Inducing and tuning Kondo screening in a narrow-electronic-band system

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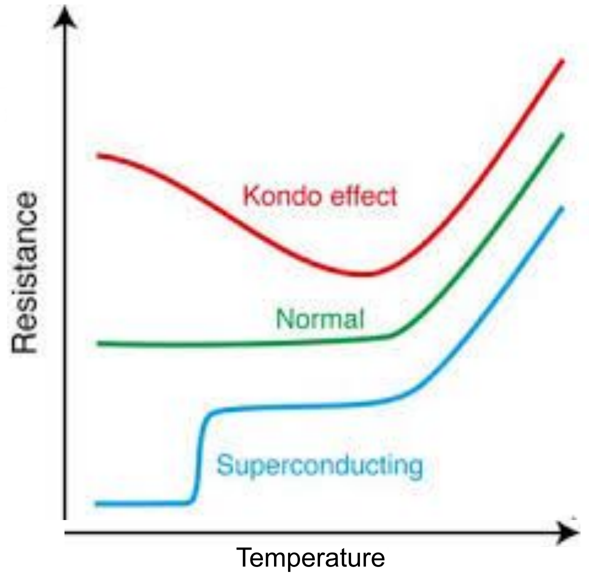
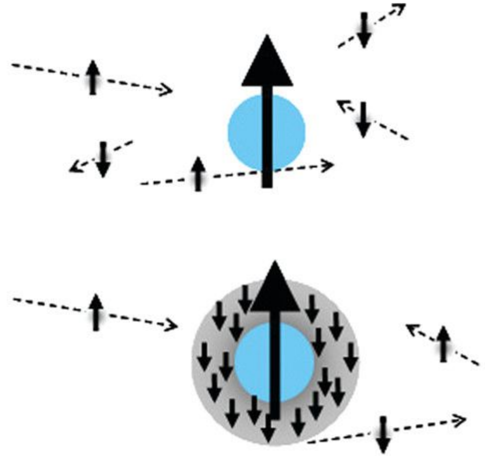
10/7/2022

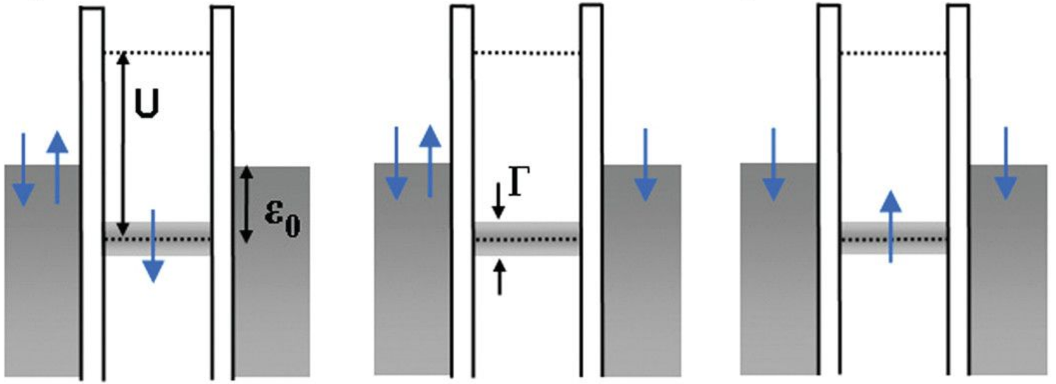
References:

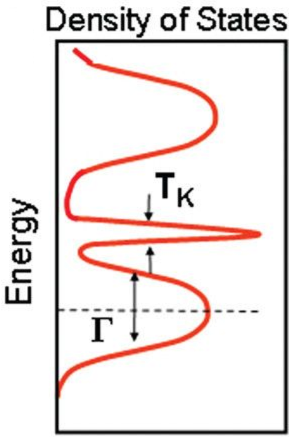
- **S. Shen et al., Nat. Commun. 13, 2156 (2022).**

Background: Kondo Effect

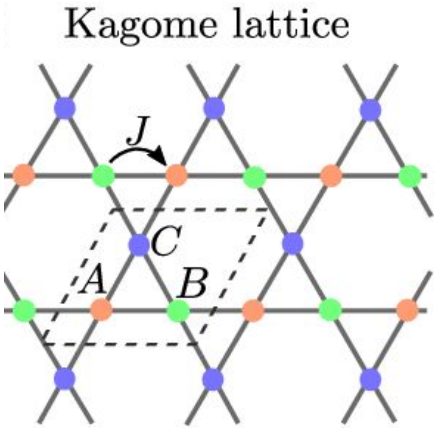


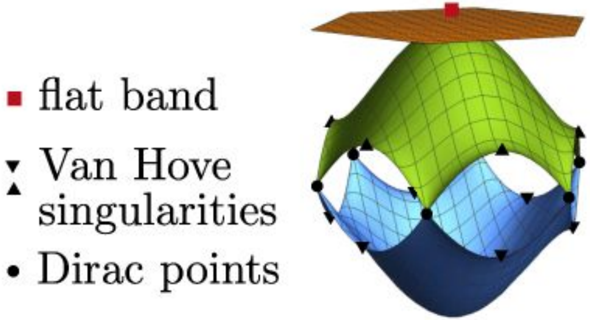


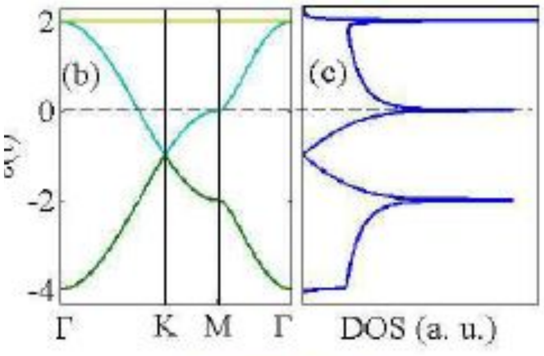




Background: Narrow or Flat Band Systems





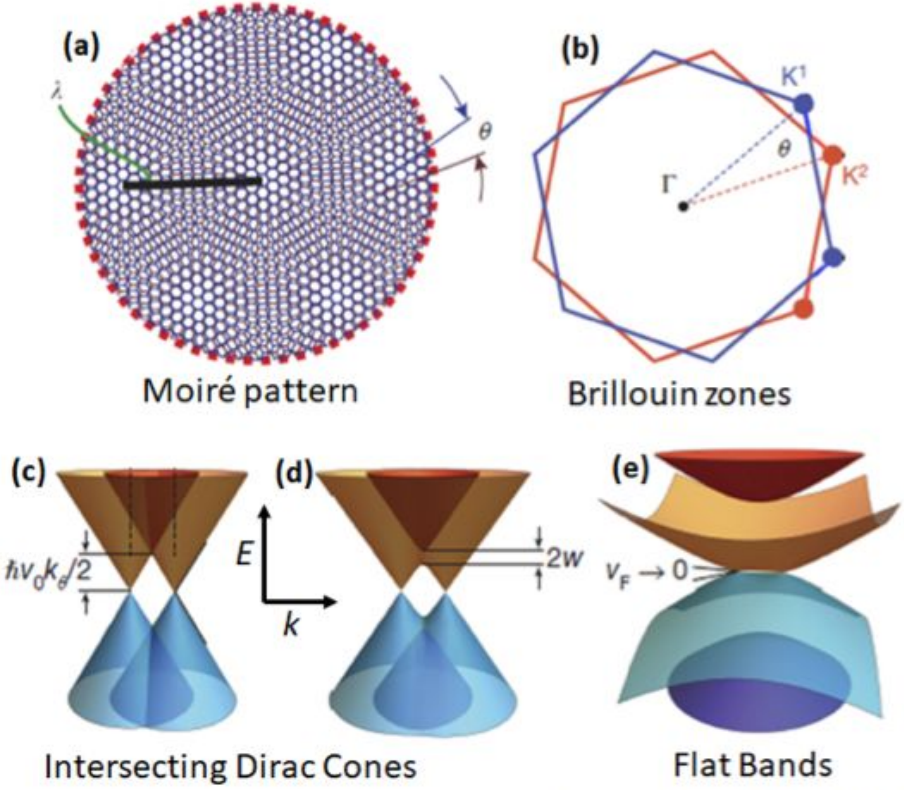


- Dispersionless, highly degenerate states where **kinetic energy is quenched** and **interactions between electrons** often create strongly correlated phases.

- Destructive interference of degenerate states often leads to **localization** in flat band systems.
    - Can also be seen by considering divergent effective mass $$m^* = \frac{\hbar^2}{d^2E/dk^2}$$

Background: Narrow or Flat Band Systems

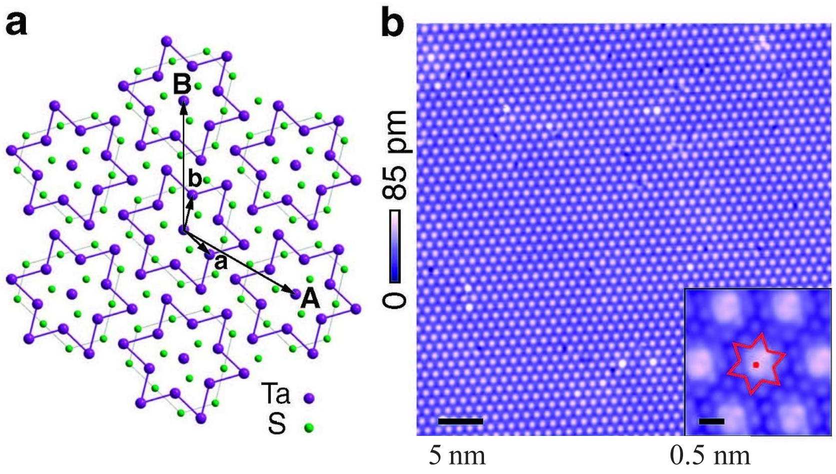
Twisted Bilayer Graphene: Moiré-induced Electronic Structure



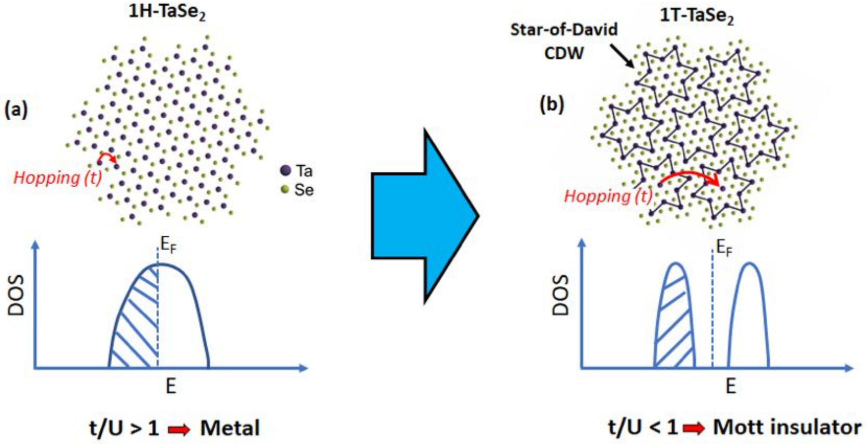
Images from Y. Cao, et al., *Nature* 556, 80 (2019)

Charge Density Wave (CDW) in 1T-TaS2

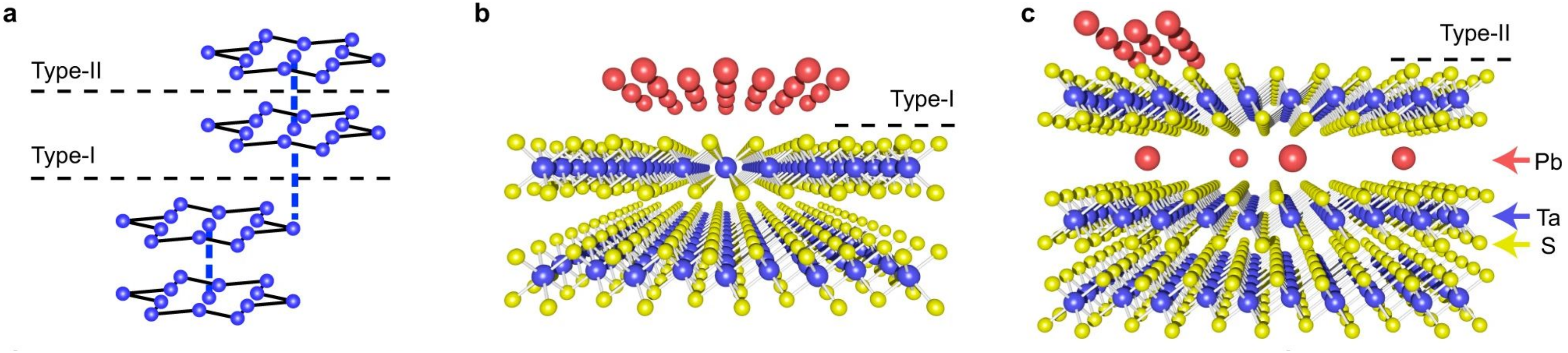
- Localized “star of david” (SD) sites each host one unpaired electron, form a superlattice on surface.
  - Unpaired electrons act as local magnetic moments.



- Coulombic interactions between SD sites leads to a gap opening, can’t be explained with single particle band theory (Mott insulator).



Two Types of Cleaved 1T-TaS2 Surfaces

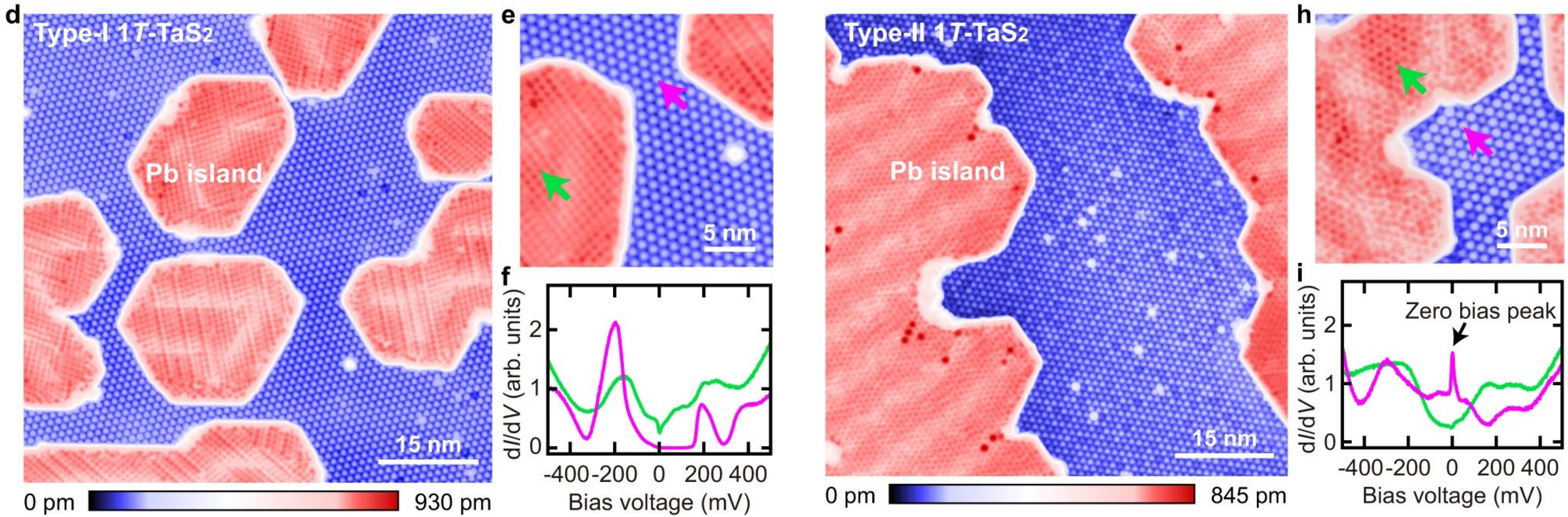


Two possible surfaces are seen upon cleaving in UHV at room temperature:

1. Type-I: Dimerized surface. Interlayer bonding between SD sites pairs the localized electrons, surface is a **typical band insulator**.

2. Type-II: Undimerized surface. Unpaired electrons only weakly coupled to layer underneath, SD site interactions make the surface a **correlated insulator**.
   - Larger vdw gap allows for Pb intercalation between layers.

Pb Intercalation on Cleaved 1T-TaS2



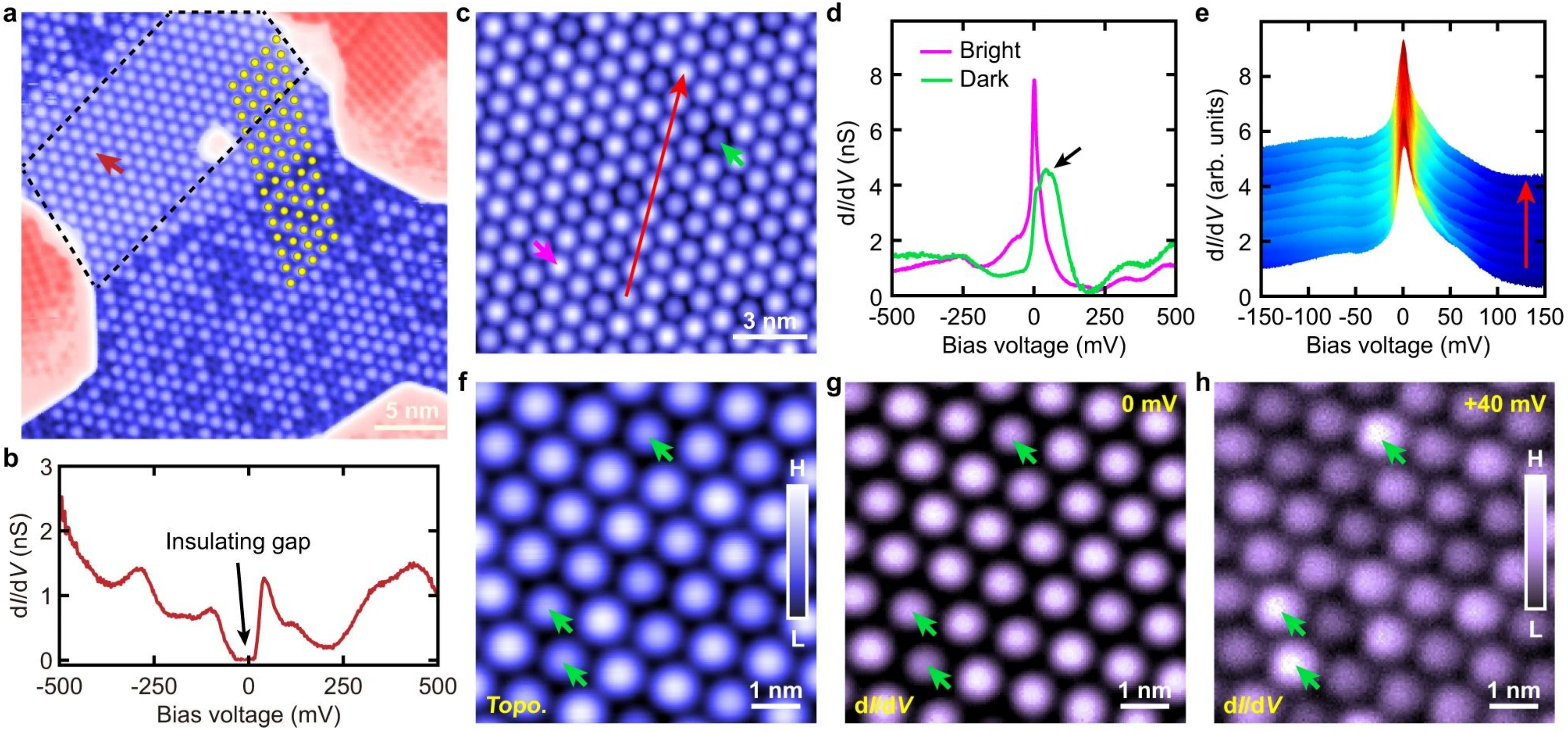
Type-I:

- Bulk surface unchanged by Pb evaporation.
- ~150 mV dimerization-induced insulating gap is preserved.

Type-II:

- Instead of Mott insulator gap, strong zero bias peak (ZBP) at Fermi energy appears on SD spots.
- Some SD sites now appear “dark,” only in regions where ZBP appears.

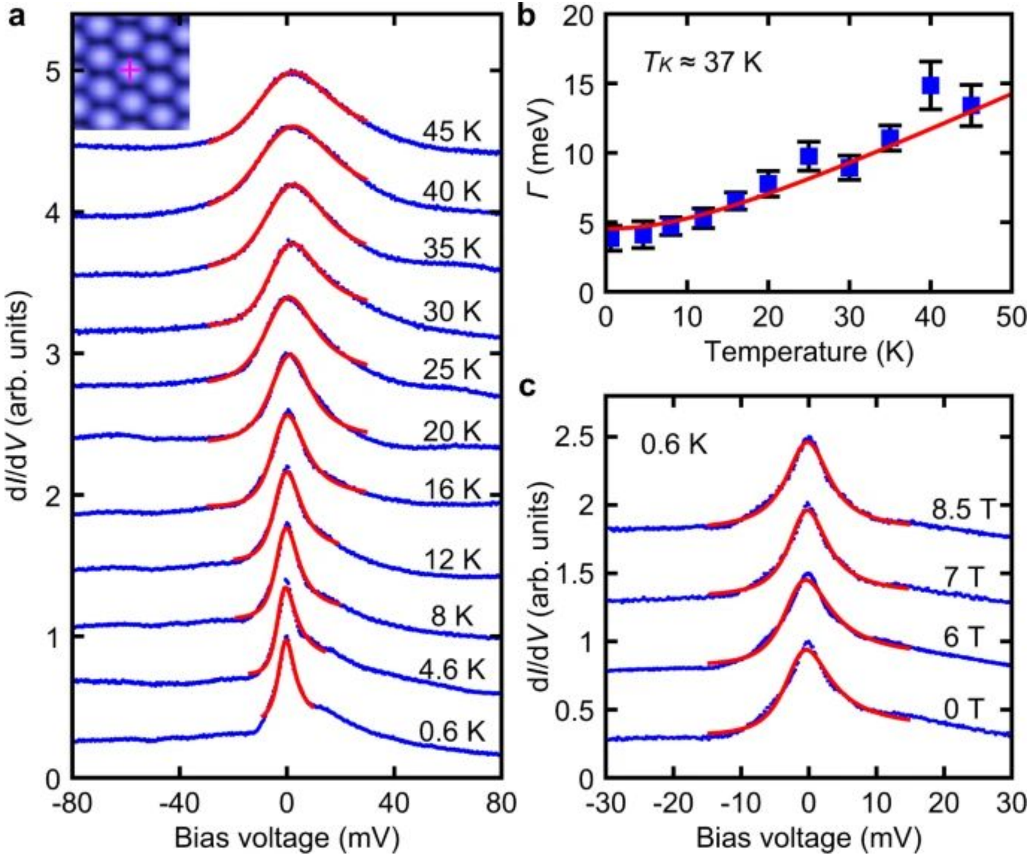
Effect of Pb sub-layer on SD Sites



Concluding ZBP is a Kondo Resonance

- Magnetic field dependence: would expect splitting of peak due to Zeeman effect, but none observed up to 8.5 T.

- Splitting *was* observed for single layer 1T-TaS2 at 10 T in another paper.
  - Kondo resonance linewidth for monolayer is 4x linewidth measured here, requires larger field to see splitting.

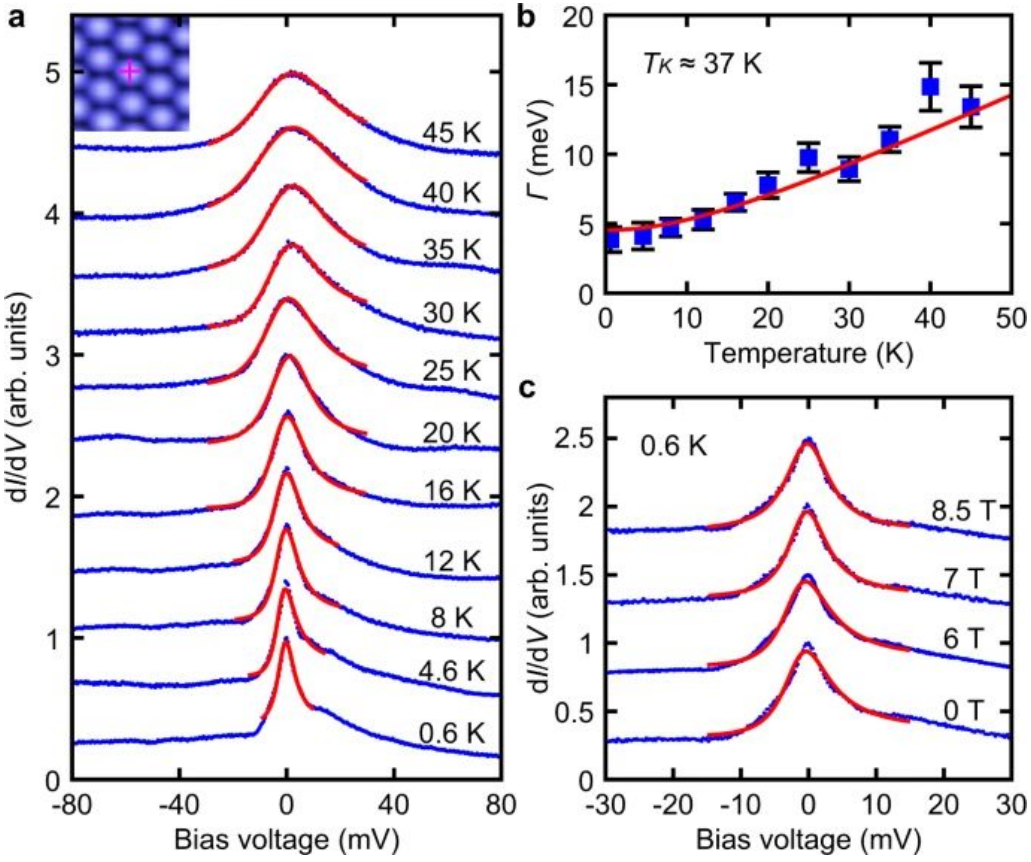


Concluding ZBP is a Kondo Resonance

- Temperature dependence: Fano lineshape used to model asymmetric Kondo peaks in dI/dV at each temperature.

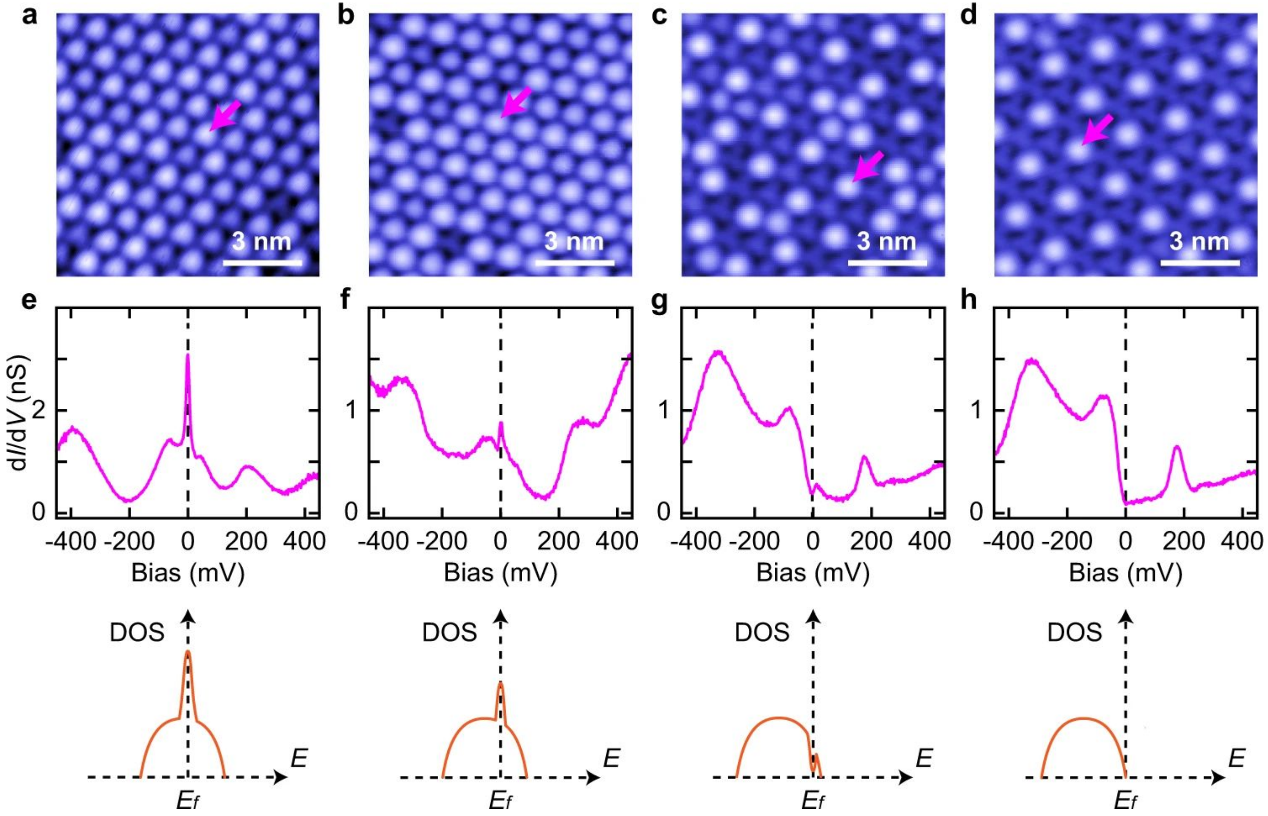
- Measure linewidth vs. temperature and fit lorentzian function to estimate Kondo temperature.

$$\text{width} = 2\sqrt{(\pi k_B T)^2 + 2(k_B T_K)^2}$$



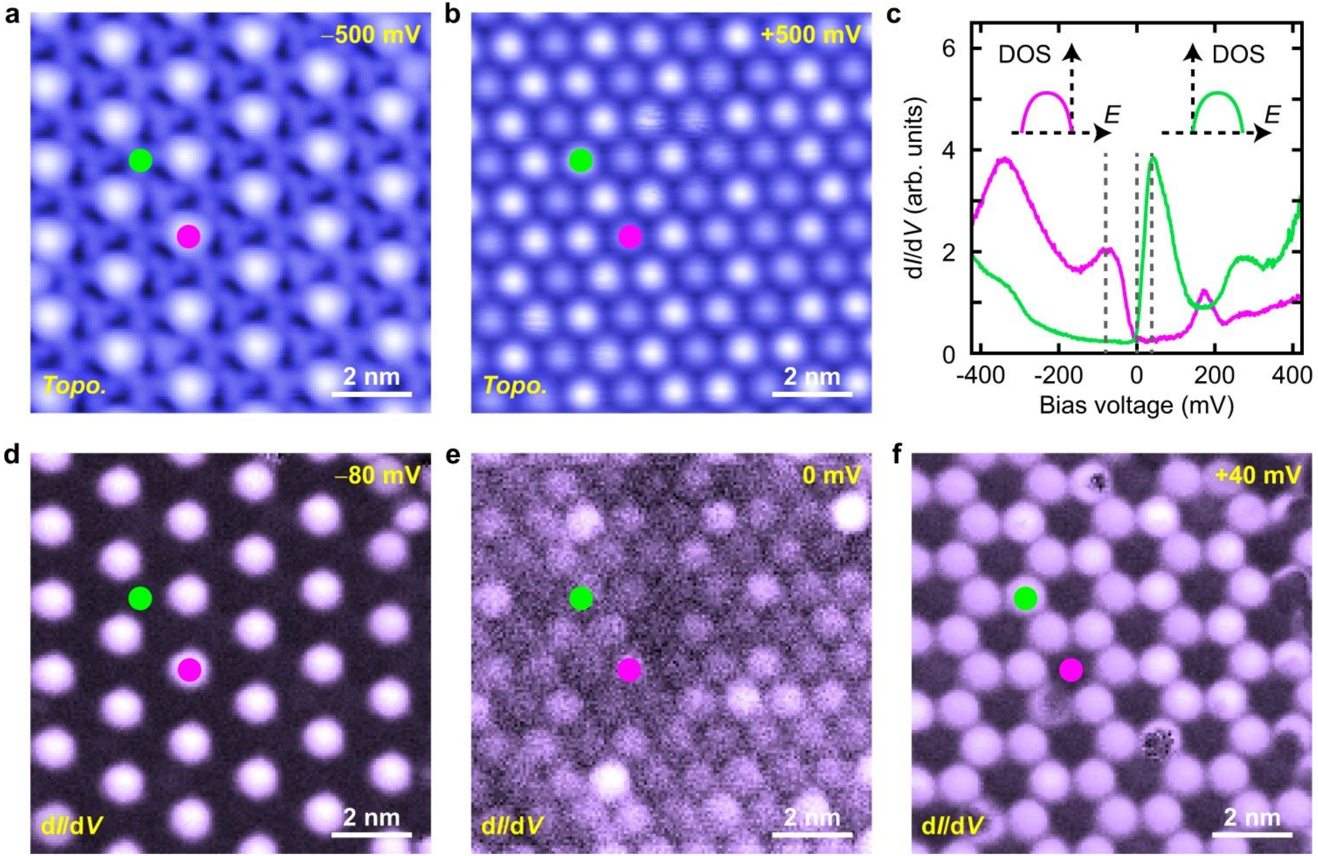
Tuning Kondo Effect with Pb Concentration

- In addition to Kondo screening, the Pb intercalants act to dope the SD sites, shift narrow band below Fermi level.
- As the concentration is raised, the Kondo effect is suppressed and eventually eliminated.
- At high Pb concentration, charge on surface redistributes, new superlattice appears.



Emergent Superstructure with increasing Pb Concentration

- New dark and bright sites appear, more pronounced for negative bias topograph.
- dI/dV on each site suggests Pb intercalants force charge modulation, splitting of narrow band into e-doped and hole-doped sites.
- Conductance maps show contrast inversion between superlattice sites.

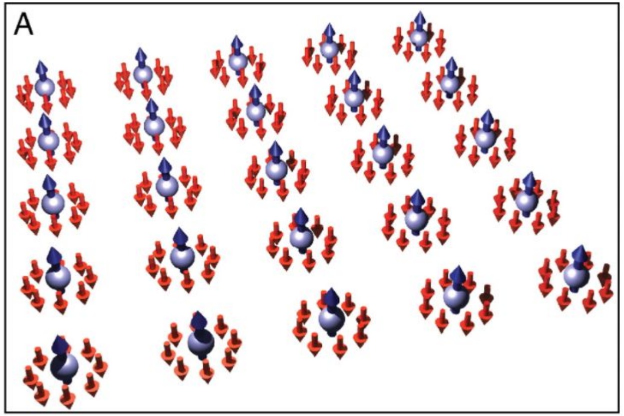


Summary/Conclusions

- Demonstrates a way to transition between many-body electronic states by varying concentration of a dopant.

- Ability to add a bottom layer on cleaved surface, making vdw heterostructure without stacking.

- Platform for studying Kondo lattice systems with TMD bulk surfaces.



Changing the position of the SD cluster during the STM measurements