From bulk descriptions to emergent interfaces

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Switzerland

AVALANCHE 2022
Avalanche dynamics and precursors of catastrophic events
August 29th, 2022

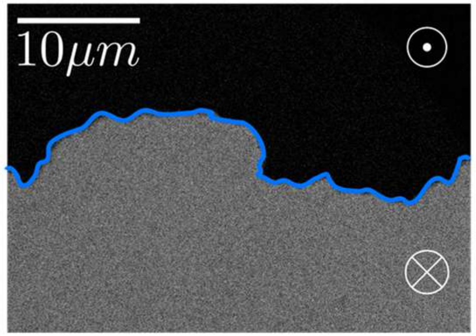
DQMP Department of Quantum Matter Physics

Interfaces

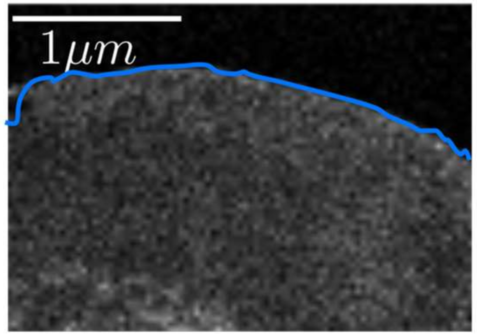
Are ubiquitous in Nature

Ferroelectrics

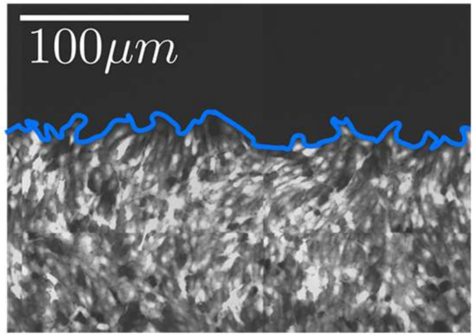
Ferromagnets



Cell membranes



Cell colony



Rapin, Ehrensperger, Blaser, NC, Paruch APL 2021
Obtained in Paruch Lab
UNIGE- Geneva

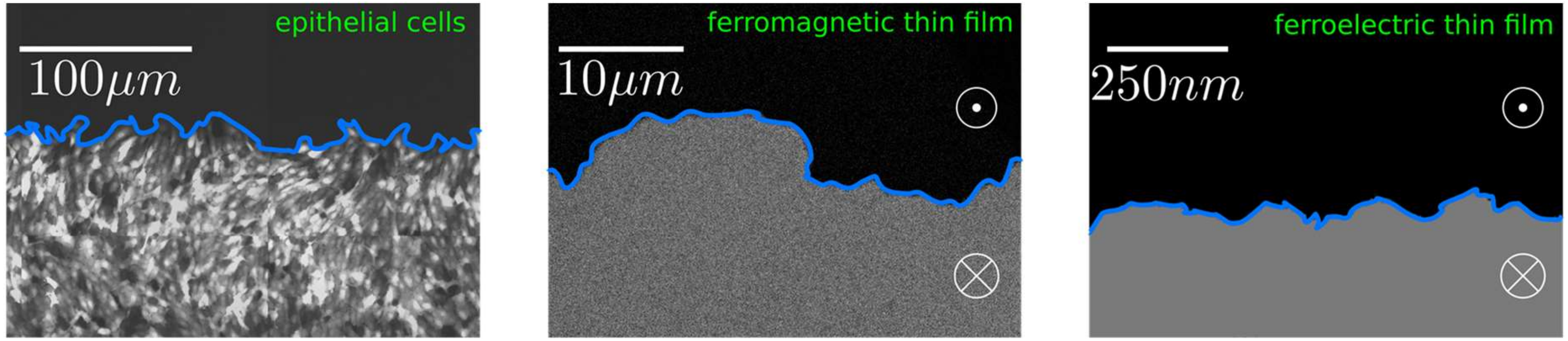
NC et al PRB 2017
Obtained in Magnetic Resonances Laboratory
Bariloche Atomic Centre- Argentina

Obtained in Roux Lab in collaboration with A. Colom (Ikerbasque)
Biochemistry Department
UNIGE-Geneva

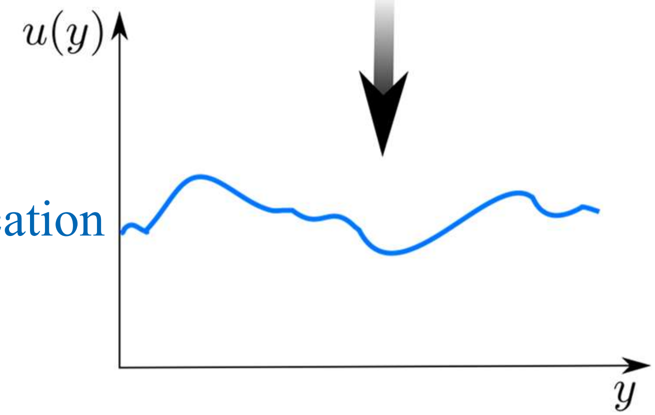
Rapin, C, NC, Sci Rep 2021.
Obtained in Brown's Lab
UZH- Zurich

Tools to study interfaces

Disordered elastic systems framework



Brutal, but effective simplification



$u(y)$ Smooth, univalued

K. Wiese. Theory and experiments for disordered elastic manifolds, depinning, avalanches, and sandpiles, Reports on progress in Physics (2022)

T. Giamarchi, et al. *Dynamics of Disordered Elastic Systems*. Lecture Notes in Physics, vol 688. Springer, Berlin, Heidelberg (2006)

G. Rapin, NC, I. Gaponenko, A. Rawleigh, E. Moriggi, T. Giamarchi, S. A. Brown, P. Paruch, *Roughness and dynamics of proliferating cell fronts as a probe of cell-cell interactions*. Sci Rep. (2021)

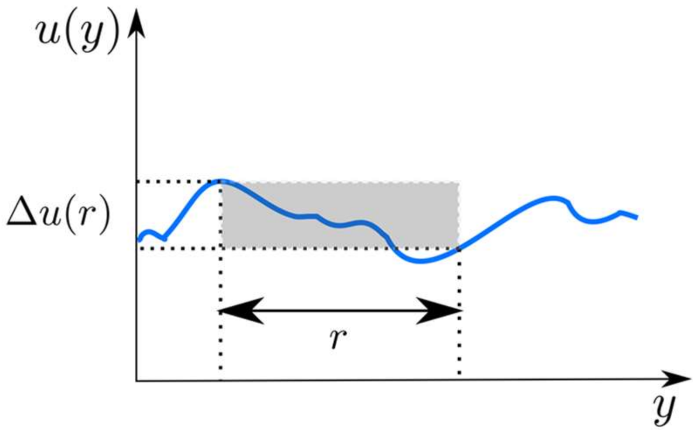
G. Rapin, et al, *Dynamic response and roughening of ferroelectric domain walls driven at electrode edges*. APL (2021)

P. Tuckmantel et al, *Local probe comparison of ferroelectric switching event statistics in the creep and depinning regimes in Pb(Zr0.2Ti0.8)O3 thin films*. PRL (2021)

NC, et al, *Excess velocity of magnetic domain walls close to the depinning field*. PRB (2017)

Tools to study interfaces

Disordered elastic systems framework



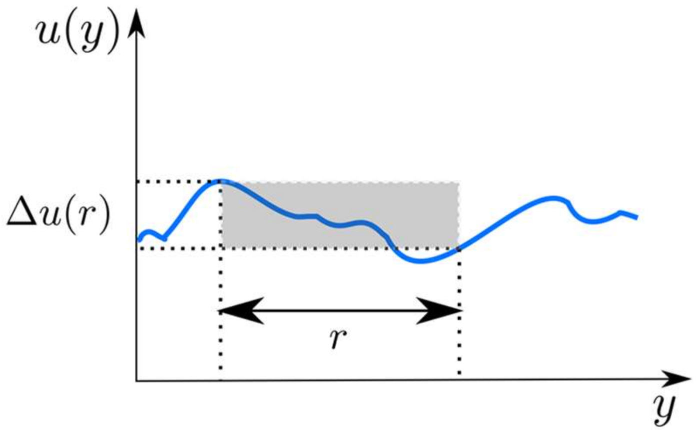
$$\tilde{\eta}\partial_t u(y,t) = c\partial_y^2 u(y,t) + F_p(u,y) + F + \sqrt{T}\tilde{\zeta}(y,t)$$

quenched Edwards-Wilkinson equation

the geometrical and dynamical properties of an interface are intrinsically related

Tools to study interfaces

Disordered elastic systems framework



Roughness

$$B(r) = \overline{\langle [u(y+r) - u(y)]^2 \rangle}$$

$$\tilde{\eta}\partial_t u(y,t) = c\partial_y^2 u(y,t) + F_p(u,y) + F + \sqrt{T}\tilde{\zeta}(y,t)$$

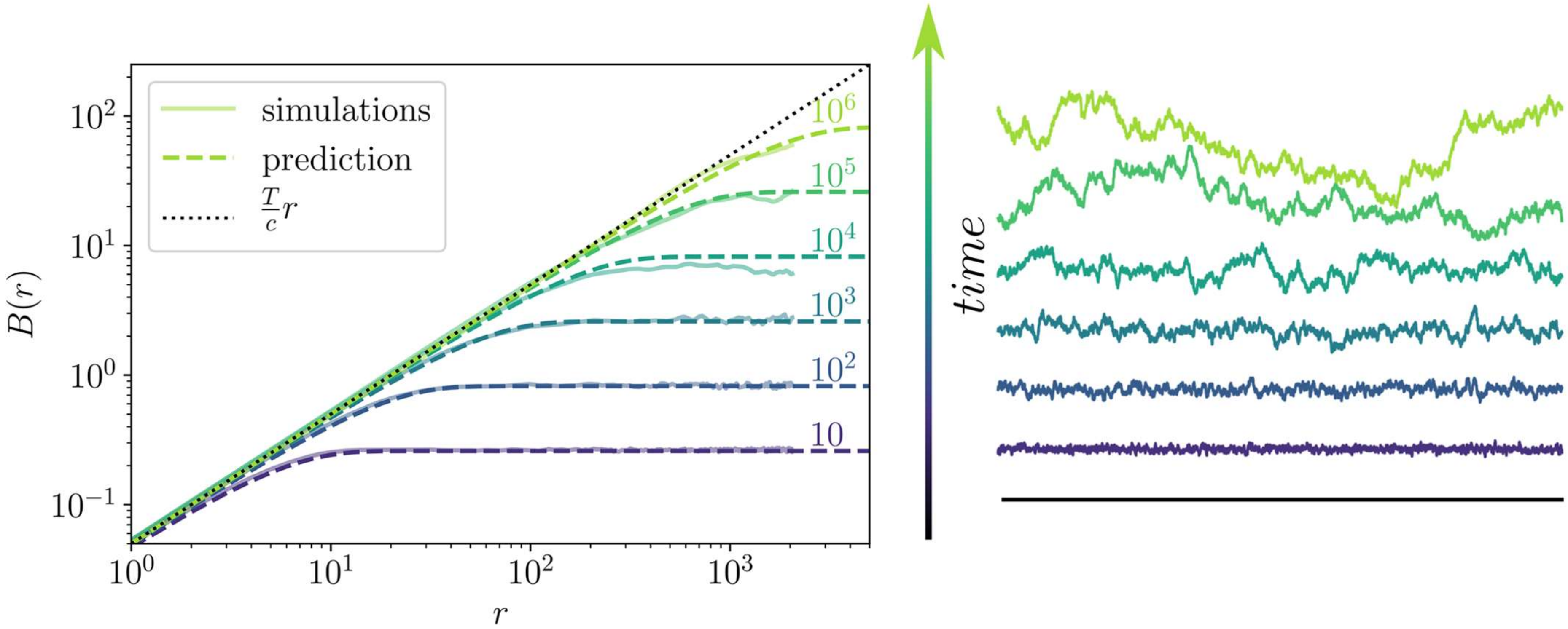
quenched Edwards-Wilkinson equation

the geometrical and dynamical properties of an interface are intrinsically related

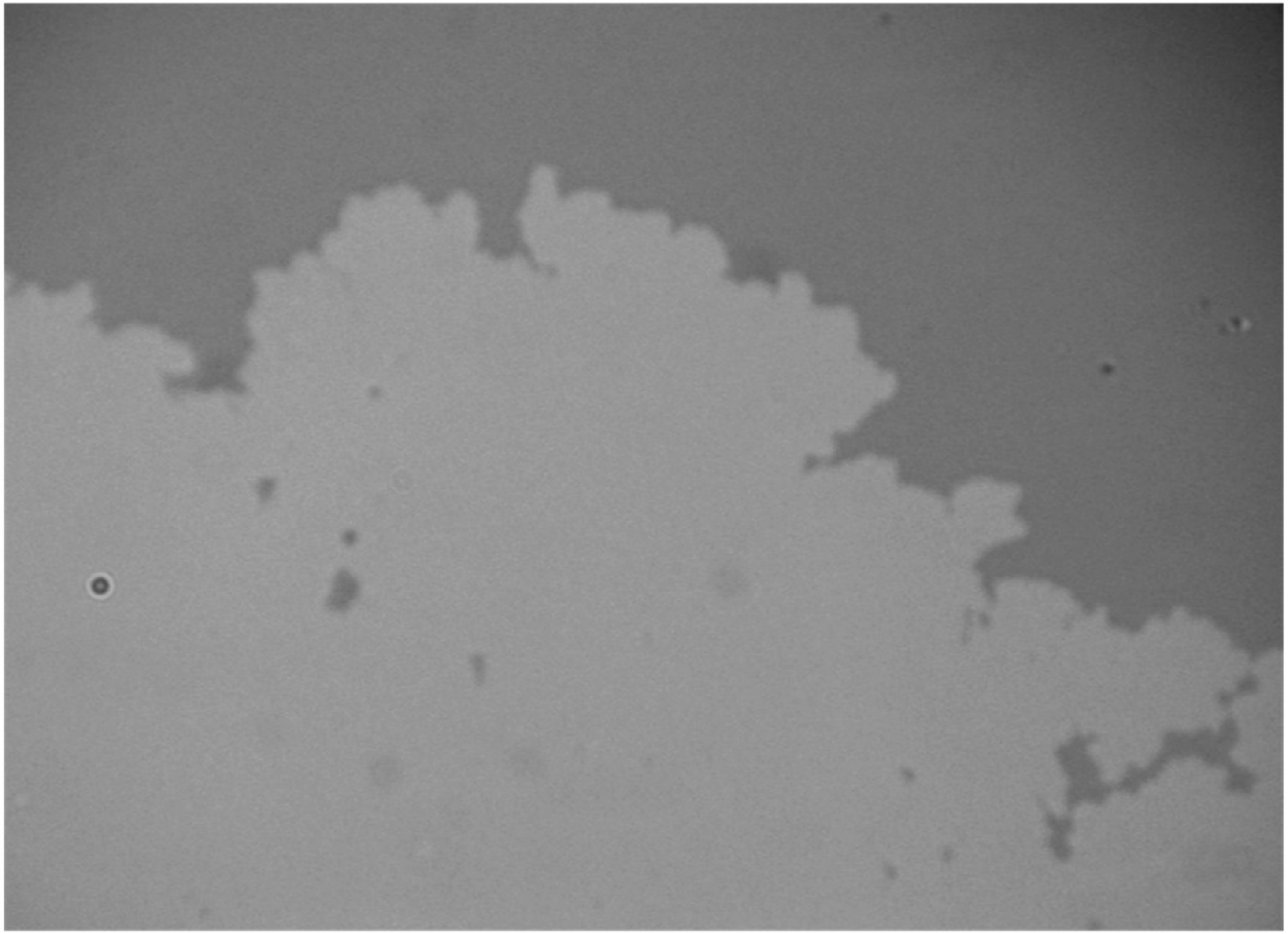
Tools to study interfaces

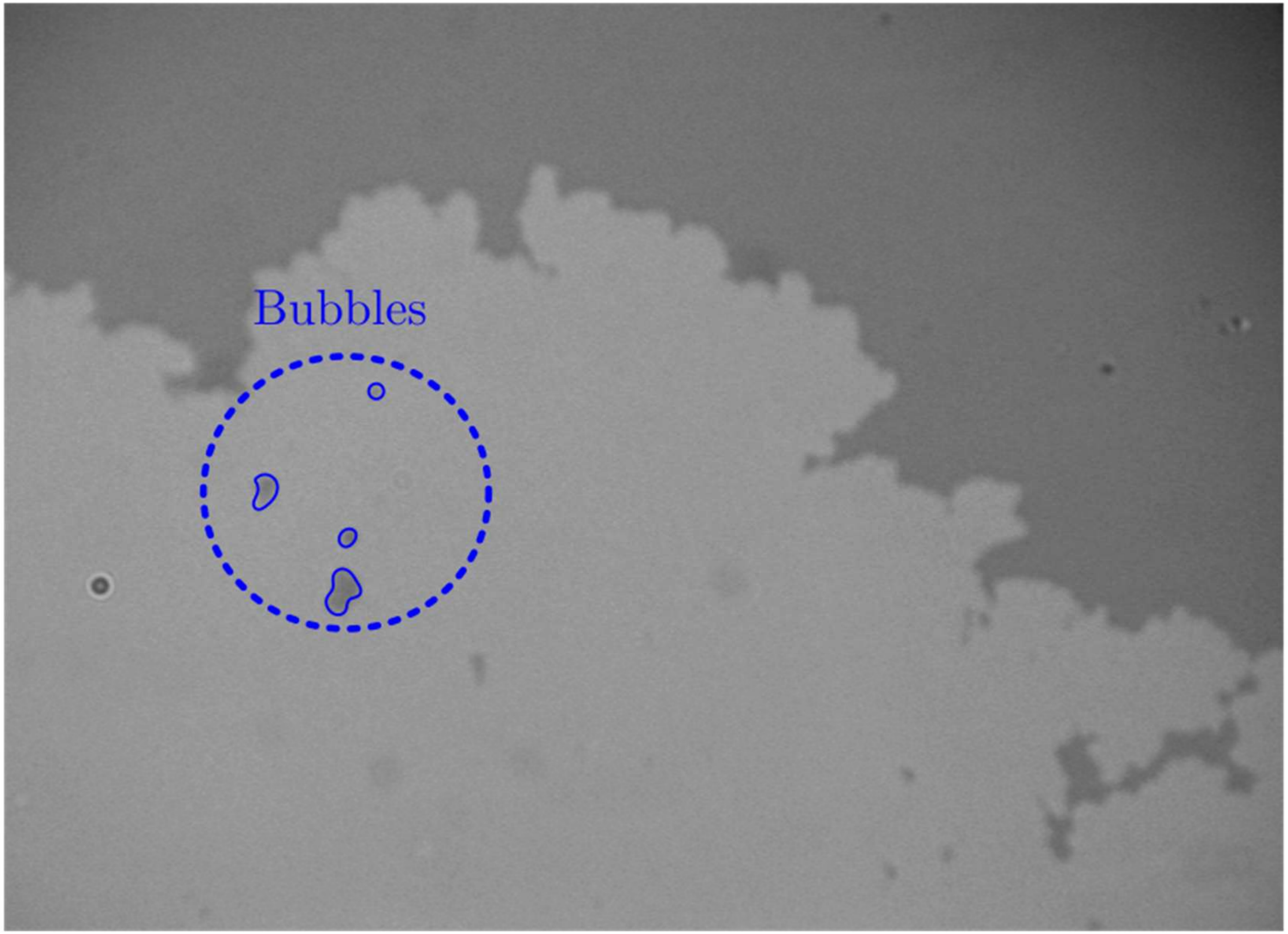
Disordered elastic systems framework

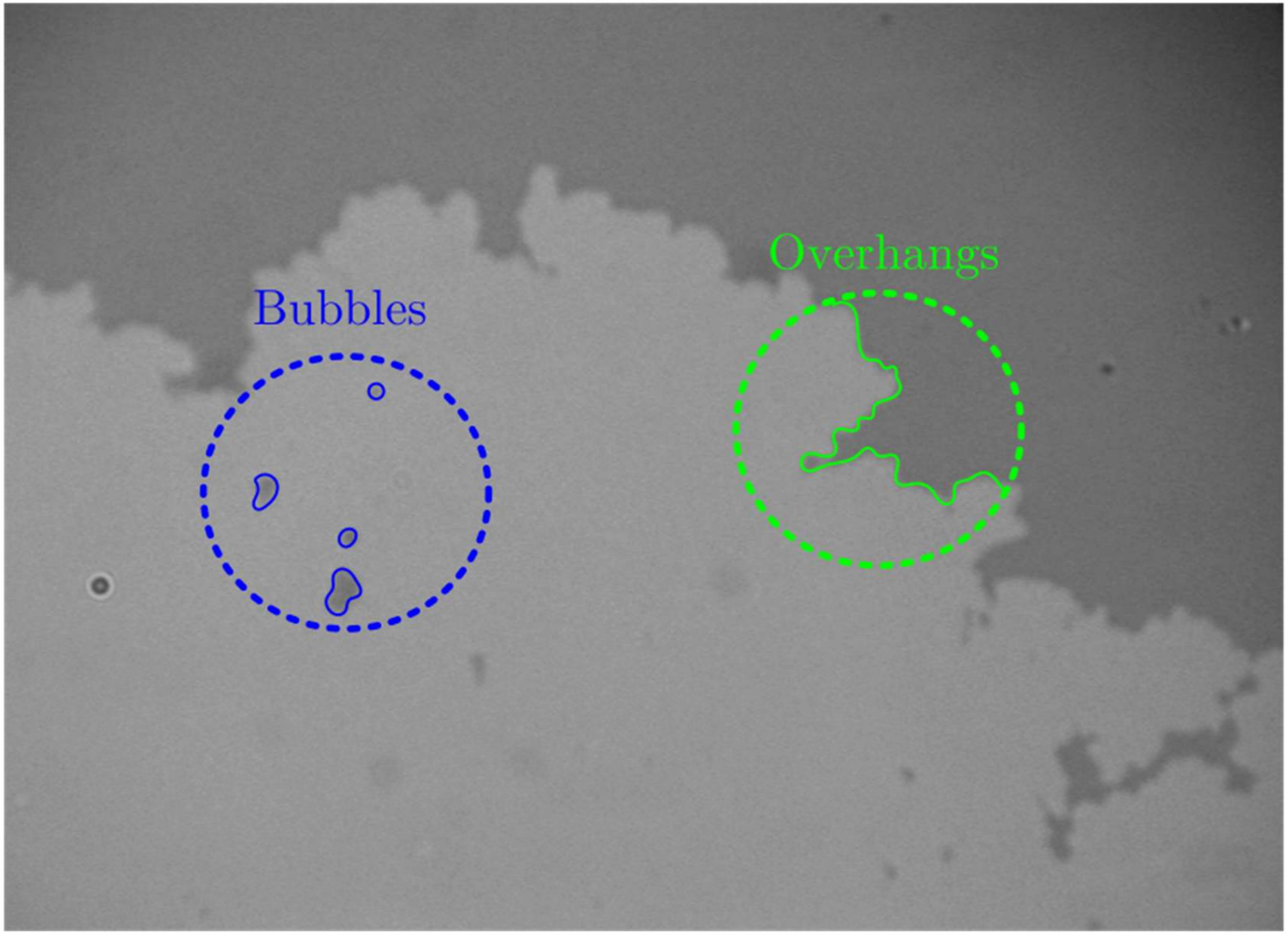
$$B(r,t) = \frac{Tr}{c}\left[1 - \frac{1}{\sqrt{\pi}zr}\left(e^{-z^2r^2} - 1\right) - \frac{2}{\sqrt{\pi}}\int_0^{zr} e^{-t^2}dt\right] \quad z = \sqrt{\frac{\tilde{\eta}}{8ct}}$$

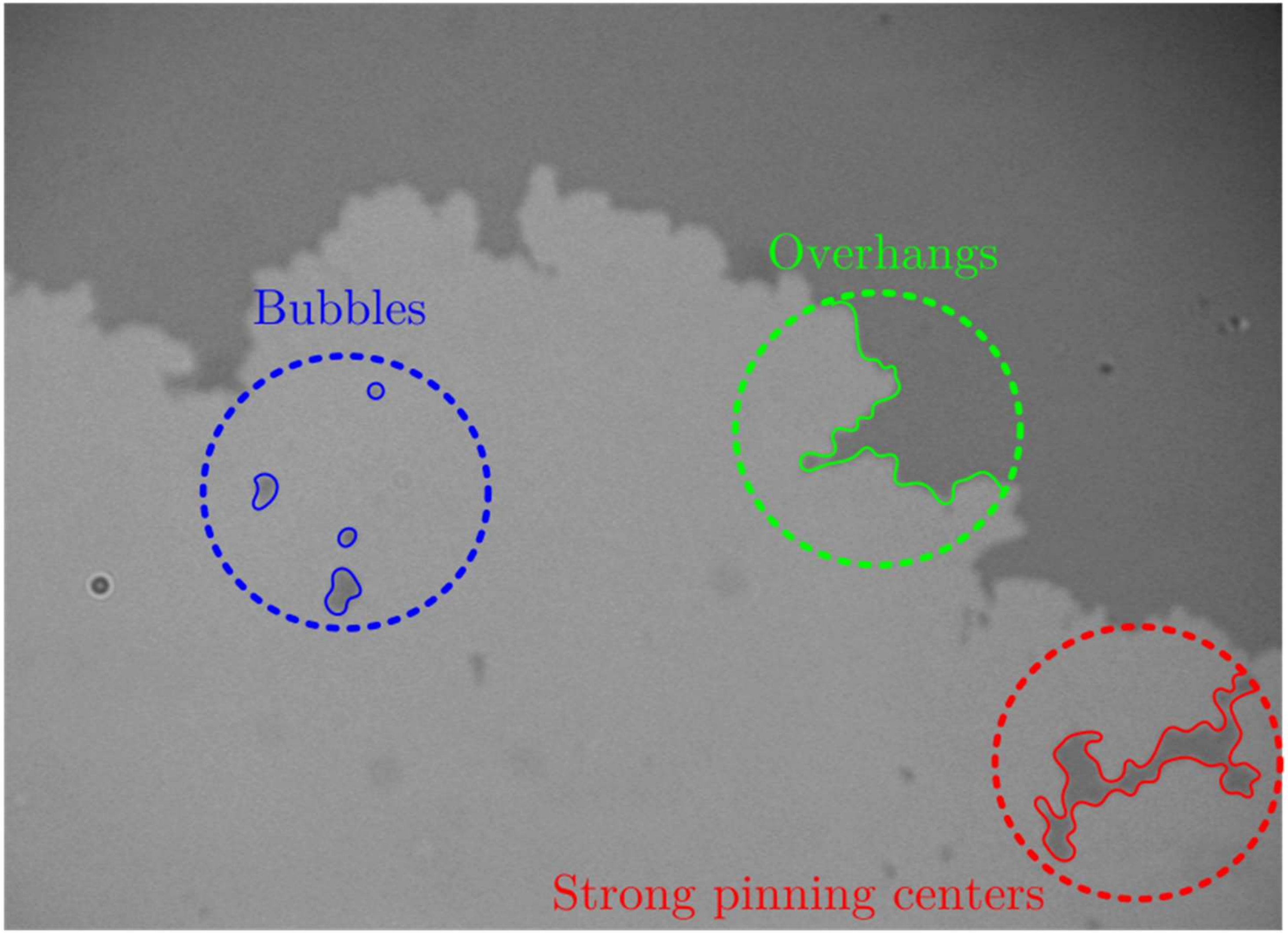


The framework allows us to perform very precise analytical calculations

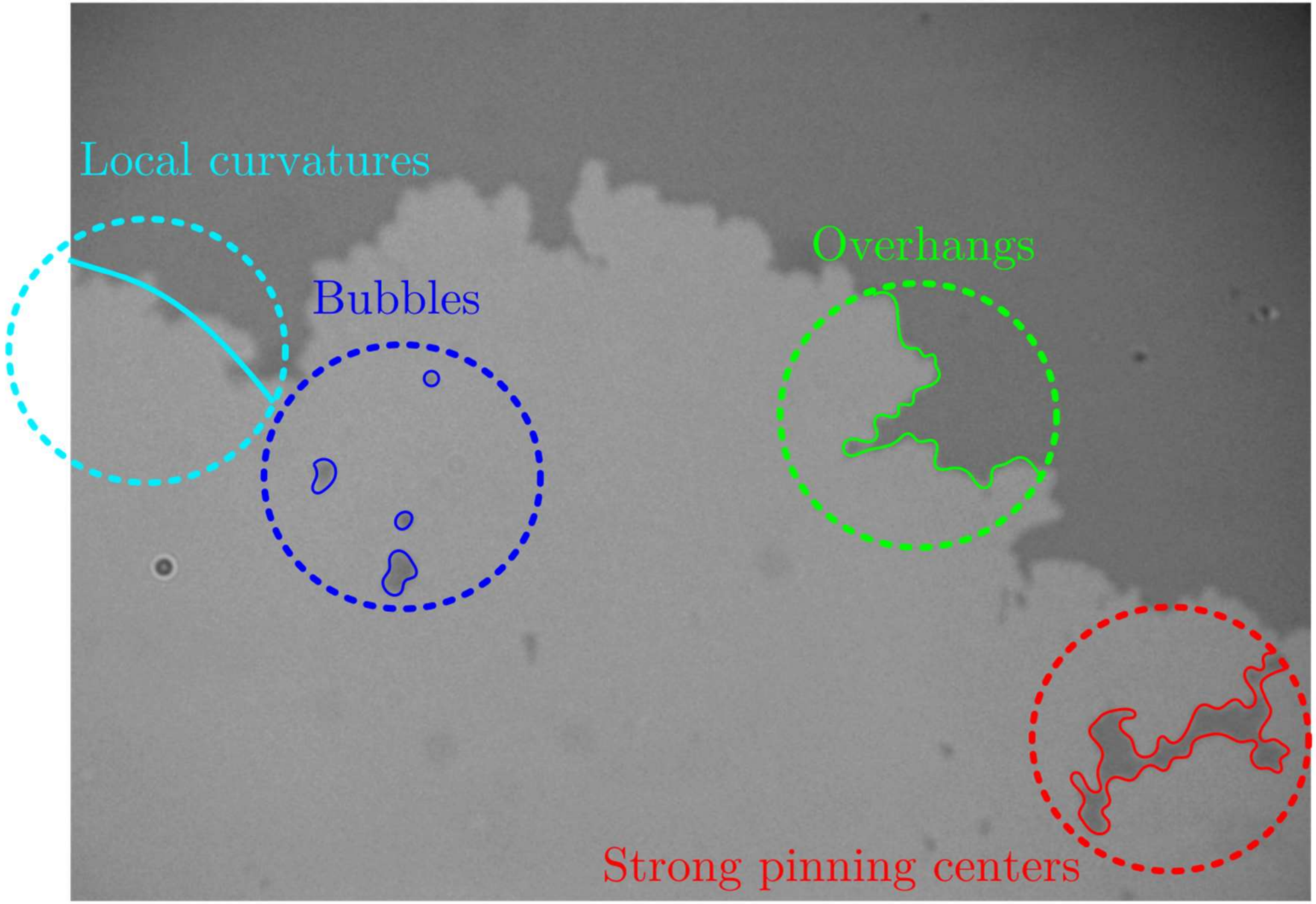



Bubbles


Bubbles
Overhangs

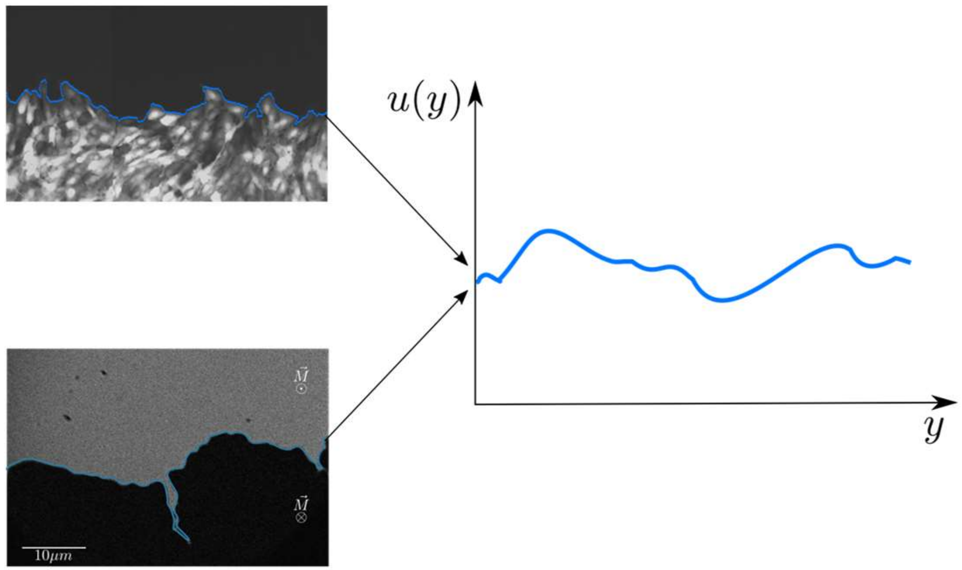


Overhangs
Bubbles
Strong pinning centers


Local curvatures
Bubbles
Overhangs
Strong pinning centers

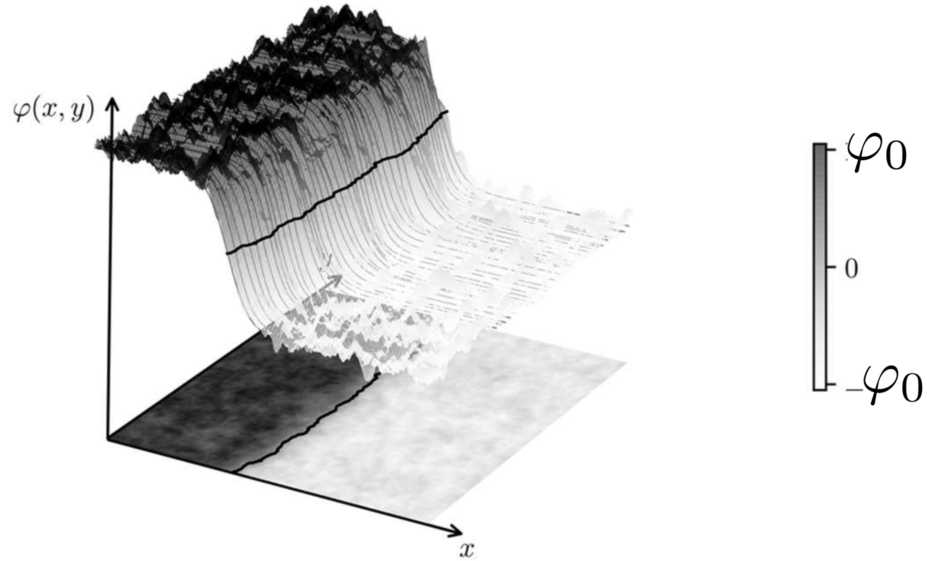
Interface position

$$u(y)$$



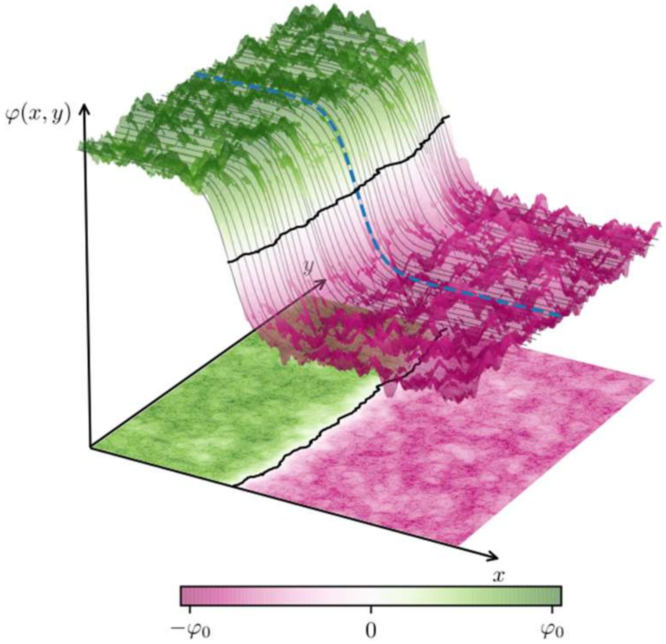
System state

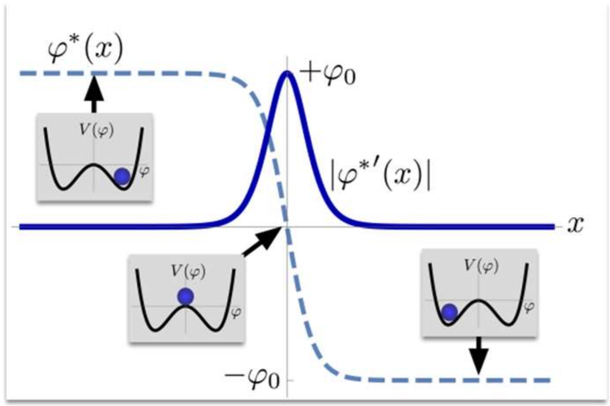
$$\varphi(x, y)$$



Tools to study interfaces

Ginzburg-Landau approach



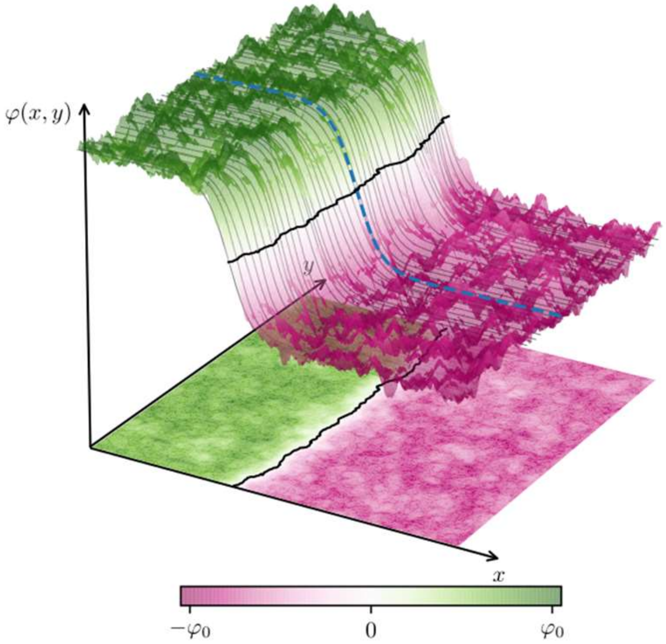


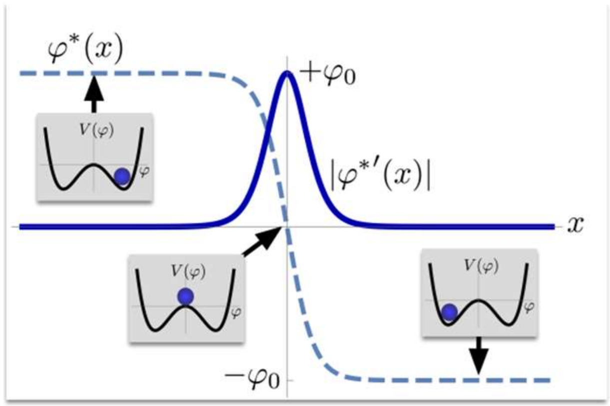
$$\mathcal{H}_{\mathrm{GL}}[\varphi] = \int d\vec{r}\, \frac{\gamma}{2} |\nabla_{\vec{r}}\varphi|^2 + V(\varphi) - h\varphi \qquad V(\varphi) = -\frac{\alpha}{2}\varphi^2 + \frac{\delta}{4}\varphi^4$$

NC, E. Ferrero, A. Kolton, J. Curiale, V. Jeudy, S. Bustingorry, *Magnetic domain wall creep and depinning: A scalar field model approach*. PRE (2018)
NC, E. Agoritsas, V. Lecomte, T. Giamarchi, *From bulk descriptions to emergent interfaces: Connecting the Ginzburg-Landau and elastic-line models*. PRB (2020)
NC. *Degradation of domains with sequential field application*. JSTAT (2021)

Tools to study interfaces

Ginzburg-Landau approach





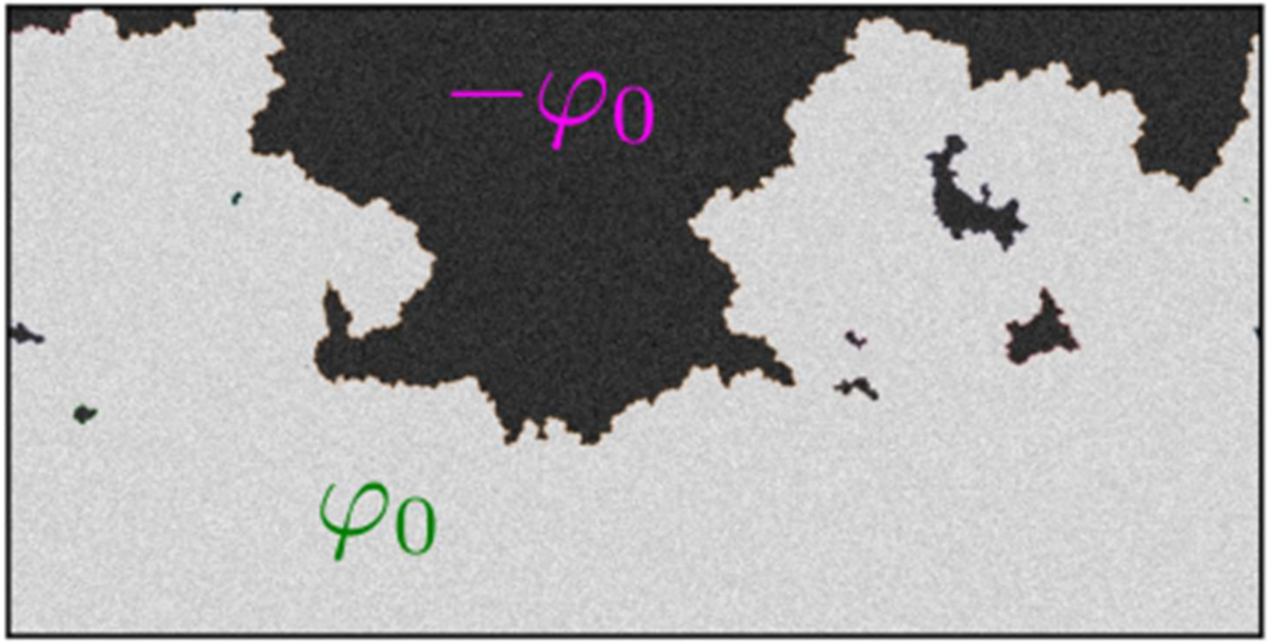
$$\eta \partial_t \varphi = -\frac{\delta \mathcal{H}_{GL}[\varphi]}{\delta \varphi} + \xi$$

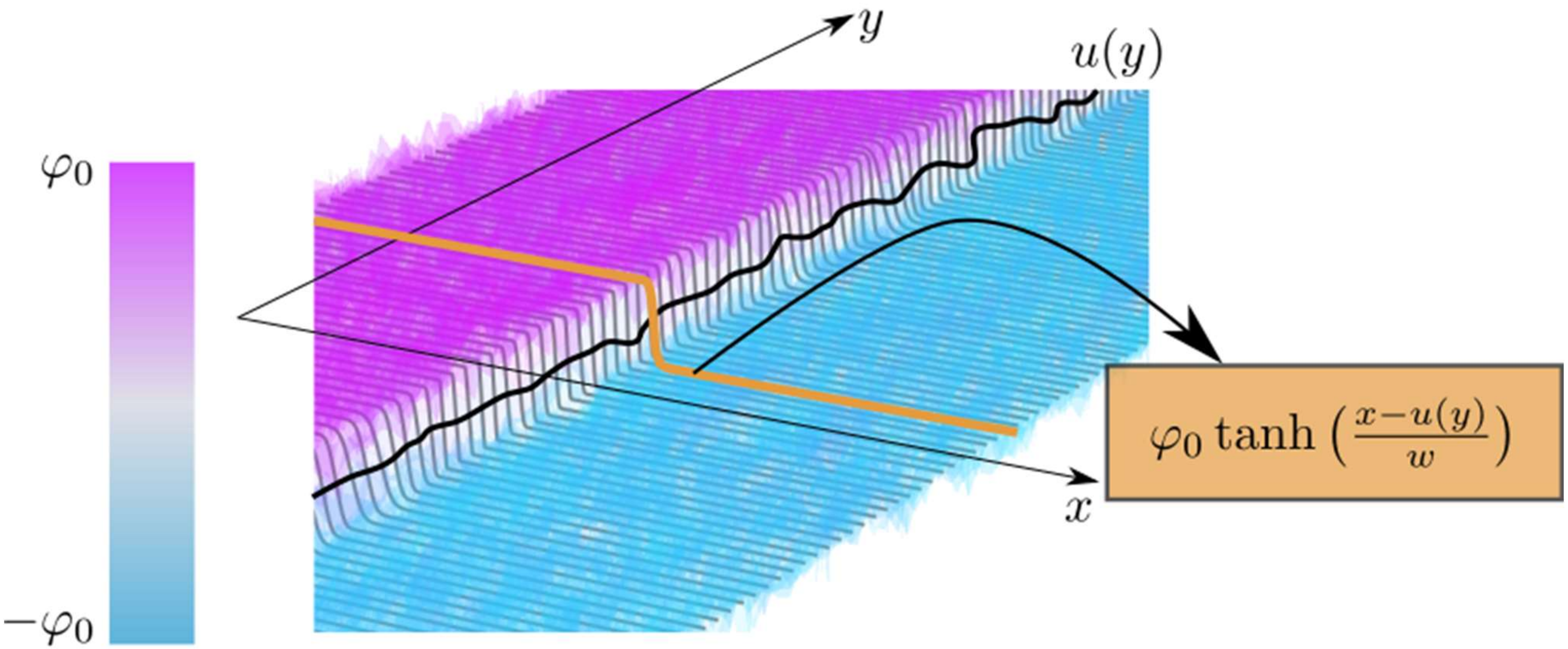
$$\langle \xi(\vec{r}_1, t_1)\xi(\vec{r}_2, t_2)\rangle = 2\eta T \delta^2(\vec{r}_2 - \vec{r}_2)\delta(t_2 - t_1)$$

NC, E. Ferrero, A. Kolton, J. Curiale, V. Jeudy, S. Bustingorry, *Magnetic domain wall creep and depinning: A scalar field model approach*. PRE (2018)
NC, E. Agoritsas, V. Lecomte, T. Giamarchi, *From bulk descriptions to emergent interfaces: Connecting the Ginzburg-Landau and elastic-line models*. PRB (2020)
NC. *Degradation of domains with sequential field application*. JSTAT (2021)

Tools to study interfaces

Domains obtained with a Ginzburg-Landau approach

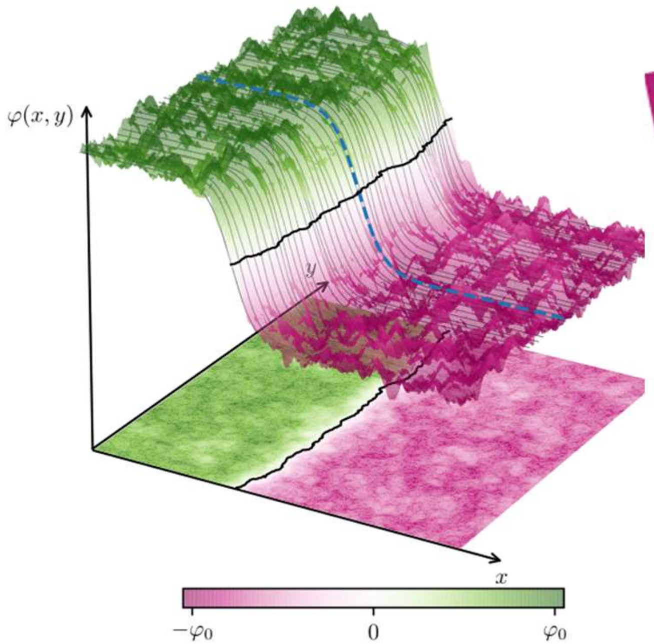


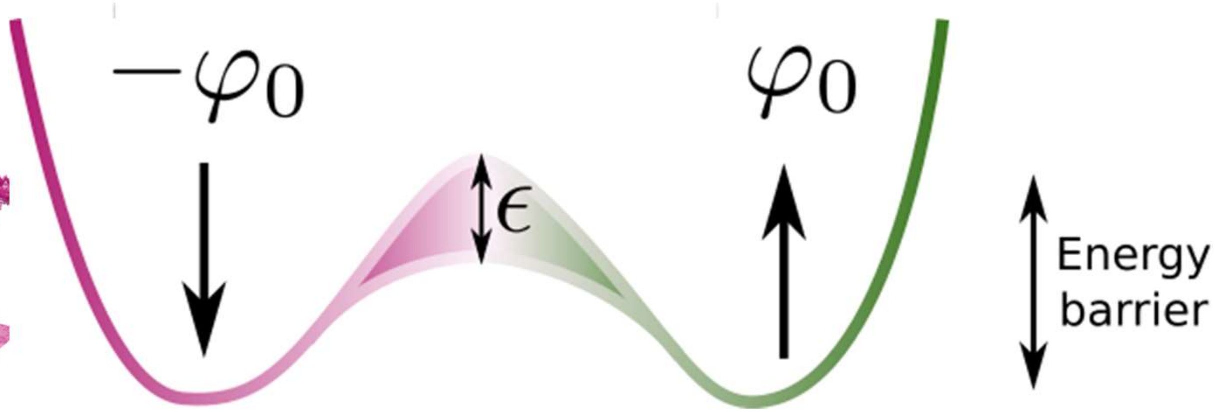


The most probable configuration is the one which minimizes the energy:

$$\frac{\delta \mathcal{H}}{\delta \varphi} = 0 \to \varphi^* = \varphi_0 \tanh\left(\frac{x - x_0}{w}\right) \quad \varphi_0 = \sqrt{\frac{\alpha}{\delta}} \quad w = \sqrt{\frac{2\gamma}{\alpha}}$$

Disordered Ginzburg-Landau model



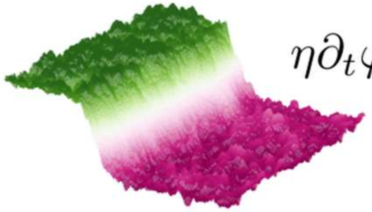


$$V_\zeta(\varphi(\vec{r})) = V(\varphi(\vec{r}))(1 + \epsilon\zeta(\vec{r}))$$

$$\langle\zeta(\vec{r}_i)\zeta(\vec{r}_j)\rangle = \delta^2(\vec{r}_i - \vec{r}_j)$$

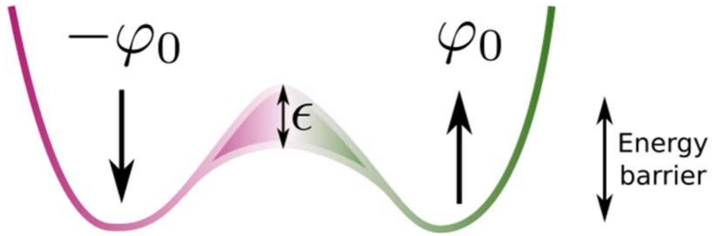
Ginzburg-Landau

State: φ



disorder

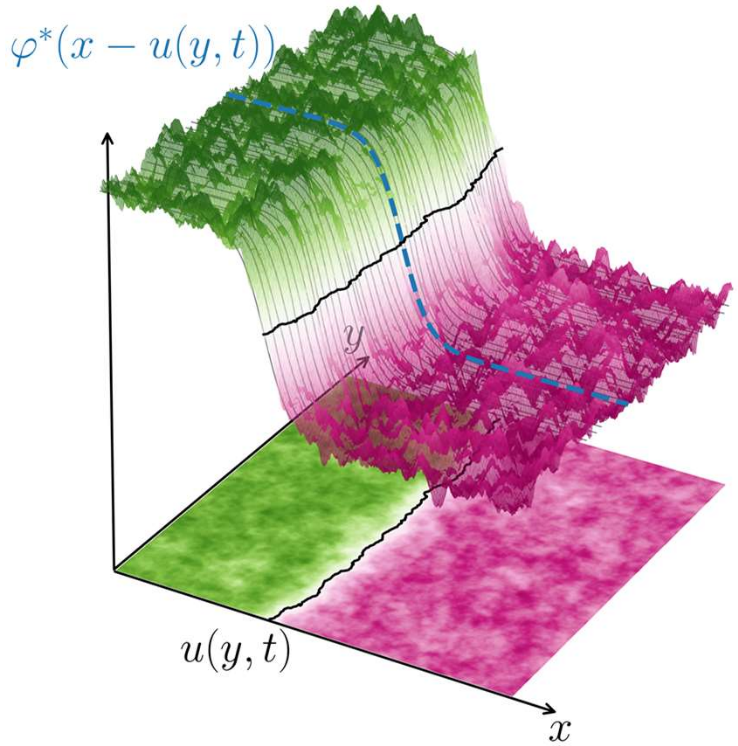
$$\eta \partial_t \varphi = \gamma \nabla^2 \varphi - (1 + \epsilon \zeta(\vec{r})) V'(\varphi) + h + \xi(\vec{r}, t)$$



We use an ansatz

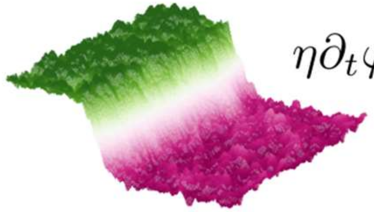
$$\varphi(x, y, t) = \varphi^*(x - u(y, t))$$

$$-\left.\frac{\delta \mathcal{H}_{\mathrm{GL}}[\varphi]}{\delta \varphi}\right|_{\varphi^*} = \gamma \varphi^{*\prime\prime} - V'(\varphi^*) = 0$$



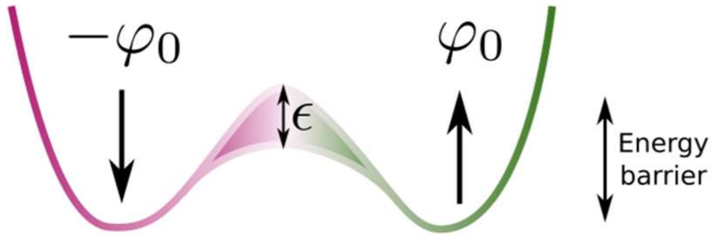
Ginzburg-Landau

State: φ



disorder

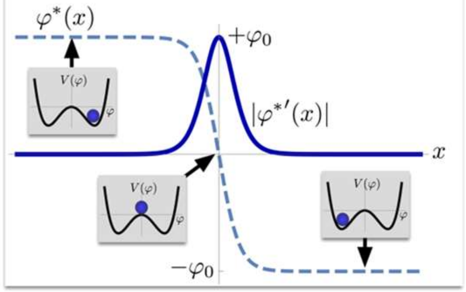
$$\eta\partial_t\varphi = \gamma\nabla^2\varphi - (1+\epsilon\zeta(\vec{r}))V'(\varphi) + h + \xi(\vec{r},t)$$



1) By using our ansatz, the Langevin equation becomes

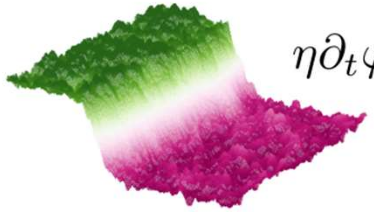
$$-\eta\varphi^{*'}\partial_t u = \gamma\left(\varphi^{*''}(\partial_y u)^2 - \varphi^{*'}\partial_y^2 u\right) - \varepsilon\zeta(x,y)V'(\varphi^*) + \xi(x,y,t)$$

2) We "localize" the equation around the position of the interface by multiplying by $\varphi^{*\prime}$



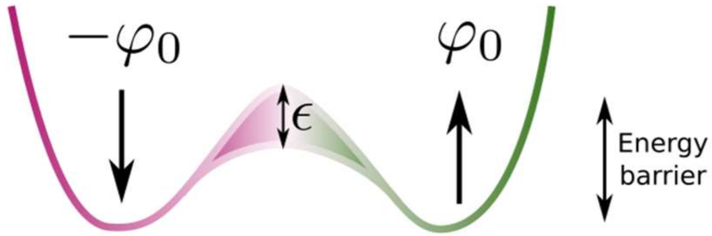
Ginzburg-Landau

State: φ



disorder

$$\eta\partial_t\varphi = \gamma\nabla^2\varphi - (1+\epsilon\zeta(\vec{r}))V'(\varphi) + h + \xi(\vec{r},t)$$



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2) We "localize" the equation around the position of the interface by multiplying by $\varphi^{*\prime}$

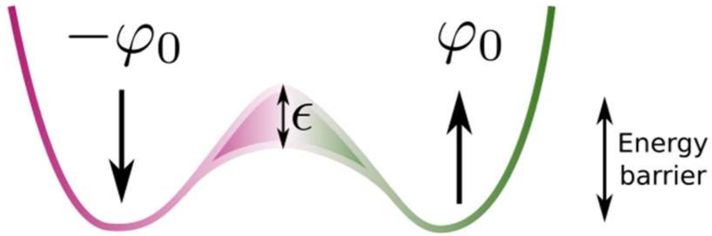
3) We integrate x over the whole space

Ginzburg-Landau

State: φ

disorder

$$\eta\partial_t\varphi = \gamma\nabla^2\varphi - (1 + \epsilon\zeta(\vec{r}))V'(\varphi) + h + \xi(\vec{r}, t)$$



Quantitative system reduction

quenched Edwards-Wilkinson

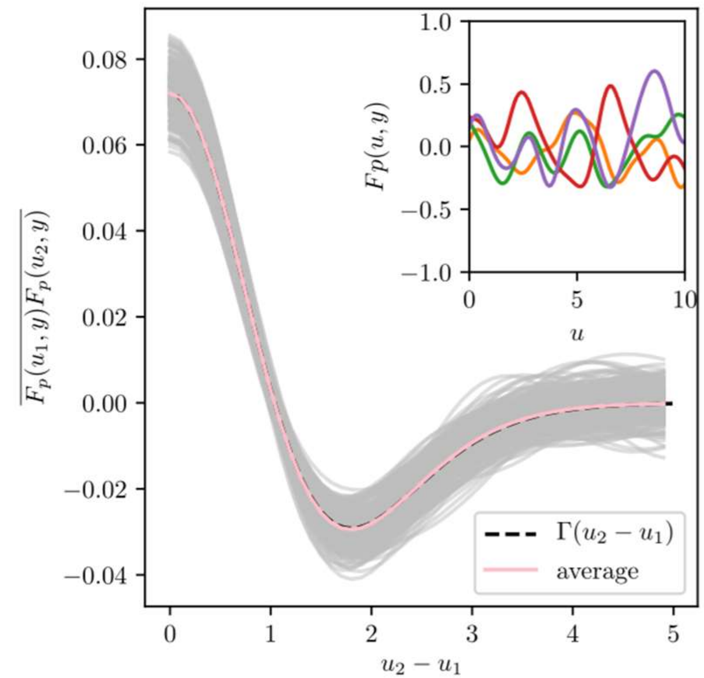
Interface: u

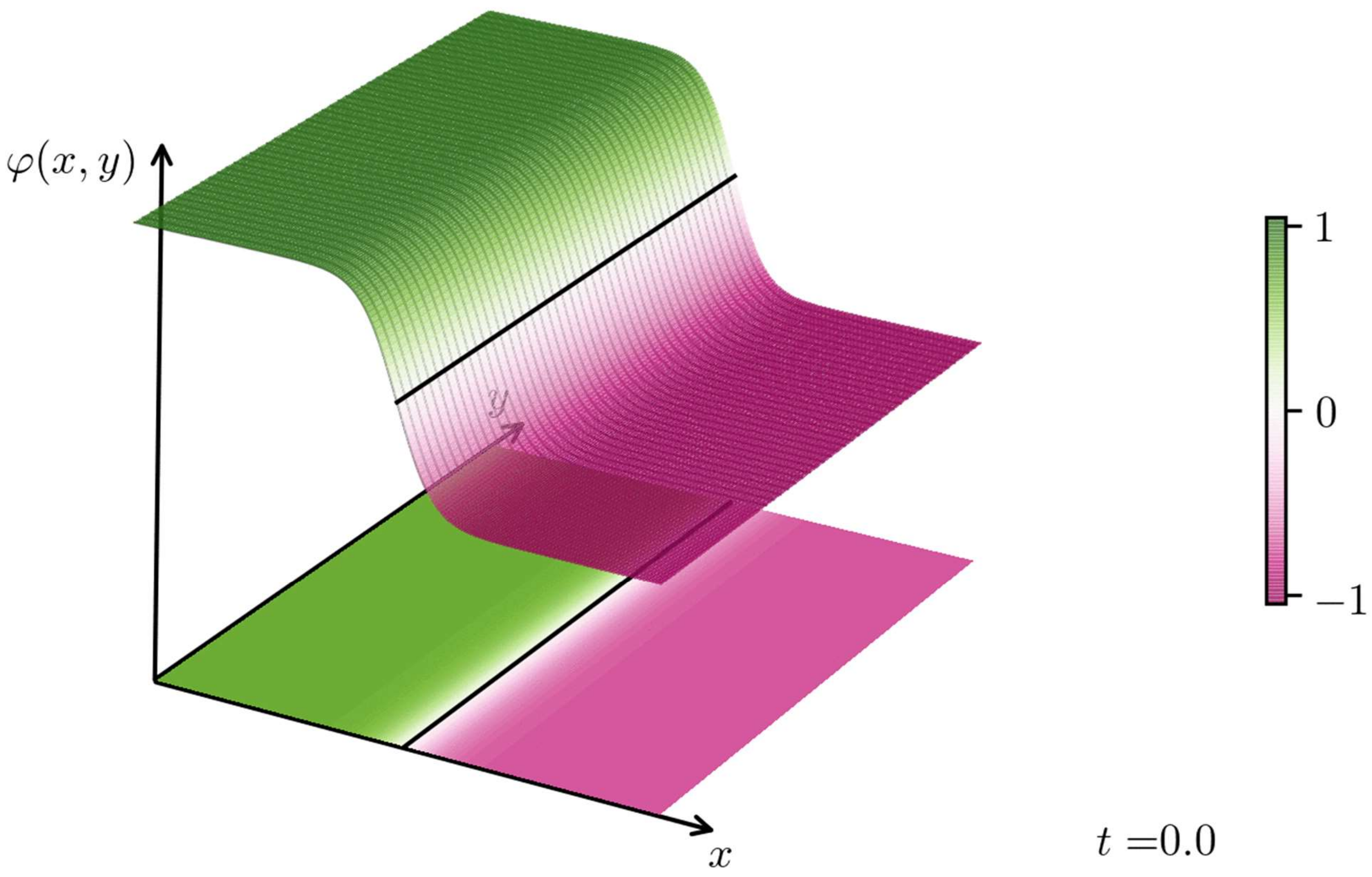
disorder

$$\tilde{\eta}\partial_t u = c\partial_y^2 u + F_p(u(y,t), y) + F + \tilde{\xi}(y, t)$$

$$\overline{F_p(u_1, y_1)F_p(u_2, y_2)} = \epsilon^2\delta(y_1 - y_2)\Gamma(u_2 - u_1)$$

$$\Gamma(u) = \gamma^2 \int_{-\infty}^{\infty} dx\, (\varphi^{*\prime}\varphi^{*\prime\prime})(x)(\varphi^{*\prime}\varphi^{*\prime\prime})(x - u)$$





$\varphi(x, y)$
y
x
1
0
-1
$t = 0.0$

Evolution from an initially flat configuration with equivalent parameters

Edwards-Wilkinson

One solves for $u(y,t)$

With parameters

$\tilde{\eta} = \eta \mathcal{N}(\alpha, \delta, \gamma)$

$c = \gamma \mathcal{N}(\alpha, \delta, \gamma)$

$F_p(\varepsilon, \alpha, \delta, \gamma)$

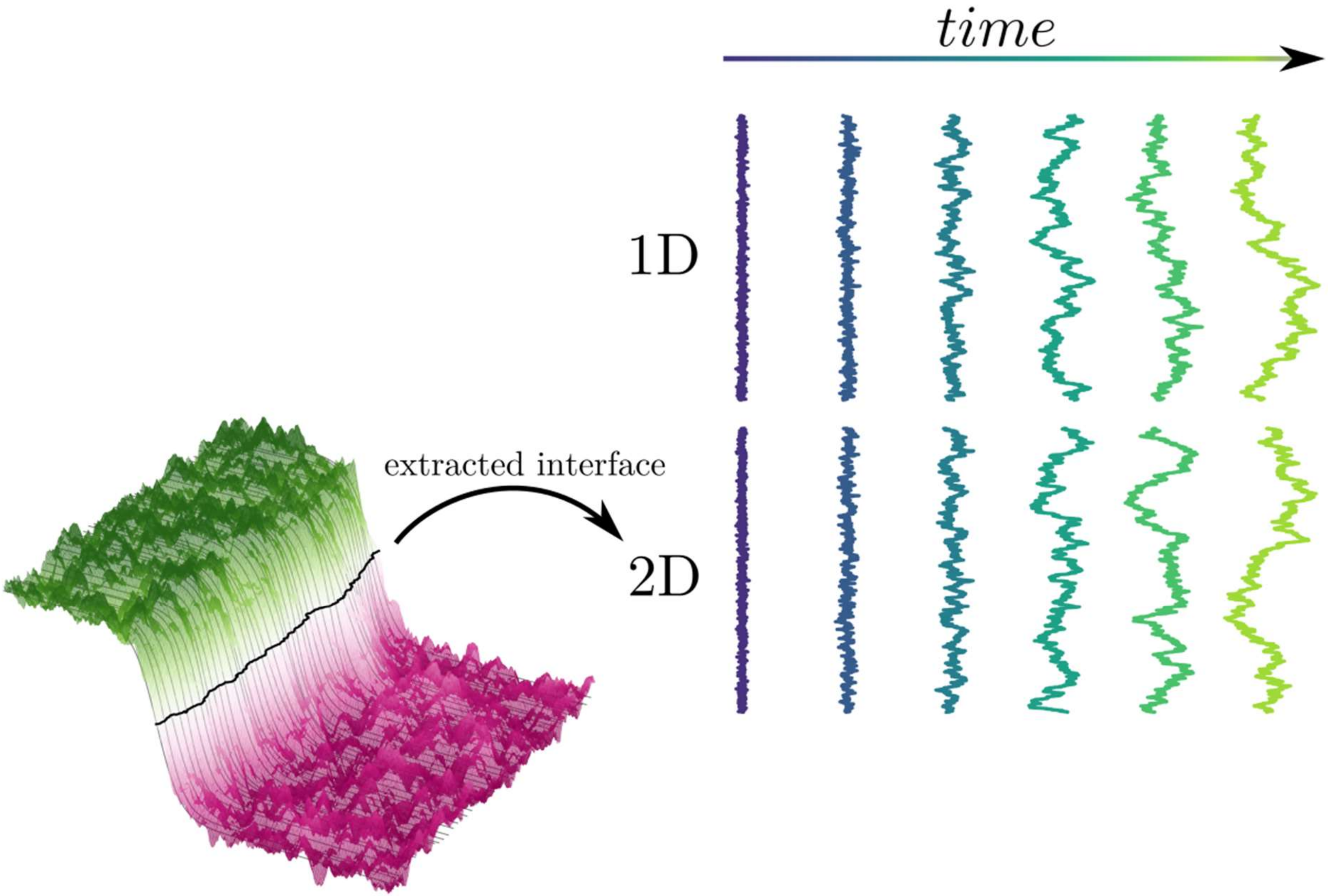
T

Ginzburg-Landau

One solves for $\varphi(x,y,t)$

With parameters

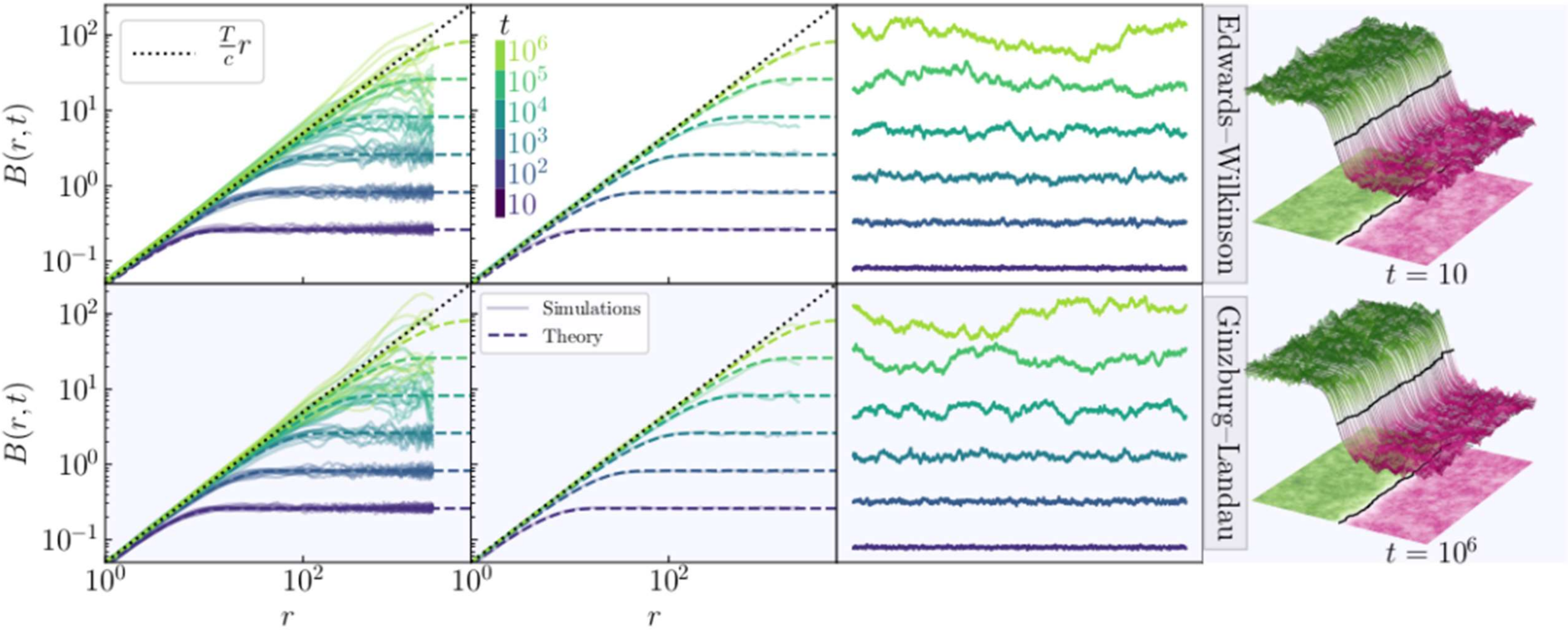
$\eta, \alpha, \delta, \gamma, T, \varepsilon$



Evolution from an initially flat configuration

Clean systems: Roughness at different evolution times

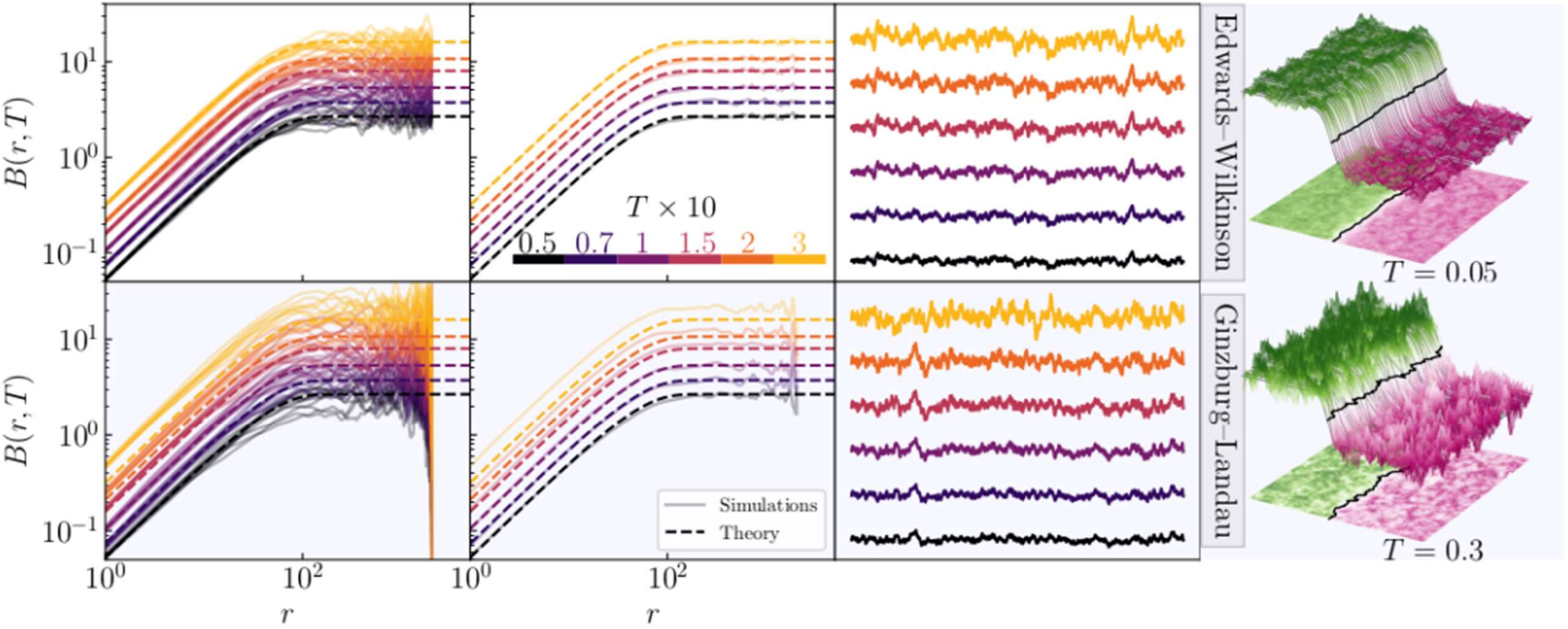
$F = 0$



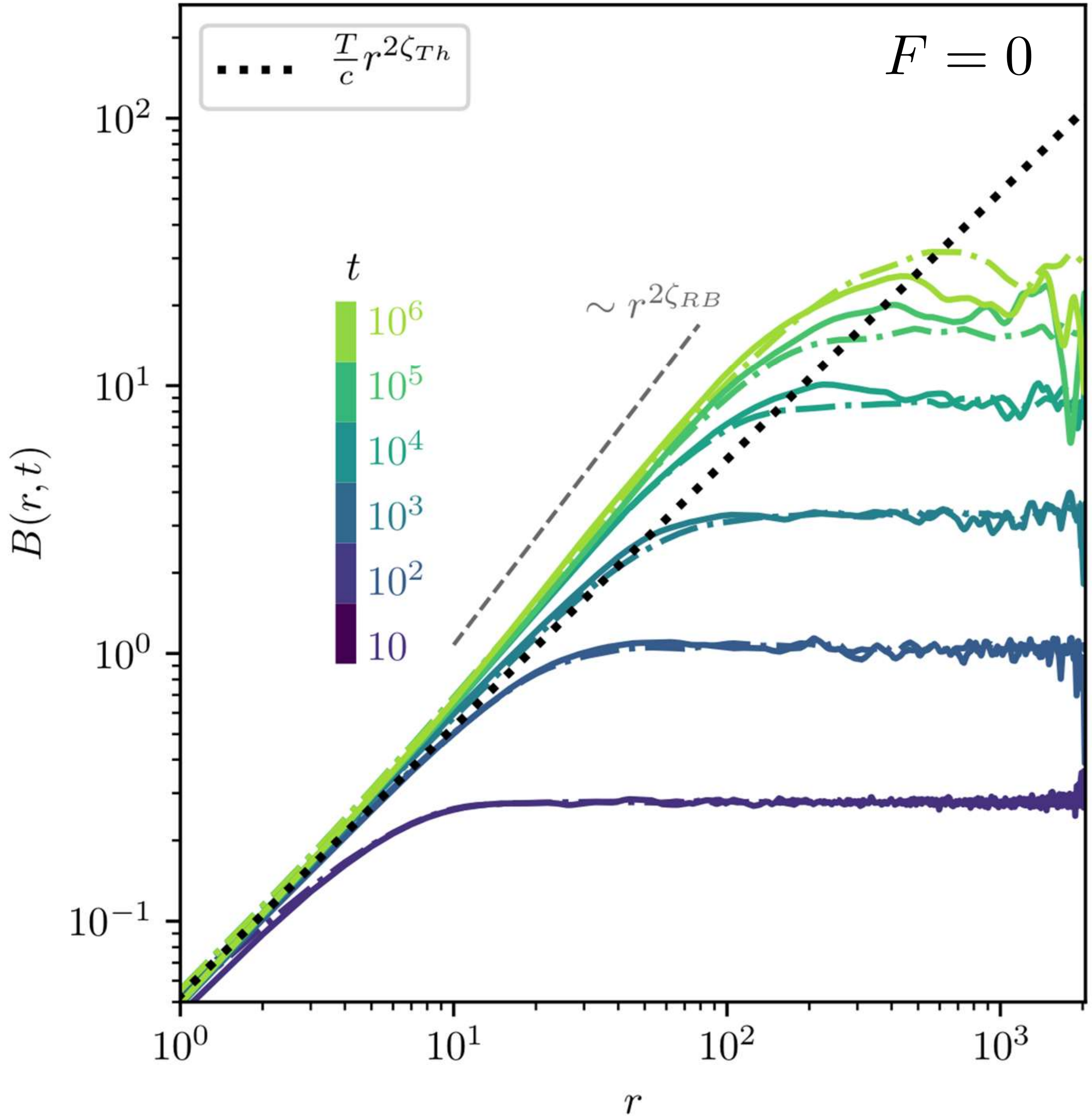
Evolution from an initially flat configuration

Clean systems: Roughness at different temperatures

$F = 0$



$$T << T^* = \frac{\alpha}{\delta}\gamma$$



Disordered systems

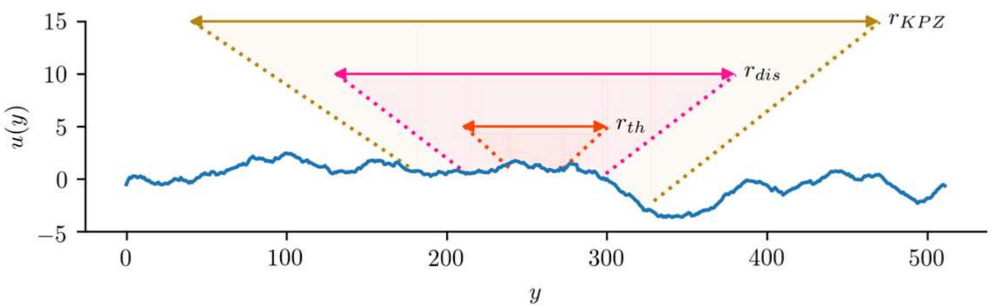
Roughness at different evolution times

Edwards–Wilkinson

Ginzburg–Landau

Microscopic interplay of temperature and disorder in an interface

Interfaces' fluctuating shape reveal the systems' microscopic physics



Roughness

$$B(r)=\overline{\langle[u(y+r)-u(y)]^2\rangle}$$

Microscopic interplay of temperature and disorder in an interface

Quenched Edwards-Wilkinson equation

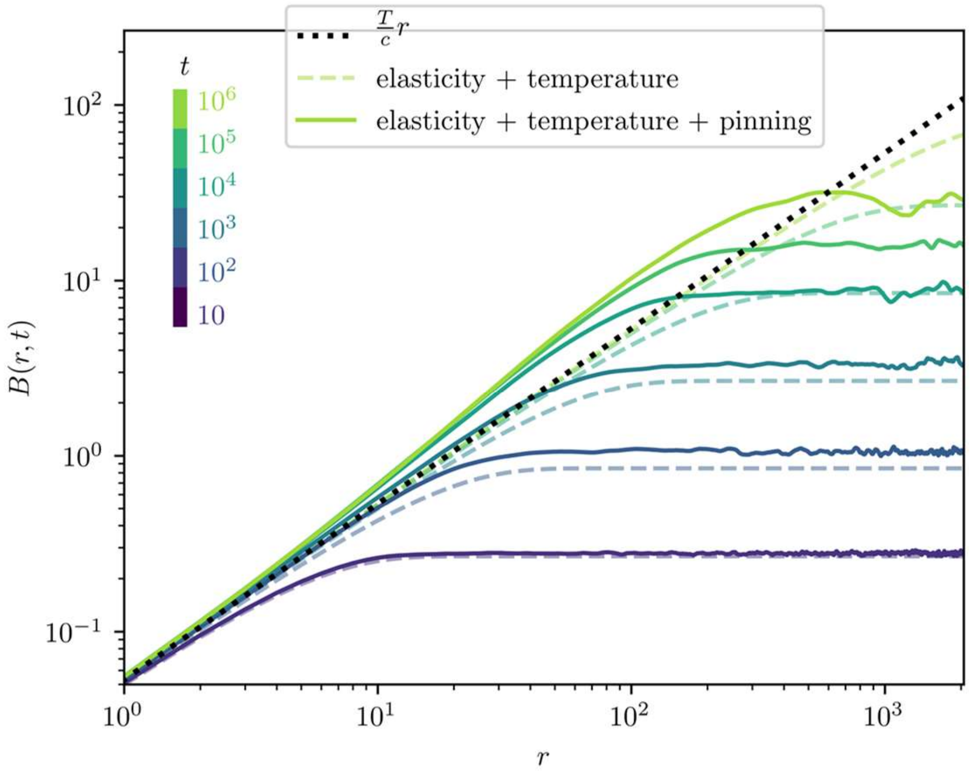
$$\eta\partial_t u(y,t) = c\partial_y^2 u(y,t) + \xi(y,t) + F_p(y,u(y,t))$$

Thermal fluctuations

$$\langle \xi(y_1,t_1)\xi(y_2,t_2)\rangle = 2\eta T\delta(y_2-y_1)\delta(t_2-t_1)$$

Pinning force
with short-length correlations

$$\overline{F_p(y_1,u_1)F_p(y_2,u_2)} = \Delta_\xi(u_2-u_1)\,\delta(y_2-y_1)$$



Microscopic interplay of temperature and disorder in an interface

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Thermal fluctuations

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Pinning force
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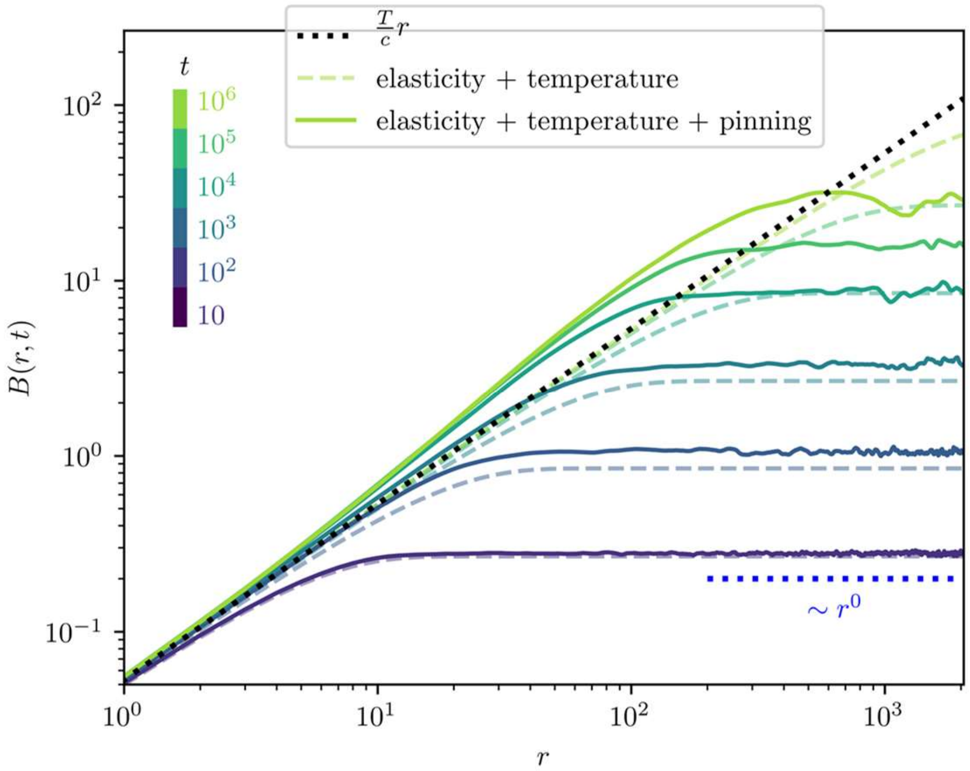


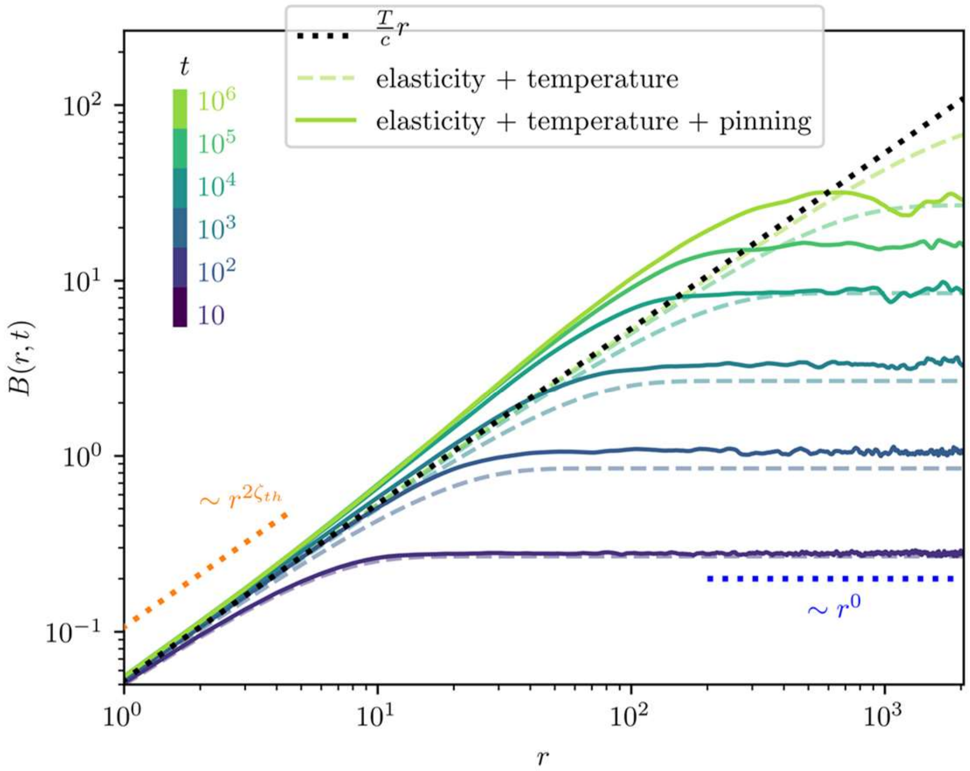
Microscopic interplay of temperature and disorder in an interface

Quenched Edwards-Wilkinson equation

$$\eta\partial_t u(y,t) = c\partial_y^2 u(y,t) + \xi(y,t) + F_p(y,u(y,t))$$

temperature

$$\zeta_{th} = \frac{1}{2}$$



Microscopic interplay of temperature and disorder in an interface

Quenched Edwards-Wilkinson equation

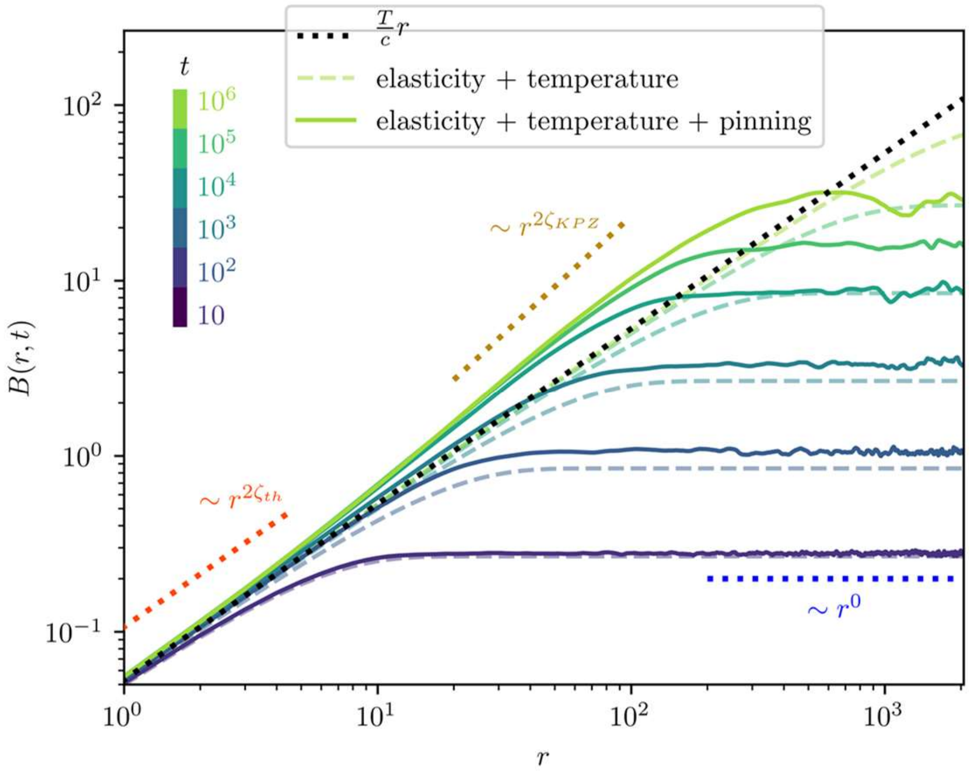
$$\eta\partial_t u(y,t) = c\partial_y^2 u(y,t) + \xi(y,t) + F_p(y,u(y,t))$$

temperature

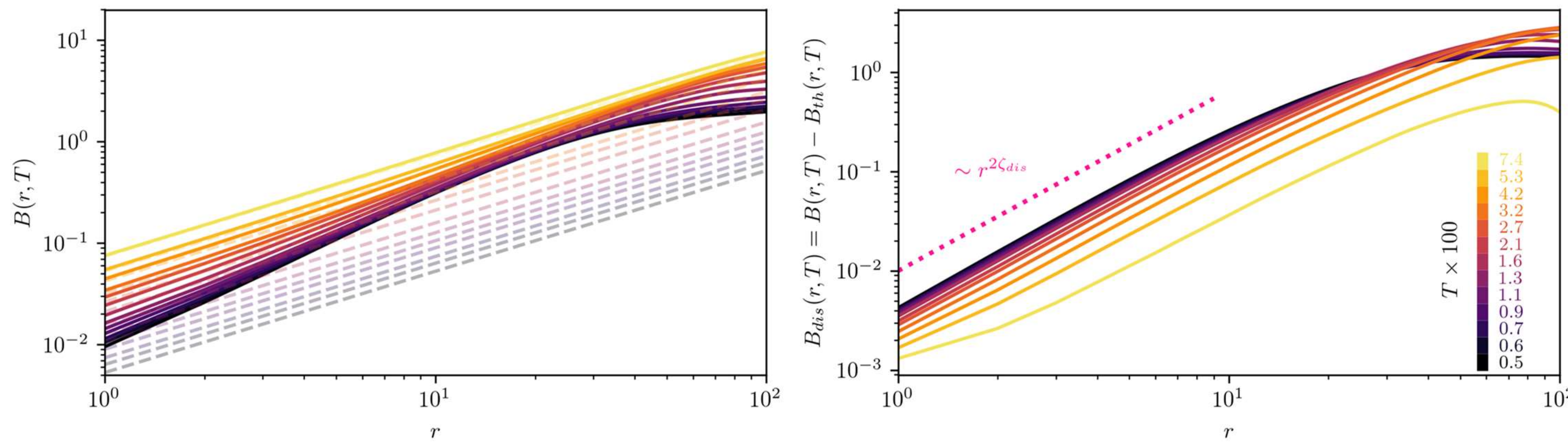
$$\zeta_{th} = \frac{1}{2}$$

disorder

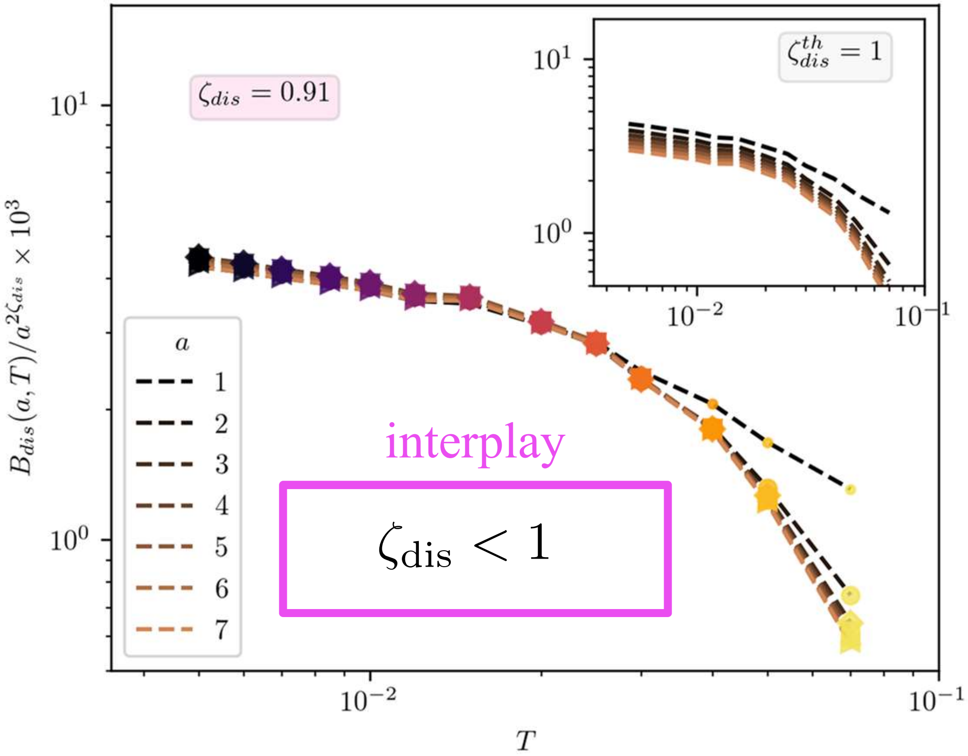
$$\zeta_{KPZ} = \frac{2}{3}$$



Microscopic interplay of temperature and disorder in an interface



Microscopic interplay of temperature and disorder in an interface



Rescaling arguments:

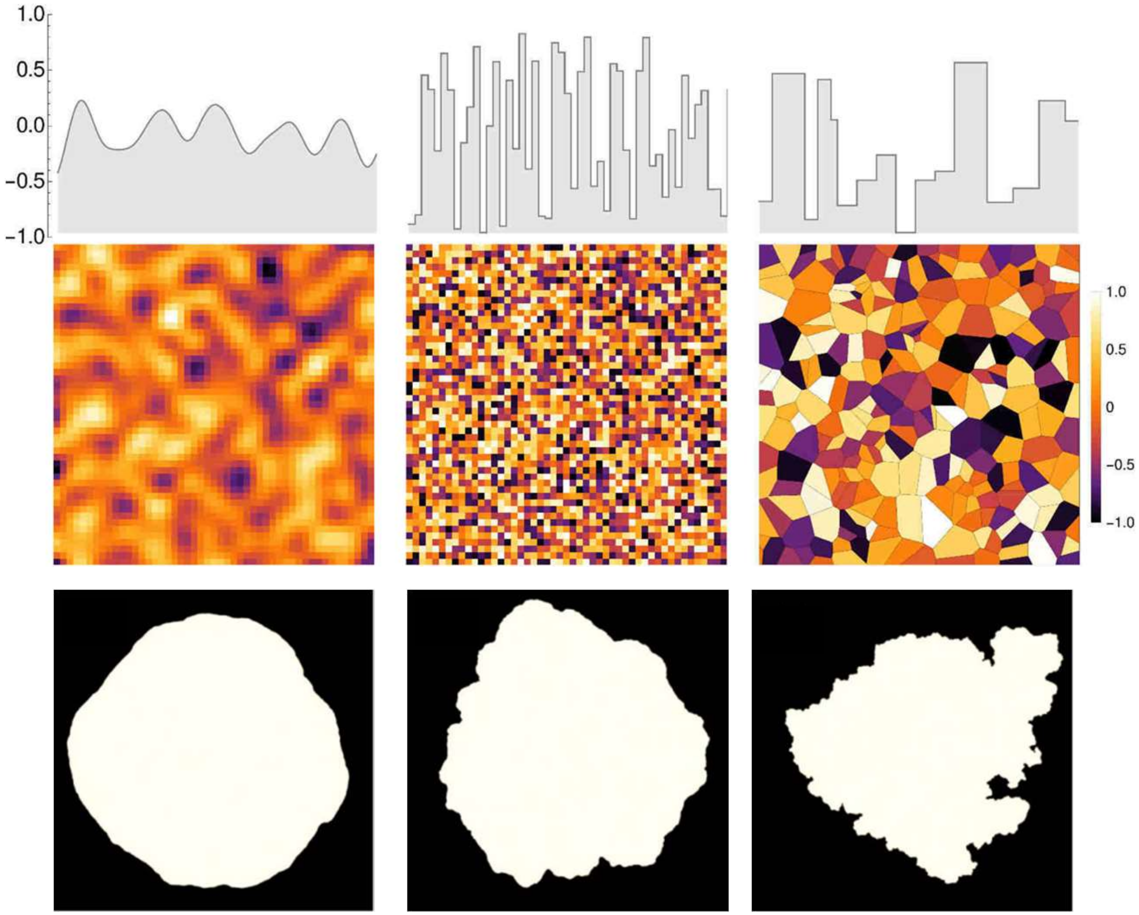
$$A_{\text{dis}}(T) = \frac{B_{\text{dis}}(r \leqslant r_0)}{r^{2\zeta_{\text{dis}}}} \propto \frac{\xi^2 T_c^2}{(c\xi^2)^{2\zeta_{\text{dis}}}} \left(\frac{f}{T}\right)^{2(1-\zeta_{\text{dis}})}$$

$\zeta_{\text{dis}} = 1$ would yield a temperature-independent

We have shown a numerical confirmation of this regime

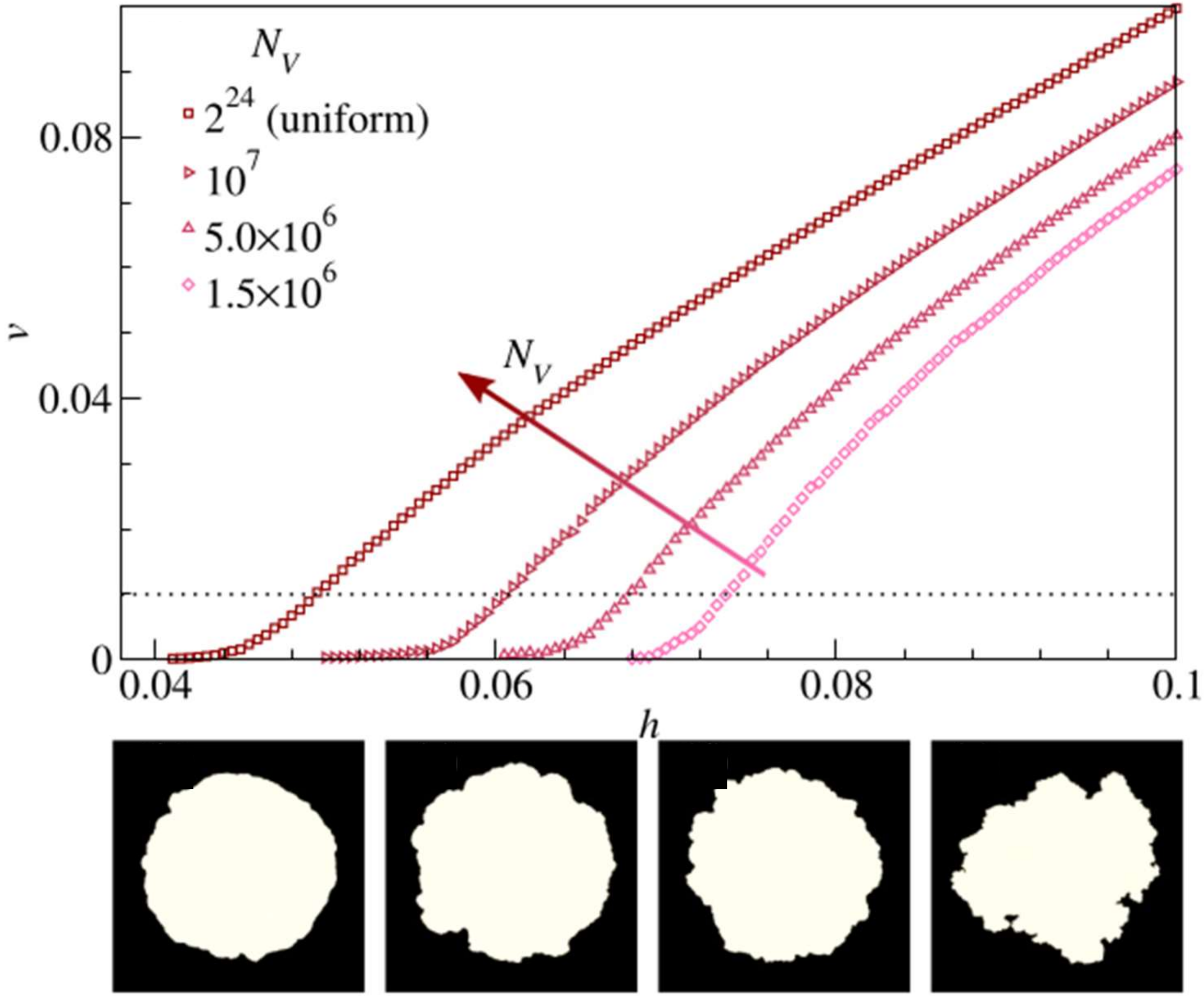
NC, Thierry Giamarchi, Vivien Lecomte, and Elisabeth Agoritsas. *Microscopic interplay of temperature and disorder of a 1D elastic interface.* PRE (2022)

Versatility of a Ginzburg-Landau approach



NC, E. E. Ferrero, A. B. Kolton, J. Curiale, V. Jeudy, S. Bustingorry, *Magnetic domain wall creep and depinning: A scalar field model approach*. PRE (2018)

Versatility of a Ginzburg-Landau approach



Allows us to emulate typical experimental I

$$\eta \frac{\partial \varphi}{\partial t} = \gamma \nabla^2 \varphi + (D\alpha\varphi + H)(1-\varphi^2) + \xi$$

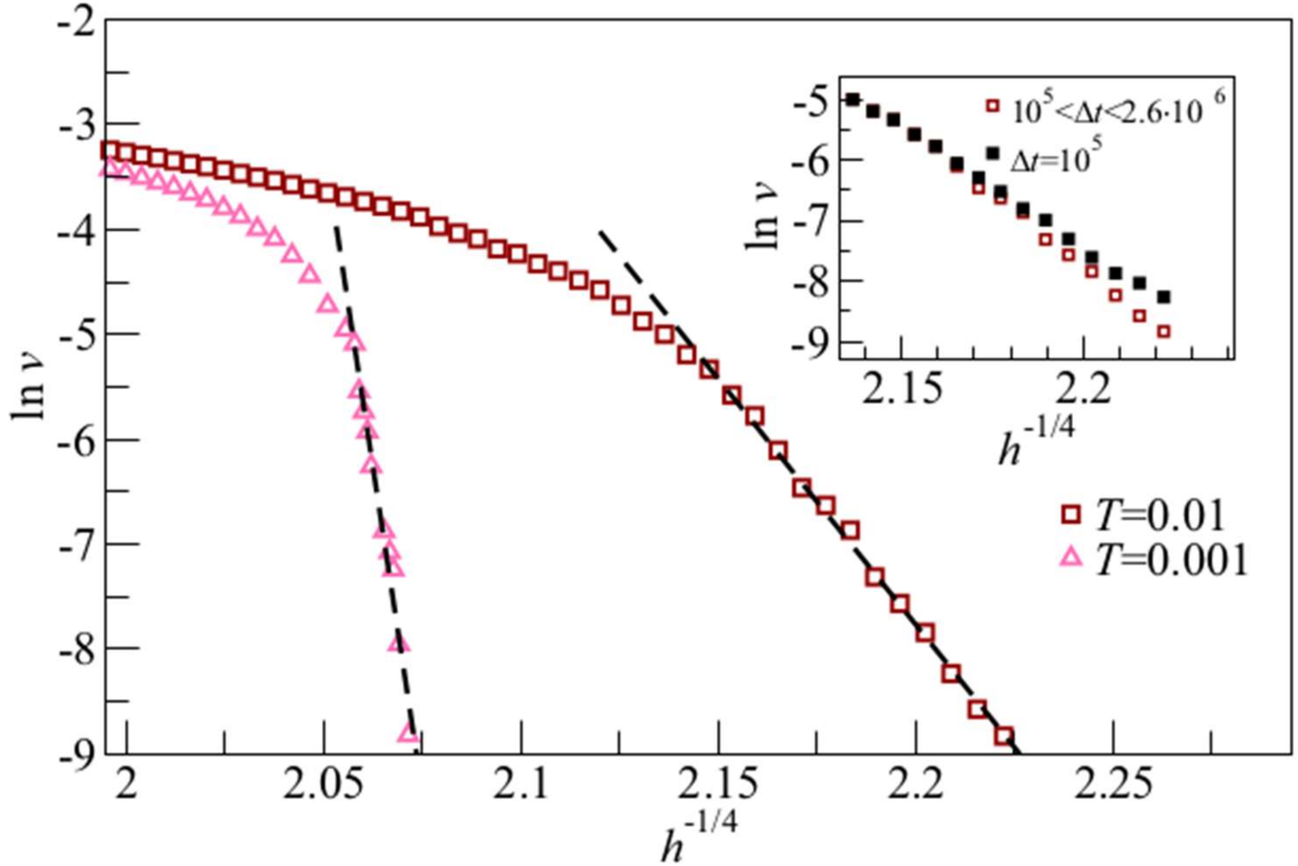
$$D = D(\varepsilon, \vec{r}) = (1 + \epsilon \chi(\vec{r}))$$

$$\langle \chi(\vec{r}_i)\chi(\vec{r}_j) \rangle = \delta^2(\vec{r}_i - \vec{r}_j)$$

NC, E. E. Ferrero, A. B. Kolton, J. Curiale, V. Jeudy, S. Bustingorry, *Magnetic domain wall creep and depinning: A scalar field model approach*. PRE (2018)

Versatility of a Ginzburg-Landau approach

Observation of the creep regime

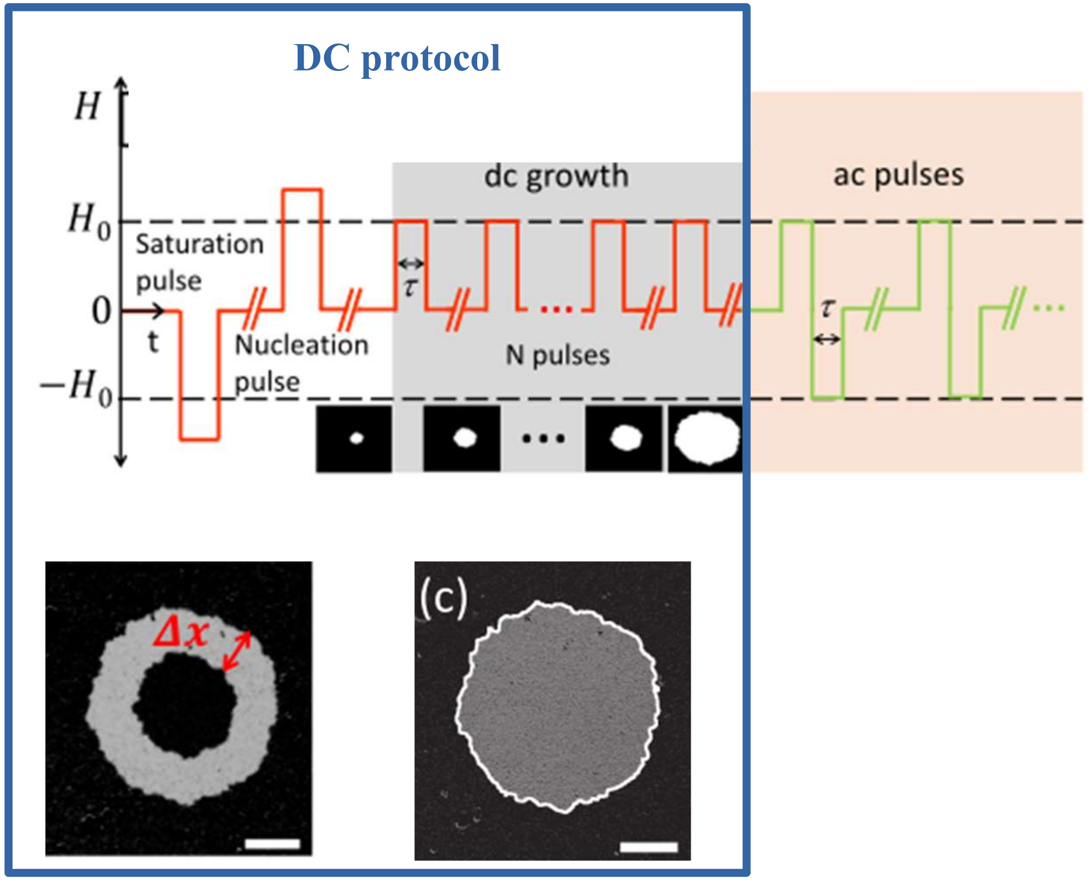


NC, E. E. Ferrero, A. B. Kolton, J. Curiale, V. Jeudy, S. Bustingorry, *Magnetic domain wall creep and depinning: A scalar field model approach*. PRE (2018)

Applications

Recent experiments revealed complex interface behaviours

Typical PMOKE protocol to estimate domain wall velocities



P. Domenichini, et al. *Transient magnetic-domain-wall ac dynamics by means of magneto-optic Kerr effect microscopy*. Highlighted in PRB, 2019.

Applications

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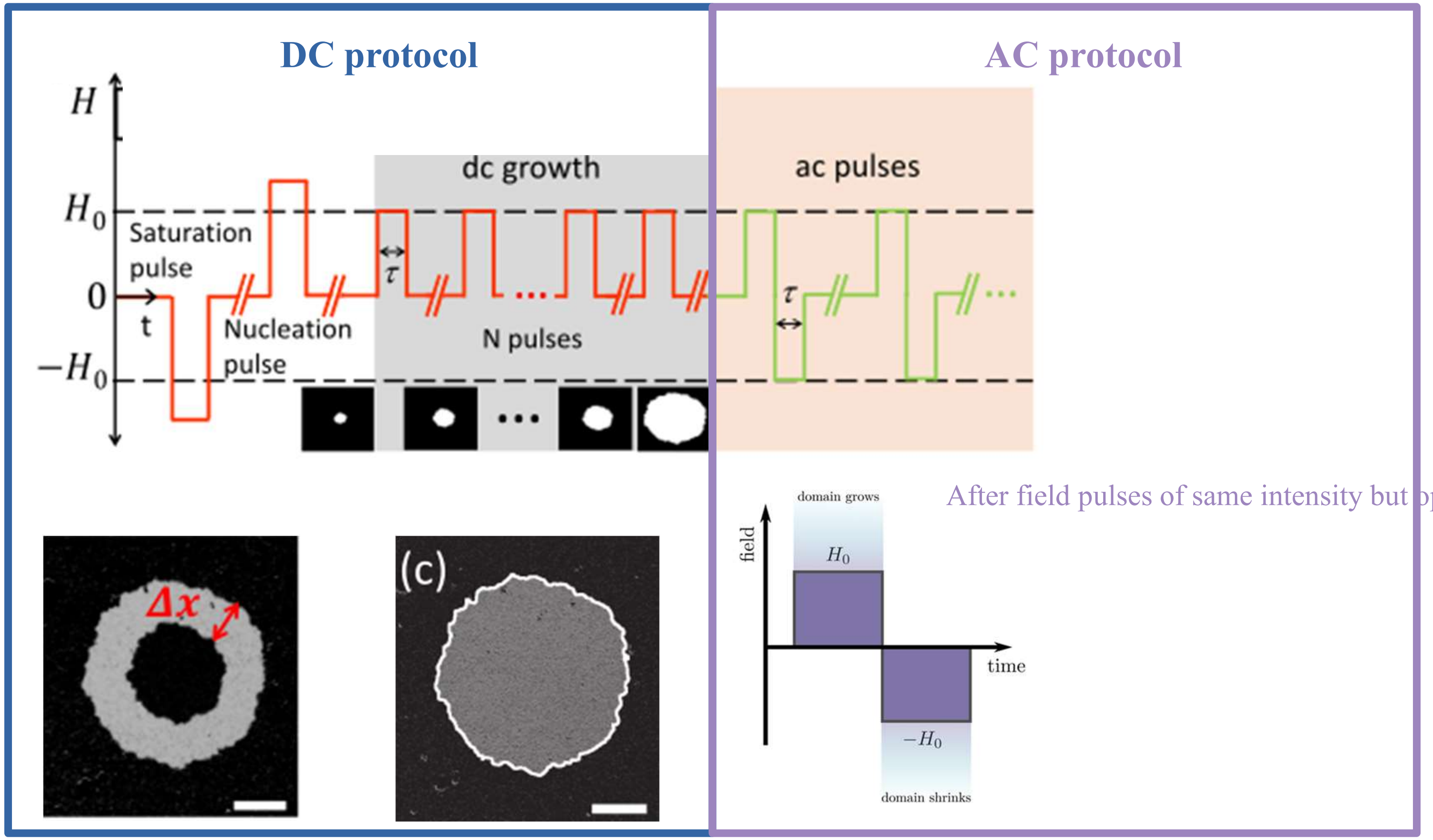


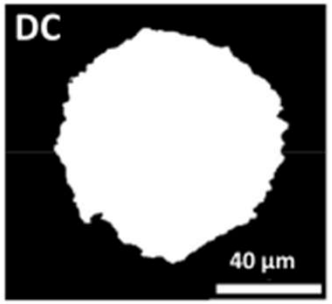
After field pulses of same intensity but opposite polarity

P. Domenichini, et al. *Transient magnetic-domain-wall ac dynamics by means of magneto-optic Kerr effect microscopy*. Highlighted in PRB, 2019.

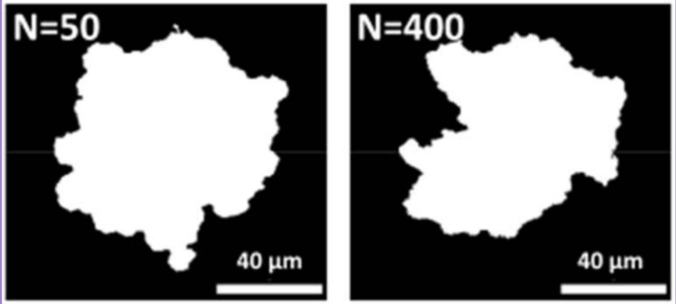
Applications

Recent experiments revealed complex interface behaviours

DC protocol



AC protocol



$$\zeta_{DC} = \zeta_{RB} = \frac{2}{3}$$

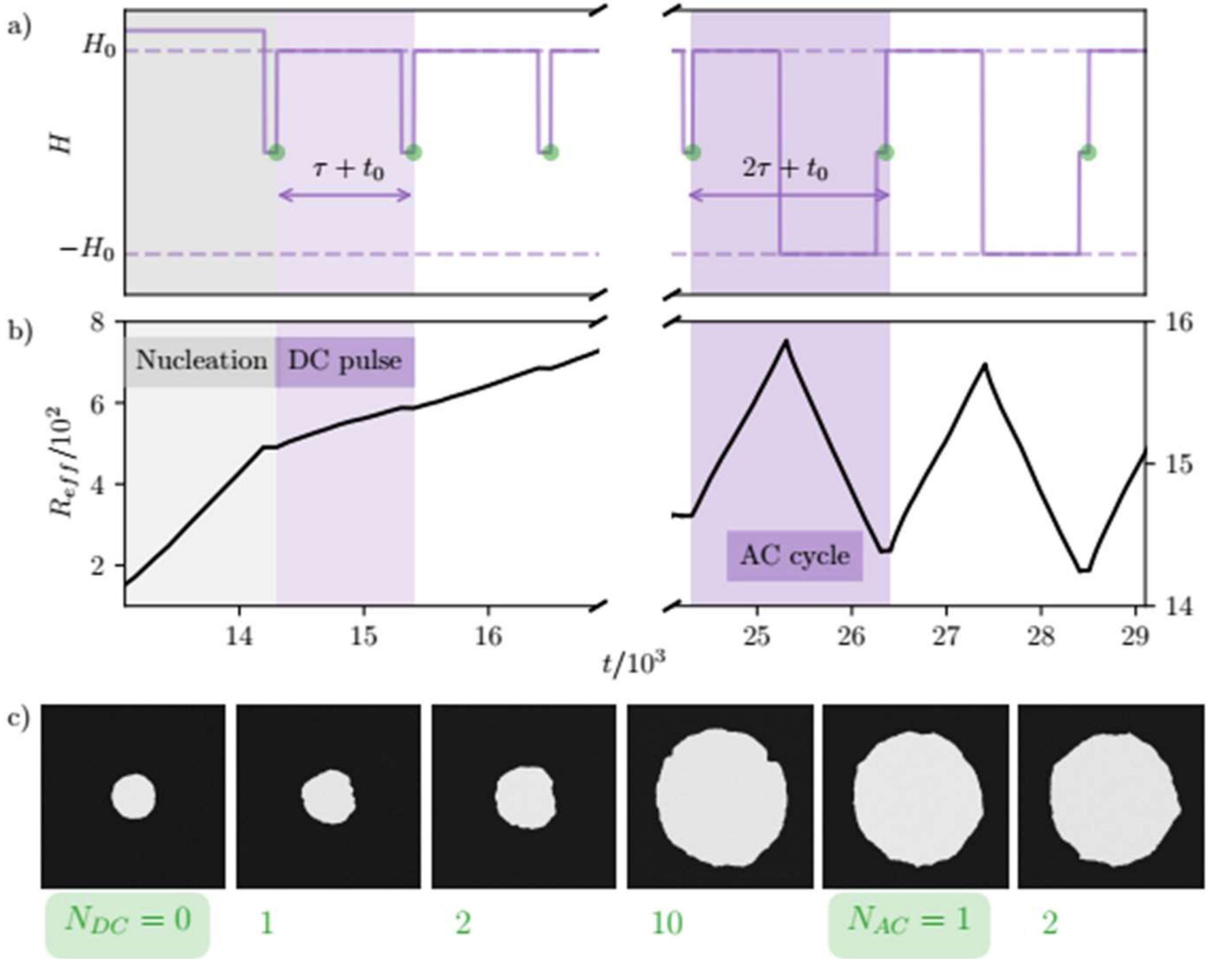
$$\zeta_{AC} \sim 0.8 > \zeta_{RB}$$

Domains lose area

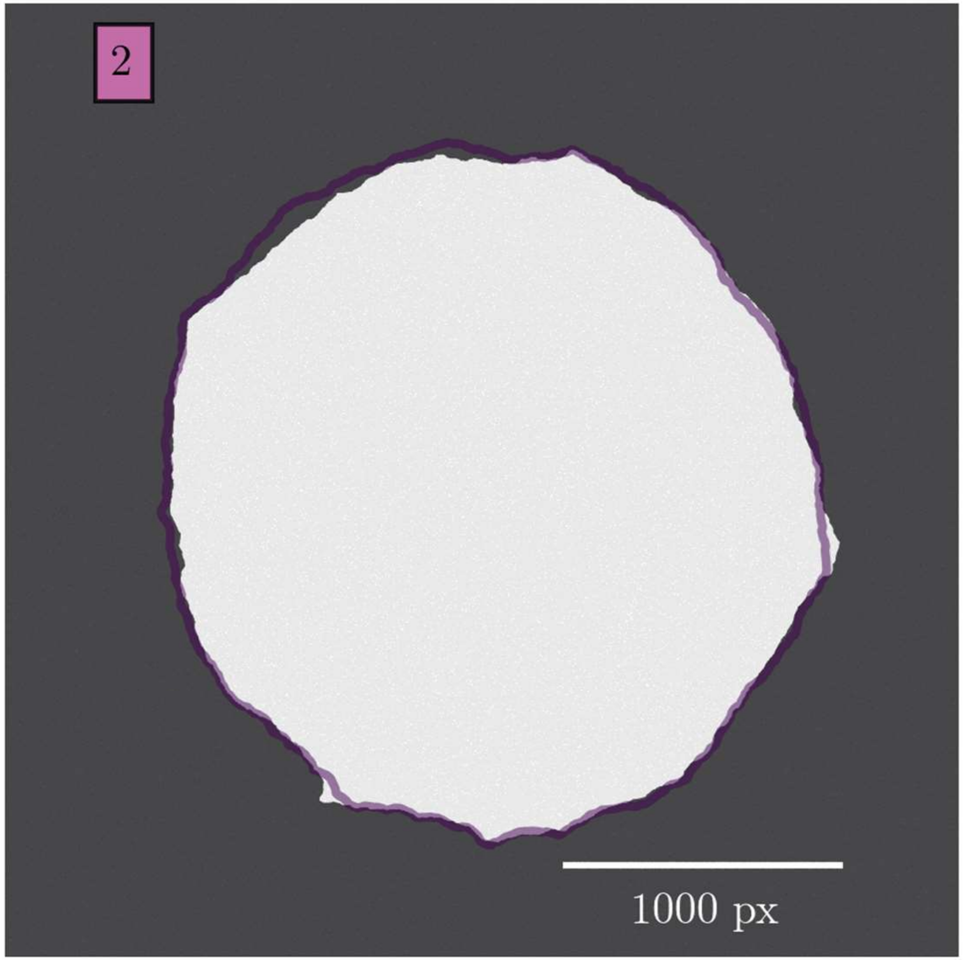
-Why the roughness is increased
-Why domains lose area

Experimental protocol emulation

Ginzburg-Landau simulations



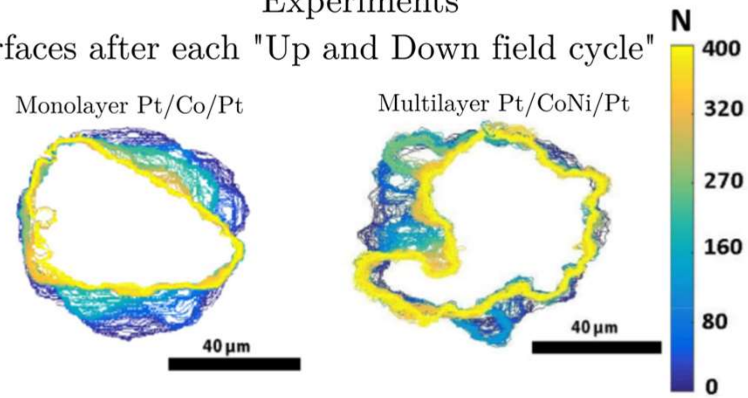
NC. *Degradation of domains with sequential field application*. JSTAT 2021


2
1000 px

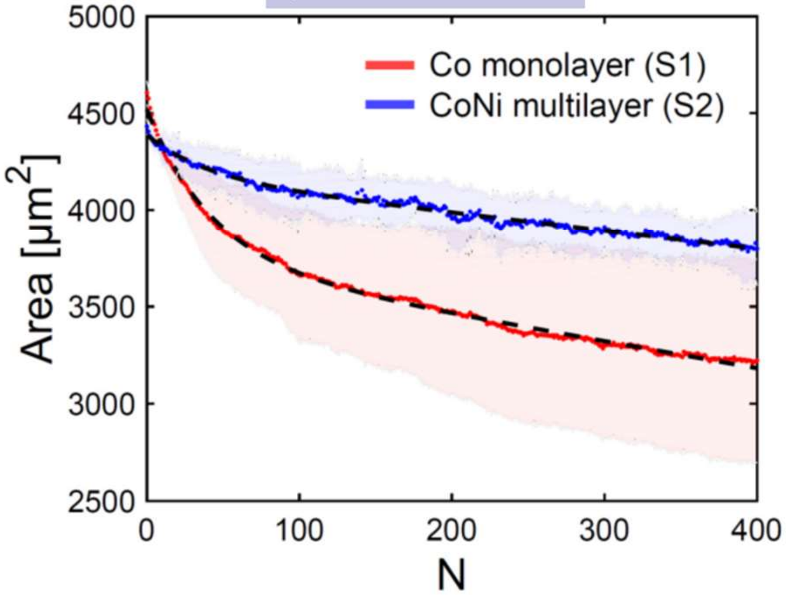
Experiments and simulations have the same scaling behavior

Experiments

Interfaces after each "Up and Down field cycle"

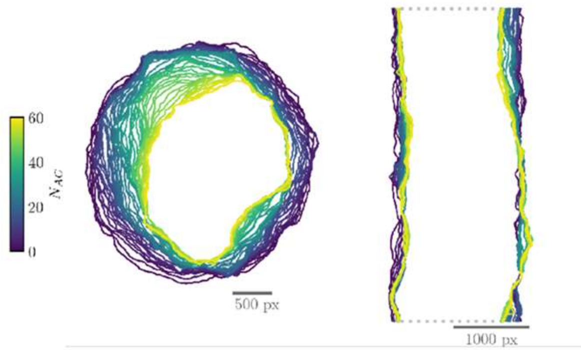


$\zeta_{AC} = 0.79 \pm 0.03$

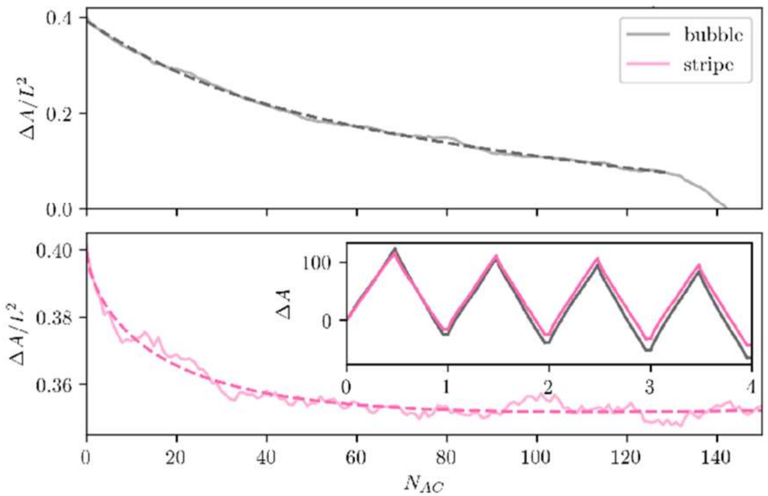


Simulations

Ginzburg-Landau



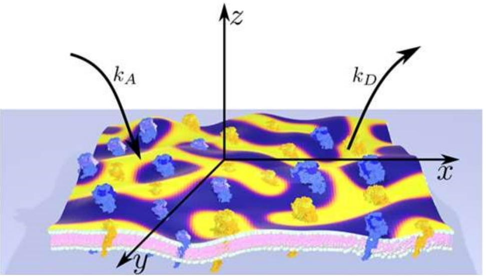
$\zeta_{AC} = 0.86 \pm 0.05$



The effective field is the external field modified by the force due to the

Conclusions and perspectives

- Ginzburg-Landau type models allow us to emulate typical experimental protocols to study velocity-field responses
- We show how a Ginzburg-Landau model can be reduced to an elastic line description
- We are now developing new observables to characterise interfaces



Other applications: NC, Kruse, Giamarchi. *Phase separation in surfaces due to matter exchange*. Arxiv: 2205.03306

– **University of Geneva**

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Patrycja Paruch
Karsten Kruse
Jean-Pierre Eckmann
Bastien Chopard
Iaroslav Gaponenko

– **University of Zurich**

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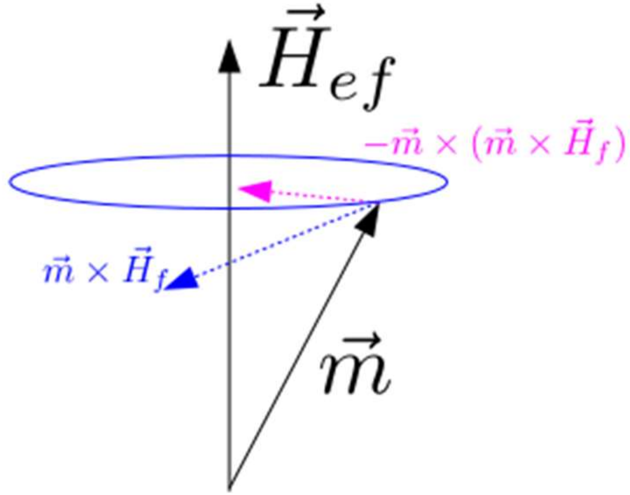
Alejandro Kolton – CNEA, Bariloche
Ezequiel Ferrero – CNEA, Bariloche
Javier Curiale – CNEA, Bariloche

UNIVERSITÉ DE GENÈVE

DQMP Department of Quantum Matter Physics

Stochastic Landau-Lifshitz-Gilbert equation

sLLG $$d_t\vec{M} = \frac{-\gamma_0}{1+\eta_0^2}\vec{M}\times\left[(\vec{H}_{eff}+\vec{H}_t)+\frac{\eta_0}{M_S}\vec{M}\times(\vec{H}_{eff}+\vec{H}_t)\right]$$



Stochastic field $$\vec{H}_t = (f_x, f_y, f_z)$$

$$\langle f_i\rangle = 0 \qquad \langle f_i(t_1)f_j(t_2)\rangle = 2D\delta_{ij}\delta(t_2-t_1) \qquad D = \frac{\eta_0 k_B T}{\gamma_0 V M_S}$$

Effective field Zeeman + Exchange + Perpendicular magnetic anisotropy (z-direction)

$$\vec{H}_{eff} = -\frac{1}{M_S}\frac{\delta E}{\delta\vec{m}}$$

$$H_{eff}^{x,y} = \frac{2A}{M_S}\nabla^2 m_{x,y} + H_{x,y}$$

$$H_{eff}^{z} = \frac{2A}{M_S}\nabla^2 m_z + \frac{2K_u}{M_S}m_z + H_z$$

$$\frac{\partial m_z}{\partial t} = \frac{-\gamma_0}{1+\eta_0^2}\{\frac{2A}{M_S}(m_x\nabla^2 m_y - m_y\nabla^2 m_x)$$

$$+ m_x f_y + m_y f_x$$

$$+ \eta_0[\frac{2A}{M_S}(-m_z)((\nabla m_x)^2 + (\nabla m_y)^2 + (\nabla m_z)^2)$$

$$+ m_x m_z f_x - m_y m_z f_y +$$

sLLG

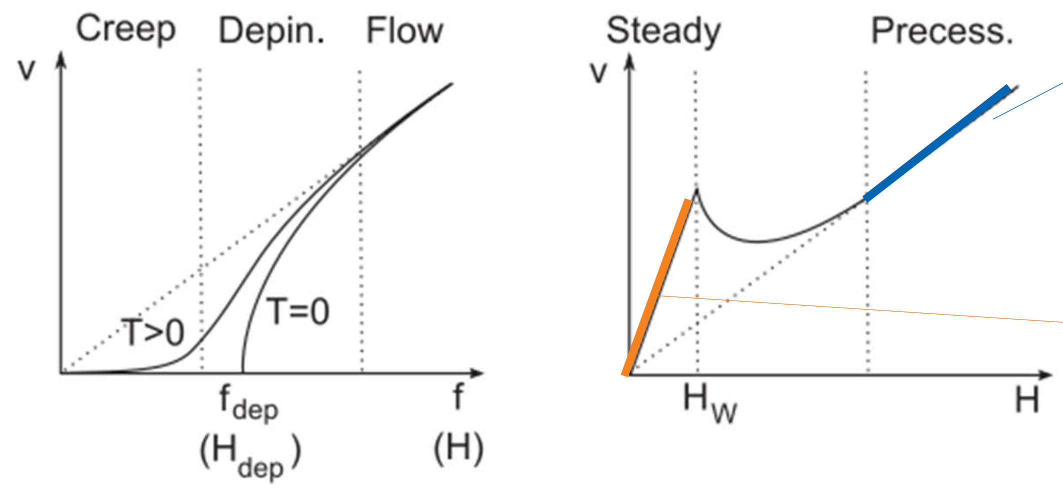
$$\frac{\eta_0\gamma_0}{1+\eta_0^2}(1-m_z^2)(\frac{2K_u}{M_S}m_z + H_z + f_z) - \frac{2A}{M_S}\nabla^2 m_z]$$

Ginzburg-Landau

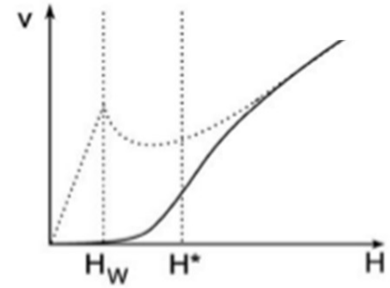
$$\frac{\partial \varphi}{\partial t} = \Gamma(1-\phi^2)\left(\alpha\phi + h_0\right) + \Gamma\gamma\nabla^2\phi + \xi$$

Flow regime

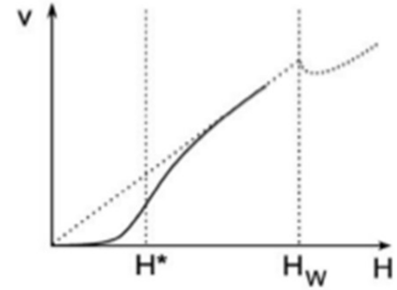
$$v_{flow} = mH_z$$



$$m = \frac{\gamma_0 \Delta}{\eta_0 + \frac{1}{\eta_0}} \quad \eta_0 \sim 0.3$$



$$m = \frac{\gamma_0 \Delta}{\eta_0} \quad \eta_0 \sim 4$$



amet, A. Mougin, M. Cormier, J. Ferre, V. Baltz, B. Rodmacq, B. Dieny, and R. L. Stamps. *Creep and flow regimes of Magnetic domain wall motion in ultrathin Pt/Co/Pt films with perpendicular an*

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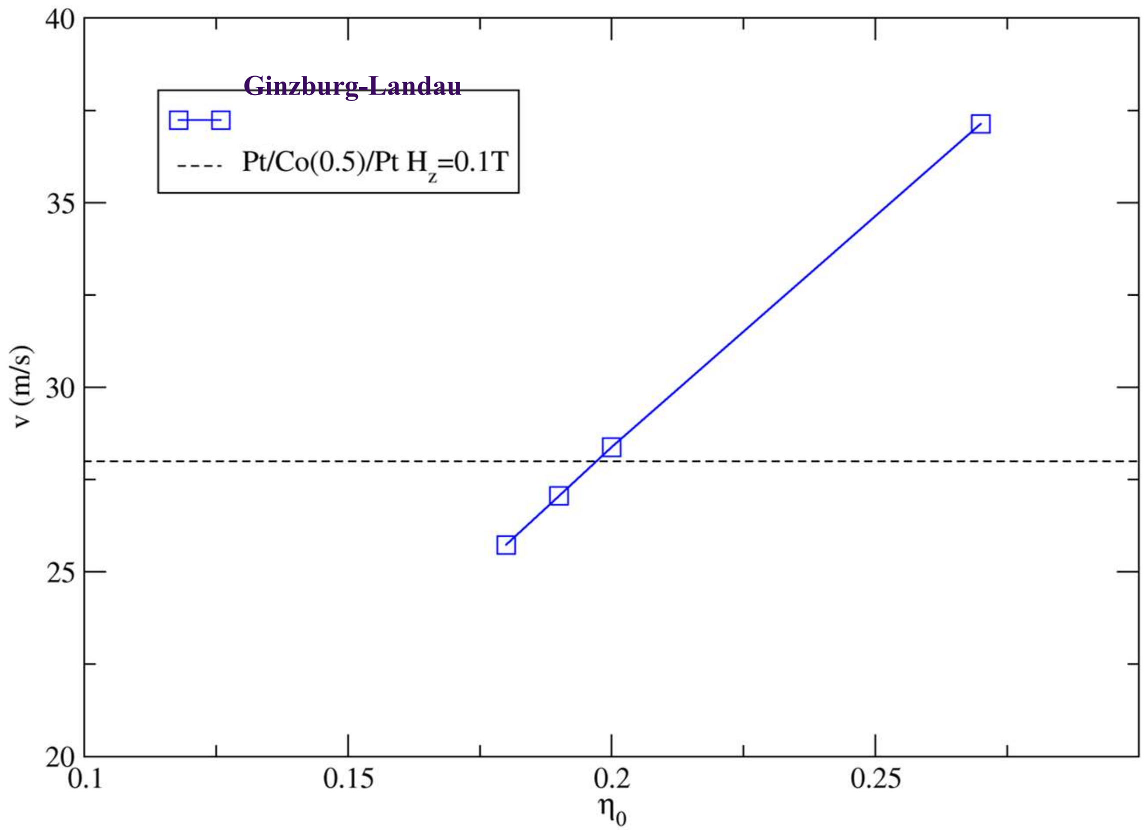

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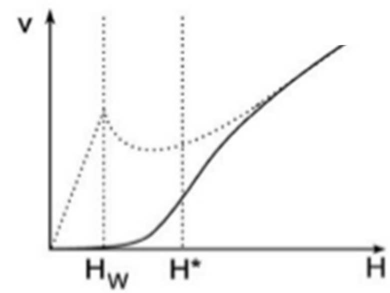
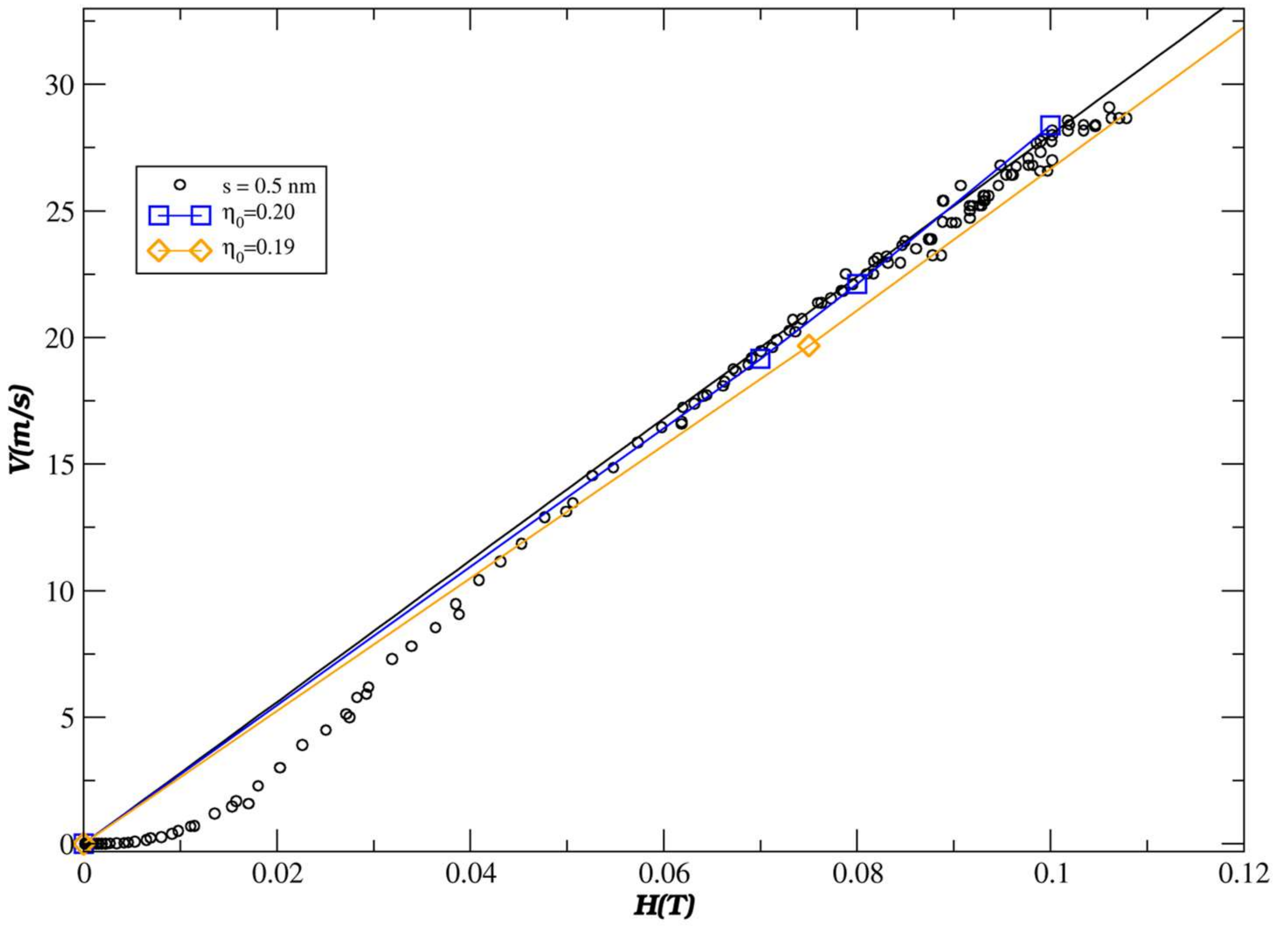


Precessional regime

amet, A. Mougin, M. Cormier, J. Ferre, V. Baltz, B. Rodmacq, B. Dieny, and R. L. Stamps. *Creep and flow regimes of Magnetic domain wall motion in ultrathin Pt/Co/Pt films with perpendicular an*

Flow regime: Ginzburg-Landau simulations and Pt/Co/Pt experiments



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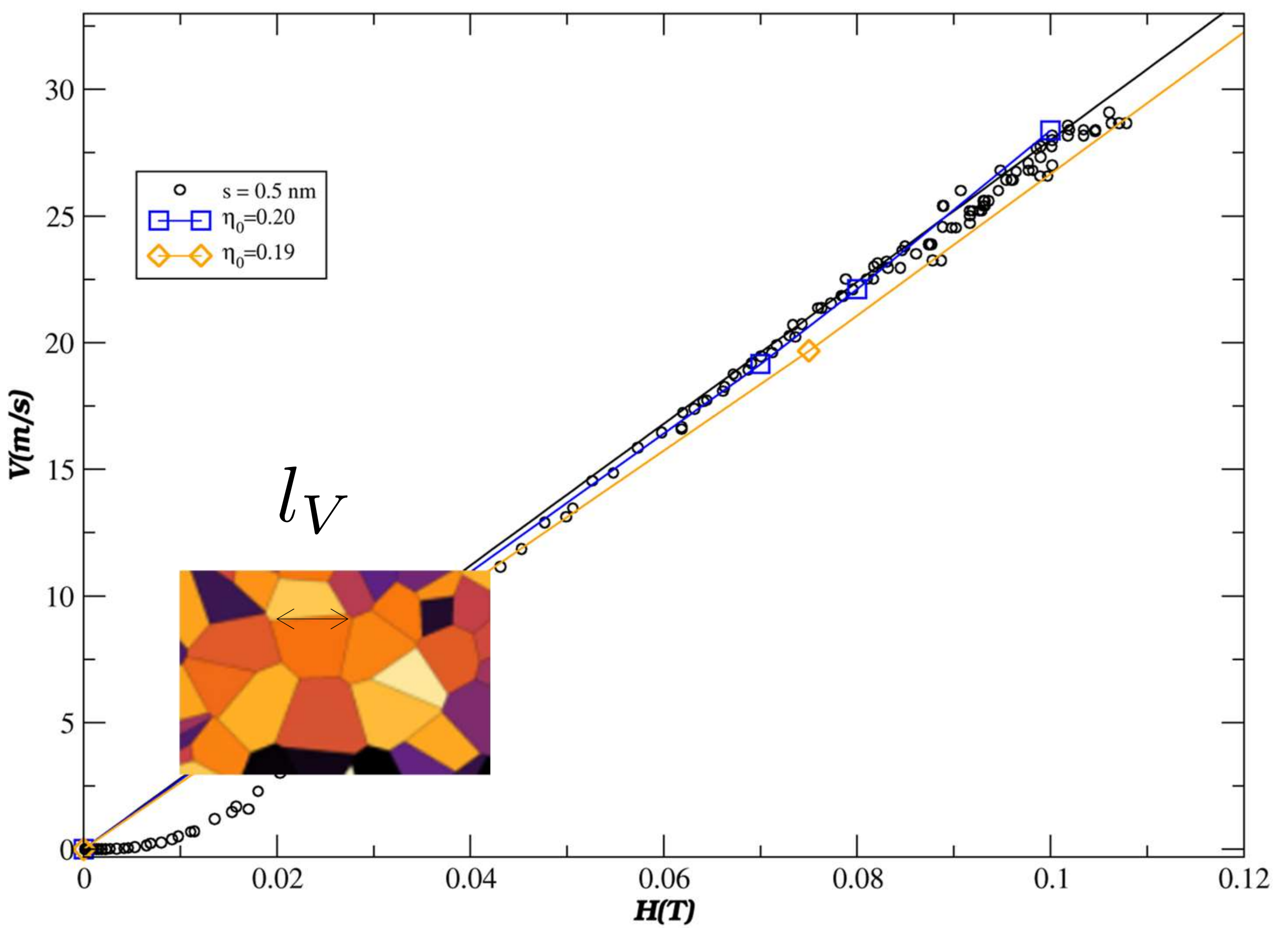
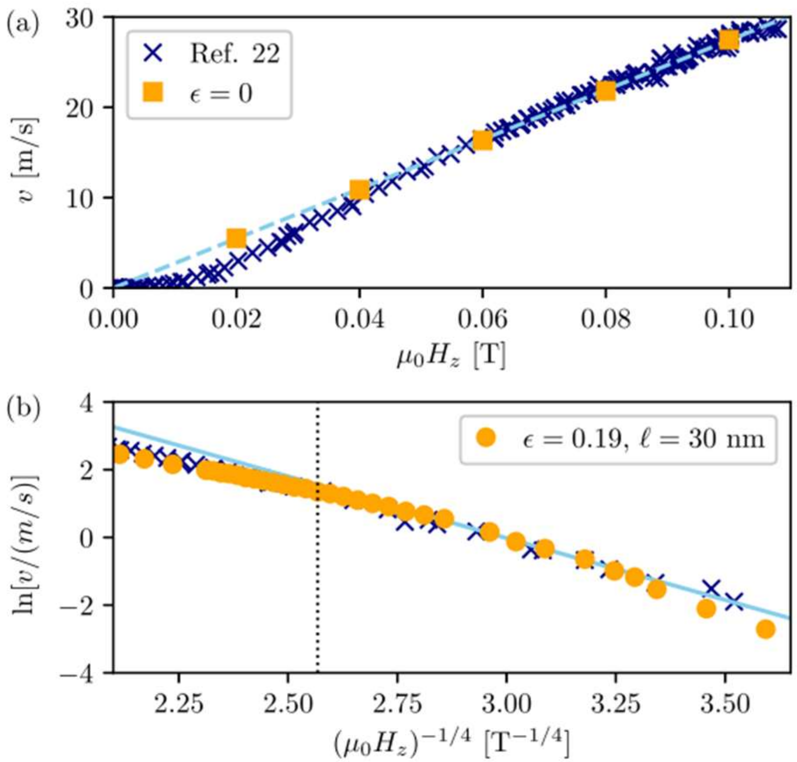
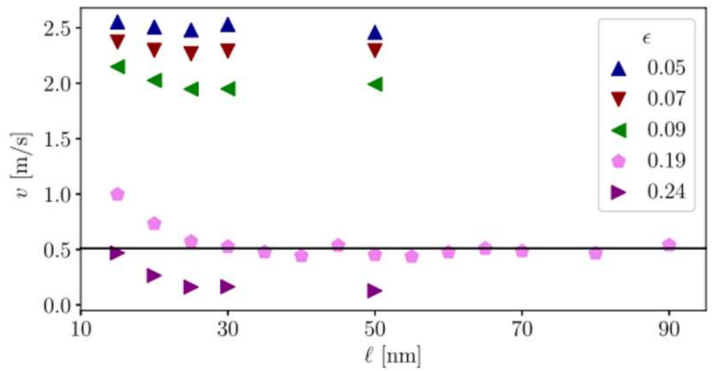
Flow regime: Ginzburg-Landau simulations and Pt/Co/Pt experiments



P.J. Metaxas, J. P. Jamet, A. Mougin, M. Cormier, J. Ferre, V. Baltz, B. Rodmacq, B. Dieny, and R. L. Stamps. PRL 2007
P. Guruciaga, NC, V. Jeudy, J. Curiale, and S. Bustingorry. JSTAT 2021

$$\boldsymbol{m}_{xy} = \sqrt{1 - m_z^2}\left[\cos\theta \frac{\nabla m_z}{|\nabla m_z|} + \sin\theta \frac{\nabla \times (m_z \hat{\mathbf{e}}_z)}{|\nabla \times (m_z \hat{\mathbf{e}}_z)|}\right]$$





P. Guruciaga, NC, V. Jeudy, J. Curiale, and S. Bustingorry. JSTAT 2021

Elastic approximation

The energy required to create an interface may be written as

$$E_{el} = \varepsilon_0 \ell.$$

where ε_0 is the energy cost of the interface per unit length.
We can approximate

$$d\ell = \sqrt{dy^2 + du^2} = dz\sqrt{1 + (\frac{du}{dy})^2}.$$

So, $E_{el} = \varepsilon_0 \int_0^L d\ell = \epsilon_0 \int_0^L dy\sqrt{1 + (\frac{du}{dy})^2}$.
If u varies smoothly with y, then $\frac{du}{dy}$ is small, and

$$E_{el} \simeq \frac{\varepsilon_0}{2} \int_0^L dy(\nabla u(y))^2.$$

Assuming an Ansatz:

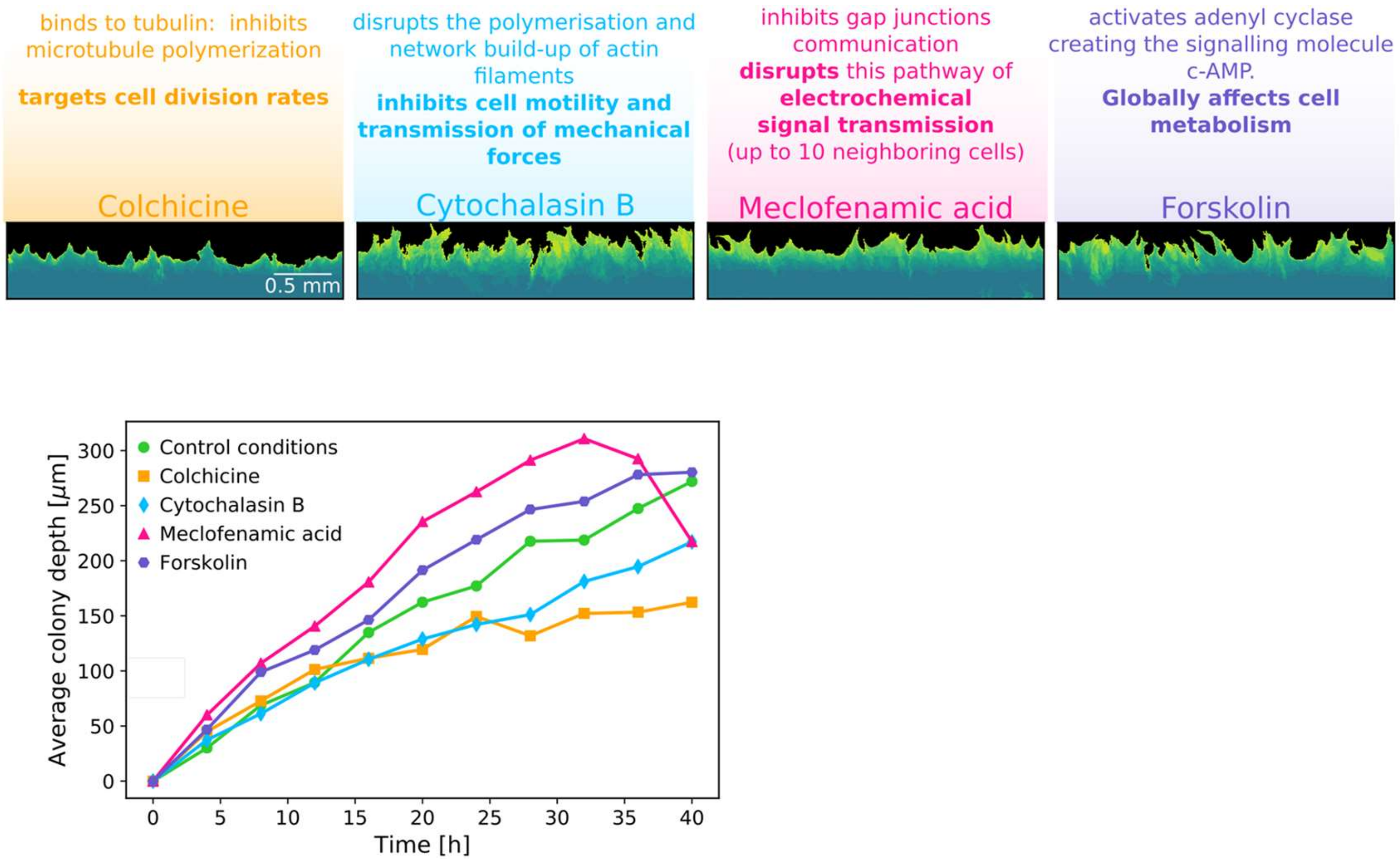
$$\varphi(x, y, t) = \varphi^*(x - u(y, t)),$$

its derivatives are given by

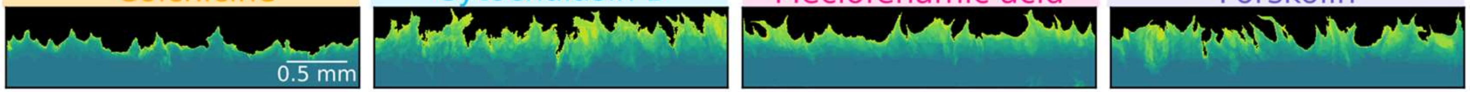
$$\partial_t \varphi^* = -{\varphi^*}' \partial_t u$$

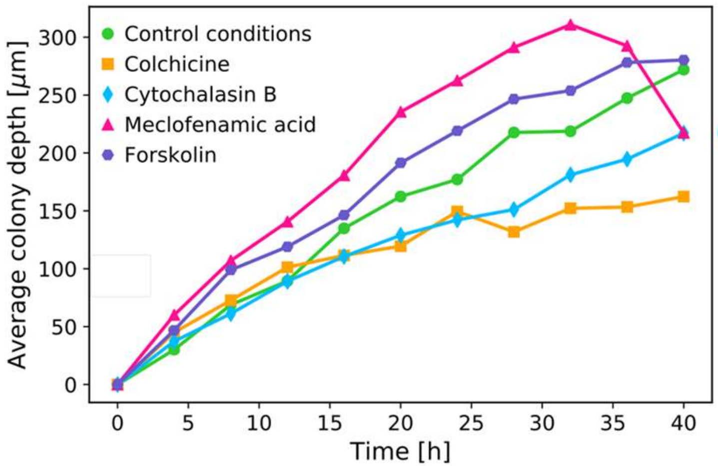
$$\partial_x \varphi^* = {\varphi^*}'; \quad \partial_x^2 \varphi^* = {\varphi^*}''$$

$$\partial_y \varphi^* = -{\varphi^*}' \partial_y u; \quad \partial_y^2 \varphi^* = {\varphi^*}'' (\partial_y u)^2 - {\varphi^*}' \partial_y^2 u.$$


binds to tubulin: inhibits microtubule polymerization
targets cell division rates
Colchicine
0.5 mm
disrupts the polymerisation and network build-up of actin filaments
inhibits cell motility and transmission of mechanical forces
Cytochalasin B
inhibits gap junctions communication
disrupts this pathway of electrochemical signal transmission
(up to 10 neighboring cells)
Meclofenamic acid
activates adenyl cyclase creating the signalling molecule c-AMP.
Globally affects cell metabolism
Forskolin
Control conditions
Colchicine
Cytochalasin B
Meclofenamic acid
Forskolin
Average colony depth [μm]
Time [h]
0
50
100
150
200
250
300
0
5
10
15
20
25
30
35
40

binds to tubulin: inhibits microtubule polymerization **targets cell division rates**	disrupts the polymerisation and network build-up of actin filaments **inhibits cell motility and transmission of mechanical forces**	inhibits gap junctions communication **disrupts** this pathway of **electrochemical signal transmission** (up to 10 neighboring cells)	activates adenyl cyclase creating the signalling molecule c-AMP. **Globally affects cell metabolism**
Colchicine	Cytochalasin B	Meclofenamic acid	Forskolin





Cytochalasin B

Colchicine

decrease front velocity

binds to tubulin: inhibits microtubule polymerization

targets cell division rates

Colchicine

disrupts the polymerisation and network build-up of actin filaments

inhibits cell motility and transmission of mechanical forces

Cytochalasin B

inhibits gap junctions communication

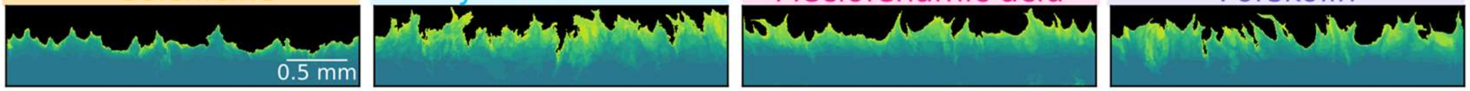
disrupts this pathway of **electrochemical signal transmission** (up to 10 neighboring cells)

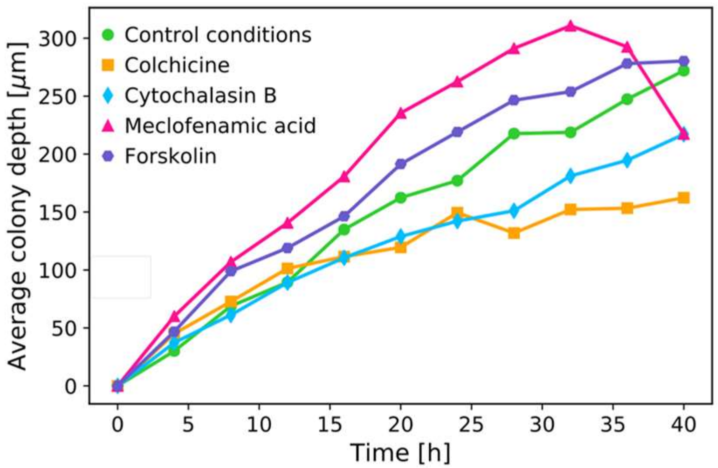
Meclofenamic acid

activates adenyl cyclase creating the signalling molecule c-AMP.

Globally affects cell metabolism

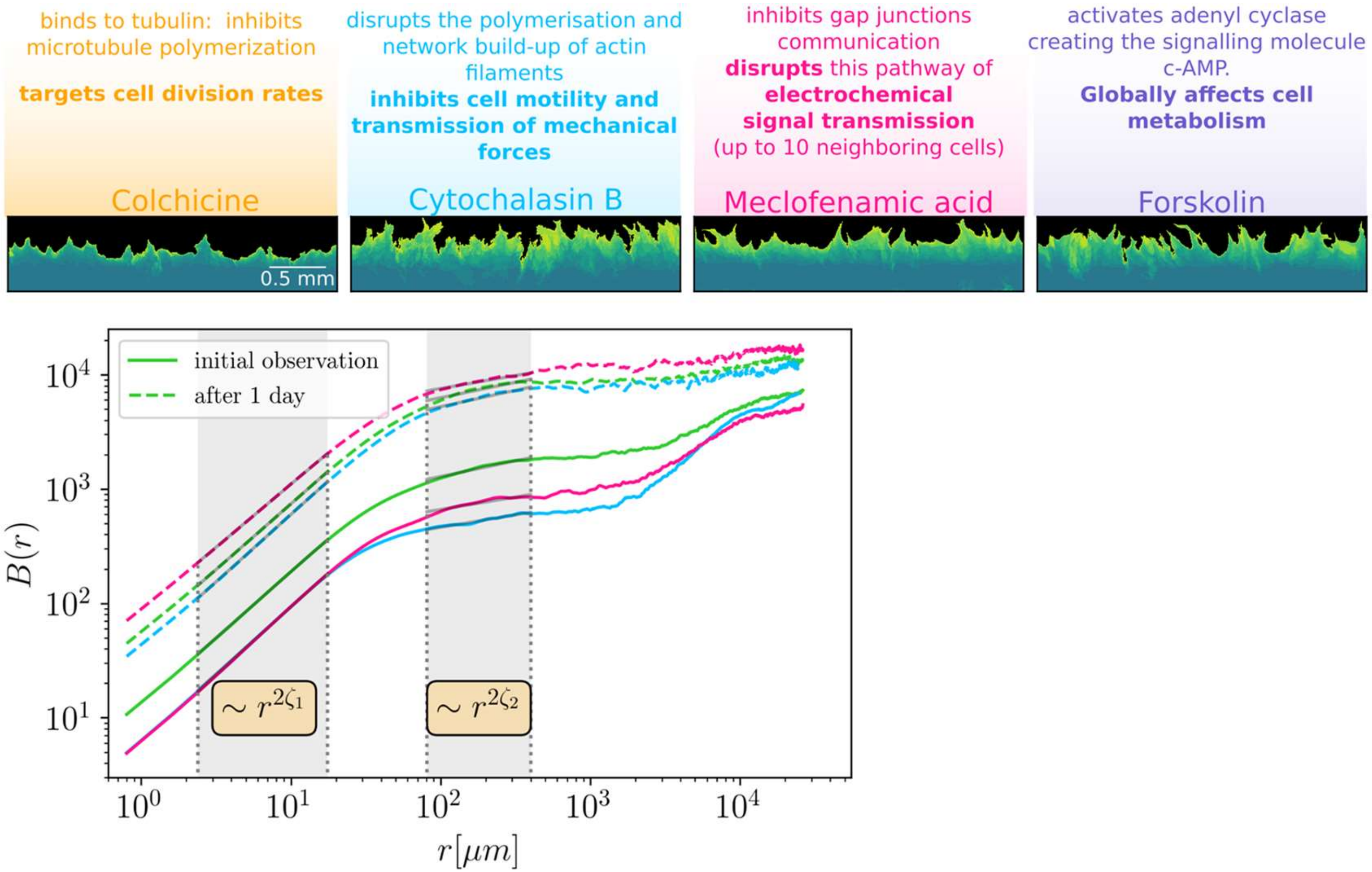
Forskolin





Meclofenamic acid
Forskolin

increase front velocity



binds to tubulin: inhibits microtubule polymerization
targets cell division rates
Colchicine
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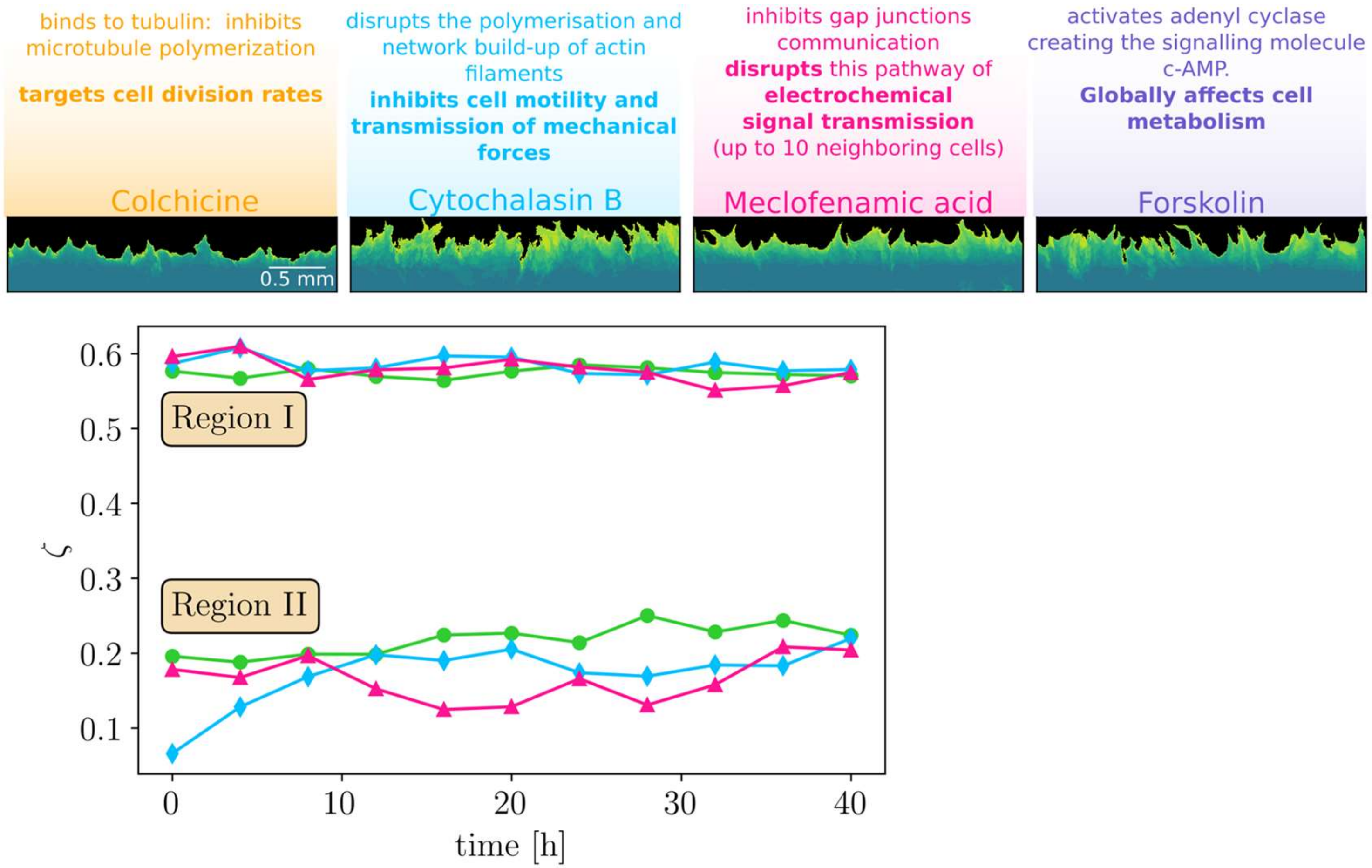
inhibits cell motility and transmission of mechanical forces
Cytochalasin B
inhibits gap junctions communication
disrupts this pathway of electrochemical signal transmission
(up to 10 neighboring cells)
Meclofenamic acid
activates adenyl cyclase creating the signalling molecule c-AMP.
Globally affects cell metabolism
Forskolin
0.5 mm
initial observation
after 1 day
$\sim r^{2\zeta_1}$
$\sim r^{2\zeta_2}$
$B(r)$
$r[\mu m]$



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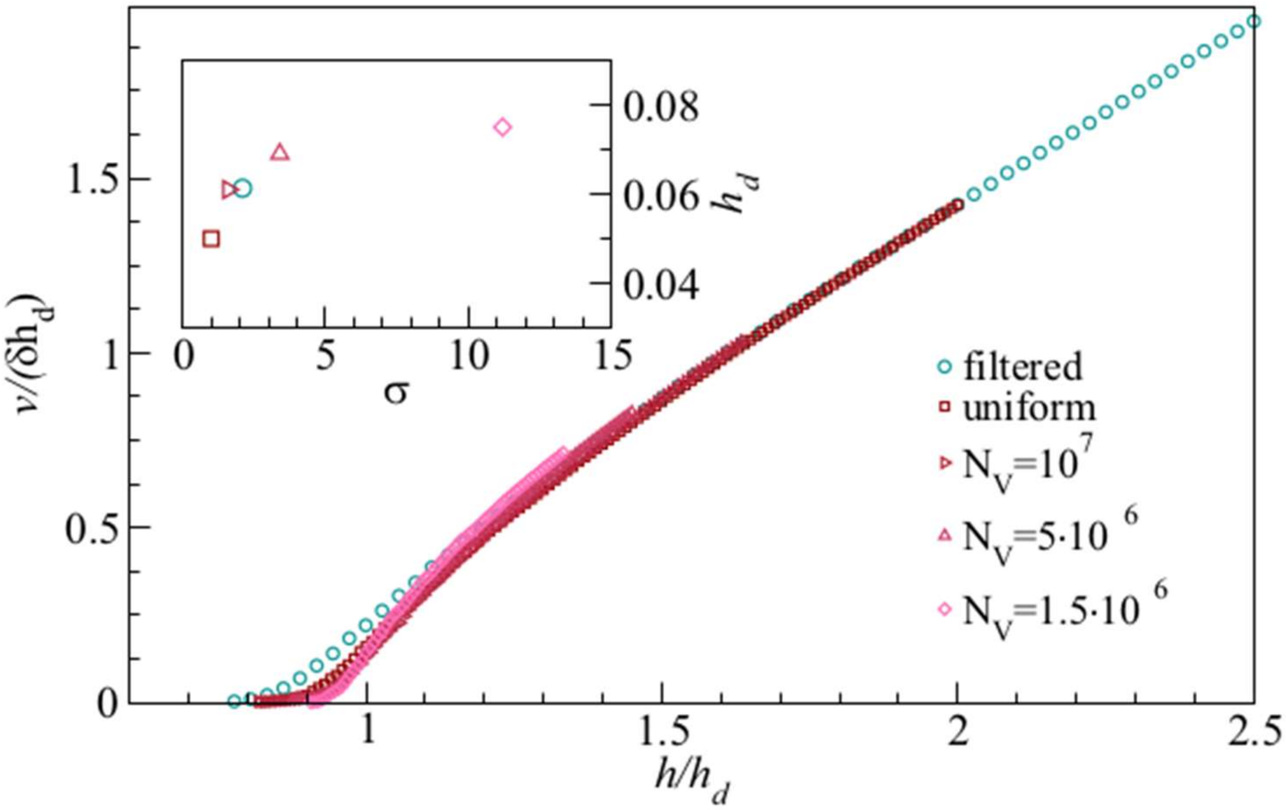
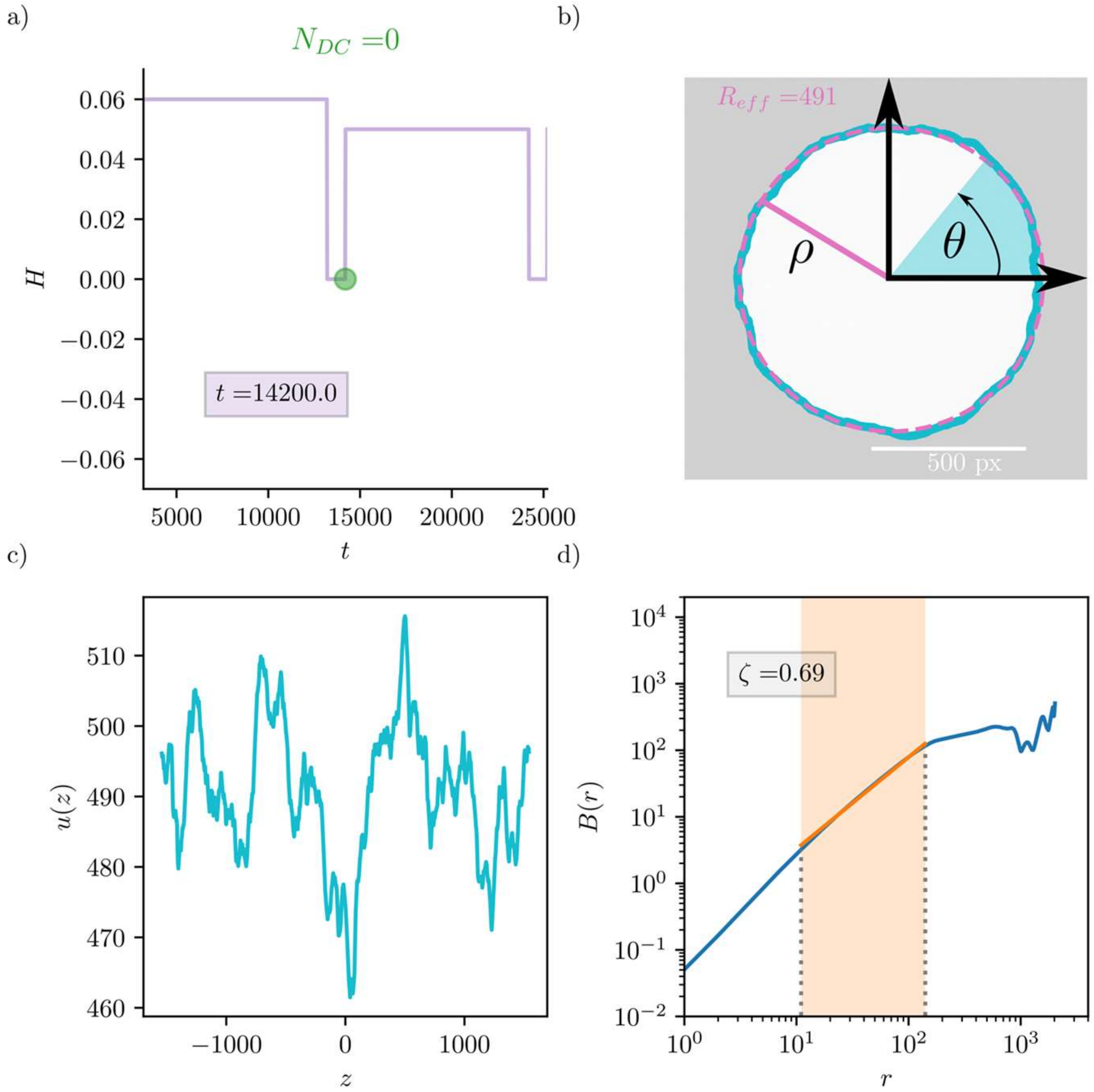
Globally affects cell metabolism
Forskolin
0.5 mm
Region I
Region II
ζ
time [h]

Ginzburg-Landau approach

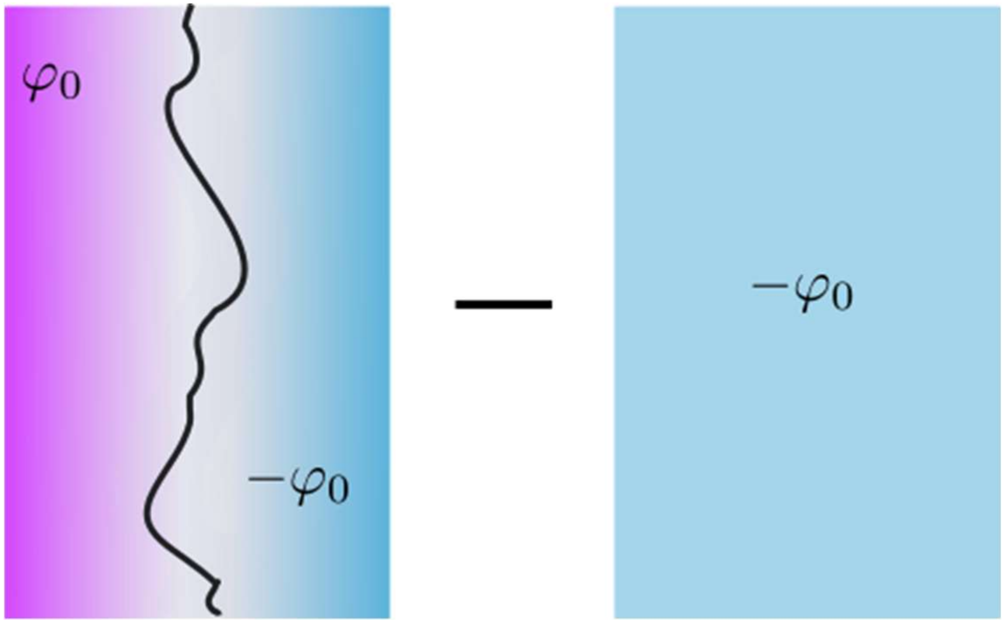


NC, E. E. Ferrero, A. B. Kolton, J. Curiale, V. Jeudy, S. Bustingorry, *Magnetic domain wall creep and depinning: A scalar field model approach*. PRE (2018)


a)
N_{DC} =0
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
H
t =14200.0
5000
10000
15000
20000
25000
t
b)
R_{eff} =491
ρ
θ
500 px
c)
510
500
490
480
470
460
$u(z)$
−1000
0
1000
z
d)
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
$B(r)$
ζ =0.69
10^0
10^1
10^2
10^3
r

With our method we find

$$c = \frac{2\sqrt{2}}{3}\frac{\alpha}{\delta}\sqrt{\alpha\gamma}$$



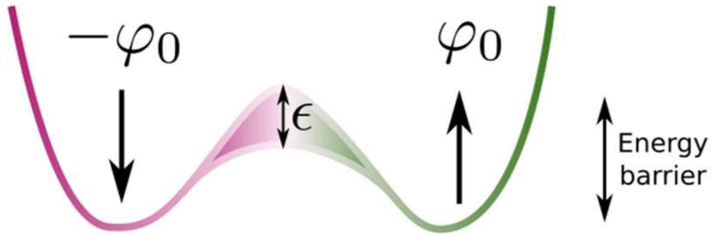
Which is the same relation that one finds by computing the energy cost of creating a domain wall in th

Ginzburg-Landau

State: φ

disorder

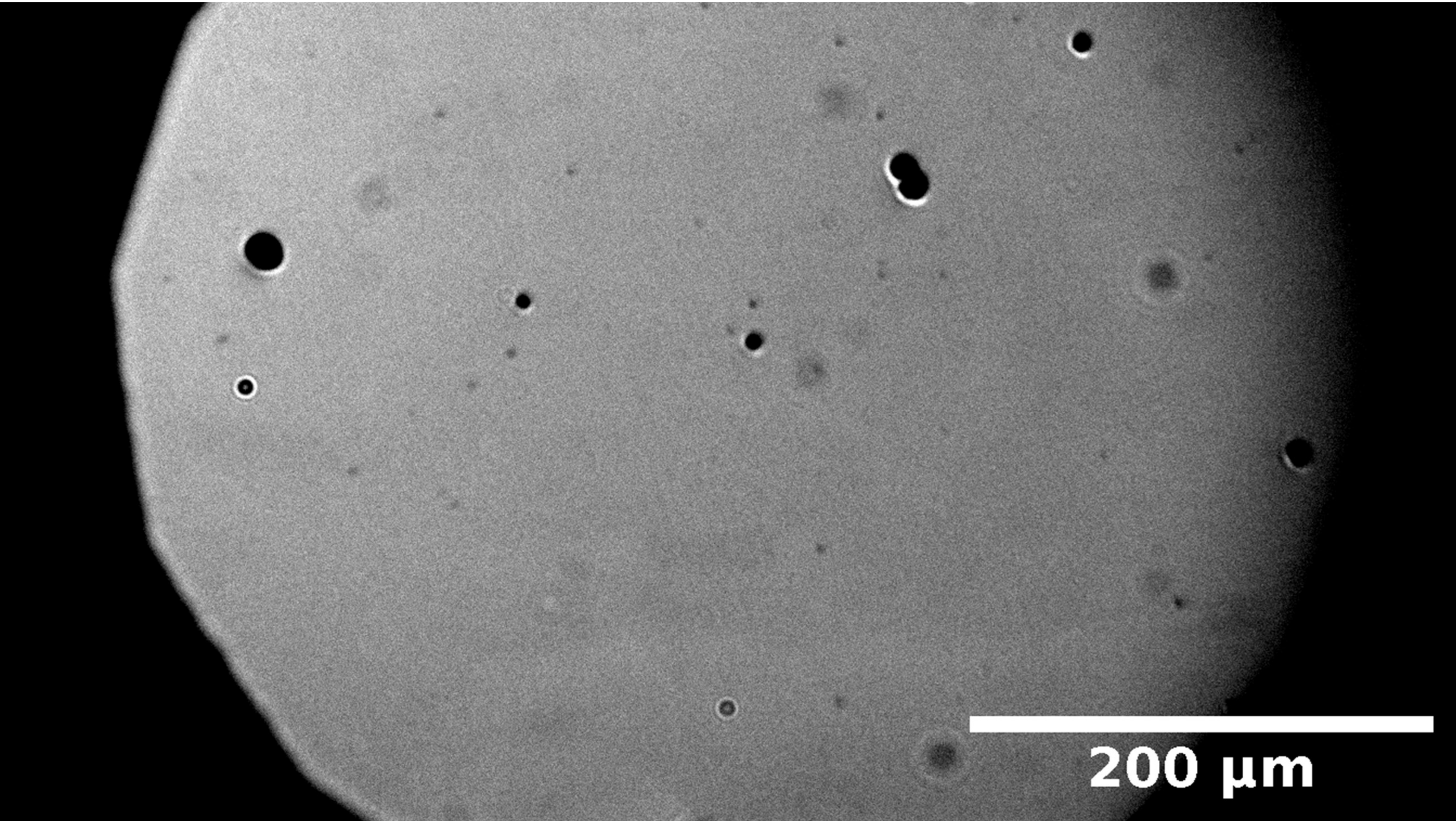
$$\eta\partial_t\varphi = \gamma\nabla^2\varphi - (1+\epsilon\zeta(\vec{r}))V'(\varphi) + h + \xi(\vec{r},t)$$

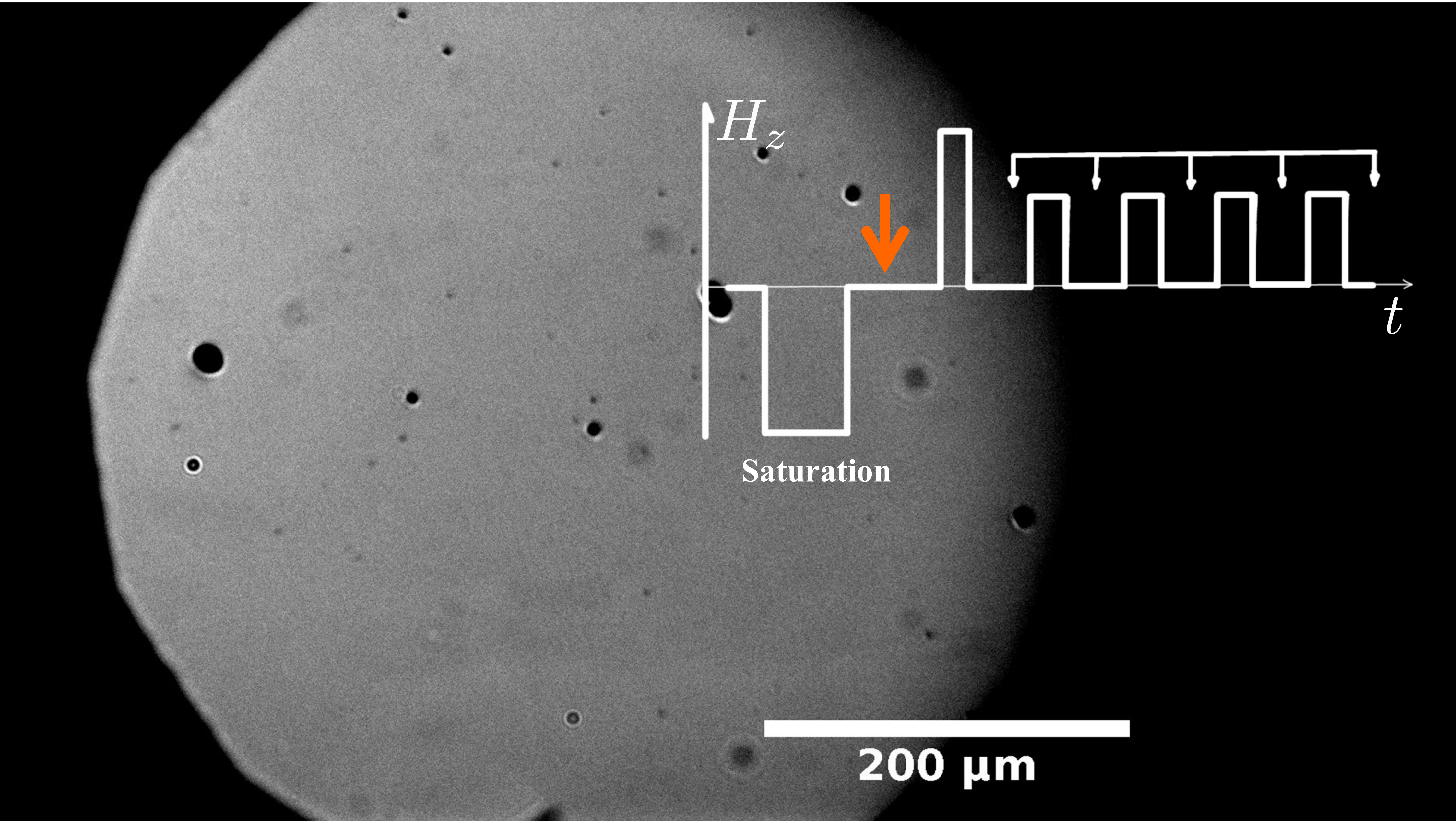


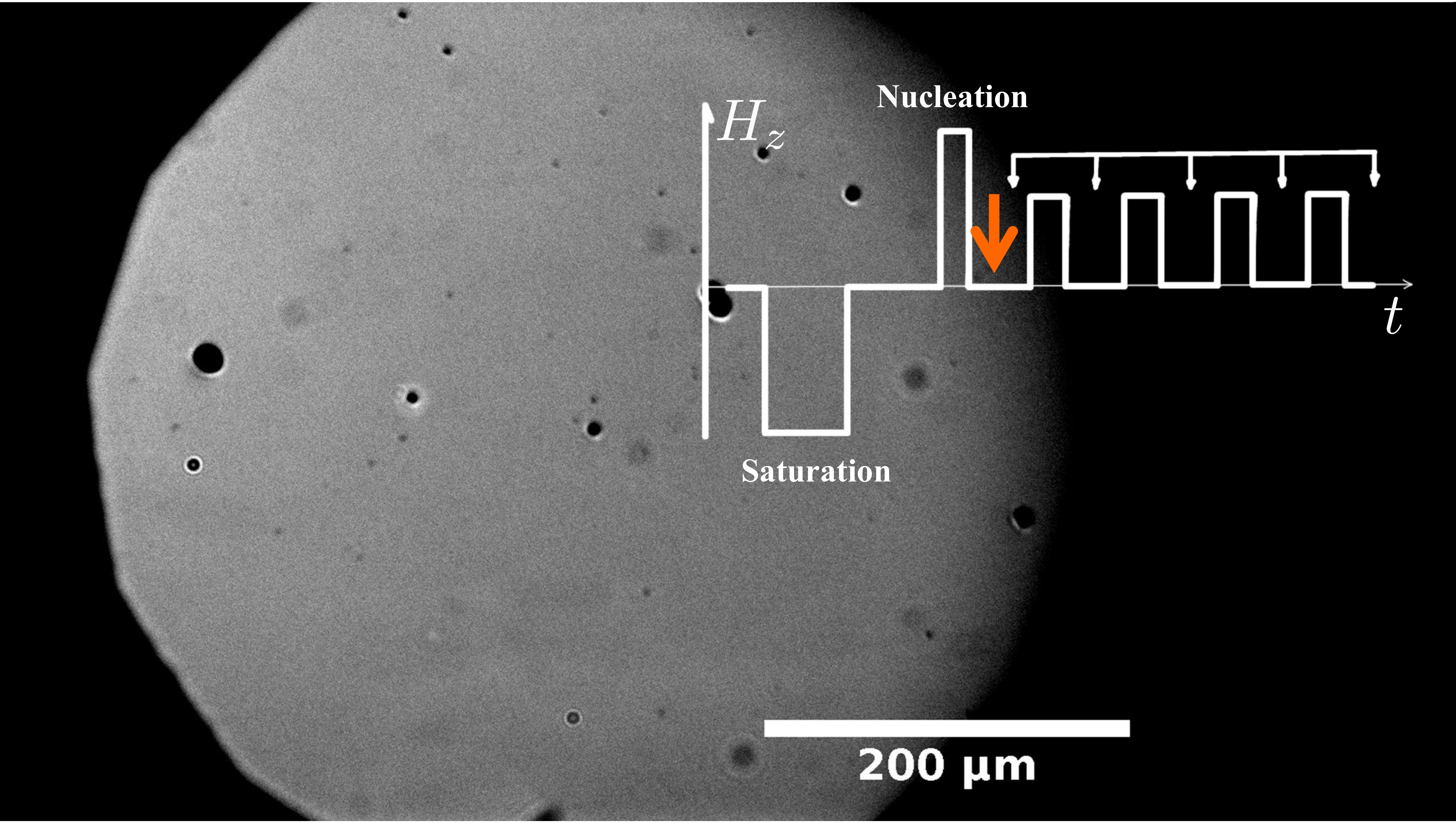
We use an ansatz

$$\varphi(x,y,t) = \varphi^*(x-u(y,t))$$

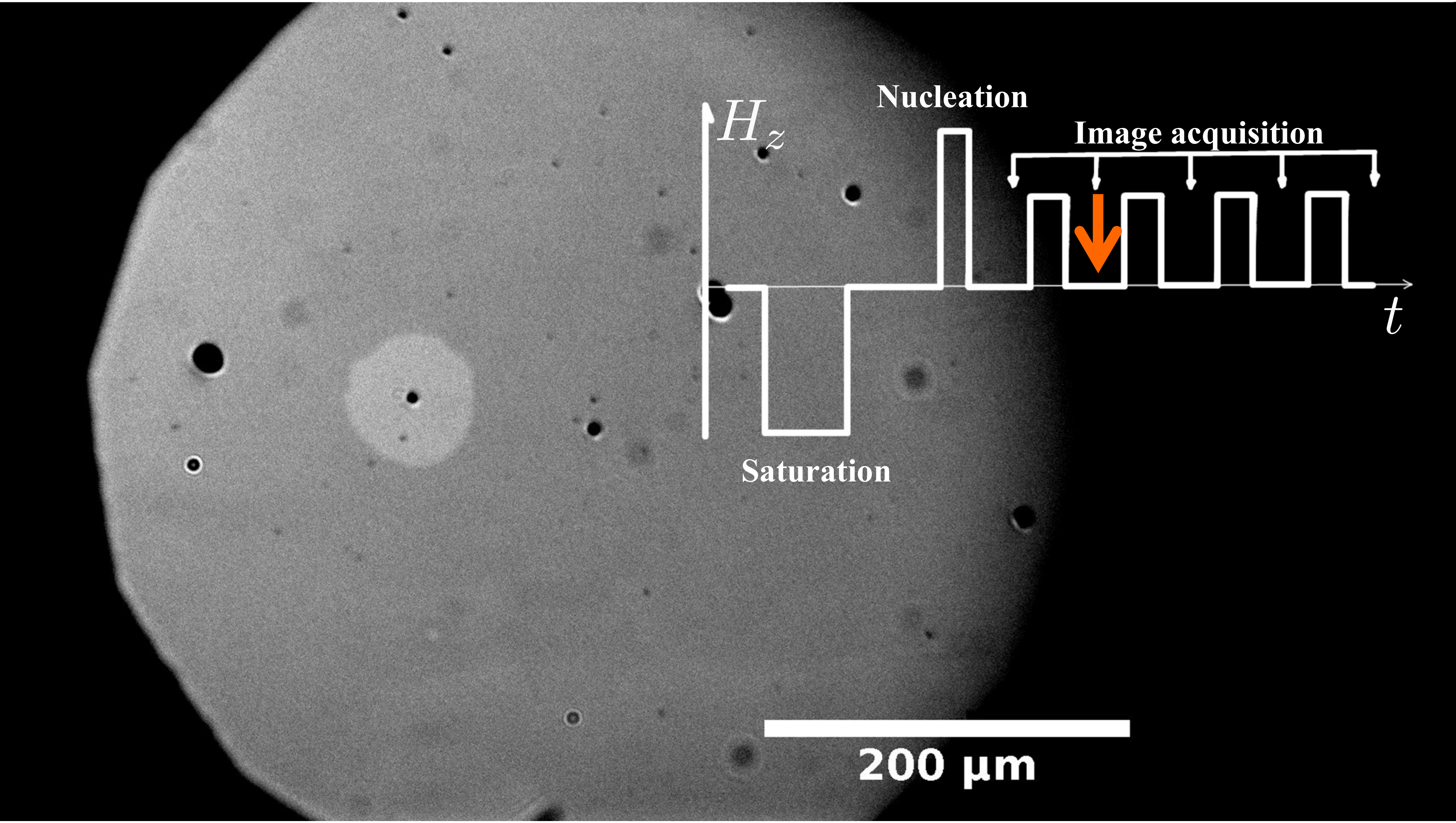
$$-\eta{\varphi^*}'\partial_t u \;=\; \gamma\Big({\varphi^*}'' + {\varphi^*}''(\partial_y u)^2 - {\varphi^*}'\partial_y^2 u\Big) - V'(\varphi^*) - \varepsilon\zeta(x,y)V'(\varphi^*) + \xi(x,y,t)$$


200 µm

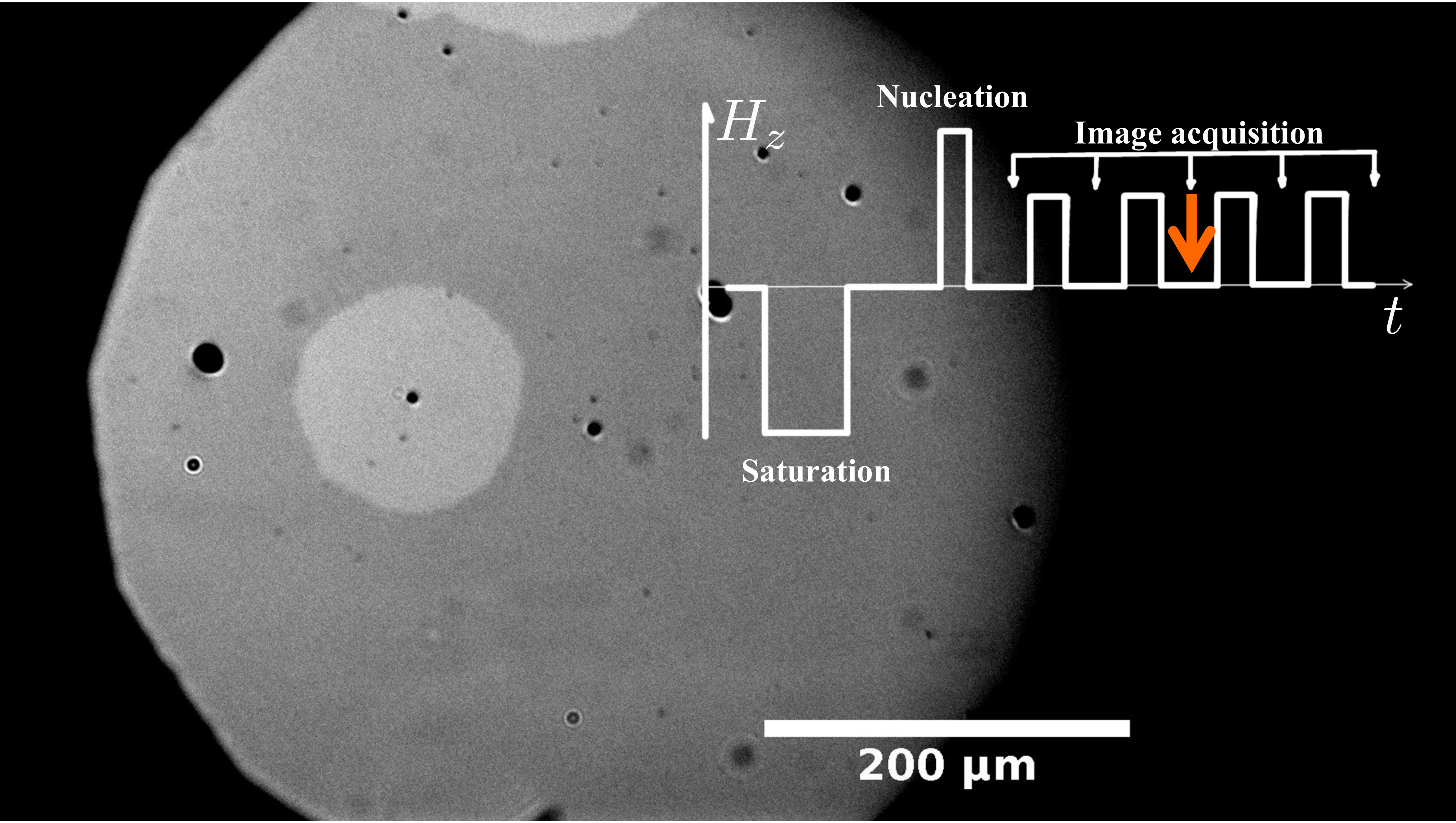

H_z
t
Saturation
200 μm



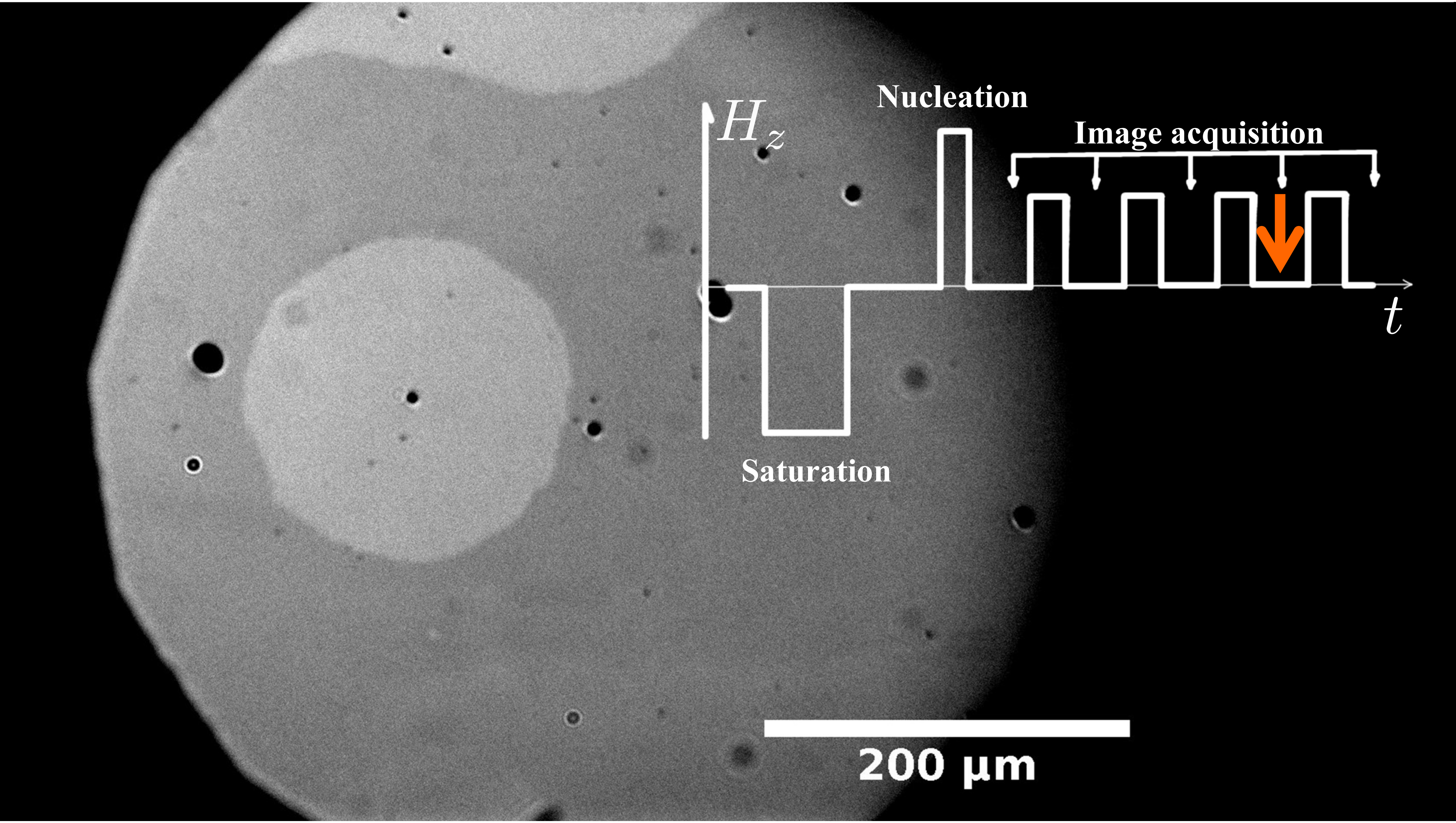
Nucleation
H_z
t
Saturation
200 µm



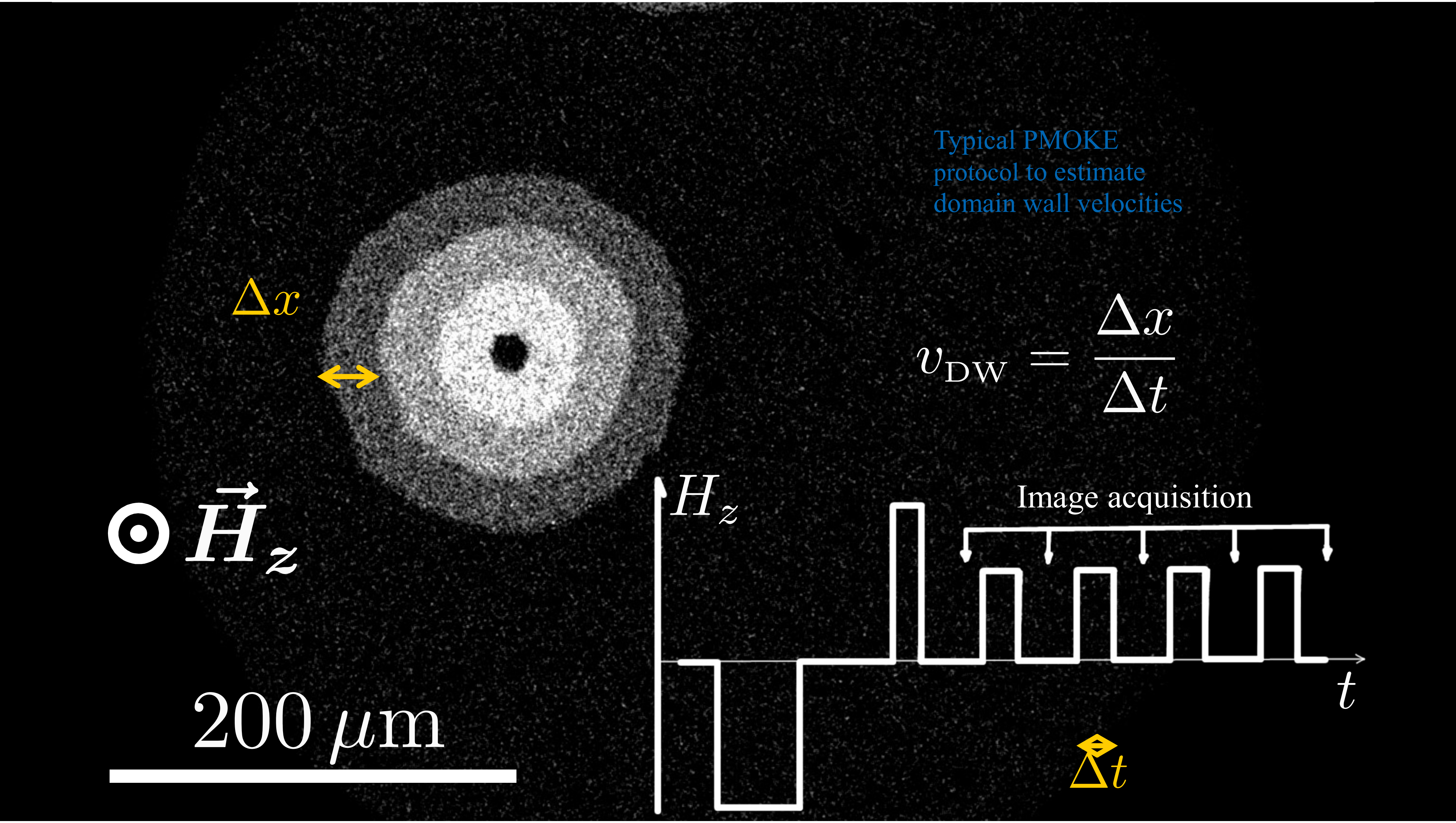
Nucleation
H_z
Image acquisition
t
Saturation
200 µm



Nucleation
Image acquisition
H_z
t
Saturation
200 µm



Nucleation
H_z
Image acquisition
t
Saturation
200 µm


Typical PMOKE
protocol to estimate
domain wall velocities
Δx
$v_{\mathrm{DW}} = \frac{\Delta x}{\Delta t}$
$\vec{H}_z$
200 μm
H_z
Image acquisition
t
Δt

temperature

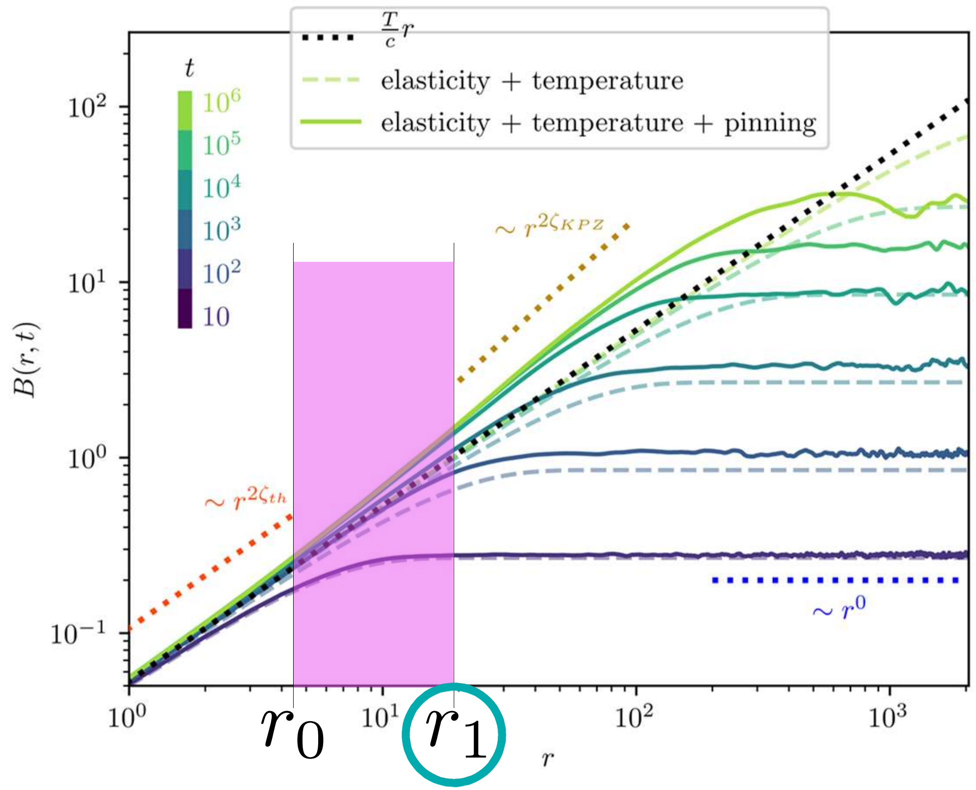
$$\zeta_{th} = \frac{1}{2}$$

disorder

$$\zeta_{RB} = \frac{2}{3}$$

interplay

$$\zeta_{dis} \sim 0.9$$



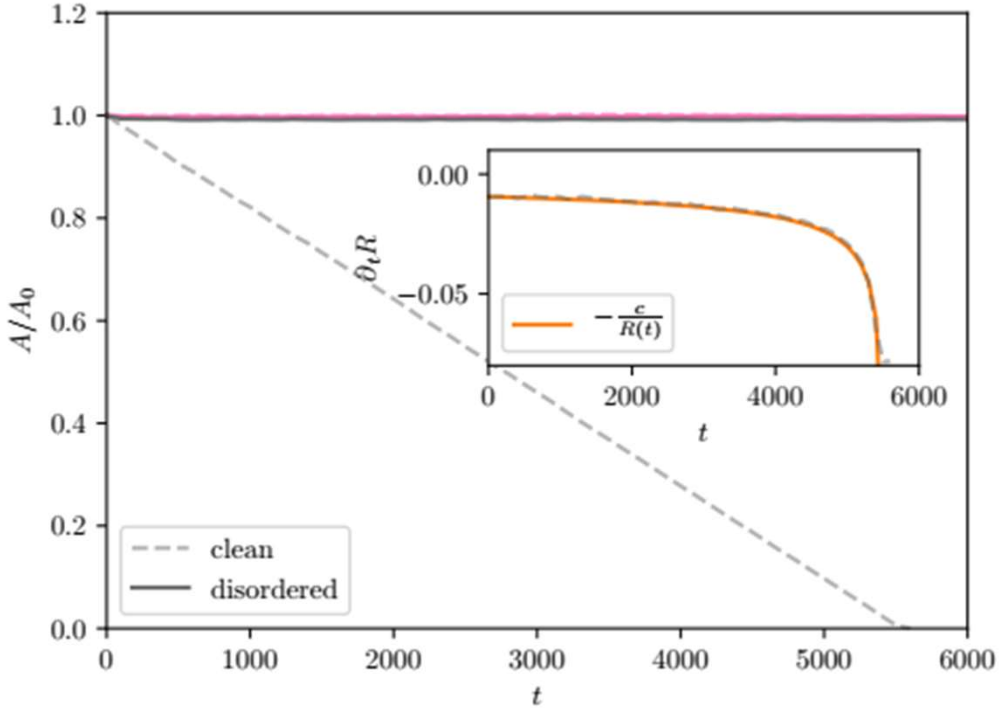
depends on the disorder correlation

With AC cycles the disorde

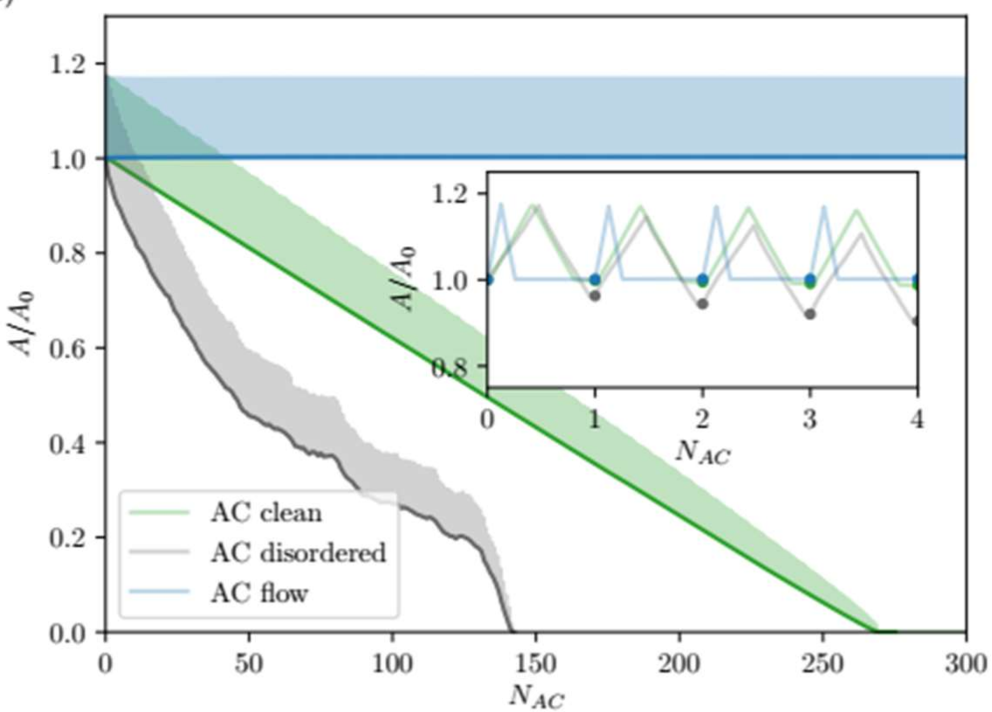
The area is lost due to local curvatures that induce a force:
the effective field felt by the interface is

$$\sim H_0 - \frac{c}{R(t)}$$

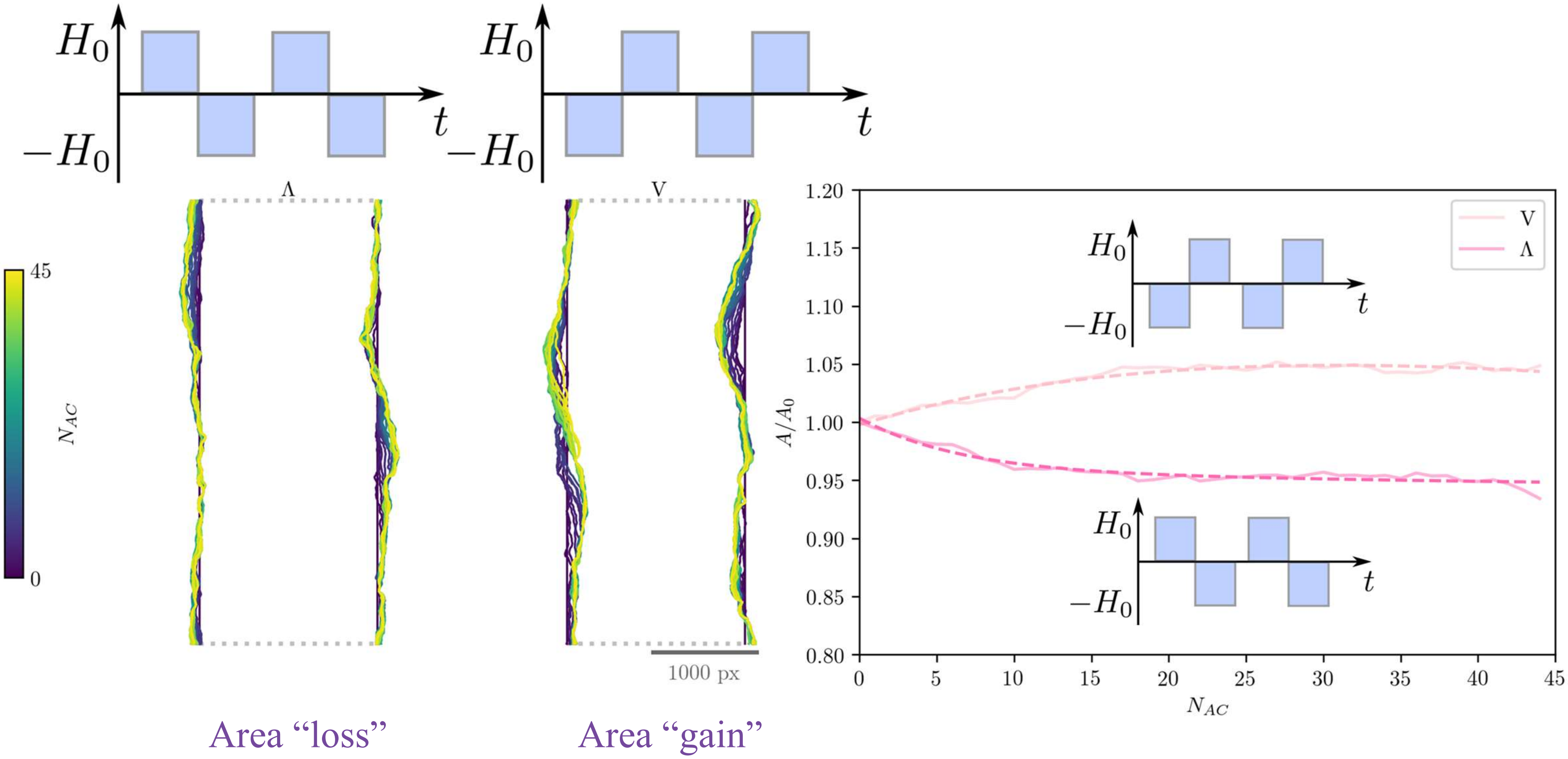
a)

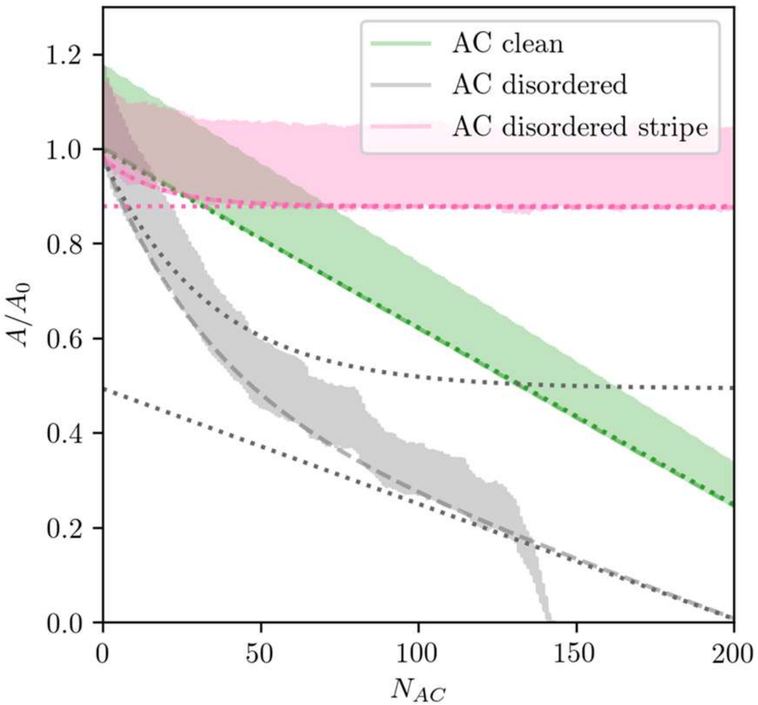


b)

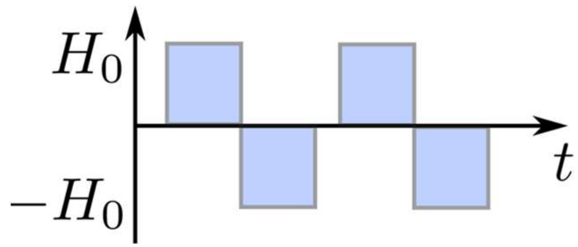


But that is not all...





AC clean
AC disordered
AC disordered stripe
1.2
1.0
0.8
0.6
0.4
0.2
0.0
A/A_0
0
50
100
150
200
N_{AC}



When domains are subjected to AC dynamics:
the disorder correlation length is changed (compared to the DC case)

This explains:

- the change in the observed exponent $\zeta_{DC} \rightarrow \zeta_{AC}$

- the non linear part of the area loss