STM study of topological superconductivity in Pb/Si(111)

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25e Congrès Général de la Société Française de Physique

Current adress: CEA Saclay - SPEC
Nanoelectronics group

Plan

I. STM-STS & superconductivity - Magnetic impurities in superconductors

II. Individual magnetic impurities in Pb/Si(111)

III. Topological superconductivity

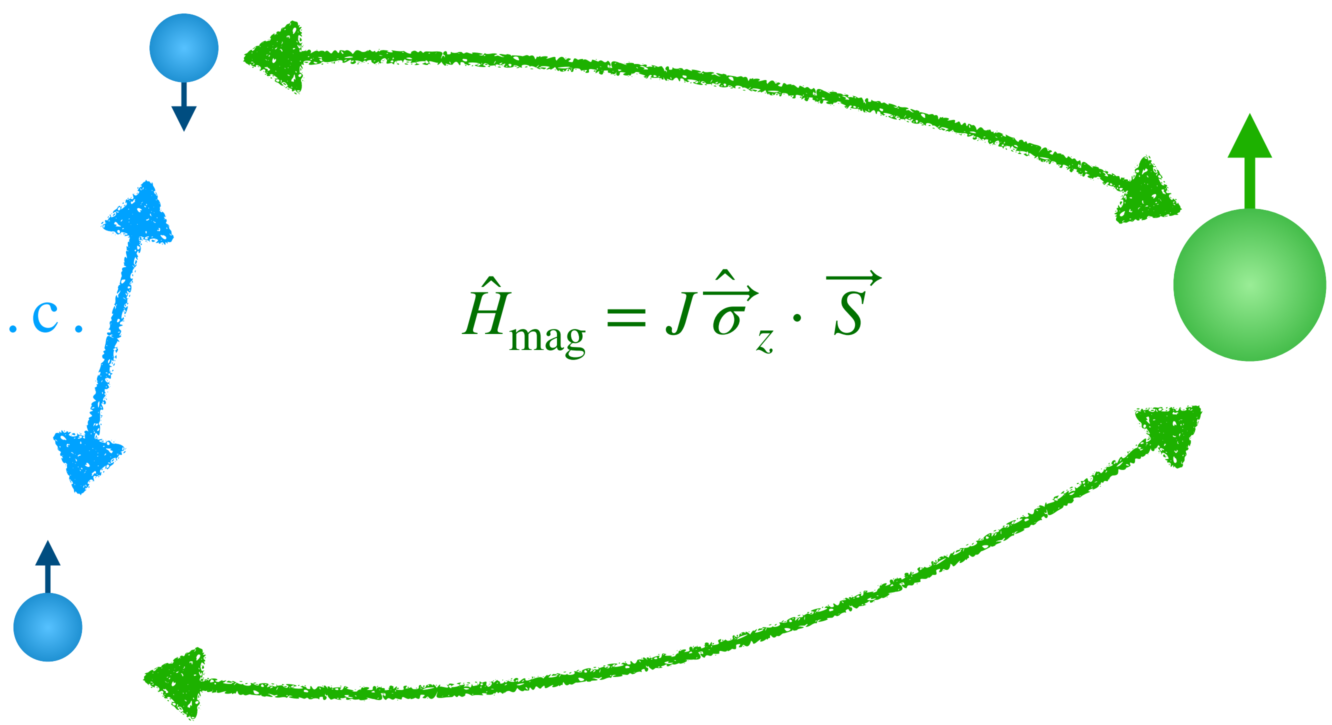
IV. Majorna edge states and bound states.

V. Conclusion

STM & Yu-Shiba-Rusinov bound states

Yu-Shiba-Rusinov bound states

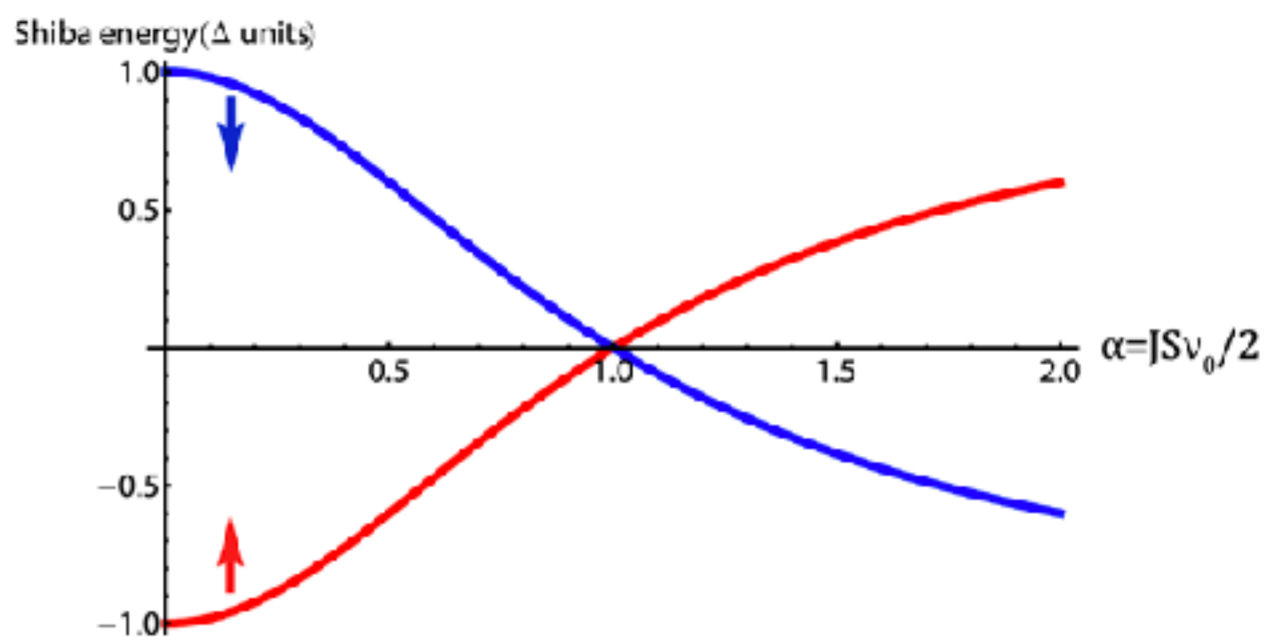
Cooper pairs split under a Zeeman field



$$\hat{H}_{\mathrm{BCS}} = \Delta \hat{c}_{k,\uparrow}\hat{c}_{-k,\downarrow} + \mathrm{h.c.}$$

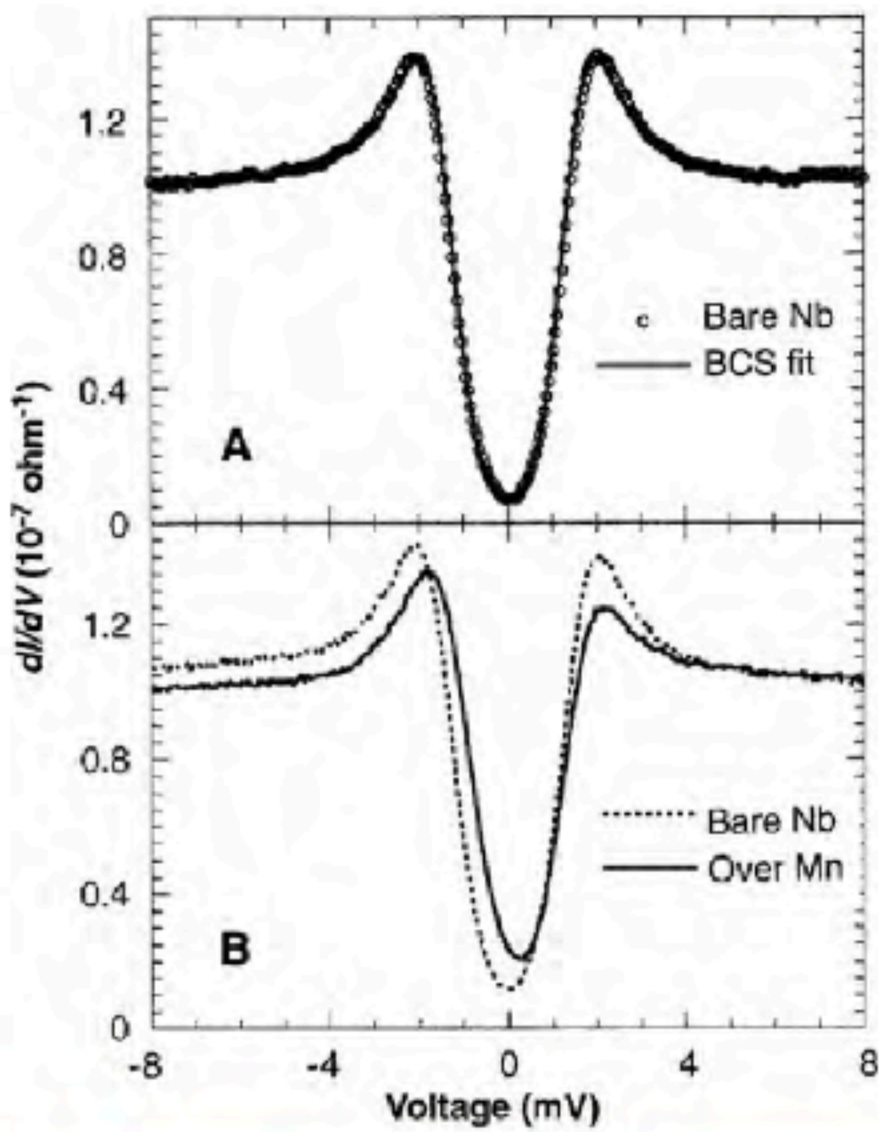
$$\hat{H}_{\mathrm{mag}} = J\,\vec{\hat{\sigma}}_z \cdot \vec{S}$$

The number of states depends on the spatial extension of the interaction. For a point defect, only one pair of Shiba states will appear within the gap.

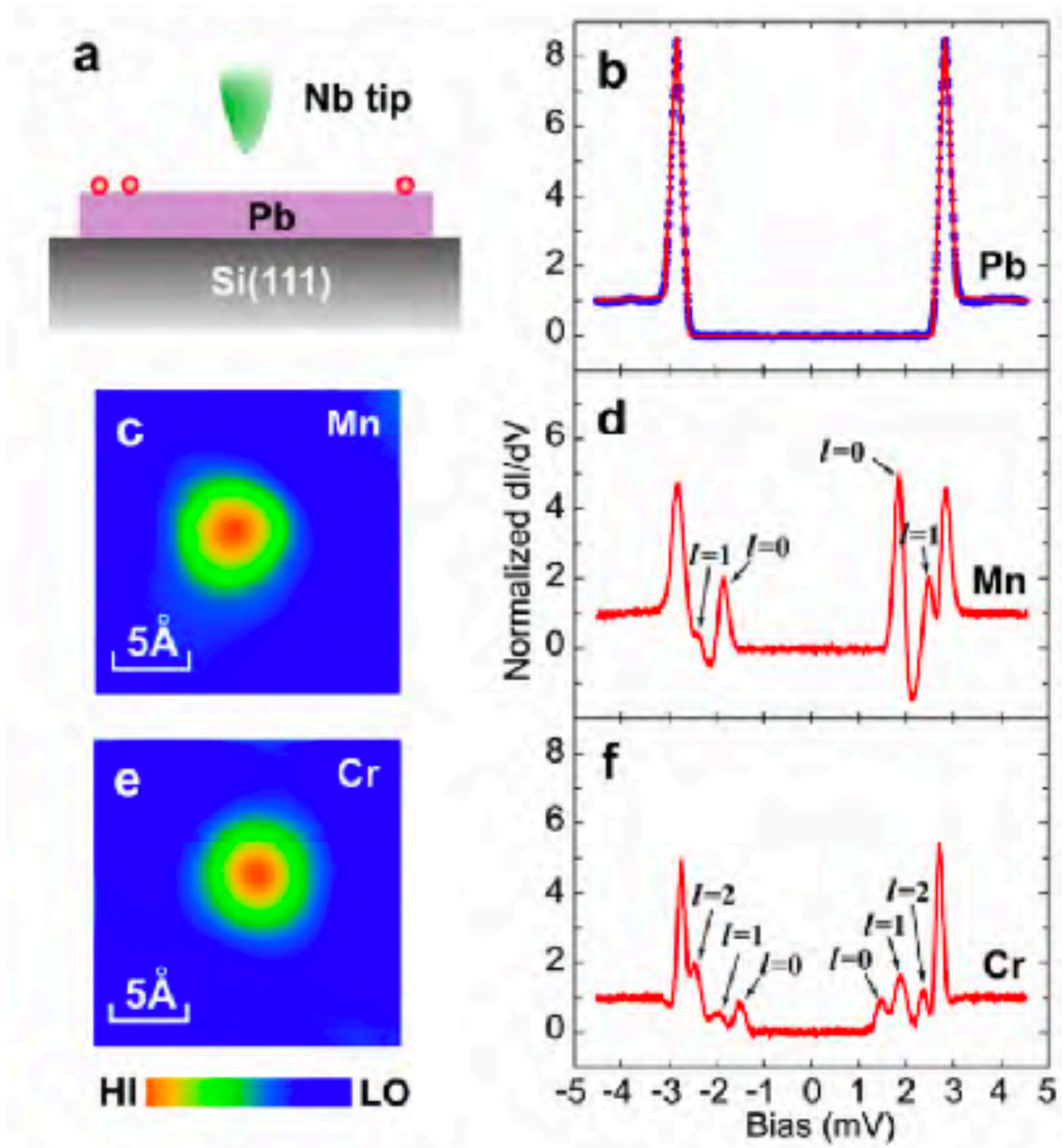


Yu-Shiba-Rusinov bound states

First STM measurement of YSR bound states.



A. Yazdani et al. Science **275** 1767-1770 (1997)

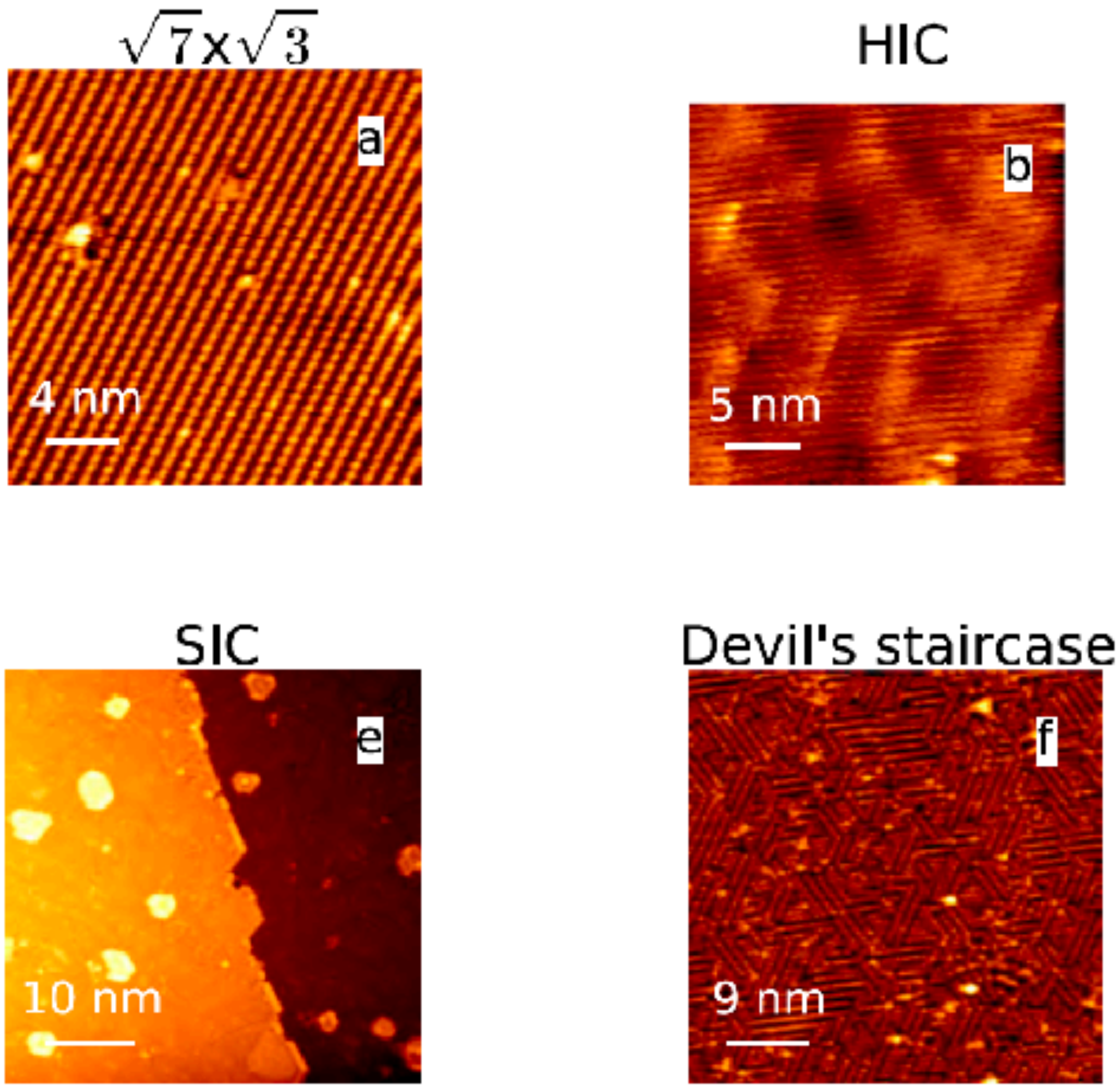


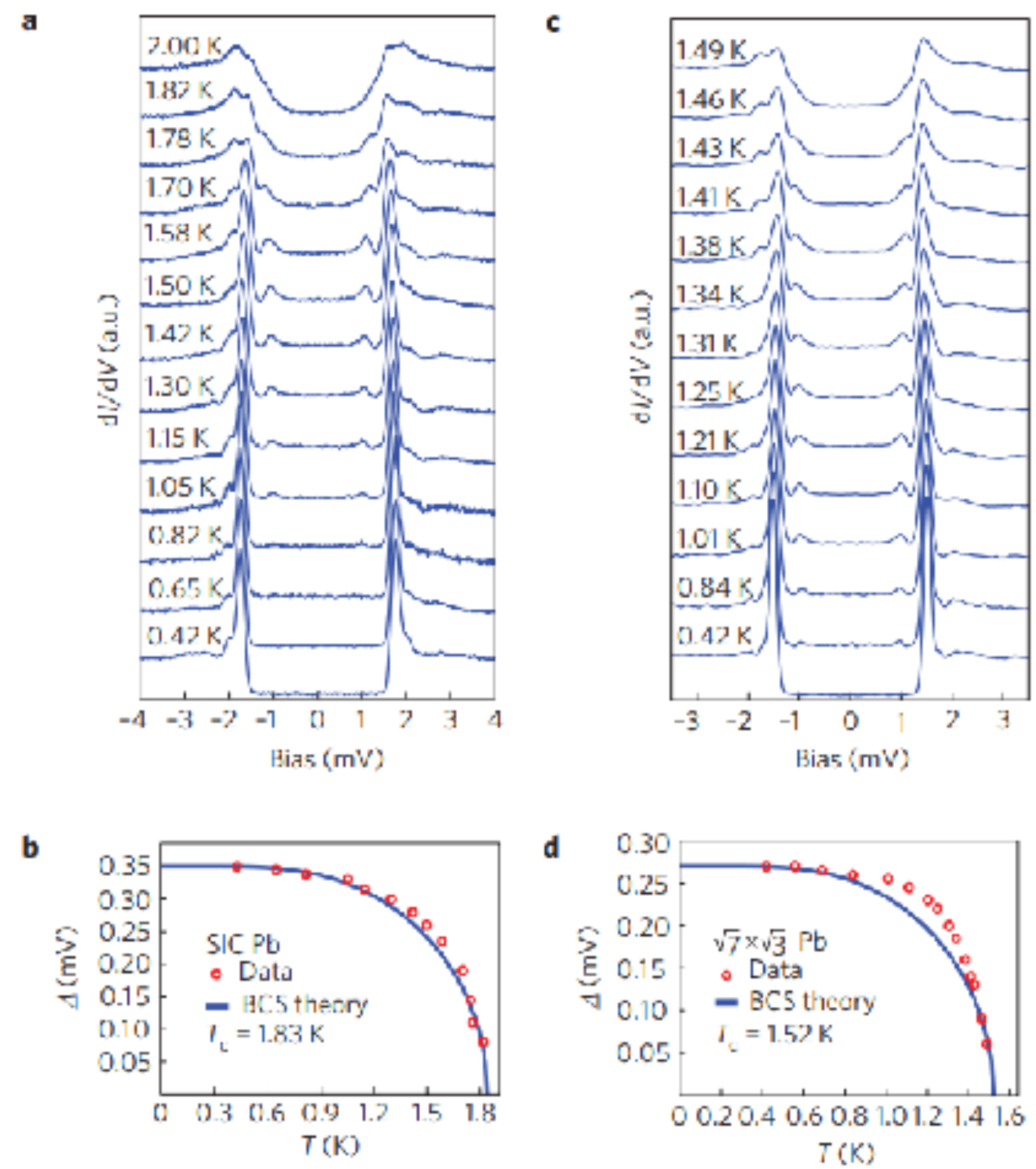
S.-H. Ji et al. PRL **100** 226801 (2008)

Magnetic impurities in Pb/Si(111)

Monolayer of Pb/Si(111)

There exists different superconducting phases in monolayer Pb/Si(111)

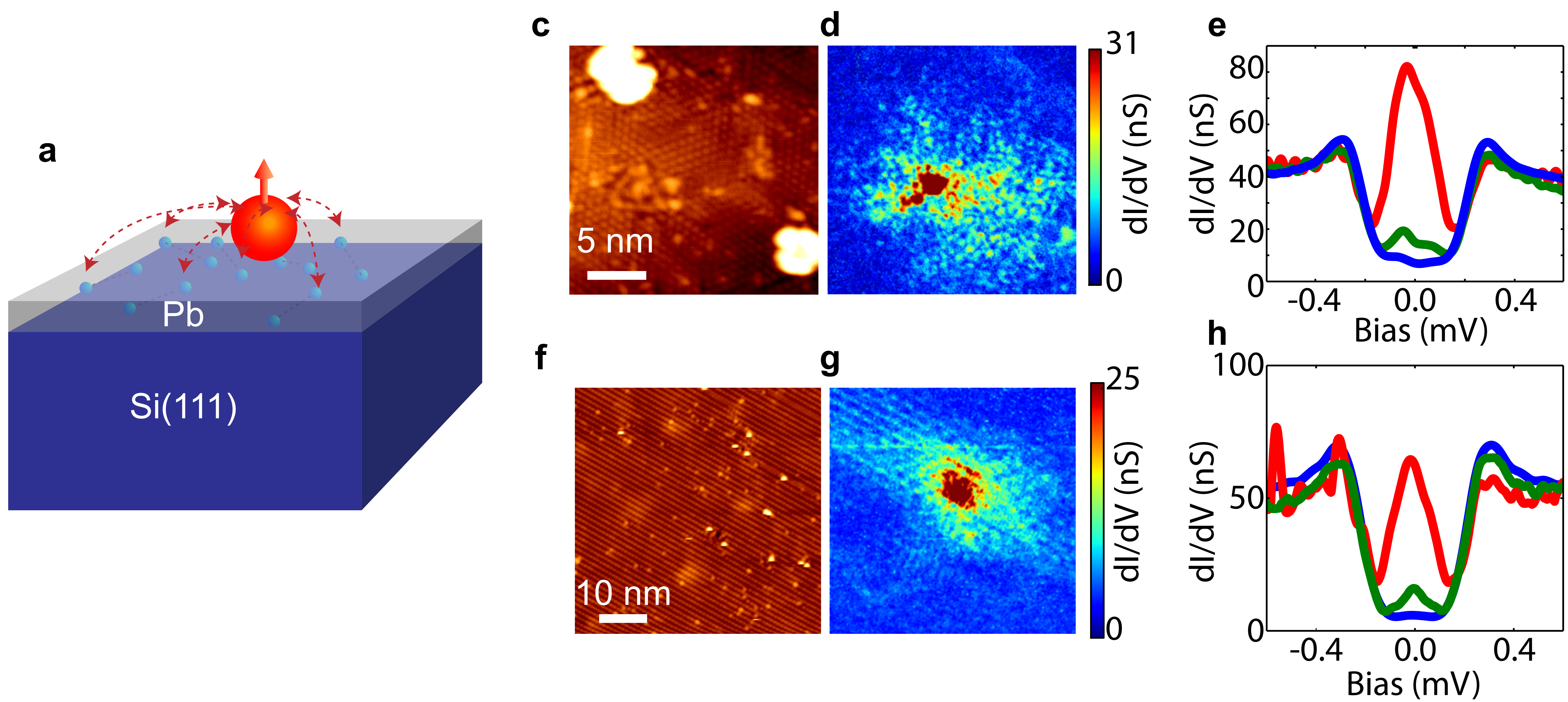




T. Zhang et al. Nature Physics **6**, 104 (2010)

Example of bound states in Pb/Si(111)

Case of the SIC phase and $\sqrt{7} \times \sqrt{3}$

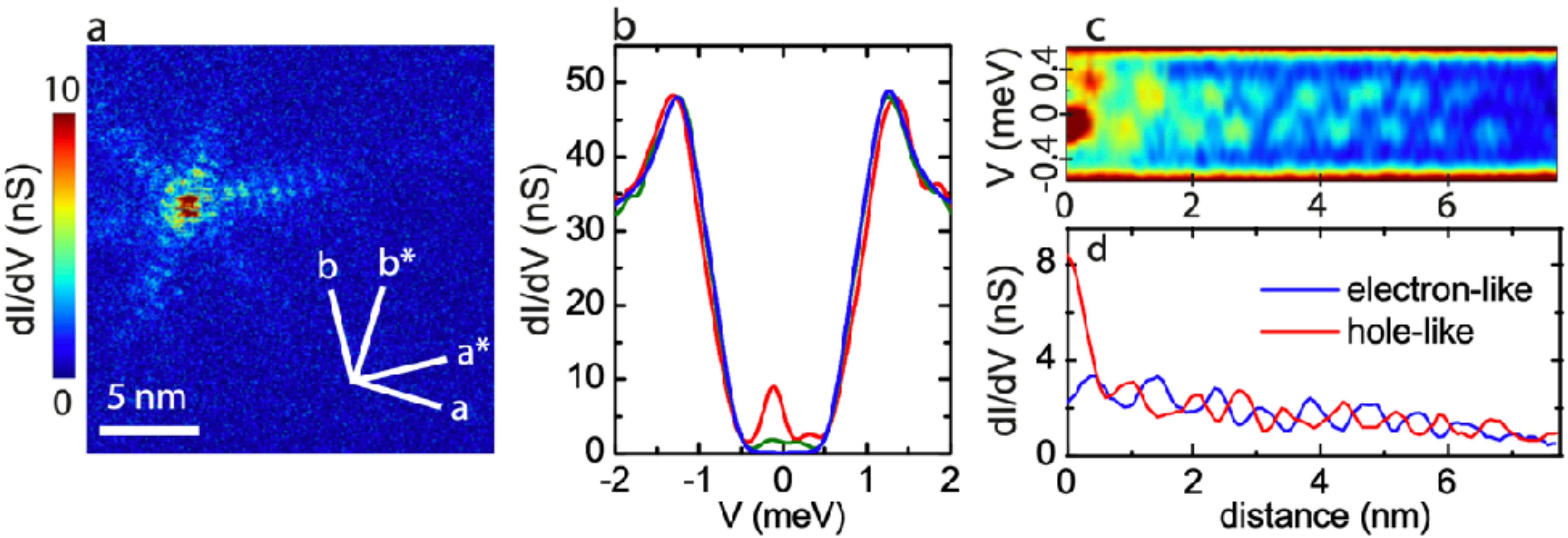


Ménard, G.C. et al. Eur. Phys. J. Spec. Top. (2019)

Example of bound state (NbSe2)

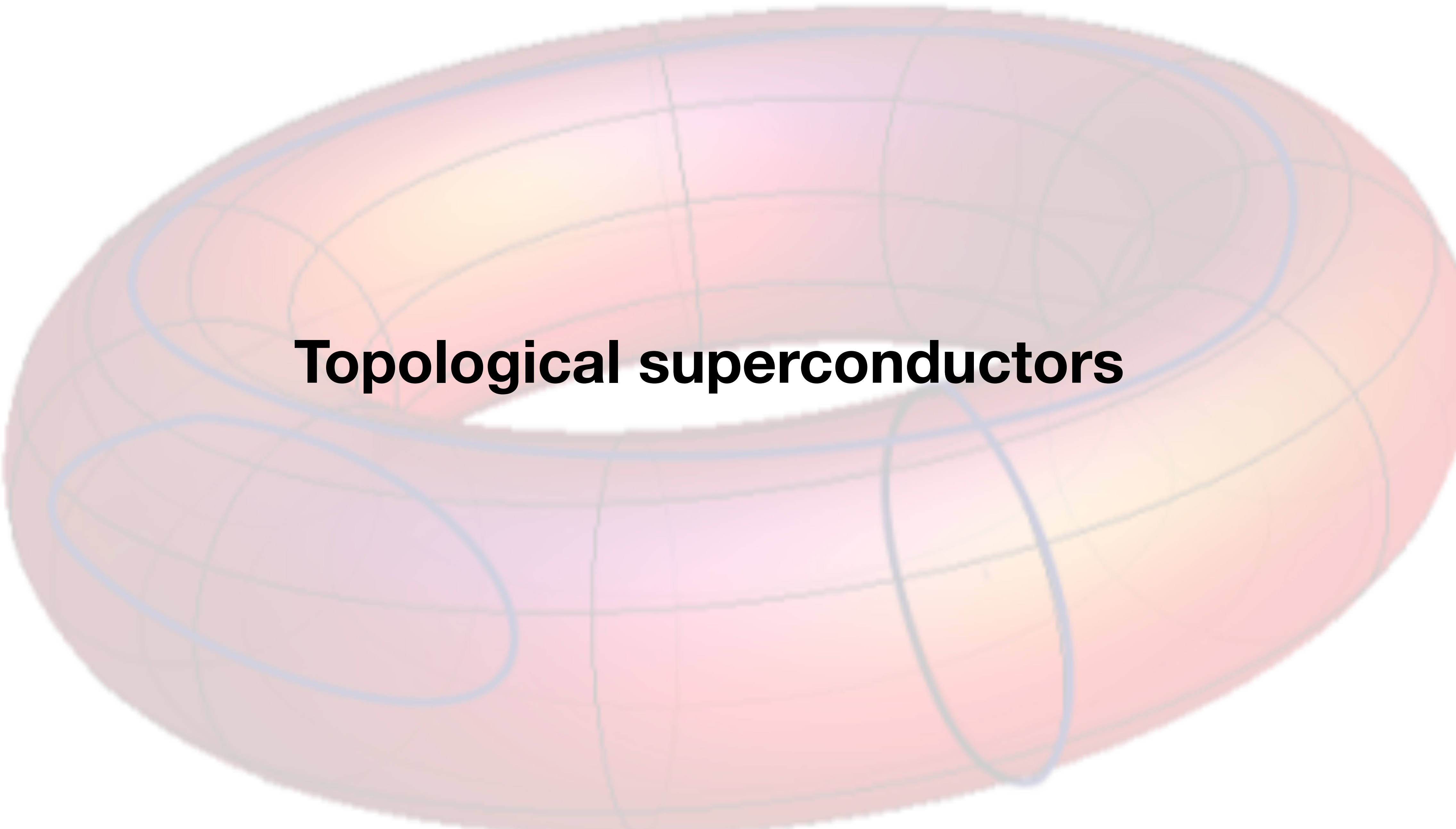
Imaging of a single Fe atom embedded in 2H-NbSe2

The dephasing between the electron & hole like state is linked to the relation between the gap, the magnetic interaction and the non magnetic interaction.



G. Ménard et al. Nat. Phys. **11** 1013-1016 (2015)

Furthermore, using a 2D material increases by order of magnitude the extent of the wave-function associated with the YSR bound states.



Topological superconductors

Topology & solid state physics

3 ingredients are required for topological superconductivity:

- Superconductivity
- Spin orbit interaction
- Magnetism

These are provided by:

- Electron phonon interaction
- Surface effect/Heavy element
- Magnetic atoms/External field

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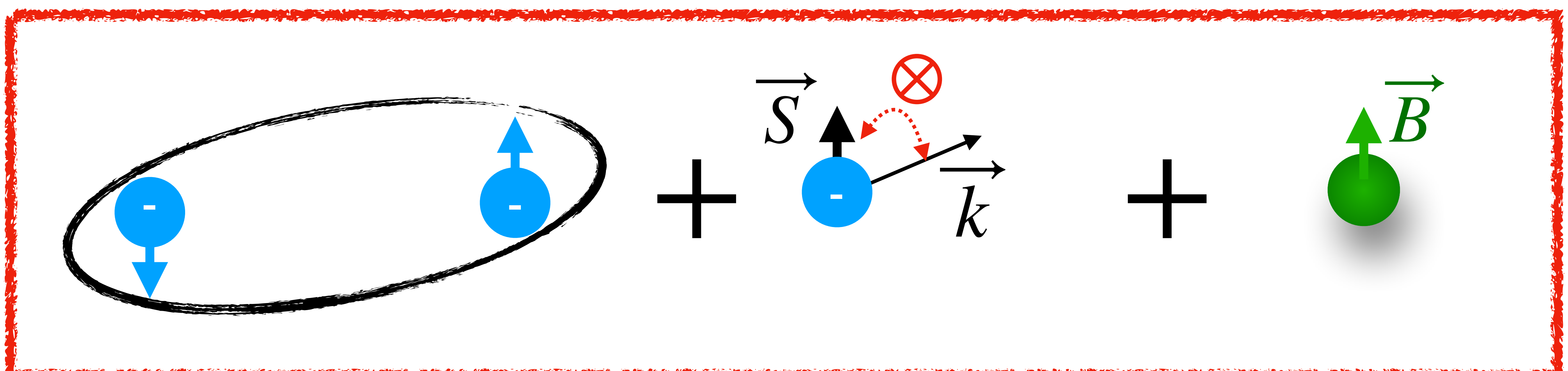
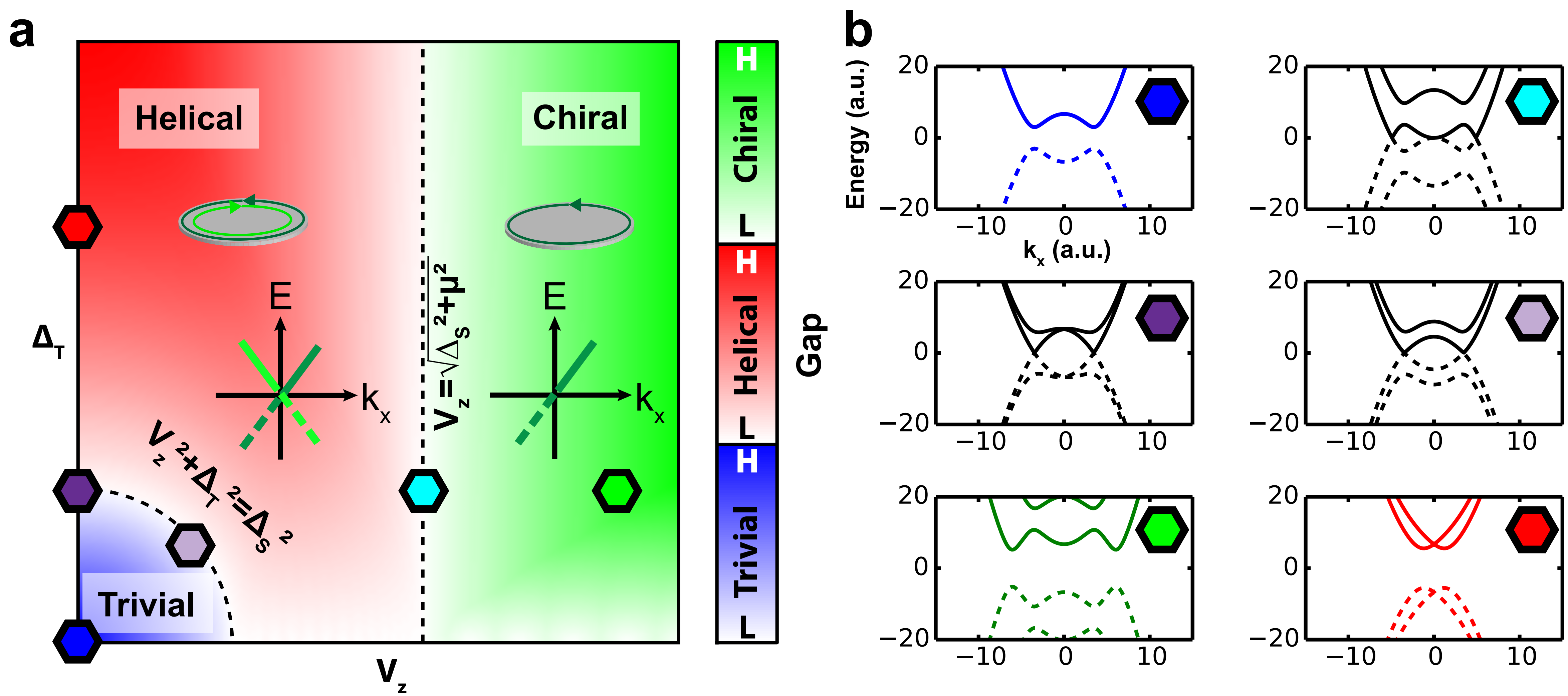


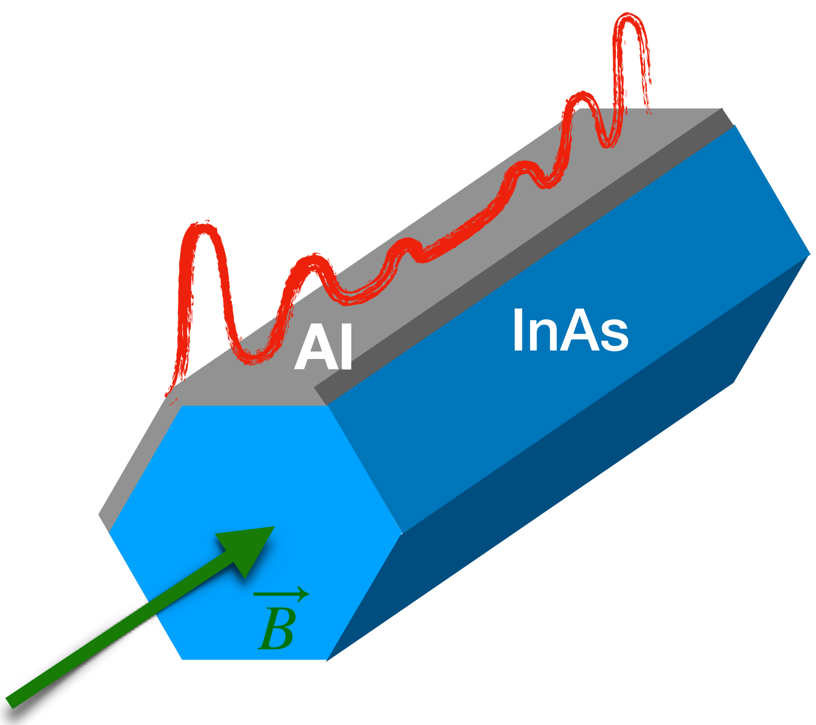
Topology & solid state physics

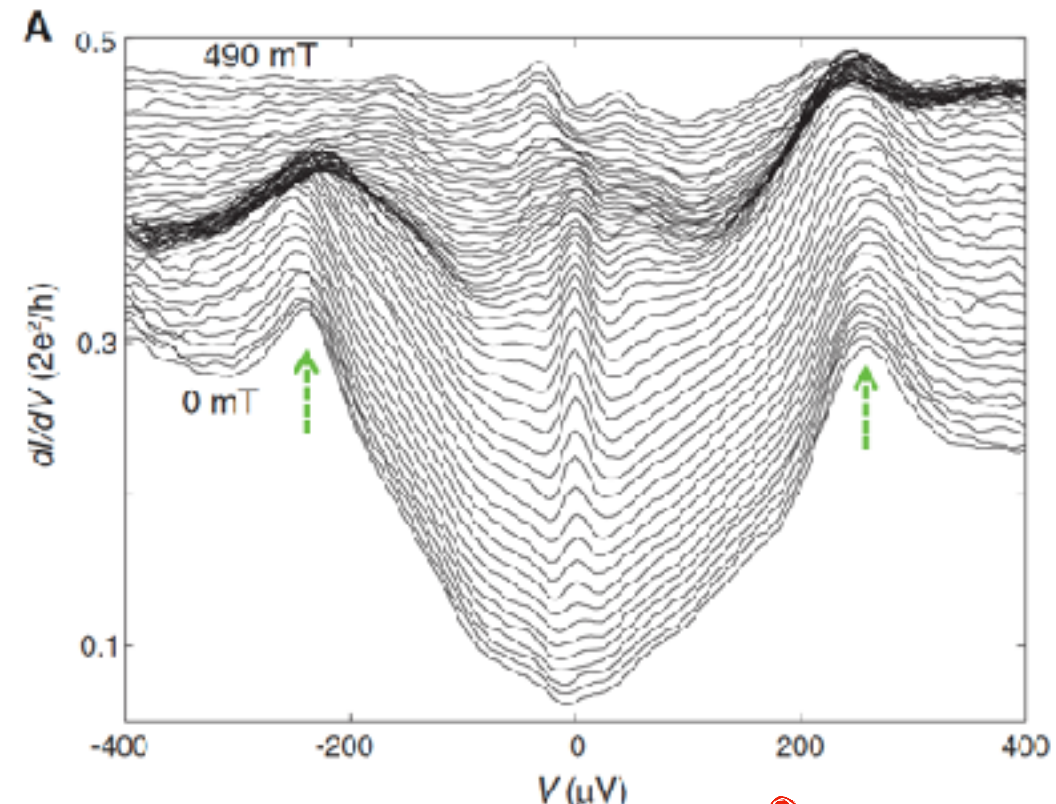
Phase diagram of topological superconductivity



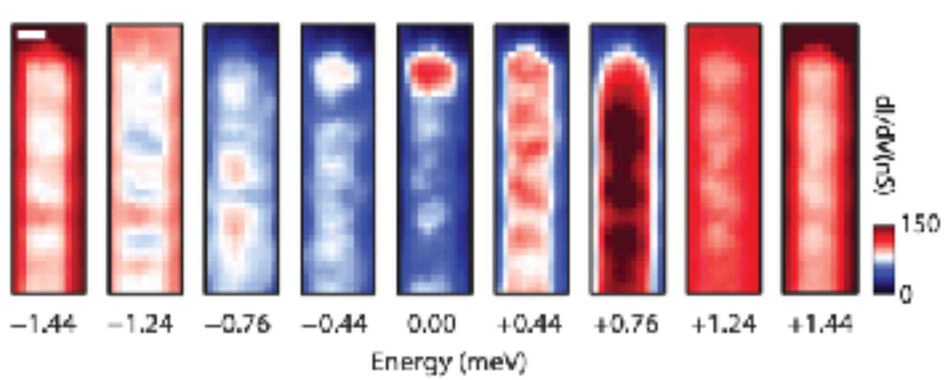
The edge state associated to topological superconductivity is called a **Majorana fermion**
They are anyons that possesses non Abelian statistics.

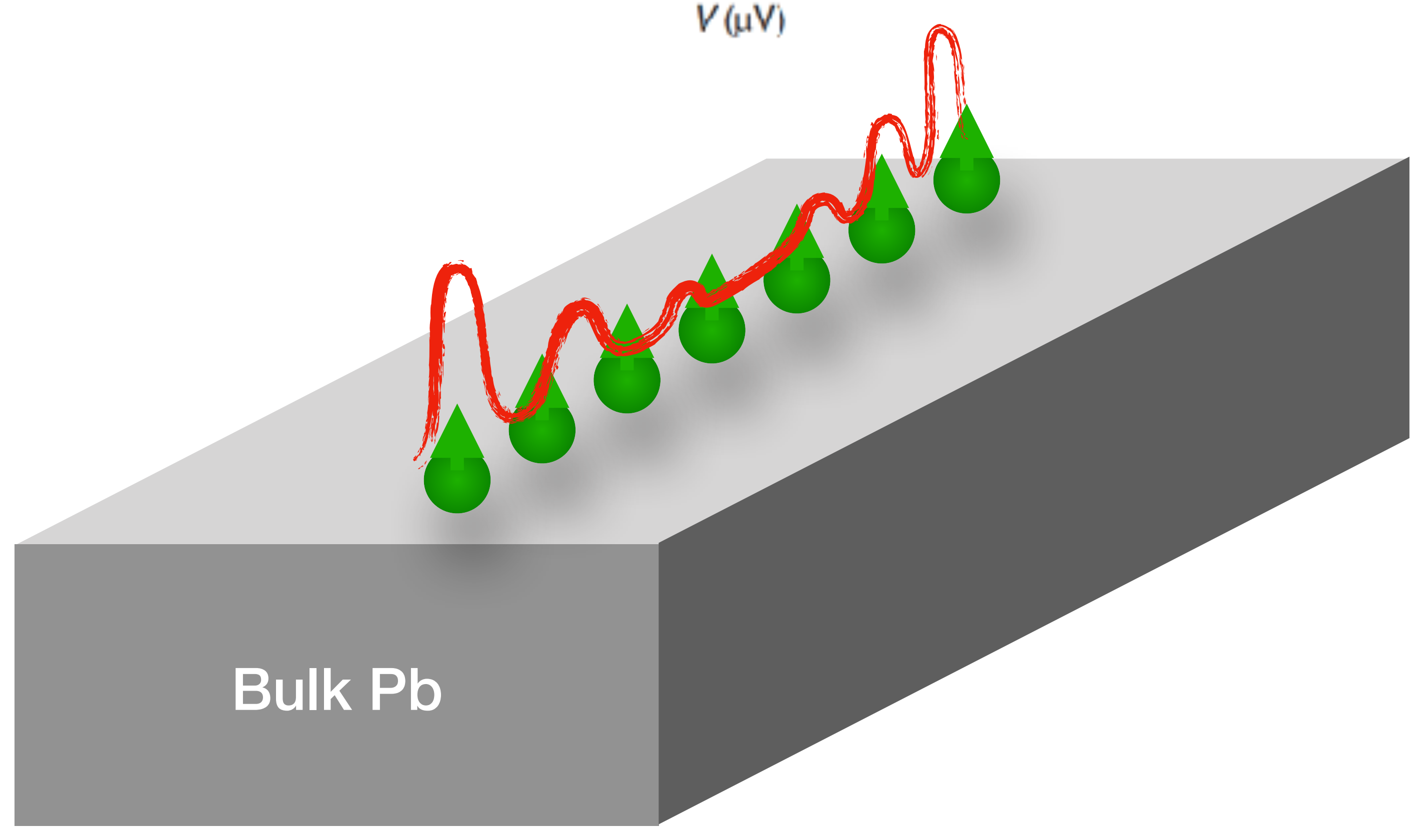
Previous observations of ZBP





V. Mourik et al. Science 336 **1003-1007** (2012)





S. Nadj-Perge et al. 346 **602-607** Science (2014)

Majorana edge states & Majorana bound states in Pb/Co/Si(111)

Theory of Majorana edge states

$$\hat{H}_0 = \boxed{\xi_k \tau_z + \Delta_S \tau_x}$$ Trivial superconductor

$$\hat{H}_{topo} = \boxed{V_z \sigma_z} + \boxed{\left(\alpha \tau_z + \frac{\Delta_T}{k_F} \tau_x \right) (\sigma_x k_y - \sigma_y k_x)}$$

Magnetic interaction

Triplet superconductivity & Spin-orbit interaction

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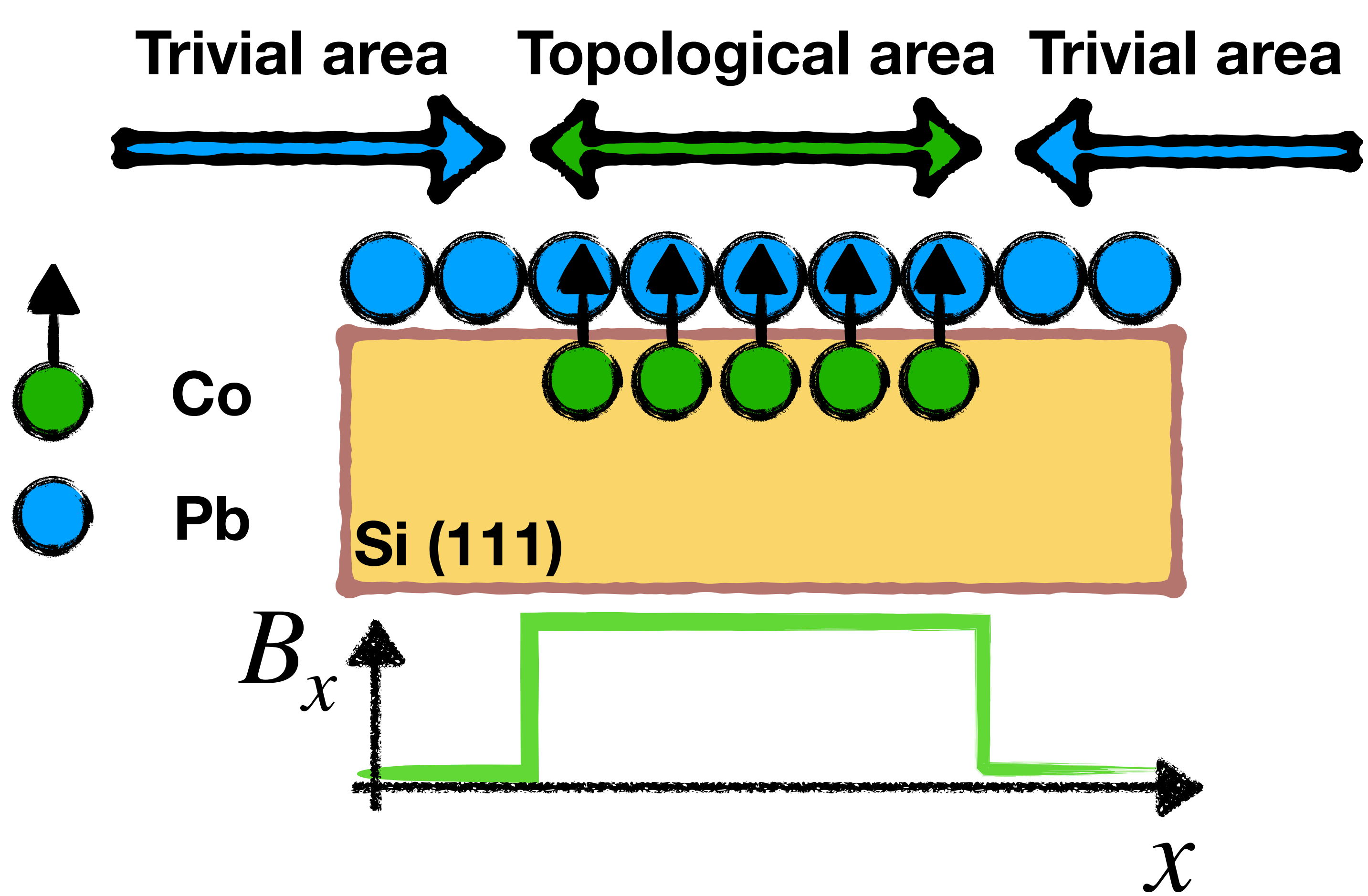
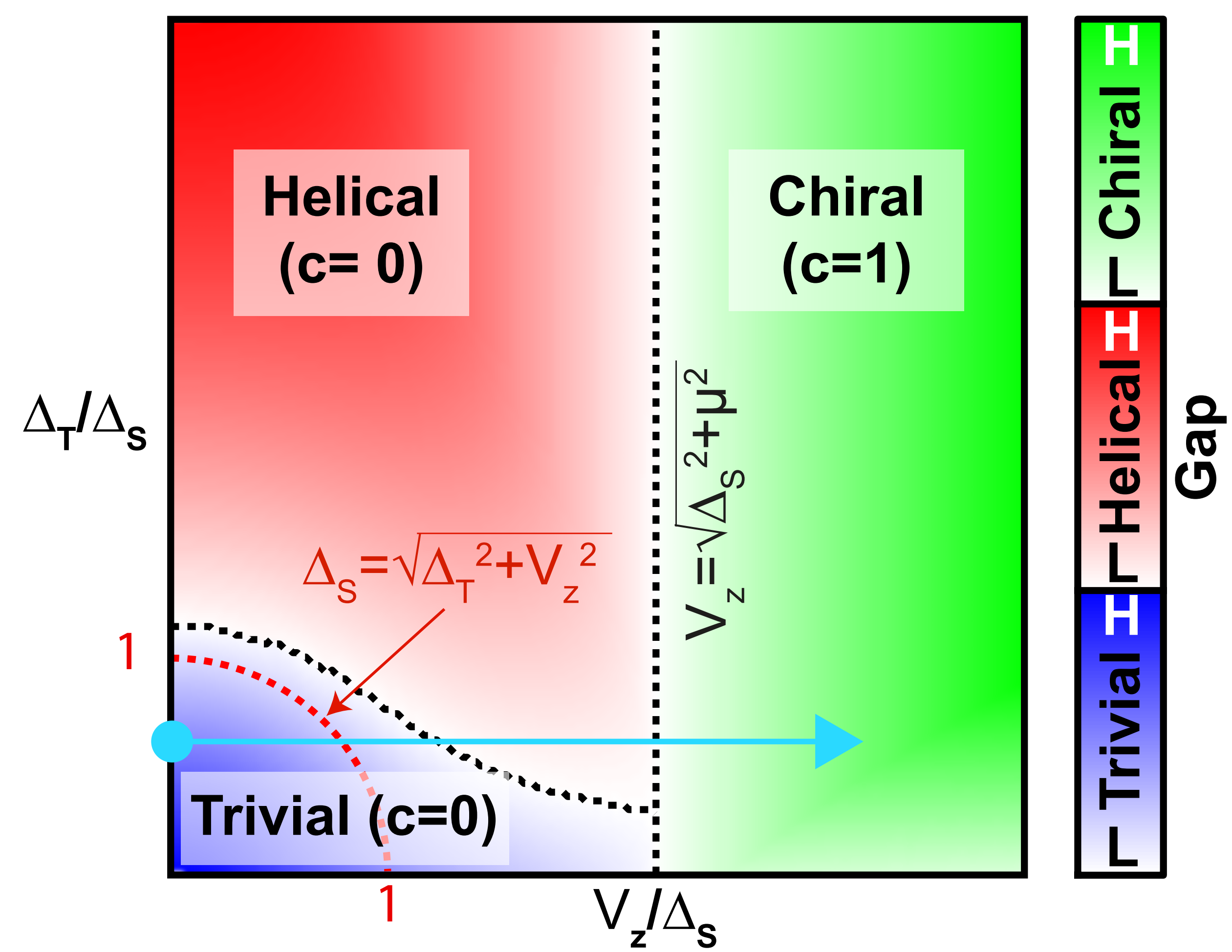
Magnetic interaction

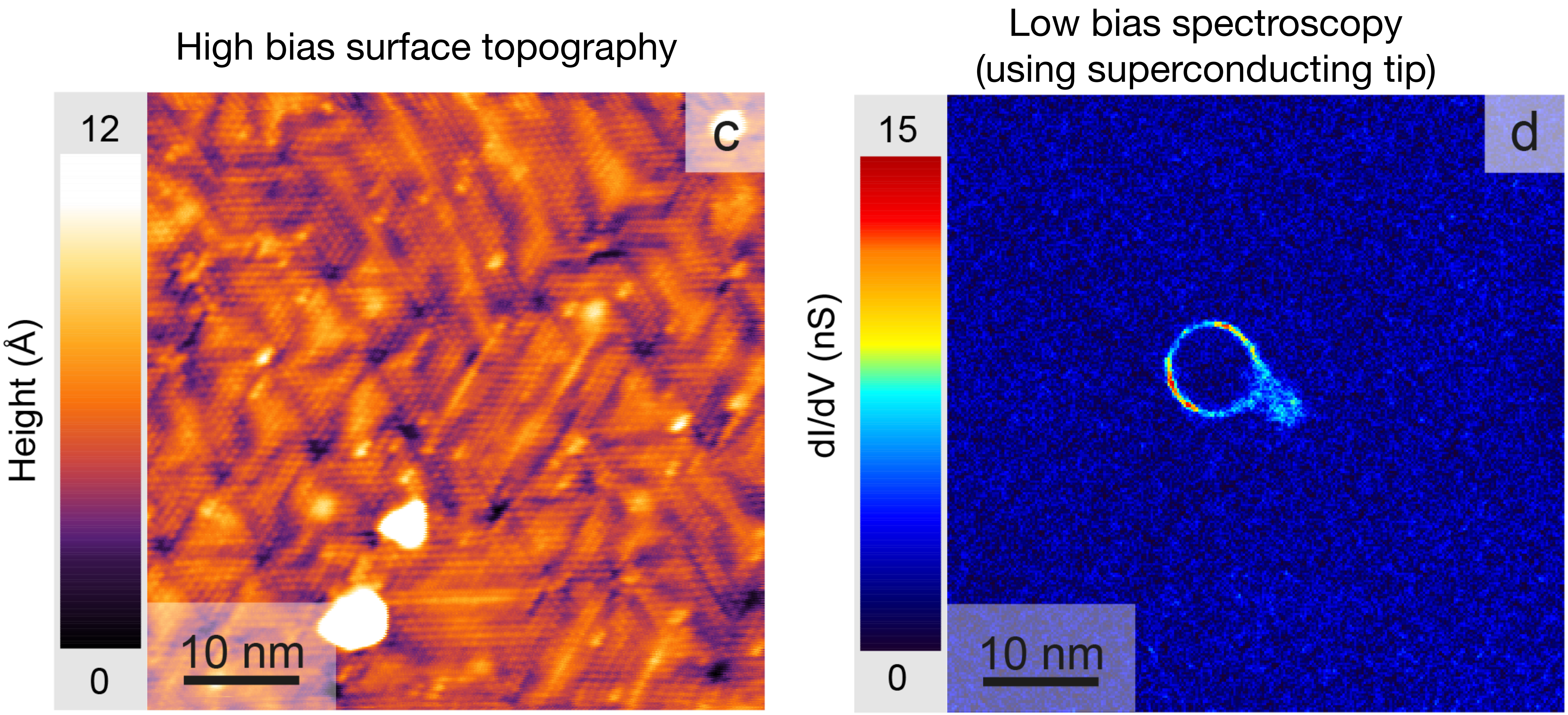
Triplet superconductivity & Spin-orbit interaction

A spatially varying magnetic field in a triplet superconductor can induce a topological transition in space.



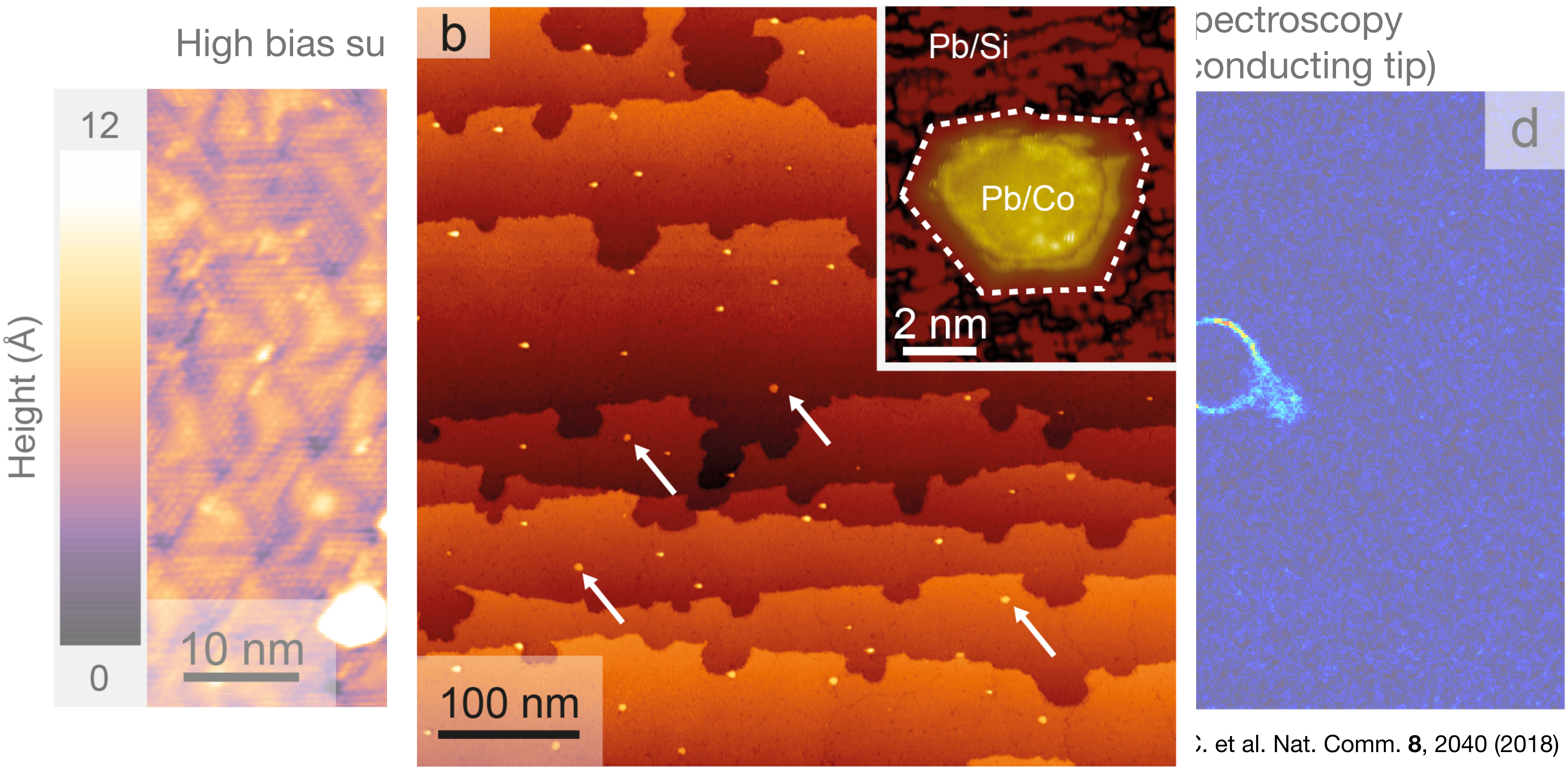


Topological Majorana edge states



Ménard, G.C. et al. Nat. Comm. **8**, 2040 (2018)

Topological Majorana edge states



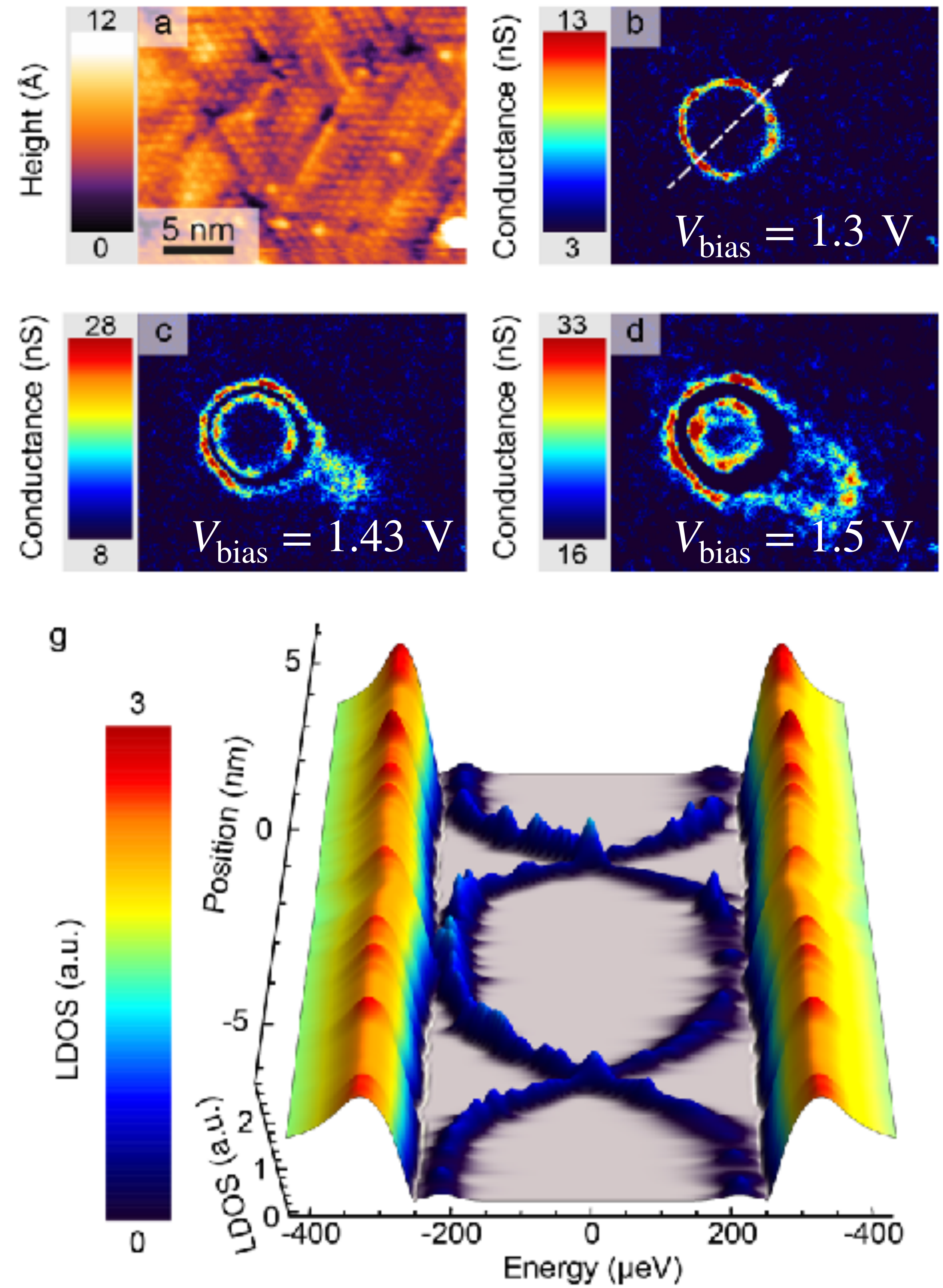
:. et al. Nat. Comm. **8**, 2040 (2018)

Ménard, G.C. et al. Nat. Comm. **8**, 2040 (2018)

Topological Majorana edge states

What shows up as a perfect ring at zero energy splits at finite bias into two well separated structures.

By taking a cut through the center of the cluster we can image the spatial dispersion of the topological edge band.



Ménard, G.C. et al. Nat. Comm. **8**, 2040 (2018)

Theory of Majorana bound states

We take the Hamiltonian that was previously used adding a vortex term in the spin-orbit coupling such that

Superconductivity

Magnetic interaction

$$\hat{H} = \int d^2 r \Psi^\dagger_{\vec{r}} \boxed{\left[(-\eta \nabla^2 - \mu)\tau_z + \Delta_S \tau_x\right.} + \boxed{\left.V_z(\vec{r})\sigma_z\right]} \Psi_{\vec{r}} + H_{\text{SO-defect}}(\vec{r})$$

$$\hat{H}_{\text{SO-defect}}(\vec{r}) = \boxed{\hat{c}^\dagger_{\vec{r}\uparrow} \left\{ \alpha e^{i\theta(\vec{r})}, \nabla_x - i \nabla_y \right\} \hat{c}_{\vec{r}\downarrow} + \mathrm{h.c.}}$$

Spin-orbit interaction with vortex in phase

Theory of Majorana bound states

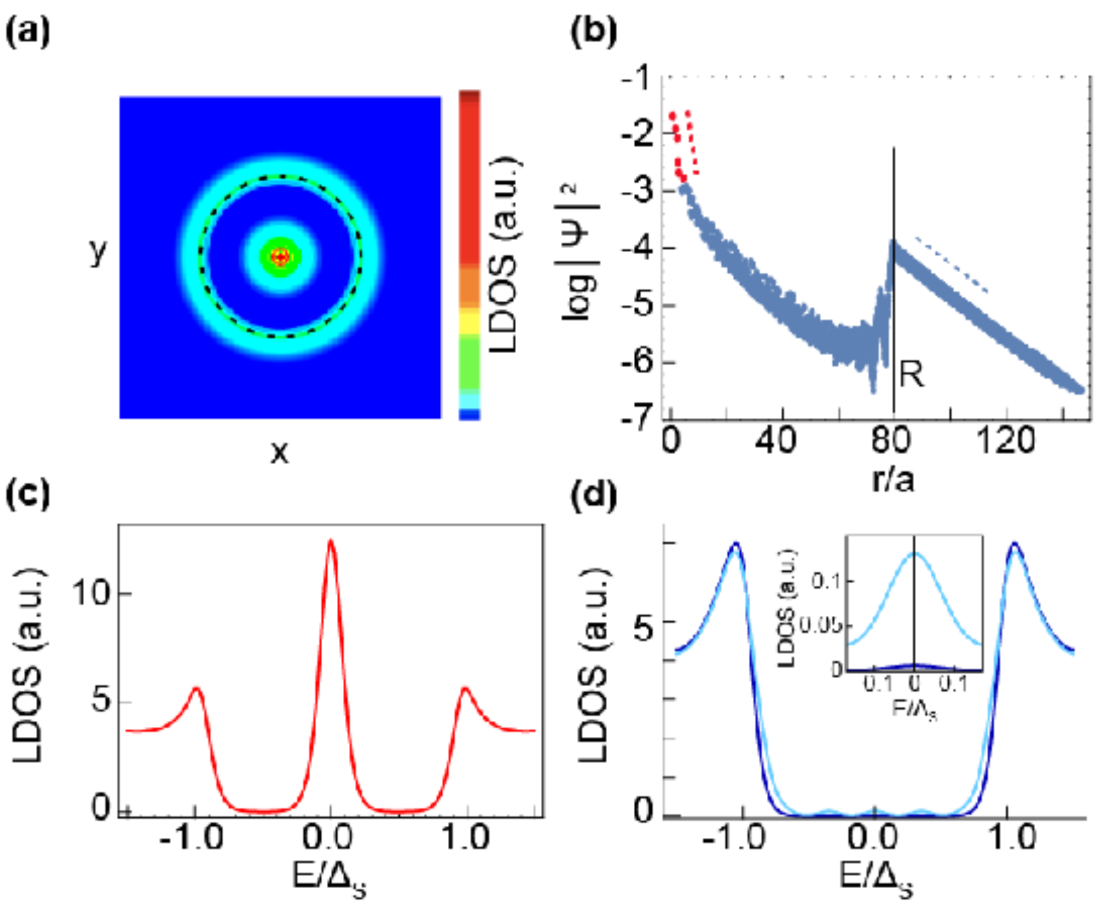
From a continuum of state we now only have one pair of well-separated zero-bias states within the gap

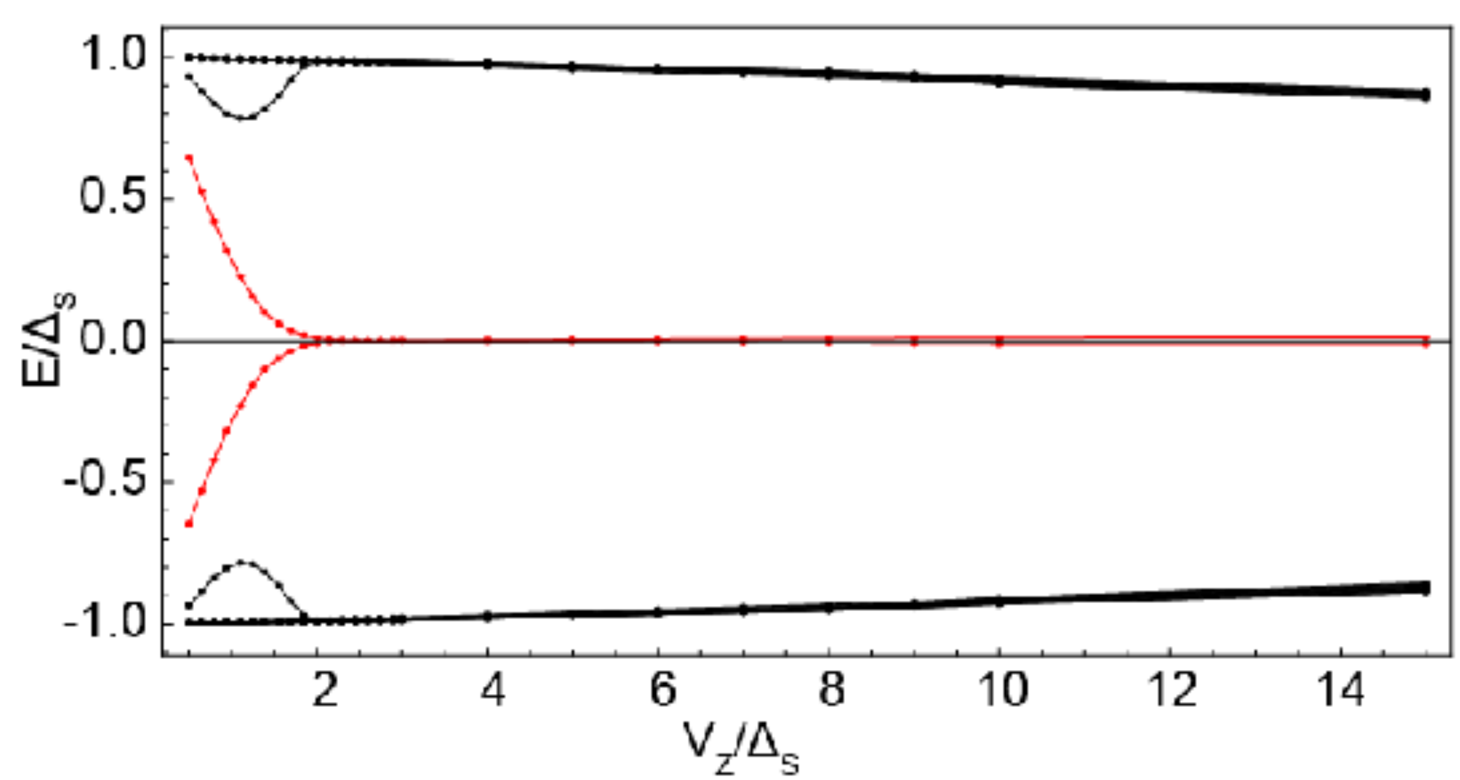
Superconductivity **Magnetic interaction**

$$\hat{H} = \int d^2r\,\Psi^\dagger_{\vec r}\,\boxed{[(-\eta\nabla^2-\mu)\tau_z + \Delta_S\tau_x} + \boxed{V_z(\vec r)\sigma_z]}\,\Psi_{\vec r} + H_{\mathrm{SO-defect}}(\vec r)$$

$$\hat{H}_{\mathrm{SO-defect}}(\vec r) = \boxed{\hat c^\dagger_{\vec r\uparrow}\left\{\alpha e^{i\theta(\vec r)}, \nabla_x - i\nabla_y\right\}\hat c_{\vec r\downarrow} + \mathrm{h\,.\,c\,.}}$$

Spin-orbit interaction with vortex in phase

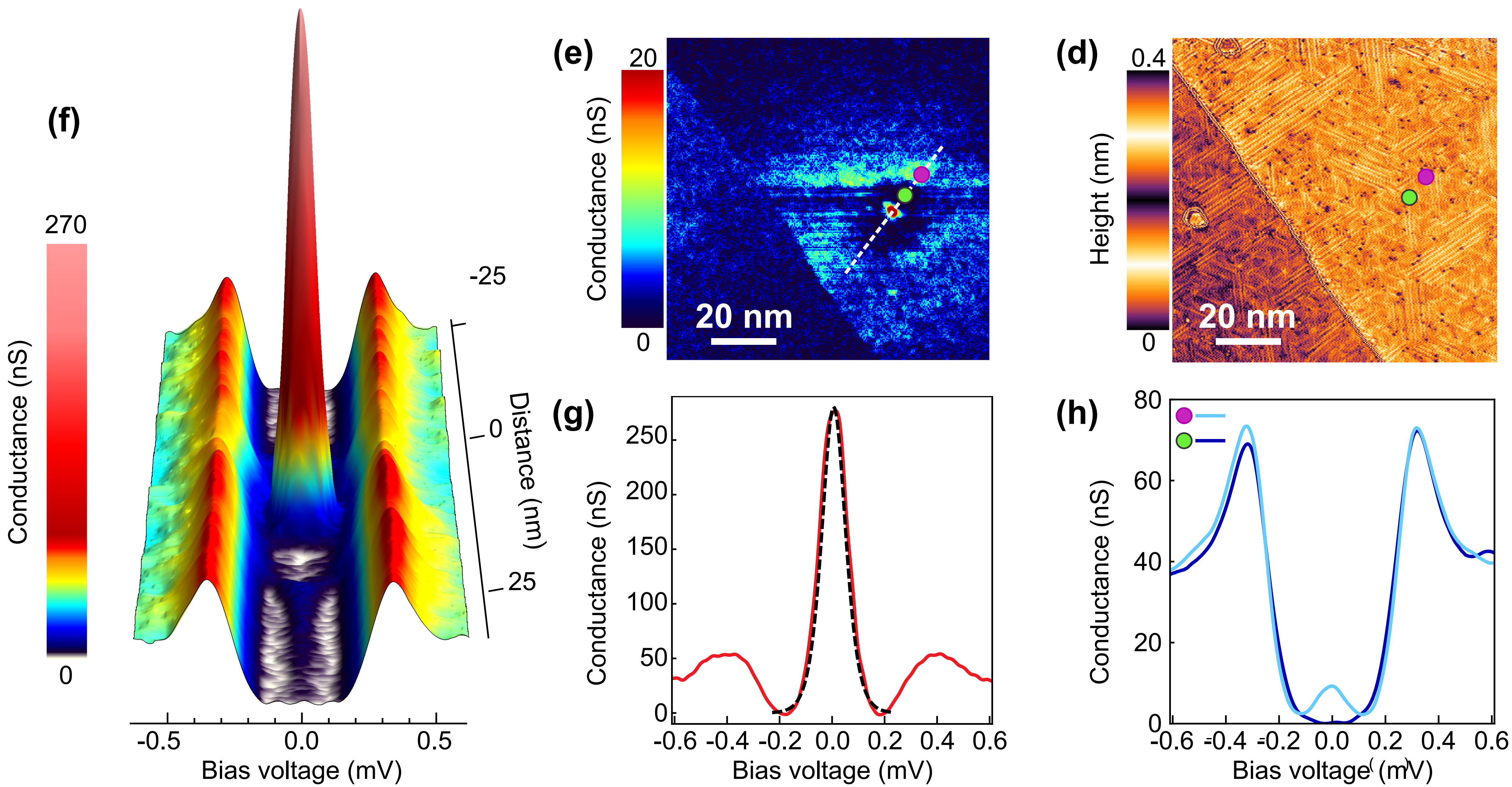




Ménard, G.C. et al. Nat. Comm **10**, 2587 (2019)

Topological Majorana bound states

Slightly changing the amount of Co on the surface changes the size of the cluster and zero bias peak can be observed at the center of magnetic clusters.



Ménard, G.C. et al. Nat. Comm **10**, 2587 (2019)

Conclusion

* We measured individual impurities in a variety of phases

* We grew disordered nano clusters of Co buried under Pb on a Si(111) substrate and observed YSR bands.

* We grew ordered nanoclusters and observed topological edge states

* In slightly different configuration we observed disorder-proof zero-bias peaks

Collaborators

STM team in INSP:

C. Brun, T. Cren, F. Debontridder, D. Demaille, R. Leriche, D. Roditchev.

Theory team in LPS:

S. Guissard, A. Mesaros, P. Simon, M. Triff

Thank your for your attention