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

what happens at interfaces where

$\left.\begin{array}{r}\text{electronic} \\ \text{chemical} \\ \text{crystallographic} \\ \text{magnetic}\end{array}\right\}$ properties do not match?

SC and magnetism avoid each other
— unless forced together on an atomic scale

$\Rightarrow$ how do they arrange?

used system:
multilayers of the type

$$[\text{SC/FM}]_n/\text{STO}$$

grown by *pulsed laser doposition*
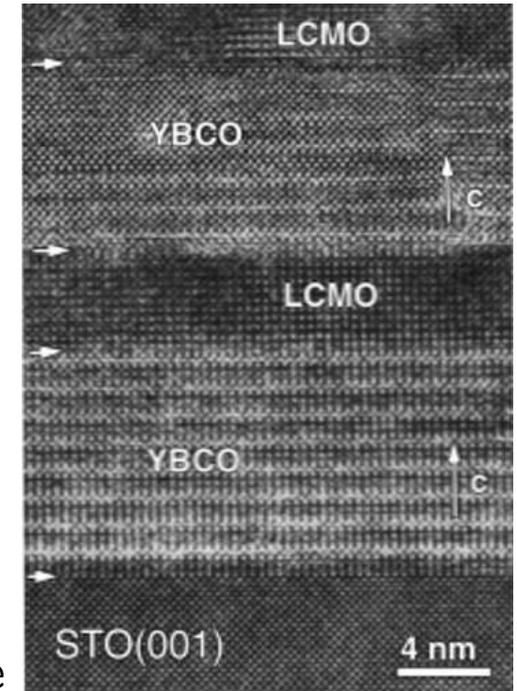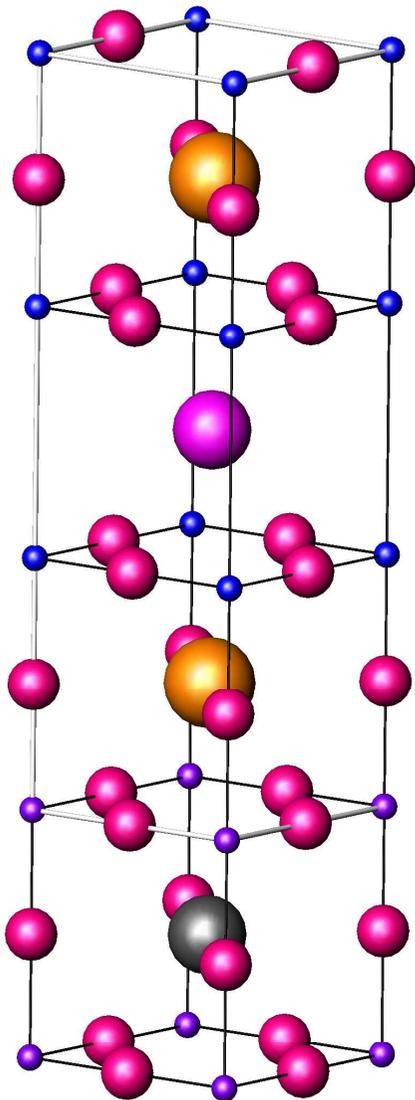
TEM image

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

Y
Pr

Cu

Ba

La
Ca   O

Mn
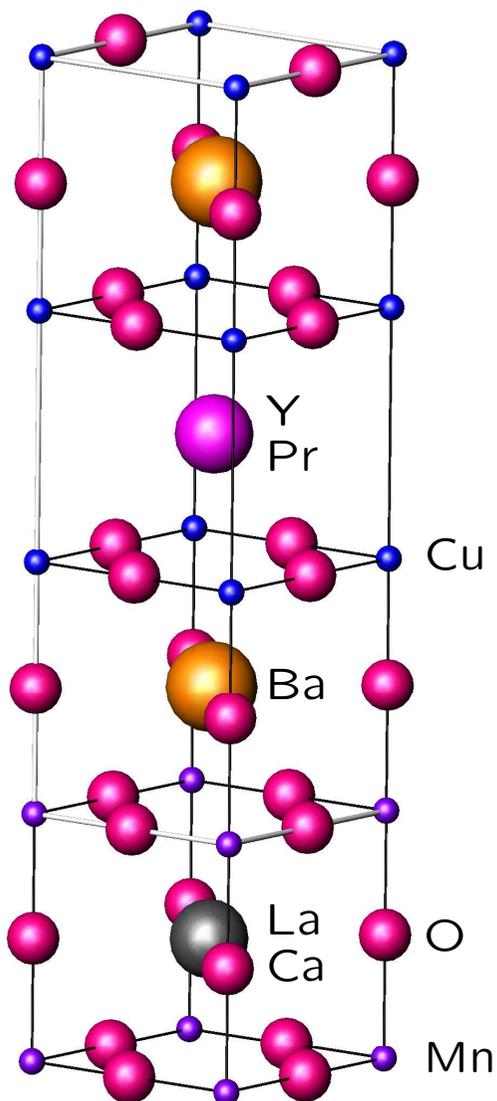
crystal types:
(close to) perovskite-like

T_{Curie}

pseudogap

T_c

AFM   SC   FL

carrier concentration in CuO planes

T

T_{Curie}

$c \rightarrow t$

$t \rightarrow o$

T_c

0
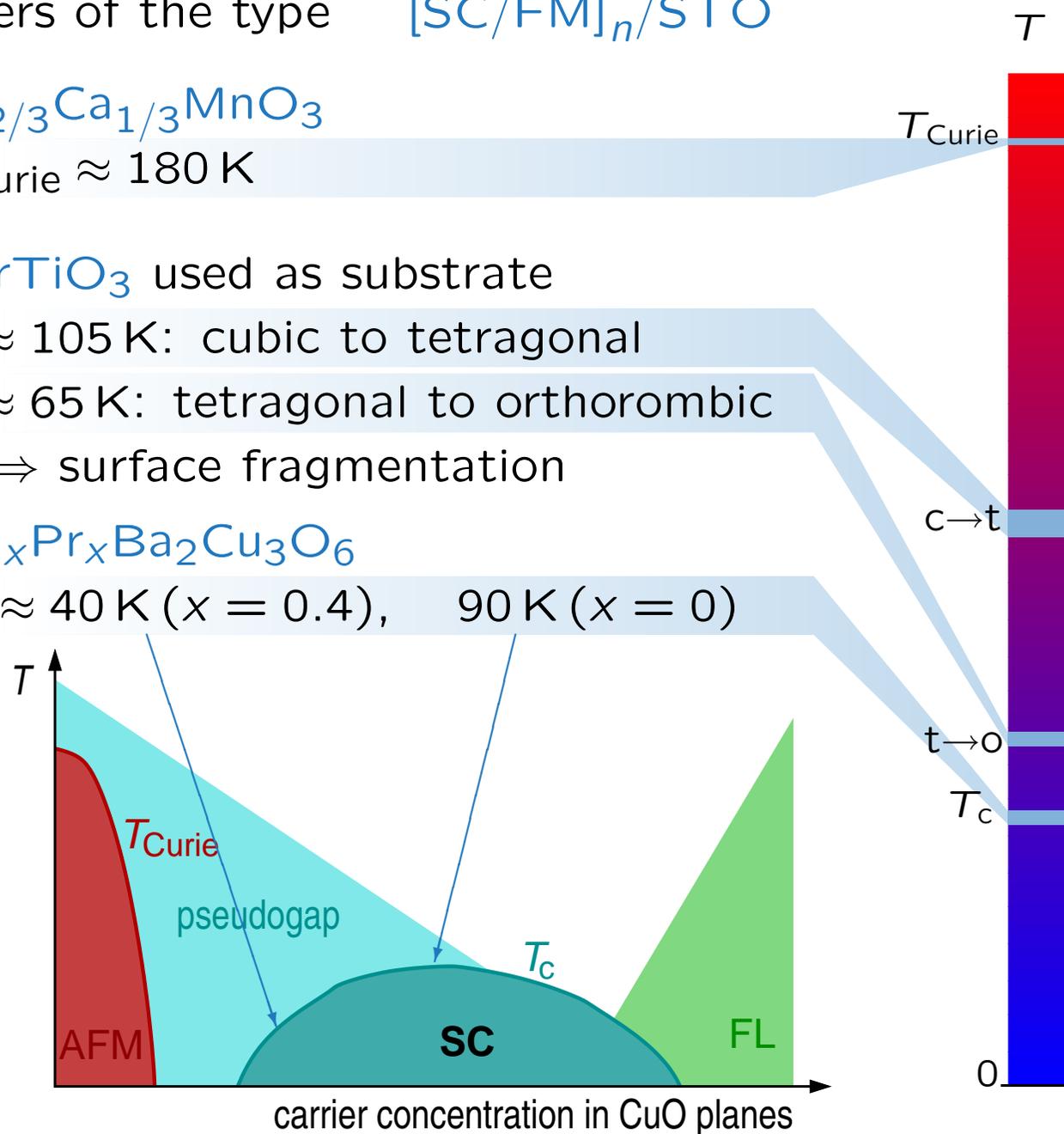
how does the magnetisation in the film look like?

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
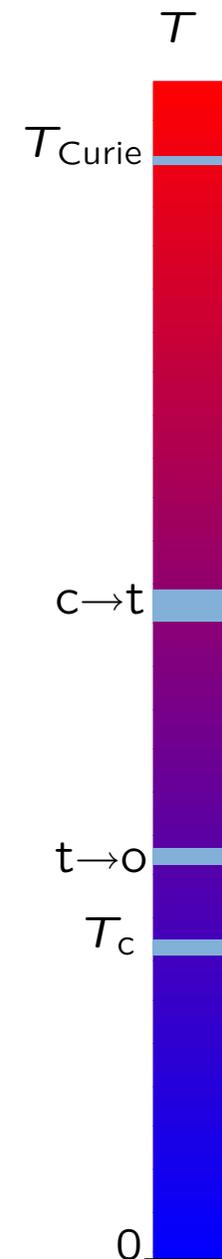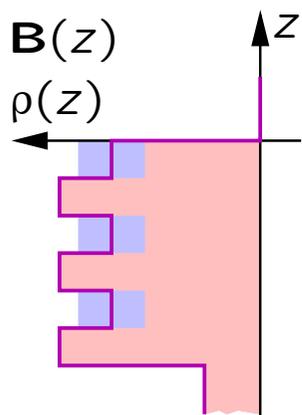
$\mathbf{B}(z)$
$\rho(z)$

T

T_{Curie}

c→t

t→o

T_{c}

0

index of refraction n (as for visible light:)

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

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

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

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

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

measured quantity:

intensity *vs.* normal momentum transfer q_z

q_z

z

$\delta = \delta_{\text{n}} \pm \delta_{\text{m}}$

period

substrate
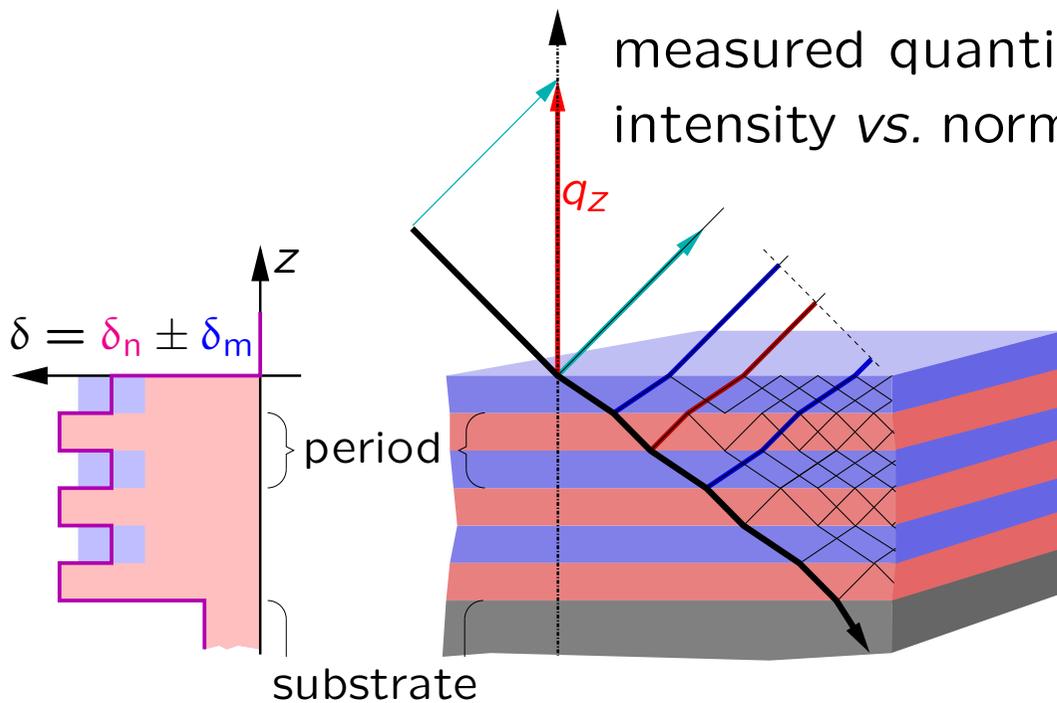
for parallel interfaces:

interference of (multiply)

reflected beams

index of refraction n (as for visible light:)

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

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

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

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

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

measured quantity:

intensity *vs.* normal momentum transfer q_z

$$\delta = \delta_{\text{n}} \pm \delta_{\text{m}}$$

period

substrate
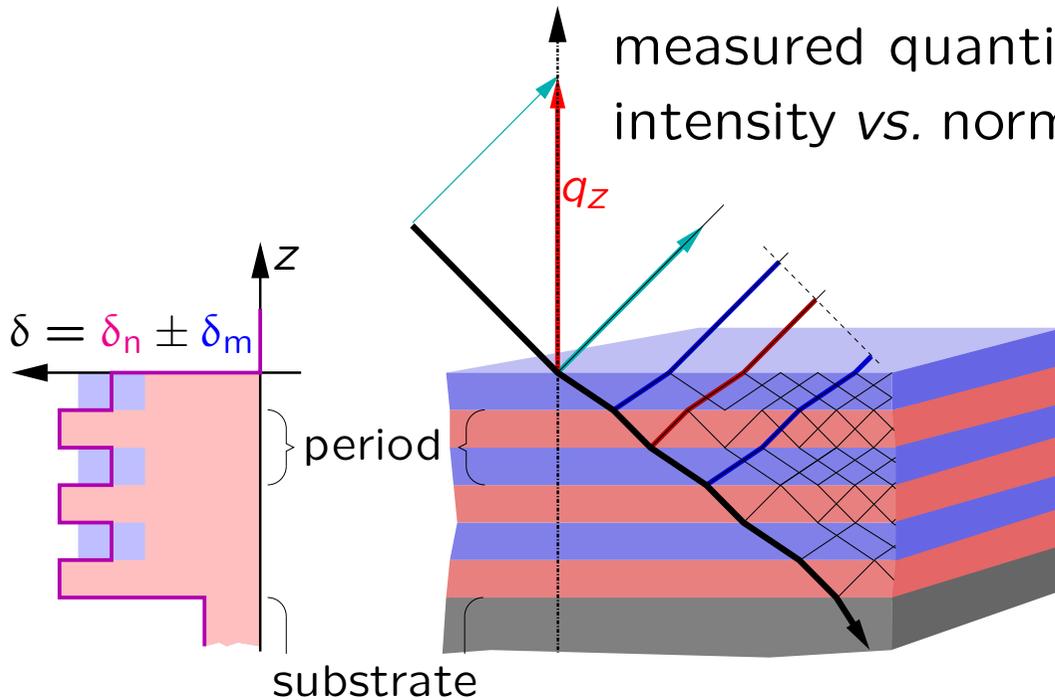
angle dispersive mode
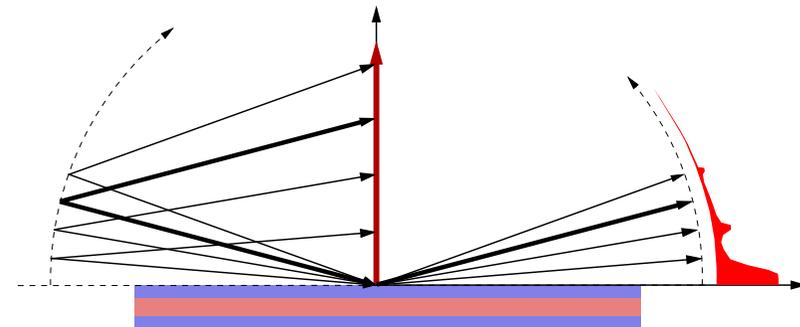
index of refraction n (as for visible light:)

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

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

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

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

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

measured quantity:

intensity *vs.* normal momentum transfer q_z

q_z

$\delta = \delta_\text{n} \pm \delta_\text{m}$

period

substrate
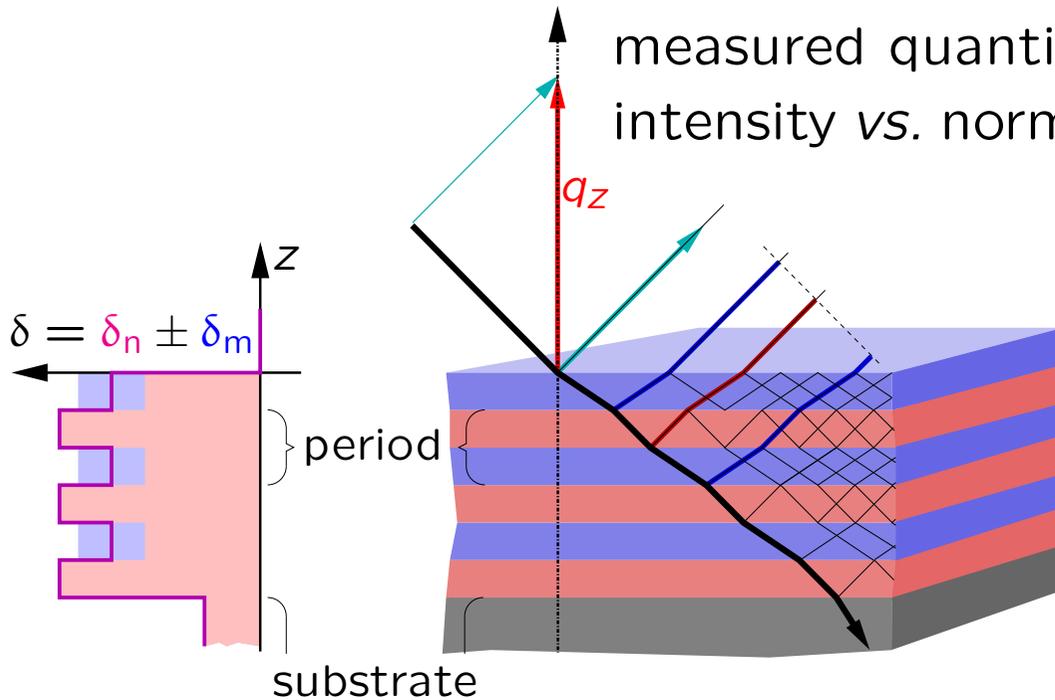
energy dispersive mode
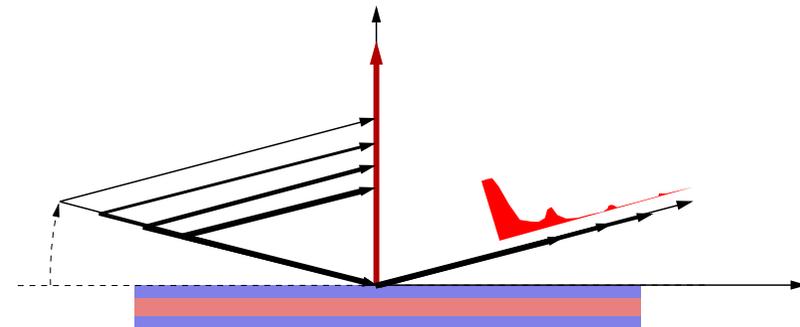
neutron reflectometer
AMOR
at SINQ, PSI

time-of-flight
spin polarisation

measured quantity:

intensity *vs.* normal momentum transfer q_z

q_z

z

$\delta = \delta_n \pm \delta_m$

period

substrate

energy dispersive mode

substrate

measured quantity:

intensity *vs.* normal momentum transfer q_z

q_z

$\delta = \delta_n \pm \delta_m$

z

period

substrate
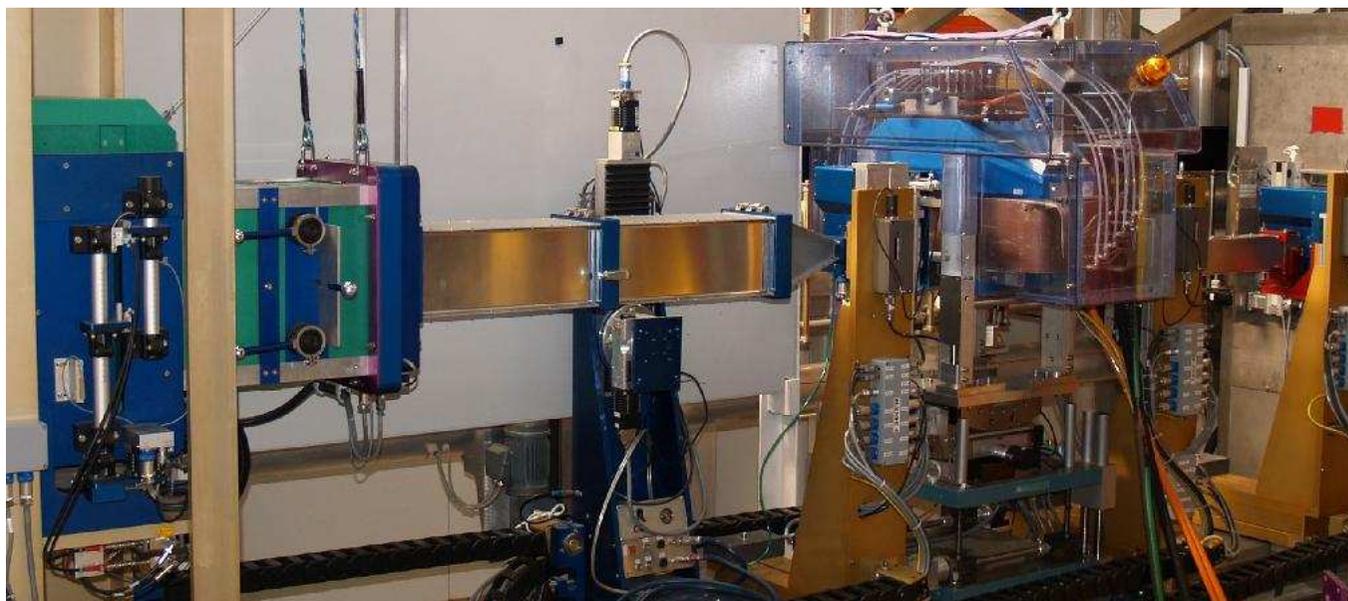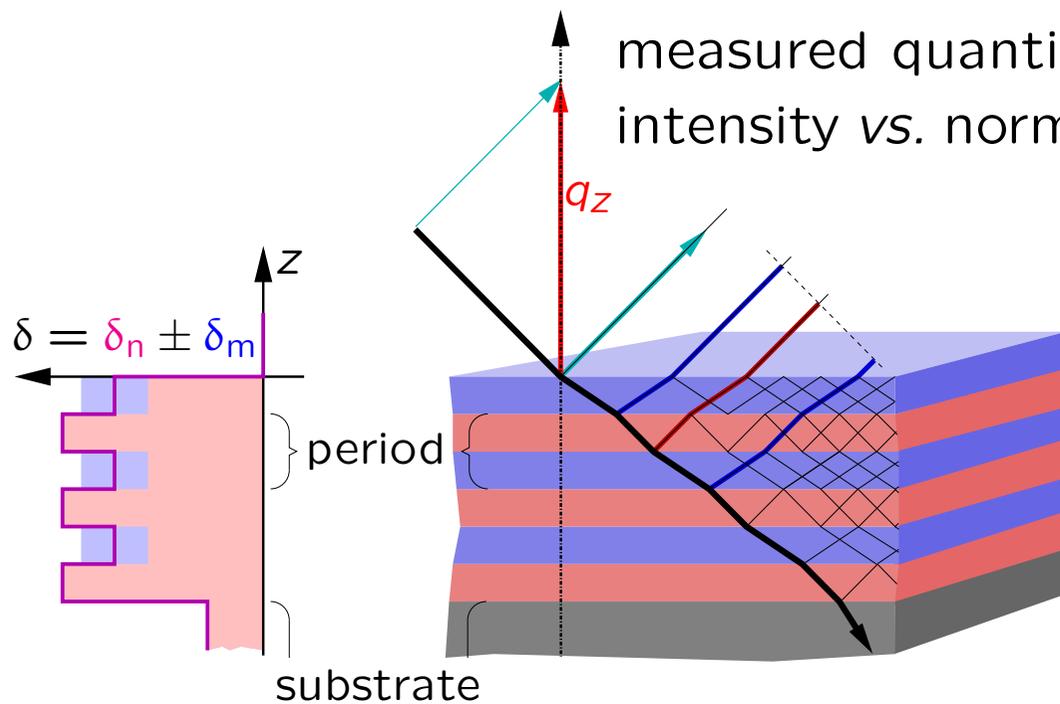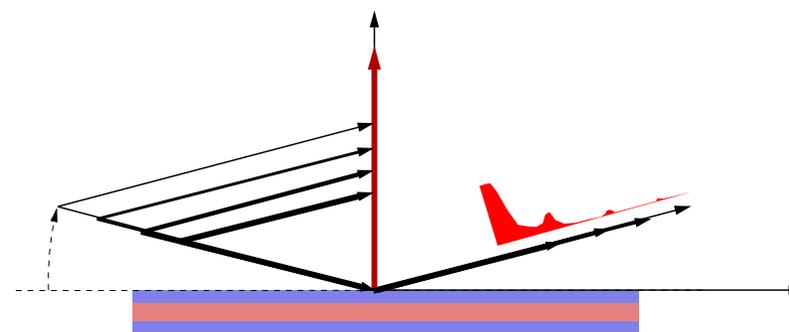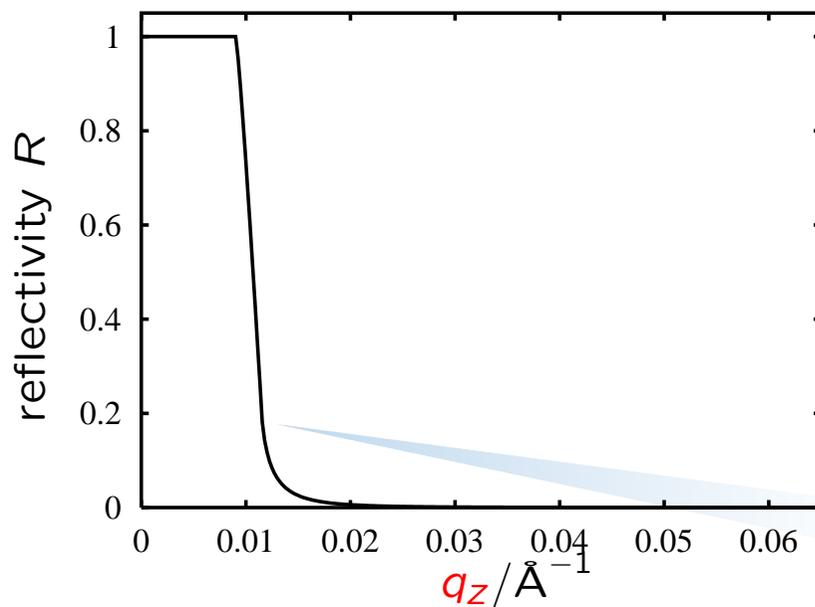
energy dispersive mode

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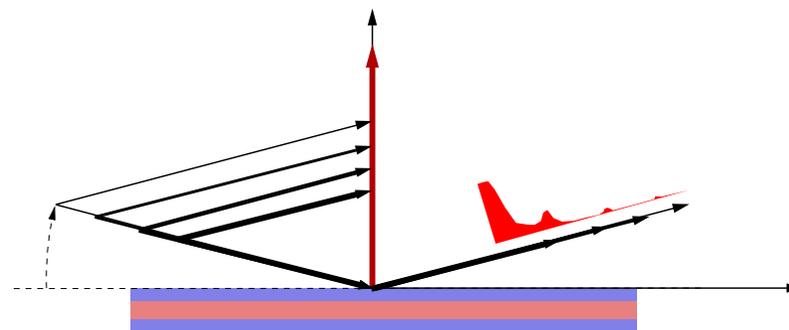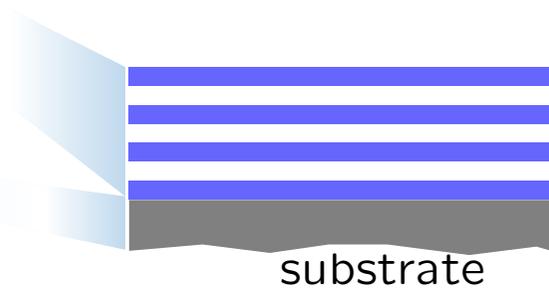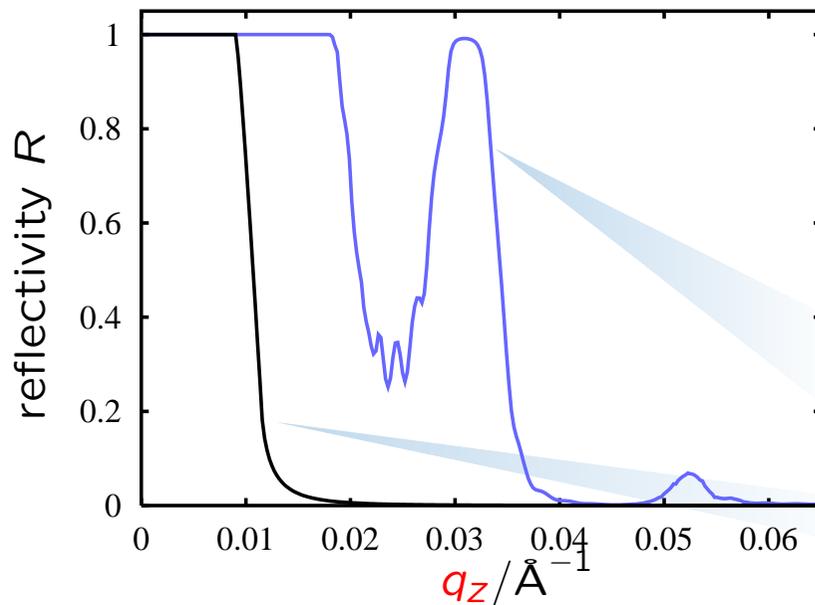
intensity *vs.* normal momentum transfer q_z

$\delta = \delta_n \pm \delta_m$

energy dispersive mode

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PSI & **ETH** Zurich
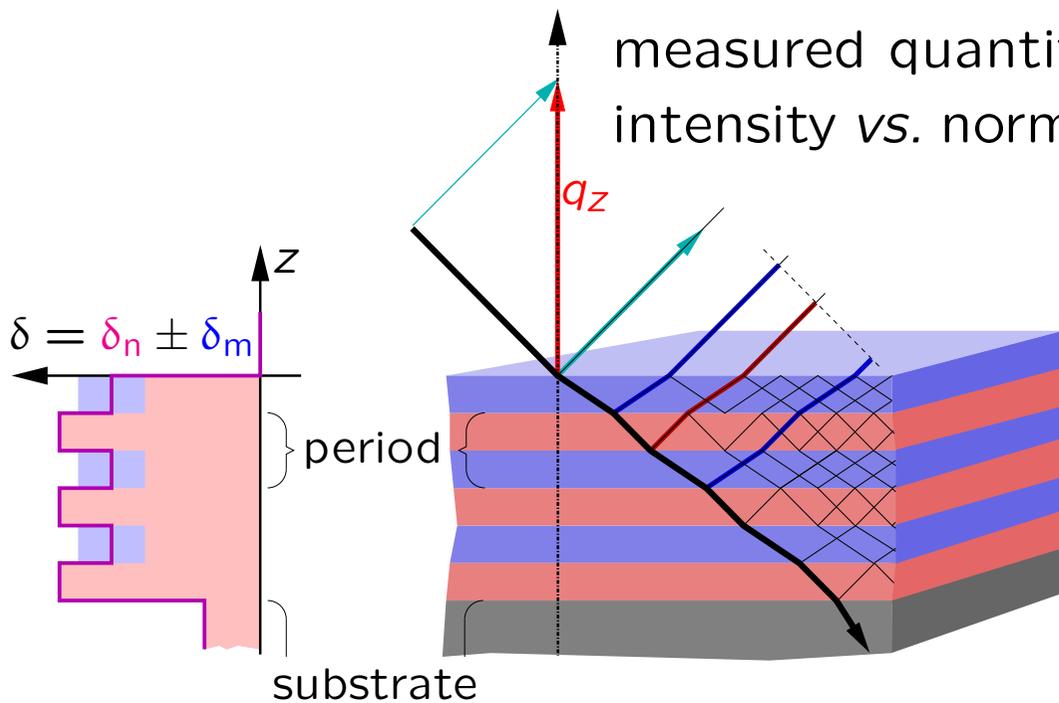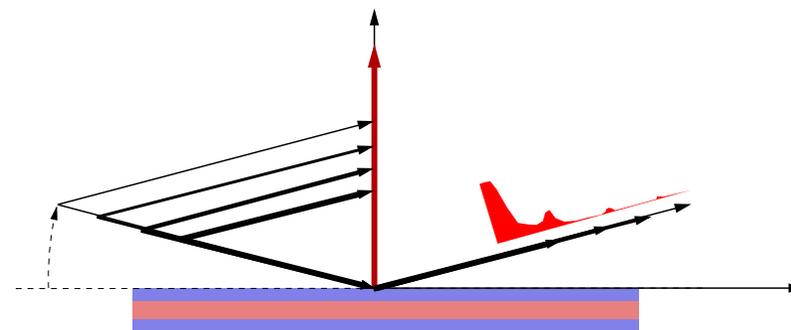
T dependence of $R(\omega)$ for an ML with underdoped SC

field cooled and measured in $H = 100\,\mathrm{Oe}$
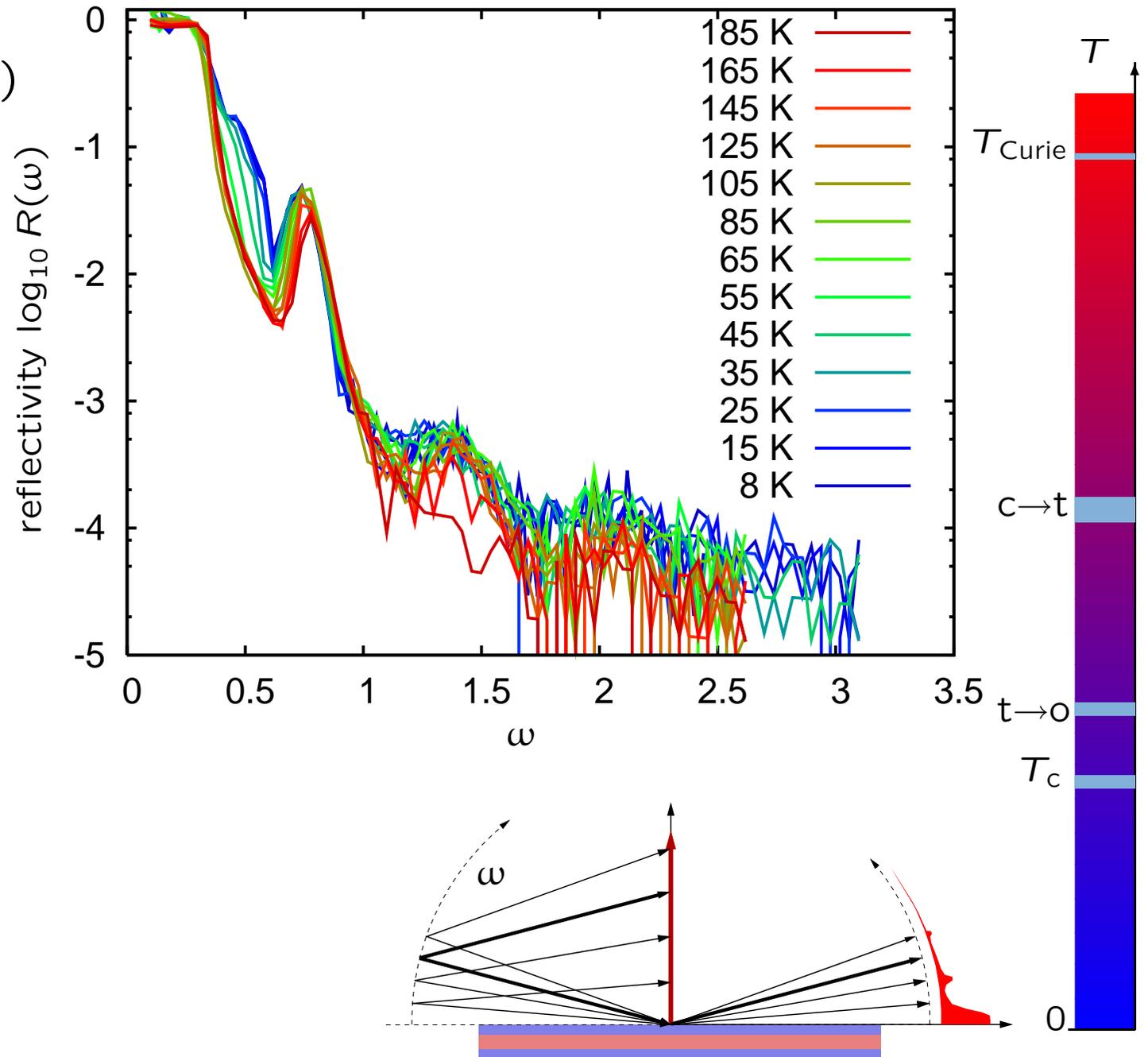
T dependence of $R(\omega)$ for an ML with underdoped SC

new peak below T_c

1st Bragg peak displays increasing B

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

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PSI   &   ETH Zurich
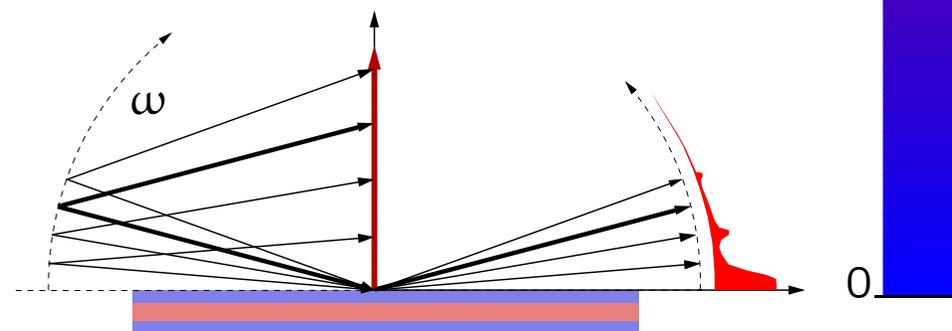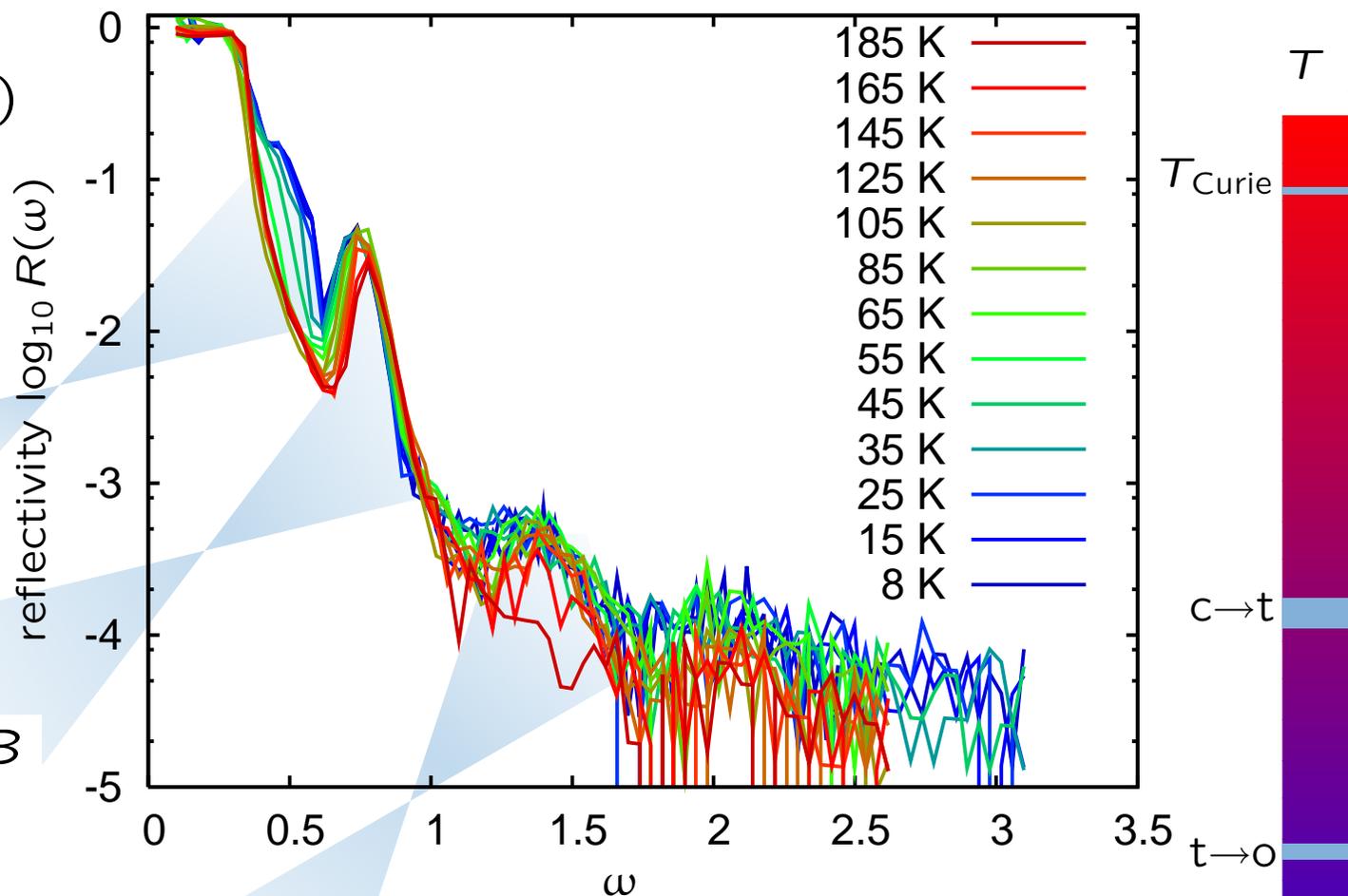
T dependence of $R(\omega)$ for an ML with underdoped SC
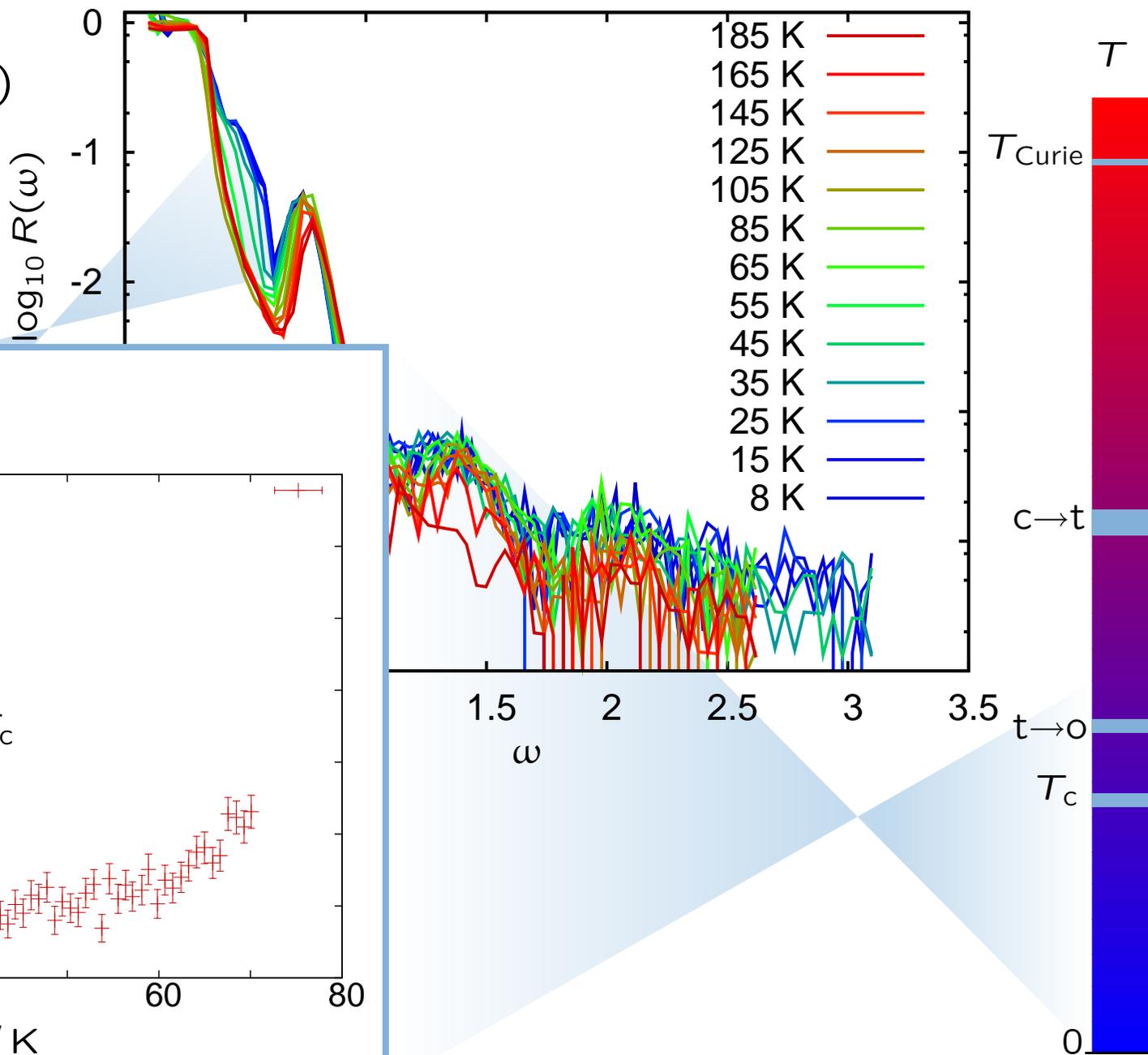
new peak below T_{c}
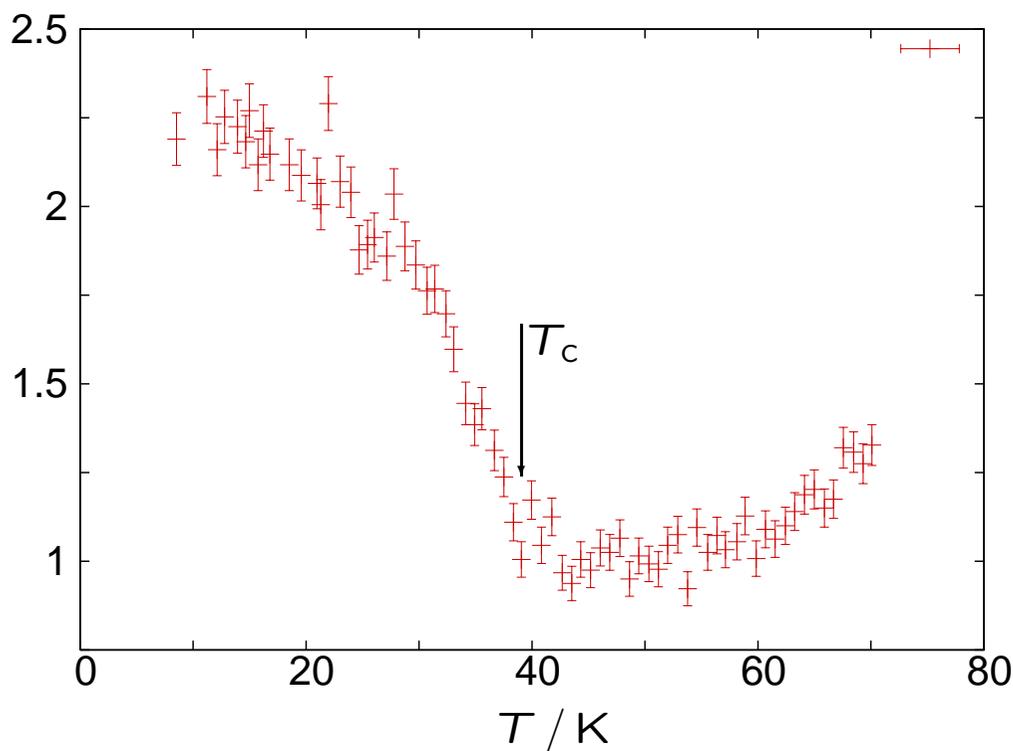
magnetic peak

  comparable to a fractional Bragg peak in diffraction

  indication for a (magnetic) superstructure

model assumpton:

  $T_c < T < T_{Curie}$
  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: $2.1 \pm 1.9\,\mu_B$

YPBCO   LCMO

z

$B_\perp(z)$

z

$B_\perp(z)$

T

T_{Curie}

c→t

t→o

T_c

0
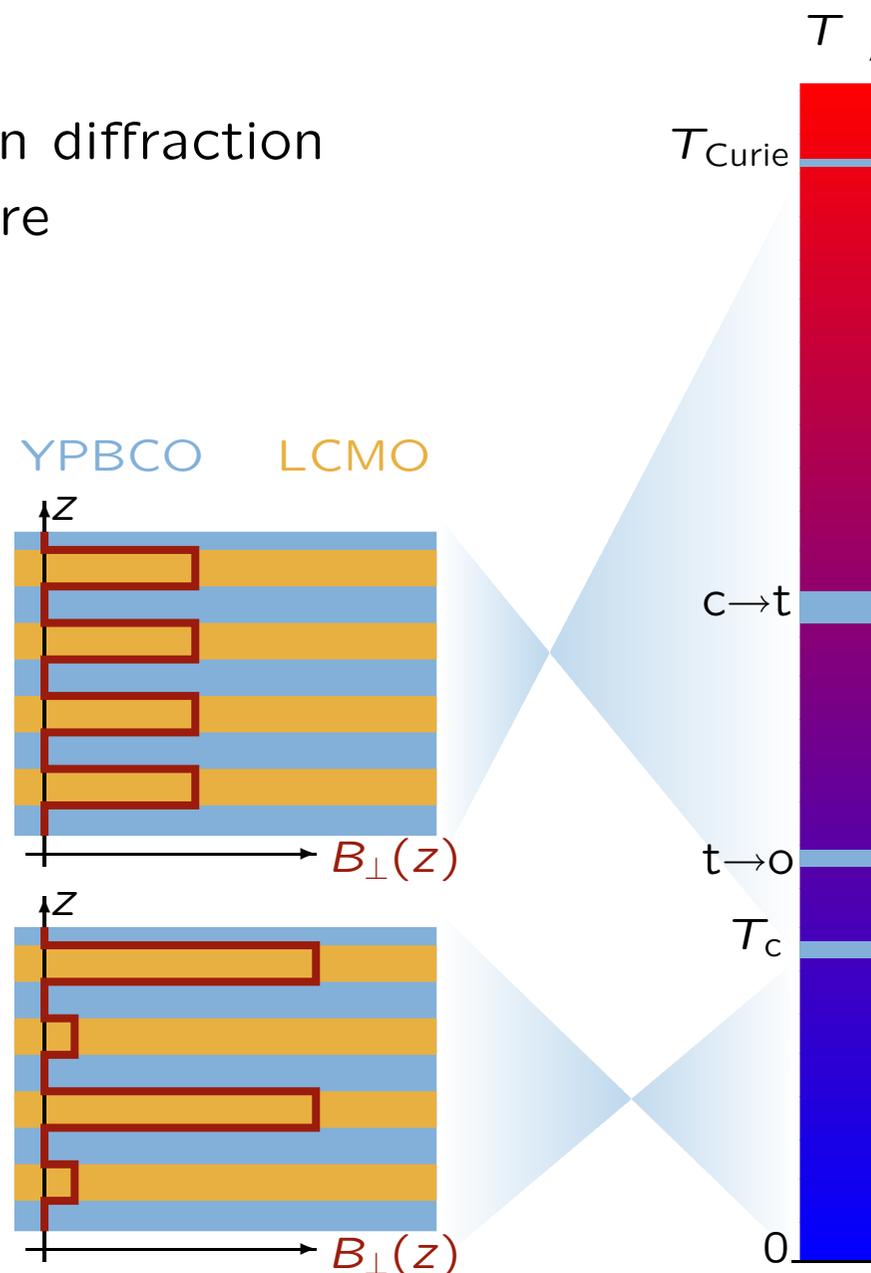
STO undergoes phase transitions

$\Rightarrow$ twinning, buckling of the surface

$\Rightarrow$ surface is fragmented into facets

$\Rightarrow$ varying angle of incidence over the sample

$\Rightarrow$ lots of specularly reflected beams

scattering angle 2θ

wavelength (2 to 10 Å)

area detector to cover
large angular range

2θ

T

T_{Curie}

c→t

t→o

T_{c}

0

scattering angle 2θ

wavelength (2 to 10 Å)

T

T_{Curie}

c→t

t→o

T_{c}

0

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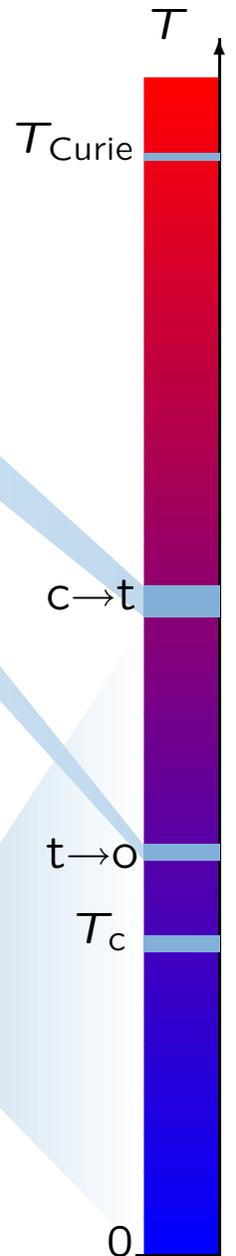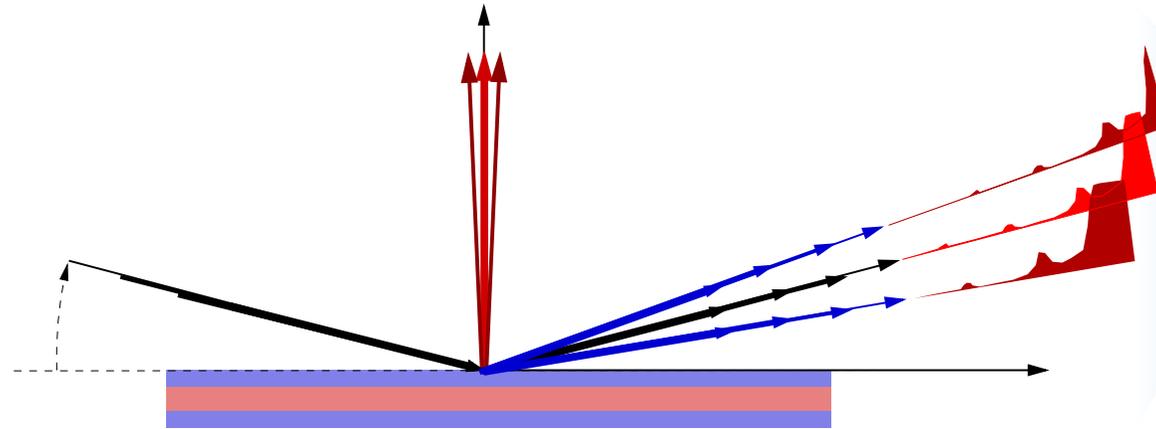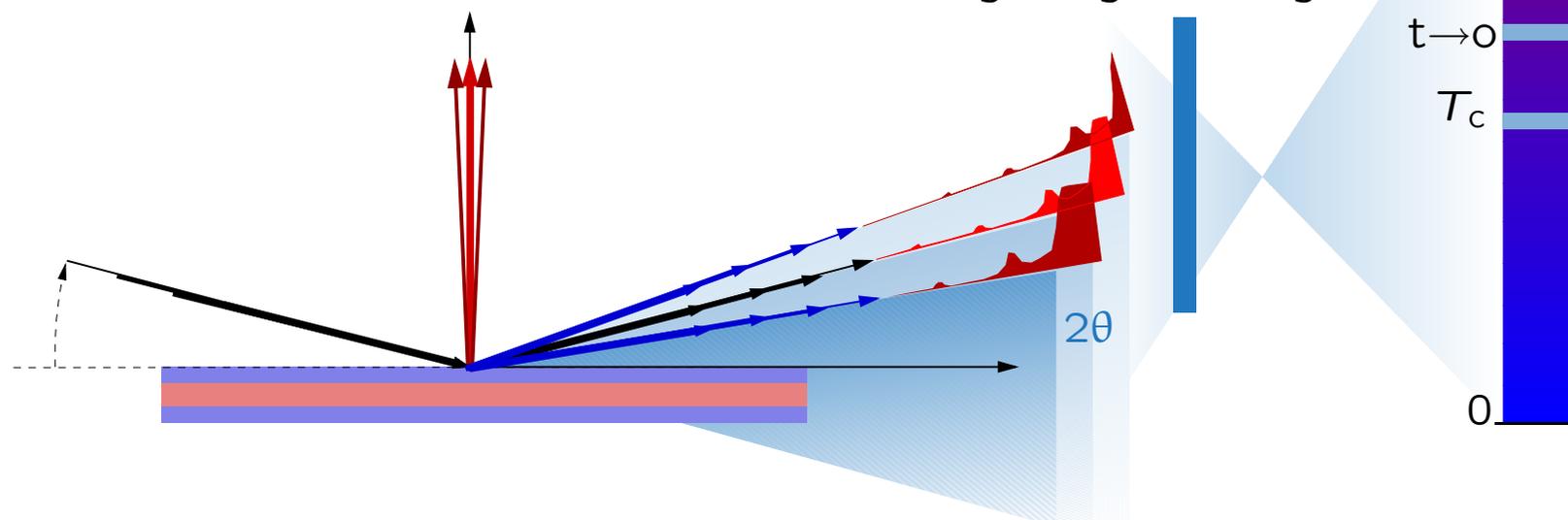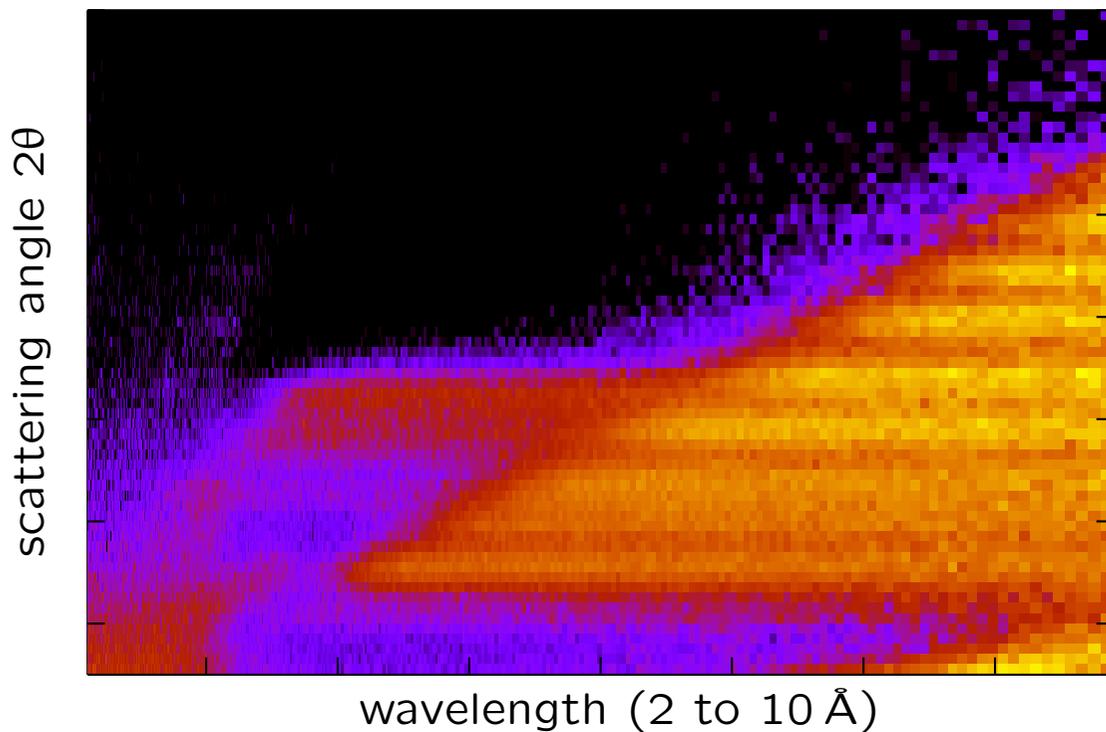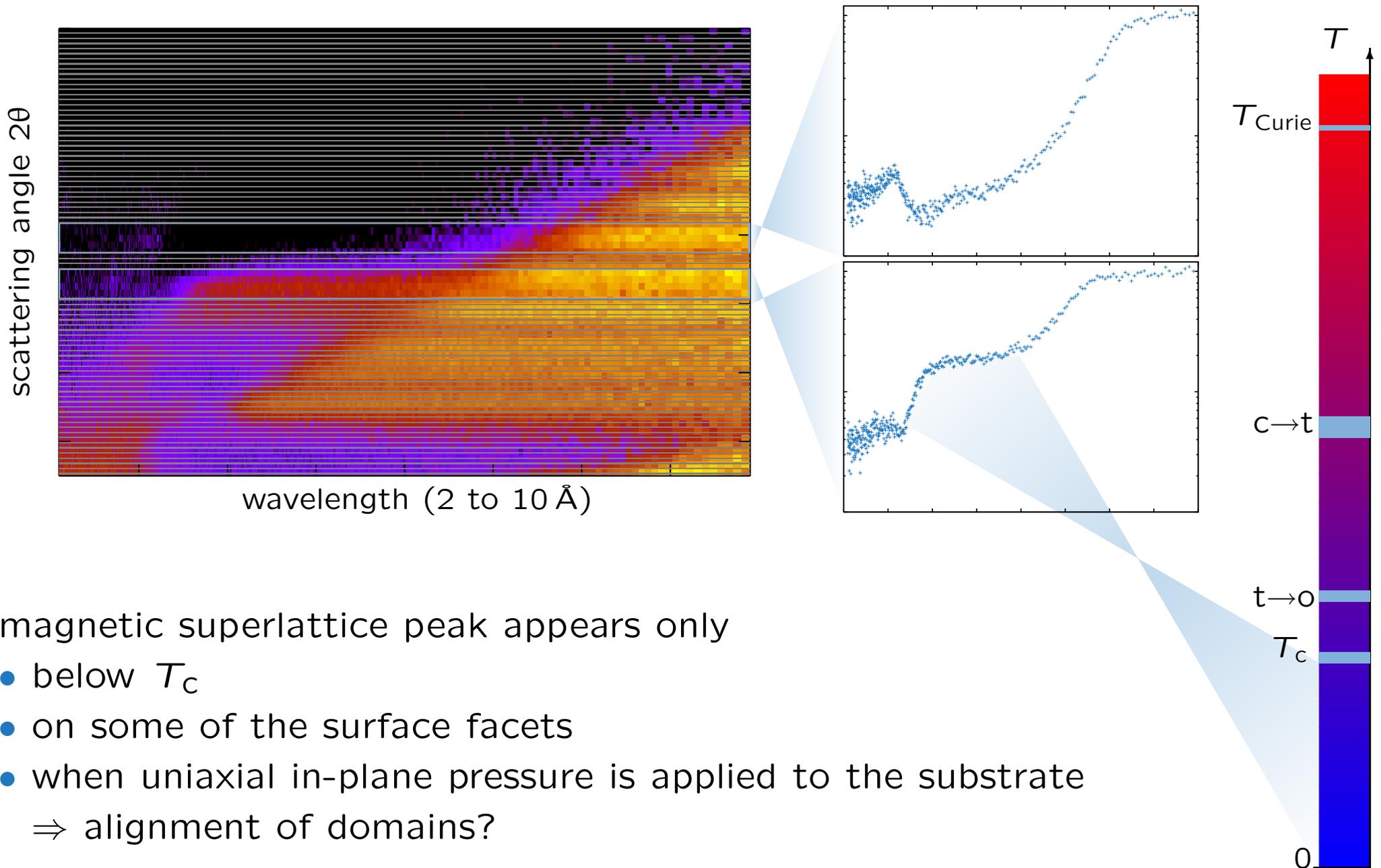
- **LCMO** has a complicated phase diagram and
  shows phase separation of structural and magnetic properties

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

STO shows eletrostriction   (lattice is distorted by an external **E** field)

$\Rightarrow$ strain is induced by **E**   (and not by uniaxial pressure)

first result with $E = 160\,\text{V/mm}$:
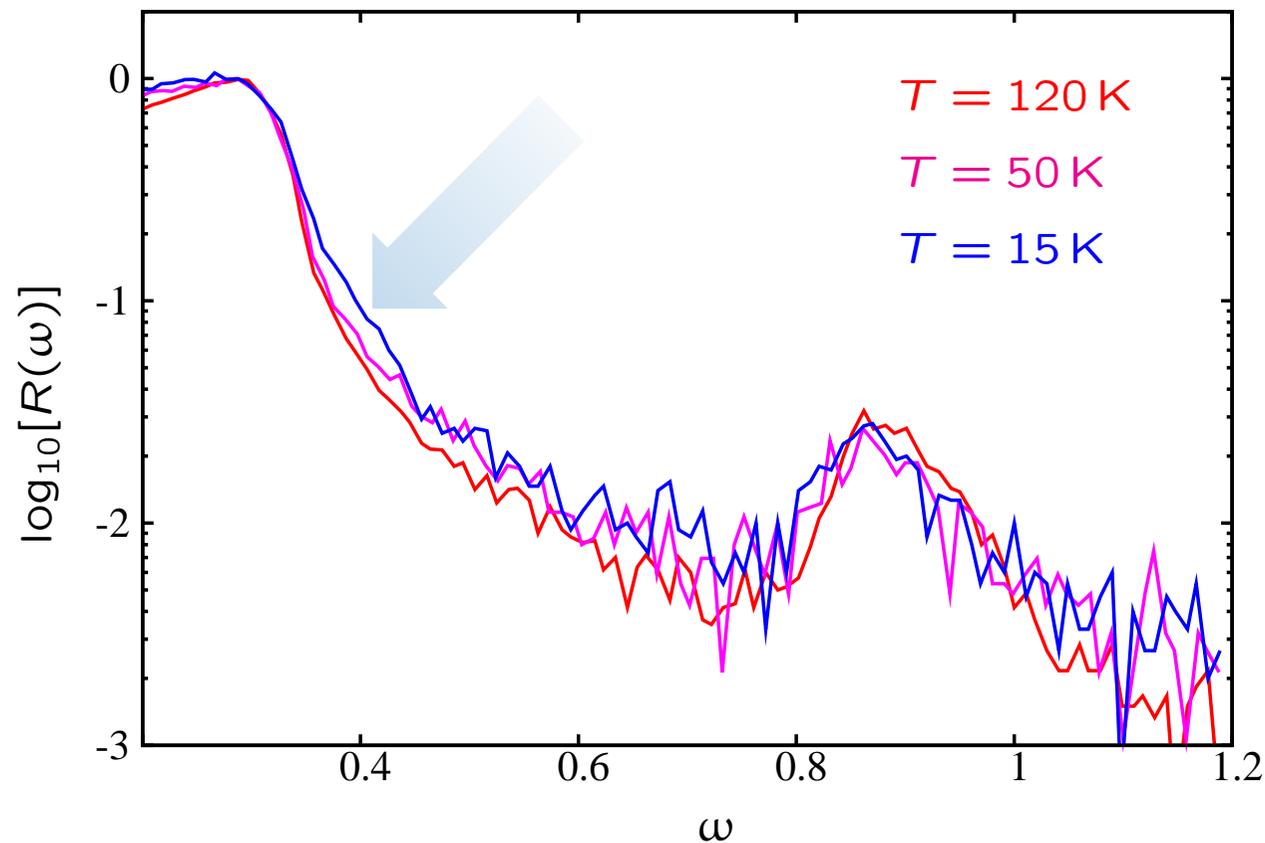
can we switch $\Delta\mathbf{B}$ with $\mathbf{E}$?

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 Dalgliesh	(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 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

modulated FM in
LCMO only with
strained STO

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