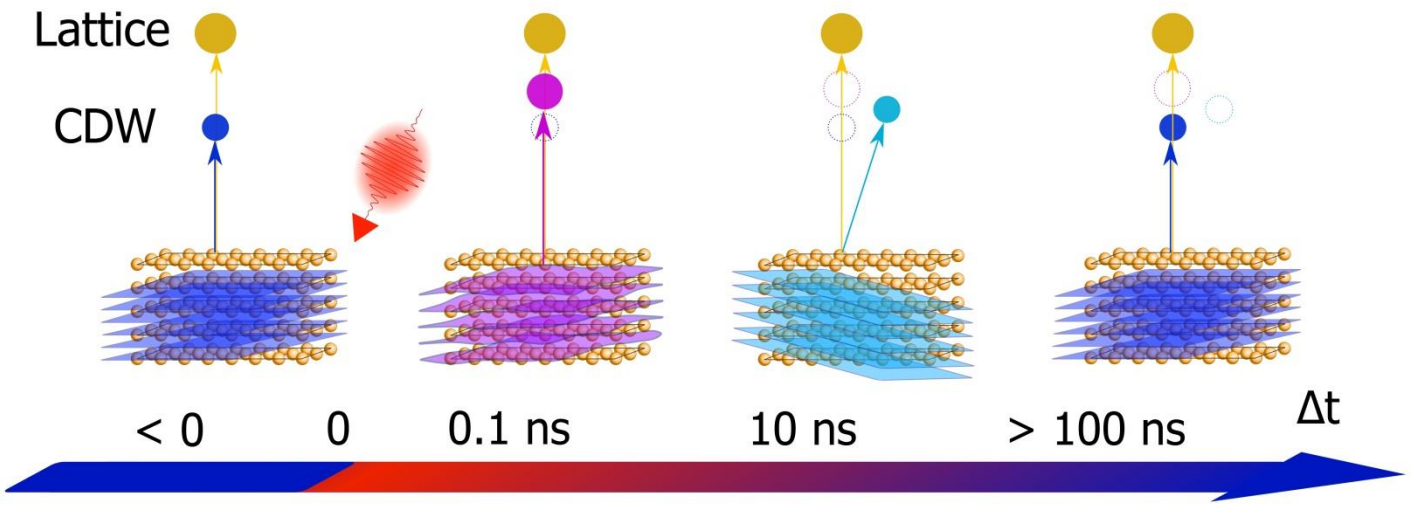
Spin and charge density waves in chromium through the spin-flip transition : statics and ultrafast dynamics



V.L.R. Jacques[1], C. Laulhé[1,2], D. Ghoneim[1] , A. Gallo-Frantz[1], S. Ravy[1] & D. Le Bolloc'h[1]

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[2]Synchrotron SOLEIL, L'Orme des Merisiers, Saint-Aubin, 91192 Gif-sur-Yvette, France

ECRYS2022 – Cargèse – 11/08/2022

Outline

- Introduction to the density waves of chromium
- SDW and CDW static orders through the spin-flip transition
- CDW behavior after laser-pulse excitation from fs to ns timescales
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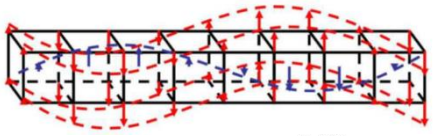
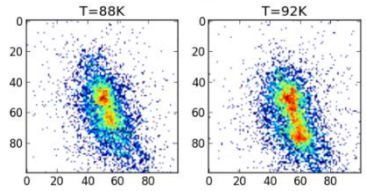
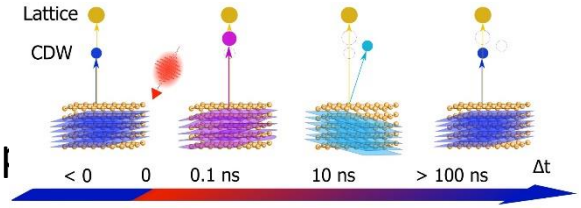
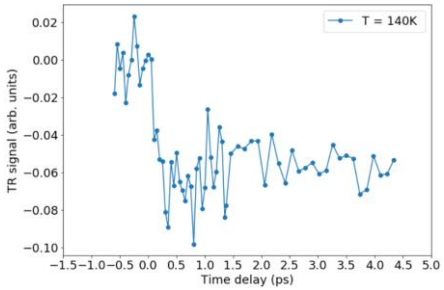
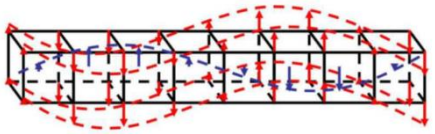


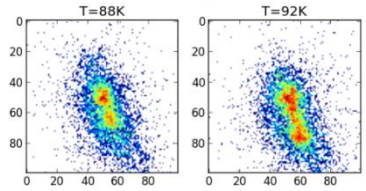






Outline





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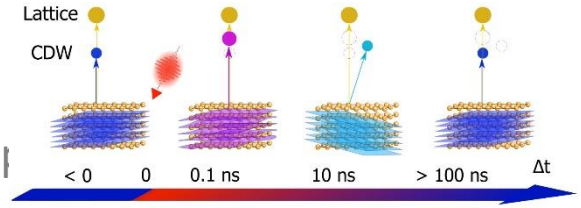
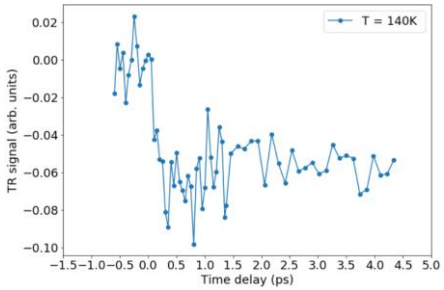
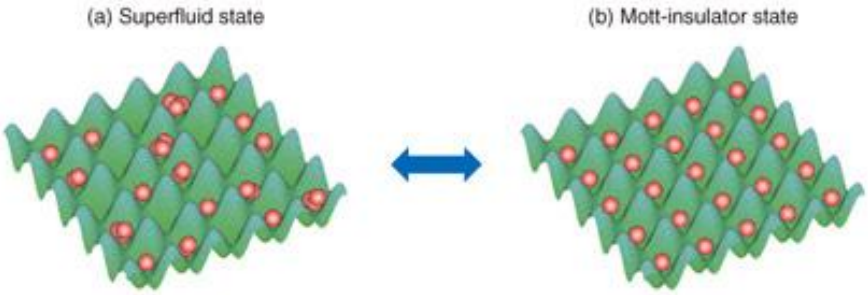
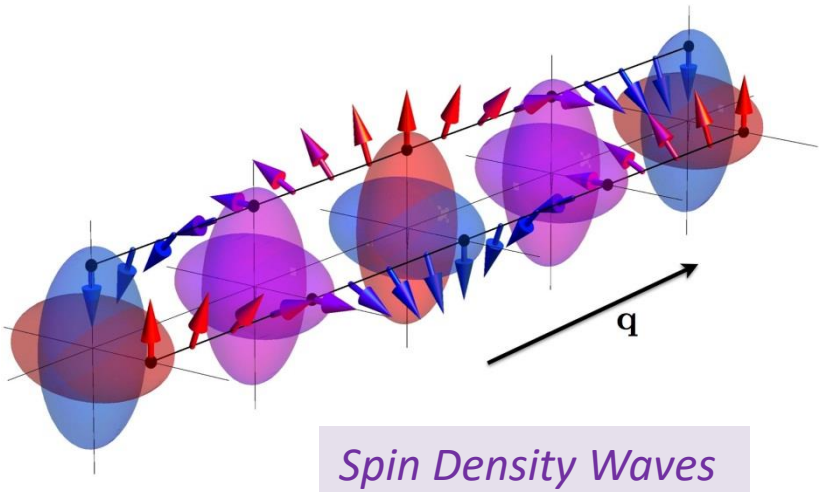




Correlated electron systems: a rich world

Correlations ➔ drive physical properties
Ex: metal ➔ insulator

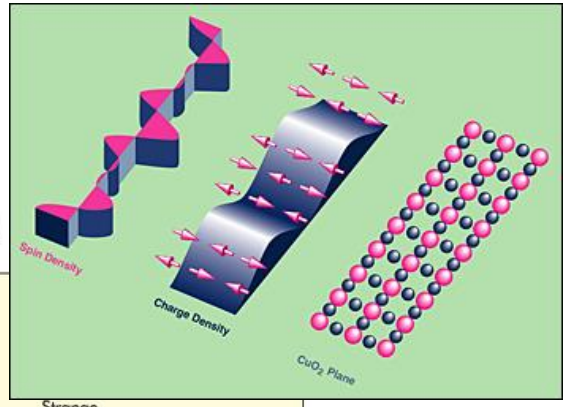


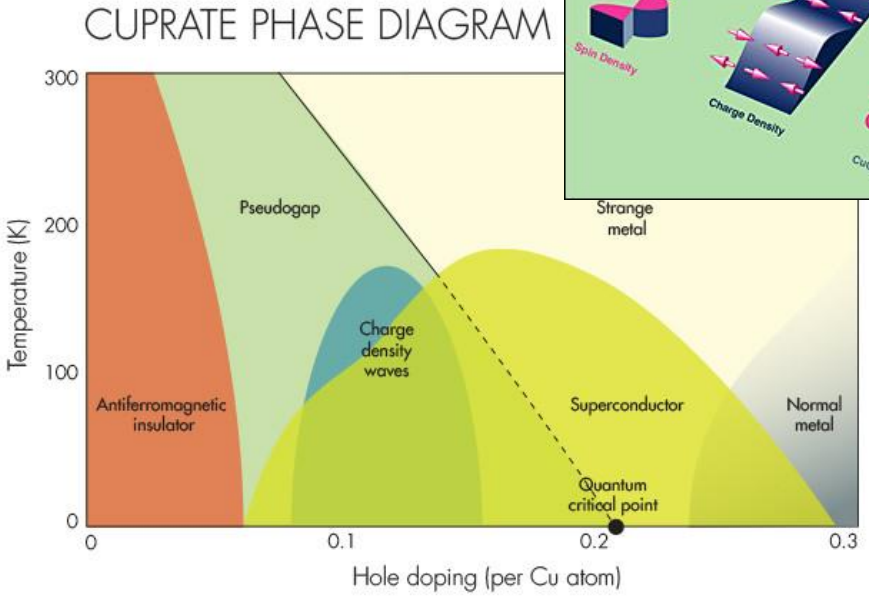


Spin Density Waves

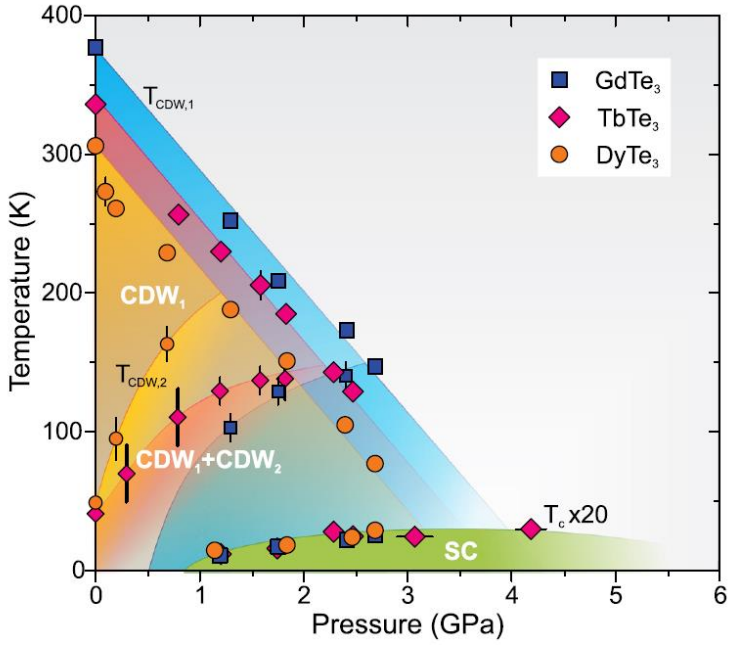
Mott insulators

Superconductors



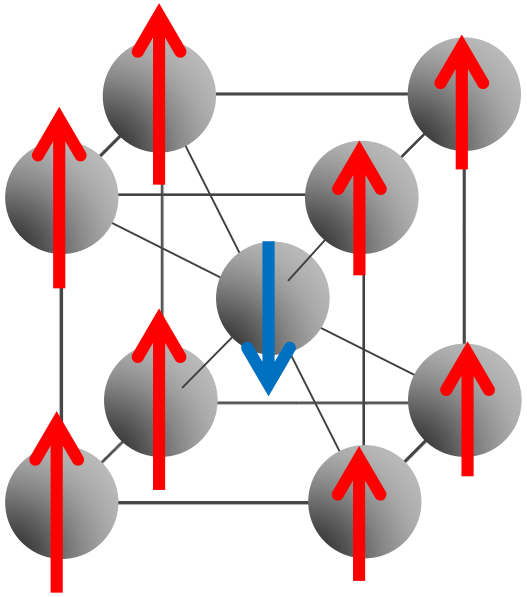


Charge Density Waves

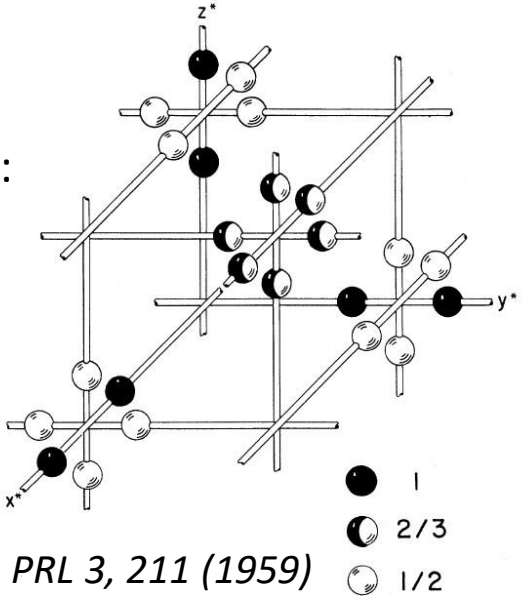


A SDW transition in a simple metal

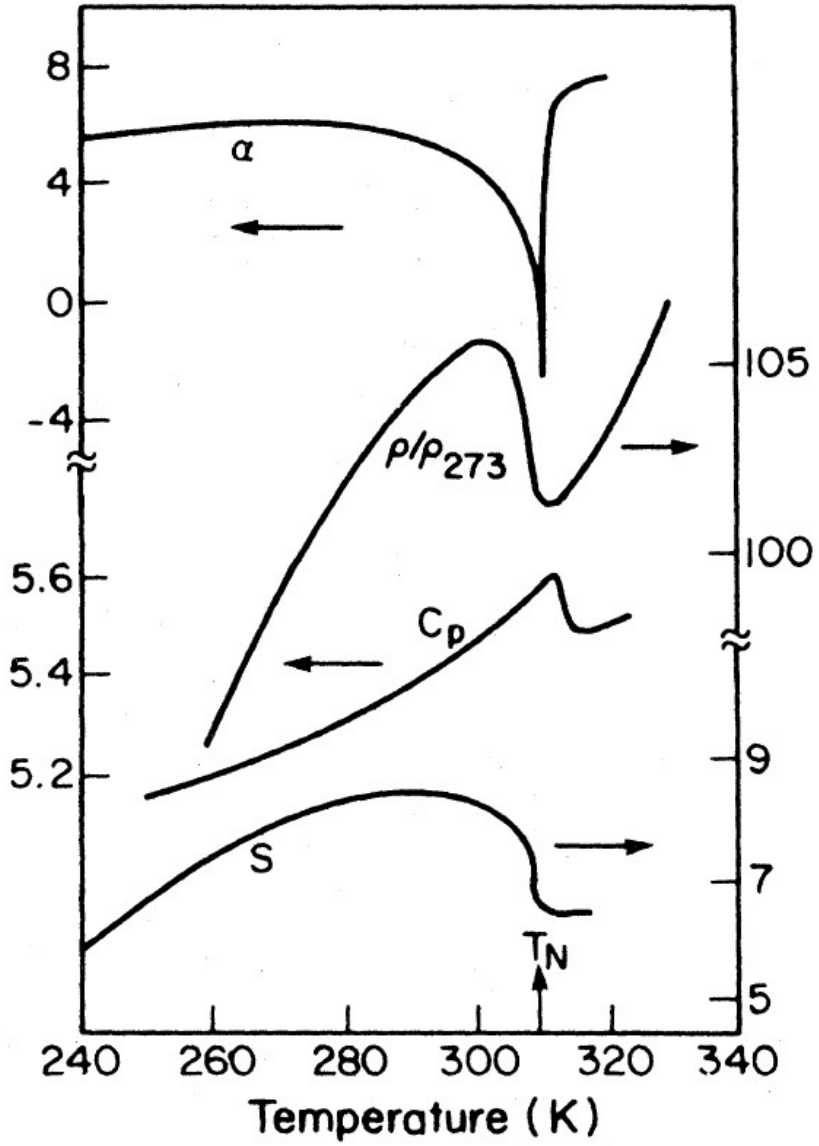
Cr



Neutron Diffraction:

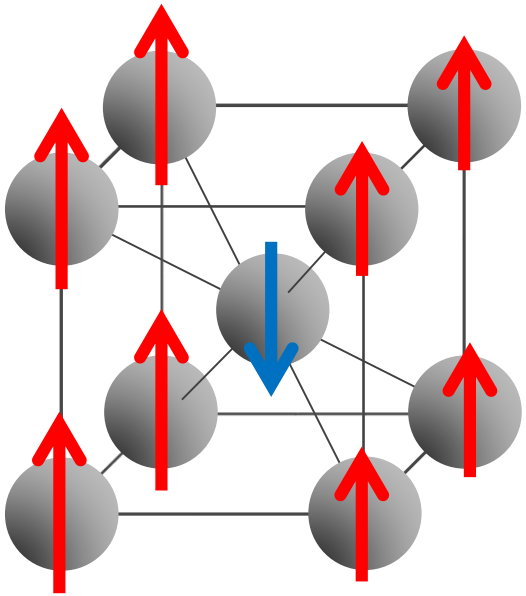


Corliss et al. PRL 3, 211 (1959)



Fawcett, Rev. Mod. Phys. 60, 209 (1988)

SDW in a 3D metal: a peculiar Fermi surface nesting

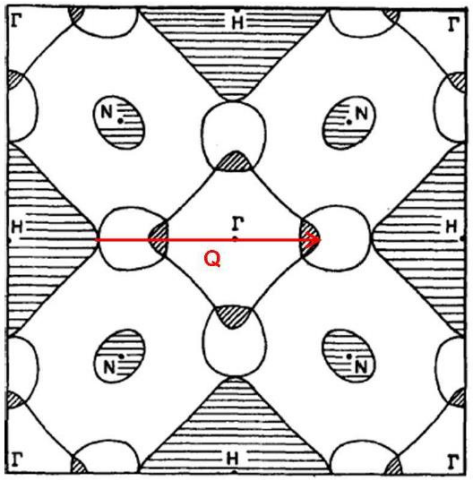


For $T<T_N$:
AFM + SDW along <001>:
➔ Periodic modulation of $|\mathbf{m}|$

Two transitions :

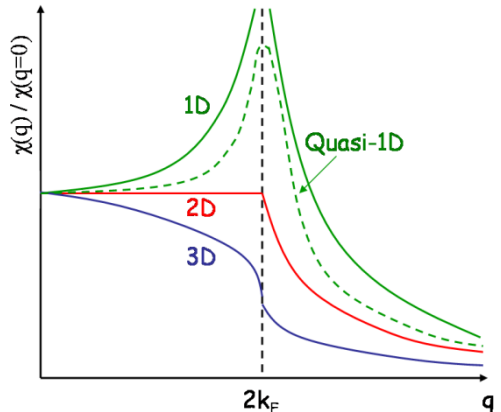
$T_N = 311K$

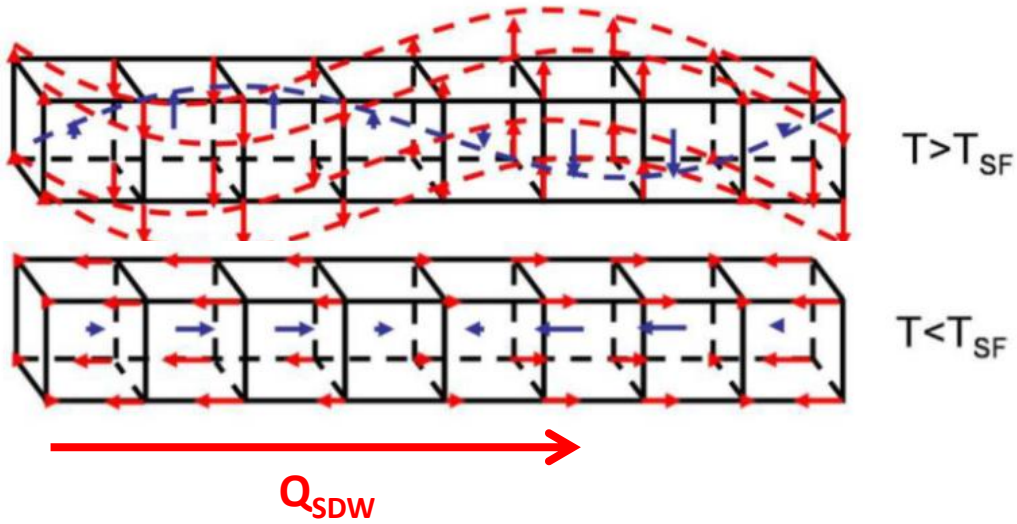
$T_{SF} = 123K$



Cr Fermi surface

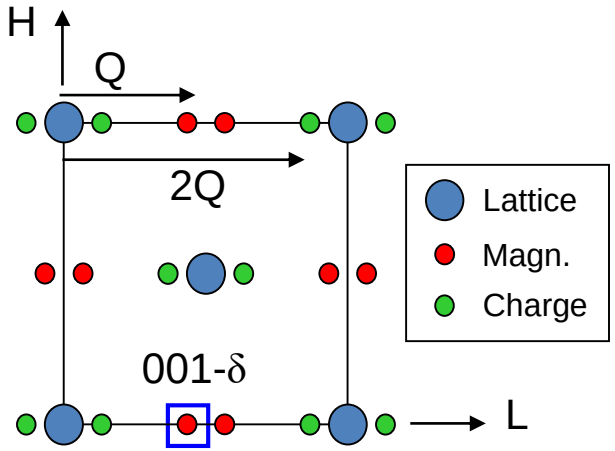
$$\chi(\vec{q}) = \int \frac{d\vec{k}}{(2\pi)^d} \frac{f_k - f_{k+q}}{\varepsilon_k - \varepsilon_{k+q}}$$

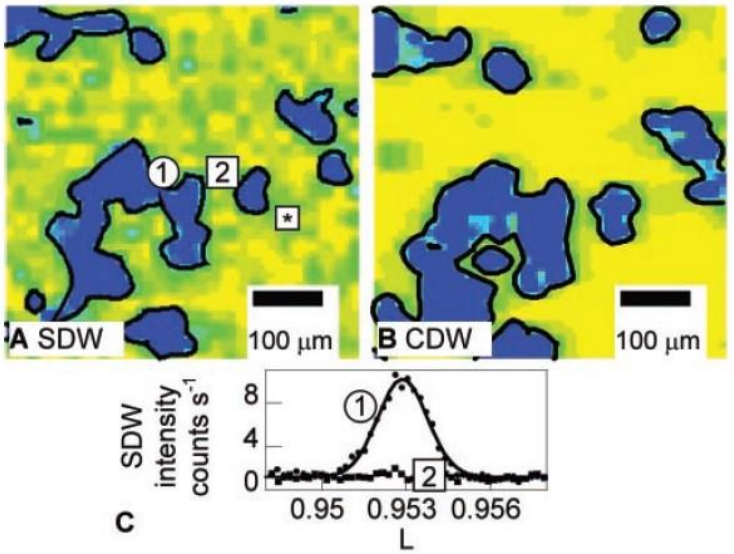




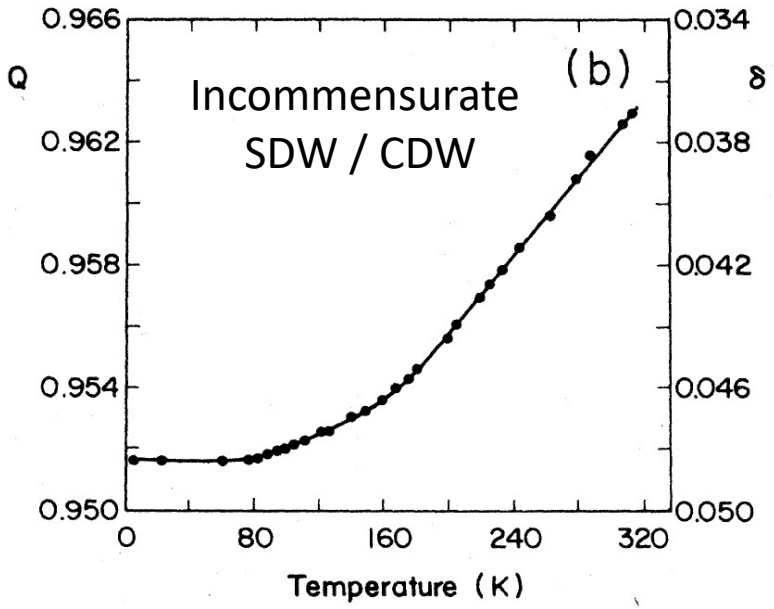
SDW does not come alone : CDW also appears at 2Q

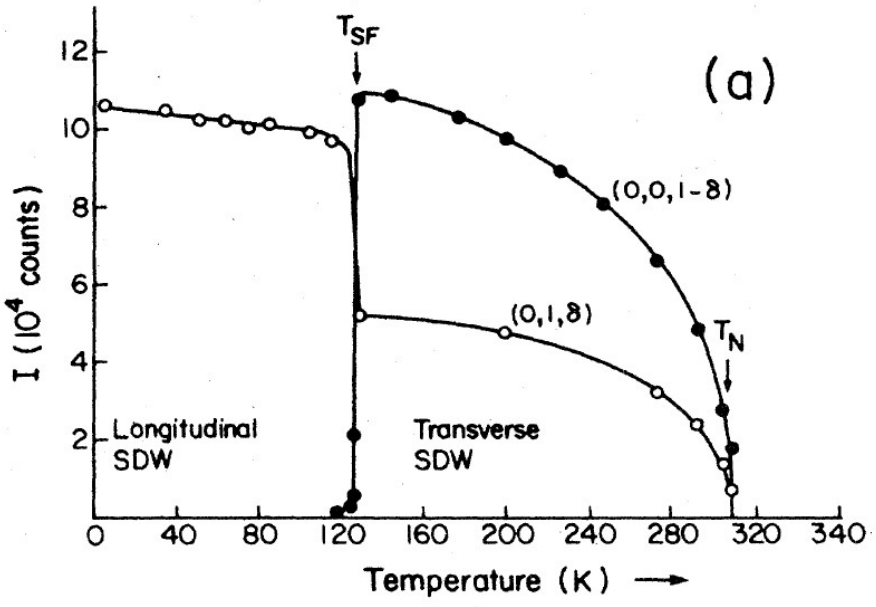
In x-ray diffraction (for single-Q sample):





*Evans et al., Science **295**, 1042 (2002)*



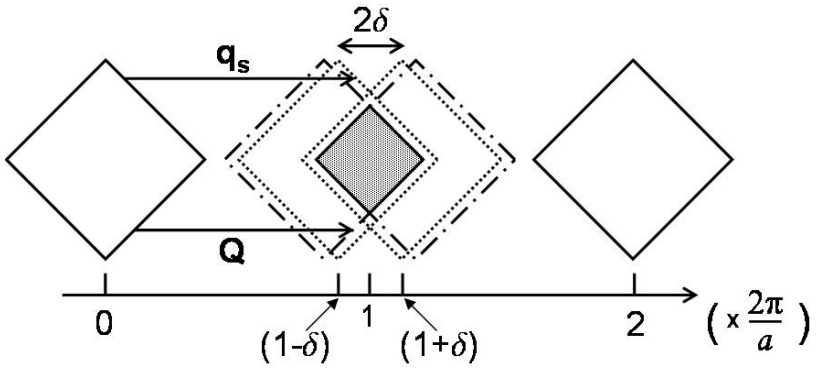


How does the CDW appear?

SDW: modulation with wavevector Q + harmonics nQ.
- n even: charge component
- n odd: spin component

band model

2 successive nesting:
- electron-hole → SDW
- hole-hole → CDW



Young and Sokoloff, J. Phys. F: Metal Phys., **4**, 1304 (1974)

Magnetostriction

The SDW creates a strain wave at 2Q

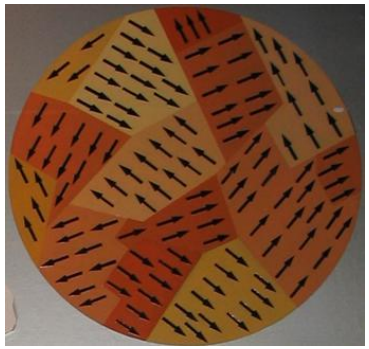
It explains the Spin-Flip Transition at T=123K

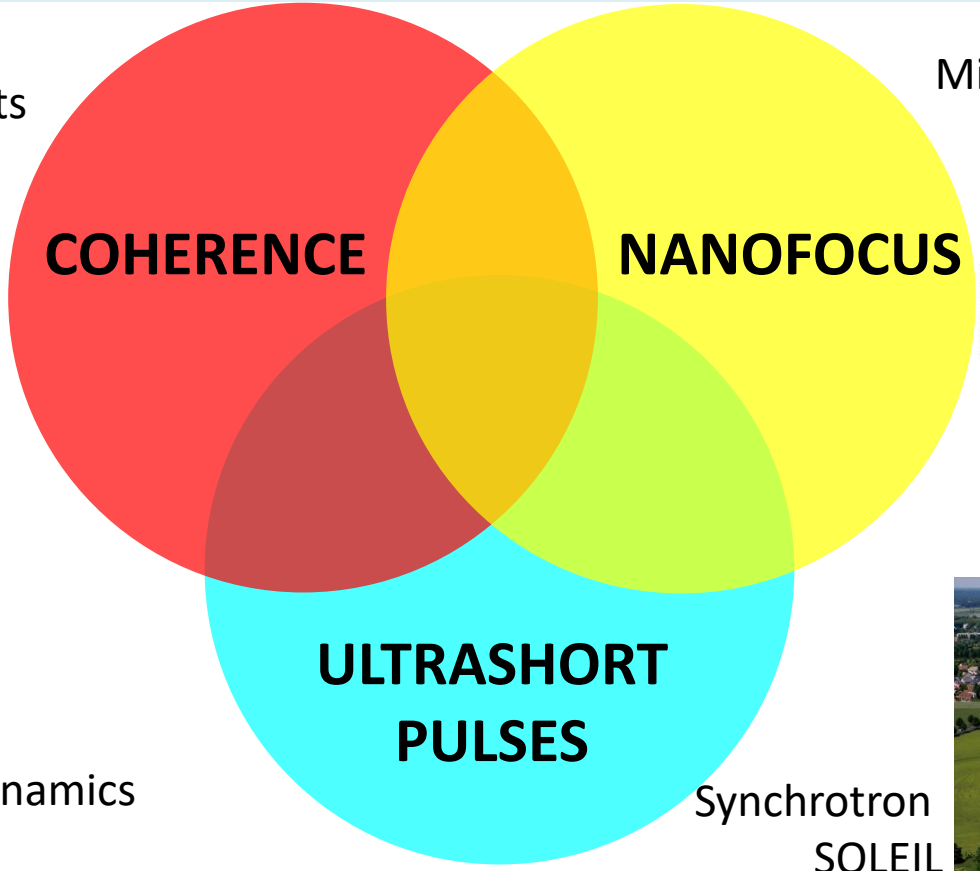
Cowan, J. Phys. F: Metal Phys., **8**, 423 (1978)

We use novel techniques to get a new vision of CDW/SDW coupling in Cr:
coherent x-ray diffraction and ***time-resolved x-ray diffraction***

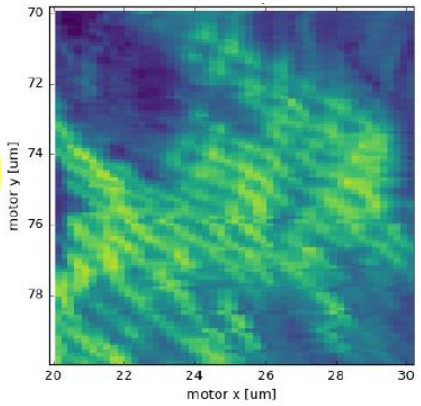
X-ray beam properties at large scale instruments

Imaging
Phase Objects/Defects

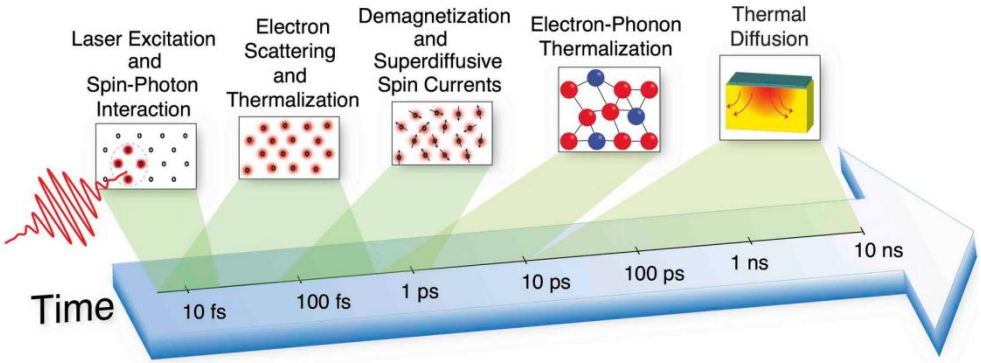




Micro/Nano Structure

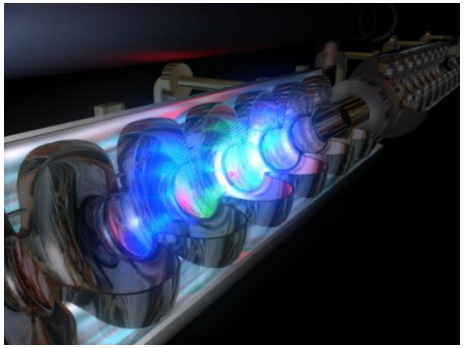


Ultrafast Dynamics



Synchrotron
SOLEIL

European
XFEL



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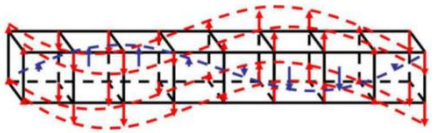
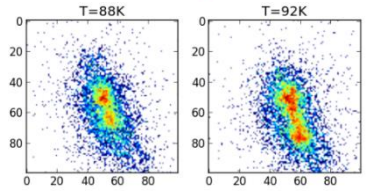
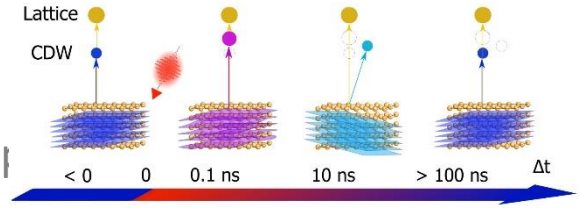
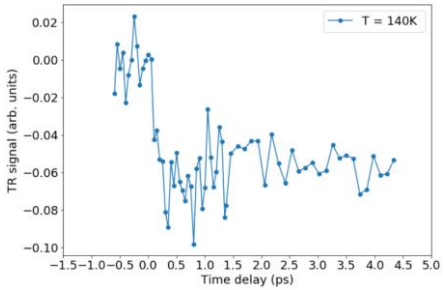


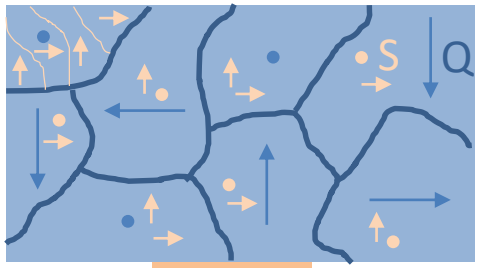




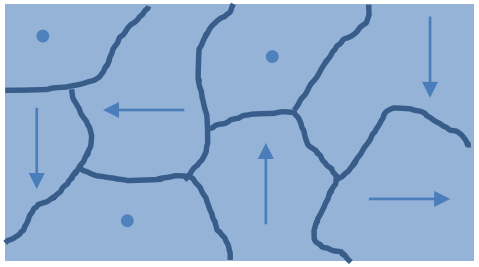


SDW and CDW through the spin-flip transition

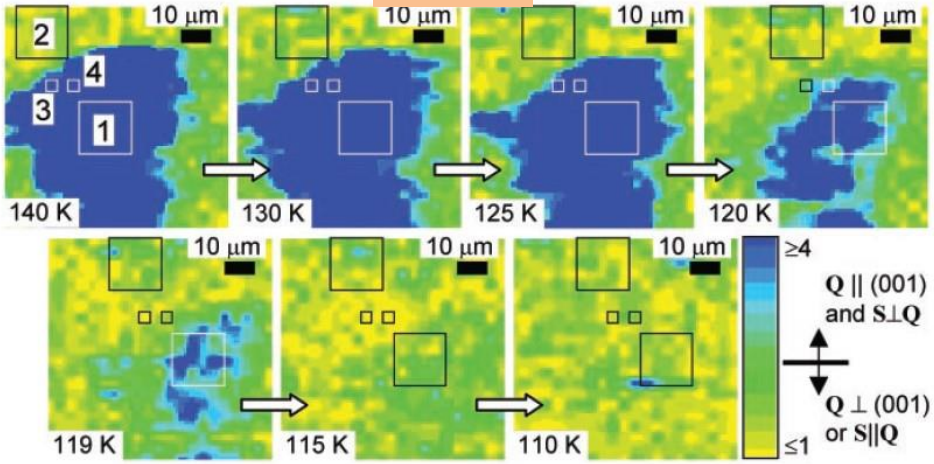
*Evans et al., Science **295**, 1042 (2002)*



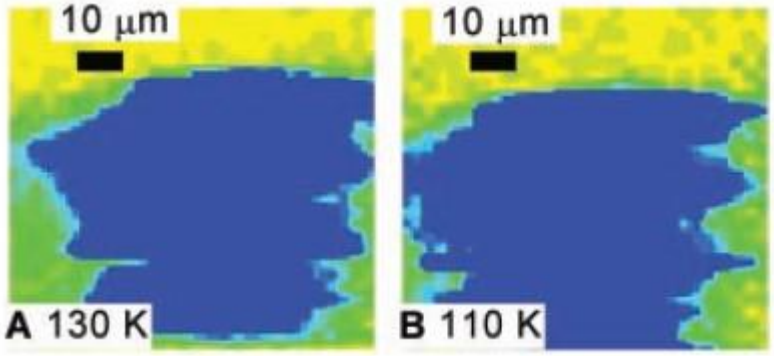
$T > T_{SF}$



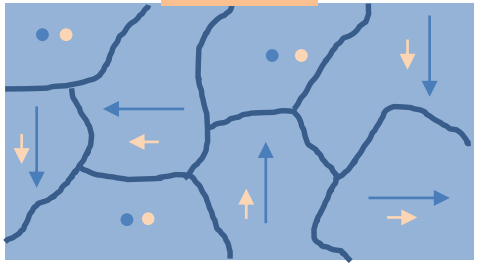
TSDW



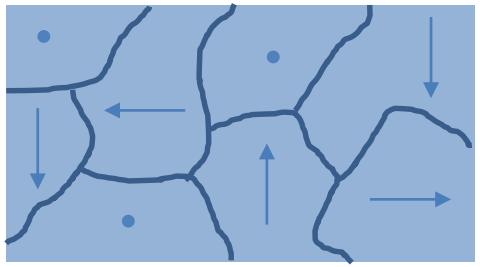
CDW



LSDW

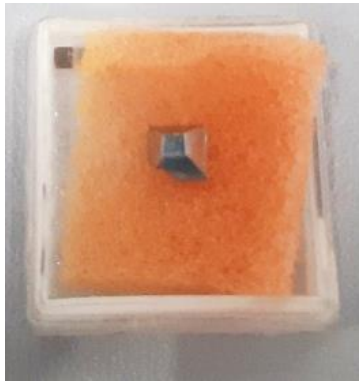


$T < T_{SF}$

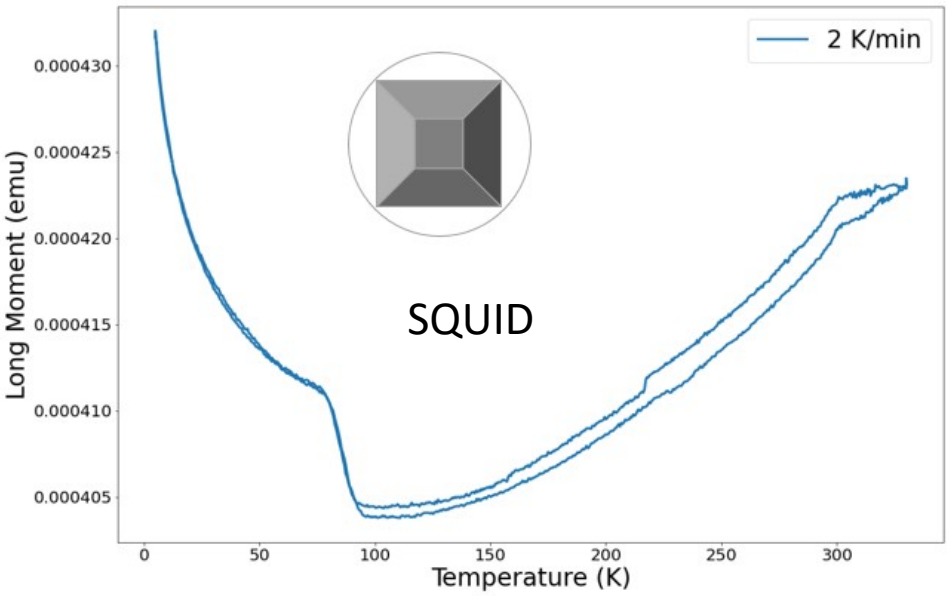


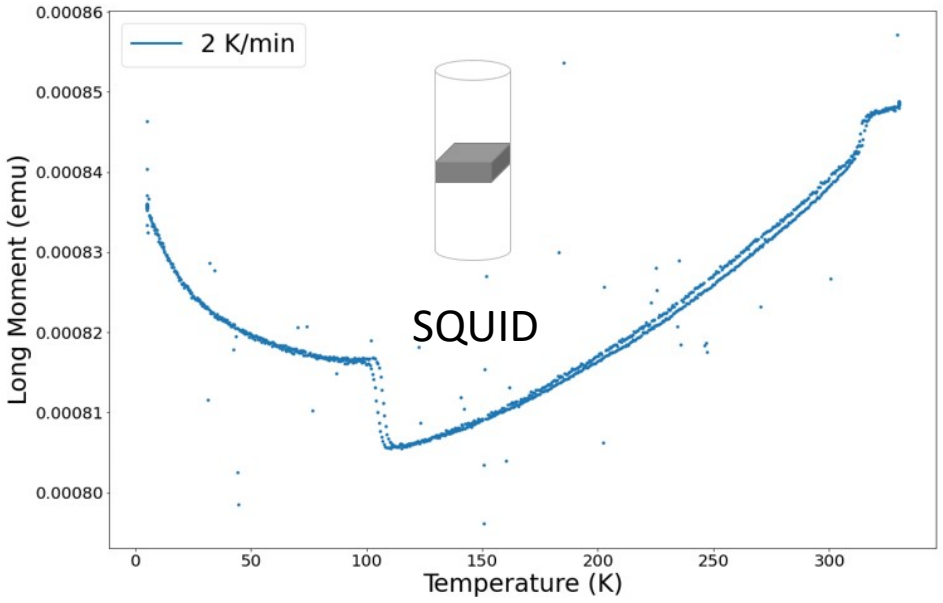
Bulk samples used in our studies

Single-Q
truncated pyramid



Multi-Q
square sample



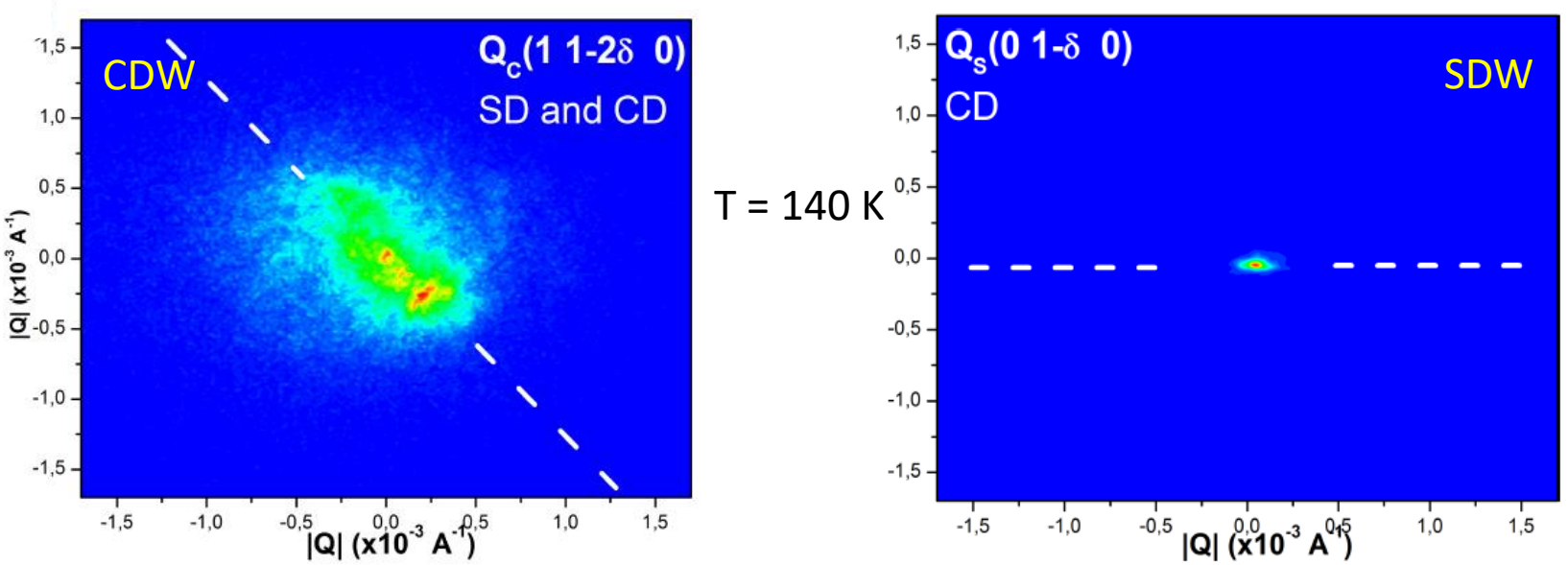


T_N = 300 K
T_{SF} = 85 K

T_N = 314 K
T_{SF} = 105 K

Static SDW and CDW : two very different orders

Coherent and **simultaneous** x-ray diffraction on CDW and SDW reflections



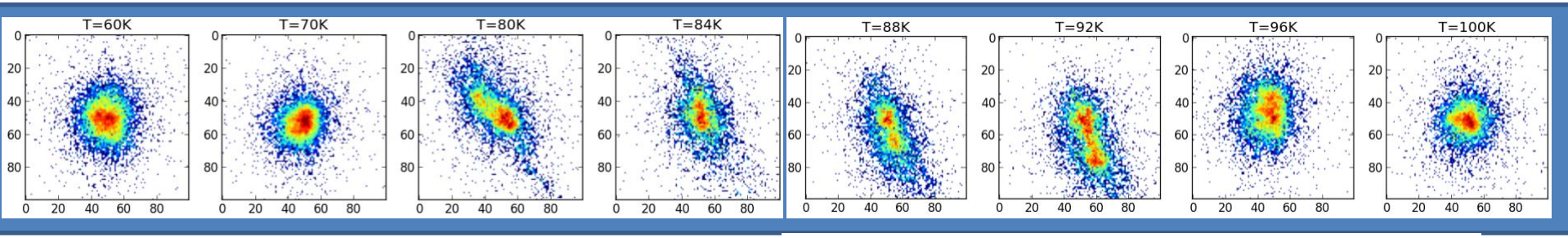
SDW : perfect order with infinite correlation lengths
CDW : many phase defects with sub-micrometer correlation lengths

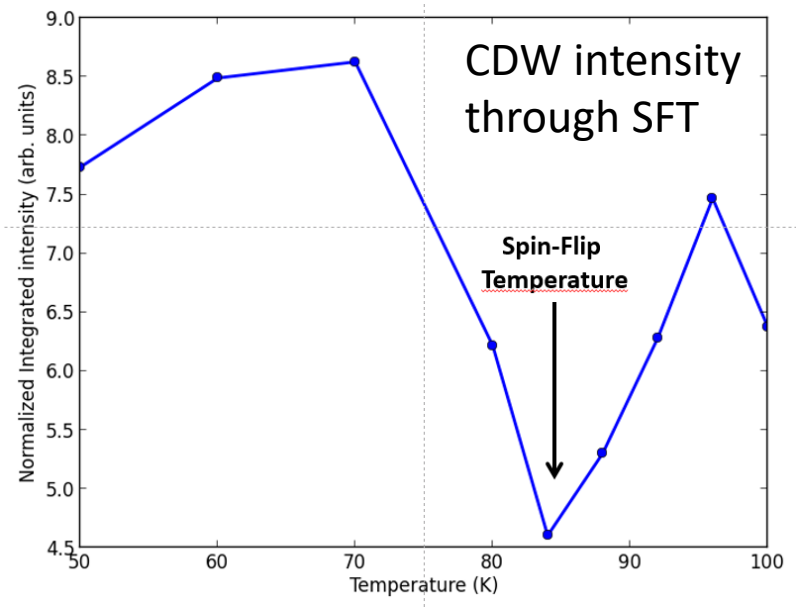
Not the same amount of defects on CDW and SDW:
Not in agreement with CDW formation through magnetistrictive coupling

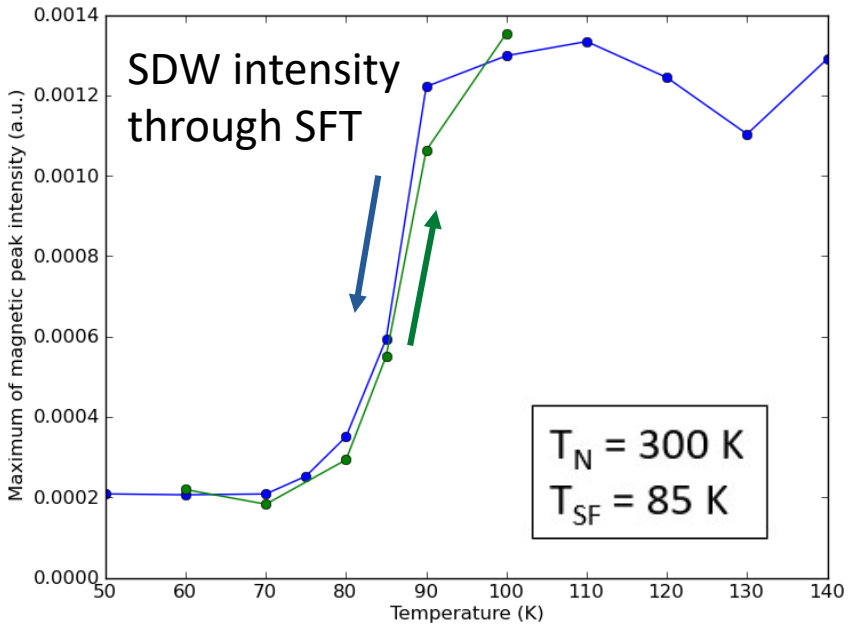
➔ To get more information on the coupling: compare their dynamics of formation
➔ Laser Pump – x-ray probe diffraction experiment to perform this

*Jacques et al. PRB **89**, 245127 (2014)*

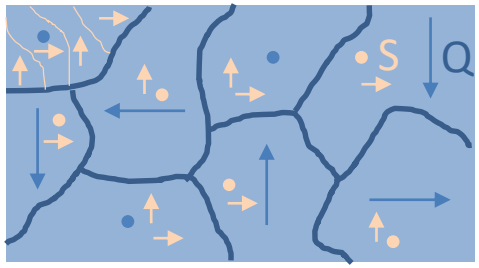
CDW through the spin-slip transition – a clear structural change





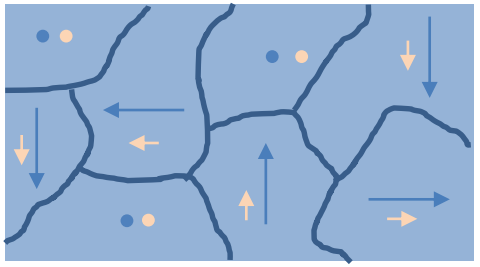


TSDW



CDW sensitive to magnetic domain wall reorganization

LSDW



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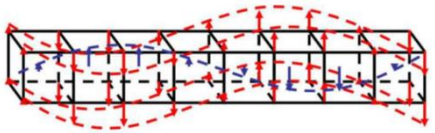
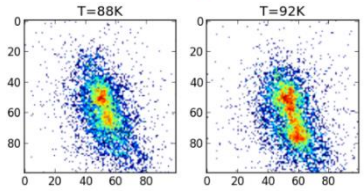
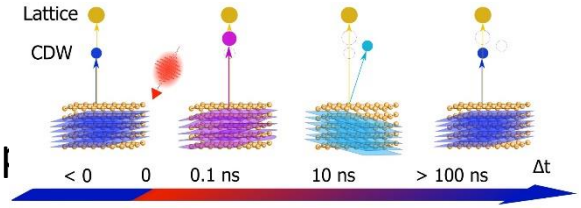
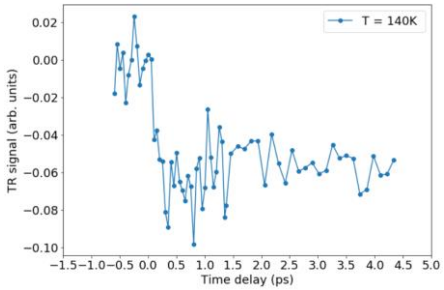
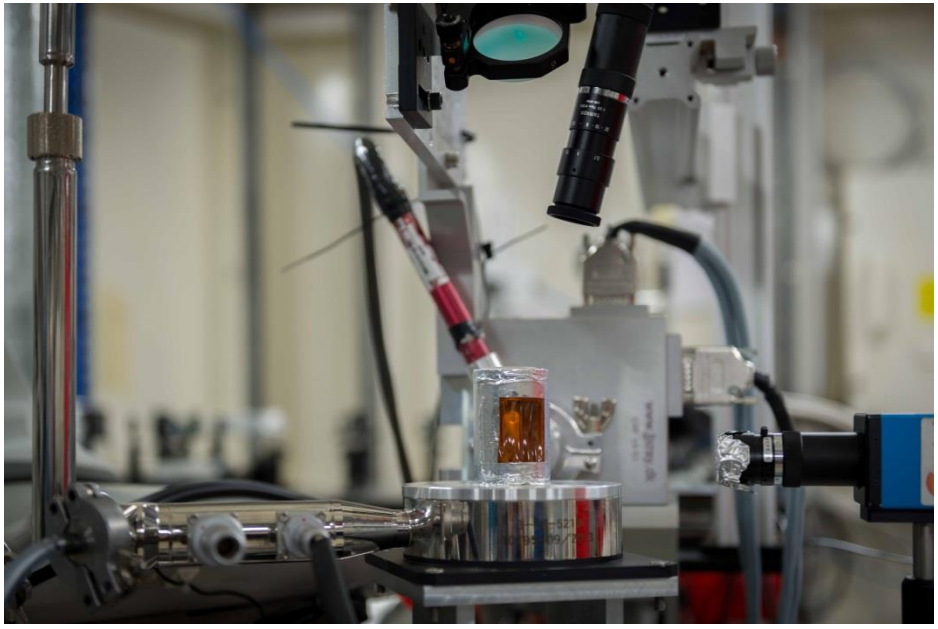


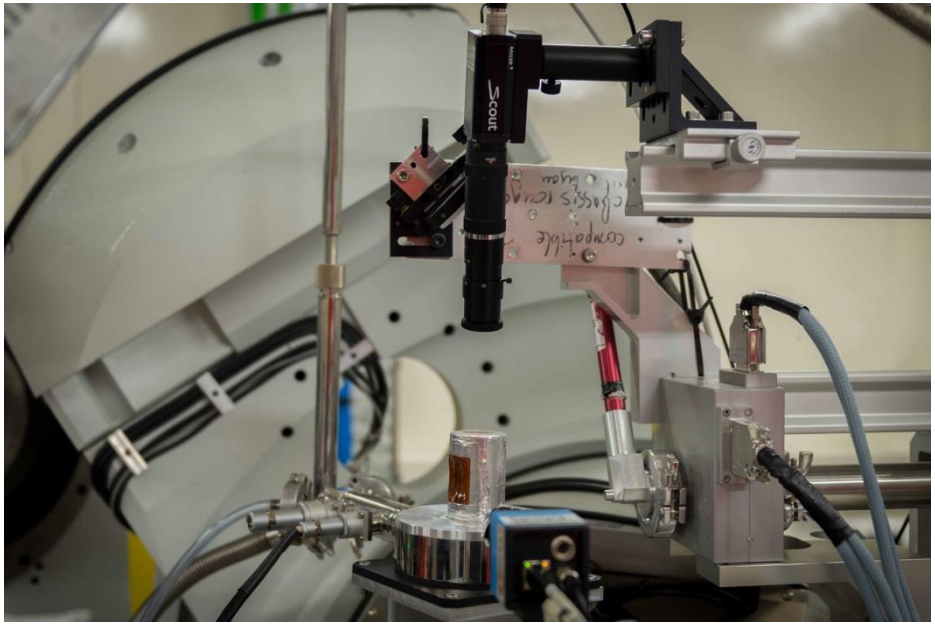


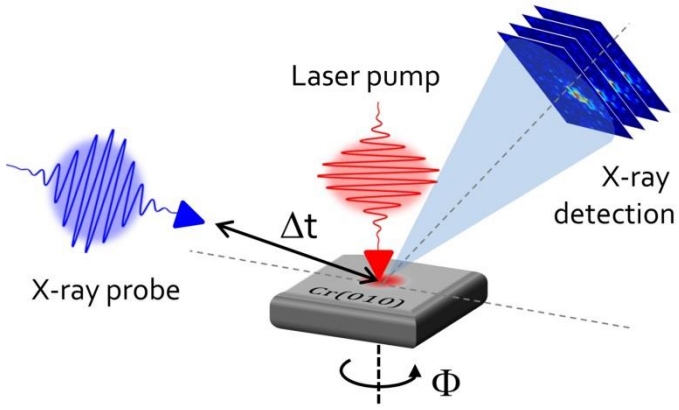




ps time-resolved x-ray diffraction @ CRISTAL, Soleil Synchrotron







Multi-Q chromium sample

X-rays:

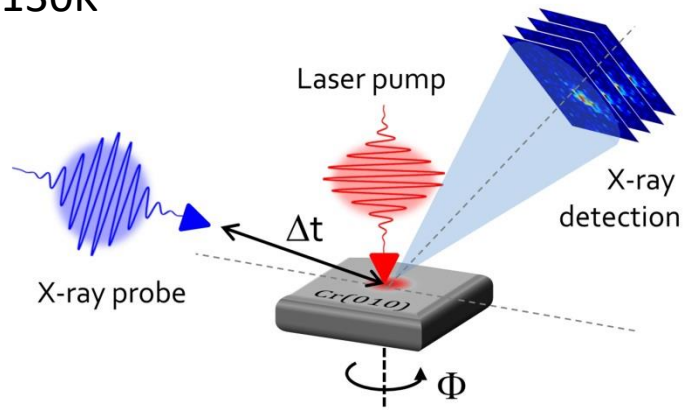
- 7keV
- 100nm penetration
- Detection: XPAD 3.2

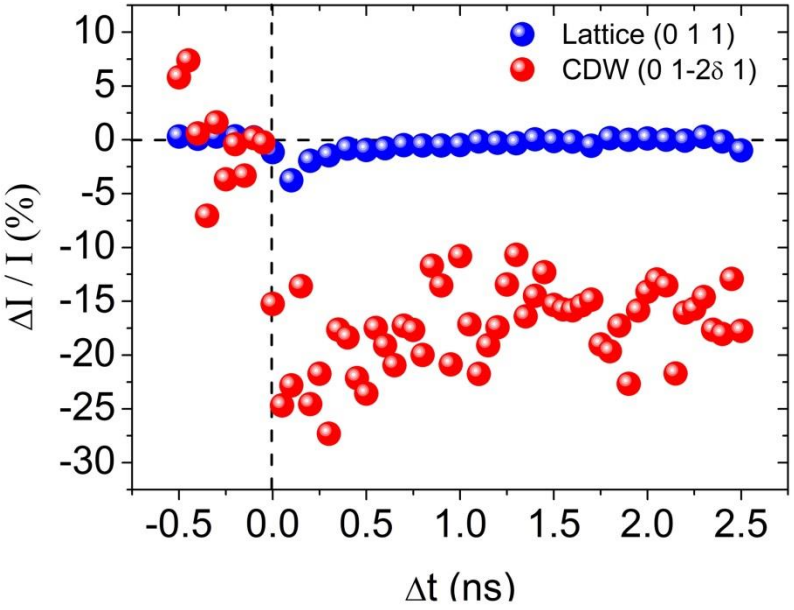
Laser:

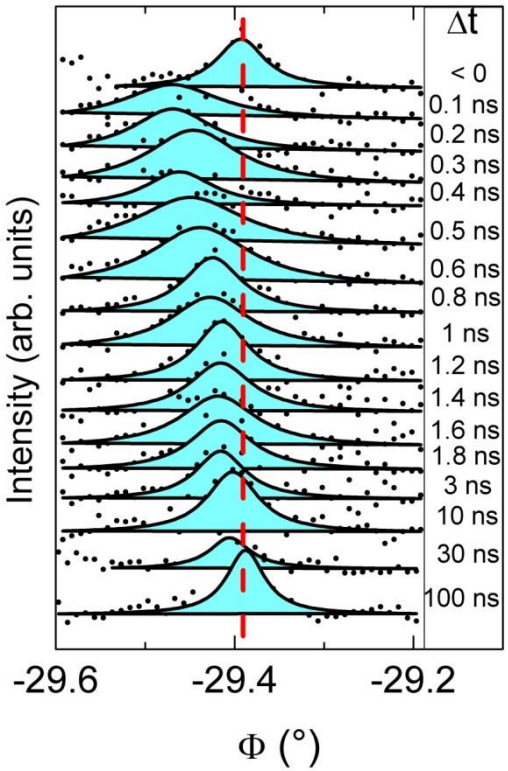
- 800nm, 30fs
- Up to 6.2mJ/pulse
- spot diameter: 2mm
- Rep rate: 1kHz

Time evolution of CDW and atomic lattice

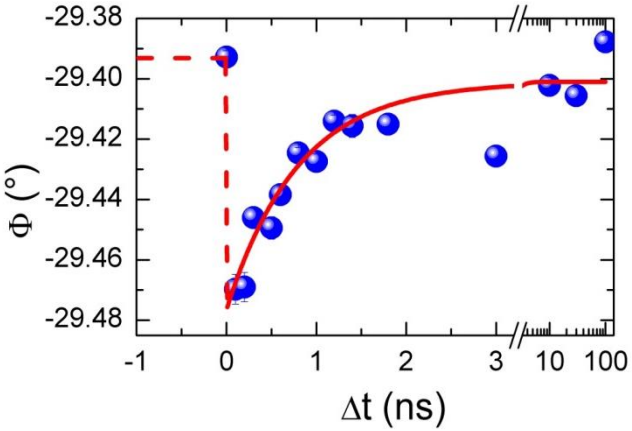
T = 130K



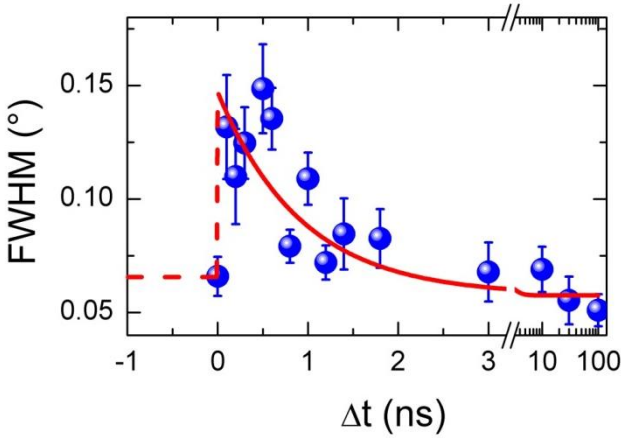




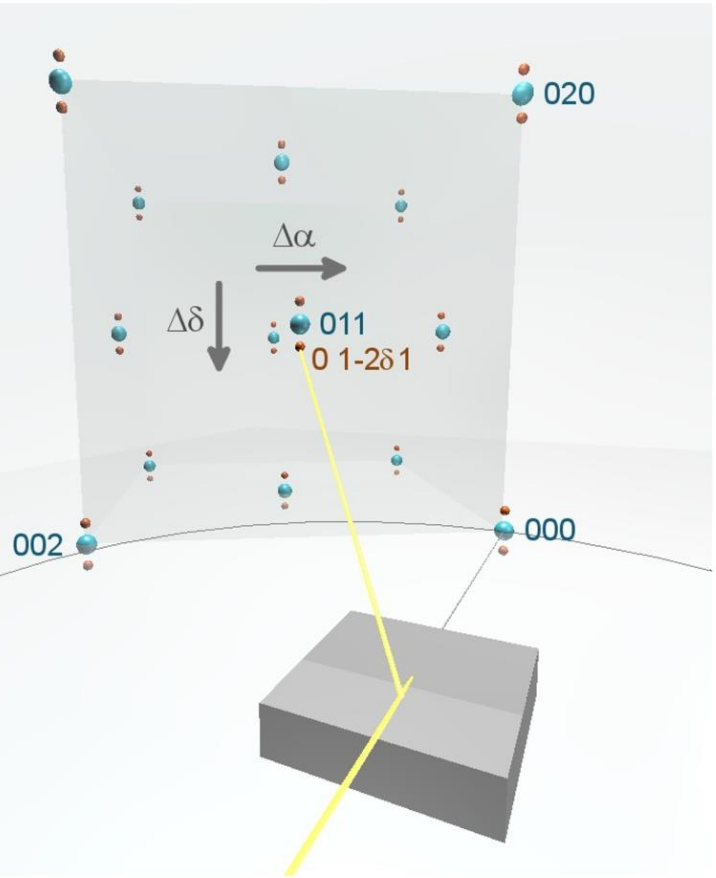
Pic position

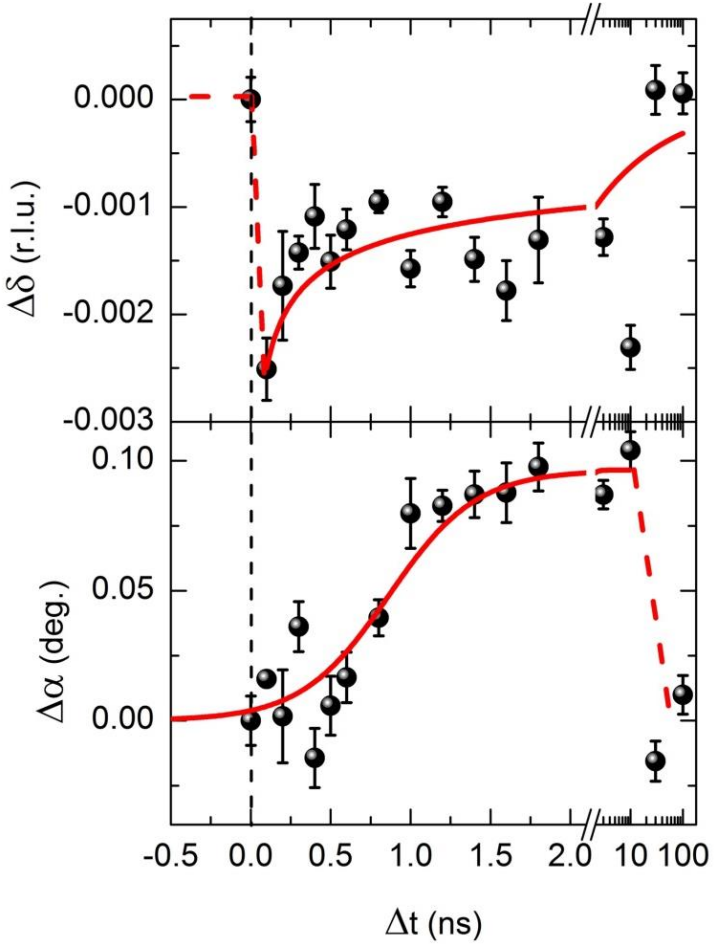


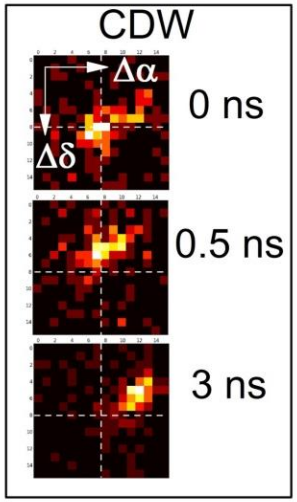
Pic width

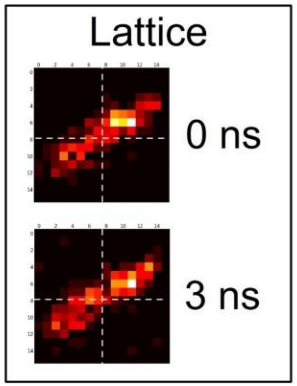


A different temporal evolution of the rotational component



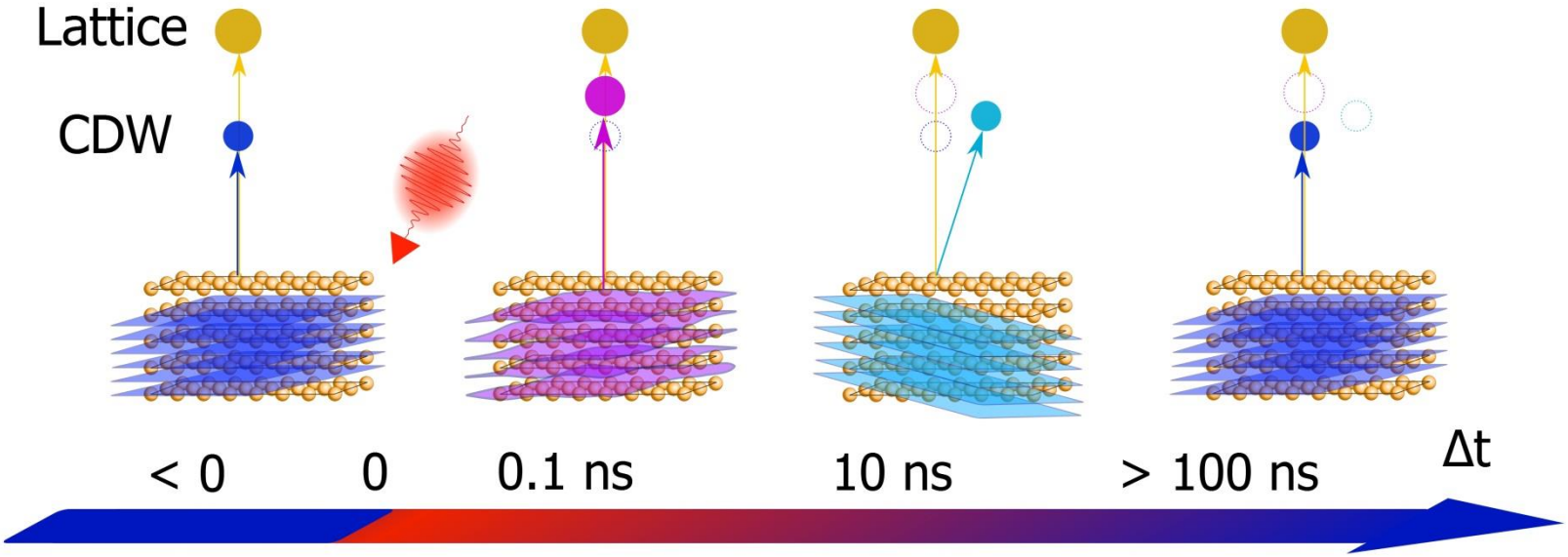






Real space picture of out-of-equilibrium system

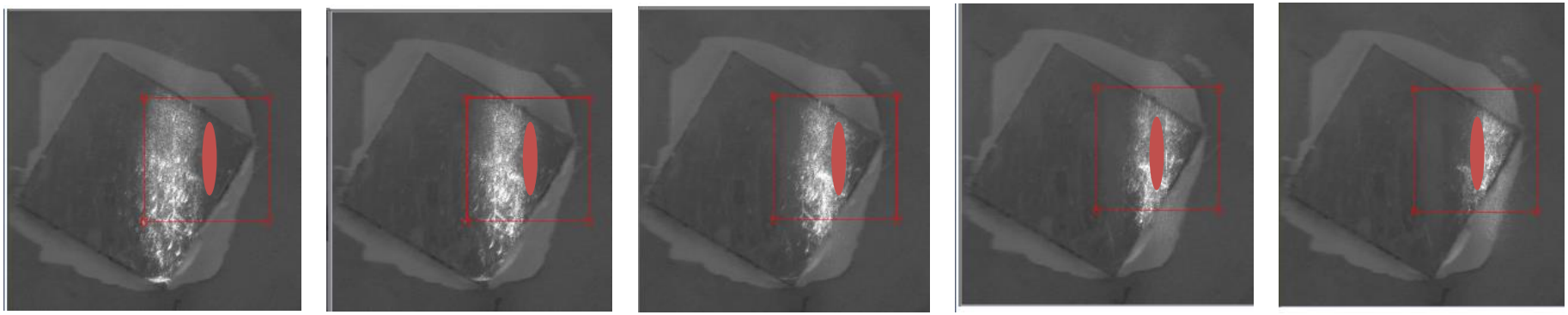
V. Jacques et al., PRL ***117***, 156401 (2016)

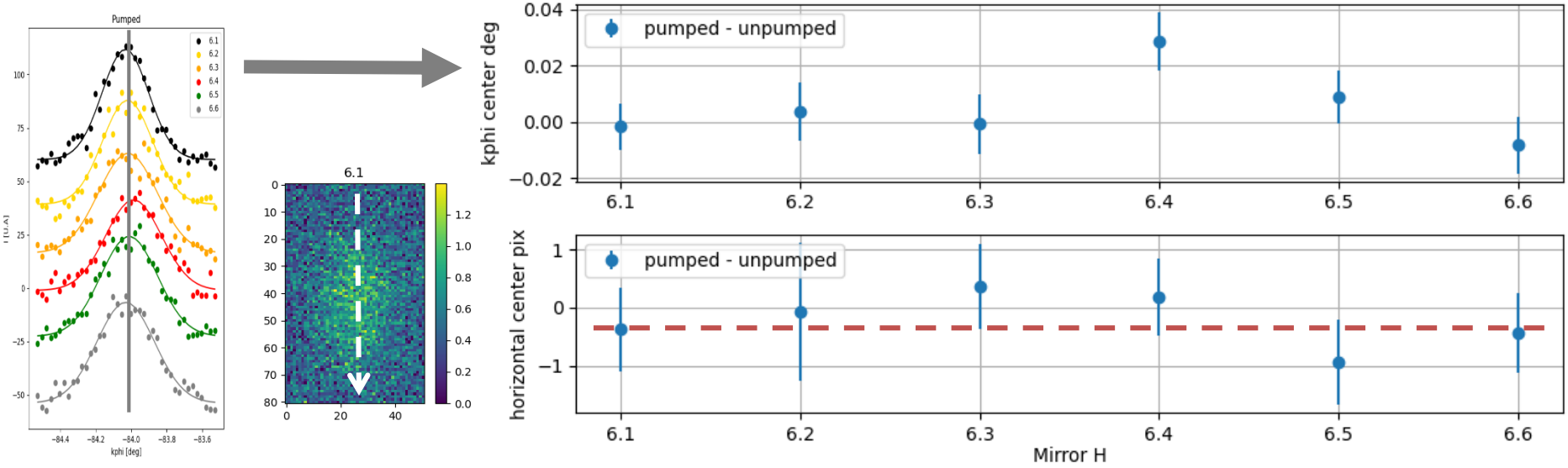


- CDW expands within time resolution and recontracts after 2ns
- Tilt takes place at longer timescales (2-100 ns)

Tilt ➔ CDW decouples from atomic lattice → CDW able to slide in chromium?

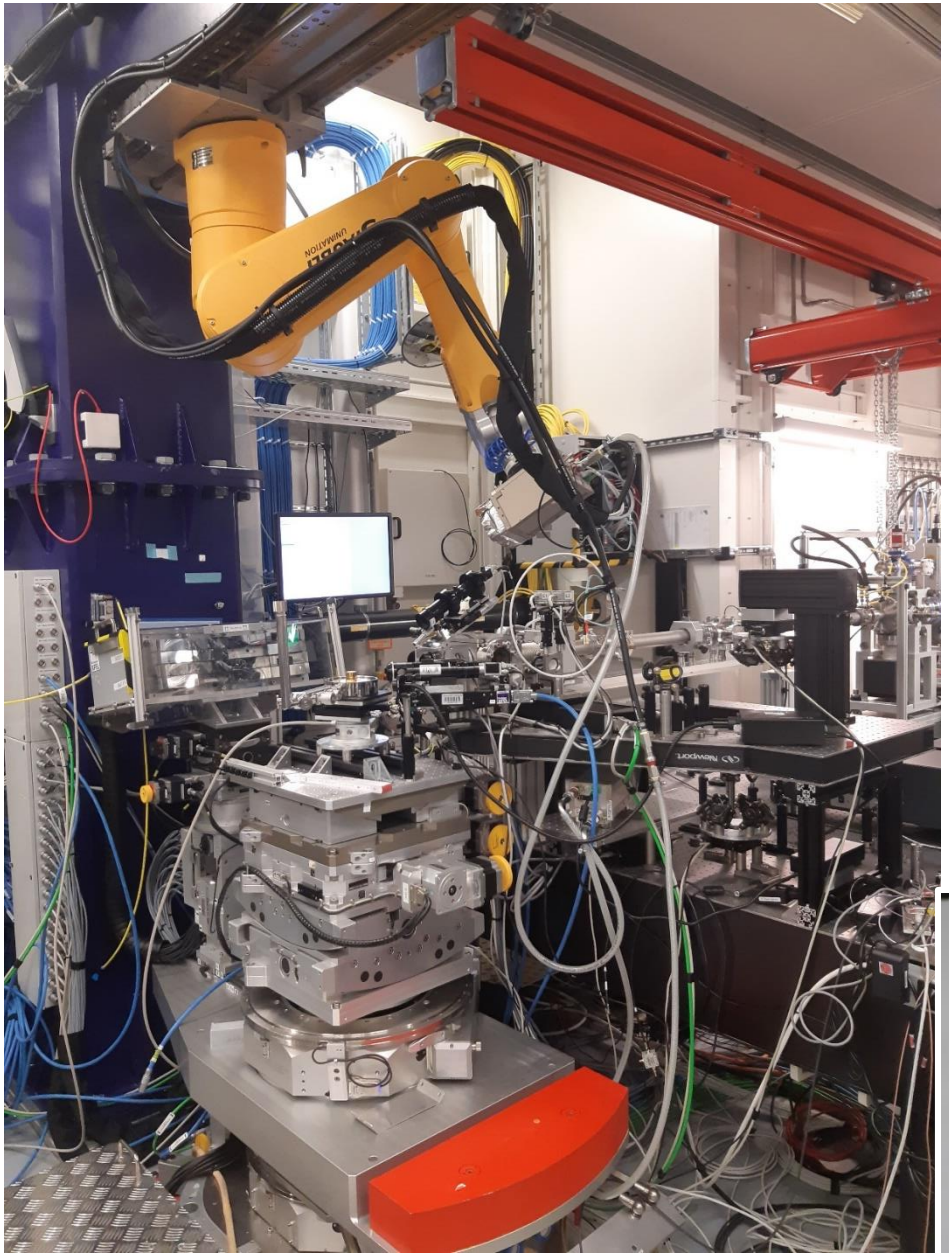
ps time-resolved x-ray diffraction @ CRISTAL, Soleil Synchrotron

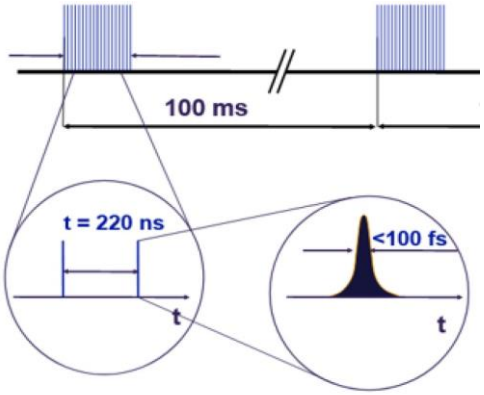




➔ Tilt of the CDW due to strain gradient depending on laser position

fs time-resolved x-ray diffraction @ FXE, European XFEL





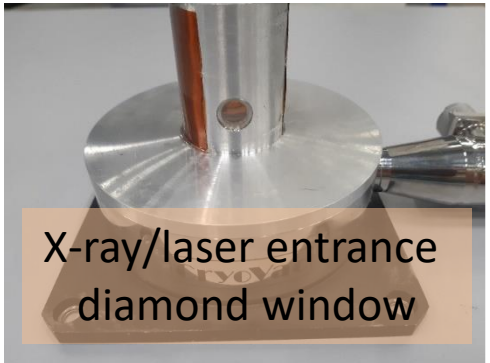
X-rays

- 1 bunch/train
- 30fs x-ray pulses
- E = 5.989 keV
- 10µm spot

Laser

- 30fs pulses
- 800 nm
- 10µm spot

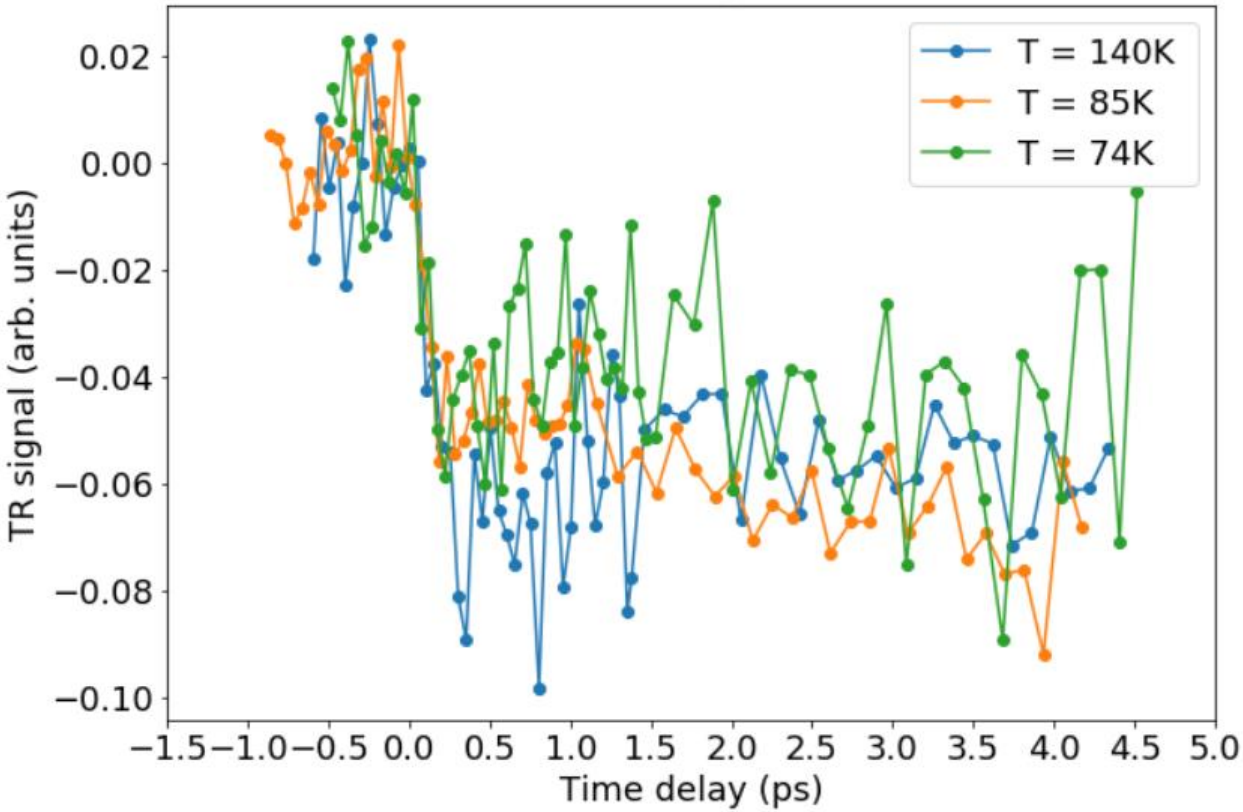
Nearly - Colinear and grazing incidence of x-ray and laser beams



X-ray/laser entrance diamond window

X-ray exit window kapton (125µm)

Time-resolved measurement of the CDW through the spin-flip



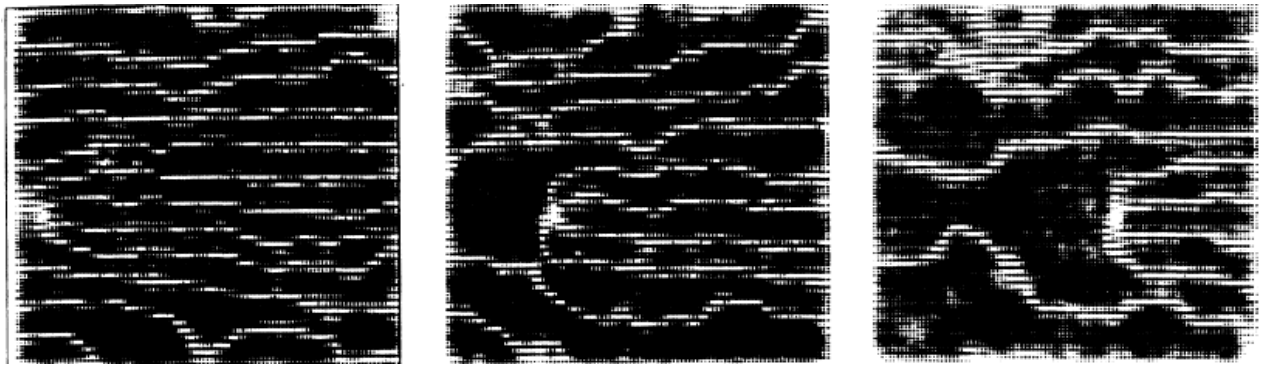
- 3 successive steps :
  1. Ultrafast decay (~100fs) → CDW excitation
  2. Partial recovery (~1ps) → CDW reapparition
  3. Longer-time decay (>1ps) → start of thermal transfer

Dynamics of step 2 (CDW reapparition) is different (longer) near Spin-Flip temperature

Time-sequence: excitation process, dislocations, decoupling

1. Excitation process <100 fs: most probably athermal excitations above gap (150 meV)
2. CDW partial recovery > 1 ps
3. Few ps: thermal effects : Debye-Waller + heat diffusion.

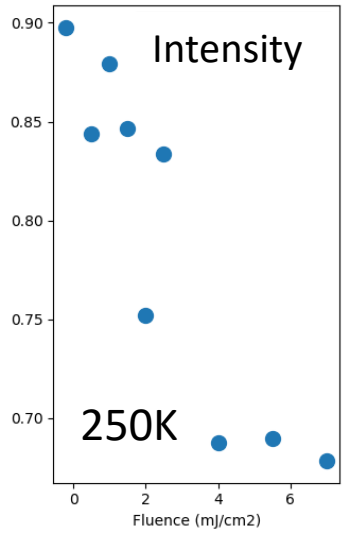
   Debye Waller ➔ $\Delta a/a \sim 2.10^{-4}$ < experimental resolution $\Delta q/q = 3.94.10^{-4}$
4. Within 500 ps: q_{cdw} change ➔ Dislocations involved?

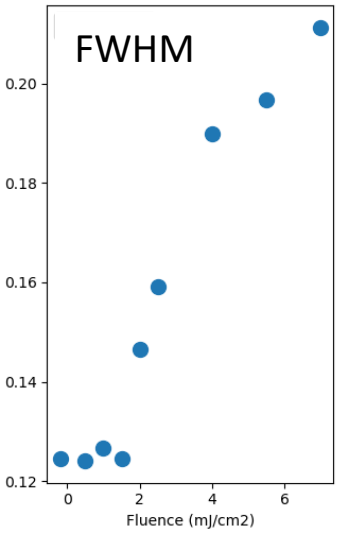


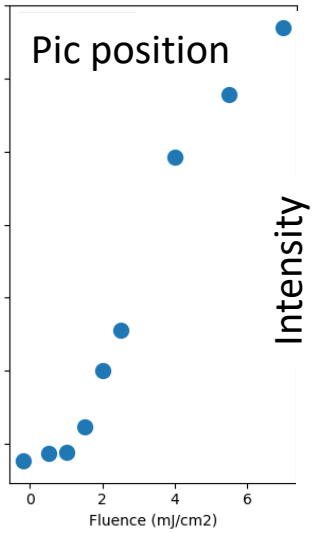
*Parlinski, PRB **35**, 8680 (1987)*

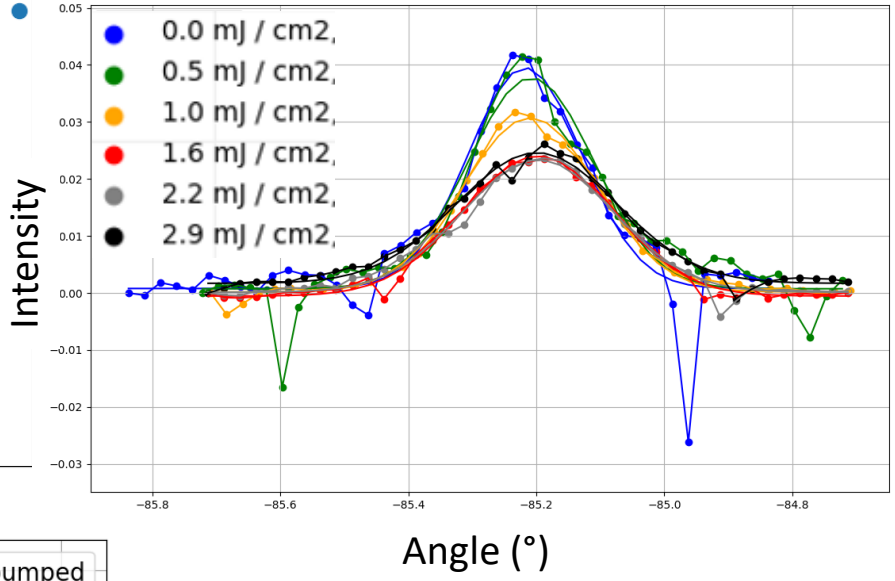
5. Tilt above 1 ns most probably to introduction of a strain-gradient by laser pulse

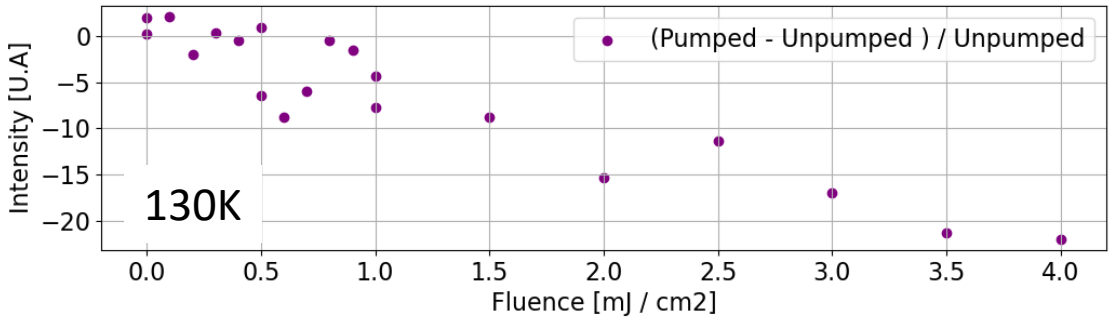
Threshold fluence for CDW excitation in multi-Q sample

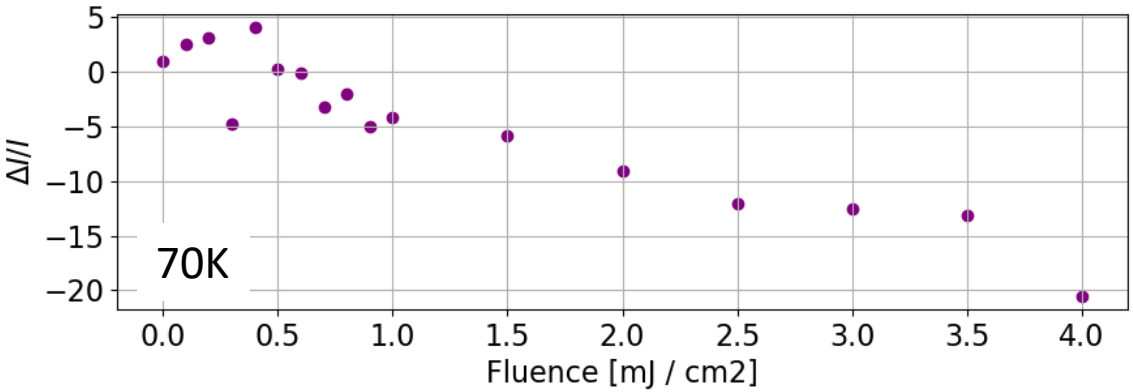


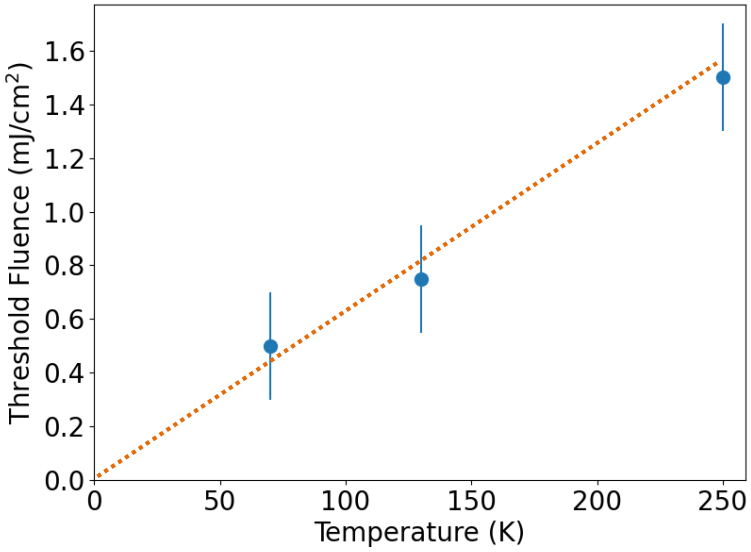












Summary and perspectives

- Static SDW and CDW have **very different correlation length** ξ
  - SDW : $\xi_{SDW} \rightarrow \infty$
  - CDW : $\xi_{CDW} < 1\mu m$

- CDW through the spin-flip transition :
  - CDW **domains are preserved** but **CDW 'feels' the transition** :
    - correlation length decreases
    - Amplitude decreases
    - After laser excitation : CDW partial recovery dynamics is different at SFT

- **CDW decoupling from lattice** ~2ns after laser excitation, due to strain gradient

- **Threshold fluence** for excitation of the CDW

➢ Need to probe the SDW dynamics in the same conditions as CDW.
➢ Get more XFEL beamtime !

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