

Distinct Behaviors of Inner and Outer CuO_2 Planes in Quadruple-Layer Cuprate $(\text{Cu,C})\text{Ba}_2\text{Ca}_3\text{Cu}_4\text{O}_{11+\delta}$

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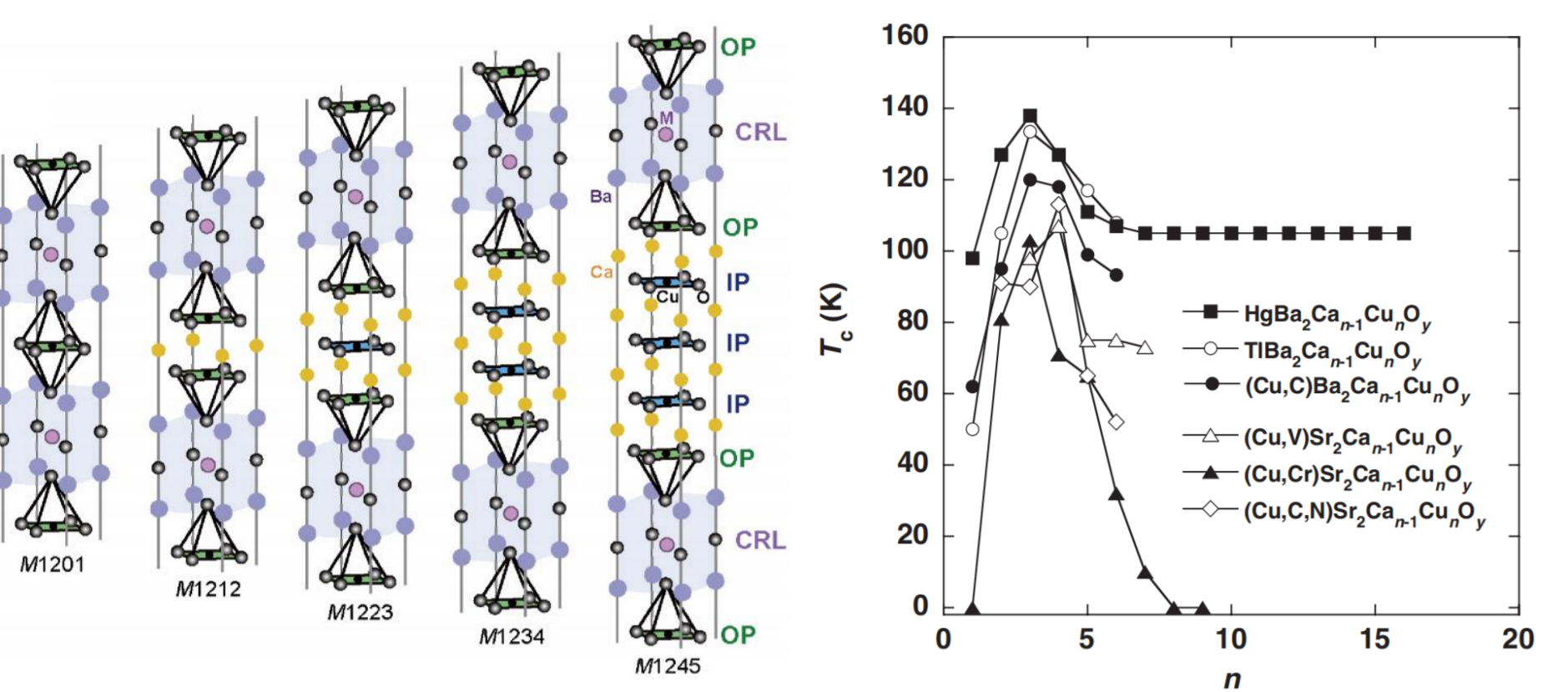
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Background

Why T_c reaches its maximum at tri- or quadruple layered cuprate?

Multi-layered cuprate superconductor



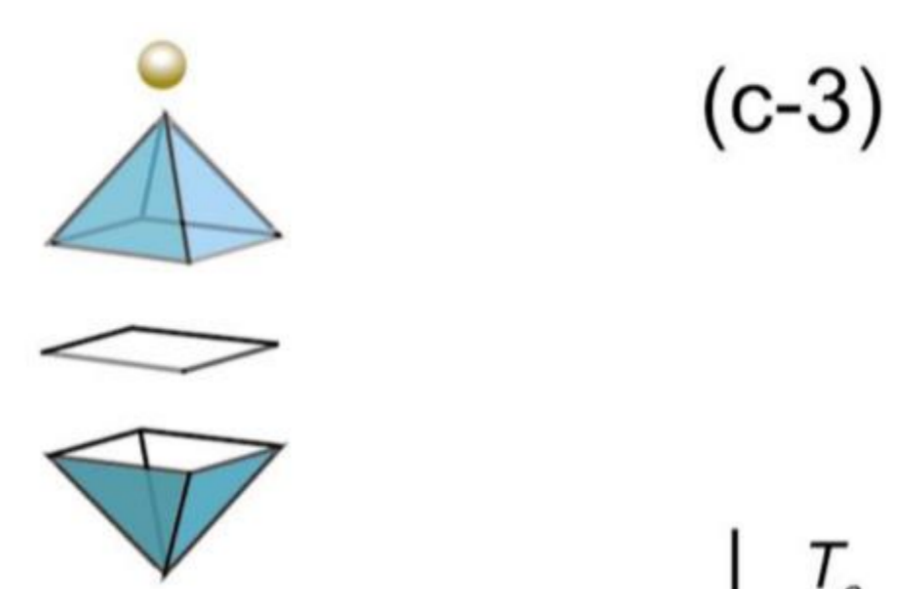
H. Mukuda, et al., *J. Phys. Soc. Jpn.* **81**, 011008 (2012)

Akira Iyo, et al., *J. Phys. Soc. Jpn.* **76**, 094711 (2007)

➤ Multilayered ($n \geq 3$): **Inner and outer CuO_2 plane (IP&OP).**

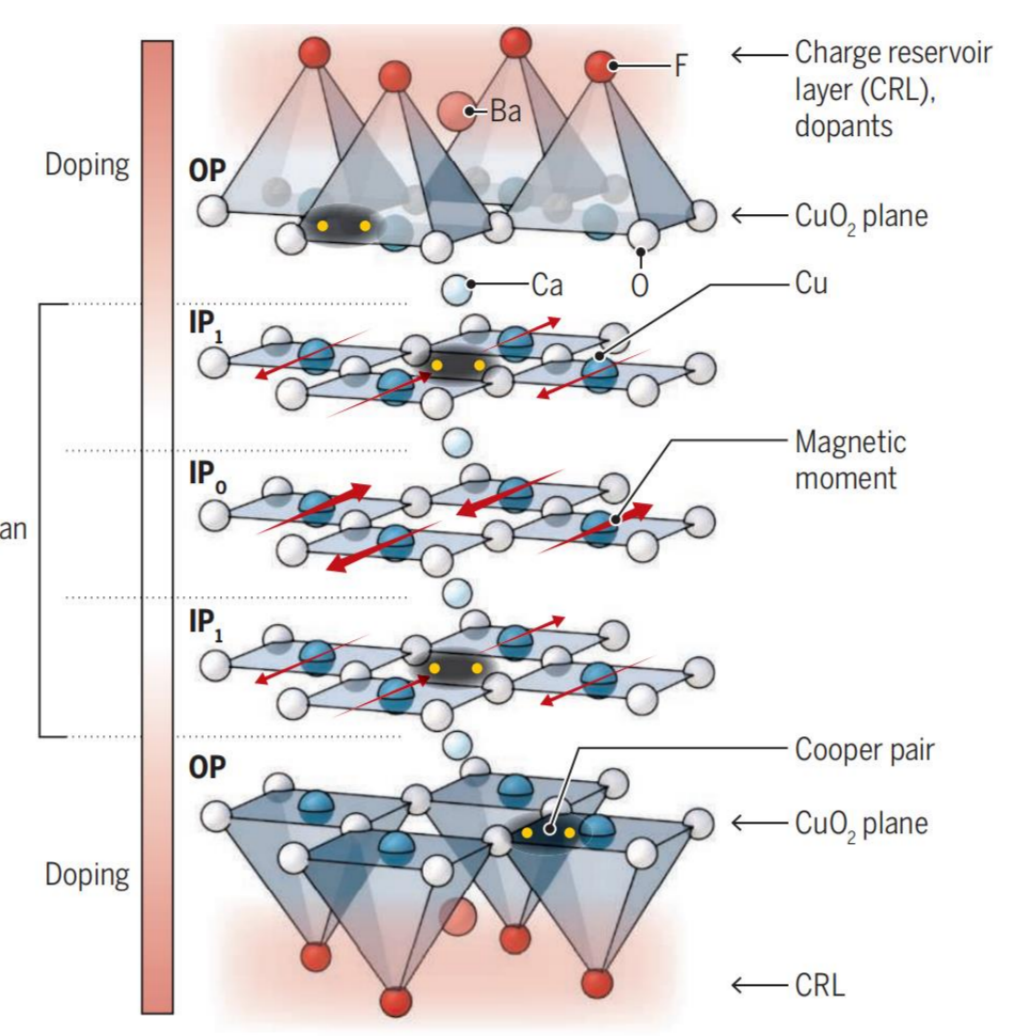
➤ T_c reaches maximum at $n=3$ or 4 , but its mechanism is not clear.

Scenario 1: Intrinsic cleaner IPs



Compound	T_c (K)
$\text{TiBa}_2\text{Ca}_2\text{Cu}_3\text{O}_{9+\delta}$	133
$\text{Ti}_2\text{Ba}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+\delta}$	125
$\text{HgBa}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+\delta}$	135

H. Eisaki, et al., *Phys. Rev. B* **69**, 064512 (2004)

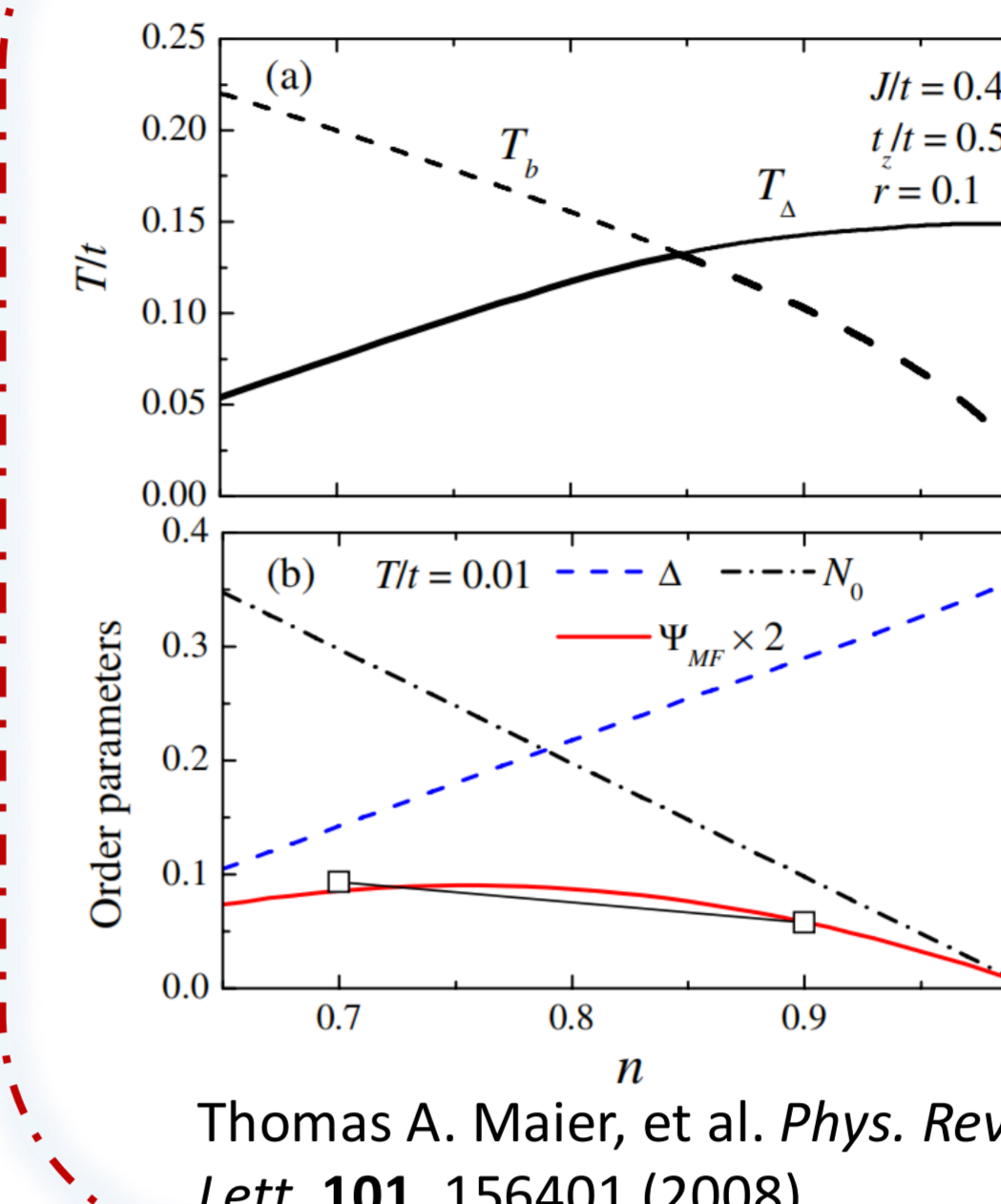


Inna Vishik, et al., *Science* **369**, 775-776 (2020)

➤ IP: underdoped; OP: overdoped.

➤ IP protected by OP from impurities in CRL.

Scenario 2: Composite picture



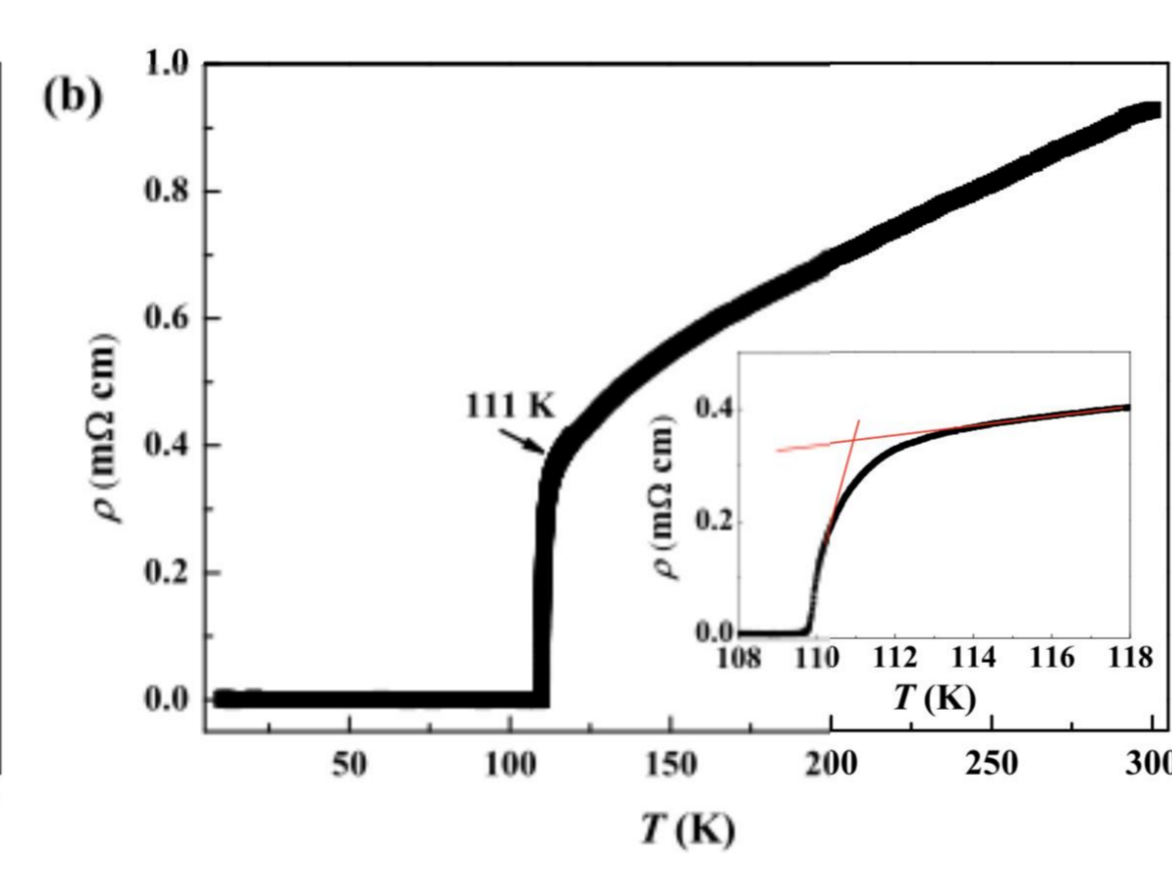
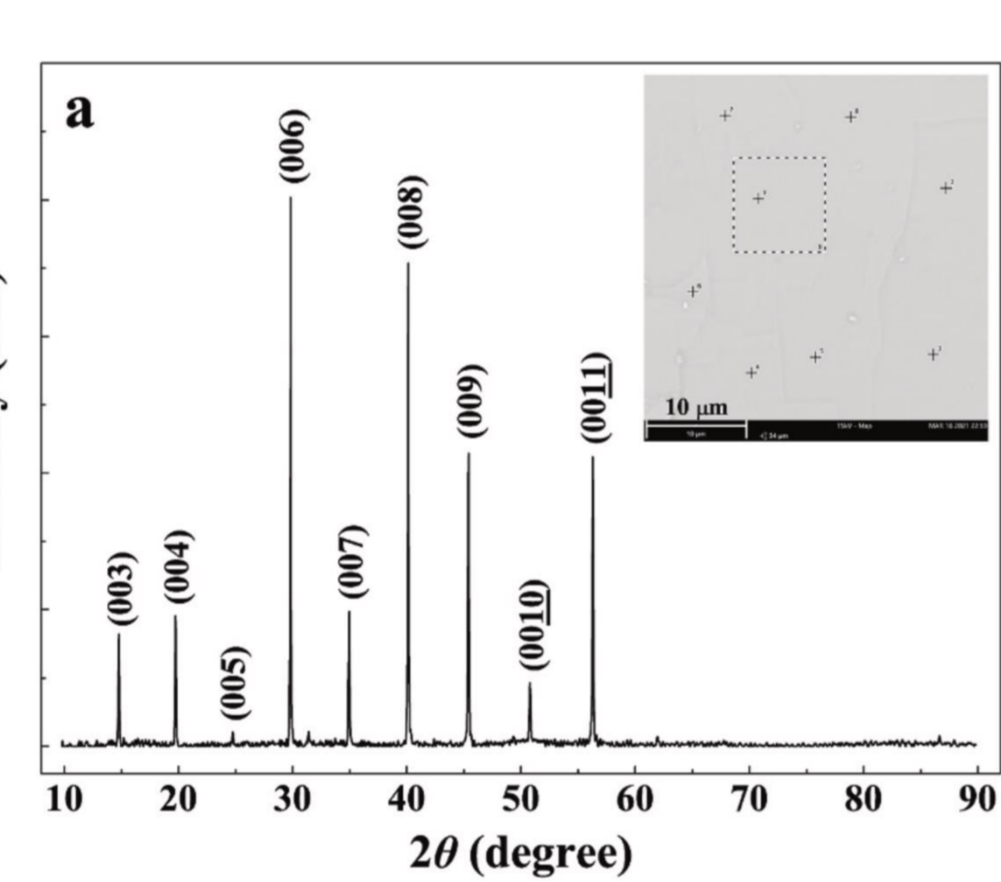
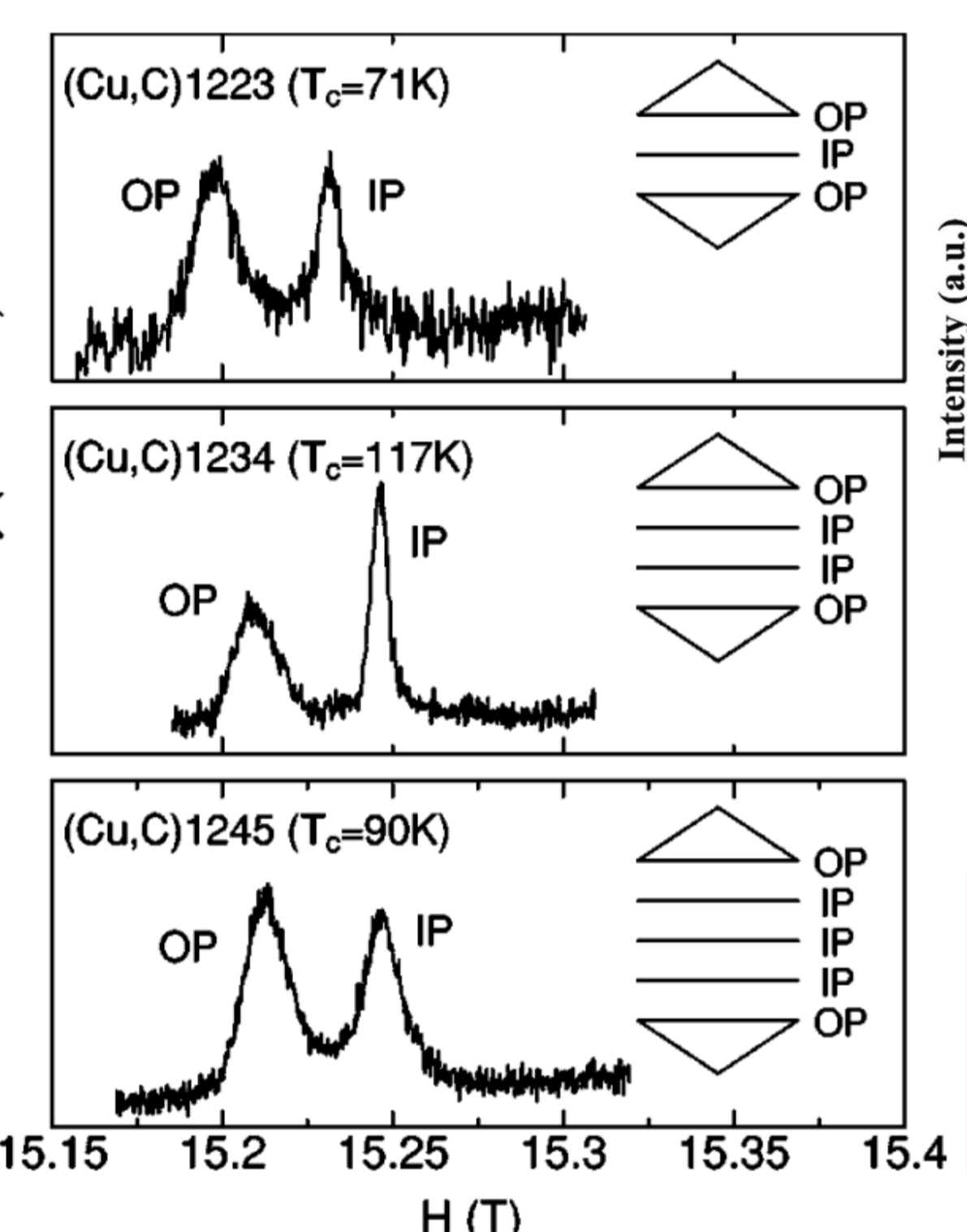
- Underdoped IP: Pairing strength (T_Δ).
- Overdoped OP: Phase stiffness (T_b).
- IP & OP coupling: Enhanced T_c .

Definitive experimental to identify the role of IP and OP is lacking!

➔ Tuning IP or OP non-superconducting?

Experiment results

1. $(\text{Cu,C})\text{Ba}_2\text{Ca}_3\text{Cu}_4\text{O}_{11+\delta}$: Ideal system to study factors influencing T_c

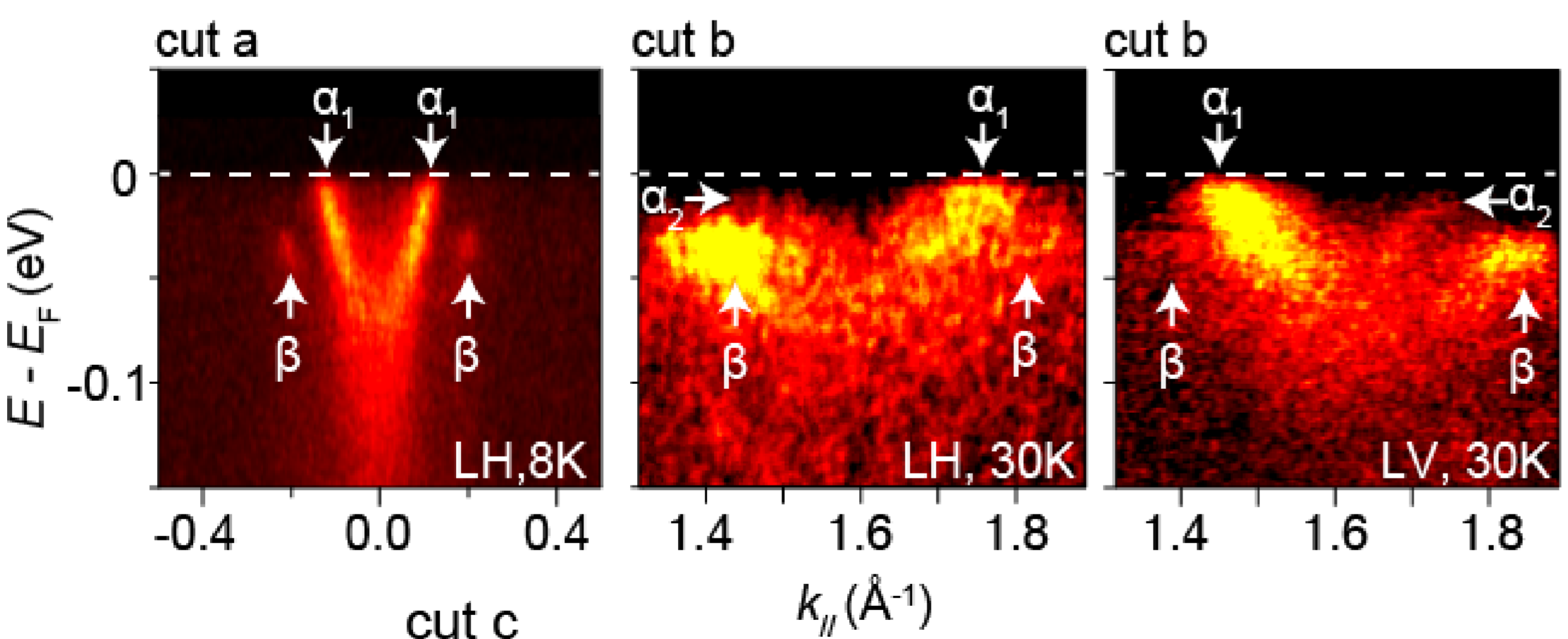
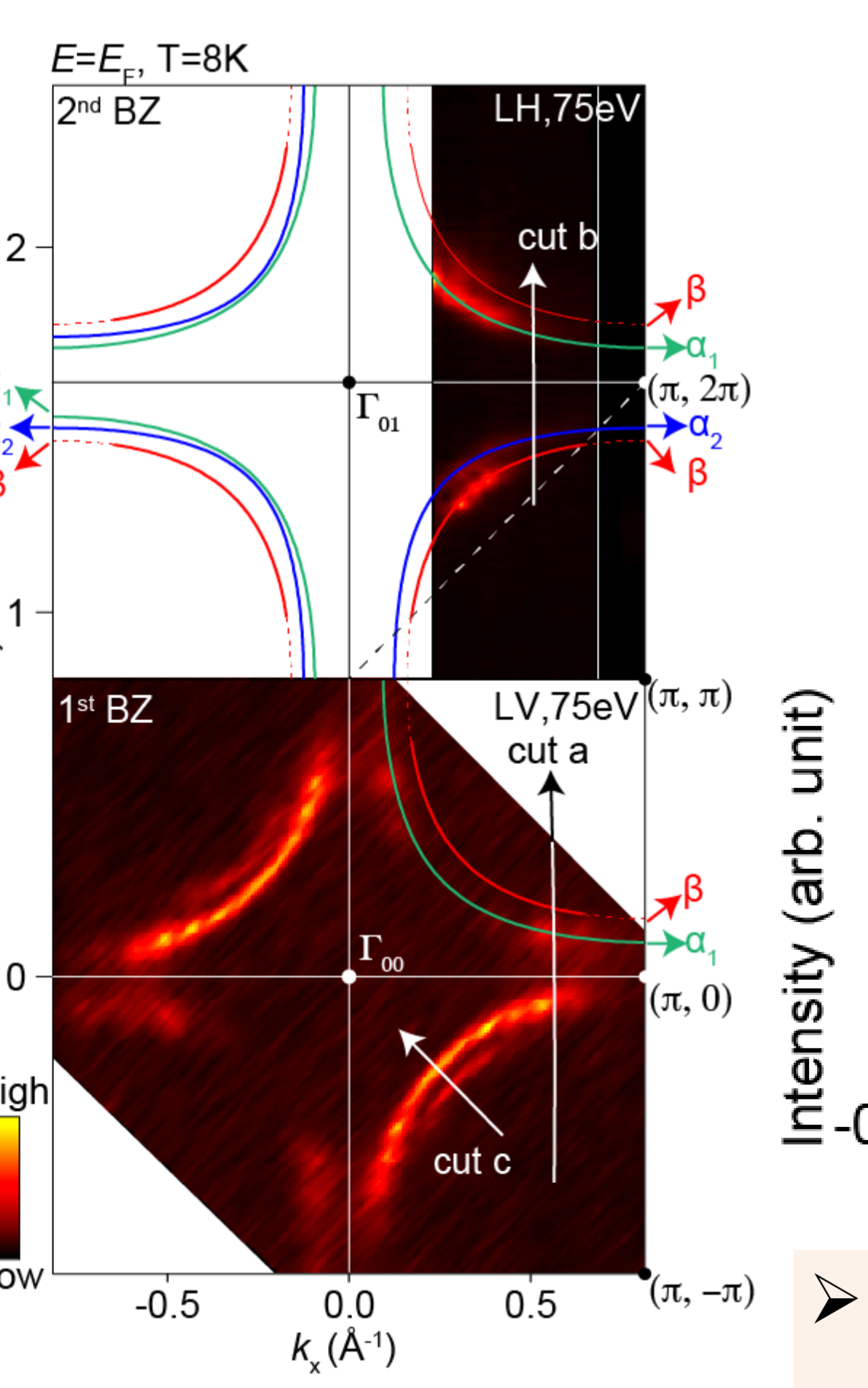


➤ $(\text{Cu,C})\text{Ba}_2\text{Ca}_3\text{Cu}_4\text{O}_{11+\delta}$ (CuC-1234): **Highest T_c within CuC family.**

➤ Single crystal CuC-1234: **High quality with $T_c=111\text{K}$.**

H. Kotegawa, et al., *Phys. Rev. B* **64**, 064515 (2001)

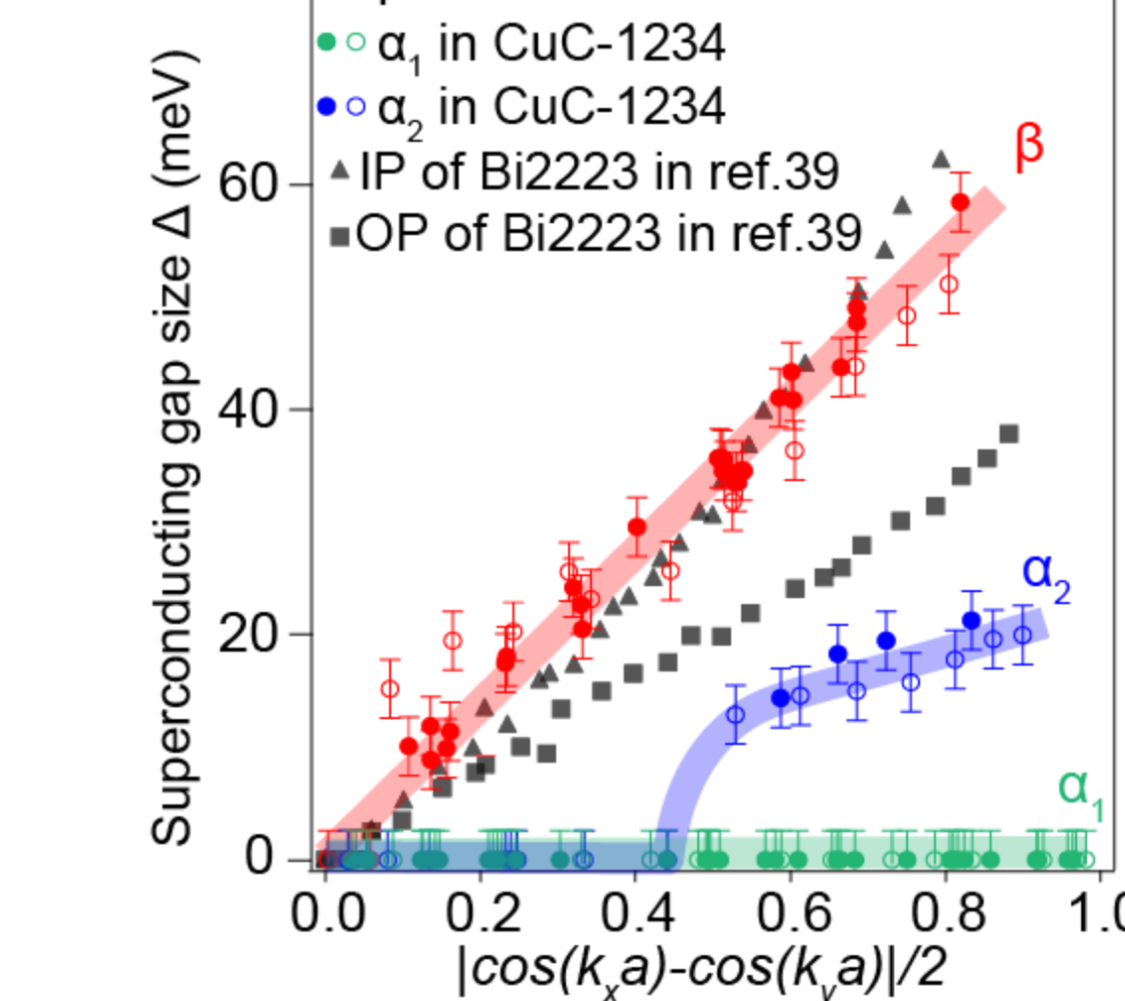
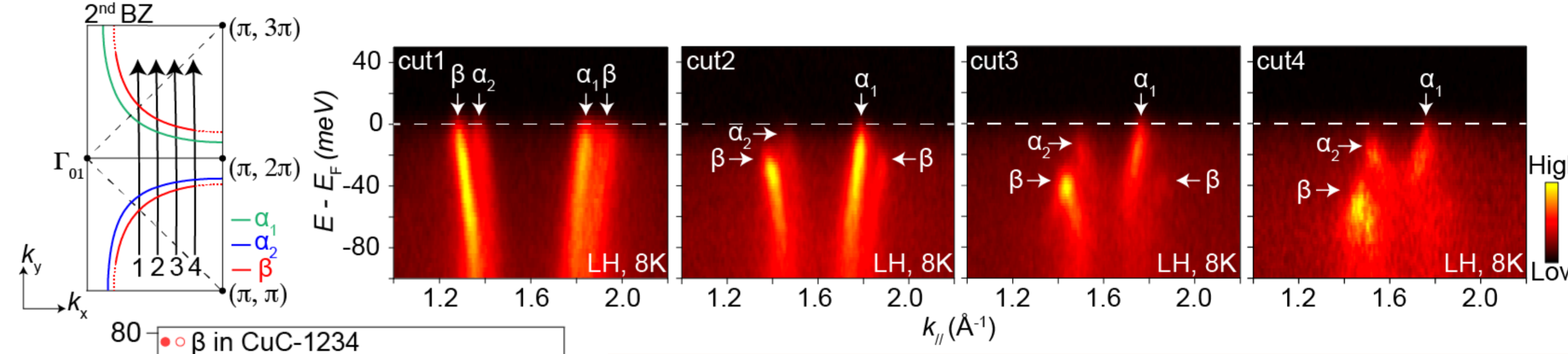
2. Fermi surface topology of CuC-1234



➤ Lower scattering rate in β band.

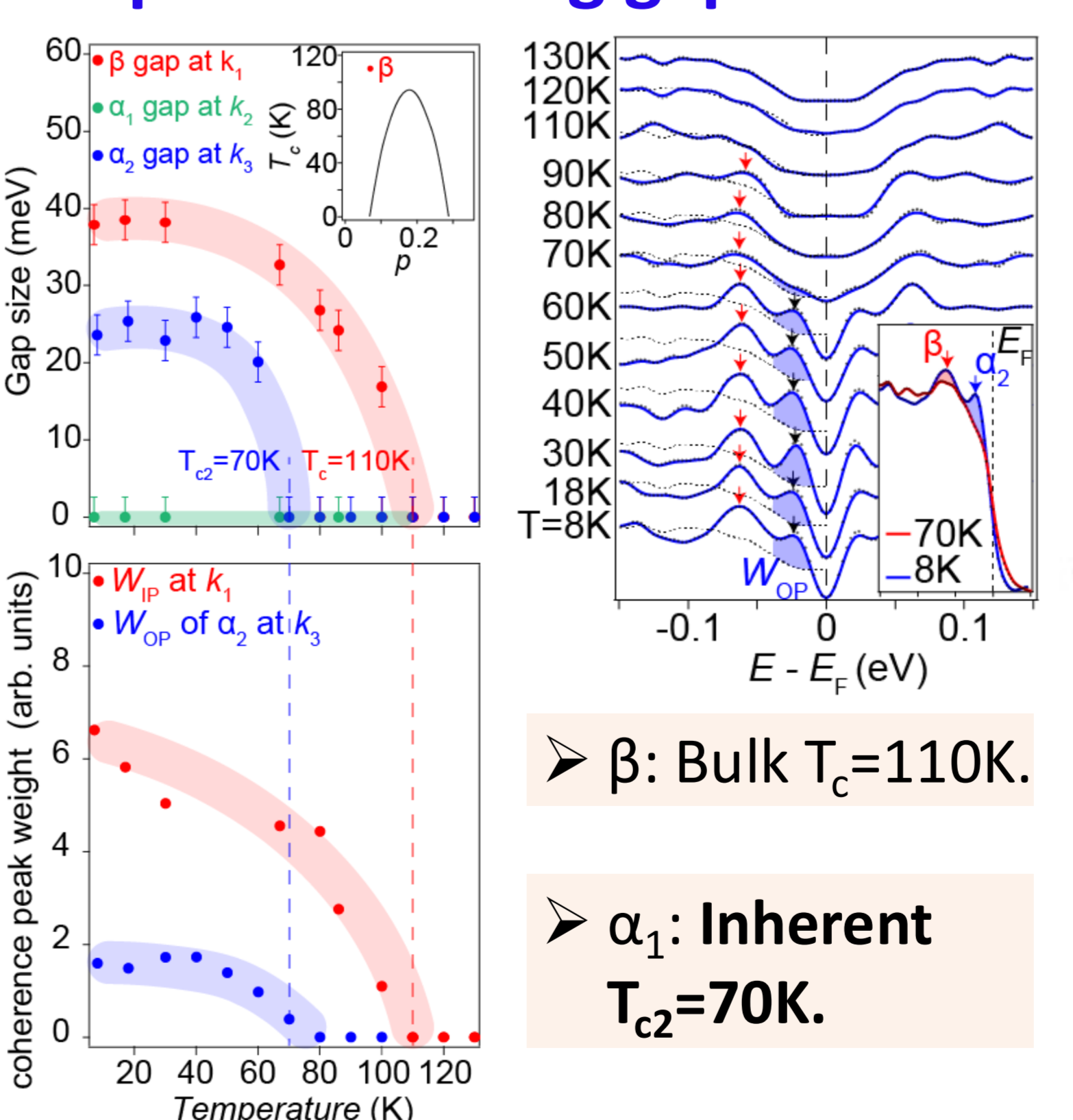
Sheet label	Originated CuO_2 plane	Doping level
β	Inner CuO_2 plane	0.07 holes per Cu
α_1	Outer CuO_2 plane	0.32 holes per Cu
α_2	Outer CuO_2 plane	0.25 holes per Cu

3. Momentum-dependent superconducting gap structure



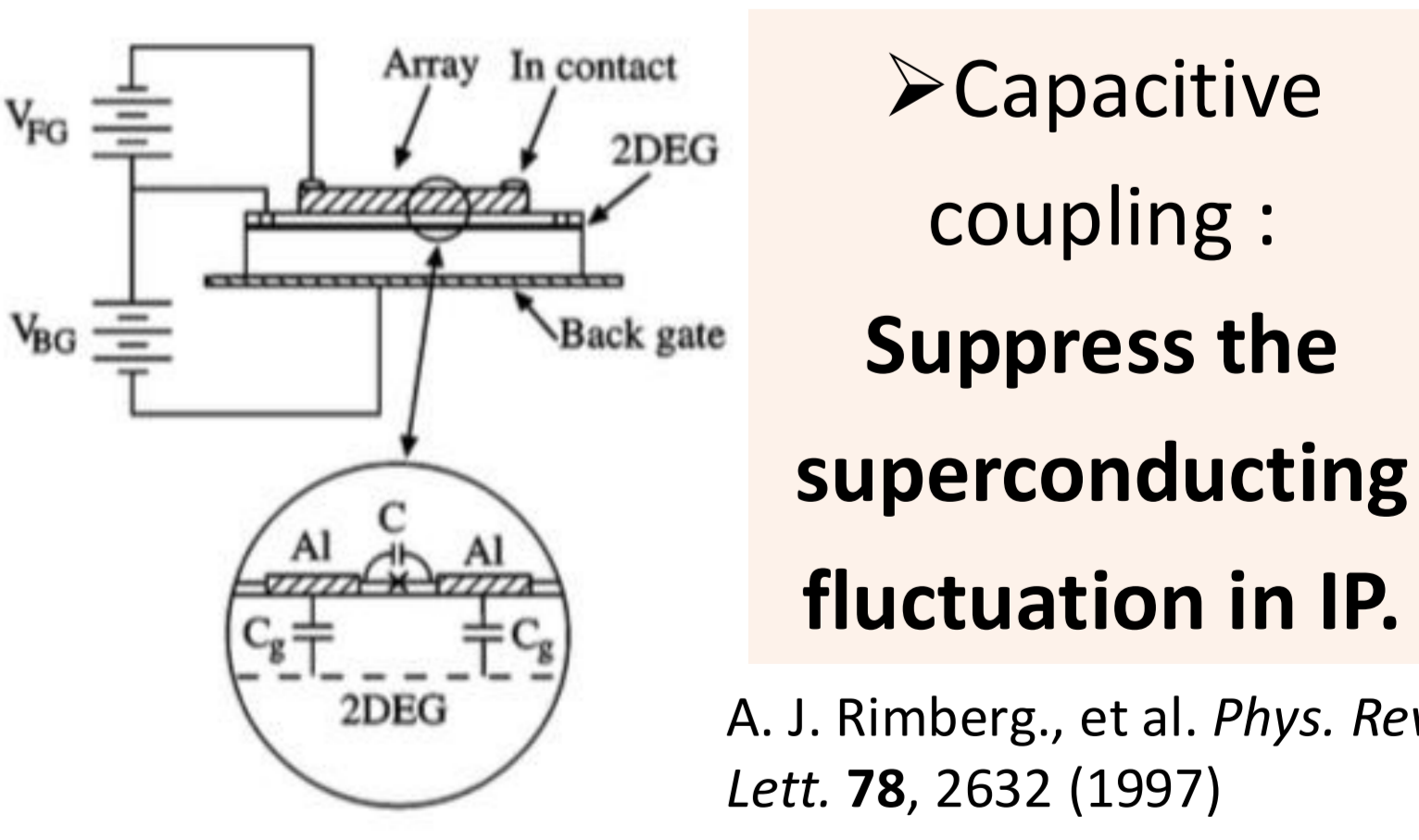
- β band: d-wave form with large SC gap (comparable to IPs in Bi2223).
- α_1 band: No SC gap at all momenta.
- α_2 band: Dirty d-wave form with partial smaller SC gap (smaller than OPs in Bi2223).
- IP plays important roles in achieving high T_c in CuC-1234!

4. Temperature-dependent superconducting gap structure



5. Supporting roles of OPs in CuC-1234

- Aspect 1: Protect IPs from disorders**
- Lower scattering rate in IPs, which dominate the high- T_c in CuC-1234.
- Aspect 2: Capacitive coupling between IP and OP**
- Capacitive coupling: Suppress the superconducting fluctuation in IP.



A. J. Rimberg, et al. *Phys. Rev. Lett.* **78**, 2632 (1997)

Conclusions

Our ARPES studies on the quadruple-layer cuprate CuC-1234 ($T_c=111\text{K}$) have revealed:

- ◆ Inner CuO_2 planes: Large d-wave SC gap; Low impurity; absence of apical oxygen; **Contribute the high T_c superconductivity of CuC-1234.**
- ◆ Outer CuO_2 planes: No SC gap above 70K; Weak interlayer coupling with IP; **Not driving force, but playing supporting roles in achieving high T_c .**

Two scenarios are proposed to explain the roles of OP in achieving high- T_c in multilayer cuprates:

Scenario 1: OP protected IP. **Cleaner IP without apical oxygen; Possible new phase diagram of cuprates without apical oxygen.**

Scenario 2: Capacitive coupling between IP and OP → **Suppress the superconducting fluctuation in IP.**

Reference: *Phys. Rev. Lett.* **136**, 186401 (2026)