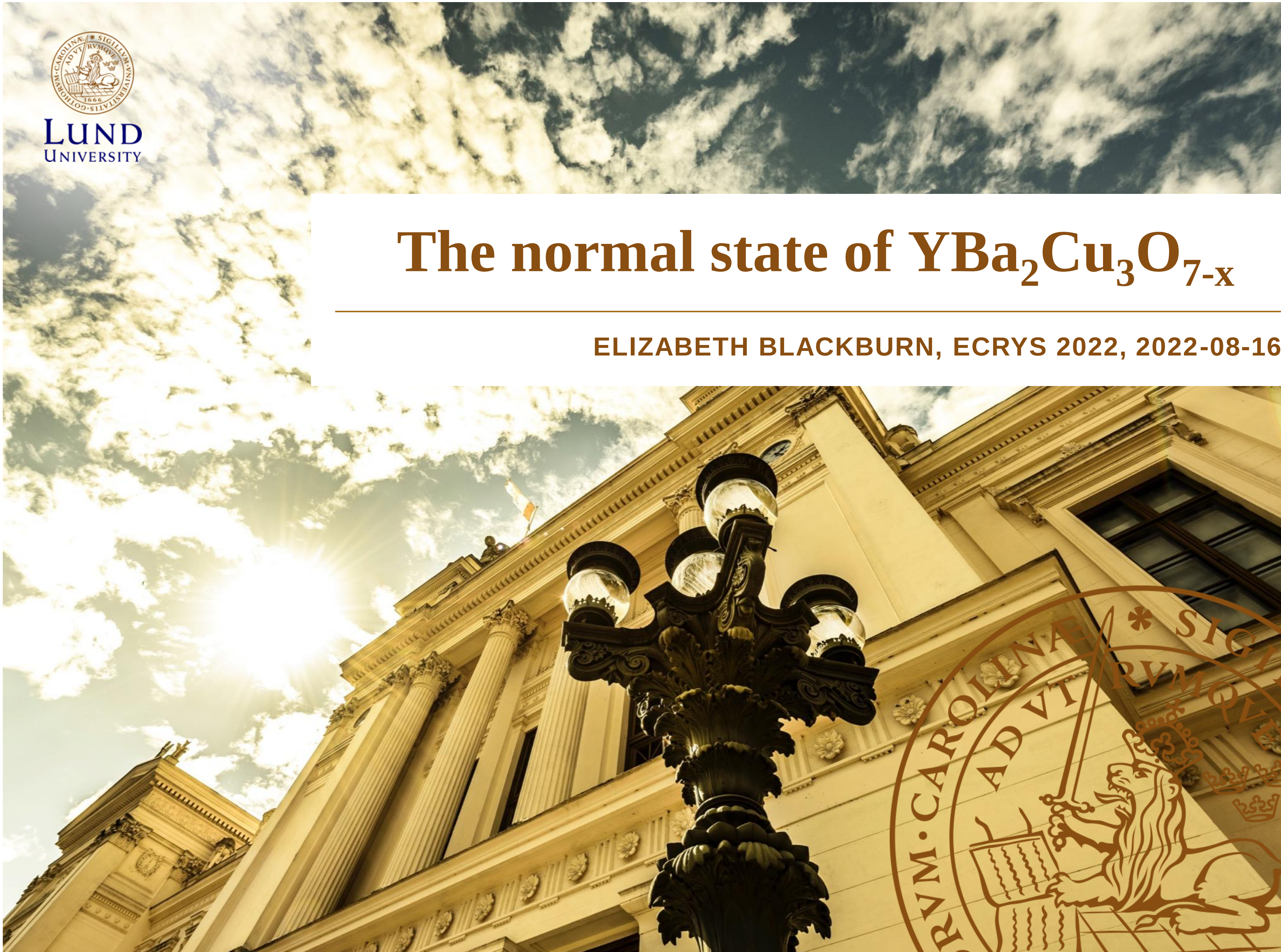

The normal state of $YBa_2Cu_3O_{7-x}$

ELIZABETH BLACKBURN, ECRYS 2022, 2022-08-16

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Emma Campillo

University of Birmingham — Ted Forgan

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University of Bristol — Stephen Hayden

Universität Zürich UZH — Johan Chang

BAdW — Andreas Erb

DESY — Oleh Ivashko, Martin von Zimmerman

Outline – experimental data from YBCO

- Introduction to YBCO

- The vortex lattice at high magnetic fields

  - introducing the vortex lattice
  - how does it normally behave?
  - deviations from the London model

- Looking for a diffraction signature from the pair density wave
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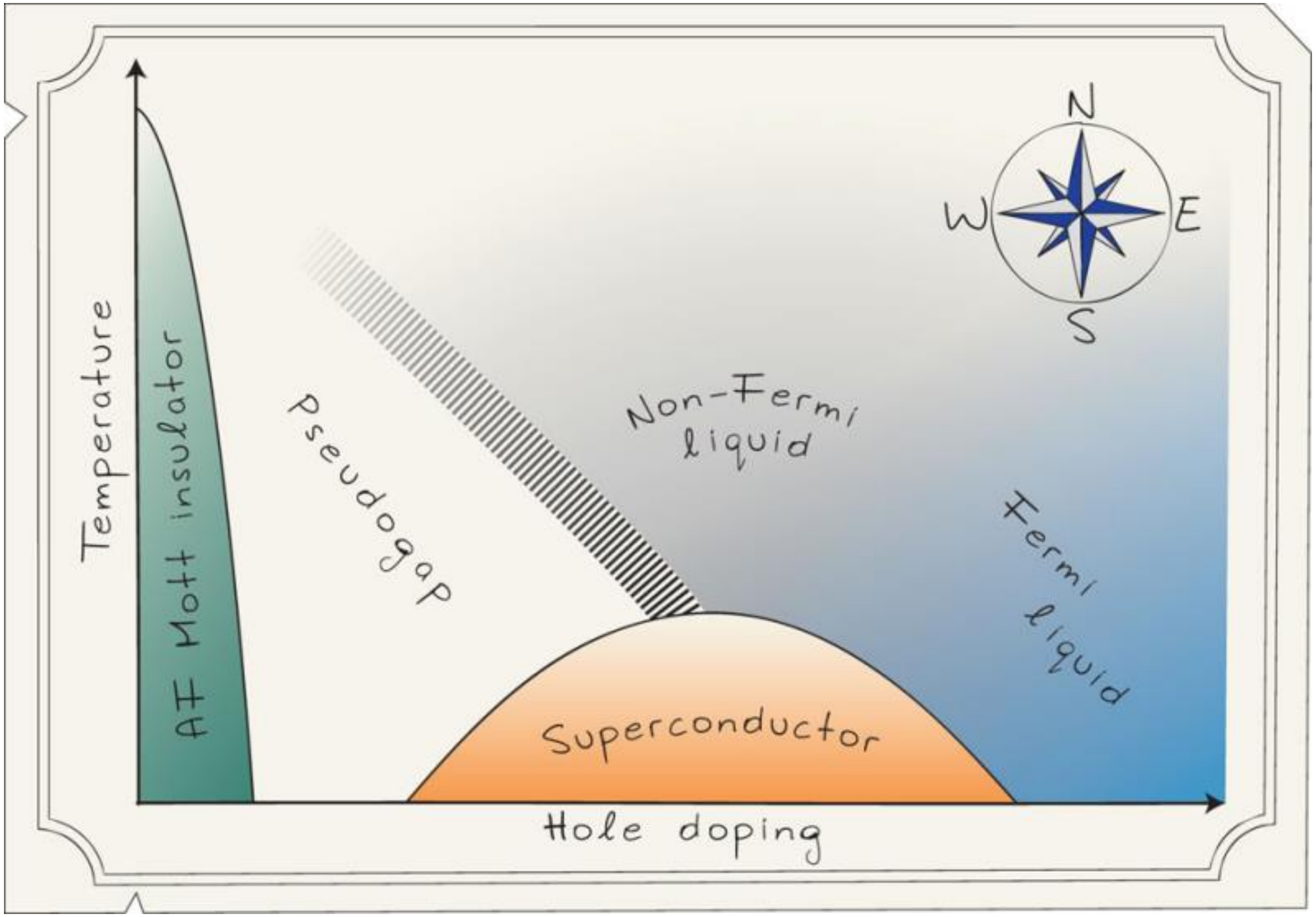
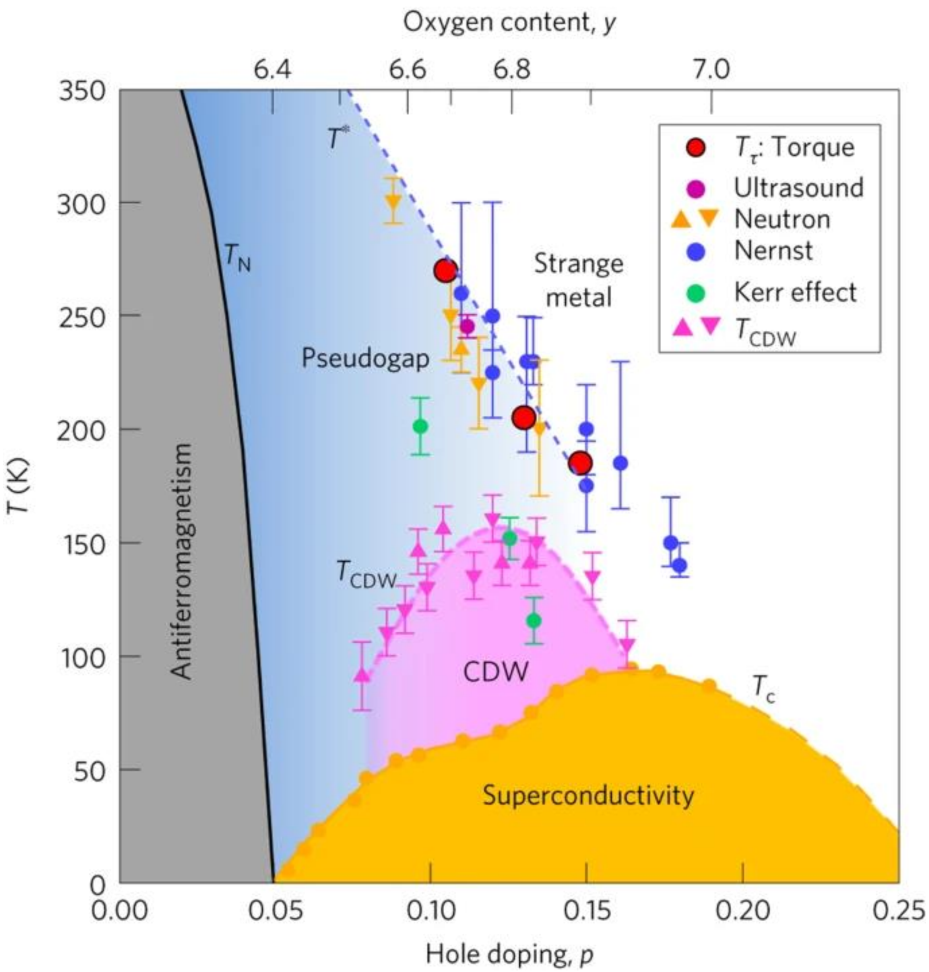
Cuprate phase diagram



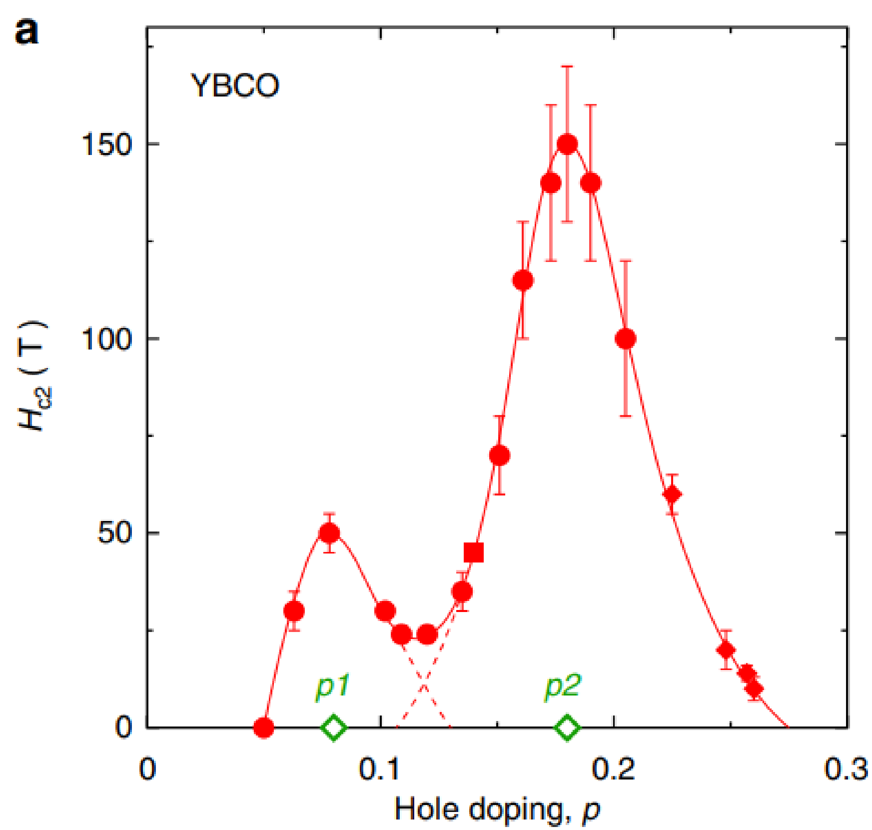
Wahl, Nature Physics (2012)

Electronic instabilities in the cuprates



Sato *et al.*, Nature Physics **13**, 1074 (2017)

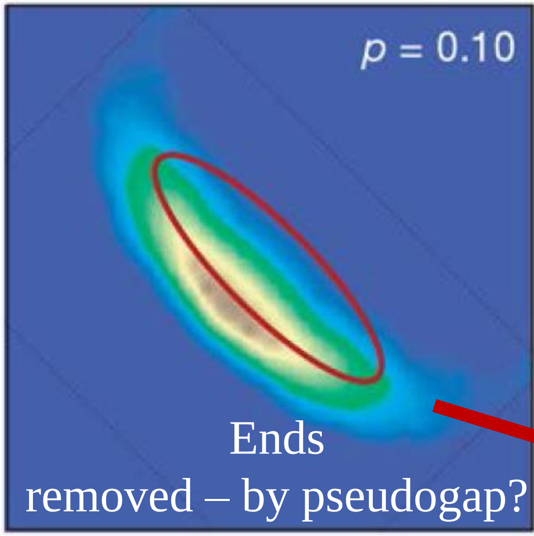
Grissonnanche *et al.*,
Nature Comms **5**, 3280 (2014)

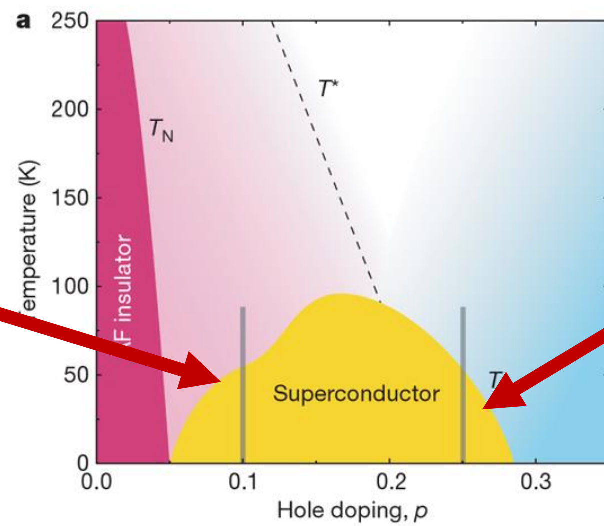


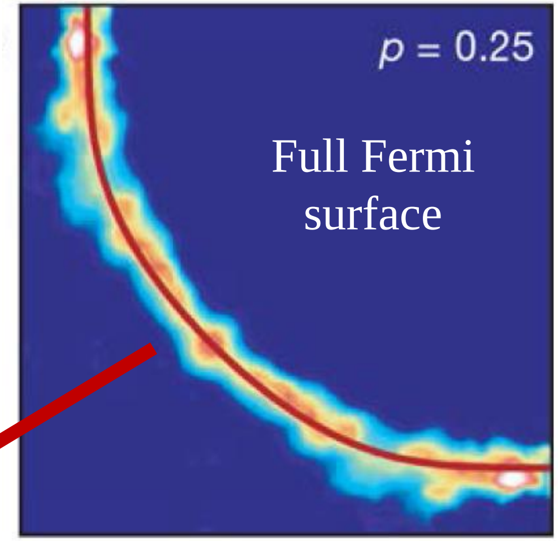
Hc2 is defined as the onset of the vortex-solid phase as T → 0, as measured from high-field resistivity data

Underdoping to overdoping

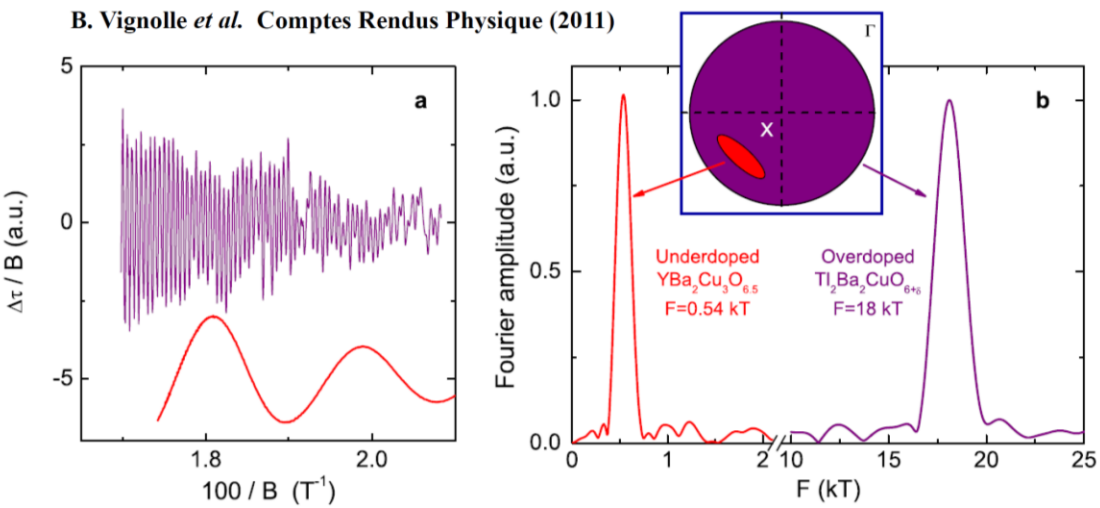
Doiron-Leyraud *et al.*, Nature (2007); Plate *et al.*, PRL (2005); Shen *et al.*, Science (2005)



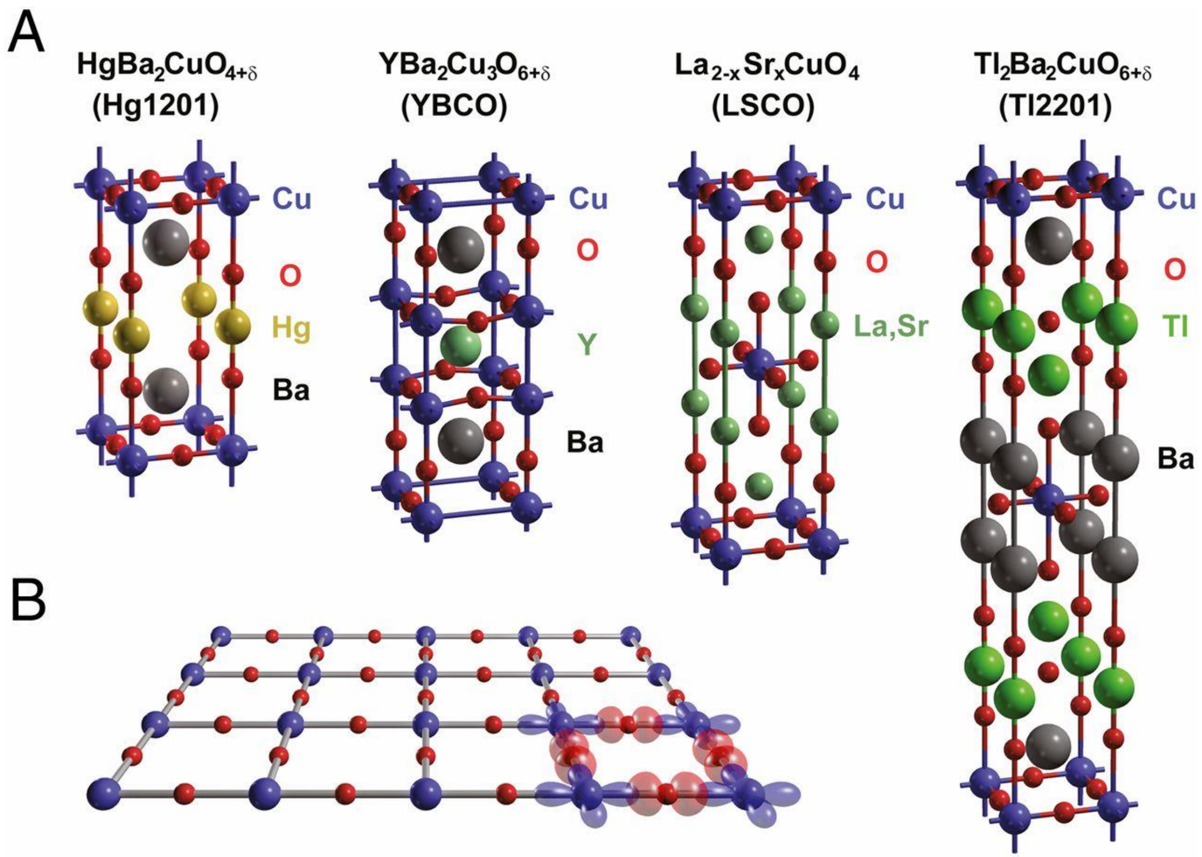




B. Vignolle *et al.* Comptes Rendus Physique (2011)



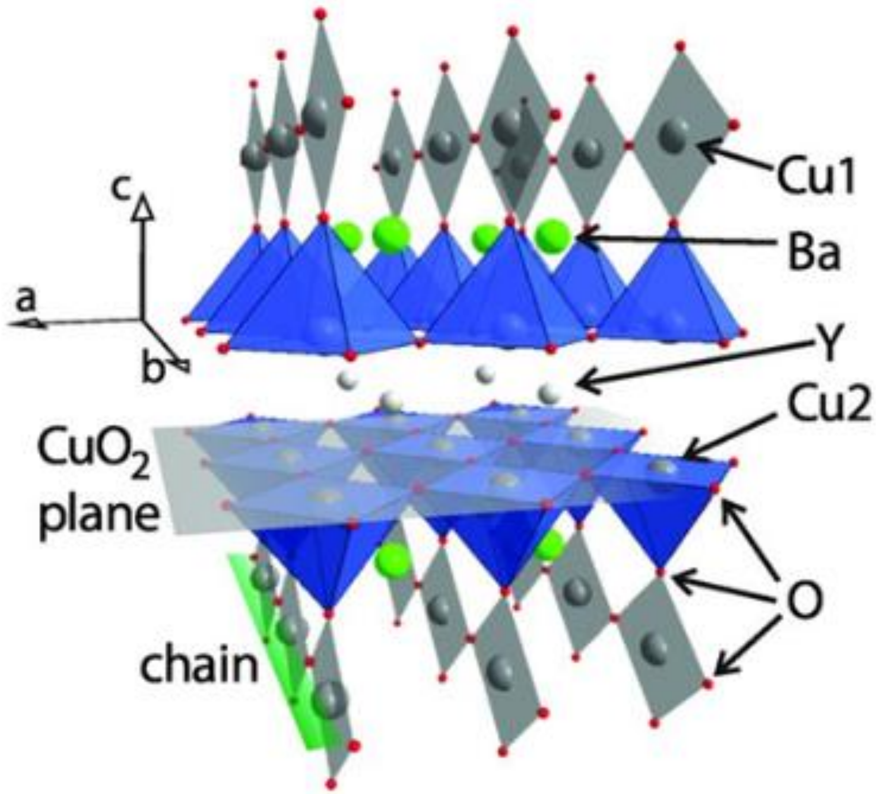
Introduction to $YBa_2Cu_3O_{7-d}$ (YBCO)



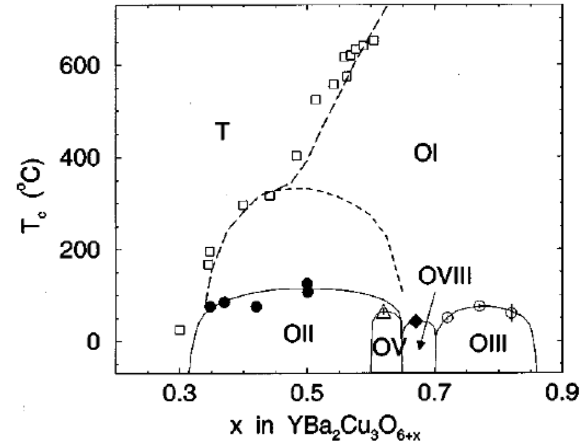
Copper-Oxygen Planes

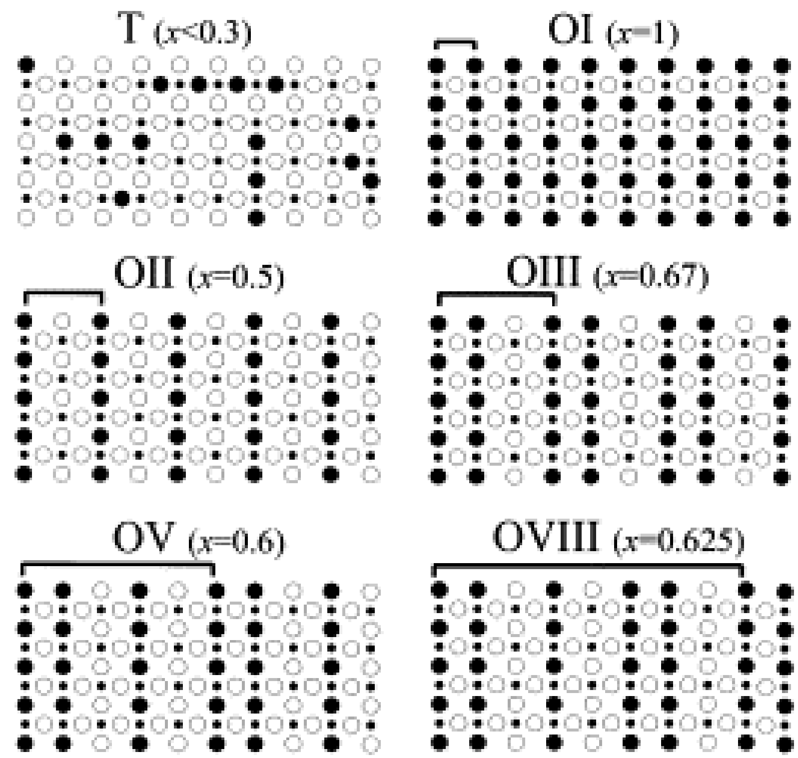
Barisic *et al.*, PNAS (2013)

Oxygen ordering in YBCO – the chains



Ghiringhelli *et al.*, Science **337**, 821 (2012)





Andersen *et al.*, Physica C **317**, 259 (1999).

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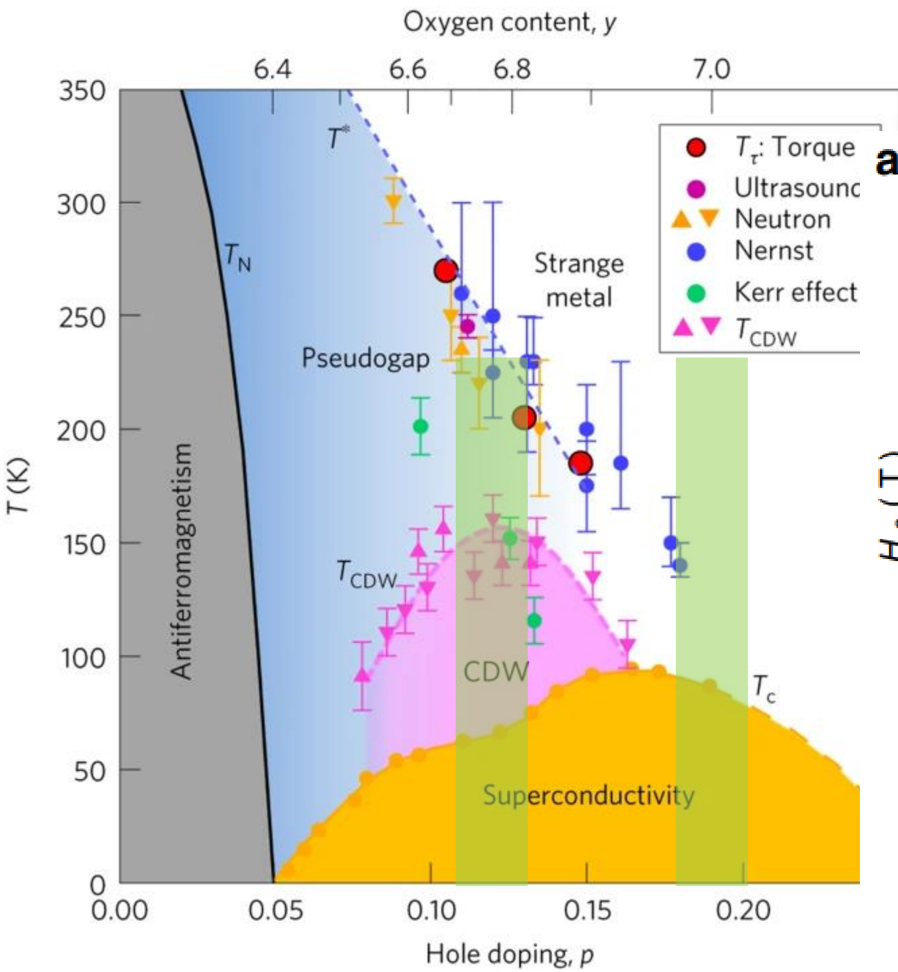

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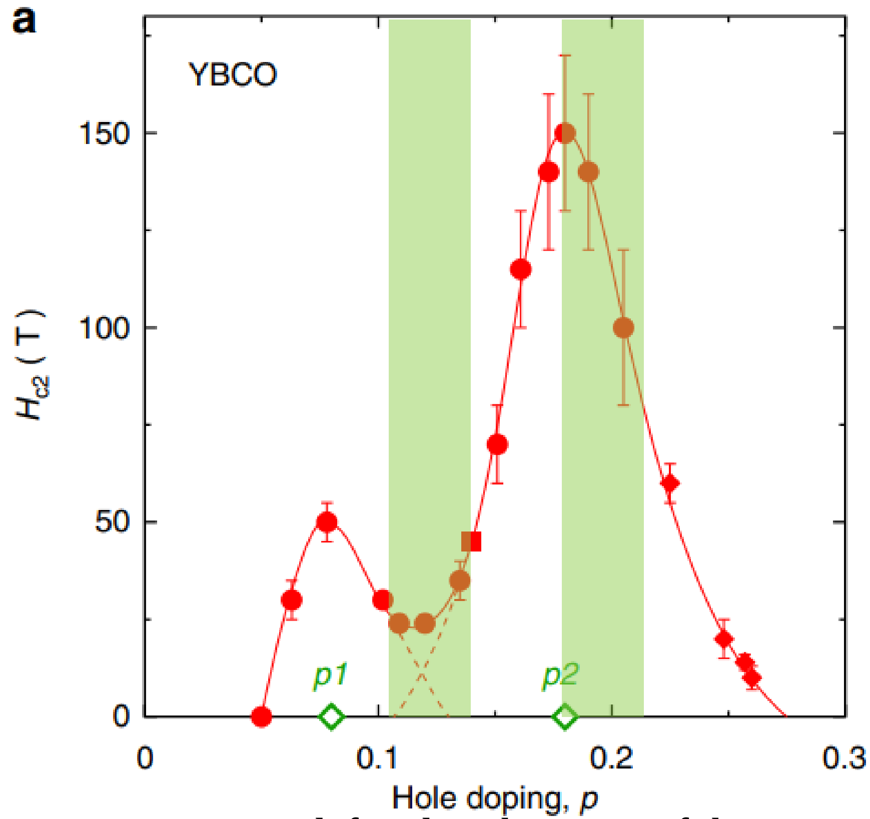

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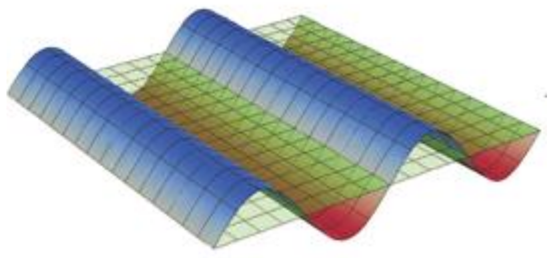
  - deviations from the London model

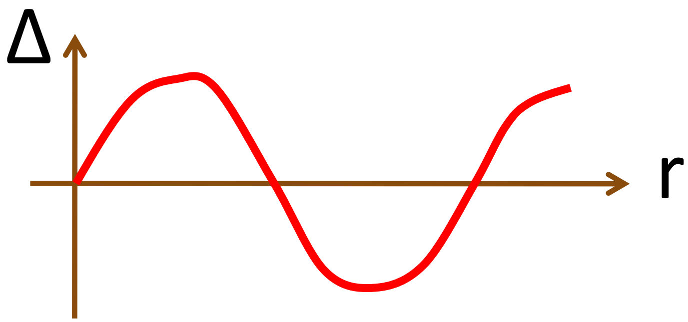
What are pair density waves?

A pair density wave is a superconducting state in which the order parameter varies periodically as a function of position in such a way that its spatial average vanishes.

Agterberg *et al.*, Annu. Rev. CMP **11**, 231 (2020)

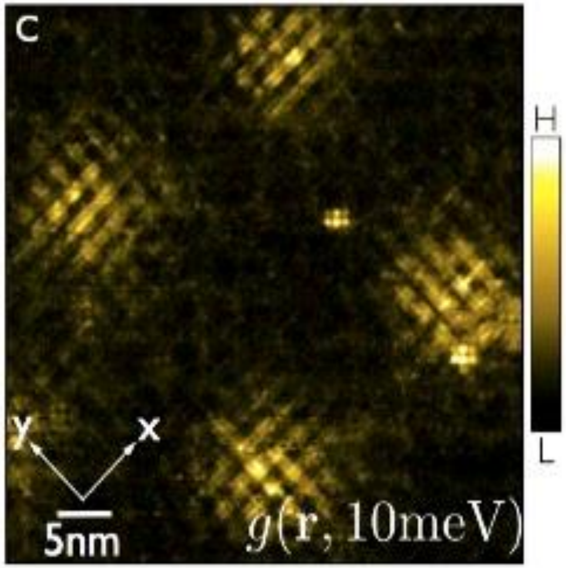


The PDW state does not necessarily break time-reversal symmetry

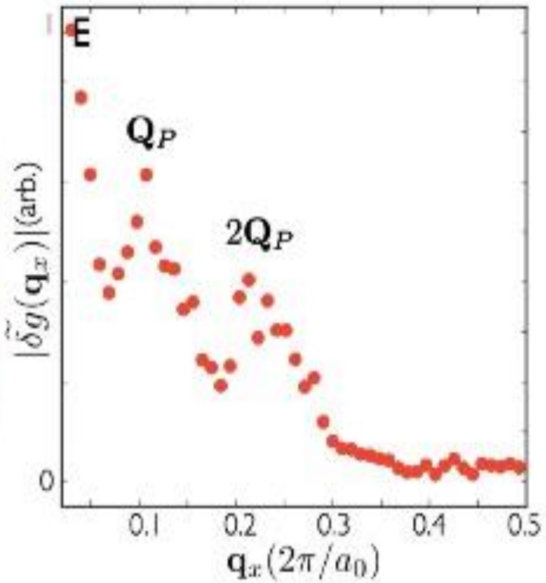


STM data – the PDW seen in field

STM (differential tunnelling conductance)



Amplitude Fourier transform



S. D. Edkins *et al*., Science **364**, 976 (2019).

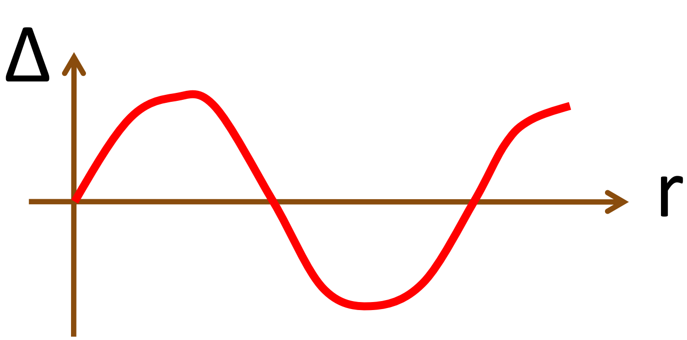
The right hand plot is obtained from data measured at 8.25 T, with the 0 T data subtracted.

What can we see with X-rays?

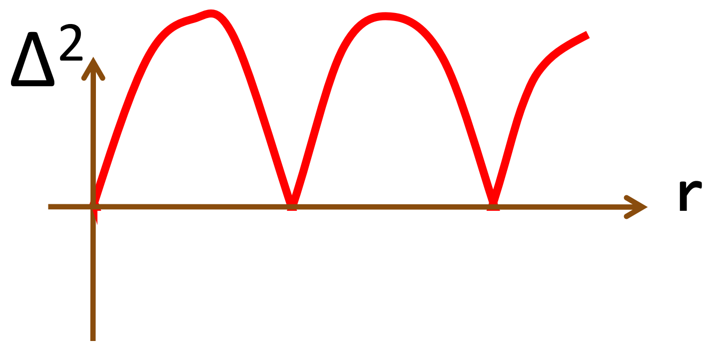
For the charge density wave, the X-rays are scattered by the electrons, and so we are sensitive to spatial variation in the electron density.

The high energy X-rays are more sensitive to (induced) atomic displacements than purely charge displacements.

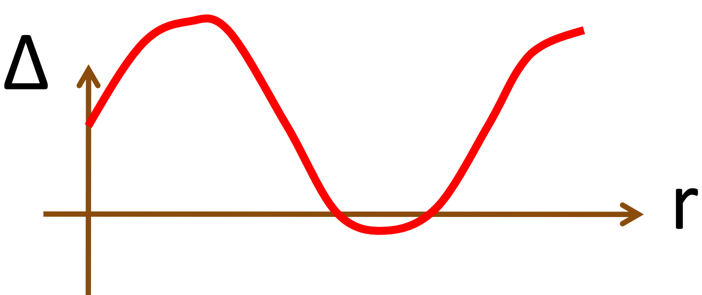
→ not directly sensitive to the pair density wave



$\rho_e(r) \propto |\Delta(r)|^2$



$\rho_e(r) \propto \Delta_1^2 \sin^2(qr)$ **2Q**PDW



Uniform SC OP PDW OP

$$\rho_e(r) \propto (\Delta_0^2 + 2\Delta_0\Delta_1 \sin(qr) + \Delta_1^2 \sin^2(qr))$$

QPDW **2Q**PDW

Y. Wang *et al.*, PRB 97, 174510 (2018)

STM data – the PDW seen in field

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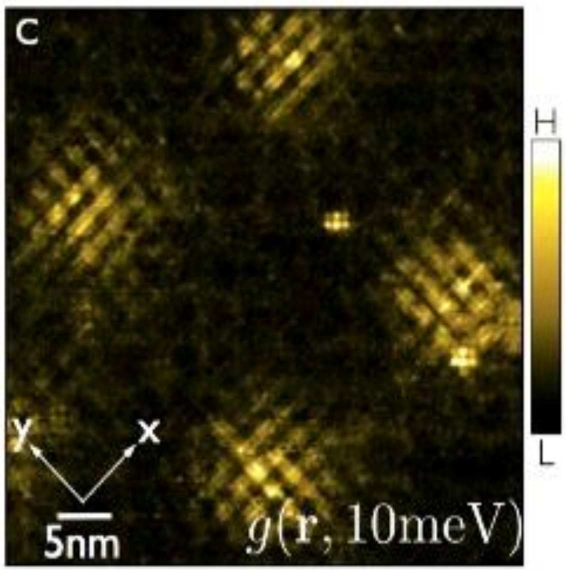

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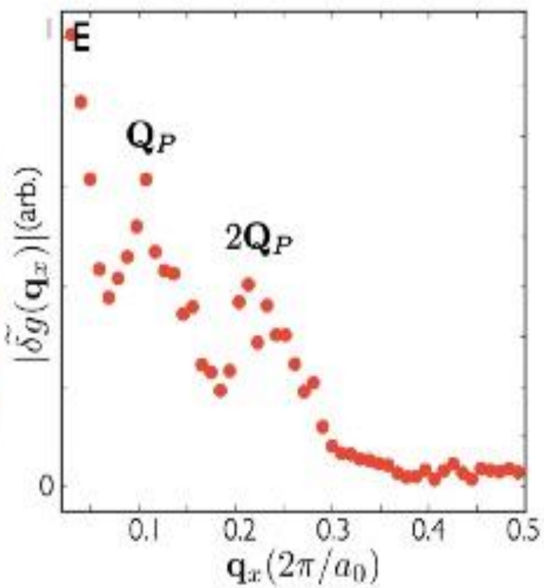

S. D. Edkins *et al*., Science **364**, 976 (2019).

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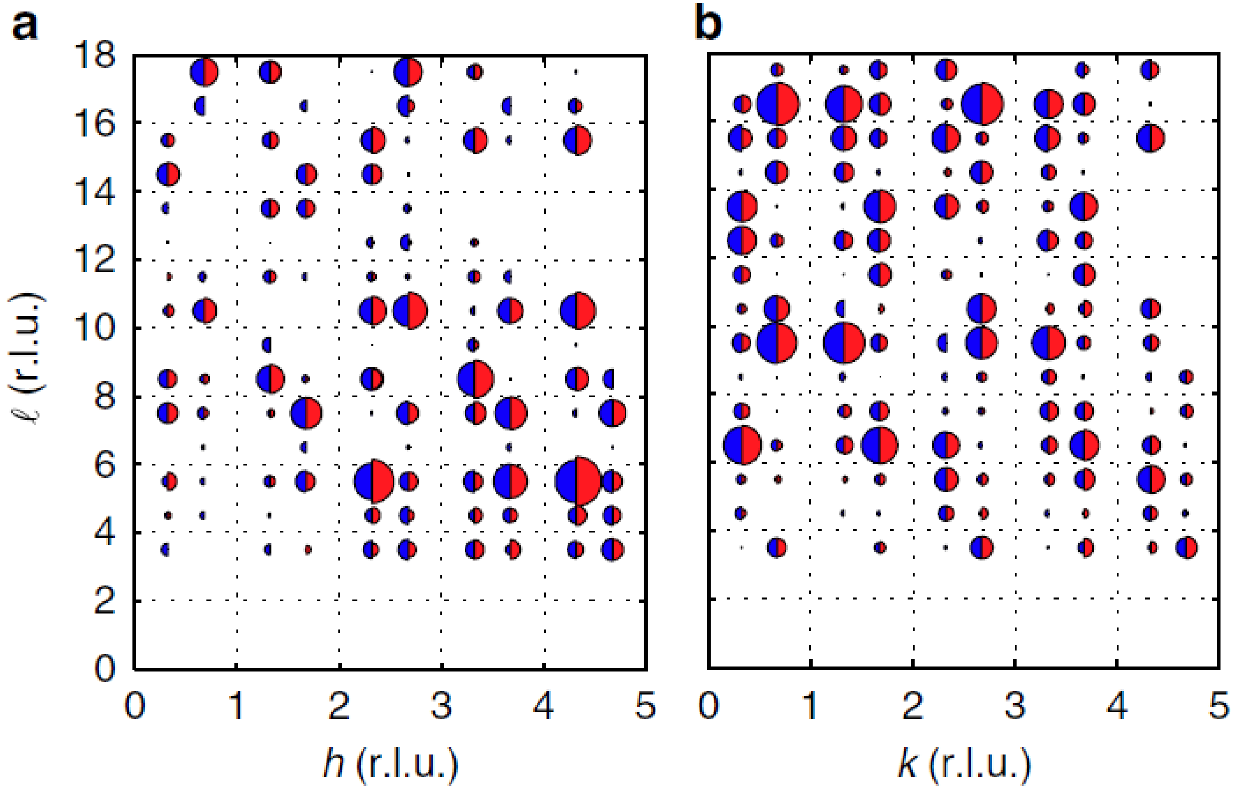
Where to look in reciprocal space?

The CDW satellites in ortho-II (data, fit) @ 0 T



Forgan *et al*., *Nature Comms* **6**, 10064 (2015).

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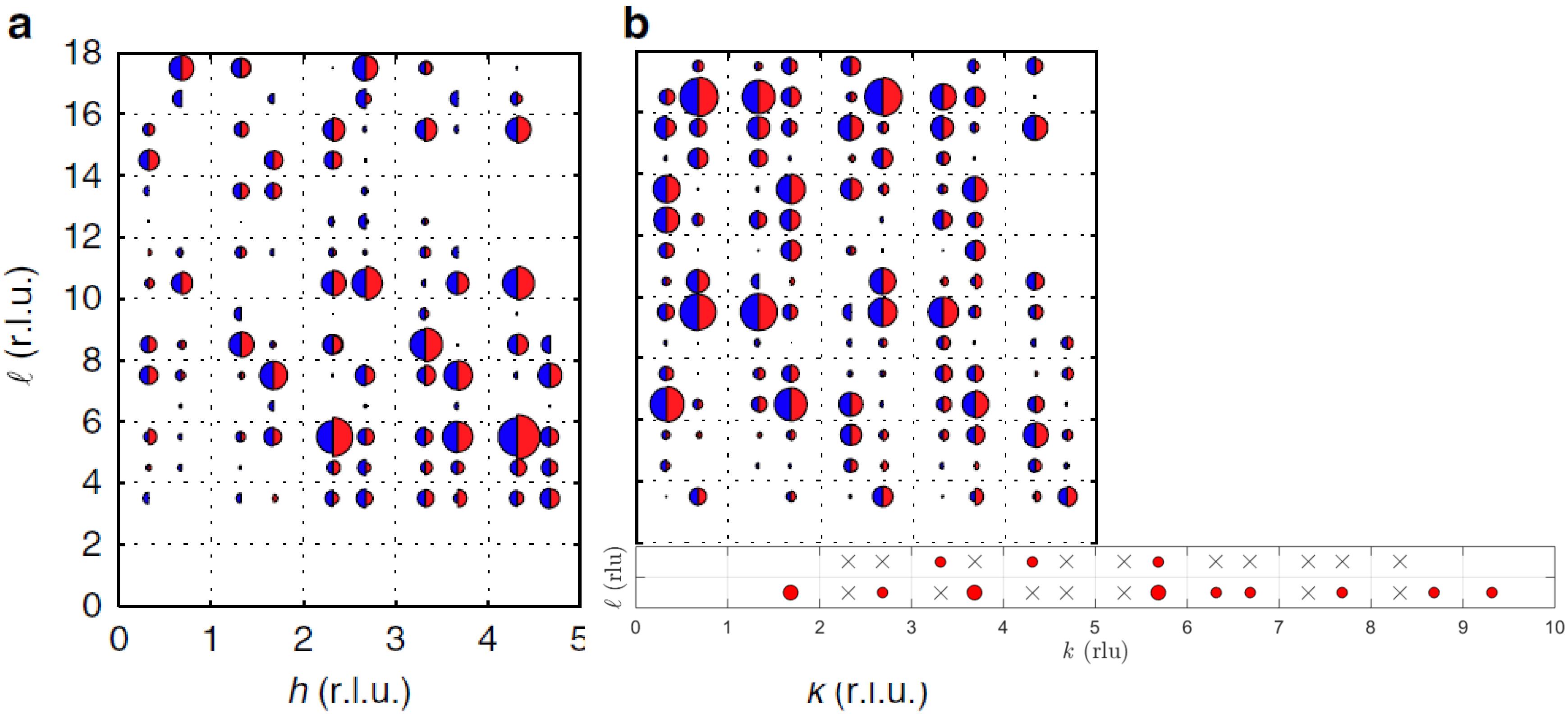


Forgan *et al.*, *Nature Comms* **6**, 10064 (2015).

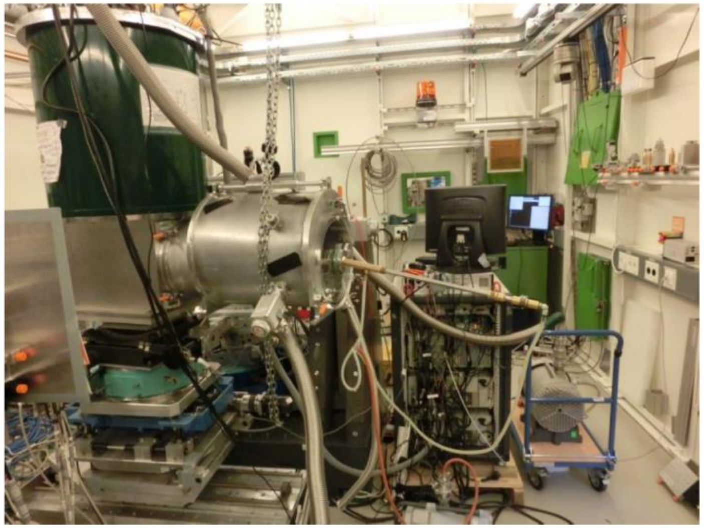
● good CDW signal

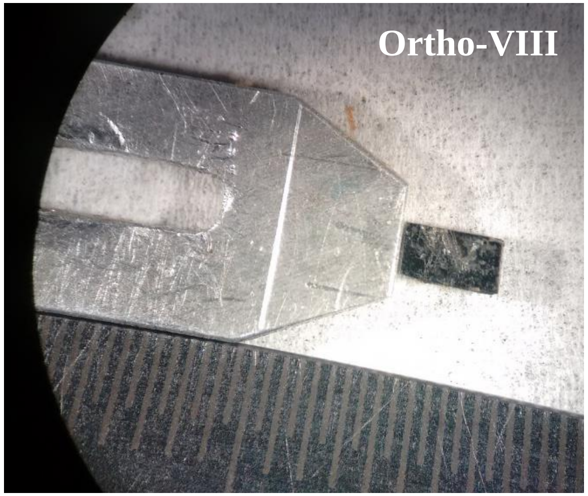
● weak CDW signal and/or background issues

✖ no clear CDW signal

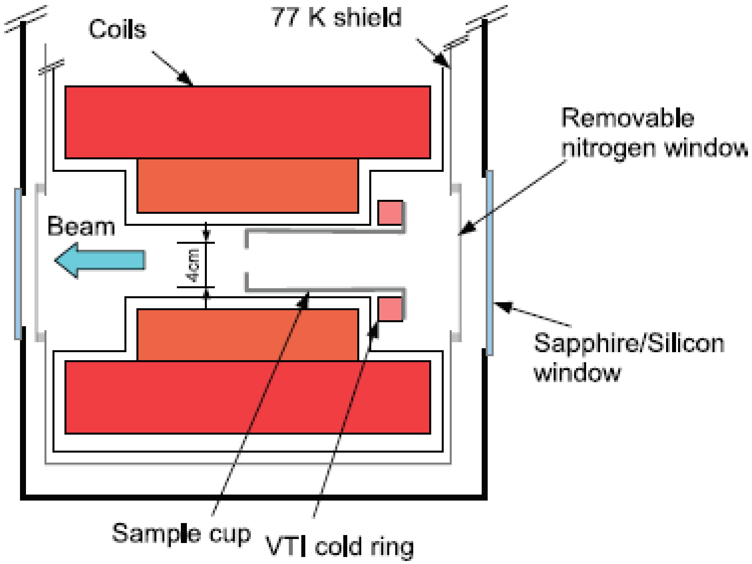
We also need high field

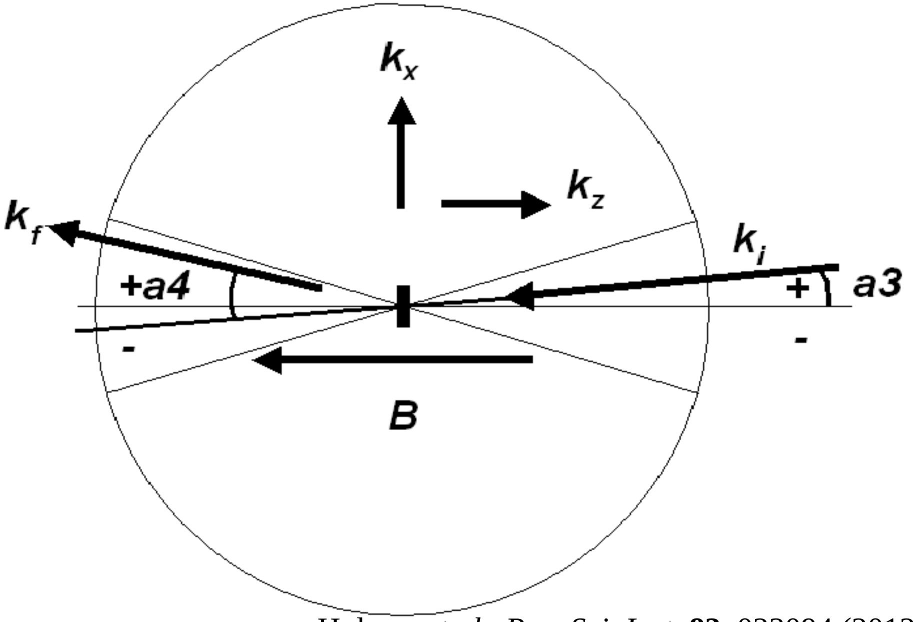
P07 @ PETRA





Liang, Bonn, Hardy

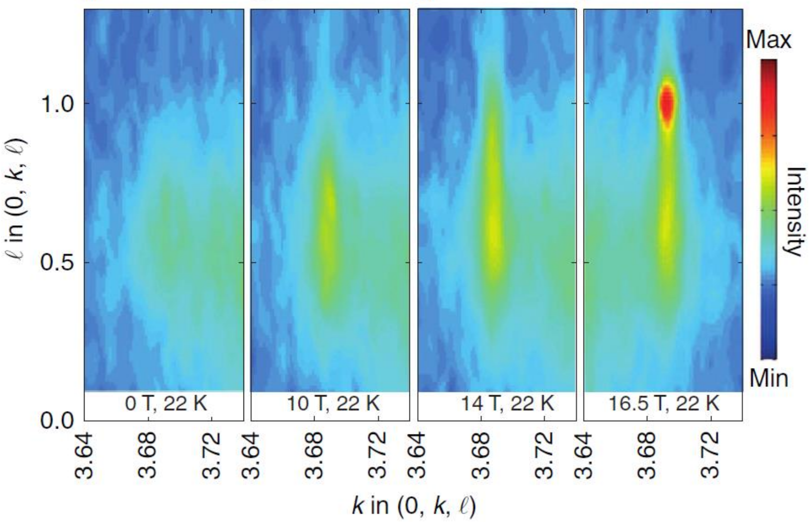




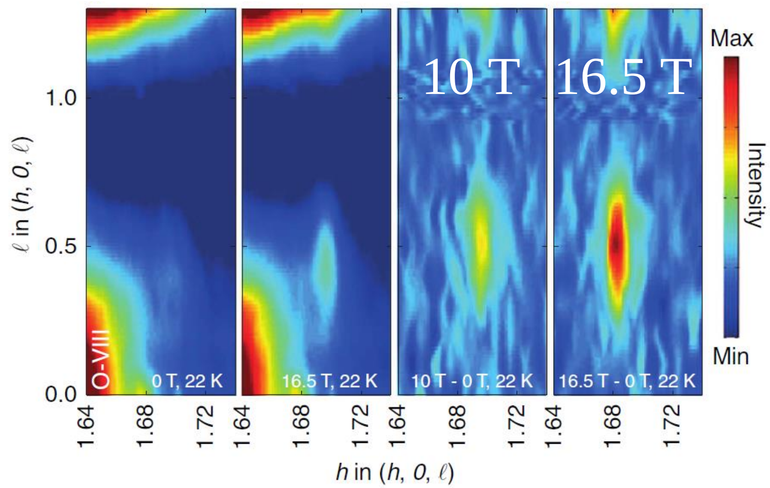
Holmes *et al.*, *Rev. Sci. Inst.* **83**, 023094 (2012).

CDW order in a large B field

0 T 10 T 14 T 16.5 T

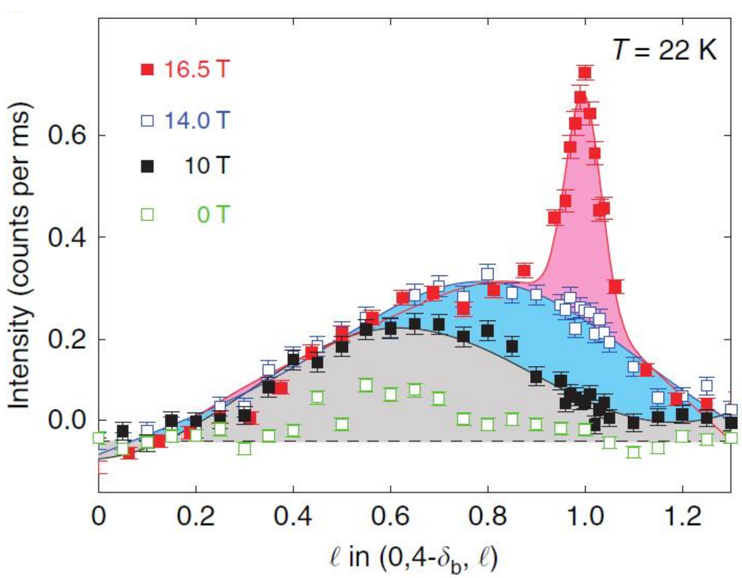


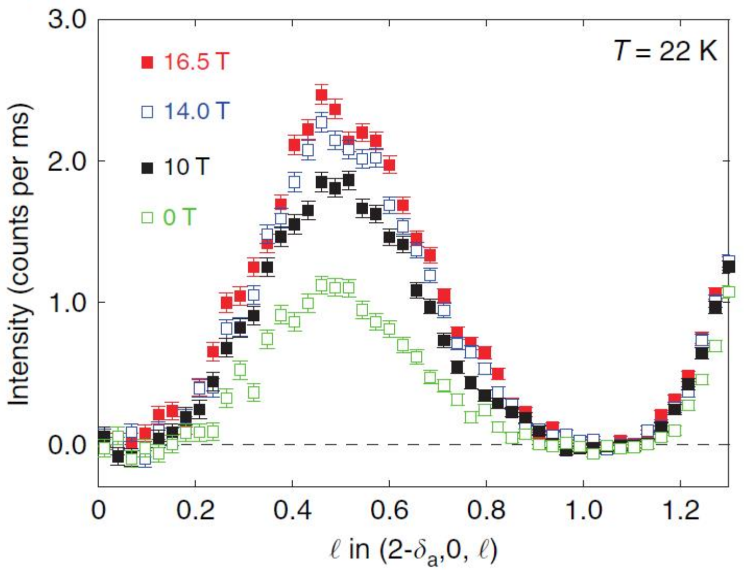
Chain order signal Subtract off 0 T



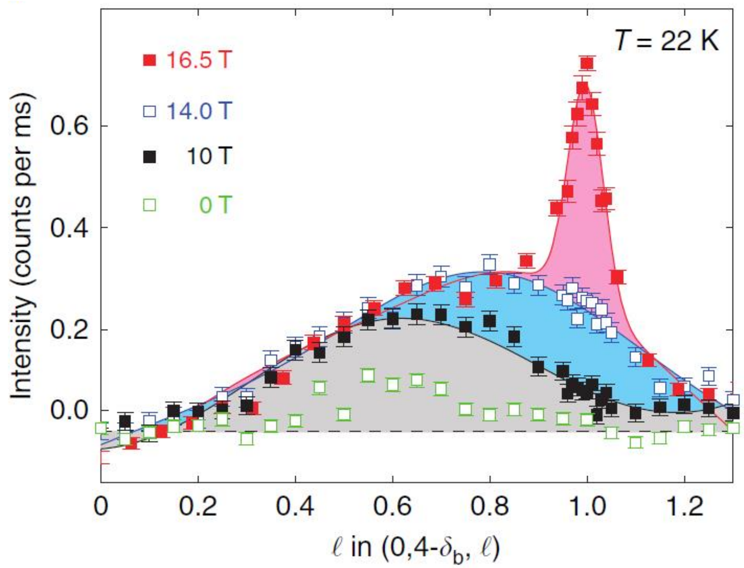
Chang *et al.*, Nature Comms **7**, 11494 (2016).

Now the $\boldsymbol{q}_a$ part





CDW order in a large B field



Chang *et al.*, Nature Comms **7**, 11494 (2016).

Correlation lengths (0 T):

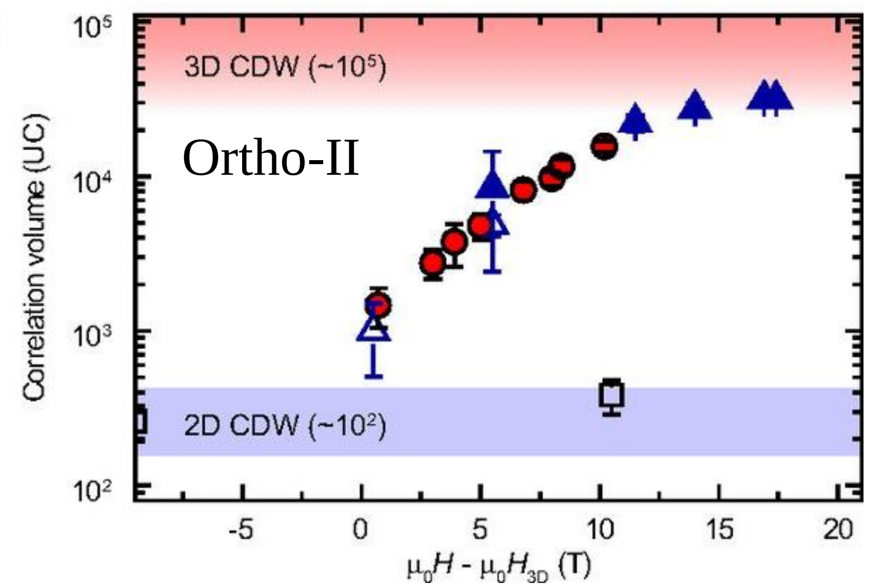
$\xi_a = 95$ Å

$\xi_c \approx 0.6$ c

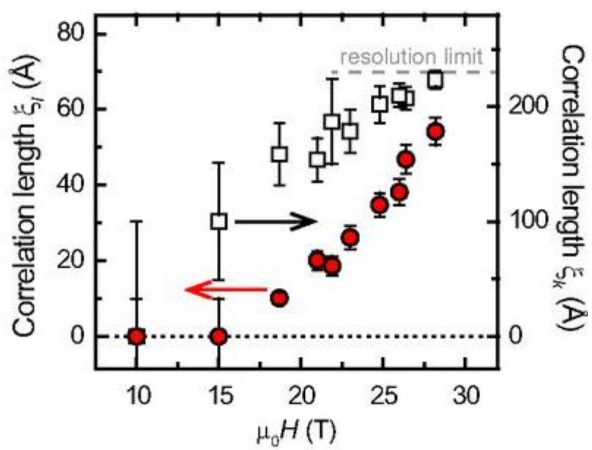
Correlation lengths (16 T):

$\xi_a = 310$ Å

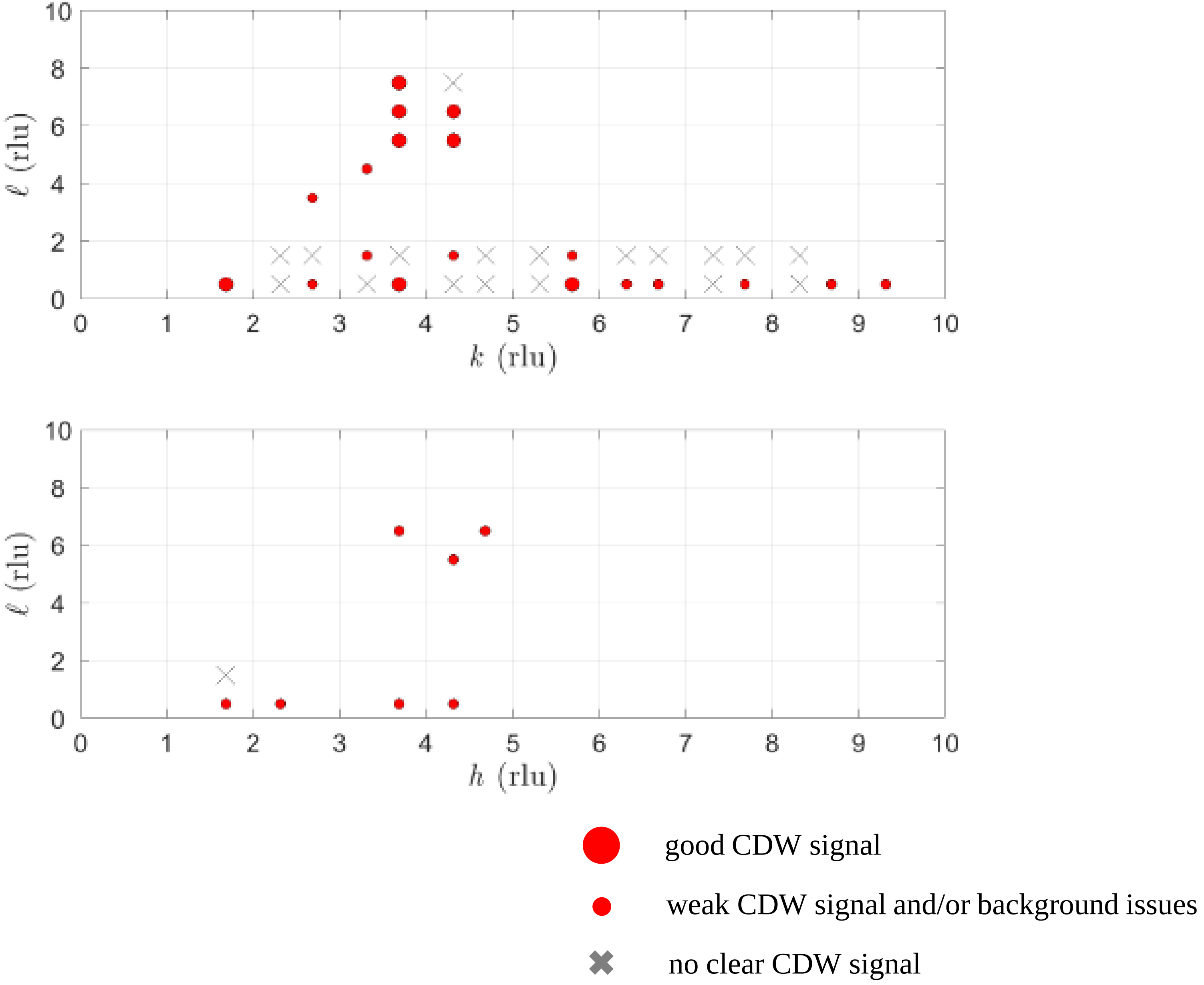
$\xi_c \approx 4$ c (47 Å)



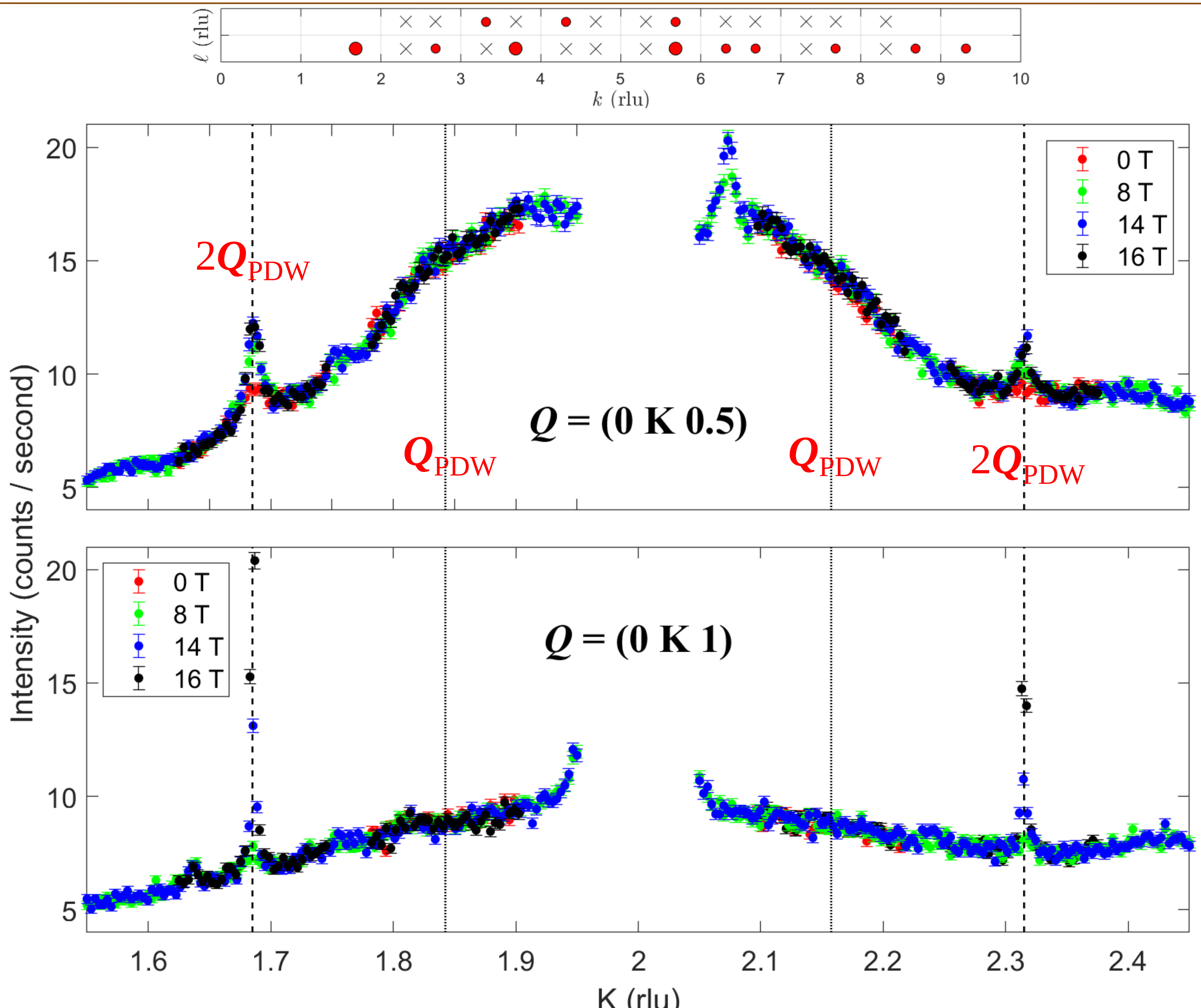
Jang *et al.*, PNAS **113**, 14645 (2016).



Where to look for the PDW in Q space?



Example data at (0 K 0.5) and (0 K 1) – 3 K



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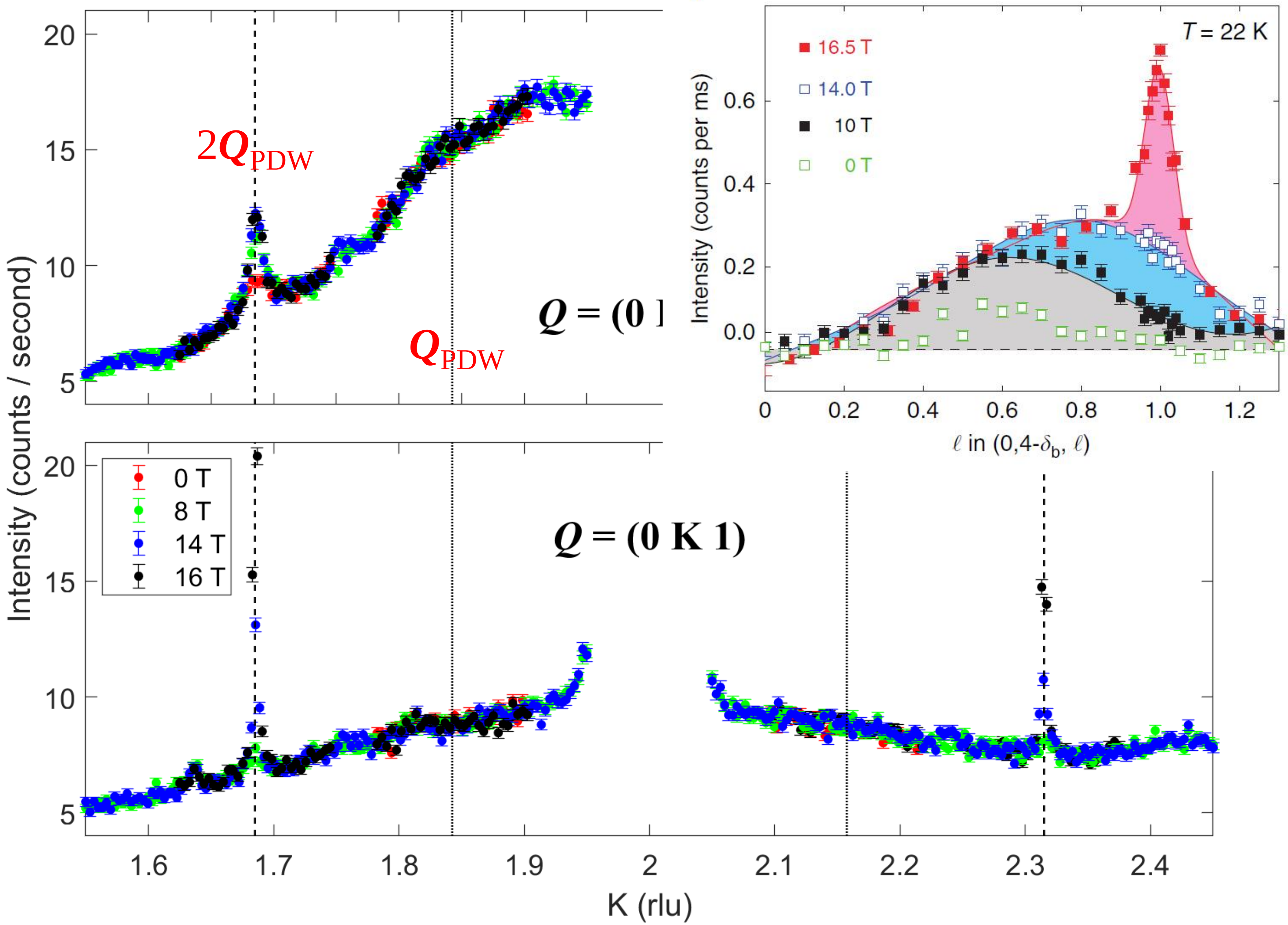
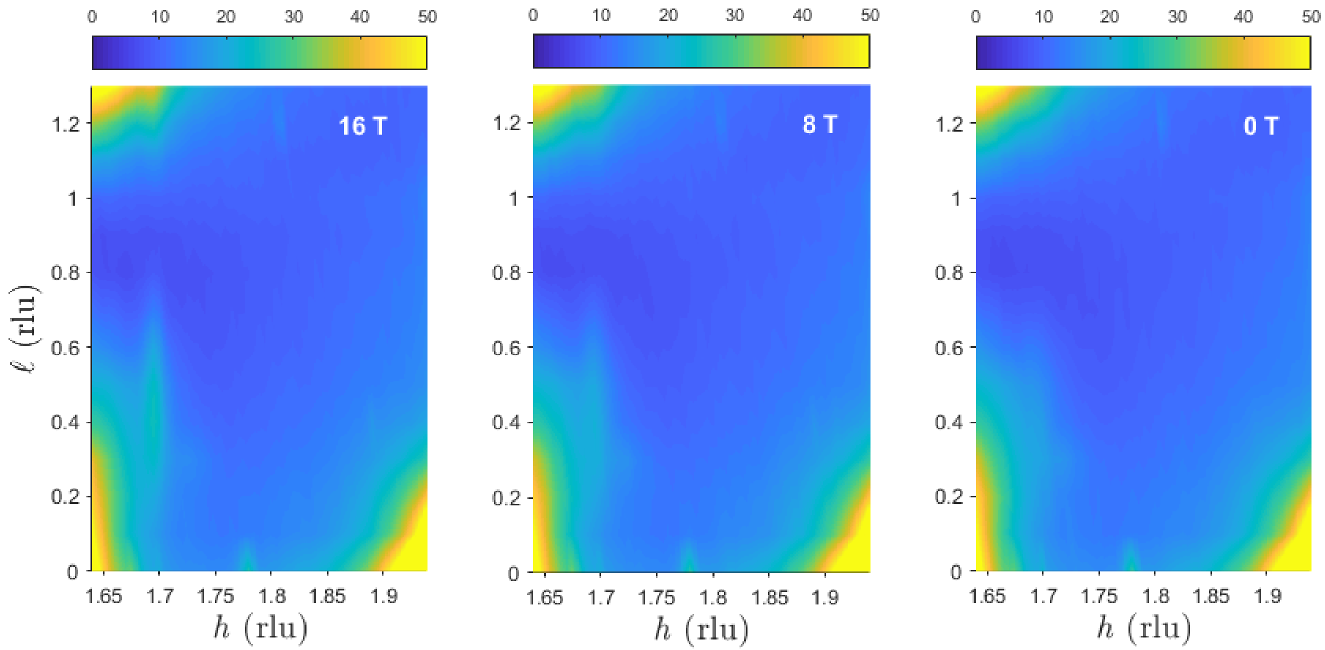
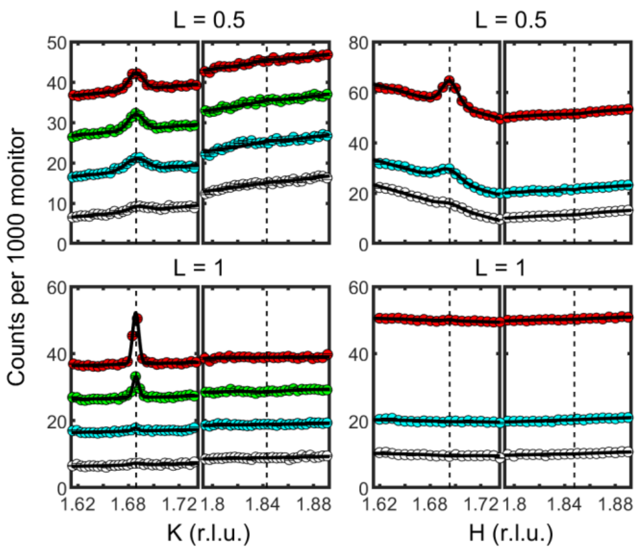
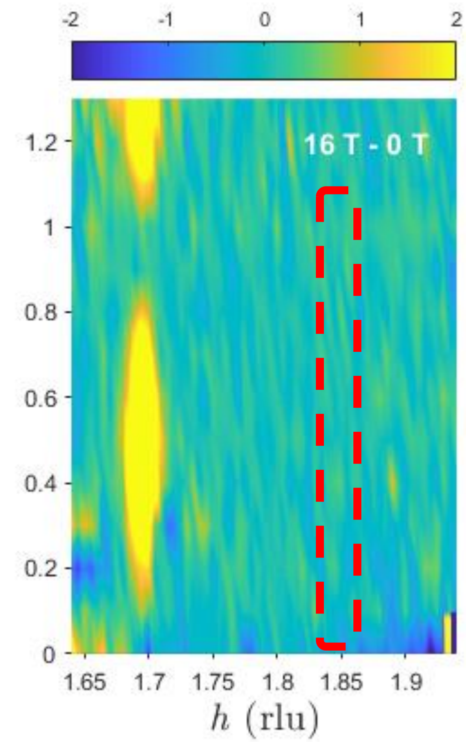


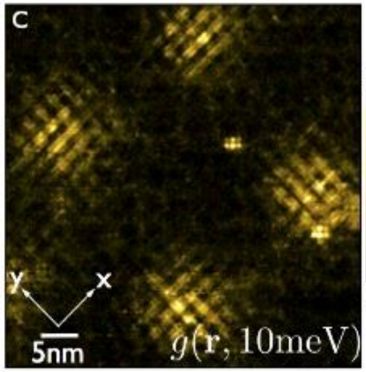
Along the **a*** axis – (H 0 L) - 3 K

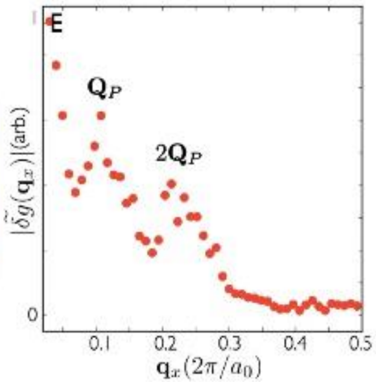


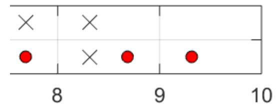




(0 K 1) – 16 T, 3 K







good CDW signal

weak CDW signal and/or background issues

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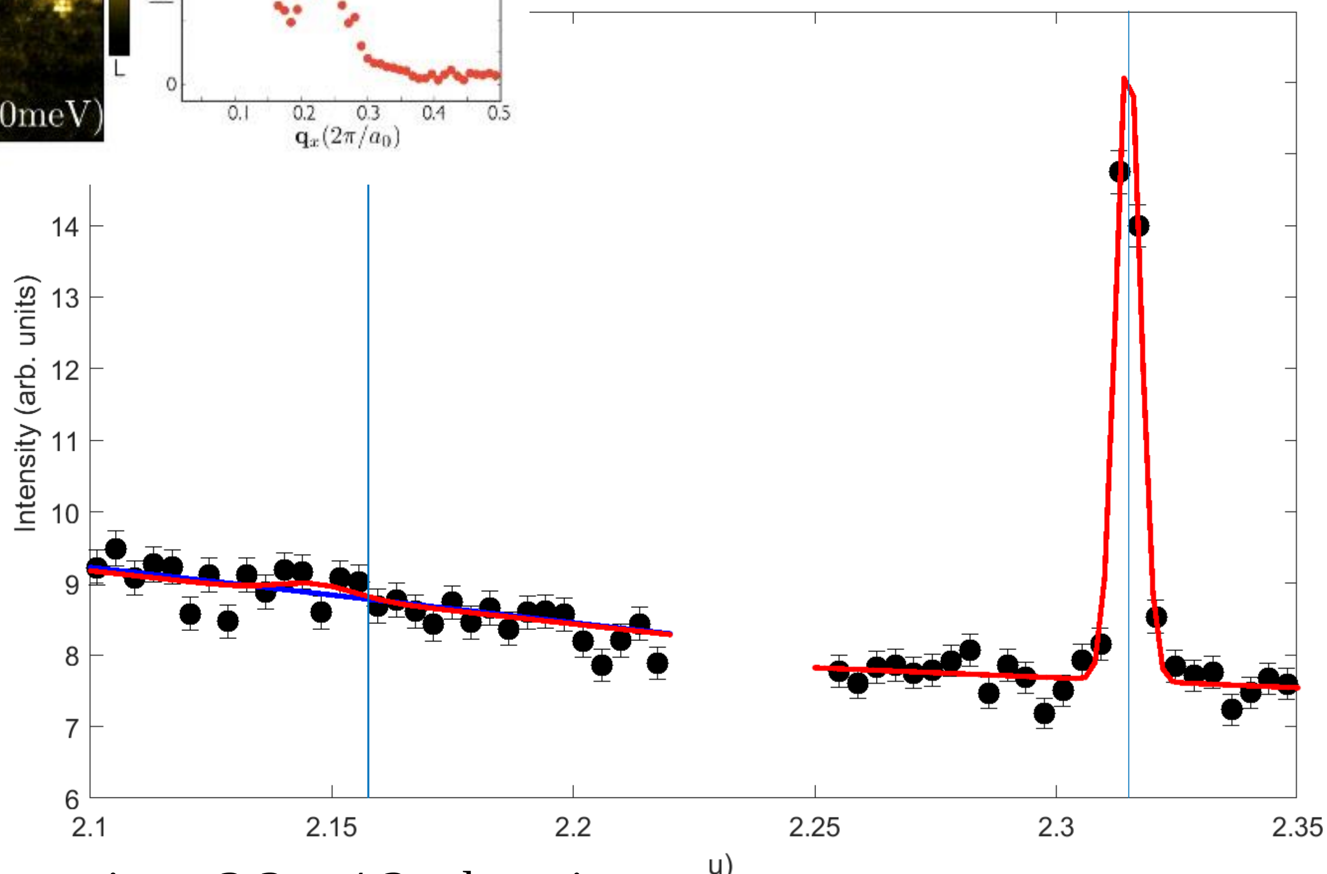
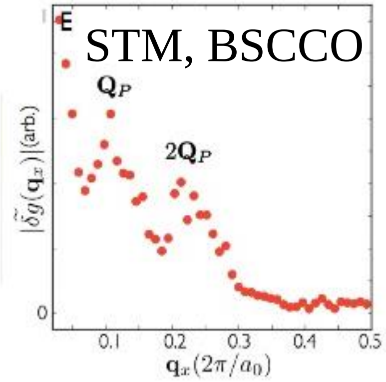


Integrated intensity = 3.3 ± 4.3 arb. units

Width ~ 3 x the CDW peak

Conclusions

- A diffraction signature from the pair density wave?
  - ➢ not seen – Δ_0 at least one order of magnitude smaller than $\Delta_1 = \Delta_{PDW}$ in YBCO ortho-II



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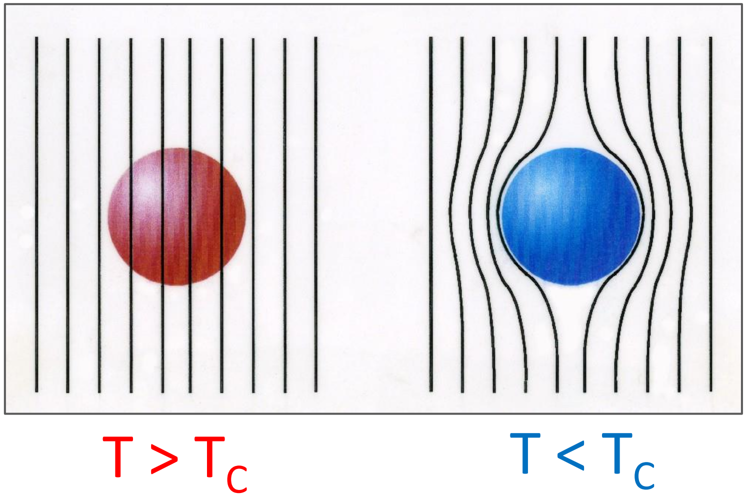
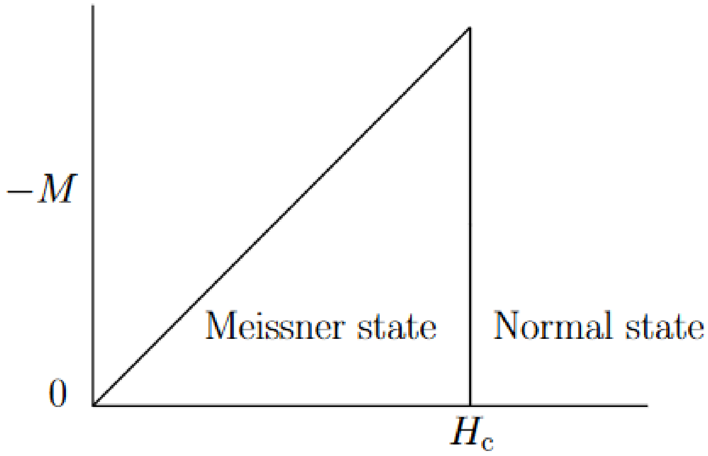
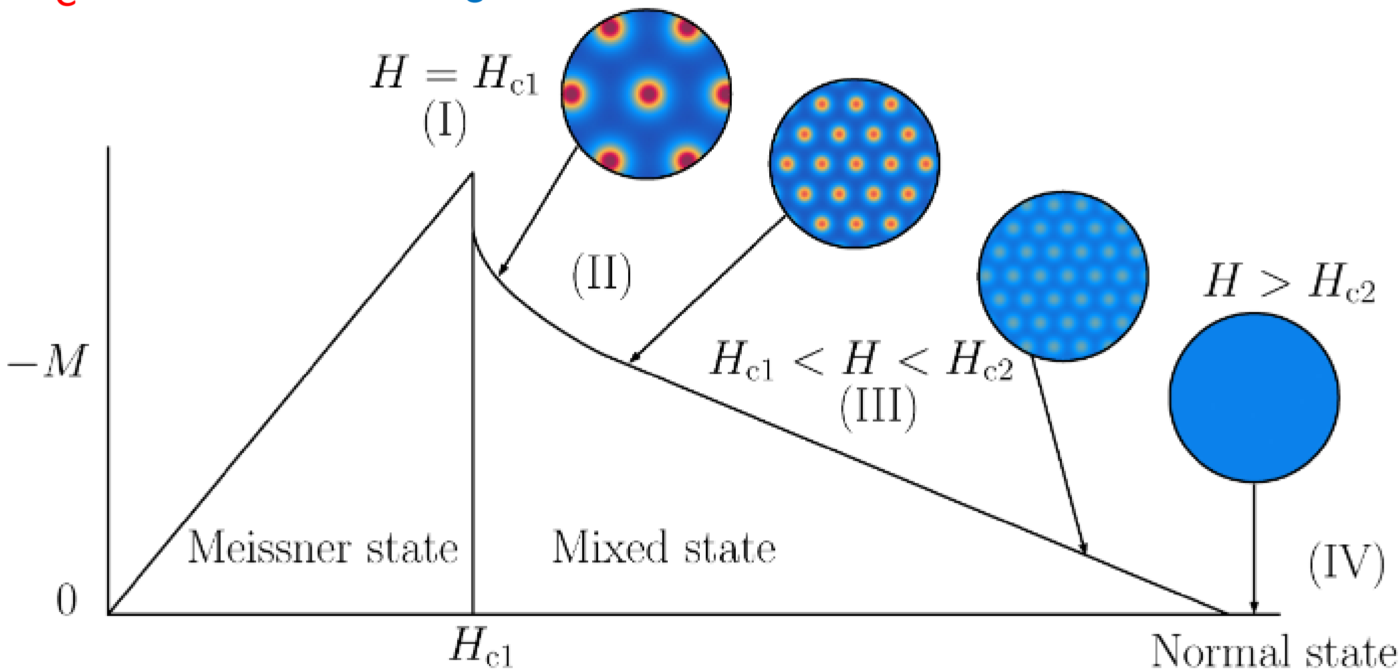
Vortices in Type-II superconductors

Meissner-Ochsenfeld effect



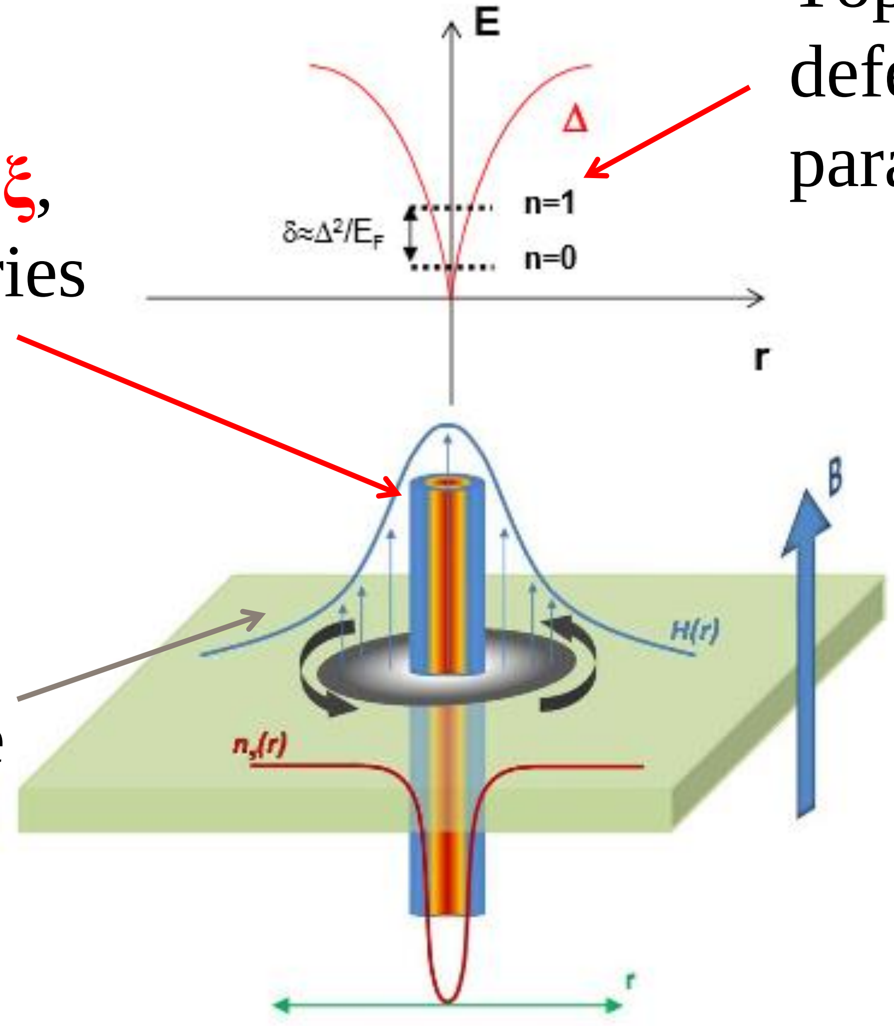




Vortices in superconductors

Topological defects in the order parameter

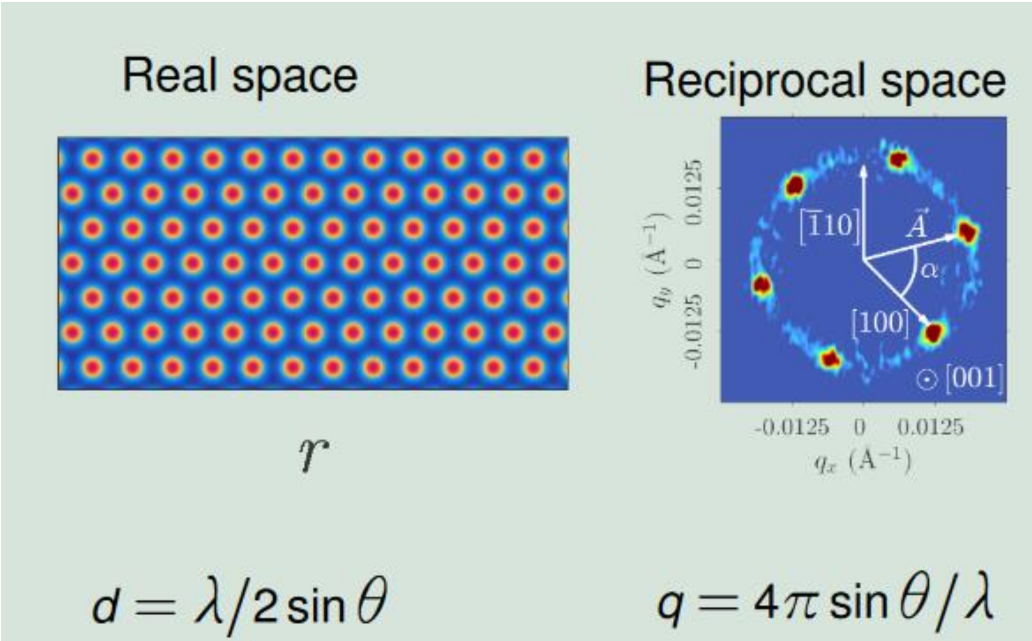
Vortex core, size ξ, over which OP varies rapidly



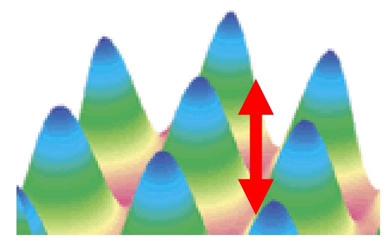
Field drops off to zero over distance λ_L

Review of STM imaging of vortices
Suderow *et al.*, Supercond. Sci. Tech. **27**, 063001 (2014).

Diffraction from the vortex lattice



$$a \cong \sqrt{\frac{\Phi_0}{B}} \approx 950 \text{ Å at } B = 0.2 \text{ T}$$



few × F_{10}

$$B(\mathbf{r}) = \sum_{hk} F(\mathbf{q}_{hk}) e^{i\mathbf{q}_{hk}\cdot\mathbf{r}}$$

F_{hk}, "form factor" = Fourier component at q_{hk} of spatial variation of field inside FLL

We can measure this using small angle neutron diffraction.

The form factor as a function of field

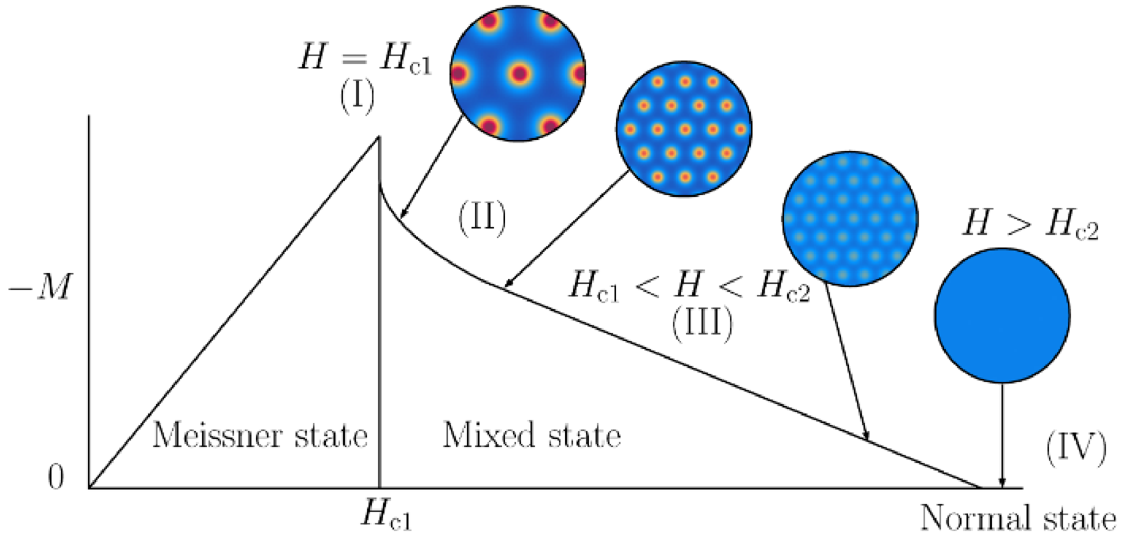
London Model

$$F(q)_{\text{London}} = \frac{B}{1+(\lambda q)^2}.$$

For $B_{c1} < B << B_{c2}$, the London model gives:

$$F_{10} = \left(\frac{\sqrt{3}}{8\pi^2}\right) \times \frac{\Phi_0}{\lambda_L^2}$$

... where λ_L is the magnetic penetration depth, and λ_L = 2500 Å <=> F_{10} ~ 0.7 mT



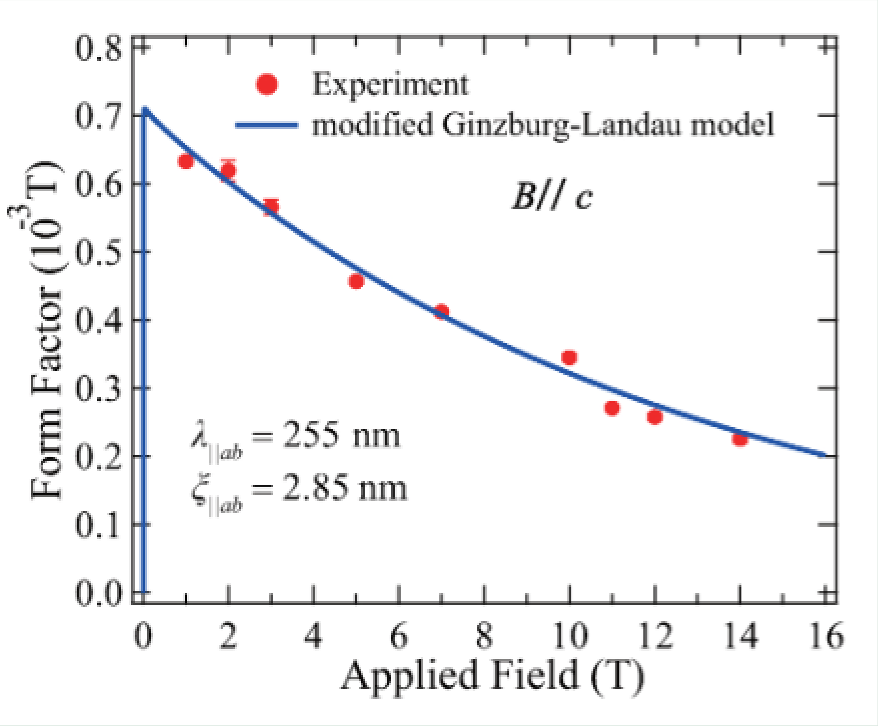
The form factor as a function of field

Brandt Model

$$F(q)_{\text{Brandt}} = \frac{B}{1+(\lambda q)^2} e^{-c(\xi q)^2}.$$

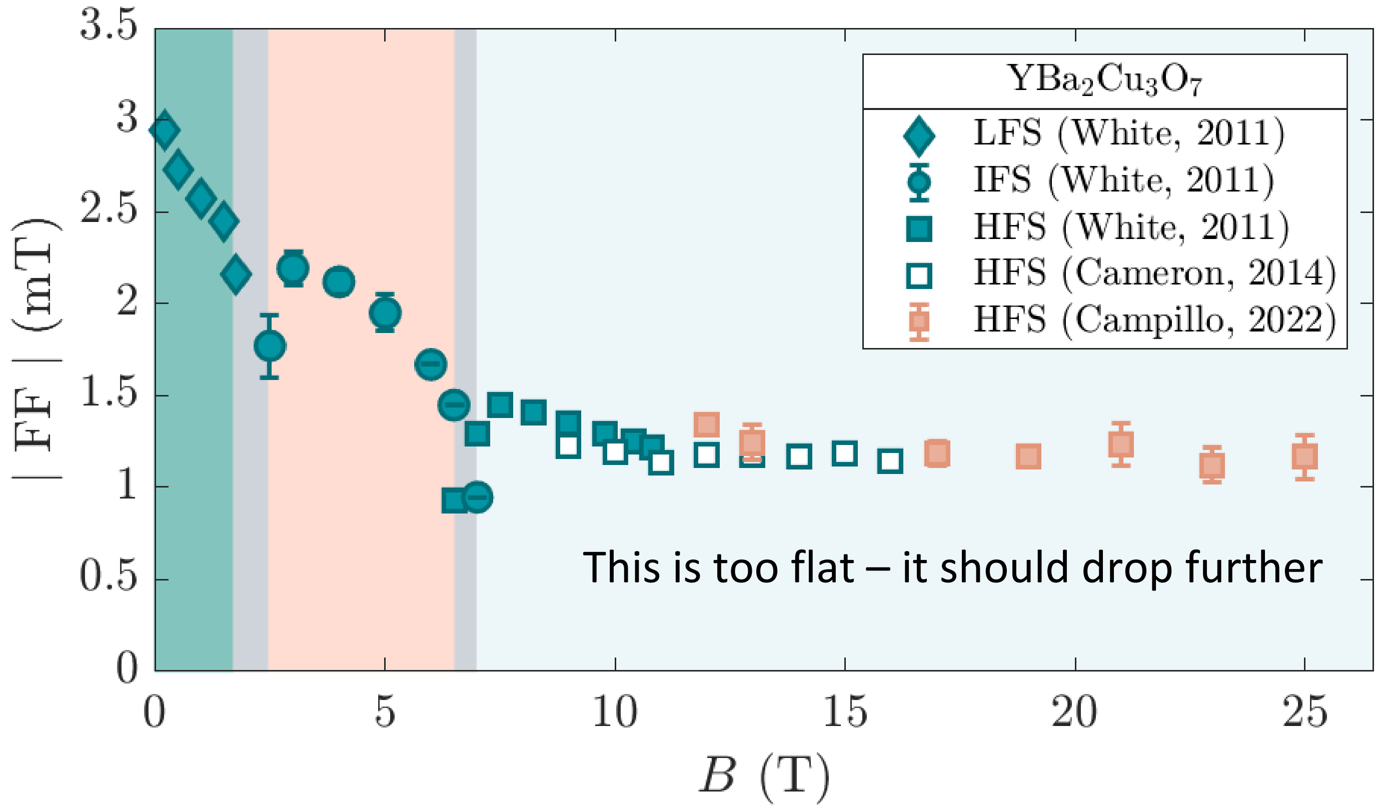
Brandt, Rep. Prog. Phys. **58**, 1465 (1995)
Brandt, Phys. Rev. Lett. **78**, 2208 (1997)

$BaFe_2(As_{0.67}P_{0.33})_2$

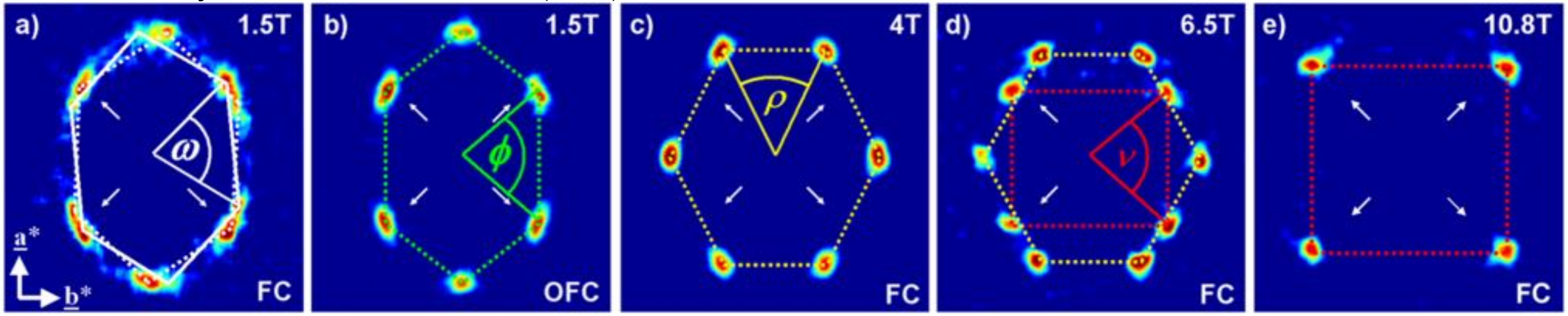


R. Morisaki-Ishii, *et al.*, *Phys. Rev. B*, **90**, 125116 (2014).

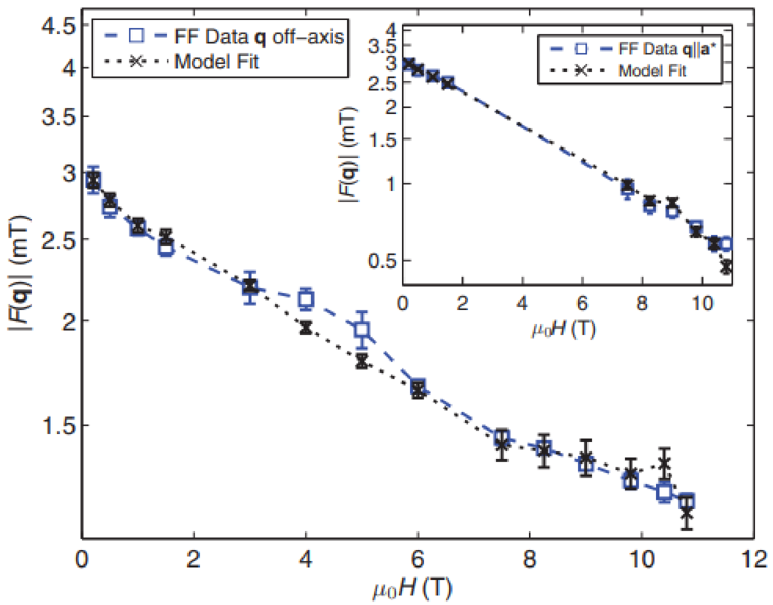
YBCO7 – fully occupied chains



White *et al.*, Phys. Rev. Lett. **102**, 097001 (2009)



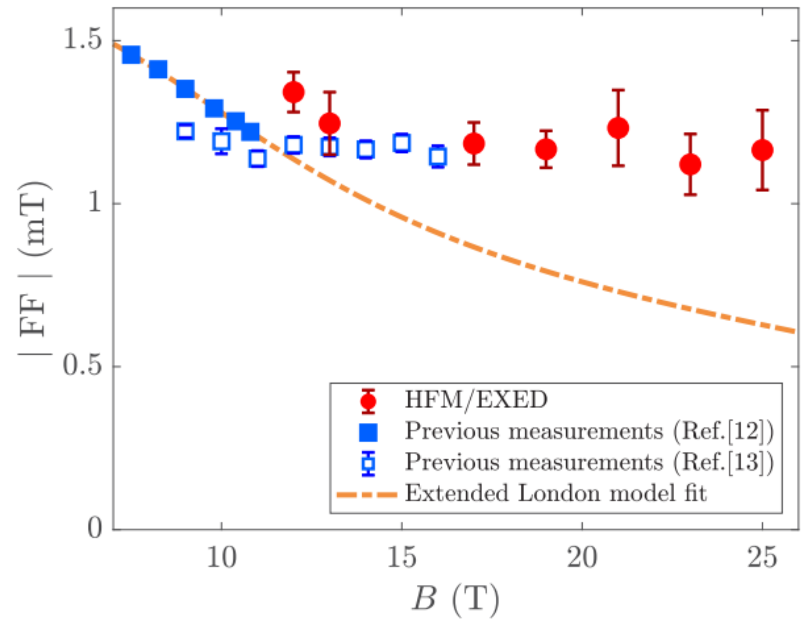
The form factor of the VL in YBCO



λ_a (nm)	λ_b (nm)
138(2)	107(1)

ξ_a (nm)	ξ_b (nm)
3.04(4)	3.54(11)

$$F(q)_{\text{Brandt}} = \frac{B}{1+(\lambda q)^2} e^{-c(\xi q)^2}.$$



λ_a = 172(1) nm

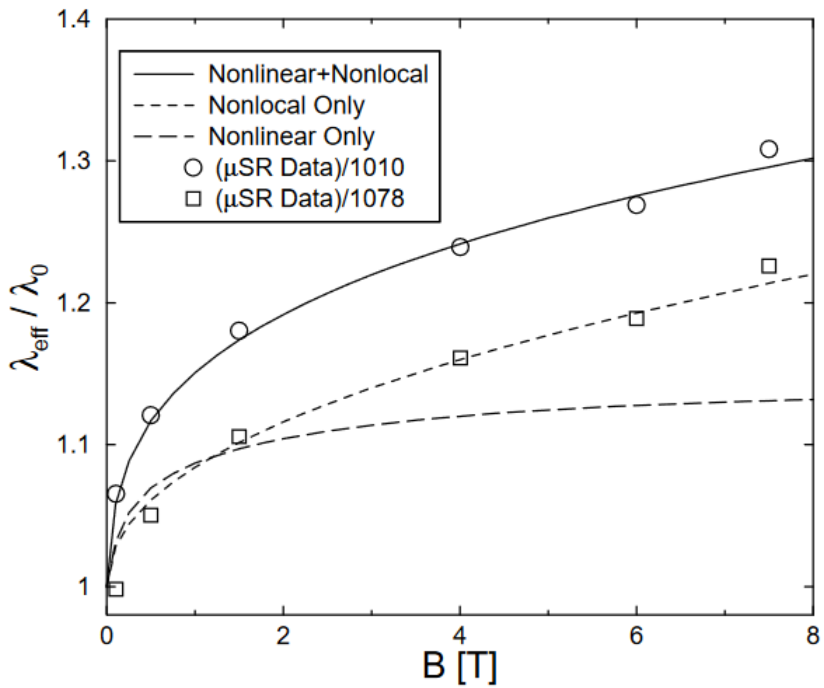
ξ = 1.9(1) nm

White *et al*., Phys. Rev. B. **84**, 104519 (2011)

Campillo *et al*., Phys. Rev. B. **105**, 184508 (2022)

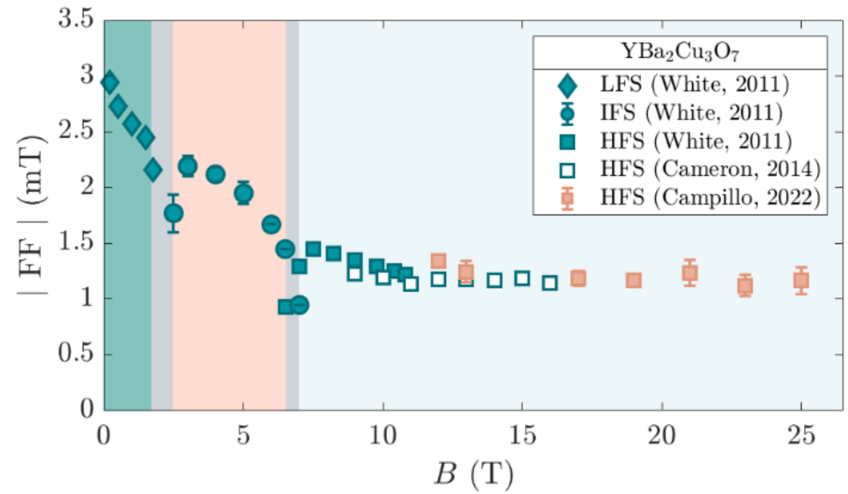
Explanations?

- The superconducting characteristic lengths are changing. The penetration depth changes with field.



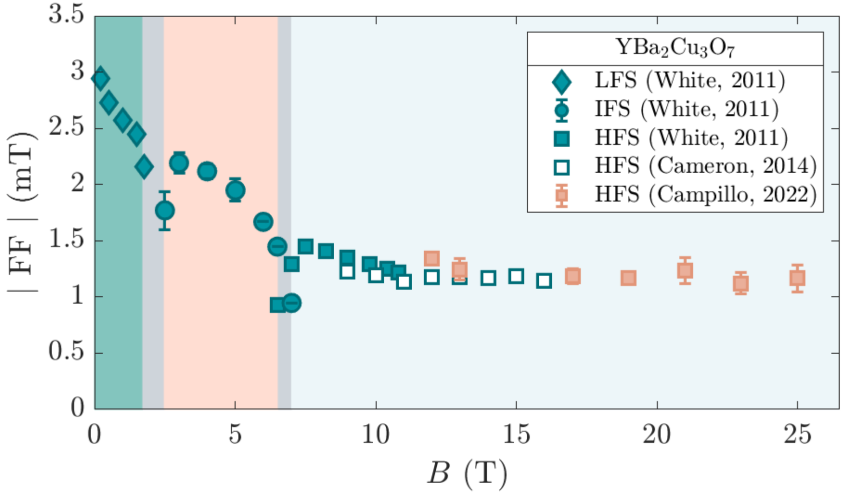
Amin *et al*., Phys. Rev. Lett. **84**, 5864 (2000)

$$F(q)_{\mathrm{Brandt}} = \frac{B}{1 + (\lambda q)^2} e^{-c(\xi q)^2}.$$



Explanations?

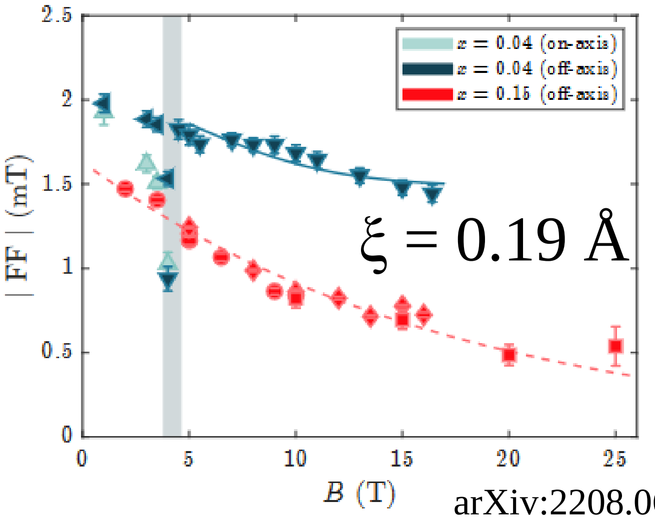
- The superconducting characteristic lengths are changing. The coherence length should also change with field.



It has to decrease a lot (e.g. to a few Angstroms).

Ca-doped YBCO (more overdoped)

$$B_{c2} = \frac{\Phi_0}{2\pi\xi^2}$$

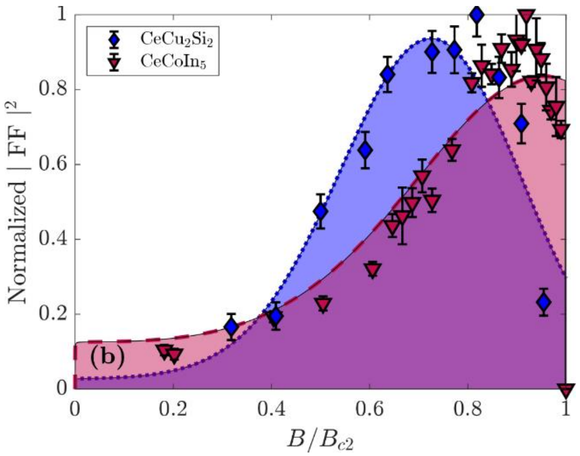


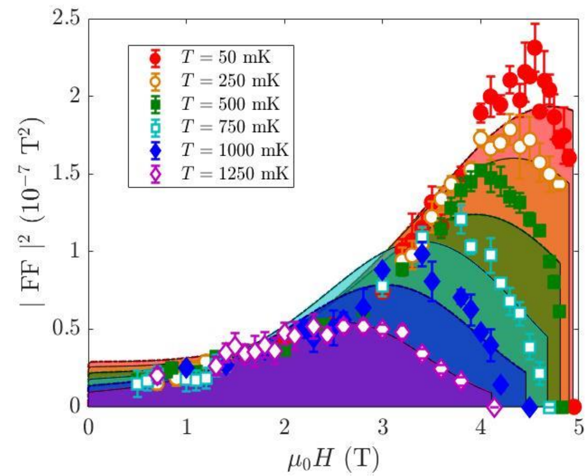
ξ = 0.19 Å

arXiv:2208.06706

Explanations?

- Additional magnetization in the core (e.g. Pauli paramagnetic effects)



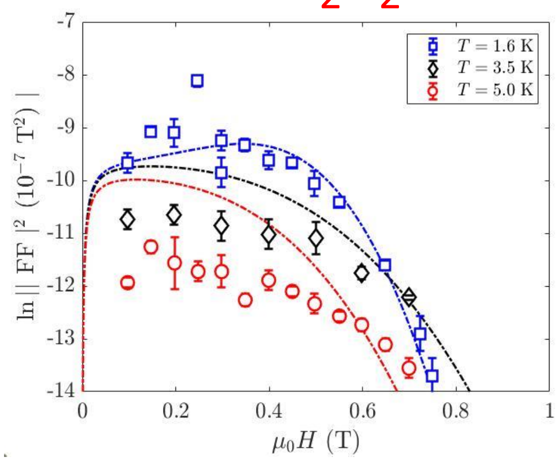


CeCoIn$_5$

$TmNi_2B_2C$

CeCu$_2$Si$_2$

Model used described in Campillo *et al.*, Phys. Rev. B. **104**, 184508 (2021)

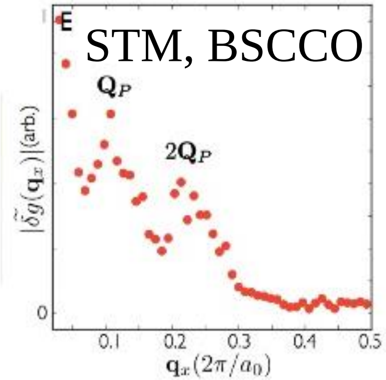


Data from DeBeer-Schmitt *et al.*, PRL **99**, 167001 (2007).

Conclusions

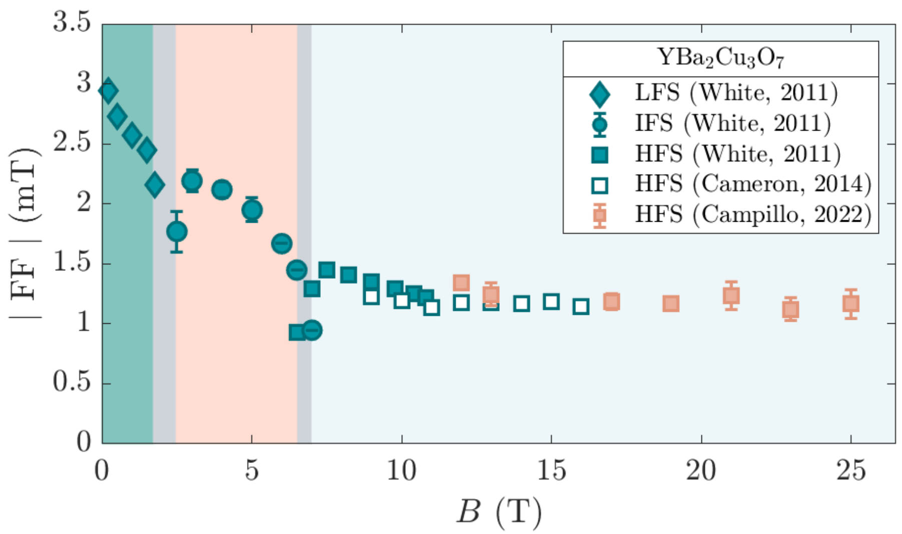
- A diffraction signature from the pair density wave?
  - not seen – Δ_0 at least one order of magnitude smaller than $\Delta_1 = \Delta_{PDW}$ in YBCO ortho-II

STM, BSCCO



$$\rho_e(r) \propto (\Delta_0^2 + 2\Delta_0\Delta_1 \sin(qr) + \Delta_1^2 \sin^2(qr))$$

- The vortex lattice at high magnetic fields



This is too flat – it should drop further