Topological superconductivity in designer van der Waals heterostructures

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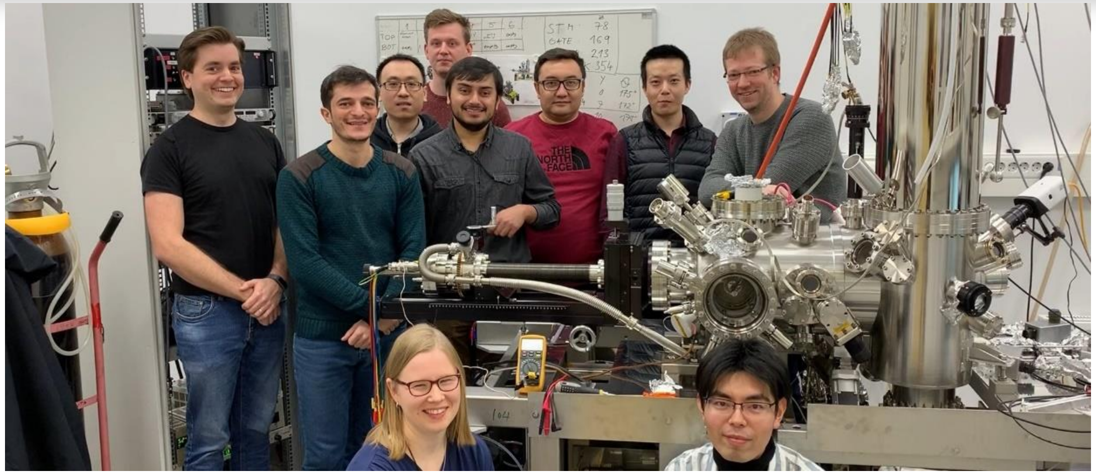
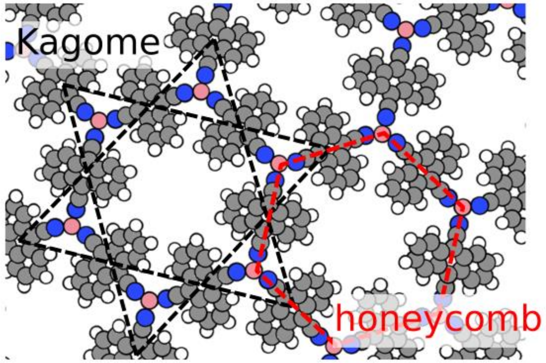
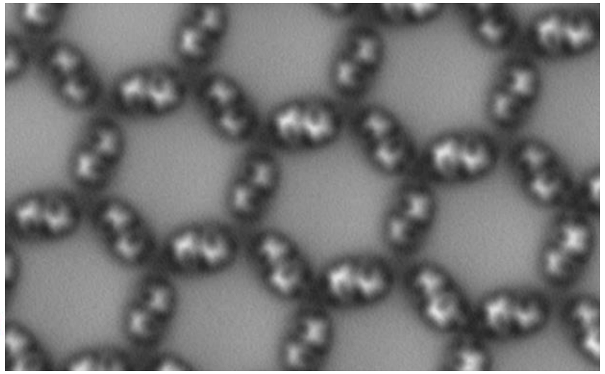
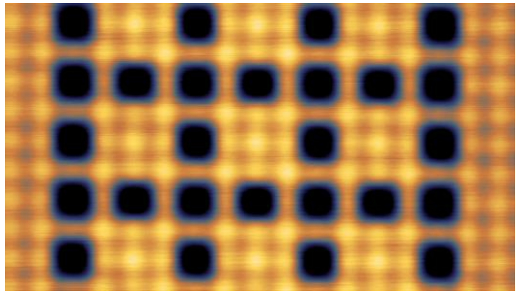


Physics of designer materials

- **Designer materials**: control geometry, unit cell, interactions...
  - You can think in terms of simple tight-binding $\Rightarrow$ engineered electronic structure
  - modulate hoppings
  - lattice symmetry (honeycomb, kagome, Lieb etc.)
  - spin-orbit interaction and magnetism (topological insulators etc.)
- Different experimental realizations



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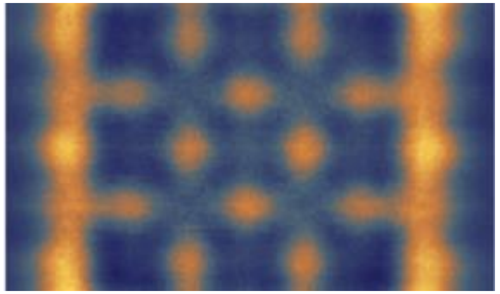
LDOS

ADVANCES IN PHYSICS: X
2019, VOL. 4, NO. 1, 1651672
https://doi.org/10.1080/23746149.2019.1651672

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REVIEW

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Engineered electronic states in atomically precise artificial lattices and graphene nanoribbons

Linghao Yan and Peter Liljeroth

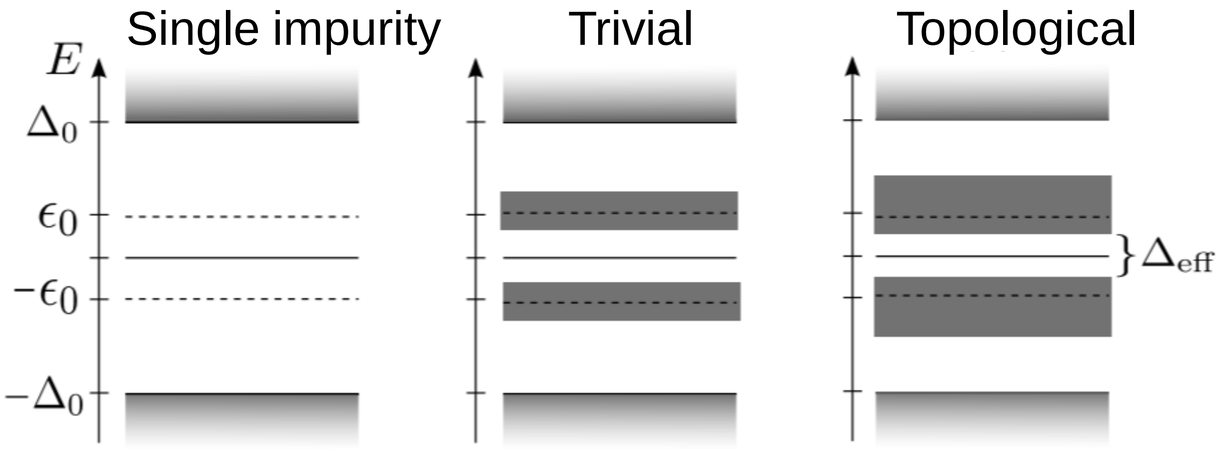
Creating designer quantum states of matter atom-by-atom

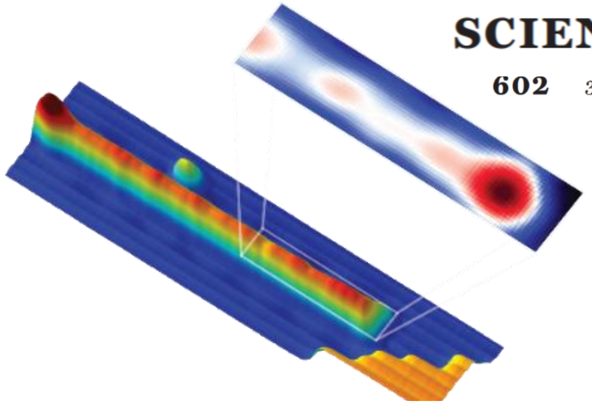
Alexander A. Khajetoorians, Daniel Wegner, Alexander F. Otte & Ingmar Swart

Nature Reviews Physics (2019) | Download Citation

Mixing magnetism and superconductivity

- Single spins give rise to Yu-Shiba-Rusinov bound states
  - see all the work from the Pascual and Franke groups (e.g. B. Heinrich, Prog. Surf. Sci. 93, 1 (2018))
- Neighboring YSR states can hybridize and form coupled states
- Larger assemblies – YSR bands and possibly topological superconductivity





SCIENCE

602 31 OCTOBER 2014 • VOL 346 ISSUE 6209

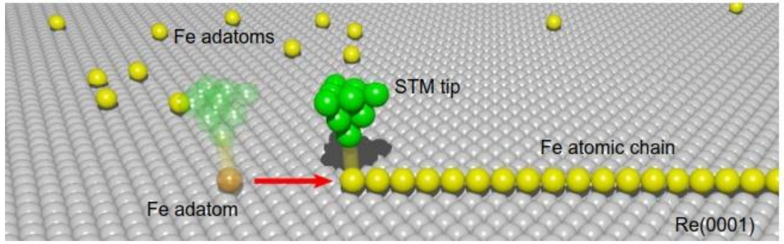
Observation of Majorana fermions in ferromagnetic atomic chains on a superconductor

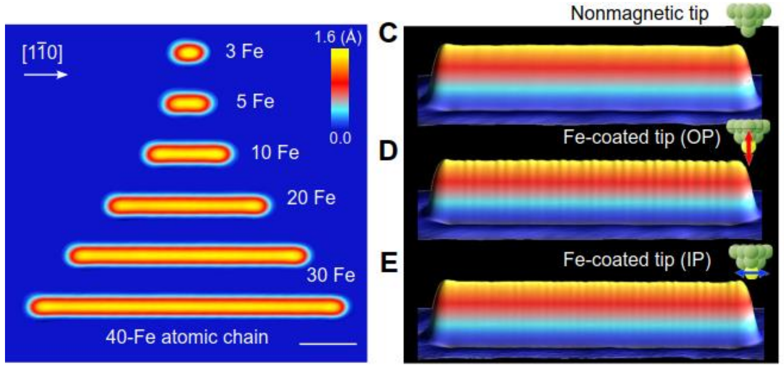
Stevan Nadj-Perge,[1*] Ilya K. Drozdov,[1*] Jian Li,[1*] Hua Chen,[2*] Sangjun Jeon,[1] Jungpil Seo,[1] Allan H. MacDonald,[2] B. Andrei Bernevig,[1] Ali Yazdani[1]†

Toward tailoring Majorana bound states in artificially constructed magnetic atom chains on elemental superconductors

Kim *et al.*, *Sci. Adv.* 2018; **4**:eaar5251

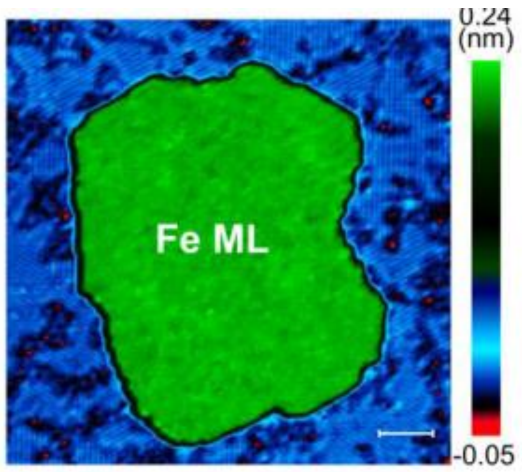
Howon Kim,[1]* Alexandra Palacio-Morales,[1] Thore Posske,[1] Levente Rózsa,[1] Krisztián Palotás,[2,3] László Szunyogh,[4] Michael Thorwart,[1] Roland Wiesendanger[1]*



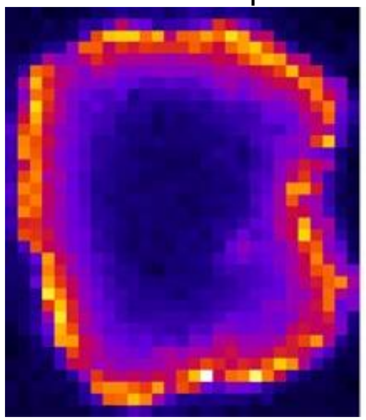


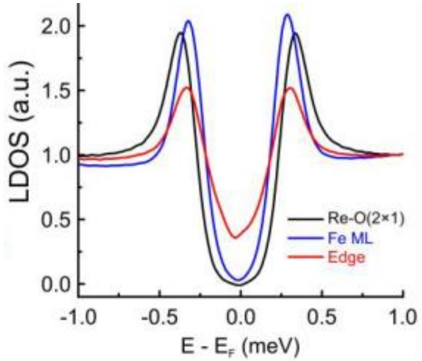
Topological superconductivity in 2D

- 1D Majorana edge modes
- Depends on substrate spin-orbit and magnetic texture of the lattice
- Potentially a rich variety of different Chern numbers



LDOS at E_F





A. Palacio-Morales et al., Sci. Adv. 5, eaav6600 (2019)

PRL 114, 236803 (2015) PHYSICAL REVIEW LETTERS week ending 12 JUNE 2015

Topological Superconductivity and High Chern Numbers in 2D Ferromagnetic Shiba Lattices

Joel Röntynen and Teemu Ojanen*
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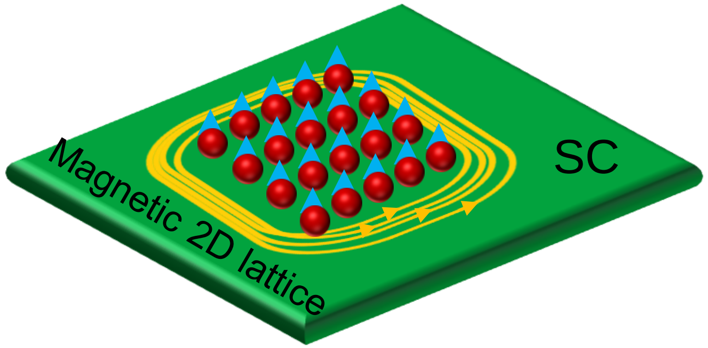
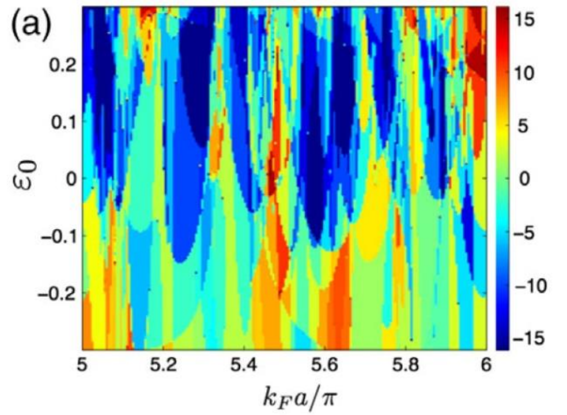
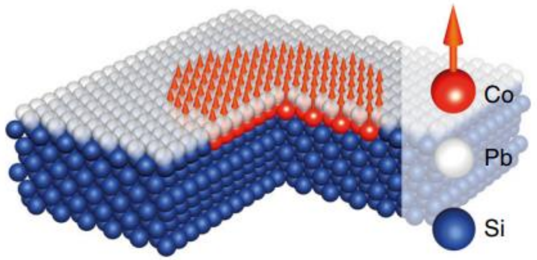
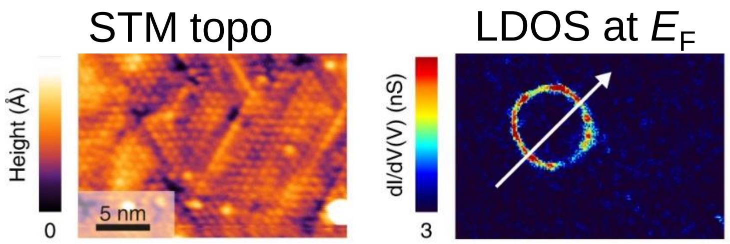
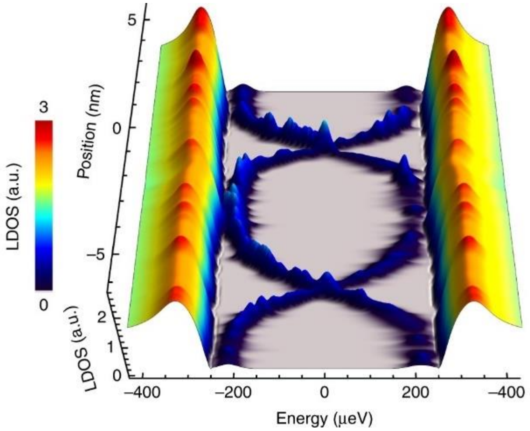
(Received 18 December 2014; published 12 June 2015)









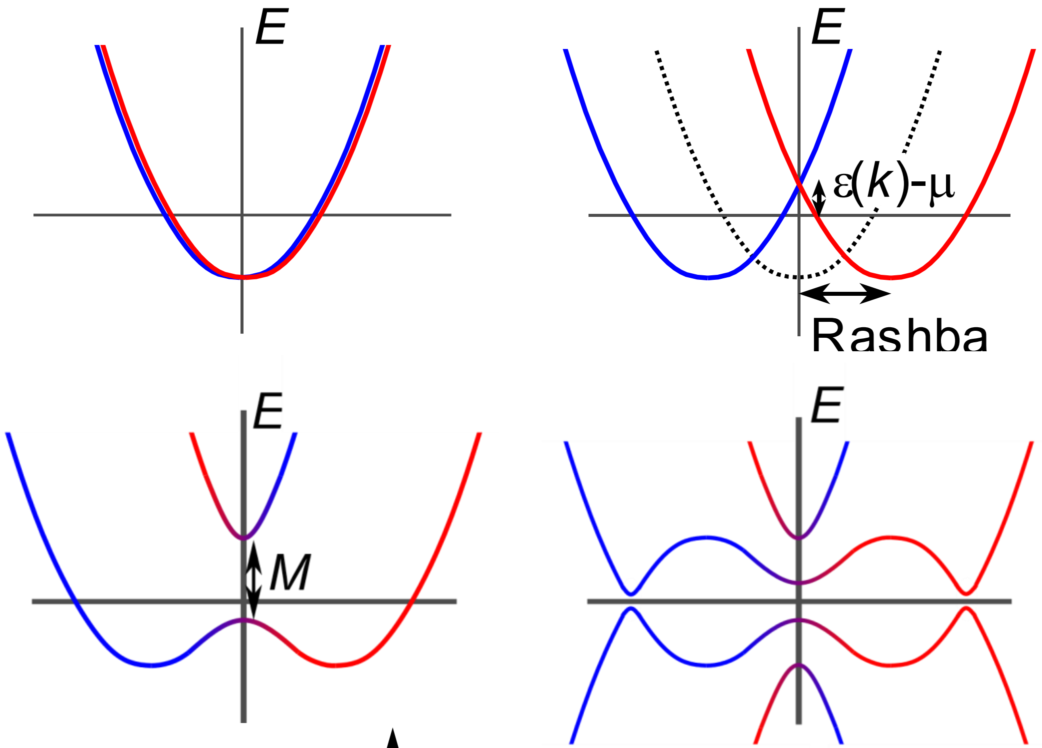


G. Ménard et al. Nat. Commun. 8, 2040 (2017)

Topological superconductivity

Standard recipe

1. Start with a simple parabolic band
2. Add Rashba spin-orbit coupling α
3. Add Zeeman term *M* (perpendicular to spin-orbit)
4. Add superconductivity Δ

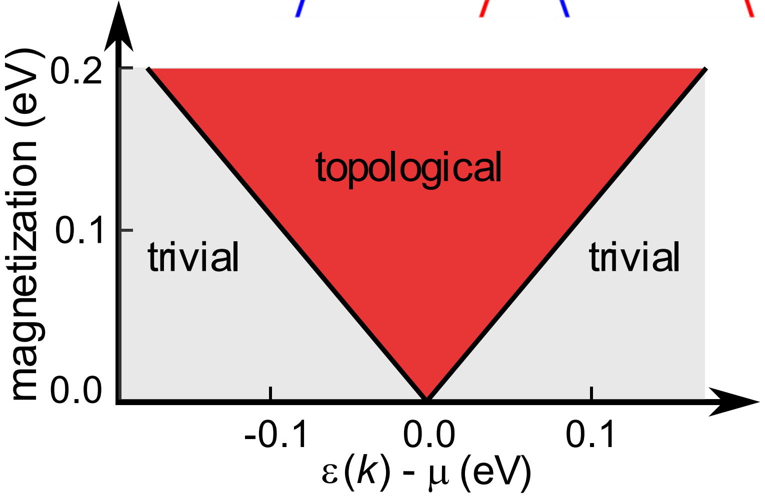


- Condition for the topological phase

$$|\epsilon(\vec{k_0}) - \mu| \leq M$$

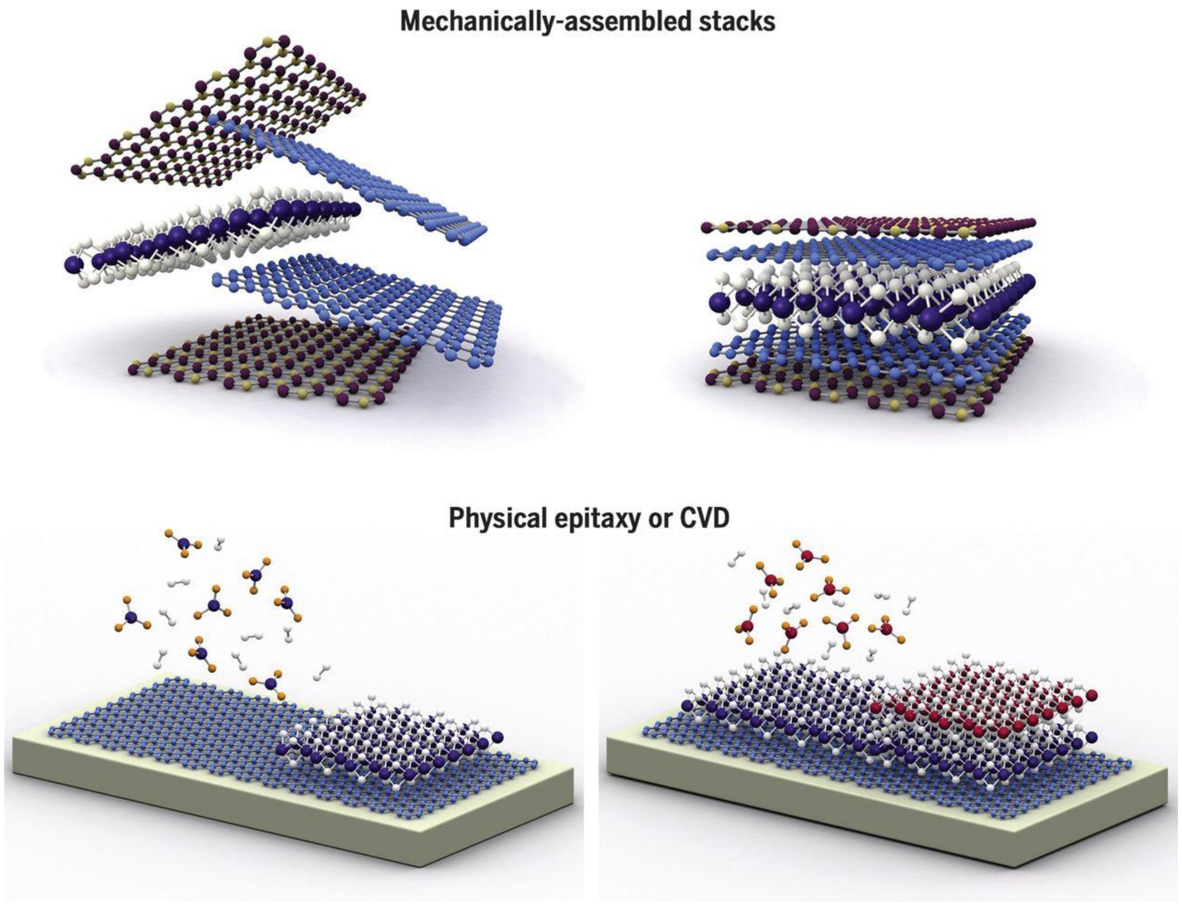
- The topological gap is

$$\Delta_t = \frac{\alpha k_F}{[(\alpha k_F)^2 + M^2]^{1/2}} \Delta$$



Van der Waals designer materials?

- Combine completely different materials in lateral or vertical heterostructures
- Weak vdW bonding between the layers
  ⇒ Layers retain their intrinsic properties
- Look for new phenomena that arise from the interaction between the layers
- Sample preparation: ensure clean edges and interfaces by using in-situ growth via e.g. molecular-beam epitaxy (MBE)



Review: K. S. Novoselov et al. Science 353, aac9439 (2016)

Combine 2D magnetic layers with interesting substrates

- Discovery of ferromagnetism in van der Waals crystals: CrI_3 and $Cr_2Ge_2Te_6$
- Need to be able to grow in situ e.g. by molecular beam epitaxy with out of plane magnetization
- Several TMDs (or similar) exhibit ferromagnetism down to a monolayer
  - **VSe_2**: Bonilla et al. Nat. Nanotech. 13, 289 (2018)
  - **VSe_2 / $NbSe_2$**: Kezilebieke et al. Commun. Phys. 3, 116 (2020).
  - **$MnSe_2$**: O'Hara et al. Nano Lett. 18, 3125 (2018)
  - Exact mechanism in TMDs unclear: very weak temperature dependence, small hysteresis and large saturation magnetization

Layer-dependent ferromagnetism in a van der Waals crystal down to the monolayer limit

Bevin Huang[1]*, Genevieve Clark[2]*, Efrén Navarro-Moratalla[3]*, Dahlia R. Klein[3], Ran Cheng[4], Kyle L. Seyler[1], Ding Zhong[1], Emma Schmidgall[1], Michael A. McGuire[5], David H. Cobden[1], Wang Yao[6], Di Xiao[4], Pablo Jarillo-Herrero[3] & Xiaodong Xu[1,2]

270 | NATURE | VOL 546 | 8 JUNE 2017

Discovery of intrinsic ferromagnetism in two-dimensional van der Waals crystals

Cheng Gong[1]*, Lin Li[2]*, Zhenglu Li[3,4]*, Huiwen Ji[5], Alex Stern[2], Yang Xia[1], Ting Cao[3,4], Wei Bao[1], Chenzhe Wang[1], Yuan Wang[1,4], Z. Q. Qiu[3], R. J. Cava[5], Steven G. Louie[3,4], Jing Xia[2] & Xiang Zhang[1,4]

8 JUNE 2017 | VOL 546 | NATURE | 265

REVIEW

https://doi.org/10.1038/s41586-018-0631-z

Magnetism in two-dimensional van der Waals materials

Kenneth S. Burch[1], David Mandrus[2,3] & Je-Geun Park[4,5]*

1 NOVEMBER 2018 | VOL 563 | NATURE | 47

Magnetism in monolayer $CrBr_3$

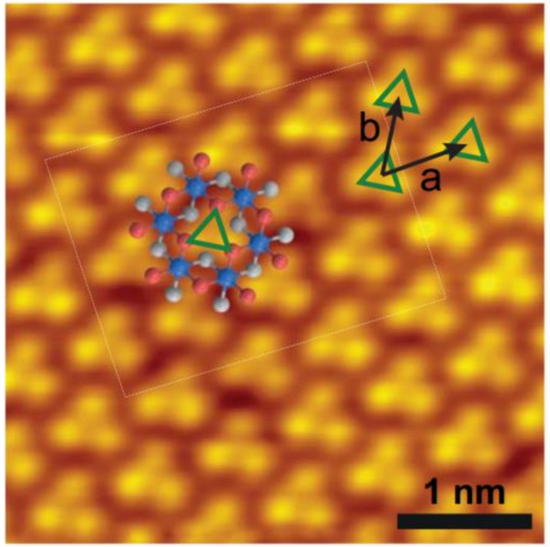
REPORT

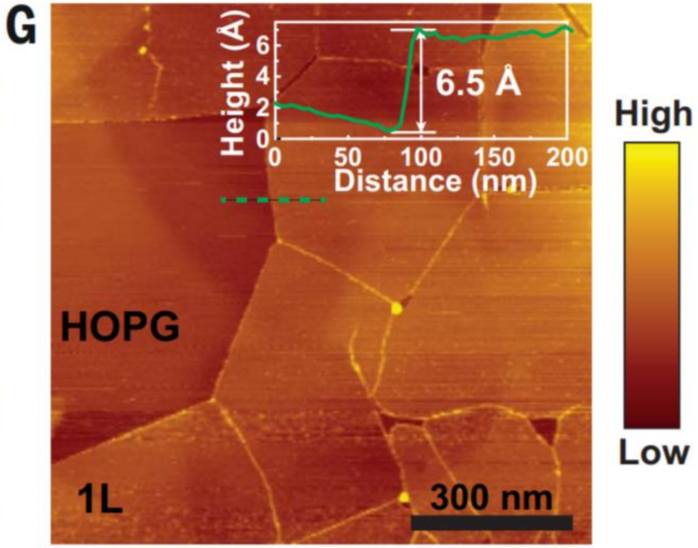
Science 366, 983–987 (2019)

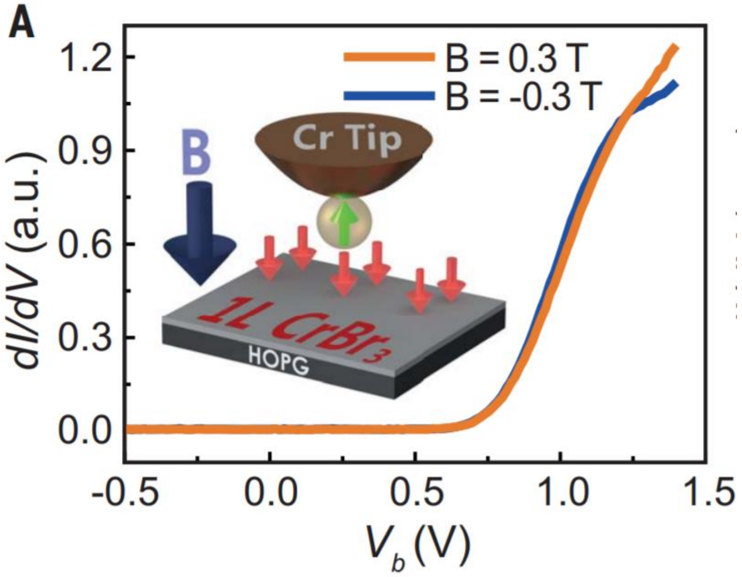
2D MAGNETISM

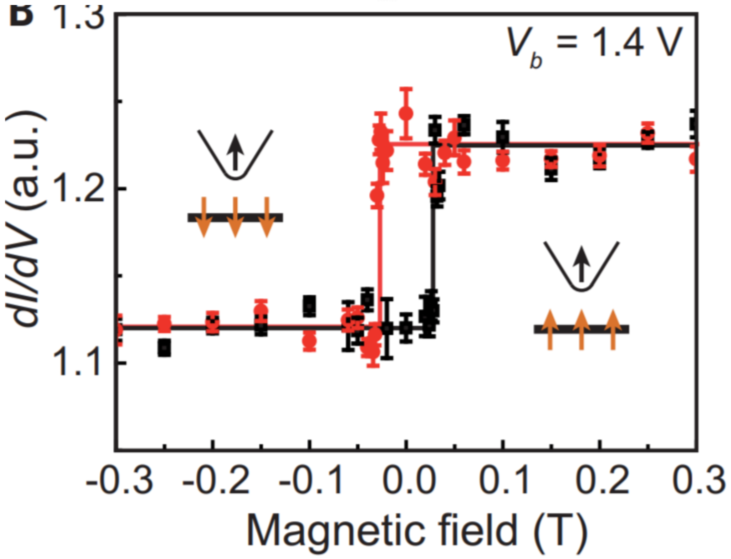
Direct observation of van der Waals stacking–dependent interlayer magnetism

Weijong Chen[1], Zeyuan Sun[1], Zhongjie Wang[1], Lehua Gu[1], Xiaodong Xu[2],
Shiwei Wu[1,3]*, Chunlei Gao[1,3]*



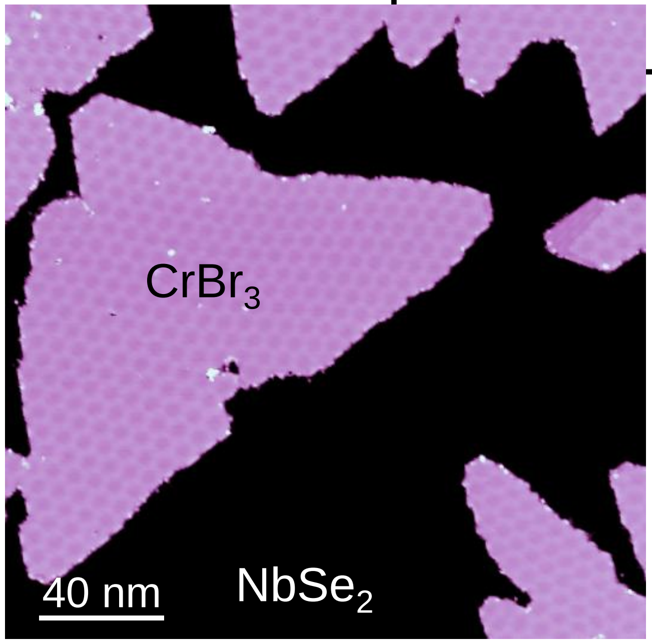


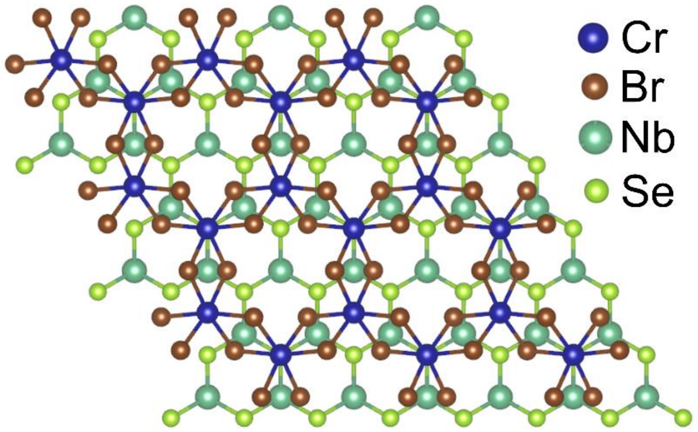


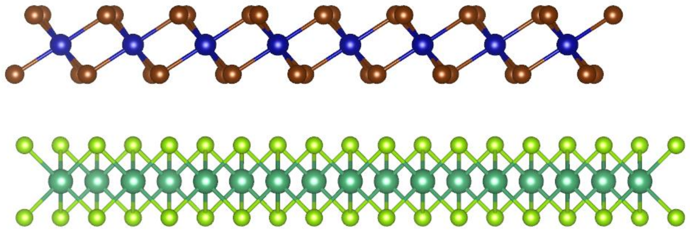


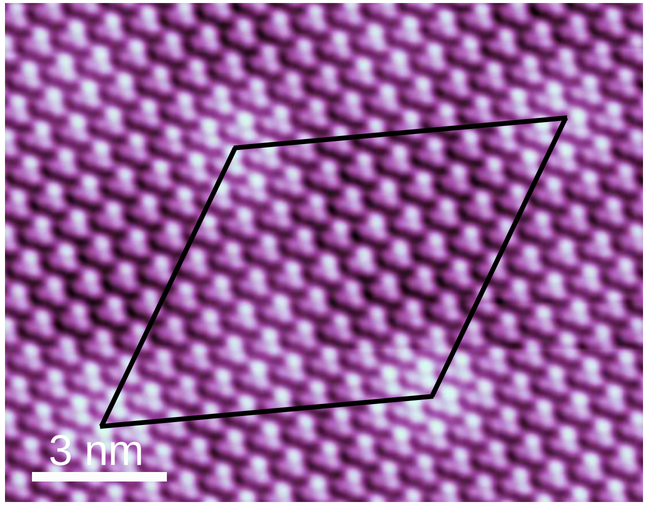
$CrBr_3$ growth on $NbSe_2$

- Compound source MBE on freshly cleaved (under vacuum) $NbSe_2$ in UHV
- $CrBr_3$ powder evaporated from a Knudsen cell
- The optimal substrate temperature for the growth of $CrBr_3$ monolayer films is ~ 270°C
  - Below this temperature, $CrBr_3$ forms disordered clusters





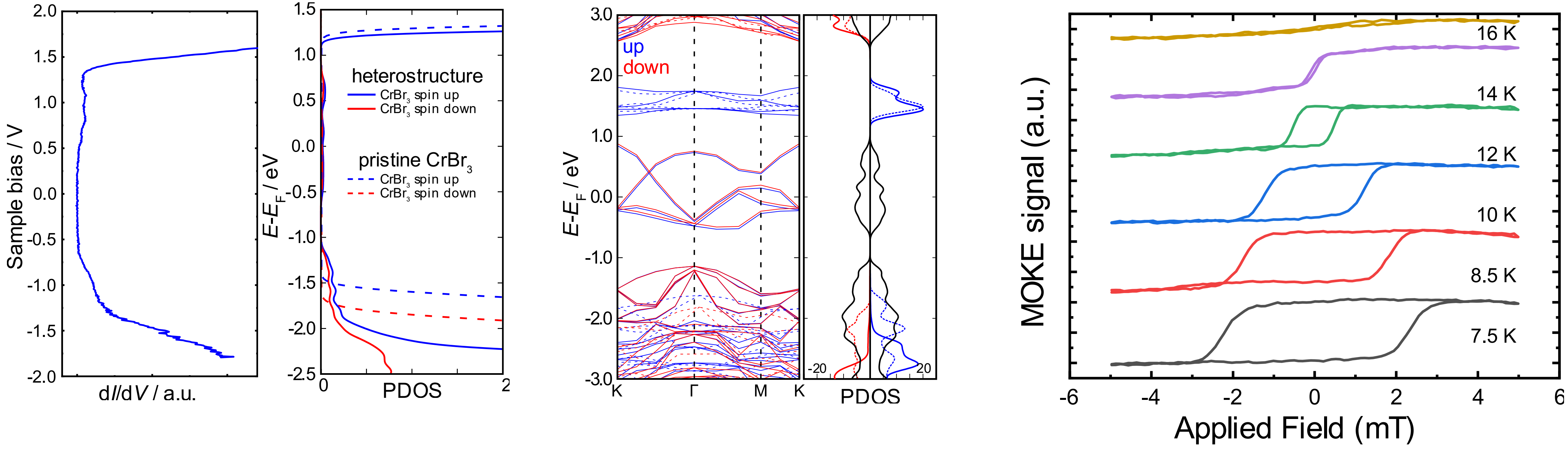




S. Kezilebieke et al. ”Electronic and magnetic characterization of epitaxial $CrBr_3$ monolayers” arXiv:2009.13465

Electronic and magnetic characerization

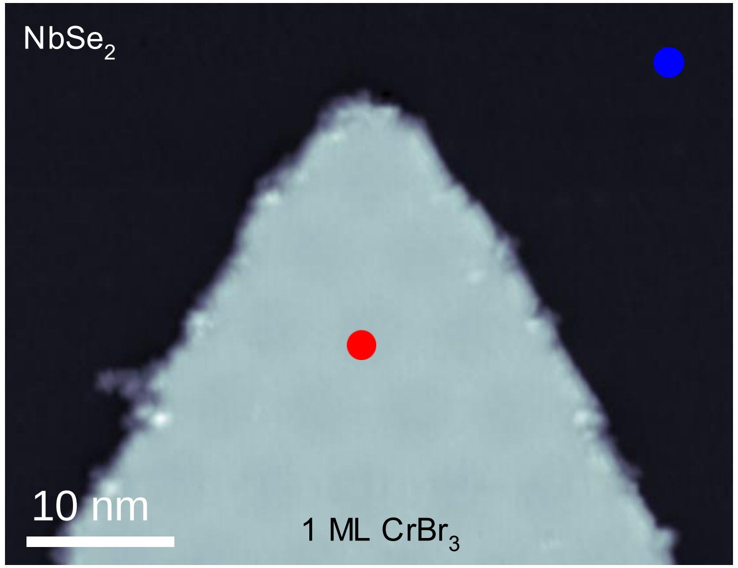
- Samples characterized with low-temperature STM, magneto-optical Kerr effect measurements and DFT calculations
  - All STM in UHV, T = 4 K or 300 mK
- $CrBr_3$ monolayer ferromagnetic with out-of-plane magnetization
  - DFT: 6.097 μ_B per unit cell
- Experiment: Curie temperature ca. 16 K



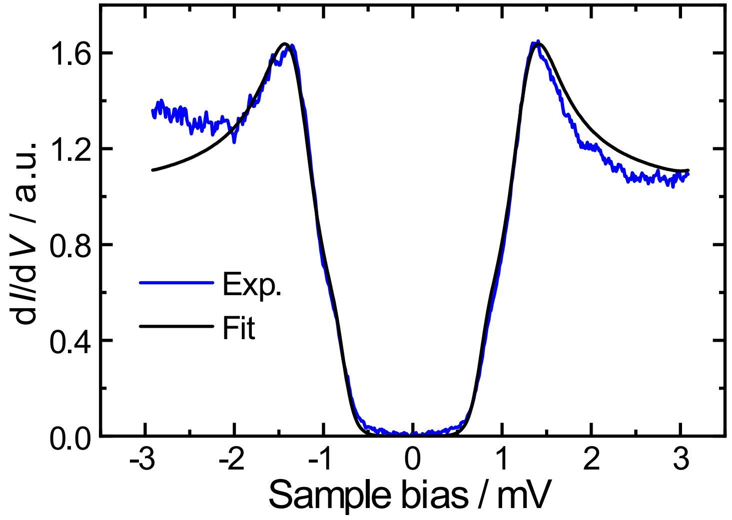
S. Kezilebieke et al. "Electronic and magnetic characterization of epitaxial $CrBr_3$ monolayers" arXiv:2009.13465

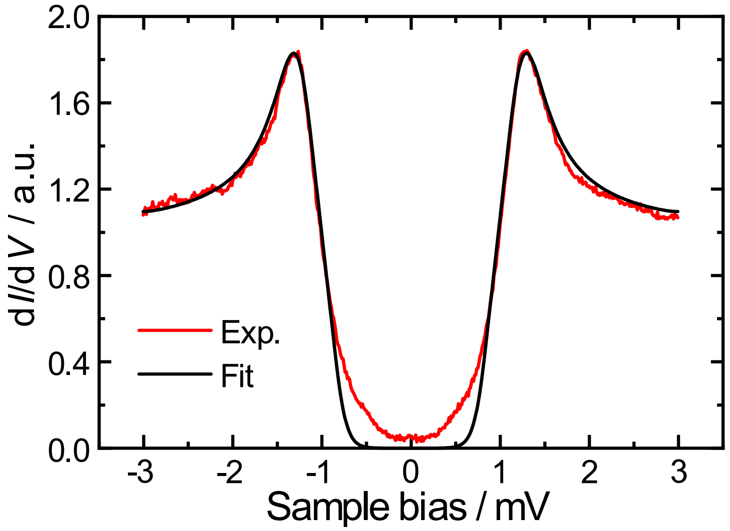
Low-bias spectroscopy

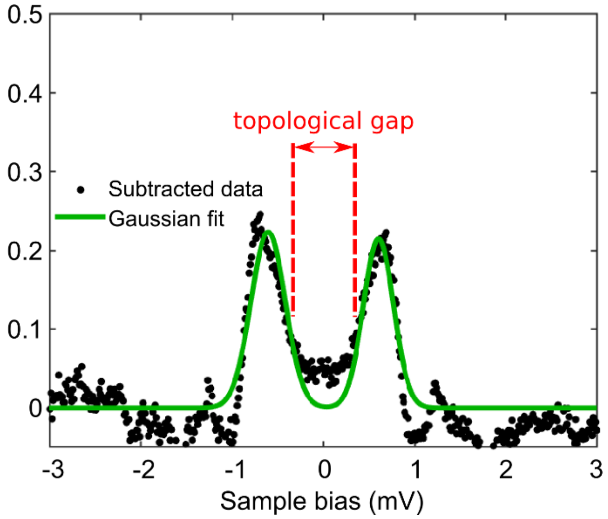
- Combining the required ingredients for topological superconductivity
- On the island, there is small but significant in-gap contribution
- Formation of Shiba bands due to the magnetic layer



STM experiments at T = 350 mK







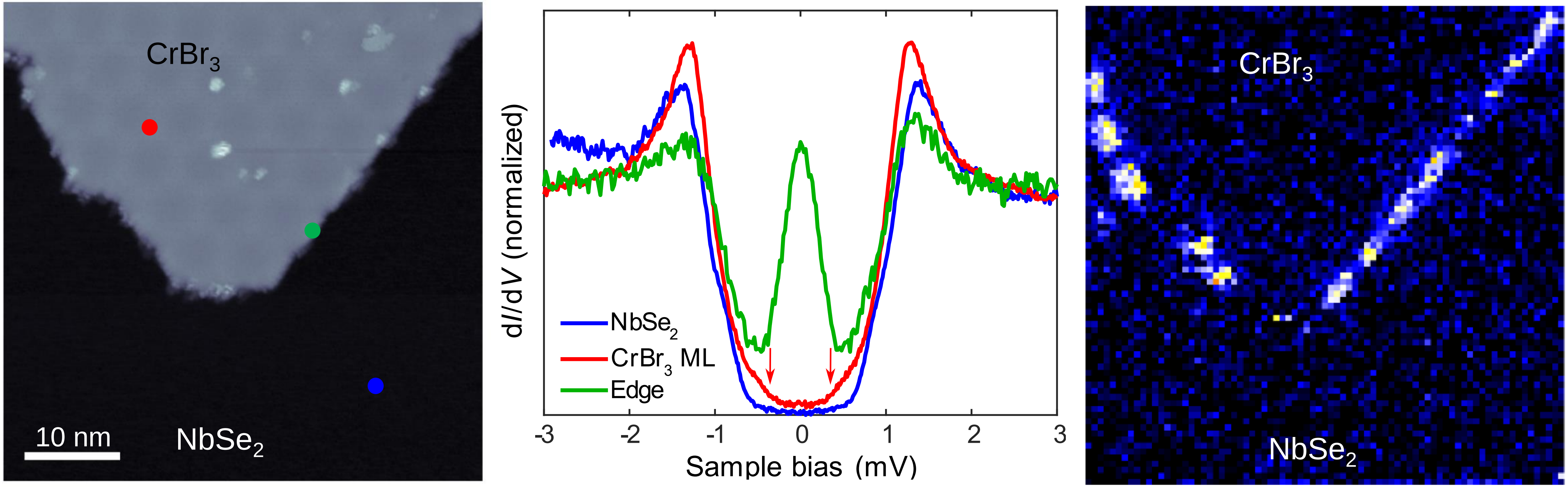
S. Kezilebieke et al. "Topological superconductivity in a van der Waals heterostructure", arXiv:2002.02141

Island edges

- Distinct zero bias signature at the island edges
- Spatial mapping: localized edge modes

STM image:

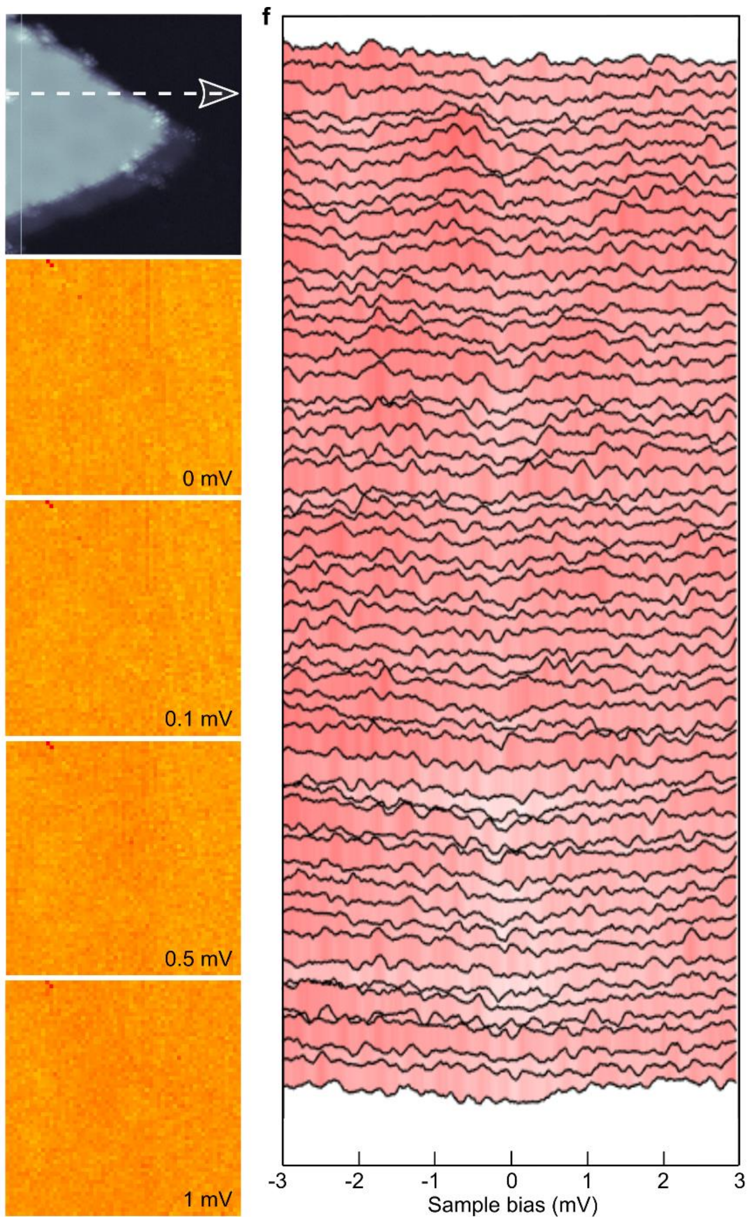
LDOS map at E_F:



S. Kezilebieke et al. ”Topological superconductivity in a van der Waals heterostructure”, arXiv:2002.02141

Is it topological superconductivity?

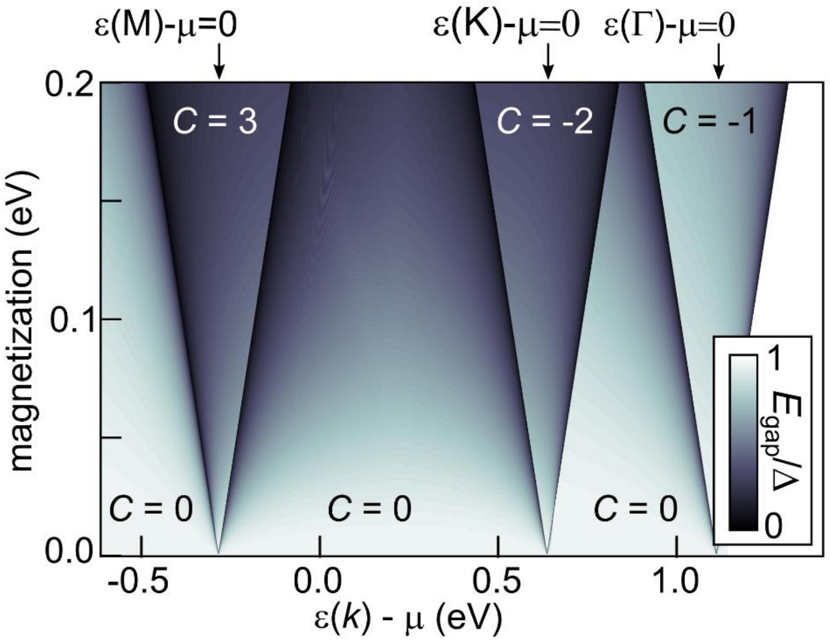
- Appears on all island edges
- Removing superconductivity (quenching with an external magnetic field) also removes the edge state completely
- Not Kondo, not standard edge state

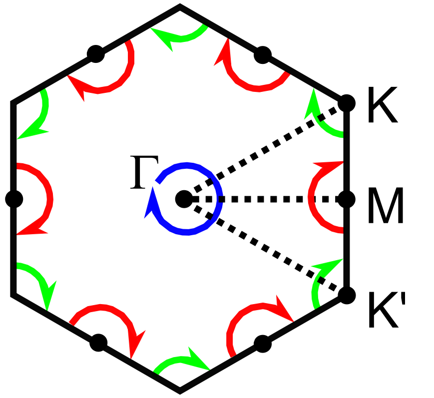


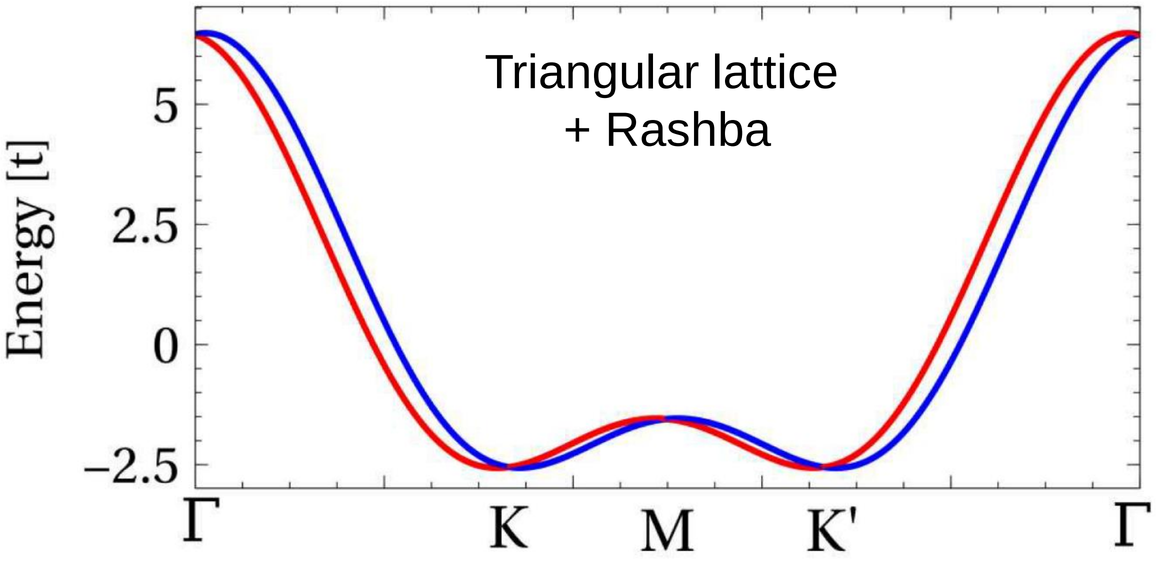
External field 4T

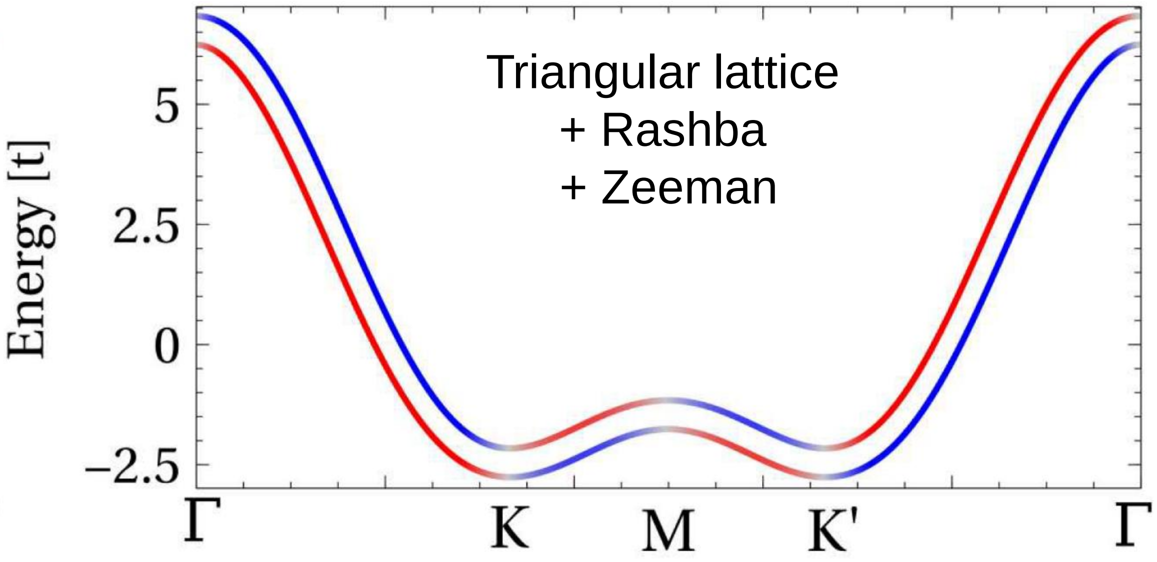
Modelling TSC on a triangular lattice

- $NbSe_2$ triangular lattice modifies the dispersion
- Can get a topological phase at the high symmetry point of the Brillouin zone
  - |*C*| = 1, 2, or 3, for the Γ, K, M



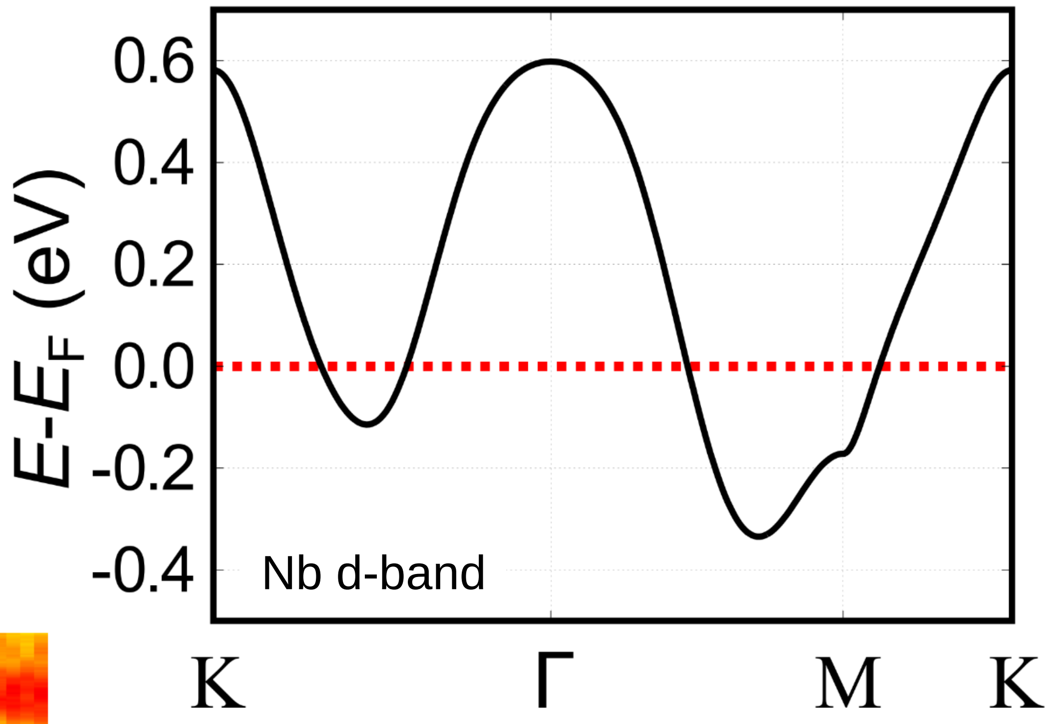


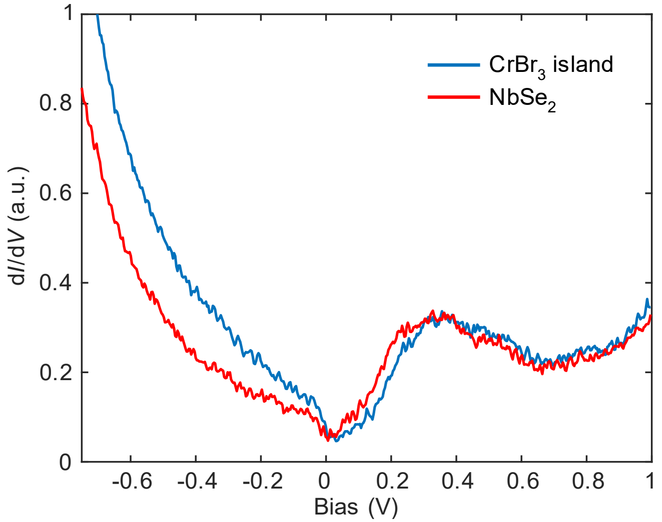


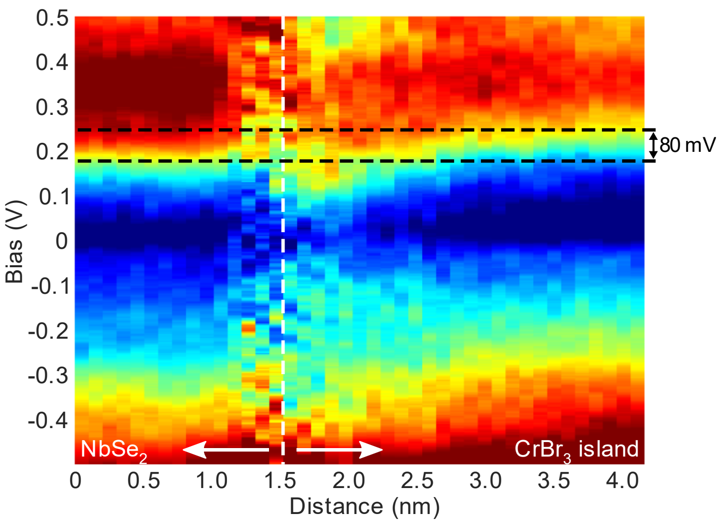


Conditions for TSC

- M-point closest to Fermi according to DFT
- Where are the bands in real life? Somewhat below Fermi
- Need to hit within magnetization of the Fermi level
  - Fine tuning?
  - Overall shift makes it more plausible





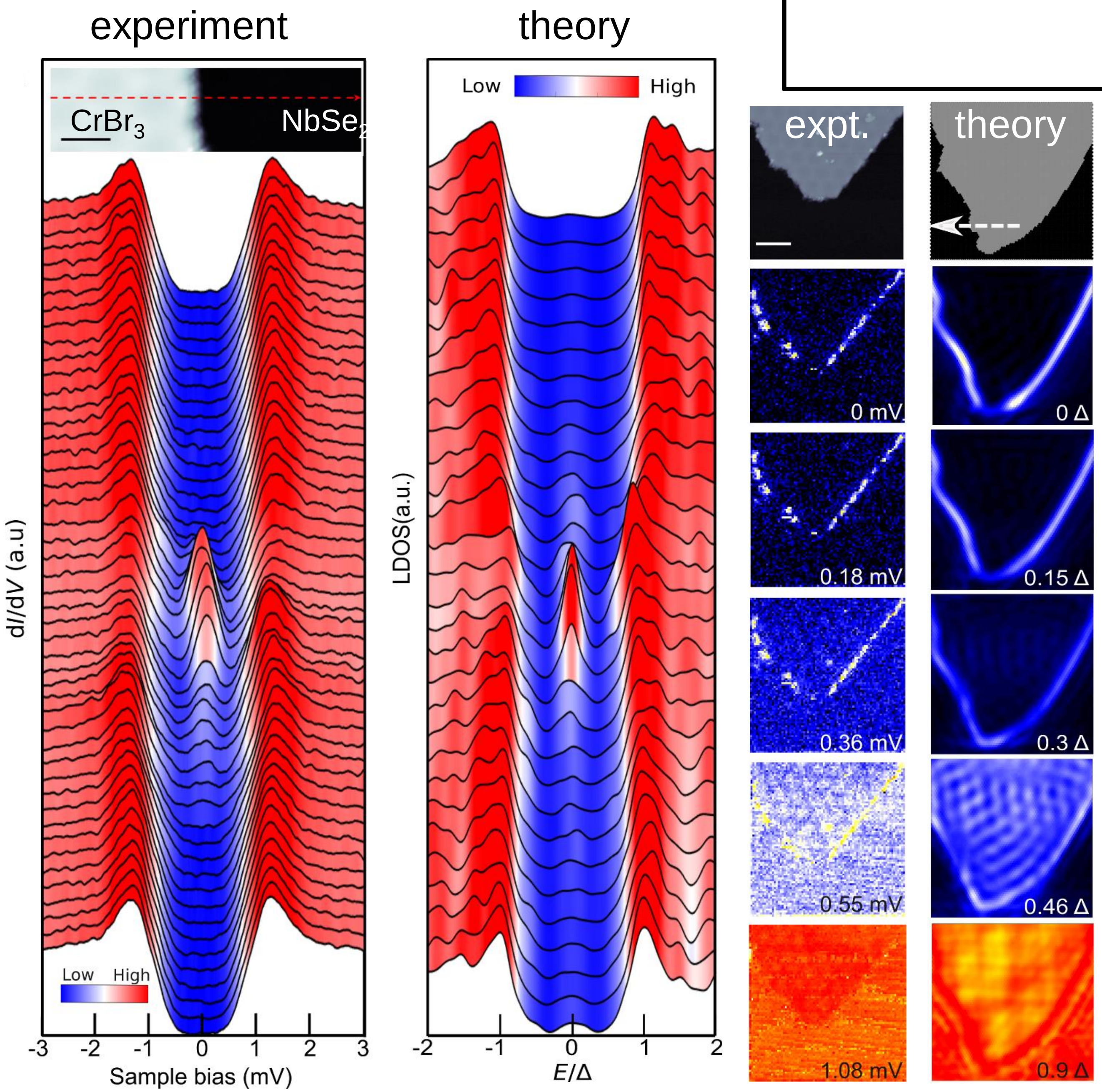


⇒ We are in the $C = 3$ topological phase

Comparison with theory at the edge

- Experiment: grid spectroscopy over an edge of a $CrBr_3$ island
- The edge modes coexist with Shiba bands at higher energies
- Quantitative match between theory and experiment:

1. the correct edge mode penetration depth of ~2.5nm (orders of magnitude smaller than simple estimates)
2. the specific form of the subgap local density of states (depends on system-specific dispersion of the topological edge modes)
3. coexistence of the topological edge modes and bulk states in a substantial energy window
4. non-uniform distribution of the edge-mode spectral weight (stems from geometric irregularities of the island boundary)

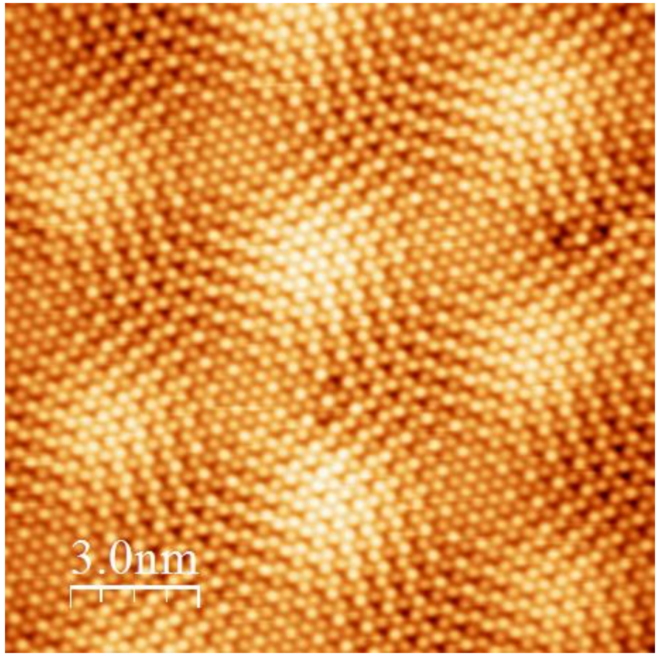


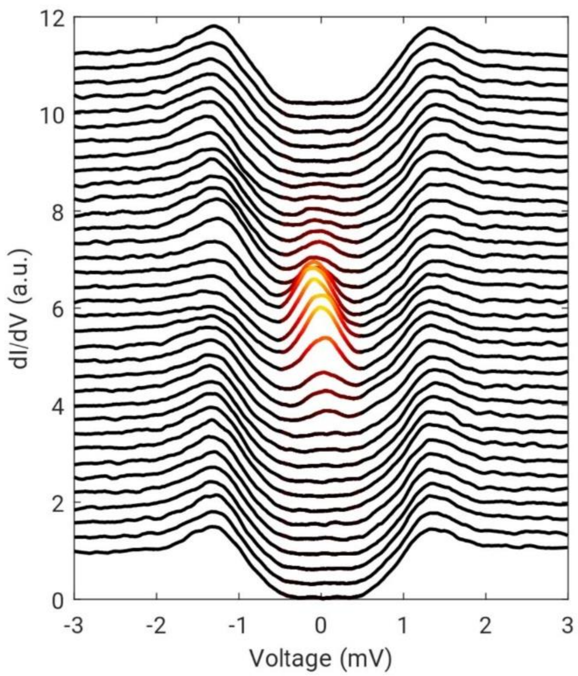
S. Kezilebieke et al. arXiv:2002.02141

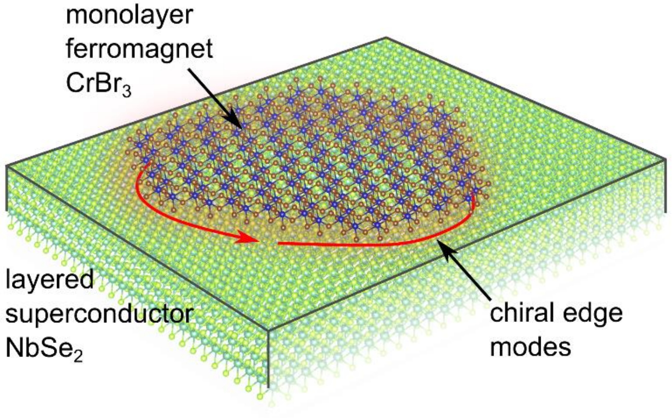
Conclusions

- Electronic and magnetic characterization of epitaxial $CrBr_3$ monolayers, **arXiv:2009.13465**
- Topological superconductivity in a designer ferromagnet-superconductor van der Waals heterostructure, **arXiv:2002.02141**

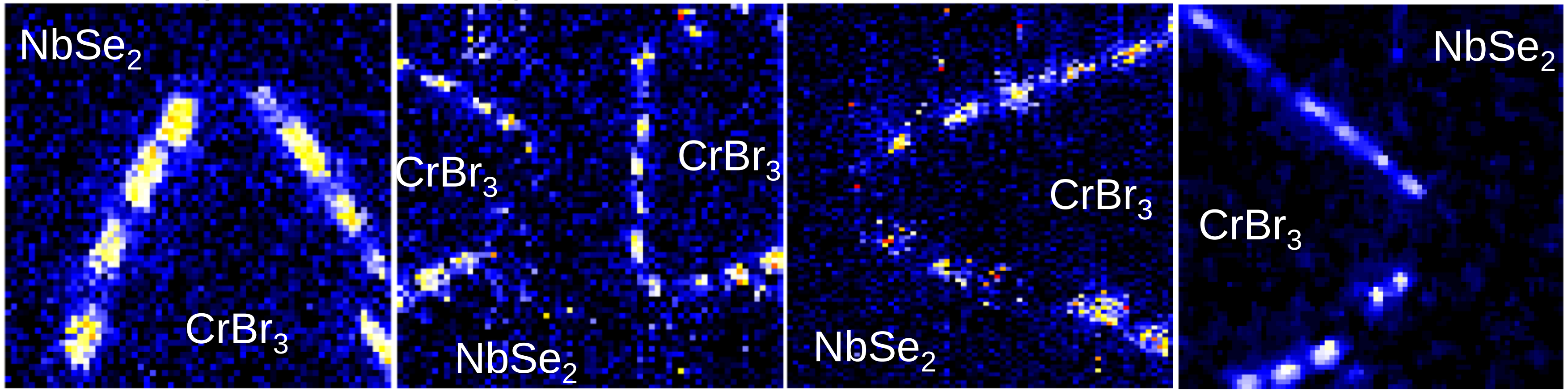
$CrBr_3$ / $NbSe_2$







LDOS maps at zero energy

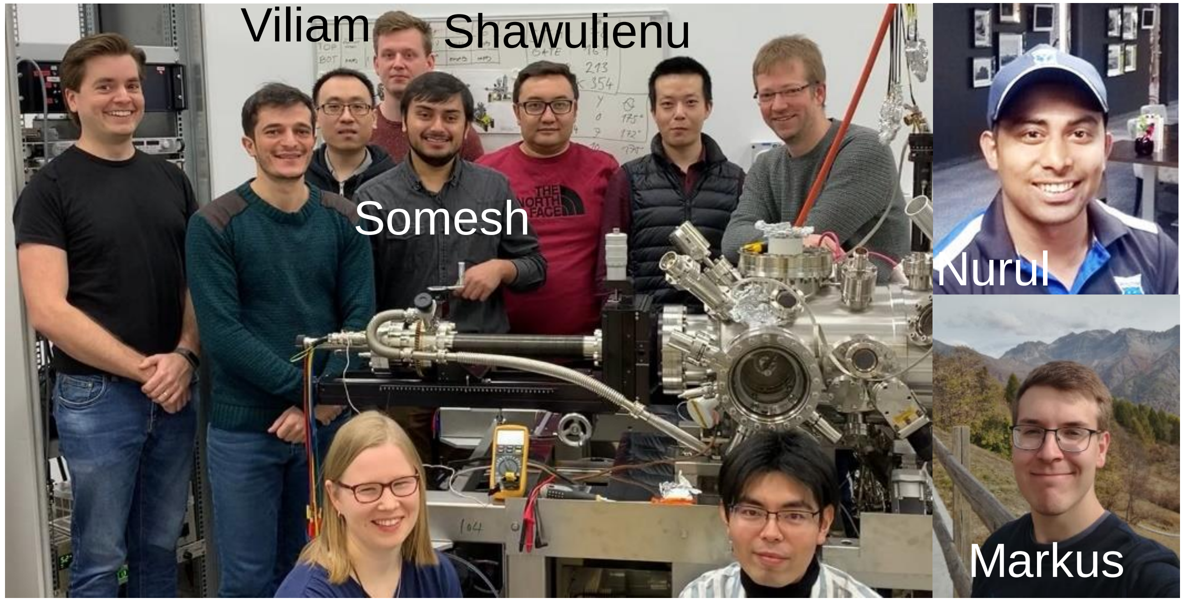


Acknowledgements

Experiments at Aalto: Shawulienu Kezilebieke, Nurul Huda, Somesh Ganguli, Viliam Vaňo, Markus Aapro, Mohammad Amini, Xin Huang, Linghao Yan, Chen Xu, Benjamin Alldritt, Shuning Cai

Theory collaborators: Teemu Ojanen (Tampere), Szczepan Głodzik (Lublin)

DFT (Aalto): Orlando Silveira, Adam Foster



Magnetic characterization:

Rhodri Mansell

Sebastiaan van Dijken

Theory:

Szczepan Głodzik

Teemu Ojanen

DFT:

Orlando Silveira

Adam Foster

Centre for Quantum Engineering

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