

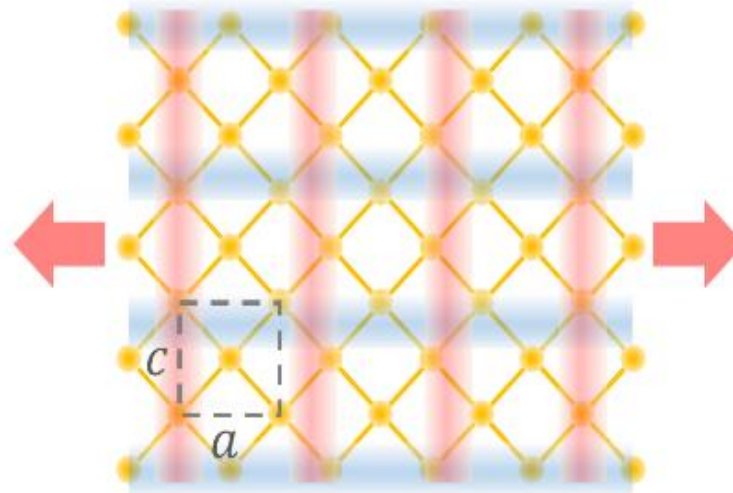
# Charge-density-waves tuned by biaxial tensile stress in the nearly-tetragonal system $\text{TbTe}_3$



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LITP

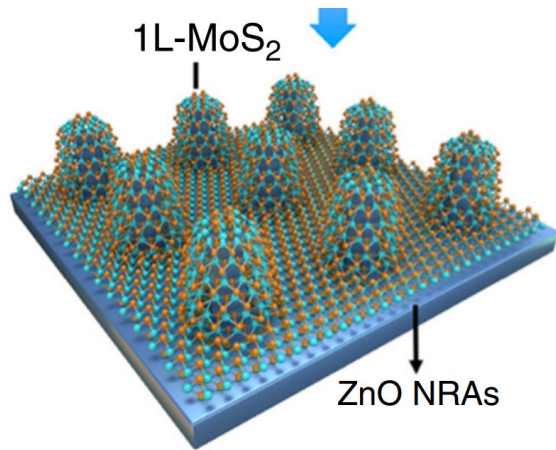
P. Grigoriev



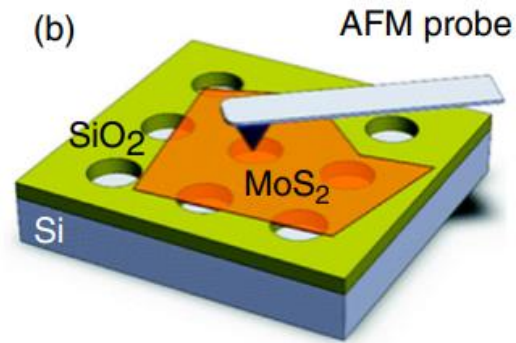
E. Bellec



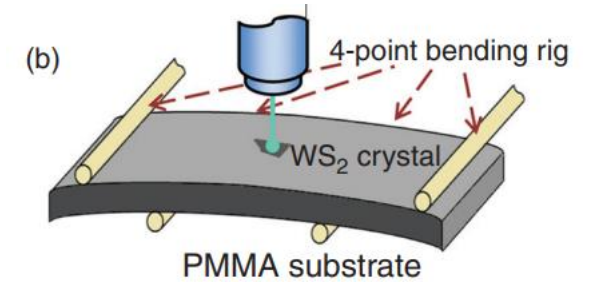
# Strain engineering in 2D systems



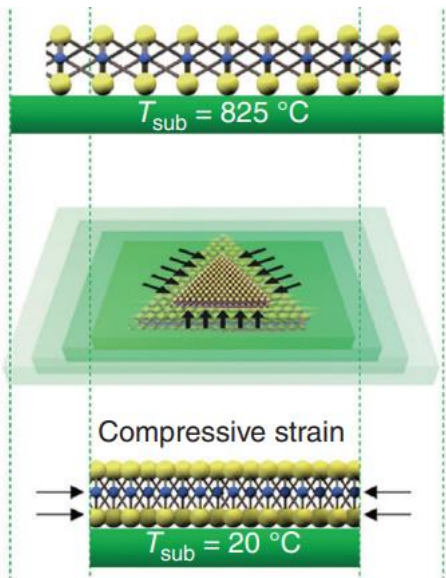
Liu et al., ACS Nano 13, 9057 (2019)



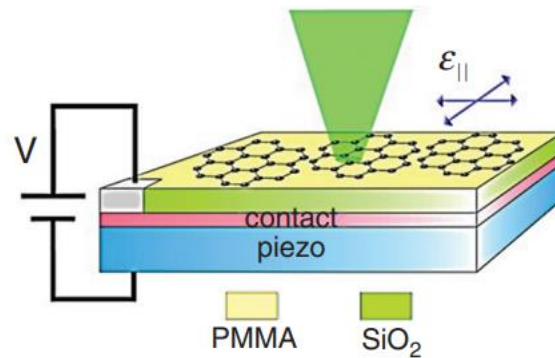
Bertolazzi et al., ACS Nano 5, 9703 (2011)



Wang et al., 2D Mater. 7, 045022 (2020)



Ahn et al., Nat. Commun. 8, 608 (2017)



Ding et al., Nano Lett. 10, 3453 (2010)

## TUNE ELECTRONIC PROPERTIES THROUGH LATTICE STRAINS

- Band structure / electronic properties
  - Optical properties
- Optoelectronic / excitonic states
  - Phase transitions
  - ...

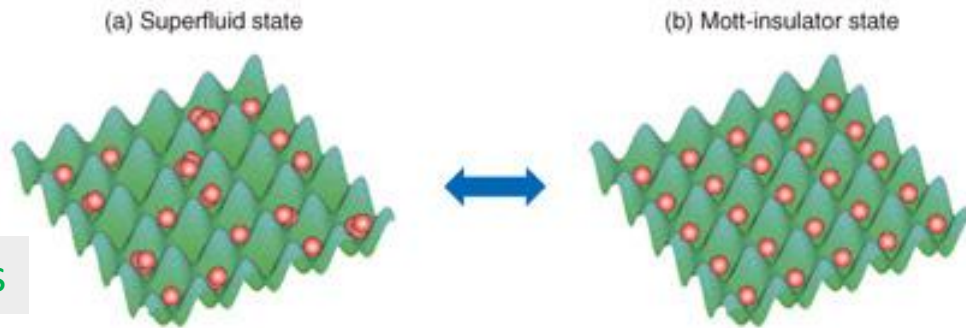
in TMDs, MXenes, Graphene, SCs, ...

# Correlated electron systems: a rich world

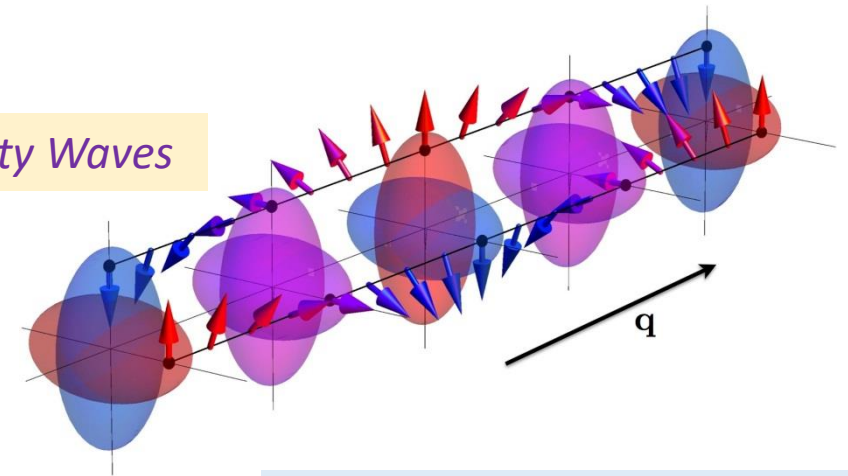
Electronic Correlations → drive physical properties

Ex: metal → insulator

Mott insulators

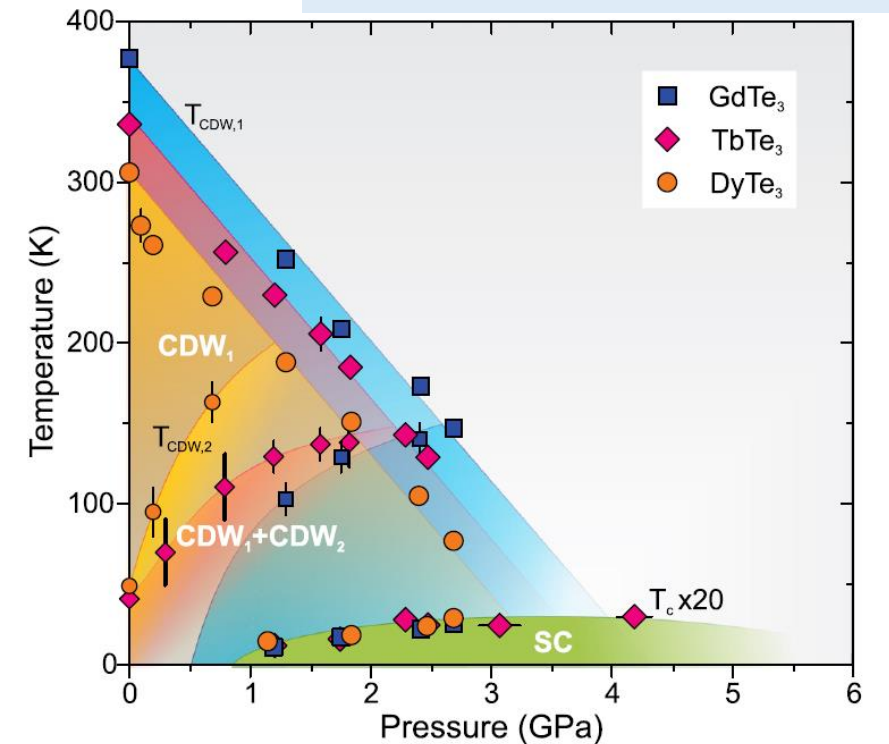
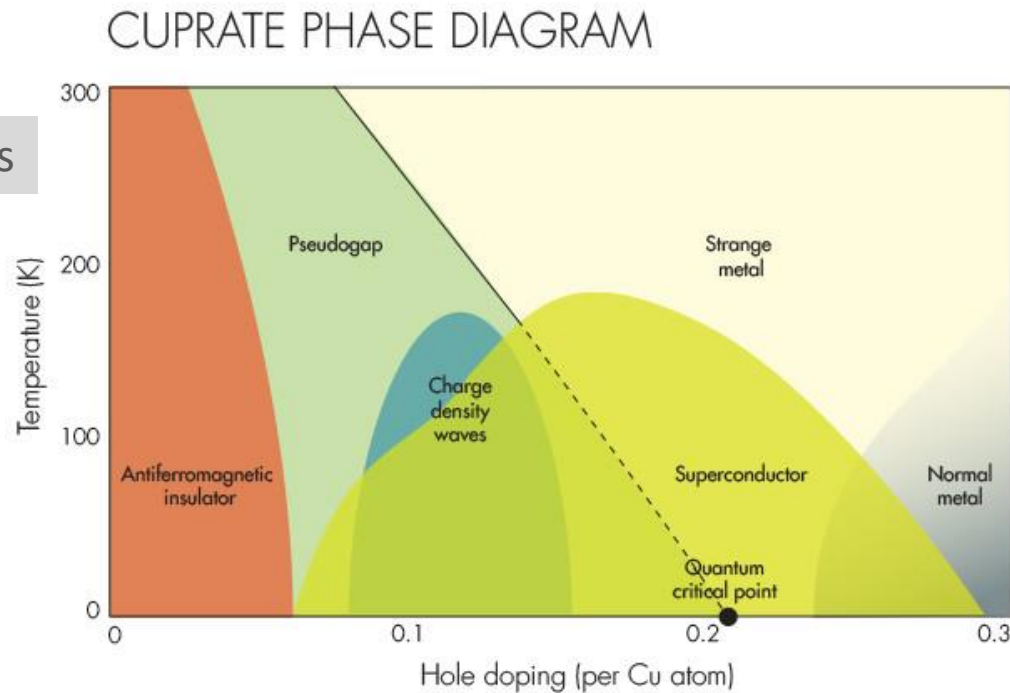


Spin Density Waves

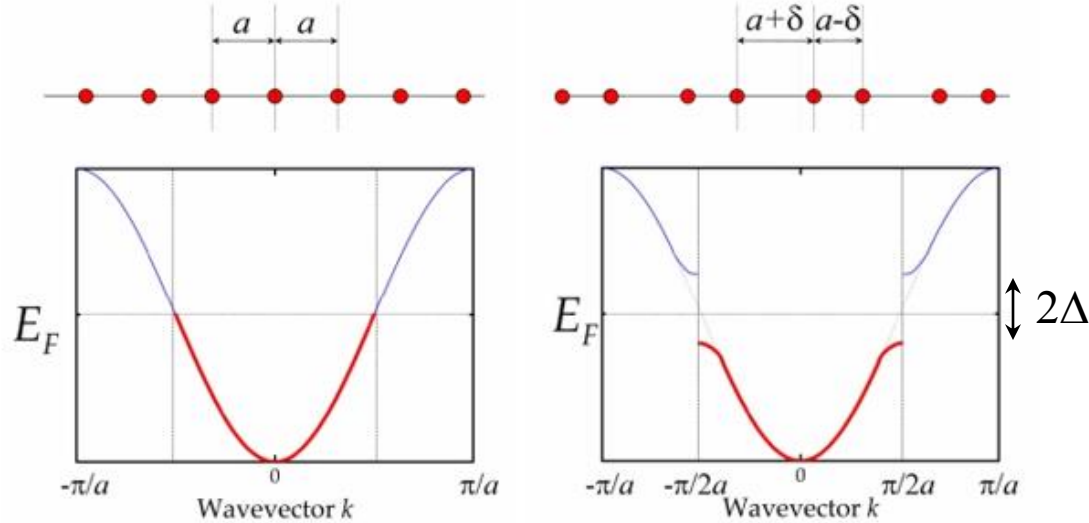


Charge Density Waves (CDW)

Superconductors



# Charge Density Waves in low-dimensional systems

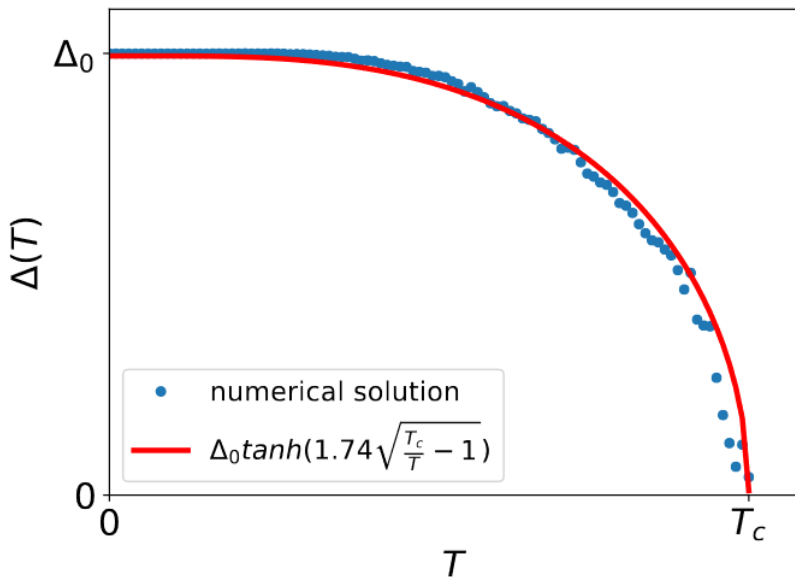


Peierls transition

$E_{el} \text{ gain } \propto |\Delta|^2 \ln \Delta$   
 $E_{\text{distortion}} \text{ increase } \propto |\Delta|^2$

Transition always favorable in 1D

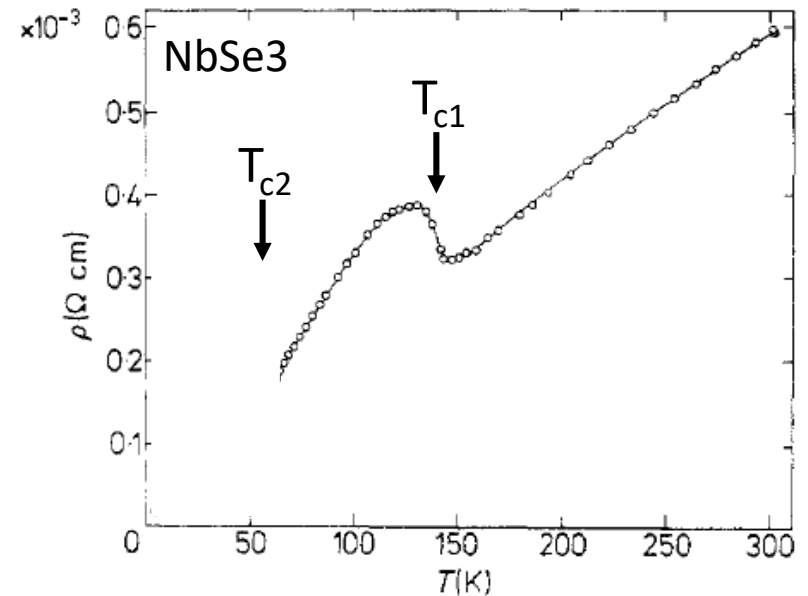
Both structural and electronic transition (metal-insulator)



BCS equation for  $\Delta(T)$   
 $\Delta_{T=0} = 1.764 k_B T_C$

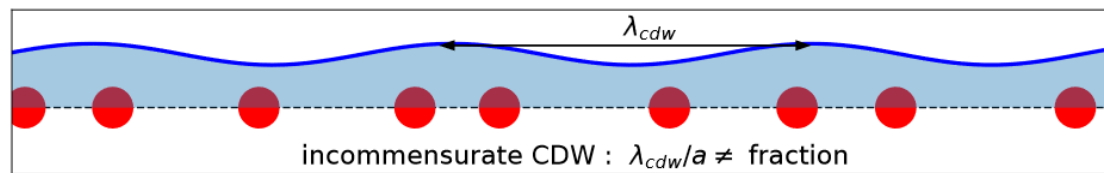
$\Delta_0 \propto T_C$

E. Bellec, PhD thesis



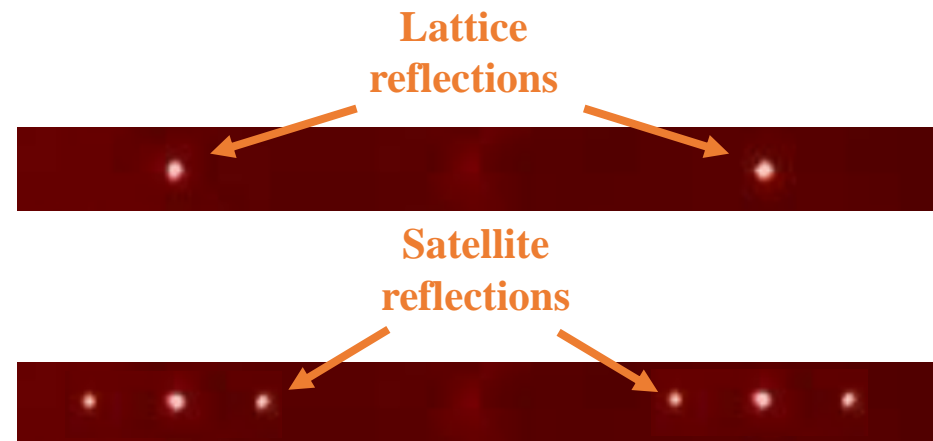
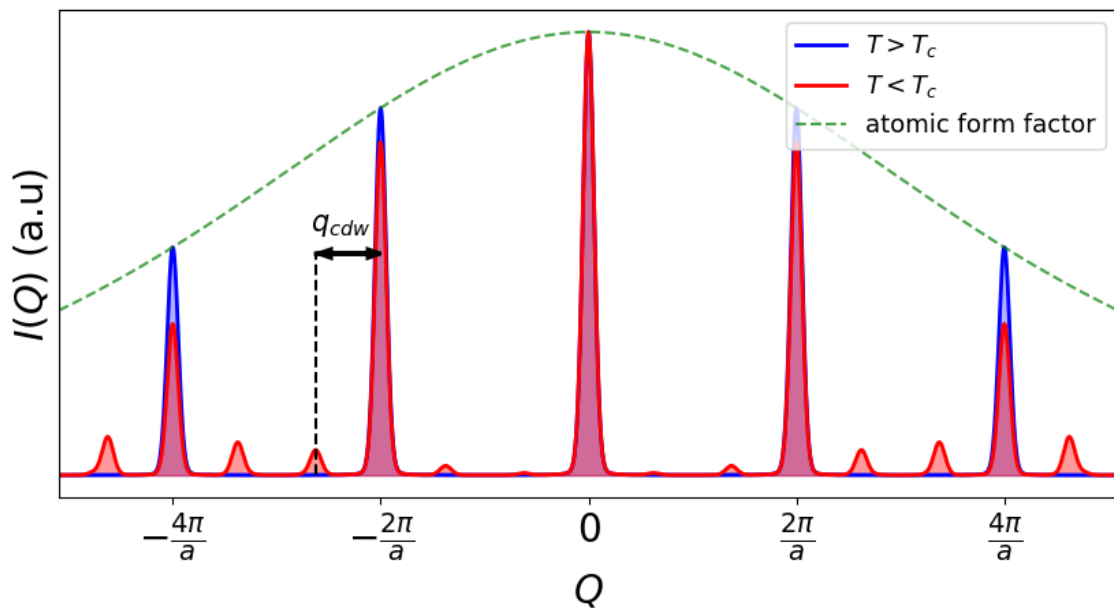
*J. Chaussy, Solid State Communications, 20(8):759 – 763, 1976*

# CDW : the PLD seen in diffraction



$$\rho(x) = \rho_0 \left( 1 + \frac{\Delta}{\hbar v_F k_F \lambda} \cos(2k_F x + \varphi(x)) \right) + \frac{e}{\pi} \nabla \varphi(x)$$

CDW = Charge density spatial modulation at  $q=2k_F$



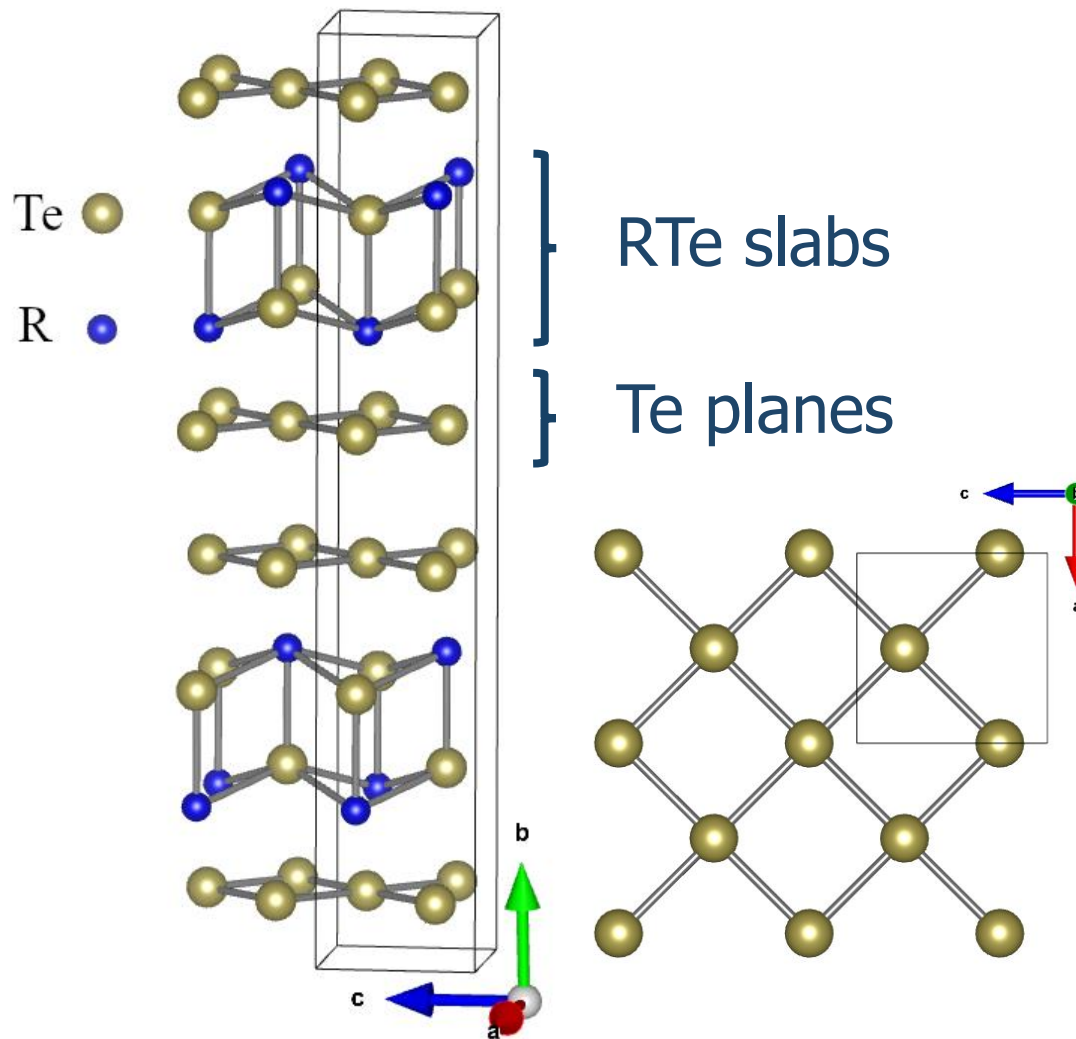
# Rare-earth tritellurides $R\text{Te}_3$ : a quasi-2D CDW system

## Rare-earth tritelluride $R\text{Te}_3$

- R = lanthanides

57	58	59	60	61	62	63	
La	Ce	Pr	Nd	Pm	Sm	Eu	
Lanthanum	Cerium	Praseodymium	Neodymium	Promethium	Samarium	Europium	
64	65	66	67	68	69	70	71
Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Gadolinium	Terbium	Dysprosium	Holmium	Erbium	Thulium	Ytterbium	Lutetium

- Stack of RTe / Te
- VdW bonds along  $\vec{b}$
- Orthorhombic with  $a \approx 0.998 c$   
(Nearly tetragonal)
- Glide plane : Cmc space group
  - Intrinsically orthorhombic

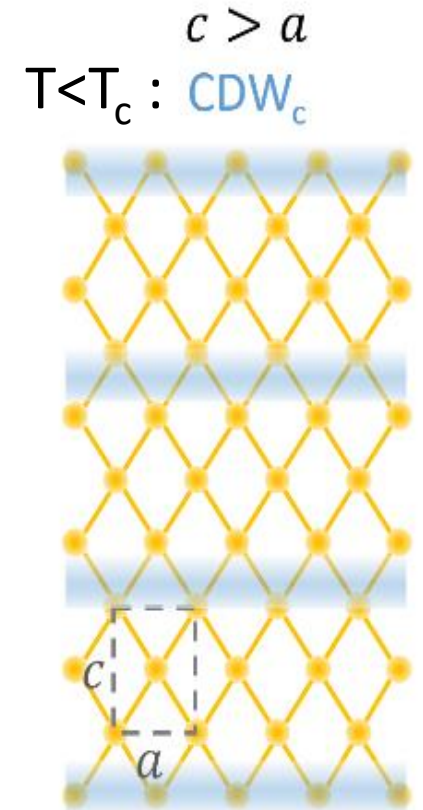
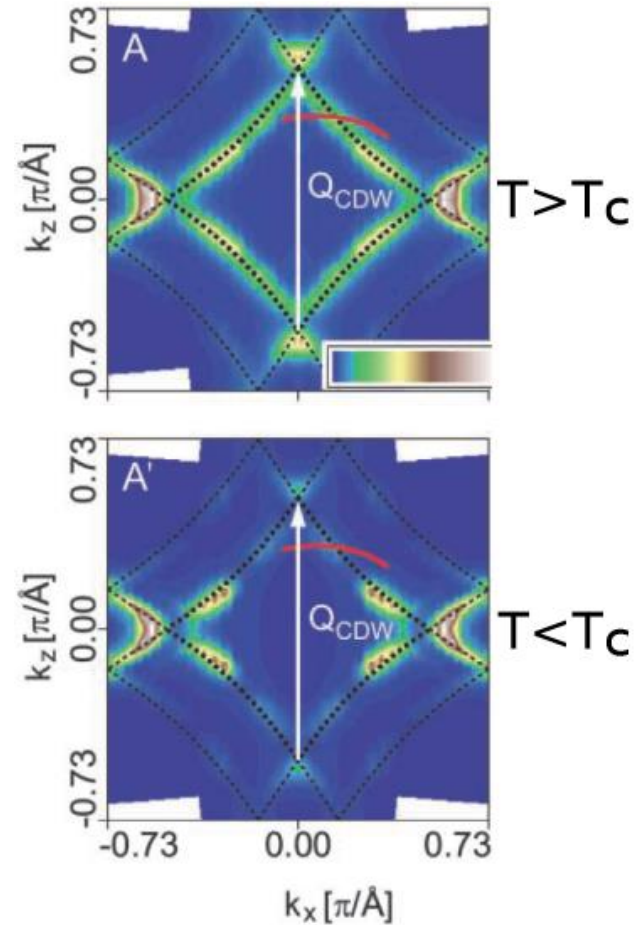
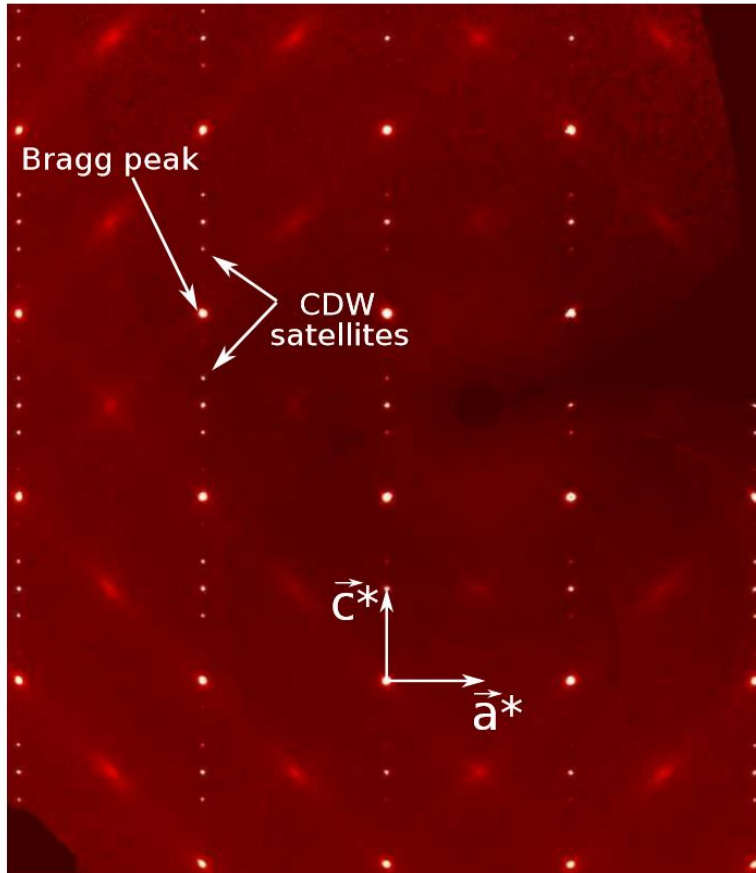


# Evidence of CDW along $\vec{c}$ in $\text{TbTe}_3$

XRD : CDW satellites along  $\vec{c}^*$  ( $\sim \frac{5}{7} rlu$ )

ARPES : gap opening along  $\vec{c}^*$  ( $\sim \frac{5}{7} rlu$ )

Te planes

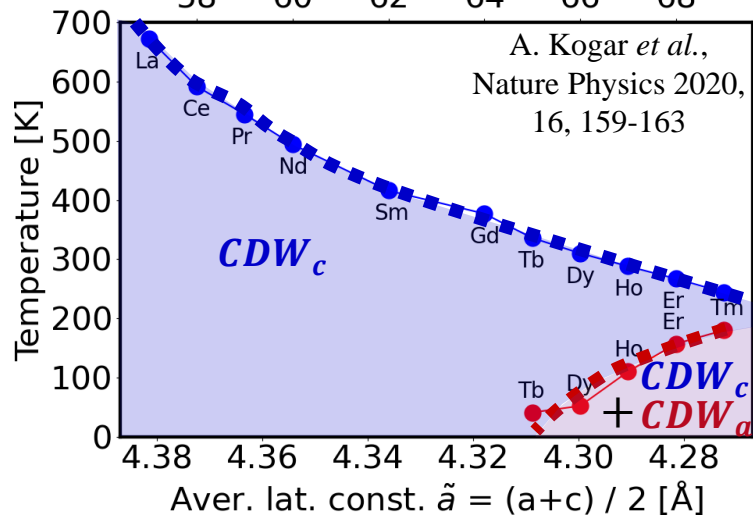
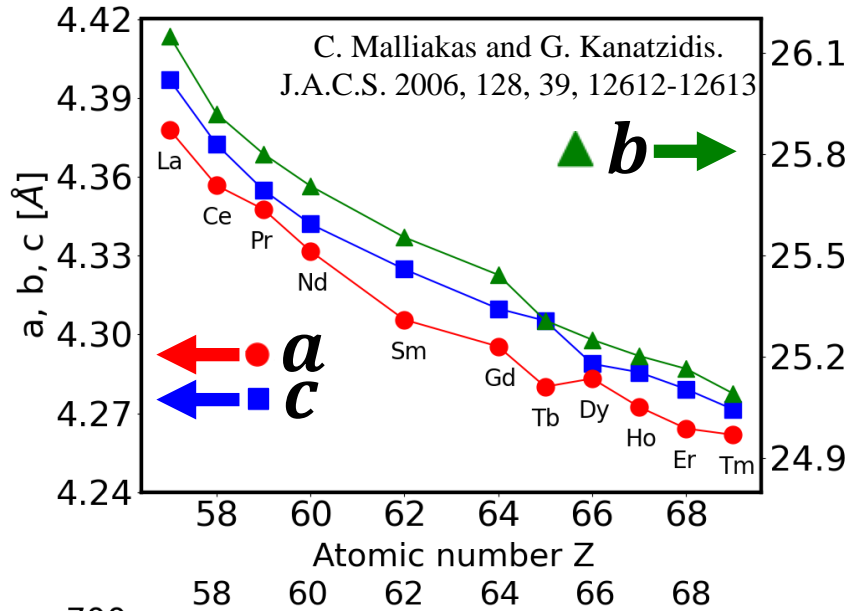


➔ Why does the CDW appear along  $\vec{c}$  first and not along  $\vec{a}$  ?

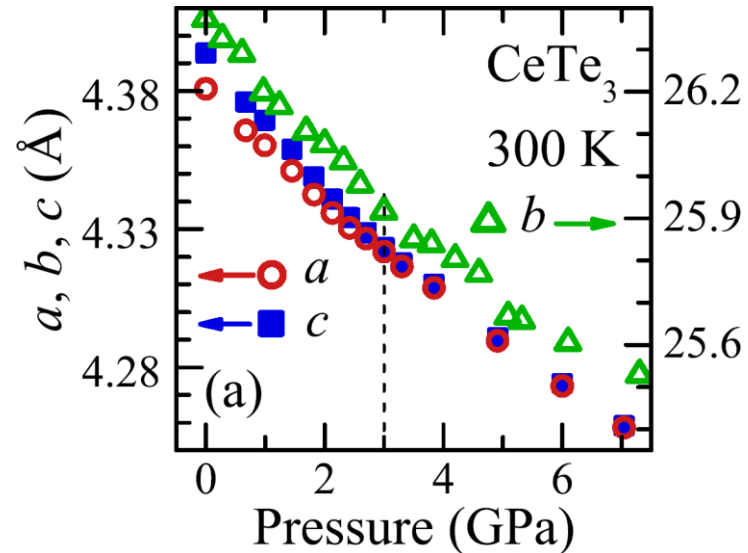
➔ Related to the non-tetragonal structure? What if  $a = c$  ? What if we make  $a > c$  ?

# Rare-earth tritellurides $R\text{Te}_3$ phase diagram

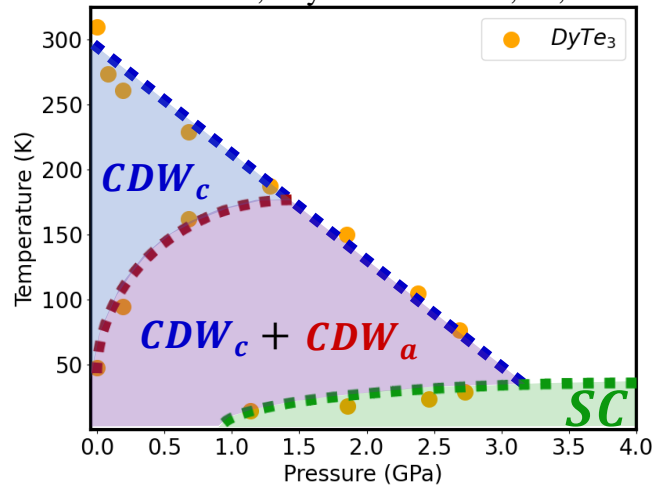
## Chemical substitution



## Hydrostatic pressure



A. Sacchetti *et al.*, Phys. Rev. B 2009, 79, 201101  
 D.A. Zocco *et al.*, Phys. Rev. B 2015, 91, 177002

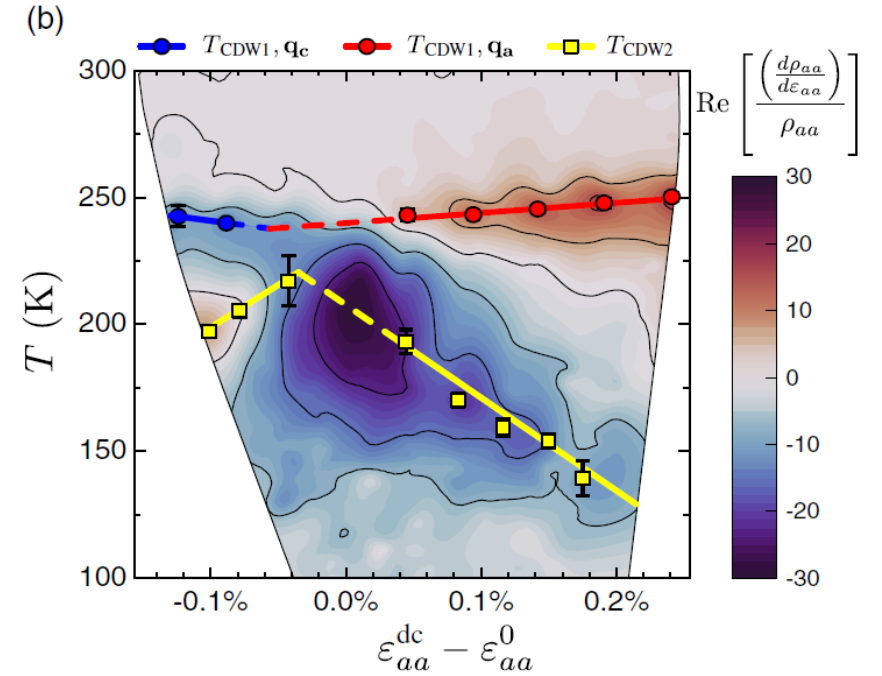
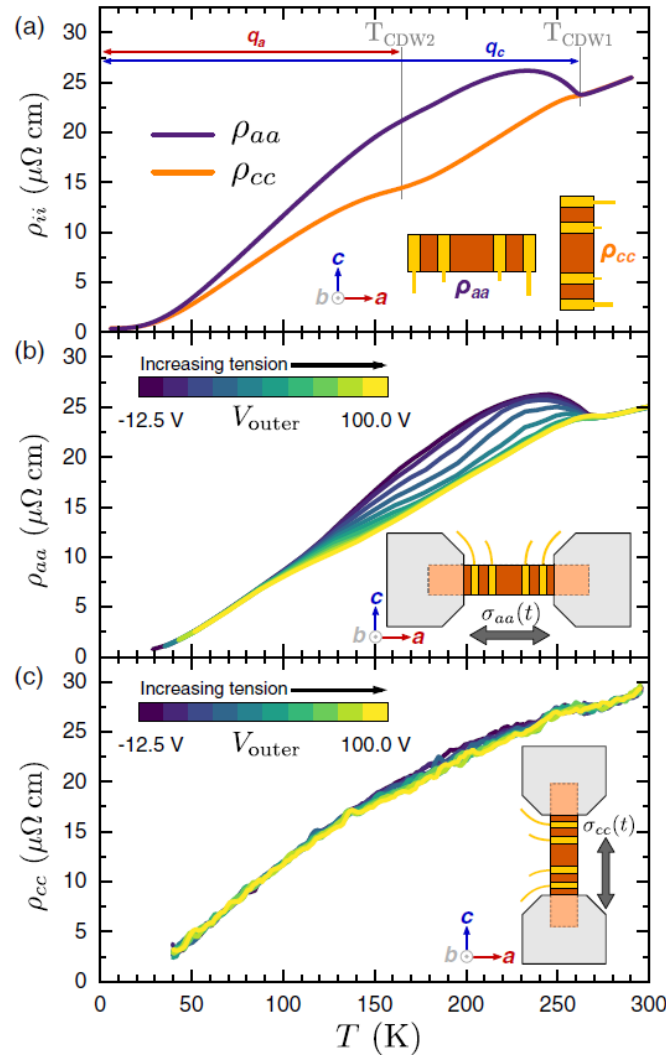
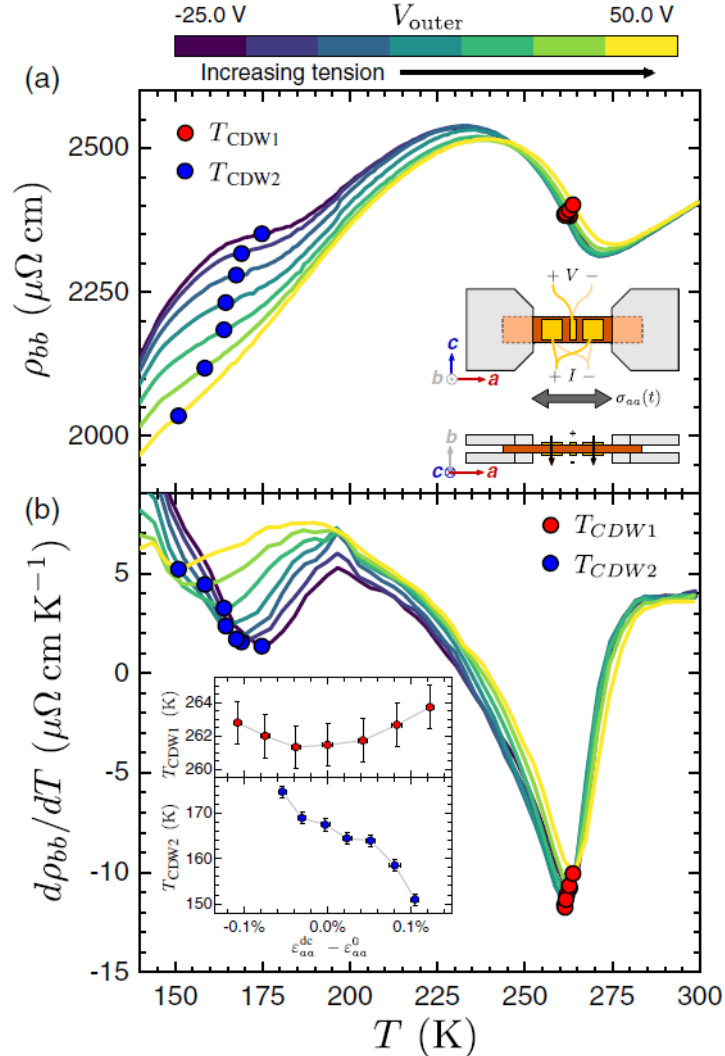


Both show :

- Decrease of all lattice parameters
- Approx. 2 % of relative variation
- 300 K variation of  $T_c$   $CDW_c$
- Second  $CDW$  with 150 K variation of  $T_c$   $CDW_a$

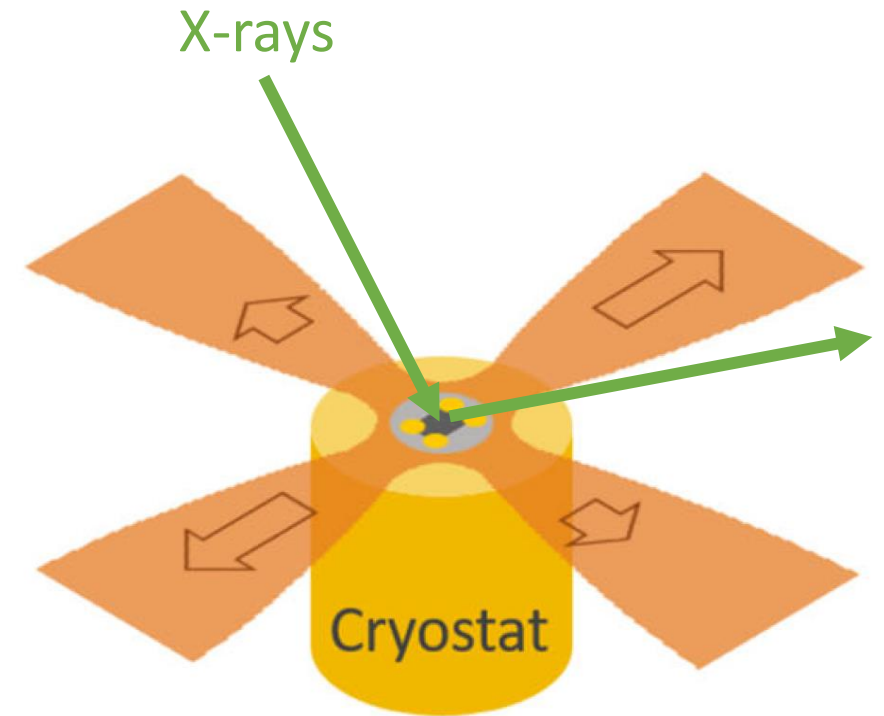
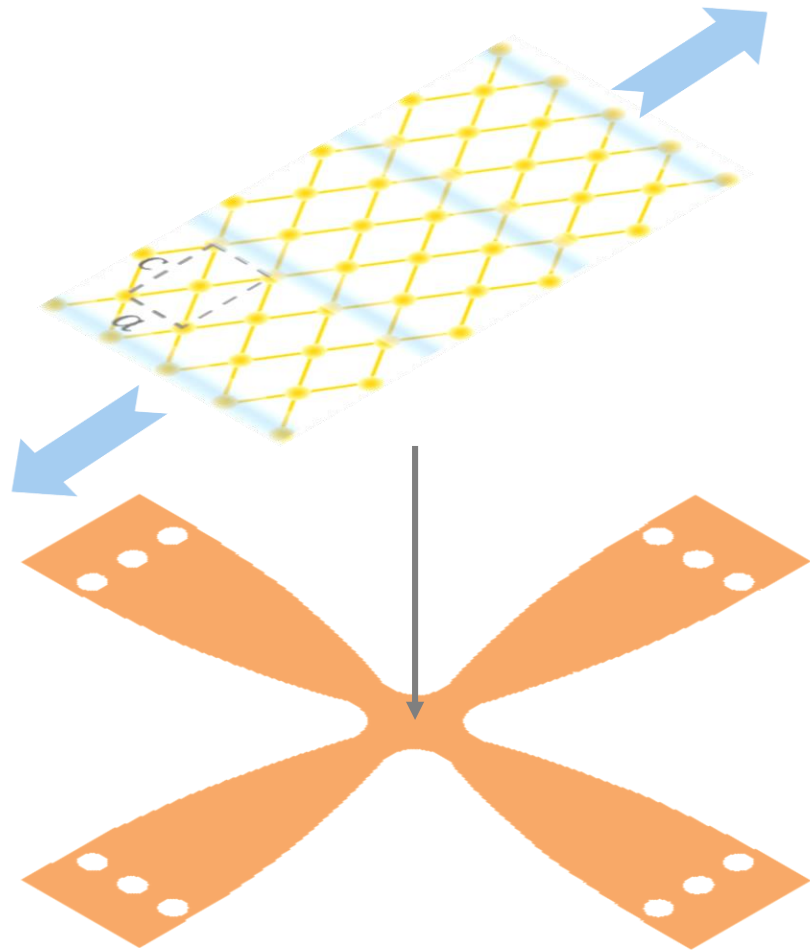
# Previous measurements under uniaxial deformation in $\text{ErTe}_3$

Straquadine et al., PRX 12, 021046 (2022)



- Interpretation : appearance of  $\text{CDW}_a$  under strain
  - Large change of  $T_{c2}$ , small change of  $T_{c1}$ .
  - Transport only measured along direction of force application
- Requires confirmation with XRD.

# Towards application of biaxial tensile stresses at cryogenic T



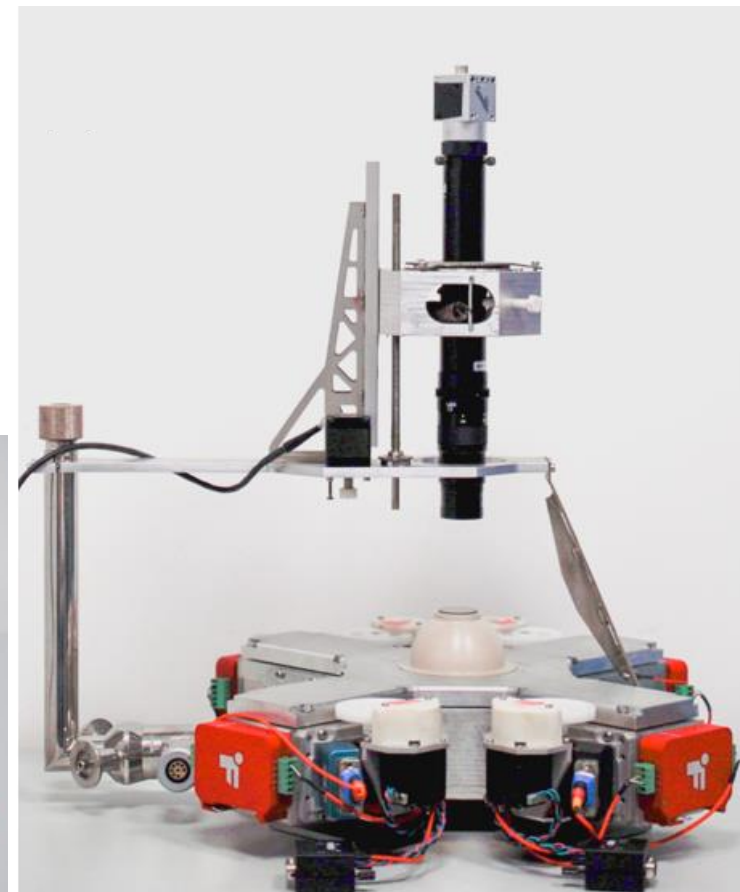
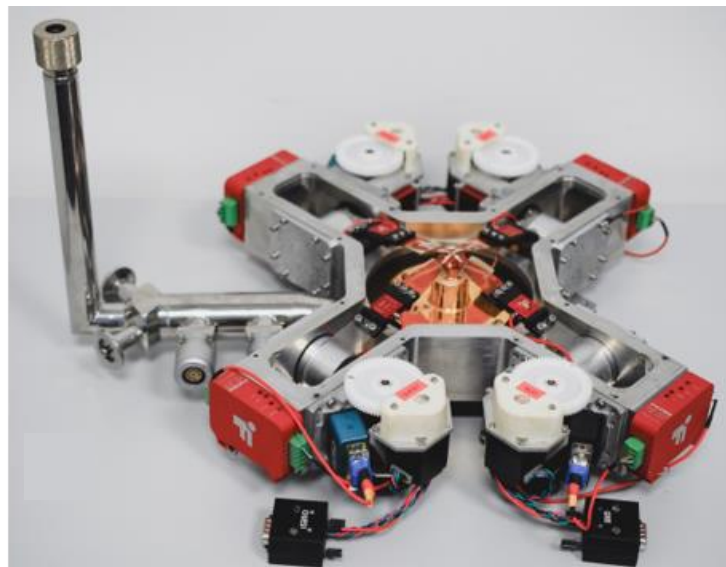
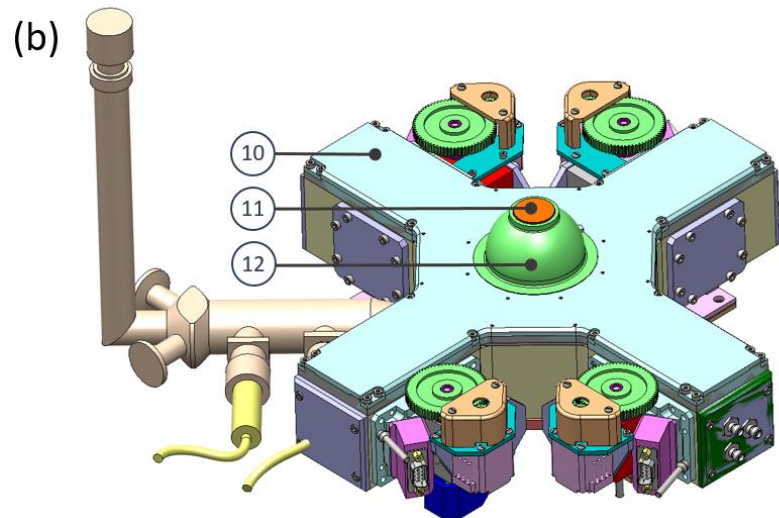
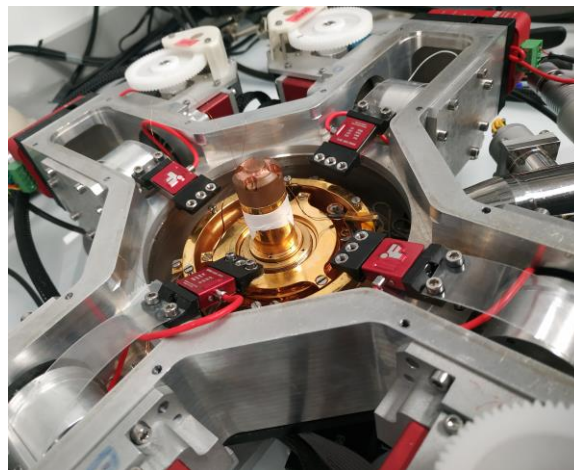
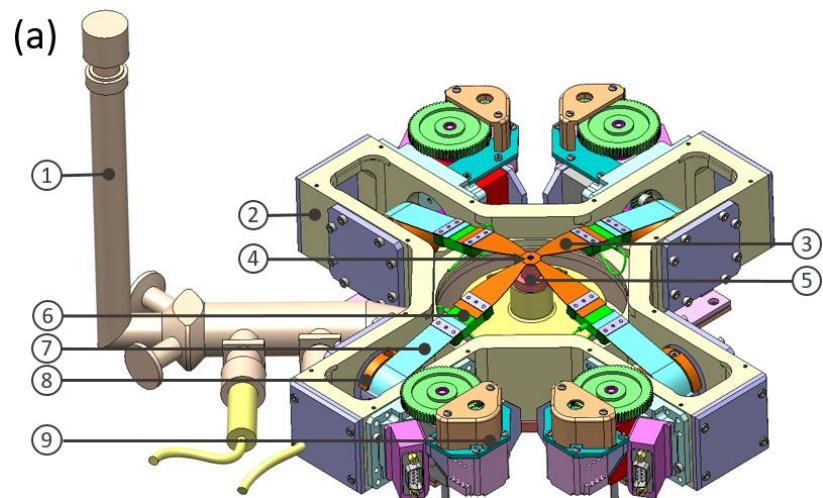
## Requirements :

- As low T as possible
- Perform in-situ XRD/ transport / optical measurements

## Challenges :

- Need to glue sample
- Low temperatures vs mechanical deformation

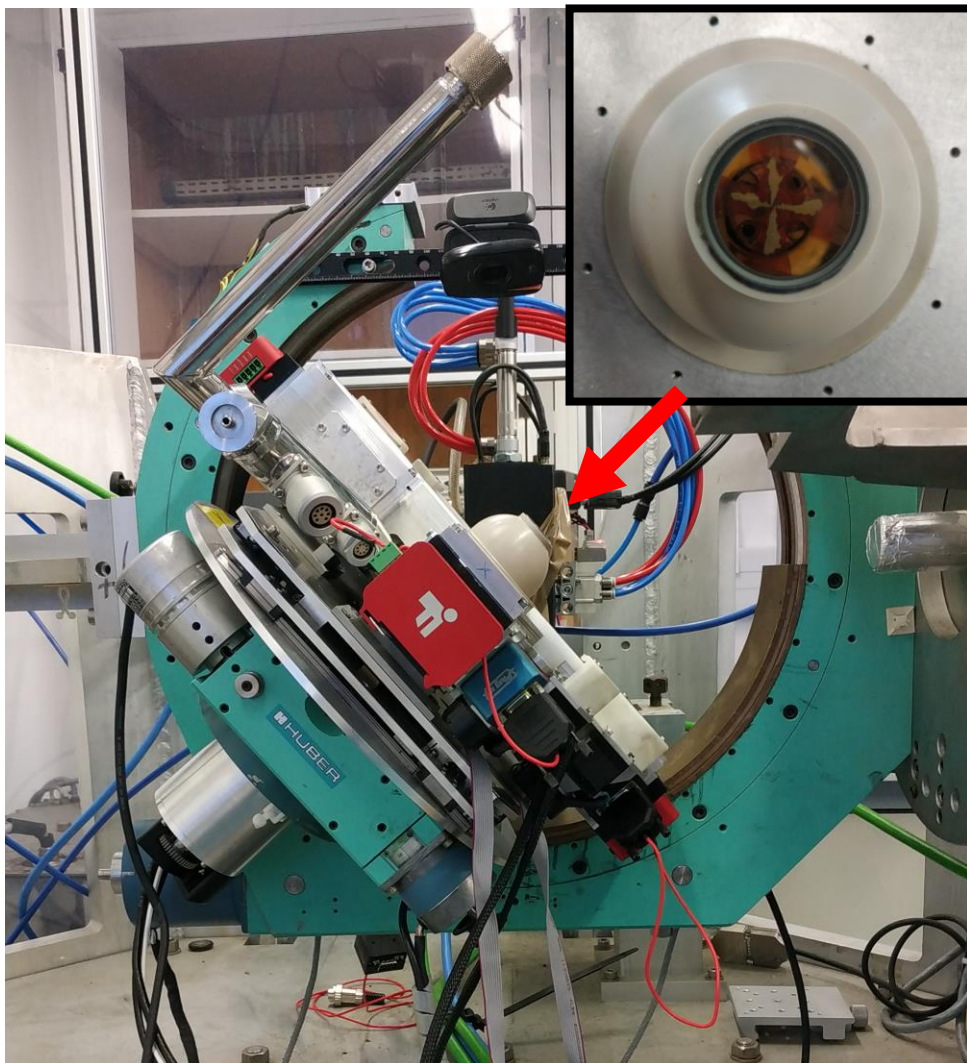
# Cryogenic Biaxial Tensile Stress Device developed @LPS



A. Gallo-Frantz et al., in preparation

# Compatibility with various techniques

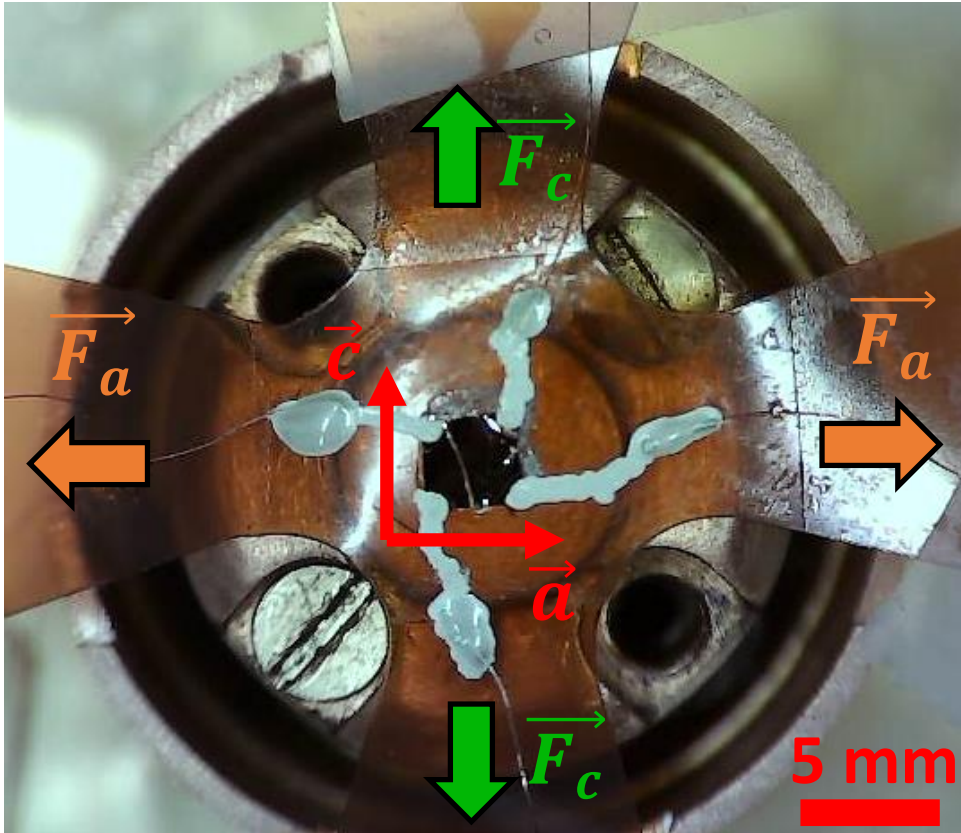
## Biaxial tensile device



- Topped by vacuum-tight cover
  - PEEK dome (x-ray transparent)
  - Optical window
    - Sample monitoring
    - Image correlation (displacement field)
    - Optical spectroscopy
- Large temperature range :
  - $15\text{K} < T < 380\text{K}$
- 4 wires transport measurements
- Compatible with large scale instrument environment (several experiments at SOLEIL: DIFFABS, CRISTAL)

# Sample preparation

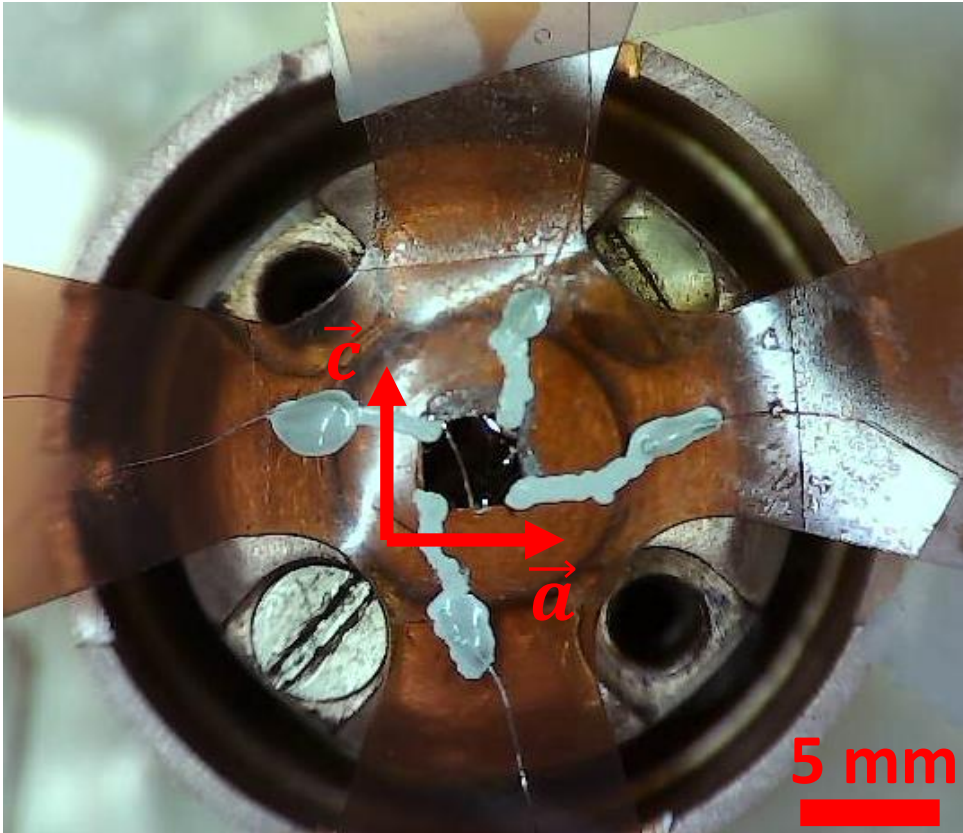
TbTe<sub>3</sub> sample



- Sample glued on kapton substrate :
  - Crystallographic axis aligned with deformation directions
- Exfoliated :
  - Dimensions : l x w x t  
2.5 mm x 2 mm x 10  $\mu\text{m}$
- Silver paste deposited on the sample and on wires for electrical contact

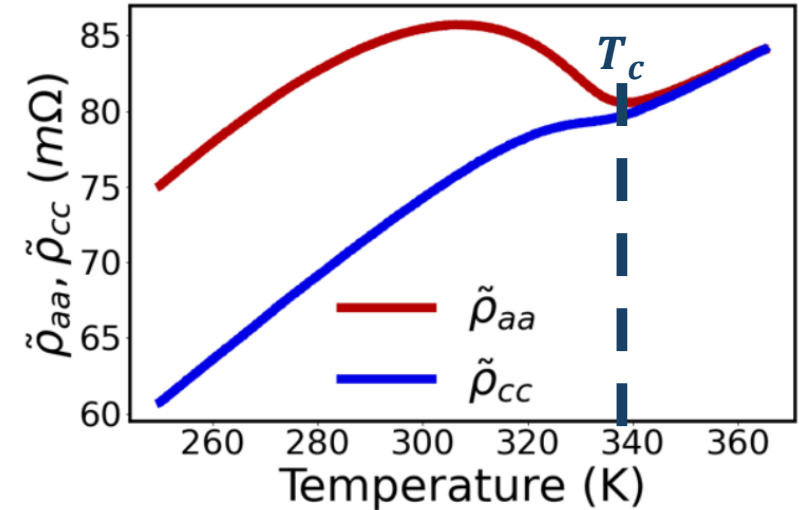
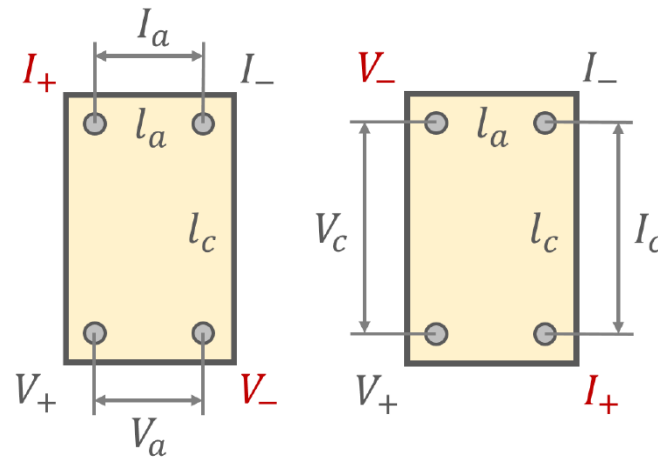
# Pristine state of TbTe3

TbTe<sub>3</sub> sample



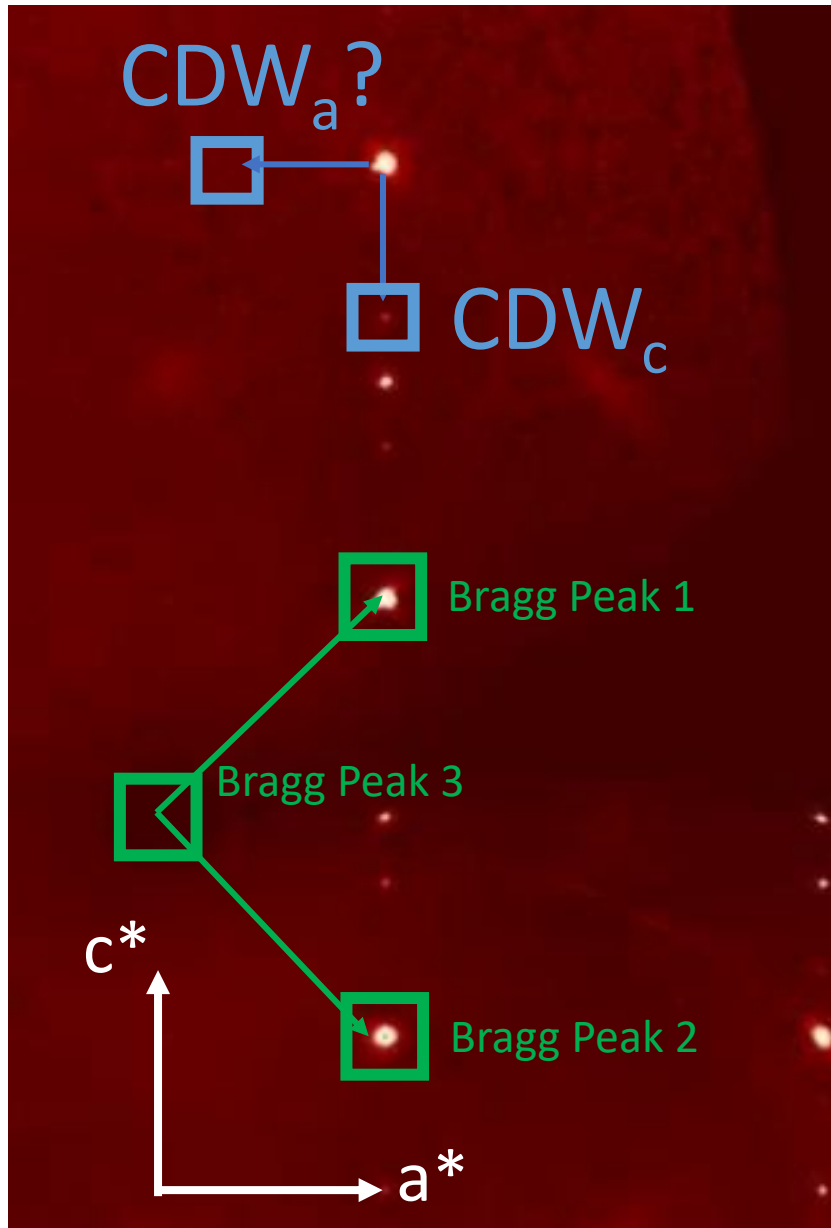
Pristine state in 250K - 350K temperature range :

- $\frac{a}{c} \approx 0.998$
- CDW along  $\vec{c}$
- $T_c = 336 K$



- On the same sample :**
- X-ray diffraction  $\rightarrow$  Lattice and CDW structure
  - Transport  $\rightarrow$  Critical temperature / resistivity jump

# Tracking lattice / CDW structure vs applied stresses by XRD



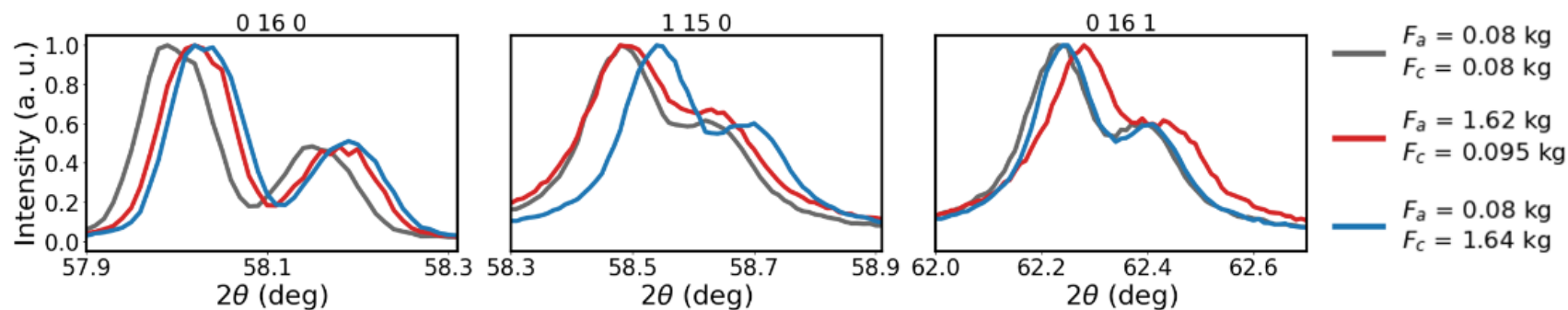
## CDW peaks along **a** and along **c**

- Intensity related to PLD amplitude
- Position related to CDW wavevector
- Width related to correlation lengths

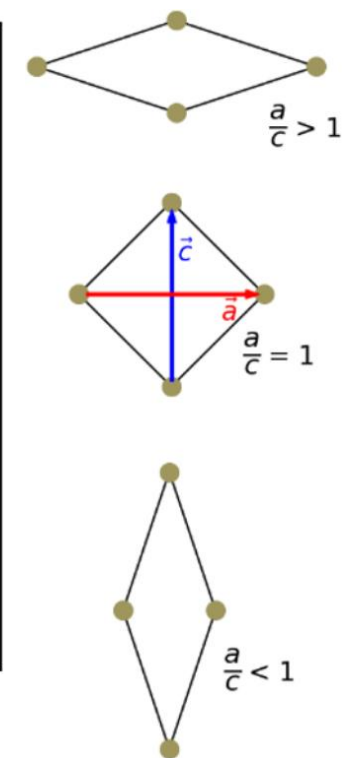
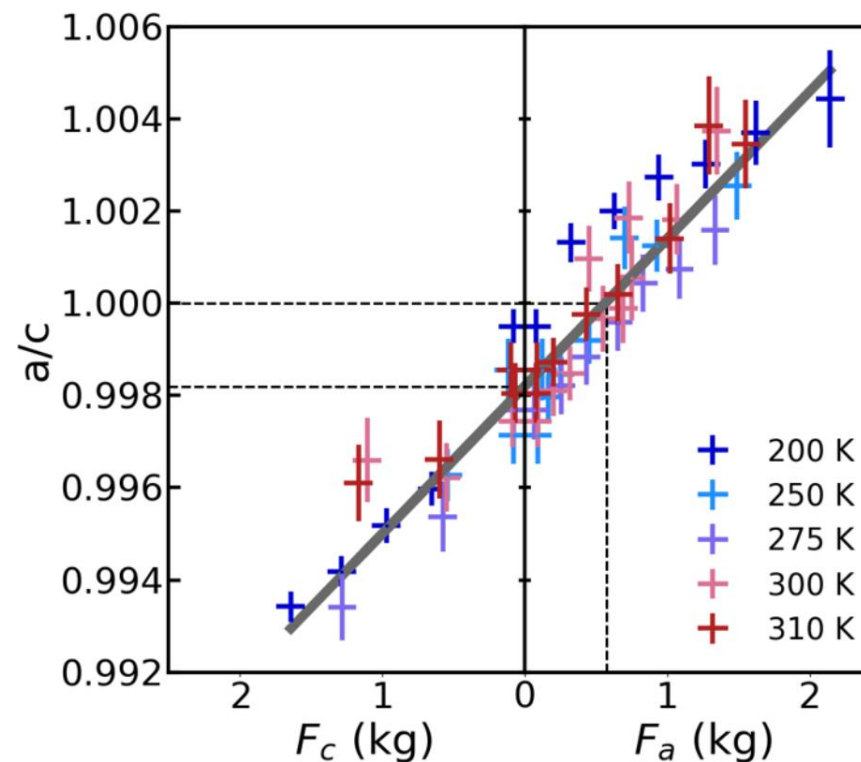
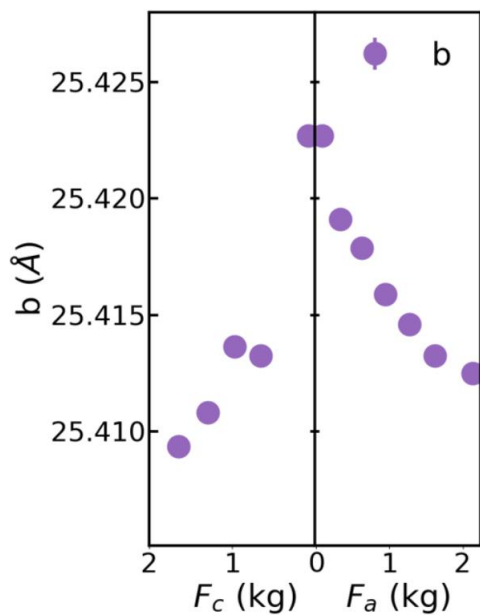
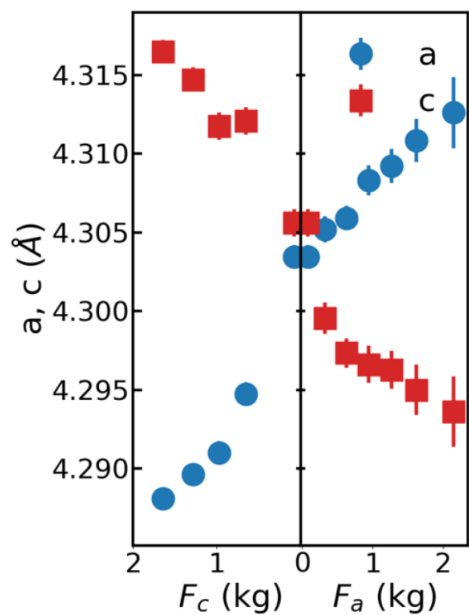
## 3 non-collinear Bragg peaks :

- Get full deformation tensor in-situ
- Can check absence of shear deformation
- Go to highest  $q$  values for precise determination of lattice parameters

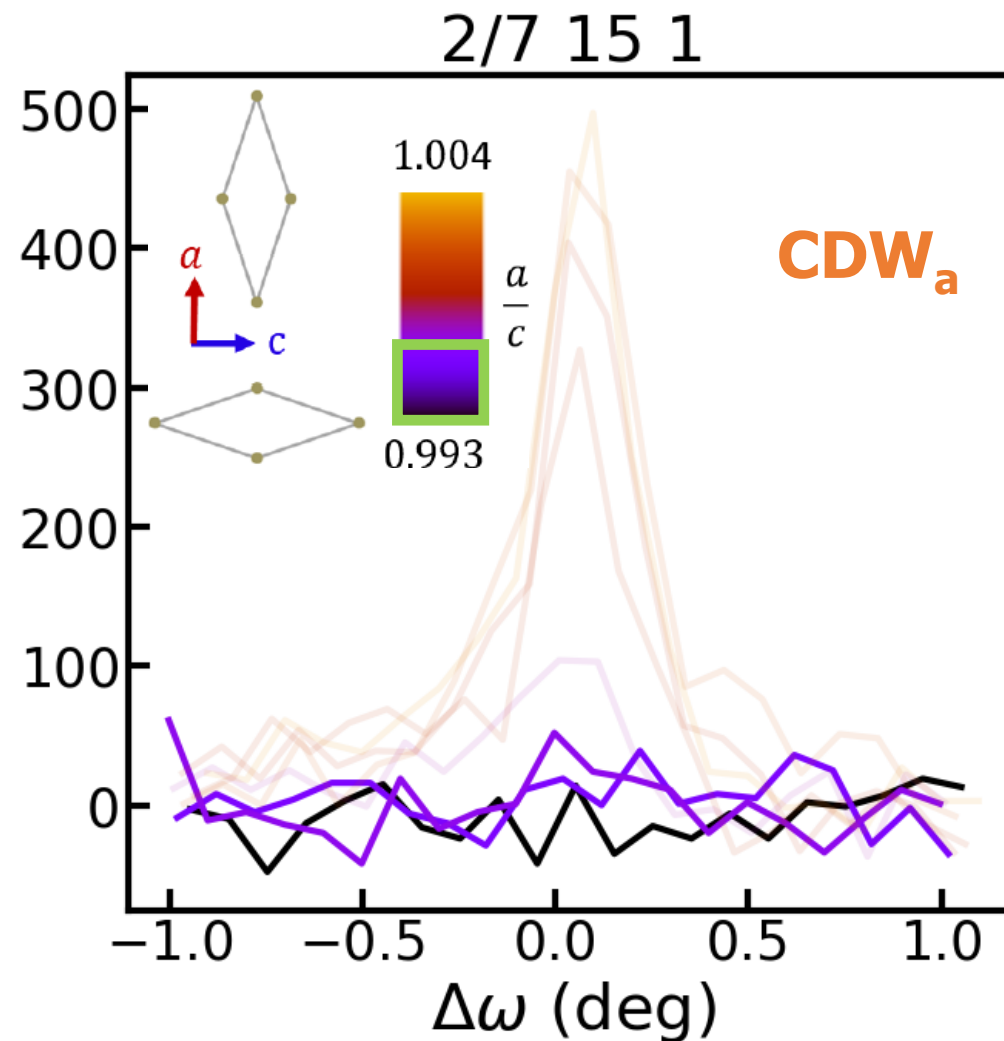
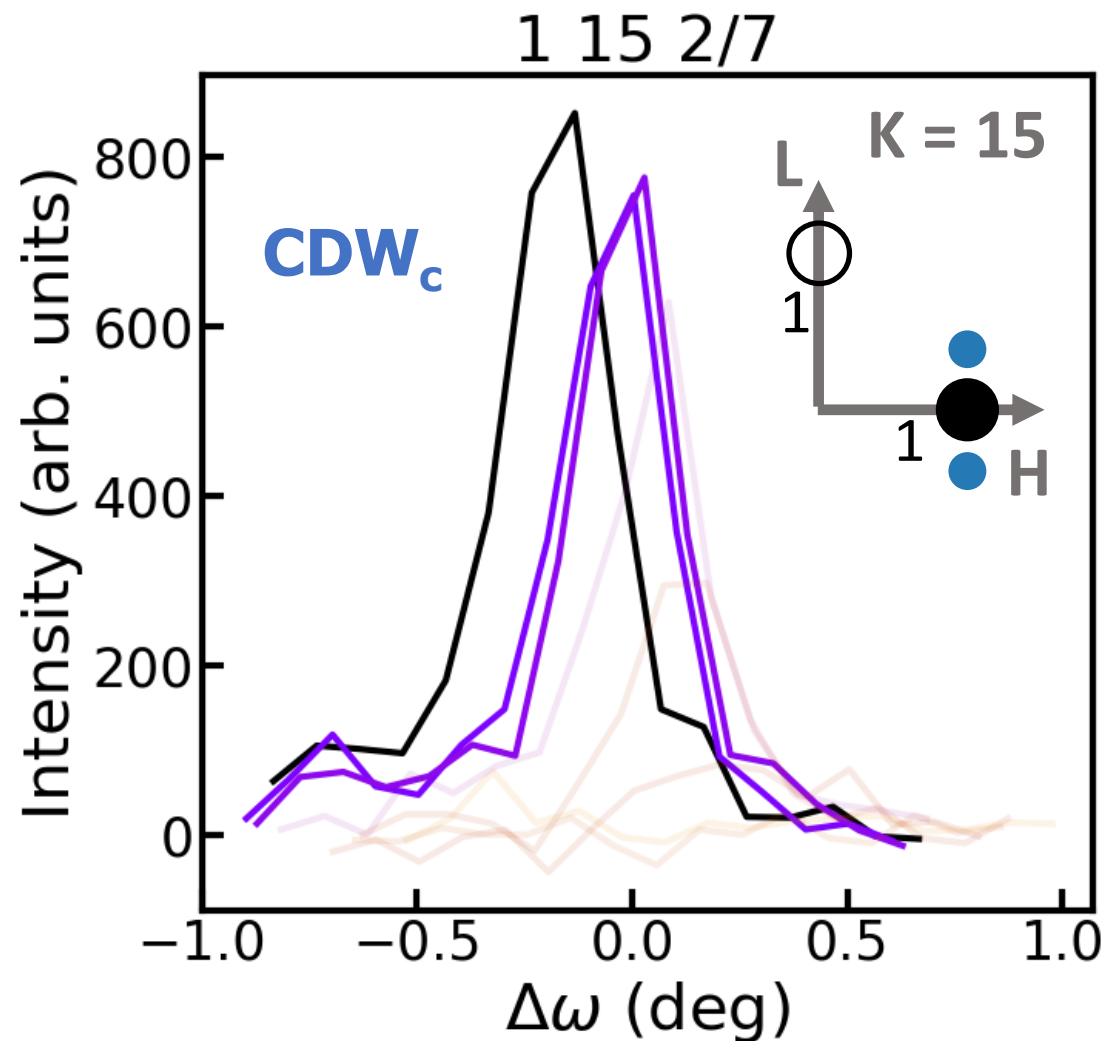
# Measurement of lattice deformations



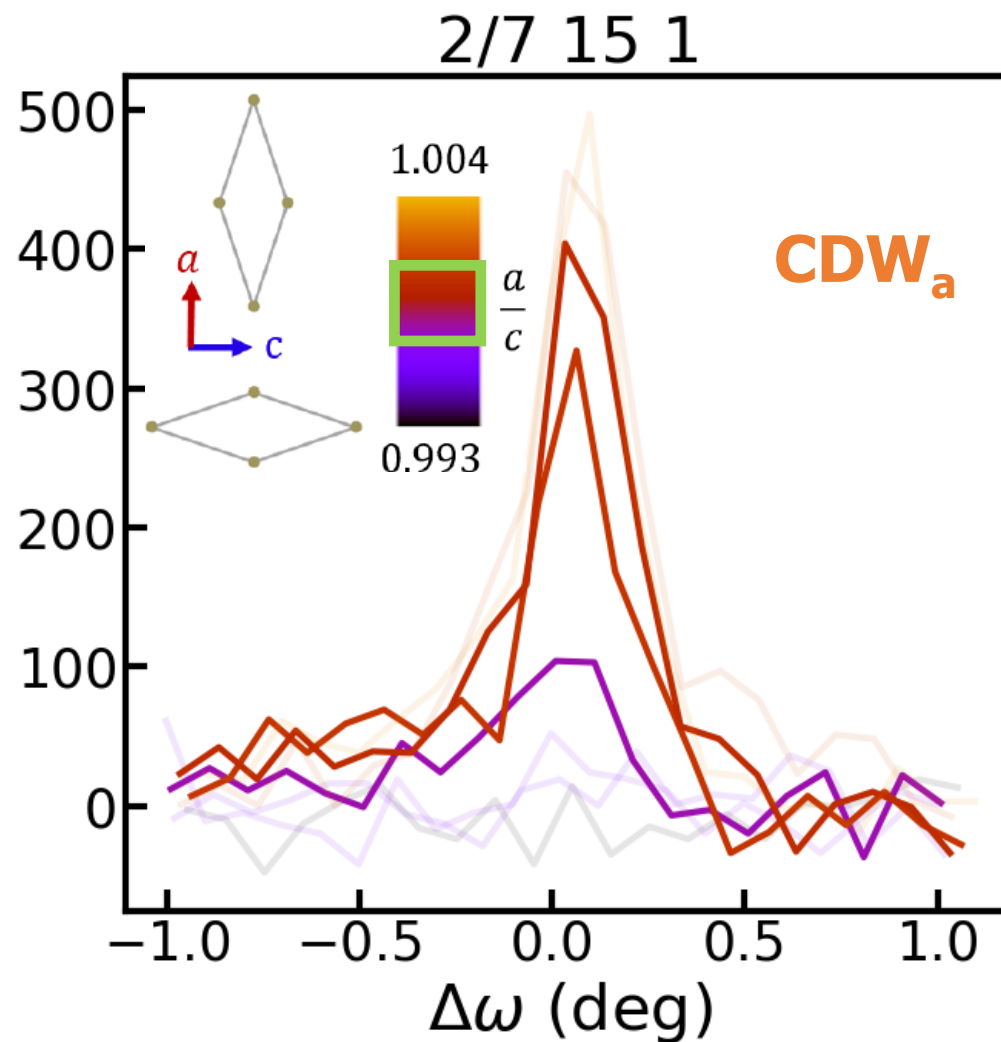
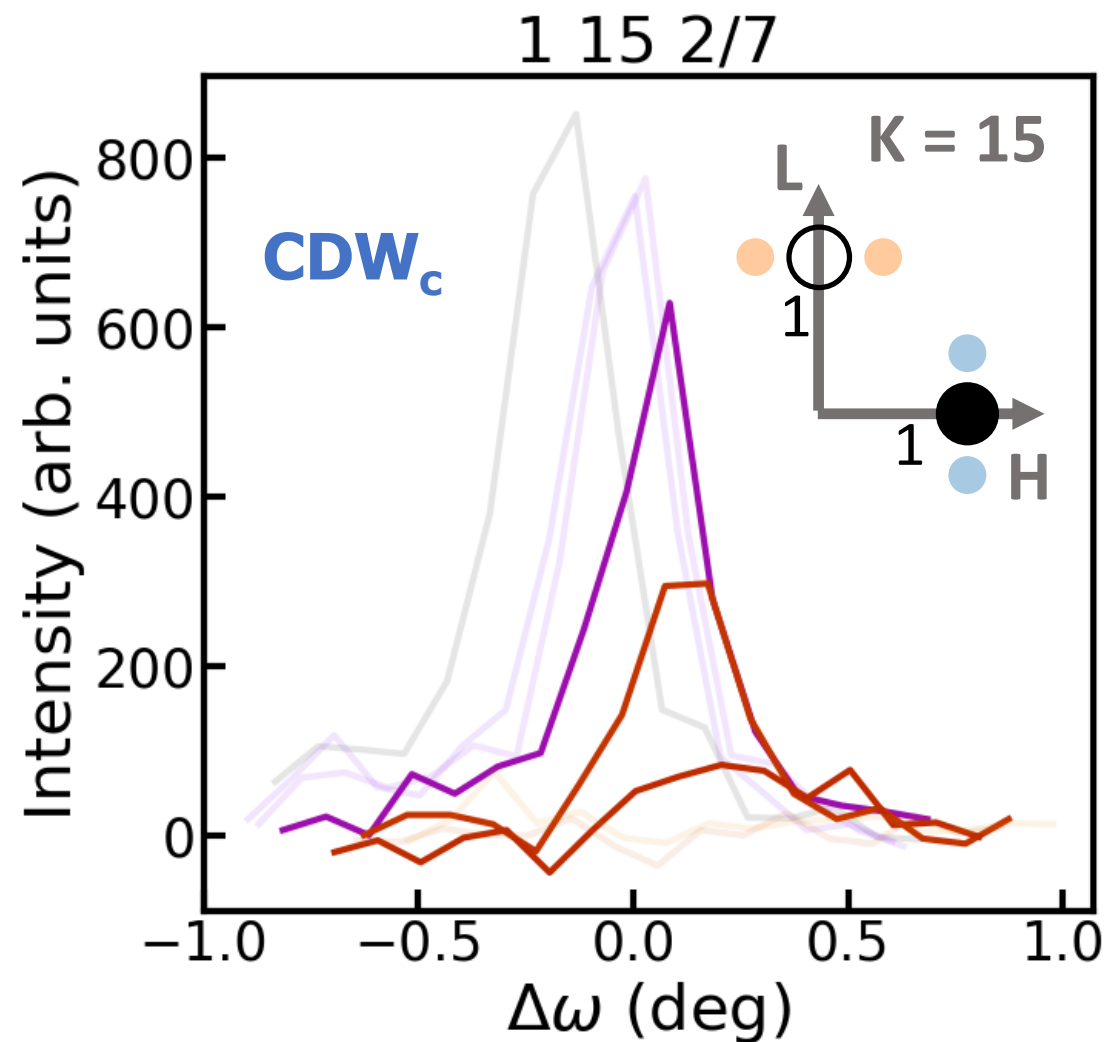
a, b, c obtained by measuring  
 3 non-colinear Bragg reflections :  
 $0\ 1\ 6\ 0 \rightarrow b$  (specular)  
 $1\ 1\ 5\ 0 \rightarrow a$  (knowing b)  
 $0\ 1\ 6\ 1 \rightarrow c$  (knowing b)



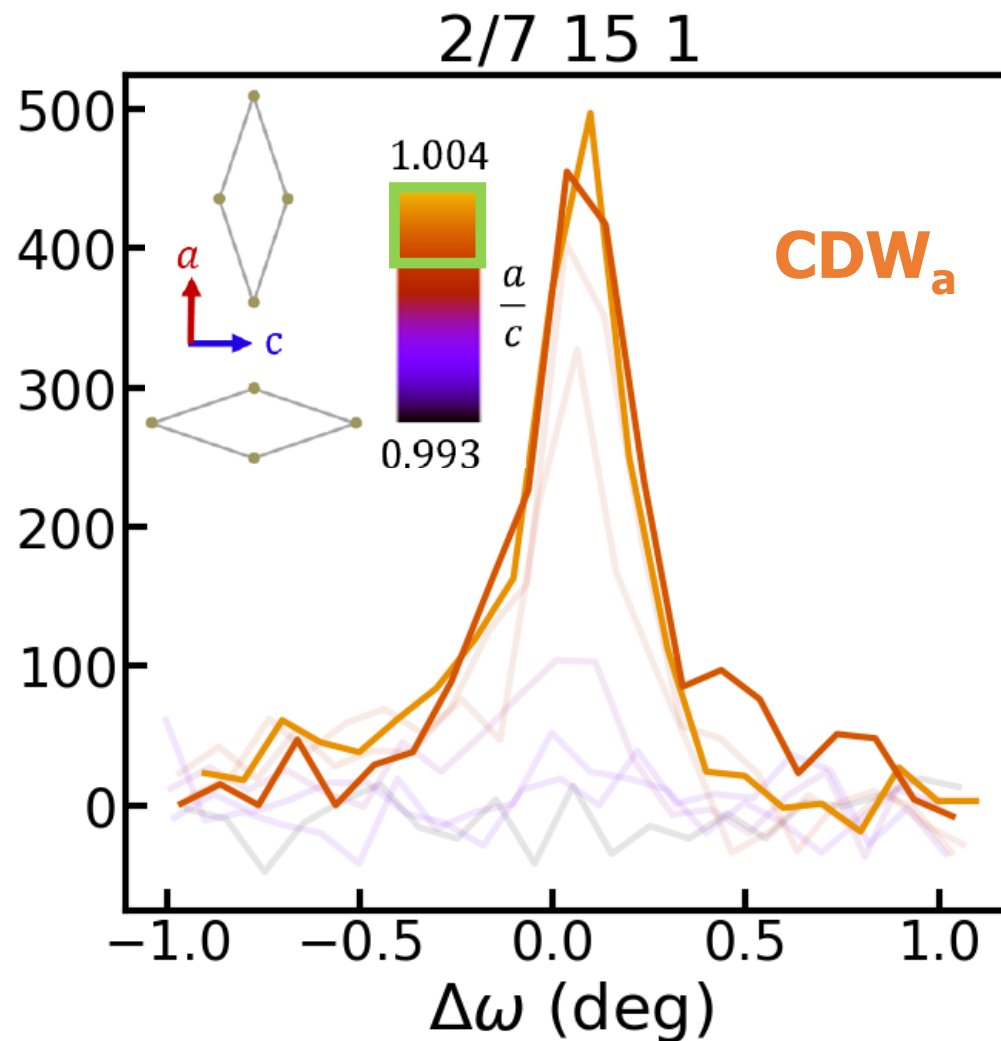
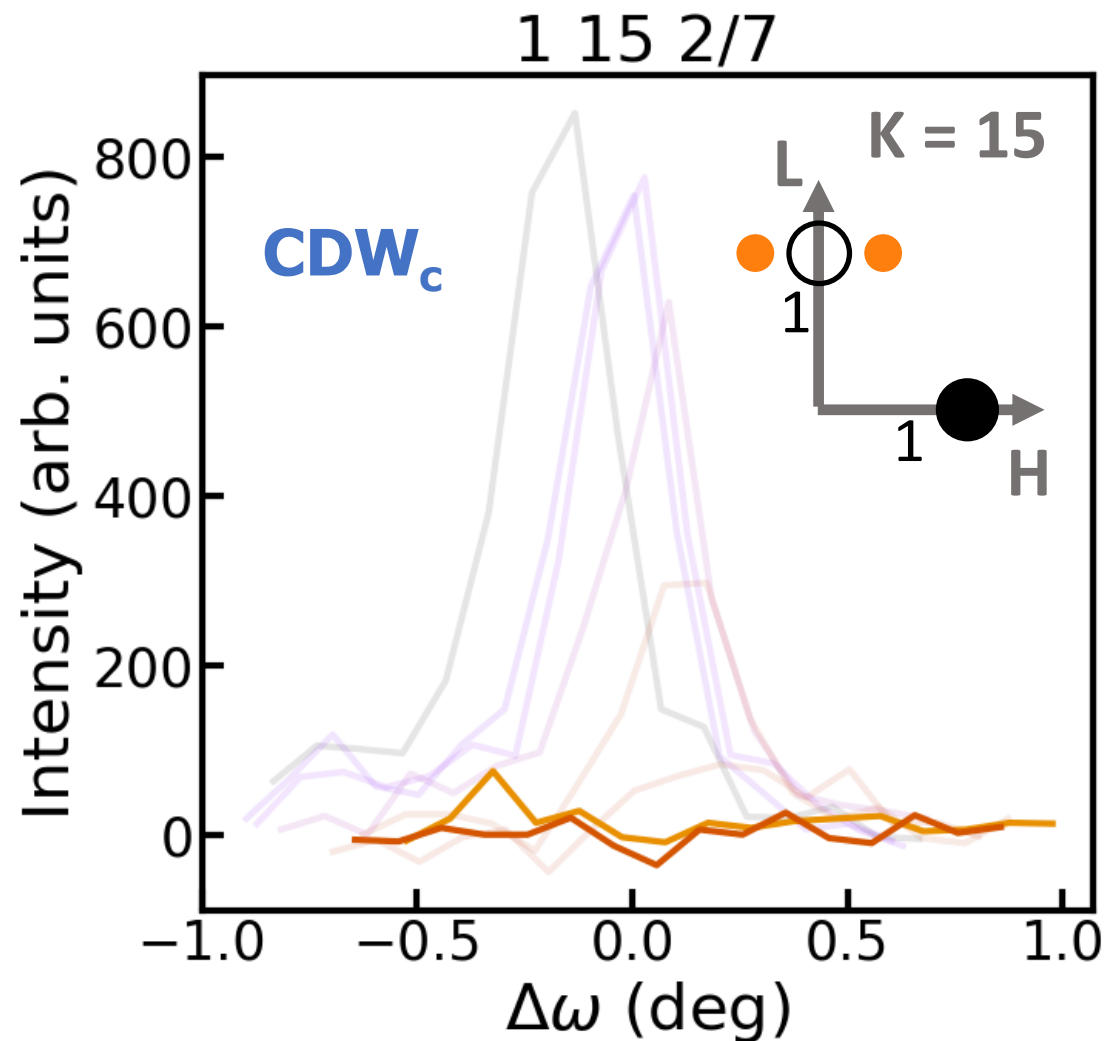
# CDW satellite reflections at fixed temperature 250 K



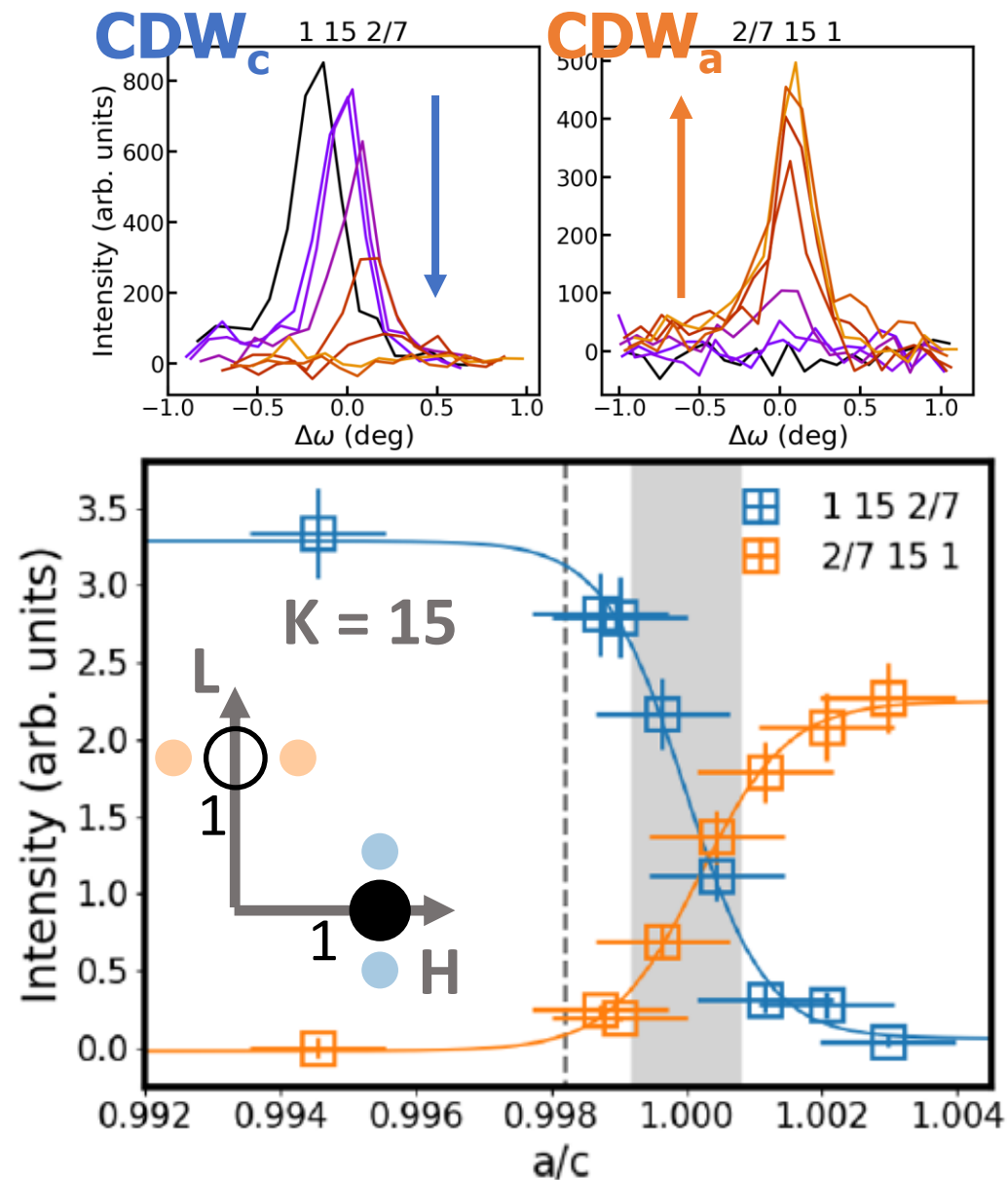
# CDW satellite reflections at fixed temperature 250 K



# CDW satellite reflections at fixed temperature 250 K

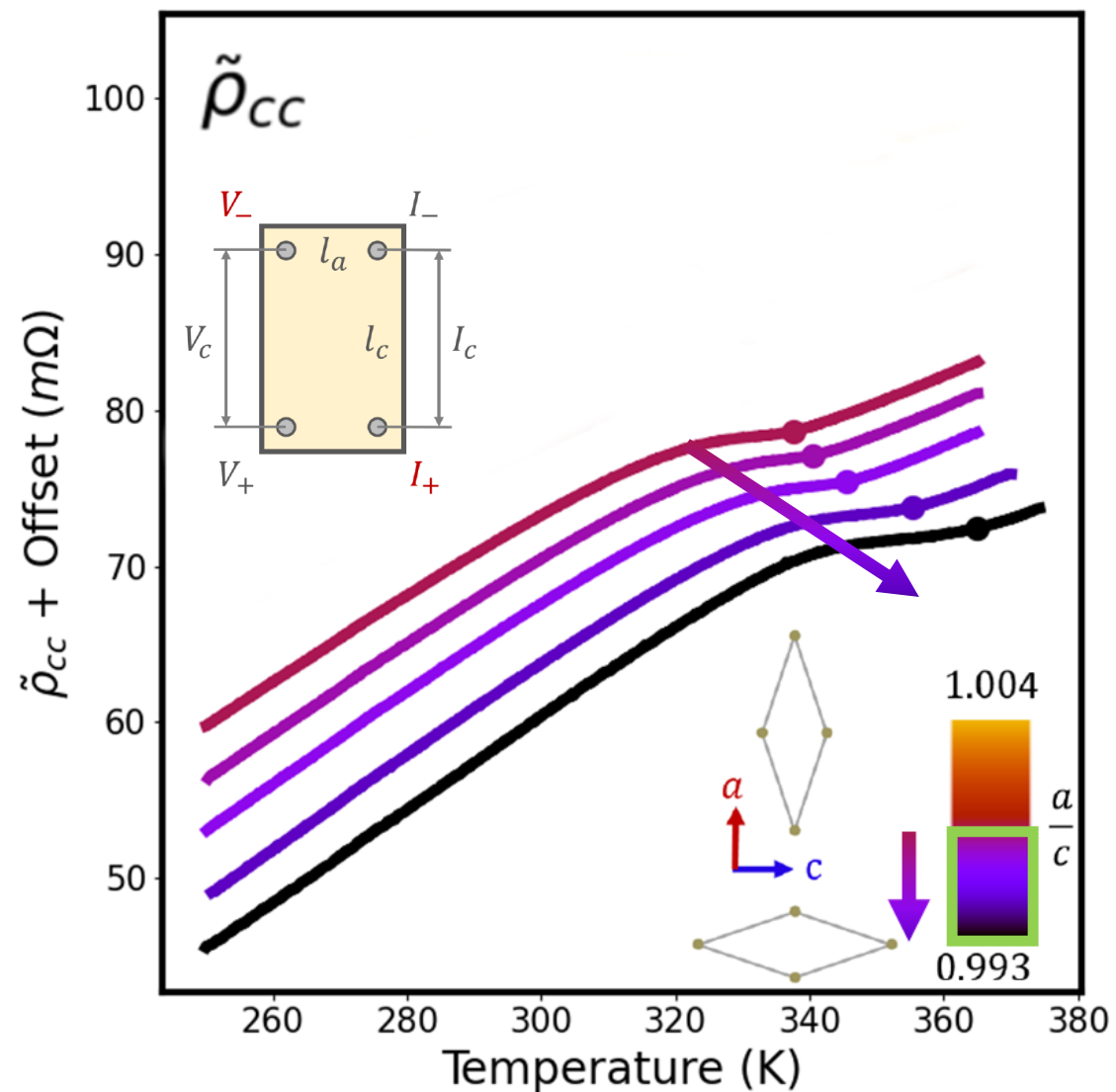
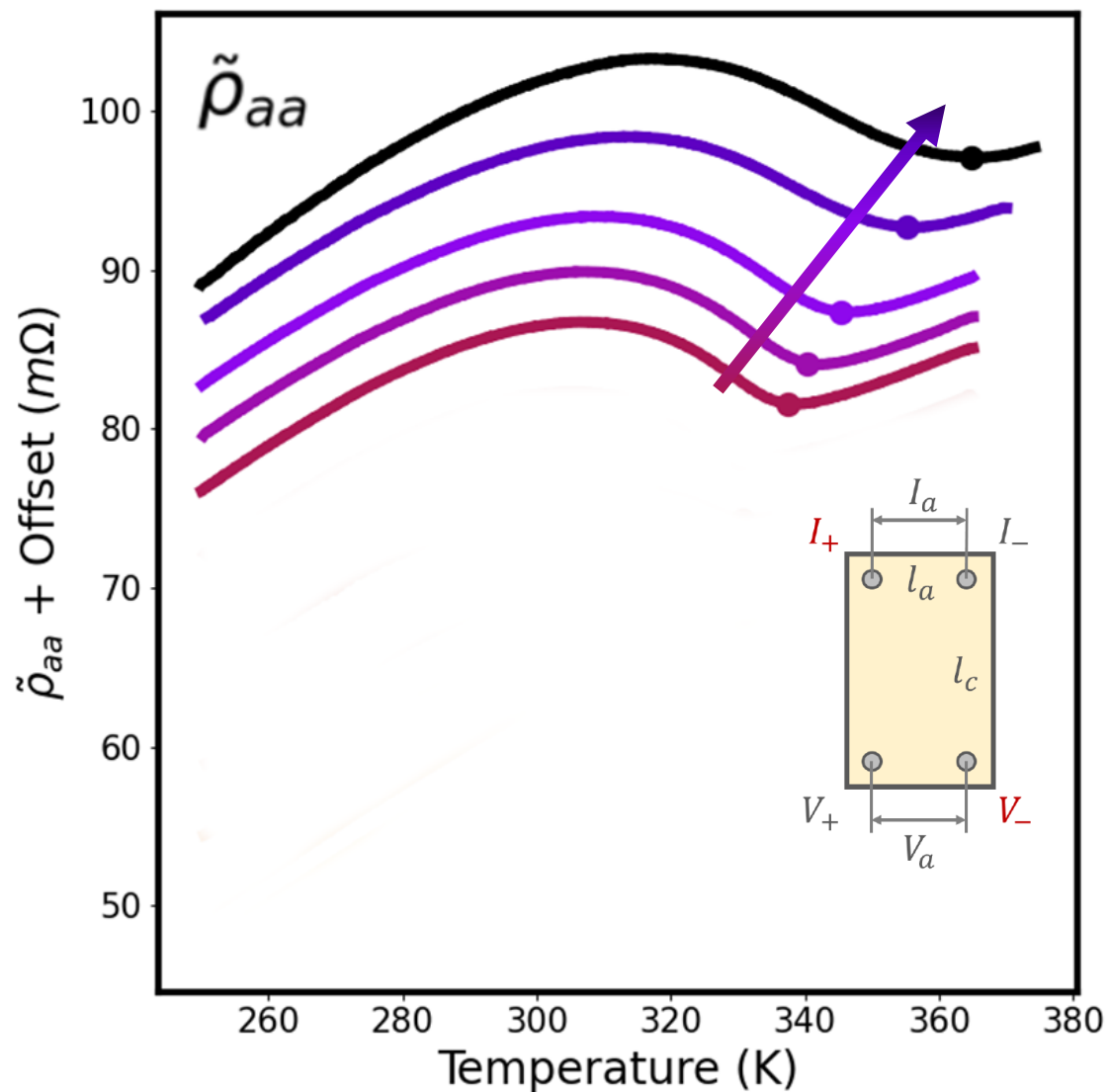


# CDW satellite reflections at fixed temperature 250 K

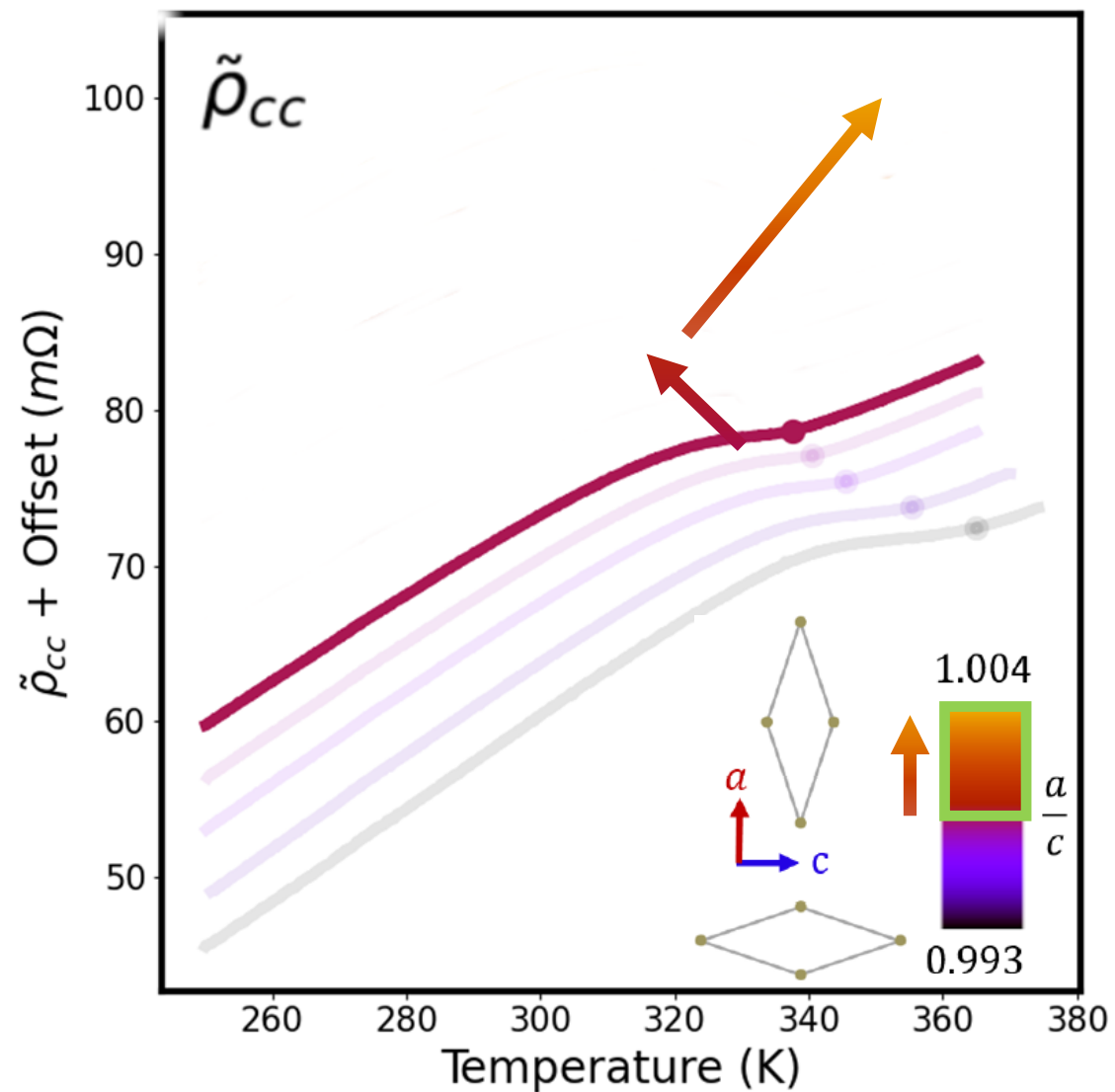
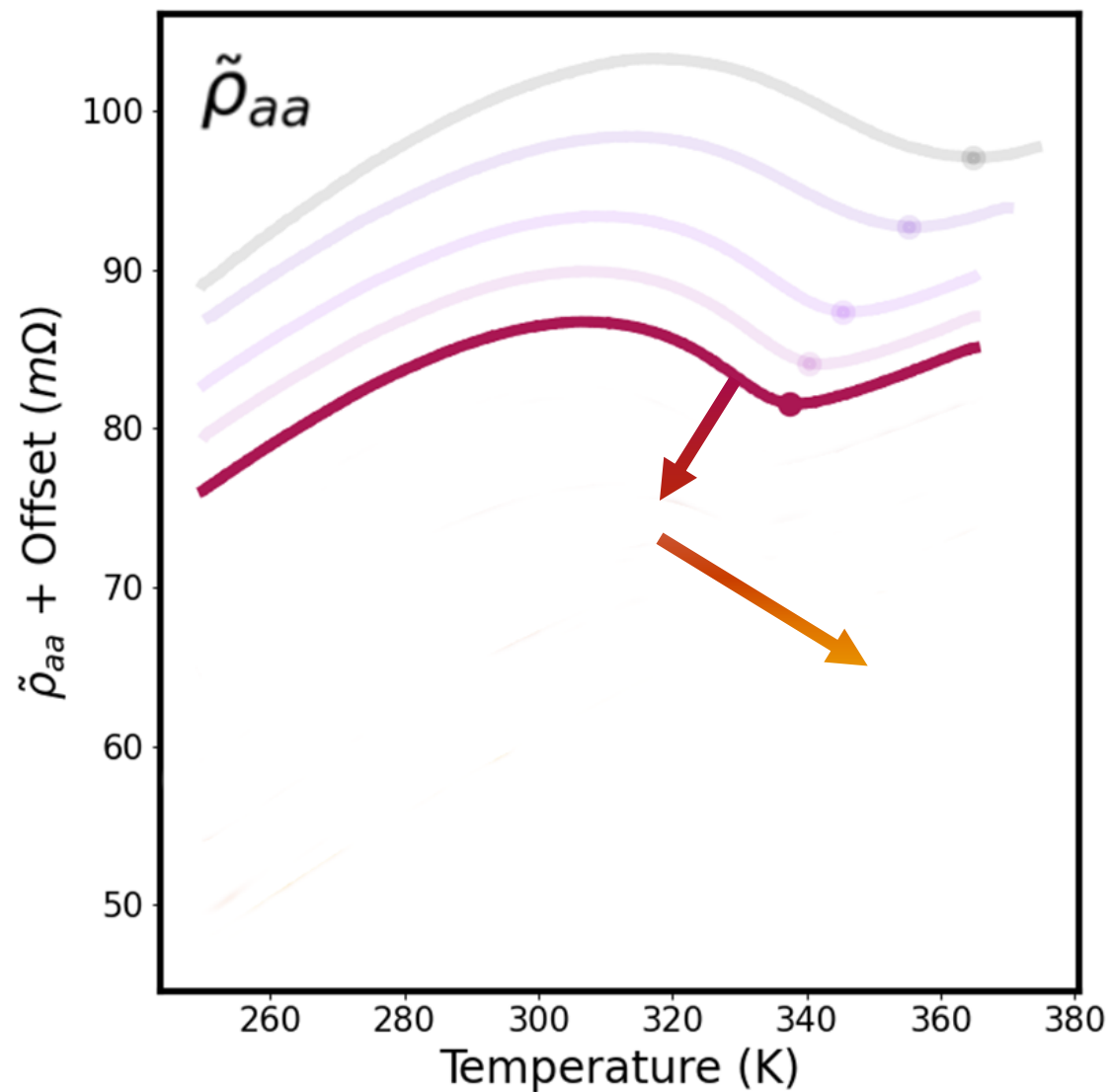


- New strain-induced CDW phase along  $\vec{a}$
- Coexistence phase for  $\frac{a}{c} \approx 1$
- Saturation regimes for both CDW
- From Peierls theory :
  - Satellite intensity is linked to the gap :  $I_{sat} \propto |\Delta|^2$
- Absolutely reversible

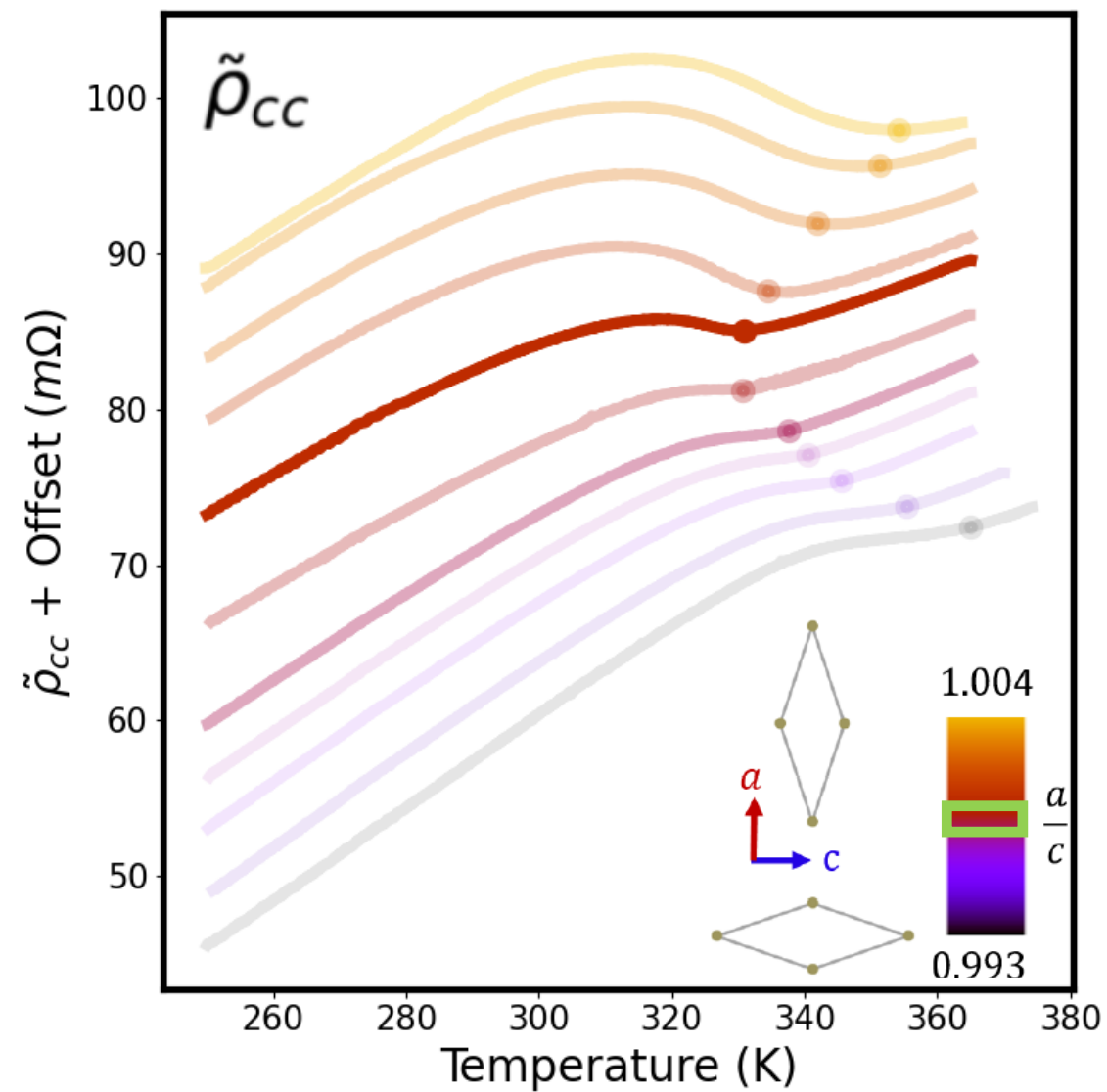
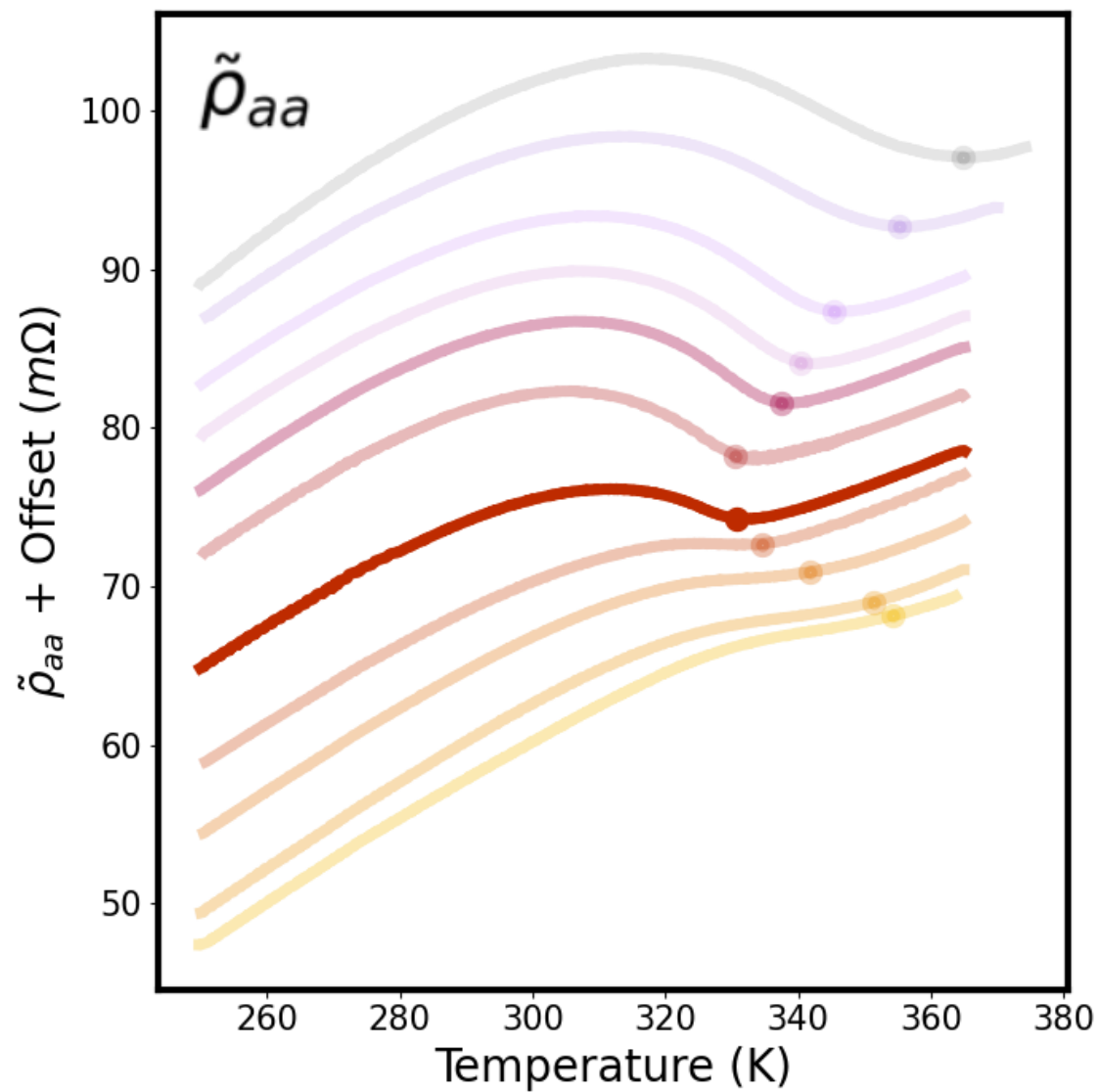
# Transport measurements : evolution of $T_c$



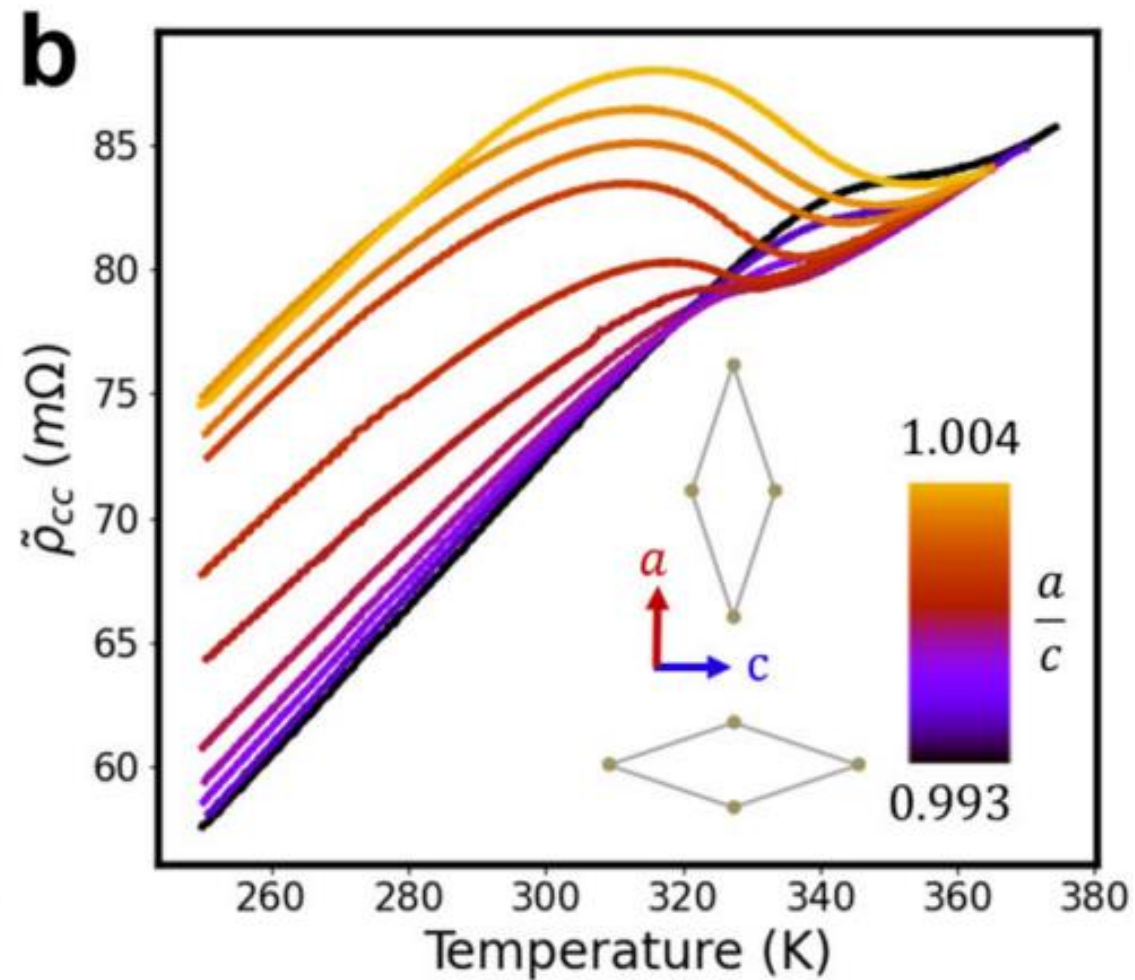
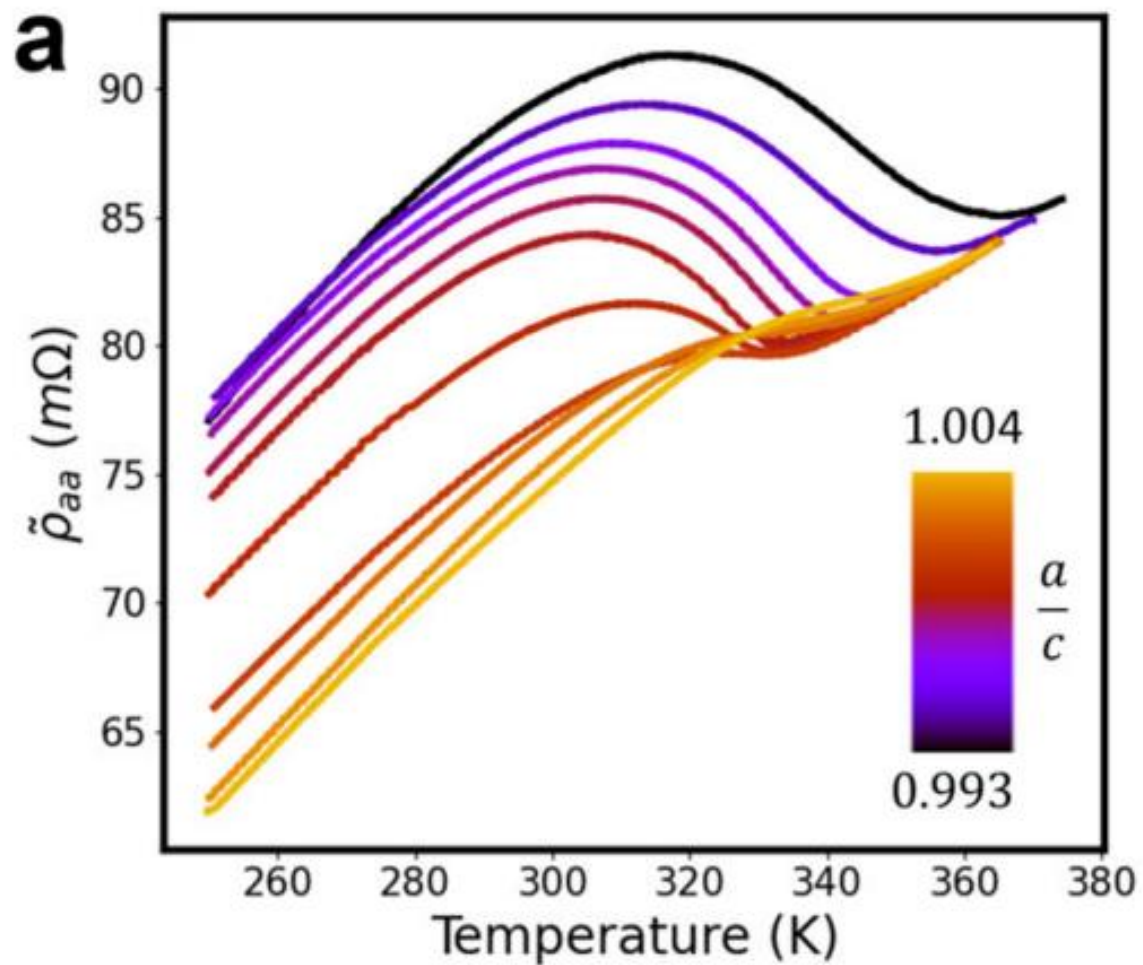
# Transport measurements : evolution of $T_c$



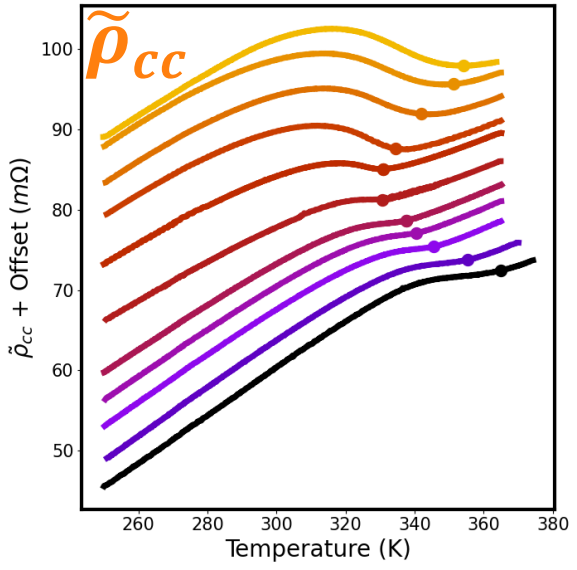
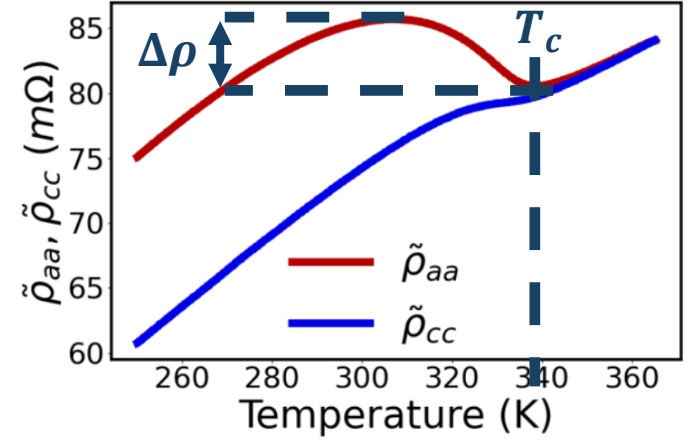
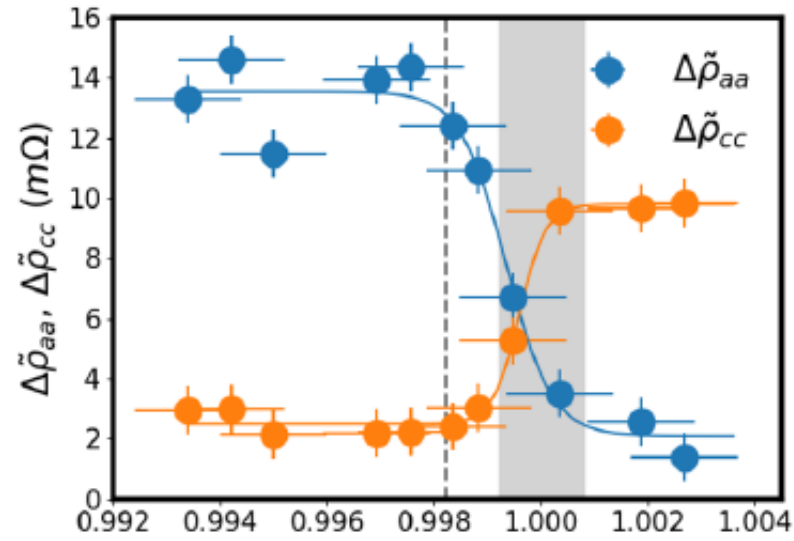
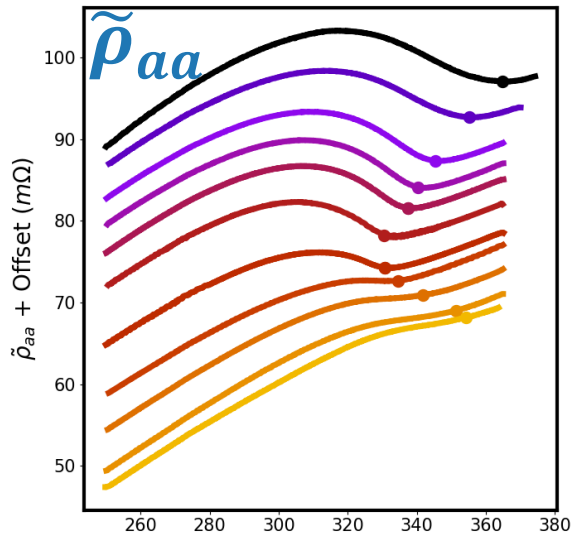
# Coexistence phase at $a = c$



# Transport measurements along a and c

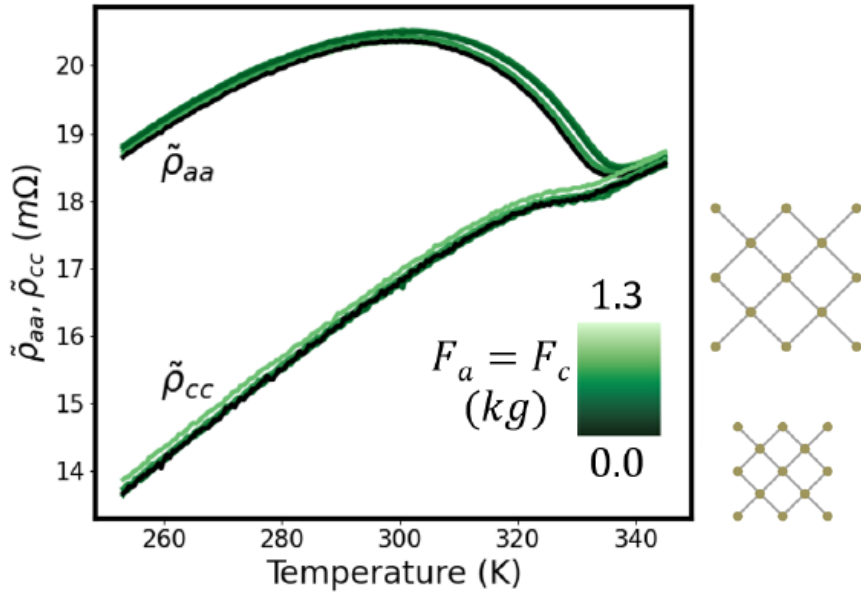


# Mismatch between gaps and critical temperature

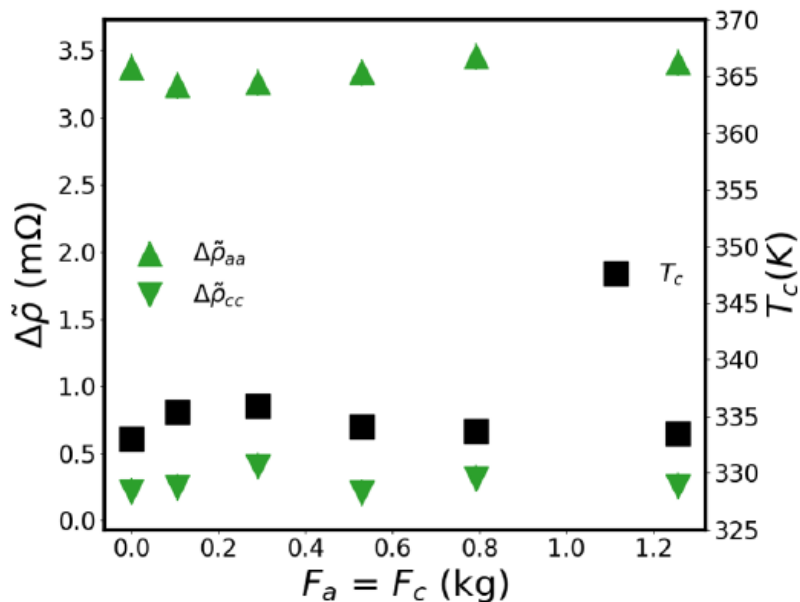
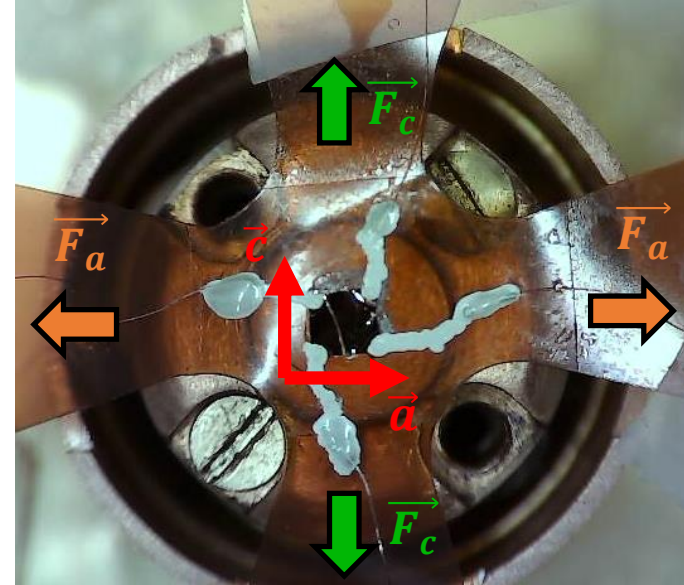


- Amplitude of resistivities follow CDW satellites behaviour
  - Related to the gap

# No effect of equibiaxial tensile stress (constant a/c)



$$\|\vec{F}_a\| = \|\vec{F}_c\|$$

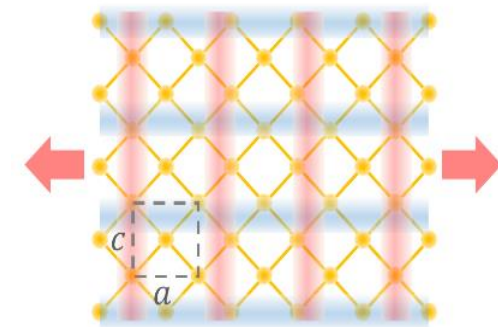
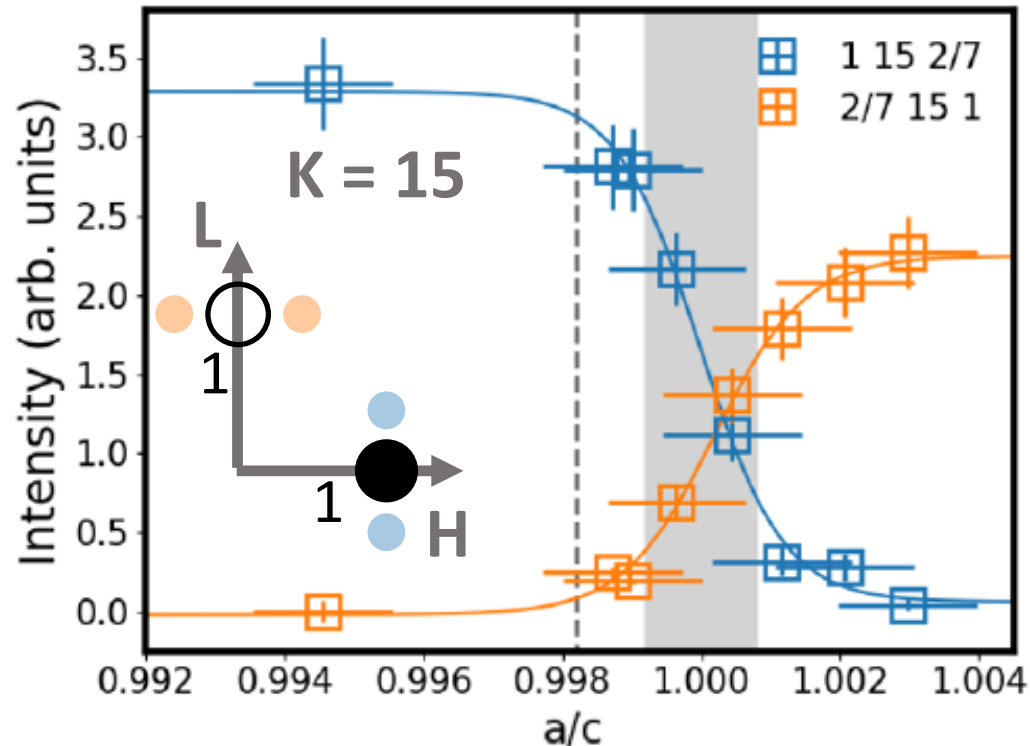


- Biaxial tensile stress
  - keeps a/c ratio constant
  - decreases b parameter
- No variation in resistivity curves: constant  $\Delta$  and  $T_c$
- a/c ratio meaningful parameter for CDW in RTe<sub>3</sub>

# What is the CDW structure in the coexistence region ?

Several possible scenarii :

- CDWa and CDWc separated in different domains in the same Te planes  
→ No change of FWHM in XRD
- CDWa and CDWc develop in full but different Te planes
- CDWa and CDWc grow in the same Te planes  
→  $q_a + q_c$  CDW satellites should appear in XRD

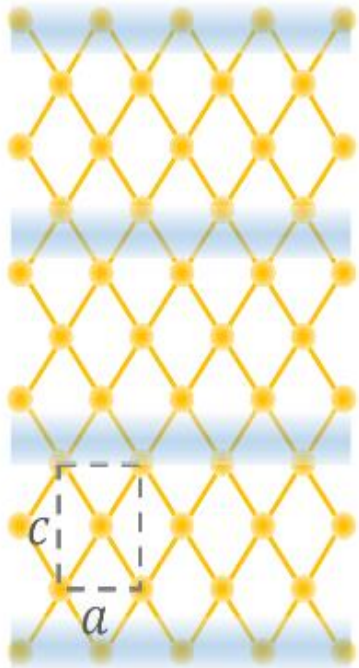


# Structural evolution of CDW as a function of deformation

*Initial state*

$$c > a$$

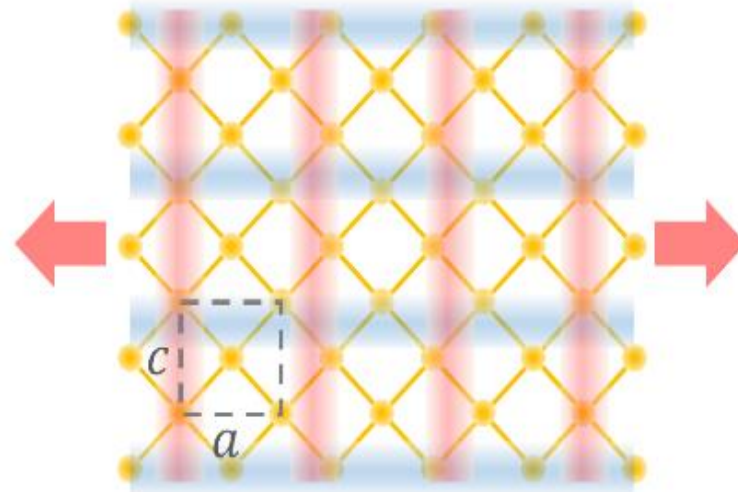
$CDW_c$



*Square lattice*

$$c = a$$

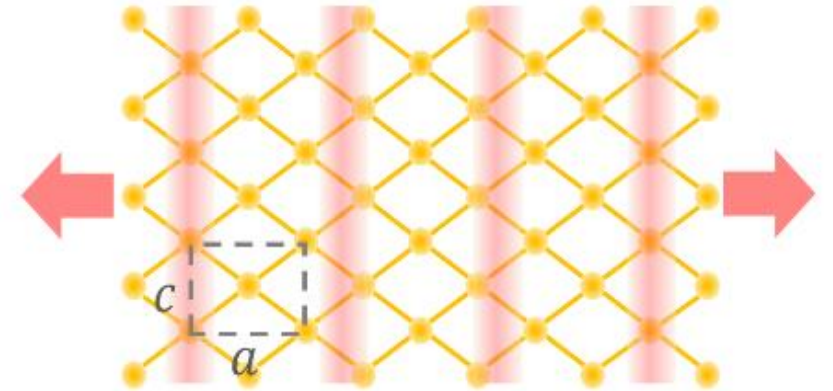
$CDW_c + CDW_a$



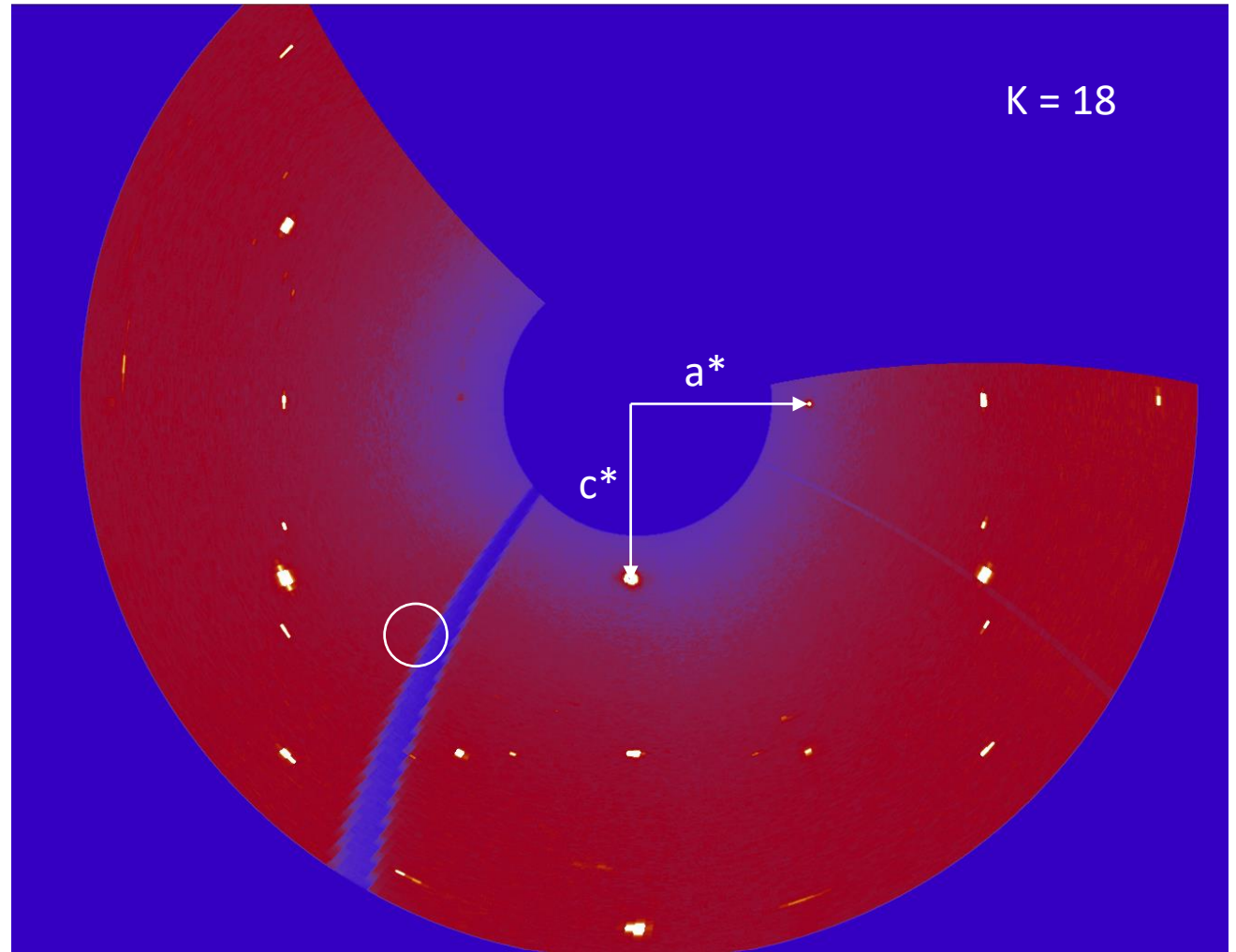
*Reversed state*

$$c < a$$

$CDW_a$

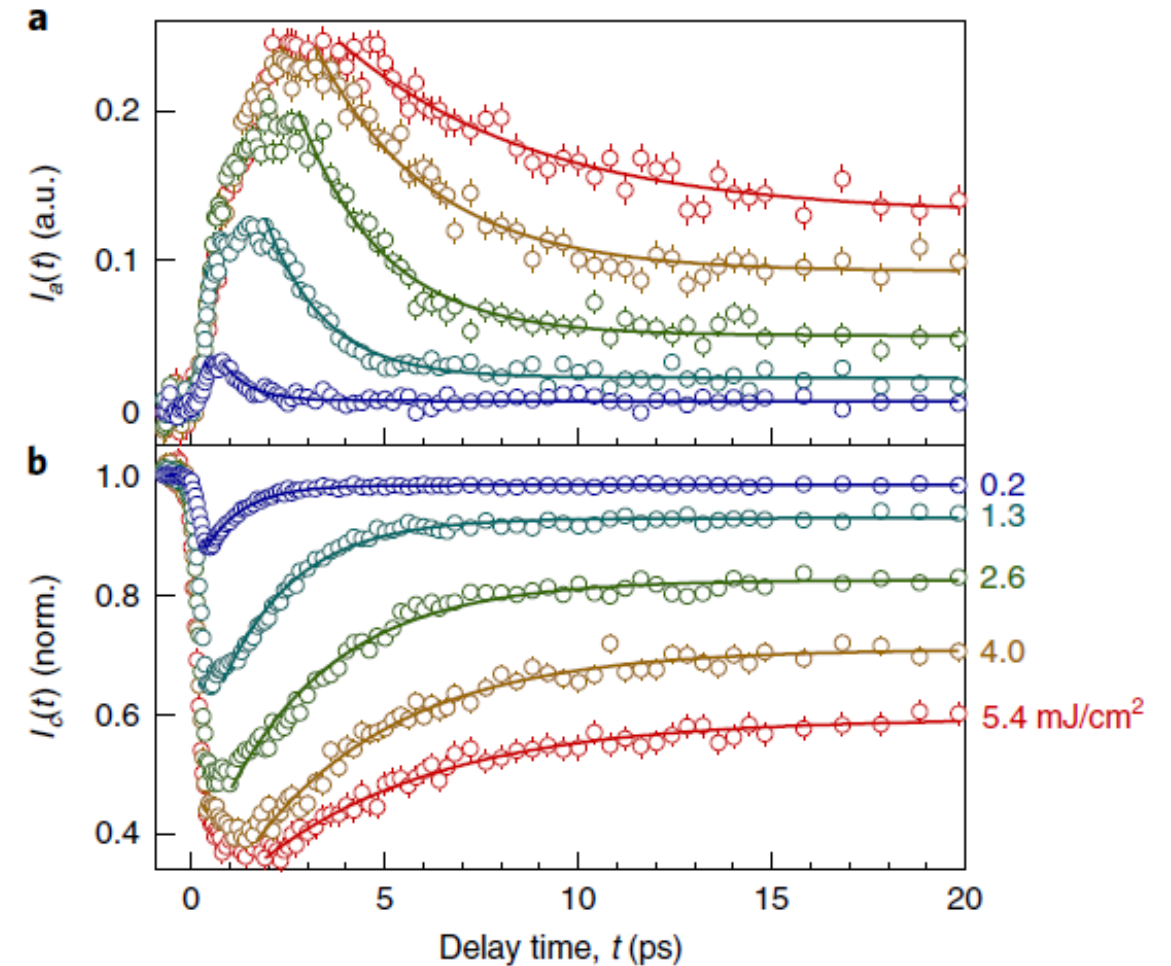
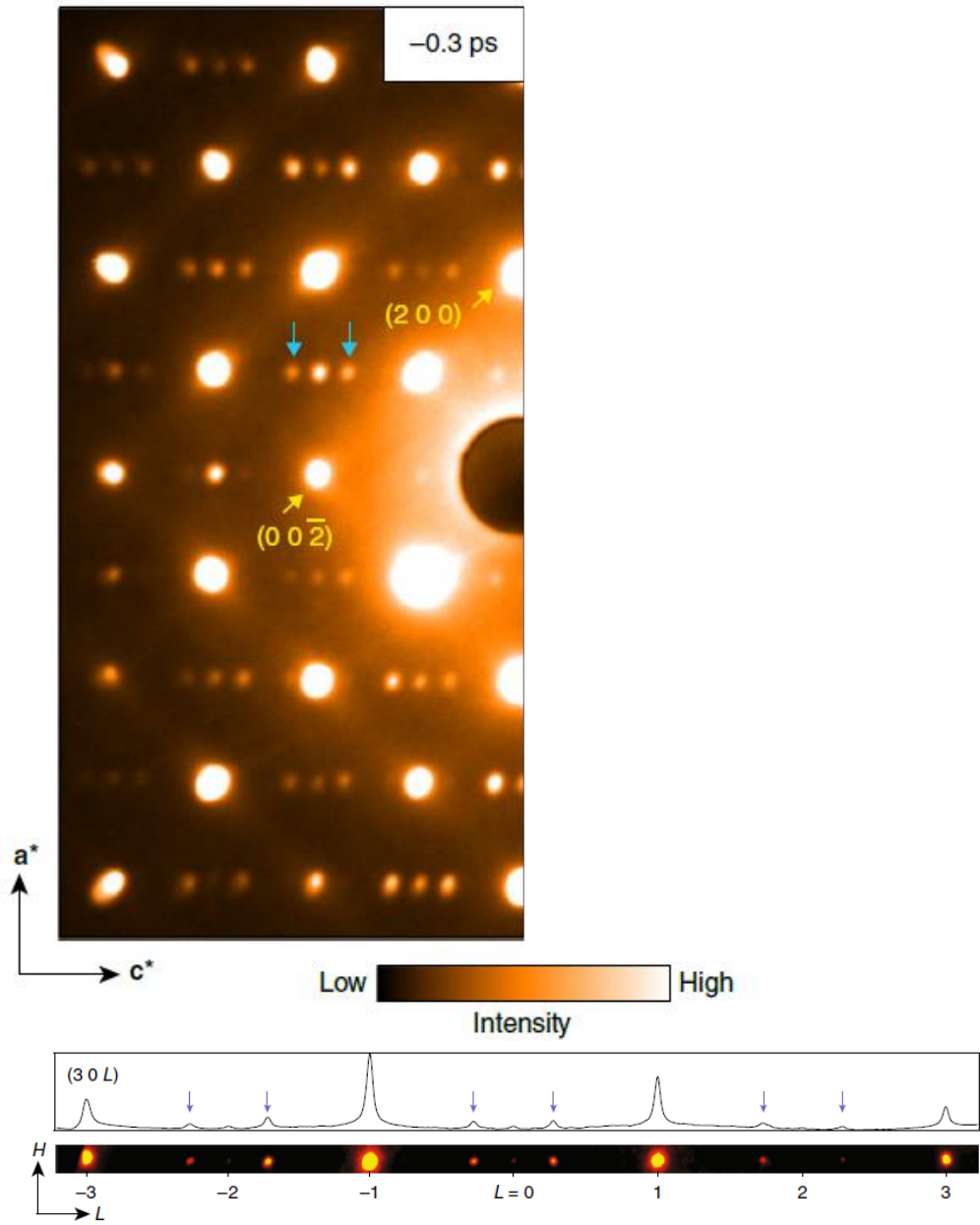


# Tracking the $q_a + q_c$ reflection @ CRISTAL



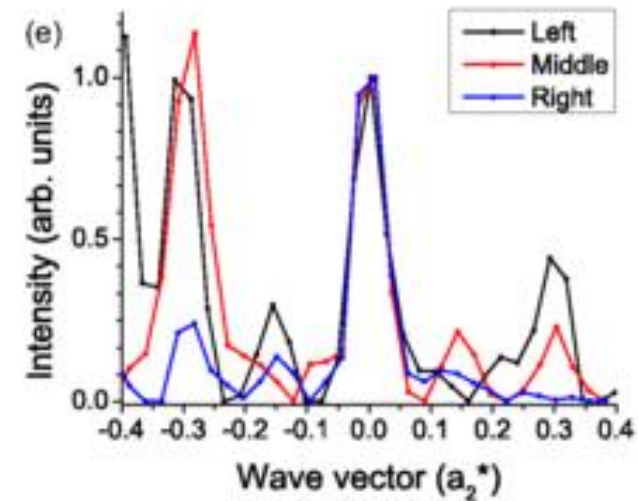
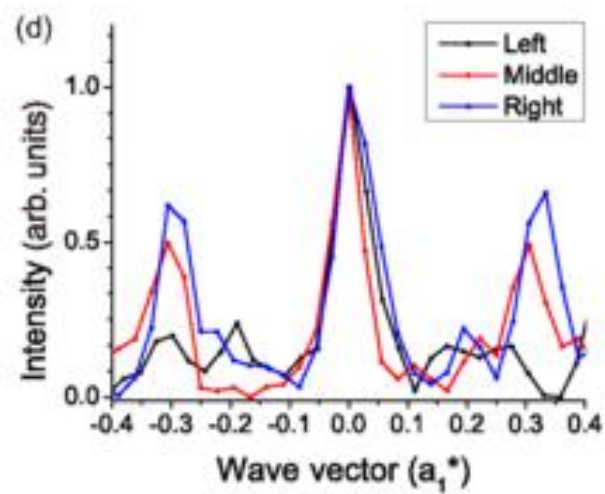
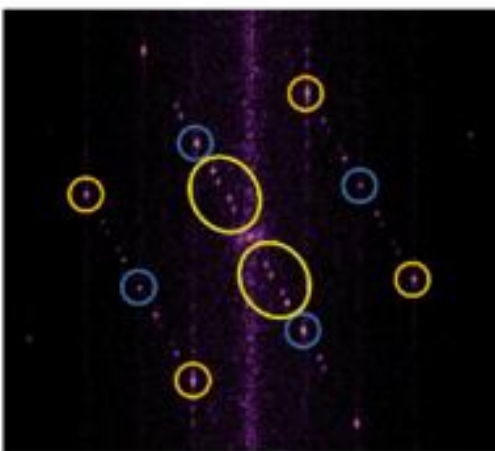
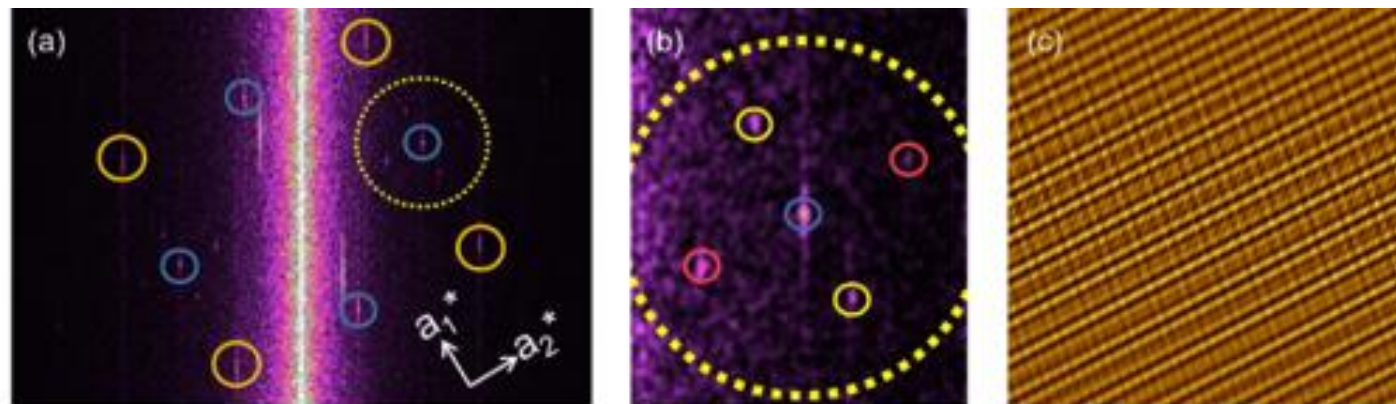
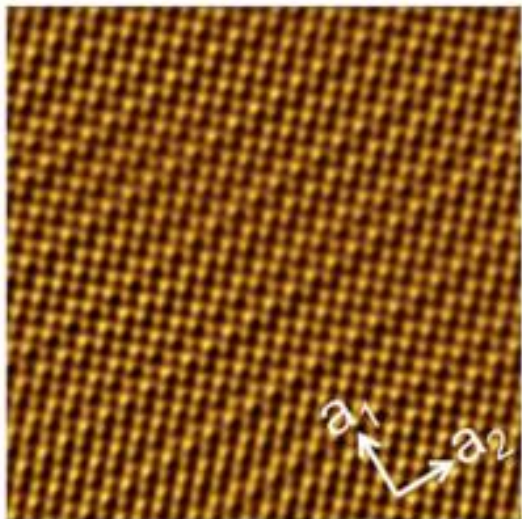
CDWa and CDWc intrinsically weak signals.  
 $q_a + q_c$  (if it exists) is MUCH weaker (second-order satellite)

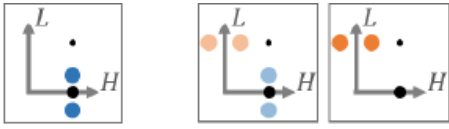
# A “hidden” transient state in LaTe3: CDW along $\vec{a}$



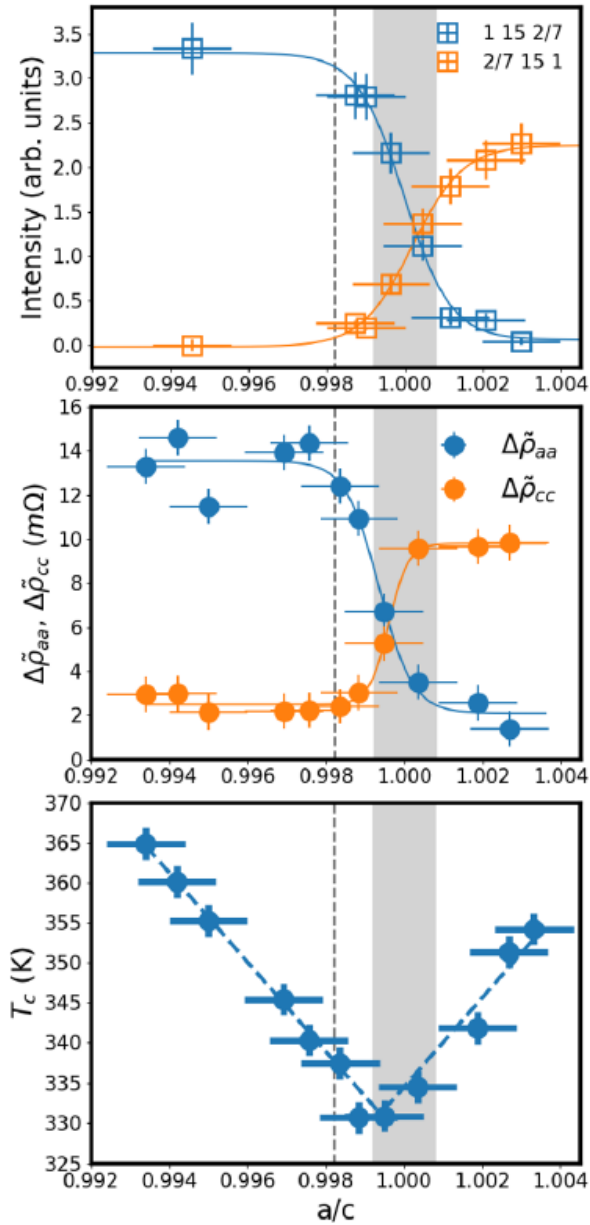
CDW along  $\vec{a}$ : Transient state that does not exist in LaTe<sub>3</sub> at equilibrium at any temperature

# STM studies : coexistence observed at the surface





# Conclusion & perspectives



- TbTe<sub>3</sub> system is very sensitive to strain in (a, c) plane
  - a/c ratio plays a key role
- New stable CDW phase along  $\vec{a}$  induced by strain ; different from temperature or pressure-induced CDW<sub>a</sub>
- CDW coexistence phase near  $\frac{a}{c} \approx 1$  : how does the two CDW along **a** and **c** coexist ? Domains ? Superposition of states ? Need further experiments
- Different behaviours for the  $\Delta$  and  $T_C$  to be explained; measurement of gaps under deformation
- Same nature as CDW<sub>a</sub> observed in laser-pumped experiments in LaTe<sub>3</sub> ?
- New biaxial tensile stress device : application to any layered material

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Thank you for your attention