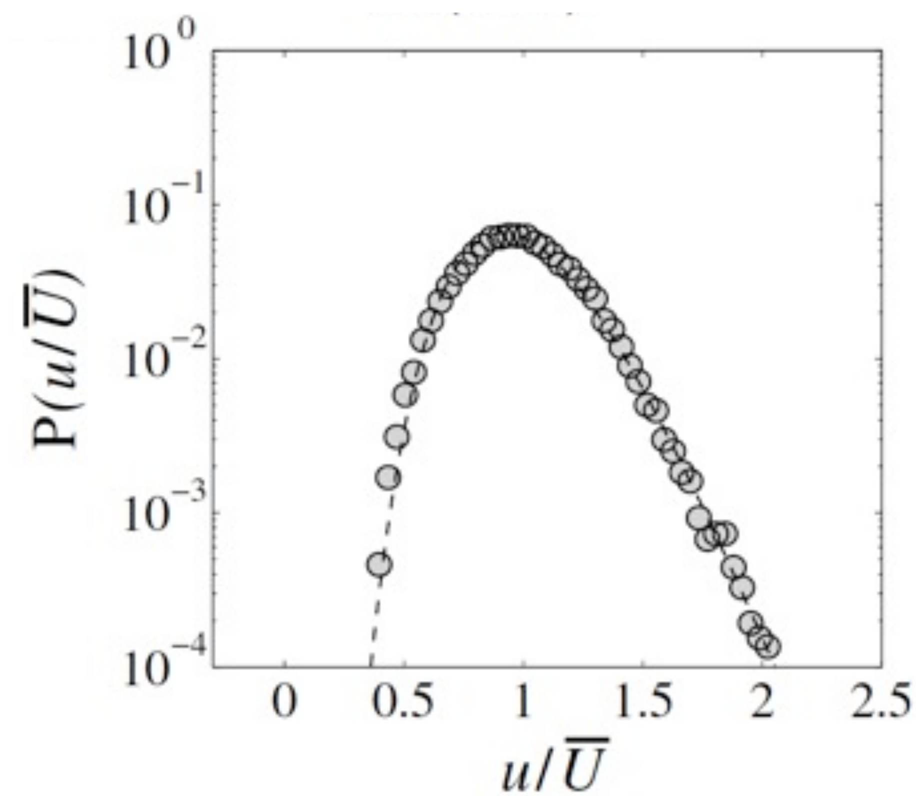
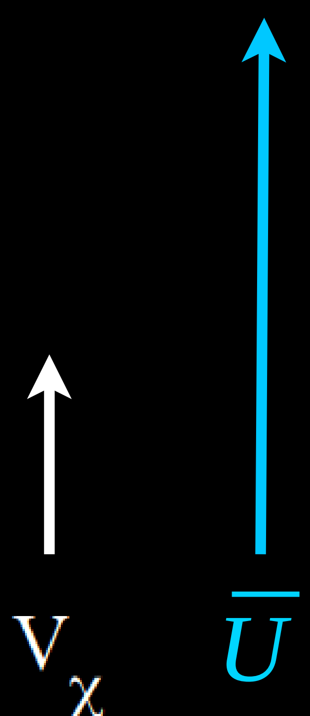
PDF of the local flow velocity fluctuations



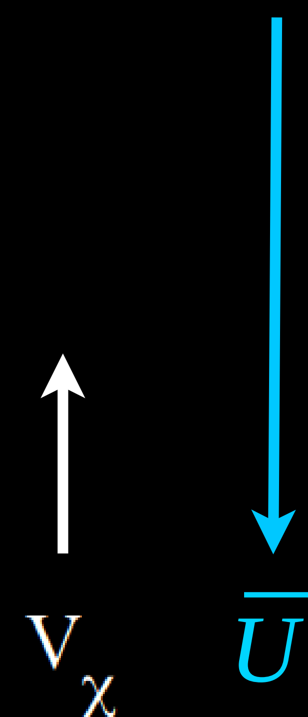
[Lebond & al. 1997]

PLAN

Supportive flow



Adverse flow



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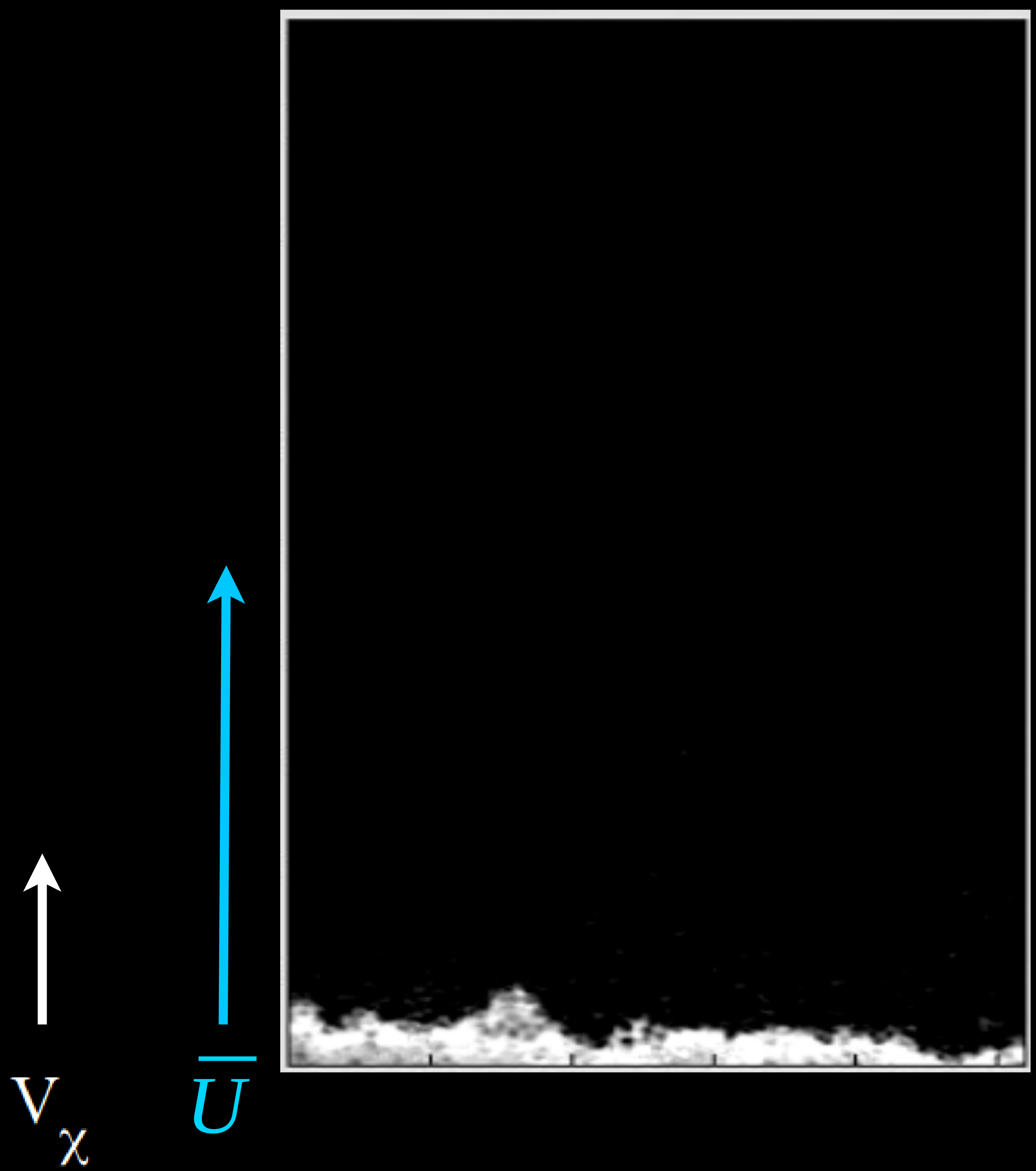

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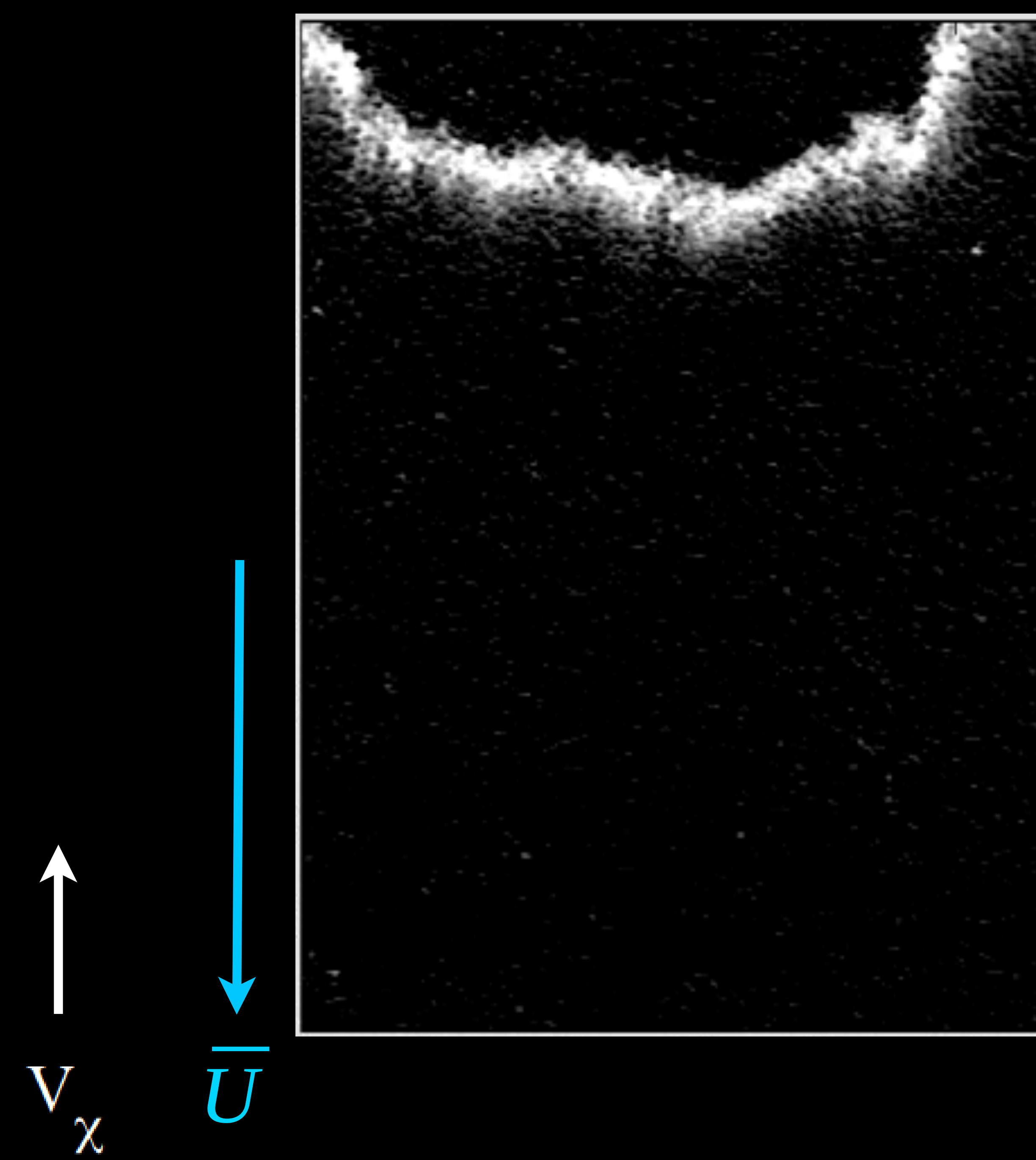

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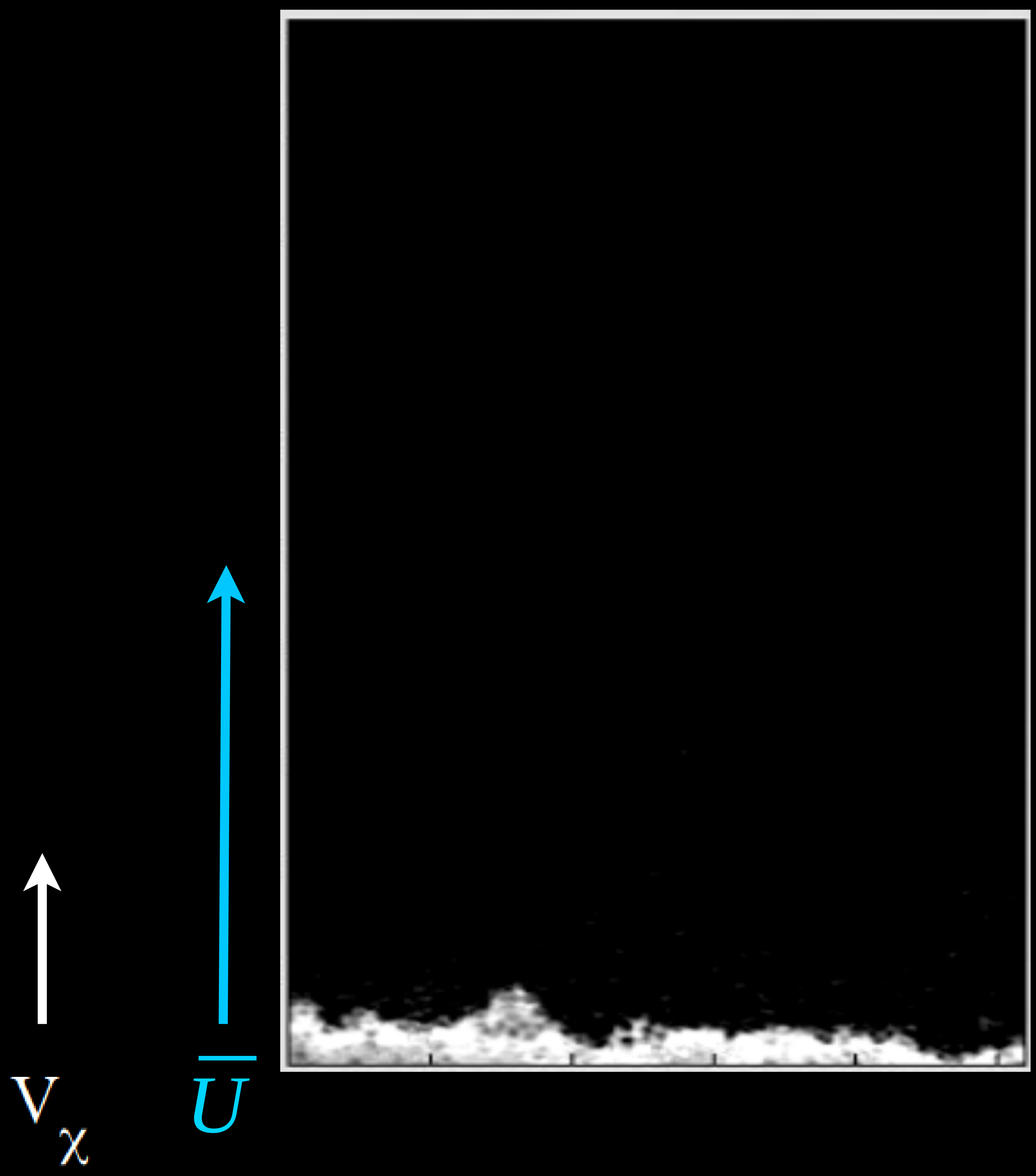

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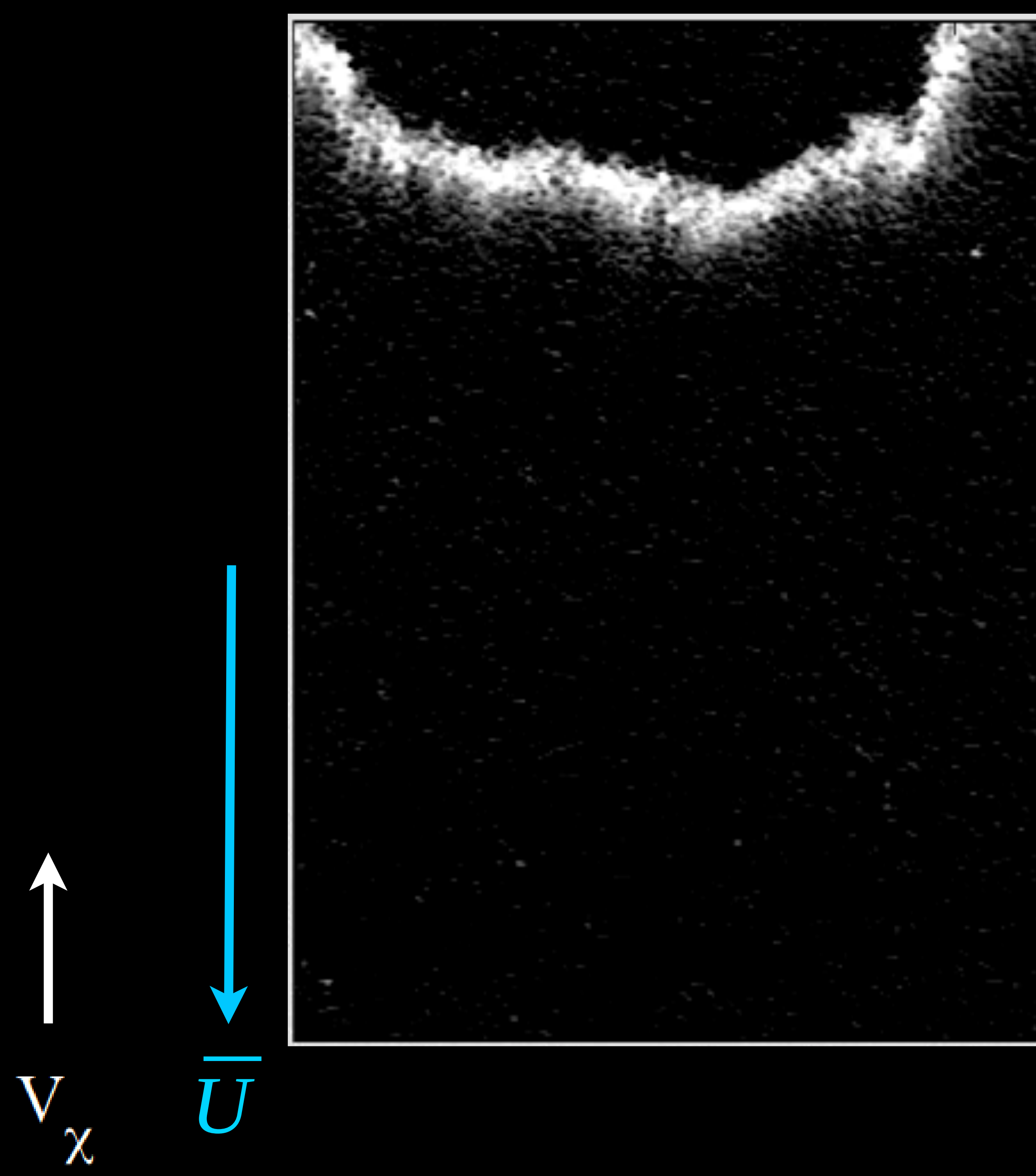
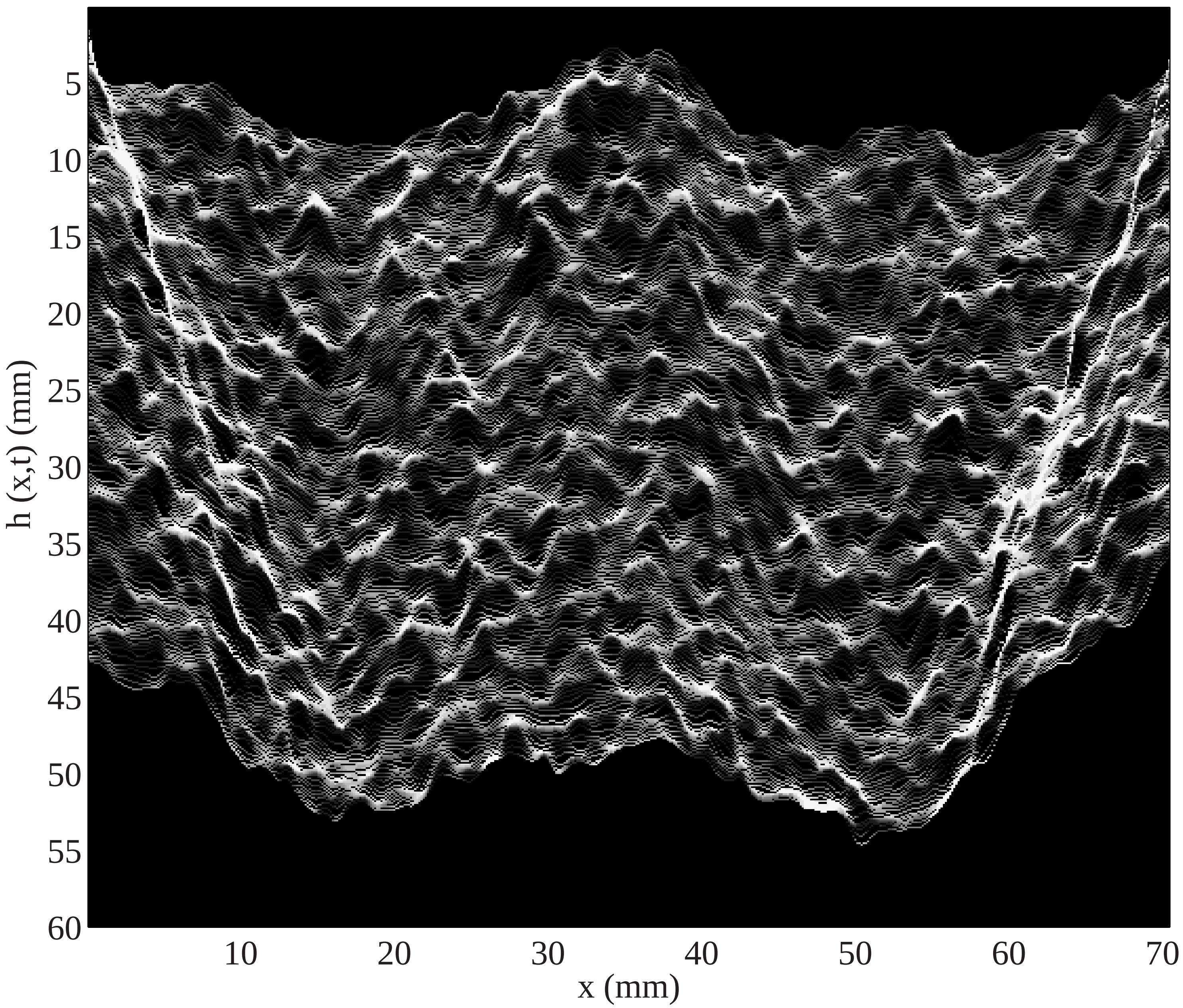


2 - Front dynamics in high flow strength

- **Front height spatiotemporal fluctuations measurements**



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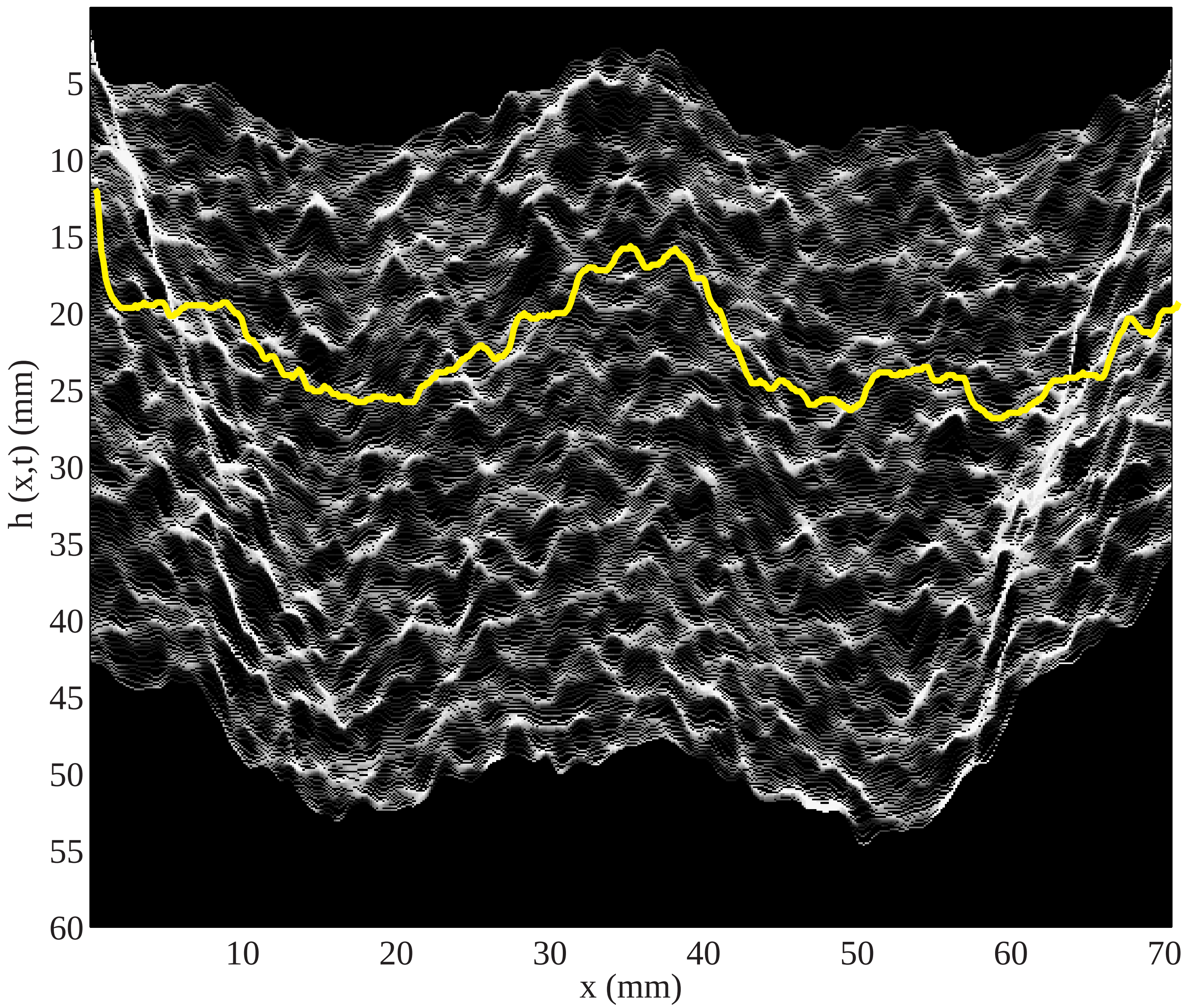

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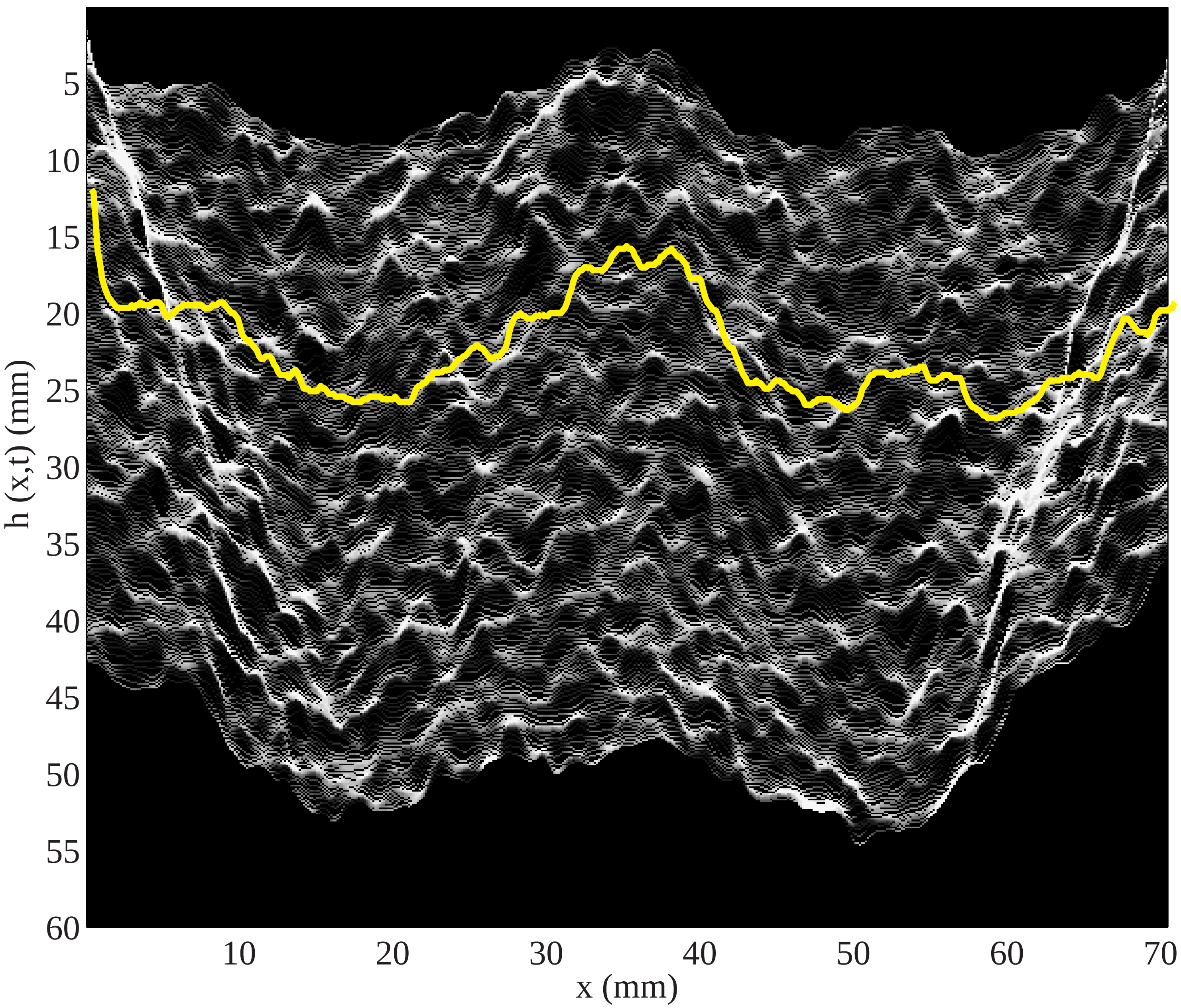

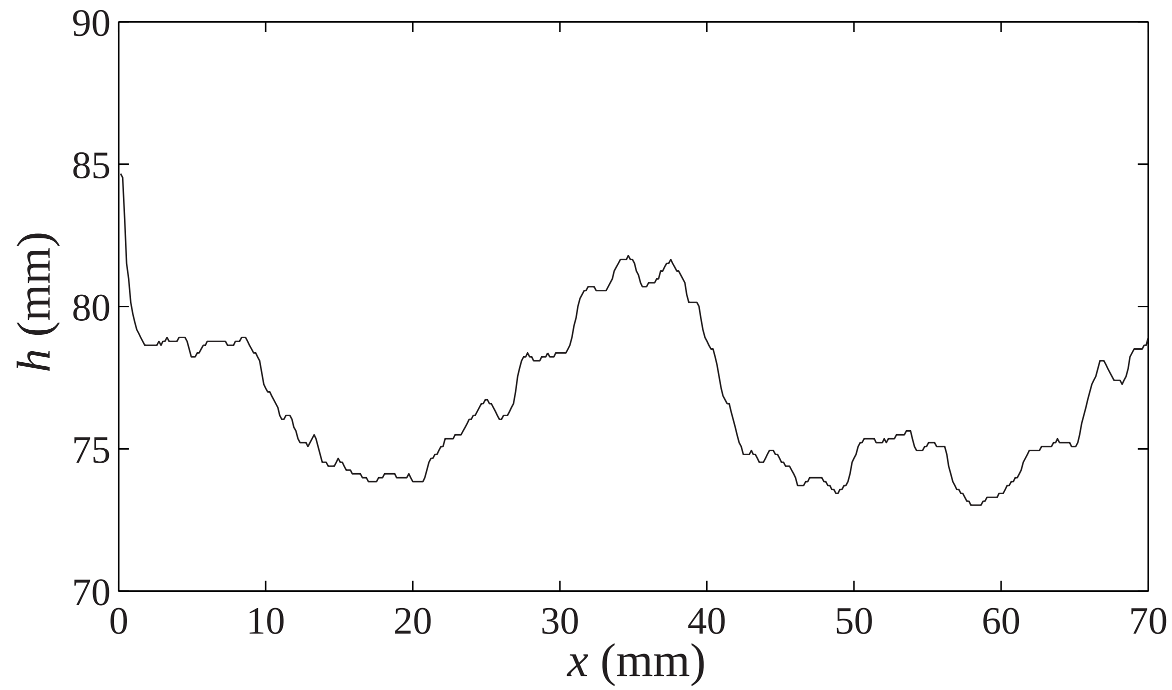

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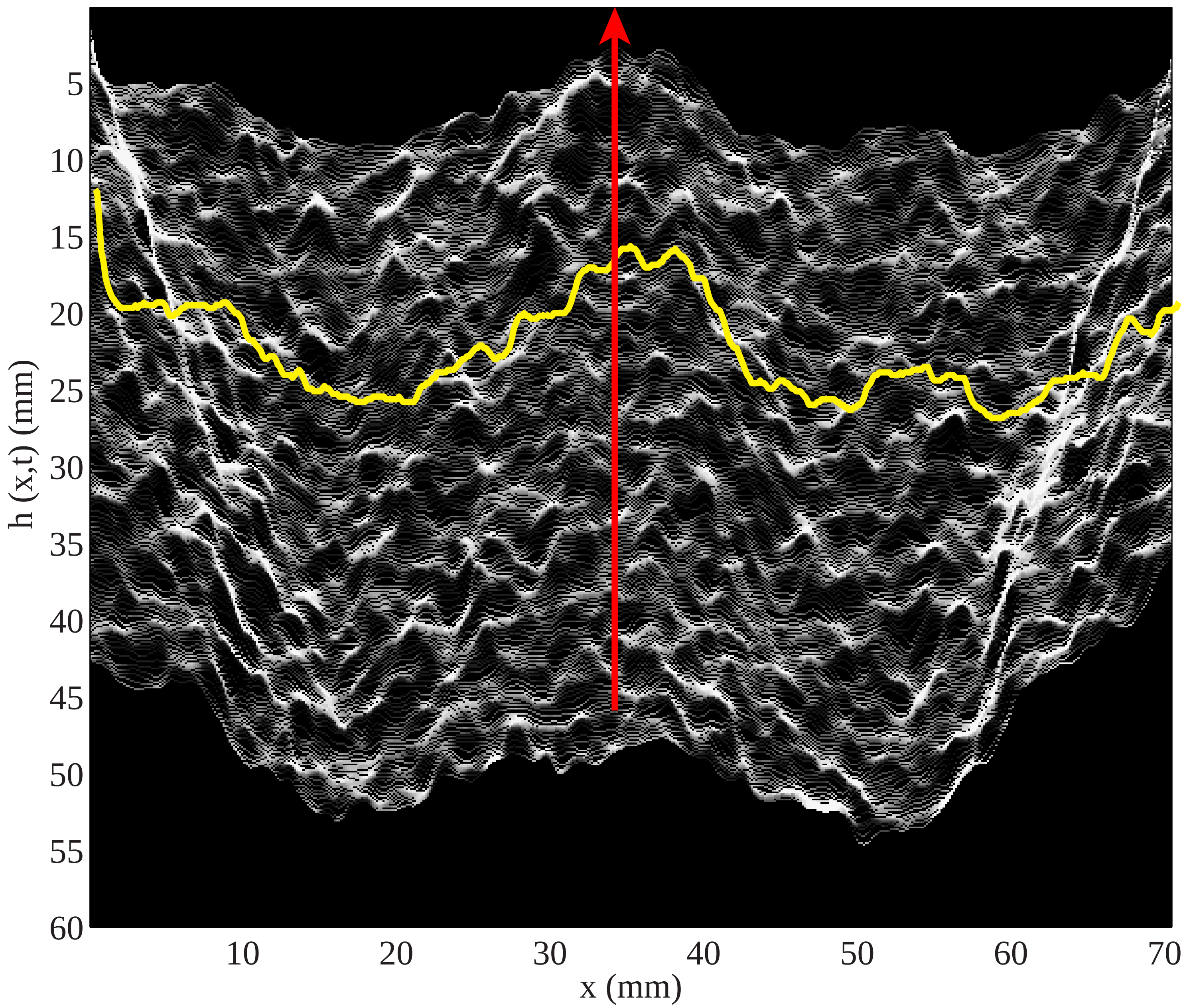

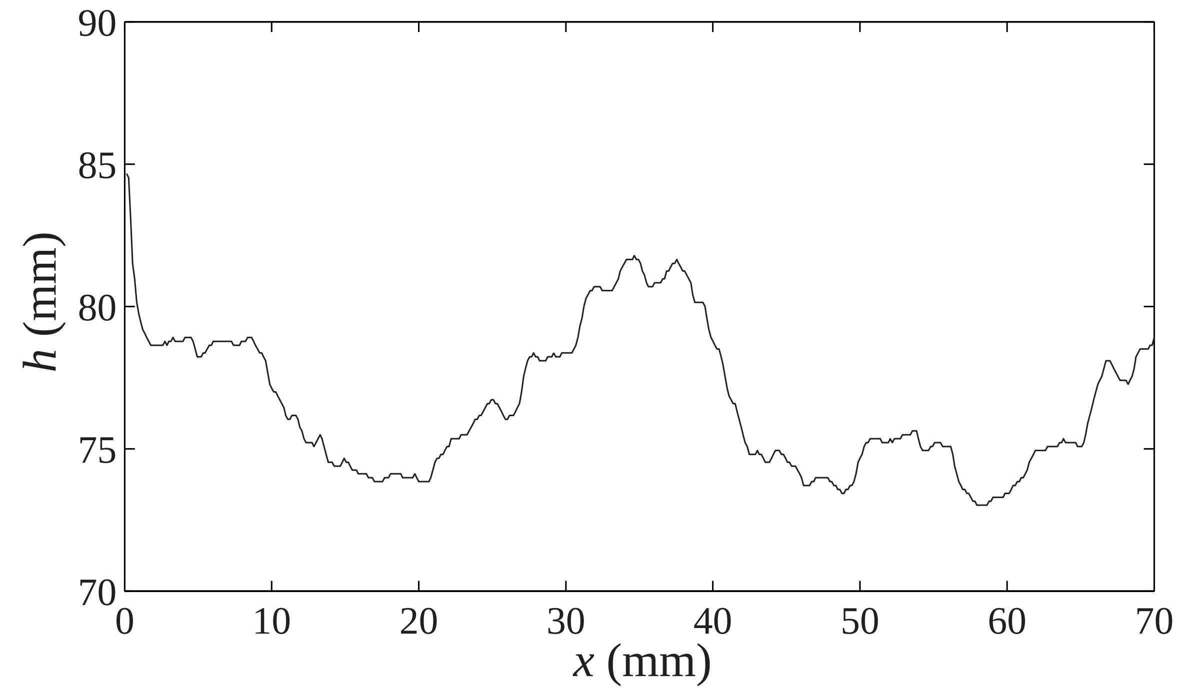

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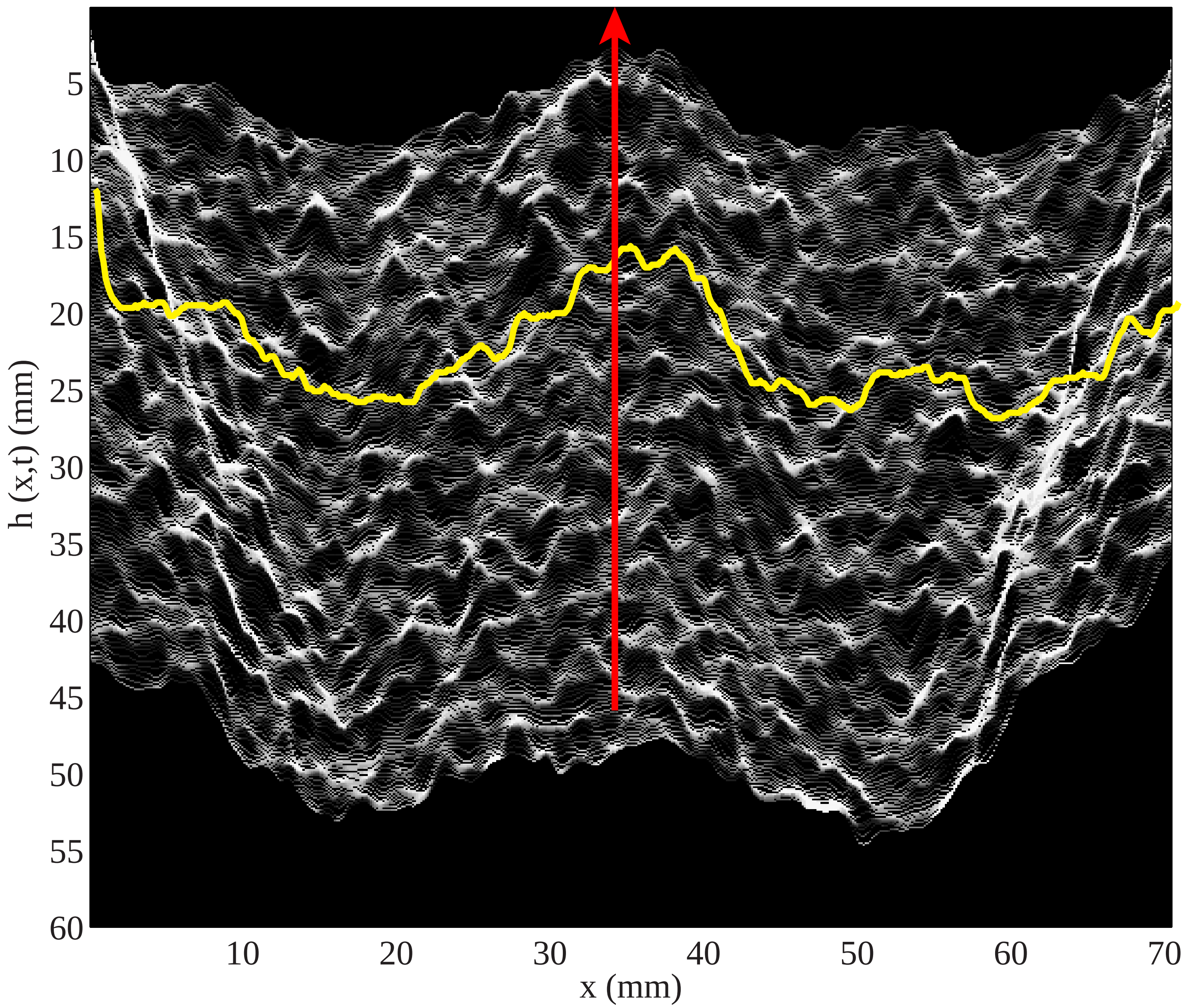

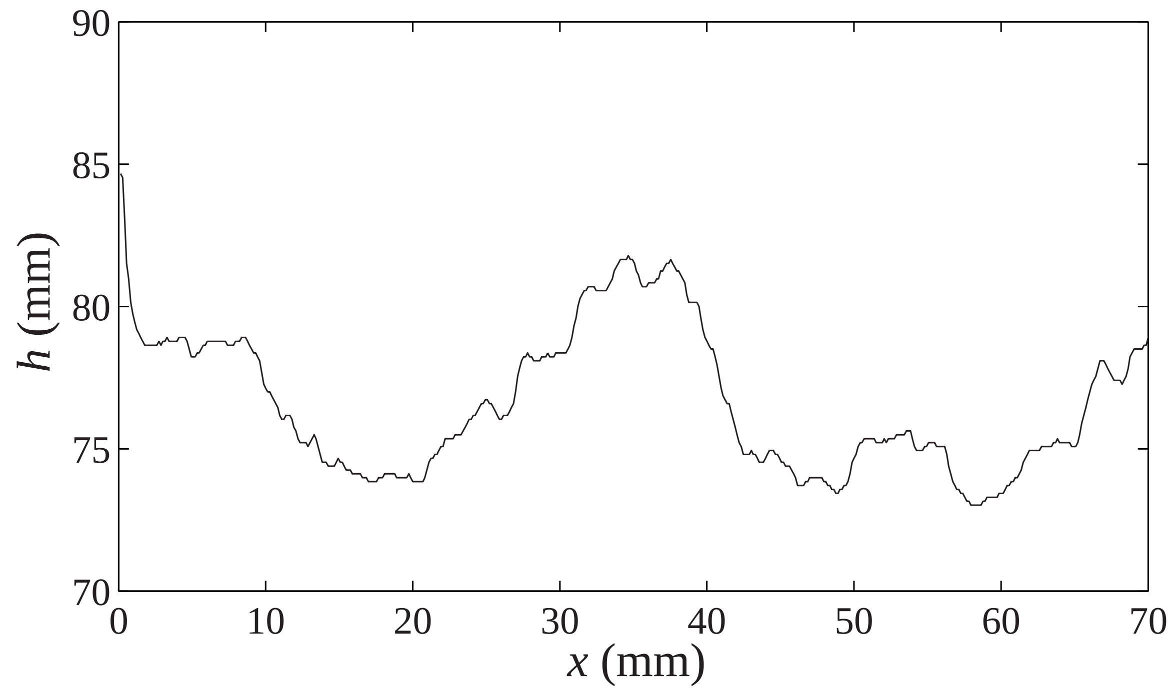

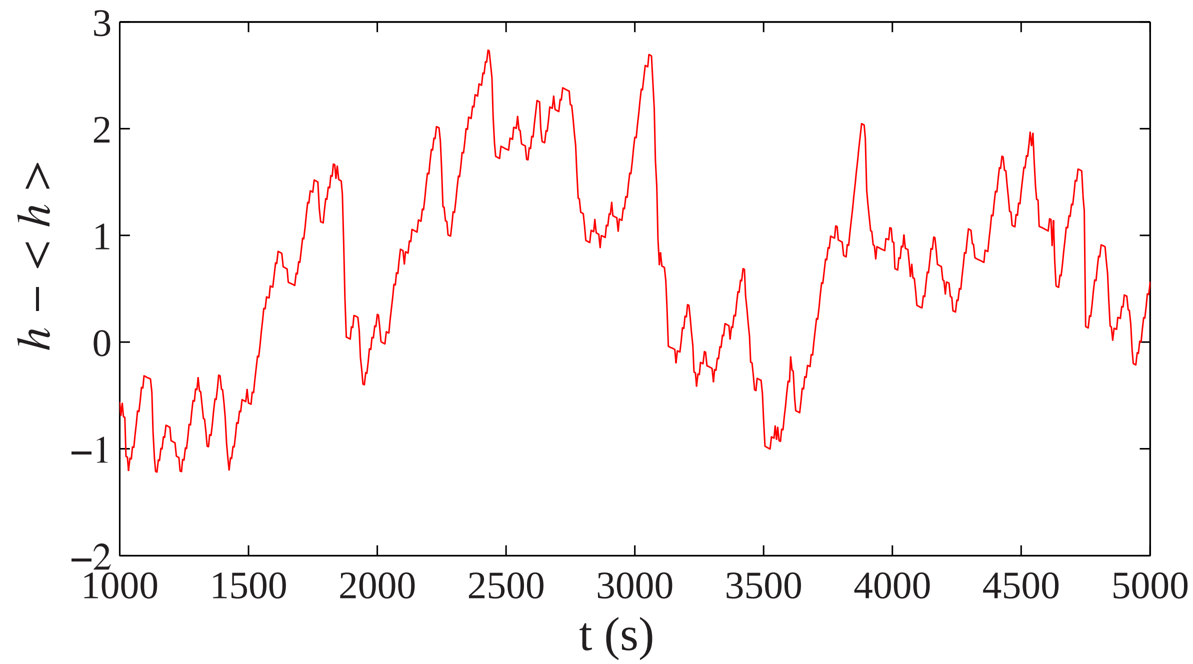

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- **Roughness** $w(\Delta x, t) = \left\langle \sqrt{\langle [h(x,t) - \langle h \rangle_{\Delta x}]^2 \rangle_{\Delta x}} \right\rangle_L$

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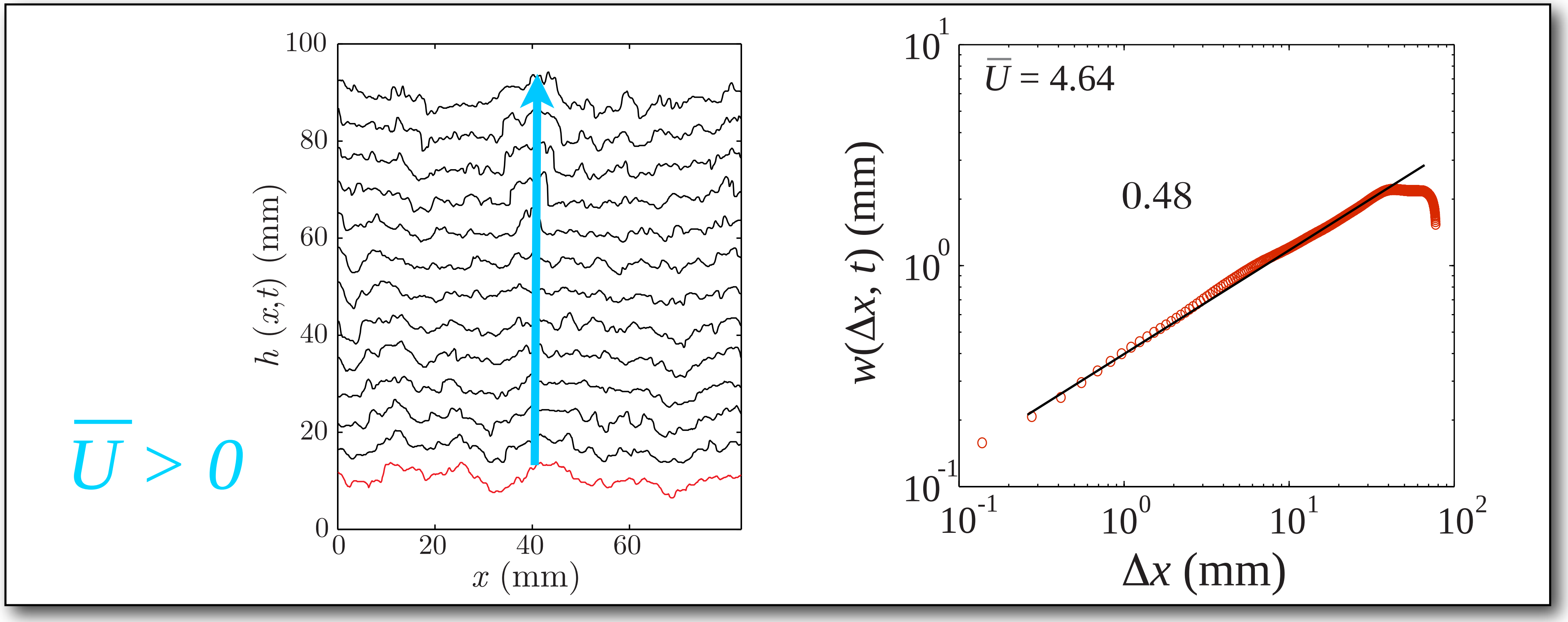

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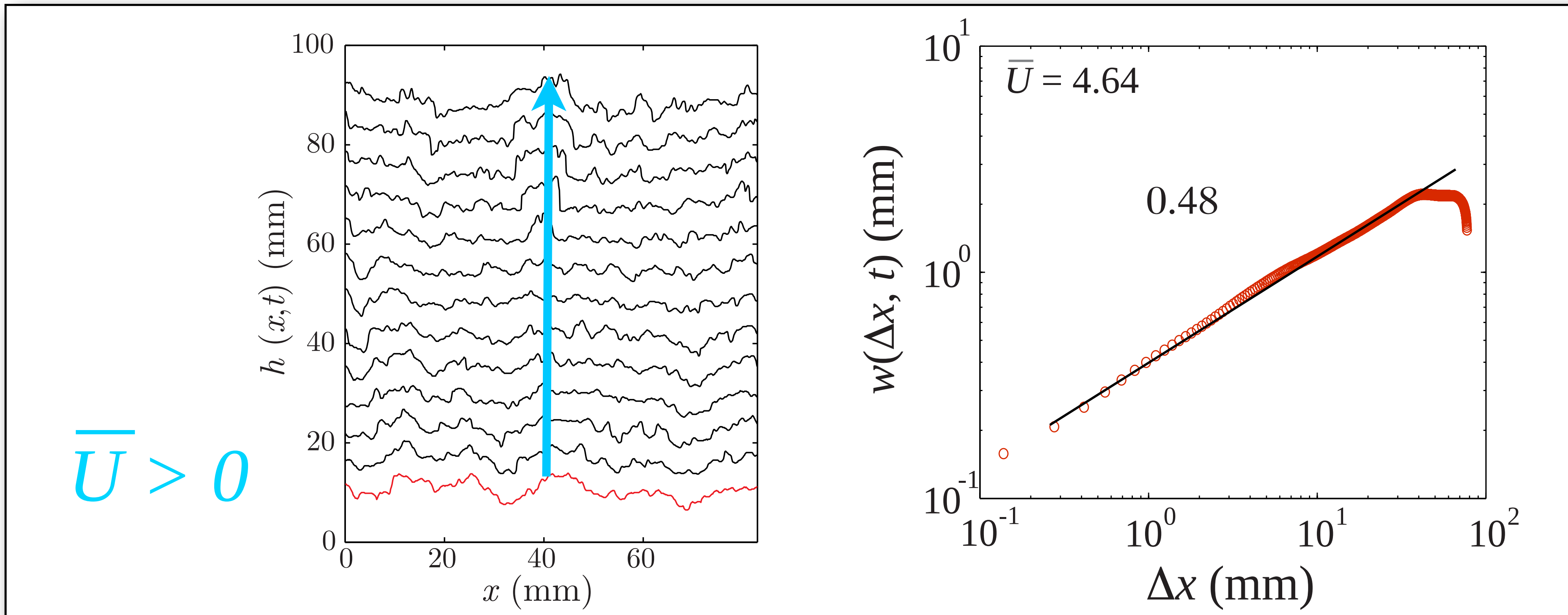

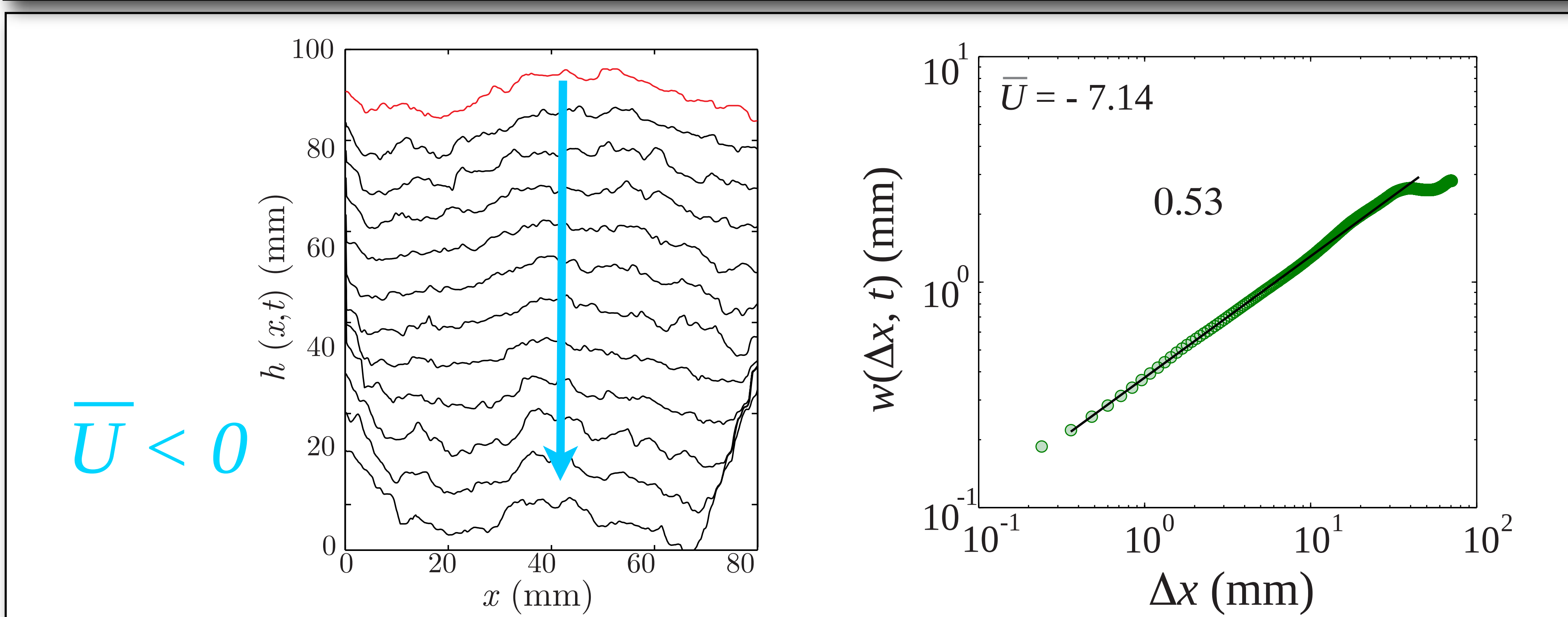

2 - Front dynamics in high flow strength

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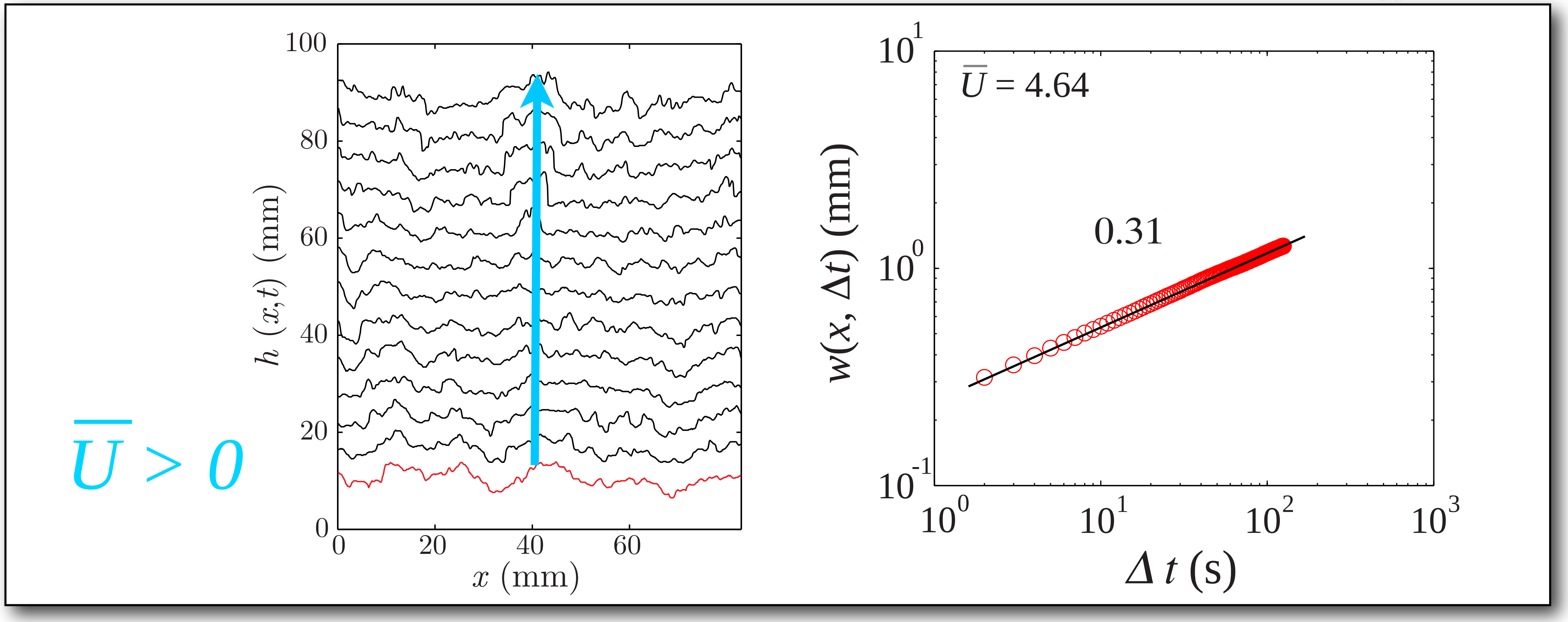
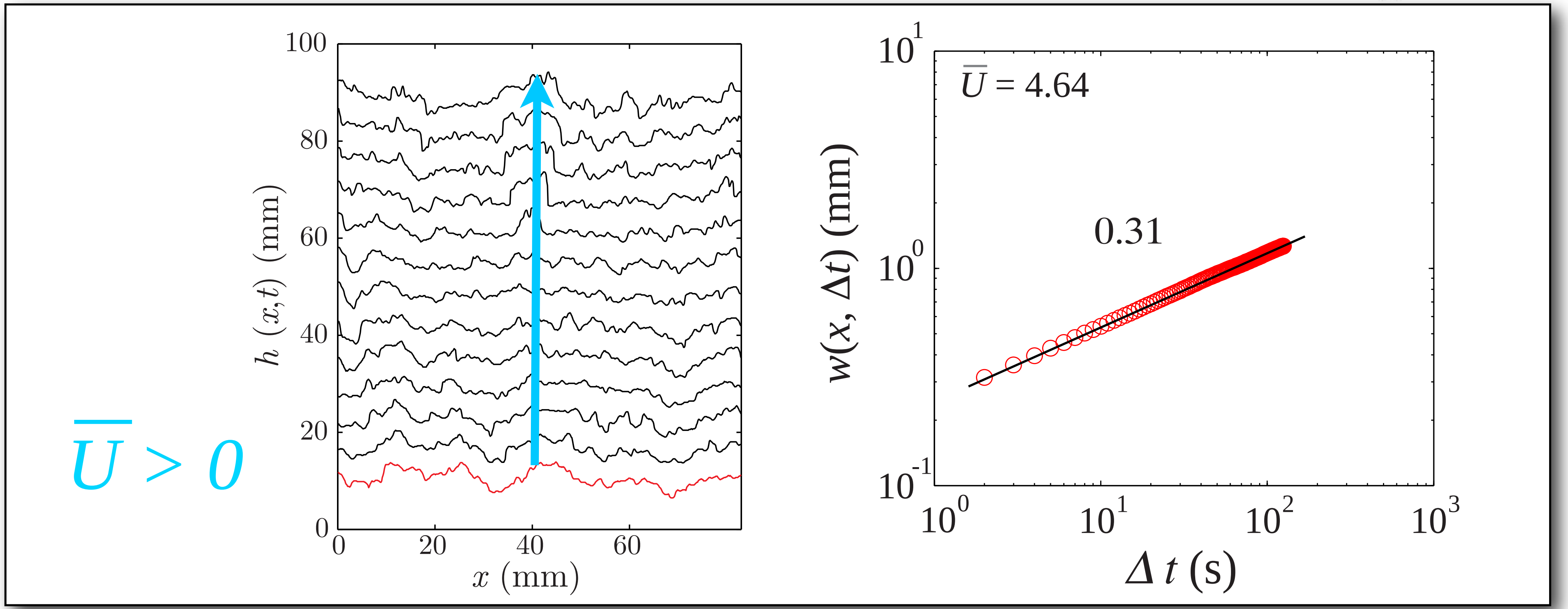


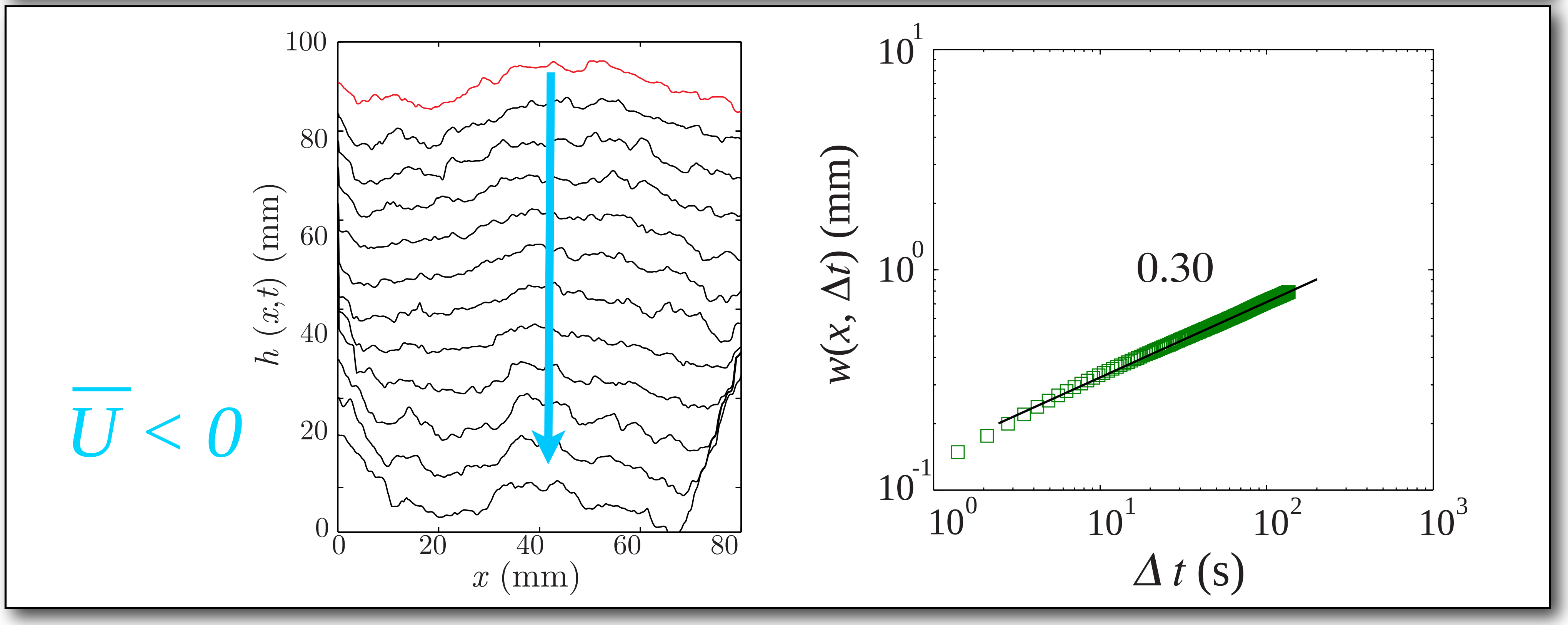
2 - Front dynamics in high flow strength

- **Temporal fluctuations** $w(x, \Delta t) = \left\langle \sqrt{\langle [h(x,t) - \langle h \rangle_{\Delta t}]^2 \rangle_{\Delta t}} \right\rangle_T$

power law:

$w(x, \Delta t) \sim \Delta t^{\beta}$





2 - Front dynamics in high flow strength

- **Theory**

Nonlinear continum growth equation

Kardar-Parisi-Zhang (KPZ) model:

$$\frac{\partial h(x,t)}{\partial t} = \nu \nabla^2 h(x,t) + \frac{\lambda}{2} \left[\nabla h(x,t)\right]^2 + \eta(x,t) + f$$

[Kardar & al. 1986]

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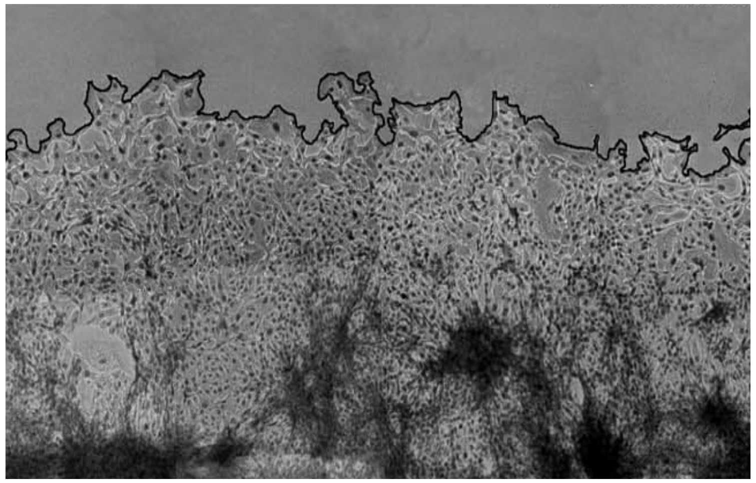
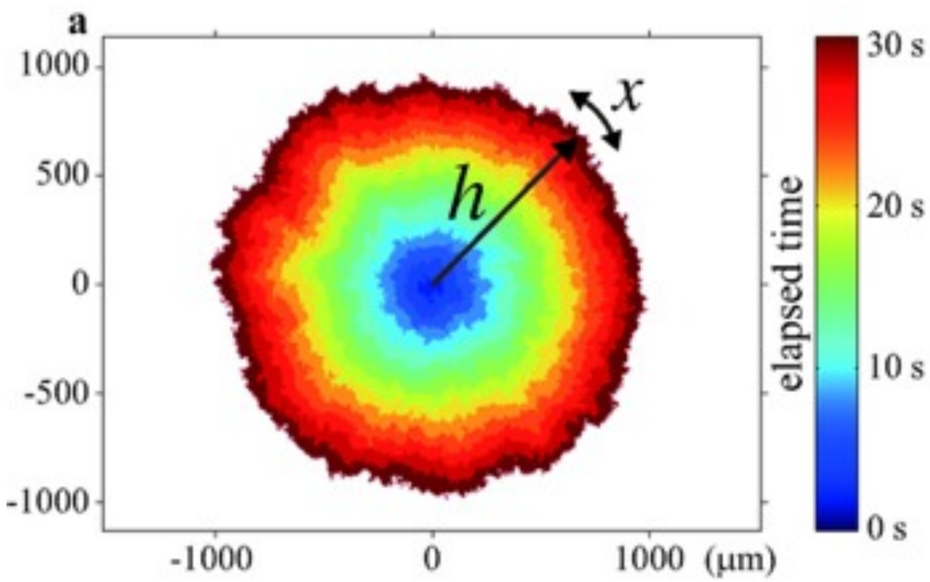
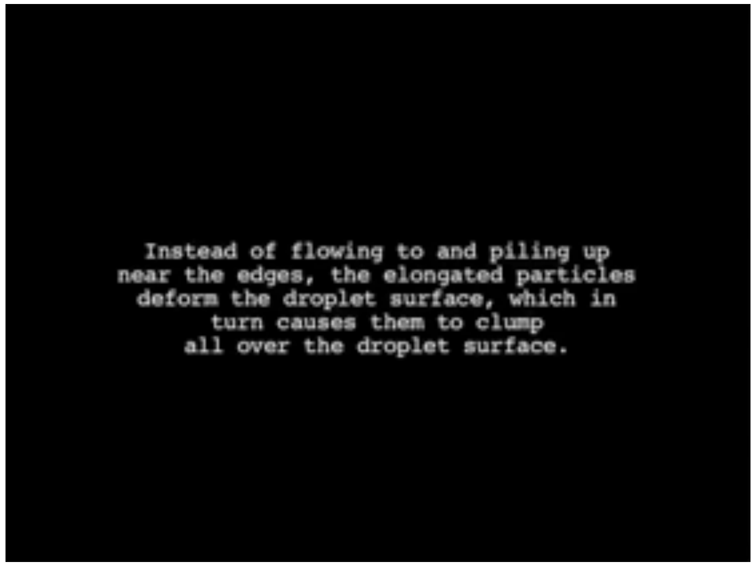
Huergo et al.2010



Takeuchi et al.2011



Yunker et al.2013



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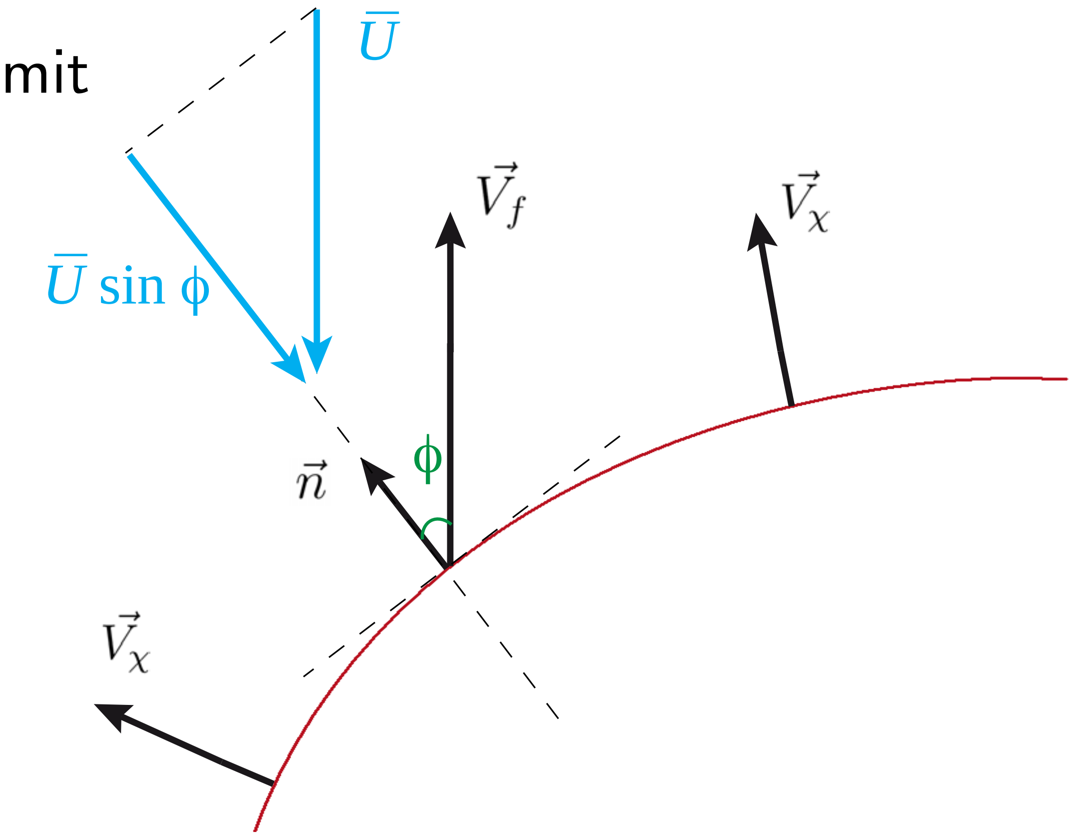

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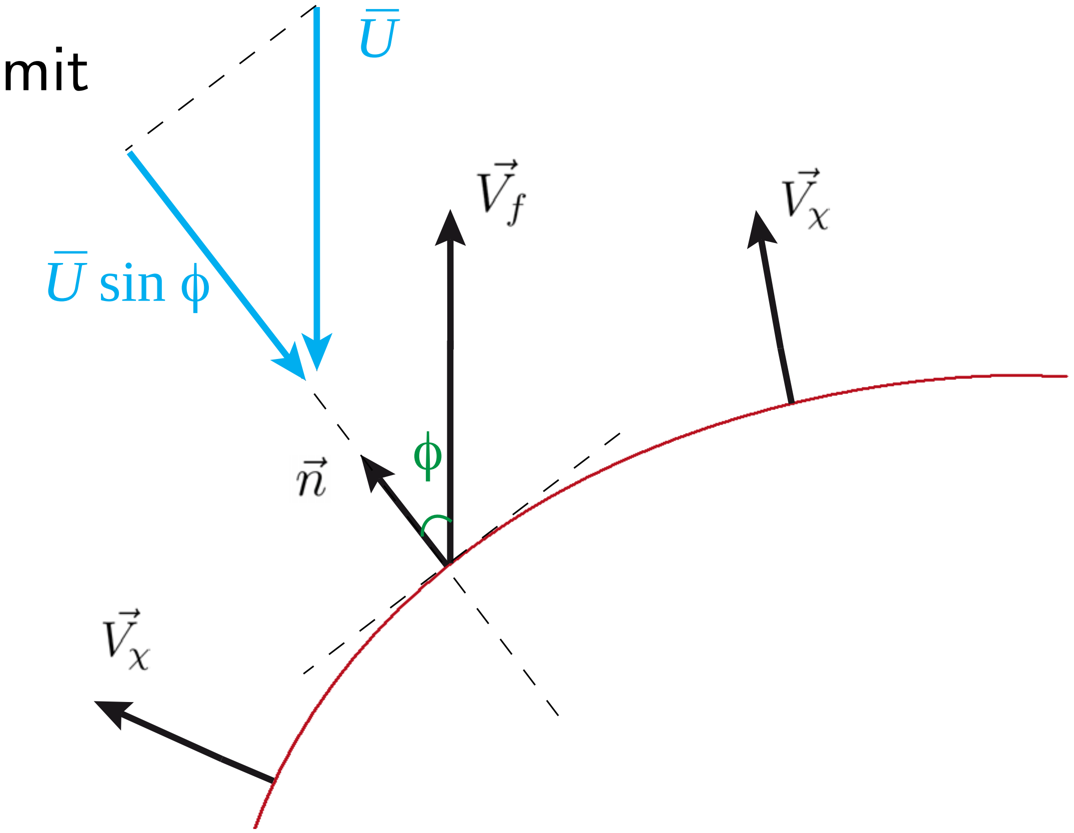

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Advection - Reaction - Diffusion equation in thin front limit

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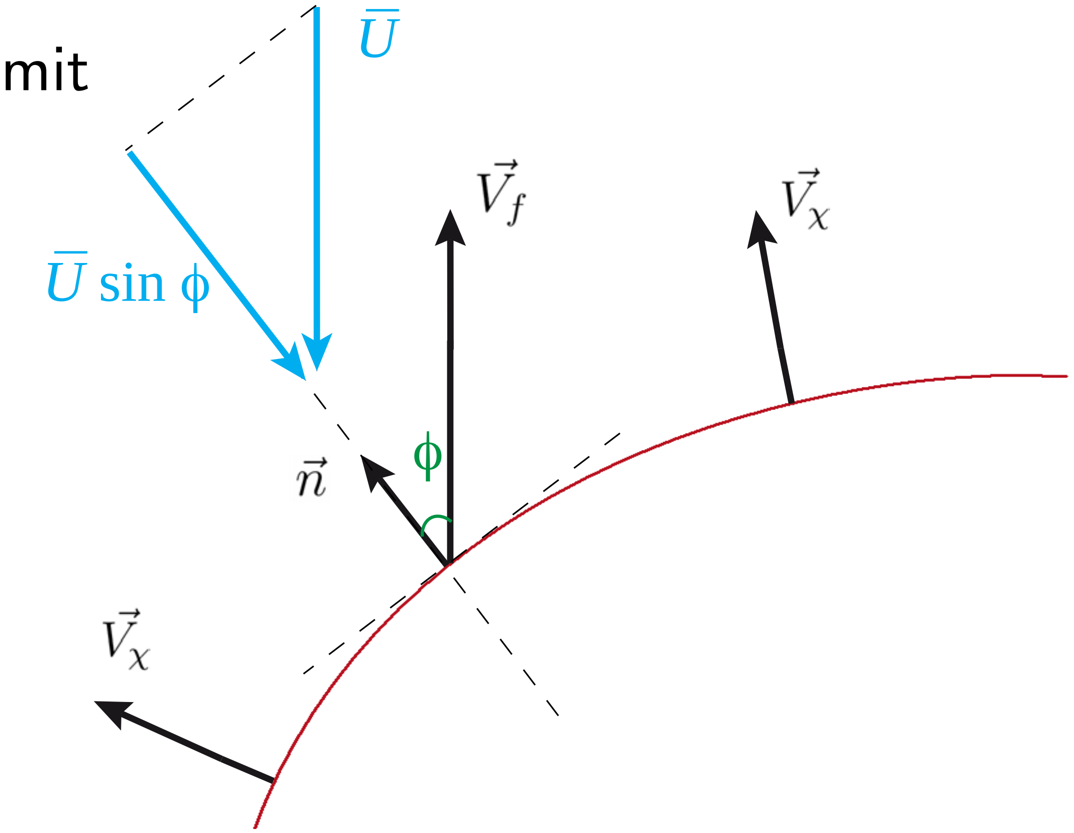

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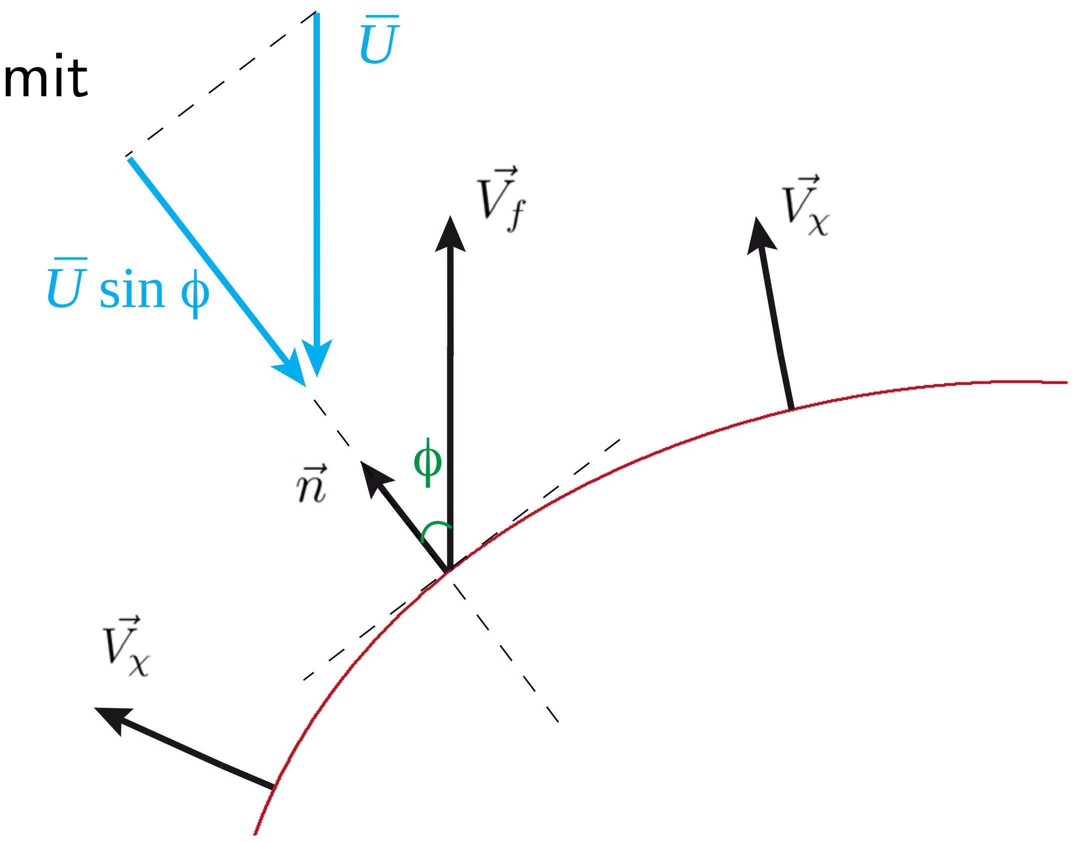

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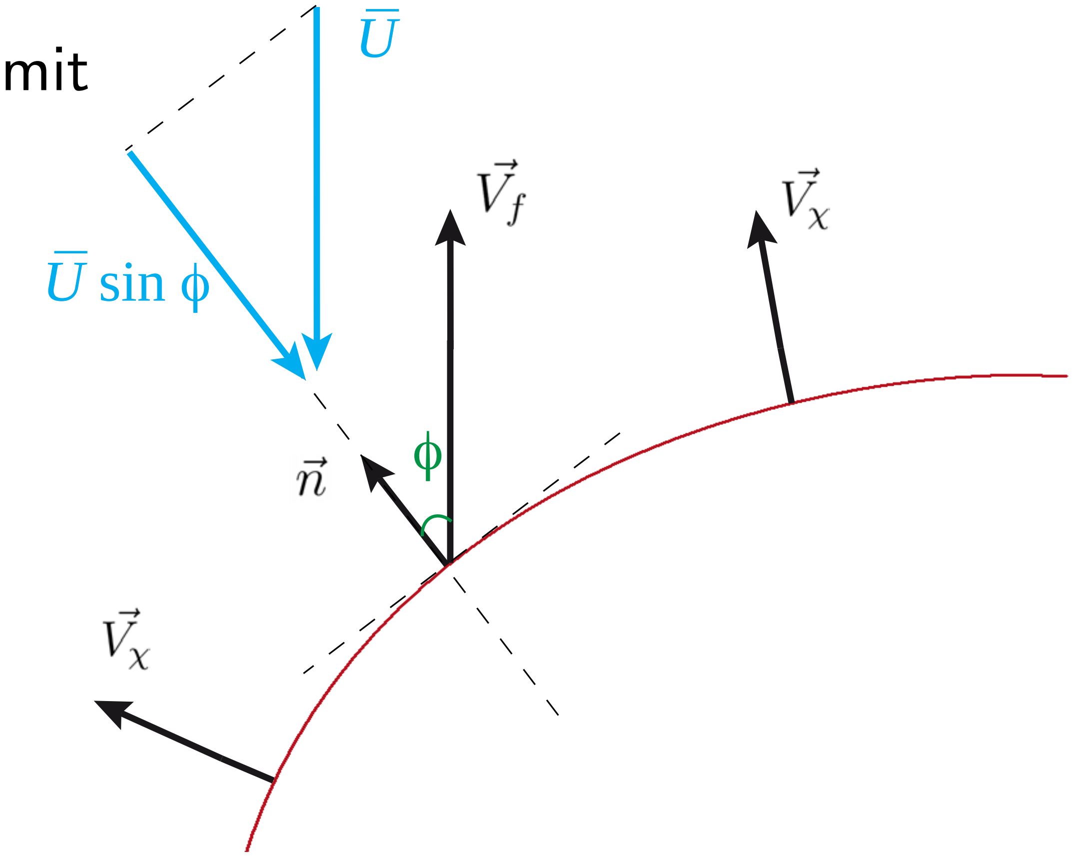

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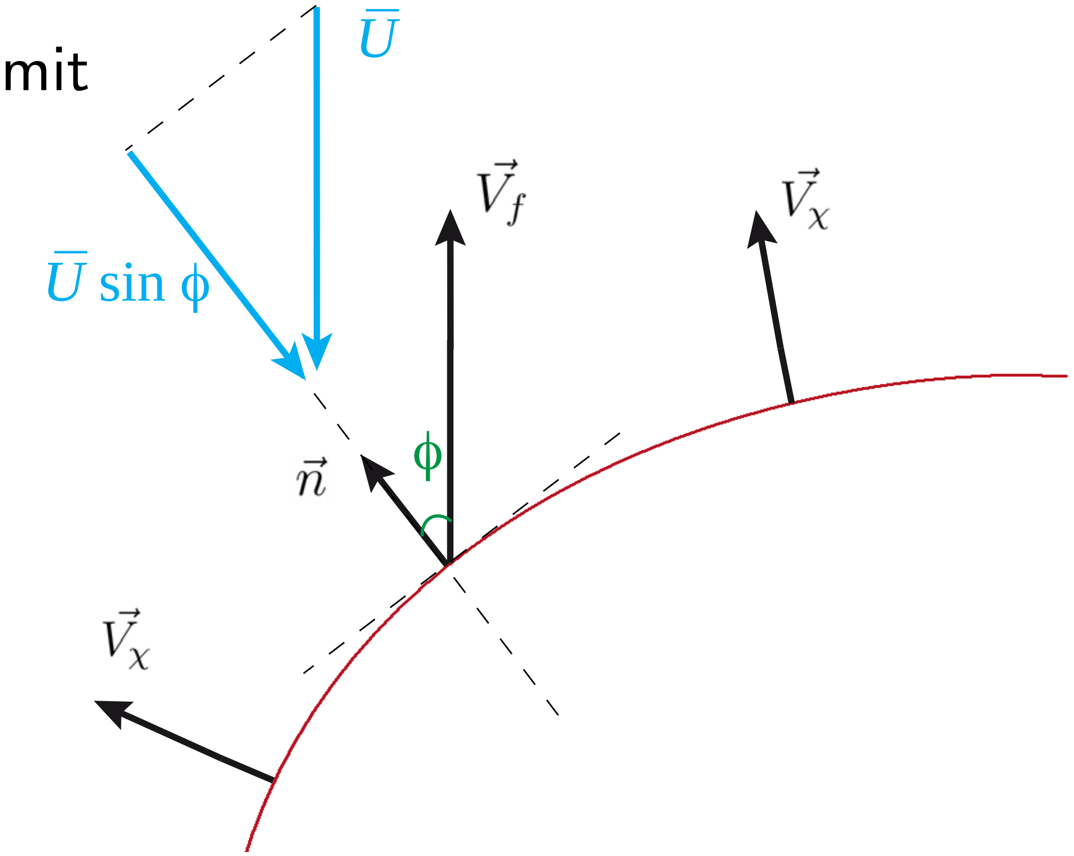

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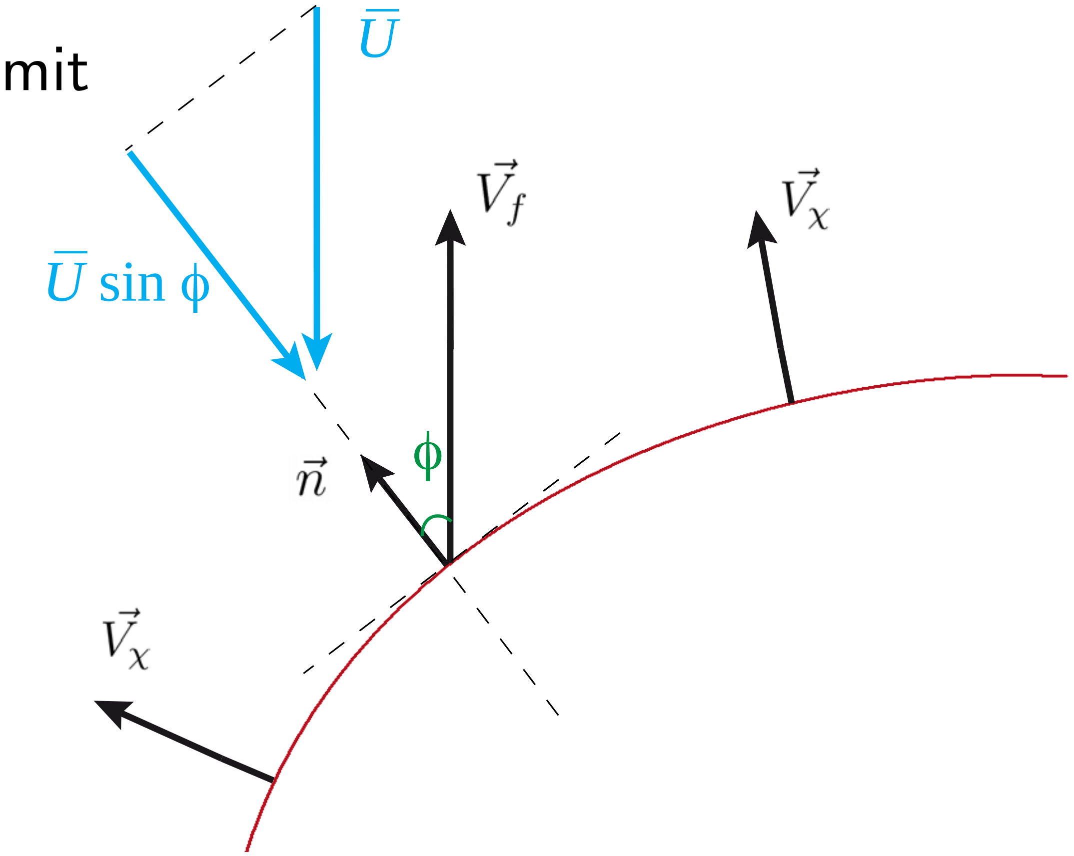

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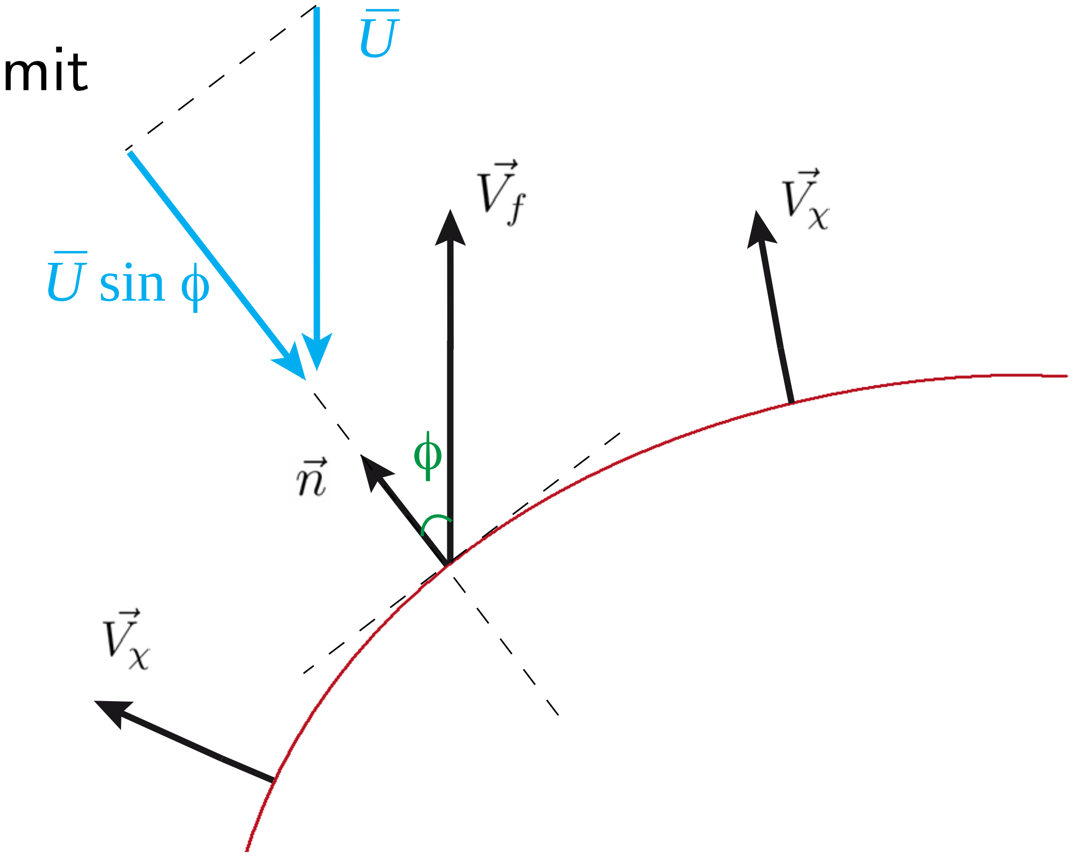

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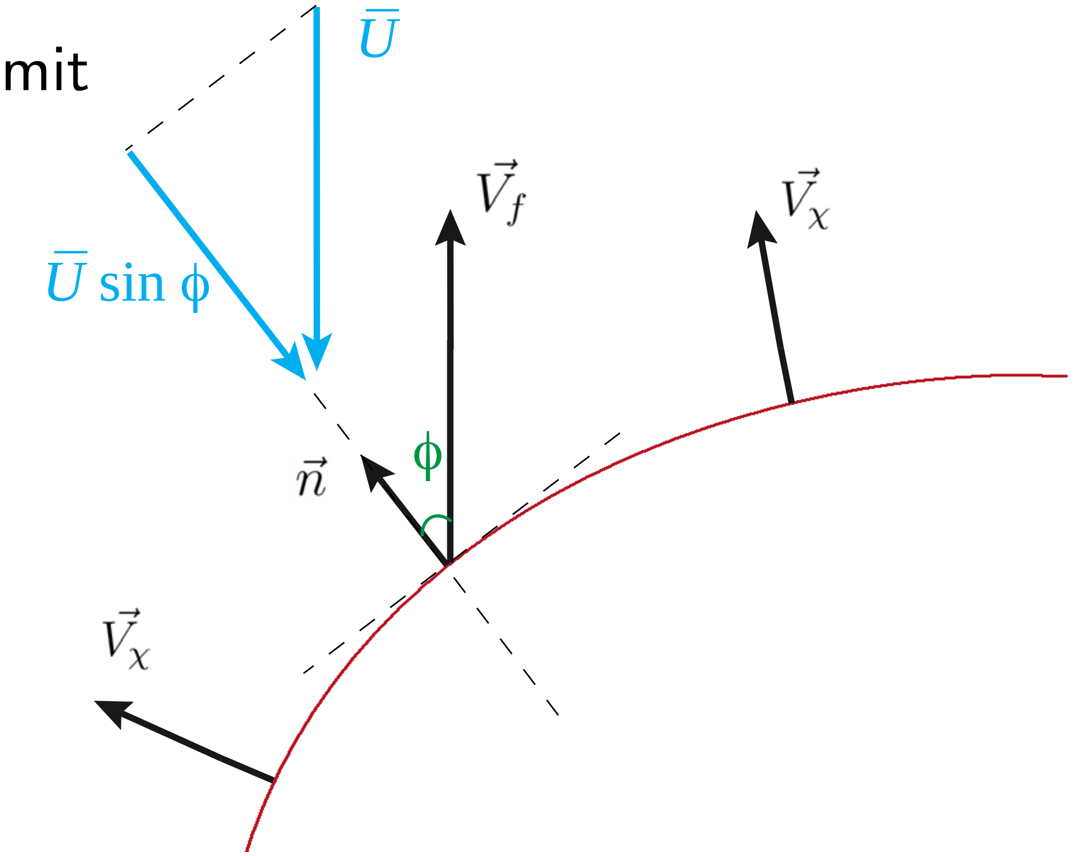

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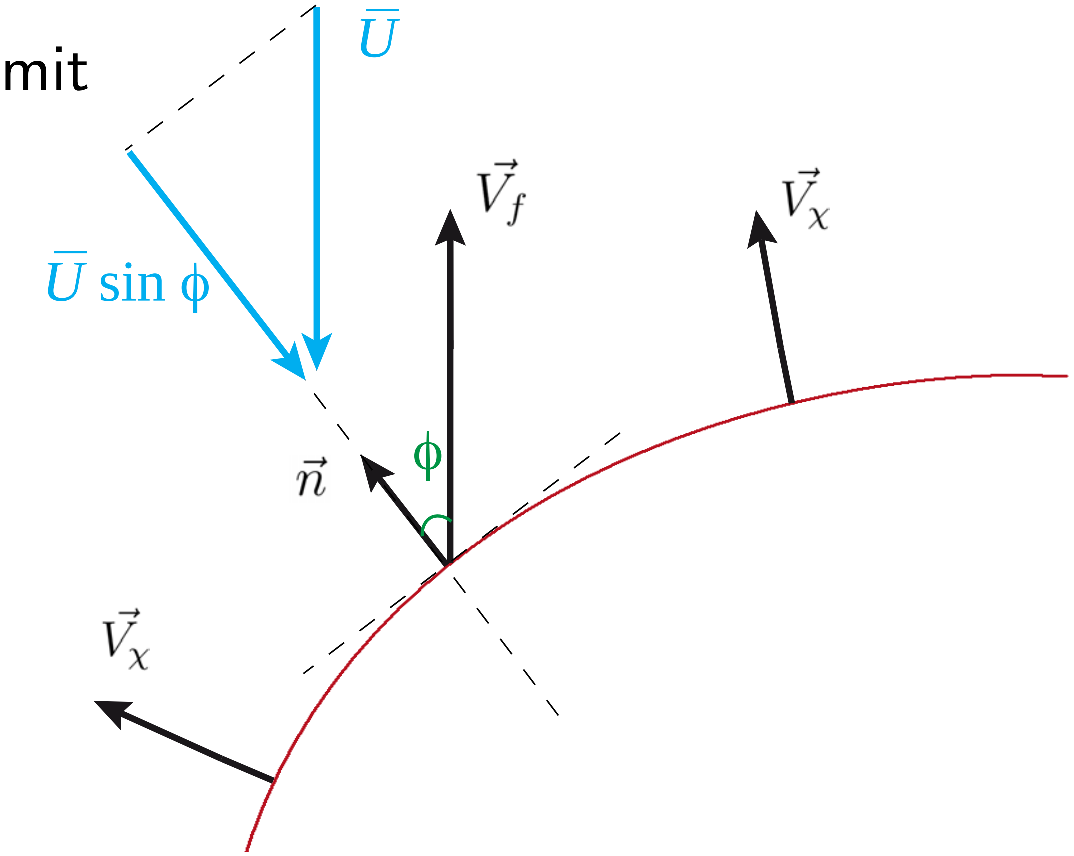

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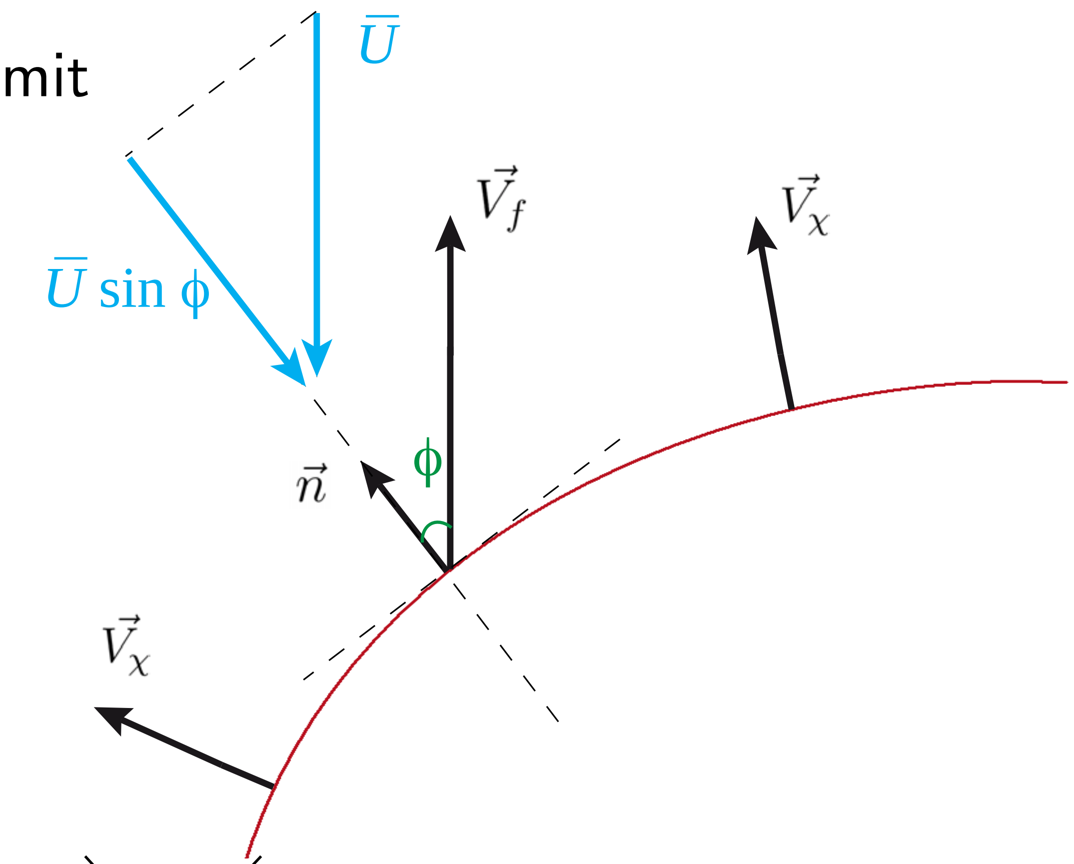

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PLAN

1 - Experimental

2 - Front dynamics in high flow strength

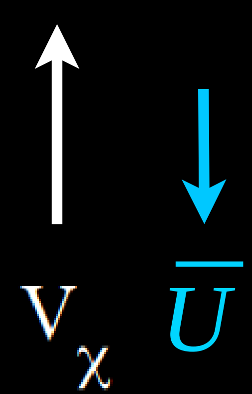
3 - Pinning process in low flow strength

4 - Transcient dynamics and universality

5 - Conclusion and perpectives

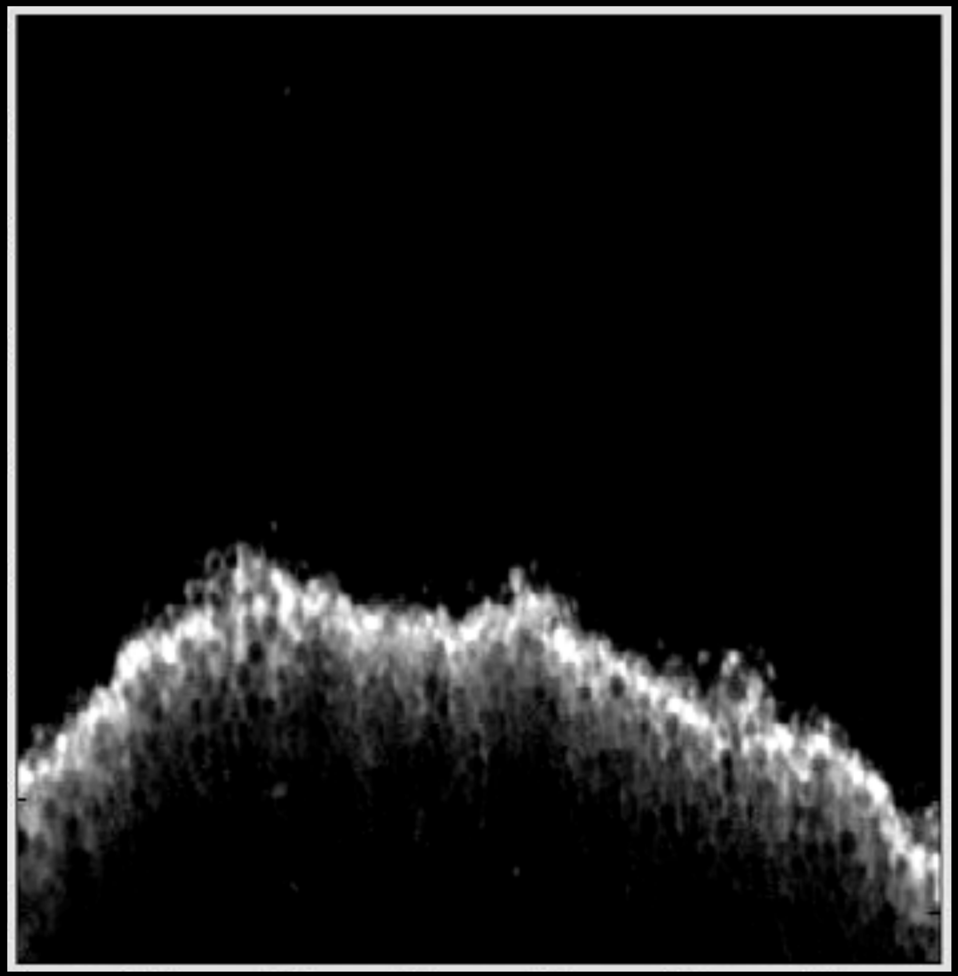
Adverse flow

upward



Adverse flow

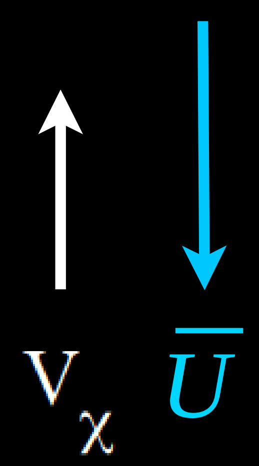
upward



V_χ $\overline{U}$

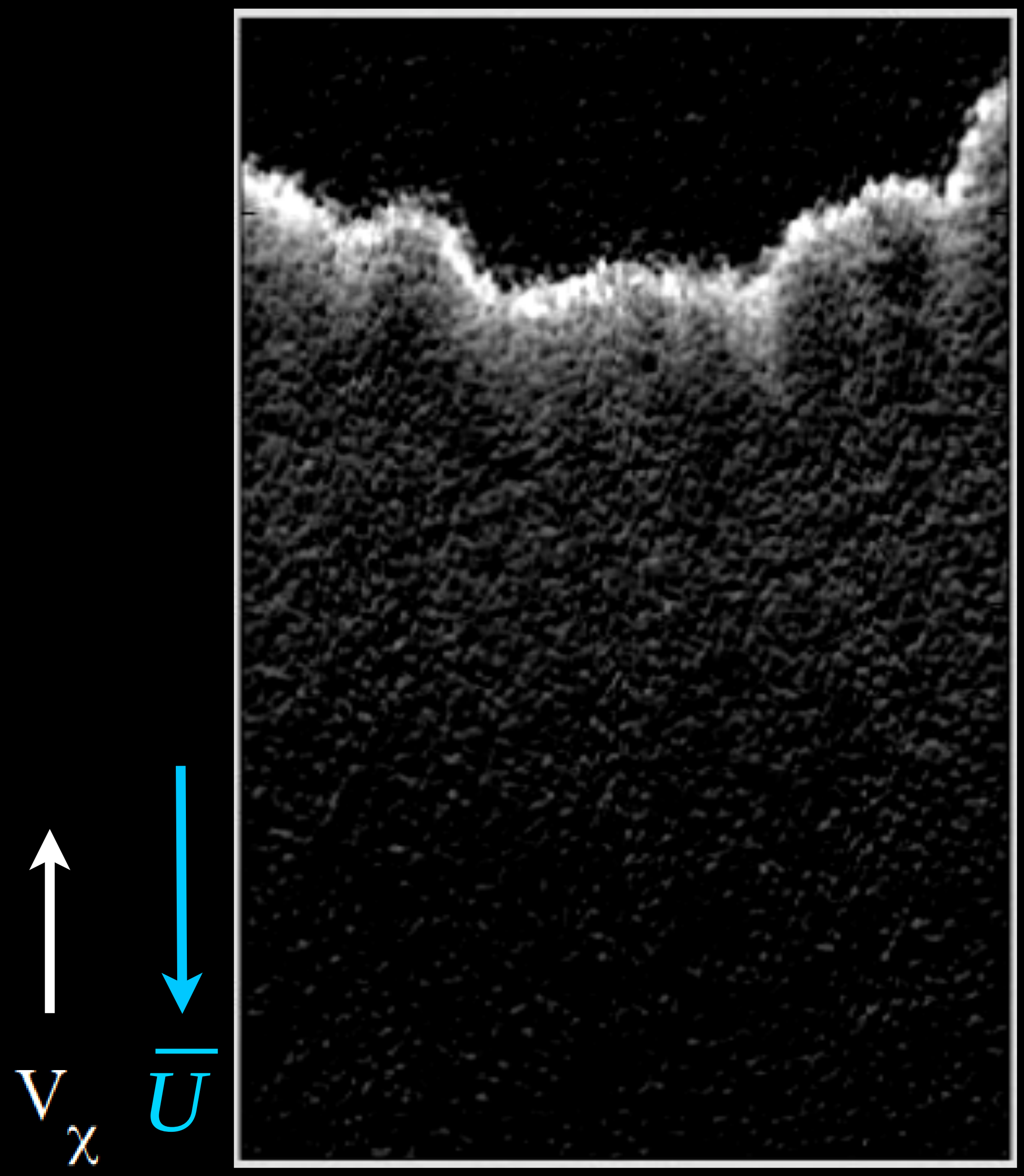
Adverse flow

backward

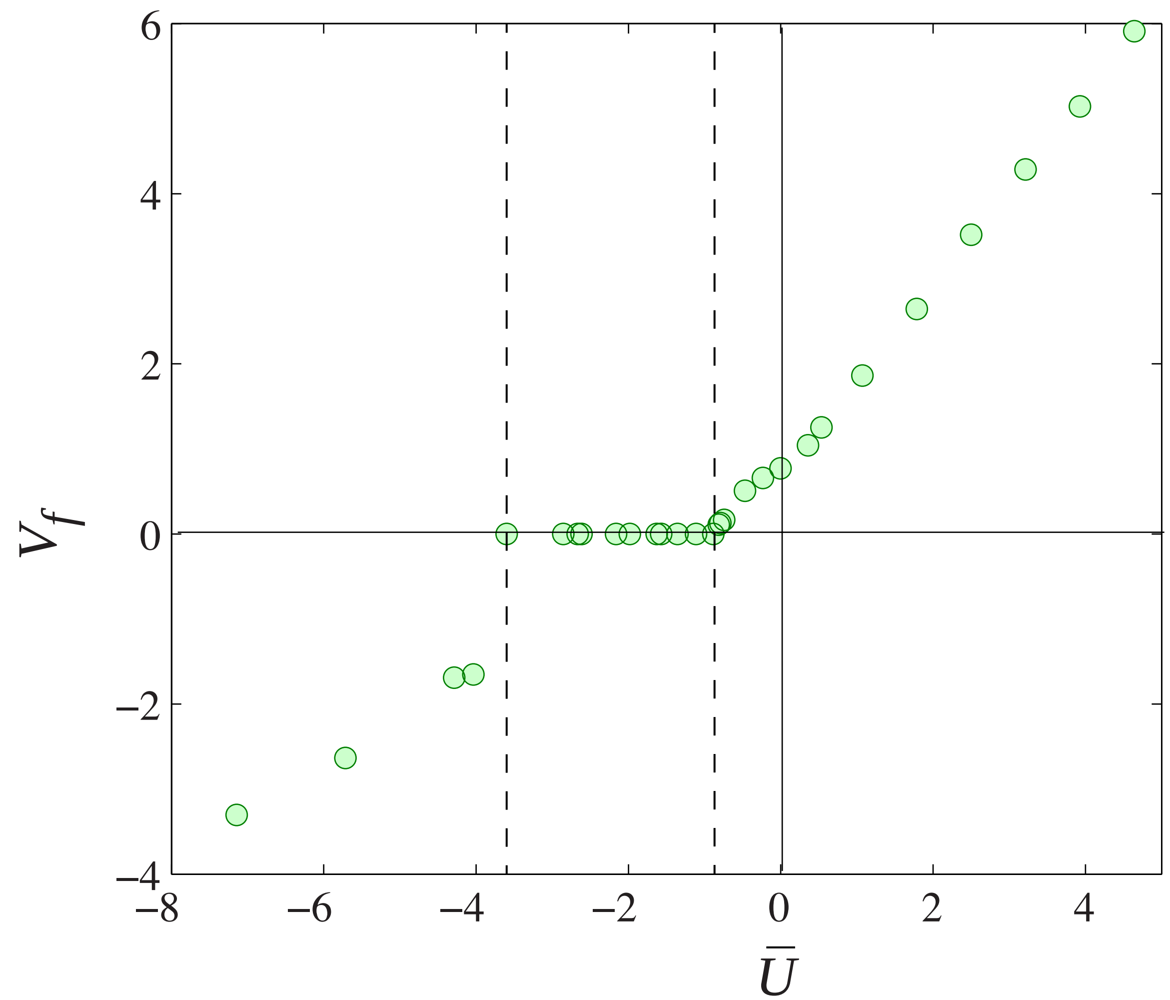


Adverse flow

backward



3 - Pinning process in low flow strength



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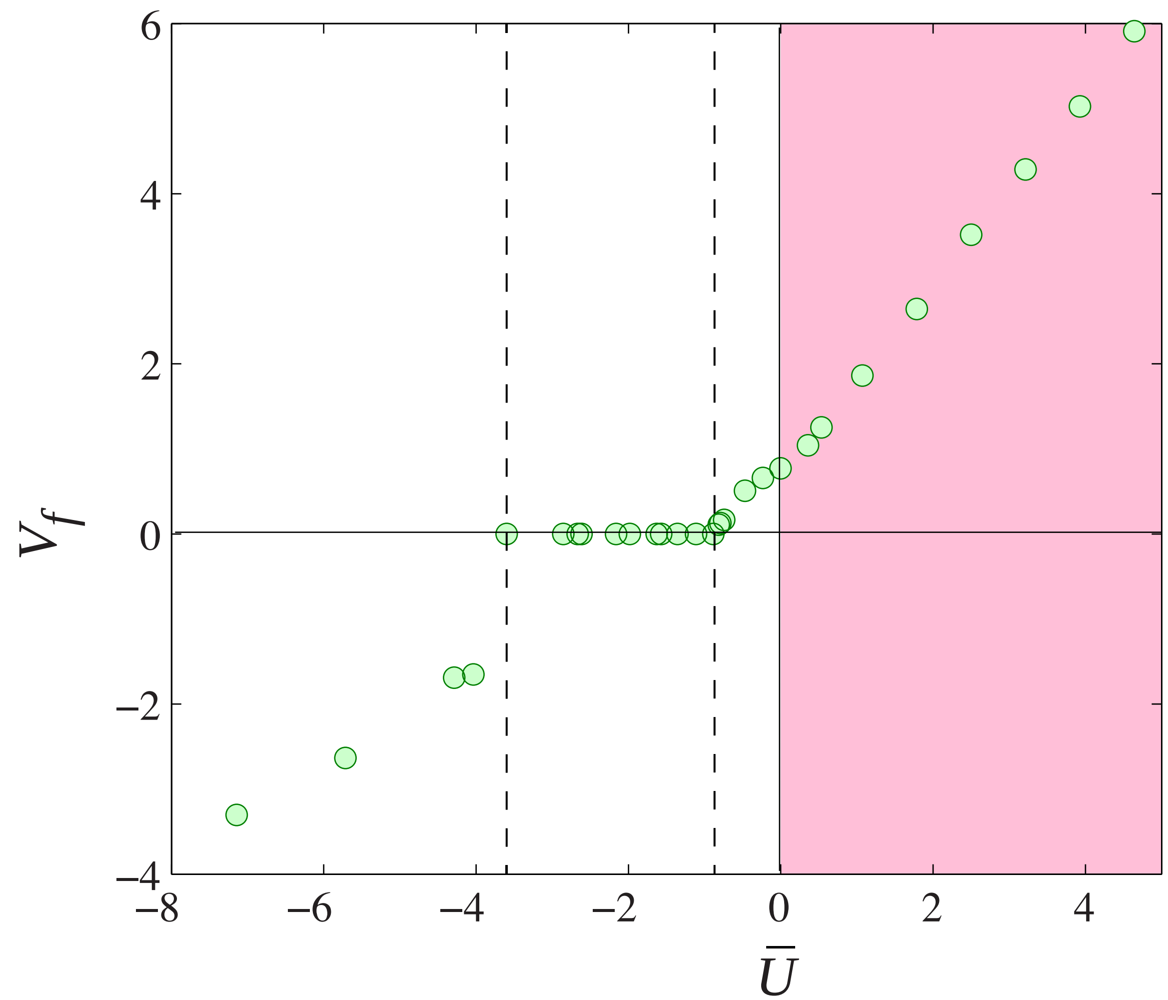

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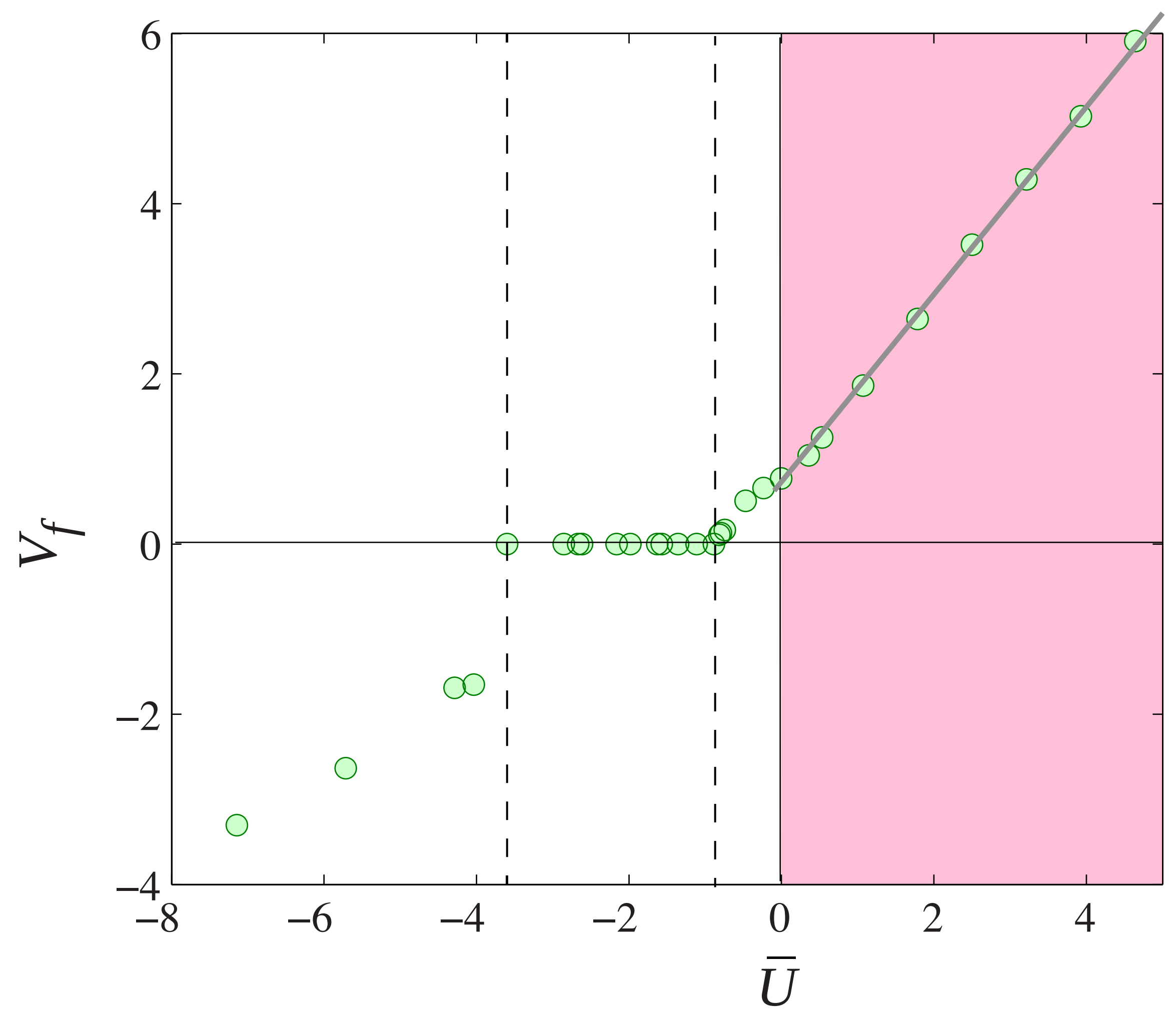

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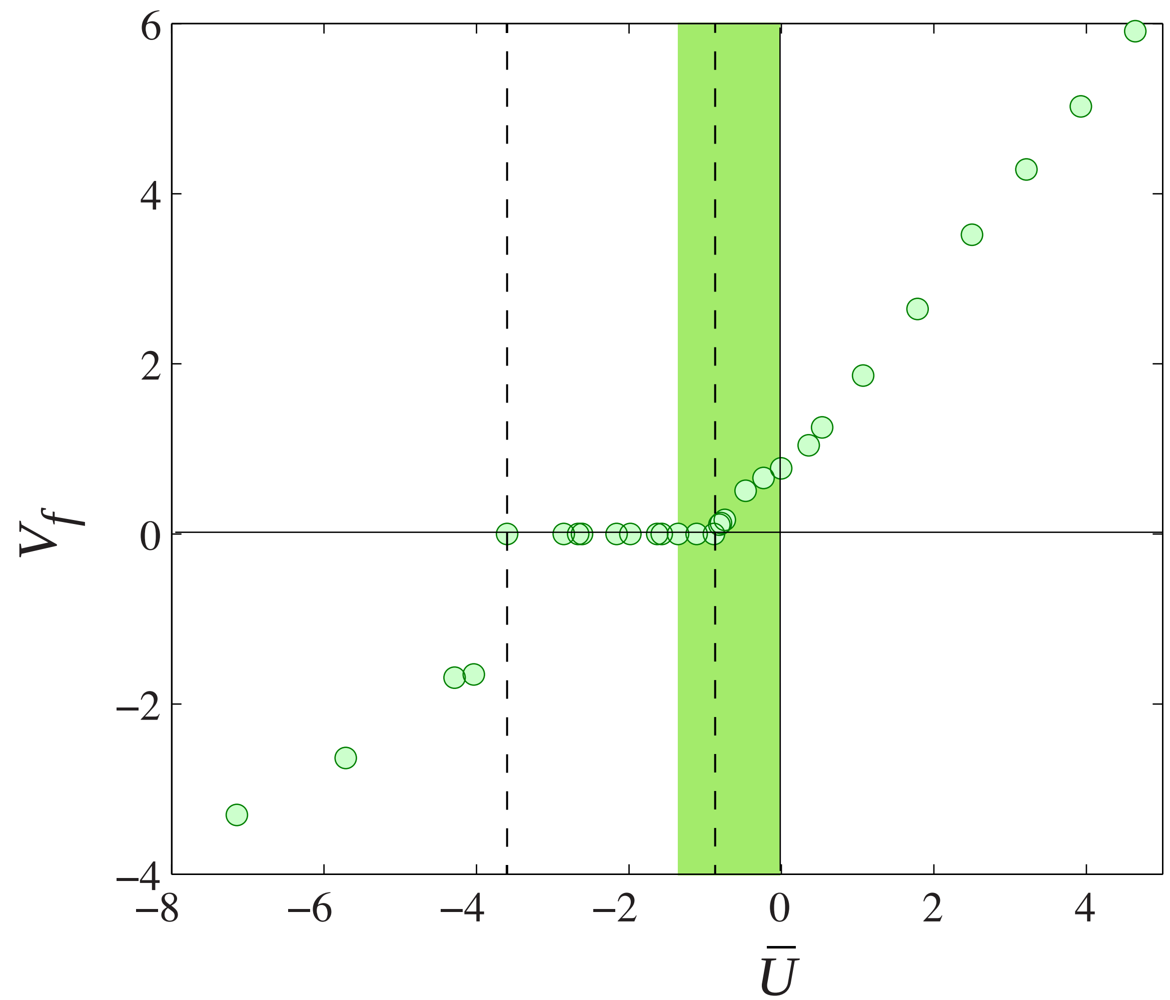

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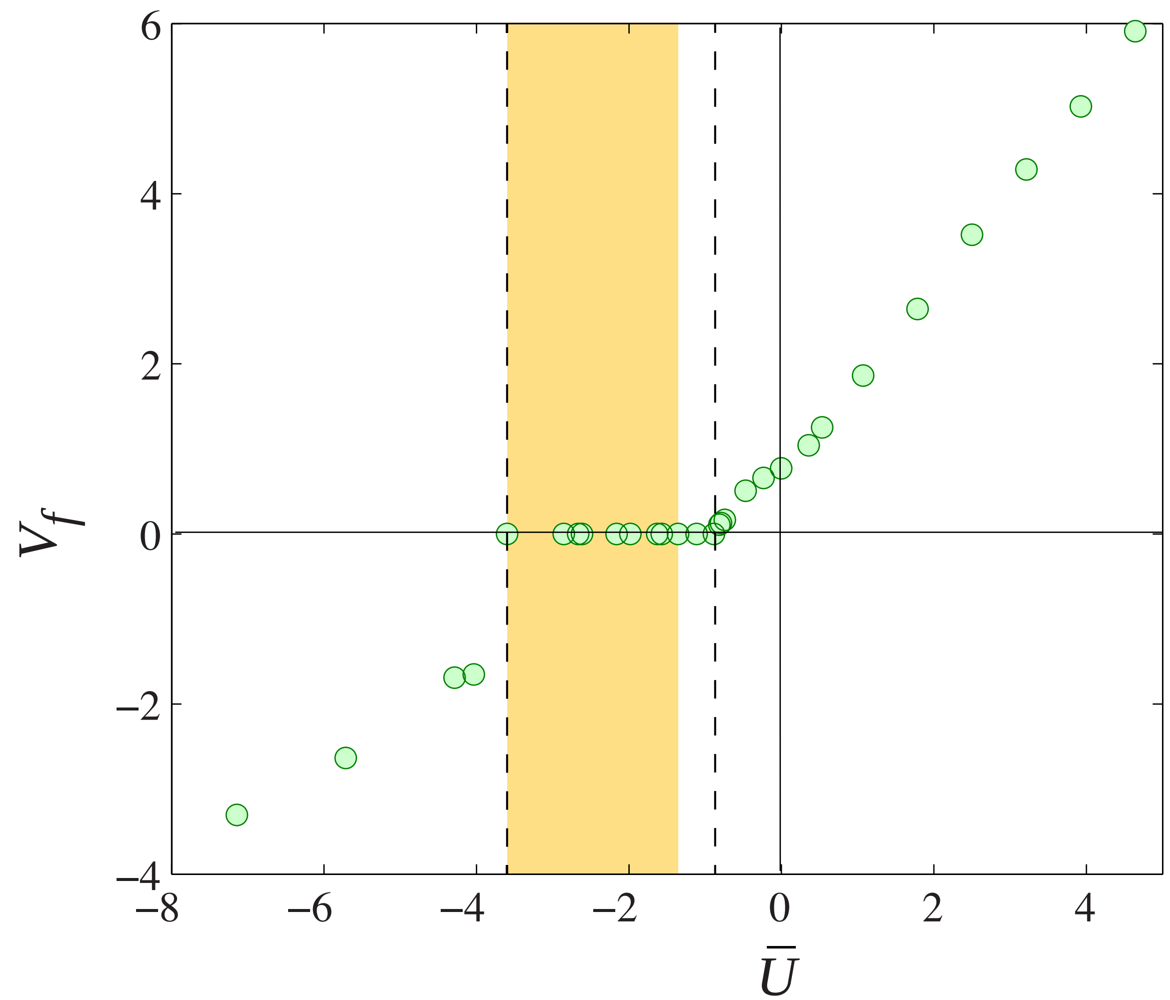

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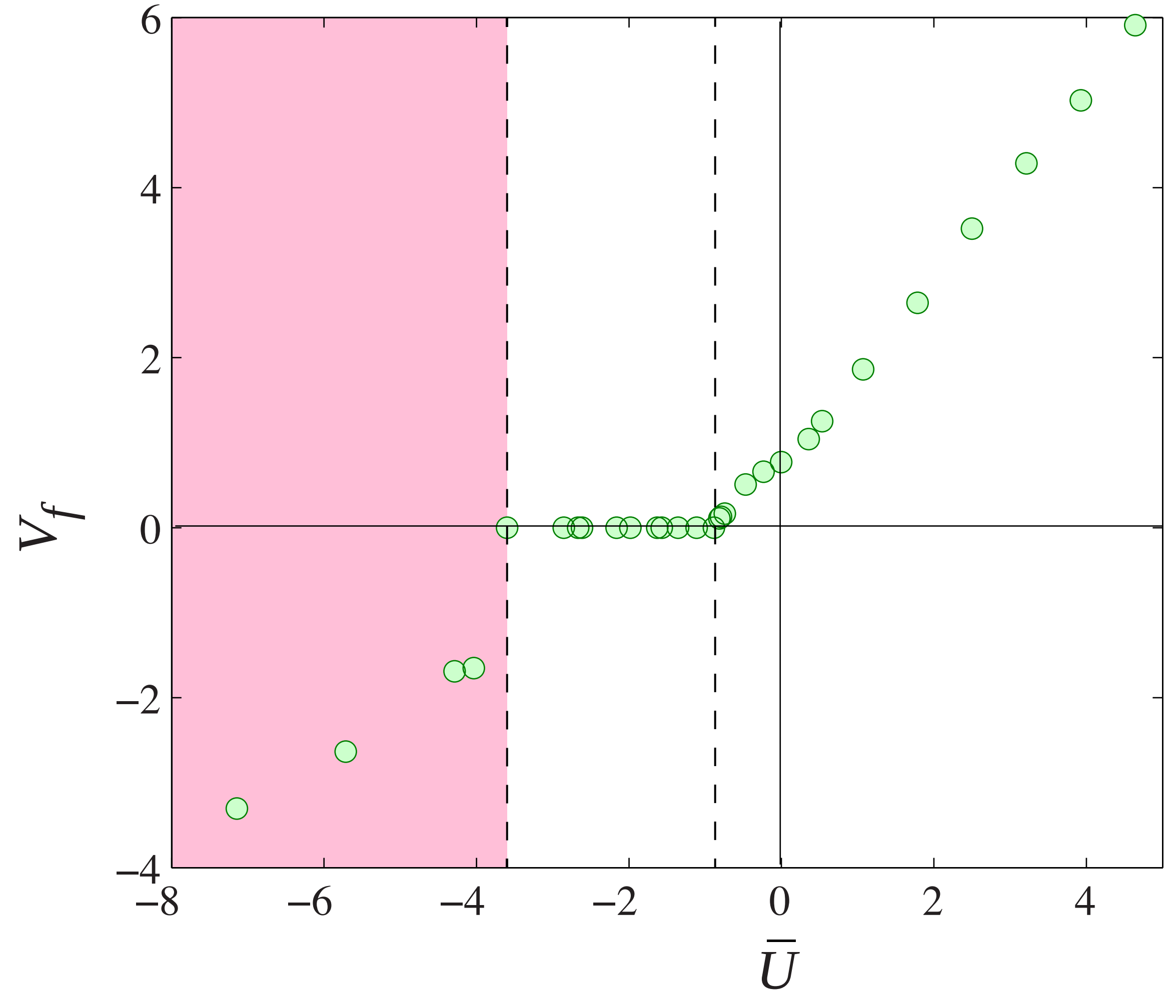

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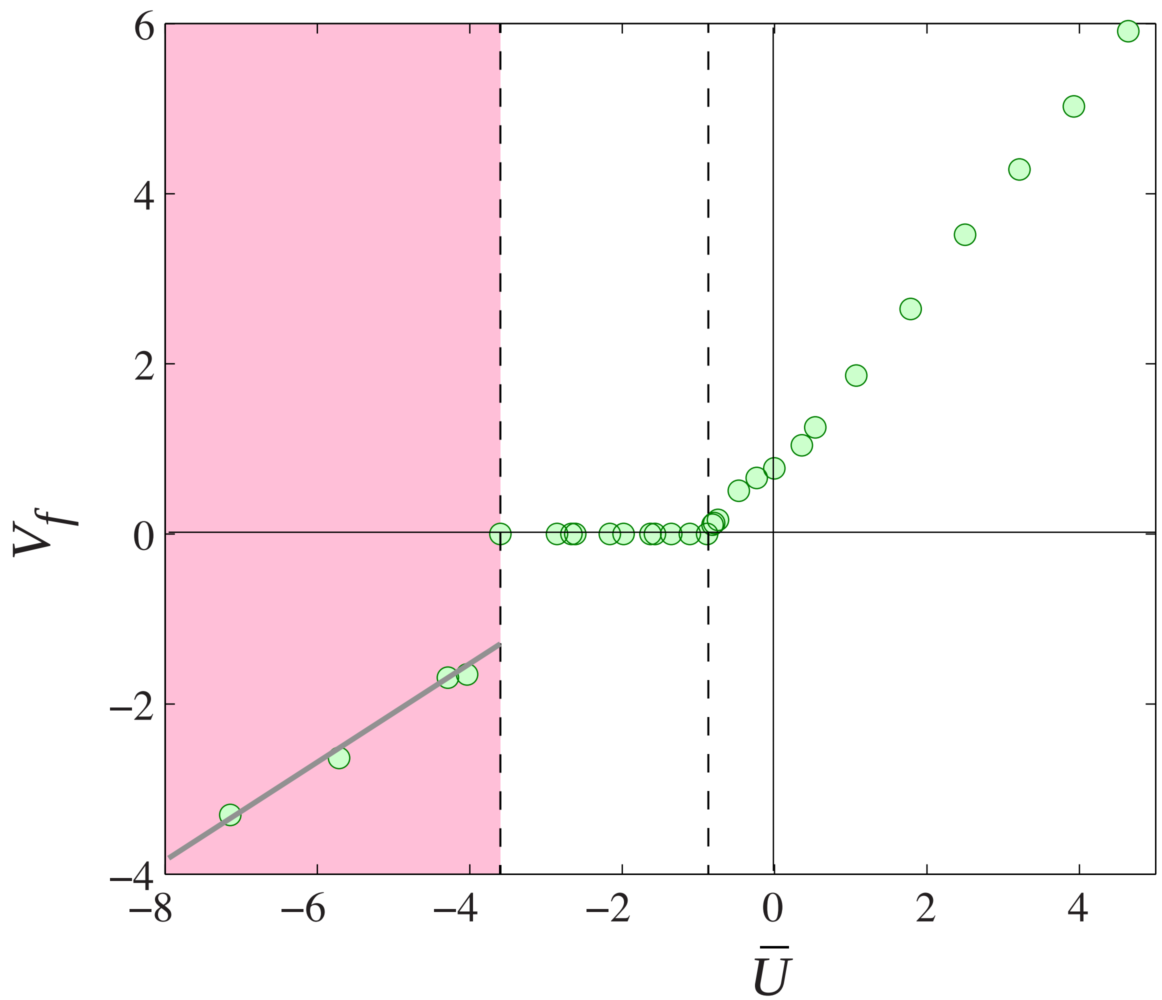

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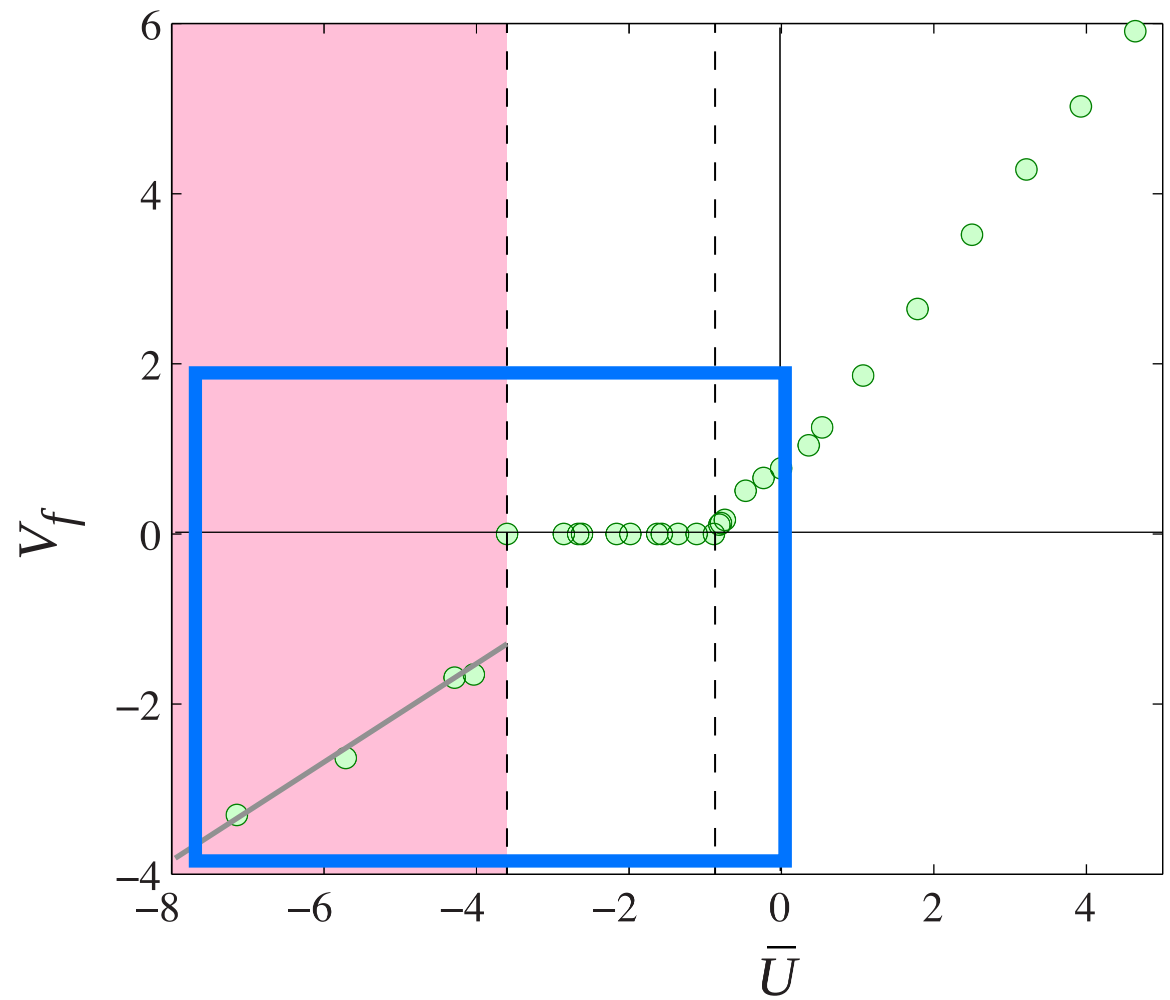
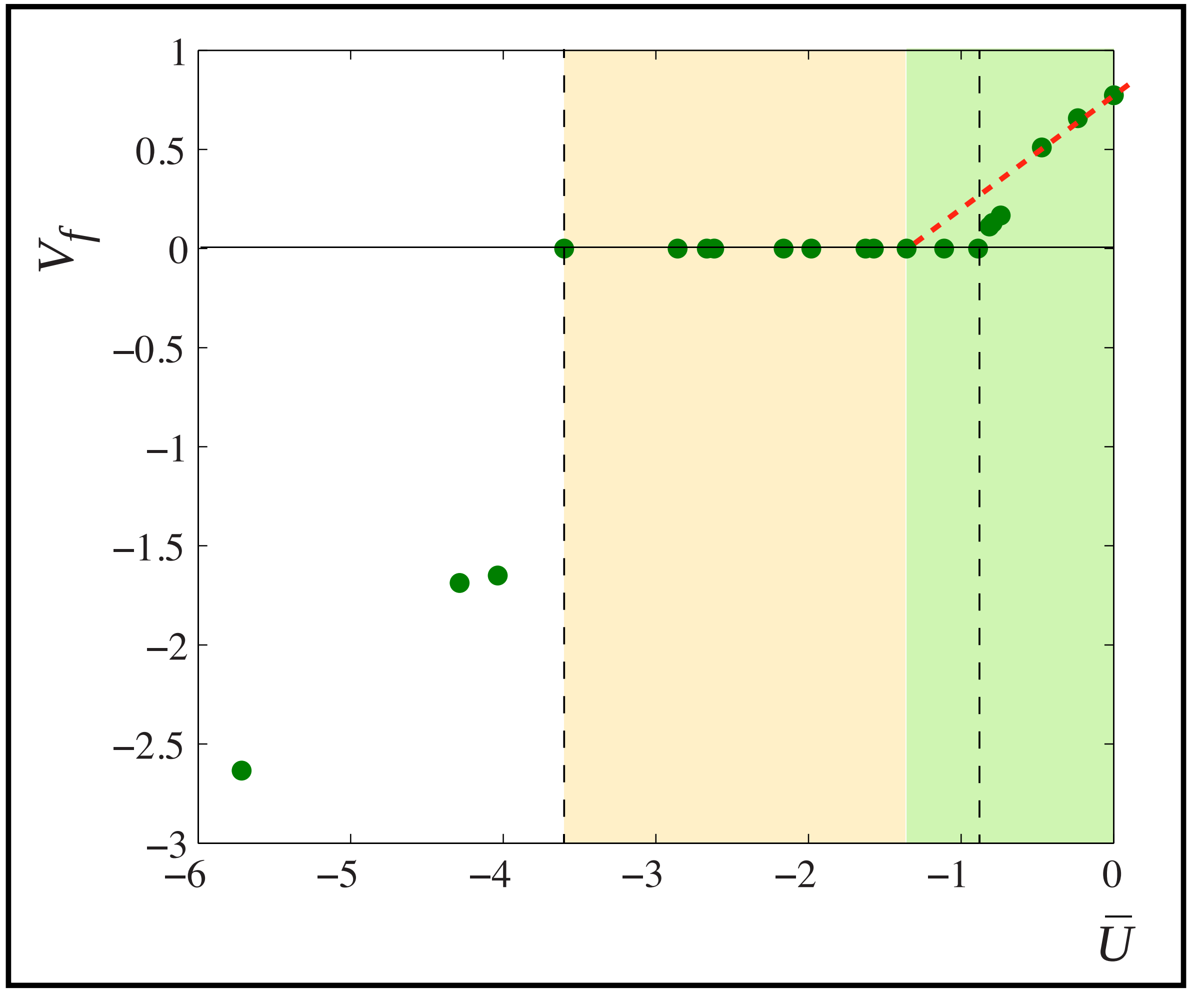
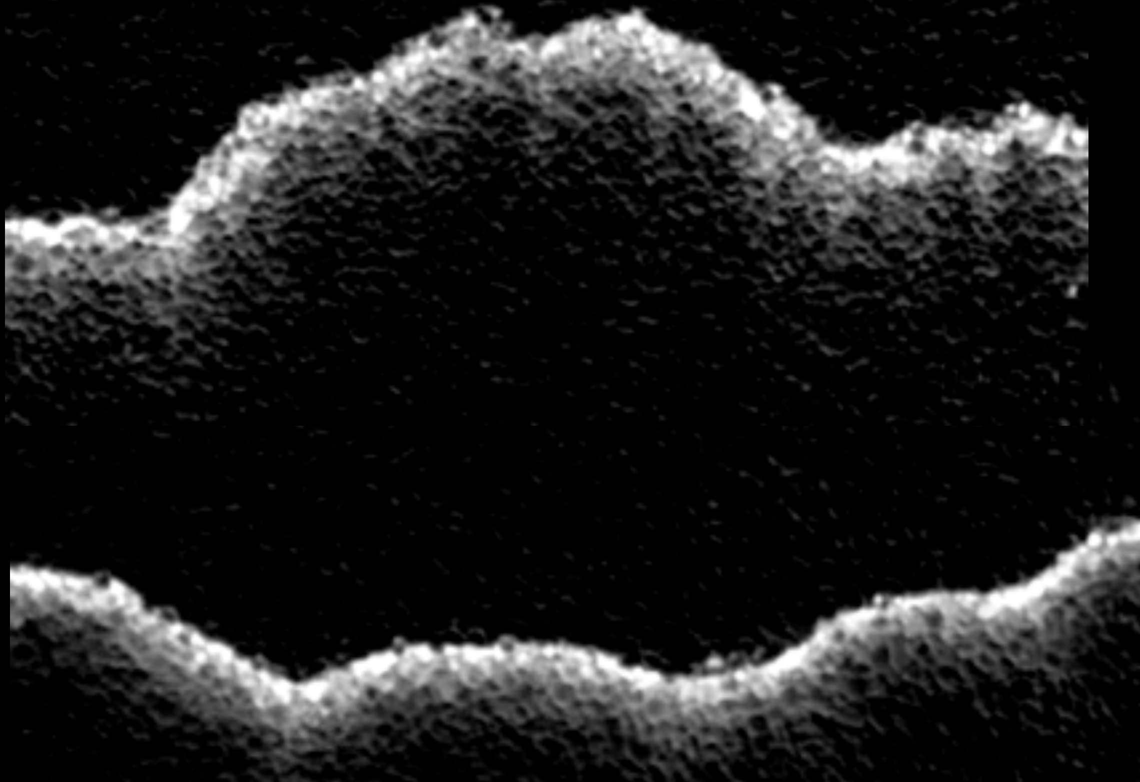
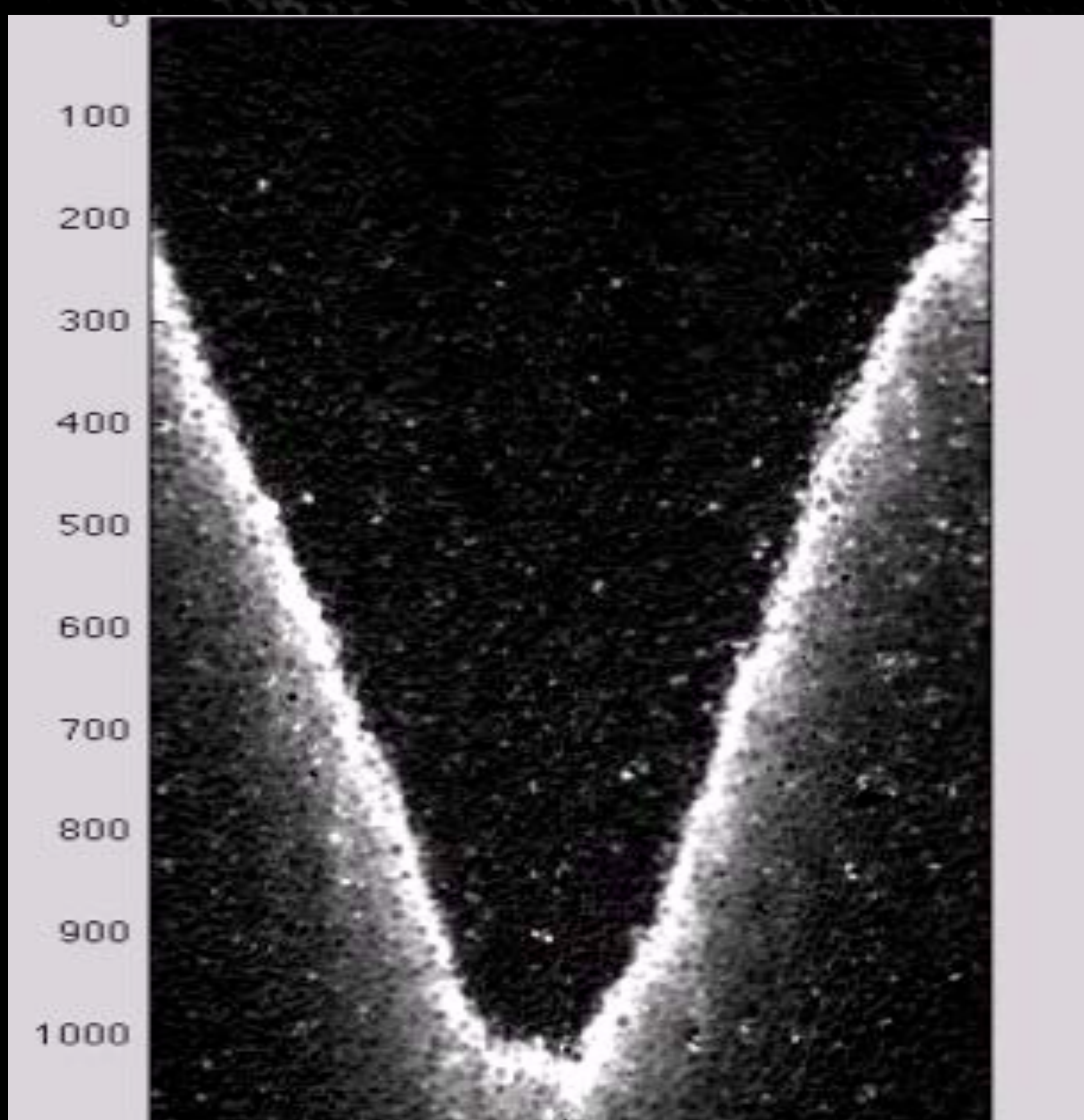
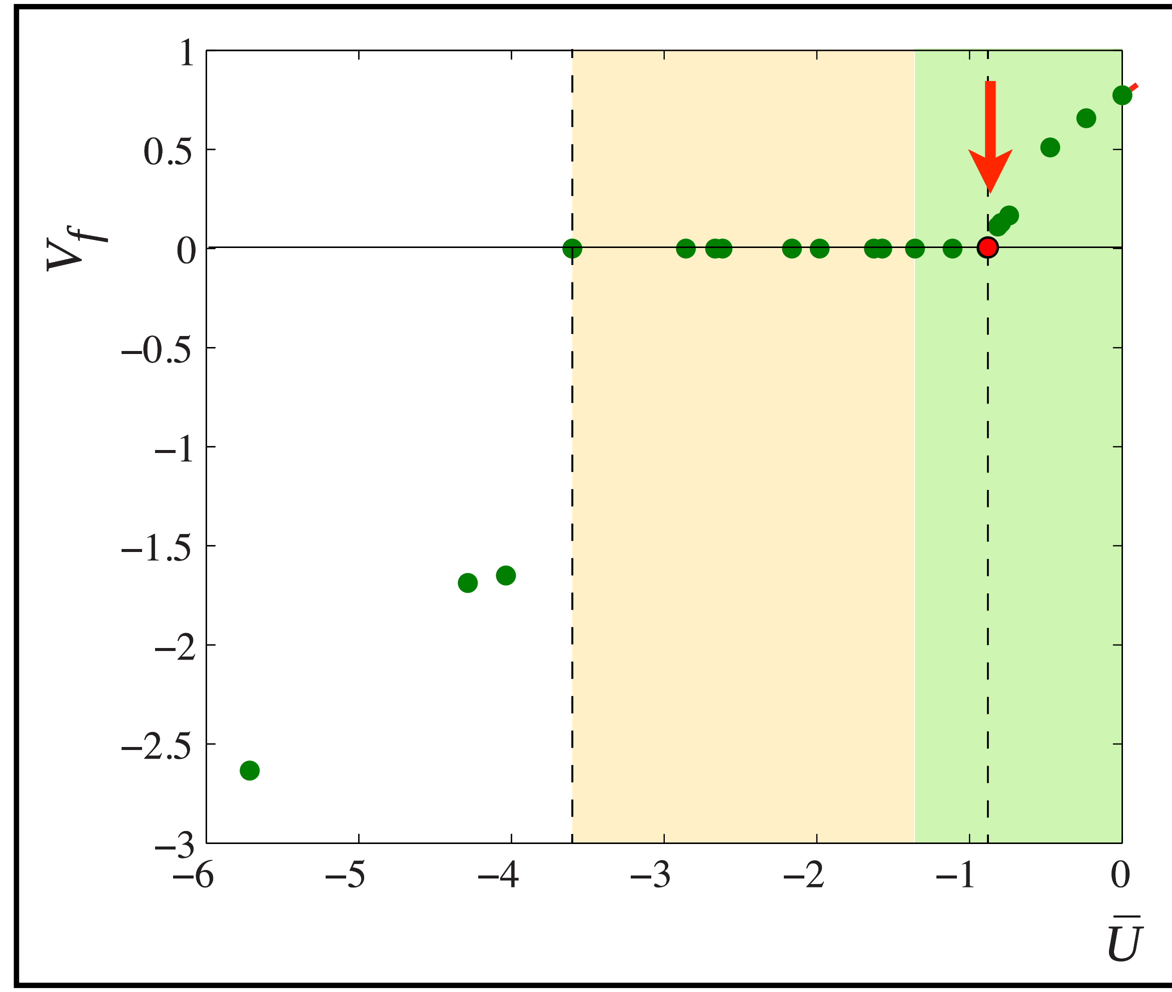


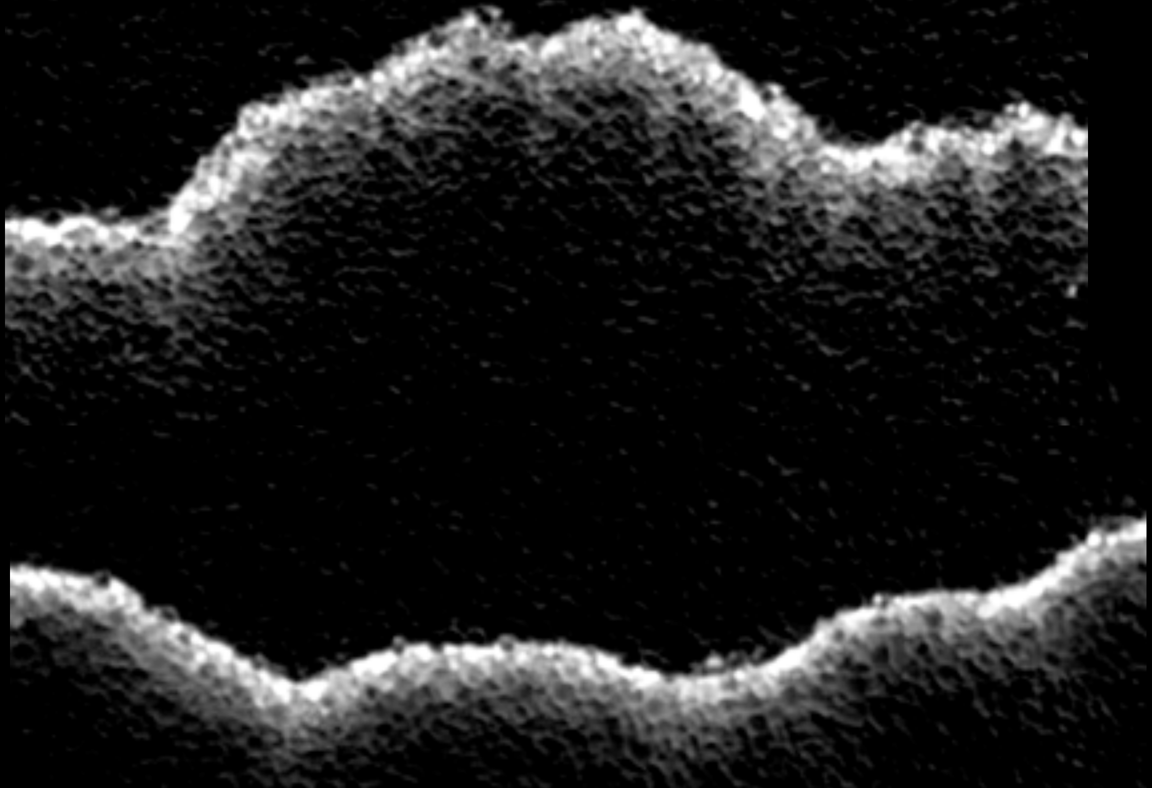


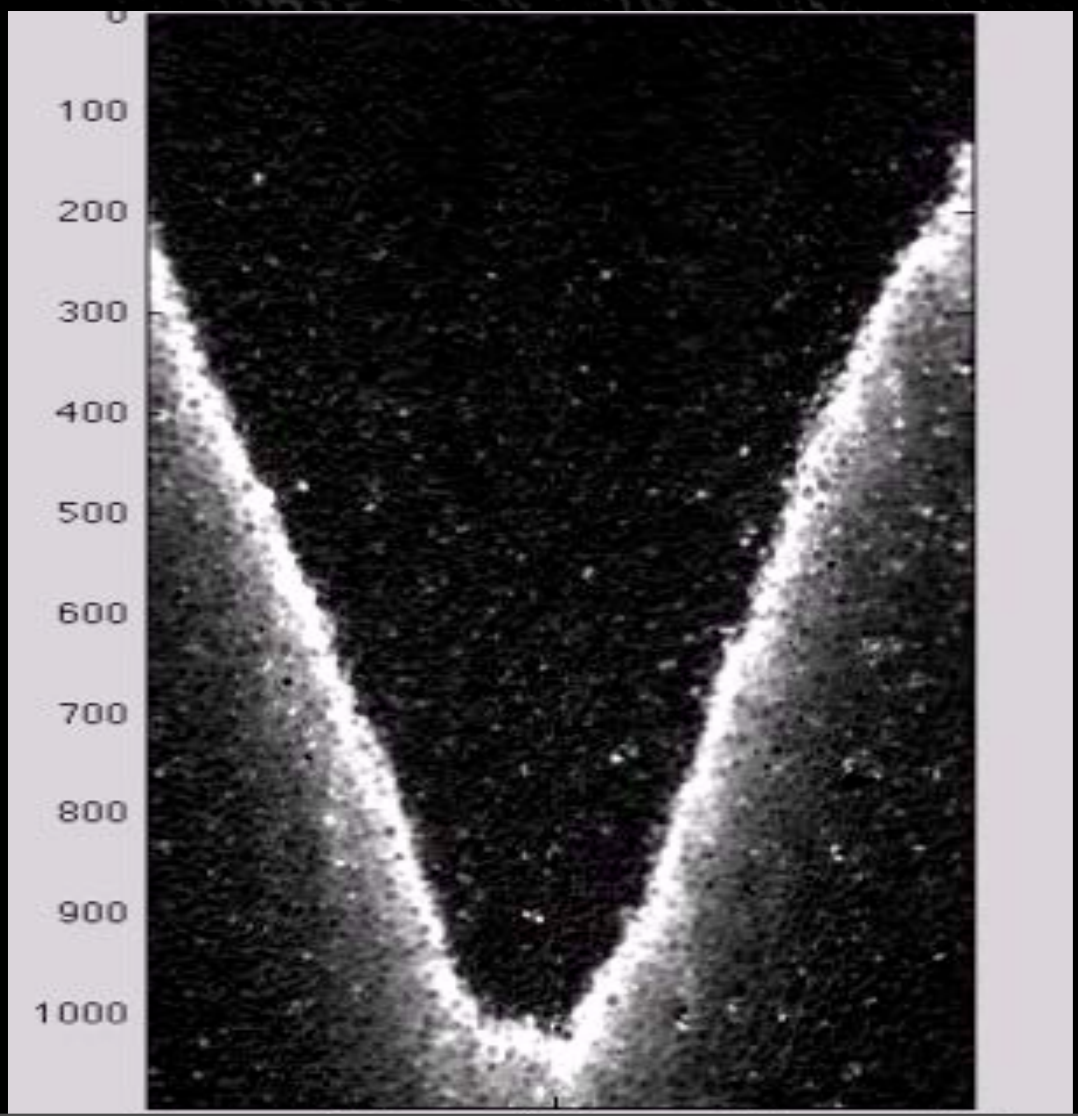
V_f
$\bar{U}$
1
0.5
0
−0.5
−1
−1.5
−2
−2.5
−3
−6
−5
−4
−3
−2
−1
0




0
100
200
300
400
500
600
700
800
900
1000


V_f
$\bar{U}$
1
0.5
0
−0.5
−1
−1.5
−2
−2.5
−3
−6
−5
−4
−3
−2
−1
0

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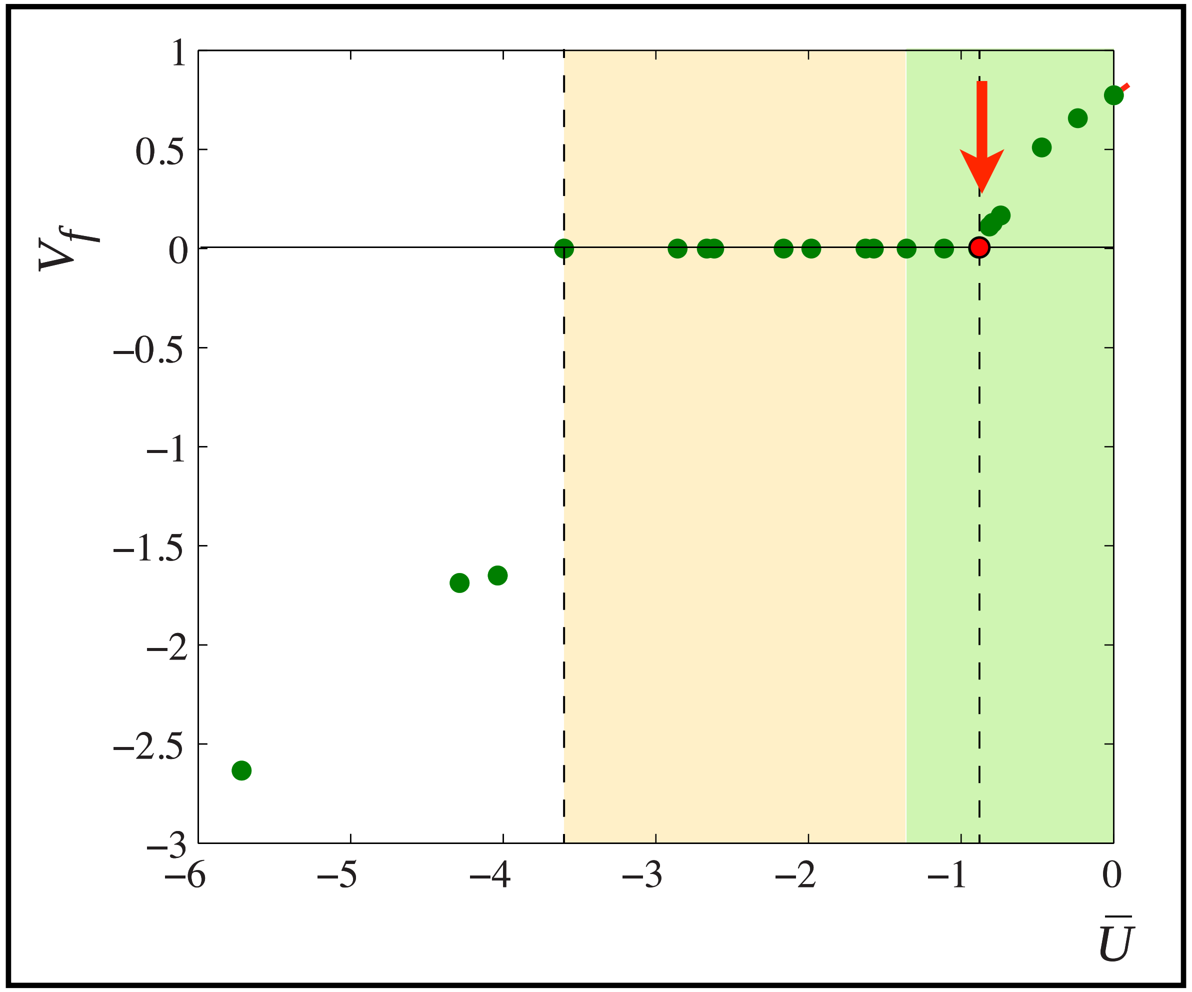
V_f
$\bar{U}$
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−0.5
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−3
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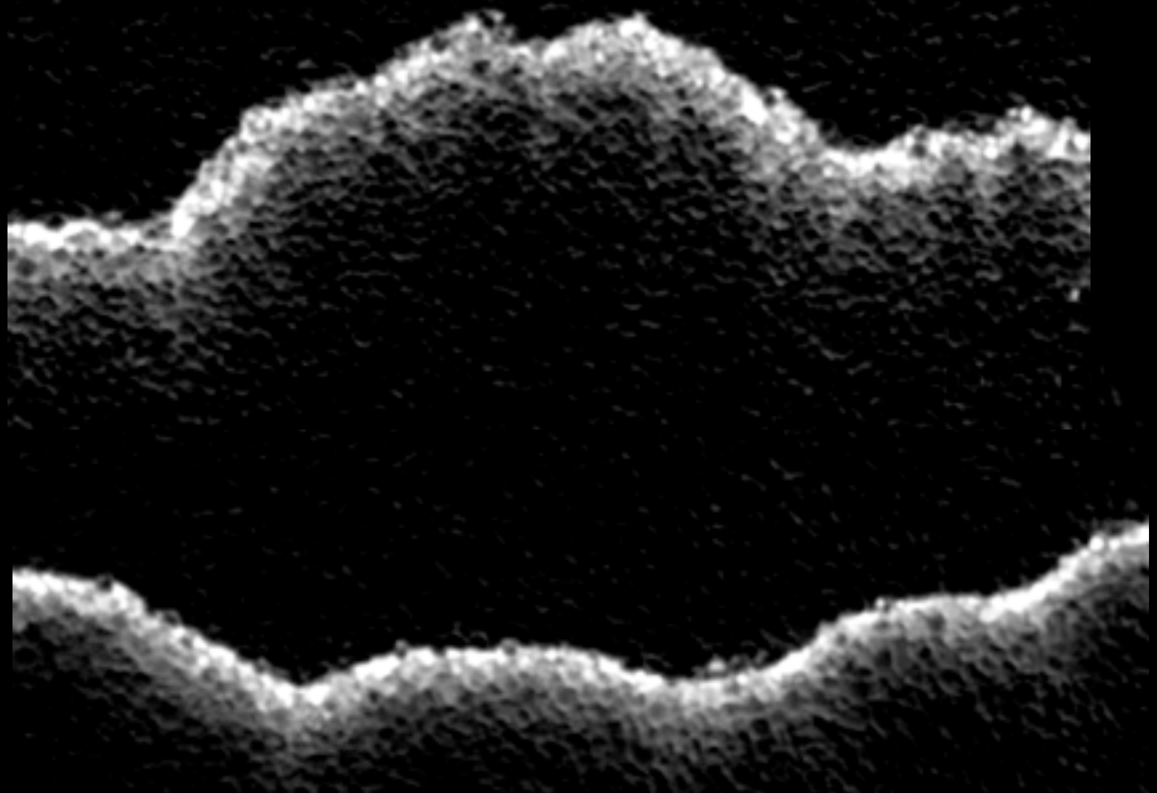

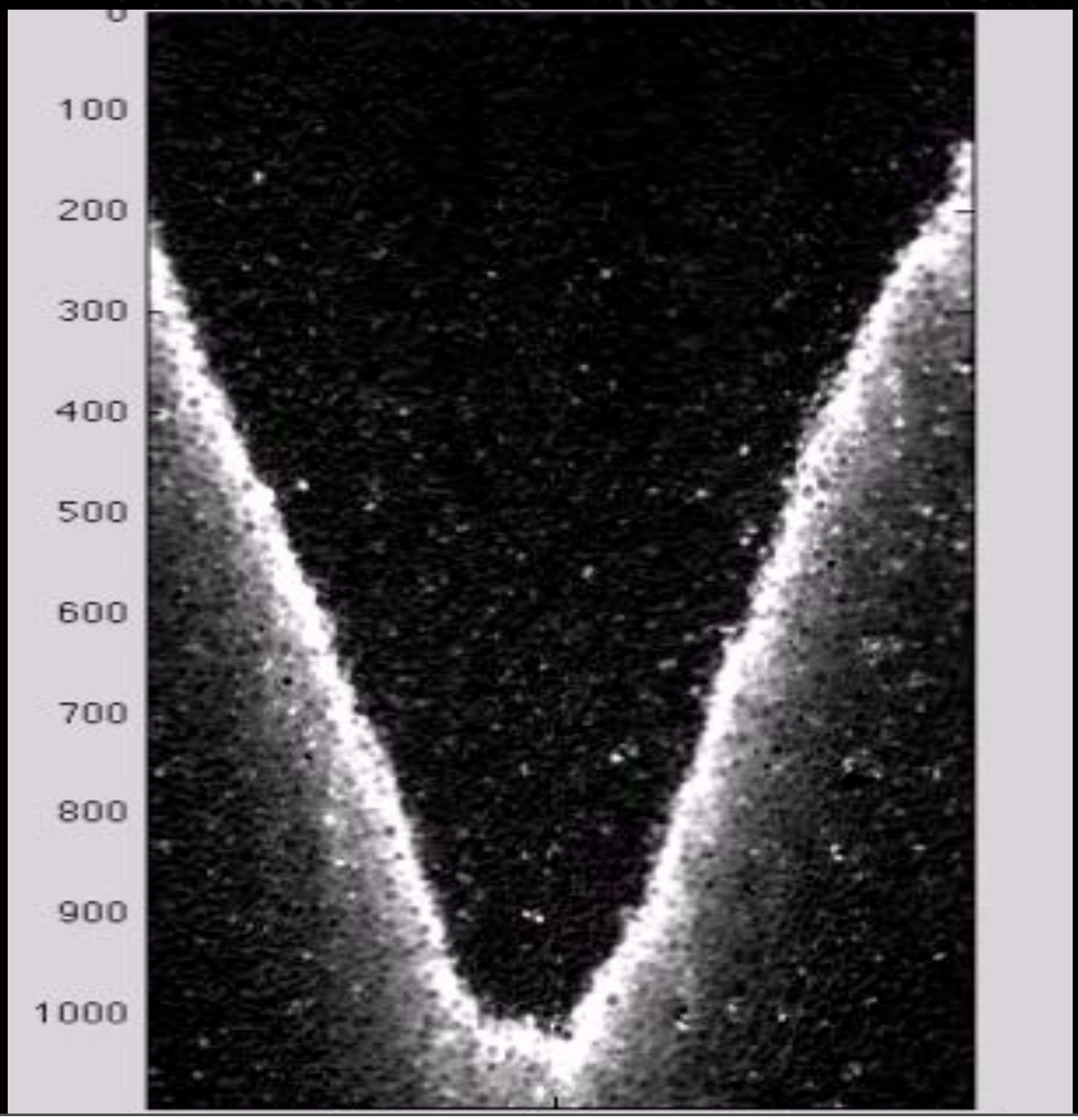

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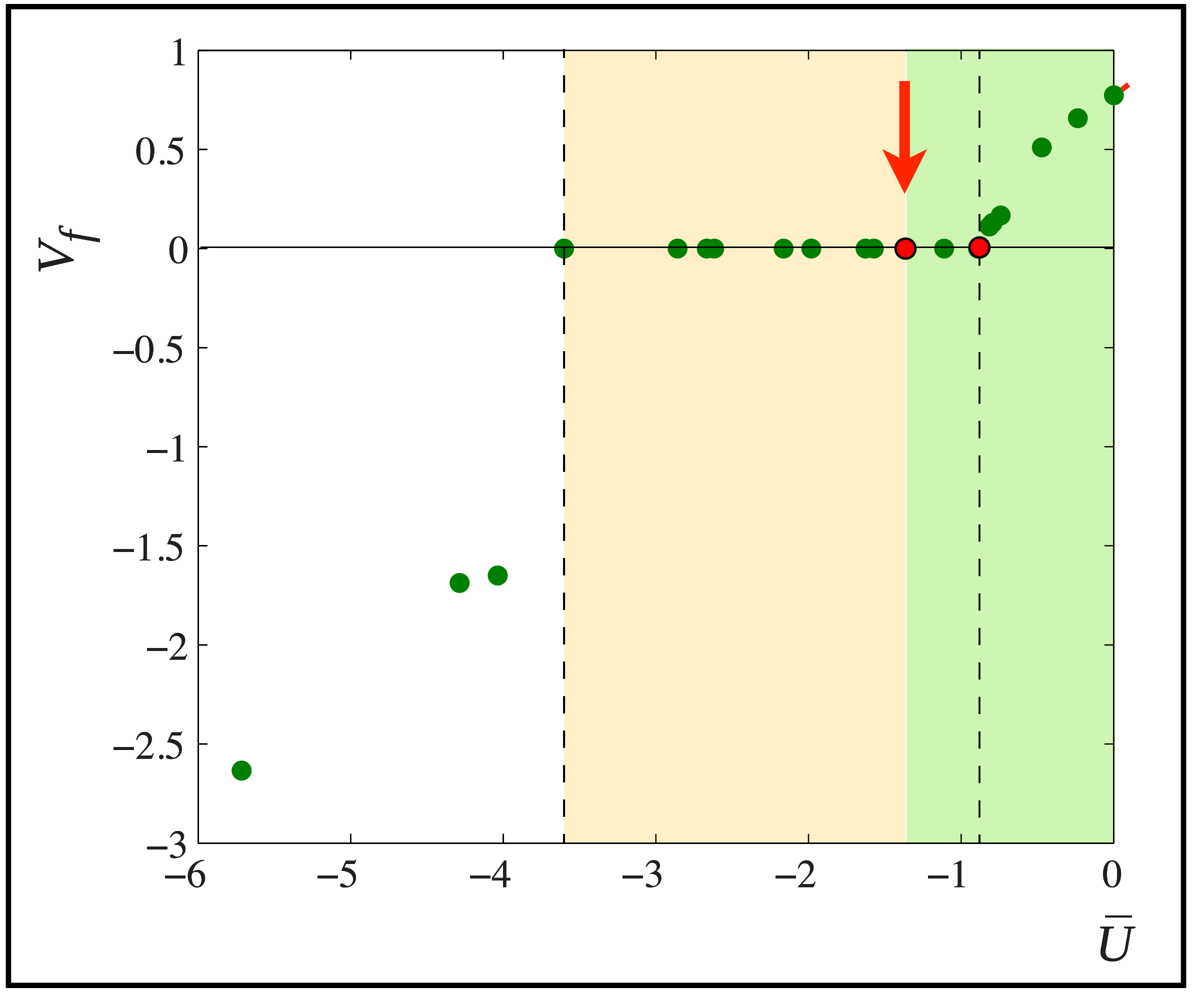

V_f
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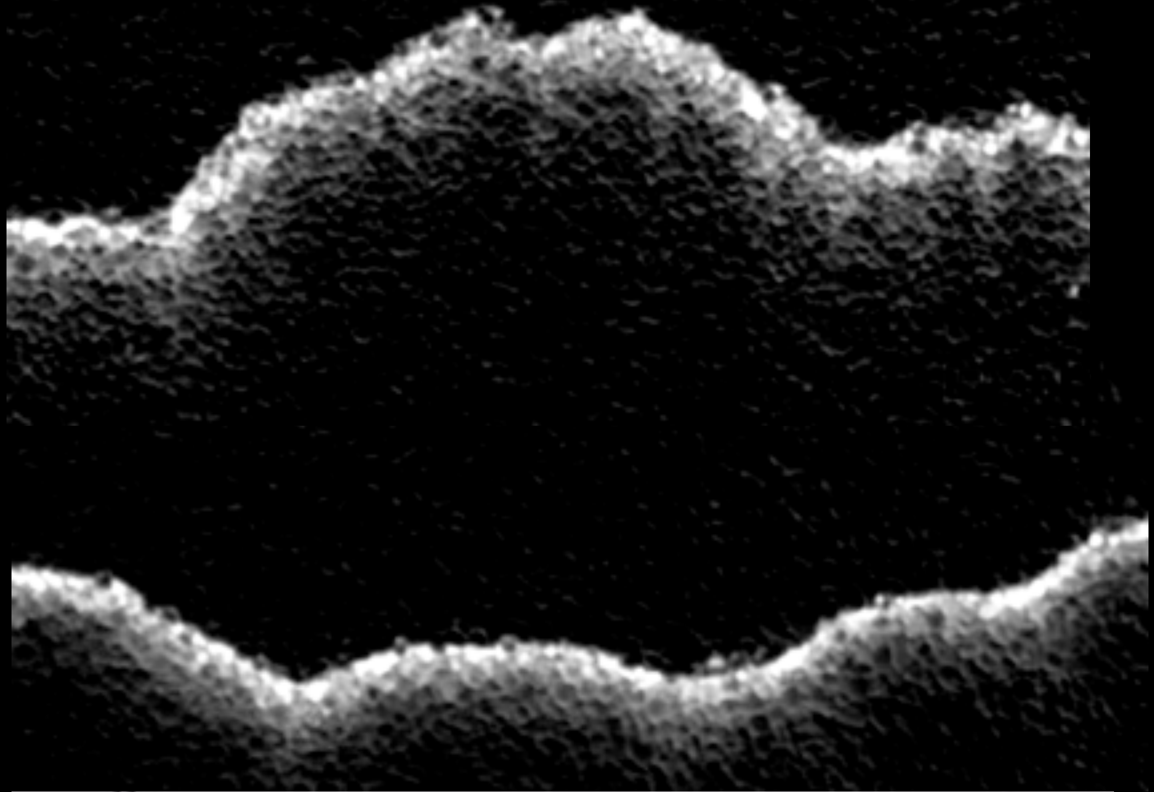

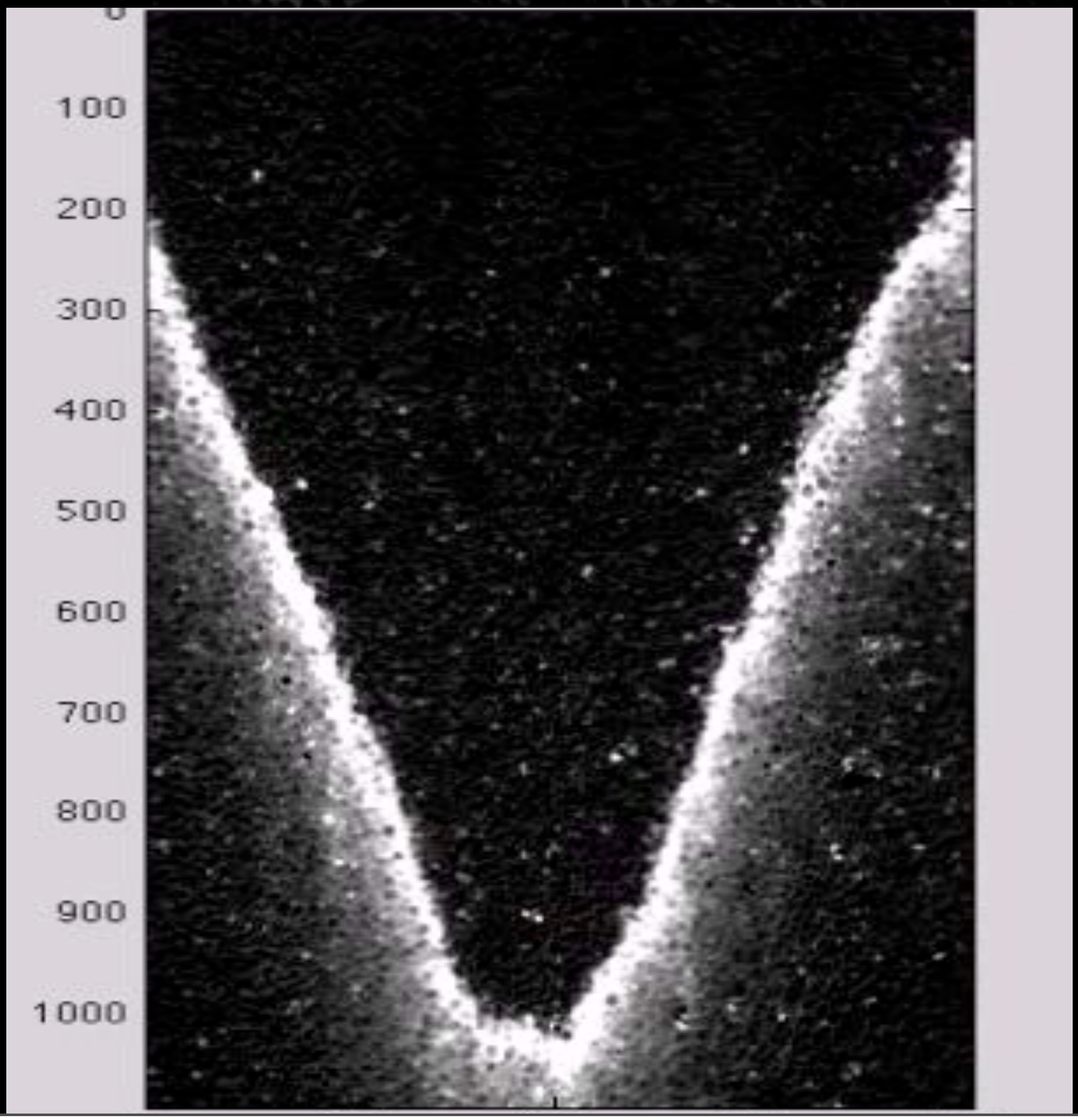

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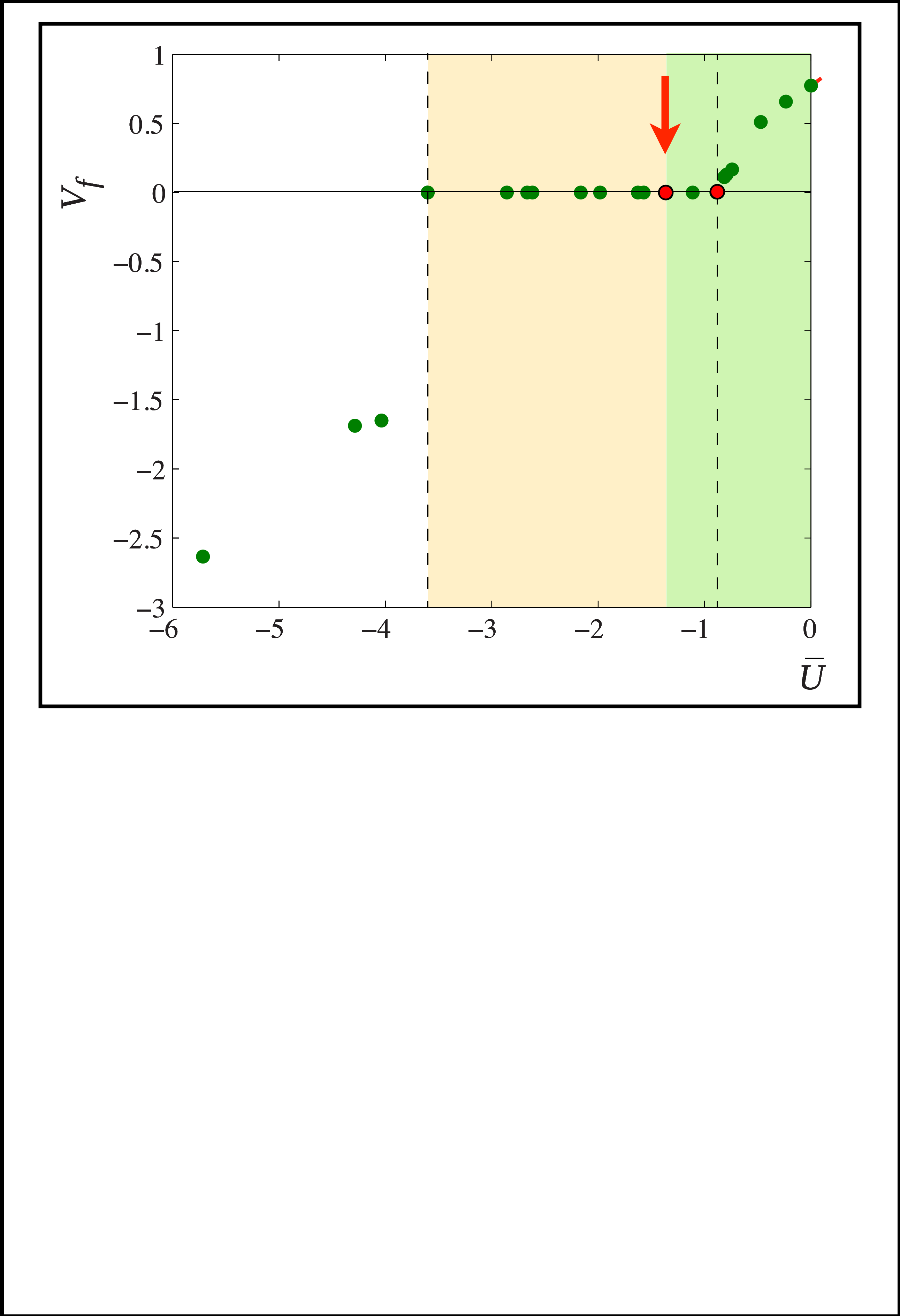

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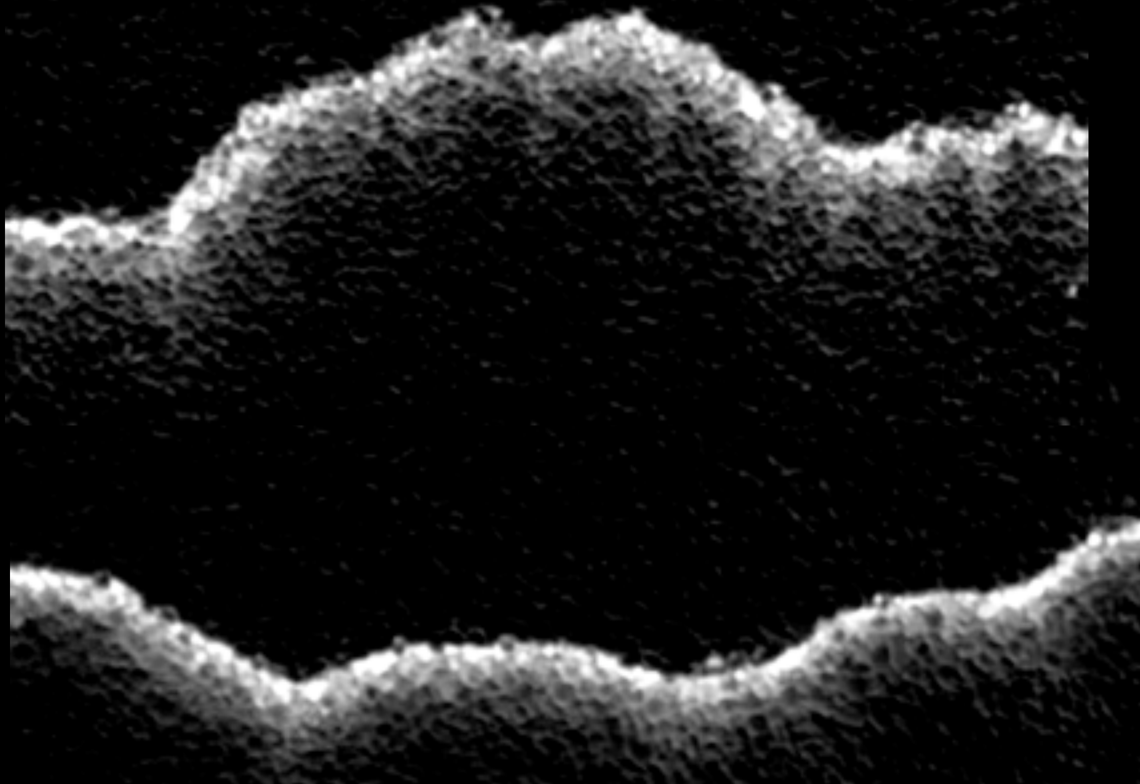
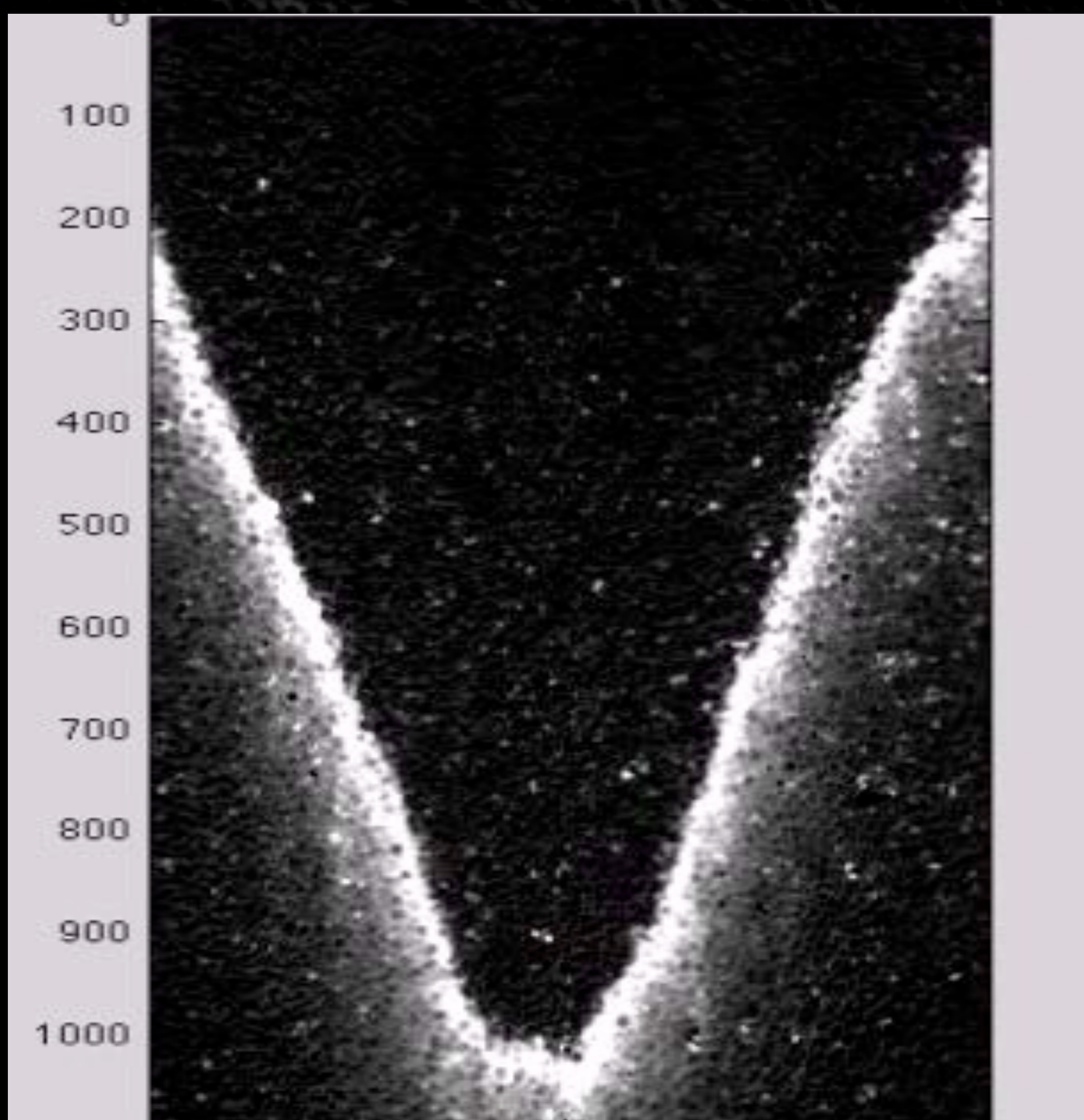
V_f
$\bar{U}$

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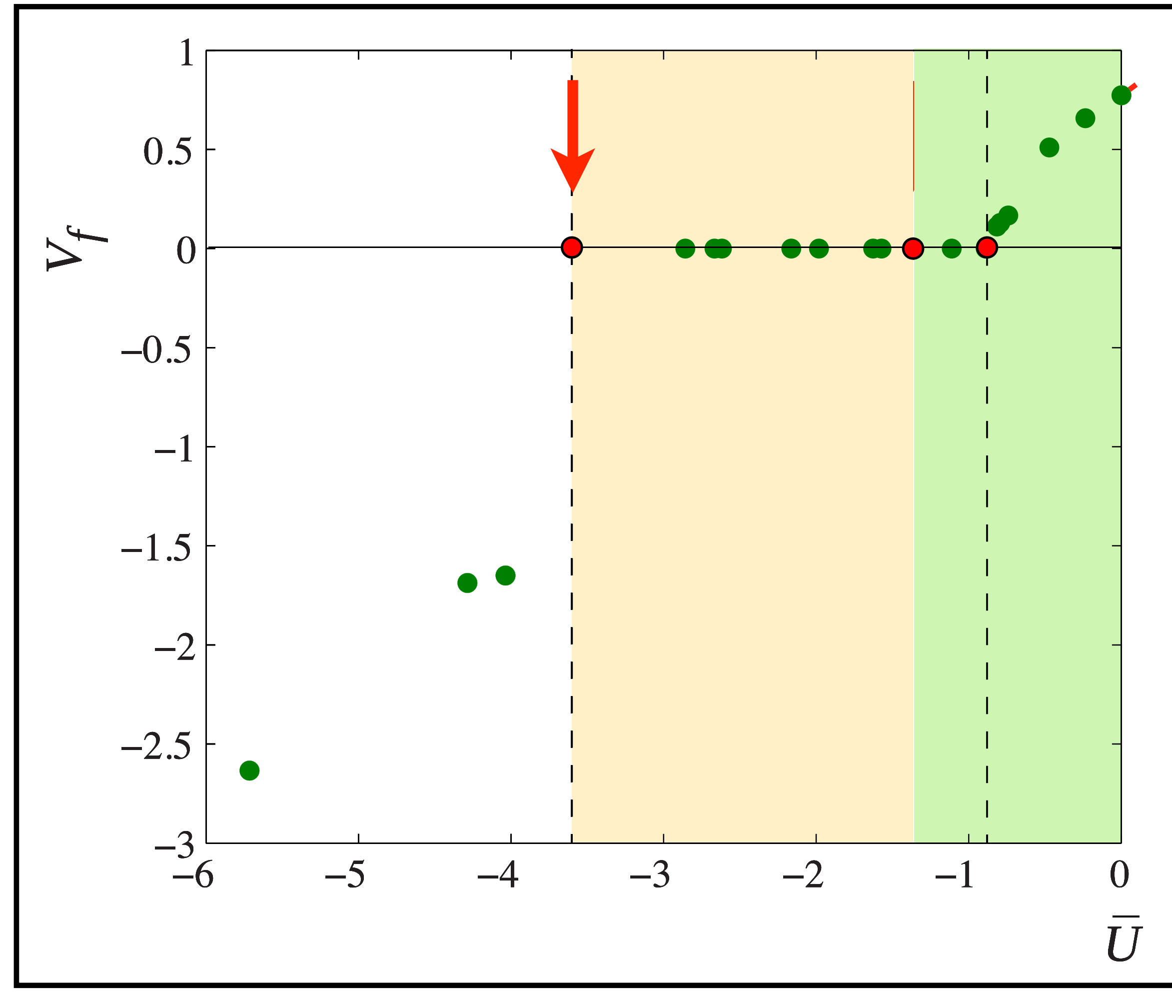
V_f
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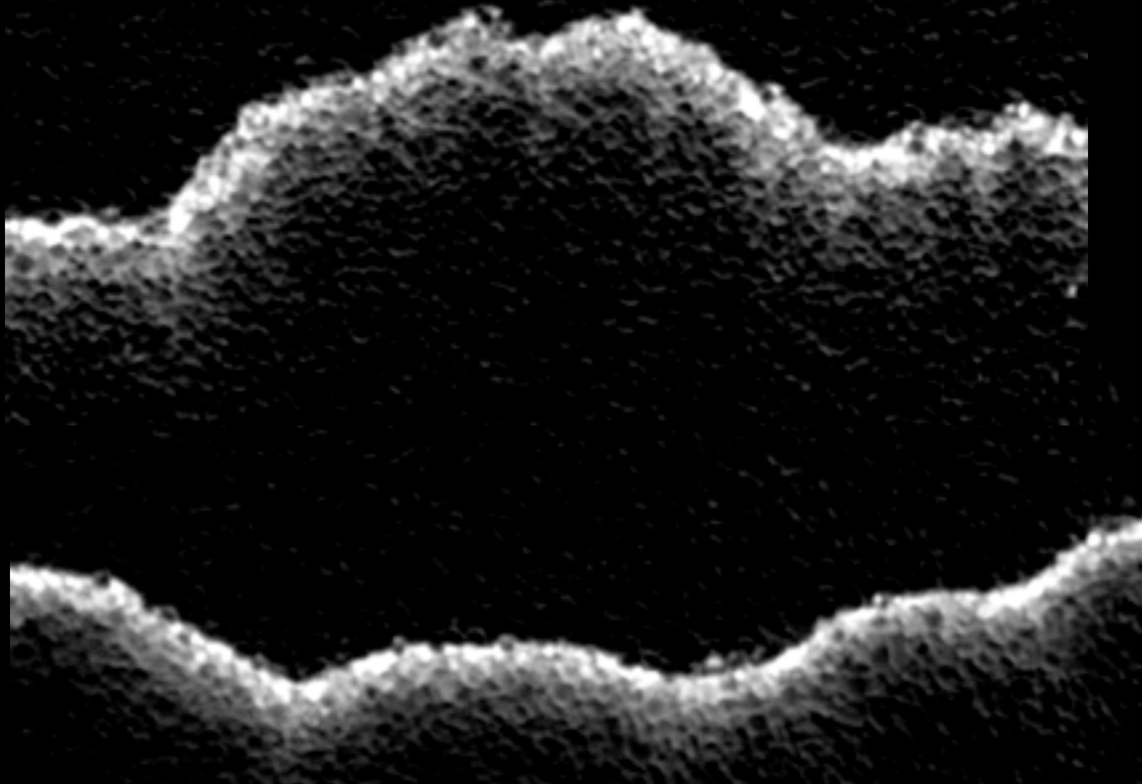

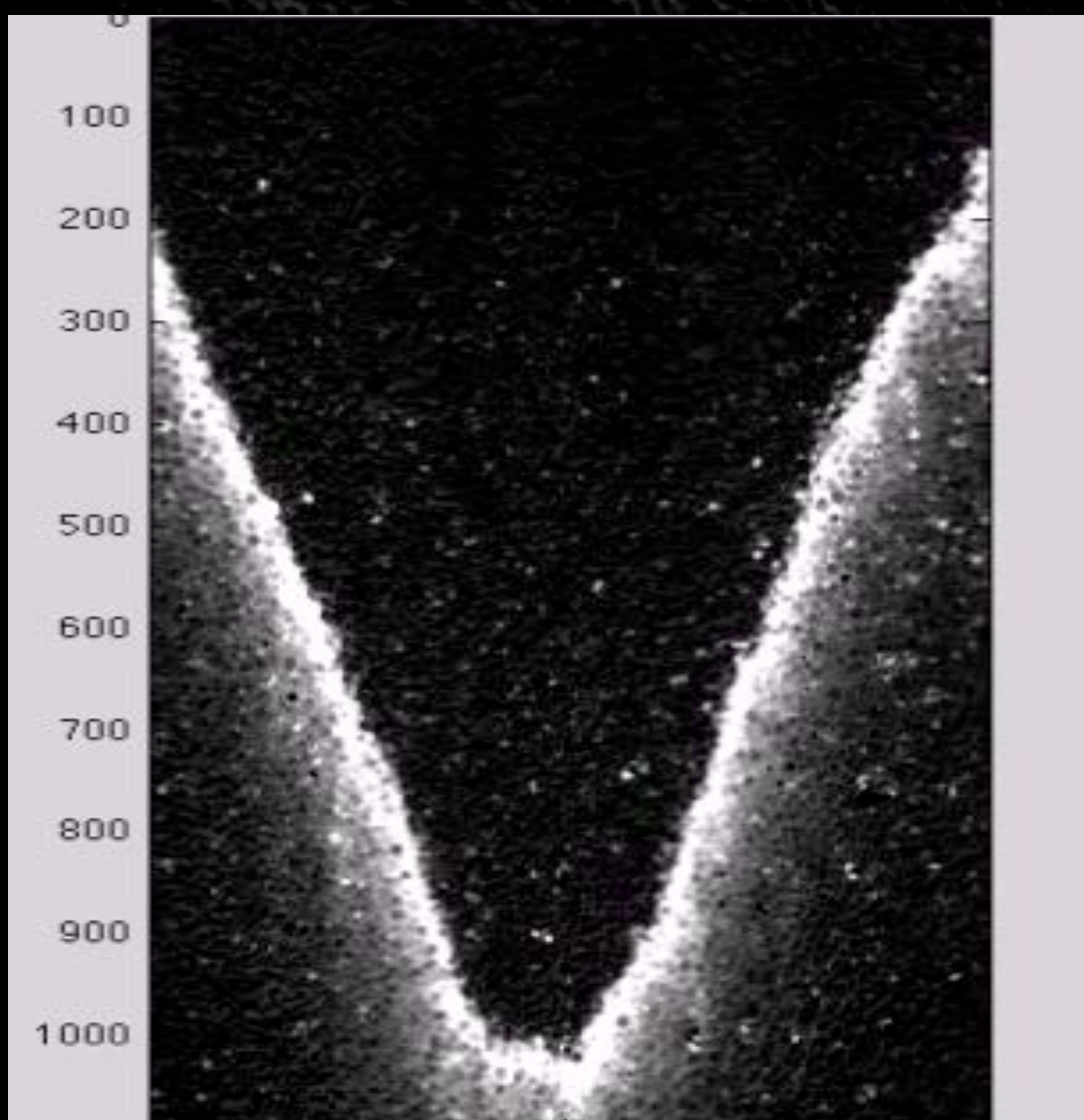
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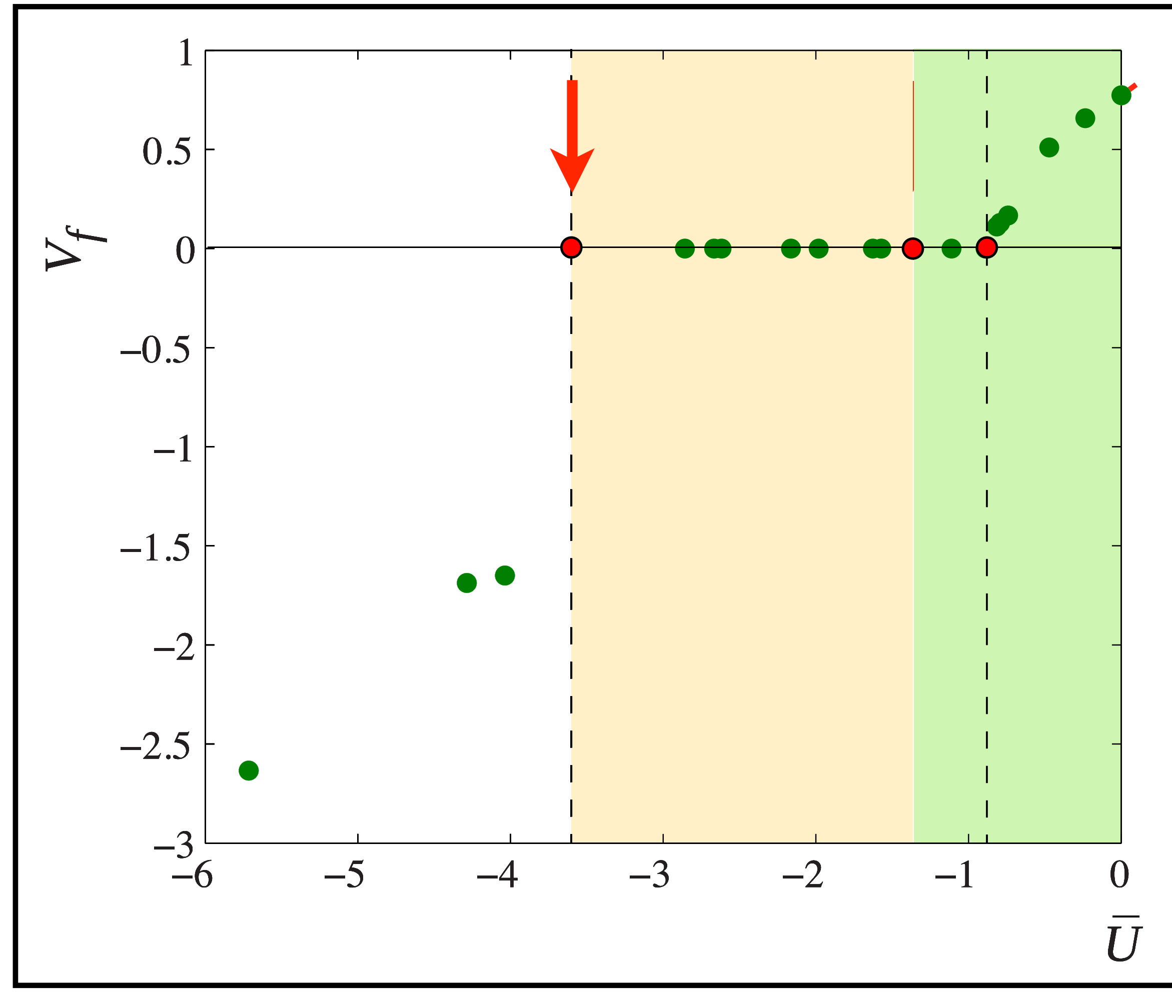
V_f
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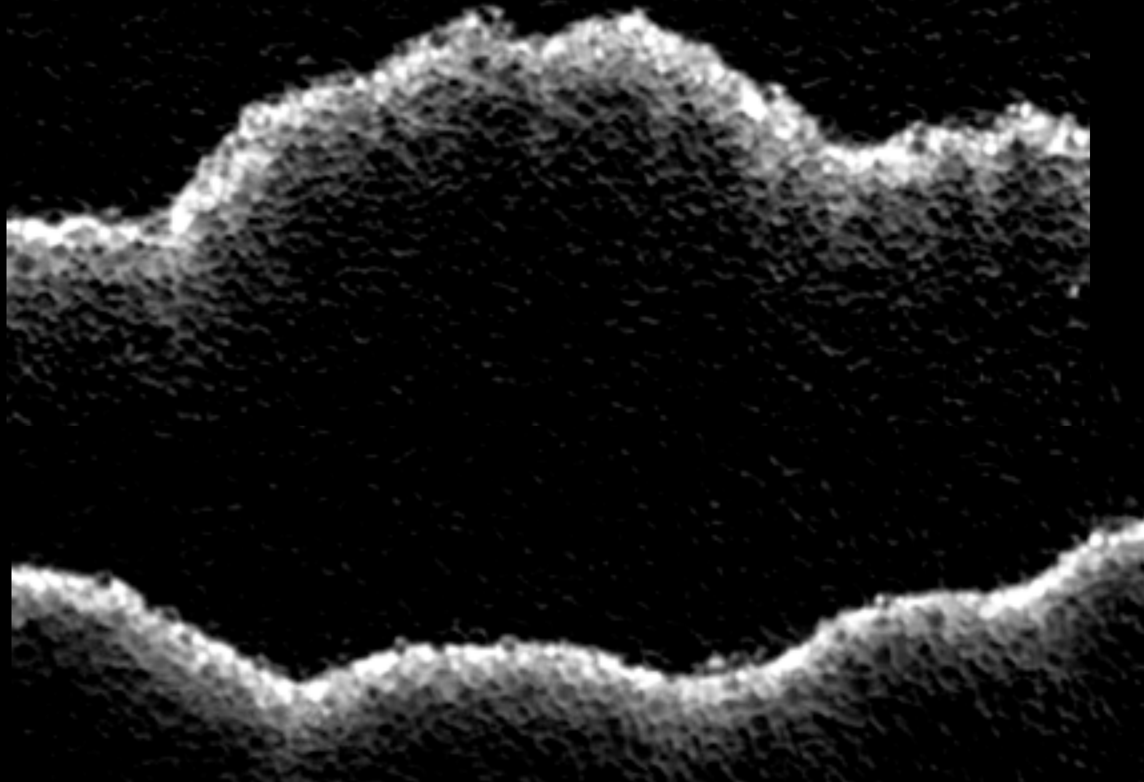
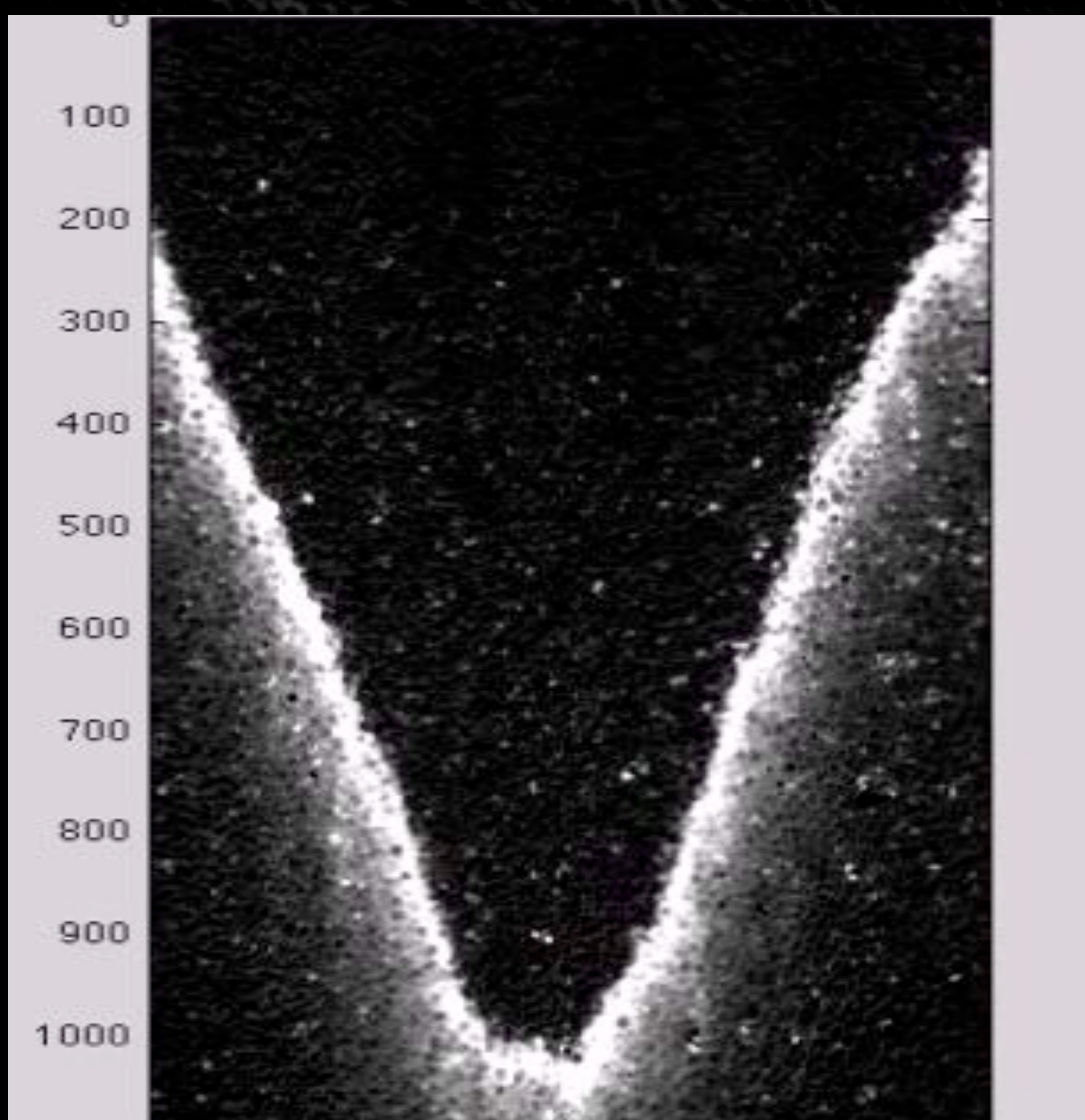
0
$\bar{U}$





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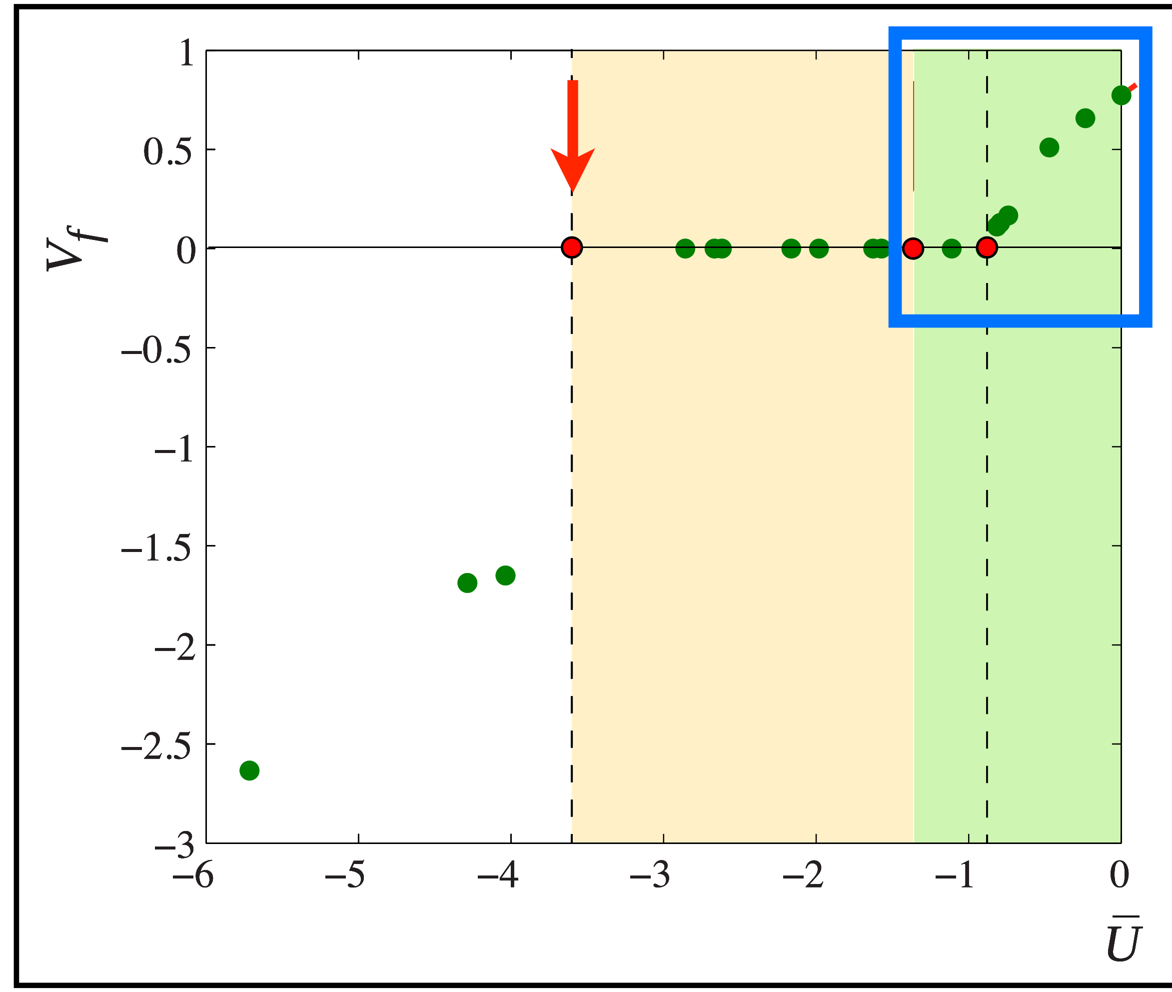

V_f
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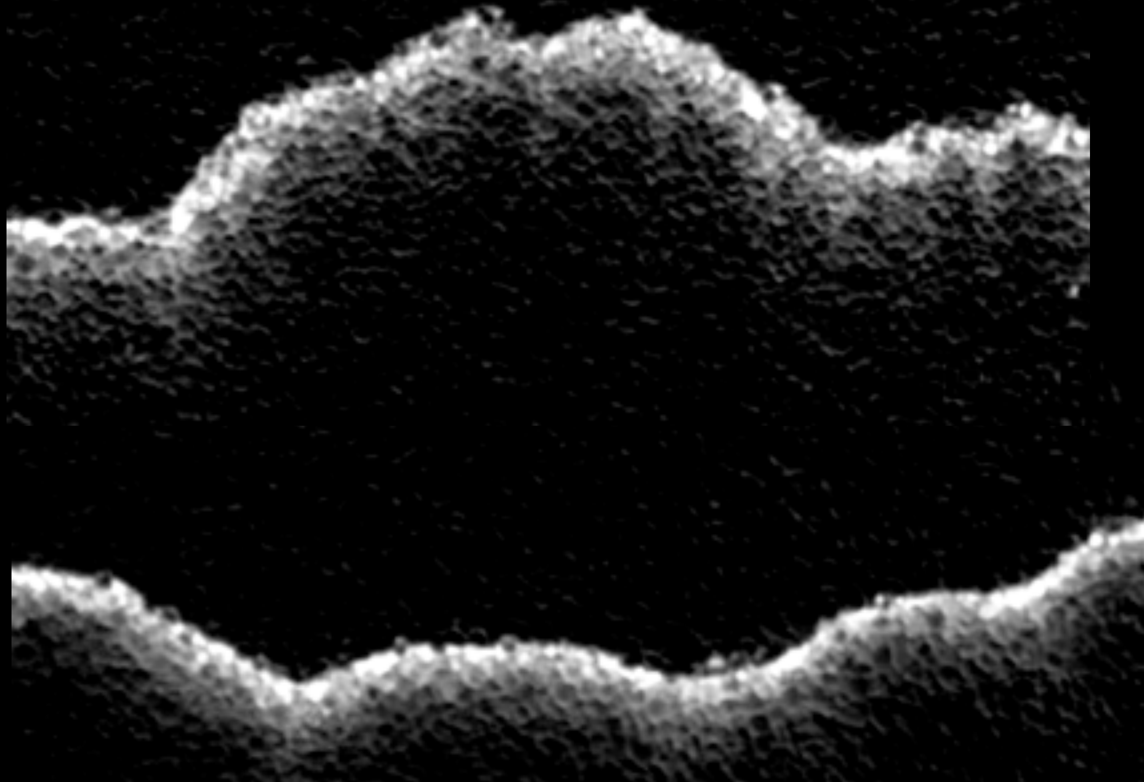
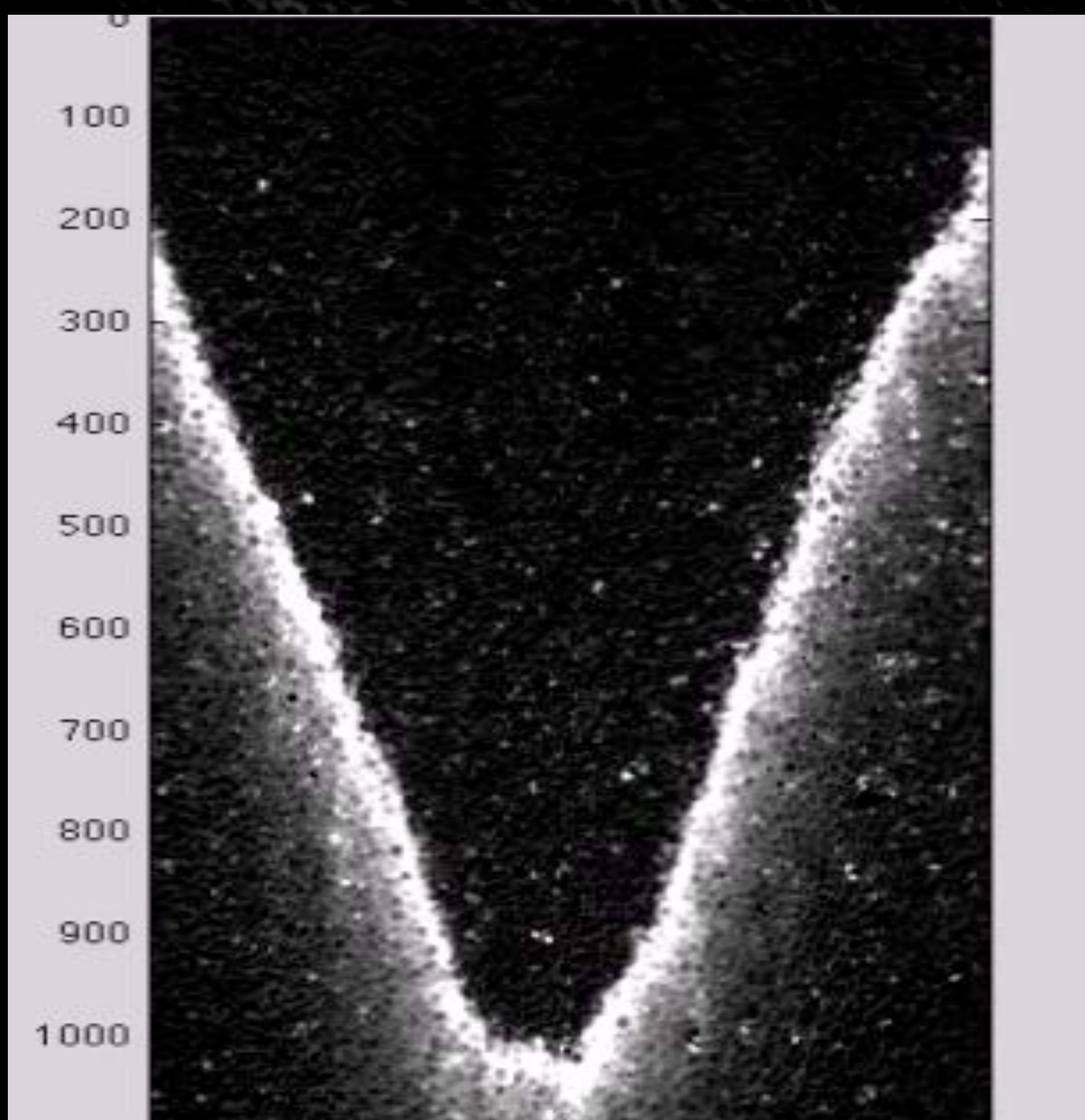
$\bar{U}$





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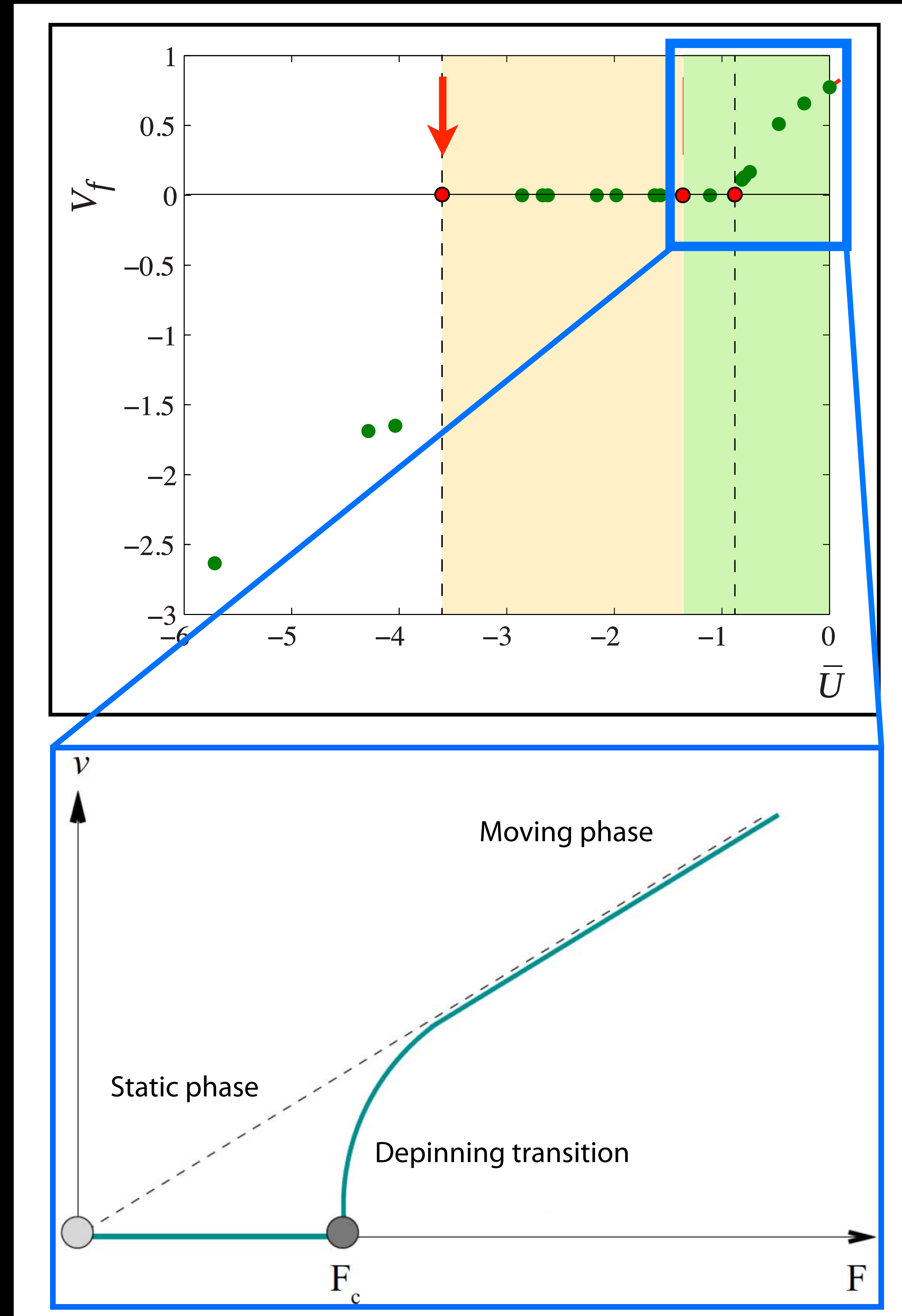

V_f
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−1.5
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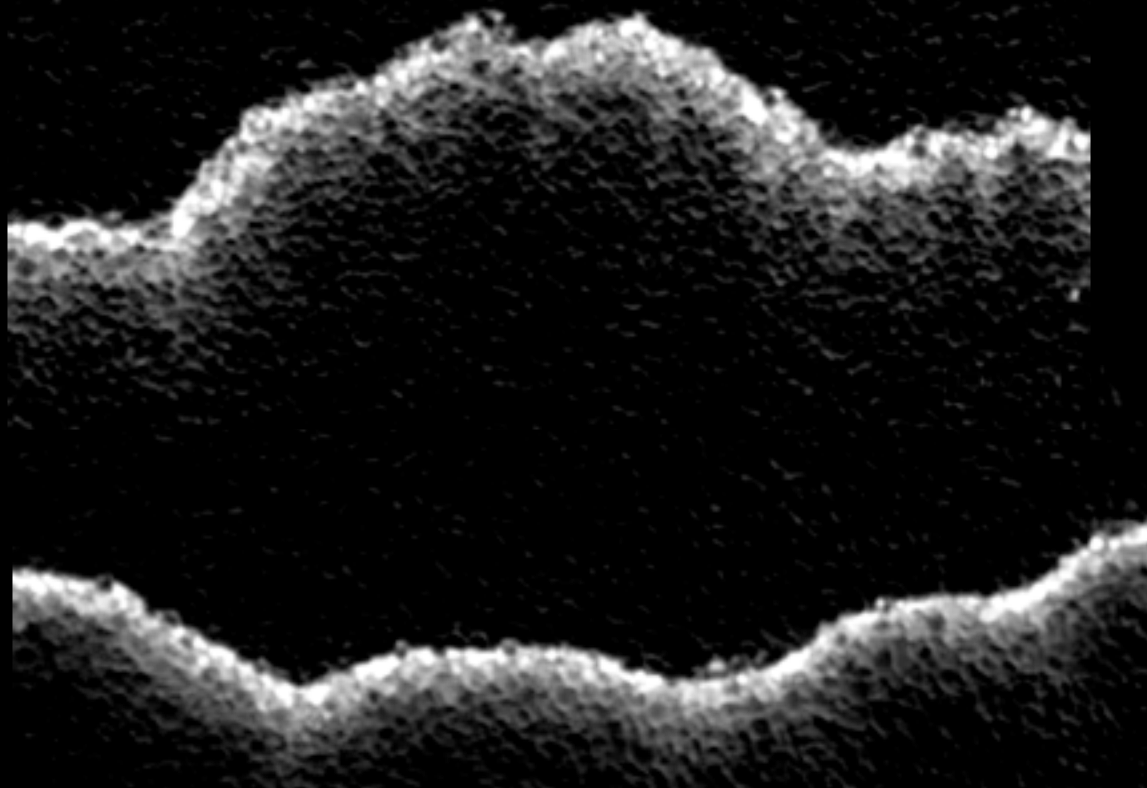
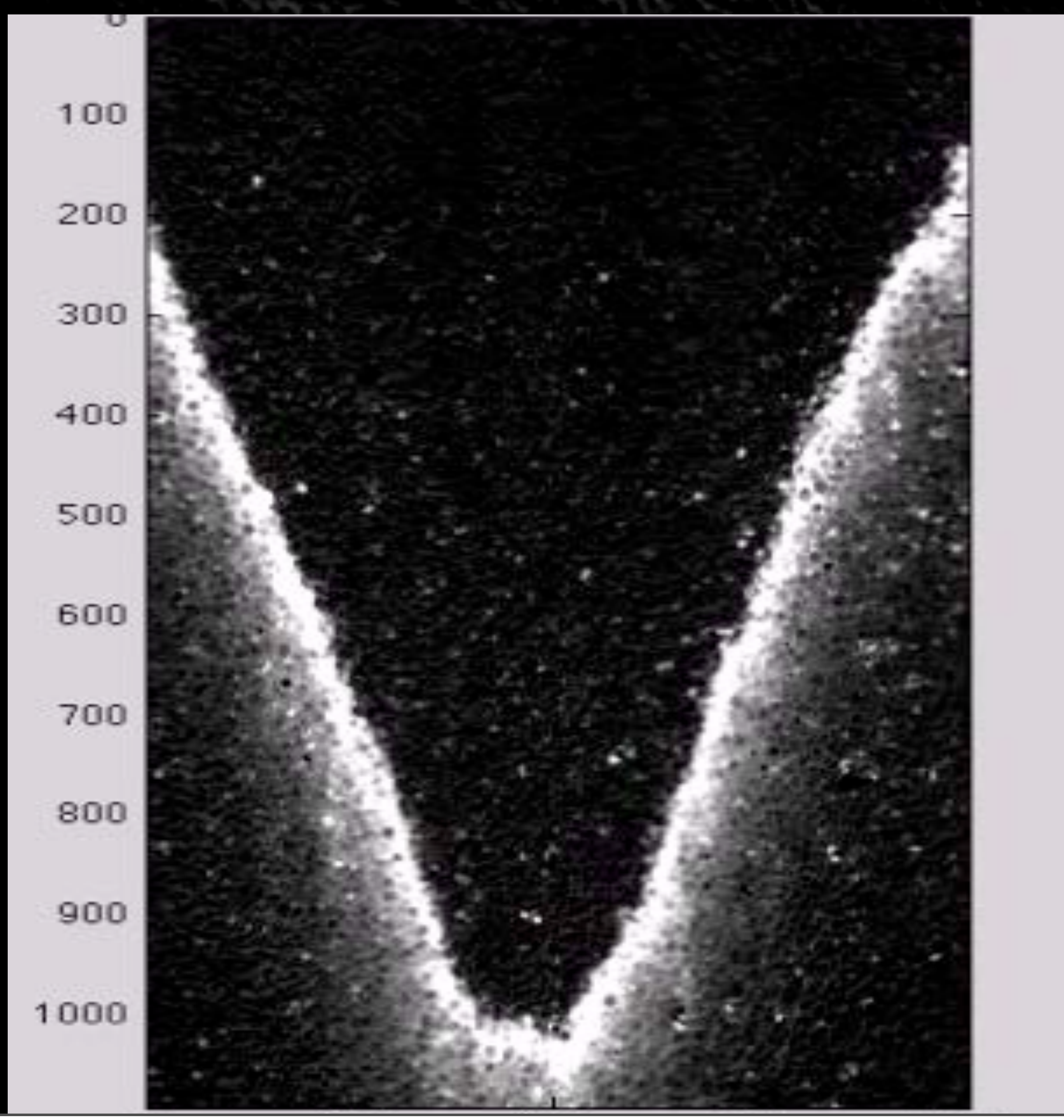
0
$\bar{U}$
v
Moving phase
Static phase
Depinning transition
F_c
F

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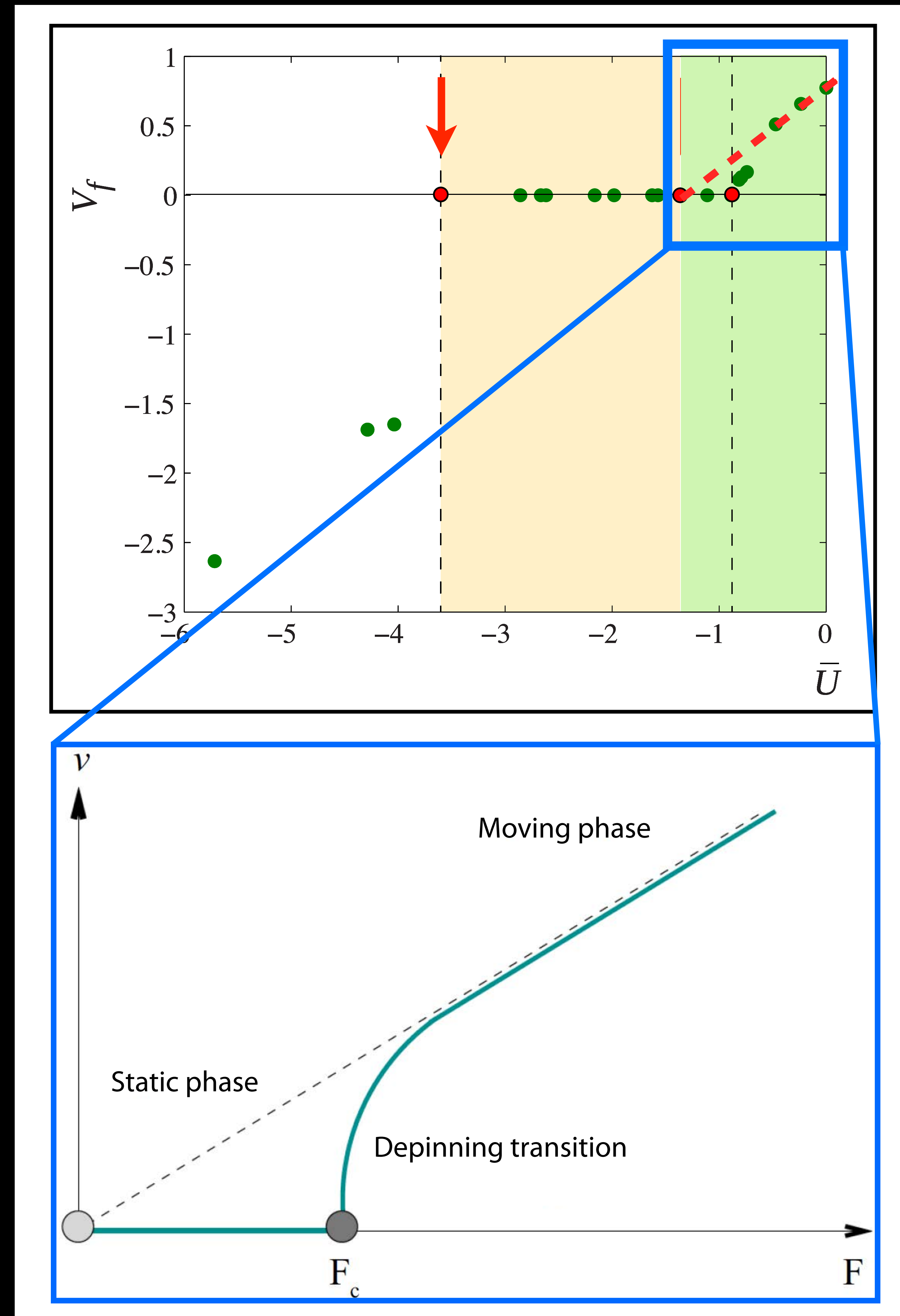
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−3
V_f
−6
−5
−4
−3
−2
−1
0
$\bar{U}$
v
Moving phase
Static phase
Depinning transition
F_c
F

3 - Pinning process in low flow strength

Control parameter:

$$F = \frac{\bar{U} + V_x}{V_x} + f_0$$

3 - Pinning process in low flow strength

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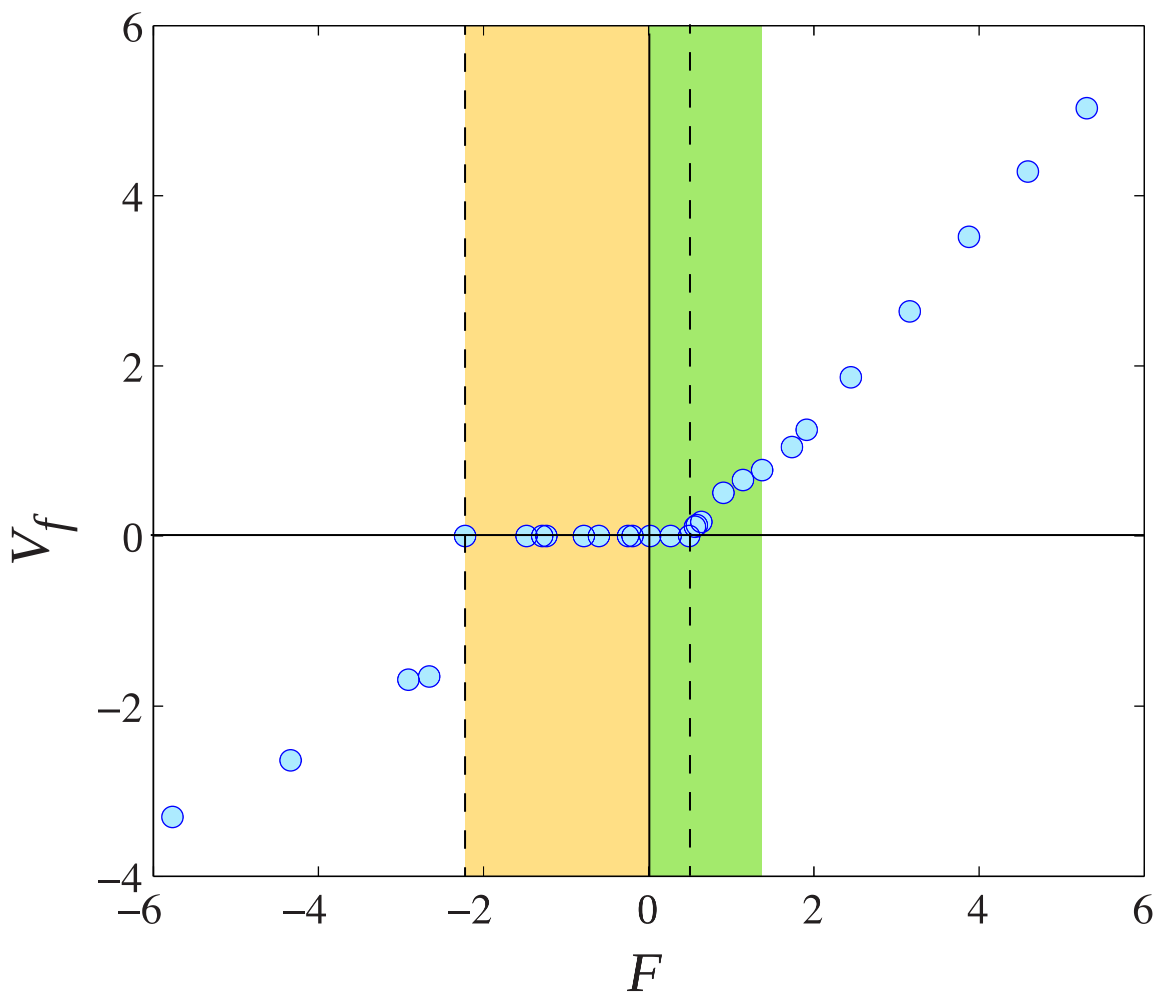
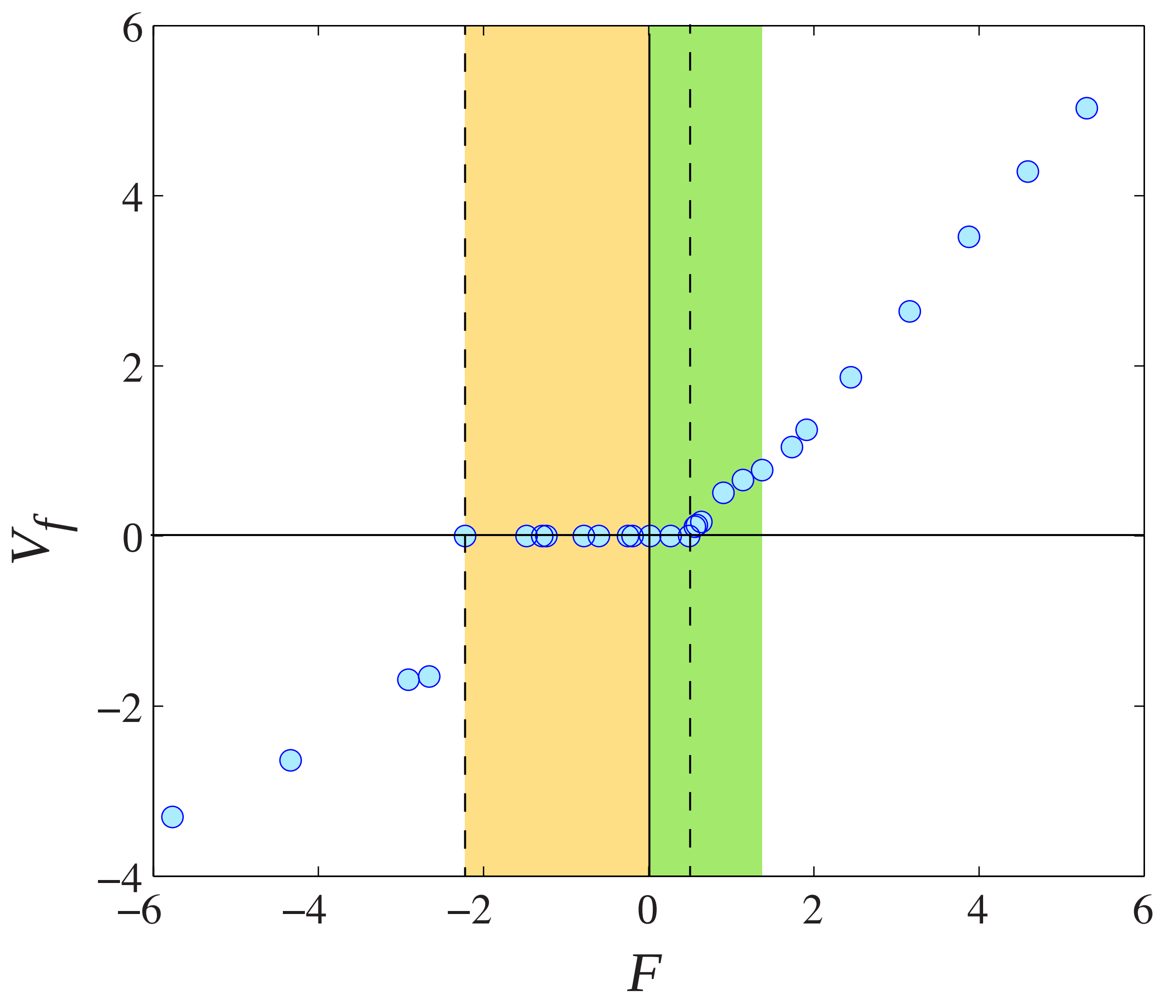


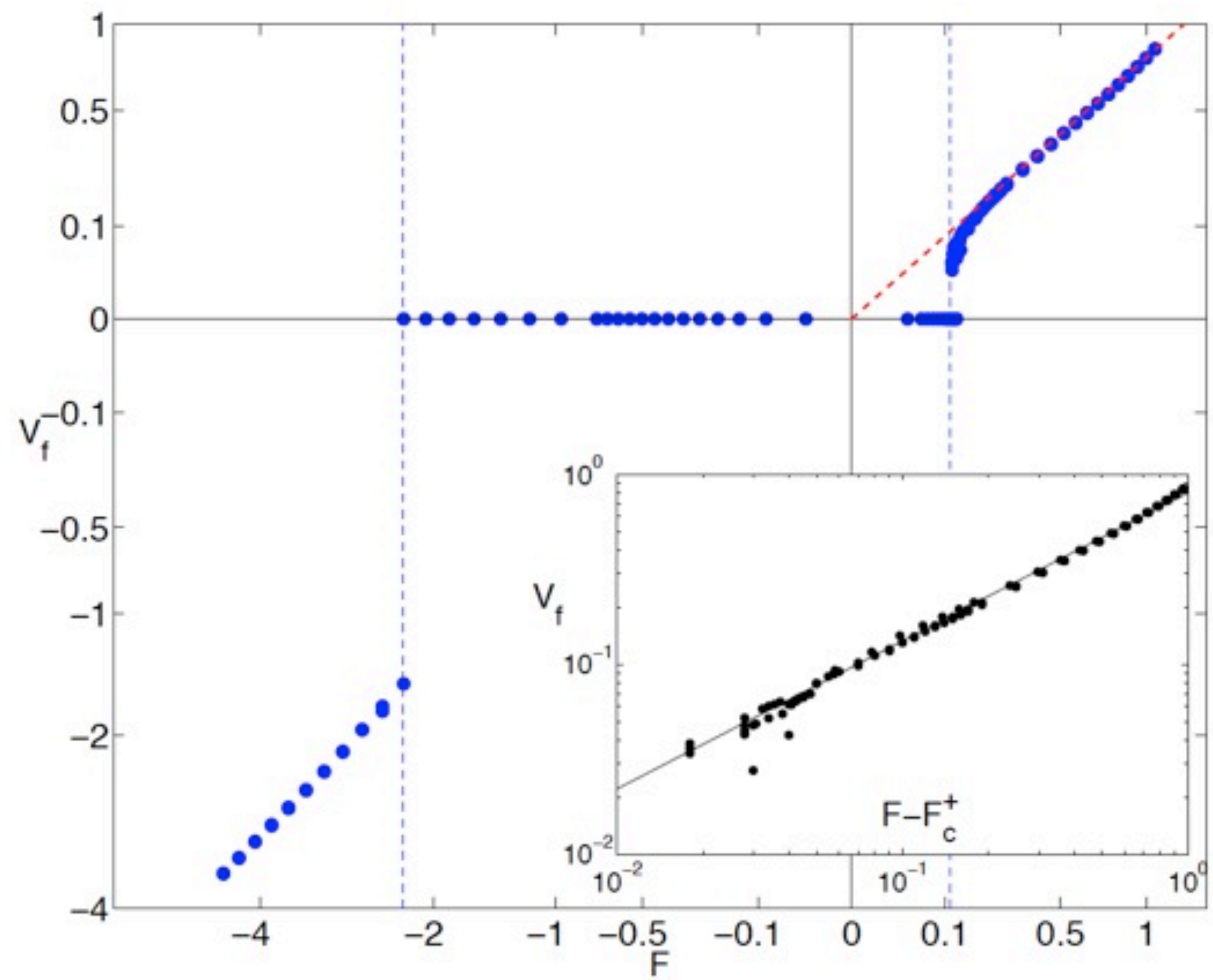
3 - Pinning process in low flow strength

Control parameter:

$$F = \frac{\bar{U} + V_x}{V_x} + f_0$$



Numerical simulations



PLAN

1 - Experimental

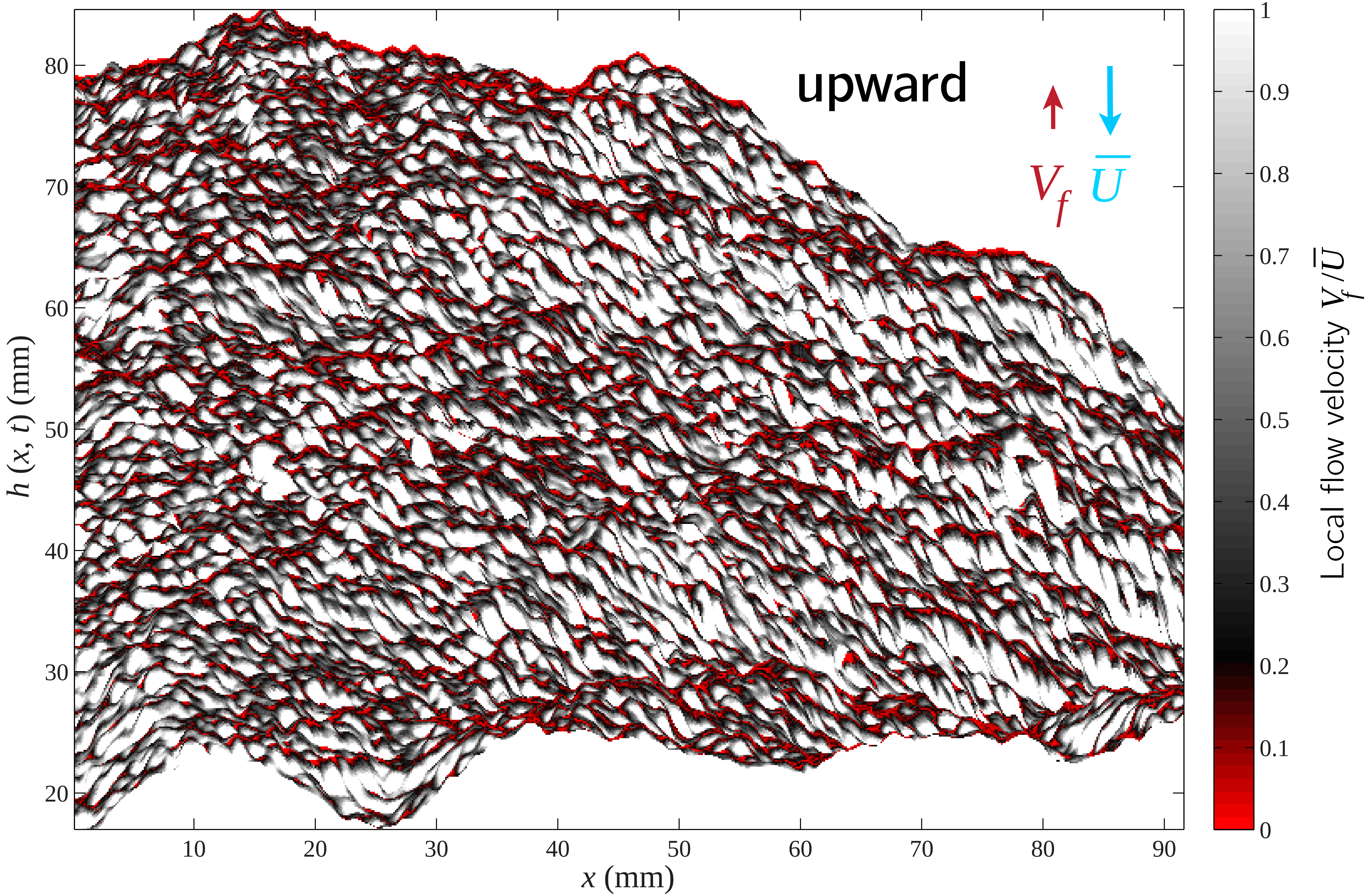
2 - Front dynamics in high flow strength

3 - Pinning process in low flow strength

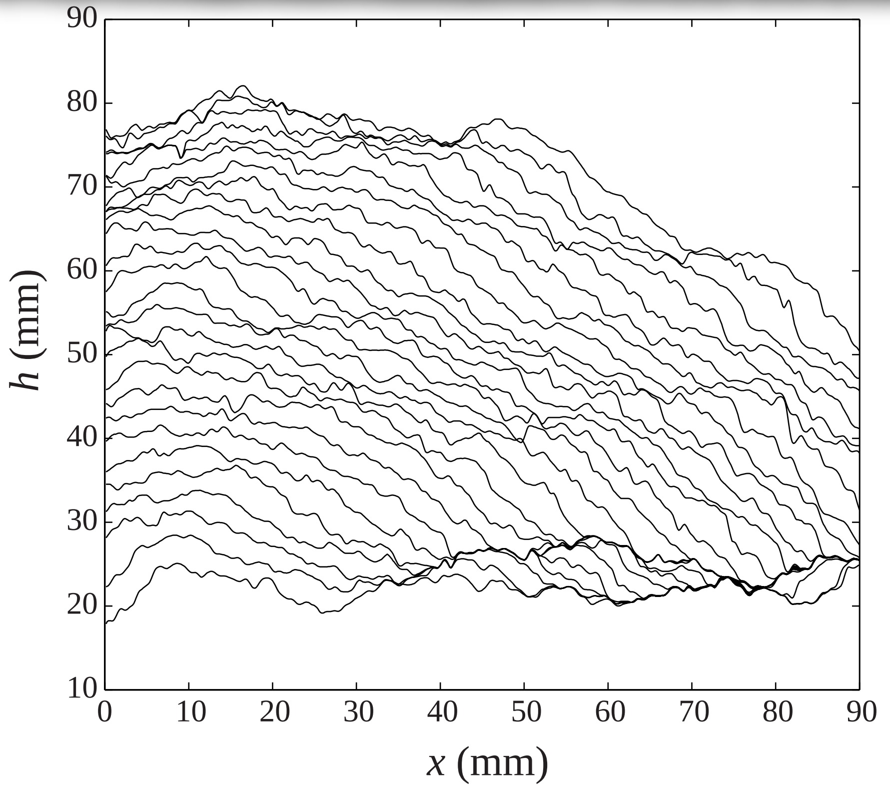
4 - Transcient dynamics and universality

5 - Conclusion and perpectives

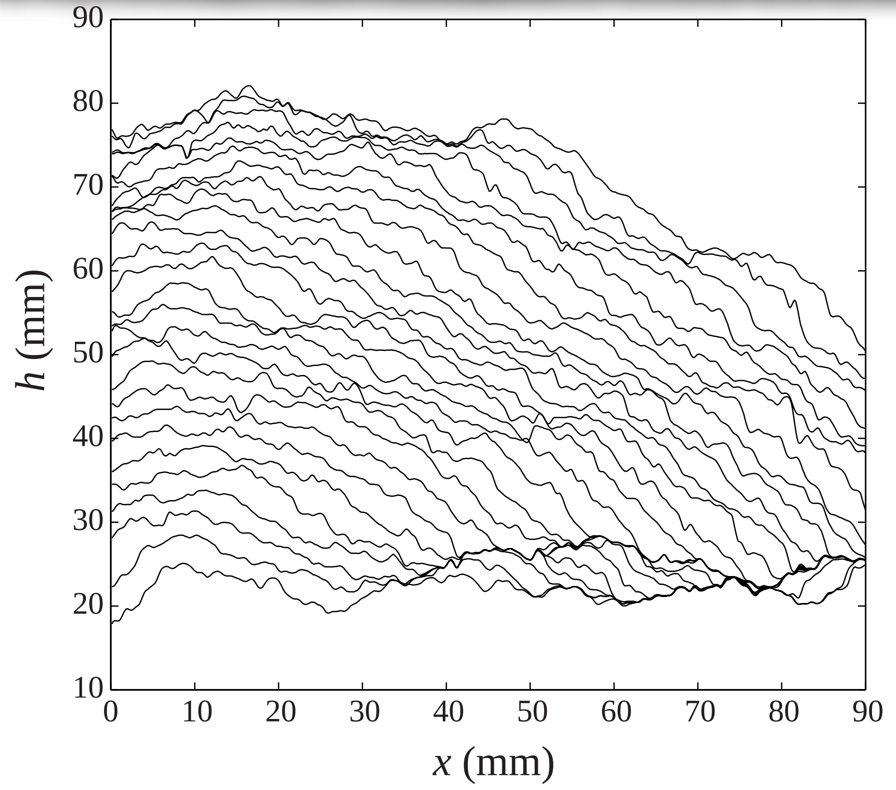
4 - Transcient dynamics and universality



4 - Transcient dynamics and universality



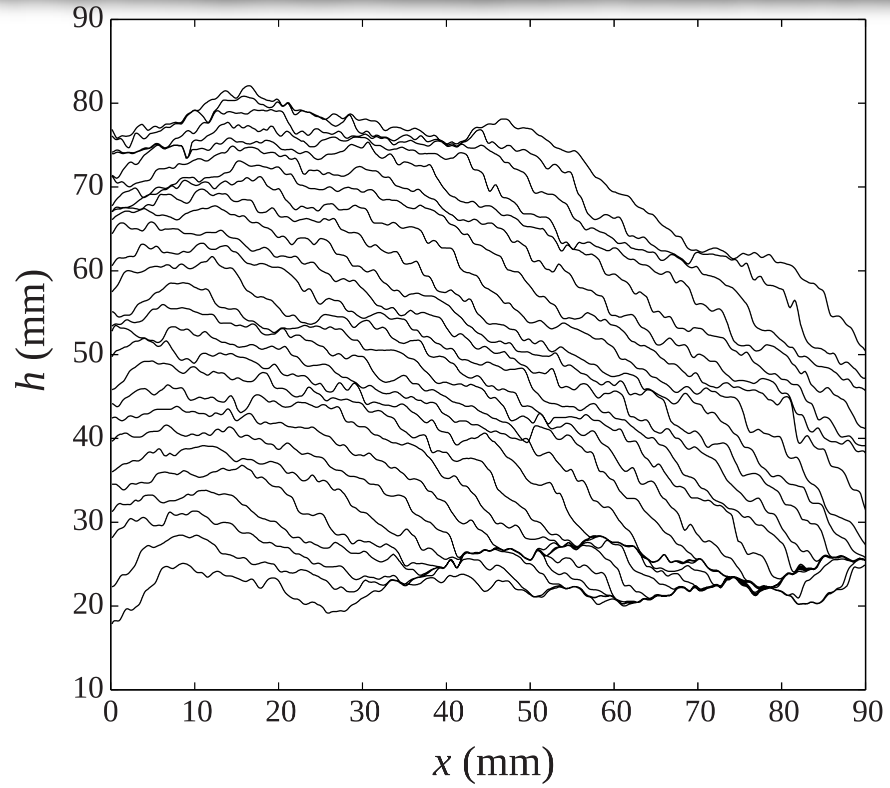
4 - Transcient dynamics and universality



- **Roughness**

$$w(\Delta x, t) = \left\langle \sqrt{\langle [h(x,t) - \langle h \rangle_{\Delta x}]^2 \rangle_{\Delta x}} \right\rangle_L$$

4 - Transcient dynamics and universality



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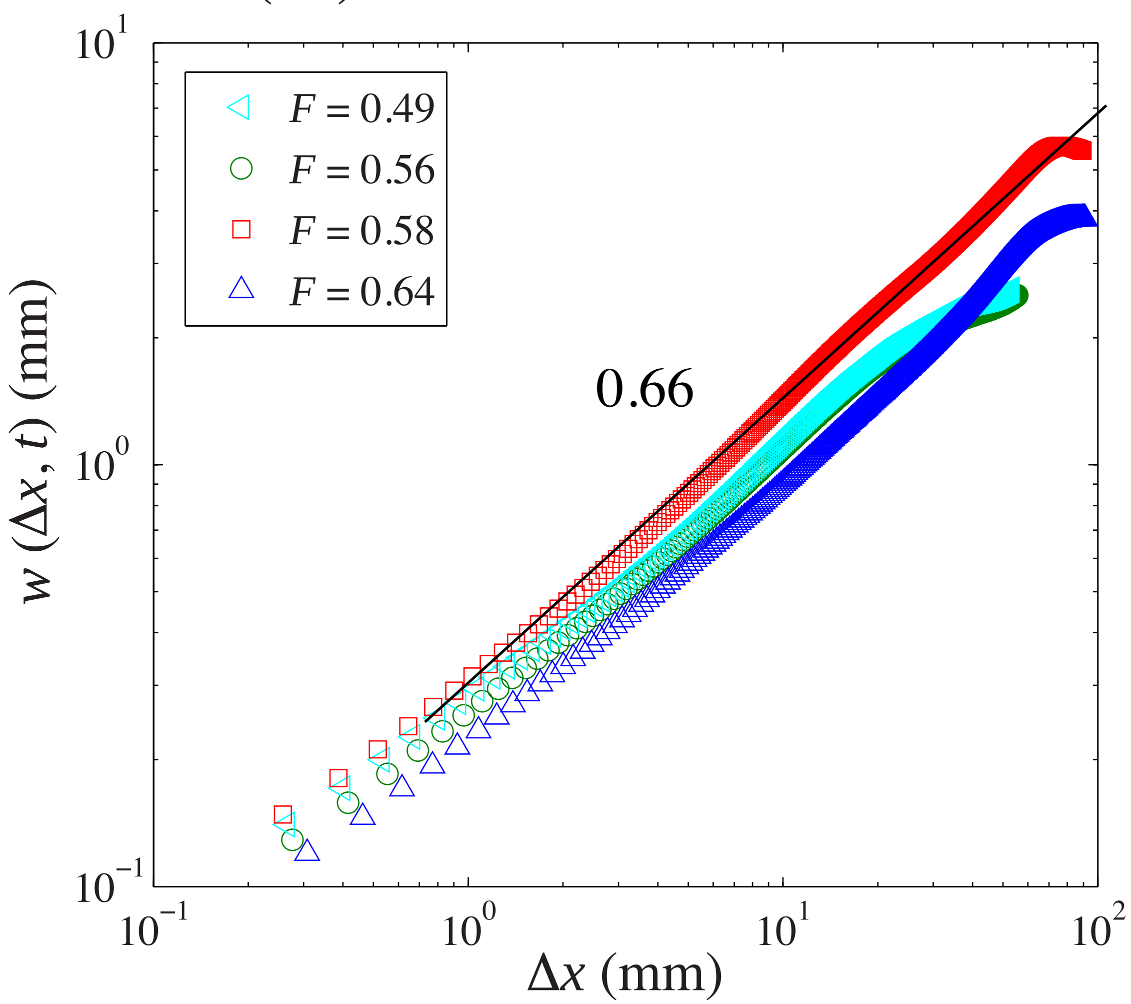
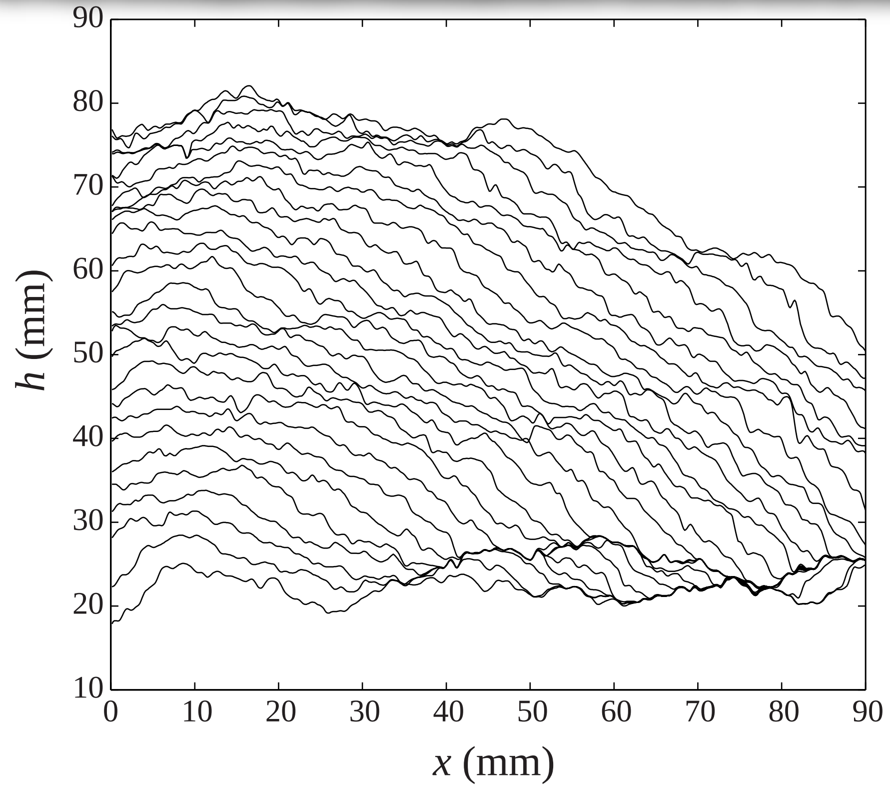


4 - Transcient dynamics and universality

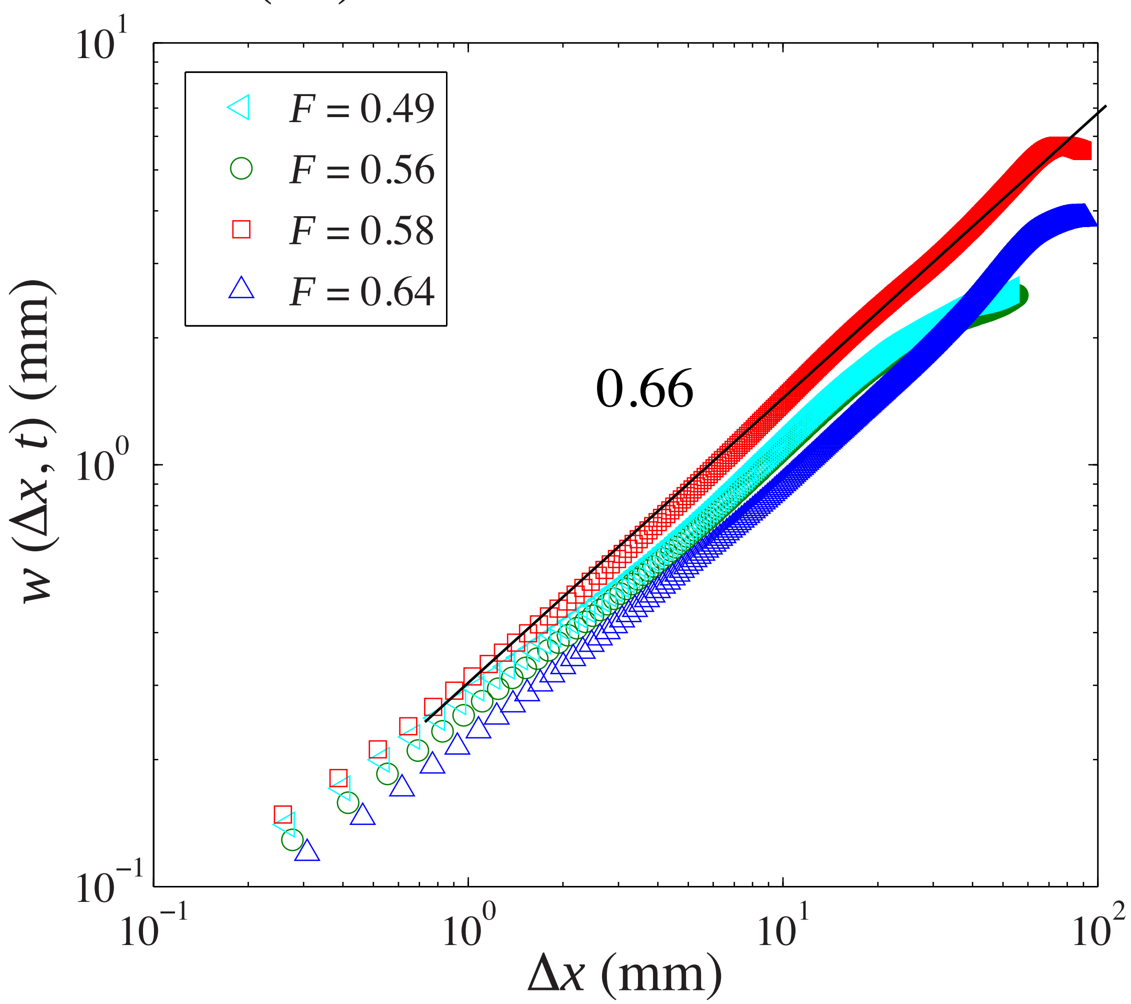


- **Roughness**

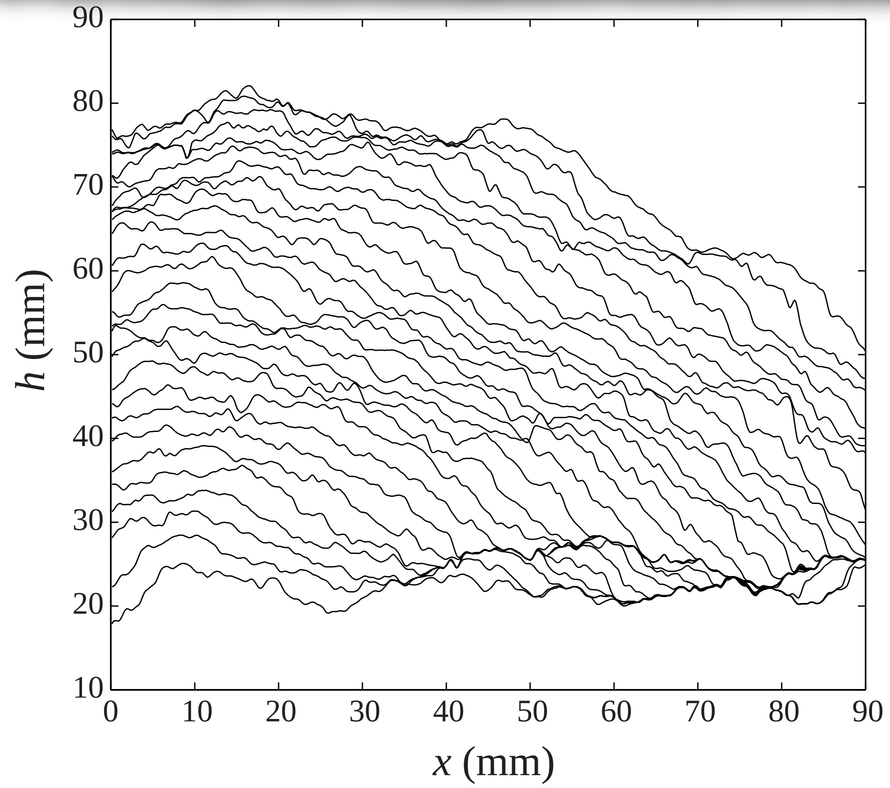
$$w(\Delta x, t) = \left\langle \sqrt{\langle [h(x,t) - \langle h \rangle_{\Delta x}\ ]^2 \rangle_{\Delta x}} \right\rangle_L$$

- **Temporal fluctuations**

$$w(x, \Delta t) = \left\langle \sqrt{\langle [h(x,t) - \langle h \rangle_{\Delta t}]^2 \rangle_{\Delta t}} \right\rangle_T$$



4 - Transcient dynamics and universality

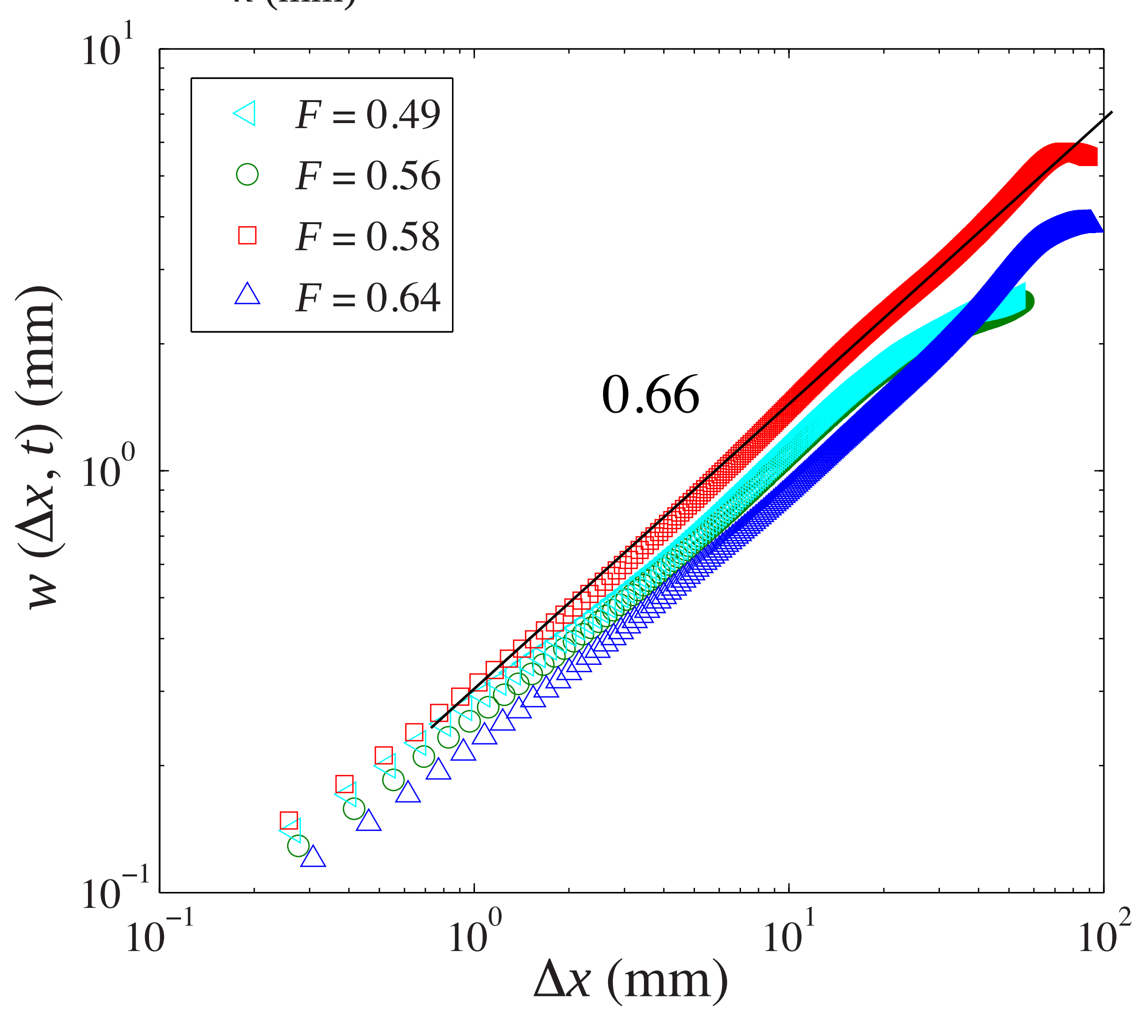


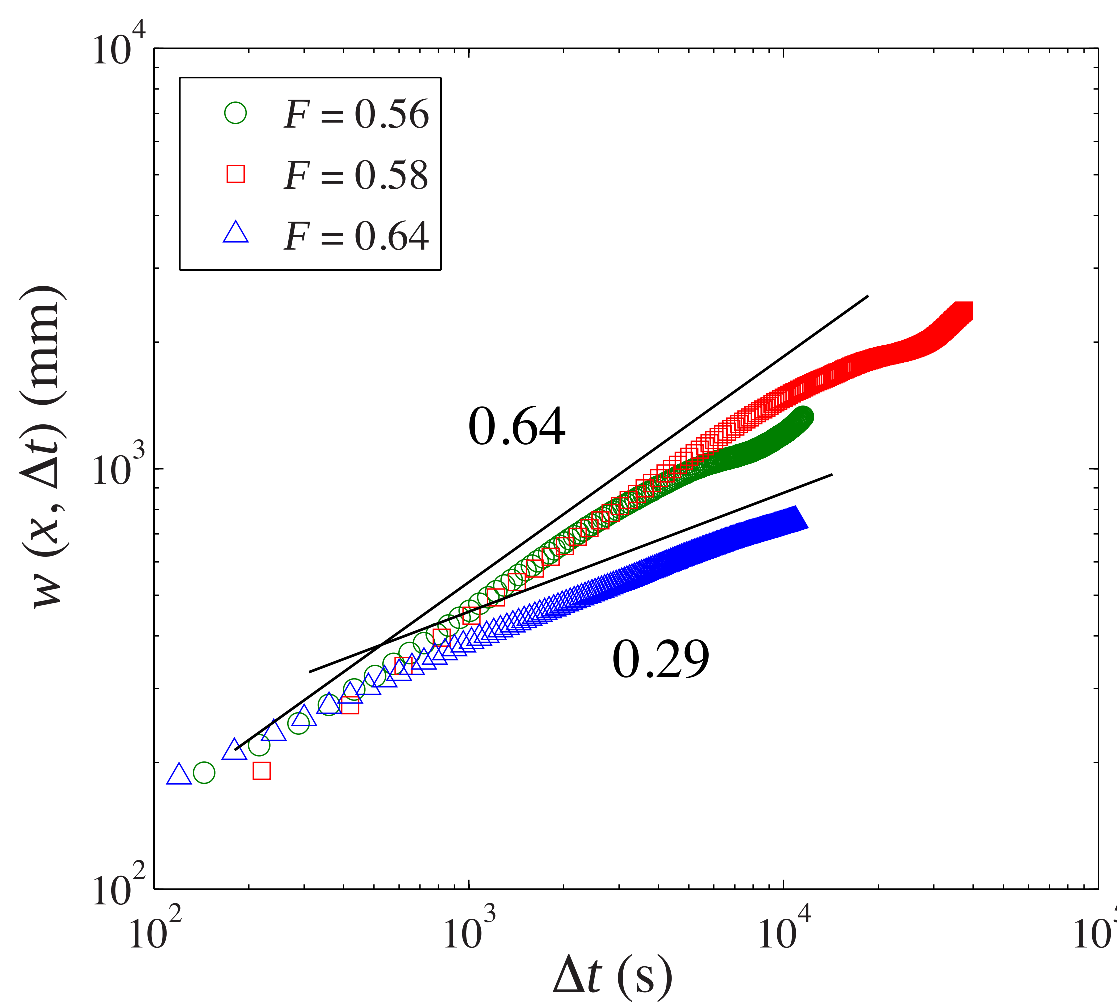
- **Roughness**

$$w(\Delta x, t) = \left\langle \sqrt{\left\langle [h(x,t) - \langle h \rangle_{\Delta x}\ ]^2 \right\rangle_{\Delta x}} \right\rangle_L$$

- **Temporal fluctuations**

$$w(x, \Delta t) = \left\langle \sqrt{\left\langle [h(x,t) - \langle h \rangle_{\Delta t}]^2 \right\rangle_{\Delta t}} \right\rangle_T$$





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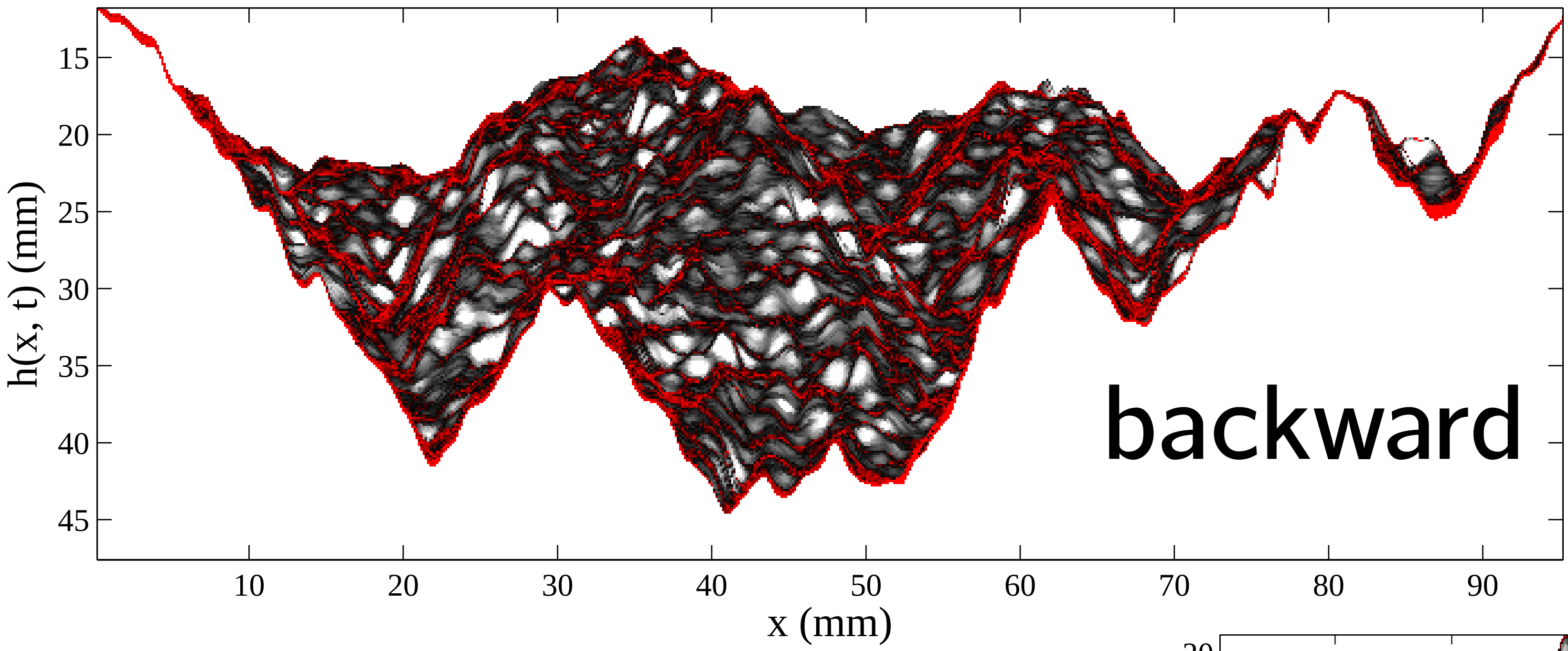
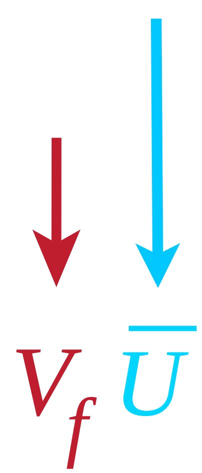
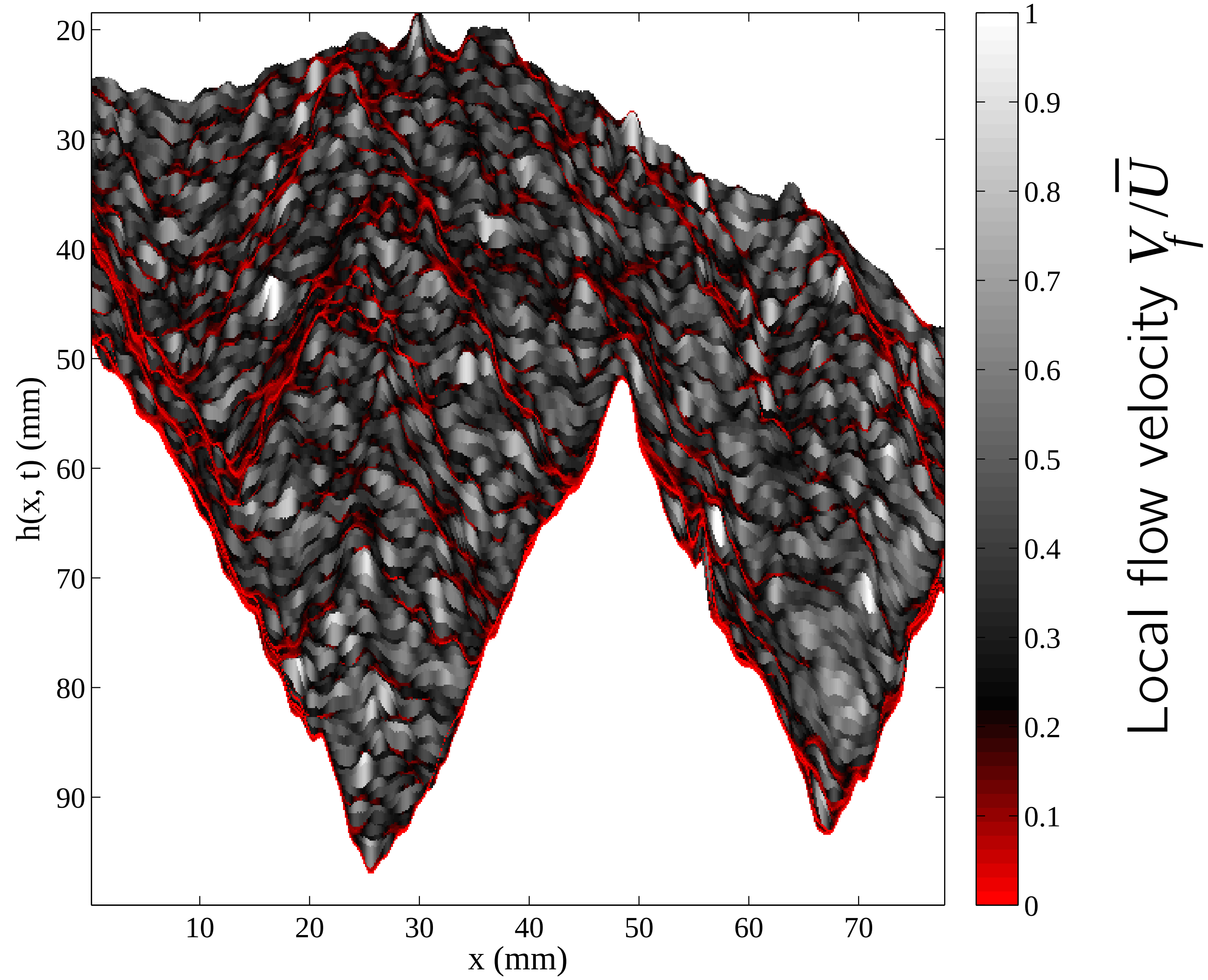
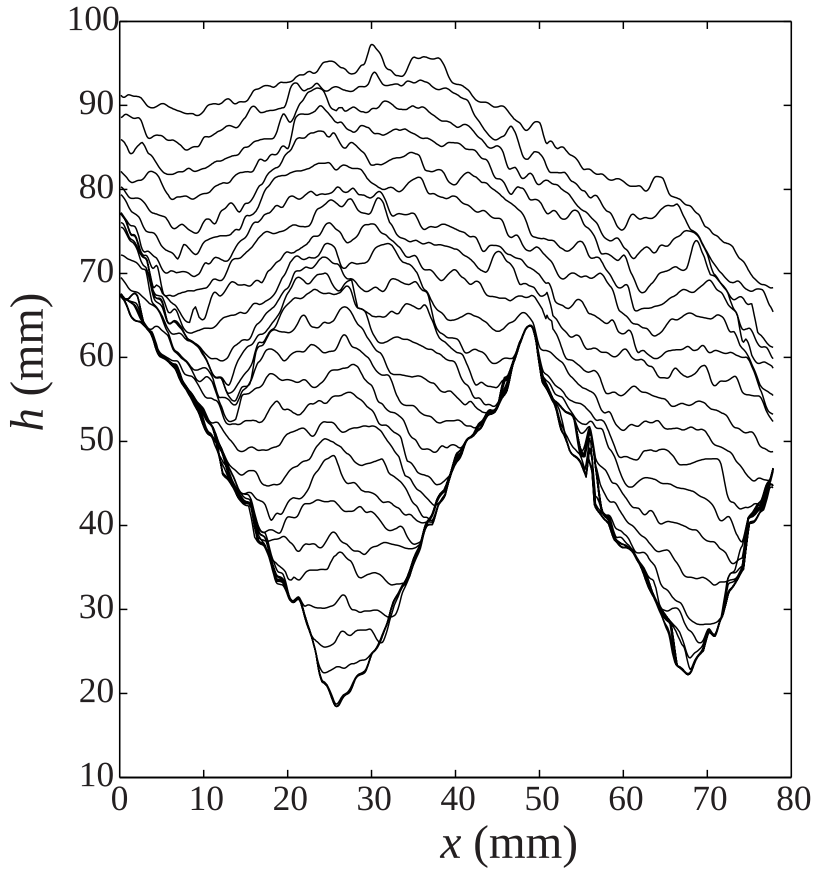






4 - Transcient dynamics and universality



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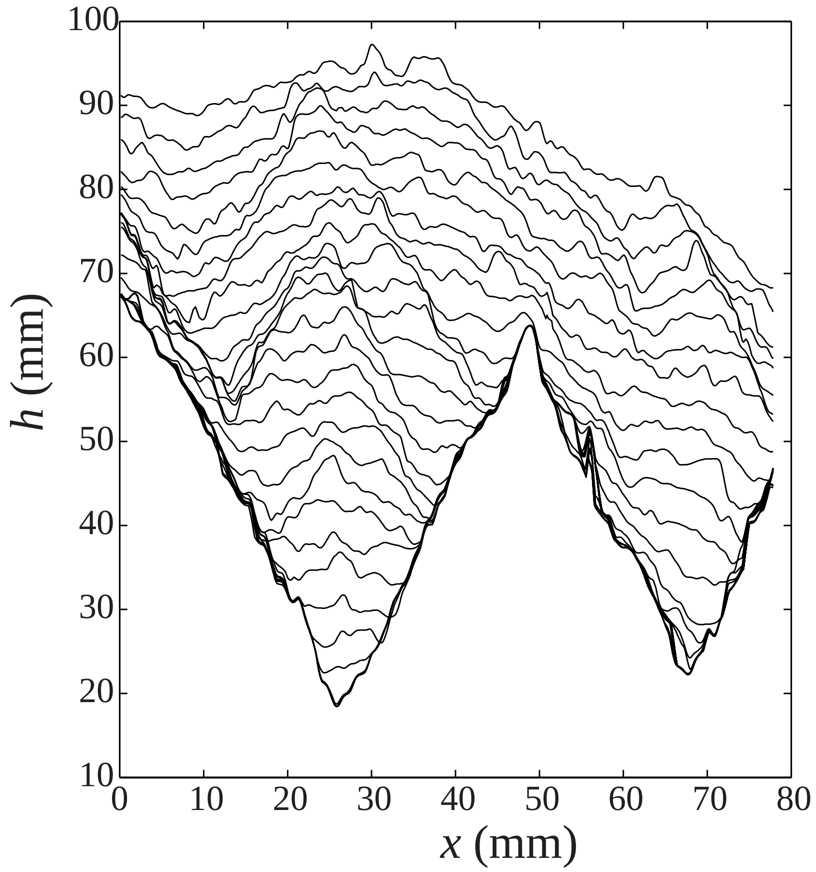
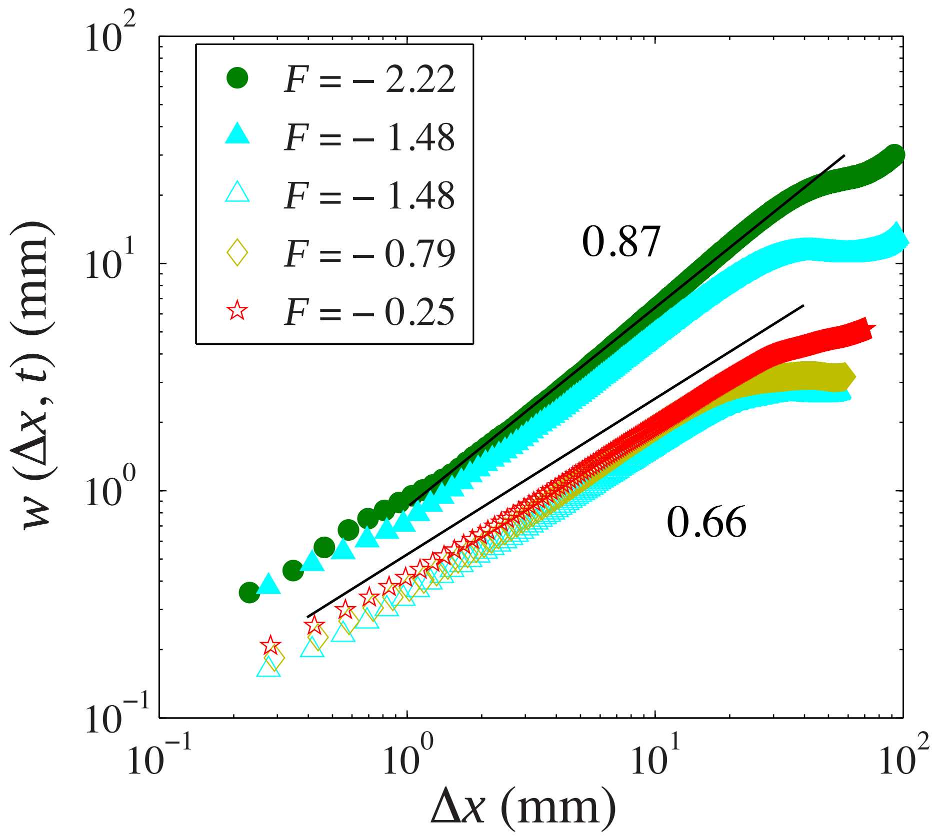
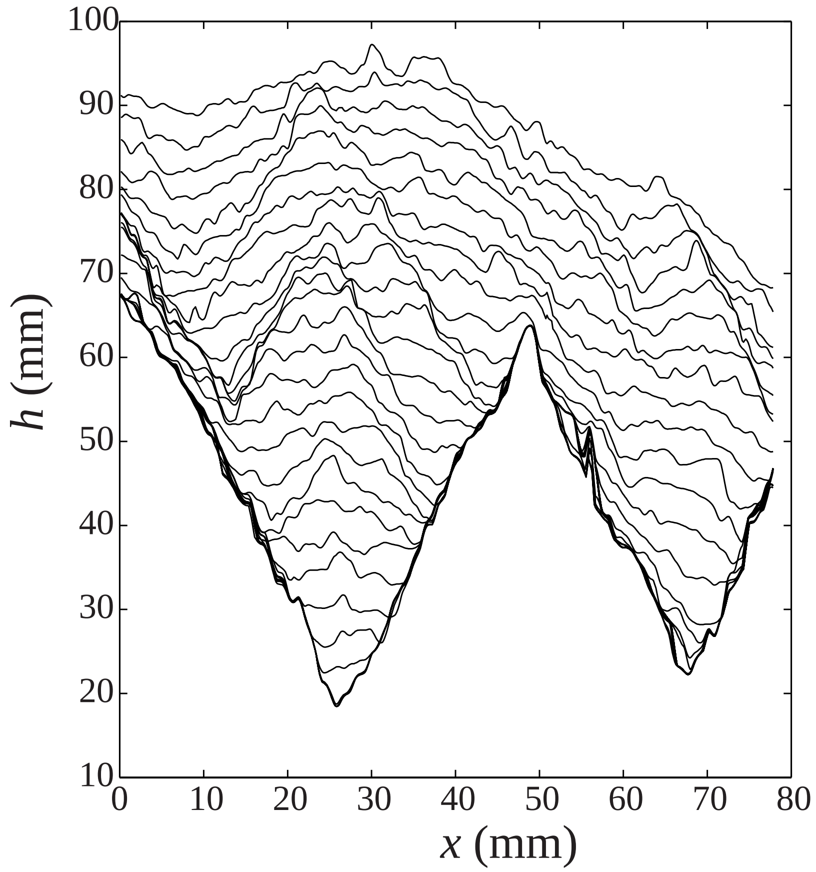


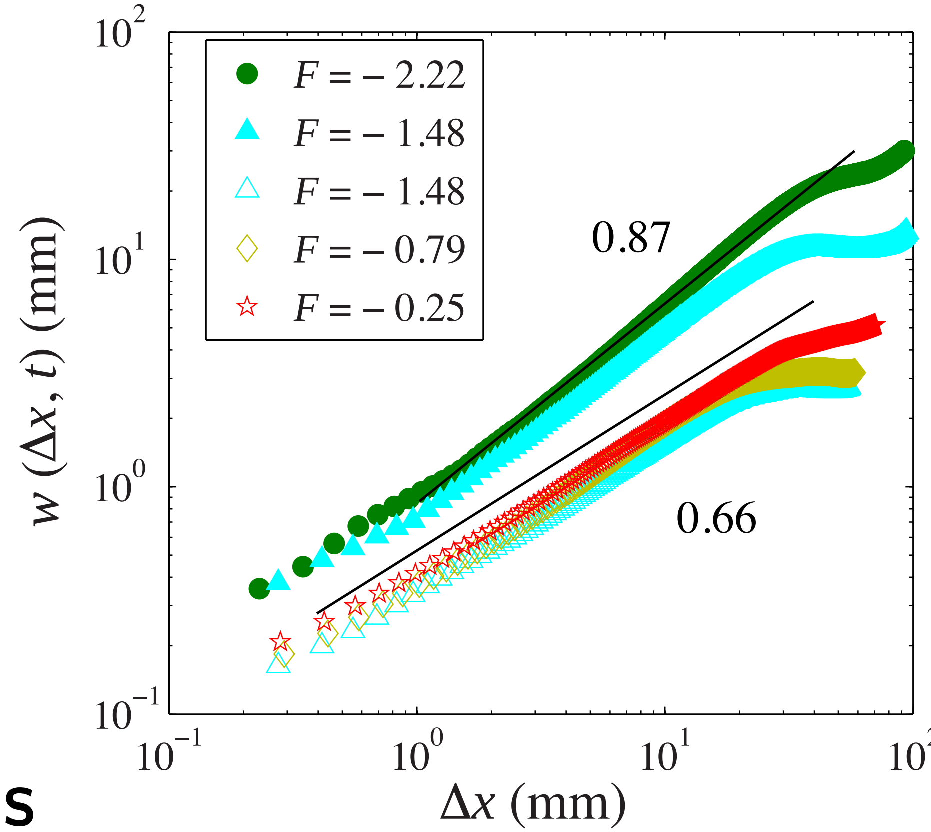
- **Roughness**



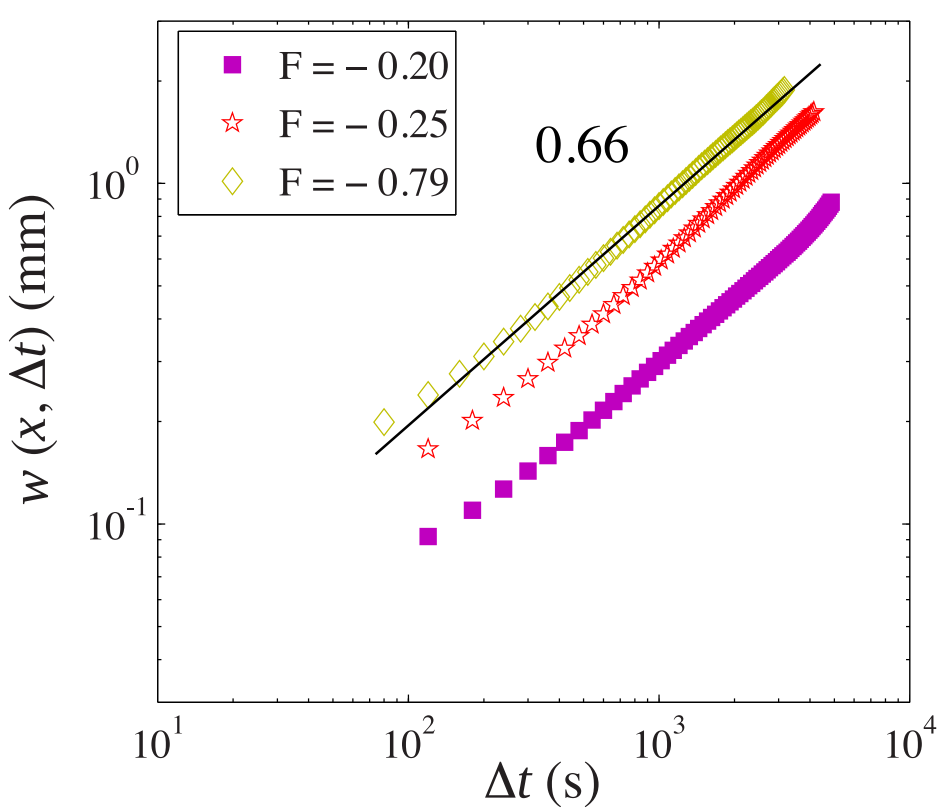
4 - Transcient dynamics and universality

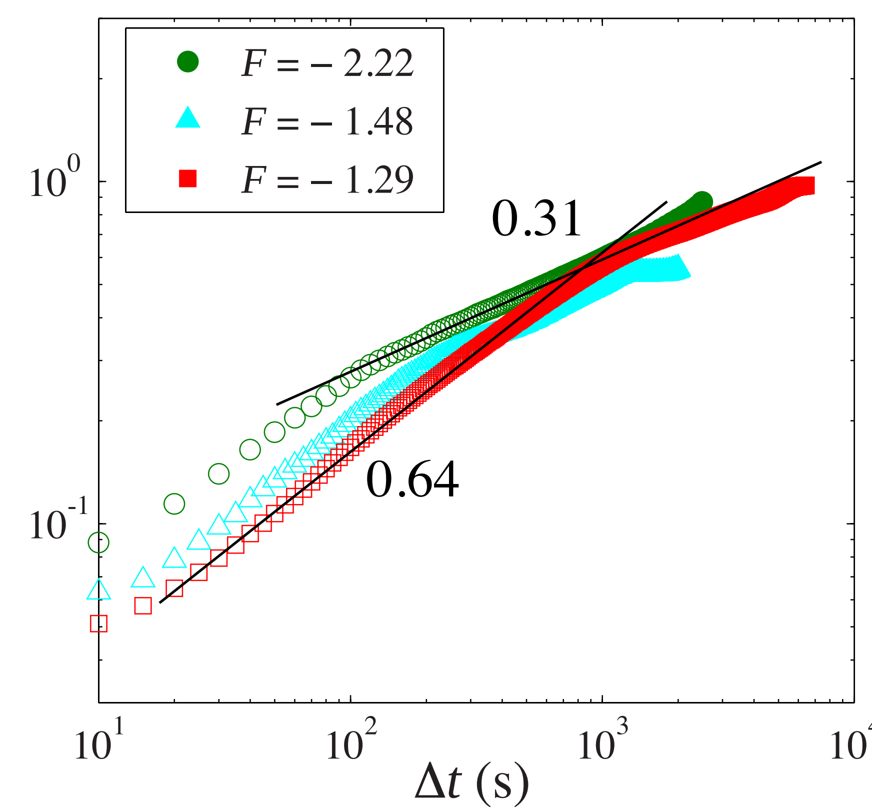


- **Roughness**



- **Temporal fluctuations**





4 - Transcient dynamics and universality

- **Positif and negatif qKPZ growth process** $\alpha = 0.63$ $\beta = 0.63$

$$\frac{\partial h(x,t)}{\partial t} = \nu \nabla^2 h(x,t) + \frac{\lambda}{2} \left[\nabla h(x,t)\right]^2 + \bar{\eta}\Big(x, h(x,t)\Big) + f$$

4 - Transcient dynamics and universality

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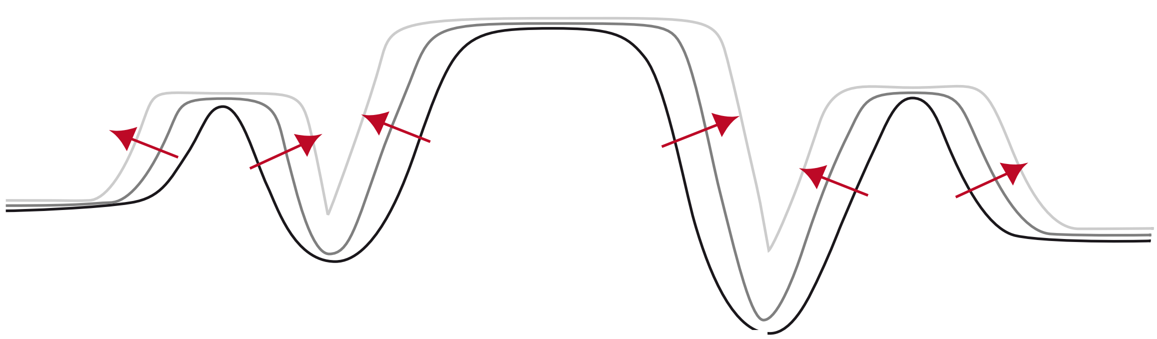

qKPZ > 0

growth term λ and the driving force term F have the same sign

4 - Transcient dynamics and universality

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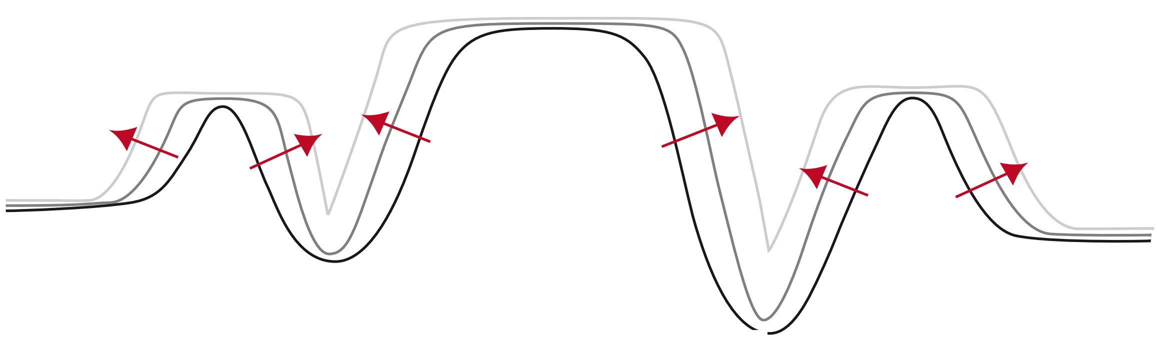

qKPZ > 0

growth term λ and the driving force term F have the same sign

$$V_f > 0$$

$$V_\chi > 0$$

4 - Transcient dynamics and universality

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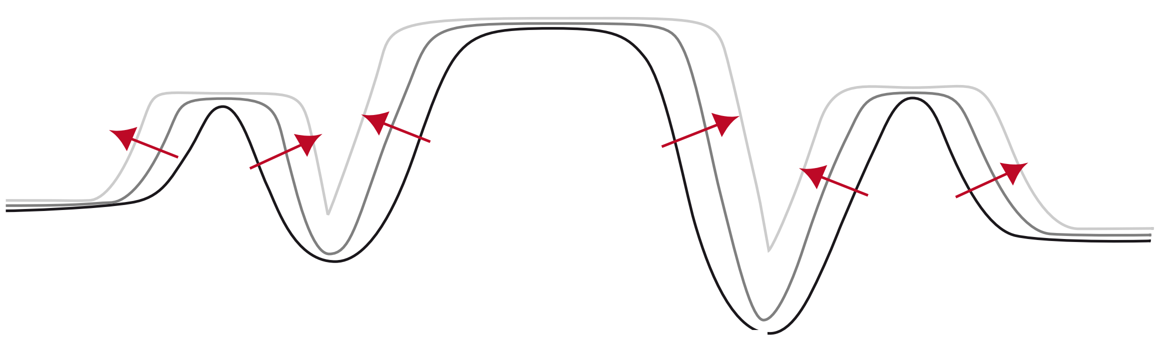
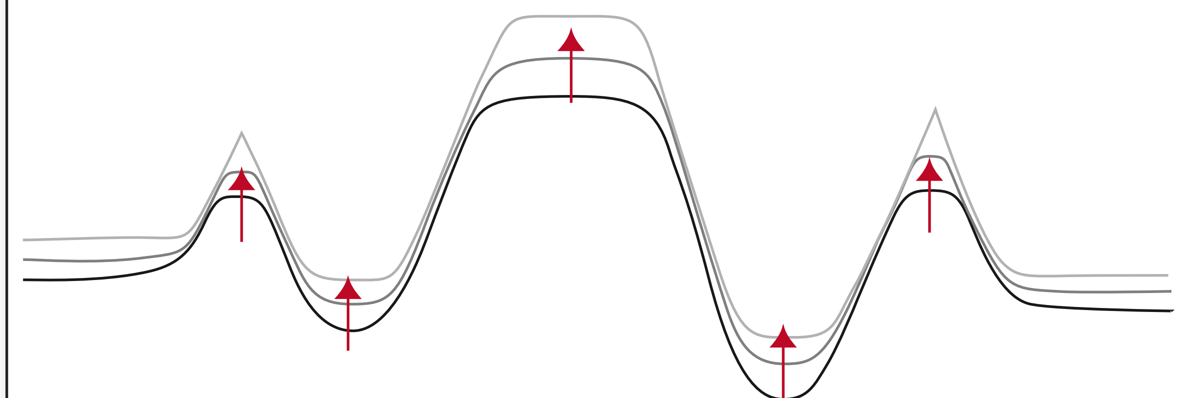


qKPZ > 0

growth term λ and the driving force term F have the same sign



qKPZ < 0

growth term λ and the driving force term F have opposite sign

$V_f > 0$

$V_\chi > 0$

4 - Transcient dynamics and universality

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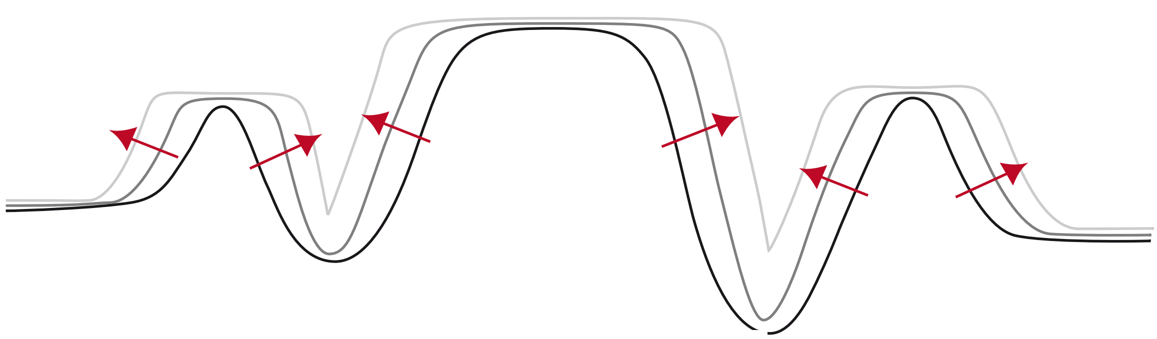
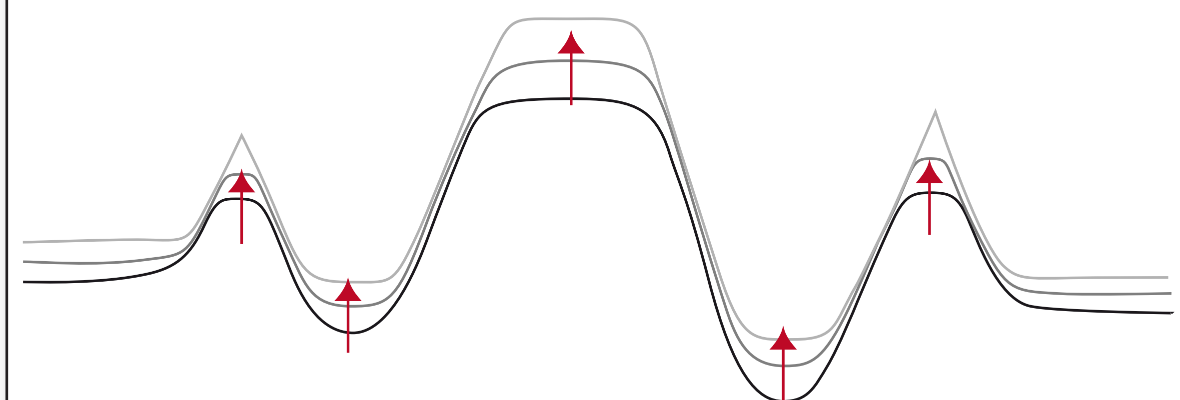


qKPZ > 0

growth term λ and the driving force term F have the same sign



qKPZ < 0

growth term λ and the driving force term F have opposite sign

$V_f > 0$

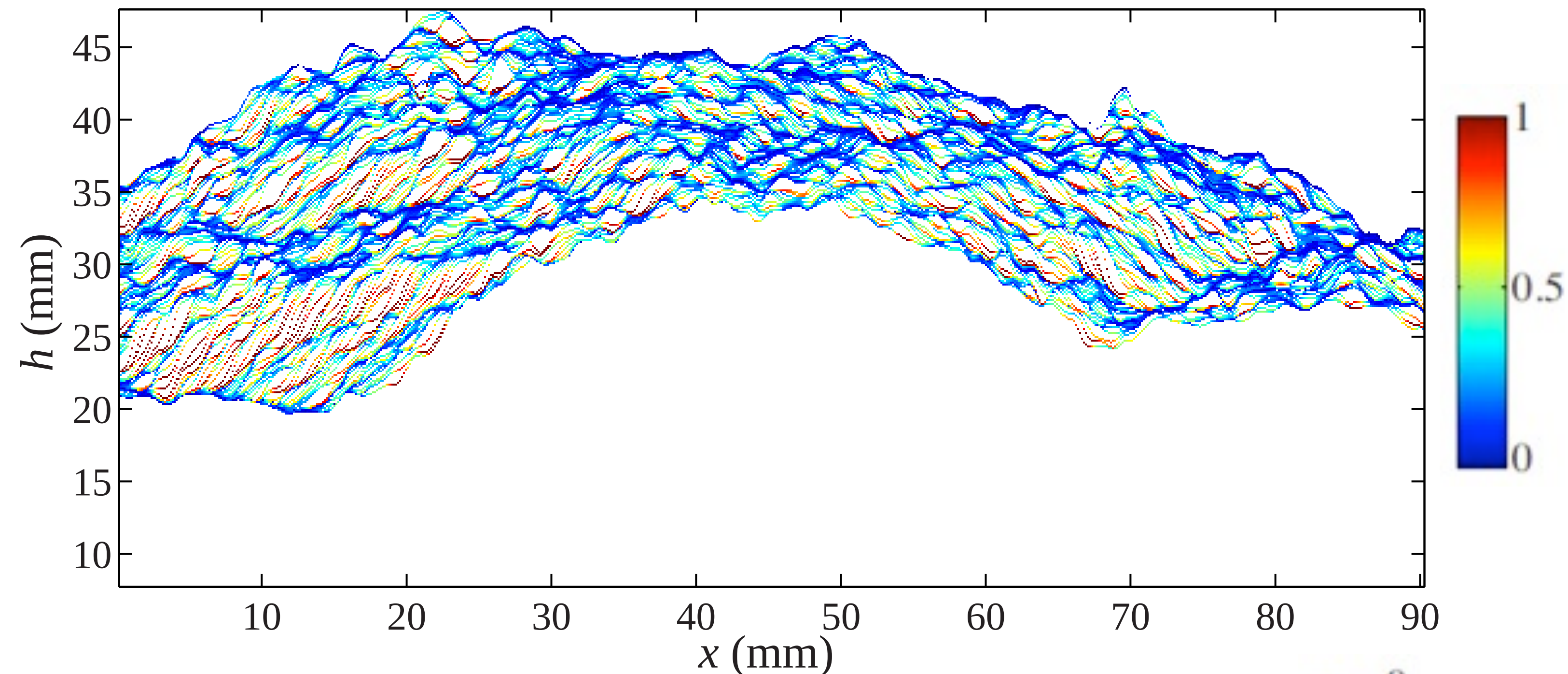
$V_\chi > 0$

$V_f < 0$

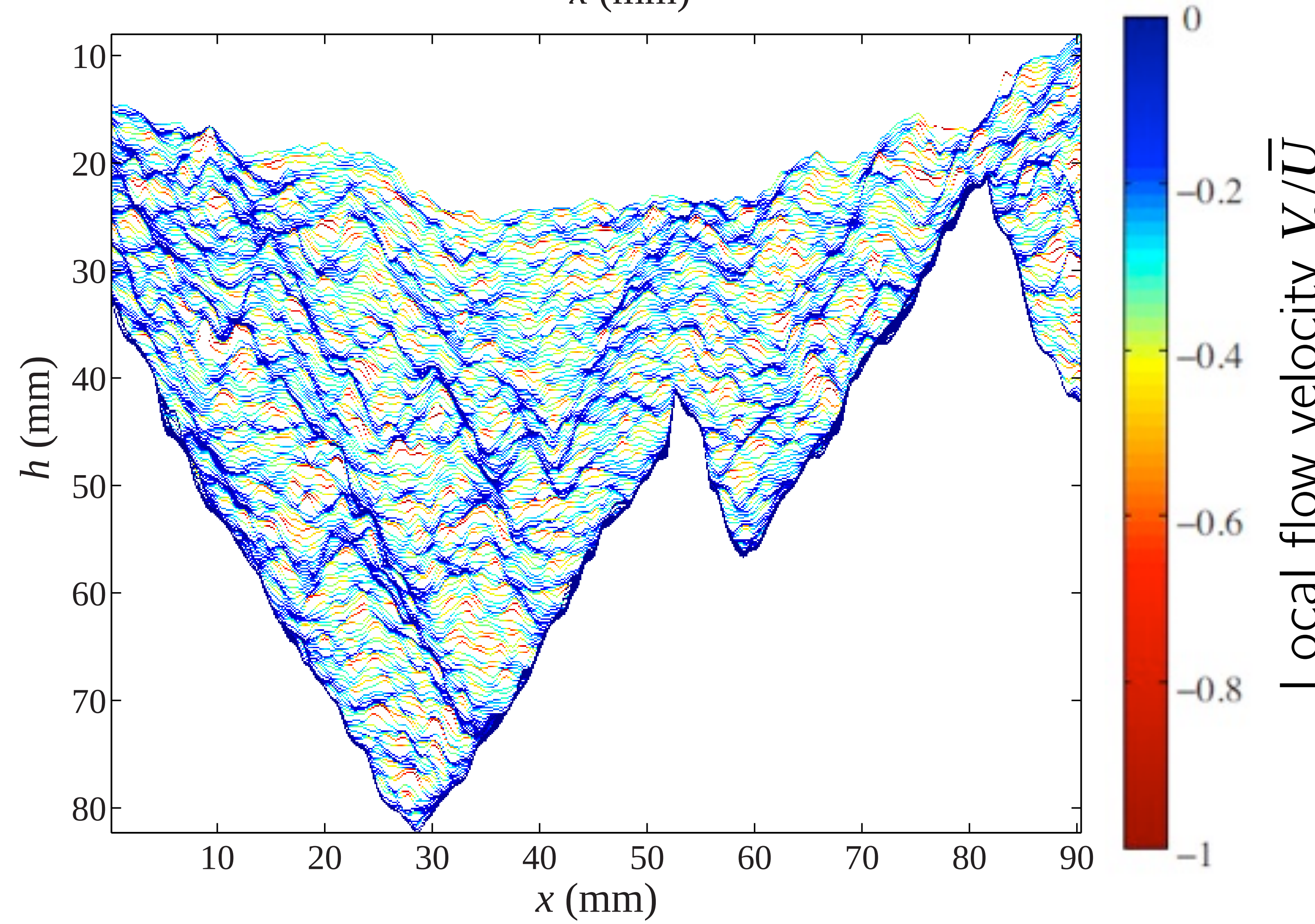
$V_\chi > 0$

4 - Transcient dynamics and universality

- inclined regions of the front advance faster



- inclined regions of the front slowdown



PLAN

1 - Experimental

2 - Front dynamics in high flow strength

3 - Pinning process in low flow strength

4 - Transcient dynamics and universality

5 - Conclusion and perpectives

5 - Conclusion and perpectives

3 universality classes

- KPZ behavior for moving phase
- Positif qKPZ growth process for upward propagating fronts
- Negatif qKPZ growth with static sawtooth pattern formation for bakward propagating fronts

- **Unique control parameter**
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5 - Conclusion and perpectives

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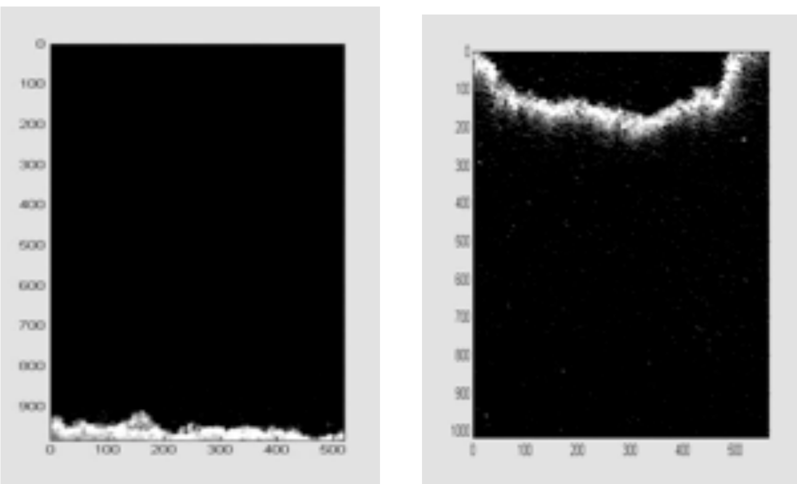

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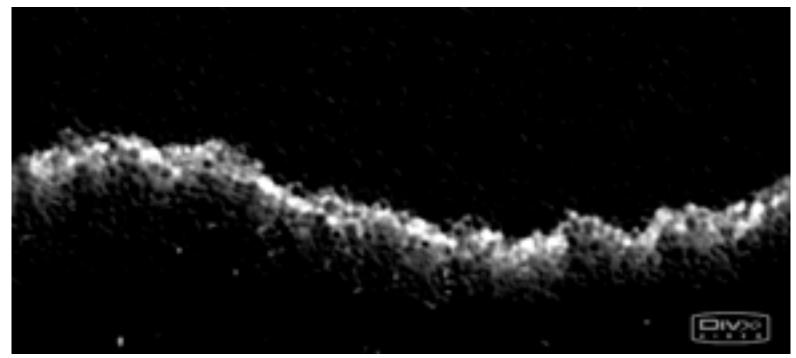

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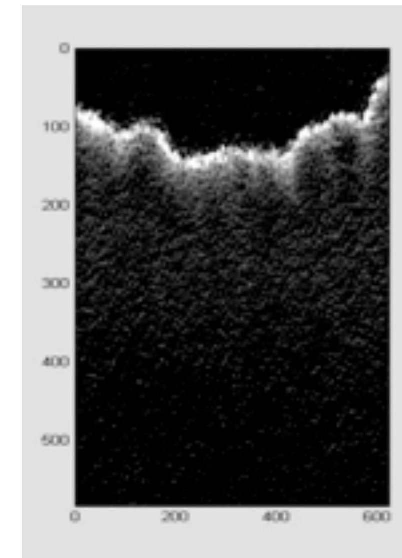

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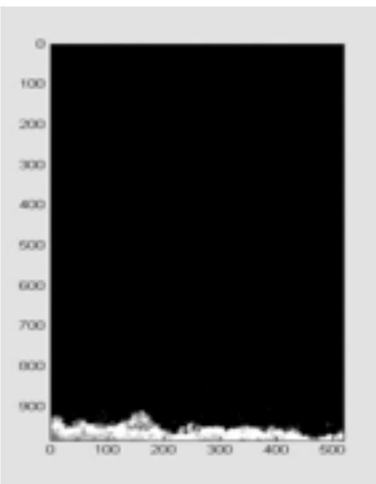

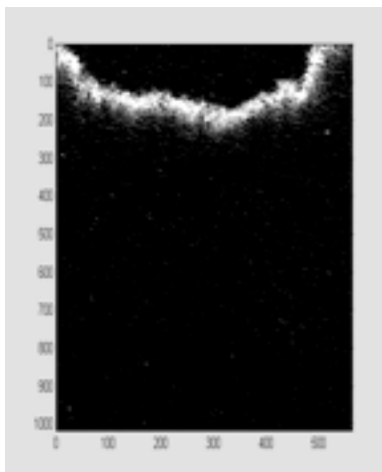

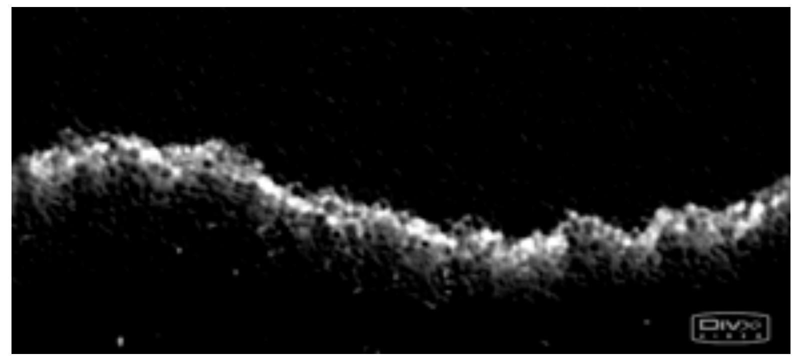

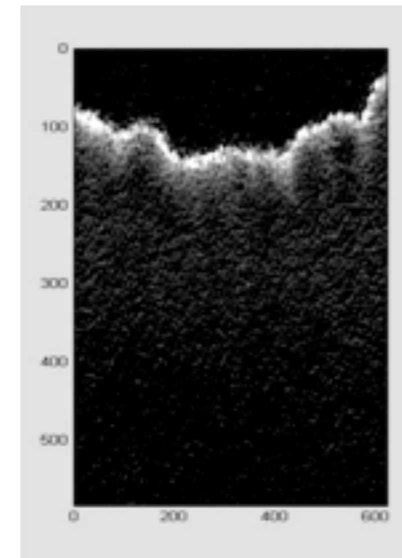

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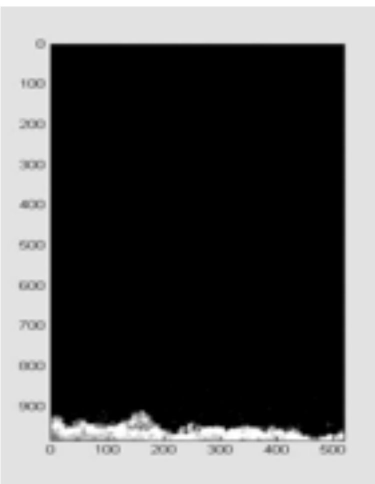

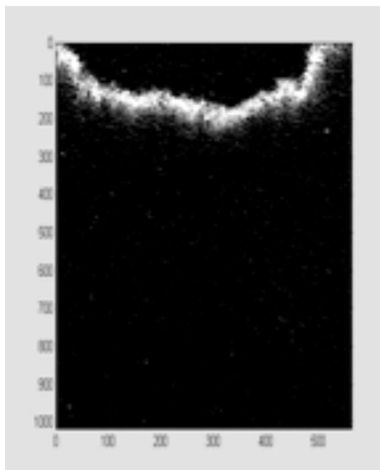

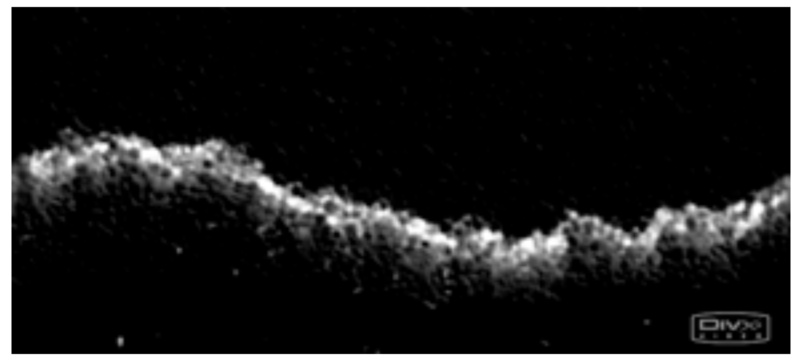

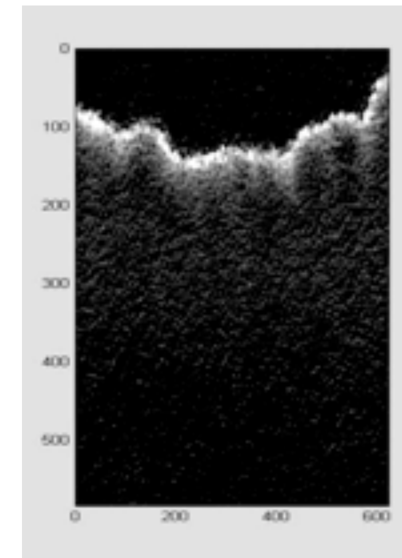

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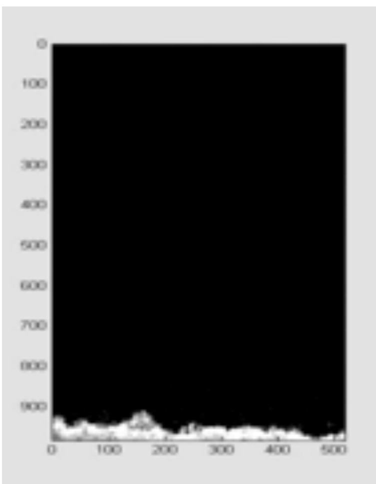

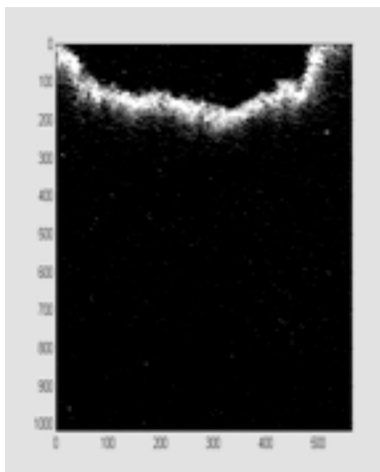

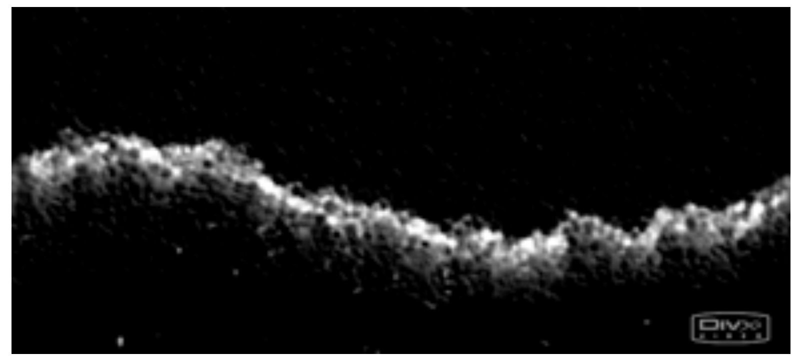

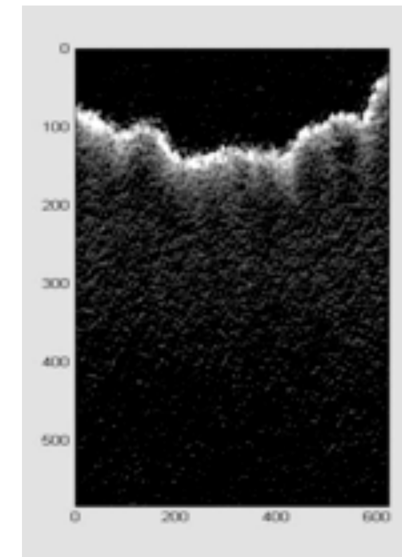

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5 - Conclusion and perpectives

- Bacteria colonies dynamics in complex flows

- Reaction front pinning control in microfluidic devices

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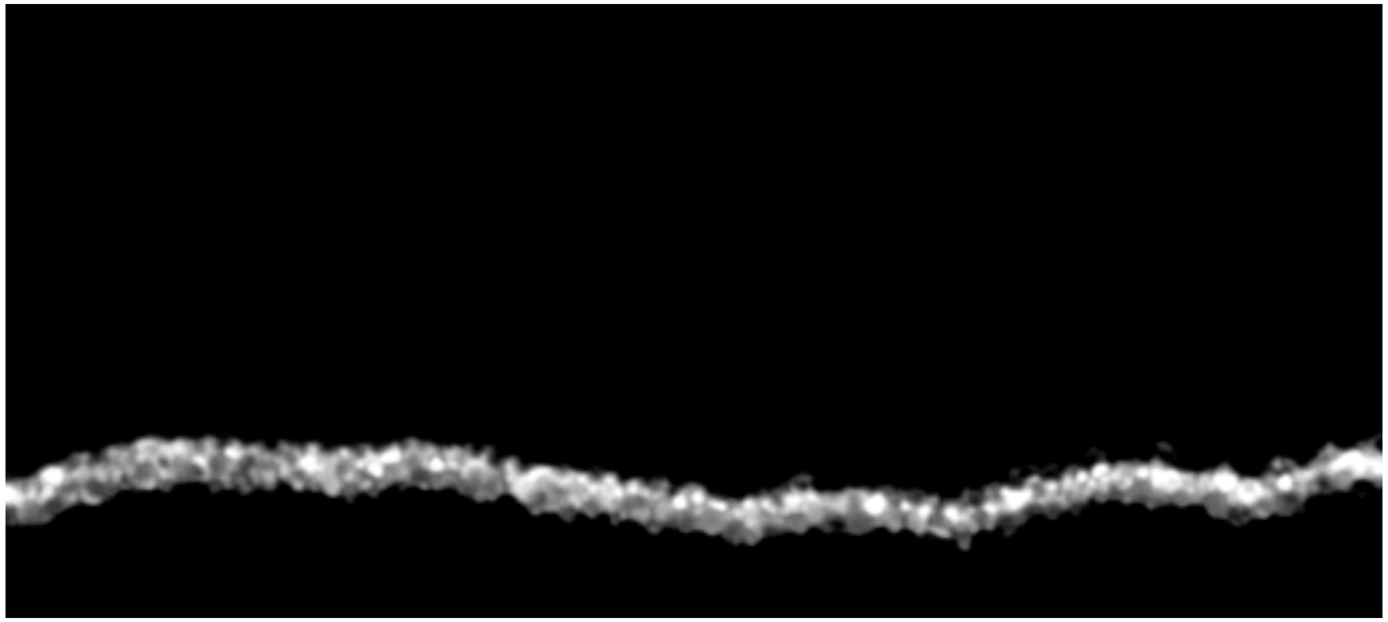
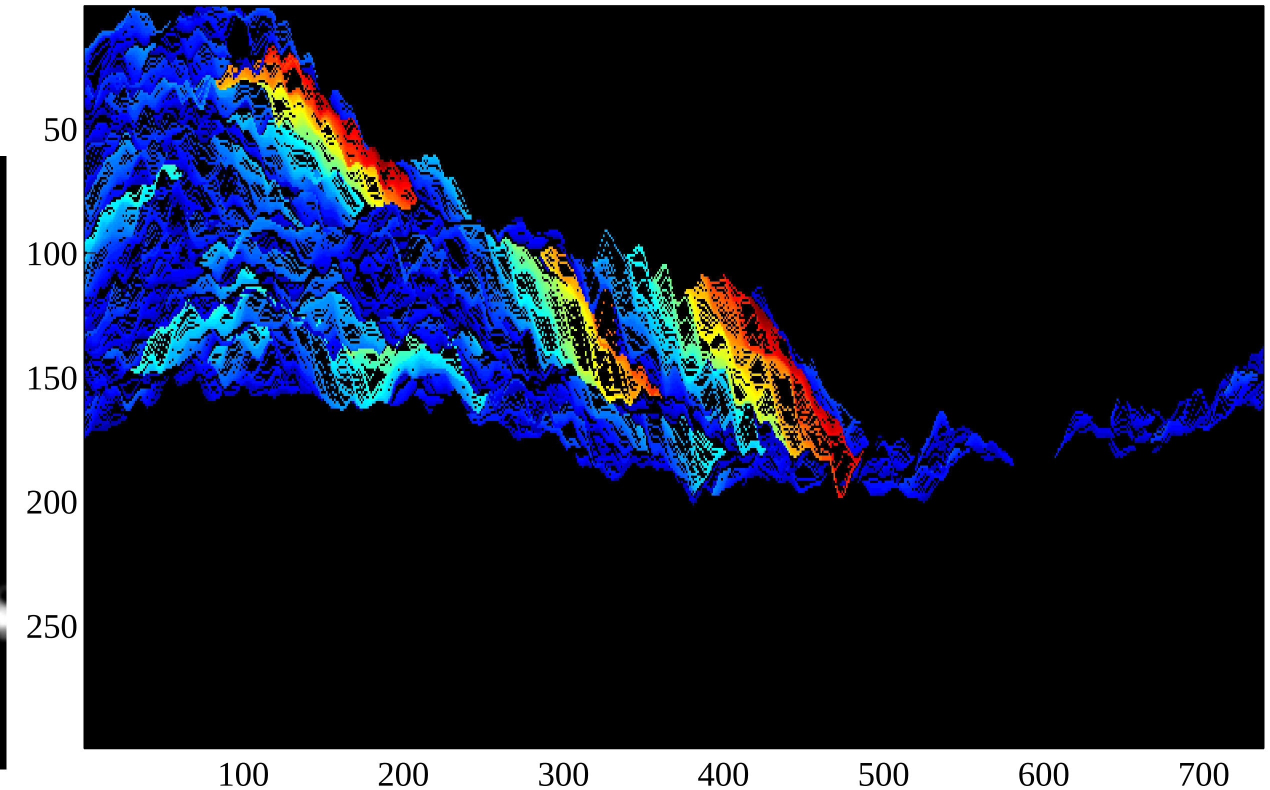
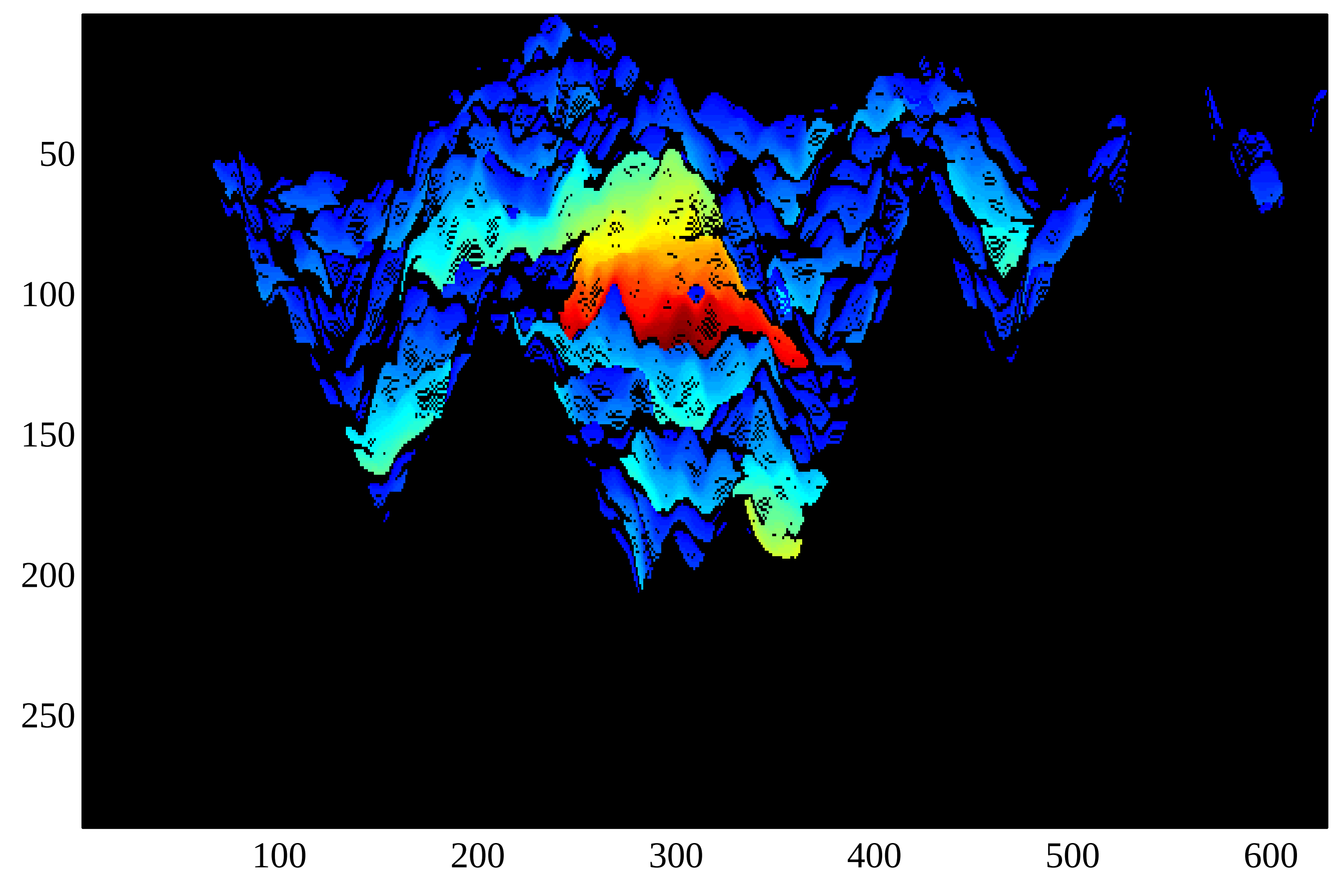
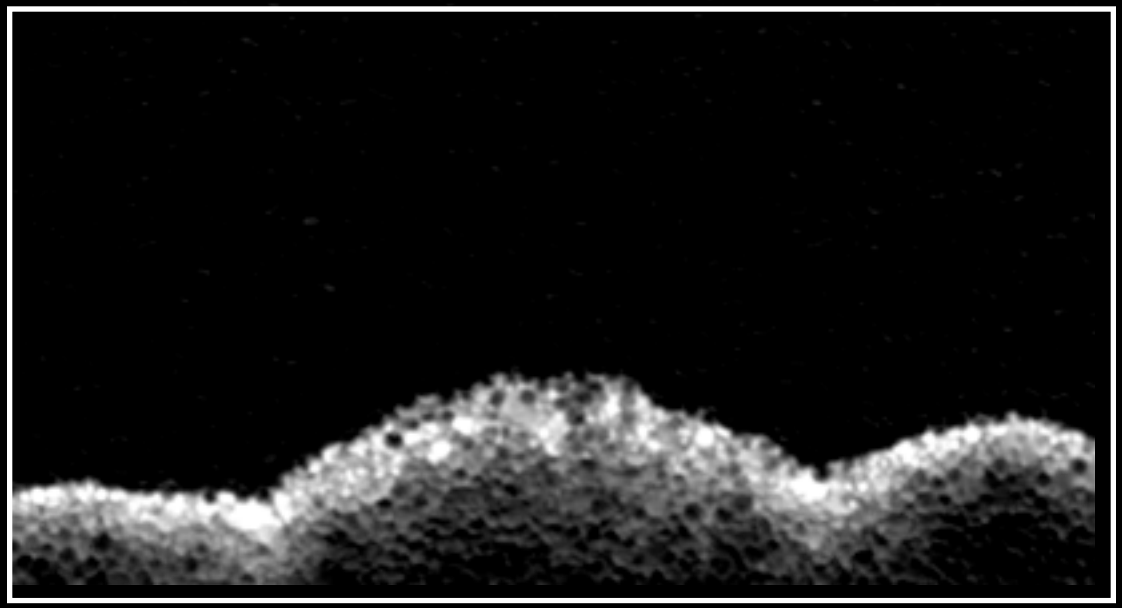
5 - Conclusion and perpectives

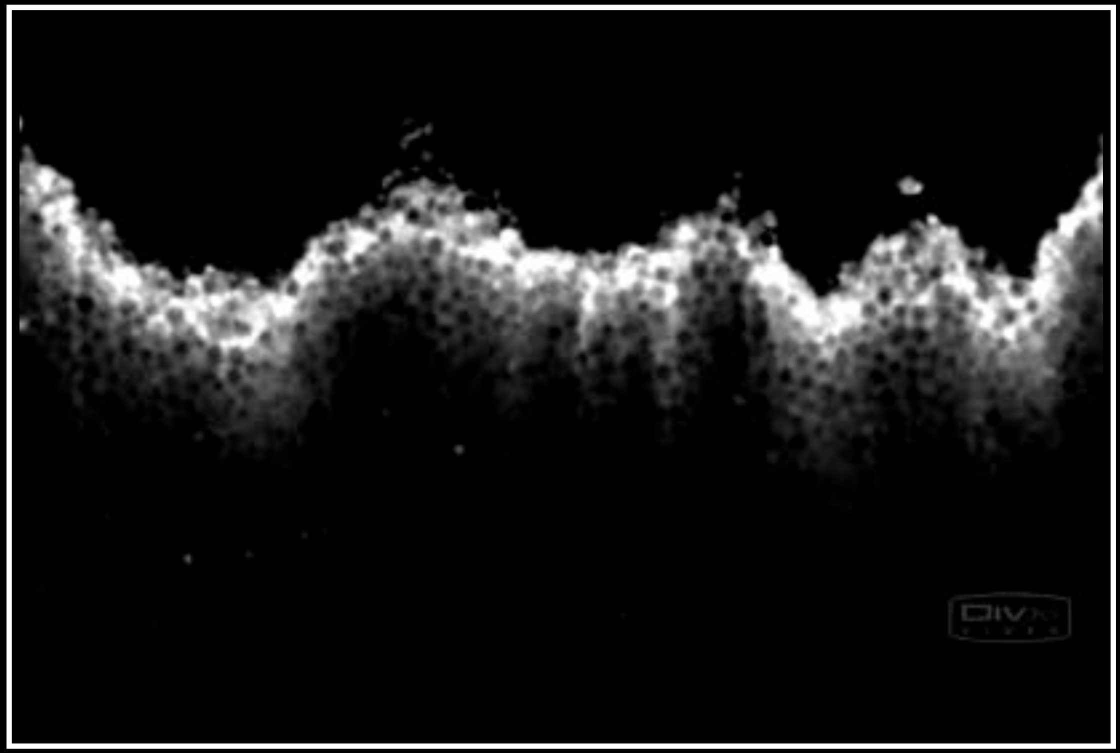
- Avalanches phenomena
  at the depinning transition

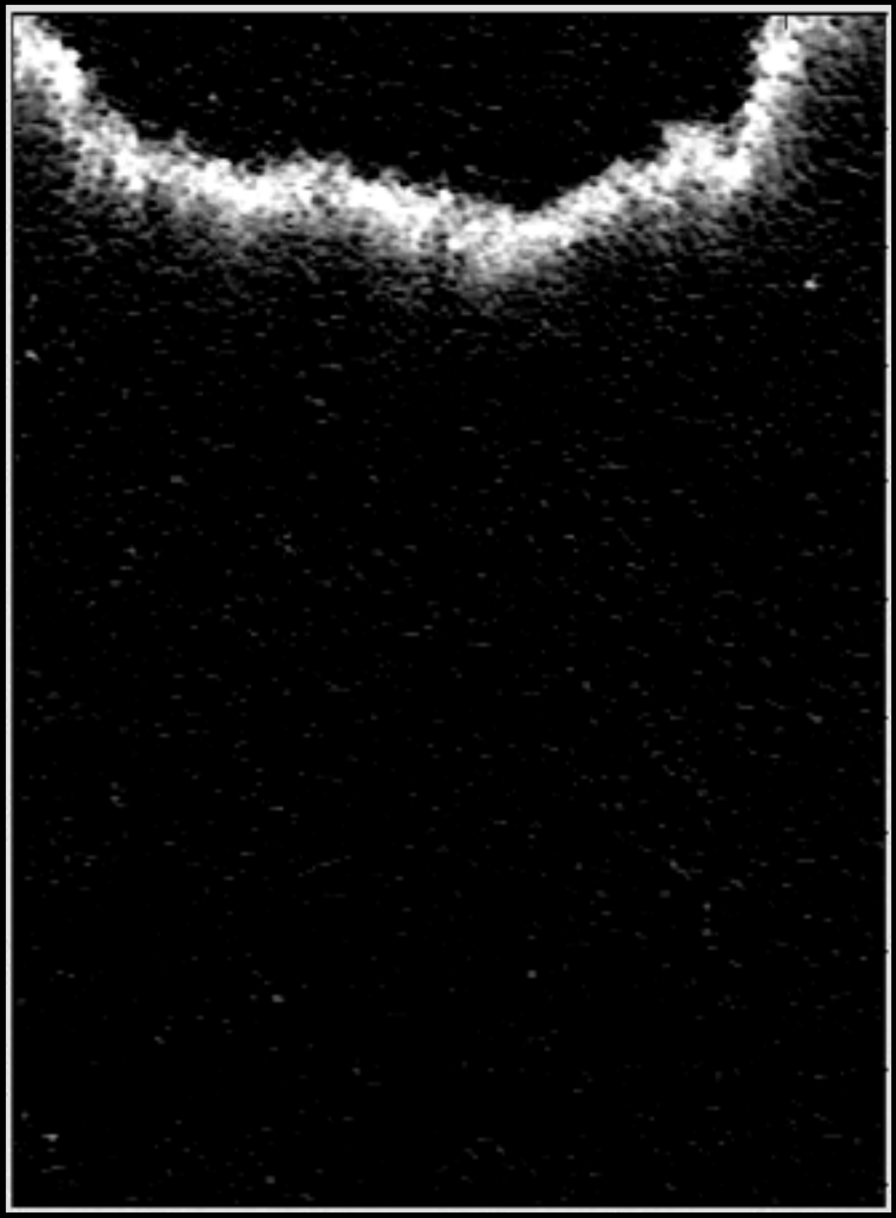








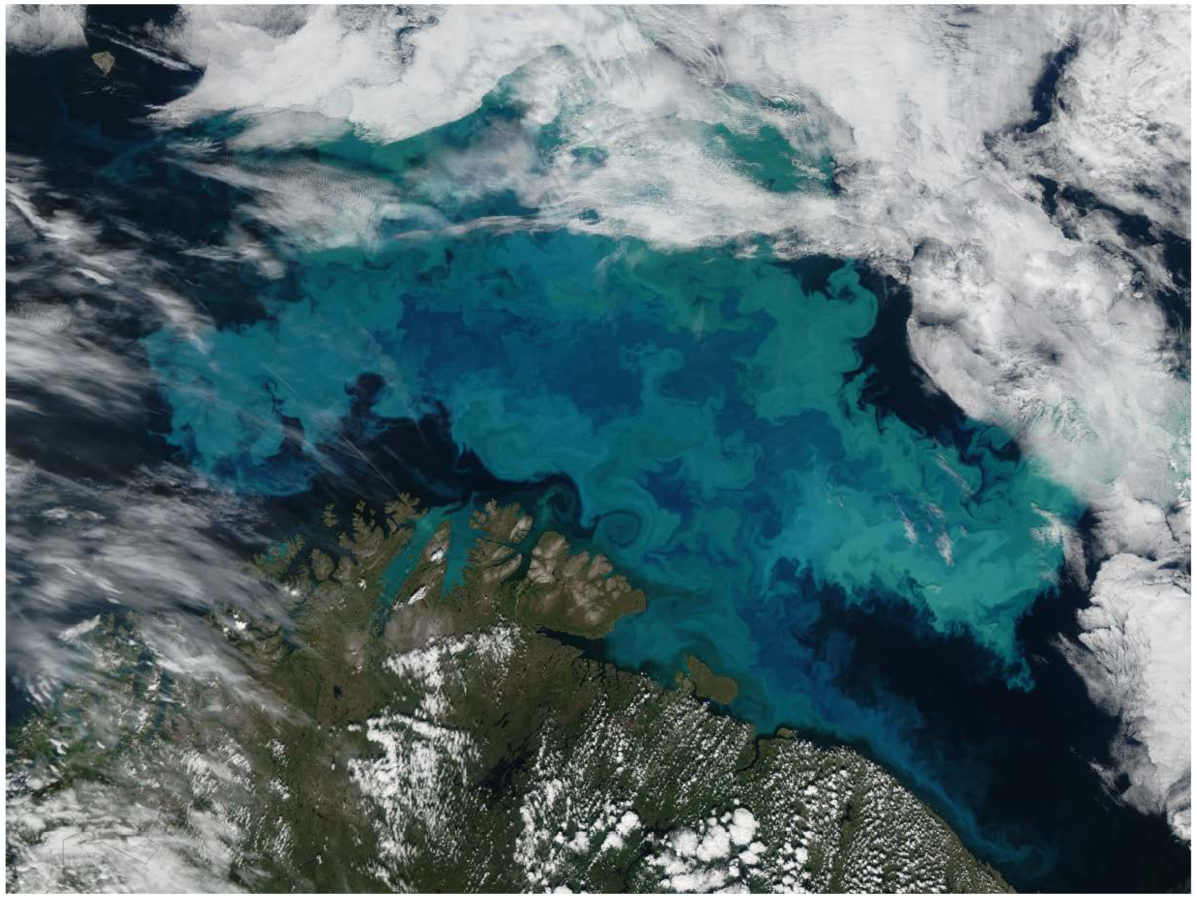




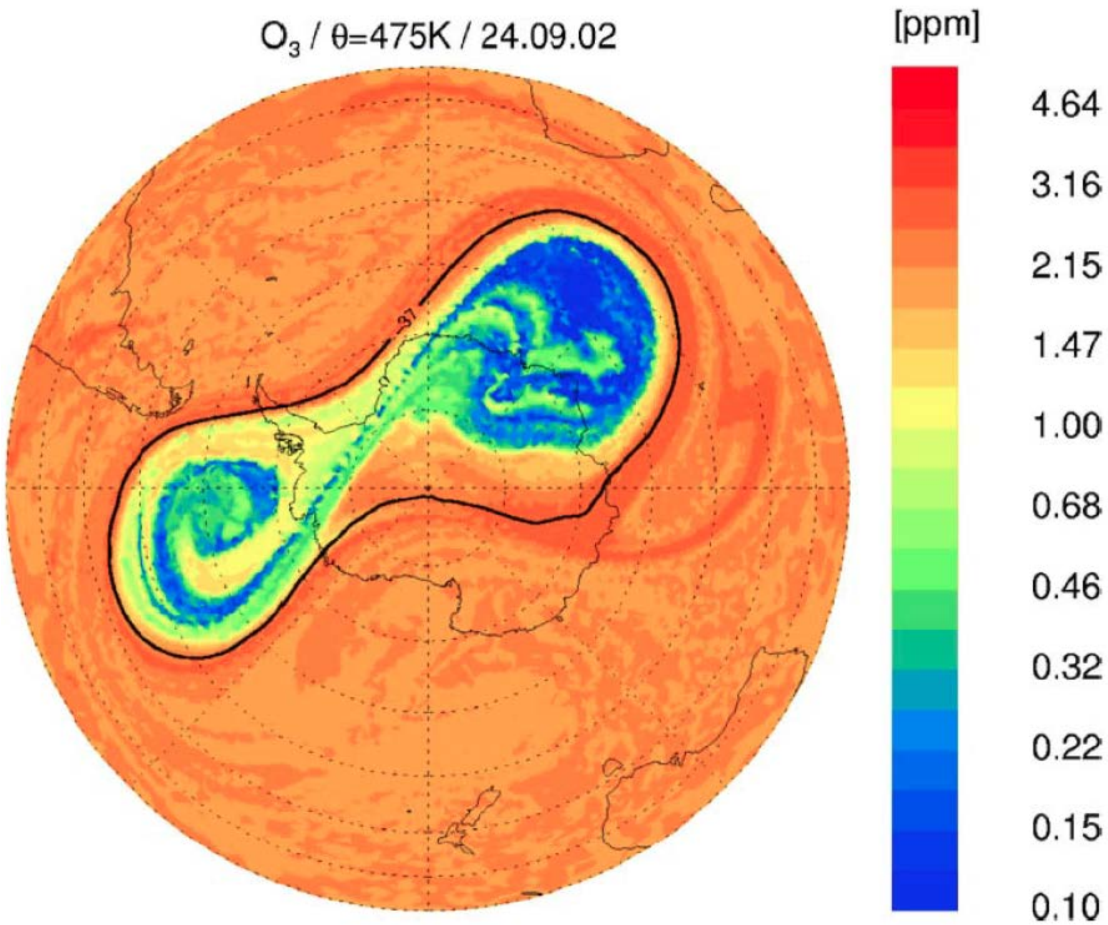
Thank you^^ !

Supplements

• Reaction fronts interaction with hydrodynamics flows



Phytoplankton blume in the Barents sea



Ozone concentration in the polar vortex

[Gross et al., 2006]

Biological population $\longrightarrow$ nonlinear dynamics

Flows in the oceans $\longrightarrow$ mixing

ozone reduction by chlorine compounds

$$Cl + O_3 \longrightarrow ClO + O_2$$
$$ClO + O_3 \longrightarrow Cl + 2O_2$$

- autocatalytic process $\qquad A + B \xrightarrow{} 2B + C$ (feedback)

- 2nd order chemical kinectics

$$\frac{d[B]}{dt} = -k[A][B]$$

$$\begin{cases} a = [A]/[A]_0 \\ b = [B]/[A]_0 \end{cases} \quad , \quad a + b = 1 \quad \text{et} \quad k' = [A]_0 k$$

- nonlinearity $\longrightarrow$

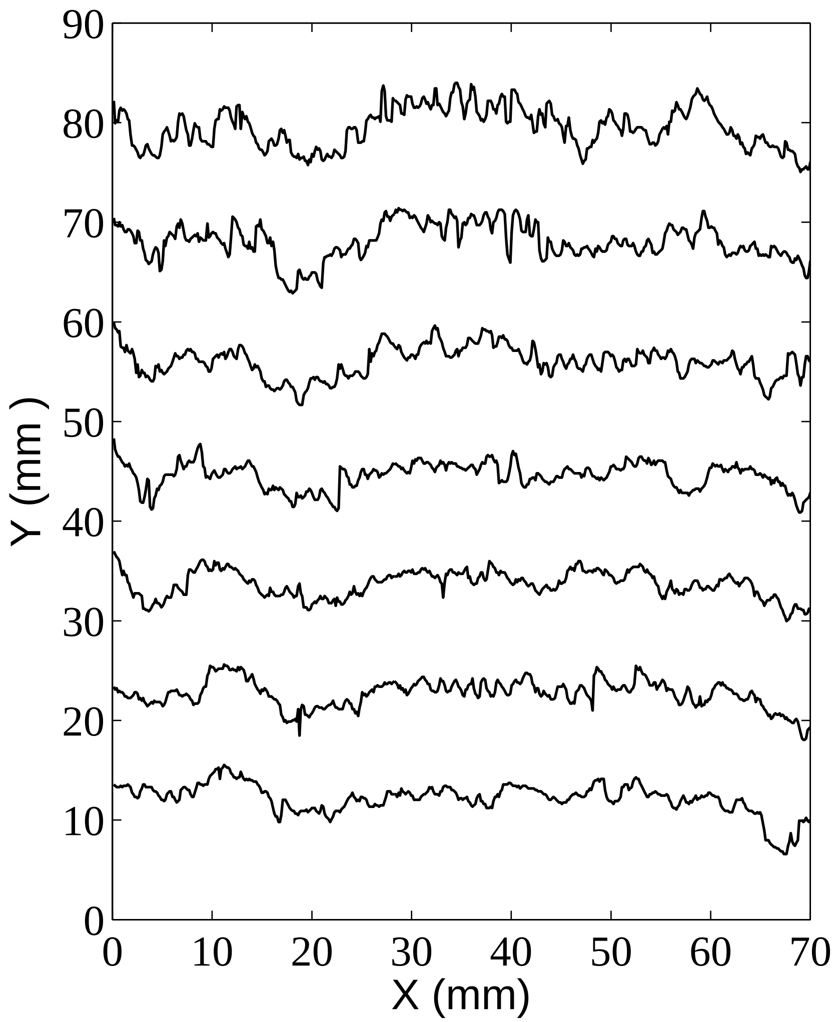
$$\frac{db}{dt} = \quad k'ab = \quad k'b(1-b)$$

1 - Experimental setup

- **Tracers dispersion experiments**

measurements of the local flow velocity

$$v(x,t) = \frac{h(x,t+\delta t) - h(x,t)}{\delta t}$$



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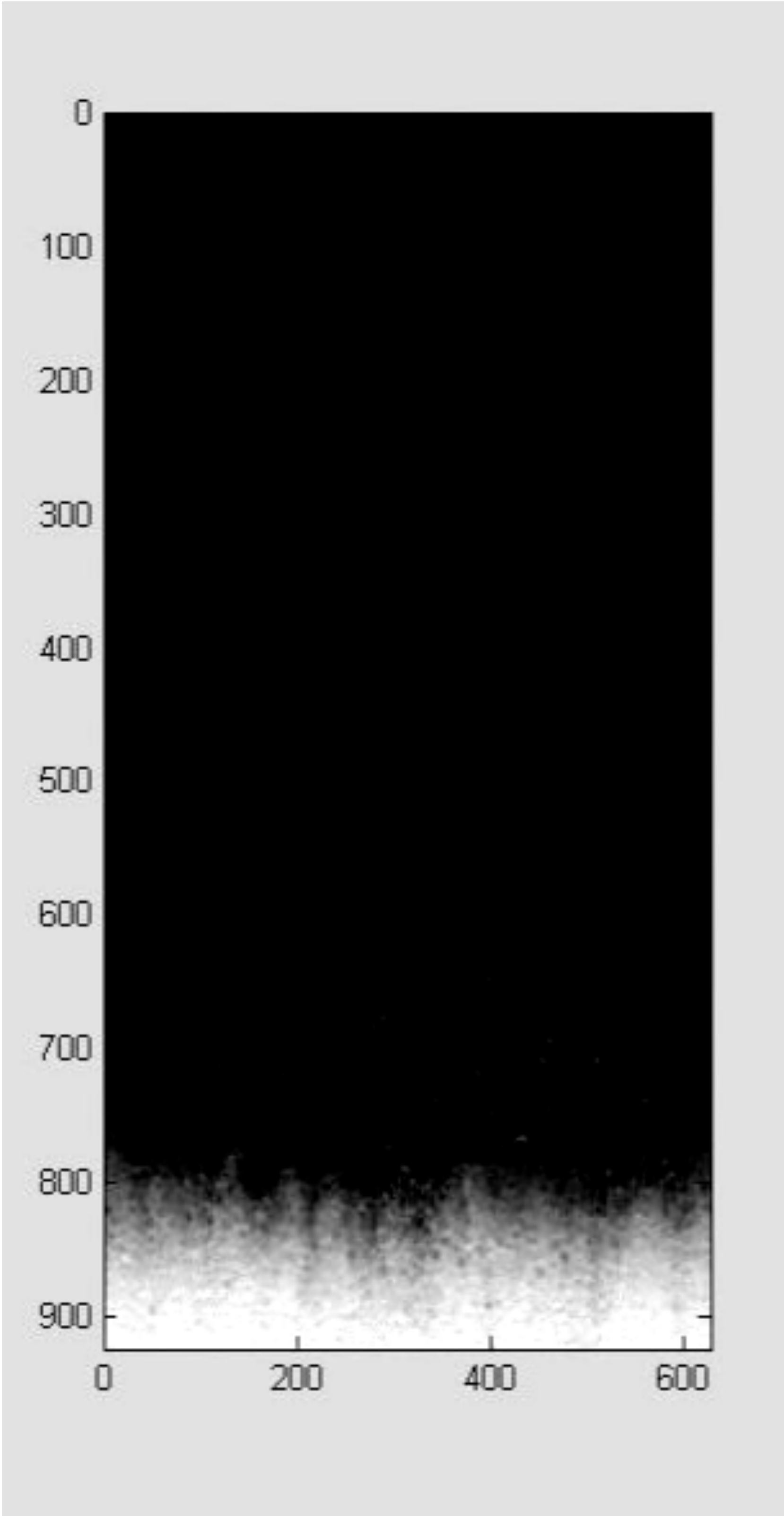

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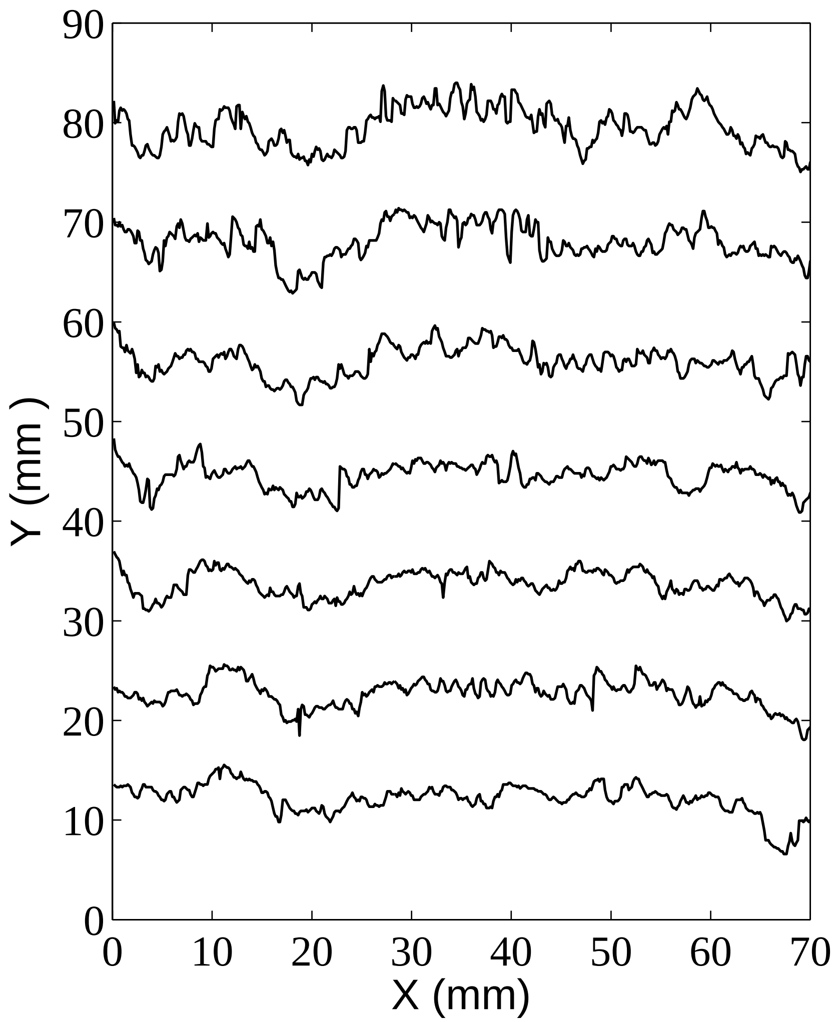

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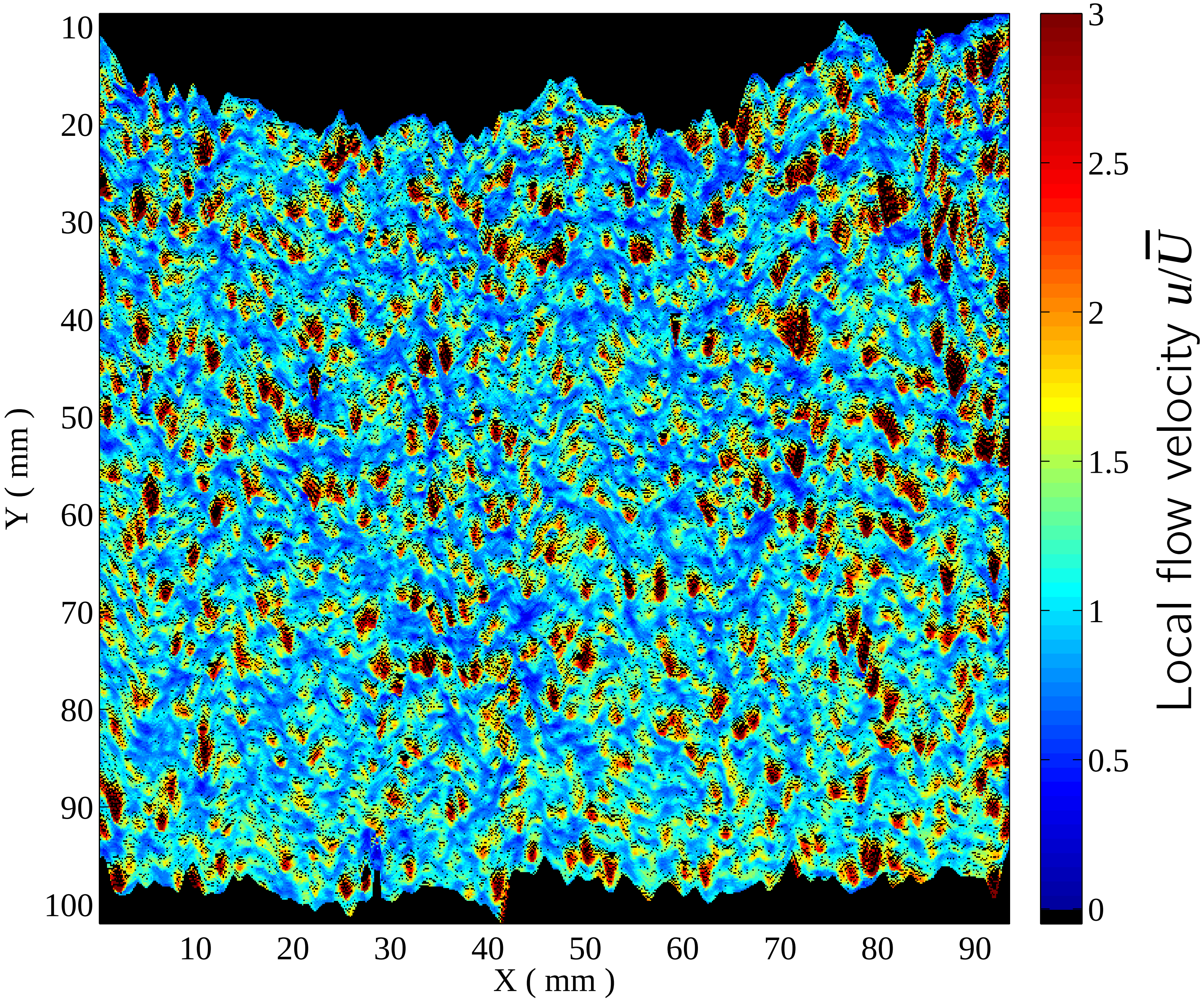
Disordered flow of mean velocity $\bar{U}$



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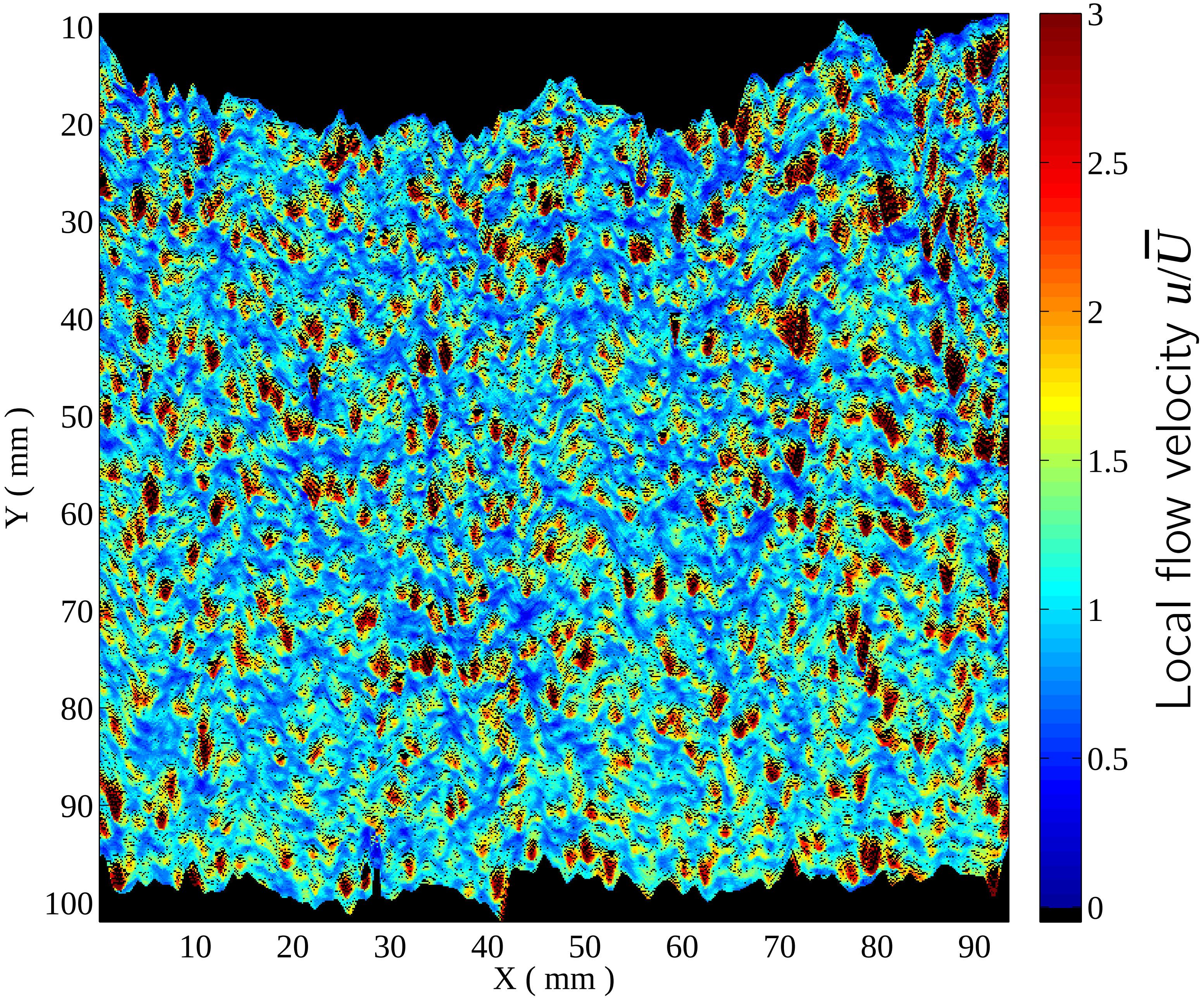

Fluctuations correlation length:

$$d_{\parallel} = 1.8 \pm 0.1\,\mathrm{mm}$$

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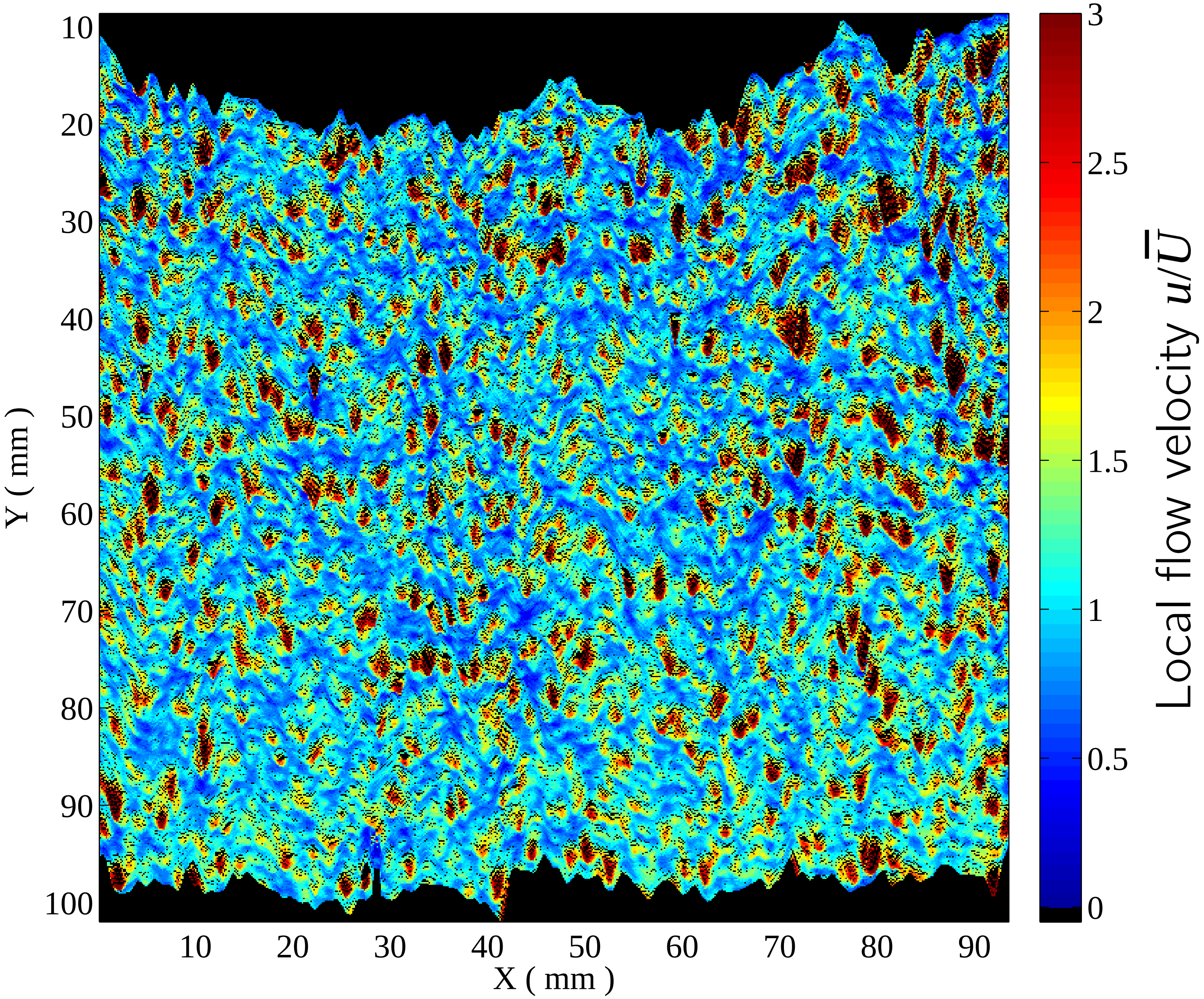
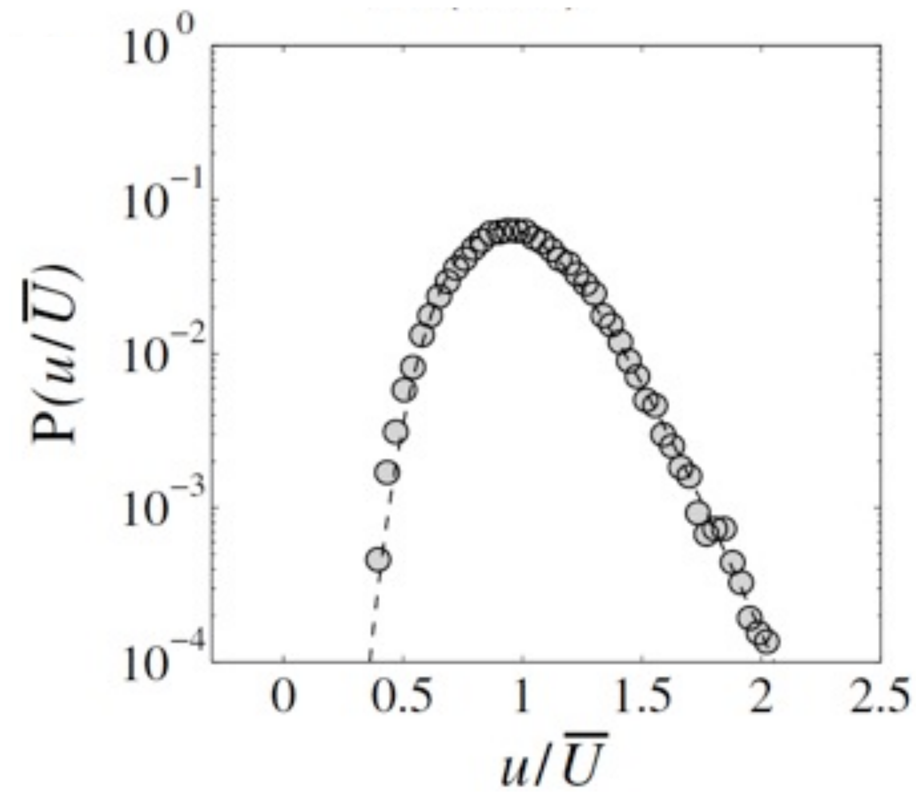


PDF of the local flow velocity fluctuations



[Lebond & al. 1997]

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