

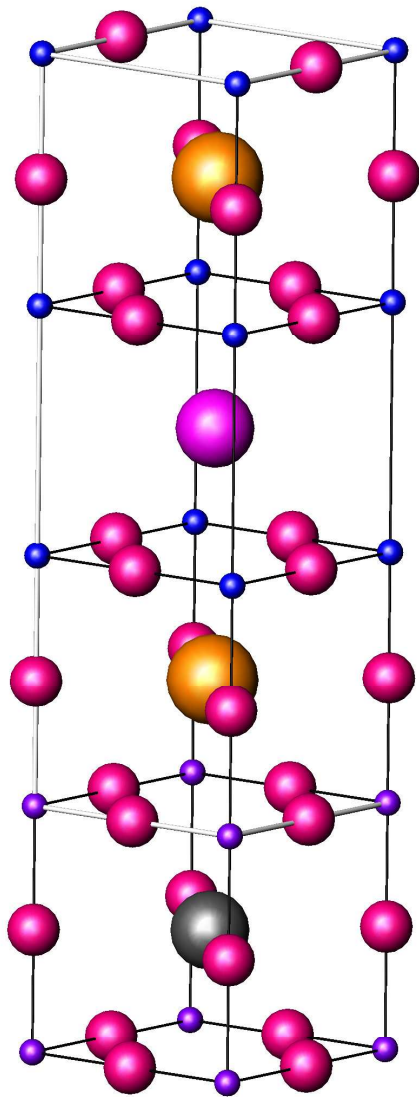
Jochen Stahn Laboratory for Neutron Scattering
Justin Hoppler ETH Zurich & Paul Scherrer Institut
Christof Niedermayer and
Christian Bernhard University Fribourg, FriMat

Giant superconductivity-induced modulation of the ferromagnetic magnetization in a cuprate-manganite superlattice

Nature Materials **8**, 315-319 (2009)

Phys. Rev. B **78**, 134111 (2008)

Phys. Rev. B **71**, 140509(R) (2005)



what happens at interfaces where

electronic
 chemical
 crystallographic
 magnetic

} properties do not match?

SC and magnetism avoid each other

— unless forced together on an atomic scale

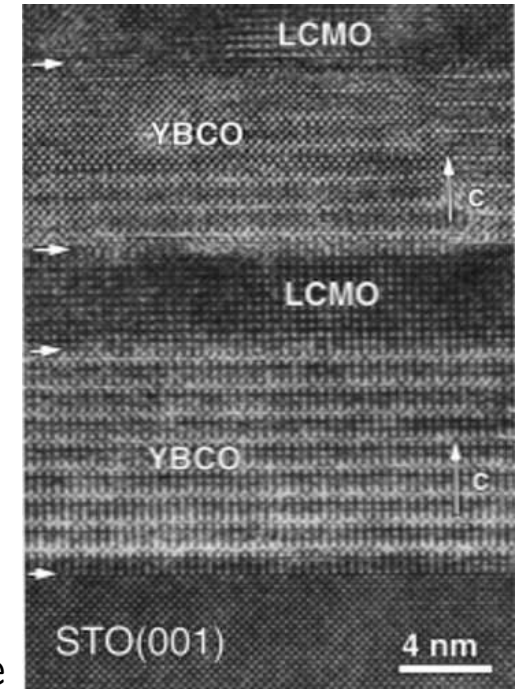
⇒ how do they arrange?

used system:

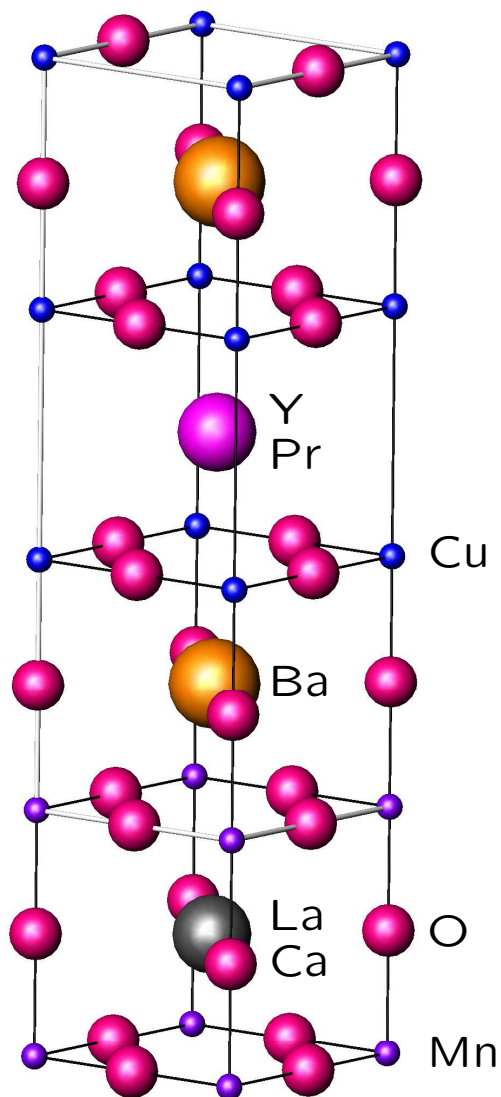
multilayers of the type



grown by *pulsed laser deposition*



TEM image



crystal types:
(close to) perovskite-like

multilayers of the type $[\text{SC}/\text{FM}]_n/\text{STO}$

FM: $\text{La}_{2/3}\text{Ca}_{1/3}\text{MnO}_3$

$T_{\text{Curie}} \approx 180 \text{ K}$

STO: SrTiO_3 used as substrate

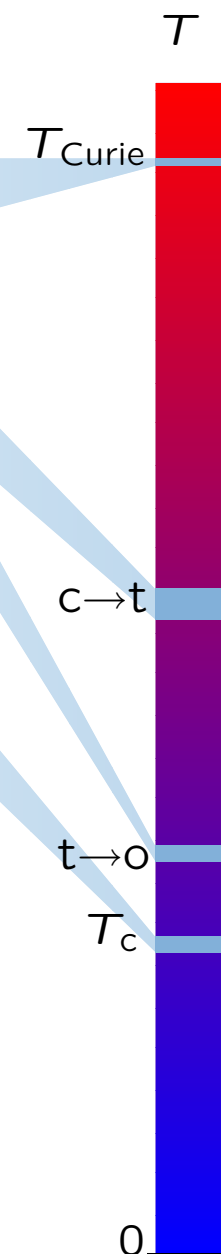
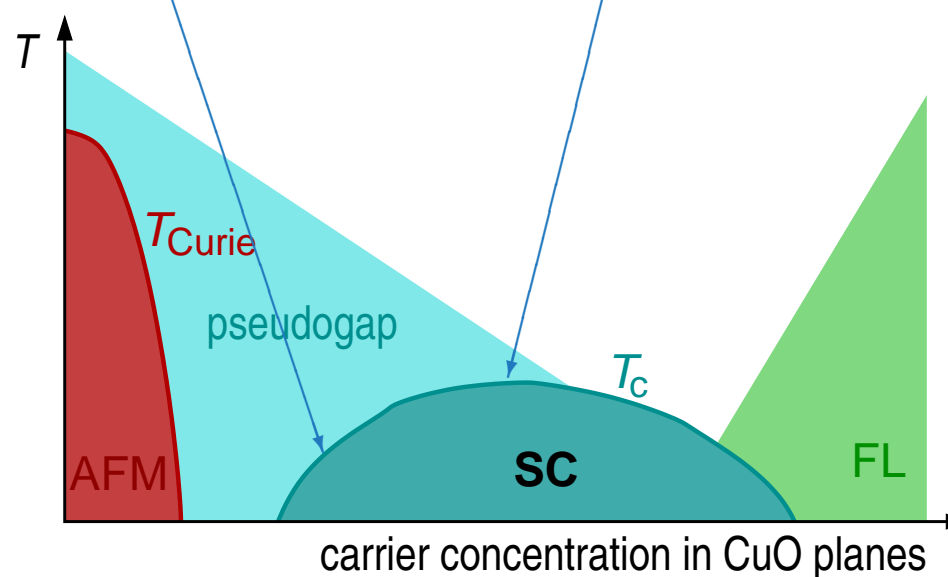
$T \approx 105 \text{ K}$: cubic to tetragonal

$T \approx 65 \text{ K}$: tetragonal to orthorhombic

\Rightarrow surface fragmentation

SC: $\text{Y}_{1-x}\text{Pr}_x\text{Ba}_2\text{Cu}_3\text{O}_6$

$T_c \approx 40 \text{ K}$ ($x = 0.4$), 90 K ($x = 0$)



how does the magnetisation in the film look like?

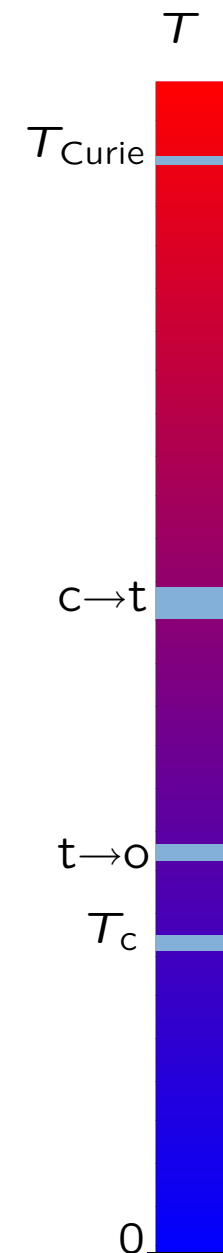
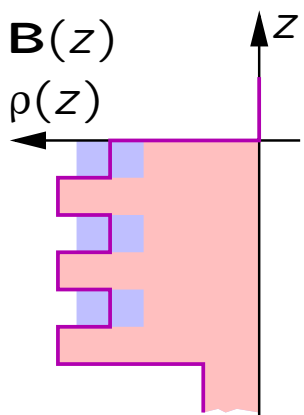
depth profile of magnetic induction: $\mathbf{B}(z)$

has SC an influence? $\Rightarrow T$ -dependence of $\mathbf{B}(z)$

\Rightarrow need for a method to probe $\mathbf{B}(z)$ and $\rho(z)$

- with $0 < z < 2000 \text{ \AA}$
 $\Delta z \approx 1 \text{ \AA}$
- in the range $10 \text{ K} < T < 200 \text{ K}$
- in a magnetic field $H < 1000 \text{ Oe}$

\rightarrow polarised neutron reflectometry



index of refraction n (as for visible light:)

$$|n - 1| = |\delta| < 10^{-5}$$

$$\delta = \delta_{\text{nuclear}} \pm \delta_{\text{magnetic}}$$

$$\delta_{\text{magnetic}} \propto \mu_n \mathbf{B}_{\perp}$$

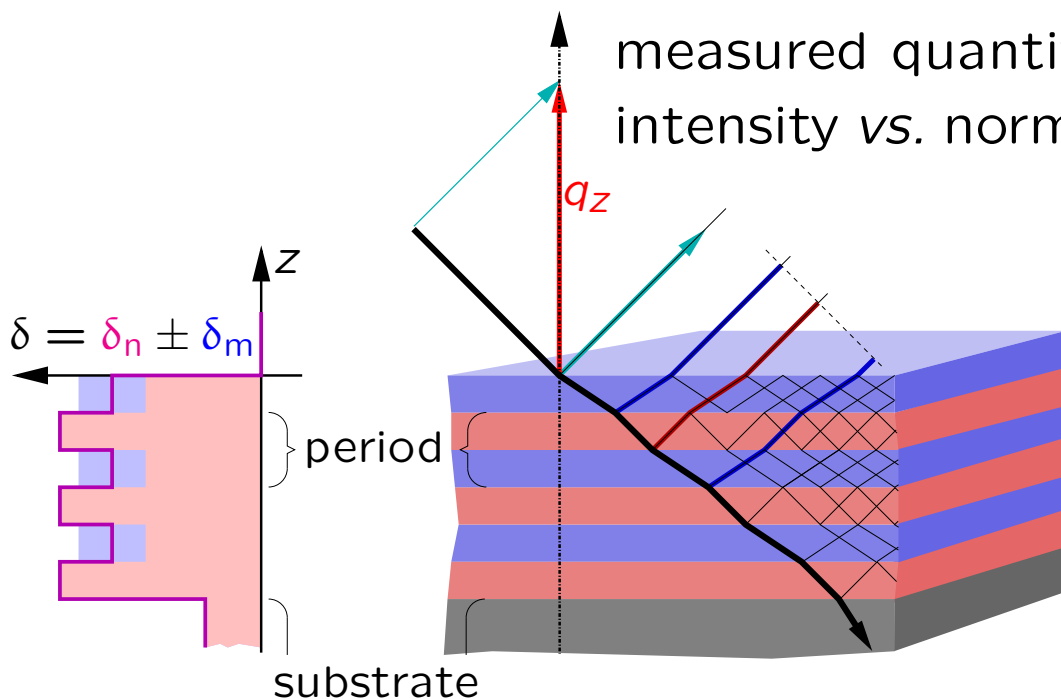
neutron magnetic moment: μ_n

in-plane magnetic induction: \mathbf{B}_{\perp}



measured quantity:

intensity vs. normal momentum transfer q_z



for parallel interfaces:
interference of (multiply)
reflected beams

index of refraction n (as for visible light:)

$$|n - 1| = |\delta| < 10^{-5}$$

$$\delta = \delta_{\text{nuclear}} \pm \delta_{\text{magnetic}}$$

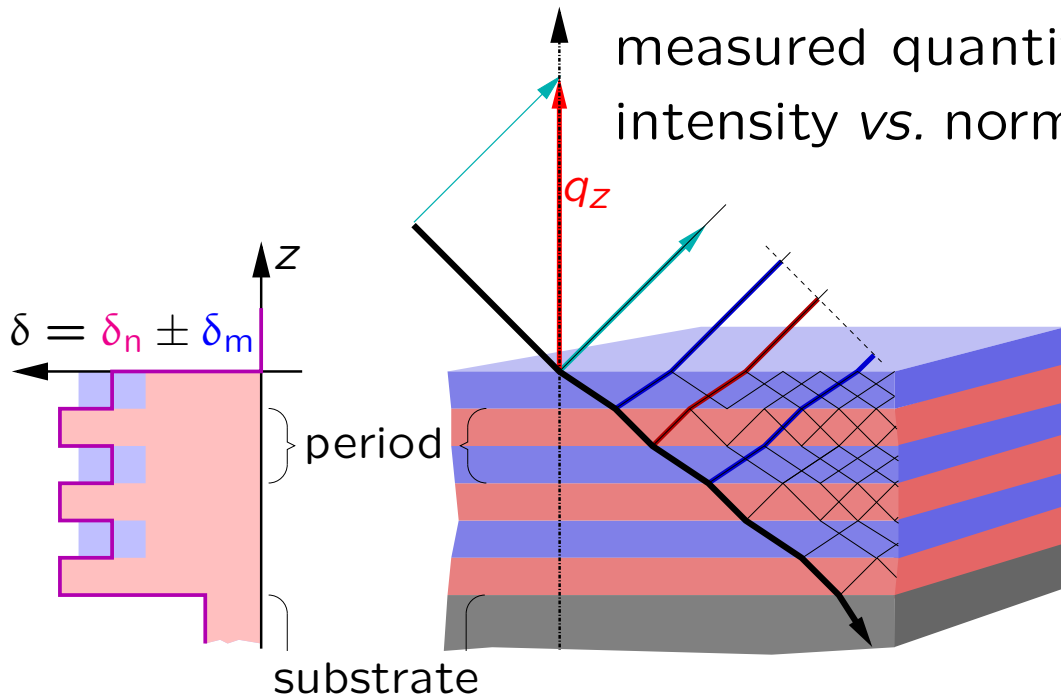
$$\delta_{\text{magnetic}} \propto \mu_n \mathbf{B}_{\perp}$$

neutron magnetic moment: μ_n

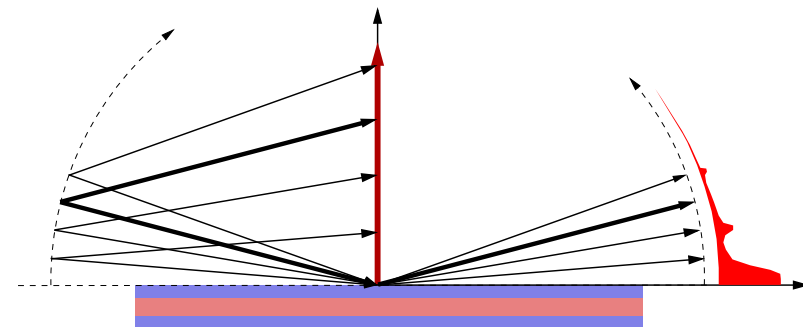
in-plane magnetic induction: \mathbf{B}_{\perp}



measured quantity:
 intensity vs. normal momentum transfer q_z



angle dispersive mode



index of refraction n (as for visible light:)

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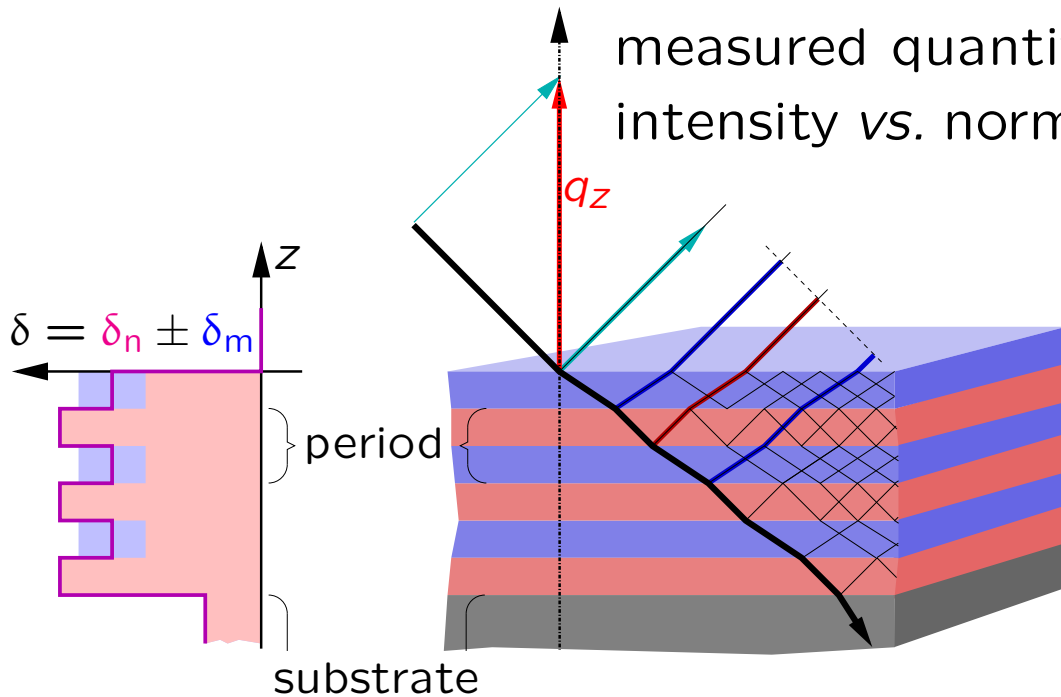
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neutron magnetic moment: μ_n

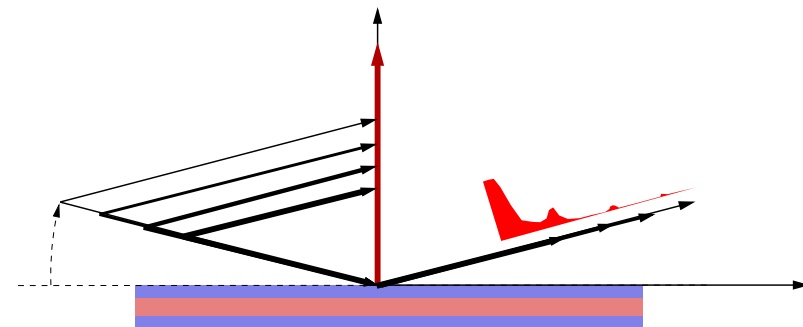
in-plane magnetic induction: \mathbf{B}_{\perp}



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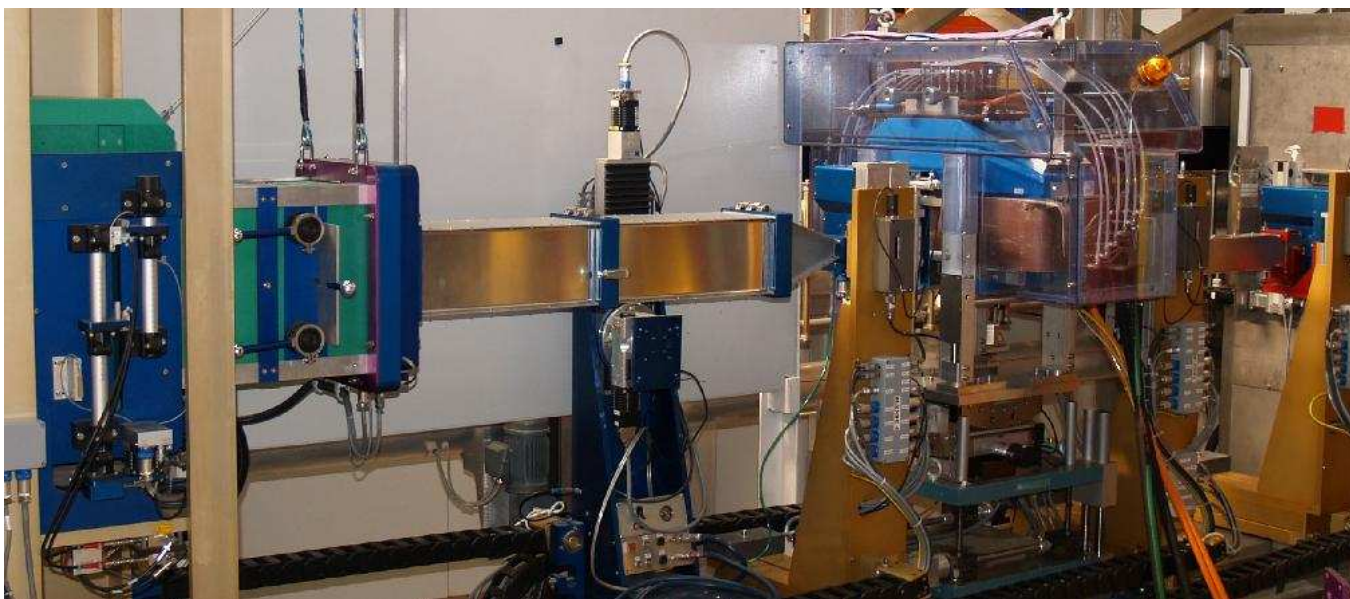


energy dispersive mode

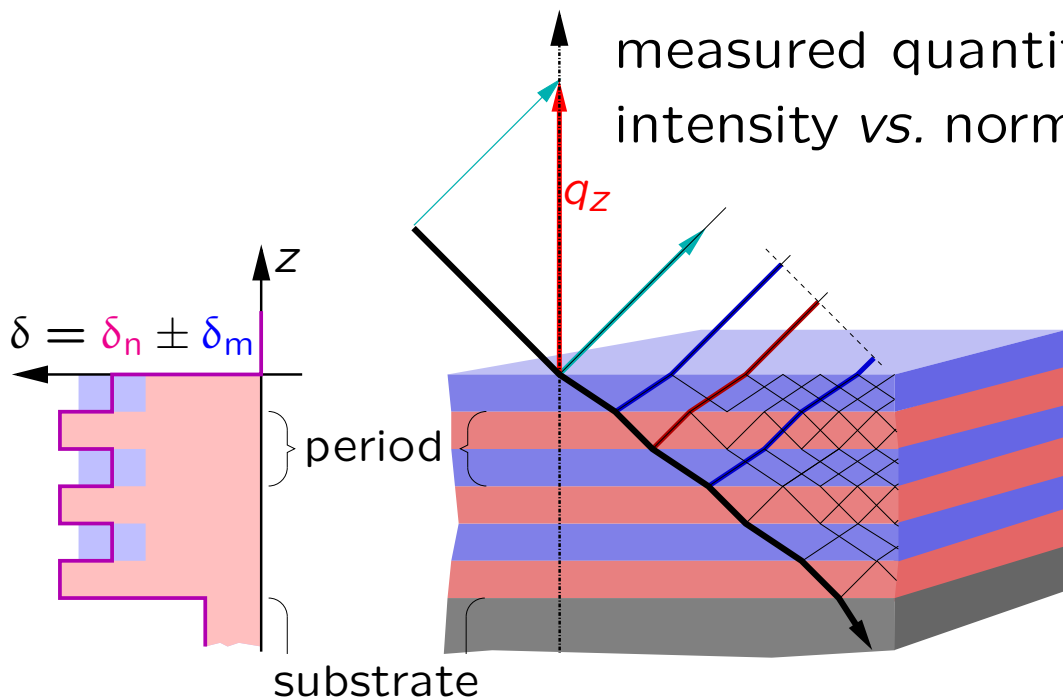


neutron reflectometer
AMOR
 at SINQ, PSI

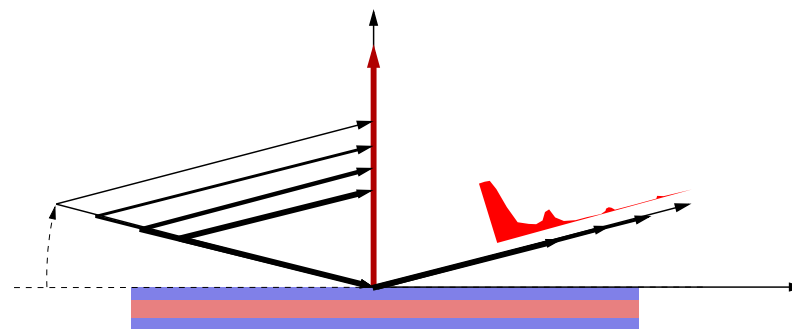
time-of-flight
 spin polarisation

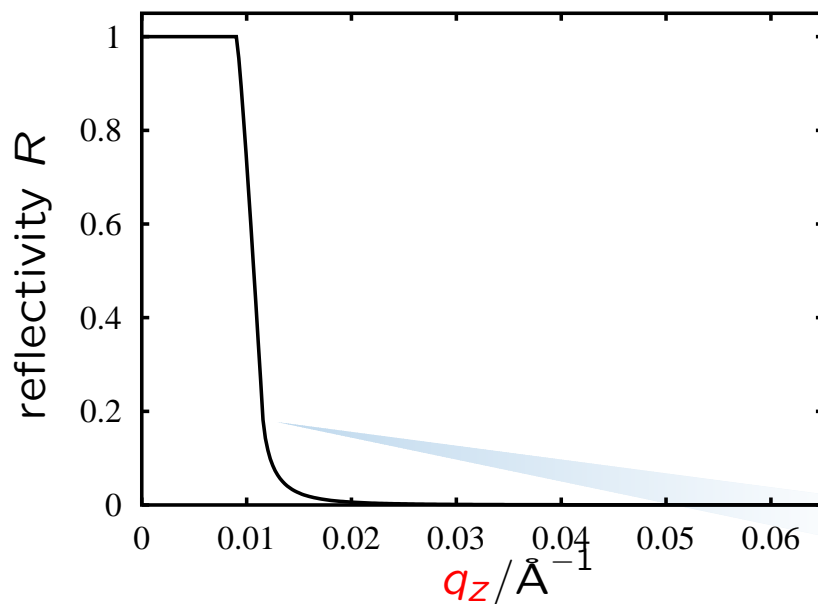


measured quantity:
 intensity vs. normal momentum transfer q_z

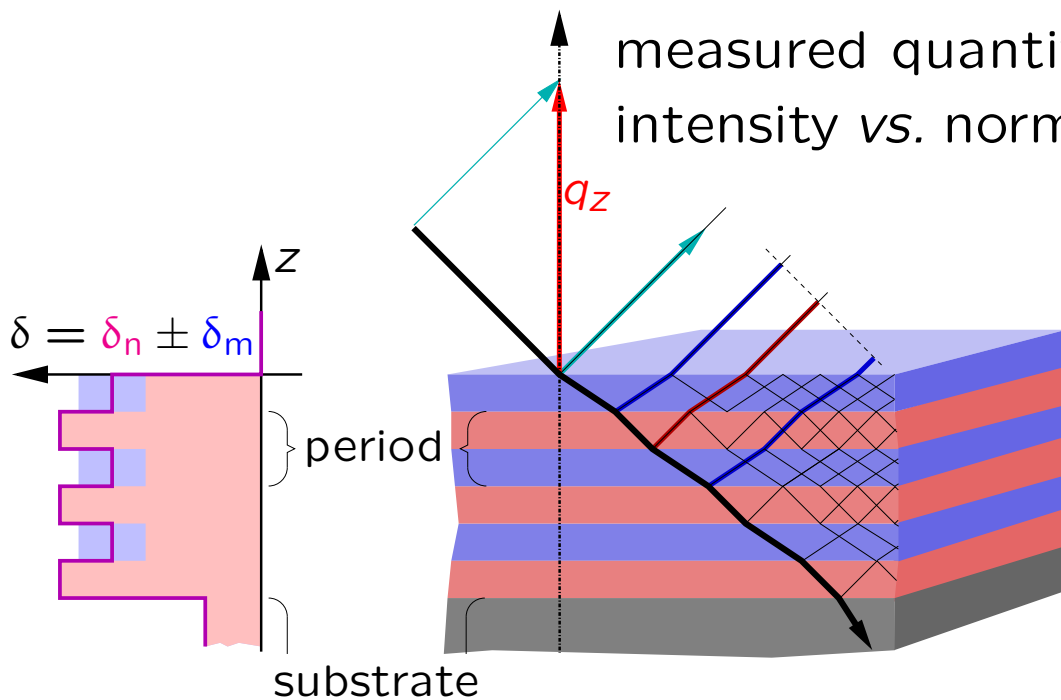


energy dispersive mode

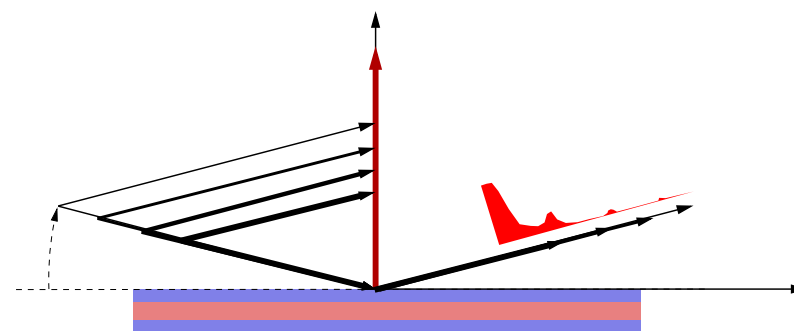


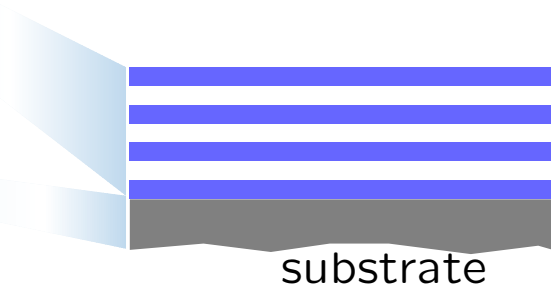
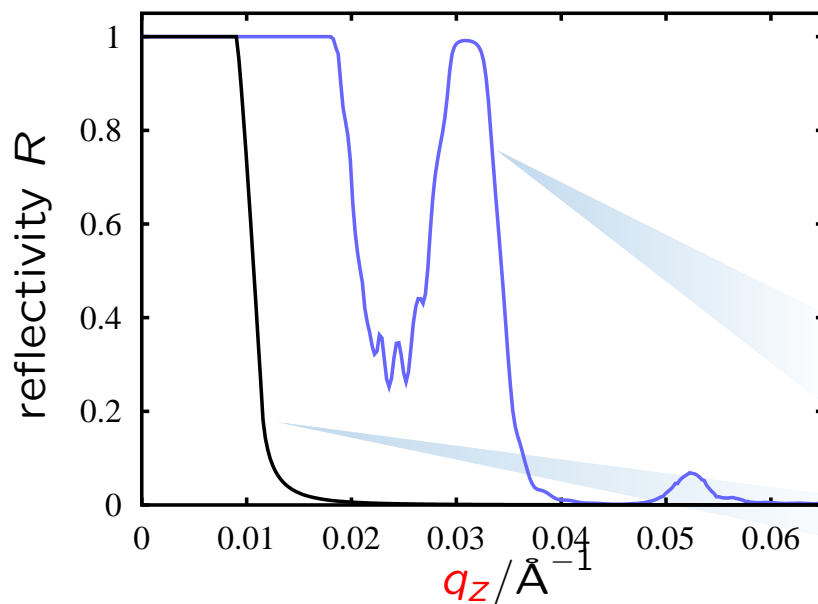


measured quantity:
intensity vs. normal momentum transfer q_z

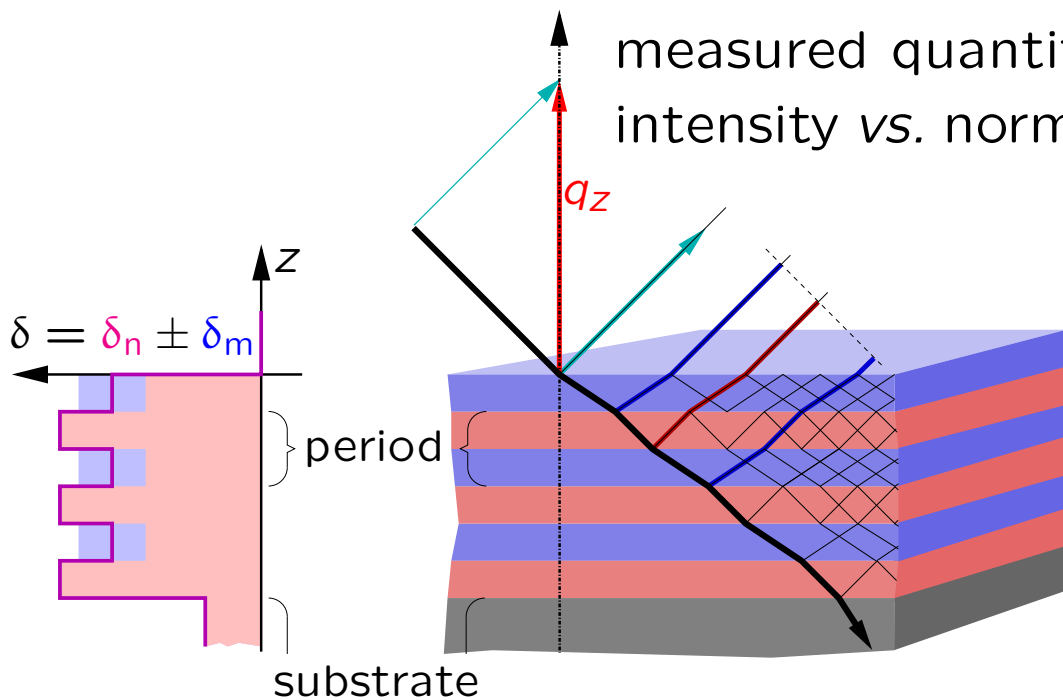


energy dispersive mode

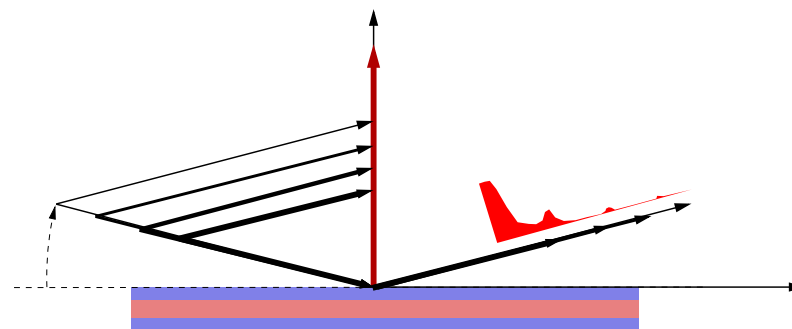




measured quantity:
intensity vs. normal momentum transfer q_z

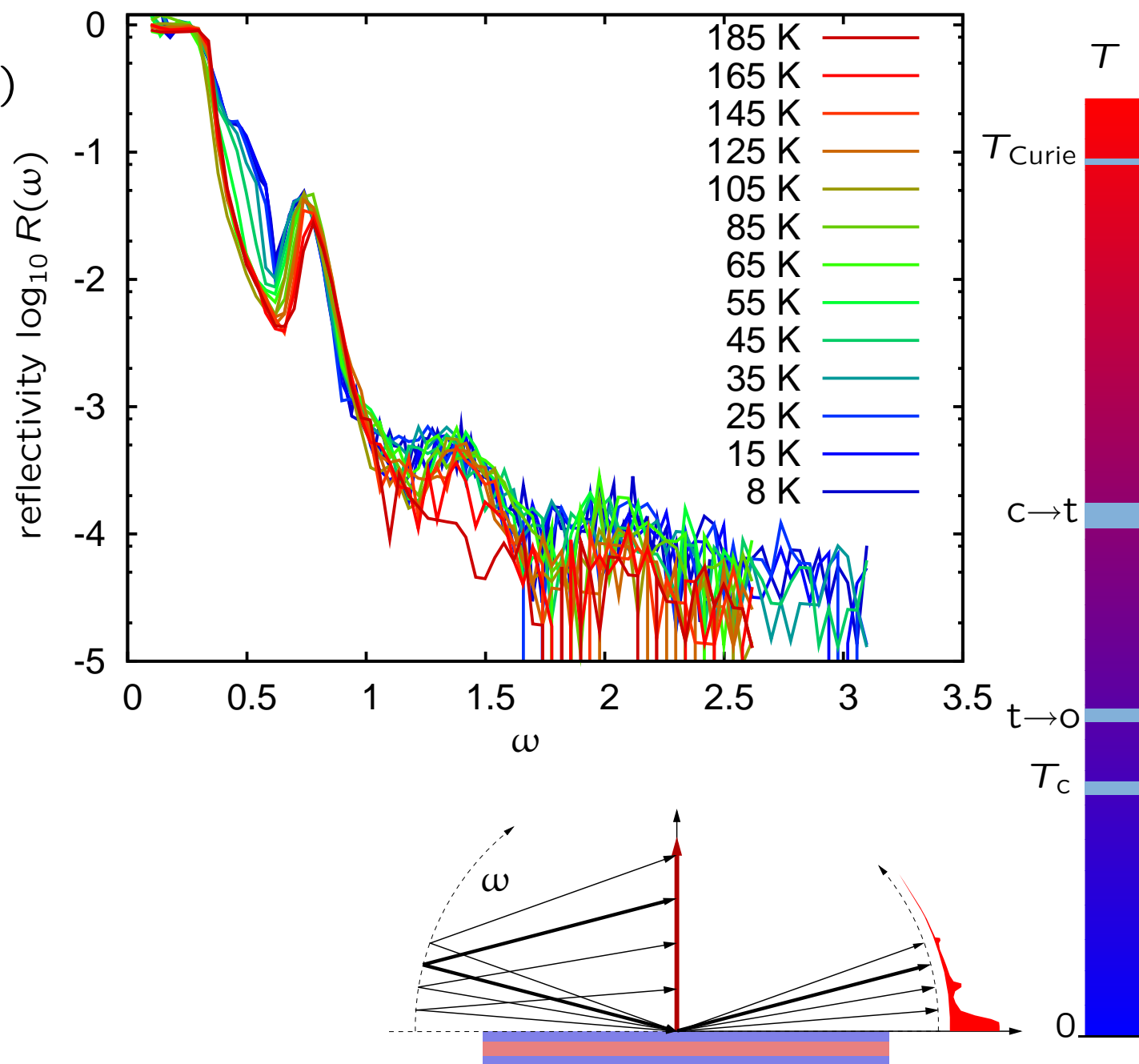


energy dispersive mode



T dependence of $R(\omega)$
for an ML with
underdoped SC

field cooled and
measured in
 $H = 100$ Oe

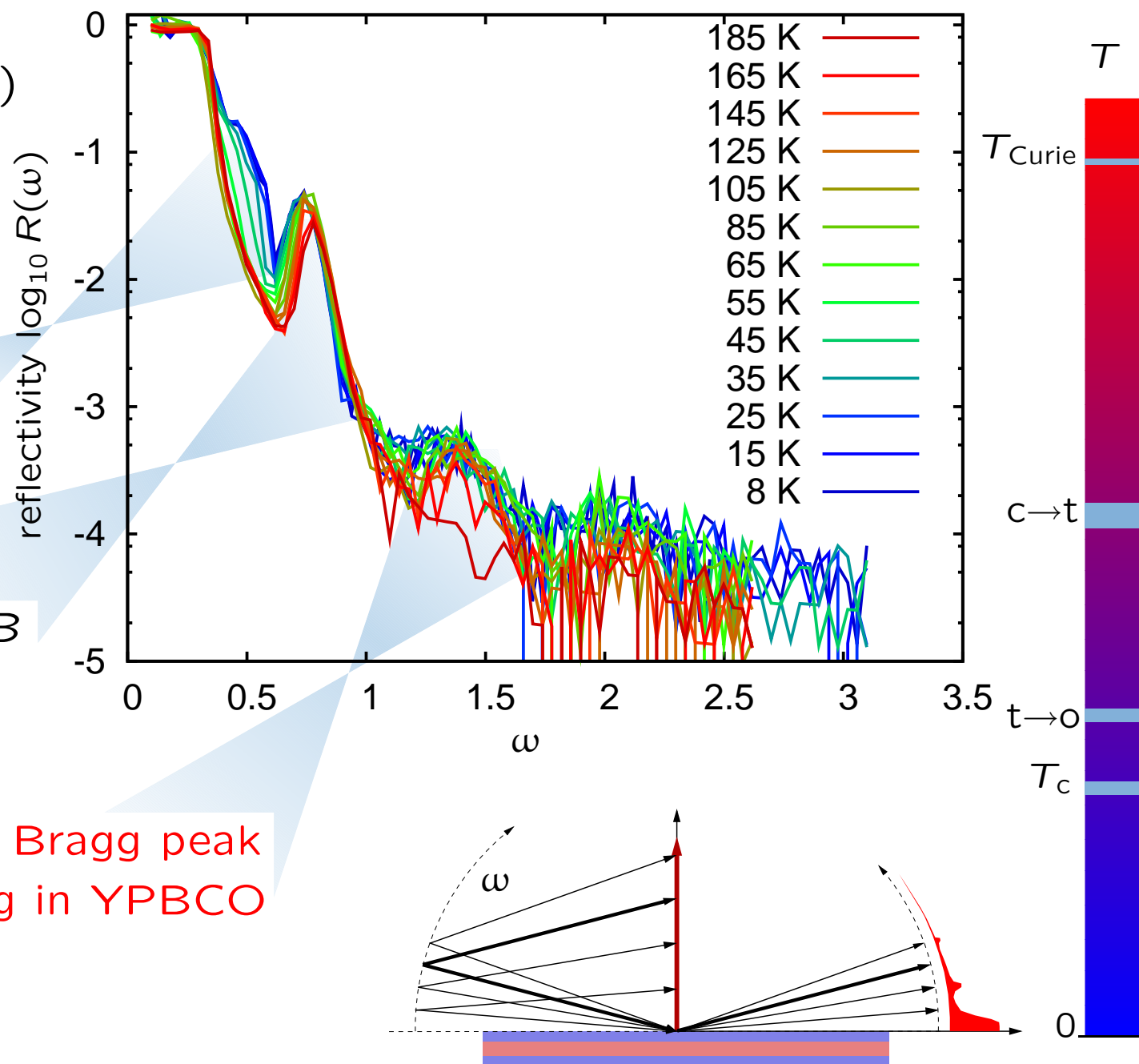


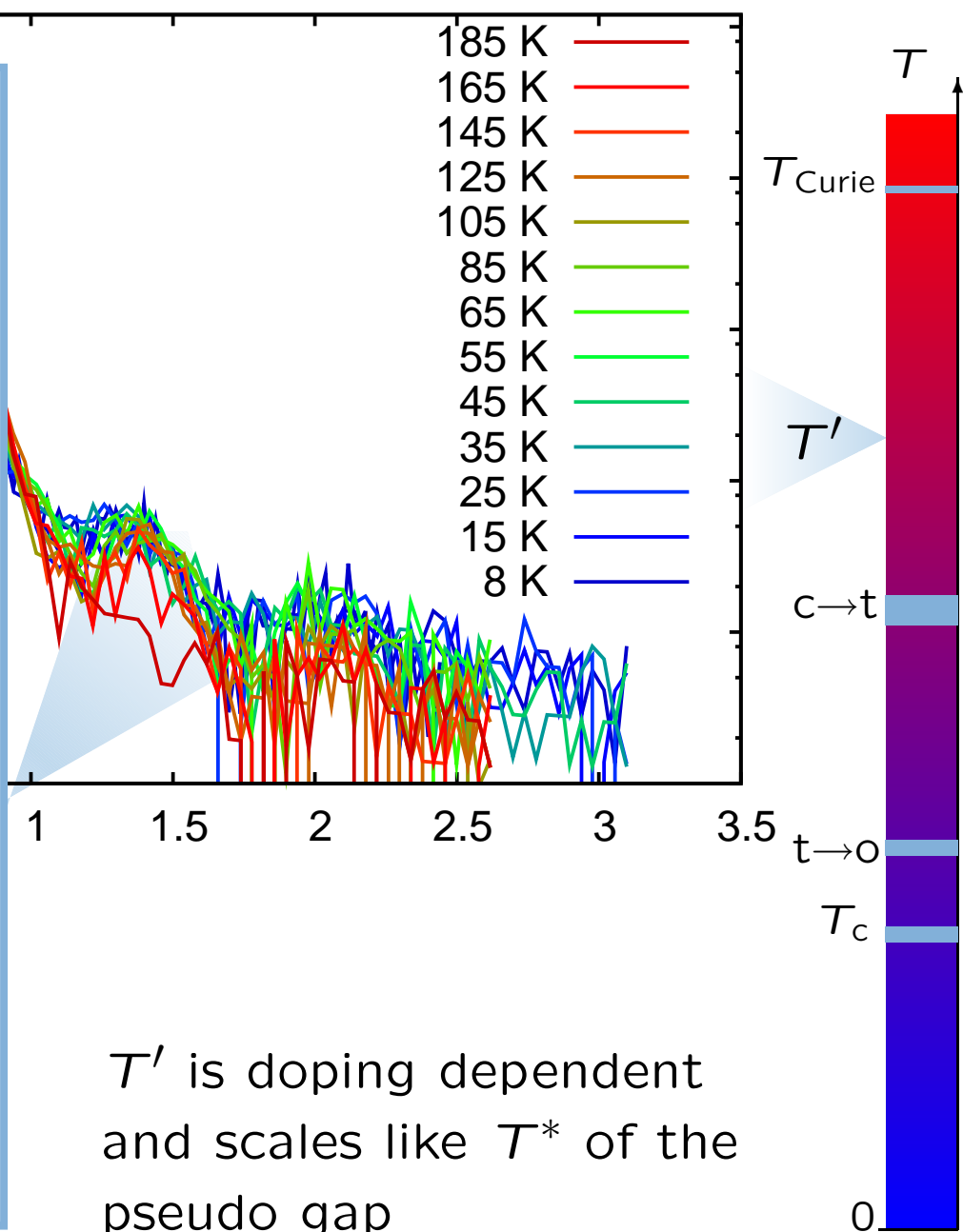
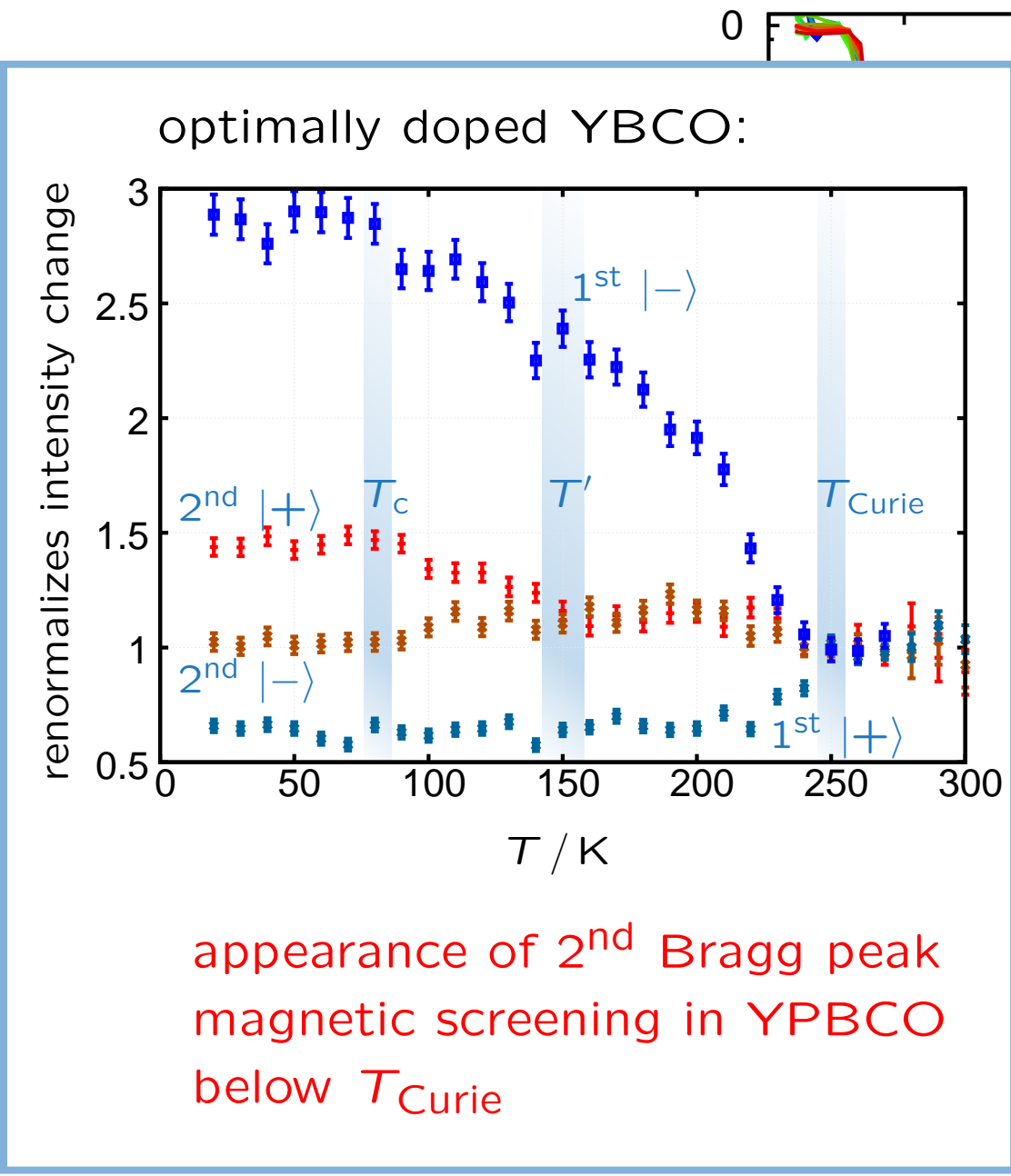
T dependence of $R(\omega)$
for an ML with
underdoped SC

new peak below T_c

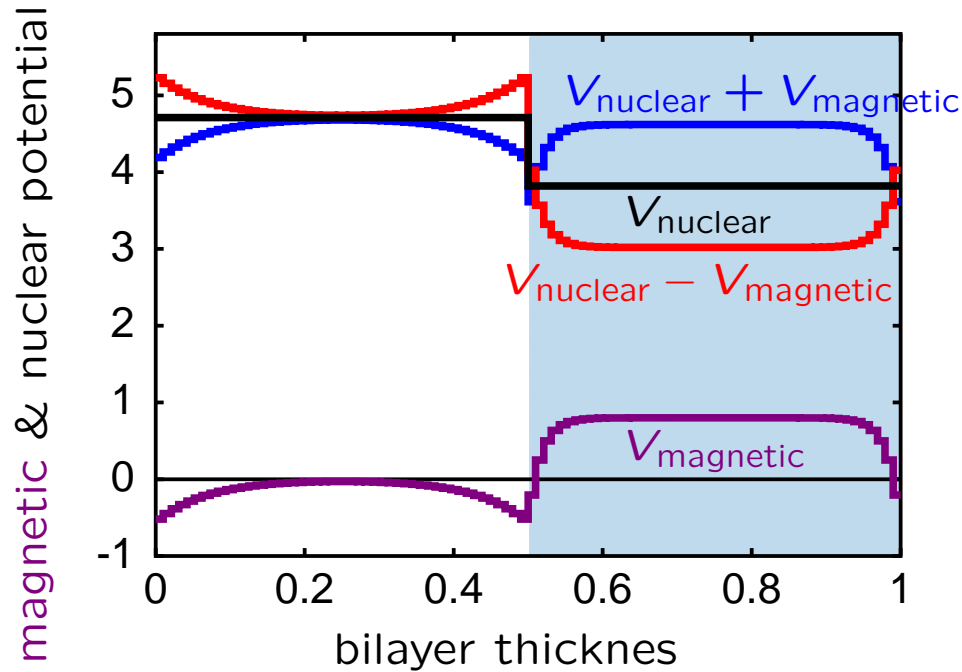
1st Bragg peak
displays increasing B

appearance of 2nd Bragg peak
magnetic screening in YBCO
below T_{Curie}

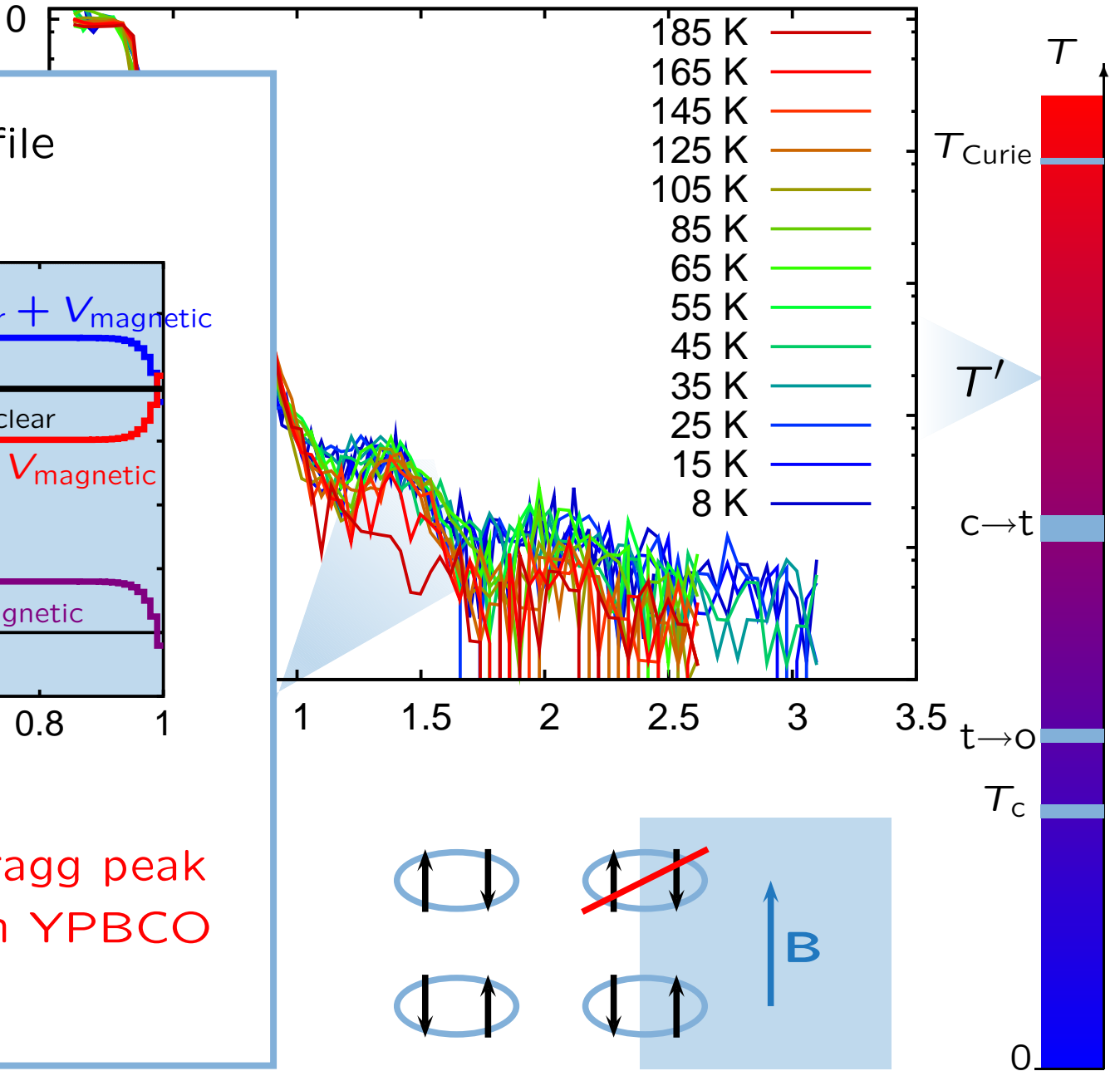




simulated depth profile
of the potentials



appearance of 2nd Bragg peak
magnetic screening in YPBCO
below T_{Curie}

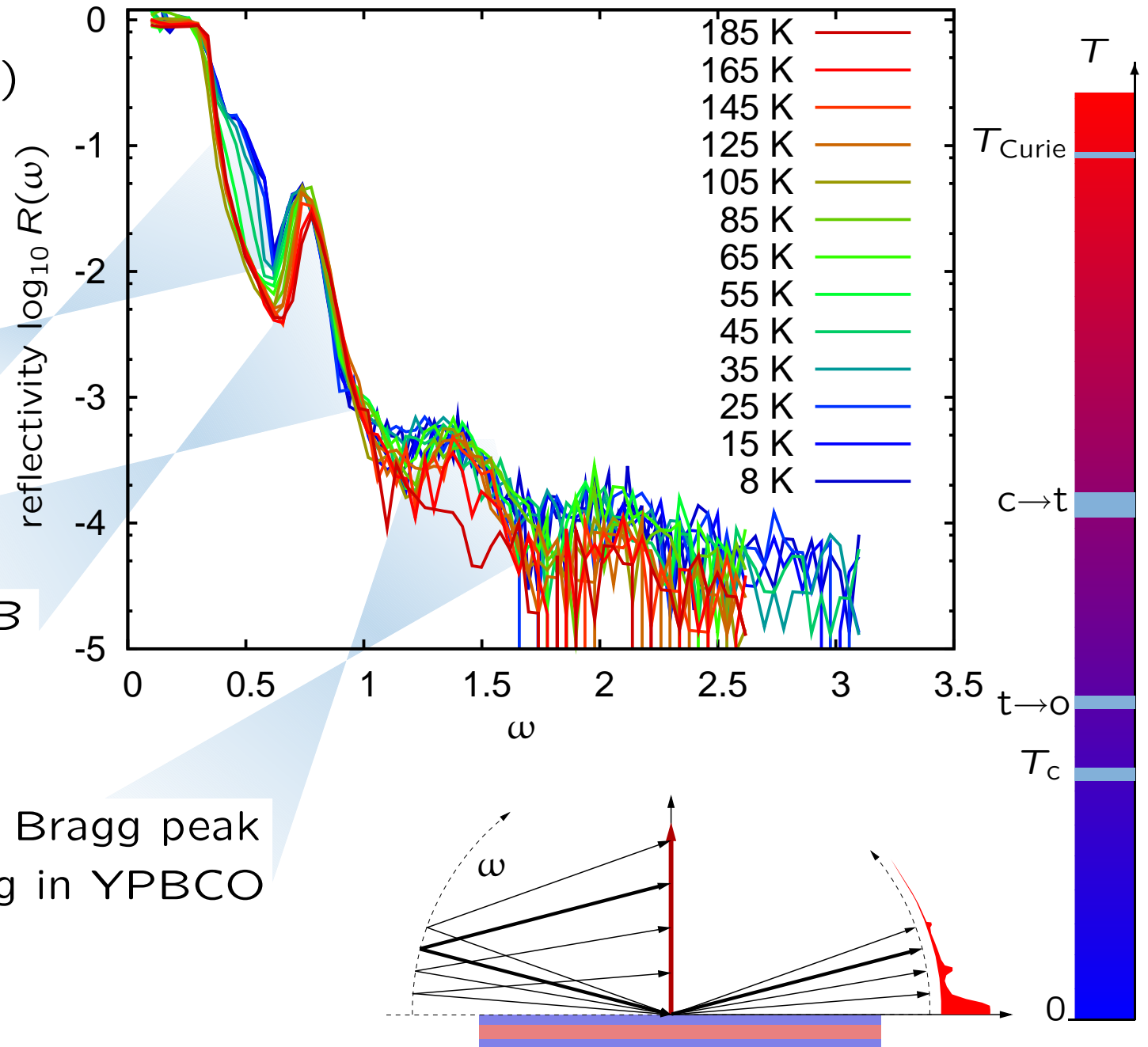


T dependence of $R(\omega)$
for an ML with
underdoped SC

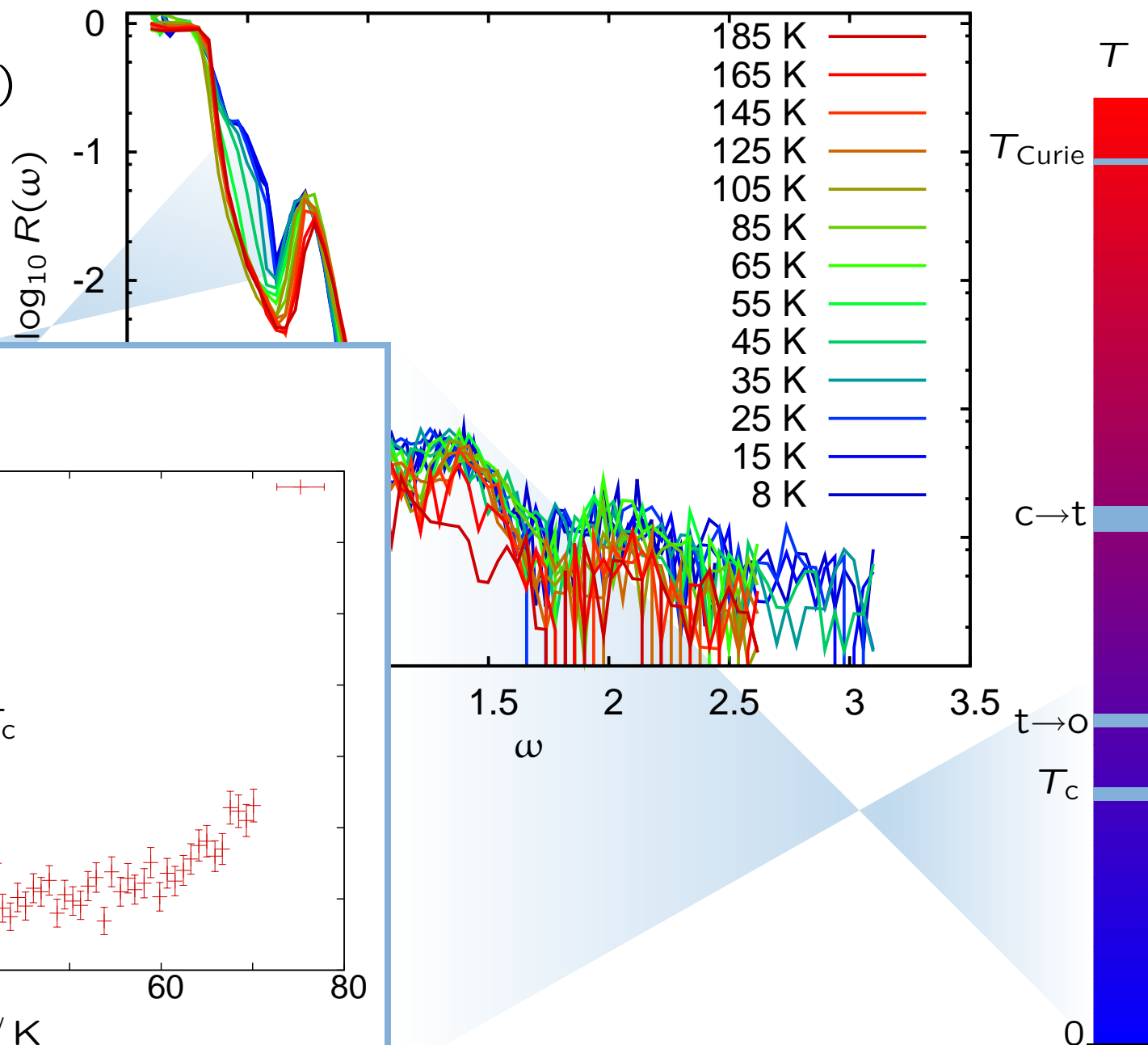
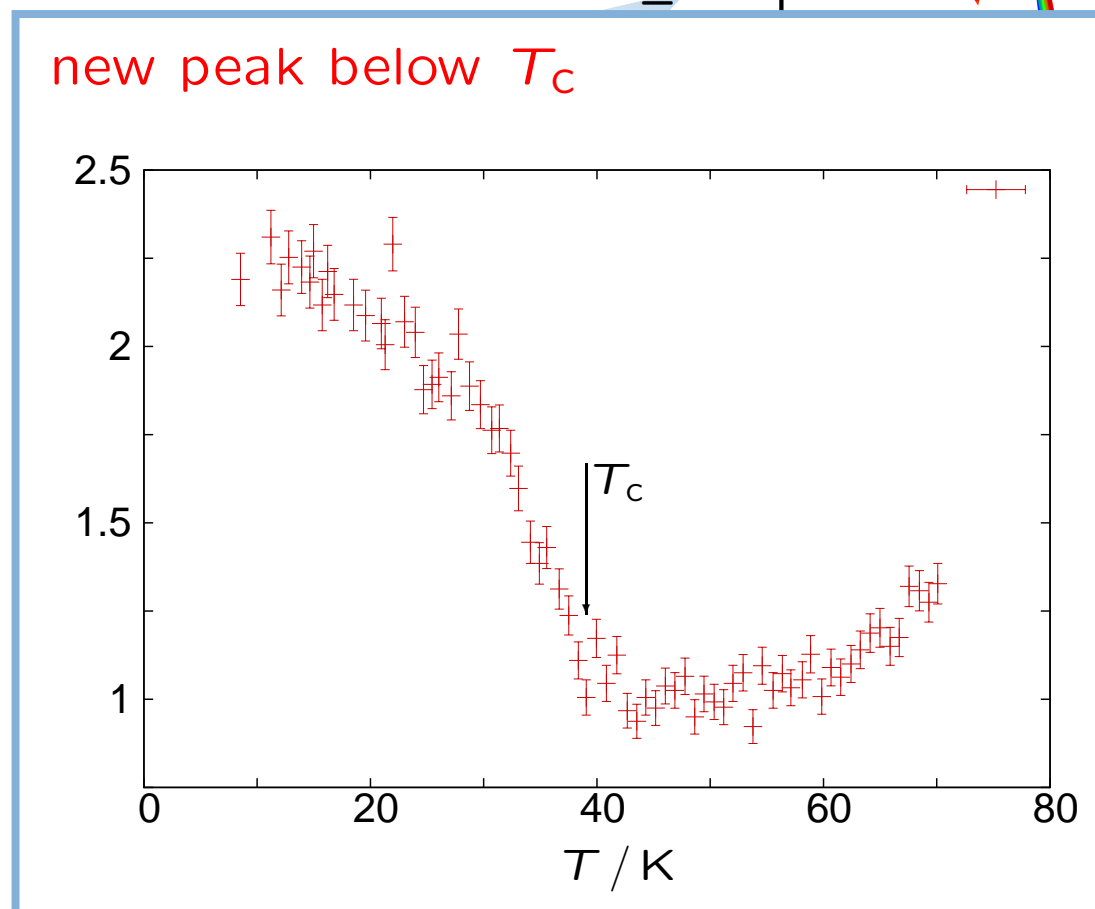
new peak below T_c

1st Bragg peak
displays increasing B

appearance of 2nd Bragg peak
magnetic screening in YPBCO
below T_{Curie}



T dependence of $R(\omega)$
for an ML with
underdoped SC



magnetic peak

comparable to a fractional Bragg peak in diffraction
 indication for a (magnetic) superstructure

model assumption:

$$T_c < T < T_{\text{Curie}}$$

all LCMO layers have the same $\mathbf{B} = \mathbf{B}_0$

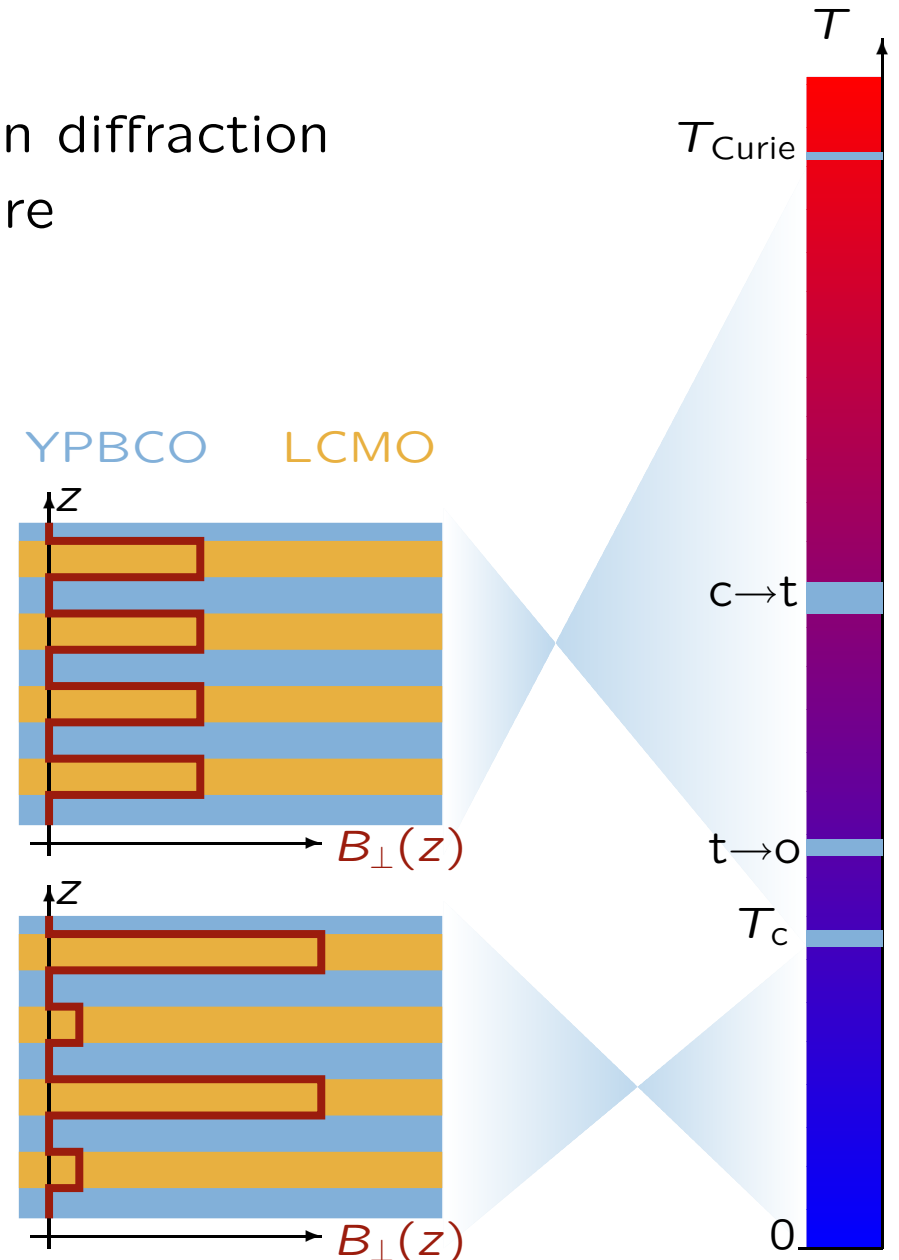
$$T < T_c$$

$$\mathbf{B} = \mathbf{B}_0 \pm \Delta\mathbf{B}$$

where sign changes each period

\Rightarrow layerwise AFM on top of the FM

respective moments on Mn: $2.1 \pm 1.9 \mu_B$



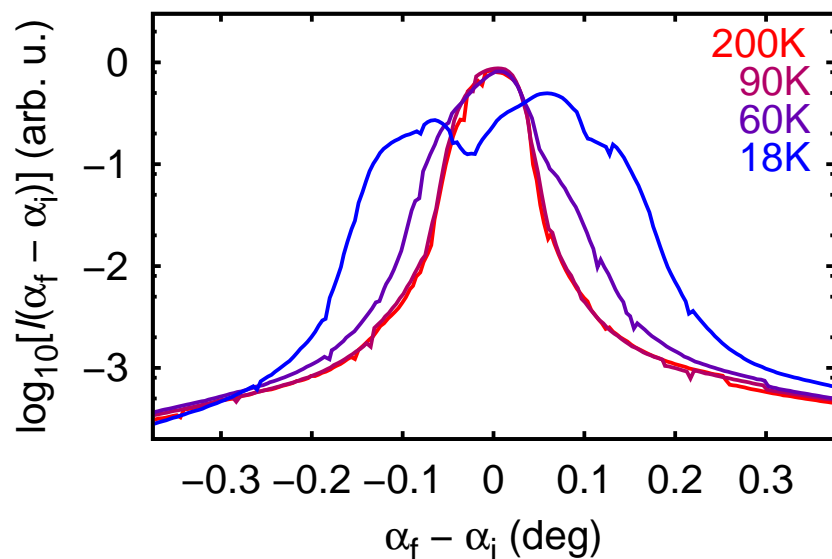
STO undergoes phase transitions

⇒ twinning, buckling of the surface

⇒ surface is fragmented into facets

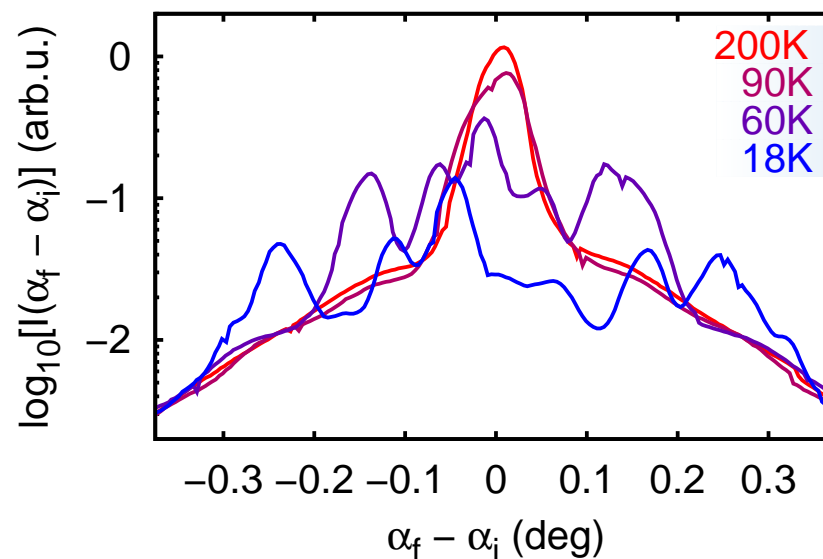
x-rays: ω -scans on

crystal reflection (002) of
STO substrate

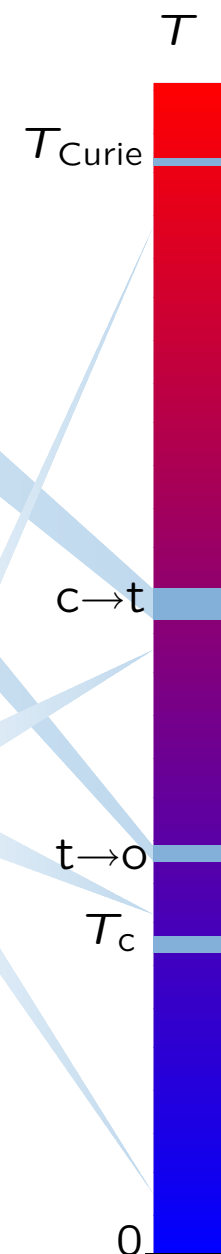


crystallite orientation

superlattice peak of the
multilayer

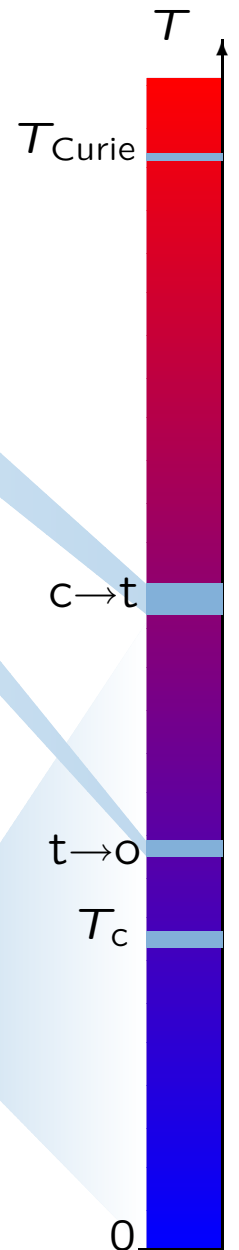
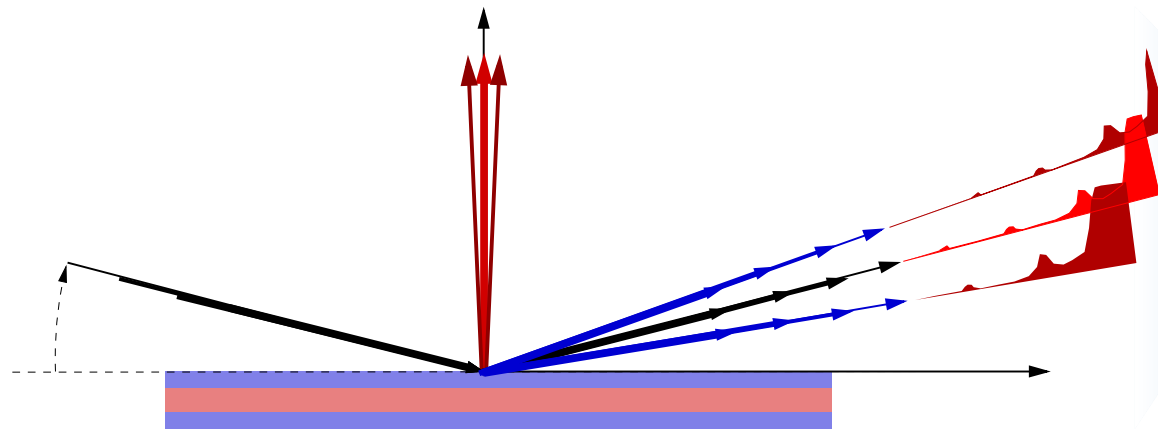


surface orientation

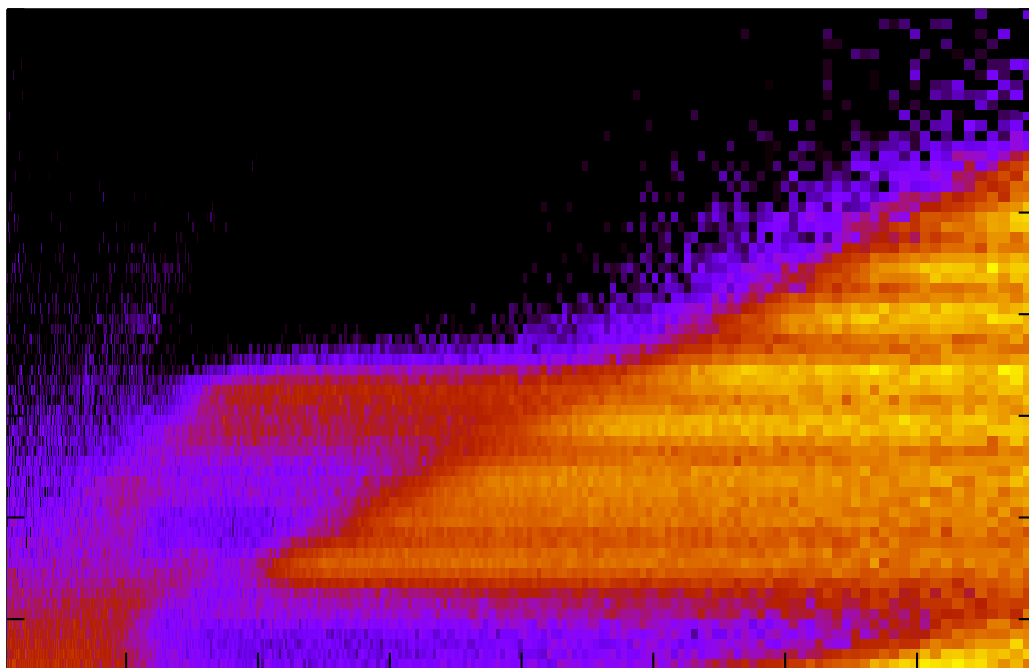


STO undergoes phase transitions

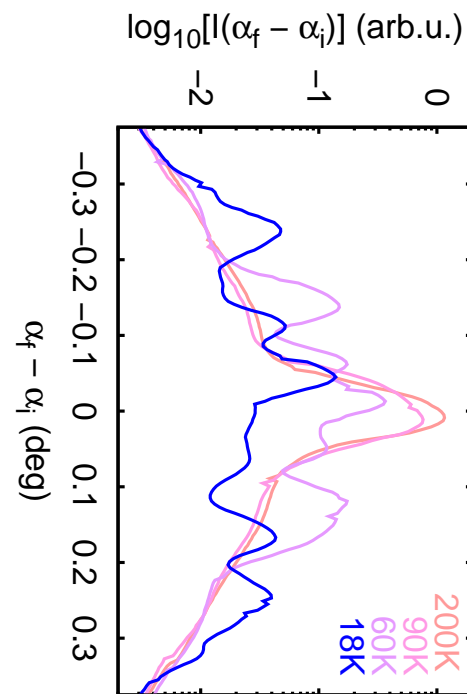
- ⇒ twinning, buckling of the surface
- ⇒ surface is fragmented into facets
- ⇒ varying angle of incidence over the sample
- ⇒ lots of specularly reflected beams



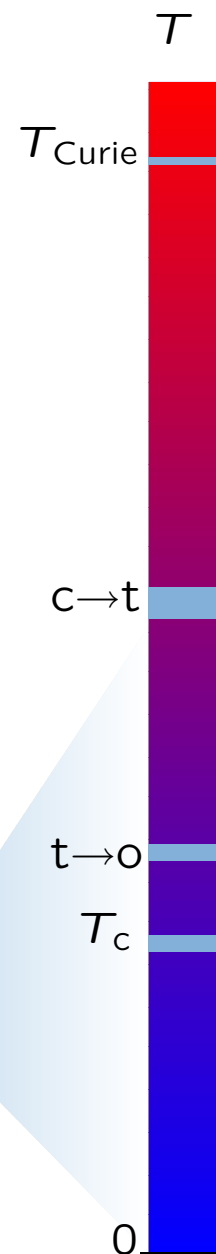
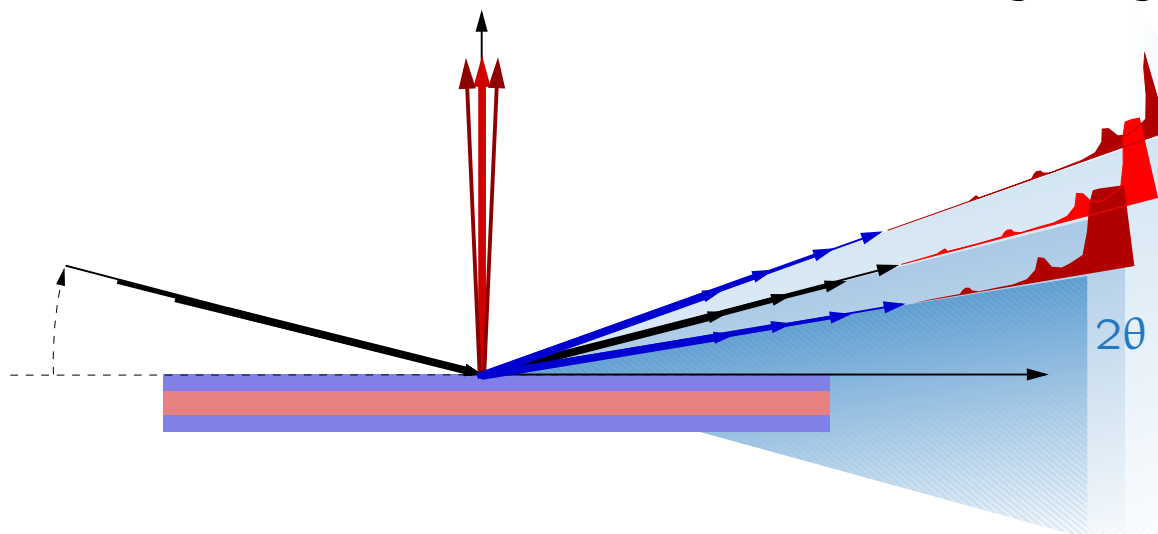
scattering angle 2θ

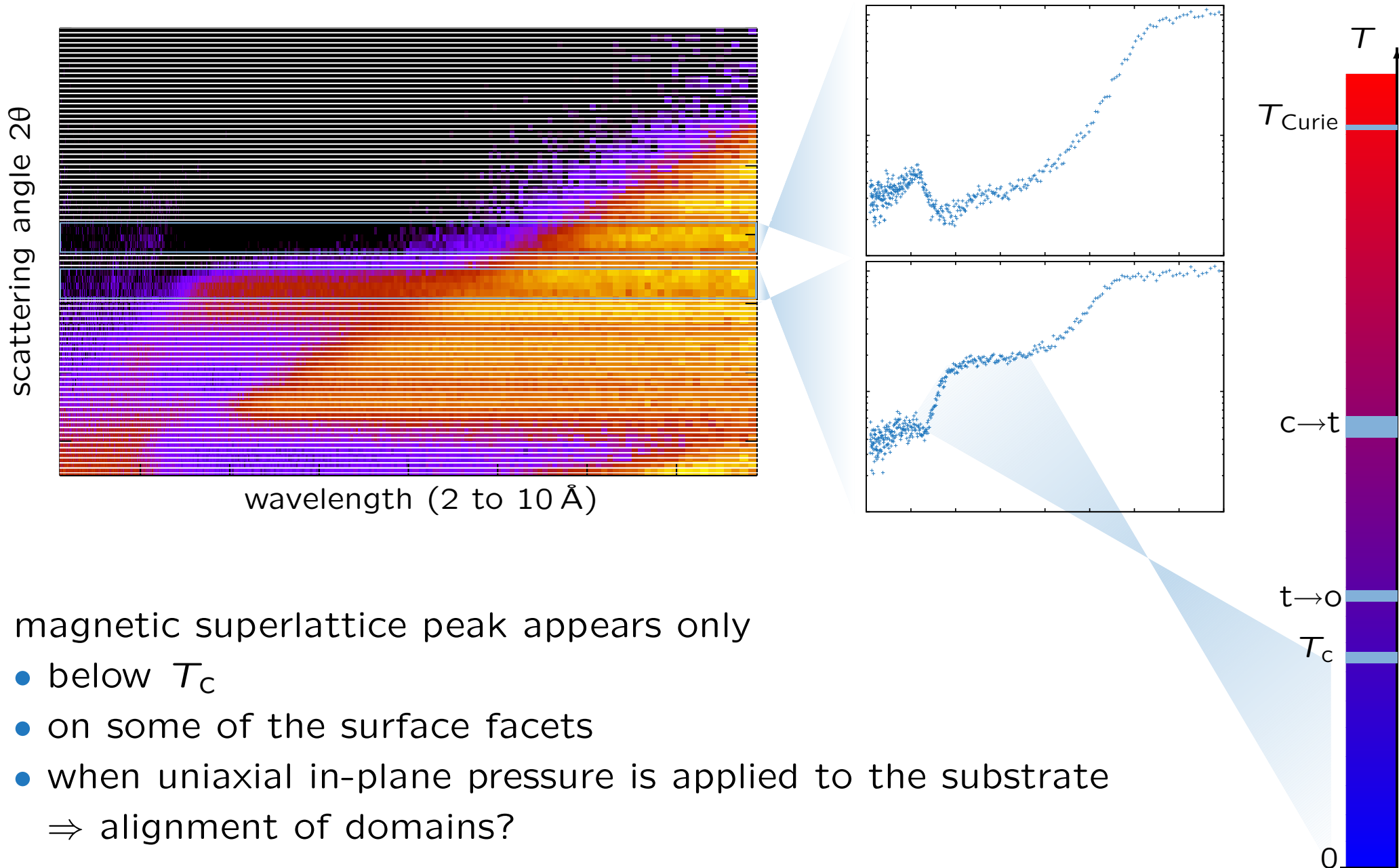


wavelength (2 to 10 Å)



area detector to cover large angular range



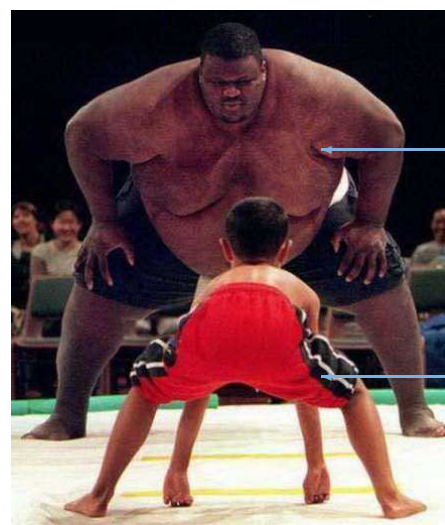


- LCMO has a complicated phase diagram and shows **phase separation** of structural and magnetic properties

{ strain
 finite dimension in z
 coupling to neighboring FM layers } might change the energies of competing magnetic states

- the changed coupling through YPBCO in the (energetically weak) SC state can then switch the ground state in the FM

- the SC gains surface energy



if he is strained

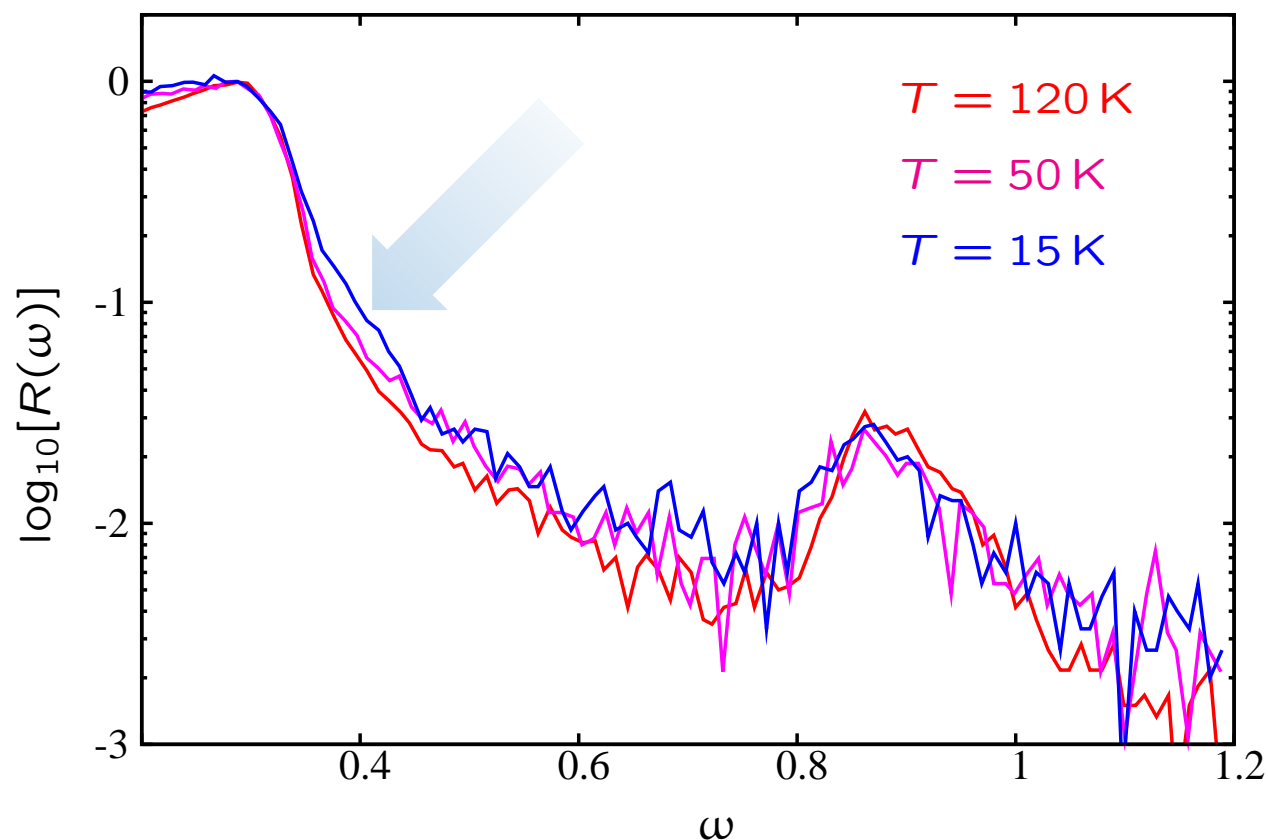
he can win!

STO shows electrostriction

(lattice is distorted by an external \mathbf{E} field)

\Rightarrow strain is induced by \mathbf{E} (and not by uniaxial pressure)

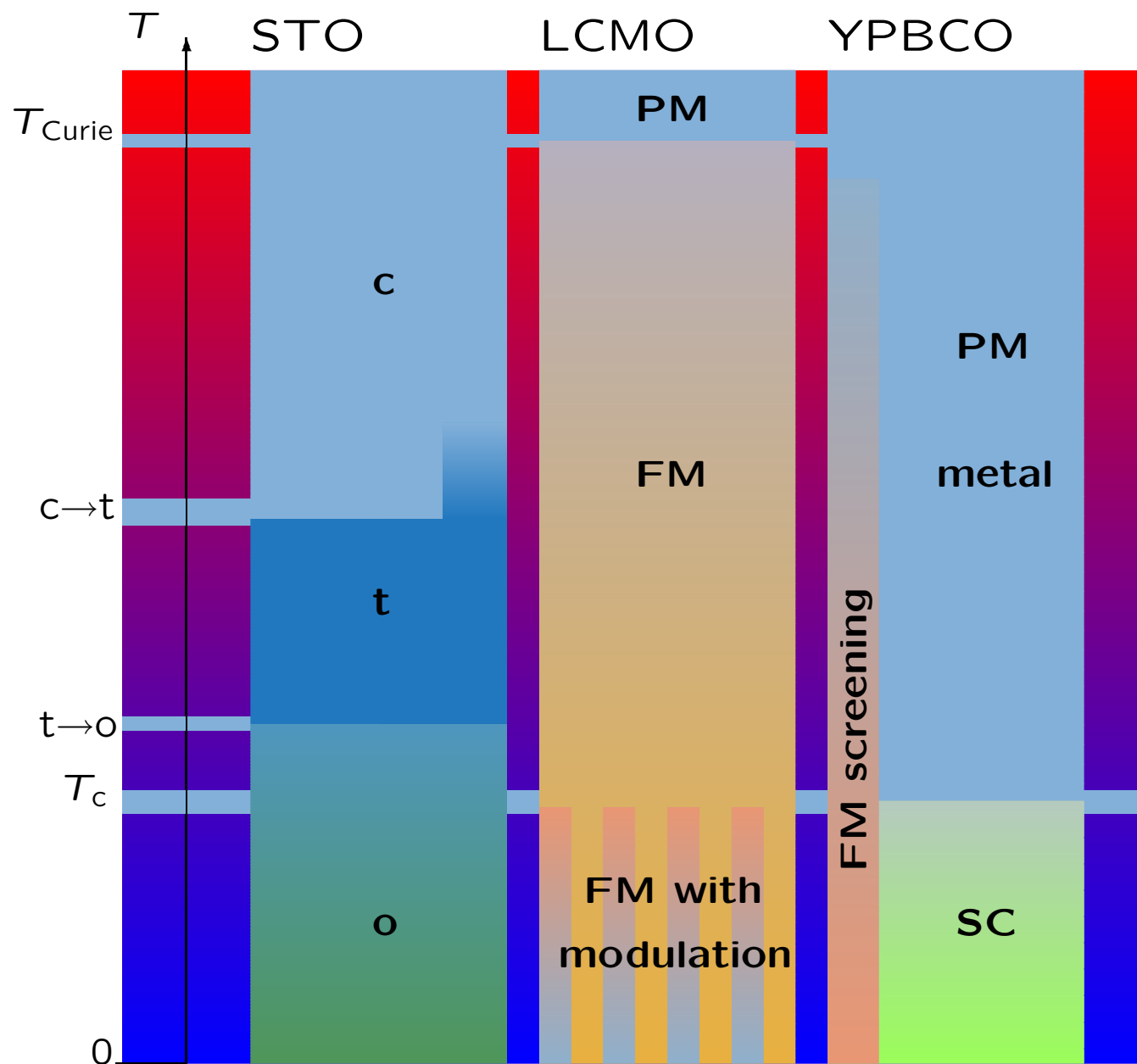
first result with $E = 160 \text{ V/mm}$:



can we switch $\Delta\mathbf{B}$ with \mathbf{E} ?

modulated FM in
LCMO only with
strained STO

PM paramagnetic
FM ferromagnetic
SC superconducting
c cubic
t tetragonal
o orthorhombic



sample preparation: Hanns-Ulrich Habermeier (MPI Stuttgart)
 Georg Cristiani (MPI Stuttgart)

experiments: Justin Hoppler (PSI, Fribourg)
 Max Wolff (ADAM, ILL)
 Helmut Fritsche (Chalk River, Canada)
 Rob Dalglish (ISIS)
 Vivek Malik (Fribourg)
 Alan Drew (Fribourg)

... with E -field: Cecile Garcia (ETHZ, PSI)

analysis: Christian Bernhard (Fribourg)
 Christof Niedermayer (PSI)
 Alexandre Buzdin (Amiens, France)

audience: **YOU**

- PNR *can* probe $\rho(z)$ and $B_{\perp}(z)$ with almost atomic resolution
- samples: $[Y_{1-x}Pr_xBa_2Cu_3O_6/La_{2/3}Ca_{1/3}MnO_3]_{10}/SrTiO_3$
- FM layers are aligned parallel
- exception: in strained films below T_c
a modulation is initiated by SC spacer
- hypothetical explanation:
 - strain lowers energy of modulated FM states
 - gain in surface energy in SC is enough to
switch the ground state in FM
- "normal" case: energy scale of FM is much larger than of SC
 \Rightarrow competition normally below 1K
- here: 40K