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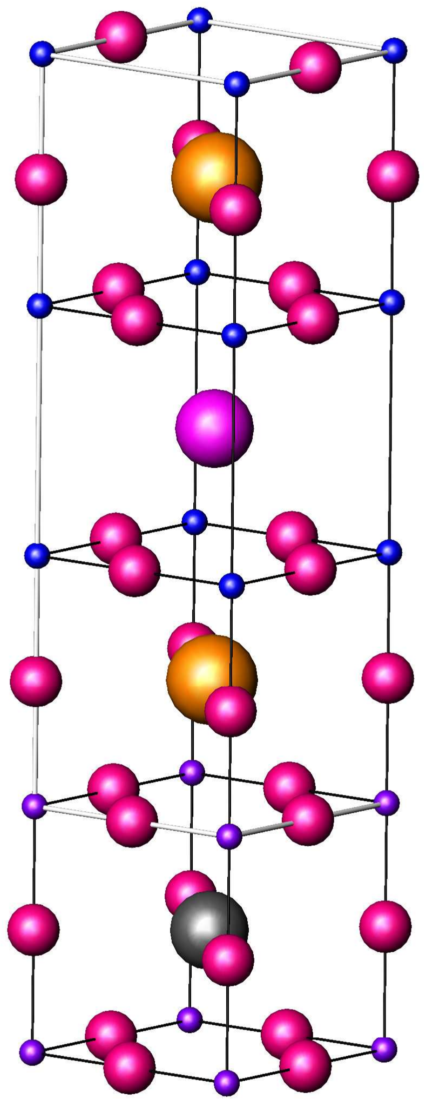
Superconductivity-induced magnetic modulation in adjacent ferromagnetic layers

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?

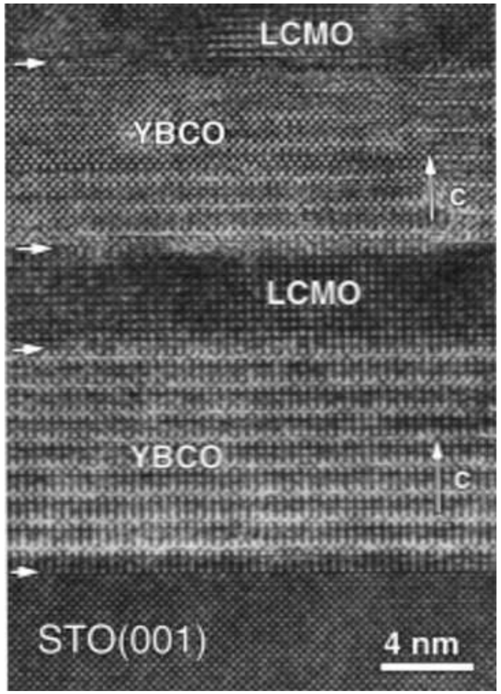
used system:

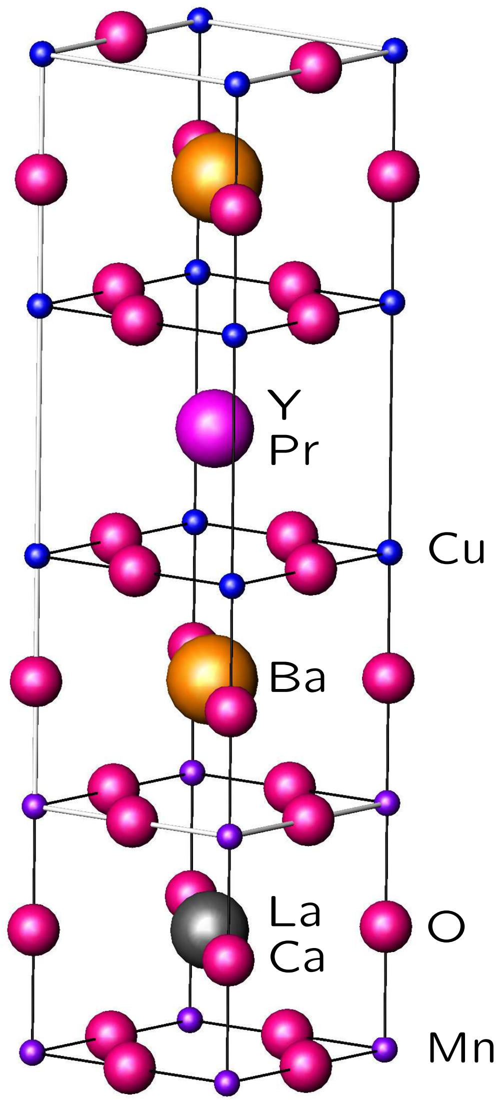
multilayers of the type

$[SC/FM]_n/STO$

grown by *pulsed laser doposition*

TEM image





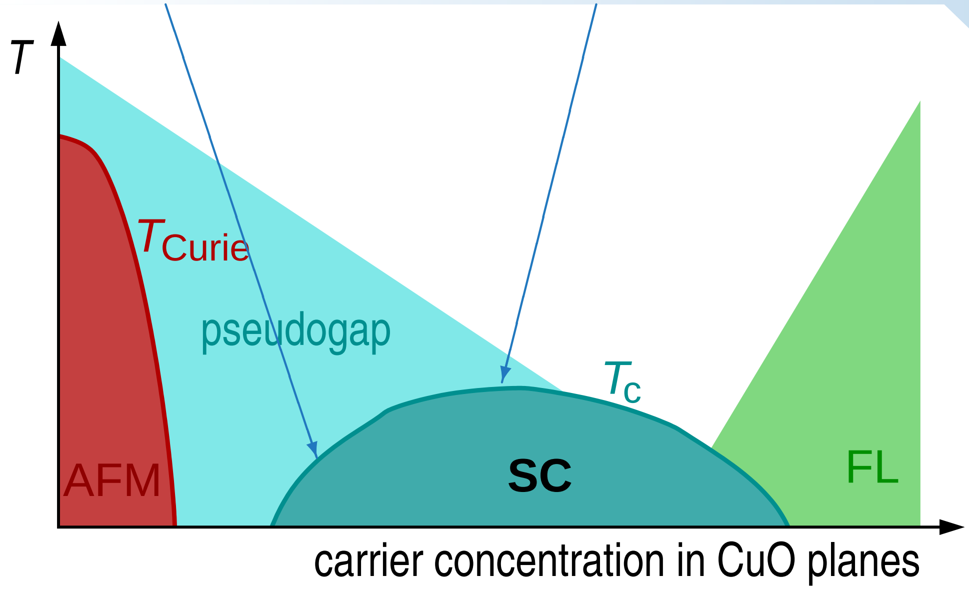
crystal types:
(close to) perovskite-like

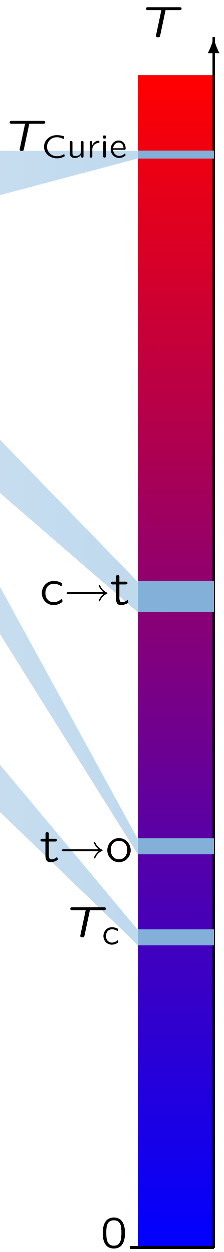
multilayers of the type $[SC/FM]_n/STO$

FM: $La_{2/3}Ca_{1/3}MnO_3$
$T_{Curie} \approx 180\,K$

STO: $SrTiO_3$ used as substrate
$T \approx 105\,K$: cubic to tetragonal
$T \approx 65\,K$: tetragonal to orthorombic
$\Rightarrow$ surface fragmentation

SC: $Y_{1-x}Pr_xBa_2Cu_3O_6$
$T_c \approx 40\,K\,(x = 0.4)$, $90\,K\,(x = 0)$





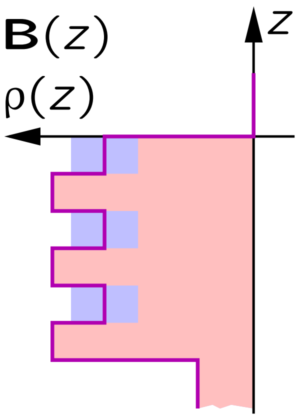
how does the magnetisation in the film look like?

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

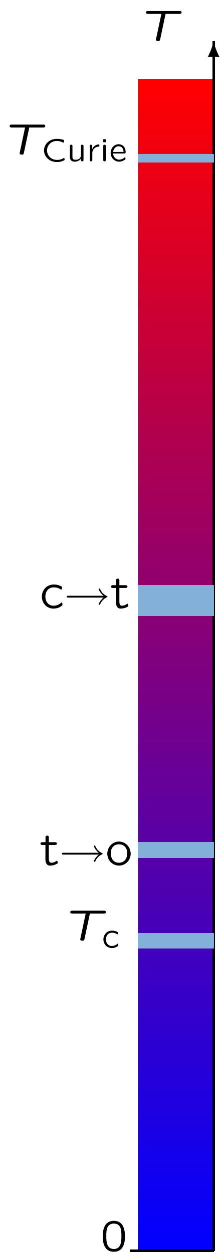
has SC an influence? $\Rightarrow$ T-dependence of $\mathbf{B}(z)$

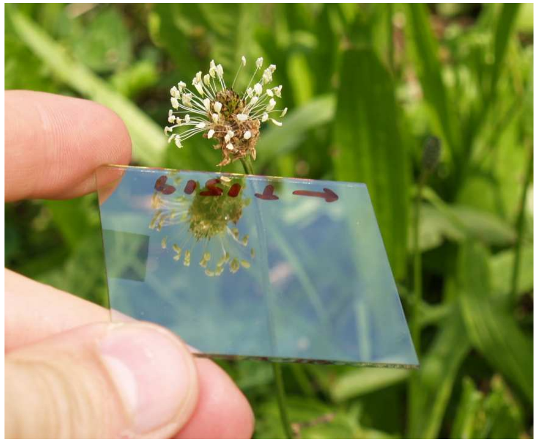
$\Rightarrow$ need for a method to probe $\mathbf{B}(z)$ and $\rho(z)$

- with $0 < z < 2000\,\text{Å}$, $\Delta z \approx 1\,\text{Å}$
- 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: )

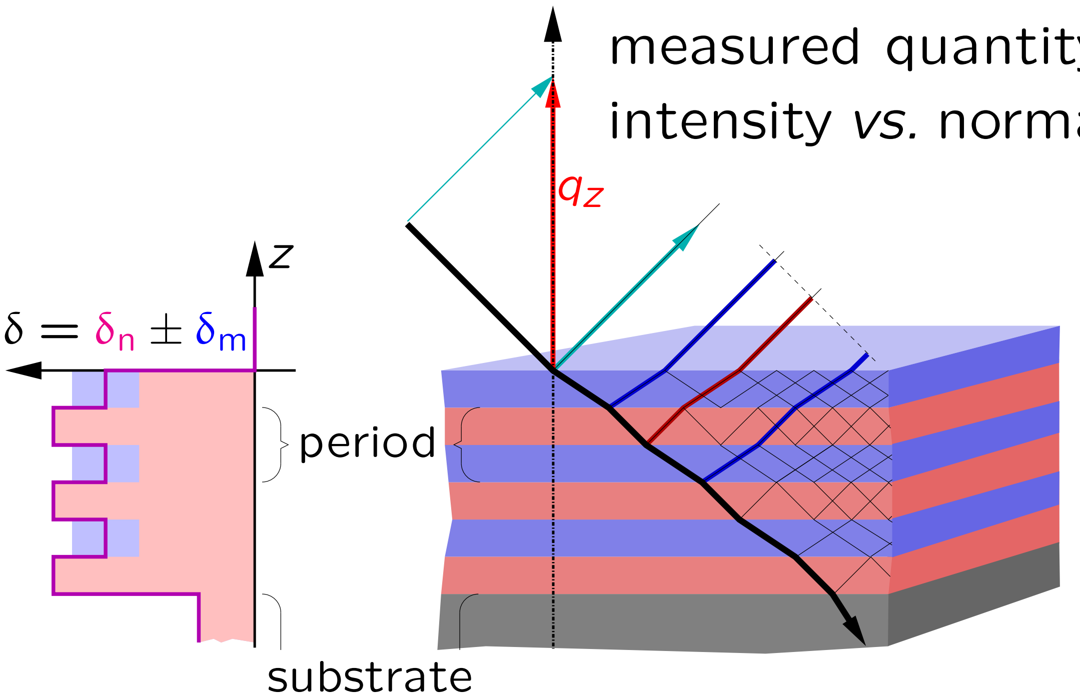
$|n-1| = |\delta| < 10^{-5}$

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

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

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

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

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

$$\delta_{\text{magnetic}} \propto \boldsymbol{\mu}_{\text{n}} \mathbf{B}_{\perp}$$

neutron magnetic moment: $\boldsymbol{\mu}_{\text{n}}$

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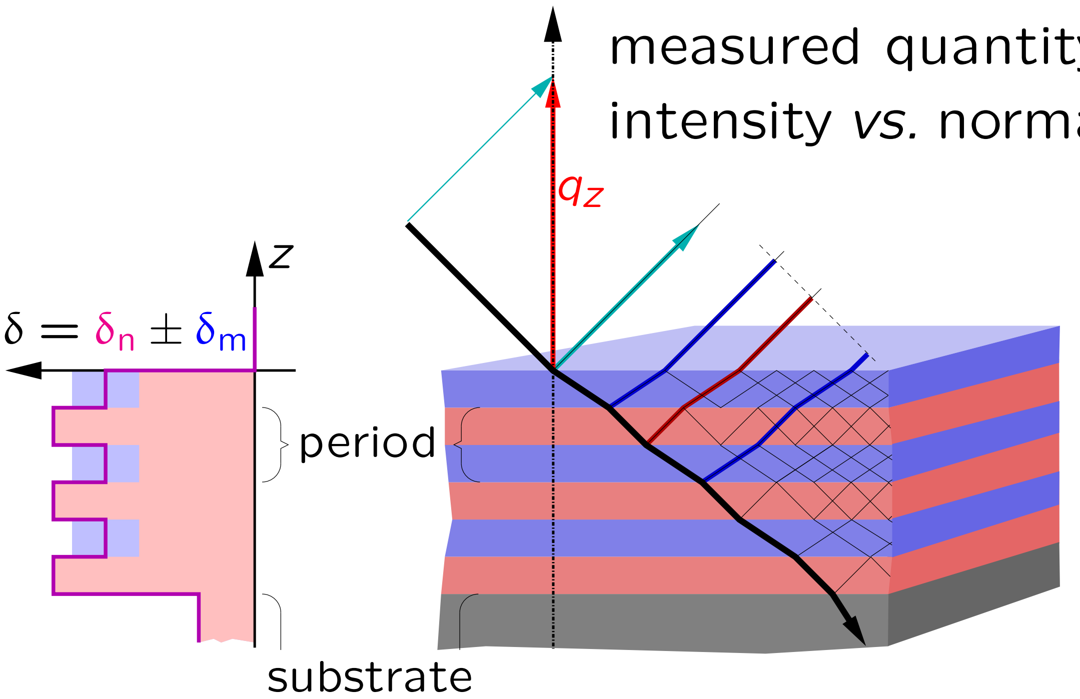
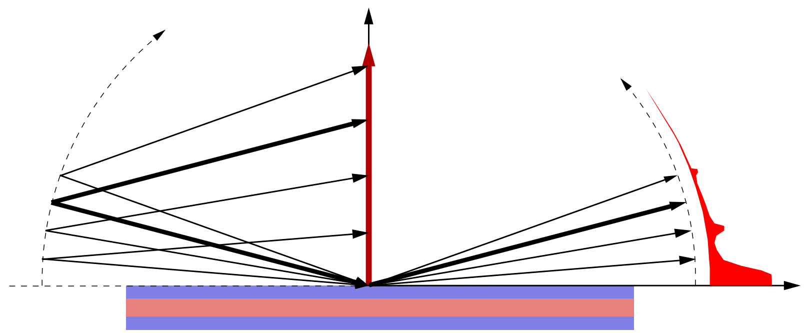


angle dispersive mode



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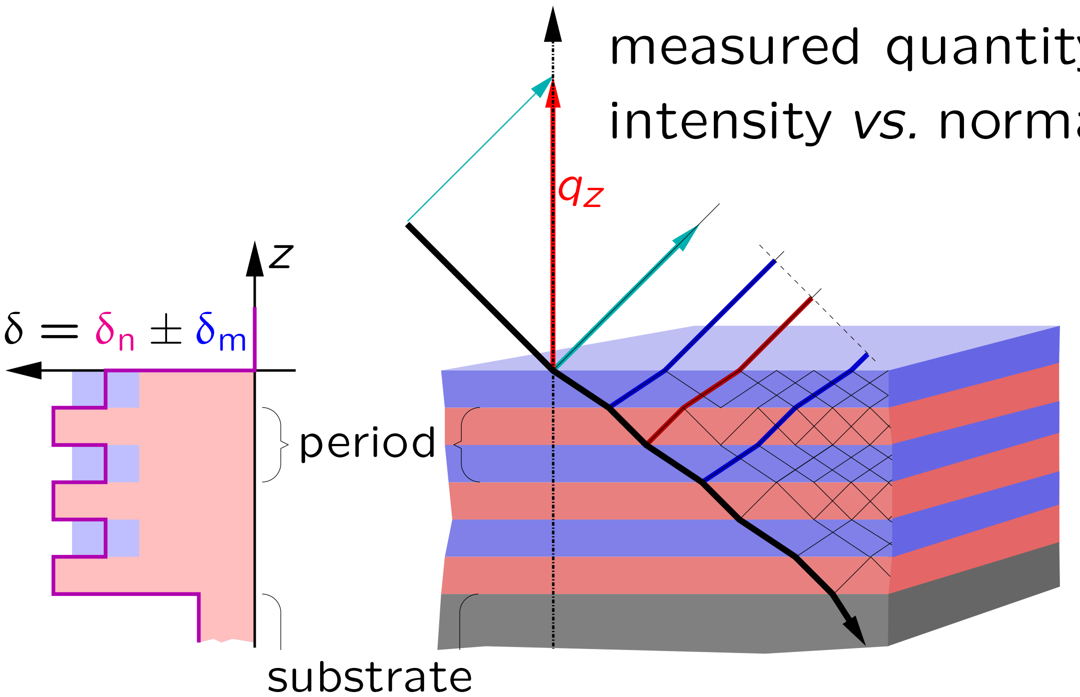
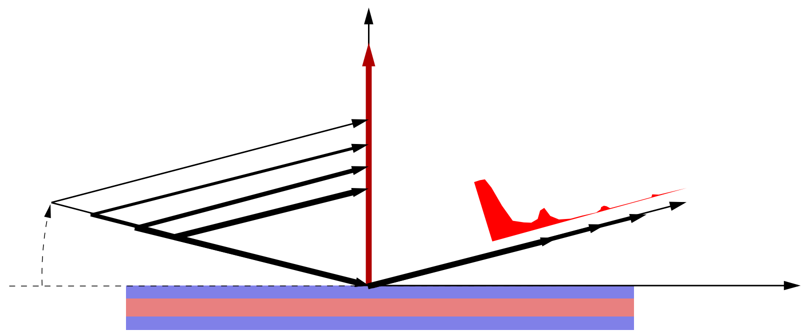
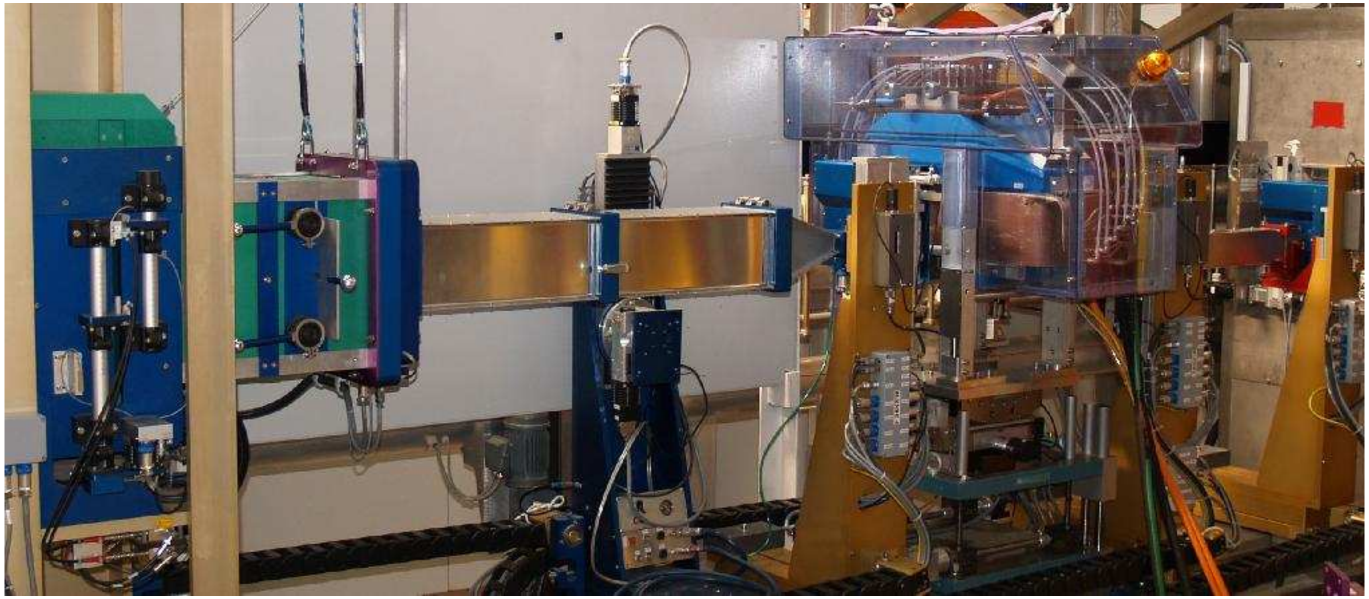


energy dispersive mode

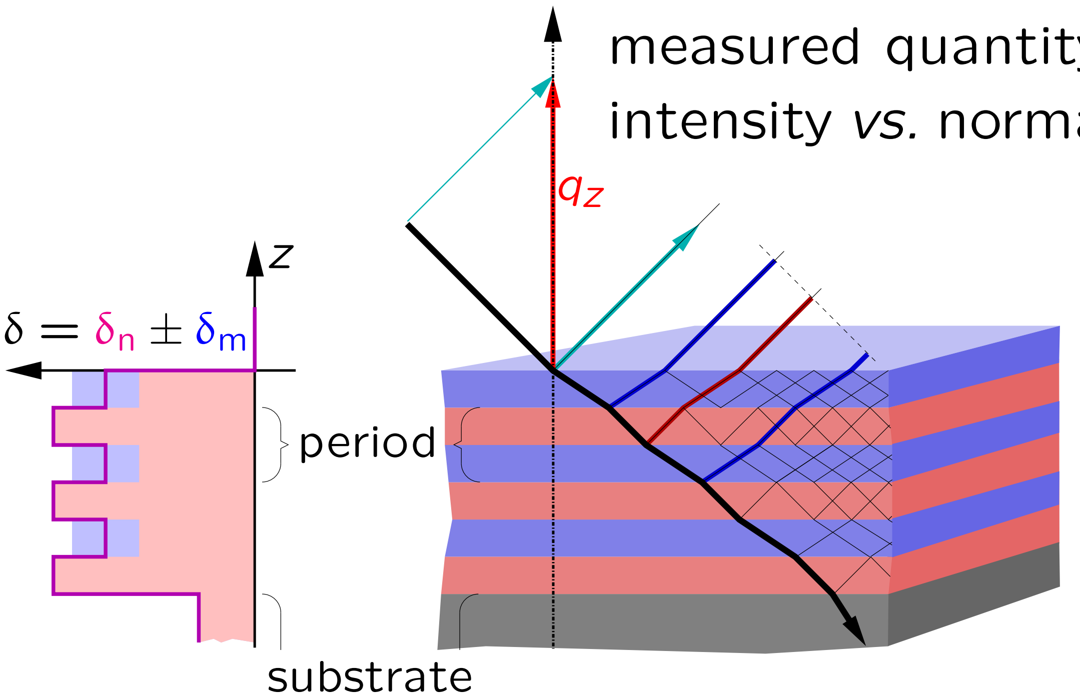


neutron reflectometer
AMOR
at SINQ, PSI

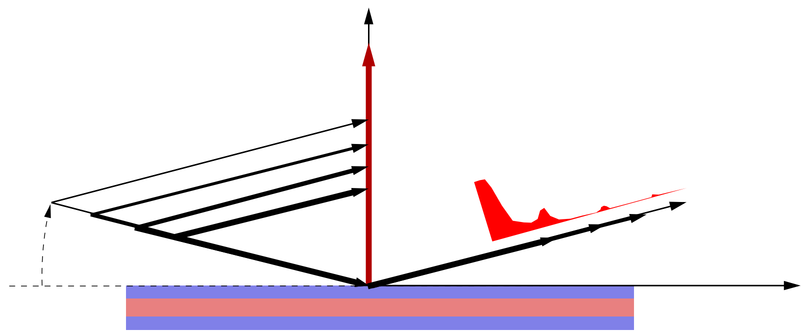
time-of-flight
spin polarisation



measured quantity:
intensity *vs.* normal momentum transfer q_z

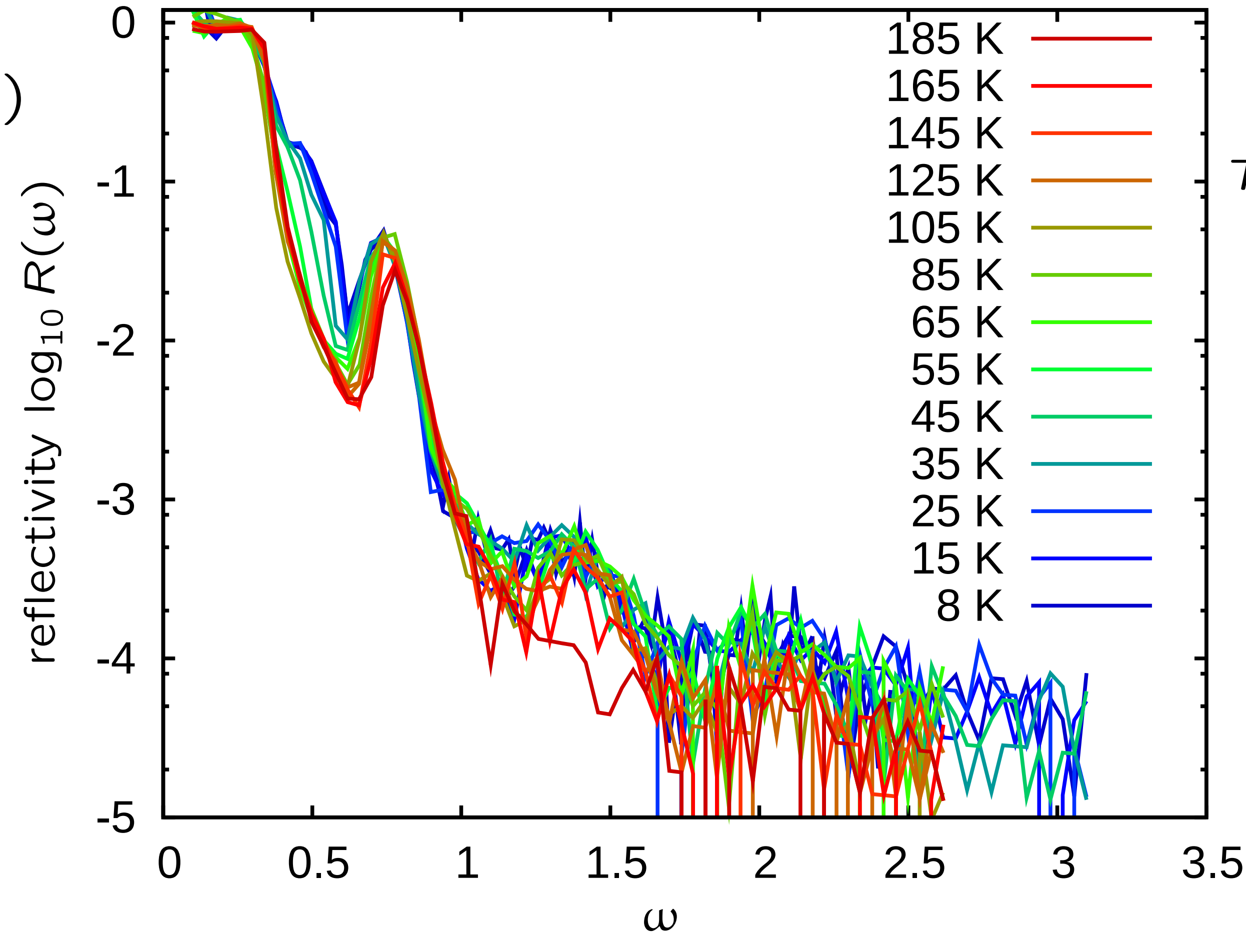


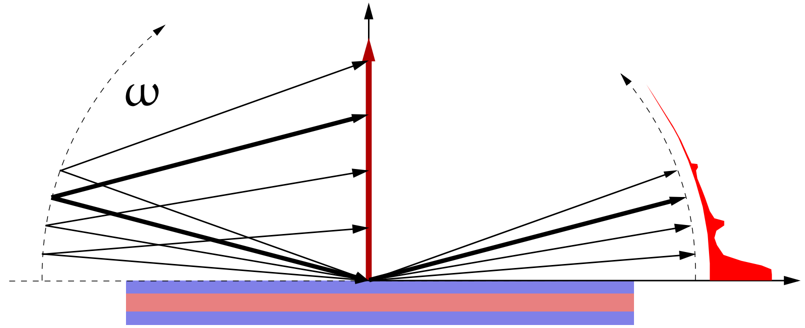
energy dispersive mode

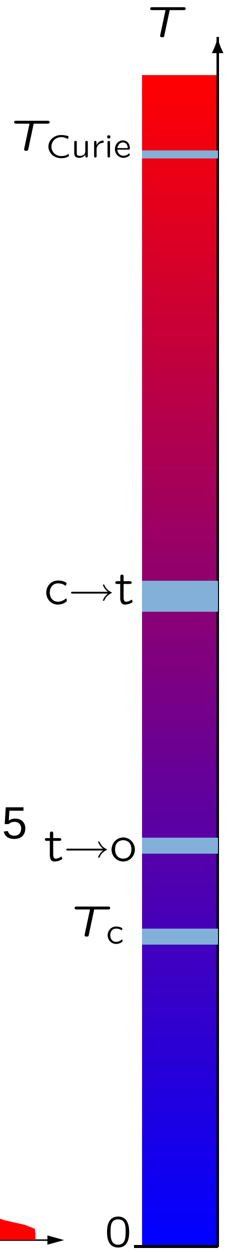


T dependence of $R(\omega)$ for an ML with underdoped SC

field cooled and measured in $H = 100\,\mathrm{Oe}$





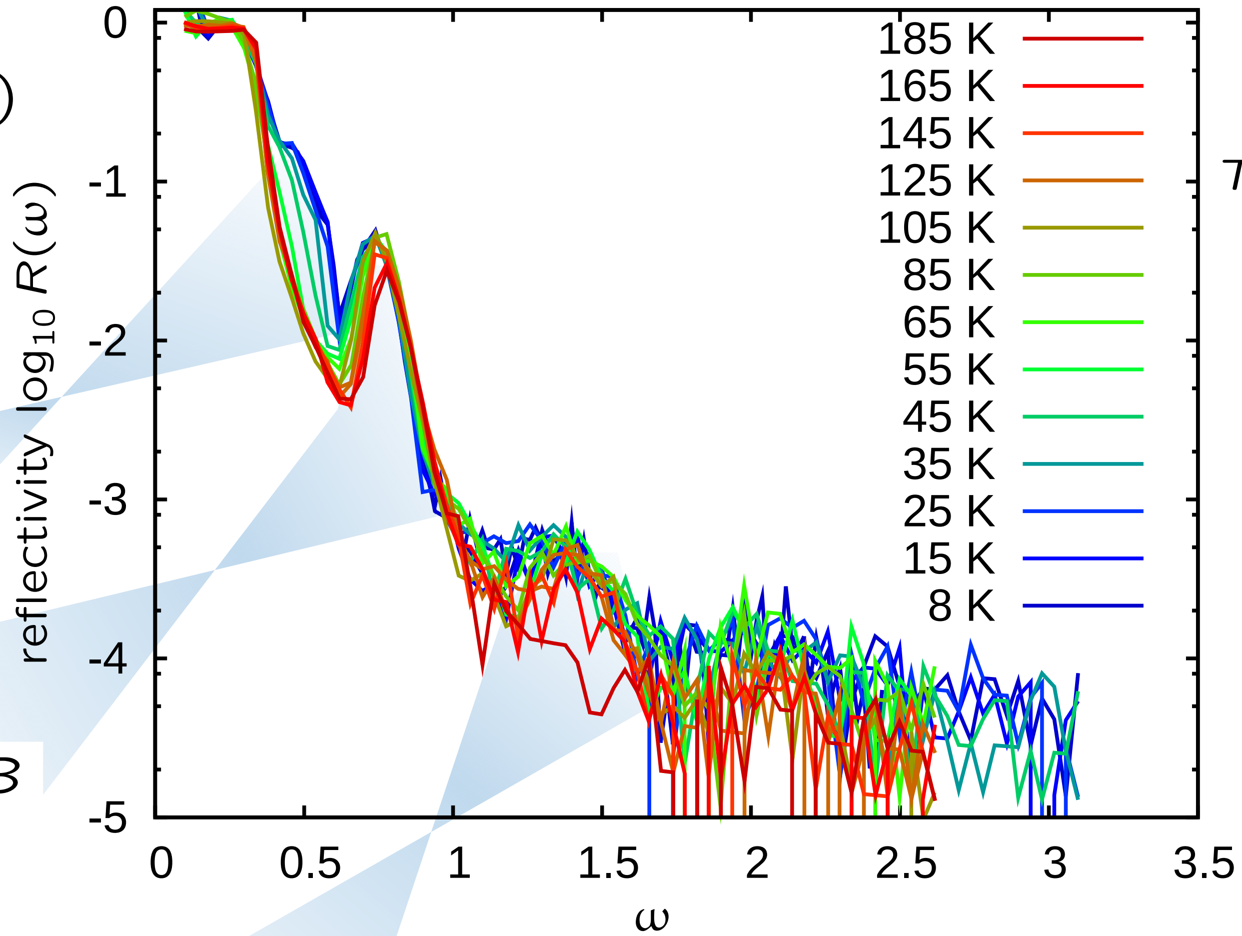


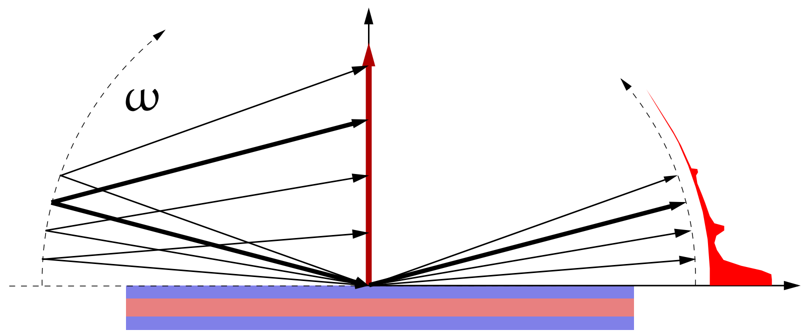
T dependence of $R(\omega)$ for an ML with underdoped SC

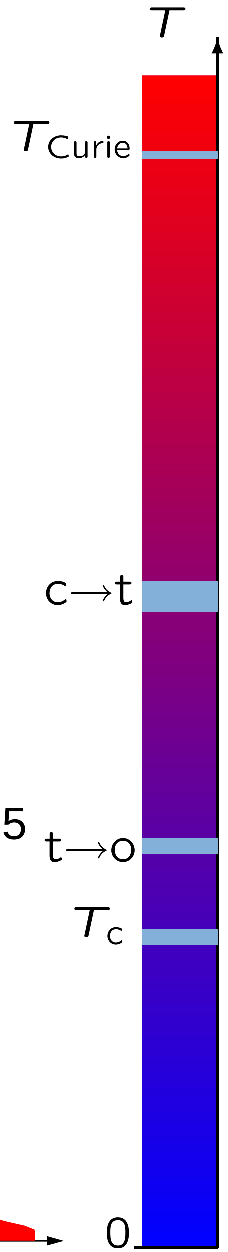
new peak below T_c

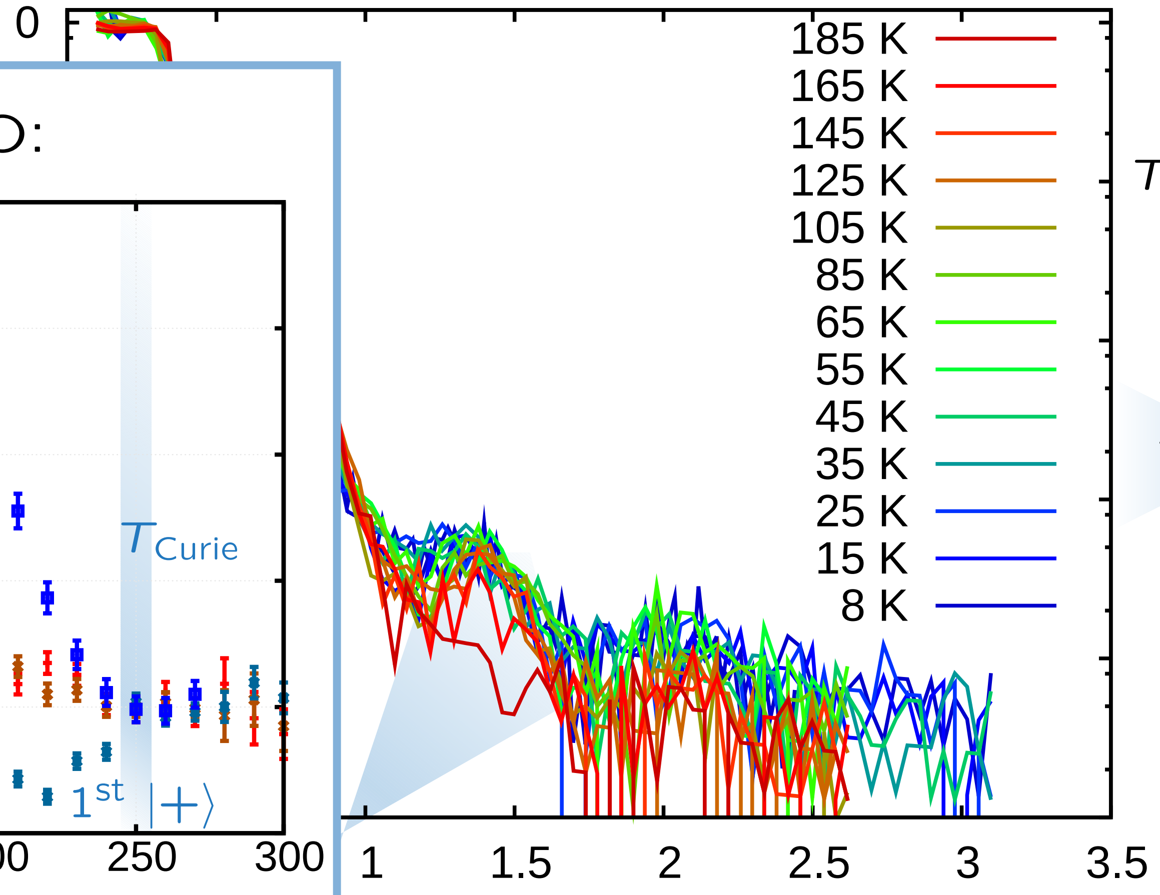
1^{st} Bragg peak displays increasing B

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

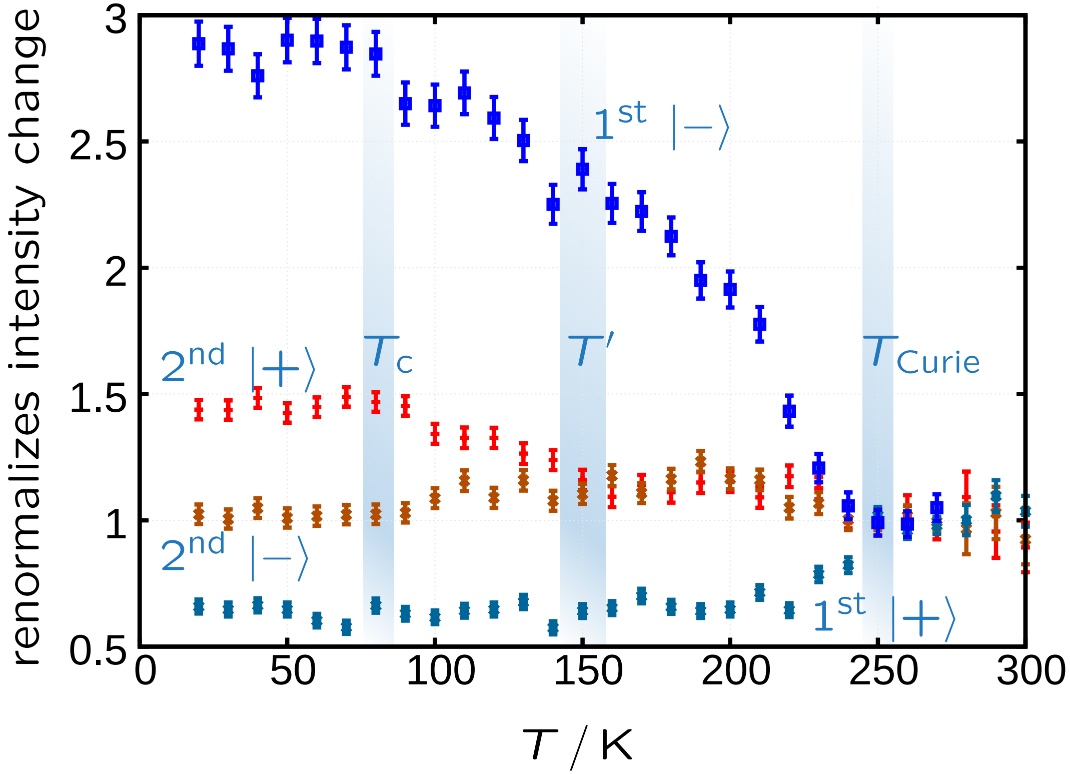








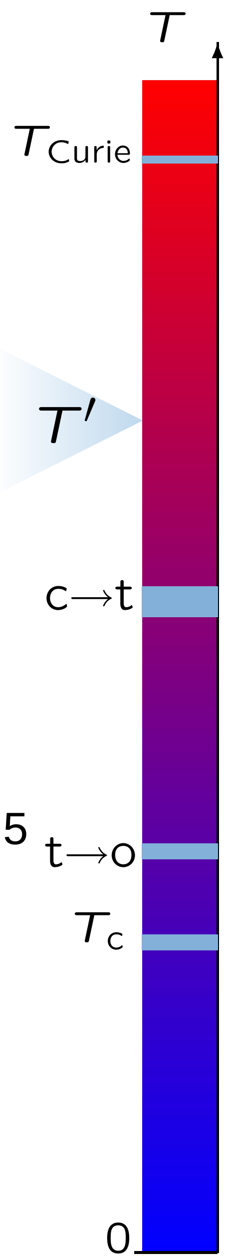
optimally doped YBCO:



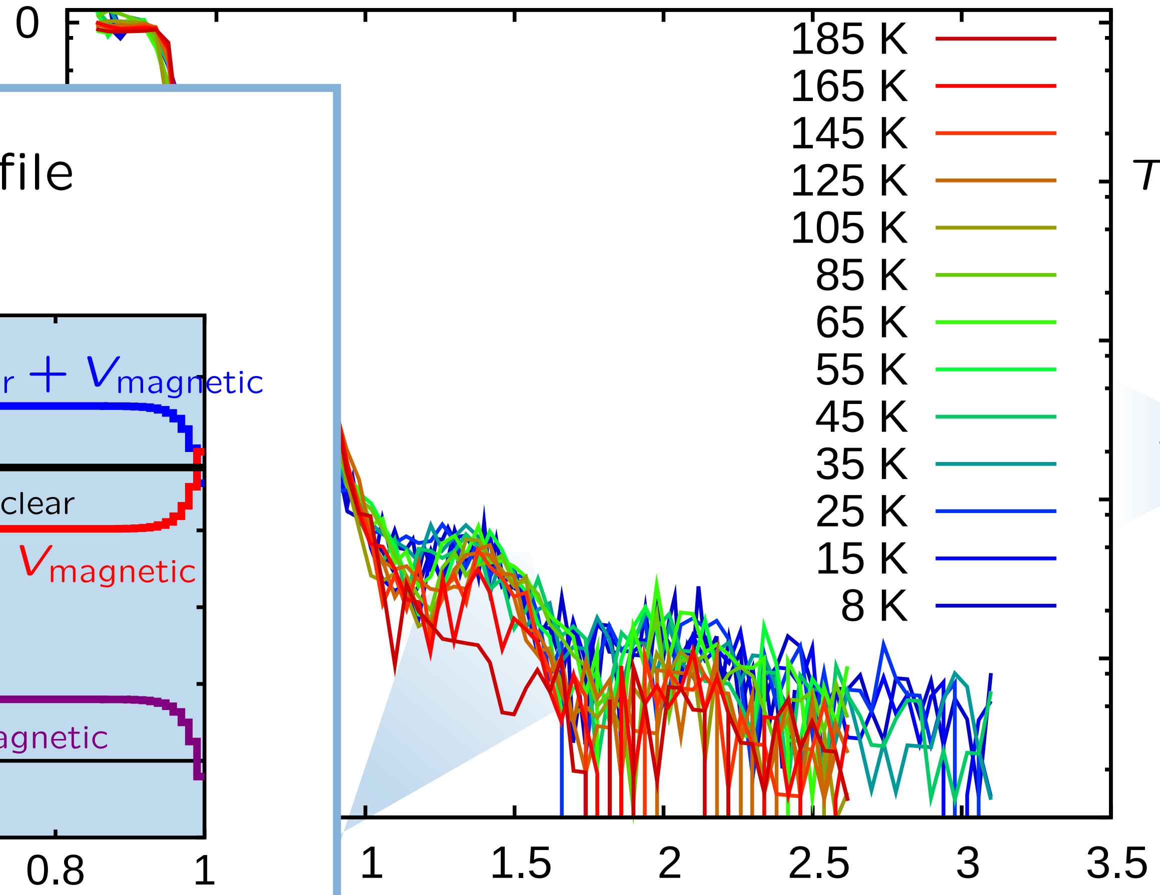
appearance of 2nd Bragg peak

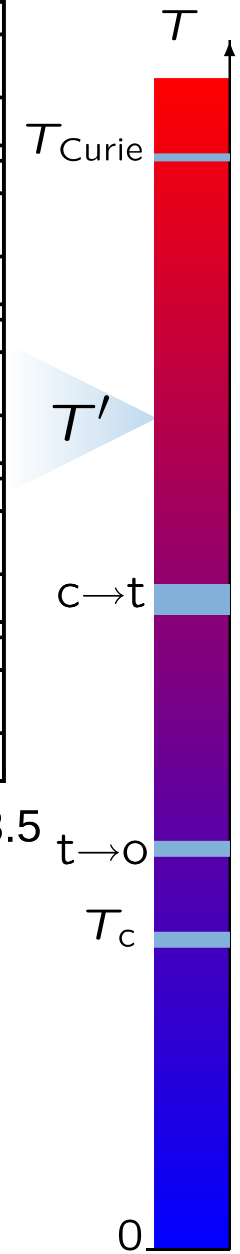
magnetic screening in YPBCO

below T_{Curie}

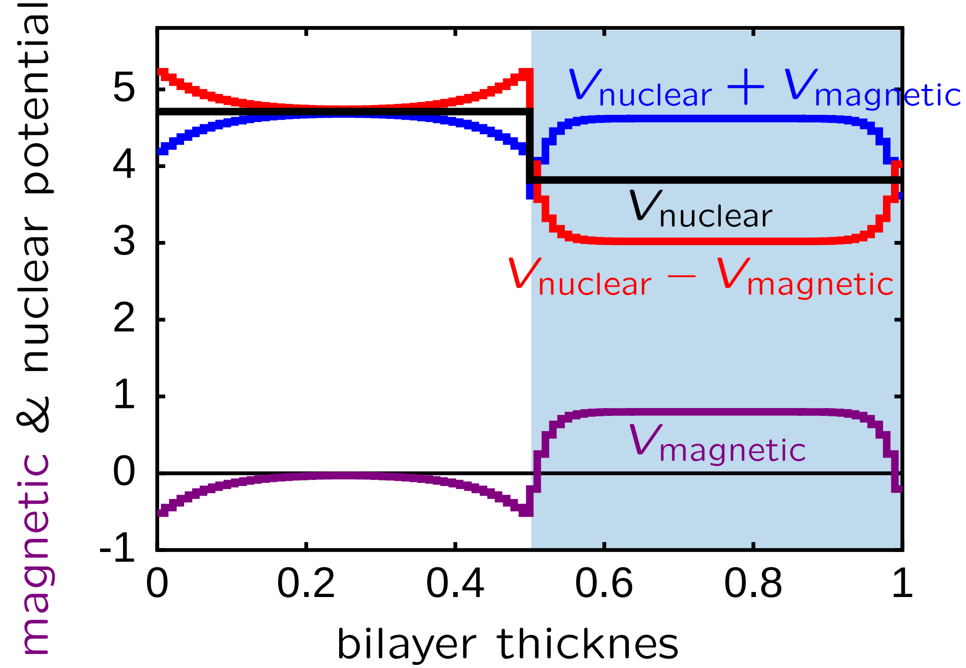


T' is doping dependent and scales like T^* of the pseudo gap

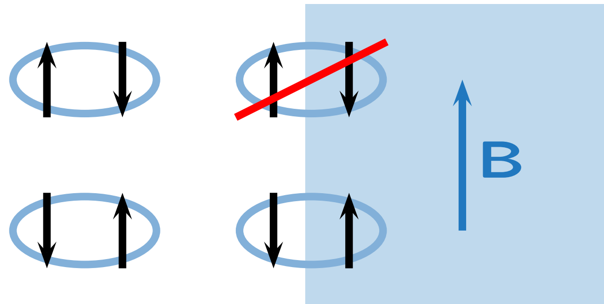




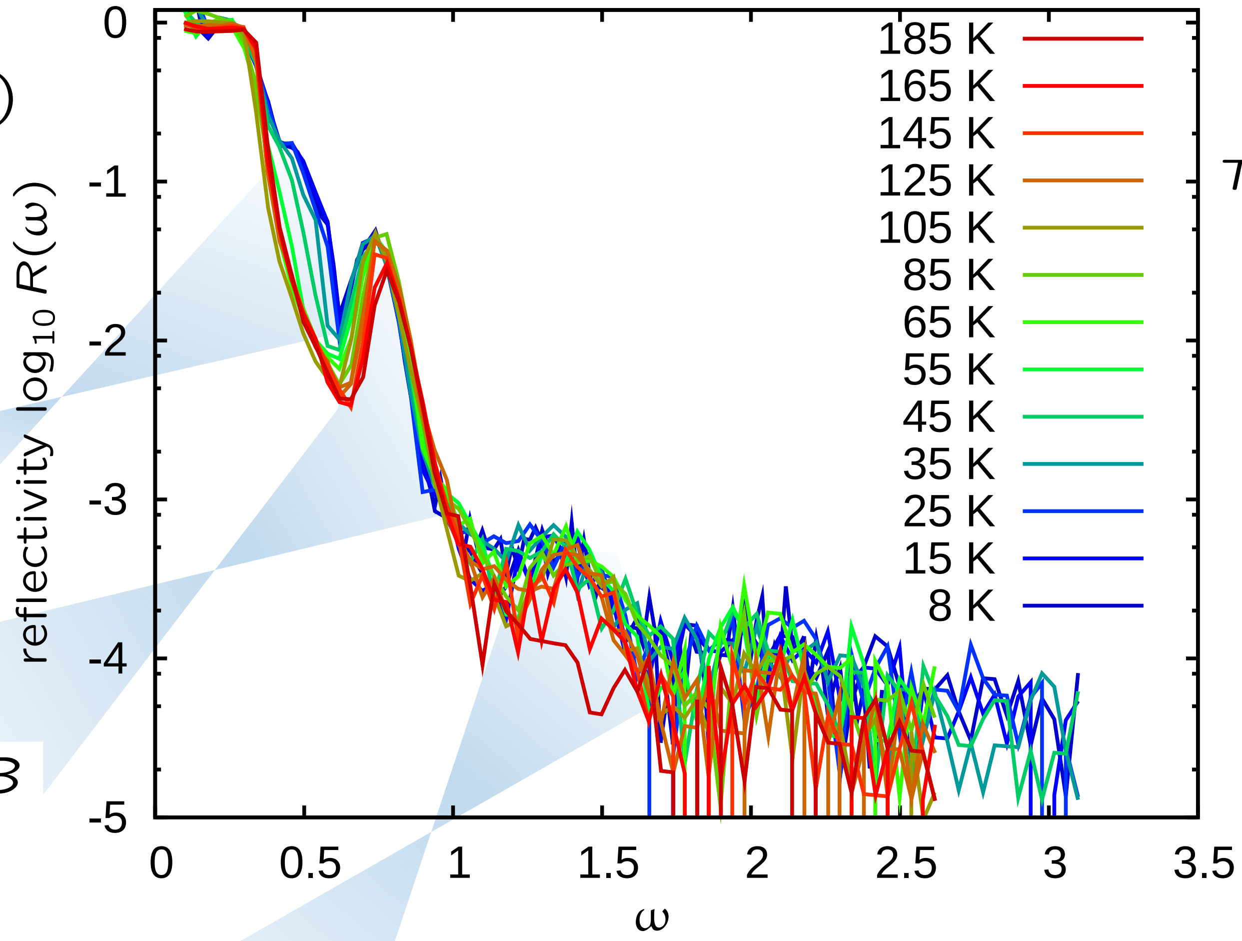
simulated depth profile
of the potentials



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



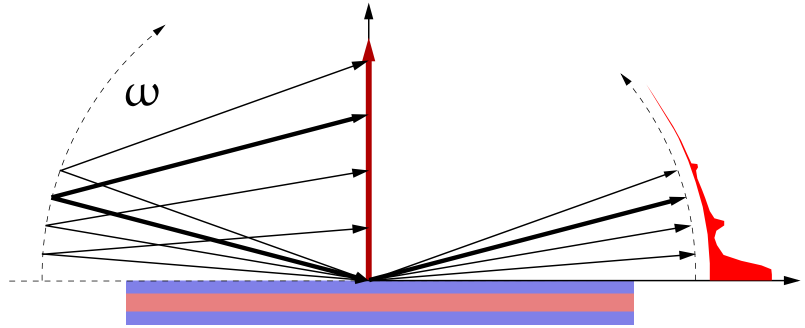
T dependence of $R(\omega)$ for an ML with underdoped SC

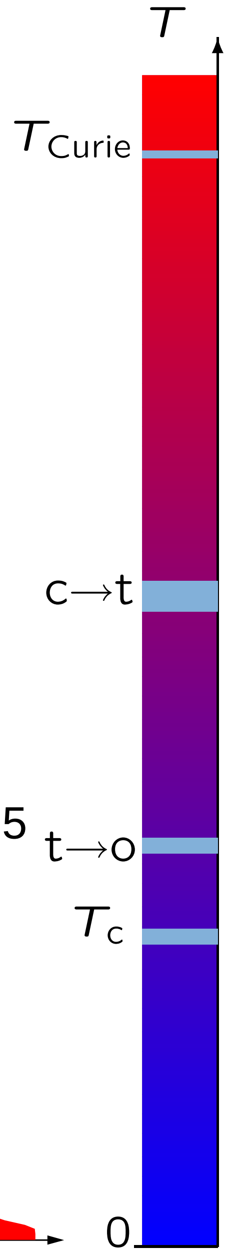


new peak below T_c

1^{st} Bragg peak displays increasing B

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





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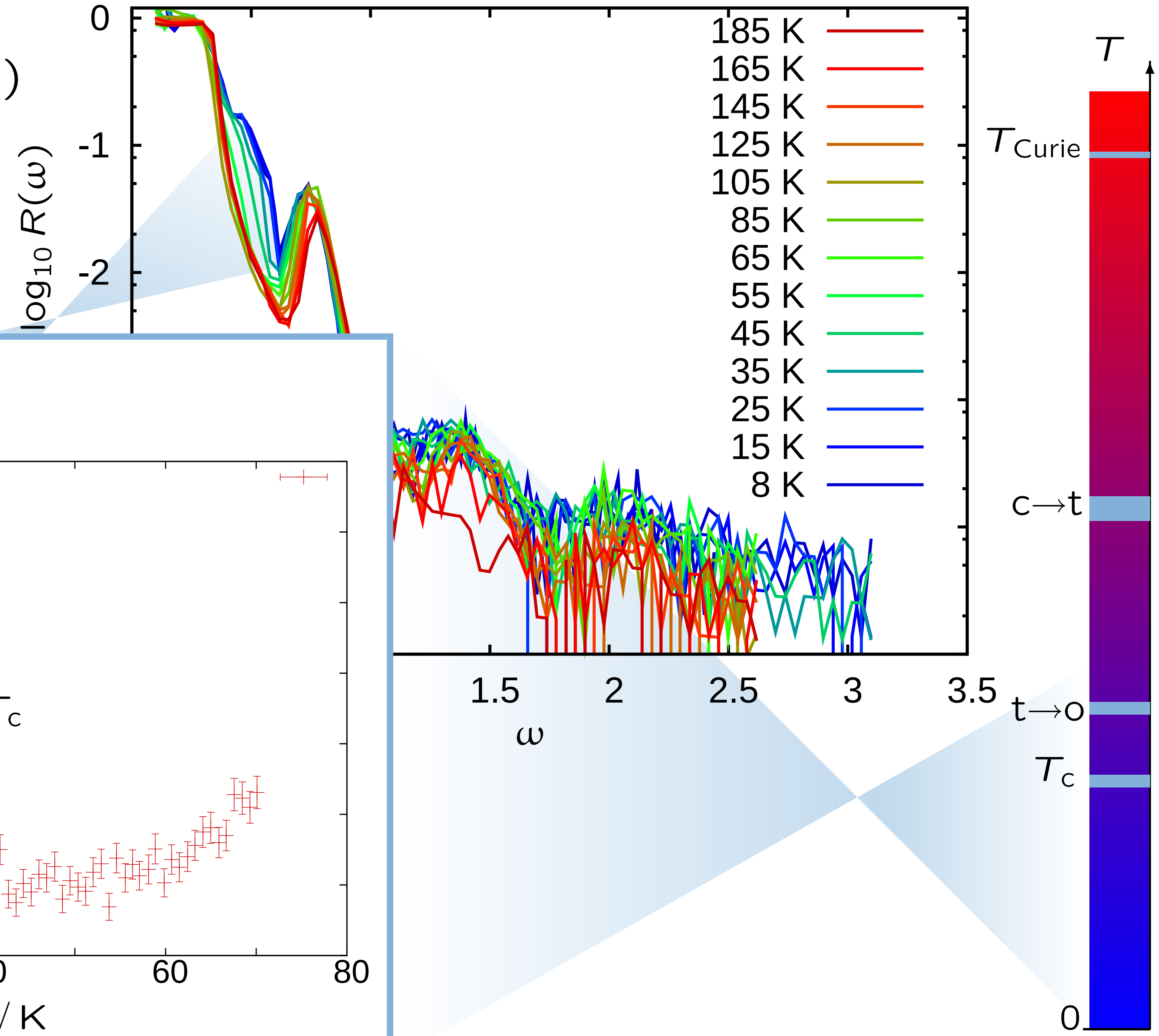
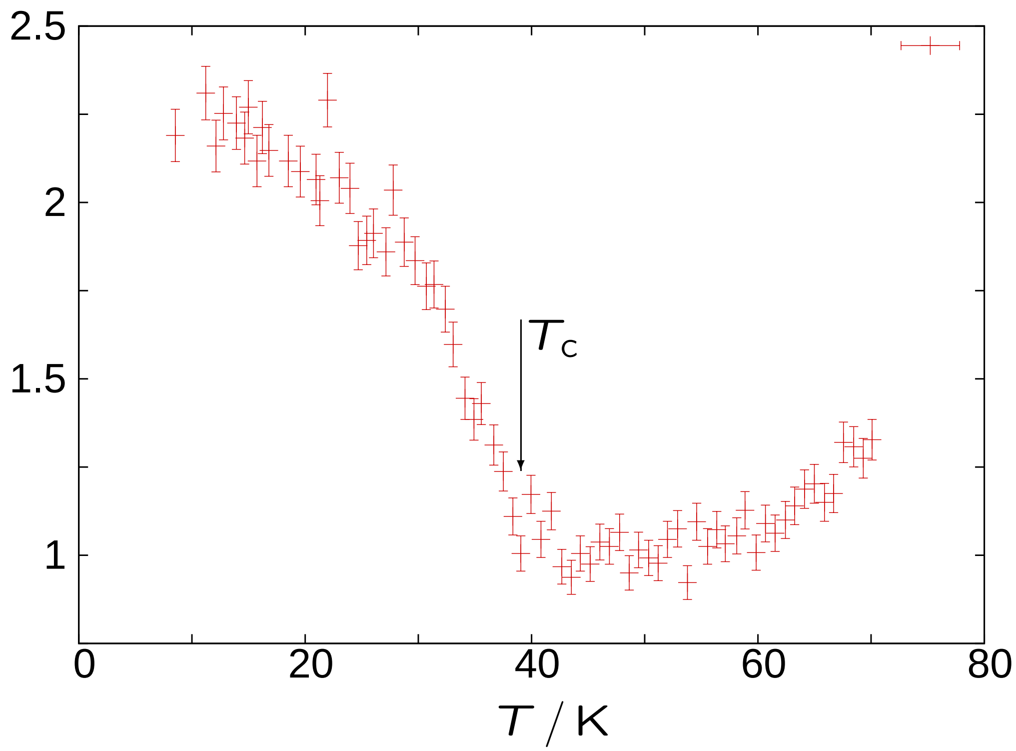
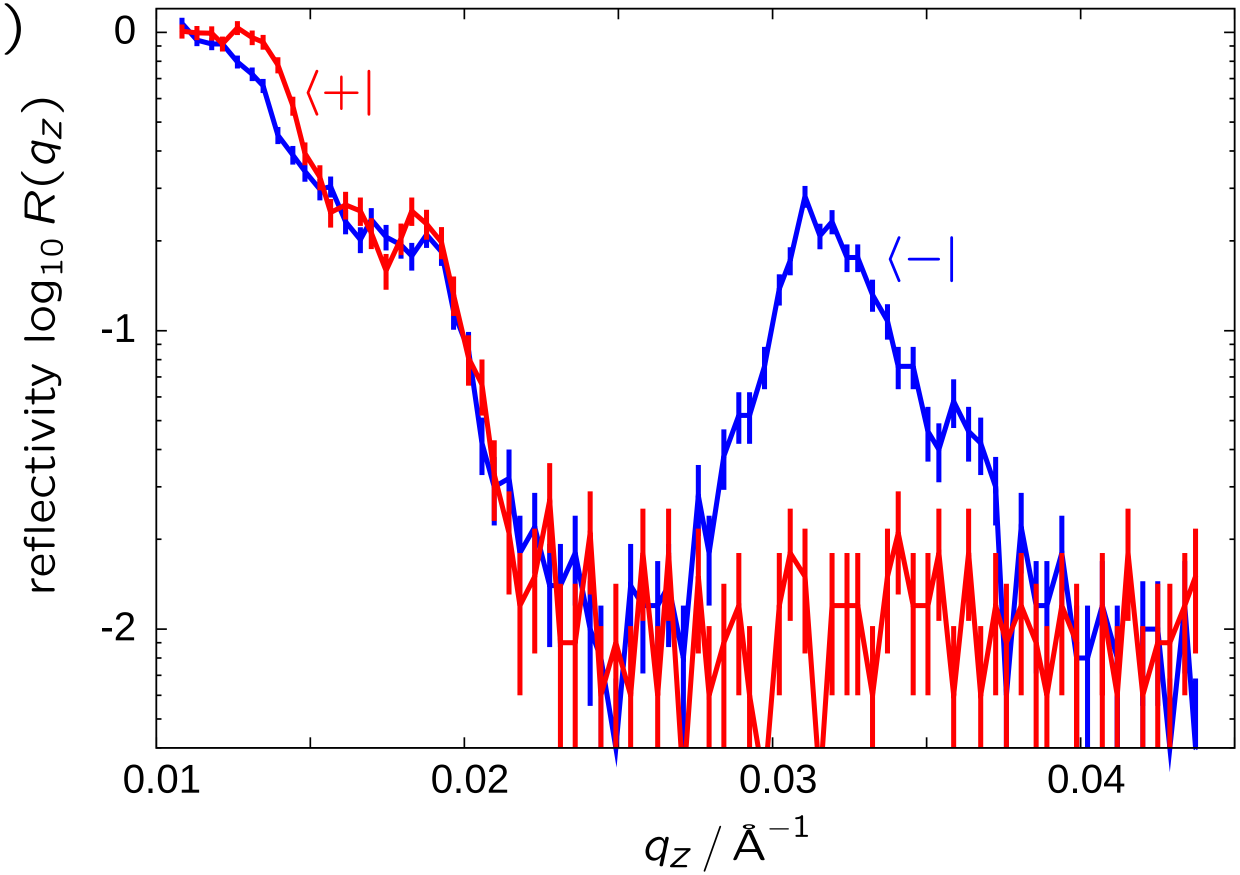


new peak below T_c



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

field-cooled
$H_{\text{external}} = 100\,\text{Oe}$
$T = 15\,\text{K}$
with
spin-polarisation



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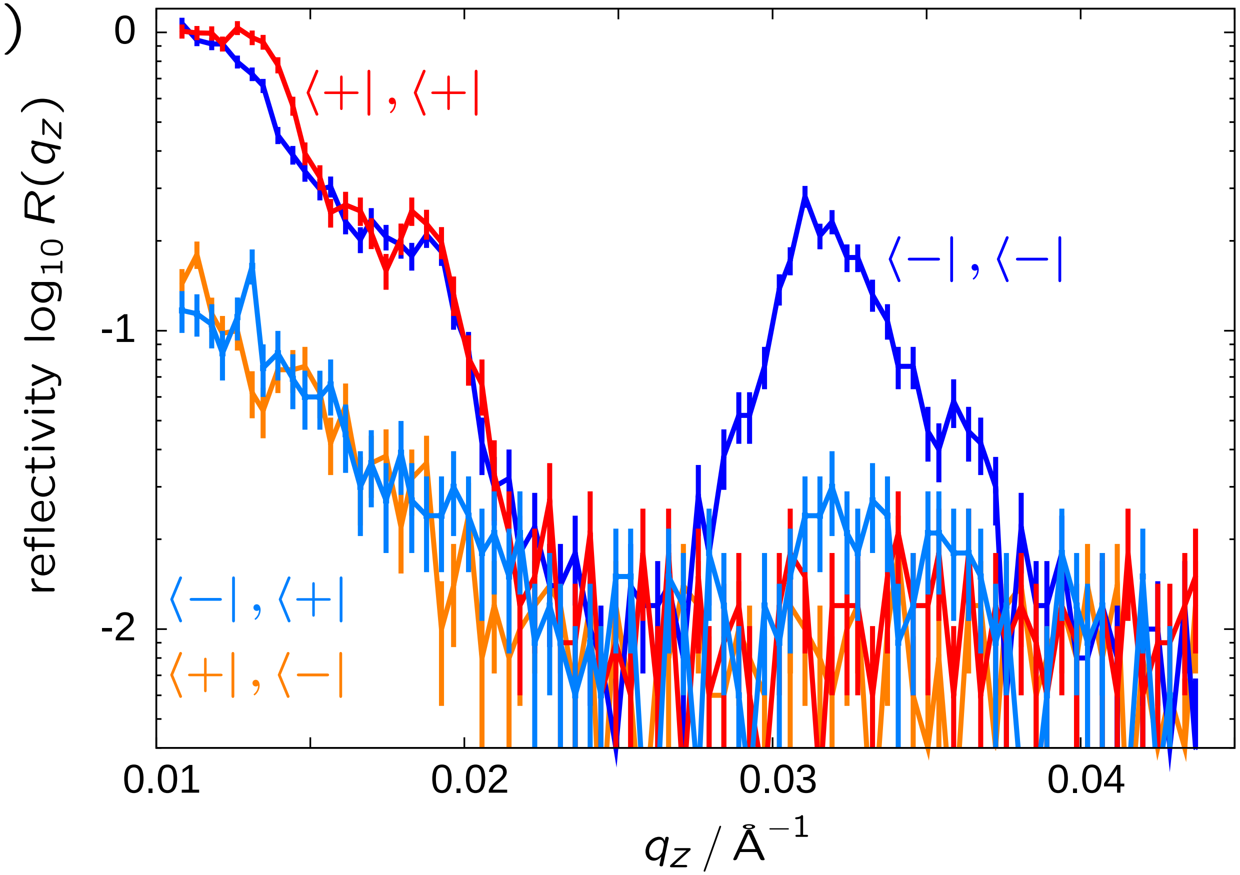


field-cooled
$H_{\text{external}} = 100\,\text{Oe}$
$T = 15\,\text{K}$
with
spin-polarisation
and
spin analysis

no (strong) spin-flip visible

$\Rightarrow$ **B** is (allmost) parallel to $\mathbf{H}_{\text{external}}$

interpretation: modulation of B

magnetic peak

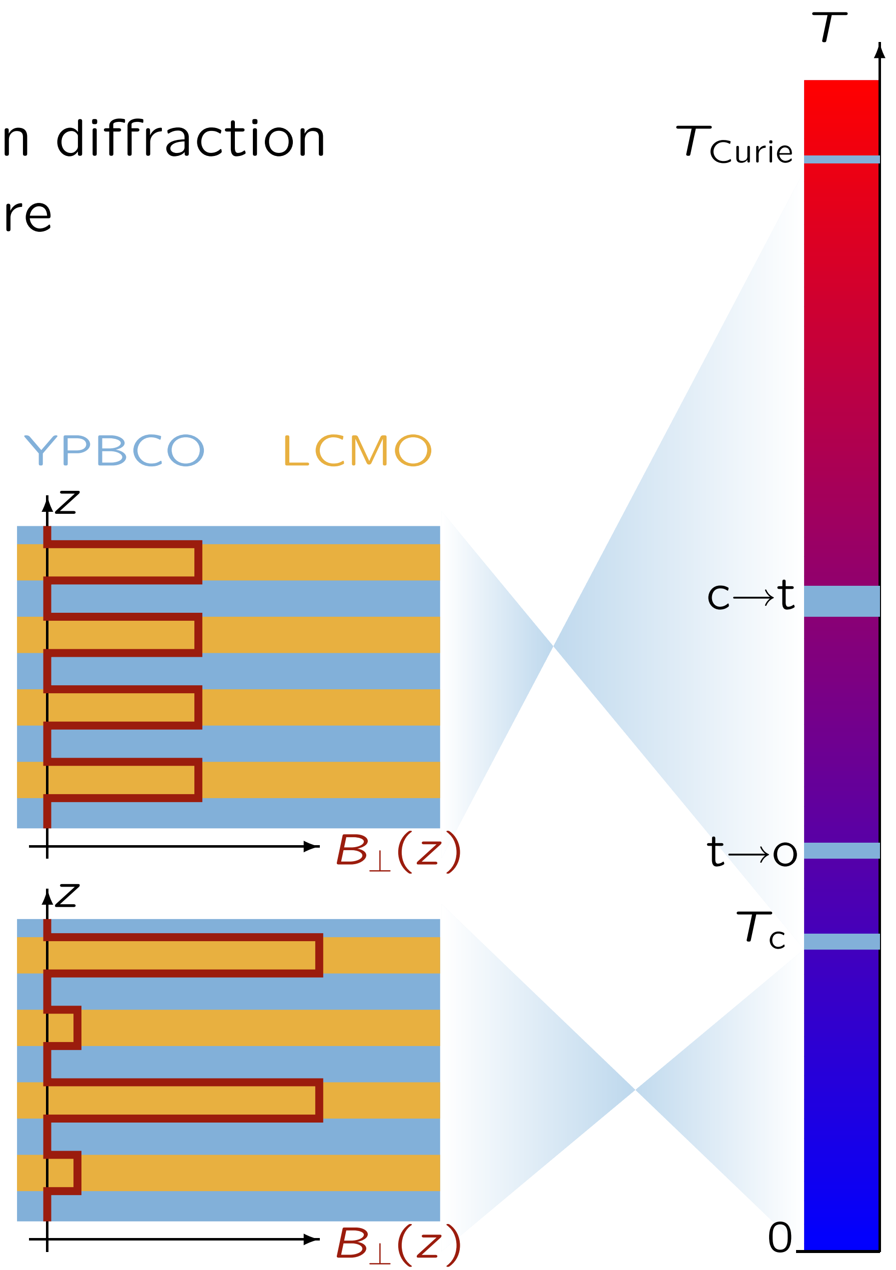
- comparable to a fractional Bragg peak in diffraction
- indication for a (magnetic) superstructure

model assumpton:

- $T_\mathrm{c} < T < T_\mathrm{Curie}$
- all LCMO layers have the same $\mathbf{B} = \mathbf{B}_0$

- $T < T_\mathrm{c}$
- $\mathbf{B} = \mathbf{B}_0 \pm \Delta\mathbf{B}$
  - where sign changes each period
- $\Rightarrow$ layerwise AFM on top of the FM

respective moments on Mn: $2.1 \pm 1.9\,\mu_\mathrm{B}$



STO undergoes phase transitions

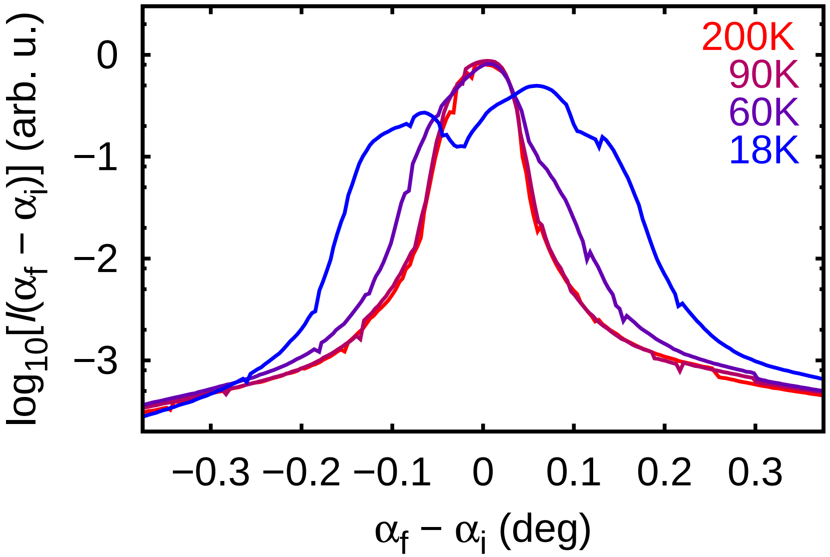
⇒ twinning, buckling of the surface

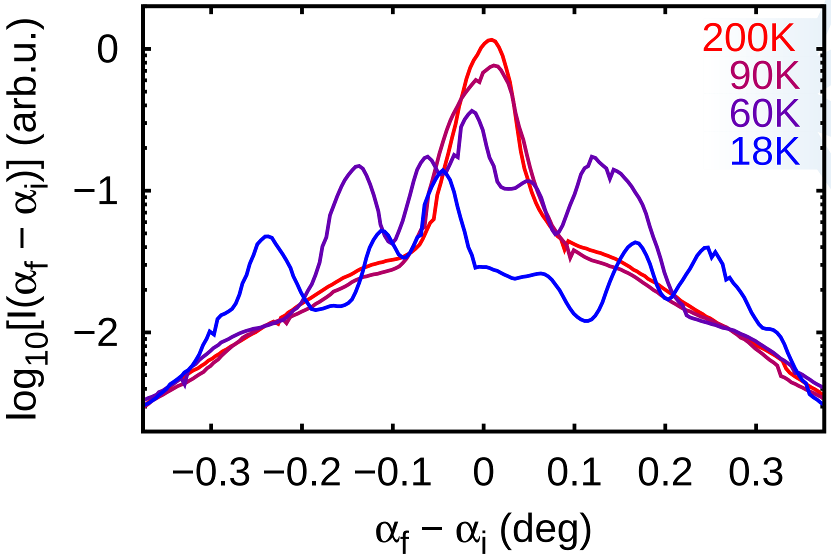
⇒ surface is fragmented into facets

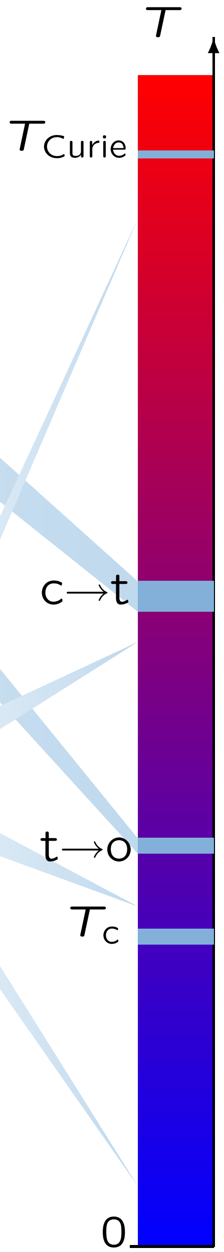
x-rays: ω-scans on

crystal reflection (002) of STO substrate

superlattice peak of the multilayer







crystallite orientation

surface orientation

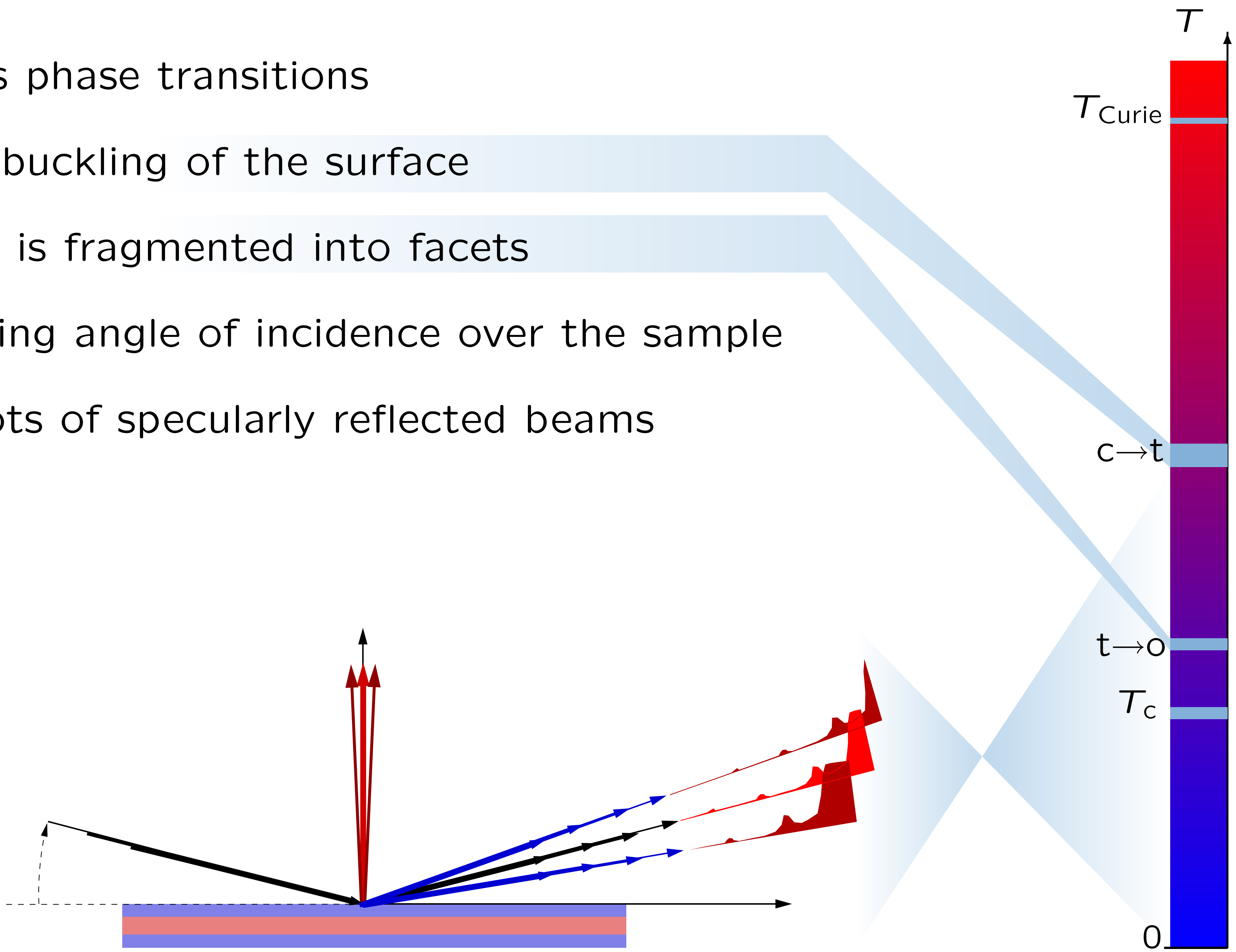
STO undergoes phase transitions

⇒ twinning, buckling of the surface

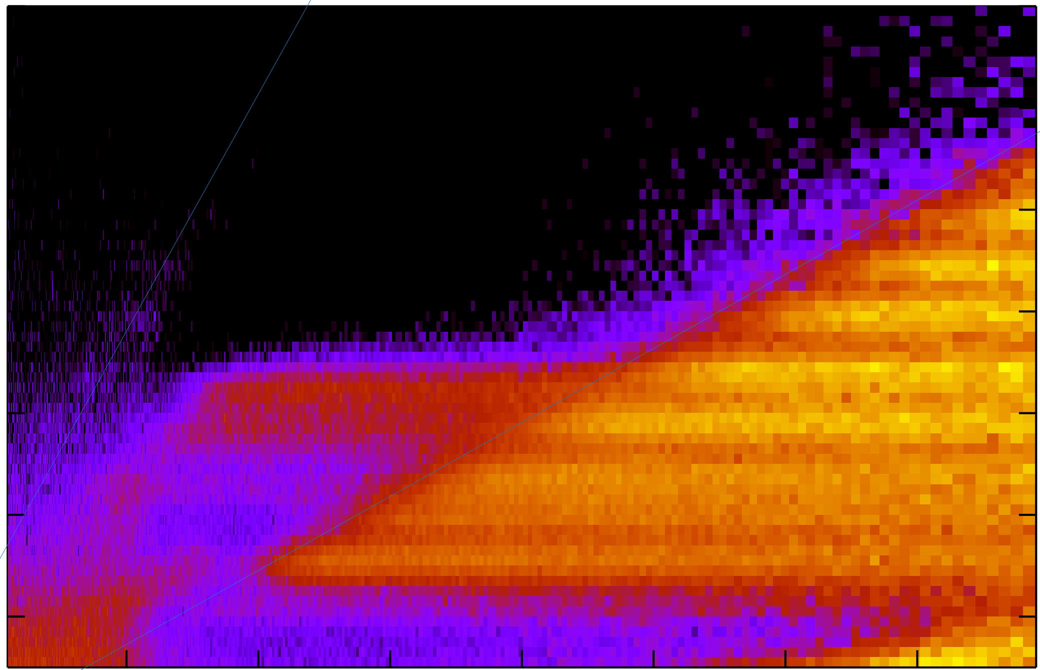
⇒ surface is fragmented into facets

⇒ varying angle of incidence over the sample

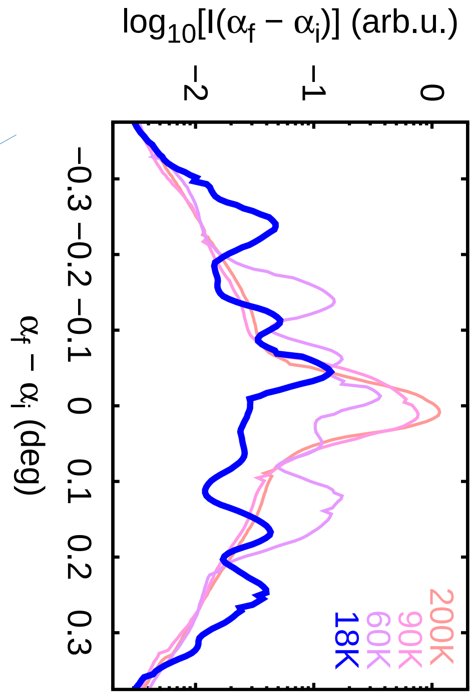
⇒ lots of specularly reflected beams



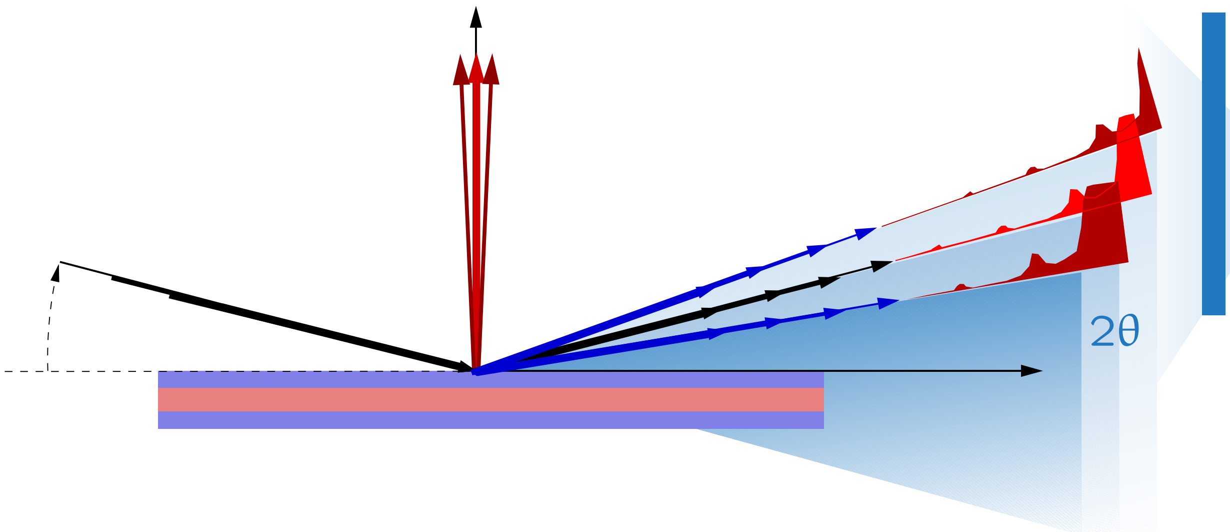
influence of the substrate

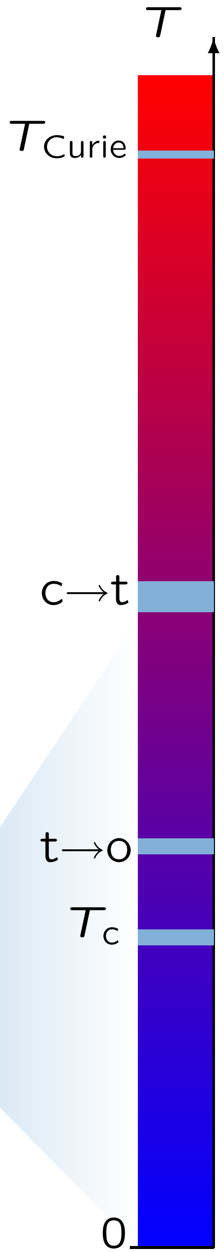


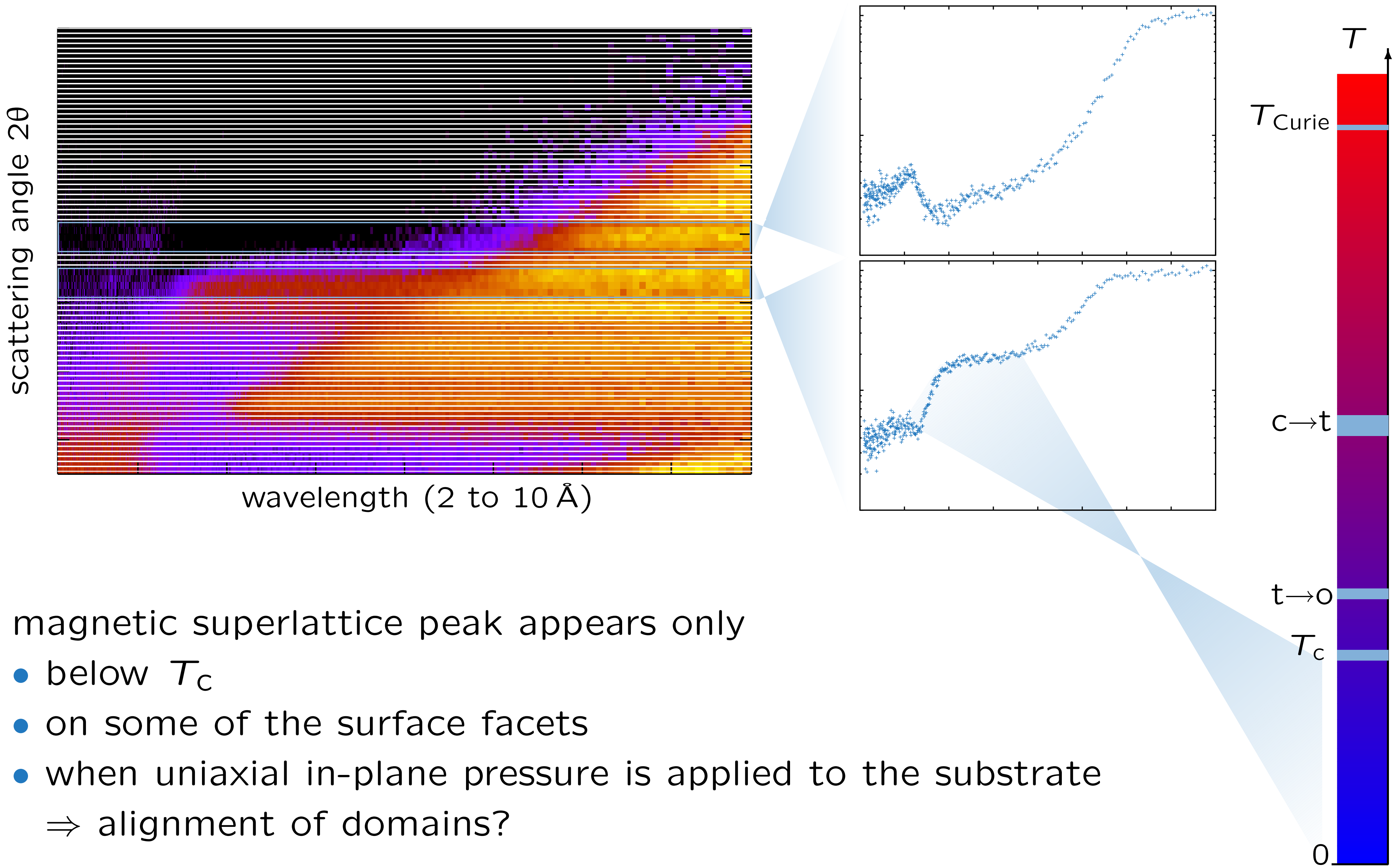
$$\theta \approx \sin\theta = \frac{q}{4\pi}\lambda$$



area detector to cover large angular range







magnetic superlattice peak appears only

- below T_c
- on some of the surface facets
- when uniaxial in-plane pressure is applied to the substrate

  ⇒ alignment of domains?

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

$\left\{\begin{array}{l}\text{strain}\\ \text{finite dimension in } z\\ \text{coupling to neighboring FM layers}\end{array}\right\}$ might change the energies of competing magnetic states

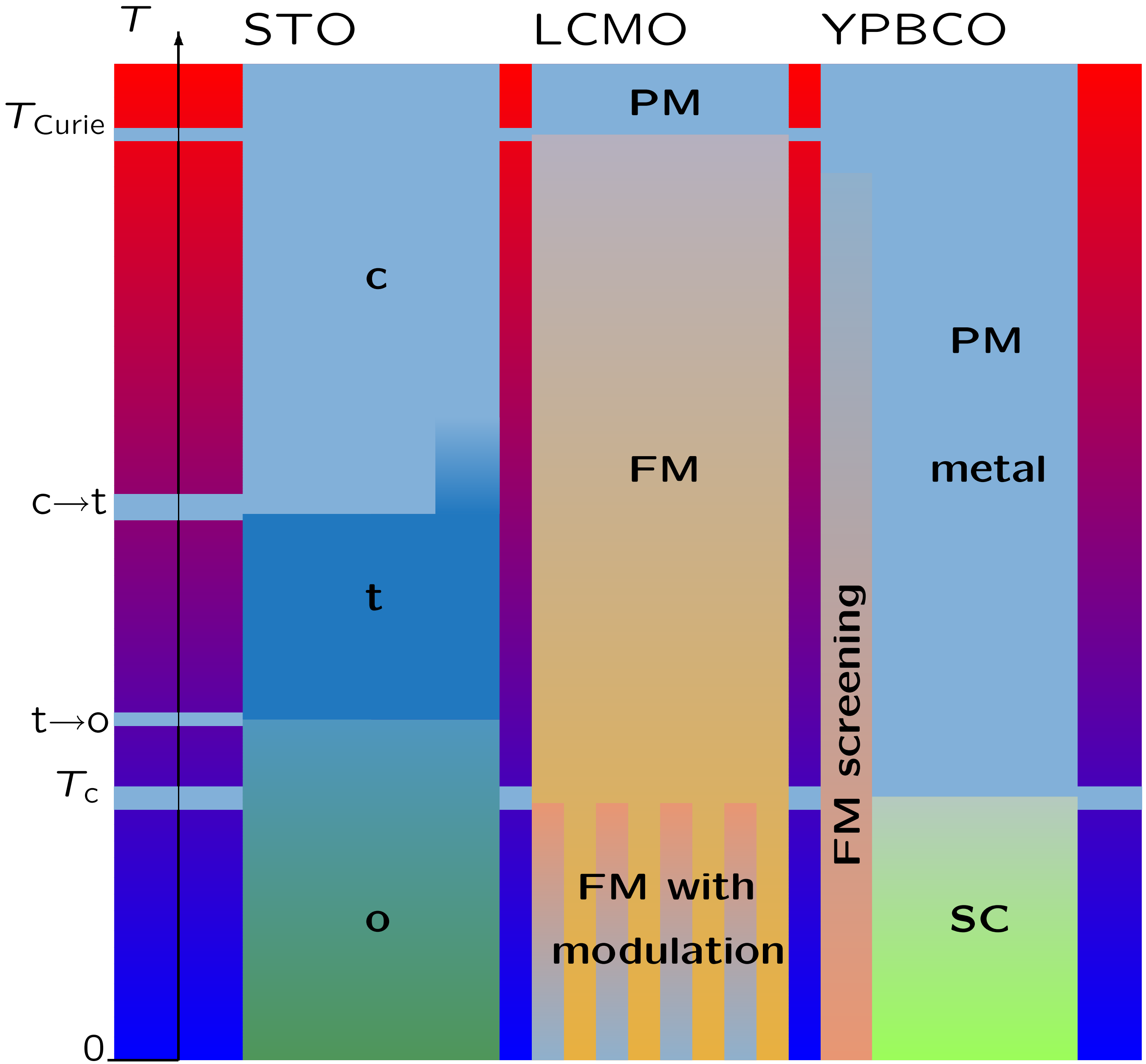
- the changed coupling through YPBCO in the (energetically weak) SC state can then switch the ground state in the FM

- the SC gains surface energy $\Rightarrow$

if he is strained

he can win!

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 Dalgliesh	(ISIS)
	Vivek Malik	(Fribourg)
	Alan Drew	(Fribourg)
	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 initated 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