# Unusual magnetic excitations in a cuprate high-$T_c$ superconductor

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# Collaborators

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**Laboratoire Léon Brillouin, Saclay, France**

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**Institut Laue-Langevin, Grenoble, France**

P. Steffens

**FRM II, Garching, Germany**

R. A. Mole, K. Hradil

# Outline

## 1. Introduction

- The pseudogap phase in high-$T_c$ cuprates
- Magnetic excitations measured by neutron scattering

## 2. Results

- Discovery of unusual magnetic excitations
- First branch: ~53 meV
- Second branch: 30 – 40 meV
- Relation to antiferromagnetic fluctuations

## 3. Discussion

# The pseudogap phase in high-$T_c$ cuprates

➢ Superconducting fluctuations do not seem to persist up to $T^*$ (but only up to ~20 K above $T_c$ and varying with the measurement technique):

Corson et al., Nature (1999)

Dagan et al., PRB (2000)

Chang et al., PRB (2001)

Bergeal et al., Nat. Phys. (2008)

Lee et al., Science (2009)

Salem-Sugui et al., PRB (2009)

Grbić et al., PRB (2009)

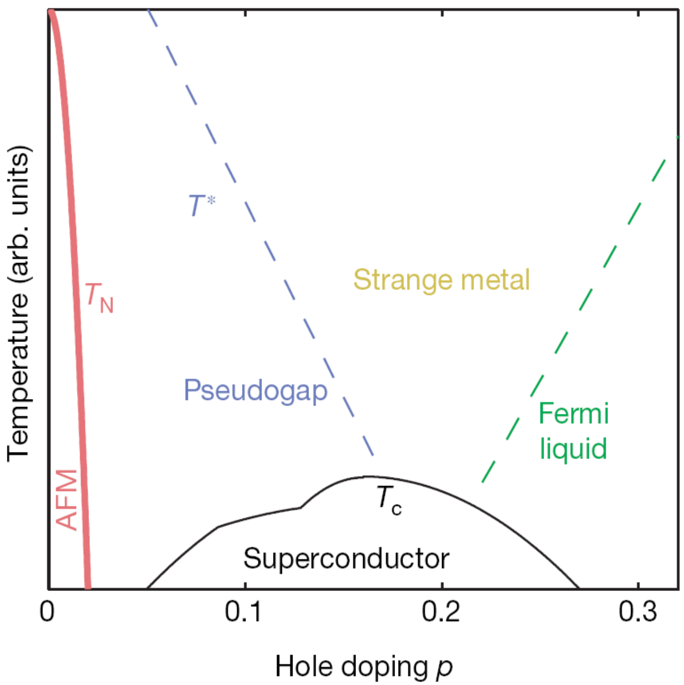
Daou et al., Nature (2010)

Iye et al., J. Phys. Soc. Jap. (2010)

Bilbro et al., Nat. Phys. (2011)

G. Yu et al., unpublished (poster session)

Phase diagram



# The pseudogap phase in high-$T_c$ cuprates

➢ Various evidence for a genuine phase transition at *T**:

Kaminski et al., Nature (2002)

Fauqué et al., PRL (2006)

Xia et al., PRL (2008)

Mook et al., PRB (2008)

Li et al., Nature (2008)

Leridon et al., EPL (2009)

Daou et al., Nature (2010)

Hashimoto et al., Nat. Phys. (2010)

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He et al., Science (2011)

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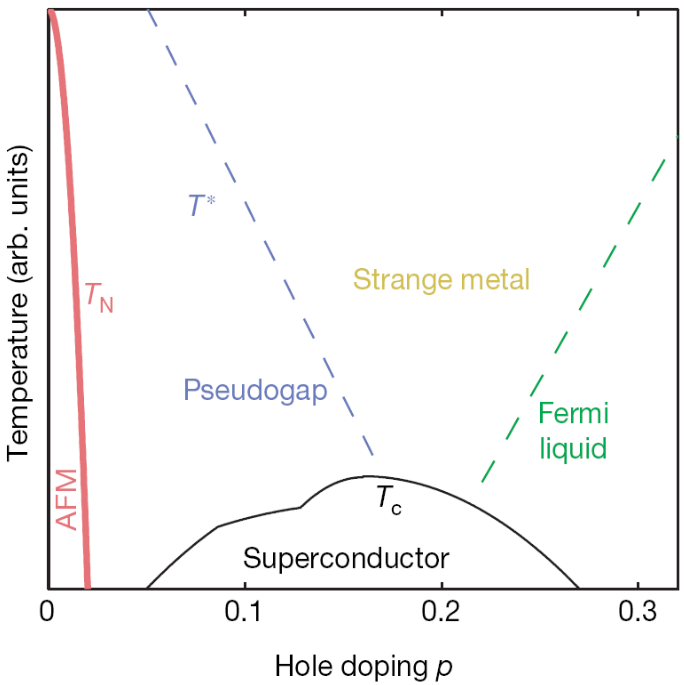

# The pseudogap phase in high-$T_c$ cuprates

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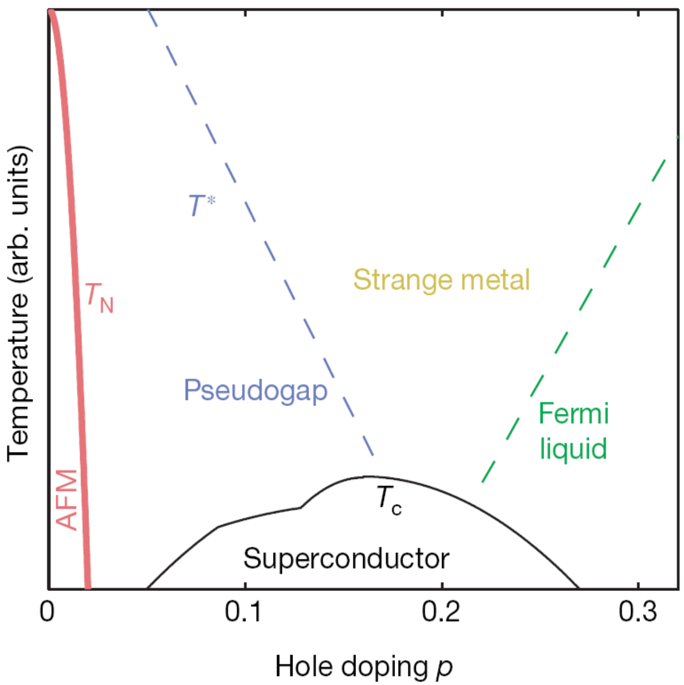
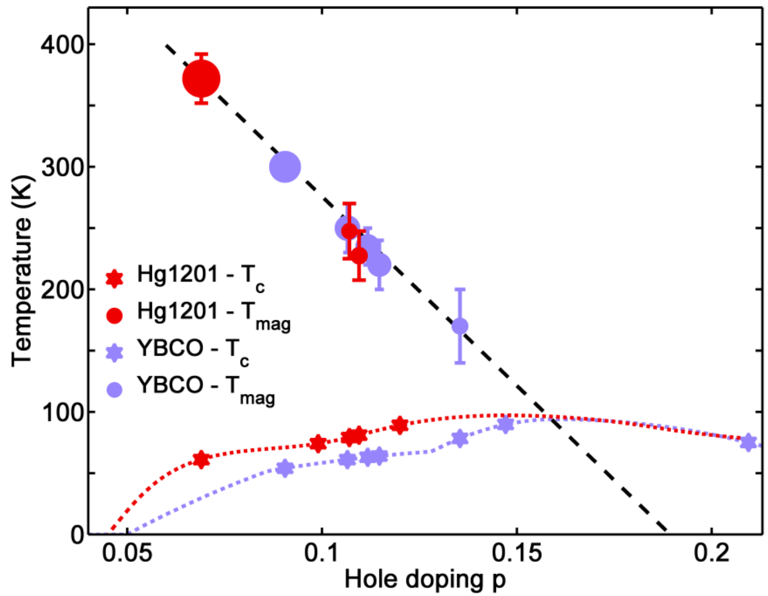
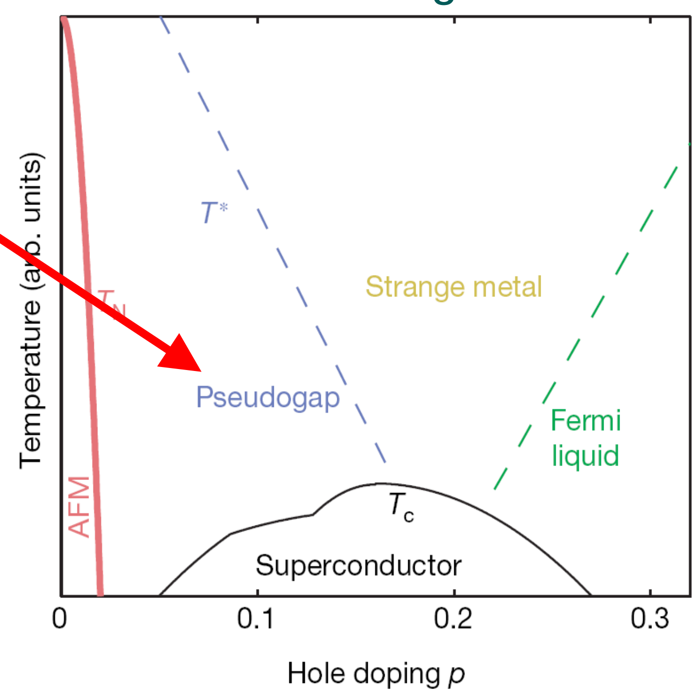


# Magnetic excitations from the *q* = 0 order

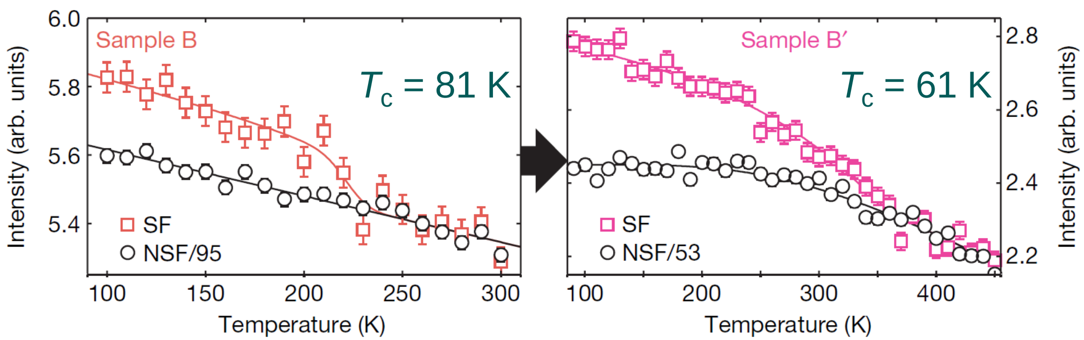
## $HgBa_2CuO_{4+\delta}$ (Hg1201)




## Phase diagram




Li et al., Nature **455**, 372 (2008)



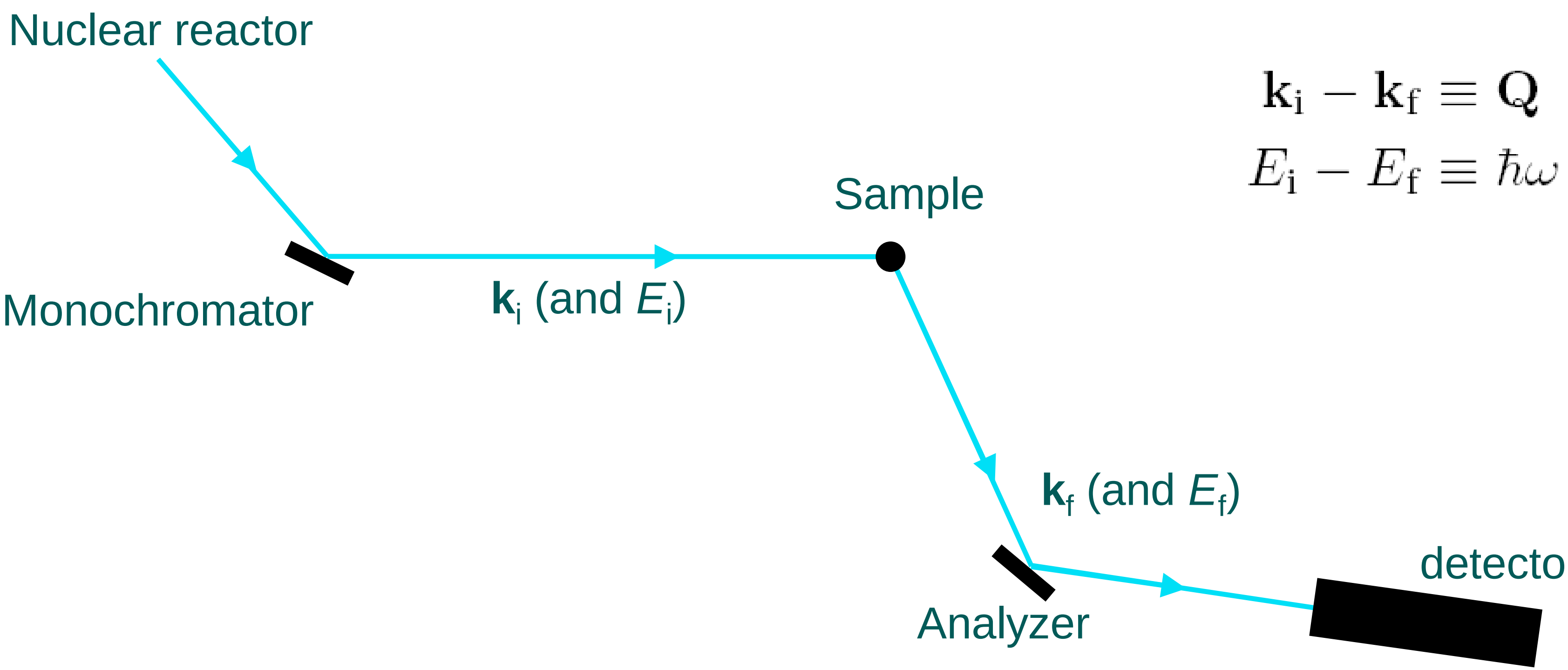
# The INS technique

Inelastic neutron scattering (INS) measures:

$$I(\mathbf{Q},\omega) \propto \mathcal{F}_{\boldsymbol{r},t} \int \mathrm{d}\mathbf{r}' \langle b(\mathbf{r}' - \mathbf{r}, 0) b(\mathbf{r}', t) \rangle$$

$$\mathbf{k}_{\mathrm{i}} - \mathbf{k}_{\mathrm{f}} \equiv \mathbf{Q}$$

$$E_{\mathrm{i}} - E_{\mathrm{f}} \equiv \hbar\omega \rightarrow \omega$$



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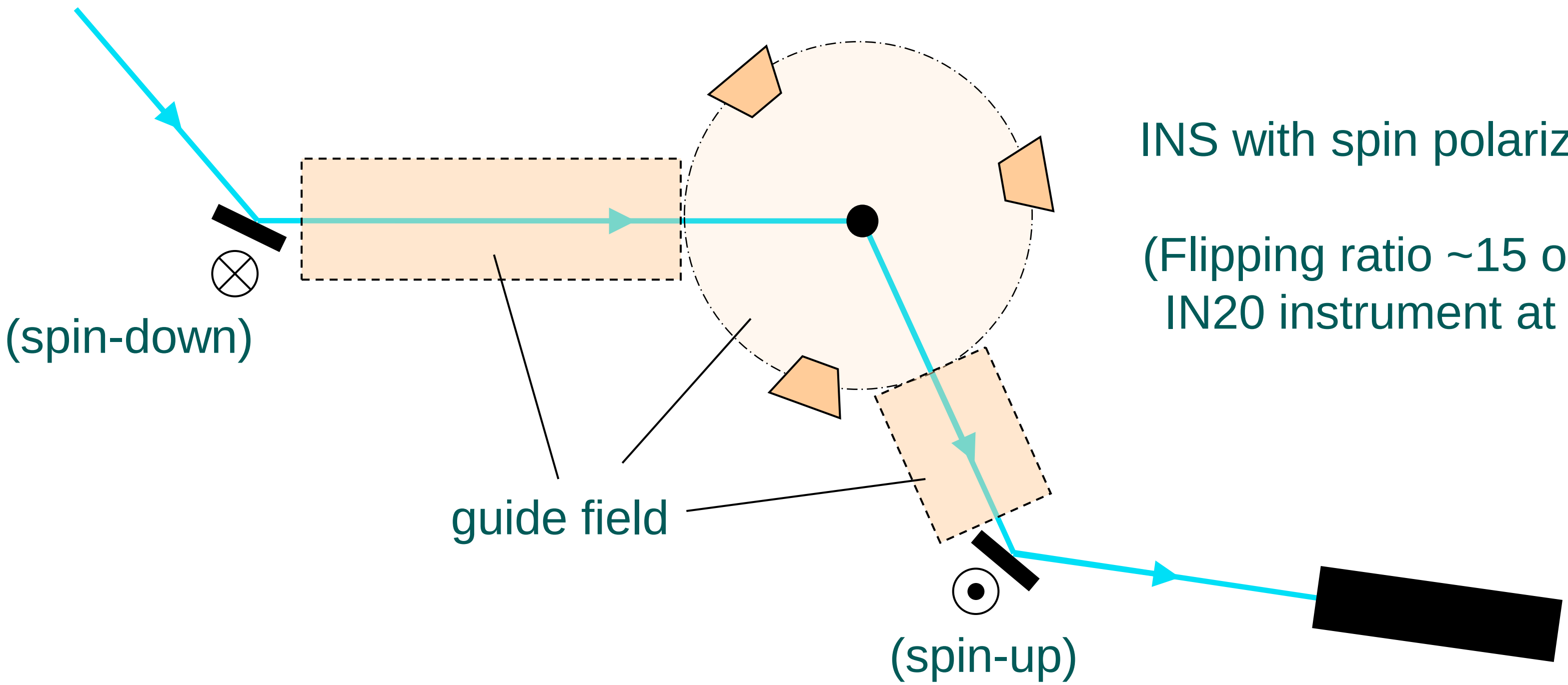



INS with spin polarization

(Flipping ratio ~15 on the IN20 instrument at ILL)

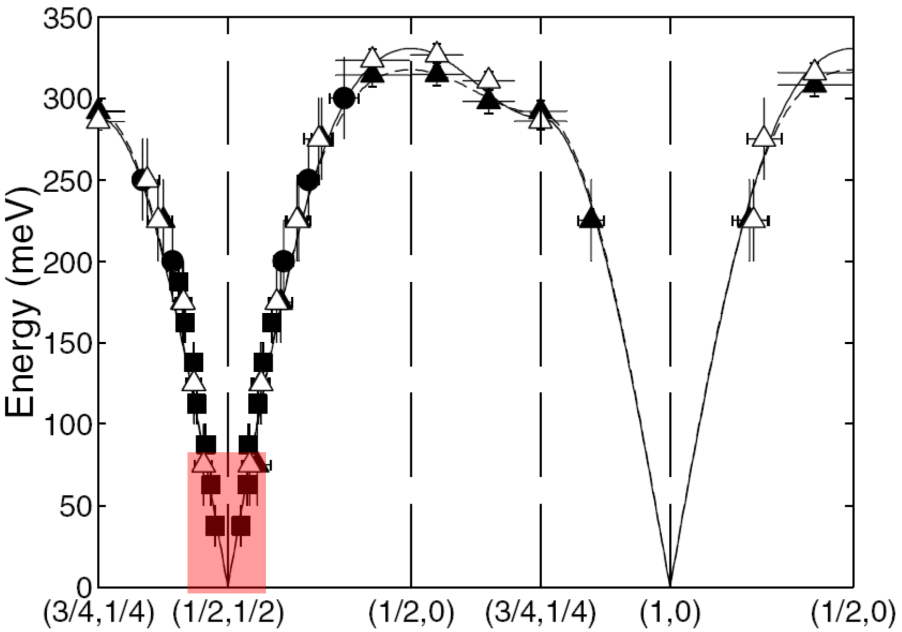
# An overview

Magnetic excitations in the cuprates…

(π, π) “resonance”

(π, π)  normal-state excitations

(π, π) “hourglass” and “nematicity”



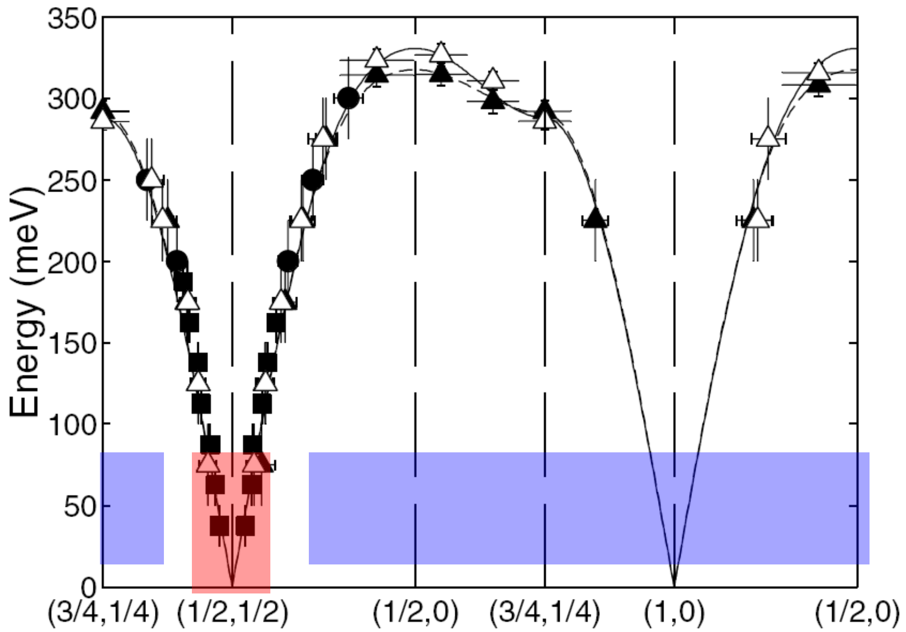

Spin waves in $La_2CuO_4$

Coldea et al., PRL (2001)

# An overview

Magnetic excitations in <u>this talk</u>:

Not limited to (π, π)!

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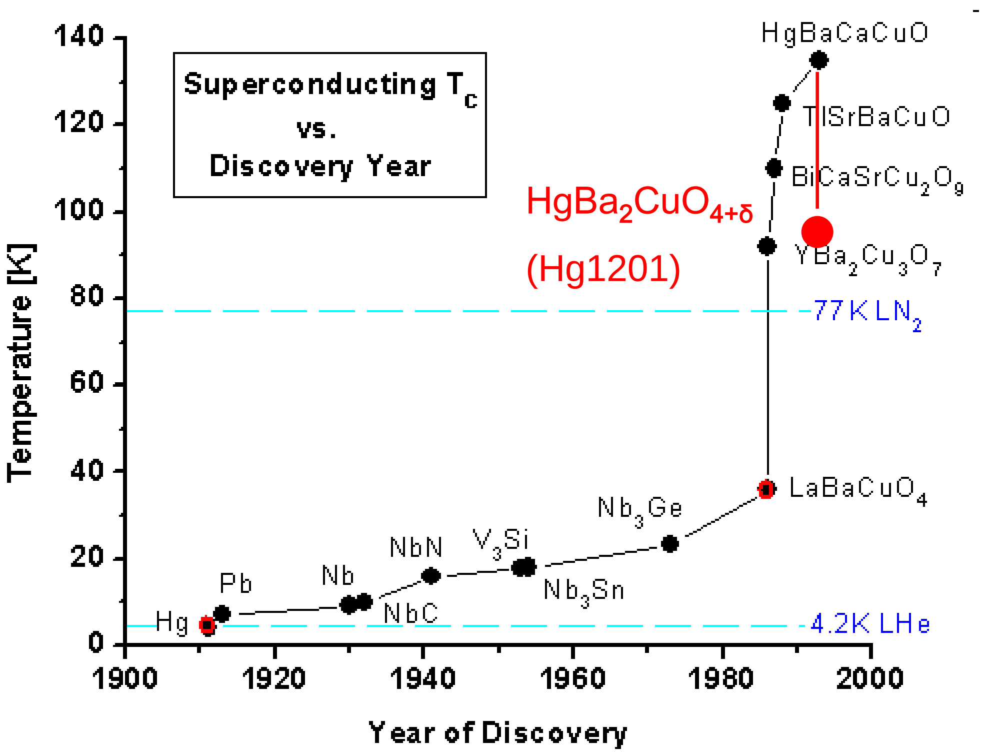
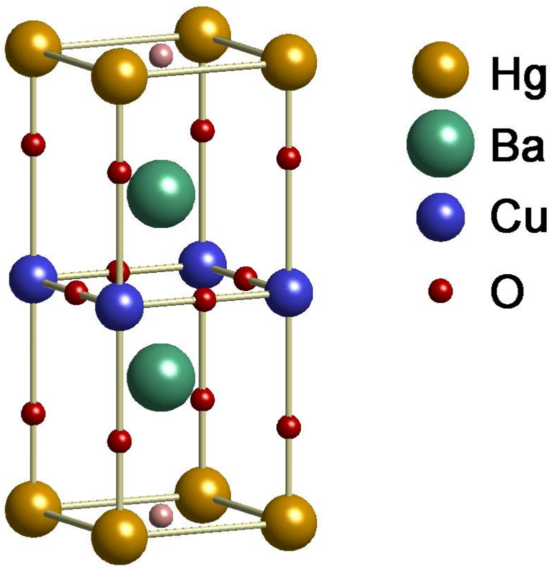
## 3. Discussion

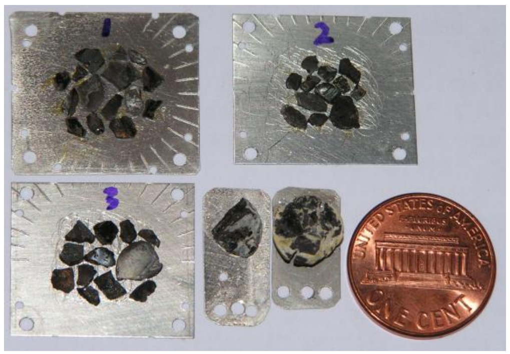
# Model cuprate $HgBa_2CuO_{4+\delta}$ (Hg1201)




- Highest $T_c$ (max. 97 K) among all single-layer cuprates
- Simple tetragonal structure (space group P4/*mmm*)

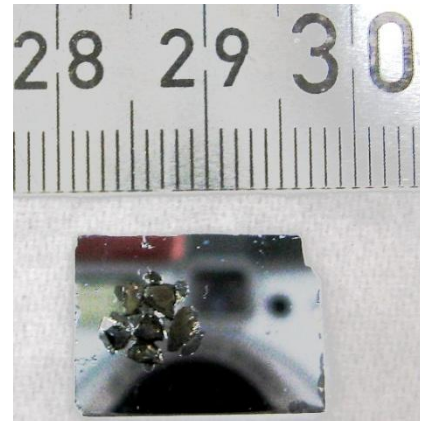
# Sample information

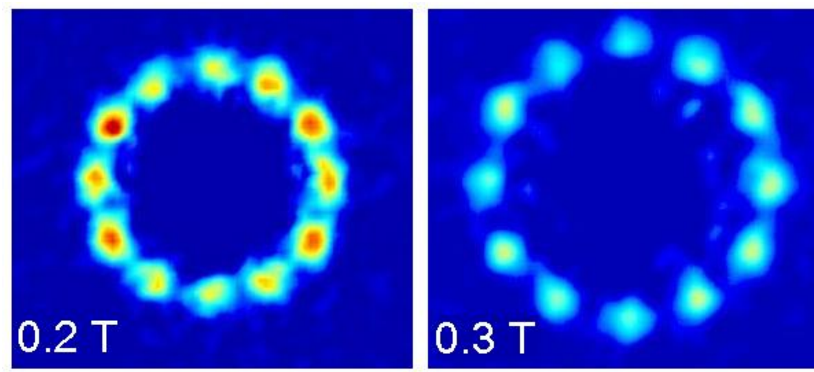


Zhao et al., Adv. Mater. **18**, 3243 (2006)

Barišić et al., PRB **78**, 054518 (2008)

High sample quality shown by F.L.L.



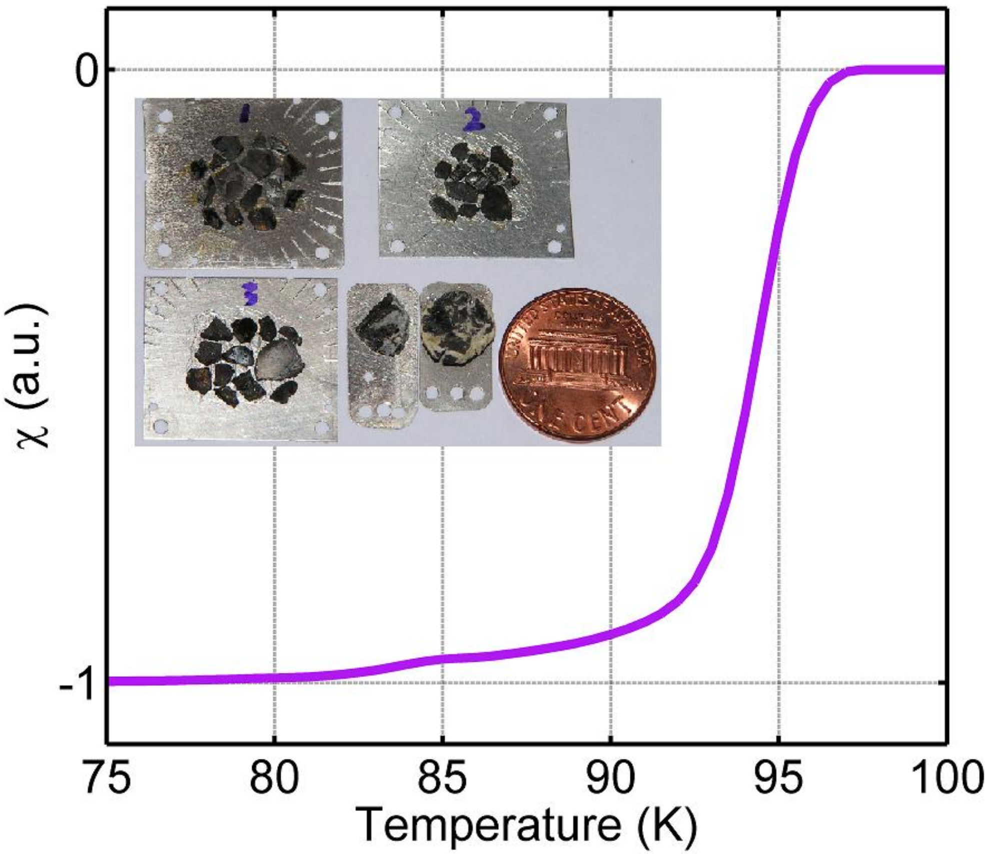

With N. Egetenmeyer and J. L. Gavilano, PSI, Switzerland

Li et al., PRB **83**, 054507 (2011)

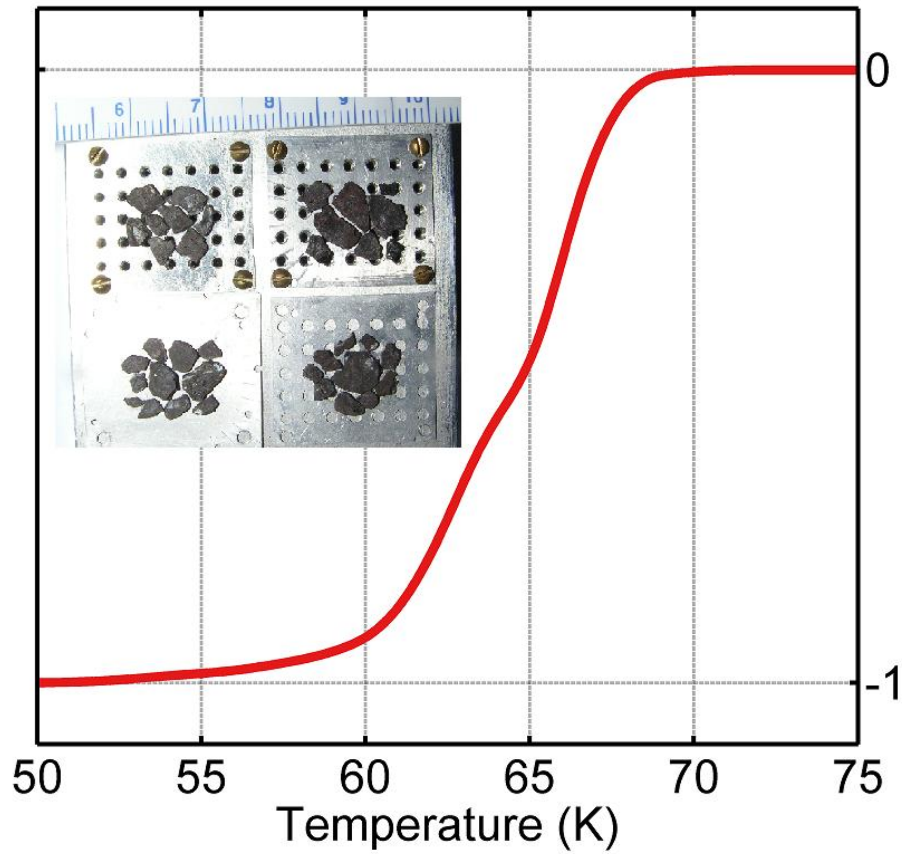
# Sample information

Two samples for INS study:

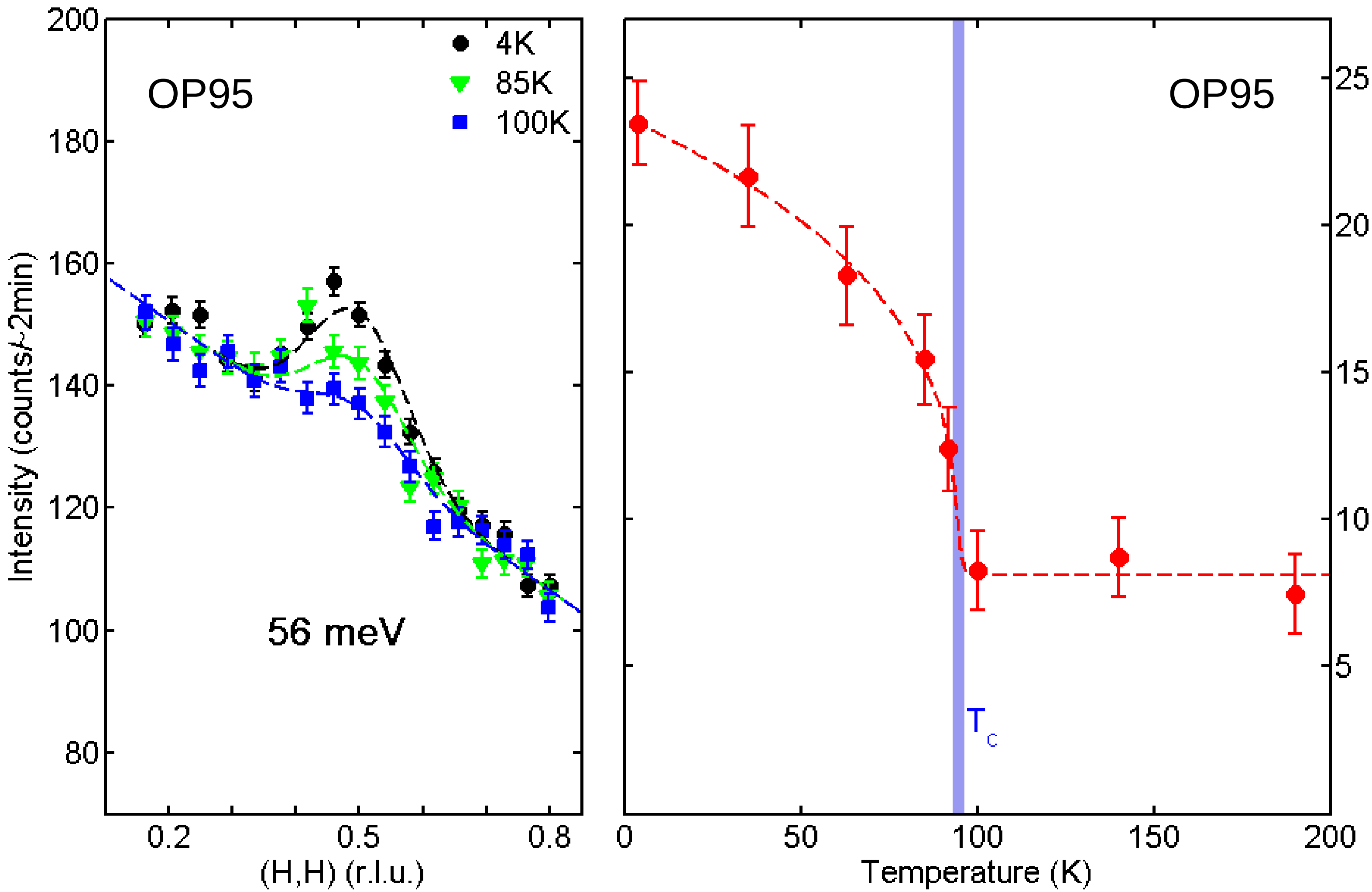
**“OP95”**




**“UD65”**

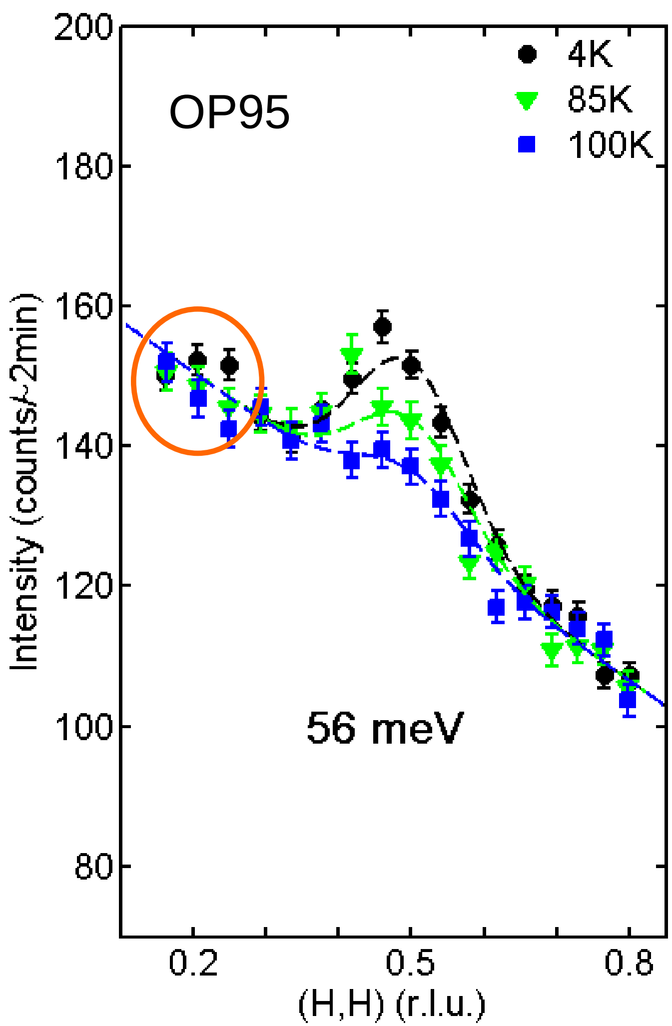


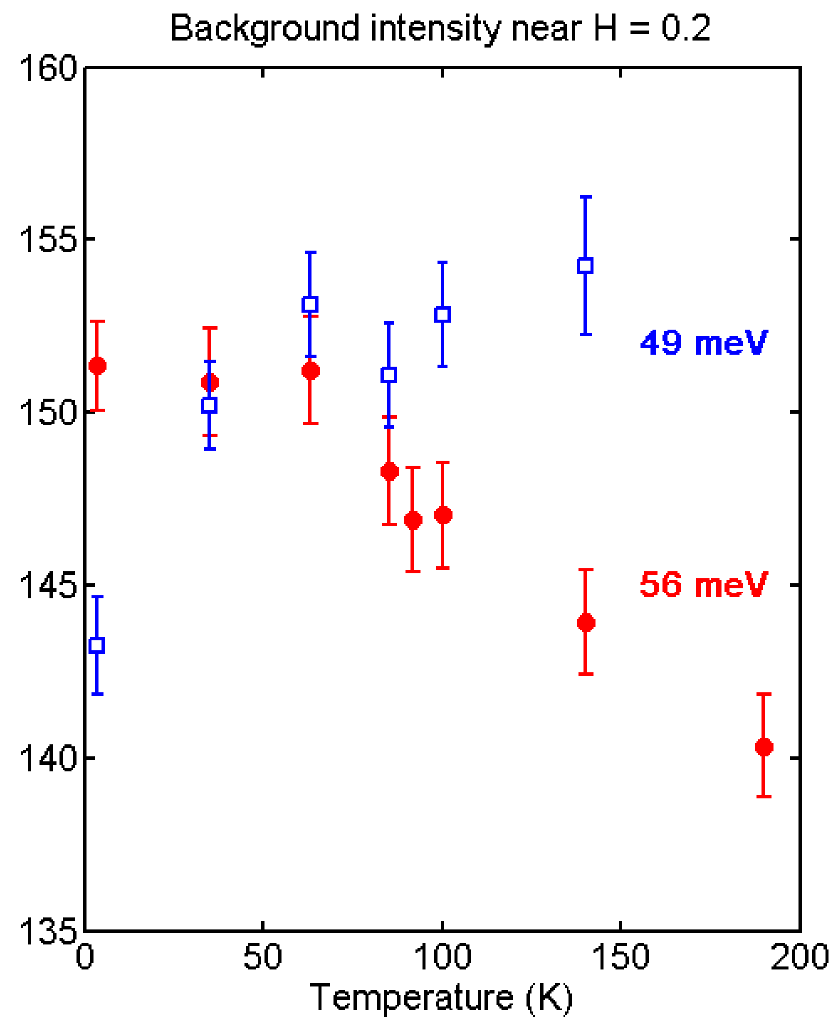
# Conventional (π, π) “resonance”




Yu et al., PRB **81**, 064518 (2010)

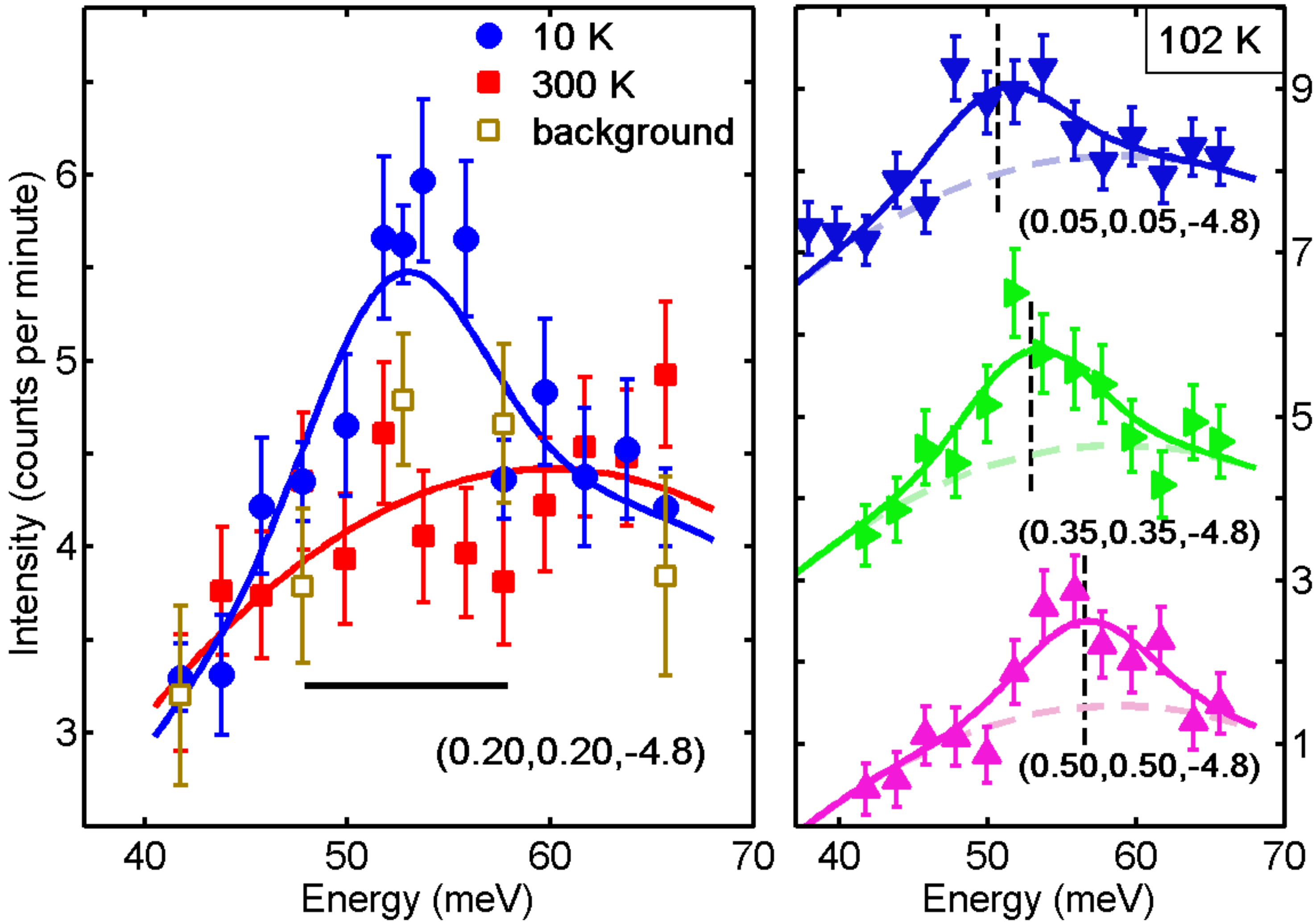
# Unusual "background" behavior



# Spin-polarized measurement

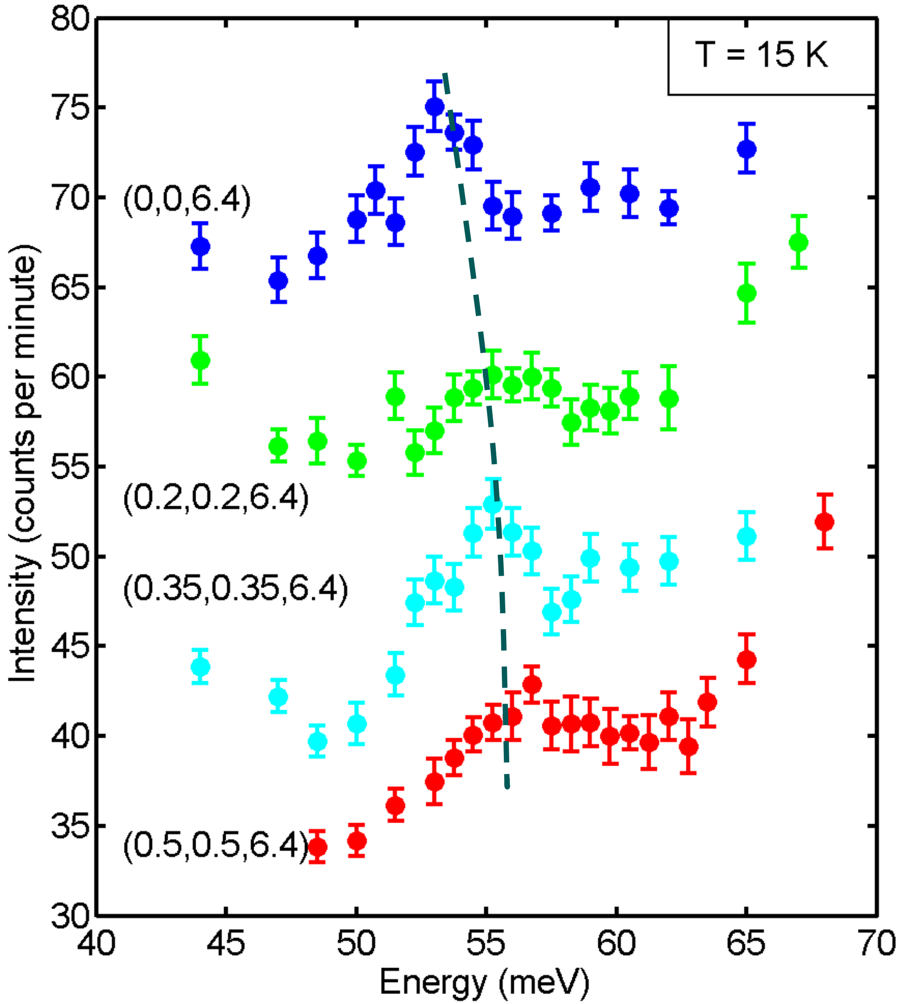
Sample: OP95



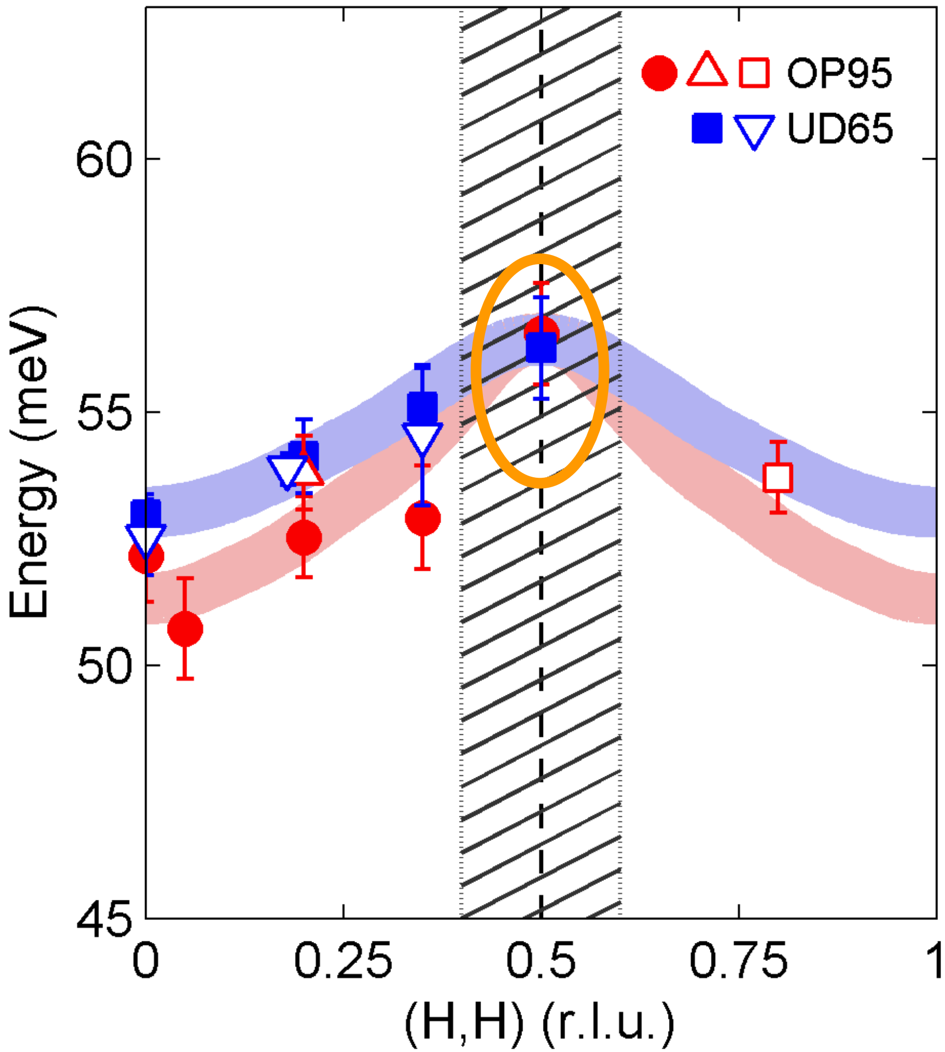

Li et al., Nature **468**, 283 (2010)

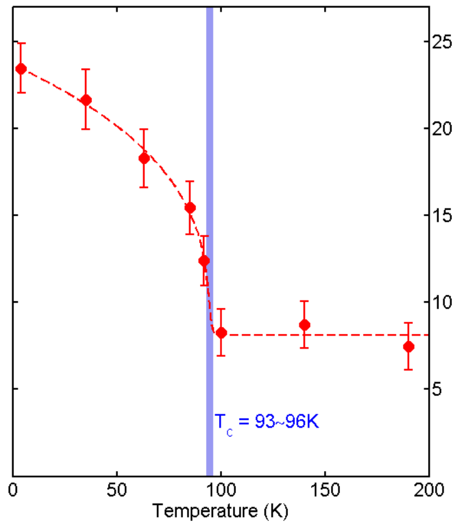
# Unpolarized measurement

Sample: UD65

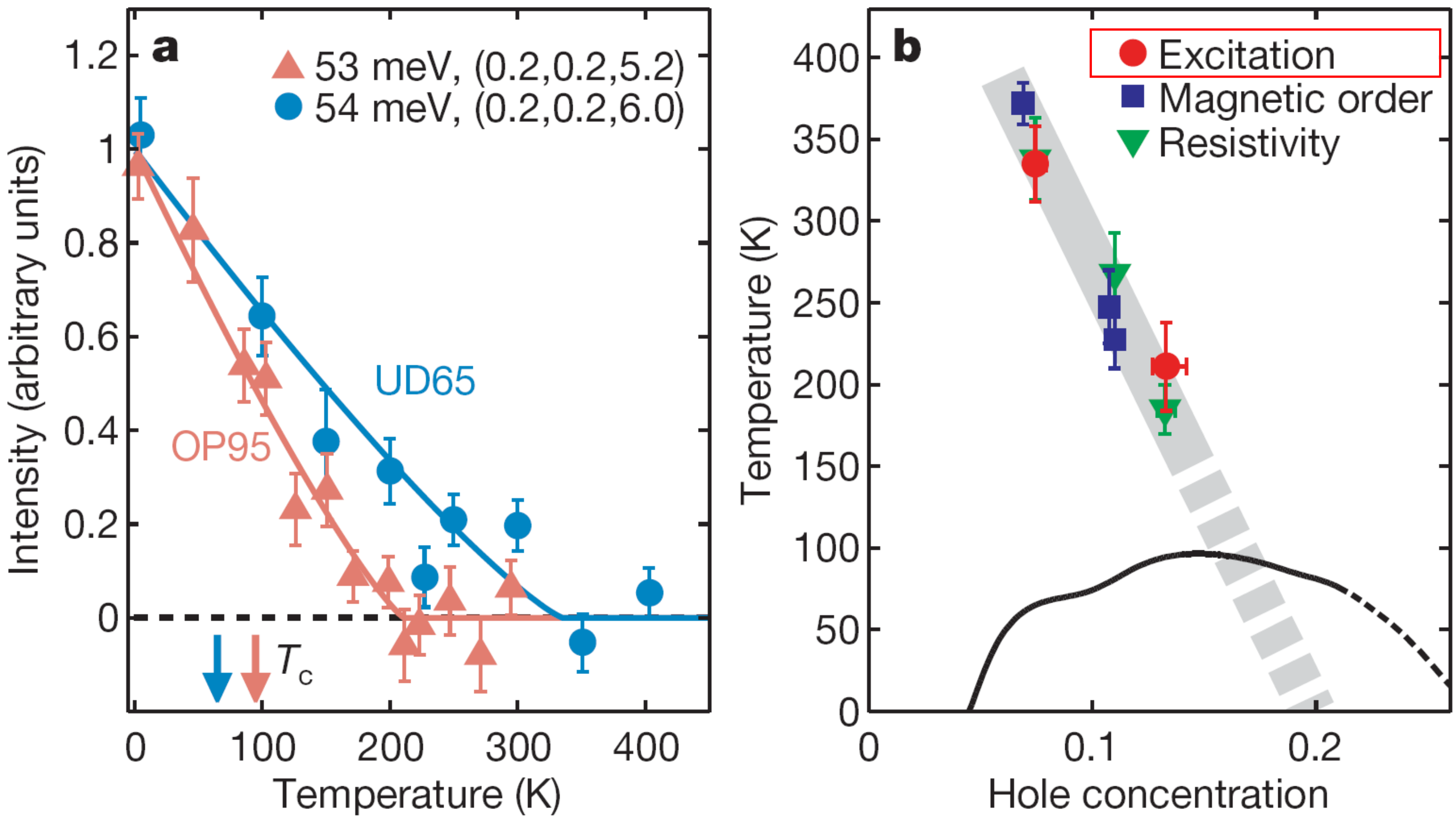


# Dispersion along the (1,1,0) direction



# Temperature dependence of intensity




Li et al., Nature **468**, 283 (2010)

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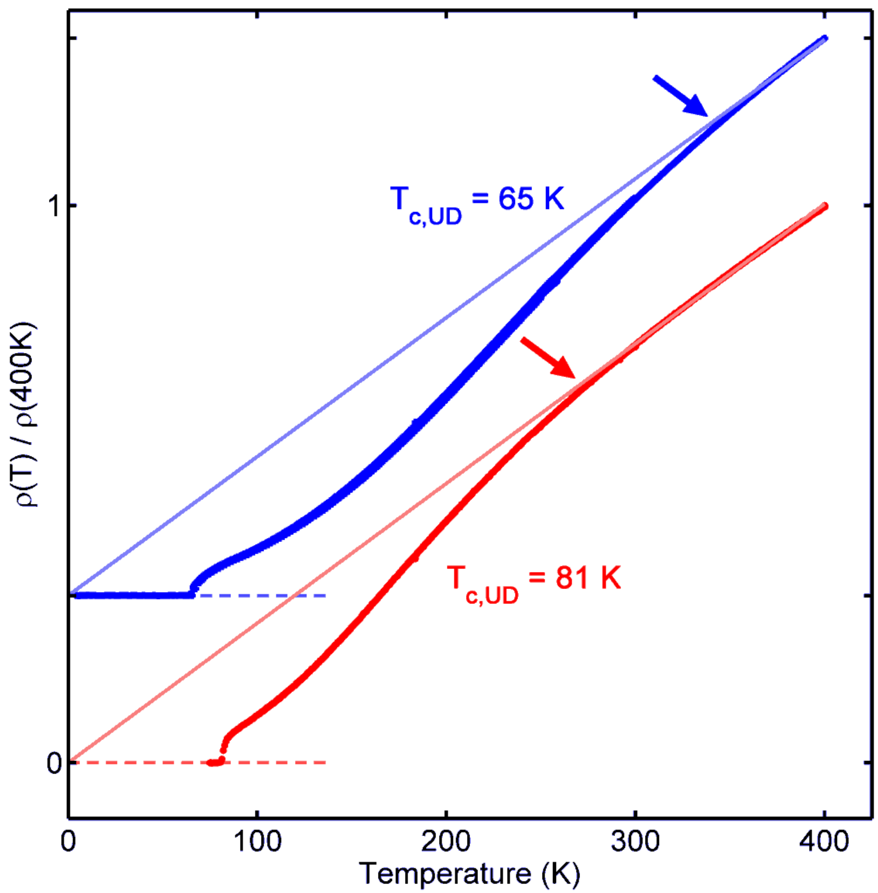
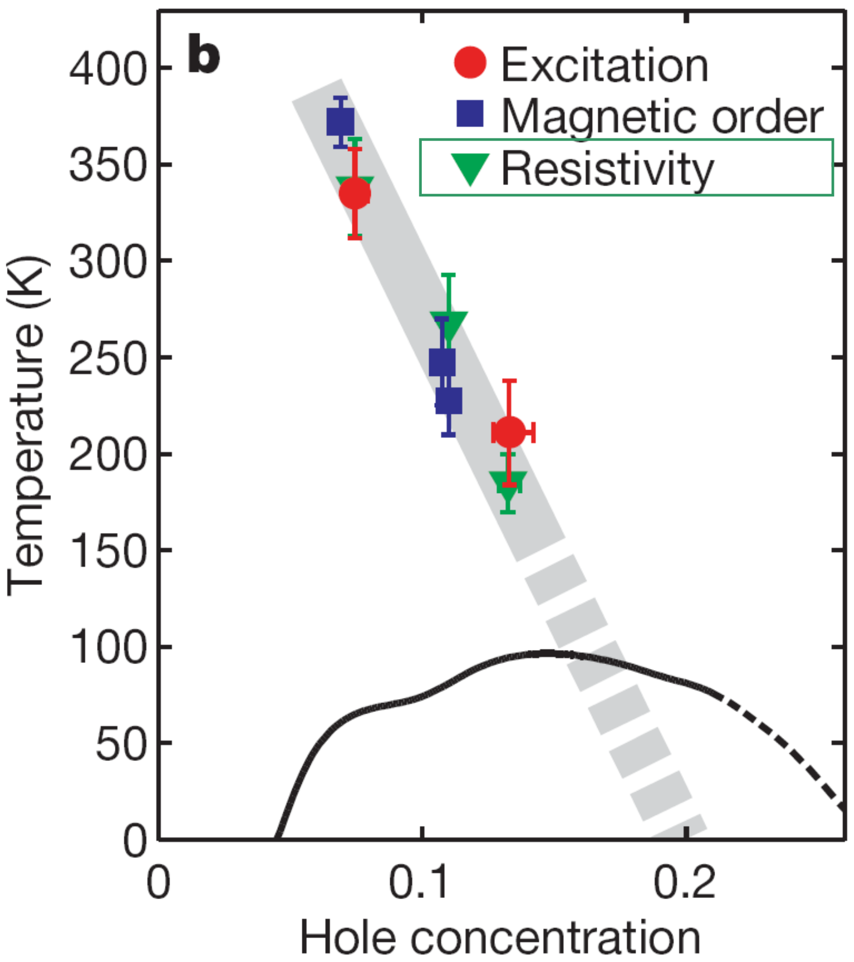
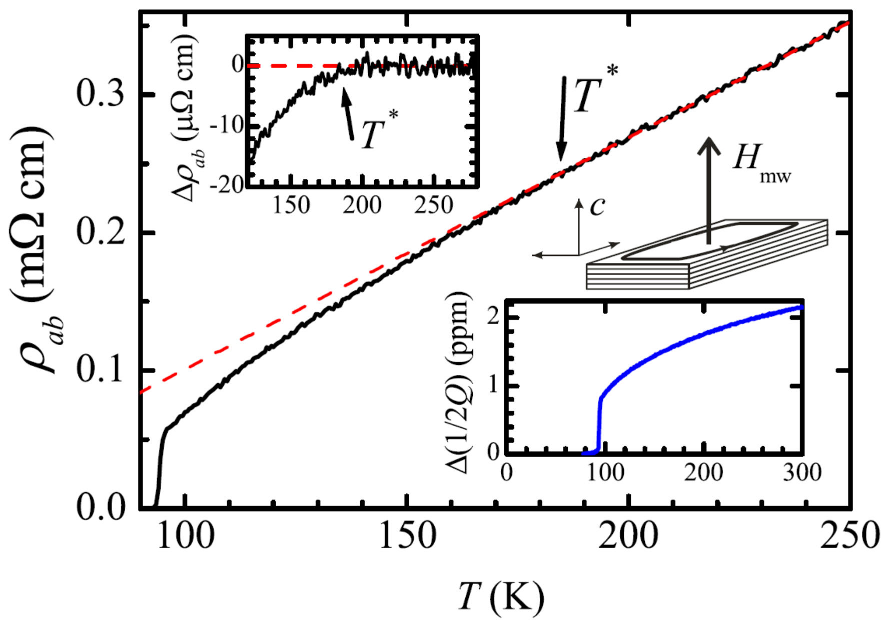


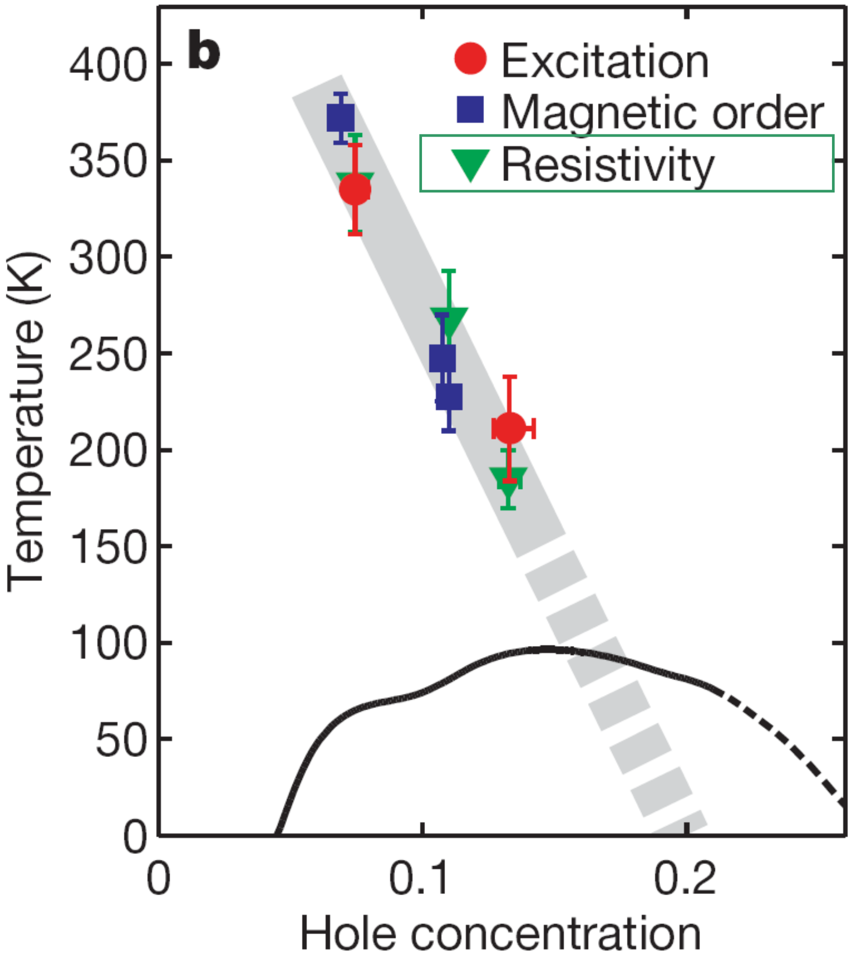

Li et al., Nature **468**, 283 (2010)

# Temperature dependence of intensity

$T^*$ in OP95




Grbić et al., PRB **80**, 094511 (2009)




Li et al., Nature **468**, 283 (2010)

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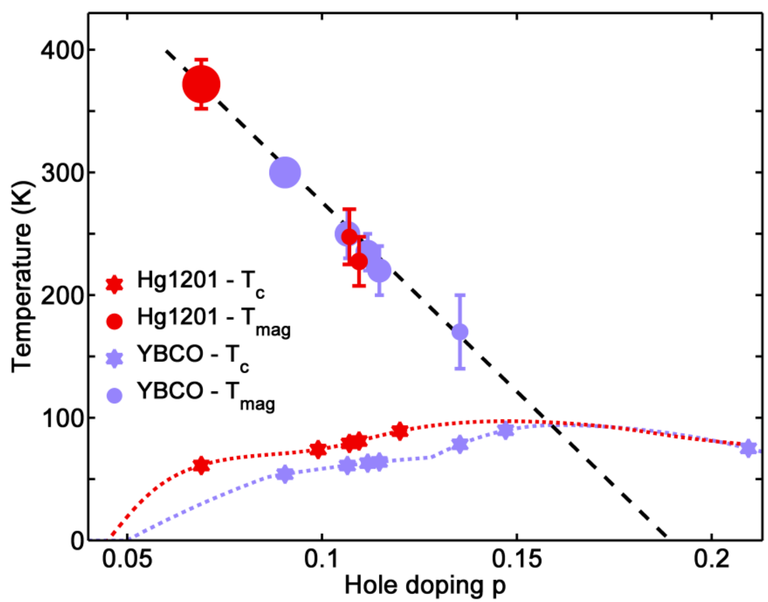
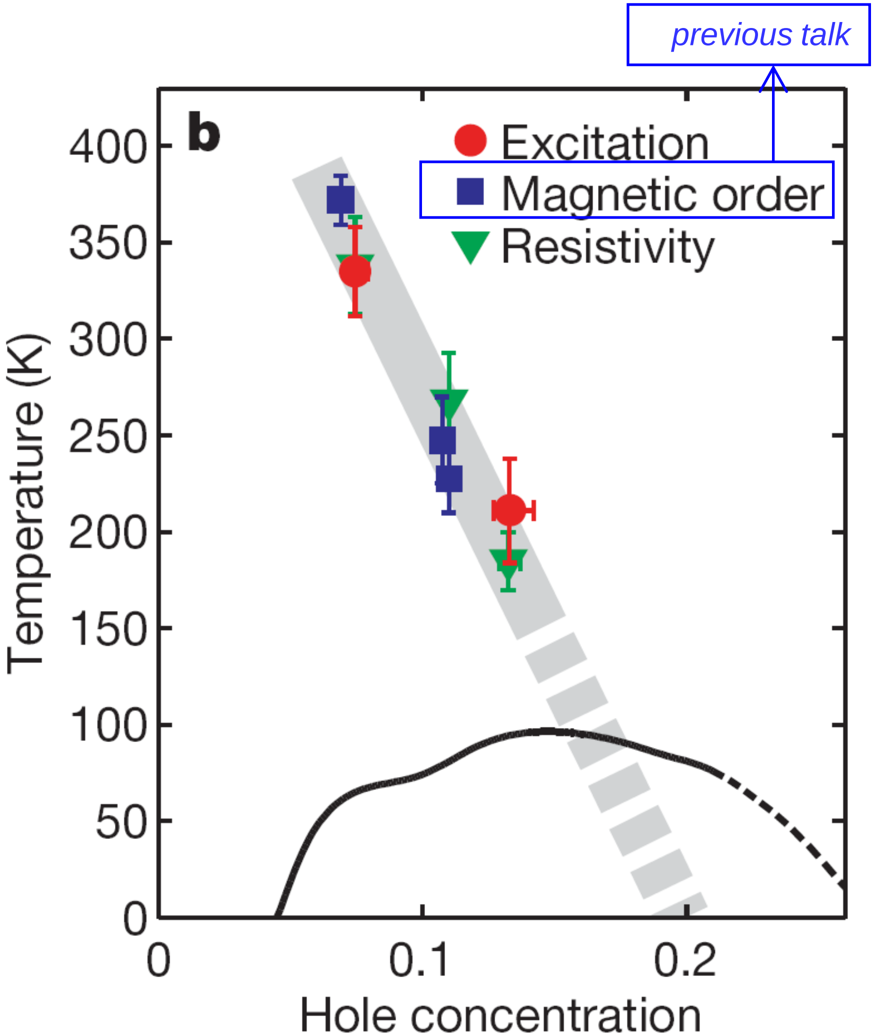



Li et al., Nature **455**, 372 (2008)




Li et al., Nature **468**, 283 (2010)

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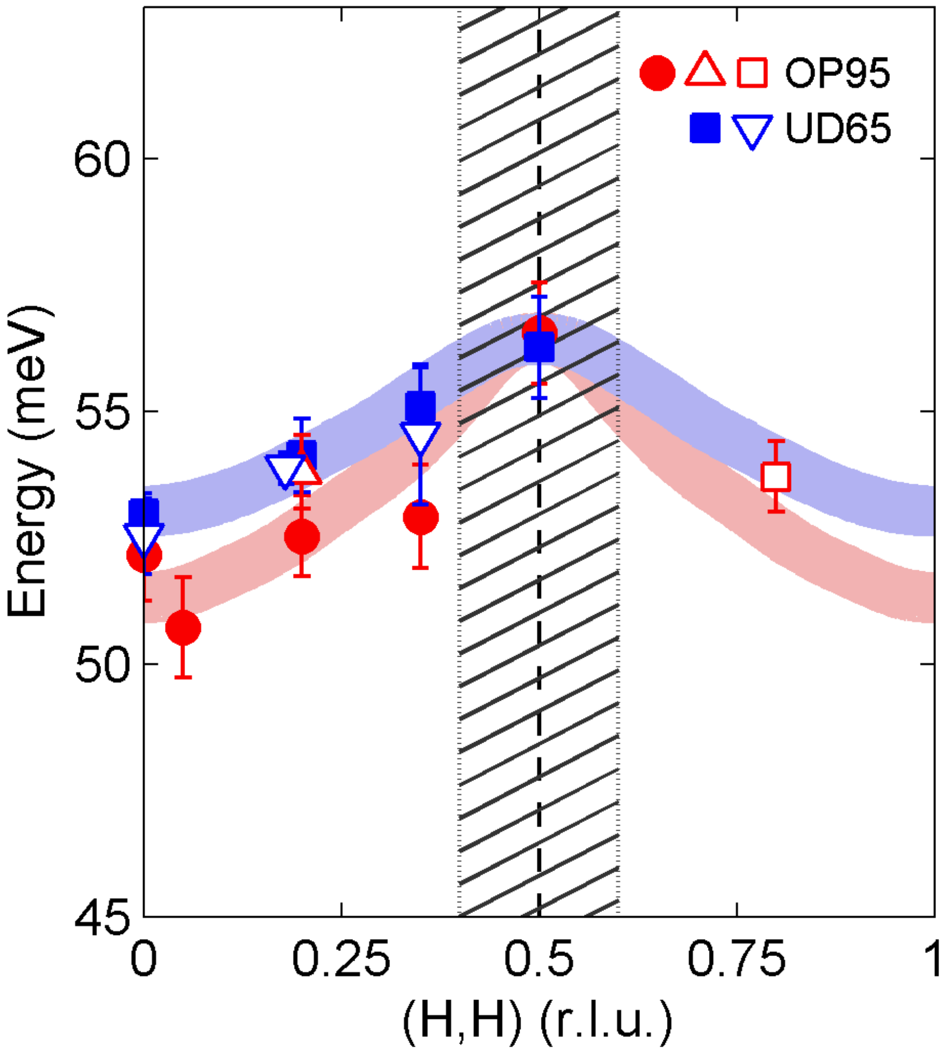
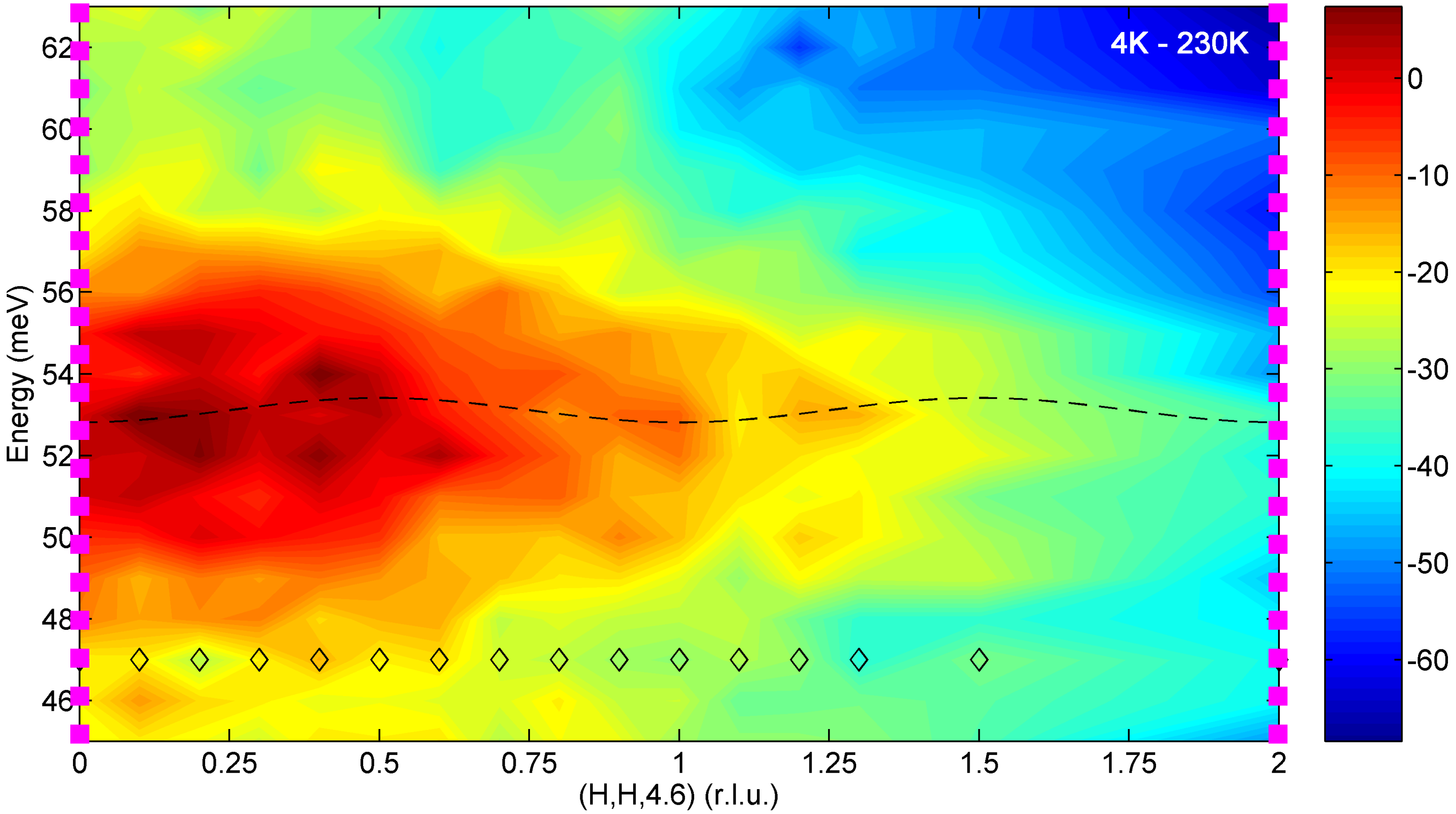


# Intensity map

## Sample: OP95



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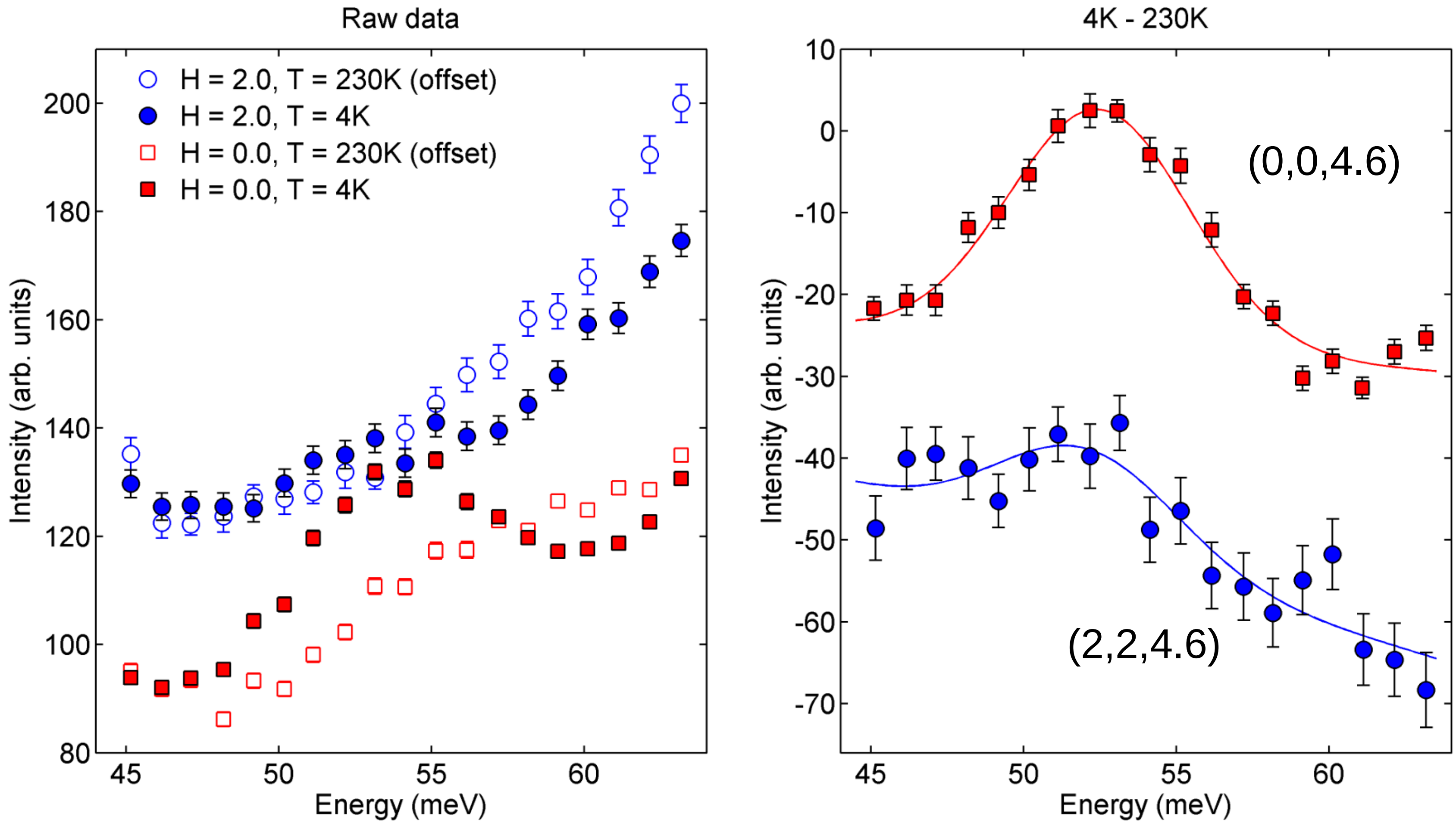

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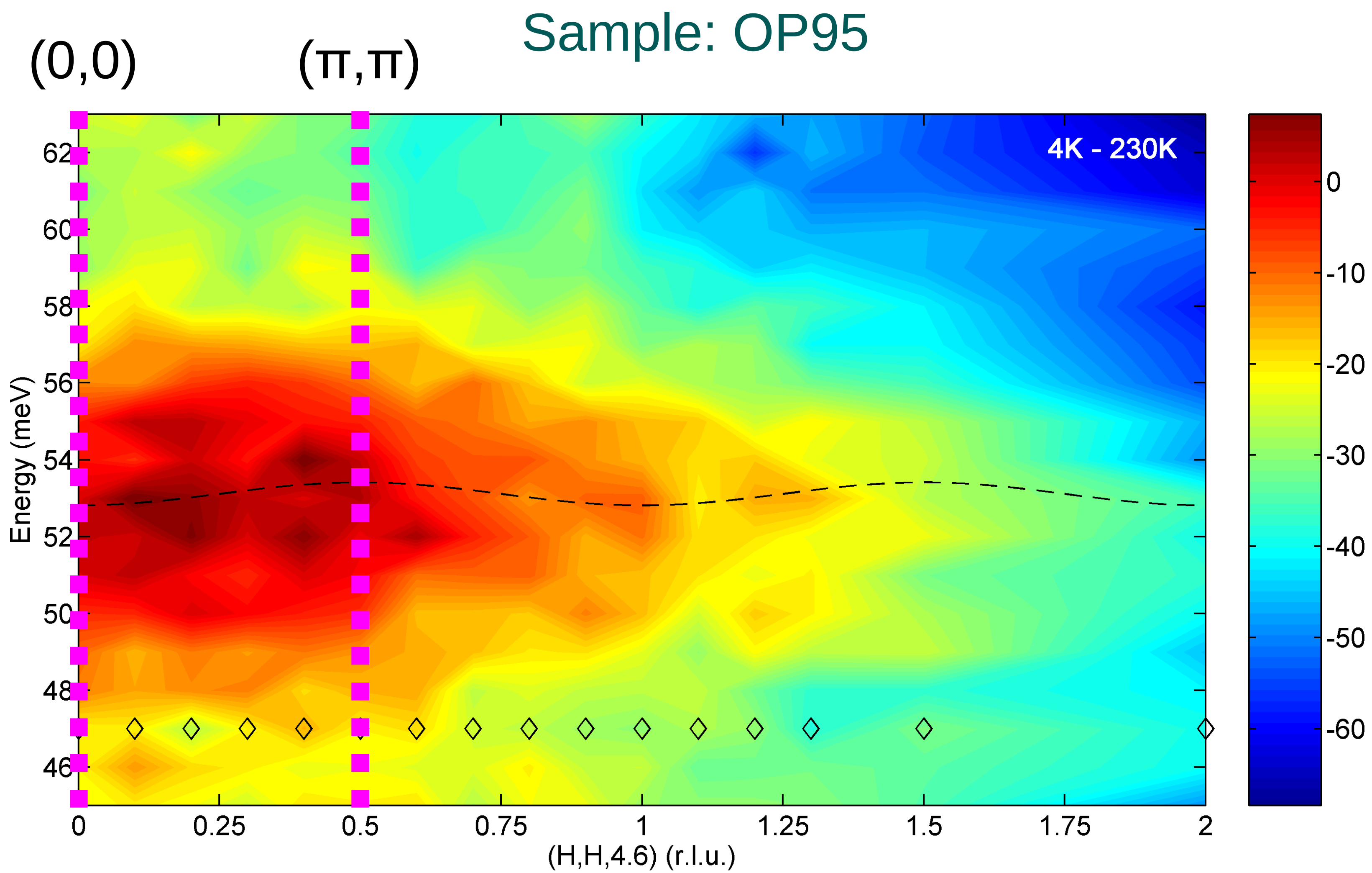

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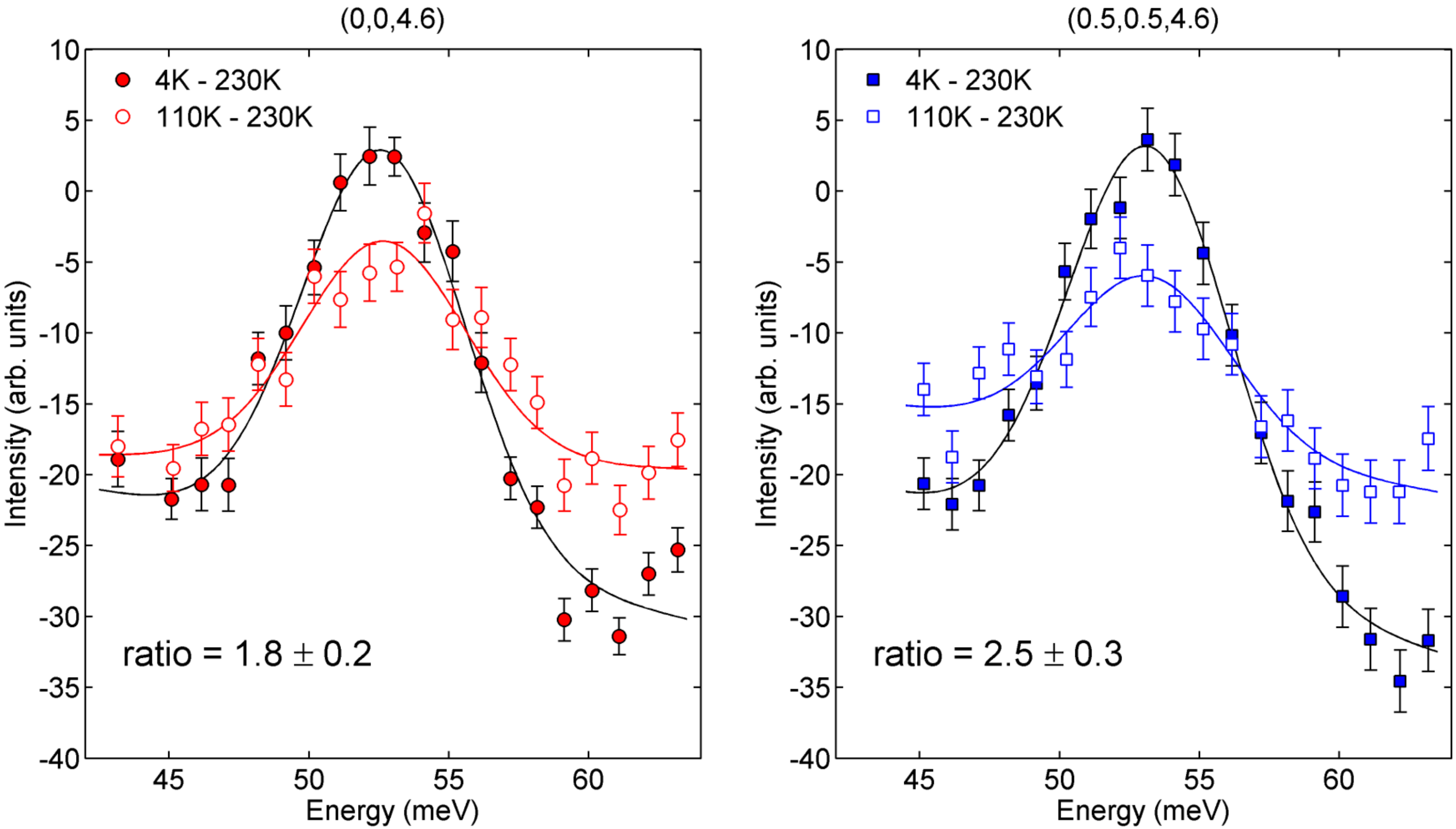

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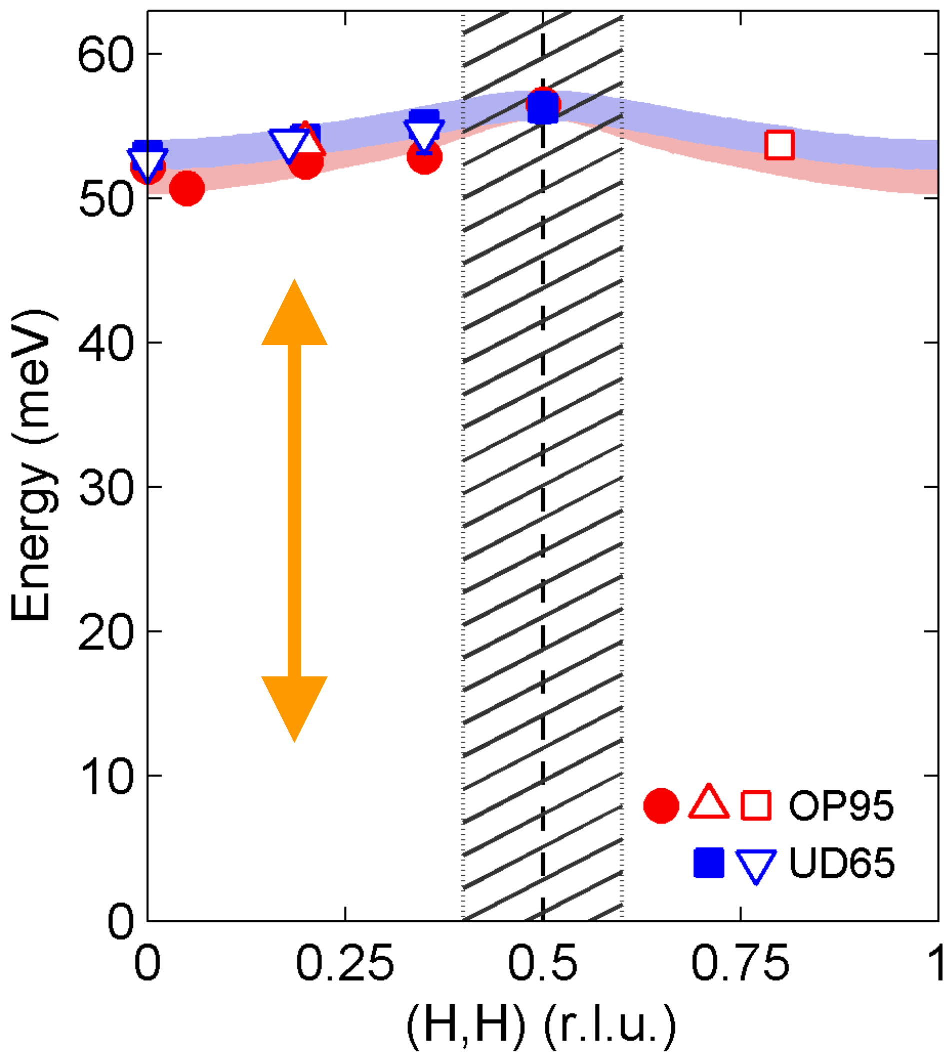
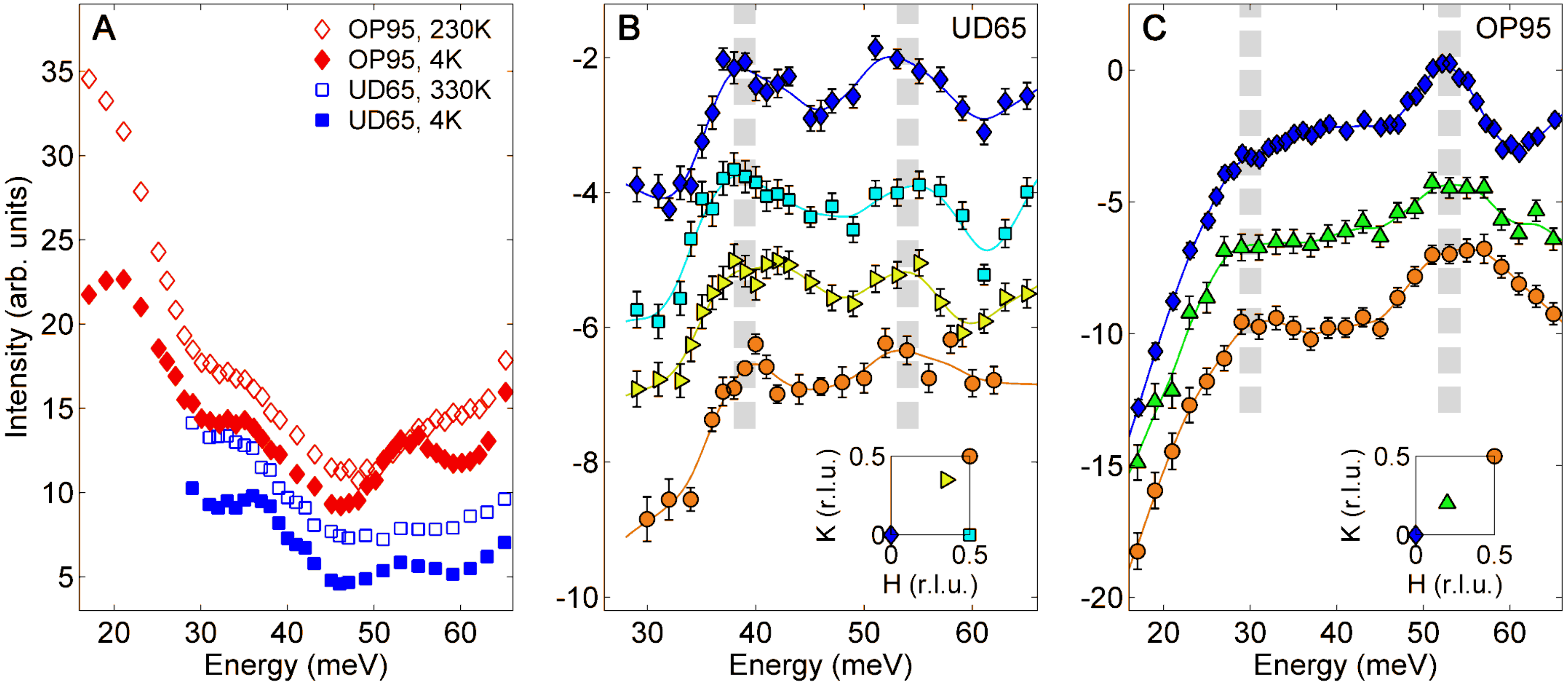


# A second mode at lower energy

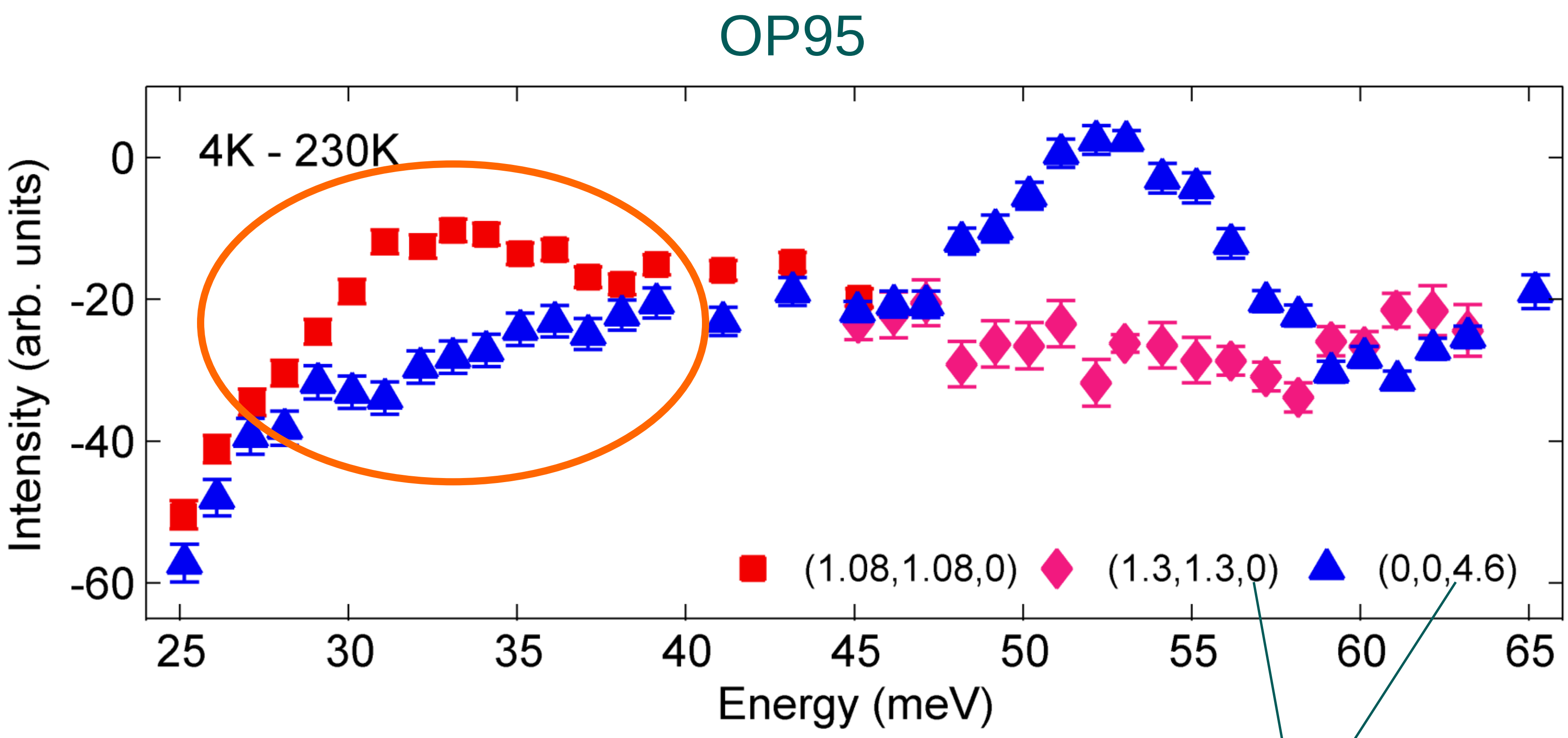
Raw data
**Q** = (0, 0, 4.6)

UD65, 4K – 330K

OP95, 4K – 230K



# Intriguing momentum “selection rule”




90° sample rotation

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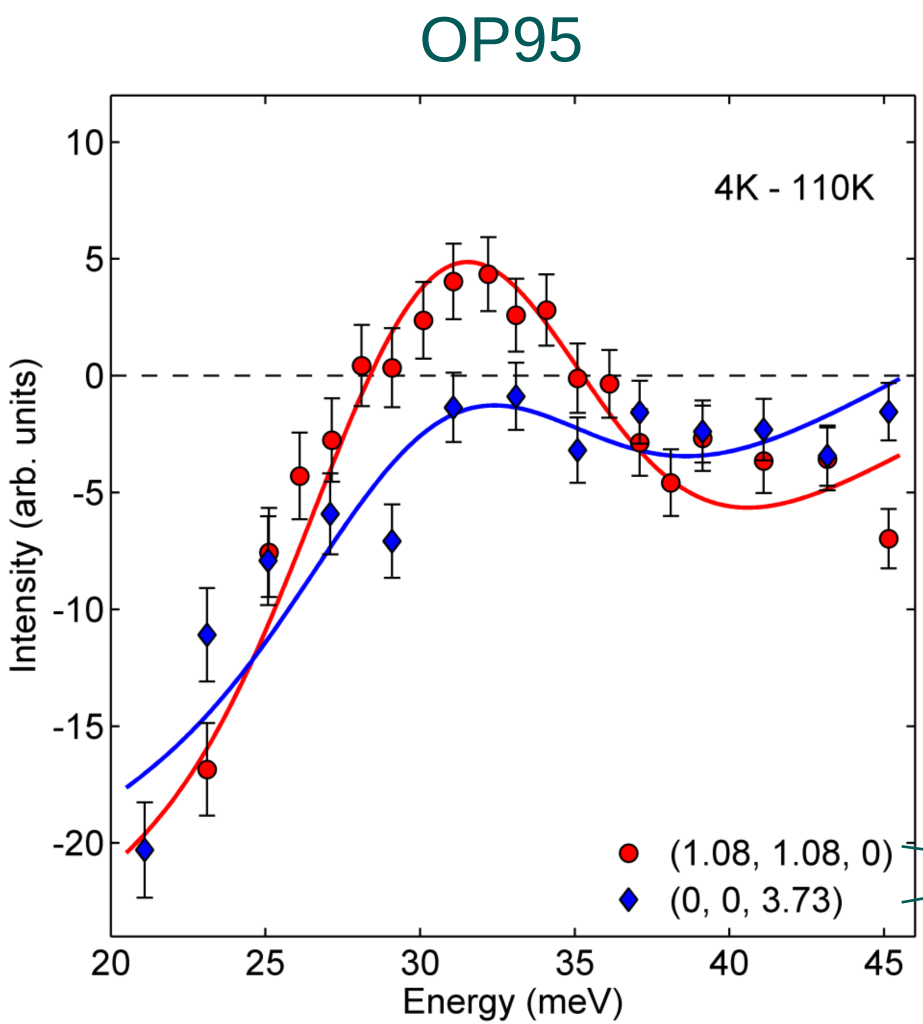
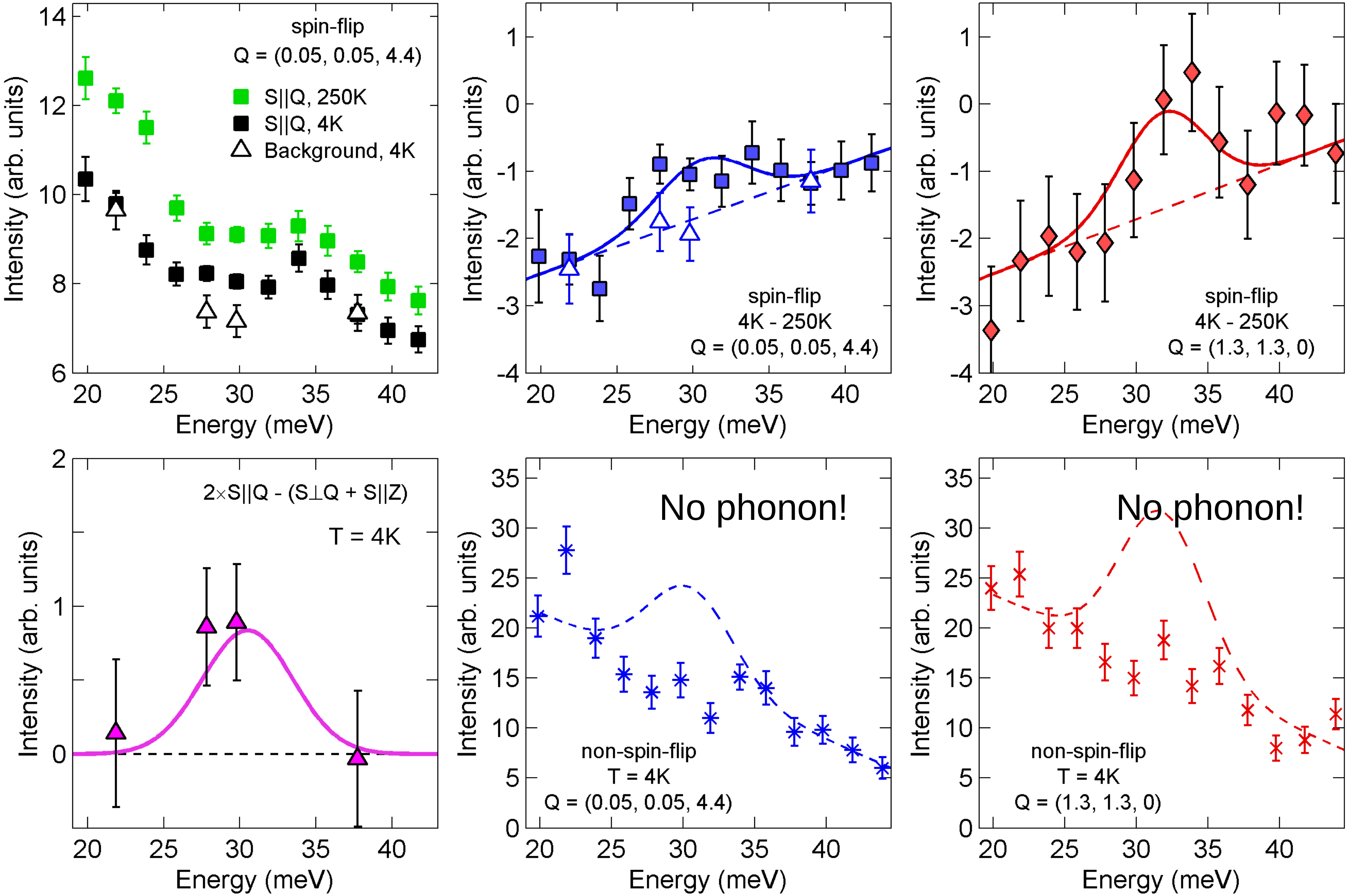
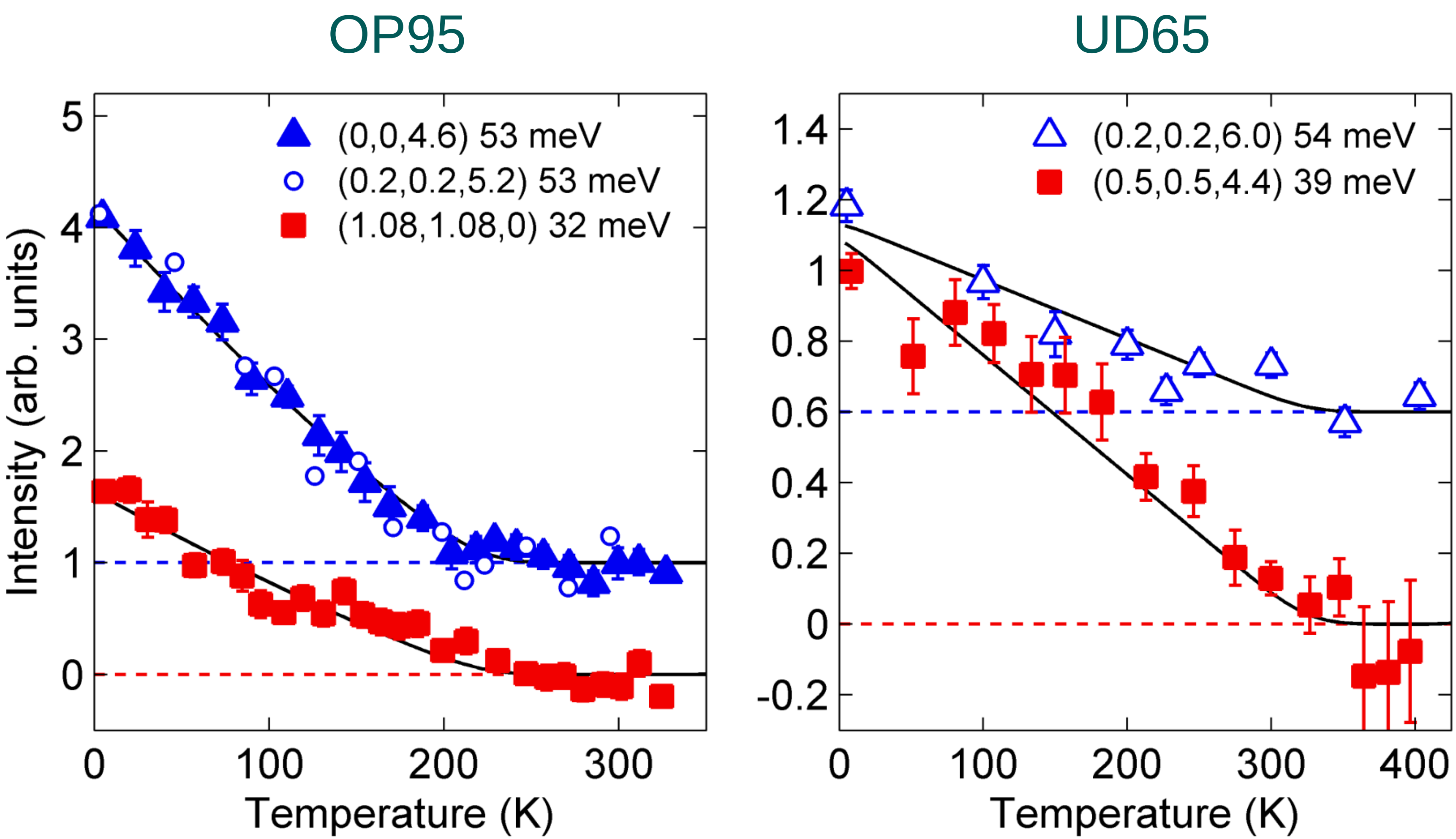



90° sample rotation

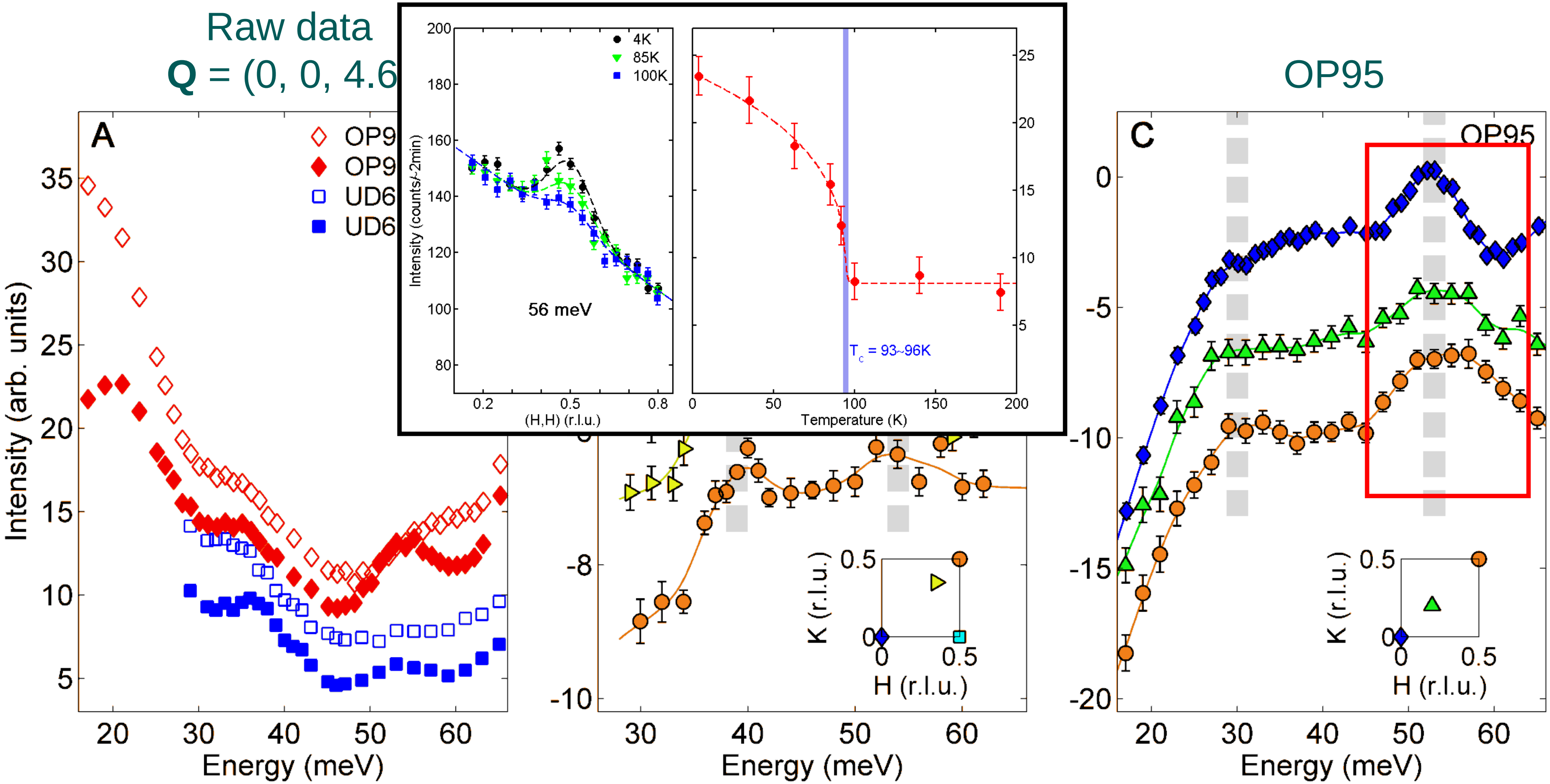
# Spin-polarized measurements



# Temperature dependence



# Connection to (π, π)



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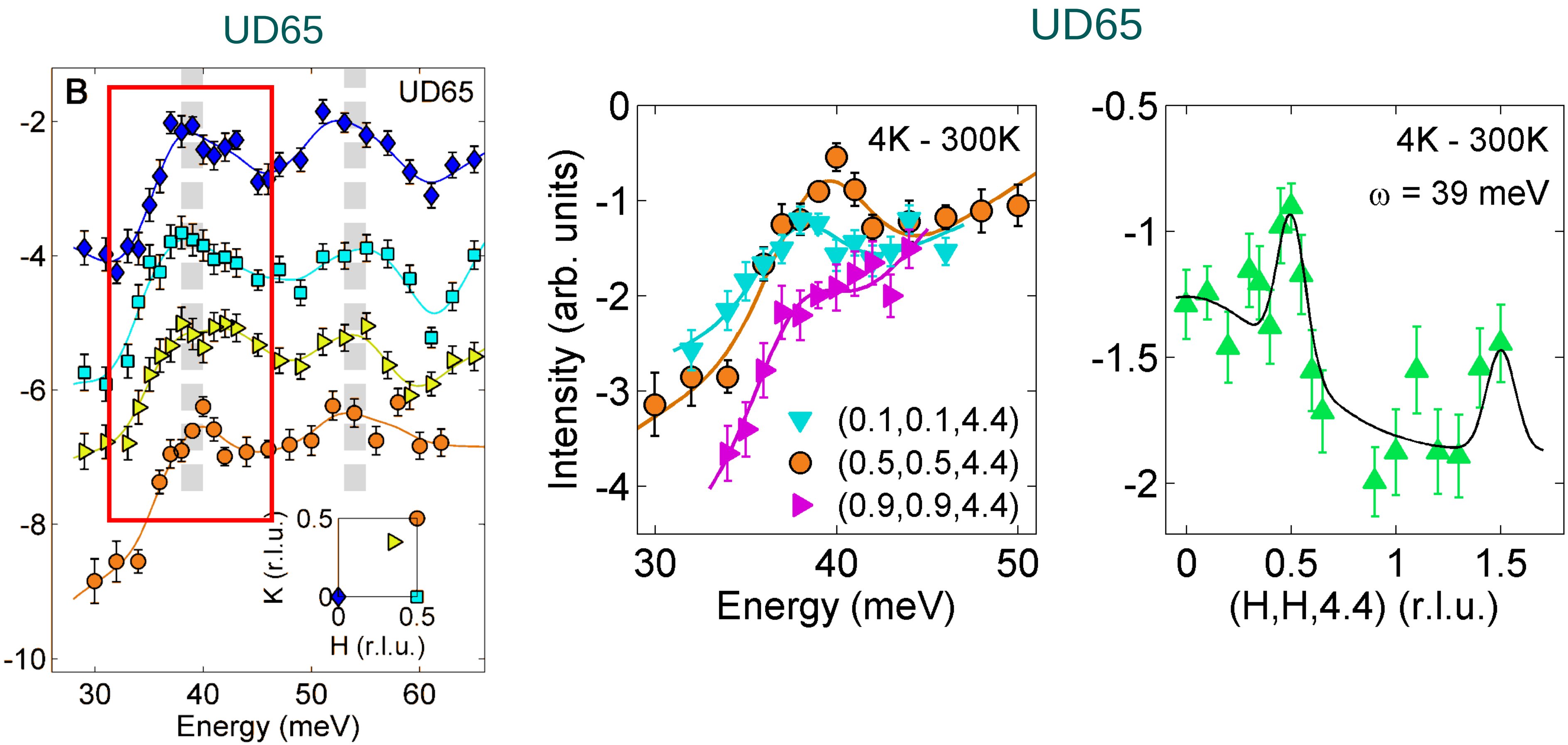
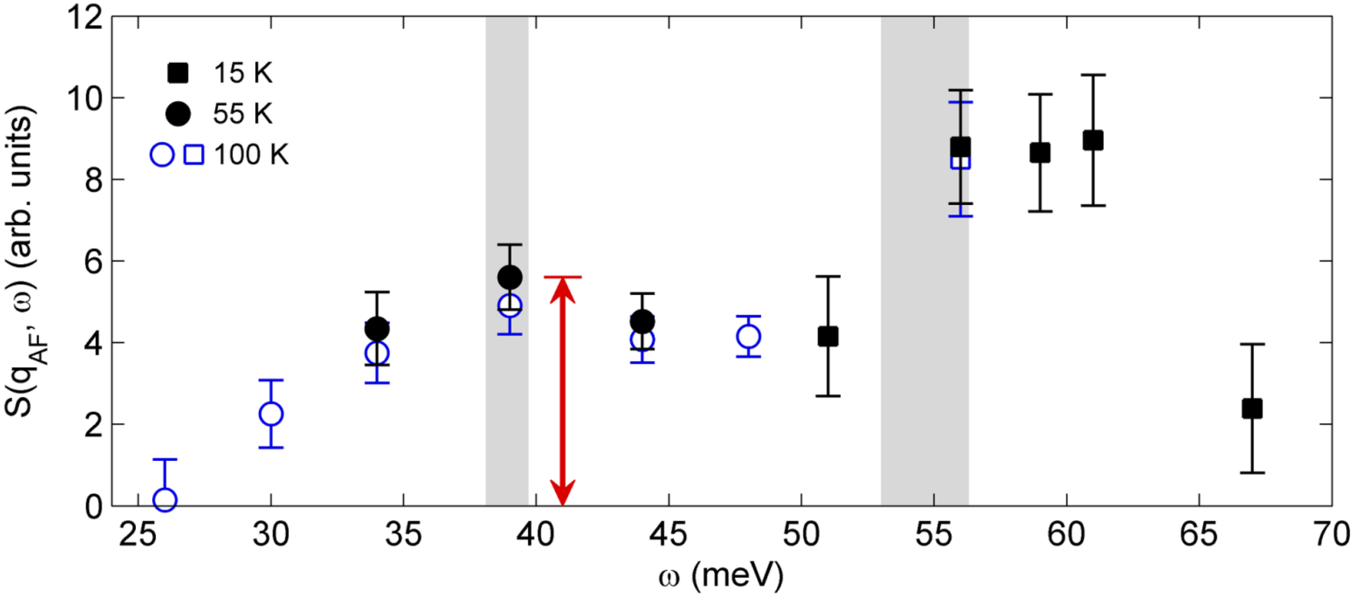
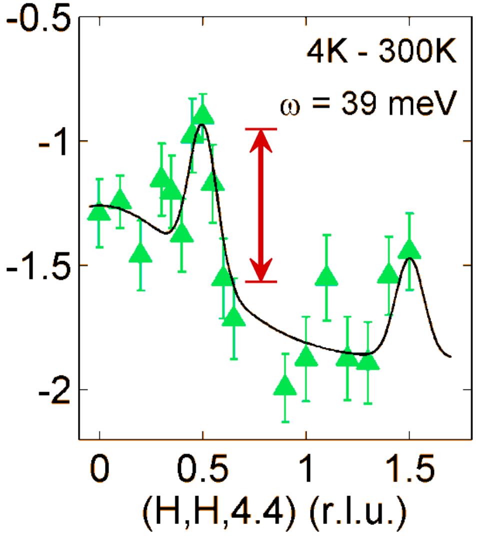


# Connection to (π, π)

UD65

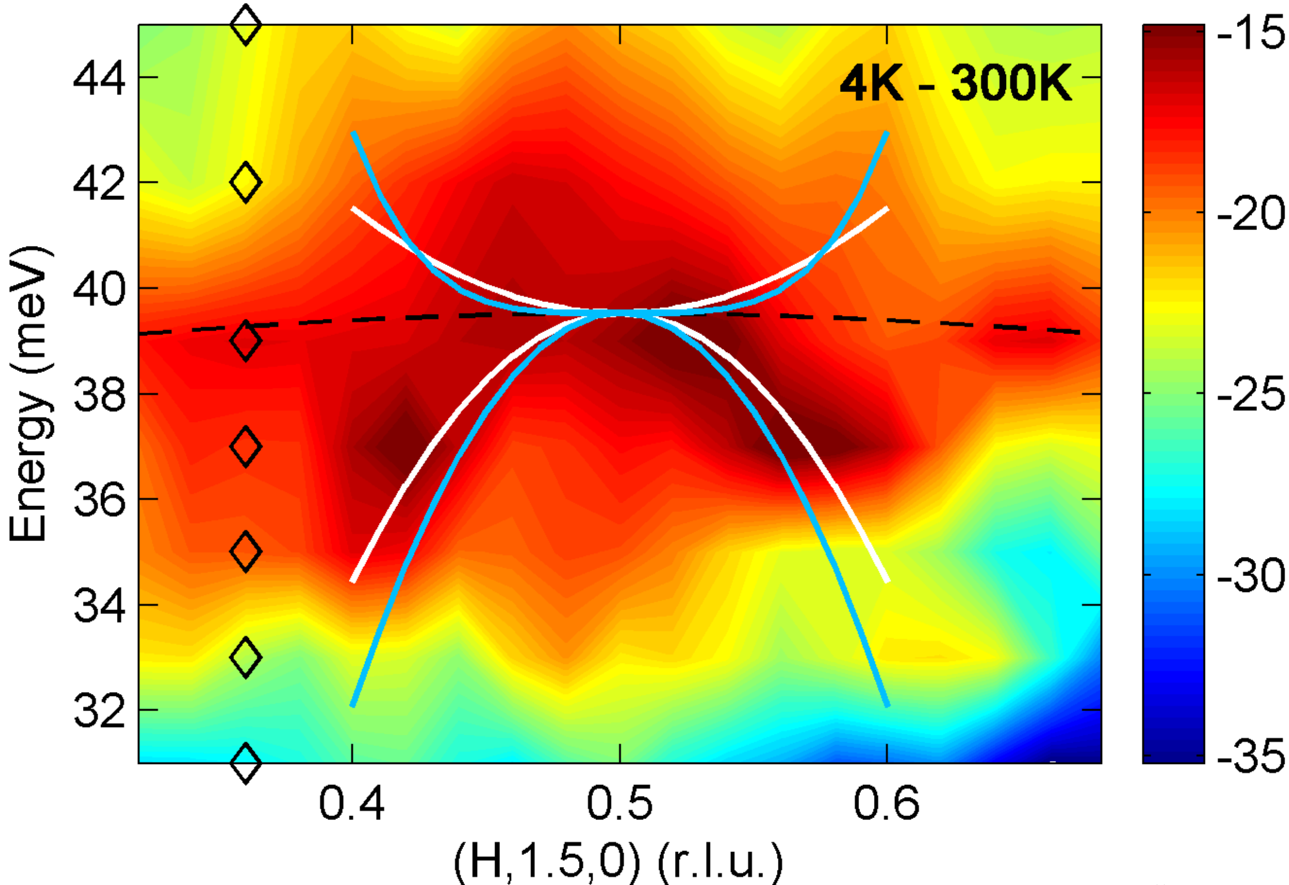



UD65



# Connection to (π, π)

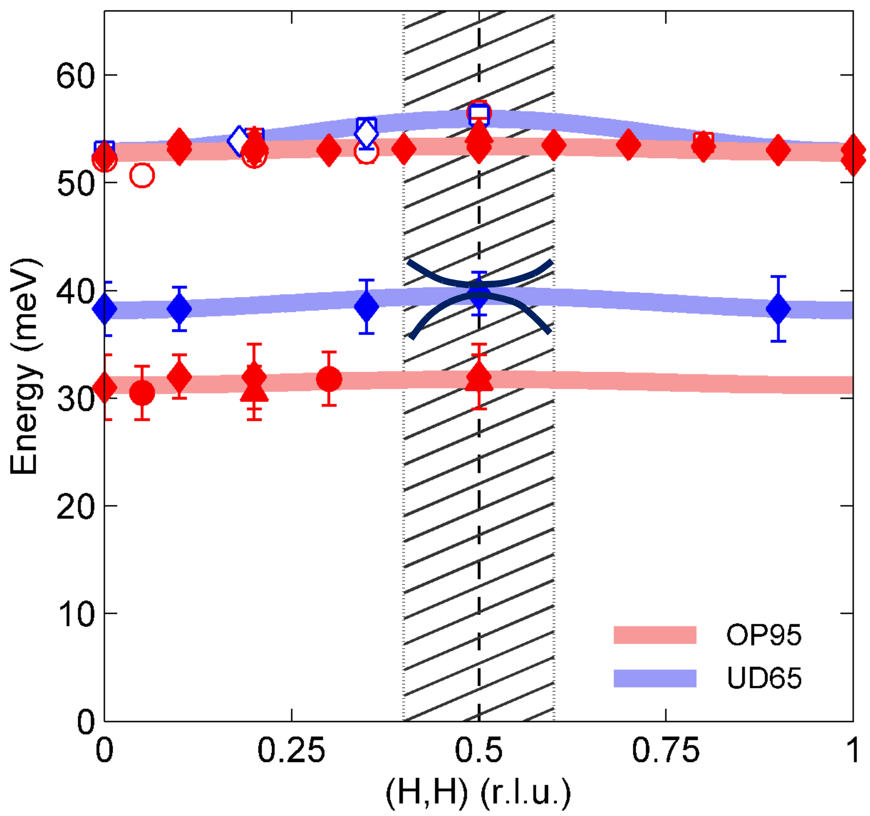
Sample: UD65




Lines: “hourglass” in YBCO

# INS summary

- Two weakly dispersing modes
- Confirmed to be magnetic
- Appear below *T**
- One mode softens with doping
- “Connected” to signal maxima at (π, π)




Y. Li et al., Nature **468**, 283 (2010)

Y. Li et al., unpublished

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- First branch: ~53 meV
- Second branch: 30 – 40 meV
- Relation to antiferromagnetic fluctuations

## 3. Discussion

# Relation with the pseudogap order

| Order → | Excitation |
| --- | --- |
| Lattice with single-atom u.c. | Acoustic phonons |
| Lattice with multi-atom u.c. | Acoustic + optical phonons |
| Antiferromagnetic order at $\mathbf{q}_{AF} = (1/2, 1/2)$ | From $\mathbf{q}_{AF}$ and $\omega = 0$ ($\omega_{max} \sim 2J$) |
| "Hidden" magnetic order at $q = 0$ | From $q = 0$ and finite $\omega$<br>Two modes with one $CuO_2$-layer |

# Theoretical model

Multi-band models which allow for n > 1 magnetic centers in the unit cell

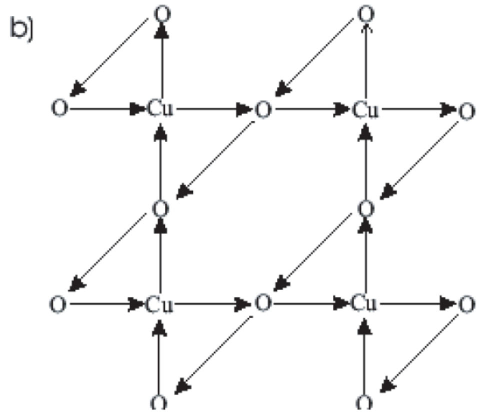
→ Intra-unit-cell decorated magnetic ground state

→ Excitations from finite $\omega$ (analogue to optical phonons)

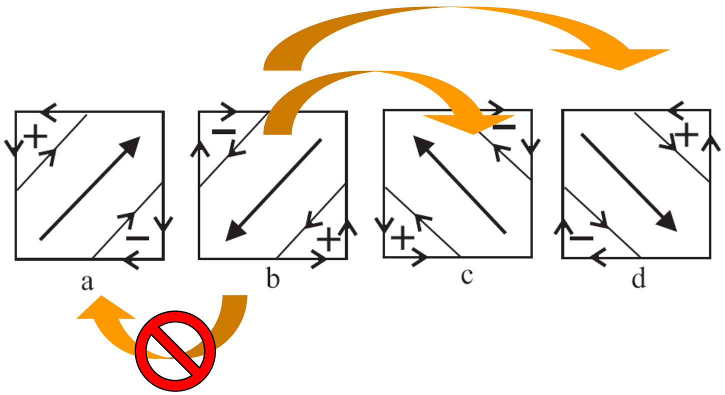
"Hidden" magnetic order at $q = 0$

From $q = 0$ and finite $\omega$
Two modes with one $CuO_2$-layer

# Orbital-current-loop theory

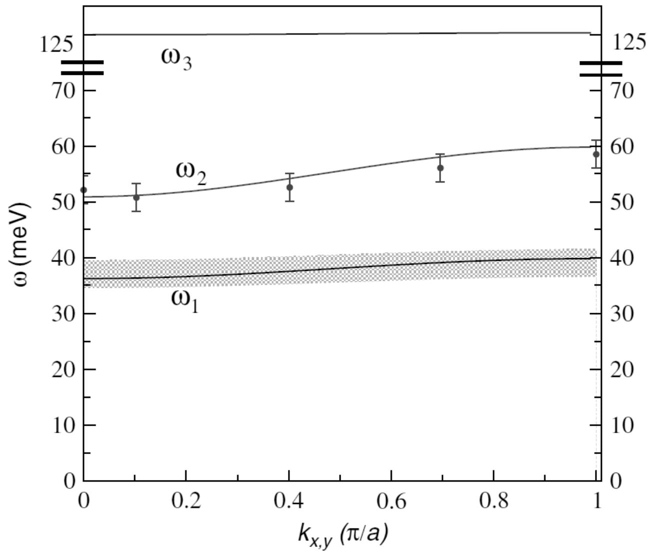



C.M. Varma, PRB (1997, 2006)



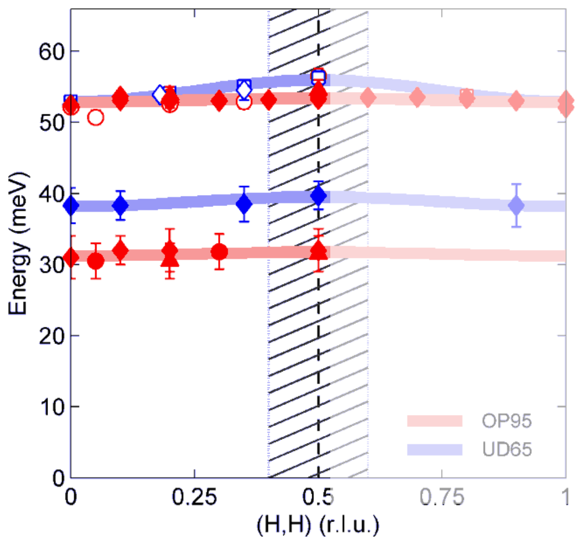

Classical ground states with Ising-like symmetry

theory

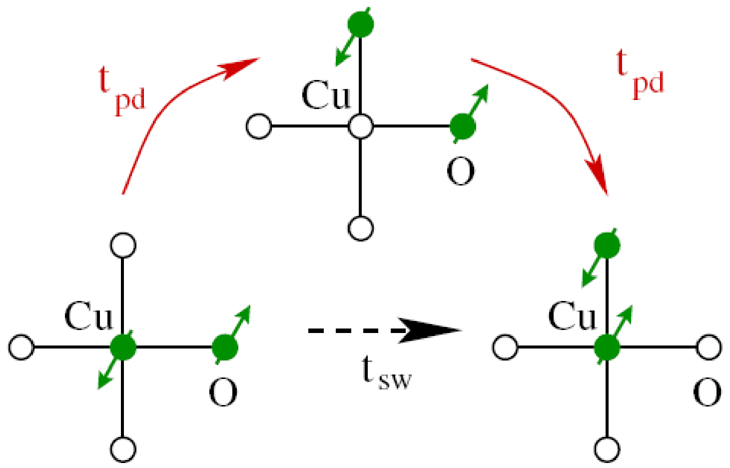


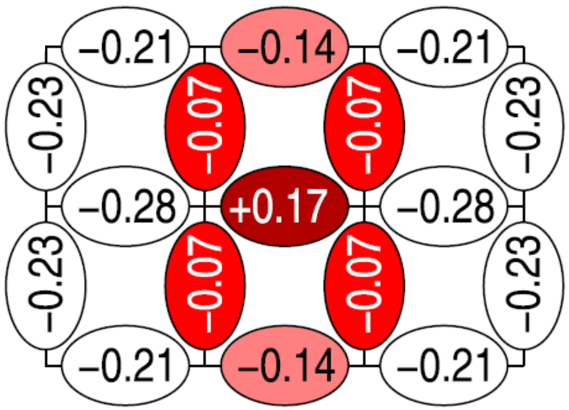

Y. He and C.M. Varma, PRL **106**, 147001 (2011)

experiment



# Multi-band spin model




Numbers indicate Cu-Cu spin correlation via O bonds in the *q*=0 lowest-energy state: singlet= -0.75, AFM= -0.33, triplet= +0.25

B. Lau, M. Berciu & G.A. Sawatzky, PRL **106**, 036401 (2011)

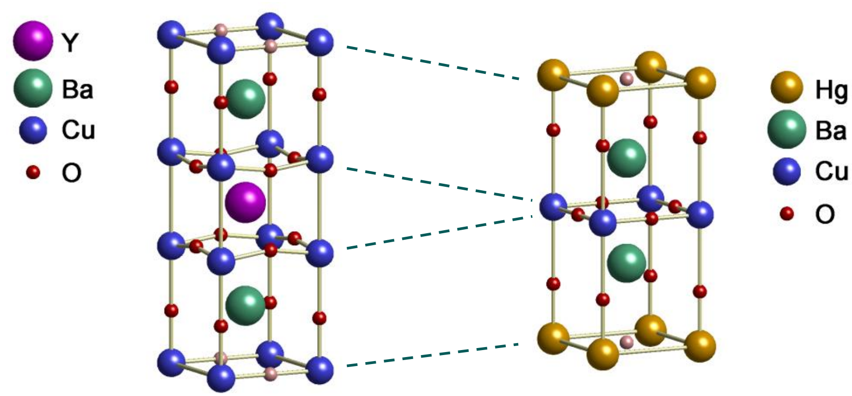
poster session

# Summary

- Demonstration of universality of $q = 0$ pseudogap order in Hg1201
- Observation of two weakly dispersing magnetic modes in the pseudogap phase of a single-layer system
- Experimental results consistent with orbital-current-loop theory
- General need for a multi-band description of the high-$T_c$ cuprates

# Ongoing effort

- Test of universality in $YBa_2Cu_3O_{6+x}$

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