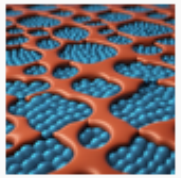


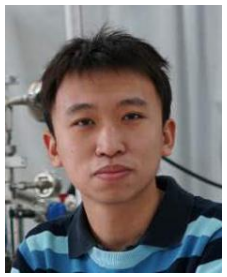
TIDES2026

Anomalous metal phase & resistance/gap oscillations in Li_xTiSe_2 superconductors

Ding Zhang

Department of Physics, Tsinghua University

Acknowledgements


Menghan Liao


Jia-Yi Ji


Zongzheng Cao


Heng Wang


Yi Hu


Yuying Zhu


Qi-Kun Xue

Outline

- **Introduction**
  Ionic solids and superconductivity in $TiSe_2$

- **Li_xTiSe_2**
  Superconductivity and anomalous metal

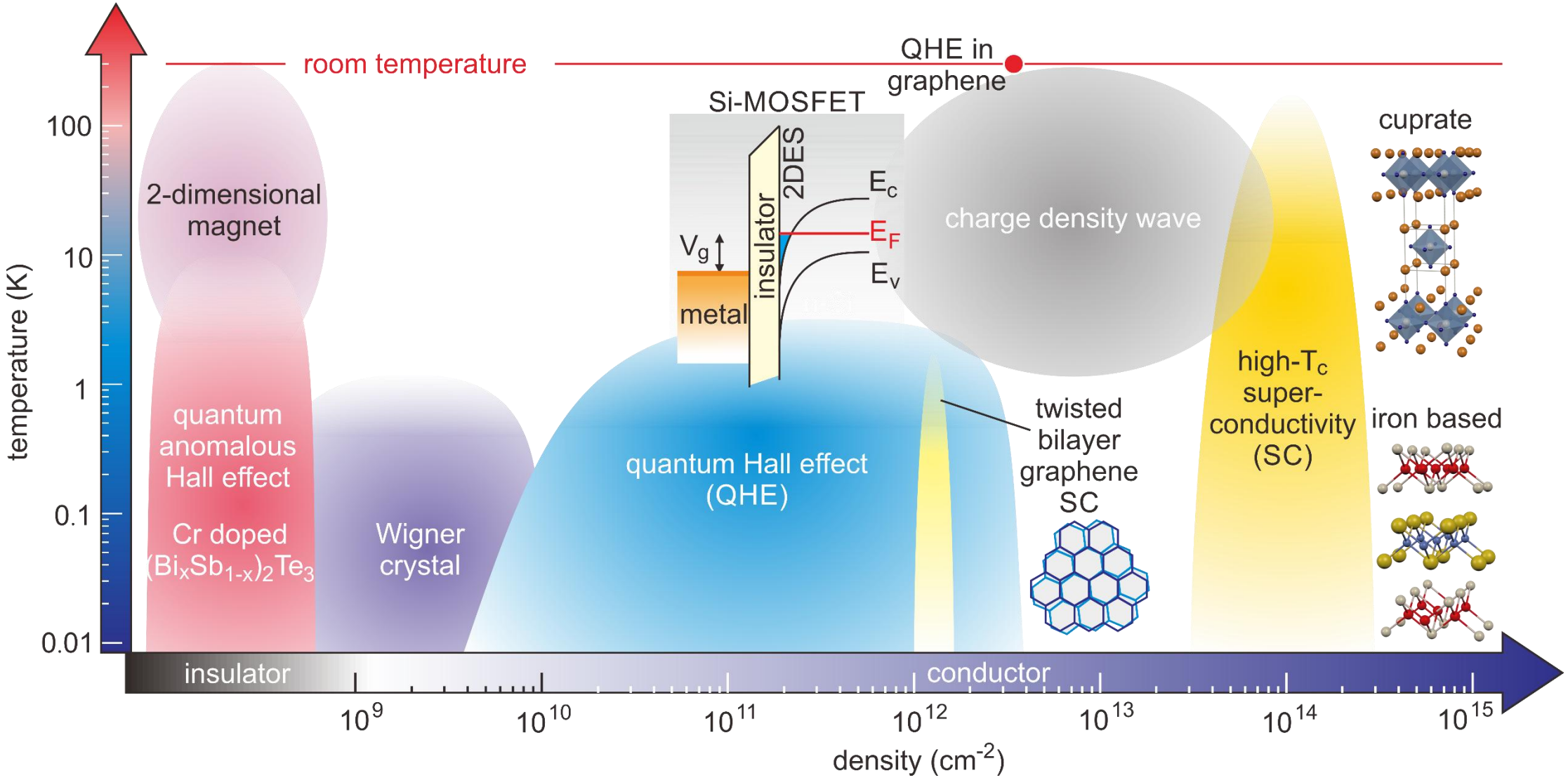
  Little-Parks-like oscillations

  Gap in the anomalous metal phase and gap oscillations

- **Li_xFeSe**

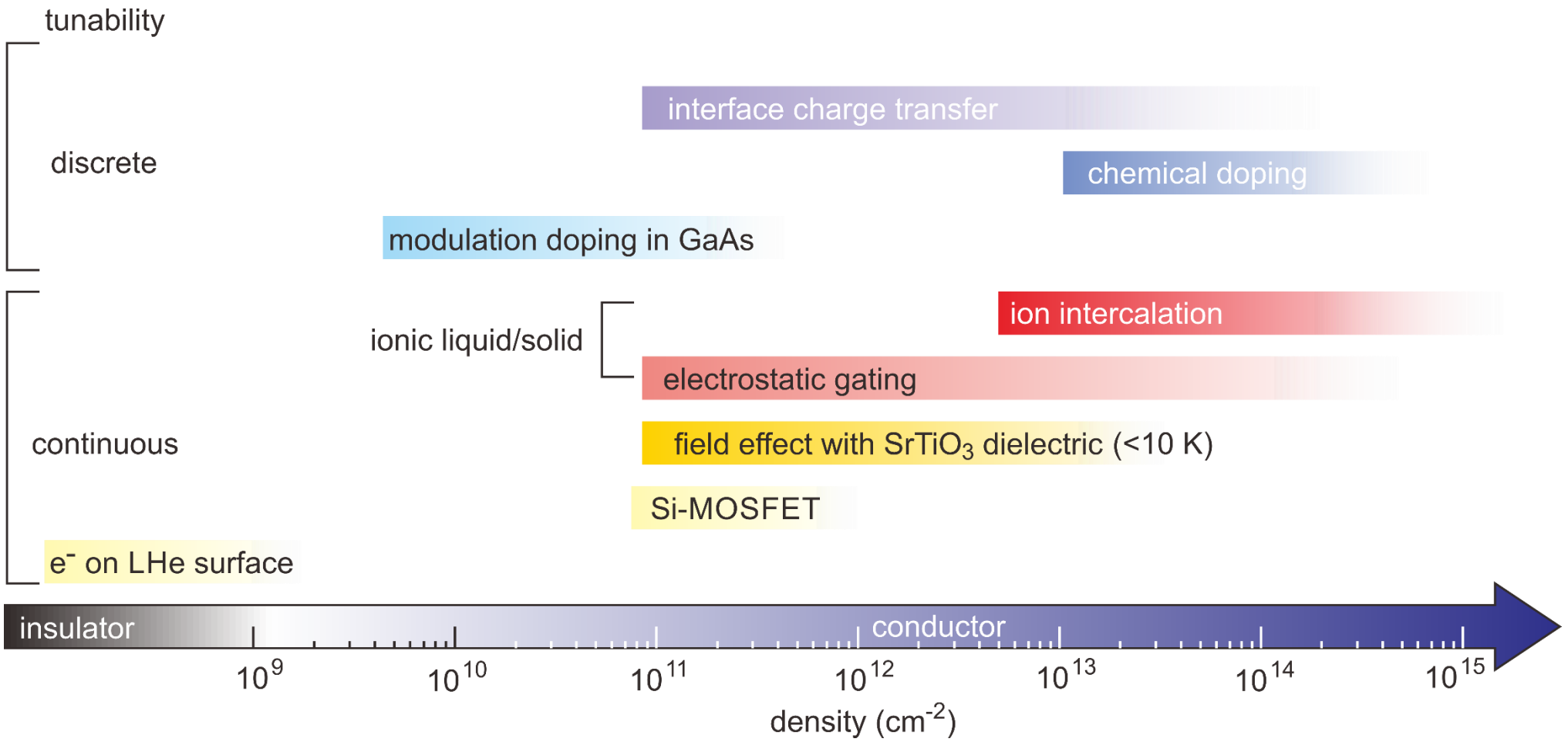
Tuning the carrier density

- **Many interesting phenomena occur at different ranges of density**

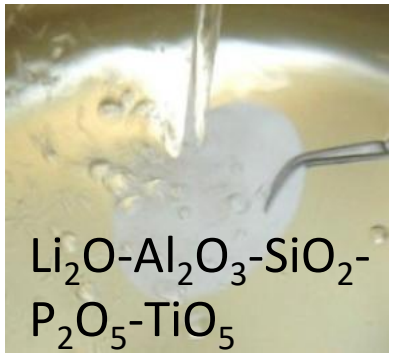


Tuning the carrier density

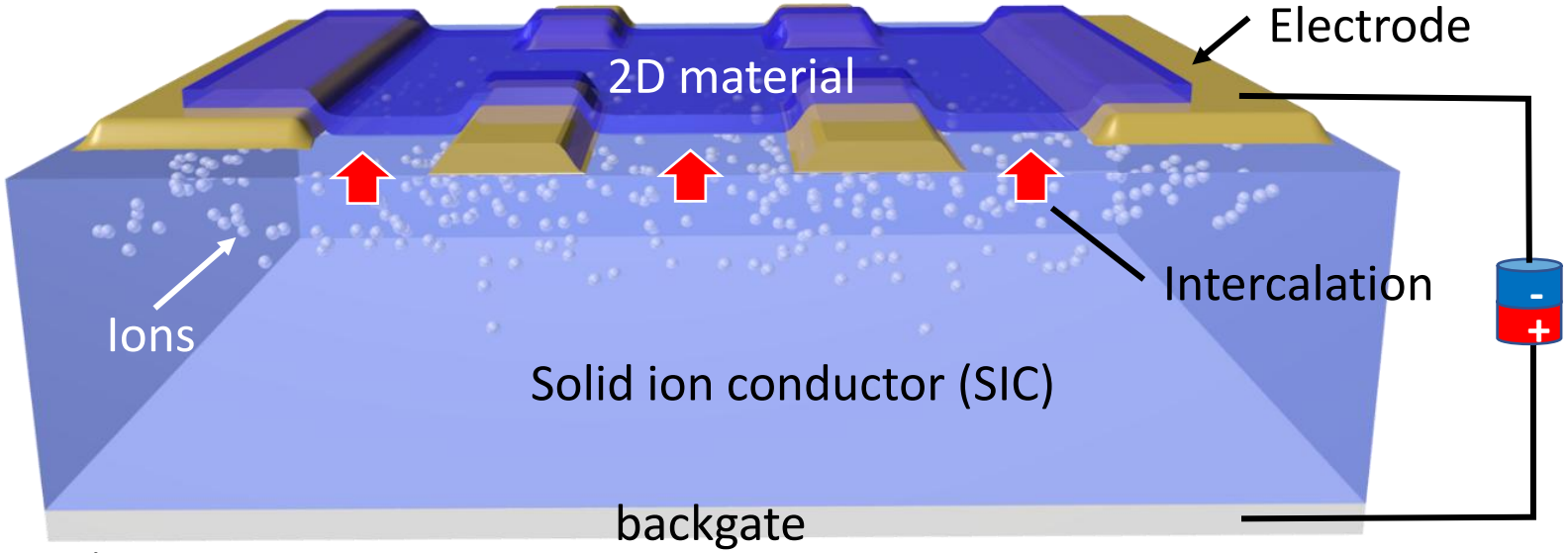
- **Ionic liquid/solid: powerful for tuning the density in a wide range**



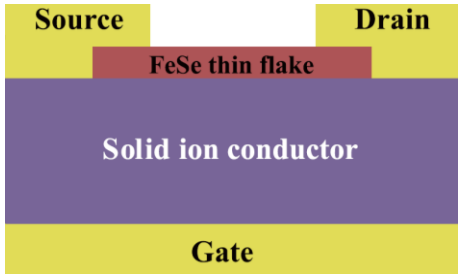
Lithium intercalation via an ion backgate



www.ohara-inc.co.jp/cn/product/

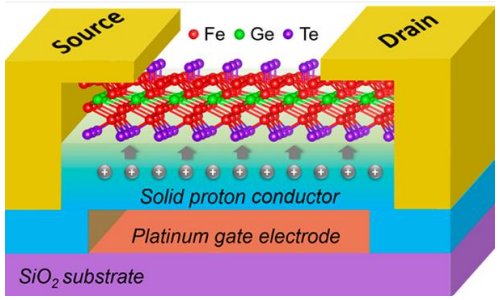


Lithium ion



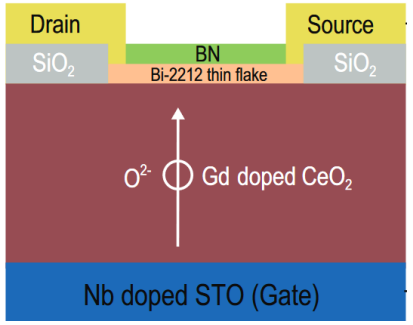
B. Lei, *et al., Phys. Rev. B* **95**, 020503(R) (2017)

Hydrogen ion



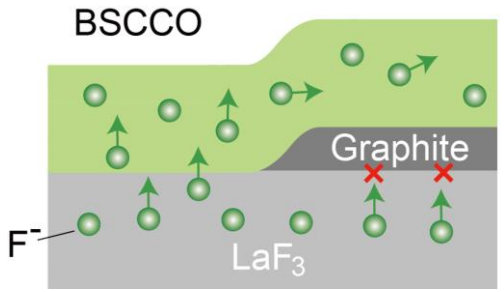
C. Tan, *et al., Nano Lett.* **21**, 5599 (2021)

Oxygen ion



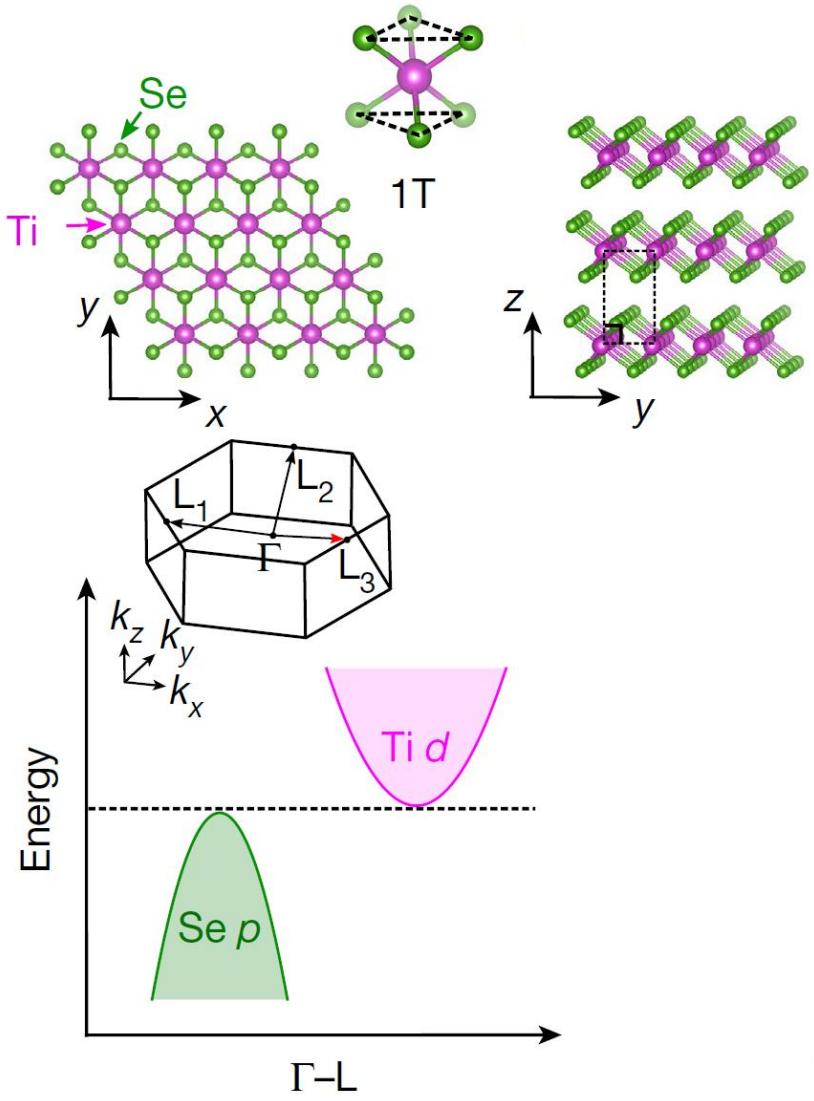
B. Lei, *et al., Natl. Sci. Rev.* **9**, nwac089 (2022)

Fluoride ion



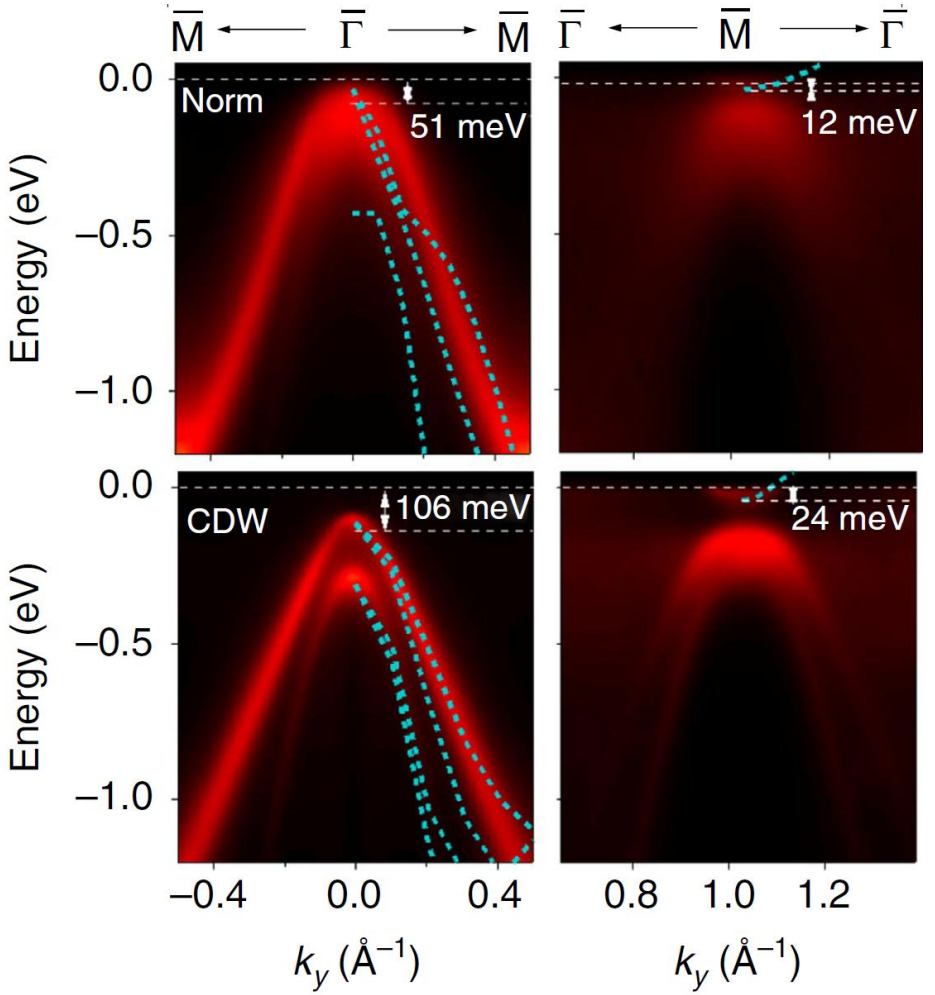
H. Wang, *et al., J. Appl. Phys.* **132,** 214301 (2022)

Introduction to $TiSe_2$



S.-Y. Xu, et al., *Nature* **578**, 545 (2020)

- CDW ~200 K

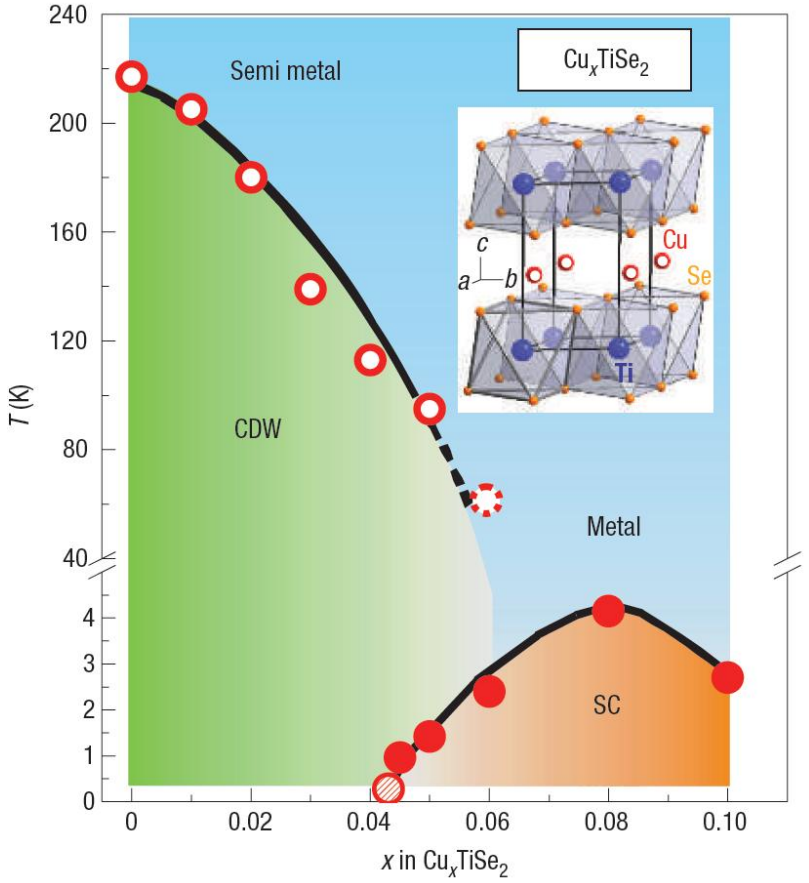


P. Chen, et al., *Nat. Commun.* **6**, 8943 (2015)

Single electron pocket

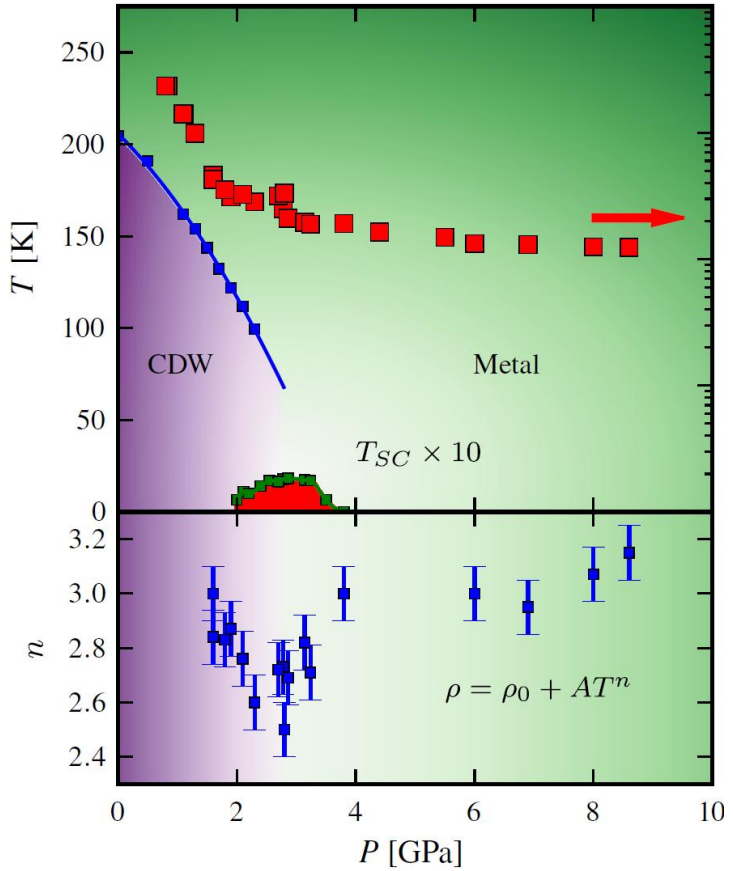
Superconductivity in $TiSe_2$

- Intercalation (Cu, Li), pressure, ionic liquid gating can induce superconductivity

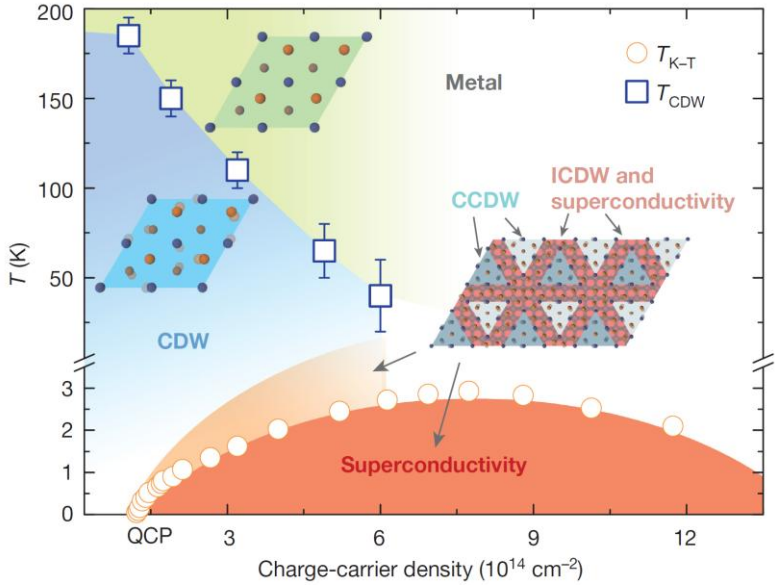


E. Morosan, et al., *Nat. Phys.* **2**, 544 (2006)

K. Sato, et al., *J. Phys. Soc. Jpn.* **86**, 104701 (2017)



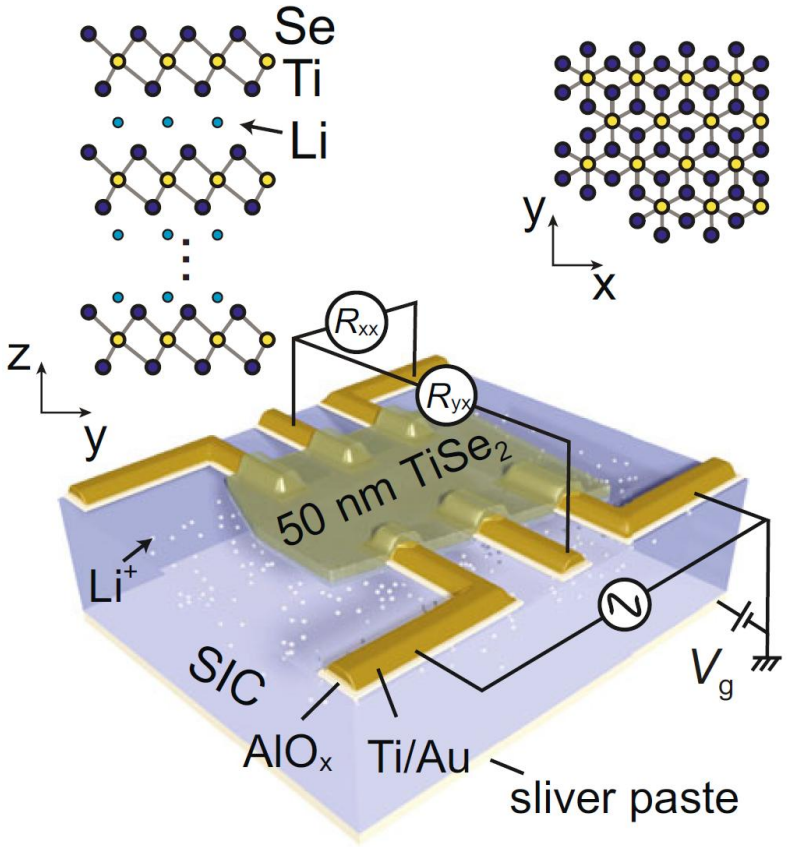
A. Kusmartseva, et al., *Phys. Rev. Lett.* **103**, 236401 (2009)

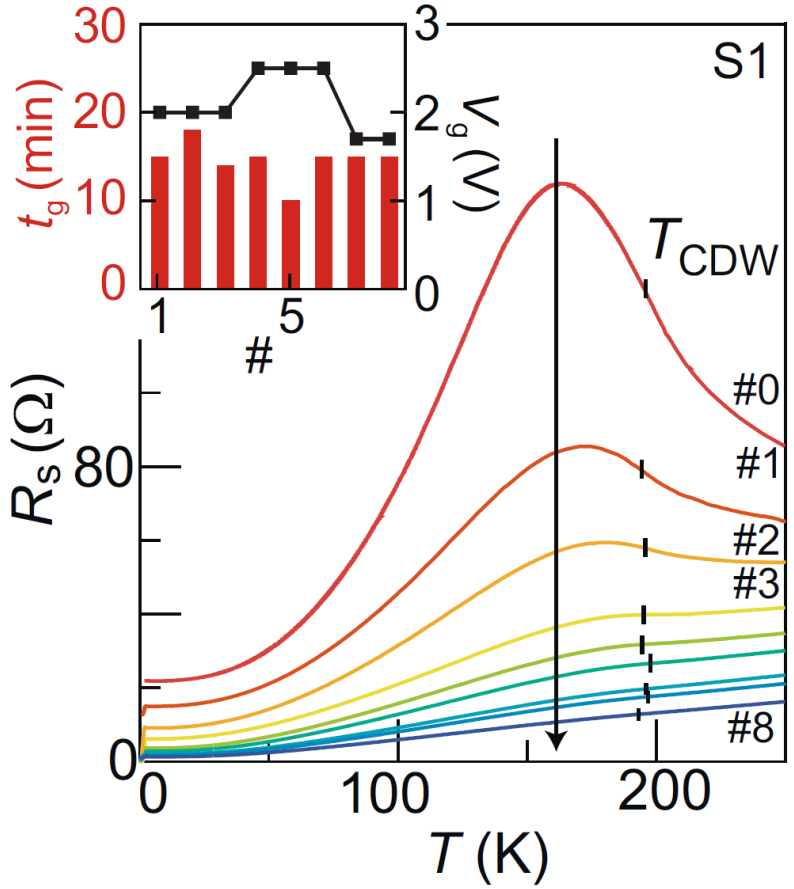


L. J. Li, et al., *Nature* **529**, 185 (2016)

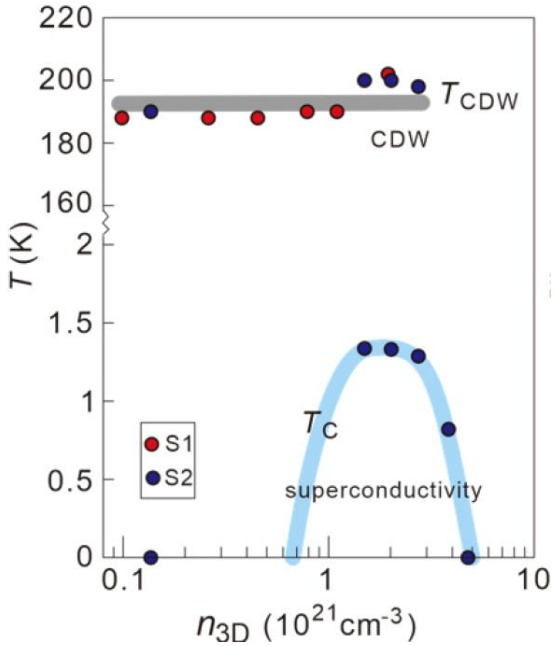
- **Phase diagram under continuous lithium intercalation?**

Lithium intercalation into $TiSe_2$



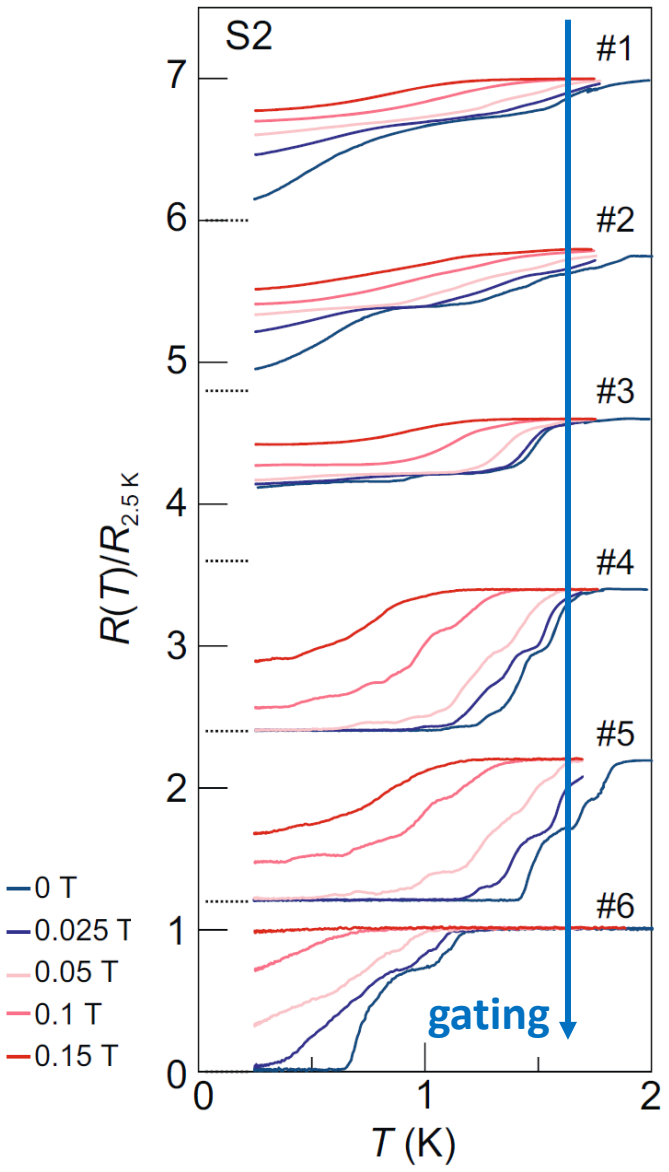


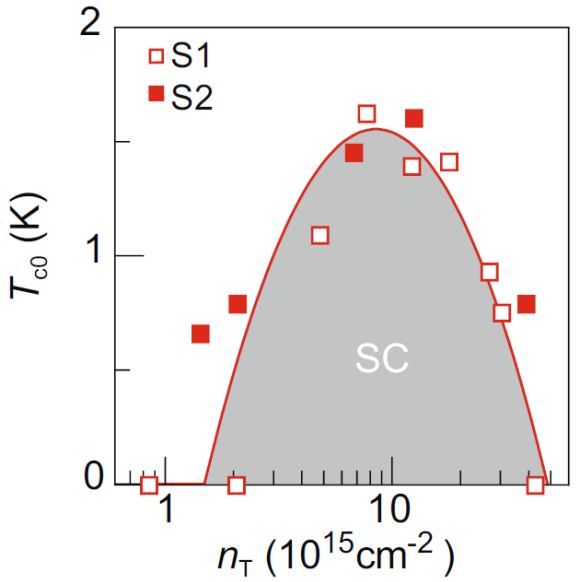
- 50 nm thick $TiSe_2$
- CDW peak does not shift in T with doping

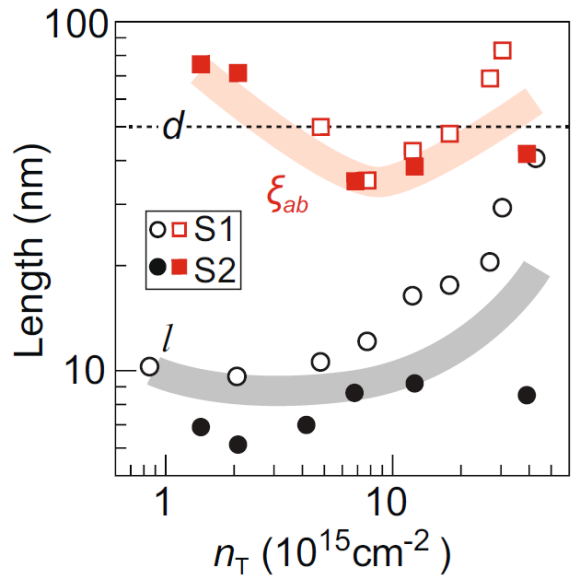


M. Liao, **DZ***, Q.-K. Xue*, *et al., Nat. Commun.* **12**, 5342 (2021)

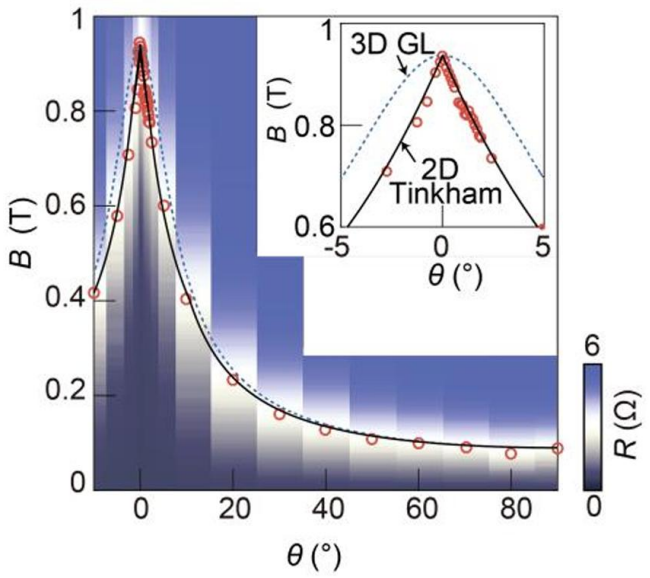
Superconductivity of Li_xTiSe_2



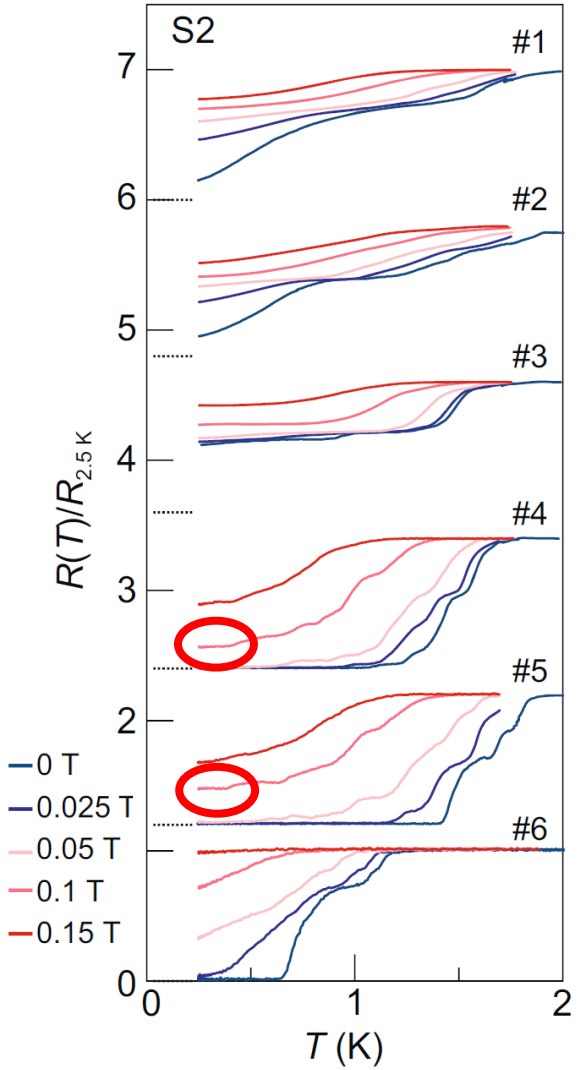


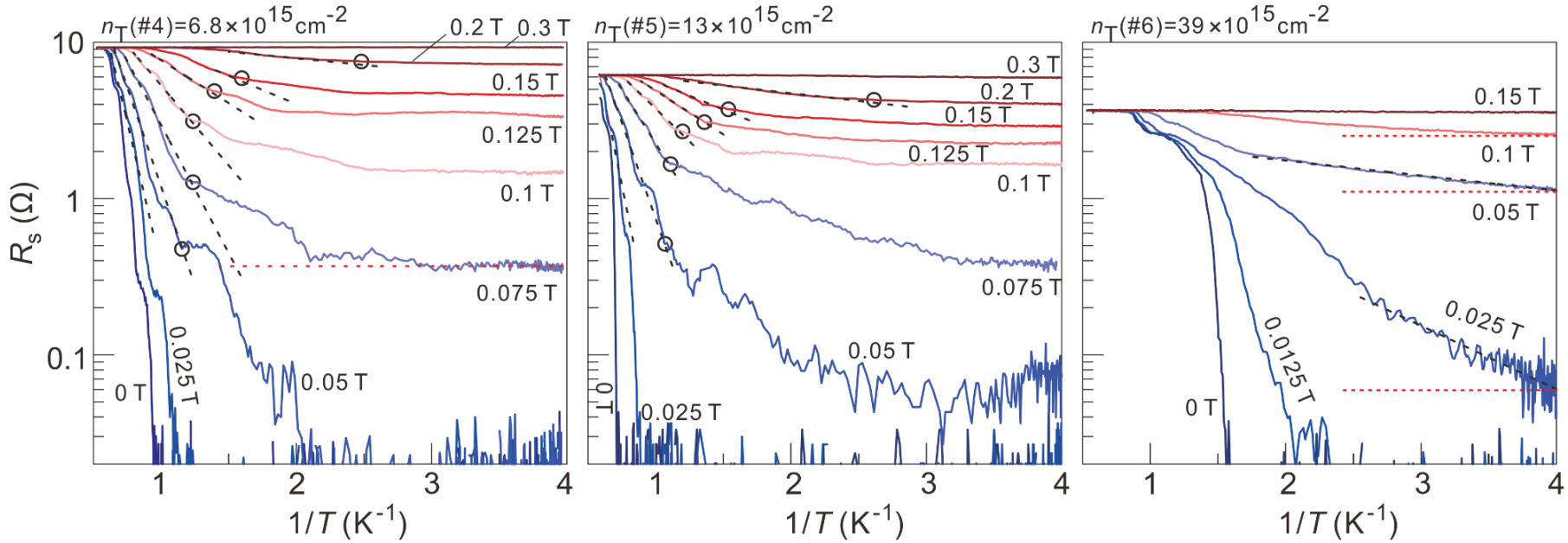


- Superconducting dome, T_c max: 1.5 K
- Dirty superconductor:
  Mean free path < coherence length
- Angular dependent critical field: 2D superconductor



Anomalous metal state



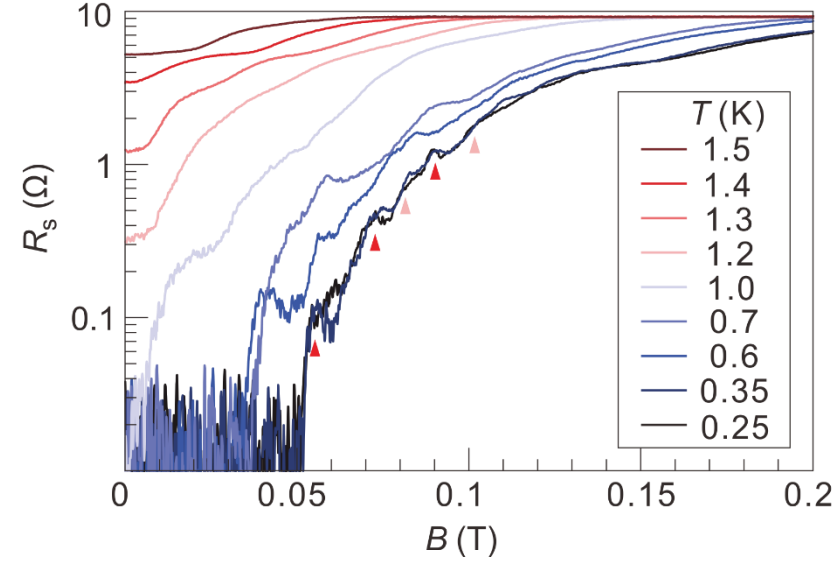


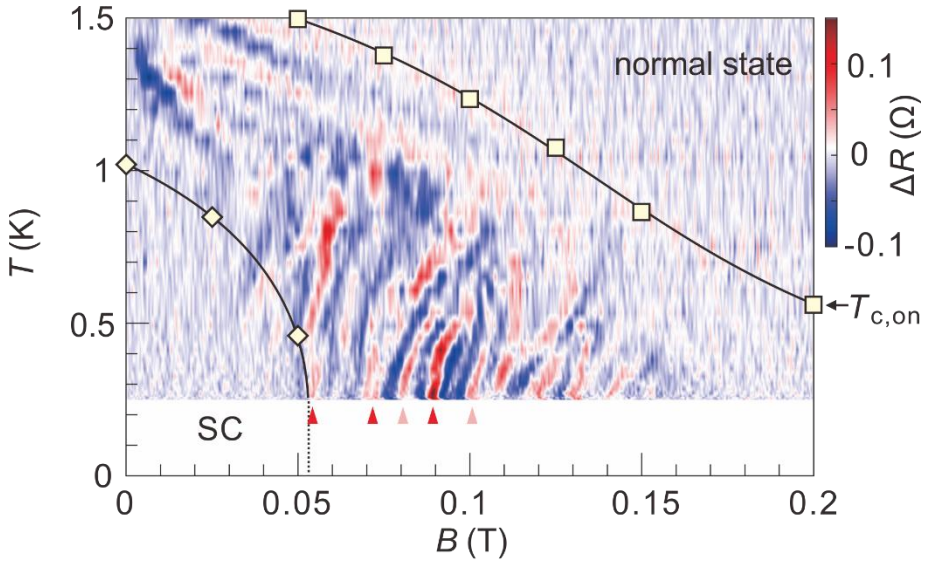
- Resistance plateau at low *T* and small *B*
- Over-doped: no plateau
- Classical percolation model fails:

  0.075T: 4%Rn→0.2 μm non-SC region (proximitized by SC at T<0.3 K)

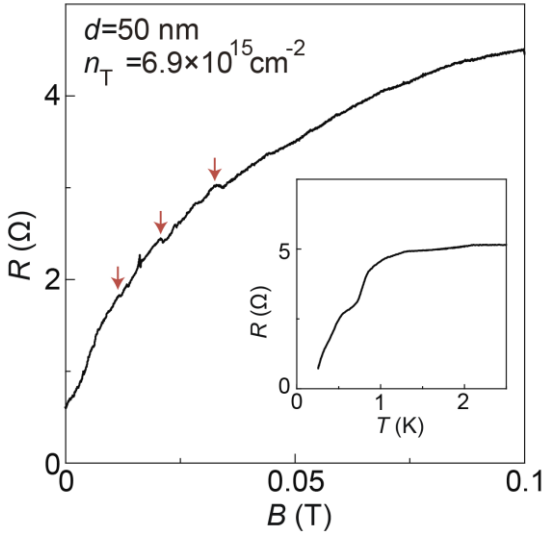
Resistance oscillations

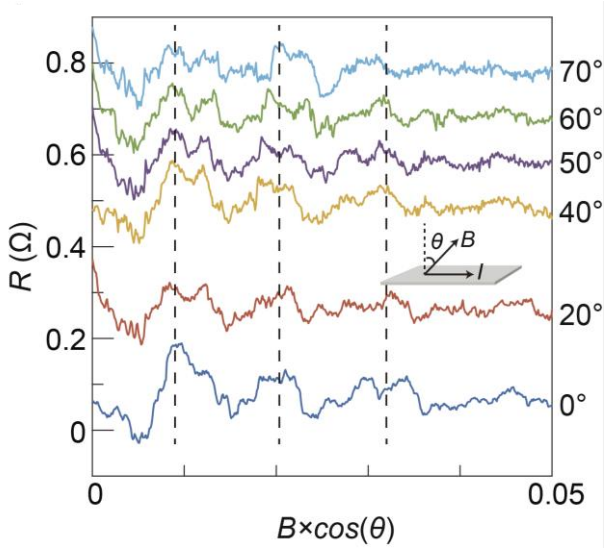
- Spikes in the magnetoresistance at low-*T*





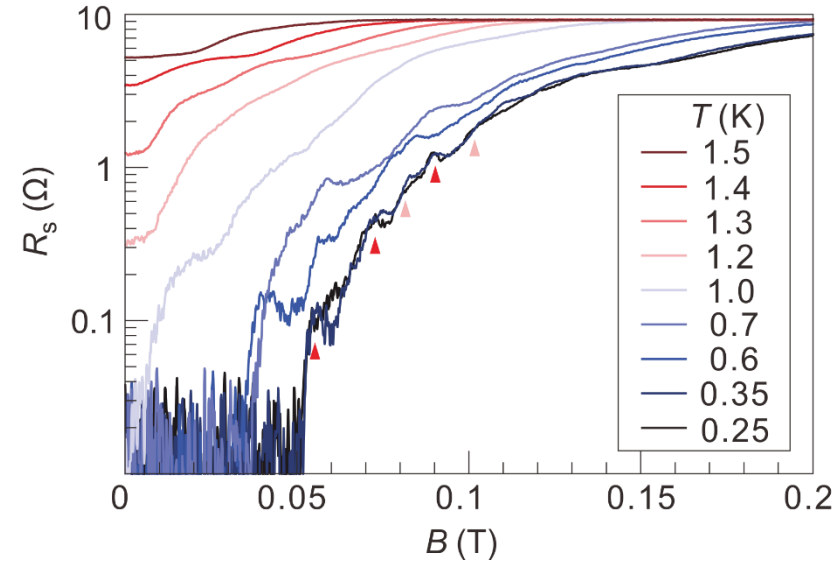
- Evidence for a 2D electronic structure

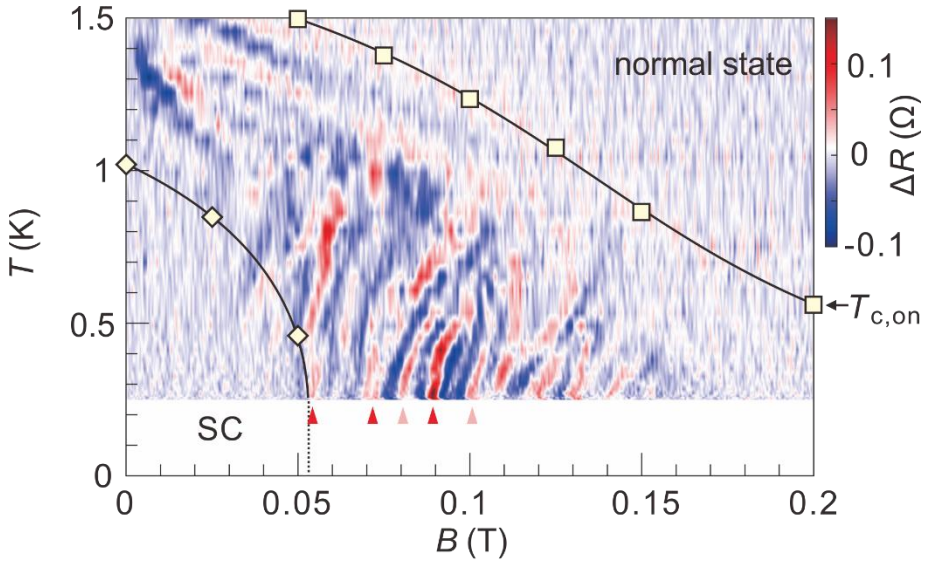




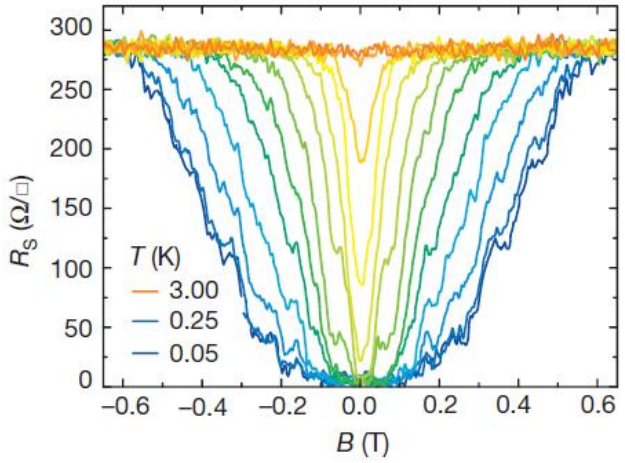
Resistance oscillations

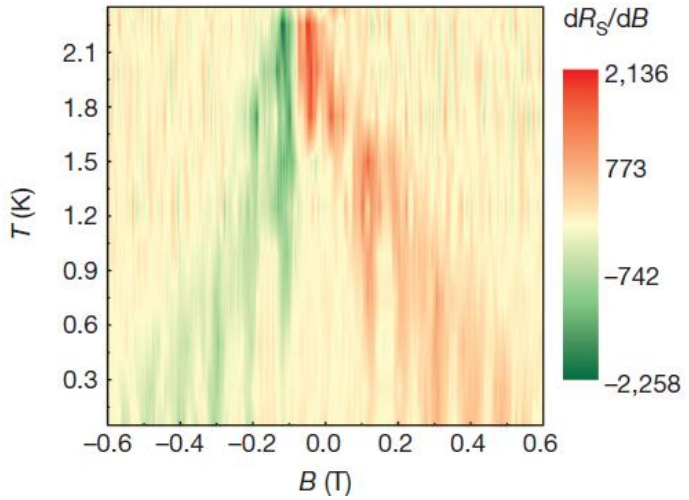
- Spikes in the magnetoresistance at low-*T*





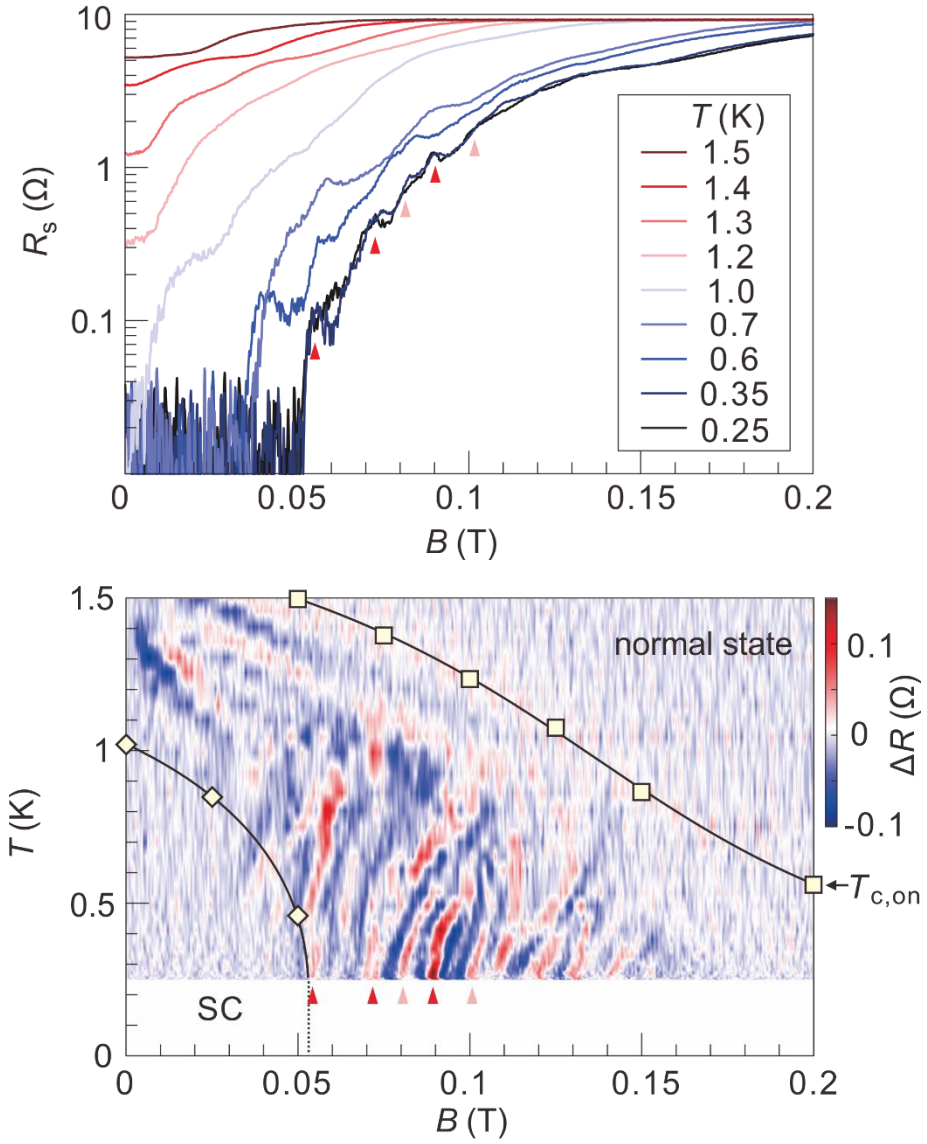
Ionic liquid gated ultrathin $TiSe_2$



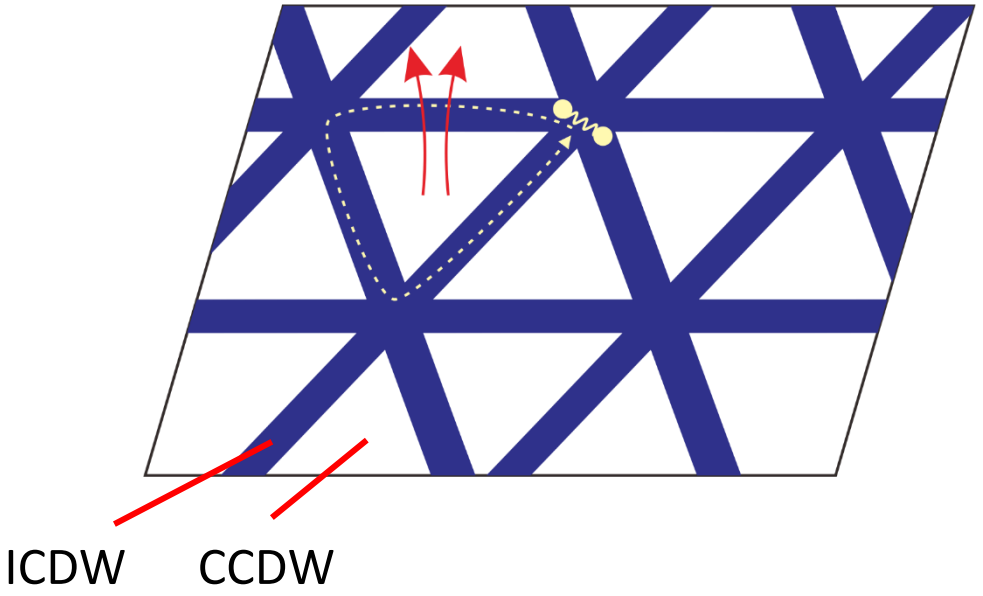


L. J. Li, et al., *Nature* **529**, 185 (2016)

Possible origin for the oscillations



- Little-Parks effect in a periodic superconducting array

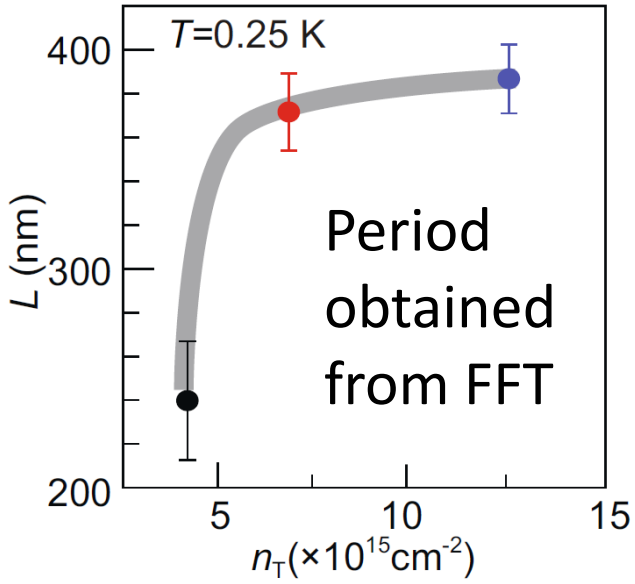


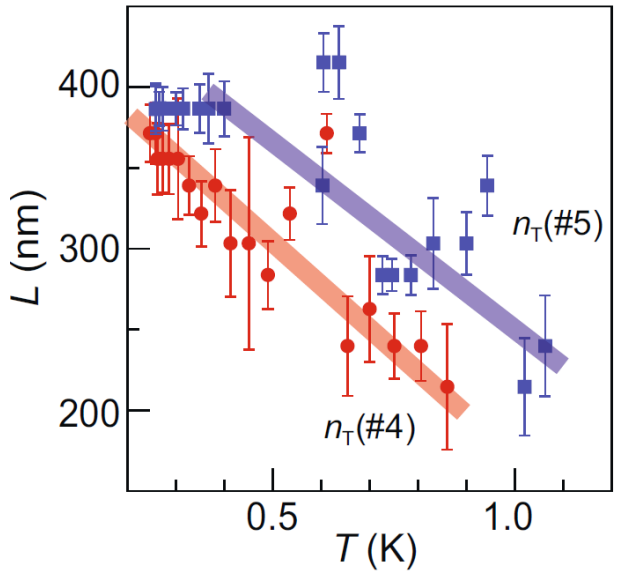
Spontaneous formation of superconducting loops

L. J. Li, et al., *Nature* **529**, 185 (2016)

Comparison

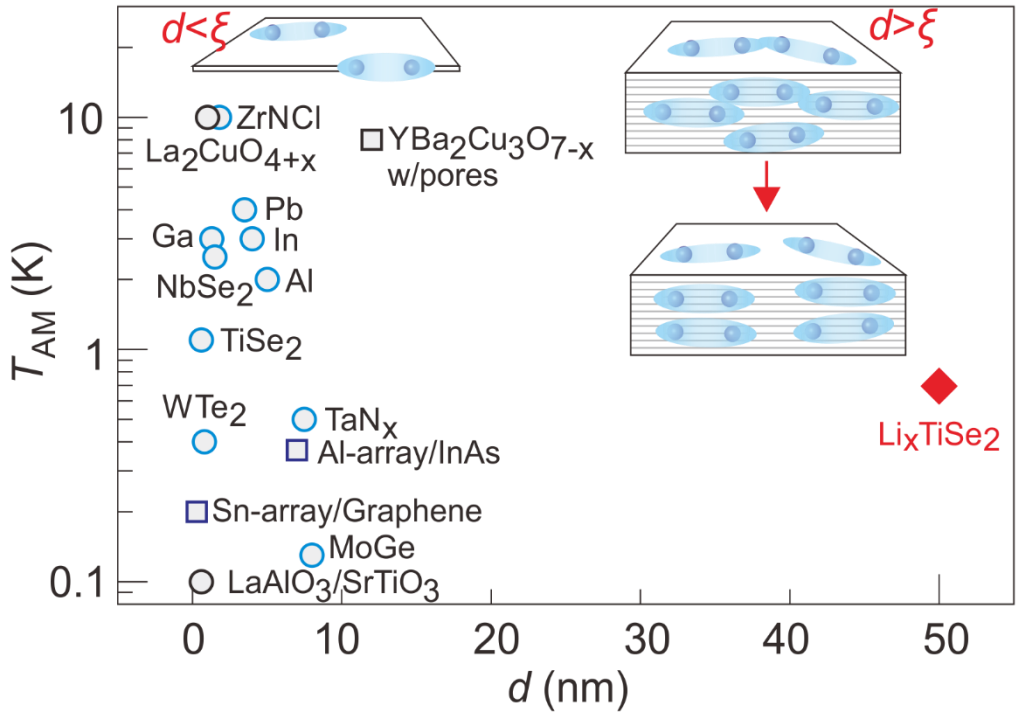
	Li_xTiSe_2	liquid gated $TiSe_2$
Thickness (nm)	50 nm	≤10 nm
Doping regime	optimal to overdoped	underdoped
2D or 3D?	2D	–
Period vs. doping	**larger size at higher doping**	smaller size at higher doping
T-dependence	**smaller size at higher *T***	independent of *T*

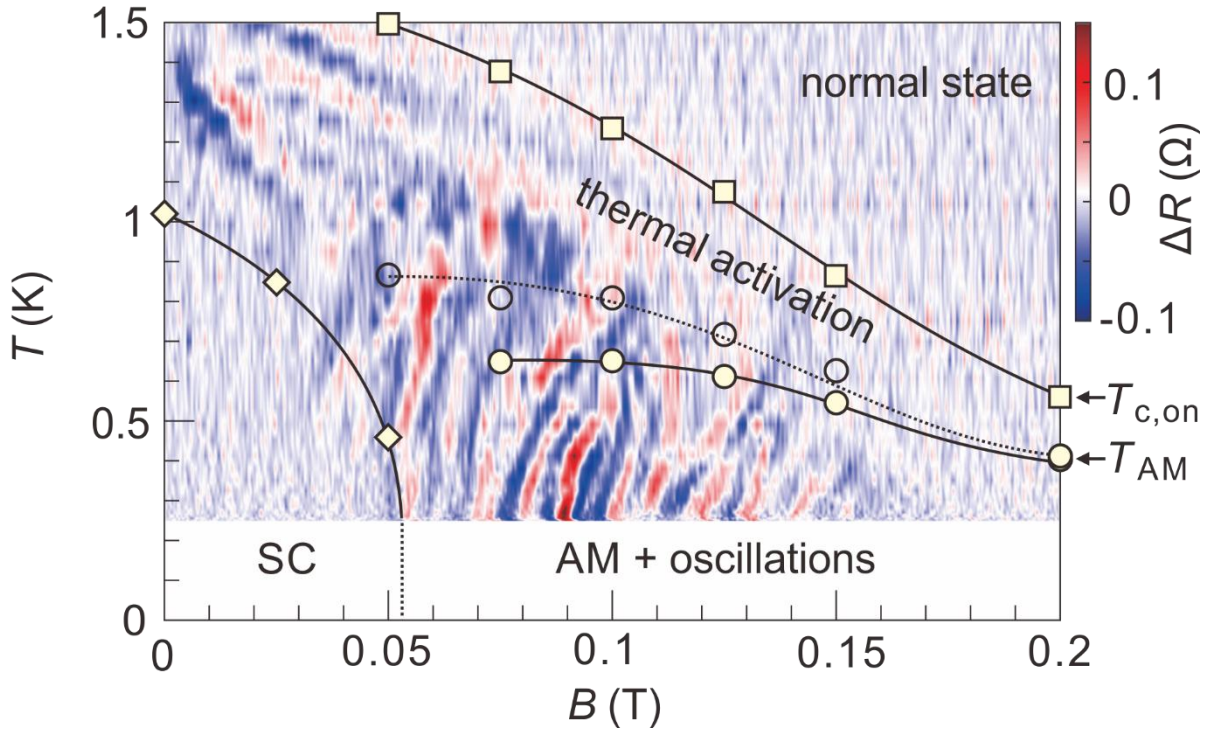




L. J. Li, et al., *Nature* **529**, 185 (2016)

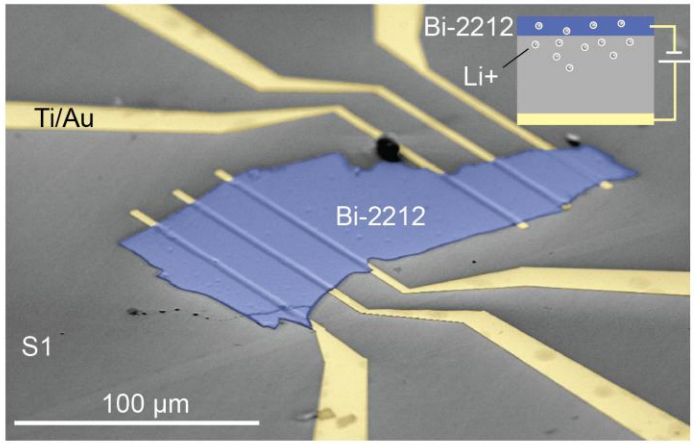
Anomalous metal in 2DSCs

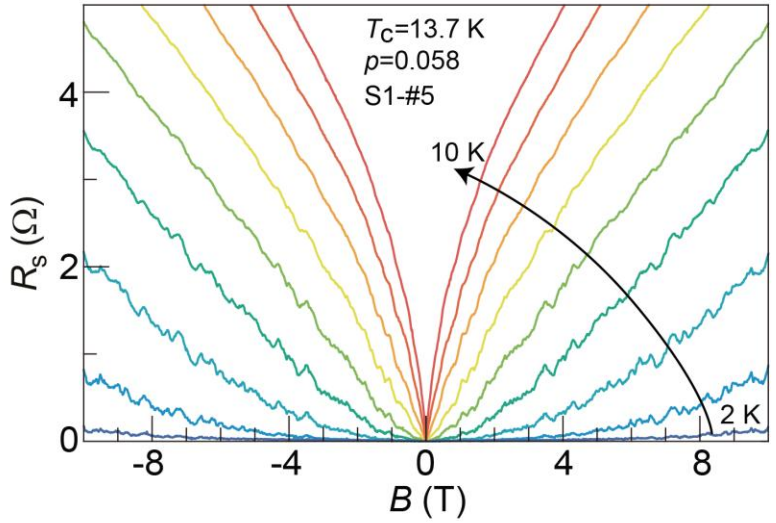


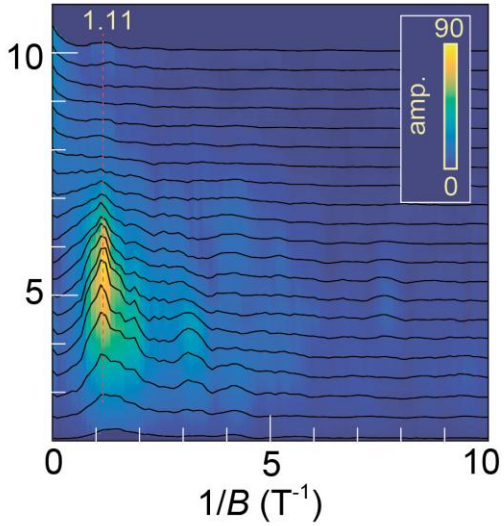


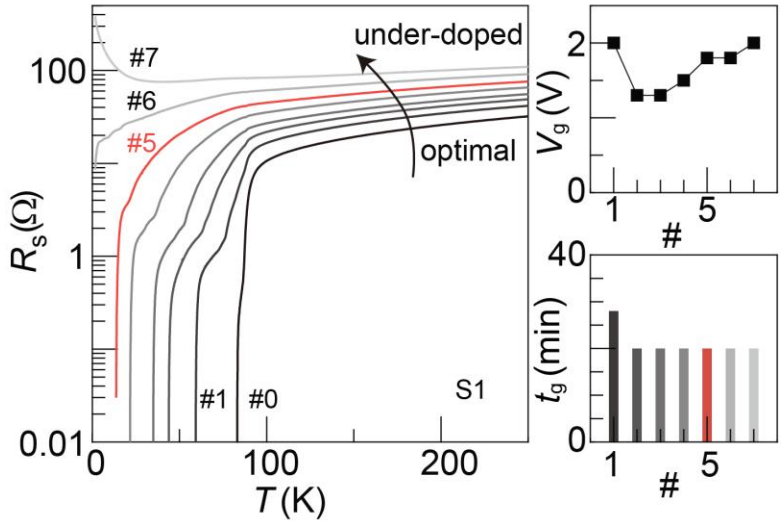
- Resistance oscillations and anomalous metal occur in the same *B*-*T* region
- Periodic structure enhances superconducting fluctuations, giving rise to the anomalous metal

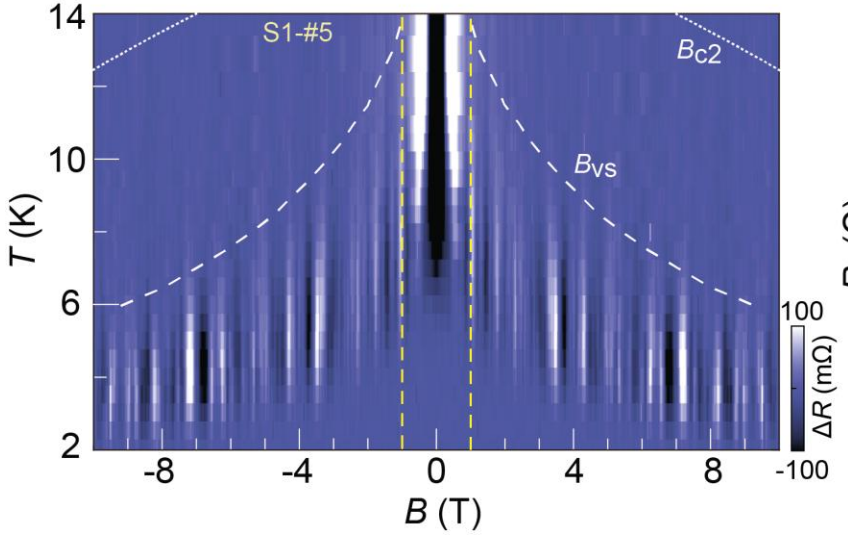
Oscillations in high-T_c superconductors

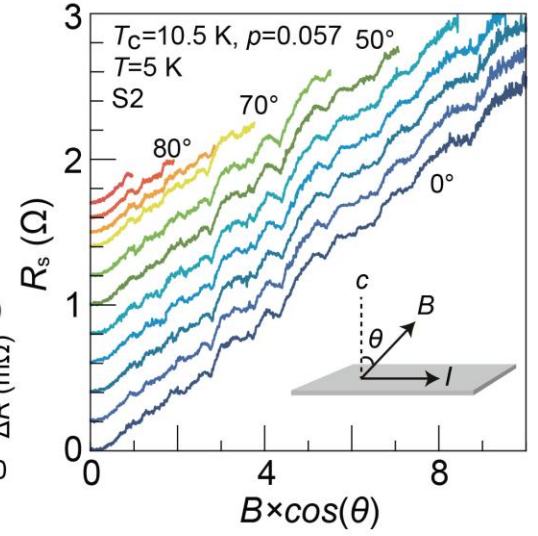












M. Liao, **DZ***, Q.-K. Xue*, *et al., Nat. Commun.* **13**, 1316 (2022)

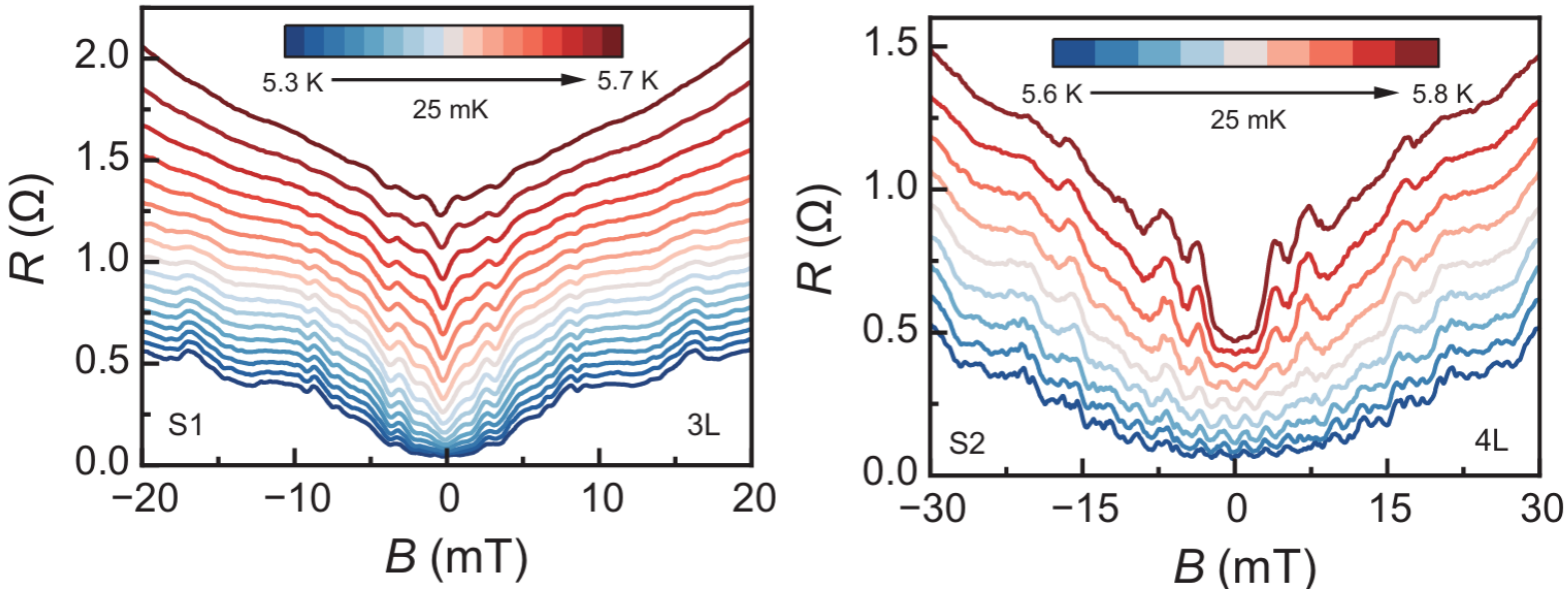
Oscillations in $NbSe_2$

PHYSICAL REVIEW LETTERS **136,** 146301 (2026)

Editors' Suggestion

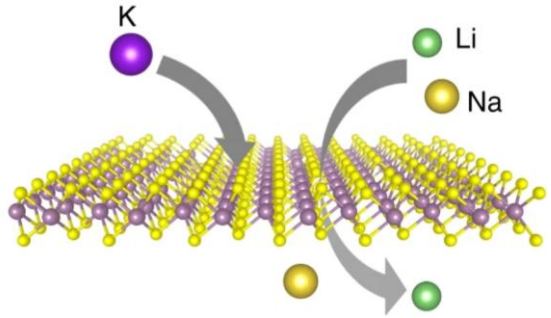
Magnetoresistance Oscillations in Few-Layer $NbSe_2$ in Superconducting Fluctuation Regime

Xiaolong Yin,[1,*] Congzhe Cao,[1,*] Yibin Feng,[1] Kenji Watanabe,[3] Takashi Taniguchi,[4] Jiawei Mei,[1,†] Qi-Kun Xue,[1,2,5,‡] and Shuo-Ying Yang[1,2,§]



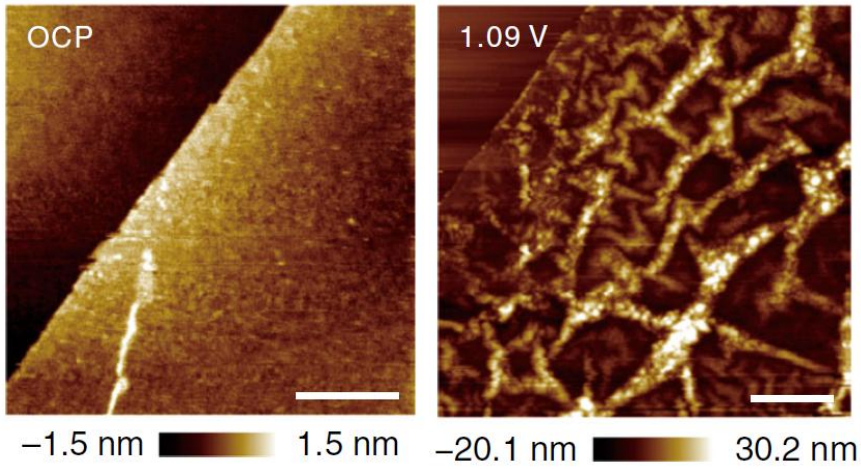
Lateral intercalation

- Vertical intercalation mainly via defects



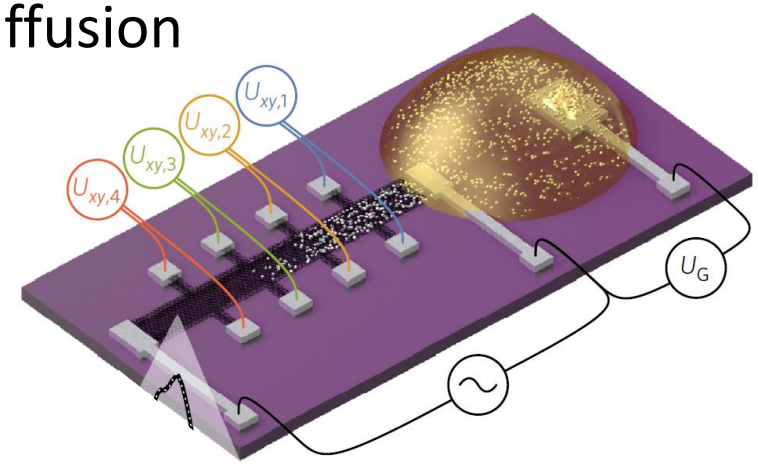
J. Zhang, *et al., Nat. Commun.* **9**, 5289 (2018)

- Homogeneity may be compromised



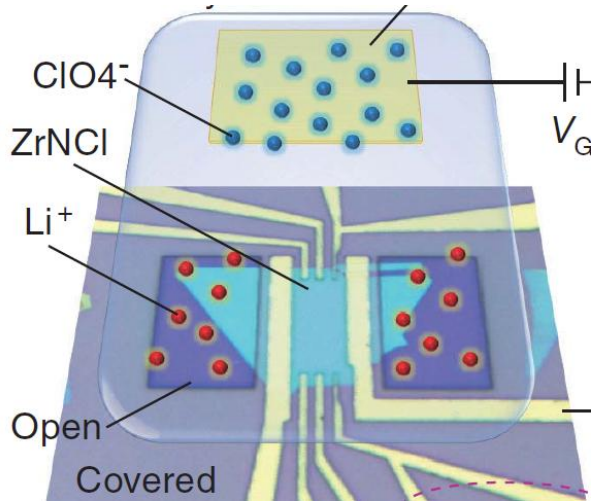
J. Wan, *et al., Nat. Commun.* **10**, 3265 (2019)

Lithium diffusion in bilayer graphene



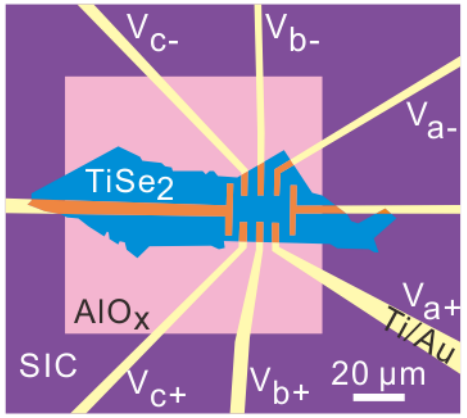
M. Kuhne, *et al., Nat. Nano.* **12**, 895 (2017)

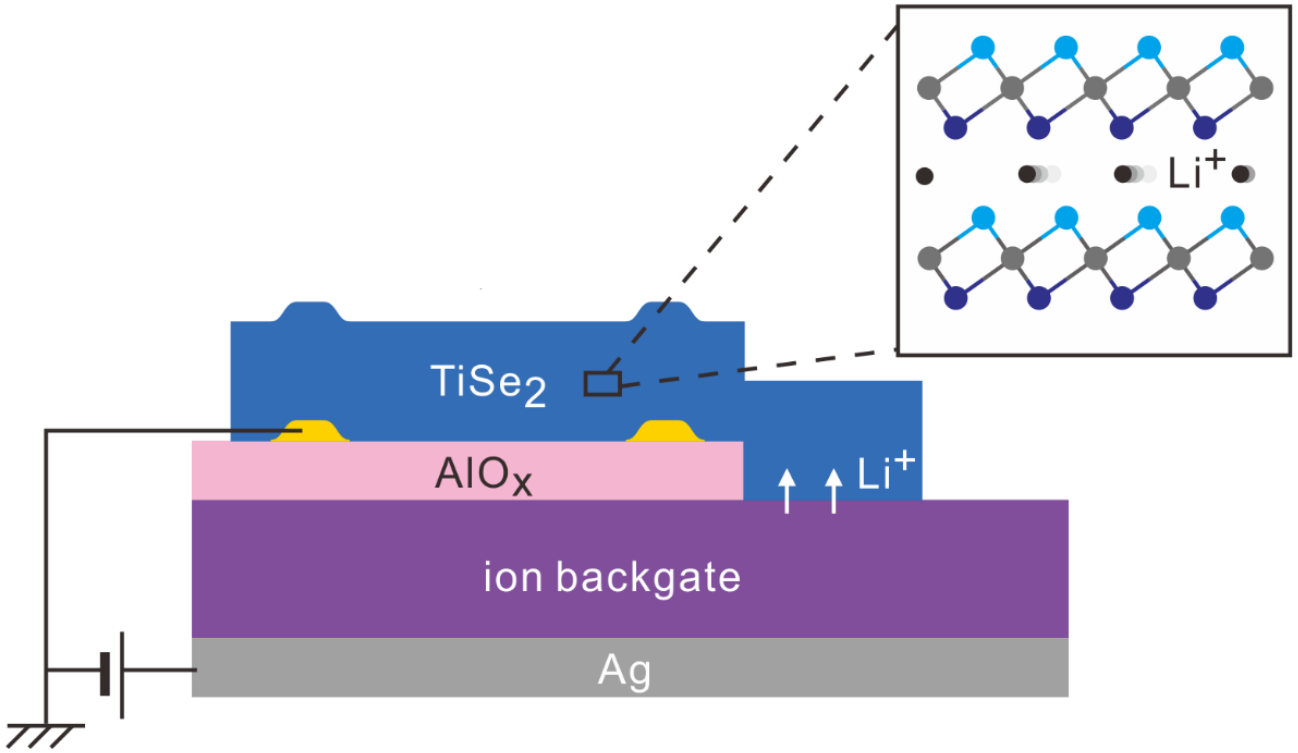
Lateral intercalation in ZrNCl



Y. Nakagawa, *et al., Science* **372**, 190 (2021)

Lateral intercalation with ion backagte

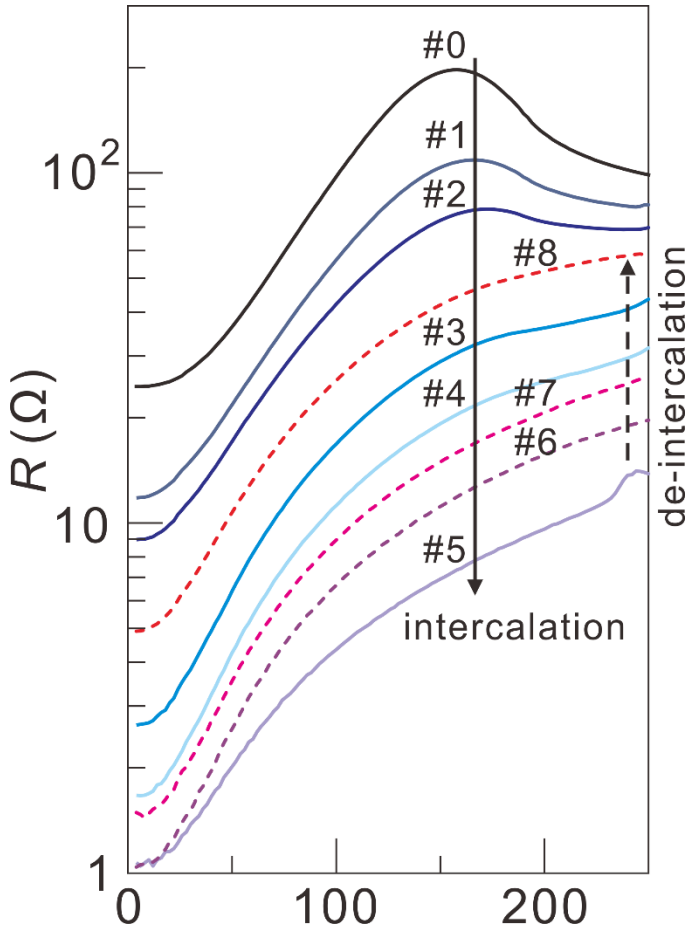


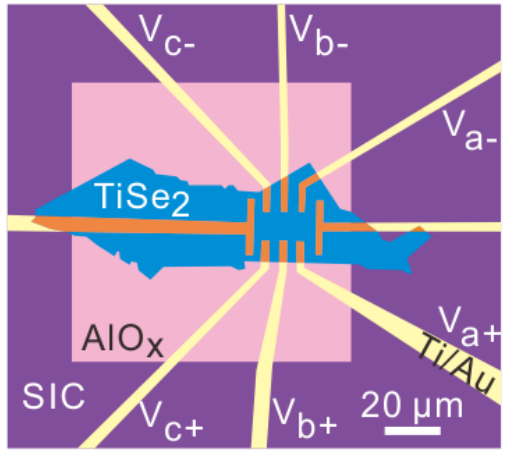


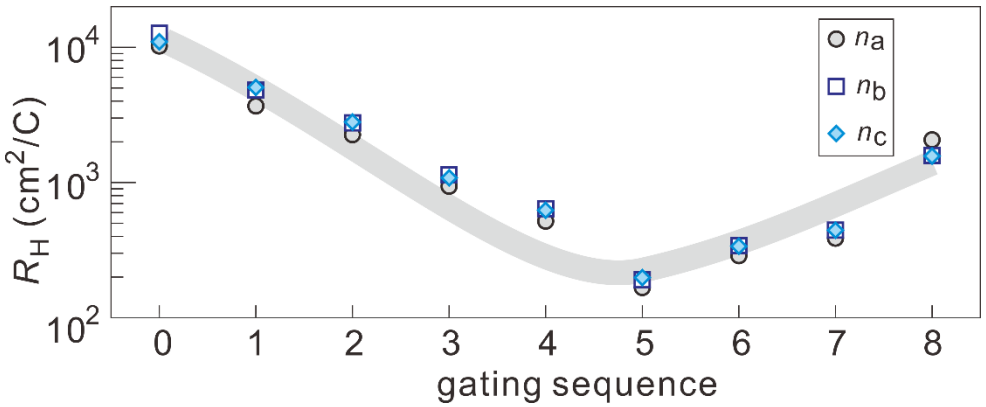
- AlO_x can block lithium ions

J.-Y. Ji, **DZ***, *et al.*, *Nano Lett.* **22**, 7336 (2022)

Hall measurement







- Homogeneous distribution of intercalated dopants

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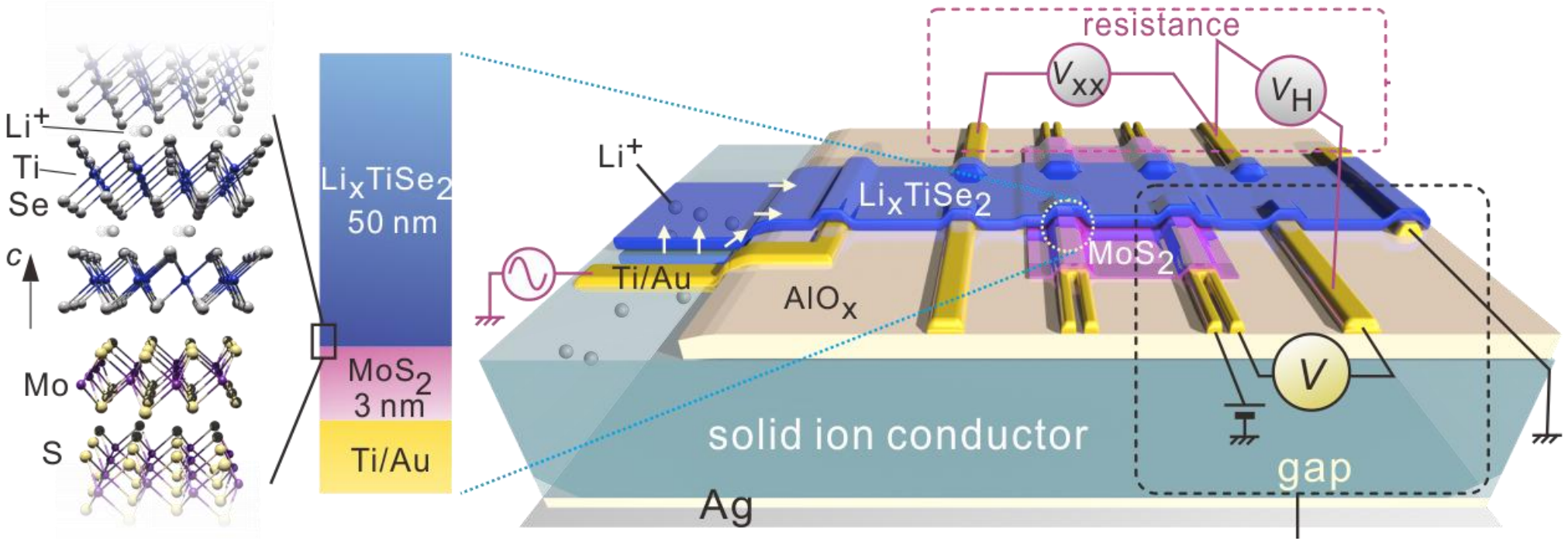
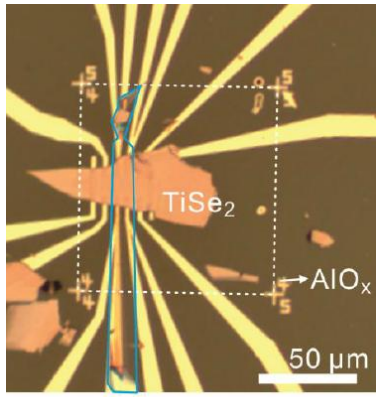
Superconducting gap in Li_xTiSe_2





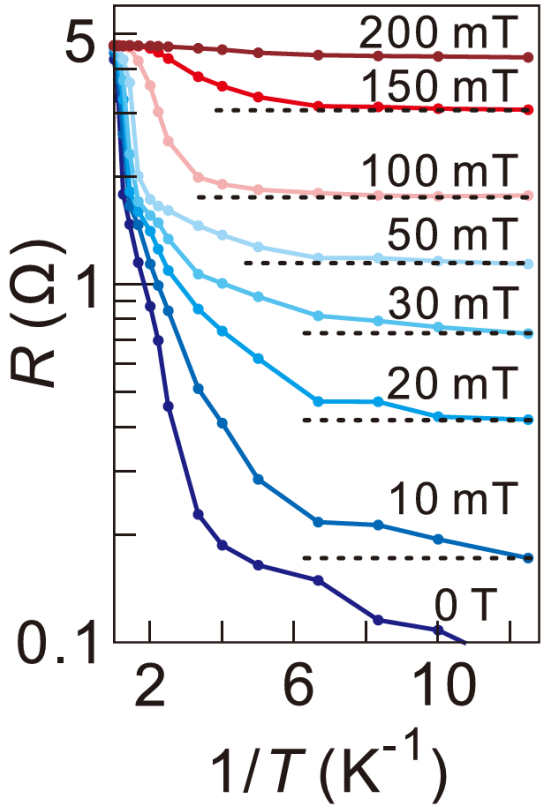
MoS_2

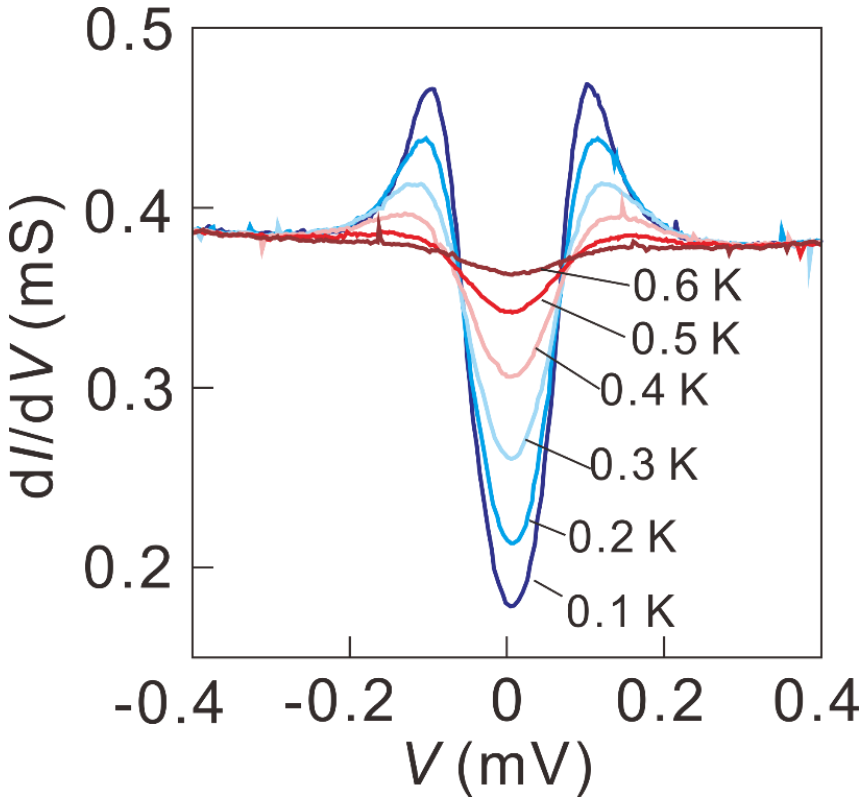
J.-Y. Ji#, Z. Cao#, Q.-K. Xue*, **DZ***, *et al.*, *Nano Lett.* **25**, 10641 (2025)

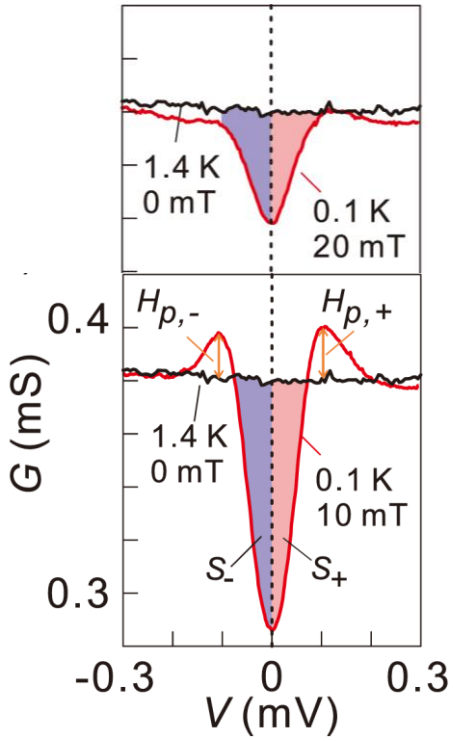
Gap in the anomalous metal phase

- AM phase in a dil-fridge with thermocoax cables
  + Cu powder and RC filters

- Symmetric gap in the AM phase







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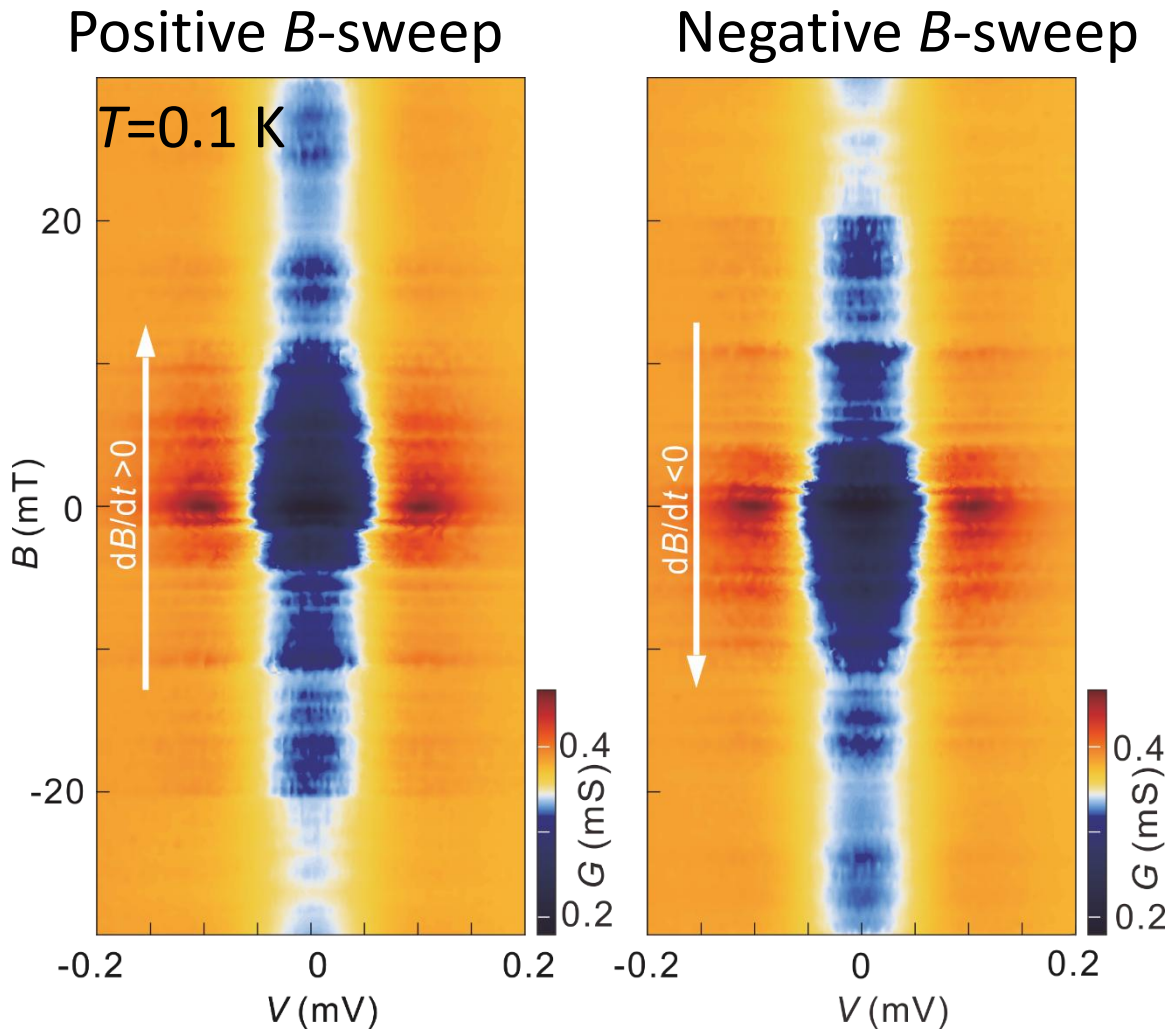
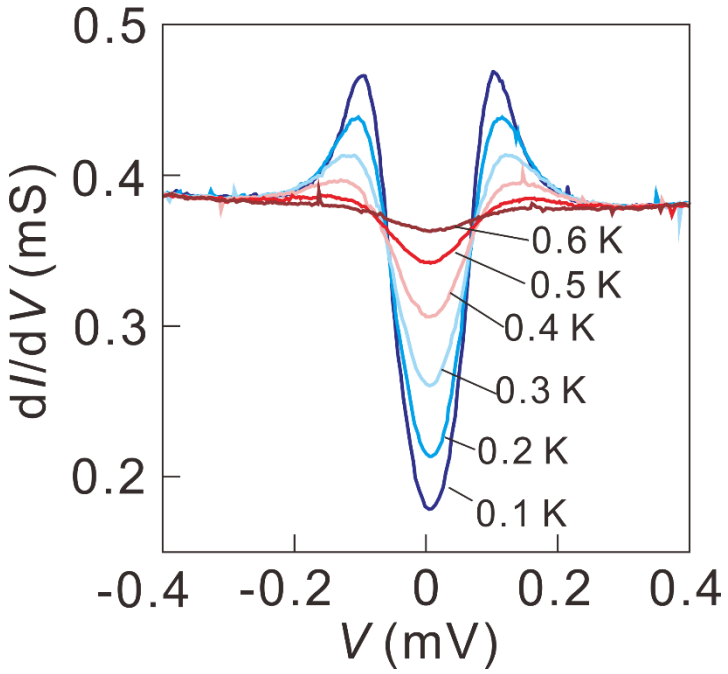
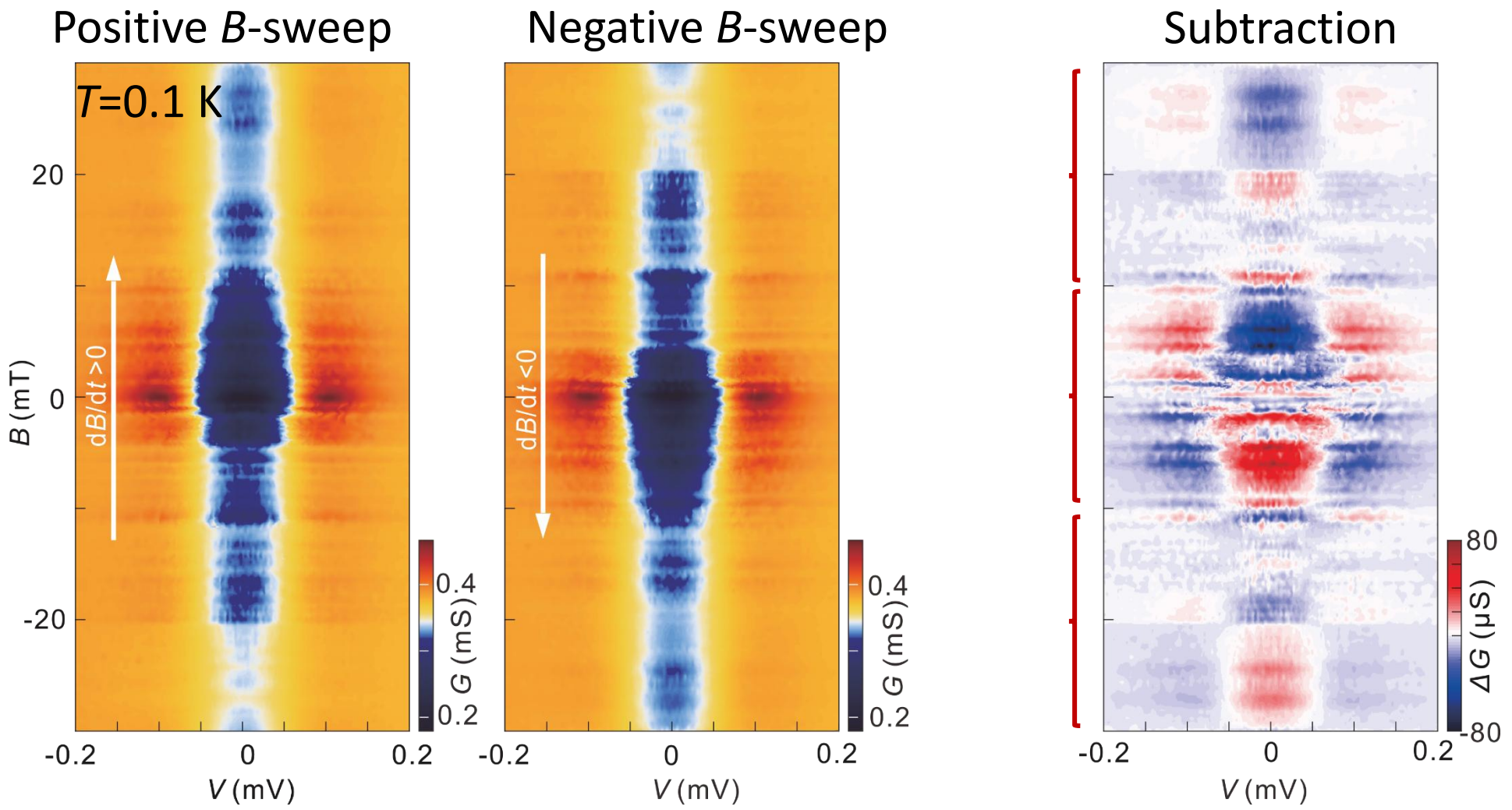
Gap oscillations





J.-Y. Ji[#], Z. Cao[#], Q.-K. Xue*, **DZ***, *et al.*, *Nano Lett.* **25**, 10641 (2025)

Gap oscillations



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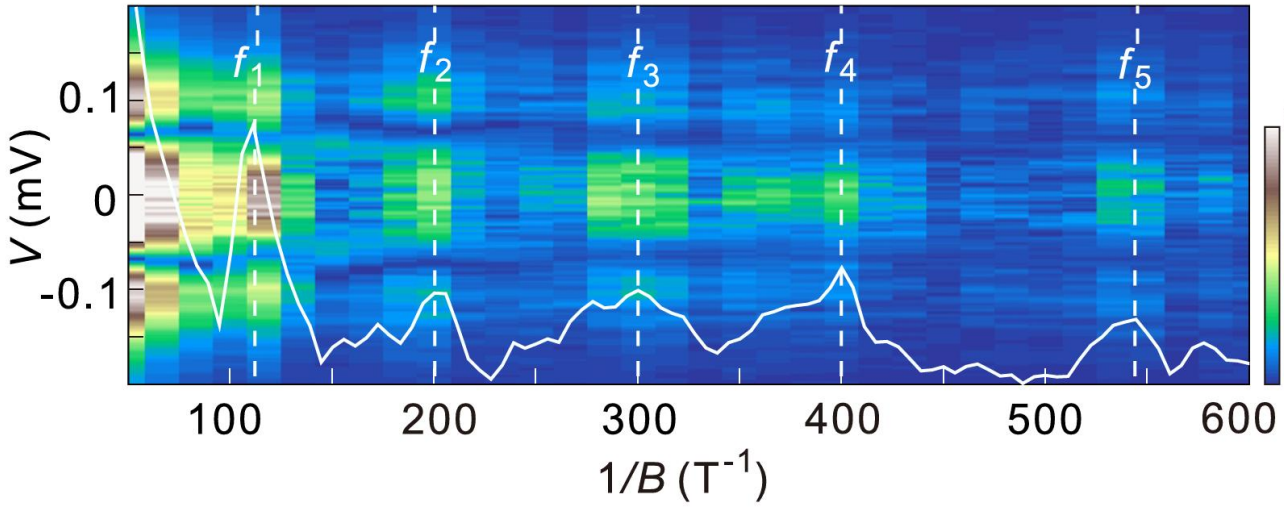
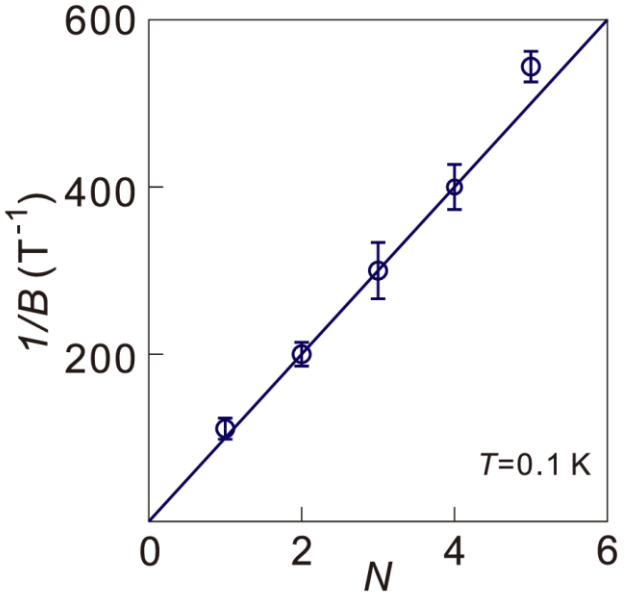
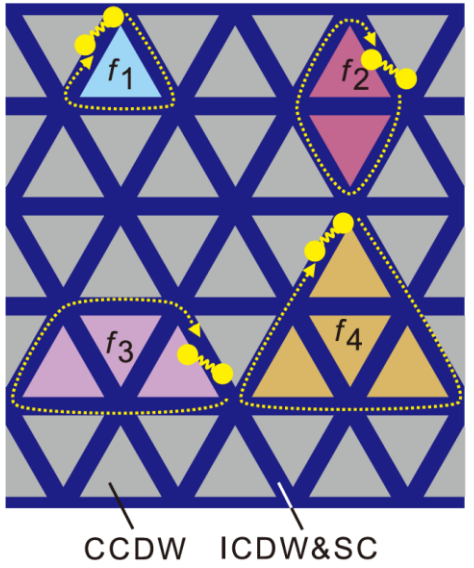
Gap oscillations

- Fourier transform reveals higher harmonics







- Regularly shaped superconducting network

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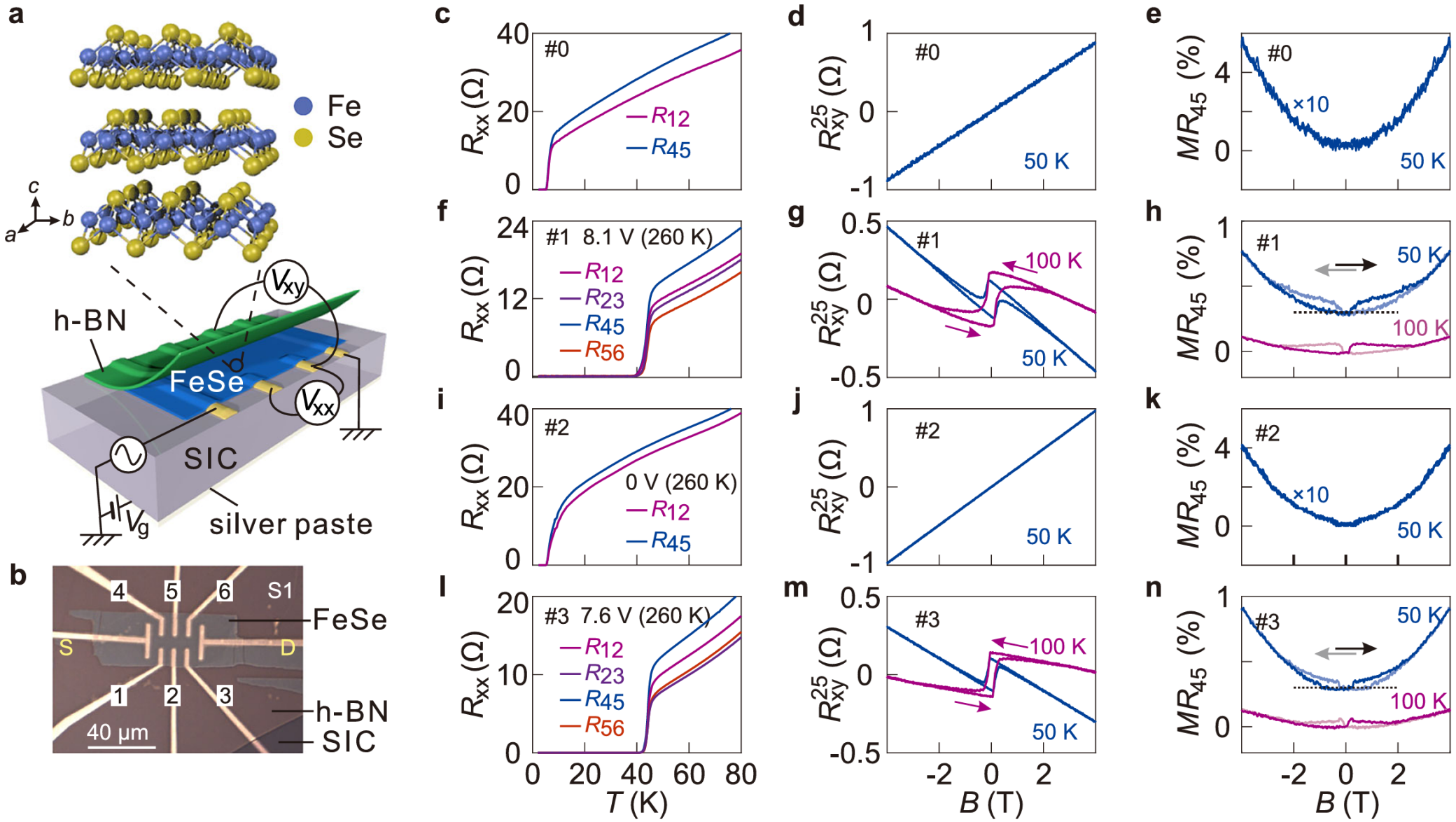
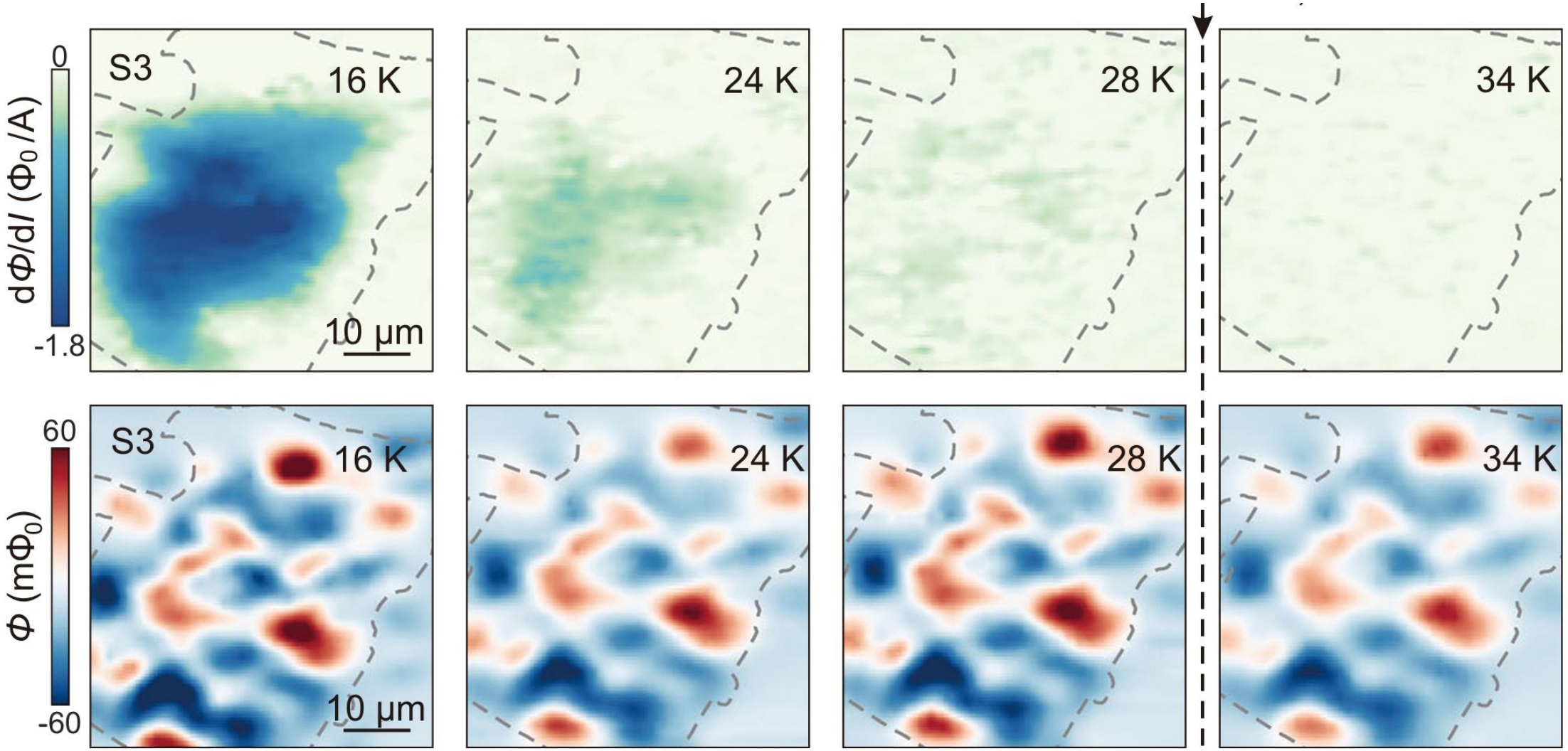
Summary on Li_xTiSe_2

- **Li_xTiSe_2 (50-70 nm)**
  - Superconducting dome
  - Anomalous metal
  - Little-Parks-like oscillations in the resistance and gap

Revisit to Li_xFeSe



Coexistence of SC and FM from scanning SQUID



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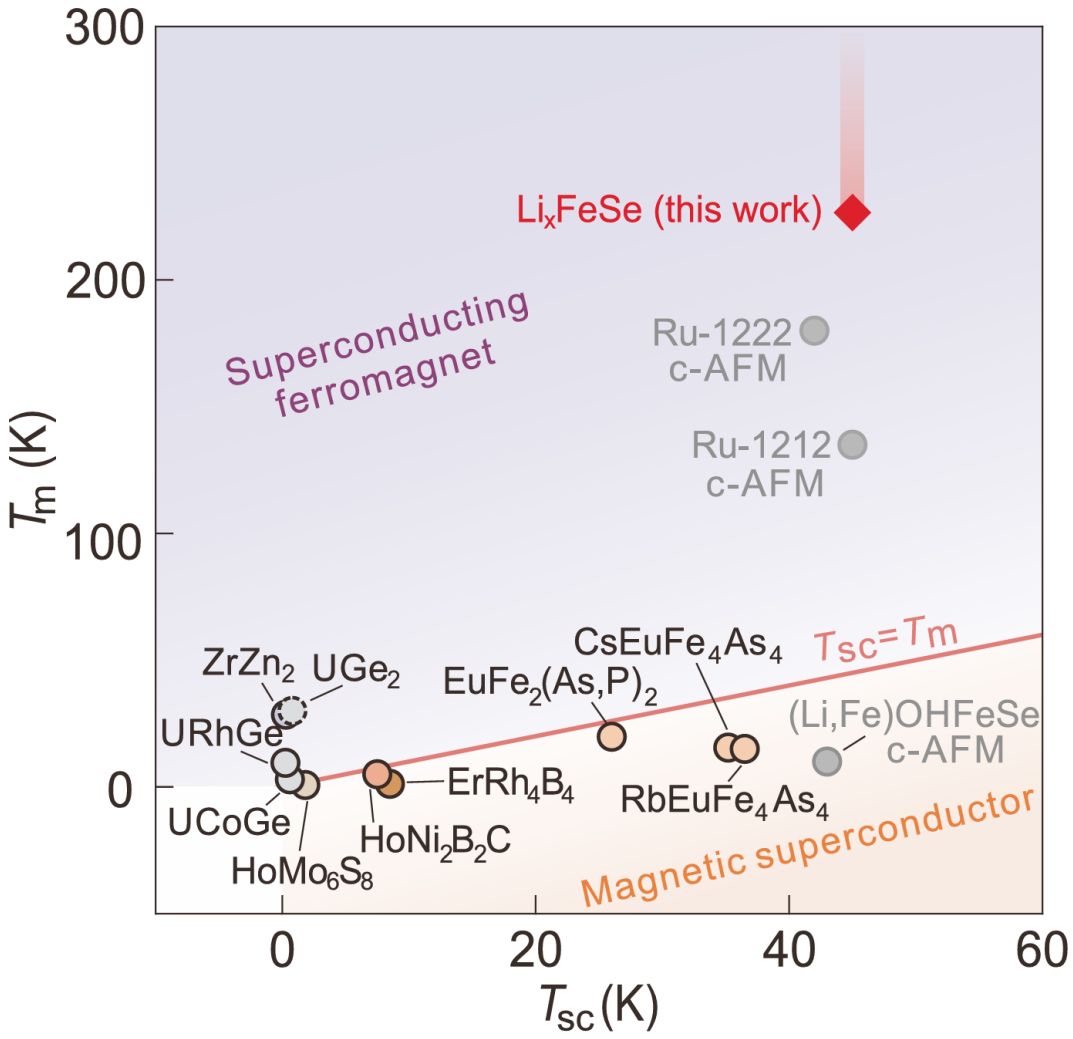
Li_xFeSe: a high temperature superconducting ferromagnet



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Thank you!

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