Scanning tunneling microscopy and its application in studying quantum materials

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Outline

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- Introduction for STM: principles and instrumentation
- Application of STM in the study of superconductivity
- Inelastic tunneling spectroscopy, spin-resolved STM, time-resolved STM

STM principles: the concept of tunneling

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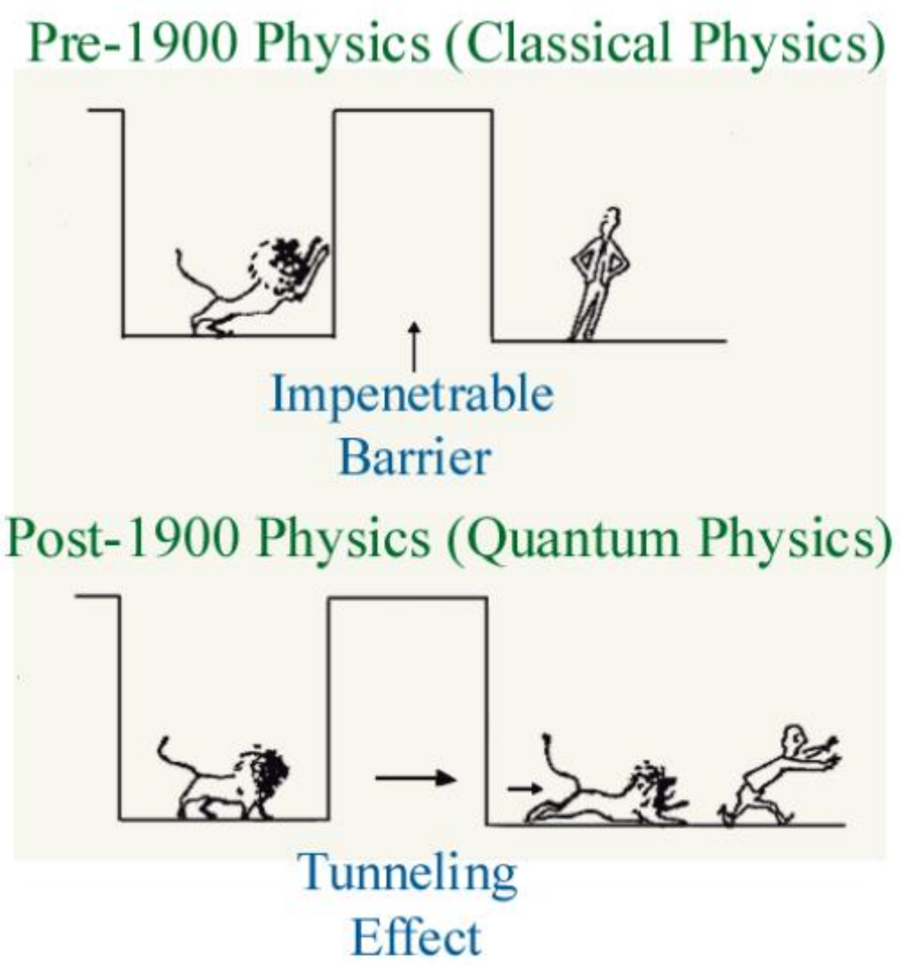
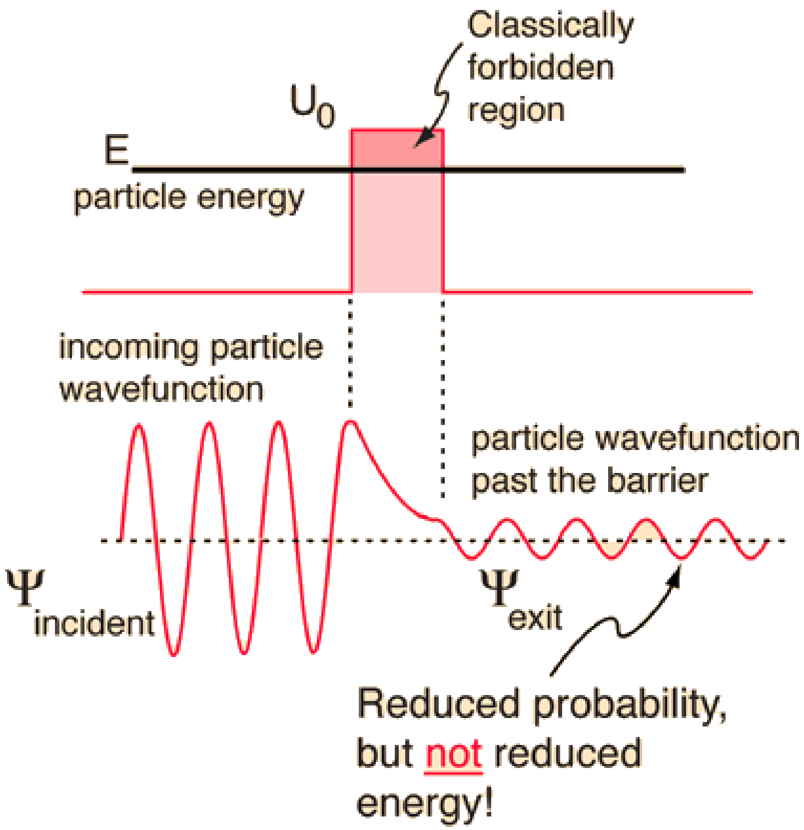




$$\frac{-\hbar^2}{2m}\frac{\partial^2\psi(x)}{\partial x^2} = (E - U_0)\psi(x)$$

$$T \approx e^{-2\alpha d}$$

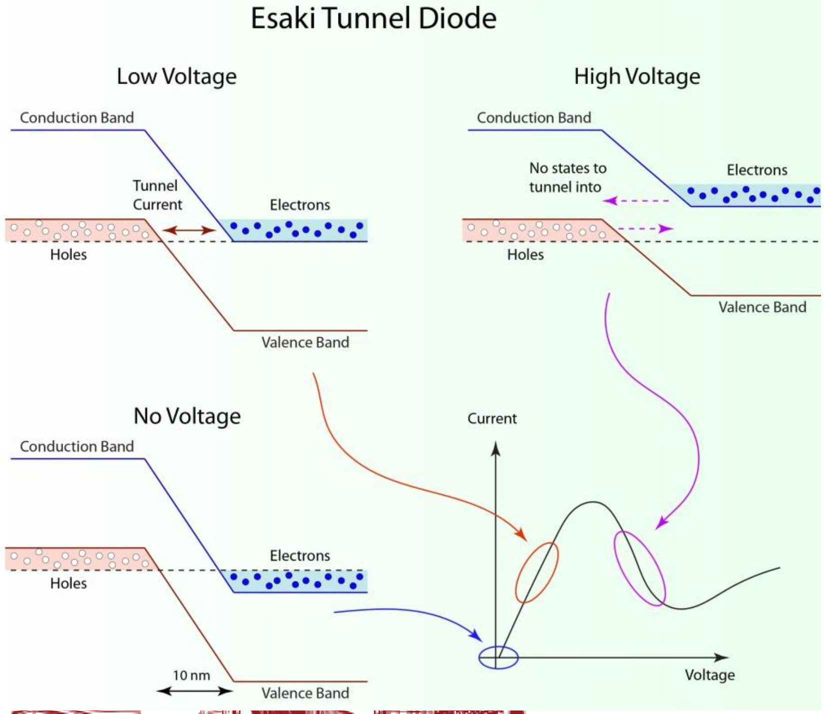
where

$$\alpha = \sqrt{\frac{2m(U_0 - E)}{\hbar^2}}$$

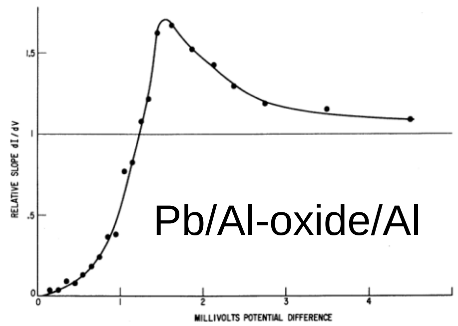
Solid-state tunneling

- **Solid-state electron tunneling**

Leo Esaki

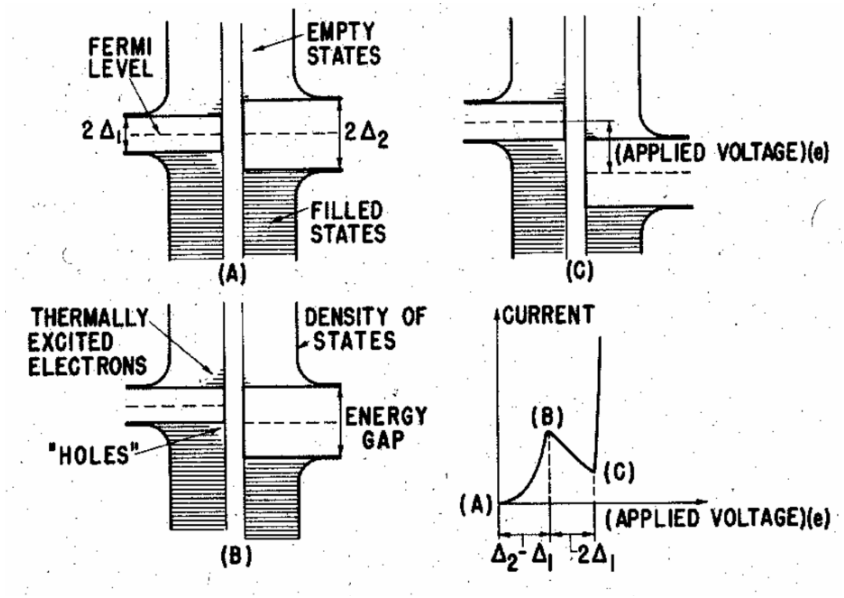


- **Superconducting tunneling**

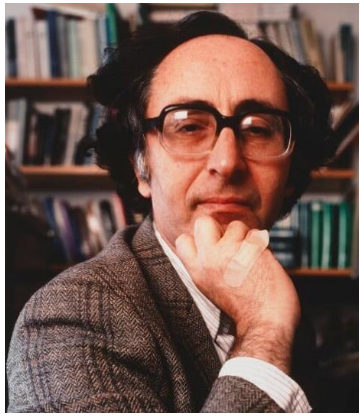


Superconducting gap of lead (at 1.6K)

Ivar Giaever



- **Josephson effect**



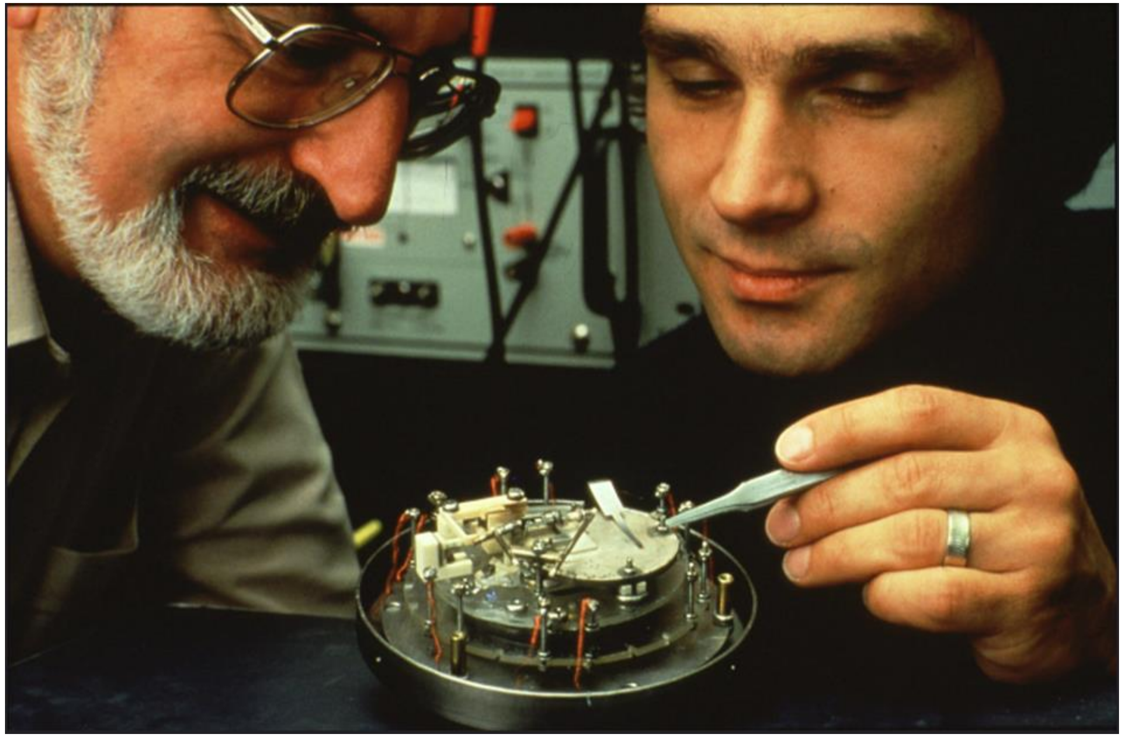
Brian Josephson

DC effect:
Supercurrent can flow through insulating layers with no resistance.

AC effect:
With an applied voltage, V, across the insulating layer, the junction would radiate at a frequency of 2eV/h.

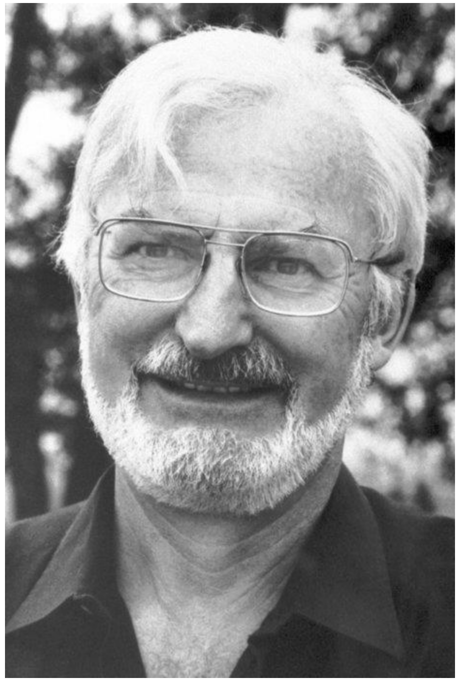
The birth of STM

- **Invented by Gerd Binnig and Heinrich Rohrer in 1981**

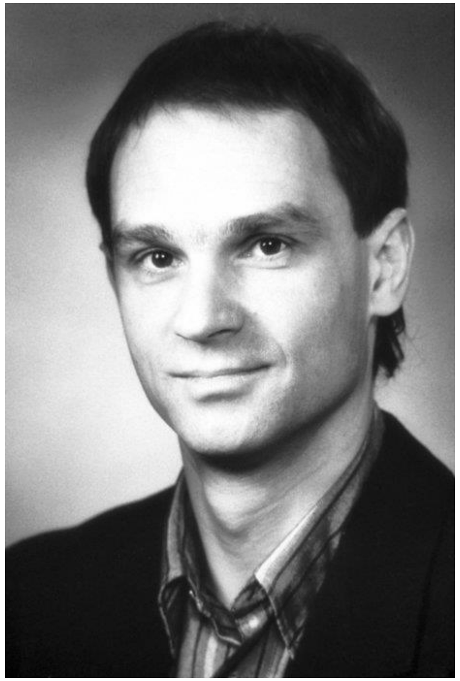


Heinrich Rohrer and Gerd Binnig
IBM Research – Zurich

The Nobel Prize in Physics 1986



Heinrich Rohrer
Prize share: 1/4

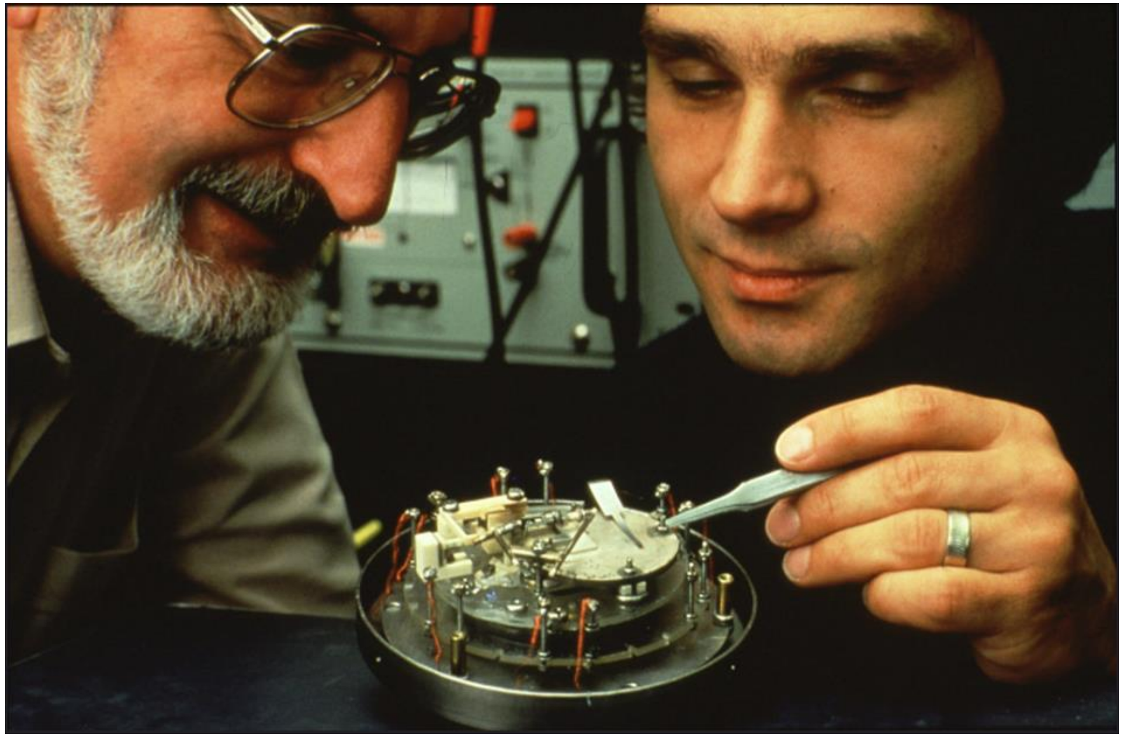


Gerd Binnig
Prize share: 1/4

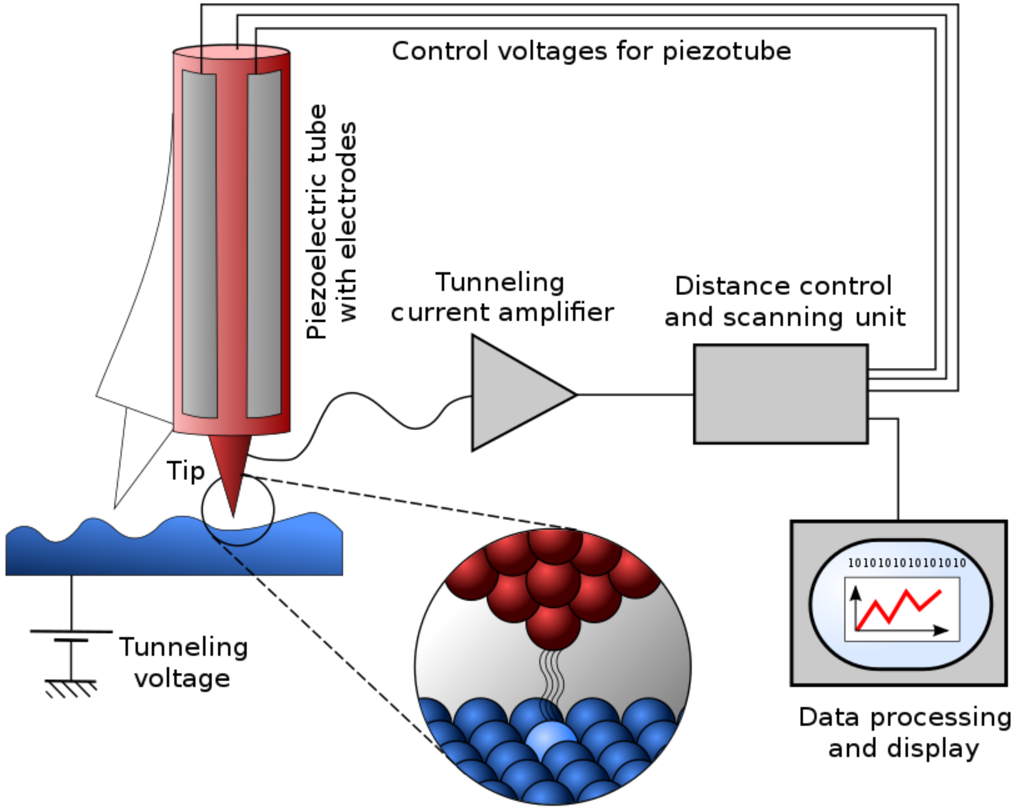
"for their design of the scanning tunneling microscope"

The birth of STM

- **Invented by Gerd Binnig and Heinrich Rohrer in 1981**

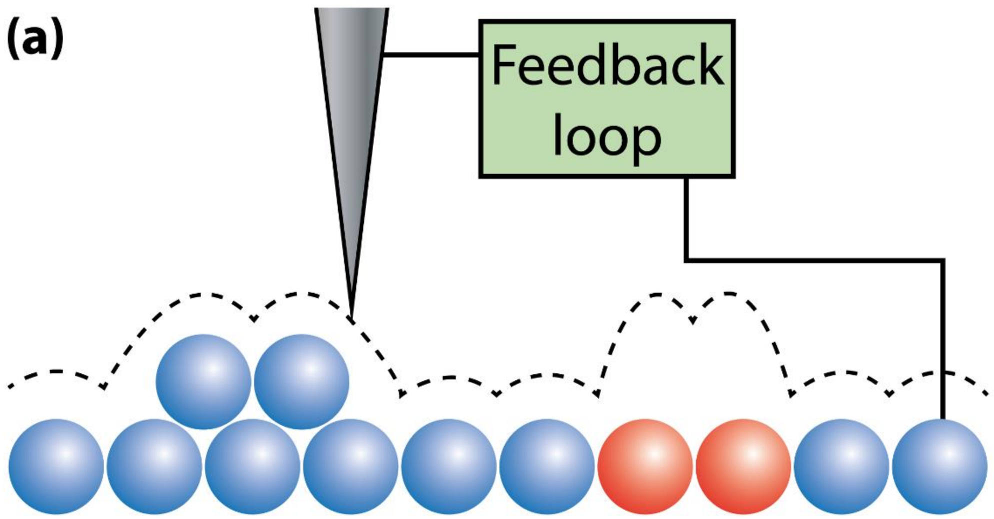


Gerd Binnig and Heinrich Rohrer
IBM Research – Zurich



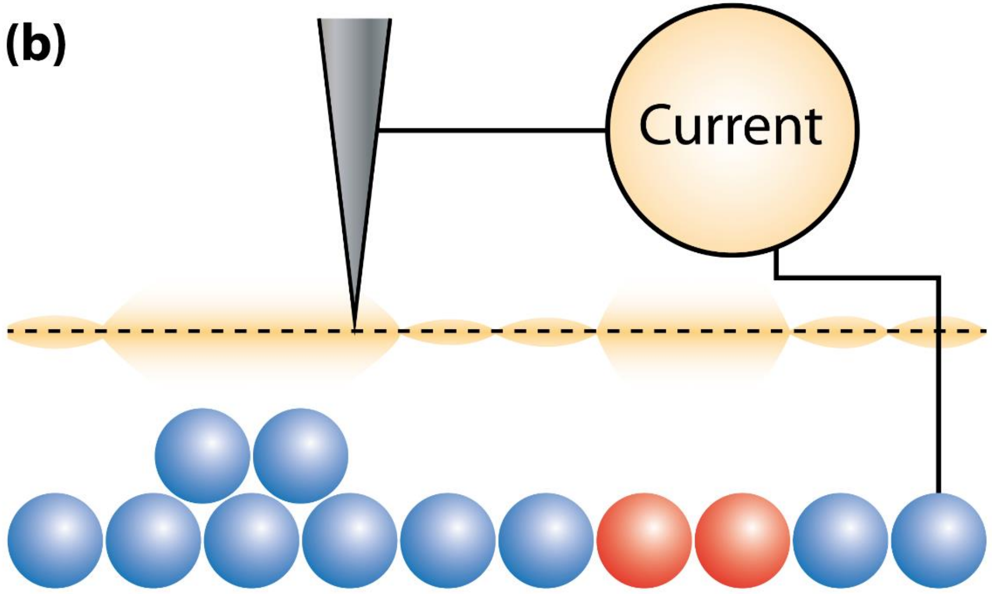
Scan mode of STM

- **Constant current mode**



➢ Feedback keeps current as constant
➢ The mostly used mode

- **Constant height mode**



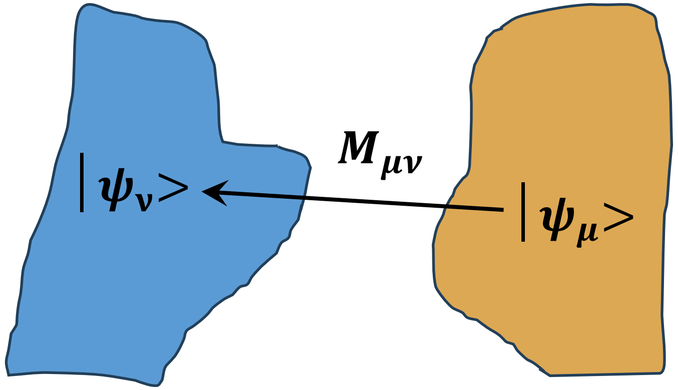
➢ Feedback is disabled
➢ Only suitable for very flat surface and low thermal drift case

Bardeen's theory of tunneling

- Tip and sample are considered as two electrodes
- Transmission rate calculated by perturbation
- Neglect tip-sample interaction

- Tunneling matrix: $$M_{\mu\nu} = \frac{\hbar^2}{2m} \int d\vec{S} \cdot (\psi_\mu^* \vec{\nabla} \psi_\nu - \psi_\nu \vec{\nabla} \psi_\mu^*)$$

$\boldsymbol{M_{\mu\nu}}$ is the tunneling matrix element between states $\boldsymbol{\psi_\mu}$ of the tip and $\boldsymbol{\psi_\nu}$ of the sample surface



Bardeen's theory of tunneling

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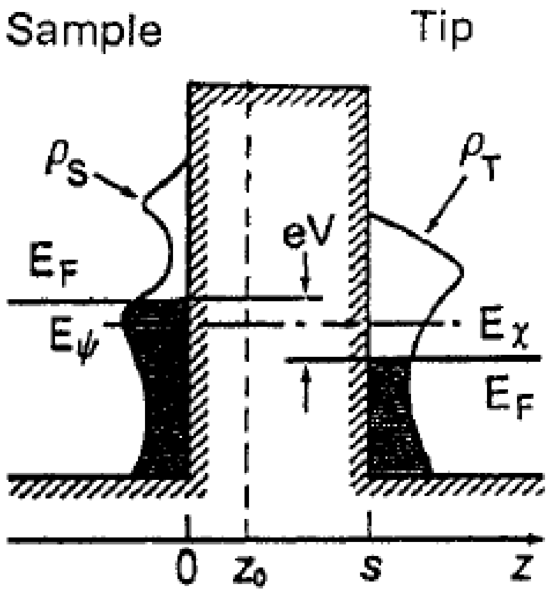

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$\boldsymbol{M_{\mu\nu}}$ is the tunneling matrix element between states $\boldsymbol{\psi_\mu}$ of the tip and $\boldsymbol{\psi_\nu}$ of the sample surface

When Bias Voltage is applied, the net tunneling current can be described as:

$$I = \frac{-4\pi e}{\hbar}\int_{-\infty}^{+\infty} |M|^2 \rho_s(\varepsilon)\,\rho_t(\varepsilon - eV)\{f(\varepsilon - eV)[(1 - f(\varepsilon)] - f(\varepsilon) * [(1 - f(\varepsilon - eV)]\}d\varepsilon$$

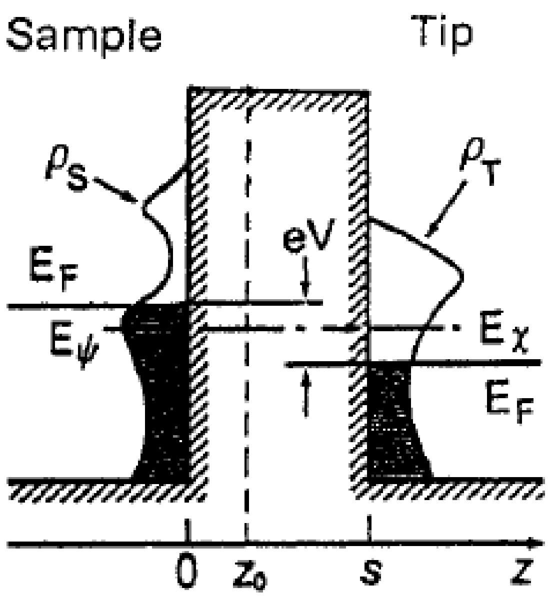
$$= \frac{-4\pi e}{\hbar}\int_{-\infty}^{+\infty} |M|^2 \rho_s(\varepsilon)\,\rho_t(\varepsilon - eV)[f(\varepsilon - eV) - f(\varepsilon)]d\varepsilon$$

Where $|M|^2$ is the tunneling Matrix element, which is proportional to the overlap of tip and sample wave functions, ρ is density of states (DOS) of sample or tip, f(x) is the Fermi function.

Bardeen's theory of tunneling

Consider T = 0 K and a simple metal tip with a "flat" DOS:

$$I \approx -\frac{4\pi e}{\hbar}\rho_t(0)\int_0^{+eV} |M|^2 \rho_s(\varepsilon)\mathrm{d}\varepsilon$$



If we further assume the tunneling matrix is constant, at T = 0 K:

$$I \propto |M|^2 \int_0^{+eV} \rho_s(\varepsilon)\,\mathrm{d}\varepsilon \quad \Rightarrow \quad \frac{dI}{dV} \propto \rho_s(\varepsilon)$$

When T > 0 K:

$$\frac{dI}{dV} \propto \int_{-\infty}^{+\infty} \rho_s(\varepsilon) f'(\varepsilon + eV)\mathrm{d}\varepsilon$$

- Where *f'* is the derivative of the Fermi function.
- Therefore the tunneling conductance measures the thermally smeared LDOS !
- Other factors can also broaden d*I*/d*V* spectrum, such as electrical (RF) noise.

Bardeen's theory of tunneling

- Tunneling matrix

$$M_{\mu\nu} = \frac{\hbar^2}{2m} \int d\vec{S} \cdot (\psi_\mu^* \vec{\nabla} \psi_\nu - \psi_\nu \vec{\nabla} \psi_\mu^*)$$

$\boldsymbol{M_{\mu\nu}}$ is the tunneling matrix element between states $\boldsymbol{\psi_\mu}$ of the tip and $\boldsymbol{\psi_\nu}$ of the sample surface

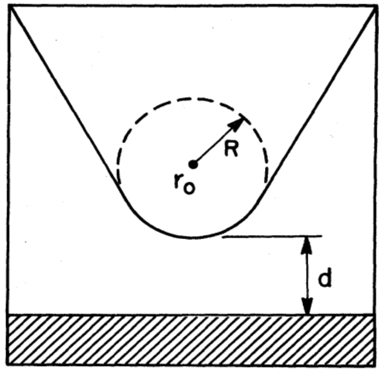
- We model the tip as a locally spherical potential well where it approaches nearest to the sample surface

$$M_{\mu\nu} \propto \psi_\nu(\vec{r}_0) \qquad |\psi_\nu(\vec{r}_0)|^2 \propto e^{-2\kappa(R+d)}$$

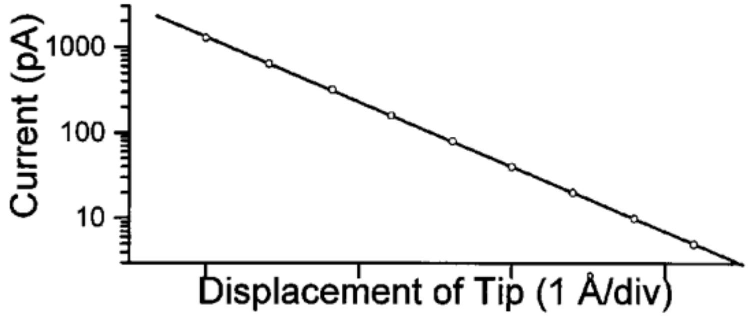
$$I \propto |M|^2 \propto e^{-2\kappa(R+d)} \qquad \kappa = \sqrt{\frac{2m\varphi}{\hbar^2}}$$

Tunneling current decays exponentially as increasing the tip-sample distance

Tersoff-Hamann Model



Tersoff *et al.* *PRL* 50, 1998 (1983)



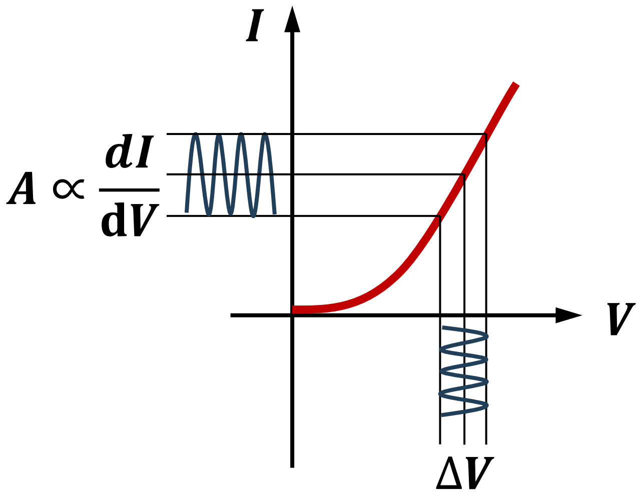
Pan *et al.* *APL* 73, 2992 (1998)

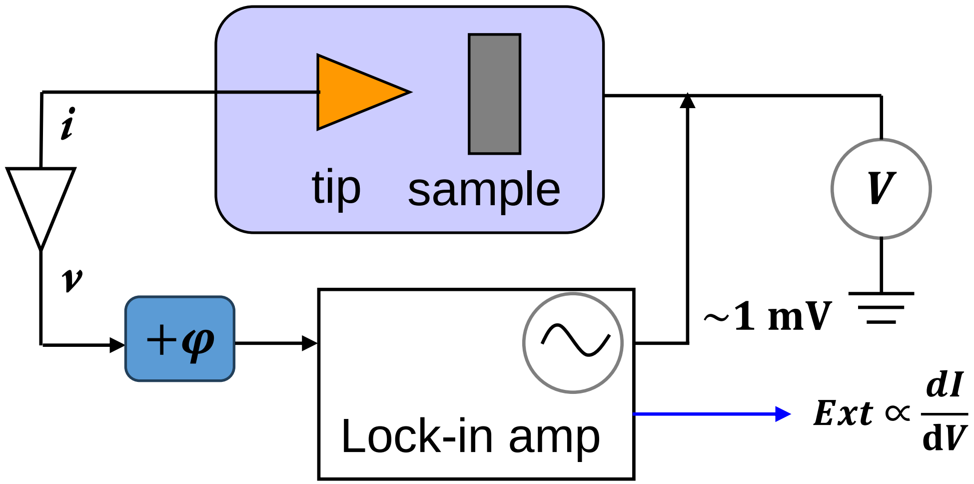
Scanning tunneling spectroscopy (d*I*/d*V* spectroscopy)

- **To obtain high quality d*I*/d*V* spectroscopy, we need:**
  - A stable tunneling junction (low drift, low vibration）
  - A clean and metallic tip (with "flat" DOS)
  - Use Lock-in amplifier
  - Careful shielding, grounding, and RF filters

- **Lock-in technique:** $\Delta V = V' cos(\omega t)$

$$I(V_0 + \Delta V) = I(V_0) + \frac{dI}{dV}\Big|_{V_0} V' cos(\omega t) + \frac{1}{2}\frac{d^2 I}{dV^2}[V' cos(\omega t)]^2 + \cdots$$





d*I*/d*V* mapping

- Local density of states spectrum at a single location $\vec{r}$ is related to the $\vec{k}$ -space eigenstates $\psi_k(\vec{r})$ by:

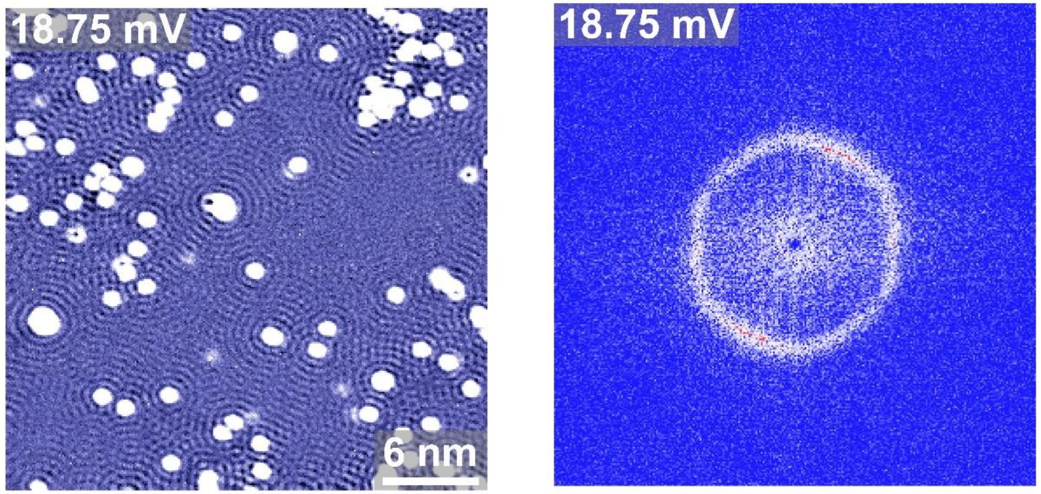
$$\rho_s(E,\vec{r}) \propto \sum_k |\psi_k(\vec{r})|^2 \delta(E - \varepsilon(\vec{k}))$$

- Sources of disorder such as impurities or crystal defects cause **elastic scattering** which mixes eigenstates of different $\vec{k}$ but the same $\varepsilon(\vec{k})$.
- When scattering mixes states $\vec{k}_1$ and $\vec{k}_2$, the result is a **standing wave** in the quasiparticle wavefunction ψ_k of wavevector $\vec{q}_{wfn}$ = $(\vec{k}_1 - \vec{k}_2)$/2.
- LDOS will contain an interference pattern with wavevector $\vec{q}$ = $(\vec{k}_1 - \vec{k}_2)$/2, or wavelength λ = 2π/q. It is called "**quasi-particle interference**" (QPI).

- In a simple metal, the amplitude of scattering obeys Fermi's golden rule:

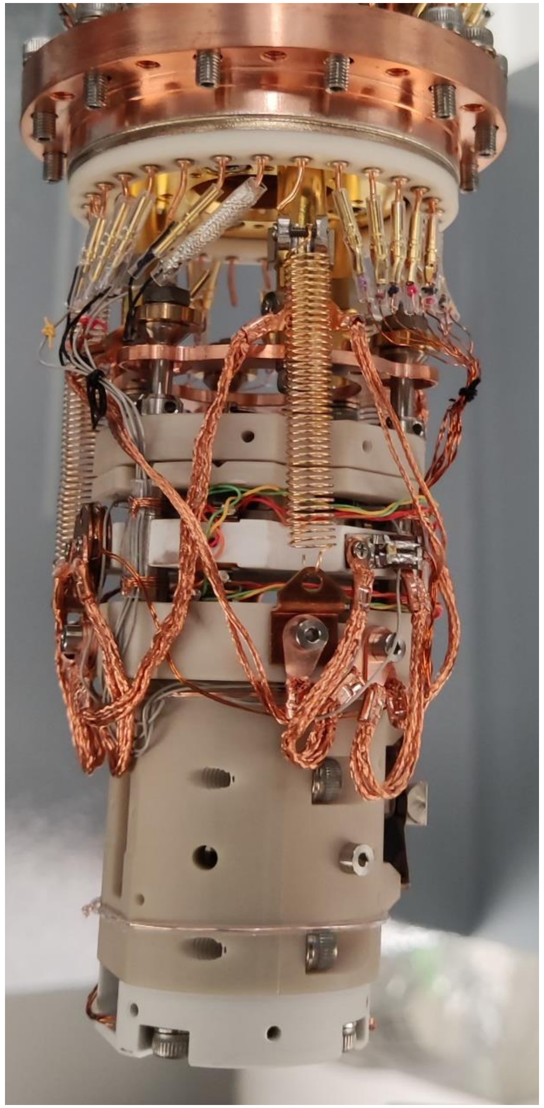
$$\omega(i \rightarrow f) \propto \frac{2\pi}{\hbar} |V(\vec{q})|^2 \rho_i(E_i, \vec{k}_i)\ \rho_f(E_f, \vec{k}_f)$$

- The scattering vectors can be obtained from the FFT of the QPI, which provide the information from $\vec{k}$ -space.



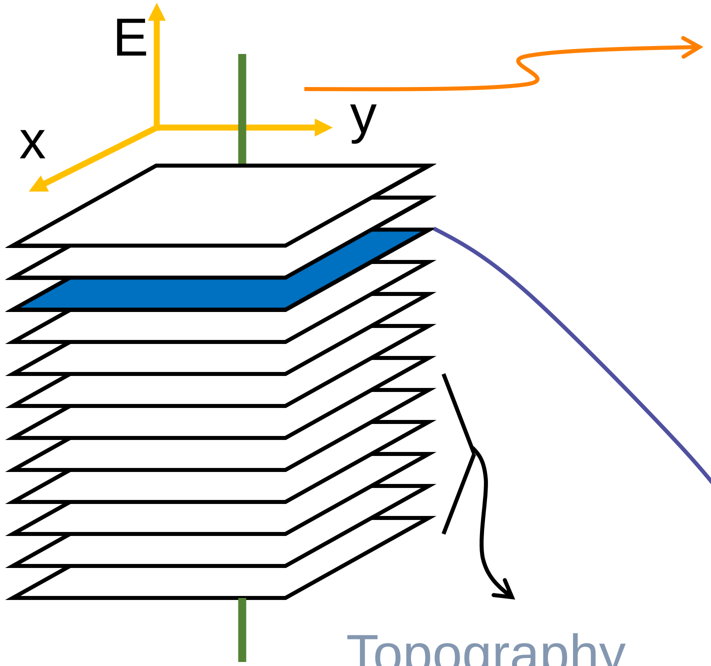
Kong *et al. Nano Lett.* (2022)

Scanning tunneling microscopy/spectroscopy

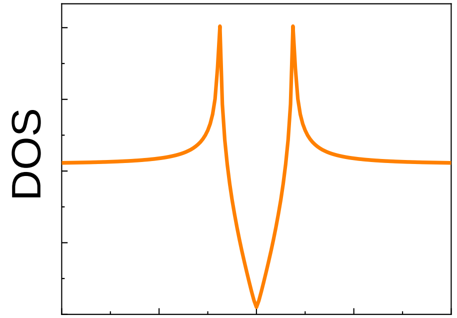


Low temperature STM scanner

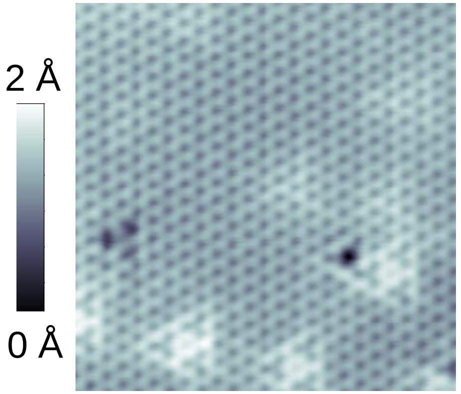
Local Density of States (x, y, E)



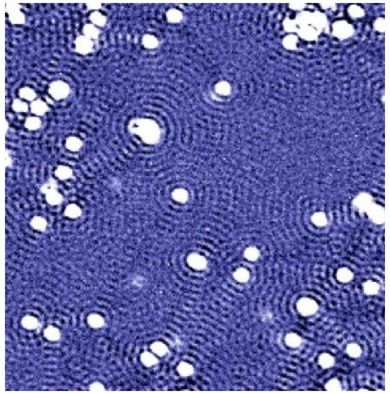
dI/dV Spectrum



Topography



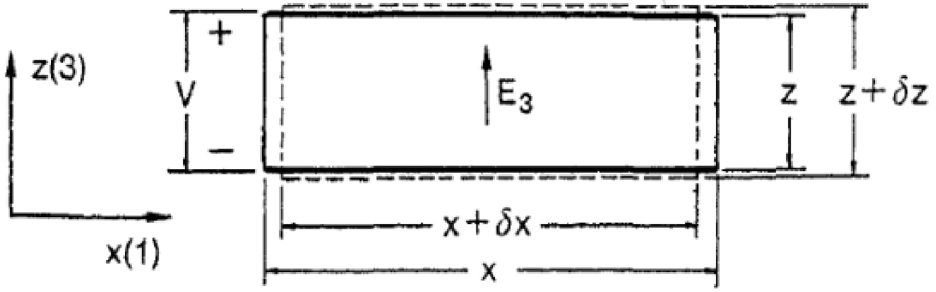
dI/dV Map

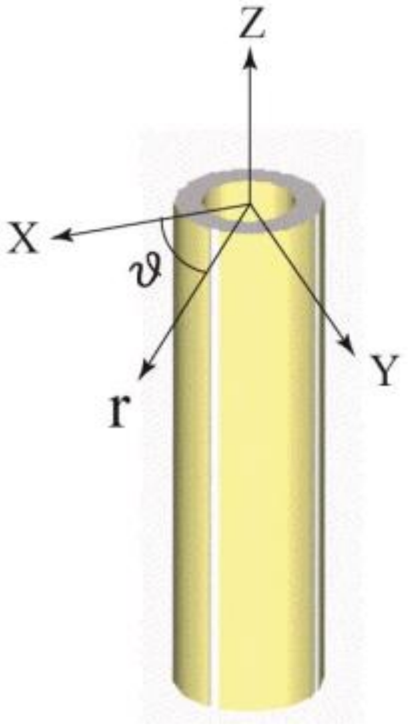


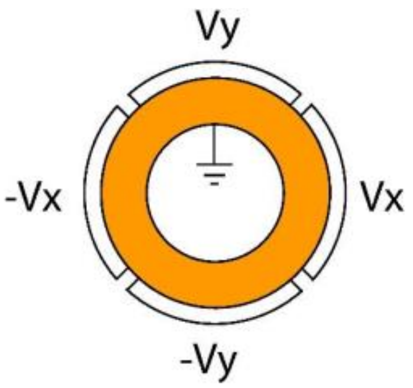
Most commonly acquired data set

Instrumentation-STM scanner

- Piezoelectric ceramics
- Lead zirconate titanate (PZT)





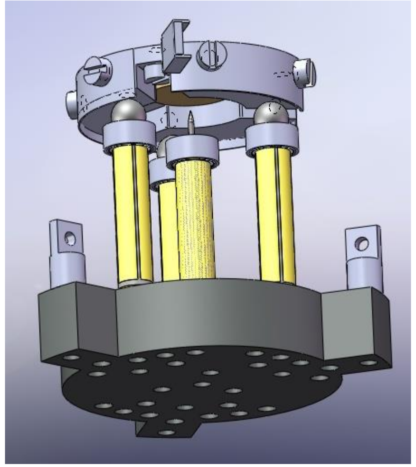


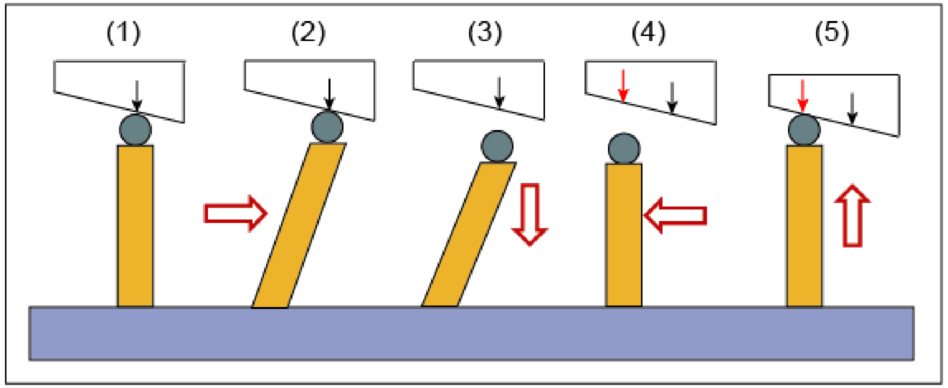
$\Delta x = 0.9\, d_{31} \cdot V \cdot L^2/D$

1V~10A

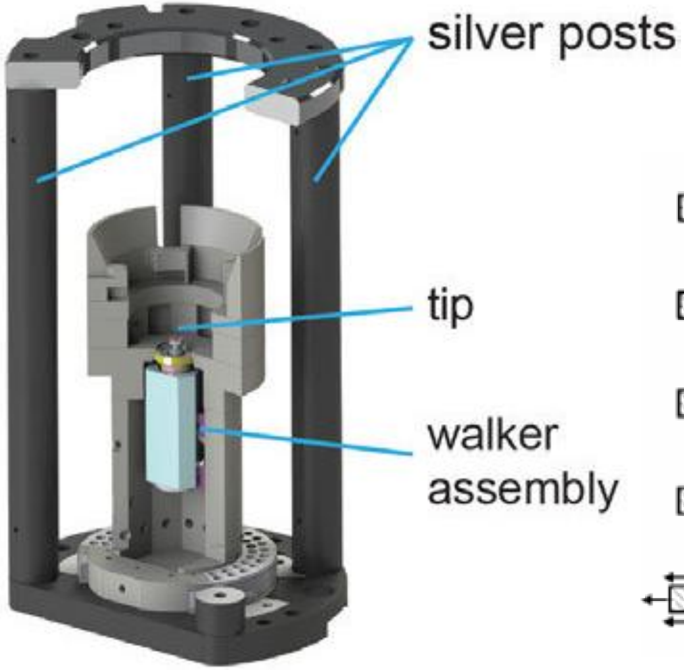
Instrumentation-STM scanner

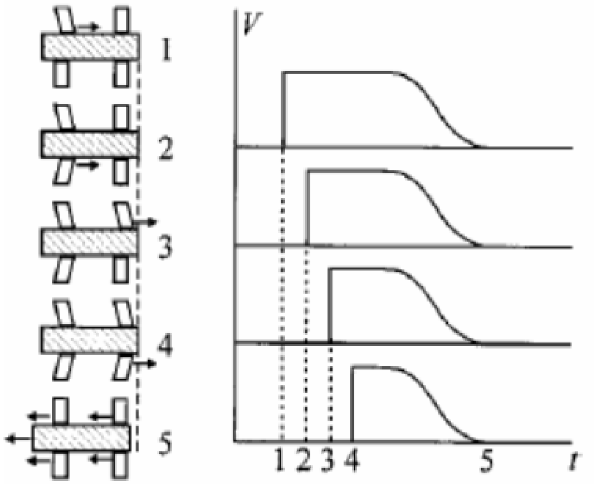
- Besocke design (beetle type)





- Pan design (the walker)





- ➢ Advantage：Very low thermal drift, good vibration isolation
- ➢ Disadvantage: Short travel length of coarse motion

- ➢ Advantage：Compact design, Low thermal drift, easy to integrate with magnets

Vibration isolation

➢ Vibration isolation is critical for achieving atomic resolution and high quality spectroscopy
< 1pm vibration is desired for STM

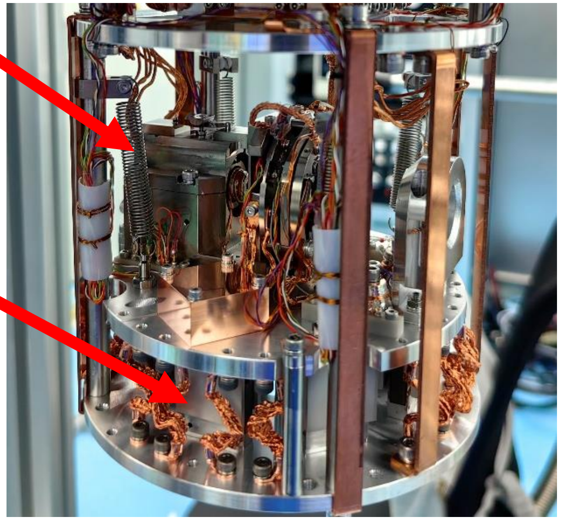
Methods:

- Basement with solid foundation
- Isolation table
- Spring with damping
- Rigid design
- Turn off Vibration source (pumps)
- Acoustic-isolation room

Isolation table

Spring

Eddy current damper



Low-temperature STM

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- ➢ Investigate phenomena only occur at low temperature (Superconductivity)
- ➢ High energy resolution
- ➢ Low thermal drift (critical for spectroscopy, mapping)
- ➢ Slow down dynamics (diffusion, desorption,...)

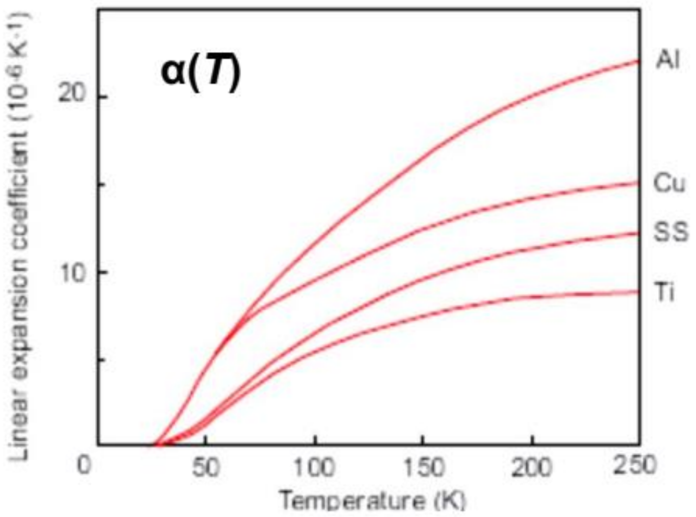
- Energy resolution: $$\frac{dI}{dV} \propto \int_{-\infty}^{+\infty} \rho_s(\varepsilon) f'(\varepsilon + eV) d\varepsilon$$

- Thermal broaden: $\Delta E \approx 3.2\, k_B T$

	RT	77 K	4.2 K
ΔE	~83 meV	~21 meV	~1.2 meV

	400 mK	40 mK
ΔE	~0.1meV	~10 μeV

- Thermal drift: $\Delta L = \alpha(T)\, L\, \Delta T$



Low-temperature STM

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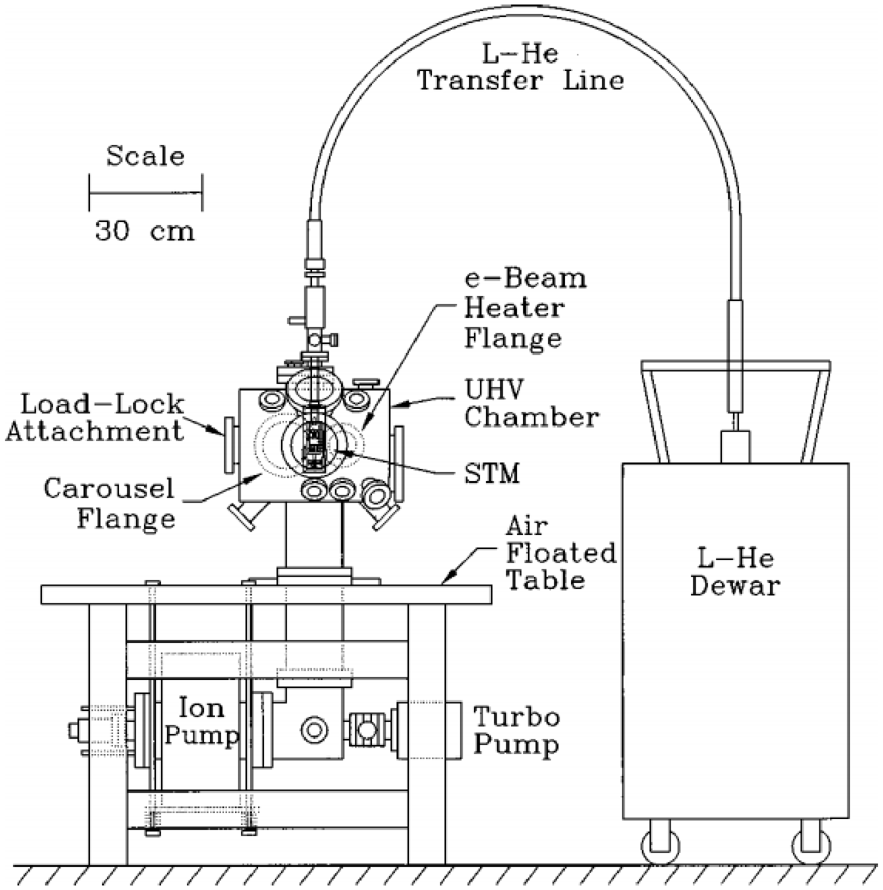
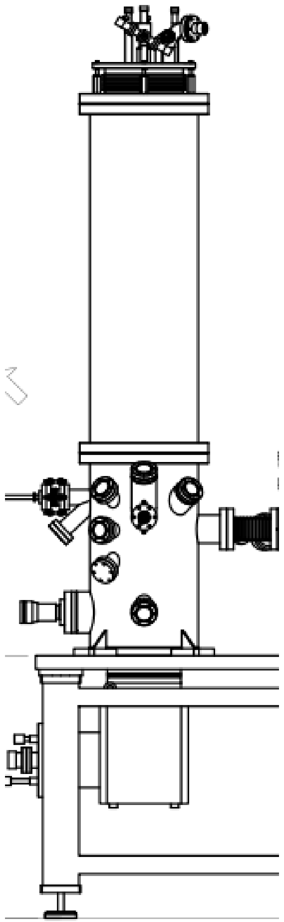
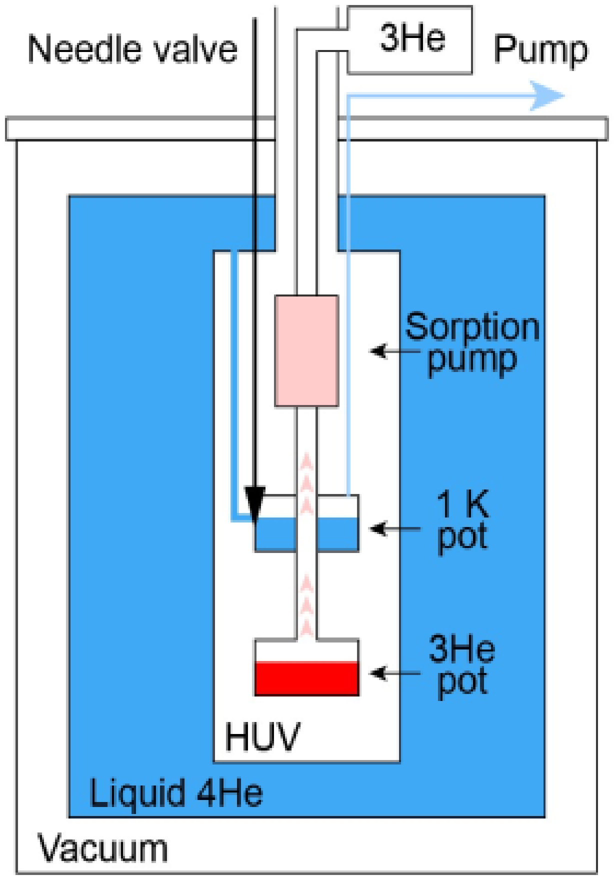
- Continuous flow



- LHe cryostat



- LHe cryostat with He-3 insert



Outline

上海科技大学 ShanghaiTech University

- Introduction to STM: principles and instrumentation
- Application of STM in the study of superconductivity
- Inelastic tunneling spectroscopy, spin-resolved STM, time-resolved STM

STM in the study of superconductivity

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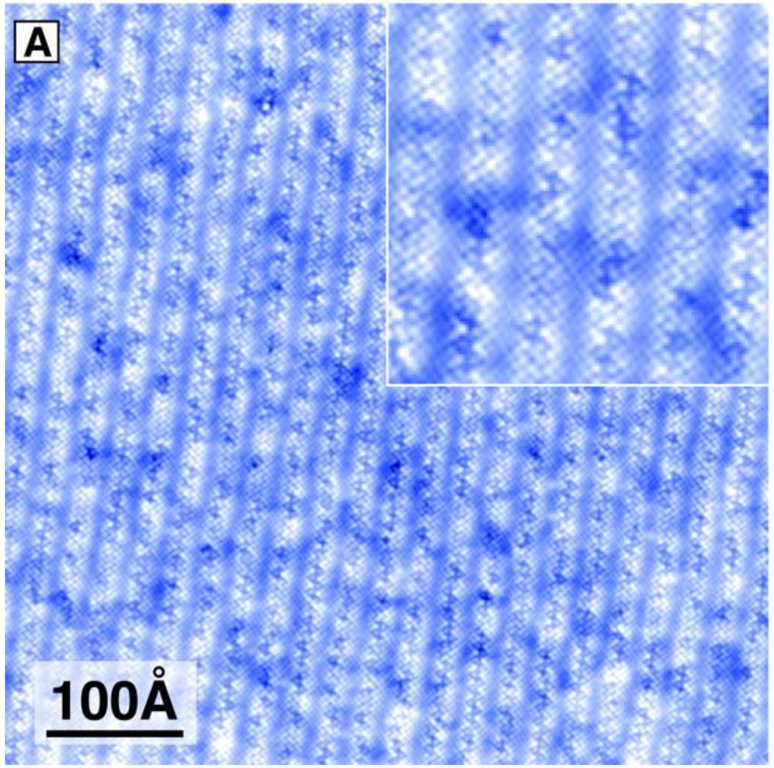
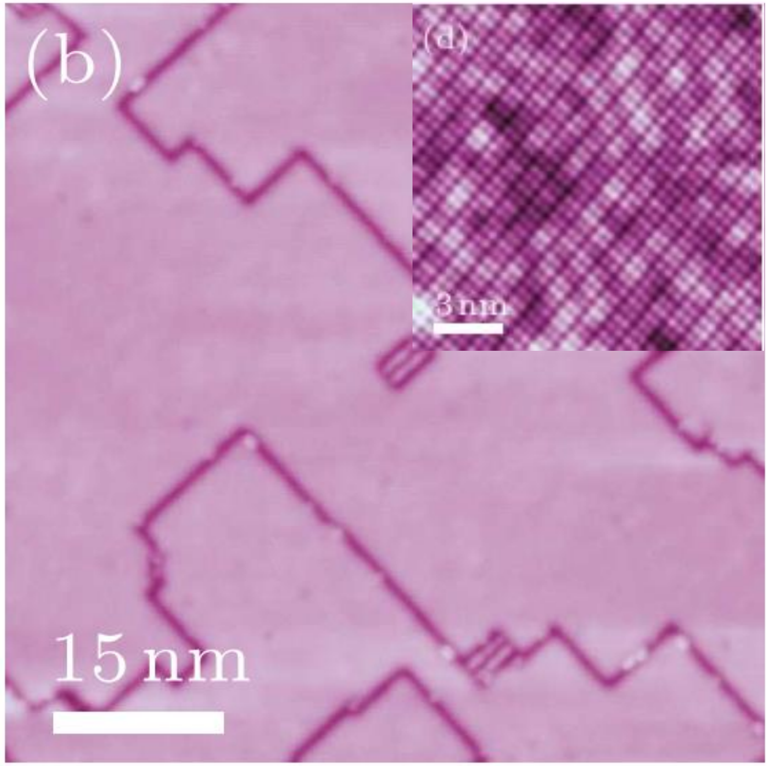
- Surface imaging: atomic structure, reconstruction, domains, defects, *etc*…
- Tunneling Spectroscopy (STS):
  - Measurement of superconducting gap
  - Local states (impurity states, vortex states…)
- Spectroscopy mapping:
  - The imaging of quasi-particle interfere (QPI)
  - Other static orders (CDW, SDW, nematic order…)

STM in the study of superconductivity

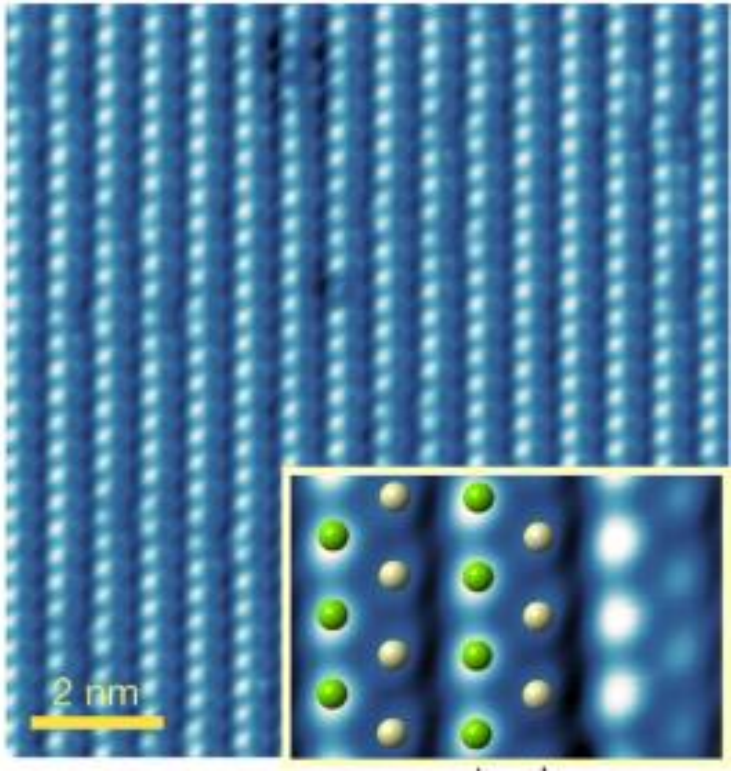
- **Surface imaging**



BSCCO (2212)



FeSe/STO



UTe_2

Hoffman *et al. Science* 295, 466 (2002)

Wang *et al. CPL* 29, 037402 (2012)

Lin *et al. Nature* 579, 523 (2020)

STM in the study of superconductivity

➢ Tunneling Spectroscopy: measuring superconducting gap

- The gap opening at E_F in DOS is the important characteristic of superconductivity
- Due to the gap opening, the quasi-particle energy changed to:

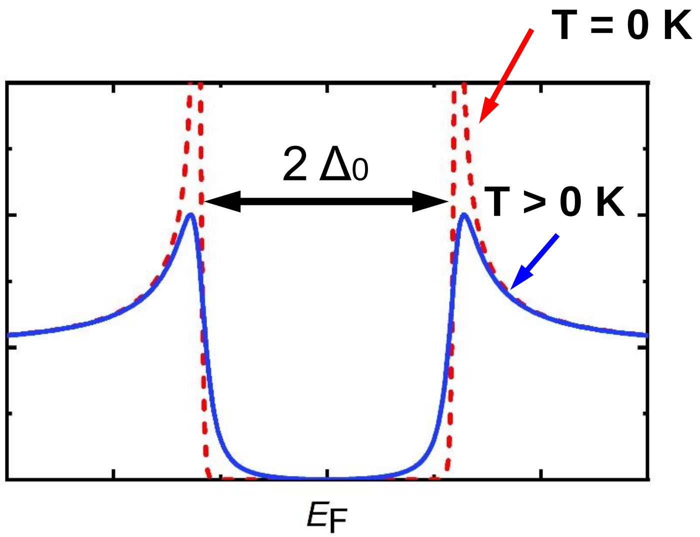
$$\boldsymbol{E_k} = \sqrt{\boldsymbol{\varepsilon_k^2} + \Delta(\boldsymbol{k})^2}$$

where $\Delta(\boldsymbol{k})$ is the SC gap or order parameter

- DOS is given by: $$\boldsymbol{\rho_\varepsilon} = \boldsymbol{Re}\left(\frac{|\boldsymbol{E}|}{\sqrt{(\boldsymbol{E}^2 - \Delta(\boldsymbol{k})^2)}}\right)$$

where *Re* indicates the real part of the expression that follows

- For a isotropic s-wave superconductor, Δ(k) is independent of *k*: Δ(k) = Δ_0. Which means the Fermi surface is fully gapped.



The DOS of a isotropic s-wave superconductor

STM in the study of superconductivity

- **Tunneling Spectroscopy: measuring superconducting gap**

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- Due to the gap opening, the quasi-particle energy changed to:

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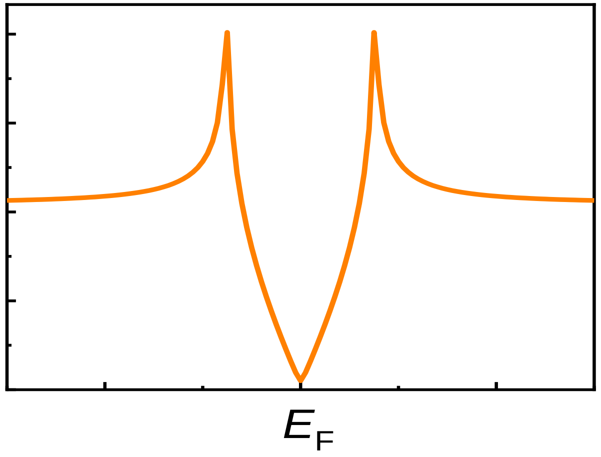
- DOS is given by: $$\boldsymbol{\rho_\varepsilon} = \boldsymbol{Re}\left(\frac{|\boldsymbol{E}|}{\sqrt{(\boldsymbol{E}^2 - \Delta(\boldsymbol{k})^2}}\right)$$

where *Re* indicates the real part of the expression that follows

- For a d-wave superconductor, the order parameter is:

$$\Delta(\boldsymbol{k}) = \Delta_0 \cos(2\boldsymbol{\theta})$$

$$(\tan \boldsymbol{\theta} = \frac{\boldsymbol{k_x}}{\boldsymbol{k_y}})$$

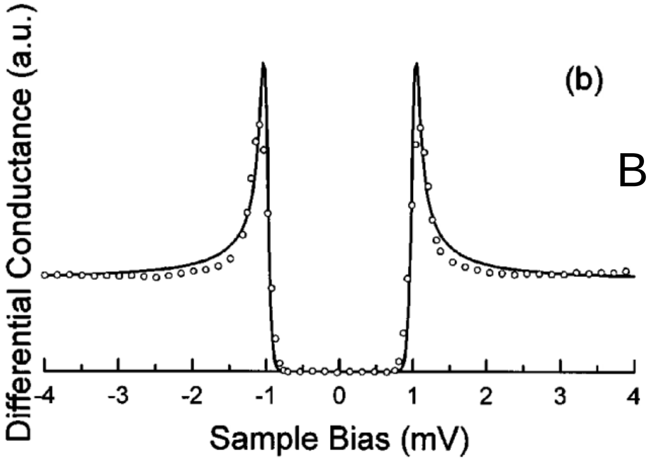


The DOS of a d-wave superconductor

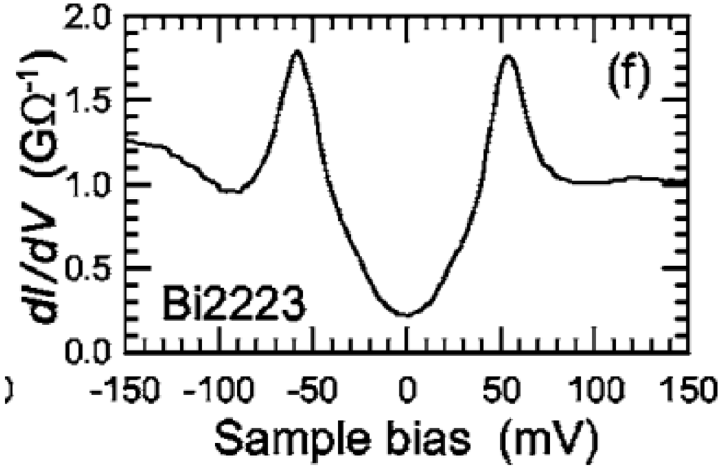
It is not fully gapped, and the V-shaped dI/dV implies the existence of nodes in the SC gap.

STM in the study of superconductivity

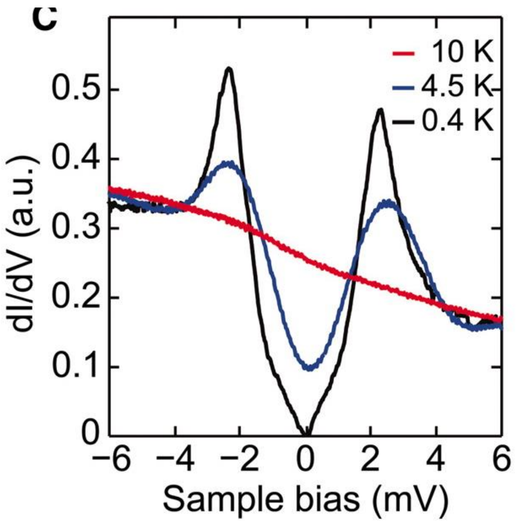
- **Tunneling Spectroscopy: measuring superconducting gap**



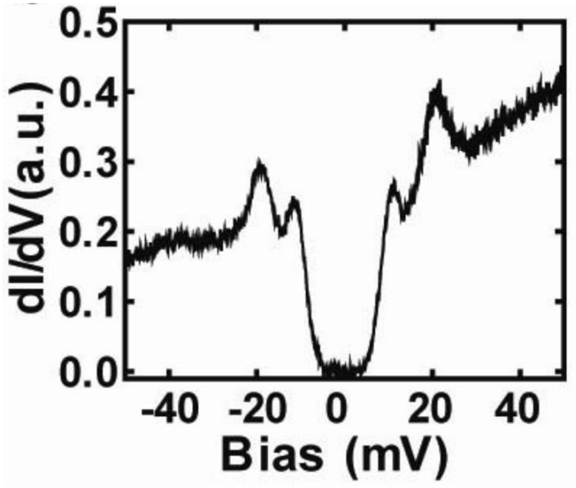
Bulk Nb (s-wave)



Cuprate (d-wave)



FeSe films (nodal)



Single layer FeSe/STO (nodeless)

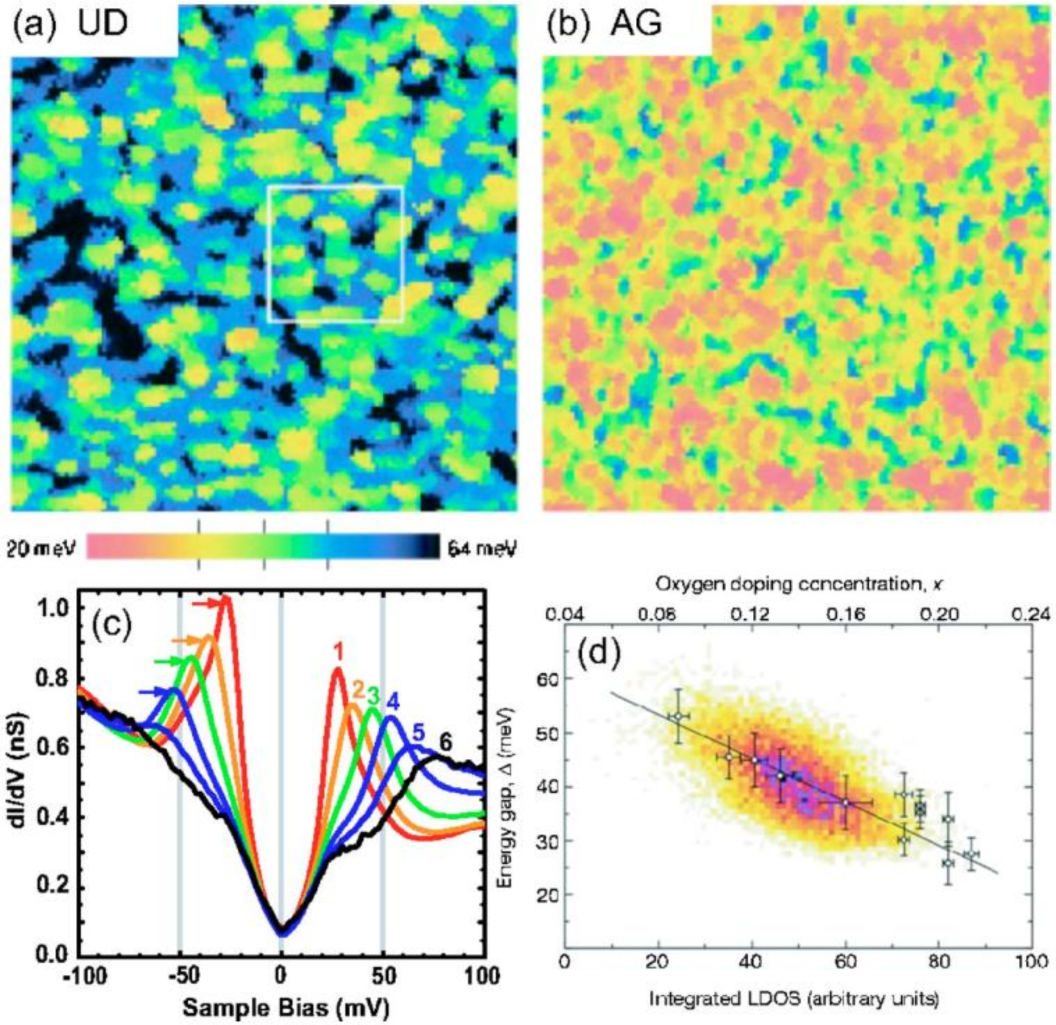
STM in the study of superconductivity

➤ **Spatial variation of SC gap**

- As a real space probe, STM is capable of detecting the spatial dependence of the gap.

- The spatial inhomogeneity of the SC gap may be attribute to:

✓ Doping inhomogeneity
✓ Low sample quality
✓ Intrinsic factors



Ø. Fischer, et al., *Rev. Mod. Phys.* 79, 363 (2007)

STM in the study of superconductivity

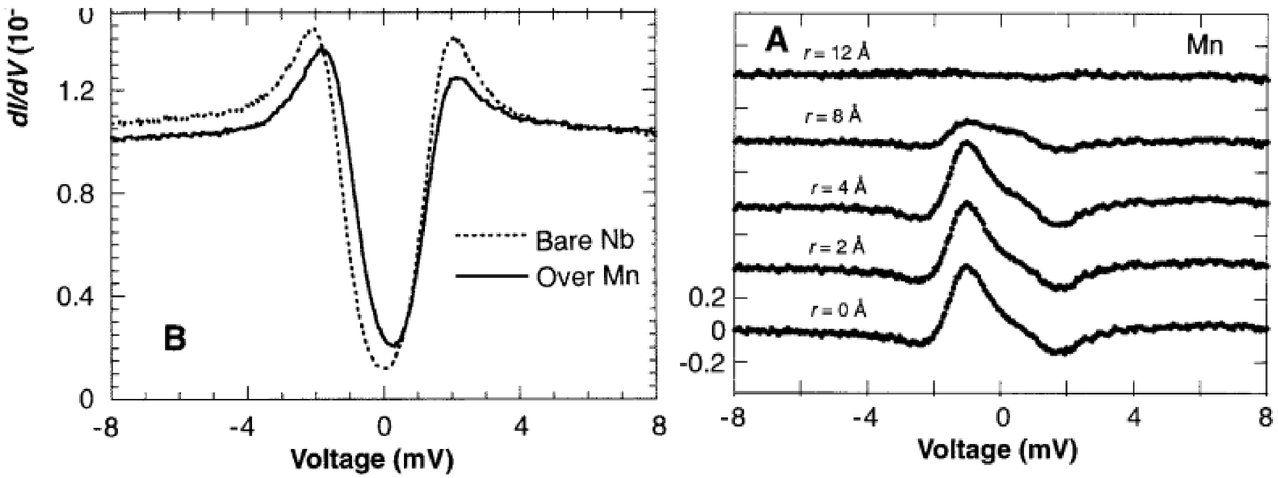
上海科技大学 ShanghaiTech University

- **In-gap states**

Anderson's theorem:

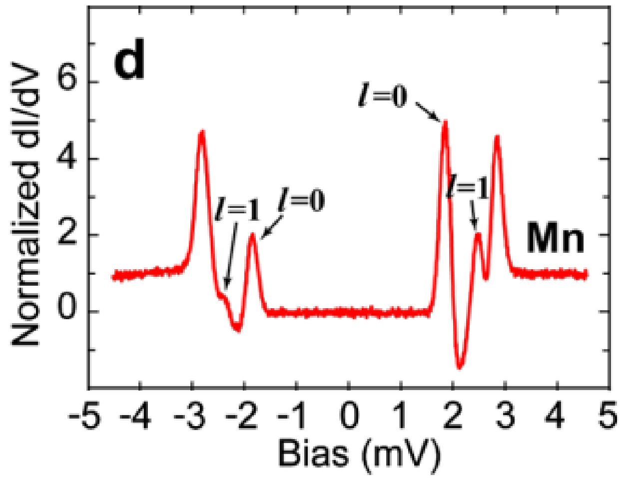
- For a s-wave superconductor, the bound states that generated by potential scattering (Non-magnetic scattering) are on the gap edge. Therefore non-magnetic impurities do not suppress the s-wave superconductivity.
- For magnetic impurities, which can flip the spin of paired electrons, will suppress the superconductivity and introduce bound states inside of the superconducting gap.

Mn impurity in Nb



Yazdani *et al. Science* 275, 1767 (1997)

Mn impurity in Pb



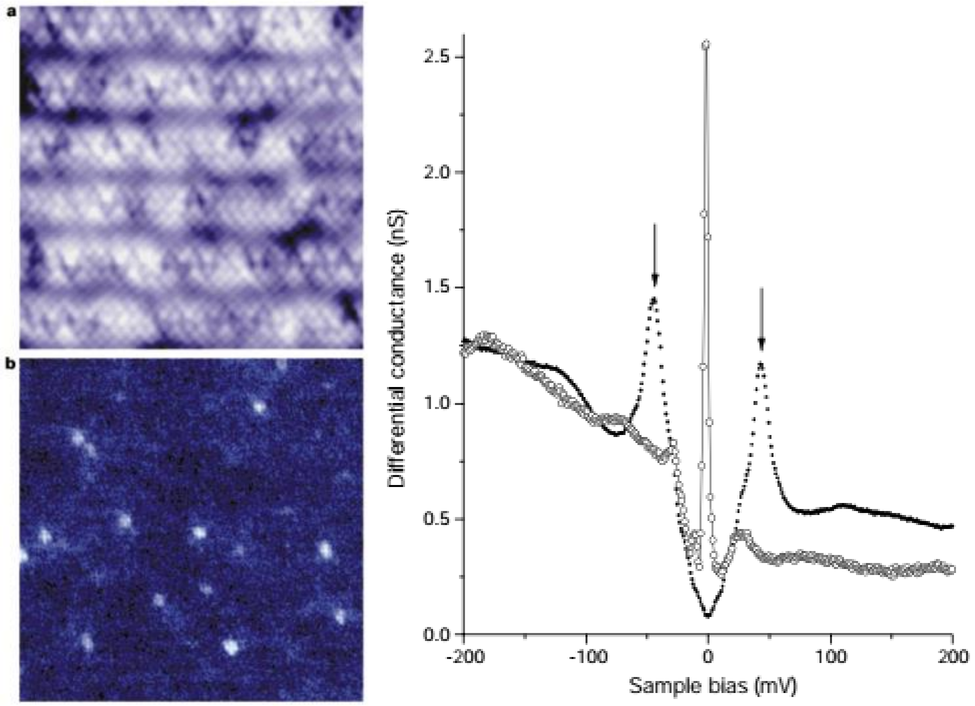
Ji *et al. PRL* 100, 226801 (2008)

STM in the study of superconductivity

➢ In-gap states

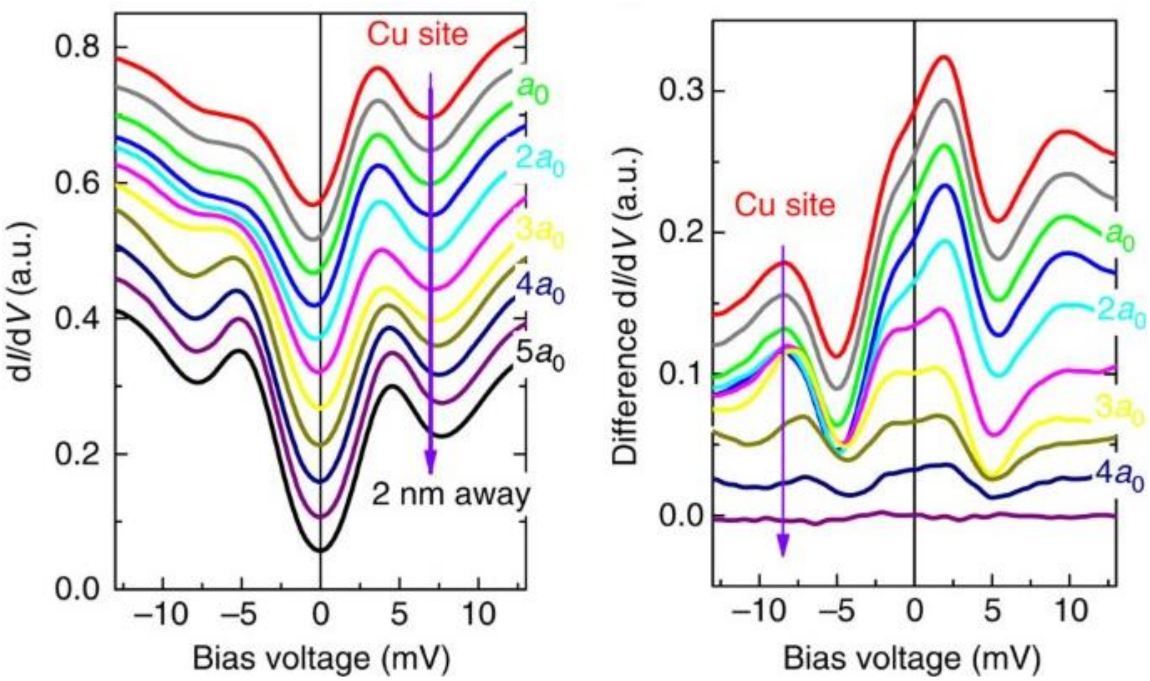
- For phase change pairing (such as d–wave, s+-) , nonmagnetic impurities can also suppress superconductivity.

Zn in BSCCO



Pan *et al., Nature* 403, 746 (2003)

Cu in NaFeAs

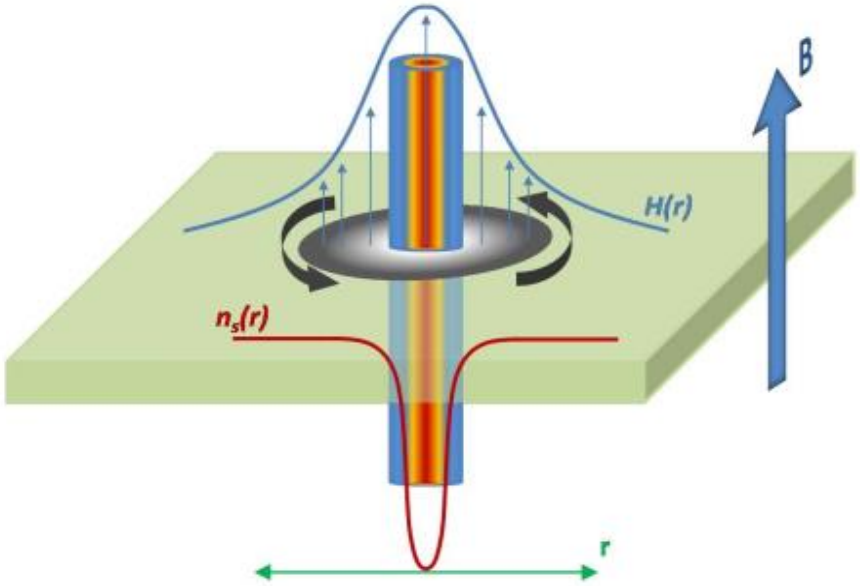


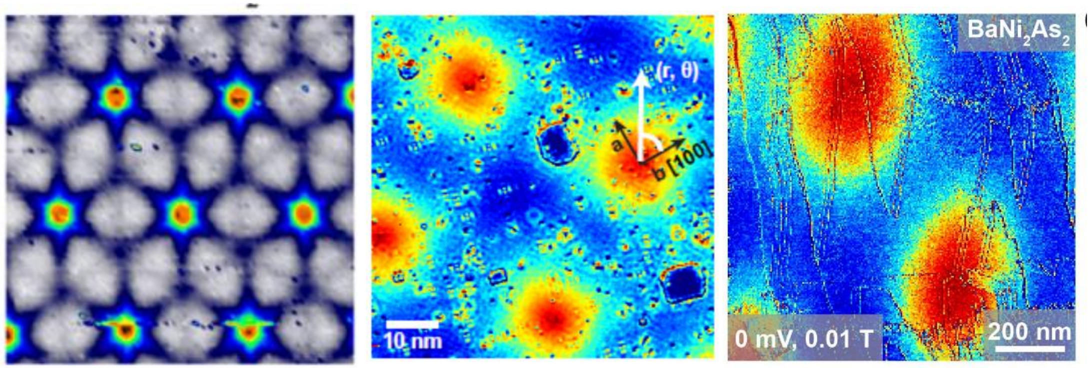
Yang, H. *et al., Nat. Comm.* 4, 2749 (2013)

STM in the study of superconductivity

➢ Vortex imaging

- For type II superconductor, the ***B*** field can penetrate into the bulk in the form of Vortices.
- Supercurrent circulates around the normal core of the vortex.
- The core has a size the superconducting coherence length ξ (parameter of a Ginzburg–Landau theory).
- The supercurrents decay on the distance about λ (London penetration depth) from the core.
- For type-II superconductor, $\lambda > \xi/\sqrt{2}$
- Vortex with quantized flux of $\Phi_0 = h/2e = 2.07 \times 10^{-15}$ Wb





➢ Mapping vortex can provide useful information:
- Coherence length (ξ)
- Vortex pinning and dynamics
- The shape of the vortex core reflects the anisotropy of Δ(k)

STM in the study of superconductivity

上海科技大学 ShanghaiTech University

- ➢ **Vortex core states**

Volume 9, number 4 PHYSICS LETTERS 1 May 1964

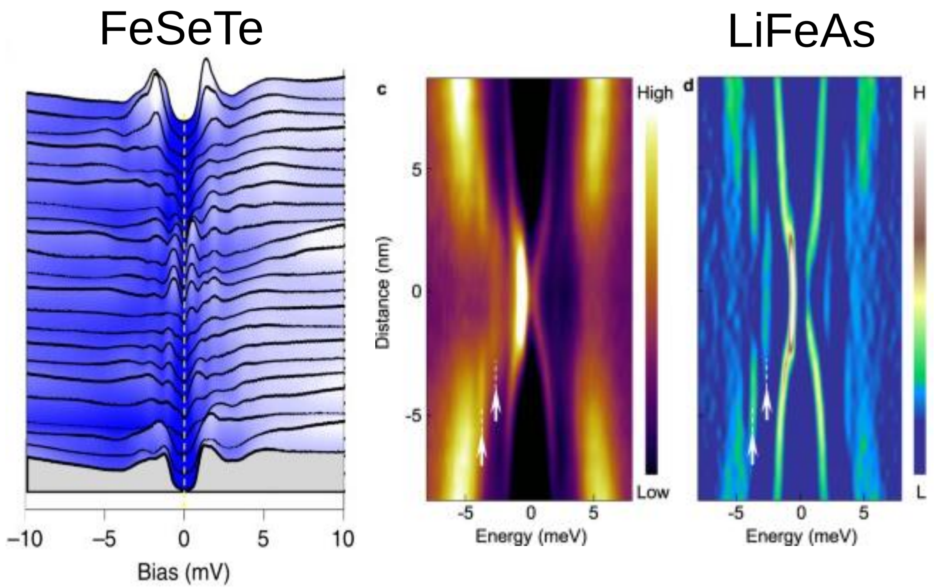
BOUND FERMION STATES ON A VORTEX LINE IN A TYPE II SUPERCONDUCTOR

C. CAROLI, P. G. DE GENNES, J. MATRICON
Service de Physique des Solides, Faculté des Sciences, Orsay (S & O)

Received 31 March 1964

This note discusses the excitations of low energy $\epsilon \ll \Delta_\infty$ (where Δ_∞ is the gap in zero field) which exist near an Abrikosov vortex line [1)] in a pure superconductor of type II. The energy gap ϵ_0 for these excitations is very small $\epsilon_0 \sim \Delta_\infty^2/E_F$ where E_F is the Fermi energy. Above ϵ_0 the density of states is finite and comparable to that of a cylinder of normal metal of radius ξ (the coherence length). These low lying states will play a major role in the discussion of transport and relaxation phenomena in type II superconductors at low temperatures.

- ➢ Due to the confinement to the quasiparticles by the vortex core, Caroli-de Gennes-Matricon (CdGM) predicted that there are confined low-energy bound states with the energy levels at about $E_\mu = \pm \mu\Delta^2/E_F$ (μ = 1/2, 3/2, 5/2, …) with Δ the superconducting energy gap and E_F the Fermi energy.



Chen *et al.*, Nature Commun. (2018)
Kong *et al.*, Nature Commun. (2021)

- ➢ The energy of core states relies on the pairing symmetry.
  - For fully gapped s-wave, the core states are discrete
  - For d-wave, the core states are expected to be continuous
  - For p-wave, the core states are at Zero energy

STM in the study of superconductivity

➢ **QPI in SC: Bogoliubov quasiparticles**

$$\boldsymbol{\omega(i \to f) \propto \frac{2\pi}{\hbar}\left|u_{ki}u_{kf}^{*} \pm v_{ki}v_{kf}^{*}\right|^{2}|V(\vec{q})|^{2}\rho_{i}(E_{i},\vec{k}_{i})\ \rho_{f}(E_{f},\vec{k}_{f})}$$

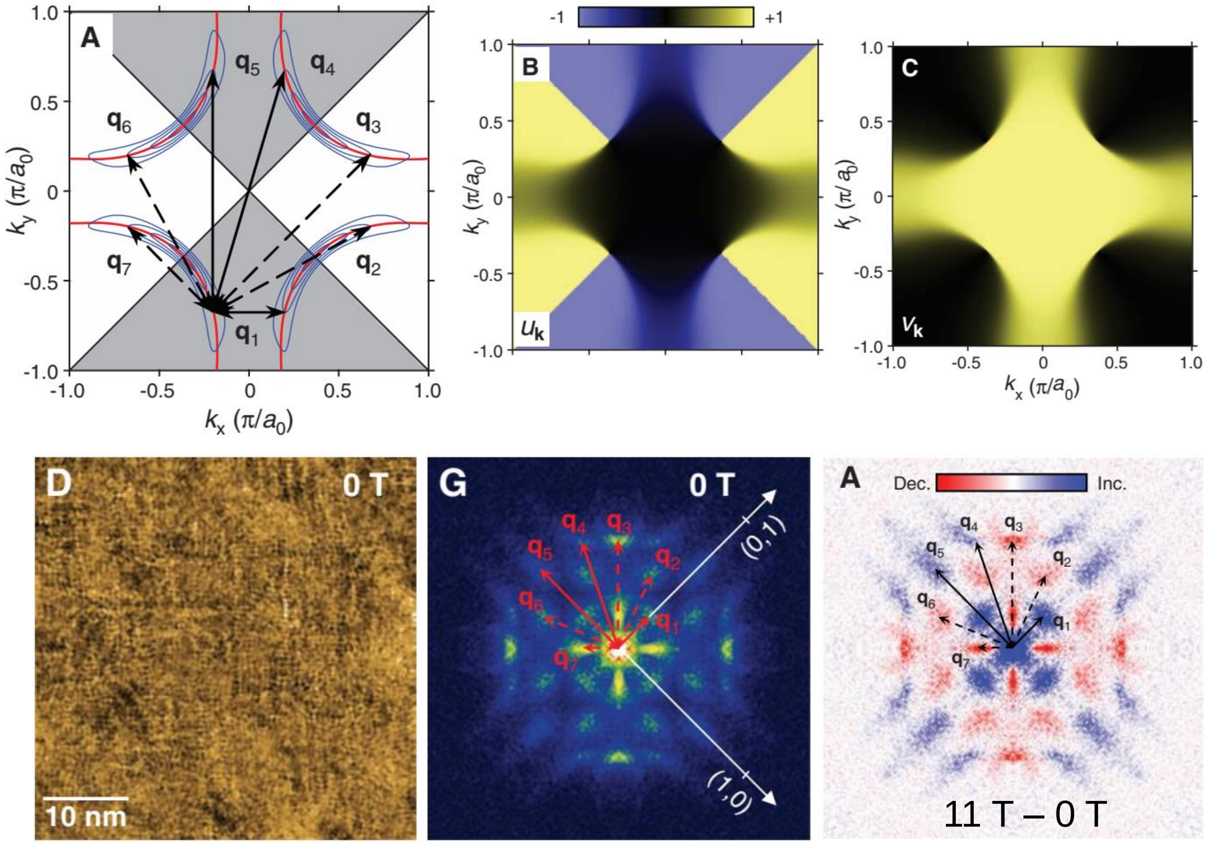
$\boldsymbol{u_k}$ and $\boldsymbol{v_k}$ are Bogoliubov coefficients:

$$\boldsymbol{u_k = sign\,[\Delta(k)]\sqrt{\frac{1}{2}\left[1+\frac{\varepsilon(k)}{E(k)}\right]}} \qquad \boldsymbol{v_k = \sqrt{1-|u_k|^2}}$$

$\left|u_{ki}u_{kf}^{*} \pm v_{ki}v_{kf}^{*}\right|^{2}$ is called coherence factor, the plus sign is for magnetic scatterers, and the minus sign is for non-magnetic scatters.

- For non-magnetic scatterers, the coherence factor is suppressed for $\vec{q}$ that preserve the sign of Δ(k), but enhanced for $\vec{q}$ that change the sign of Δ(k).
- For magnetic scatterers (such as vortices), the coherence factor is suppressed for $\vec{q}$ that change the sign of Δ(k), but enhanced for $\vec{q}$ that preserve the sign of Δ(k).

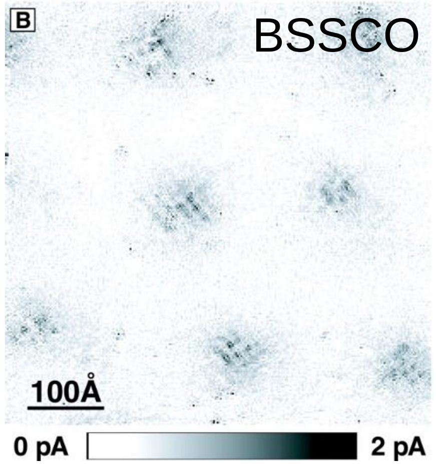
QPI is phase sensitive!



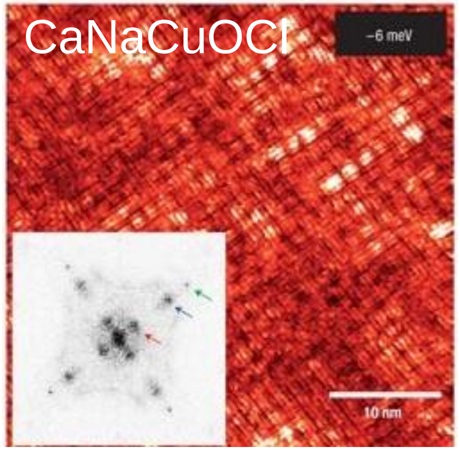
Hanaguri *et al. Science* 323, 923 (2009)

STM in the study of superconductivity

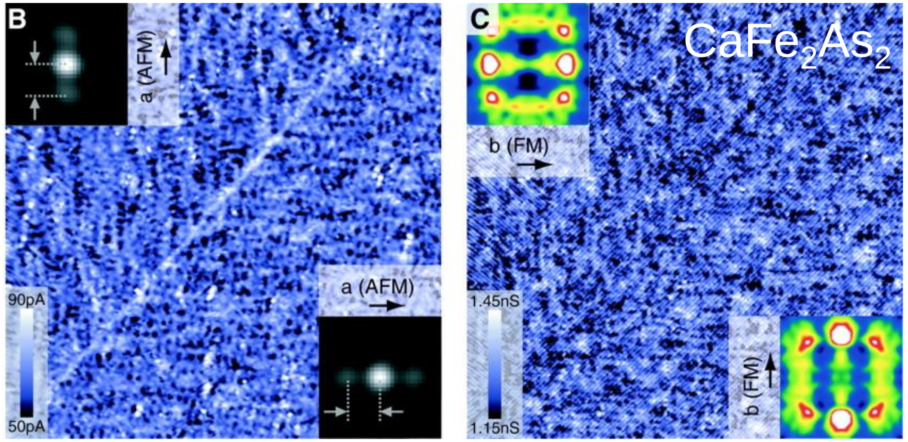
- **Besides QPI, STM discovered other static spatial modulations in superconductors:**



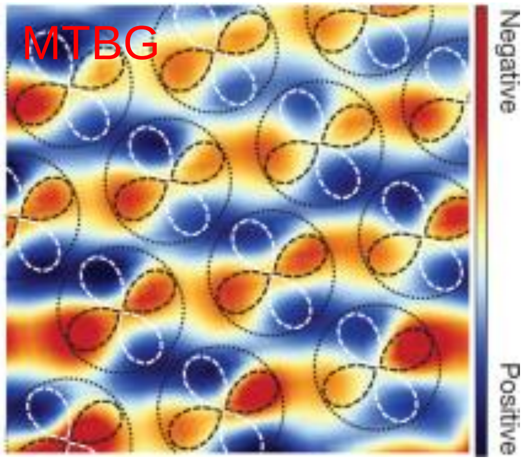
Hoffman, *et al.*, *Science* (2002)



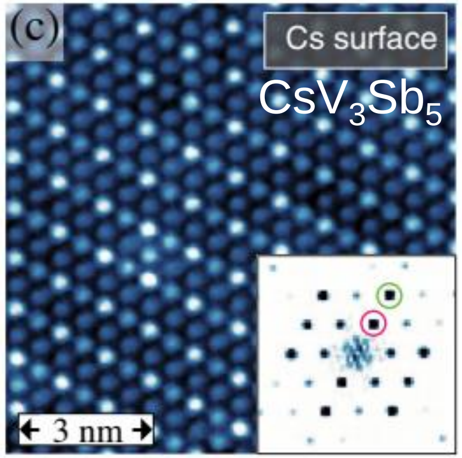
Hanaguri, *et al.*, *Nature Phys.* (2007)



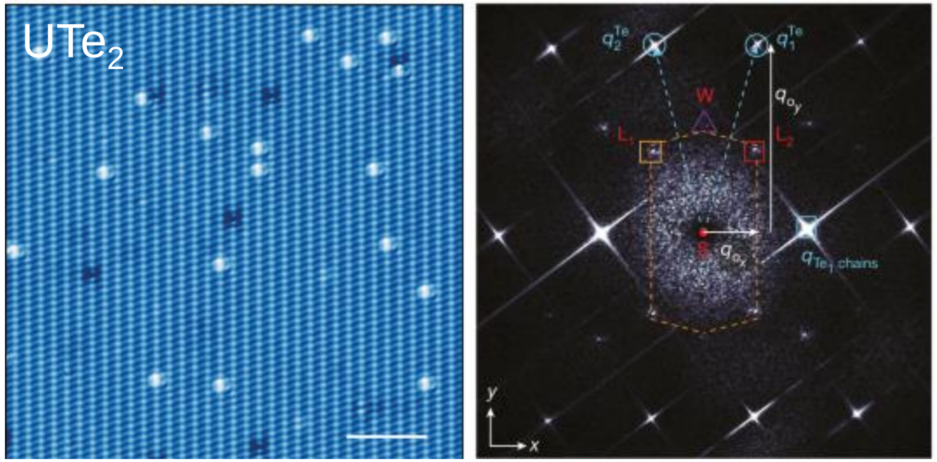
Chuang, *et al.*, *Science* (2010)



Jiang, *et al.*, *Nature* (2019)



Liang, *et al.*, *PRX* (2021)

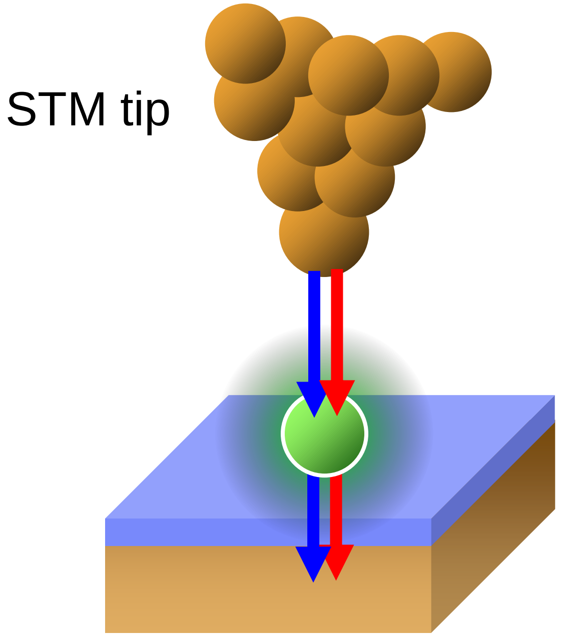


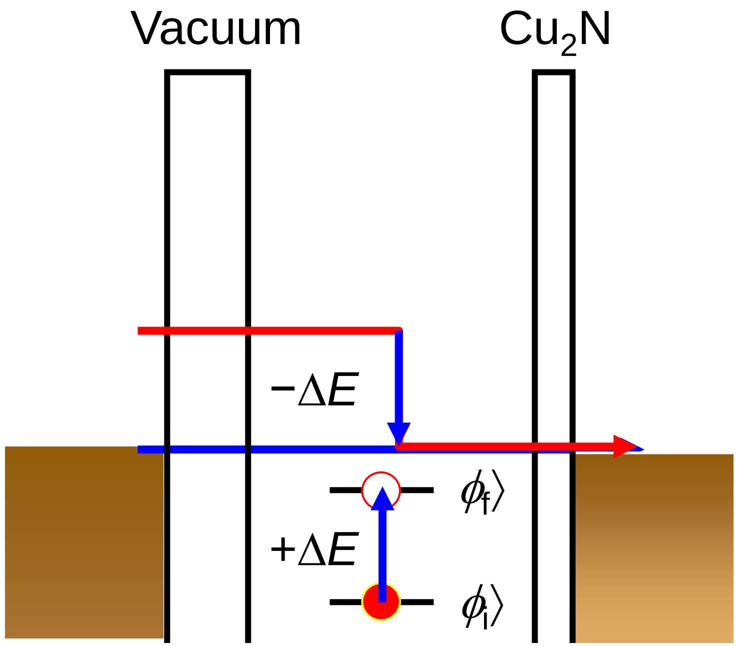
Aishwarya, *et al.*, *Nature* (2023)

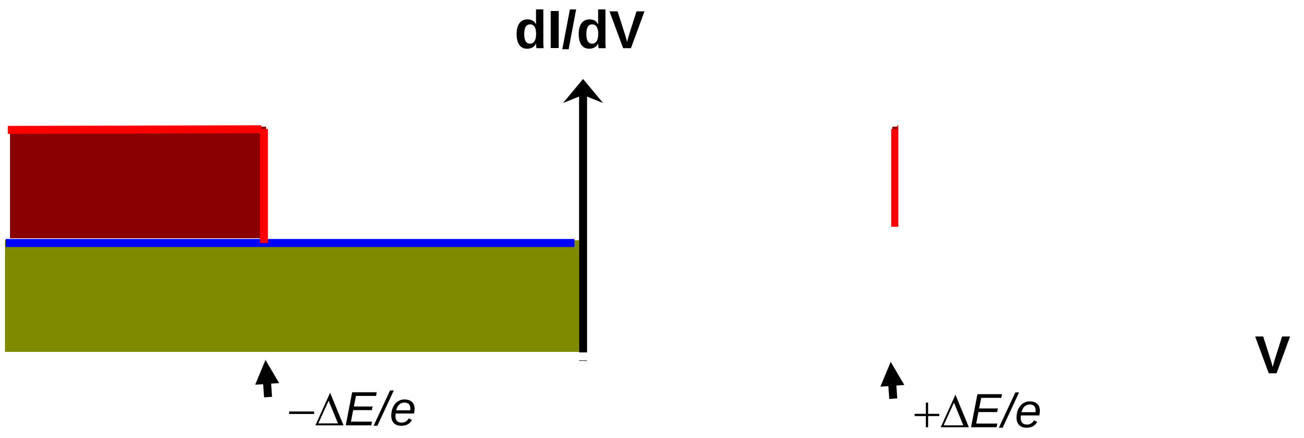
Outline

- ➢ **Introduction to STM: principles and instrumentation**
- ➢ **Application of STM in the study of superconductivity**
- ➢ **Inelastic tunneling spectroscopy, spin-resolved STM, time-resolved STM**

Inelastic tunneling spectroscopy



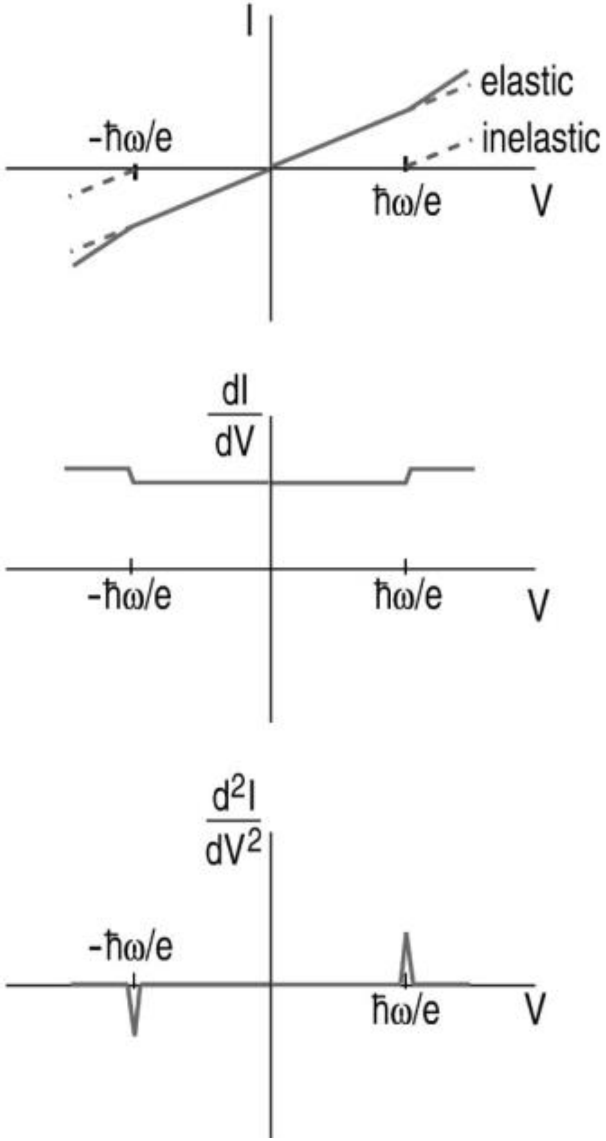




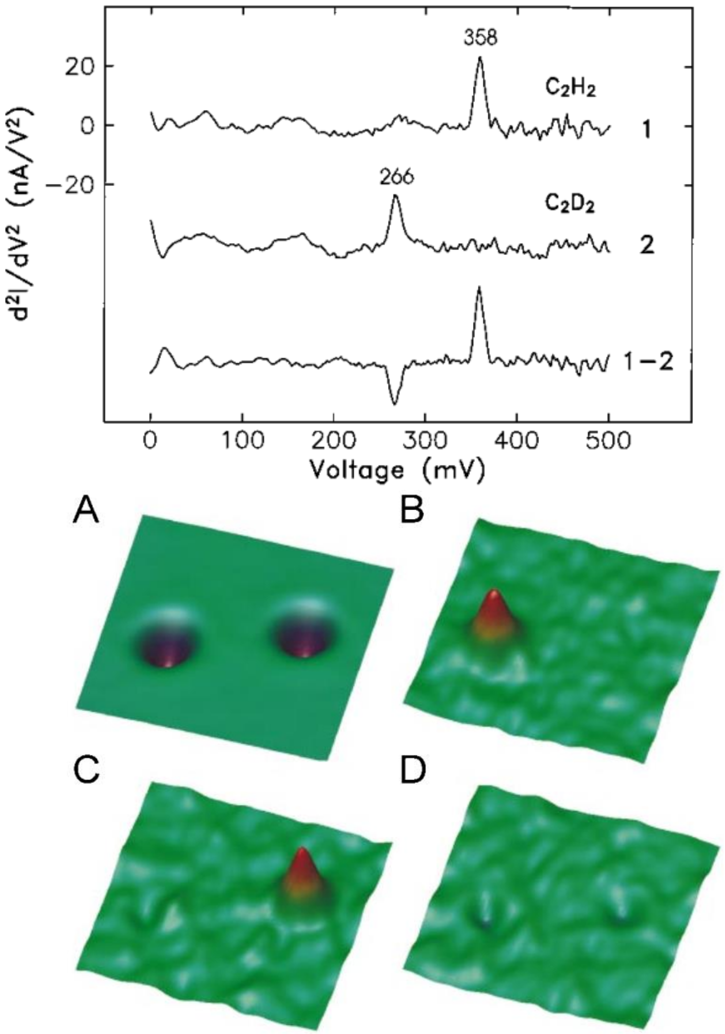
Inelastic co-tunneling
Interaction Hamiltonian: $\vec{s}\cdot\vec{S}+u$

e.g. Schrieffer, Wolff *Phys. Rev.* **149** 491 (1966)

Inelastic tunneling spectroscopy

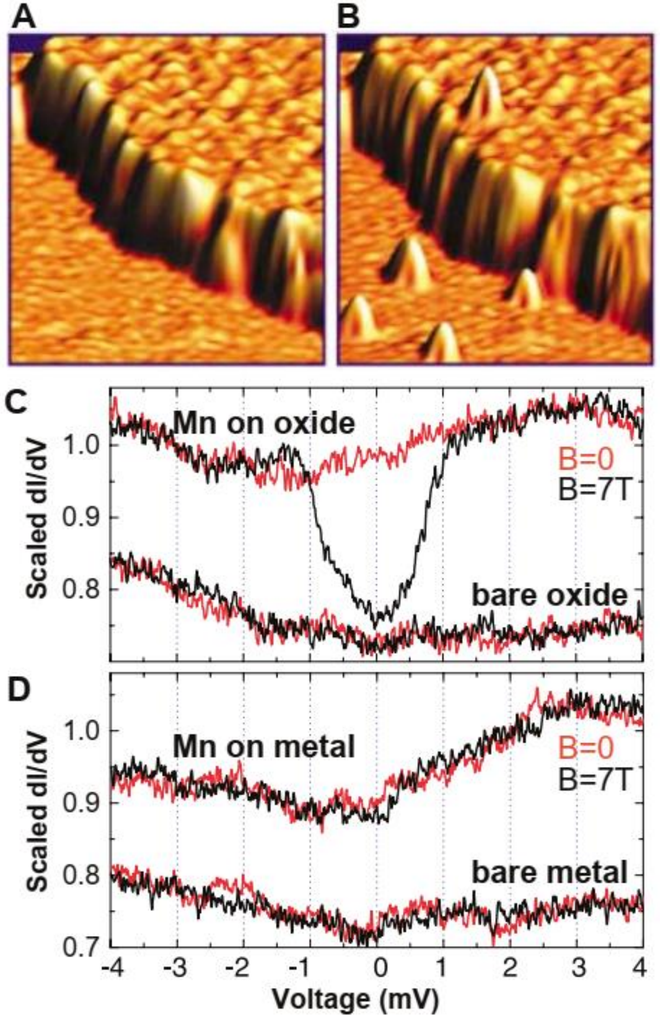


- Single molecule vibration



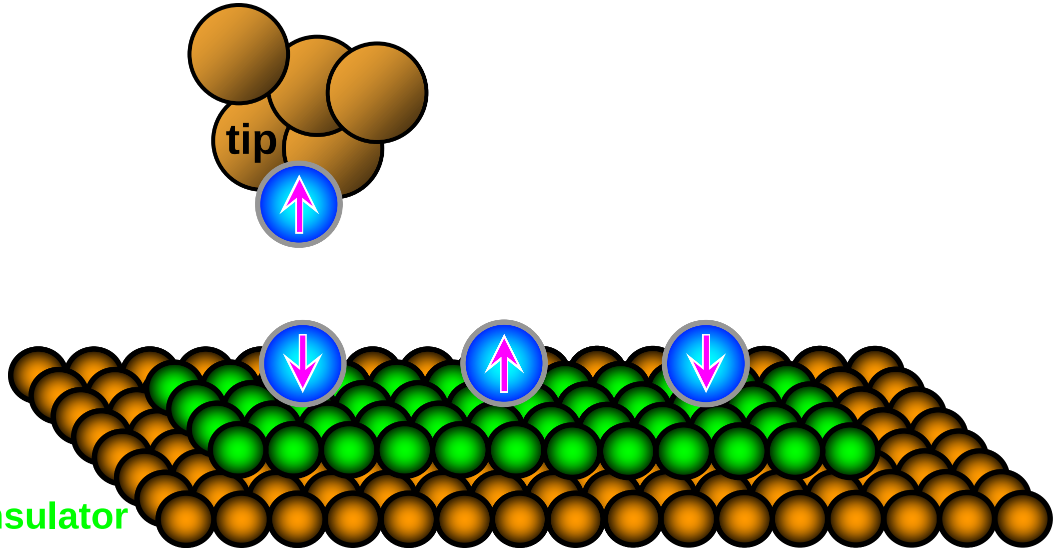
Stipe *et al.* Science (1998)

- Single atom spin excitation



Heinrich *et al.* Science (2004)

Spin-polarized tunneling



High current TMR: atom appears tall in STM image

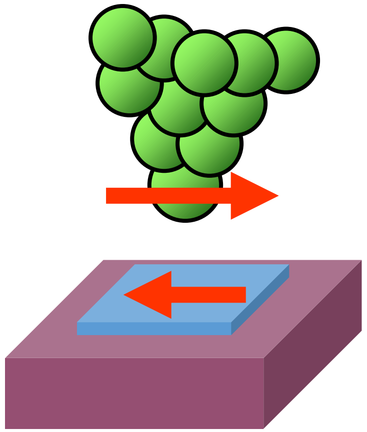
Low current TMR: atom appears small in STM image

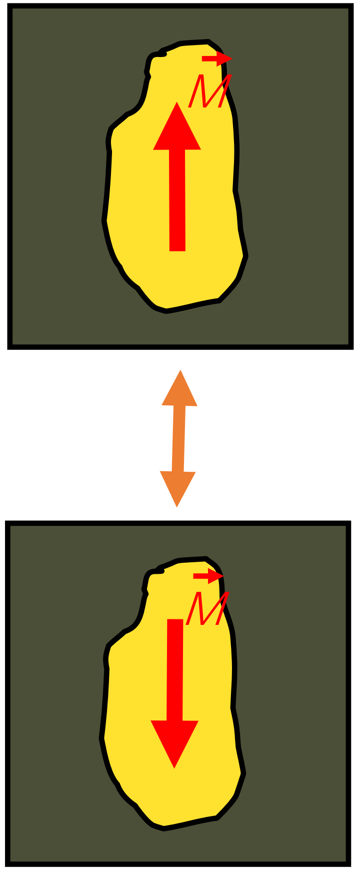
- STM is an atomic-scale tunneling magneto-resistance junction.

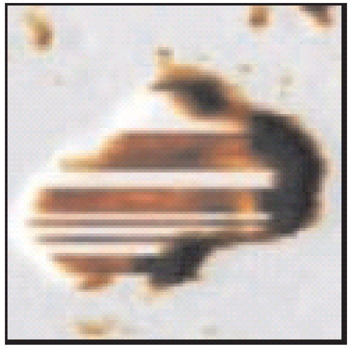
Spin-polarized tunneling

- Classical magnetism

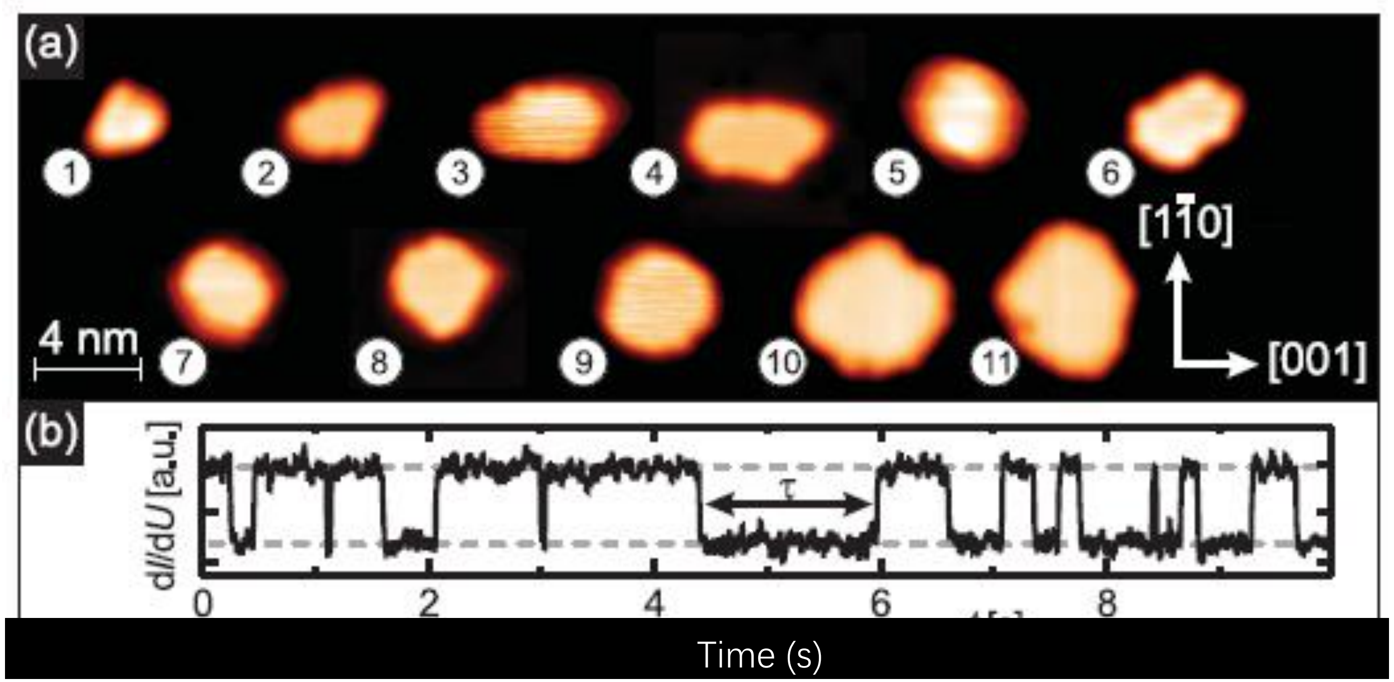
Spin-polarized tip







Fe-island on W(110)
T = 56 K



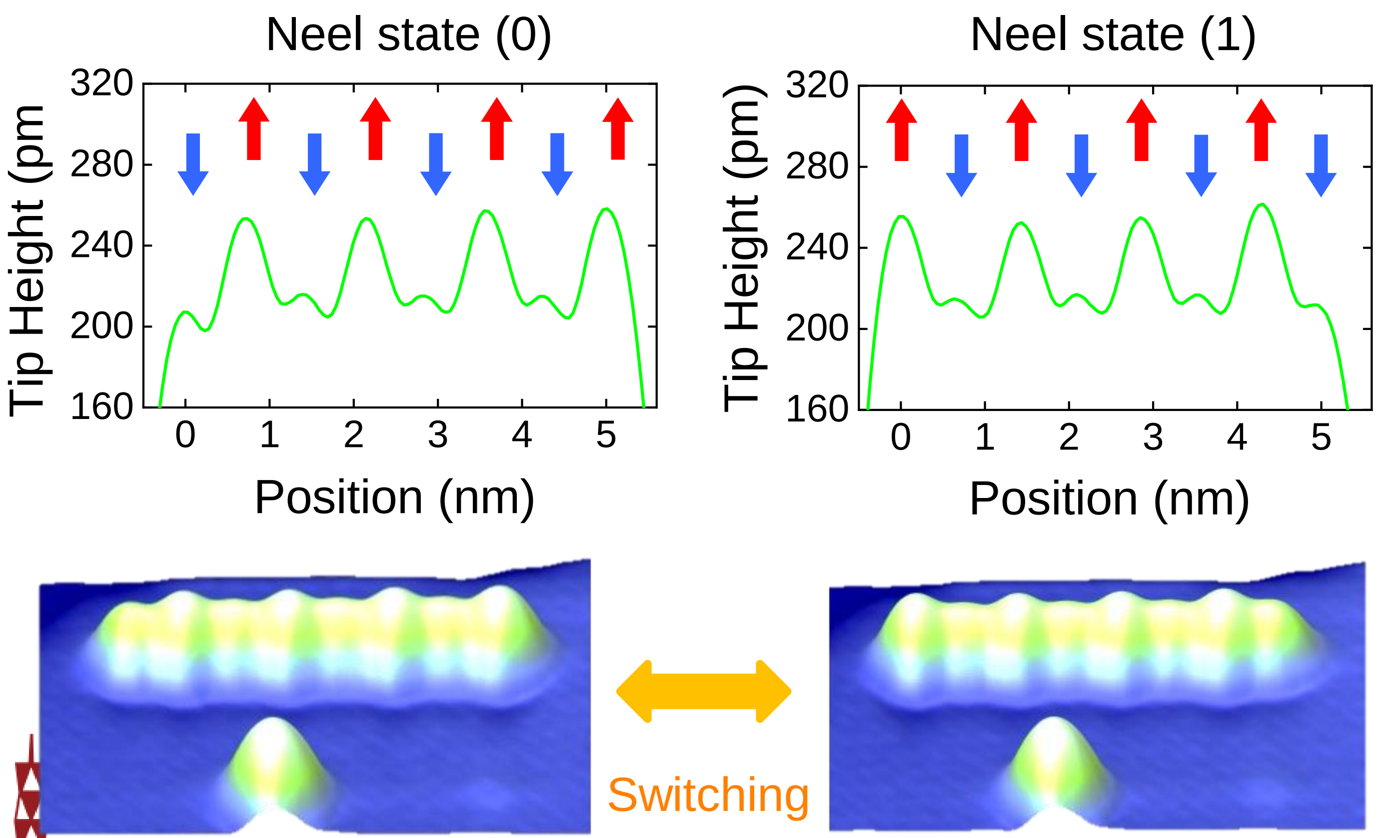
- Detect magnetic orientation by tunnel magnetoresistance
- Thermally activated switching
- Real-time recording of magnetic switching
- Time resolution: ms (−μs), noise limited at low tunnel currents

Krause et al. *PRL* (2009)
Krause *et al. Science* 317 1537 (2007)

Spin-polarized tunneling

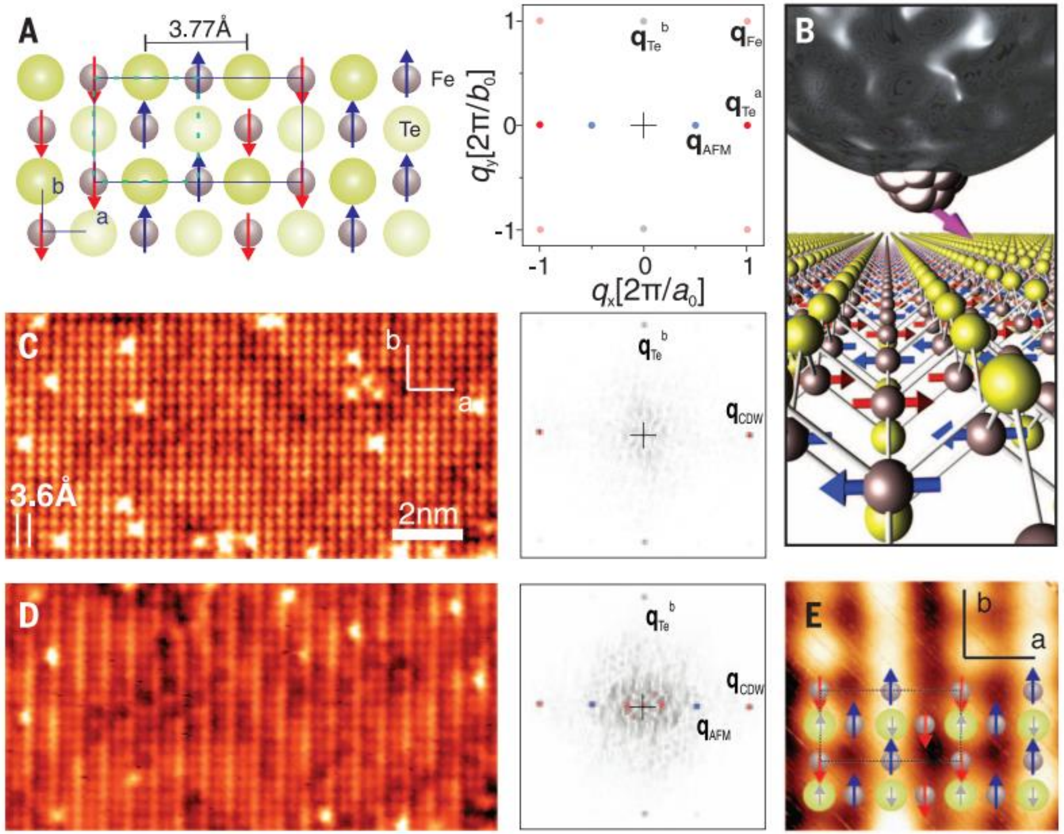
➢ Classical magnetism

Fe chain created by STM atom manipulation



Loth, *et al. Science* (2012)

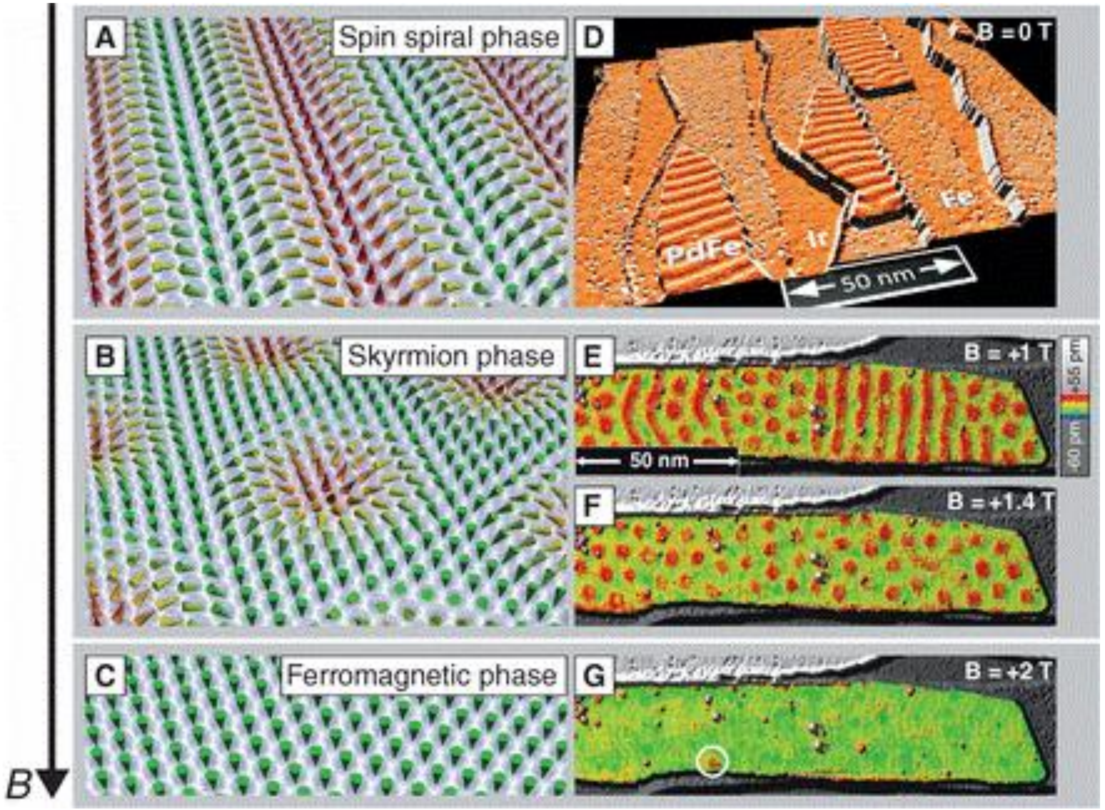
Surface of $Fe_{1+y}Te$ single crystal



Enayat, *et al. Science* (2014)

Spin-polarized tunneling

- Magnetic skyrmion

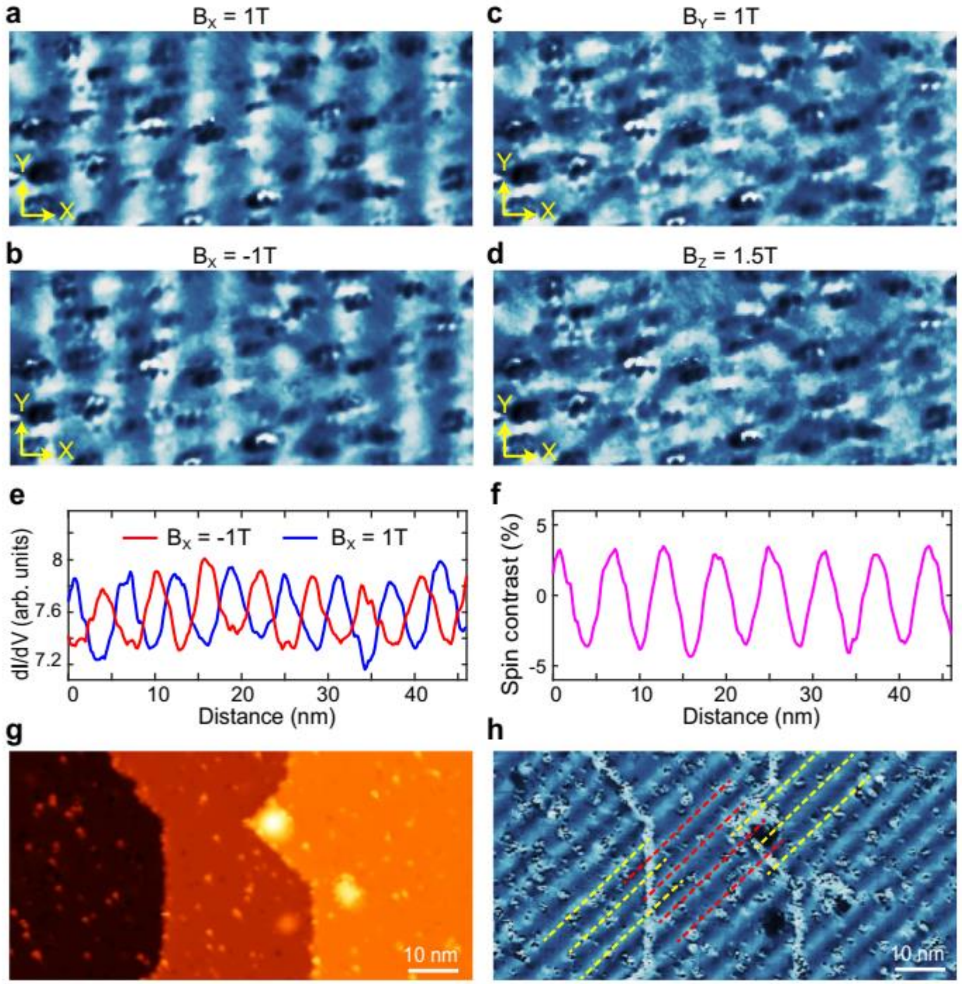


- Magnetic skyrmion: PdFe bilayer on Ir(111) surface

Romming, *et al. Science* (2013)

- Spin density wave

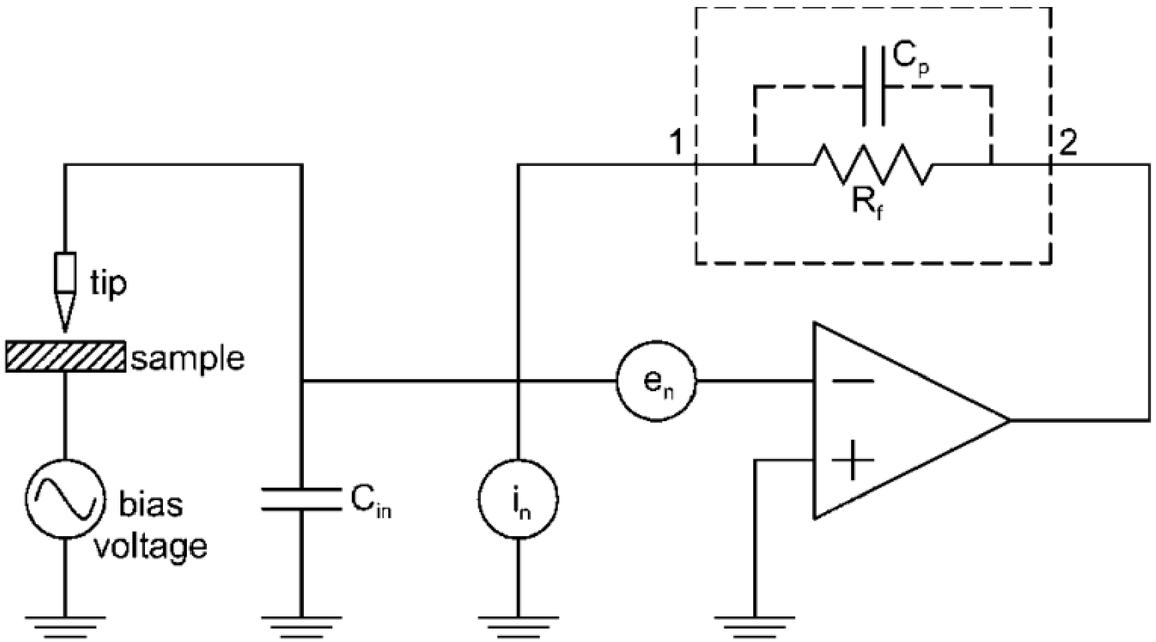
Cr(001) surface



Hu, *et al. Nature Commun.* (2022)

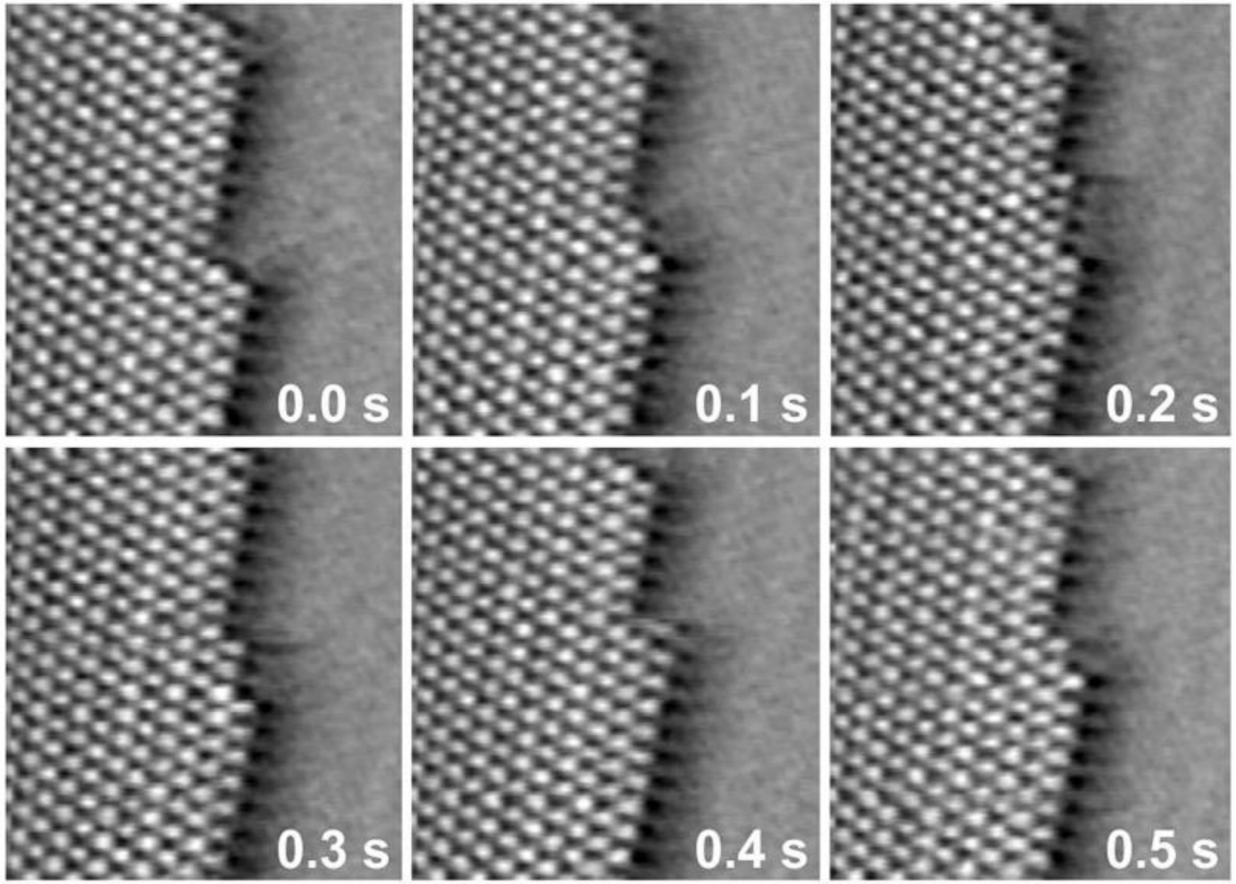
Time-resolved STM

- STM preamplifier



- Bandwidth: 10 KHz to 1MHz
- Time resolution: 1-100 μs

- Video-rate STM

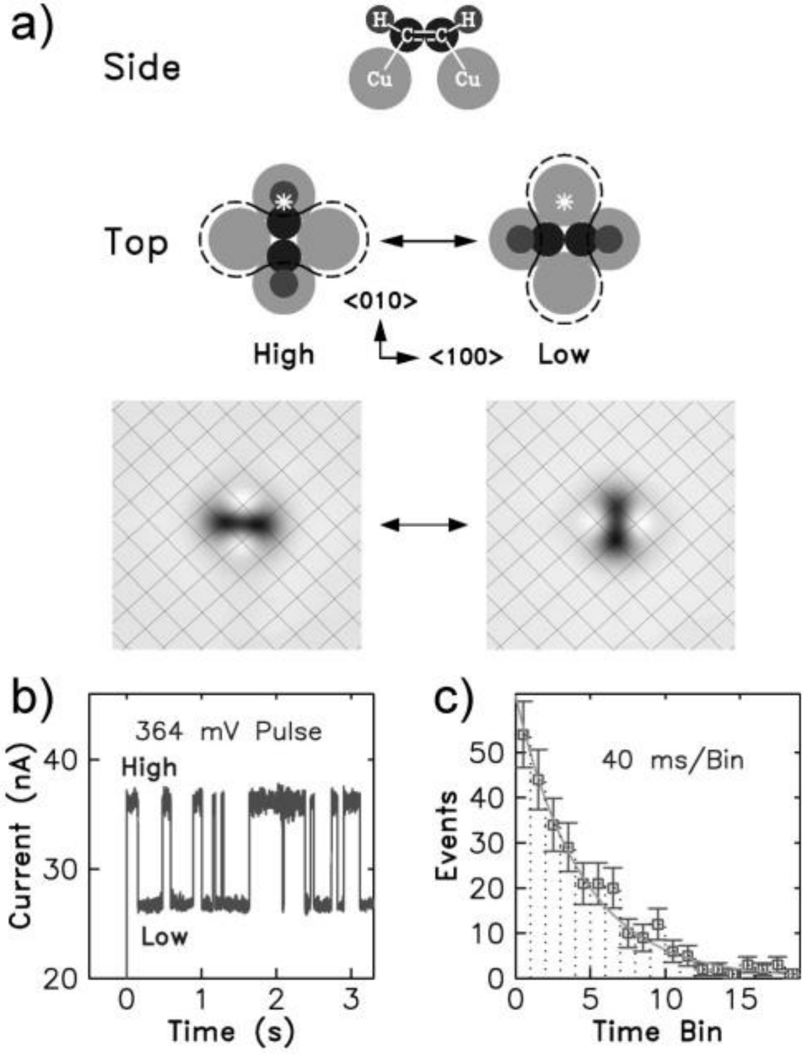


Sequences of STM images of Bi deposits on Au(100)

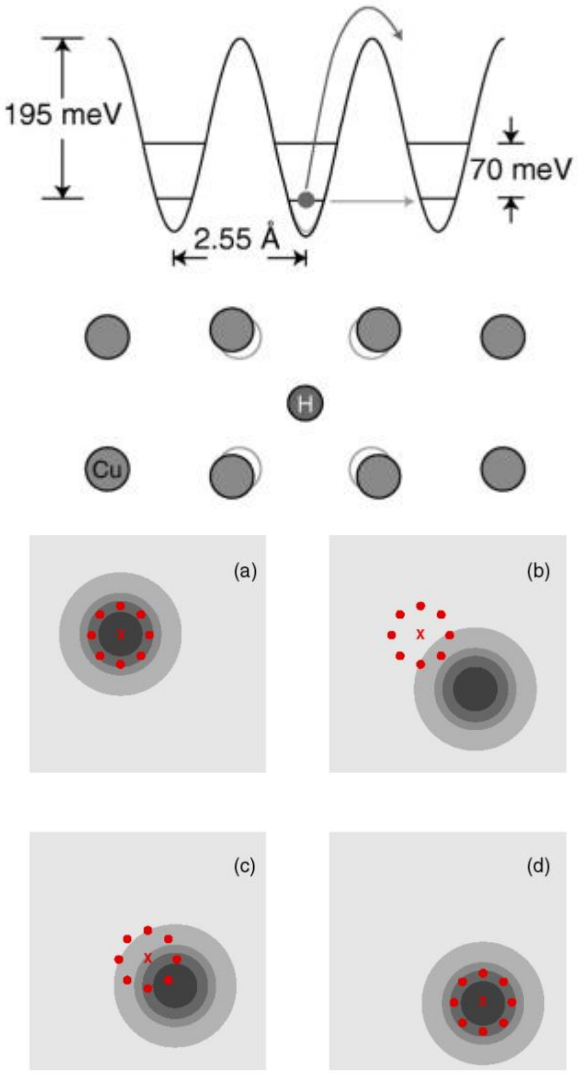
Matsushima, *et al. Faraday Discuss.* (2016)

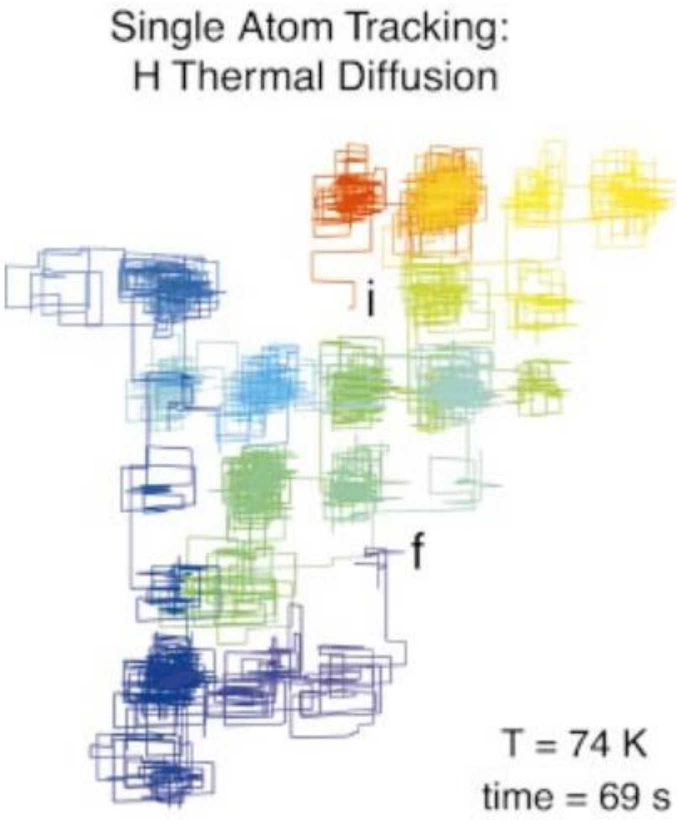
Time-resolved STM

- Recording *I*(t) curve



- Single atom tracking

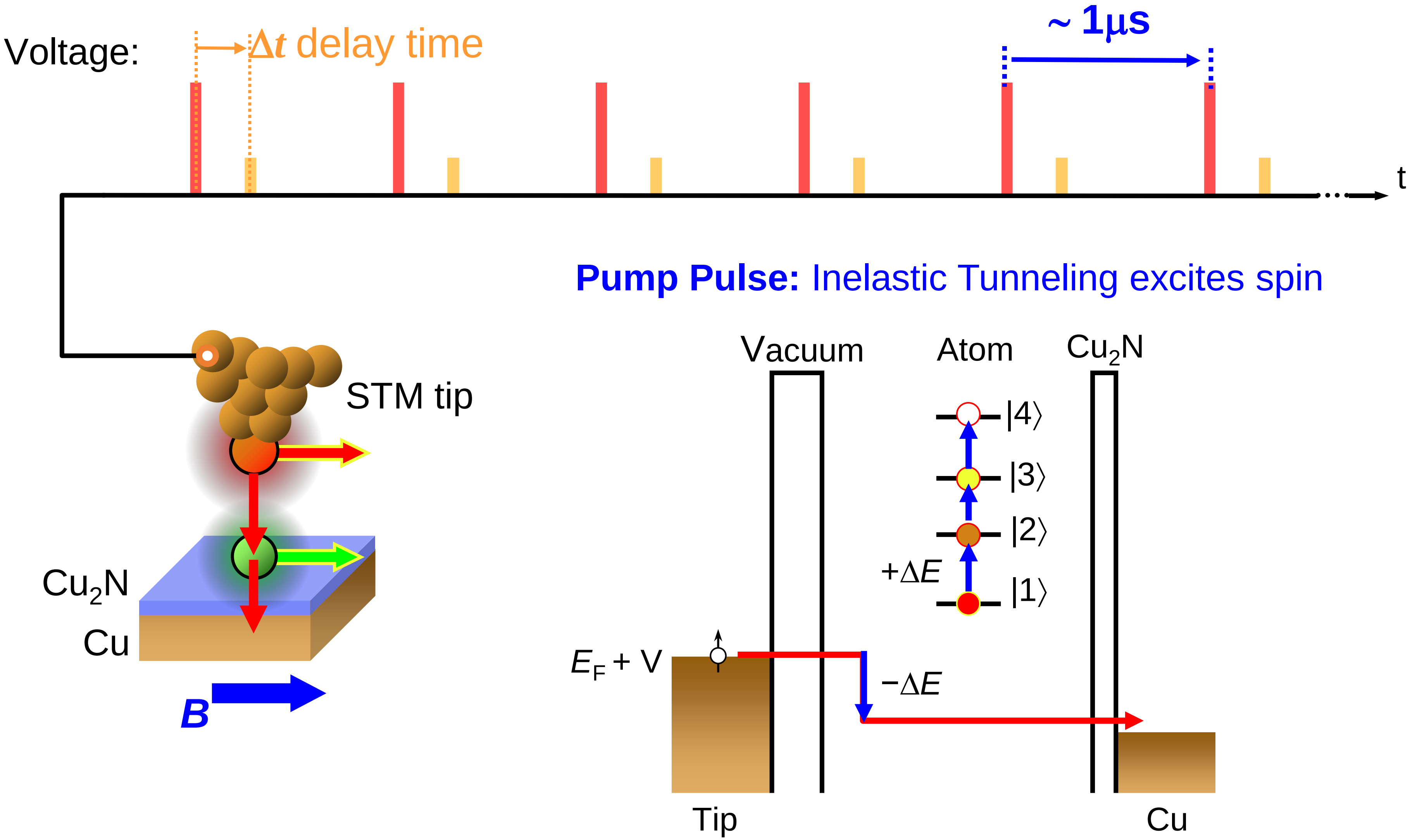




W. Ho, *et al. JCP* (2002)

Time-resolved STM

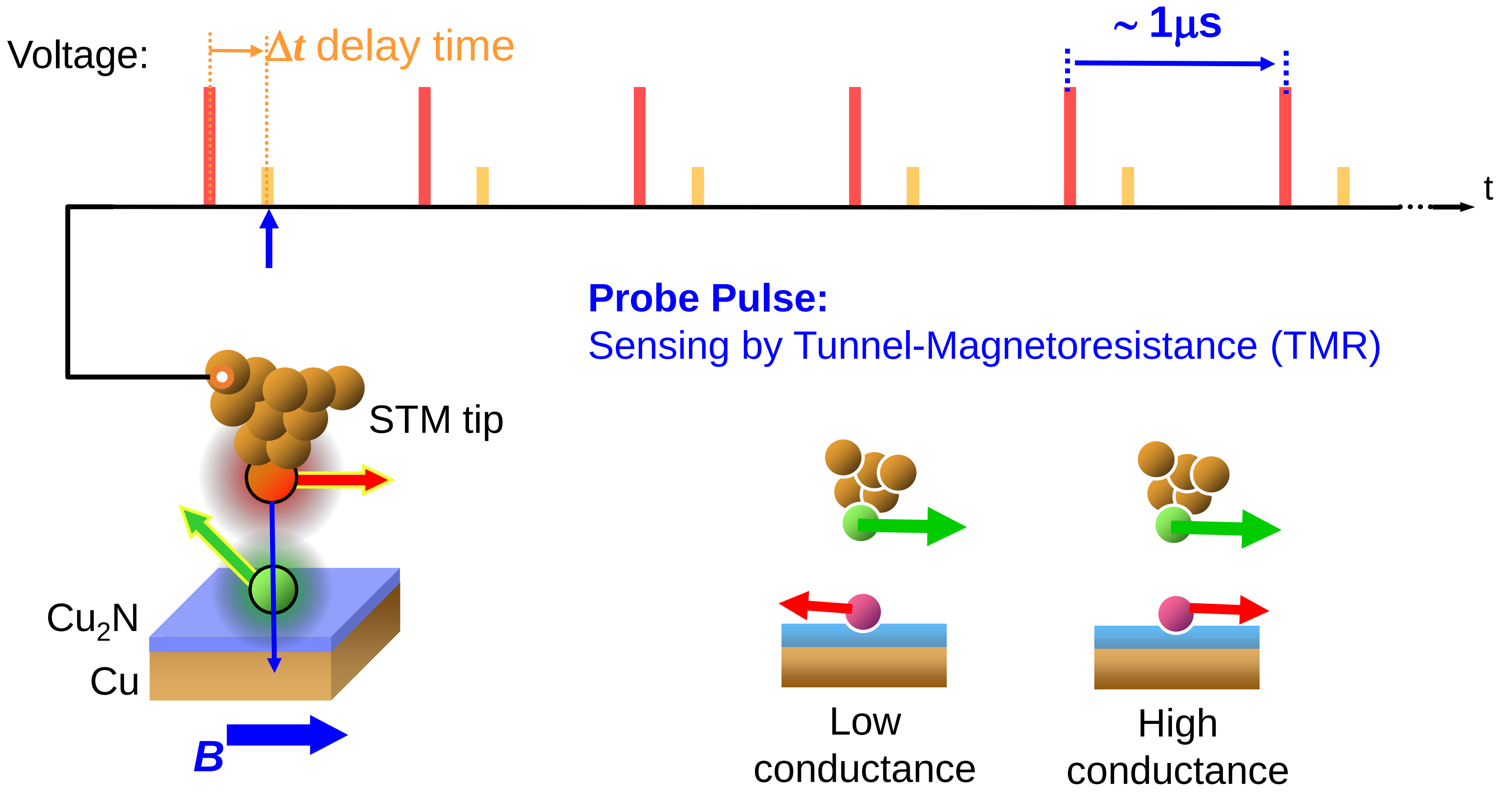
- Electronic pump-probe technique



Delgado *et al. PRL* 104 026601 (2010), Loth *et al. Nature Physics* (2010)

Time-resolved STM

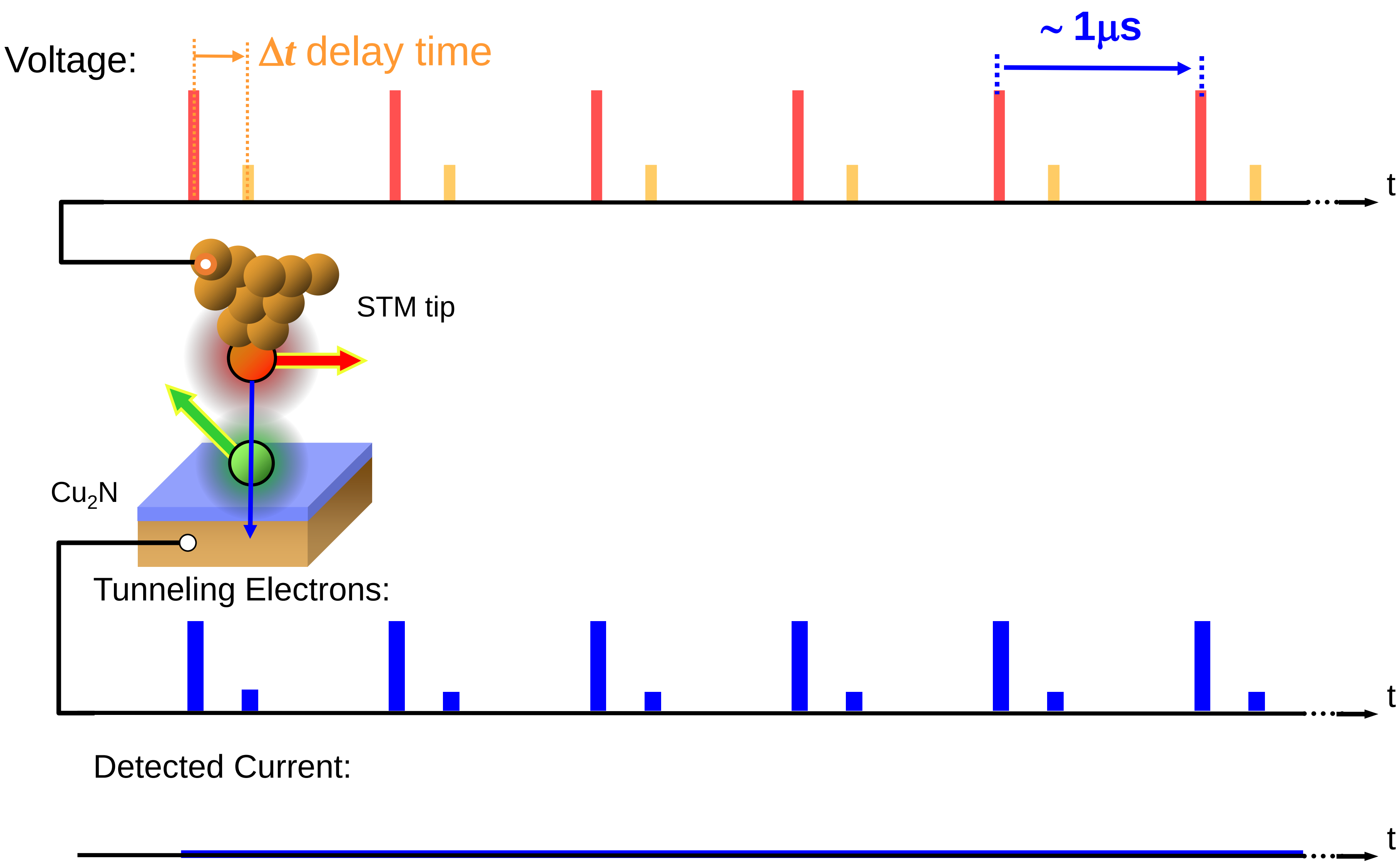
- Electronic pump-probe technique



Loth *et. al.*, *Science* (2010)

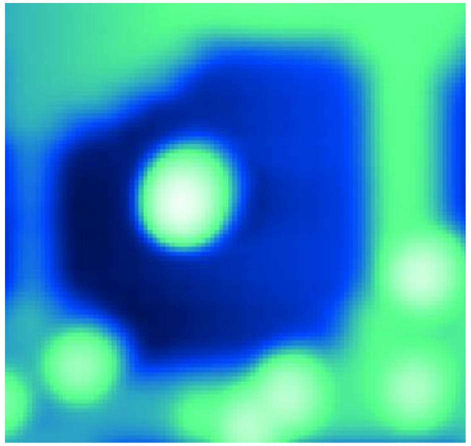
Time-resolved STM

- Electronic pump-probe technique

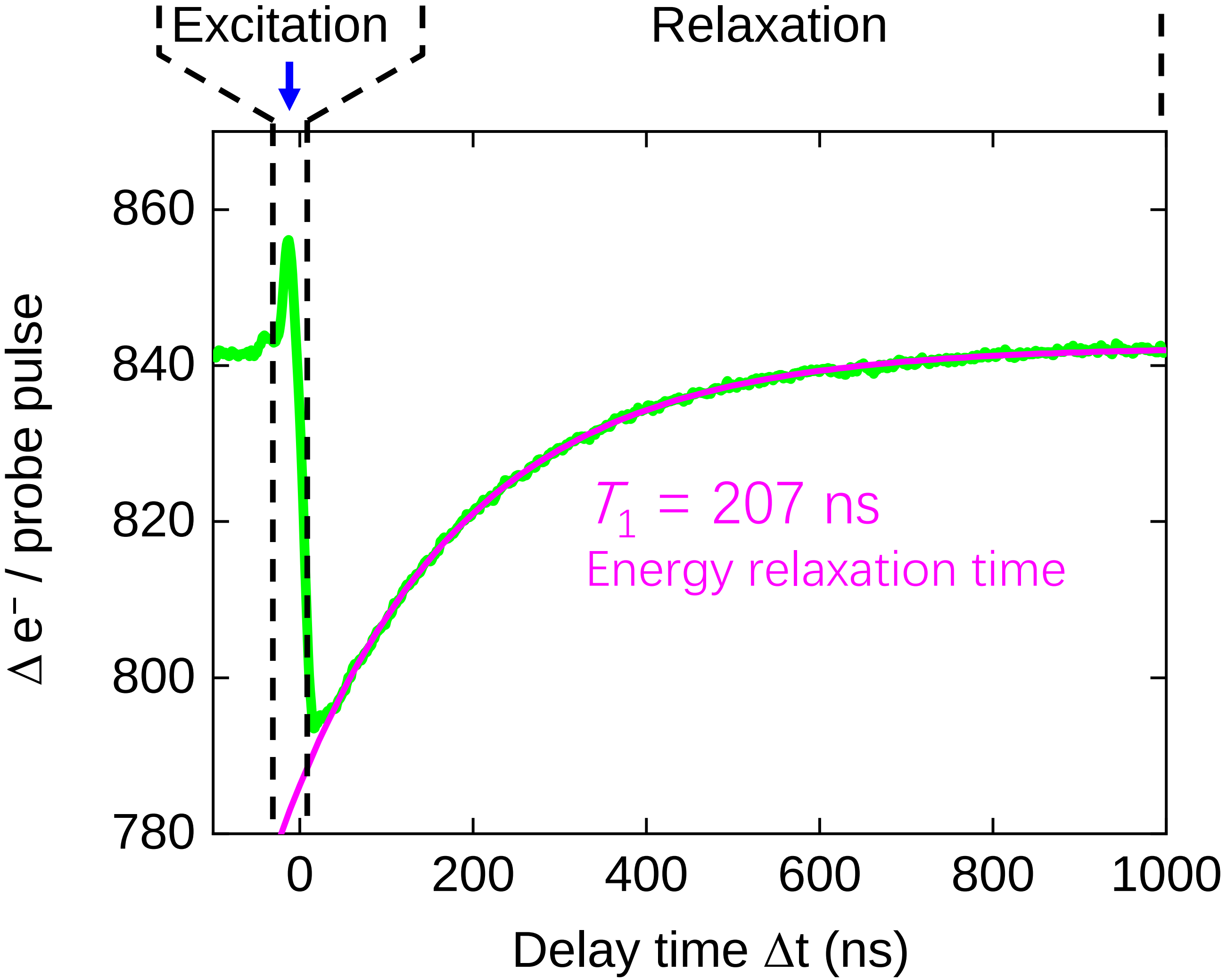


Time-resolved STM

- Electronic pump-probe technique



Close spaced
Fe-Cu dimer
B = 6.5 T

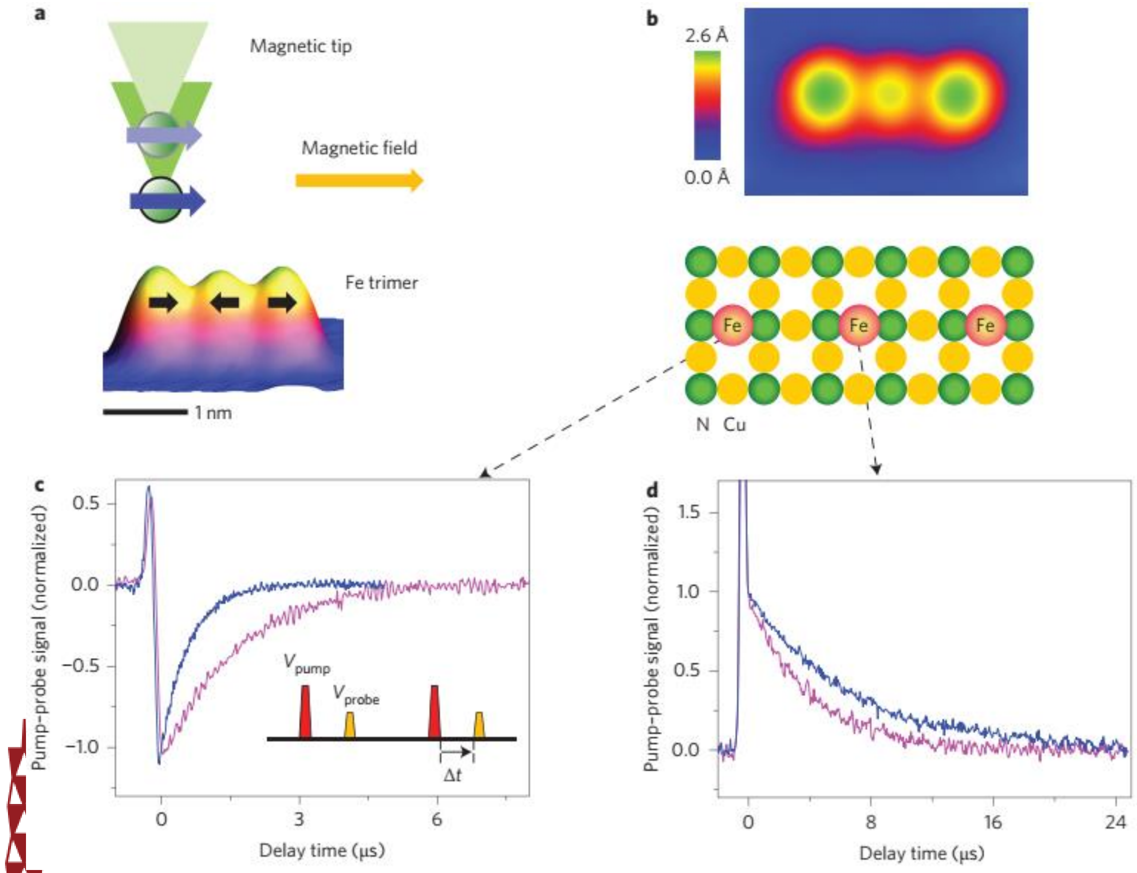


Loth *et. al.*, *Science* (2010)

Time-resolved STM

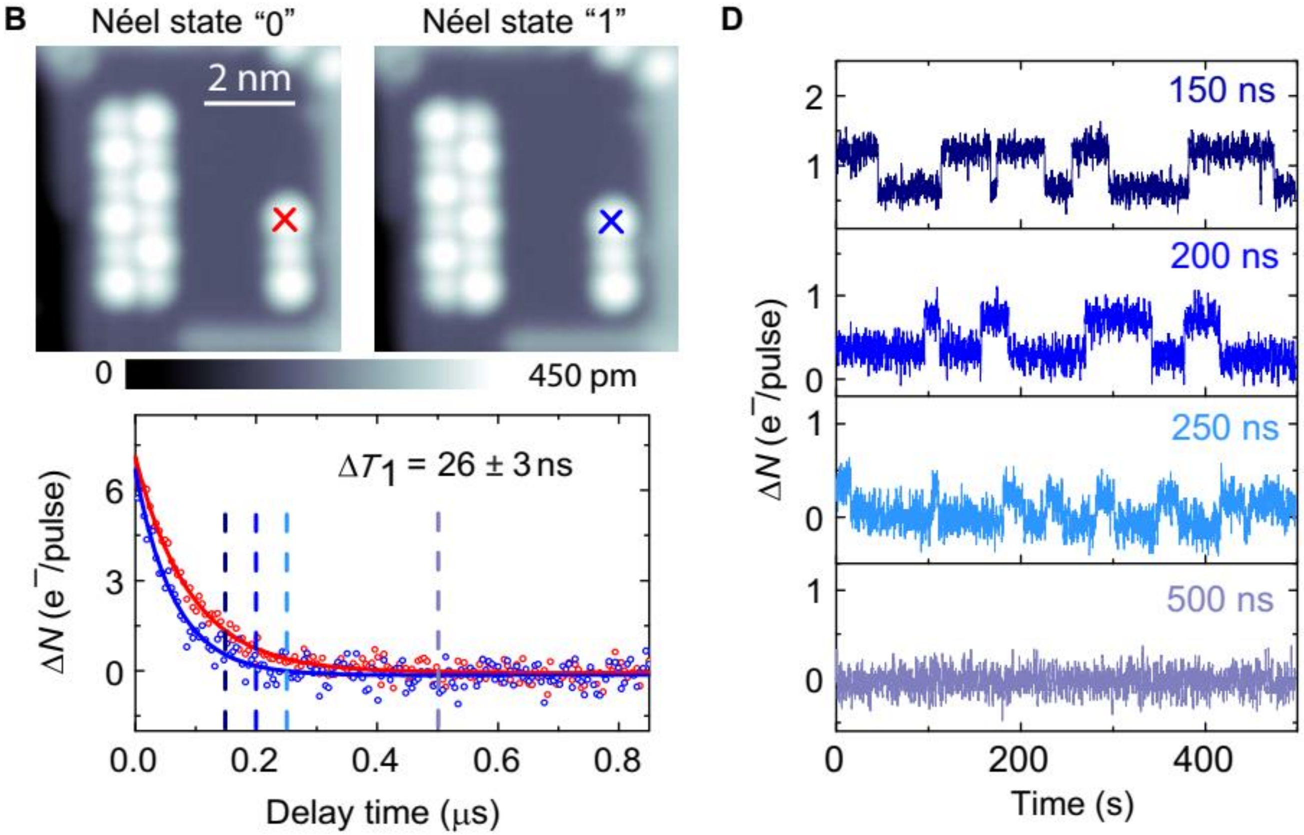
➢ Electronic pump-probe technique

- Control spin dynamics with SP-tip



S. Yan *et. al.*, *Nature Nanotech.* (2015)

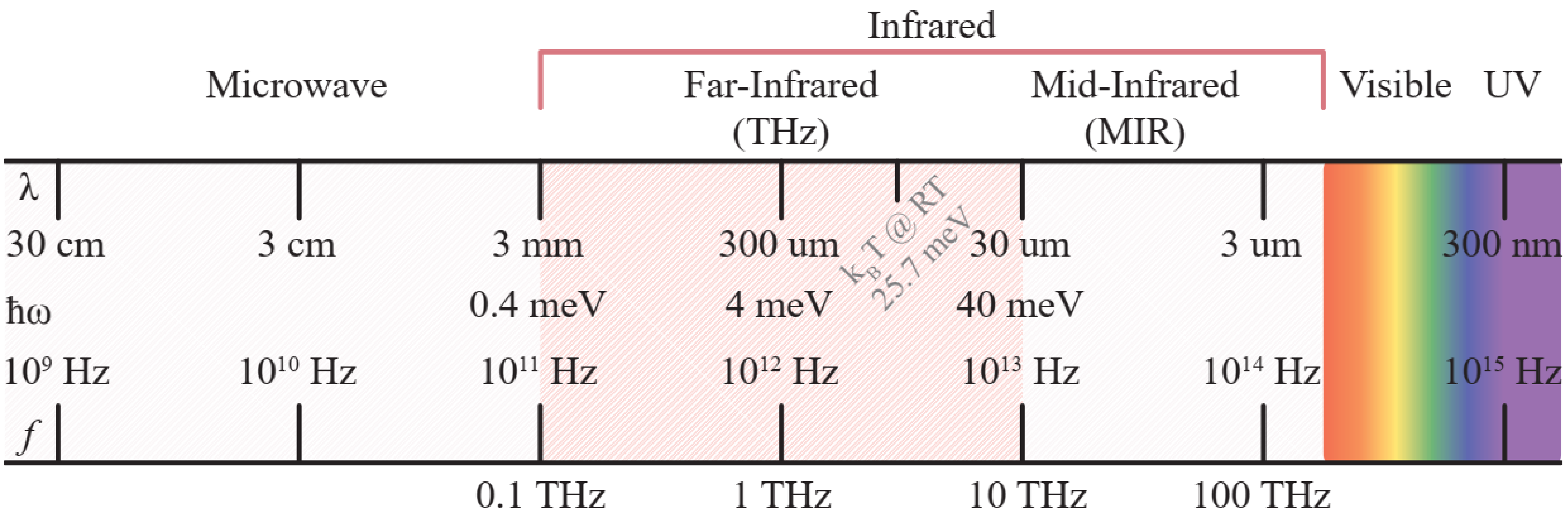
- Sensing local magnetic environment



S. Yan *et. al.*, *Science Adv.* (2017)

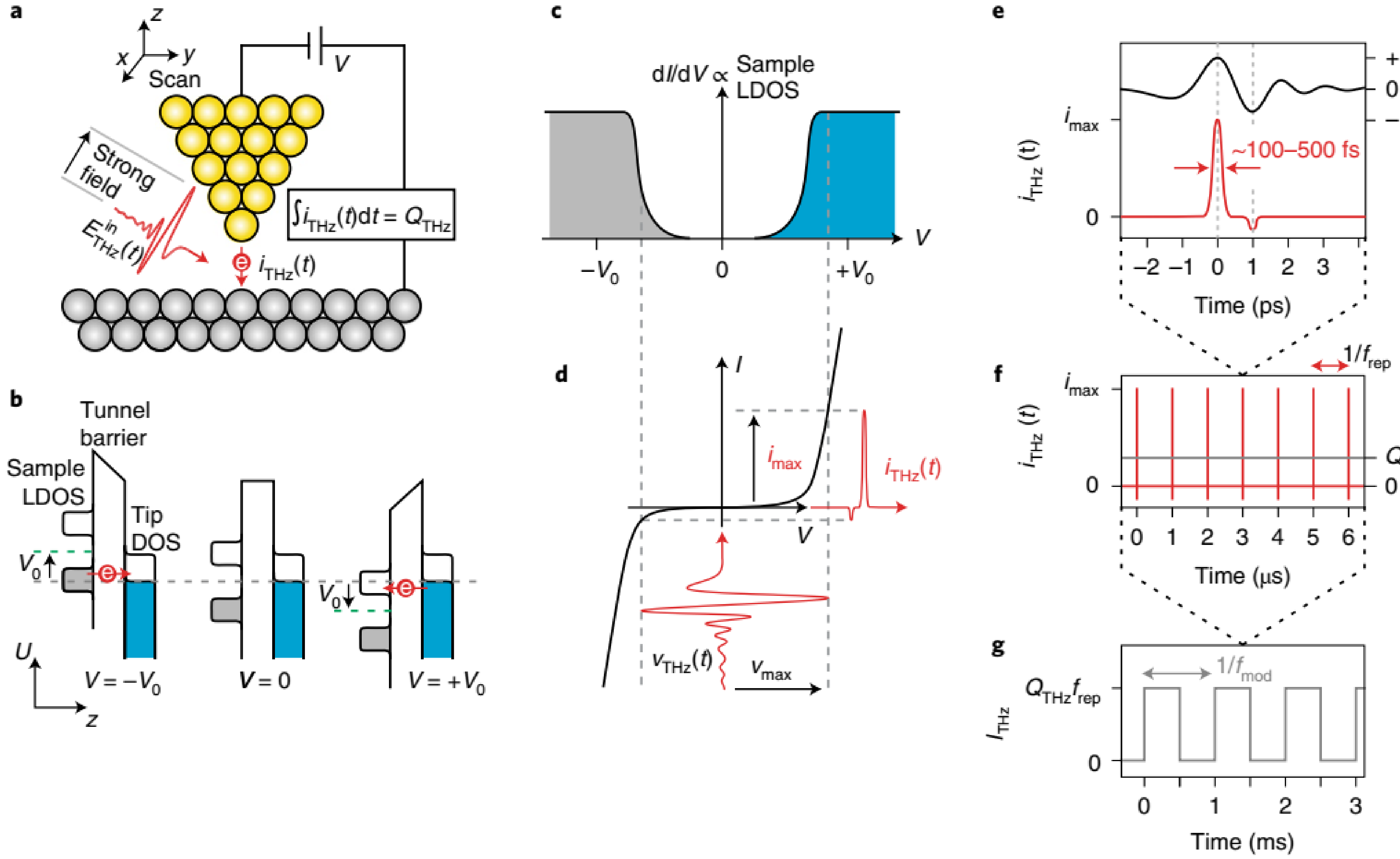
Time-resolved STM

- THz-STM technique



Time-resolved STM

- THz-STM technique

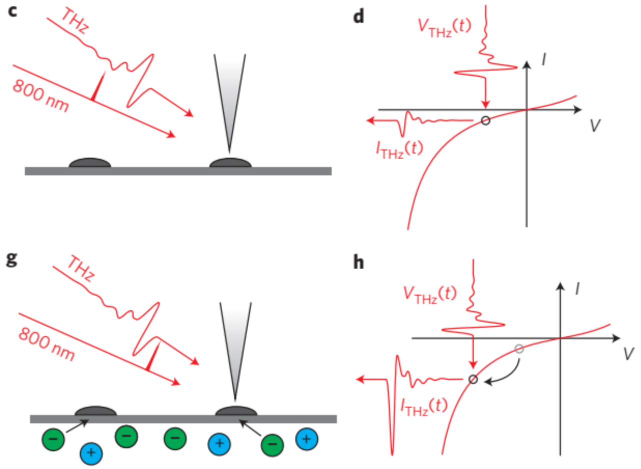


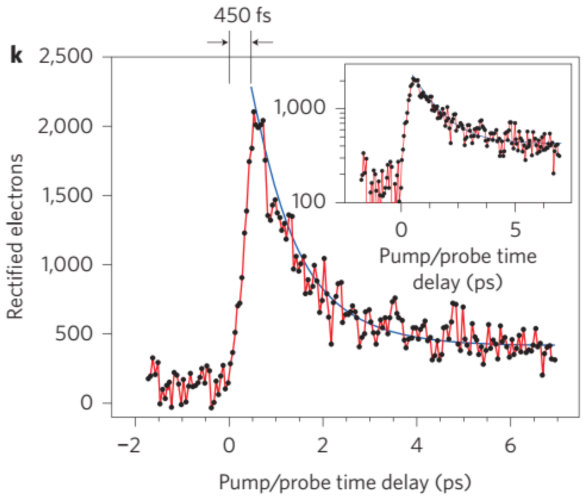
- In THz-STM, the static bias voltage (V_{DC}) is replaced by a time-dependent bias modulation ($V_{THz}(t)$) created by the electric field of a phase-stable single-cycle THz pulse coupled to the tip.

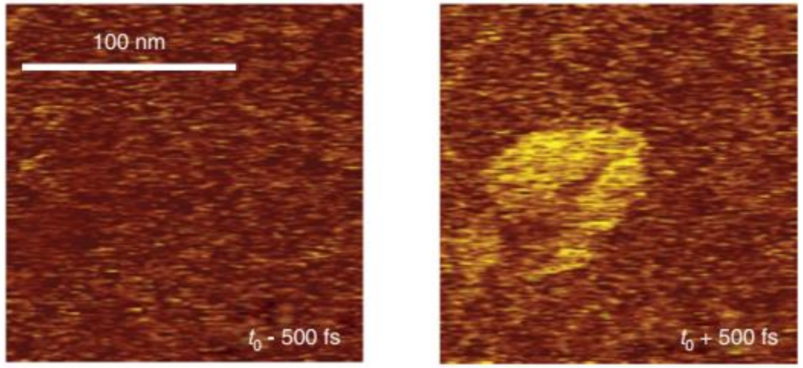
Cocker *et. al.*, *Nature Photonics* (2013)
Cocker *et. al.*, *Nature Photonics* (2021)

Time-resolved STM

- Transient charging of an InAs nanodot measured with THz-STM

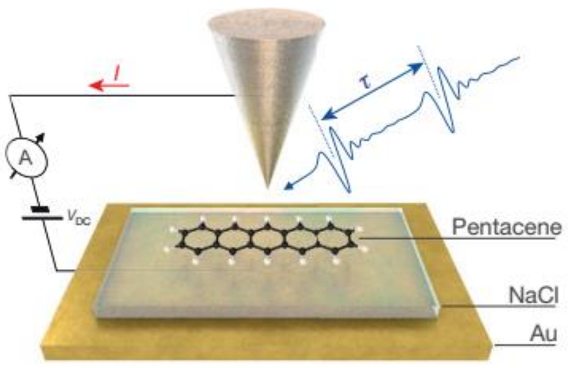


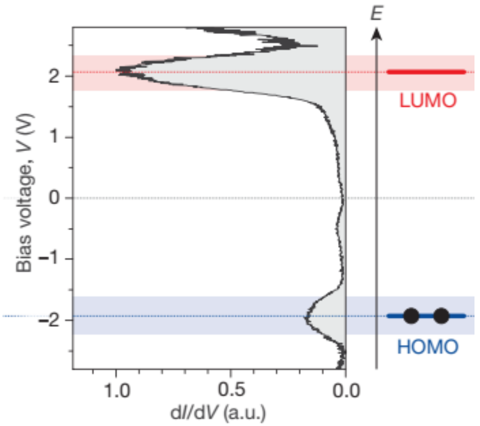


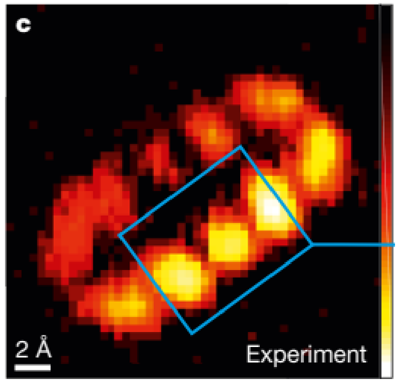


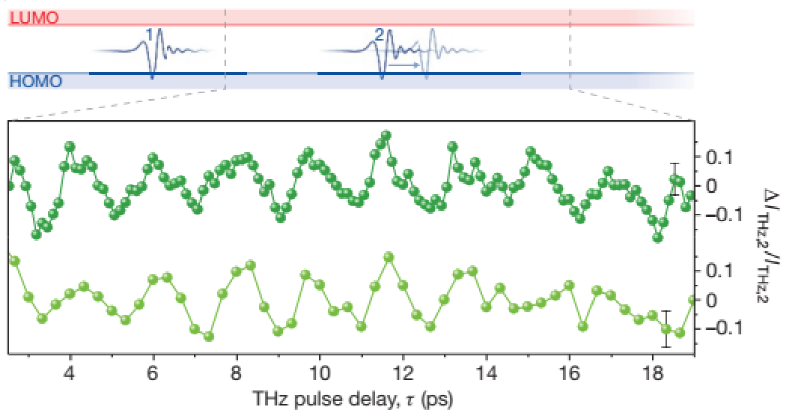
Cocker *et. al.*, Nature Photonics (2013)

- Tracking the ultrafast motion of a single molecule with THz-STM









Cocker *et. al.*, *Nature* (2016)

Summary

- Introduction for STM: principles and instrumentation
- Application of STM in the study of superconductivity
- Inelastic tunneling spectroscopy, spin-resolved STM, time-resolved STM