Manipulating Matter at the Spatial Limit

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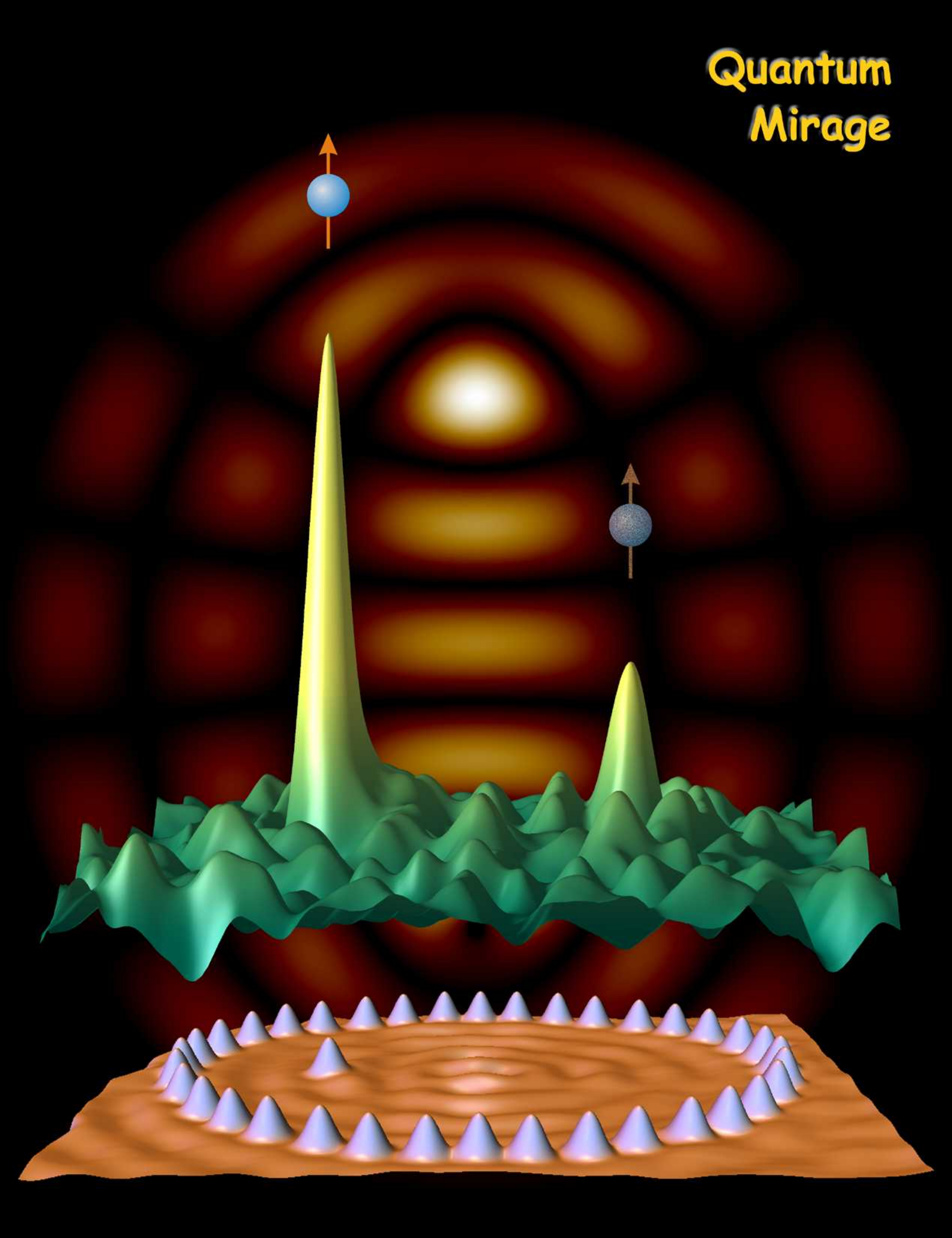
Jonathan Wrobel (P)
Gabriel Zeltzer (AP)

IBM Almaden

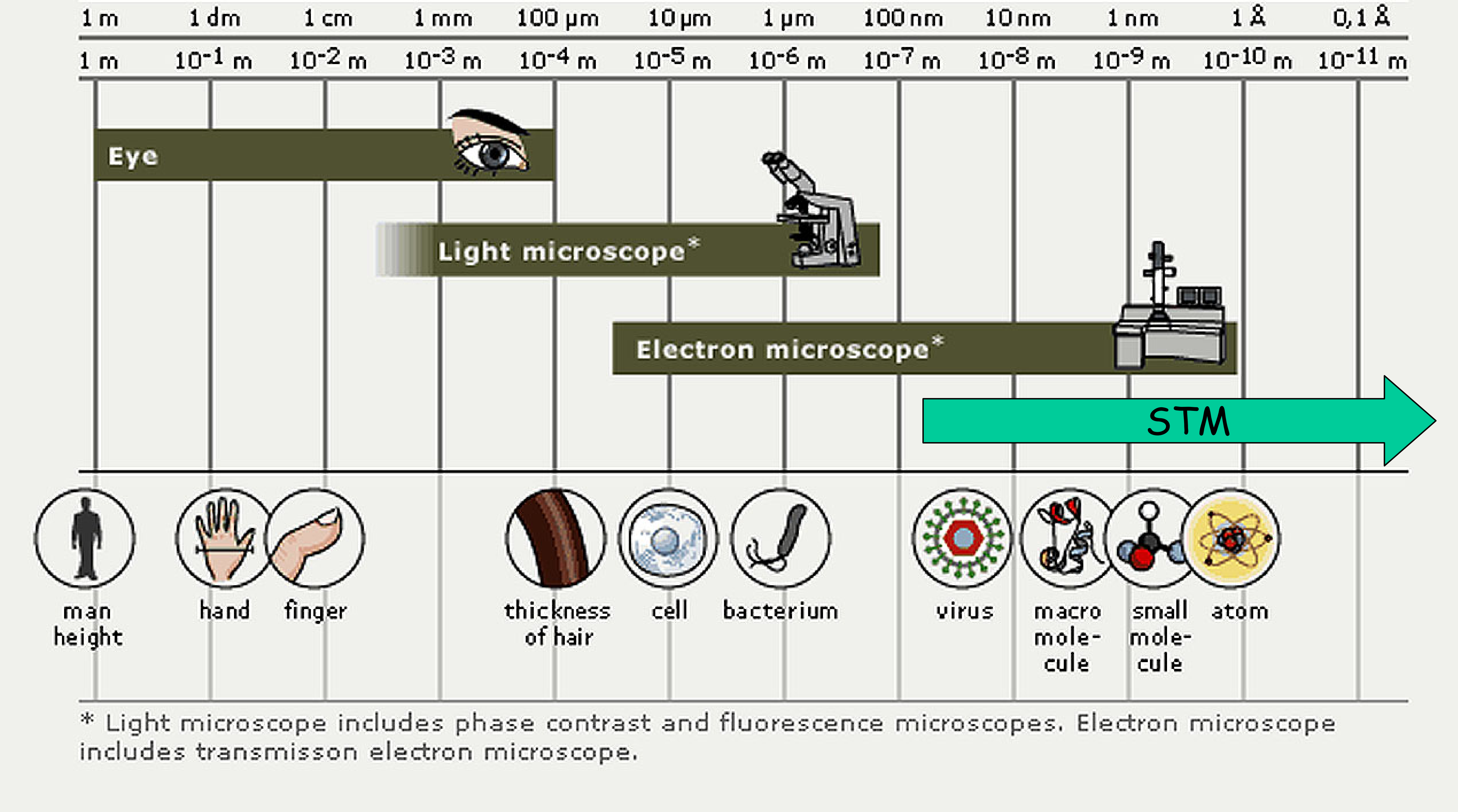
Chris Lutz
Don Eigler

[P = Physics
AP = Applied Physics
EE = Electrical Engineering]


Quantum
Mirage

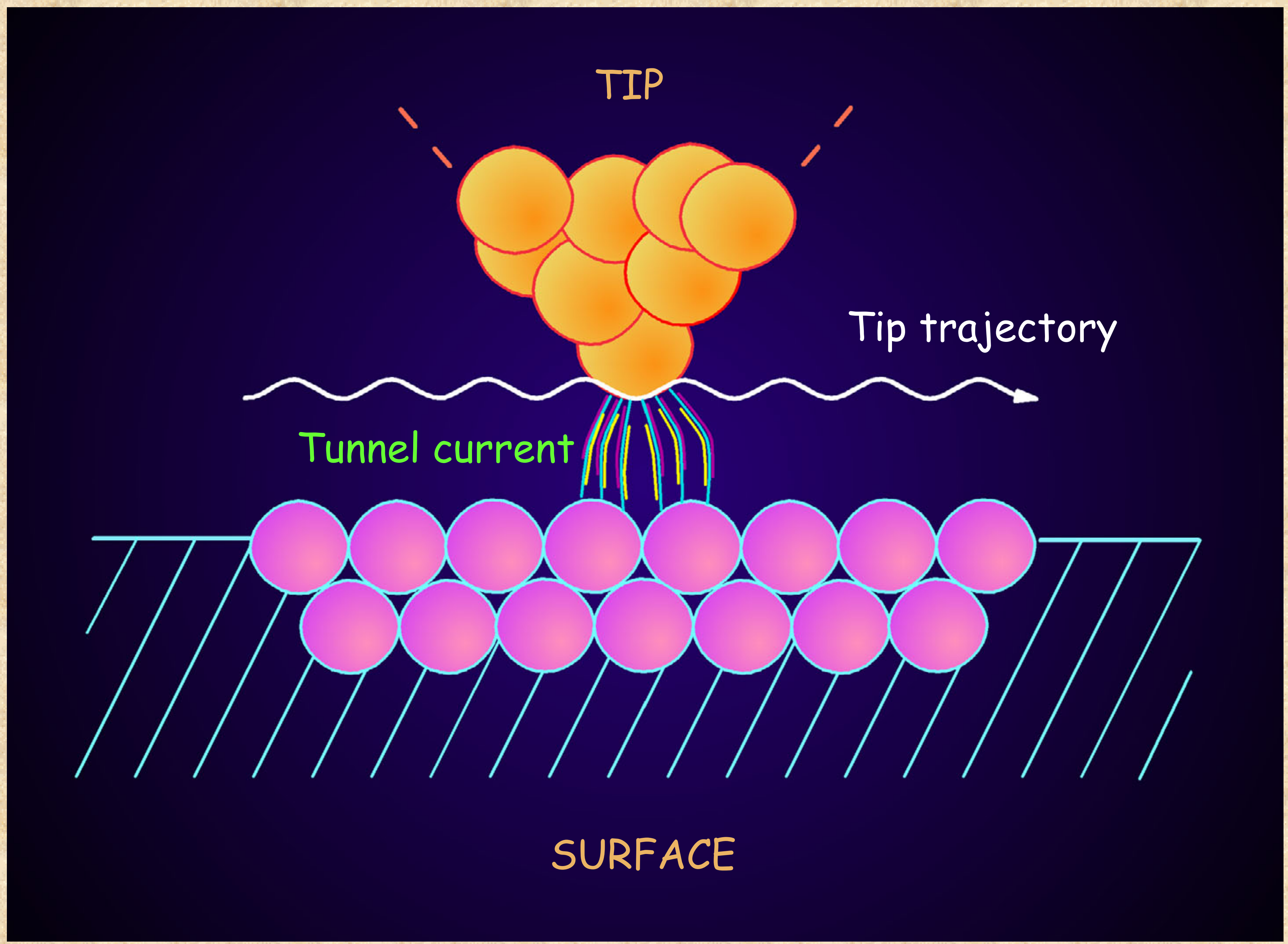
Spanning the Length Scales

- Microscope resolving power



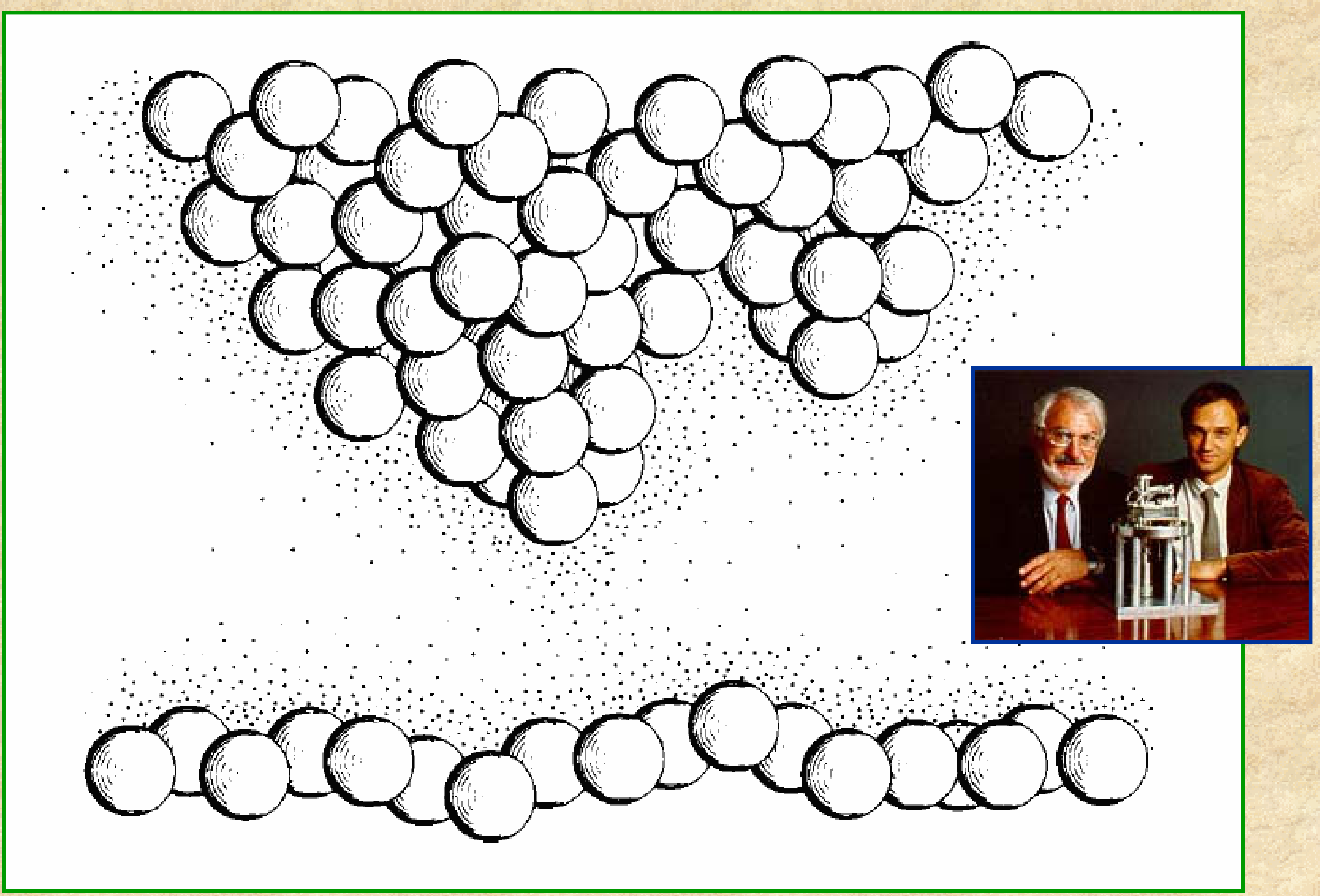
* Light microscope includes phase contrast and fluorescence microscopes. Electron microscope includes transmisson electron microscope.

Scanning Tunneling Microscopy (STM)



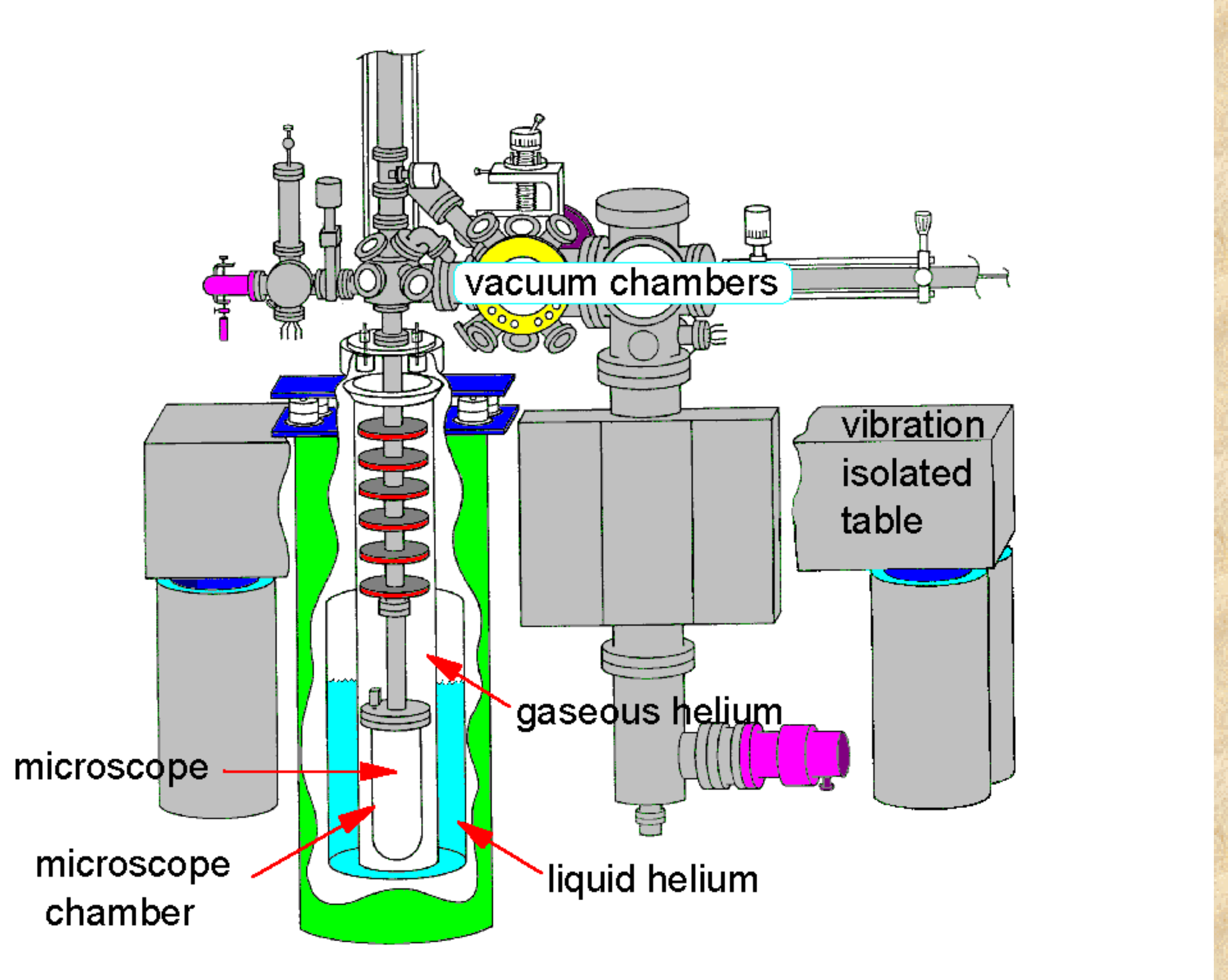
Tip Detail

- 10x current increase for every Å



Experimental Apparatus

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



- Specifications

  Sample environment:

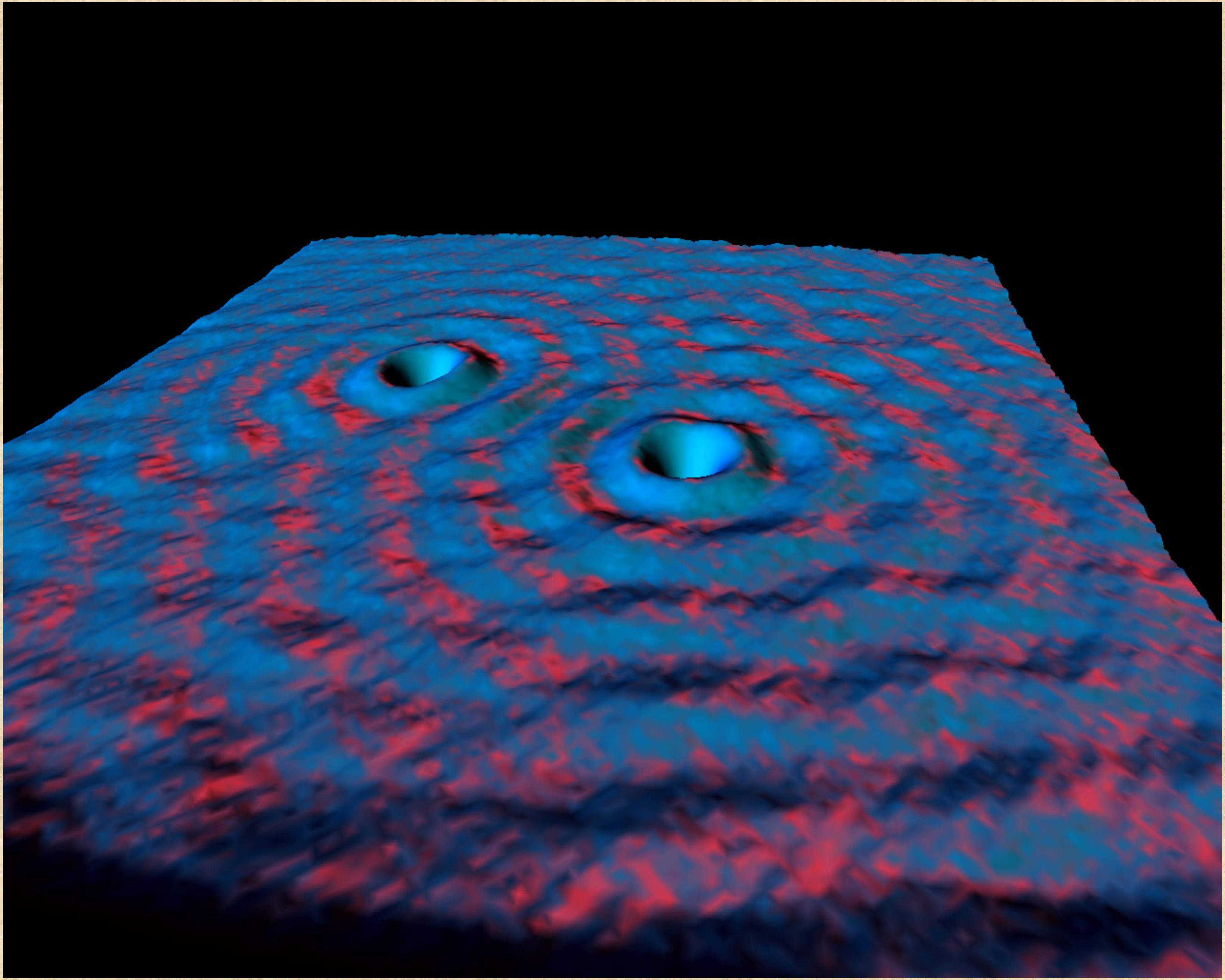
    Temperature ~ 0.5 K
    Magnetic Field ~ 15 T

  Imaging specs @ optimal frequencies:

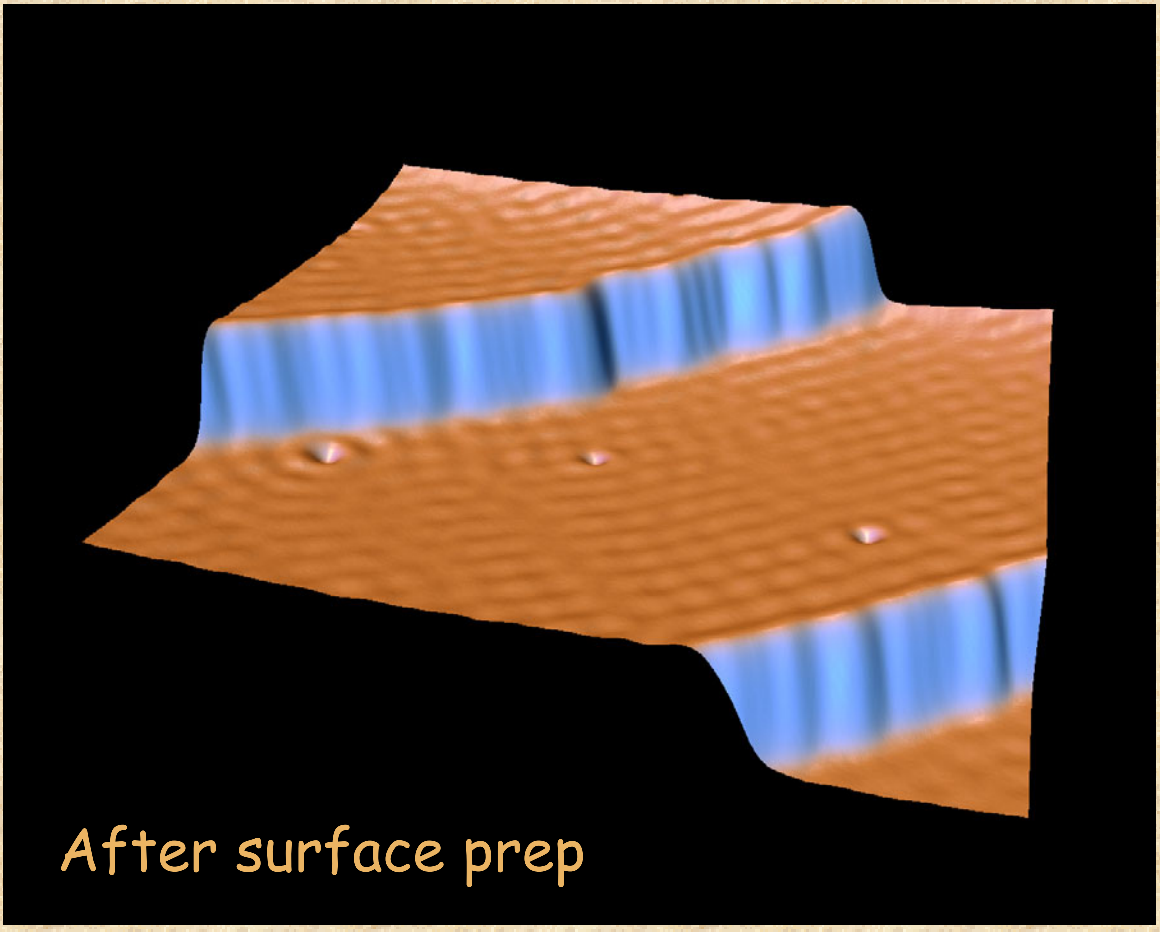
    Lateral resolution ~ 100 fm (1 mÅ)
    Vertical resolution ~ 10 fm (0.1 mÅ) rms
    Open loop drift ~ 500 fm/min (5 mÅ/min)

Electron Standing Waves

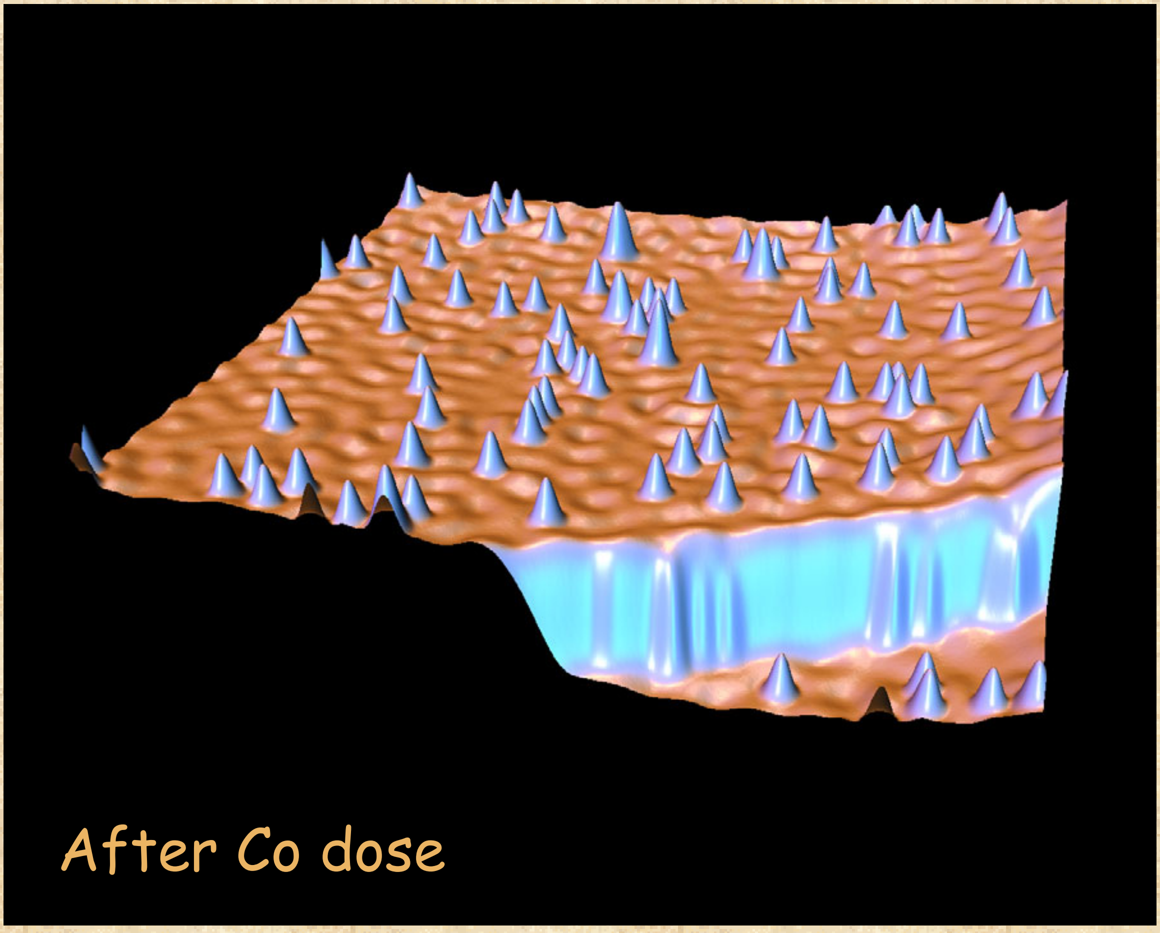
- Sulfur atoms on copper surface



Cast of Characters: Cu(111) and Co

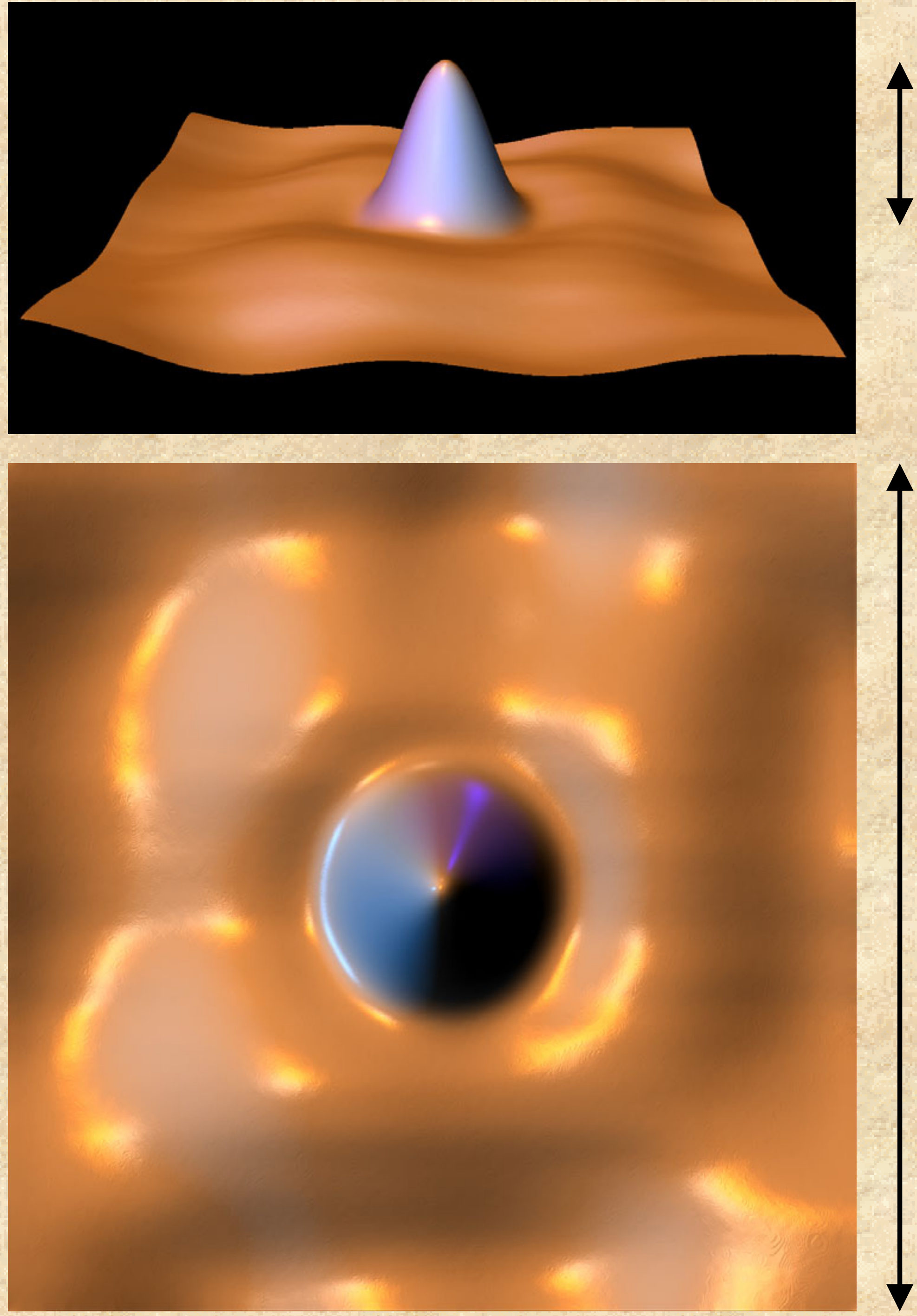


300 Å
square
topo

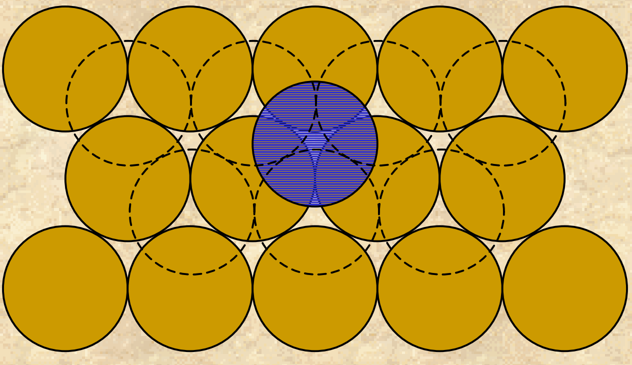


300 Å
square
topo

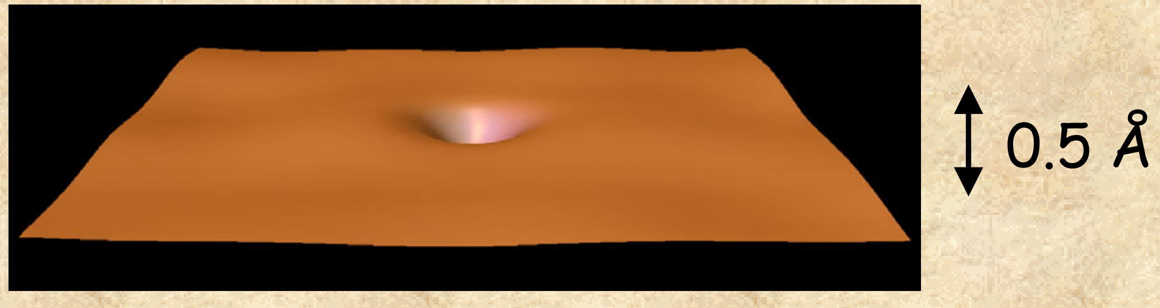
Cast of Characters: Co Atom



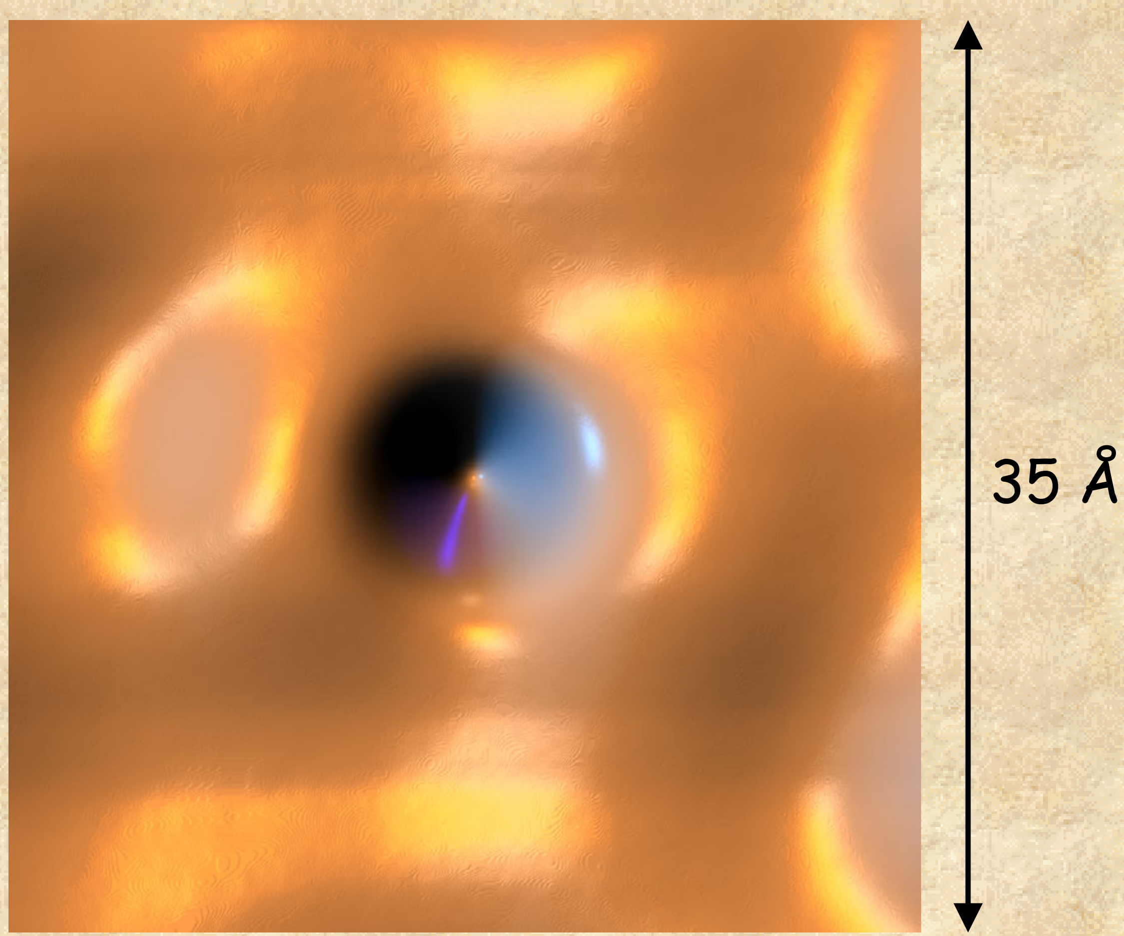
- Bonds to fcc sites on Cu(111)

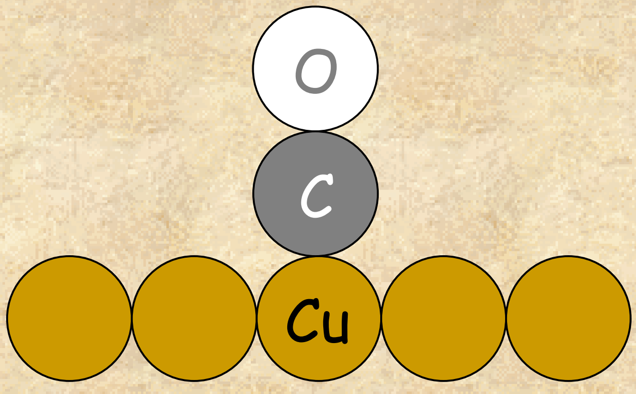


Cast of Characters: CO Molecule



- Bonds "on-top" to Cu atoms

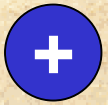




Looking “Inside” a Particle

- Quantized degrees of freedom

<u>Charge</u>



<u>Spin</u>

Looking "Inside" a Particle

- Quantized degrees of freedom

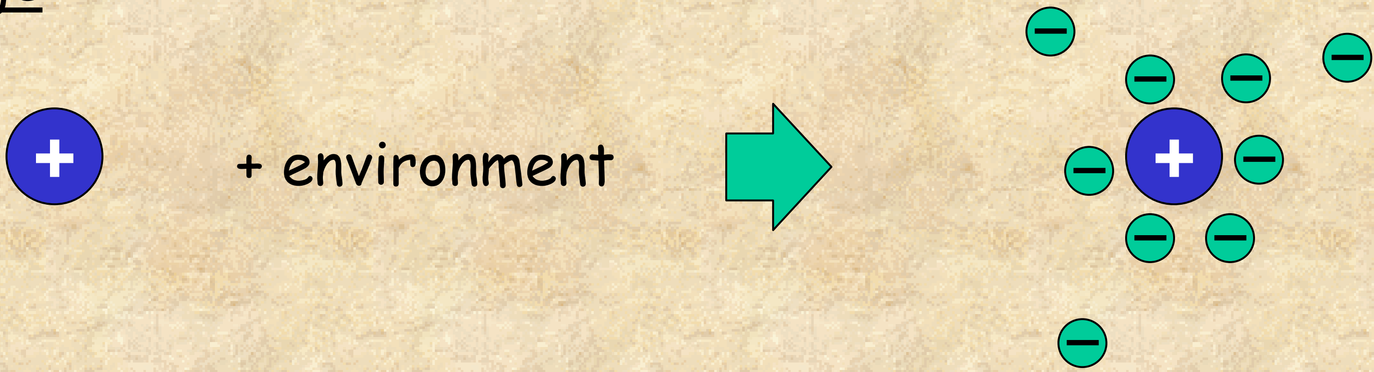
Charge

Spin

Looking “Inside” a Particle

- Quantized degrees of freedom

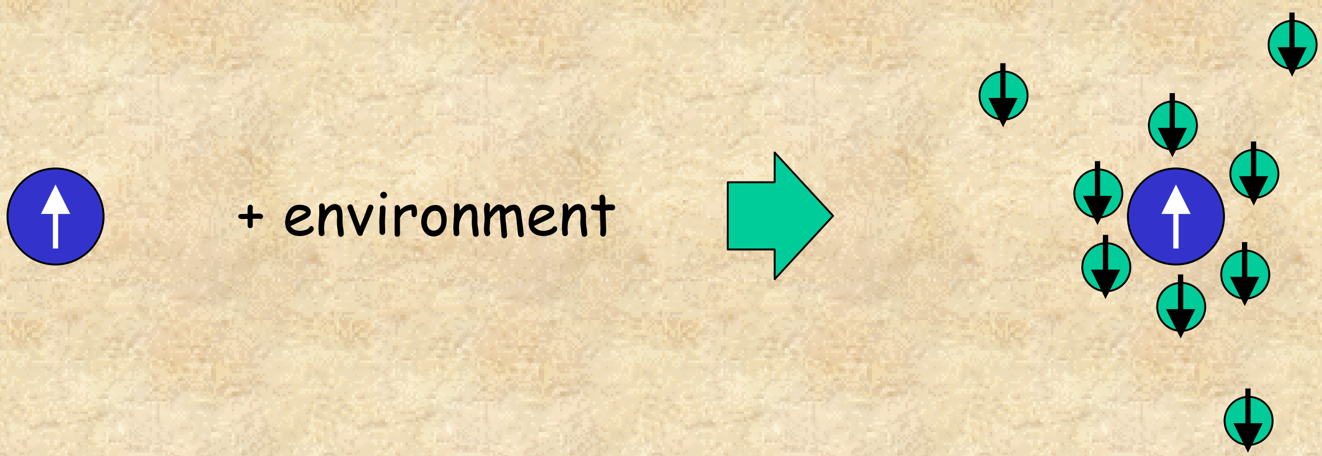
Charge



+ environment

charge screening

Spin

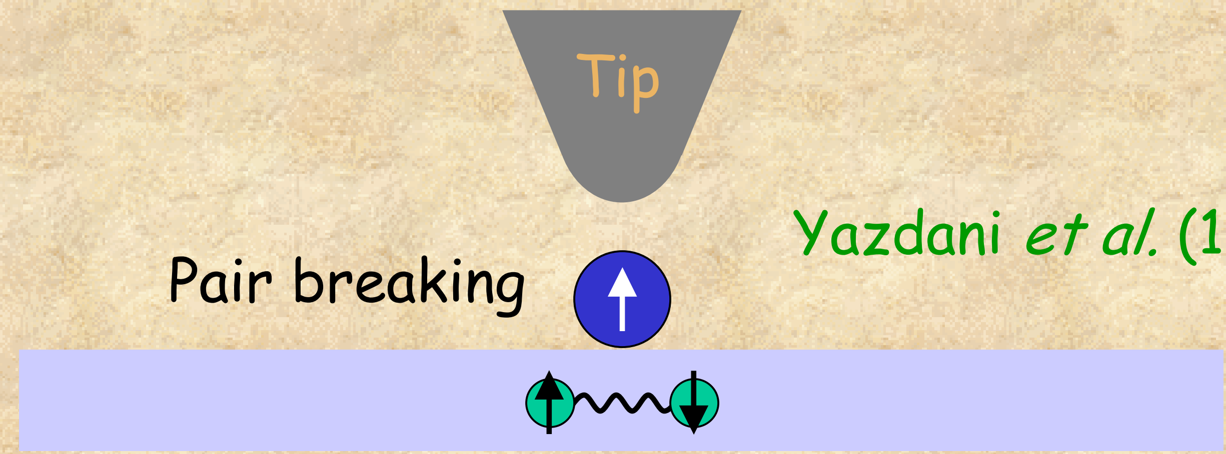


+ environment

spin screening

Probing the Spin Degree of Freedom with STM

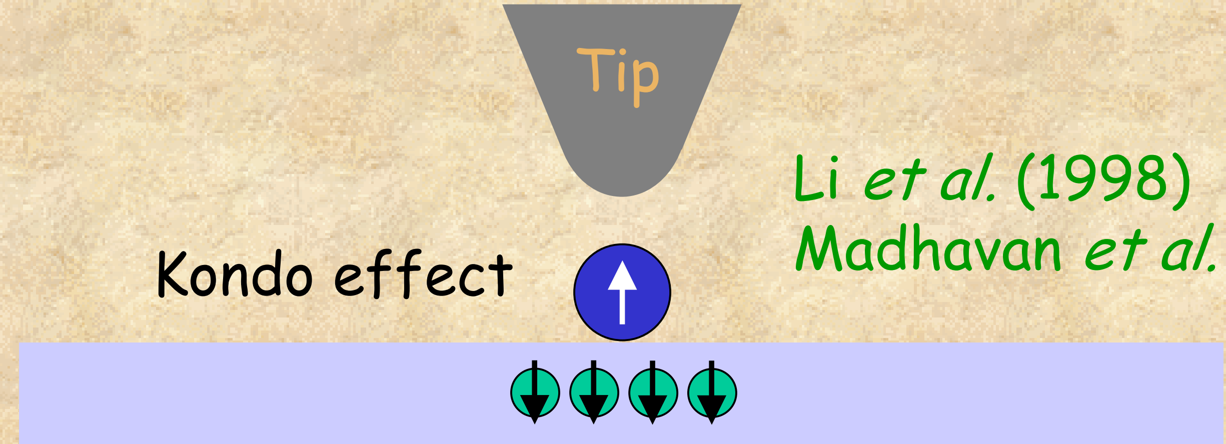
- Magnetic moment on a superconductor



Pair breaking

Yazdani *et al.* (1997)

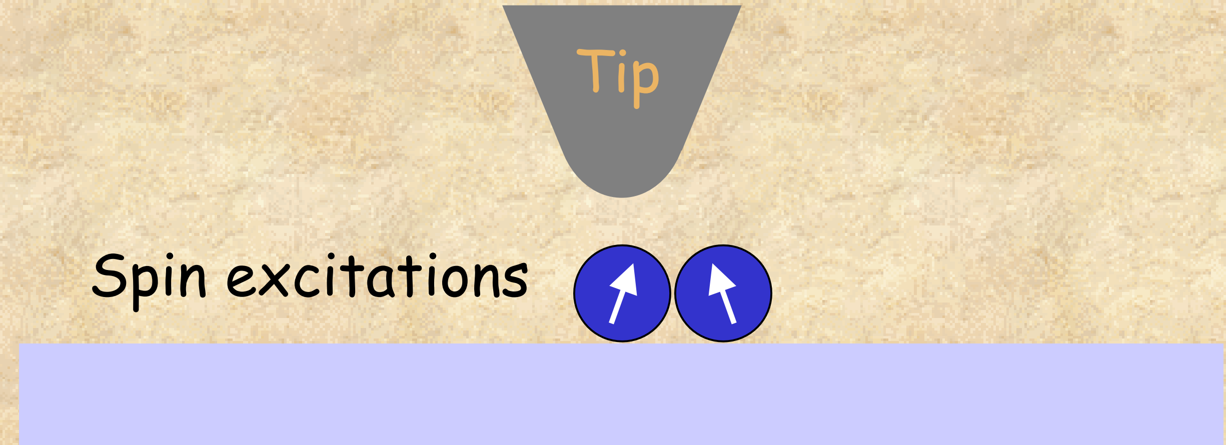
- Magnetic moment on a normal metal



Kondo effect

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

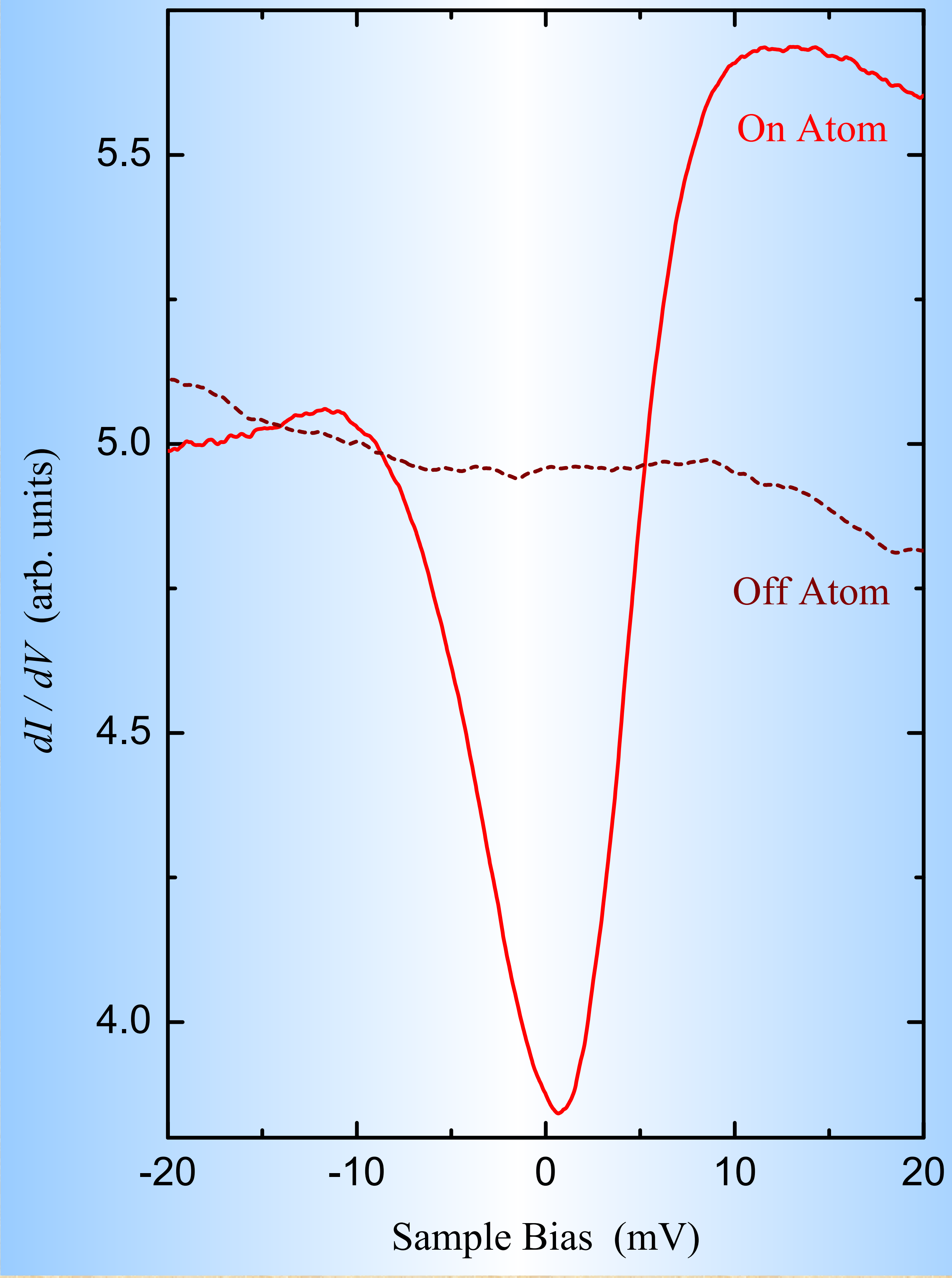
- Interacting magnetic moments



Spin excitations

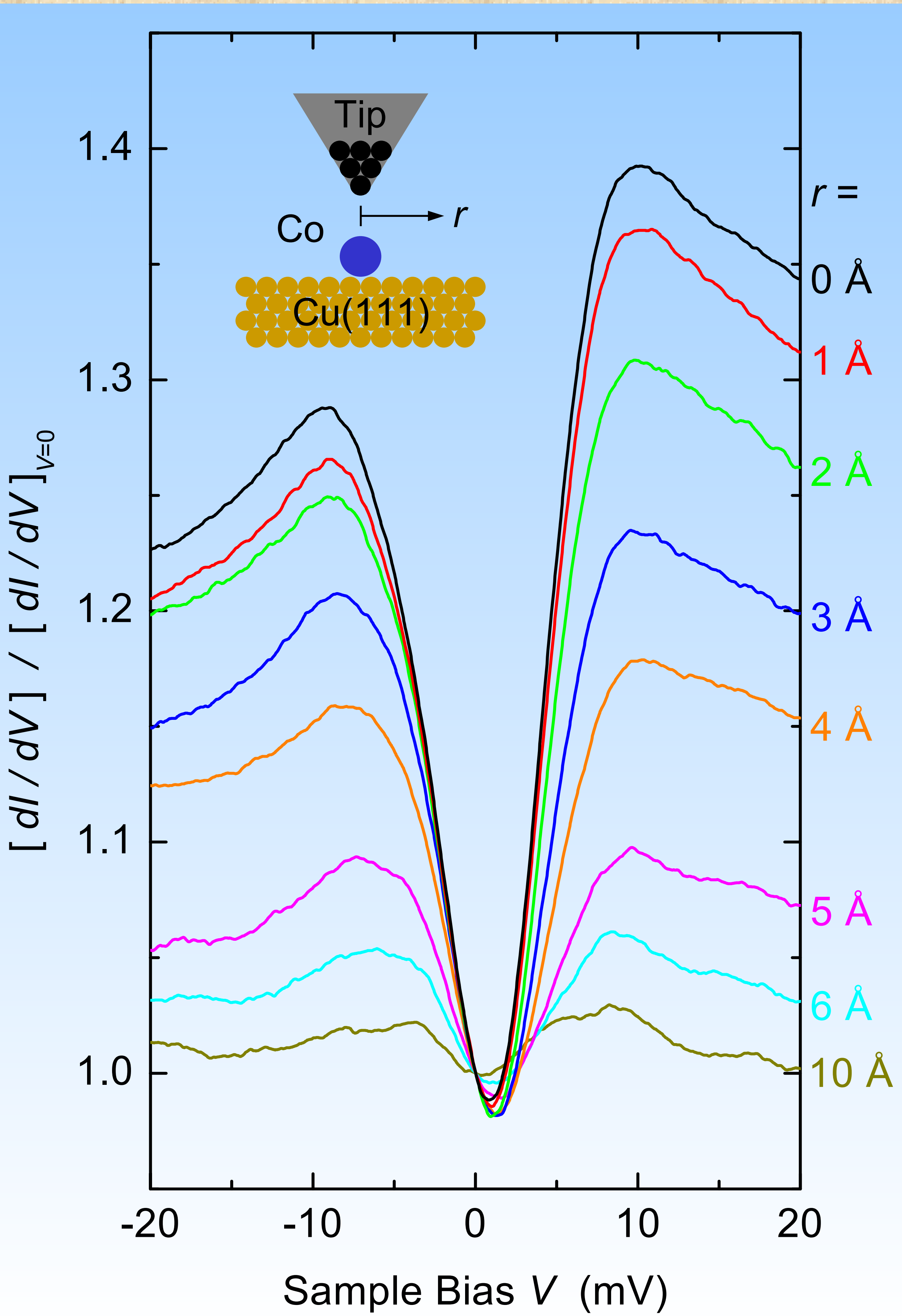
The Kondo Resonance: Co Atom on Cu(111)

www.manoharan.org



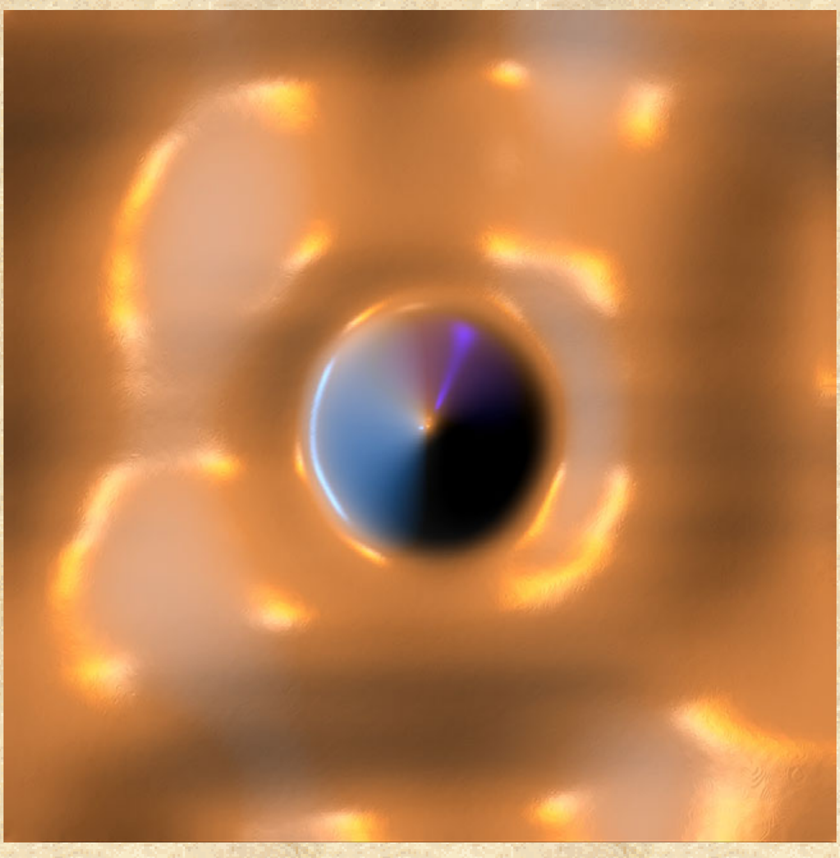
The Kondo Resonance: Co Atom Flyover

www.manoharan.org



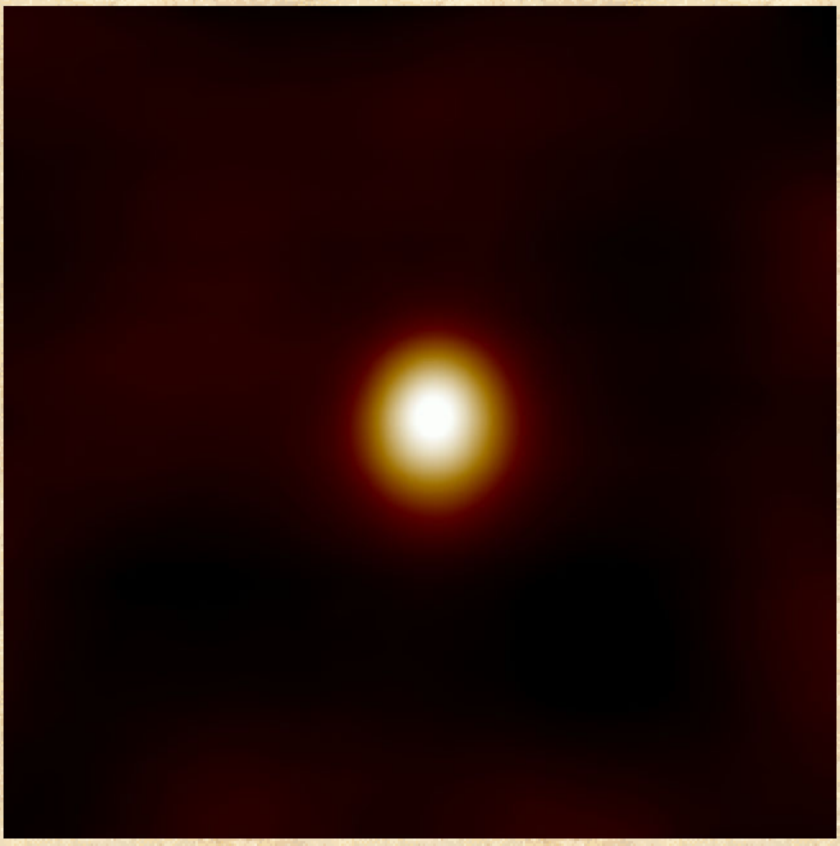
Imaging the Kondo Resonance

- Single Cobalt atom
- Simultaneously acquired 35 Å square images



Topograph

(V = 5 mV)

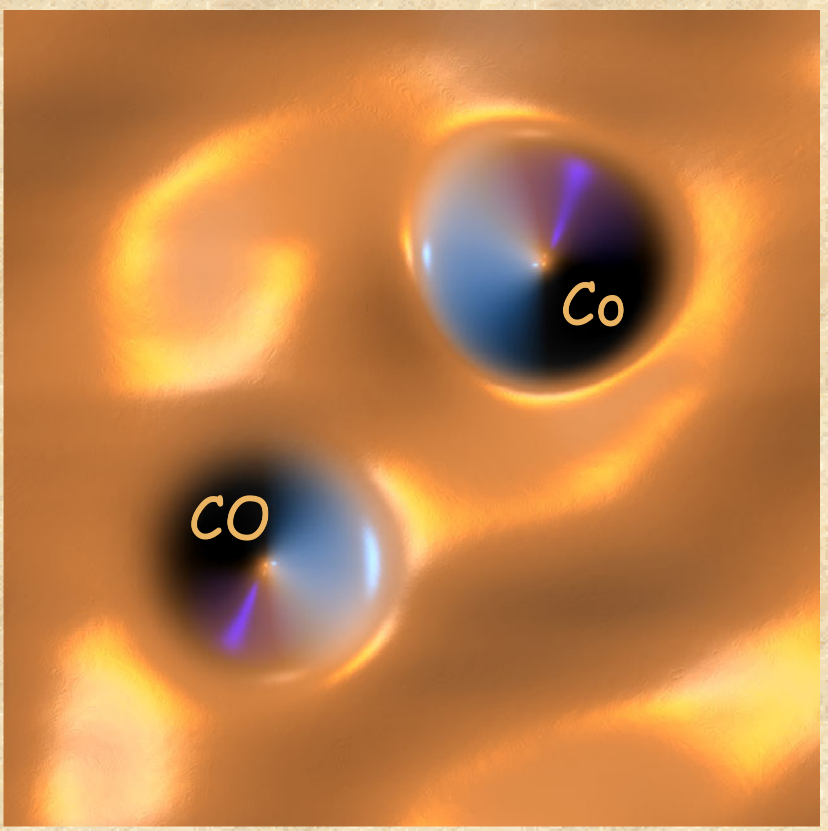


dI/dV map

(V = ±5 mV)

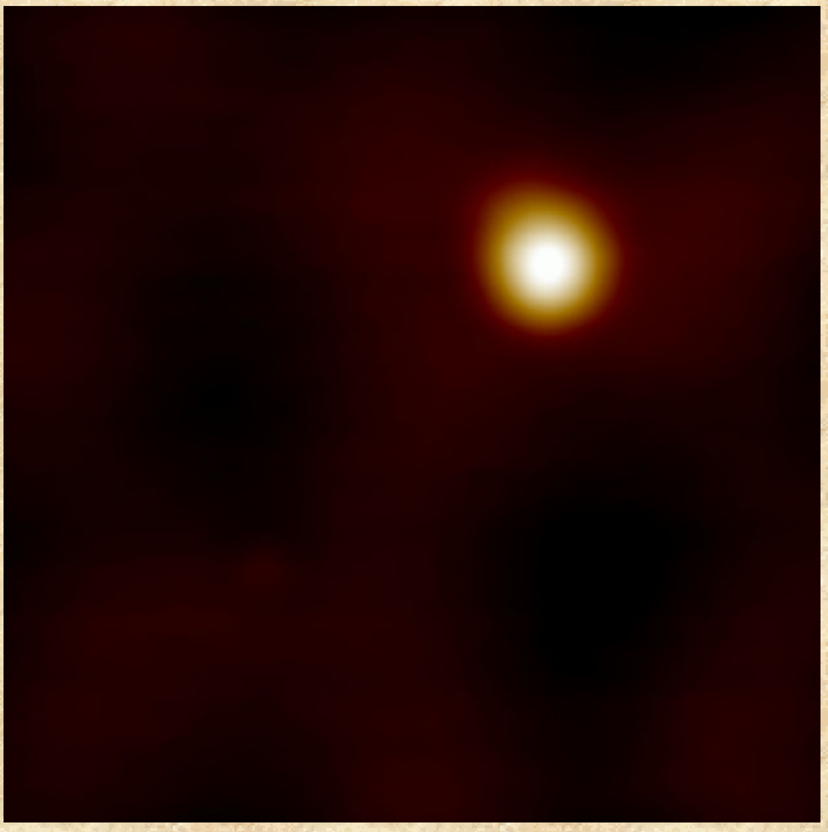
Kondo Imaging: Co vs CO

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



Topograph

(V = 5 mV)

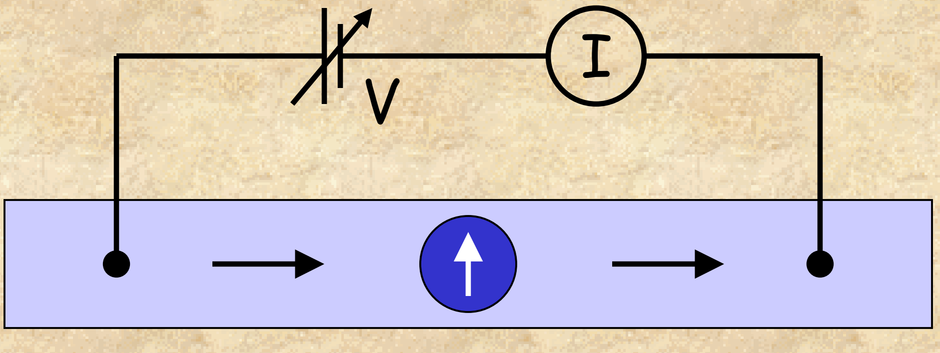


dI/dV map

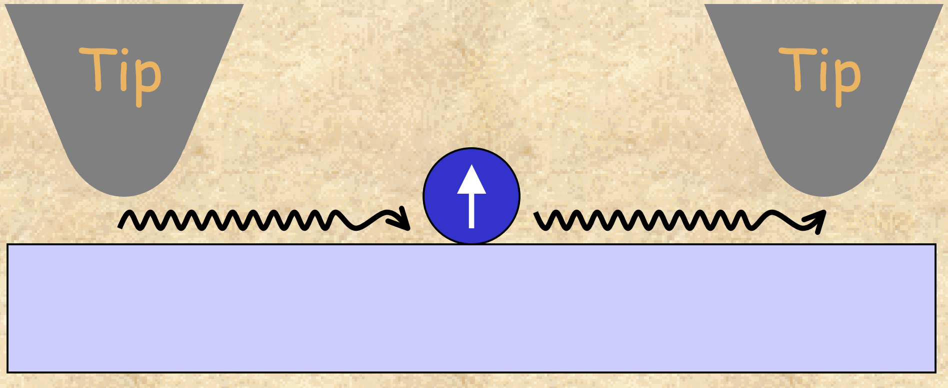
(V = 5 mV)

Motivation: Two-Tip STM Measurement?

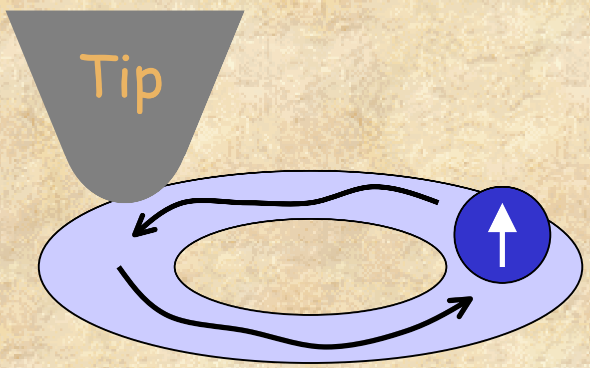
- Standard two-terminal measurement

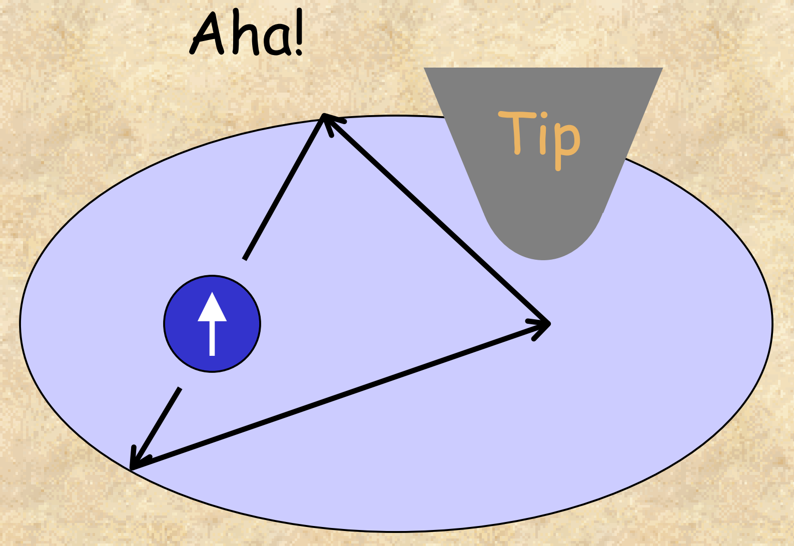


- Two tips?

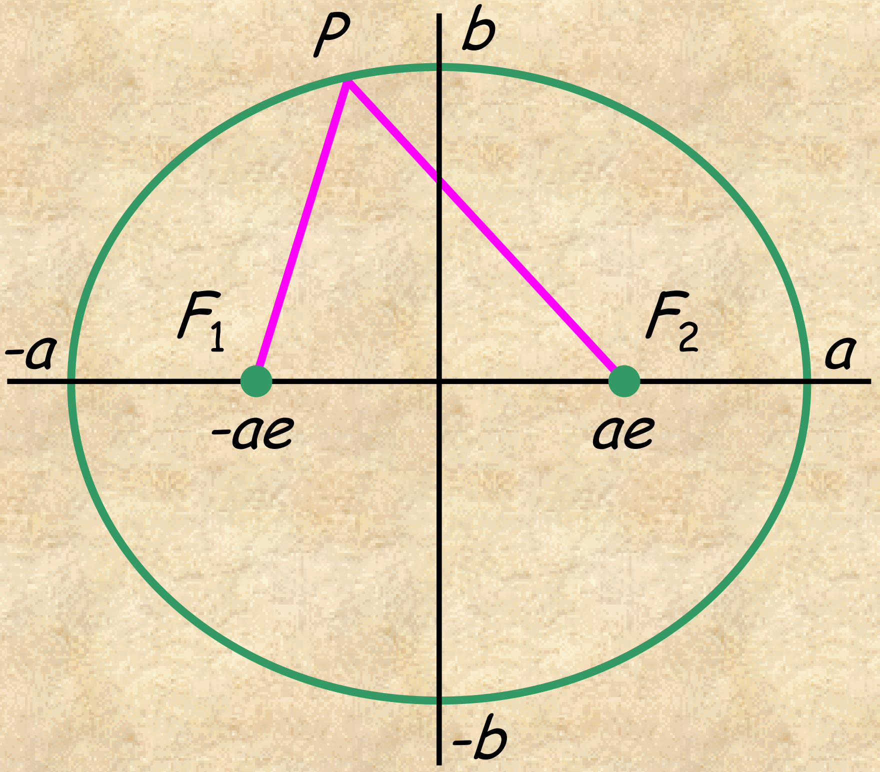


- One tip plus weird geometry





Elliptical Resonator Design

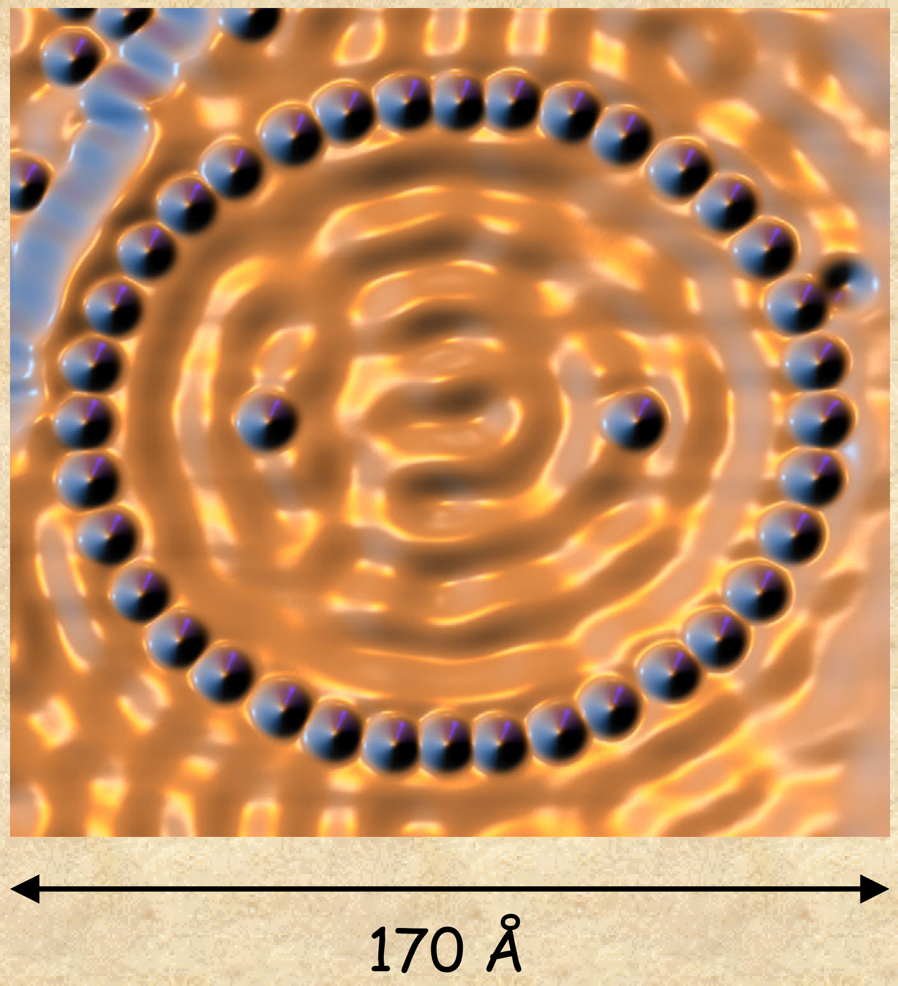


Path length:

$F_1P + PF_2 = 2a$

Eccentricity:

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

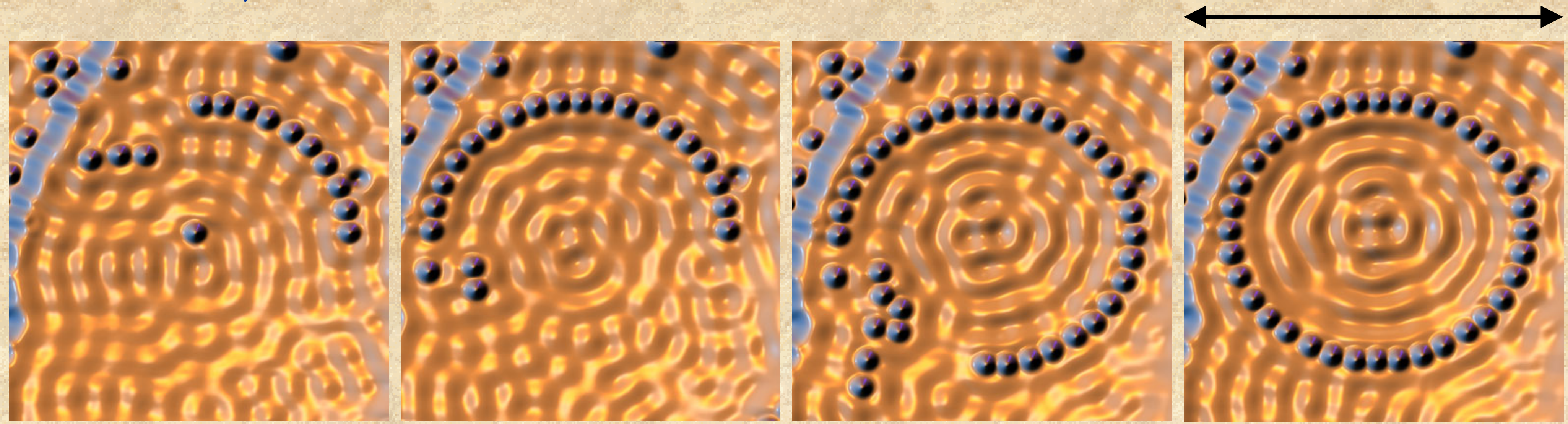


$a = 71.3$ Å

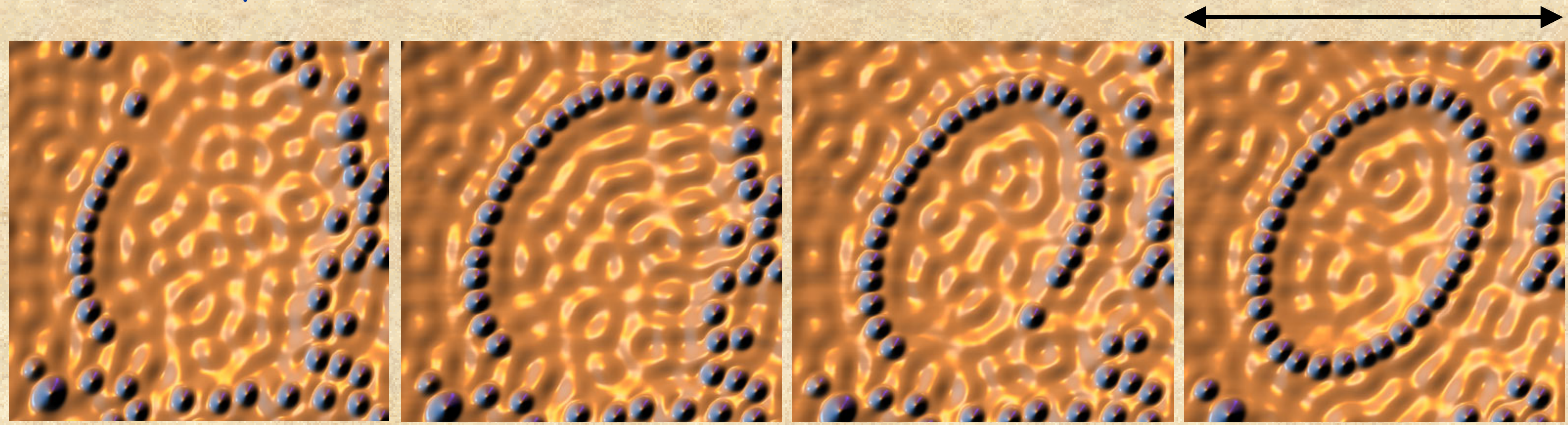
$e = 1/2$

Elliptical Resonator Assembly

- $e = 0.500$, $a = 71.3$ Å



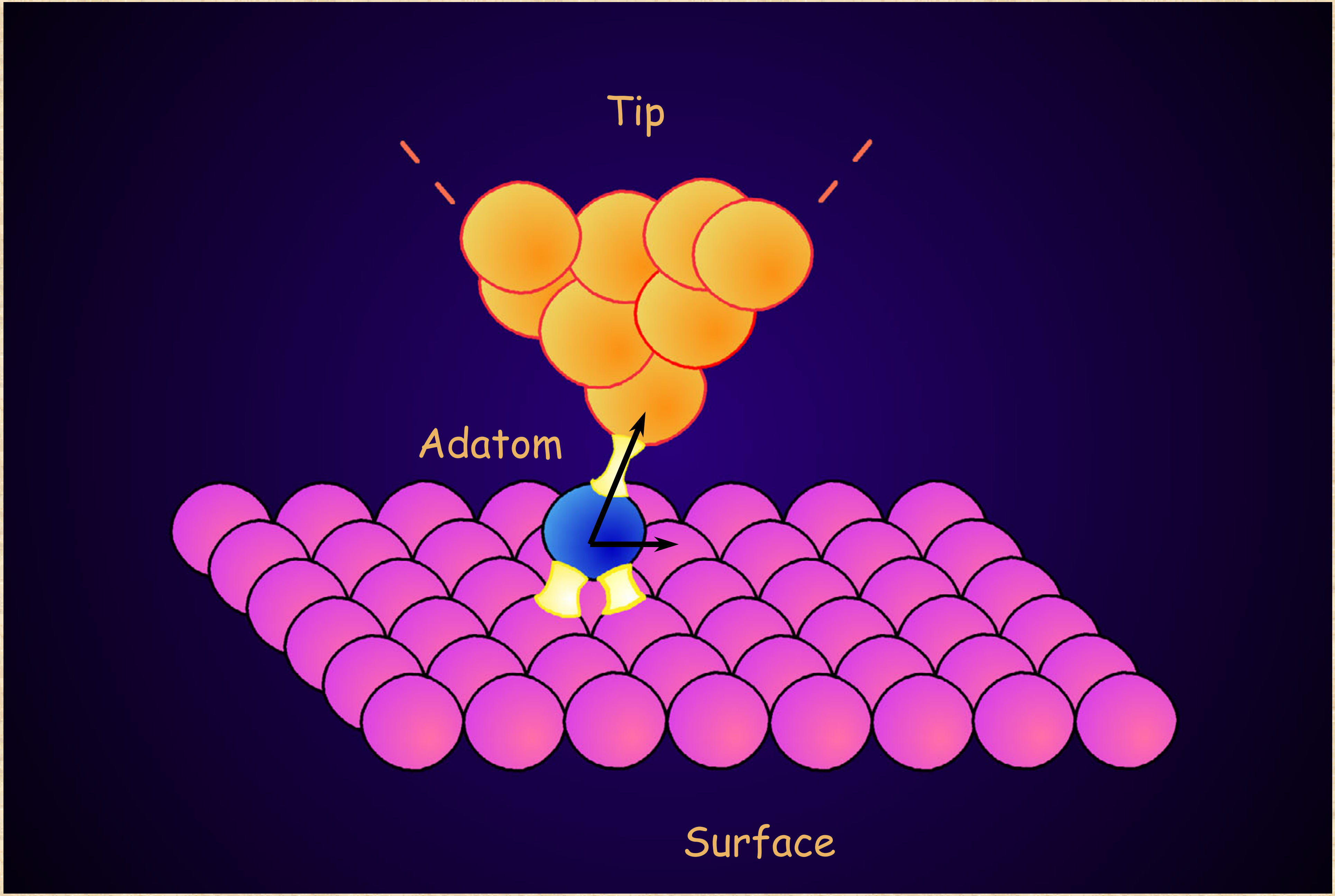
- $e = 0.786$, $a = 71.3$ Å



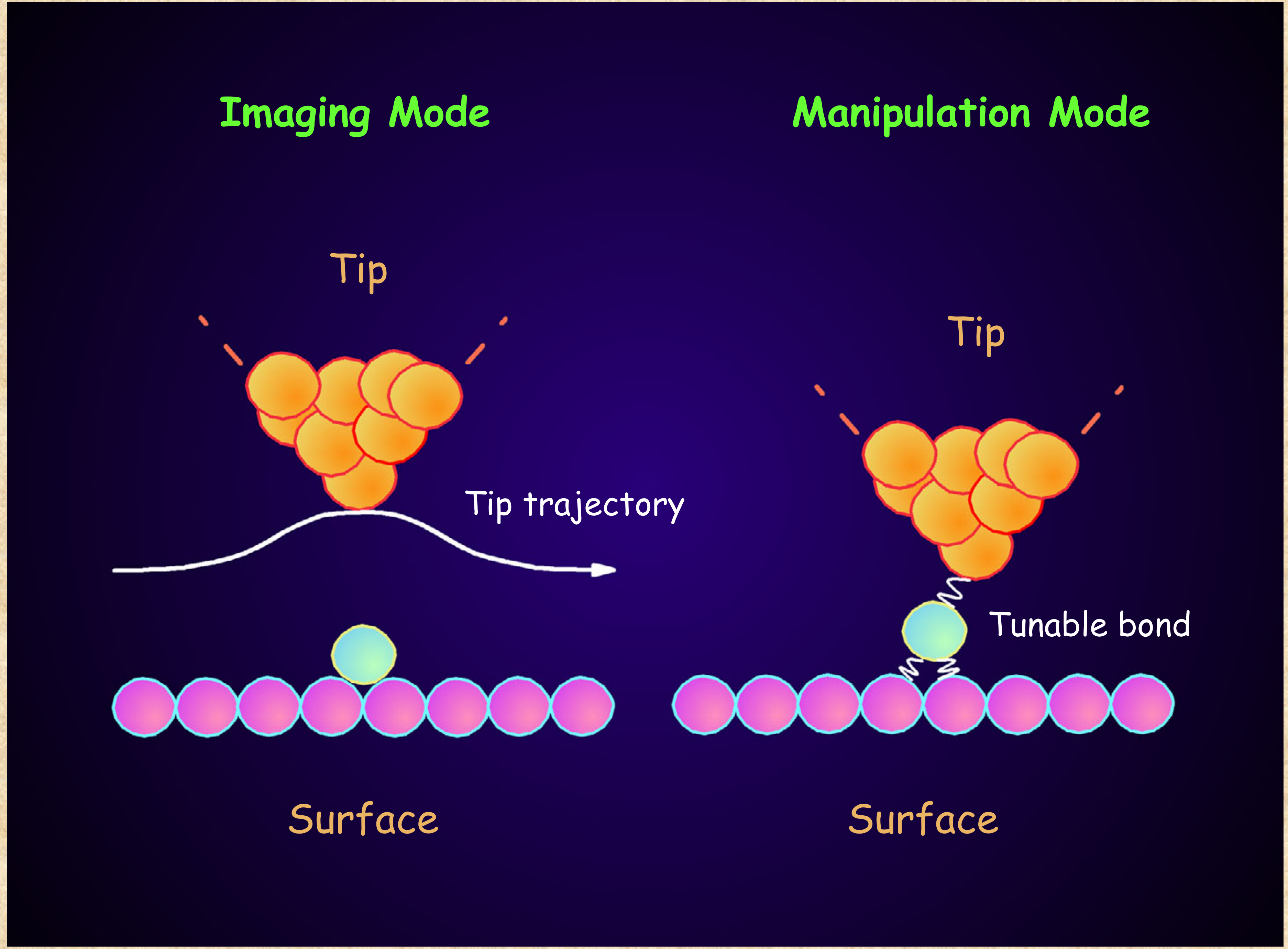
"Tunable Bond"

www.manoharan.org

- Chemical bonding force enables atom manipulation

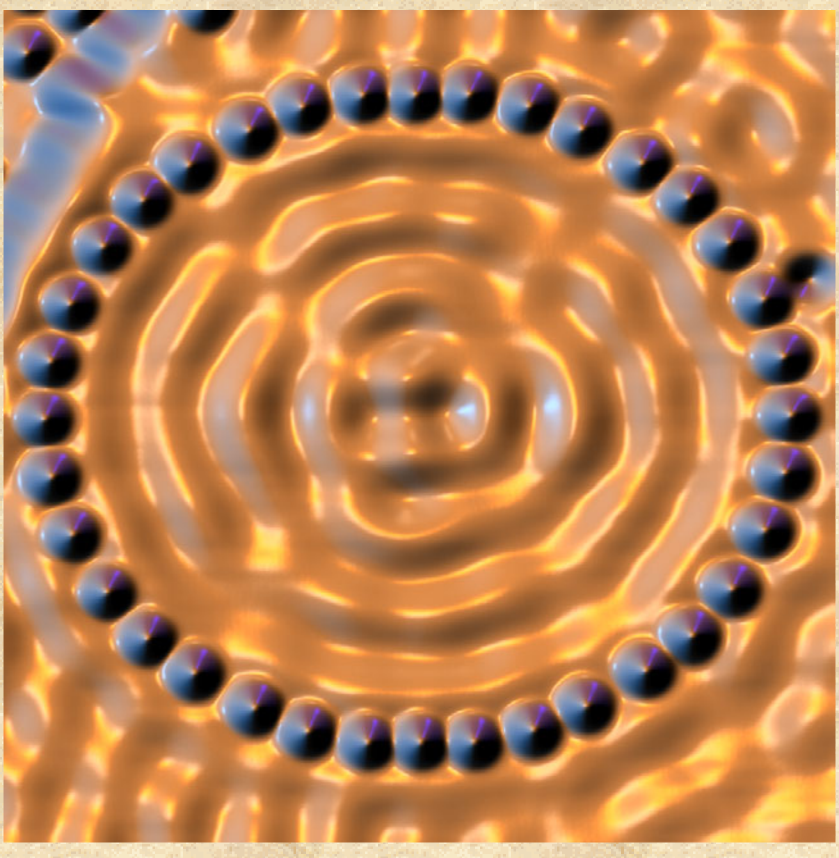


STM Operating Modes



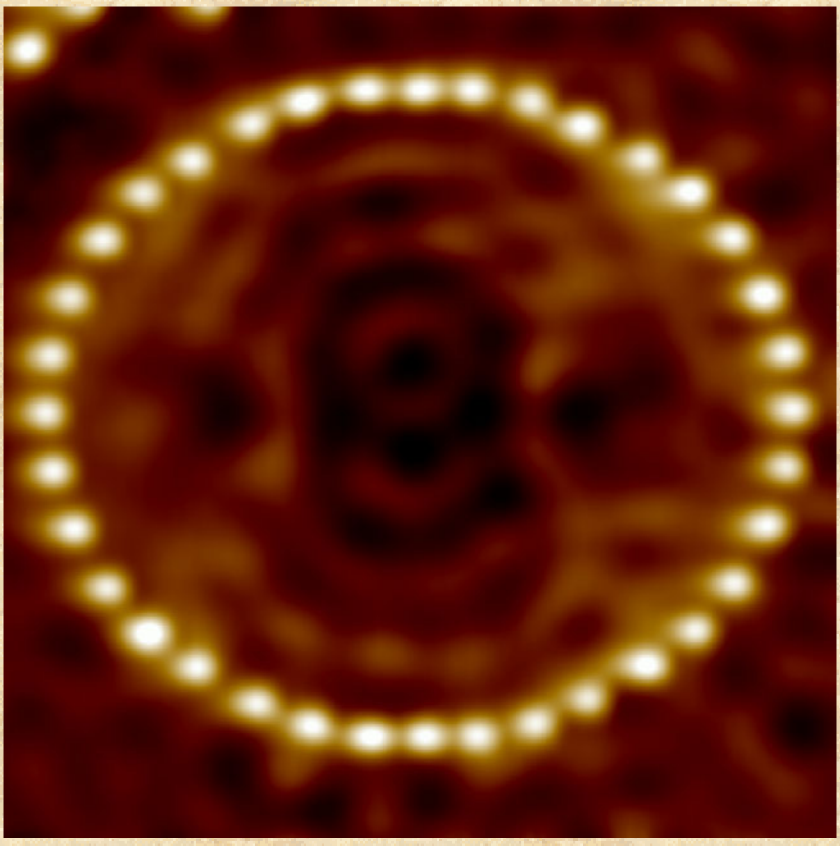
Empty Elliptical Resonator

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



Topograph

($V = 10$ mV)



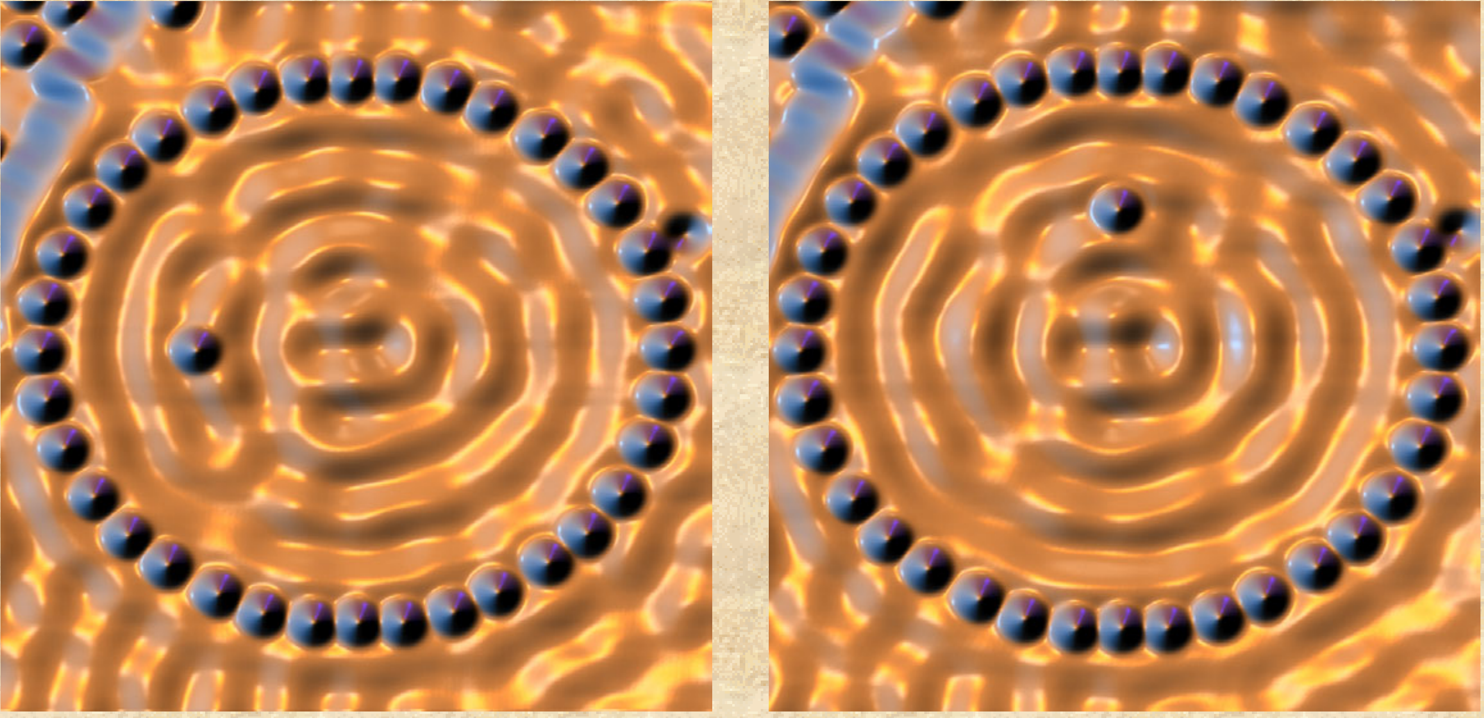
dI/dV map

($V = 10$ mV)

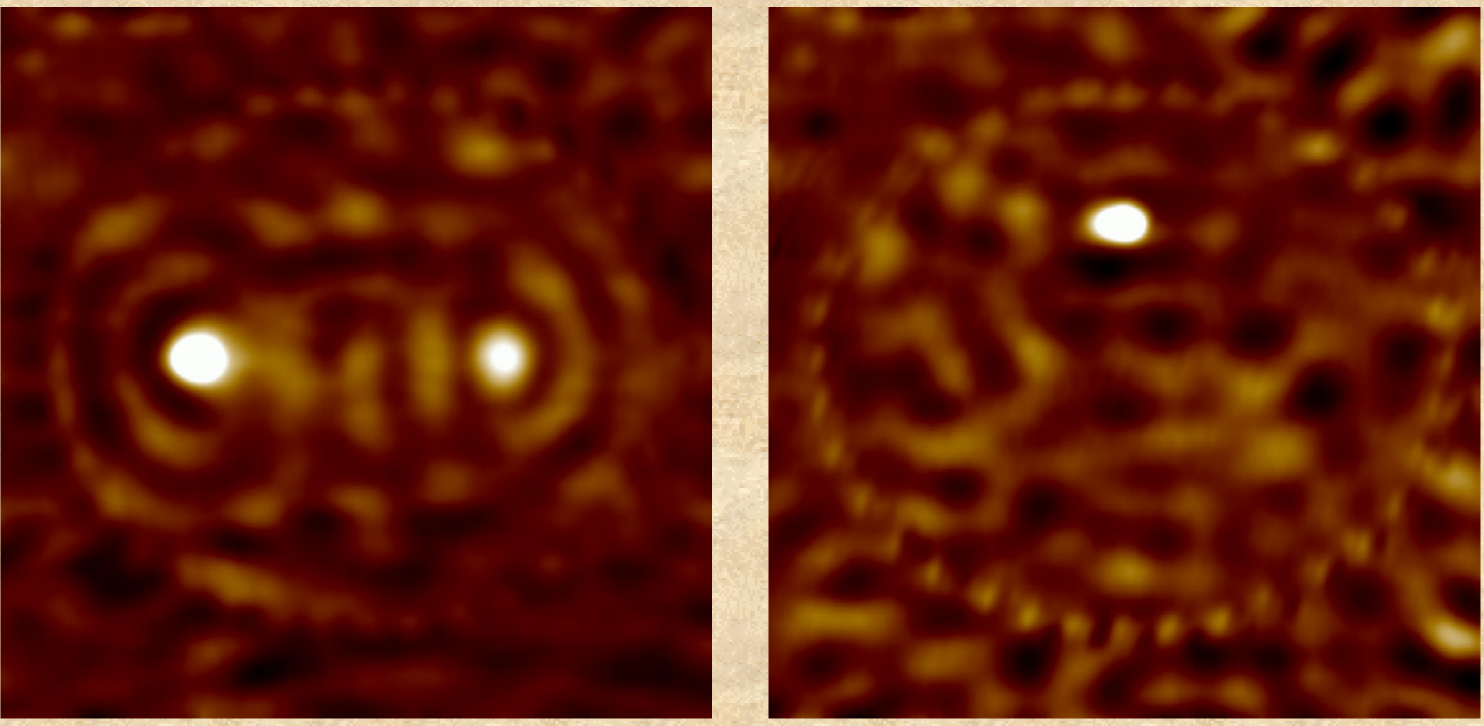
The Quantum Mirage

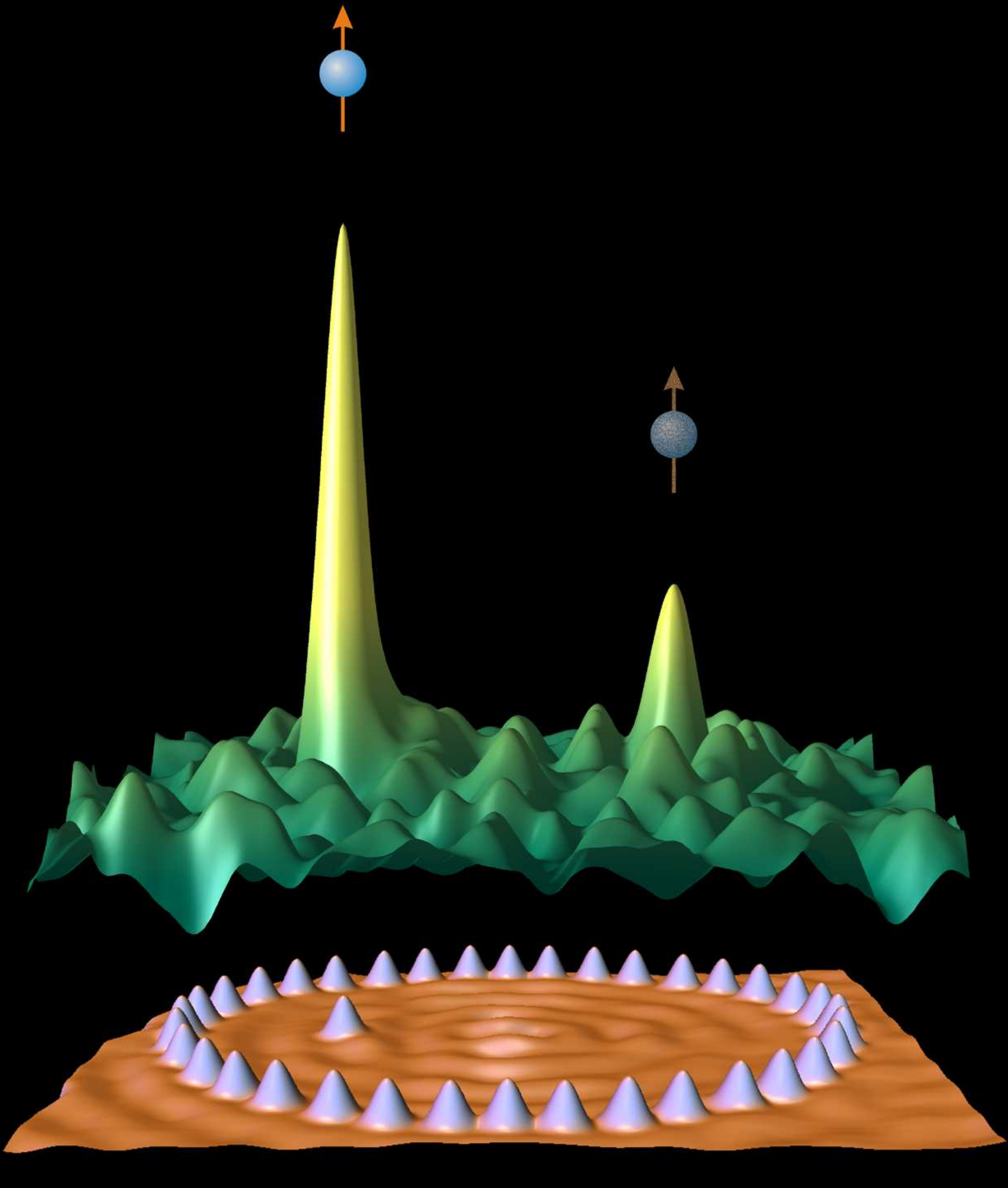
- $e = 1/2$, $a = 71.3$ Å elliptical resonator

Topograph

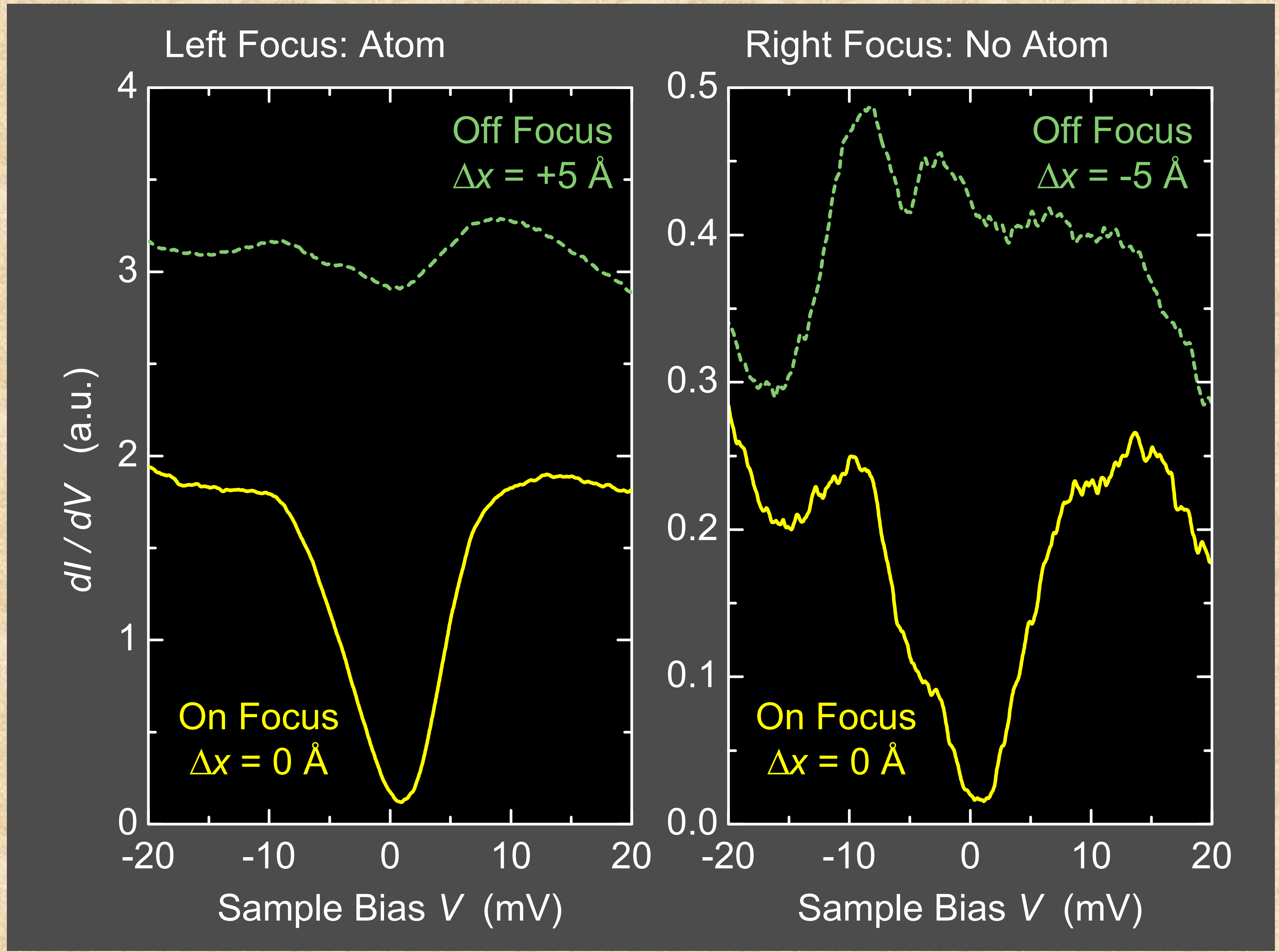


dI/*dV* difference map



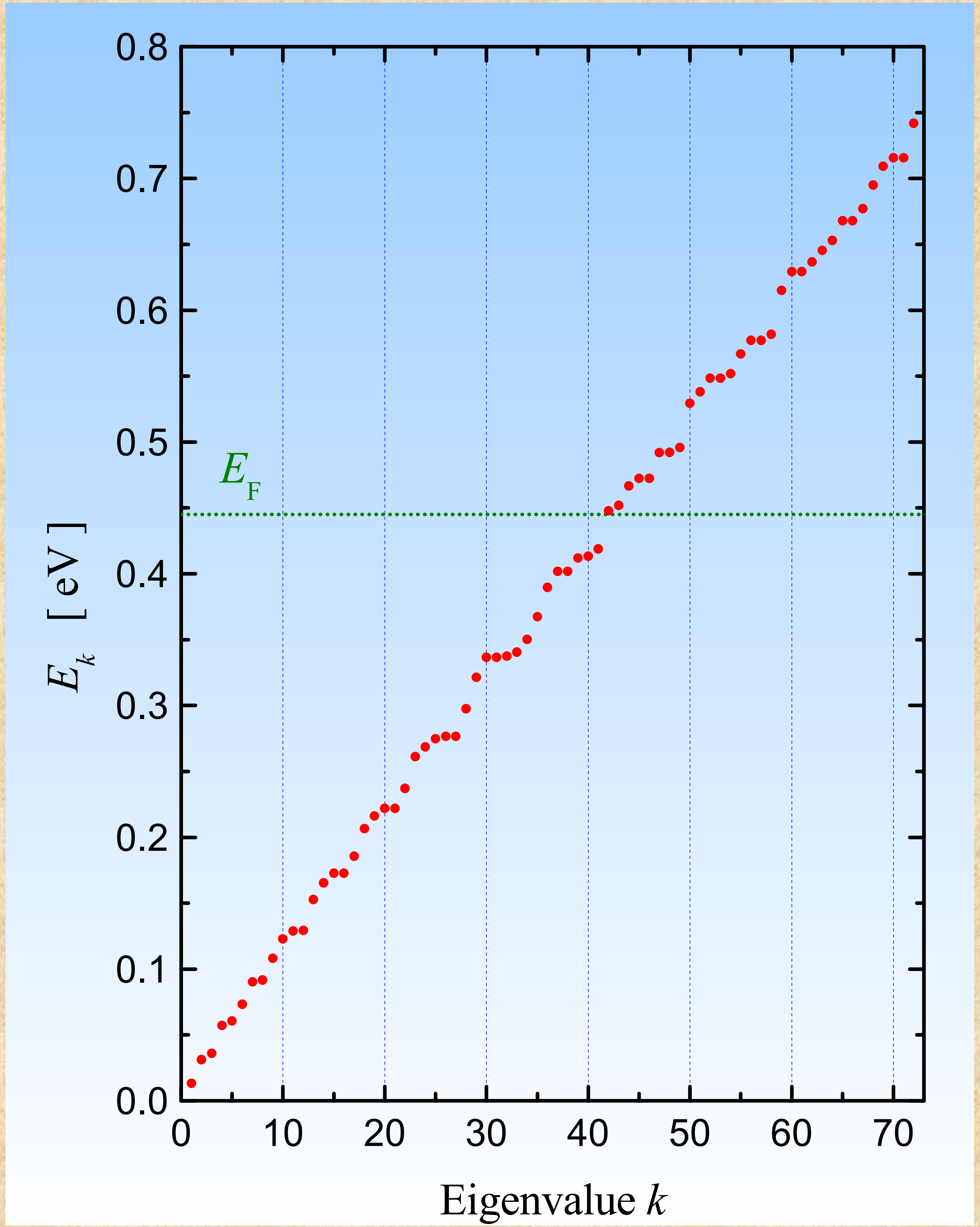


Spectroscopy on Atom and Mirage



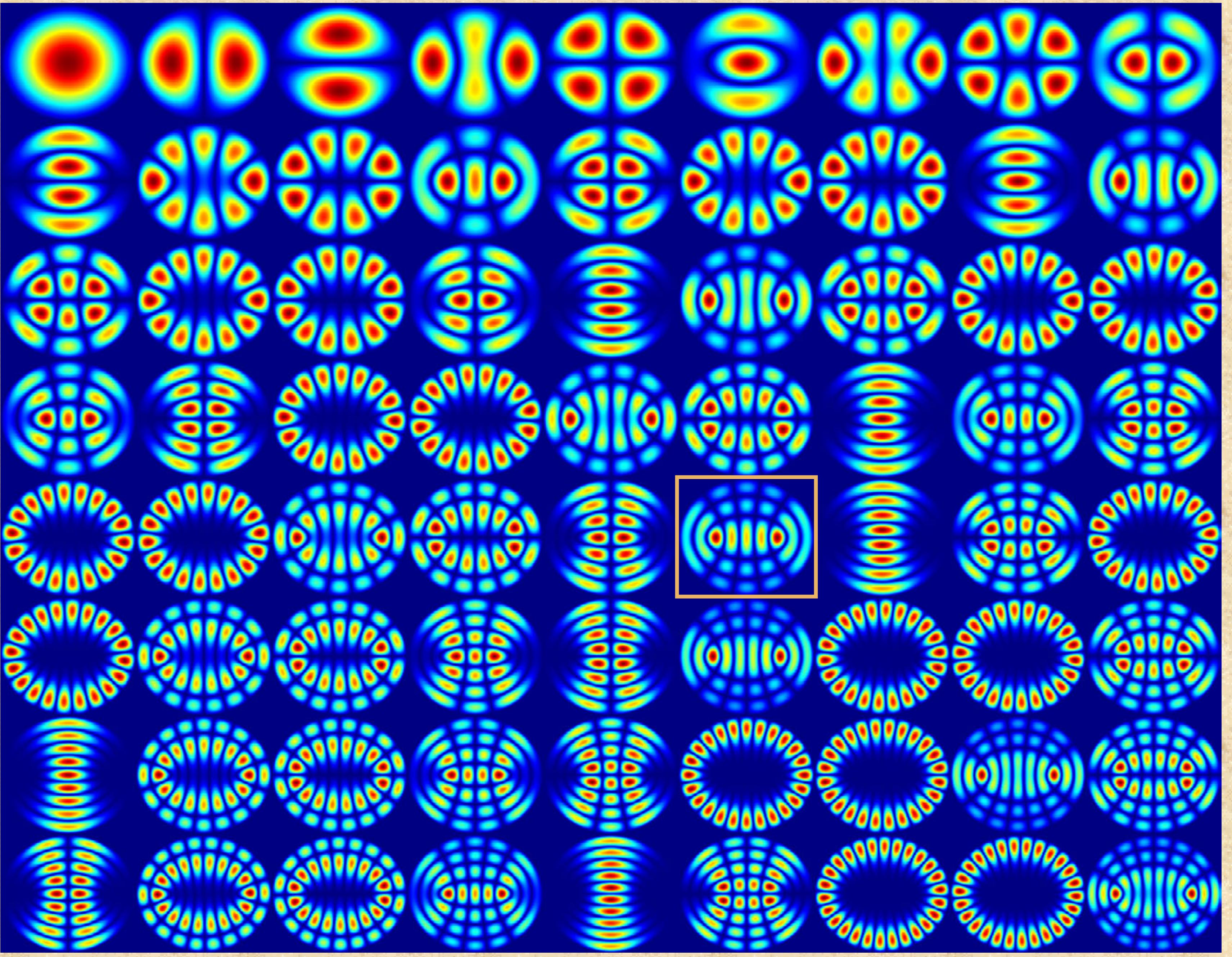
Eigenmode Calculations

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



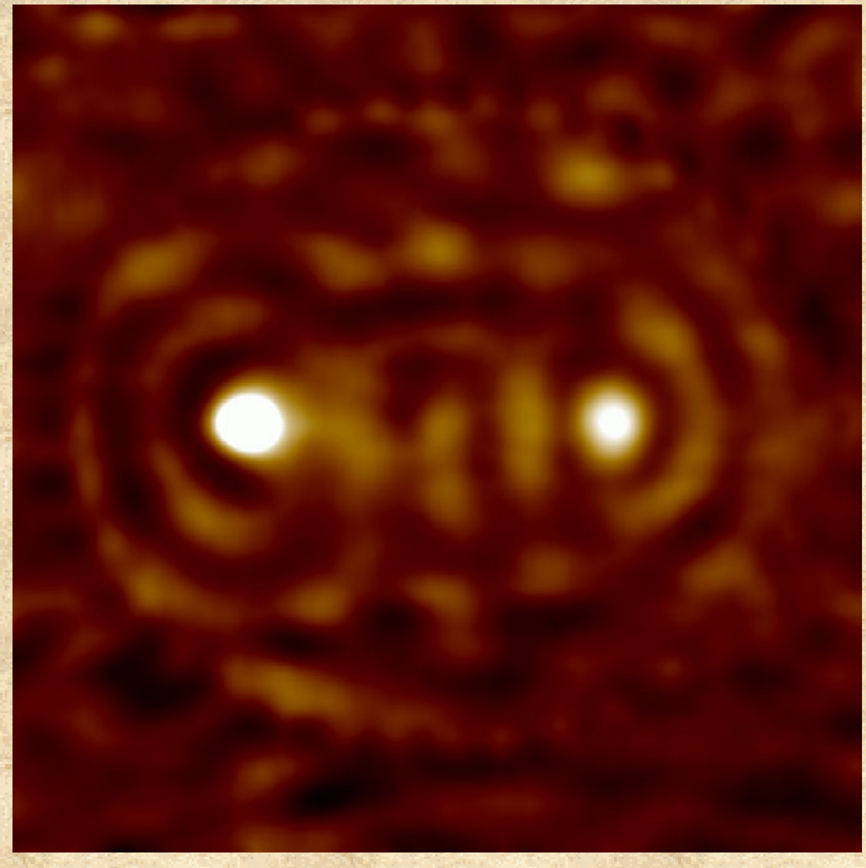
Eigenmodes

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

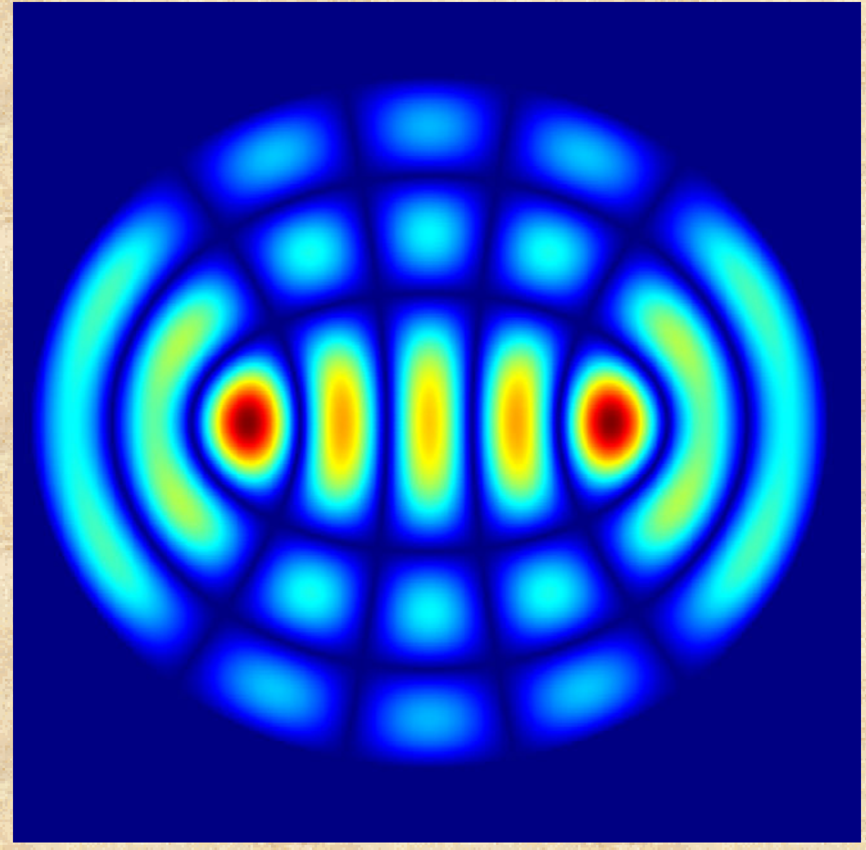


Eigenmode Modeling

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



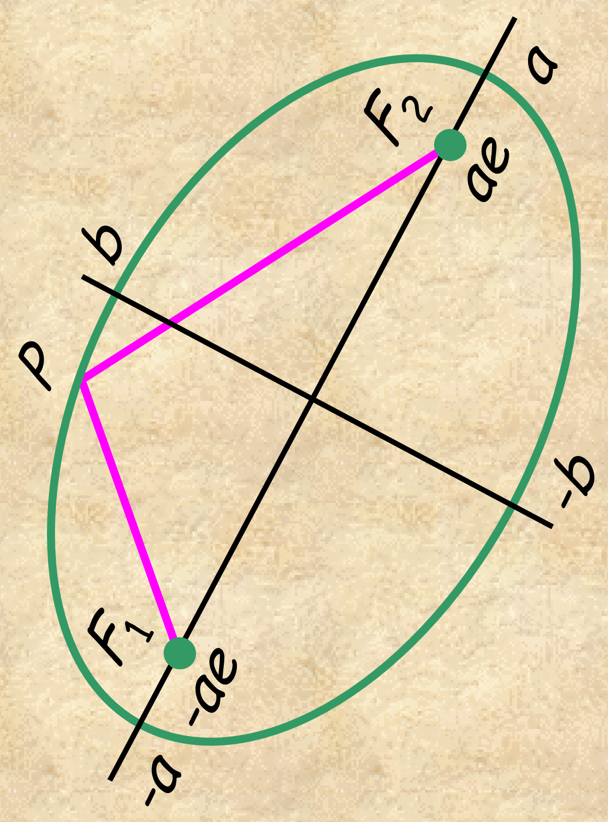
dI/*dV*
difference map



Calculated
Eigenmode at E_F

(Eigenstate 42)

Elliptical Resonator Design



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$F_1P + PF_2 = 2a$

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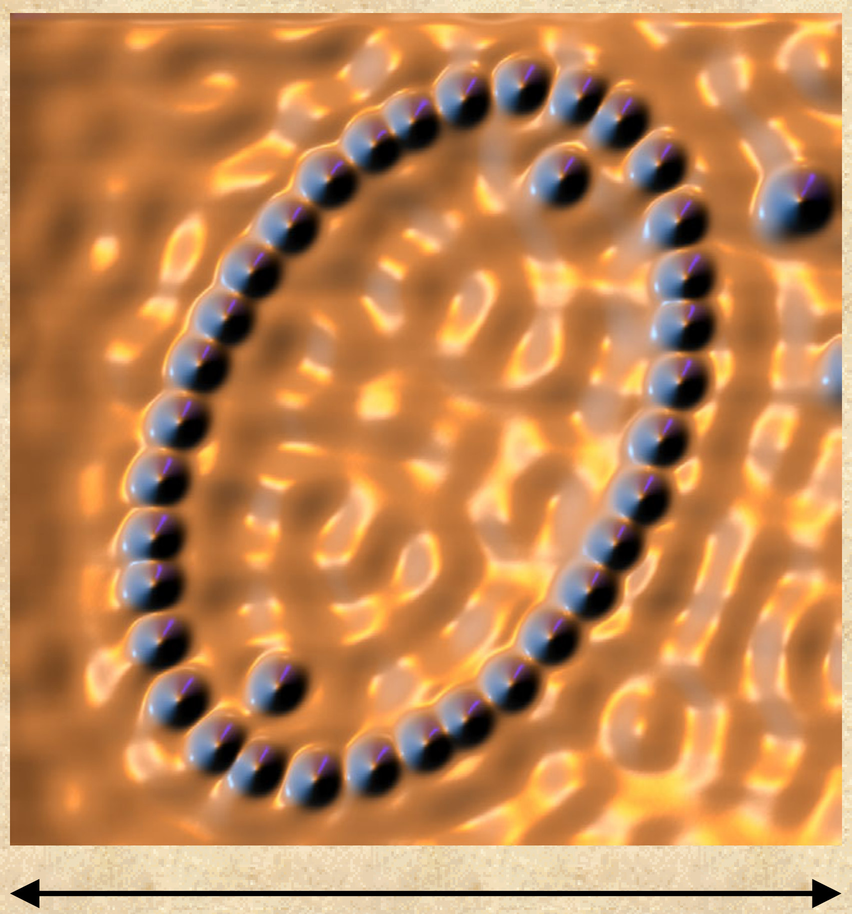


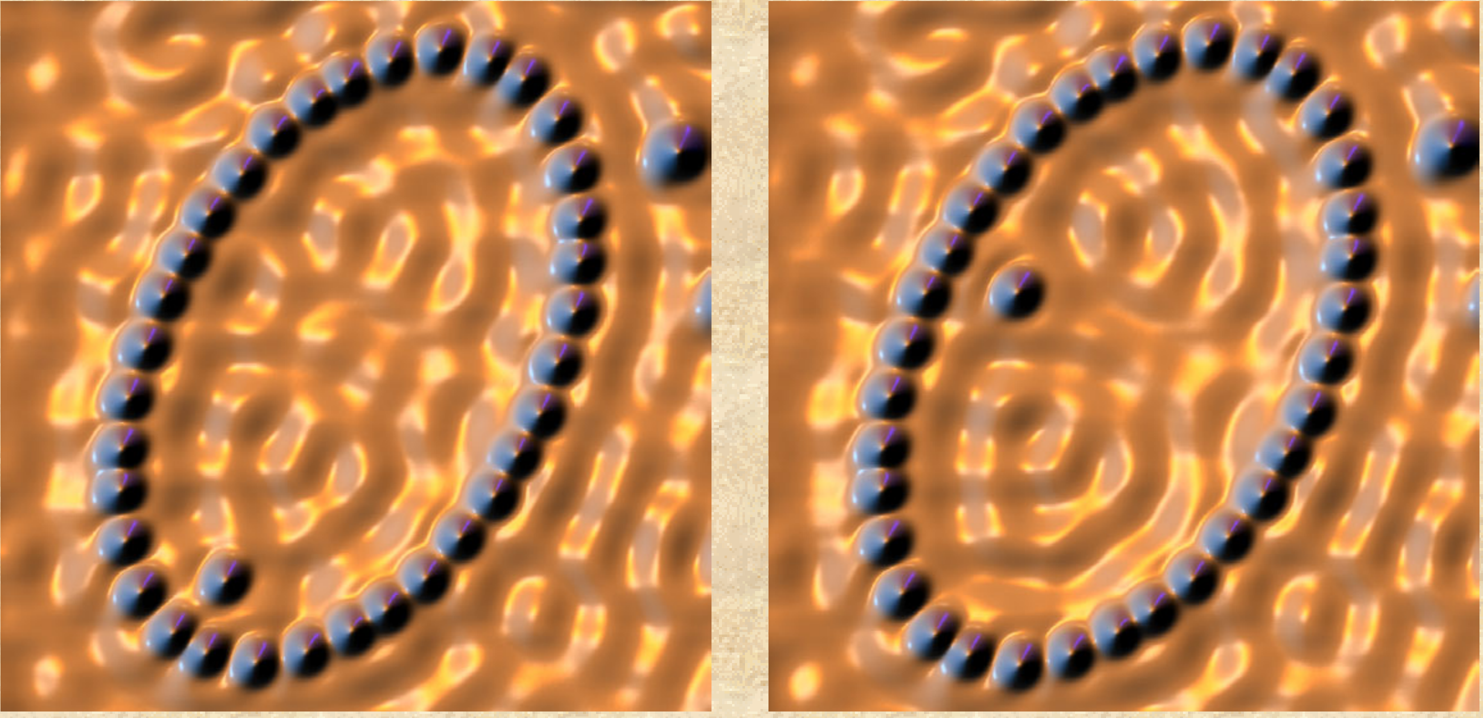
$a = 71.3$ Å

$e = 0.786$

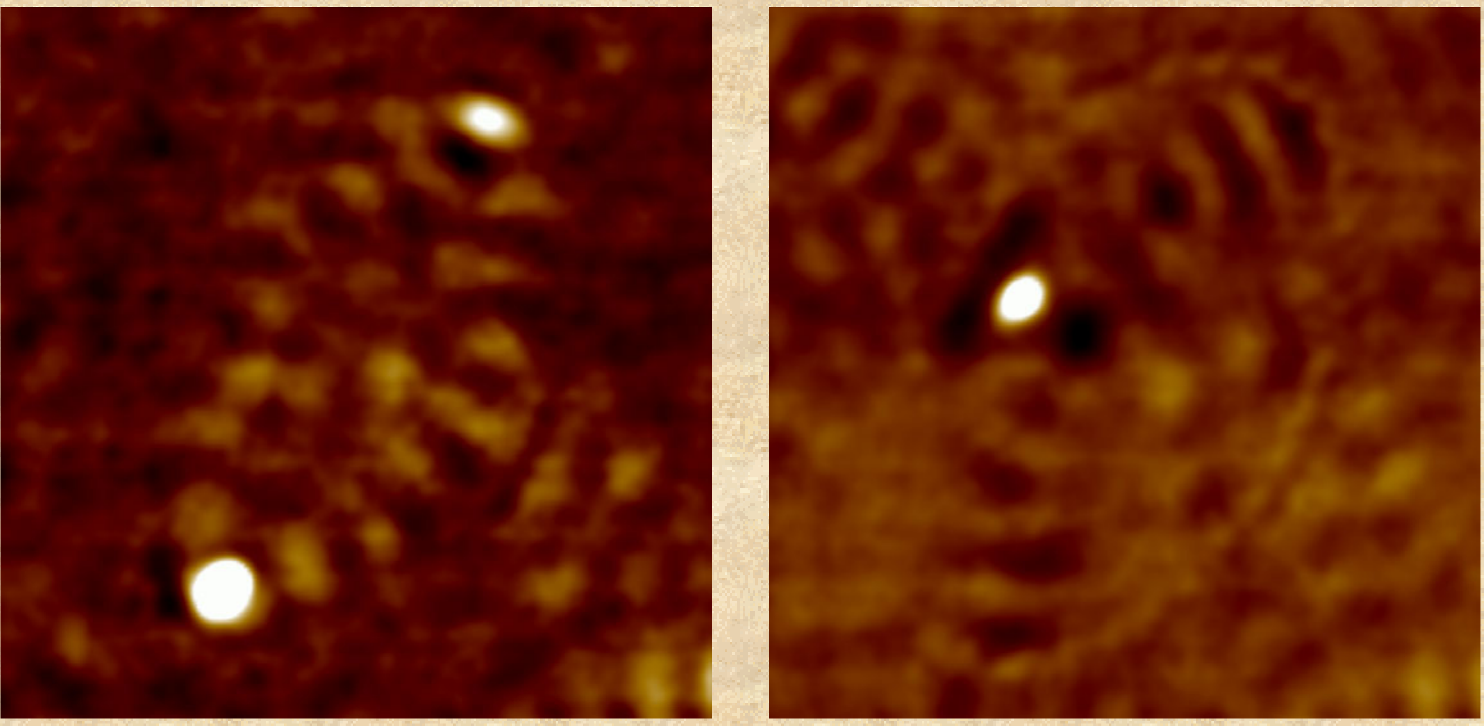
The Quantum Mirage

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

Topograph

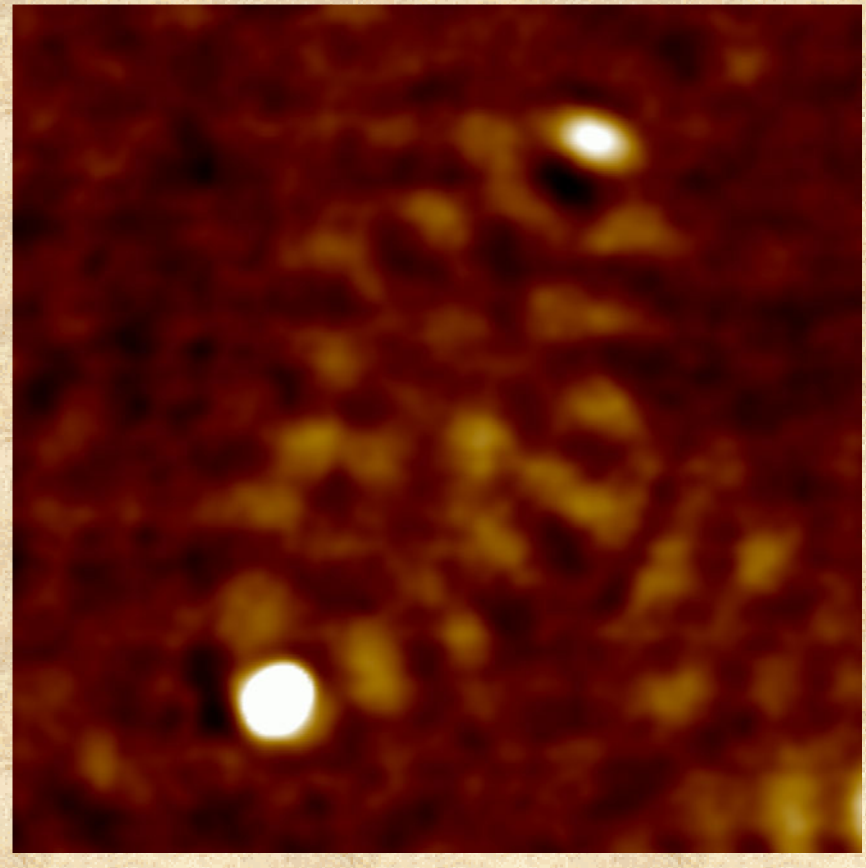


dI/dV difference map

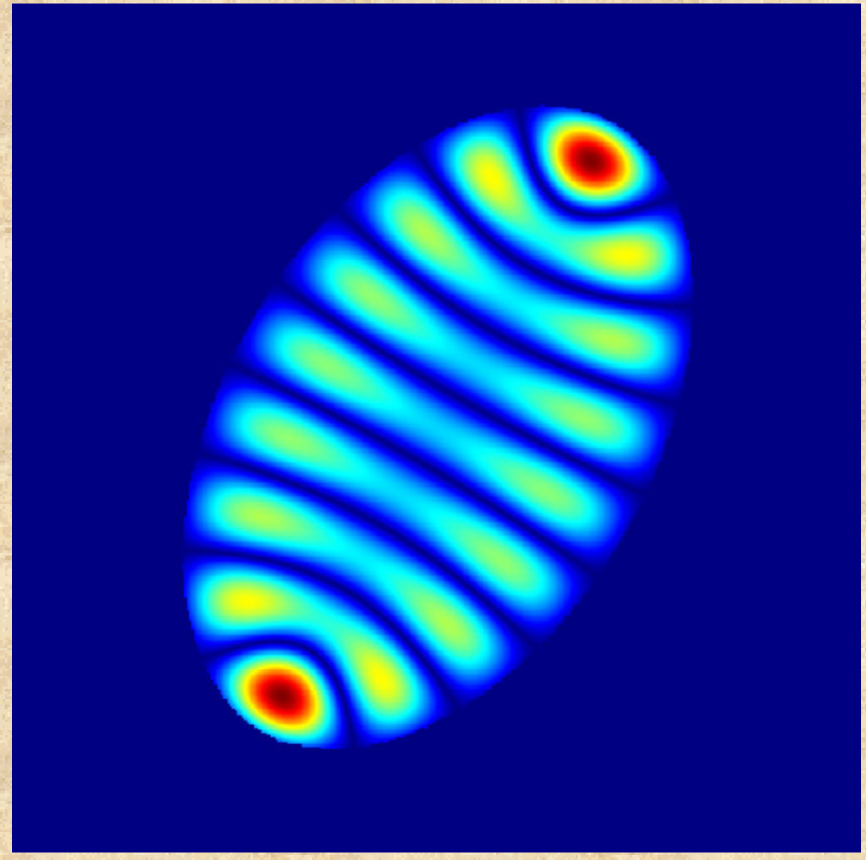


Eigenmode Modeling

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



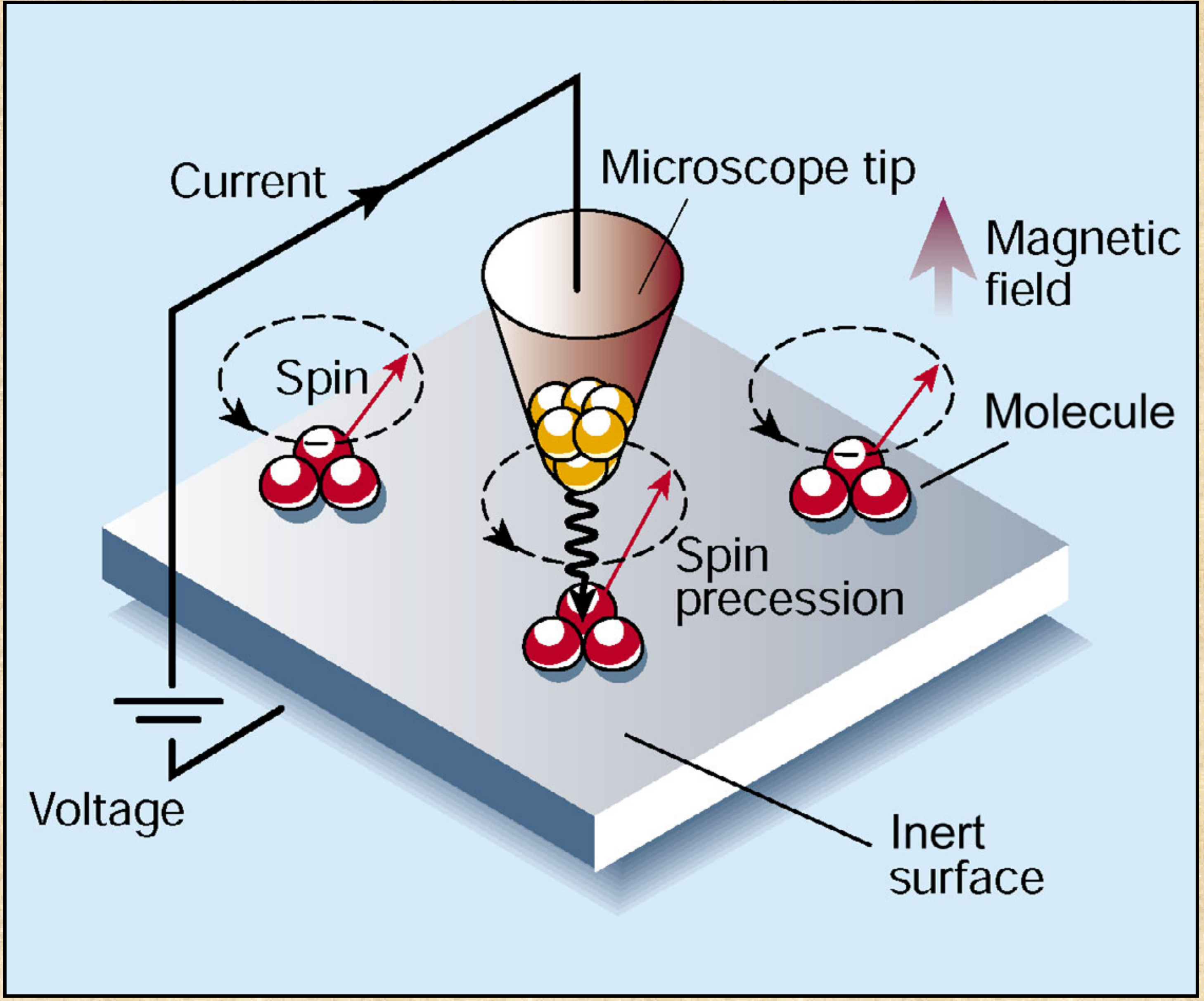
dI/dV
difference map



Calculated
Eigenmode at E_F

(Eigenstate 28)

Electron Spin Resonance STM



- Manassen *et al.*, *PRL* **62**, 2531 (1989).
- Durkan & Welland, *APL* **80**, 458 (2002).
- Manoharan, *Nature* **416**, 25 (2002).

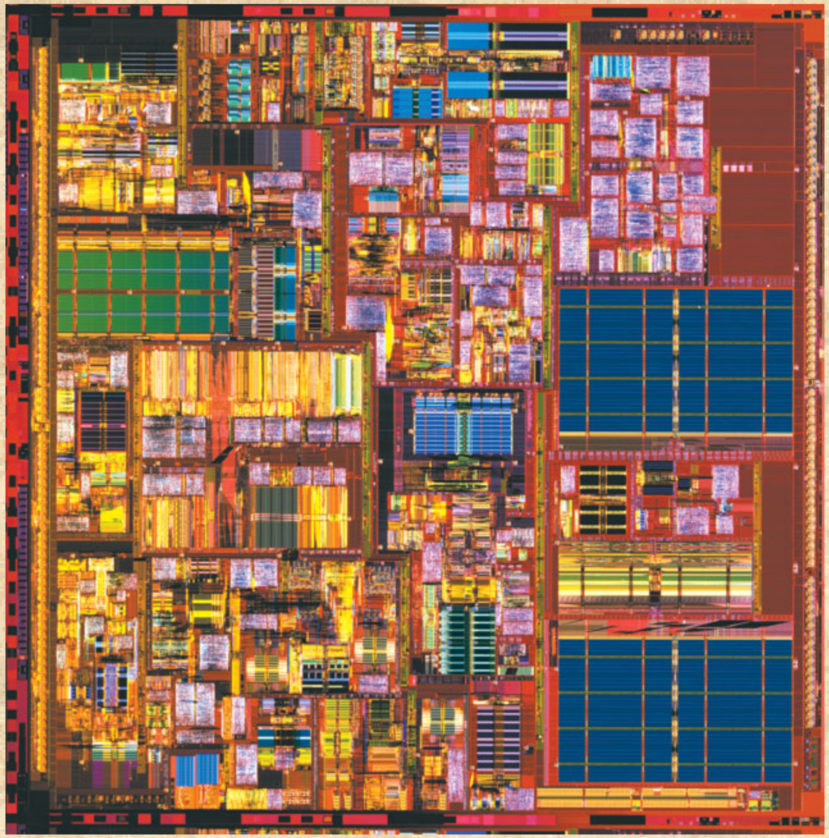
The Past

1940's

- Bell Labs Invention (1947)

  1 transistor
  ~ 5 cm
  < 20 kHz

2000's

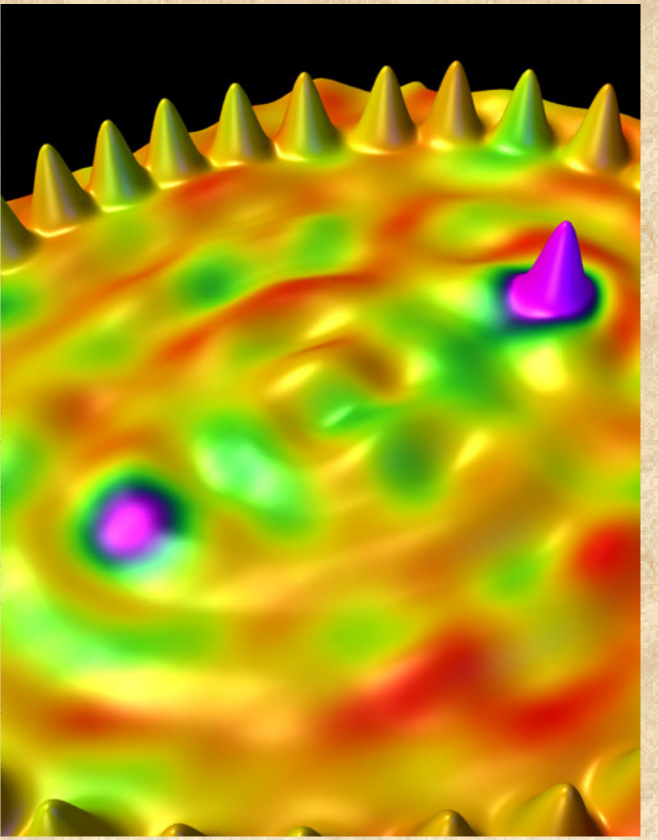


- Intel Pentium 4 (2003)

  55 million transistors
  ~ 0.13 μm
  > 3 GHz

The Future

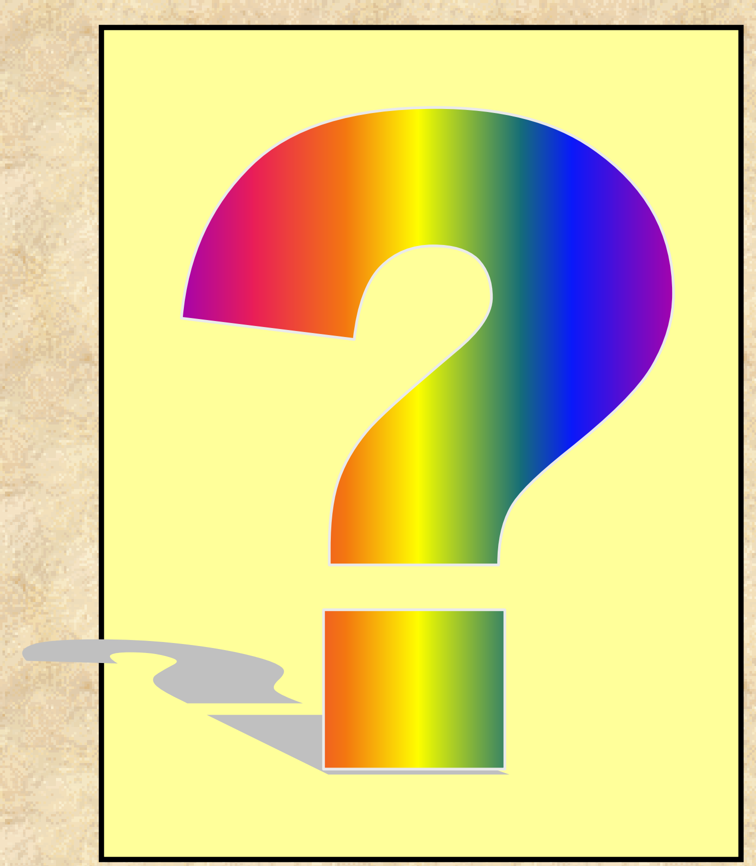
2000's



- Laboratory research

  1 atom/spin element
  ~ Å
  ~ THz

2060's



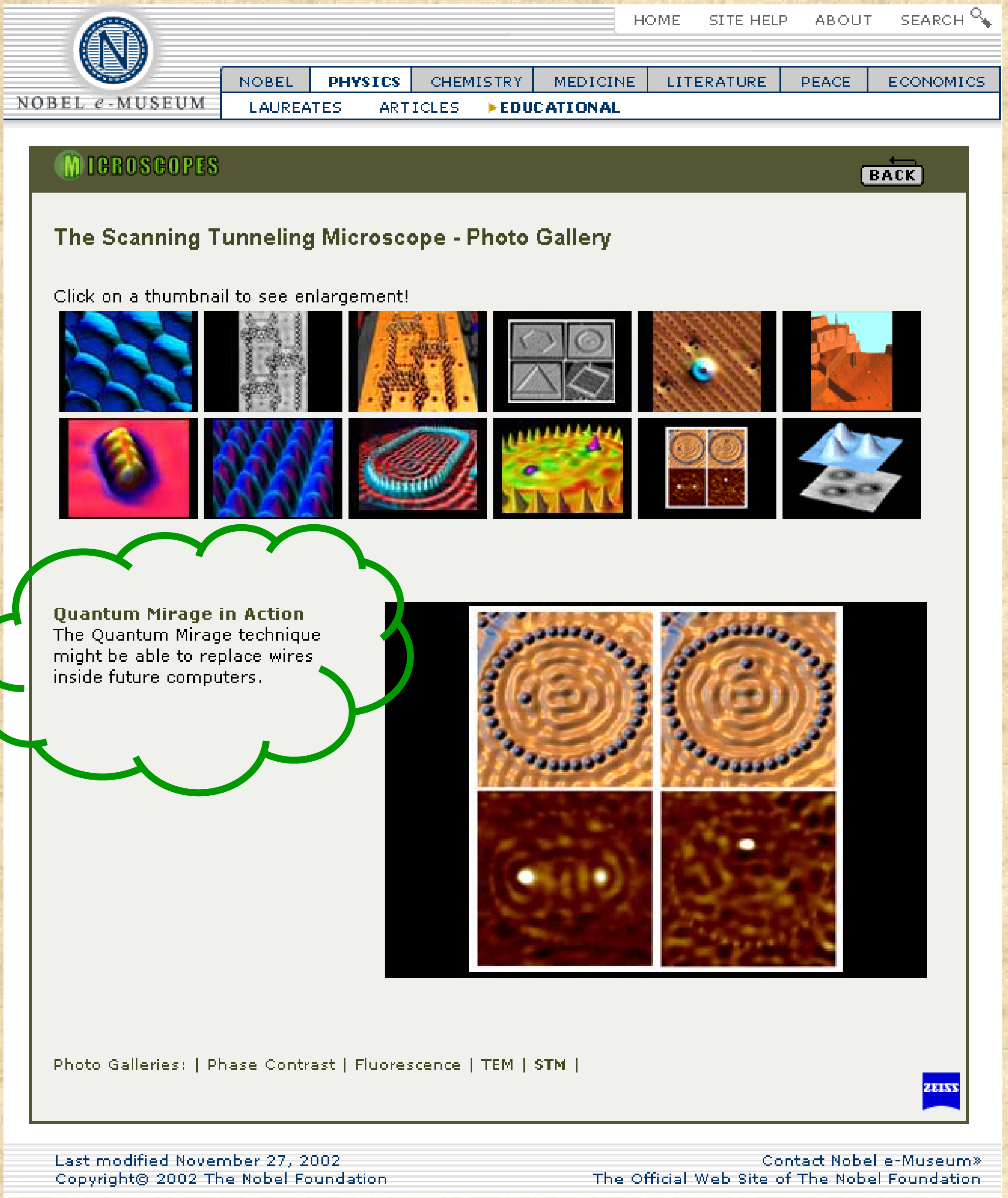
- Working product?

  Molecules, e^-'s, spins?
  How big?
  How fast?

Nobel e-Museum

www.manoharan.org

- www.nobel.se/physics/educational/microscopes/



The Scanning Tunneling Microscope - Photo Gallery

Click on a thumbnail to see enlargement!

Quantum Mirage in Action
The Quantum Mirage technique might be able to replace wires inside future computers.

Photo Galleries: | Phase Contrast | Fluorescence | TEM | STM |

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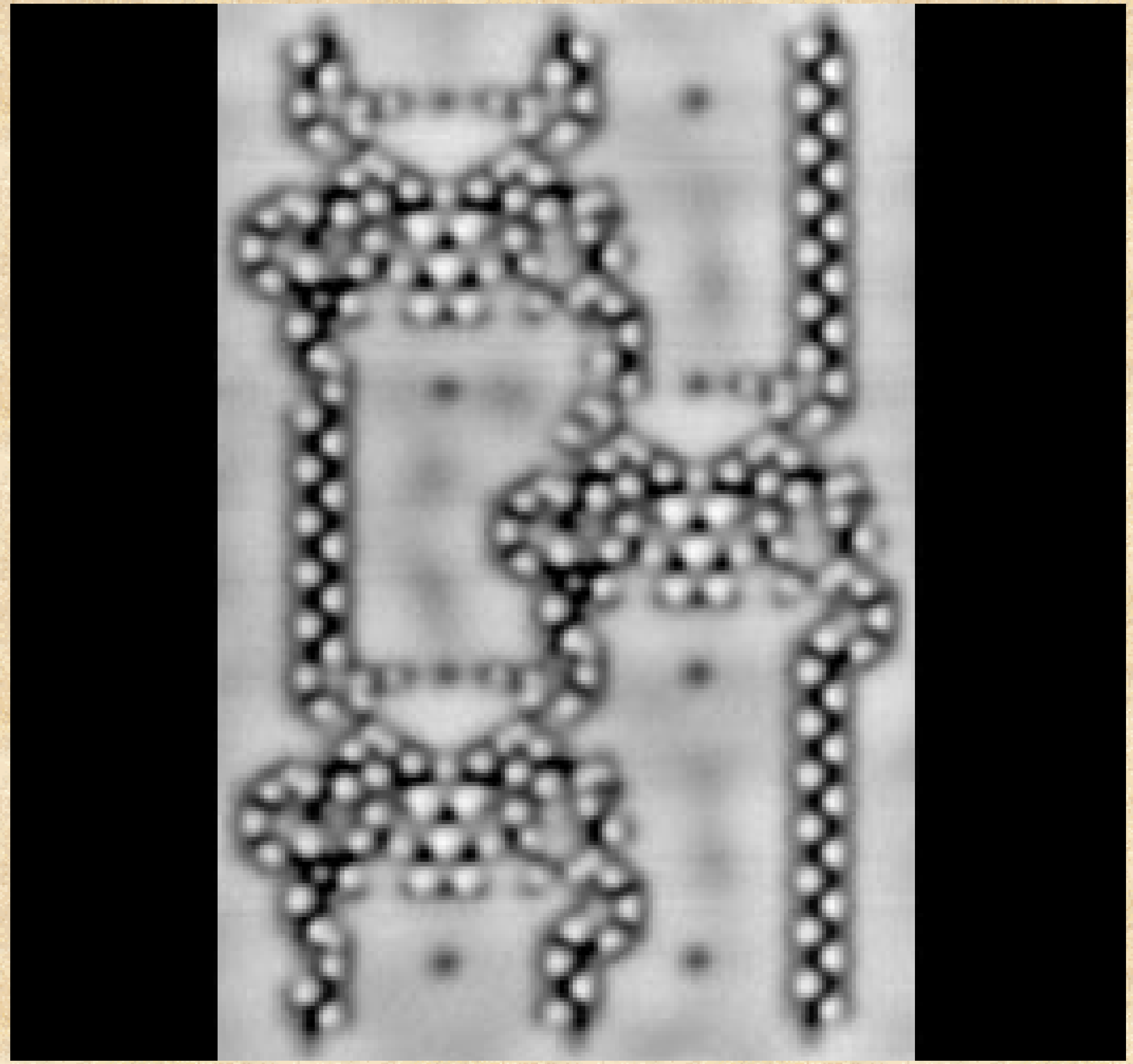
One possibility…

Molecular Cascades

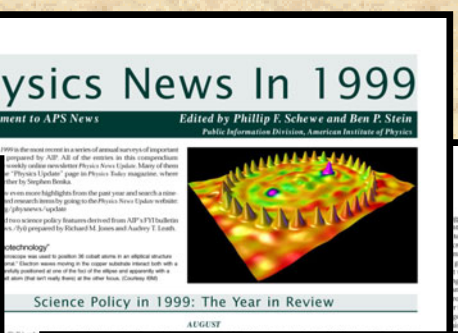
- Three-input sorter

CO molecules
&
domino logic

Another possible
route…



Nanoscale Science and Technology



Physics News In 1999

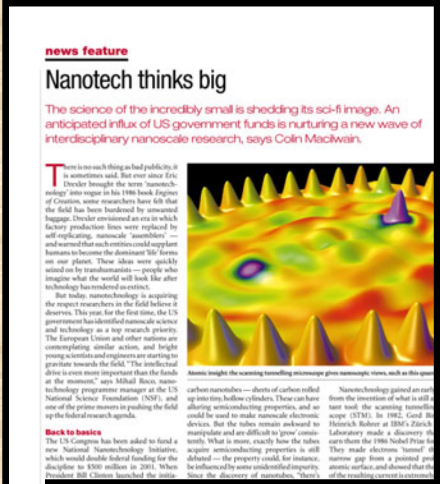
A Supplement to APS News

Edited by Phillip F. Schewe and Ben P. Stein

Public Information Division, American Institute of Physics

Science Policy in 1999: The Year in Review

AUGUST



news feature

Nanotech thinks big

The science of the incredibly small is shedding its sci-fi image. An anticipated influx of US government funds is nurturing a new wave of interdisciplinary nanoscale research, says Colin Macilwain.

There is no such thing as bad publicity, it is sometimes said. But ever since Eric Drexler brought the term 'nanotechnology' into vogue in his 1986 book *Engines of Creation*, some researchers have felt that the field has been burdened by unwanted baggage. Drexler envisioned an era in which factory production lines were replaced by self-replicating, nanoscale 'assemblers' — and warned that such entities could supplant humans to become the dominant 'life' forms on our planet. These ideas were quickly seized on by transhumanists — people who imagine what the world will look like after technology has rendered us extinct.

But today, nanotechnology is acquiring the respect researchers in the field believe it deserves. This year, for the first time, the US government has identified nanoscale science and technology as a top research priority. The European Union and other nations are contemplating similar action, and bright young scientists and engineers are starting to gravitate towards the field. "The intellectual drive is even more important than the funds at the moment," says Mihail Roco, nanotechnology programme manager at the US National Science Foundation (NSF), and one of the prime movers in pushing the field up the federal research agenda.

Back to basics

The US Congress has been asked to fund a new National Nanotechnology Initiative, which would double federal funding for the discipline to $500 million in 2001. When President Bill Clinton launched the initia-

carbon nanotubes — sheets of carbon rolled up into tiny, hollow cylinders. These can have alluring semiconducting properties, and so could be used to make nanoscale electronic devices. But the tubes remain awkward to manipulate and are difficult to 'grow' consistently. What is more, exactly how the tubes acquire semiconducting properties is still debated — the property could, for instance, be influenced by some unidentified impurity. Since the discovery of nanotubes, "there's

The New York Times

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Peeking at an Atom in a Hall of Mirrors

By GEORGE JOHNSON

Crossing a barrier that once seemed impassable, physicists in recent years have used a delicate instrument called a scanning tunneling microscope to reach down into the very substrate of matter, feeling the bumps and grooves of atoms and even picking them up and moving them around like so many grains of sand.

In a well-publicized tour de force, I.B.M. researchers in 1990 carefully arranged 35 atoms of the element xenon to spell out their company's initials.

Now, in another demonstration of subatomic nimbleness, scientists have created a kind of quantum reflector, in which an atom placed in one location appears as a ghostly

The 'Quantum Corral'

By placing an atom at one of two focal points in an ellipse of cobalt atoms (which acts like a mirror), a mirage of the inner atom appears at the other focal point with some properties of the original.

TOPOGRAPHIC IMAGE

Shows the arrangement of cobalt atoms on a field of copper.

MAGNETIC IMAGE

Shows the effect of the cobalt atom on the copper background.

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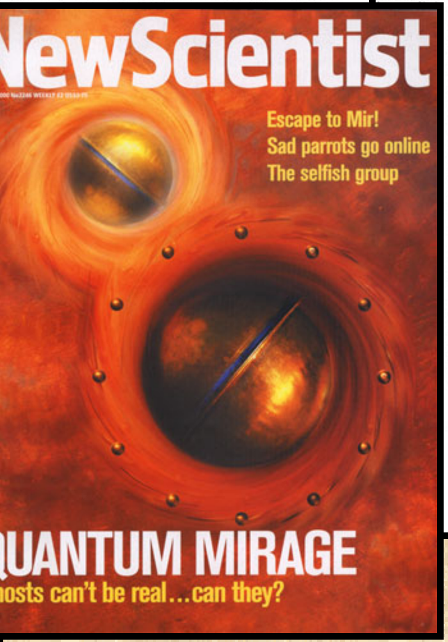
Directions in Information Technology



NewScientist

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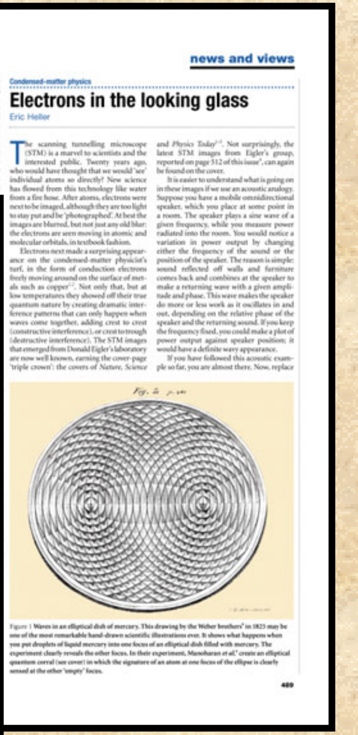

news and views

Condensed-matter physics

Electrons in the looking glass

Eric Heller

The scanning tunnelling microscope (STM) is a marvel to scientists and the interested public. Twenty years ago, who would have thought that we would 'see' individual atoms so directly? New science has flowed from this technology like water from a fire hose. After atoms, electrons were next to be imaged, although they are too light to stay put and be 'photographed'. At best the images are blurred, but not just any old blur: the electrons are seen moving in atomic and molecular orbitals, in textbook fashion.

Electrons next made a surprising appearance on the condensed-matter physicist's turf, in the form of conduction electrons freely moving around on the surface of metals such as copper[1,2]. Not only that, but at low temperatures they showed off their true quantum nature by creating dramatic interference patterns that can only happen when waves come together, adding crest to crest (constructive interference), or crest to trough (destructive interference). The STM images that emerged from Donald Eigler's laboratory are now well known, earning the cover-page 'triple crown': the covers of *Nature*, *Science* and *Physics Today*[1-3]. Not surprisingly, the latest STM images from Eigler's group, reported on page 512 of this issue[4], can again be found on the cover.

It is easier to understand what is going on in these images if we use an acoustic analogy. Suppose you have a mobile omnidirectional speaker, which you place at some point in a room. The speaker plays a sine wave of a given frequency, while you measure power radiated into the room. You would notice a variation in power output by changing either the frequency of the sound or the position of the speaker. The reason is simple: sound reflected off walls and furniture comes back and combines at the speaker to make a returning wave with a given amplitude and phase. This wave makes the speaker do more or less work as it oscillates in and out, depending on the relative phase of the speaker and the returning sound. If you keep the frequency fixed, you could make a plot of power output against speaker position; it would have a definite wavy appearance.

If you have followed this acoustic example so far, you are almost there. Now, replace

Figure 1 Waves in an elliptical dish of mercury. This drawing by the Weber brothers[5] in 1825 may be one of the most remarkable hand-drawn scientific illustrations ever. It shows what happens when you put droplets of liquid mercury into one focus of an elliptical dish filled with mercury. The experiment clearly reveals the other focus. In their experiment, Manoharan et al.[4] create an elliptical quantum corral (see cover) in which the signature of an atom at one focus of the ellipse is clearly sensed at the other 'empty' focus.

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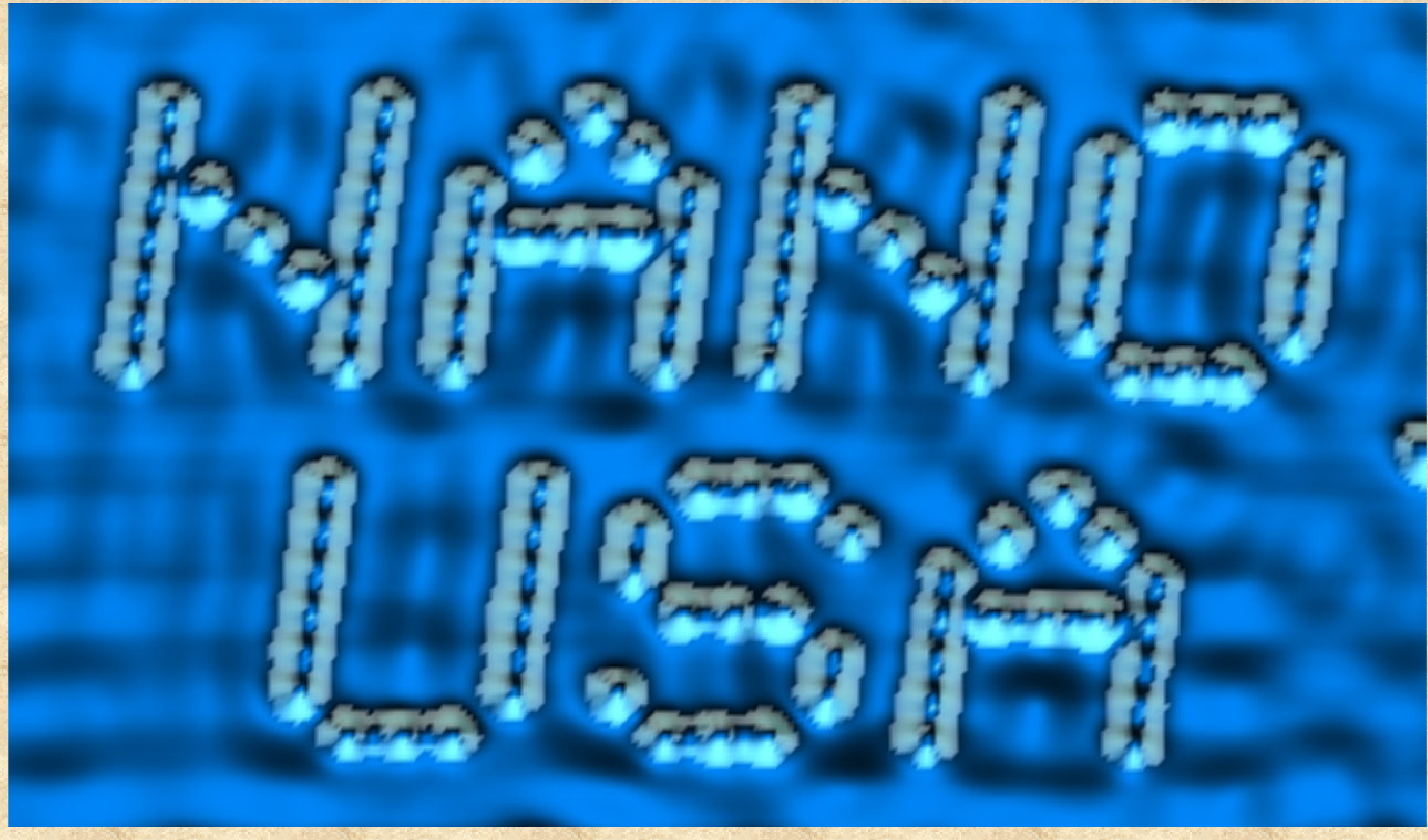
National Nanotechnology Initiative

- Launched in Presidential address, 21 January 2000.



Summary

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- Read more about it
  - Nature **403** (3 February 2000)

    Manoharan *et al.*,
    pp. 512-5
    (Cover article)

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    pp. 489-491
    (News & Views)
  - PRL **86** (12 March 2001)

    Fiete *et al.*,
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