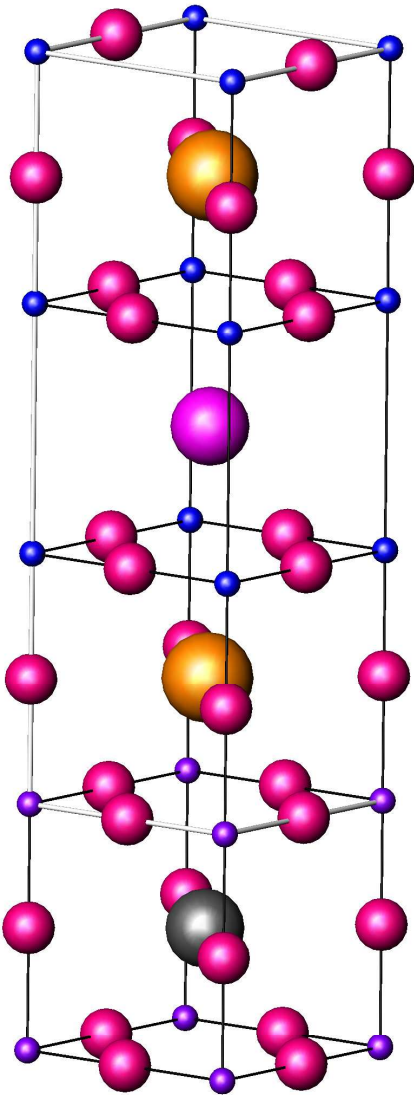


Jochen Stahn Laboratory for Neutron Scattering
Justin Hoppler ETH Zurich & Paul Scherrer Institut
Christof Niedermayer and
Christian Bernhard University Fribourg, FriMat

About the Competition of Superconductivity and Ferromagnetism in Multilayers

Nature Materials, doi:10.1038/nmat2383
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

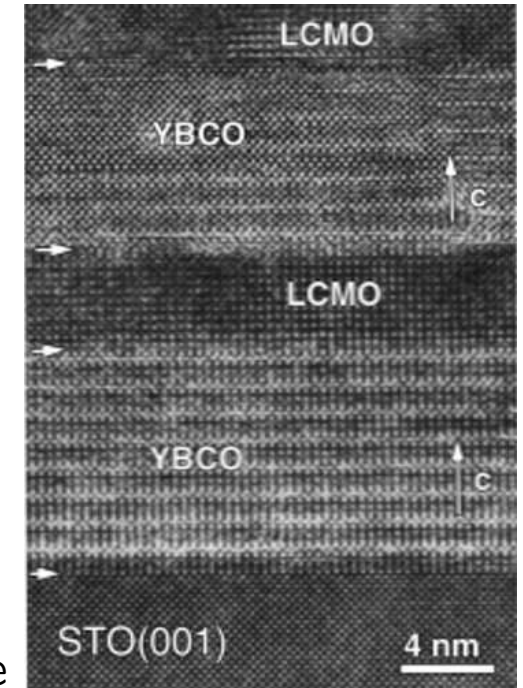
⇒ how do they arrange?

used system:

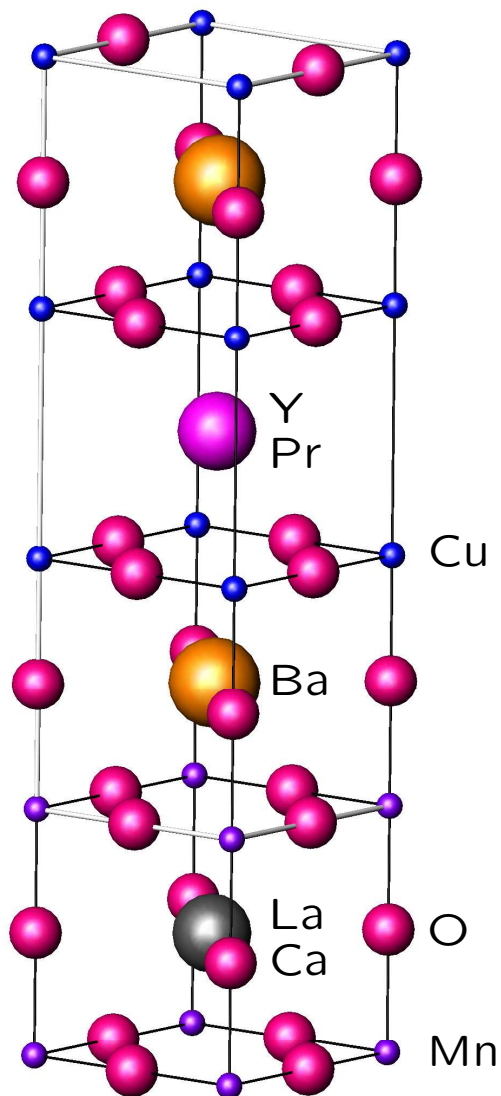
multilayers of the type

$[SC/FM]_n/STO$

grown by *pulsed laser 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

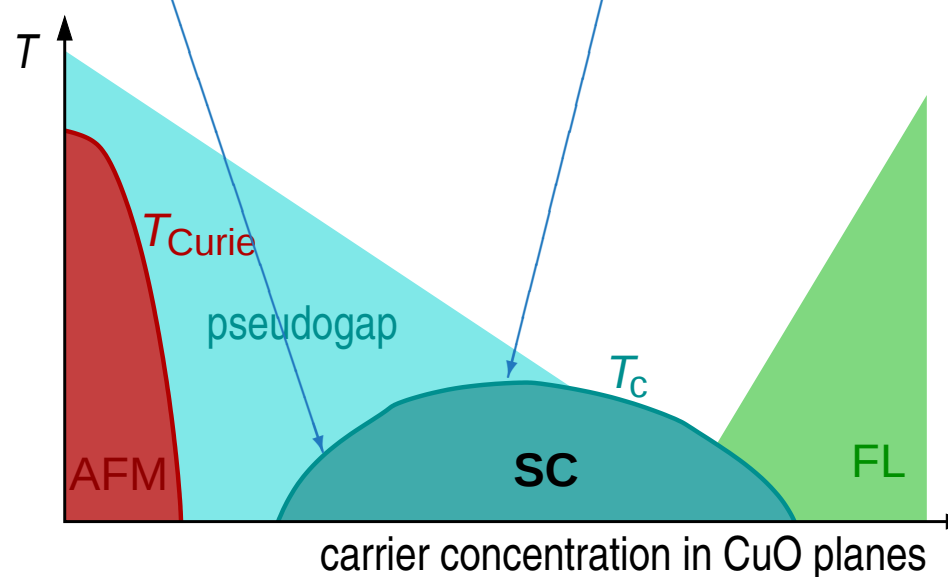
$T \approx 105 \text{ K}$: cubic to tetragonal

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

$\Rightarrow$ surface fragmentation

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

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



how does the magnetisation in the film look like?

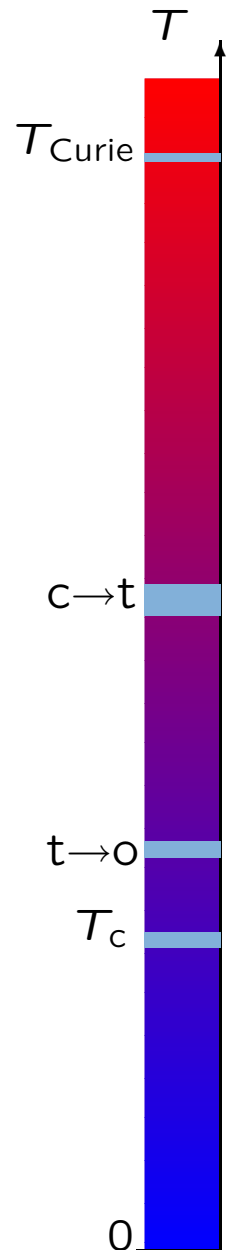
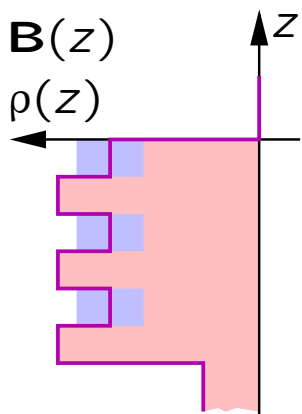
depth profile of magnetic induction: $\mathbf{B}(z)$

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:

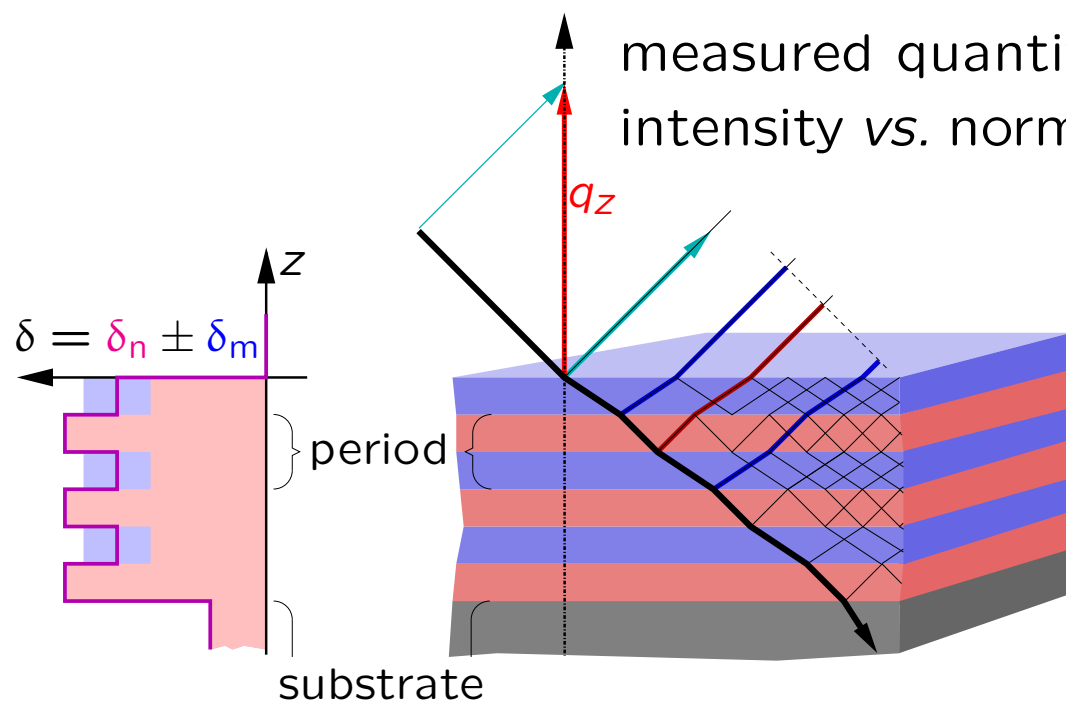
$$|n - 1| = |\delta| < 10^{-5}$$

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

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

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:

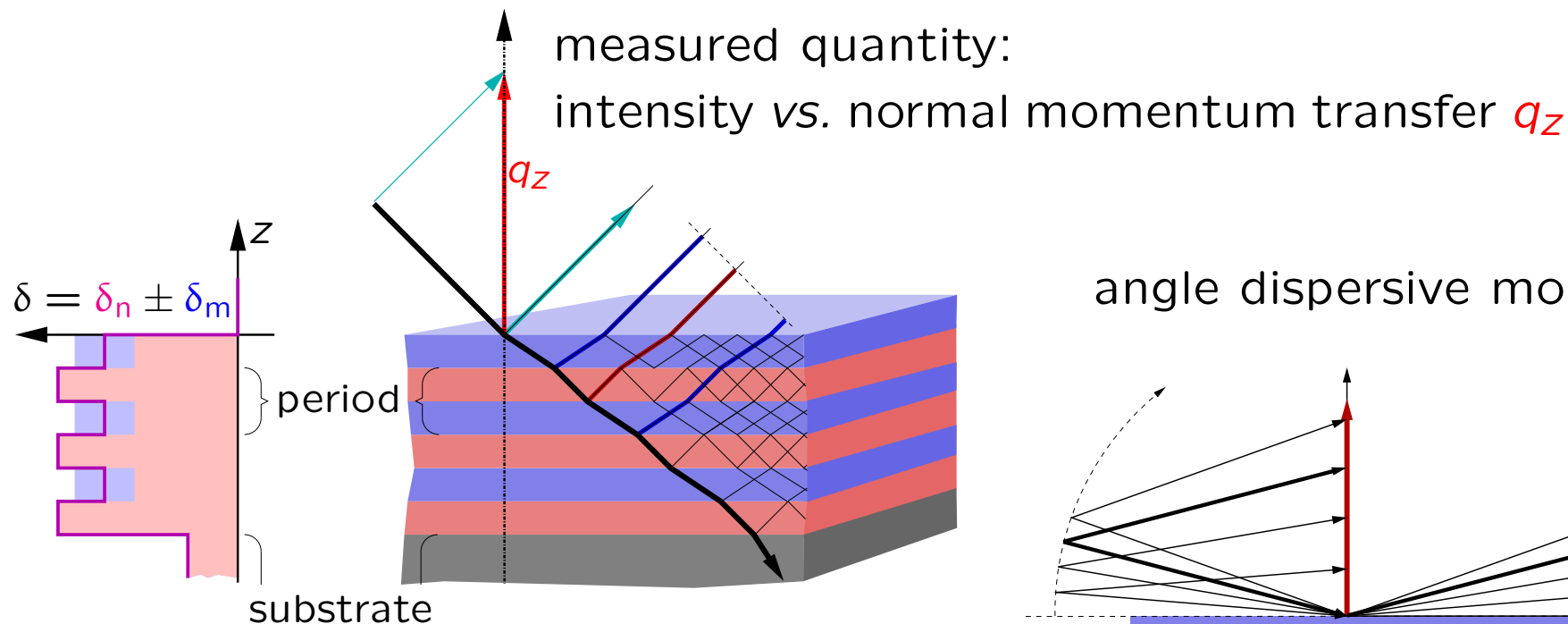
$$|n - 1| = |\delta| < 10^{-5}$$

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

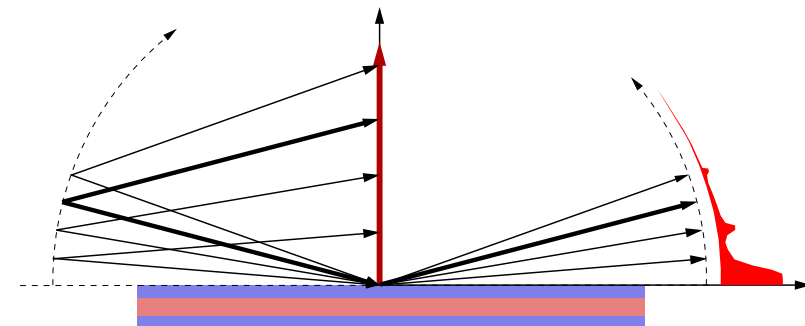
$$\delta_{\text{magnetic}} \propto \mu_n \mathbf{B}_{\perp}$$

neutron magnetic moment: μ_n

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



angle dispersive mode



index of refraction n (as for visible light:

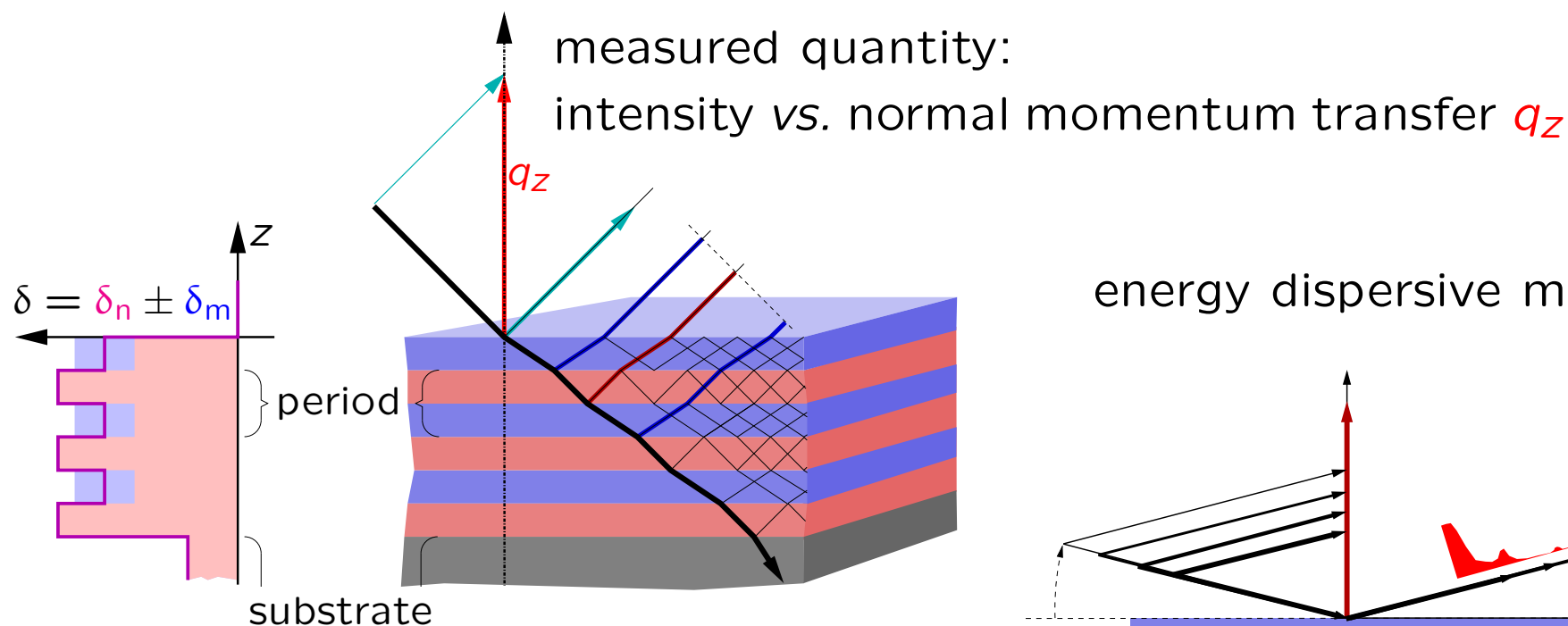
$$|n - 1| = |\delta| < 10^{-5}$$

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

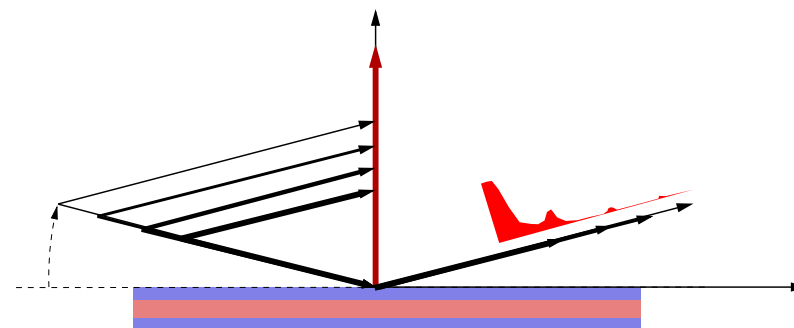
$$\delta_{\text{magnetic}} \propto \mu_n \mathbf{B}_{\perp}$$

neutron magnetic moment: μ_n

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



energy dispersive mode

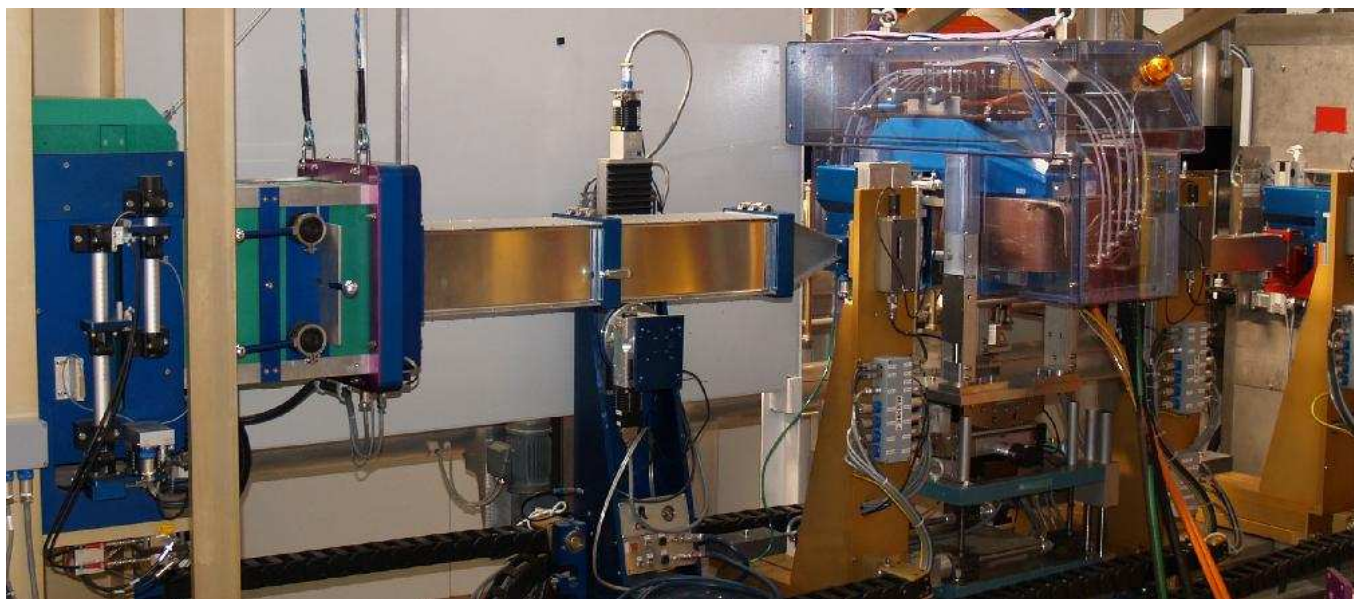


neutron reflectometer

AMOR

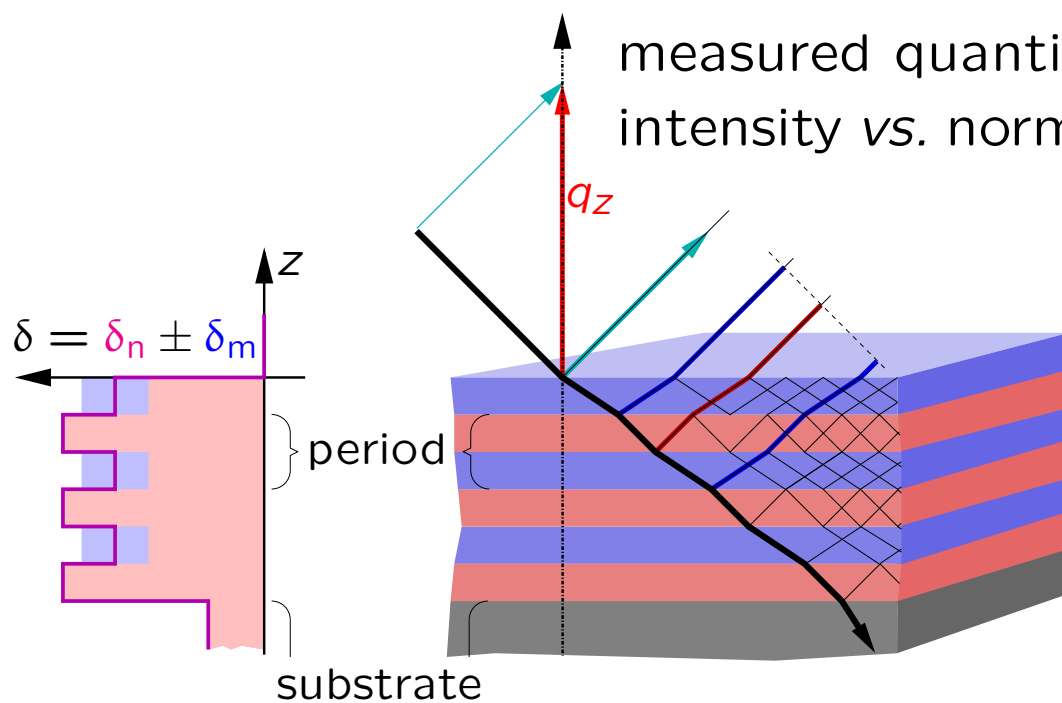
at SINQ, PSI

time-of-flight
spin polarisation

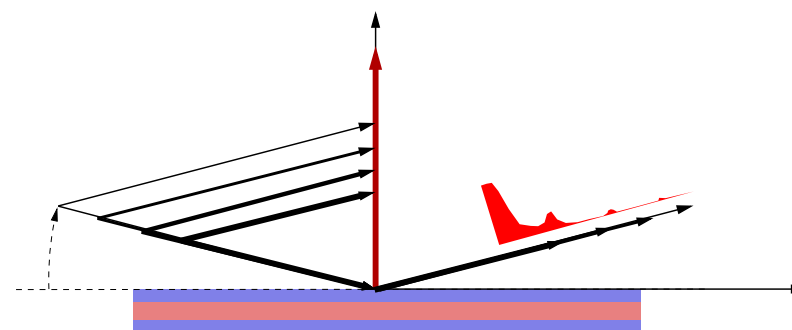


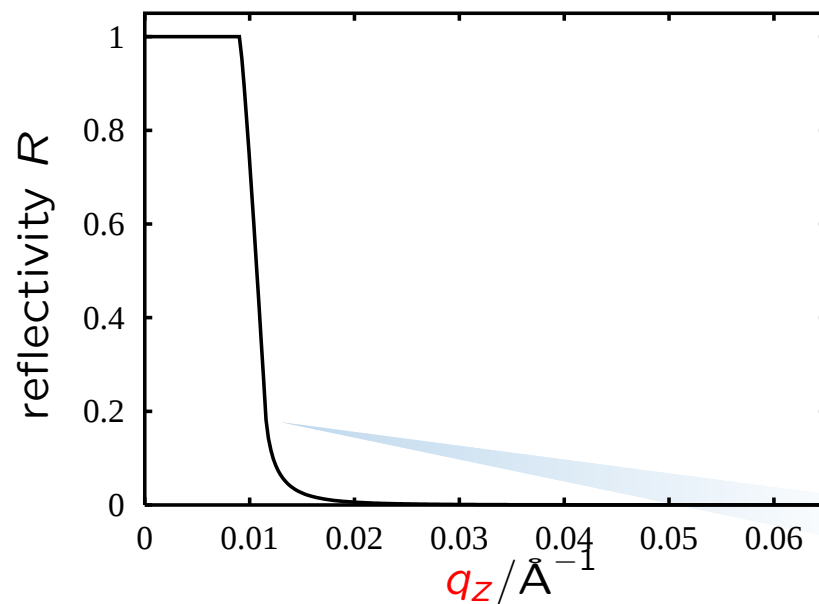
measured quantity:

intensity vs. normal momentum transfer q_z

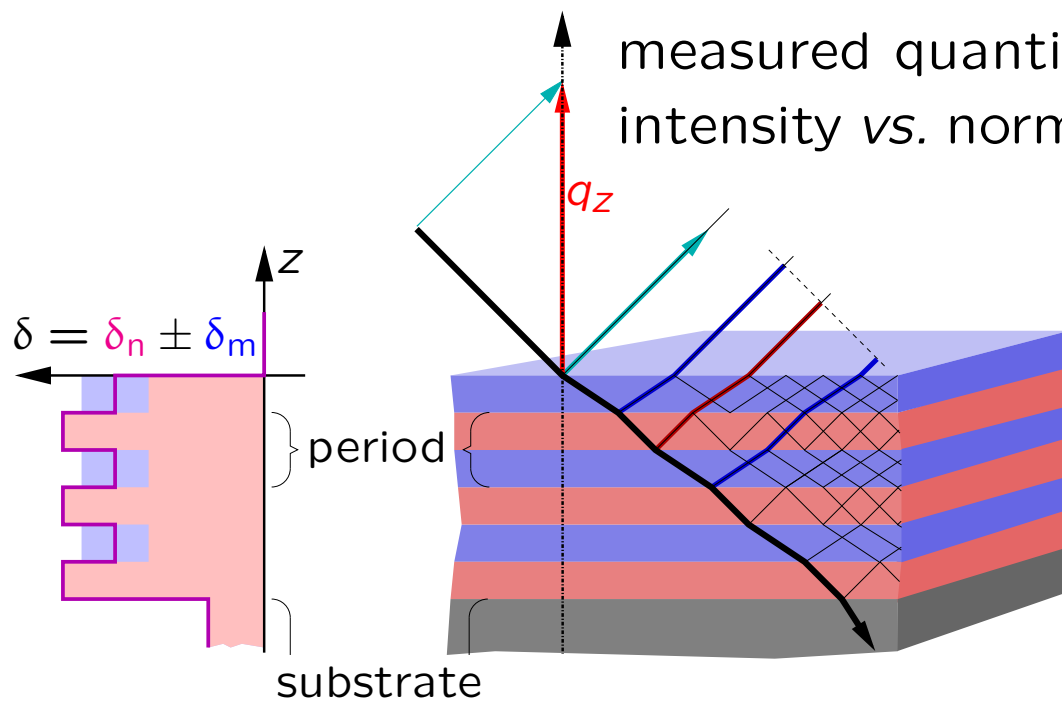


energy dispersive mode

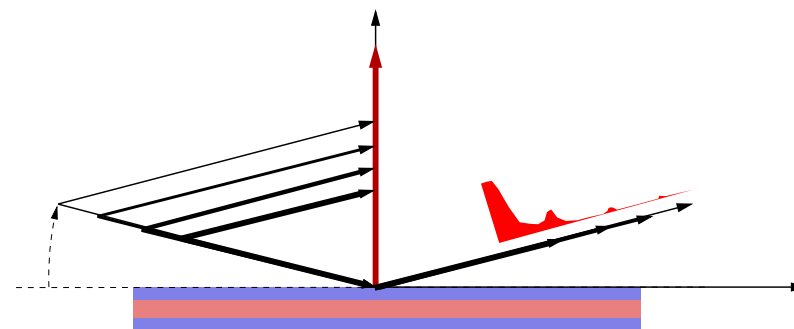


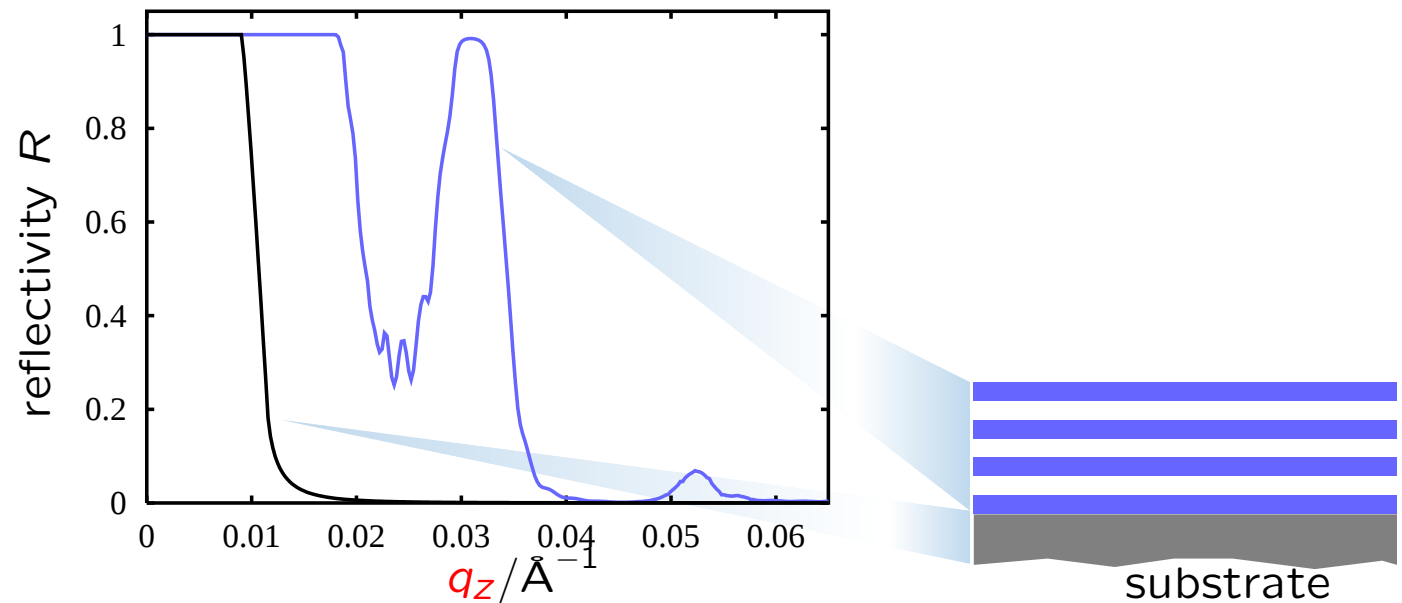


measured quantity:
intensity vs. normal momentum transfer q_z

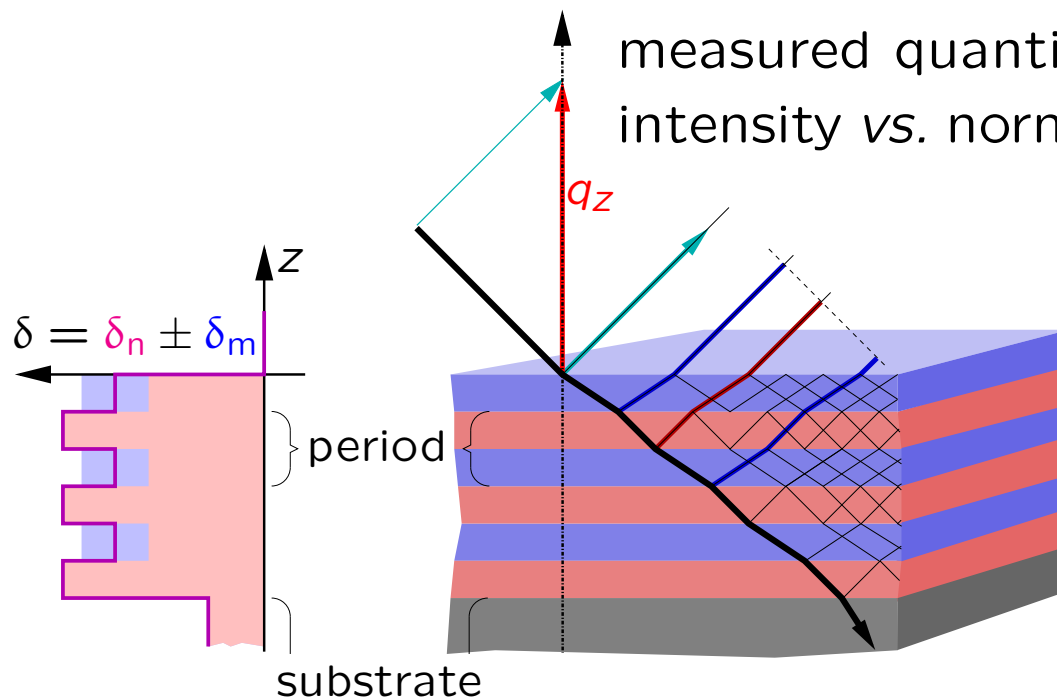


energy dispersive mode

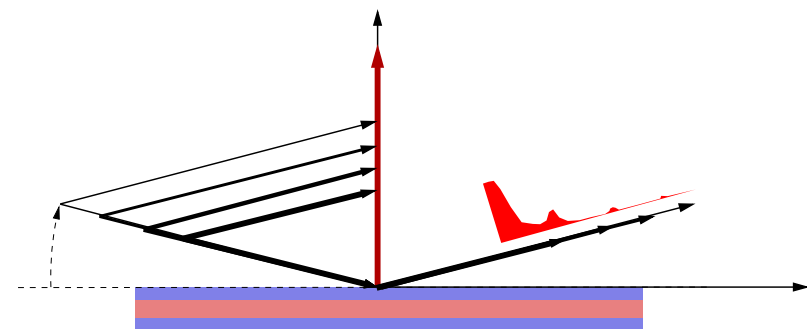




measured quantity:
intensity vs. normal momentum transfer q_z

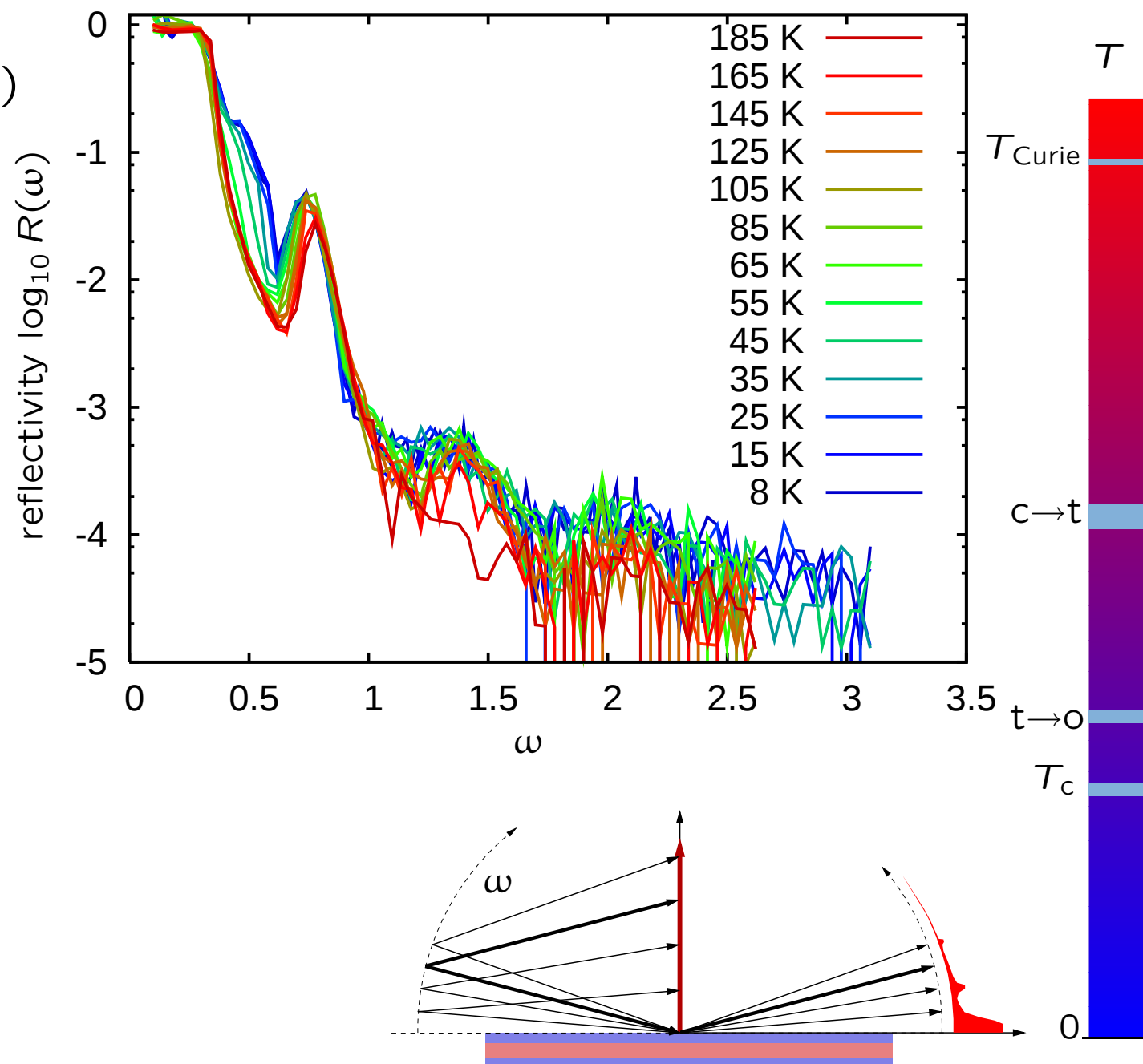


energy dispersive mode



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

field cooled and
measured in
 $H = 100$ Oe

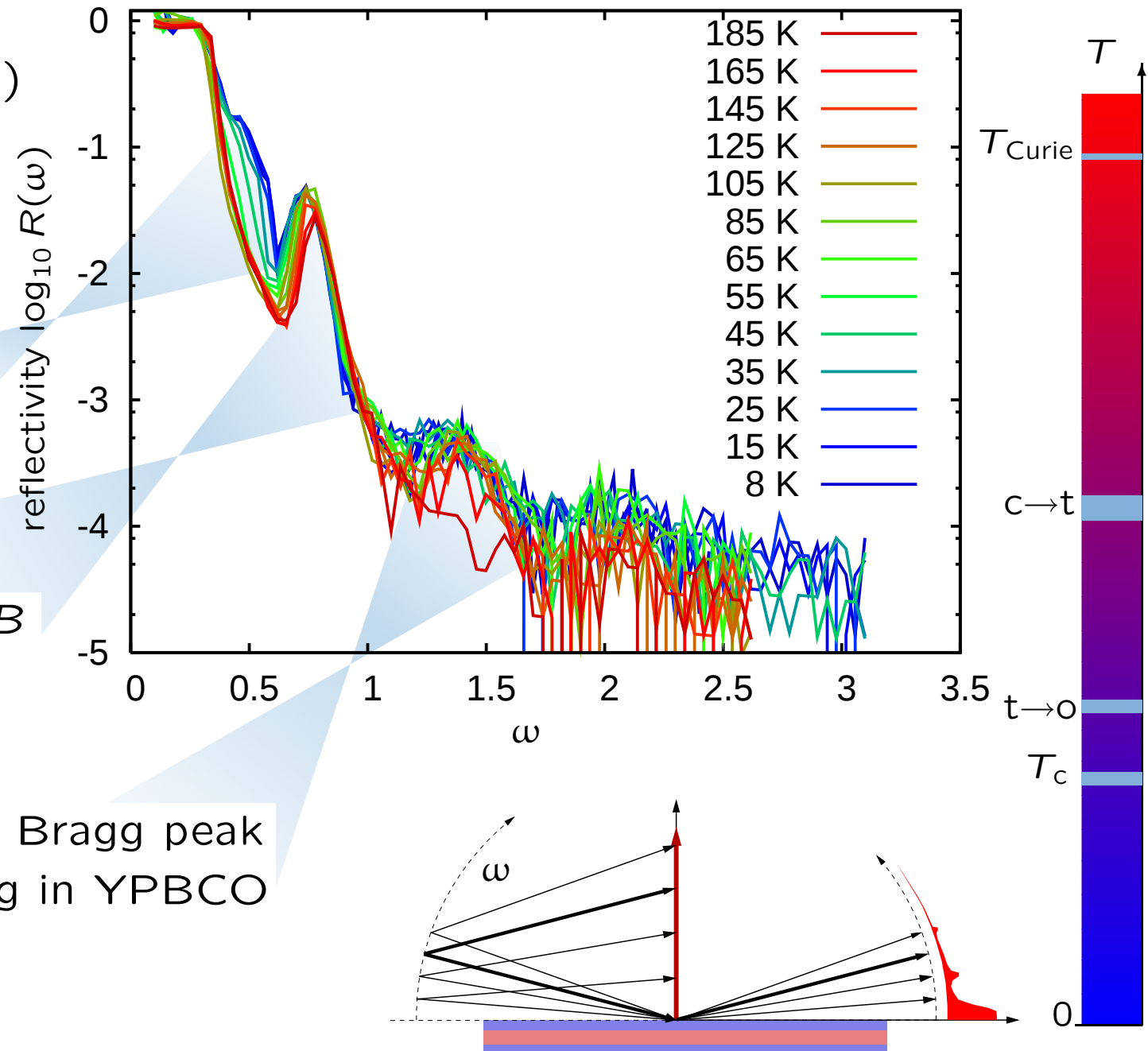


T dependence of $R(\omega)$
for an ML with
underdoped SC

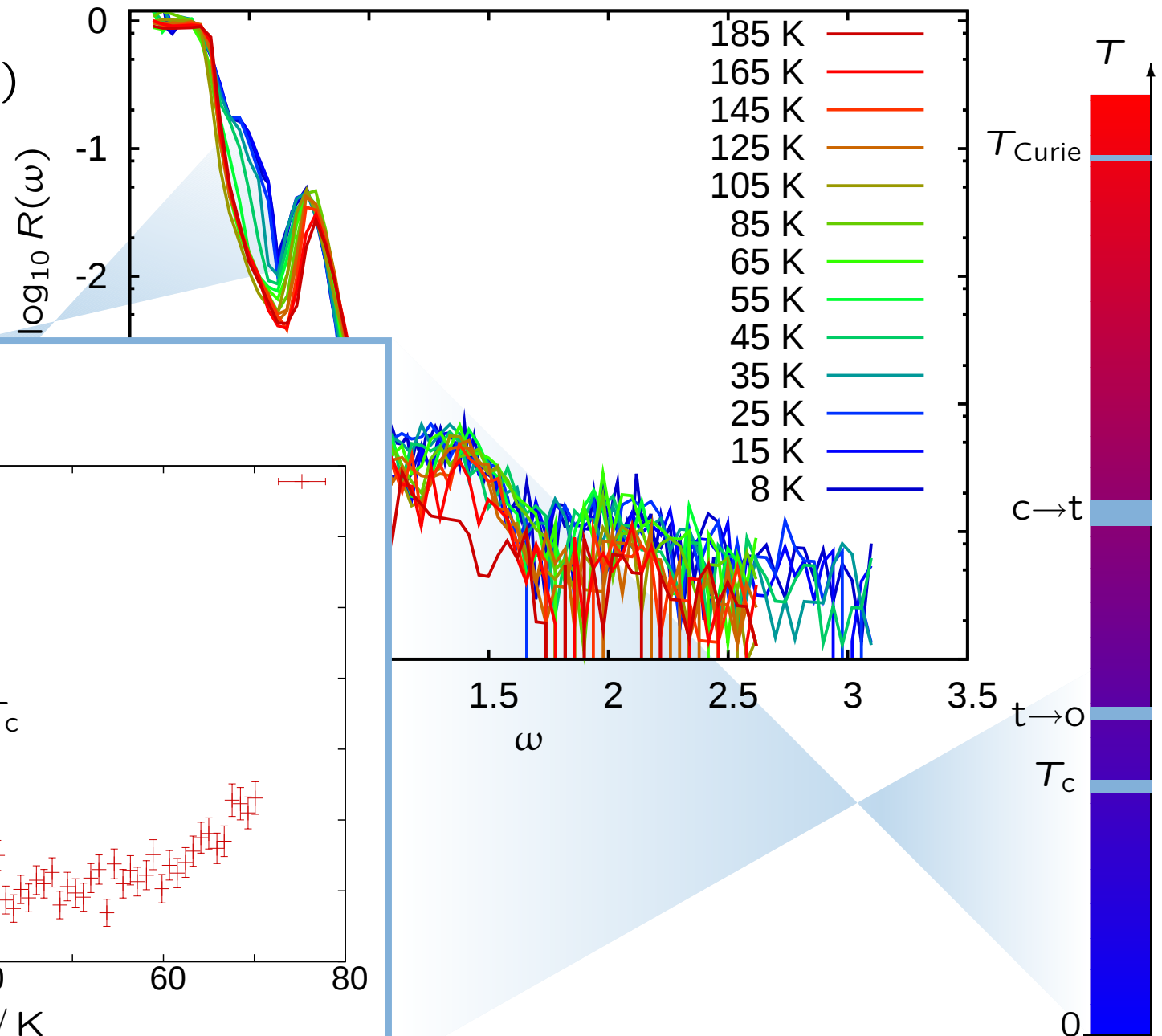
new peak below T_c

1st Bragg peak
displays increasing B

appearance of 2nd Bragg peak
magnetic screening in 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 $\mathbf{B} = \mathbf{B}_0$

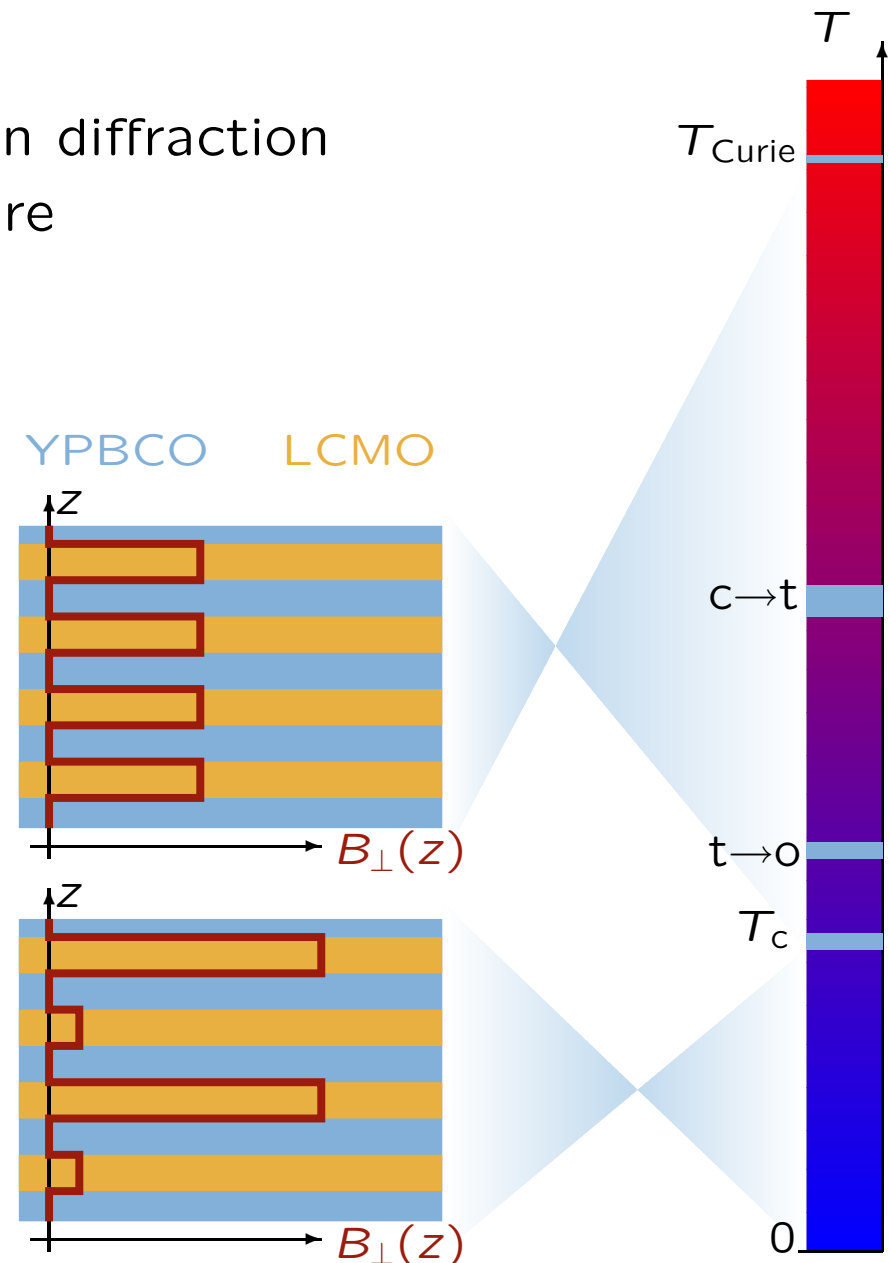
$$T < T_c$$

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

where sign changes each period

$\Rightarrow$ layerwise AFM on top of the FM

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



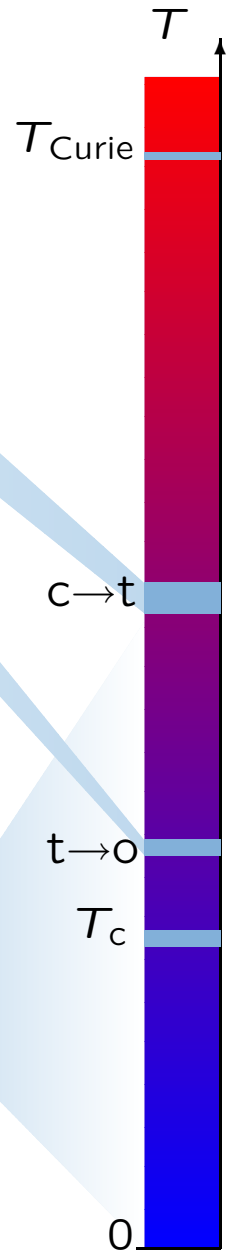
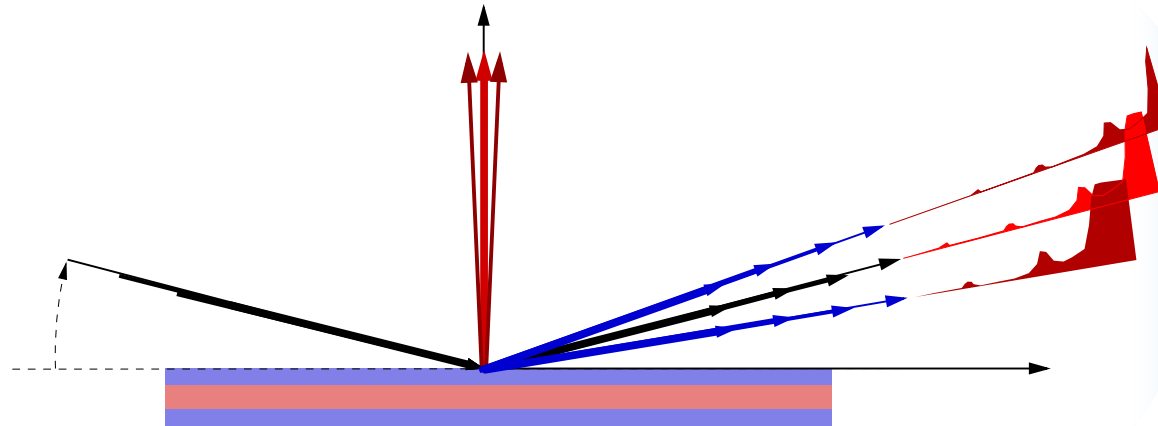
STO undergoes phase transitions

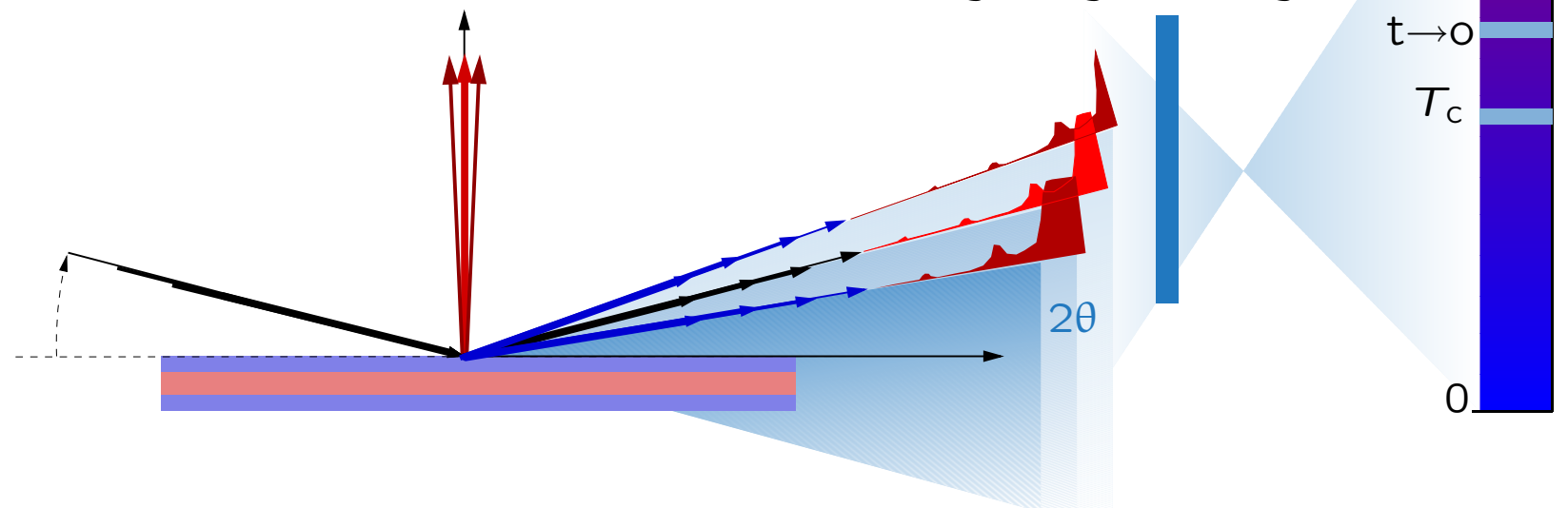
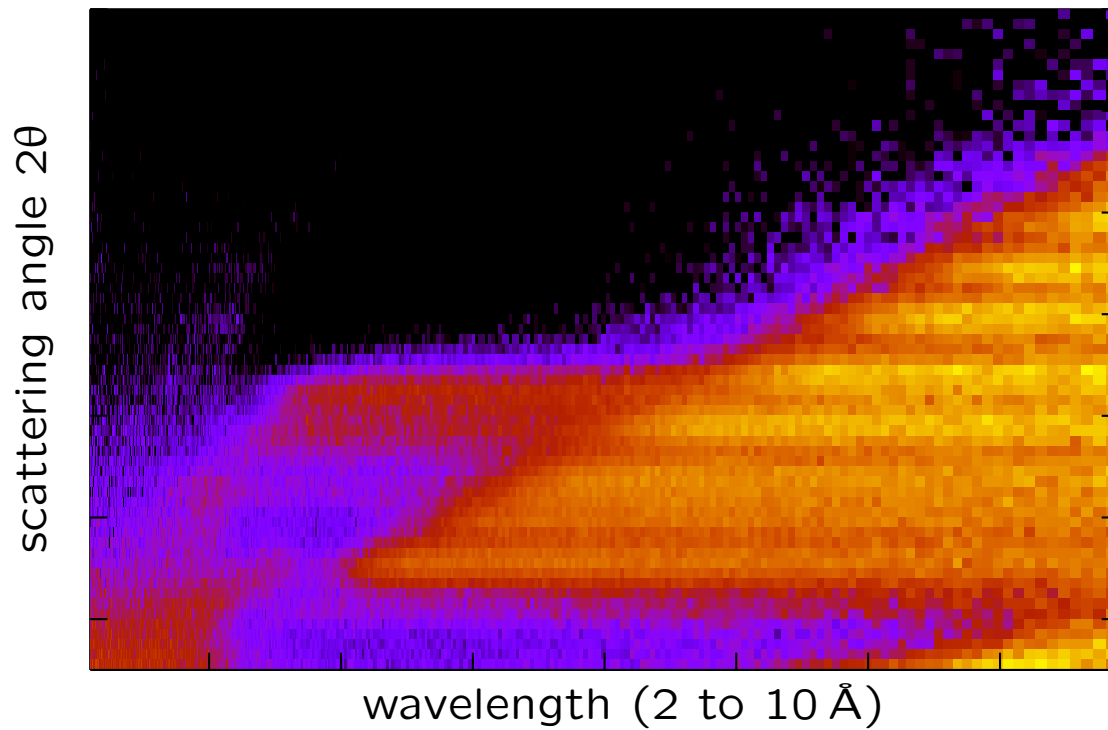
⇒ twinning, buckling of the surface

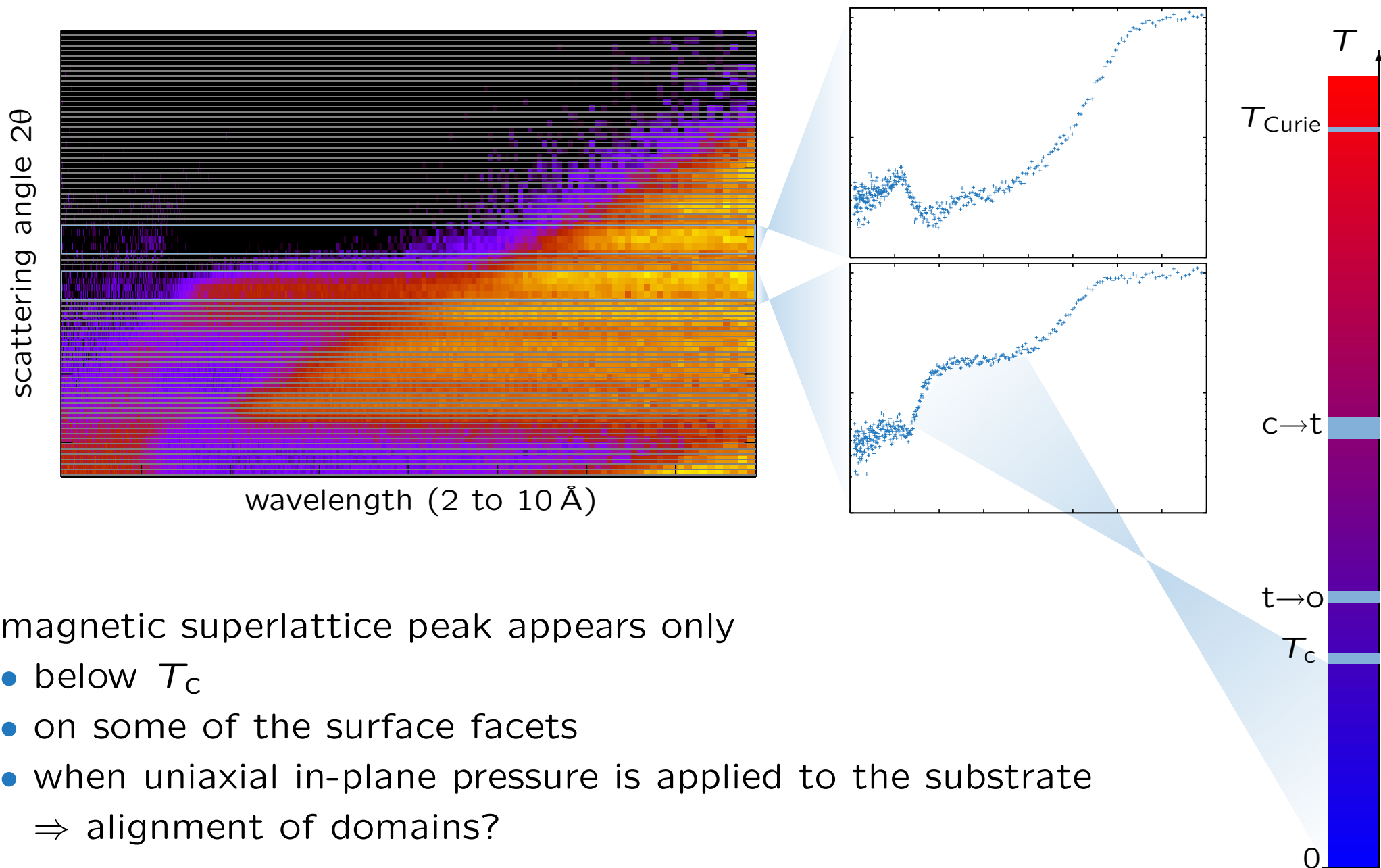
⇒ surface is fragmented into facets

⇒ varying angle of incidence over the sample

⇒ lots of specularly reflected beams





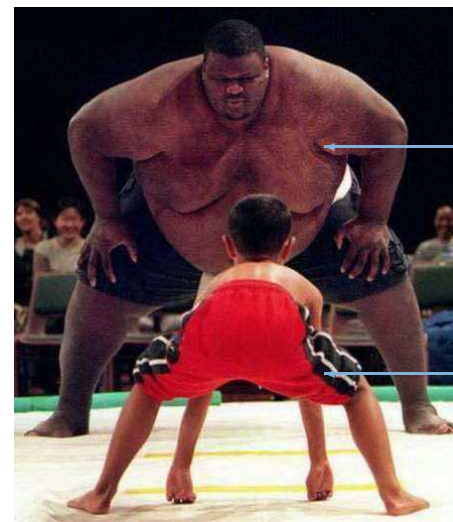


- LCMO has a complicated phase diagram and shows **phase separation** of structural and magnetic properties

$\left\{ \begin{array}{l} \text{strain} \\ \text{finite dimension in } z \\ \text{coupling to neighboring FM layers} \end{array} \right\}$ 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



if he is strained

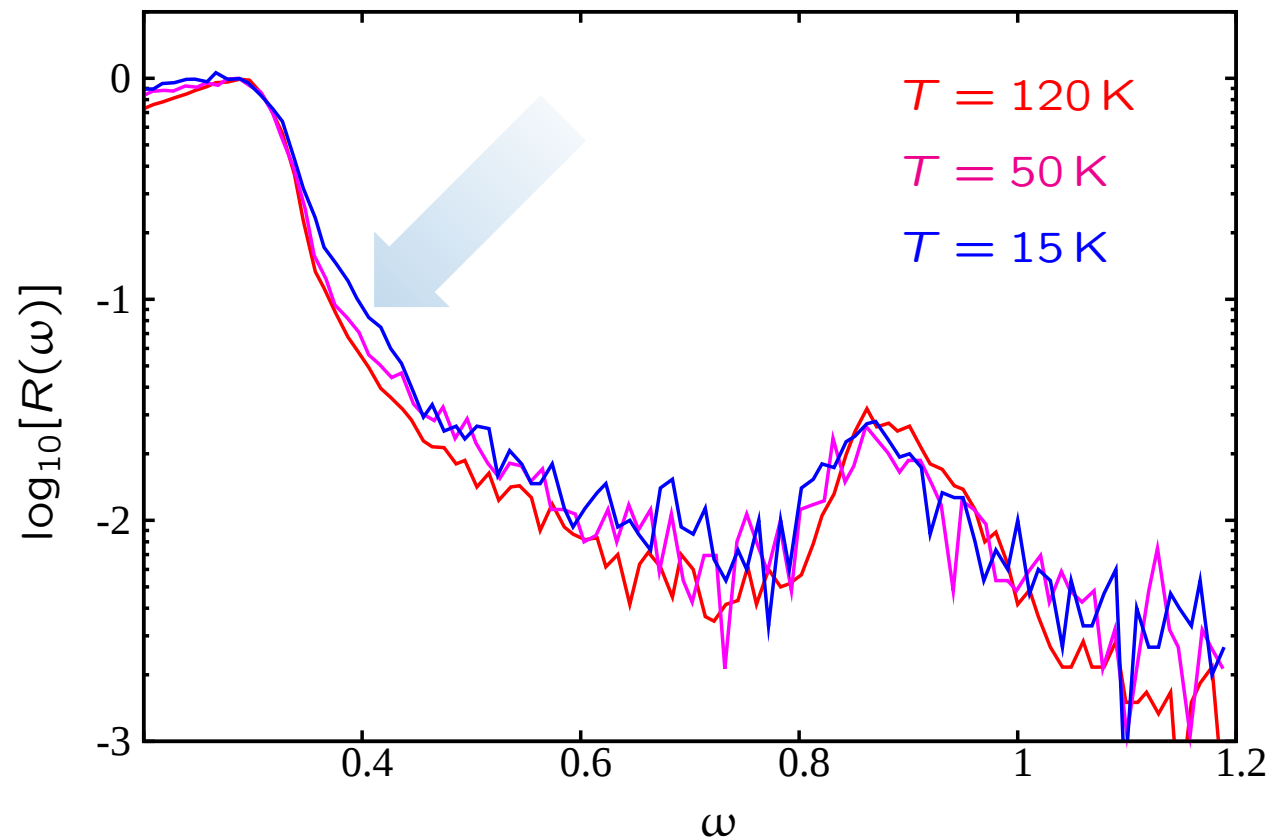
he can win!

STO shows eletrostriction

(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 $\mathbf{E}$?

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: $[\text{Y}_{1-x}\text{Pr}_x\text{Ba}_2\text{Cu}_3\text{O}_6/\text{La}_{2/3}\text{Ca}_{1/3}\text{MnO}_3]_{10}/\text{SrTiO}_3$
- 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

modulated FM in
LCMO only with
strained STO

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

