香港科技大学(广州)
THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY (GUANGZHOU)

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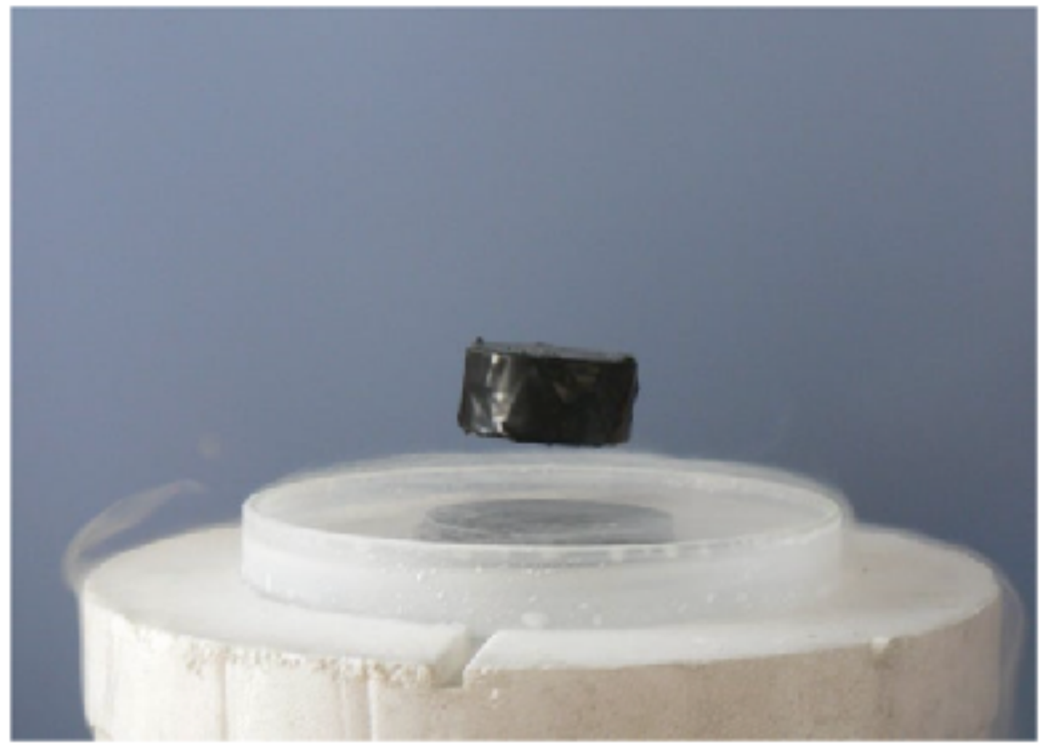
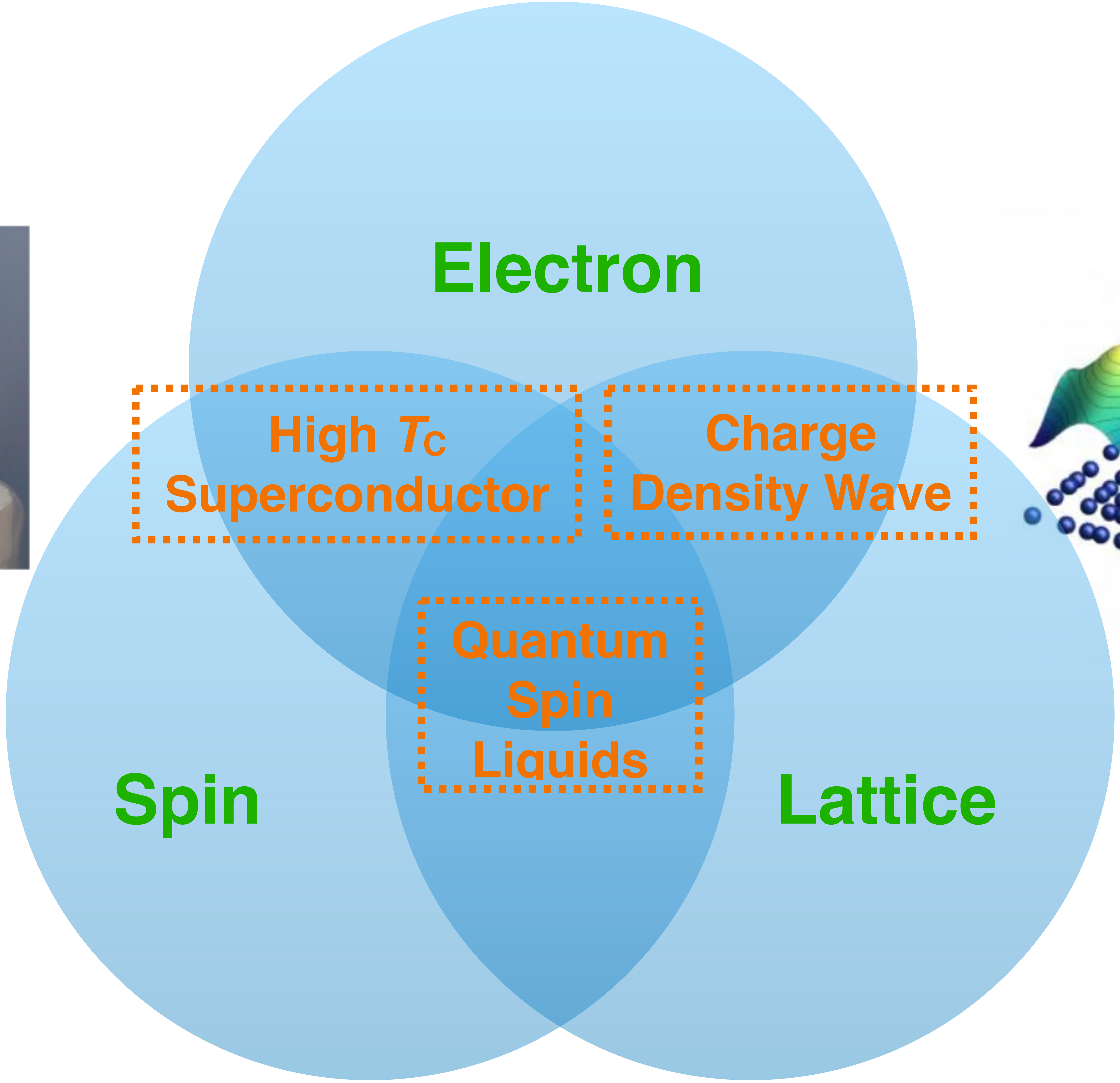
先进材料学域
Advanced Materials Thrust

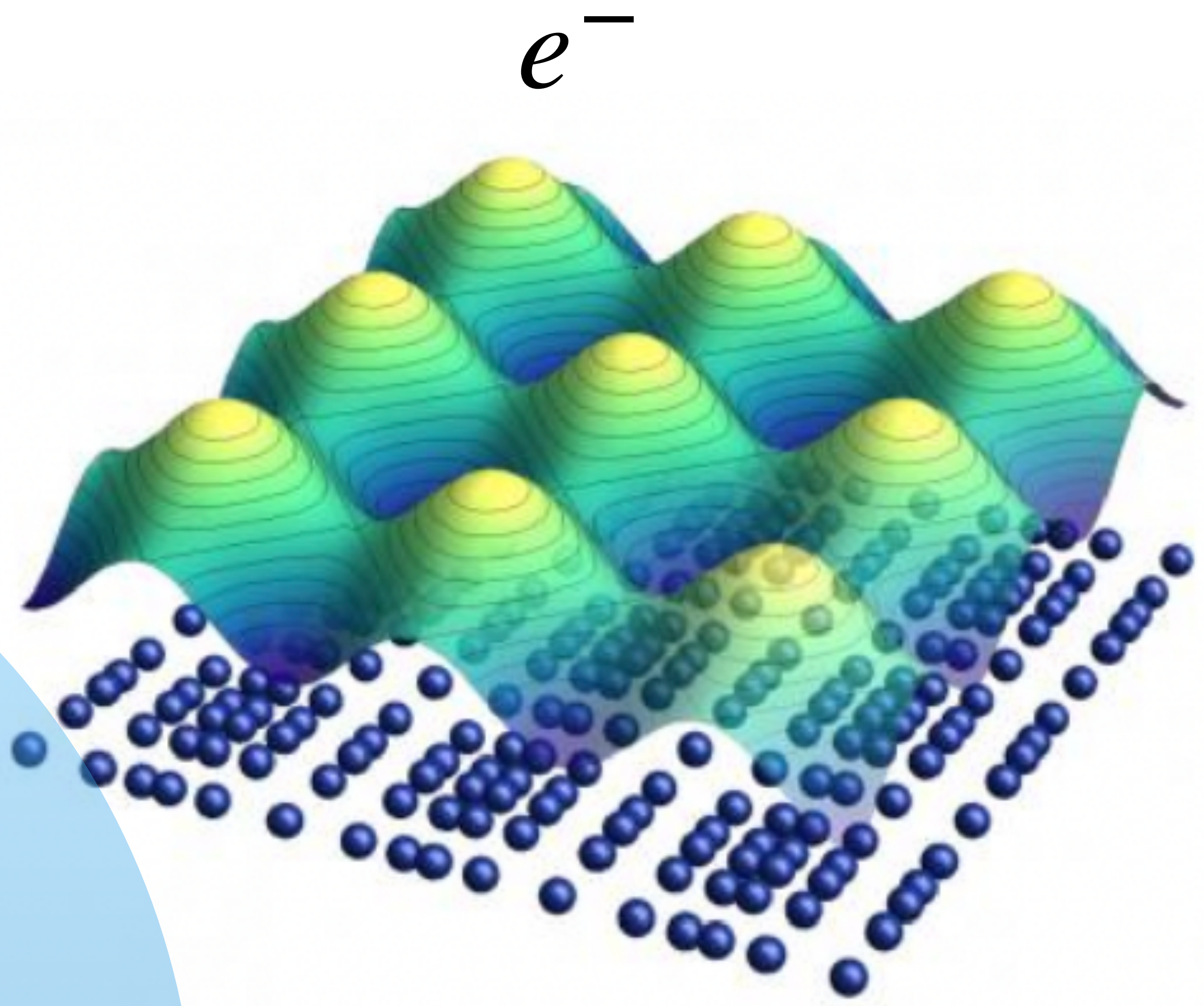
Synchrotron based X-ray Scattering Spectroscopy for Quantum Materials Research

Presenter: Haoxiang Li, 2023/07/07

Macroscopic quantum many-body states in solids

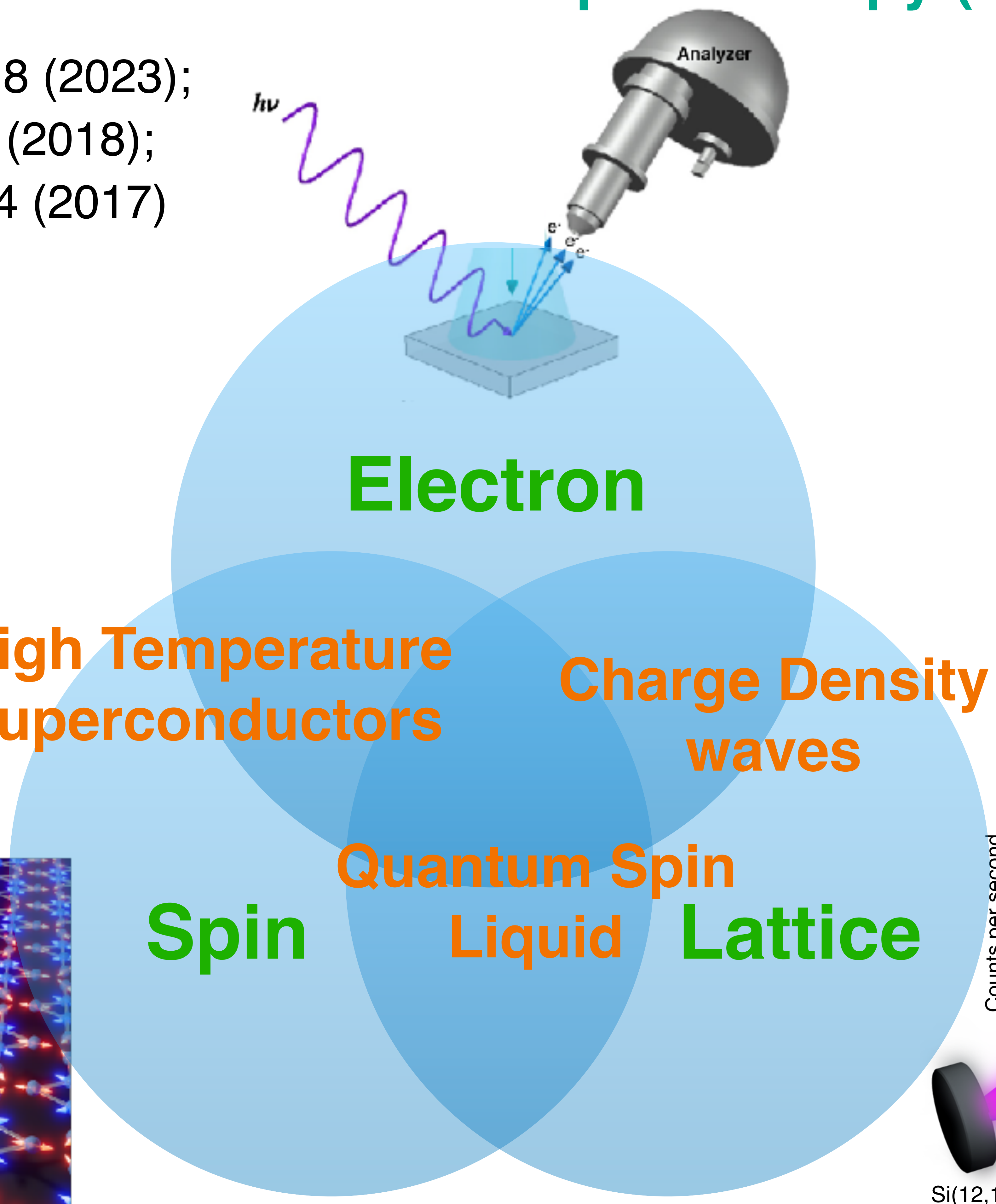


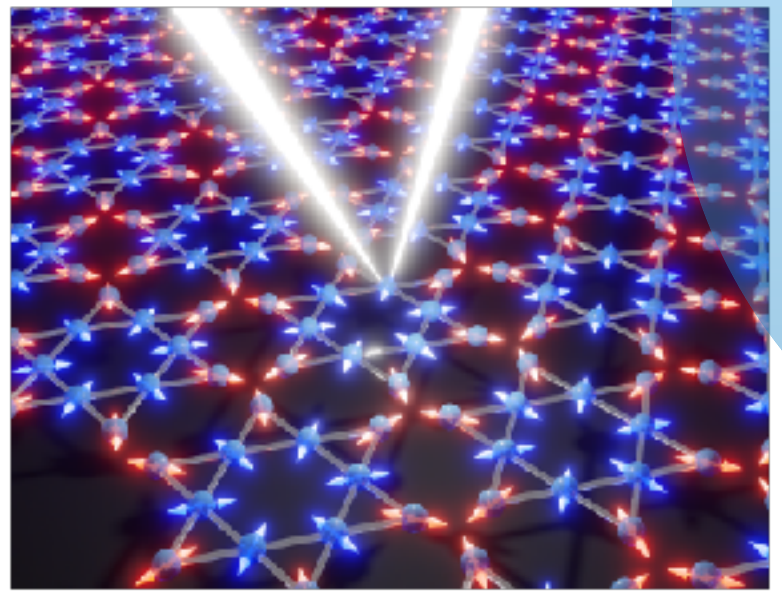


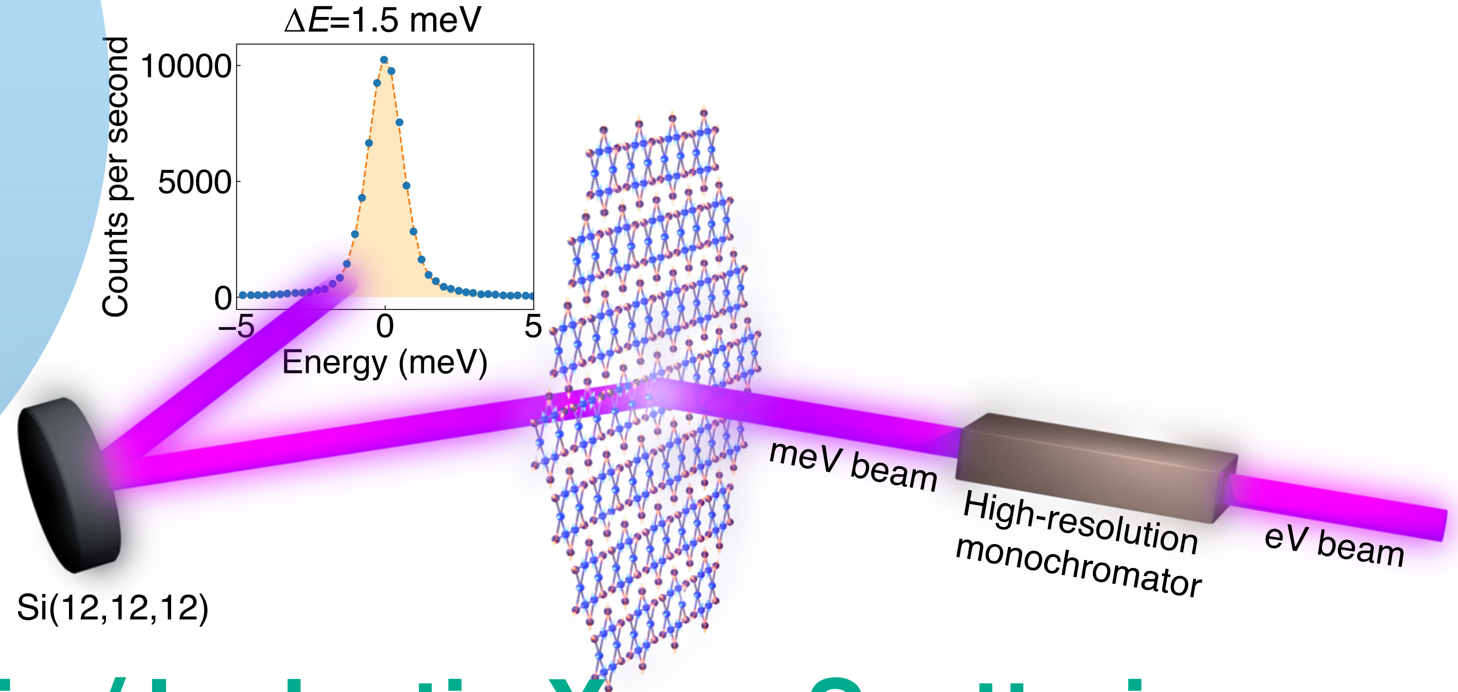


Angle-Resolved Photoemission Spectroscopy (ARPES)

H. Li et al. Science Advances 9, eade4418 (2023);
H. Li et al. Nature Communications 9, 26 (2018);
H. Li et al. Nature Communications 8, 704 (2017)







Spin-resolved ARPES
Polarized / Inelastic X-ray Scattering

H. Li et al. Nature Communications 12, 3513 (2021)

Resonant / Elastic / Inelastic X-ray Scattering
High-resolution electron scattering (HREELS)

H. Li et al. Nature Communications 13, 6348 (2022);
H. Li et al. Phys. Rev. X 11, 031050 (2021)

Example I: Giant Phonon Anomaly in Proximate Quantum Spin Liquid $RuCl_3$

Acknowledge:

- Hu Miao, Ho Nyung Lee, Jiaqiang Yan (Oak Ridge National Lab)
- Ayman Said (Argonne, APS)
- Tiantian Zhang, Shuichi Murakami (Tokyo Institute of Technology

The Kitaev Quantum Spin Liquid candidate α-RuCl3

Letter | Published: 11 July 2018

Majorana quantization and half-integer thermal quantum Hall effect in a Kitaev spin liquid

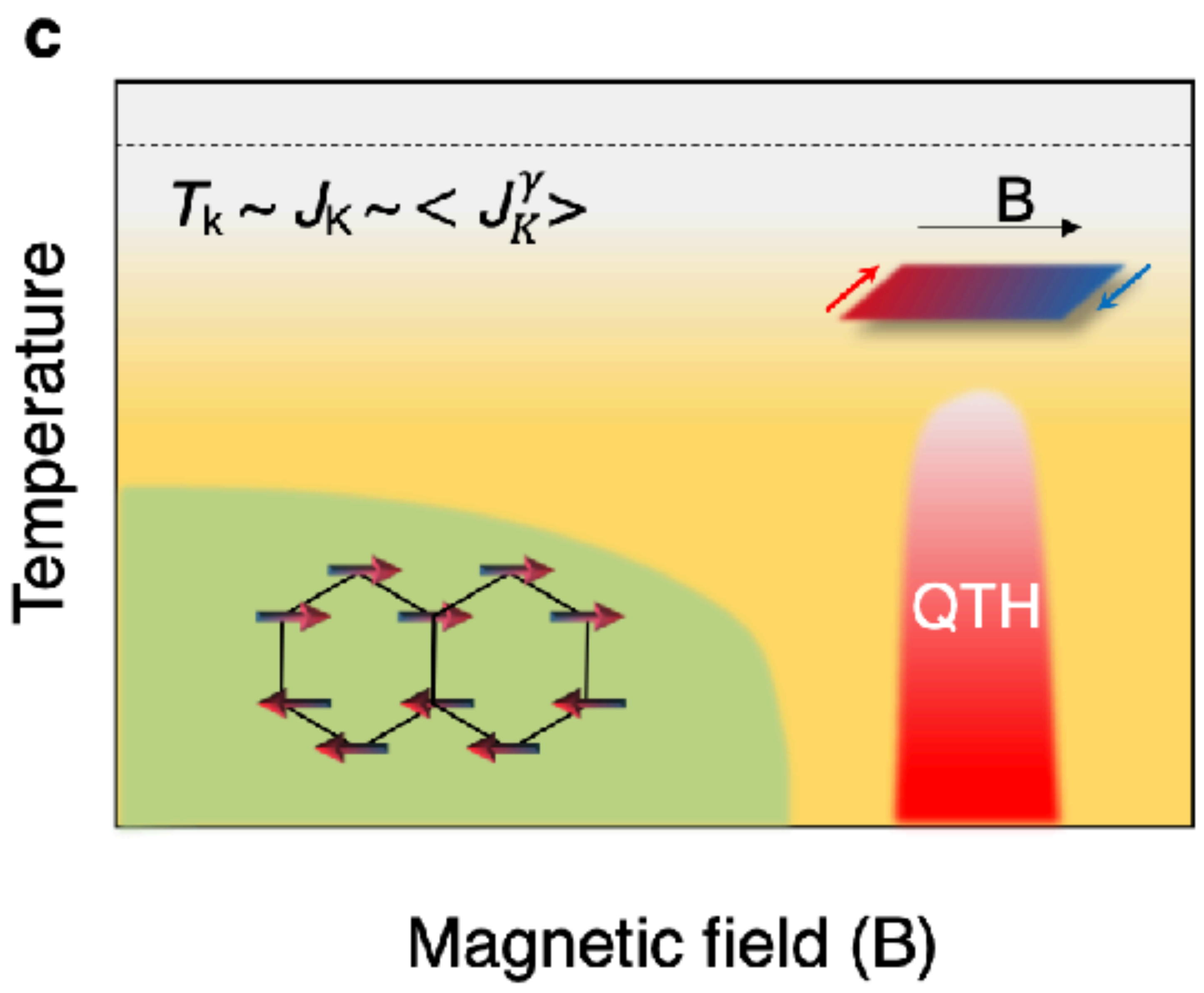
Y. Kasahara, T. Ohnishi, Y. Mizukami, O. Tanaka, Sixiao Ma, K. Sugii, N. Kurita, H. Tanaka, J. Nasu, Y. Motome, T. Shibauchi & Y. Matsuda

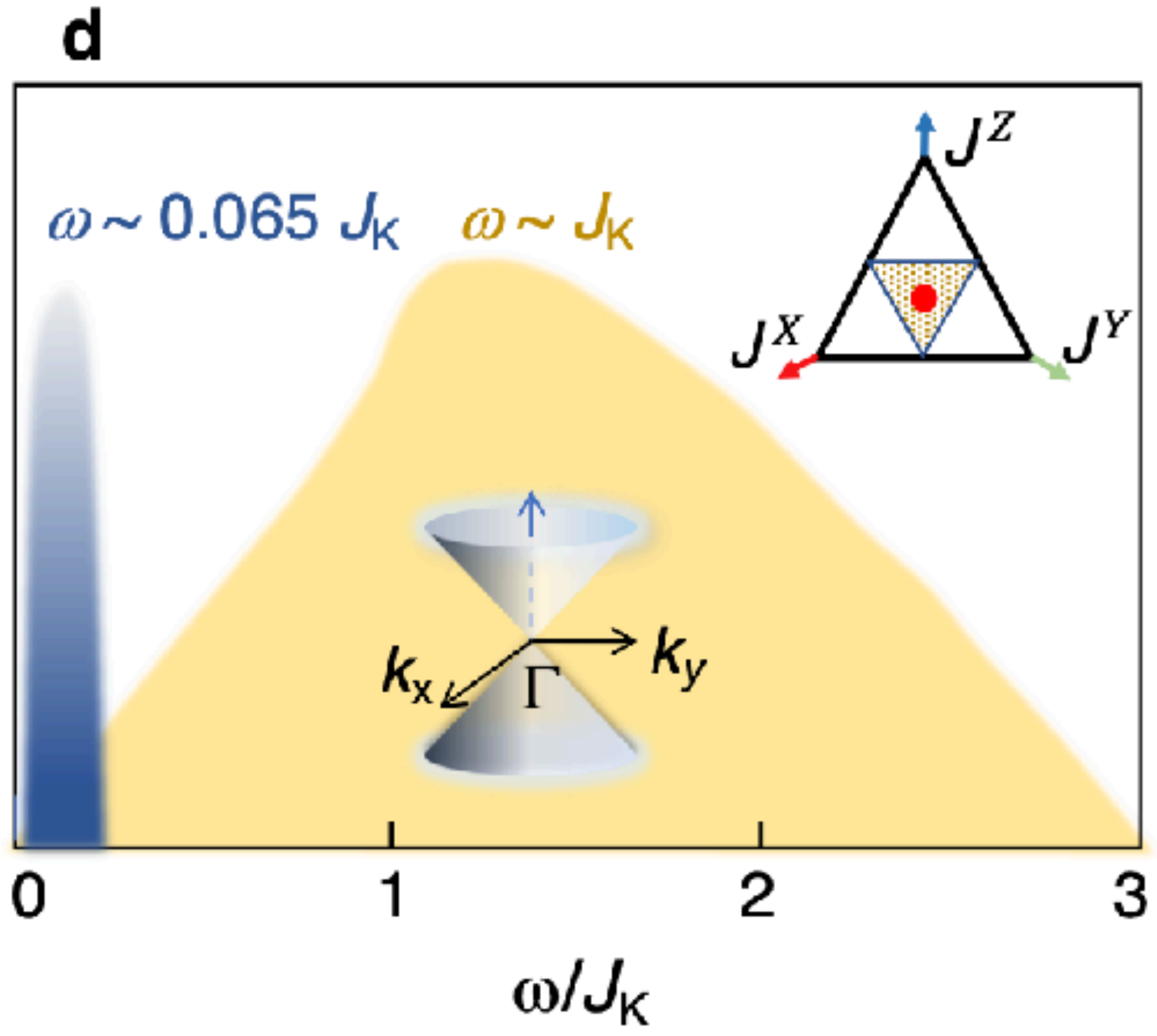
REPORTS | PHYSICS

Neutron scattering in the proximate quantum spin liquid α-$RuCl_3$

Arnab Banerjee[1,*], Jiaqiang Yan[2], Johannes Knolle[3], Craig A. Bridges[4], Matthew B. Stone[1], Mark D. Lumsden[1], David G. Mandrus[2,5], David A. Tennant[6], Roderich Moessner[7], Stephen E. Nagler[1,*]

$$H = \sum_{\gamma,<i,j>} J_K^{\gamma} S_i^{\gamma} S_j^{\gamma}$$





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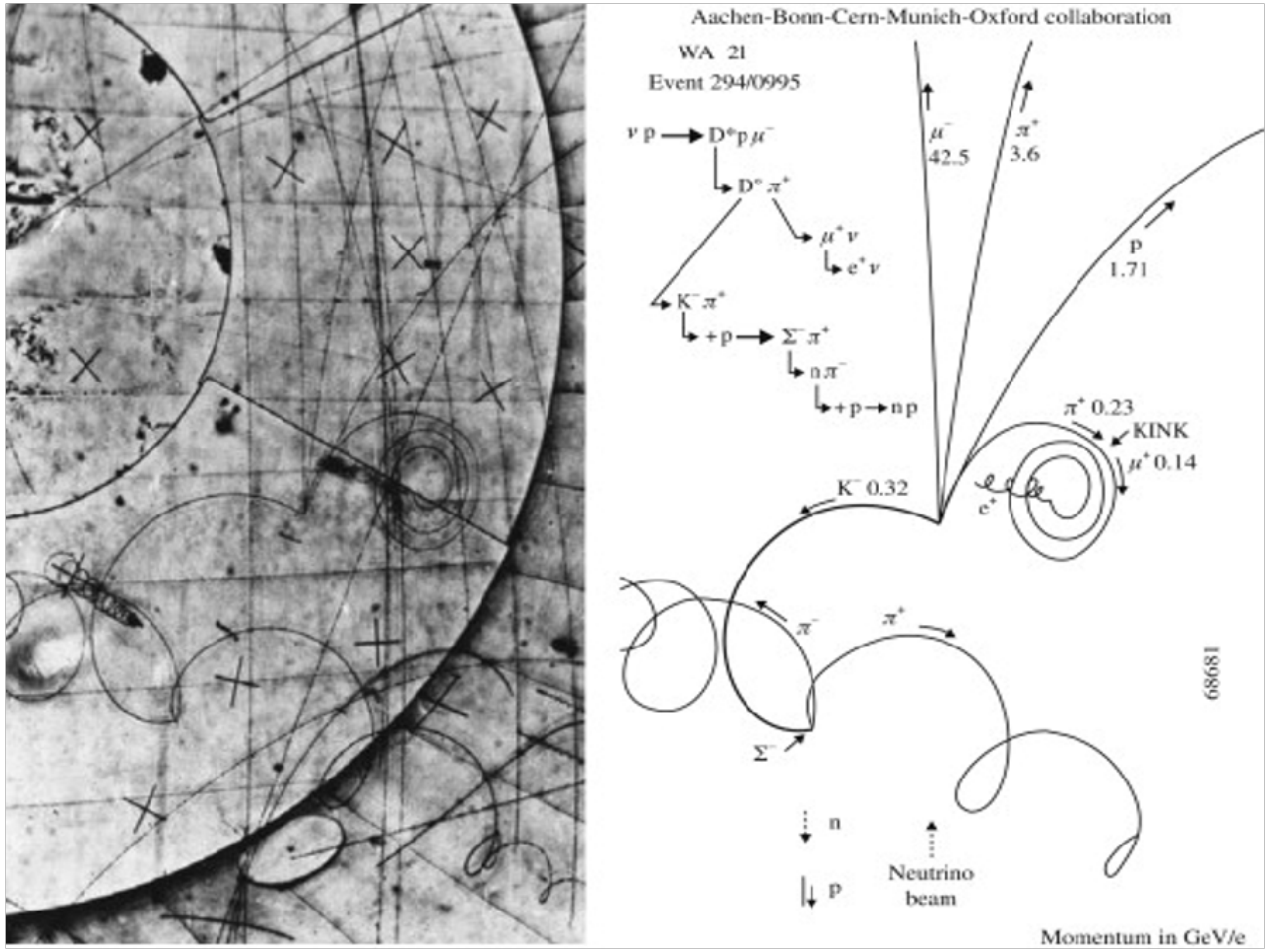
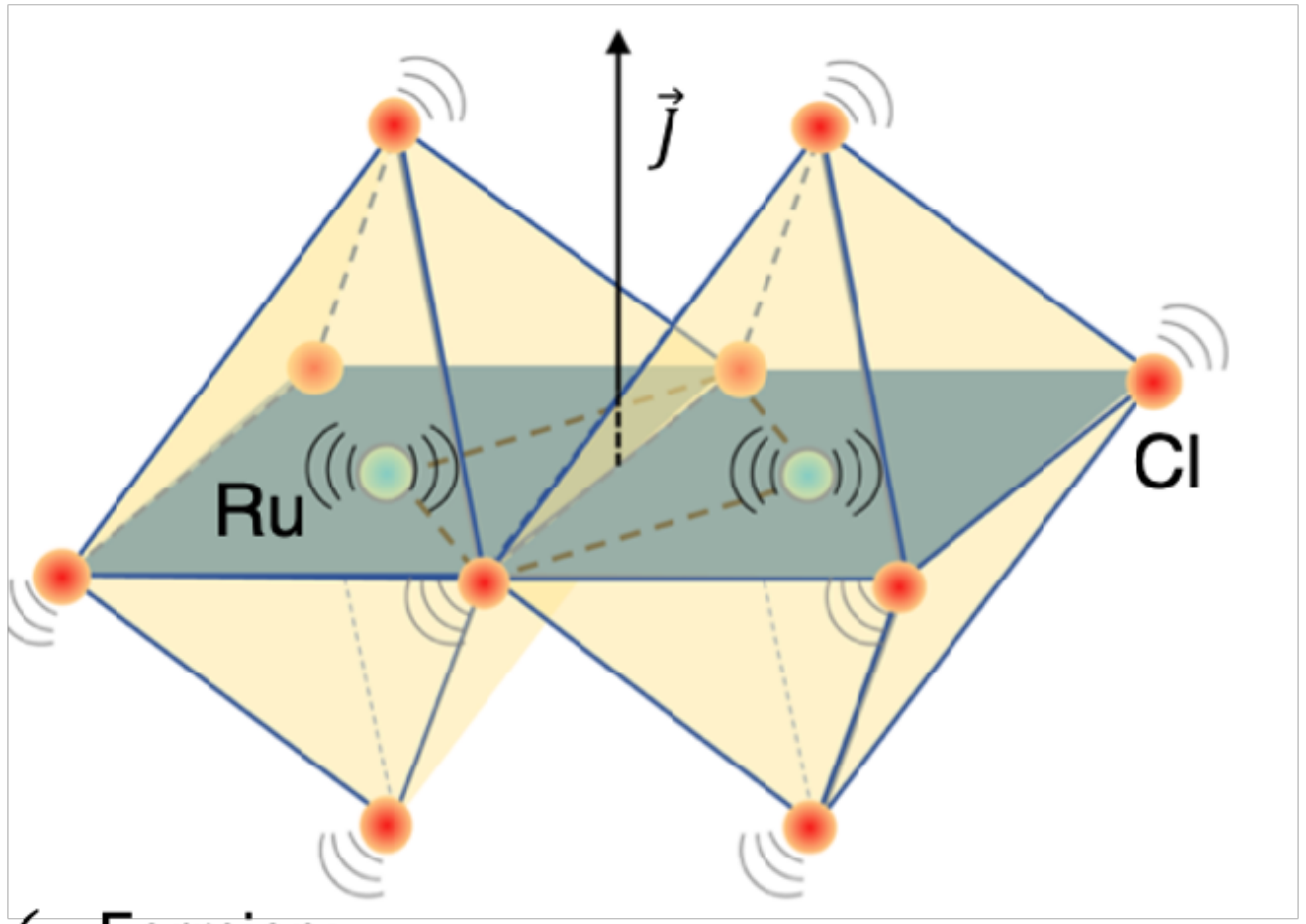
The condensed matter “bubble chamber”



Bubble chamber, a vessel filled with superheated transparent liquid, led to the discoveries of W and Z boson. (*1960 Nobel Prize*)



✓ Fermion:

- Fermi Surface

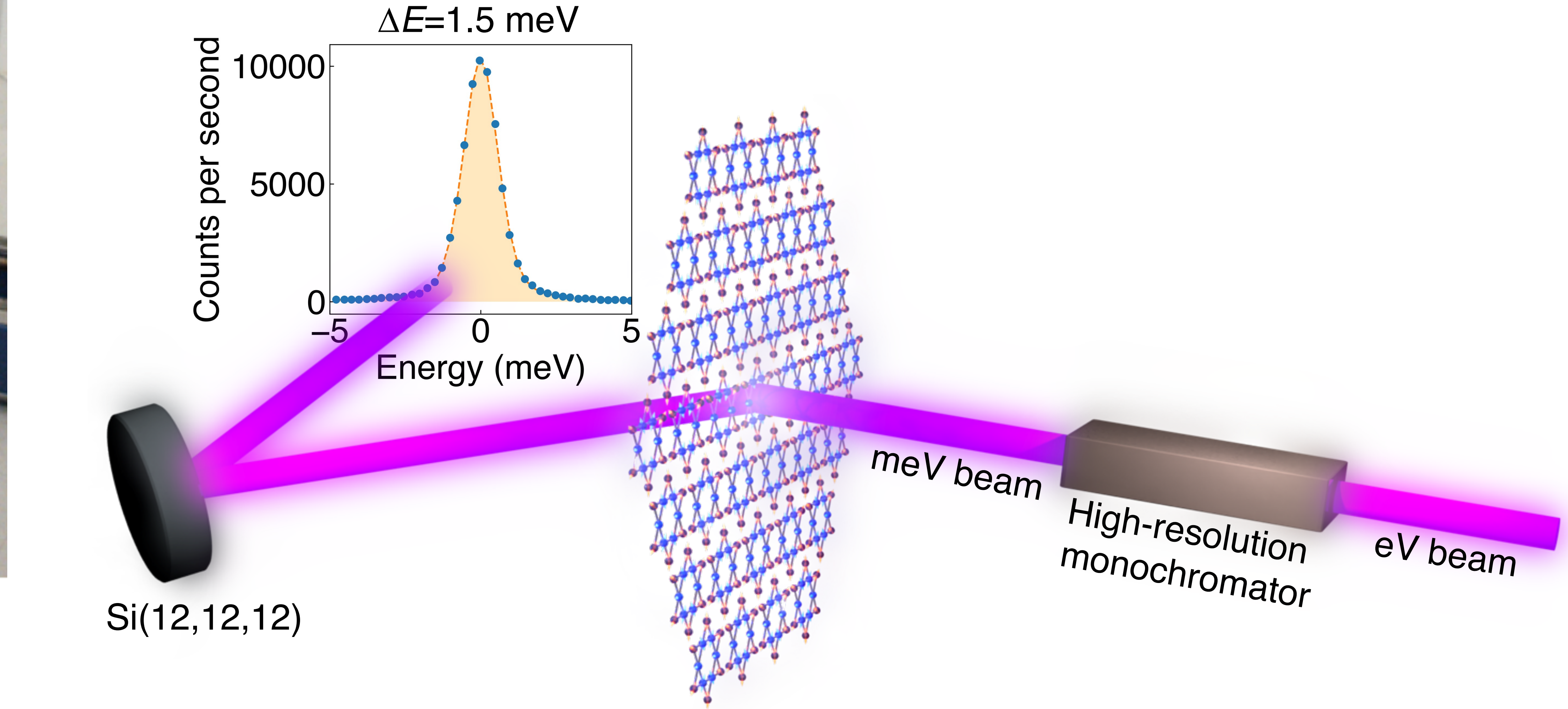
✓ Boson:

- Magnon (Magnets)
- Phason (Density waves)
- Amplituton (Density waves)
- Bogliubon (Superconductor)

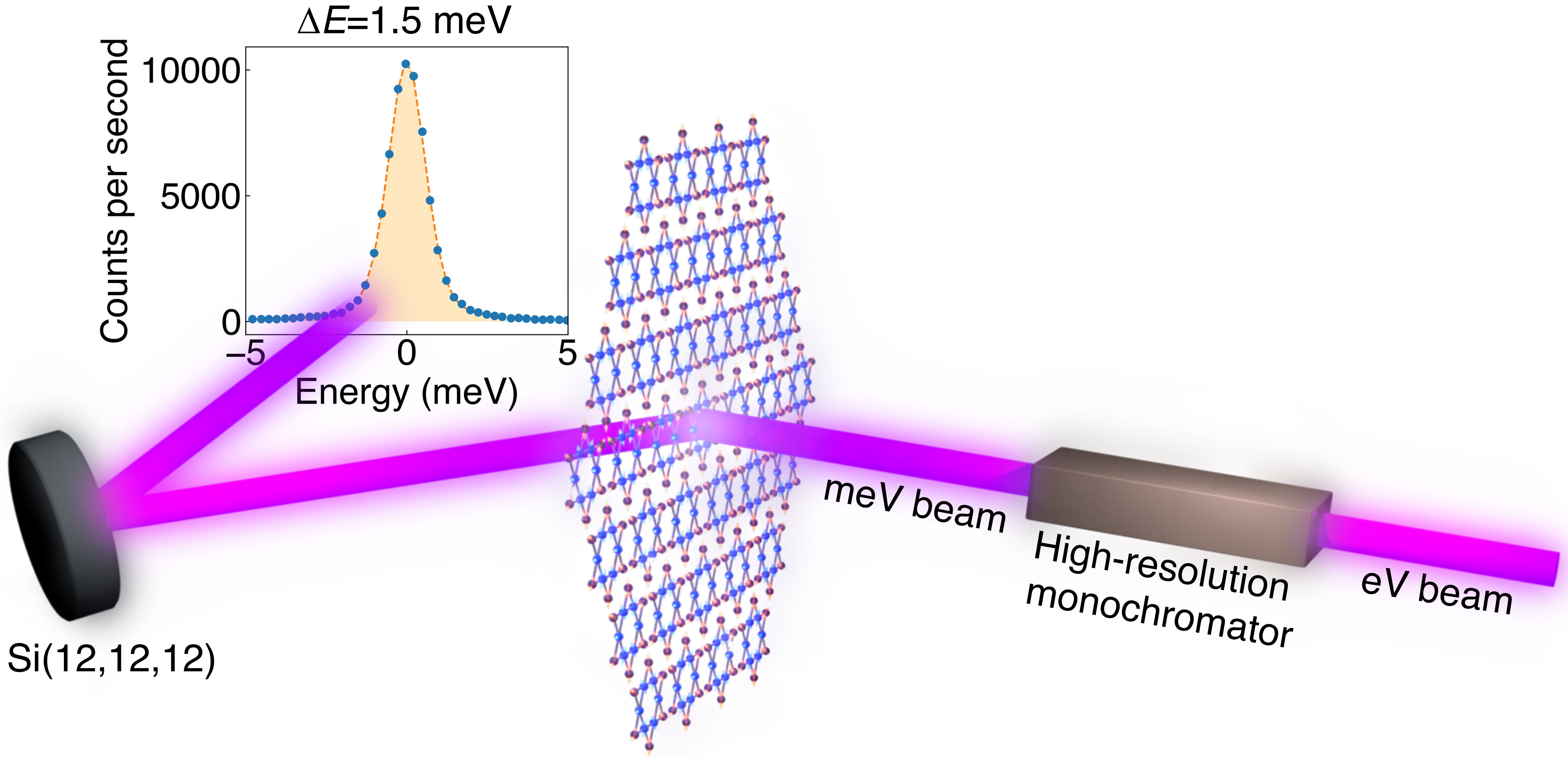
Inelastic x-ray scattering

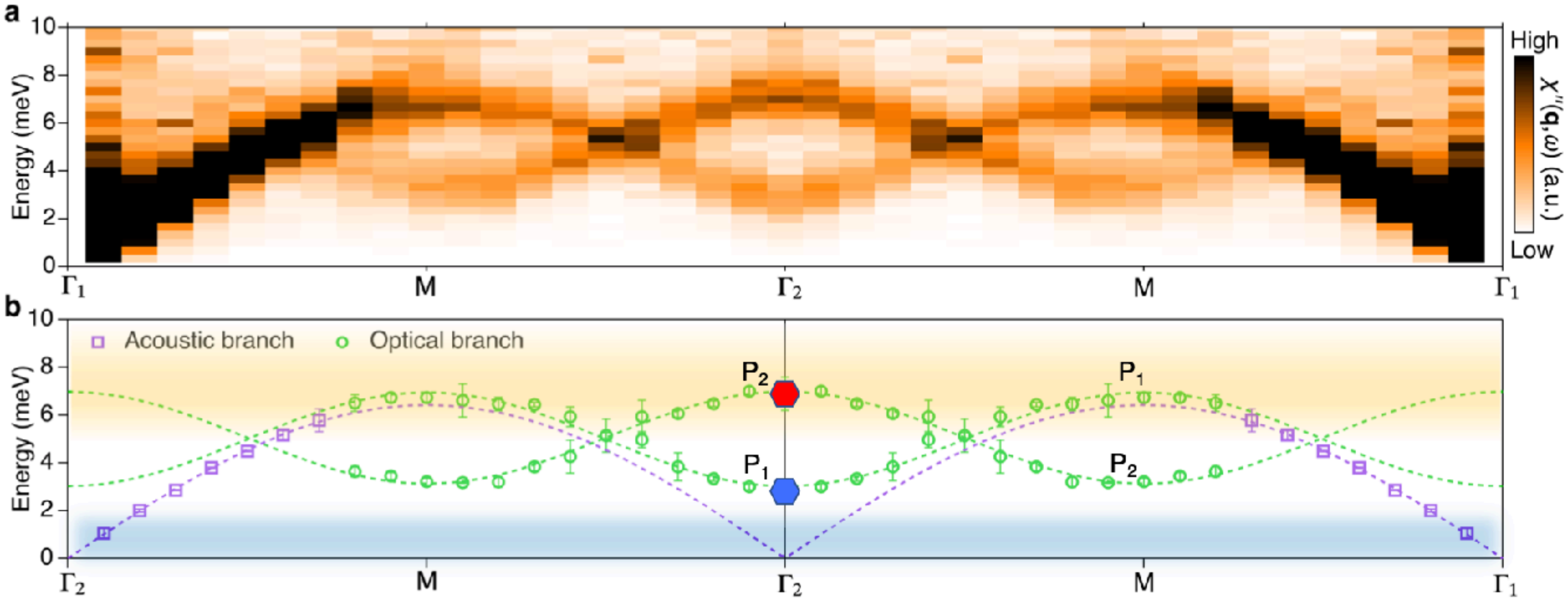
meV resolution, Phonon

dynamical structural factor



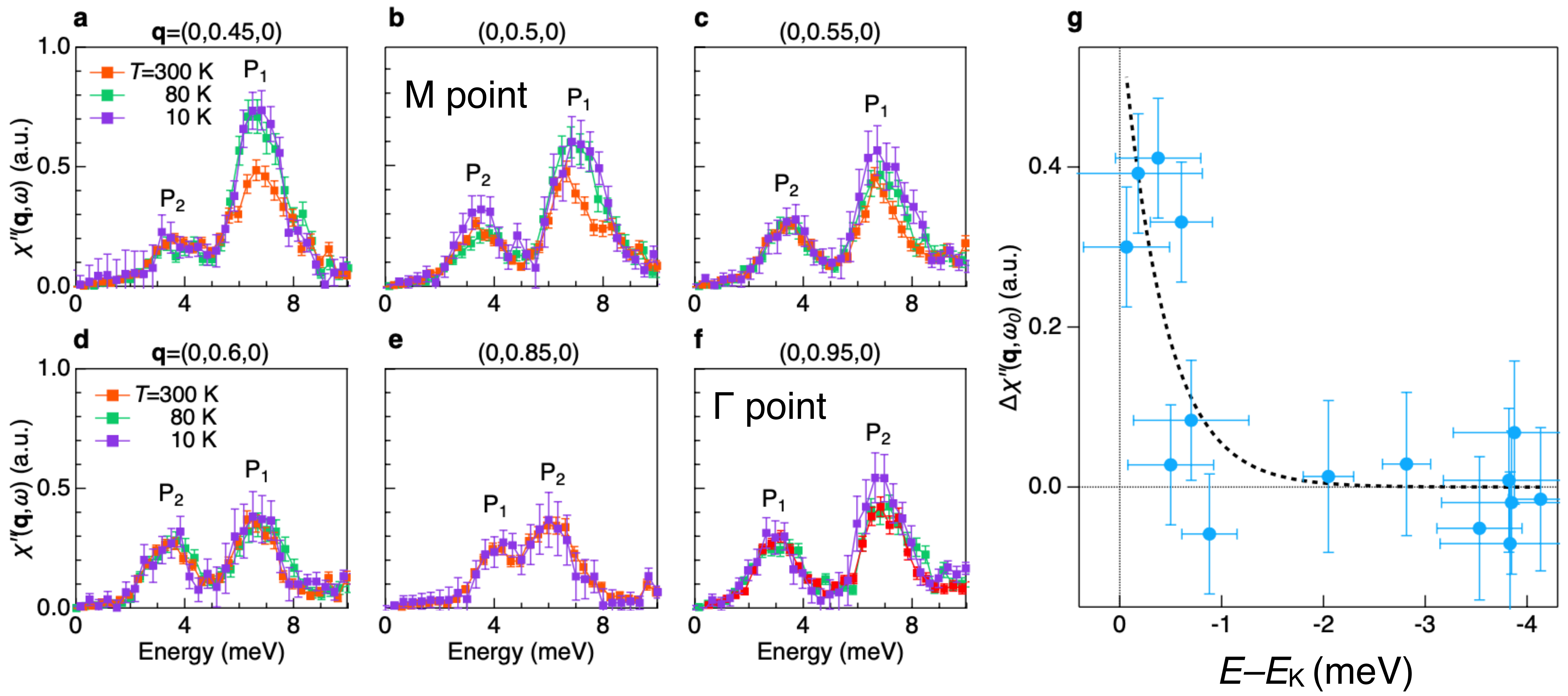
Phonon structure





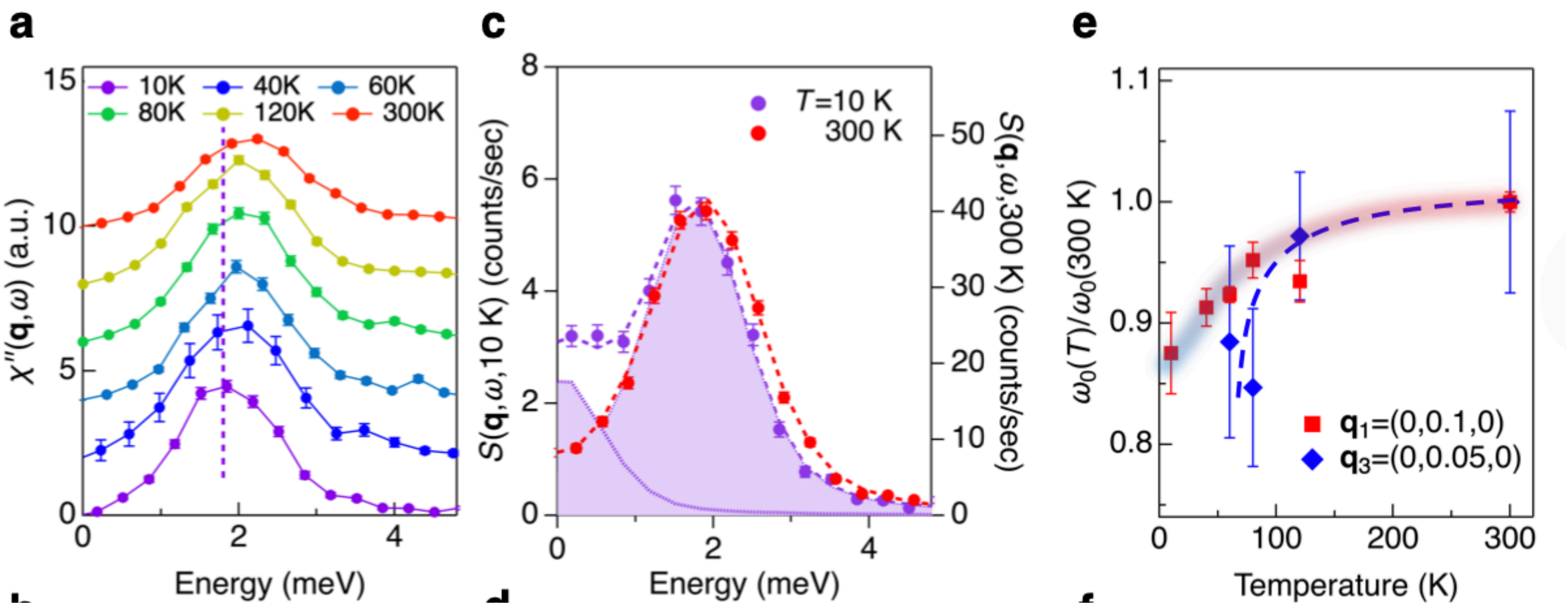
H. Li et al, Nat. Commun. 12:3513 (2021)

Spectral intensity enhancement on optical phonons



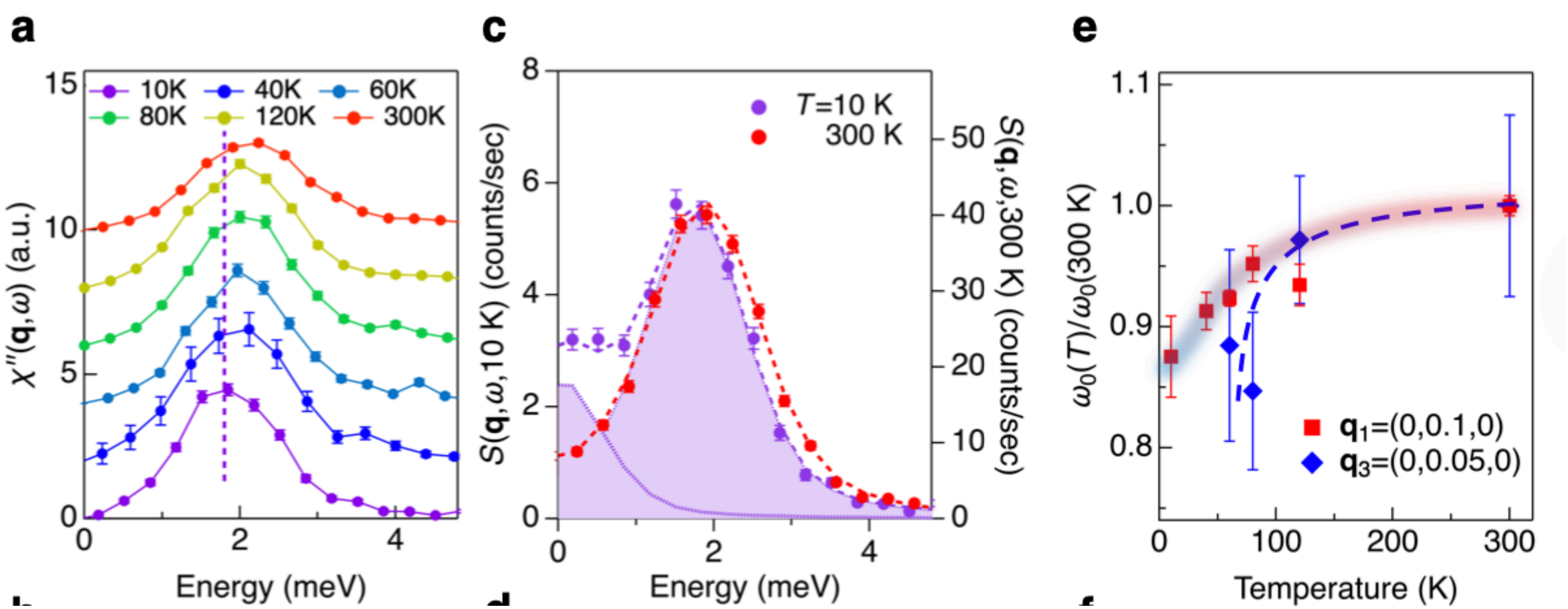
H. Li et al, Nat. Commun. 12:3513 (2021)

Phonon softening in acoustic phonon mode

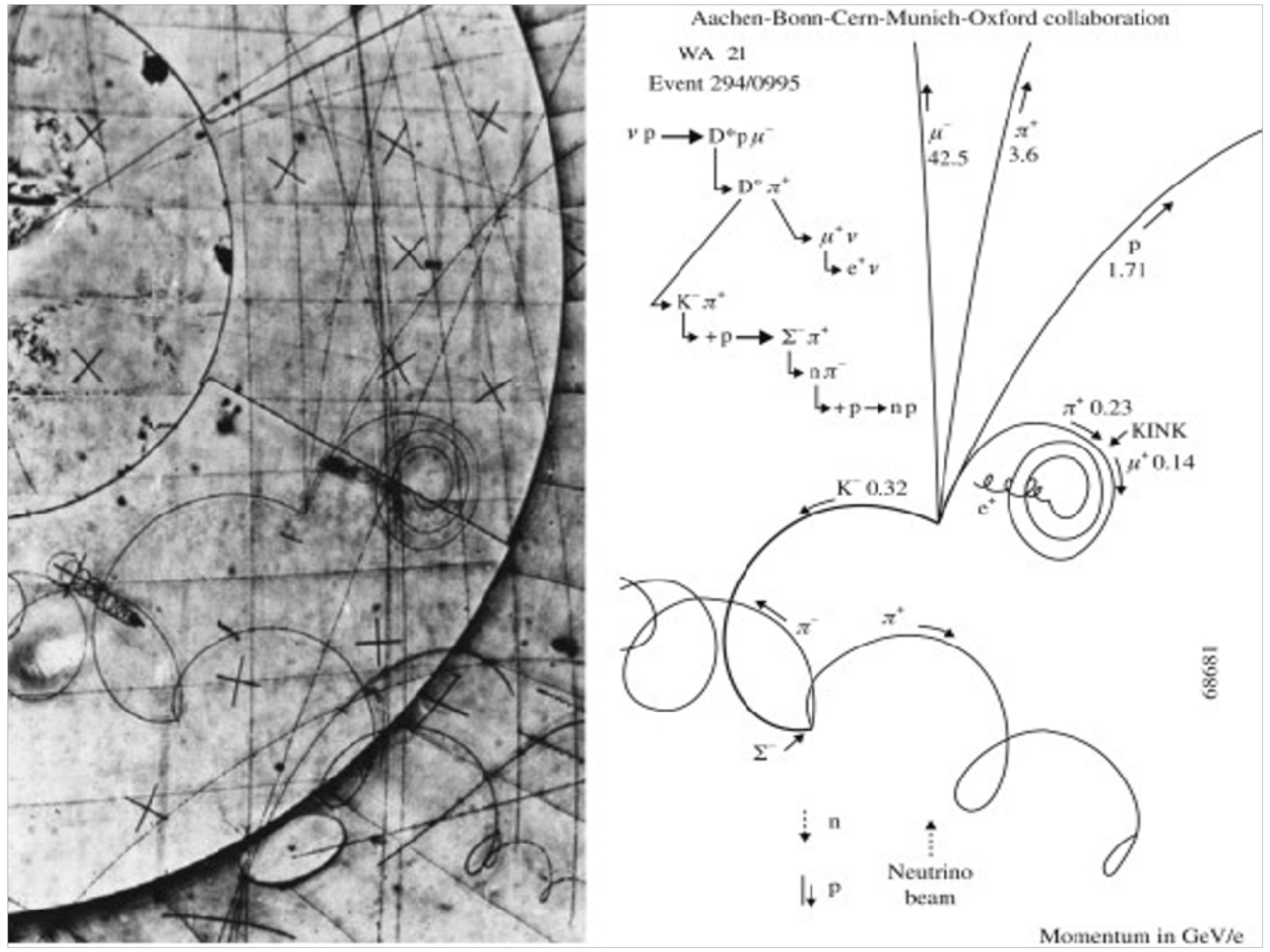


H. Li et al, Nat. Commun. 12:3513 (2021)

Phonon softening in acoustic phonon mode



Bubble chamber



Bubble chamber, a vessel filled with superheated transparent liquid, led to the discoveries of W and Z boson. (*1960 Nobel Prize*)

H. Li et al, Nat. Commun. 12:3513 (2021)

Conclusion

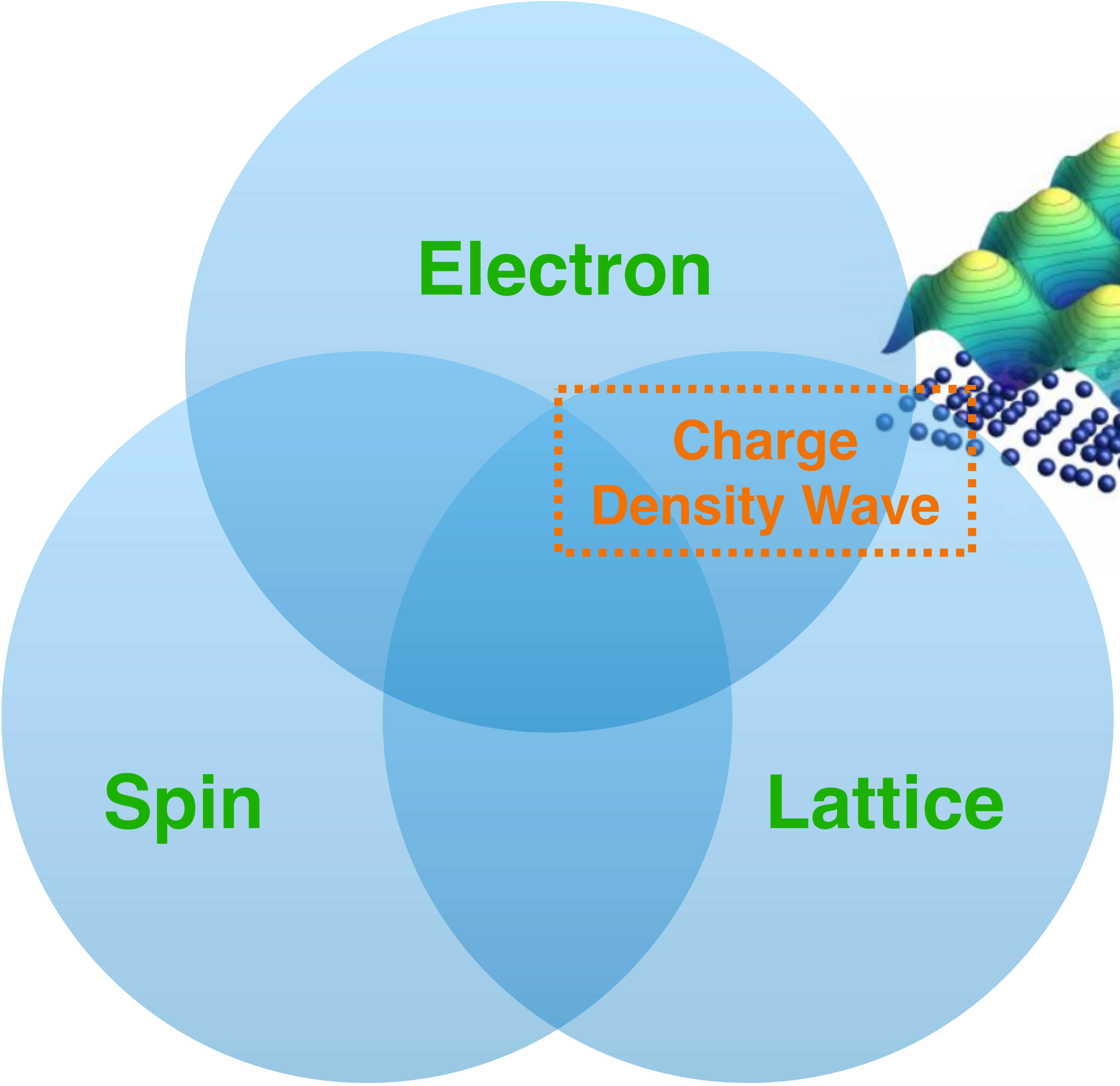
- Strong experimental evidence of fractionalized QP-phonon interaction
- Phonons can be a useful tools to explore fractional excitations (The **bubble chamber**).

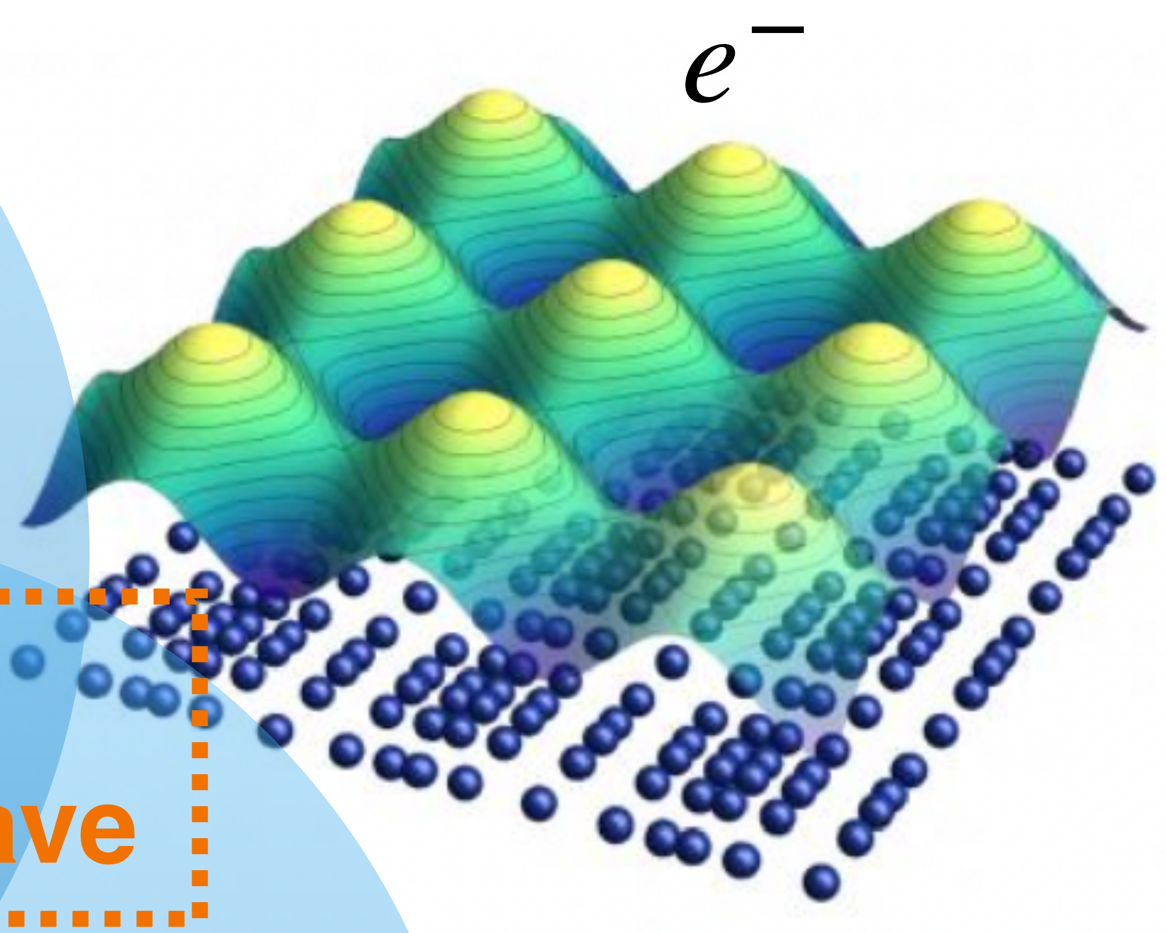
Example II: Discovery of Conjoined Charge Density in CsV_3Sb_5

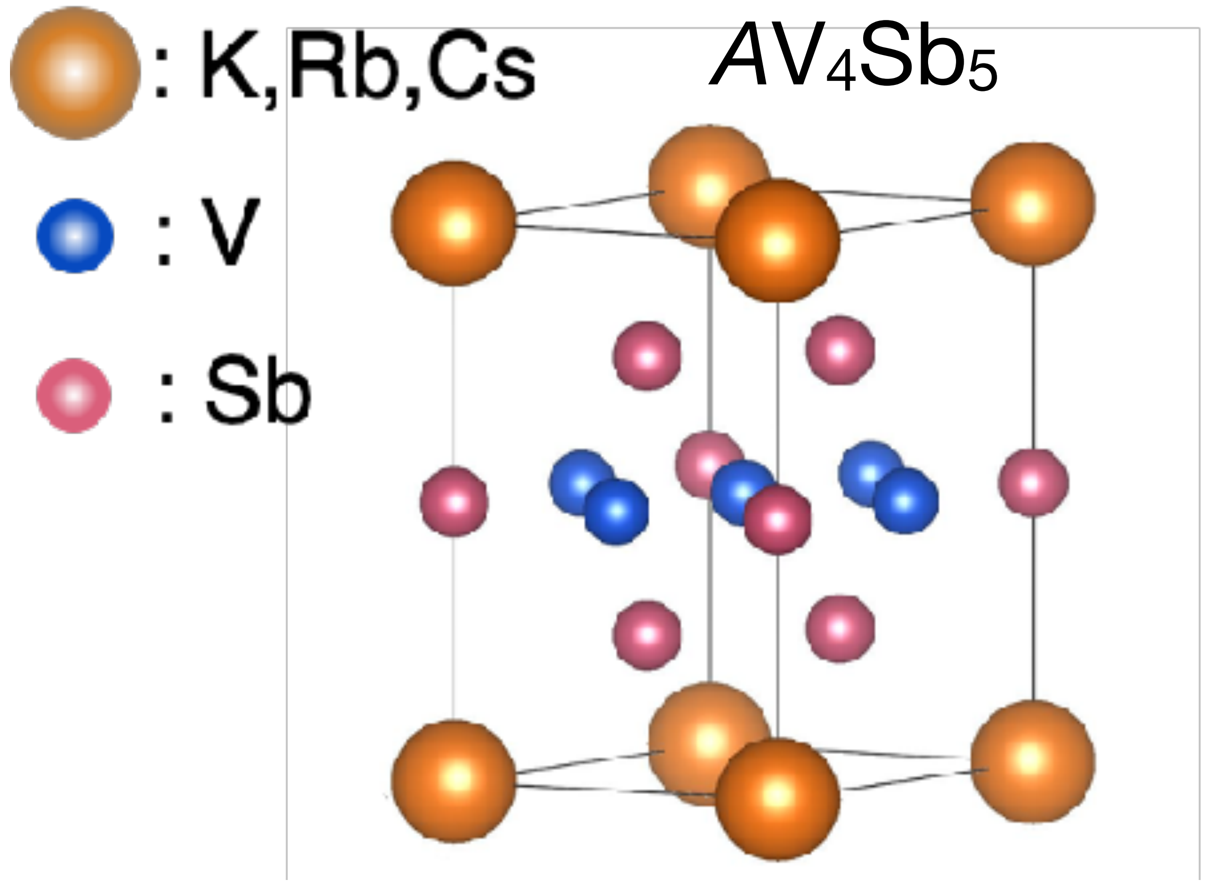
Acknowledge:

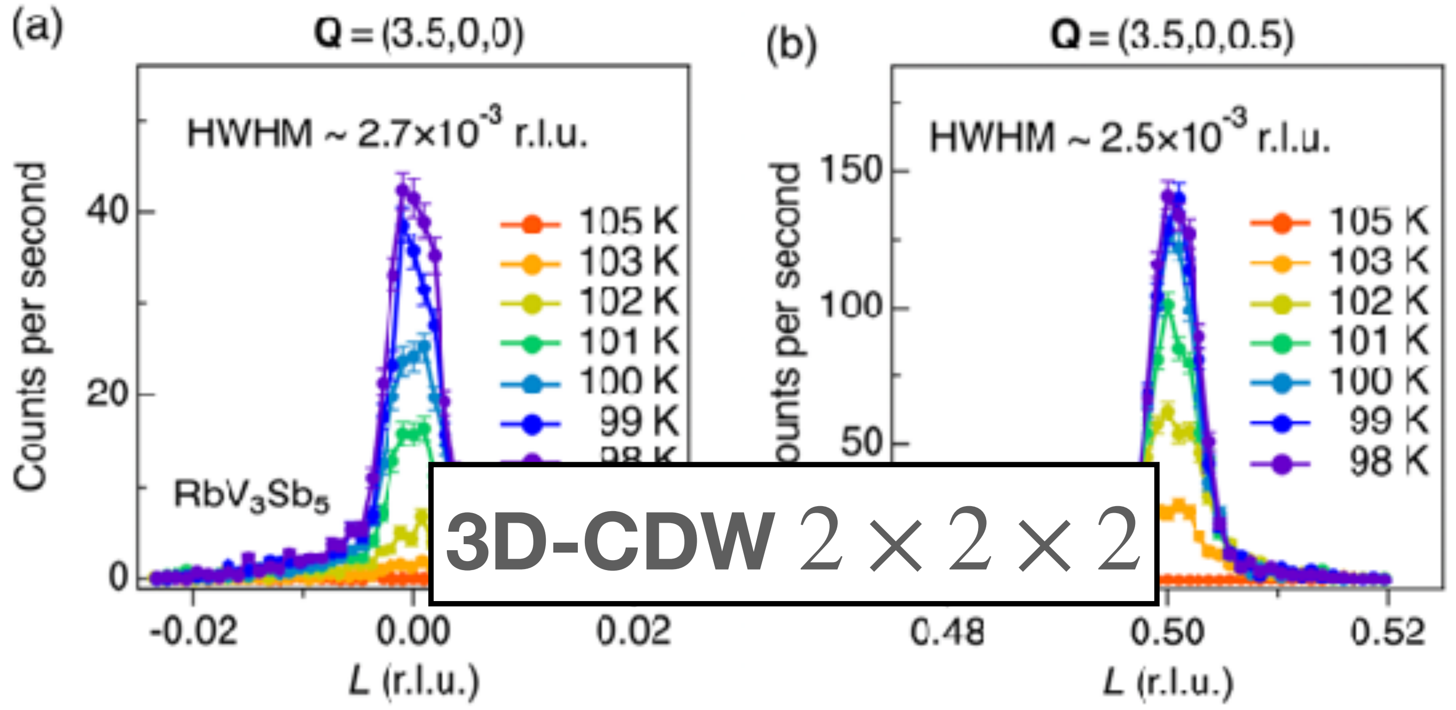
- Hu Miao, Ho Nyung Lee (Oak Ridge National Lab)
- Hechang Lei (Renmin University), Jinguang Cheng (Institute of Physics)
- Gilberto Fabbris, Ayman Said (Argonne, APS)
- Ziqiang Wang (Boston College), Binhai Yan (Weizmann Institute of Science, Israel), Tiantian Zhang, Shuichi Murakami (Tokyo Institute of Technology)
- Jia-Xin Yin, M. Z. Hasan (Princeton U)

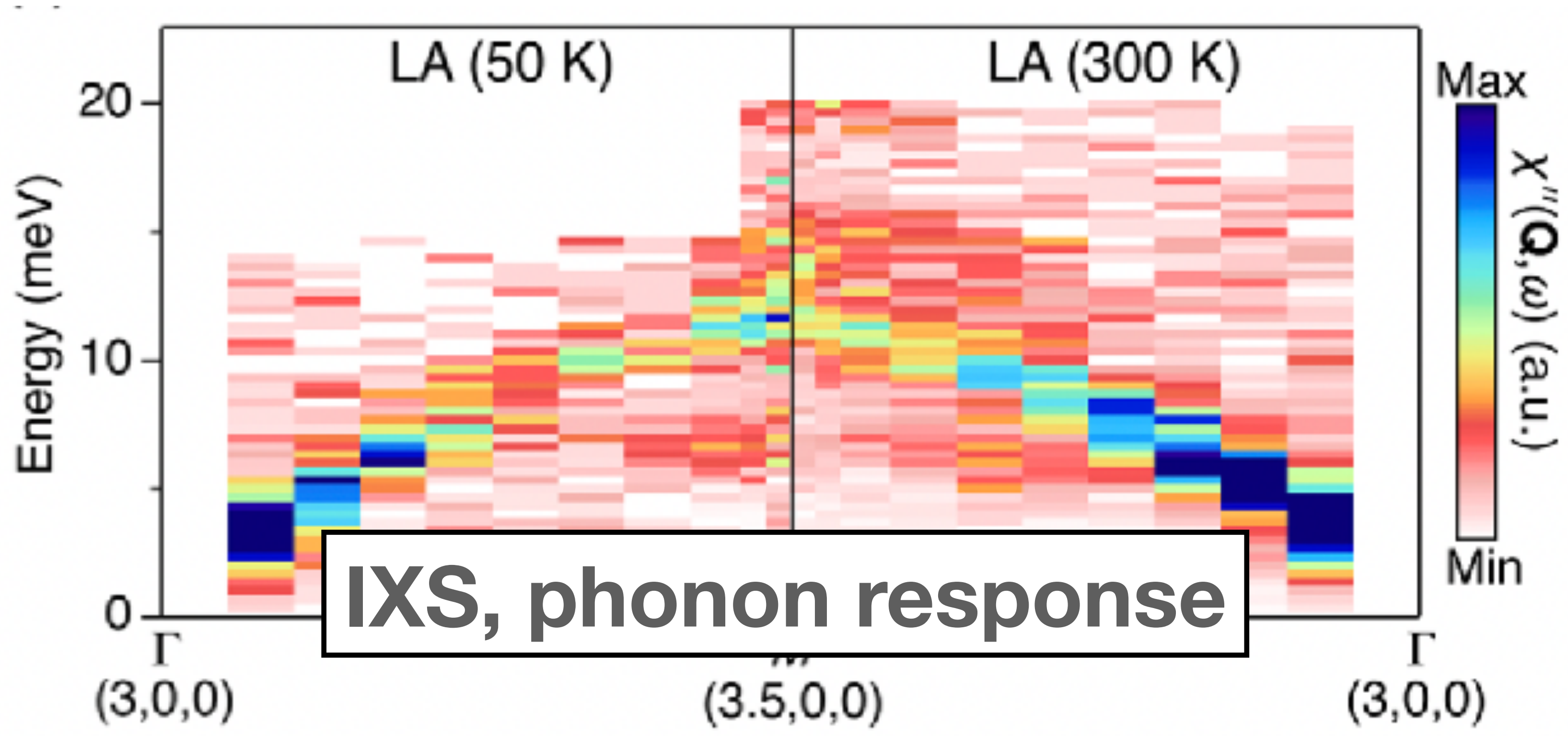
Macroscopic quantum many-body states in solids



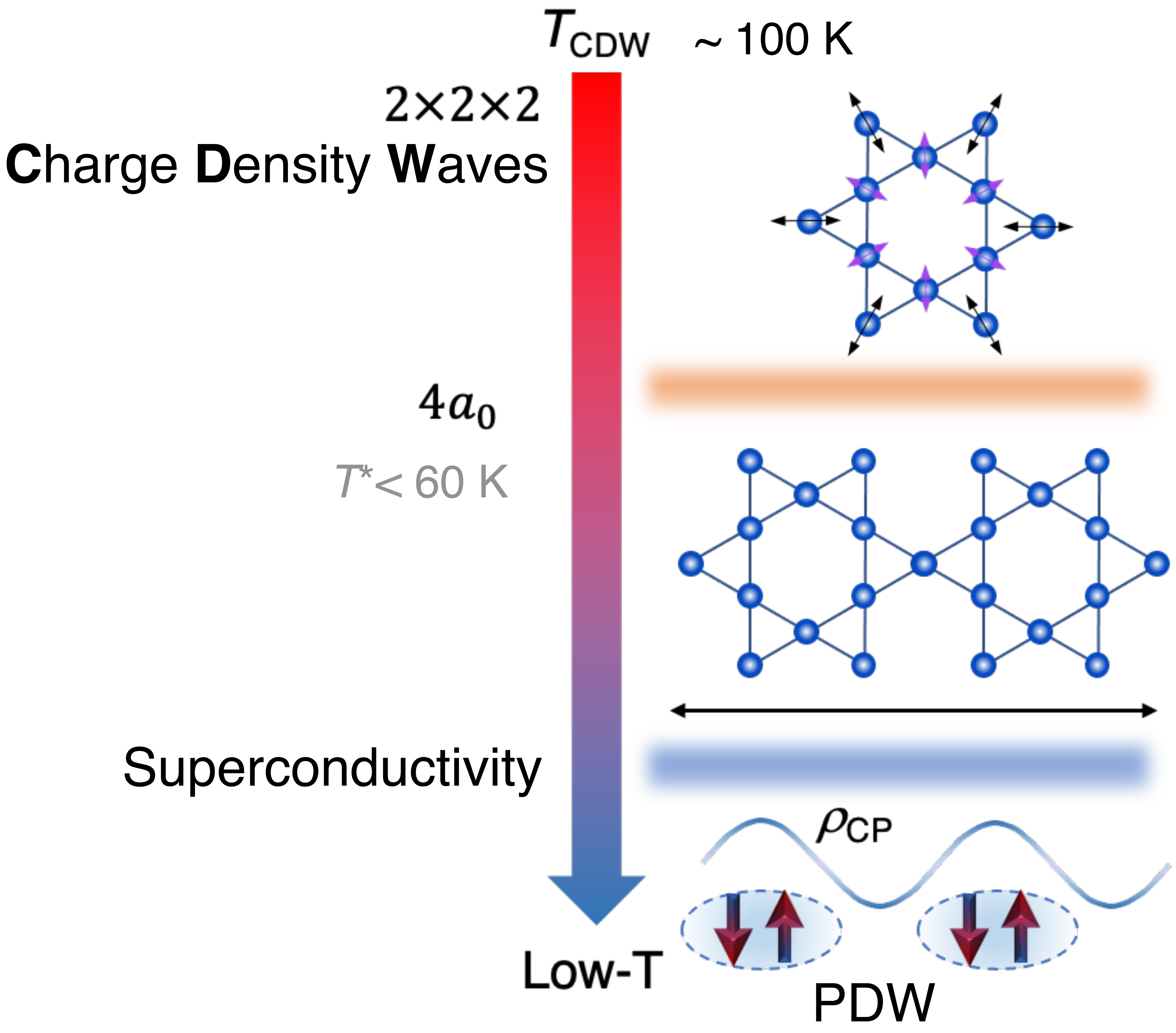


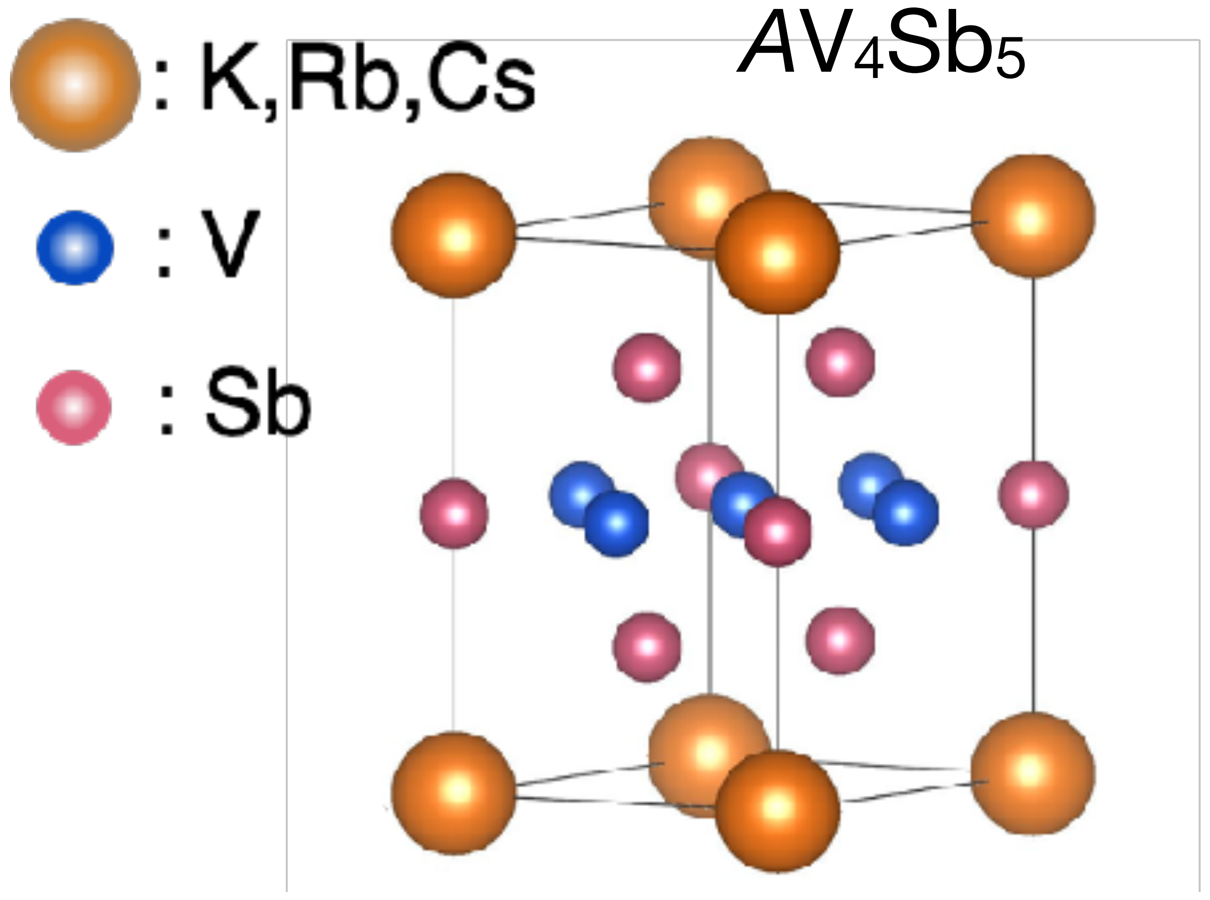




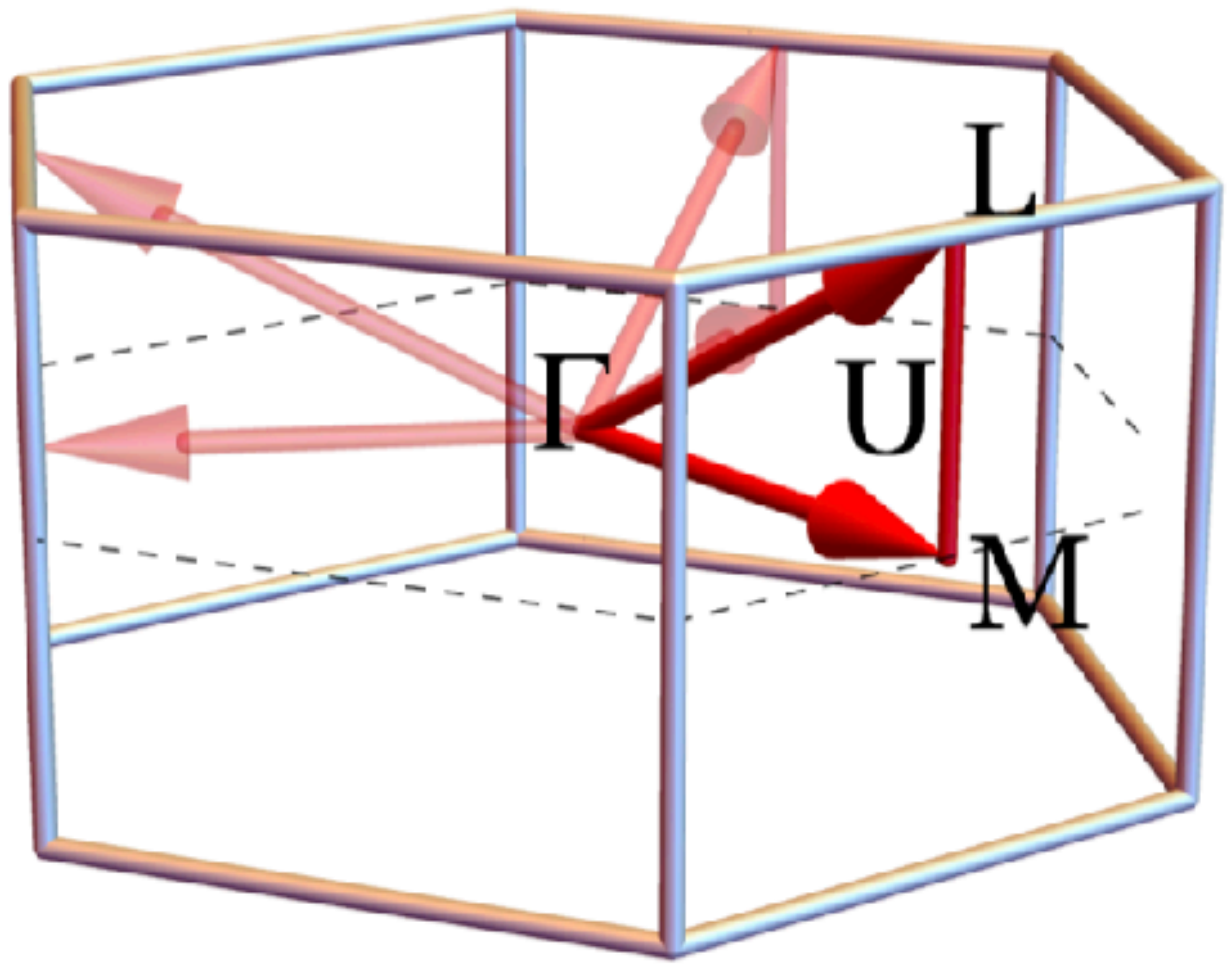


H. Li *et al.* Phys. Rev. X 11, 031050 (2021)





Brillouin zone



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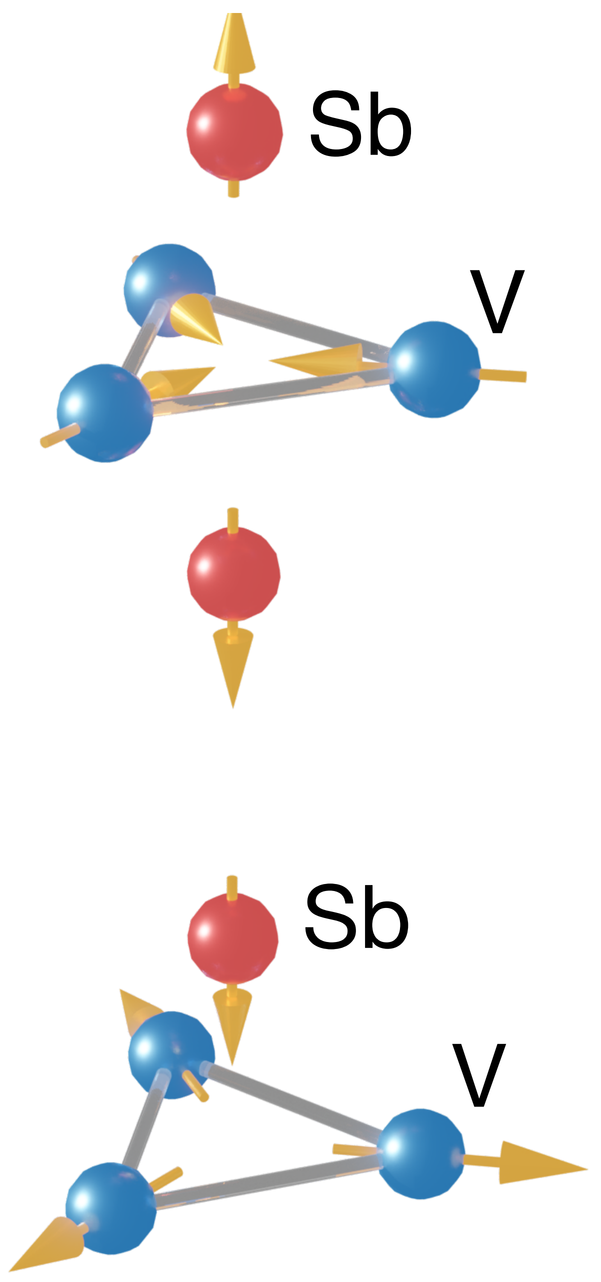
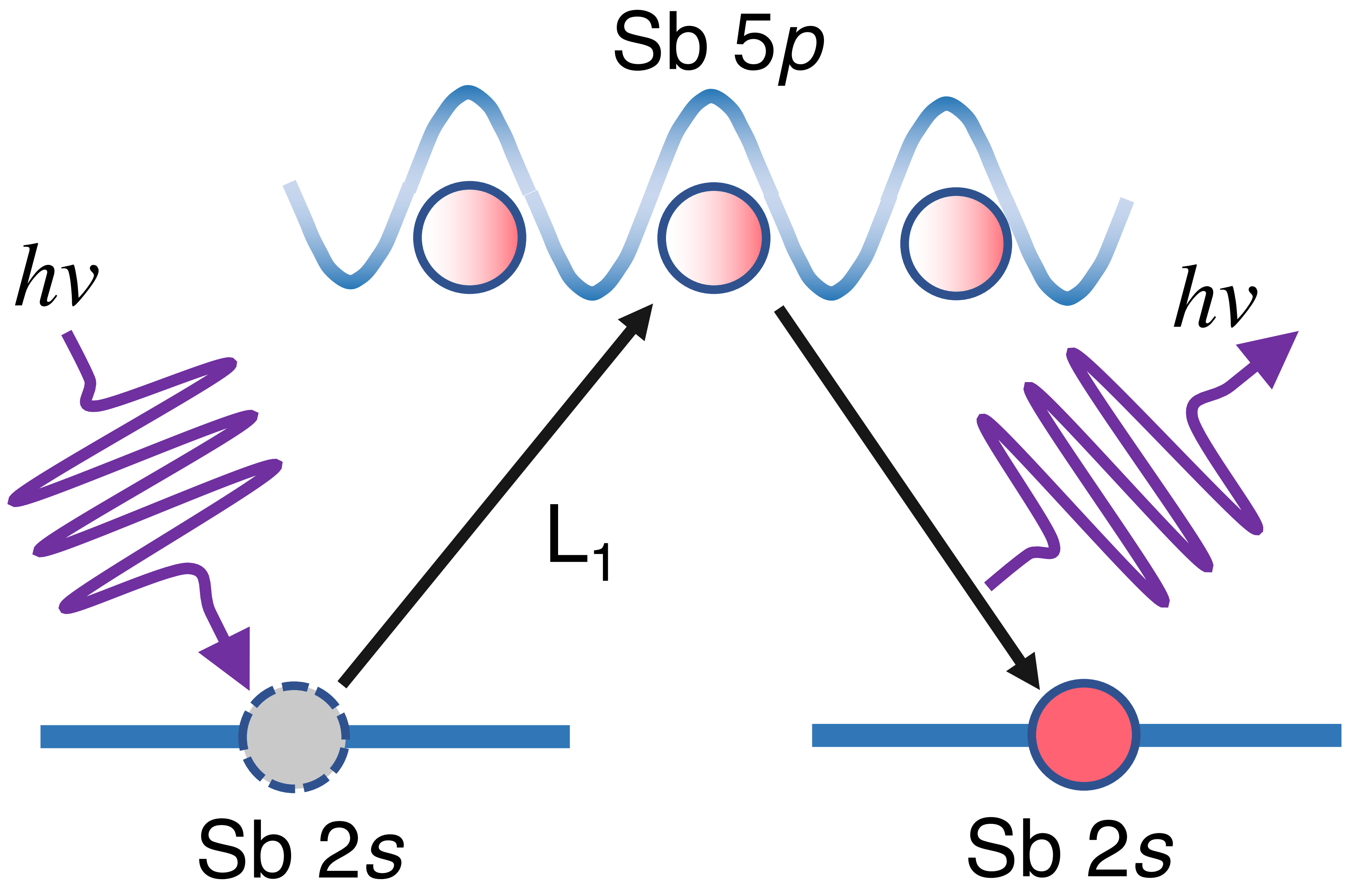
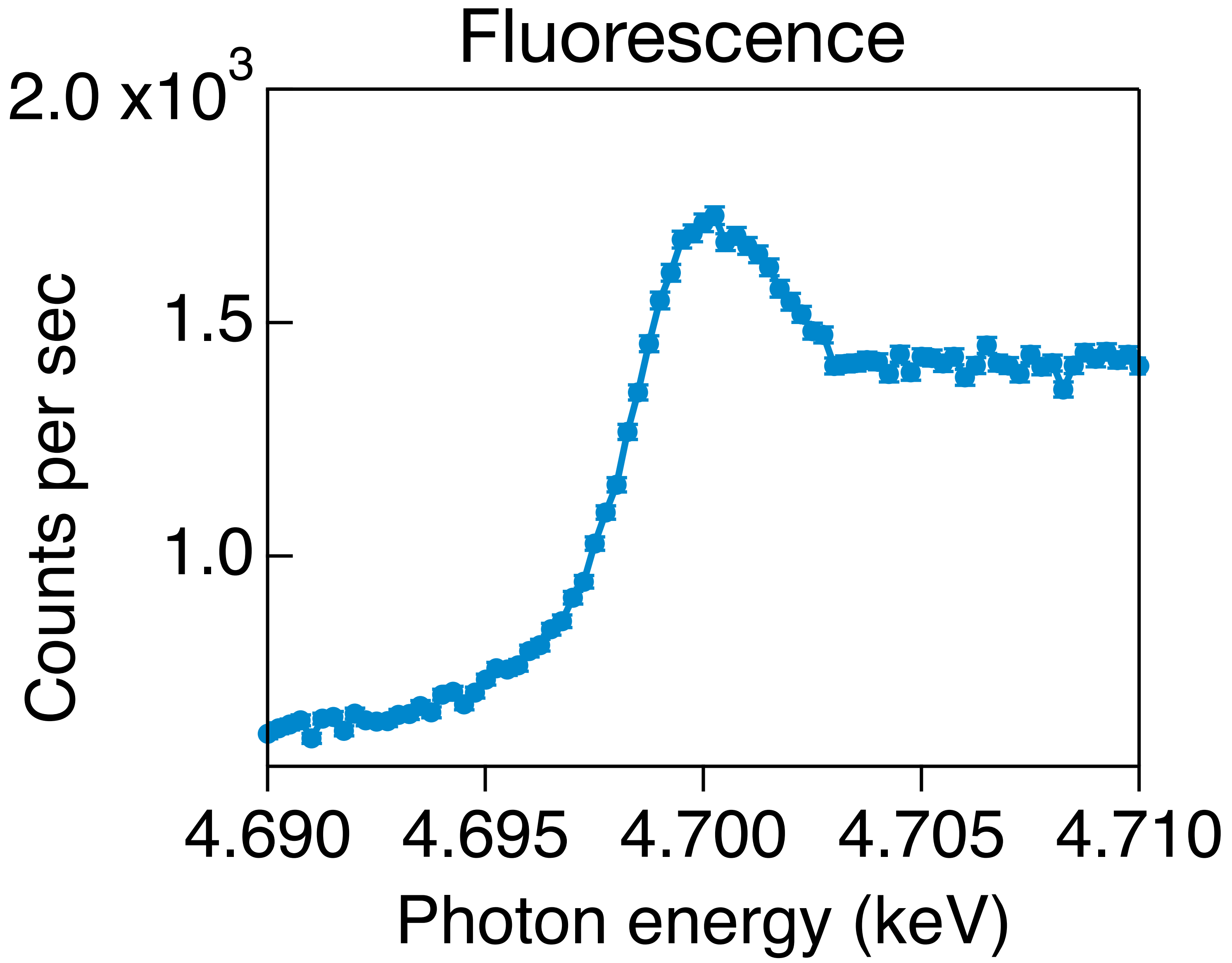
Resonant Elastic X-ray Scattering (REXS)

-To investigate the charge origin of the 3D CDW in CsV_3Sb_5 (T_{CDW}~93 K)



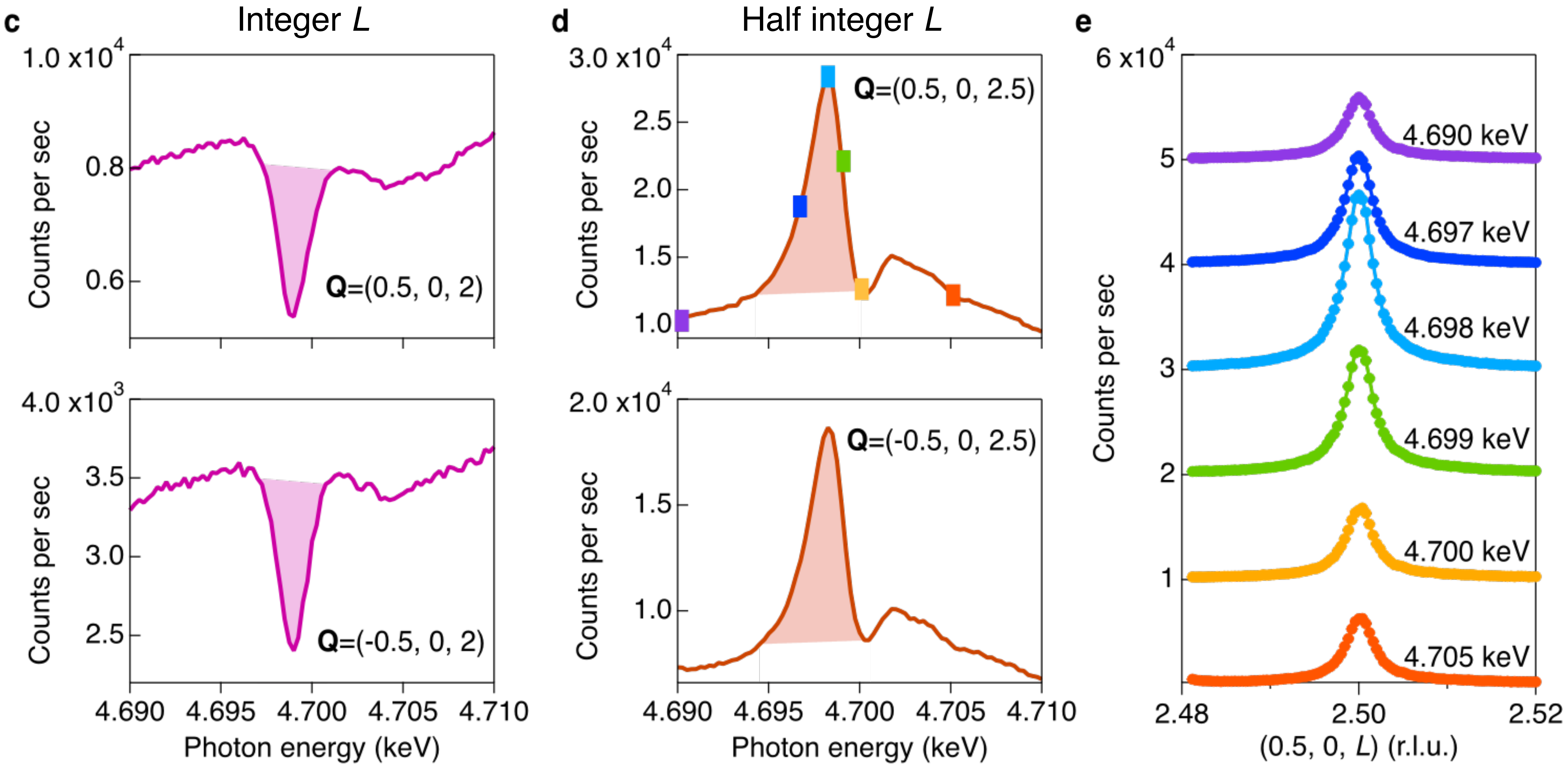




- Resonant excitations from core level to unoccupied conduction state
- Sb L_1 edge is the ideal candidate that has large enough momentum covering CDW peaks and obey the dipole selection rule.

Resonant response to Sb L_1 edge

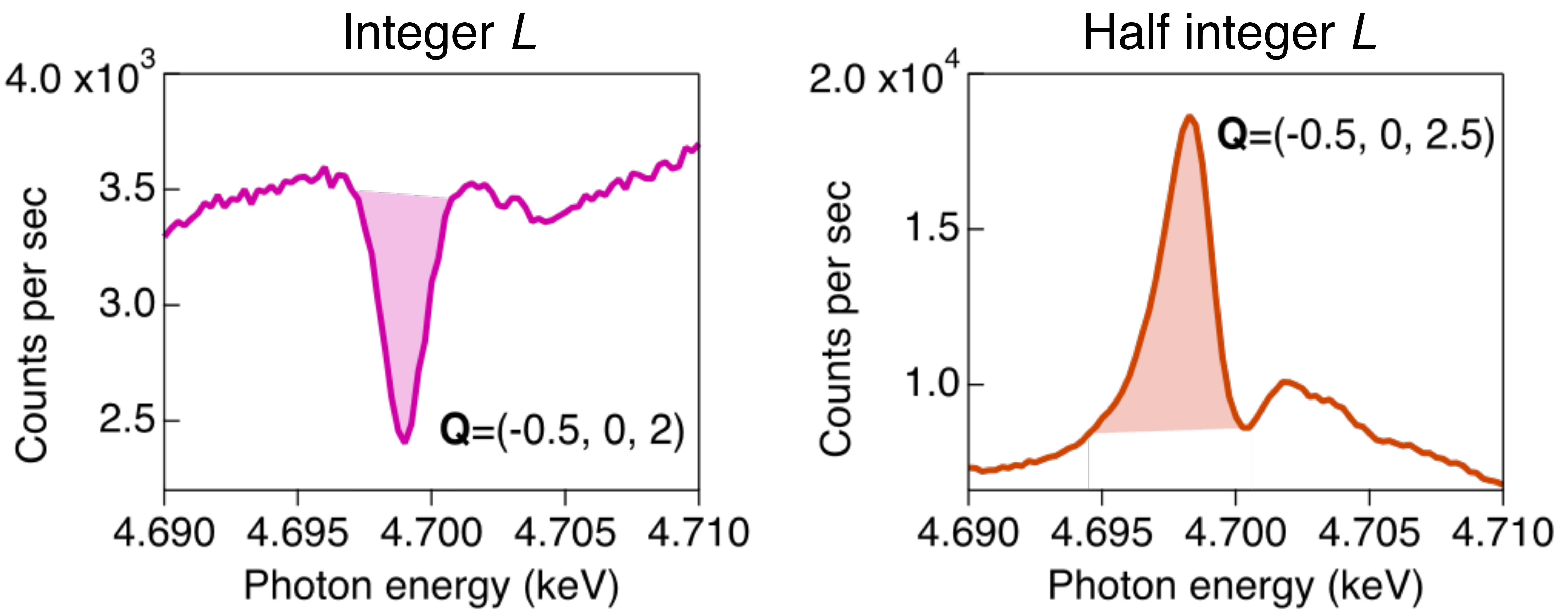
–Resonant enhancement is only shown in the half-integer L peaks



H. Li *et al. Nat Commun* 13, 6348 (2022)

Resonant Elastic X-ray Scattering (REXS)

– Resonant response to Sb L_1 edge

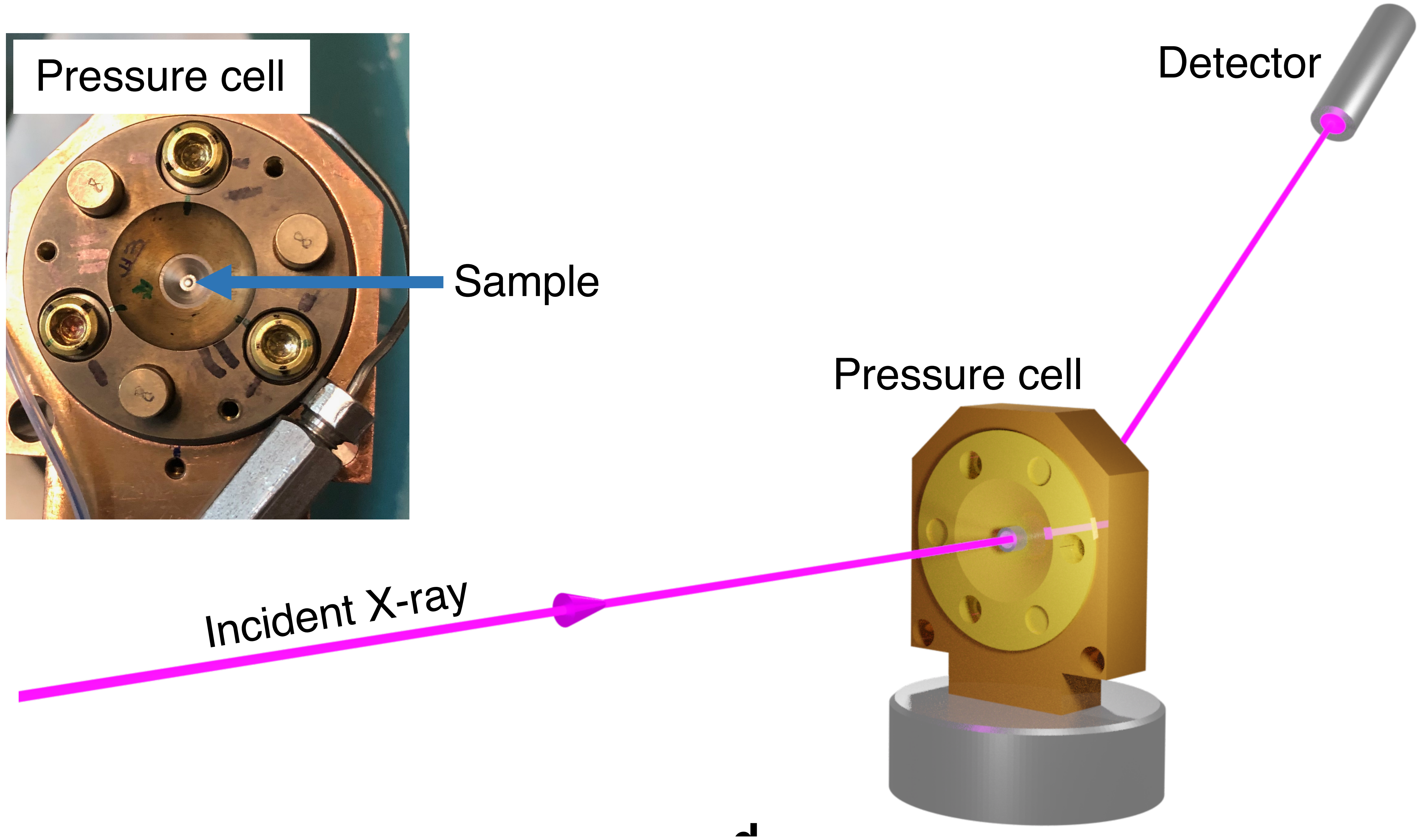


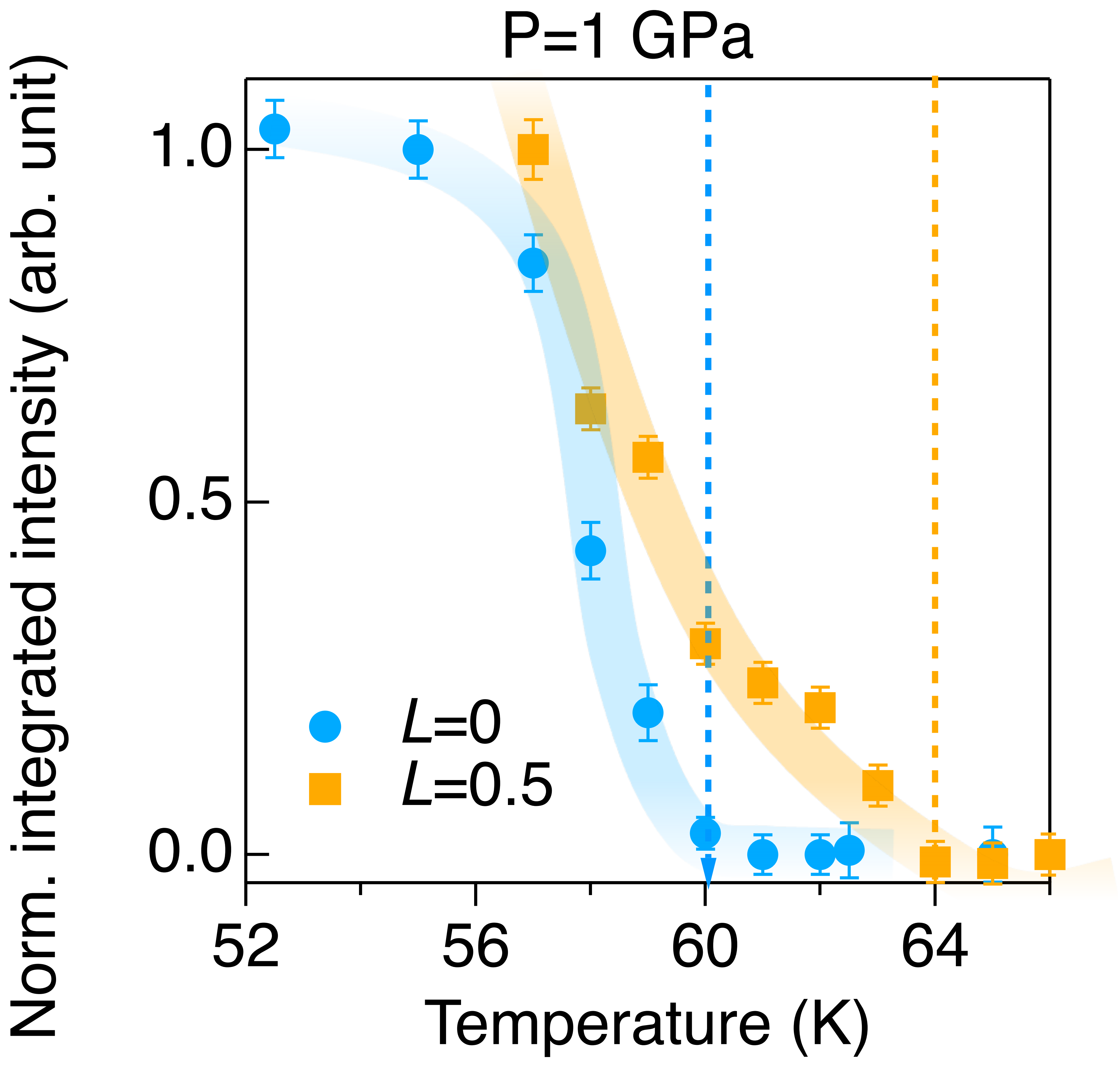
- **Two conjoined charge orders emerge in the CDW transition**
- The CDW order at integer *L* $(2 \times 2 \times 1)$ does not involve any Sb charge distortion
- The CDW order at half-integer *L* $(2 \times 2 \times 2)$ has strong contribution from the Sb charge

H. Li *et al. Nat Commun* 13, 6348 (2022)

High pressure elastic X-ray scattering

- Charge orders splitting and superconductivity

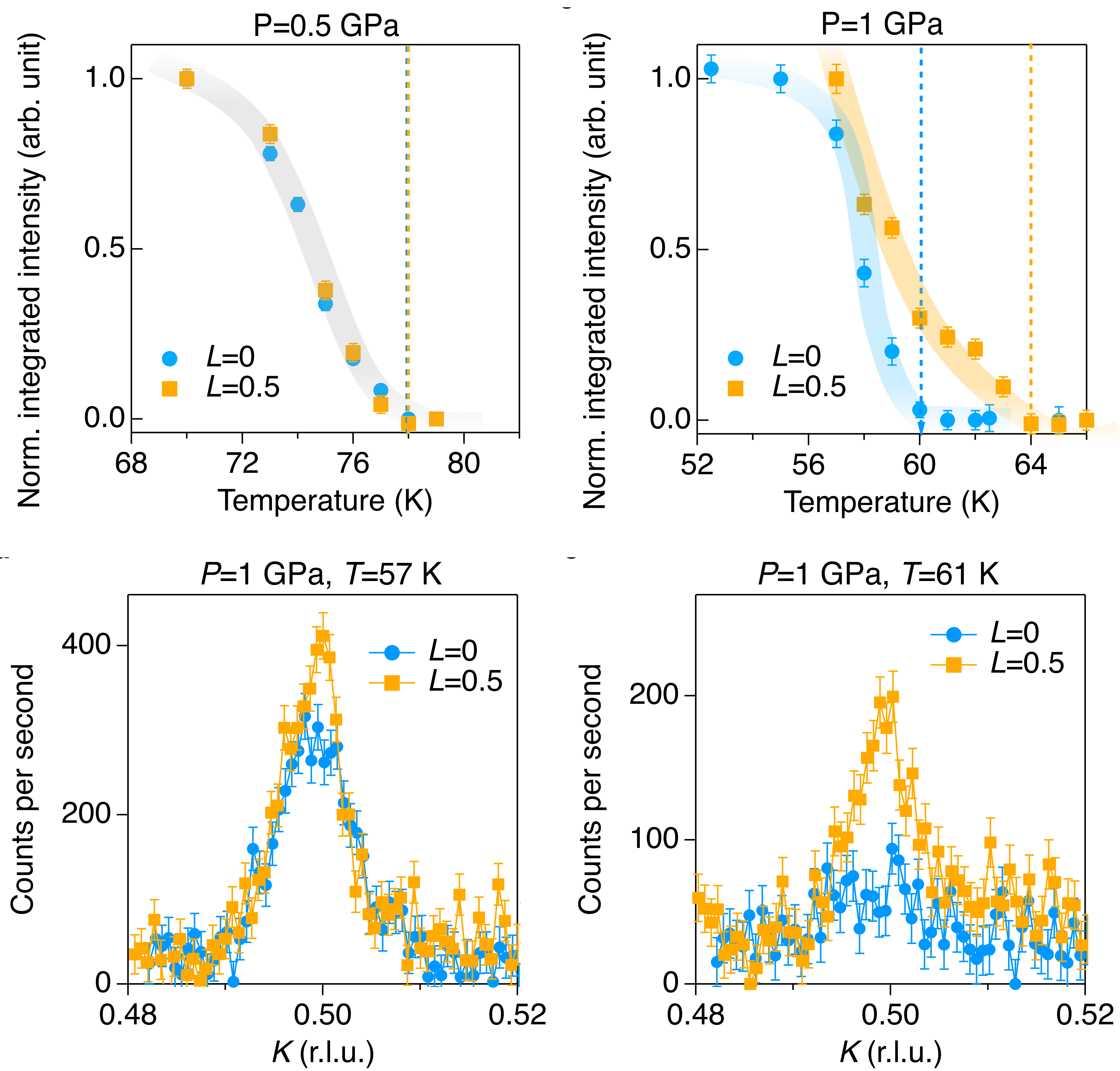




H. Li *et al. Nat Commun* 13, 6348 (2022)

High pressure elastic X-ray scattering

- Charge orders splitting and superconductivity

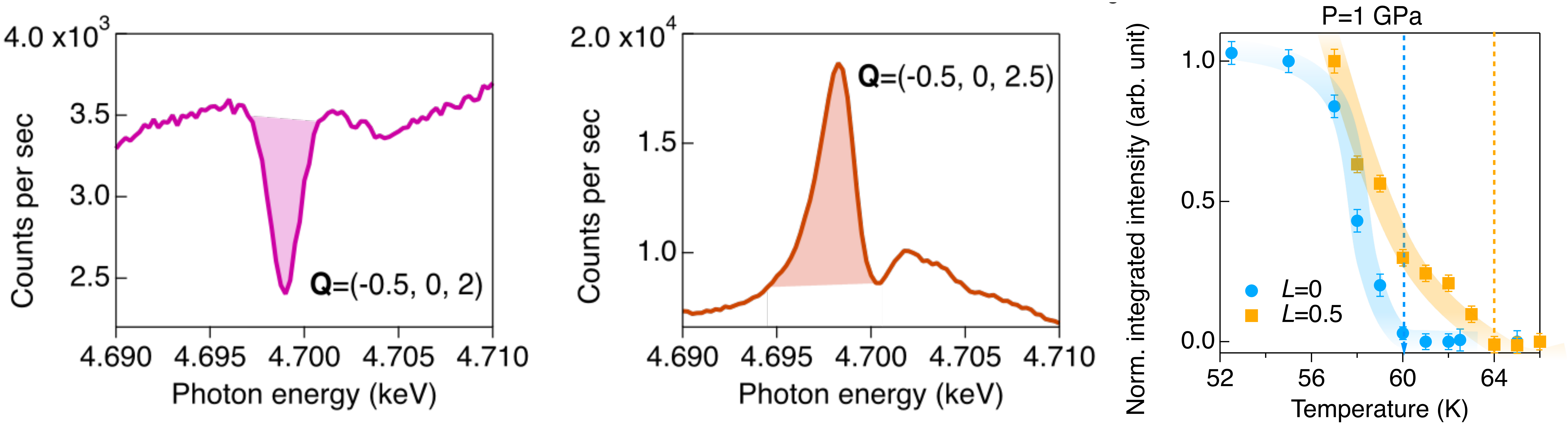


- At 0.5 GPa, identical temperature evolution for *L*= 0 and 0.5 (or $2 \times 2 \times 1$ and $2 \times 2 \times 2$)
- At 1 GPa, CDW peak at *L*=0.5 ($2 \times 2 \times 2$) precedes the one at *L*=0 ($2 \times 2 \times 1$)
- The two degenerate CDW orders are separated under high pressure

H. Li *et al. Nat Commun* 13, 6348 (2022)

Summary

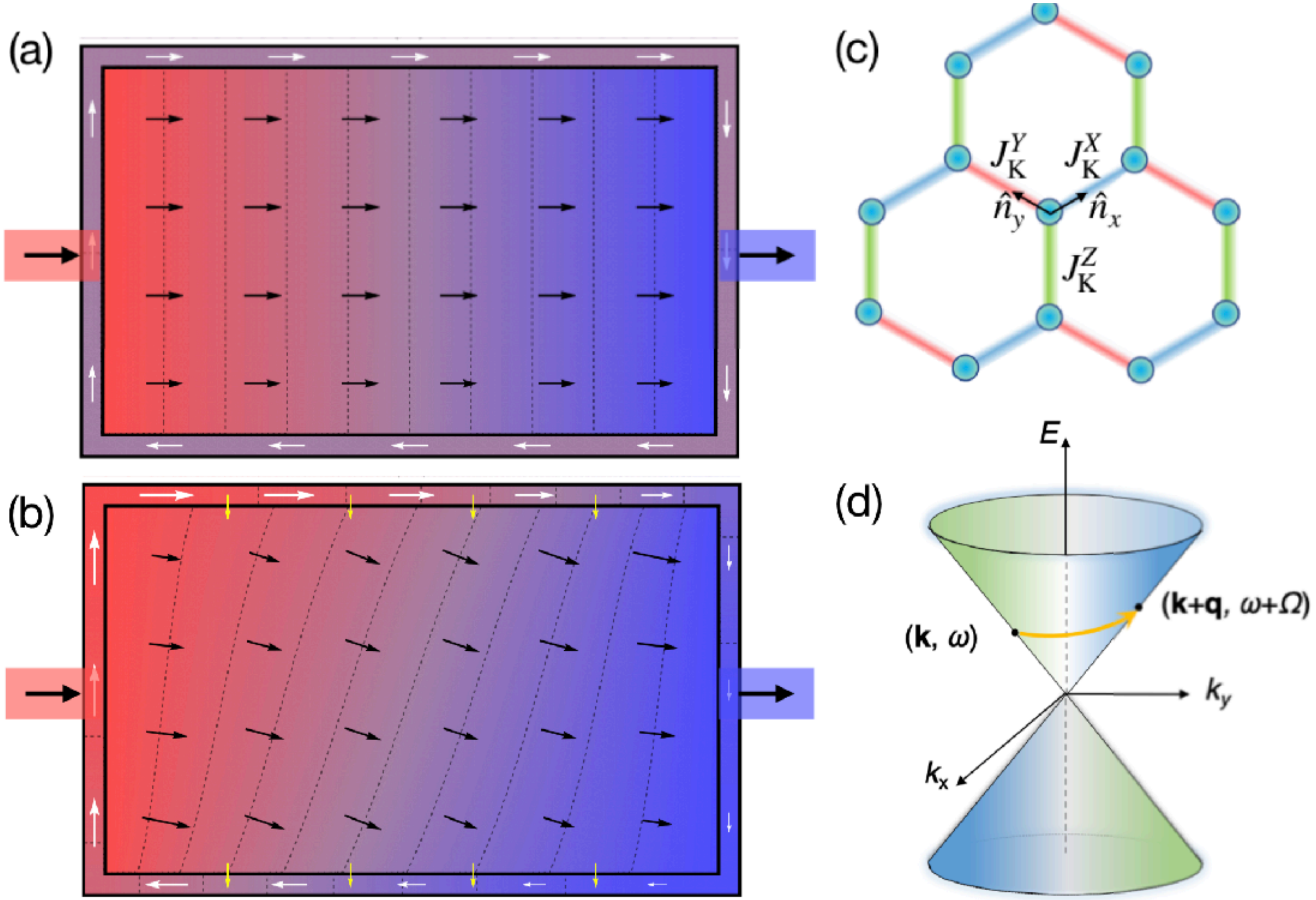
- Sb resonance only occur at $2 \times 2 \times 2$ peak (or L = half integer)
- A rare realization of two conjoined CDWs
- The two conjoined CDW can be separated by high pressure
- Potential connection to the superconductivity



H. Li *et al. Nat Commun* 13, 6348 (2022); H. Li *et al.* Phys. Rev. X 11, 031050 (2021);

Thank you for your attention!

Phonon in the thermal hall effect



Majorana-phonon coupling

PHYSICAL REVIEW X **8,** 031032 (2018)

Approximately Quantized Thermal Hall Effect of Chiral Liquids Coupled to Phonons

Yuval Vinkler-Aviv and Achim Rosch
Institute for Theoretical Physics, University of Cologne, 50937 Cologne, Germany

(Received 4 June 2018; published 1 August 2018)

PHYSICAL REVIEW LETTERS **121,** 147201 (2018)

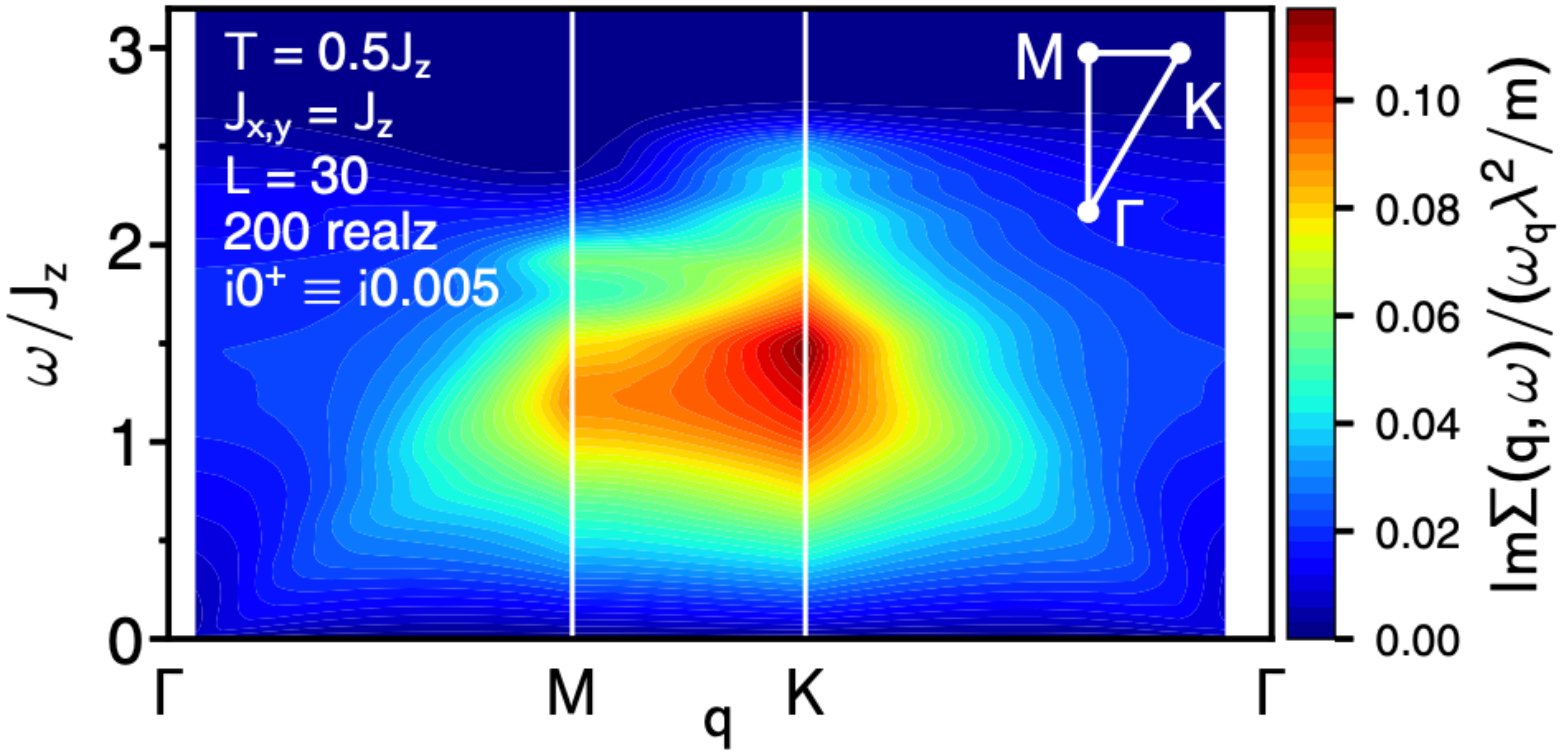
Quantization of the Thermal Hall Conductivity at Small Hall Angles

Mengxing Ye,[1,2] Gábor B. Halász,[2] Lucile Savary,[3] and Leon Balents[2]
[1]*School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA*
[2]*Kavli Institute for Theoretical Physics, University of California, Santa Barbara, California 93106, USA*
[3]*Université de Lyon, École Normale Supérieure de Lyon, Université Claude Bernard Lyon I, CNRS, Laboratoire de physique, 46, allée d'Italie, 69007 Lyon, France*

(Received 7 June 2018; published 1 October 2018)

Majorana-phonon coupling

Phonon self energy from MPC



PhysRevB.101.035103

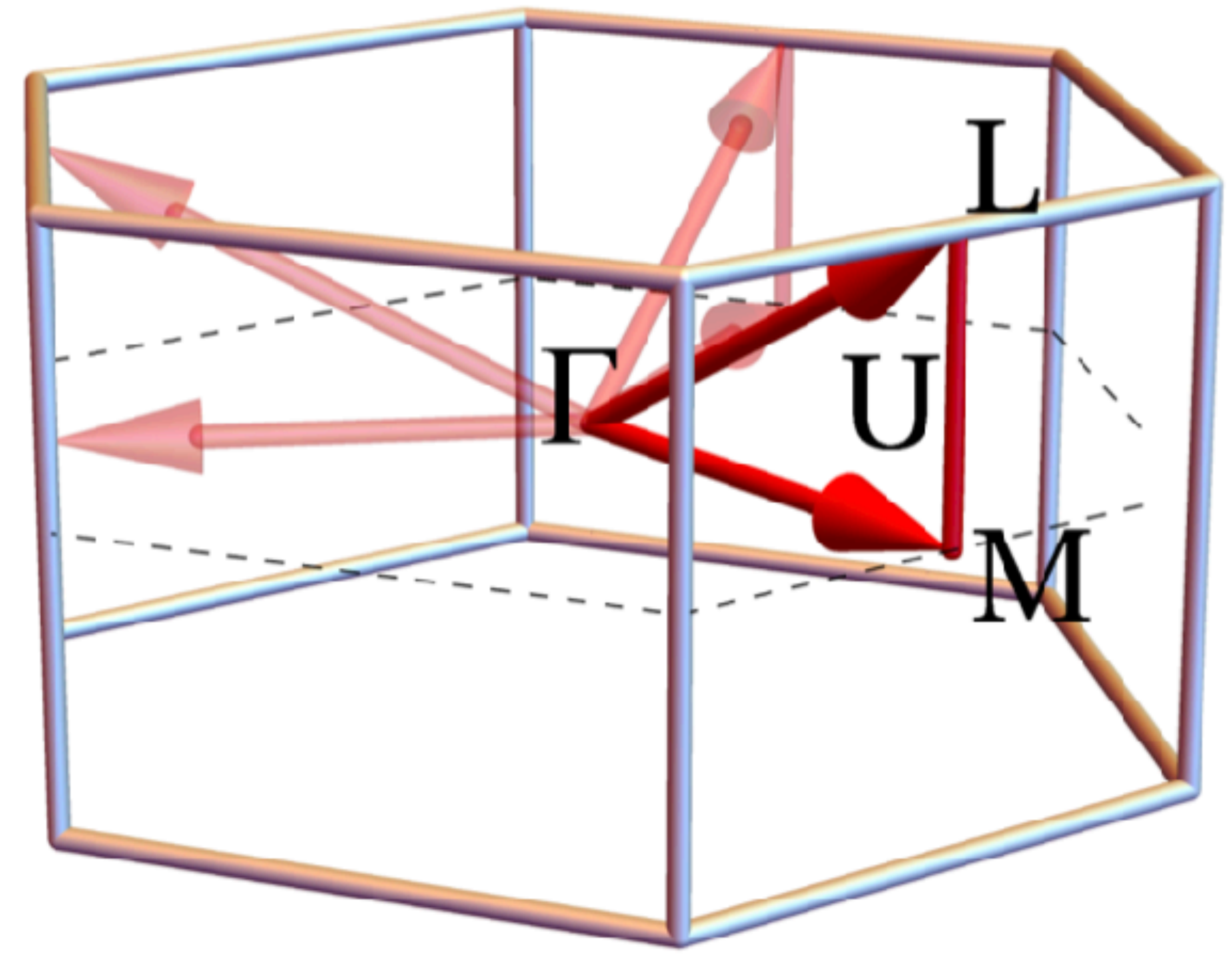
In-plane and out of plane scattering wave vector

M: $2 \times 2 \times 1$ *L*: $2 \times 2 \times 2$

$$\mathcal{F}_{ML} = \frac{\gamma_{ML}}{3}(M_1L_2L_3 + L_1M_2L_3 + L_1L_2M_3) \quad (7)$$
$$+ \frac{\lambda^{(1)}_{ML}}{4}(M_1M_2L_1L_2 + M_1M_3L_1L_3 + M_2M_3L_2L_3)$$
$$+ \frac{\lambda^{(2)}_{ML}}{4}(M_1^2L_1^2 + M_2^2L_2^2 + M_3^2L_3^2) + \frac{\lambda^{(3)}_{ML}}{4}M^2L^2 ,$$

- Rotation symmetry breaking (6-fold to 2-fold)
- First order phase transition
- Time reversal symmetry breaking

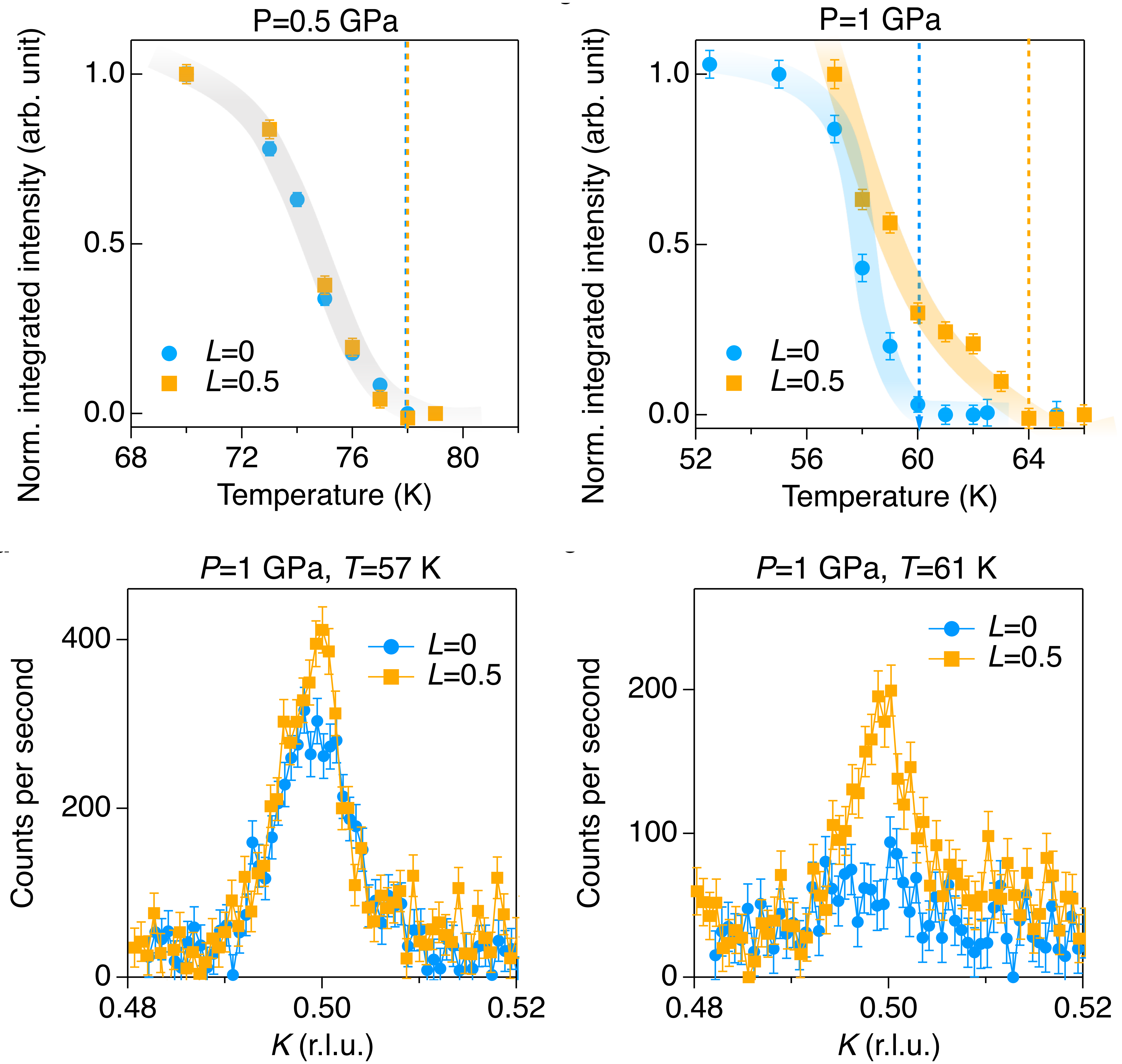
Brillouin zone

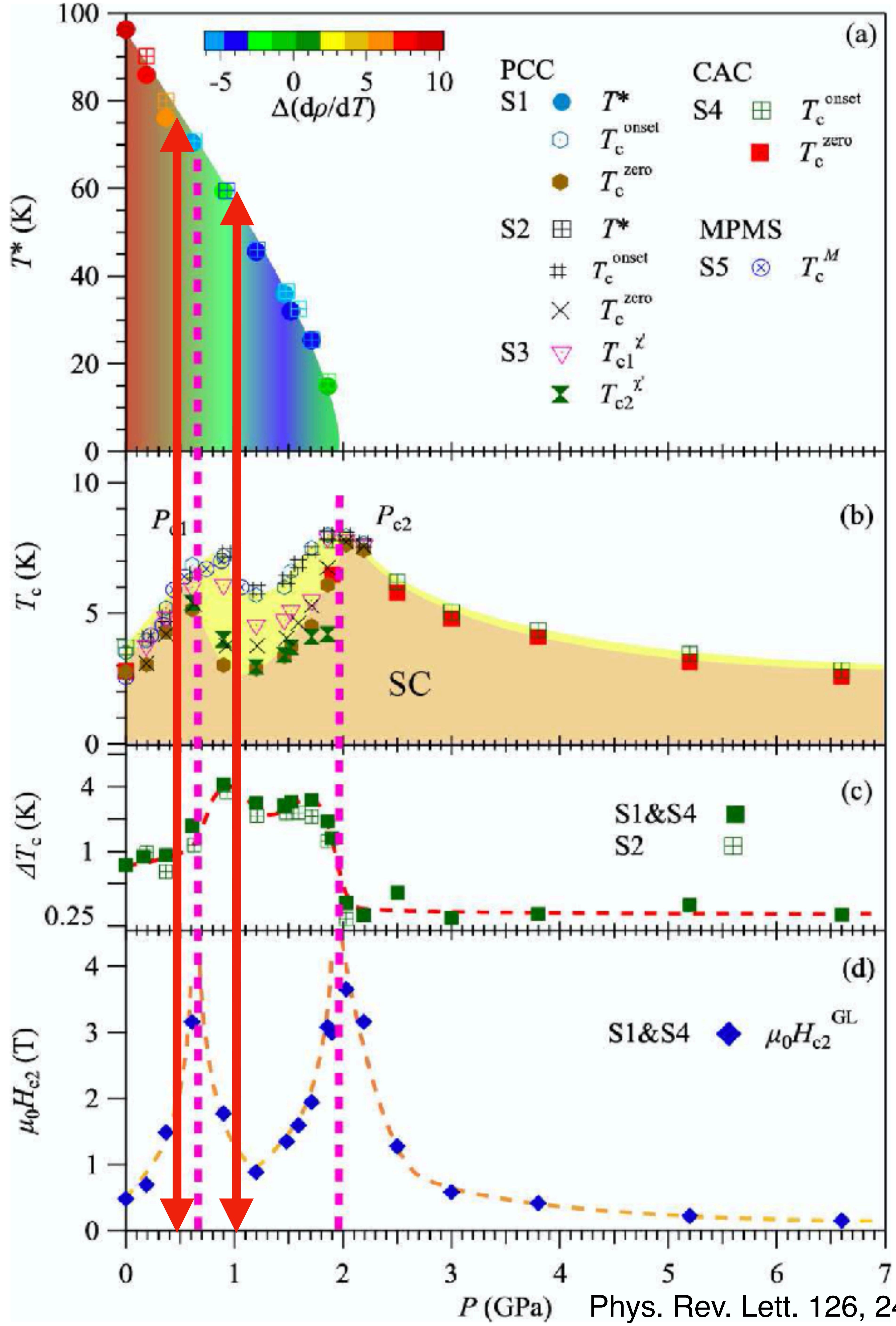


Christensen et al. *Phys. Rev. B* **104**, 214513 (2021)

High pressure elastic X-ray scattering

- Charge orders splitting and superconductivity





Phys. Rev. Lett. 126, 247001