Atomic-scale interface engineering of Majorana edge modes in a 2D magnet-superconductor hybrid system

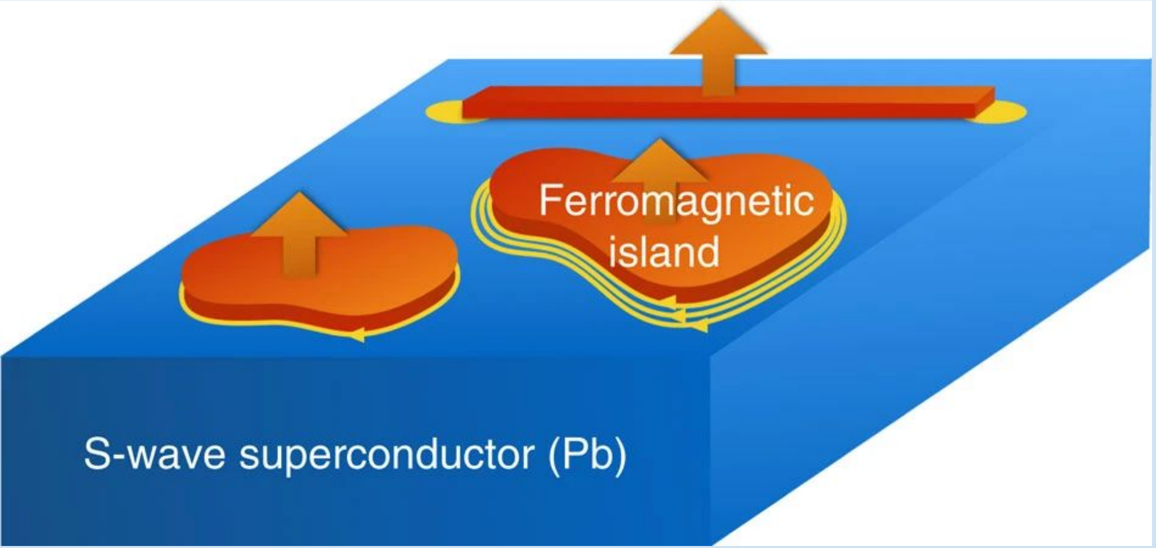
Alexandra Palacio-Morales[1*], Eric Mascot[2], Sagen Cocklin[2], Howon Kim[1†], Stephan Rachel[3], Dirk K. Morr[2†], Roland Wiesendanger[1†]

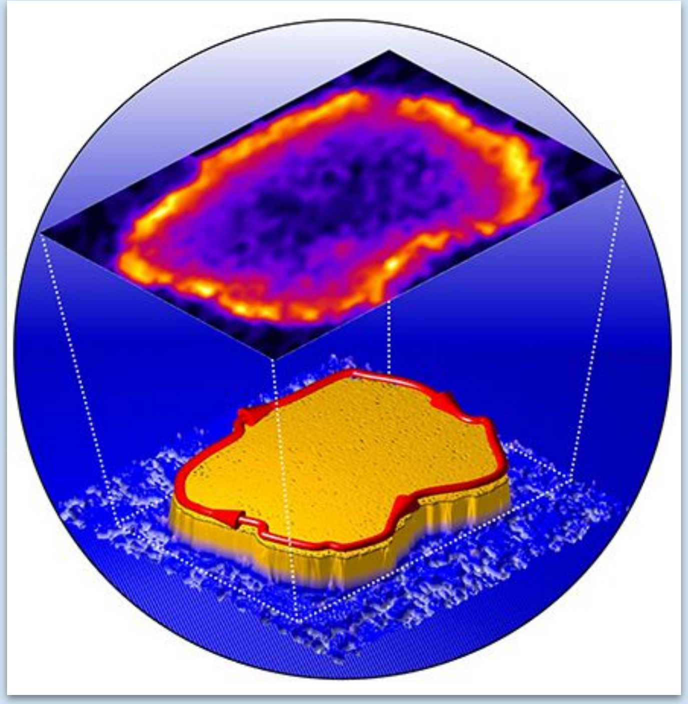
Observation of Majorana fermions in ferromagnetic atomic chains on a superconductor

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,†]

Ben Safvati

Magnet-Superconductor Hybrid (MSH) Systems





2D magnetic impurities on SC Theory

TB hopping parameter

On-site chemical potential

Rashba SO coupling:
(i.e. H = k * $\boldsymbol{\sigma}$)

SC Pairing Parameter

Spin Exchange Coupling

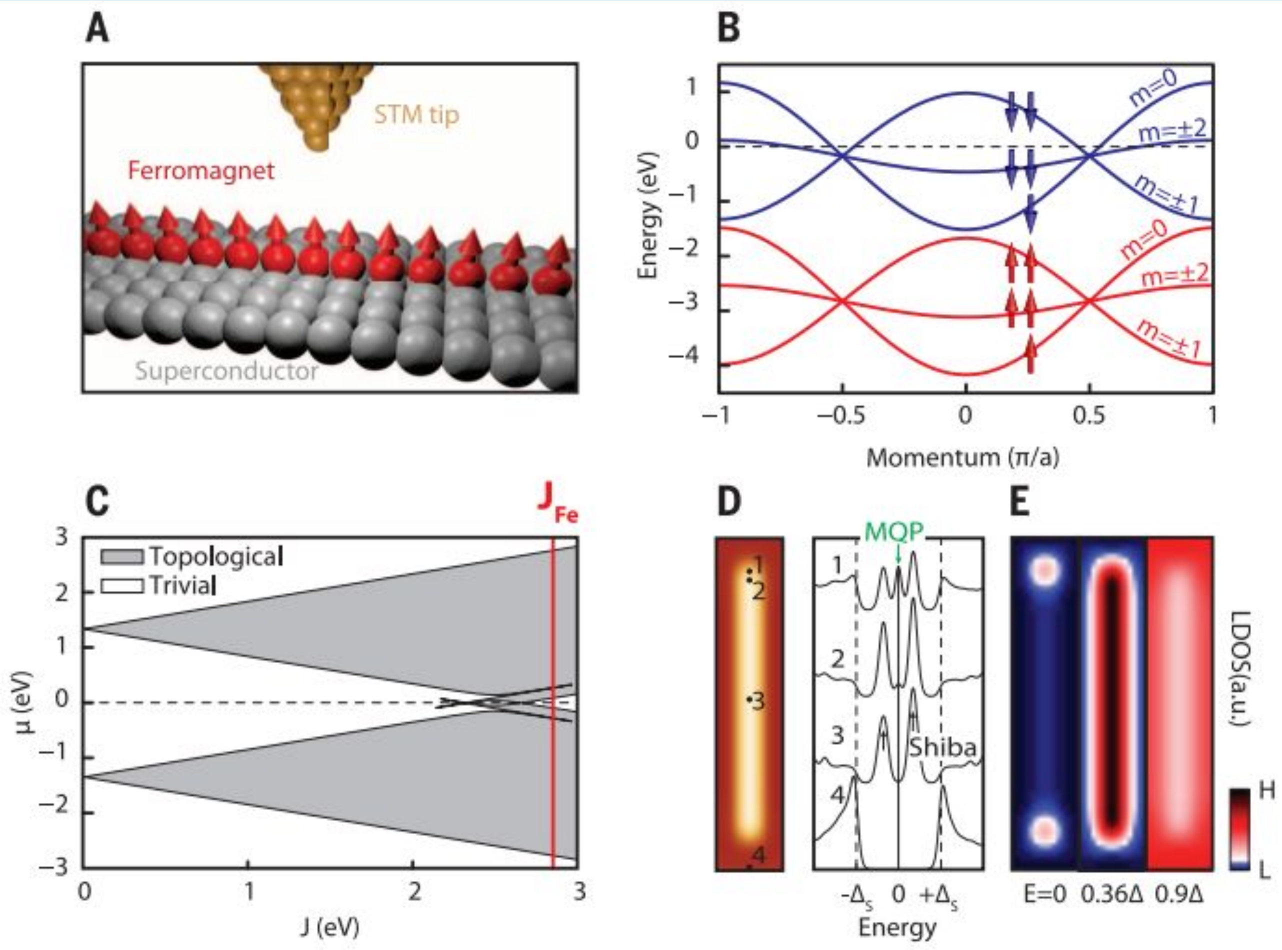
Tip-sample interaction

$$
\begin{aligned}
H_{\mathrm{SC}} = & -t \sum_{\langle \mathbf{r}\mathbf{r}' \rangle,\sigma} (c^\dagger_{\mathbf{r},\sigma} c_{\mathbf{r}',\sigma} + \mathrm{H.c.}) - \mu \sum_{\mathbf{r},\sigma} c^\dagger_{\mathbf{r},\sigma} c_{\mathbf{r},\sigma} \\
& + i\alpha \sum_{\mathbf{r},\sigma,\sigma'} \left(c^\dagger_{\mathbf{r},\sigma} \sigma^2_{\sigma\sigma'} c_{\mathbf{r}+\hat{x},\sigma'} - c^\dagger_{\mathbf{r},\sigma} \sigma^1_{\sigma\sigma'} c_{\mathbf{r}+\hat{y},\sigma'} + \mathrm{H.c.} \right) \\
& + J \sum_{\mathbf{R},\sigma,\sigma'} c^\dagger_{\mathbf{R},\sigma} \sigma^3_{\sigma\sigma'} c_{\mathbf{R},\sigma'} + \Delta_s \sum_{\mathbf{r}} (c^\dagger_{\mathbf{r},\uparrow} c^\dagger_{\mathbf{r},\downarrow} + \mathrm{H.c.}) \\
& - t_{\mathrm{tip}} \sum_{\sigma} (c^\dagger_{\mathbf{r},\sigma} d_\sigma + \mathrm{H.c.}), \qquad (1)
\end{aligned}
$$

Essential Signatures of Topological Superconductivity

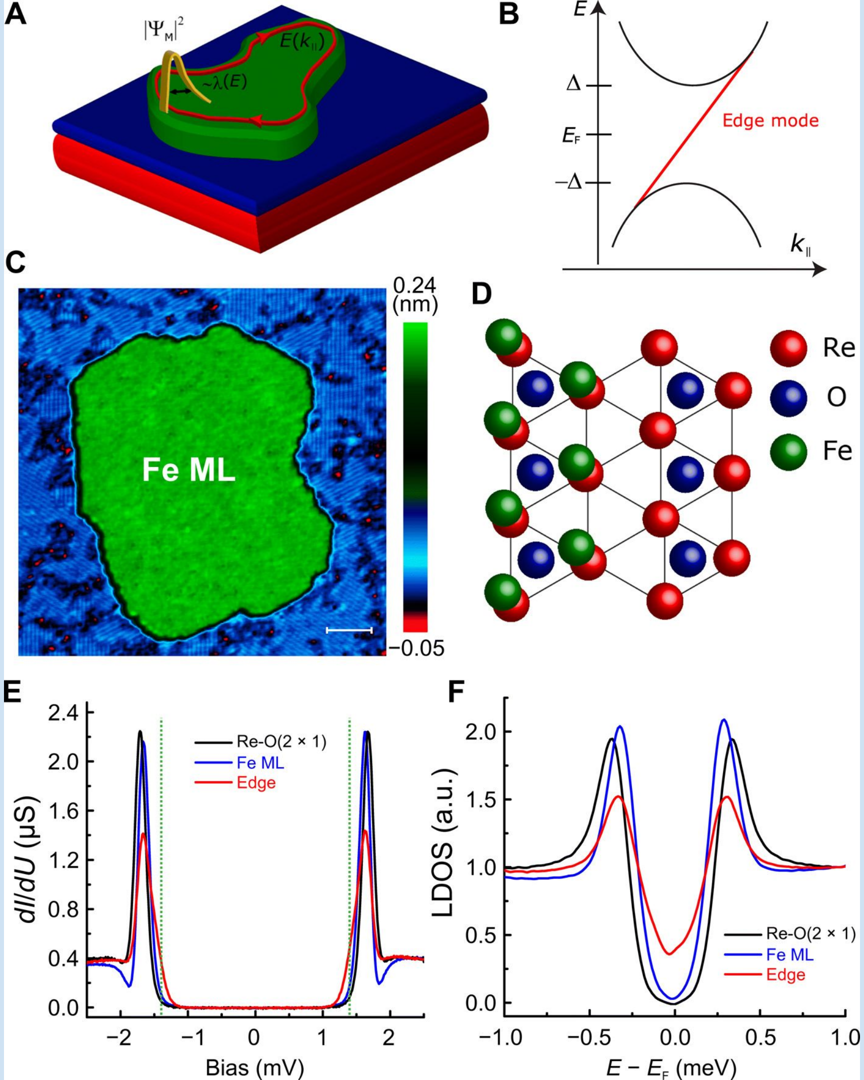
1. Ferromagnetic adatoms (Fe, Co) with large exchange interaction.
2. SO coupling on the surface of the host s-wave superconductor.
3. Proximity-induced superconducting gap in the magnetic bulk.
4. Localized zero-bias peak on the boundary that disappears with loss of superconductivity.

Majorana Fermions in Atomic Spin Chains

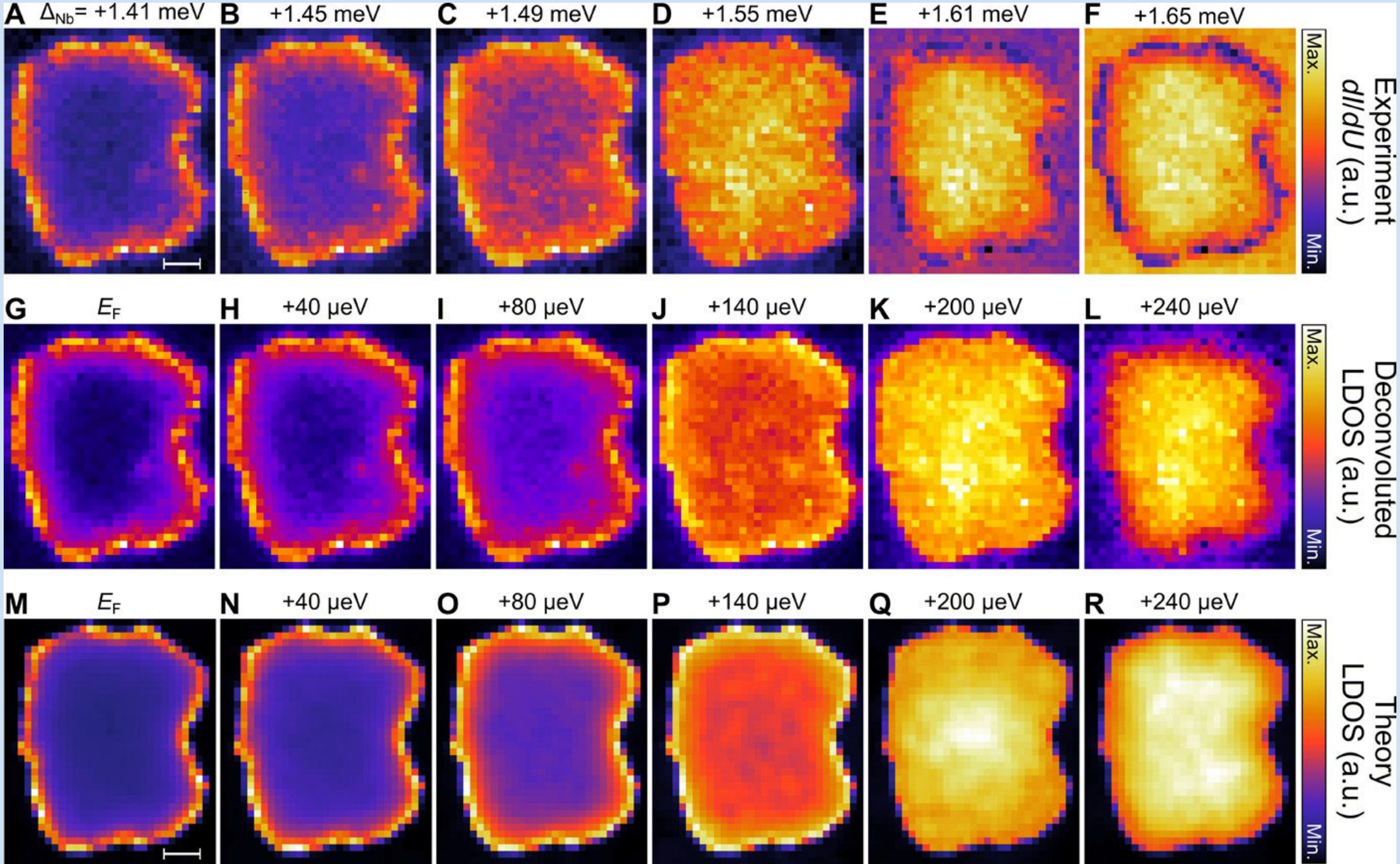


2D Chiral Majorana Modes

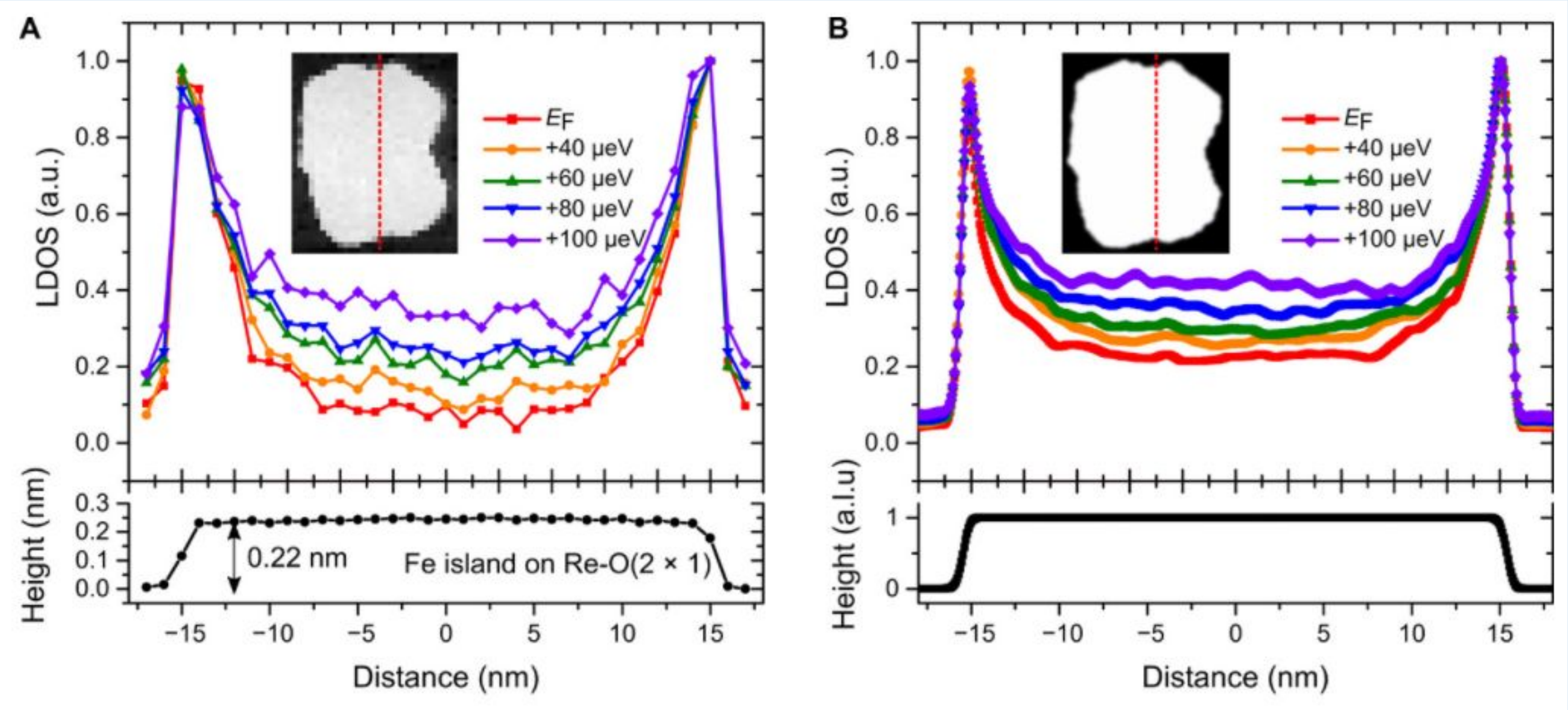
- Signatures of Majorana Edge Modes
  - Spatial localization at edges that narrows with decreasing energy.
  - Topological protection against edge disorder.
  - Dispersive edge modes that cross the superconducting gap.



Localization of Edge Modes with Increasing Energy

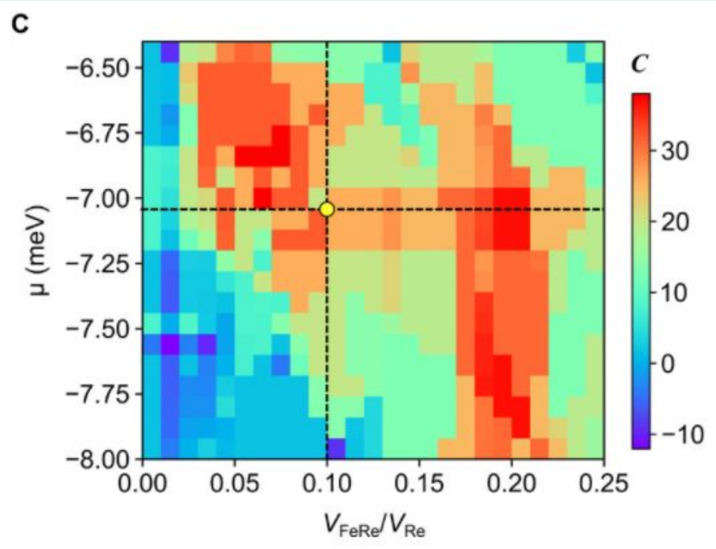


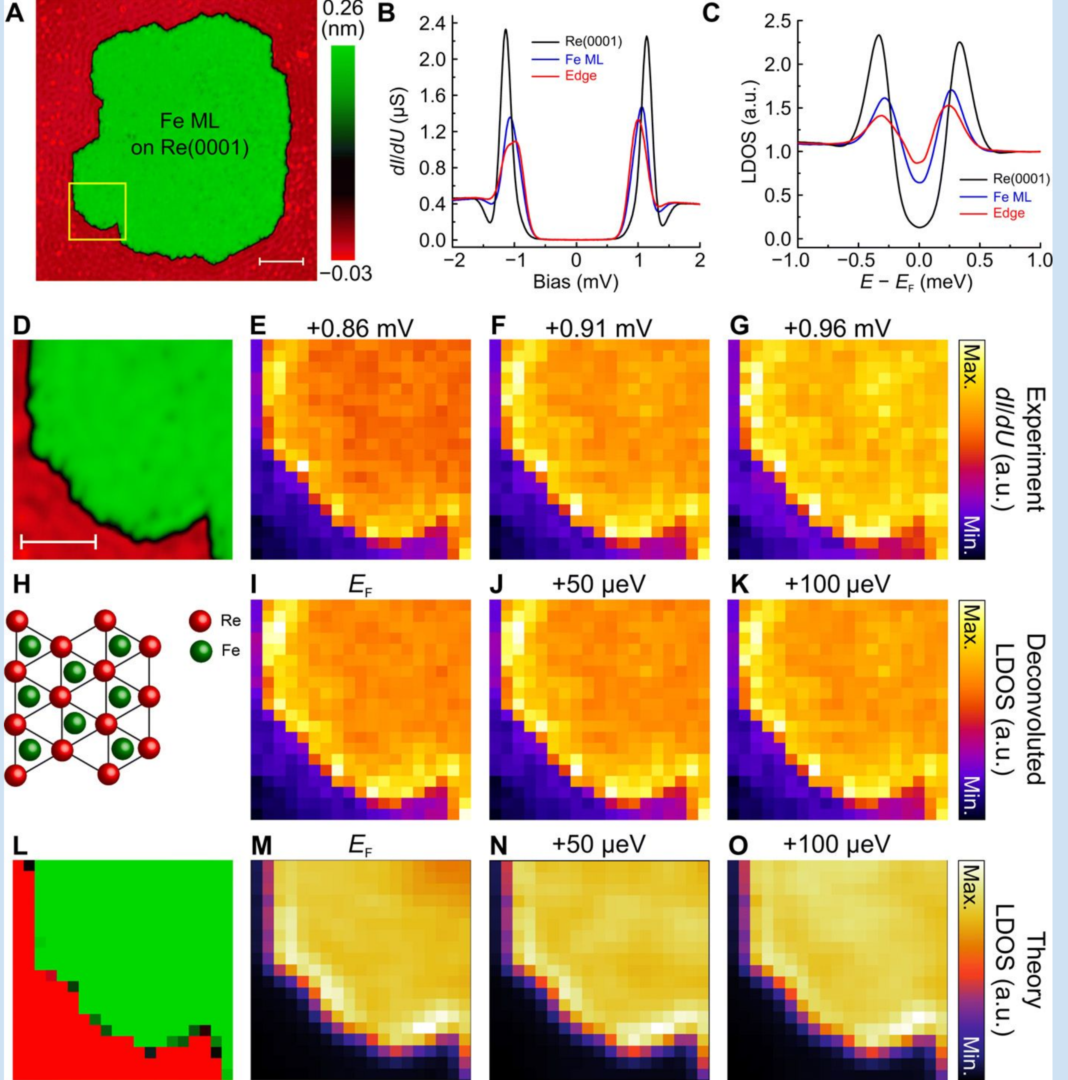
Localization of Edge Modes with Increasing Energy



Topologically Trivial Phase LDOS

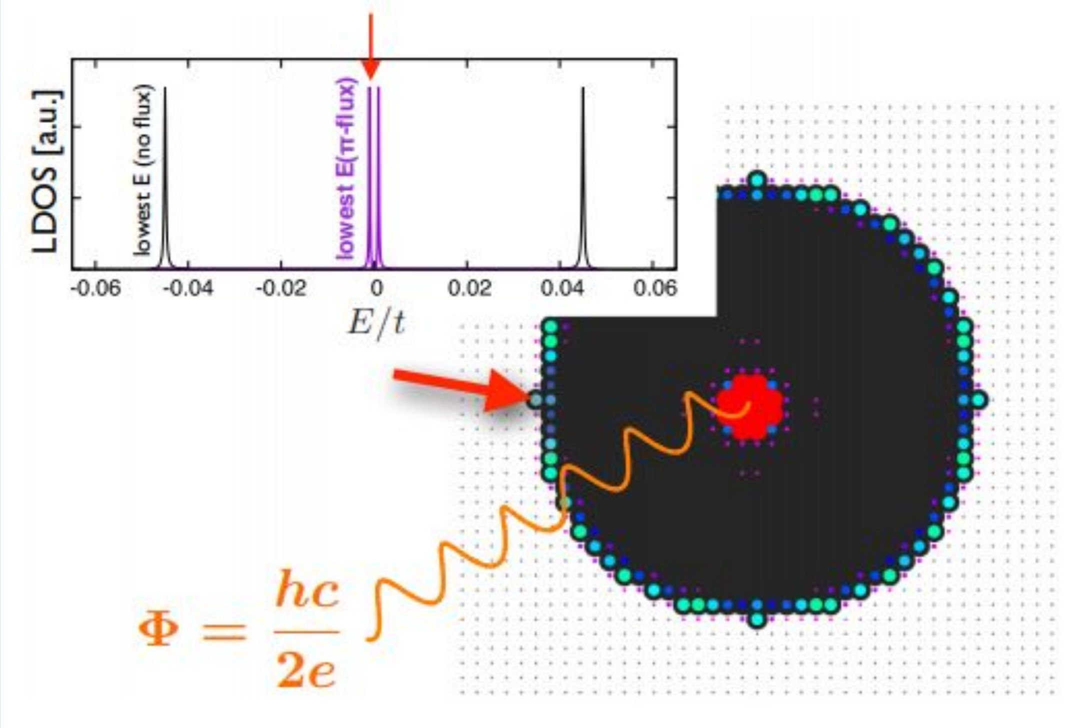
- Topological phase is dependent on Fe-surface interaction, on-site potential.
- Approximate phase diagram shows varying Chern number, various topo. phases.





2D Majorana Zero Modes with Flux Insertion

- Spatial separation of Majorana modes suppresses coupling between MFs, modes brought to zero energy.
- Majorana Fermion pairs are non-locally protected by fermion parity symmetry, can be built into topologically protected quantum processors.



Other Causes of Zero-Bias Edge Modes

- Kondo effect: in a superconductor, pairing of electrons into pairs competes with Kondo coupling to magnetic impurity.
    - Experimentally, addition of small (0.1 T) magnetic field disrupts superconductivity and in-gap zero mode disappears (Kondo effect would increase w/ loss of SC).

- Edge disorder: topological nature of the gapless edge modes means they will survive even with irregular boundaries.

- Finite size effects: Majorana quasiparticle modes are strongly suppressed when chain length is smaller, suggests coupling of the ends disrupts the gapless excitation.

- In conclusion: magnetic adatom STM with superconducting substrate yields a promising platform for topological superconducting physics, Majorana manipulation, etc...