UNIVERSITÀ DEGLI STUDI DI SALERNO
Dipartimento di Fisica E.R. Caianiello

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Scanning Probe Microscopy studies of magnetically and electrically coupled Superconductor/Ferromagnet systems

SPnM Laboratory

Scanning Probe Microscopy and nano-Matter

UNIVERSITÀ DEGLI STUDI DI SALERNO

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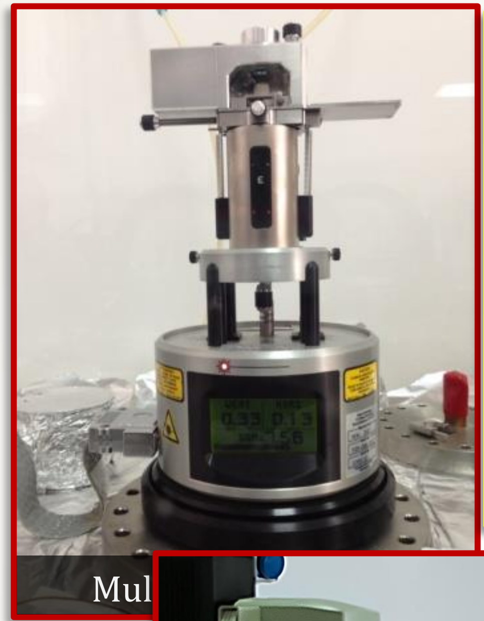
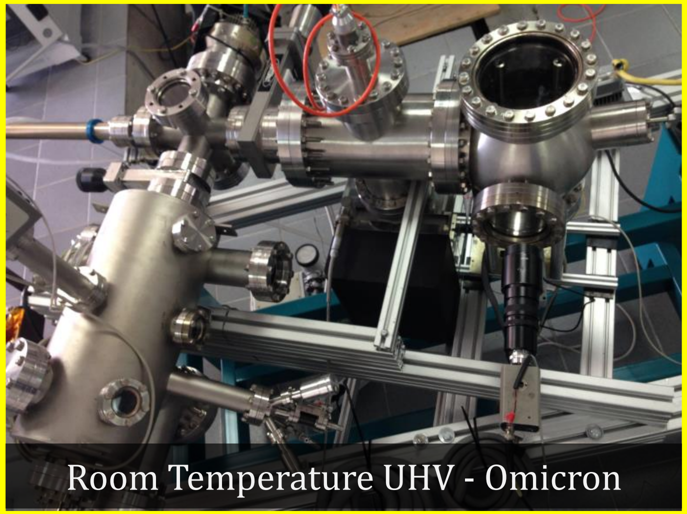
We are here!

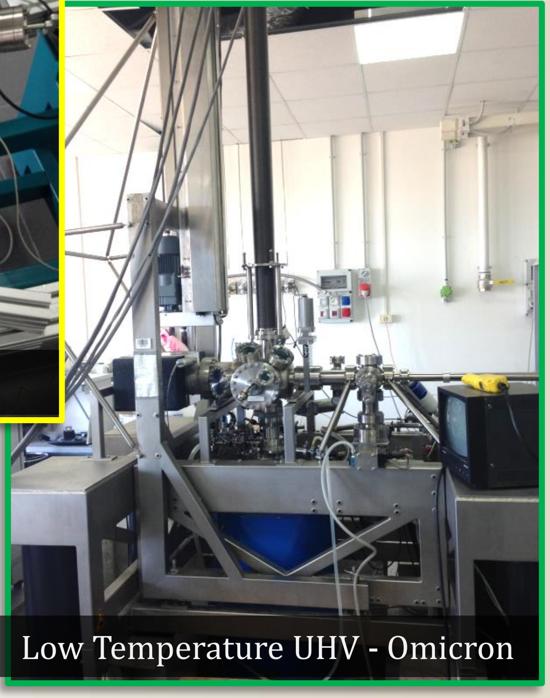
Top view of UniSa campus

Facilities at the SPnM Laboratory

Sputtering DC equipped with 3 cathodes

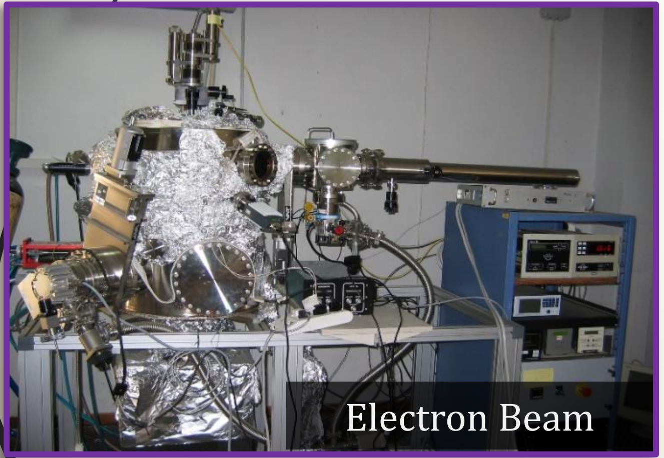






Room Temperature-UHV Atomic Force Microscope/ Scanning Tunneling Microscope

Cryogenic-UHV Atomic Force Microscope/ Scanning Tunneling Microscope, equipped with 7T out-of-plane superconducting magnet. Base temperature: 5K



Electron-beam gun equipped with 5 crucibles

Room Temperature and Pressure Atomic Force Microscopes.

The team of the SPnM Laboratory

spnm.fisica.unisa.it

Fabrizio Bobba
Associate Professor

Anna Maria Cucolo
Full Professor

Matilde Sublimi
Post Doc

Cinzia Di Giorgio
Post Doc

Domenico D'Agostino
Ph.D. Student

Ofelia Durante
Ph.D. Student

The activities of the SPnM Laboratory

- Study of **superconductivity** in S/F systems and novel superconductors by means of low-temperature UHV MFM and STM
- Study of the electric and electro-mechanical properties of **thin films** and **nano-structured semiconductors** by means of AFM, KPFM, PFM, C-AFM
- Study of **amyloids** and their aggregation on DOPC and DOPC/DHA bilayers by means of AFM and Quantitative-AFM
- Study of piezoelectric properties of ferroelectric **polymers** by PFM; Study of antimicrobial activity of polymers by AFM and Quantitative-AFM
- Study of electrical properties of **2D materials** and their dependence on stress/strain by means of AFM, Quantitative-AFM, C-AFM and KPFM
- Study of morphological and elastic properties of **mirror prototypes** for gravitational waves detectors by means of AFM, Quantitative-AFM, Force Modulation - AFM

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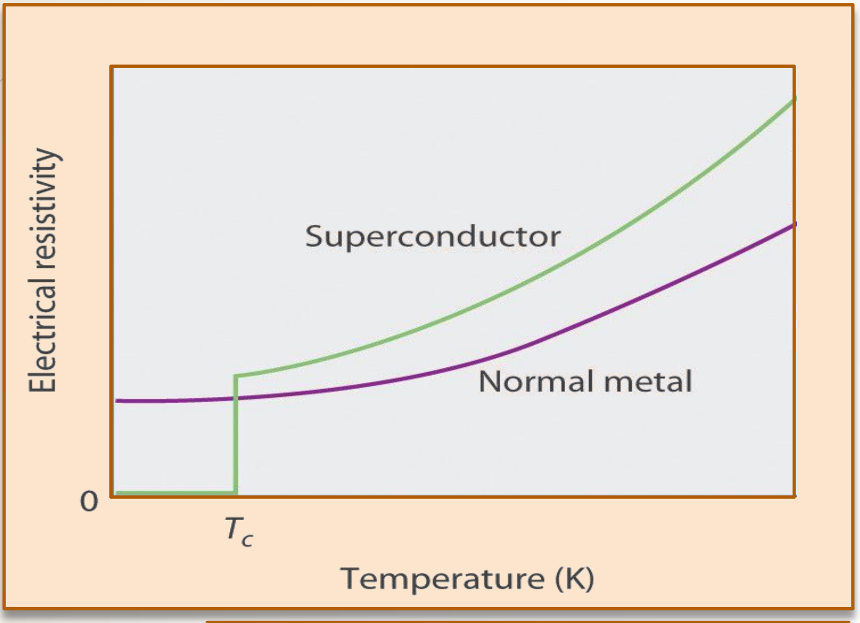
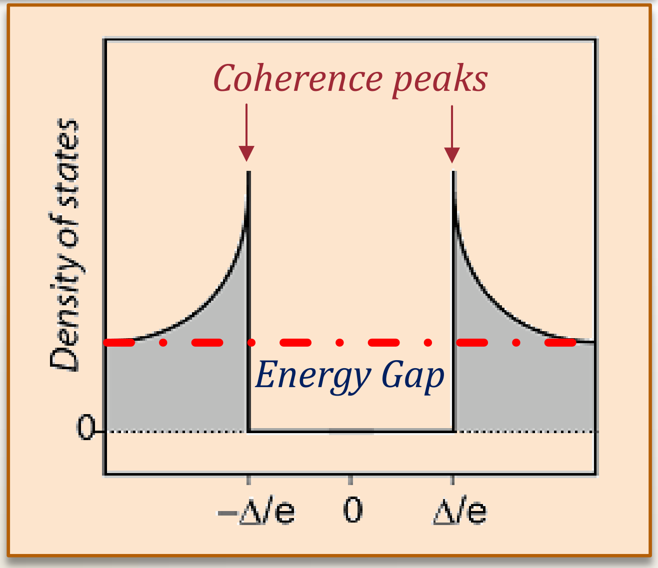
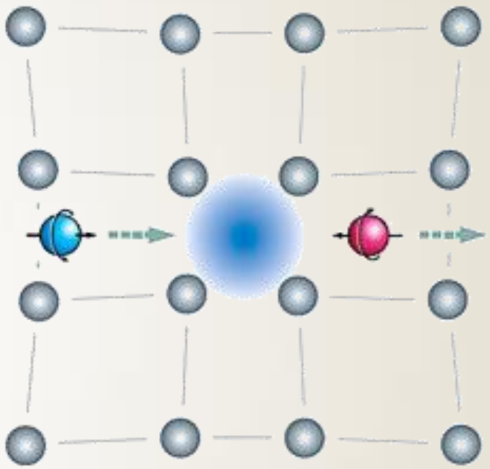
Brief refresh on superconductivity



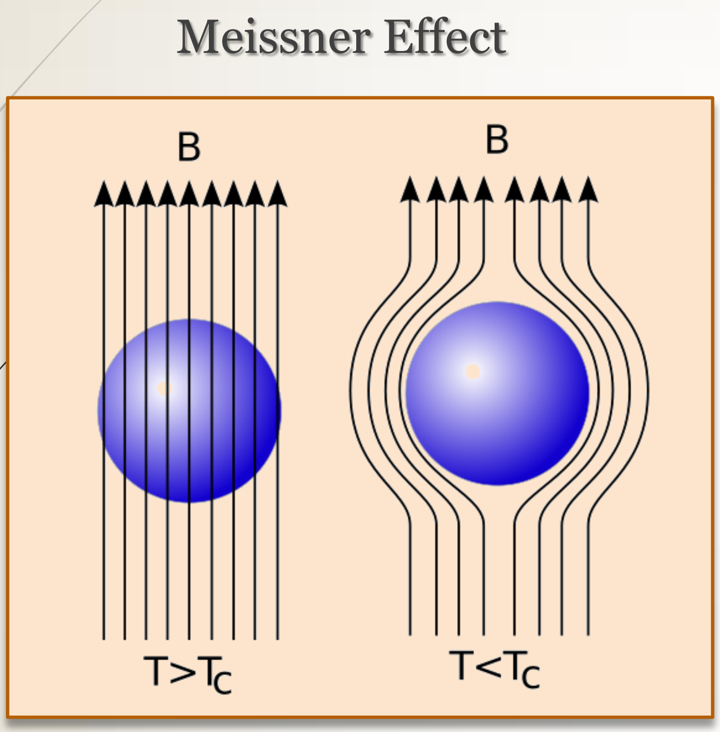


- Zero Electrical Resistance -> No dissipation due to the formation of the «Cooper pair»

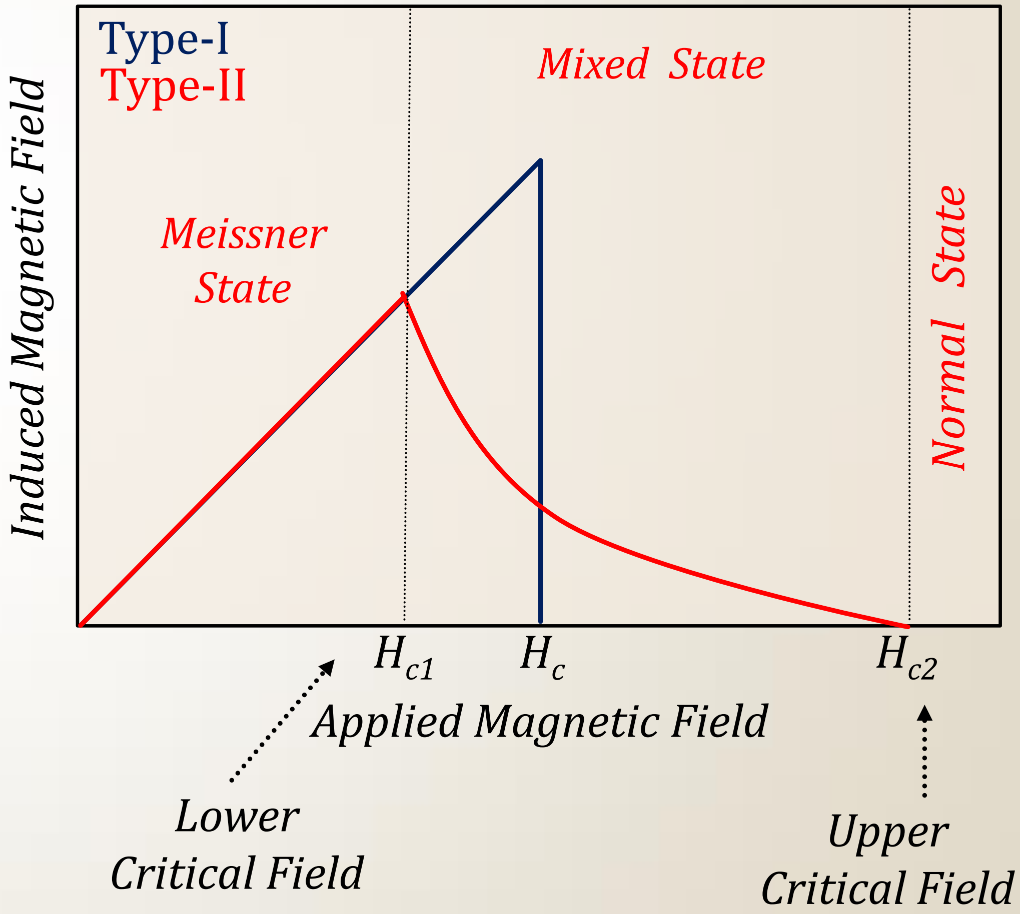


- Peculiar density of states, characterized by:
  - Energy gap (few meV)
  - Coherence peaks
- The coherence length ξ measures the size of the cooper pair $\xi_{BCS} = \frac{\hbar v_F}{\pi \Delta}$

Brief refresh on superconductivity

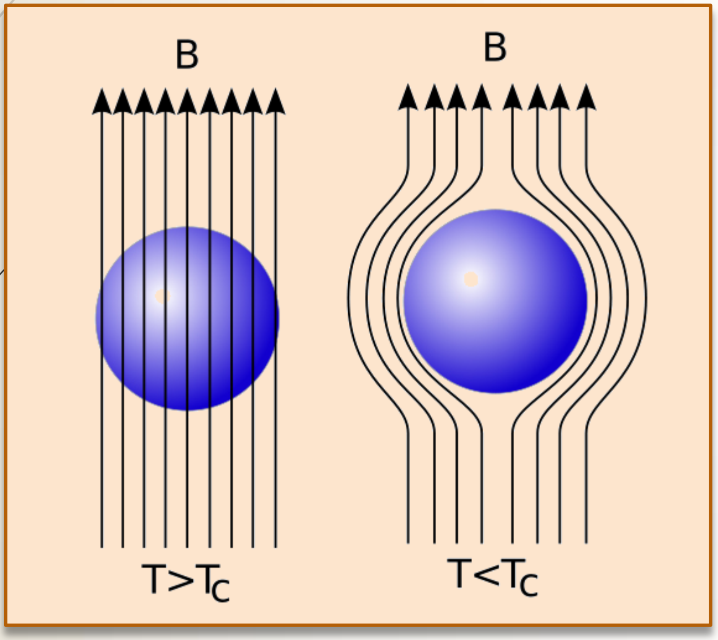


- Perfect Diamagnetism in Meissner state;
- 1st order transition in Type-I;
- 2nd order transition in Type II



Brief refresh on superconductivity

Meissner Effect



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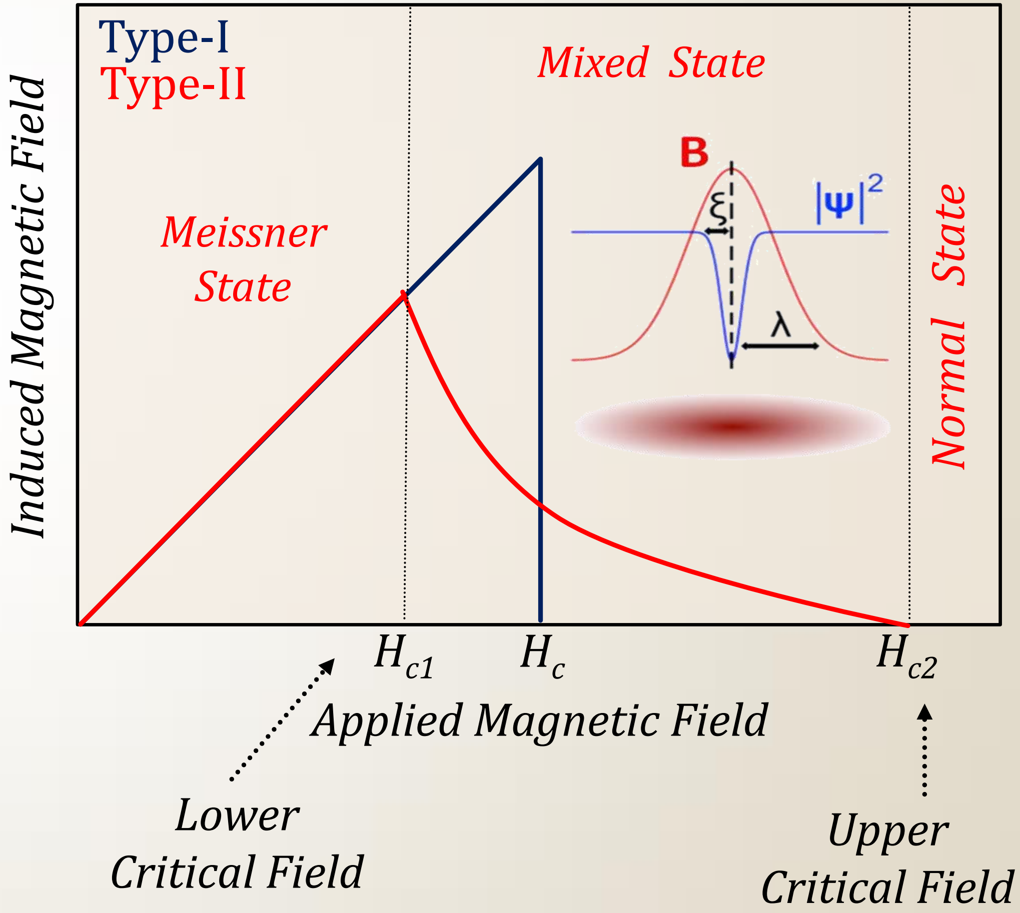
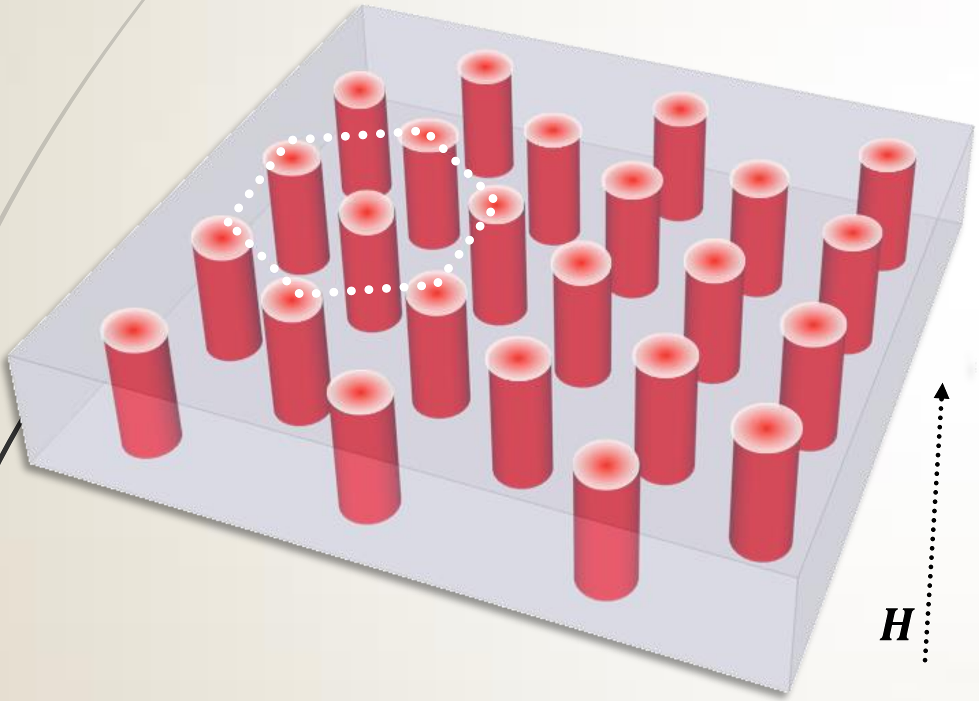


A superconducting vortex always supports a **magnetic quantum flux**:

$$\Phi_0 = \frac{hc}{2e} = 2.07 \times 10^{-7} G cm^2$$

Brief refresh on superconductivity

Abrikosov hexagonal lattice



$$H = \frac{2}{\sqrt{3}} \frac{\Phi_0}{d^2}$$

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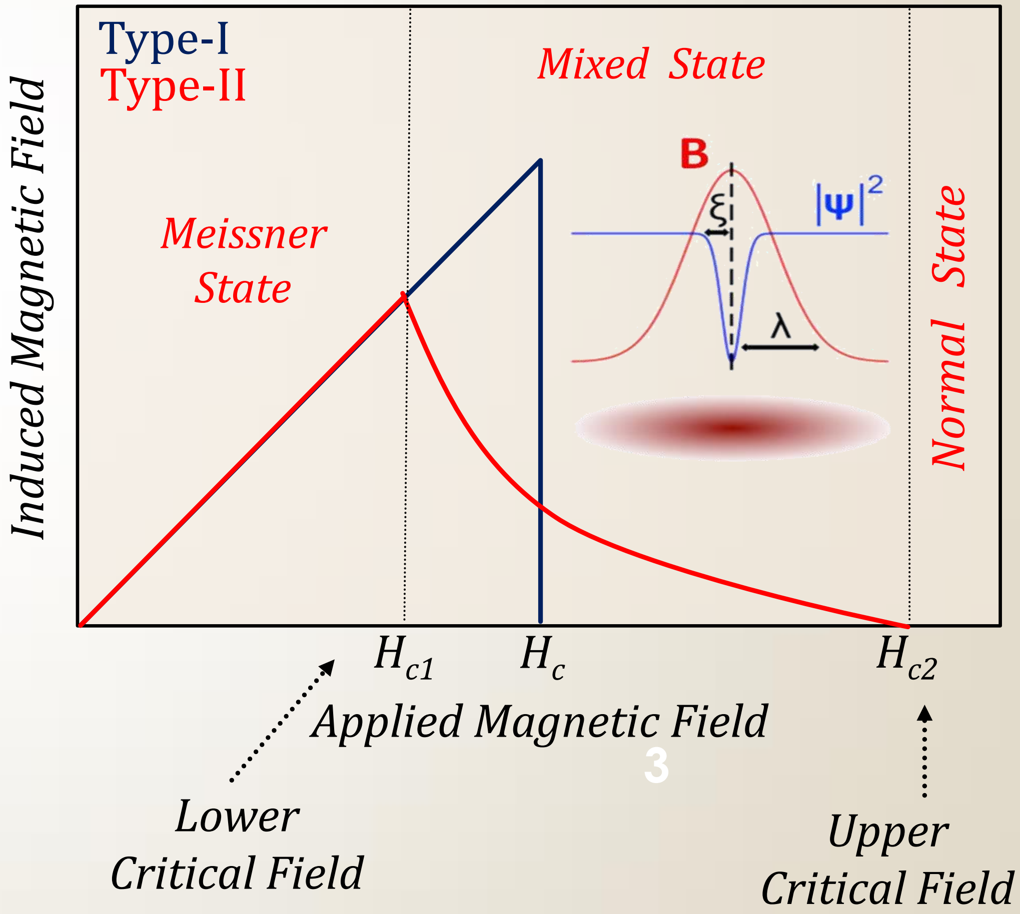


Scanning Probe Microscopy techniques

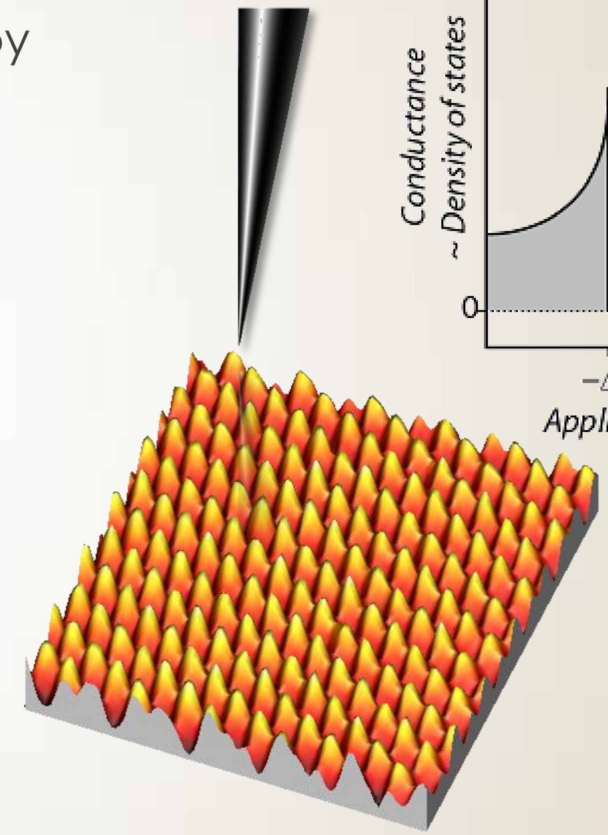
- Scanning Tunneling Microscopy and Spectroscopy

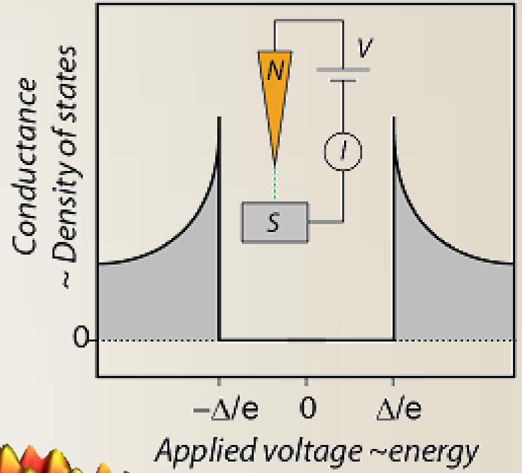
  Quantum Tunneling Current

  $$I \sim e^{-kz}$$

  $$I \sim \frac{4\pi e}{\hbar} |M|^2 \rho_t(0) \int_{-eV}^{0} \rho_s(\varepsilon)\, d\varepsilon \;\Rightarrow\; \frac{dI}{dV} \propto \rho_s(\varepsilon)$$

  T=0K - Low Temperature approximation





- Magnetic Force Microscopy

  Magnetostatic Interaction

  $$df = \frac{f_0}{2k} \frac{dF_z}{dz}$$

Scanning Probe Microscopy techniques

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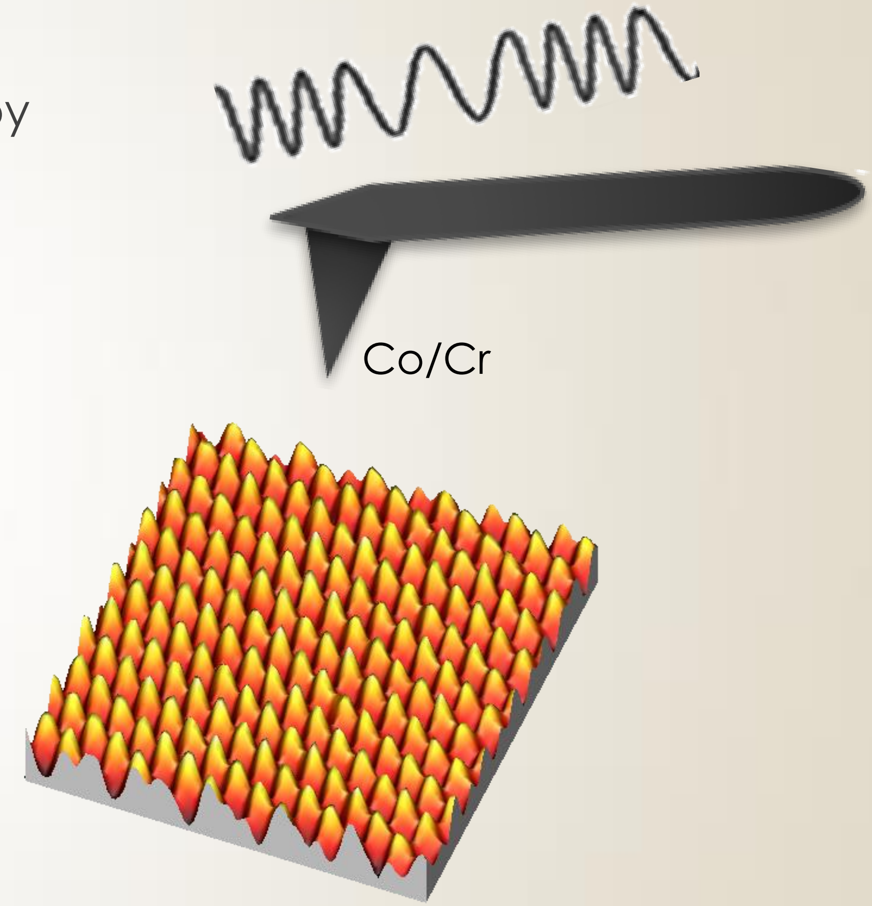

Scanning Probe Microscopy techniques

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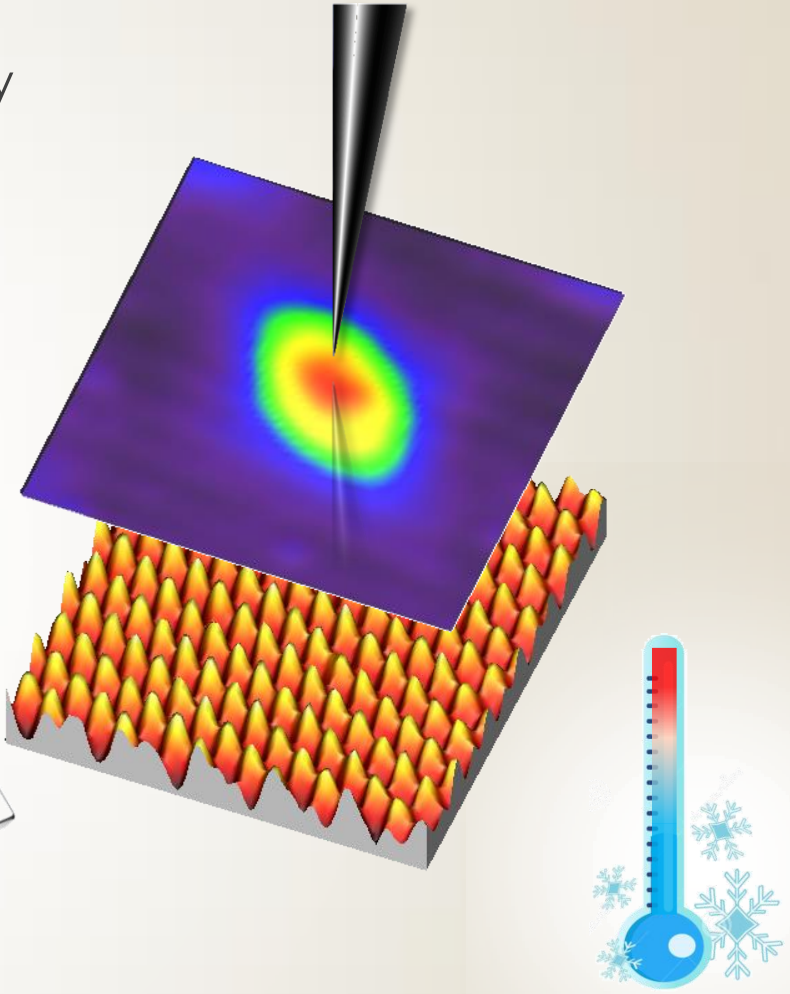
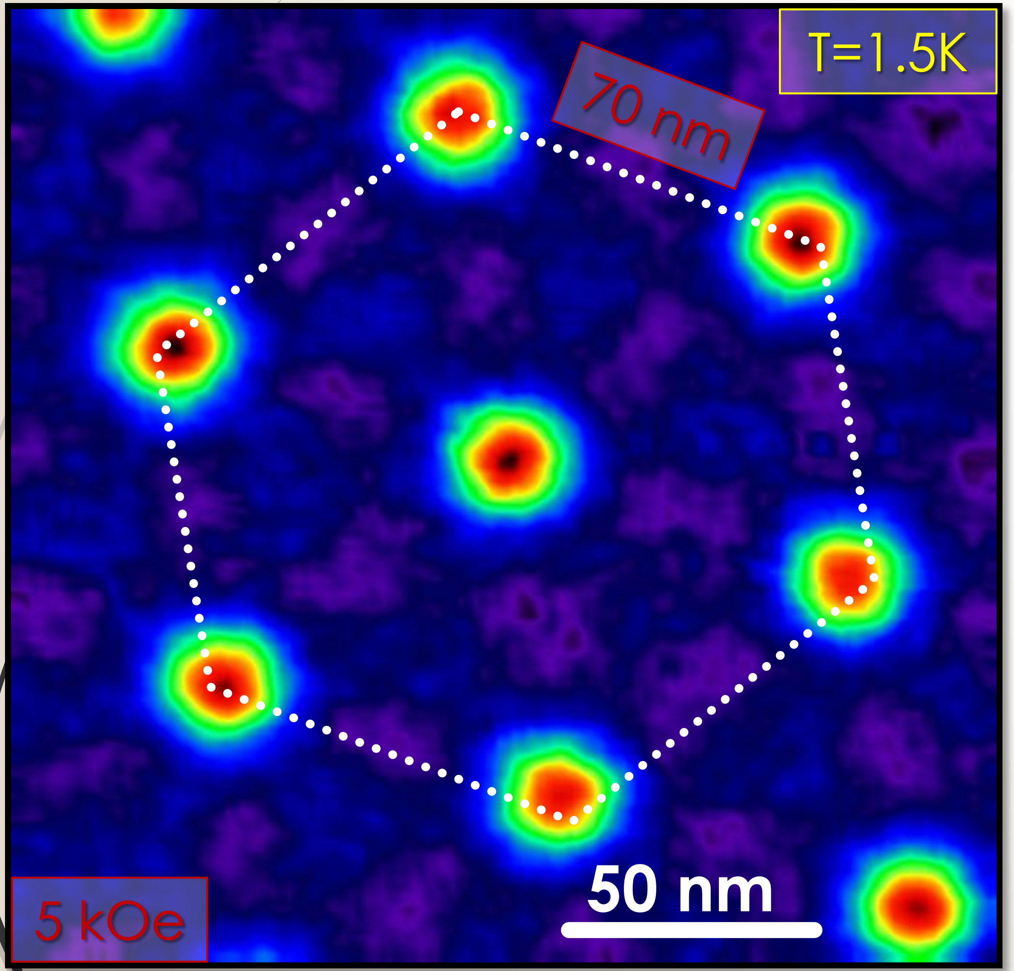
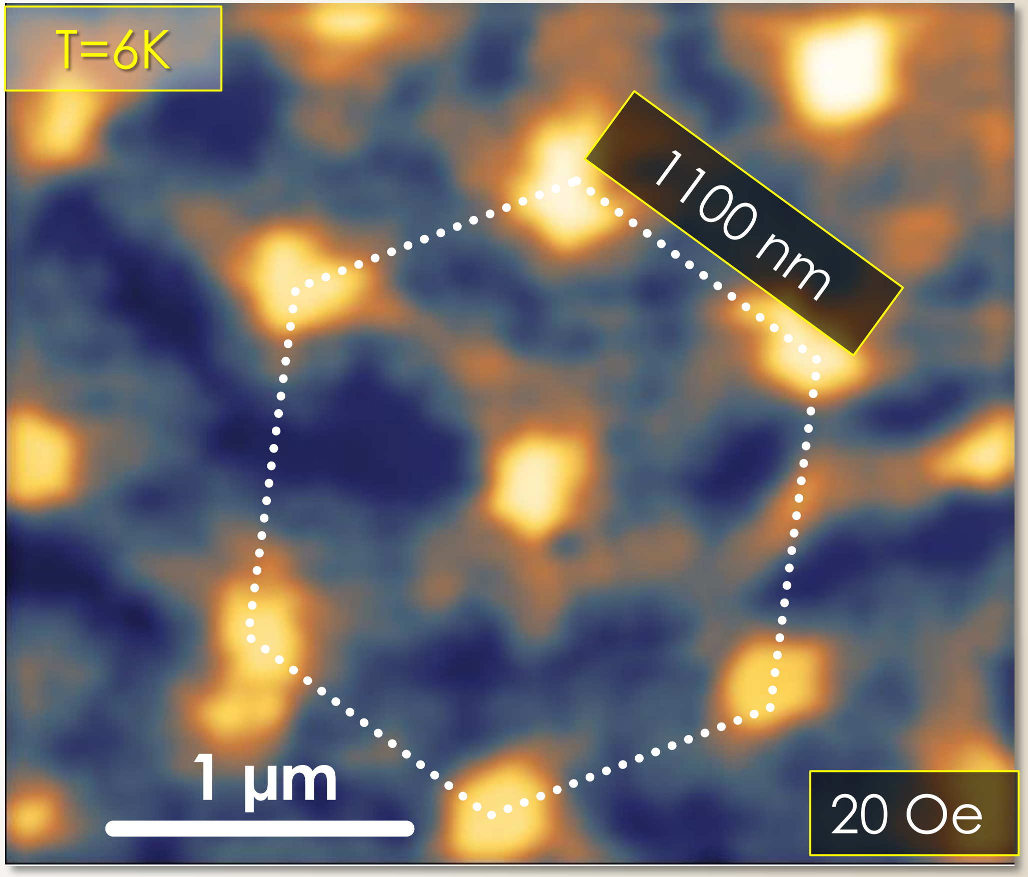


Scanning Probe Microscopy techniques

Low Temperature – STM on $NbSe_2$



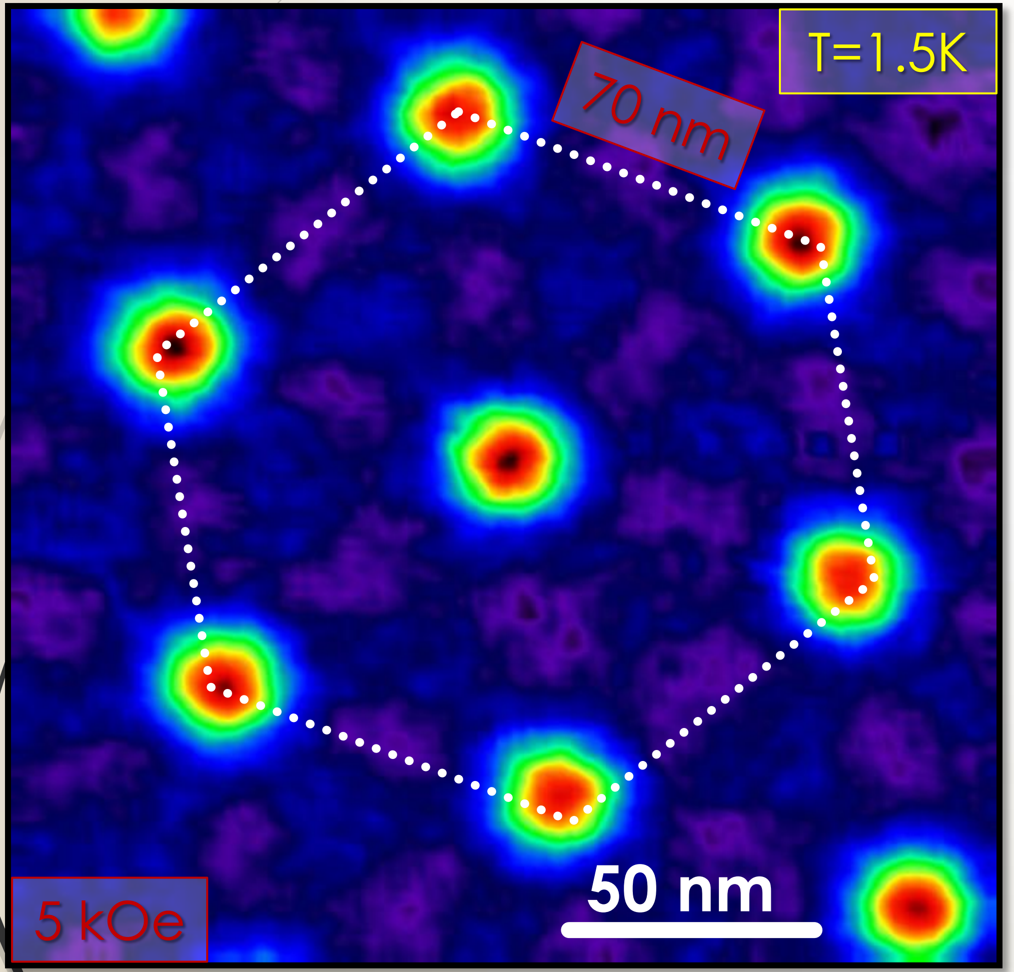
Low Temperature - MFM on $NbSe_2$



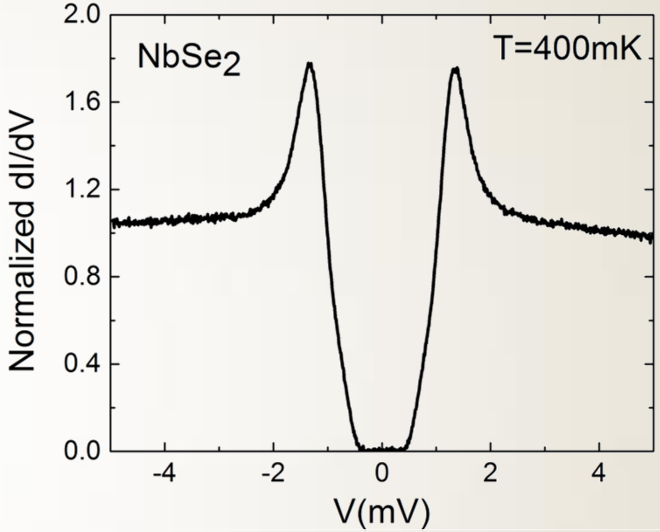
$$H = \frac{2}{\sqrt{3}} \frac{\Phi_0}{d^2} \qquad \xi \approx 50Å \qquad \lambda \approx 200nm$$

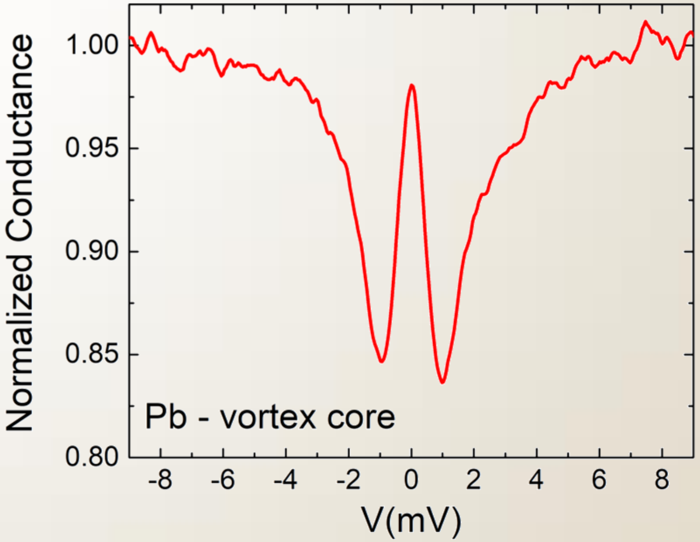
Scanning Probe Microscopy techniques

Low Temperature – STM on $NbSe_2$



Low Temperature - STS

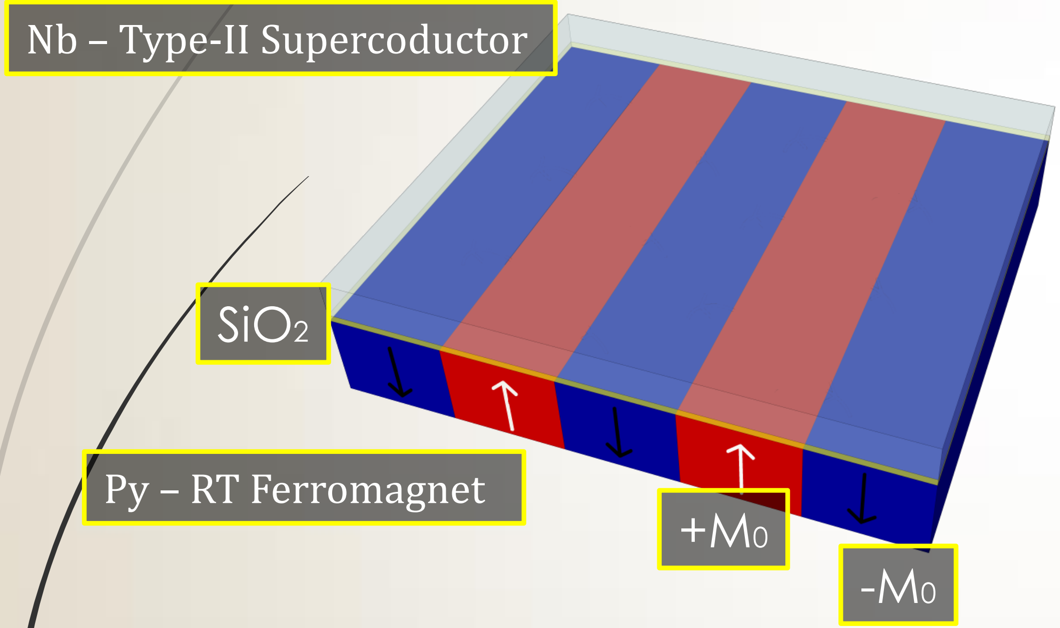




Superconductor/Ferromagnet systems

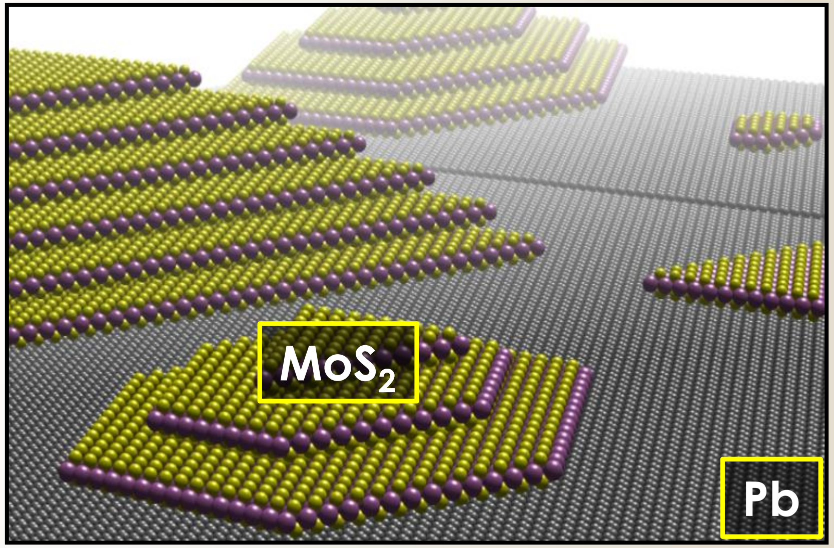
We used Low-Temperature MFM and STM/STS to investigate the following Superconductor/Ferromagnet systems:

Magnetically coupled Nb/Py ($Ni_{80}Fe_{20}$)



- Nb is a type-II superconductor with a T_c of 9.2K
- Py has stripe-configuration of magnetic domains
- A thin layer of SiO2 electrically decouples Nb and Py

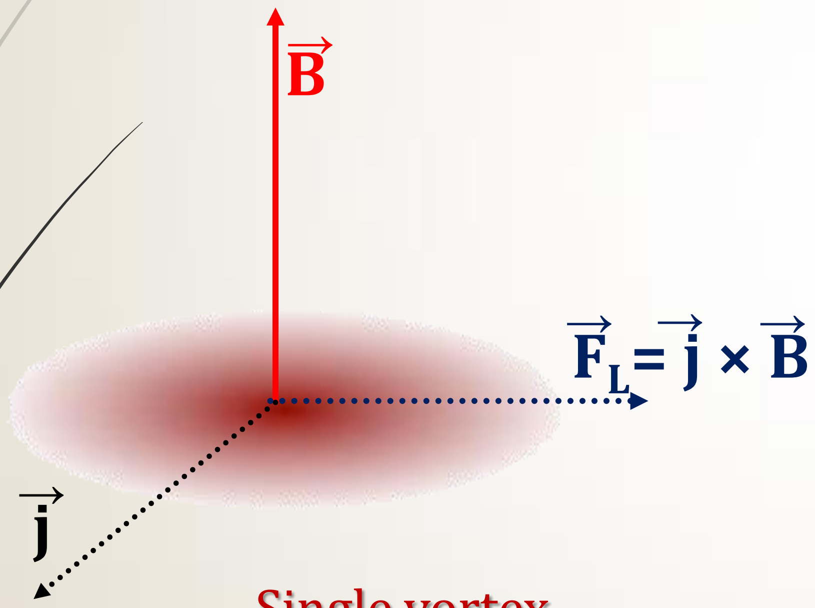
Electrically coupled MoS_2/Pb



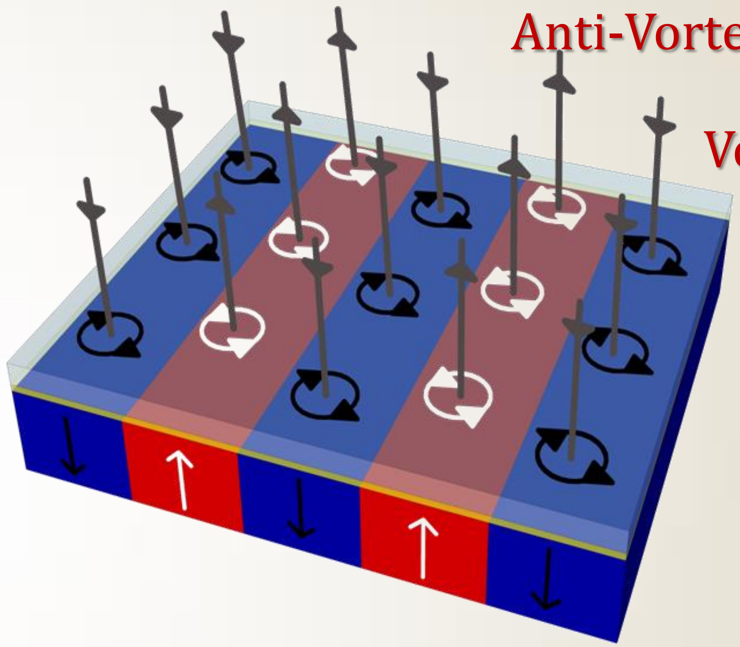
- Pb is a type-II superconductor with a T_c of 7K
- MoS2 is generally a semiconductors, but a non-zero magnetization is predicted to appear at the edge states of mono-layer islands

Magnetically coupled S/F systems - motivations

Vortices are forced into motion by the Lorentz Force causing dissipation.



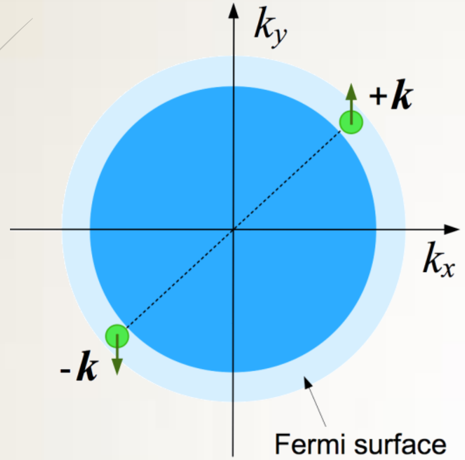
Single vortex



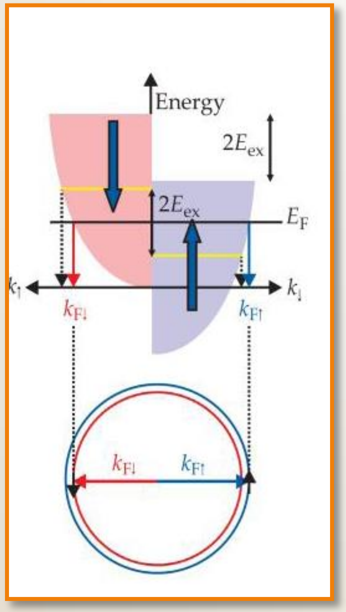
- Vortex motion across the stripes is prohibited
- Vortex motion along the stripe is strongly suppressed

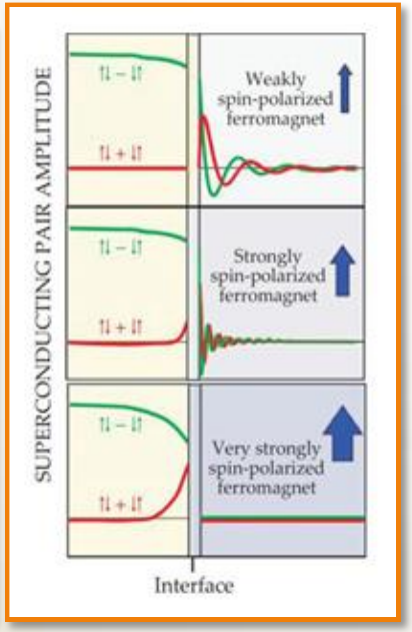
Vortex pinning is increased
Dissipation free regime is kept at higher magnetic field

Electrically coupled S/F systems - motivations

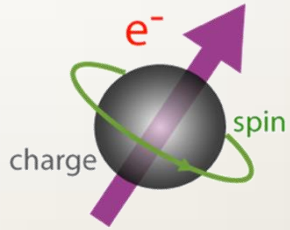


- The BCS theory predicts the existence of a sc condensate of Cooper pairs, with zero-center of mass momentum, opposite spin (zero total spin) and charge 2e

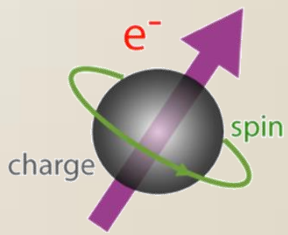




- The exchange field of F splits the energy bands for up and down spin, thus killing the Cooper pair (which has opposite spins)
- In order to survive the Cooper pair can acquire equal spins, giving rise to **supercurrents totally spin-polarized**

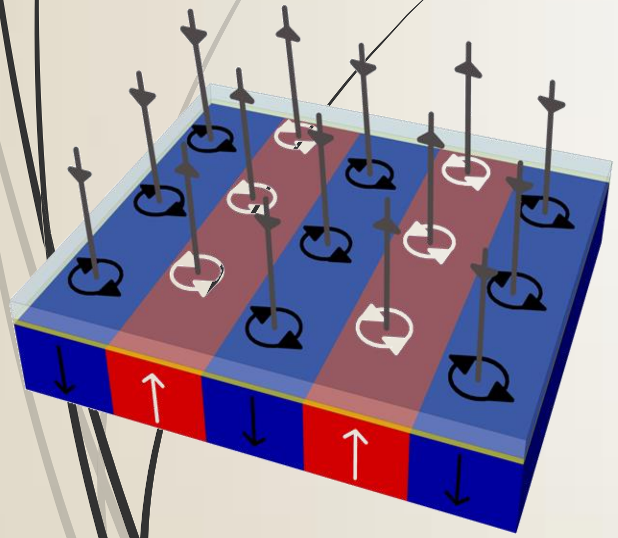


Spintronics!



Magnetically coupled S/F systems - motivations

We studied **magnetically coupled S/F** systems
in strong collaboration with Physics Department of Temple University
(Philadelphia, USA)

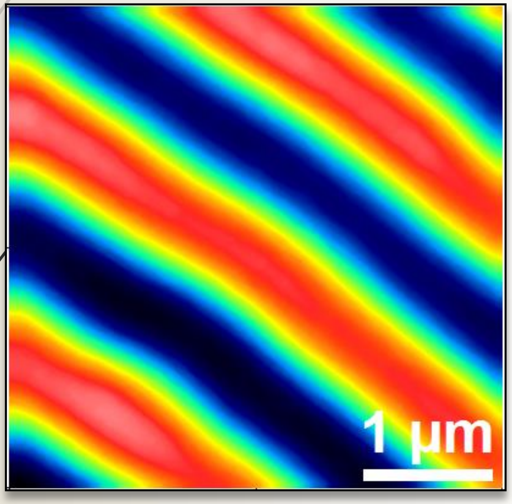


Our activity can be wrapped up in three main results:

- Nucleation of vortices in S/F;
- Study of enhanced pinning effect due to magnetic defects;
- Advances in Quantitative-MFM.

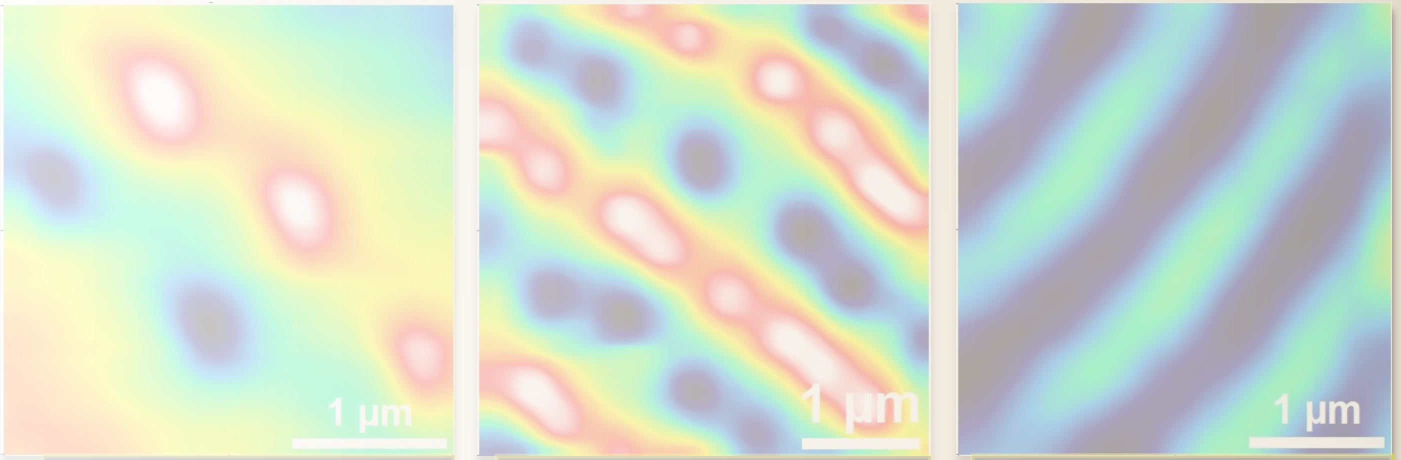
Vortex Nucleation

Typical MFM image of Py at T=13K (above Nb T_c)



- Peculiar stripe-arrangement of magnetic domains
- Stripe width proportional to Py thickness

Zero field cooling – T=6K (below Nb T_c)



Py(4µm)/Nb(200nm) | Py(2µm)/Nb(200nm) | Py(1µm)/Nb(200nm)

- Spontaneous Vortex-Antivortex pairs are formed in Py(4µm)/Nb(200nm) and Py(2µm)/Nb(200nm) whereas no vortex occurrence is recorded in Py(2µm)/Nb(200nm).
- Opposite polarized vortices correctly lye on proper magnetized stripes.

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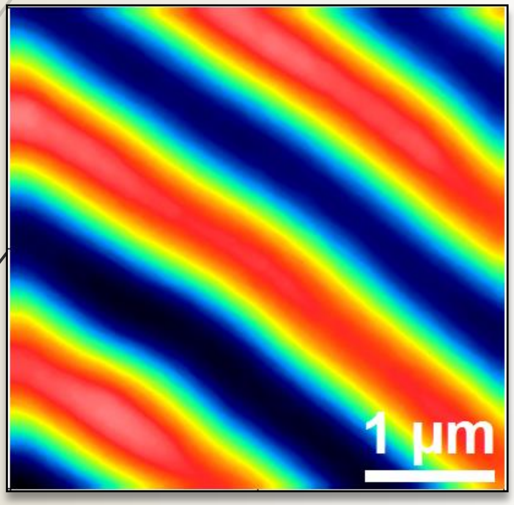

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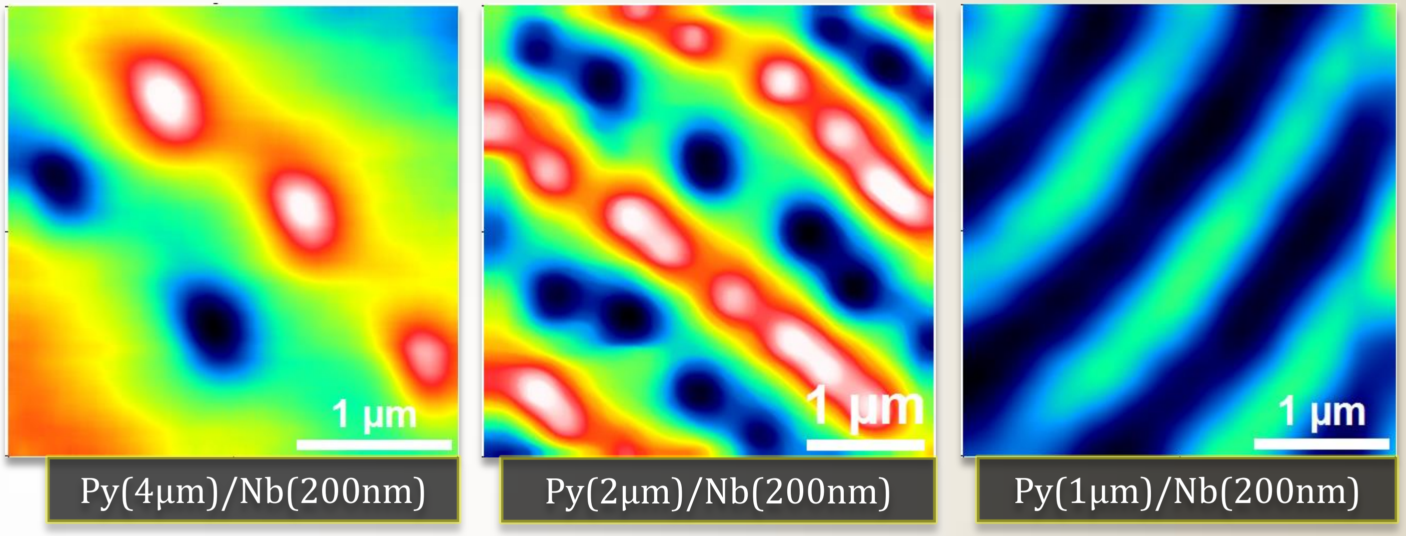

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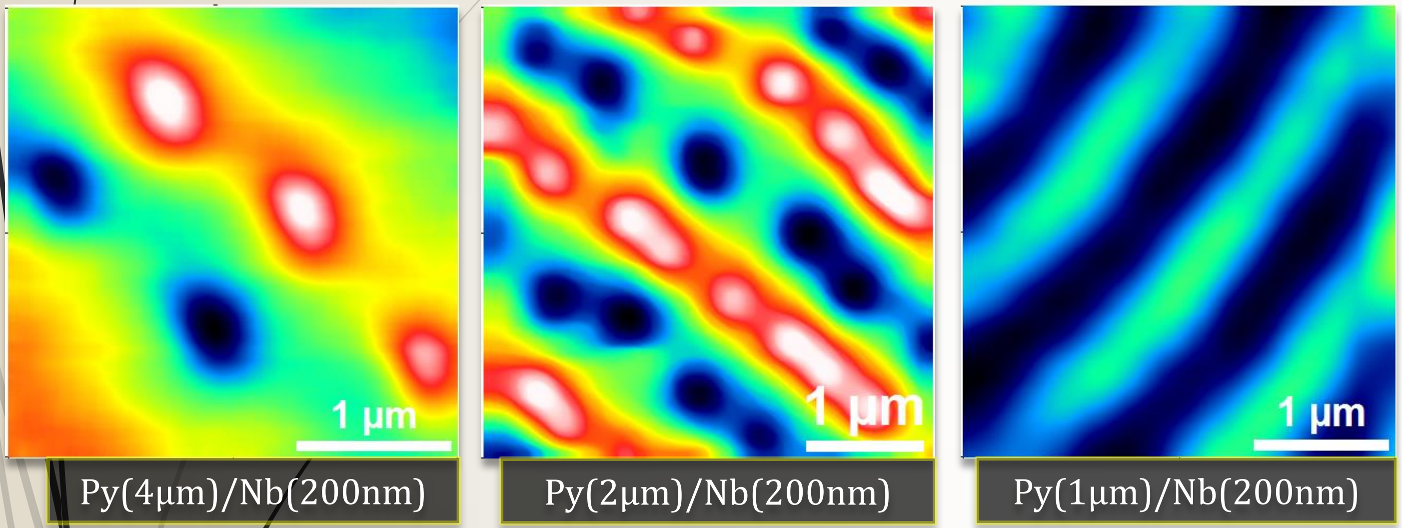

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- Opposite polarized vortices correctly lye on proper magnetized stripes.

Theoretical Model

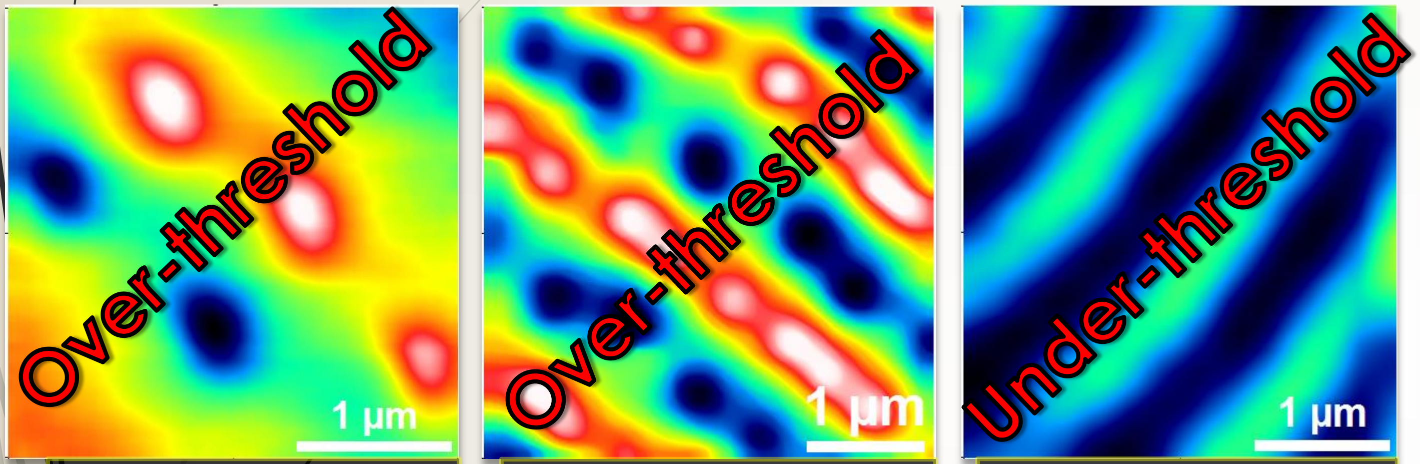
- Spontaneous V-AV can be formed in S/F only when the M_o value of F is over-threshold

$$M_0 > M_c$$

$$M_c = 0.2 \frac{d_s}{w} H_{c1}$$

Vortex Nucleation

Zero field cooling – T=6K (below Nb T_c)



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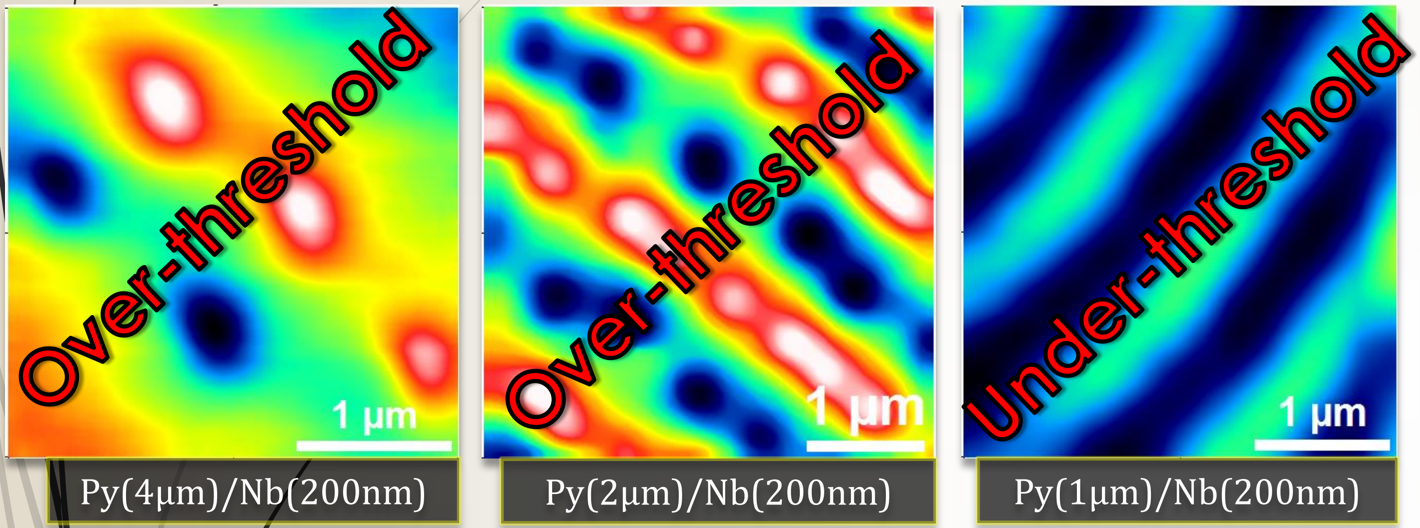


Nb [nm]	Py [µm]	M_c(6K) [G]
200	4	16.6
200	2	11.9
200	1	33.9

Threshold value

Theoretical Model

- Spontaneous V-AV can be formed in S/F only when the M_o value of F is over-threshold

$$M_0 > M_c$$

$$M_c = 0.2\frac{d_s}{w}H_{c1}$$

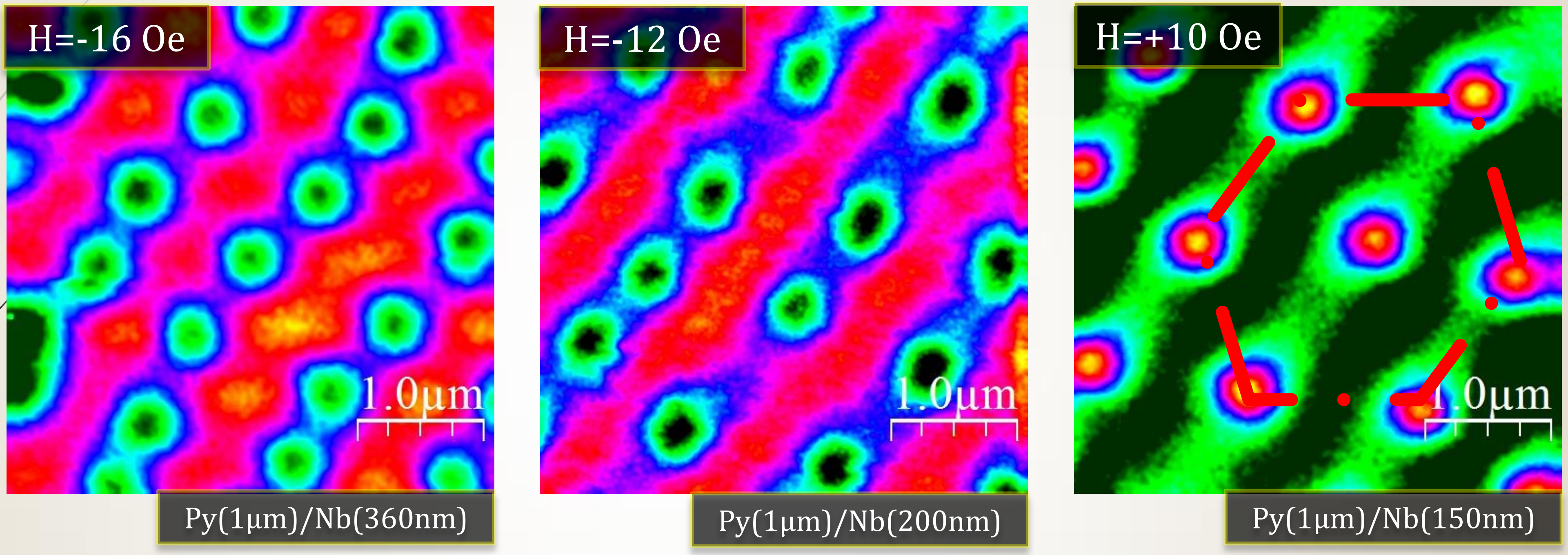
$$M_0(Py - 4\mu m) > 16.6G$$

$$M_0(Py - 2\mu m) > 11.9G$$

$$M_0(Py - 1\mu m) < 33.9G$$

Vortex Nucleation

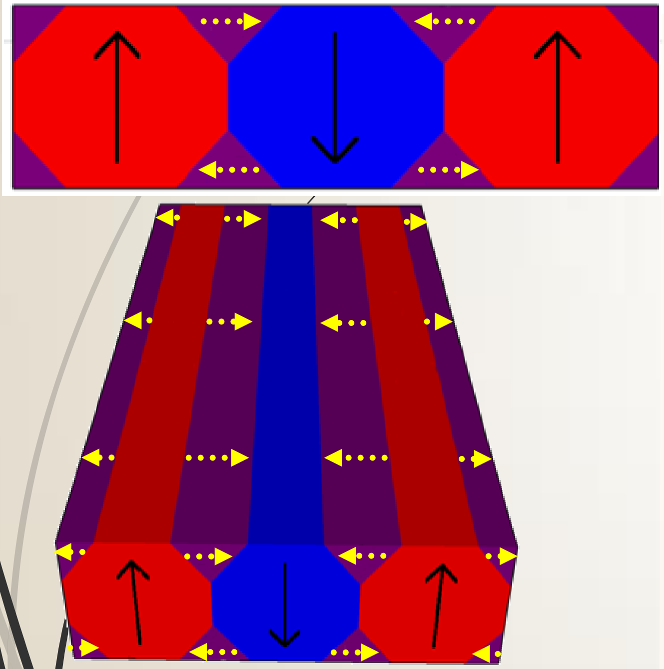
Field cooling – T=6K (below Nb T_c)



- Field incuded Vortices (or Antivortices) are formed with the same polarity as the external magnetic field on the proper polarized stripes;
- The tuning of the magnetic field intensity with respect to the stripe periodicity can lead to the formation of the hexagonal lattice (**Matching Field**)

$$H = \frac{2}{\sqrt{3}} \frac{\Phi_0}{d^2}$$

Pinning Enhancement



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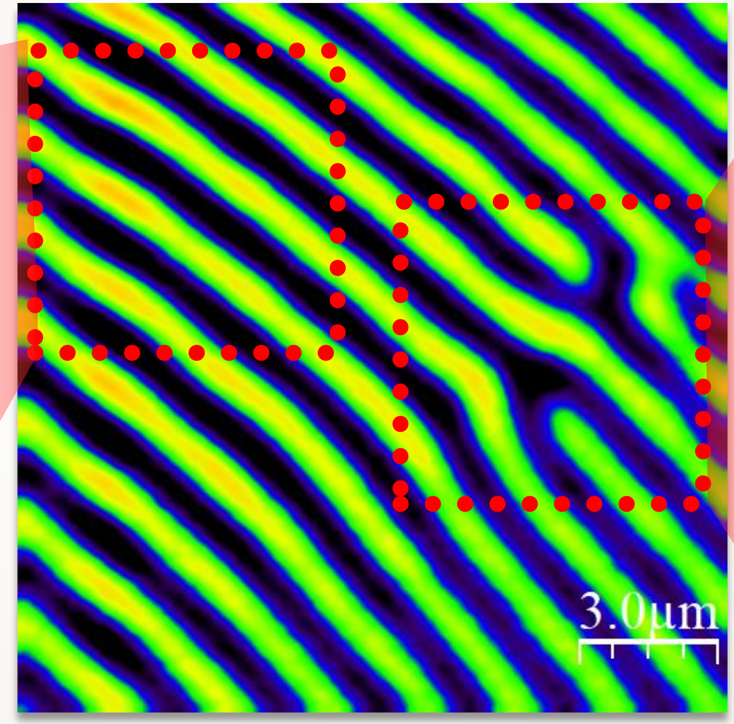

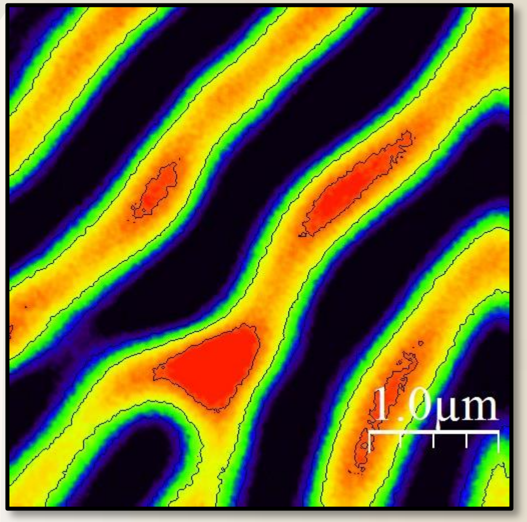

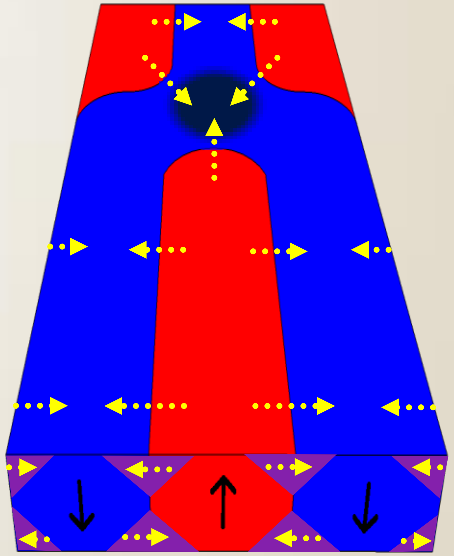

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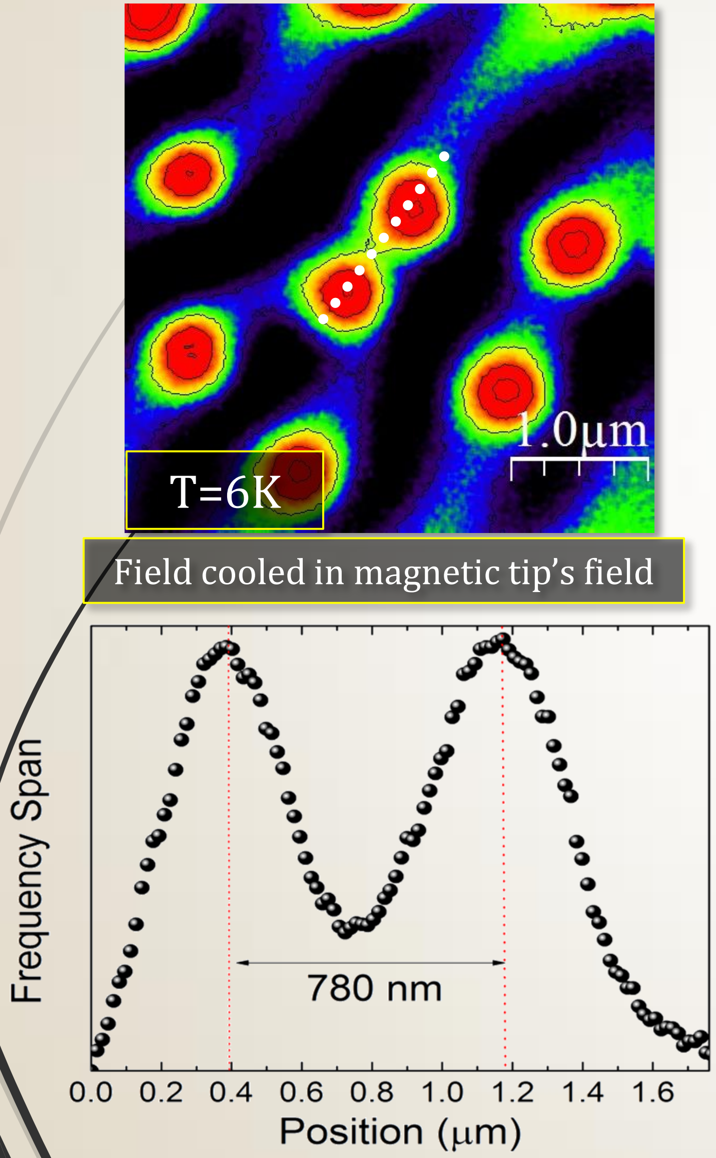
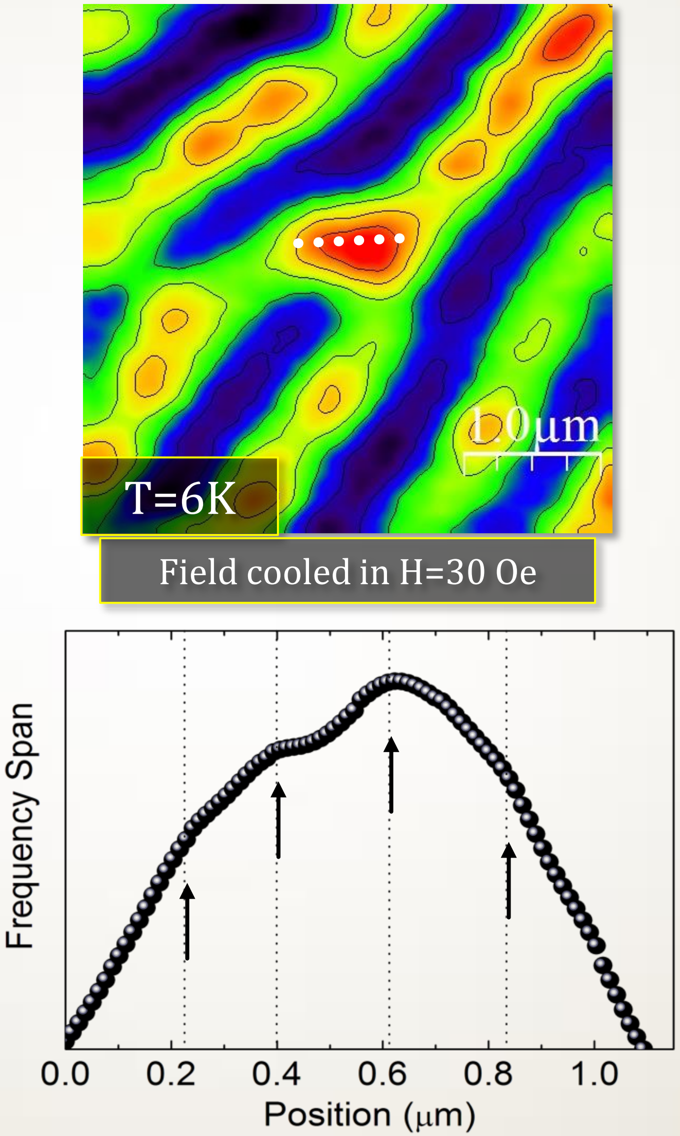
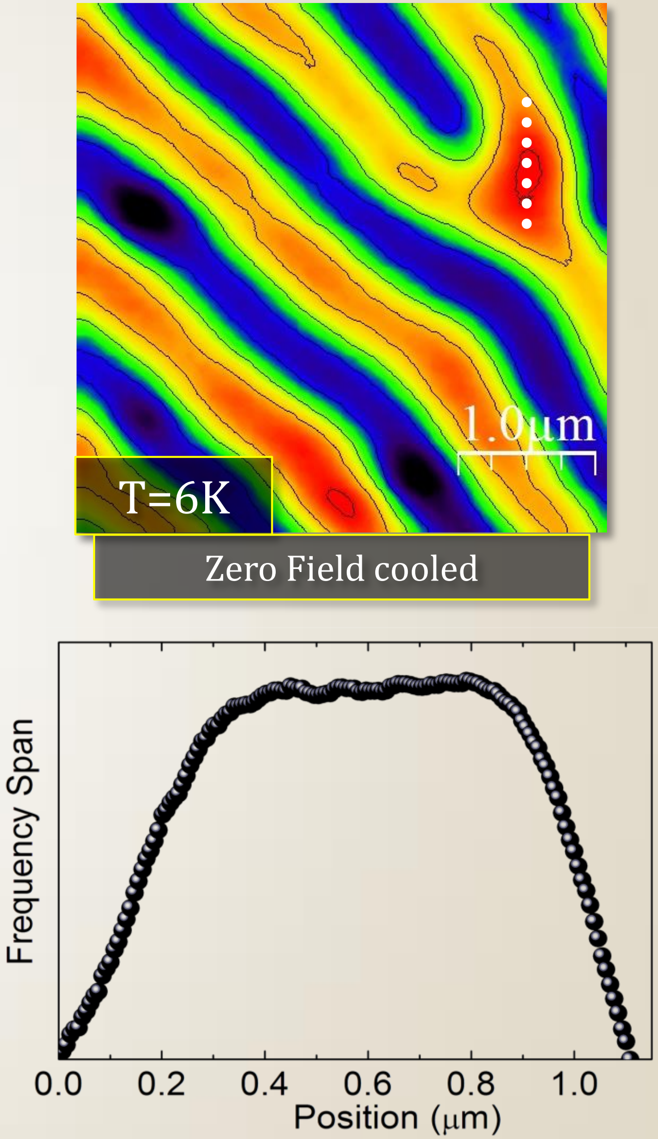
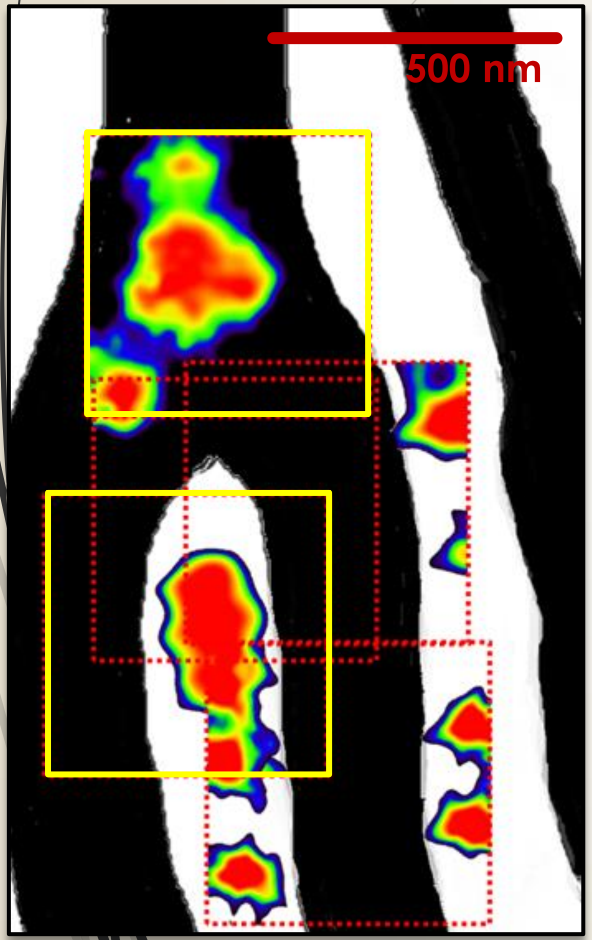


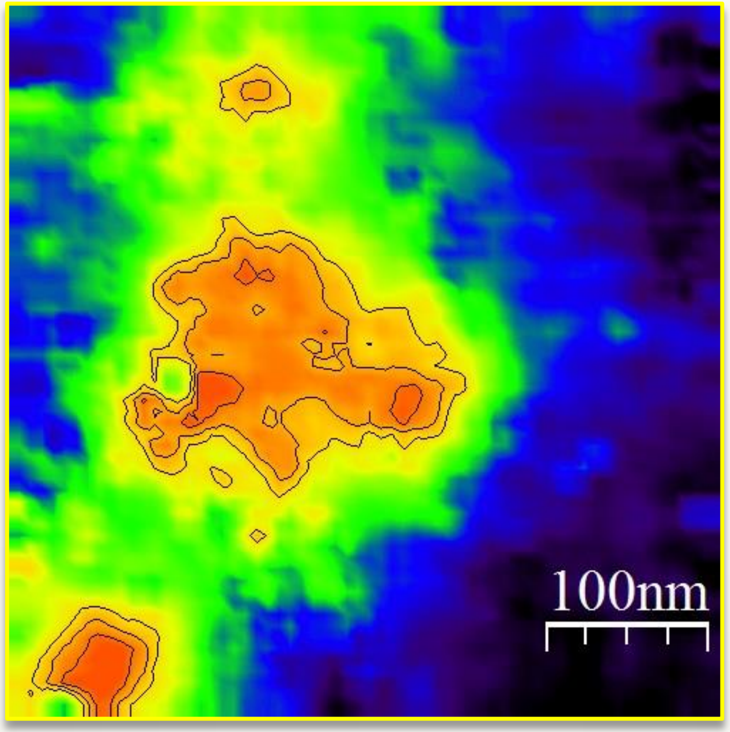




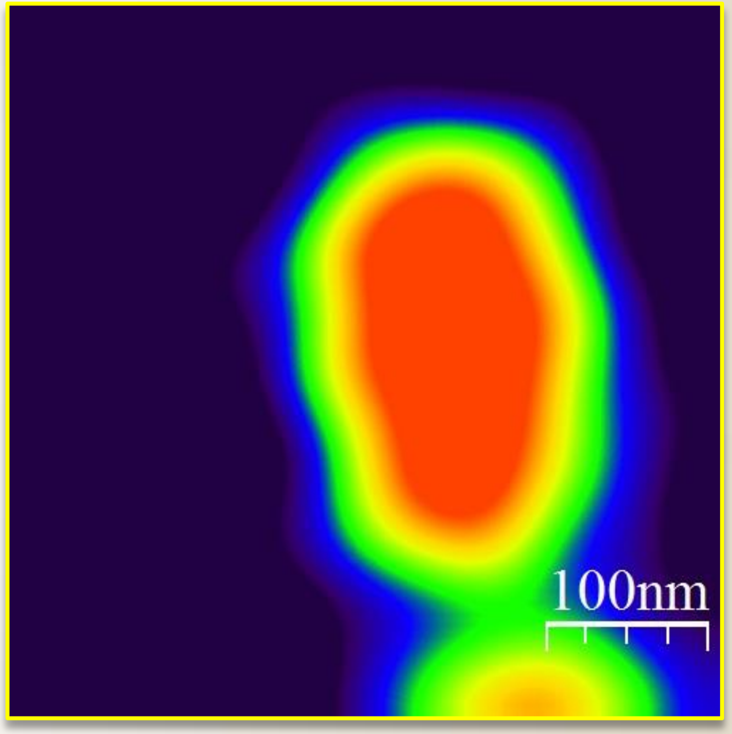
Pinning Enhancement



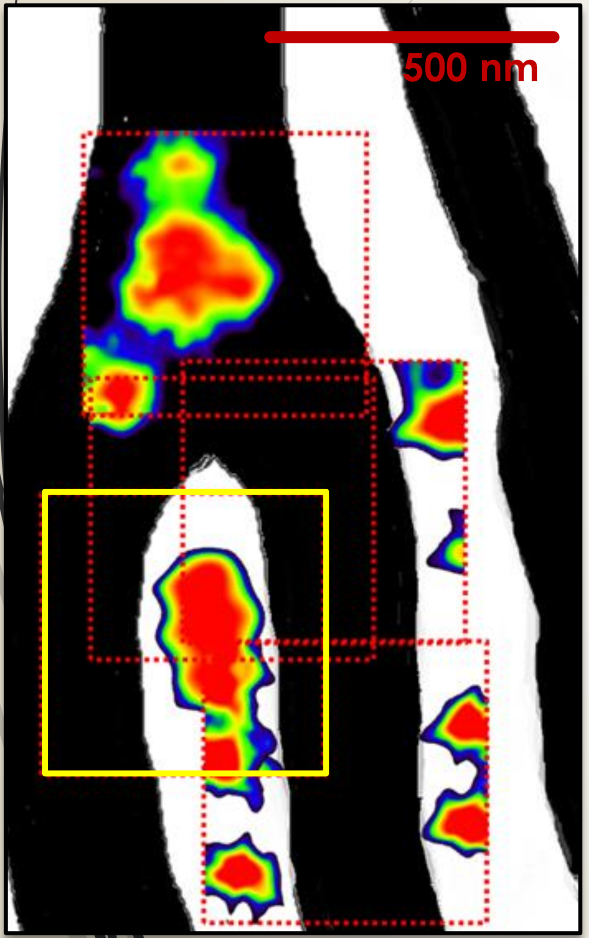
- Top of the fork



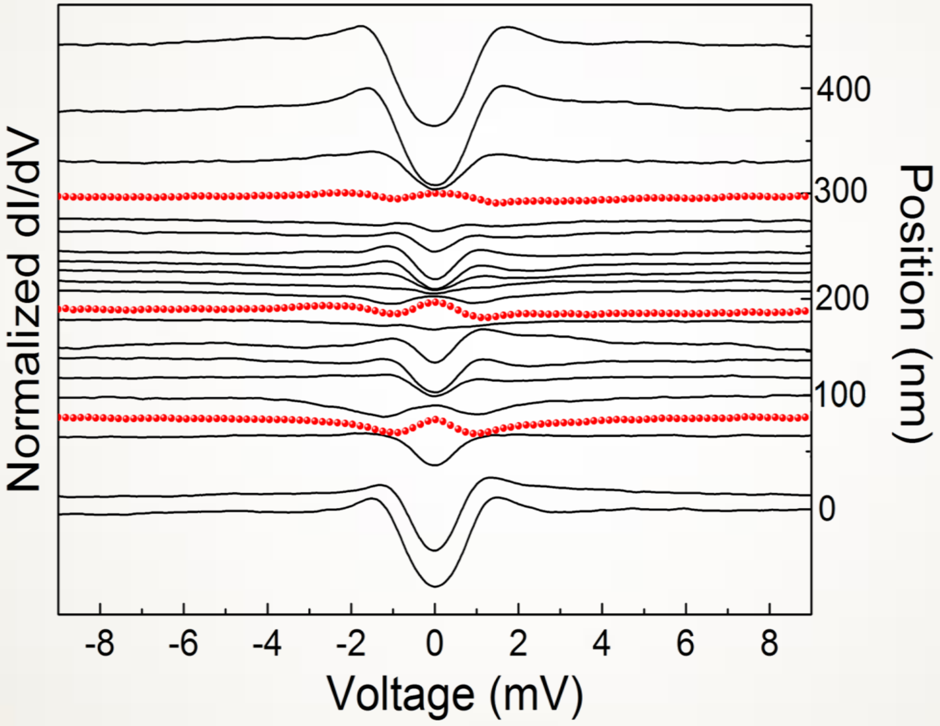
- Stripe endpoint

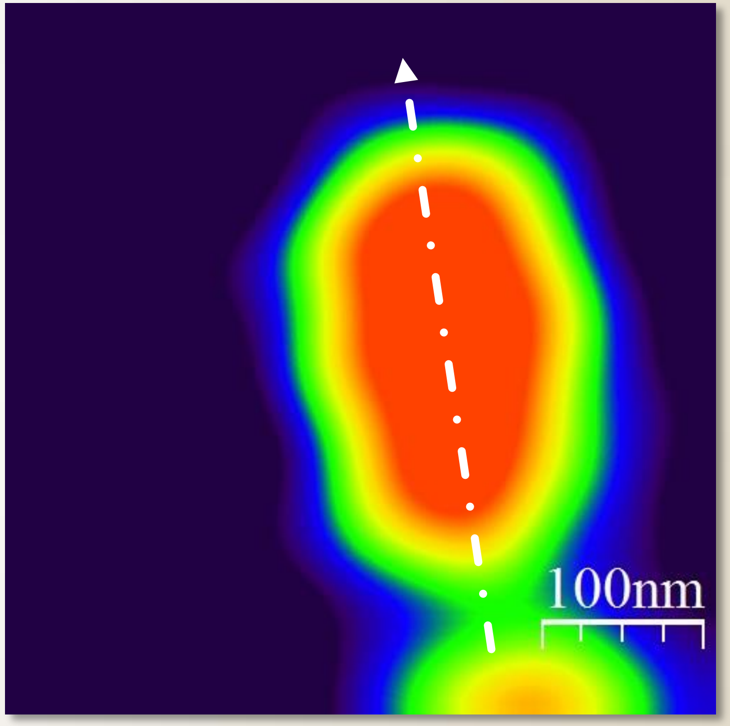


Pinning Enhancement

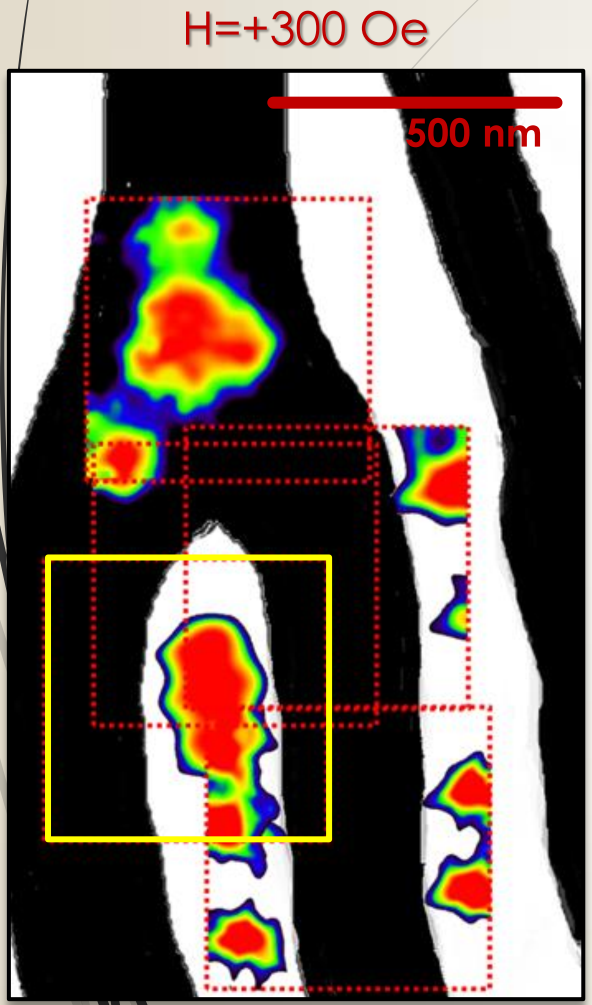


- Stripe endpoint

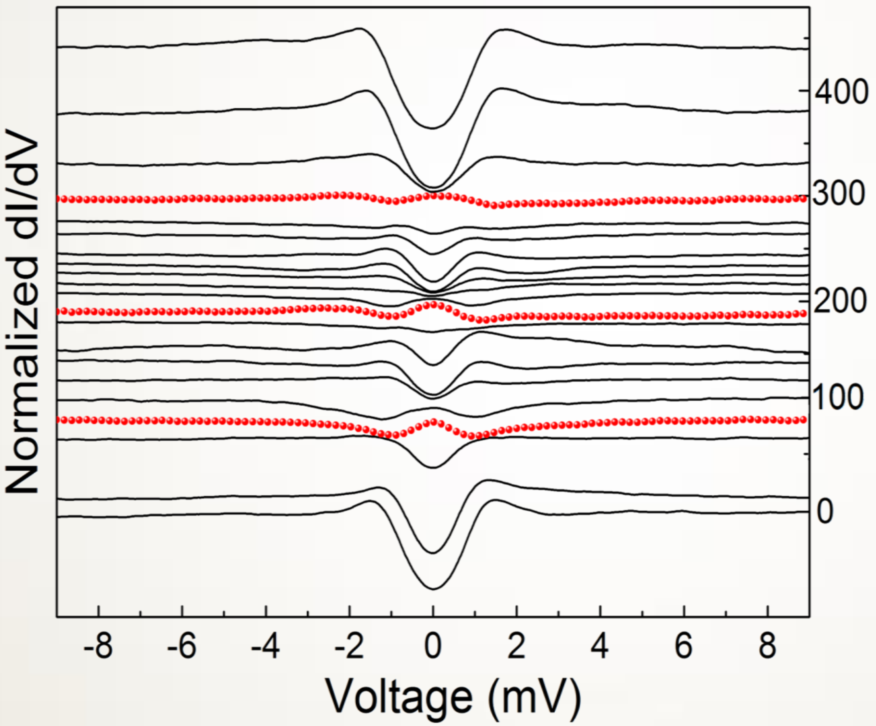


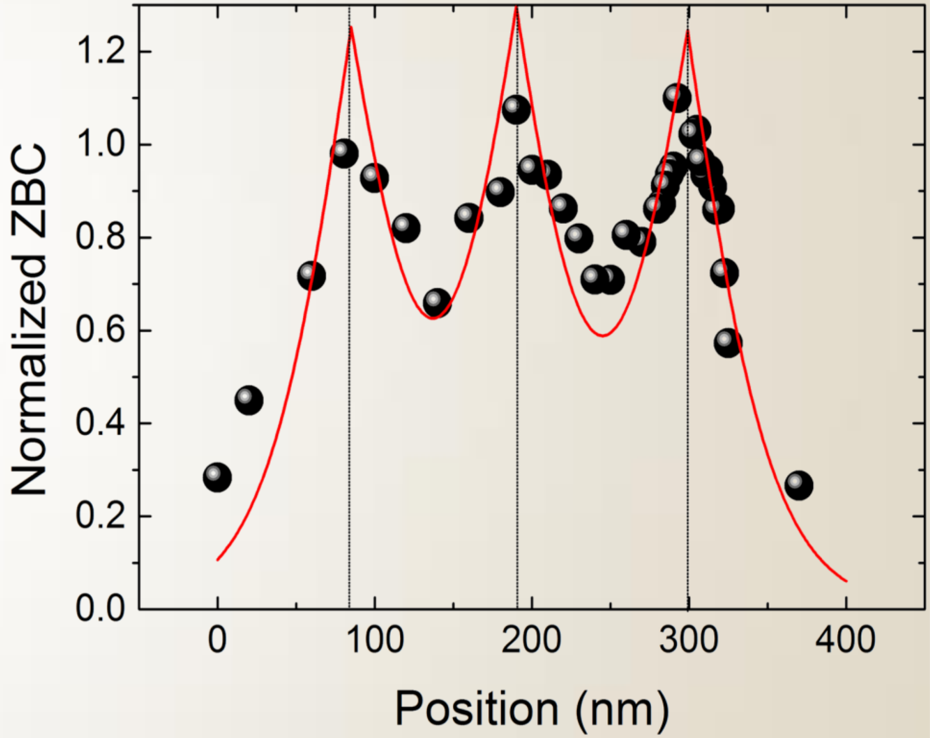


Pinning Enhancement



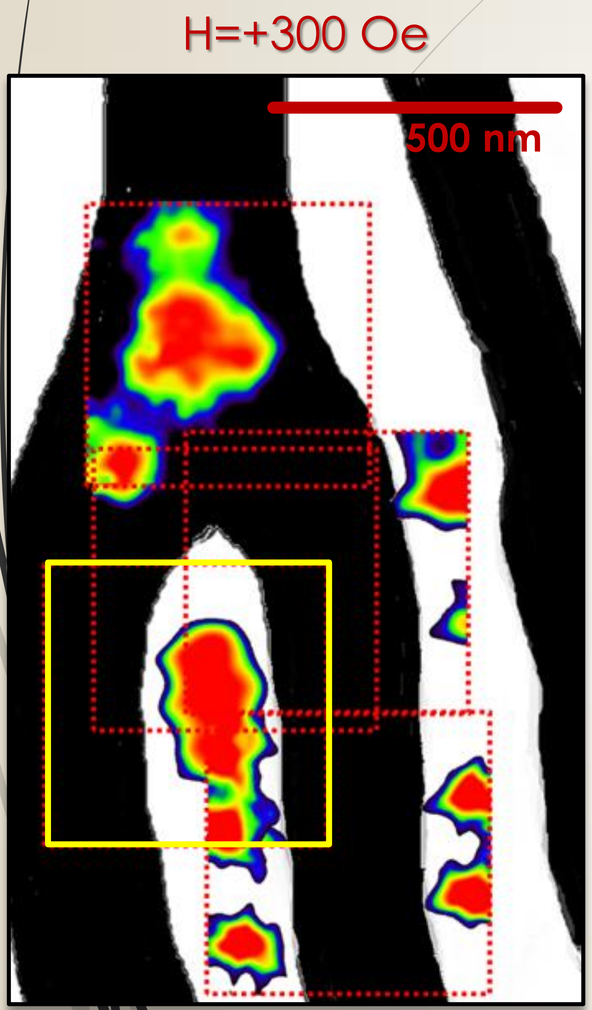
- Stripe endpoint





V-V distance (nm)	ξ (nm) – 1.5K
105-109	55

Pinning Enhancement



V-V distance (nm)	ξ (nm) - 1.5K
105-109	55

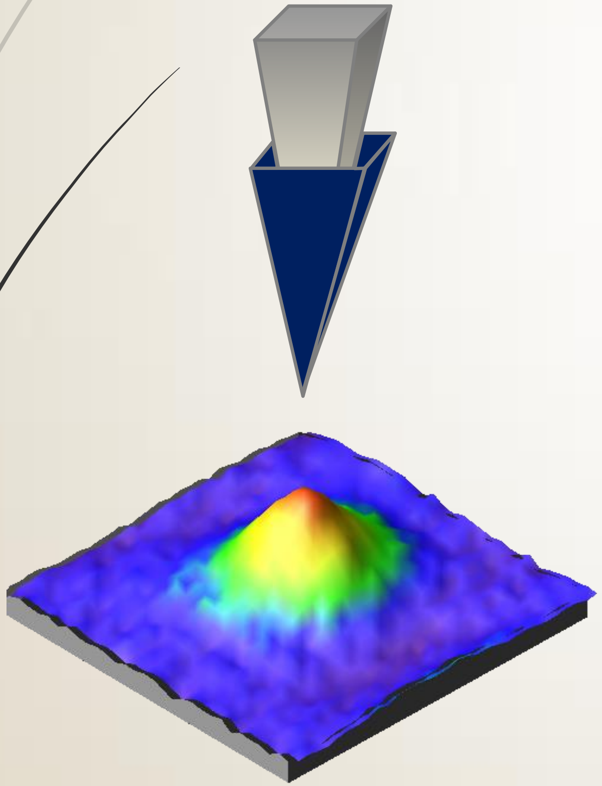
- Condition for fully separated vortices at H_{c2}:

$$H = \frac{2}{\sqrt{3}} \frac{\Phi_0}{d^2} \qquad d(H_{c2}) \approx 2.8 \times \xi$$

- Bifurations can induce vortex clusters with intervortex distance shorter than the minimum value achievable at H_{c2}.

Advances in Quantitative-MFM

We always deal with samples carrying out
a well know magnetic field:
the superconducting vortex!



A superconducting vortex always supports a magnetic quantum flux:

$$\Phi_0 = \frac{hc}{2e} = 2.07 \times 10^{-7} Gcm^2$$

Advances in Quantitative-MFM

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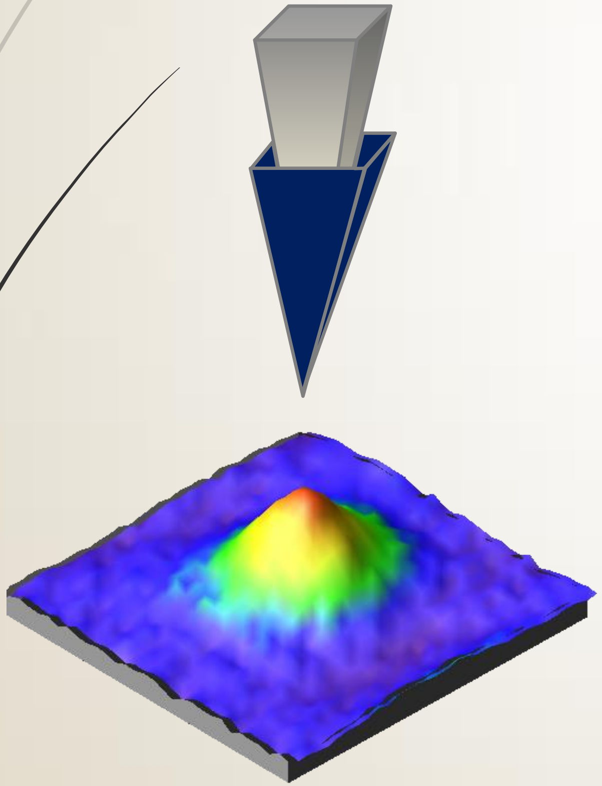


A superconducting vortex always supports a magnetic quantum flux:

$$\Phi_0 = \frac{hc}{2e} = 2.07 \times 10^{-7} G\,cm^2$$

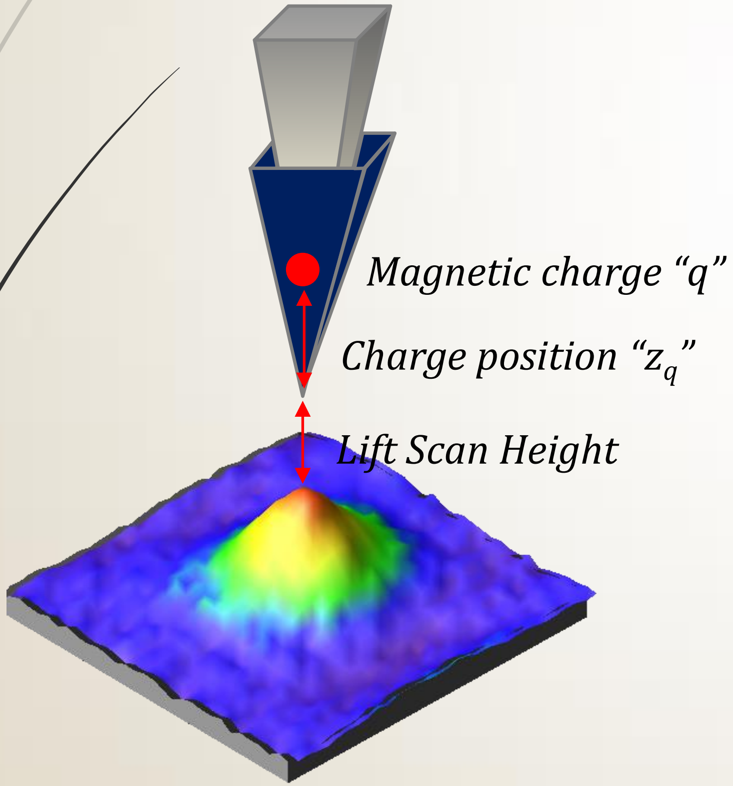
Many tip characterization procedures have been proposed in the approximation of:

- *Monopole* ; U. Hartmann, Adv. El. El. Phys. **47**, 49 (1994)
- *Dipole*; U. Hartmann, Phys. Lett. A **137**, 475 (1989); D. Litvinov *et al*., Appl. Phys. Lett. **81**, 1878 (2002)
- *Pseudopole*. T. Haberle, *at al*., New J. Phys. **14**, 043044 (2012)

on different samples: wires, rings, dots,…

Advances in Quantitative-MFM

We always deal with samples carrying out a well know magnetic field: the superconducting vortex!



A superconducting vortex always supports a magnetic quantum flux:

$$\Phi_0 = \frac{hc}{2e} = 2.07 \times 10^{-7}\, G\,cm^2$$

In the **point probe approximation**, the force exerted on the tip by the vortex :

$$F_z = qH_z = \frac{q}{\mu_0}\left(\vec{\nabla} \times \vec{A}\right)_z$$

can be used to determine q and z_q.

Advances in Quantitative-MFM

Cantilever frequency shift due to tip-V and tip-AV interaction:

$$df = -\frac{f_0}{2k}\frac{dF_z}{dz} = -\frac{f_0}{2k}\left(\frac{dF_{z,tip-V}}{dz} + \frac{dF_{z,tip-AV}}{dz}\right)$$

Force exerted by V (AV) on the magnetic tip:

$$F_{z,tip-V(AV)} = qH_z = \frac{q}{\mu_0}\left(\vec{\nabla} \times \overrightarrow{A_{V(AV)}}\right)_z$$

↓

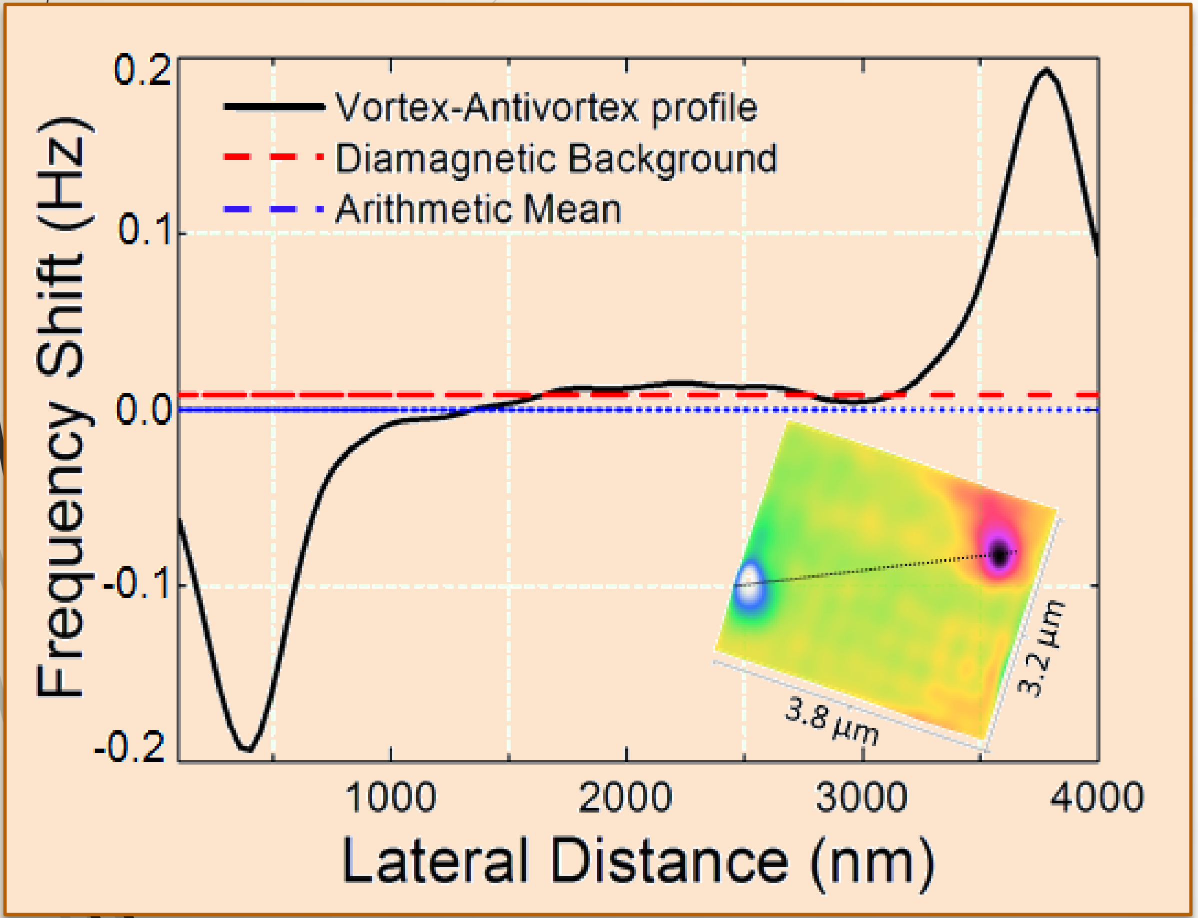
tip magnetic charge

$Z_q + Z_{lift\ scan}$

$$F_{z,tip-V(AV)} = +(-)\frac{q}{\mu_0}\int_0^{\infty} G(x)\Phi(x)e^{-xz}J_0(xr)x\,dx$$

diamagnetic contribution

Advances in Quantitative-MFM



- We nucleated a V-Av pair in Nb-200nm single layer;
- We measured the MFM signal along the V-AV profile, which shows the unbalancing in V-AV height due to the diamagnetic background;
- We fitted the measured profile by considering the contribution of V, AV and diamagnetic background to the frequency shift df;

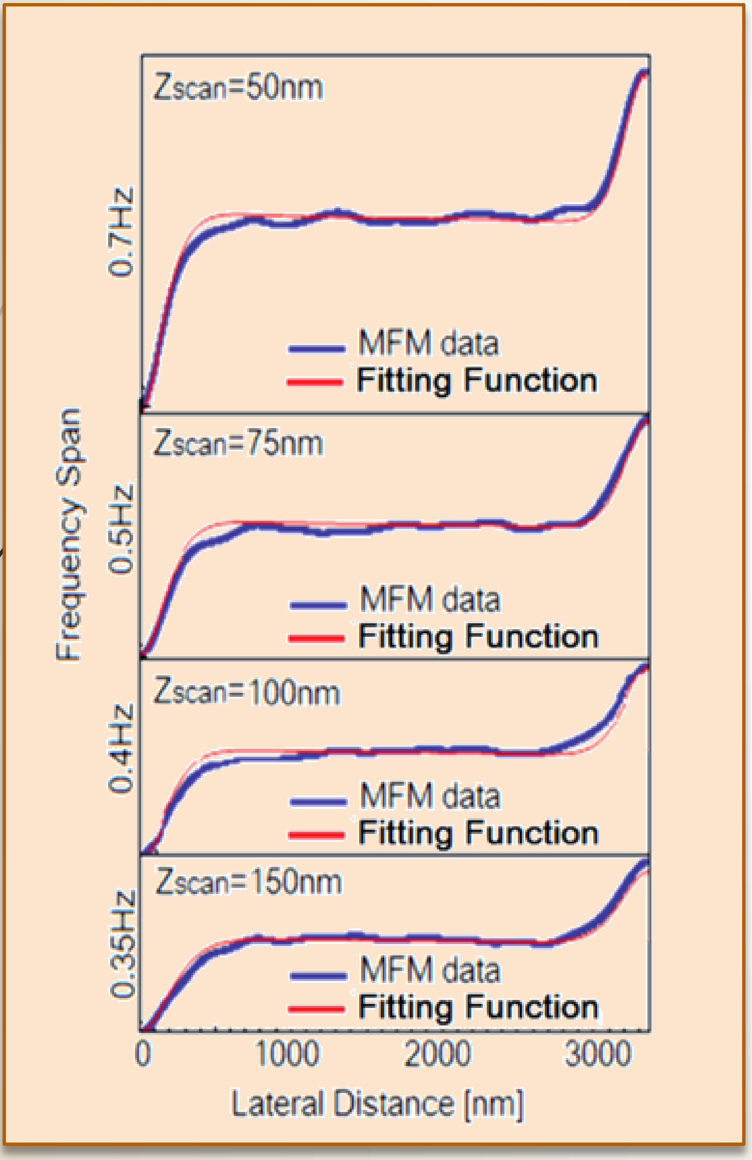
tip magnetic charge — $Z_q + Z_{lift\ scan}$

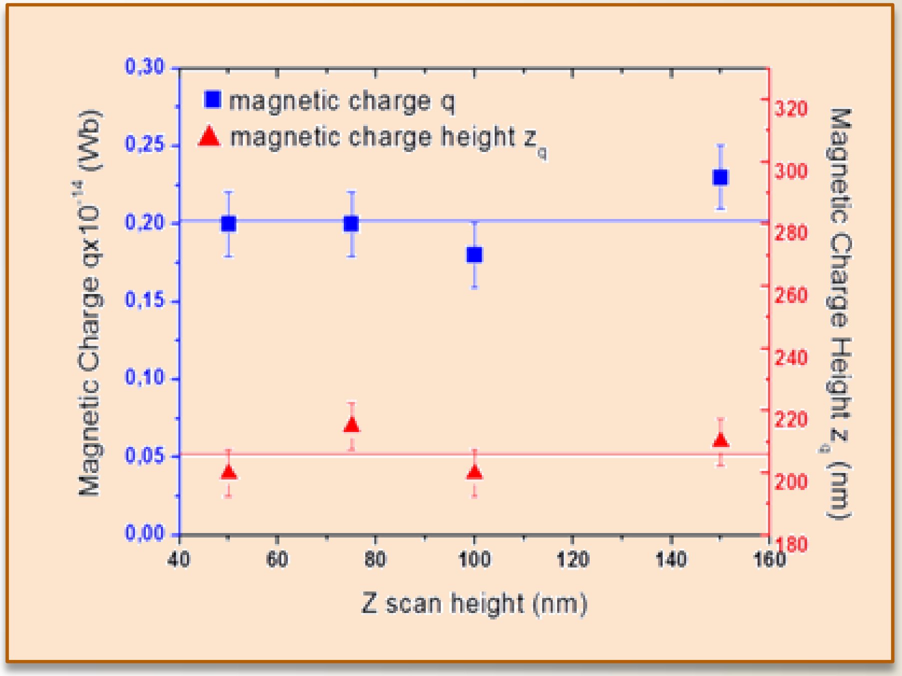
$$F_{z,tip-V(AV)} = +(-)\frac{q}{\mu_0}\int_0^{\infty} G(x)\Phi(x)e^{-xz}J_0(xr)xdx$$

diamagnetic contribution

- We extracted q and z_q as fitting parameters.

Advances in Quantitative-MFM



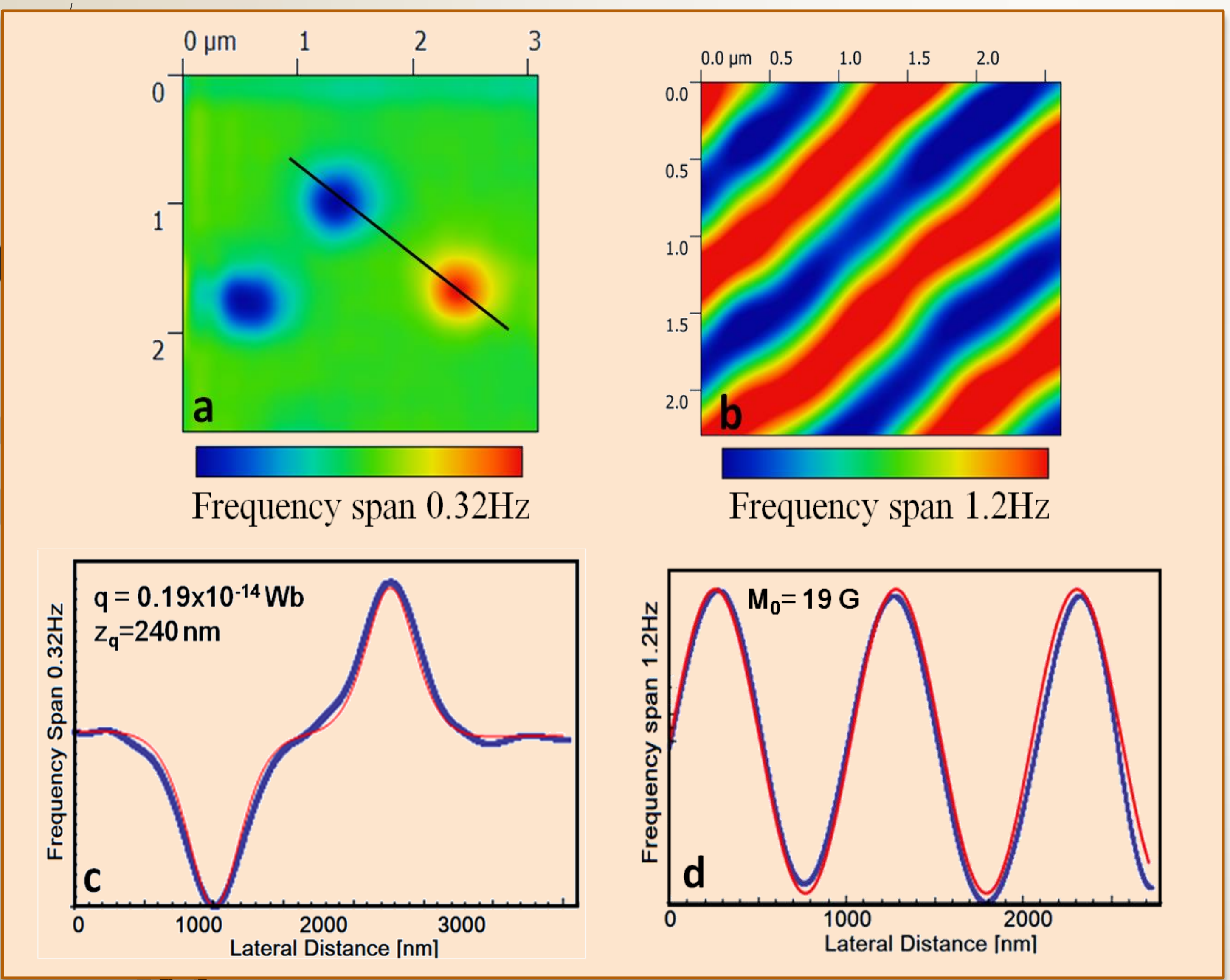


- q and z_q representative of the used MFM tip have been derived from the zero-slope linear fit, resulting in:

$$q = (0.20 \pm 0.01)10^{-14} Wb$$

$$z_q = (206 \pm 4) nm$$

Advances in Quantitative-MFM



- We characterize the MFM tip on V-AV pair in Nb;
- We used the same tip to measure a sample of Py(1µm);
- We calculated analytically the frequency shift due to Py stray field;

$$df = -\frac{f_0}{2k} q \frac{dH_{Py}}{dz}$$

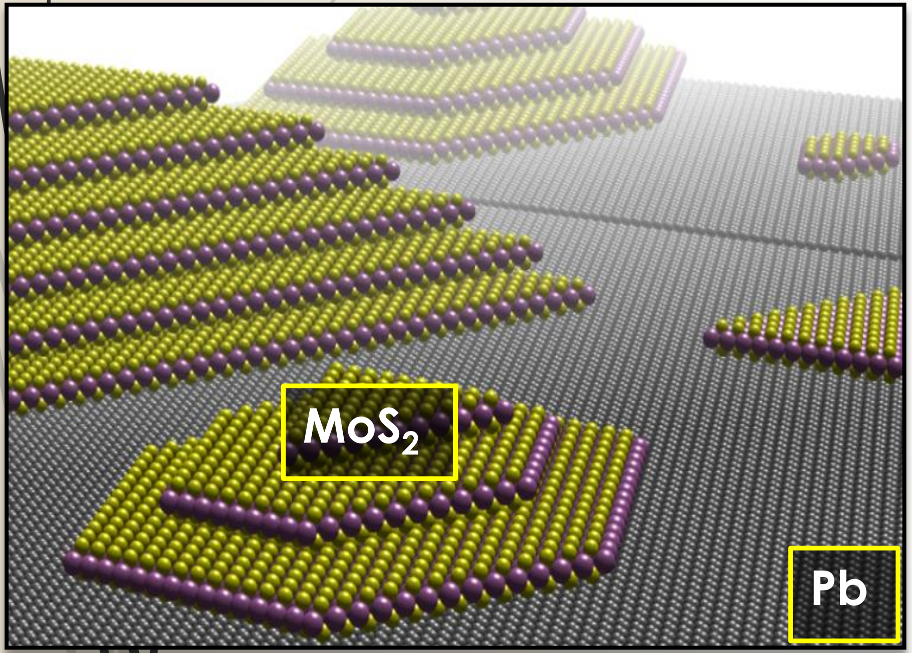
$$H_{Py} = 8M_0 \sum_k \frac{(2k+1)\left(\pi/w\right) sin\left[\left((2k+1)\left(\pi/w\right)\right)x\right]}{(2k+1)^2\left(\pi/w\right)} e^{-\frac{(2k+1)\pi}{w}z}$$

- We fit Py magnetic signal by keeping M_o as fitting parameters and we found:

$$M_0(Py - 1\mu m) = 19G$$

Electrically coupled S/F systems

We studied **electrically coupled S/F** systems by performing LT-STM experiments @ Physics Department of Temple University (Philadelphia, USA)

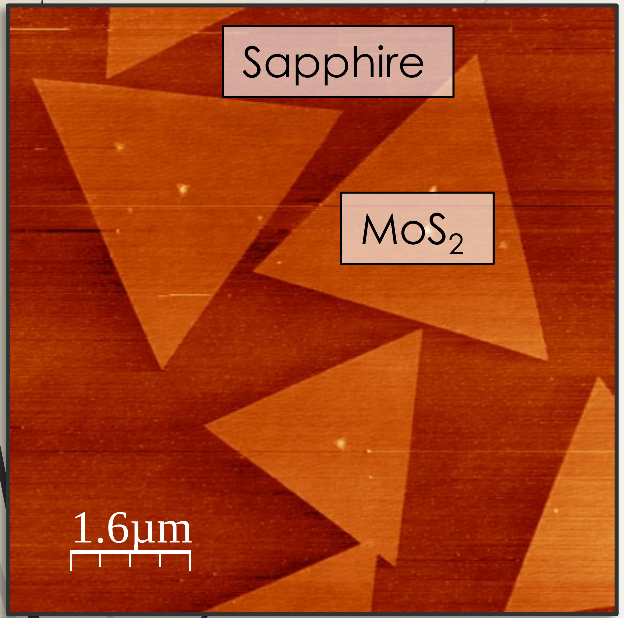


We aimed at investigating **inverse proximity effect** between a superconductor (Pb) and the ferromagnetic localized states at the edge of MoS_2 monolayer islands.

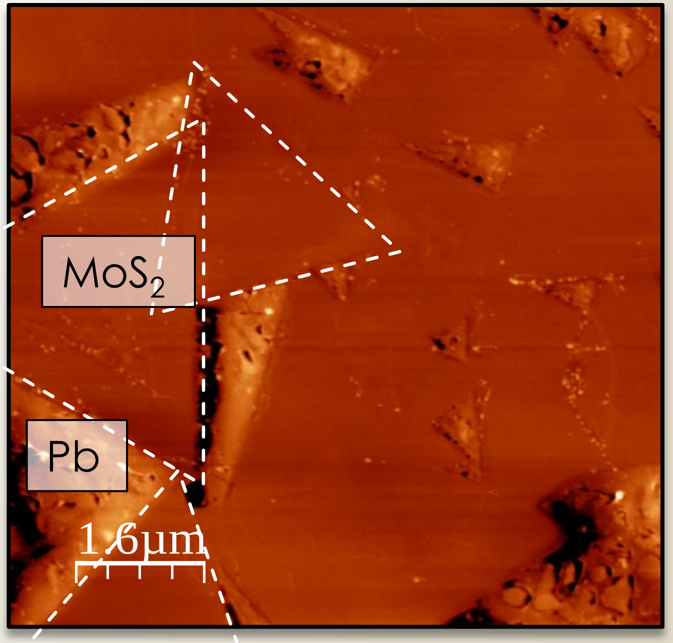
We found something different but….

….we haven't got to the top yet!

Sample preparation

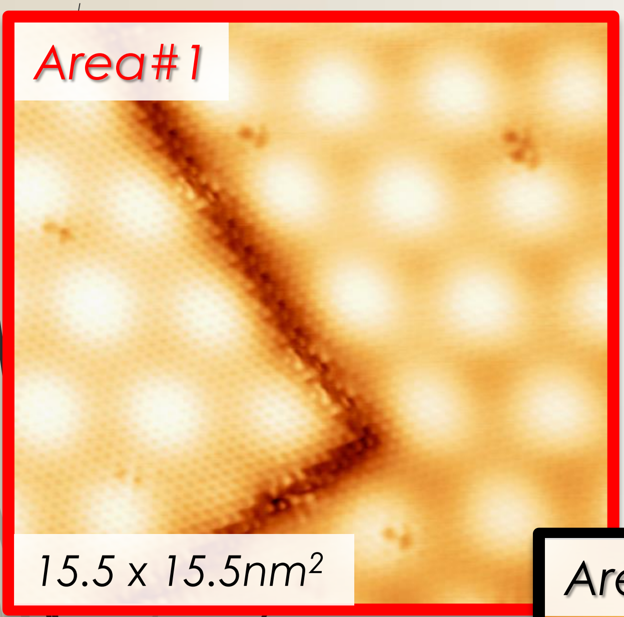


- We grew CVD-MoS_2 islands on sapphire substrate;
- We brought the samples in a UHV-chamber, annealed it and grew more than 300nm of Pb;
- We cleaved the bilayer from the bottom (in-situ) by pealing off the substrate (sapphire);

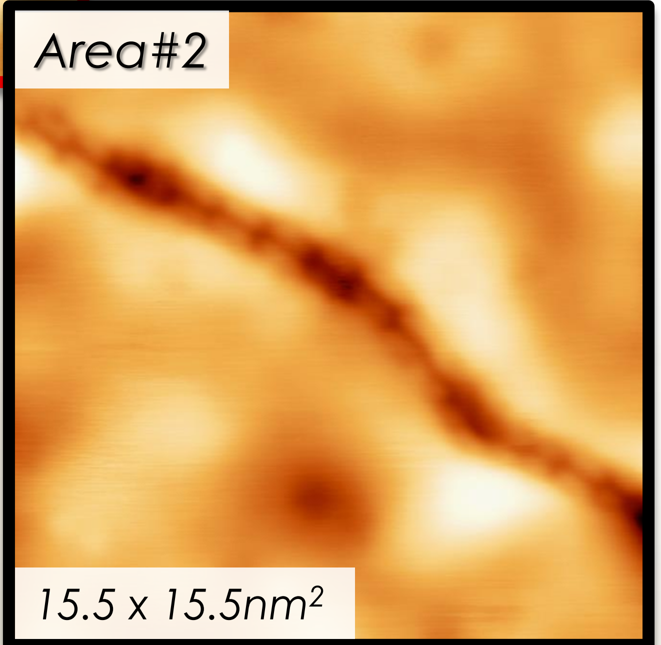


- We performed STM measurements on the bottom side of the so-grown bilayer.

Semiconducting vs Metallic MoS_2



MoS_2 lattice parameter 3.22Å



We found two possible topographies:

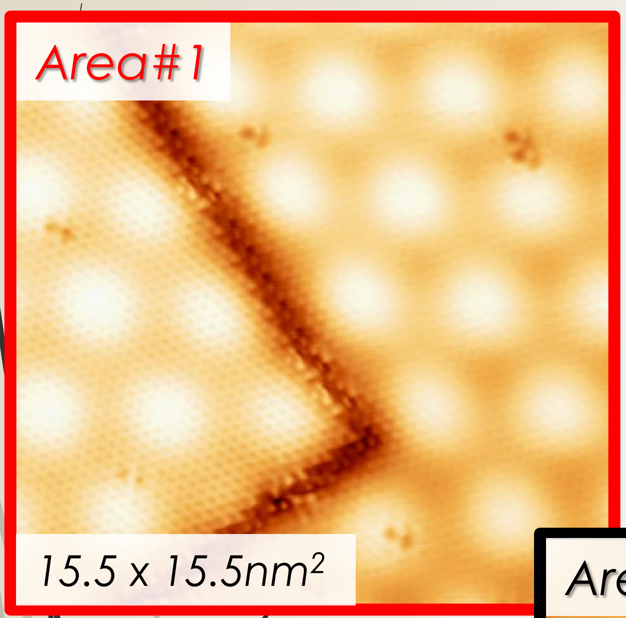
- **Area#1**: very good atomic resolution of MoS_2 and Moirè pattern

Good electric coupling with Pb underneath

- **Area#2**: no good resolution of MoS_2 and no Moire pattern

Bad electric coupling with Pb underneath (almost free standing)

Semiconducting vs Metallic MoS_2



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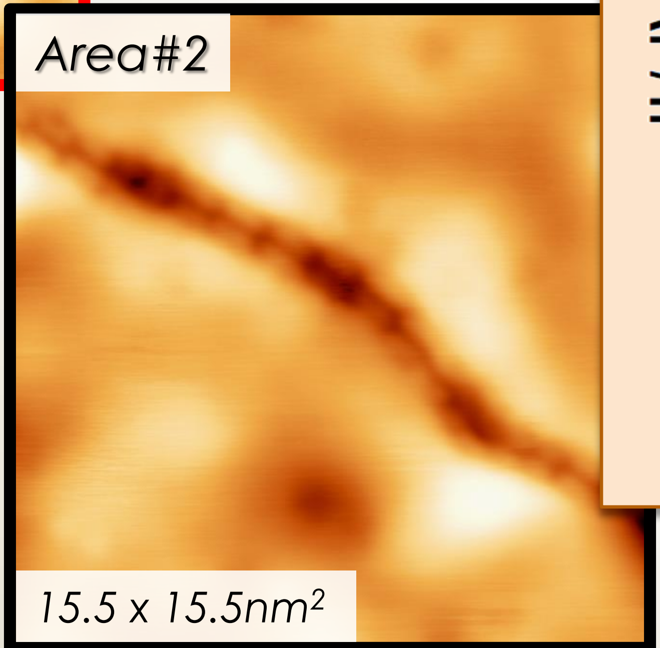
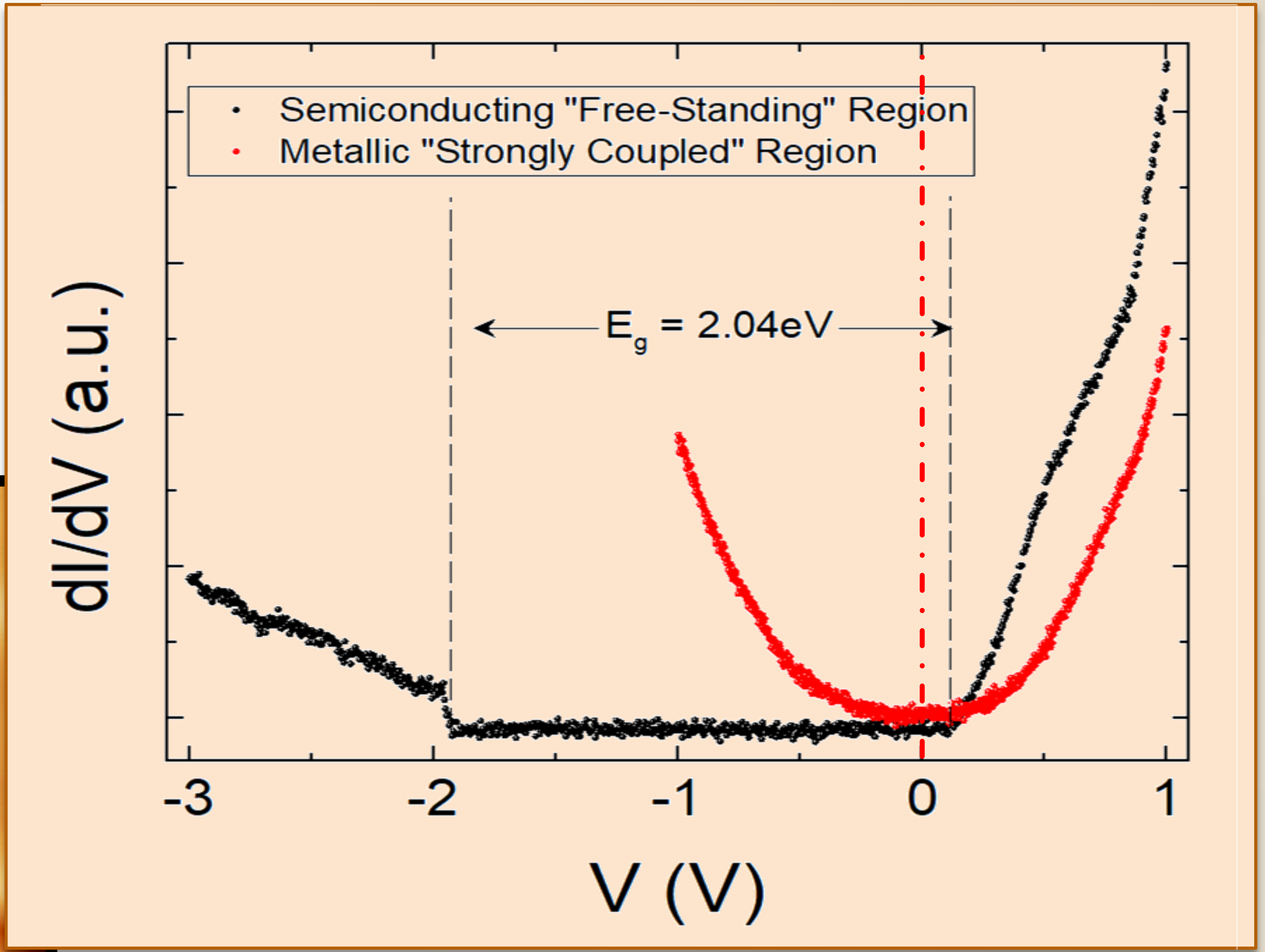
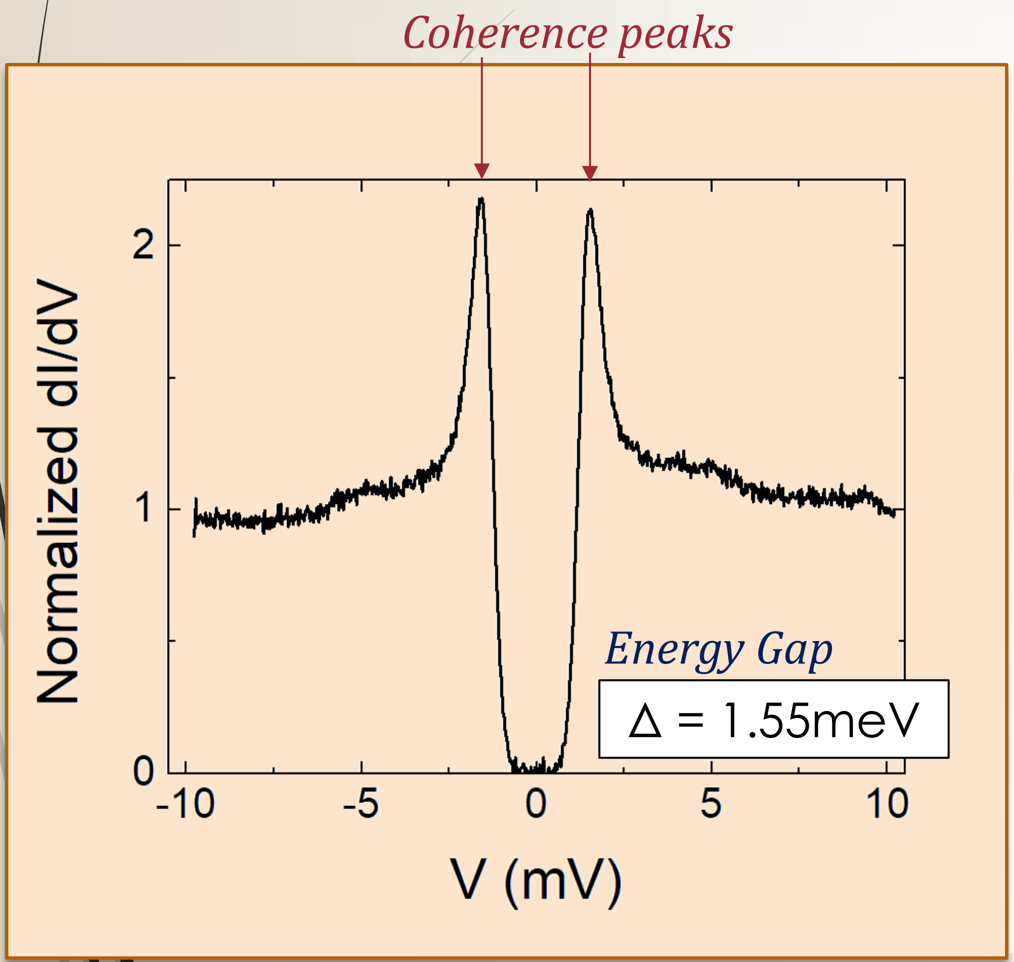
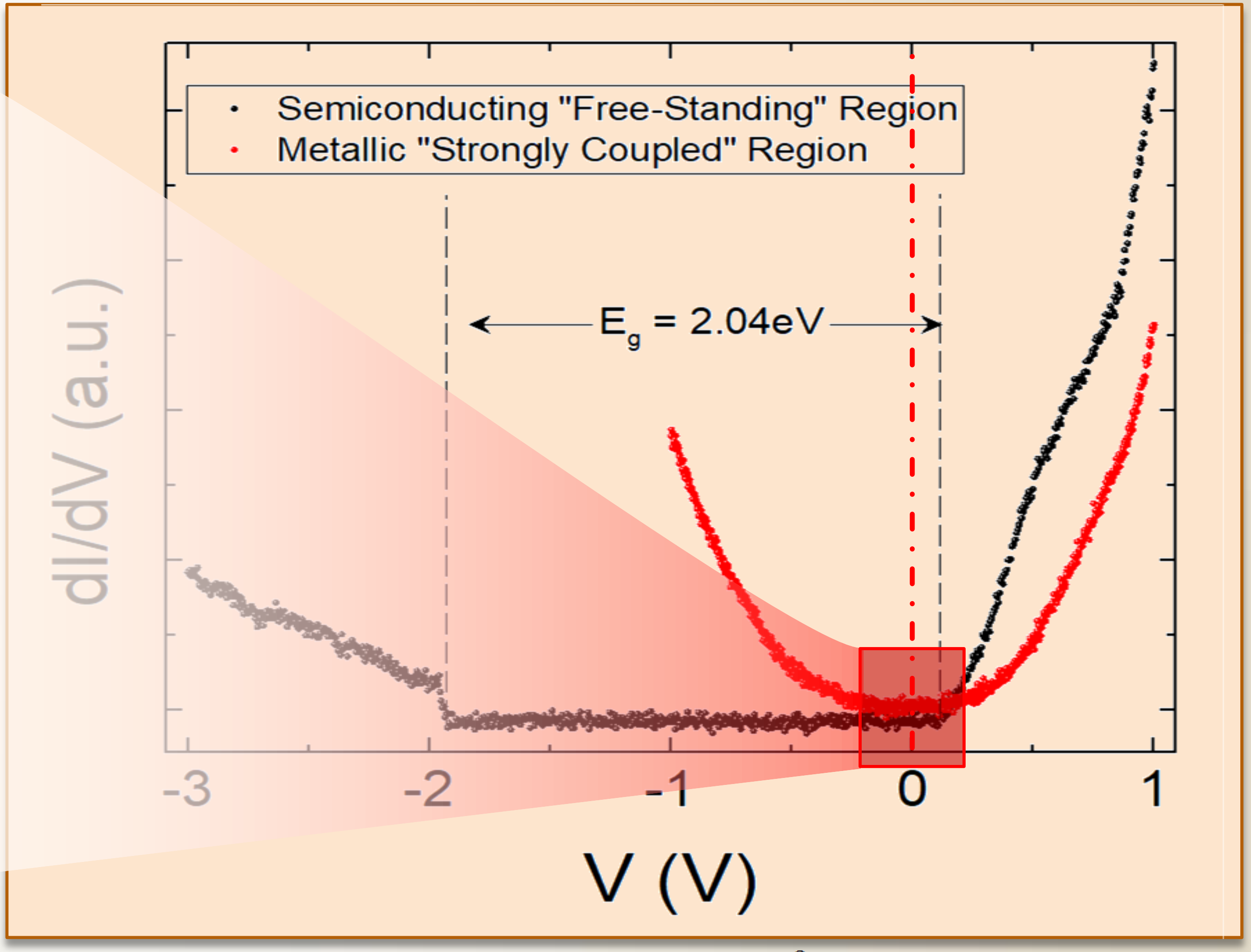




$$I \sim \frac{4\pi e}{\hbar} |M|^2 \rho_t(0) \int_{-eV}^{0} \rho_s(\varepsilon)\, d\varepsilon$$

Semiconducting vs Metallic MoS_2





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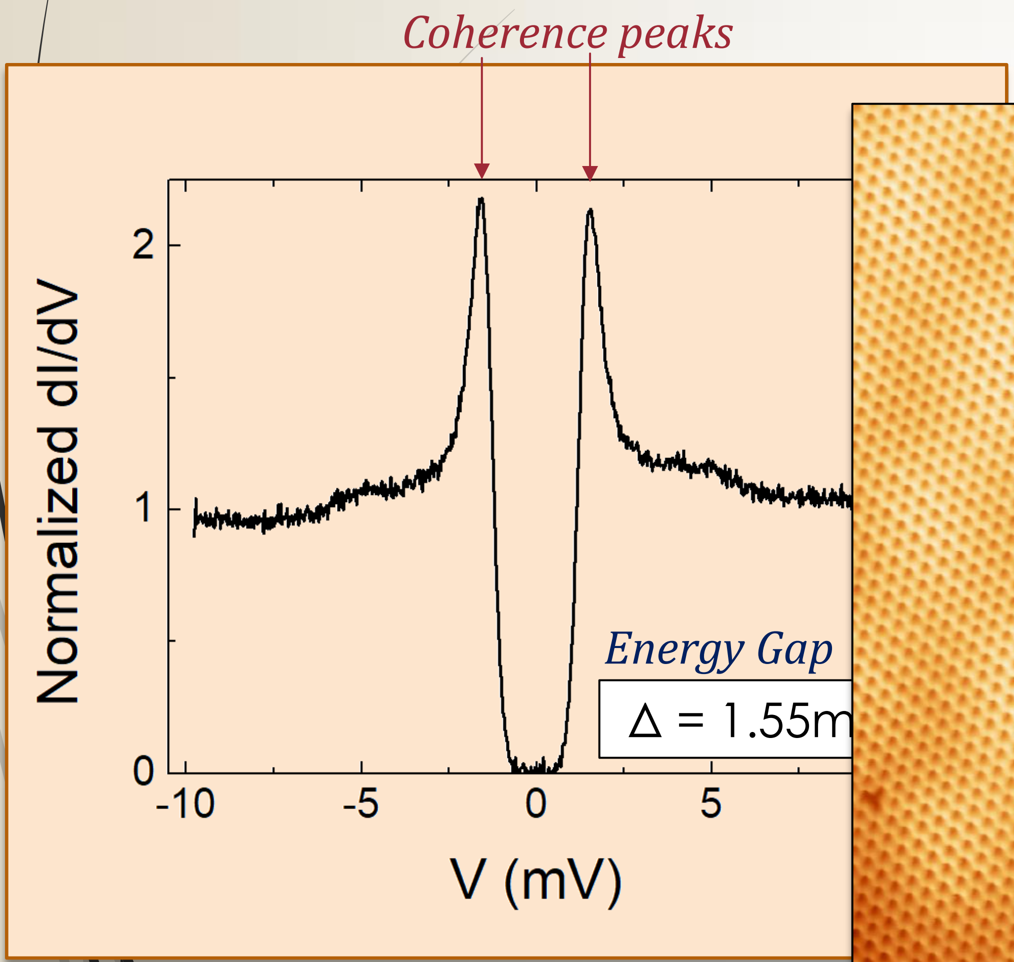
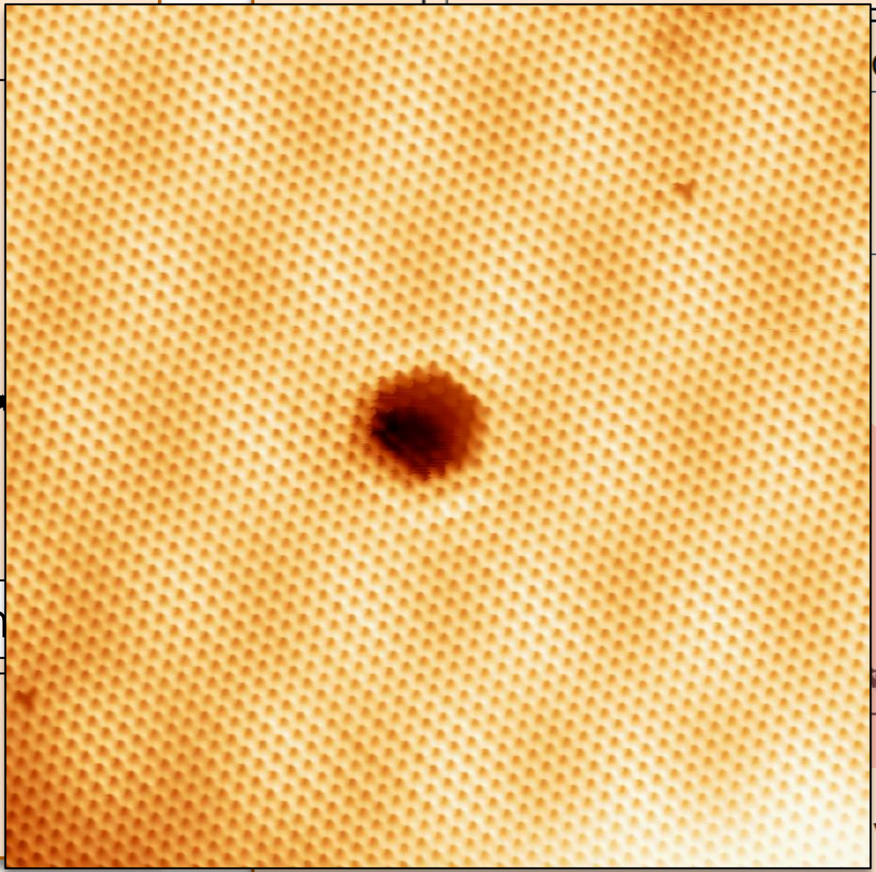
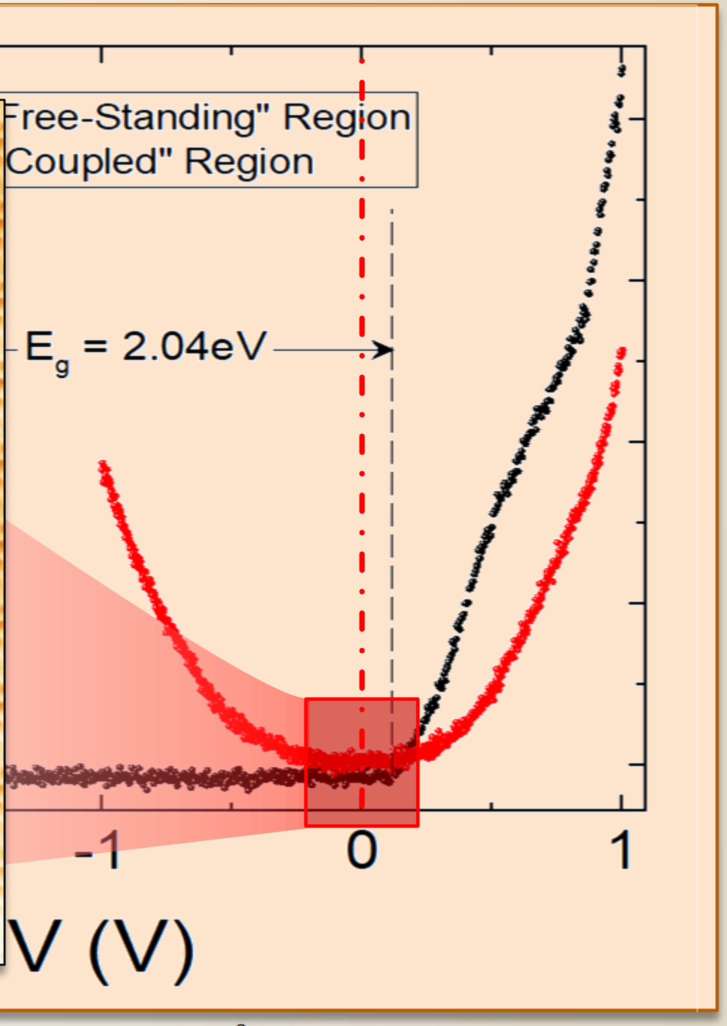
Semiconducting vs Metallic MoS_2

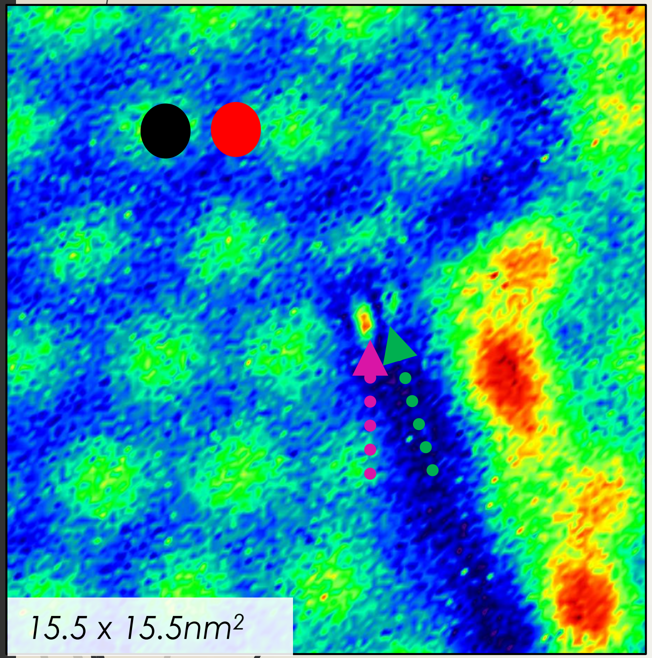


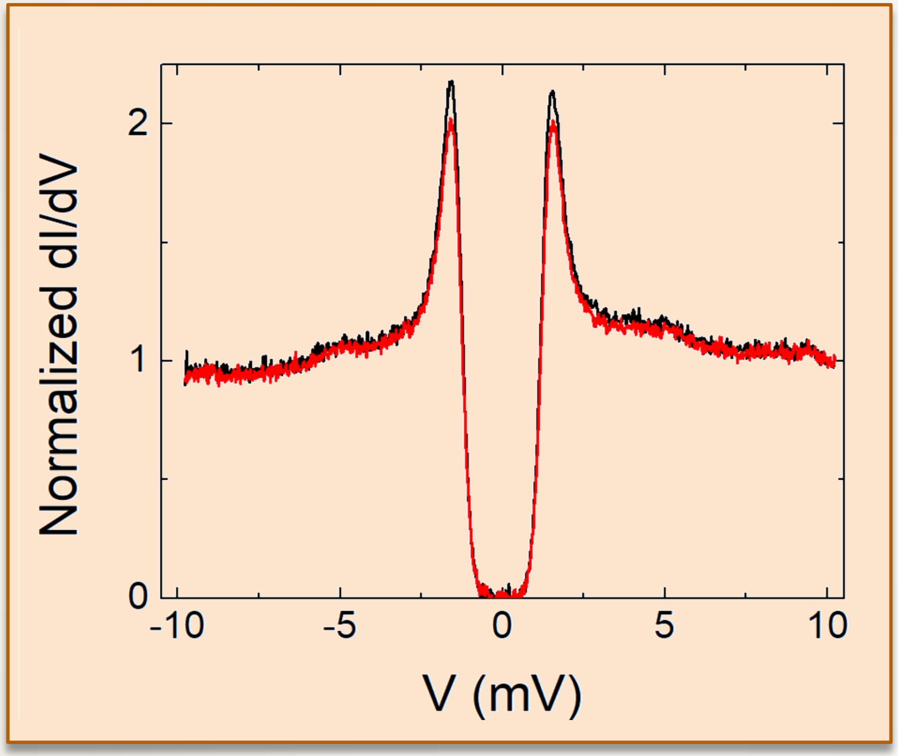


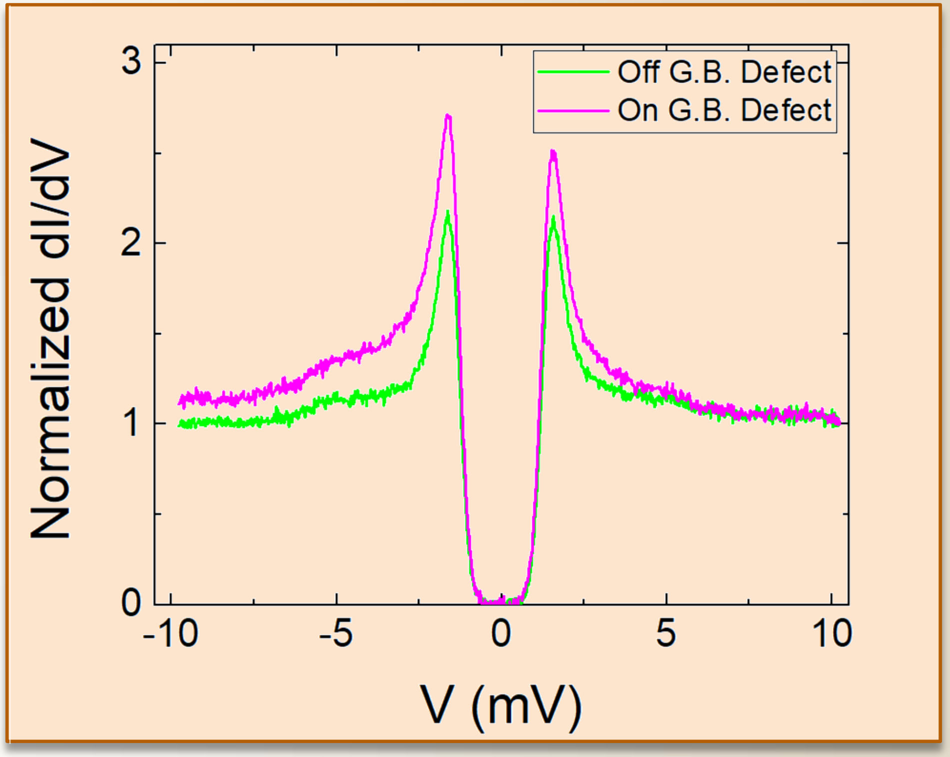


$$I \sim \frac{4\pi e}{\hbar} |M|^2 \rho_t(0) \int_{-eV}^{0} \rho_s(\varepsilon)\, d\varepsilon$$

Spectroscopy on Moirè pattern and defects





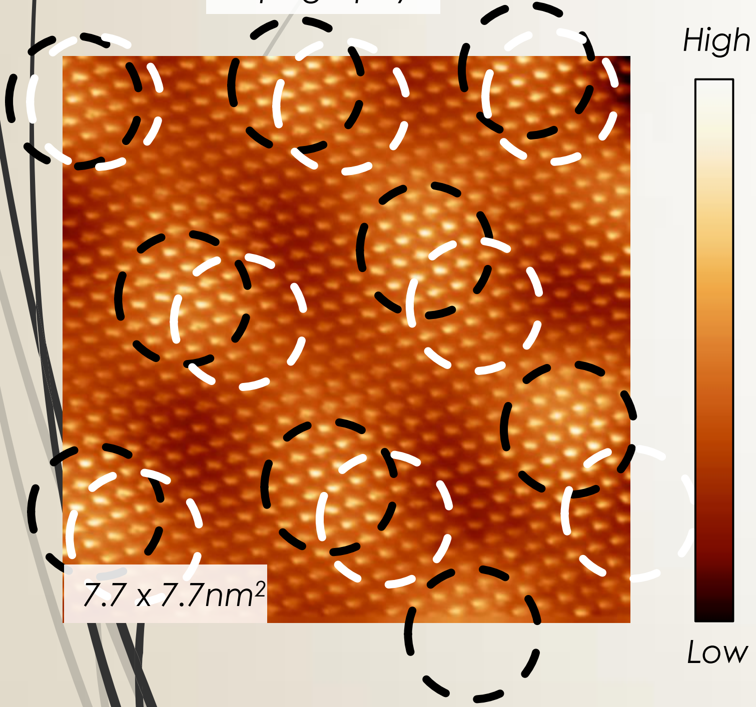


- Change in coherence peak height across the green spots
- Change in coherence peak height across the defects

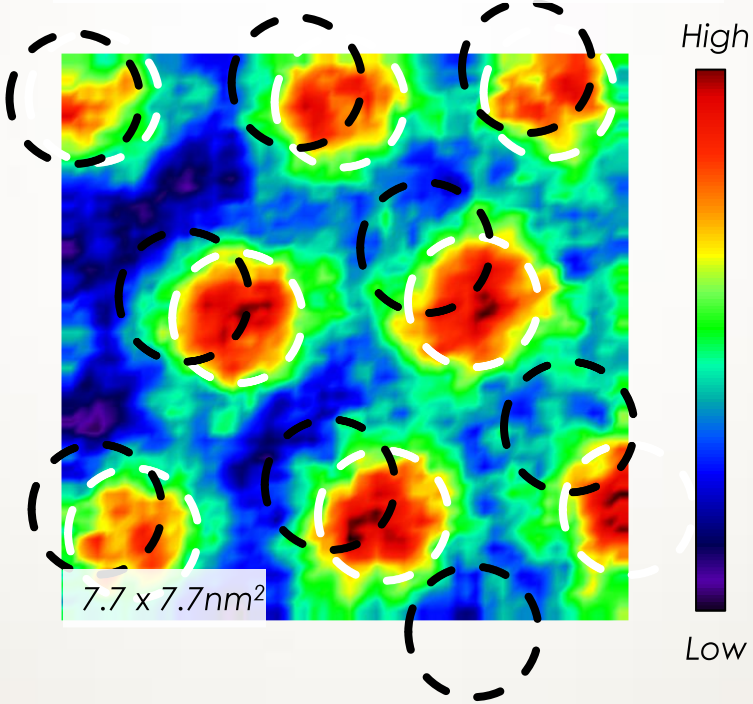
Moirè pattern and grain boundary

- If we acquire simultaneous topography and conductance maps at the coherence peak we see a mismatch of the topographic and conductance maxima

Topography



Coherence Peak Conductance Map



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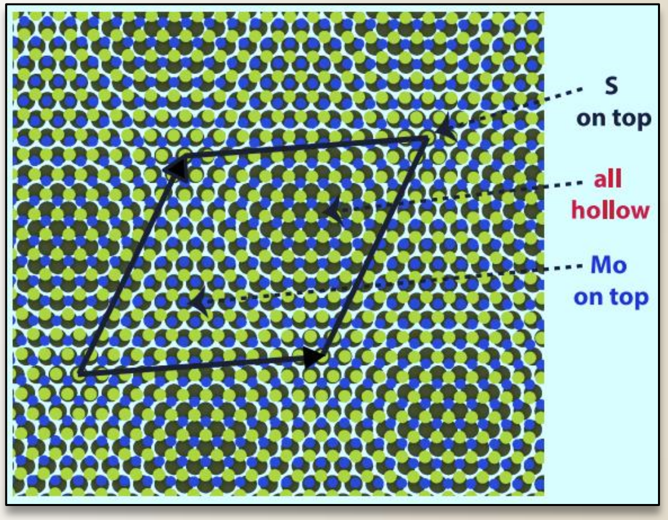
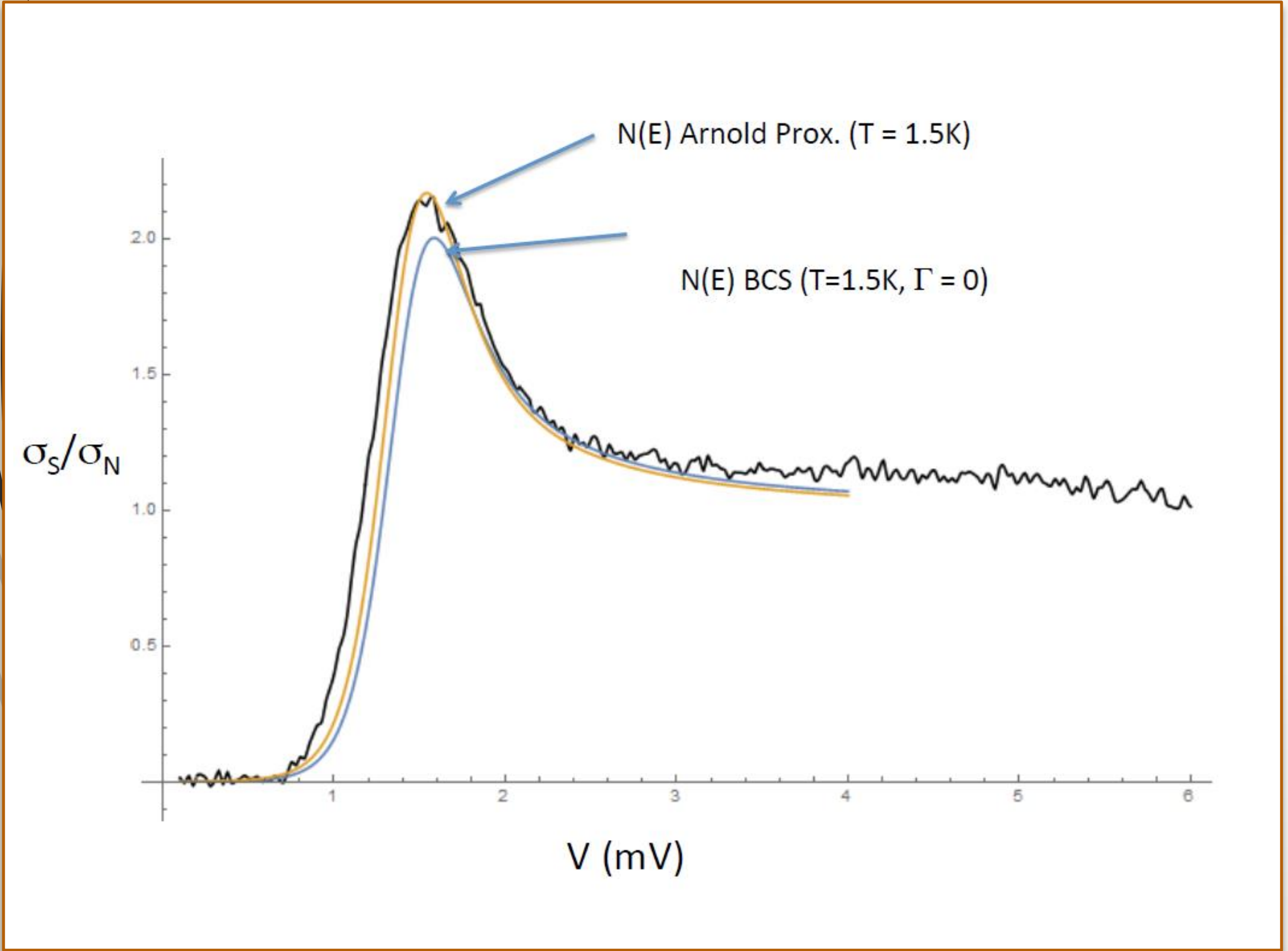


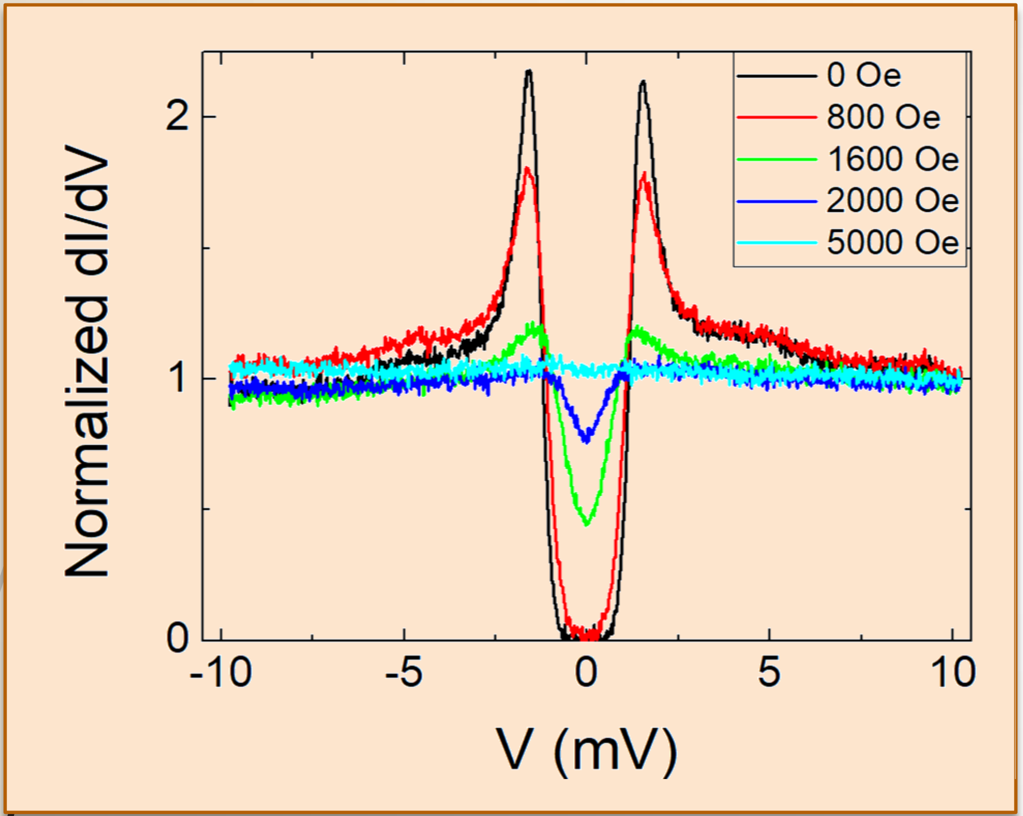
Fit of Spectroscopy

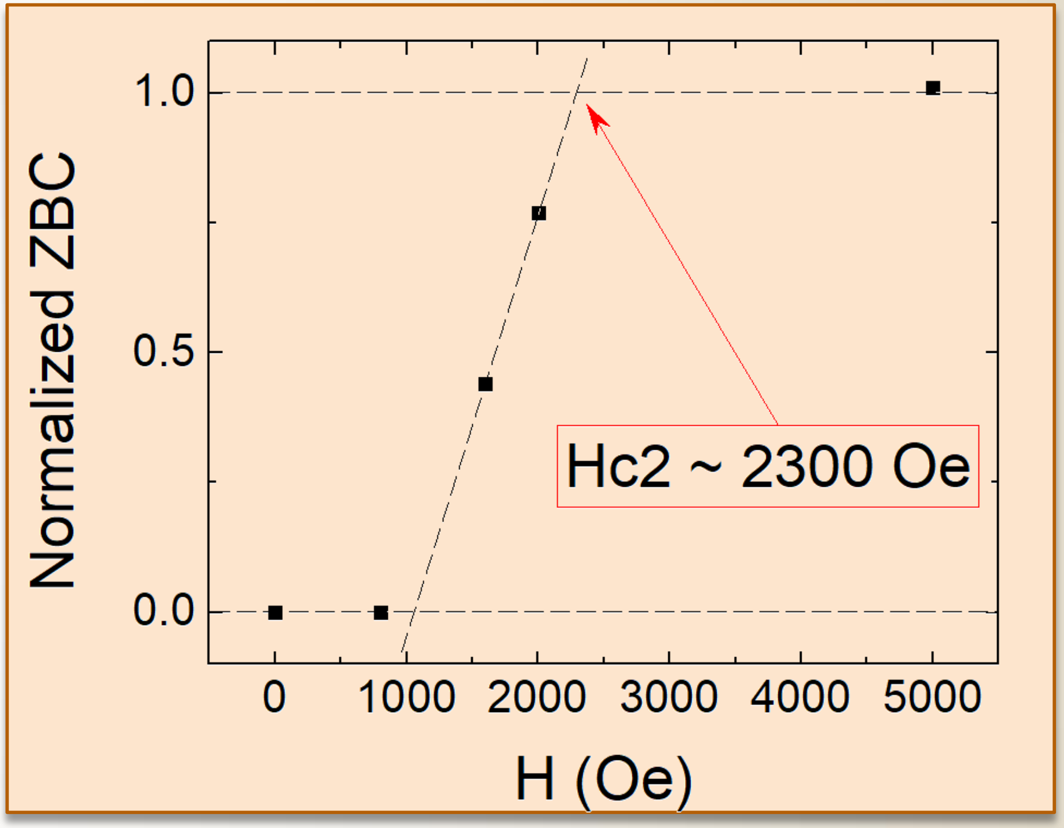


- If we fit the LDOS with standard BCS theory, we are not able to reproduce the coherence peak height;
- If we fit the LDOS with a model taking into account the **proximity** between a **SC** and a **metal**, it is almost perfect on the peak height.

Does MoS_2 monolayer become metallic and then superconductor when proximized to Pb?

Magnetic Field Dependence





- We observed the suppression of superconductivity around 2300 Oe;
- The critical field estimated from ZBC vs H is higher than the one in single-Pb.

Typical feature of proximized structures!

Conclusions

- **Magnetically coupled S/F** have been studied to get out insights into vortex nucleation and pinning at the nanoscale;

- **Electrically coupled S/F** are studied aiming at finding triplet superconductivity but, to date, performed STM experiments gave indications of possible metallicity of MoS_2 monolayer, when coupled to Pb, and its proximation to SC below Pb T_c.

Thank you for the attention!!!