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Condensed Matter Theory Group
Paul Scherrer Institute

Flattering* Superconductivity: the case of UTe_2

* To flatter: to choose to believe something favourable about oneself, typically when this belief is unfounded.

FlatClub - University of Geneva - 24/Mar/2023

Swiss National Science Foundation

Disclaimer: What is flat here?

1) Heavy fermions are strongly interacting systems usually associated to a renormalized band structure with flat bands originated from localized f-electrons;

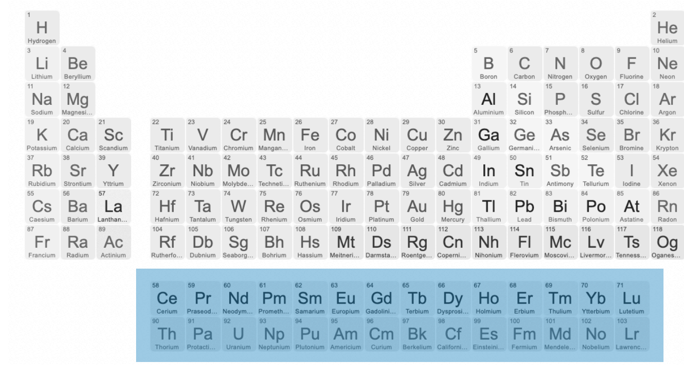
2) Here I report on the puzzling results from STM experiments on the surface of UTe_2;

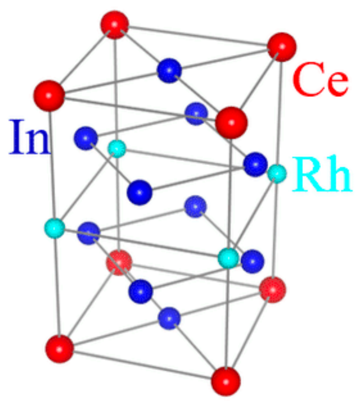
3) There might be some interesting parallels to be drawn between the phenomenology of UTe_2 and twisted trilayer graphene, a genuine 2D material;

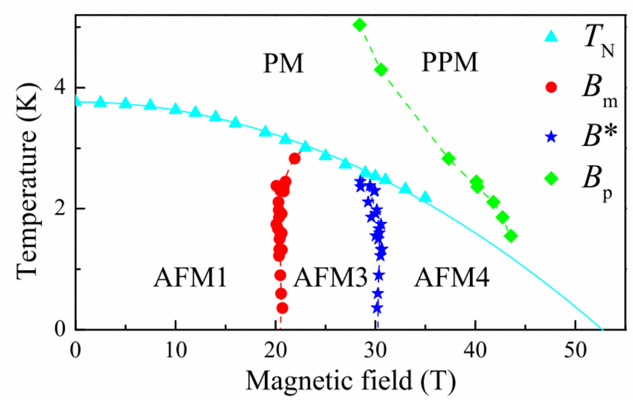
Introducing Heavy Fermions

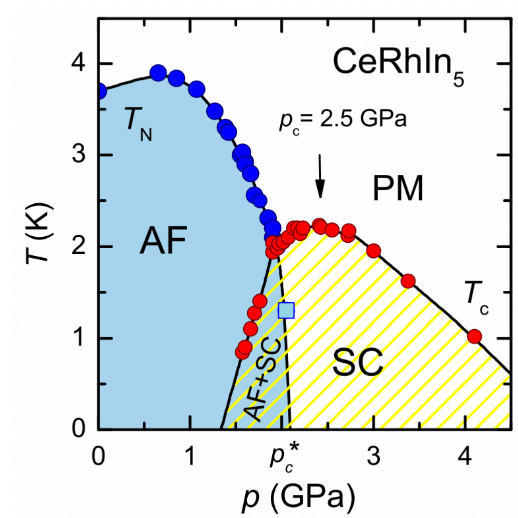
- Bulk/3D Materials
- Key ingredients: Lanthanides and Actinides

  [f-orbitals ⇒ Local moments]
- Examples: $CeRhIn_5$, UTe_2, $YbRh_2Si_2$,…

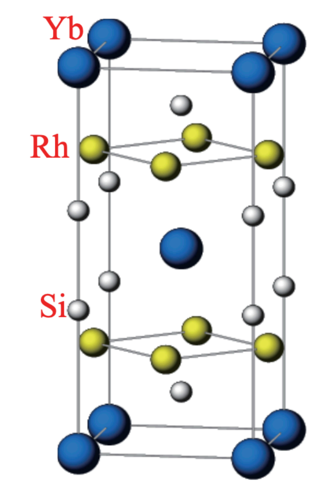


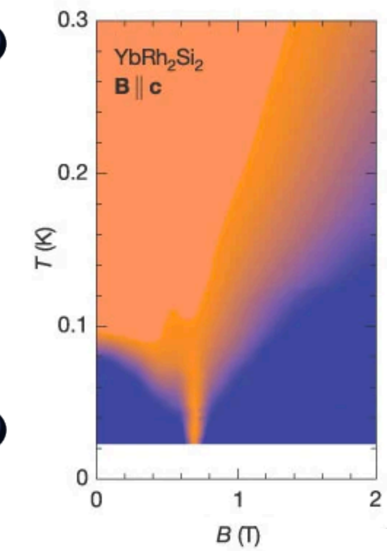


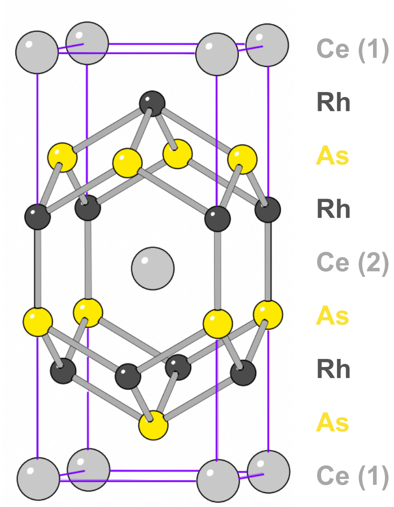


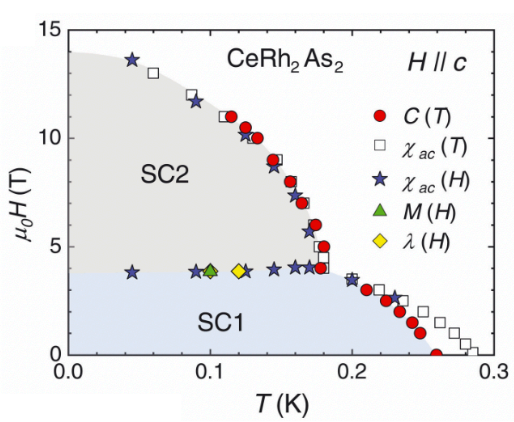


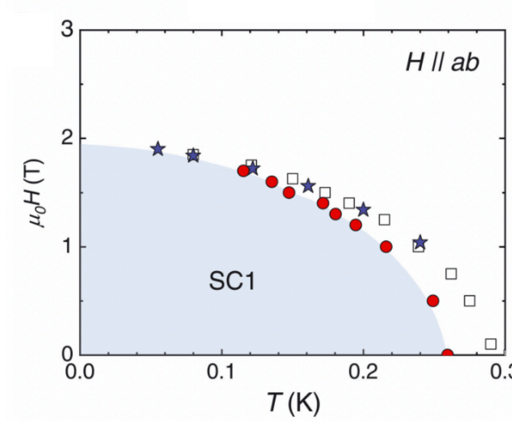
Mishra et al., Phys. Rev. B **103**, 165124 (2021)
Yashima et al., Phys. Rev. B **76**, 020509 (2007)



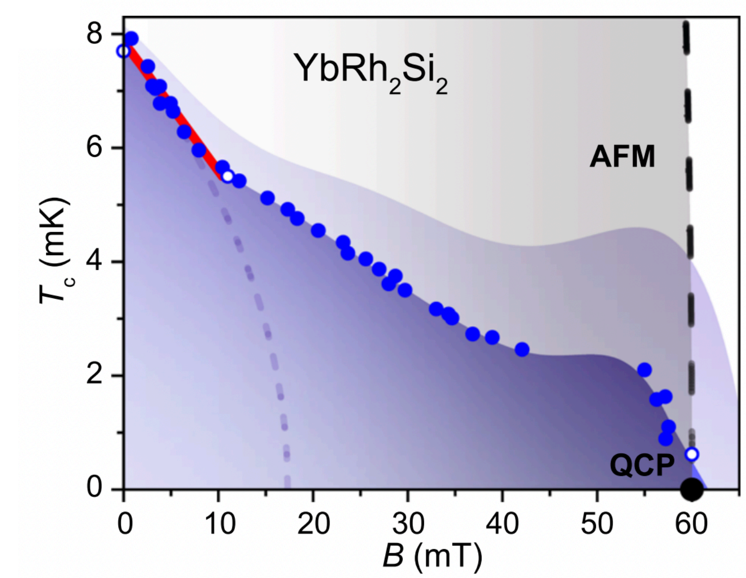








K. Kudo et al., J. Phys. Soc. Jpn. **79**, 123710 (2010)
S. Khim et al., Science **373**, 1012 (2021)



Nguyen et al., Nat. Commun. **12**, 4341 (2021)
Custers et al., Nature **424**, 524 (2003)
Kambe et al., J. Phys.: Conf. Ser. **683** 012006 (2016)

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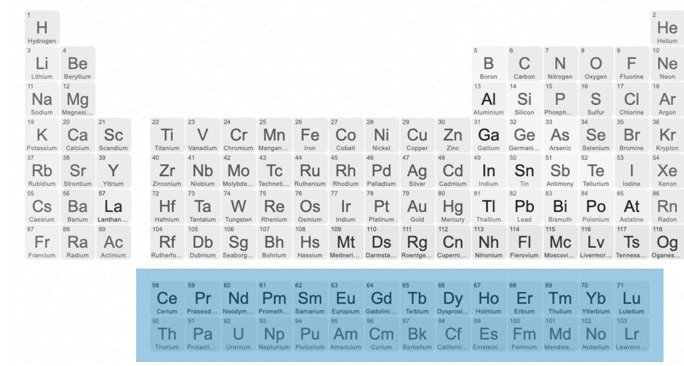
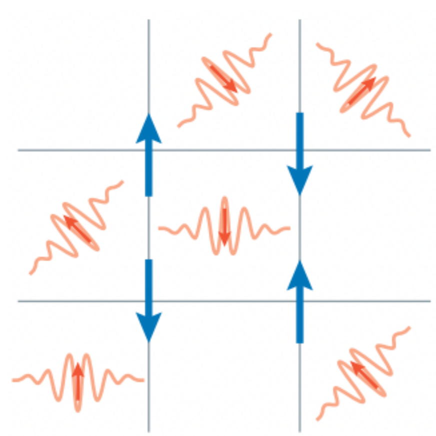
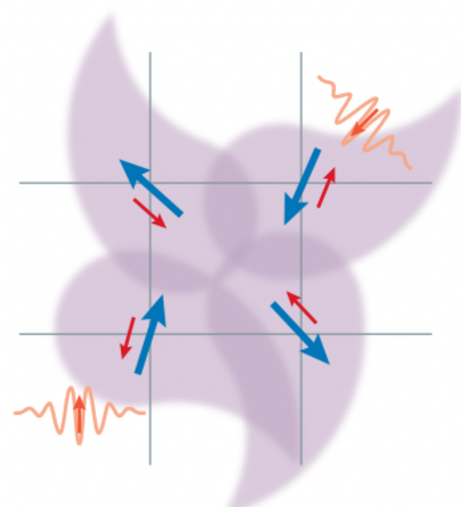
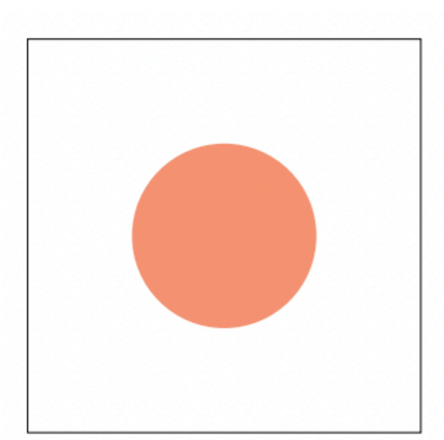


High T → Low T

Kondo Correlations

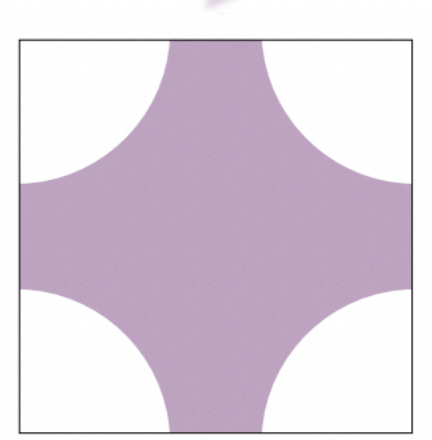






Light electrons

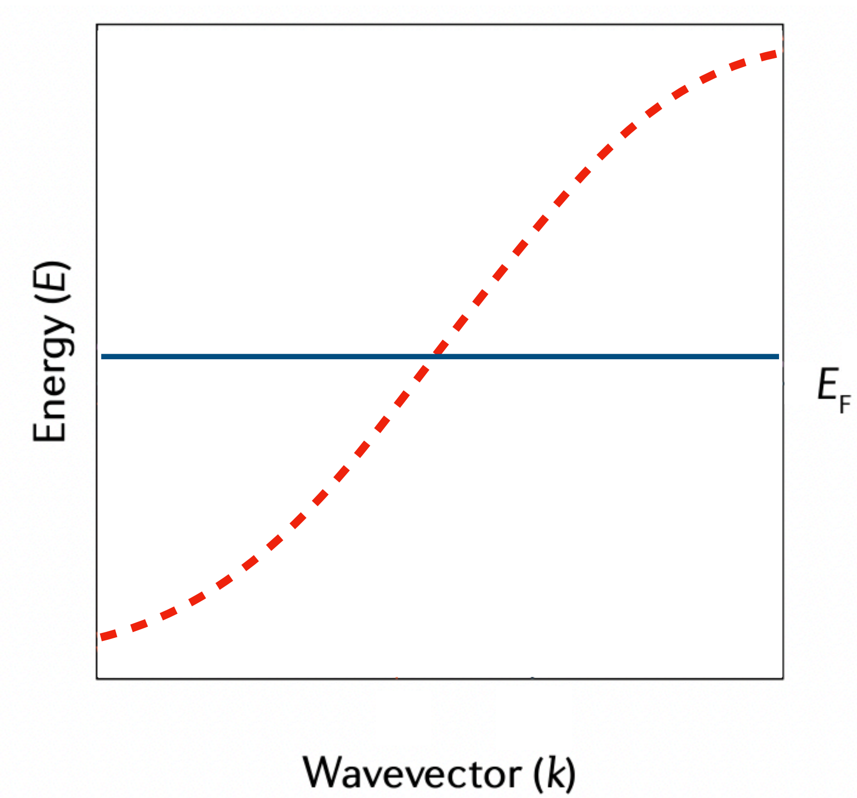
Small FS



Heavy electrons

Large FS

Dispersive light bands

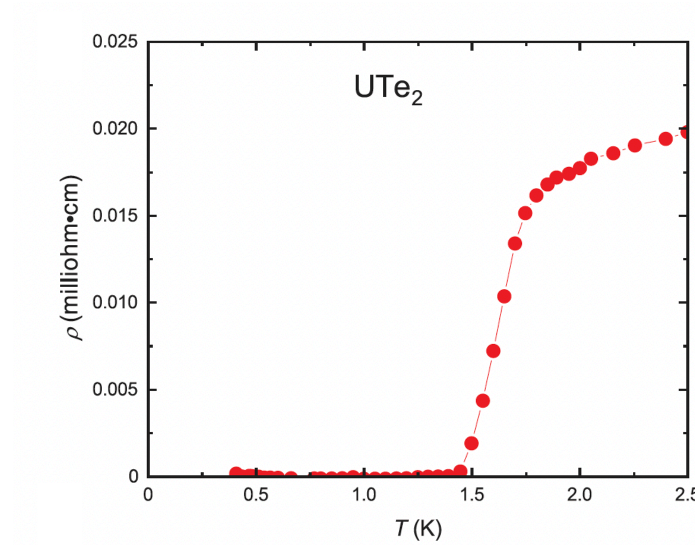


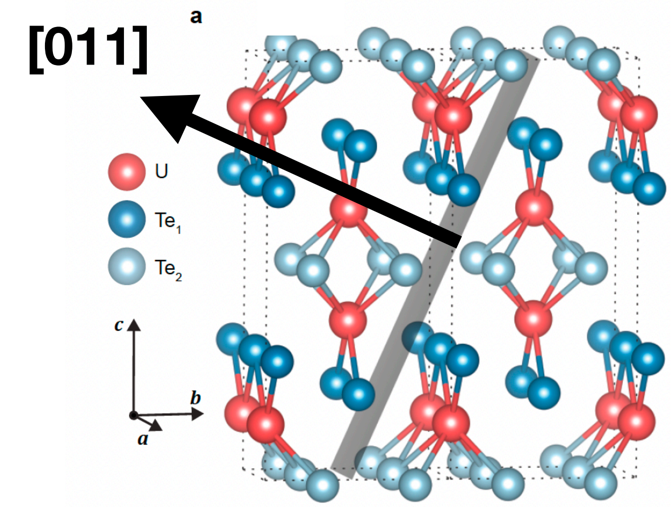
Heavy fermions ⇒ Flat bands

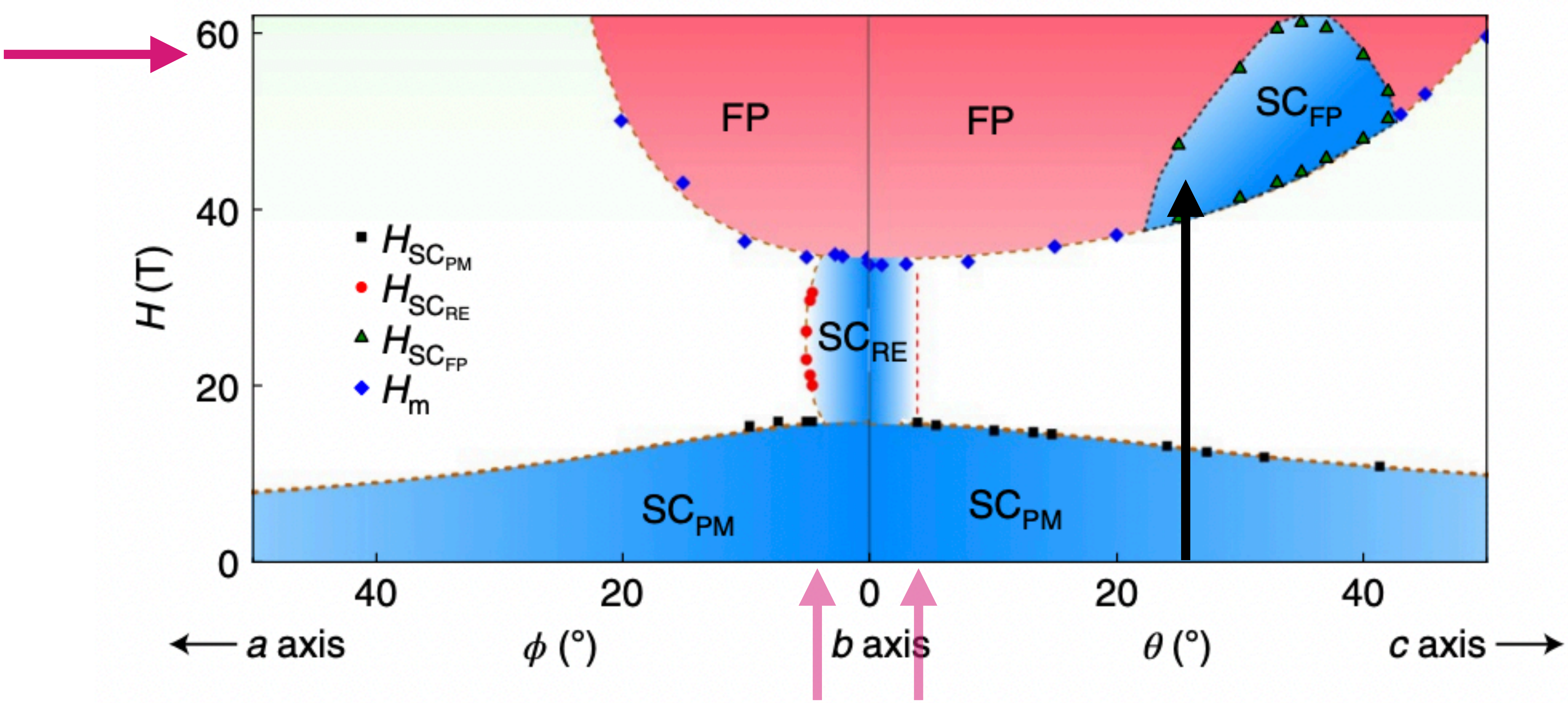
S. Paschen and Q. Si, Nat. Rev. Mat. **3**, 9 (2021)

Introducing UTe_2

- Body-centered orthorhombic;
- Space group: Immm (#71, D_{2h}^{25})
- a=4.159Å, b=6.124Å, c=13.945Å
- Superconductor: $T_c \approx 1.6K$

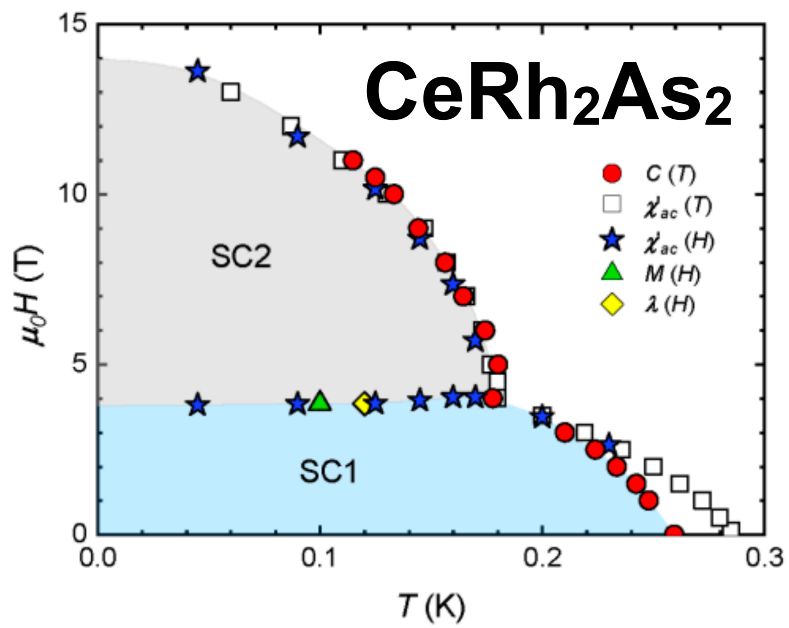


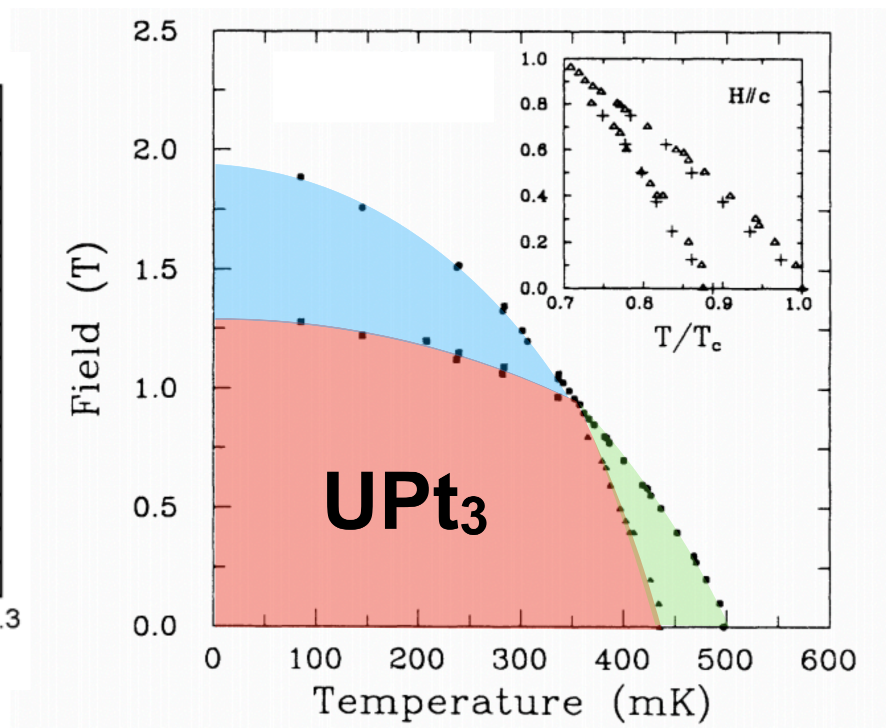


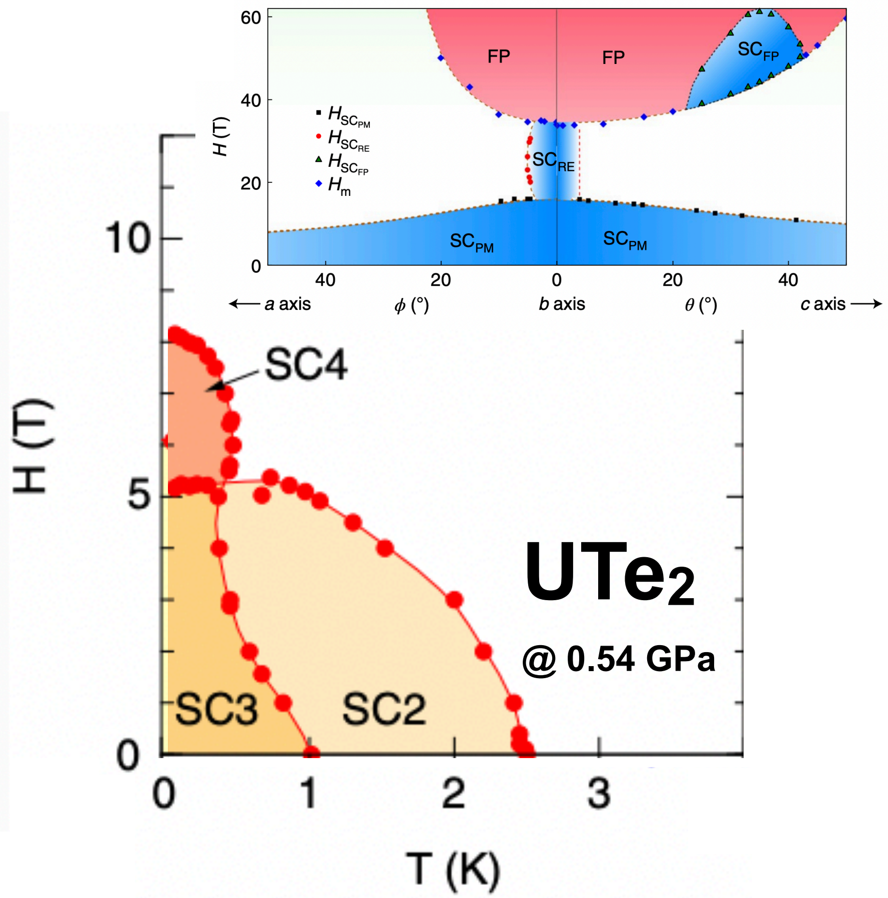


Q. Gu et al., arXiv.2209.10859 (2022)
Ran et al., Nature Physics **15**, 1250 (2019)

Multiple Superconducting Phases





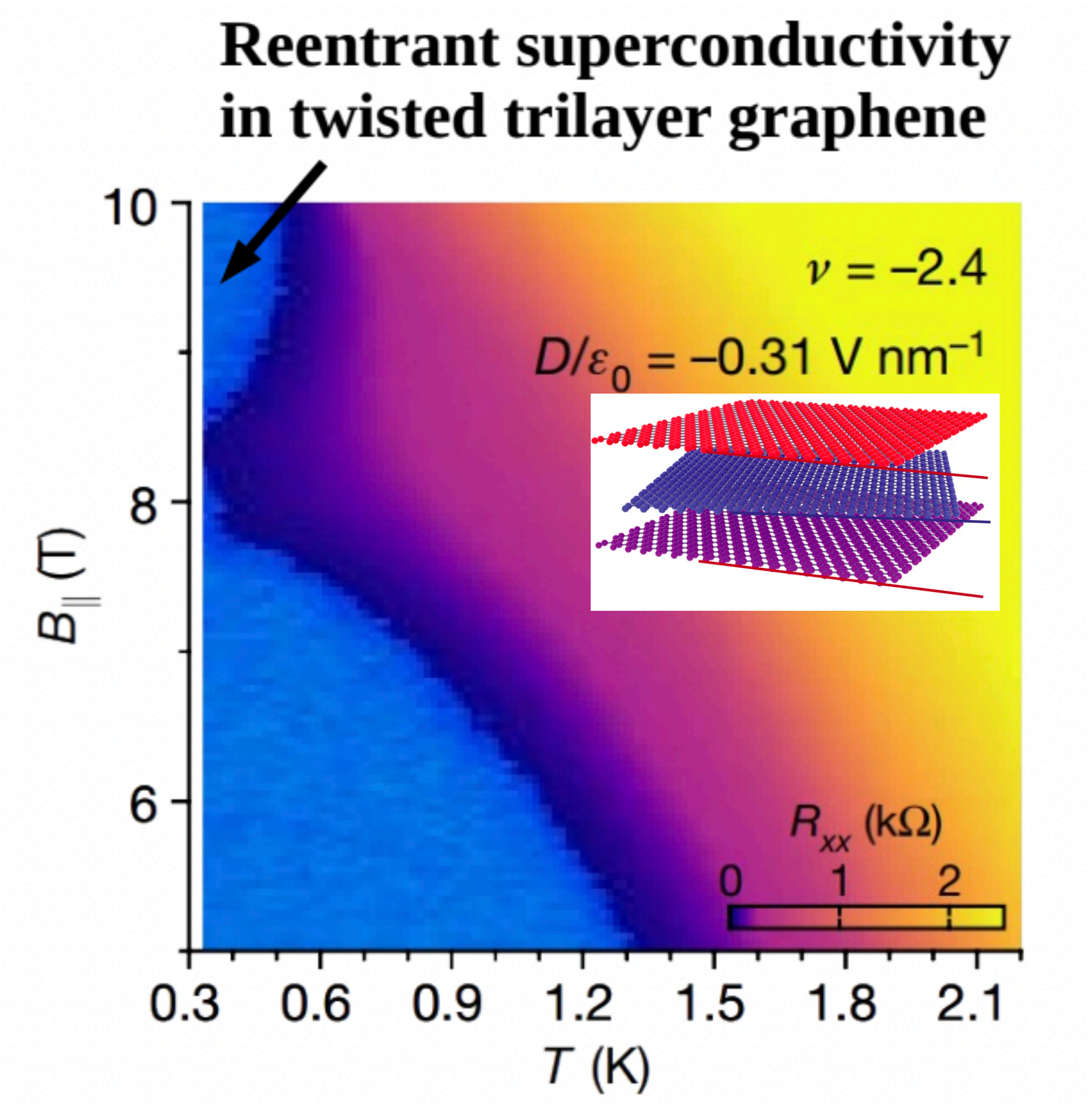


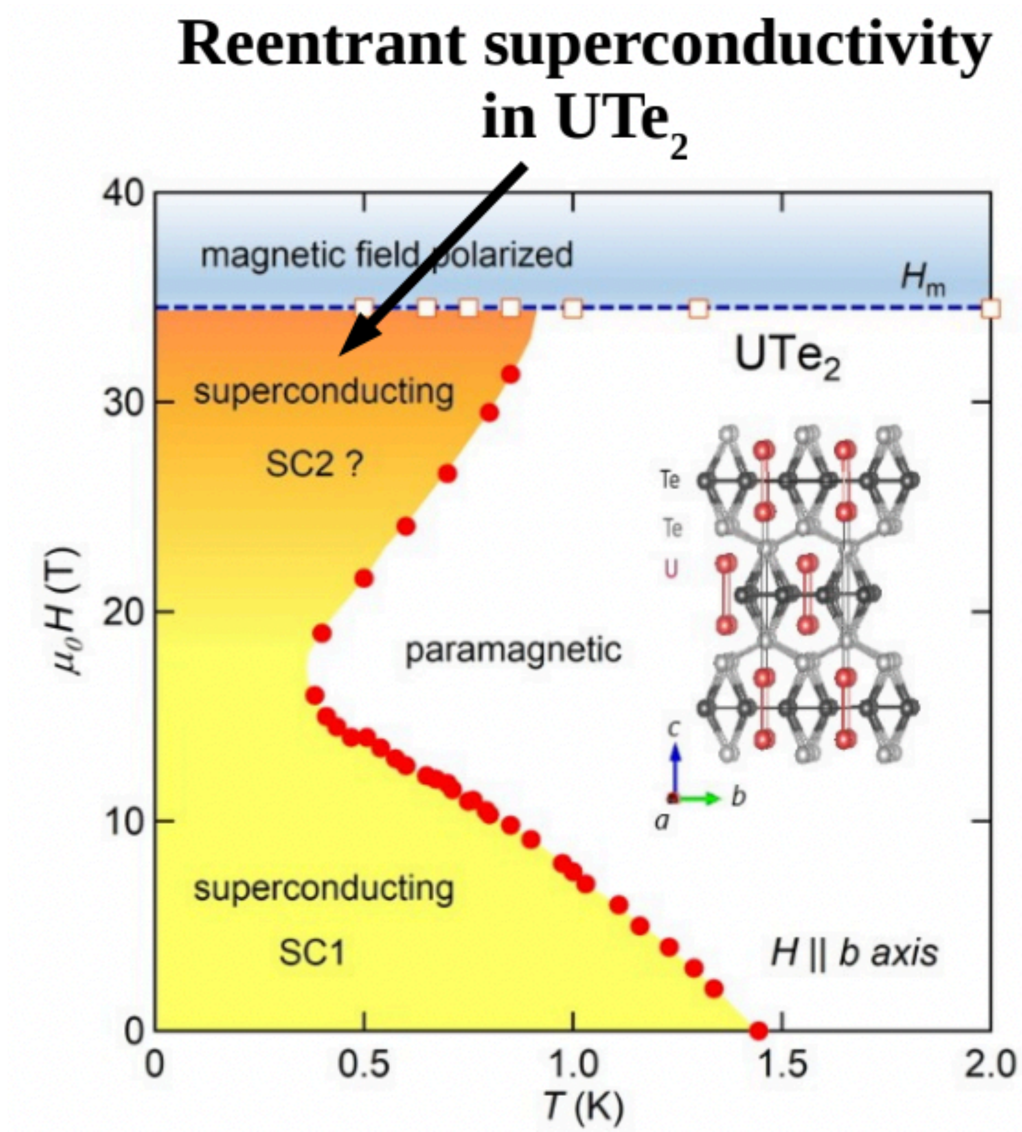
- **Phase diagrams with multiple SC phases are rare!**
- **Only observed in other two HF materials**
- **Indication of unconventional SC state!**

S. Khim et al., Science **373**, 1012 (2021)

S. Adenwalla et a., Phys. Rev. Lett. **65**, 2298 (1990)
D. Aoki et al., J. Phys. Soc. Jpn. **89**, 053705 (2020)
S. Ran et al., Nature Physics 15, 1250 (2019)

Similar phenomenology as TTG?



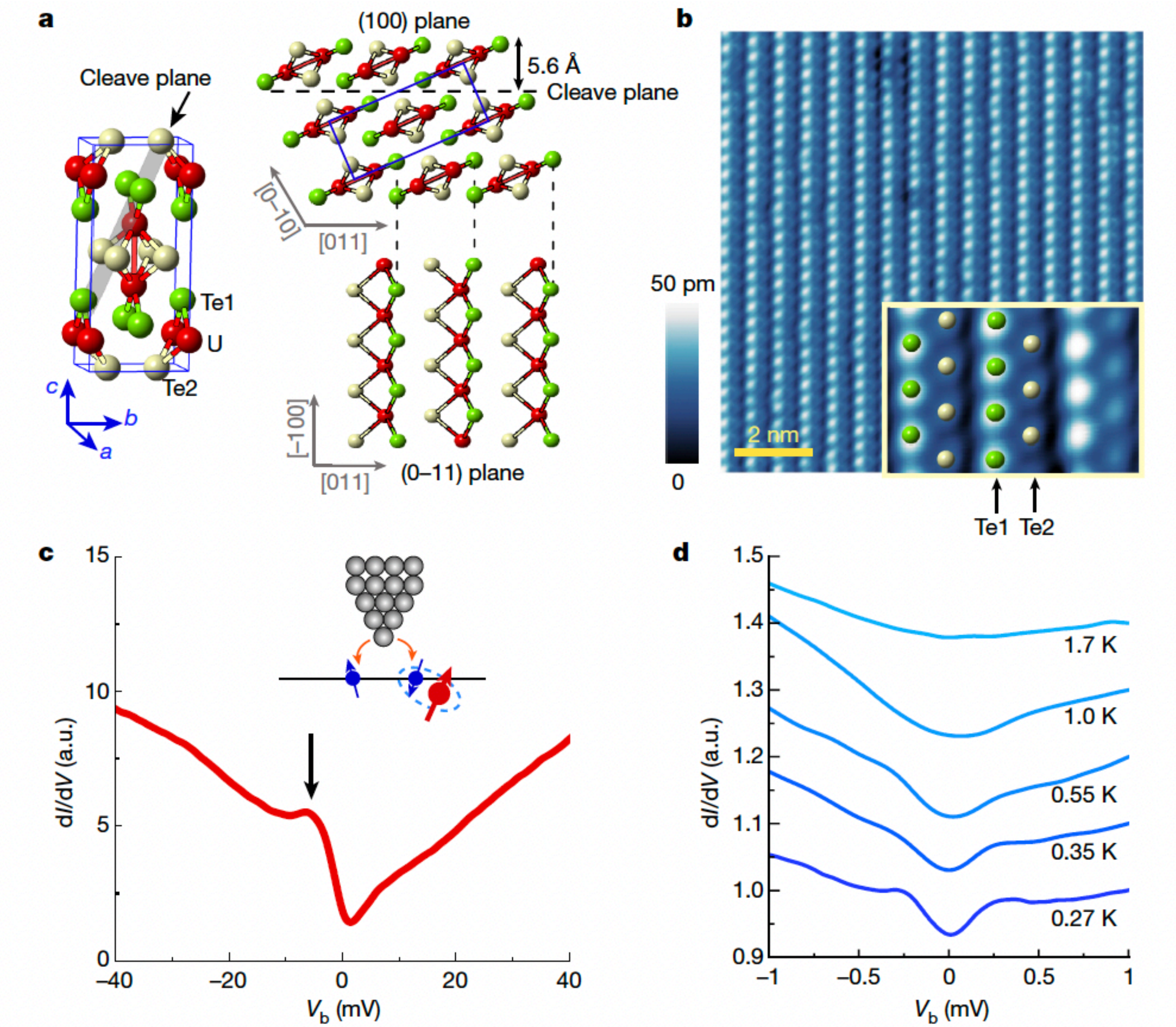


Y. Cao et al., Nature **595**, 526 (2021)

S. Ran, Nat. Phys **15**, 1250 (2019)
S. Ran, Science **365**, 684 (2019)

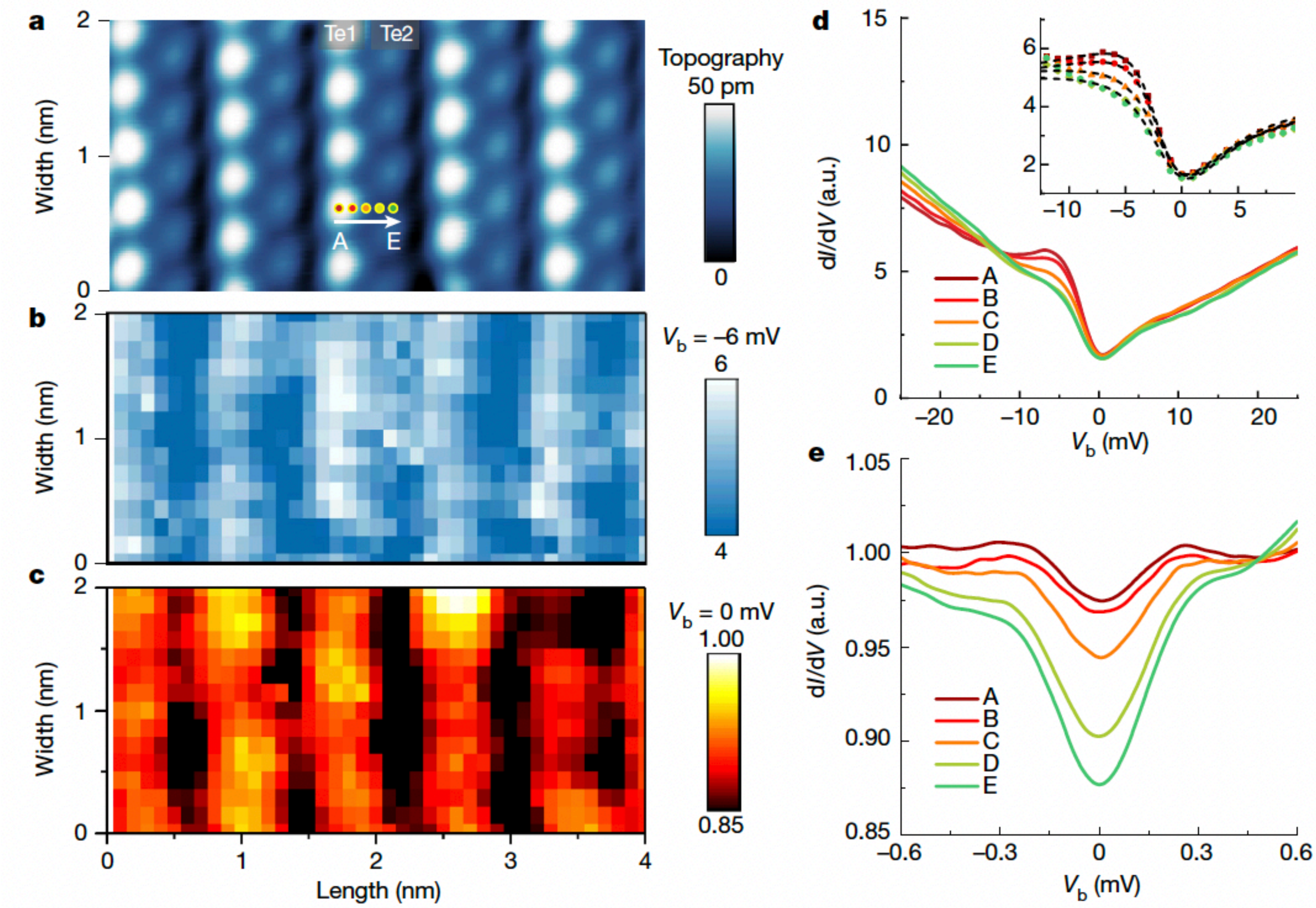
Questions?

STM Experiments in UTe_2



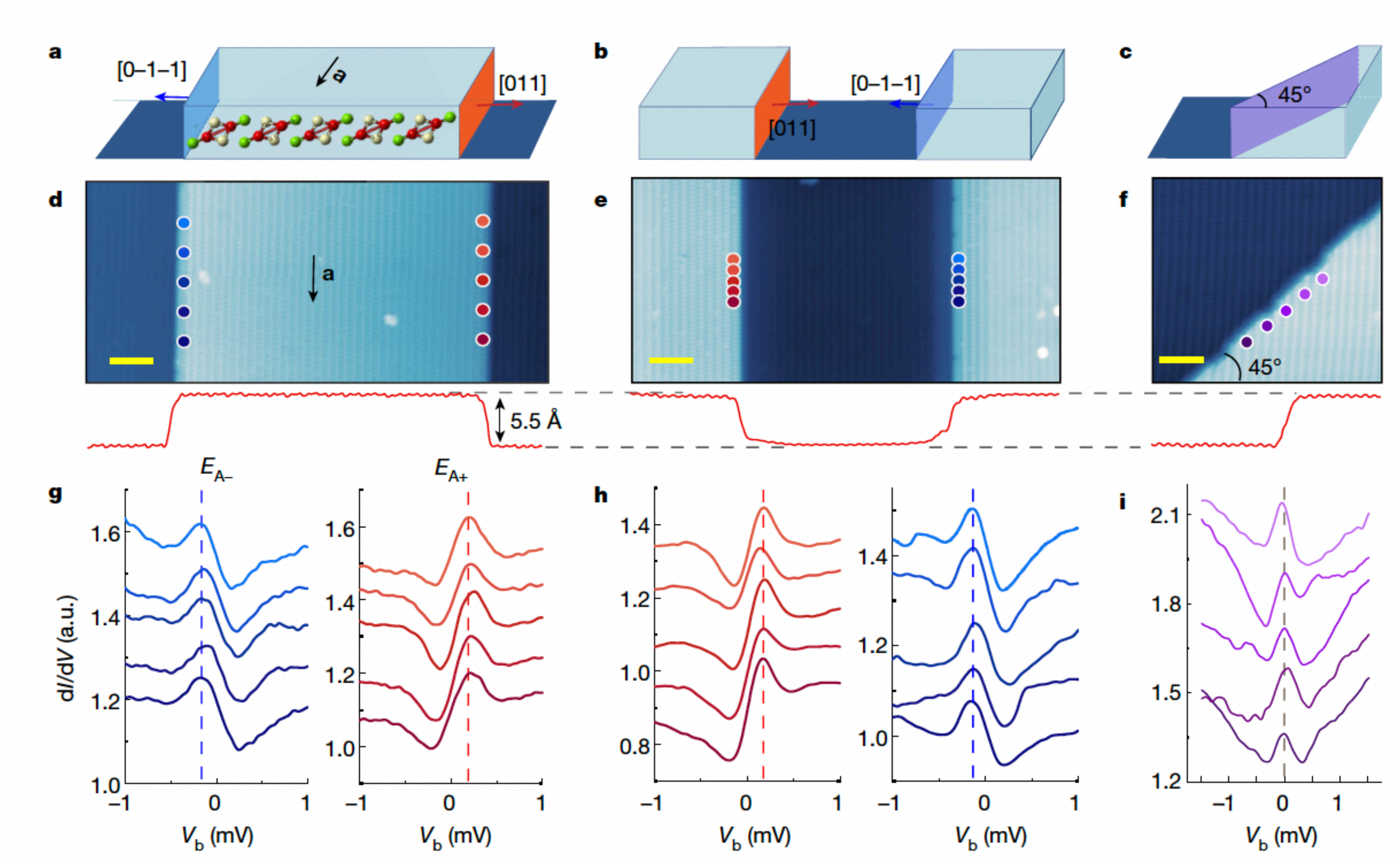
L. Jiao et al., Nature **579**, 523 (2020)

STM Experiments in UTe_2



L. Jiao et al., Nature **579**, 523 (2020)

STM Experiments in UTe_2



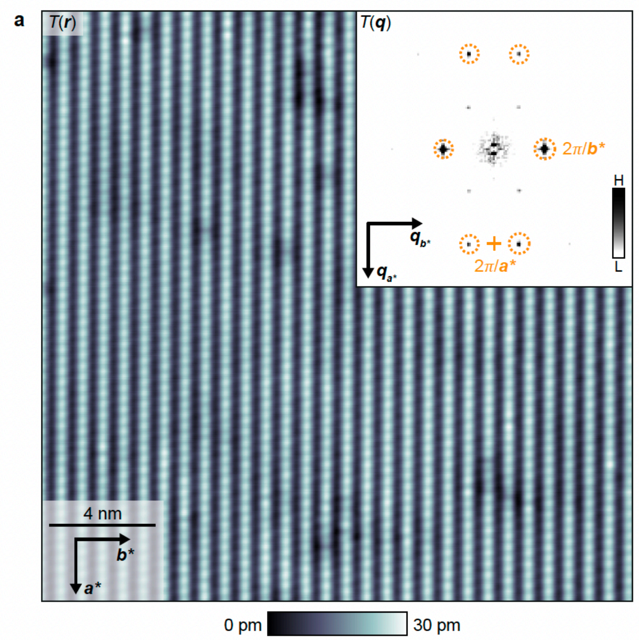
[Chiral superconductivity?]

L. Jiao et al., Nature **579**, 523 (2020)

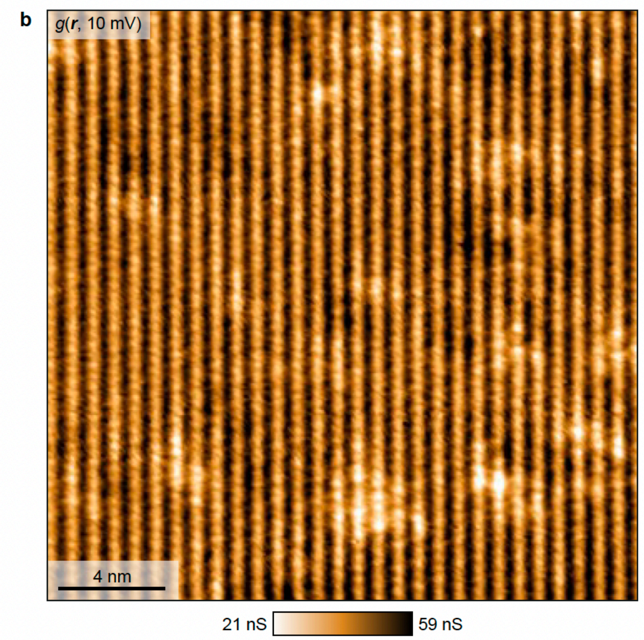
CDW+SC=PDW?

Reciprocal-lattice points
Incommensurate CDW
Incommensurate PDW

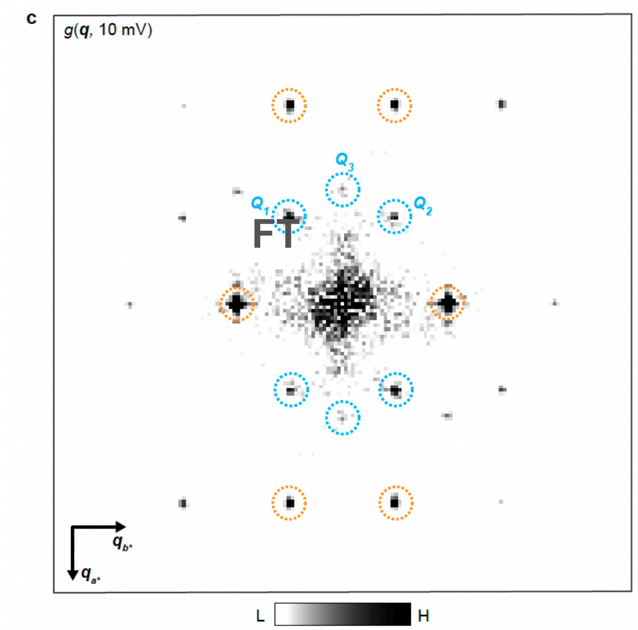
Topographic Image



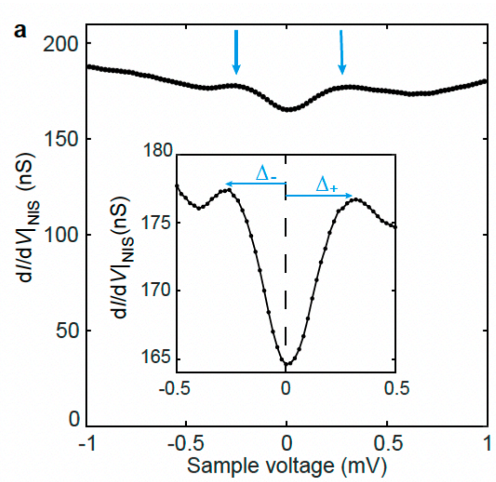
Differential Conductance @4.2K



FT



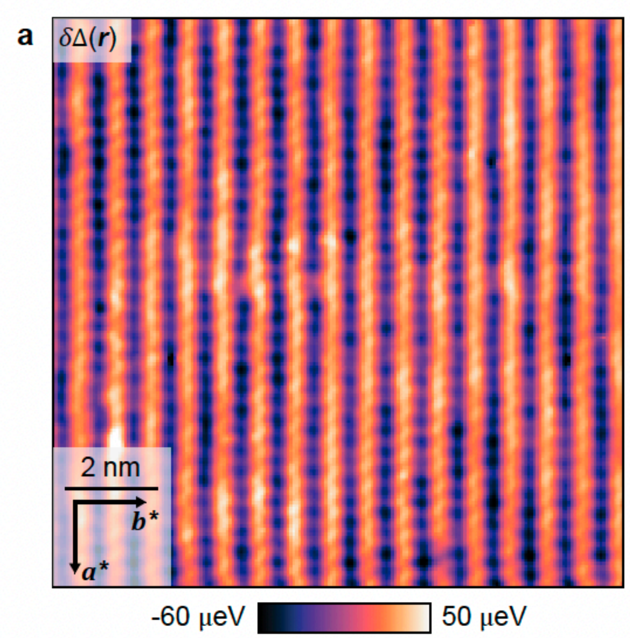
Typical Differential Conductance @0.28K

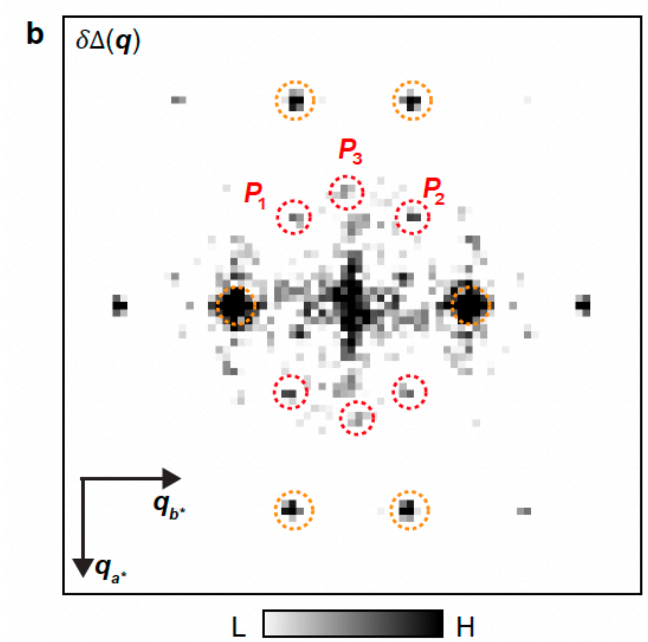


$$\Delta_{UTe_2}(\boldsymbol{r}) = (\Delta_+(\boldsymbol{r}) + \Delta_-(\boldsymbol{r}))/2$$

$$\delta\Delta(\boldsymbol{r}) \equiv \Delta_{UTe_2}(\boldsymbol{r}) - \langle\Delta_{UTe_2}(\boldsymbol{r})\rangle$$

Gap modulation



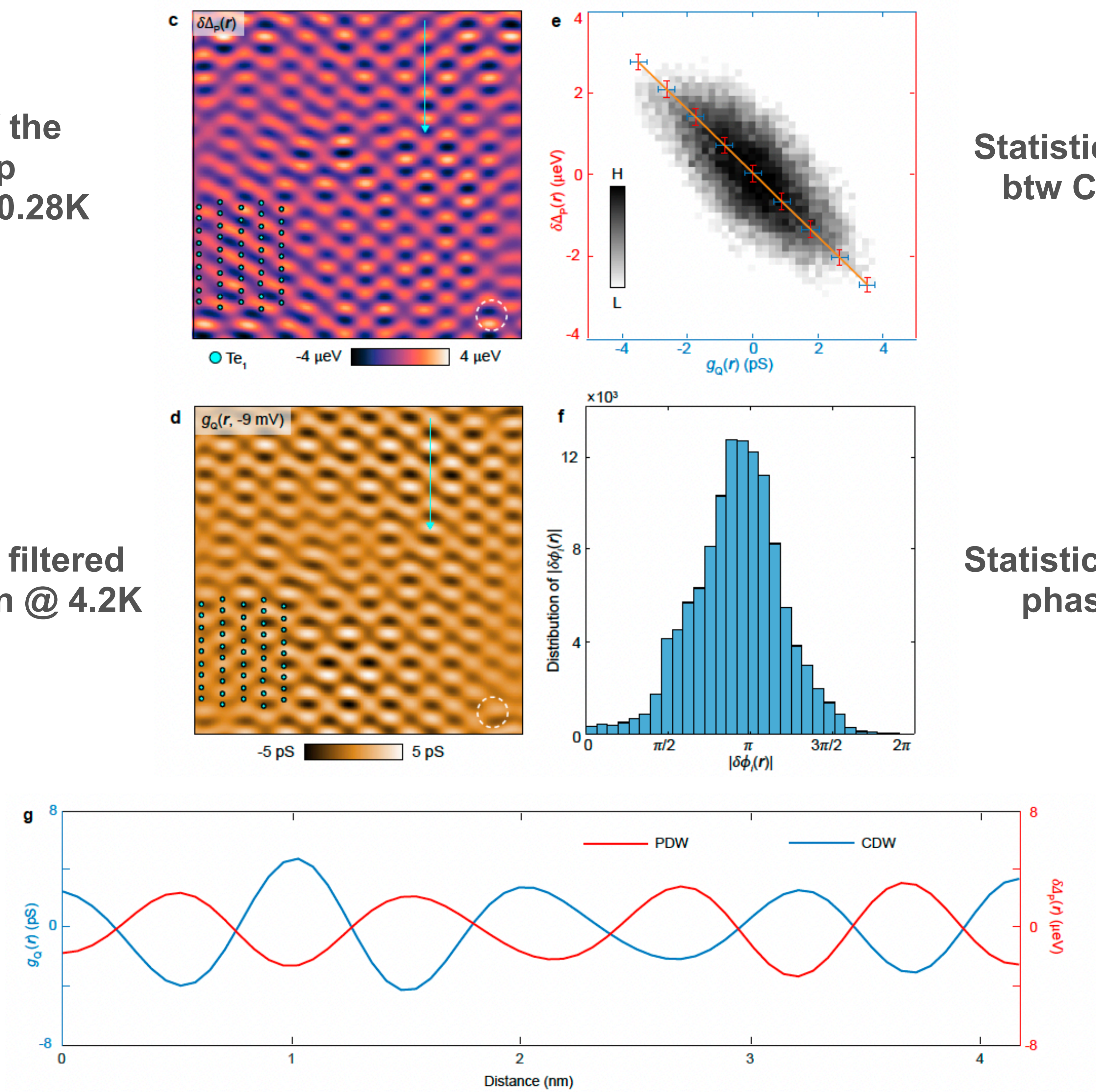


Q. Gu et al., arXiv.2209.10859

CDW+SC=PDW?

Inverse FT of the filtered gap modulation @ 0.28K

Statistical relationship btw CDW and PDW

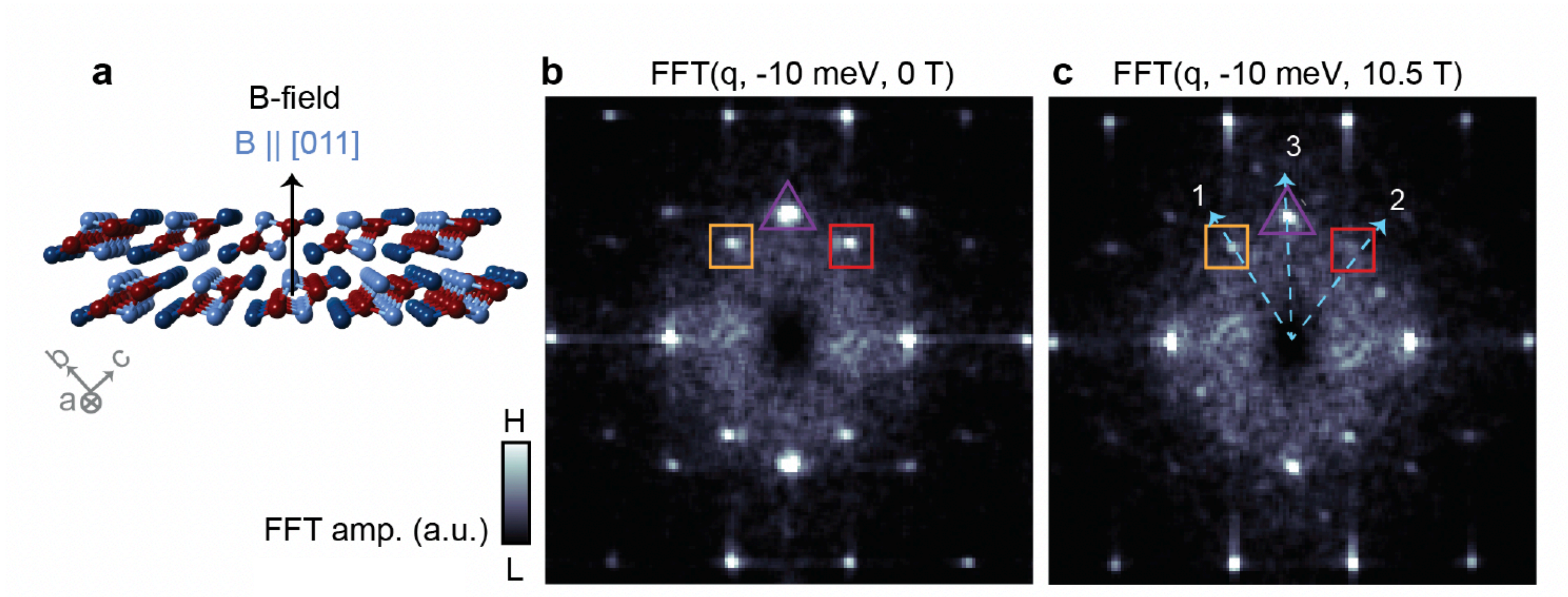


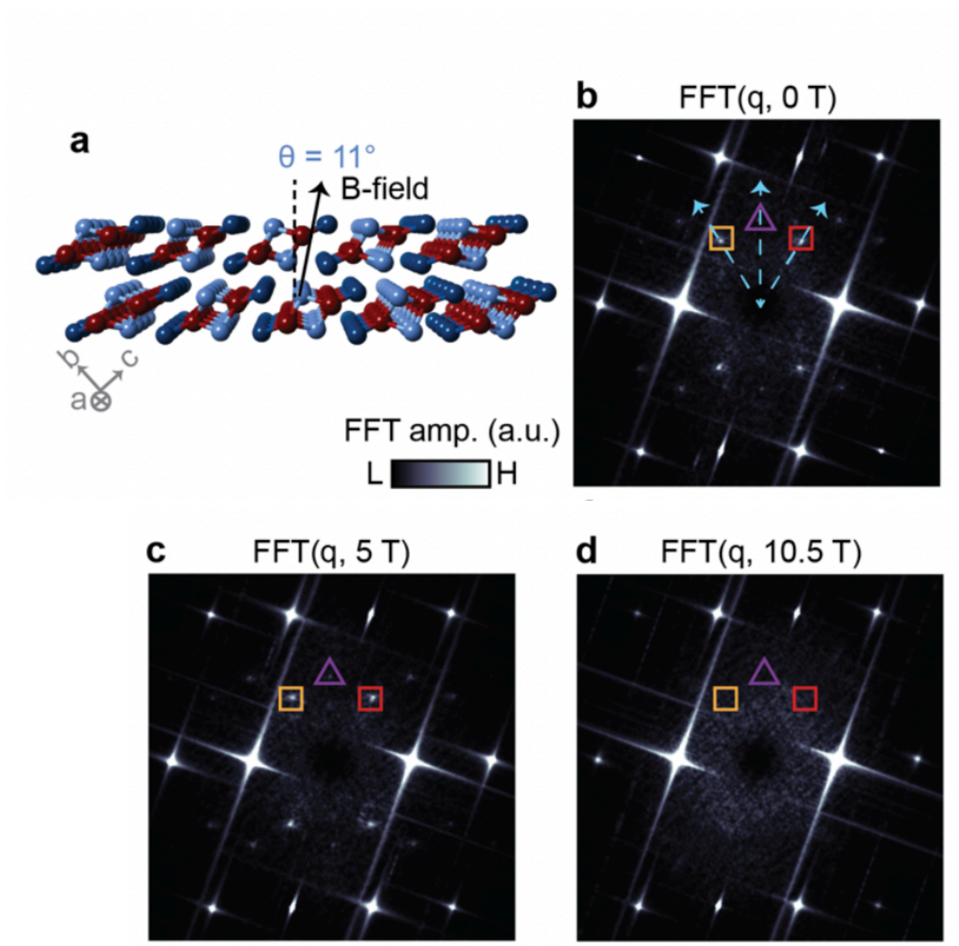
Inverse FT of the filtered charge modulation @ 4.2K

Statistics of the relative phase difference

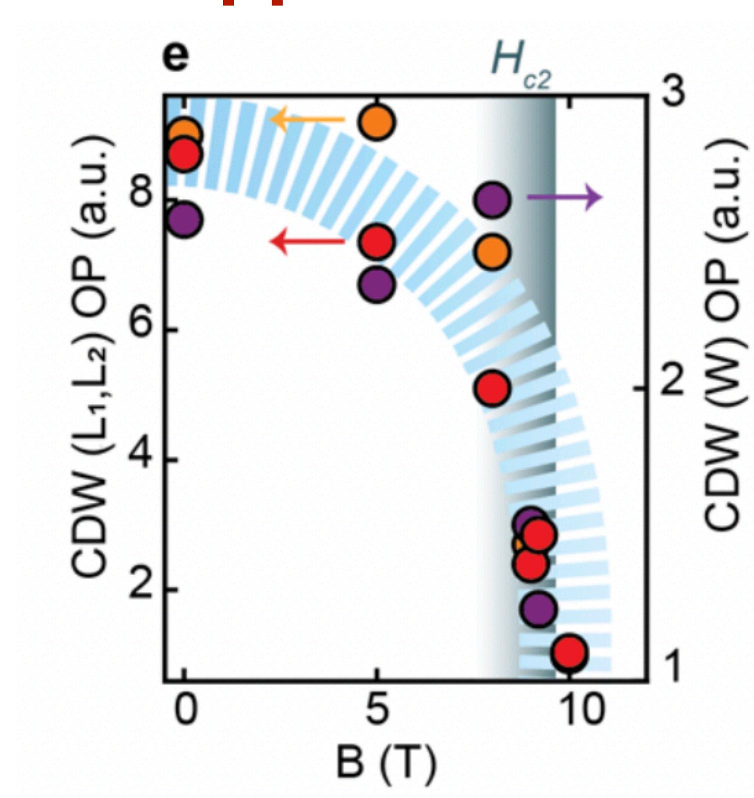
Q. Gu et al., arXiv.2209.10859

CDW under magnetic field





[CDW suppressed at H_{c2}?]



A. Aishwarya et al., arXiv.2207.09491

Questions?

What is known so far?

HF SCs are interesting materials hosting unconventional superconducting phases with exotic signatures;
The presence of multiple superconducting phases implies that all but one are necessarily unconventional;

Why is this interesting?

The exotic signatures might be associated with non-trivial topology of the SC state, or used to uniquely characterize the SC state;

What are the open questions?

Is chiral SC the only possible interpretation of the data?
Are there other systems that display similar signature but are not chiral?
What can we learn from the PH asymmetry of the spectra at defects?
Why is CDW suppressed at the SC upper critical field?
Are there other cases in which magnetic fields influence CDW?