EPSRC
Engineering and Physical Sciences Research Council
UNIVERSITY OF BIRMINGHAM
CRYOGENIC
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Hard X-ray diffraction in fields up to 17 Tesla used for direct observation of competition between superconductivity and charge density wave order in $YBa_2Cu_3O_{6.67}$

Ted Forgan

"Synemag – Synchrotron and Neutron Applications of High Magnetic Fields"

Grenoble 17th – 19th Oct 2012

Outline of talk

Details about the 17 T beamline magnet

- Which has been transported all around Europe in a white van (Hamburg => Grenoble next week)

Description of very recent X-ray results

- Published in *Nature Physics* this week

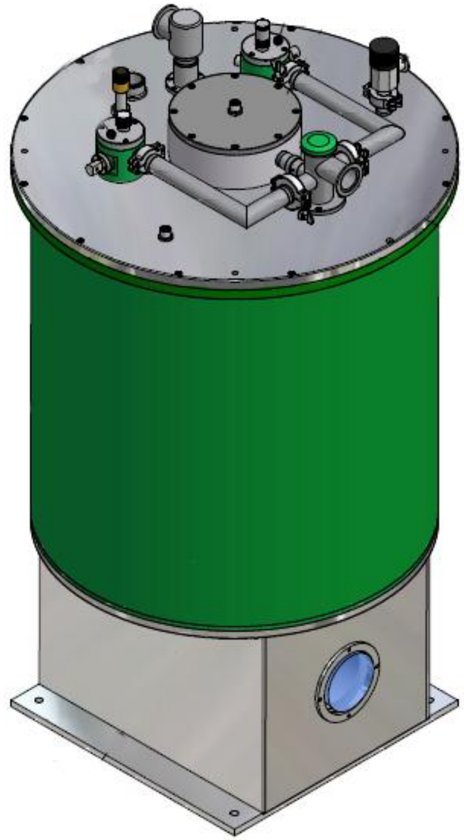
- Do you have some suggestions for collaboration using this magnet?

Existing high horizontal static field facilities for Beamlines – e.g. neutrons

- Previous contenders:

  11 T at PSI

  9 T at NIST



PAUL SCHERRER INSTITUT
PSI

NIST

- Now:

EPSRC-funded 17T magnet – available throughout Europe

ILL, PSI, DESY (hard X-ray), HZB; ESRF, ISIS in the future

~1 week initial setup time

THE BIRMINGHAM 17 T MAGNET FOR SMALL ANGLE NEUTRON/X-RAY SCATTERING

- Max field 17 T, parallel to beam
- Temperatures 1.6 K – 300 K
- $\pm 10^{\circ}$ access entry and $\pm 11^{\circ}$ exit
- 0.1% uniformity in B over 1 cm^3
- In-situ sample change (by trained operator)
- Room temperature bore (with additional insert)
- Very low background

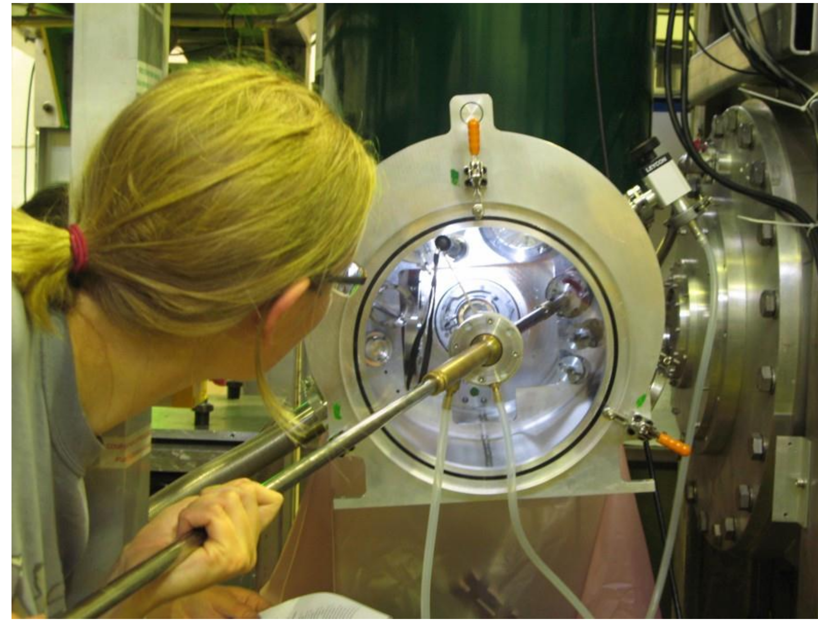
- Fast cooldown (~20 mins 300K to base) and field ramp.

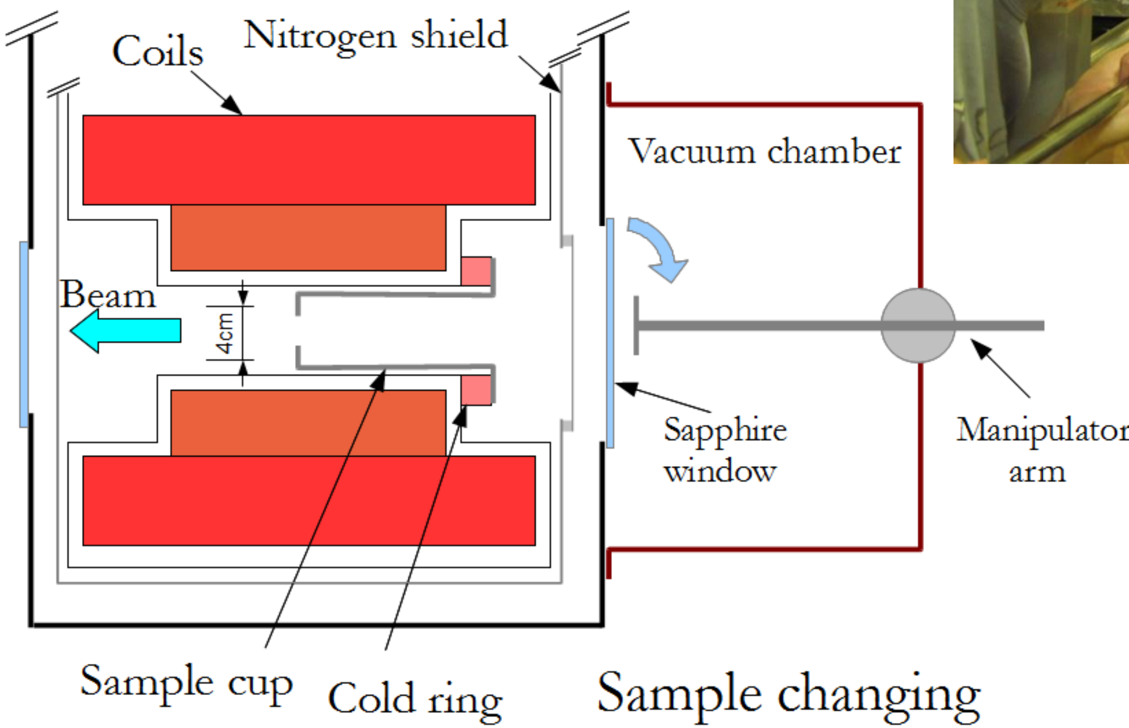
Rapid Sample change with magnet cold

Rev. Sci. Instrum. **83**, 023904 (2012)

"Reach inside" cryostat vacuum with manipulator

Can also change windows: e.g. Si => kapton

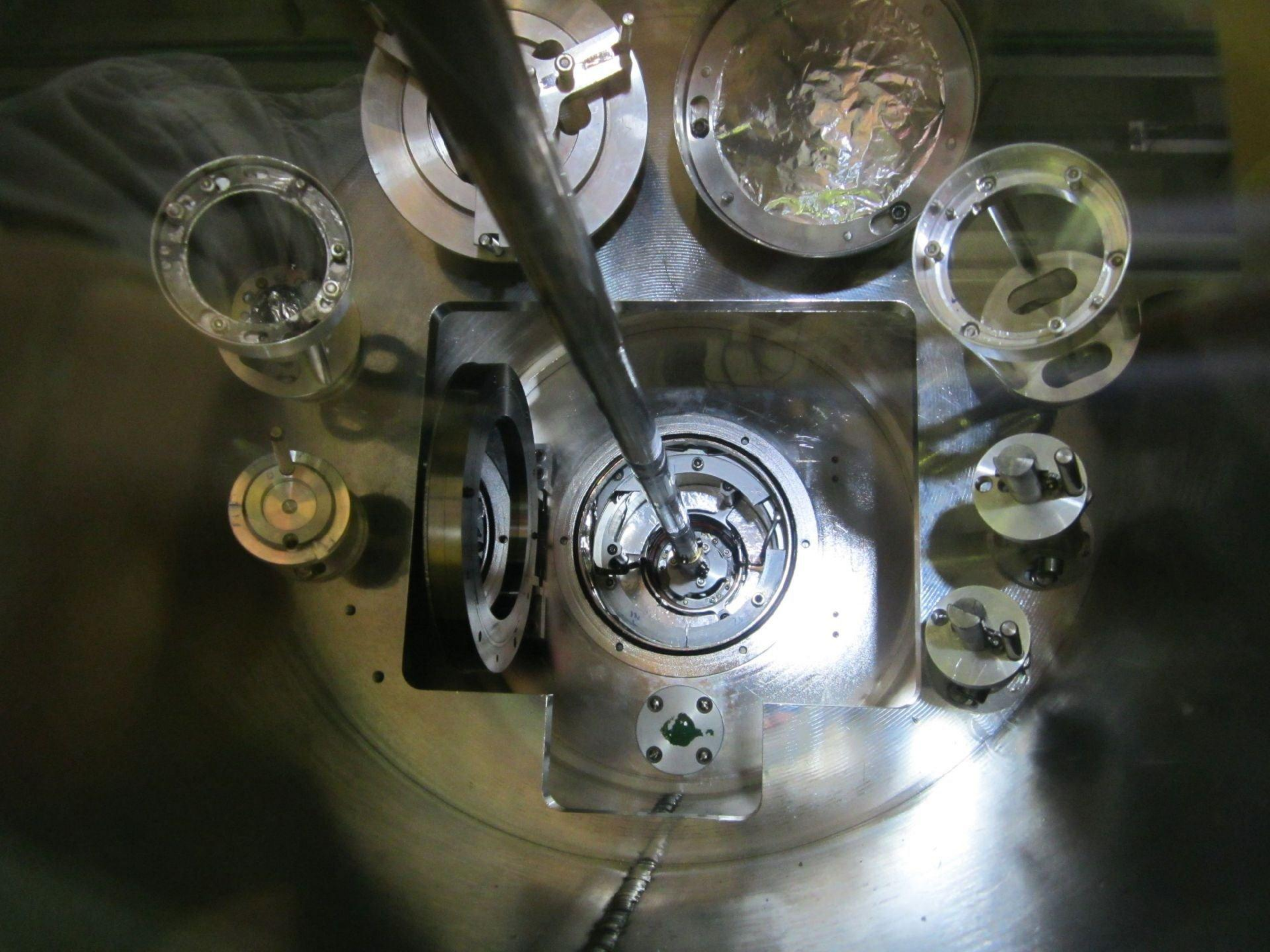




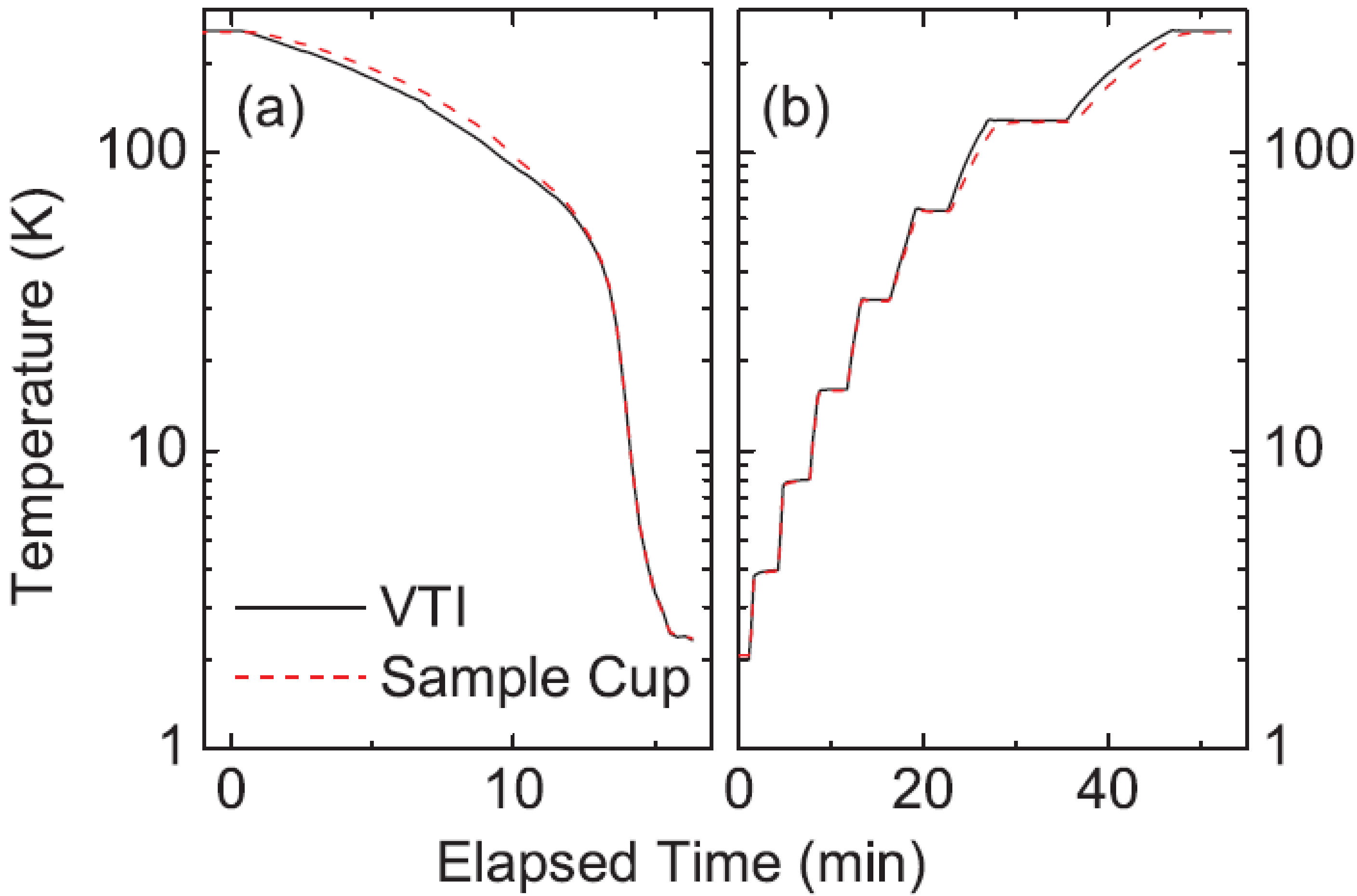
Sample changing mechanism

Can also change to room T, Atmospheric p bore

Dilution refrigerator: 50 mK insert – in 1 year's time…



Fast cooldown and thermal response



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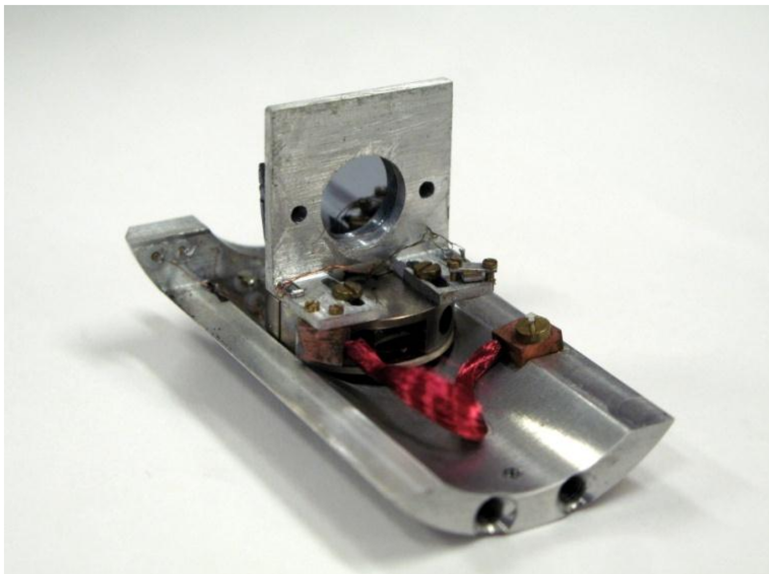
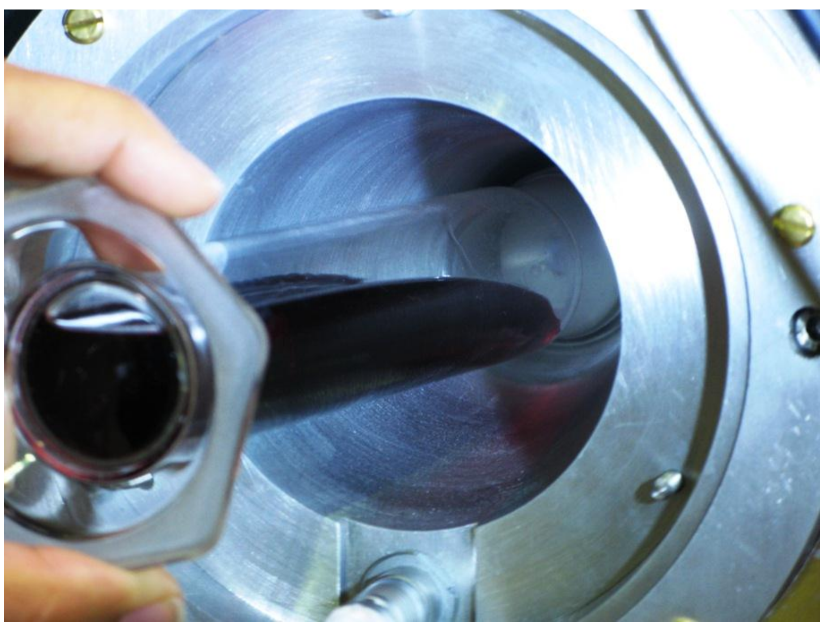
“ATTOCUBE ® SAMPLE ROTATION STAGE

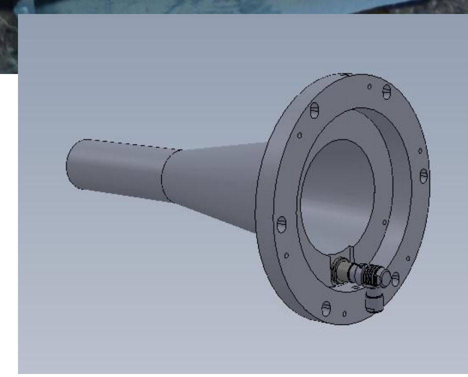


- Fits Inside 2 -300 K sample cup
- Piezoelectric rotation of sample about a vertical axis
- Angle of rotation is calibrated
- Works in 17 T
- 1000 x 25 micron Cu wires heat link gives rapid thermal response
- Could be used as a rapid sample changer for X-rays

Room temperature bore

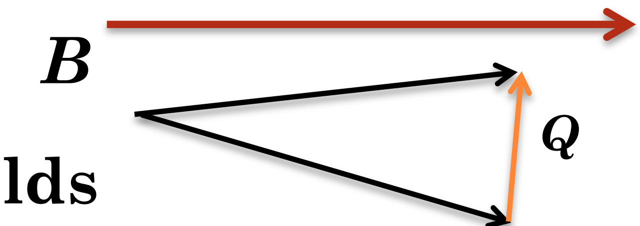
- $\pm 7^{o}$ entry access; optical access
- Temperature-controlled 10-50 °C
- Sample change at 17 T
- “Moses Effect” can be observed



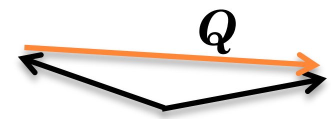


POSSIBLE AND ACTUAL APPLICATIONS

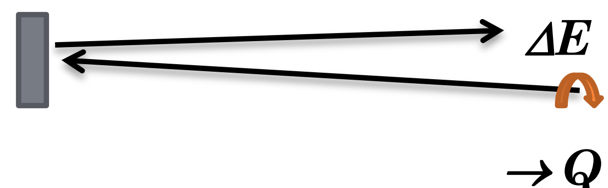
- **SANS from flux lines in superconductors**
- **SANS, optical or** SAXS **investigations of alignment of 'nonmagnetic' particles in suspension in water.**
- **SANS on hard nanomagnets.**



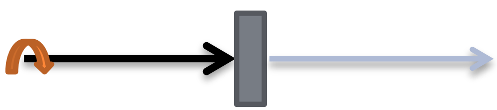
- **Hard X-ray diffraction in high fields**
  - Mid-energy diffraction in high fields



  - Spin-dependent Compton scattering



  - XMCD



  - Collaborate with us:

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e.m.forgan@bham.ac.uk

  - **Or buy your own – it was very cheap (under 200k€)**

Competition between Charge Density Wave order and Superconductivity in $YBa_2Cu_3O_y$

- Small lattice displacements, observed in slightly underdoped YBCO, suppress superconductivity

- Observations:
  - Using high energy X-ray diffraction
    - Chang *et al.*, *Nature Physics* (2012)
    - Magnetic field dependence
  - Using soft X-ray resonant scattering at zero B
    - Ghiringhelli *et al.*, *Science* (2012)
    - Achkar *et al.*, *arXiv*:1207.3667 (2012)

Why we did the experiment

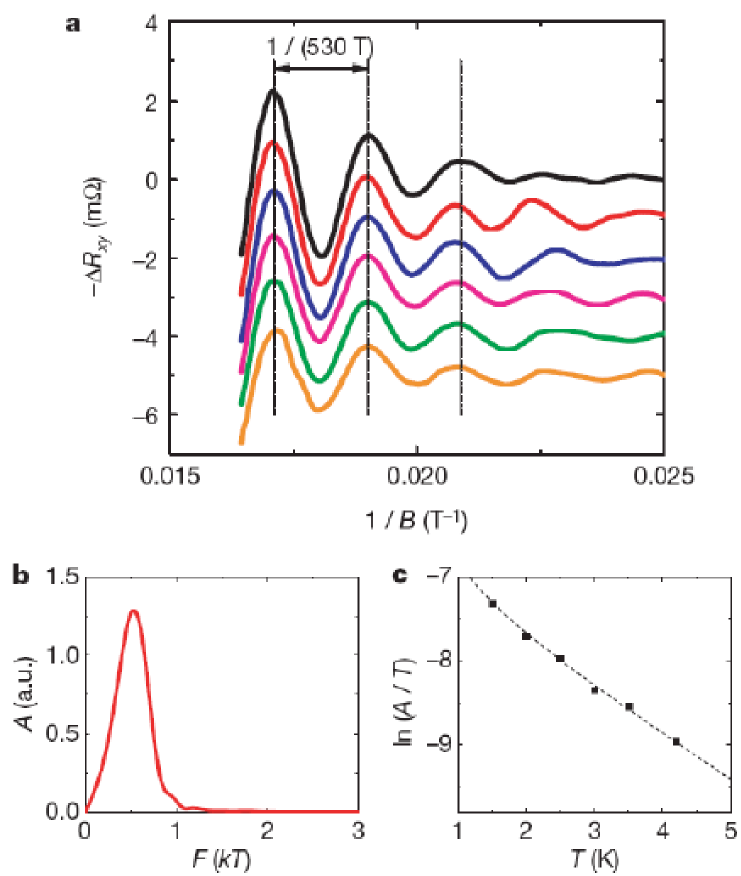


Figure 3 | Quantum oscillations in YBCO.

Quantum Oscillations at B > 40 T reveal the Fermi Surface area in underdoped $YBCO_{6.5}$ (other experiments at other dopings)

All show that a Fermi Surface exists, but is FAR smaller than ~ half Brillouin Zone expected

Also NMR results suggest that charge order is induced by a magnetic field: have the BZ & FS been reconstructed?

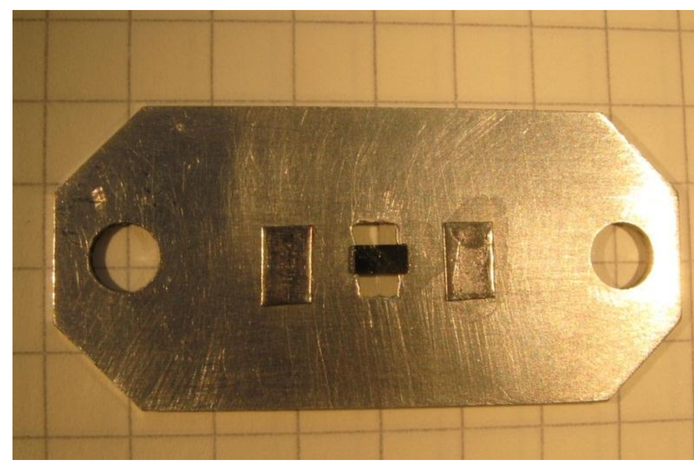
Doiron-Leyraud *et al.*, Nature **447**, 565 (2007).

Wu *et al.*, Nature **477**, 191 (2011).

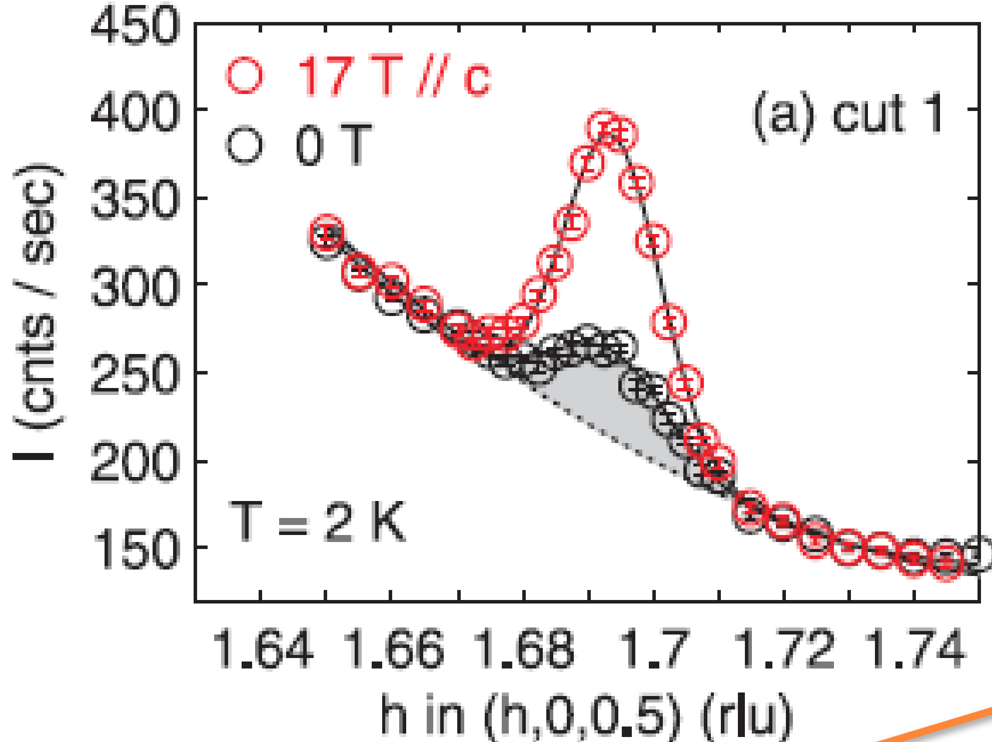
Three-axis diffractometer - 100 keV X-rays

YBCO$_{6.67}$
$3.1 \times 1.7 \times 0.6$ mm^3
mass 18 mg
99% detwinned
T_C = 67 K
width 10%-90% = 1.1 K

BW5 – on DORIS,
HASYLAB, DESY,
Hamburg



A Field- & Temp-dependent diffraction peak



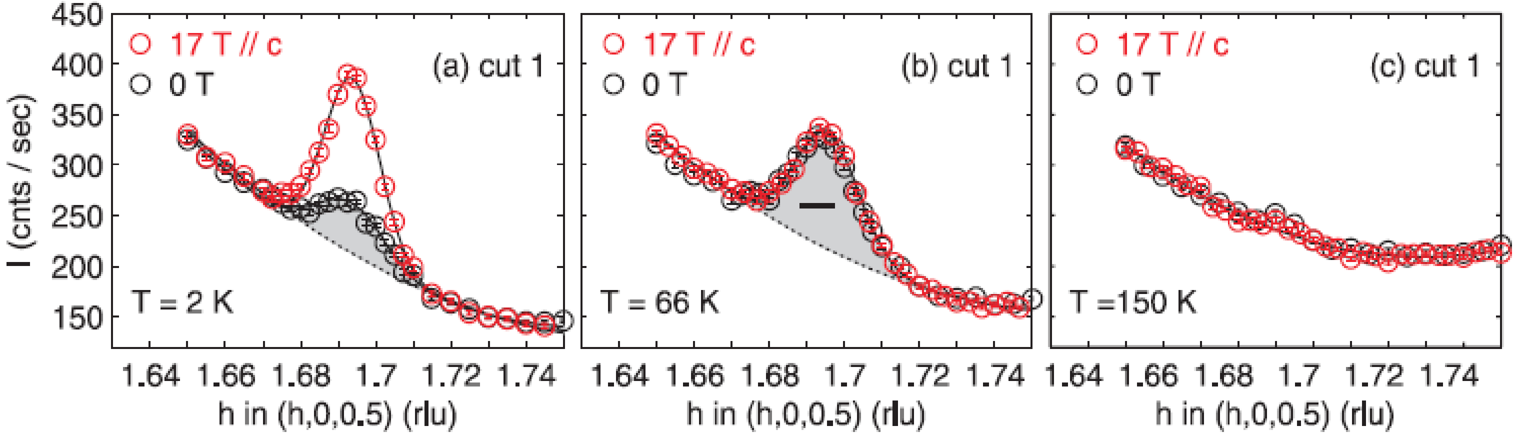
Intensity: few x 10^{-6} of the (200) (strongest charge peak)

Incommensurate

$$\boldsymbol{q}_1 = (0.305,\ 0,\ 0.5)$$

Adjacent cells along the ***c***-direction in antiphase

What happens as we change temperature?

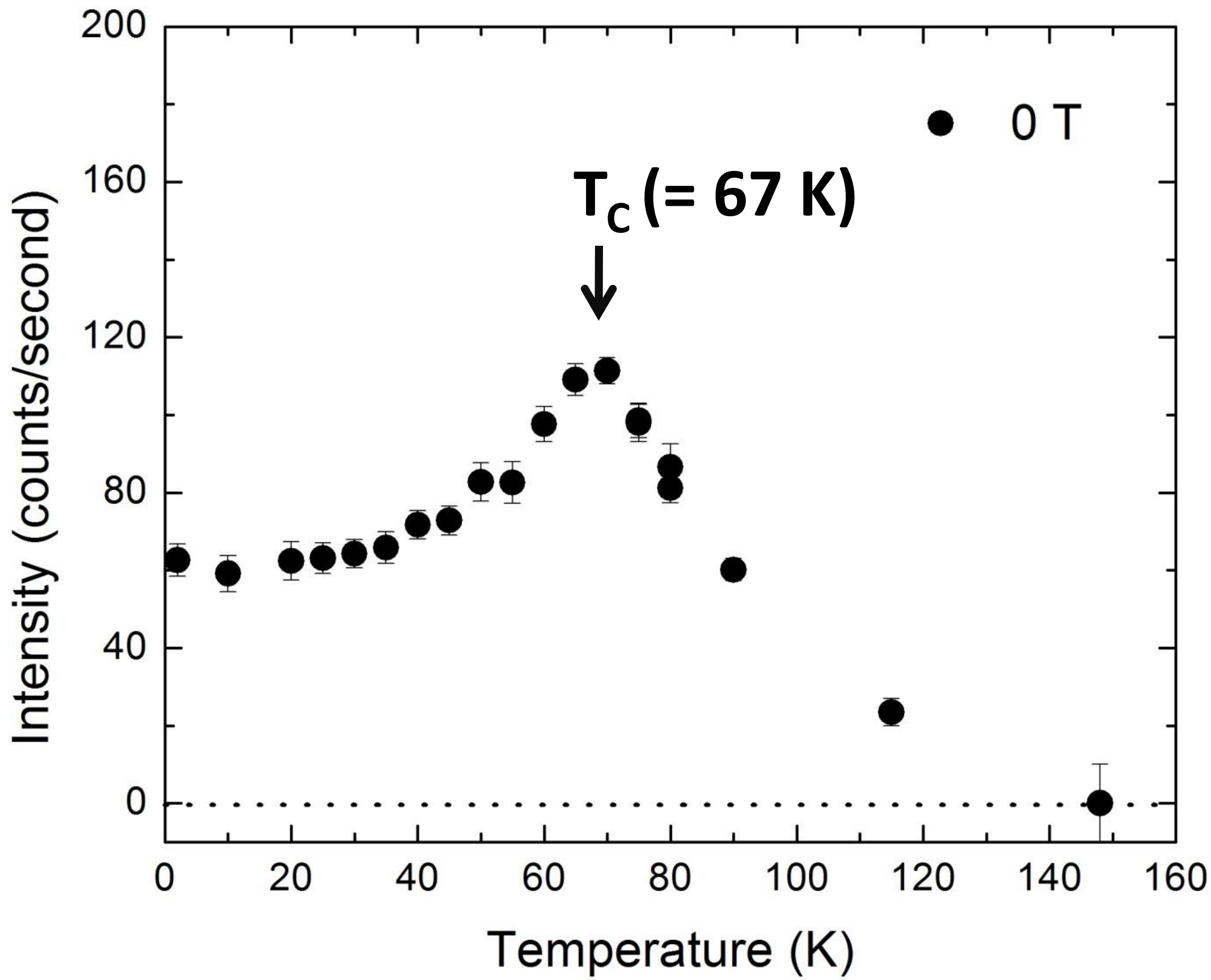


CDW Peak disappears at high T

No field-dependence above superconducting T_c

As superconductivity is suppressed by field, CDW increases

What happens as we change temperature?



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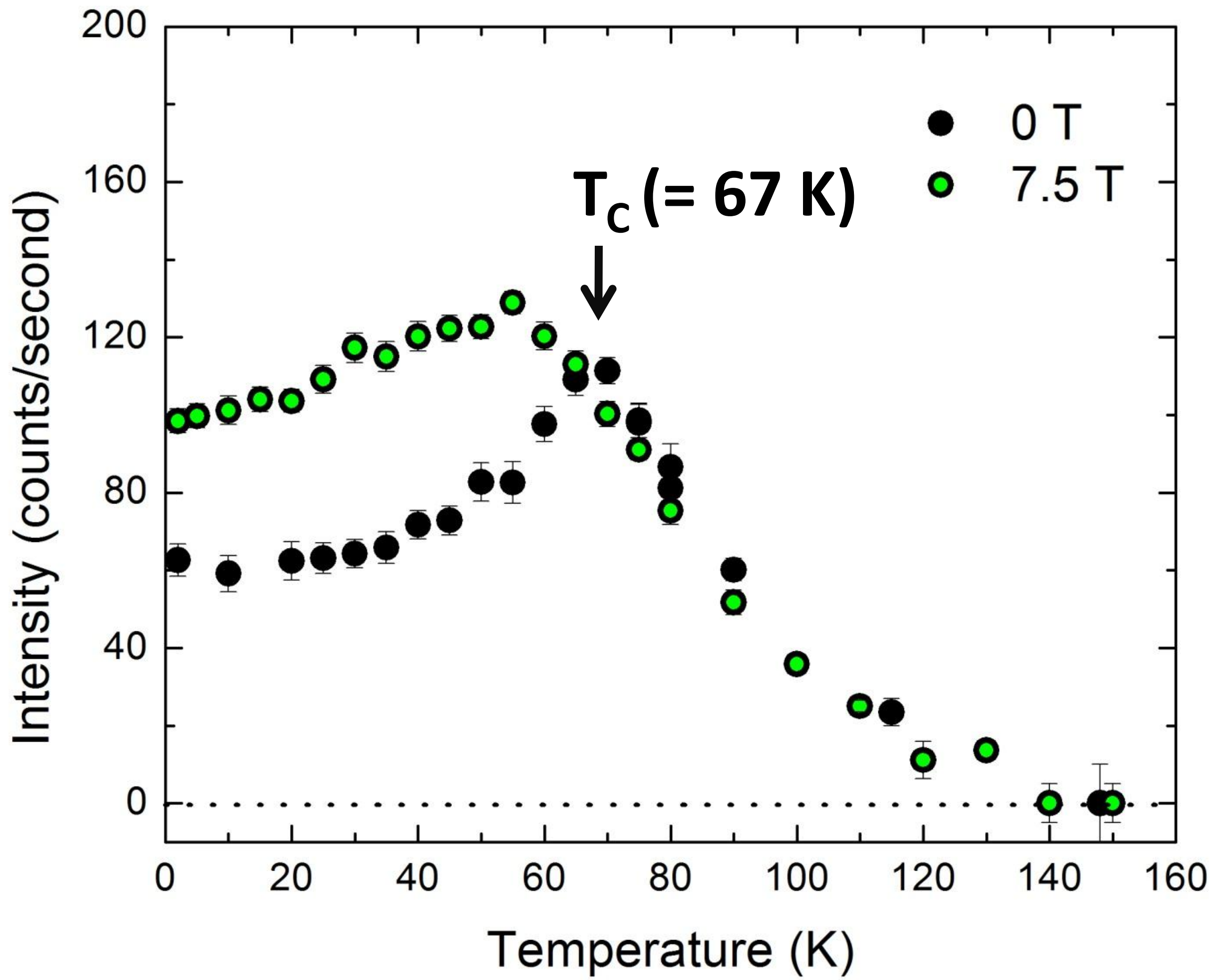

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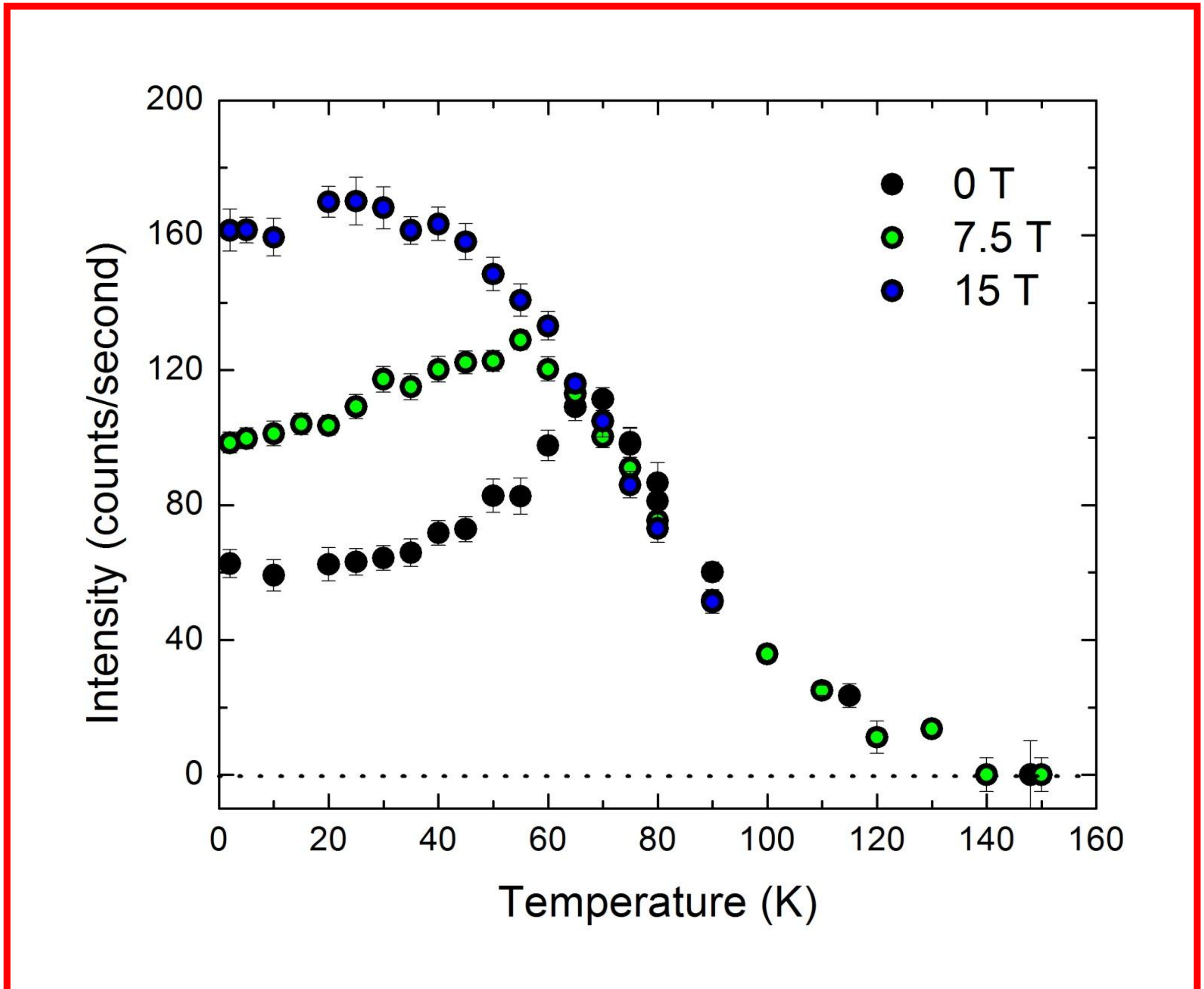

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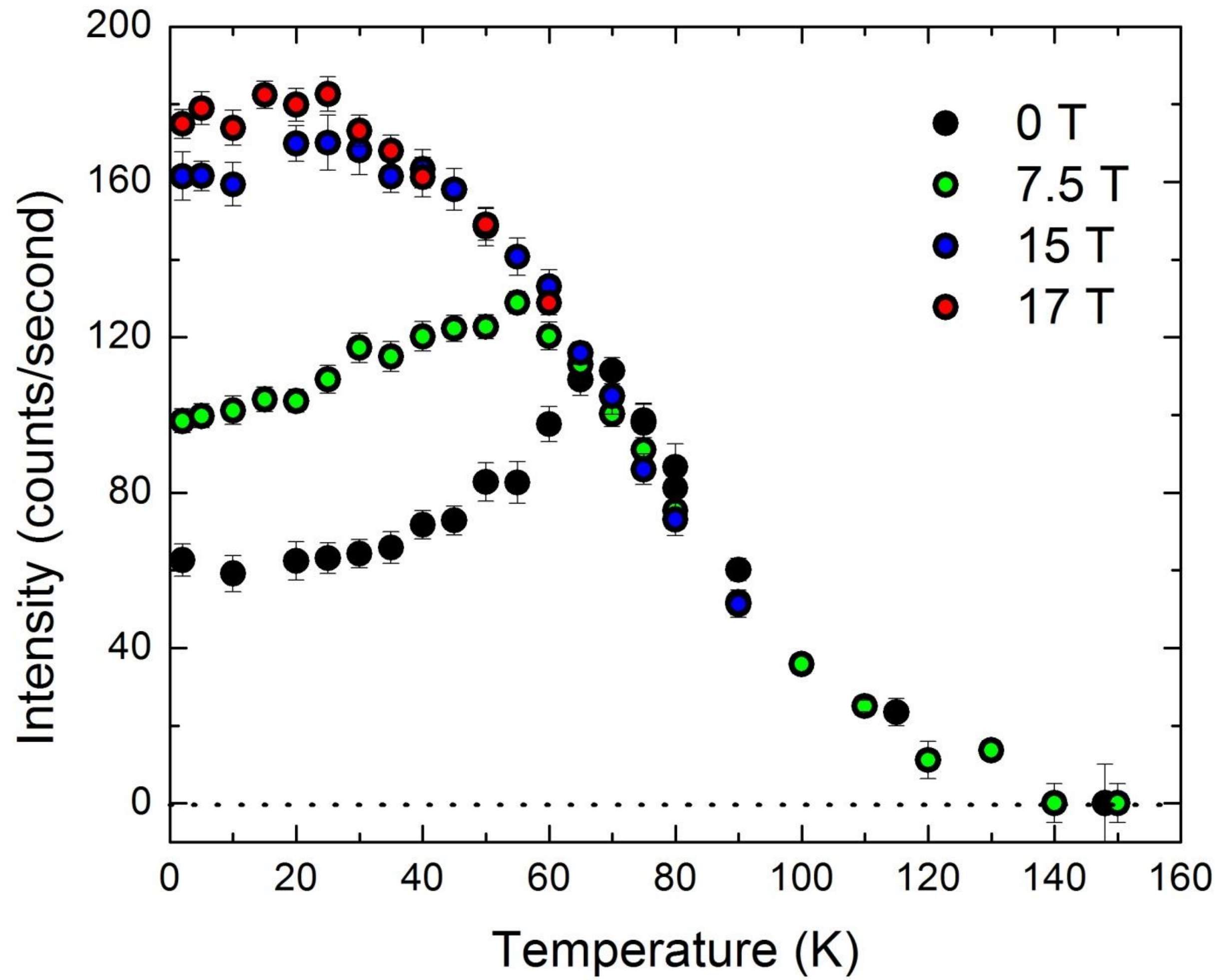
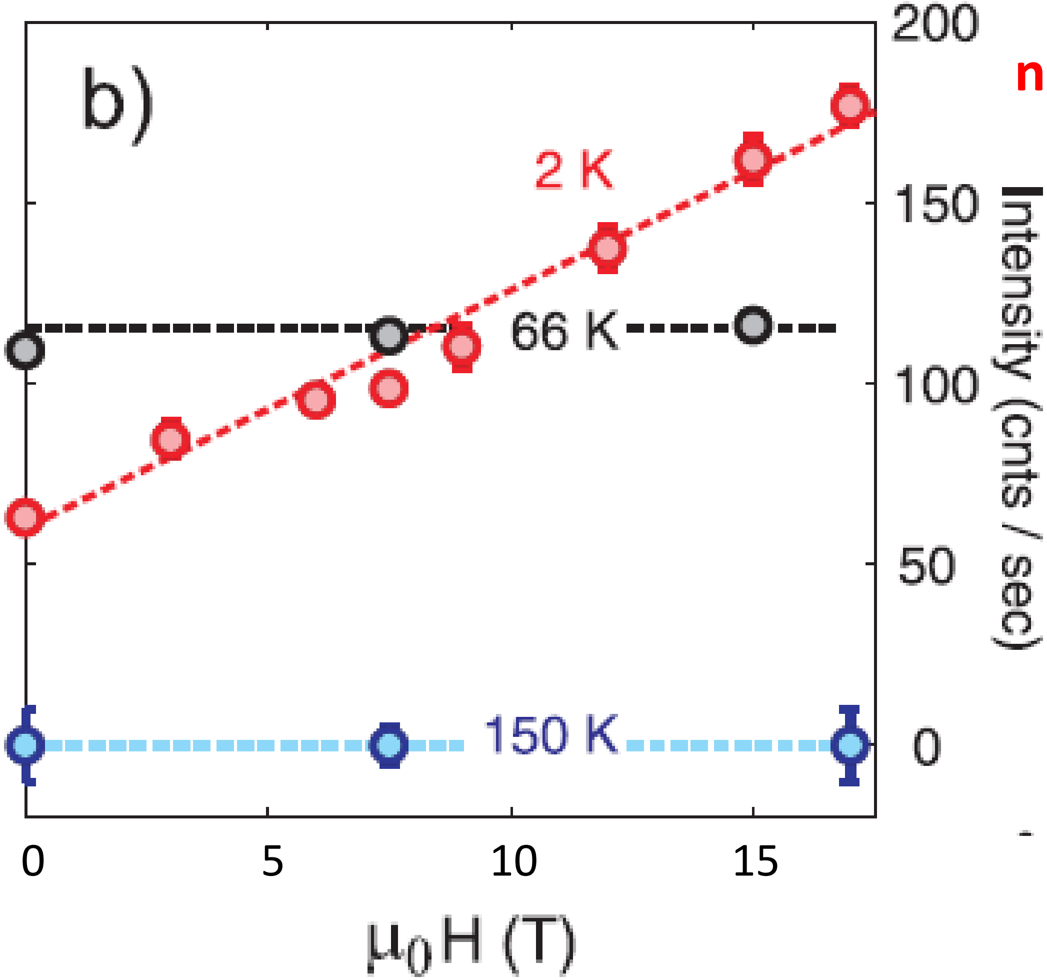
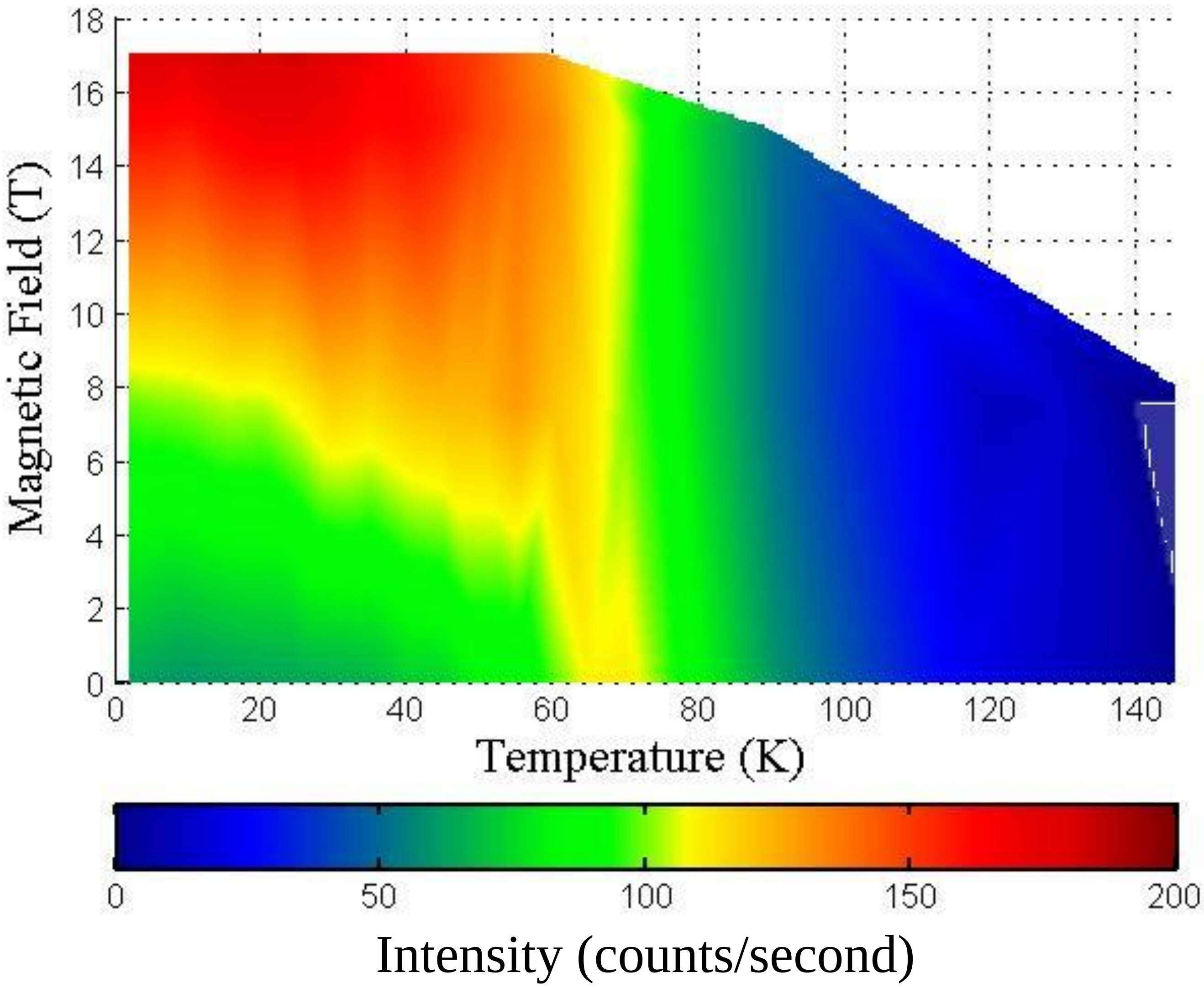


Field dependence

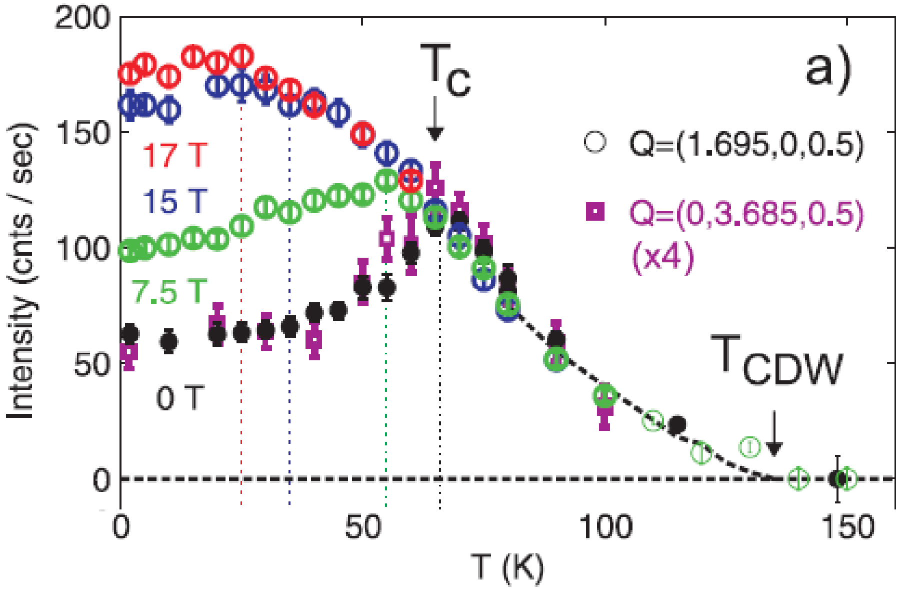


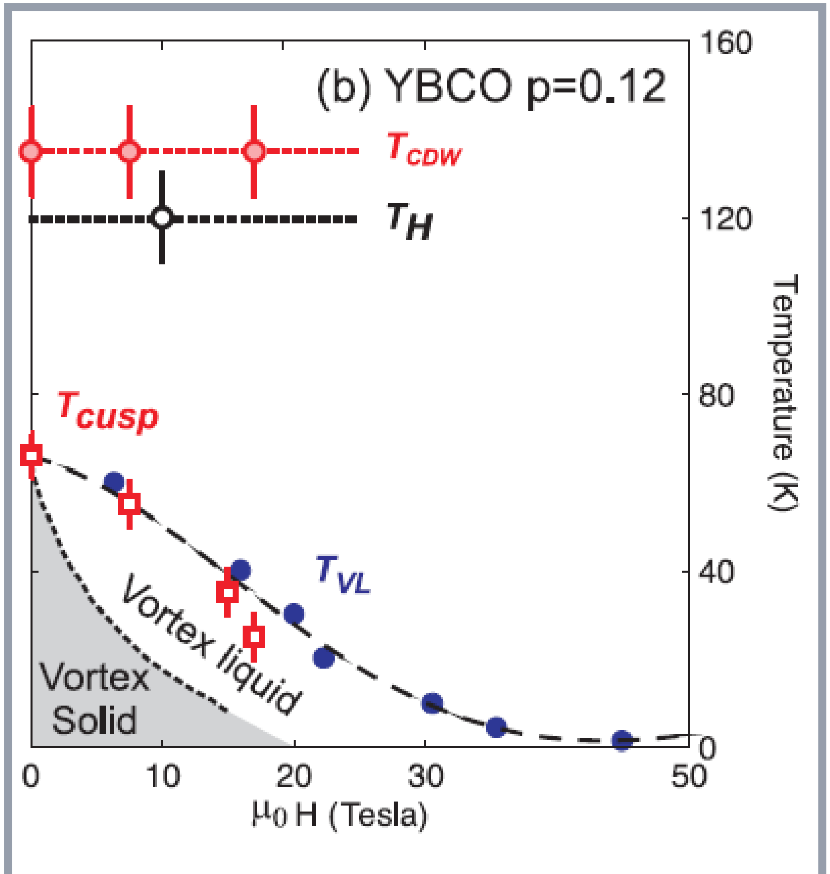
not saturated

TEMPERATURE AND FIELD DEPENDENCE



TEMPERATURE OF MAX. CDW AS $F(B)$



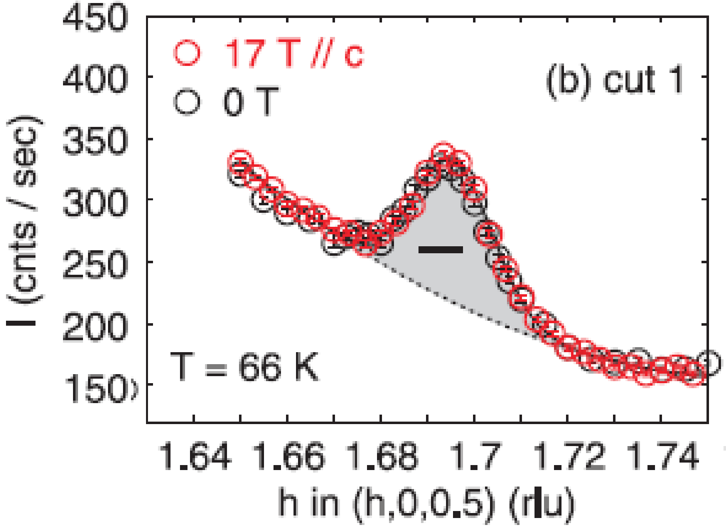


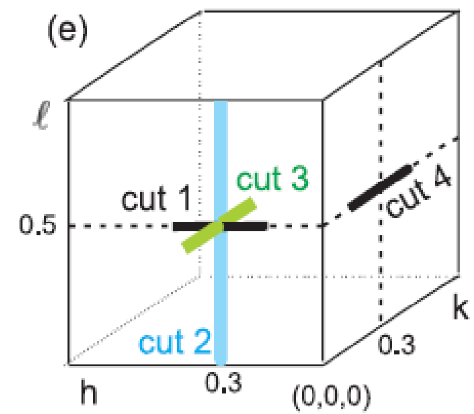
T_{cusp} is temperature of maximum CDW intensity

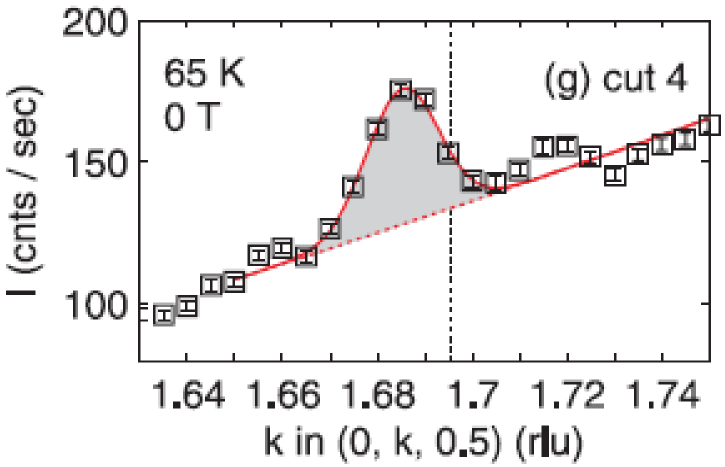
- coincides with $H_{c2}(T)$ line

T_{VL} and T_{VS} from LeBoeuf *et al.*, PRB **83**, 054506 (2011).

WHAT ABOUT THE OTHER IN-PLANE DIRECTION?



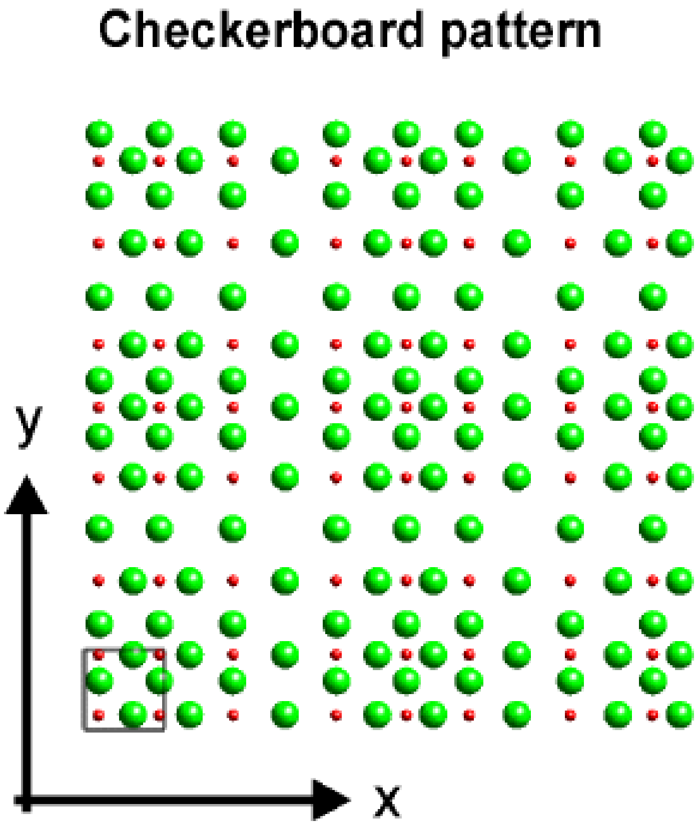


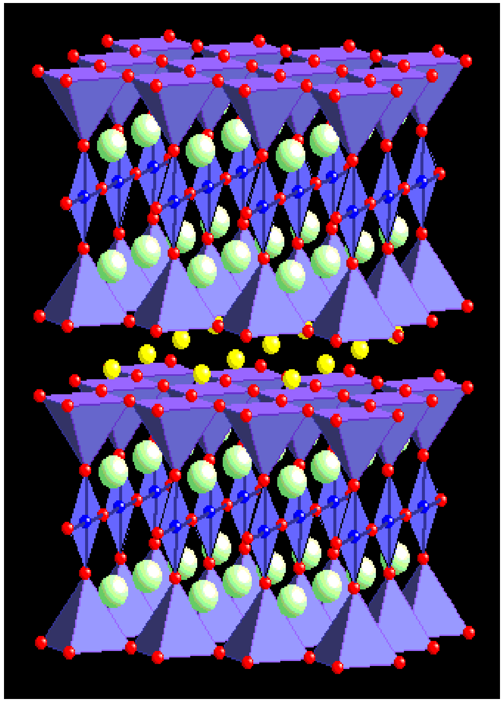


$$\boldsymbol{q_1} = (0.305,\ 0,\ 0.5)$$
$$\boldsymbol{q_2} = (0,\ 0.315,\ 0.5)$$

Two similar $\perp$ $\boldsymbol{q}$'s indicate that the CDW originates in the CuO_2 planes

POSSIBLE CuO_2 PLANE DISPLACEMENTS



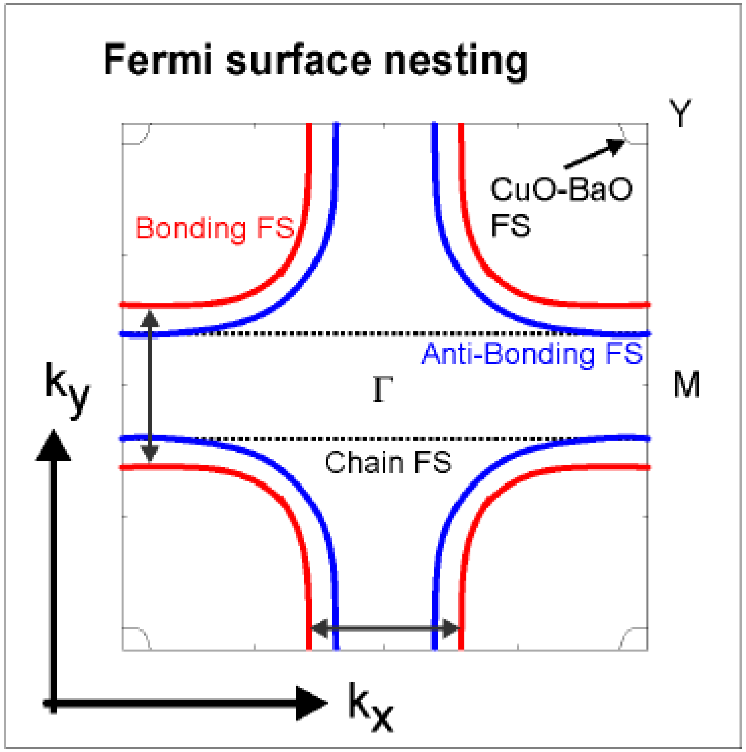


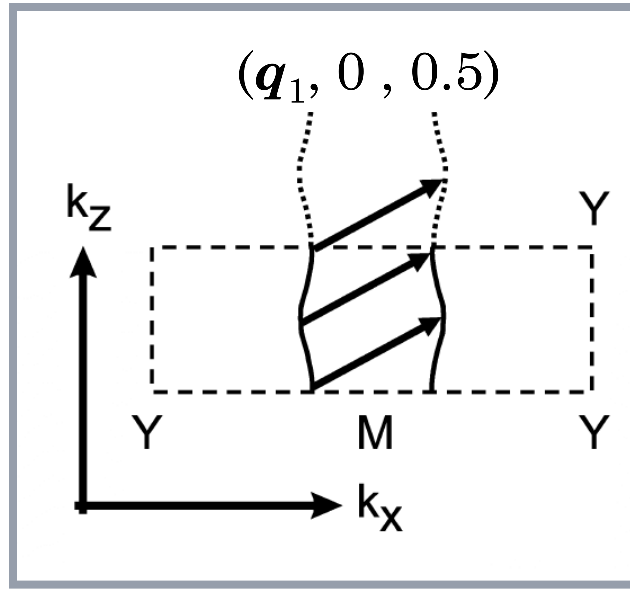
oxygen, copper

Our experiment cannot definitively distinguish 1-***q*** and 2-***q*** patterns

YBCO structure from: www.ncl.ox.ac.uk/icl/heyes/structure_of_solids/lecture4/lec4.html

Fermi Surface Nesting and the CDW?



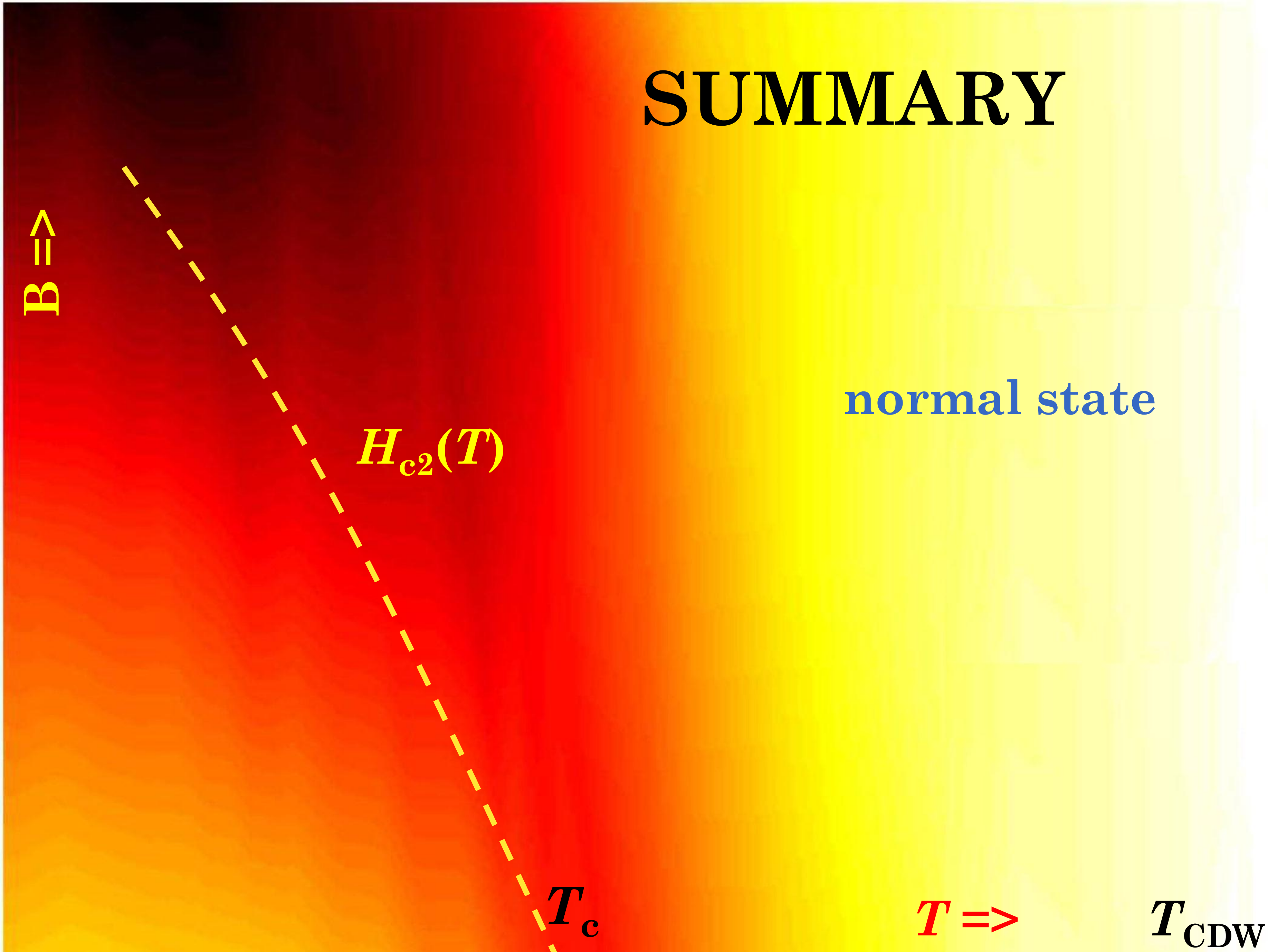


Note: (iii) $\boldsymbol{q}_{\mathrm{L}} = 0.5$ may reflect FS nesting (or Coulomb effects)

Note: (i) the $\boldsymbol{q}_{\mathrm{CDW}}$ connects two pieces of Fermi Surface with the maximum value, and same sign, of the superconducting order parameter Δ.

Note: (ii) the $\boldsymbol{q}_{\mathrm{CDW}}$ can "chop up" the Fermi surface and give the small electron-like pieces as observed by Quantum Oscillations.

SUMMARY



Angela Merkel visiting DESY last month

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