# Journal club
# Zumbühl Group

Henok Weldeyesus

09.12.2022

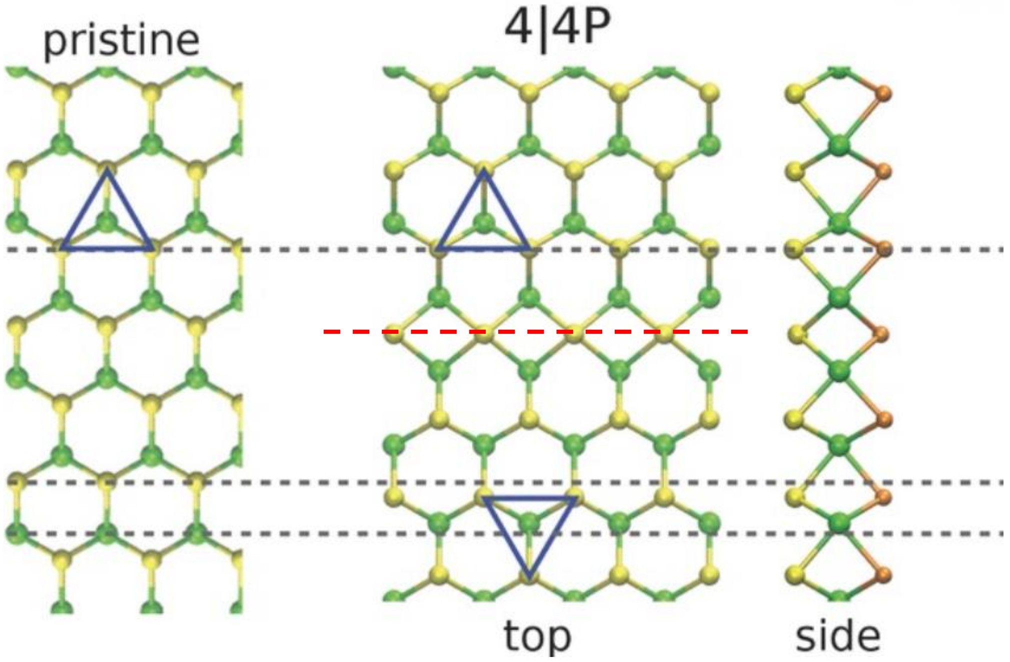
## Imaging gate-tunable Tomonaga–Luttinger liquids in 1H-$MoSe_2$ mirror twin boundaries

Tiancong Zhu[1,2,11], Wei Ruan[1,2,3,11] ✉, Yan-Qi Wang[1,2,11], Hsin-Zon Tsai[2], Shuopei Wang[4,5], Canxun Zhang[2,6], Tianye Wang[1,2], Franklin Liou[2,6], Kenji Watanabe[7], Takashi Taniguchi[8], Jeffrey B. Neaton[1,2], Alexander Weber-Bargioni[1,9], Alex Zettl[1,2,6], Z. Q. Qiu[1,2], Guangyu Zhang[4,5,10], Feng Wang[1,2,6] ✉, Joel E. Moore[1,2,6] ✉ and Michael F. Crommie[1,2,6] ✉

**One-dimensional electron systems exhibit fundamentally different properties than higher-dimensional systems. For example, electron–electron interactions in one-dimensional electron systems have been predicted to induce Tomonaga–Luttinger liquid behaviour. Naturally occurring grain boundaries in single-layer transition metal dichalcogenides exhibit one-dimensional conducting channels that have been proposed to host Tomonaga–Luttinger liquids, but charge density wave physics has also been suggested to explain their behaviour. Clear identification of the electronic ground state of this system has been hampered by an inability to electrostatically gate such boundaries and tune their charge carrier concentration. Here we present a scanning tunnelling microscopy and spectroscopy study of gate-tunable mirror twin boundaries in single-layer 1H-$MoSe_2$ devices. Gating enables scanning tunnelling microscopy and spectroscopy for different mirror twin boundary electron densities, thus allowing precise characterization of electron–electron interaction effects. Visualization of the resulting mirror twin boundary electronic structure allows unambiguous identification of collective density wave excitations having two velocities, in quantitative agreement with the spin-charge separation predicted by finite-length Tomonaga–Luttinger liquid theory.**

# 1H-$MoSe_2$ mirror twin boundaries

- Twin defect: “merger” of two lattices
- Mirror twin boundary:
  - Twinning plane creates mirror symmetries between to crystals





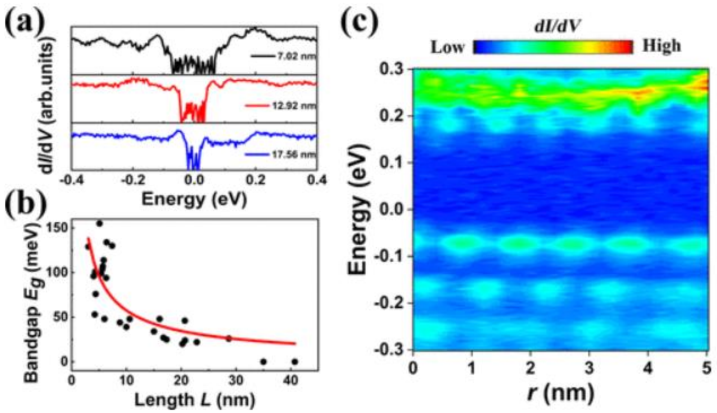

Hannu-Pekka Komsa, Arkady V. Krasheninnikov; Adv. Electron.Mater.2017, 3, 1600468

# Background

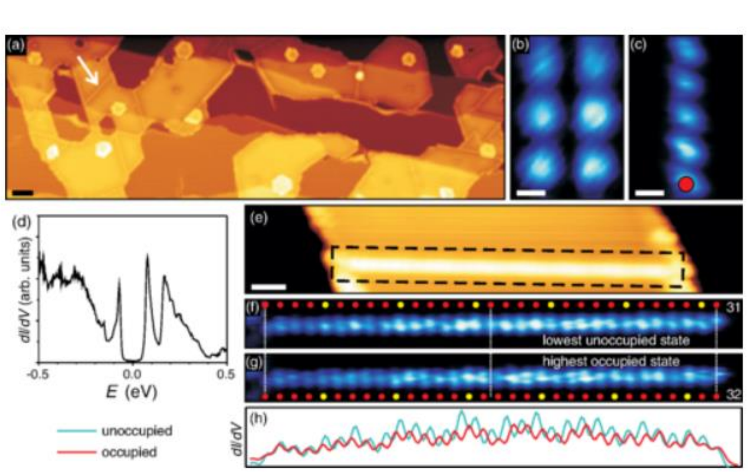
- Clean 1d systems are hard to make
  - Hard to get strong confinement (gate definend system)
  - Hard to get clean (impurities, rough potential landscape)
  - (for STM) hard to access (i.e. CEO - Wires)
- Mirror Twin boundaries are:
  - Easy to access with STM
  - Strong confinement
  - “simple” to fabricate

# Background – previous work

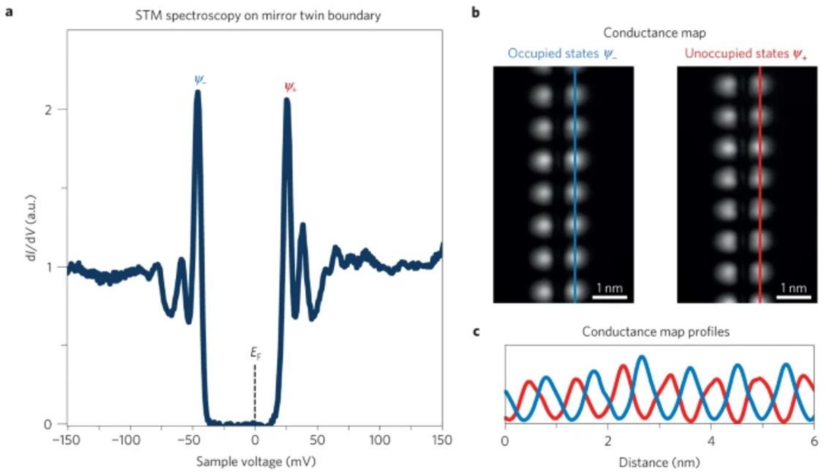
- Dispute between Charge density wave / Luttinger liquid
- Different Type of MTBs where studied
- <u>Whats new? </u> Backgate for control of density




Yipu Xia et al.,
ACS Nano 2020 14 (8), 10716-10722




W. Jolie et al.; Phys. Rev. X 2019 9, 011055

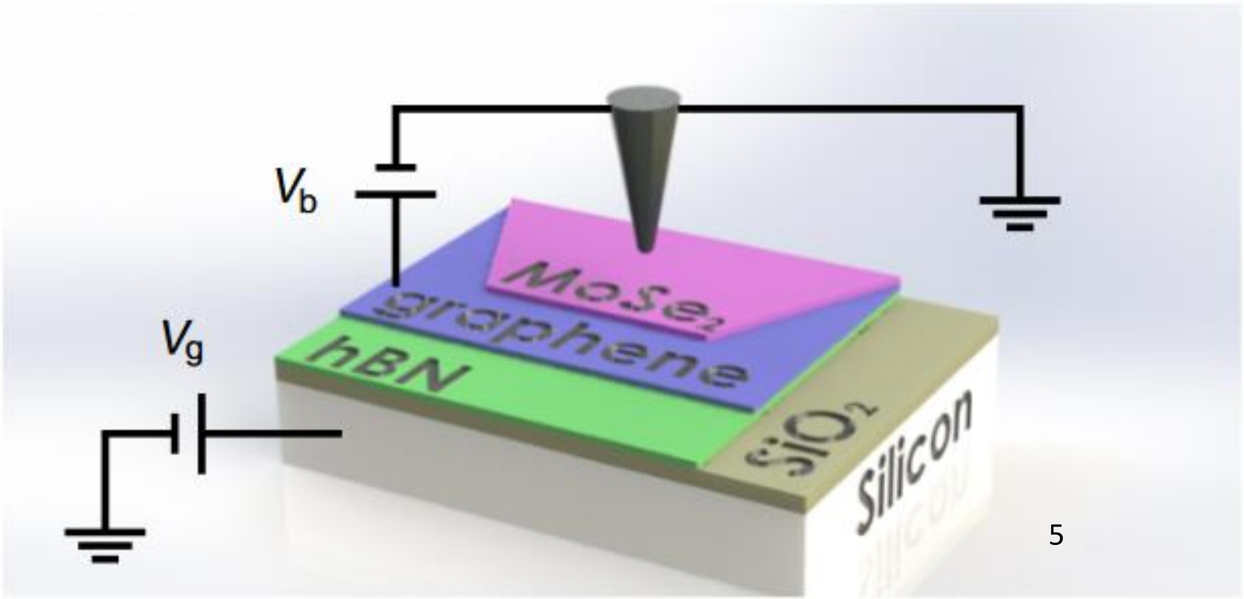



Barja, S. et al.. Nature Phys 12, 751–756 (2016)

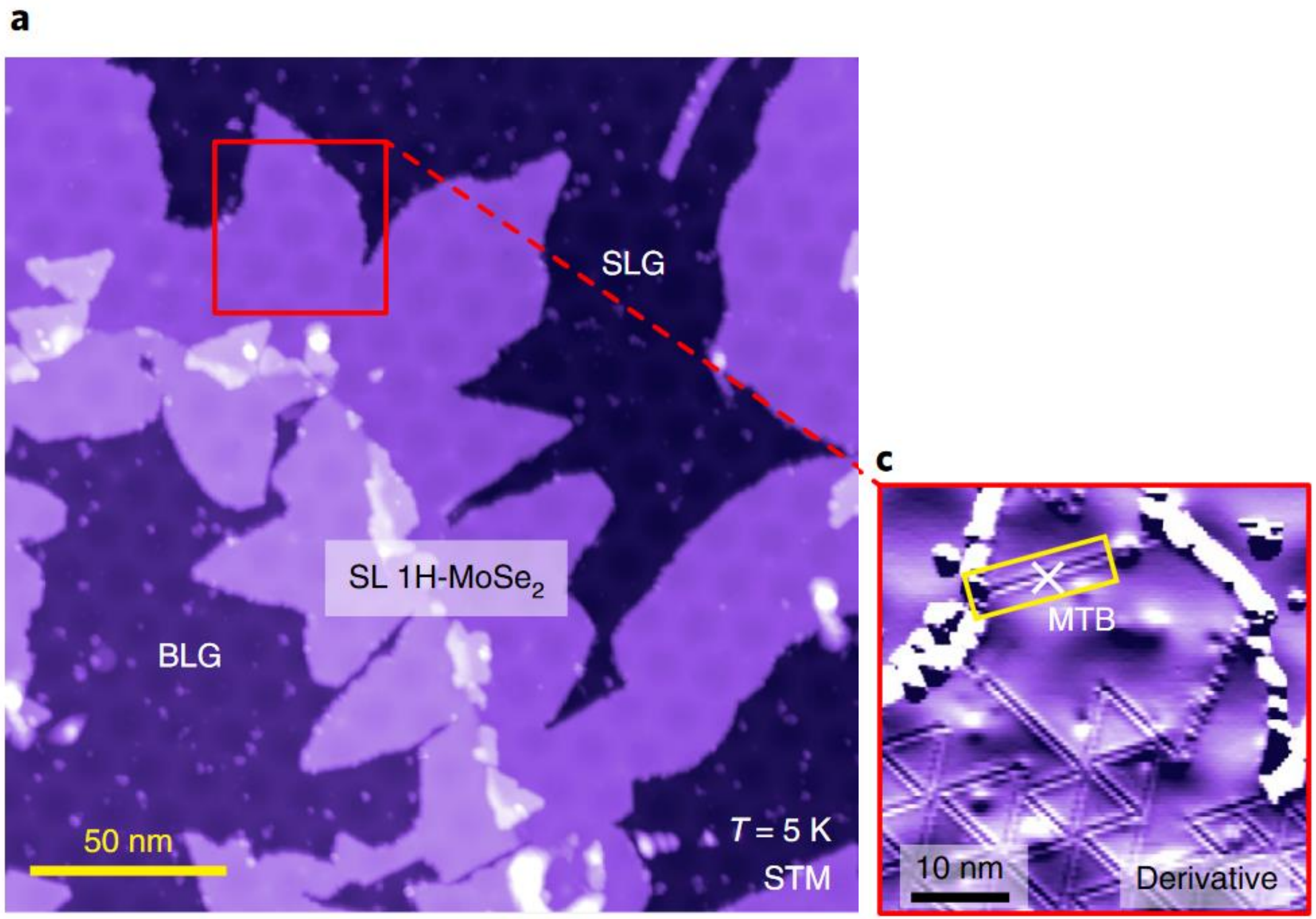
# Device

- Epitaxial Graphen on h-BN (R-PECVD)
- MoSe2 grown in MBE
- Sample  is capped with Se
  - Secapping-layer removed before measurement

b

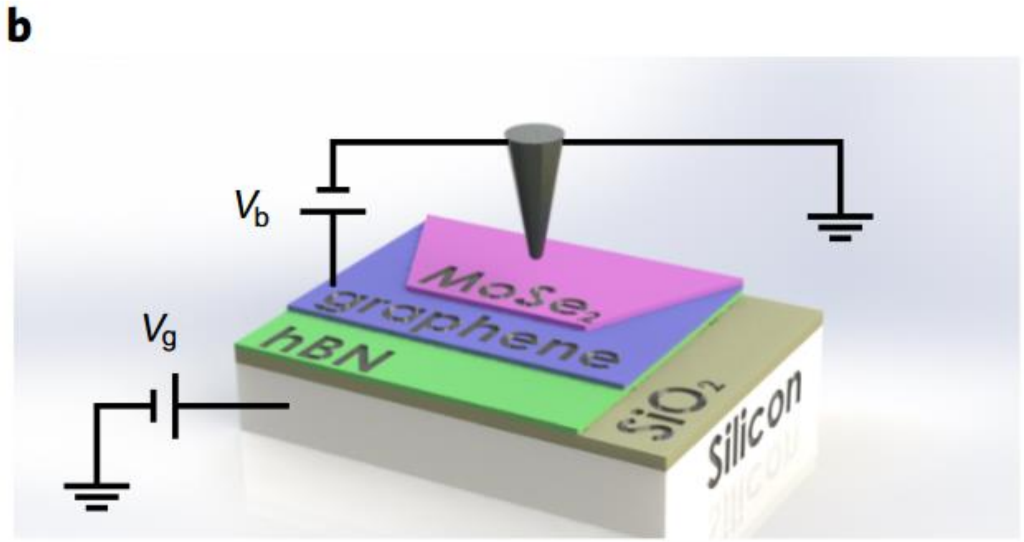


# Large scale STm measurement

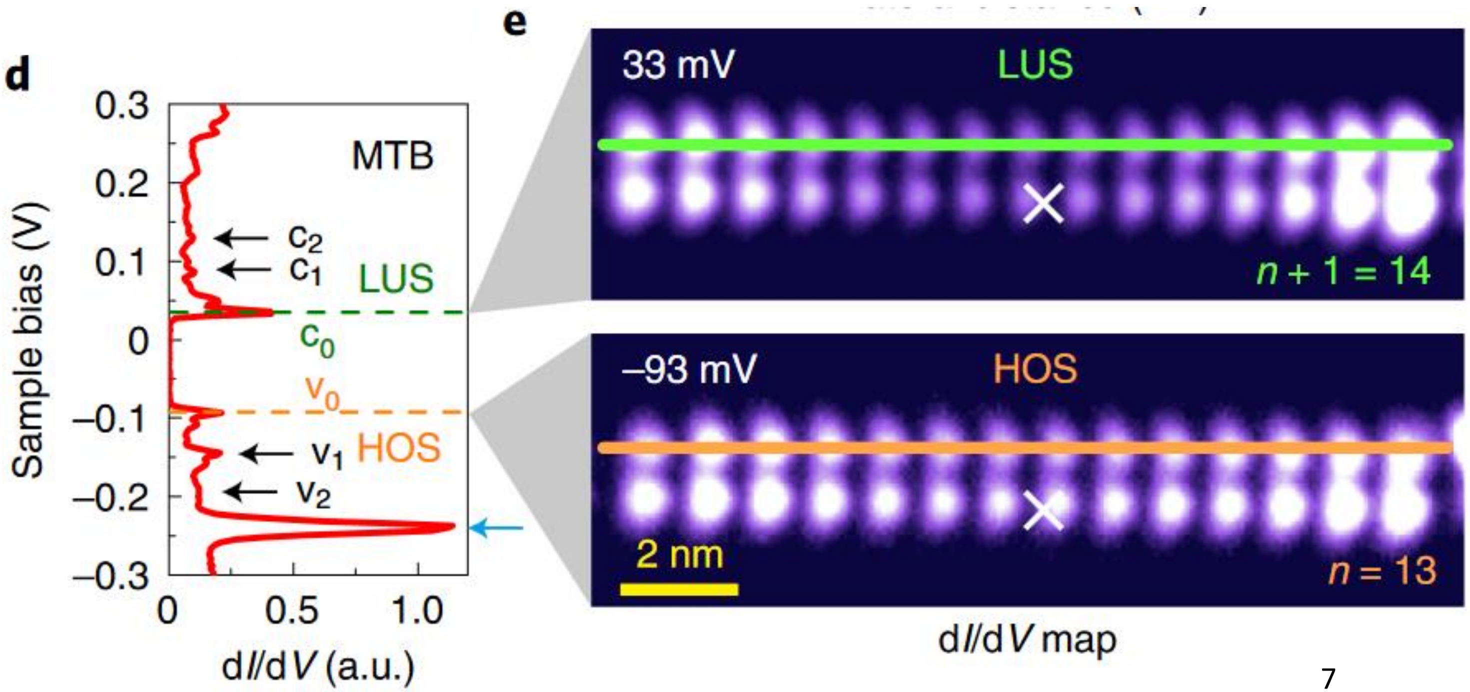


# Local density of states(LDOS)

- *dI/dV* ~ LDOS ~ $|\psi(x)|^2$

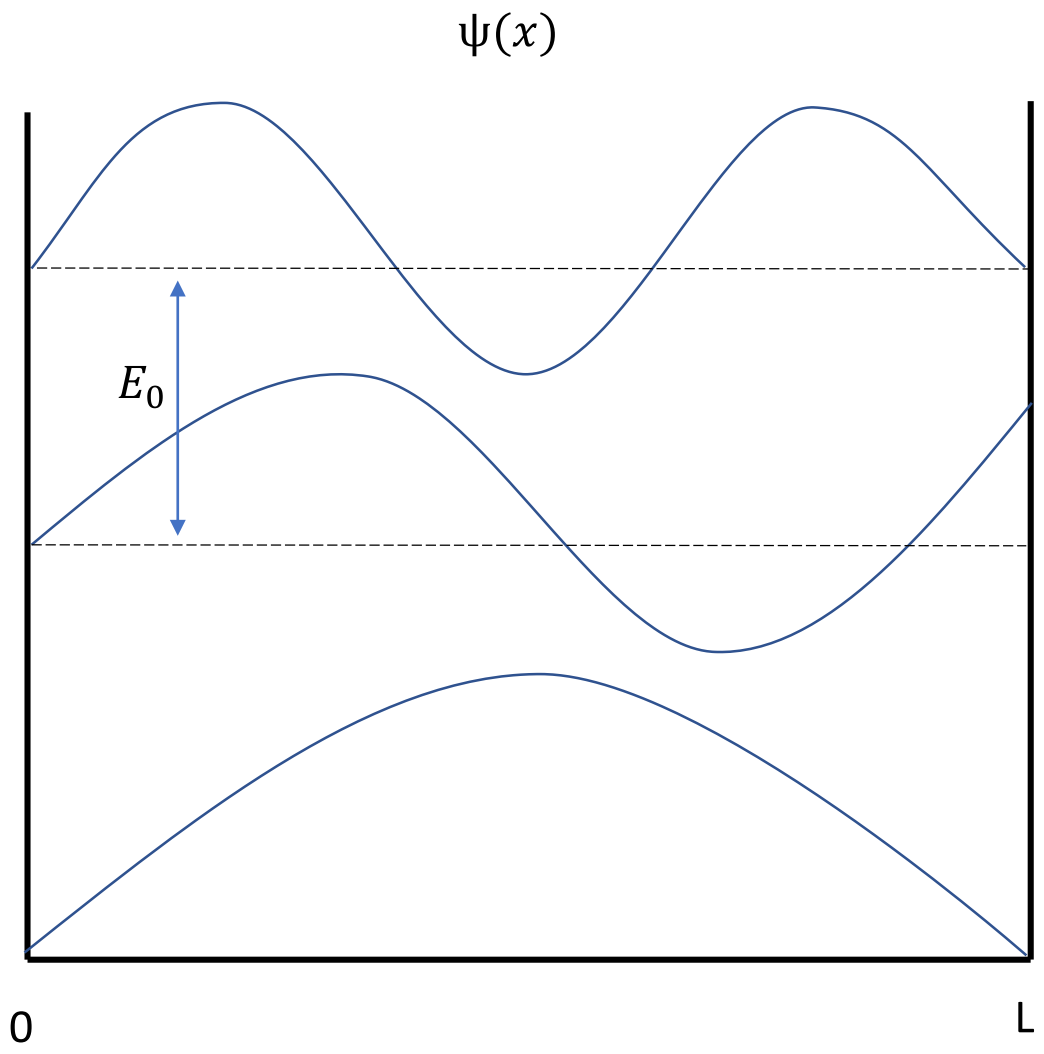


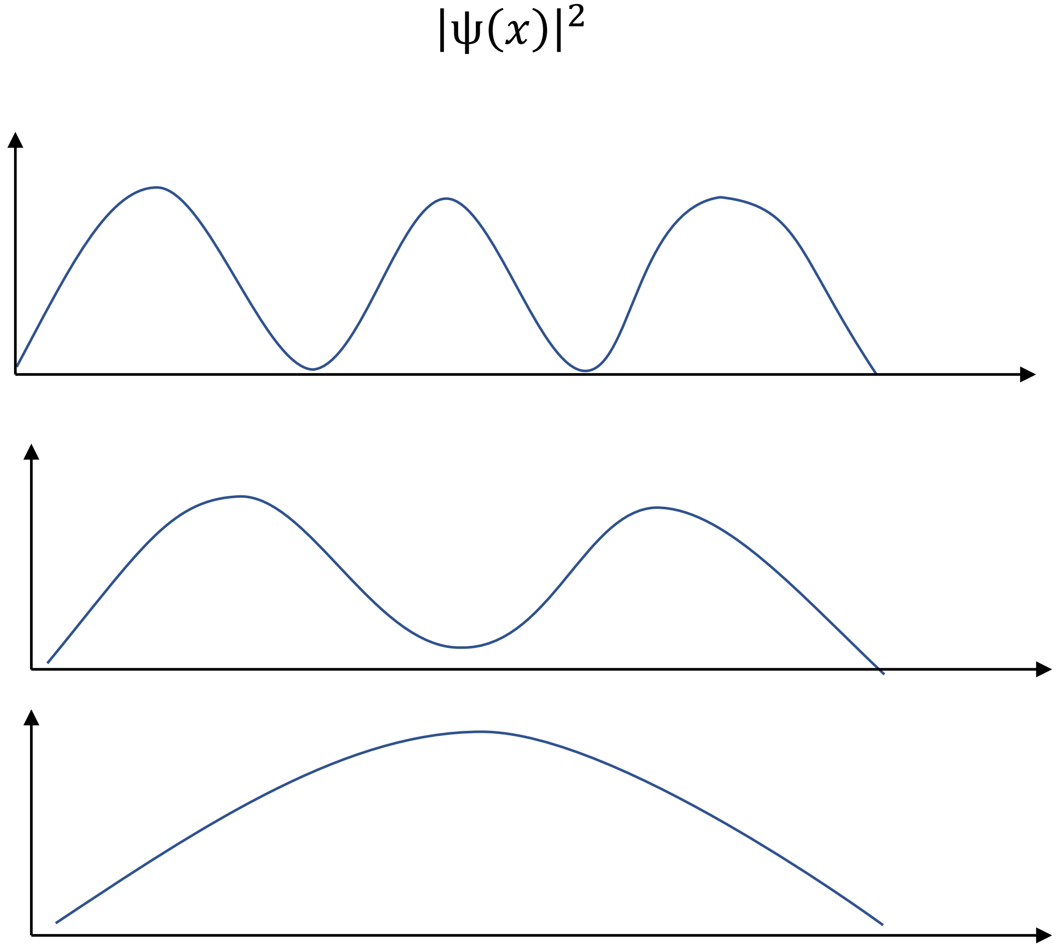

Constant height + bias voltage




LUS = Lowest Unocupied State
HOS = Highest Occupied State

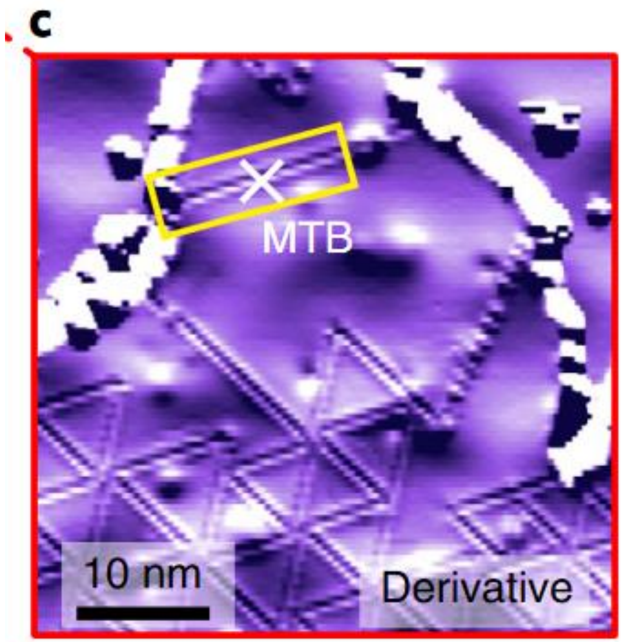
# "Excursion": infinitely deep quantum well

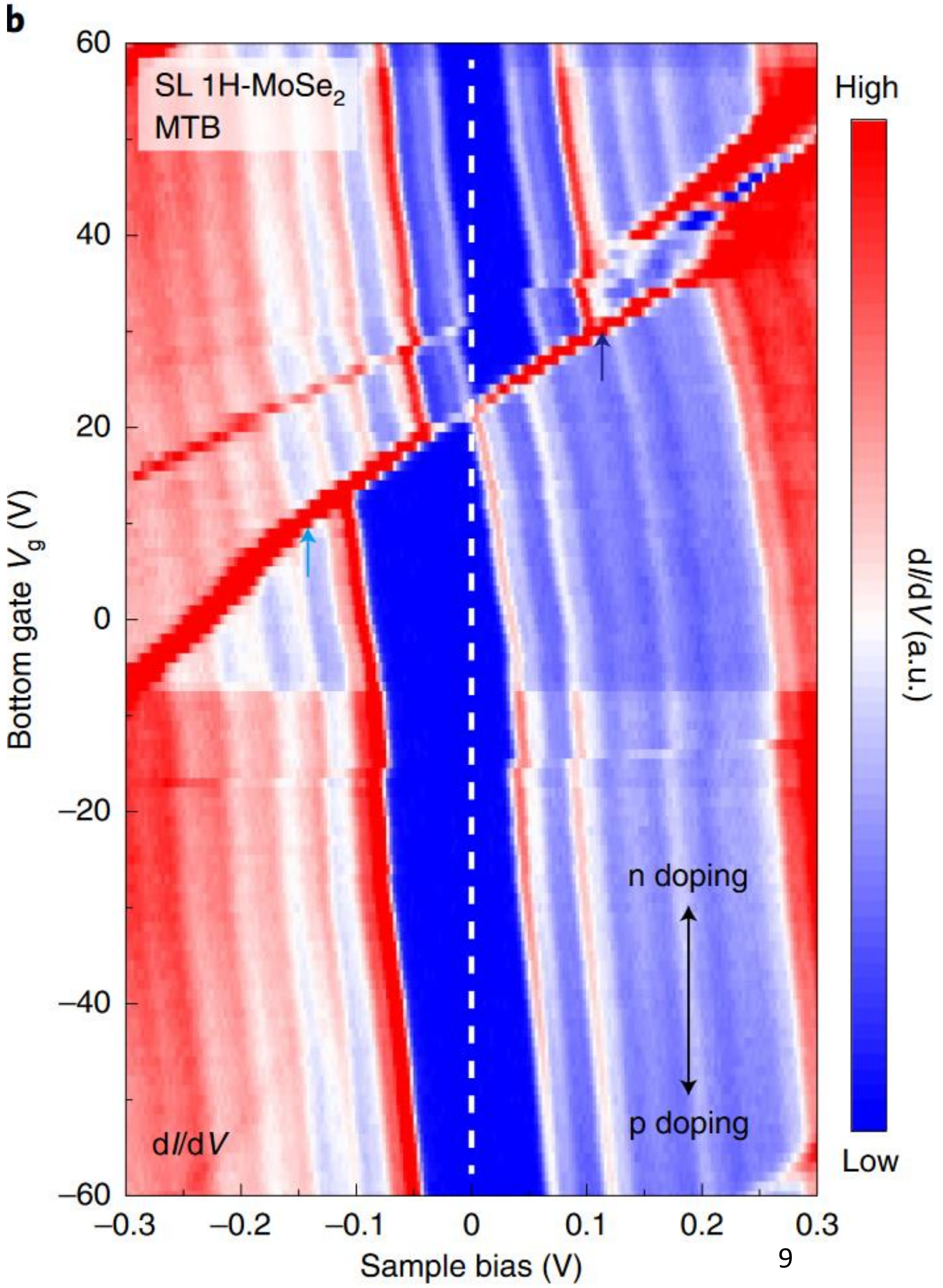


# Density dependence

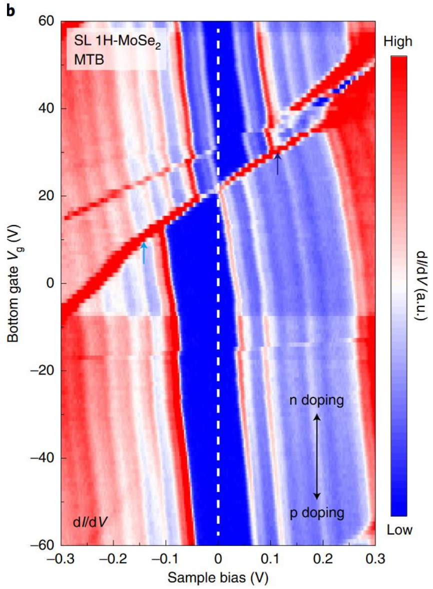
- Doped silicone used as backgate
- Gap size varies with occupation



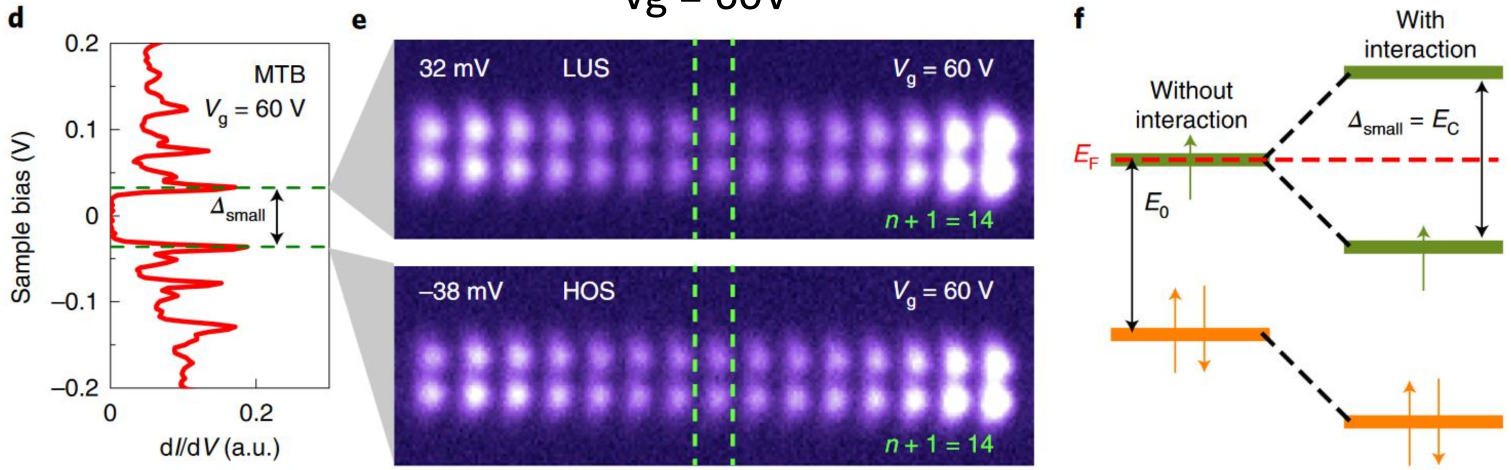



- Number of nodes changes for big gap

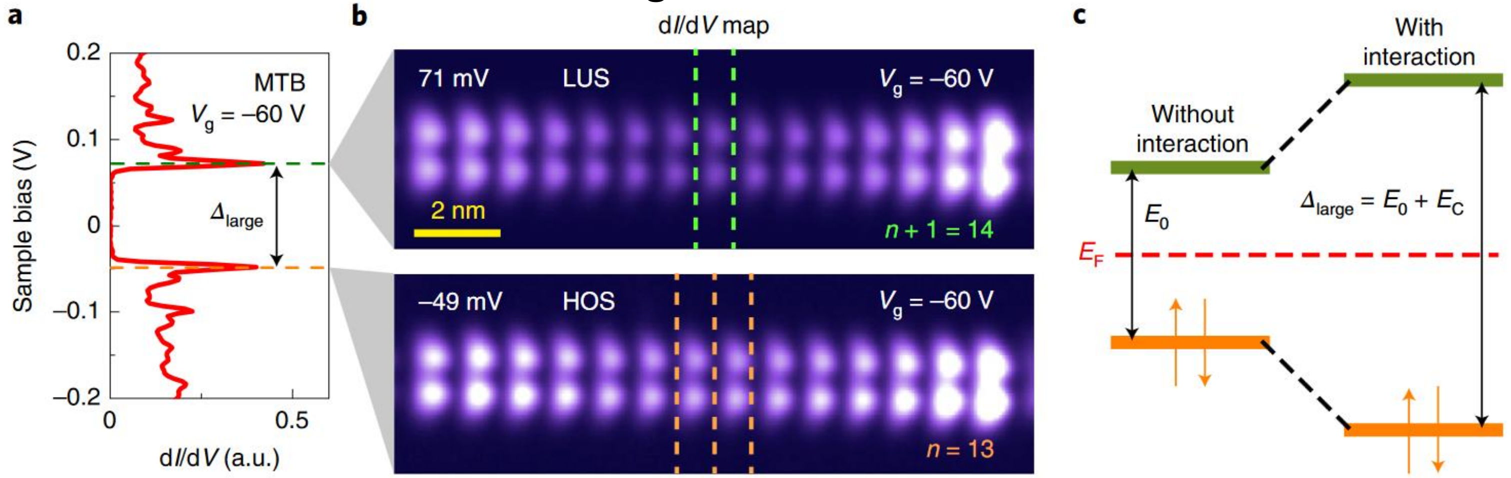
- stays same for small gap

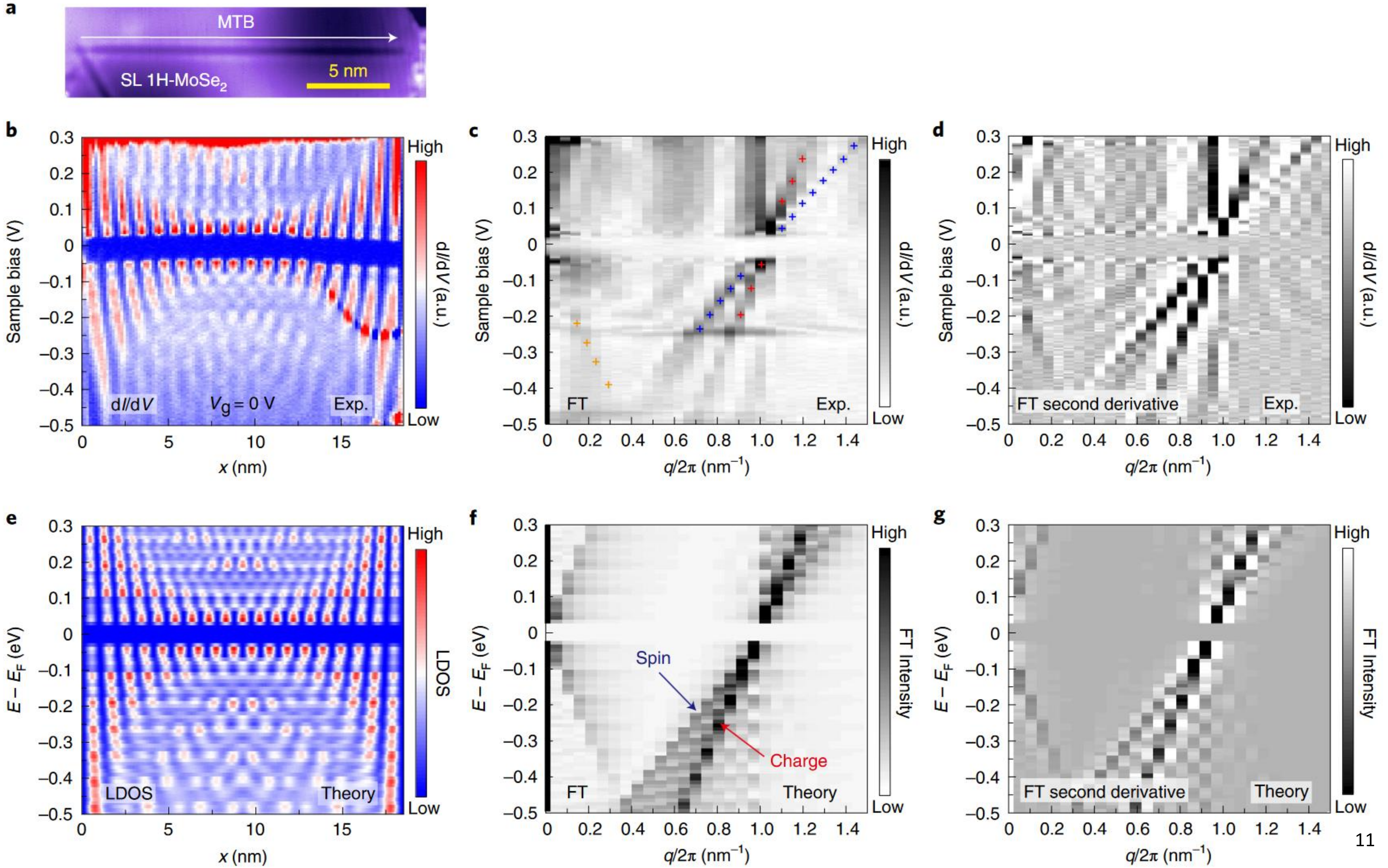



Vg = 60V




Vg = -60V

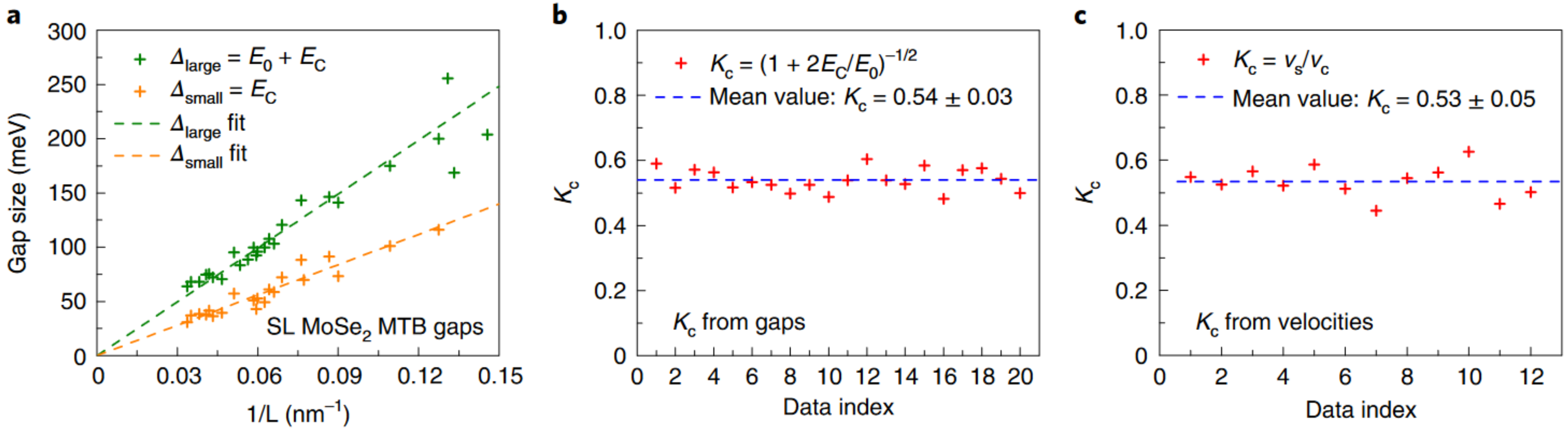




a
MTB
SL 1H-MoSe2
5 nm
b
Sample bias (V)
dI/dV
$V_g = 0$ V
Exp.
x (nm)
High
Low
dI/dV (a.u.)
c
FT
Exp.
q/2π (nm⁻¹)
d
FT second derivative
Exp.
e
$E - E_F$ (eV)
LDOS
Theory
f
Spin
Charge
FT Intensity
g

# Result:

- Two ways of extracting $K_c$
  - From velocities: $K_c = v_s / v_c$
  - From Gap sizes: $K_c = \left(1 + \frac{2E_c}{E_0}\right)^{-\frac{1}{2}}$



# Summary

- Mirror twin boundaries in $MoSe_2$ host 1d systems
- Back-gate allows to study different configurations
- Interaction parameter from different methods agree well