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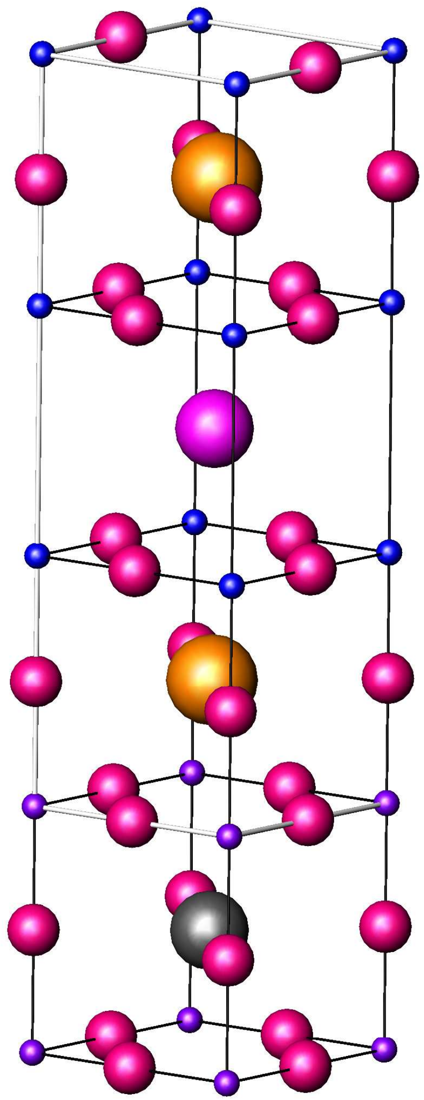
Giant superconductivity-induced modulation of the ferromagnetic magnetization in a cuprate-manganite superlattice

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

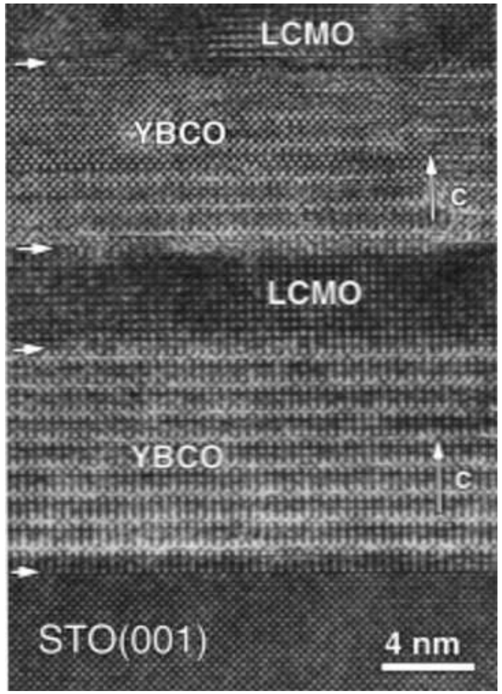
— unless forced together on an atomic scale

$\Rightarrow$ how do they arrange?

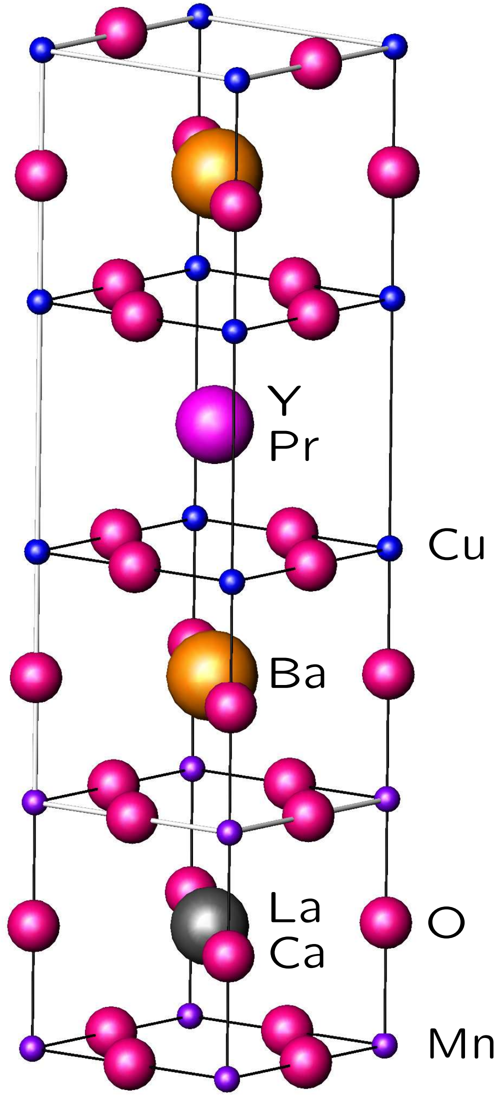
used system:
multilayers of the type

$[SC/FM]_n/STO$

grown by *pulsed laser doposition*



TEM image



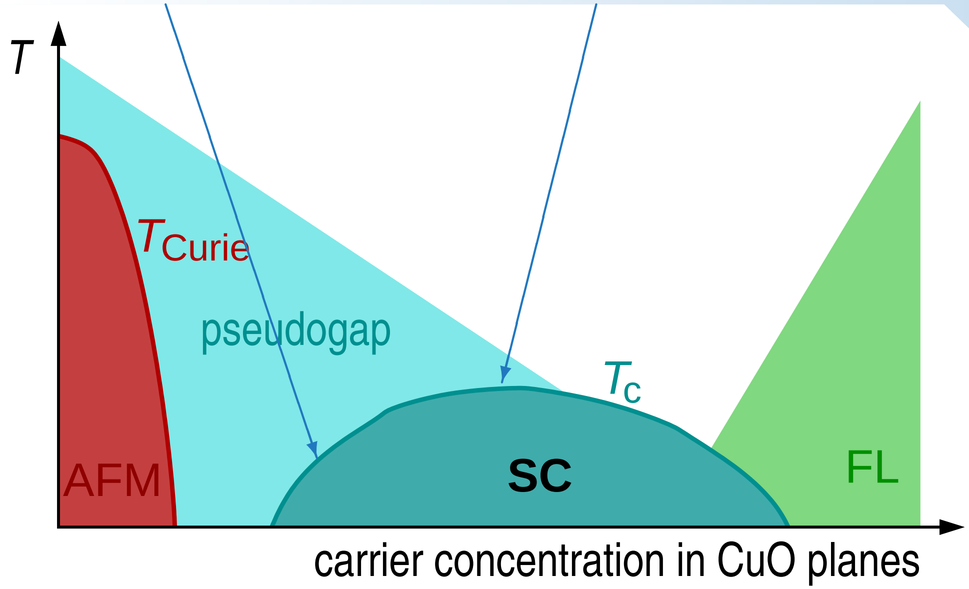
crystal types:
(close to) perovskite-like

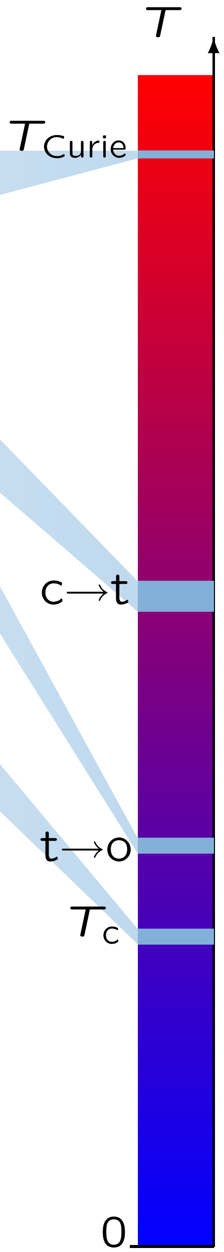
multilayers of the type $[SC/FM]_n/STO$

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 $\mathbf{B}(z)$

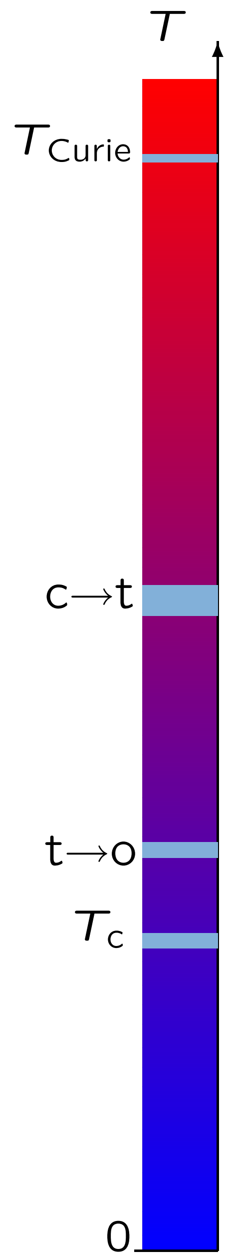
$\Rightarrow$ need for a method to probe $\mathbf{B}(z)$ and $\rho(z)$

– with $0 < z < 200\,\text{nm}$
$\Delta z < 1\,\text{nm}$

– in the range $10\,\text{K} < T < 200\,\text{K}$

– in a magnetic field $H < 1000\,\text{Oe}$

$\rightarrow$ polarised neutron reflectometry



basis: *index of refraction* varies at the interface

$$n = k/k_0$$

$$\left| \begin{array}{ll} k & = 2\pi/\lambda \propto \sqrt{E - V} \\ E & \text{total energy} \\ V & \text{potential} \end{array} \right.$$

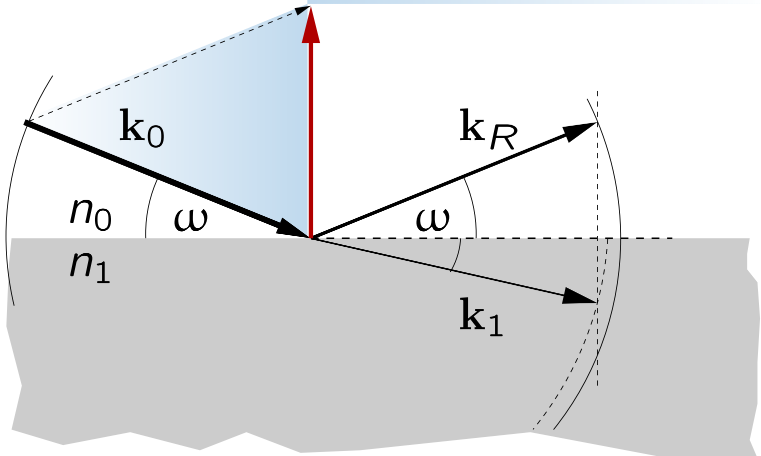
$$= \sqrt{1 - V/E}$$

$$\approx 1 - V/2E$$

$$= 1 - \delta$$

$$q_z = \mathbf{k}_R - \mathbf{k}_0$$

momentum transfer



$$q^c \propto \sqrt{\delta}/\lambda$$

$$r(q_z) = \frac{1 - \sqrt{1 - (q^c/q_z)^2}}{1 + \sqrt{1 - (q^c/q_z)^2}}$$

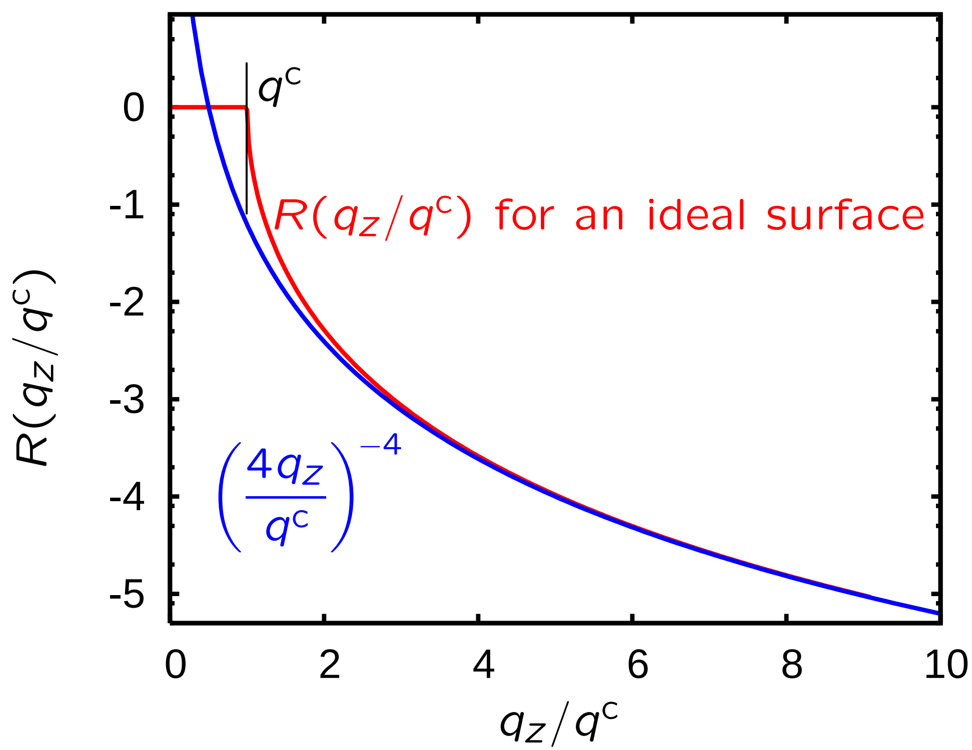
$$R^F(q_z) = |r(q_z)|^2$$

$$\propto q_z^{-4} \quad \text{for } q_z > 3q^c$$

case with one interface:

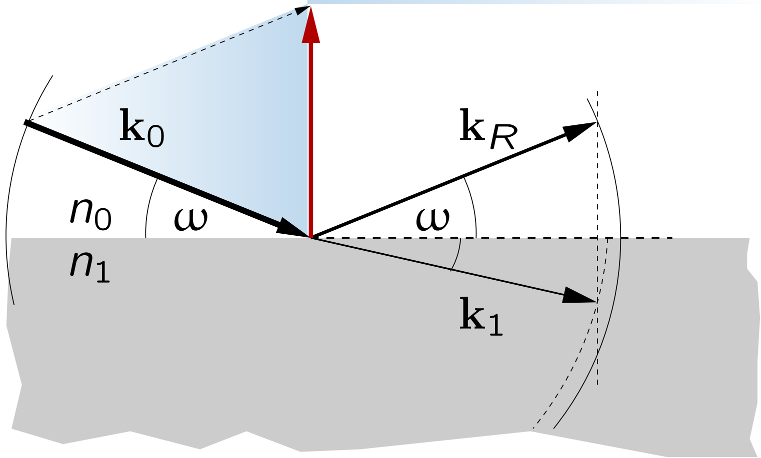
total reflection R for $q_z < q^c$

partial reflection R for $q_z > q^c$



$q_z = \mathbf{k}_R - \mathbf{k}_0$

momentum transfer



Fresnel reflectivity

$$R^F(q_z) = |r(q_z)|^2$$

$$\propto q_z^{-4} \quad \text{for } q_z > 3q^c$$

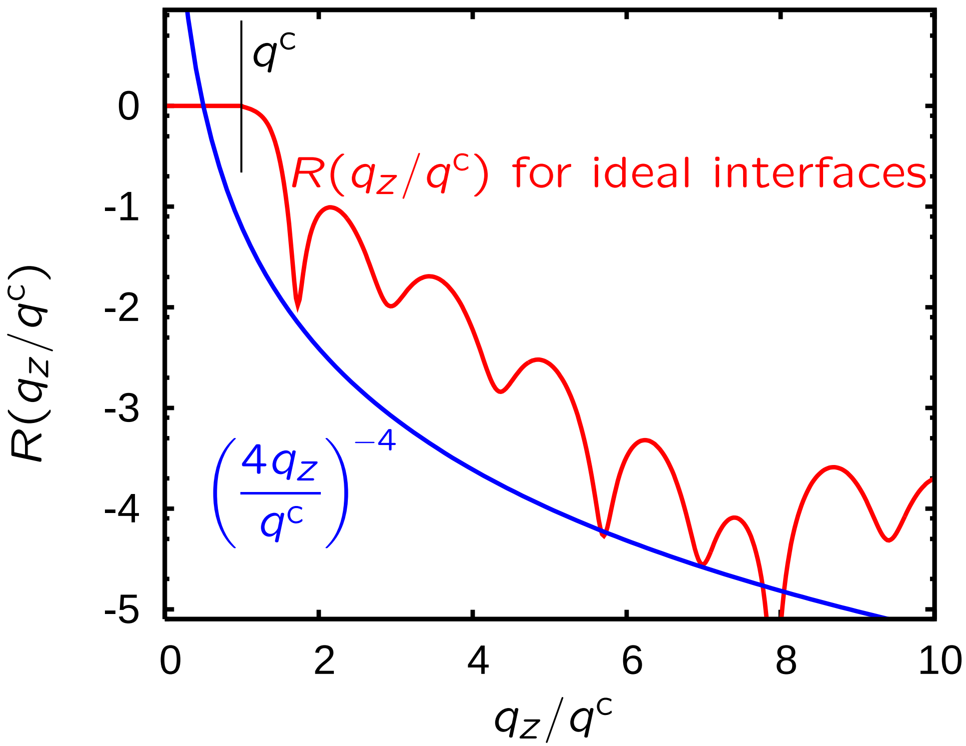
case with several parallel interfaces:

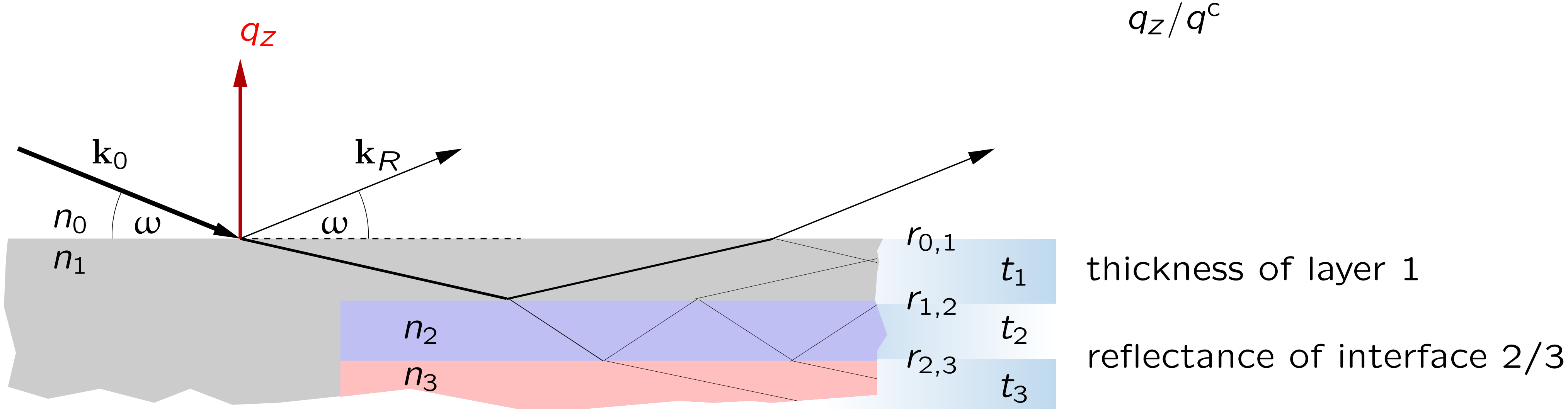
$\Rightarrow$ interference of all waves

– $r_{i,j}$ defines amplitude
– t_i adds a phase

kinematic theory
($q_z \gg q^c$, weak interaction):

$$R(q_z)/R^F(q_z) \propto |\mathcal{F}[\delta(z)]_{q_z}|^2$$



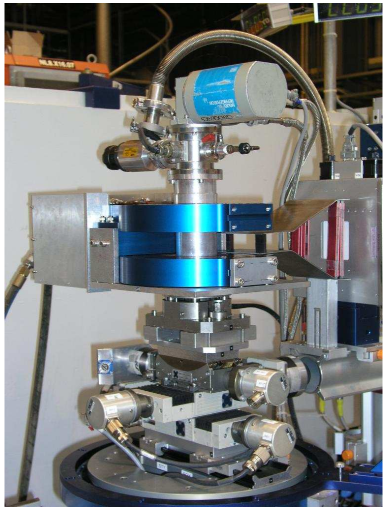


some properties and the consequences:

no charge

– no interaction with electric fields / electron density

$\Rightarrow$ high transmission ($>$ 100 mm Al or Si)



spin 1/2

– potential energy depends on magnetic environment

$\Rightarrow$ polarisable in external magnetic field

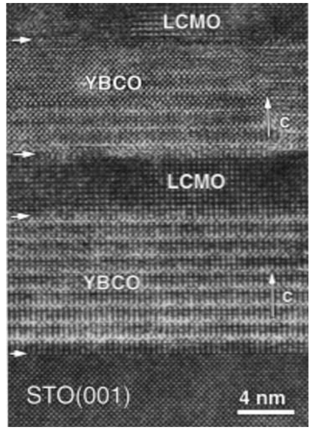
$\Rightarrow$ probe of local magnetic fields

$\Rightarrow$ spin-flip analysis

interaction with nuclei

– isotope dependent

$\Rightarrow$ isotope contrast to highlight / hide phenomena



low kinetic energy

– $1\,\text{Å} < \lambda < 20\,\text{Å}$

$\Rightarrow$ atomic to molecular dimensions

– energy in the range of kristal excitations and diffusion activation

index of refraction n

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

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

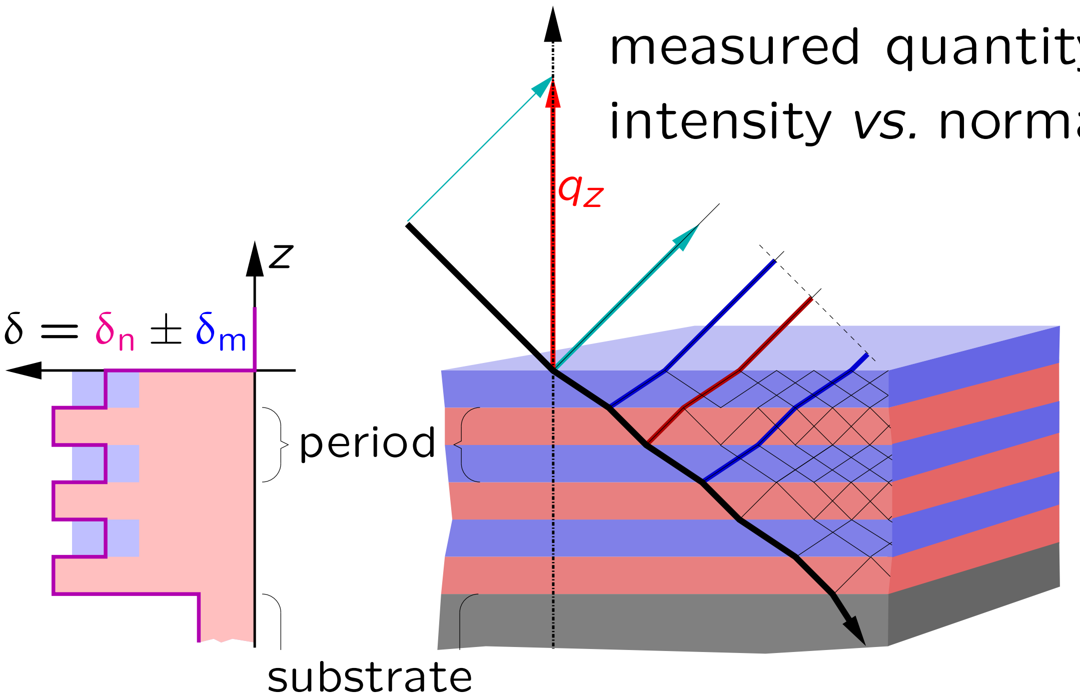
$$\delta_{\text{magnetic}} \propto \boldsymbol{\mu}_{\text{n}} \, \mathbf{B}_{\perp}$$

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

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

measured quantity:

intensity *vs.* normal momentum transfer q_z



for parallel interfaces:

interference of (multiply) reflected beams

index of refraction n

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

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

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

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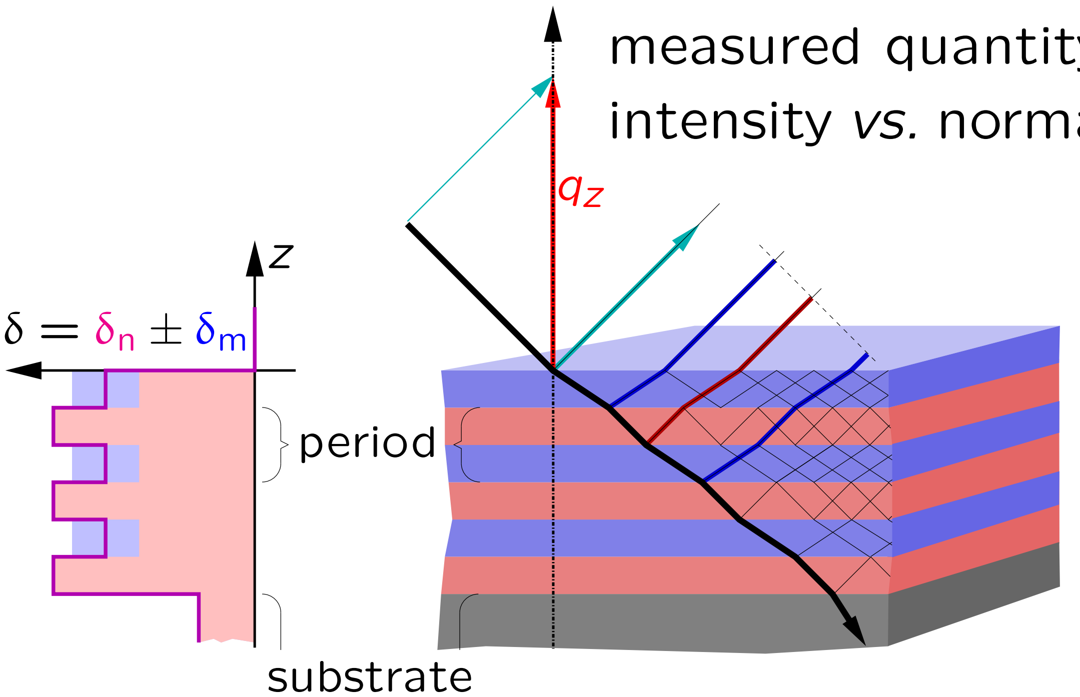
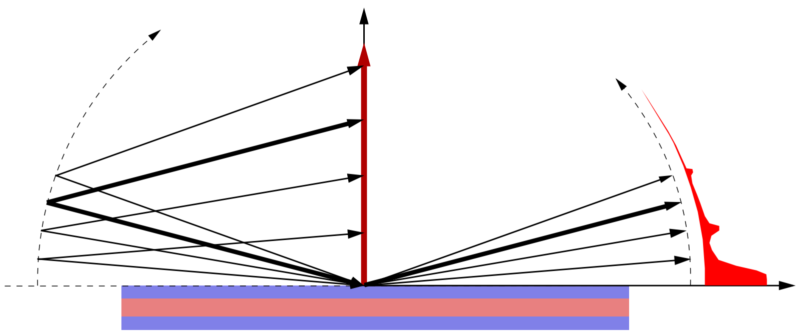


angle dispersive mode



index of refraction n

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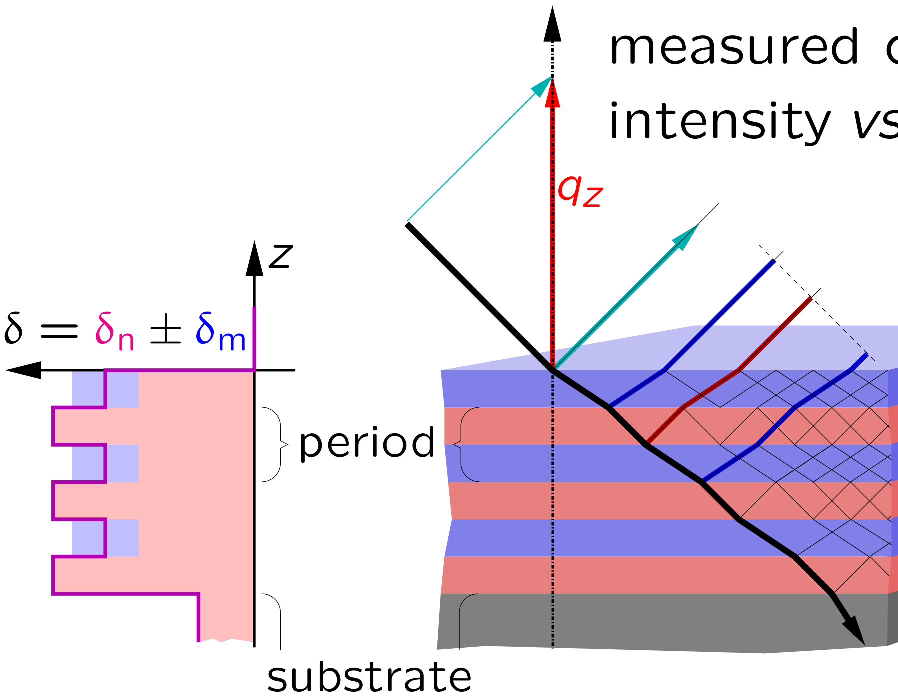
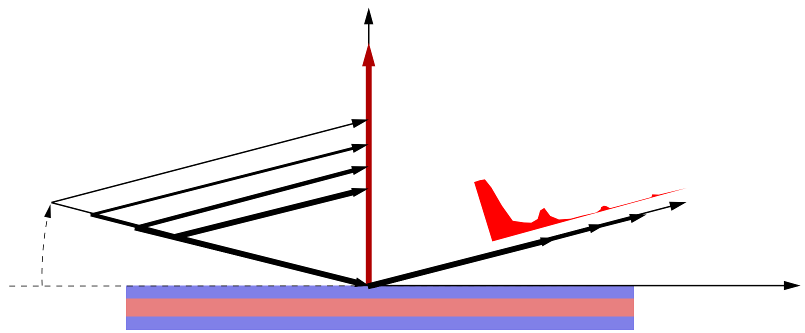
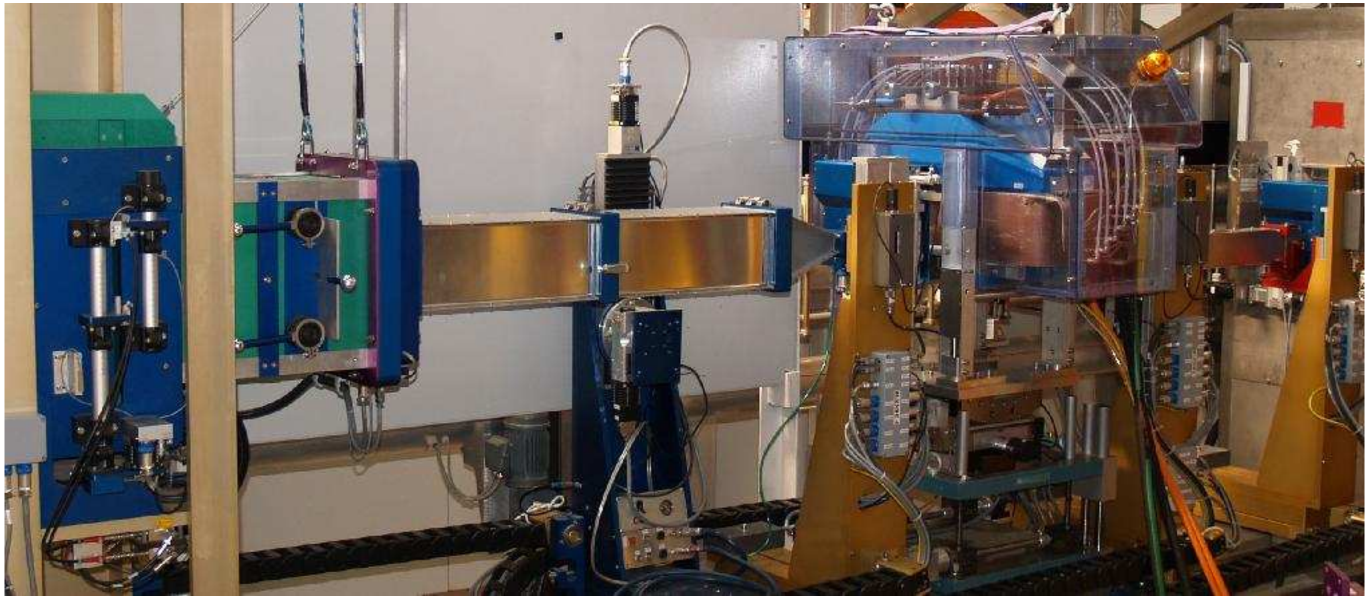


energy dispersive mode



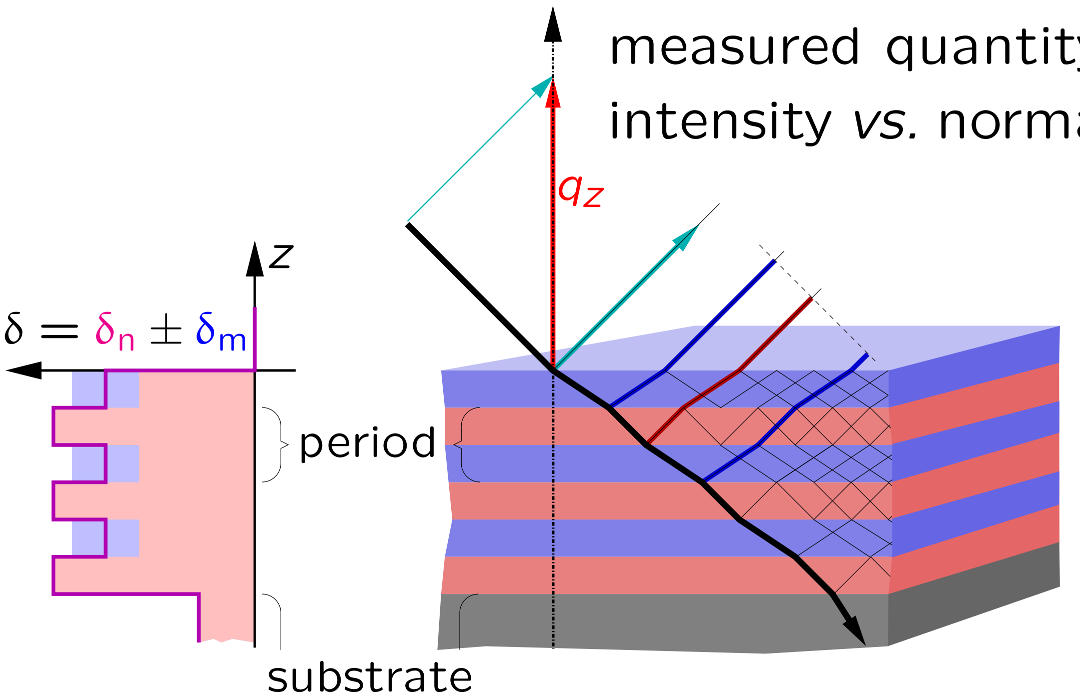
neutron reflectometer
AMOR
at SINQ, PSI

time-of-flight
spin polarisation

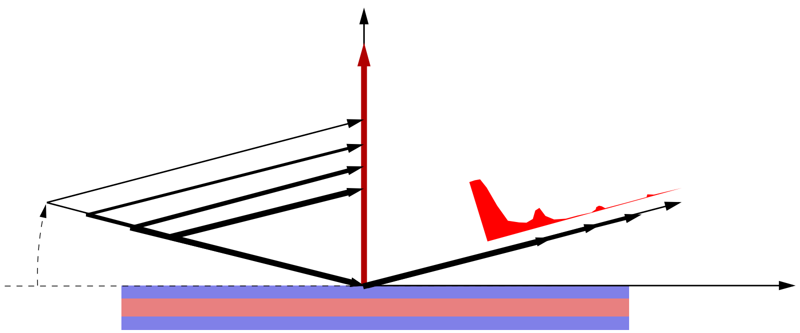


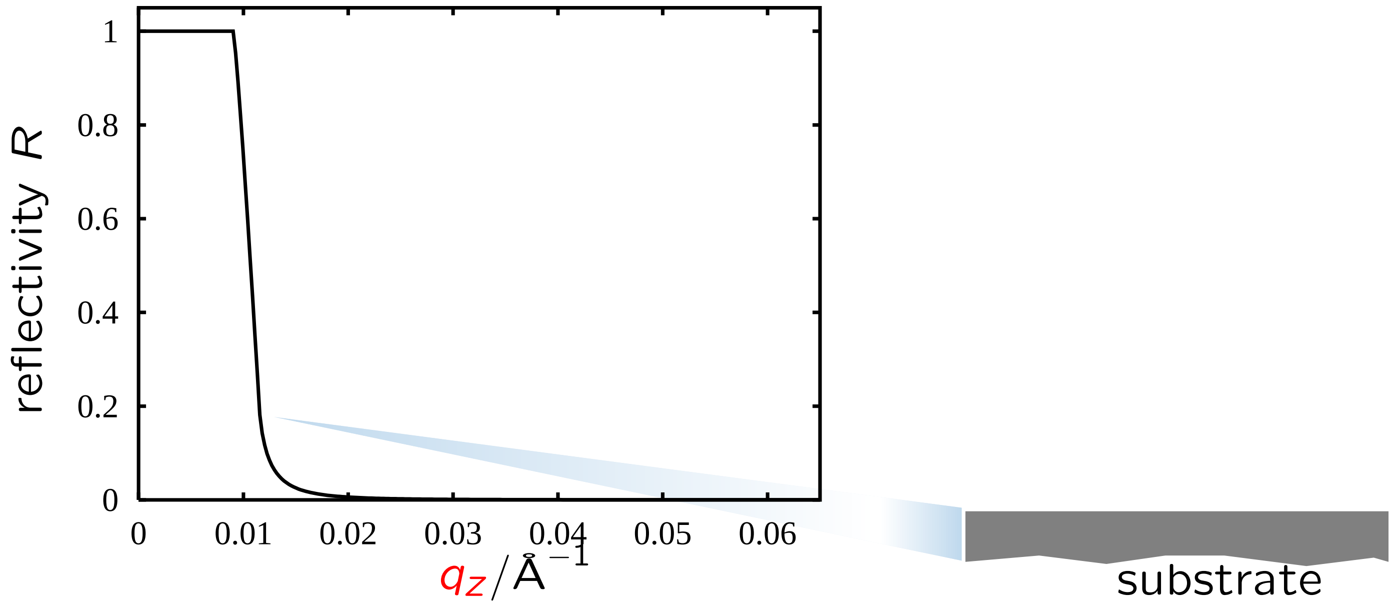
measured quantity:

intensity *vs.* normal momentum transfer q_z



energy dispersive mode





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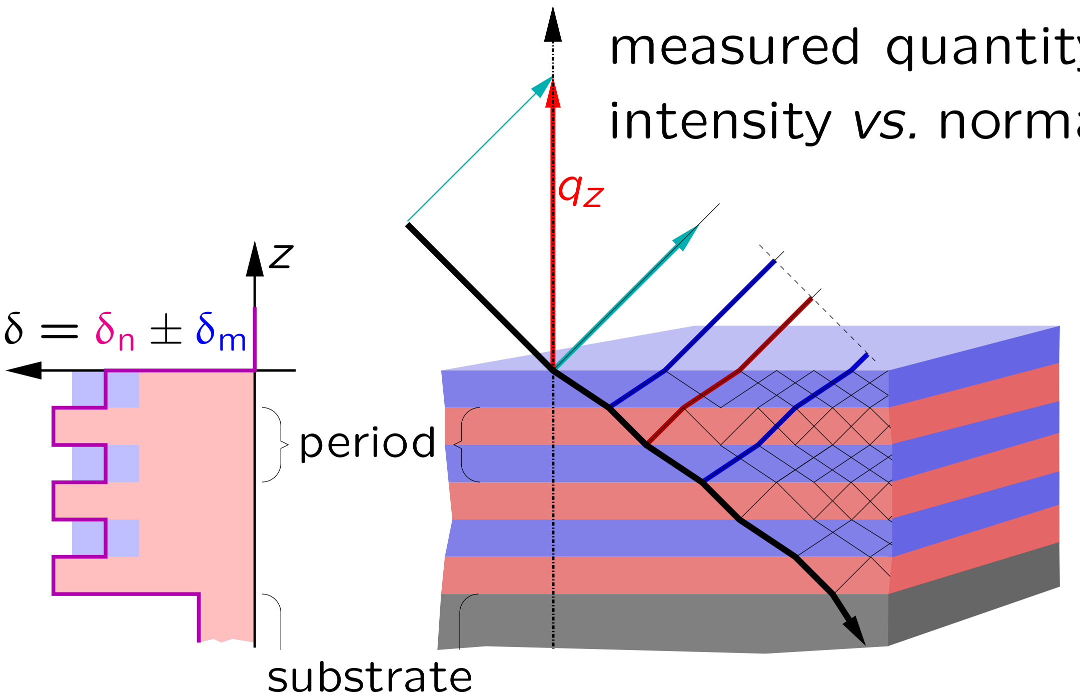
intensity *vs.* normal momentum transfer q_z



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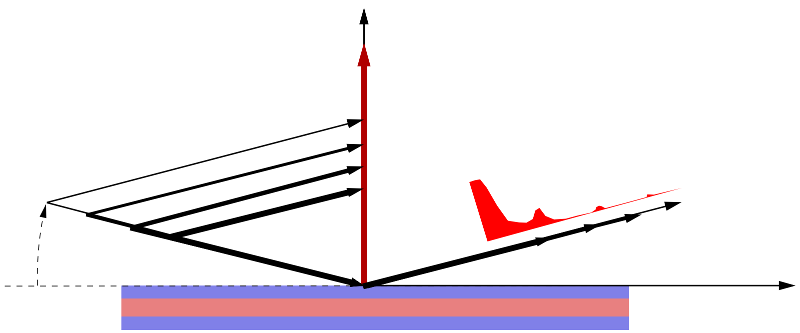
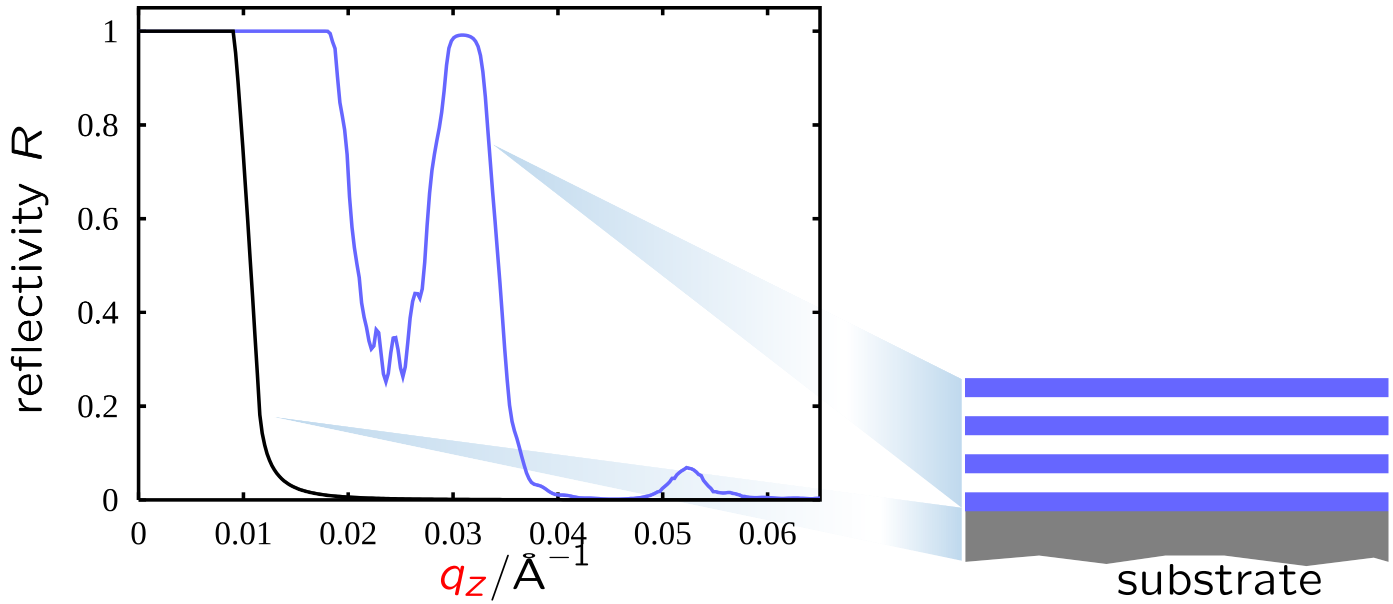
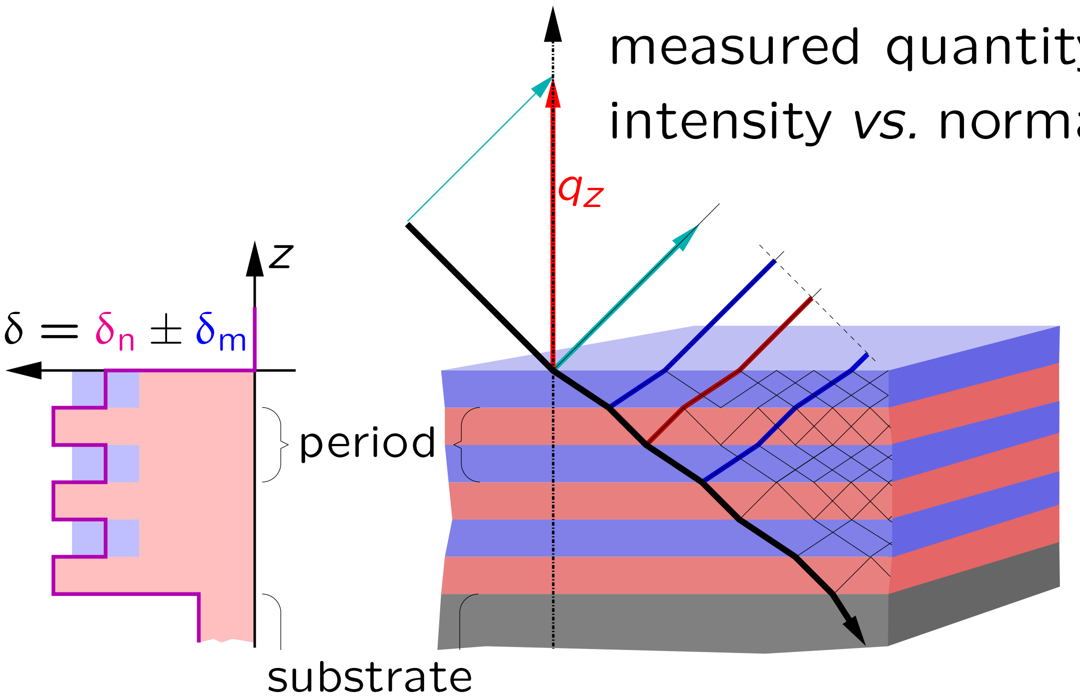


polarised neutron reflectometry

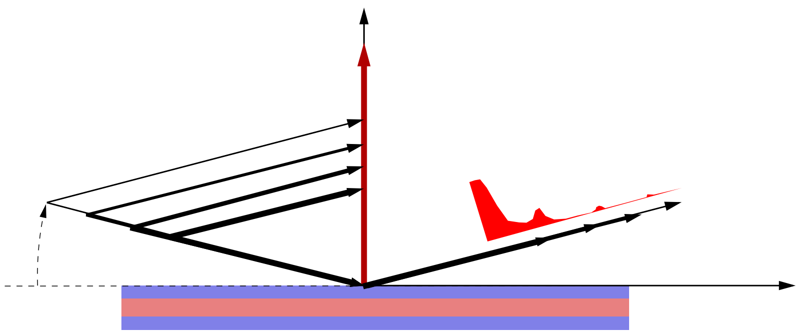


measured quantity:

intensity *vs.* normal momentum transfer q_z

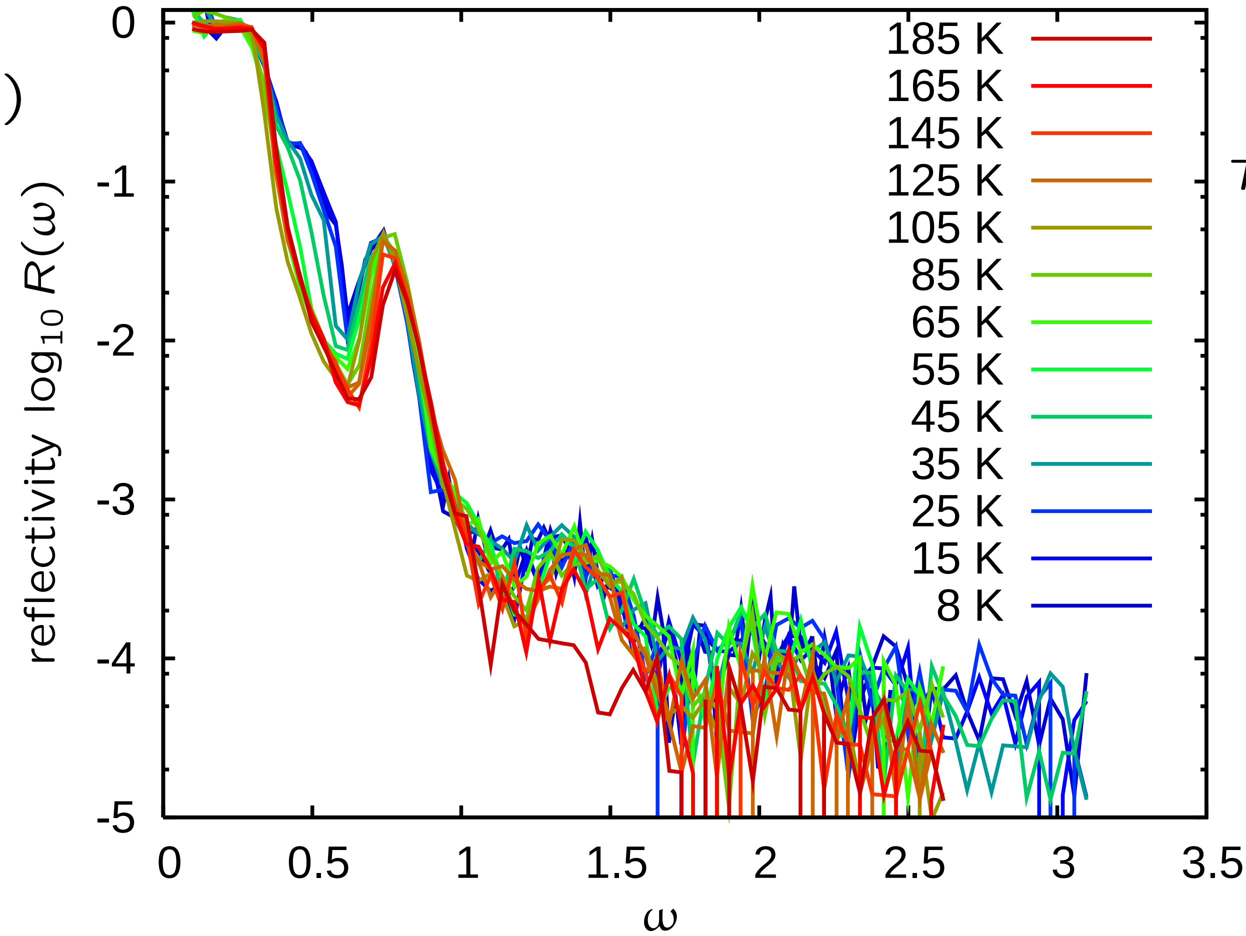


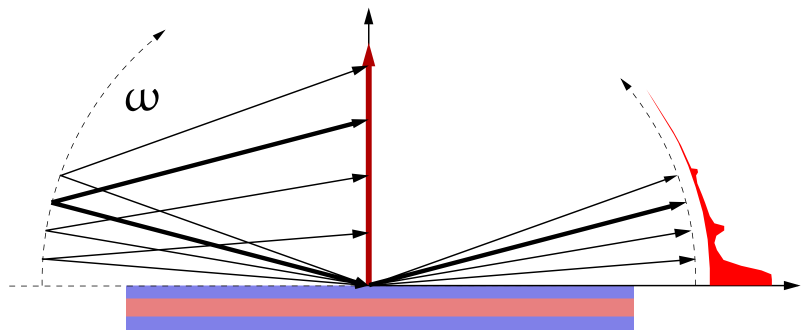
energy dispersive mode

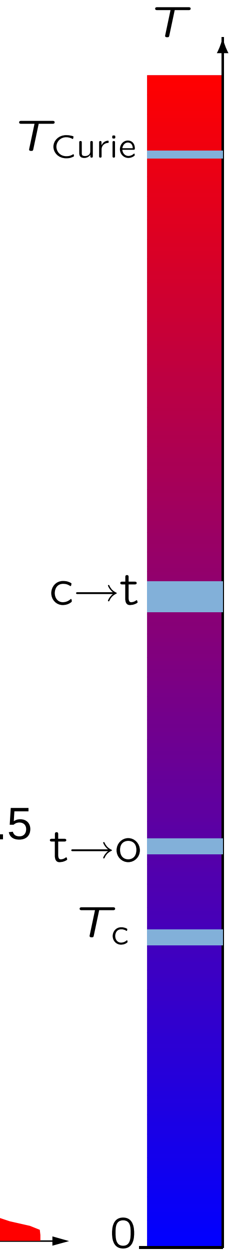


T dependence of $R(\omega)$
for an ML with
underdoped SC

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





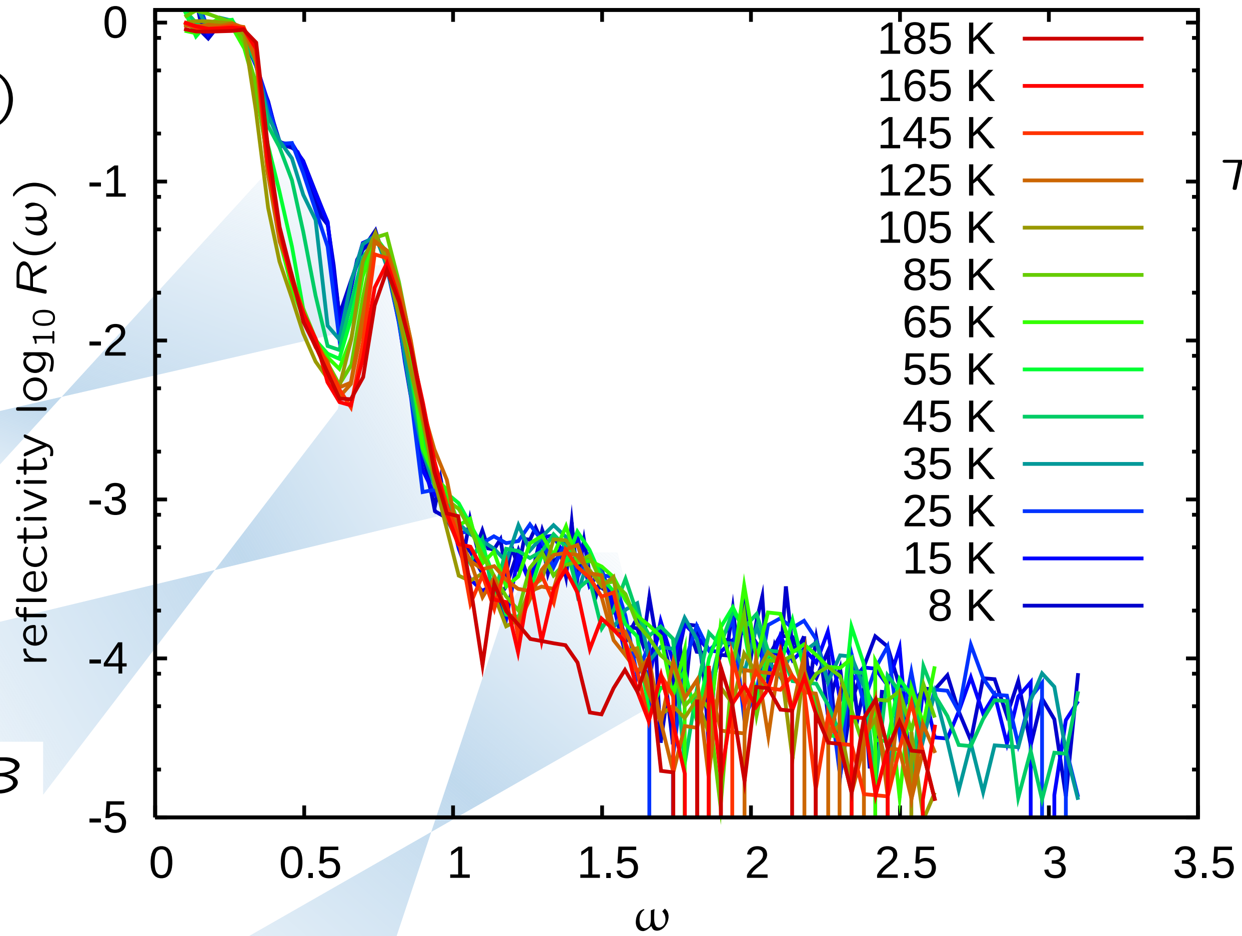


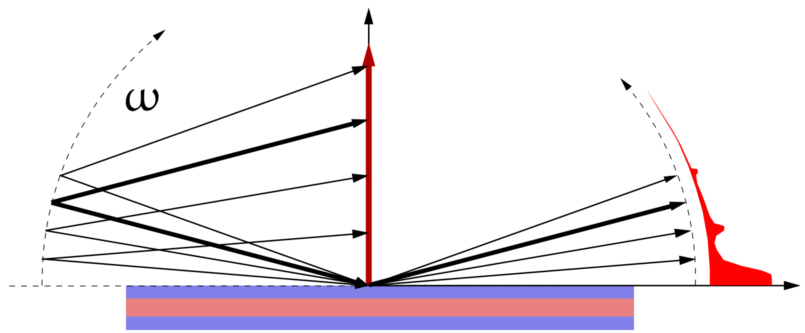
T dependence of $R(\omega)$
for an ML with
underdoped SC

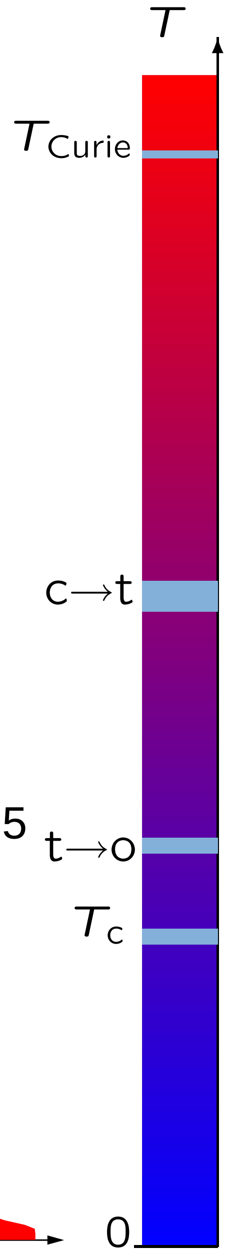
new peak below T_c

1st Bragg peak
displays increasing B

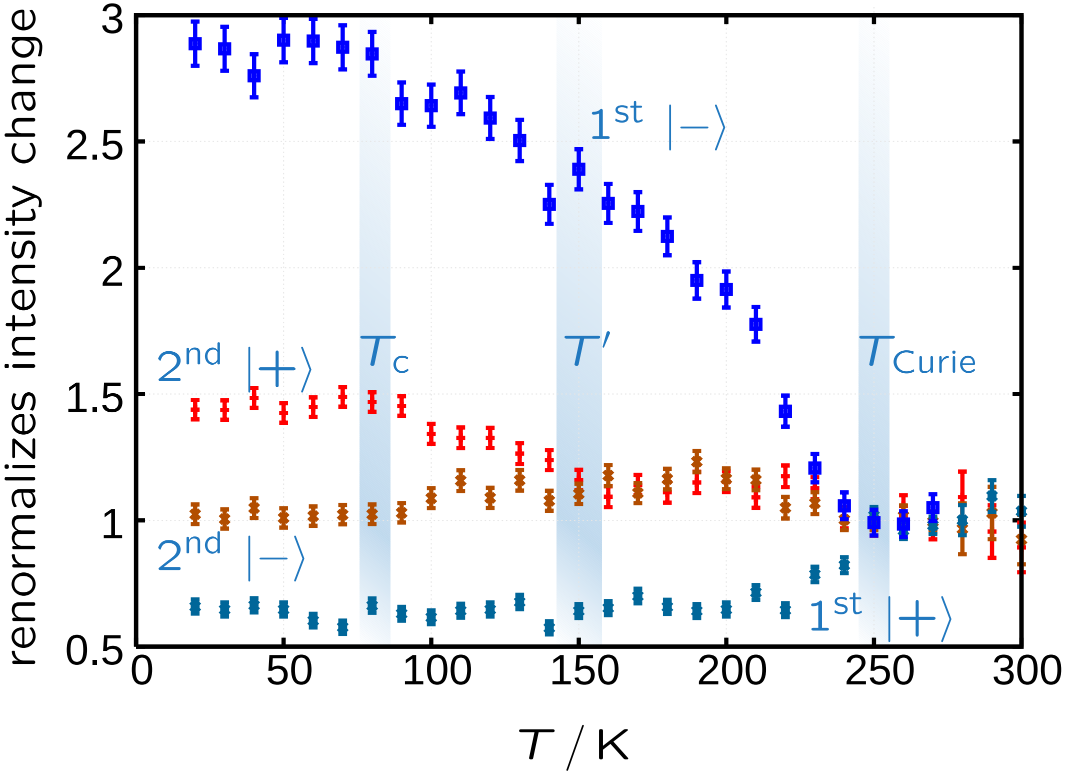
appearance of 2nd Bragg peak
magnetic screening in YPBCO
below T_{Curie}



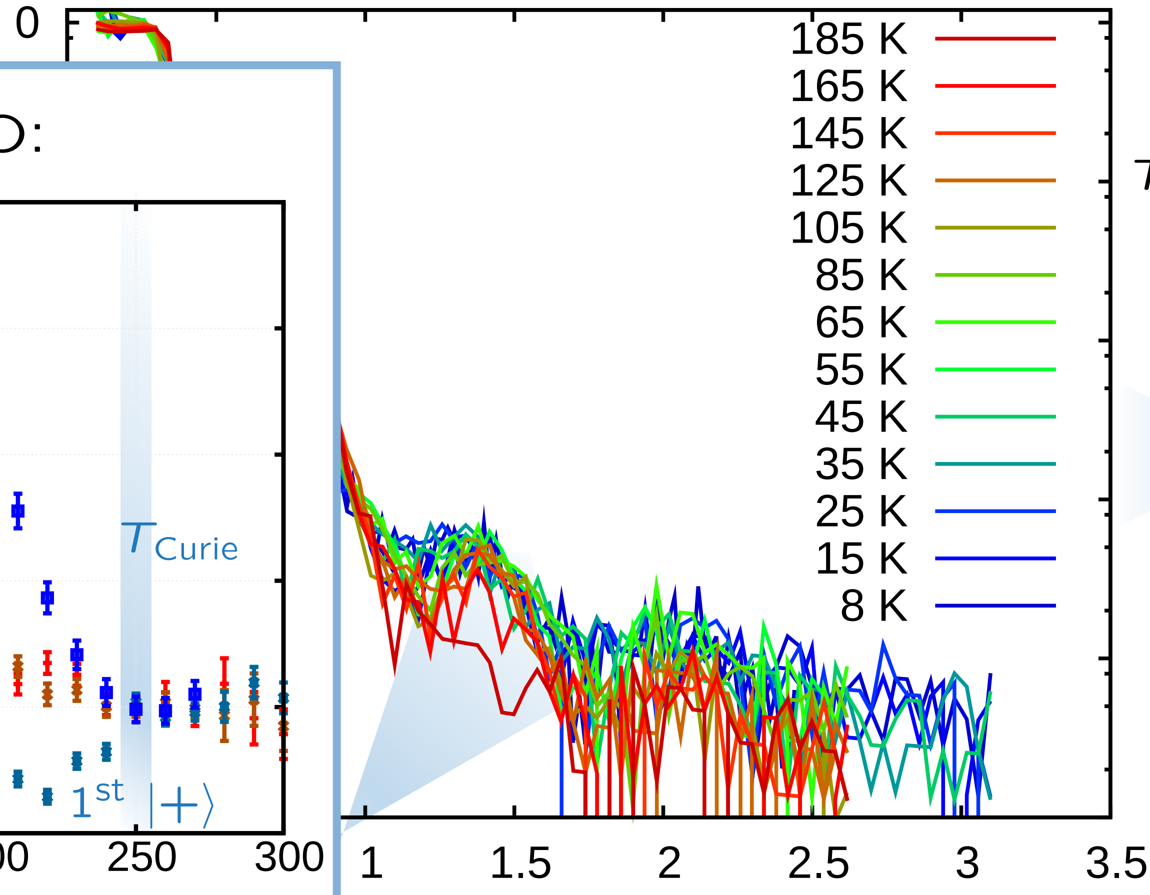


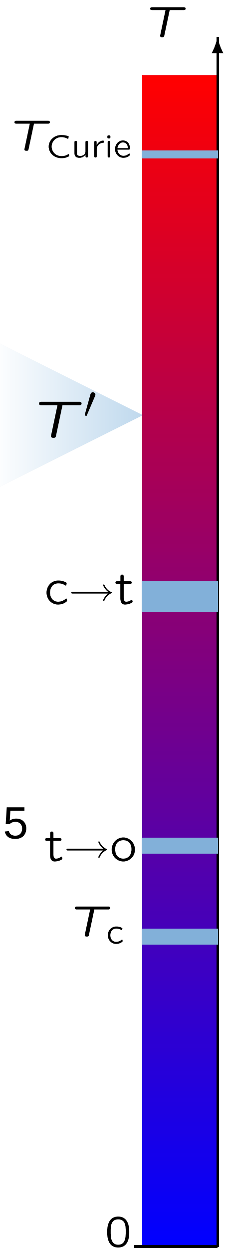


optimally doped YBCO:

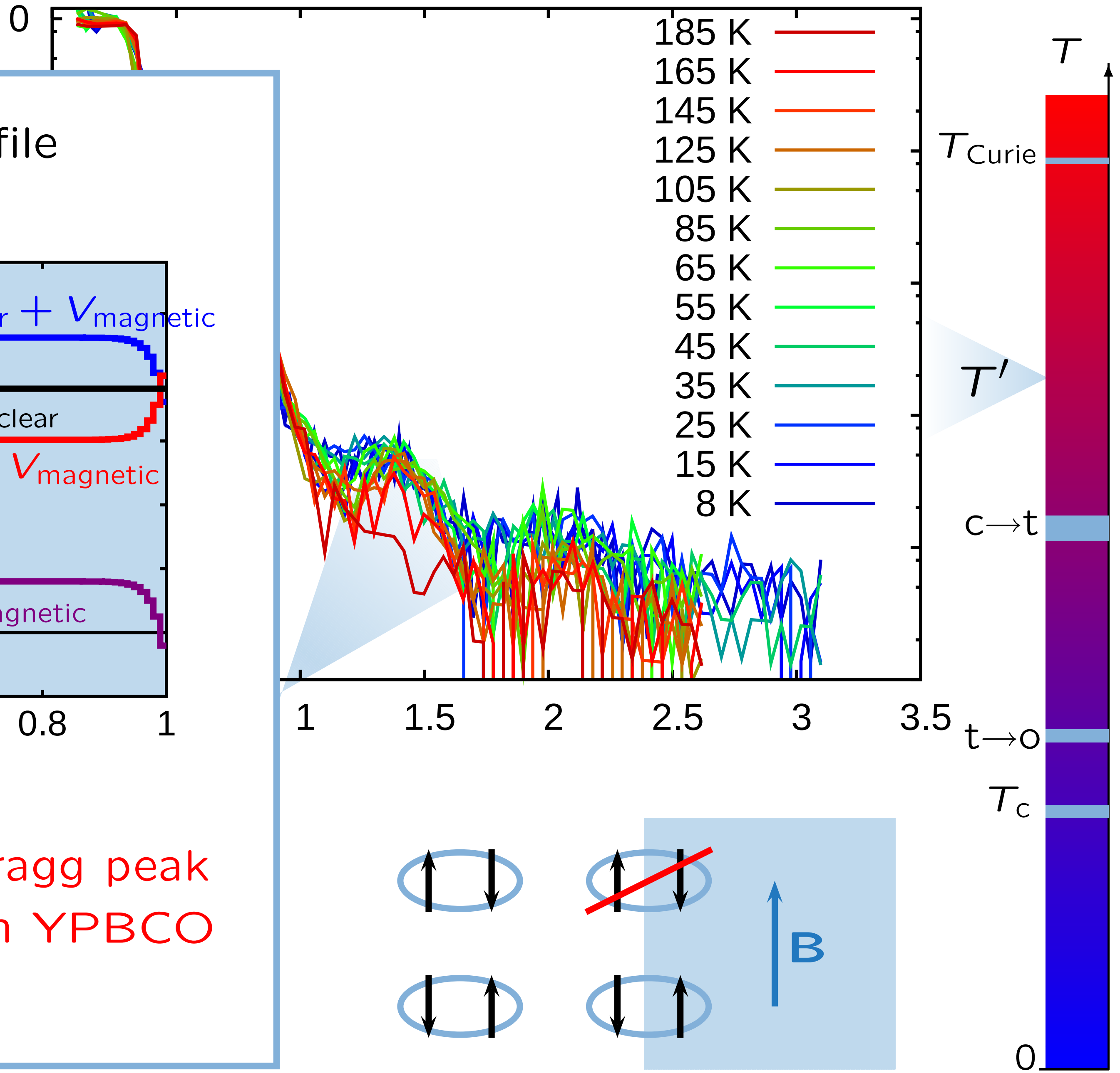


appearance of 2^{nd} Bragg peak
magnetic screening in YPBCO
below T_{Curie}

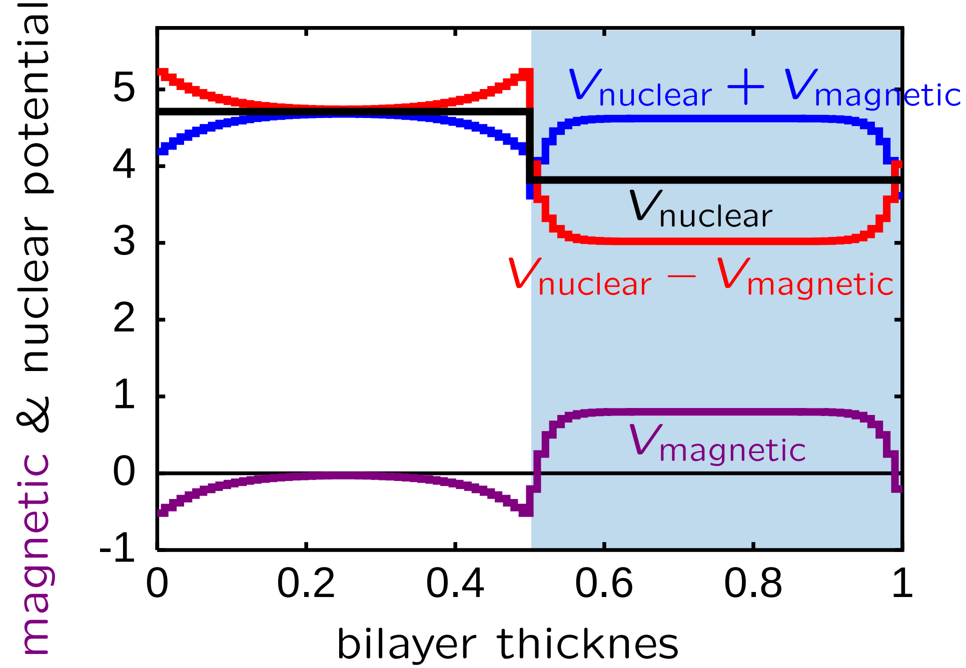




T' is doping dependent and scales like T^* of the pseudo gap

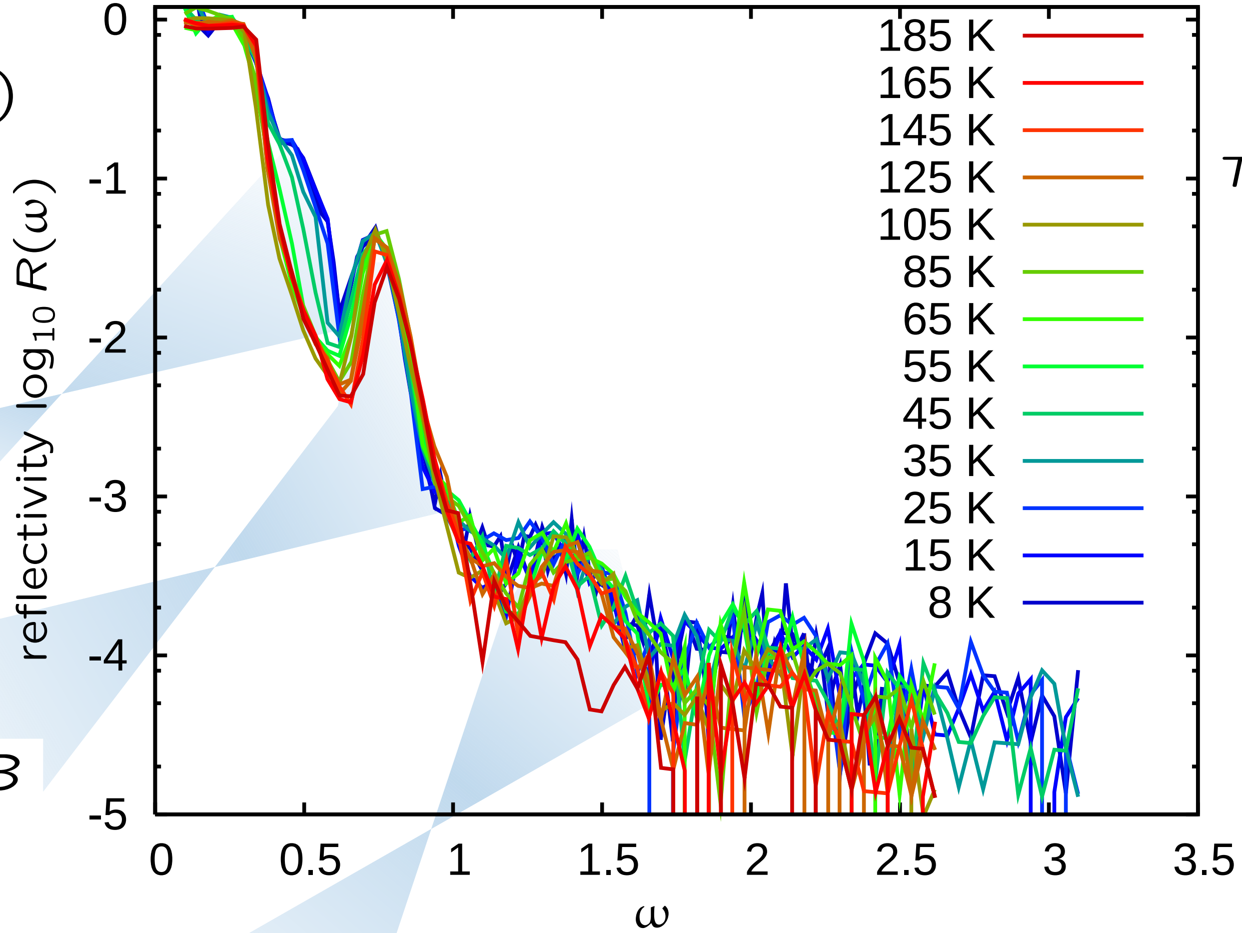


simulated depth profile
of the potentials



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

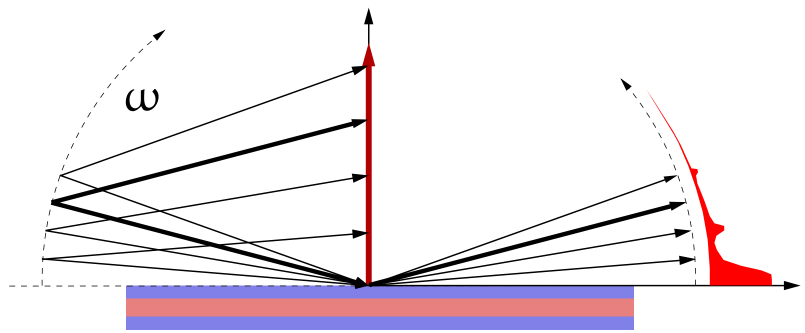
T dependence of $R(\omega)$ for an ML with underdoped SC

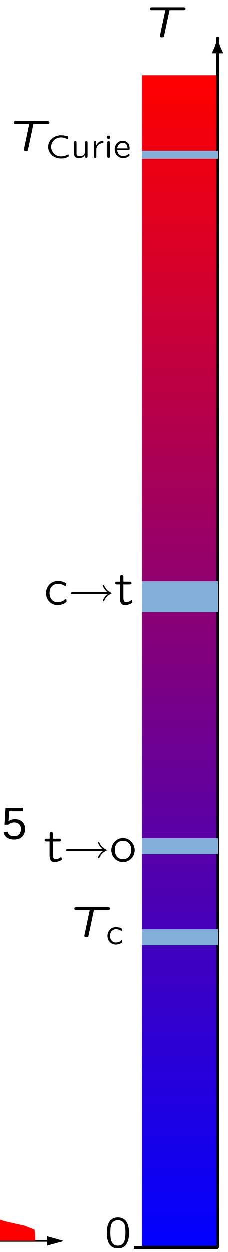


new peak below T_c

1^{st} Bragg peak displays increasing B

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





T dependence of $R(\omega)$
for an ML with
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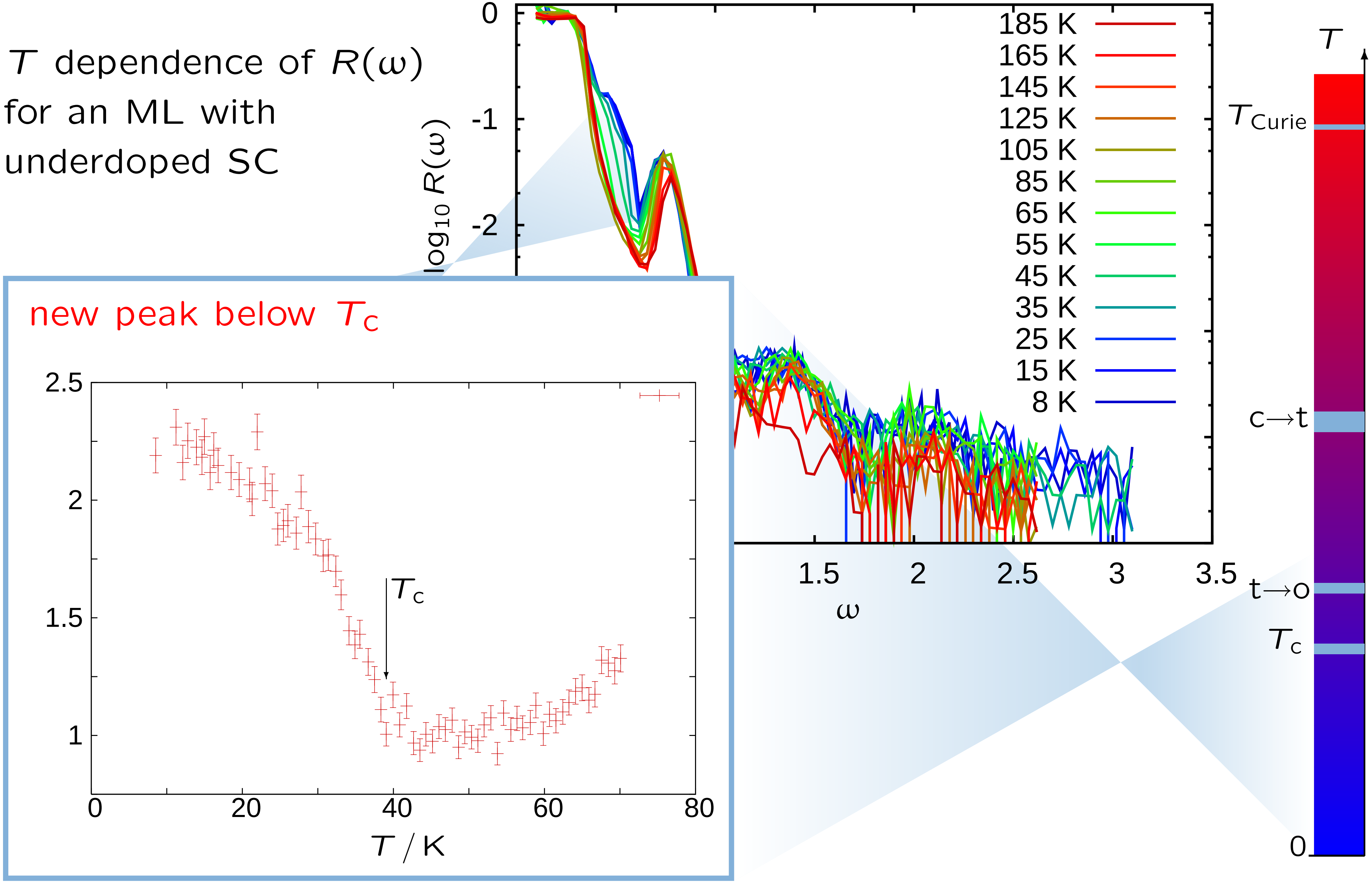
new peak below T_c



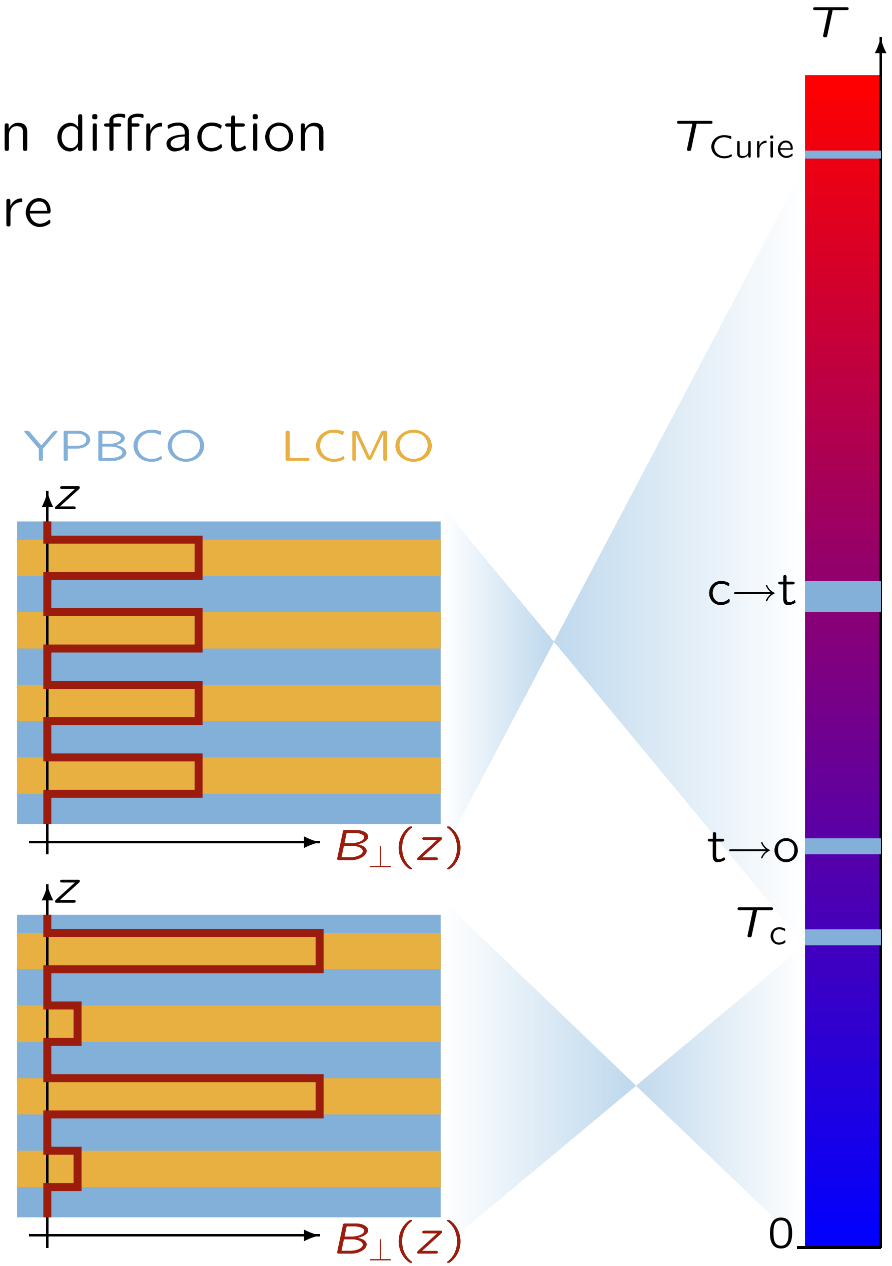
magnetic peak

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

model assumpton:

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

influence of the substrate

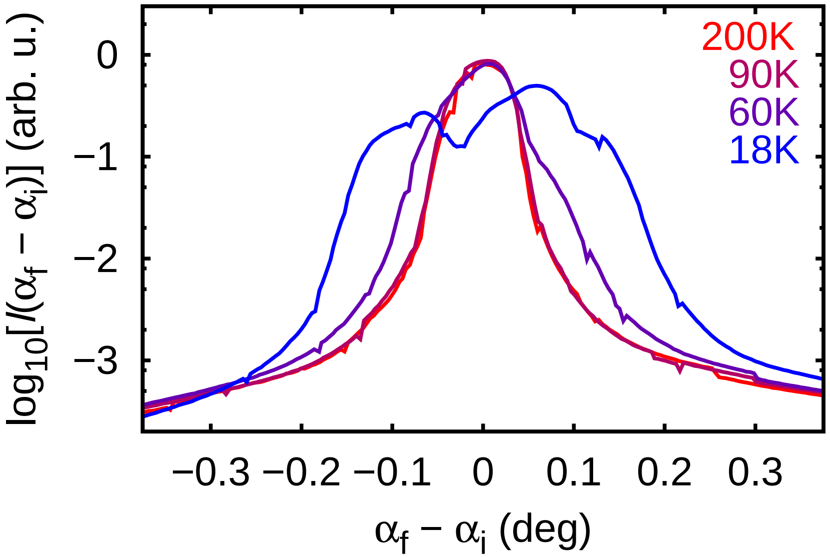
STO undergoes phase transitions

⇒ twinning, buckling of the surface

⇒ surface is fragmented into facets

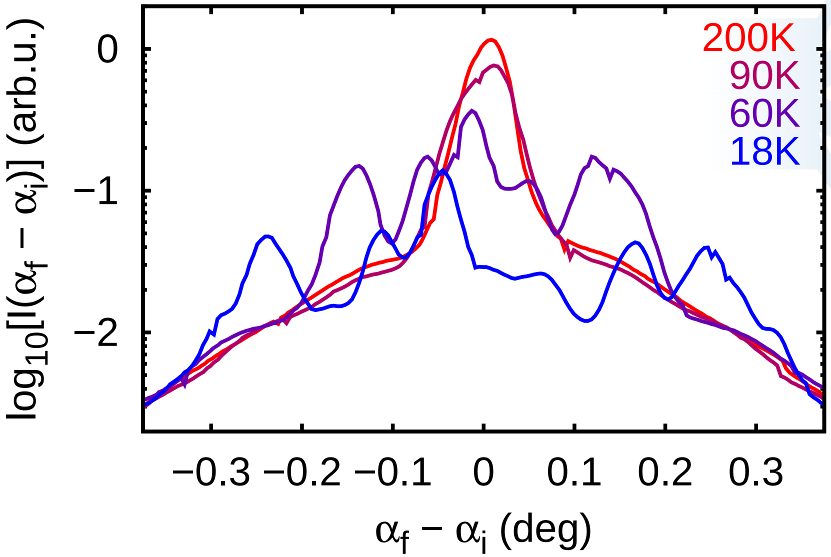
x-rays: ω-scans on

crystal reflection (002) of STO substrate

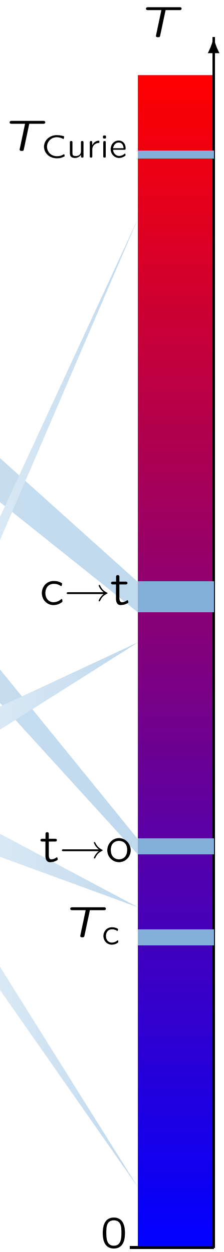


crystallite orientation

superlattice peak of the multilayer



surface orientation



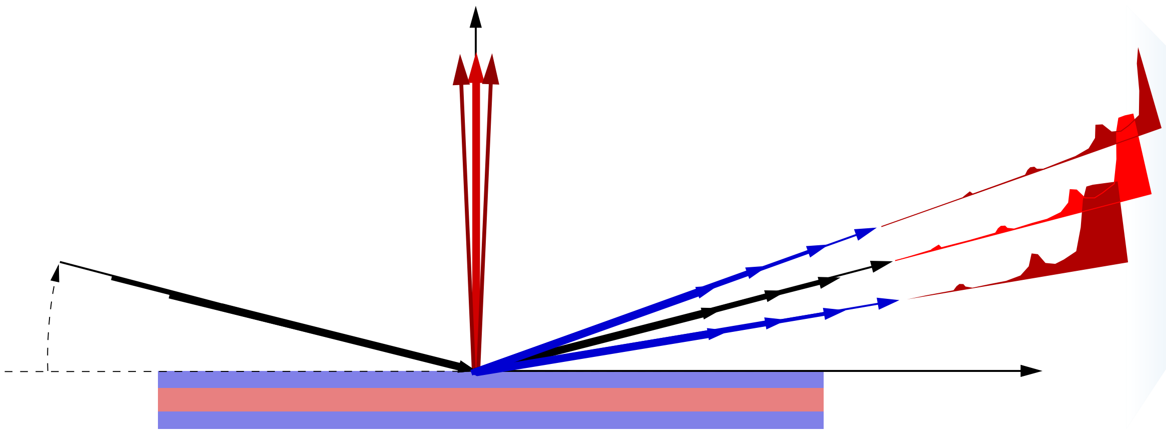
STO undergoes phase transitions

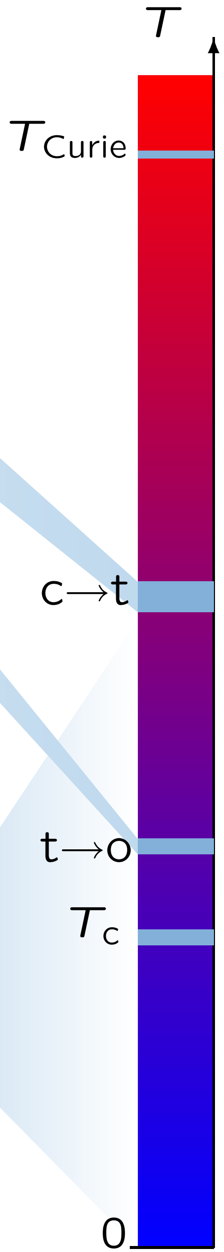
⇒ twinning, buckling of the surface

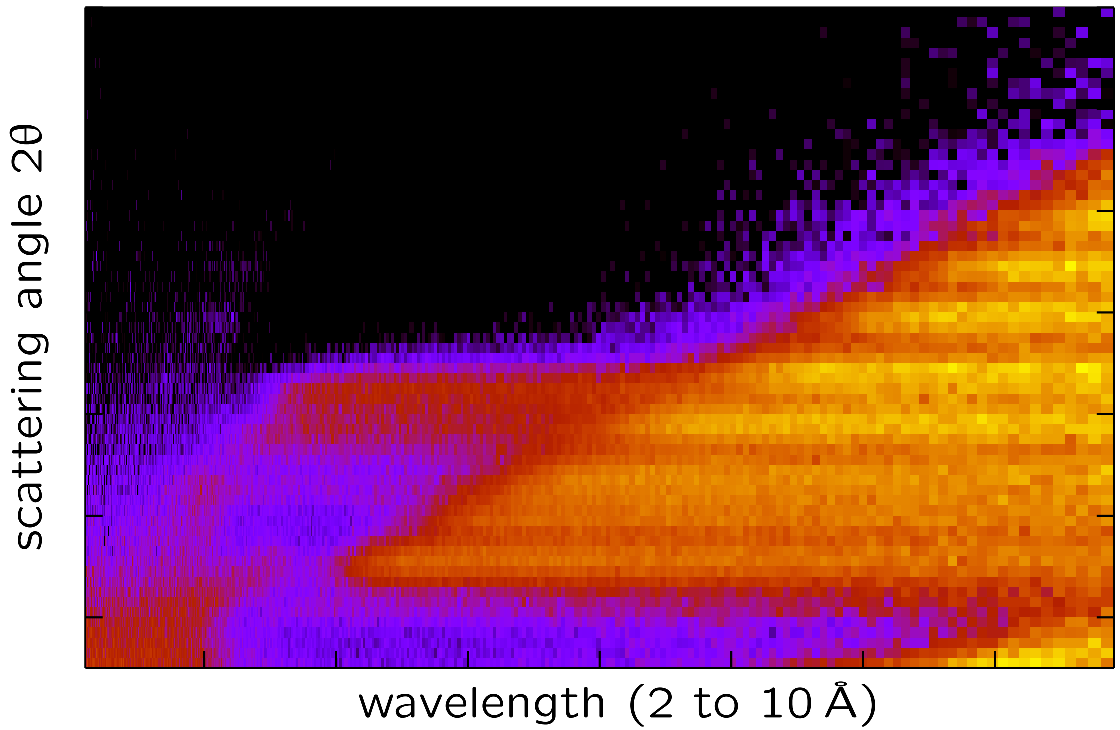
⇒ surface is fragmented into facets

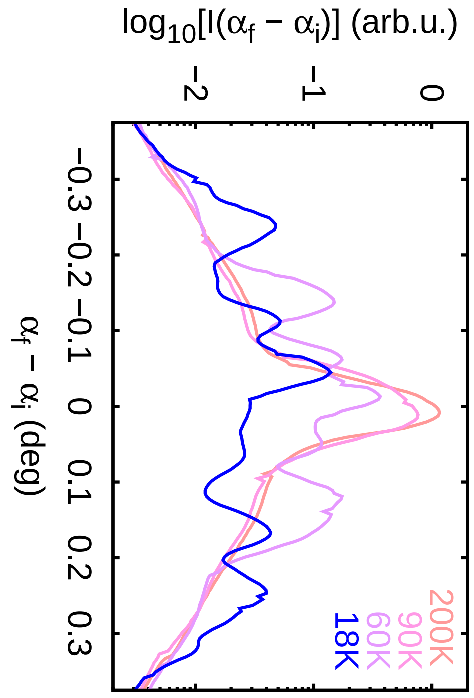
⇒ varying angle of incidence over the sample

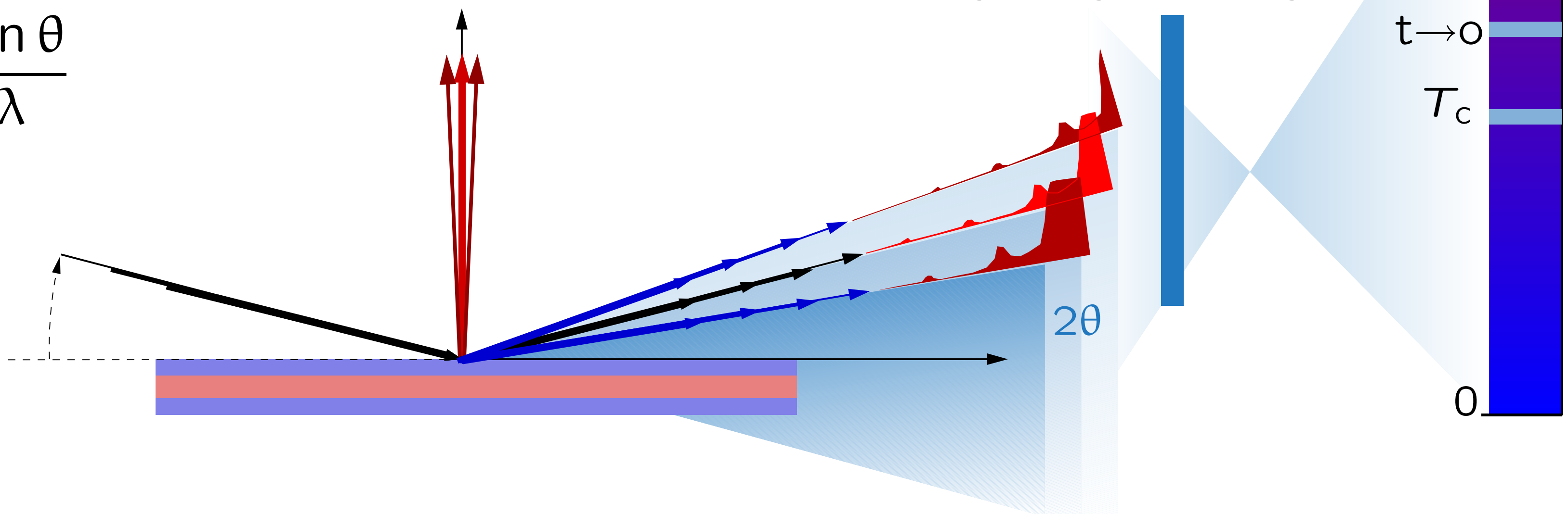
⇒ lots of specularly reflected beams







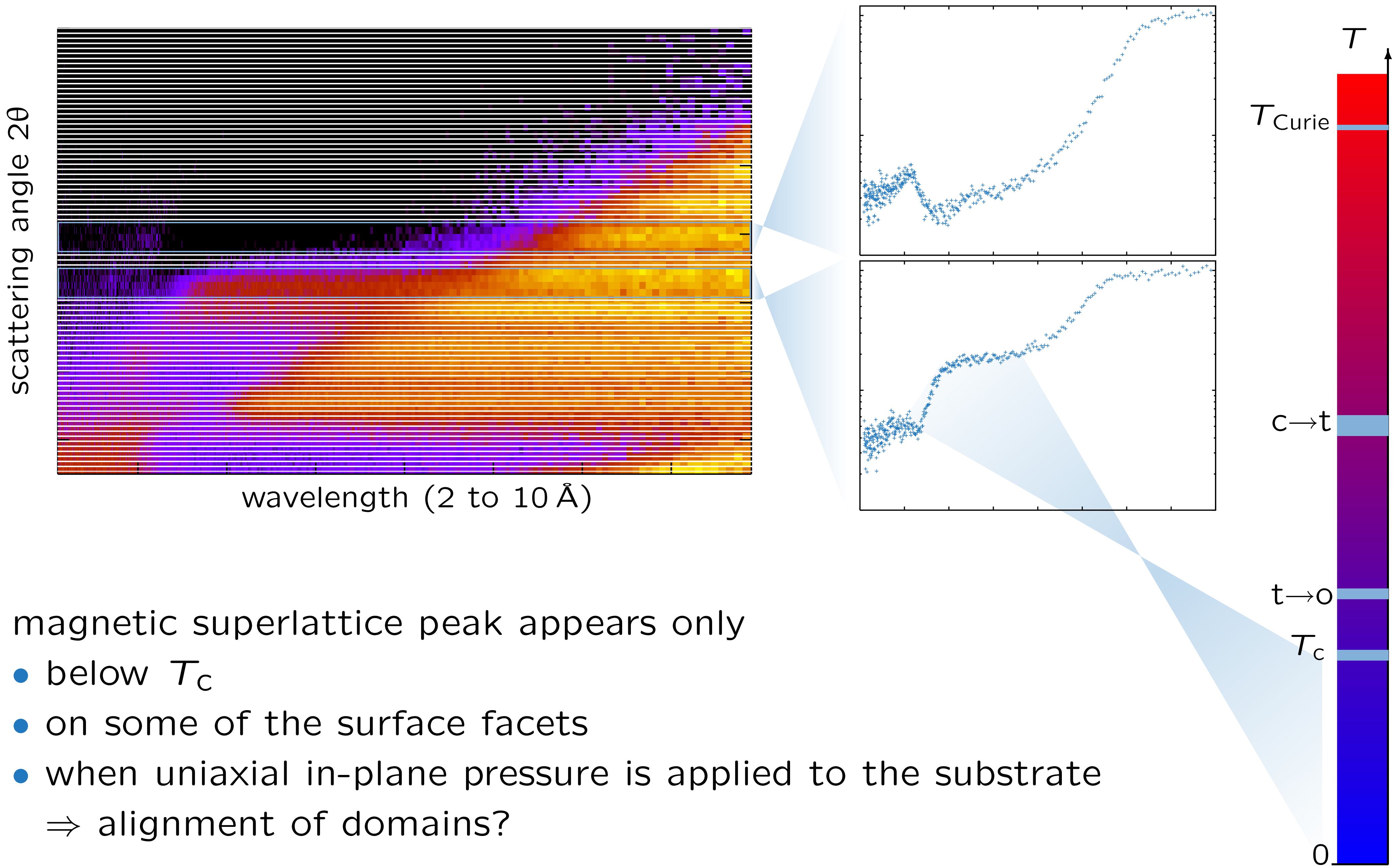




area detector to cover large angular range

$$q_z = 4\pi \frac{\sin\theta}{\lambda}$$

influence of the substrate



magnetic superlattice peak appears only

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

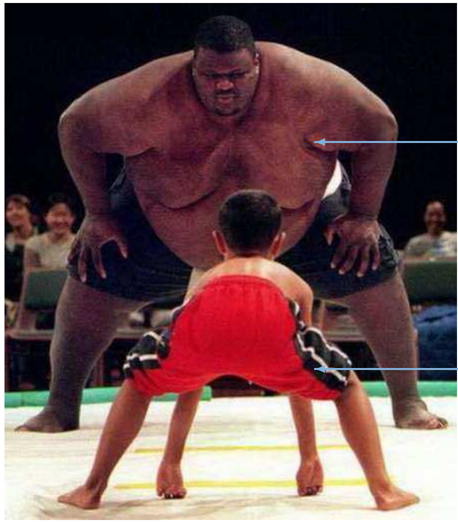
  ⇒ alignment of domains?

- 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 $\Rightarrow$

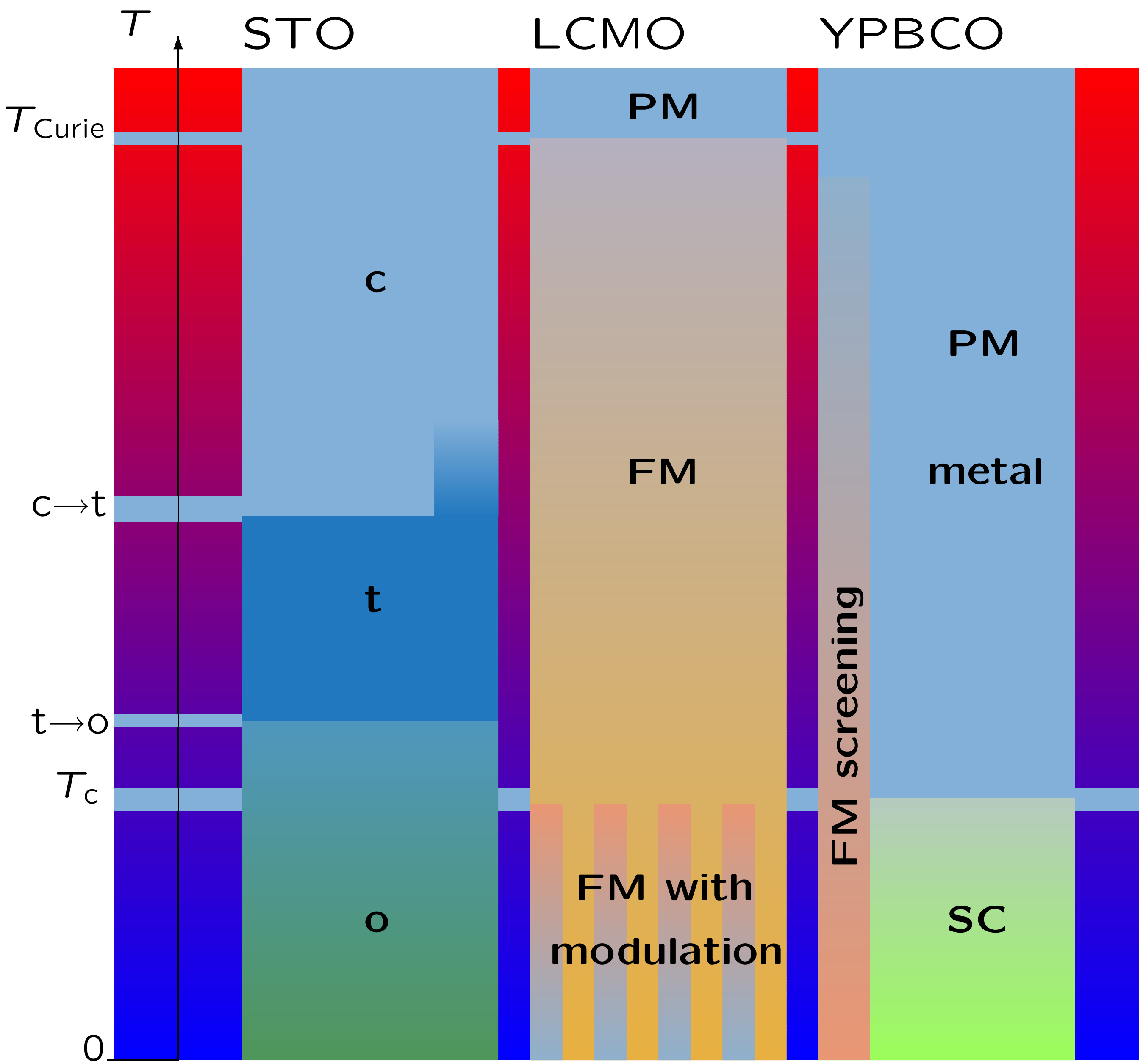


if he is strained

he can win!

phase diagram of the entire sample

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)
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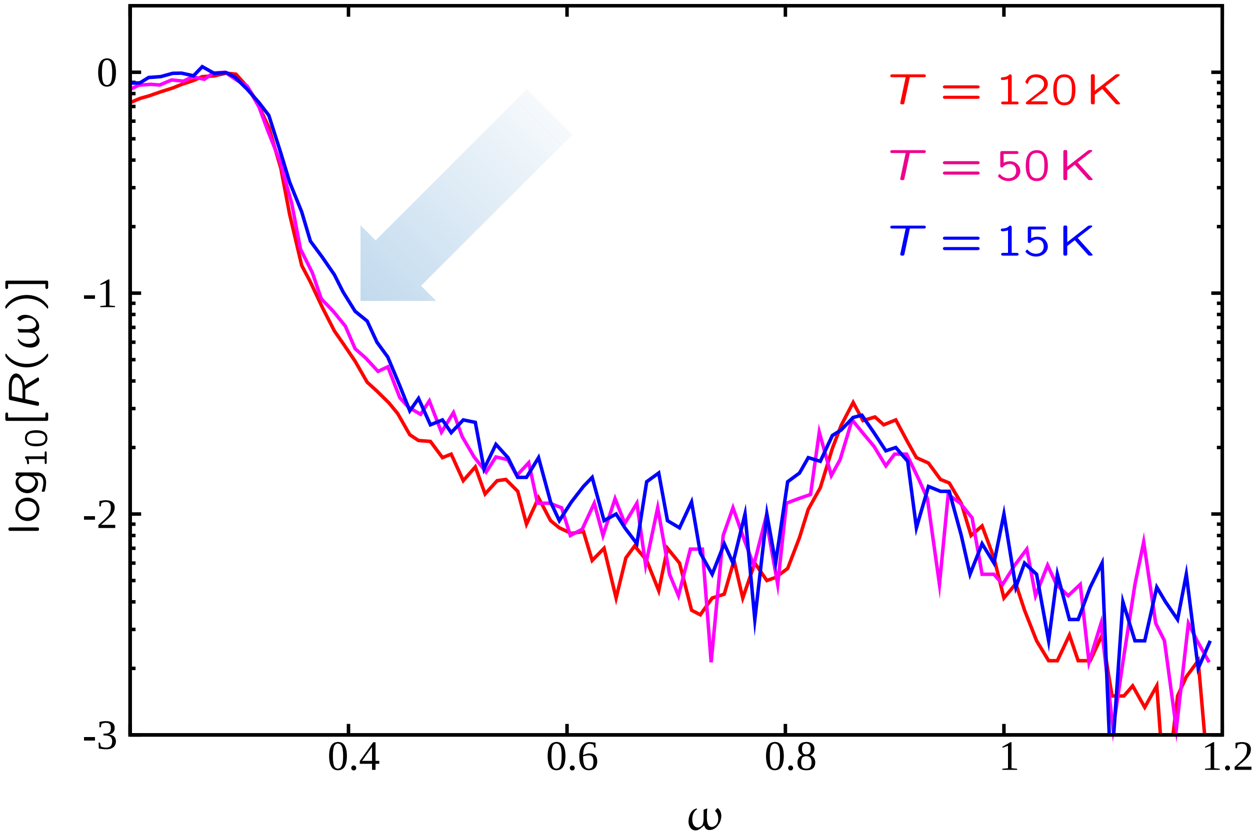
audience:	**YOU**	

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 $E = 160\,\mathrm{V/mm}$:



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

- 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