Manipulating Matter, Charge, and Spin at the Spatial Limit

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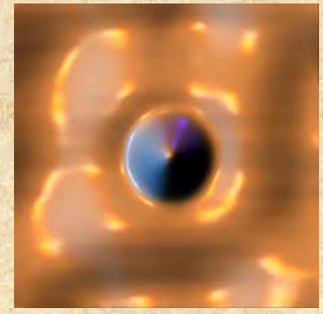
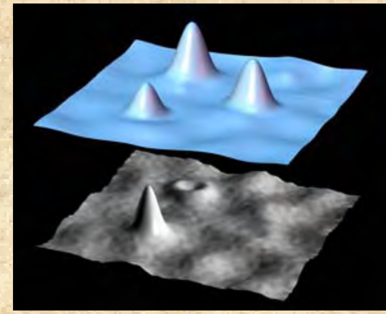
- Detection and Manipulation of Atomic Scale Magnetism

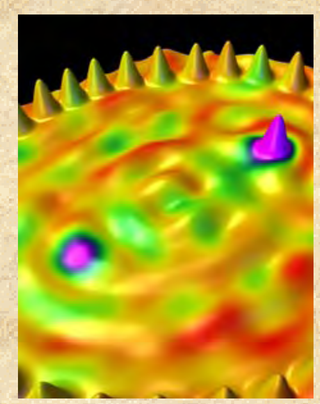
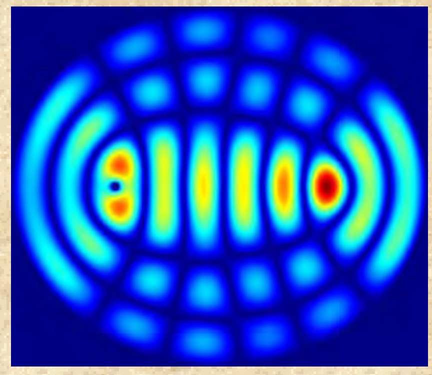
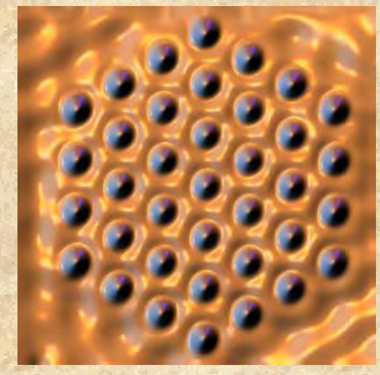
Lecture 1





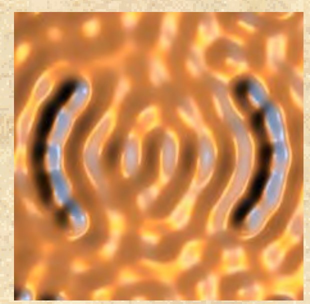
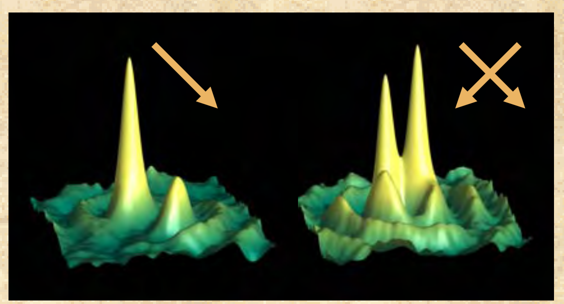
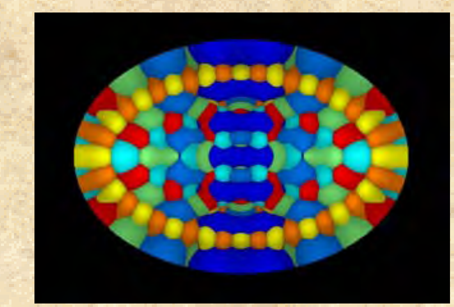
- Quantum Mirages and Kondo Lattices

Lecture 2

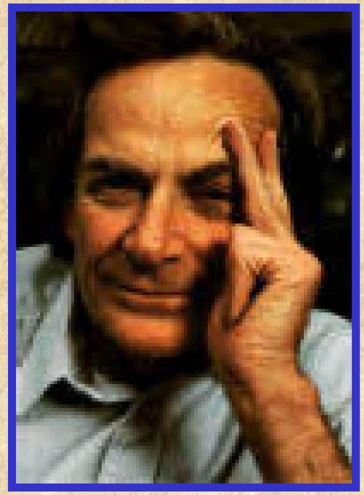
- Atoms, Spins, and Superpositions

Lecture 3

"But I am not afraid to consider the final question 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?"



\- Richard Feynman, 1959

. . . Or Not

"The individual particle is not a well-defined permanent entity of detectable identity or sameness.

We *never* experiment with just *one* electron or atom or (small) molecule. In thought experiments we sometimes assume that we do; this invariably entails ridiculous consequences."

"The individual particle is not a well-defined permanent entity of detectable identity or sameness.

We *never* experiment with just *one* electron or atom or (small) molecule. In thought experiments we sometimes assume that we do; this invariably entails ridiculous consequences."

- Erwin Schrödinger, 1952

Quantum Mirage

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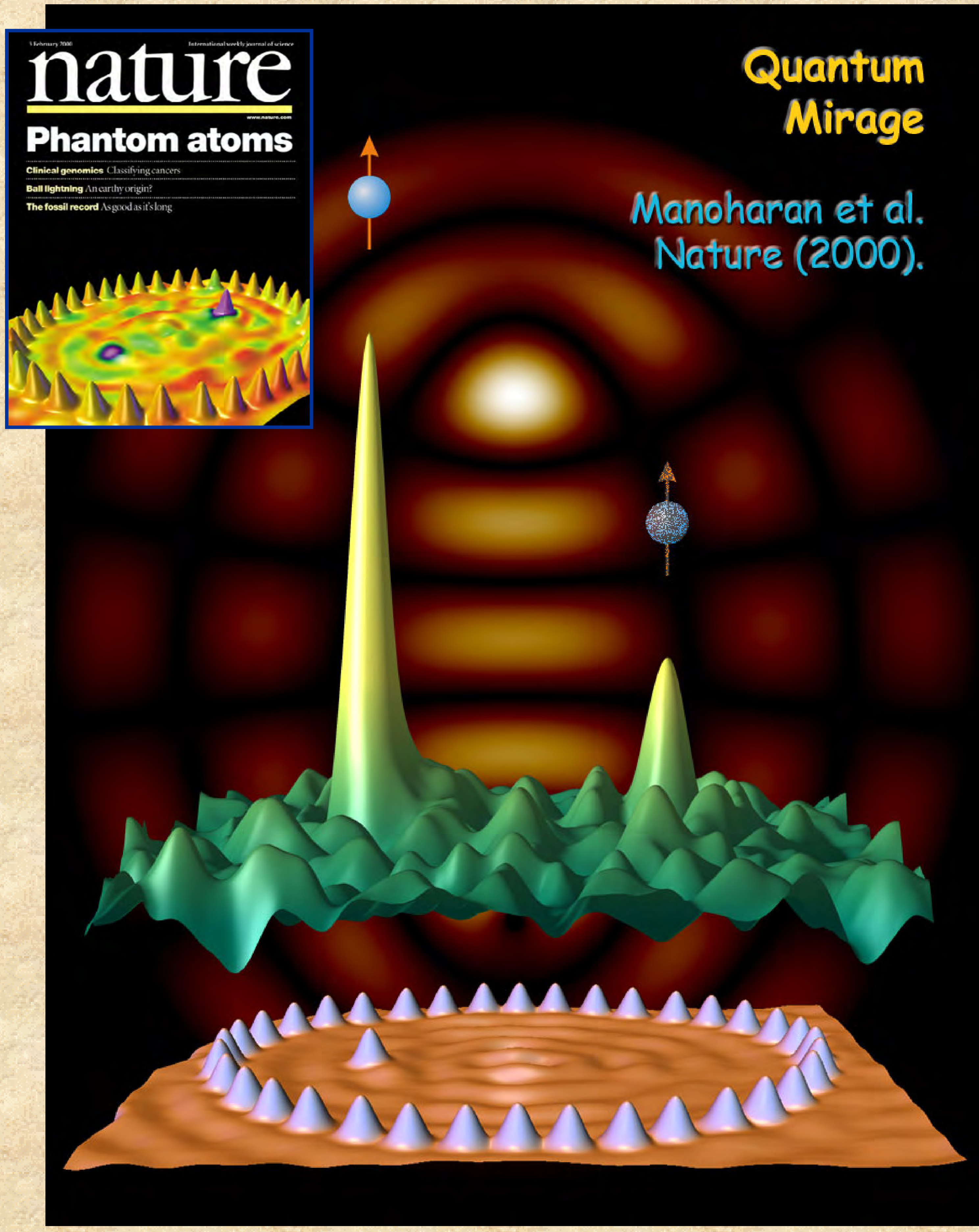
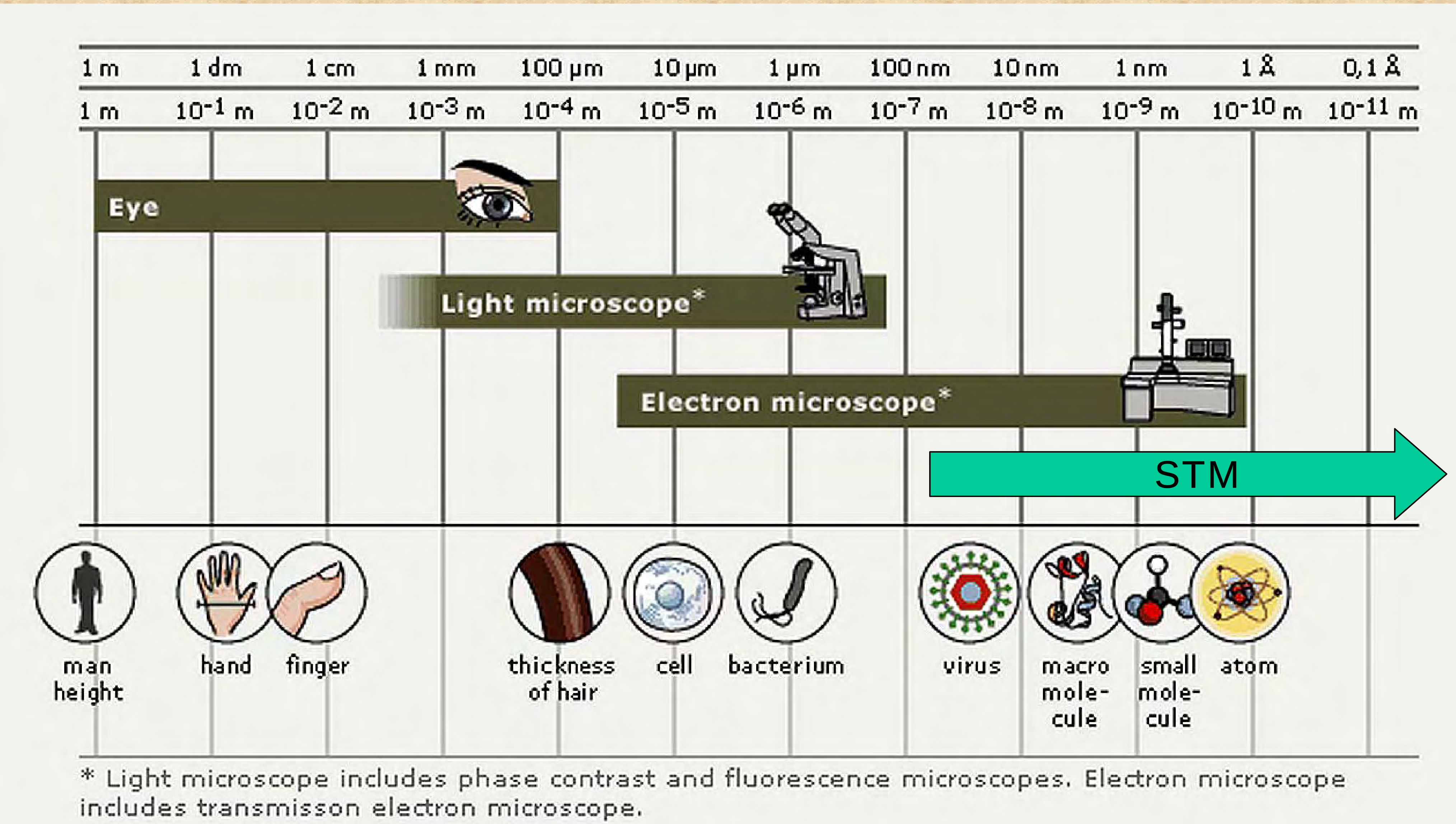


SCANNING PROBE MICROSCOPES

Spanning the Length Scales

- Microscope resolving power



(Adapted from www.nobel.se)

Scanning Tunneling Microscopy (STM)

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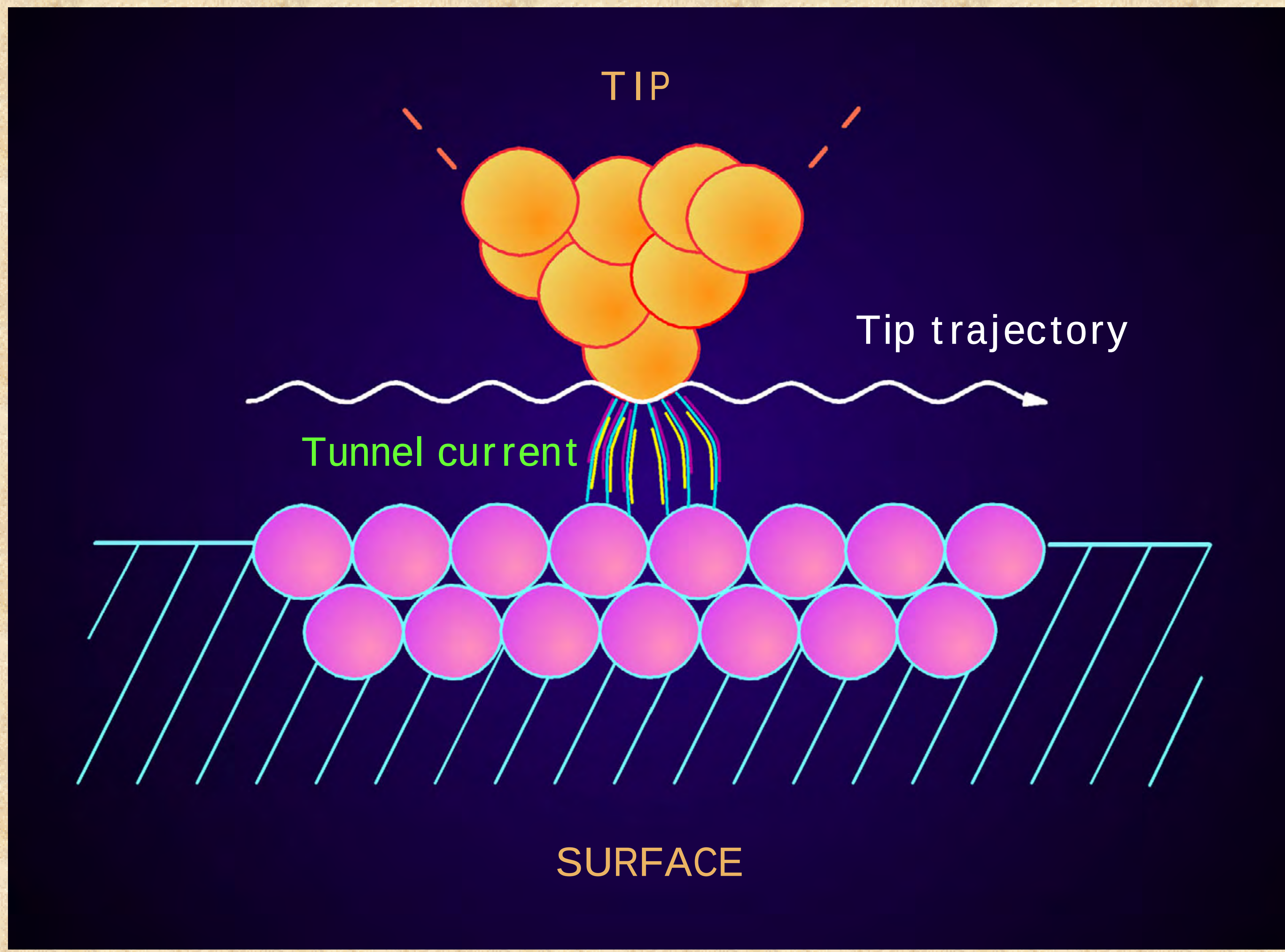
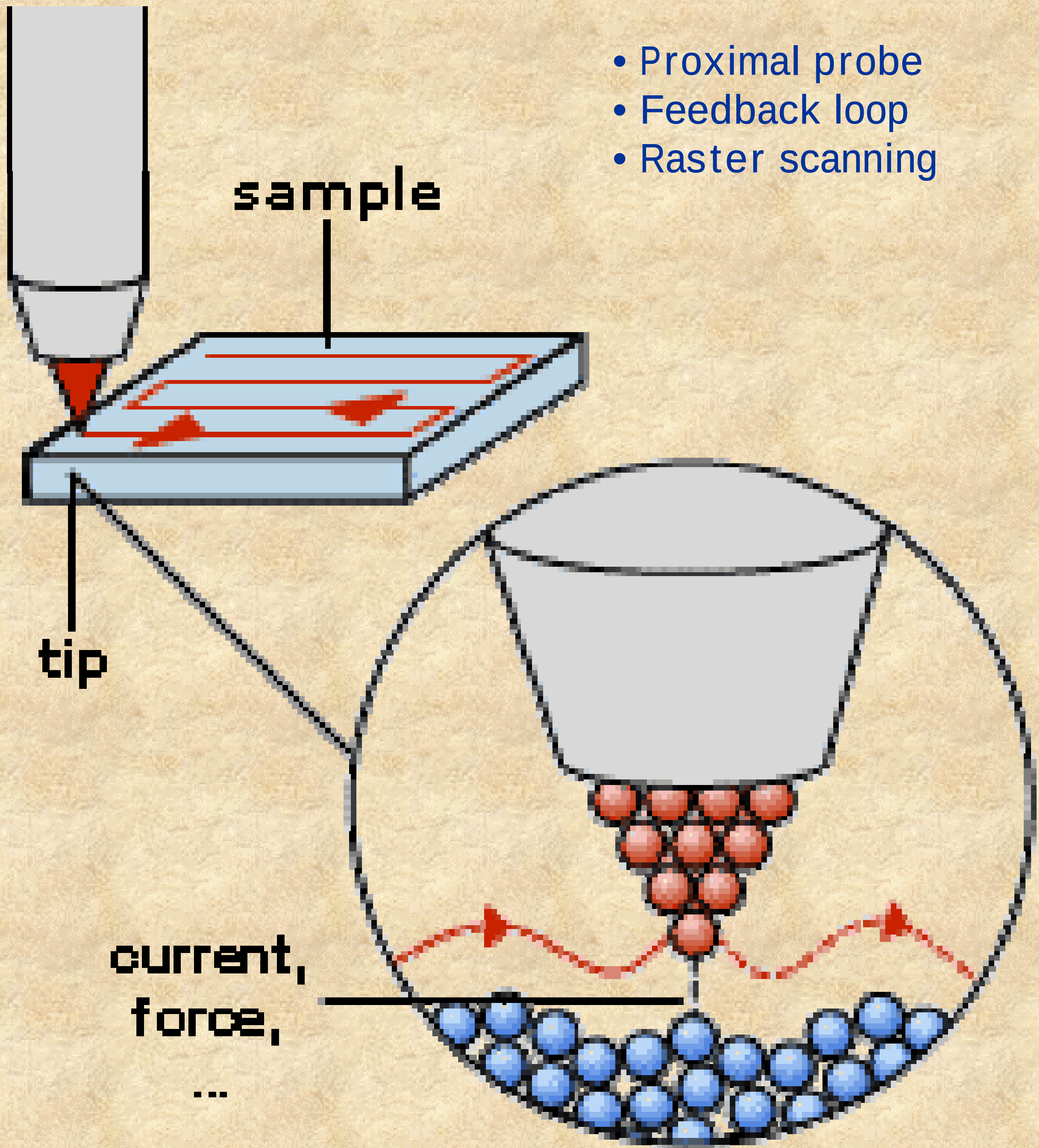


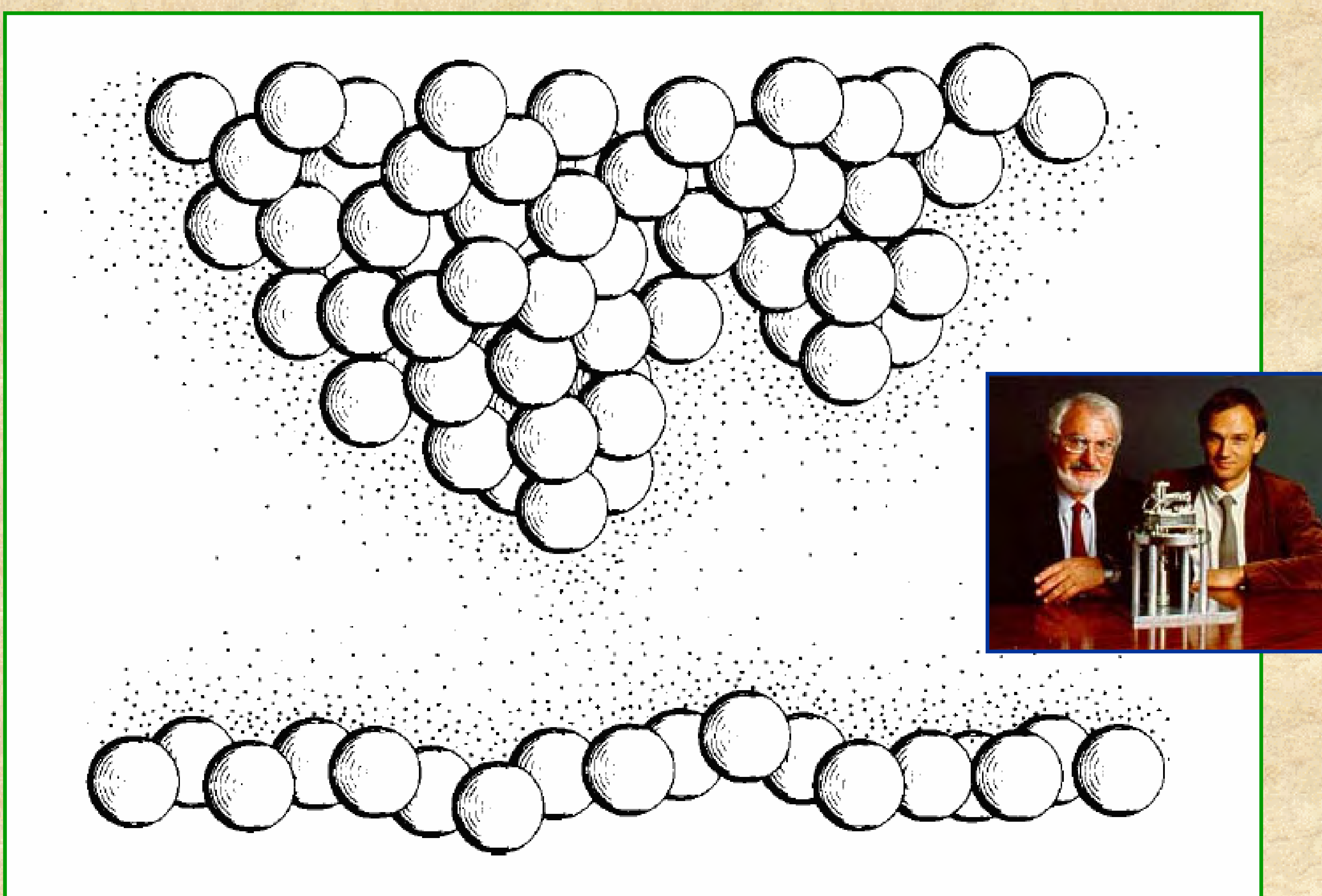
- Proximal probe
- Feedback loop
- Raster scanning



(Adapted from www.nobel.se)

Tip Detail

- 10x current increase for every Å



- Lilienfeld: Observation of field emission from metals (1922)
- Oppenheimer: Ionize H by electron tunneling (1928)
- Fowler-Nordheim: Explanation of field emission (1928)
- Zener: Theory of interband tunneling in solids (1934)
- Chynoweth: Observation of Zener tunn. in semiconductors (1957)
- Giaever: Measure superconducting gap (1960)
- Josephson: Cooper pair tunneling (1962)

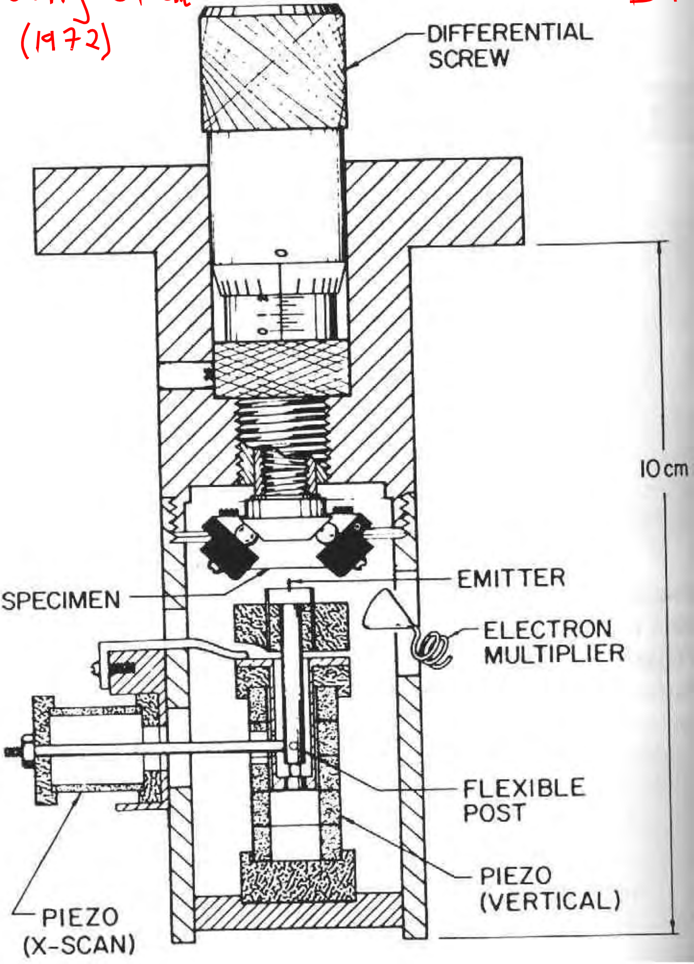
. . . IETS, Spin-polarized, etc.

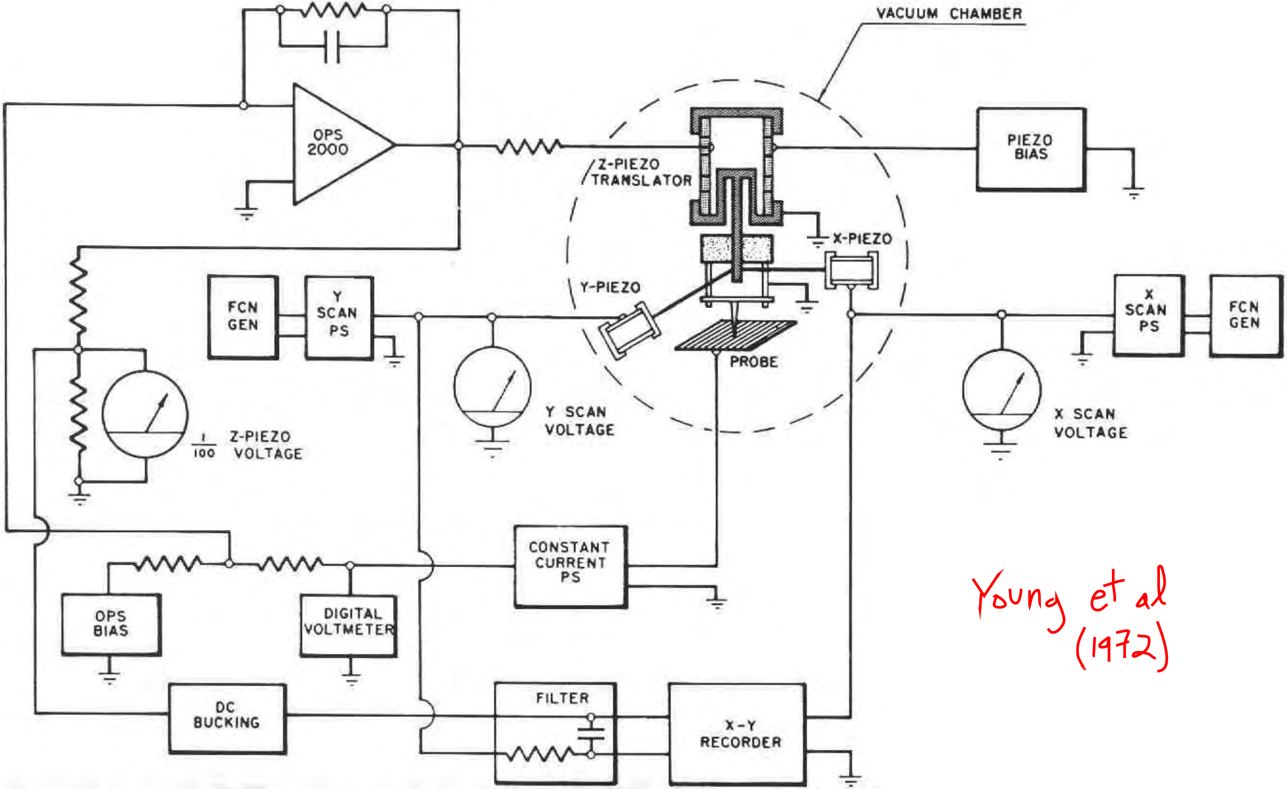
Apparatus Landmarks

• Müller:	Field Emission Microscope	(1937)
• Young:	Topografiner & Vacuum Tunneling	(1971)
• Binnig & Rohrer:	Scanning Tunneling Microscope	(1982)

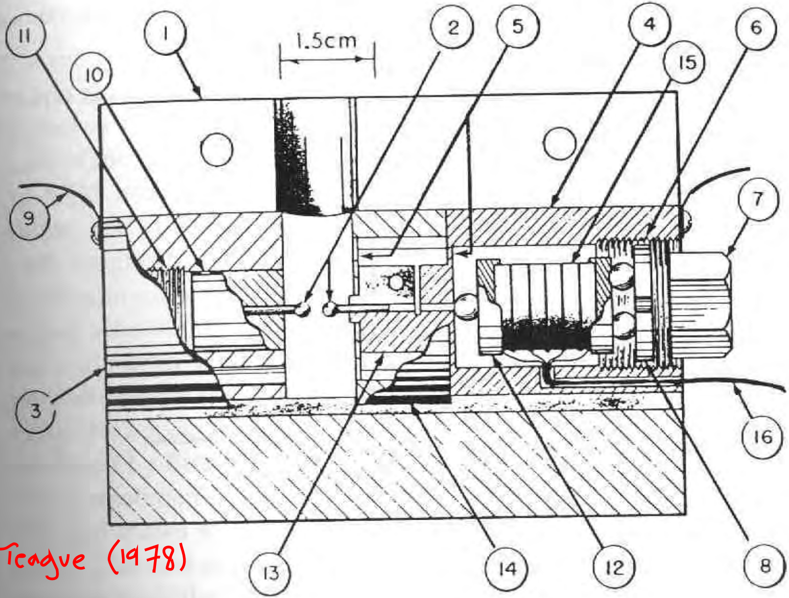
Young et al
(1972)

TOPOGRAFINER

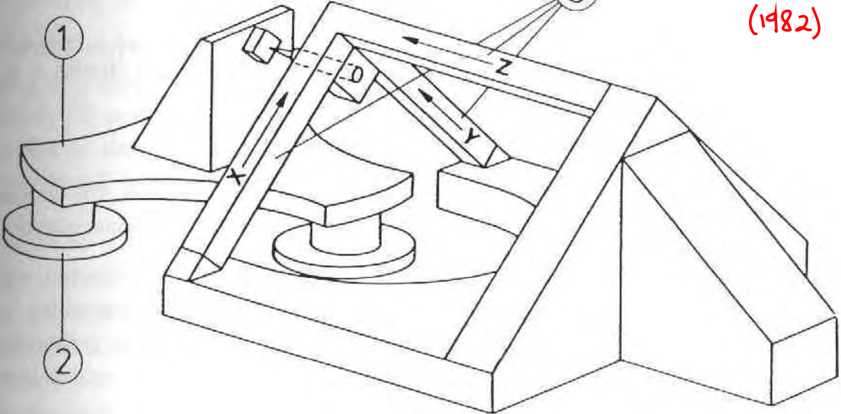




Young et al
(1972)



Teague (1978)



Binnig & Rohrer
(1982)

Vibration Isolation (a.k.a. "The Pit and the Pendulum")

- Three cascaded stages to achieve nG/Hz$^{1/2}$

Experimental Apparatus

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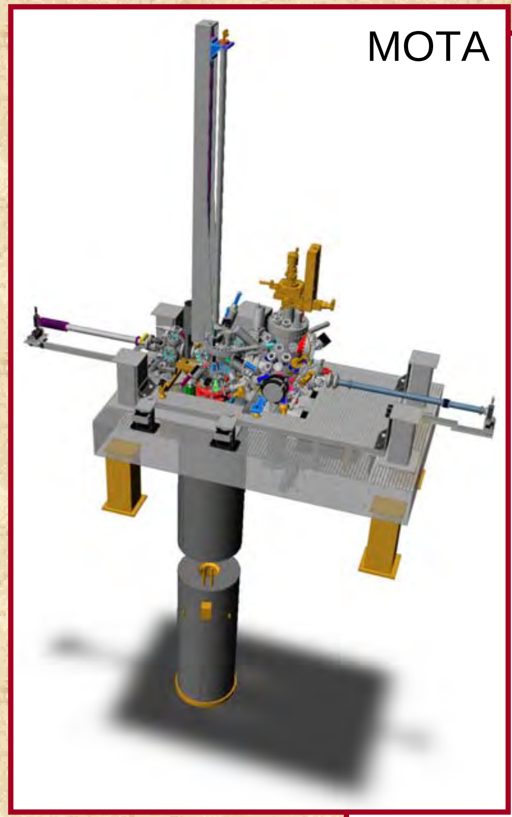
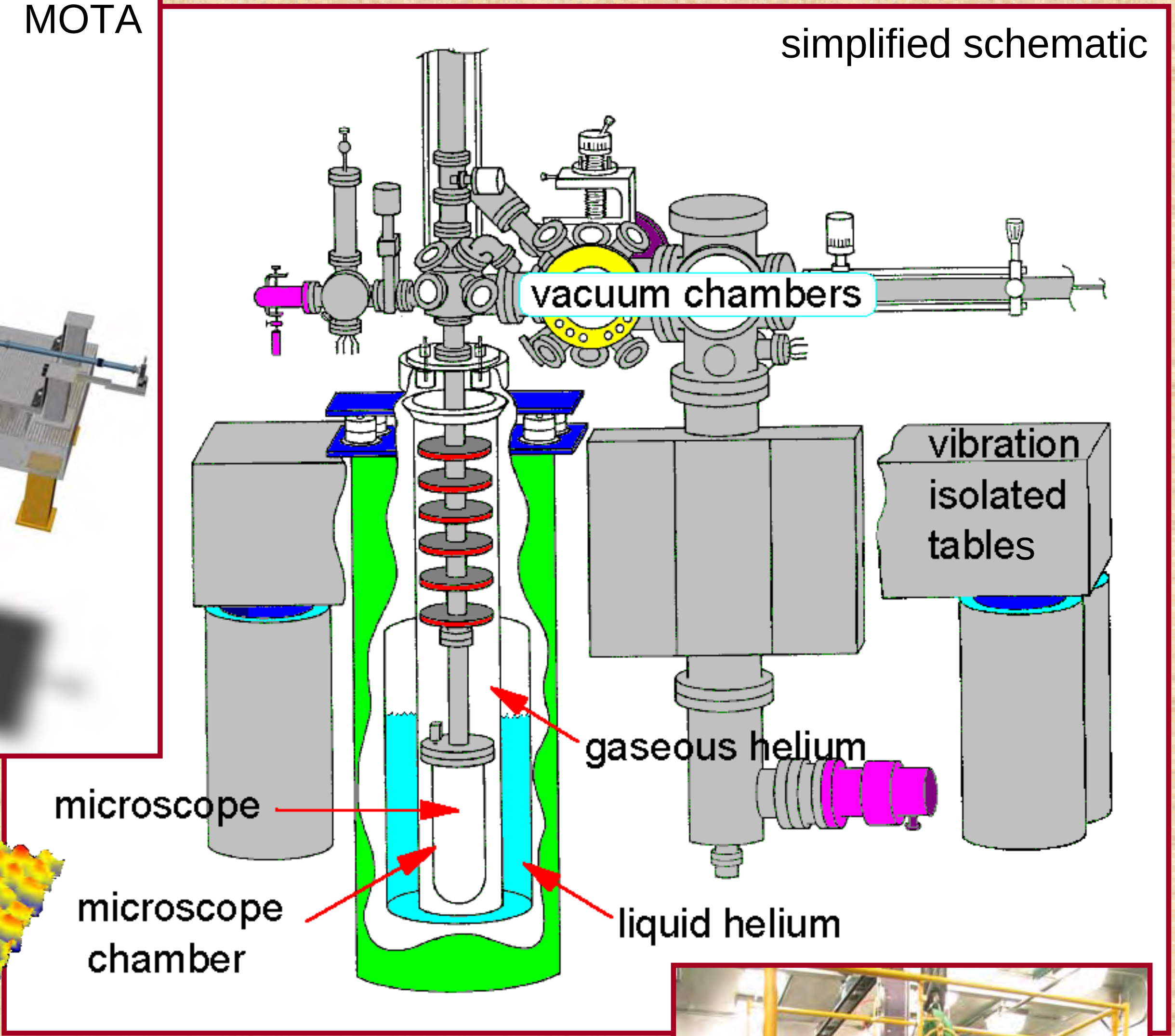
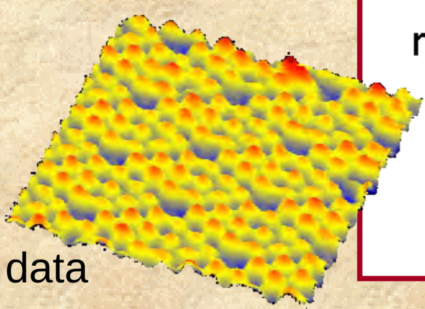
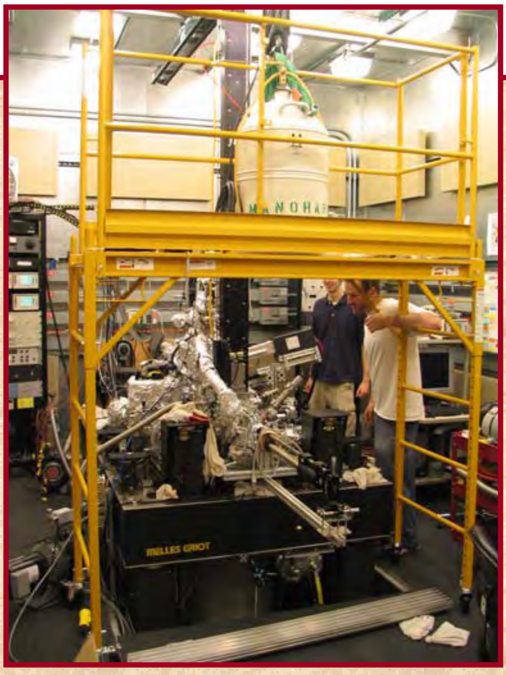
• 4 K / 1 K / 0.5 K UHV Scanning Probe Microscope






data



photo

• Specifications

Sample environment:

Temperature ~ 0.5 K
Magnetic Field ~ 11 T

Vibration and electronics limits:

Current noise ~ 18 fA/√Hz
Lateral resolution ~ 100 fm
Vertical resolution <~ 30 fm/√Hz

moire

ATOM

Tunneling Equations

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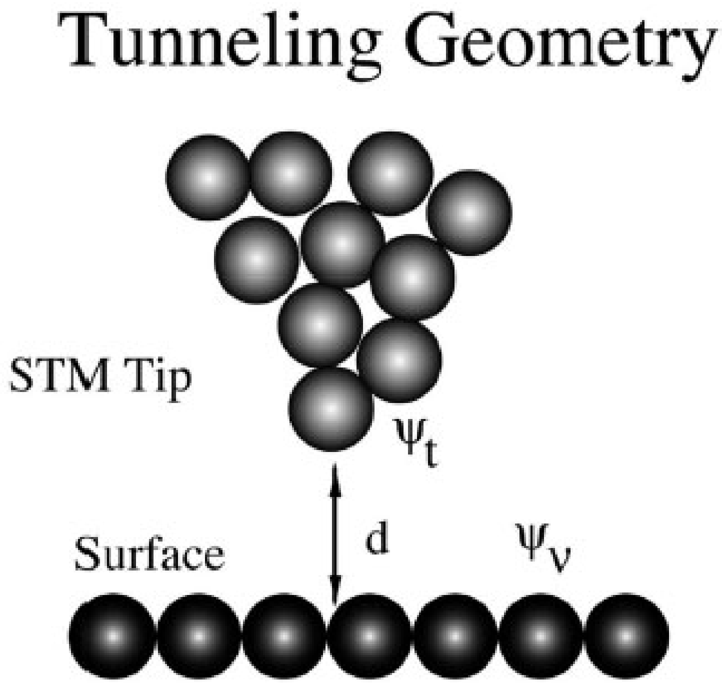

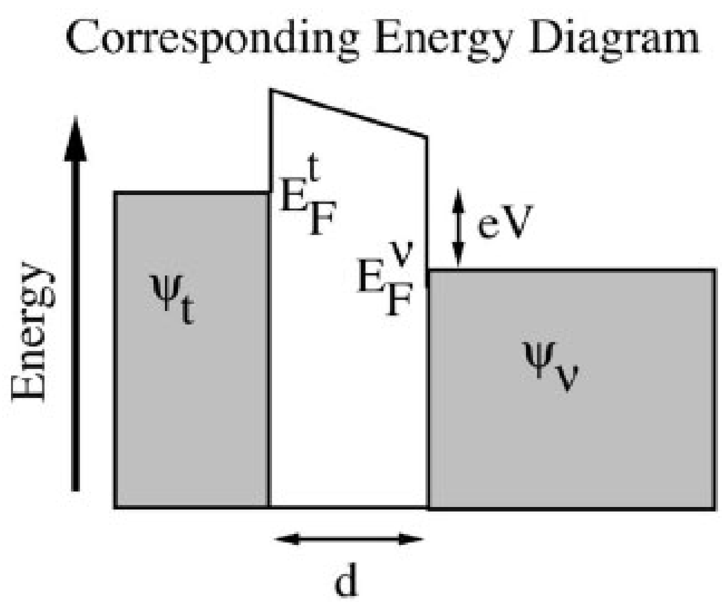

$$I(\mathbf{r}) = \frac{2\pi e}{\hbar} \sum_{t,\nu} |M_{t,\nu}(\mathbf{r})|^2 f(\epsilon_t)$$

$$\times [1 - f(\epsilon_\nu)] \delta(\epsilon_t + eV - \epsilon_\nu)$$

$$I(\mathbf{r}) \propto \int_0^{eV} \varrho_t(\epsilon) \mathrm{LDOS}(\mathbf{r}, \epsilon) d\epsilon$$

$$\mathrm{LDOS}(\mathbf{r}, \epsilon) = \sum_\nu |\psi_\nu(\mathbf{r})|^2 \delta(\epsilon - E_\nu)$$

$$I(\mathbf{r}) \propto \int_0^{eV} \mathrm{LDOS}(\mathbf{r}, \epsilon) d\epsilon$$

$$\frac{dI}{dV}(\mathbf{r}, \epsilon) \propto \mathrm{LDOS}(\mathbf{r}, \epsilon)$$

EXPLORING THE ATOMIC REALM

Cast of Characters: Cu(111) and Co

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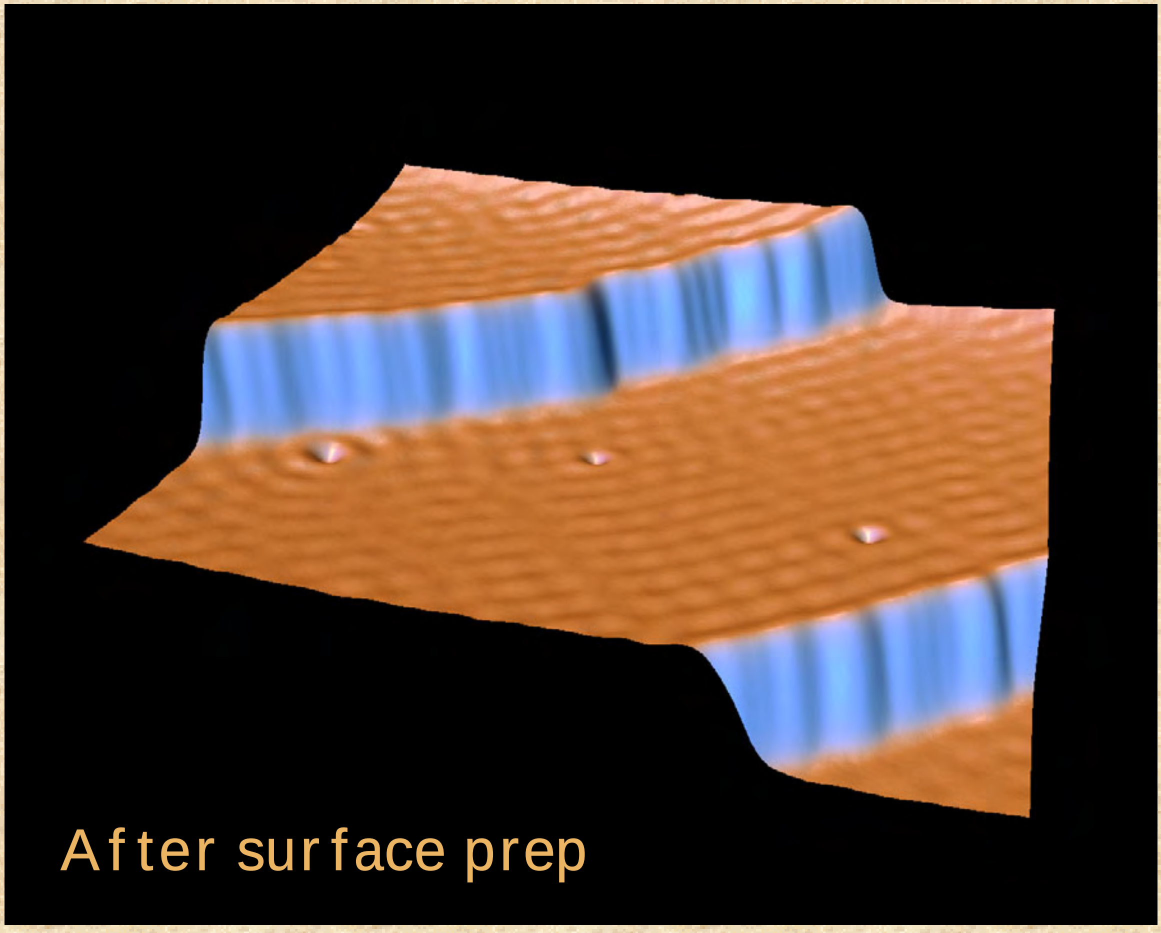
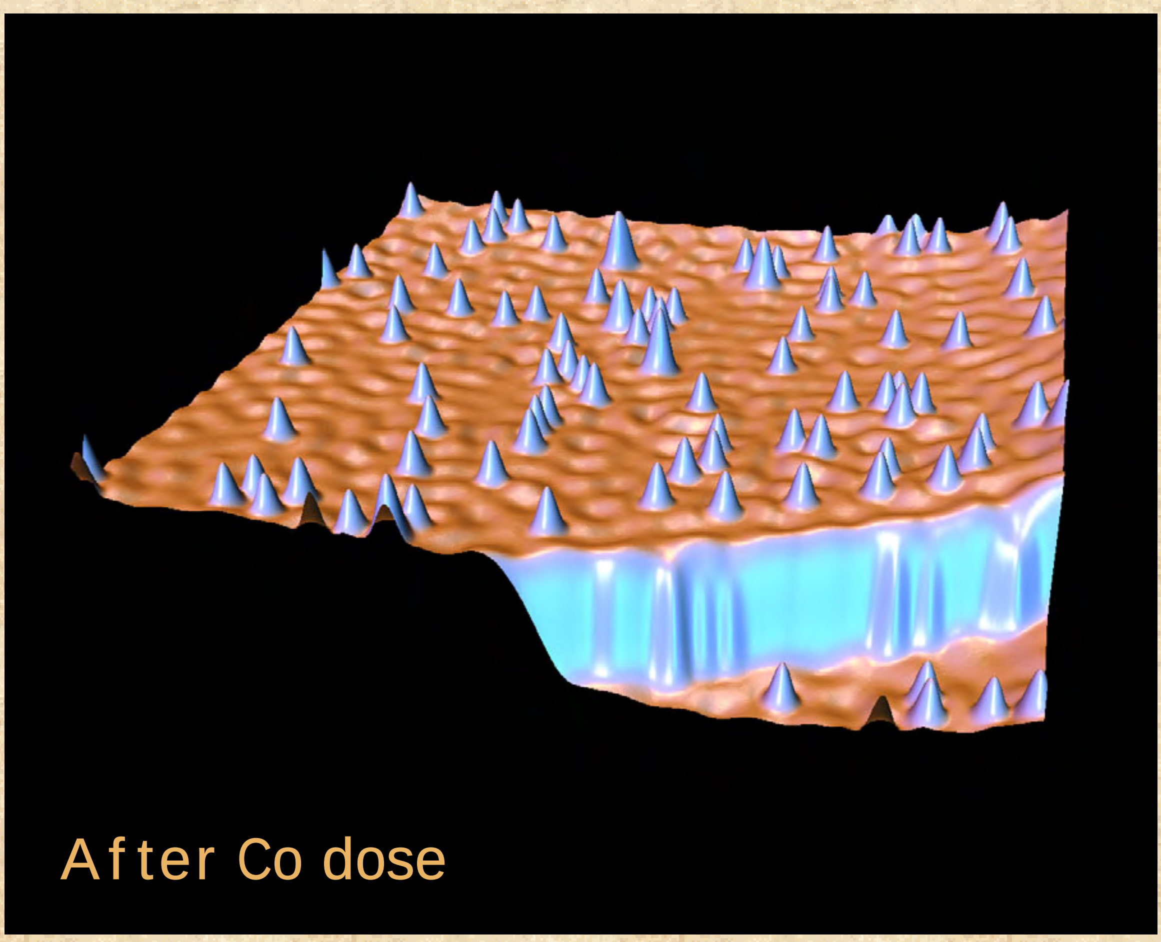
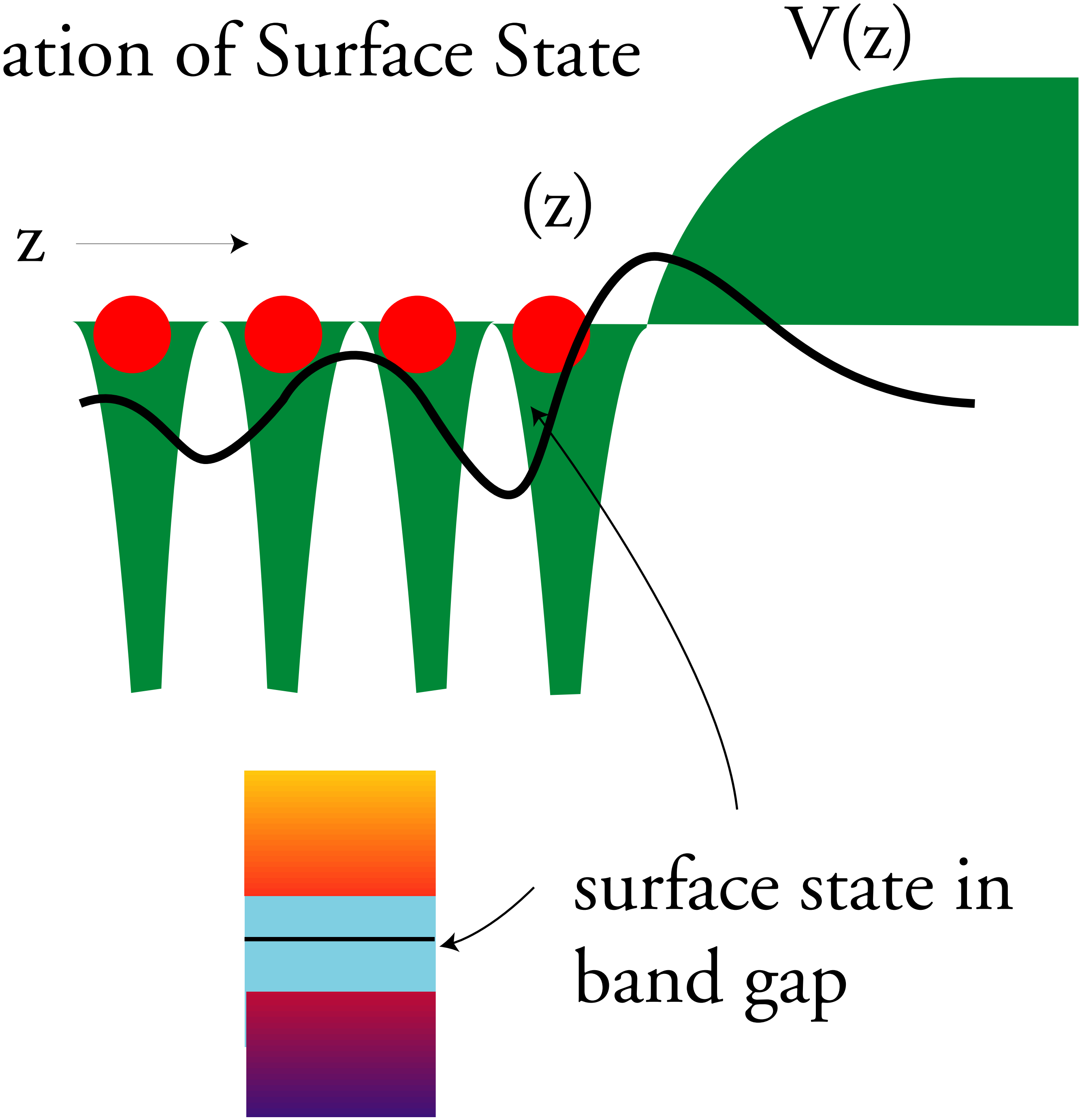


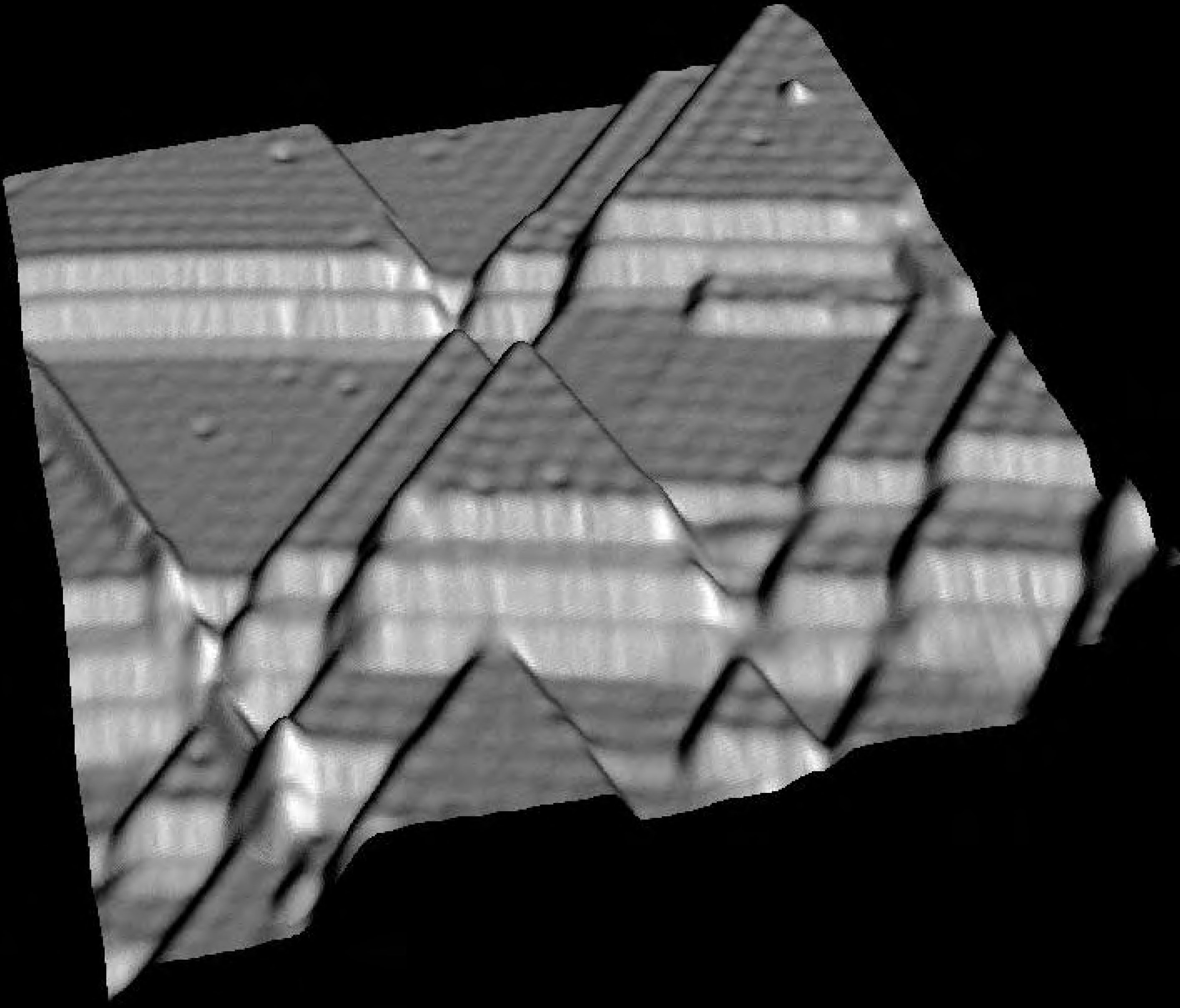
300 Å square topo



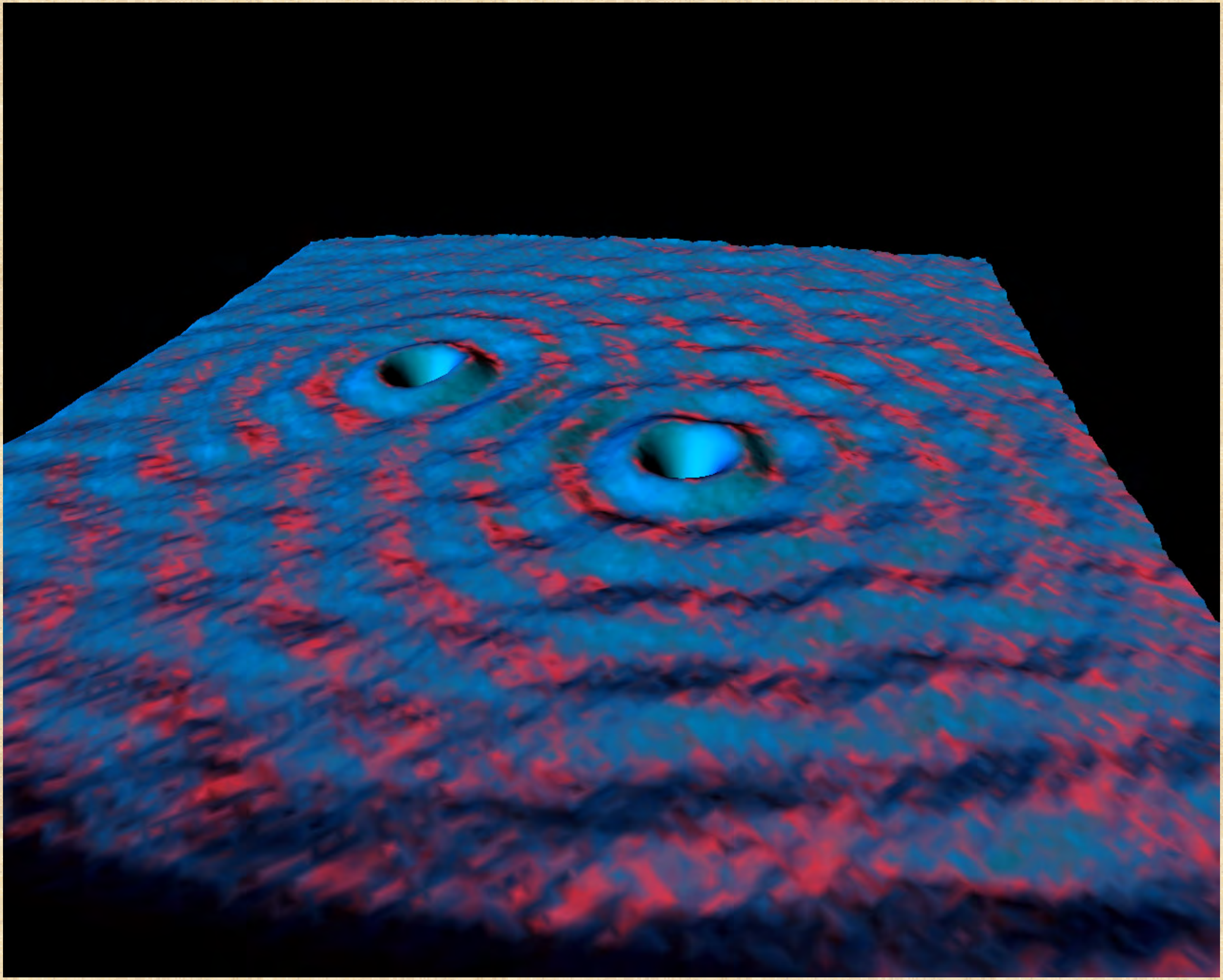
300 Å square topo

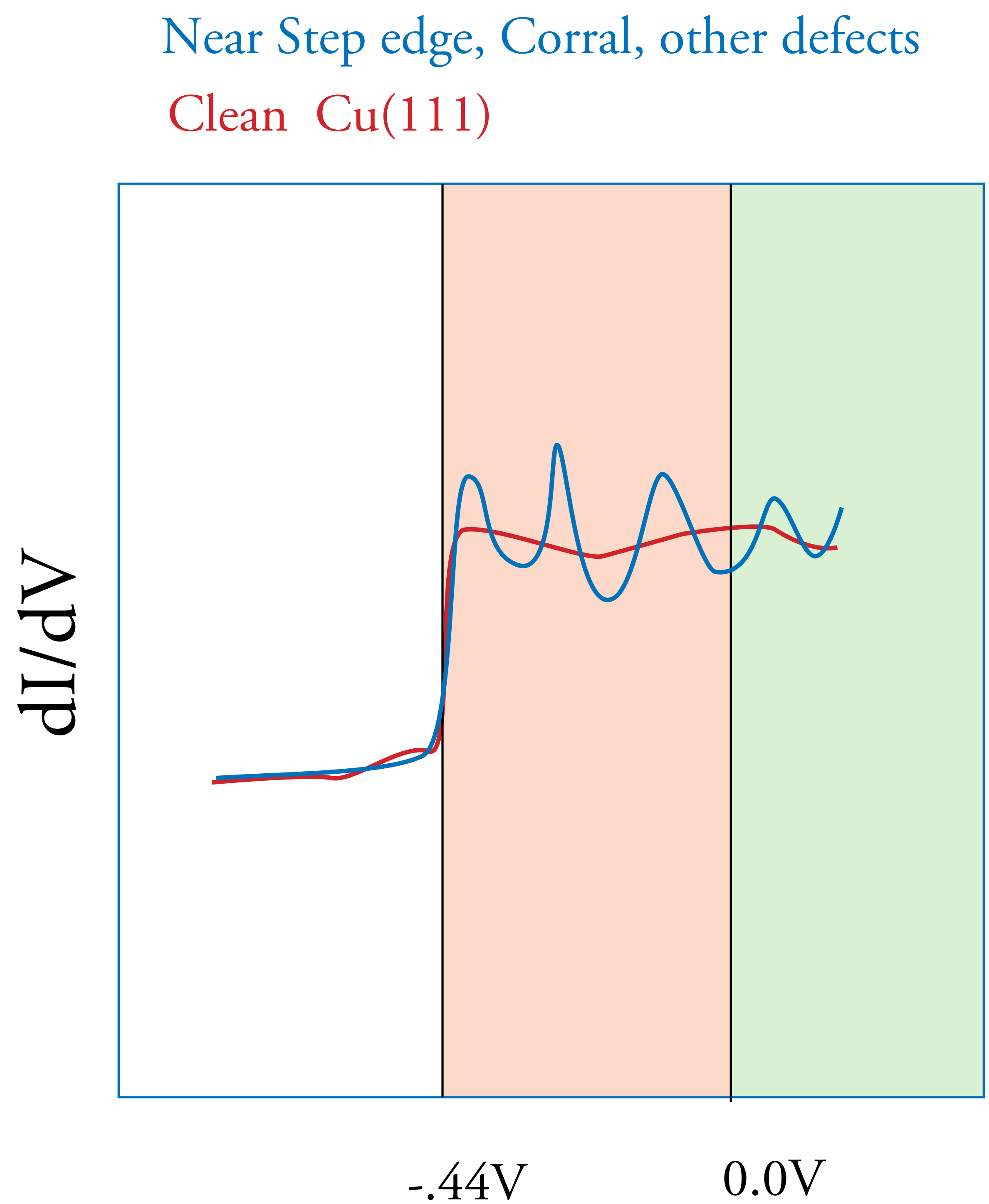
Formation of Surface State

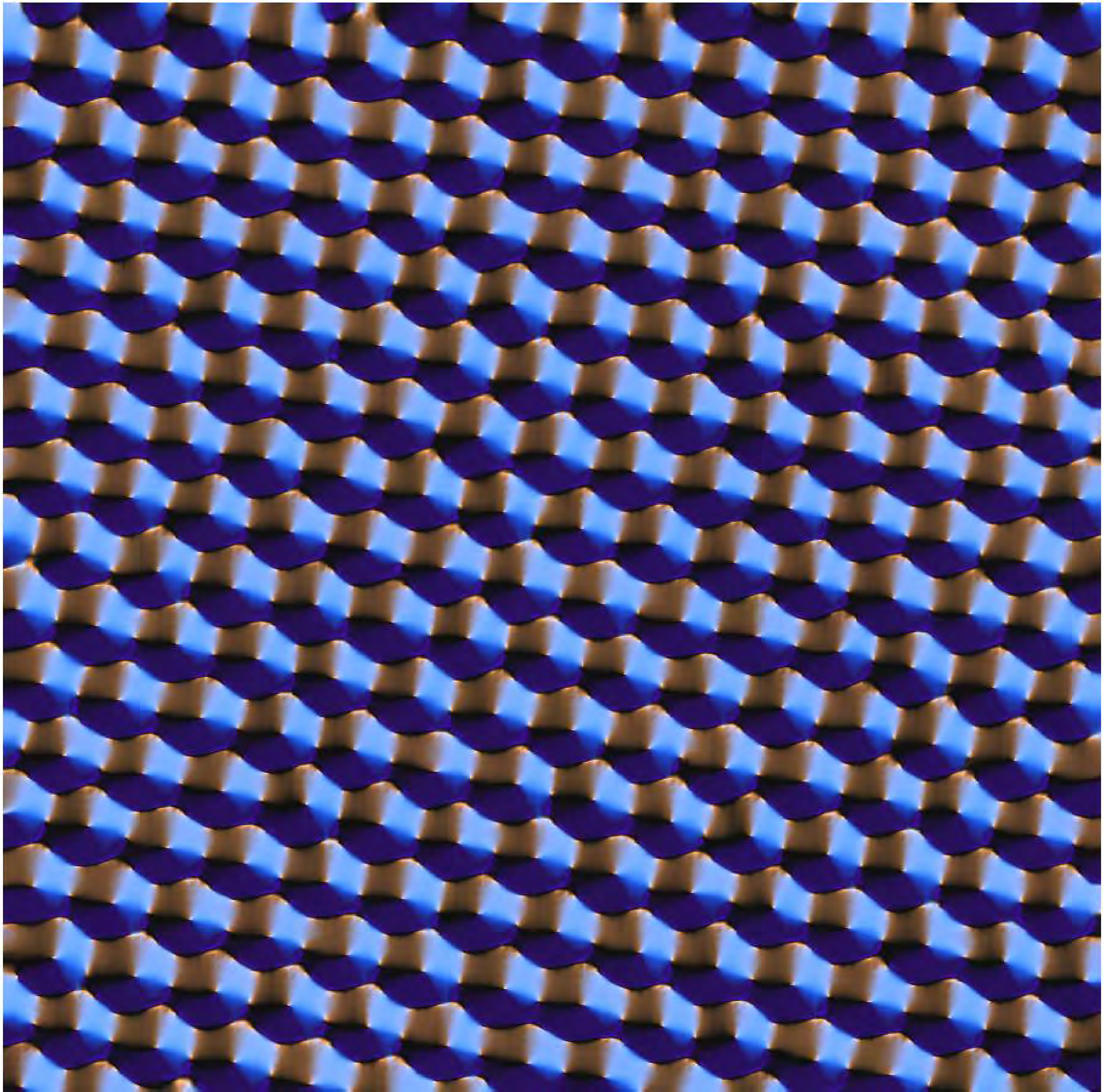


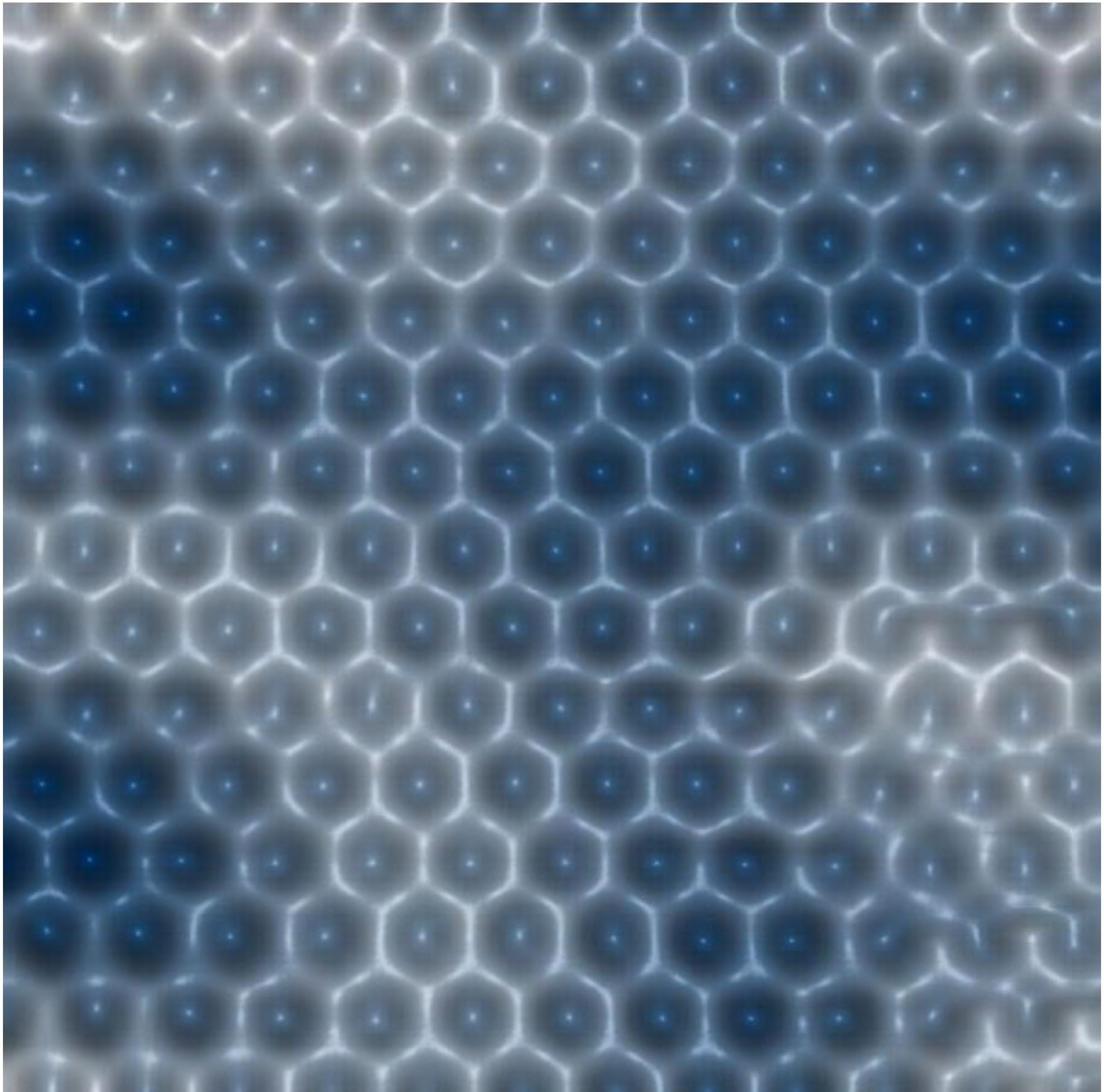


- Sulfur atoms on copper surface

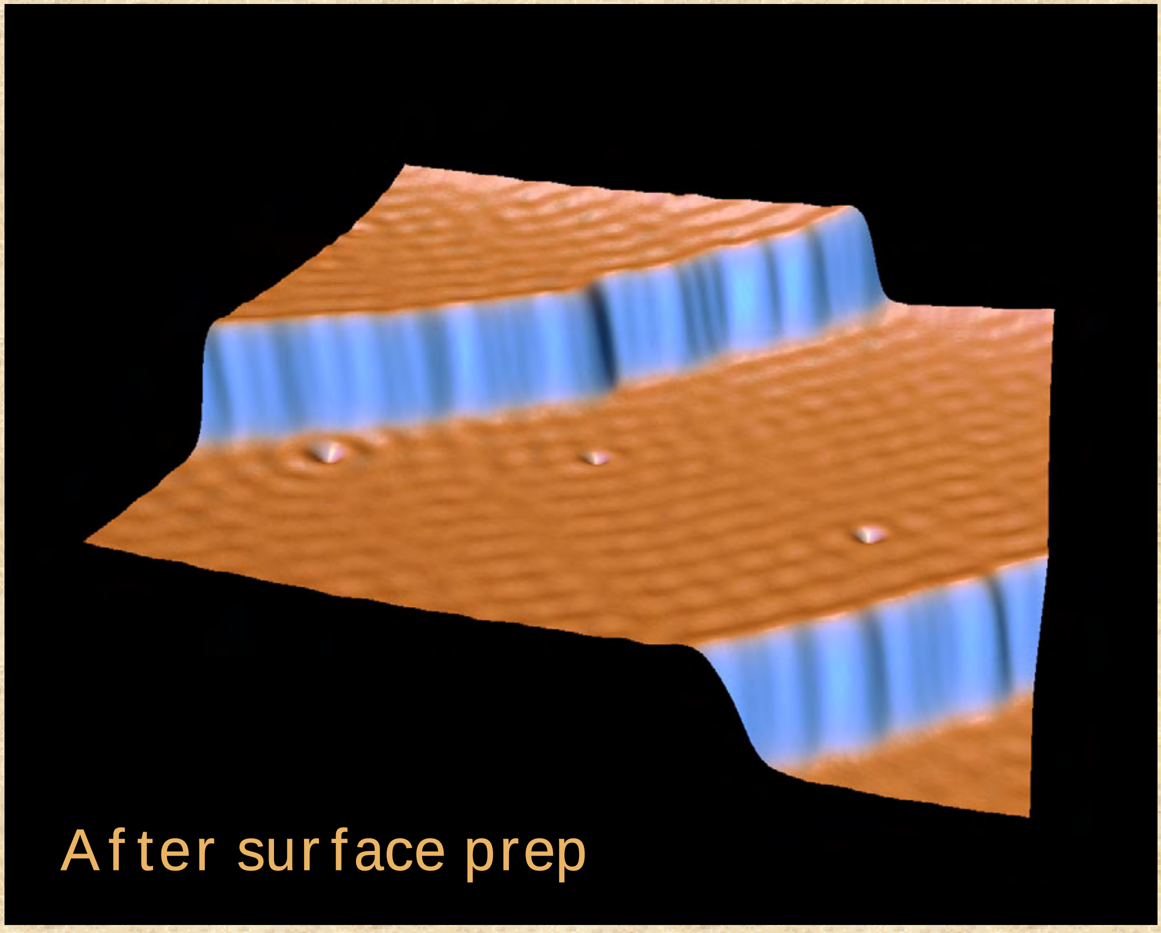



Near Step edge, Corral, other defects
Clean Cu(111)
dI/dV
-.44V
0.0V

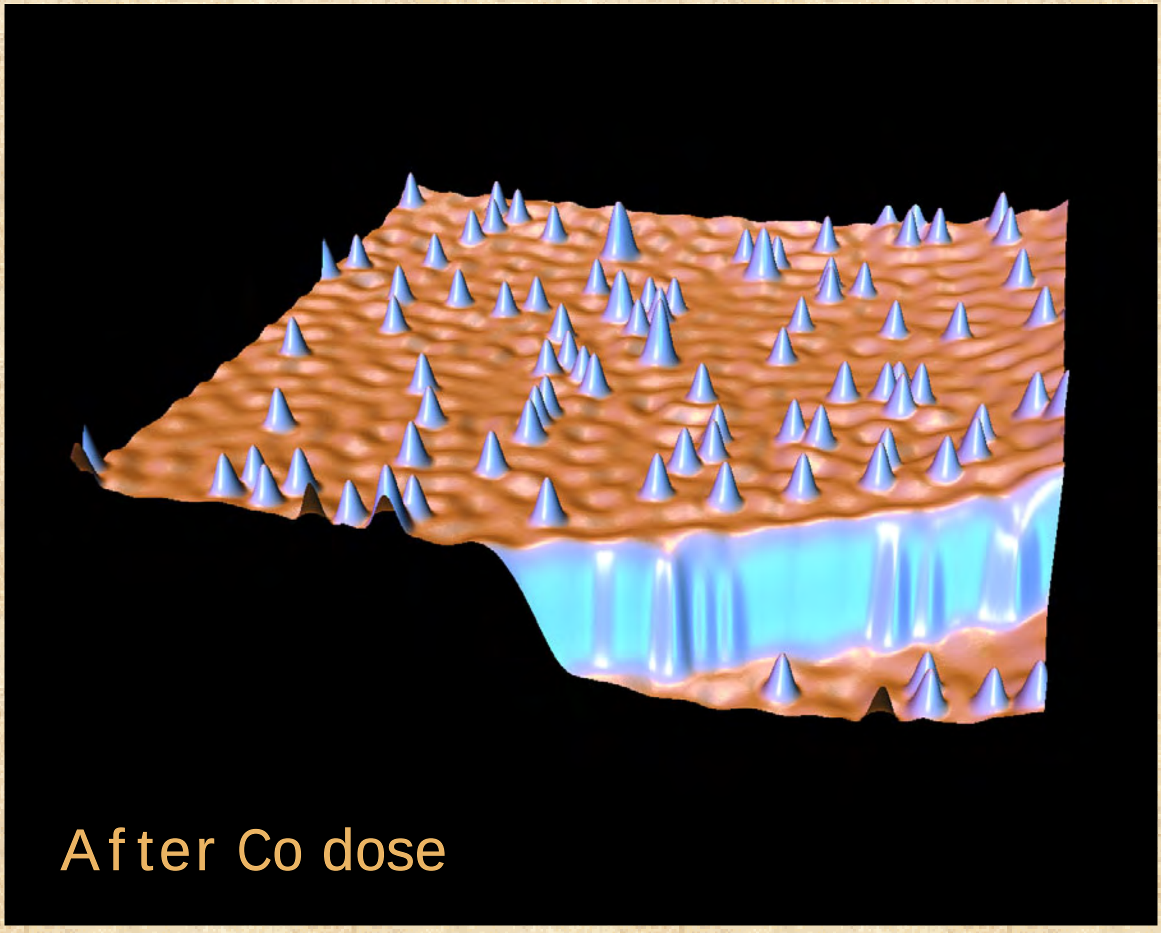




Cast of Characters: Cu(111) and Co

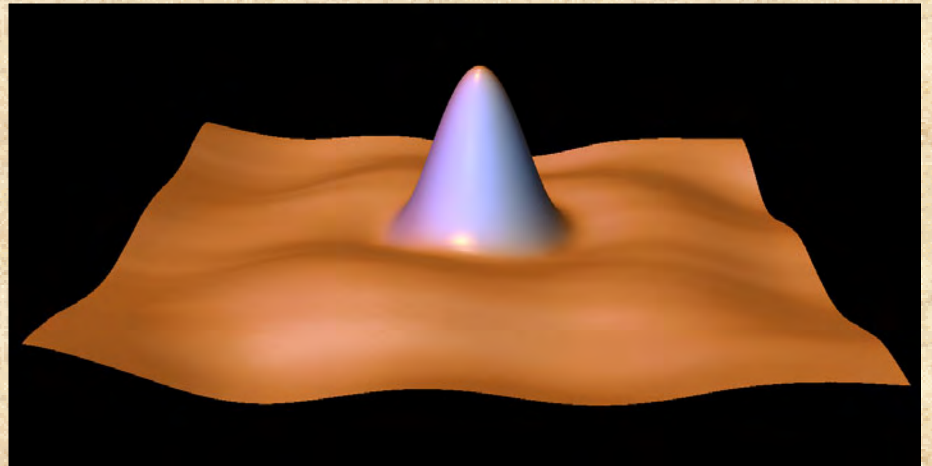


300 Å
square
topo



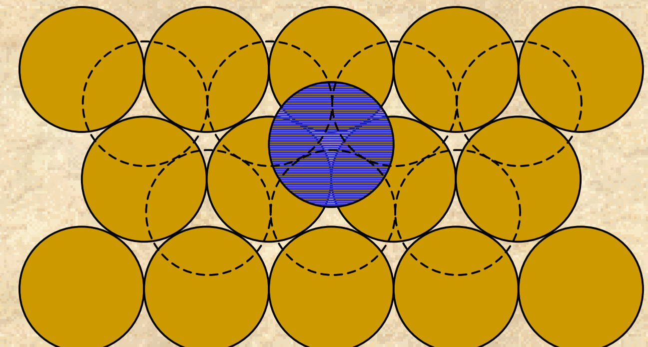
300 Å
square
topo

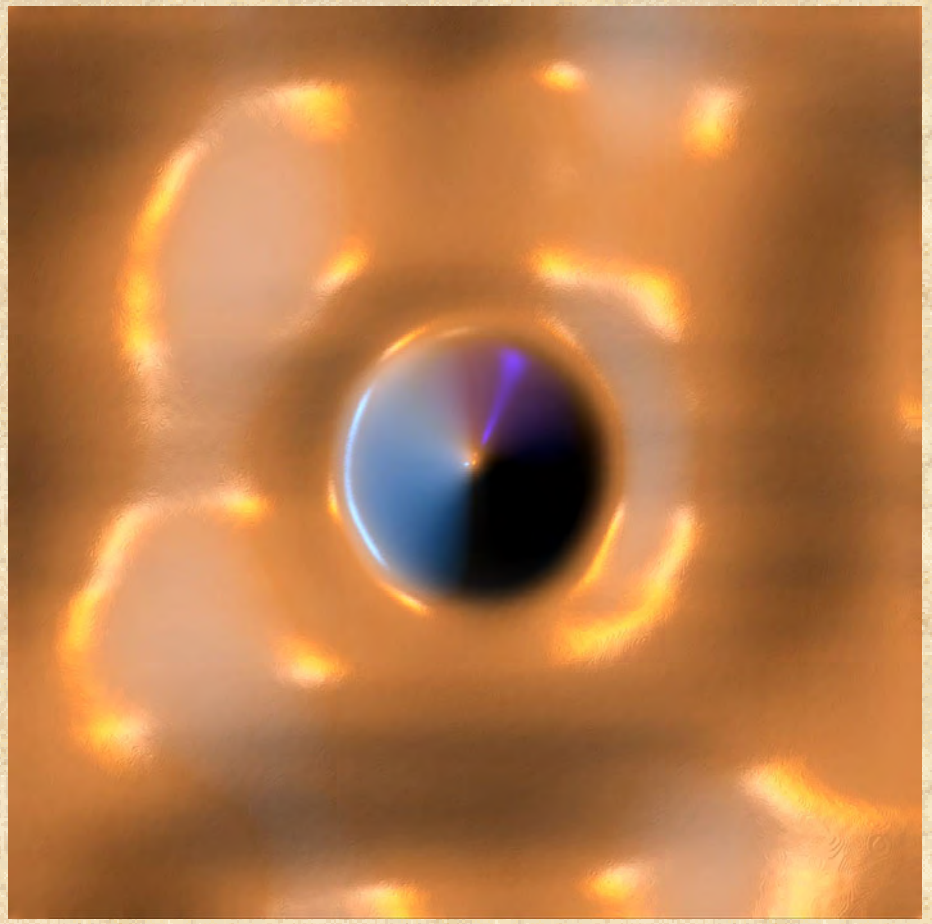
Cast of Characters: Co Atom



0.8 Å

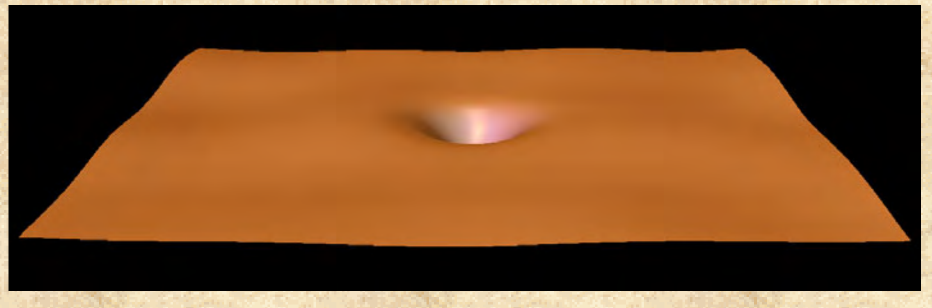
- Bonds to fcc sites on Cu(111)

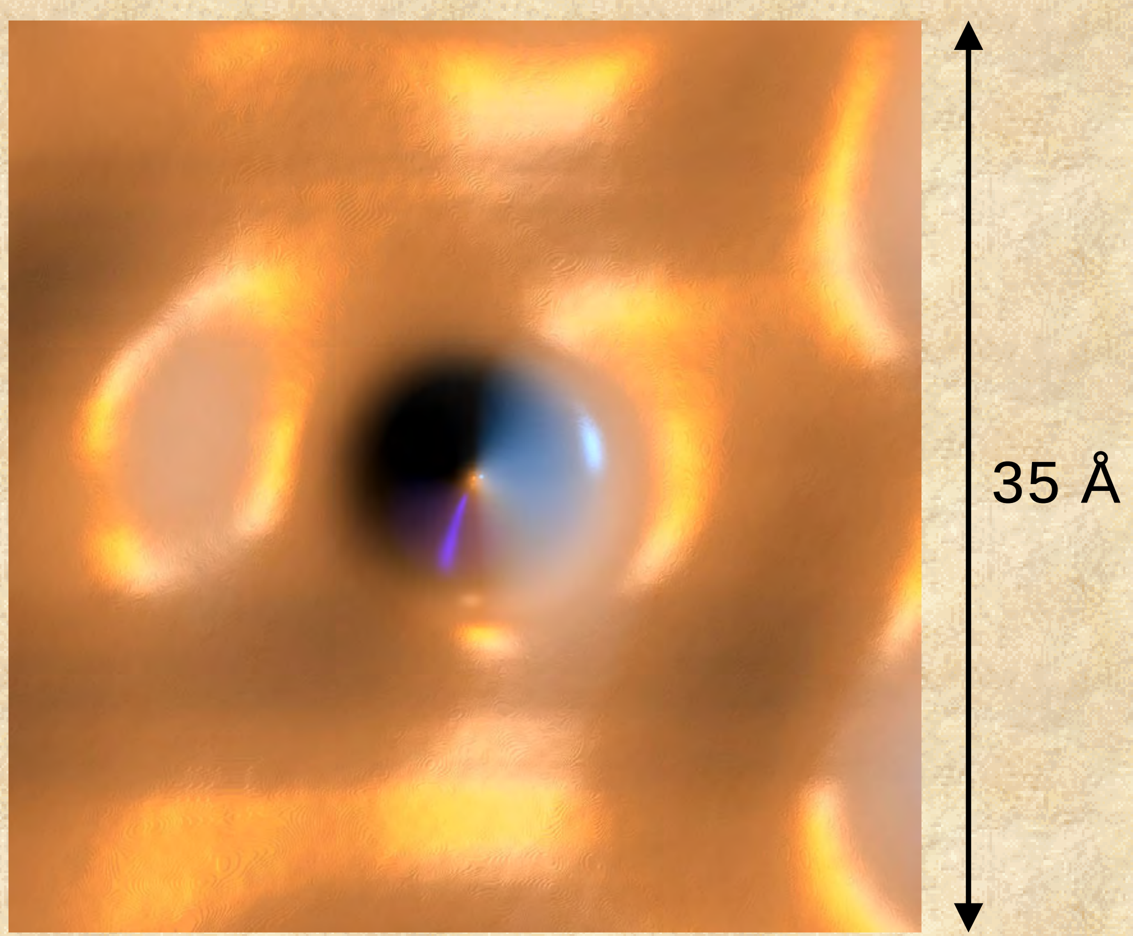




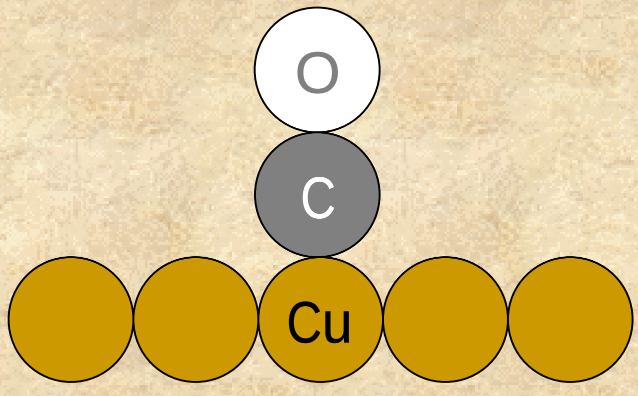
35 Å

Cast of Characters: CO Molecule





- Bonds "on-top" to Cu atoms

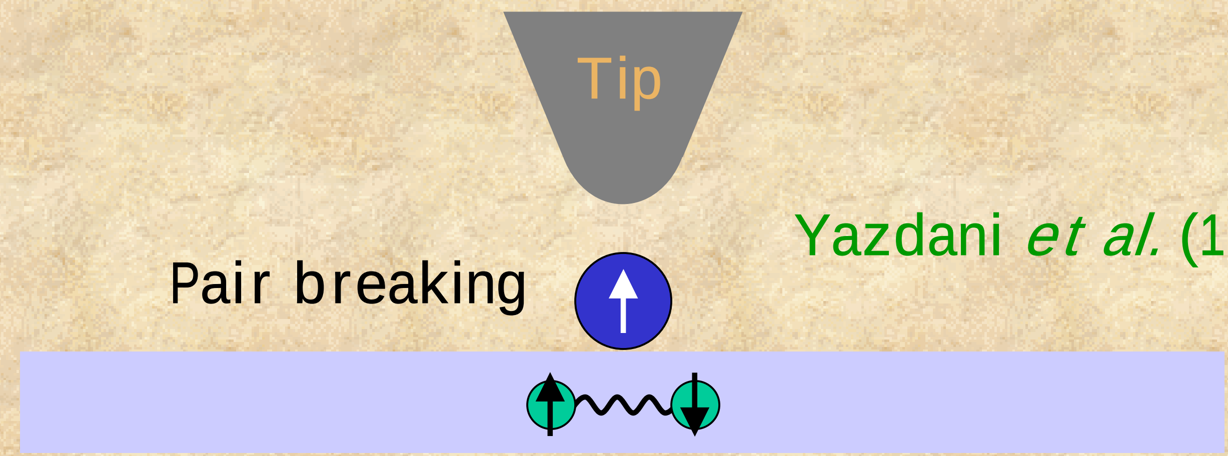


CHARGE: THE OLD WAY

SPIN: THE NEW FRONTIER

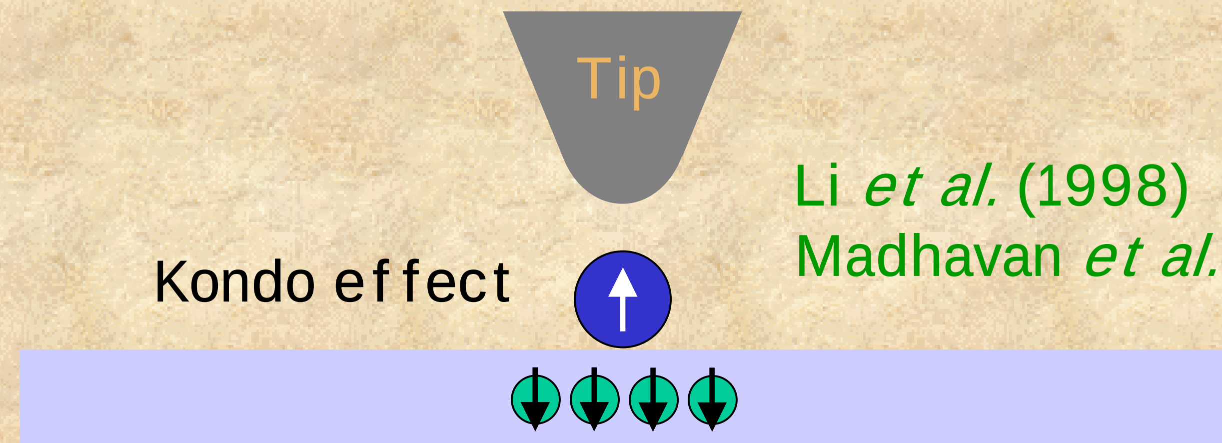
Probing the Spin Degree of Freedom with STM

- Magnetic moment on a superconductor



Yazdani *et al.* (1997)

- Magnetic moment on a normal metal



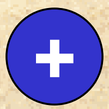
Li *et al.* (1998)
Madhavan *et al.* (1998)

- Interacting magnetic moments

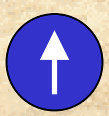
Looking “Inside” a Particle

- Quantized degrees of freedom

Charge



Spin



Looking "Inside" a Particle

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- Quantized degrees of freedom

<u>Charge</u>

\+ + environment

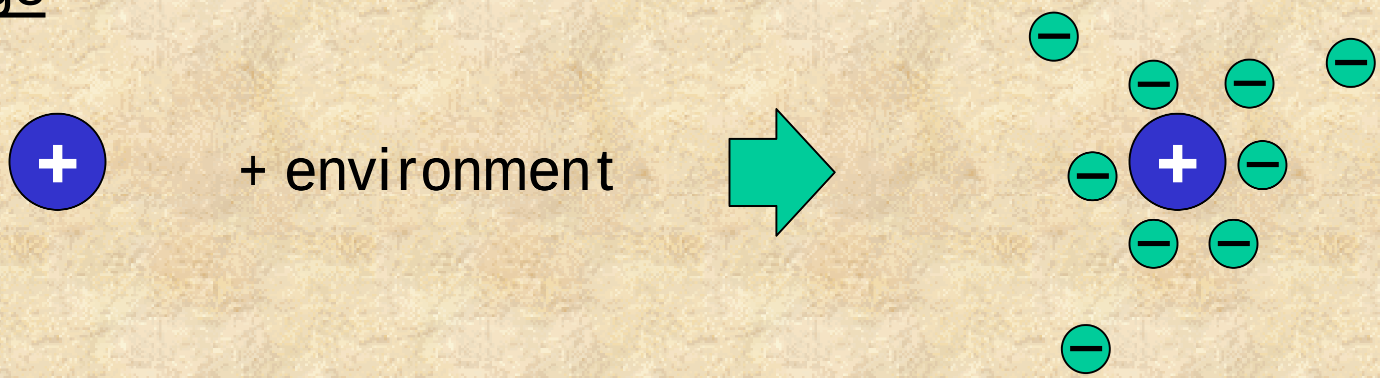
<u>Spin</u>

\+ environment

Looking “Inside” a Particle

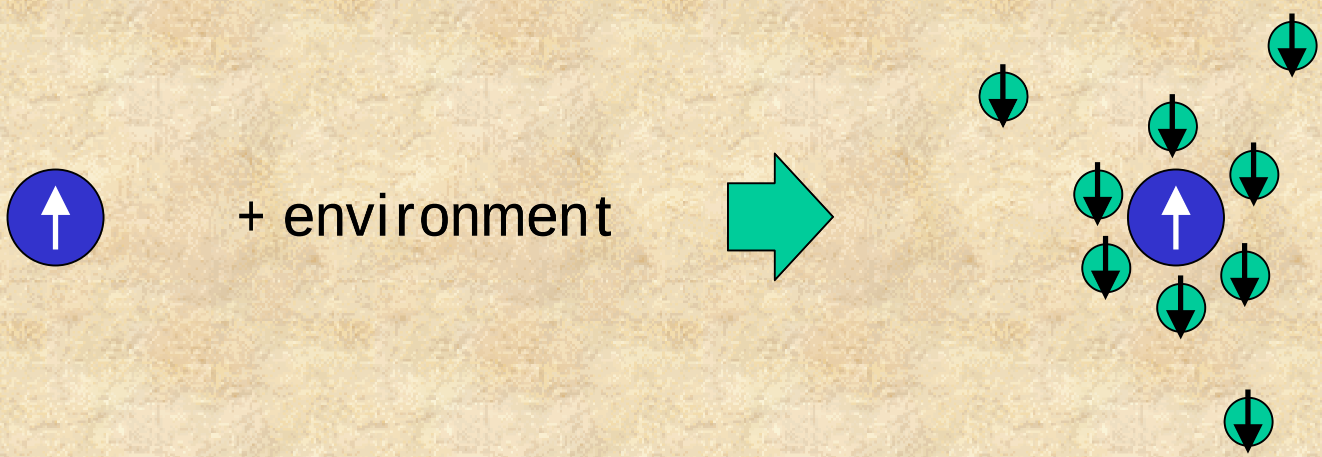
- Quantized degrees of freedom

<u>Charge</u>



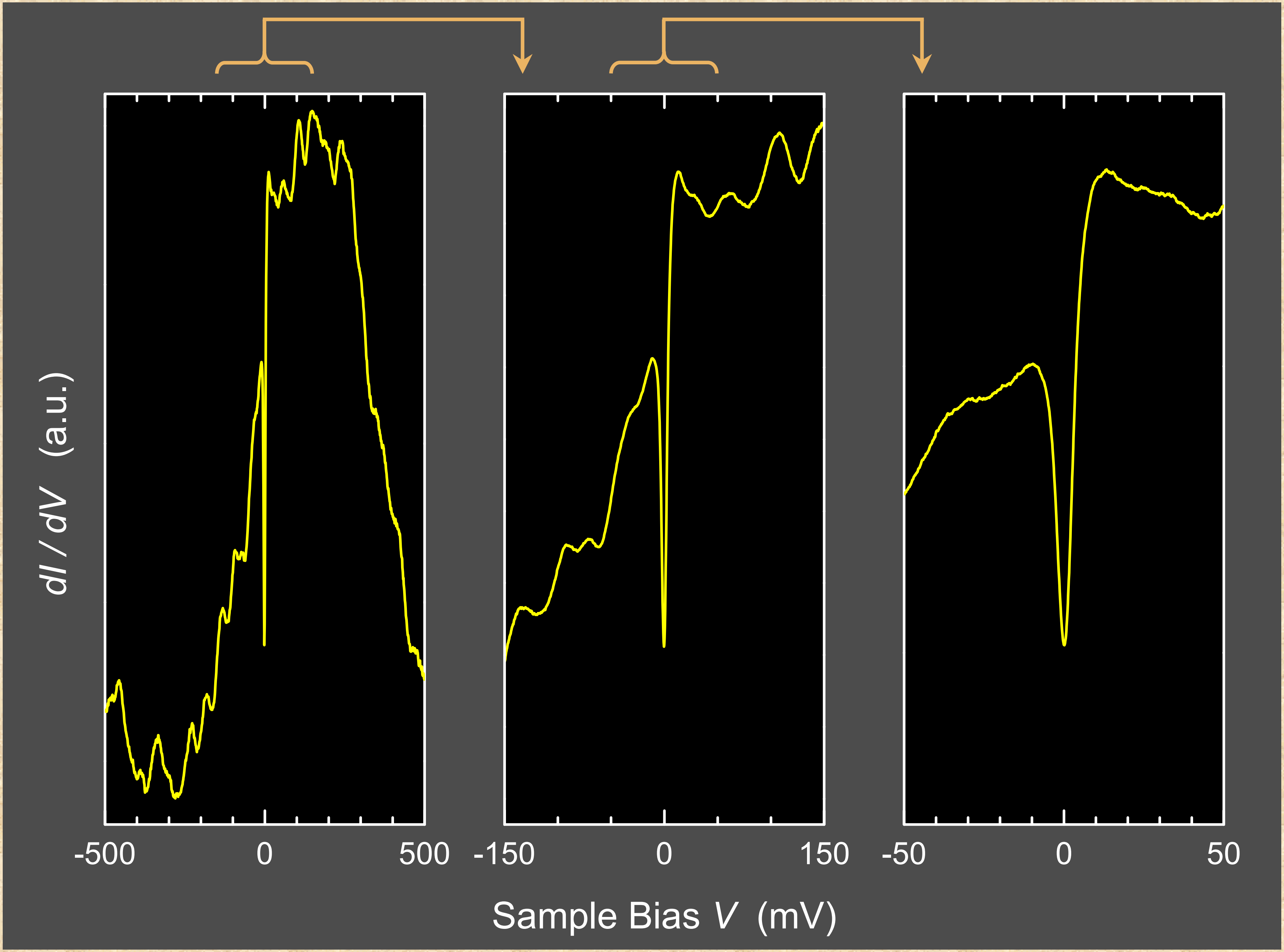
charge screening

<u>Spin</u>

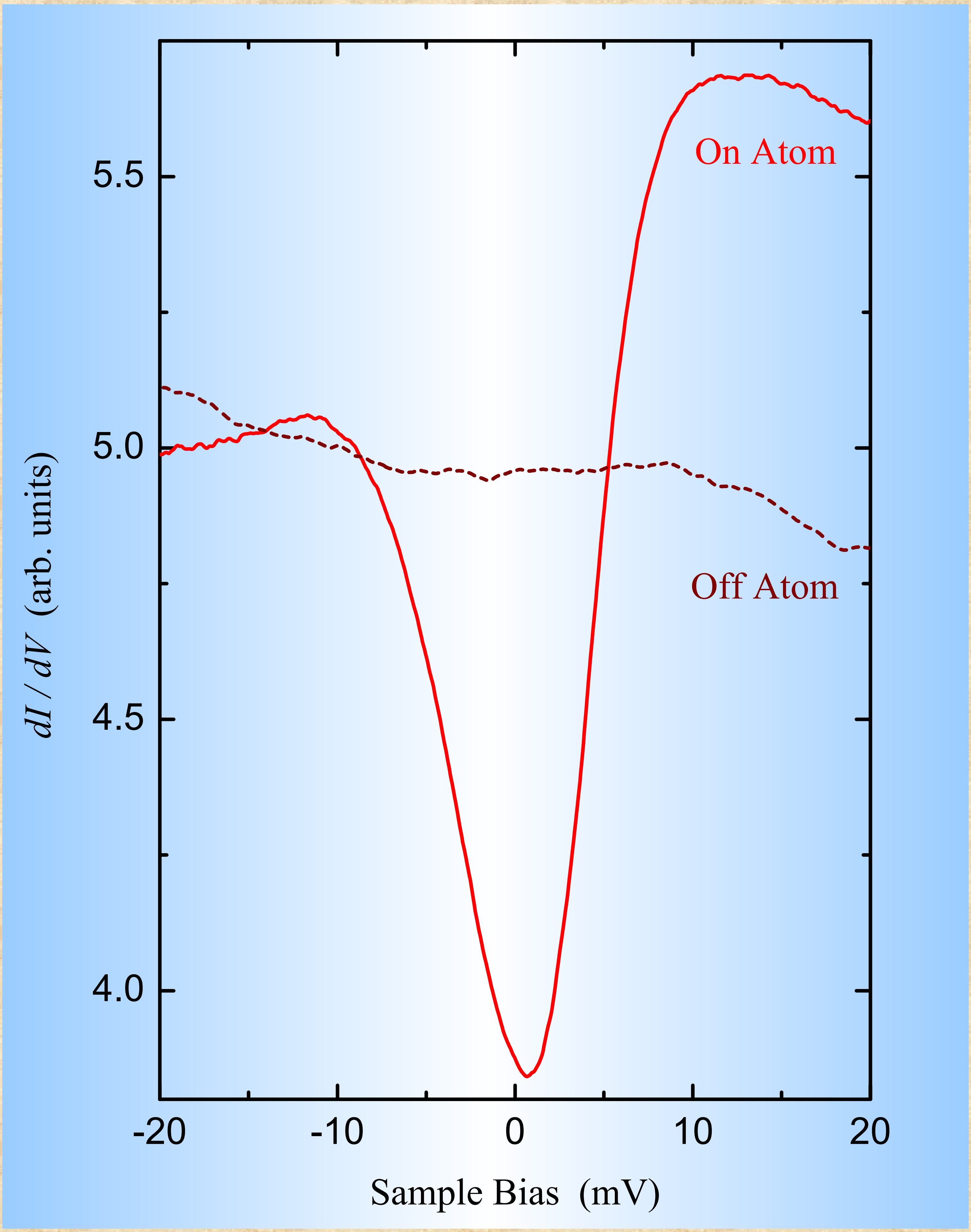


spin screening

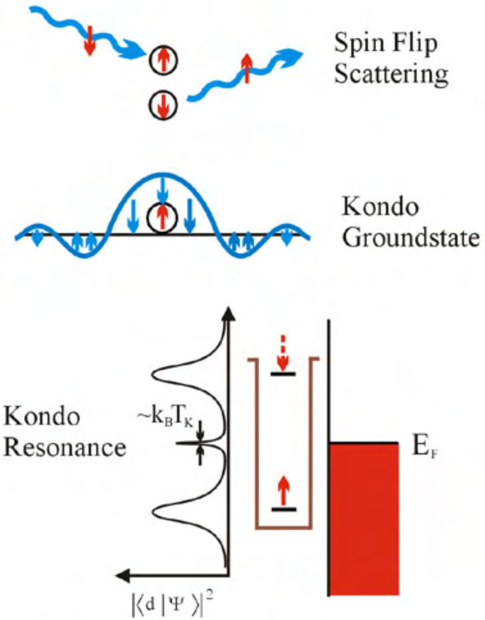
The Kondo Resonance



The Kondo Resonance: Co Atom on Cu(111)

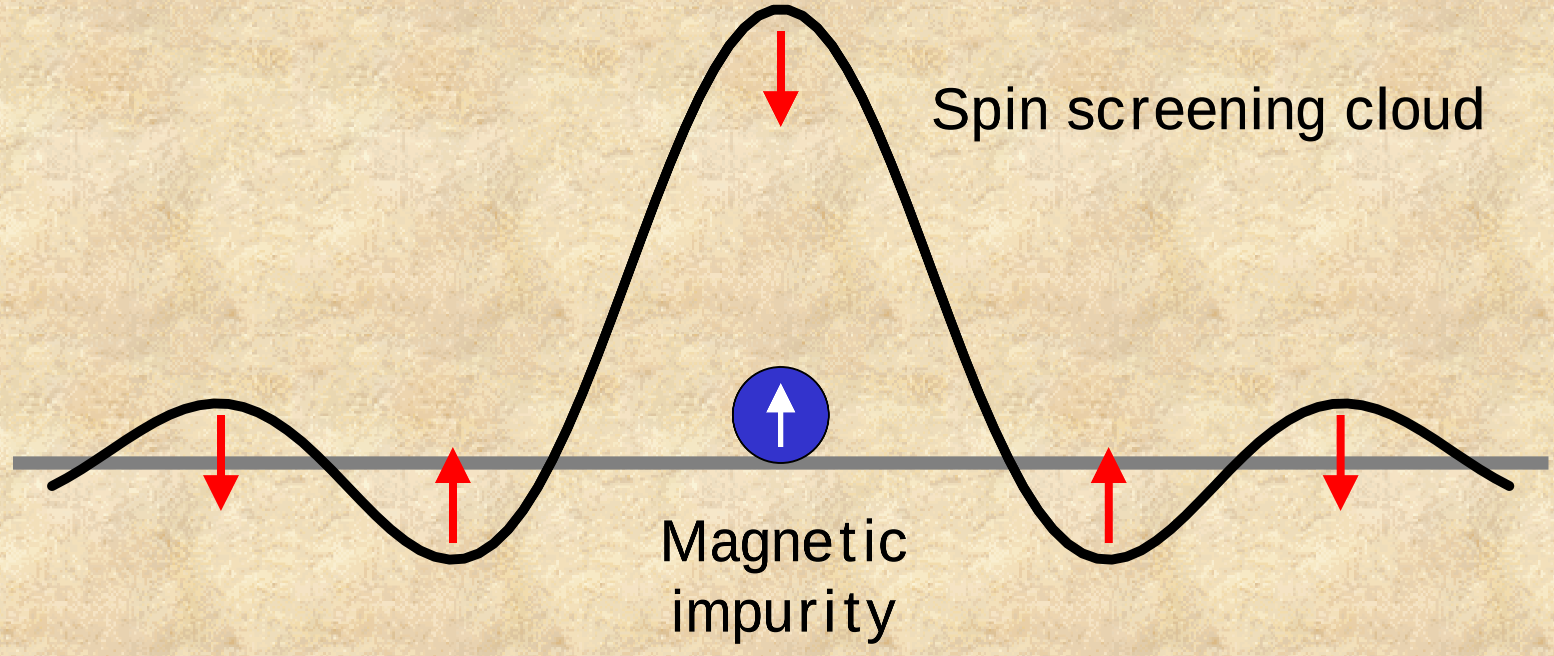


Kondo Effect



The Kondo effect comes about from spin-flip scattering between the free electrons of a metal and the local moment of a magnetic impurity. This scattering leads to a highly correlated manybody groundstate where the conduction electrons form a spin-polarized "cloud" around the magnetic impurity. The Kondo cloud forms at temperatures below a characteristic "Kondo temperature", and leads to anomalous behavior in the transport properties and magnetic susceptibility of dilute magnetic alloys (and some rare-earth compounds). The low-energy excitations of a Kondo impurity result in a narrow resonance at the Fermi energy of the host metal.

• Kondo ground state



•Kondo effect and STM

- Co on Au(111)
  [Madhavan *et al.*, Science **280**, 567 (1998)].
- Ce on Ag(111)
  [Li *et al.*, PRL **80**, 2893 (1998)].

→ Fano resonance

The Kondo Temperature

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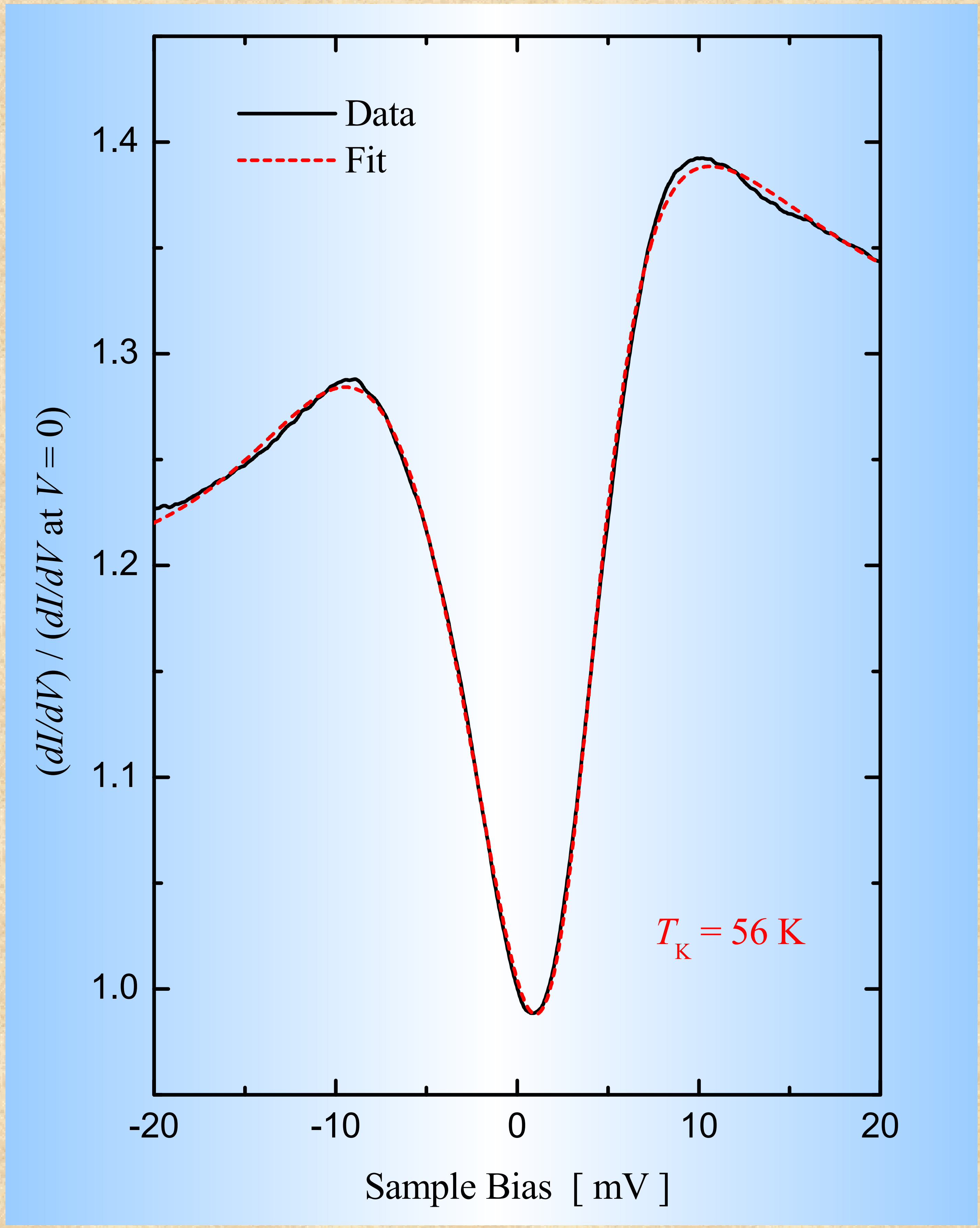
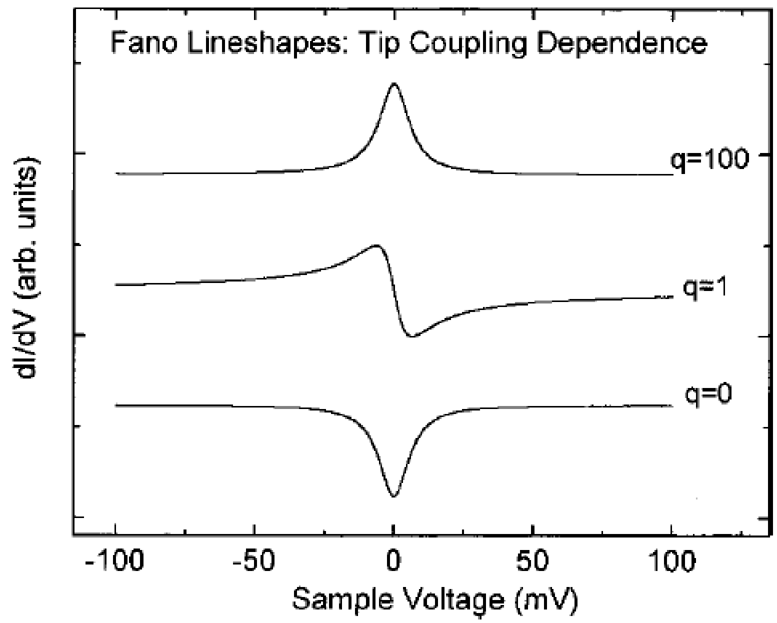
- Fit tunnel spectrum to Fano resonance



Fano Lineshape

$$F = F_0 \frac{(q+\varepsilon')^2}{1+\varepsilon'^2}, \varepsilon' = \frac{\varepsilon - \alpha}{k_B T_K}$$



V. Madhavan *et al*, PRB **64** (2001)

The Kondo Resonance: Co Atom Flyover

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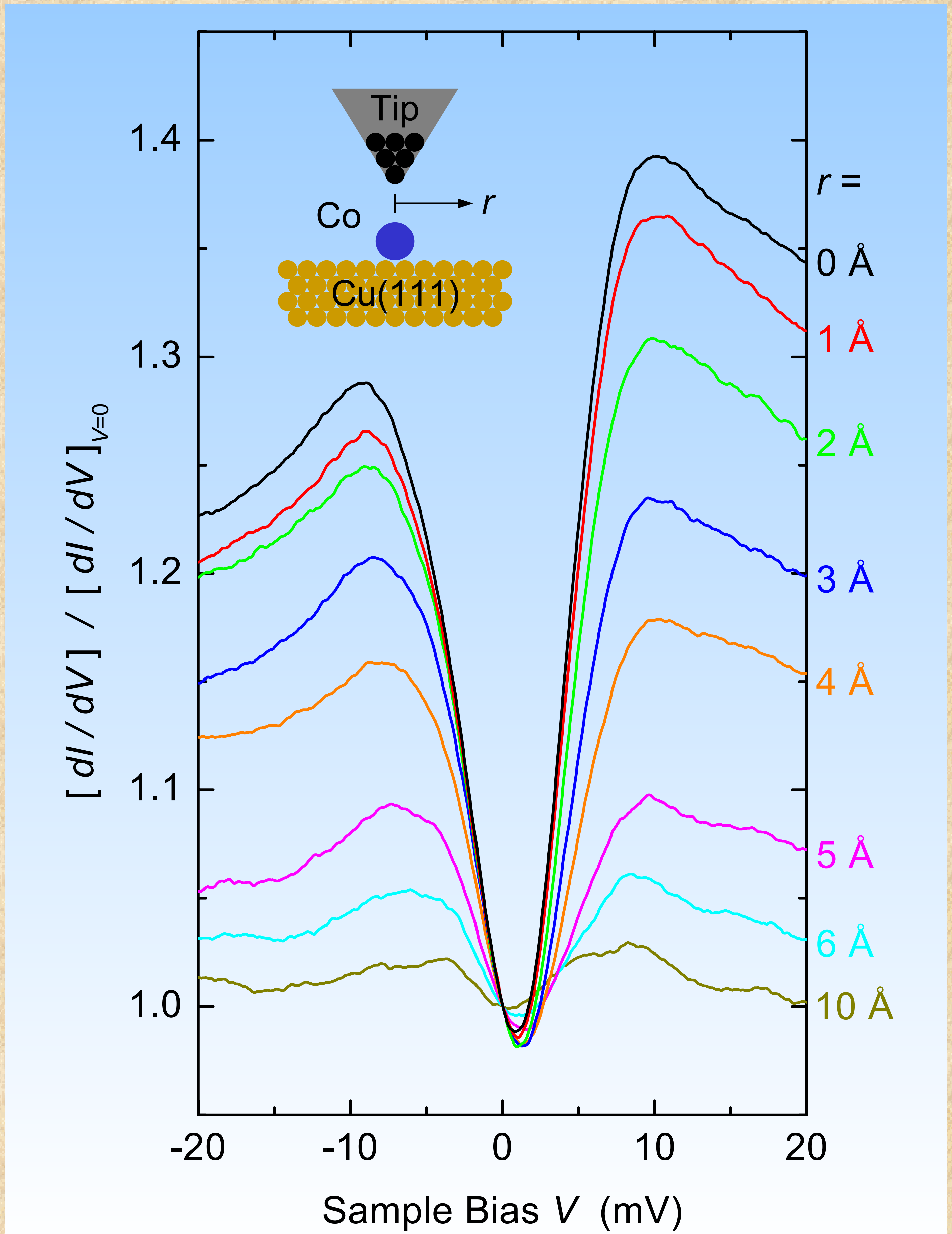
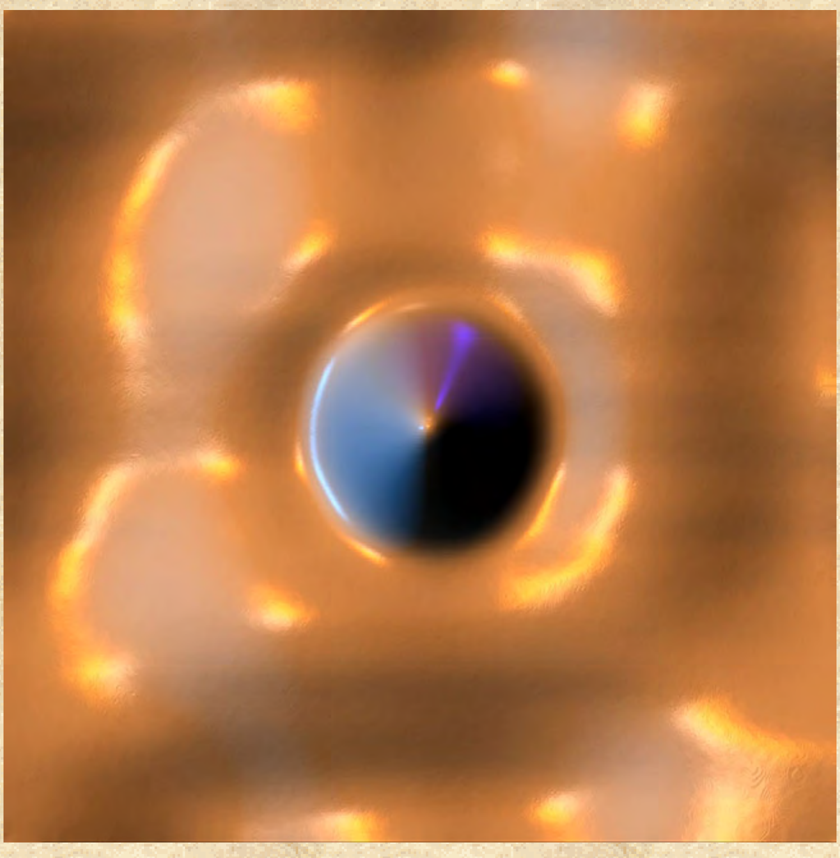


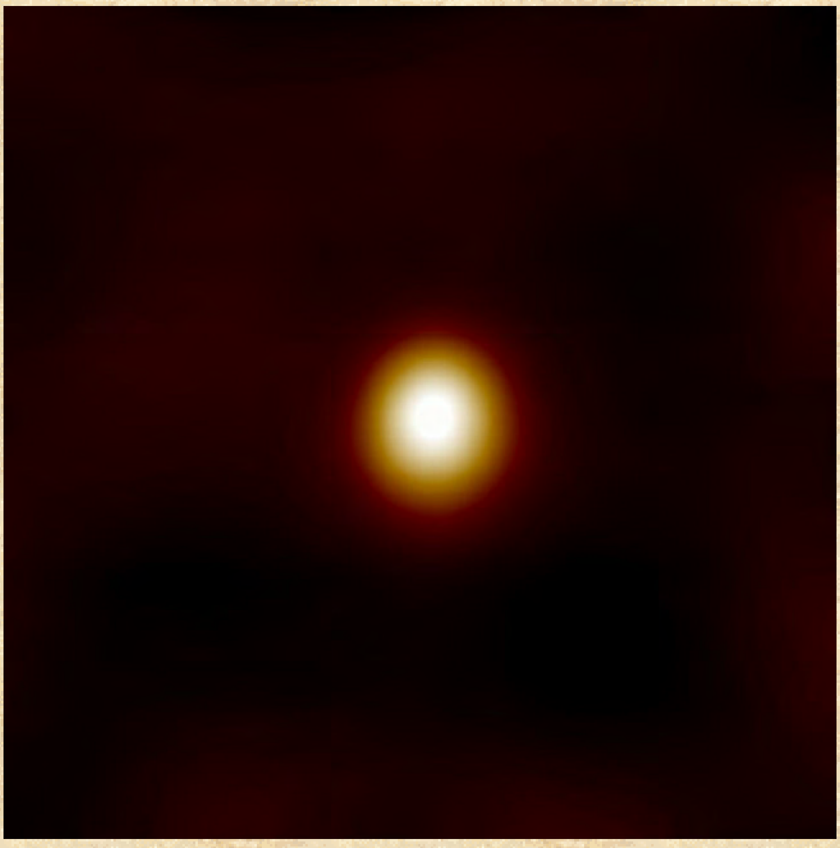
Imaging the Kondo Resonance

- Single Cobalt atom
- Simultaneously acquired 35 Å square images



Topograph

(V = 5 mV)

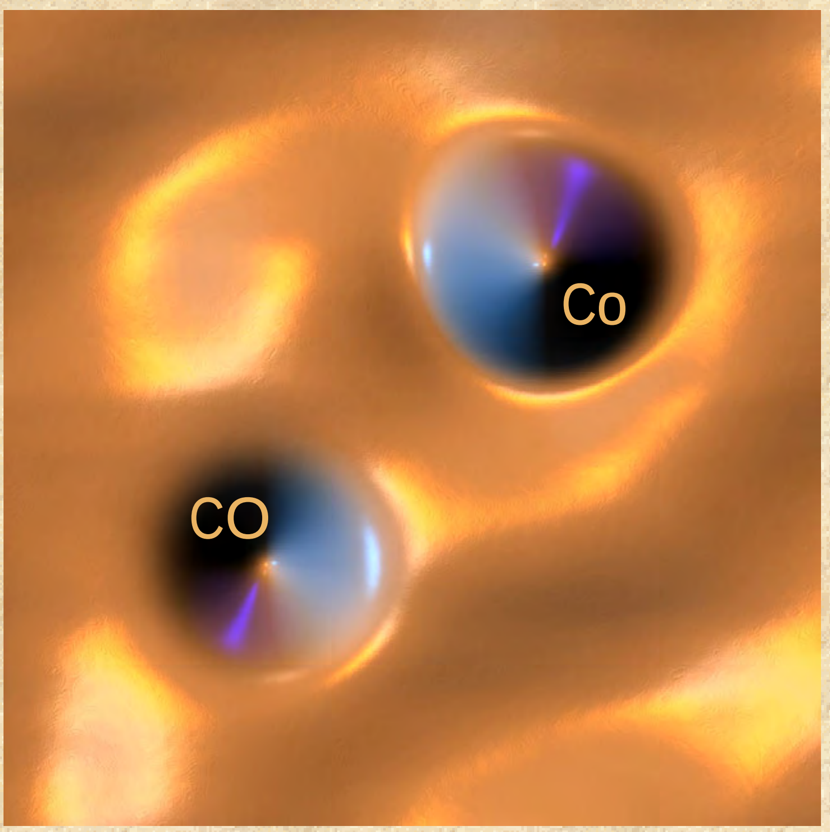


dI/dV map

(V = ±5 mV)

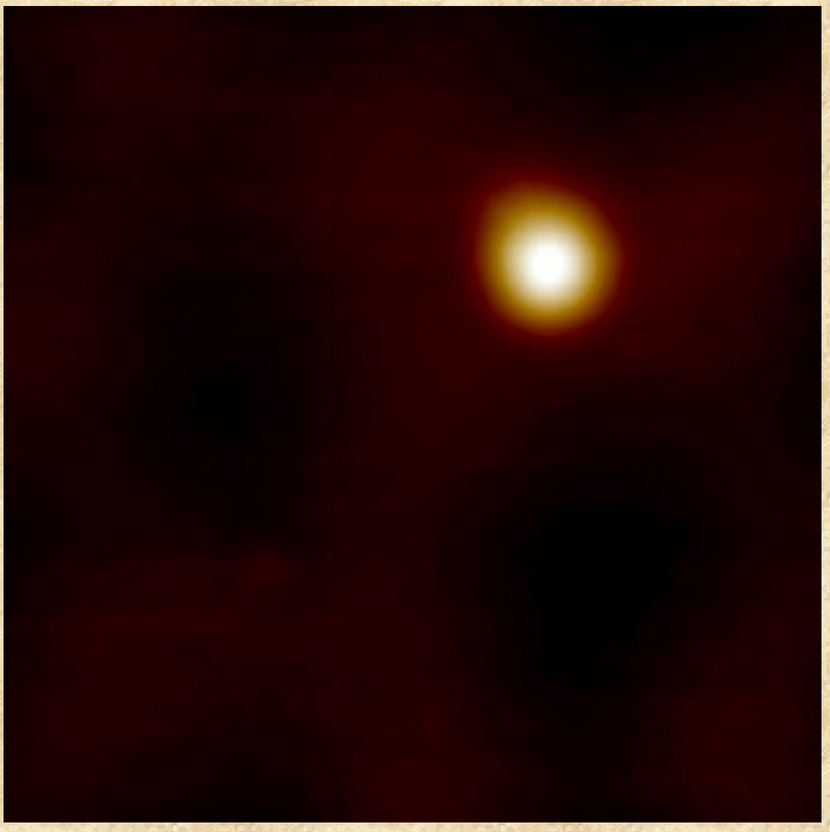
Kondo Imaging: Co vs CO

- 1 cobalt atom + 1 carbon monoxide molecule
- Simultaneously acquired 35 Å square images



Topograph

(V = 5 mV)

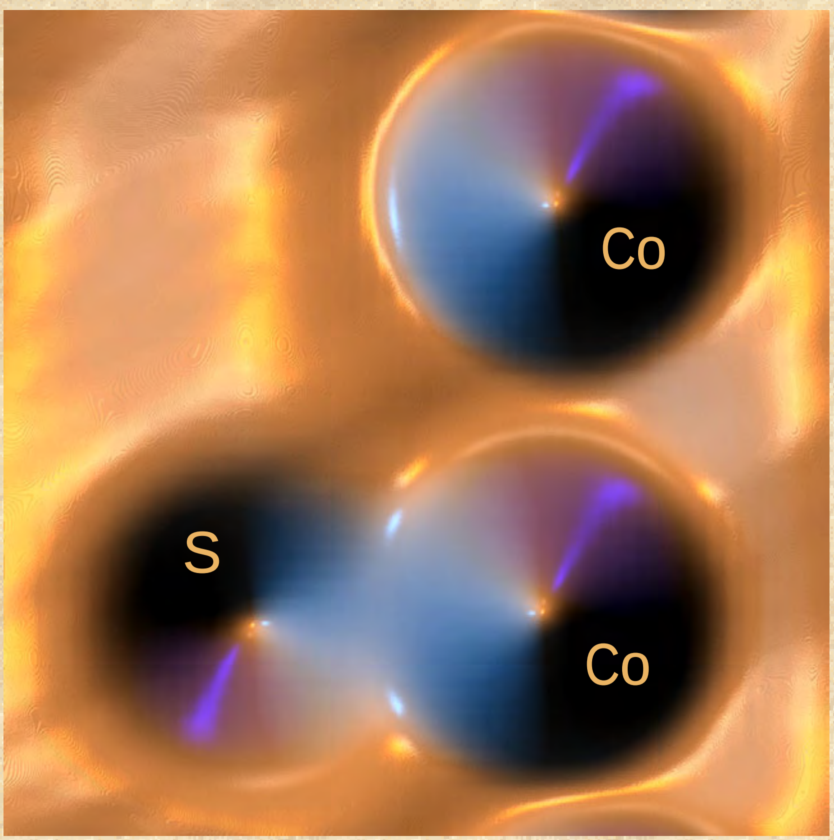


dI/dV map

(V = 5 mV)

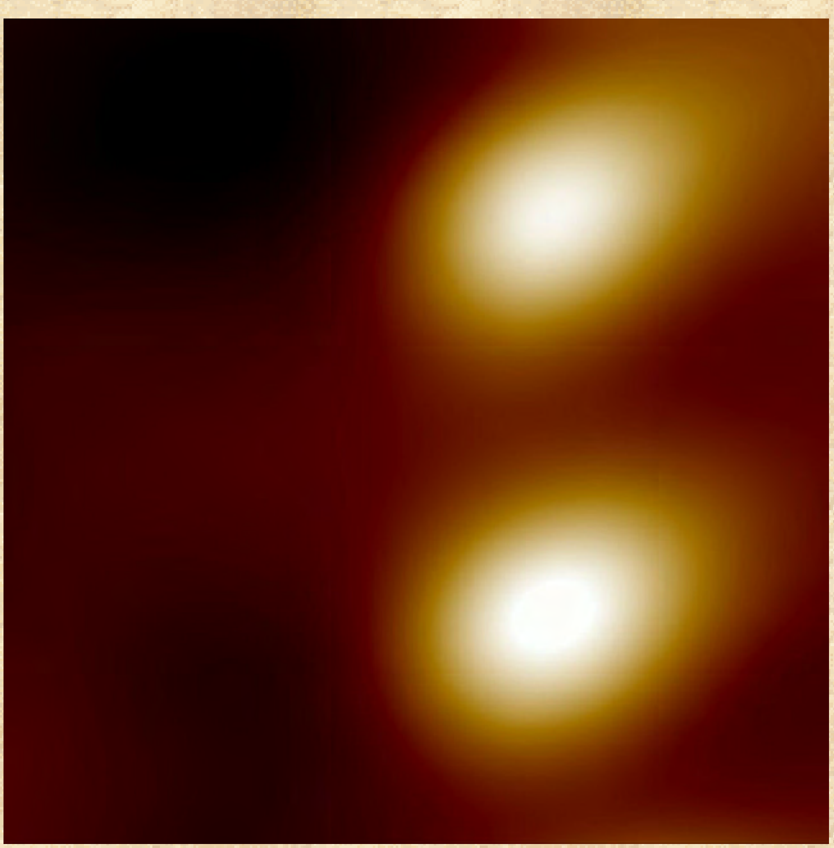
Kondo Imaging for Atom Identification

- 2 Cobalt atoms + 1 Sulfur atom
- Simultaneously acquired 27 Å square images



Topograph

(V = 10 mV)



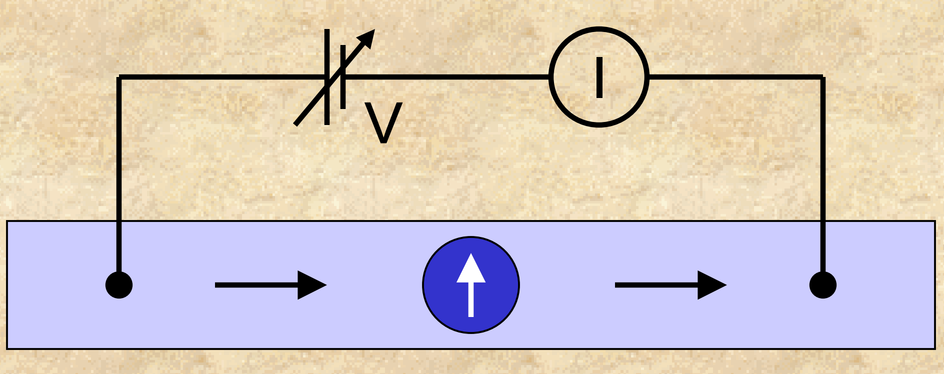
dI/dV map

(V = 10 mV)

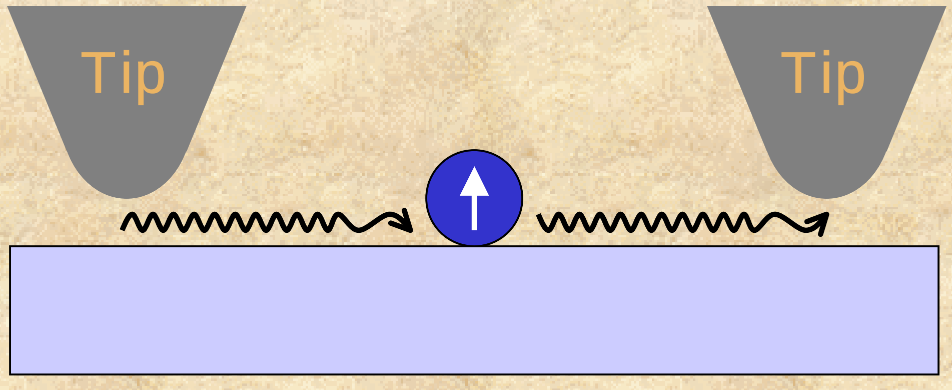
ATOMS
WHERE YOU
WANT THEM

Toward Multiple Terminals

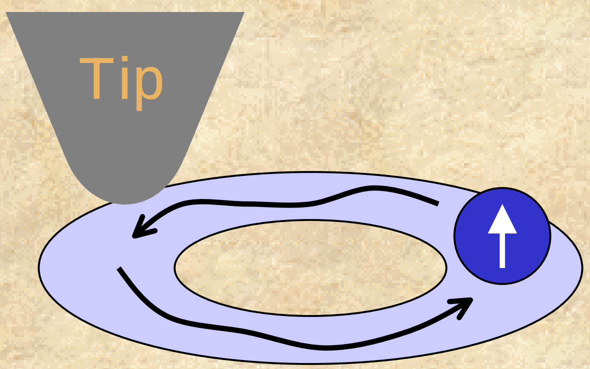
- Standard two-terminal measurement

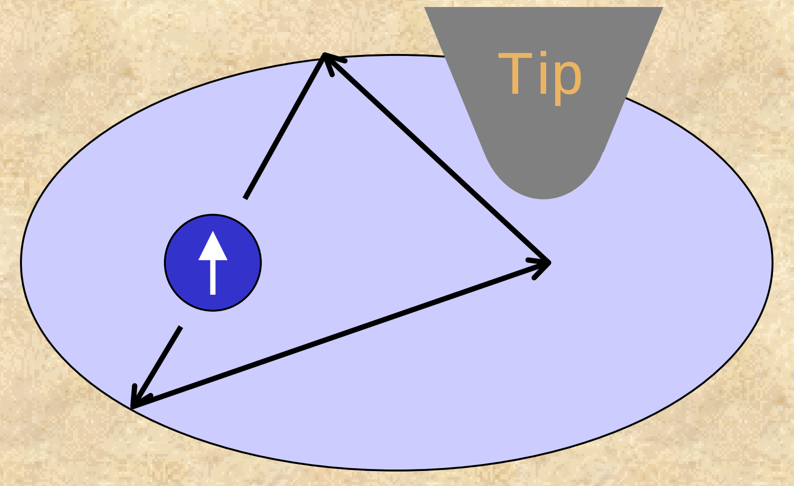


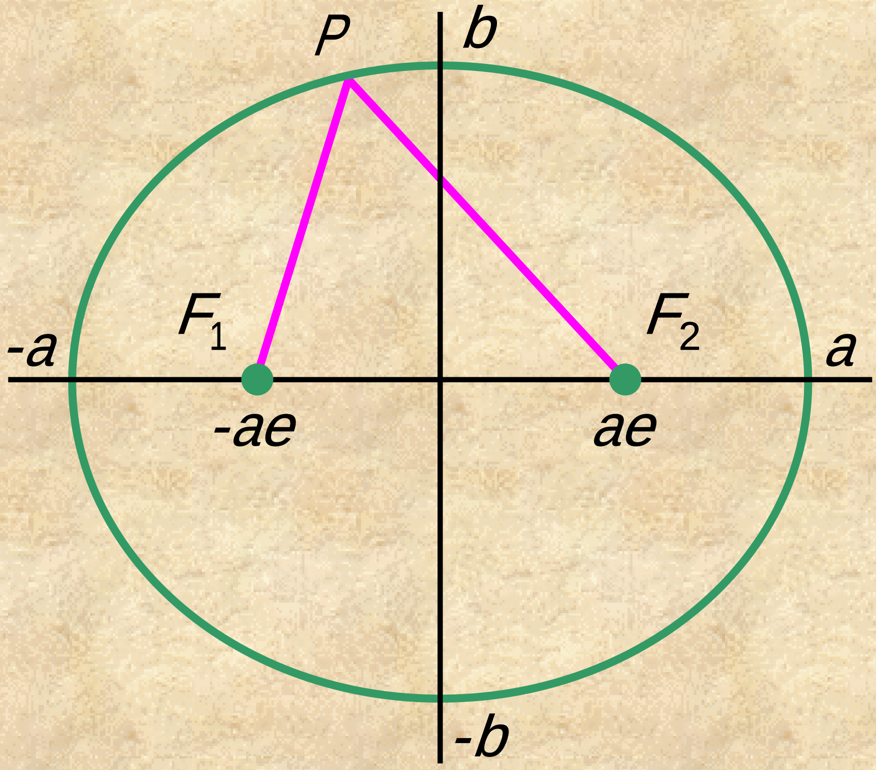
- Two tips?



- One tip plus weird geometry

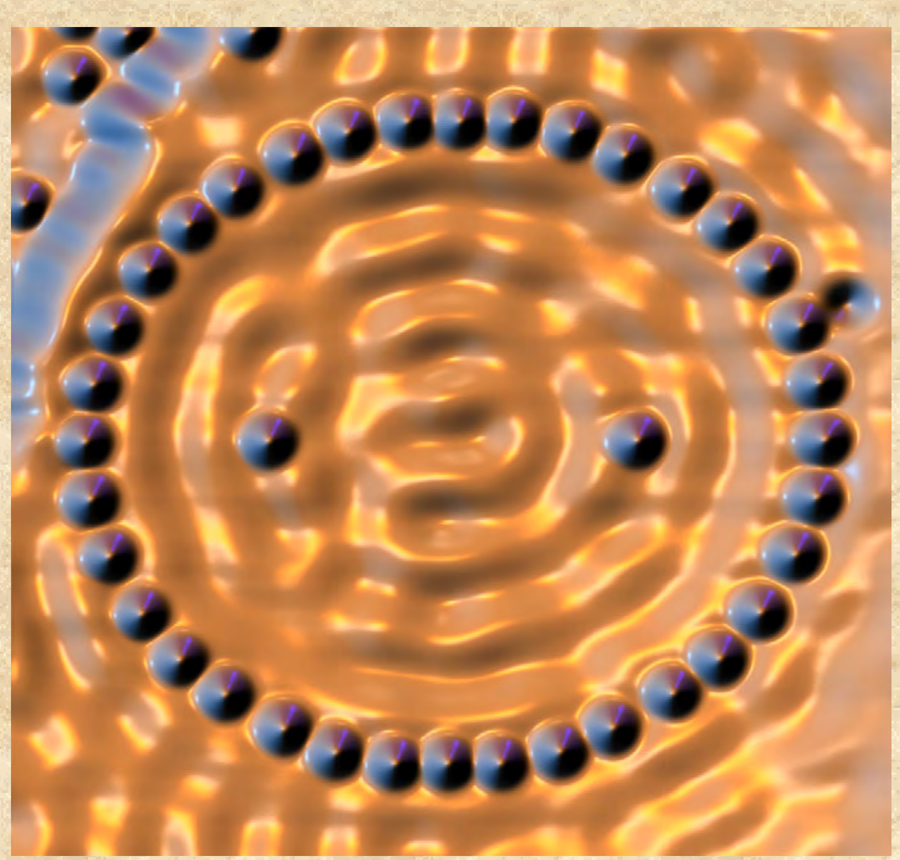






Path length:
$F_1P + PF_2 = 2a$

Eccentricity:
$e^2 = 1 - b^2/a^2$



170 Å

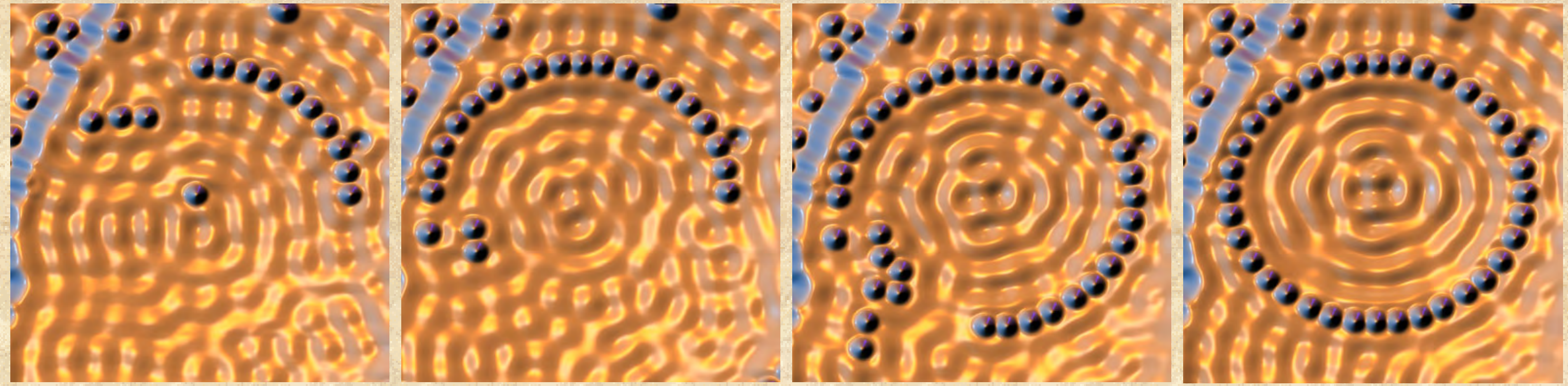
$a = 71.3$ Å

$e = 1/2$

Atom-by-Atom Assembly of Nanostructures

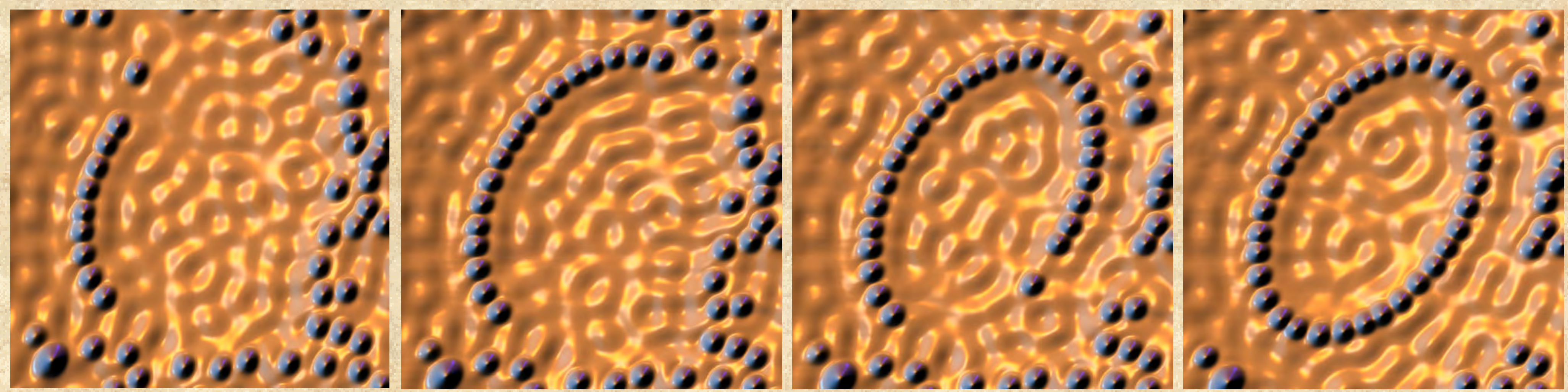
- $e = 0.500$, $a = 71.3$ Å elliptical electron resonator

180 Å



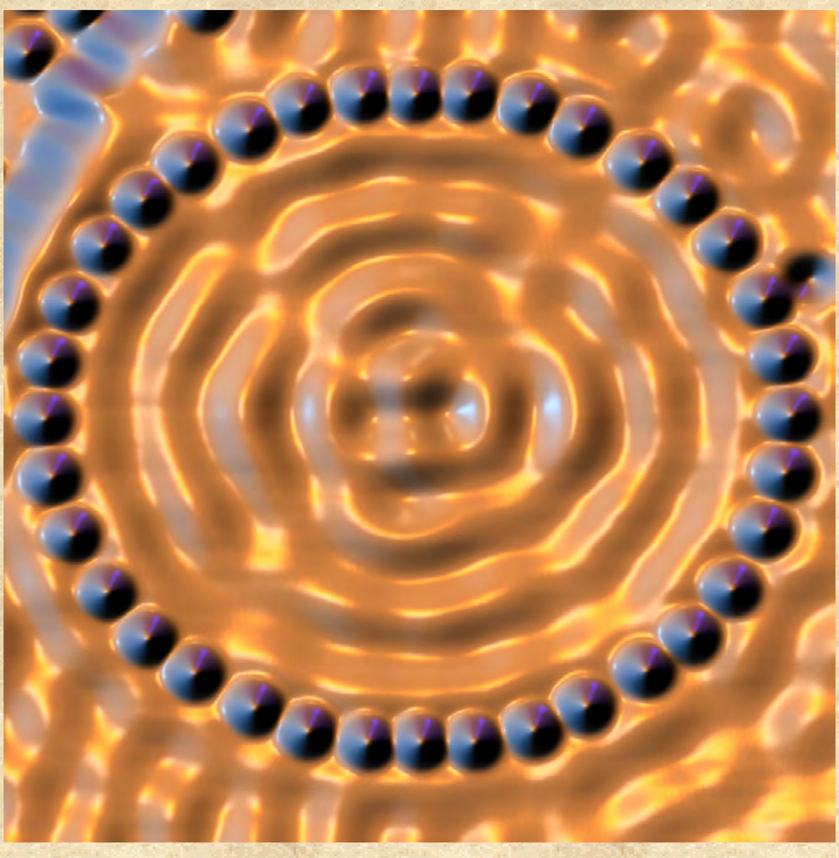
- $e = 0.786$, $a = 71.3$ Å elliptical electron resonator

180 Å



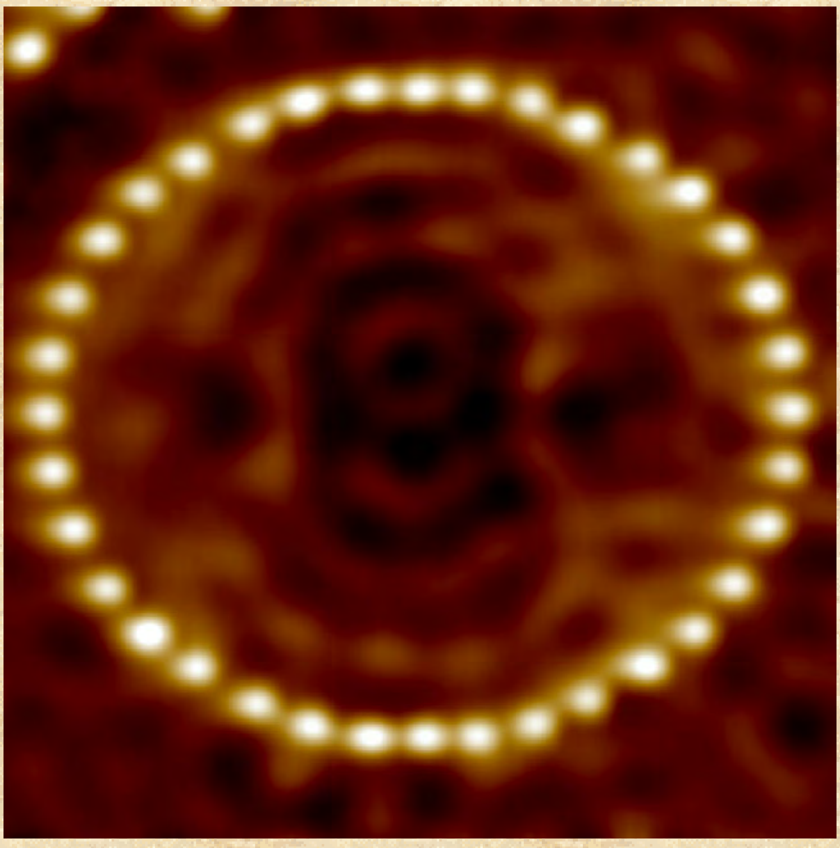
Empty Elliptical Resonator

- $e = 1/2$, $a = 71.3$ Å
- Simultaneously acquired 150 Å square images



Topograph

($V = 10$ mV)

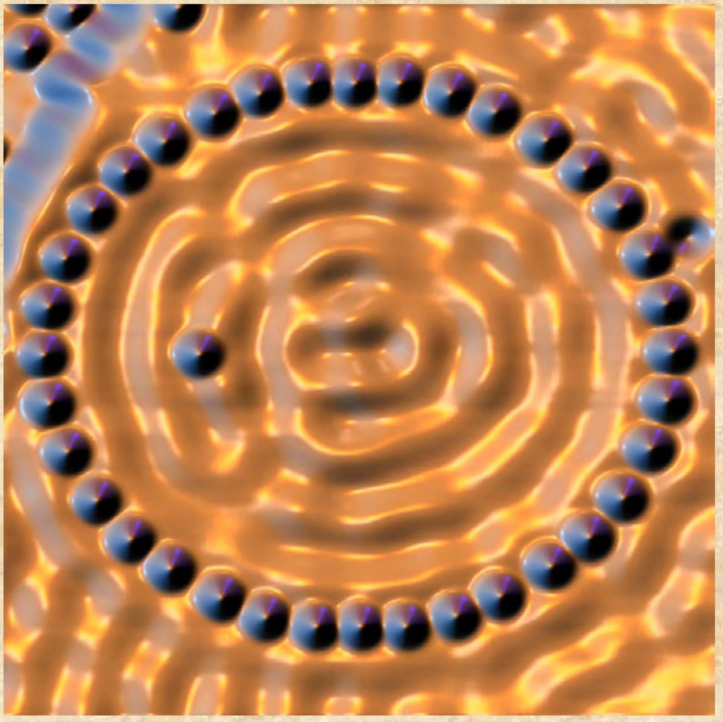


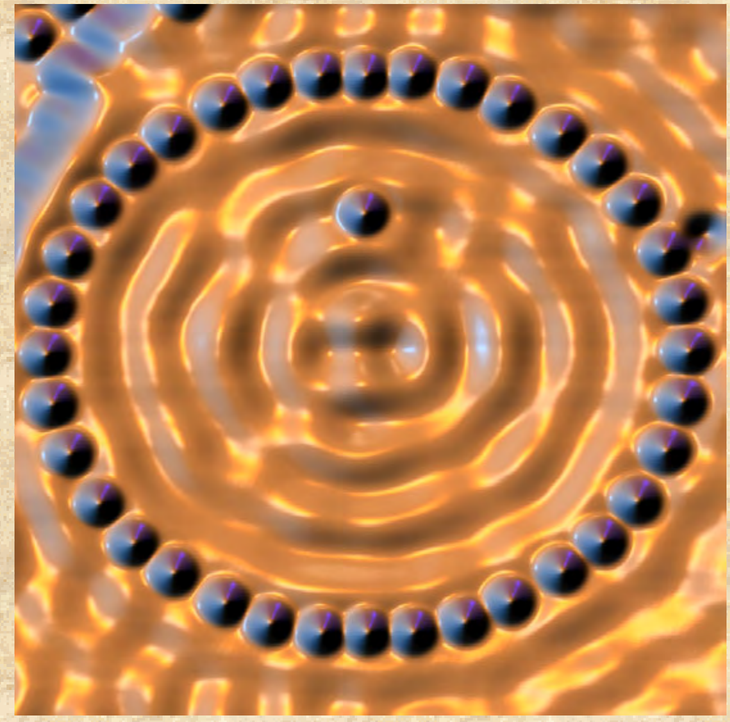
dI/dV map

($V = 10$ mV)

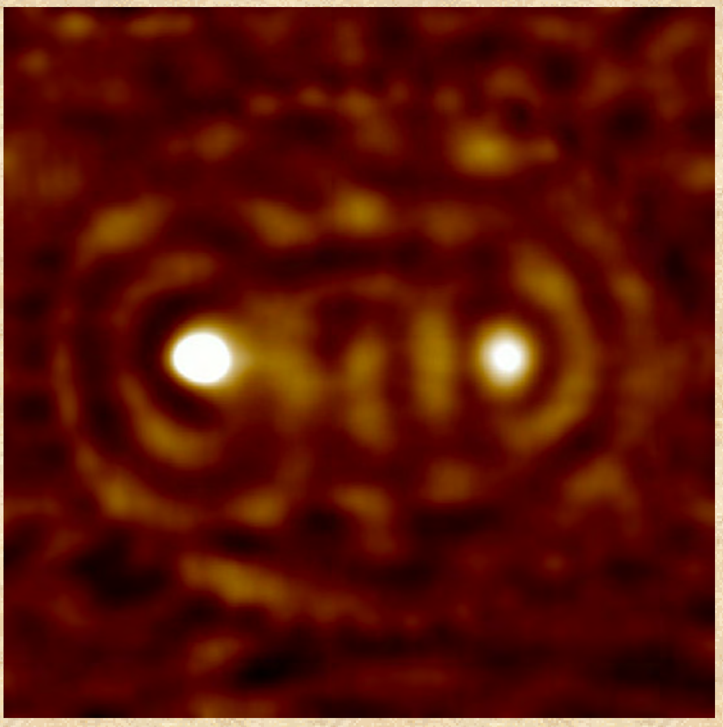
- e = 1/2, a = 71.3 Å elliptical resonator

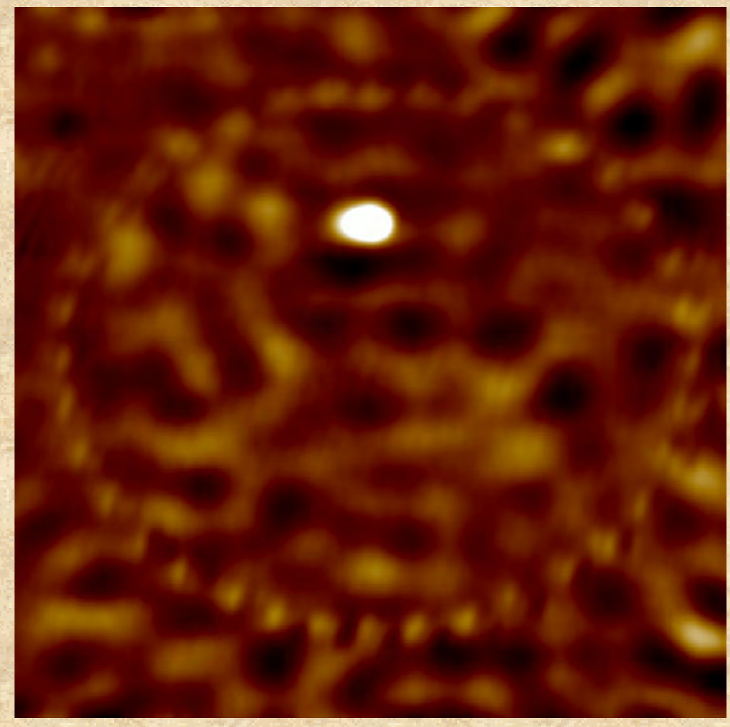
Topograph

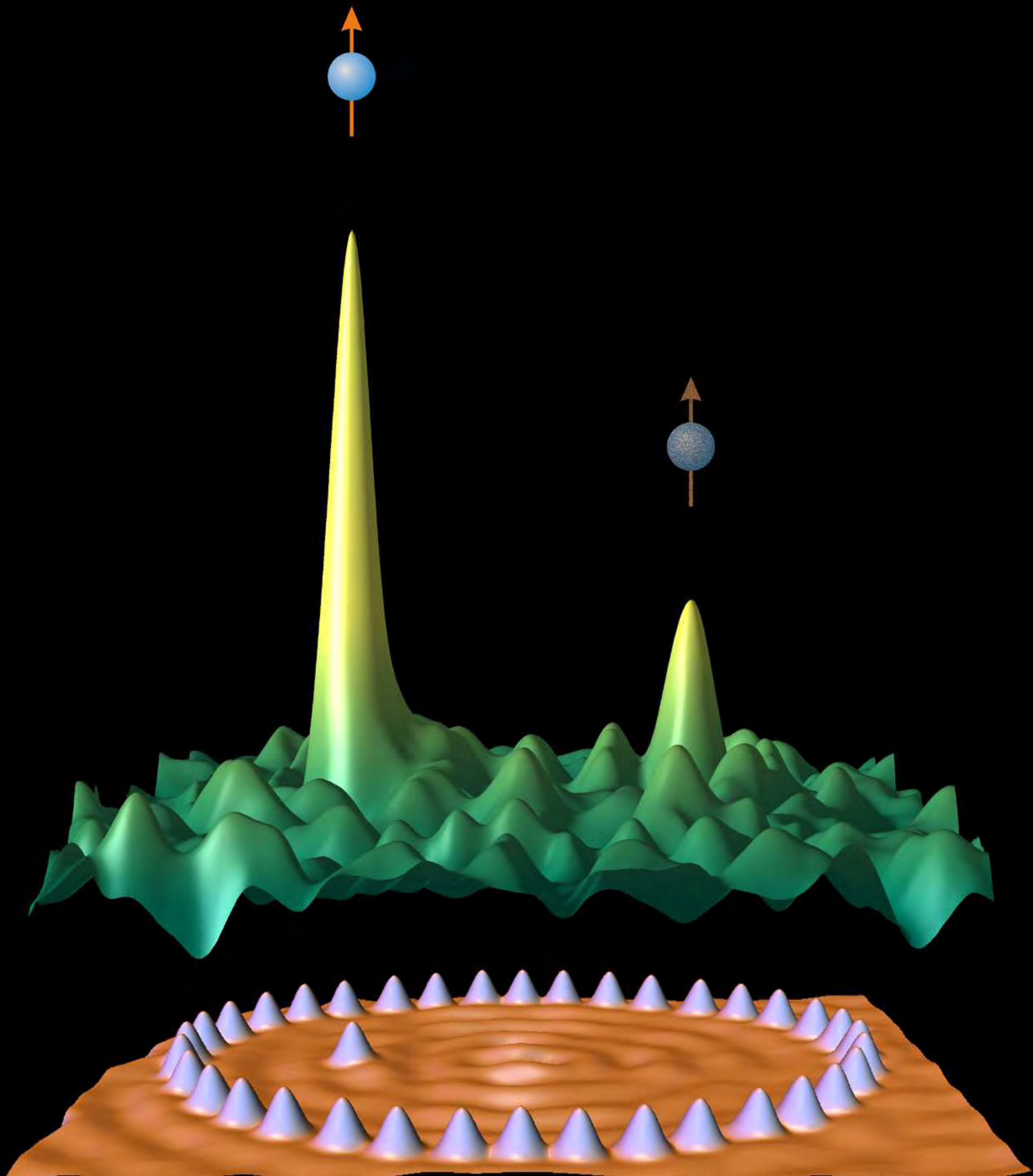




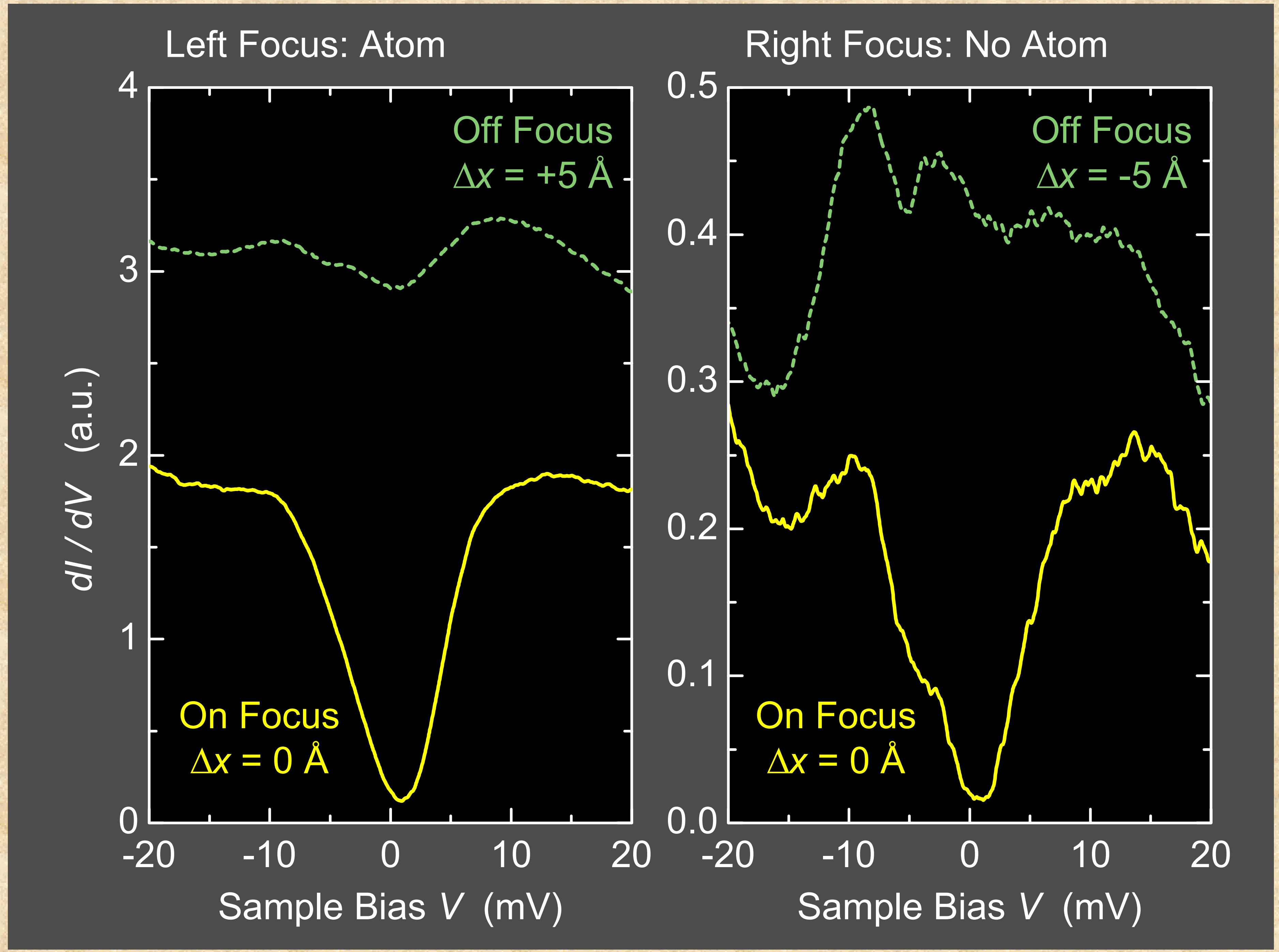
dI/dV difference map





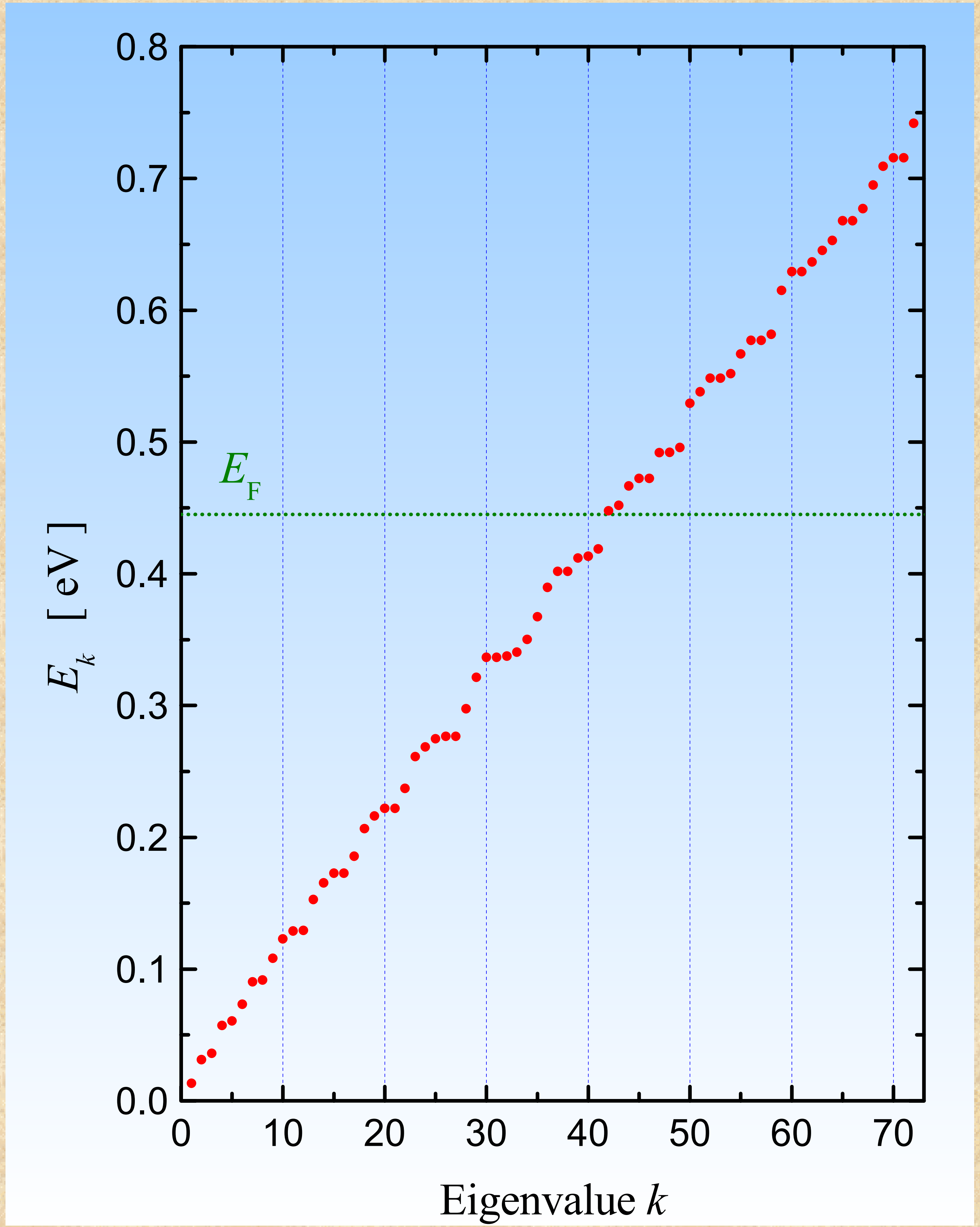


Spectroscopy on Atom and Mirage



Eigenmode Calculations

- $e = 1/2$, $a = 71.3$ Å elliptical resonator



Eigenmodes

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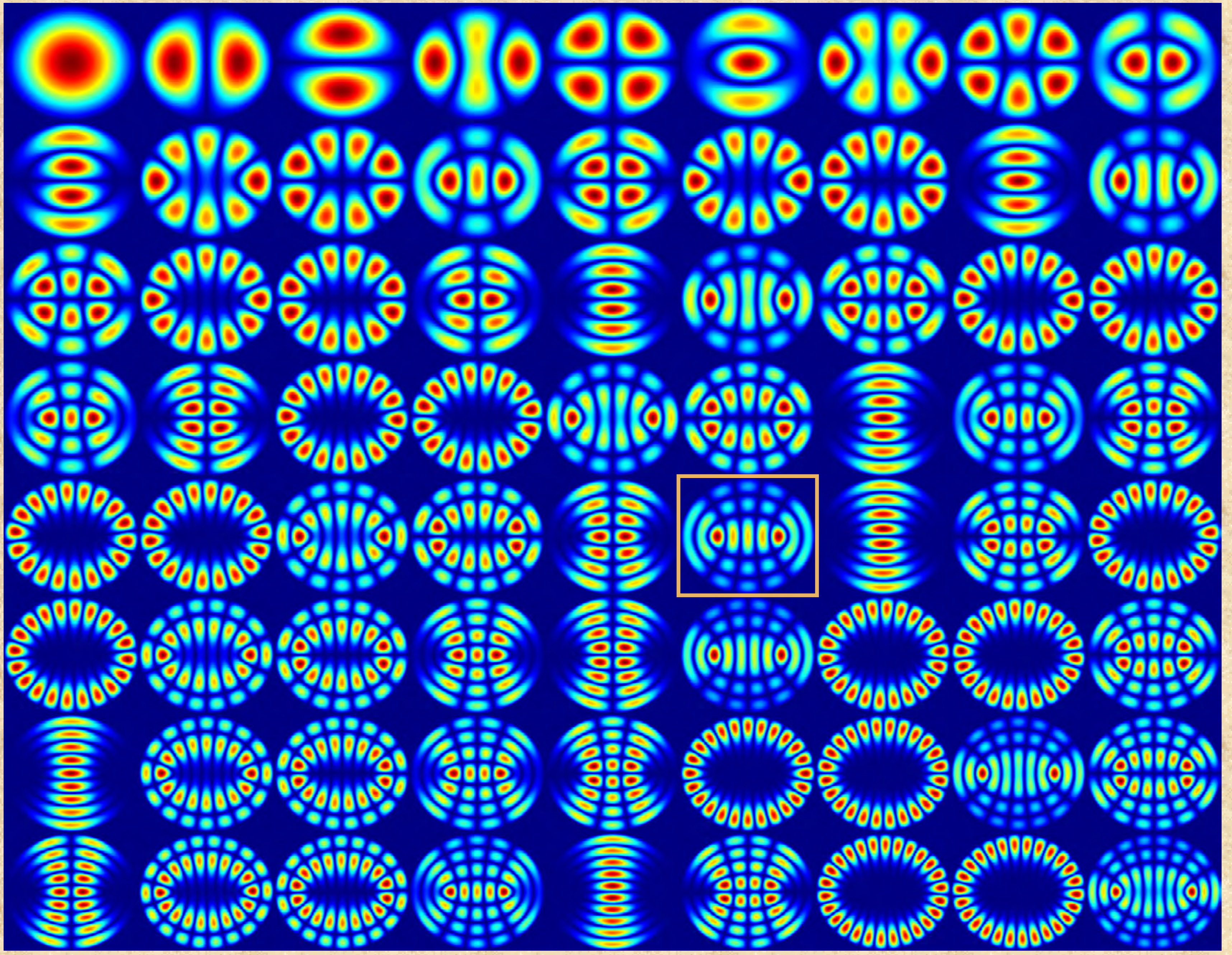
- $e = 1/2$, $a = 71.3$ Å elliptical resonator



Eigenmode Modeling

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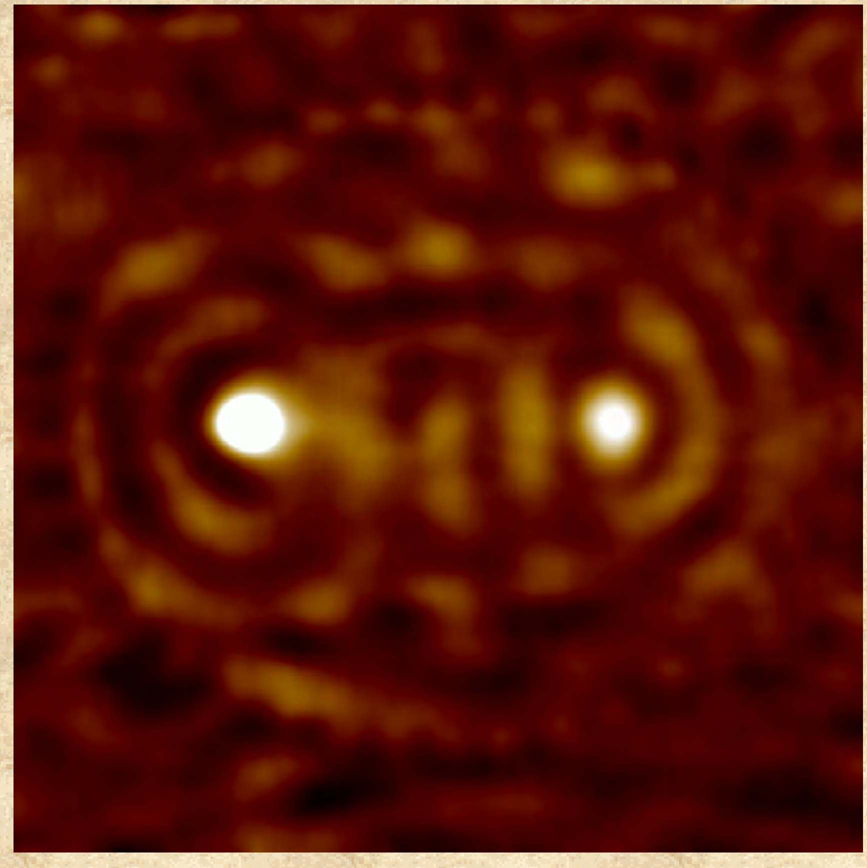
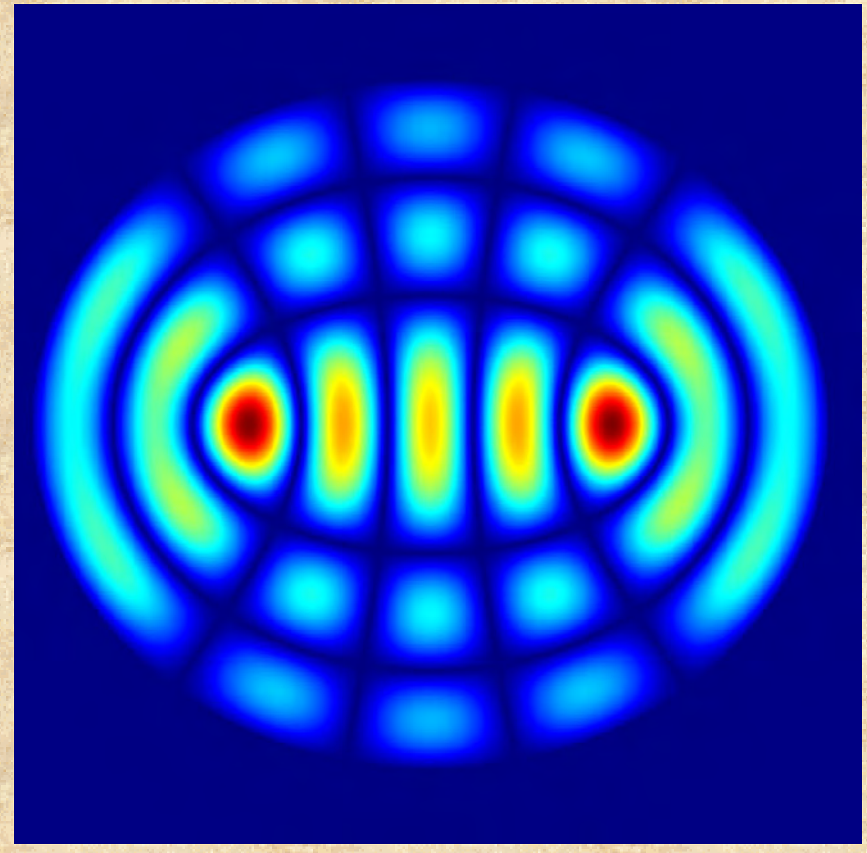
- $e = 1/2$, $a = 71.3$ Å elliptical resonator
- Solve Schrödinger equation with hard-wall boundary

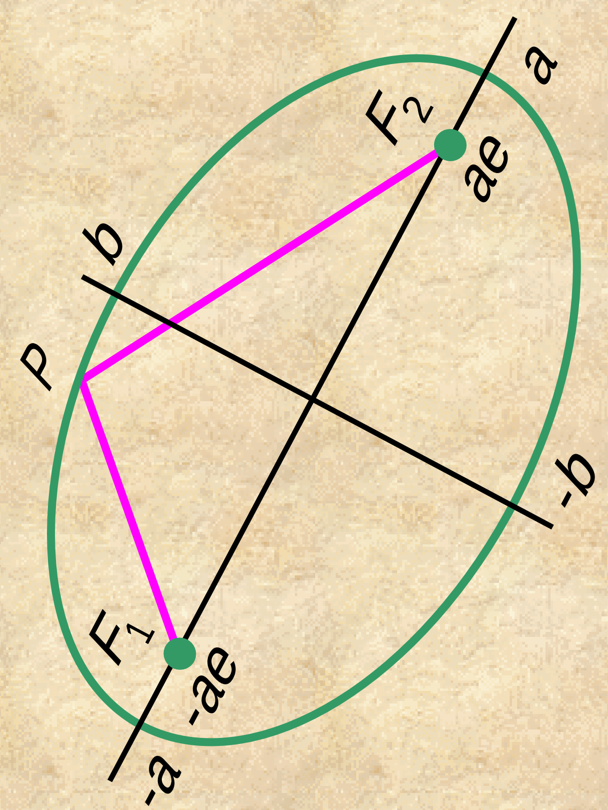


dI/dV
difference map



Calculated
Eigenmode at E_F

(Eigenstate 42)

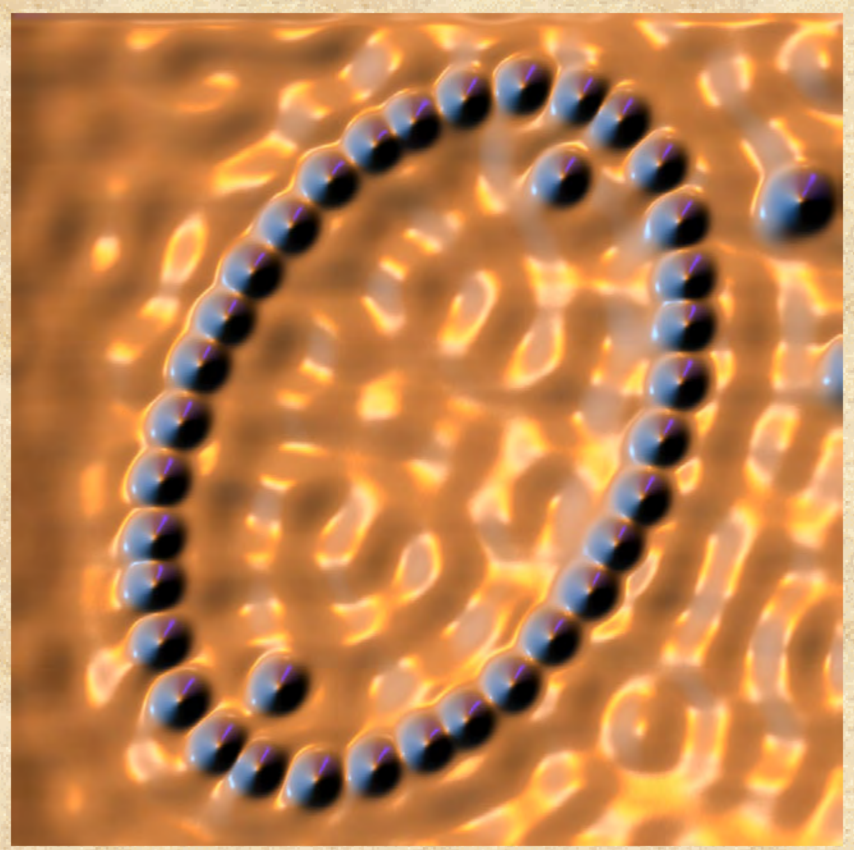


Path length:

$F_1 P + P F_2 = 2a$

Eccentricity:

$e^2 = 1 - b^2 / a^2$



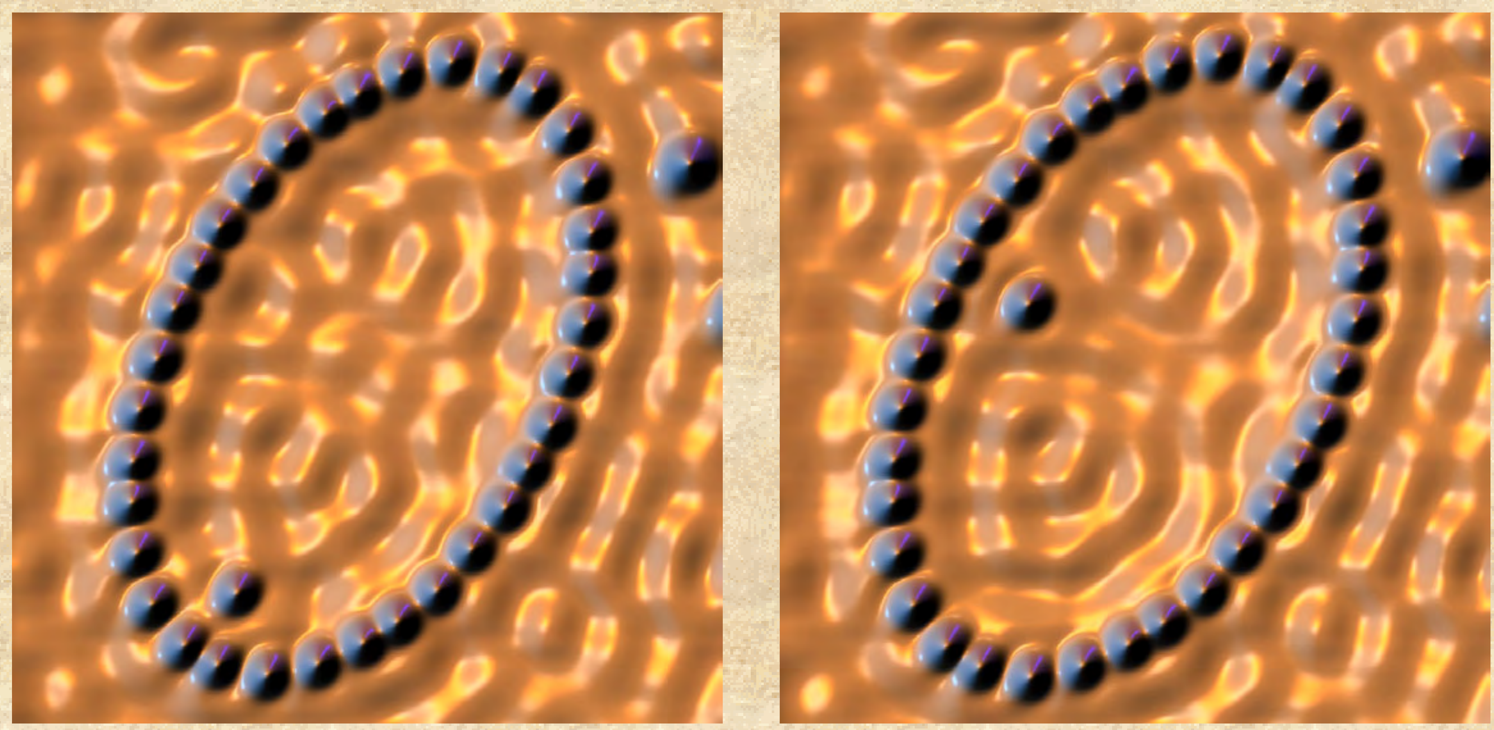
160 Å

$a = 71.3$ Å

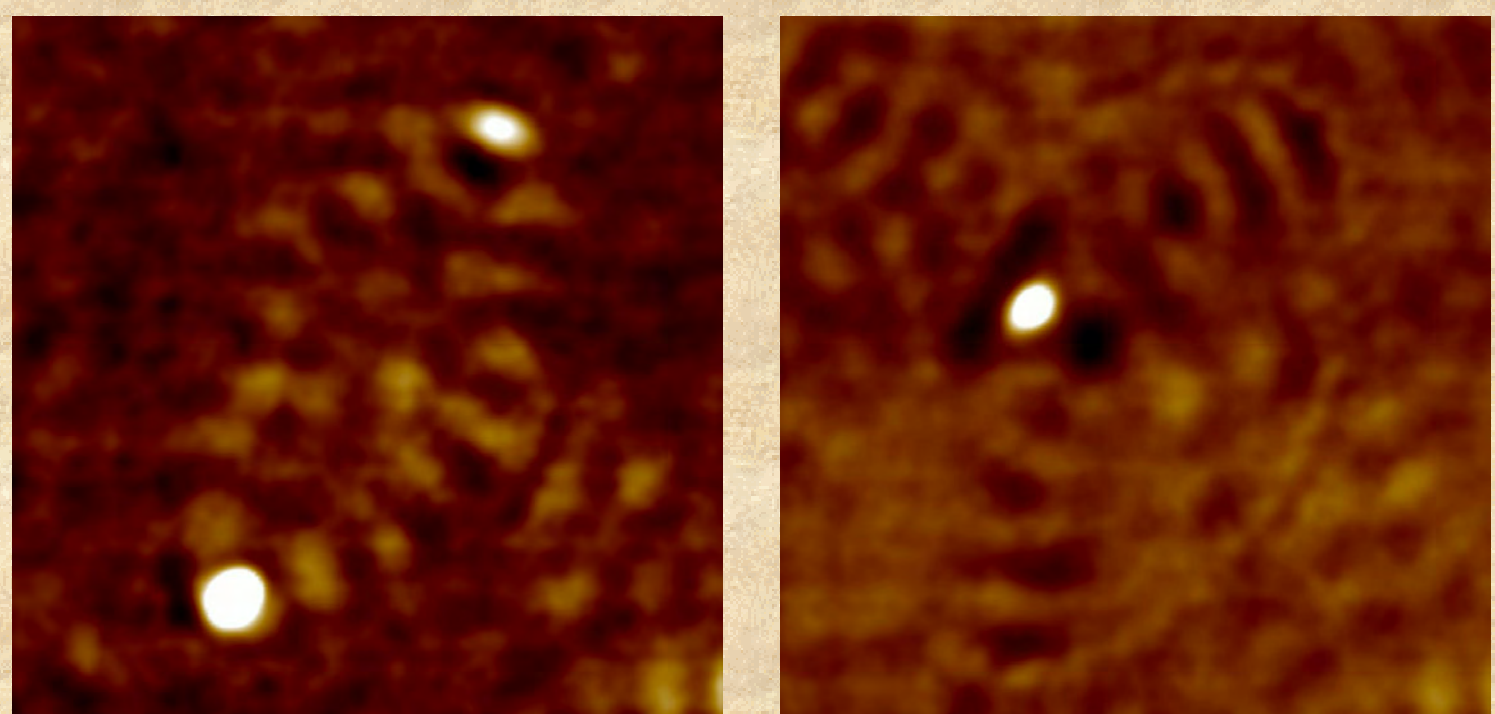
$e = 0.786$

- $e = 0.786$, $a = 71.3$ Å elliptical resonator

Topograph

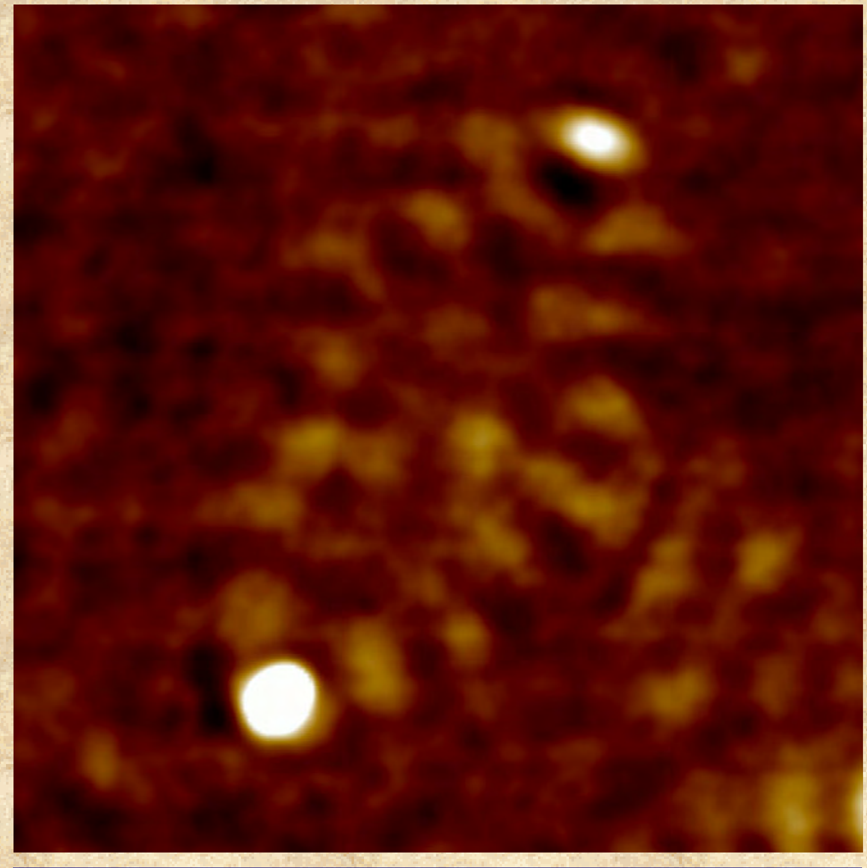


dI/dV difference map

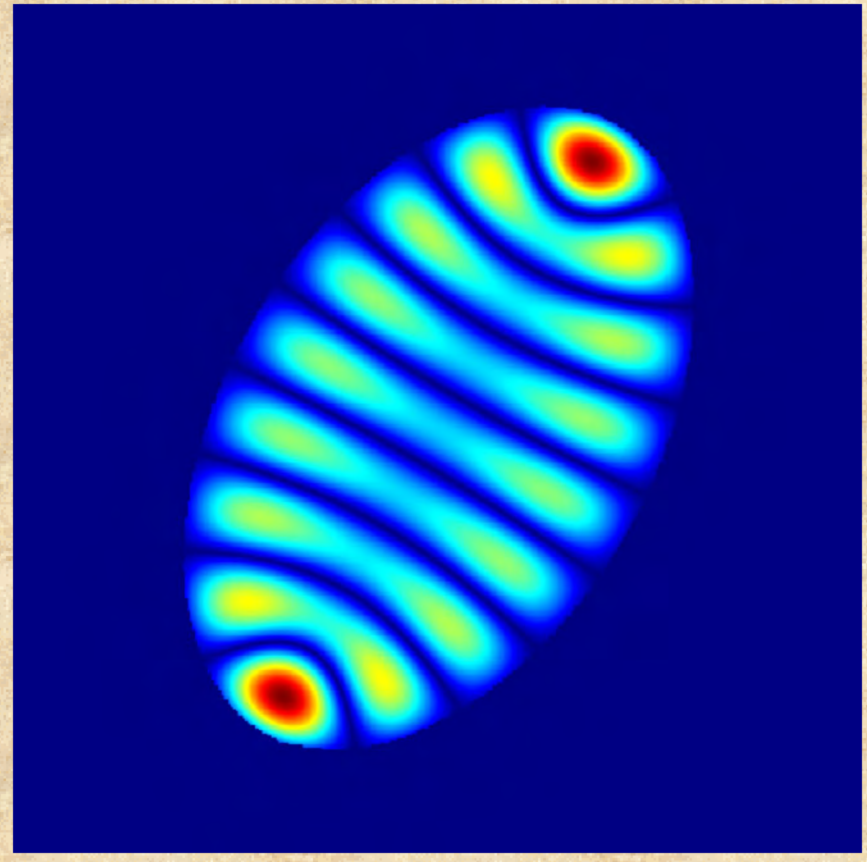


Eigenmode Modeling

- e = 0.786, a = 71.3 Å elliptical resonator
- Solve Schrödinger equation with hard-wall boundary



dI/dV difference map



Calculated Eigenmode at E_F

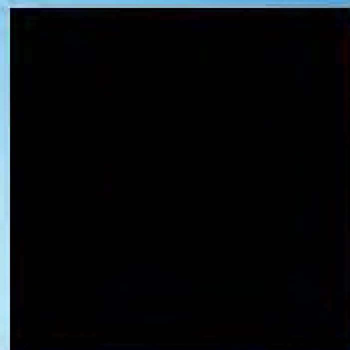
(Eigenstate 28)

Single Channel Information Transport

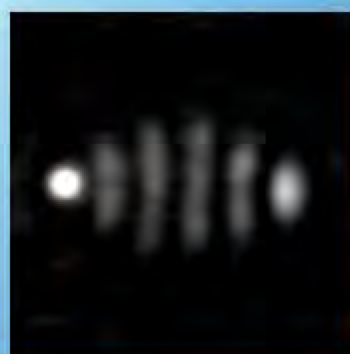
Phil. Trans. Royal Soc. A 362, 1135 (2004).

Truth Table | Topograph | dI/dV difference

In	Out
0	0



In	Out
1	1

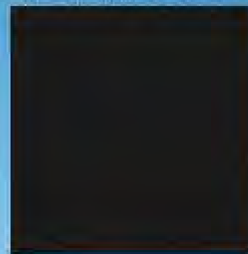


Multi Channel Information Transport

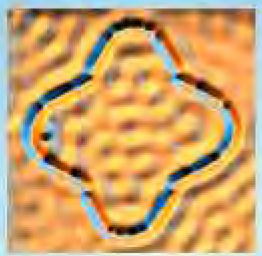
Phil. Trans. Royal Soc. A 362, 1135 (2004).

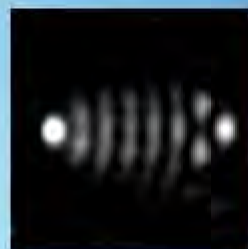
Truth Table | Topograph | dI/dV difference

	In	Out
L-R	0	0
U-D	0	0

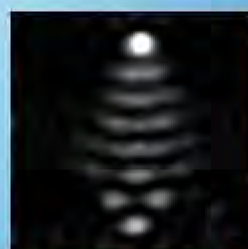


	In	Out
L-R	1	1
U-D	0	0





	In	Out
L-R	0	0
U-D	1	1

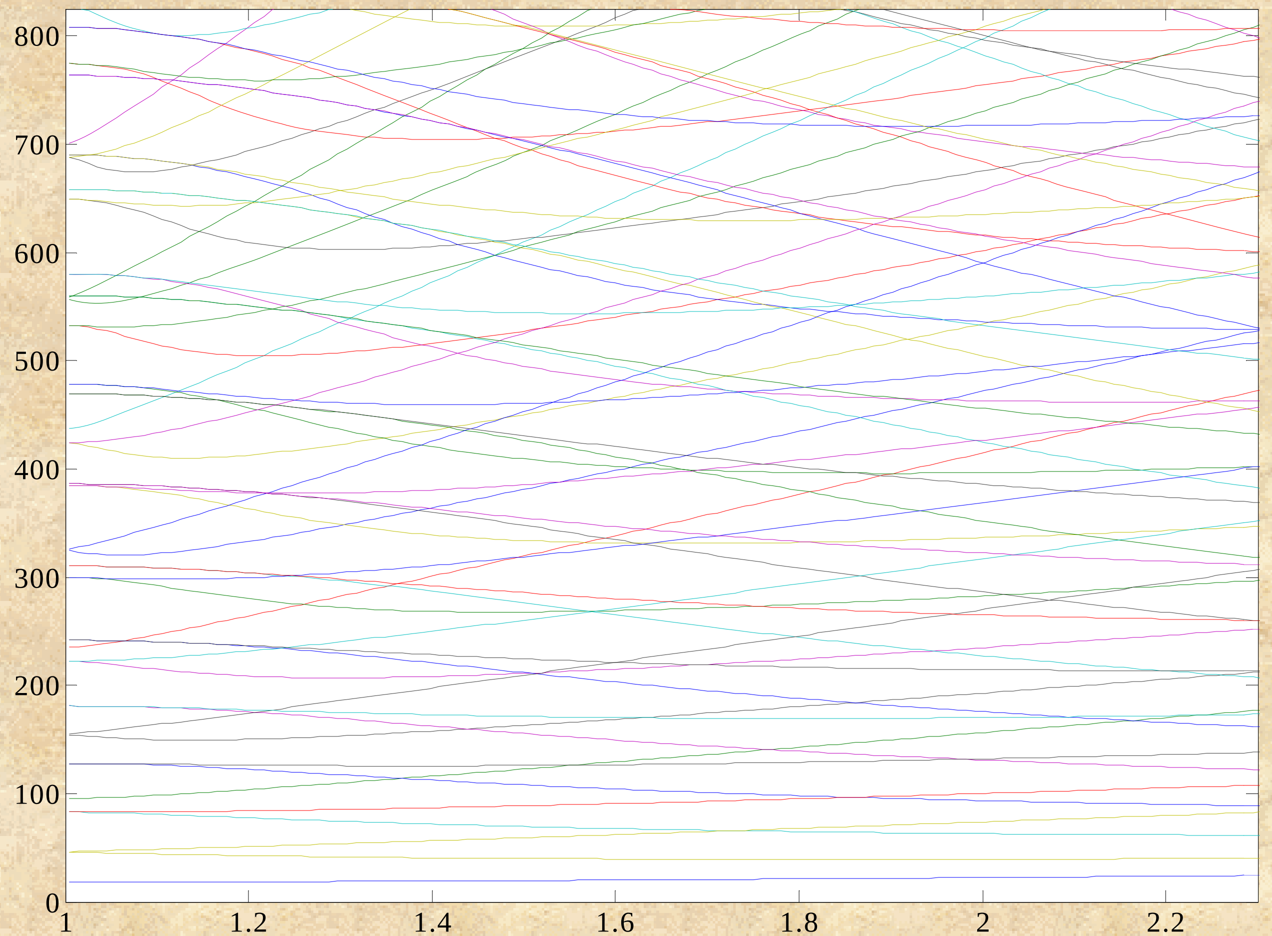


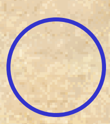
	In	Out
L-R	1	1
U-D	1	1

Eigenvalue Spectrum

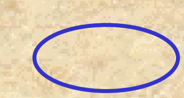
Energy

$k^2 A$





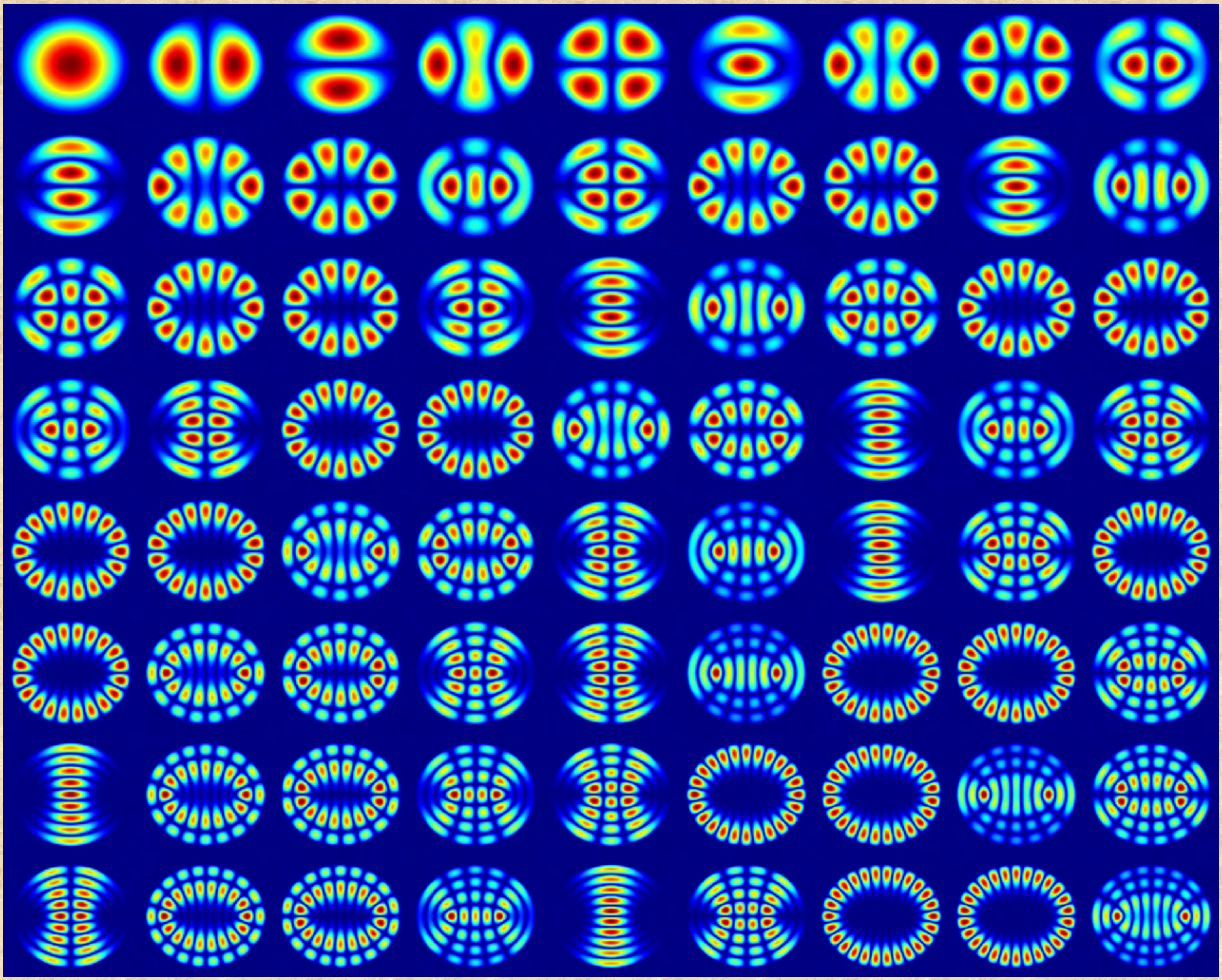
$\mu = a / b$



Deformation

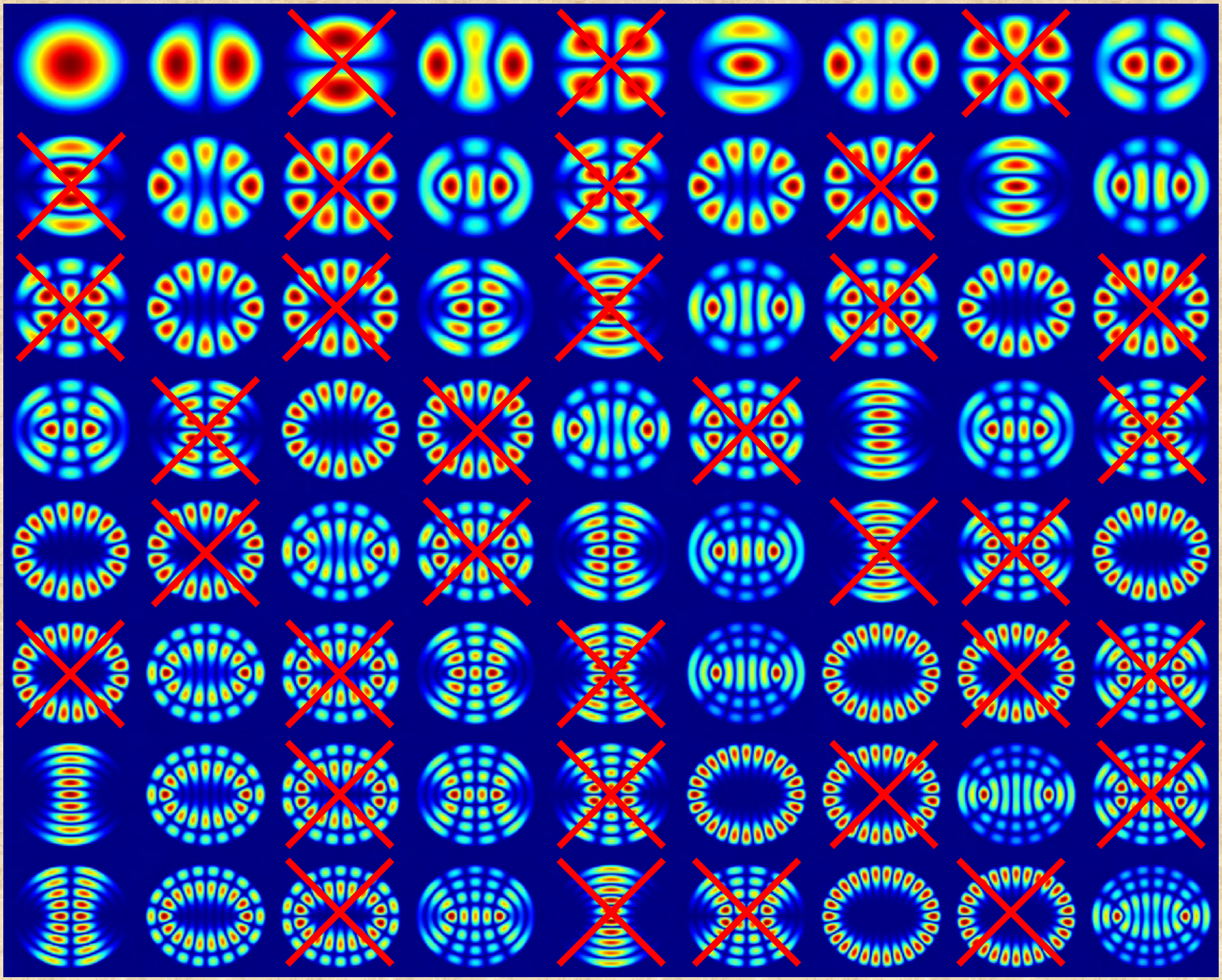
Eigenmodes

- $e = 1/2$, $a = 71.3$ Å elliptical resonator



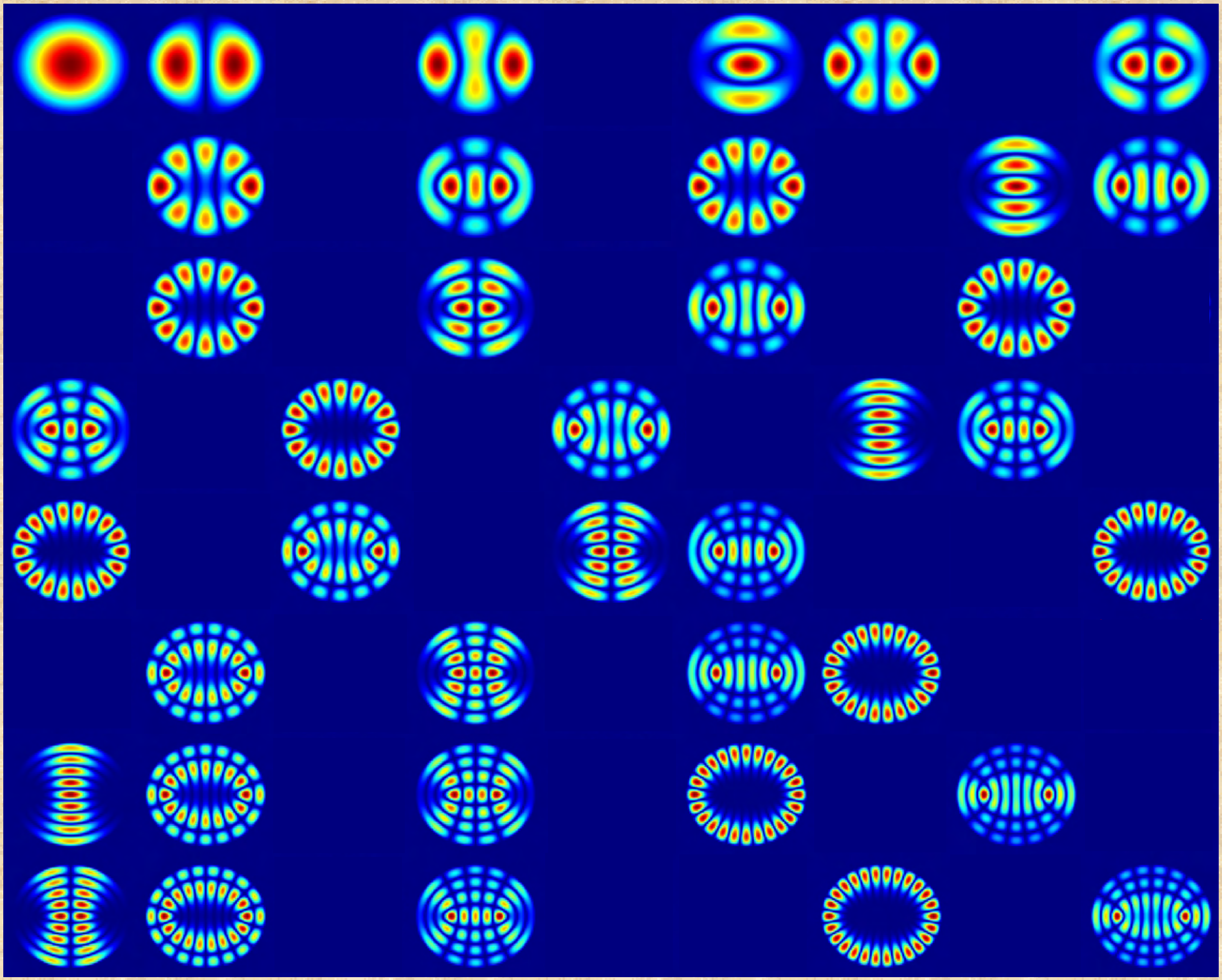
Eigenmodes: Odd Modes Removed

- $e = 1/2$, $a = 71.3$ Å elliptical resonator



Eigenmodes: Odd Modes Removed

- $e = 1/2$, $a = 71.3$ Å elliptical resonator



Eigenmodes: Even Modes Left

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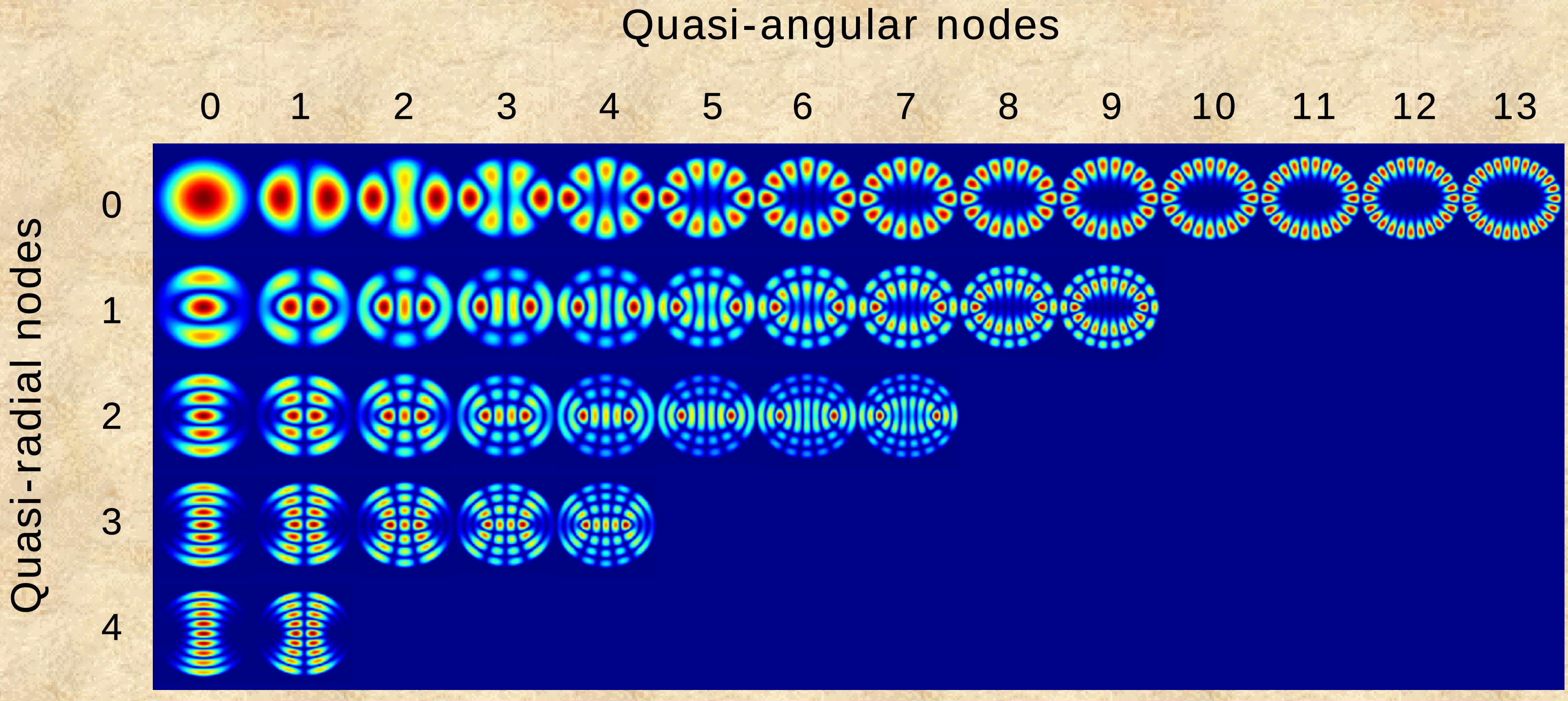
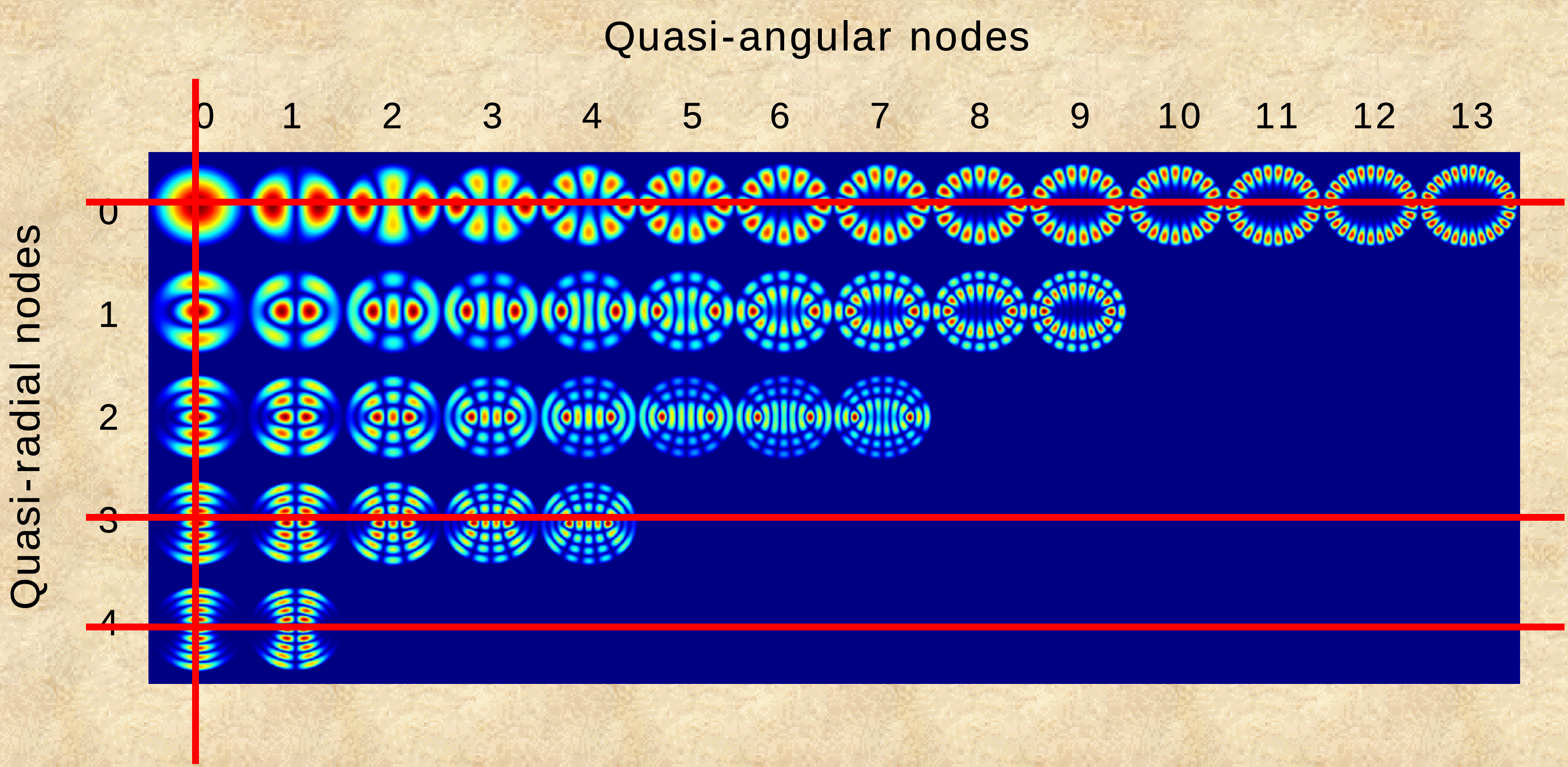
- $e = 1/2$, a = 71.3 Å elliptical resonator



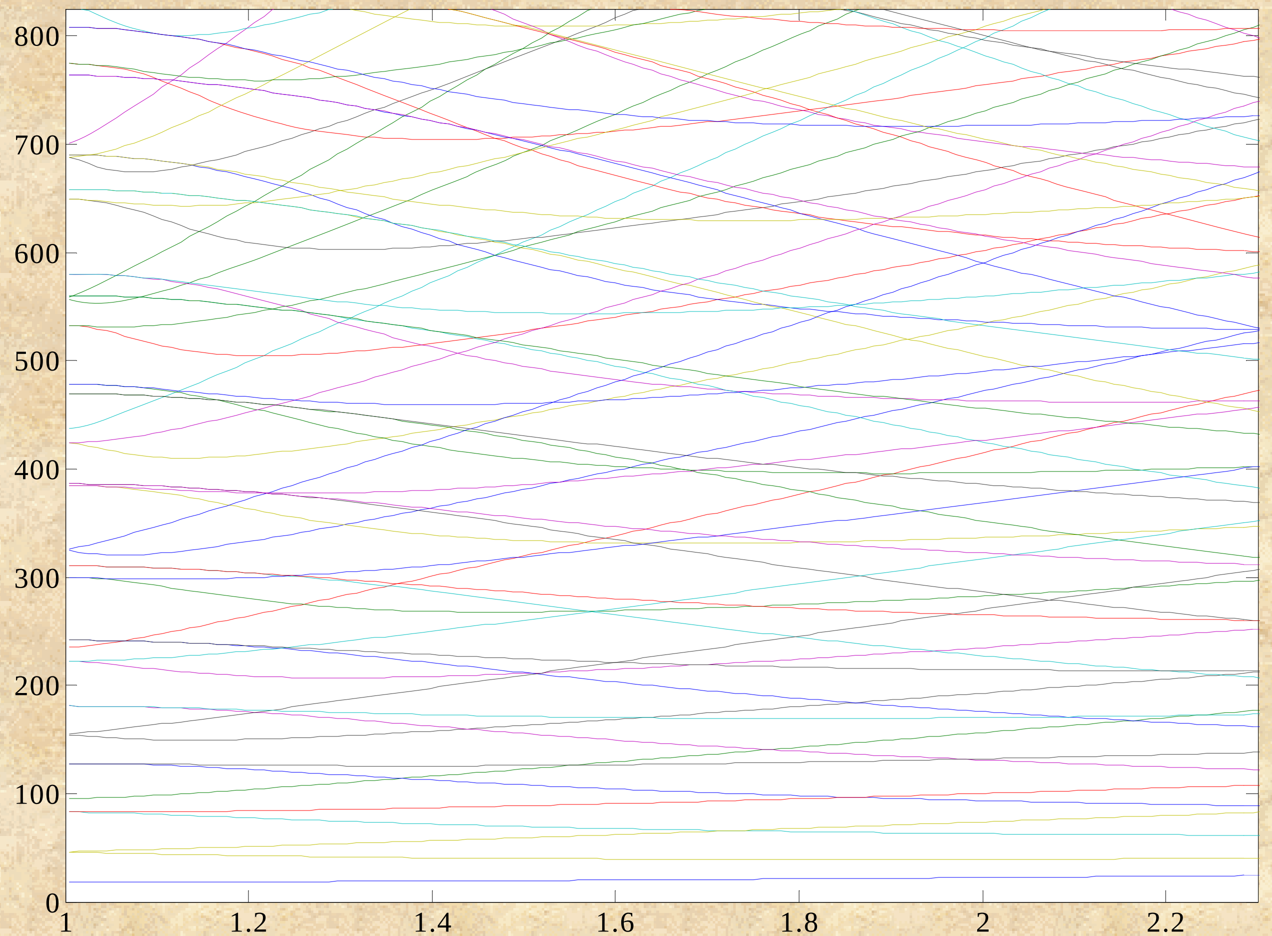
Eigenmodes: Even Modes Left

- $e = 1/2$, $a = 71.3$ Å elliptical resonator



Energy

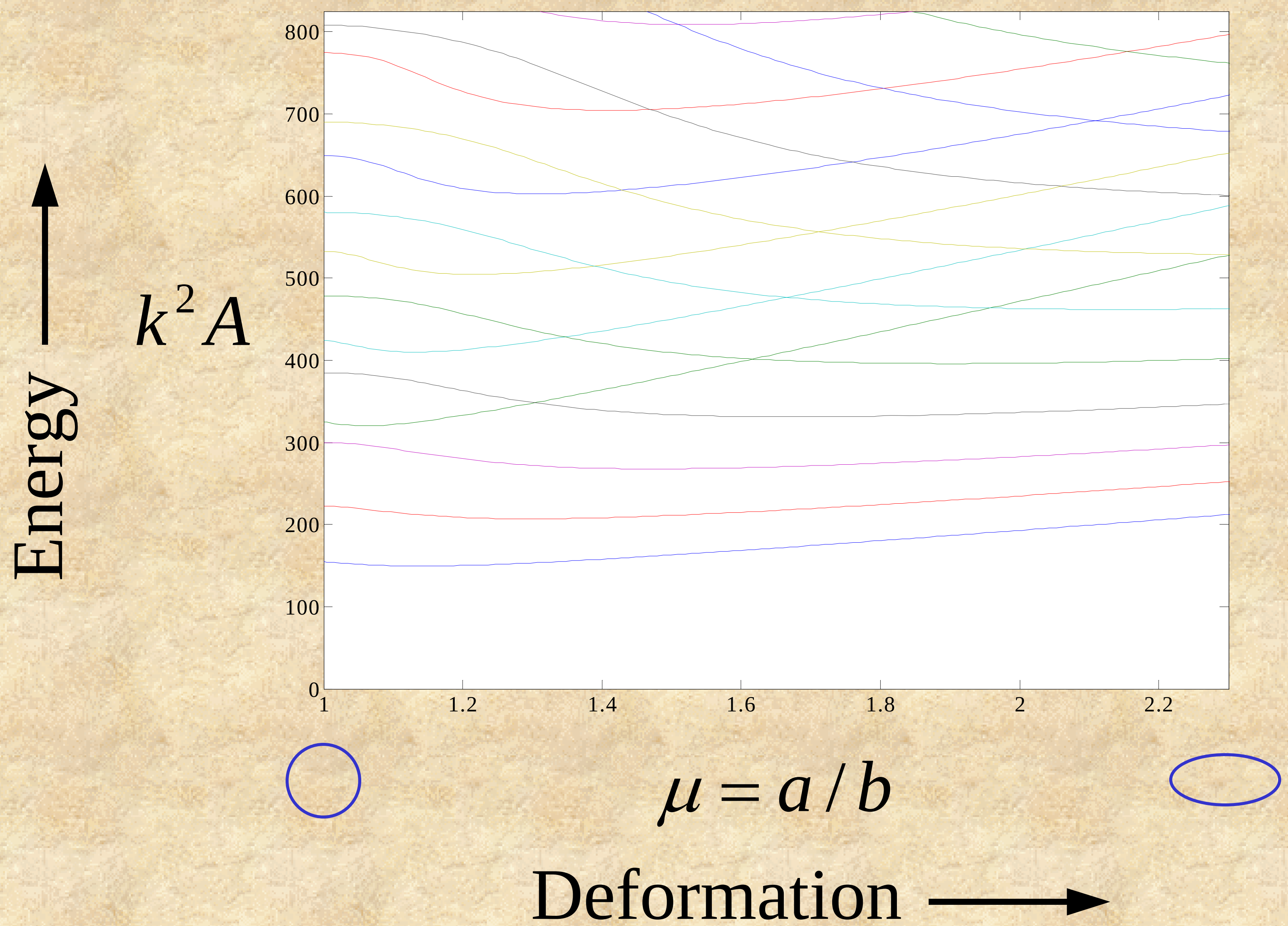
$k^2 A$



$\mu = a / b$

Deformation

Good Eigenmodes



Thanks

- The Team

web:
mota.stanford.edu

- The Funding

NSF

ONR

DOE

Sloan Foundation

Chevron

Research Corporation

KETI / MOCIE

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MOTA subgroup:
- Laila Mattos
  (Kondo lattices)

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- Chris Moon
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- Brian Foster
- Gabriel Zeltzer
- Richard Harris

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MERCI!