# 2D-melting and thermal fluctuations in a Pt/Co(0.5nm)/Pt film

**N. Bergeard, J.P. Jamet, A. Mougin, J. Ferré**

ORSAY

**E. Bourhis, J. Gierak**

Laboratoire de Photonique
et de Nanostructures

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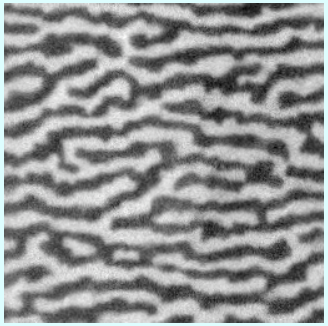
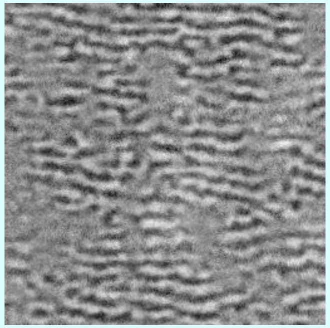


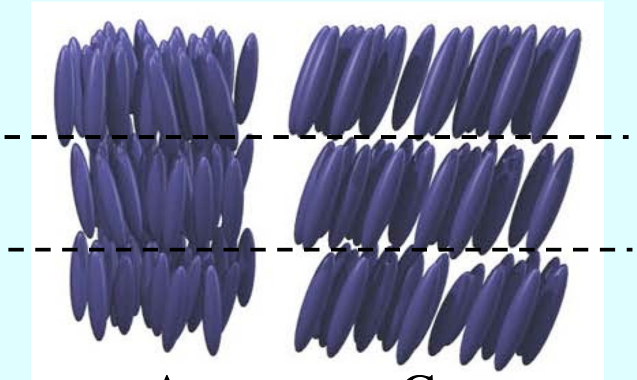


*Phenix, June 2014 (Grenoble)*

# 2D melting for liquid crystals

Increasing T

***Smectic*** ***Nematic*** ***(Hexatic)*** ***Liquid***



A C

Positionnal and Orientational order

Orientational order

liquid with hexagonal symmetry

6-fold degenerated

***Theory:***

***Kosterlitz, Thouless, Nelson, Halperin, Young (KTNHY)****'73, 78, 79*

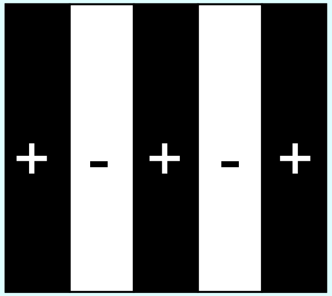
2 successive transitions mediated by the dissociation of dislocation pairs (smectic-nematic transition) or disclination pairs (nematic-hexatic transition)

# 2D melting in other systems

- **2D colloidal crystals**

- **2D vortices in superconductors**

- **Ferromagnetic films : stripe domain patterns**




(competition between exchange and dipolar interactions)

- The competition between the anisotropy and dipolar interactions, and frustration (in stripe structues) tend to destabilize the uniformly ordered state *(Villain'89)*

***Analogy to liquid crystals:*** - Ferro stripes equivalent to molecular planes
- Do dislocations and disclinations trigger 2D-melting?

***Theory for magnetic films :*** ***Statics of the 2D melting transition near the spin reorientation transition*** *(Abanov et al.'95)*

# 2D melting and fluctuations : Suitable Magnetic system

**Aim of this study:** 2D melting of a stripe domain pattern and related giant thermal magnetic fluctuations in a thin film

**Main requirements:**
- Ultrathin magnetic film with low T out-of-plane anisotropy
- Melting transition close to room temperature
- Magnetic stripe domain pattern with a favored in-plane orientation

**Consequence:**
- Metastability and slow dynamics in the vicinity of the 2D melting transition

# 2D melting and fluctuations :
# Instabilities in stripe domain structures

**Theory : Origin of thermal fluctuations - Instabilities:**

***KTNHY model for liquid crystals*** *When increasing T:*

- The proliferation of topological defects (dislocations, disclinations) drives the system into a disordered phase

- Long range Positionnal order easily destroyed, while Orientational order decreases much slowly

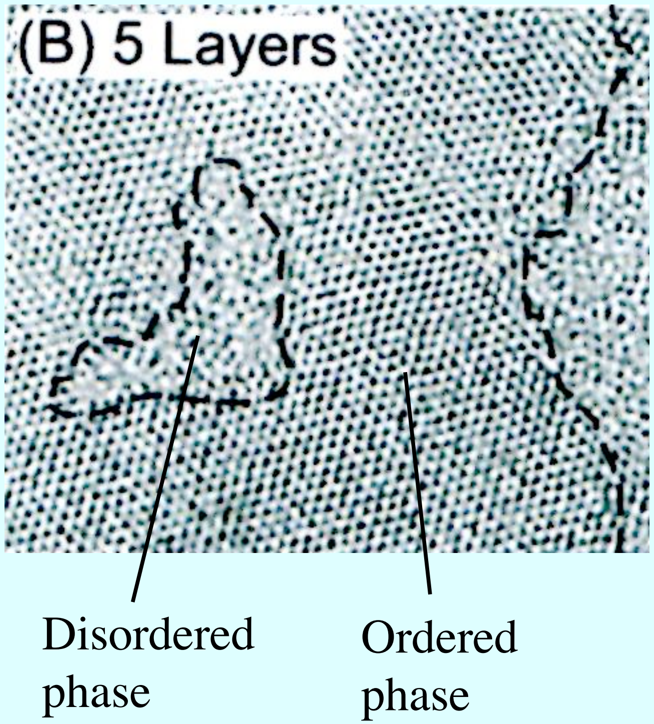
***In magnetic stripes: - Dislocations*** *(Abanov et al.'95)*, and

- ***Domain wall undulations in magnetic stripes***

*(Brazovskii'75, Czech and Villain'89, Polyakova et al.'07)*

# 2D Melting of multilayer colloidal crystals

**Colloidal multilayers confined between two walls** *(Y. Peng et al.'11)*

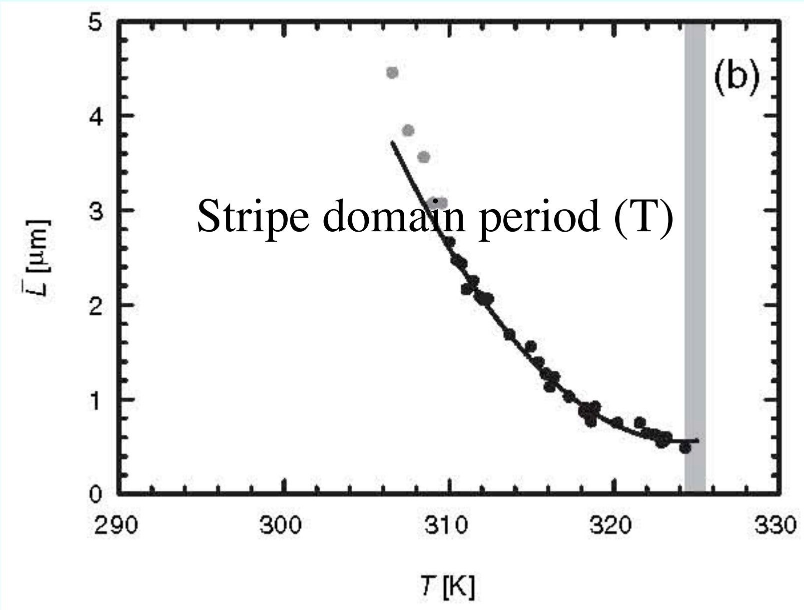


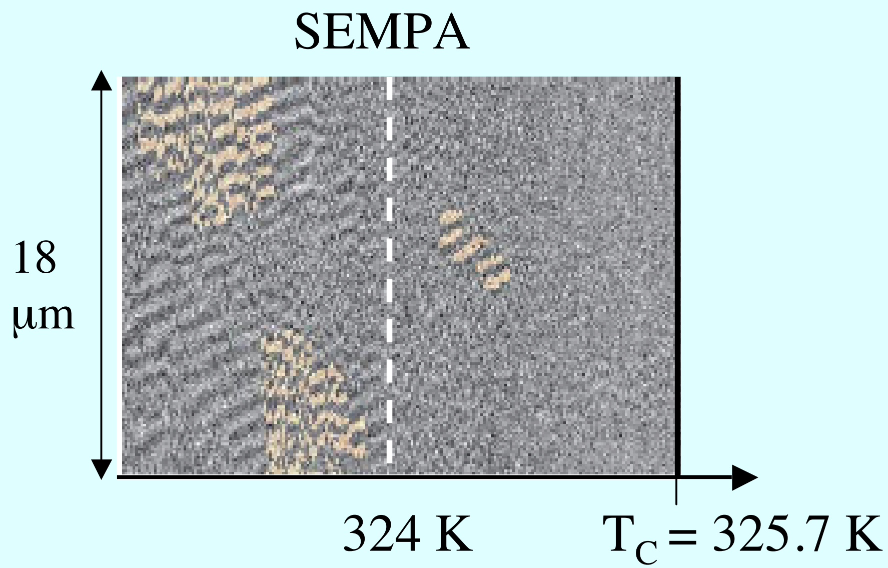

Fluorescent N- isopropylacrylamide (NIPA) colloidal microgel spheres (~ 1 μm)

**Liquid patches embeded in a solid phase**

# 2D-melting and fluctuations in a ferromagnetic film

**- In a 2D frustrated ferromagnetic film: Fe(1.96ML)/Cu(100)**
close to $T_C = 325.7$ K *(SEMPA: Portmann et al.'06, XMCD: Kuch et al.'11)*



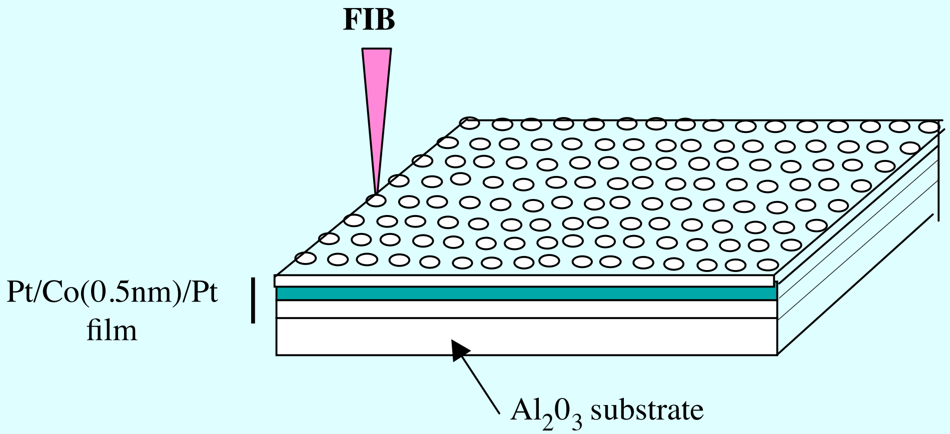

**Mobility of stripe domains (in yellow)**

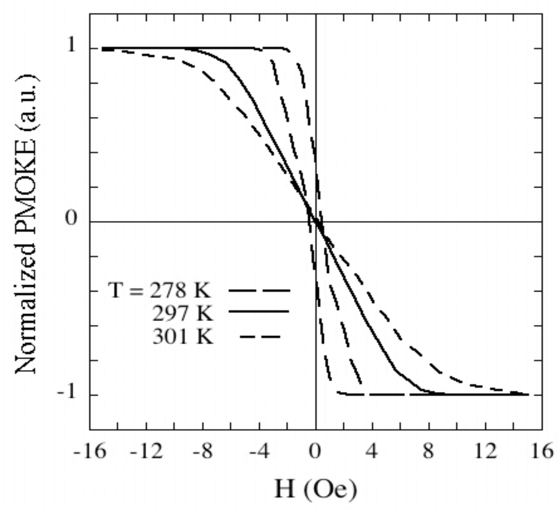
# Studied sample: Pt/Co(0.5nm)/Pt film patterned as a square array of irradiated FIB points

**Pt/Co(0.5 nm)/Pt film : Why?**

- At low T : Ferromagnetic 2D-Ising system with ⊥ anisotropy
- Spin reorientation from ⊥ to // and melting (at $T_m$) in the vicinity of room T
- Polycrystalline structure : weak domain wall pinning - in-plane magnetic **isotropy**

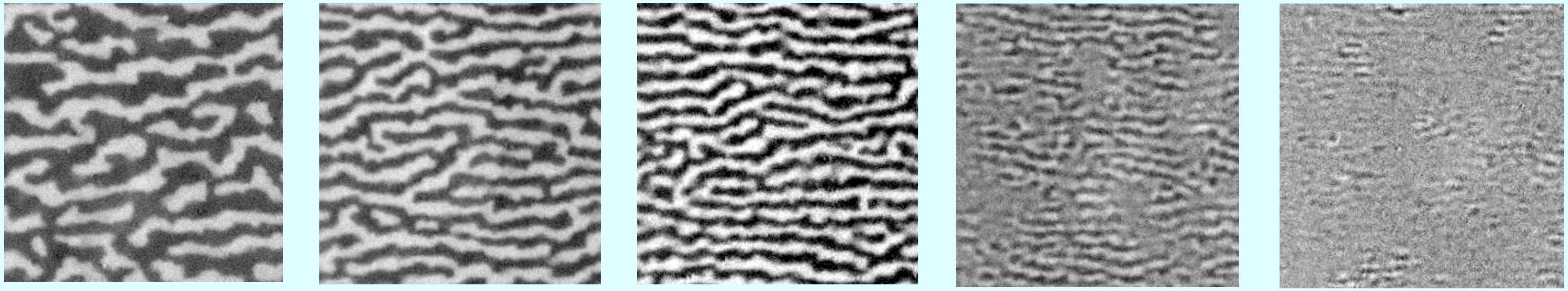
**FIB Patterning**: - to induce uniaxial anisotropy (***distorted*** FIB point square lattice along the scanning FIB direction (D ≈ 10 nm, p = 30 nm) that aligns walls



# Evidence of strong fluctuations : Temperature dependence of the stripe domain pattern

**Non-stable demagnetized ribbon-like stripe domain structure : Polar Kerr microscopy** Preparation at t = 0 after switching off a small field large enough to saturate the film magnetization (Average on 8 images (40s) to reveal fluctuations).



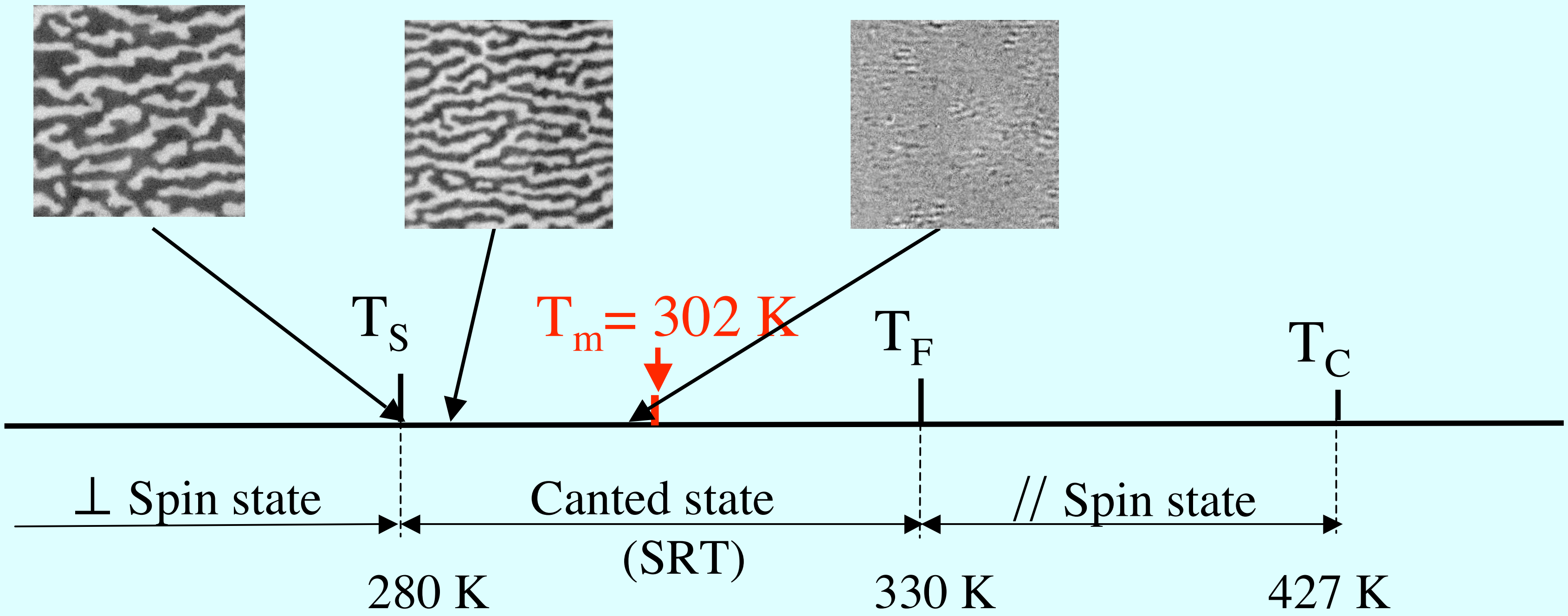
T = 282 K 287 K 290.5 K 295 K 299.5 K

- The stripe period decreases exponentially when increasing temperature
- 2D-melting: for T **> $T_m$ ~ 302 K**, the stripe pattern becomes completely blurred by strong spatio-temporal fluctuations
- Small thermal hysteresis (~ 1 K) of the stripe period: weak 1st order transition ?

# Phase diagram

**FIB patterned Pt/Co(0.5nm)/Pt film : Polar Kerr microscopy**

*(Abanov et al.'95)*

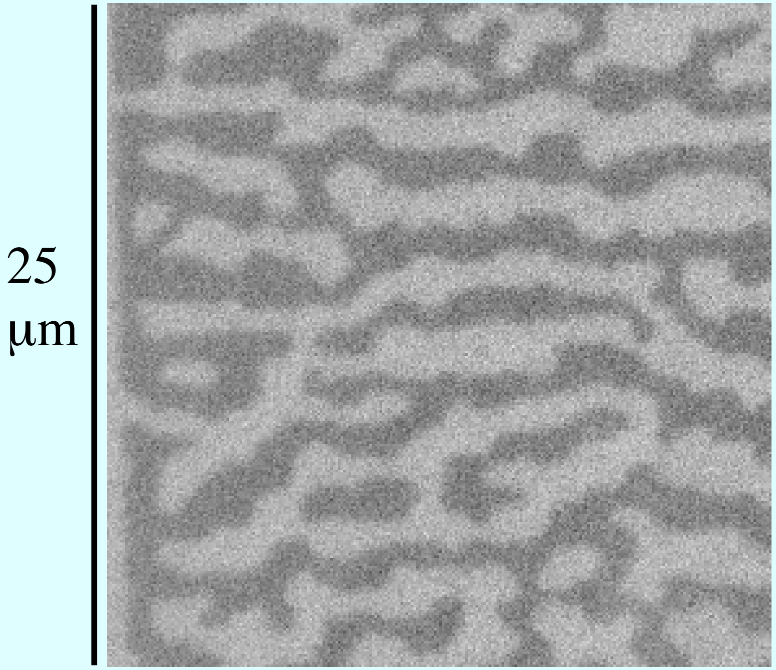


# **Stripe defects and wall meandering** - Entering the canted spin state, i.e. $(T - T_S) = 3$ K, $(T_m - T) = 19$ K

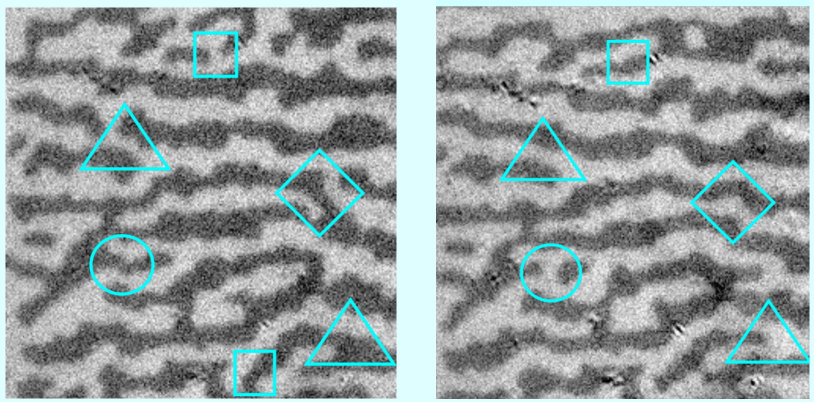
## **Time dependence of the demagnetized pattern** (prepared at t = 0)

**Stripe undulations:**

Image snapshot: 0.5 s - Delay time between images: 4.5 s




**Onset of stripe instabilities at $T_S$**



- Wall undulation (everywhere)
- Branching of two stripe segments
- Cut of stripes
- Simultaneous cut and branching between stripes

# **Local instabilities and fluctuations** - Entering the canted spin state, i.e. $(T - T_S) = 3$ K, $(T_m - T) = 19$ K

**Evolution of the stripe pattern:**

Difference between single image snapshots at $t = t_W$ and the 1st image at $t = 0.5$ s) when increasing $t_W$
(fluctuating areas appear in black/white)


**- Two types of instabilities:**

(1) at random positions :
homogeneous nucleation and reversal of small fluctuating spots
(Telegraphic noise)

(2) around localized stripe defects :
inhomogeneous nucleation for fluctuations
(Slow expansion of fluctuating regions when increasing $t_W$)

# **Dynamics of the stripe domain structure** - Inside the canted spin state, but below $T_m$ $(T_m - T) = 13$ K

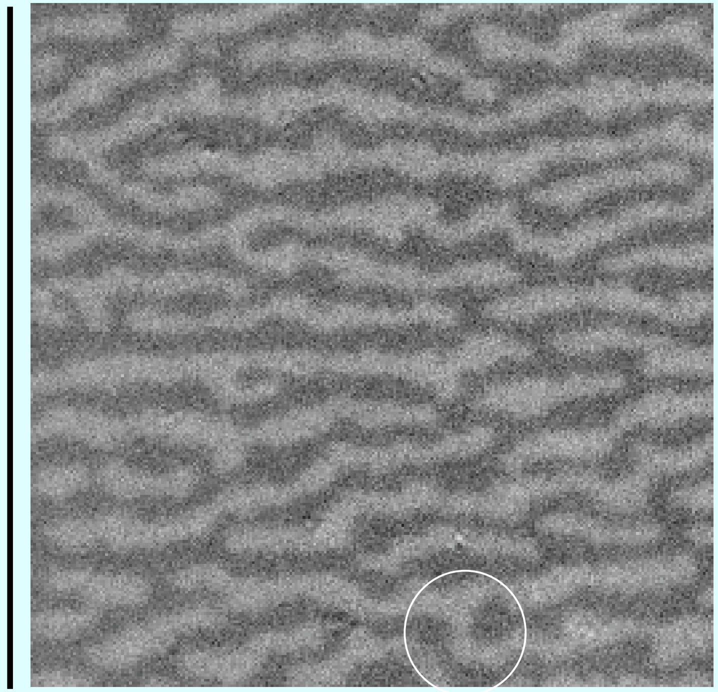
## **Time dependence of the demagnetized pattern** (prepared at $t = 0$)

- **Stripe undulations: $t_W$ dependence**

Image snapshot: 0.5 s - Delay time between images: 4.5 s

- Faster domain wall undulations at higher T
- Still triggering modes around defects
- Stripe topology changes close to defects

25 µm



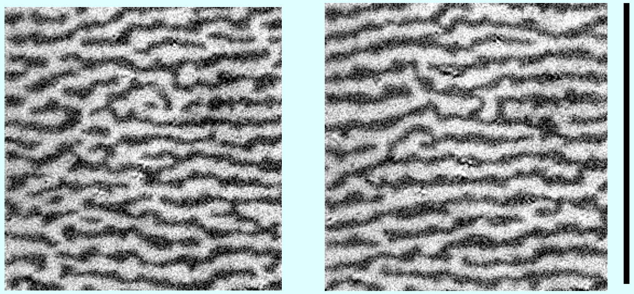
## **Localized instabilities and fluctuations** - Inside the canted spin state, but below $T_m$ $(T_m - T) = 13$ K

**Evolution of the stripe pattern: Initiation and development of fluctuating patches**

Difference between single image snapshots ($t = 0.5$ s) for $t = t_W$ and the 1st image, with increasing $t_W$ (black/white fluctuating spots or larger areas)

# **Stripe structure, nucleation rate and pattern evolution at $T = 289$ K,** inside the canted state below $T_m$ $(T_m - T) = 13$ K

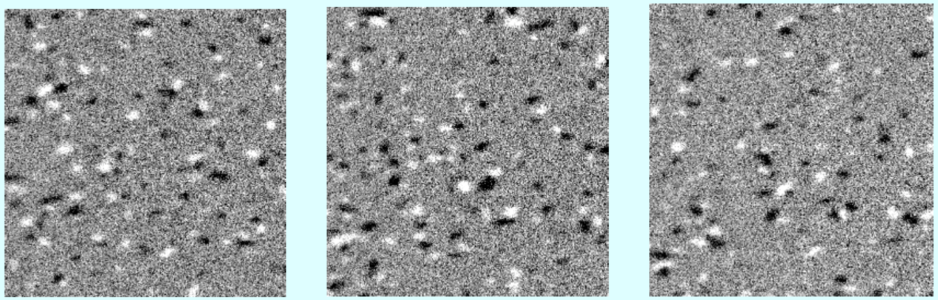
Single image snapshot ($t = 0.5$ s)



25 μm

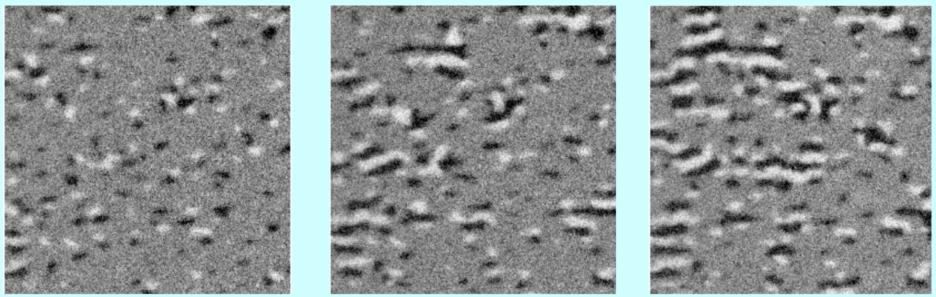
$t_W = 0.5$ s    24 minutes

**Stripe domains** (Demagnetized state)
Tend to align at long time
**Strengthening of the positional order.**



$t_W = 0.5$ s    1 minute    5 minutes

**Nucleation rate** for $\Delta t = 4.5$s
Black and white instabilities : **No net M.    Constant nucleation rate for all $t_W$ values.**



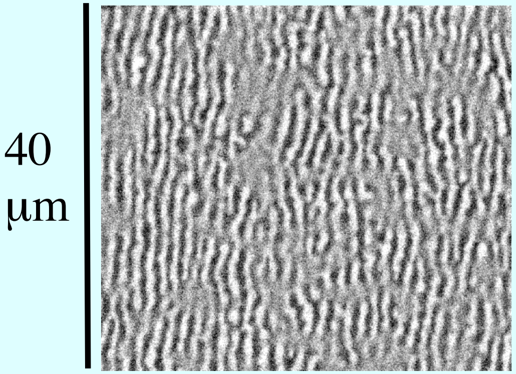
$t_W = 1$ minute    5 minutes    24 minutes

**Stripe domain evolution**
The fluctating patches spread more and more slowly with $t_W$ - **The fluctuating area increase at long time.**

# Stripe structure and fluctuations

# very close below $T_m$ $(T_m - T) = 3$ K

## Demagnetized domain pattern

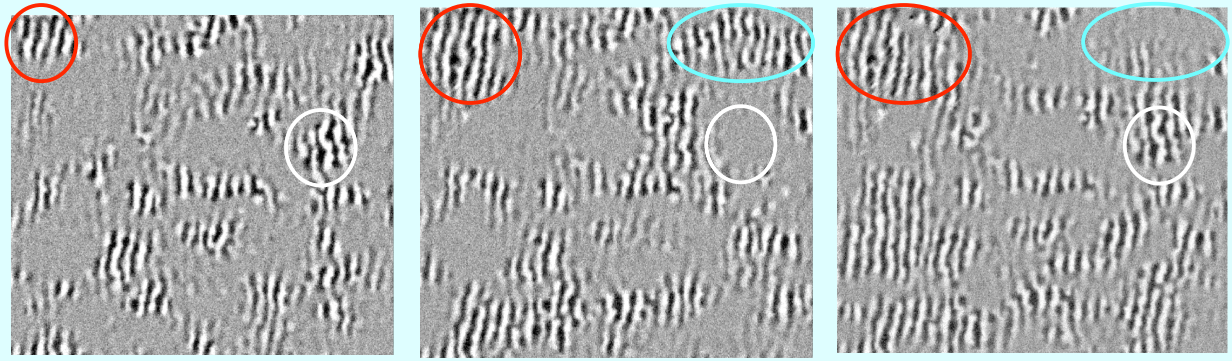



$t_W = 7$ min

8 times averaged image: Grey regions have fluctuated during image acquisition

## Stripe pattern evolution (8 times averaged)

Here, stripe patches with variable contrast **decorate** fluctuating regions. The grey regions remain ordered. The image acquisition time (36 s) is longer than the characteristic time for fluctuations.



$t_W = 1$ min 42 min 80 min

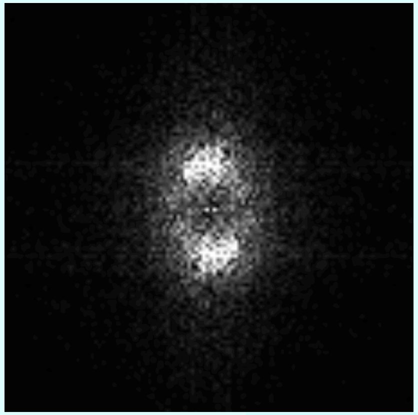
**- The fluctuating area saturates at long time.**

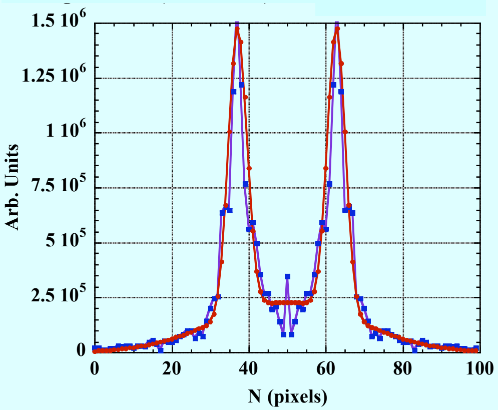
**- Fluctuating patches can disappear and reform.**

# FFT data analysis

**<u>T = 287 K</u>**

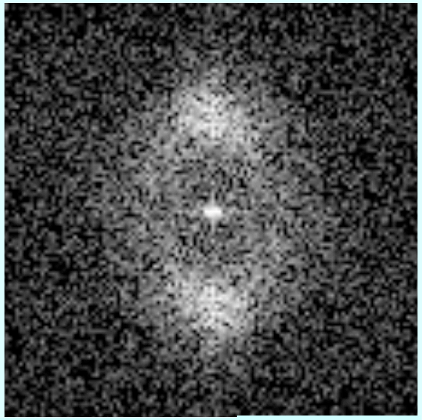
($T_m$- T) = 15 K

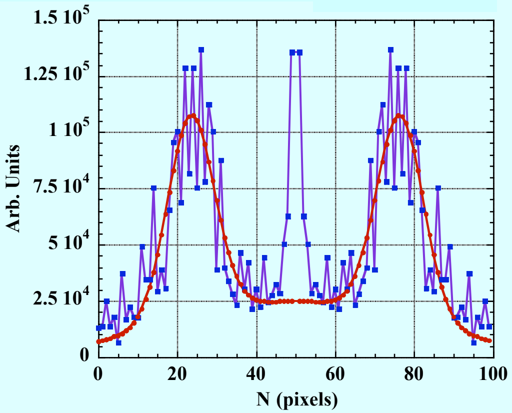




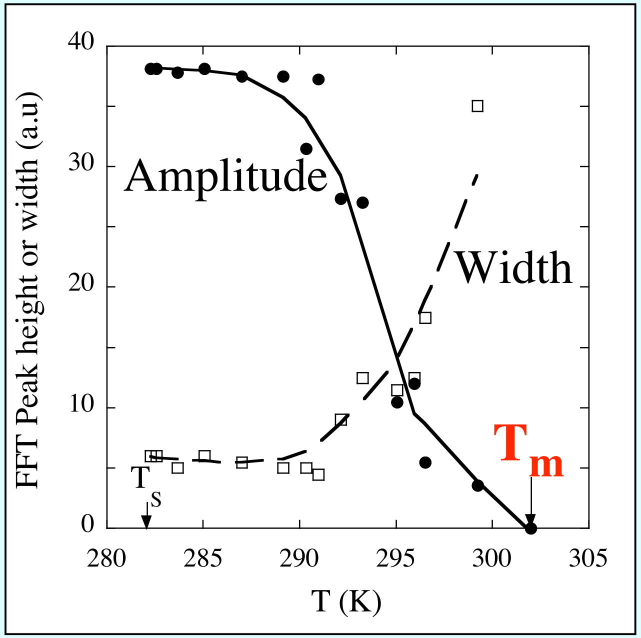

**<u>T = 298 K</u>**

($T_m$- T) = 4 K

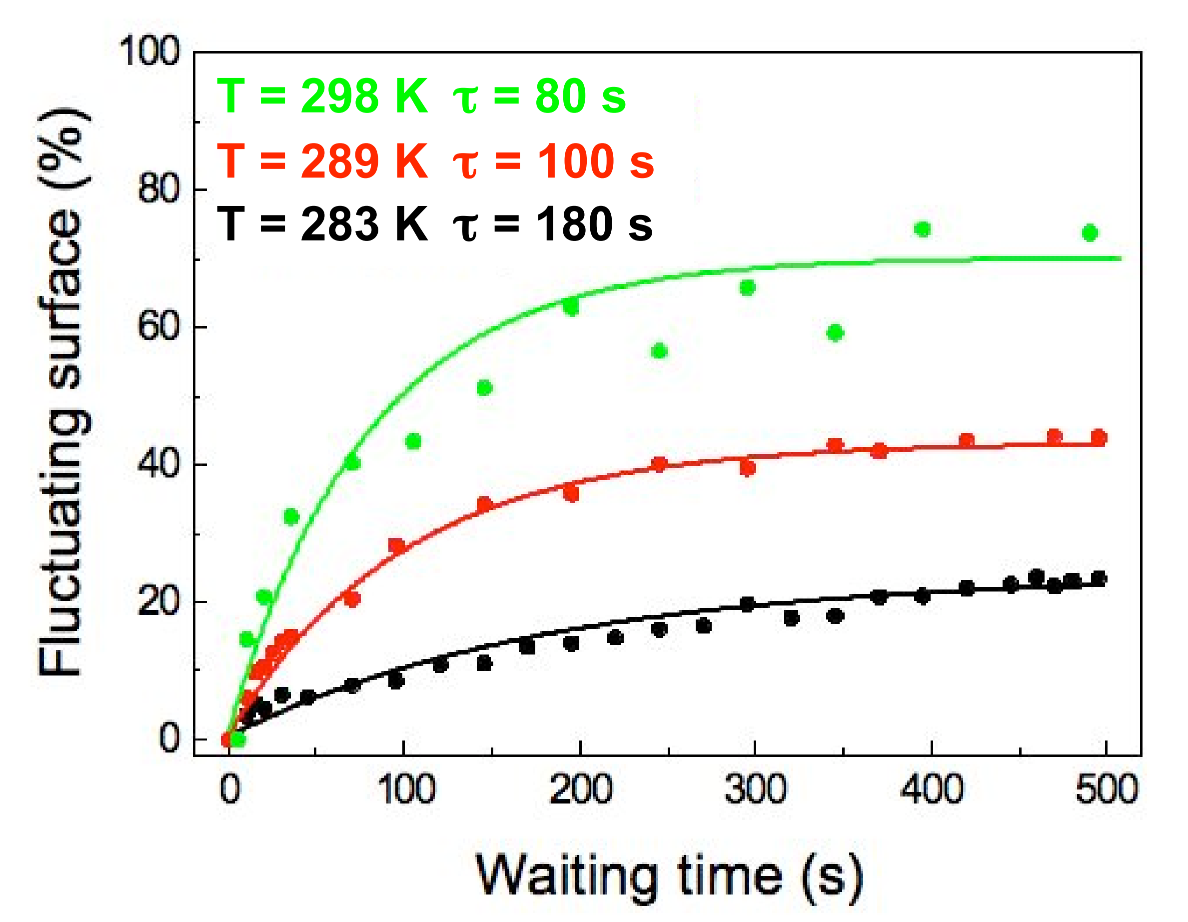





- Pattern asymmetry due to the orientational order
- Peak to peak distance ~ (1/stripe periodicity)
- Peak amplitude ~ $M^{\dagger}$x Scat
- Peak width: stripe non-homogeneity and fluctuations



# FFT data analysis




Fluctuating area fitted by:

$A_{max}[1 - \exp(- t_W/\tau)]$

**At 298 K, i.e. for T close to $T_m$ = 302 K, the FTT peak amplitude and large fluctuations reach more rapidly saturation**

# Conclusions on huge magnetic fluctuations at SRT

**- On the demagnetized stripe domain pattern in the SRT temperature range :**

- **At the onset of the SRT ($T_S$)**:

⟶ Below the 2D-melting temperature, $T_m$ ($\approx T_S + 20$ K) : stripe instabilities are precursors for strong fluctuations

- **At and above $T_m$**: the stripe domain pattern is washed out by huge transverse wall fluctuations. So, when increasing T up to $T_m$, the positional order is progressively destroyed

⟶ This results from dynamics: for $T > T_m$, the time of measurement becomes larger than the characteristic fluctuation time. Models proposed so far predicting the coexistence of phases at the melting transition are not adapted to interpret these results.

# Conclusions on huge magnetic fluctuations at SRT

**- On the demagnetized stripe domain pattern in the SRT temperature range :**

- Just below $T_m$, the area of liquid patches increases rapidly up to saturate at long time.

- Most of the fluctuating patches develop around stripe defects but the smallest ones « melt » and « reform » at the same place to show telegraphic noise, while the largest ones initiate nucleation and trigger the development of bigger patches.

- The fluctuating patches spread and move more and more rapidly when aproaching $T_m$ ⟶ Floating glass concept (J. Villain)

# Comparison with theories

**With liquid crystal** *(Halperin and Nelson)* **and magnetic thin film theories** *(Villain, Abanov et al.)*

- Slow dynamics in the stripe domain state had never been investigated theoretically

- No indication of phase transitions similar those happening in liquid crystals

- No sign of proliferation of defects at the 2D-melting transition as expected in the KTNHY model (Here, the number of defects only varies as the number of stripes).

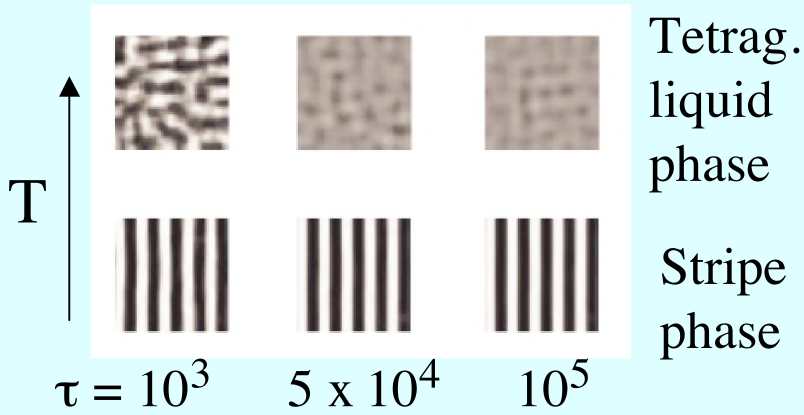
- The stripe motion is released by strong transverse fluctuations

- Fluctuation-induced first order transition of an isotropic system to a periodic state has been predicted by *Bates et al'88*. But not really valid in our case.

# Comparison with simulations

- Difficulty to treat spatio-temporal problems by simulations involving large areas and slow fluctuations.

- Nevertheless, when increasing T, limited results show some insight of a dynamic blurring of the stripe domain pattern *(Carubelli et al., PRB 2008)*




- Simulations with high spatial and time resolutions are welcome