"Interface fluctuations and KPZ universality class – unifying mathematical, theoretical, and experimental approaches"

KPZ Universality and Anomalous Scaling in the Growth of CdTe Thin films

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ゆらぎと構造の協奏
Synergy of Fluctuation and Structure

CNPq Conselho Nacional de Desenvolvimento Científico e Tecnológico
CAPES

FAPEMIG
Fundação de Amparo à Pesquisa do Estado de Minas Gerais

Universidade Federal de Viçosa, Mg, Brazil

Outline

- Why are two-dimensional KPZ experimental confirmations rare?

- The first robust 2D-KPZ growth found: CdTe films grown on Si(001) in "MBE environment" at 250°C. What can be learned from it?

- Changing the deposition temperature in this 2D-KPZ system: "Anomalous-to-Normal Scaling", Inversion in the λ's signal, crossover effects and so forth.

- Conclusions and Perspectives.

2D-KPZ Growth: Why are they experimentally rare?

- Inexorable experimental obstacles: Difficult to image 2D-growth, poor statistics, finite-time growth, etc.

- Specific obstacles depending on what system is considered:

* Morphological instabilities → *Below* ζ, there is no *critical* situation. It breaks the scaling invariance.

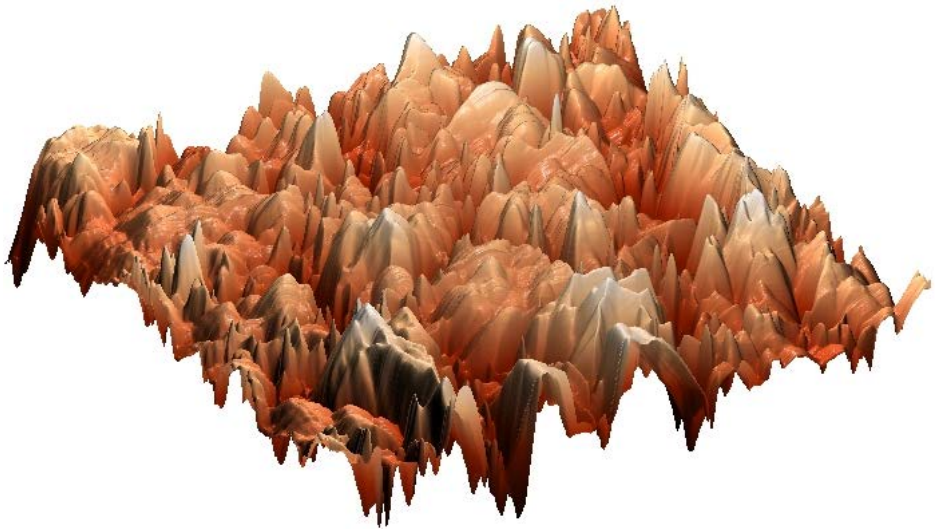
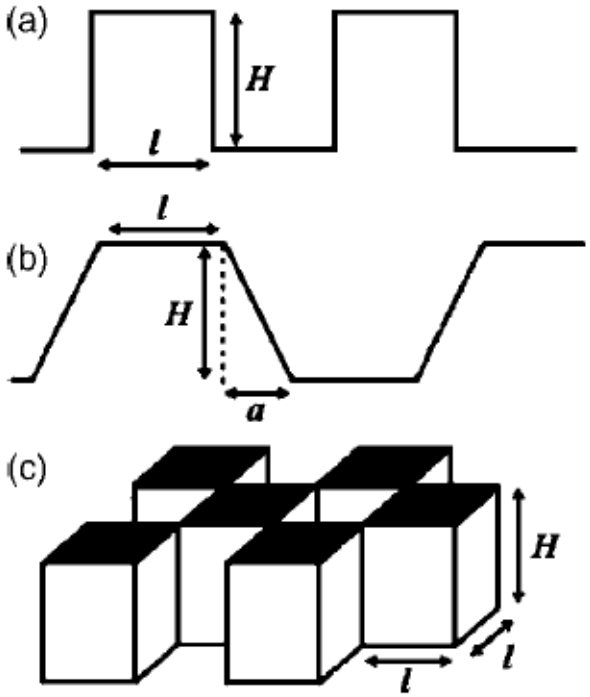


Fig. *Example of a surface containing morph. inst. AFM image for a CdTe film grown on Si(001) by HWE, at T = 300°C*

Morphological instabilities at the surface

Unfortunately, below ζ , local roughness, and HHCF, also behave as a power-law...

Idealized models → For surfaces (a)-(c), one has: $W_{loc} \sim R$



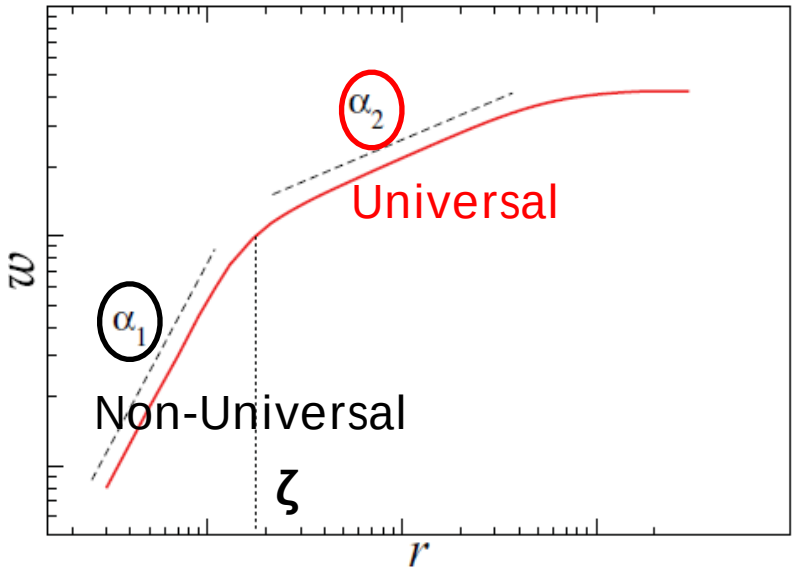
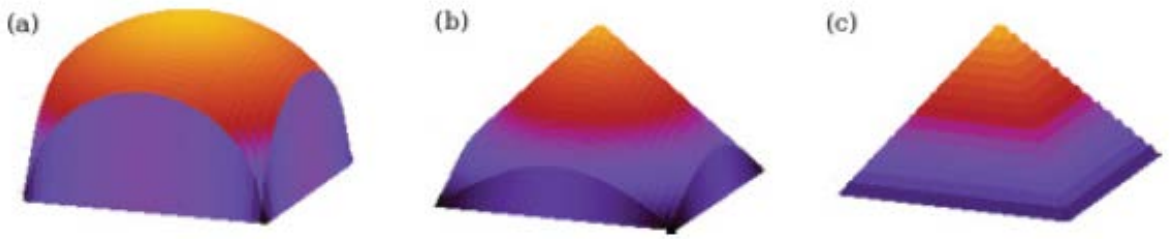


Fig. *Typical local roughness (log x log) plot for surfaces presenting a characteristic length ζ, beyond ξ and L.*

T. J. **Oliveira** and F. D. A. A. **Reis**, J. Appl. Phys. **101**, 063507 (2007).; Phys. Rev. E **83**, 041608 (2011).

Morphological instabilities at the surface

Geometric effect of the grain shape on the local scaling.



$\alpha_1 \approx 1.00$

$\alpha_1 \approx 0.6$

As flatter is the grain peak

α_2 is kept constant, with your Universal value.

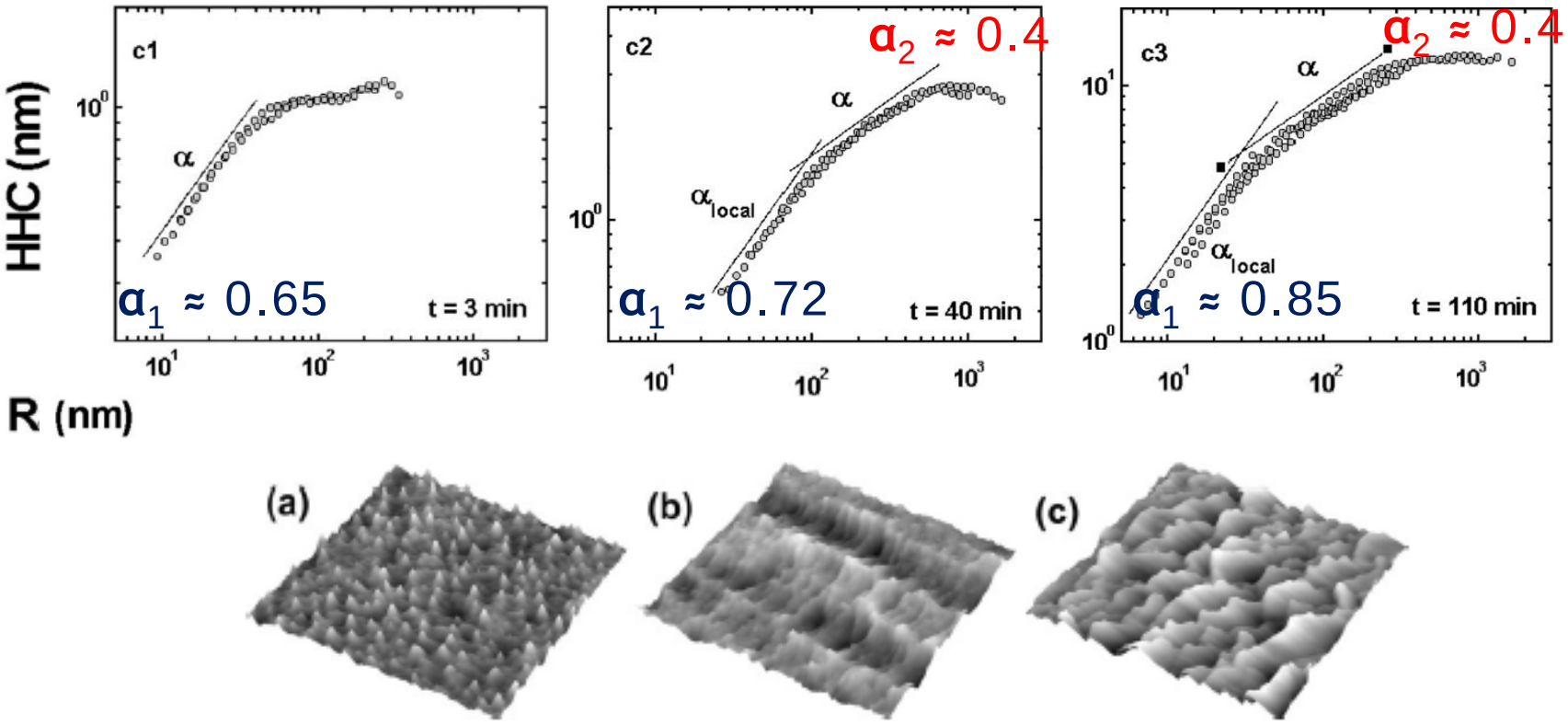
T. J. **Oliveira** and, F. D. A. A. **Reis**, Phys. Rev. E **83**, 041608 (2011).

Morphological instabilities at the surface

Experimental evidences (2D KPZ?)

Likely to be a 2D KPZ growth!

Si(111) echting by NaOH



M. E. R. Dotto and, M. U. Kleinke, Phys. Rev. B **65**, 245323 (2002).

2D-KPZ Growth: Why are they experimentally rare?

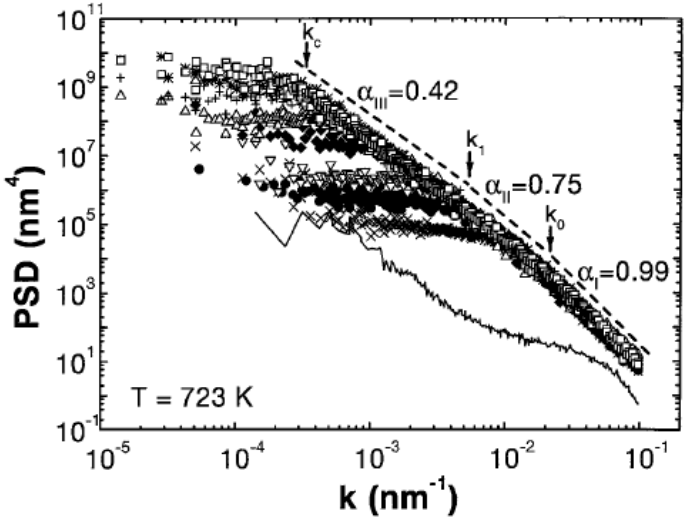
- Specific obstacles depending on what system is considered:

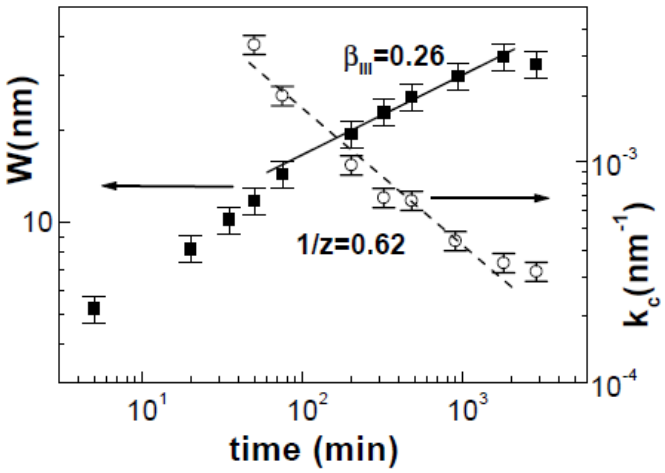
- Morphological instabilities
- Transient Anomalous Scaling (as we shall see)

* Temporal Crossovers
- Non-locality

Dimensional fragility of KPZ equation
M. Nicoli *et al., J. of Stat. Mech.* **1**, 11001 (2013).

SiO_2 grown on Si(001) by CVD





Again, α_2 just was noted after long times, where $\xi >> \zeta$.

Presents temporal crossover

F. Ojeda *et al.*,Phys. Rev. Lett. **84**, 3125 (2000).

2D-KPZ Growth: are they really rare?

List of other 2D experimental systems which, possibly, belong to the KPZ class:

1 - J. Chevrier *et al.*, EPL **16**, 737 (1991). **Fe/Si(111) by MBE**

2 - E. A. Eklund *et al.,* PRL **67**, 1759 (1991). **Sputter echting on graphite**

3 - M. U. Kleinke *et al.*, Appl. Phys. Lett **74**, 1683 (1999). **Annealed LiCoOx films**

4 - A. E. Lita *et al.,* Phys. Rev. B **61**, 7692 (2000). **Sputter-deposited polycristalline Al films**

5 - M. E. R. Dotto and, M. U. Kleinke, Phys. Rev. B **65**, 245323 (2002). **Ecthing on Si**

6 - S. O. Ferreira *et al.*, Appl. Phys. Lett. **88**, 244102 (2006). **CdTe grown on glass by HWE**

and the list goes further ...

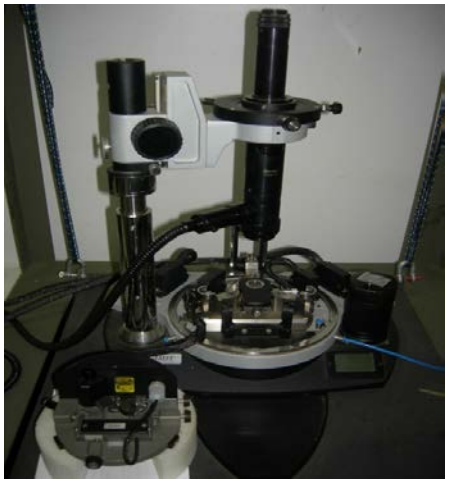
The First Robust Experimental Confirmation of 2D-KPZ Growth

R. A. L. Almeida, S. O. Ferreira, T. J. Oliveira, F. D. A. A. Reis, Phys. Rev. B. 89, 045309 (2014)

HWE system

$\Phi \approx 2.2$ Å/s T = 250°C

Growth times: 15, 30... 240 min.



AFM NT-MDT NTegra Prima

Contact mode

Images size: 1, 10 and 100 μm^2

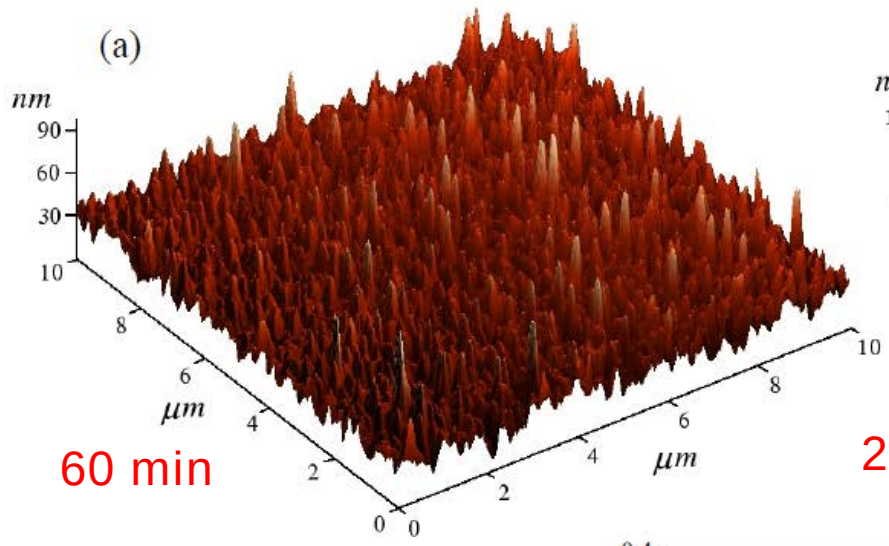
Resolution: 1024 x 1024 pixel

N. of scanned regions : 3 - 10

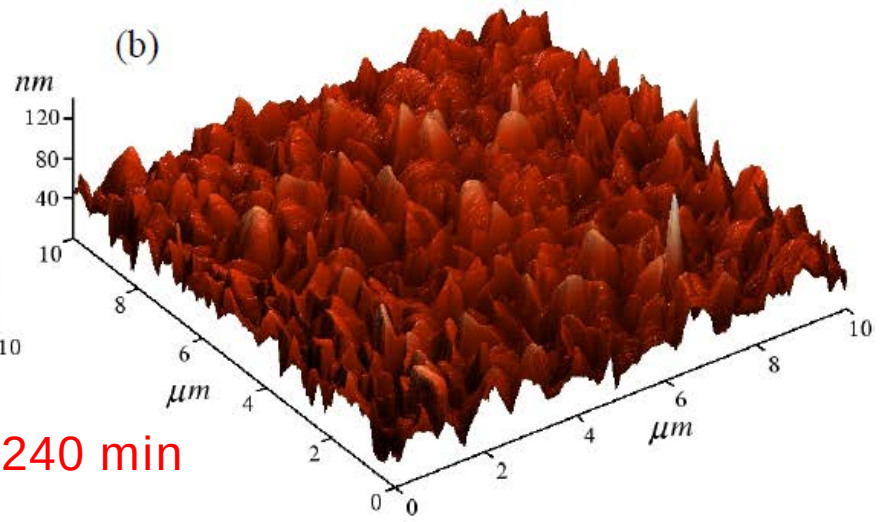
The First Robust Experimental Confirmation of 2D-KPZ Growth

R. A. L. Almeida, S. O. Ferreira, T. J. Oliveira, F. D. A. A. Reis, Phys. Rev. B. 89, 045309 (2014)

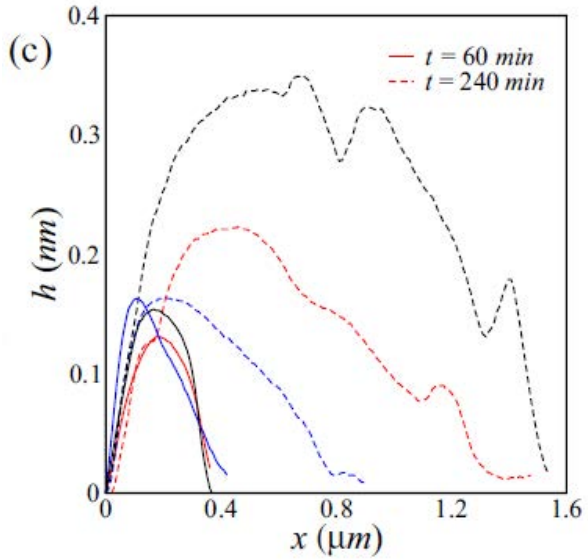
250 °C



60 min



240 min



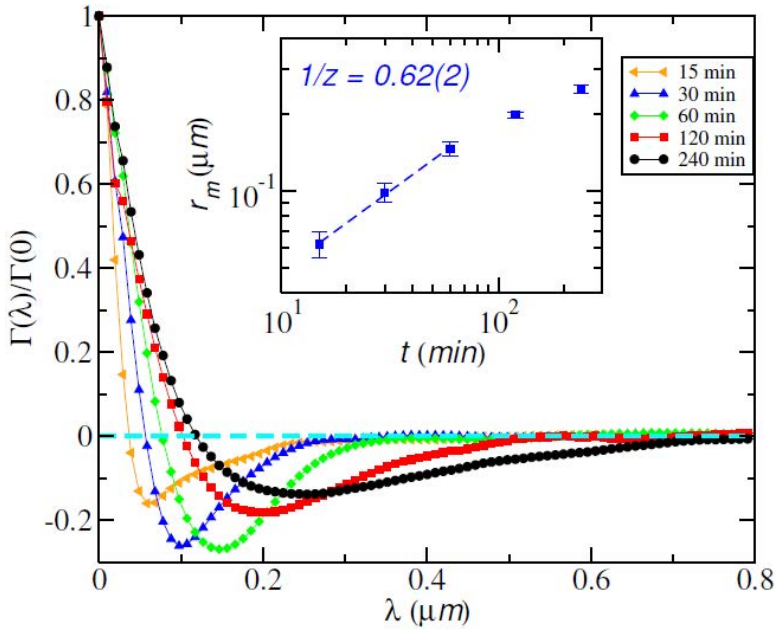
The First Robust Experimental Confirmation of 2D-KPZ Growth

R. A. L. Almeida, S. O. Ferreira, T. J. Oliveira, F. D. A. A. Reis, Phys. Rev. B. 89, 045309 (2014)

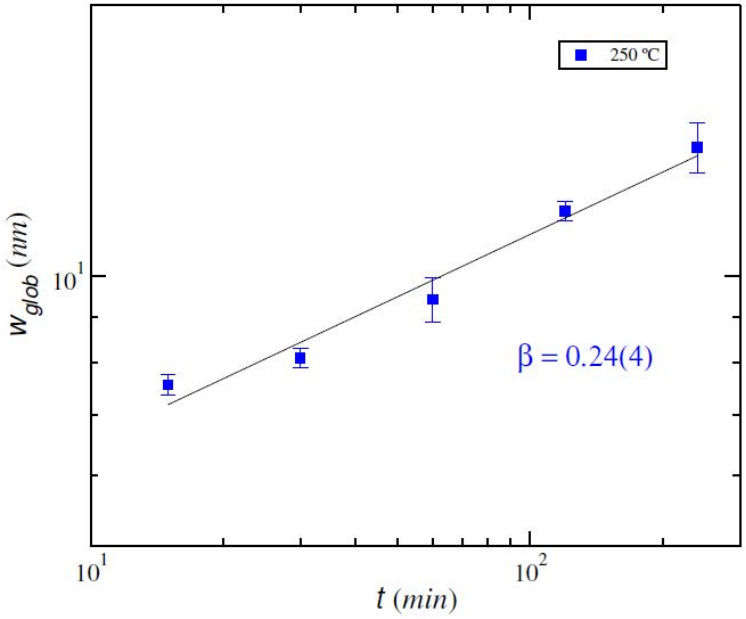
- Grains and coalescence processes modify the local scaling and, hence, the analysis of local quantities which must be made carefully.

Slope-Slope corr. function

$$\Gamma(\lambda,t) = \langle[\nabla h(\mathbf{x},t)\nabla h(\mathbf{x}+\boldsymbol{\lambda},t)]\rangle$$



Global roughness



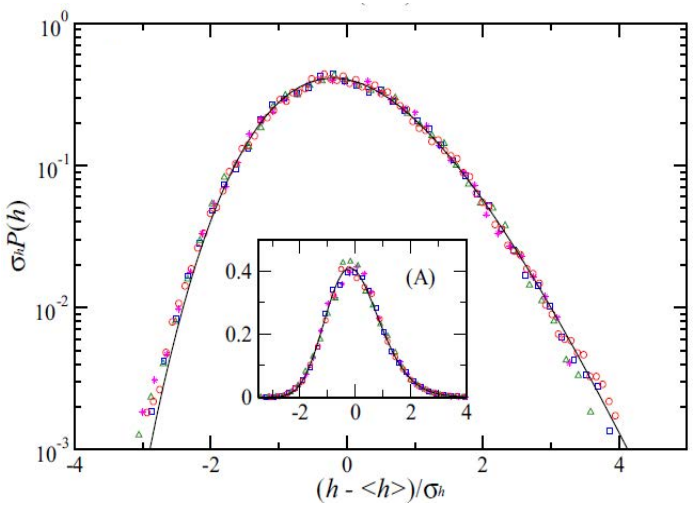
Best estimatives for the 2D KPZ exponents: **β** = 0.241(1); **α** = 0.393(3); 1/z = 0.61(1)

T. Halpin-Healy, PRE, **88** 042118 (2013).

J. Kelling and, G. Ódor, PRE, **84** 061150 (2011).

The First Robust Experimental Confirmation of 2D-KPZ Growth

R. A. L. Almeida, S. O. Ferreira, T. J. Oliveira, F. D. A. A. Reis, Phys. Rev. B. 89, 045309 (2014)

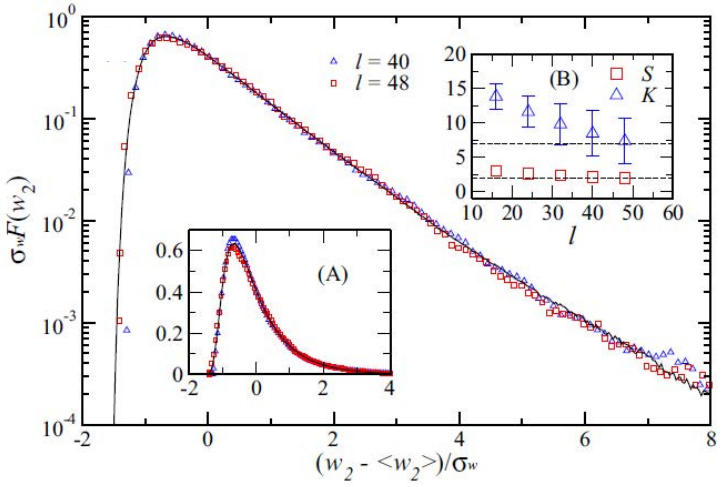


2D TW-GOE counterpart

S = 0.34(4) and K = 0.3(1)

Asymptotic values: S_{KPZ} = 0.42(2) and K_{KPZ} = 0.34(2)

T. Halpin-Healy, PRL **109**, 170602 (2012).
T. J. Oliveira, S. G. Alves, and S. C. Ferreira , PRE ***87**, 040102(R) (2013).*



Signature of Universal 2D-KPZ growth:
"The stretched exponential decail in the right tail "

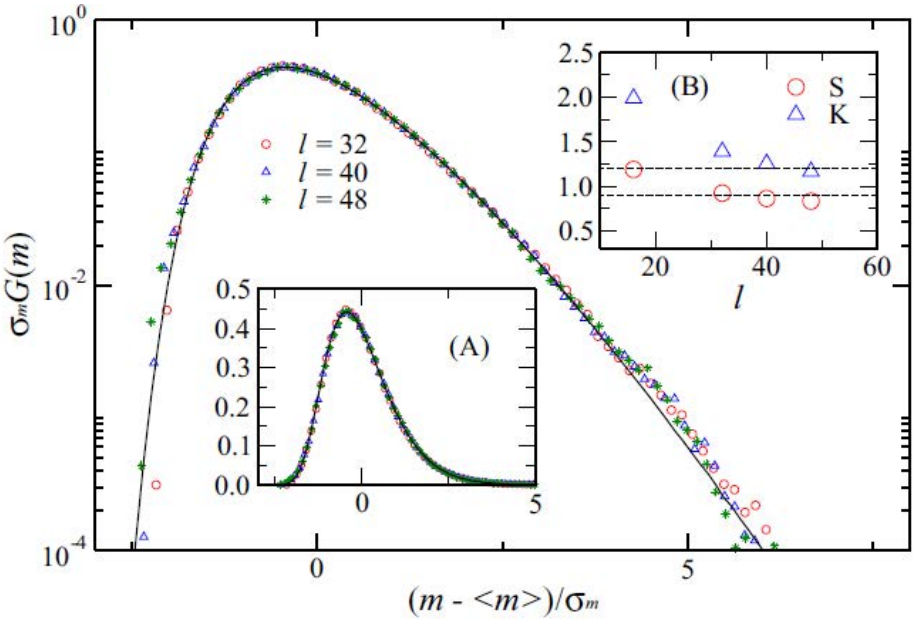
F. D. A. A. Reis, PRE E, **72** 032601 (2005).

T. Paiva and, F. D. A. A. Reis, Surf. Sci. **601**, 419 (2007).

T. Halpin-Healy *et al.,* EPL **105**, 50001 (2014).

The First Robust Experimental Confirmation of 2D-KPZ Growth

R. A. L. Almeida, S. O. Ferreira, T. J. Oliveira, F. D. A. A. Reis, Phys. Rev. B. 89, 045309 (2014)



Universal Extremal Height Distributions for 2D-KPZ surfaces at the growth regim

T. J. Oliveira and, F. D. A. A. Reis, PRE, **77** 041605 (2008).

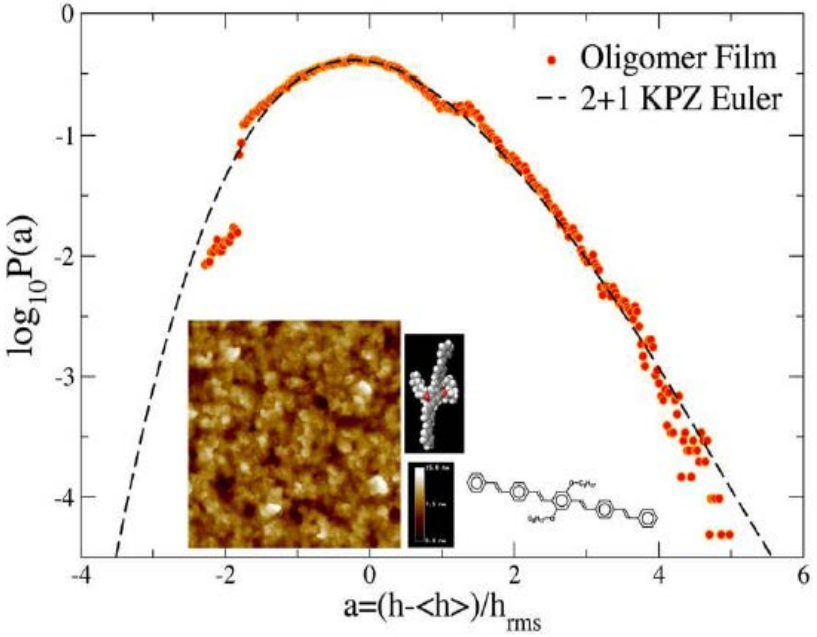
T. Halpin-Healy *et al., EPL* **105**, 50001 (2014).

Link to Extremal value statistics

S. Raychaudhuri *et al.* Phys. Rev. Lett., **87,** 136101 (2001).
D. –S Lee, Phys. Rev. Lett., **95,** 150601 (2005).

2D-KPZ Universality in Oligomer Films

"Motivated by (...) an experimental work on semiconductor films (...)"



An very important 2D-experimental confirmation [the first one]

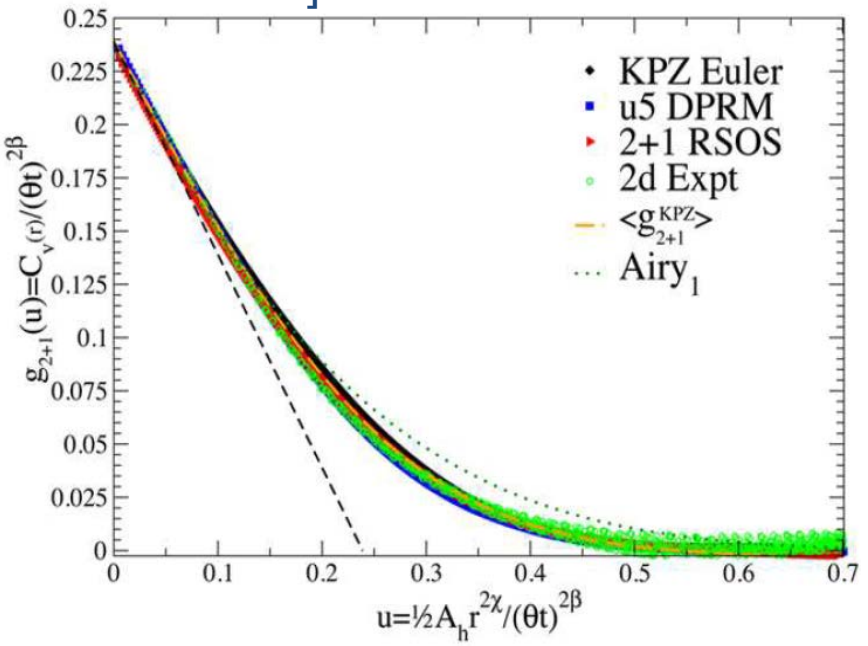


Fig. (Left): Universal 2D-KPZ height distribution in oligomer films. (Rigth) Rescaled spatial covariance for theoretical predictions and experimental realizations. Both agree with the 2D Airy1 process counterpart.

"(...) one sees the beginning of a new era in higher-dimensional KPZ experimental work."

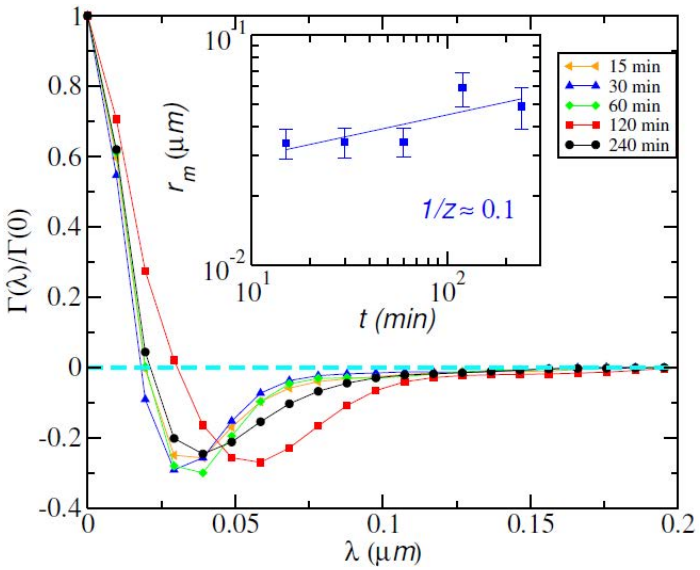
T. Halpin-Healy *et al., EPL* **105**, 50001 (2014).

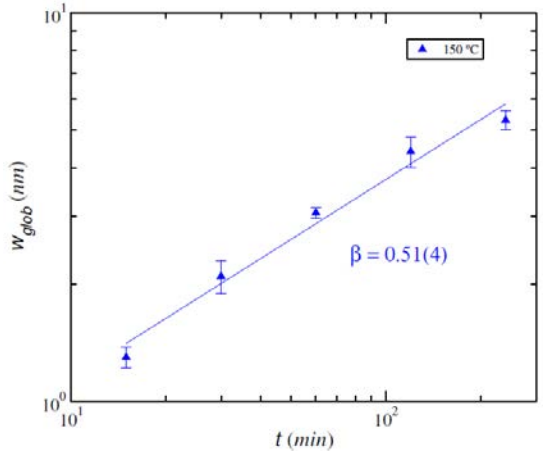
Changing the deposition temperature in the CdTe/Si(001) 2D-KPZ system

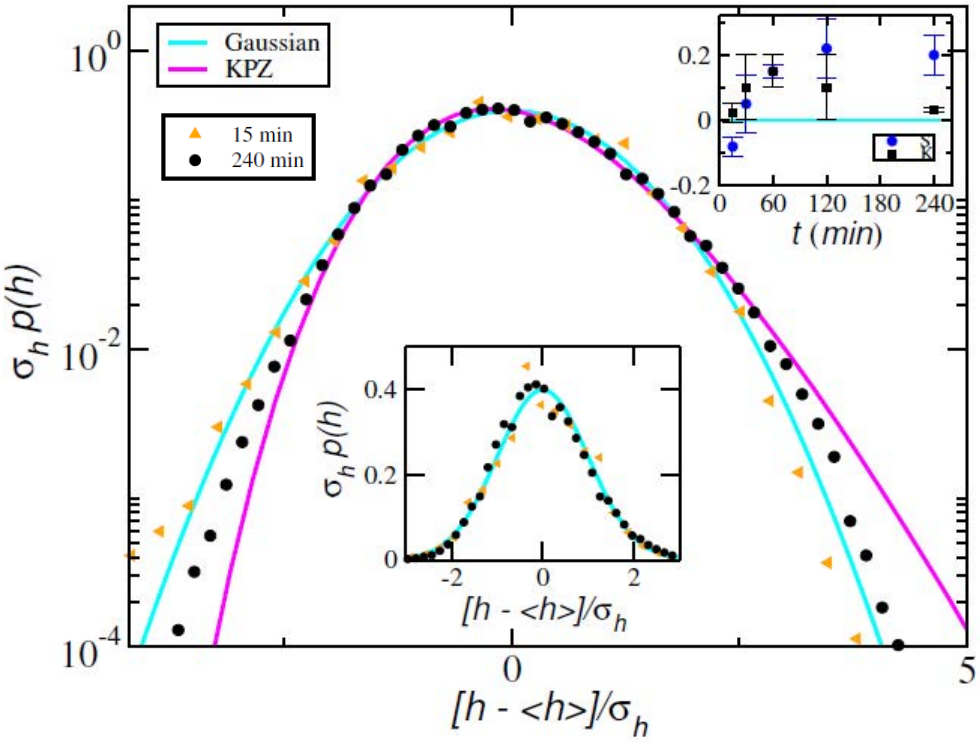
R. A. L. Almeida, S. O. Ferreira, I. R. B. Ribeiro and, T. J. Oliveira – To be submitted.

Samples grown at 150°C

- The smallest deposition temperature







Consistent with 2D- POISSON PROCESS

ν = 0 and **λ** = 0

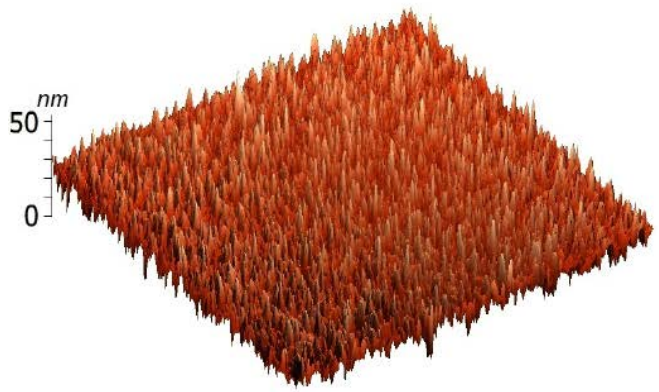
At this range of time, noise dominates the growth

Changing the deposition temperature in the CdTe/Si(001) 2D-KPZ system

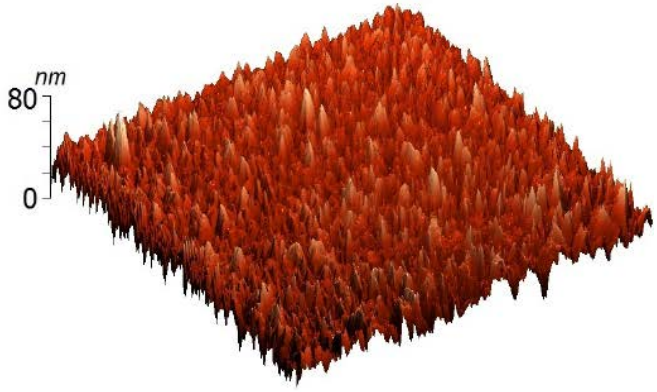
R. A. L. Almeida, S. O. Ferreira, I. R. B. Ribeiro and, T. J. Oliveira – To be submitted.

Samples grown at 200°C

- Increasing the temperature: morphological analysis.



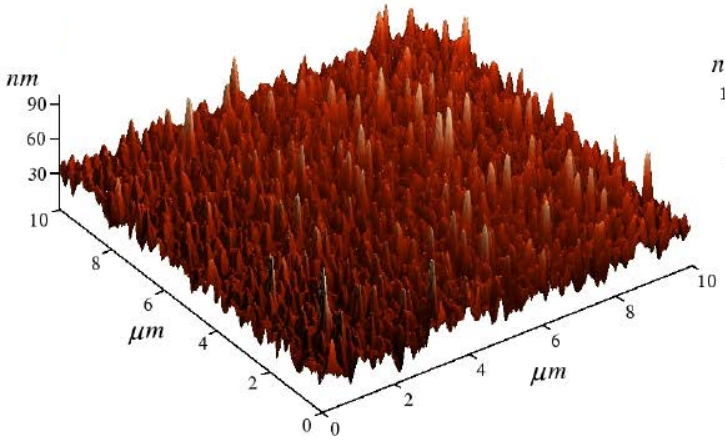
(a)



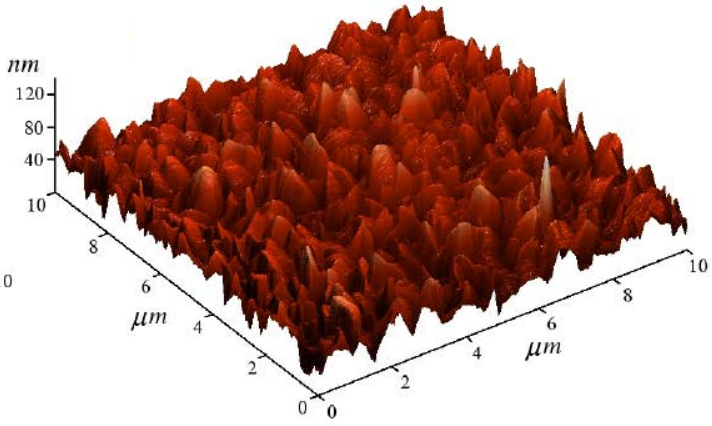
(b)

200°C

60 min



240 min



250°C

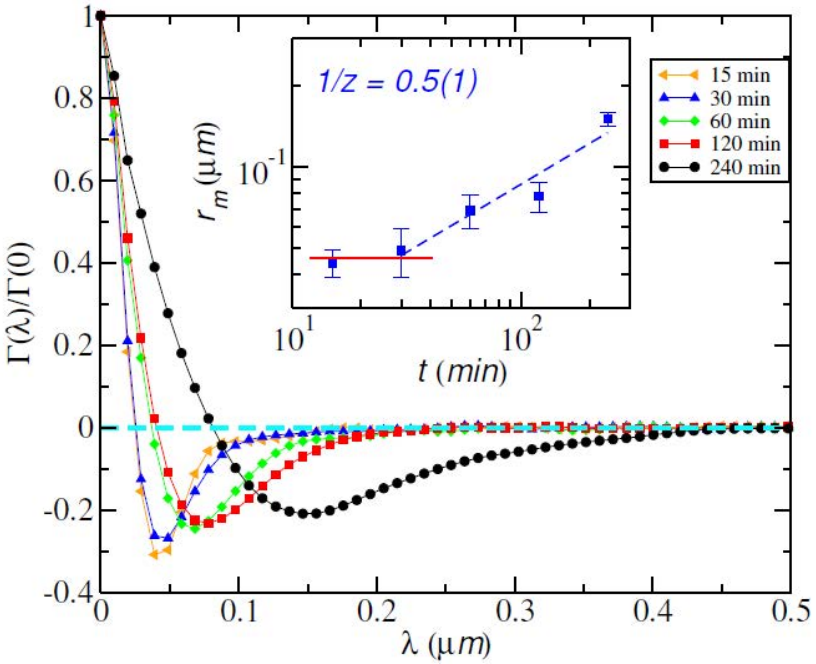
Changing the deposition temperature in the CdTe/Si(001) 2D-KPZ system

R. A. L. Almeida, S. O. Ferreira, I. R. B. Ribeiro and, T. J. Oliveira – To be submitted.

Samples grown at 200°C

2 – Local Scaling analysis.

$\langle \overline{(\nabla h)^2} \rangle \sim t^{2\kappa}$ **Lópes**, J. M., PRL ***83***, 4594 (1999).



It suggests: $1/Z_{EW} = 0.50$ or $1/Z_{KPZ} \approx 0.61$

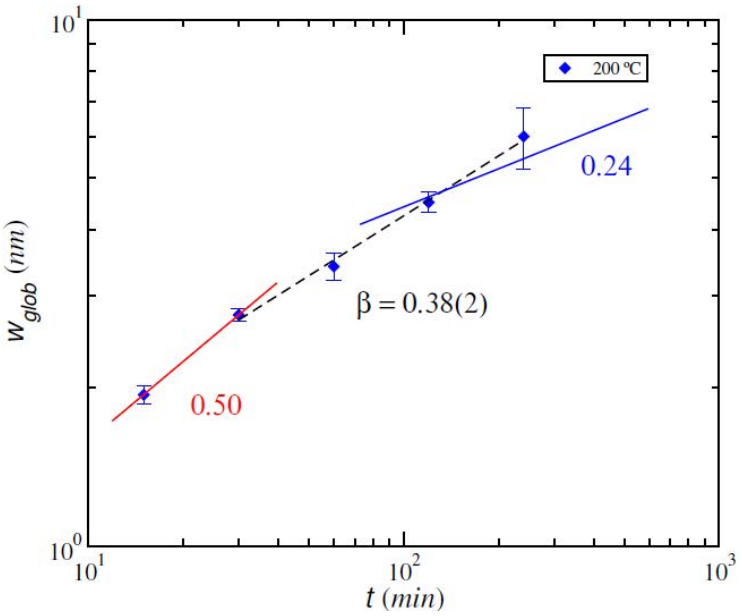
Transient Anomalous Scaling and asymptotic FV Scaling

Changing the deposition temperature in the CdTe/Si(001) 2D-KPZ system

R. A. L. Almeida, S. O. Ferreira, I. R. B. Ribeiro and, T. J. Oliveira – To be submitted.

Samples grown at 200°C

3 – Global Analysis



Again, we have clues of a temporal crossover

ß value is far away from the 2D-KPZ value

A crossover towards the KPZ regime ?

S = 0.43(5) and K = 0.5(2)

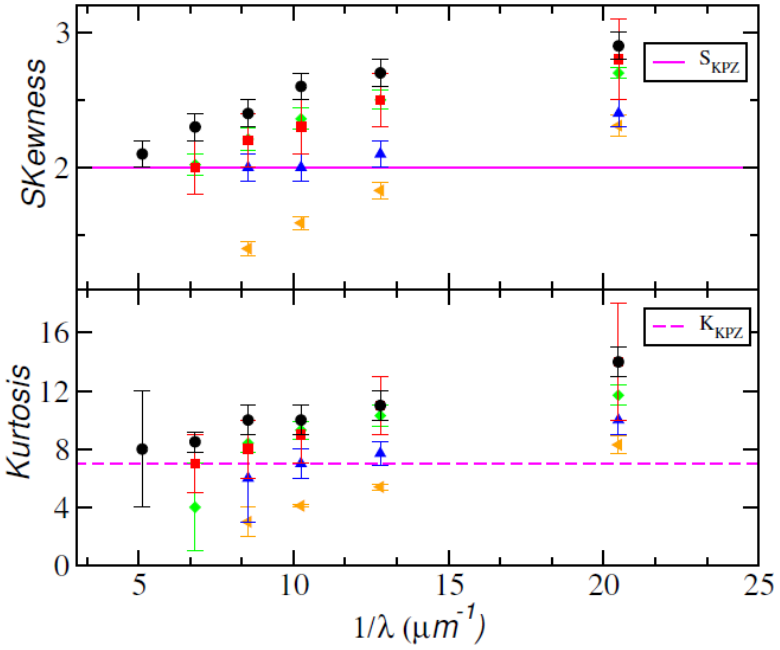
S_{KPZ} = 0.42(2) and K_{KPZ} = 0.34(2)

Changing the deposition temperature in the CdTe/Si(001) 2D-KPZ system

R. A. L. Almeida, S. O. Ferreira, I. R. B. Ribeiro and, T. J. Oliveira – To be submitted.

Samples grown at 200°C

4 – Universal Local Distributions



Signature of 2D-KPZ: “Streched exponential rigth tails for fours decade around the peak” !!!

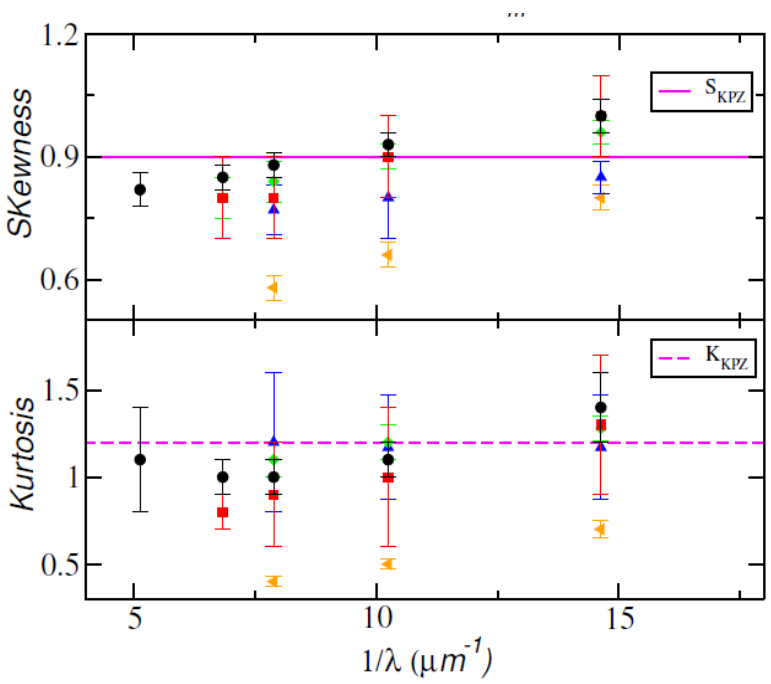
Fig. (Left) Skewness and Kurtosis as function of coarsening grained level. (Rigth) Squared Local Roughness Distribution (SRLD) for CdTe thin films compared with the Universal KPZ SLRD.

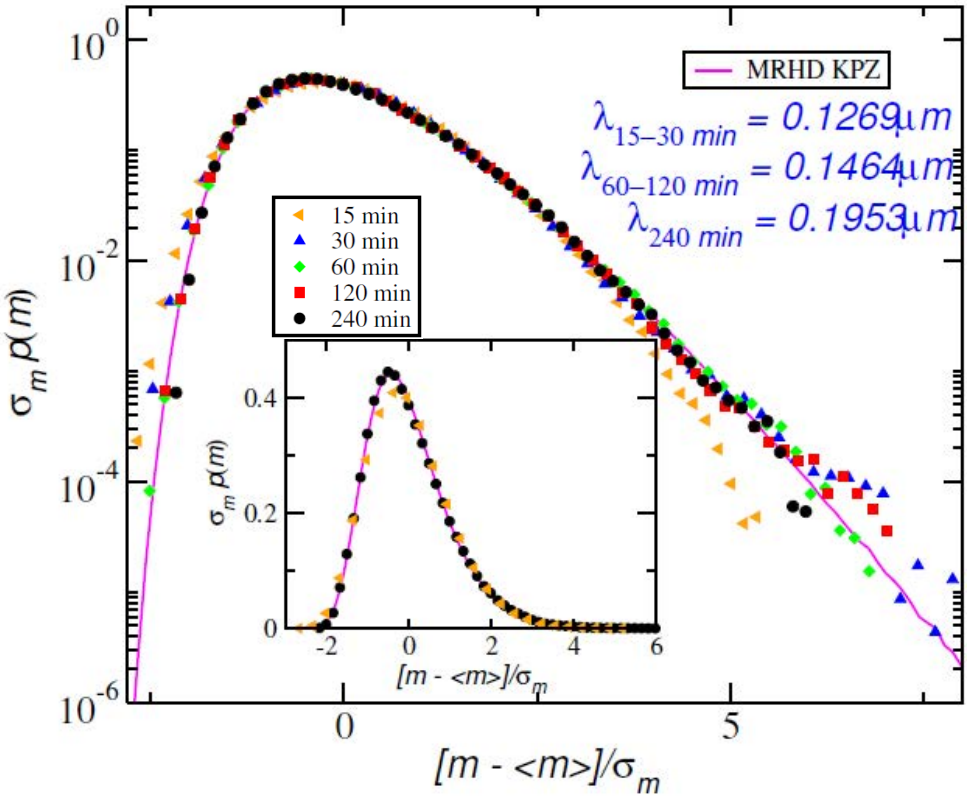
Changing the deposition temperature in the CdTe/Si(001) 2D-KPZ system

R. A. L. Almeida, S. O. Ferreira, I. R. B. Ribeiro and, T. J. Oliveira – To be submitted.

Samples grown at 200°C

4 – Universal Local Distributions





MRHD is not so accurate as SLRD, but it also indicates 2D-KPZ growth !!!

Fig. (Left) Skewness and Kurtosis as function of coarsening grained level. (Rigth) Squared Local Roughness Distribution (MRHD) for CdTe thin films compared with the Universal KPZ MRHD.

Changing the deposition temperature in the CdTe/Si(001) 2D-KPZ system

R. A. L. Almeida, S. O. Ferreira, I. R. B. Ribeiro and, T. J. Oliveira – To be submitted.

Samples grown at 200°C

4 – Partial Conclusions

- The 1/z exponent agrees with the 2D-KPZ value.
- A transient Anomalous Scaling occurs for initial growth times.
- The universal roughness exponent can not be measured directly by the local roughness curve.
- Growth exponent does not agree with any UC known due to a possible temporal crossover.

GROWTH EXPONENT, in these circunstances, "FAIL" for predicting the UC of the growth.

- GLOBAL AND LOCAL DISTRIBUTIONS provide a strong evidence of Random-to-KPZ CROSSOVER.

IN THIS CASE, THE UC WOULD NOT BE ACHIEVED WITHOUT THE DISTRIBUTION ANALYSIS

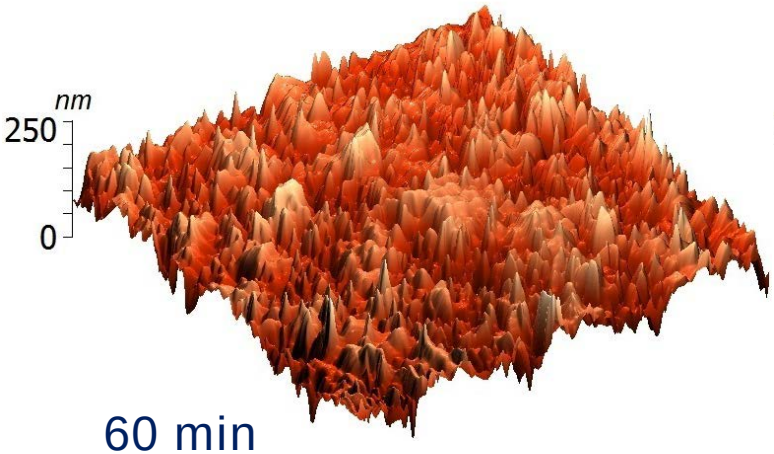
Changing the deposition temperature in the CdTe/Si(001) 2D-KPZ system

R. A. L. Almeida, S. O. Ferreira, I. R. B. Ribeiro and, T. J. Oliveira – To be submitted.

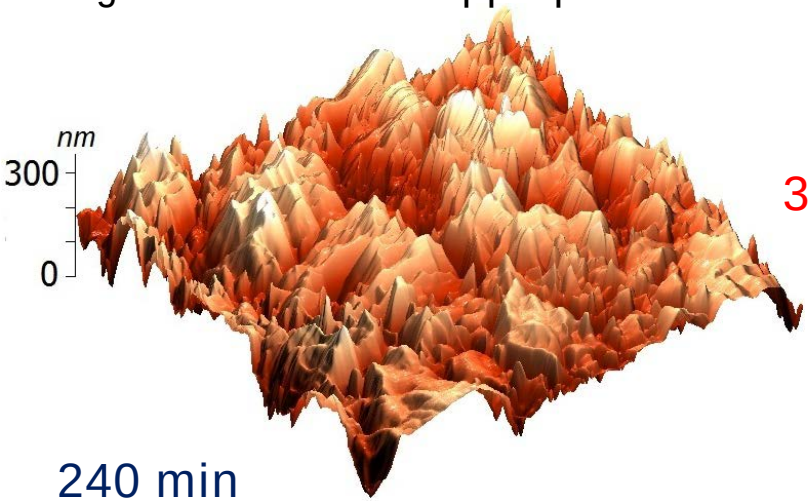
Samples grown at 300°C

- Higher deposition Temperature

Coalescence since early growth times => the procedure for measuring 1/z becomes unappropriate

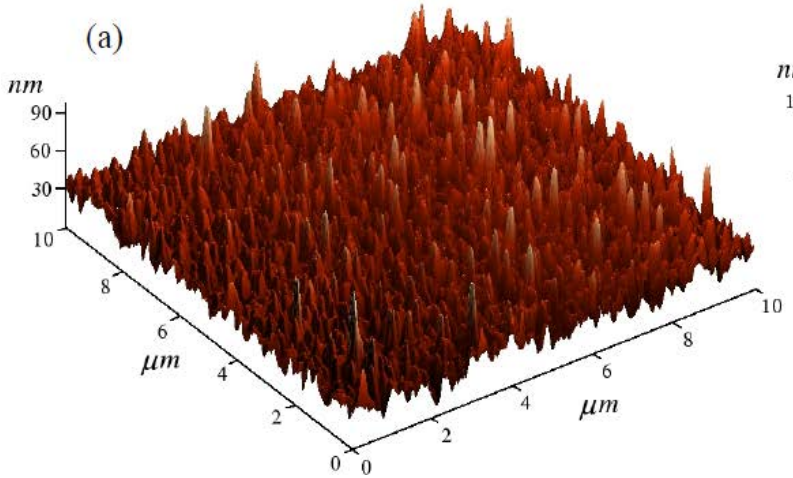


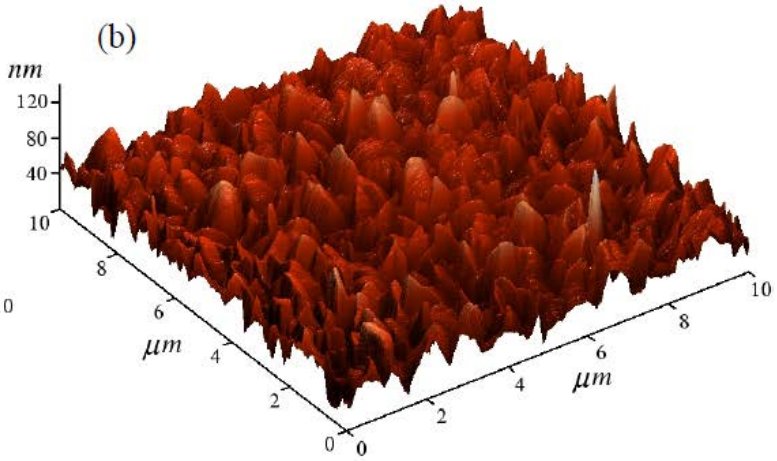
60 min



300°C

240 min





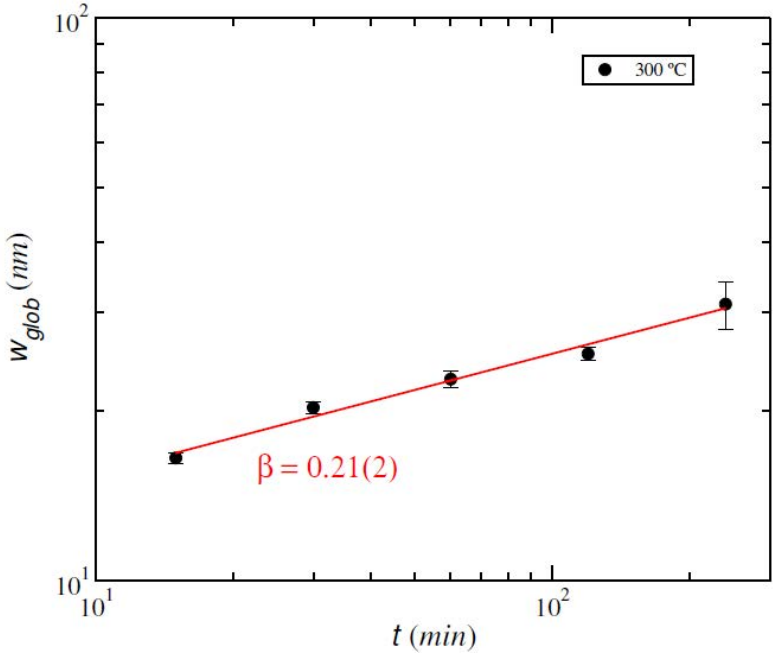
250°C

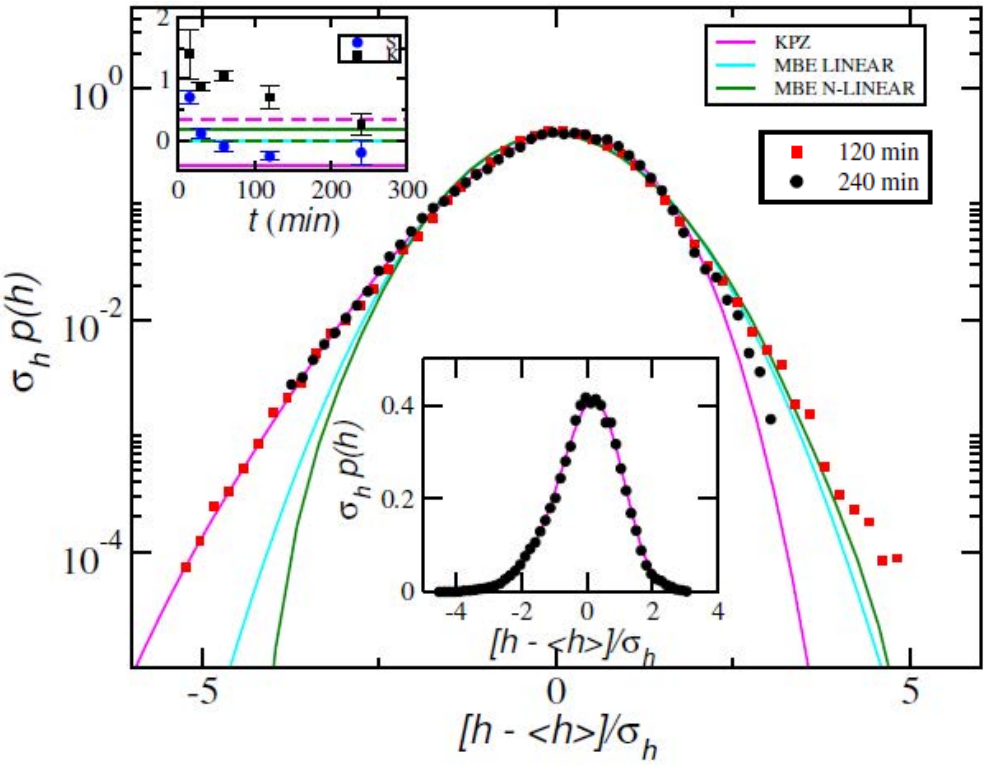
Changing the deposition temperature in the CdTe/Si(001) 2D-KPZ system

R. A. L. Almeida, S. O. Ferreira, I. R. B. Ribeiro and, T. J. Oliveira – To be submitted.

Samples grown at 300°C

- Higher deposition Temperature





These values are close to $\beta_{MBE(linear)}$ = 0.25, $\beta_{MBE(N\text{-}linear)} \approx 0.20$, and $\beta_{KPZ} \approx 0.24$

HDs approach to the 2D-KPZ one with negative skewness [It seems to discard MBE growth]

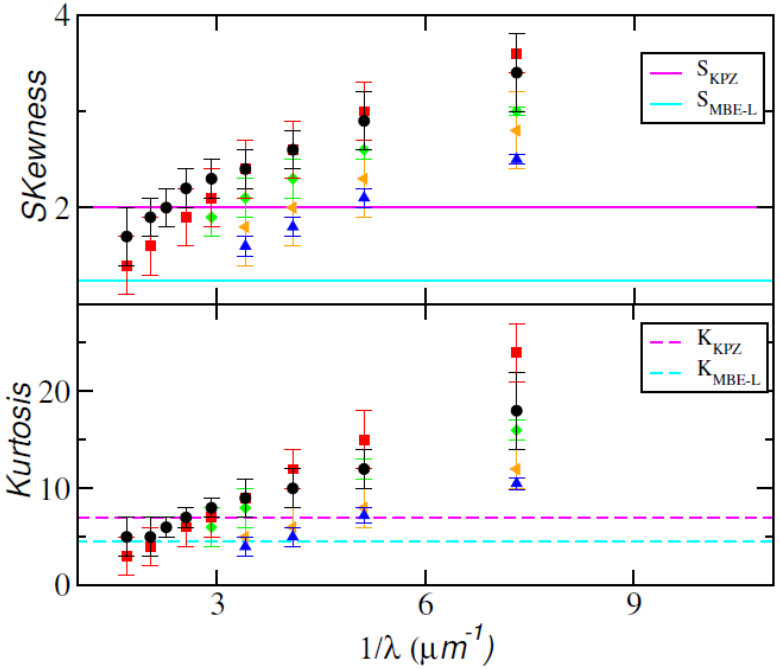
However, at this point, we can not assure the Universality Class

Changing the deposition temperature in the CdTe/Si(001) 2D-KPZ system

R. A. L. Almeida, S. O. Ferreira, I. R. B. Ribeiro and, T. J. Oliveira – To be submitted.

Samples grown at 300°C

- Higher deposition Temperature



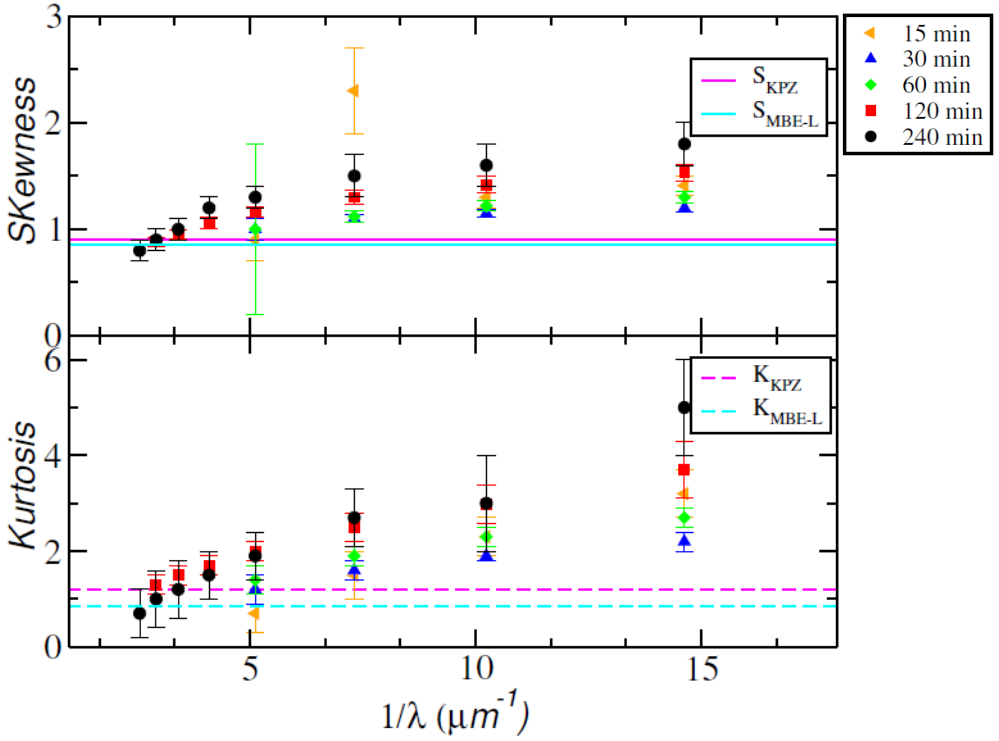
Once again, SLRDs offer the most reliable way for acessing UC of a growth. One finds the 2D-KPZ growth.

Changing the deposition temperature in the CdTe/Si(001) 2D-KPZ system

R. A. L. Almeida, S. O. Ferreira, I. R. B. Ribeiro and, T. J. Oliveira – To be submitted.

Samples grown at 300°C

- Higher deposition Temperature



MRHD's can not provide us a distiction between MBE-L and KPZ …

Changing the deposition temperature in the CdTe/Si(001) 2D-KPZ system

R. A. L. Almeida, S. O. Ferreira, I. R. B. Ribeiro and, T. J. Oliveira – To be submitted.

- Higher deposition Temperature: Partial Conclusions

  - The procedure for measuring the 1/z exponent is unappropriate, once coalescence processes occur since early growth times.
  - It is not possible to *unearth* the global exponent using the local roughness curve.
  - Growth exponent provide a value close of the KPZ and MBE classes.

HDs show a negative skewness agreeing with the S. and K. KPZ values

SLRDS also indicate a 2D-KPZ growth

Changing the deposition temperature in the CdTe/Si(001) 2D-KPZ system

R. A. L. Almeida, S. O. Ferreira, I. R. B. Ribeiro and, T. J. Oliveira – To be submitted.

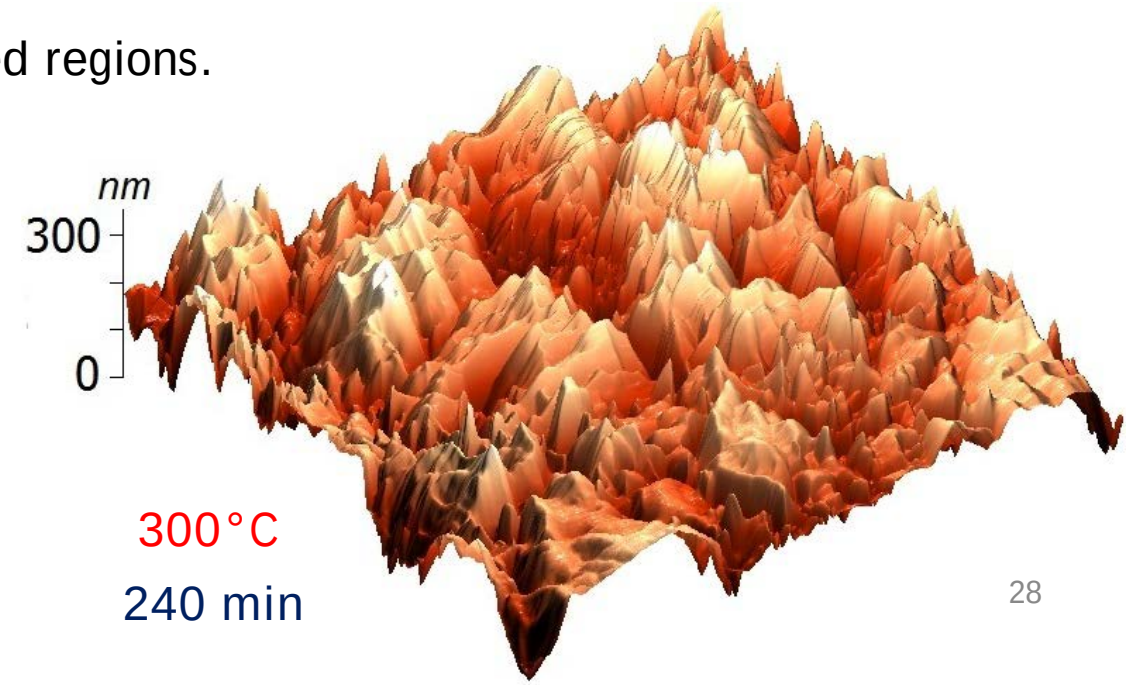
- Higher deposition Temperature: Partial Conclusions

Assuming KPZ growth even at higher temperatures, what is the POSSIBLE KPZ mechanism?

Local inclinations are, at least, 5x bigger than samples grown at 250 °C.

Particles refused at inclinated regions. (small sticking coef. ?)

Origin of large mounds and extended-defect-lines



300°C

240 min

Conclusions and Perspectives

- 2D-KPZ growth is found in CdTe/Si(001) thin films at a large range of deposition temperature.

- At the smallest T, exponents and HDs are consistent with Poisson Process.

- For T = 200°C, GROWTH EXPONENT "FAIL" due to a finite-time growth and the Random-to-KPZ crossover, indicated by DISTRIBUTIONS. A transient Anomalous Scaling is found.

- For T = 300°C, exponents do not help us to decide between KPZ and MBE classes. Universal distributions point out KPZ growth, however, with negative **λ**.

THE UC OF 2D-GROWTH IS HARDLY ACCESSED ONLY THROUGH THE ESTIMATE OF SCALING EXPONENTS. THE ANALYSIS OF DISTRIBUTIONS ARE ESSENTIALS IN THIS CONTEXT.

Strong reason why so many works have been reporting several exponents with no association with an UC

Conclusions and Perspectives

- Using the same system grown at different conditions (which provide the KPZ regime since early growth times) we'll focus in to validate the KPZ änsatze in two-dimensional growth, as well the spatial covariance (in the presence of grains).

R. A. L. Almeida, I. S. S. Carrasco *et al. [in progress]*

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CAPES
FAPEMIG Fundação de Amparo à Pesquisa do Estado de Minas Gerais

本当にありがとうございました

Muito obrigado!

UNIVERSIDADE FEDERAL DE VIÇOSA

CNPq Conselho Nacional de Desenvolvimento Científico e Tecnológico

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