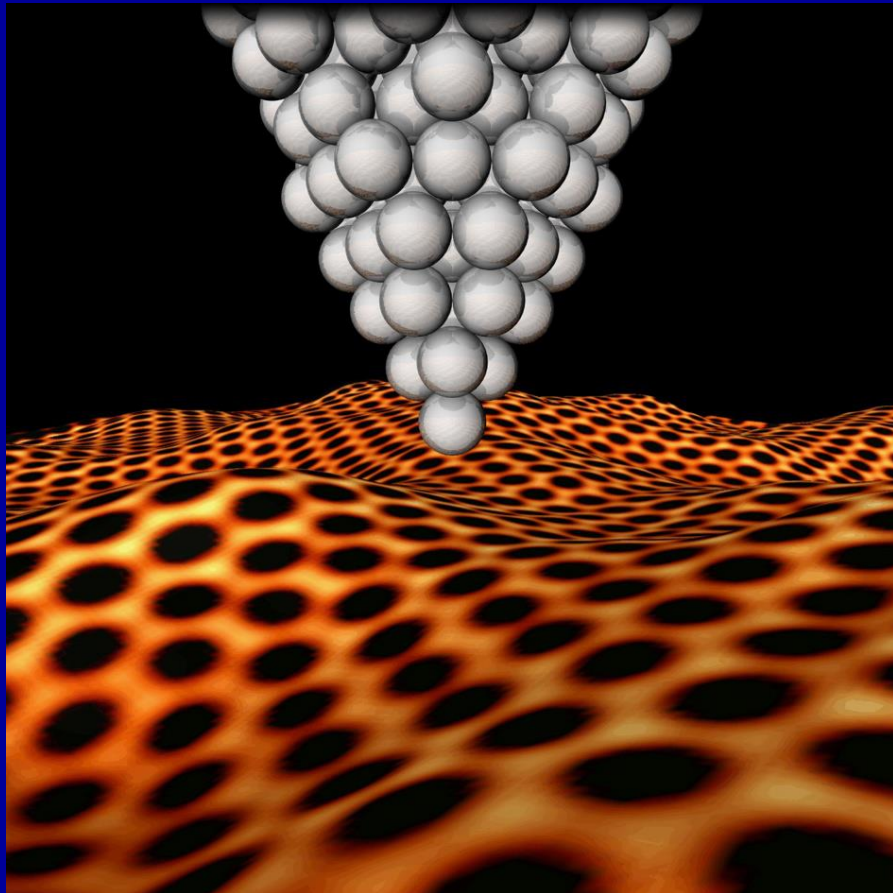
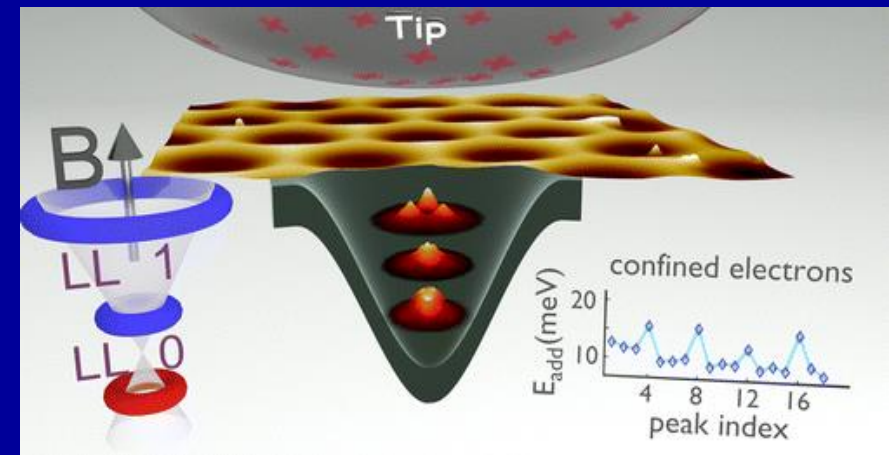
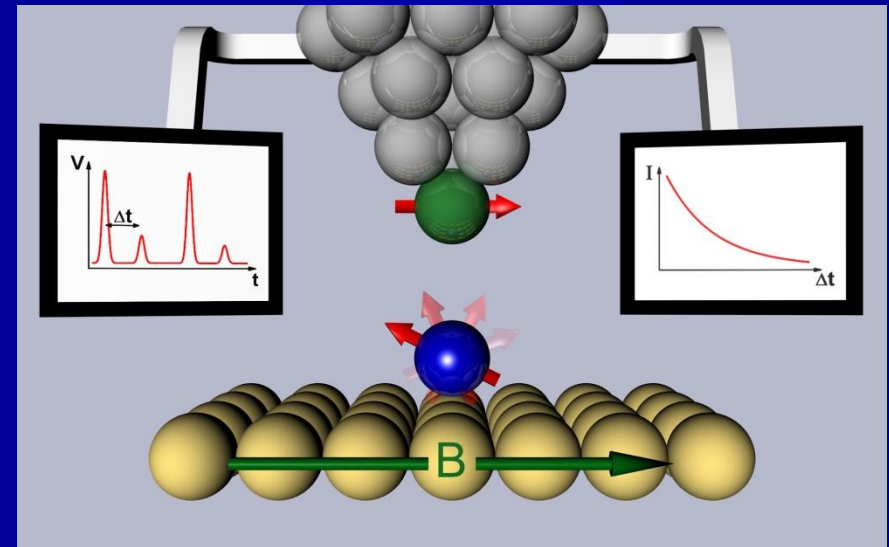


# The multiple facets of the scanning tunneling microscope

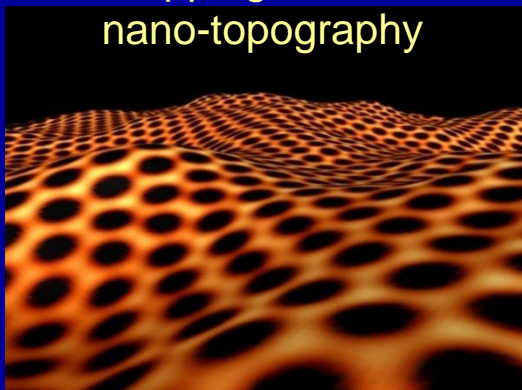


~ 3000 papers/year

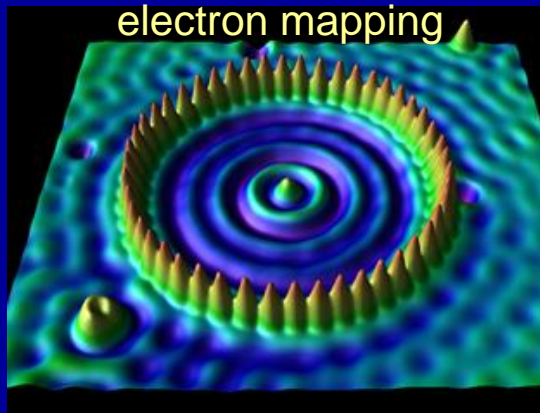


# Some options (passive)

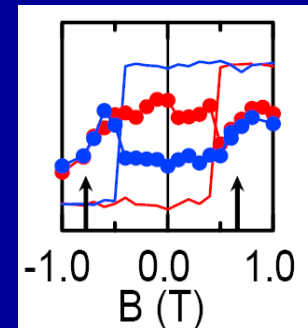
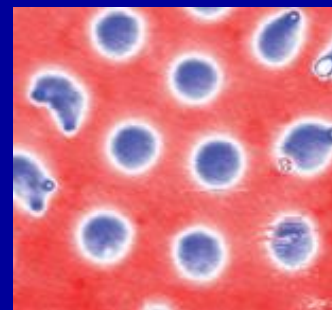
mapping atoms/  
nano-topography



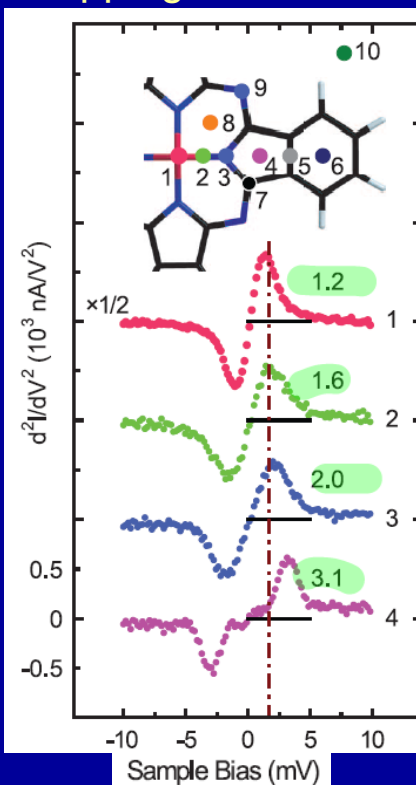
atom architecture  
electron mapping



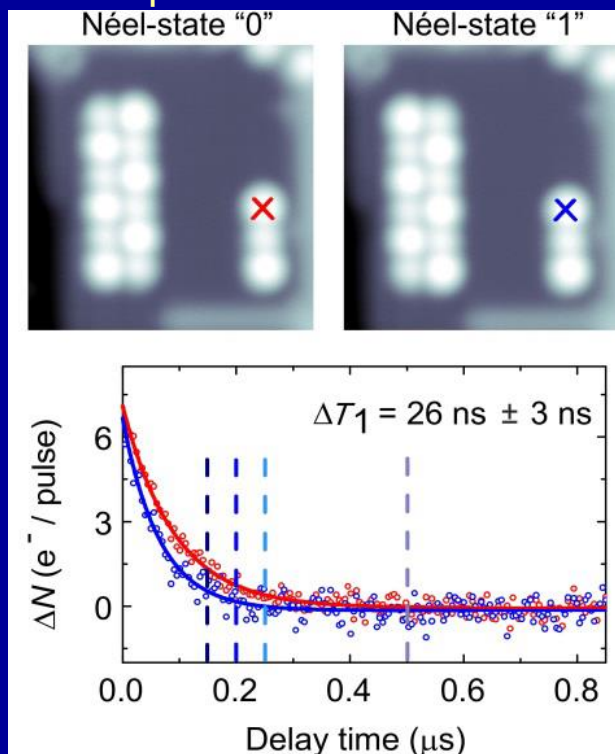
mapping spin textures/  
single atom hysteresis



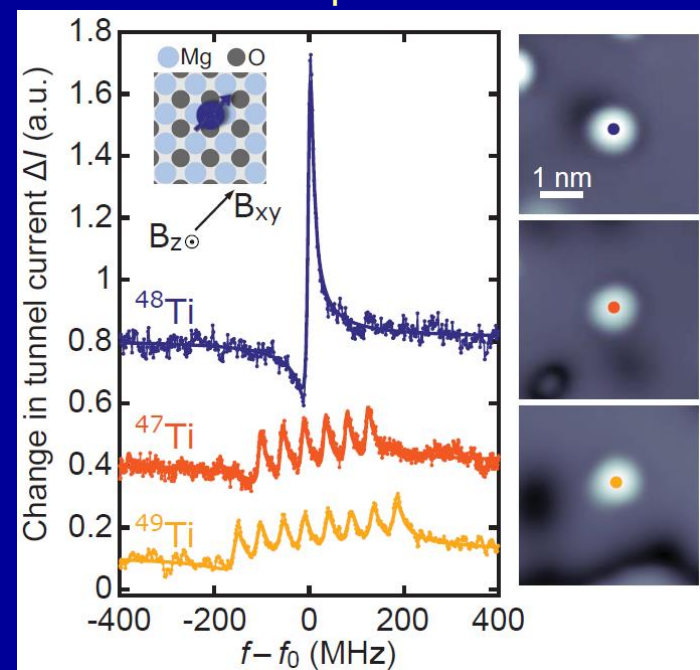
mapping vibrations



spin relaxation times

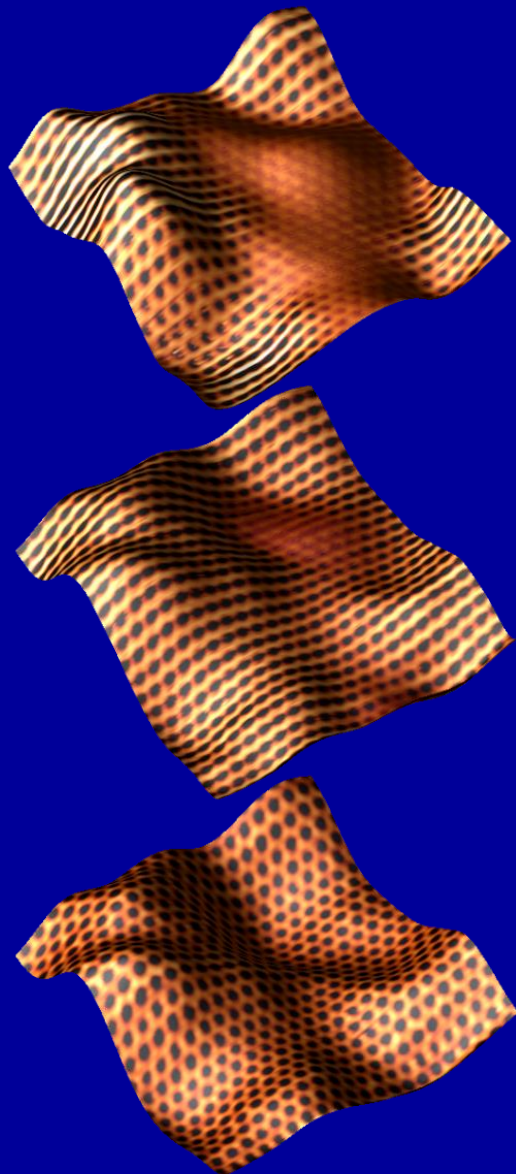


atomic scale  
electron spin resonance

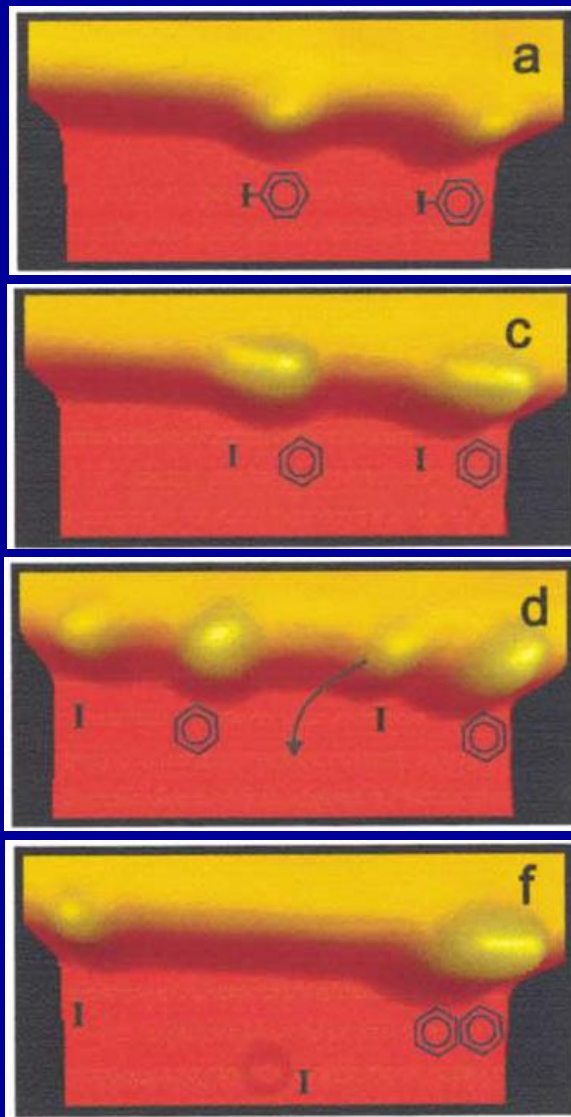


# Some options (active)

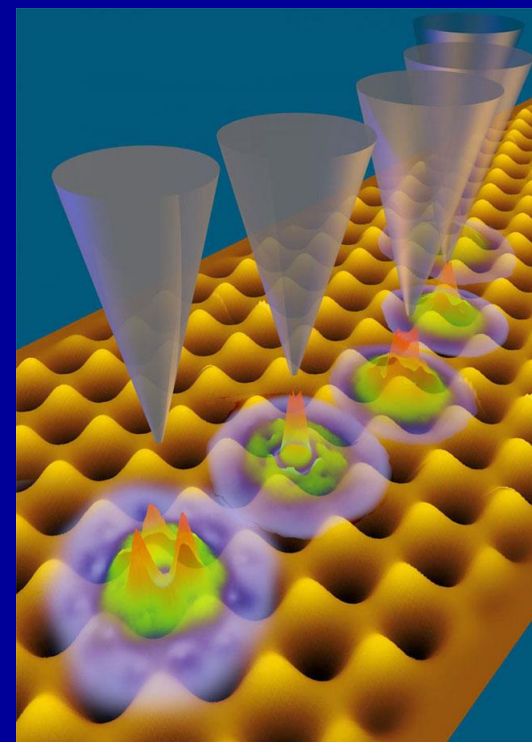
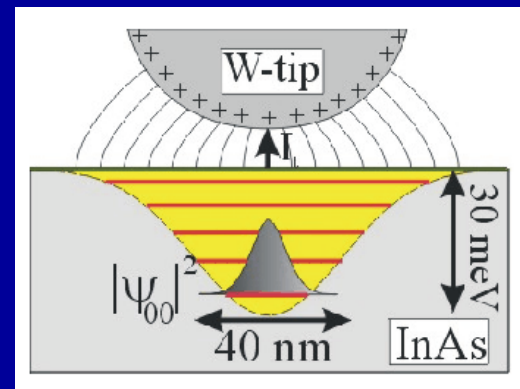
nano-stretching by  
vdW forces  
(pseudomagnetism)



chemistry step by step



gating by the tip



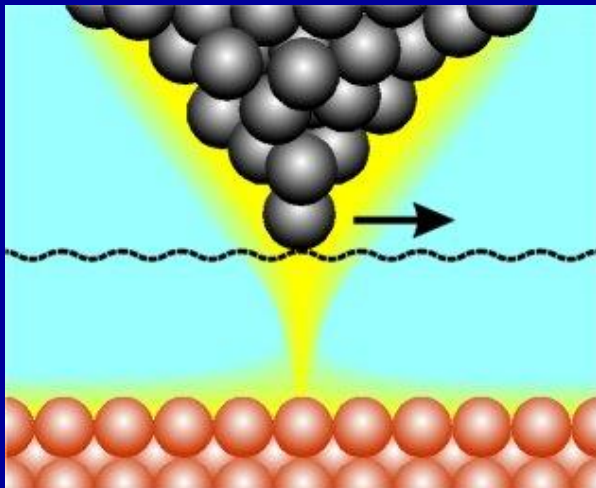
But I am not afraid to consider the final question: on as to whether, ultimately - in the great future - we can arrange the atoms the way we want; the very atoms, all the way down!

What would happen if we could arrange the atoms one by one the way we want them (within reason, of course; you can't put them so that they are chemically unstable, for example). Up to now, we have been content to dig in the ground to find minerals. We heat them and we do things on a large scale with them, and we hope to get a pure substance with just so much impurity, and so on. But

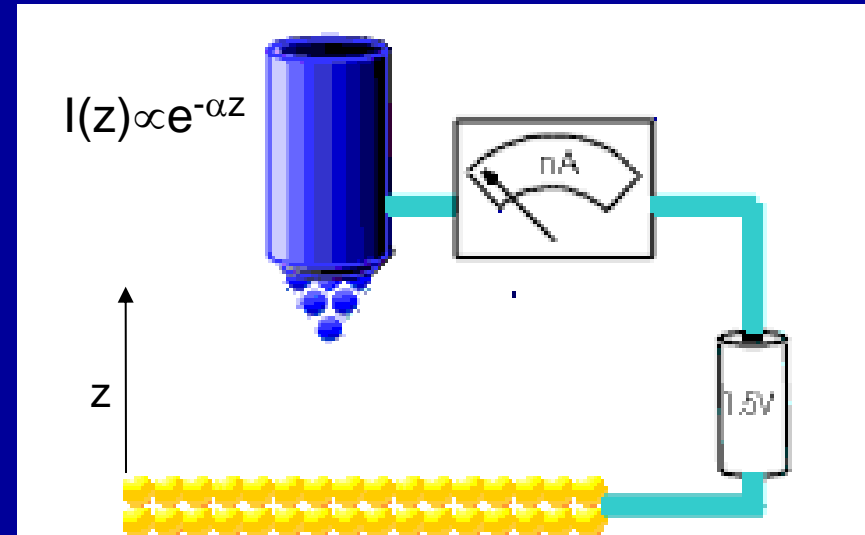
Feynman written in atomic bits (vacancies in Cl/Cu(001))

# The Basics (Instrumentation)

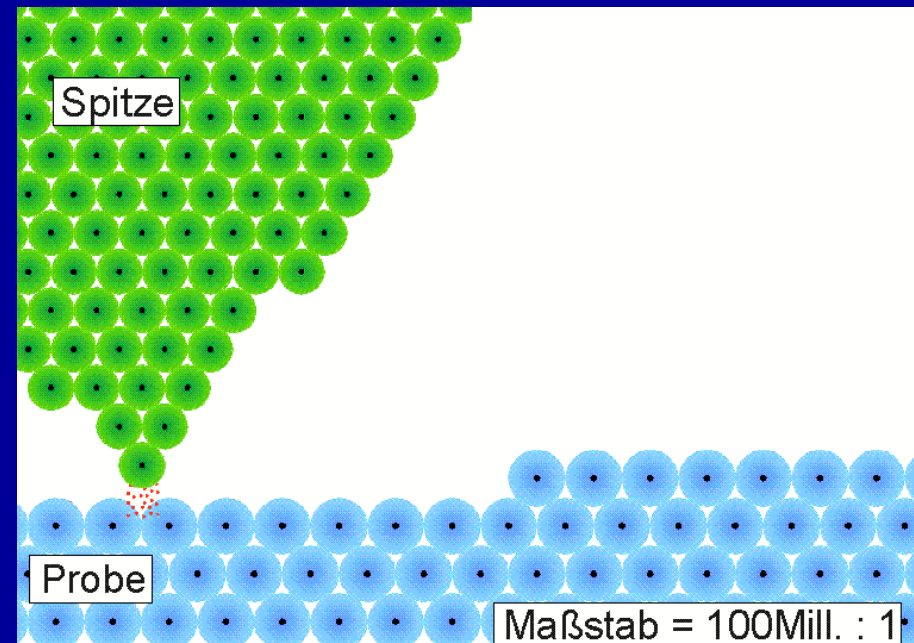
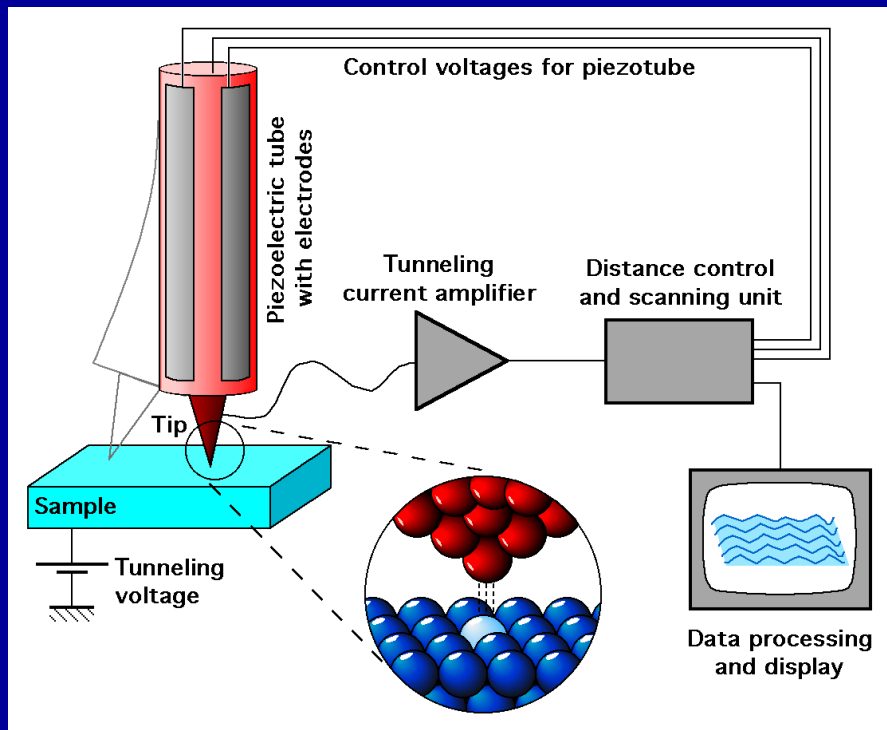
# Scanning Tunneling Microscope



probing the electron density



1 Å  $\equiv$  1 order of magnitude in current



exact control of tip-surface distance ( $\Delta \approx 1$  pm)

# Moving the tip by segmented piezo tubes

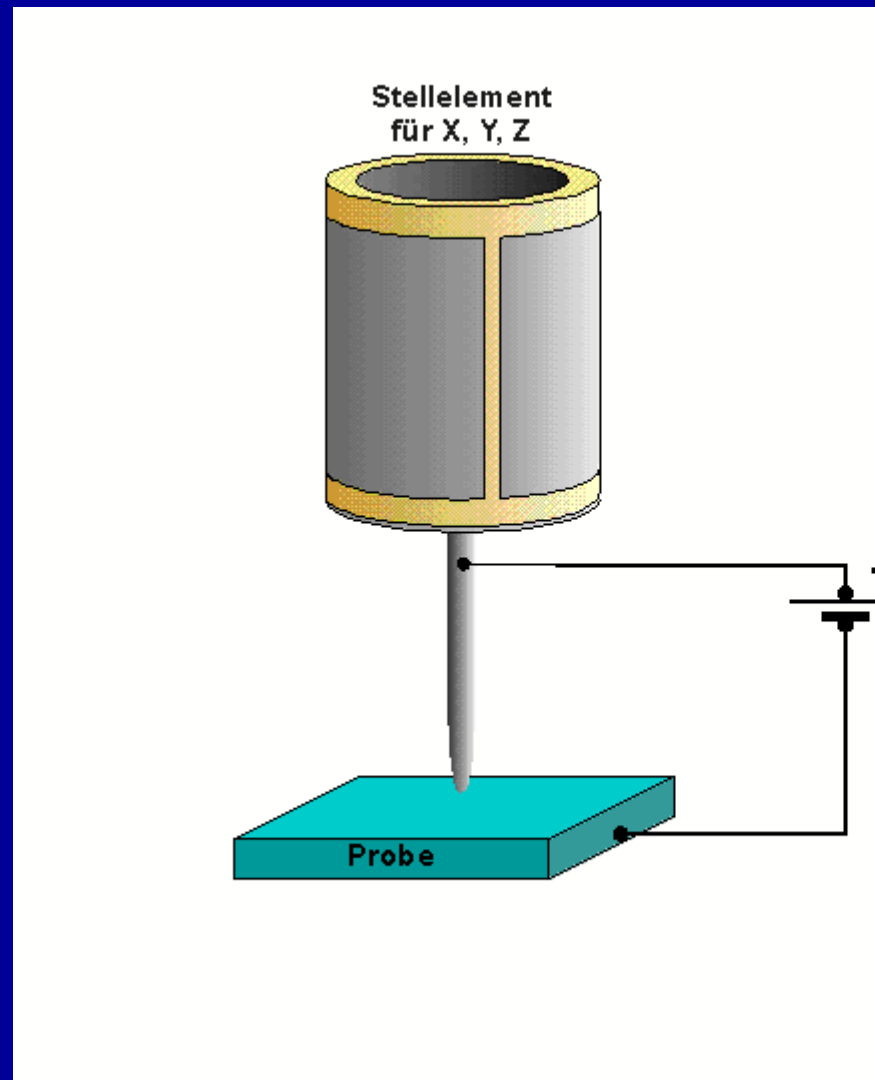
invented by

G. Binnig and H.  
Rohrer,

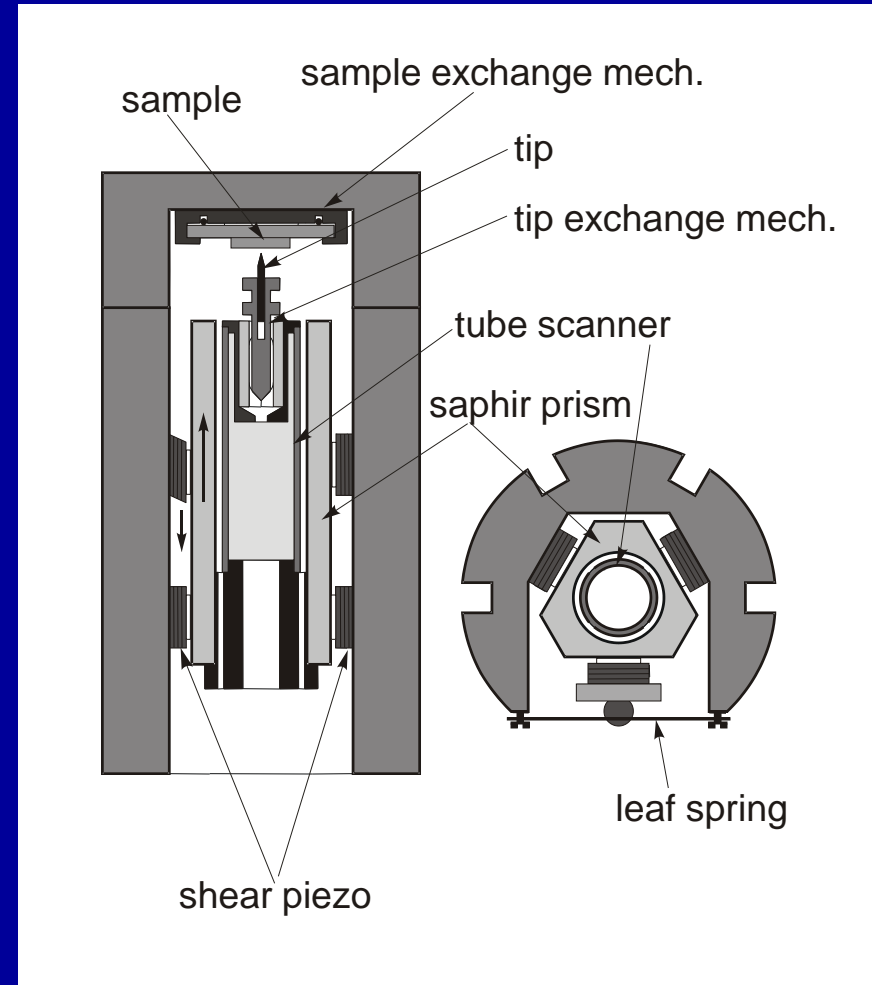
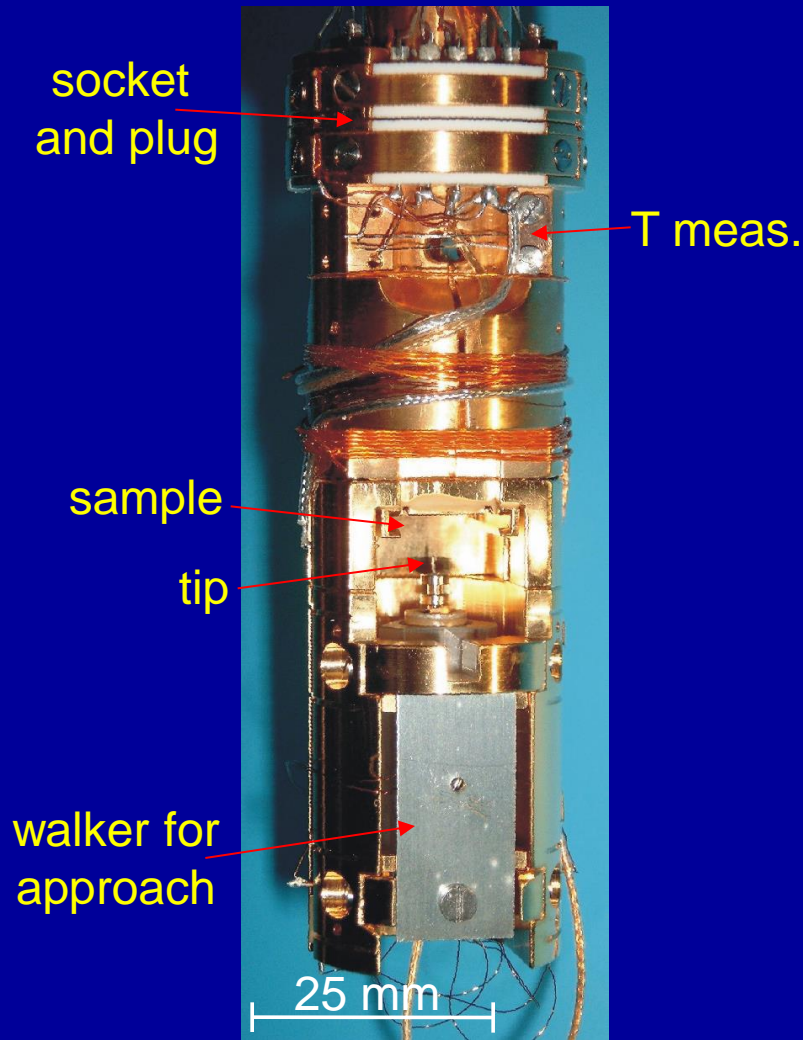
Helv. Phys. Acta **55**,  
726 (1982)

and

Phys. Rev. Lett. **50**,  
120 (1983)

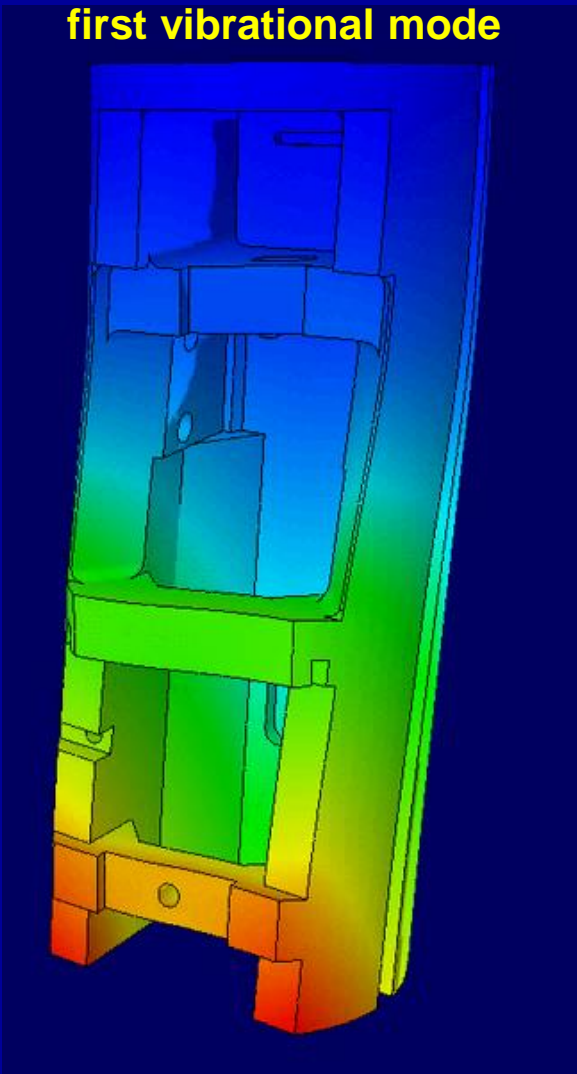
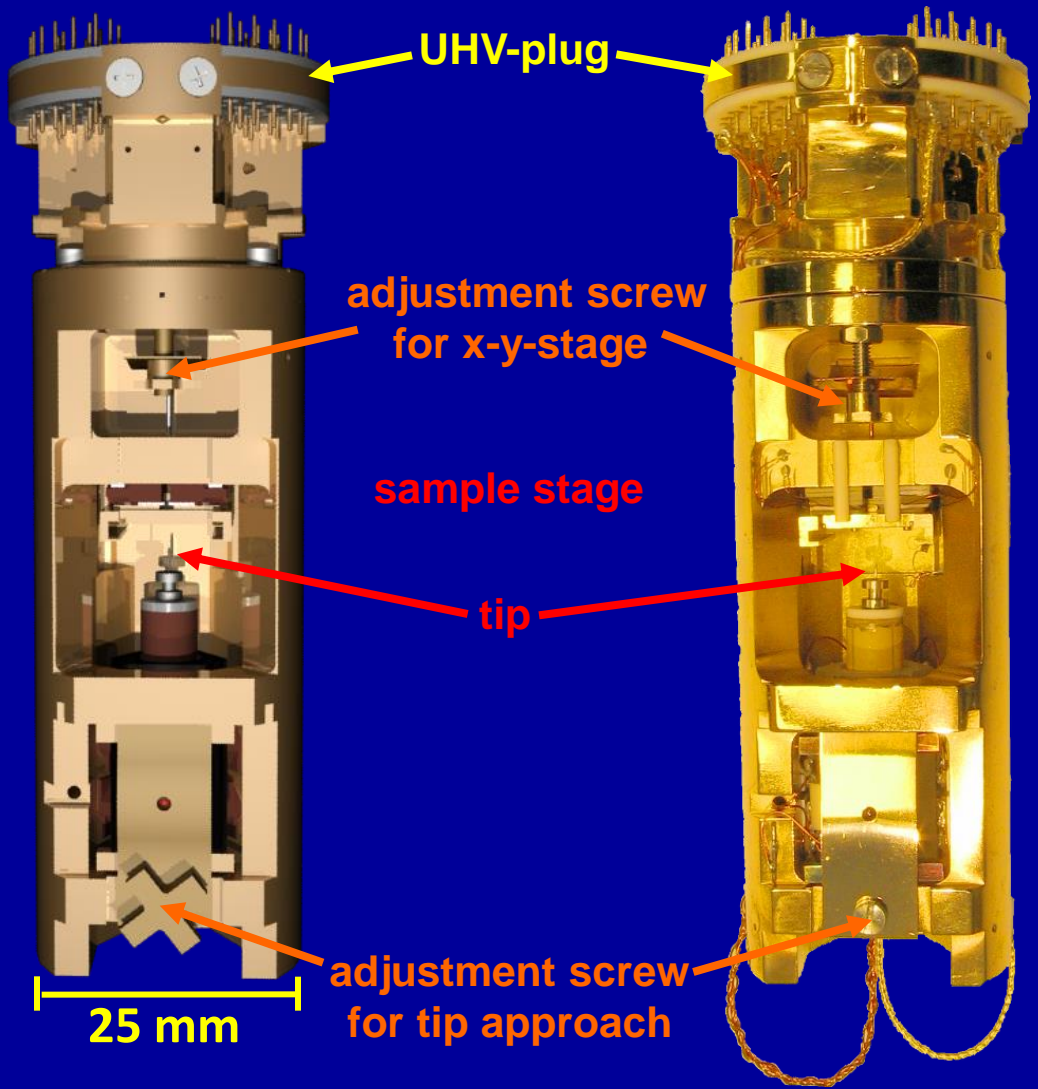


# The Microscope



• compact design: L: 85mm,  $\varnothing$ : 26mm, rigid and symmetric

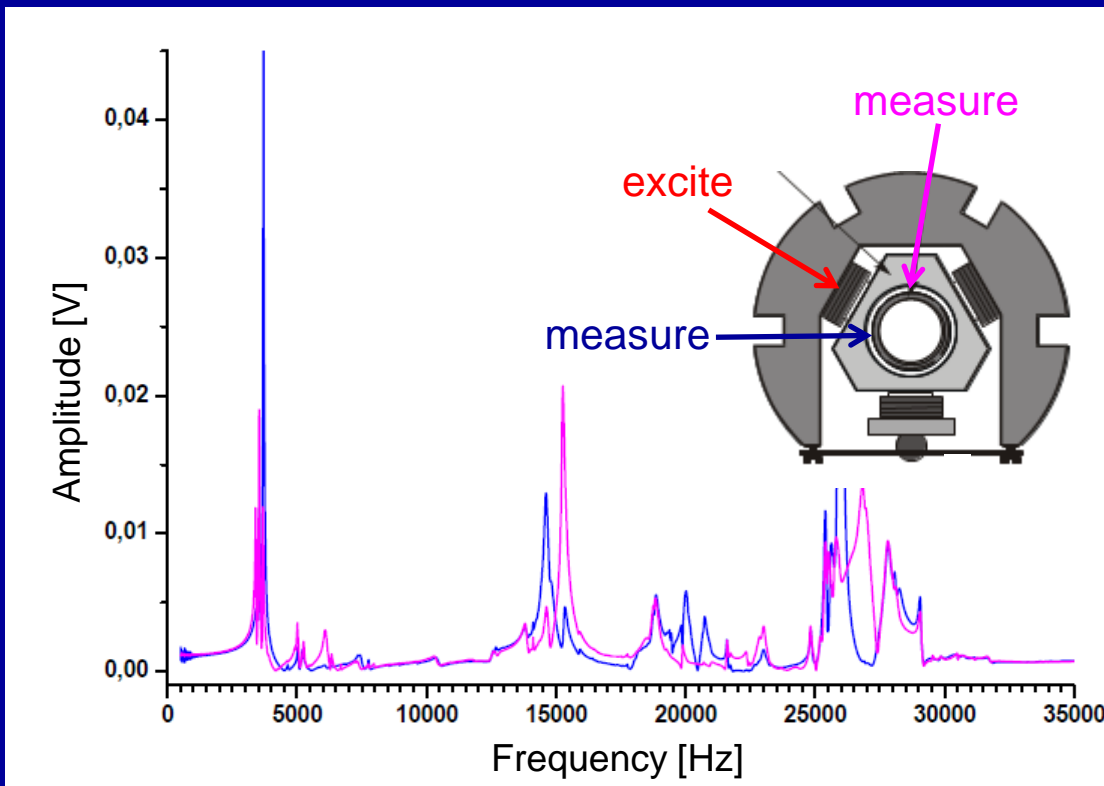
# Instrument design: STM



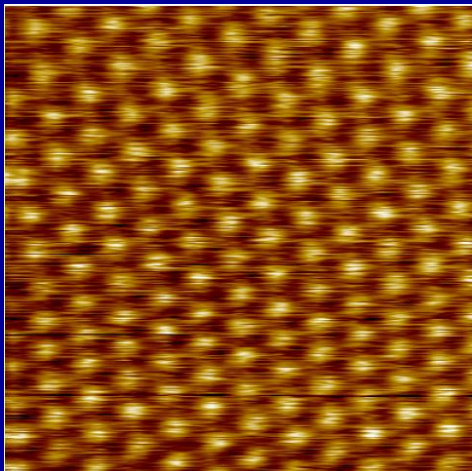
Design principles: rigid, compact, highly symmetric, adjustable in UHV

# Microscope characterization

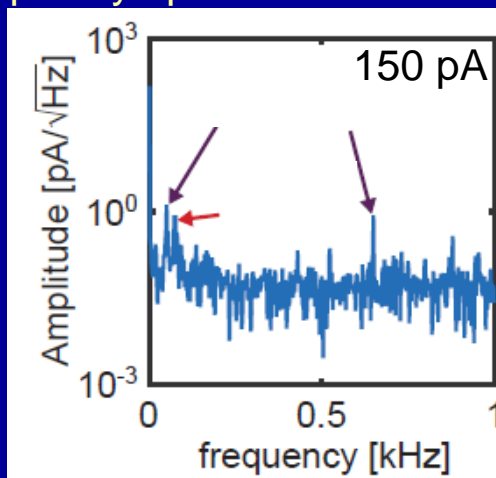
Excitation spectroscopy



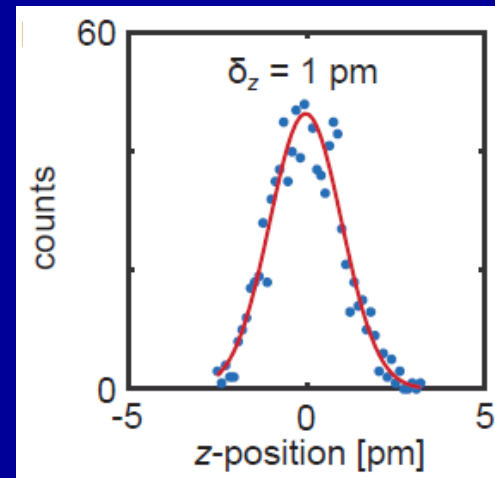
Atomic imaging



Frequency spectrum tunnel current

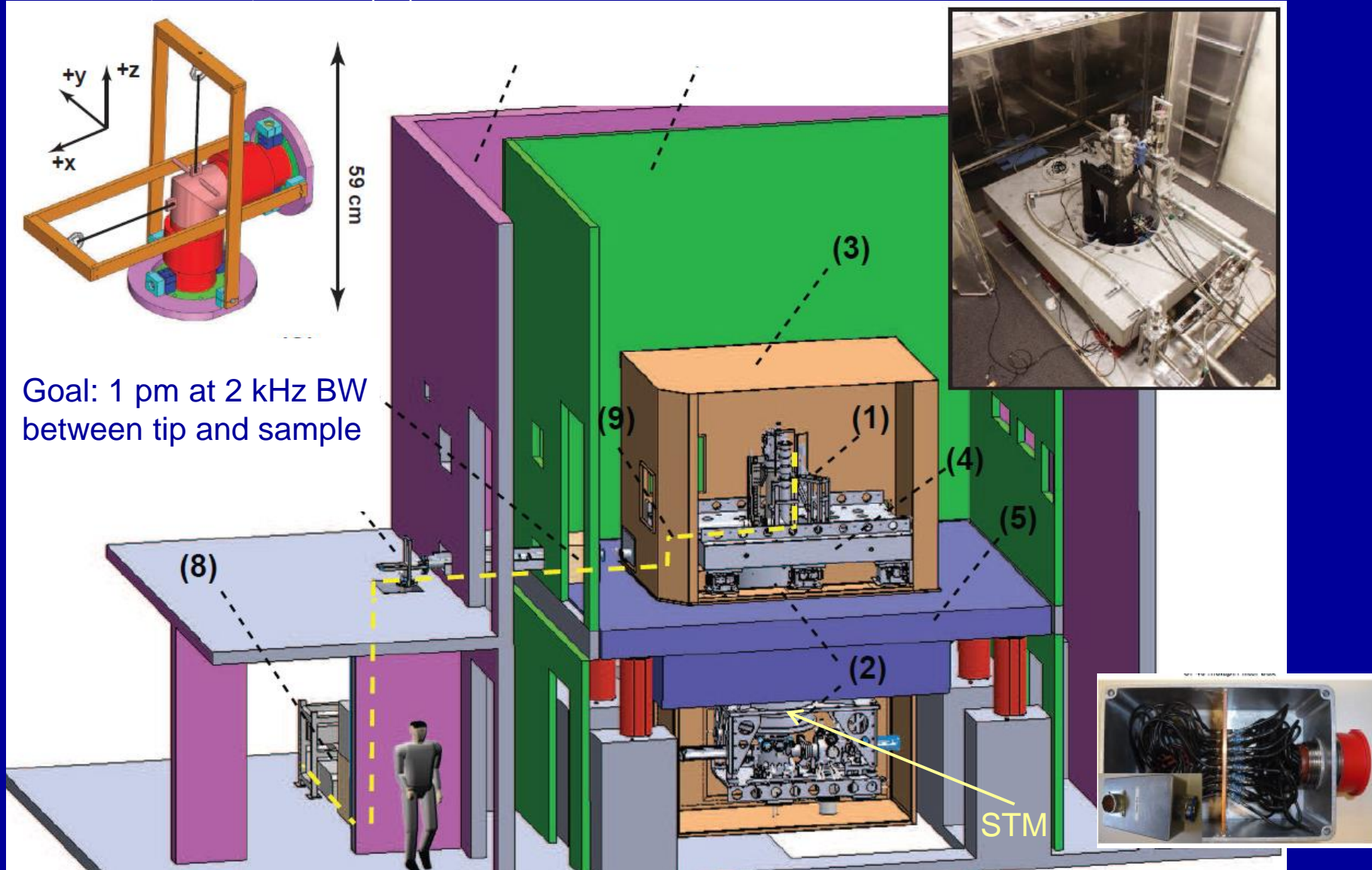


z noise w/o feedback



# Housing the STM (vibrational/electric shielding)

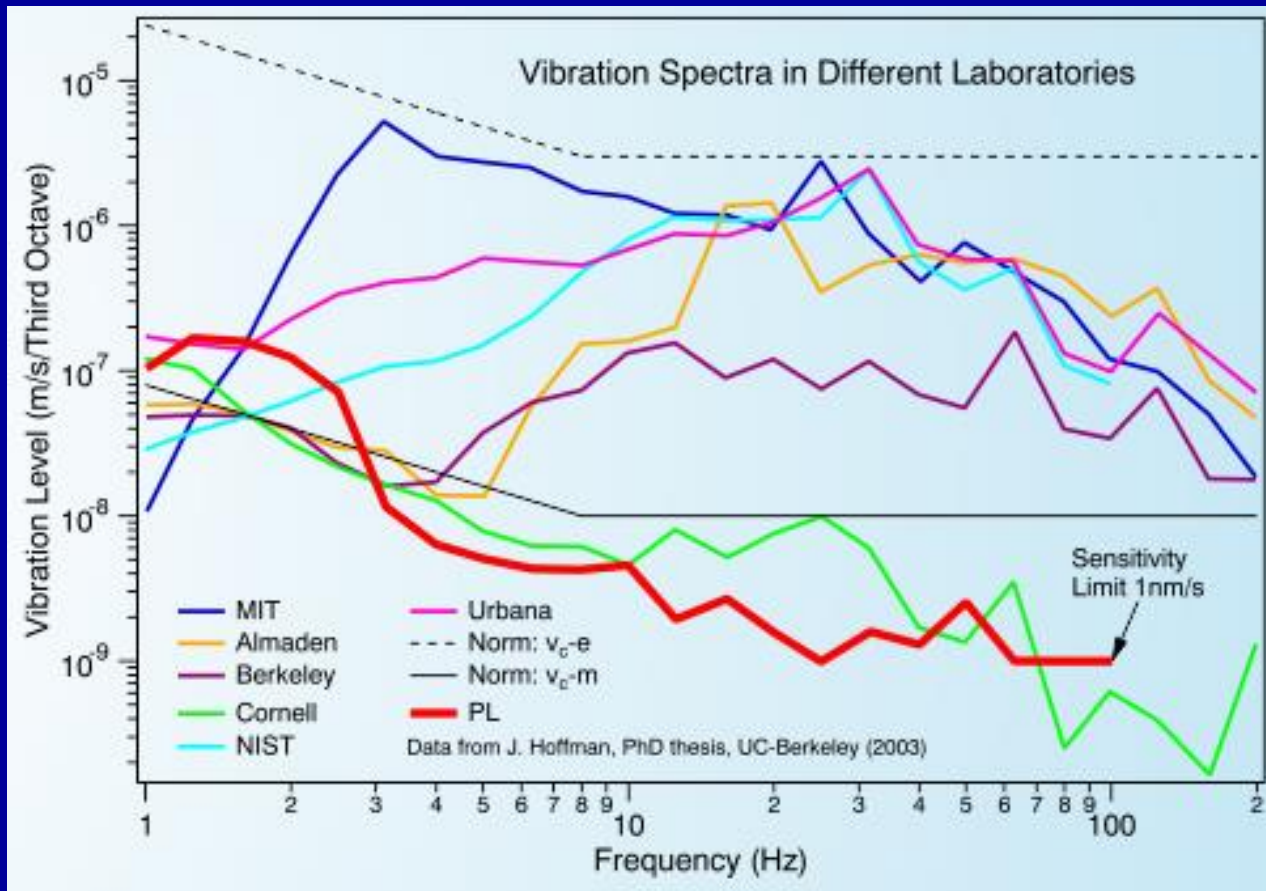
Misra et al., RSI 84, 103903 (13)



Vib.: heavy, multiple stages, 30 m below ground, decouple supply lines, decoupled foundation, operators outside, damping (sand, wood, foam, ..)

Elec.: Faraday cage(s) = UHV chamber galvanic separation of rooms, electronics outside, mΩ grounding into UHV

# Benchmark lab vibrations

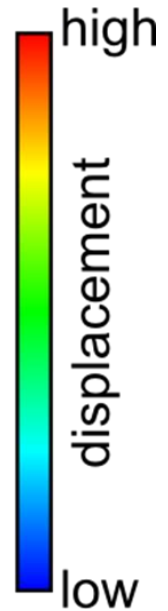
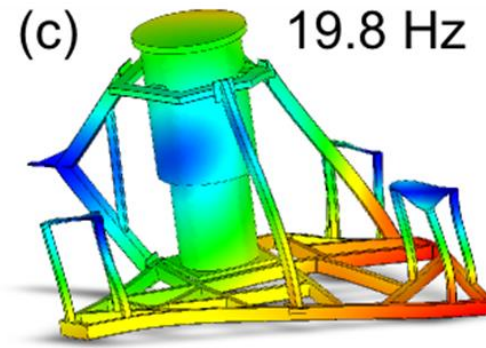
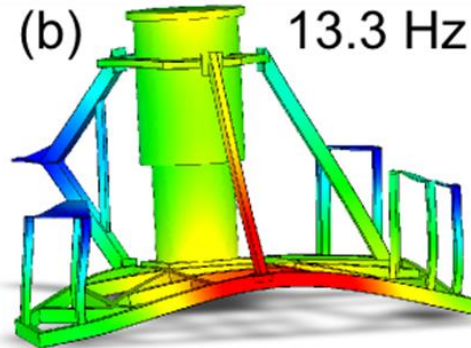
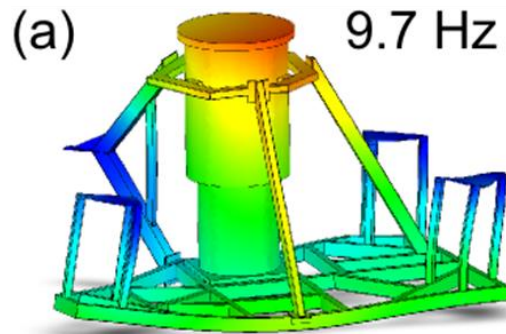


[http://www.fkf.mpg.de/2489208/001Precision\\_Laboratory](http://www.fkf.mpg.de/2489208/001Precision_Laboratory)

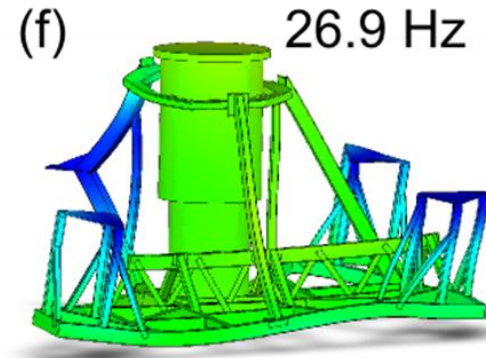
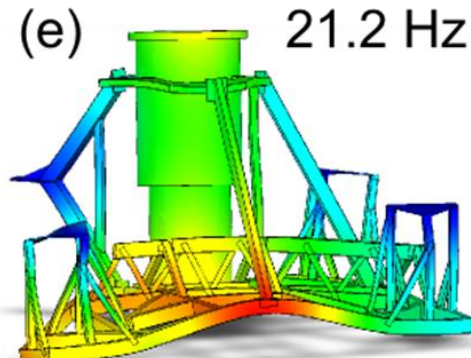
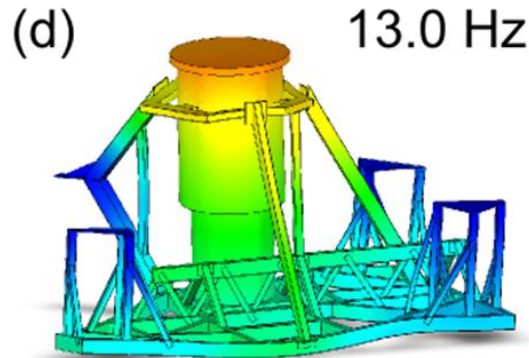
Problem: Internal vibrations of cryostat, UHV chamber, LHe vibrations, bubbling LN2, fans, ...

# Fighting internal vibrations

lowest resonance modes of plain frame:



lowest resonance modes with additional diagonal support:



timber work ground plate

resonances of supporting frame

# Build up (step by step)

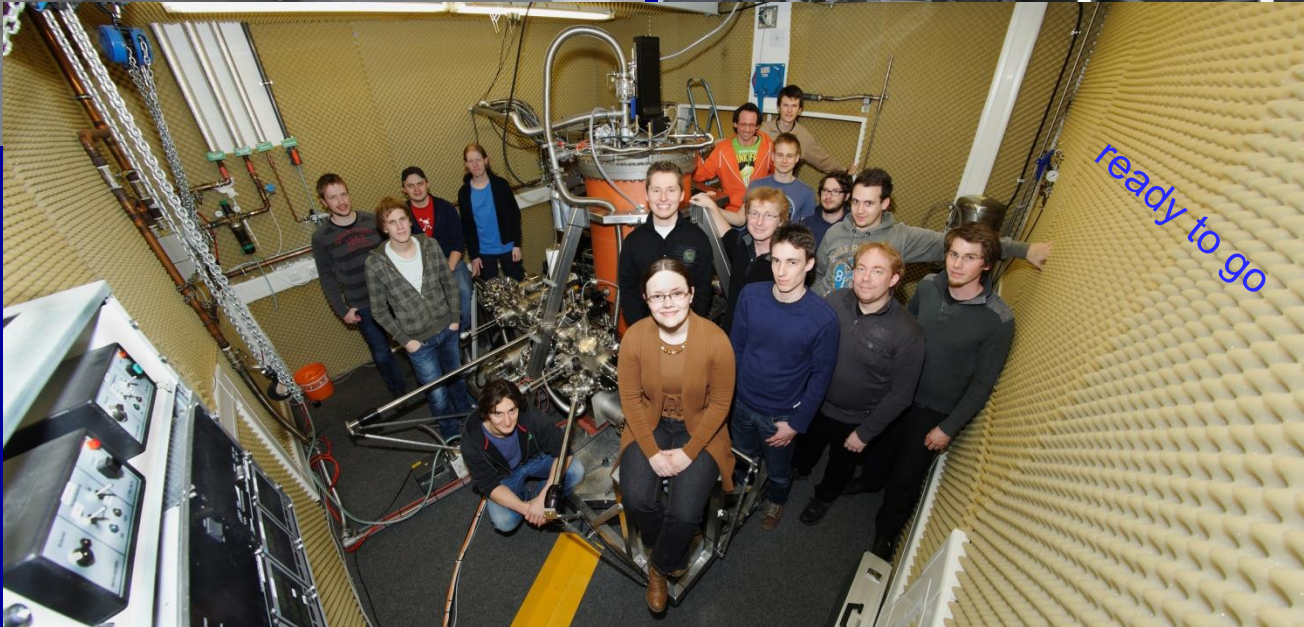
Frame 300 mK / 14 T- UHV - STM (AC)



virtual



real

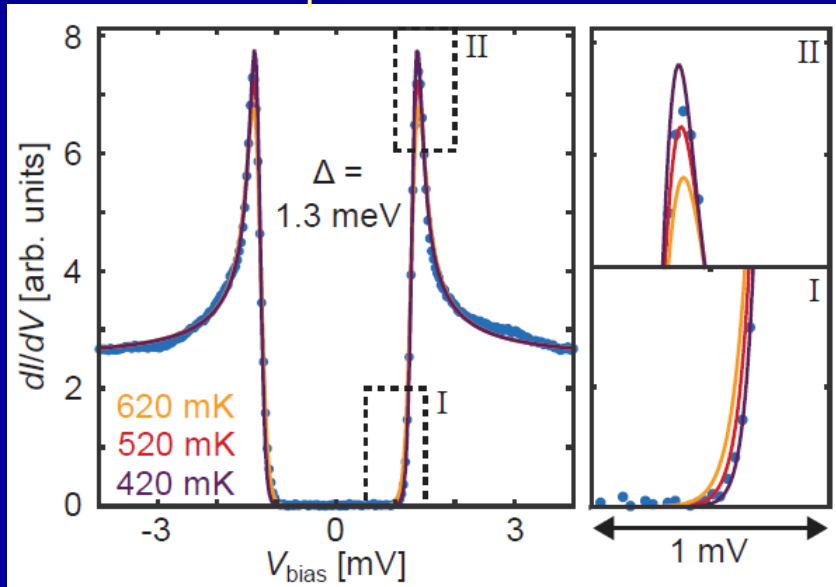


ready to go

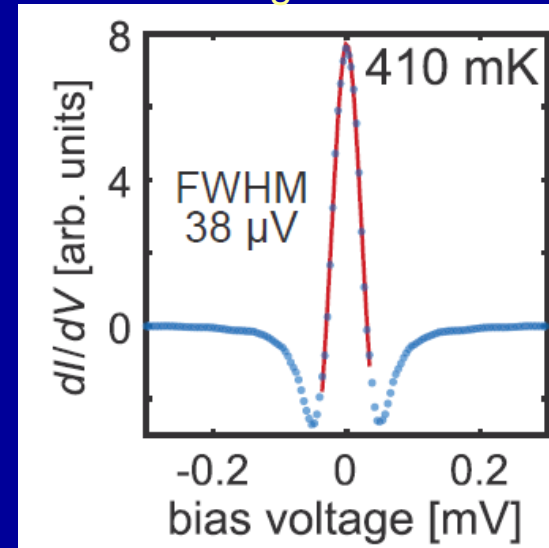
5 years  
later

# Benchmark STM operation

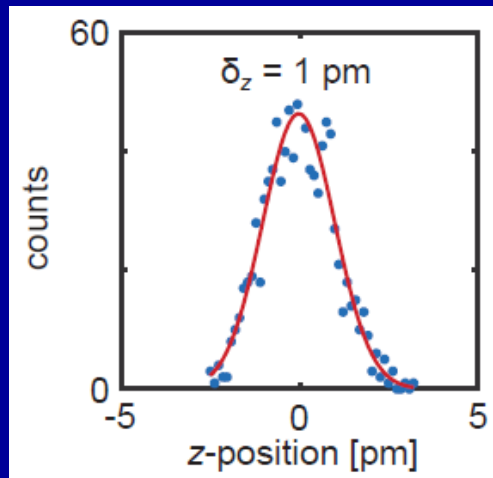
electronic temperature



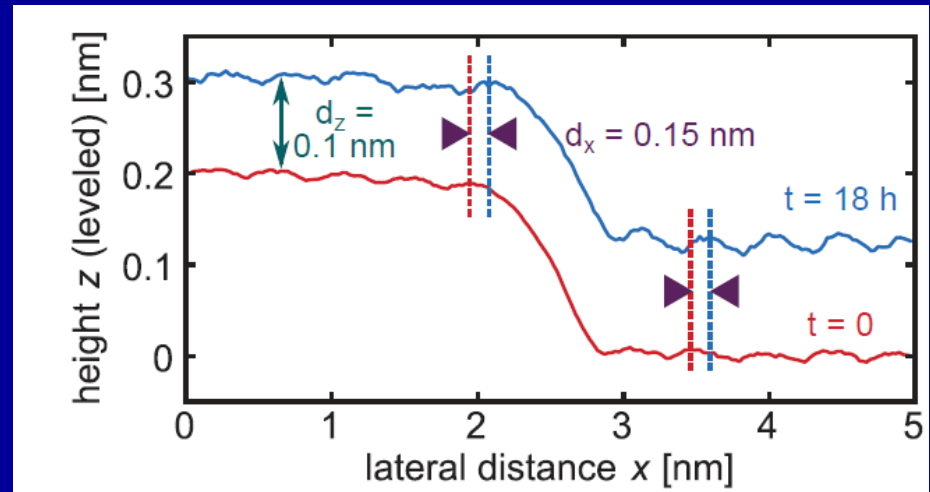
voltage noise



z noise w/o feedback



thermal drift



cycling time :  $\sim 240$  h

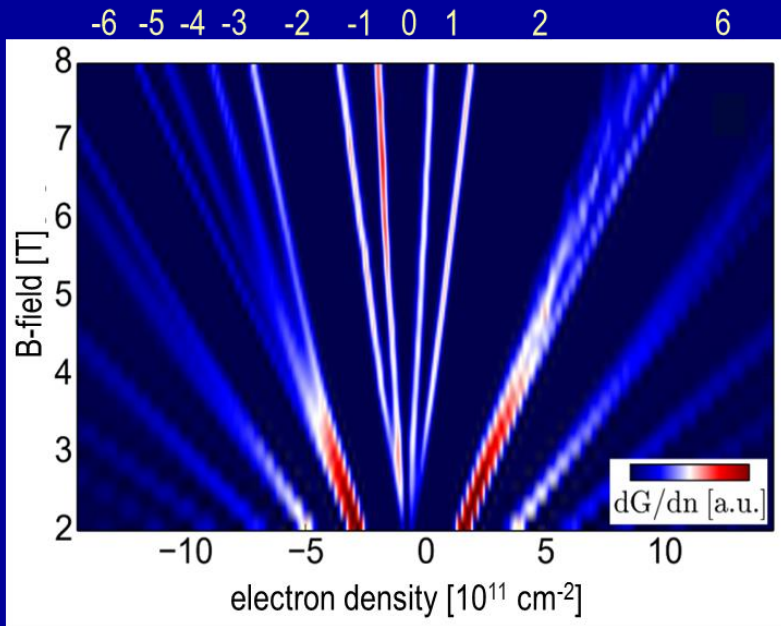
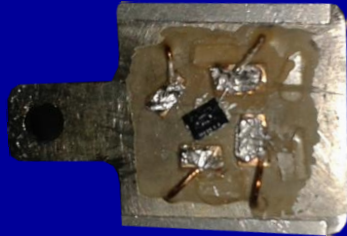
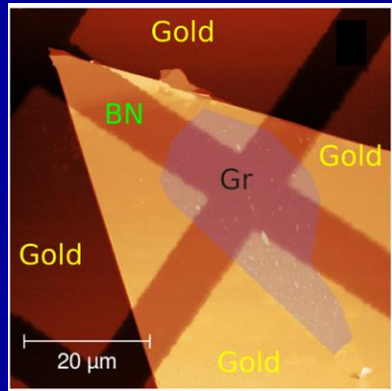
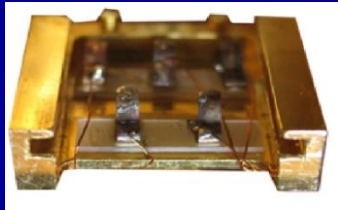
Liebmann et al., RSI 88, 123707 (17)

## World market: sub-1K STMs

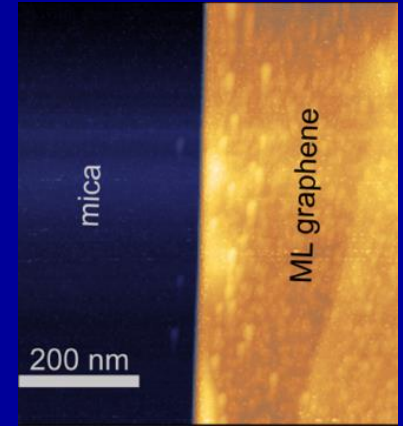
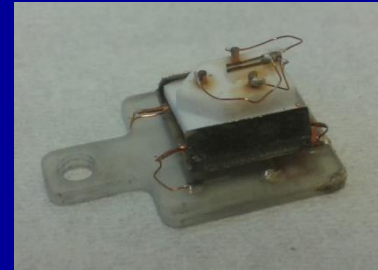
Year	Location	type	UHV	T [mK]	B [T]	optical access
1987[57]	Almaaden	$^3\text{He}$	yes	400	8	no
1999[59]	Berkley	$^3\text{He}$	no	240	7	no
2000[2]	Geneva	$^3\text{He}$	yes	275	14	outside
2004[58]	Hamburg	$^3\text{He}$	yes	315	14	outside
2007[60]	Tokyo	DR	no	30	6	no
2010[4]	Gaithersburg	DR	yes	10	15	limited
2011[61]	Madrid	DR	no	100	8	no
2011[62]	Karlsruhe	JT	yes	800	3	yes
2013[63]	Mumbai	$^3\text{He}$	no	350	9	no
2013[3]	Stuttgart	DR	no	15	14(0.5)	no
2013[64]	Princeton	DR	yes	20	14	outside
2013[65]	Stuttgart	DR	no	30	14	—
2014[66]	Maryland	DR	no	30	13.5	no
2015[67]	Madrid	DR	no	100	5(1.5)	no
2016[68]	Hamburg	$^3\text{He}$	yes	350	10	outside

# Add-ons

## Electric transport contacts



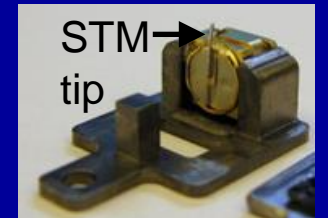
## Feedback via AFM



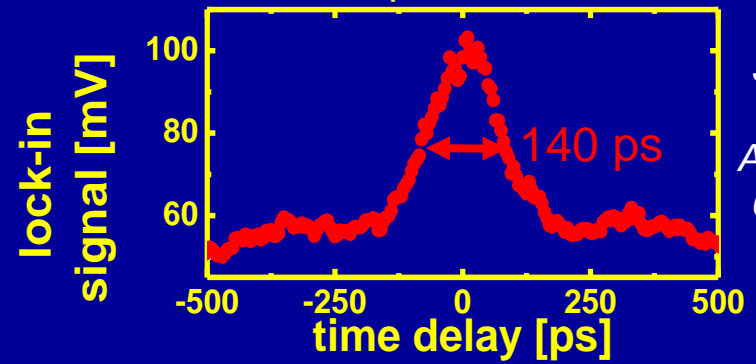
## High frequency cabling



Semi-Rigid  
17 GHz  
cable



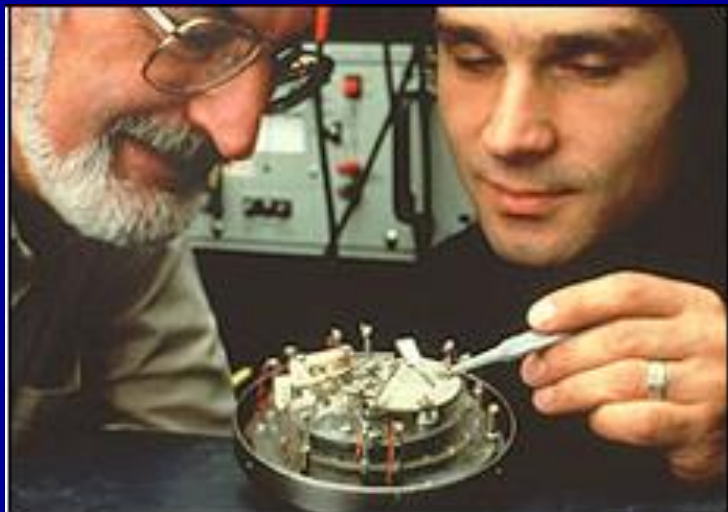
## Pump-Probe HOPG



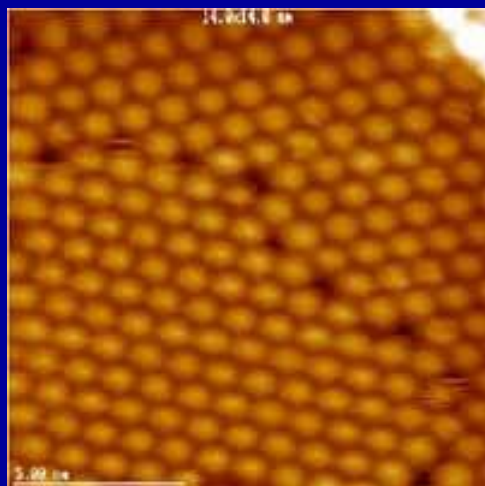
Saunus et al.,  
APL 102,  
051621  
(13)

**Back to the roots**  
**(Atoms + electron waves)**

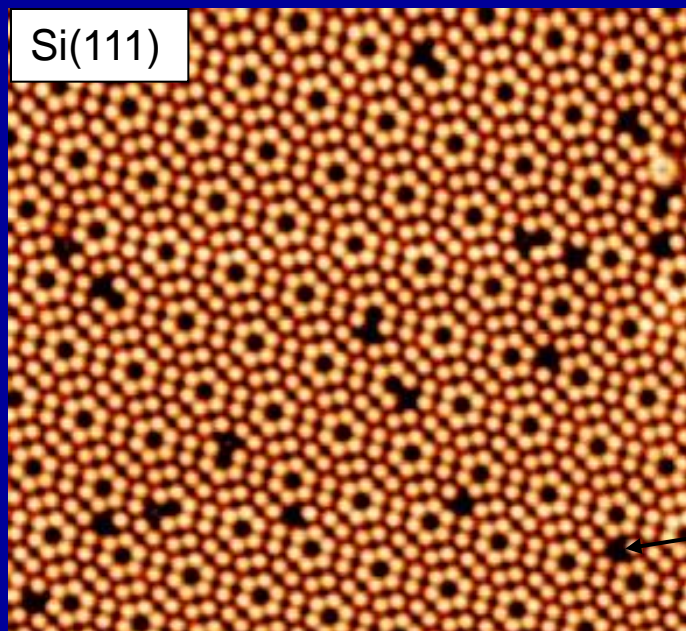
# Imaging Atoms (electron density contours) by STM



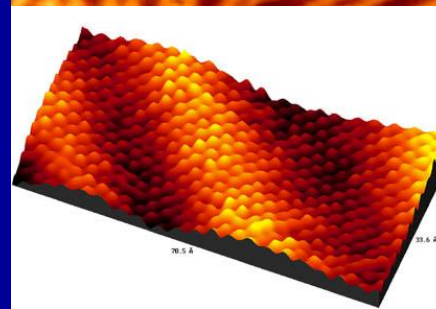
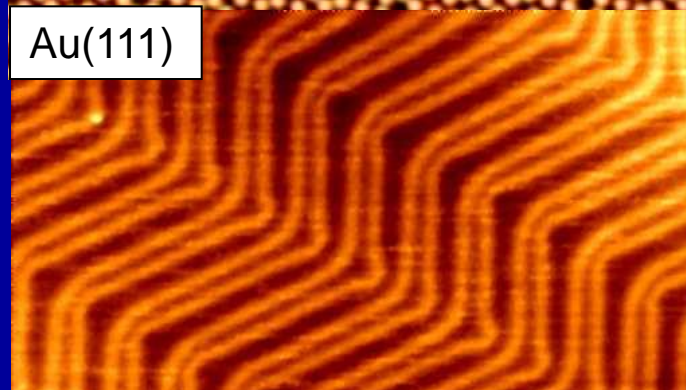
Inventors: H. Rohrer and G. Binnig  
(Noble Prize 1985)



„They look like potatoes“  
(press release 1985)



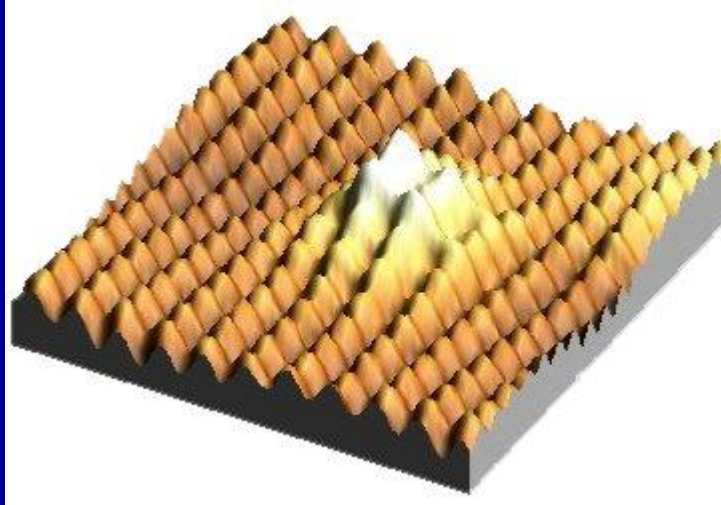
atomic defect



10 nm

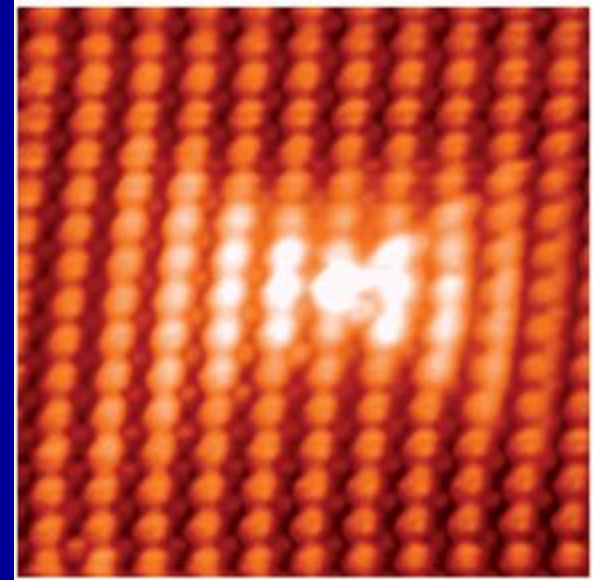
# Mapping and charging dopants

Te donor in GaAs (electron accumulation)

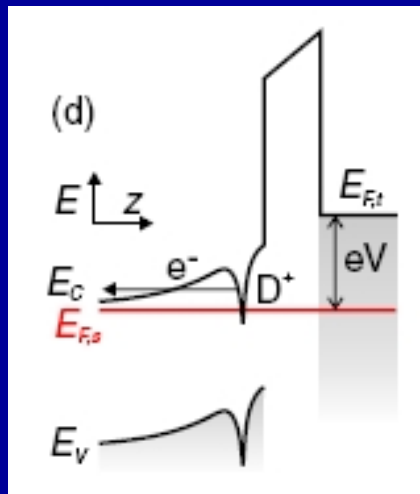


Zheng et al., PRL. 72, 1490 (1994)

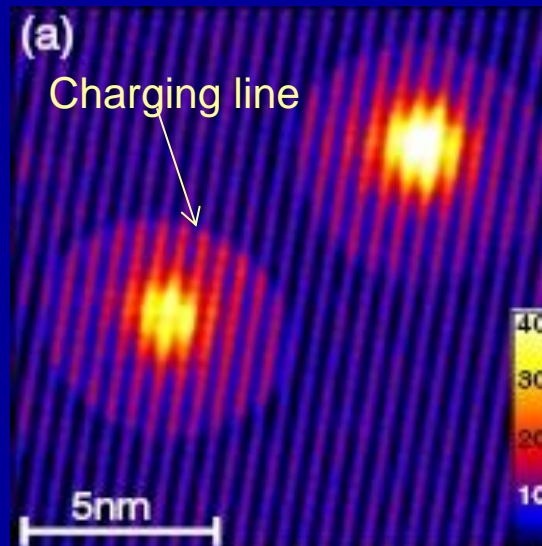
Mn acceptor in GaAs (hole wave function)



Yakunin et al., PRL. 92, 216806 (2004)

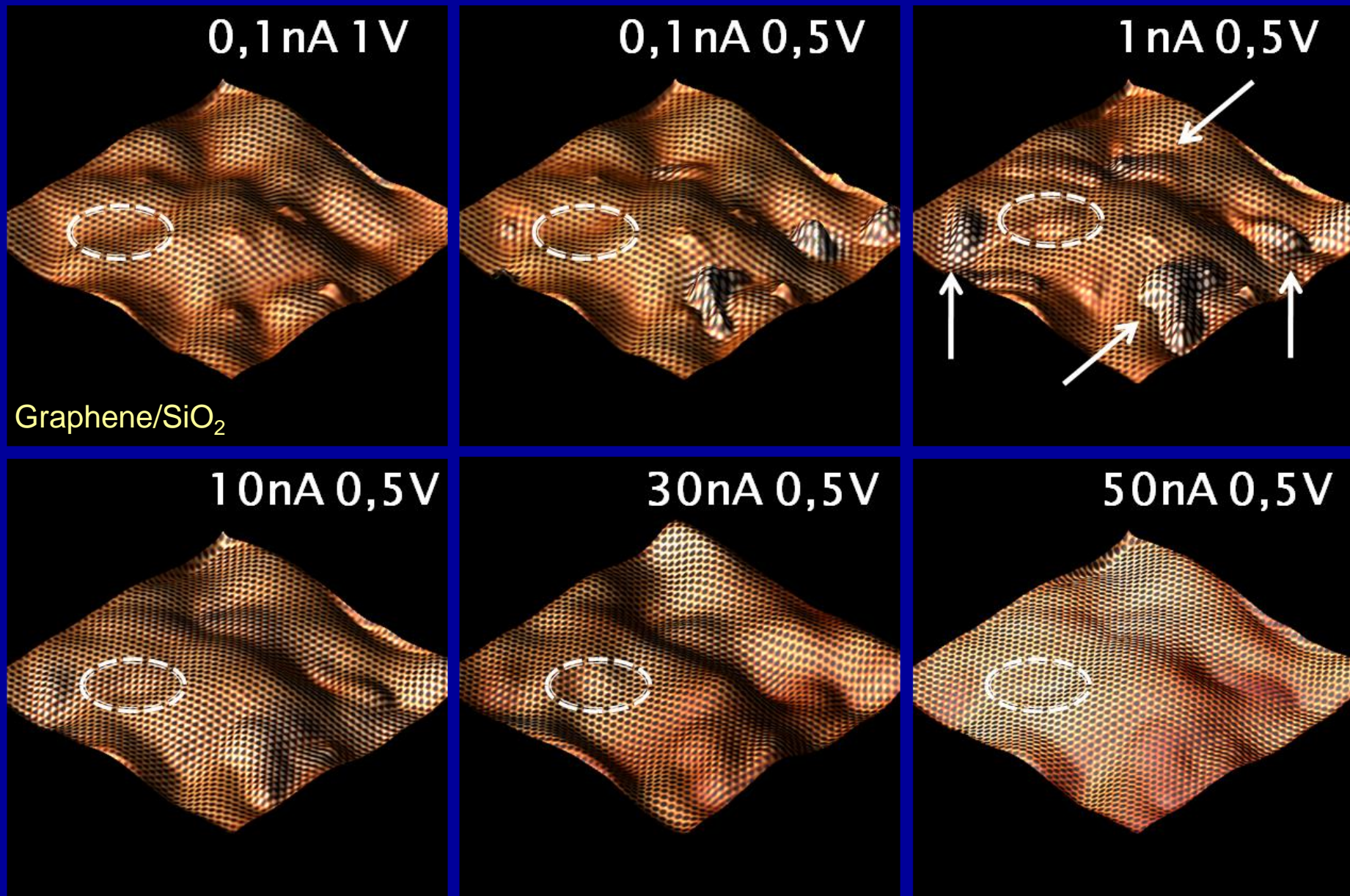


Si donor  
in GaAs  
 $V = 2$  V



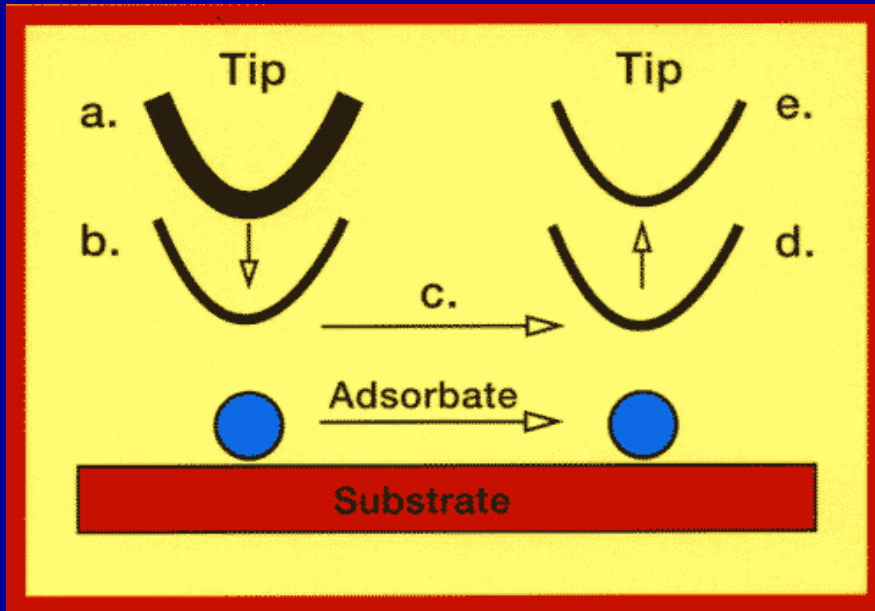
Teichmann et al.  
PRL 101, 076103 (2008)

# Stretching 2D samples by tip forces

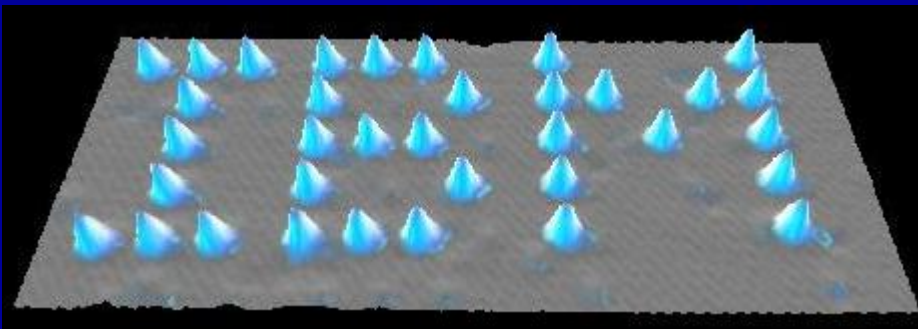
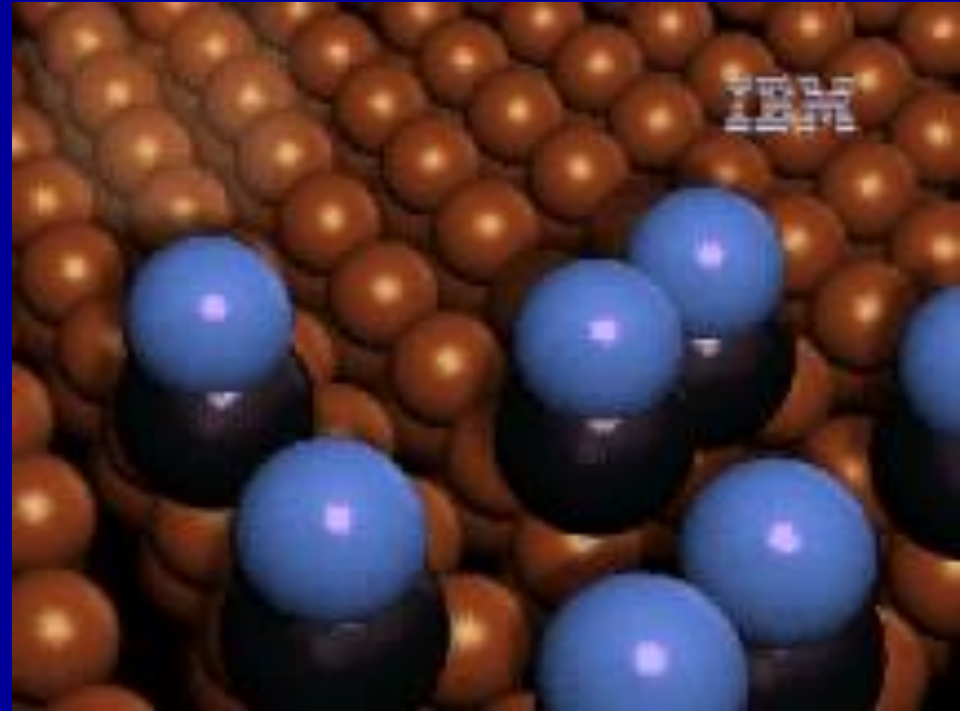


# Moving the atoms

Atom logic: CO on Cu(111)  
(repulsive CO-CO-force)



Tip-adsorbate interaction  
> tip-surface-interaction

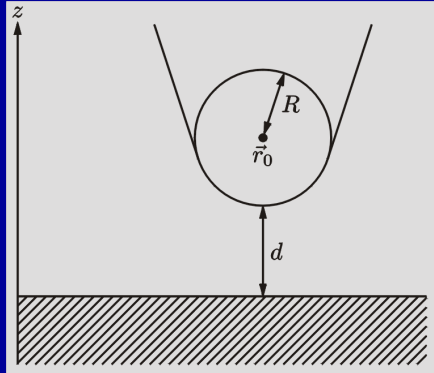


Xe-atoms on Ni(110), 4 K  
Eigler et al., Nature 344, 524 (1990)

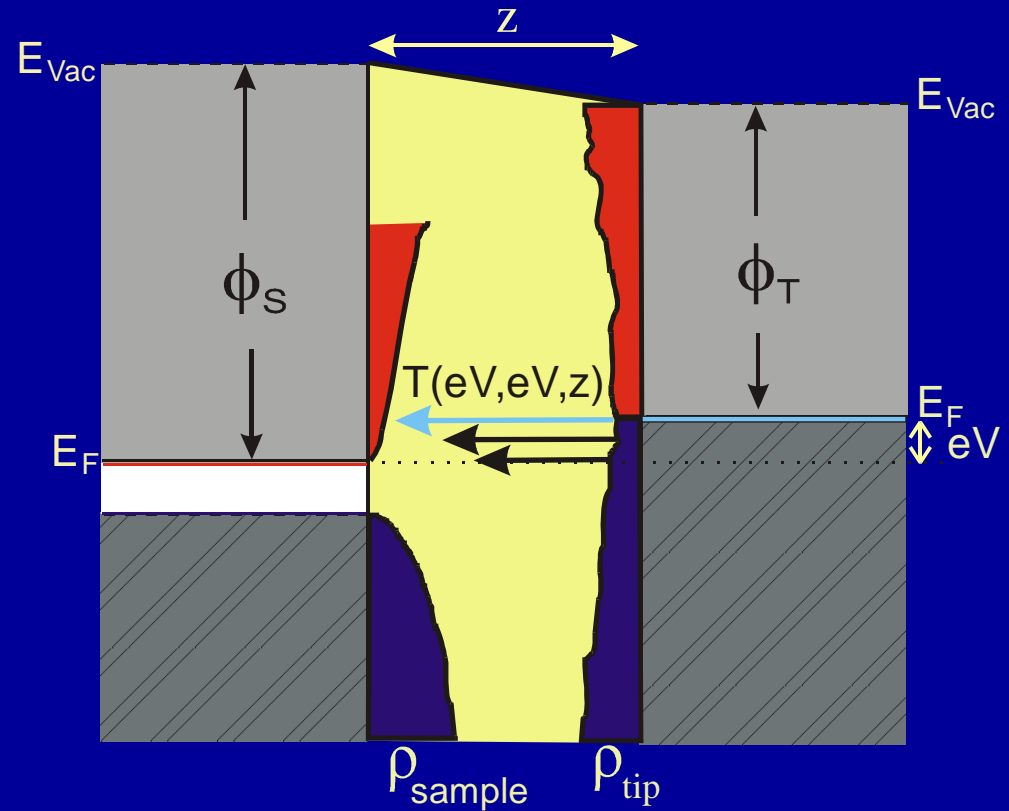
# Imaging the electrons

# Scanning Tunneling Spectroscopy

## Tersoff-Hamann-Modell



s. C.J. Chen, *Introduction to Scanning Tunneling Microscopy*



$$LDOS(x, y, E = eV) \propto \frac{dI / dV(x, y, V)}{I(z(x, y), V)}$$

local density of states (LDOS)

# Local Density of States

$$LDOS(E, x, y) = \sum \frac{|\Psi_i(E, x, y)|^2}{\delta E}$$

$\Psi_i$  : single particle wave function

$$\delta E = \sqrt{(3.6 \cdot kT)^2 + (2.5 \cdot V_{\text{mod}})^2} : \text{energy resolution}$$

temperature                      modulation voltage of lock-in

$$6 \text{ K} \Rightarrow 1.5 \text{ meV}, \quad 300 \text{ mK} \Rightarrow 75 \text{ } \mu\text{eV}$$

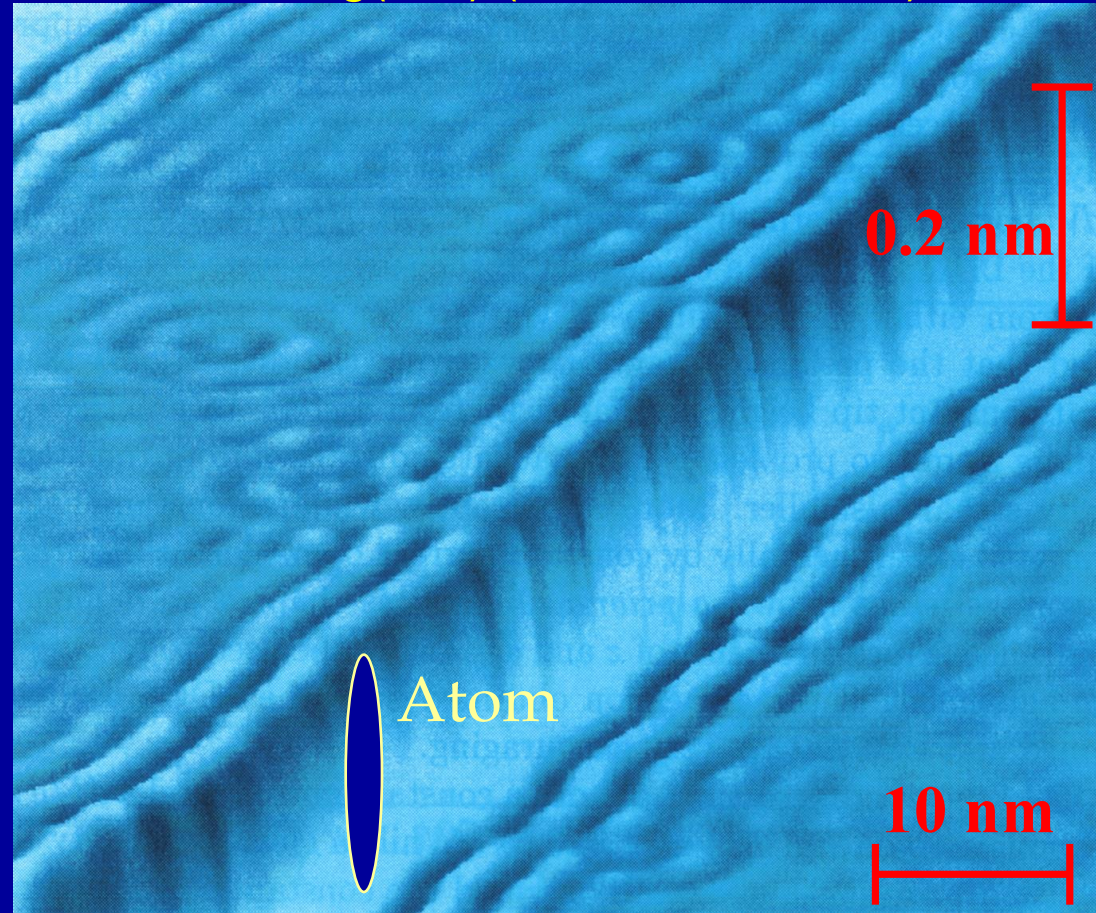
# Imaging electron waves

Ag(111) (2D surface state)

electron waves ( $e^{ikx+\varphi}$ ) are  
scattered at defects  
(step edges, impurities)

⇒

standing waves are visible  
around defects

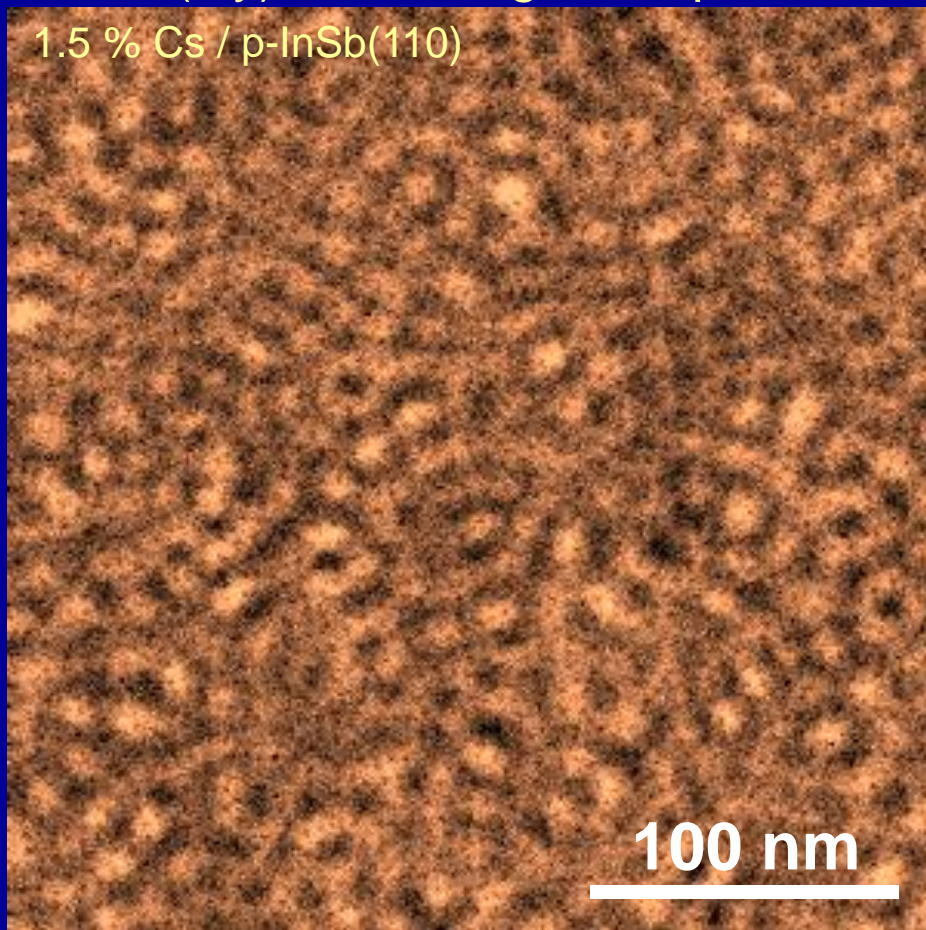


*J. Li et al., Lausanne*

# Mapping the Fermi surface: $E(\underline{k})$

$dI/dV(x,y)$  = standing wave pattern

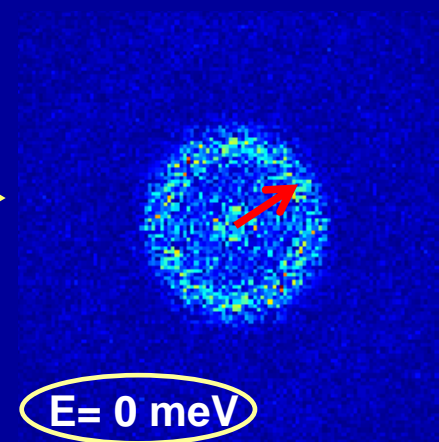
1.5 % Cs / p-InSb(110)



$V = 0$  mV,  $V_{\text{stab}} = 300$  mV,  $I_{\text{stab}} = 200$  pA,  
 $V_{\text{mod}} = 1$  mV<sub>rms</sub>,  $T = 5$  K

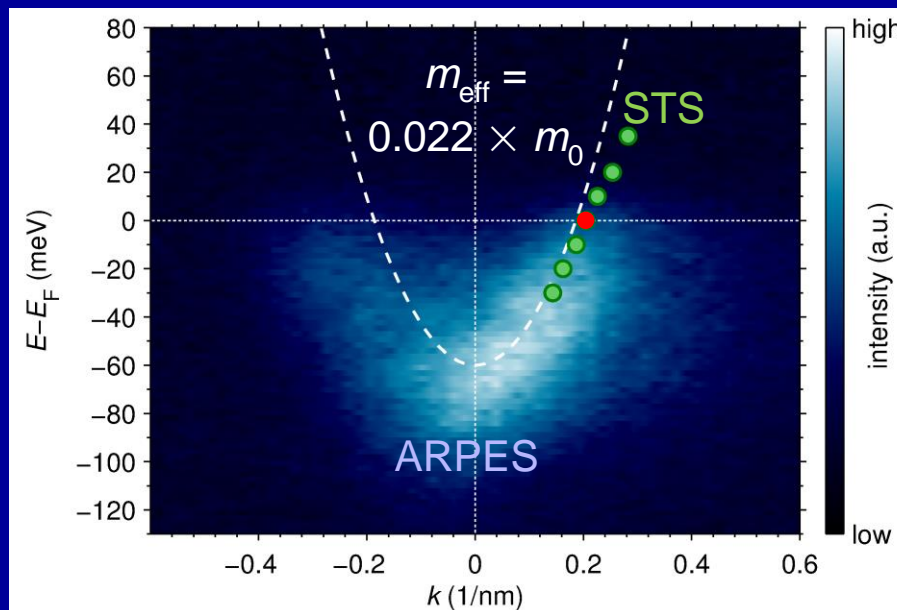
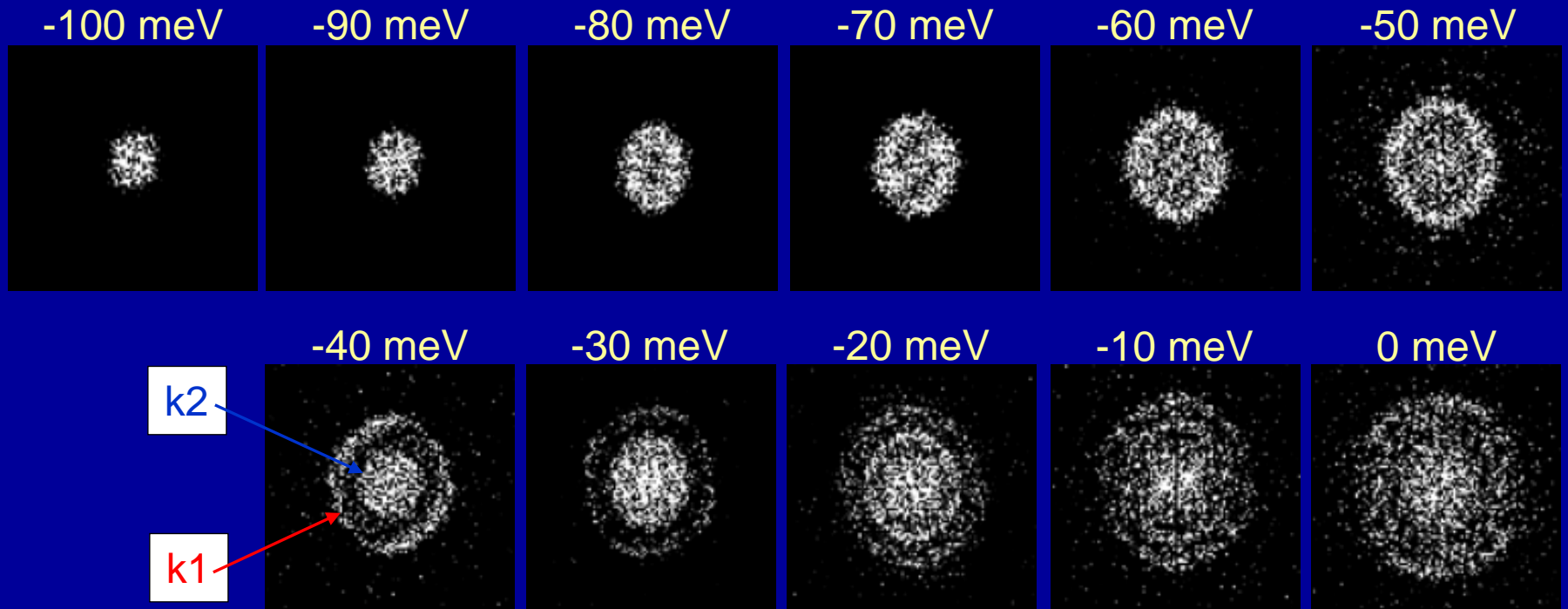
$$\begin{aligned} \Psi_1 + \Psi_2 &\propto e^{i\mathbf{k}_1 \cdot \underline{x}} + e^{i\mathbf{k}_2 \cdot \underline{x}} \\ &= e^{i(\mathbf{k}_1 \cdot \underline{x} + \mathbf{k}_2 \cdot \underline{x})/2} \cdot 2 \cdot \cos\left(\frac{\mathbf{k}_1 - \mathbf{k}_2}{2} \cdot \underline{x}\right) \\ &= 2 \cdot \cos(\mathbf{k}_1 \cdot \underline{x}) \\ &\stackrel{\mathbf{k}_1 = -\mathbf{k}_2}{\Rightarrow} |\Psi_1 + \Psi_2|^2 \propto \cos^2(\mathbf{k}_1 \cdot \underline{x}) \end{aligned}$$

Fourier  
 $\longrightarrow$



$\Rightarrow$   $\underline{k}(E)$

# Tracking energy band dispersion

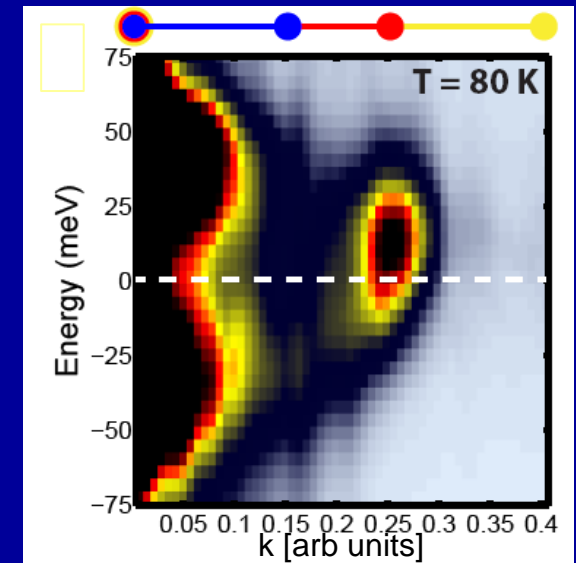
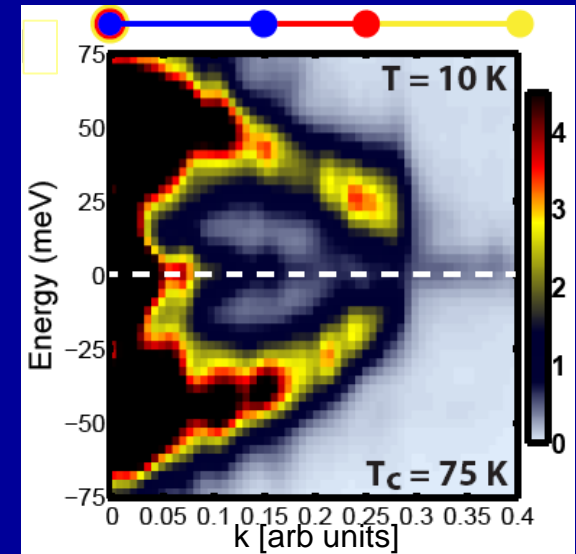
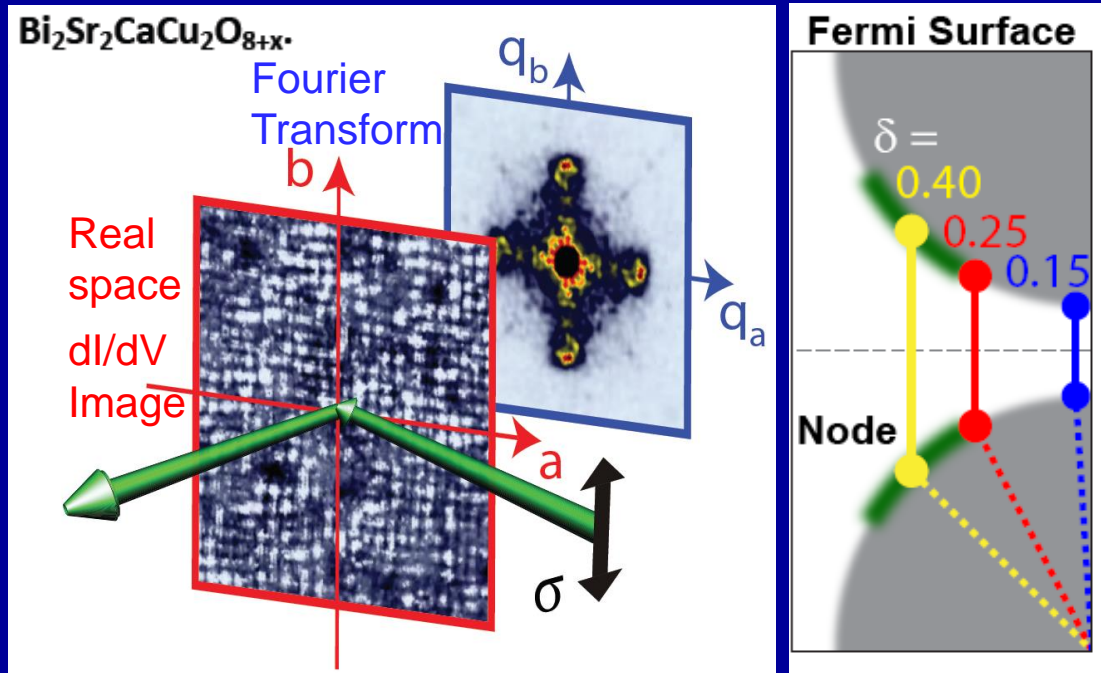


Fourier transform of  
standing wave patterns  
( $dI/dV$  images)

2DES  
2.7 % Fe/n-InAs(110)

# (Complex) Band dispersion by STM

Fourier transform of standing wave patterns at different  $E$



Important: Scattering vectors are visible

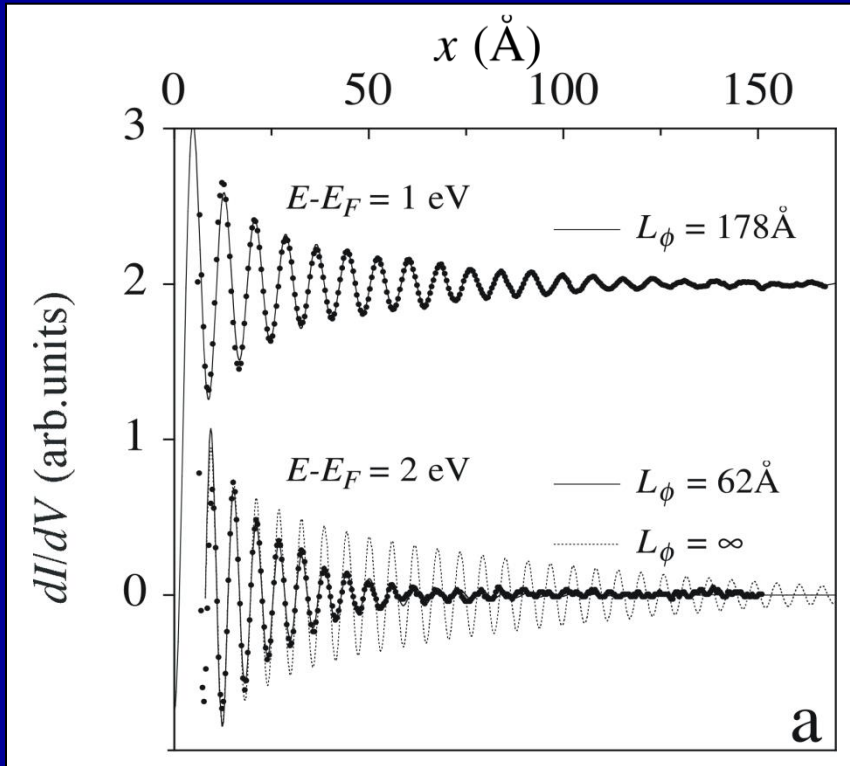
$$\Psi_1 + \Psi_2 \propto e^{ik_1x} + e^{ik_2x} = e^{i(k_1x+k_2x)/2} \cdot 2 \cdot \cos\left(\frac{k_1 - k_2}{2} \cdot x\right)$$

$$\Rightarrow |\Psi_1 + \Psi_2|^2 \propto \cos^2\left(\frac{k_1 - k_2}{2} \cdot x\right)$$

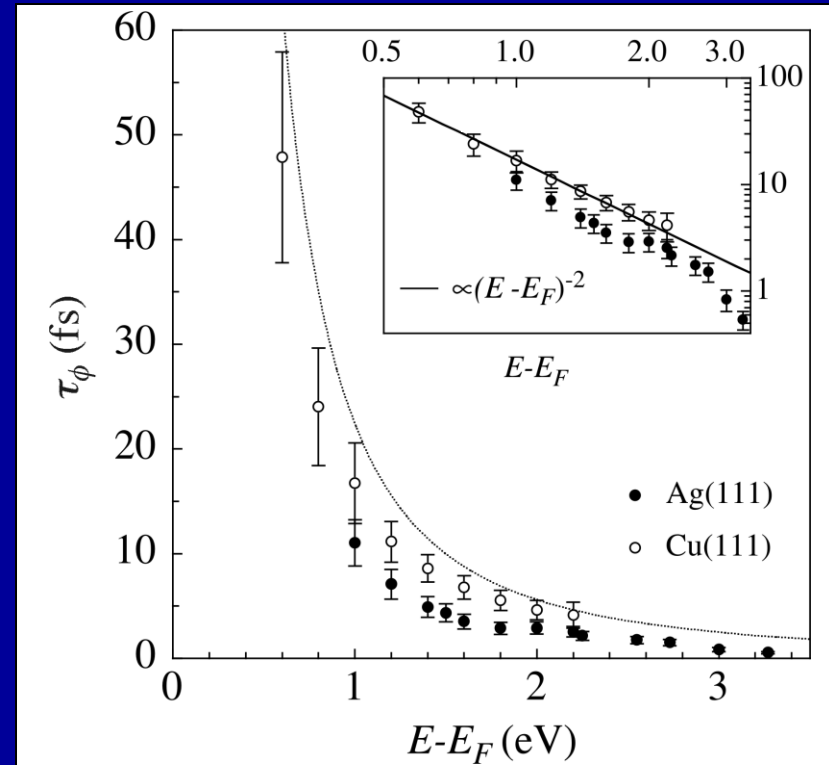
# Determination of phase coherence length

flux conservation  $\Rightarrow$  amplitude  $\propto r^{1-D}$

Cu(111): electron waves scattered at step edge



energy dependence



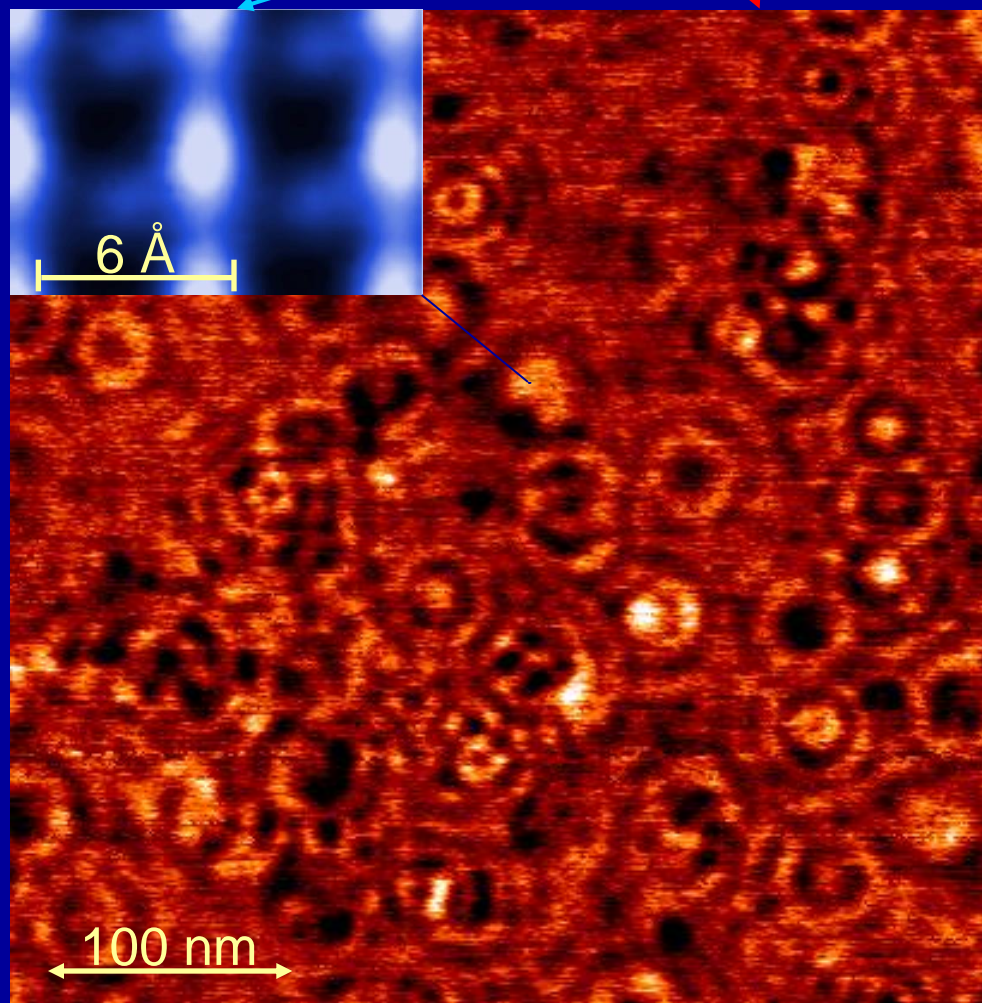
$L_\phi = \infty$  : thermal length

$L_\phi = 62$  Å: thermal + phase coherence length

$\tau_\phi \propto E^{-2} \Rightarrow$  e-e scattering

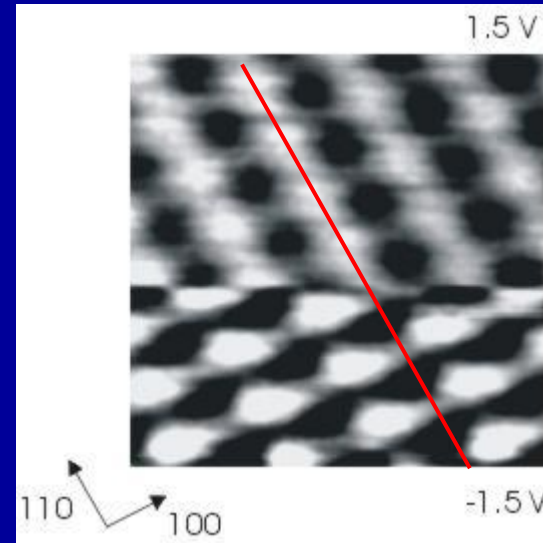
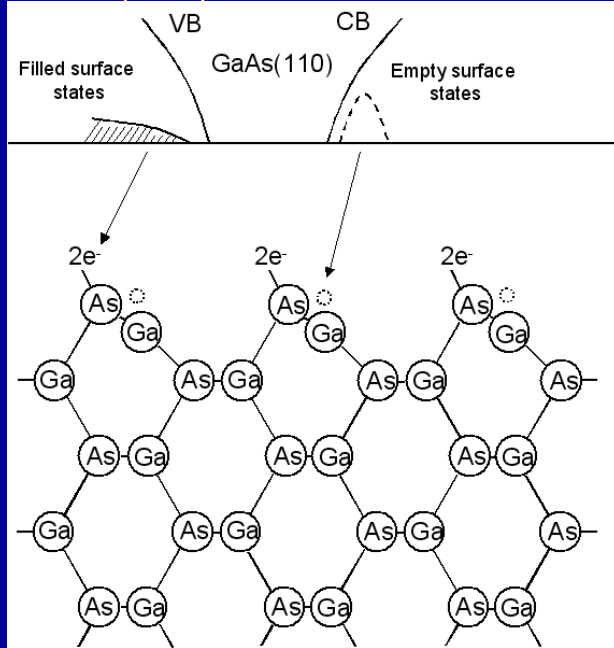
# Imaging Bloch waves

$$\Psi_i(\vec{r}_i, \sigma_i) = u_{\vec{k}}(\vec{r}) \cdot e^{i\vec{k}\vec{r}}$$



# Chemical contrast via Bloch waves

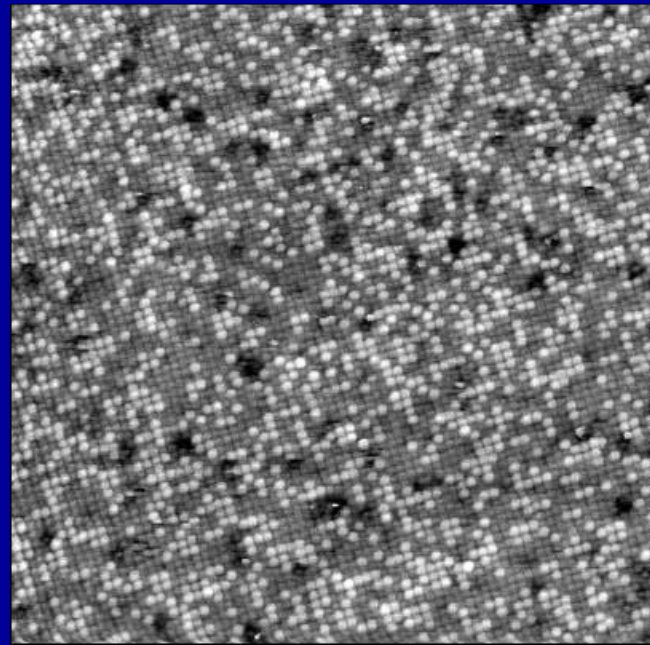
GaAs(110)



empty states (Ga)

occupied states (As)

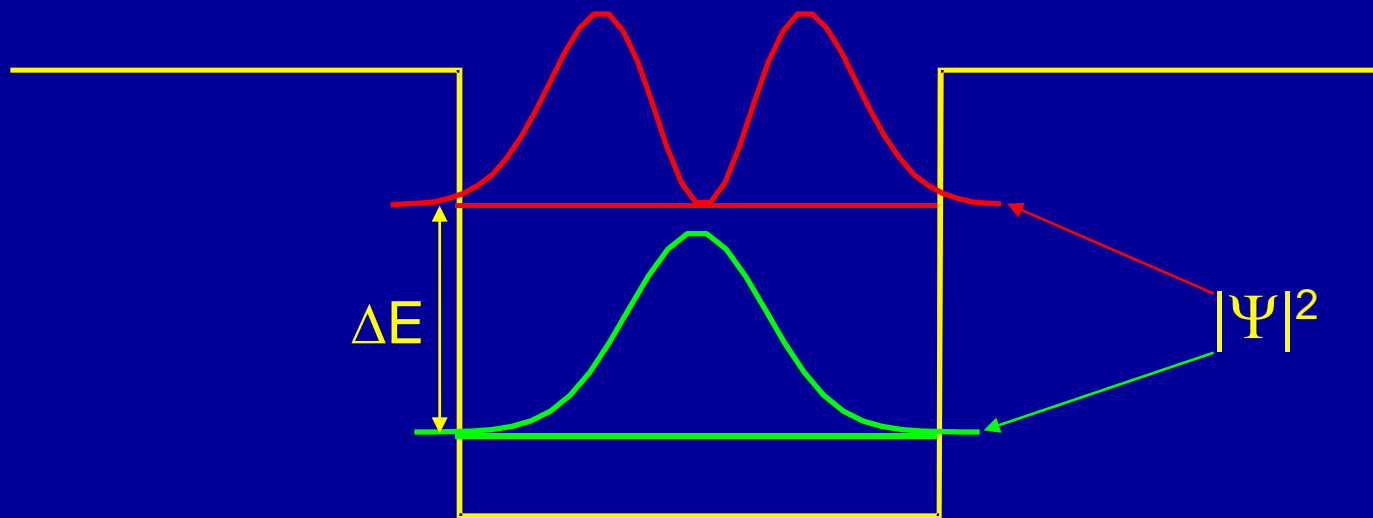
*Stroscio et al. JVST A 6, 499 (88)*



RhPt (001):  
Rh bright

*Hebenstreit et al.  
Surf. Sci. 441, 441 (99)*

# Confined electronic states

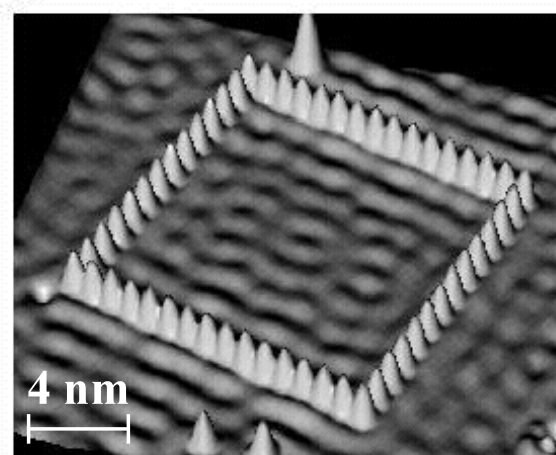
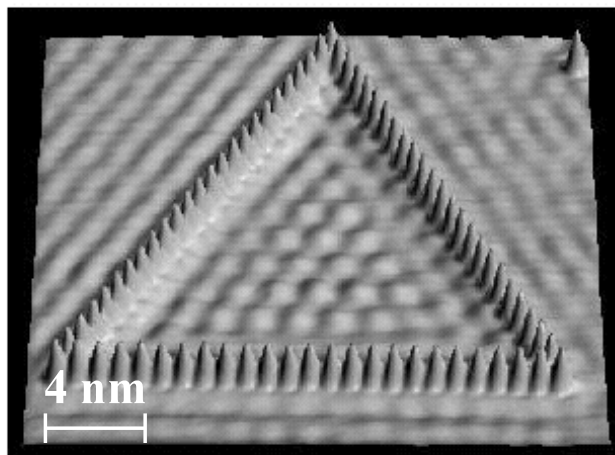
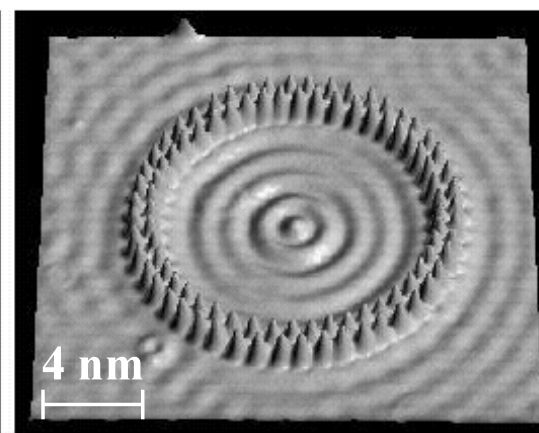
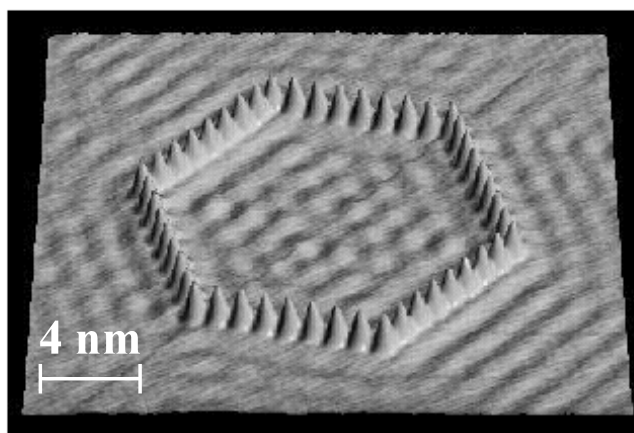


$\Rightarrow$  peaks in  $dI/dV(V)$

$\Rightarrow$  wave functions in  $dI/dV(x,y)$

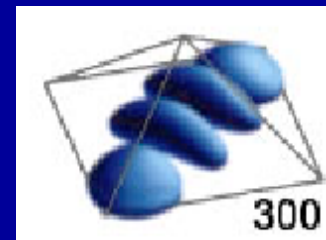
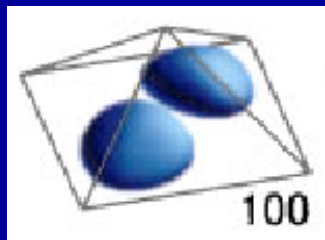
# Confined states in artificial cages

Don Eigler

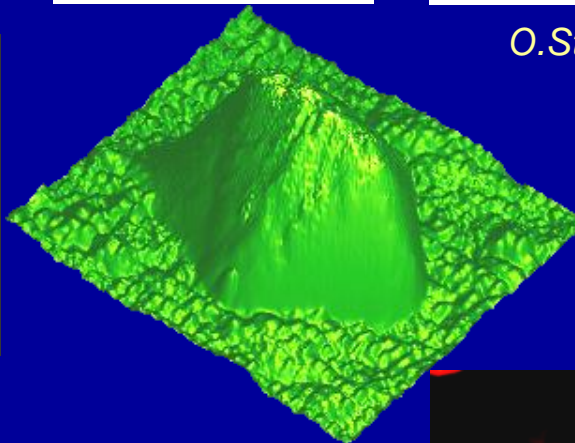
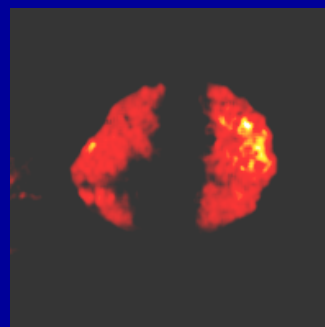
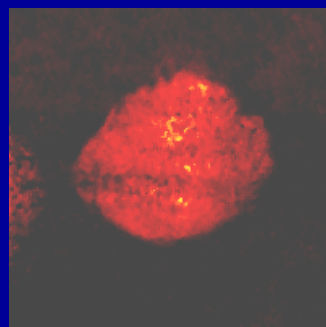


cages made from Fe atoms on Cu(111)

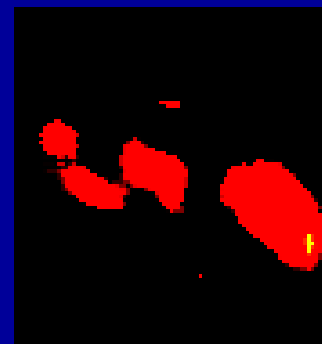
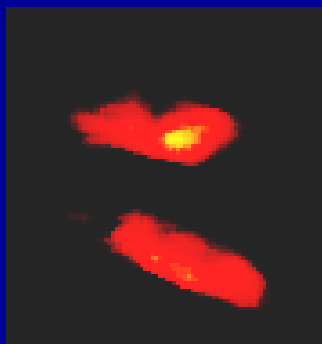
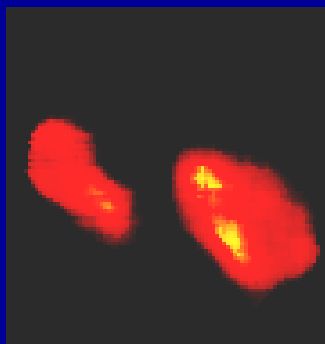
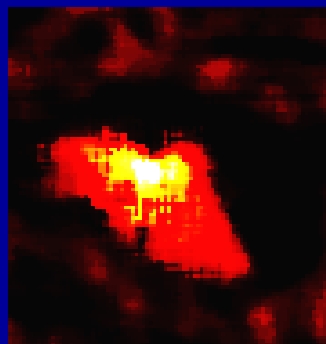
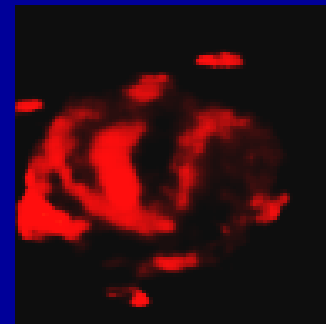
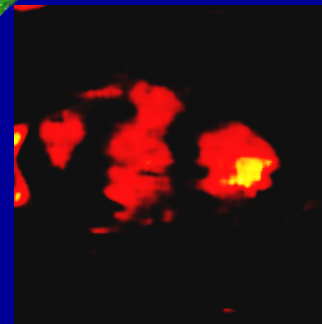
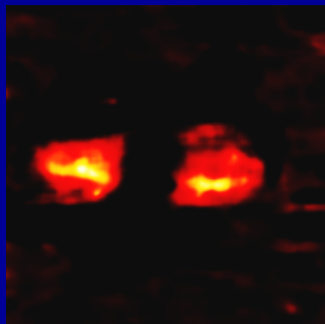
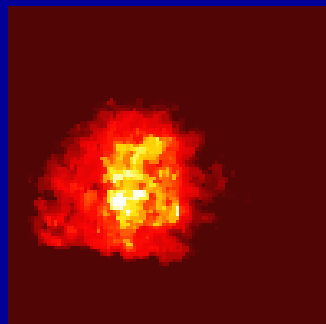
# Wave Functions in InAs quantum dot



*O. Stier et al., PRB 59, 5688 (1999)*



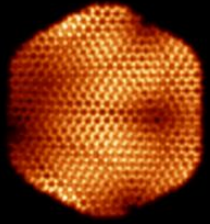
*Maltezopolous et al.  
PRL 91, 196804  
(2003)*



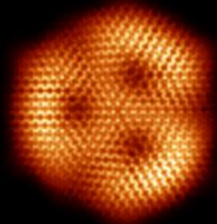
$[1\bar{1}0]$  →

# Wave function mapping: Graphene quantum dots

-0.66 eV

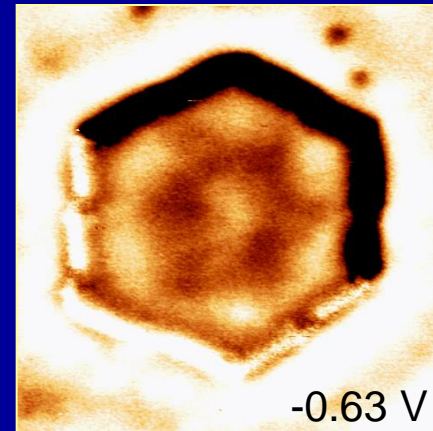
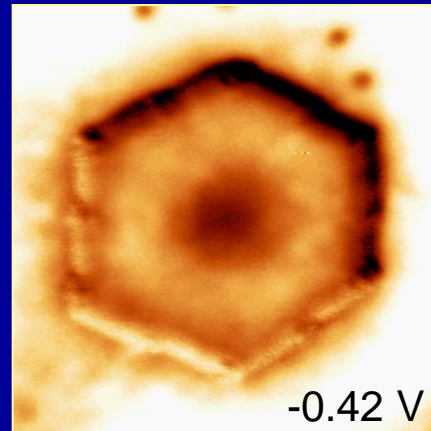
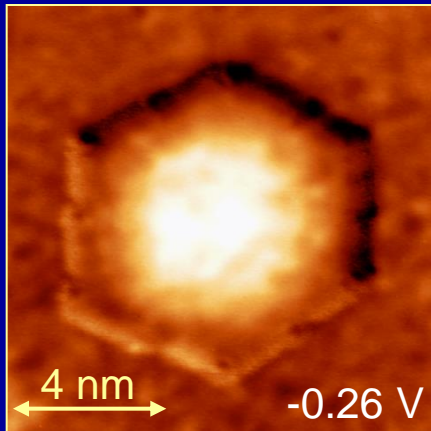


-0.67 eV

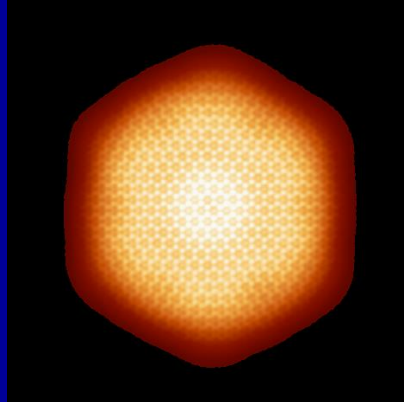


hard confinement    soft confinement

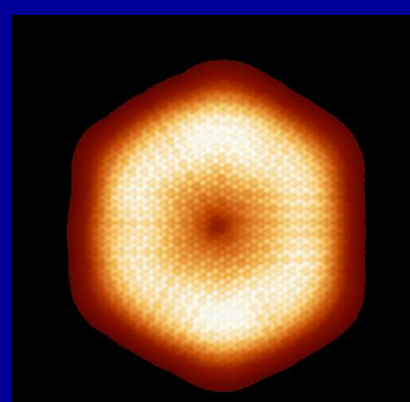
Exp.



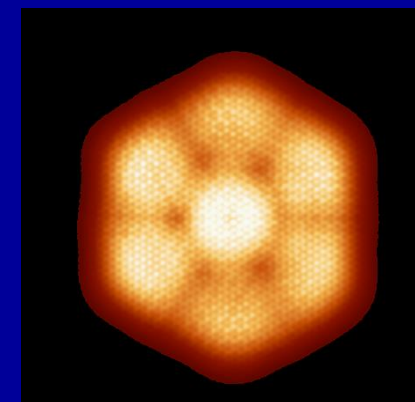
Theo.



2 states



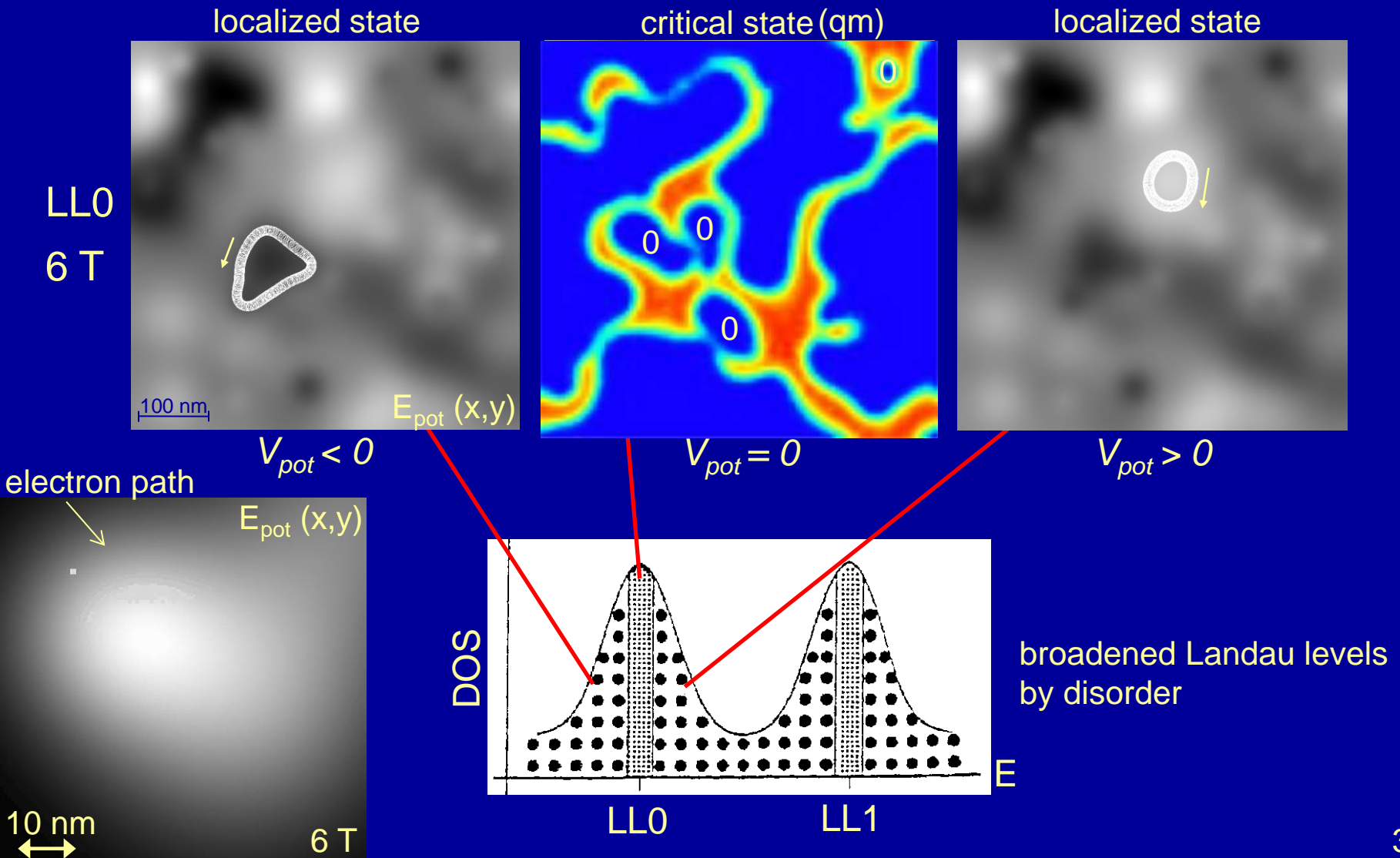
4 states



6 states

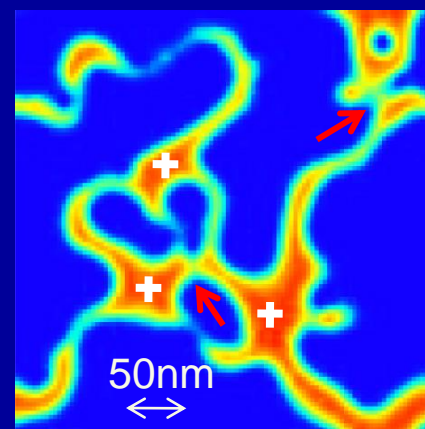
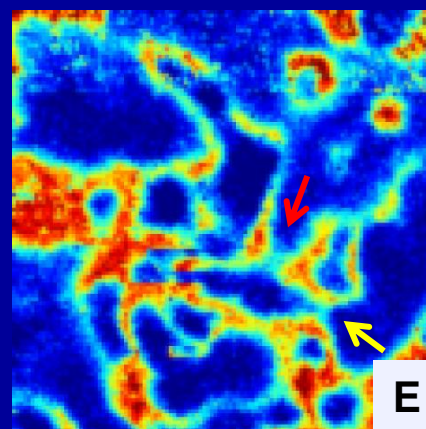
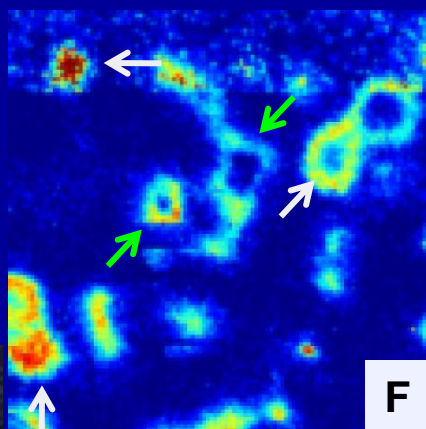
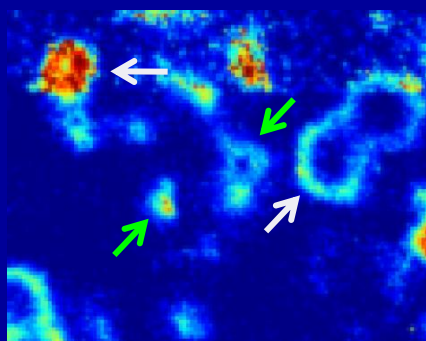
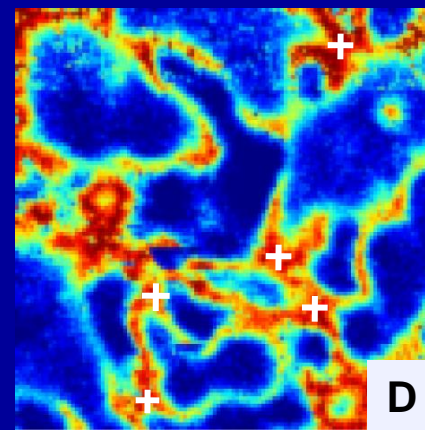
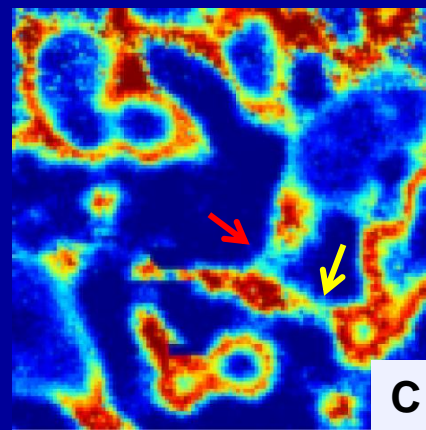
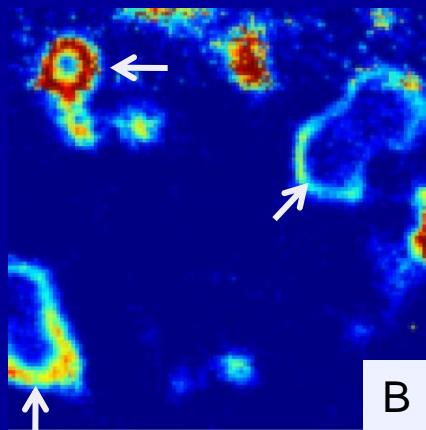
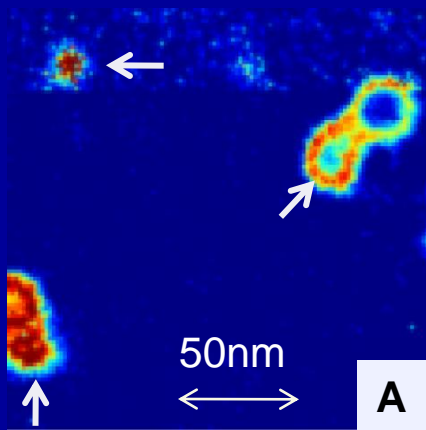
# More complex wave functions

2D + large magnetic field + disorder  $\Rightarrow$  quantum Hall wave functions



# LDOS within 1. Landau level

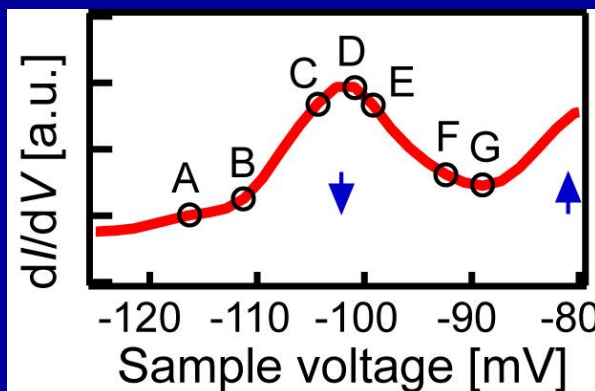
Hashimoto et al.  
PRL 101, 256802 (08)



Hartree calculation

T = 0.3 K, B = 12 T

12 T,  
-125 - -75 mV



# LDOS in Different Dimensions and B-fields

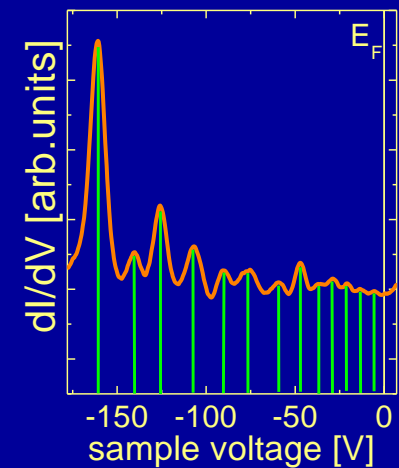
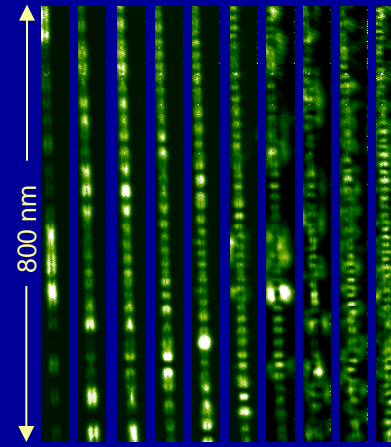
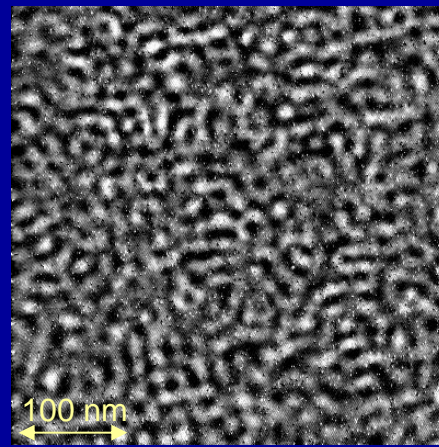
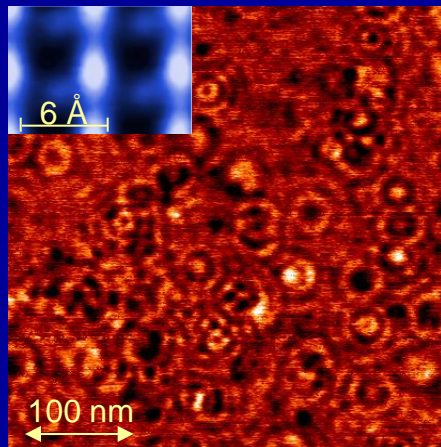
3 D

2 D

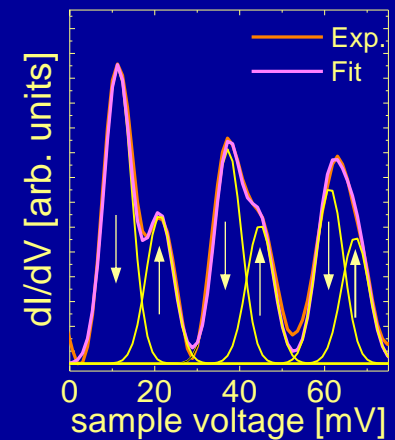
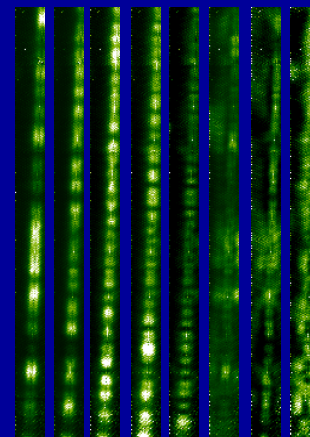
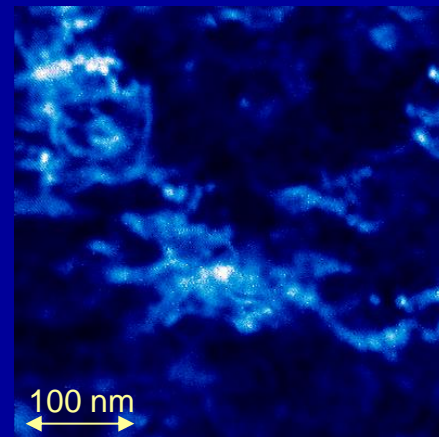
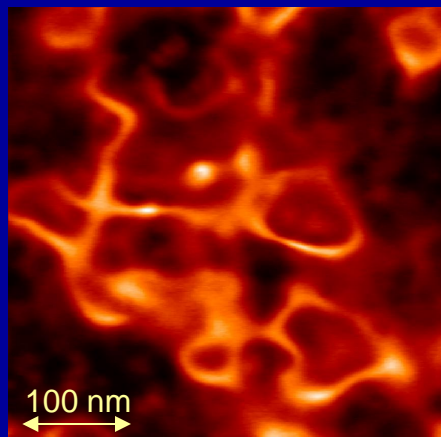
1 D

0 D

0 T



6 T



same kinetic energy  
same disorder

PRL 81, 5616  
PRL 86, 1582

PRL 89, 136806  
PRL 90, 056804

PRL 91, 076803

PRB 59, 8043  
PRL 84, 5588  
PRB 63, 201301 (R)

# Summary Part 1

STM = tunneling current with sub-nm lateral resolution

**Instrumentation:** suppress mechanical noise, electric noise, UHV

$\Delta z = 1 \text{ pm}$ ,  $T_{\text{el}} = 200 \text{ mK}$ ,  $0.01 \text{ K}$ ,  $14 \text{ T}$

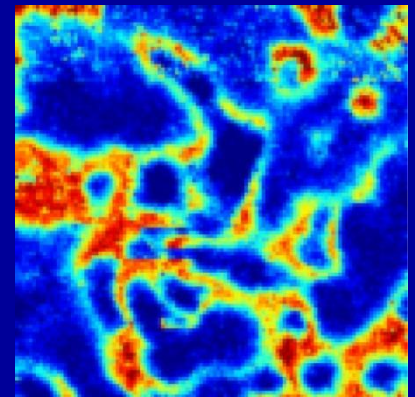
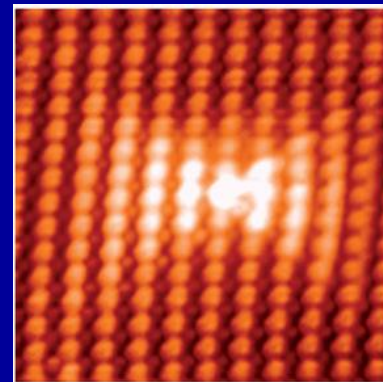
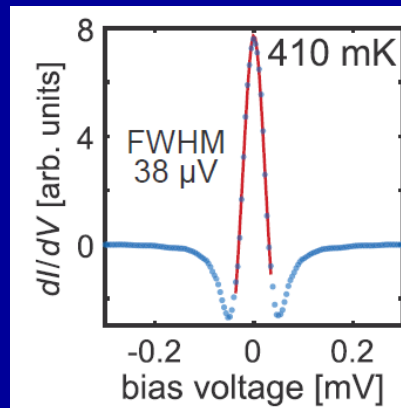
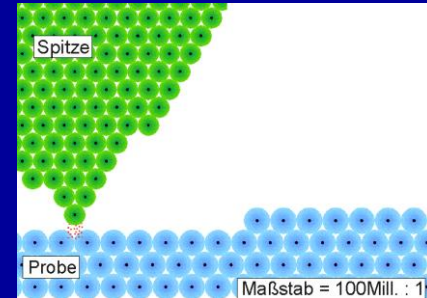
**Add-ons** are state of the art:

high frequency, simultaneous transport, AFM control ,...

**Applications:**

Atoms: reconstructions, defects, chemical contrast, atom architecture

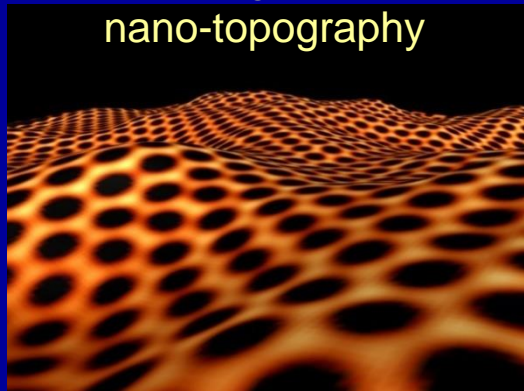
Electrons: local band structure, coherence time, confined states, B-field sates



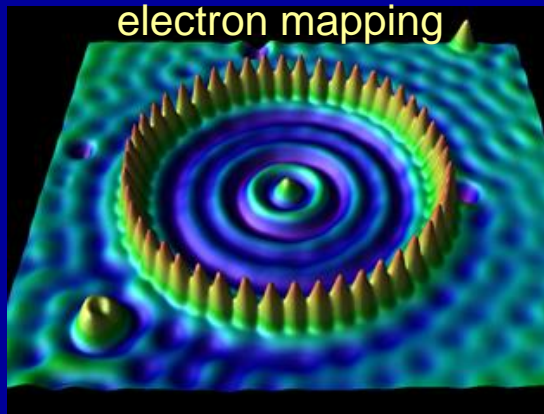
# Part II: the options

Part I

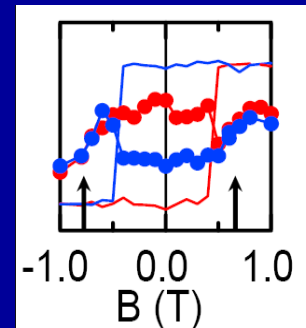
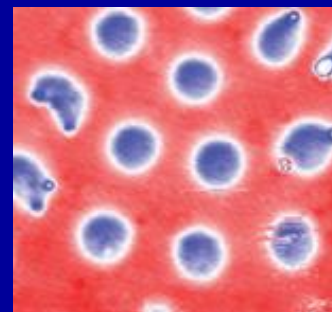
mapping atoms/  
nano-topography



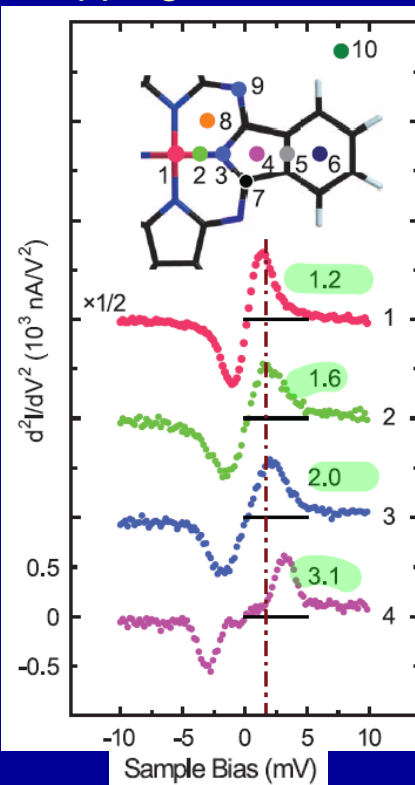
atom architecture  
electron mapping



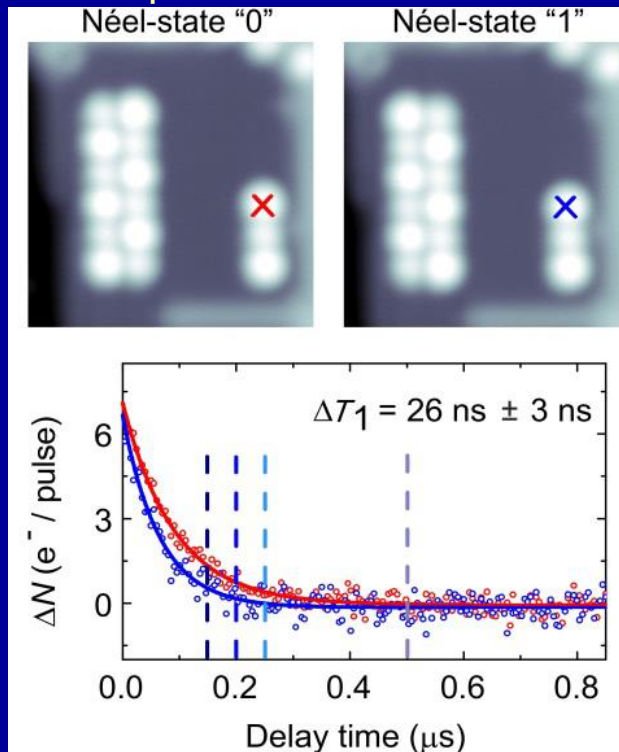
mapping spin textures/  
single atom hysteresis



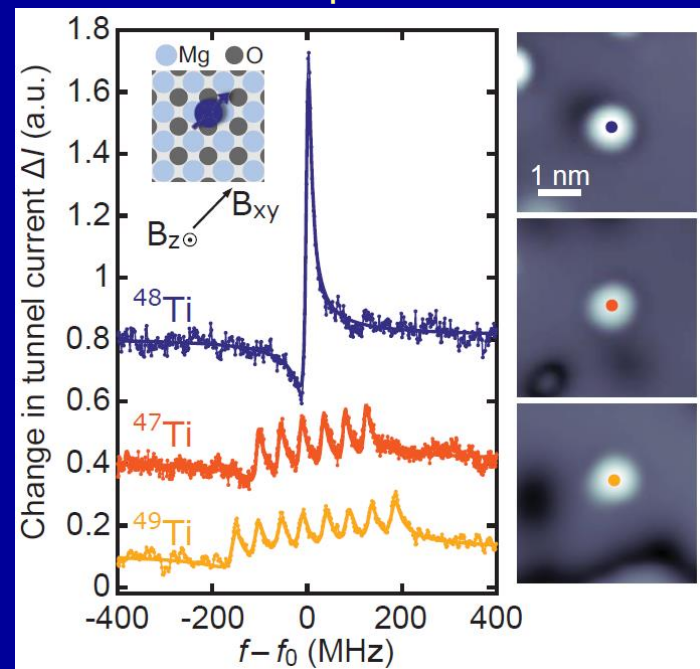
mapping vibrations



spin relaxation times



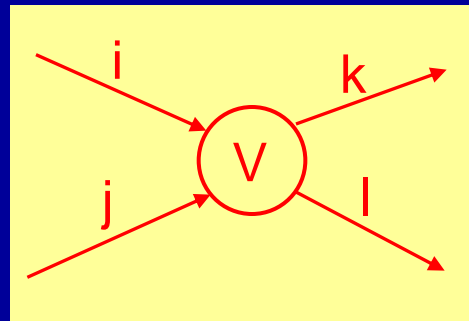
atomic scale  
electron spin resonance



**Excursion:**  
**Guiding e-e interaction**  
**The Kondo effect mirage**

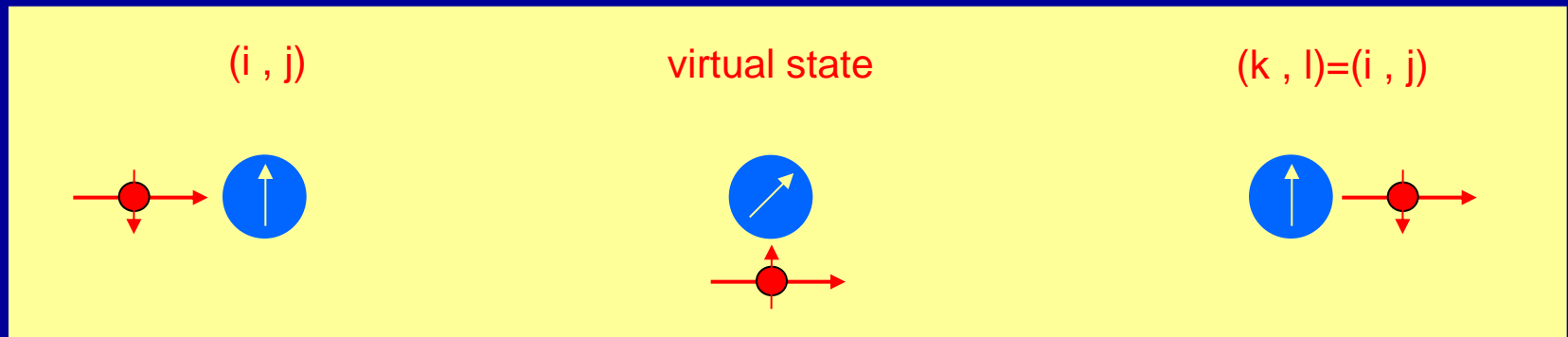
# Kondo effect (electron-electron interaction)

$$H_{ee} = \sum_{i,j,k,l} V_{ijkl} c_i^\dagger c_j^\dagger c_k c_l$$



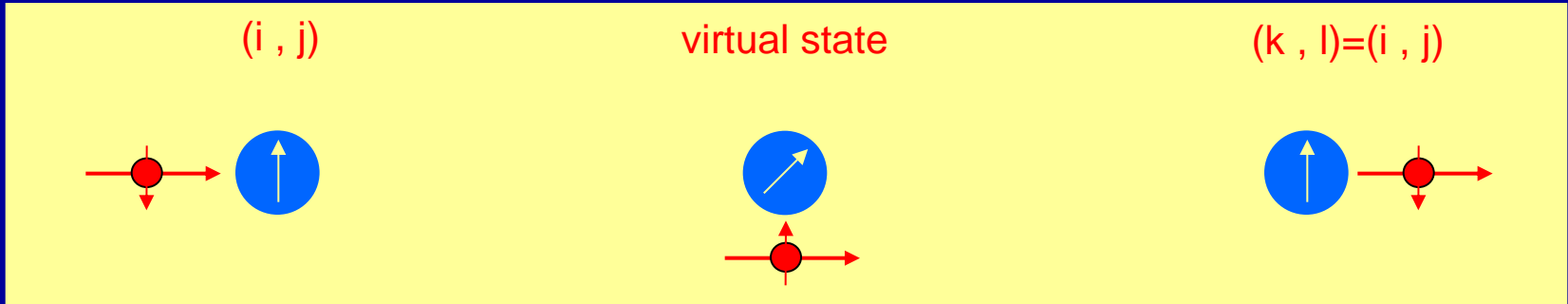
interaction as a scattering process

second order scattering between an itinerate level and a localized level ( $V=J$ =exchange)



process is divergent for  $T = 0$  K and  $E_i = E_F$  ( $\tau_{\text{scatt}} \rightarrow 0, P_{\text{scatt}} \rightarrow \infty$ )

# Kondo effect



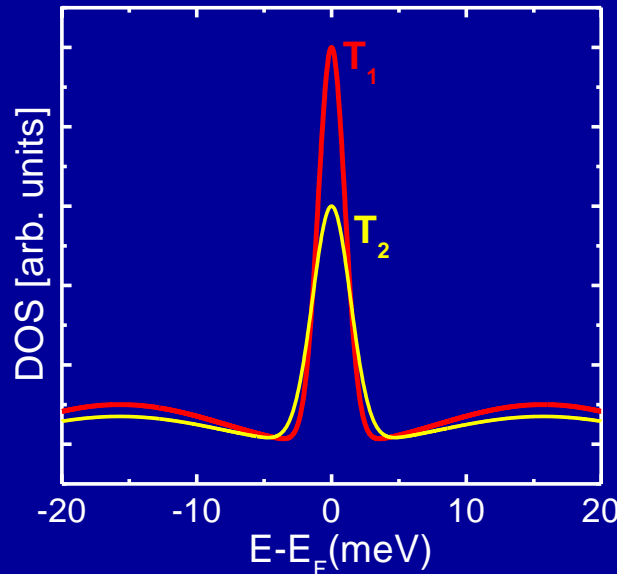
$J < 0$  (attractive)  $\Rightarrow$  scattering reduces total energy of the electron system  
scattering requires free state  $\Rightarrow$  preferred scattering at  $E_F$

$\Rightarrow$

Move occupied states from lower energy to  $E_F$  to reduce total energy !

Move free states from higher energy to  $E_F$  to increase scattering probability !

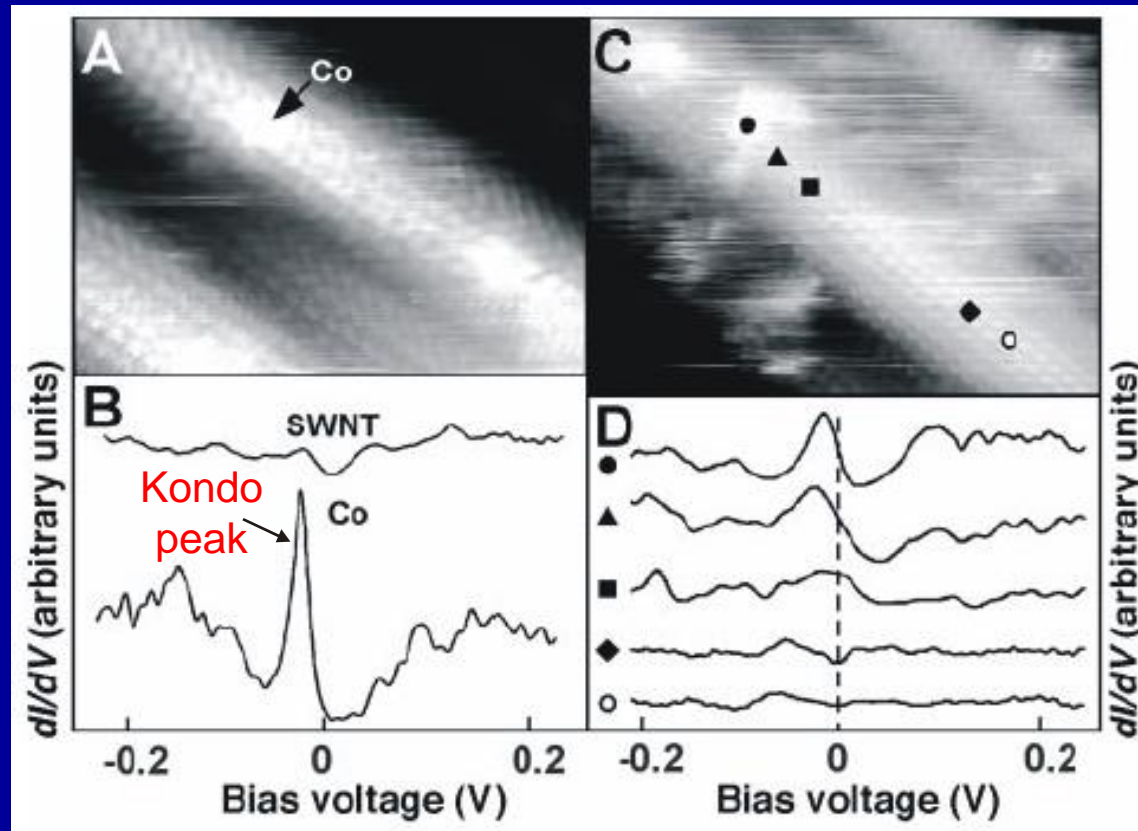
Kondo peak



see A. Hewson  
*From the Kondo Effect to Heavy Fermions*  
(Cambridge Univ. Press)

# STS of Kondo effect

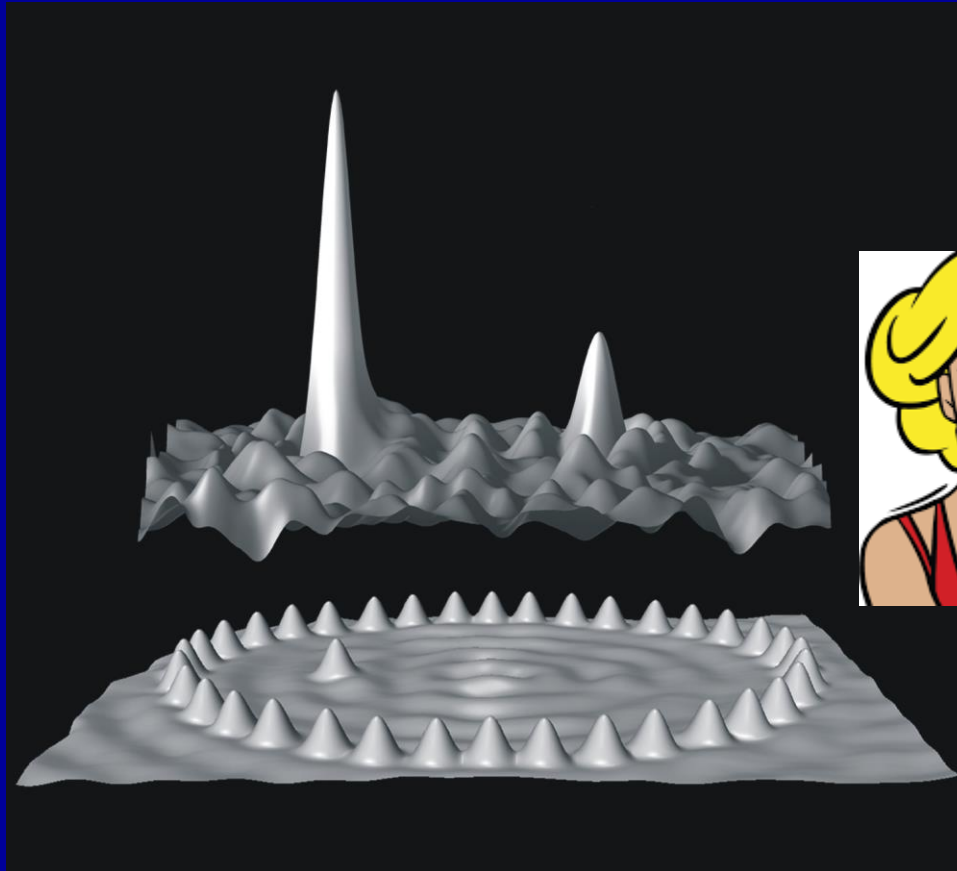
Co cluster on carbon nanotube



*T. W. Odom et al., Science 290, 1549 (2000)*

# Guiding the Kondo peak

Elliptic quantum corral on Cu(111) with one Co atom

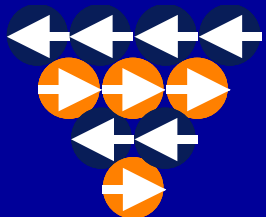


Co atom in one focus  $\Rightarrow$  Kondo peak in the other focus

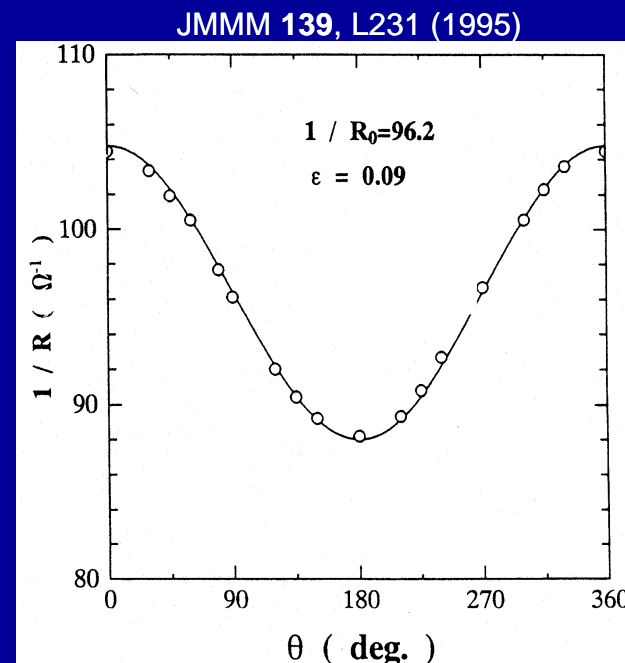
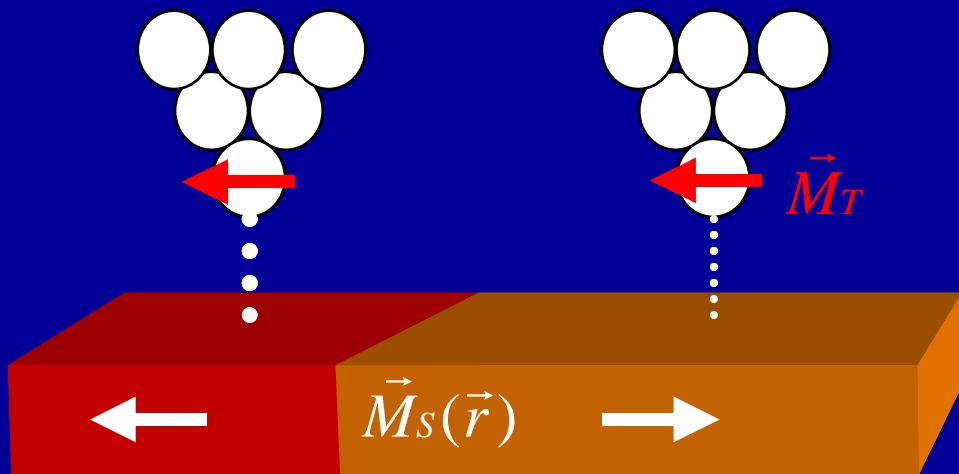
*H. C. Manoharan et al., Nature 403, 512 (2000)*

# Imaging spin configurations

# Getting spin information by STS



using a magnetic tip as a spin filter (Bode 1996)



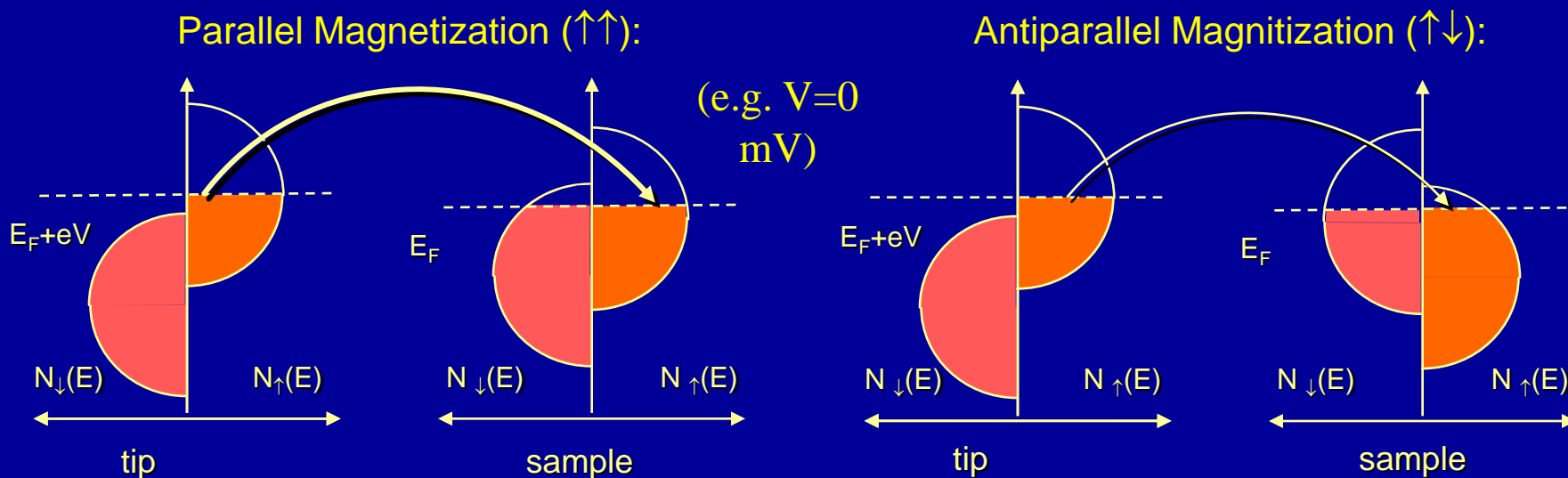
angular dependence

dI/dV depends on relative orientation of the spin  
in sample and tip

$$dI/dV_{\uparrow\uparrow} > dI/dV_{\uparrow\downarrow}$$

# Spin-Polarized Electron Tunneling

- spin is conserved in tunneling event

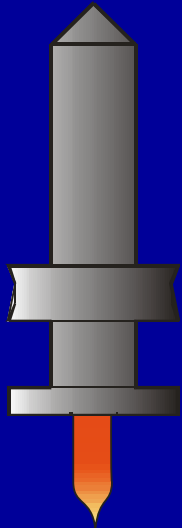


tunneling between exchange split DOS of two ferromagnets

$$dI/dV_{\uparrow\uparrow} > dI/dV_{\uparrow\downarrow}$$

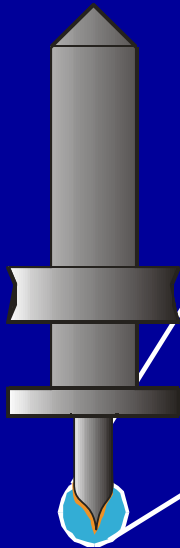
$\Rightarrow$  spin degree of freedom of electron system

# Spin-Polarized Tips



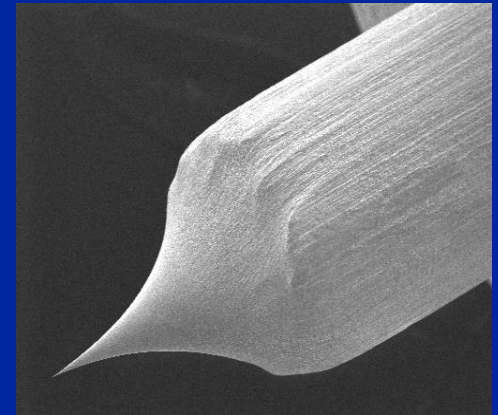
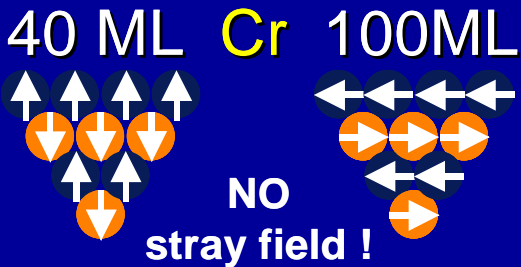
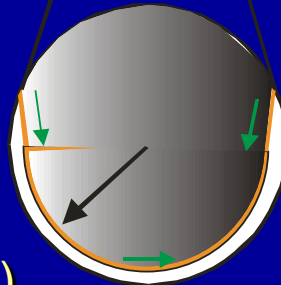
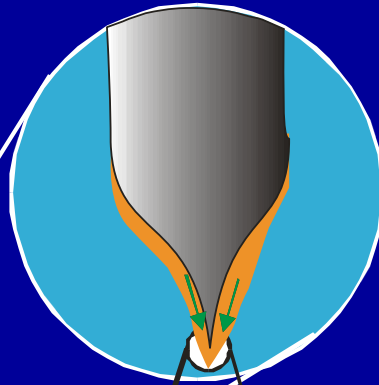
(a)

Flash to  $T > 2200$  K



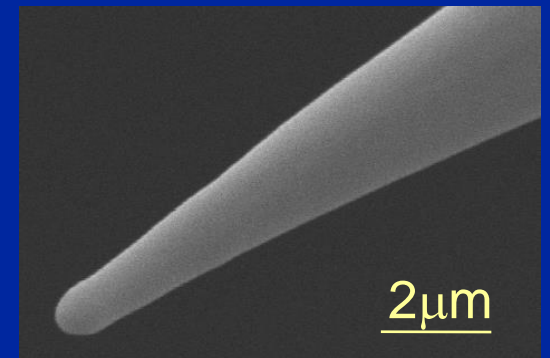
(b)

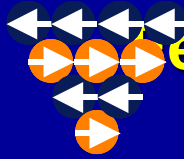
MBE-deposition of Fe/Gd/Cr (5-100 ML)



- sharp tip on a mesosc. scale
- ➔ shape anisotropy may force  $M$  along the tip axis

- flashed tip:  $R = 500$  nm
- ➔ surface and interface anisotropy dominates
- ➔  $M$  depends on coating material and film thickness

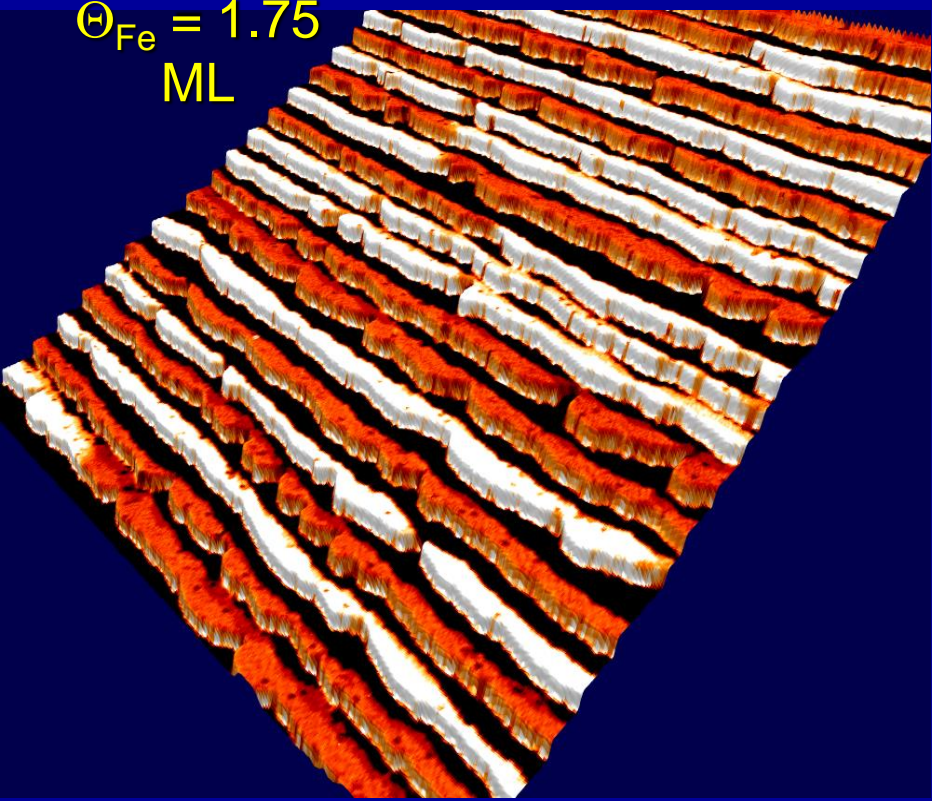




# Fe Nanowires of Different Width on W(110)

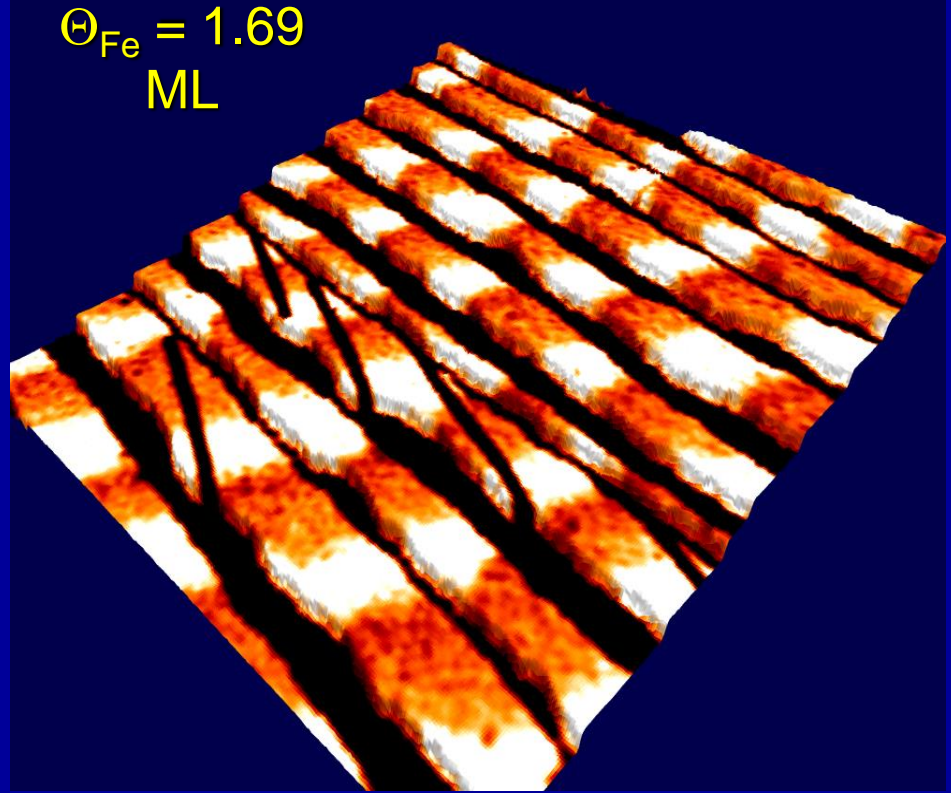
topography (height) and spin polarized  $dI/dV$  signal (color)

$\Theta_{Fe} = 1.75$   
ML



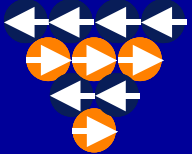
W(110)-miscut:  $1.35^\circ$   
average terrace width: 9  
nm

$\Theta_{Fe} = 1.69$   
ML

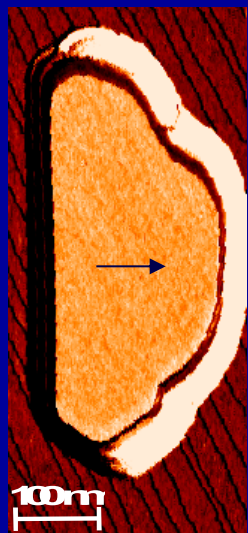


W(110)-miscut:  $0.64^\circ$   
average terrace width : 20  
nm

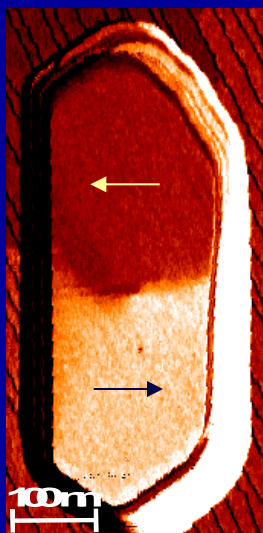
# Fe-islands with different domain configuration



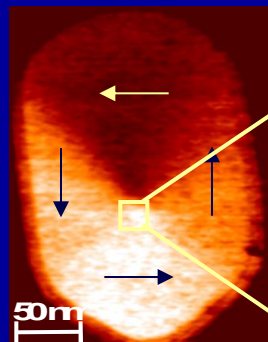
h=3.5 nm



h=4 nm

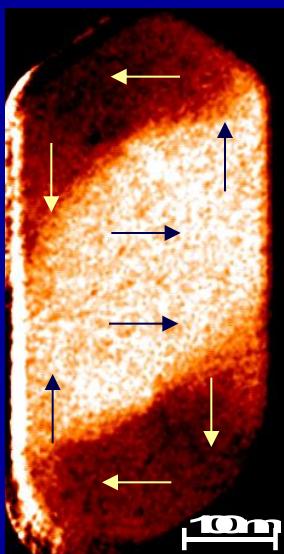
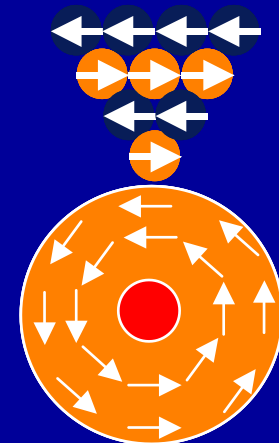
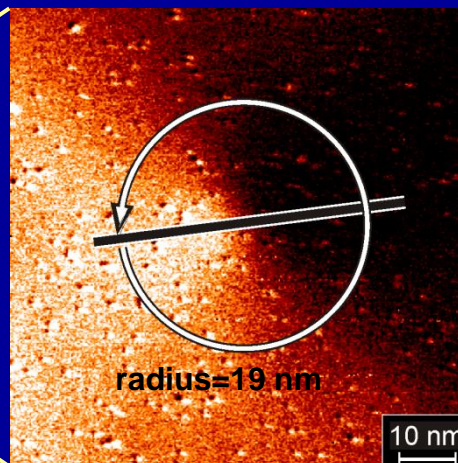


h=9 nm

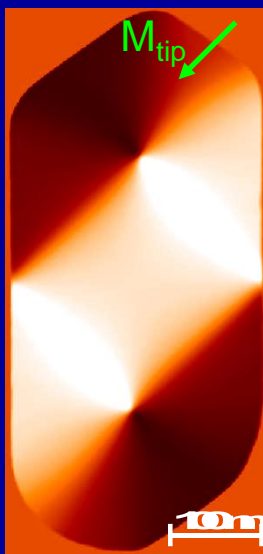


[001]  
[110]

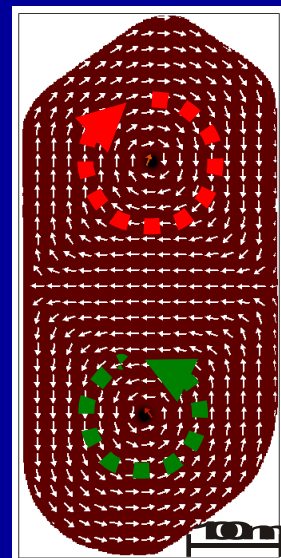
vortex core (in plane)



h=8 nm

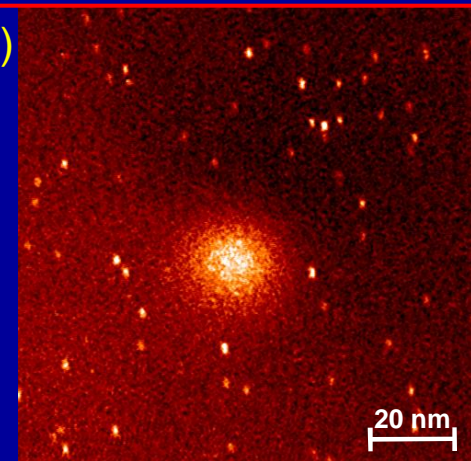
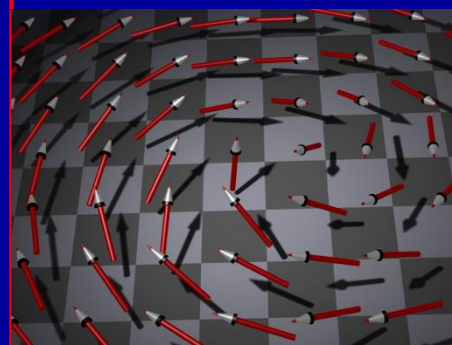
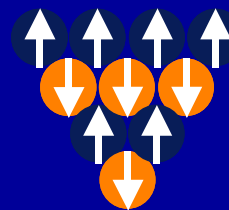


h=8 nm



h=8 nm

vortex core (out-of-plane)

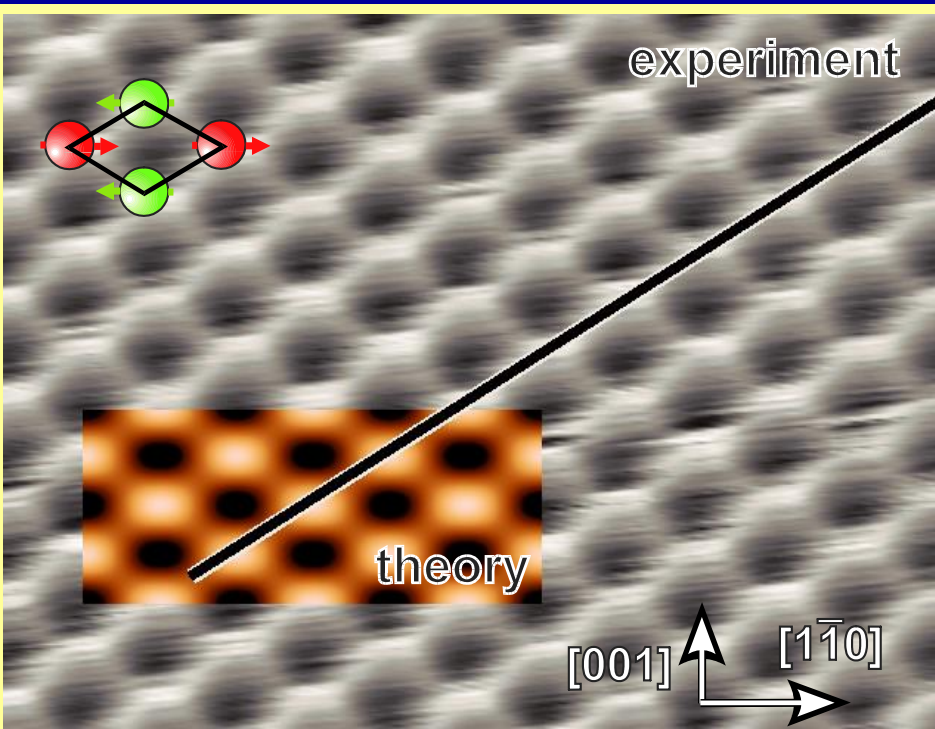


center spins turn  
out-of-plane

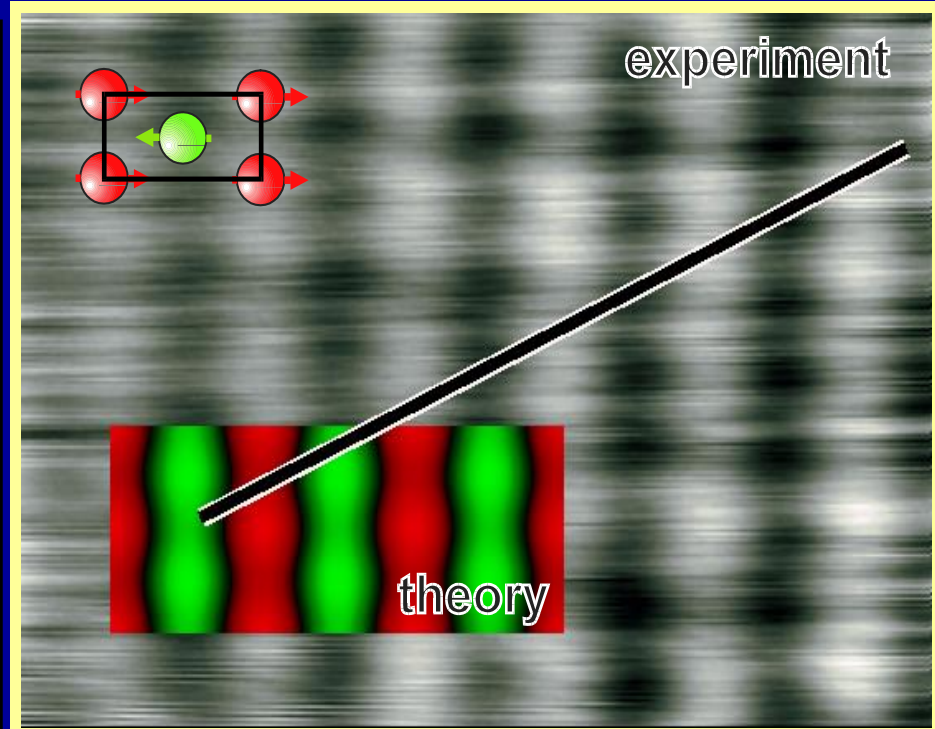
Wachowiak et al.,  
*Science* 298, 577 (02)

# Spin Polarized STM with Atomic Resolution: Antiferromagnetic Mn/W(110)

## W-Tip



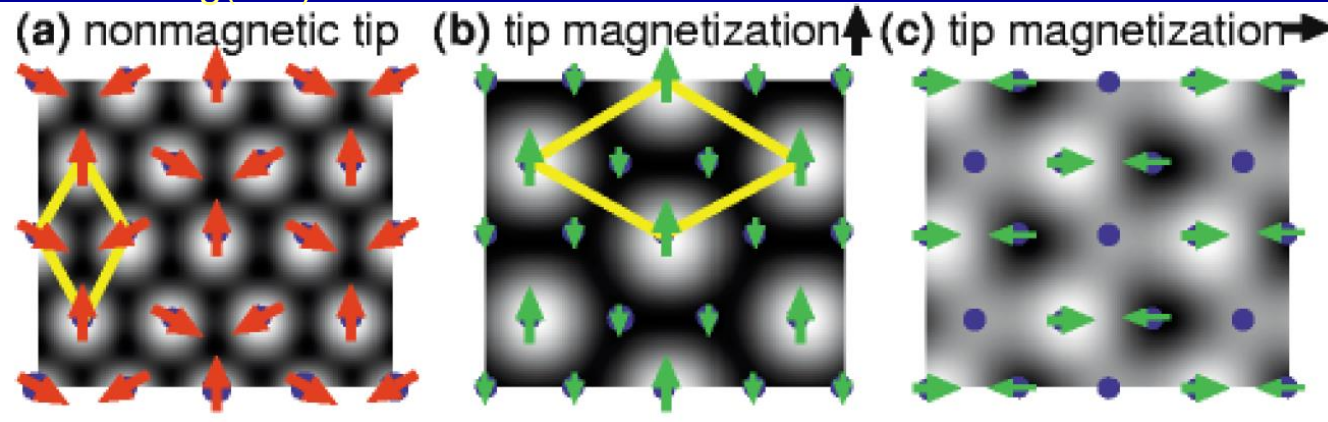
## Fe-Tip (in-plane sensitivity)



theory: DFT Calculations by FLAPW-Code

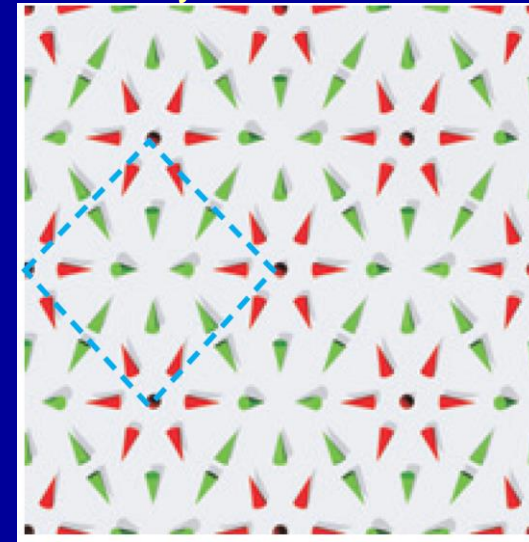
# Spin Polarized STM with Atomic Resolution: Noncolinear Magnetism

DFT: Cr/Ag(111)

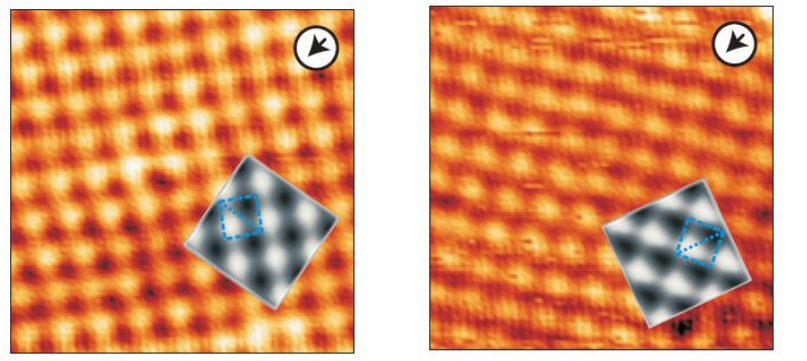


Wortmann et al., PRL 86, 4132 (01)

Skyrmion texture

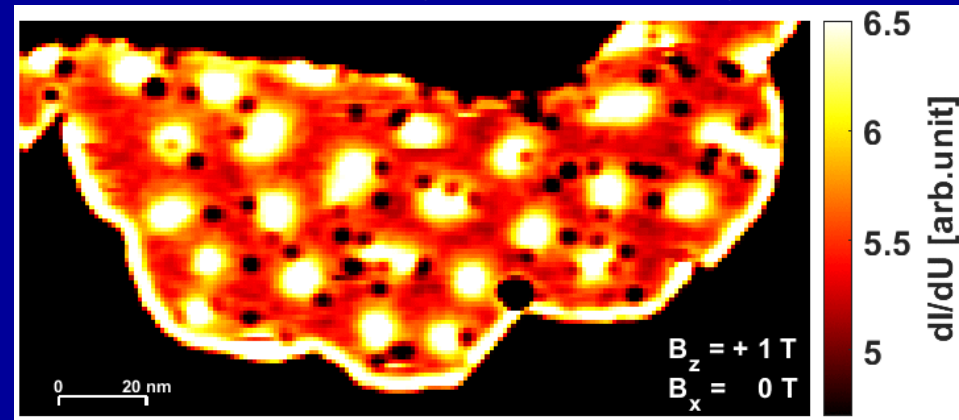


Skyrmion lattice ( 2 domains) Fe/Ir(111)

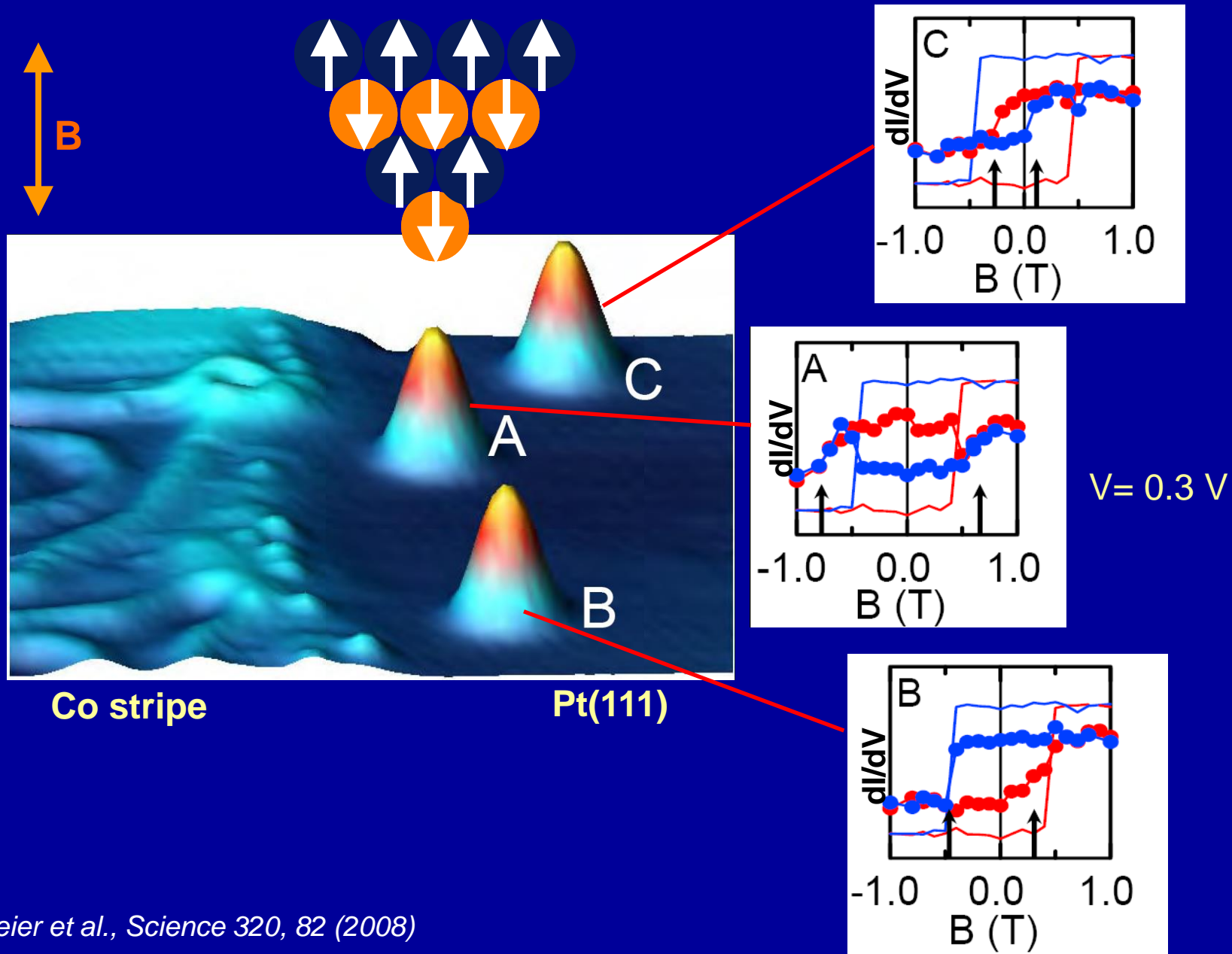


Heinze et al., Nat. Phys. 7, 713 (11)

Pd/(Fe/Ir(111) Skyrmion motion by current

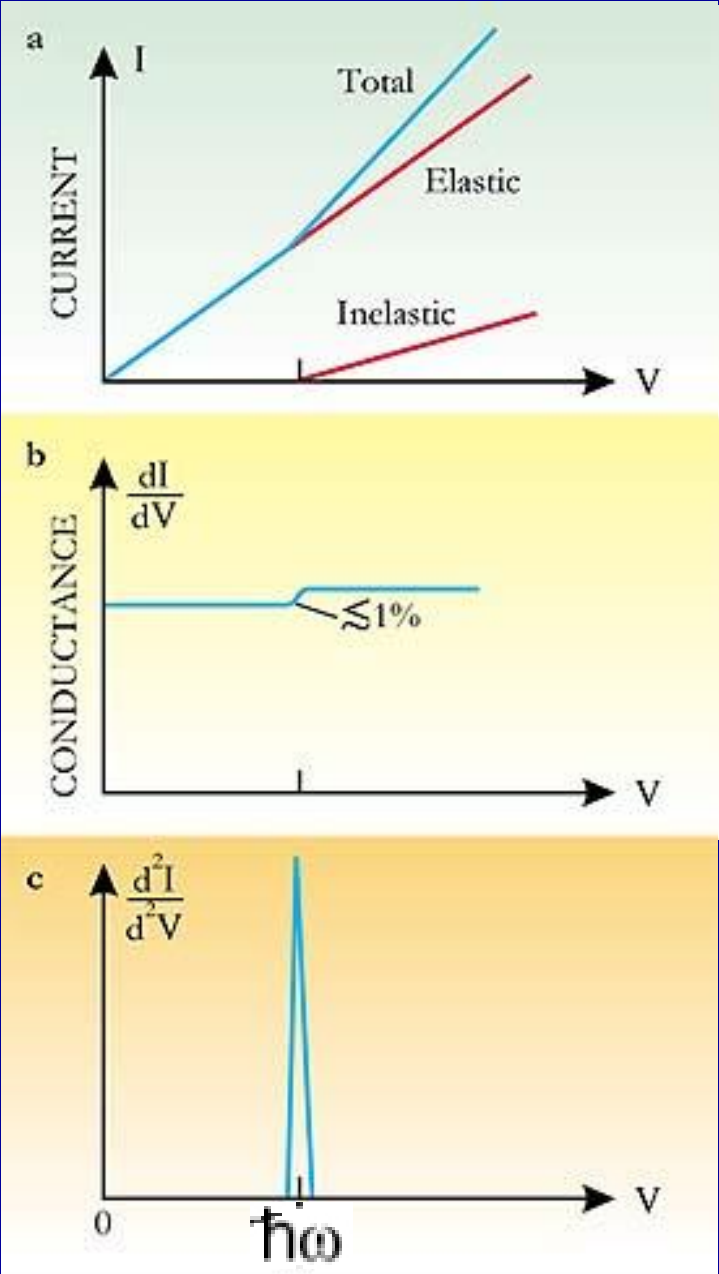
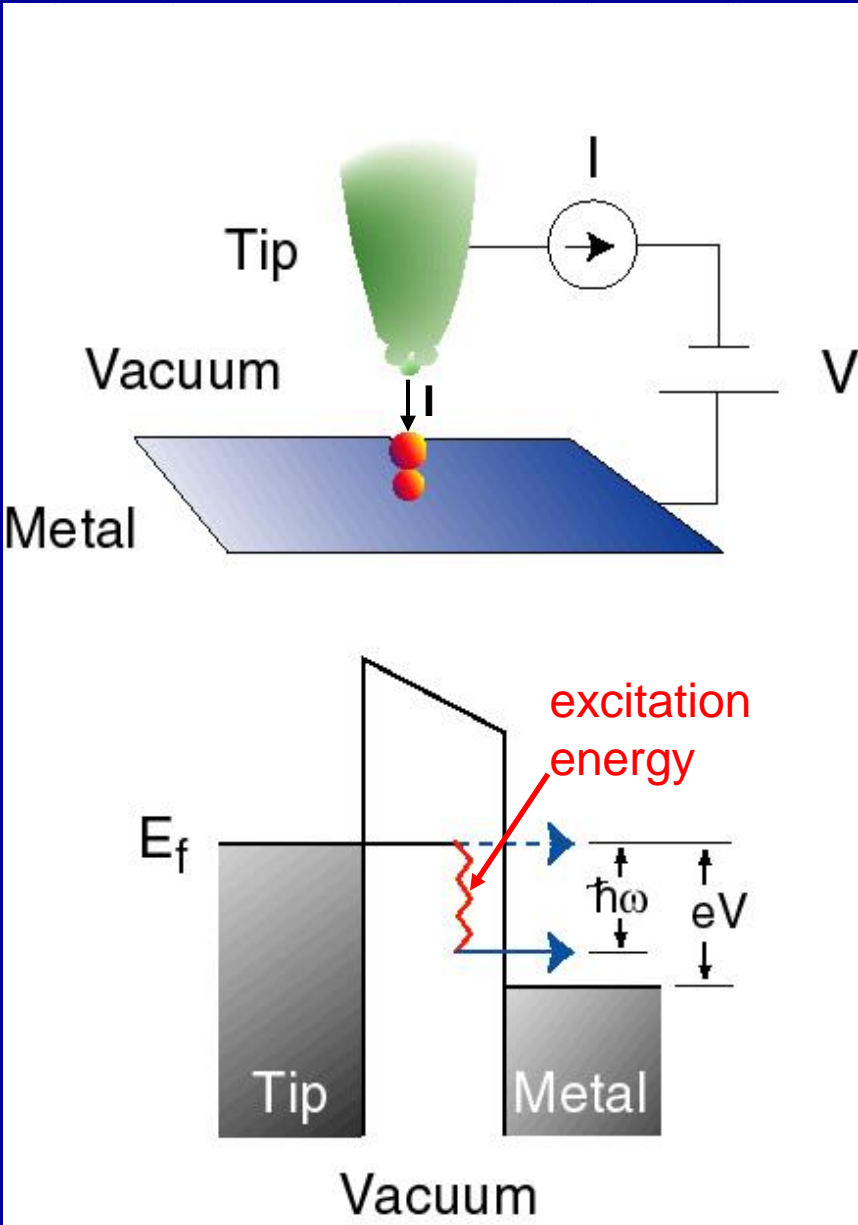


# Hysteresis of individual Co atoms



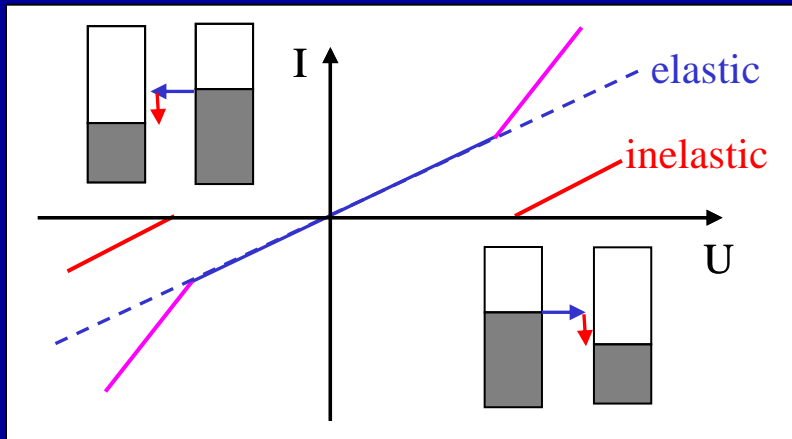
# Mapping excitations

# Seeing excitations: Inelastic tunneling spectroscopy

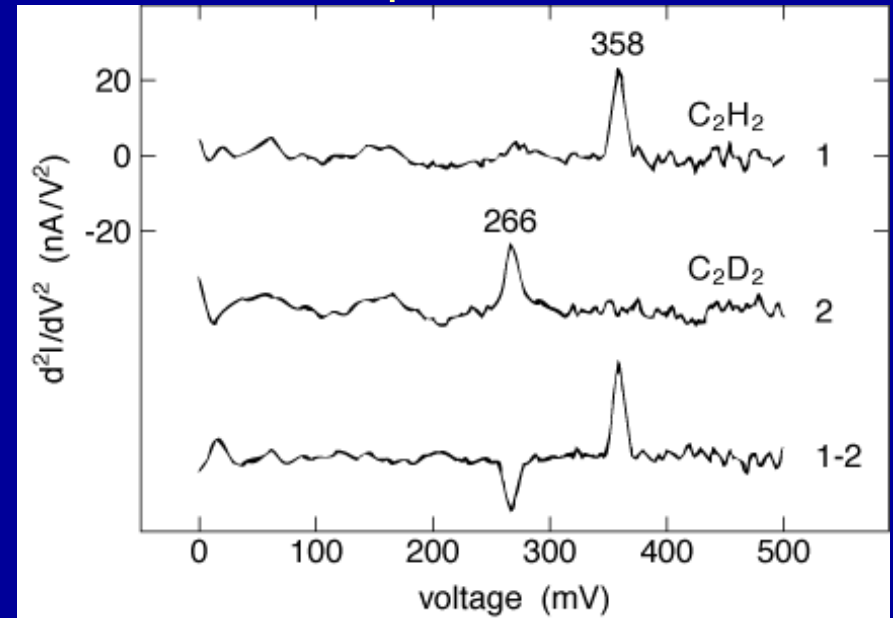


# Proof: Vibronic excitations

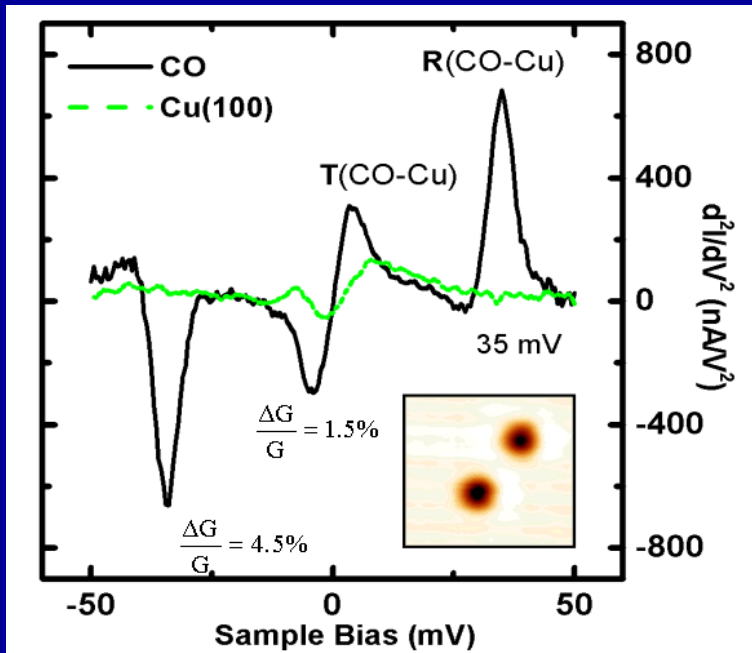
## Antisymmetry



## Isotope effect



## CO on Cu(100)



## C<sub>2</sub>H<sub>2</sub> on Cu(100)



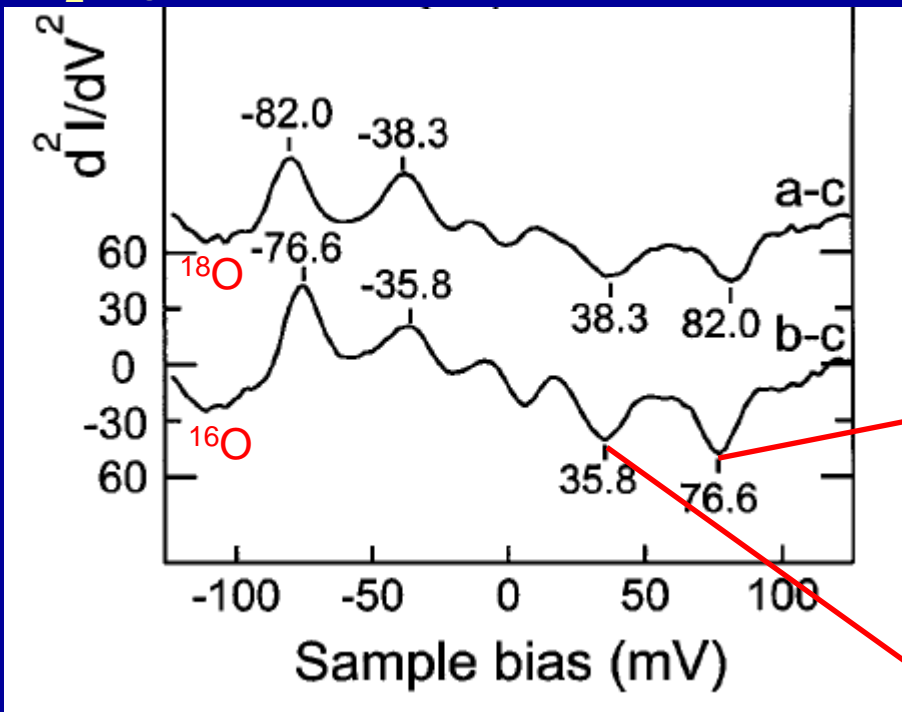
$d^2I/dV^2$  signal at 266 mV

$d^2I/dV^2$  signal at 358 mV

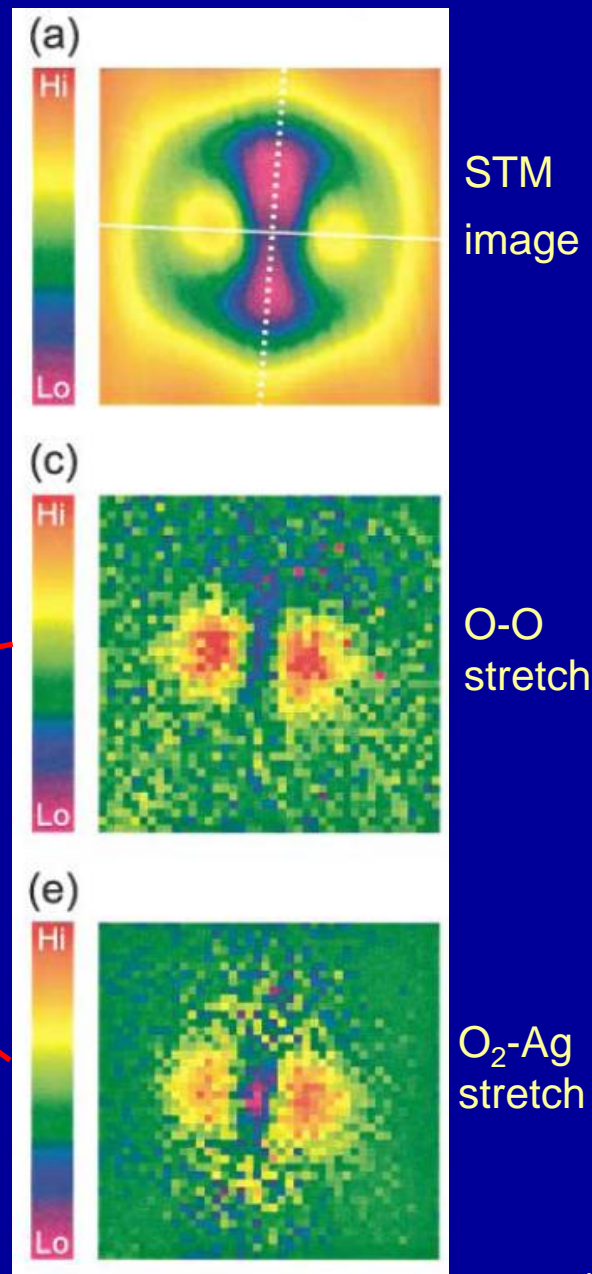
Stipe et al., Science 280, 1732 (1998)

# Mapping vibrational intensity

O<sub>2</sub>/Ag(110)

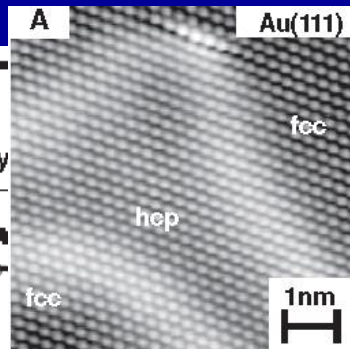
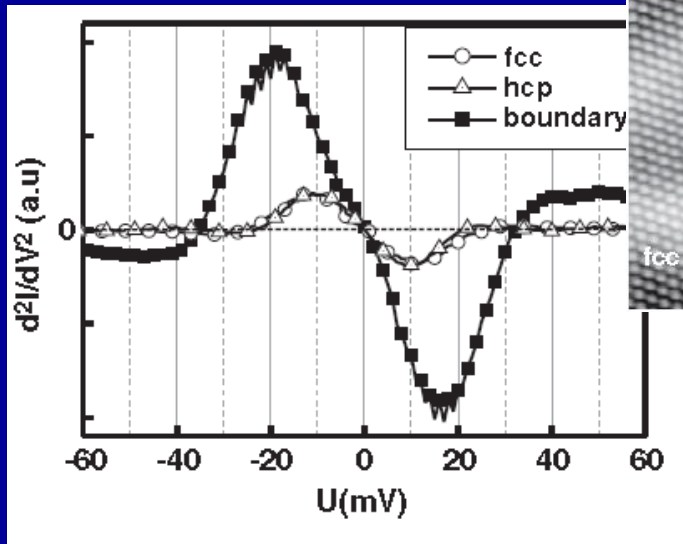


Most effective after tunneling into  $\pi_g$  orbital



# Other excitations

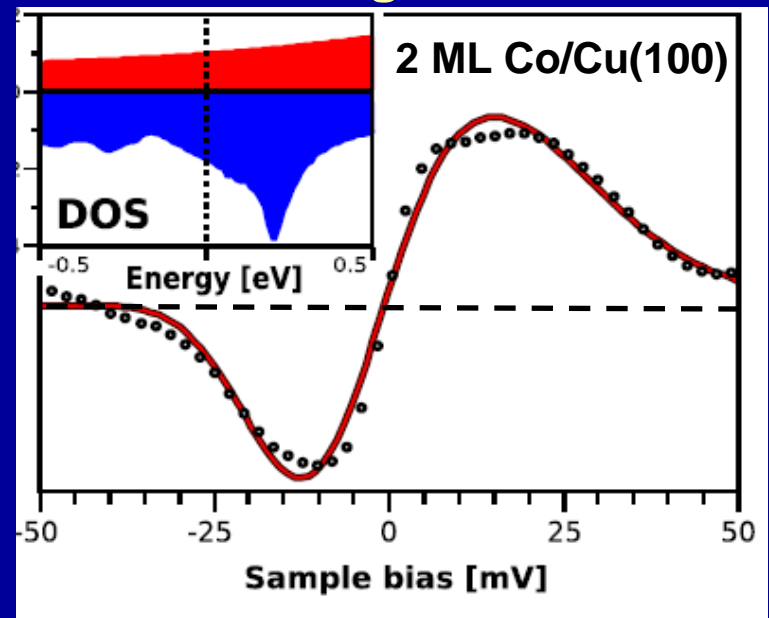
## Phonons



Au(111)

Gawronski et al., *Science* 319, 930 (2008)  
see also L. Vitali et al, *PRB* 69, 121414 (2004)

## Magnons

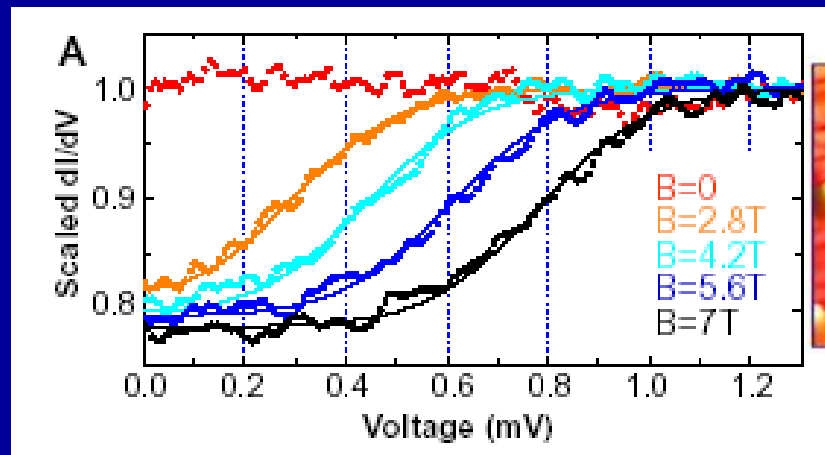
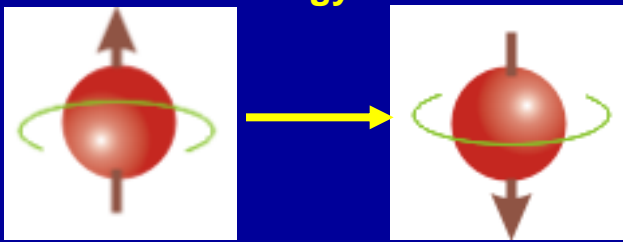


Balashov et al., *PRL* 97, 187201 (2006)

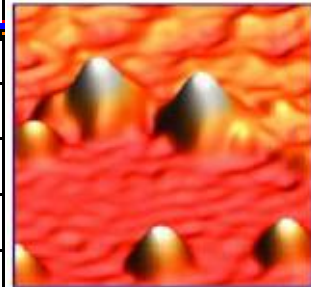
## Spin flip excitation

**B-field**

Spin flip-  
energy  $\Delta E$



Heinrich et al., *Science* 306, 466 (2004)

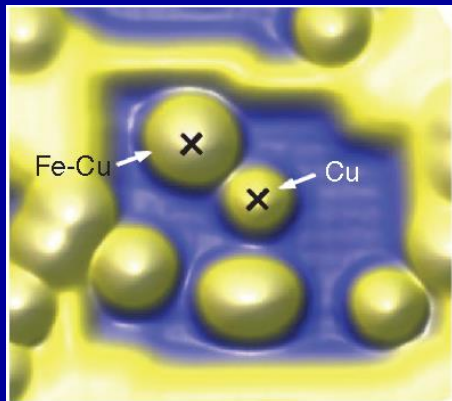


Mn-atoms  
on CuN

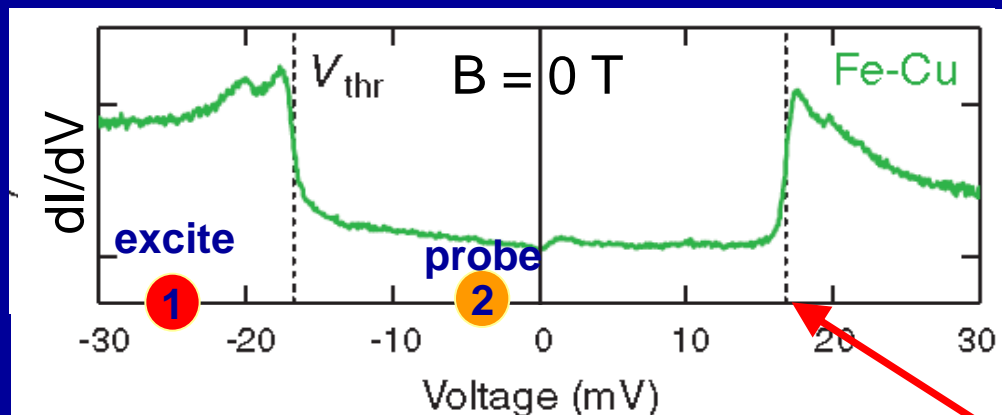
# Time resolution

# Time resolution: Spin relaxation

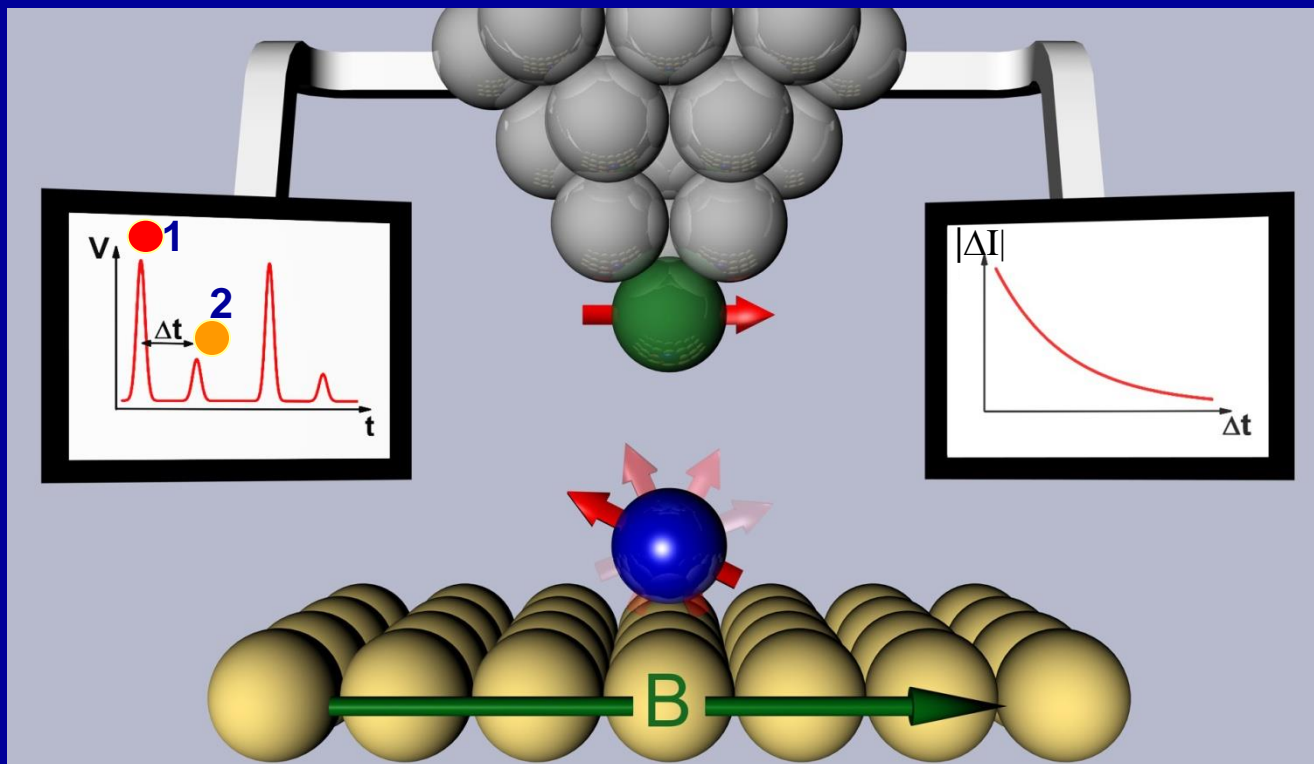
FeCu dimer on CuN



Magnetocrystalline anisotropy: 17 meV



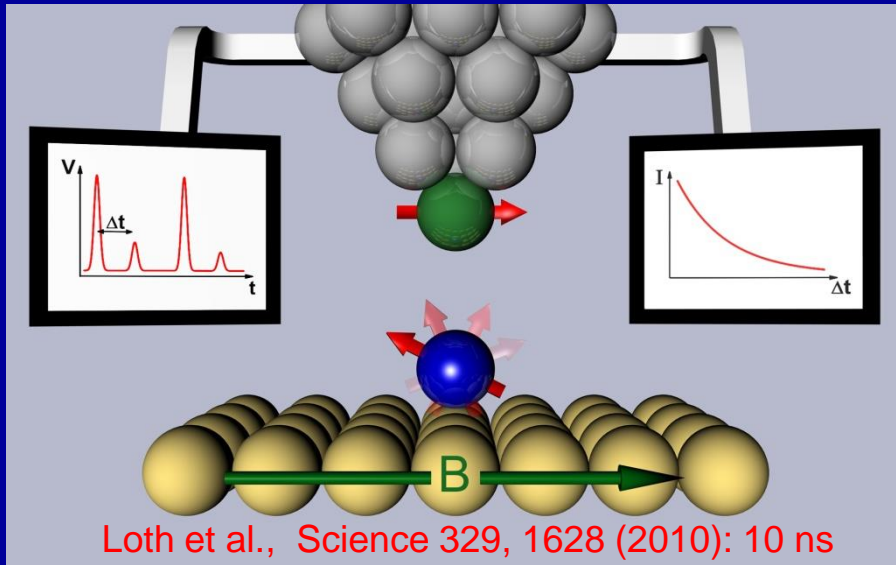
Anisotropy energy



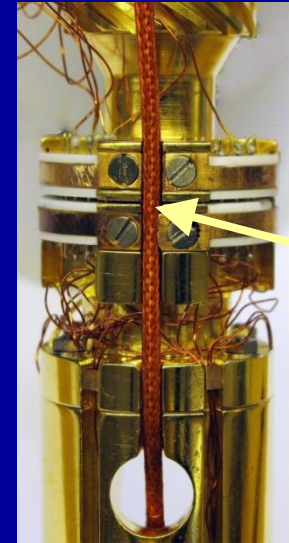
Loth et al.,  
Science 329,  
1628 (2010)

# Towards 100 ps time-resolution

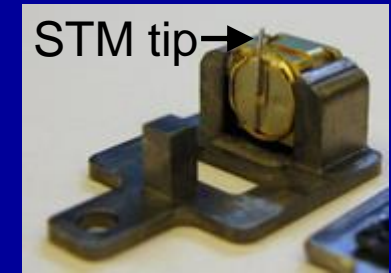
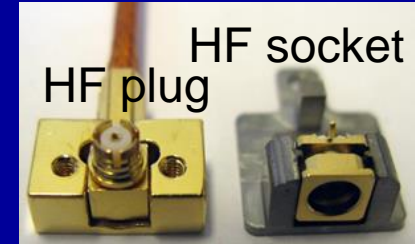
Time-resolved spin relaxation by STM



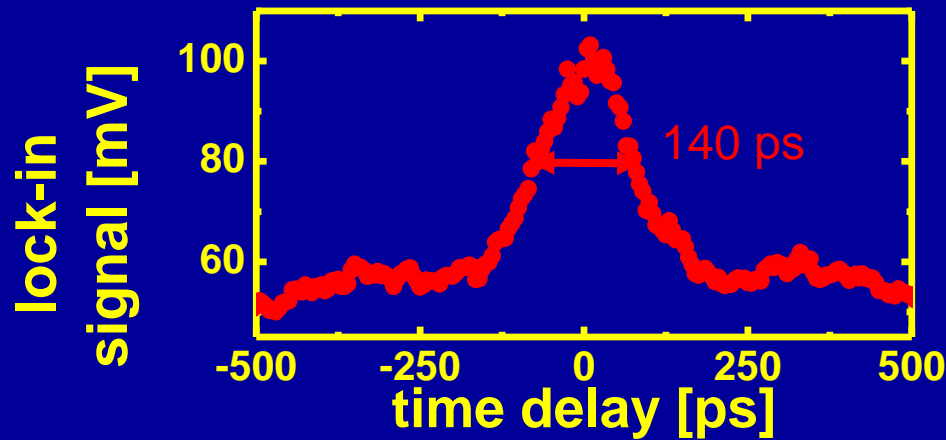
HF-STM



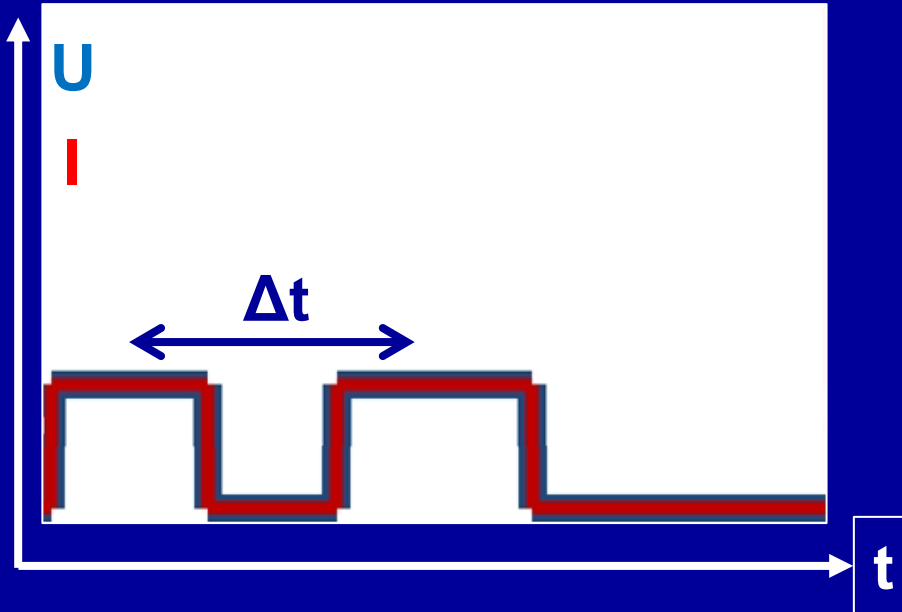
Semi-Rigid  
17 GHz  
cable



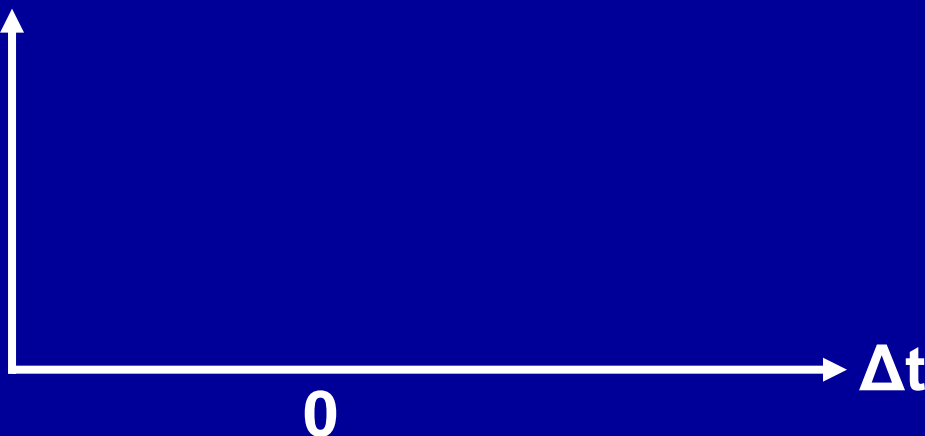
Pump-Probe HOPG



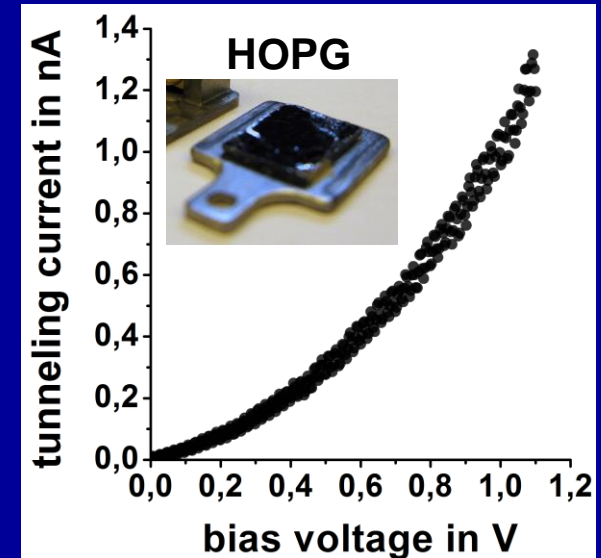
# Determination of the time resolution



Lock-in signal



non-linear I-U characteristic:

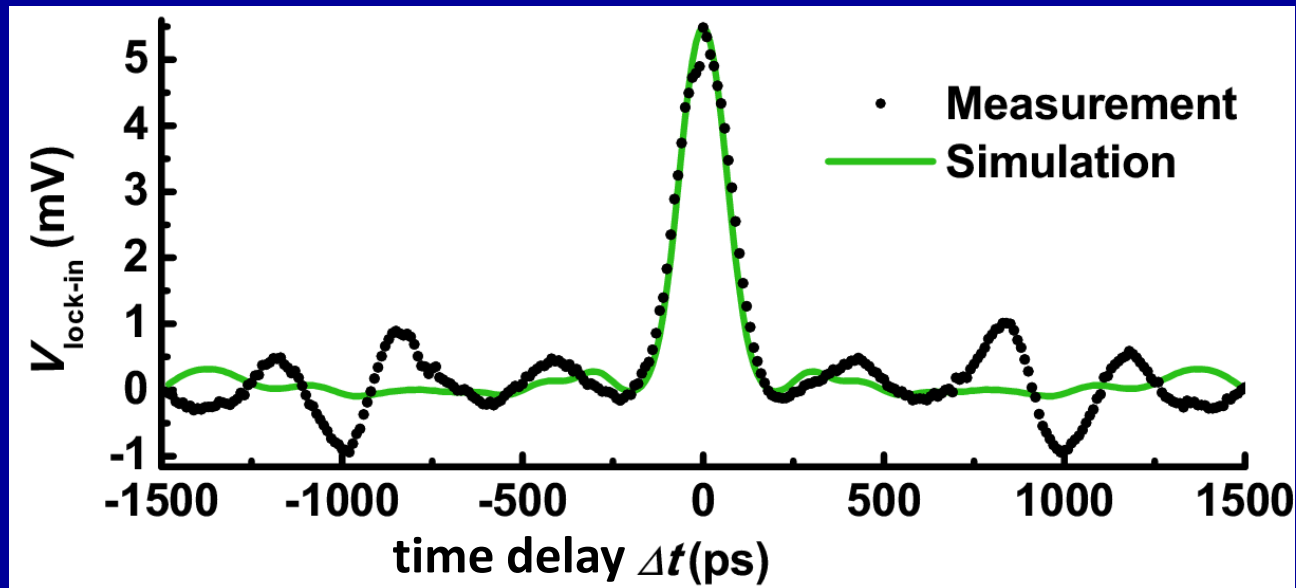
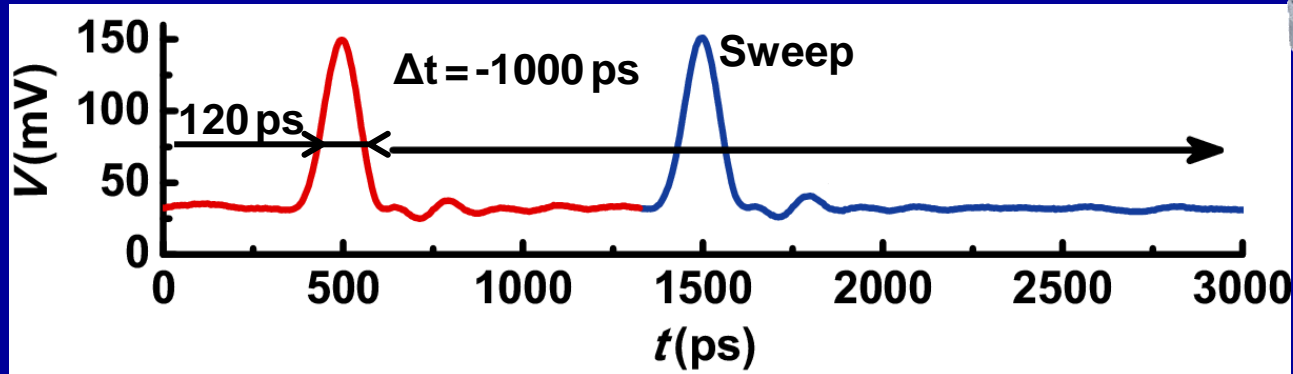


→ determination of the pulse width at the tip

→ time resolution derived from FWHM

# Determination of the time resolution

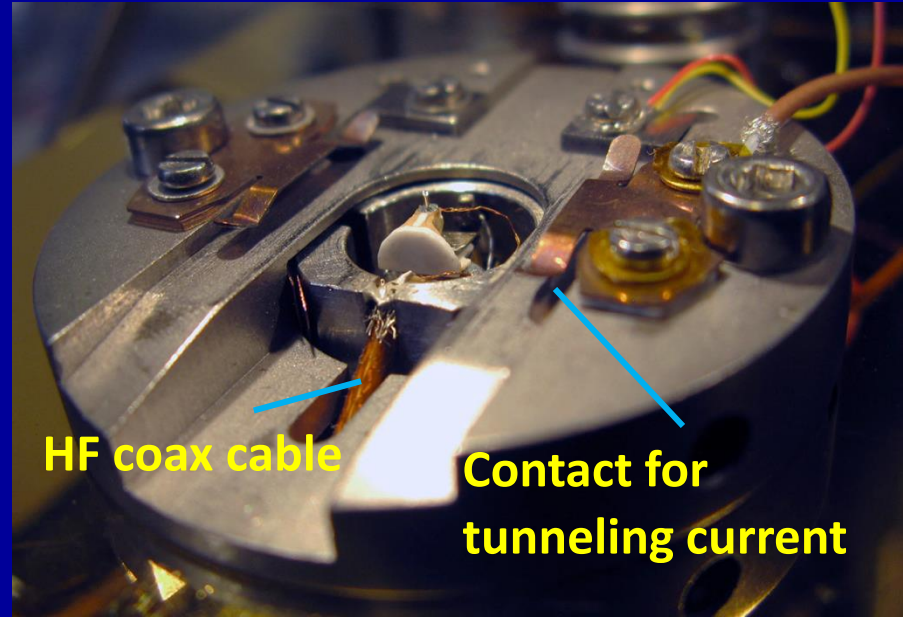
pump and probe pulse from the pulse generator



→ 120 ps time resolution

# HF modification of commercial STM

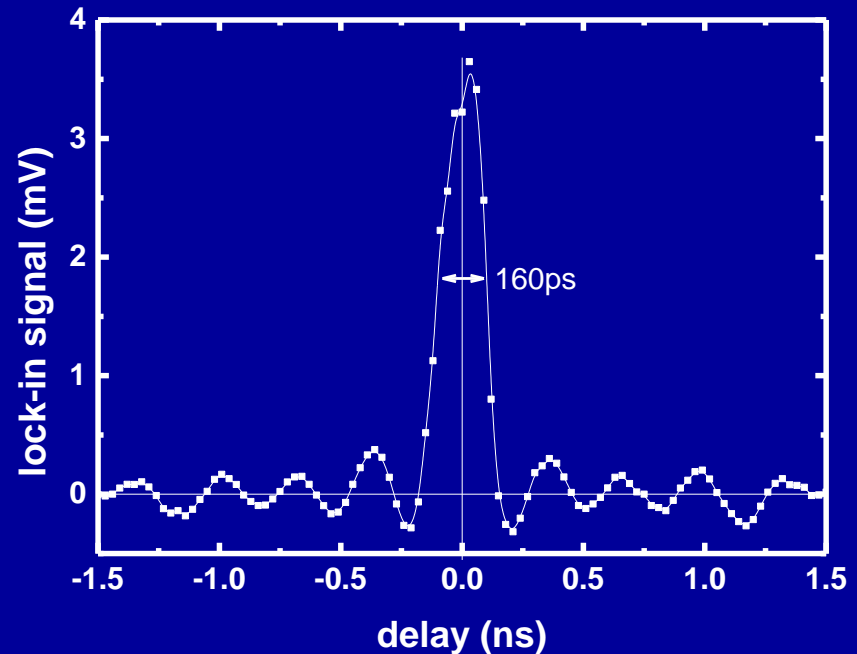
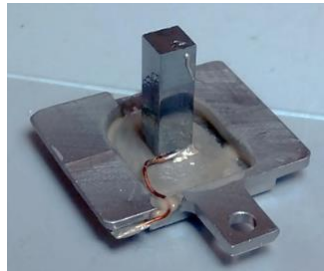
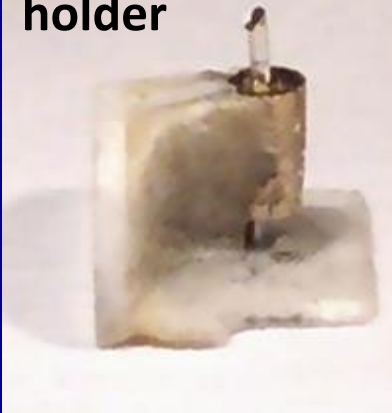
## Aarhus STM (Specs GmbH)



## HF modifications

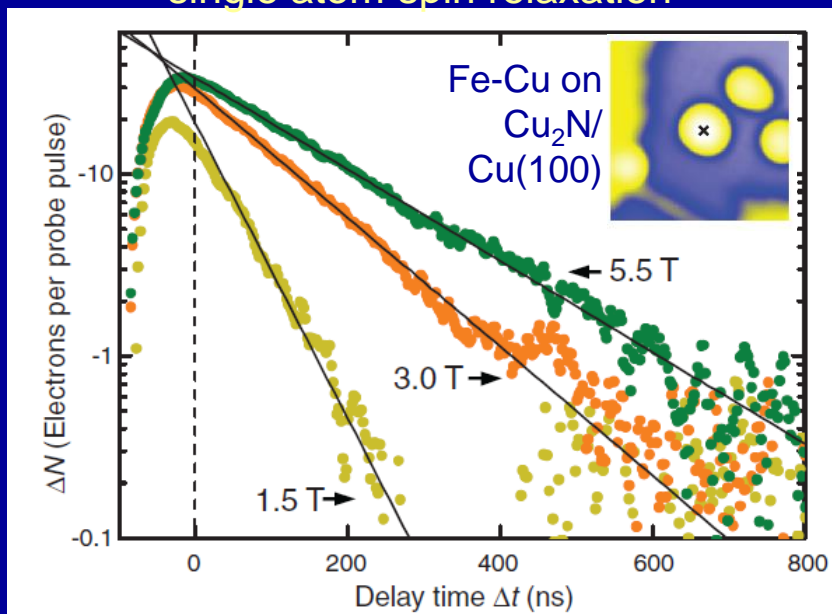
insulated HF tip holder

HF sample holder

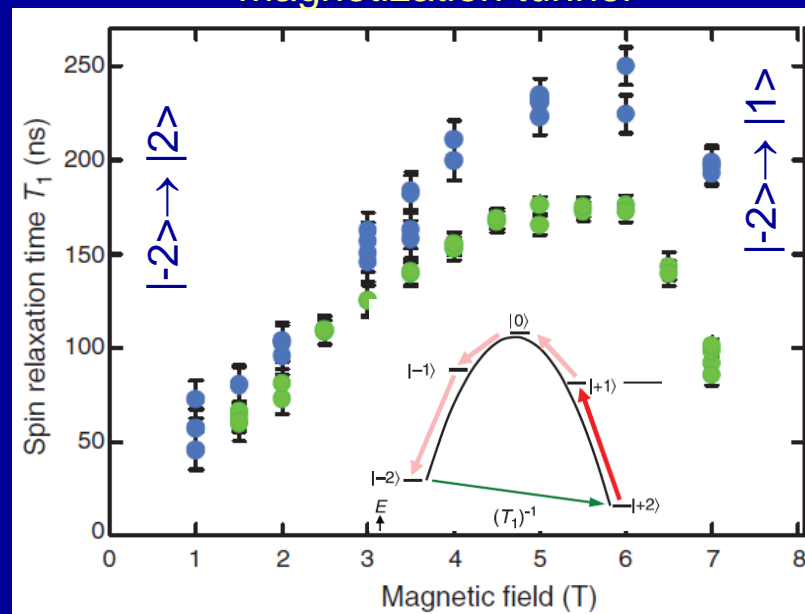


# Results with time-resolved STM (> 100 ps)

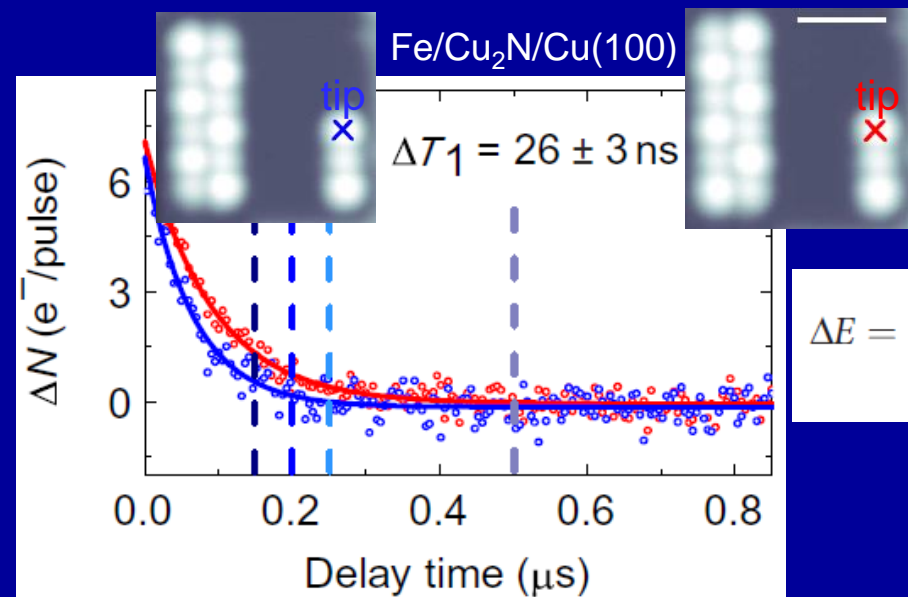
single atom spin relaxation



magnetization tunnel

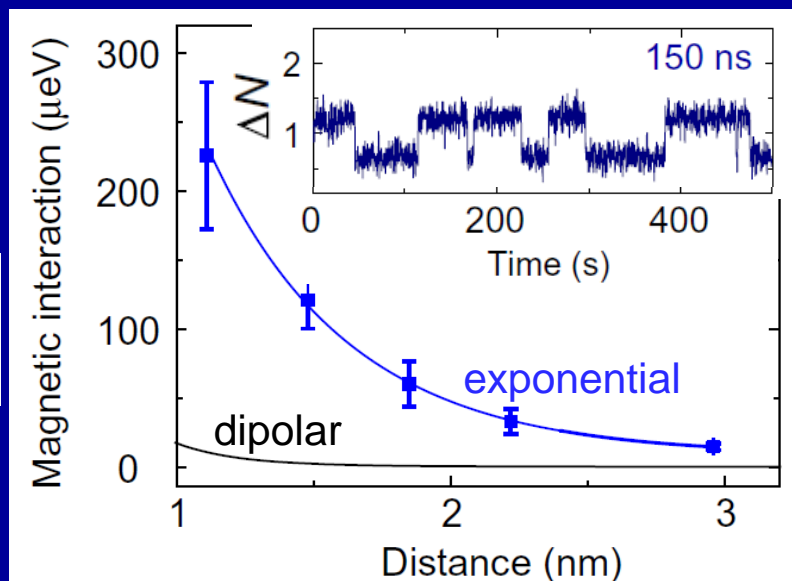


Loth et al., *Science* 329,1628 (2010)



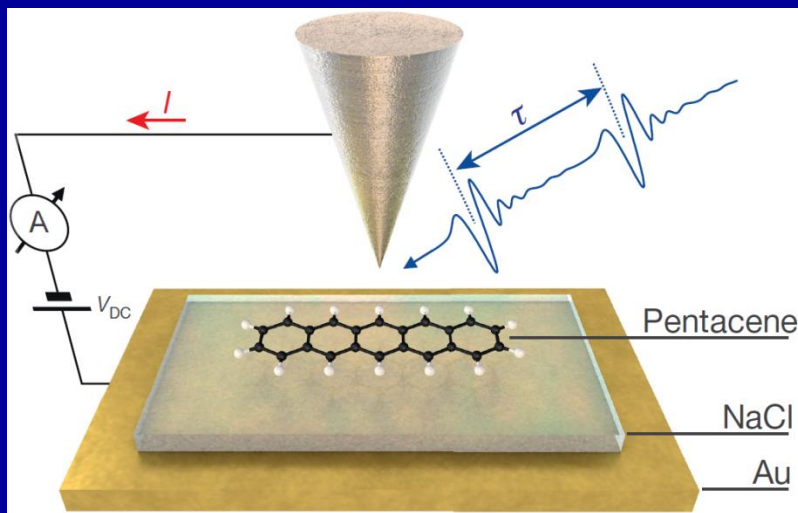
$$\Delta E = \frac{4g\mu_B}{\left(\frac{dT_1}{dB_{\parallel}}\right)} \Delta T_1$$

remote sensing by relaxation change

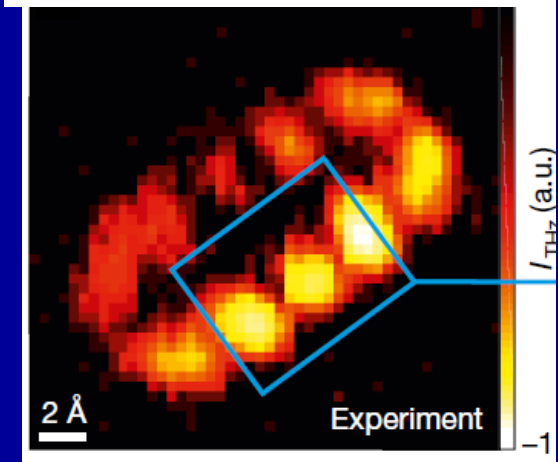
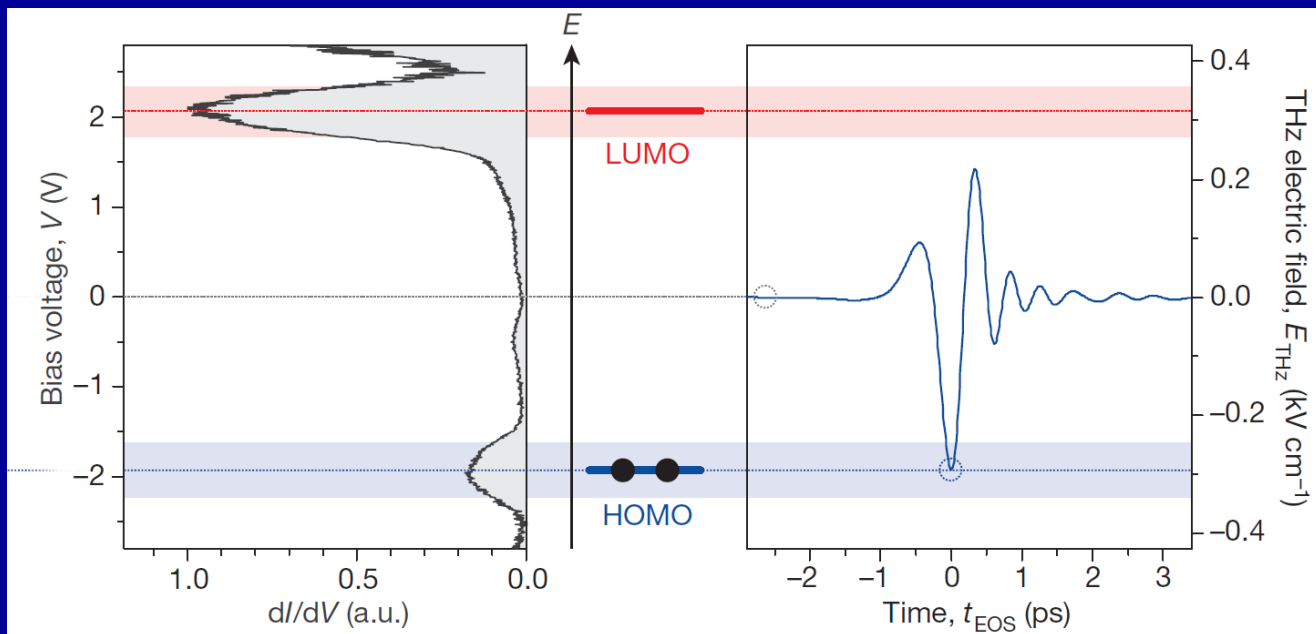
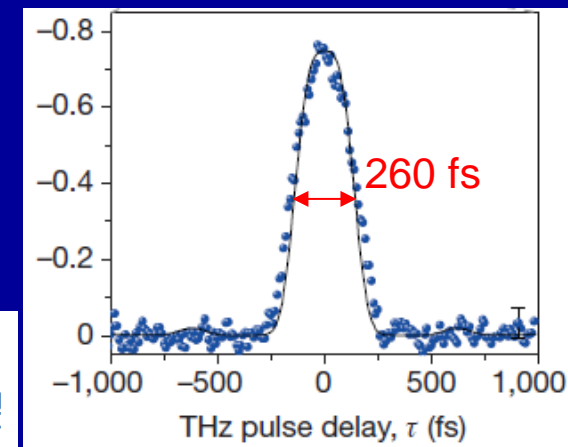
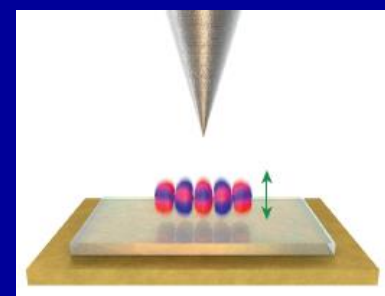
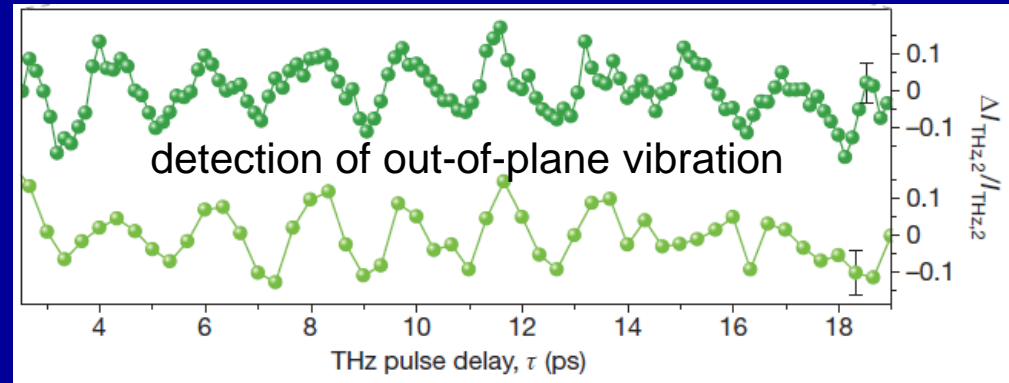


Yan et al., *Sci. Adv.* 3, e1603137 (17) 23/26

# Getting faster: THz spectroscopy



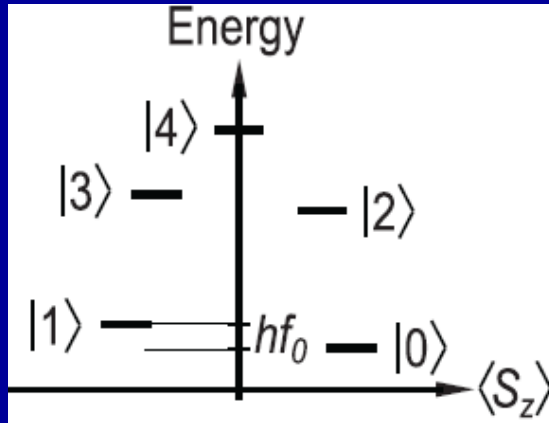
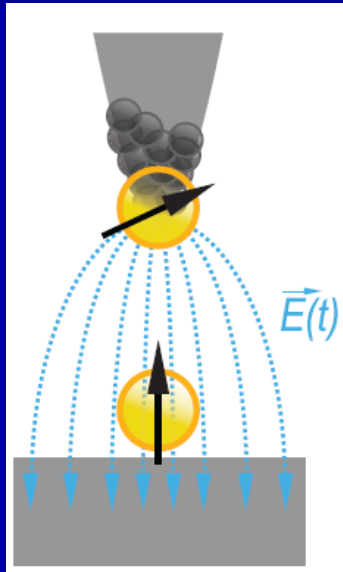
T. L. Cocker, Nature 539, 263 (16)



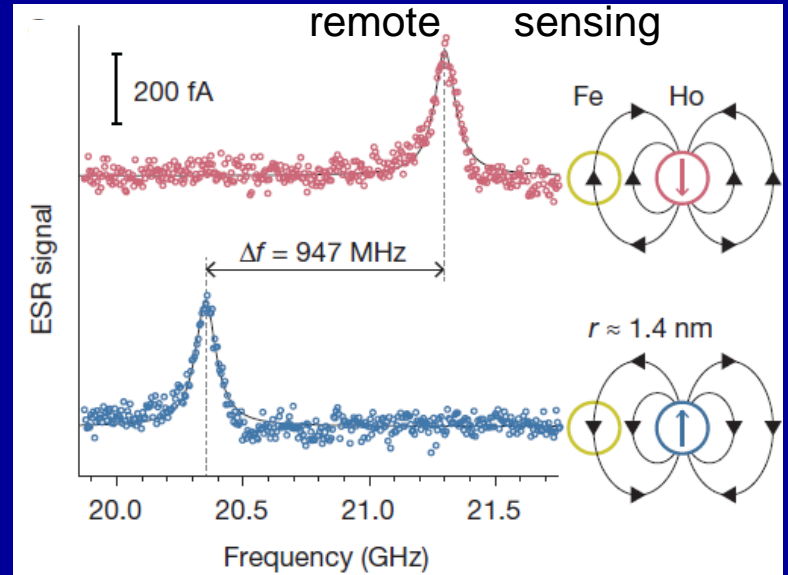
$\tau = 0.1 \text{ ns}$ ,  $V_{\text{DC}} = 0 \text{ V}$ ,  $V_{\text{THz}} = 2.05 \text{ V}$

# Frequency resolution

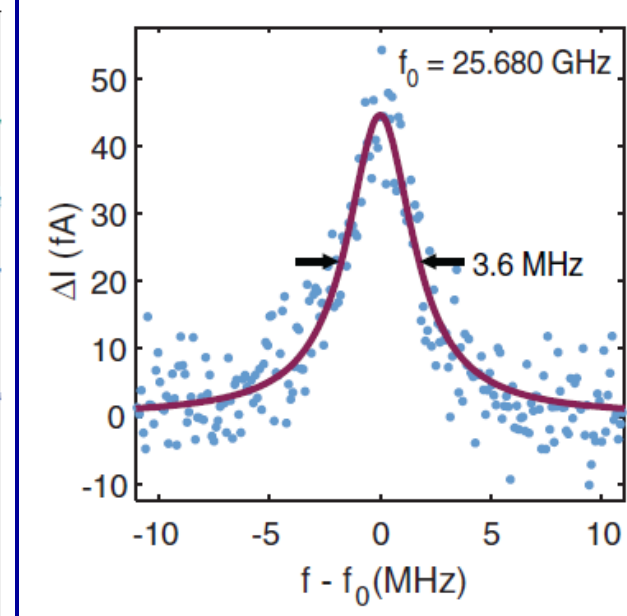
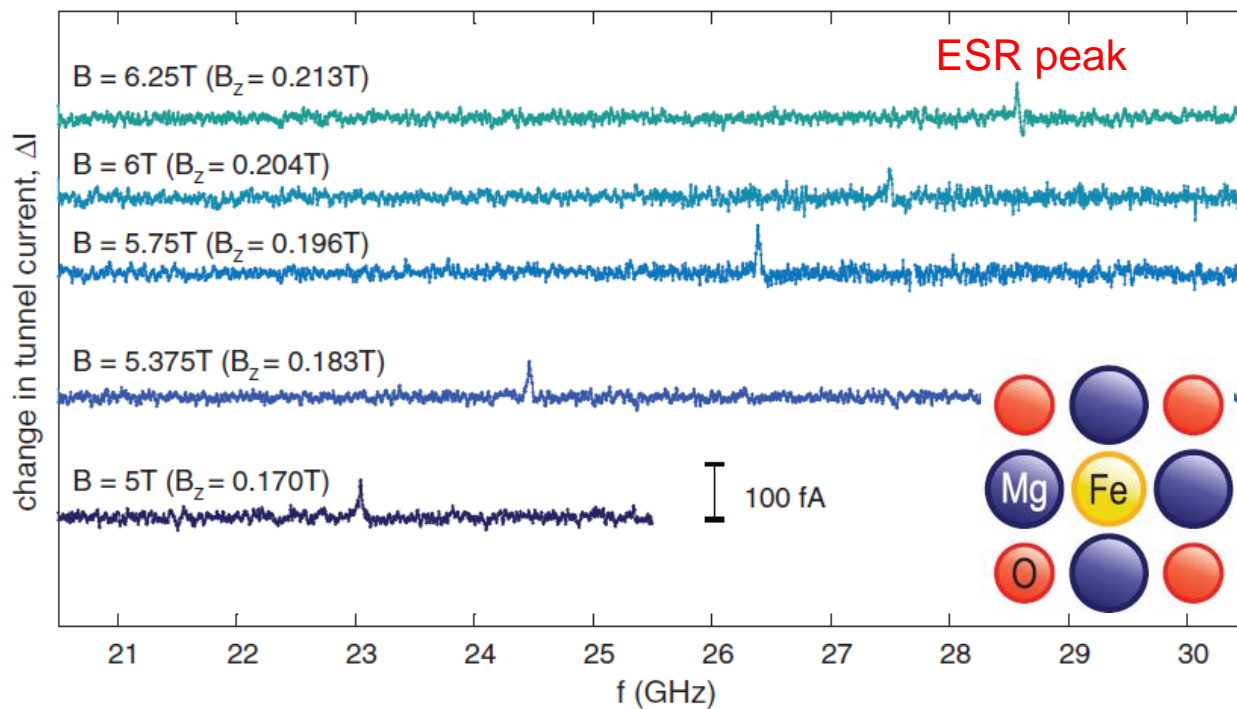
# Frequency domain: GHz electron spin resonance



Baumann et al.,  
Nature 350,417 (15)



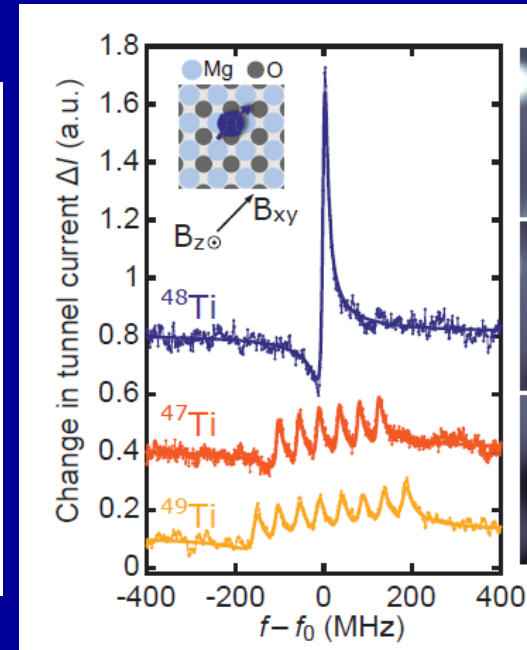
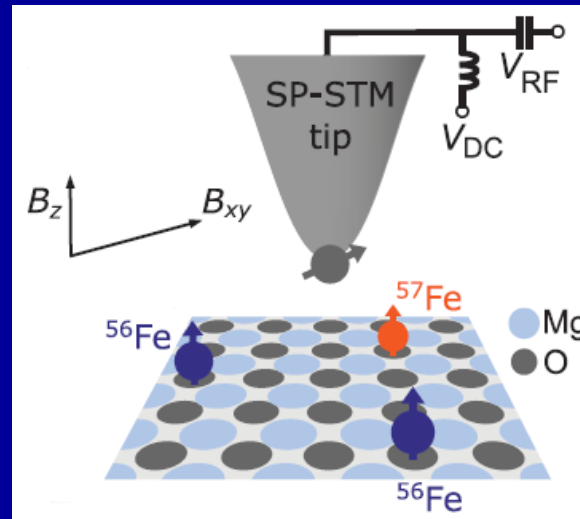
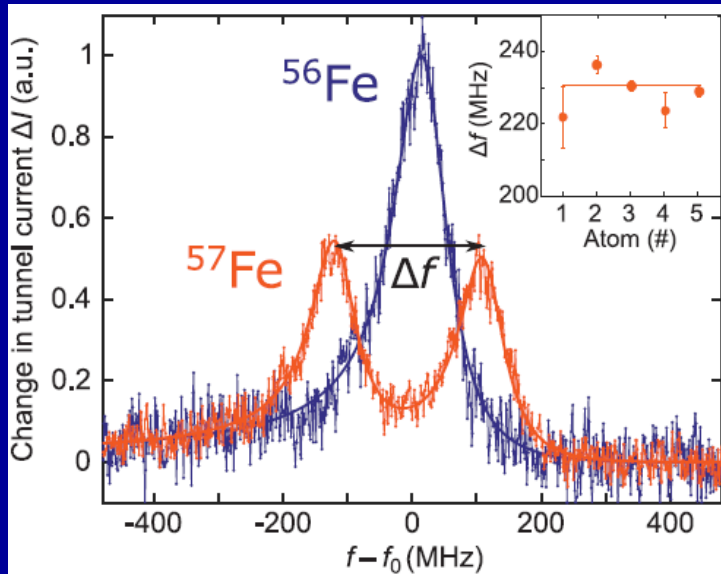
Natterer et al., Nature 543, 226 (17)



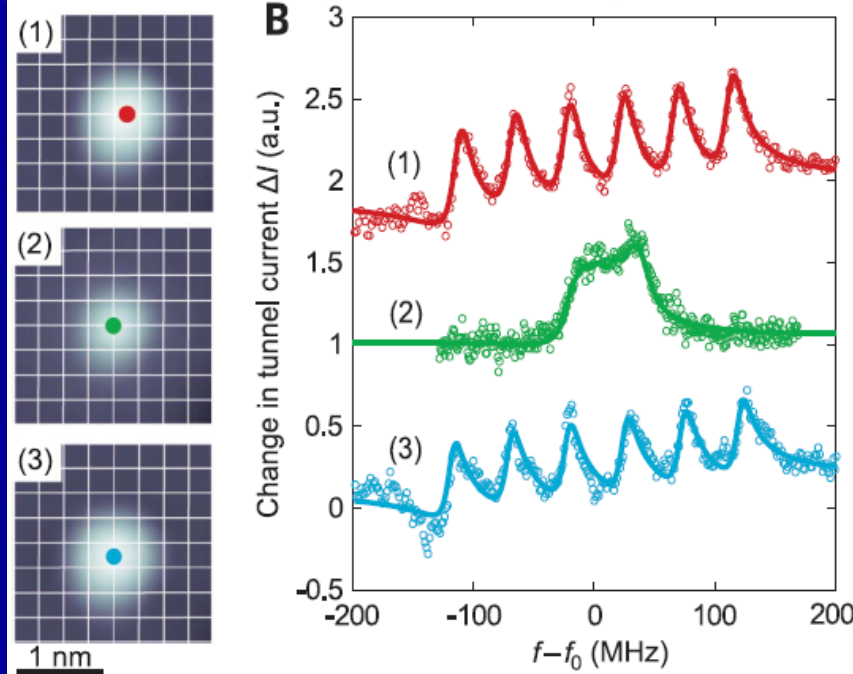
$V_{DC} = 5$  mV,  $I = 560$  fA,

$V_{RF} = 1$  mV 25/26

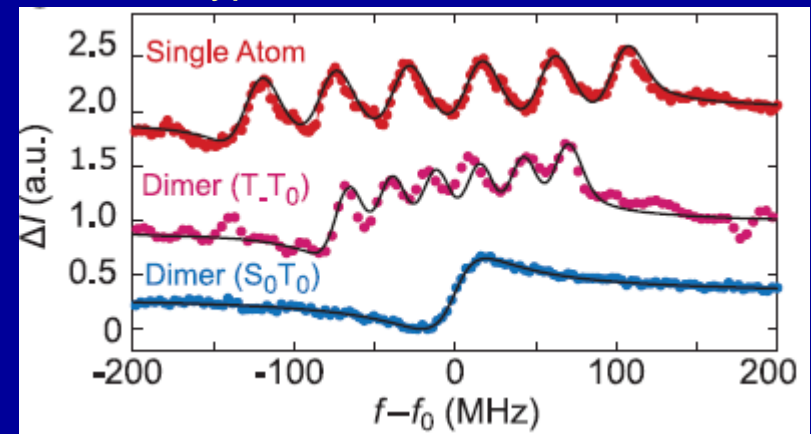
# Hyperfine splitting in STM-ESR

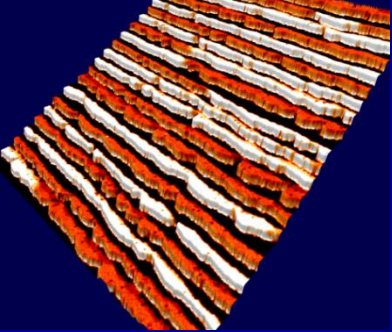


hyperfine switch by position change via orbital switch

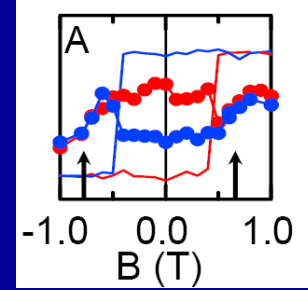
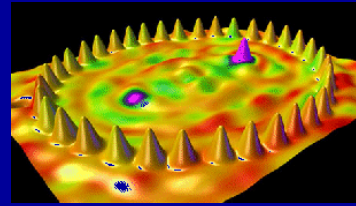


selective hyperfine interaction in Fe dimers

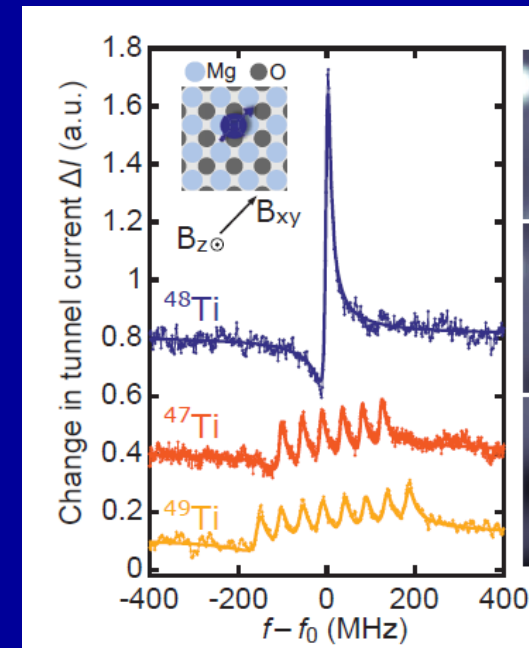
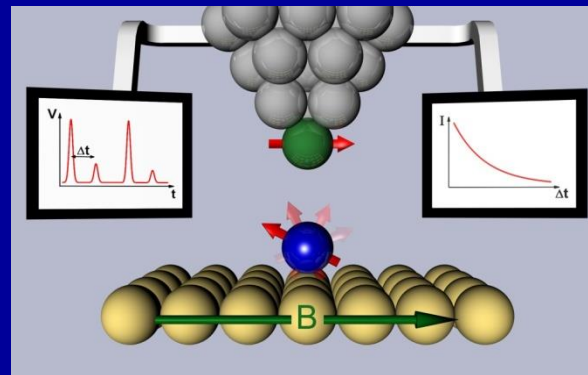
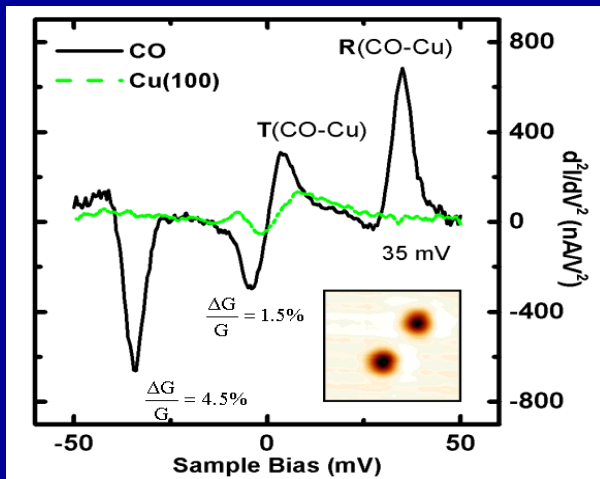




# Summary



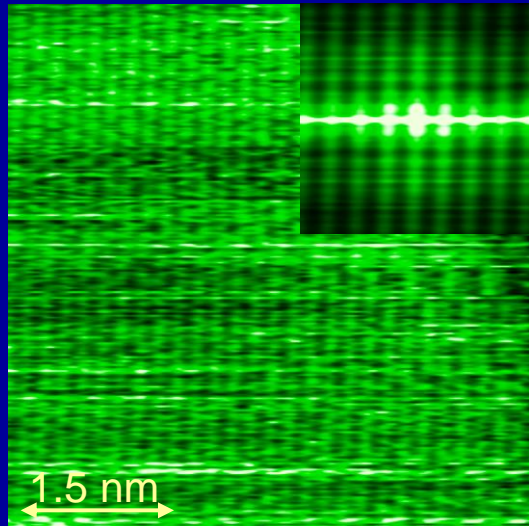
- Kondo effect can be wave-guided
- Spin polarized tips (Cr) can map spin textures (atomic scale)
  - $d^2I/dV^2$  maps excitations (vibrons, phonons, magnons)
  - Electric pump-probe down to 100 ps (atomic scale)
    - THz pump-probe down to 100 fs (atomic scale)
- HF-voltage at tip enables ESR including hyperfine interaction



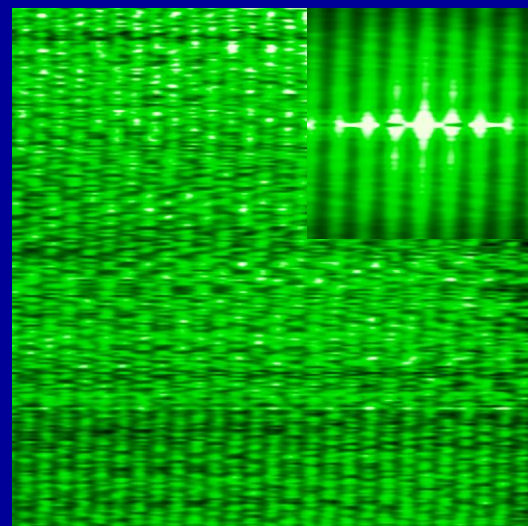
# ~ 100 ps time-resolution at the atomic scale

Lock-In-output at different time delays pump-probe

autocorrelation



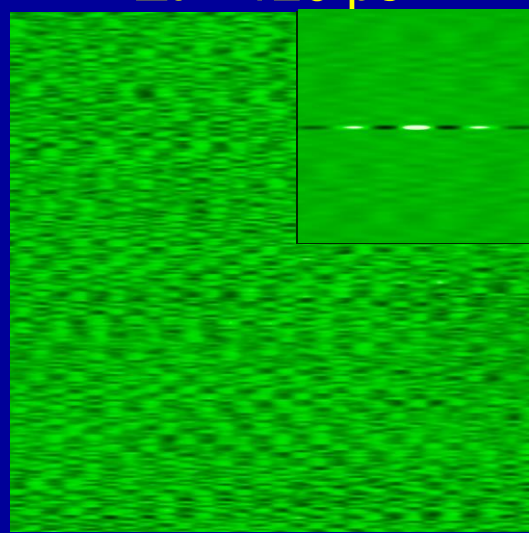
$\Delta t = 0$  ps



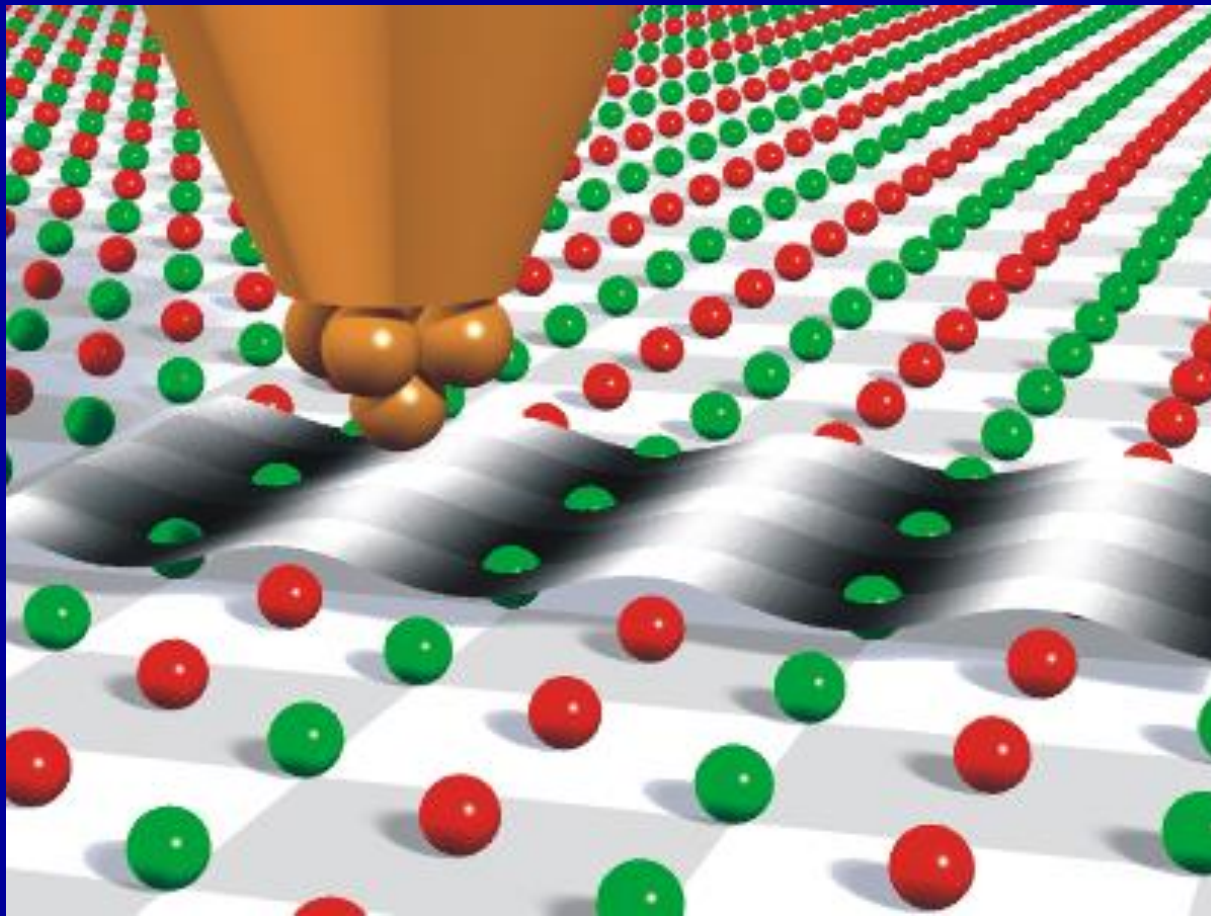
$\Delta t = 60$  ps

intensity  
to scale

$\Delta t = 120$  ps



# Scanning Tunneling Microscopy



Measure:  $I(V, x, y, z)$