# Real-space observation of $4a \times \sqrt{3}a$ charge density wave phase and Kondo effect in VSe₂ film

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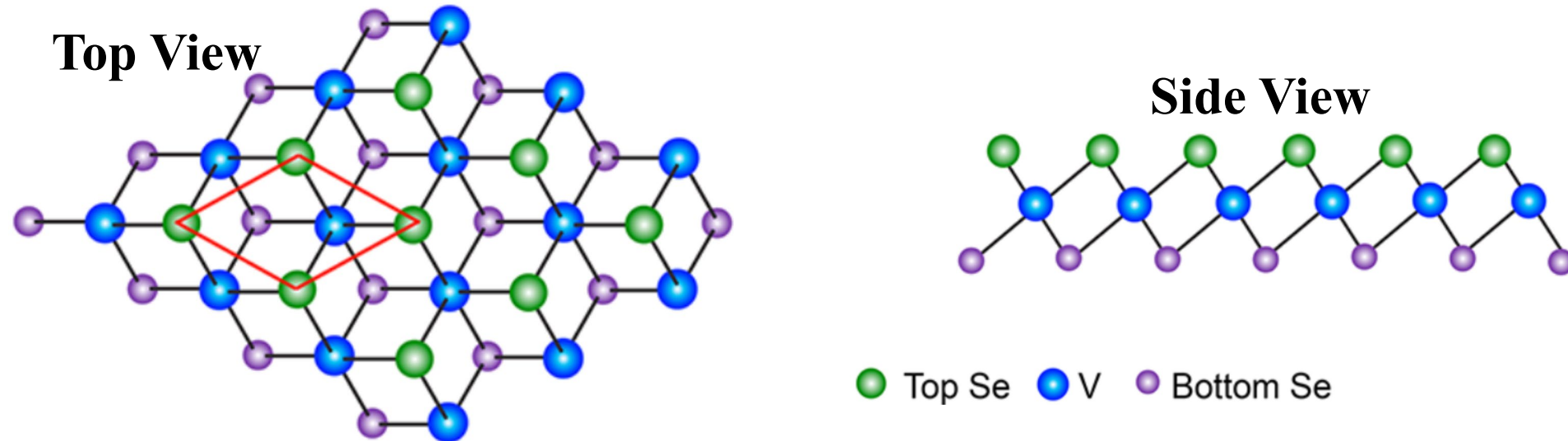[2] Hefei National Laboratory for Physical Science at Microscale and Department of Physics, University of Science and Technology of China, Hefei, Anhui 230026, China
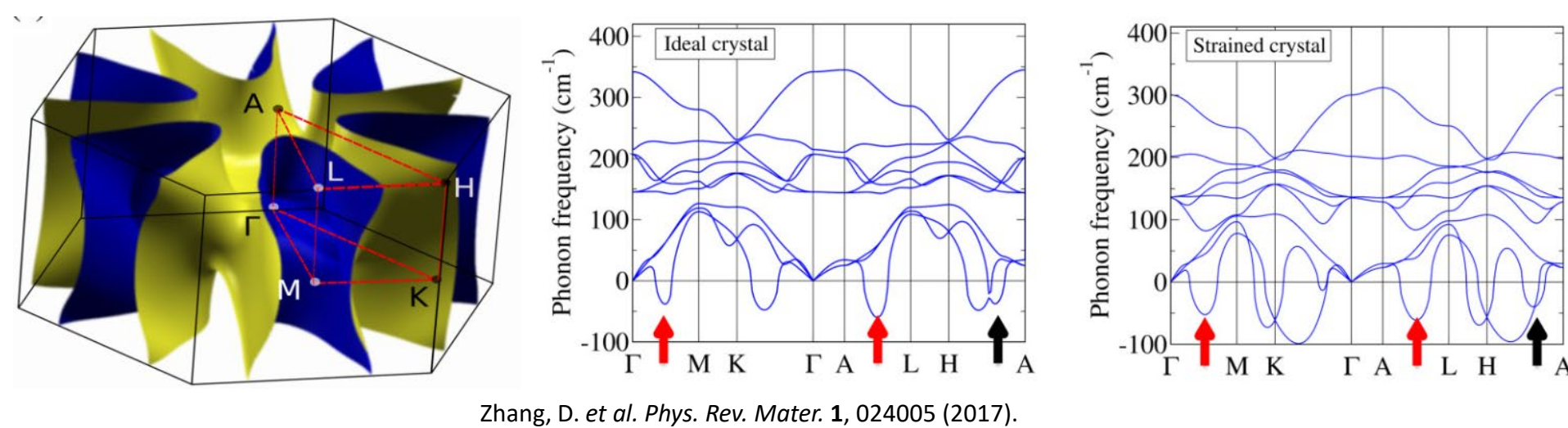[3] Collaborative Innovation Center of Advanced Microstructures, Nanjing 210093, China
[4] Shanghai Research Center for Quantum Sciences, Shanghai 201315, China
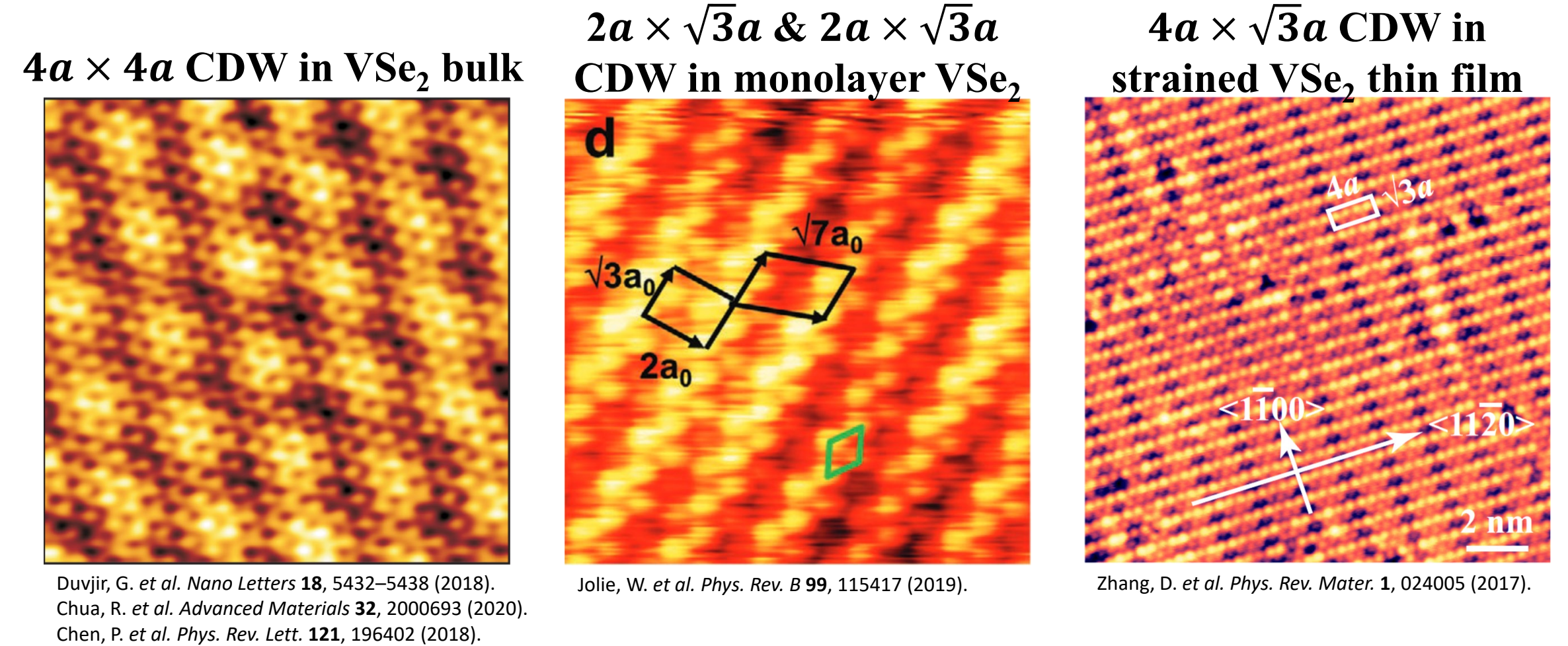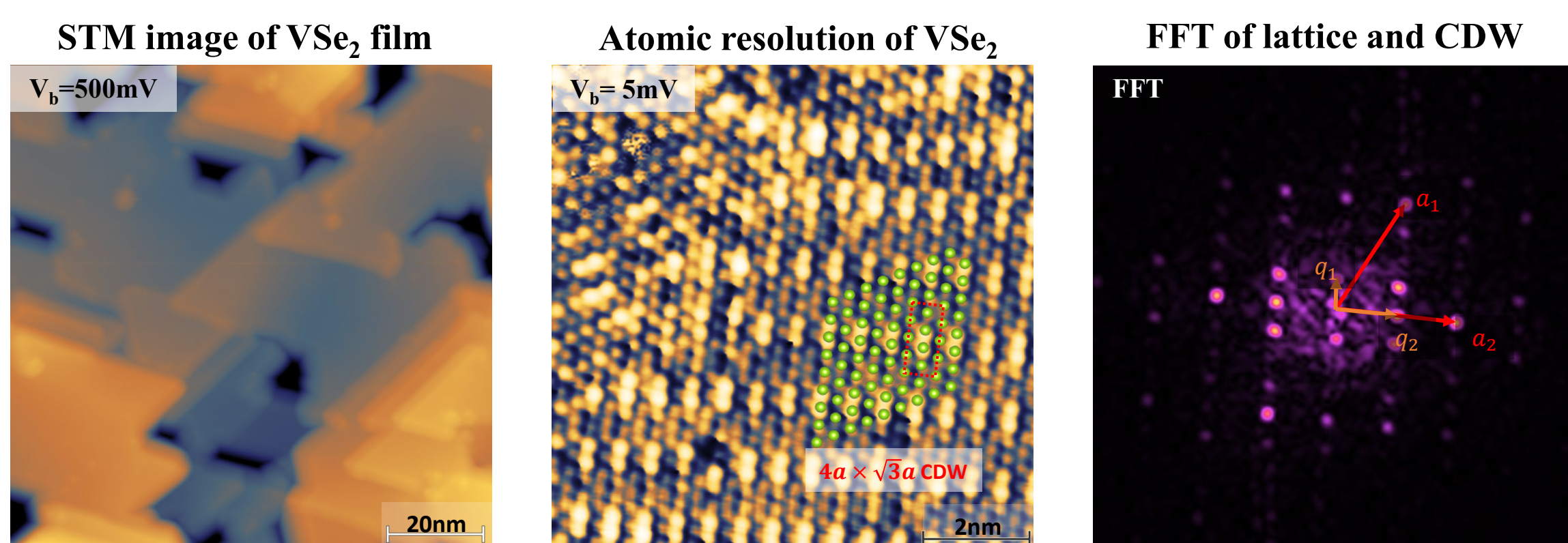
## Background

### Structure of 1T-VSe₂

**Top View** **Side View**



- Top Se
- V
- Bottom Se

### DFT Calculation of 1T-VSe₂



Zhang, D. et al. Phys. Rev. Mater. **1**, 024005 (2017).

### Multiple CDW order in 1T-VSe₂

**$4a \times 4a$ CDW in VSe₂ bulk** | **$2a \times \sqrt{3}a$ & $2a \times \sqrt{3}a$ CDW in monolayer VSe₂** | **$4a \times \sqrt{3}a$ CDW in strained VSe₂ thin film**



Duvjir, G. et al. Nano Letters **18**, 5432–5438 (2018).
Chua, R. et al. Advanced Materials **32**, 2000693 (2020).
Chen, P. et al. Phys. Rev. Lett. **121**, 196402 (2018).

Jolie, W. et al. Phys. Rev. B **99**, 115417 (2019).
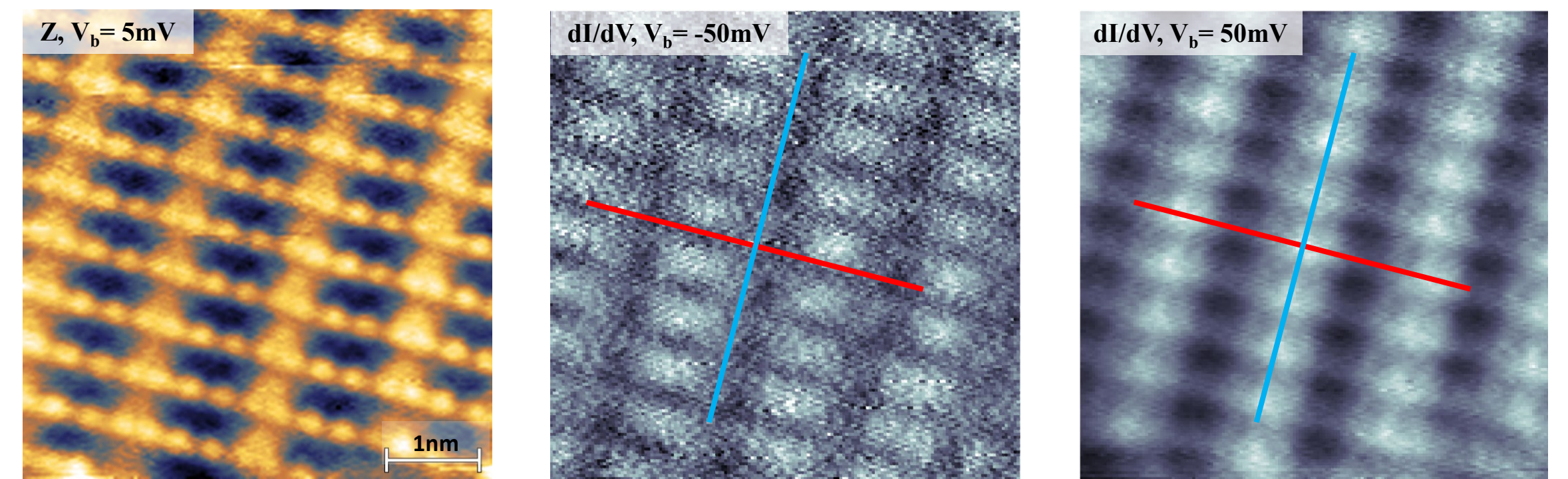
Zhang, D. et al. Phys. Rev. Mater. **1**, 024005 (2017).

- The Charge density wave order in 1T-VSe₂ is multiple, and is unlike the case in 1T-TaX₂ (X = S or Se).
- The multiple CDW order might related to the phonon spectrum.
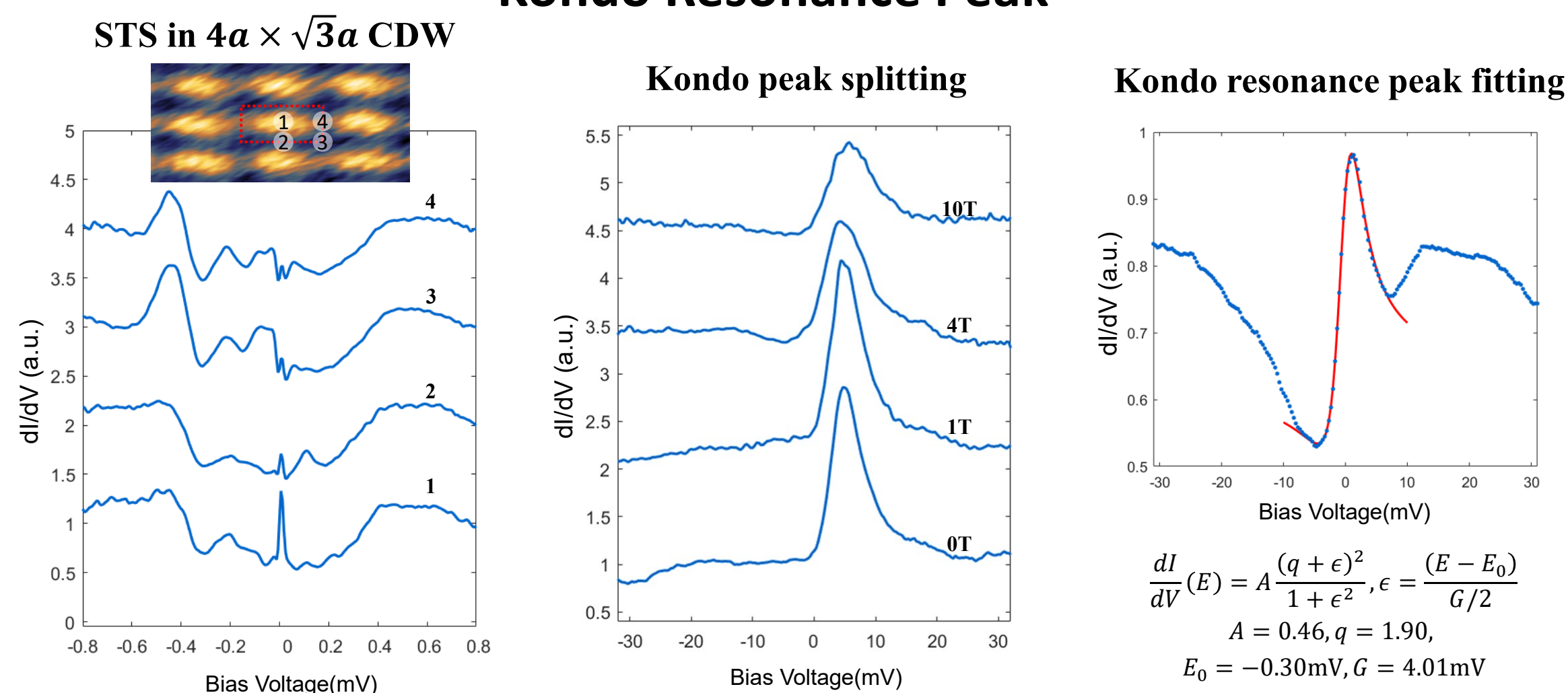- Is there any other quantum states changing as CDW changing?

## Result

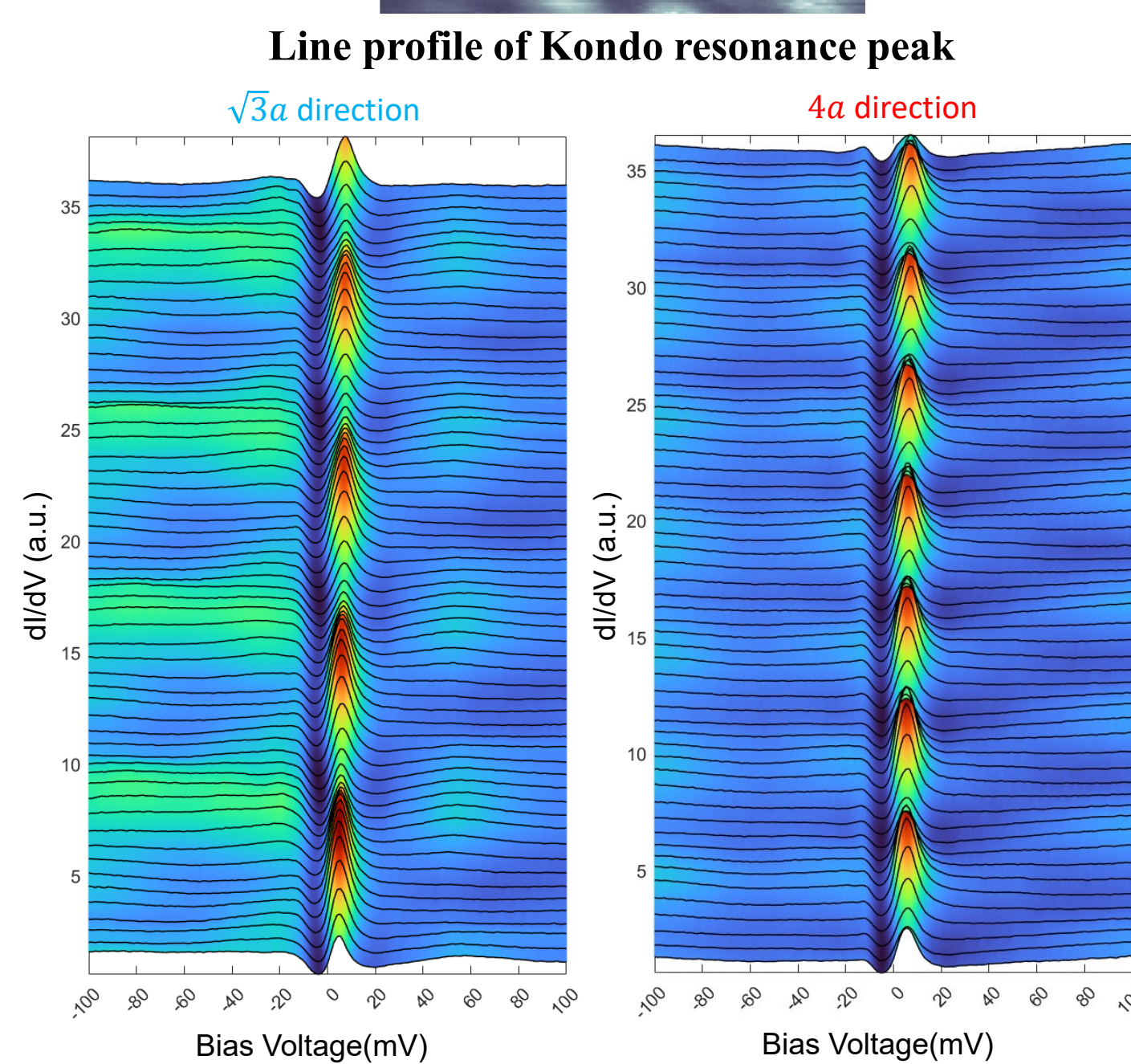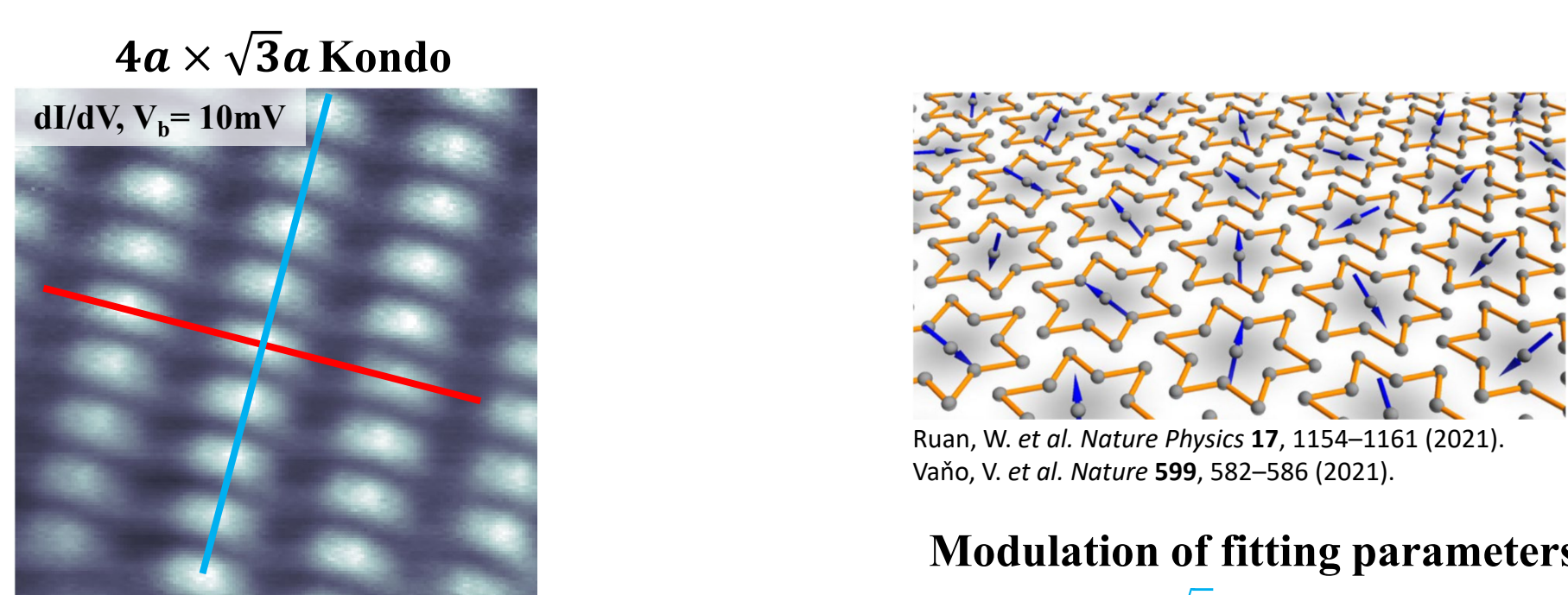### Film Characteristic of 1T-VSe₂

**STM image of VSe₂ film** | **Atomic resolution of VSe₂** | **FFT of lattice and CDW**



### Kondo Resonance Peak

**STS in $4a \times \sqrt{3}a$ CDW** | **Kondo peak splitting** | **Kondo resonance peak fitting**



$$\frac{dI}{dV}(E) = A\frac{(q+\epsilon)^2}{1+\epsilon^2}, \epsilon = \frac{(E-E_0)}{G/2}$$
$$A = 0.46, q = 1.90,$$
$$E_0 = -0.30mV, G = 4.01mV$$

### $4a \times \sqrt{3}a$ Kondo modulation

**$4a \times \sqrt{3}a$ Kondo**



Ruan, W. et al. Nature Physics **17**, 1154–1161 (2021).
Vaño, V. et al. Nature **599**, 582–586 (2021).

**Line profile of Kondo resonance peak**



**Modulation of fitting parameters**
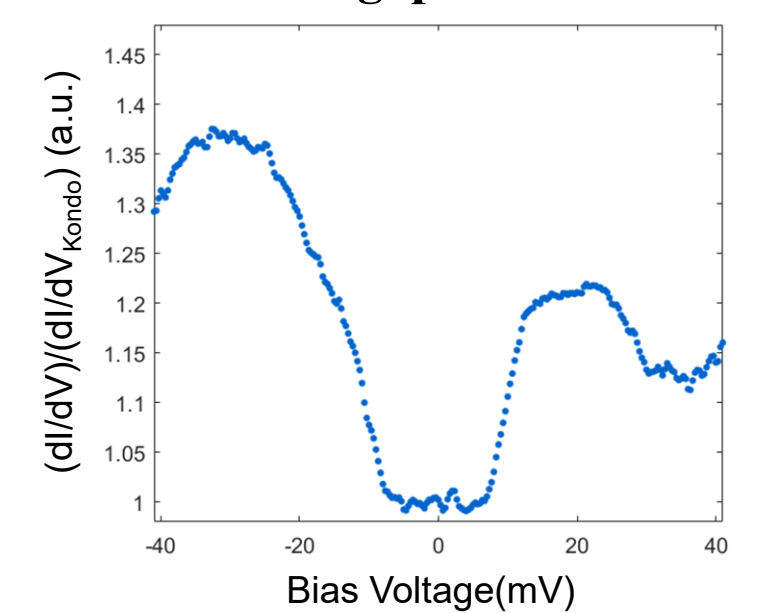


- The Kondo resonance peak exhibits a modulation with the same periodicity as the CDW, suggesting that the local moments inducing Kondo resonance peak may origin from the CDW.
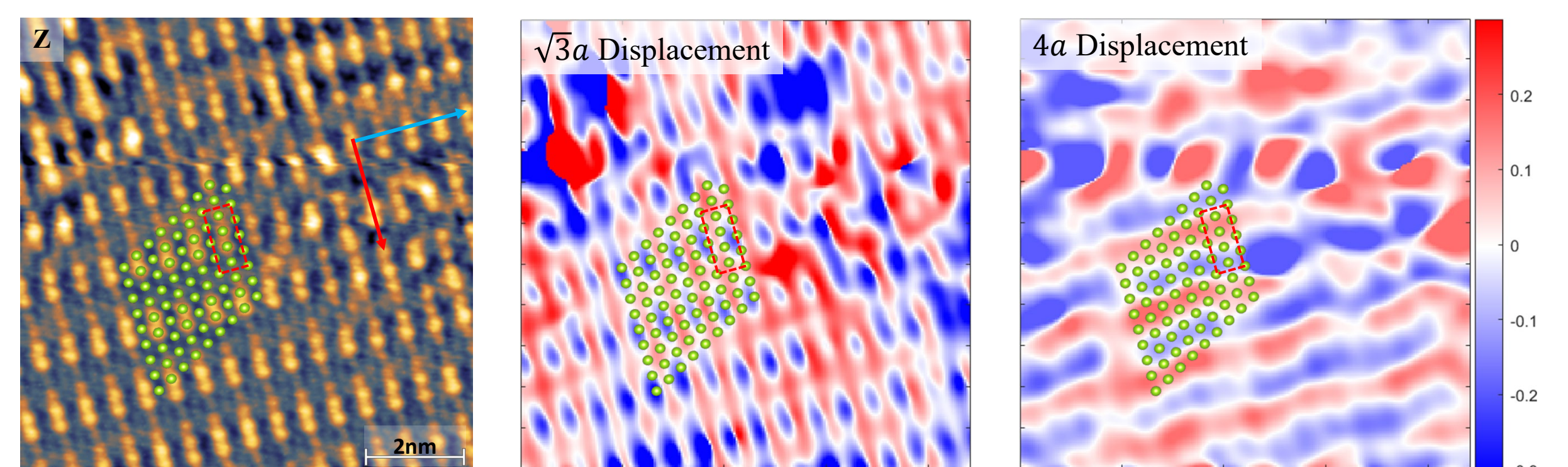
### $4a \times \sqrt{3}a$ CDW



**$\pi$ Phase Shift in CDW**
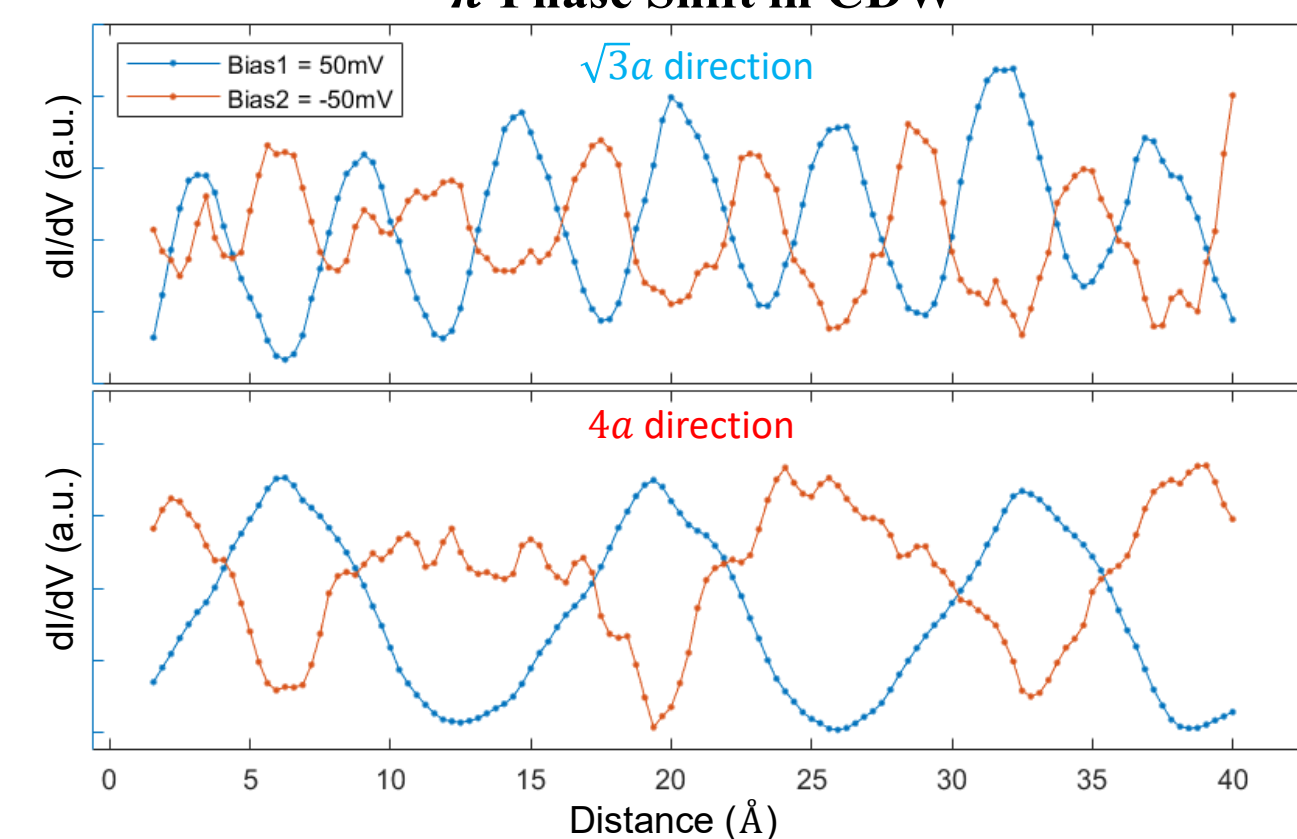


**CDW gap feature**



### Atomic Displacement Analysis



- Atomic Displacement analysis shows that the atoms in a CDW superlattice are divided into a 5-atoms cluster and a 3-atoms cluster, supporting the possible mechanism by which CDW induces local moments.

## Summary

- We observed a $4a \times \sqrt{3}a$ CDW within a VSe₂ multilayer film.
- Kondo resonance peaks are detected in the VSe₂ film, characterized by the same real-space $4a \times \sqrt{3}a$ modulation as that observed for the CDW.
- The analysis of distortion revealed atomic clusters in a $4a \times \sqrt{3}a$ superlattice, which suggest a plausible mechanism through which the CDW may induce local magnetic moments.