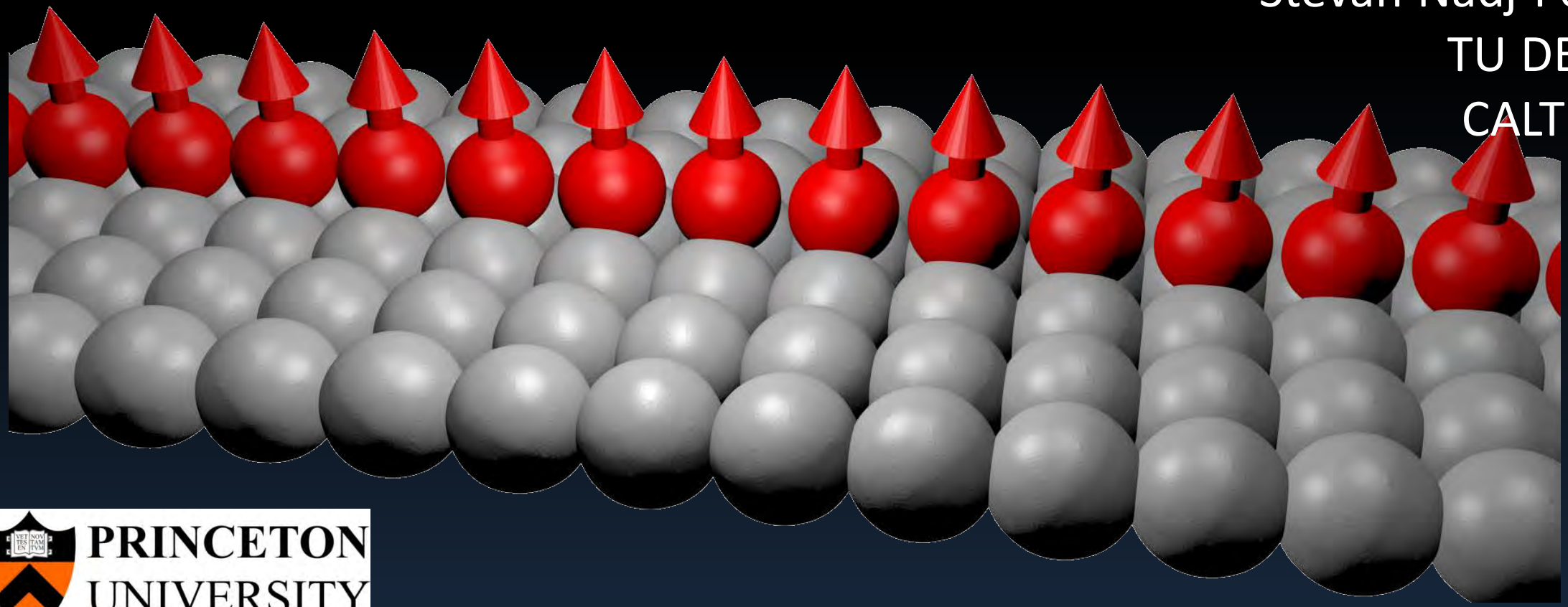
Majorana modes in Atomic Chains on the Surface of a Superconductor

Stevan Nadj-Perge
TU DELFT
CALTECH



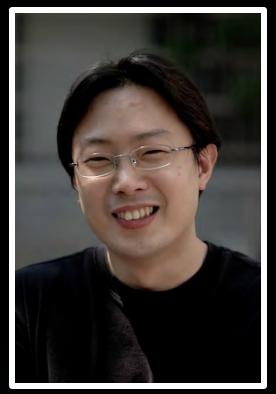
MARIE CURIE ACTIONS

PRINCETON UNIVERSITY

Acknowledgments

Experiment

Ilya Drozdov



Sangjun Jeon

Jungpil Seo

Prof. Ali Yazdani

Theory

Jian Li

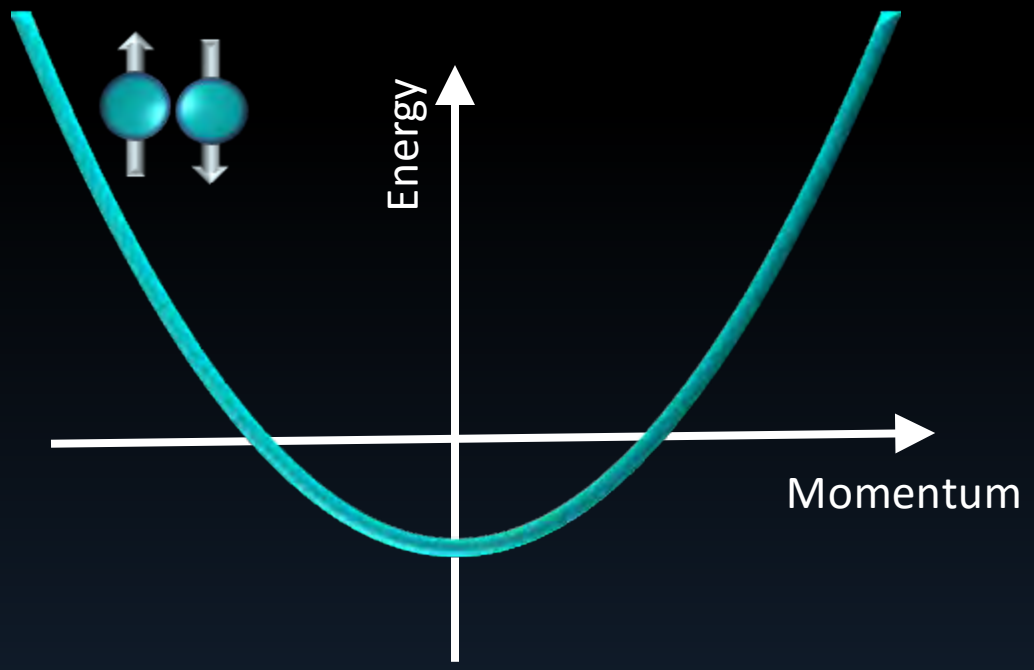
Prof. B. A. Bernevig

UT Austin

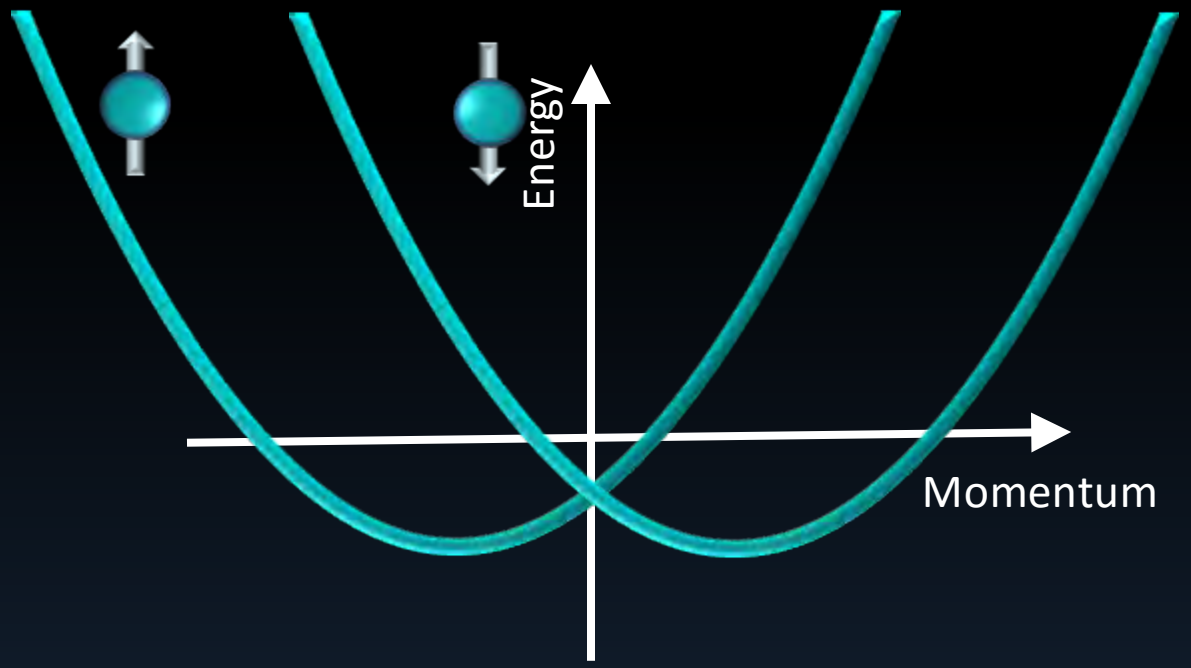
Hua Chen

Prof. Allan MacDonald

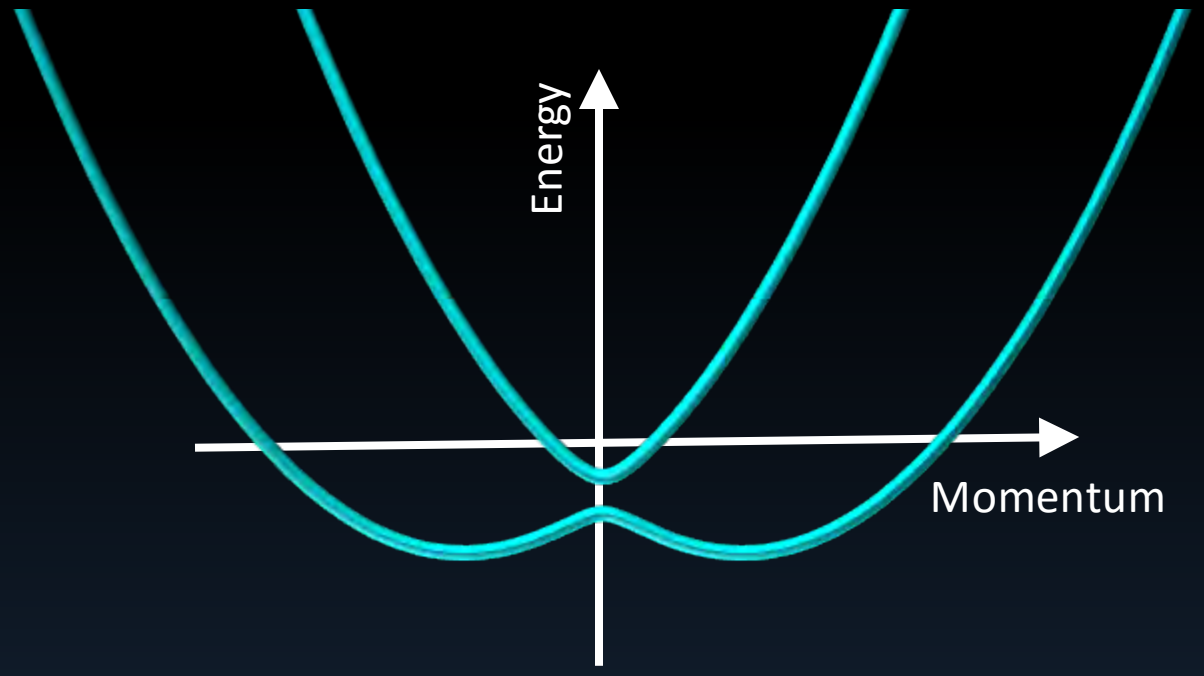
Topology & band structure



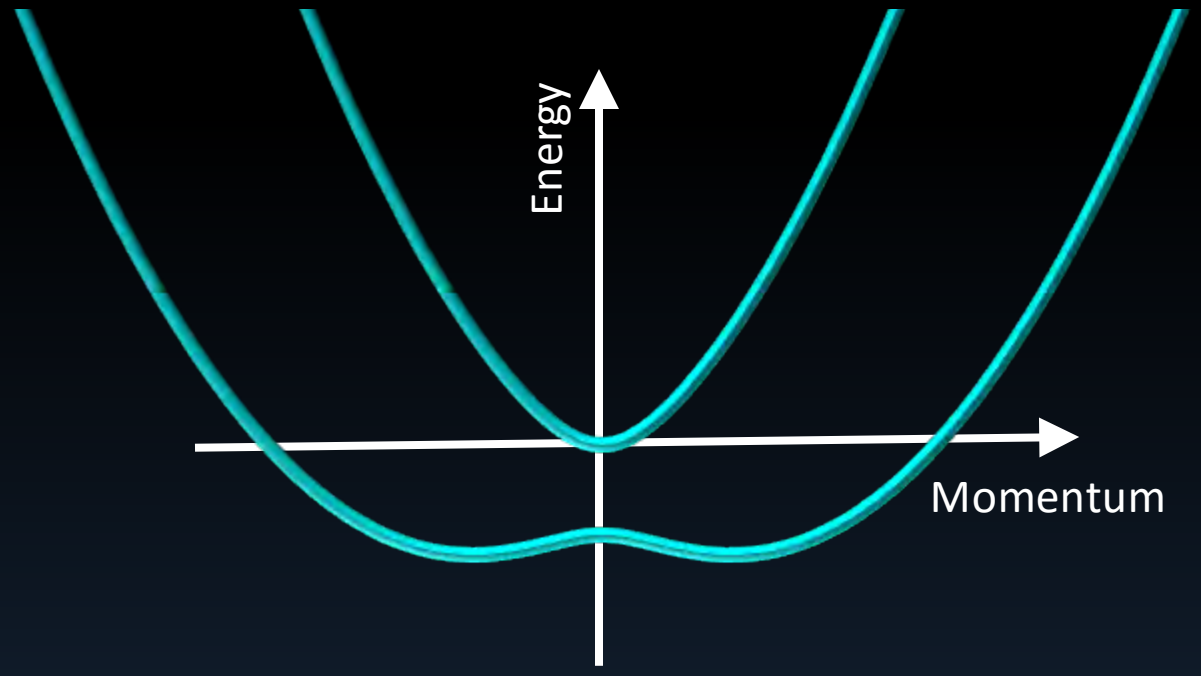
SPIN ORBIT INTERACTION (SOI)



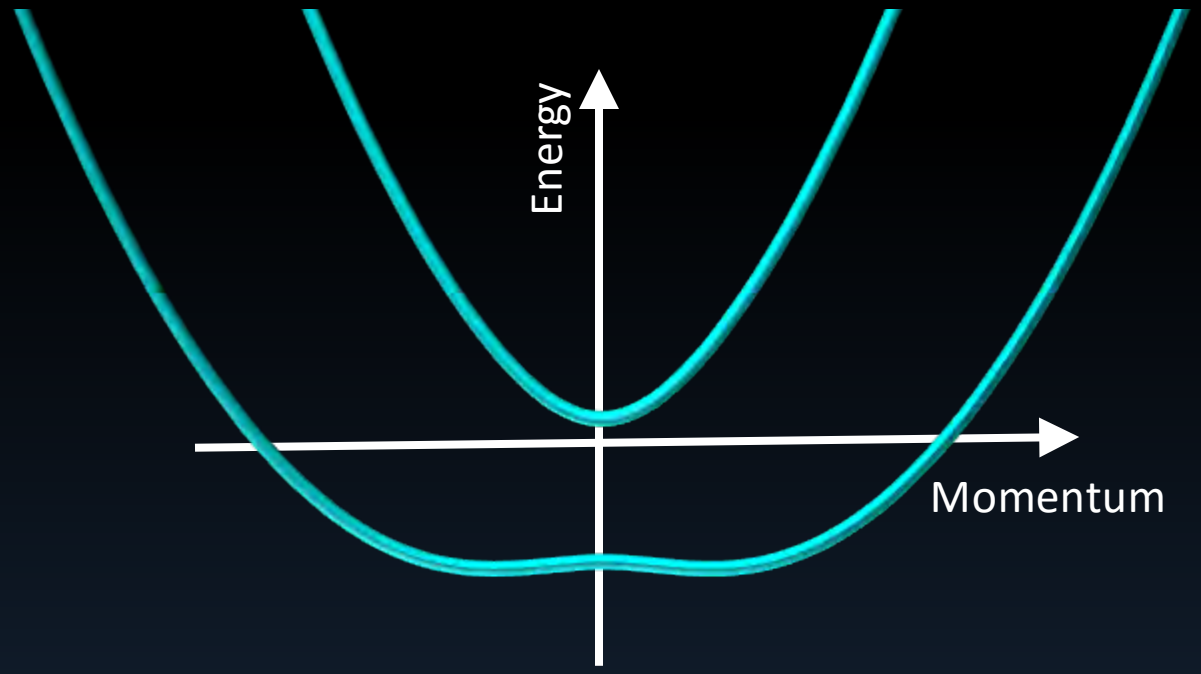
SOI+Magnetism



SOI + Magnetism

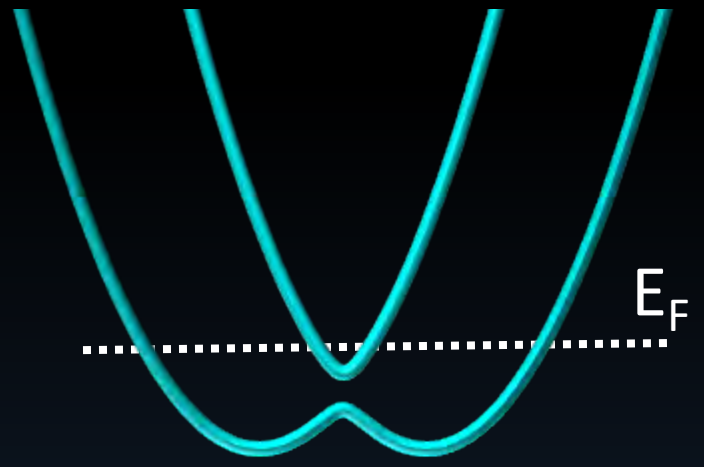


SOI + Magnetism

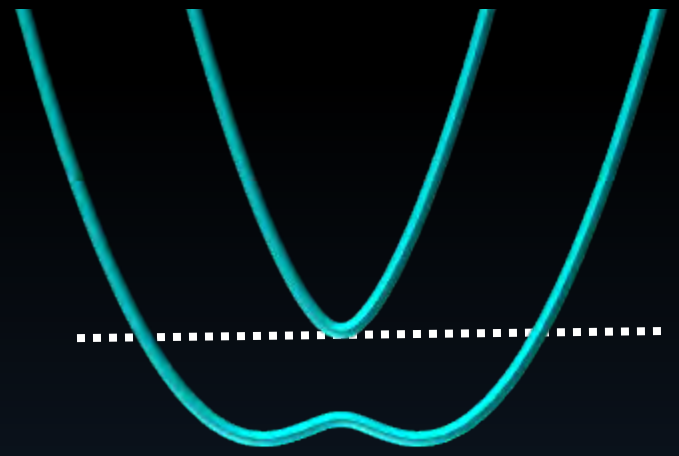


SOI + Magnetism

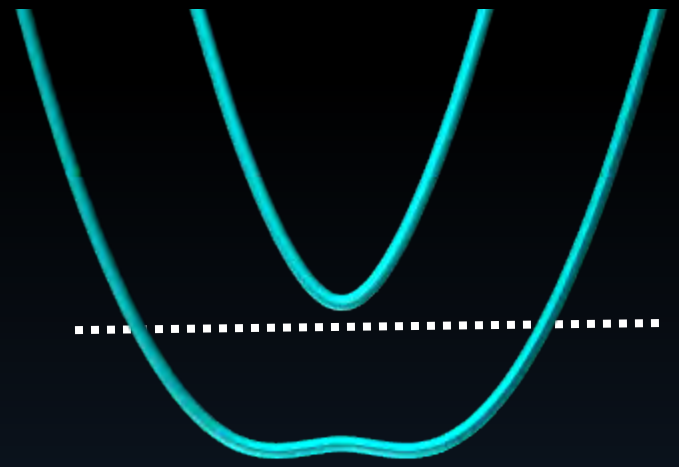
$B < B_{critical}$



$B = B_{critical}$



$B > B_{critical}$

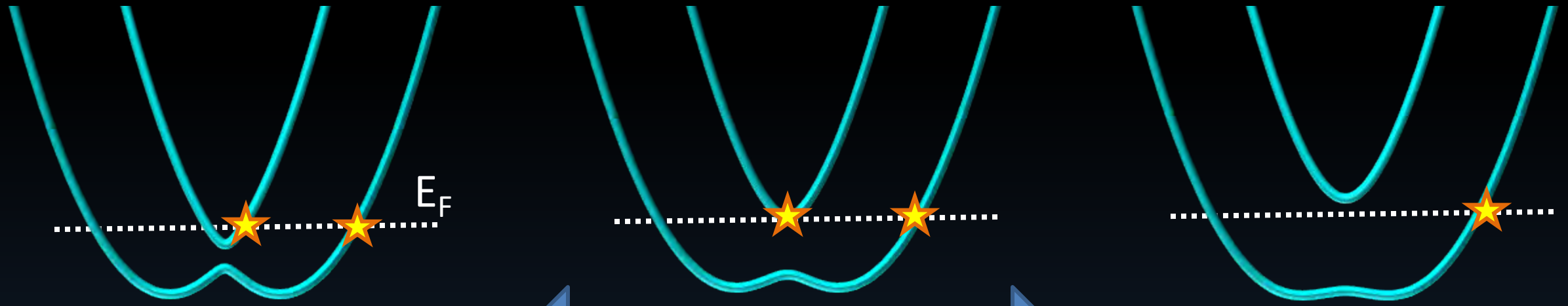


SOI + Magnetism

$B < B_{critical}$

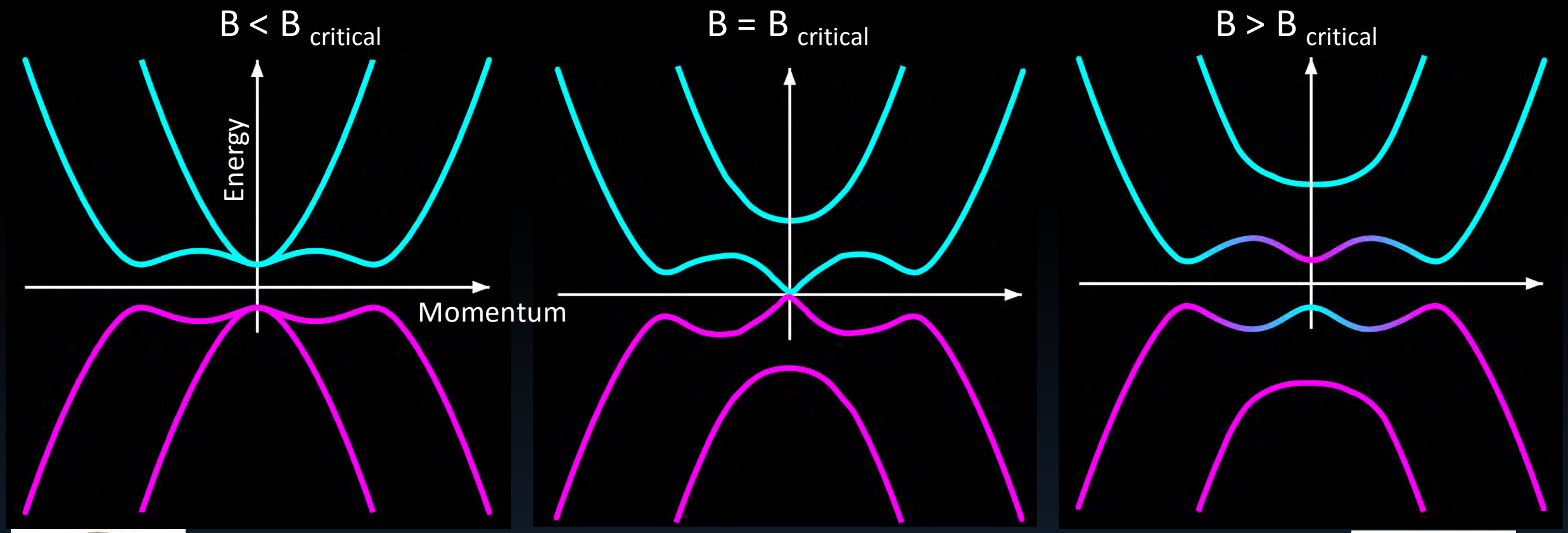
$B = B_{critical}$

$B > B_{critical}$



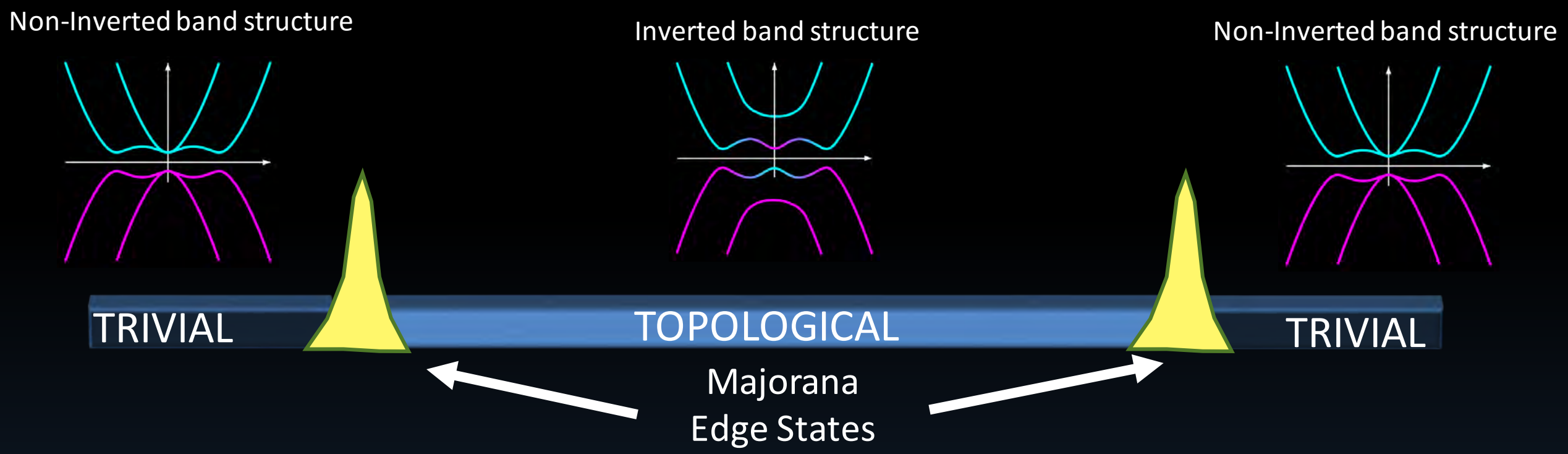
TOPOLOGICALLY DISTINCT
Number of crossing different in parity

SOI + Magnetic field + superconductivity



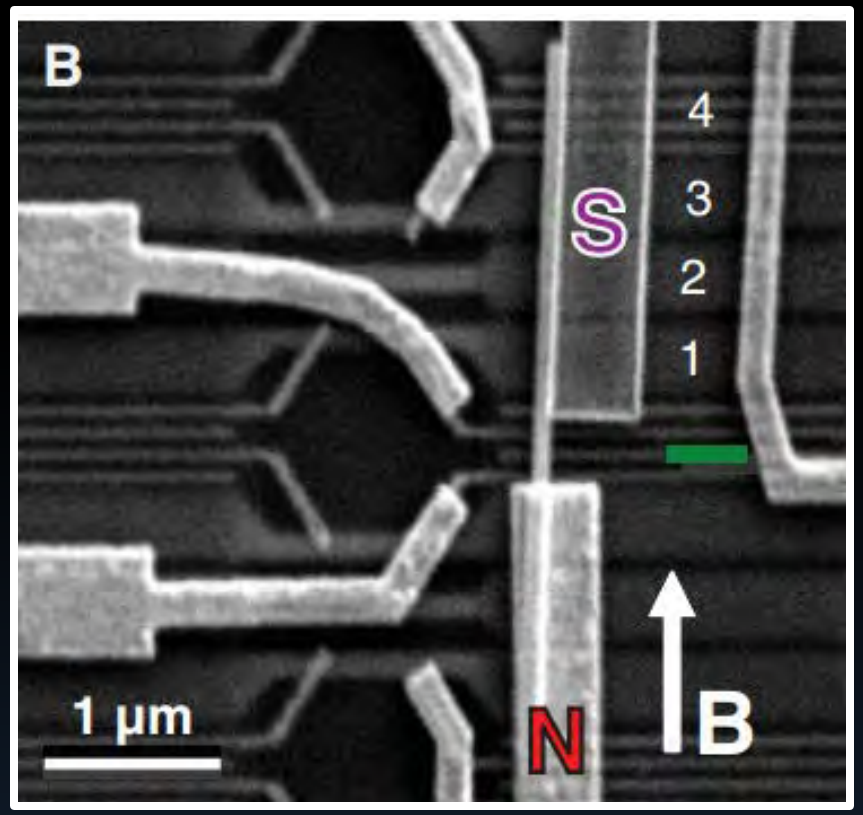
Y. Oreg et al. PRL(2010); R. M. Lutchyn et al PRL (2010);

Topology & bandstructure in 1D

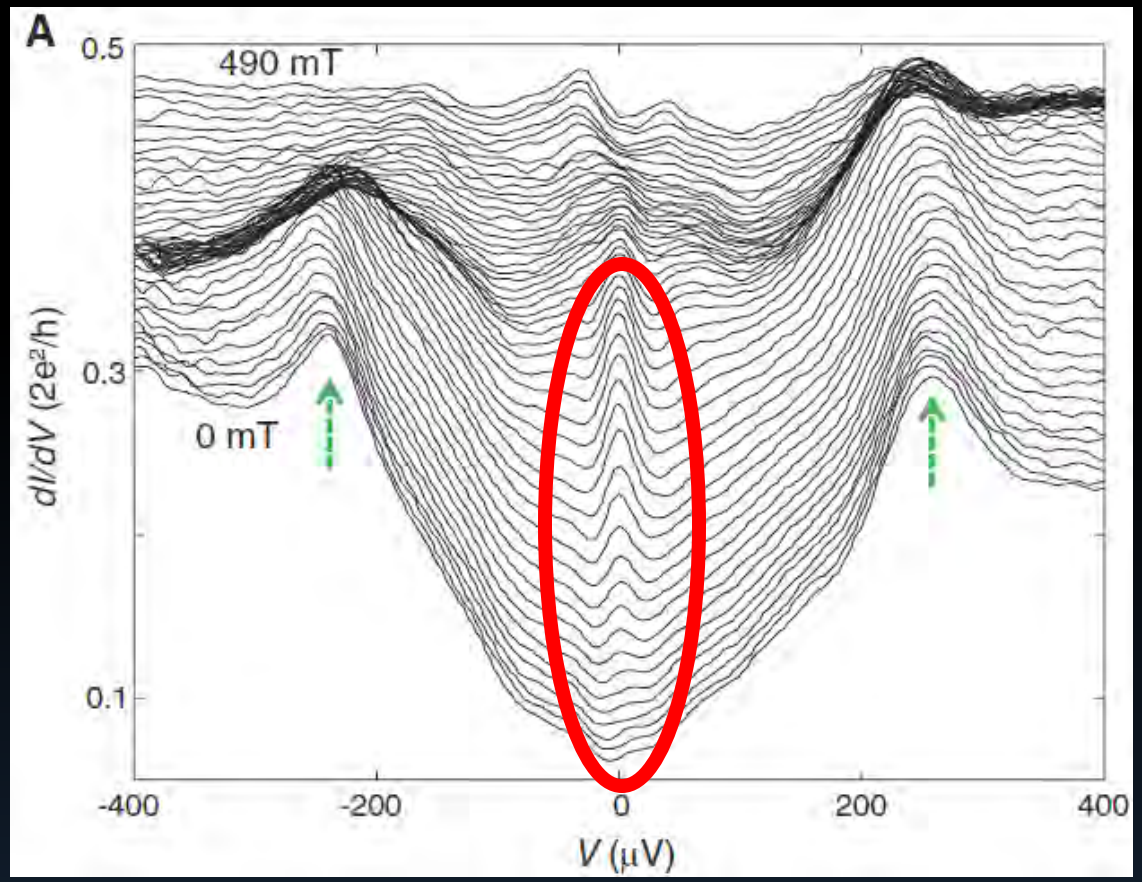


Y. Oreg et al. PRL(2010); R. M. Lutchyn et al PRL (2010);

Majorana wires



Zero bias peak in tunneling spectroscopy

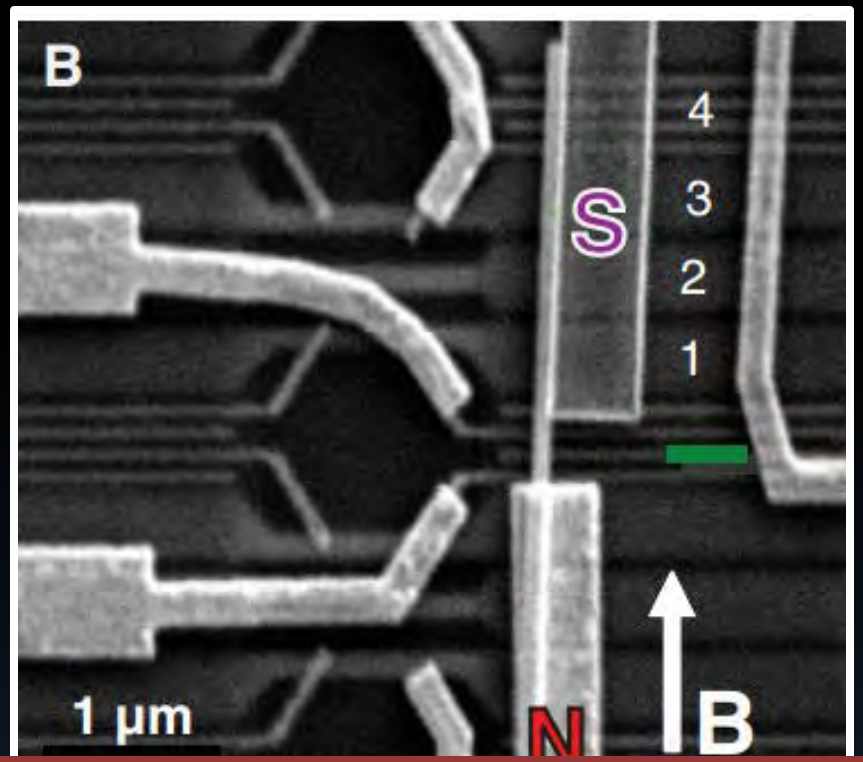


Rokhinson et al. Nat. Phys. (2012)
Das et al., Nat. Phys. (2012)

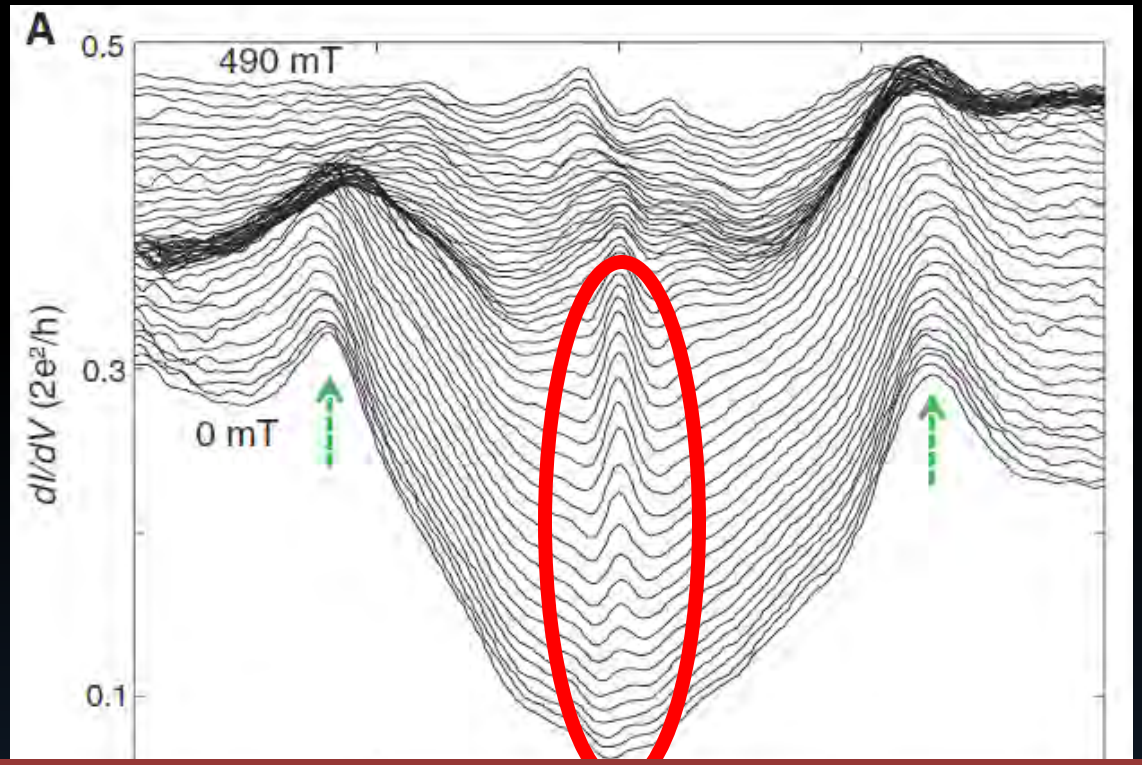
(Also: Deng et al. Nano Lett. (2012), van Harlinegen group and C. Marcus groups (2013), and others)

Mourik et al., Science (2012)

Majorana wires



Zero bias peak in tunneling spectroscopy

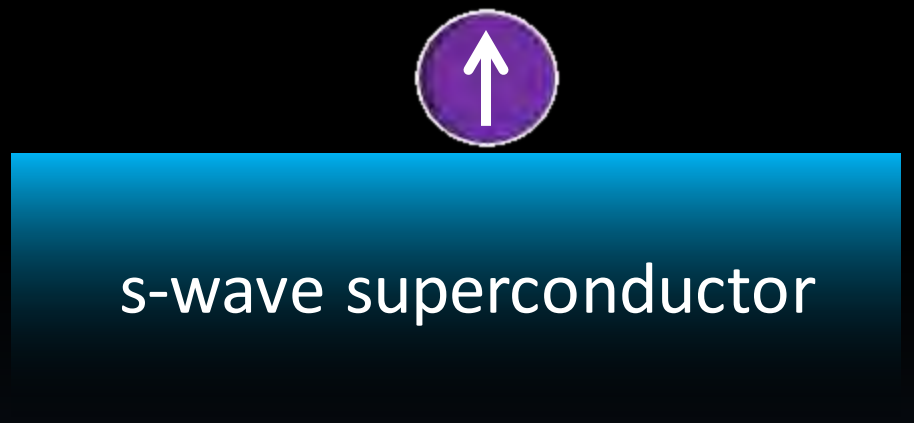


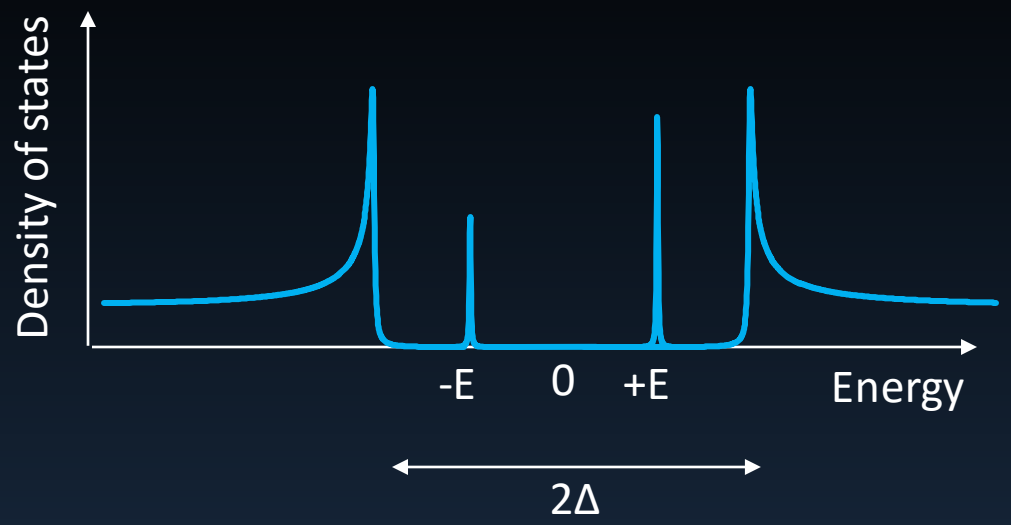
Hard to probe locally the wire ends

(Verify position of the Majorana modes)

Yu-Shiba-Rusinov states for a single atom

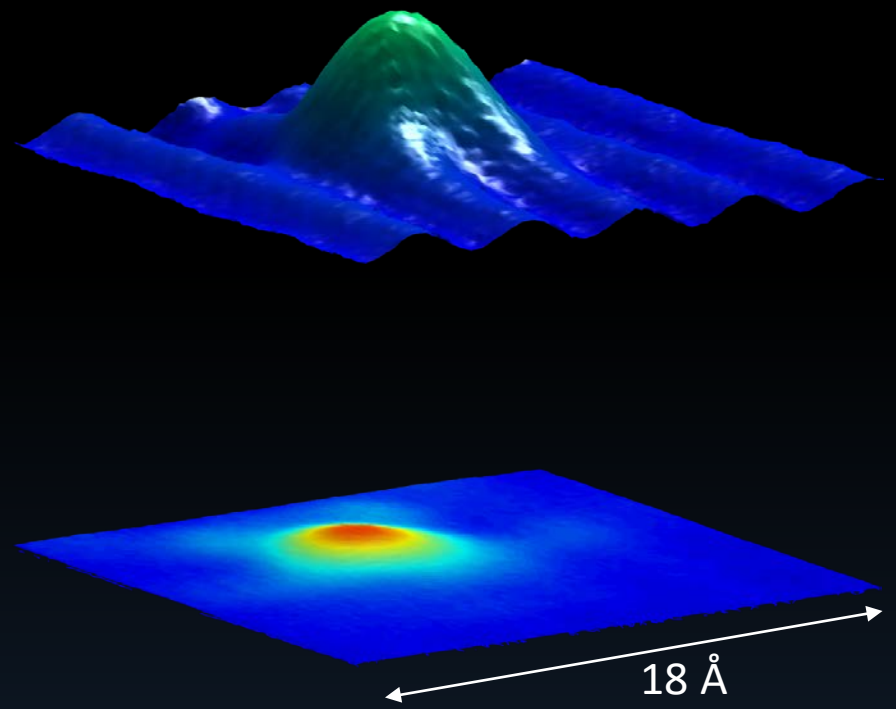
Classical spin in a superconductor $H = H_{BCS} + B\, S \cdot s$





Yu APS (1965), Shiba PTP (1968) , Rusinov JETP (1969), Balatsky et al RMP (2006)

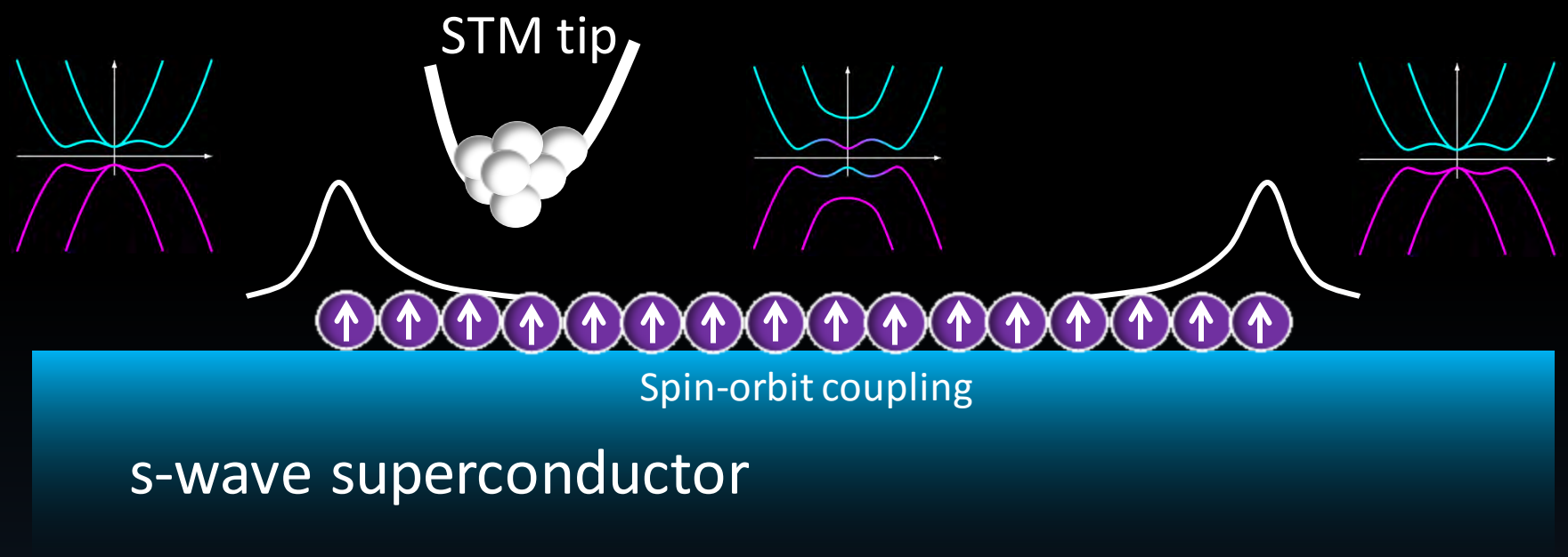
TOPOGRAPHY



dI/dV conductance
(at 1.07mV for the gap 1.35meV)

Mn, Gd on Nb Yazdani et al., Science (1997)
Cr, Mn on Pb, Ji et al., PRL (2008)

Chain of magnetic atoms on the superconductor

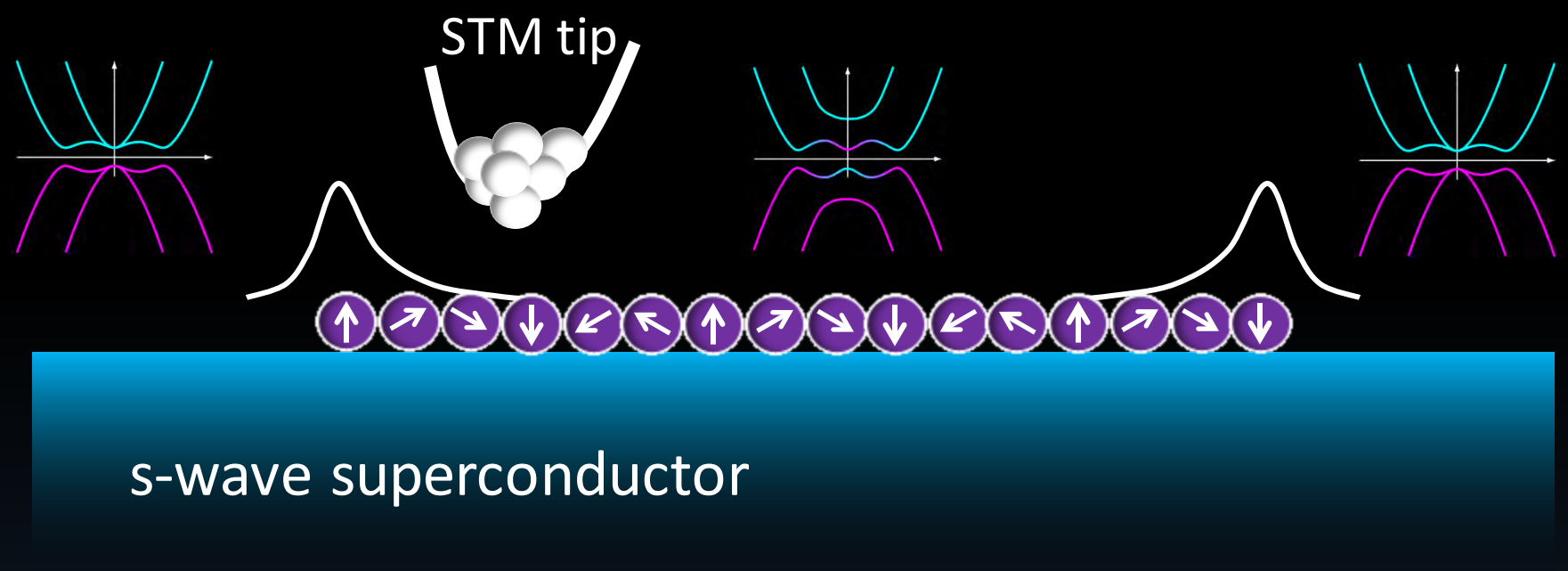


- Suitable for STM
- Can be disorder free

Magnetic atom

Magnetism + Superconductivity
Majorana proposals:
Choy et. al (PRB 2011)
Flensberg et. al (PRB 2011)
Martin and Morpurgo (PRB 2012)

Chain of magnetic atoms on the superconductor



- Suitable for STM
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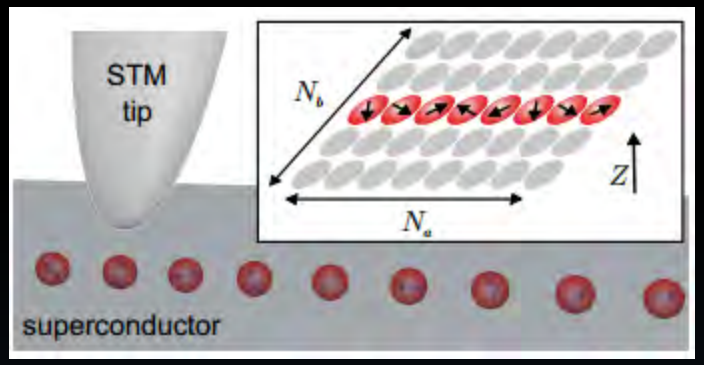
Magnetic atom

Magnetism + Superconductivity
Majorana proposals:
Choy et. al (PRB 2011)
Flensberg et. al (PRB 2011)
Martin and Morpurgo (PRB 2012)

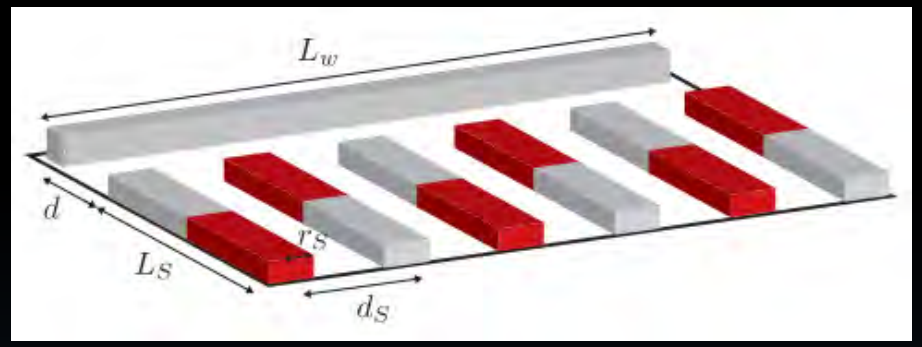
Majorana fermions and magnetic texture

Majorana fermions emerging from magnetic nanoparticles on a superconductor without spin-orbit coupling

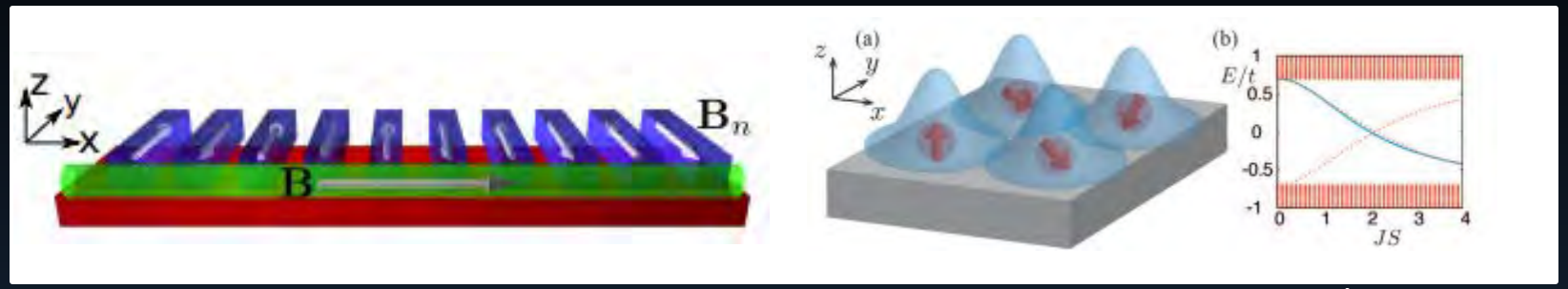
T.-P. Choy, J. M. Edge, A. R. Akhmerov, and C. W. J. Beenakker
Instituut-Lorentz, Universiteit Leiden, P.O. Box 9506, 2300 RA Leiden, The Netherlands



Nadj-Perge, Drozdov, Bernevig, Yazdani (PRB 2013)



Kjaergaard, Wölms, Flensberg (PRB 2012)

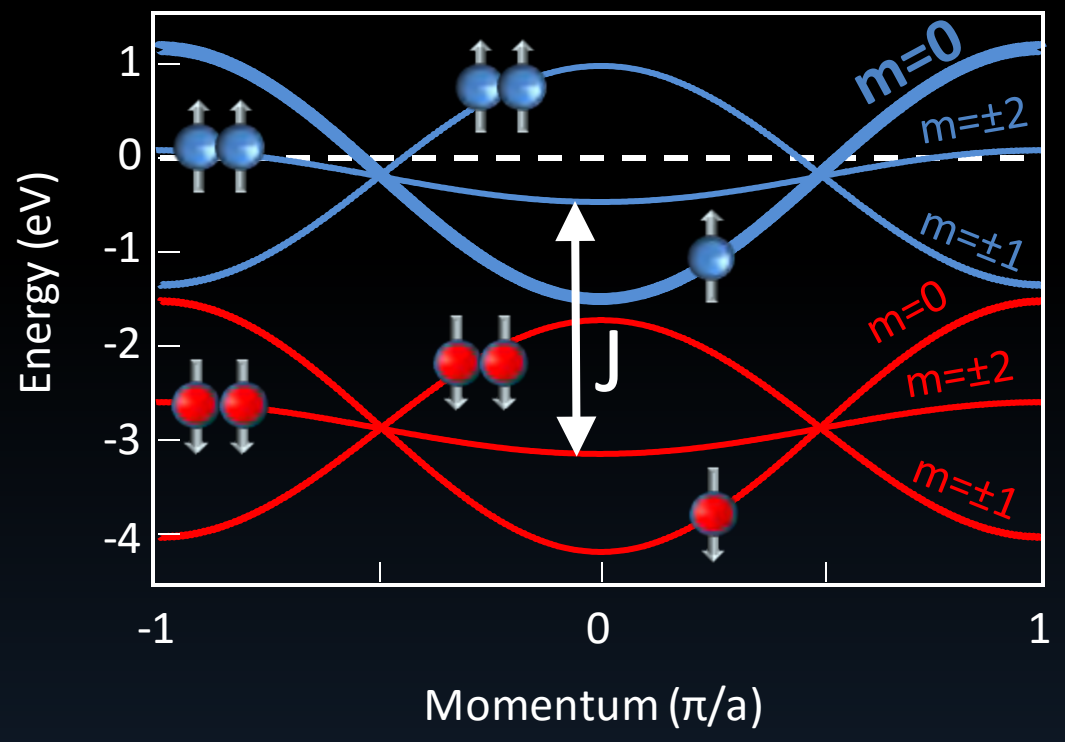


Klinovaja, Stano, Loss (PRL 2012)

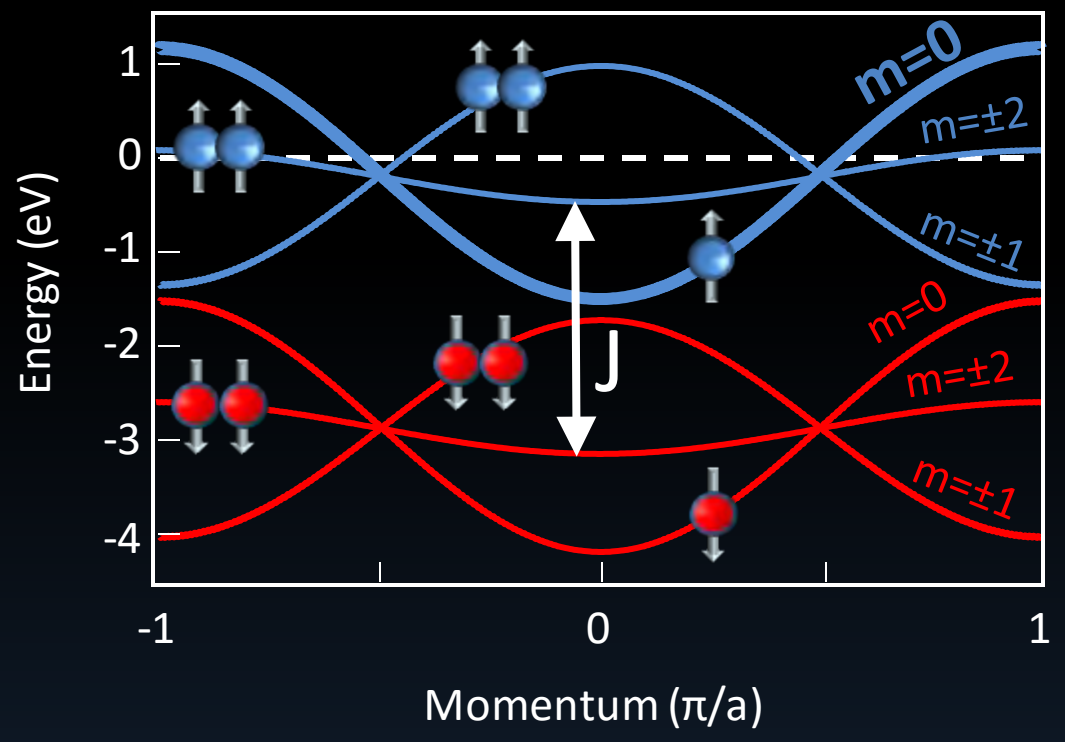
Nakosai, Tanaka, Nagaosa (PRB 2013)

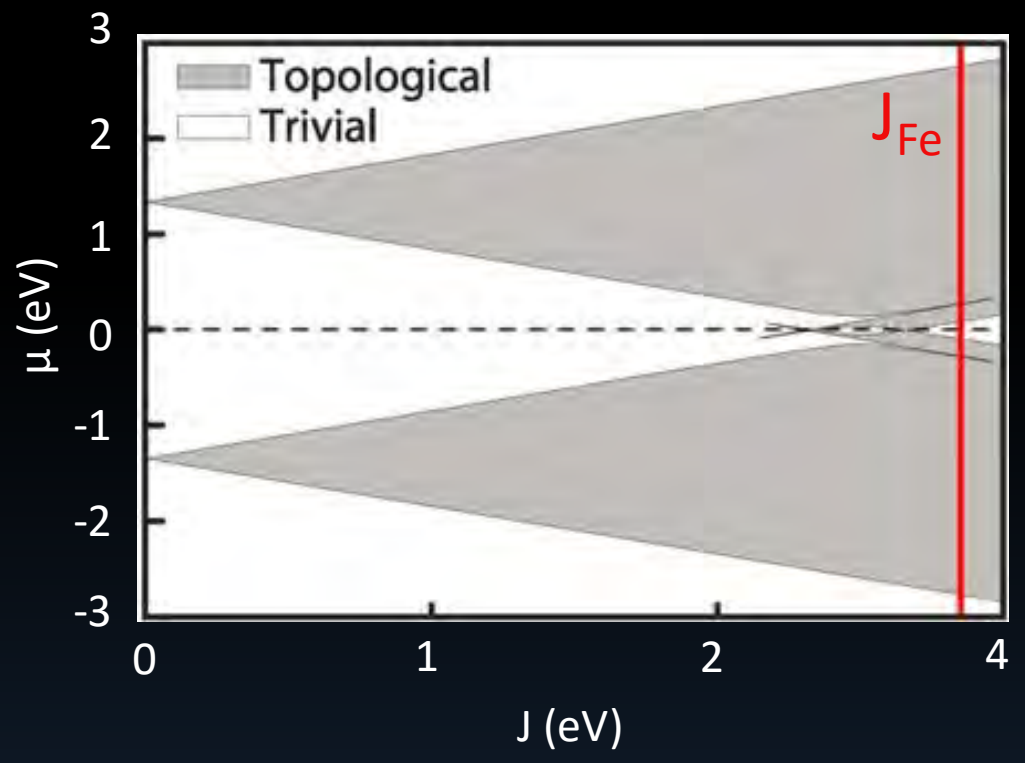
See also: Martin and Morpurgo (PRB 2012); Glazman (PRB 2013), and others ..

More than one band – Tight binding model



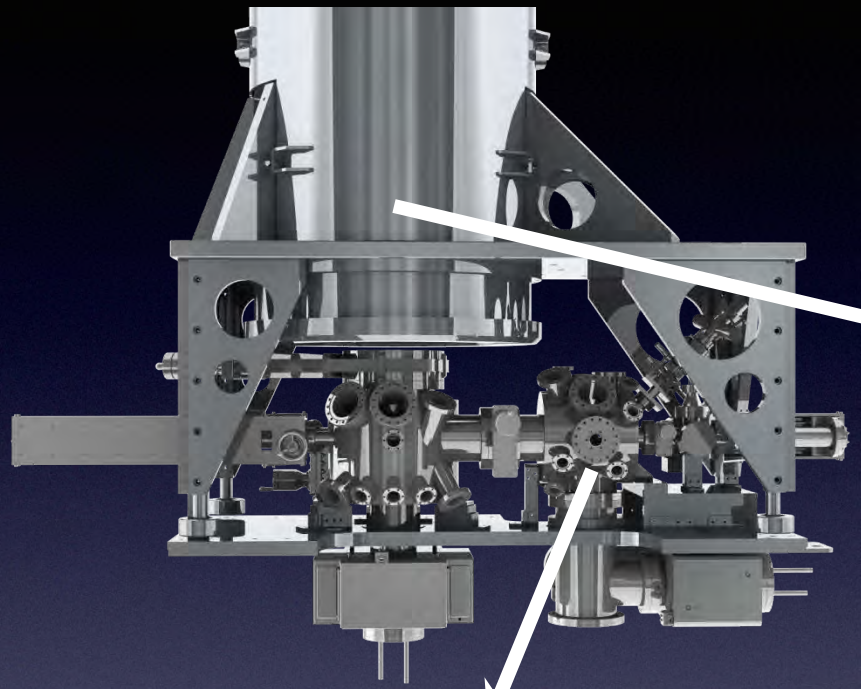
More than one band – Tight binding model

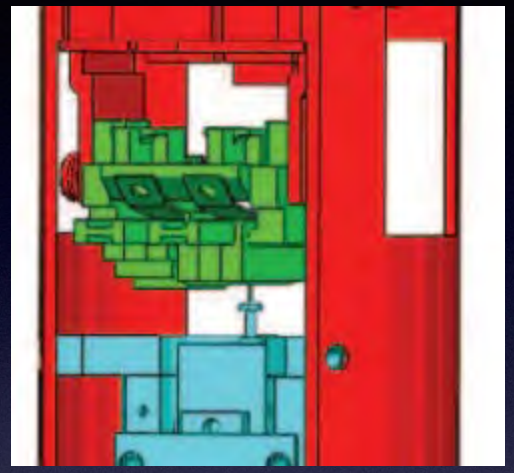


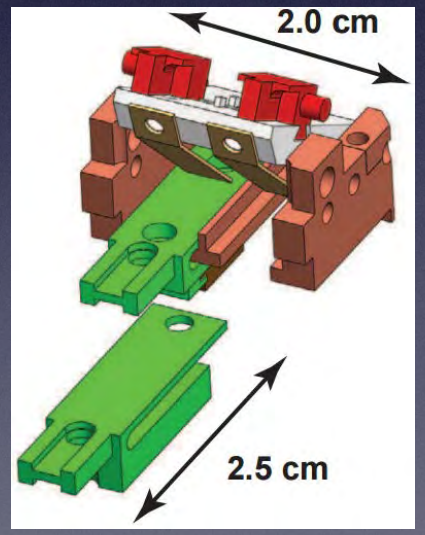


New Generation of High-Resolution STM at 1.4 K

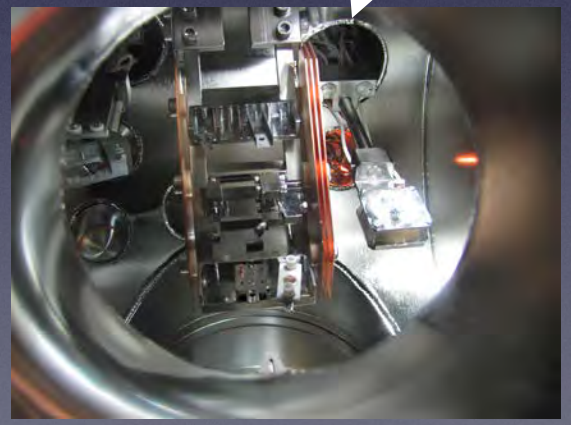
integrated STM/Growth/vector-field





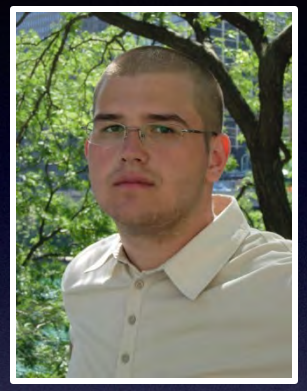


STM head: dual sample holder
Misra et al. Rev. Sci. Inst. (2013)



in situ growth capability

Assembled by:



Ilya Drozdov

Jungpil Seo

Experimental requirements

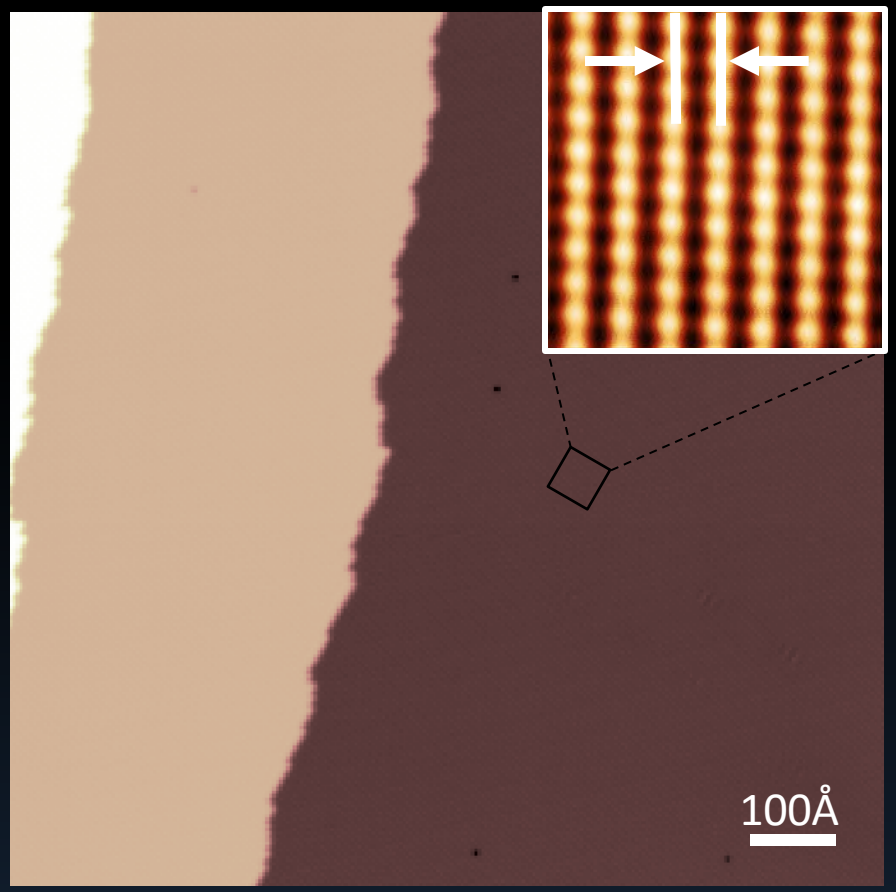
1) Atomically flat superconducting substrate

2) Magnetic atoms

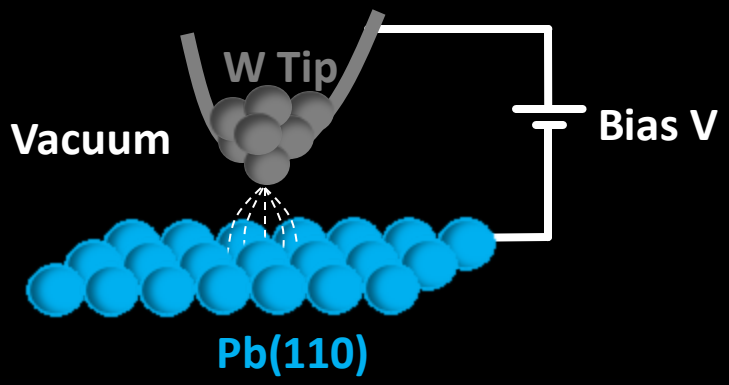
3) Spin-orbit coupling (or spin texture)

Superconducting Pb (110) substrate

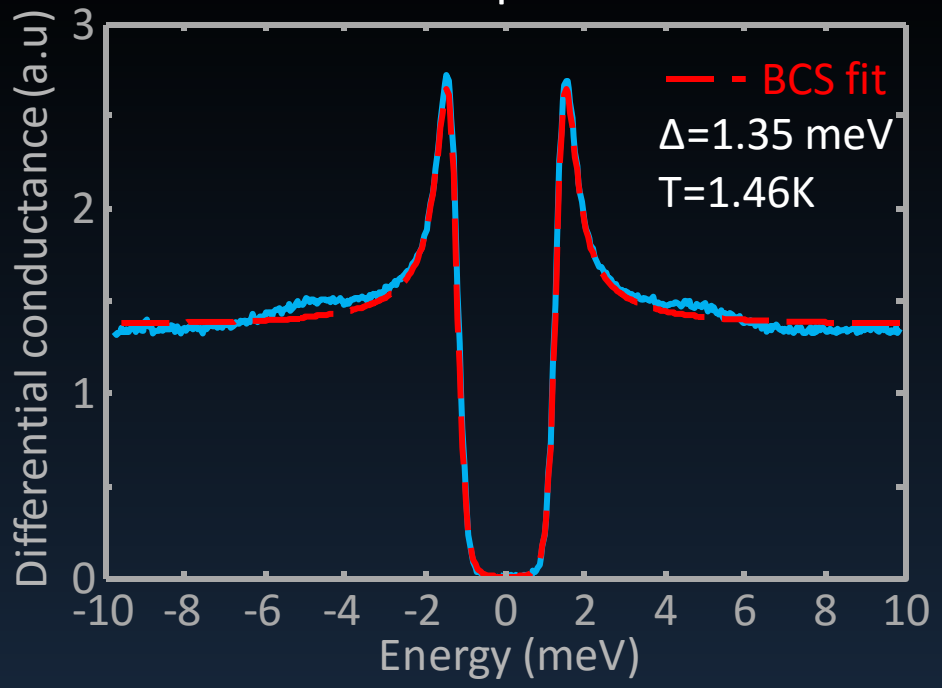
Topographic image – Pb(110) **a=4.95Å**



T_c=7.2K, ξ=830A, H_c=80mT, λ_L=370A

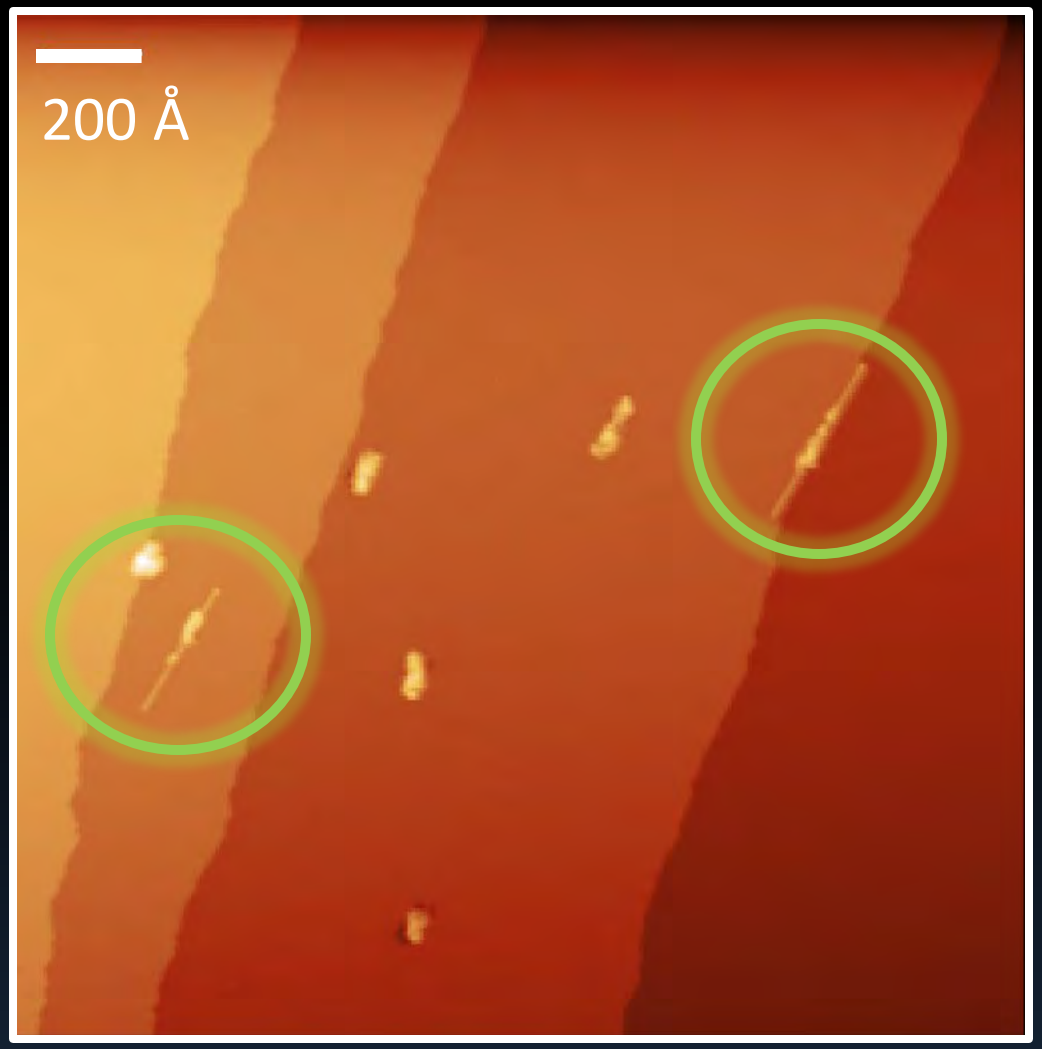


Point spectrum

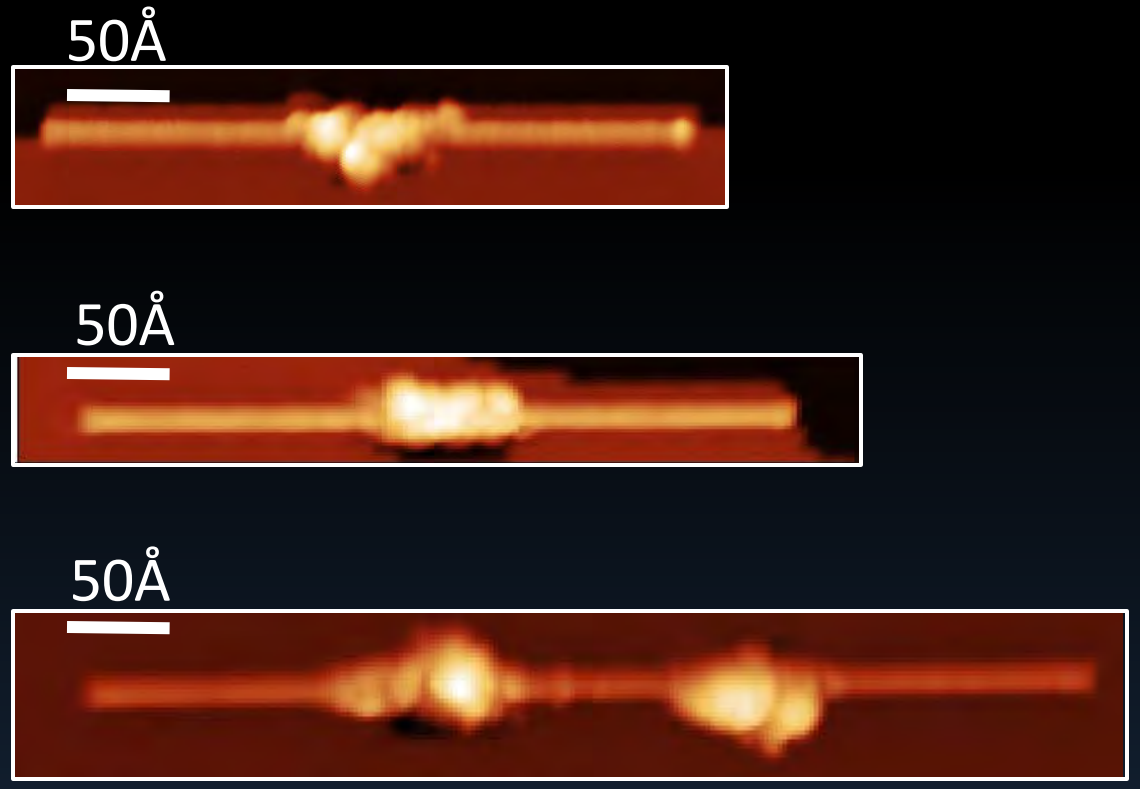


Fe atomic chain growth on Pb substrate

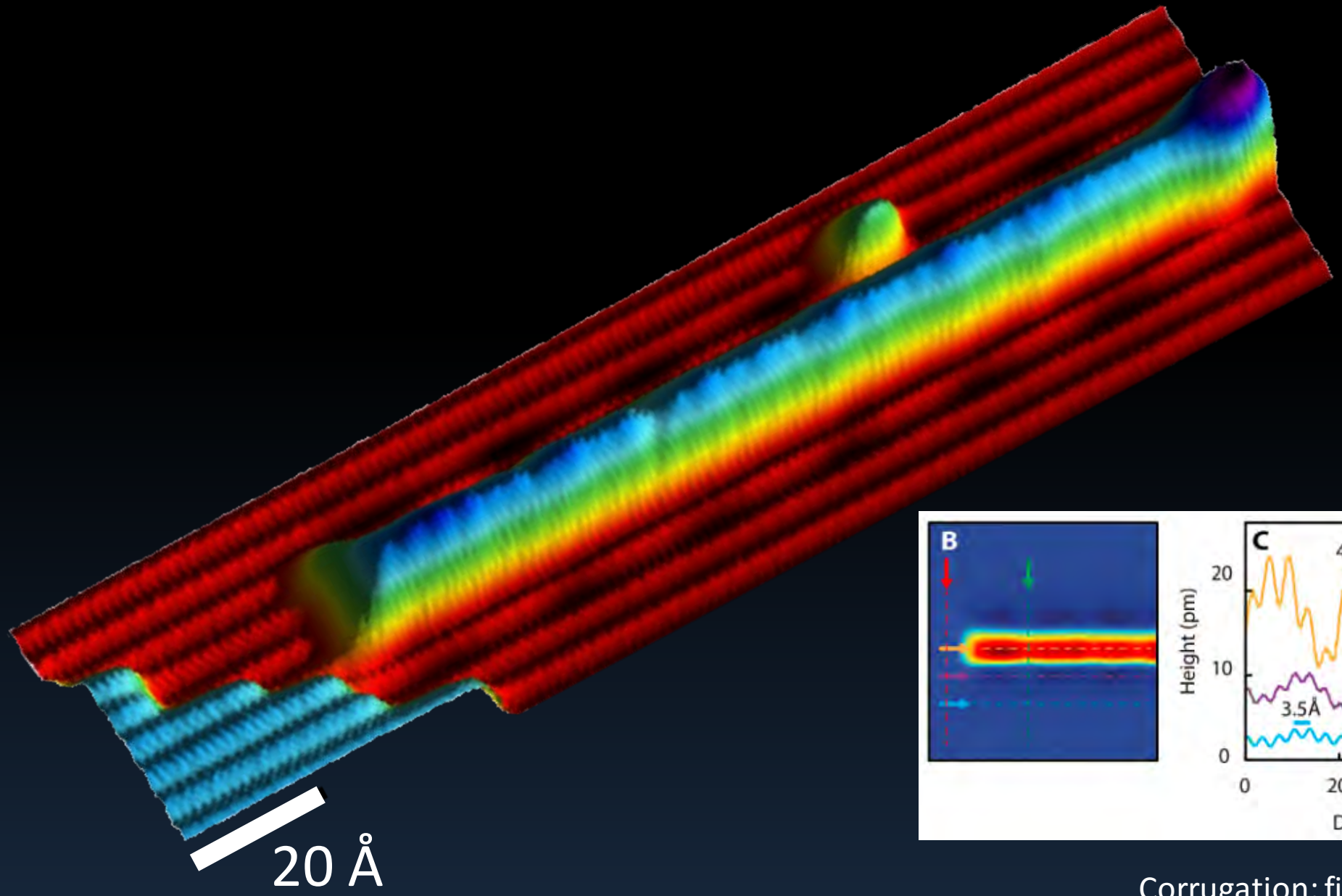
Topographic image

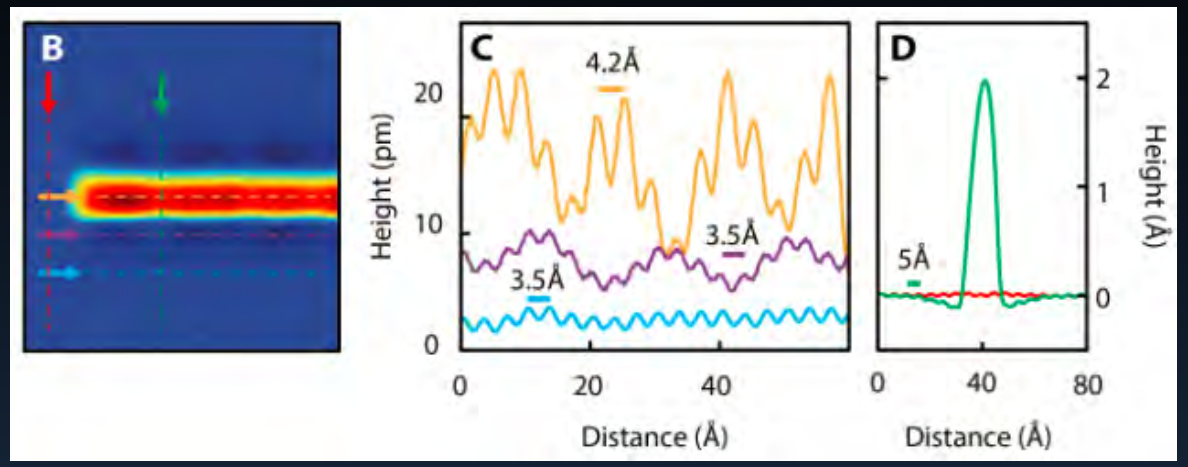


Total chain length up to 800 Å (~ 380 atoms)
"Clean" segments up to 150 Å (~ 70 atoms)



Single atom wide chains on Pb(110) substrate

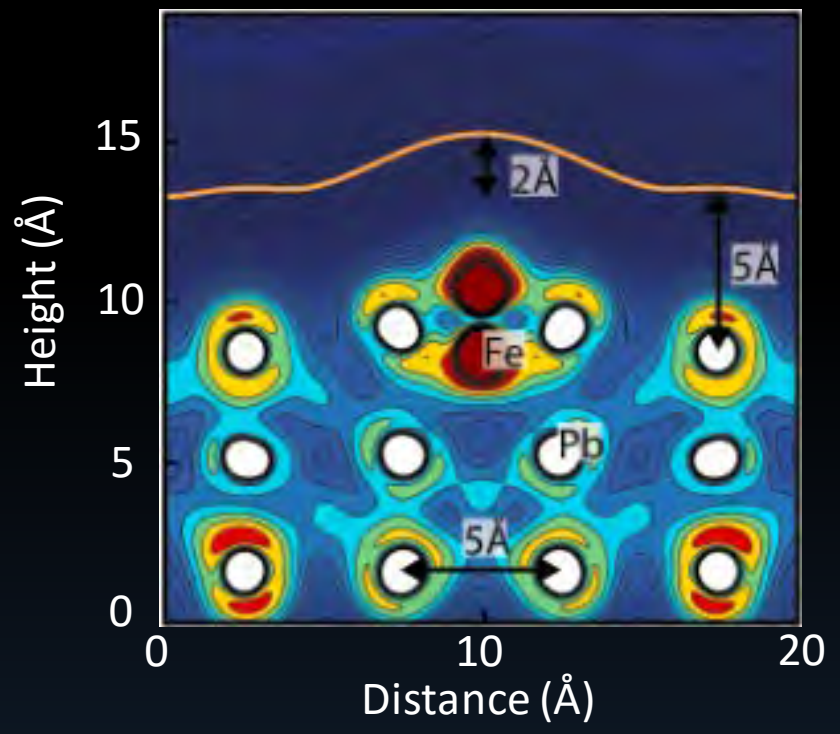




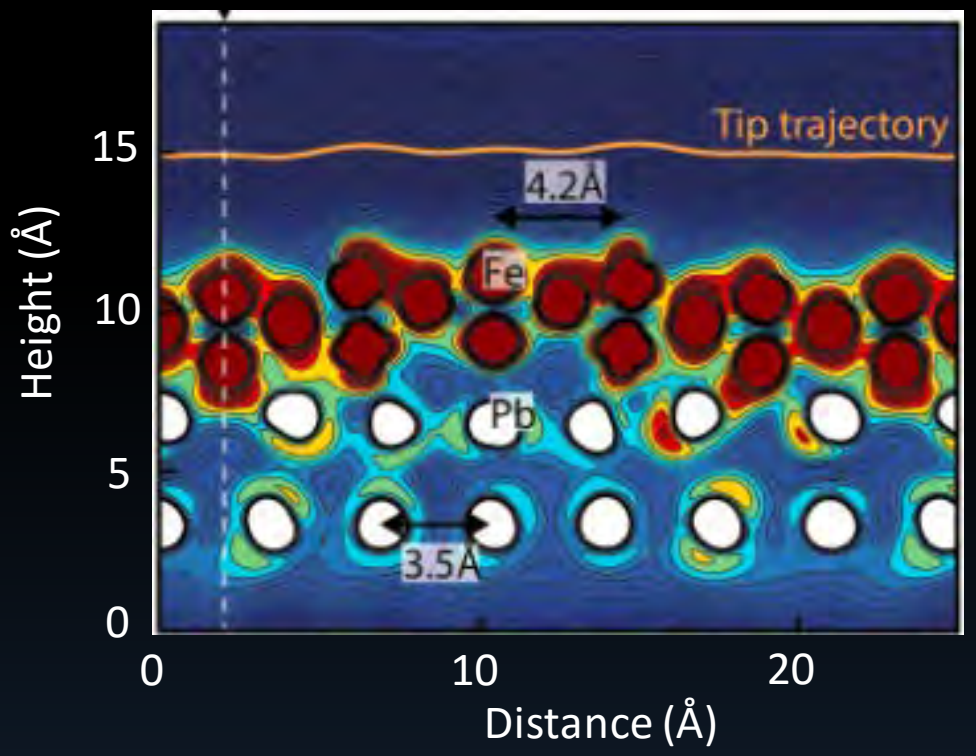
Corrugation: fitting Fe atoms onto Pb

Atomic cains on Pb(110) substrate – DFT

Cut across the chain



Cut along the middle of the chain

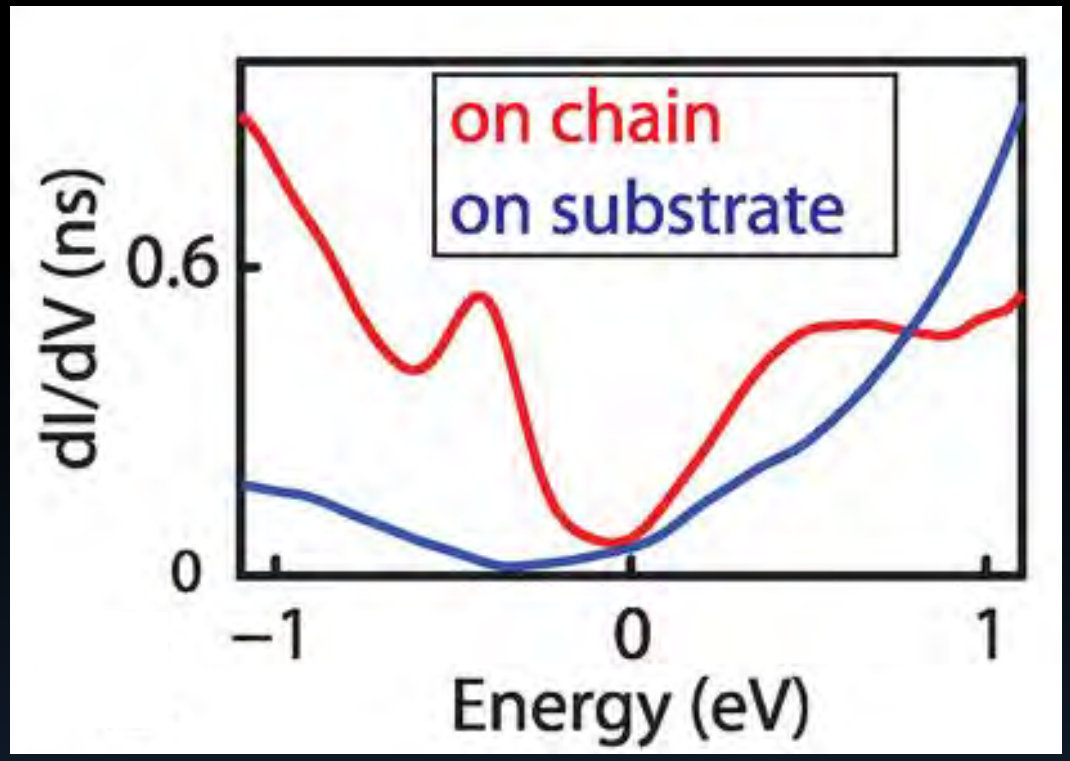


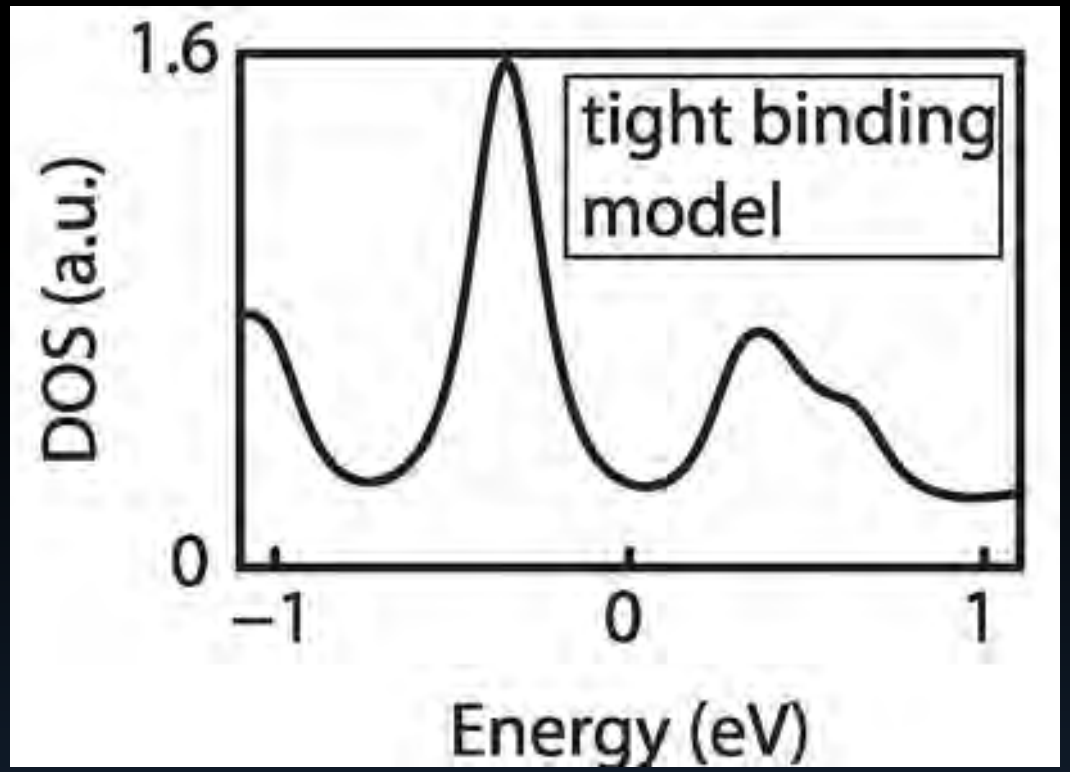
Charge density ($10^{-4} e/a_B^3$)

0 1.5

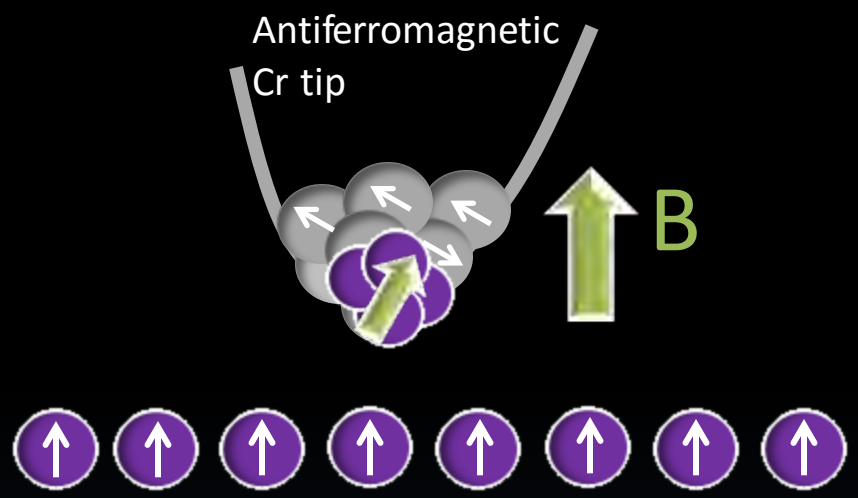
1) Chains form zig-zag structure
2) Corrugation periodicity reproduced
3) Expected height matches experiment

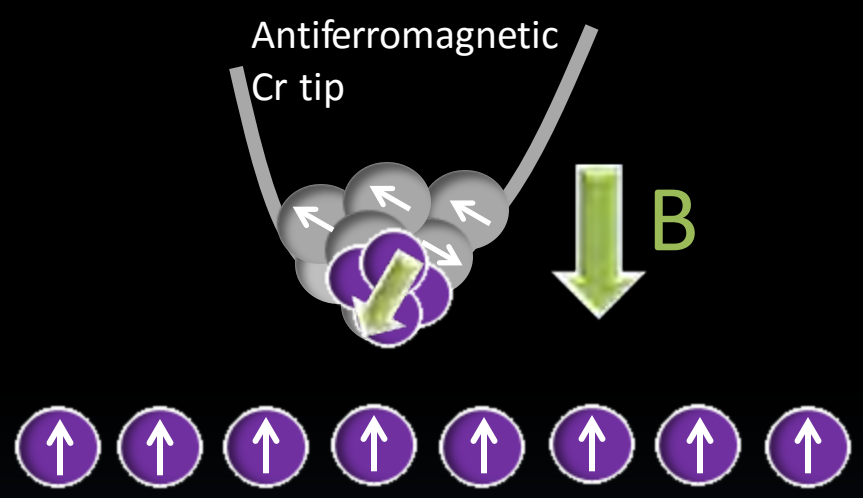
Point spectrum Experiment vs DFT modeling



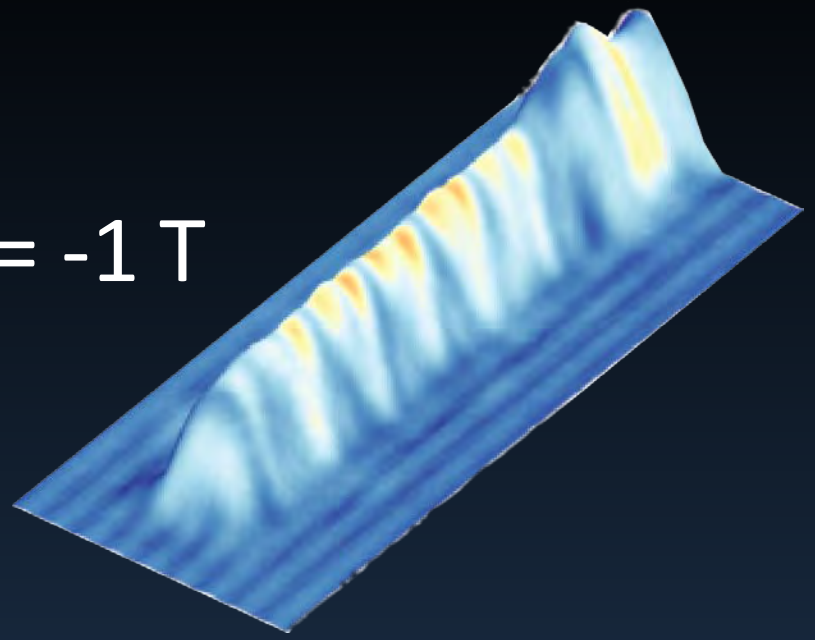


Spin-polarized measurements

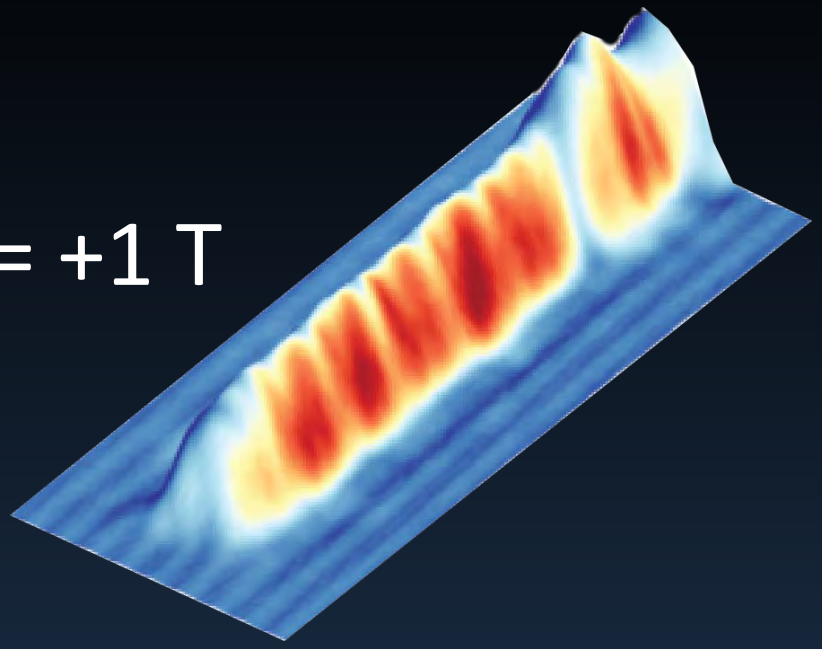




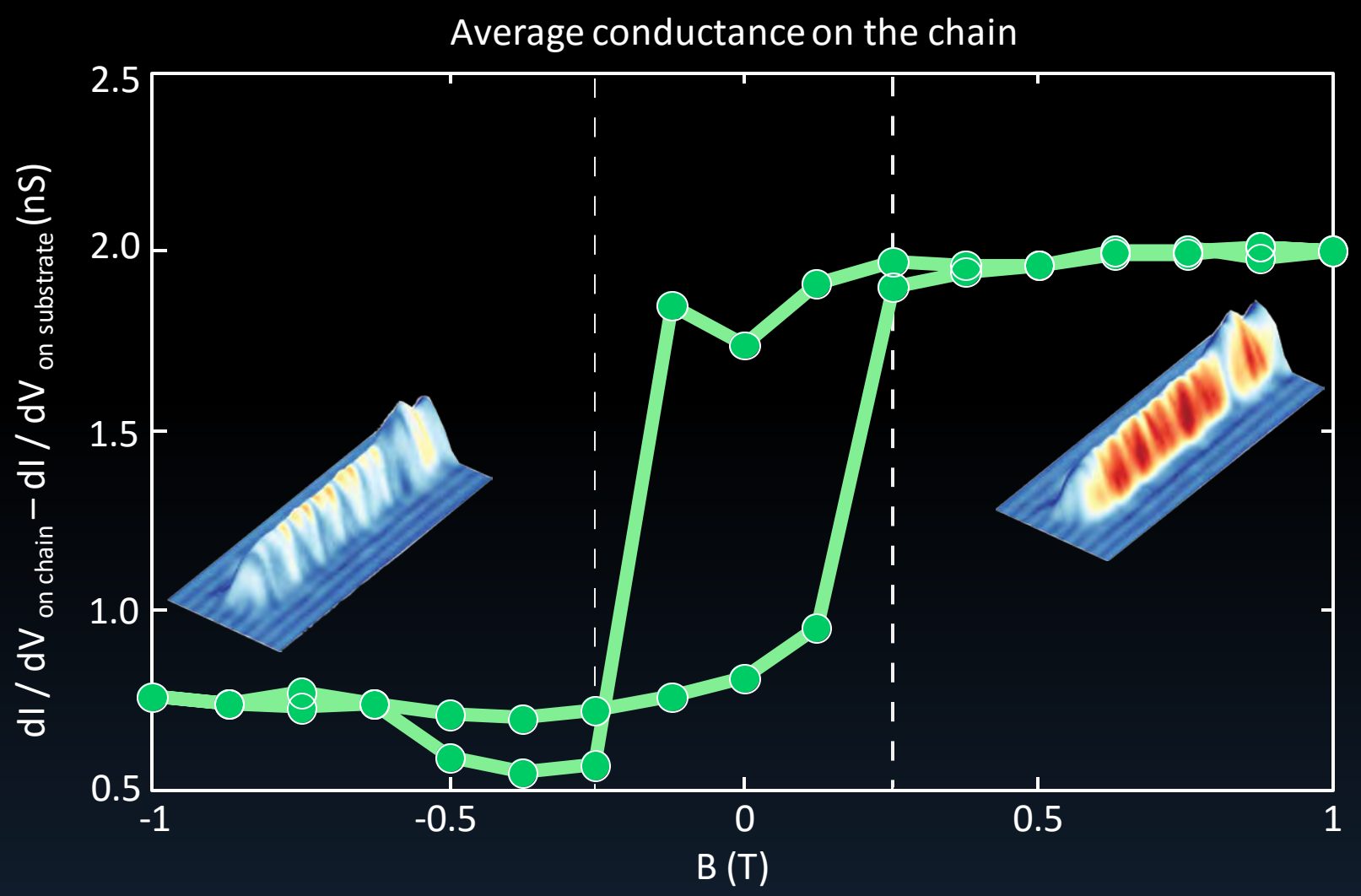
B = -1 T



B = +1 T



Fe chains on Pb(110): Spin-polarized measurements

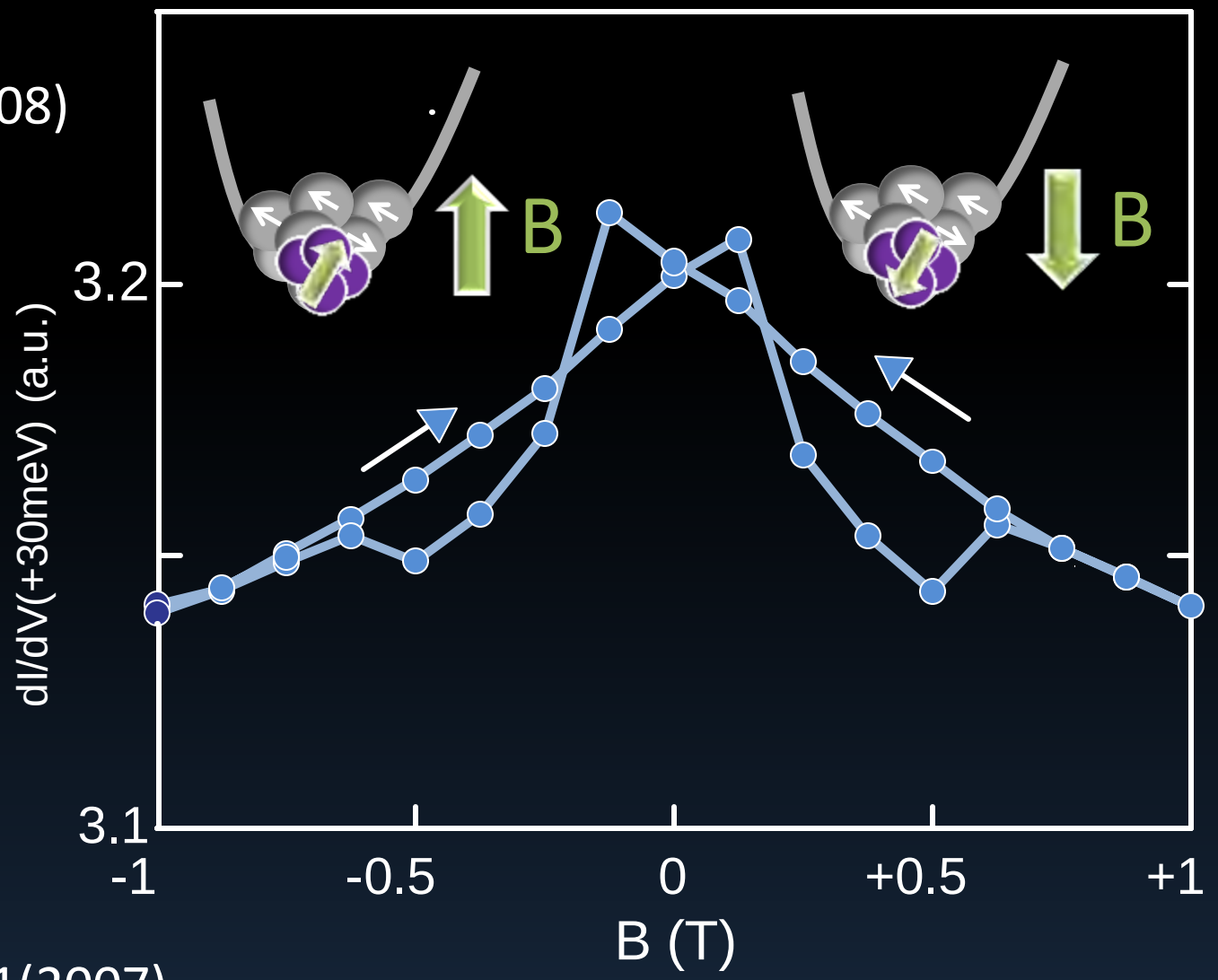


Background subtracted

Most likely tip switching (at ±0.25T)

Spin-polarized tip on the Pb(110): Hints of spin-orbit coupling

Pb –Heavy element (Z= 82, A=204-208)
Strong SOI expected
Symmetry broken at the surface



<u>Experimental signature:</u>
Tunneling suppressed when
Tip polarized out of plane
(Spins in plane)

Similar experiment in 2DEG GaAs:
Moser et al, Phys Rev. Lett. **99**, 056601(2007)

Consistent with strong SOI at the Pb surface

Experimental requirements

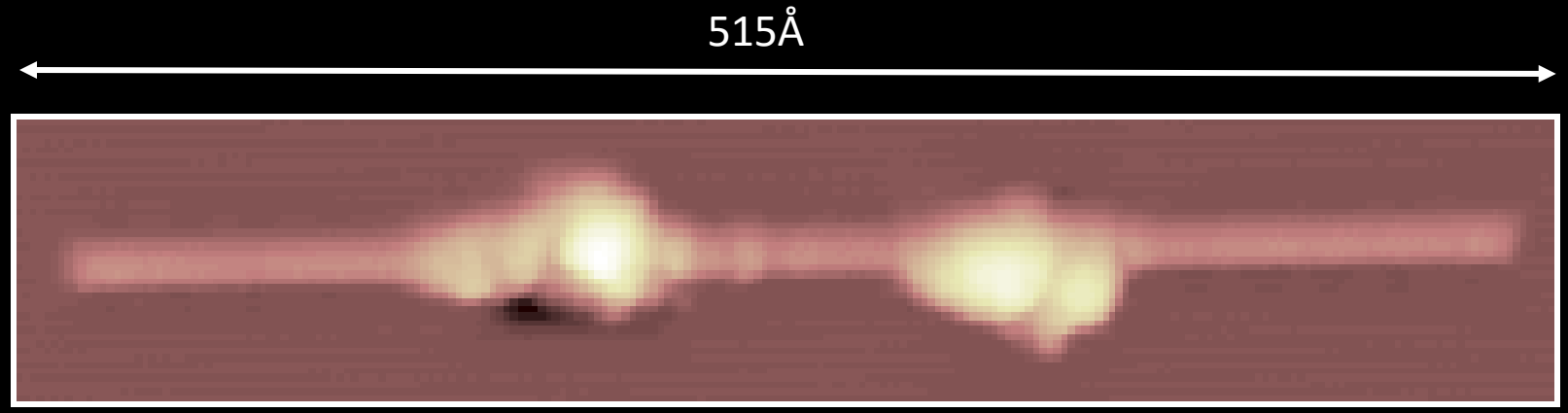
1) Atomically flat superconducting substrate ✓

2) Magnetic atoms (break spin degeneracy) ✓

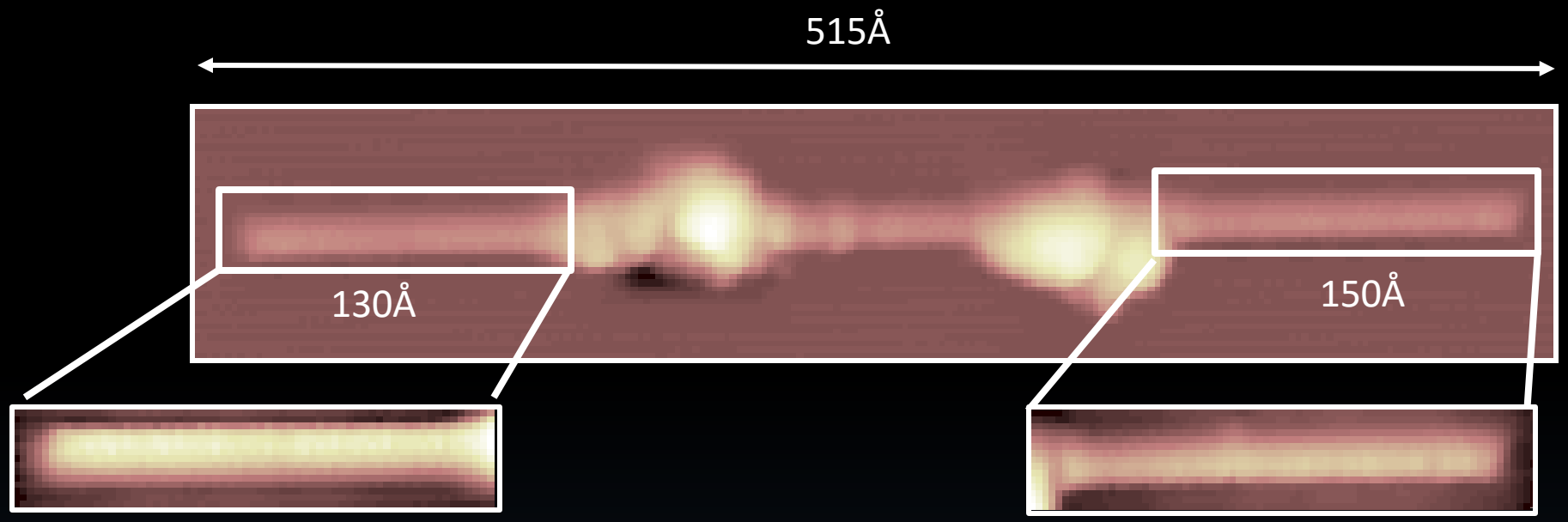
3) Spin-orbit coupling in substrate (to enable p-wave pairing) ✓

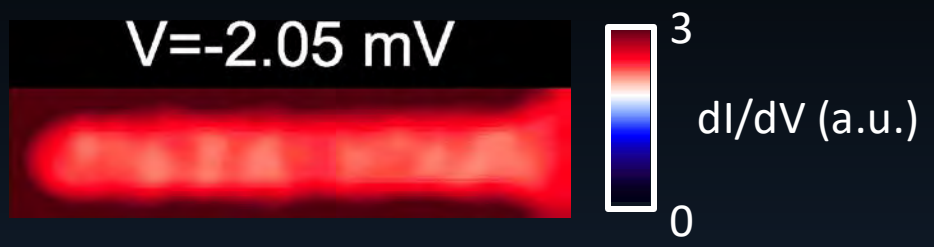
HOW DO STATES INSIDE SUPERCONDCTING GAP LOOK LIKE?????

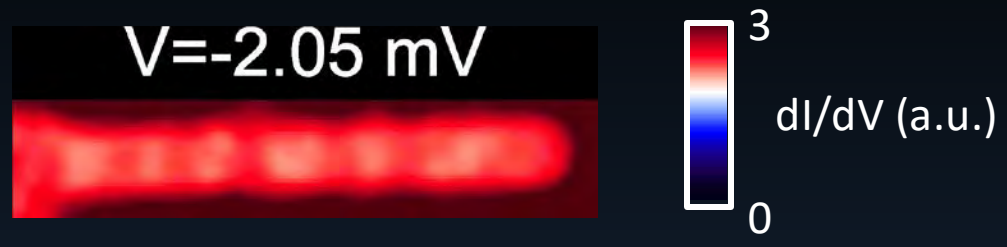
Spectroscopy of an atomic chain



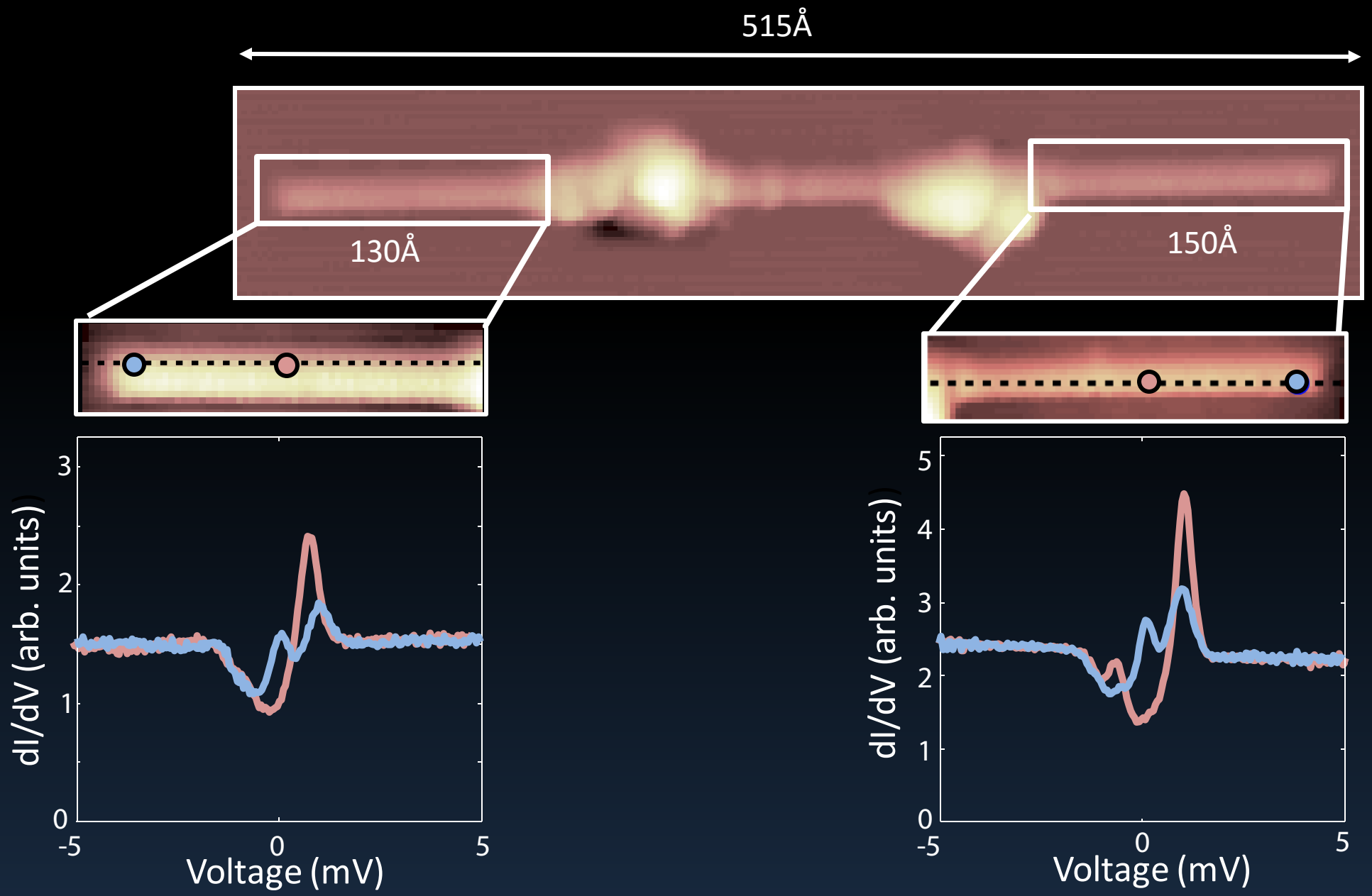
Spectroscopy of an atomic chain



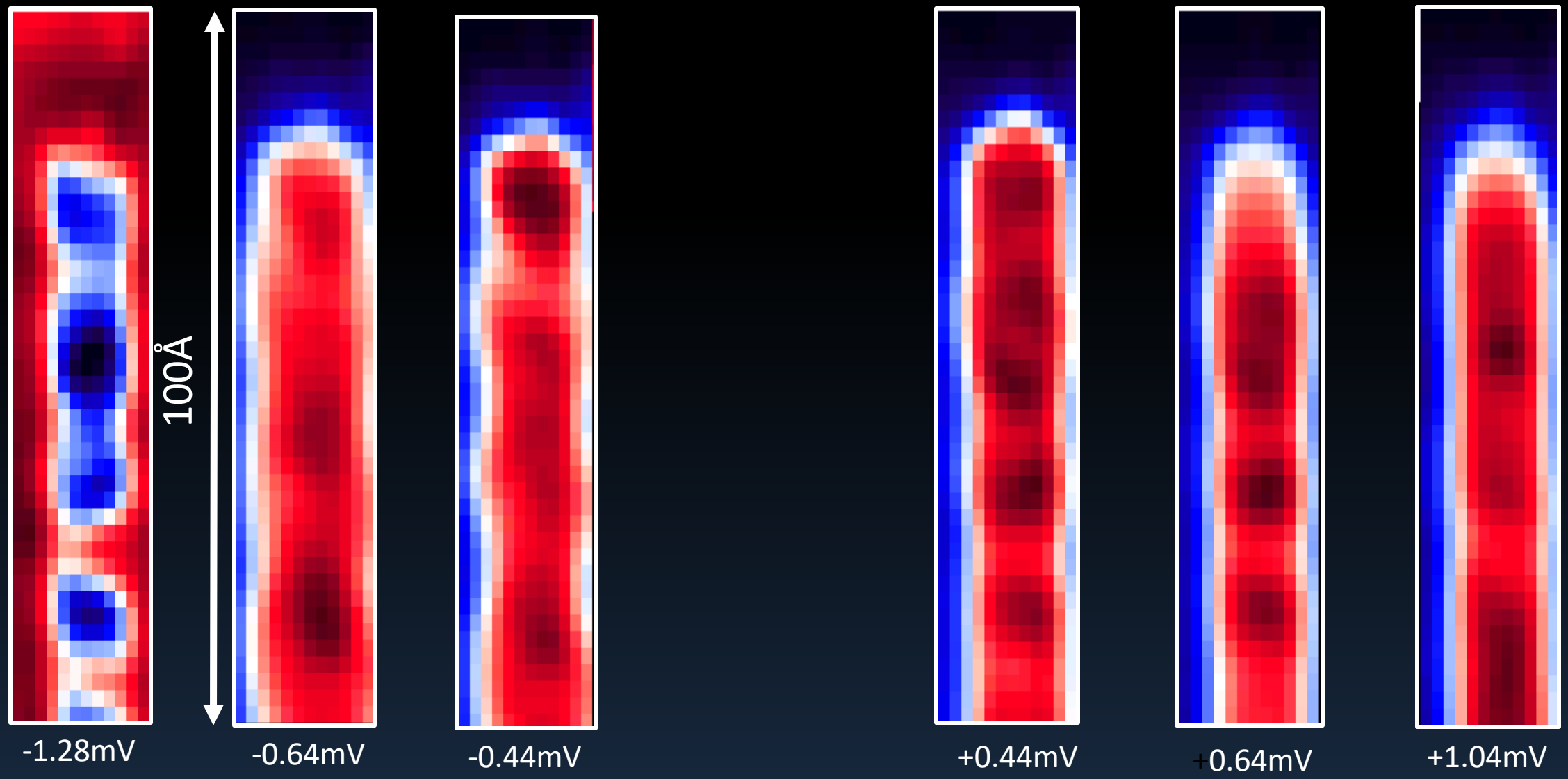




Spectroscopy of an atomic chain

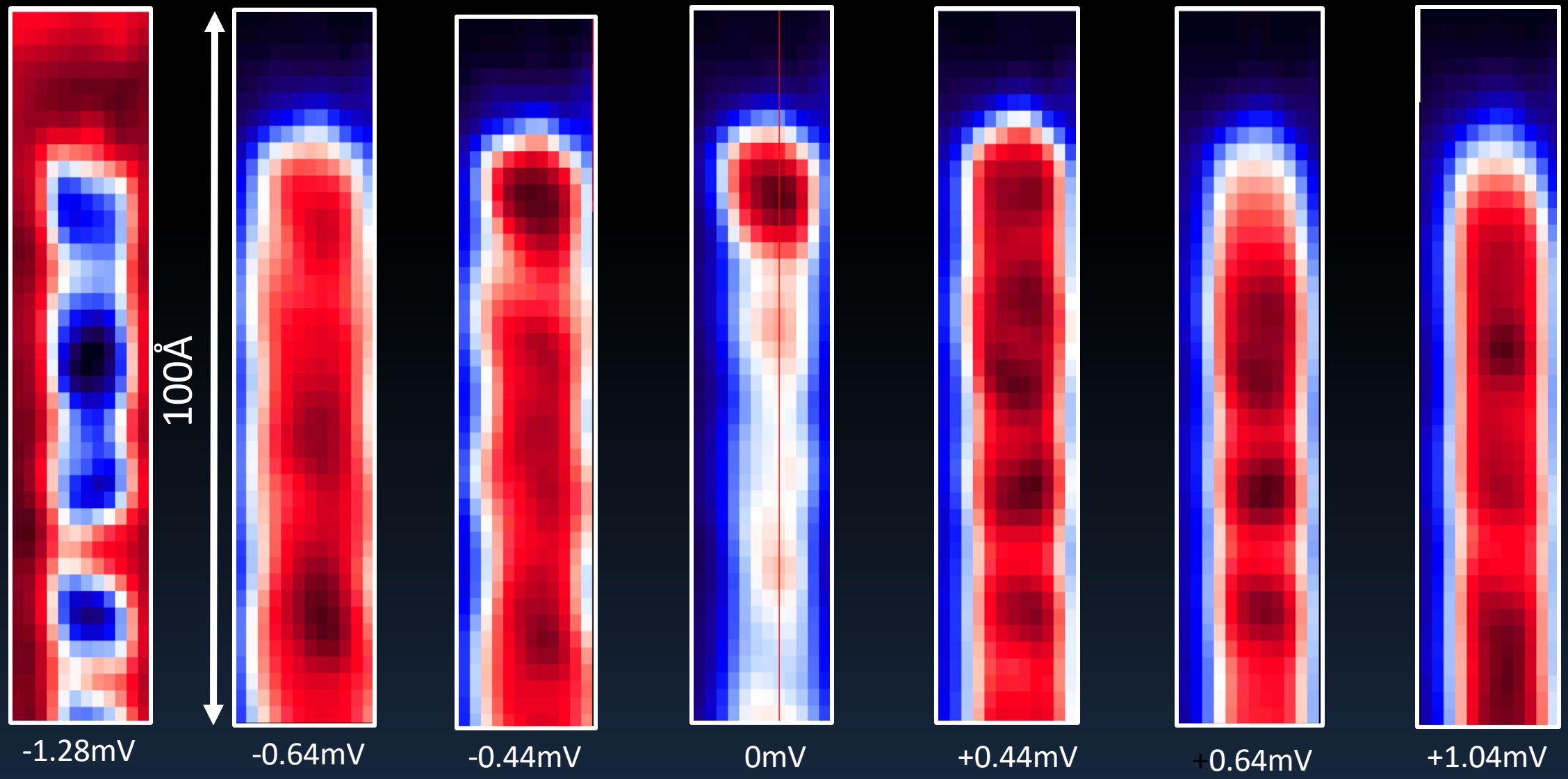


Spatial extent of the density of the states: another example



Spatial extent of the density of the states: another example

Zero bias peak feature localized on the scale of a 1nm

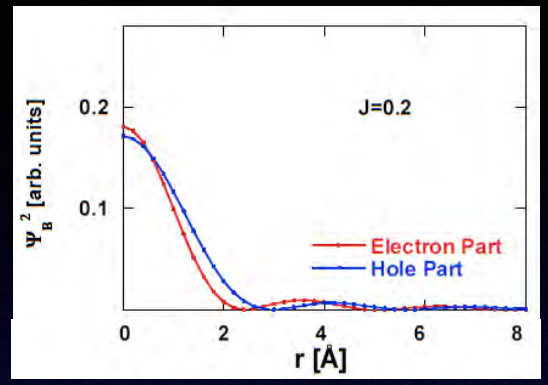


Localization length of MQP in an atomic chain

Recall Shiba states

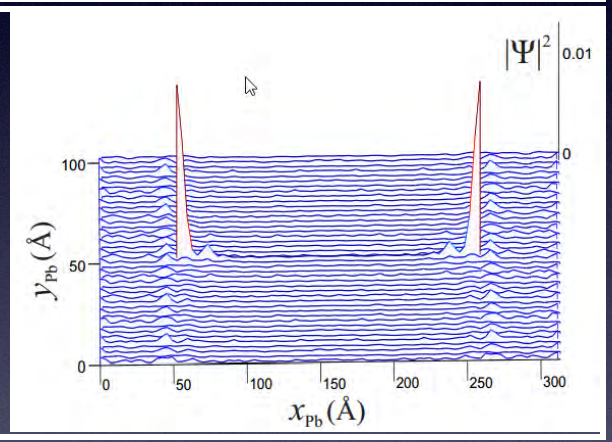
$$\psi(r) \propto \frac{2\pi\, e^{-r/\xi}}{k_F r} \qquad |\psi(r)|^2 \sim 1/r^2$$

ξ~500-1000Å $\qquad$ $\lambda_F/2$=2-3Å



Realistic model of imbedded Fe chain calculations show atomic scale localization of Majorana
D chain)

J. Li, H. Chen et al, Phys. Rev. B **90**, 235433 (2014)



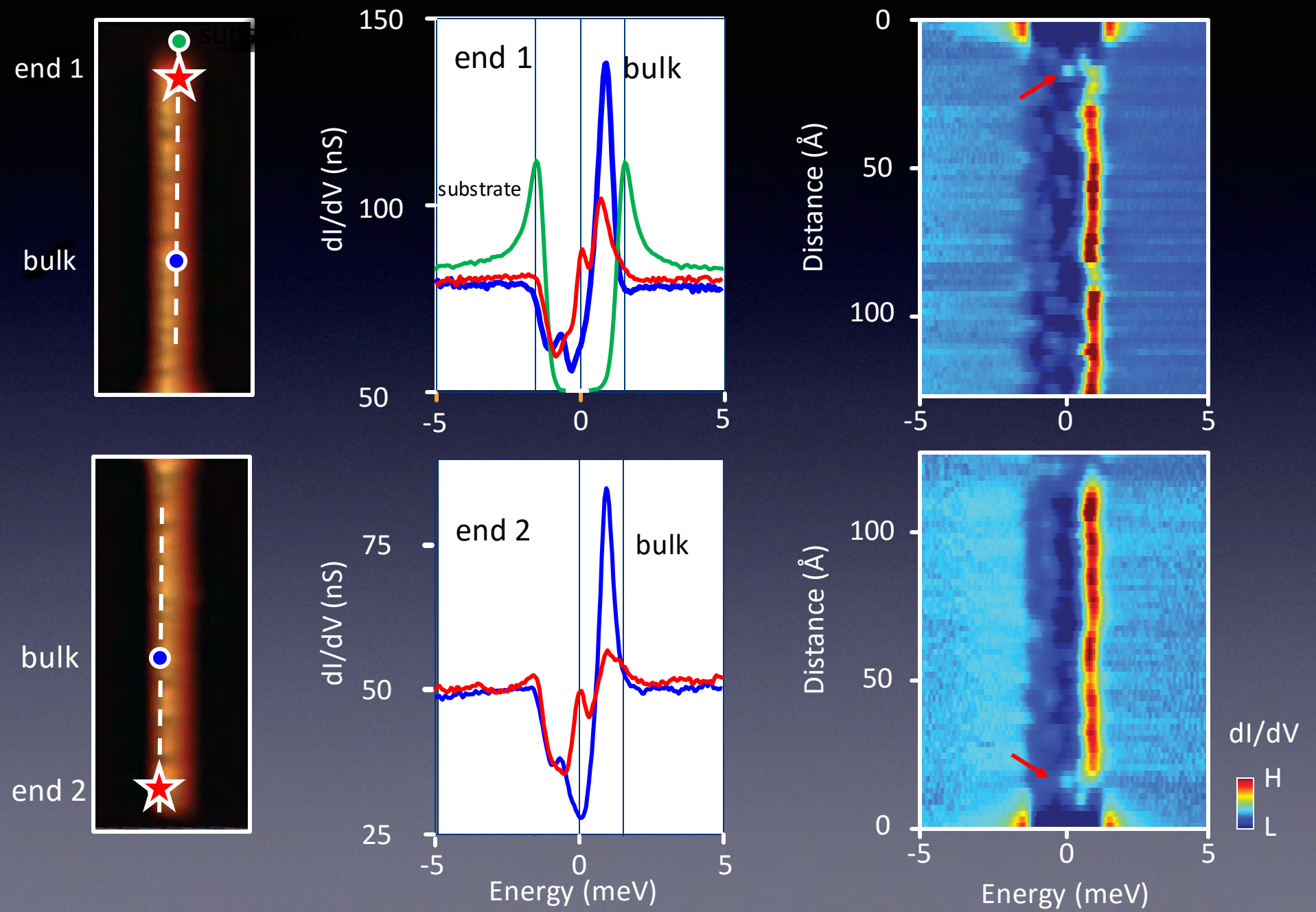
Renormalization of v_F due to d-band/Shiba hybridization

PRL **114,** 106801 (2015) PHYSICAL REVIEW LETTERS week ending 13 MARCH 2015

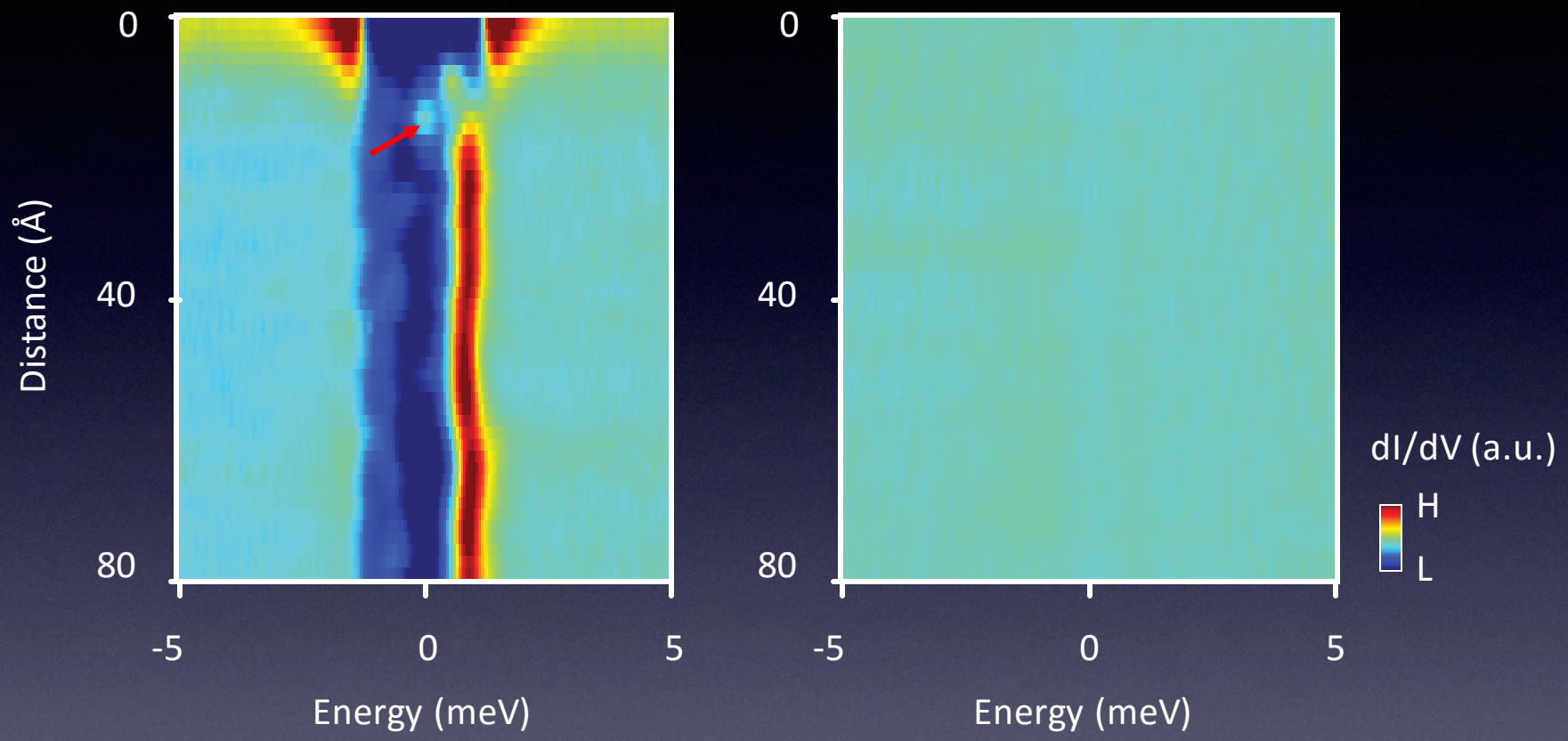
Strong Localization of Majorana End States in Chains of Magnetic Adatoms

Yang Peng,[1] Falko Pientka,[1] Leonid I. Glazman,[2] and Felix von Oppen[1]
[1]*Dahlem Center for Complex Quantum Systems and Fachbereich Physik, Freie Universität Berlin, 14195 Berlin, Germany*
[2]*Department of Physics, Yale University, New Haven, Connecticut 06520, USA*
(Received 10 December 2014; published 9 March 2015)

Zero bias peak at the chains ends



Kondo effect? ZBP due to superconductivity?



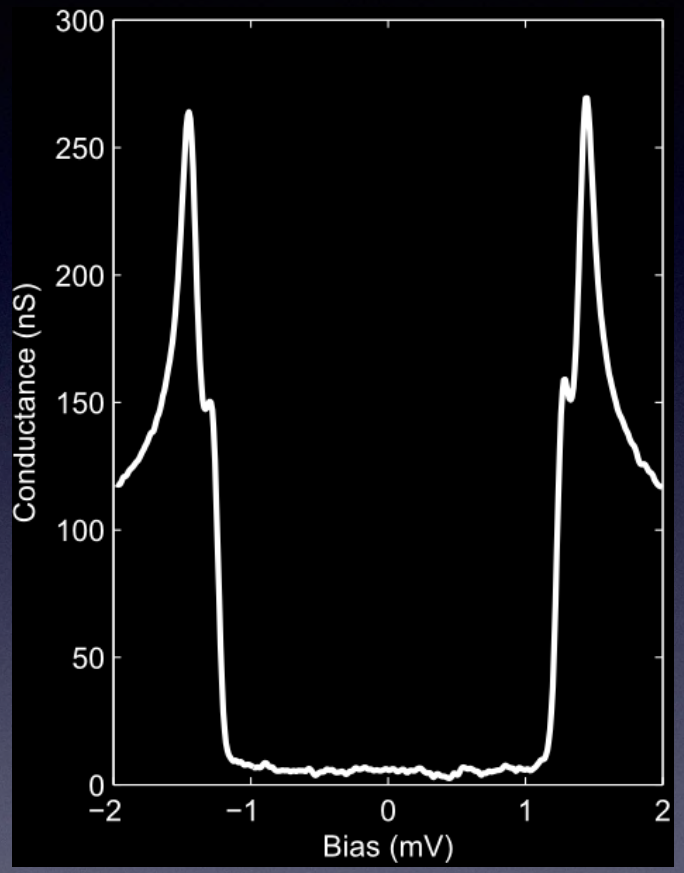
Note: ZBP end state separate from the Shiba bands which also change at the edge

B = 0

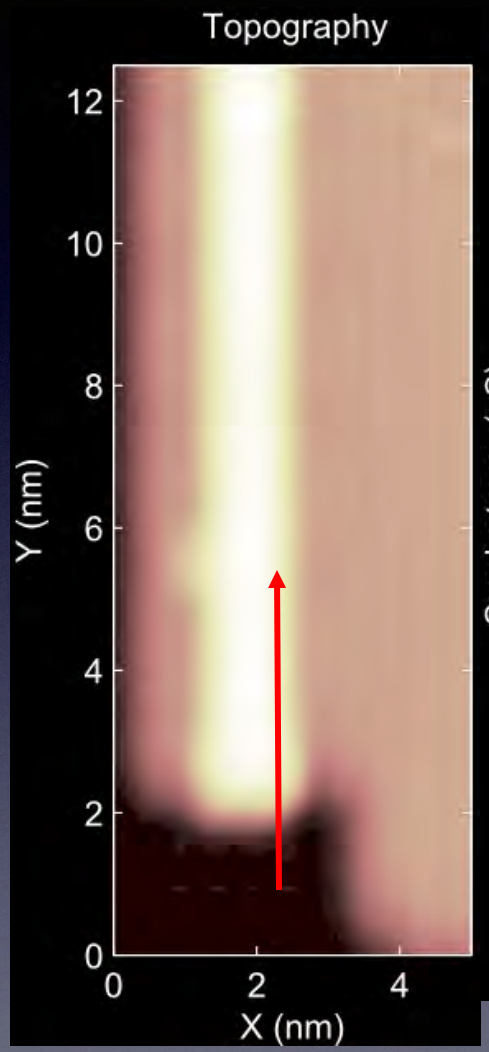
B = 100mT > B_c

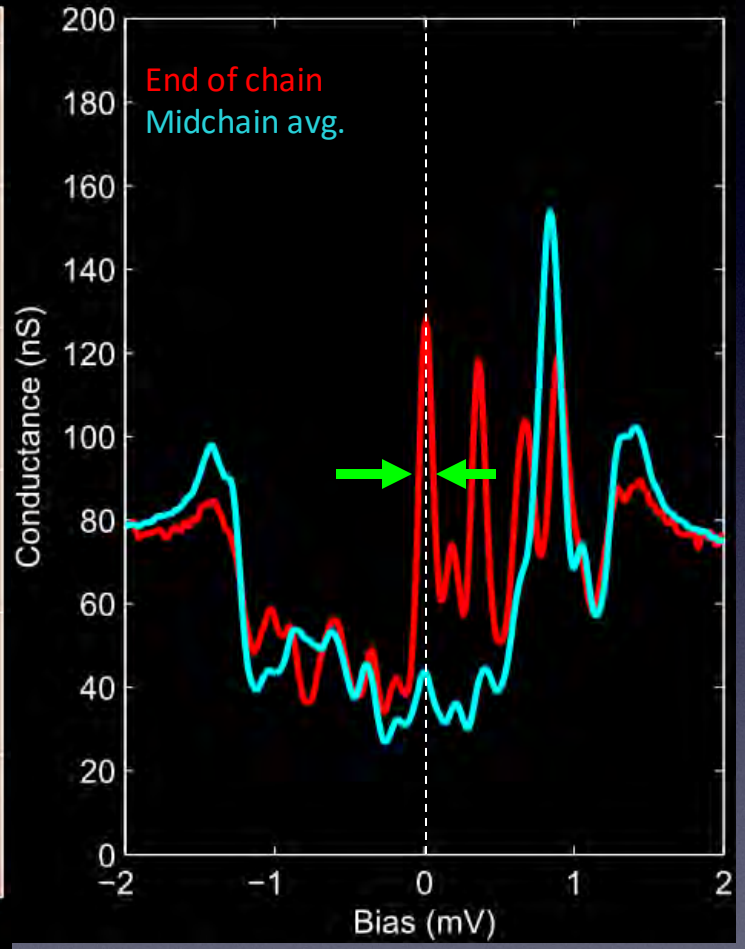
States are clearly related to superconductivity!

Current bound on ZERO with 90μeV resolution
Factor of 5 improvement from 1.4K



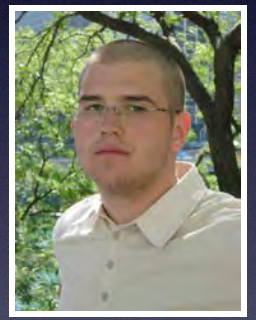
Pb at 20mK
T_electrons=250mK
Predicted
two gaps in Pb



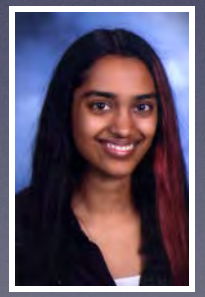


Splitting < 45μeV

Ben Feldman

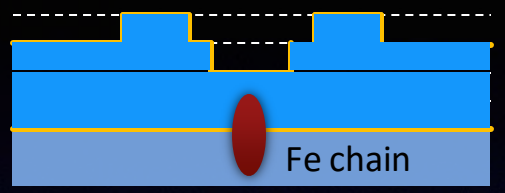


Ilya Drozdov



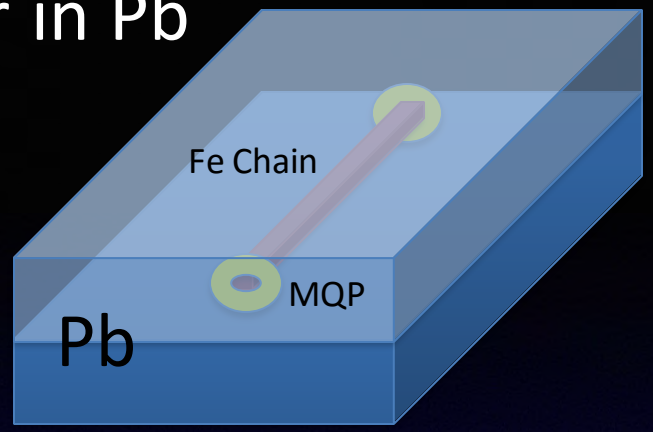
Mallika Randeria

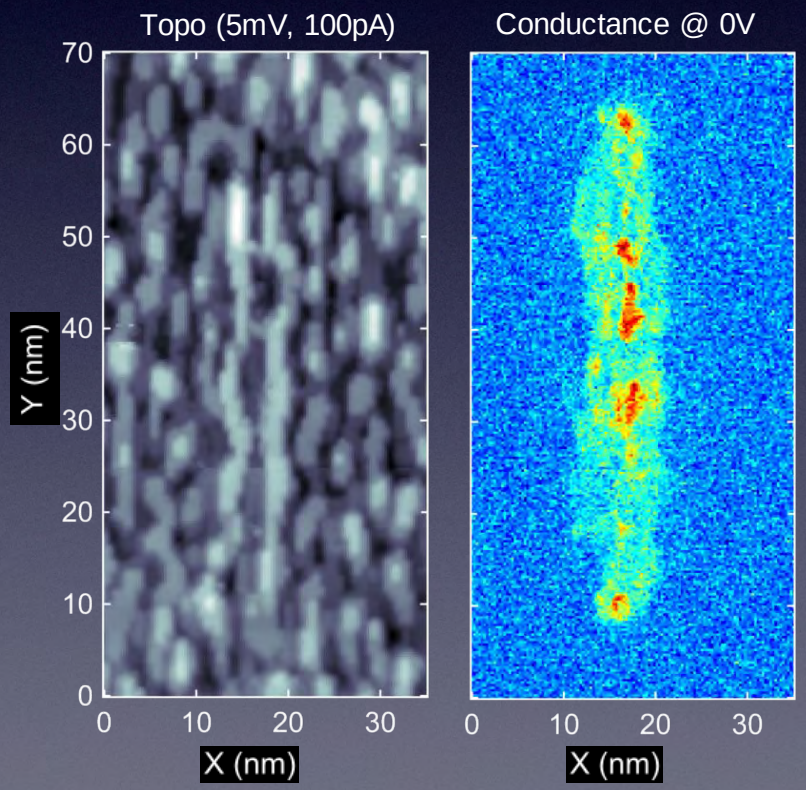
Imbedding the Fe Chains further in Pb
1.4K measurements



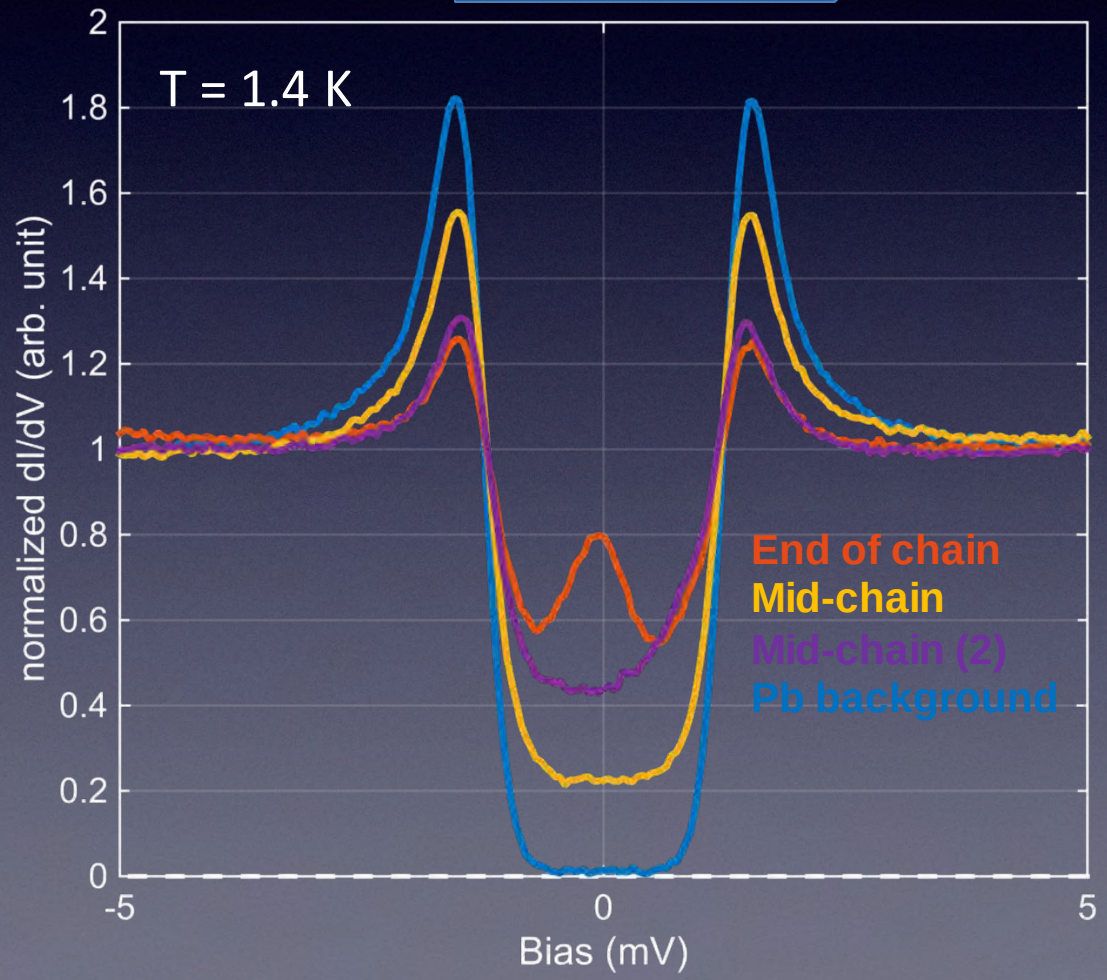
Pb overlayers

Pb Substrate

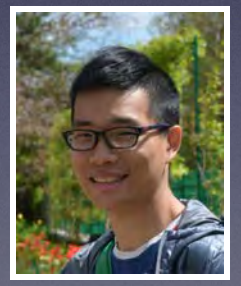




in-gap states

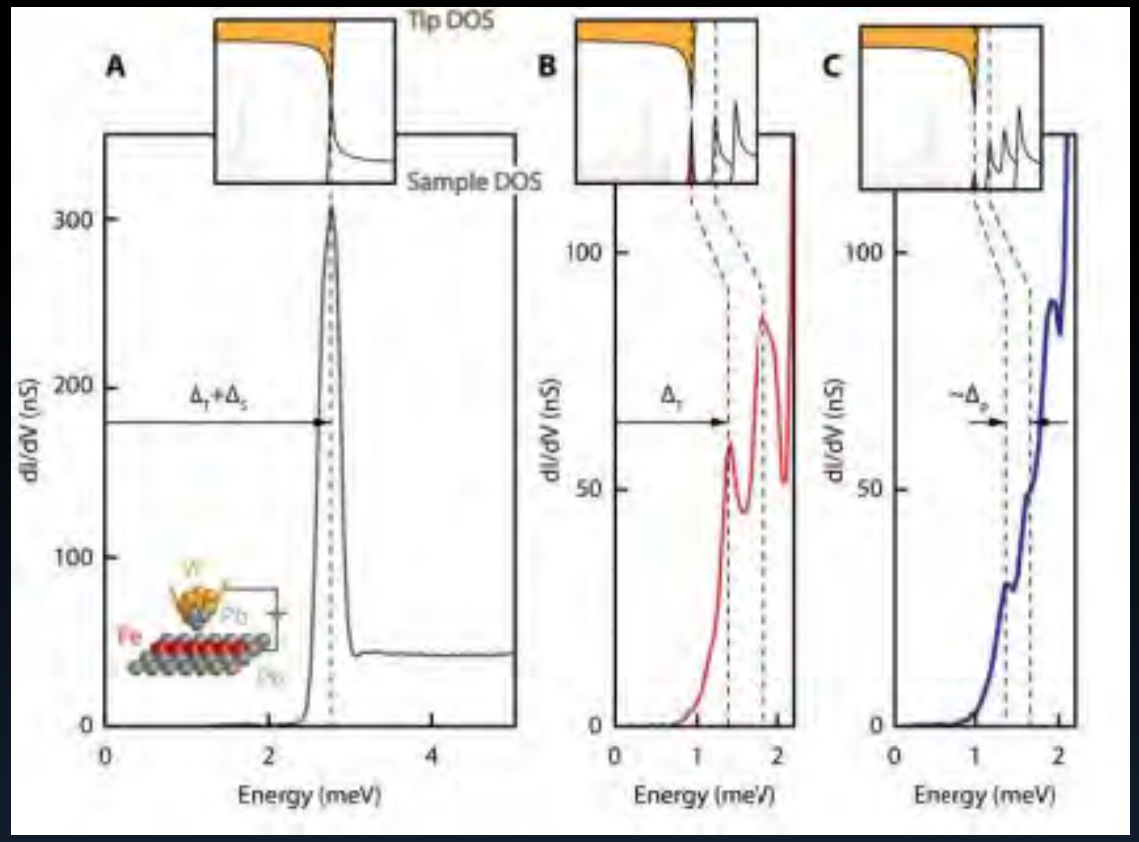


Sangjun Jeon

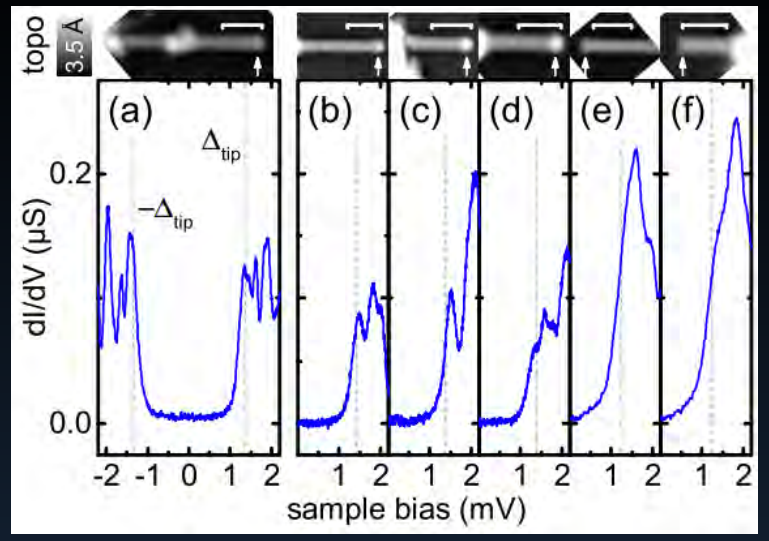


Yonglong Xie

Better energy resolution using superconducting tip



Katarina Franke's group FU Berlin,
ArXiv: 1507.03104



Also: Ernst Mayer's group Basel,
ArXiv: 1505.06078

Summary

Experimental progress:

- ✓ Magnetic chains on superconductor
- ✓ Spin polarized measurement:
  - (Modulated) Ferromagnetism
  - SOI present
- ✓ Observed end states at zero bias:
  - Reproducible on many wires
  - Related to Magnetism and Superconductivity
  - Consistent with FM + SOI scenario for Majorana fermions

THANK YOU!
QUESTIONS?