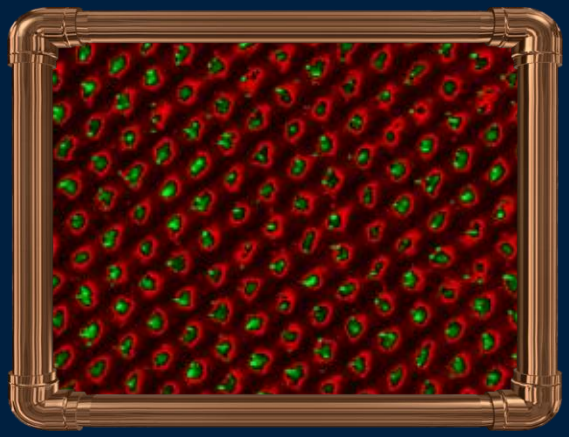
a place of mind

THE UNIVERSITY OF BRITISH COLUMBIA

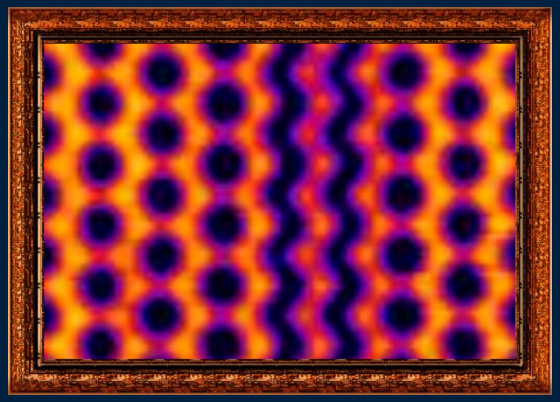
In touch with Atoms.

Dr. Yan Pennec,Vancouver, October 2011. ypennec@physics.ubc.ca

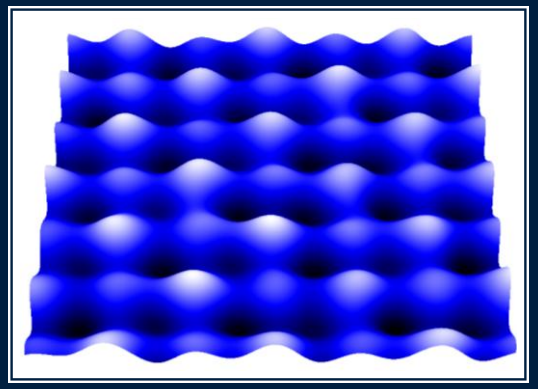
A gallery of atomic resolution.



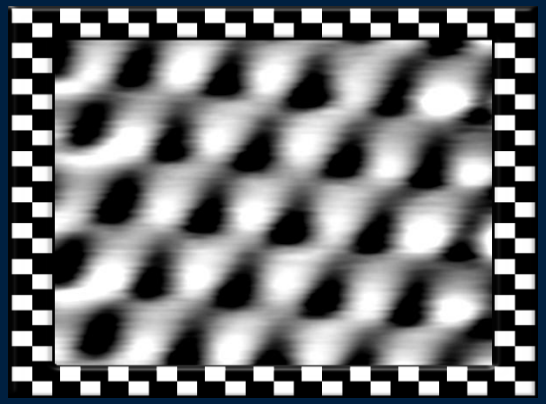
Cu (111)
Metal



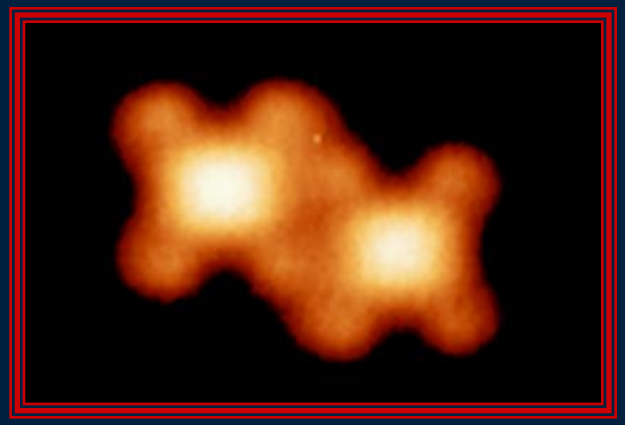
Si (100)
Semiconductor



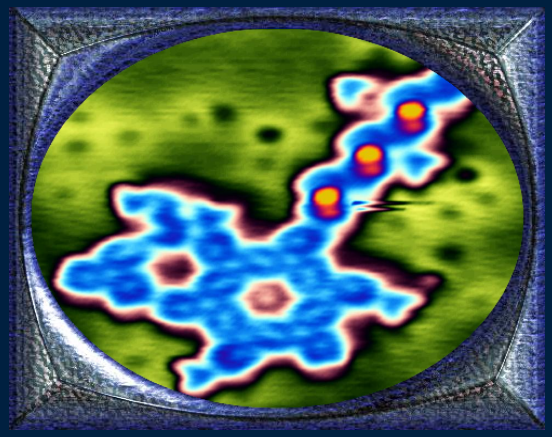
SrRuO2
Exotic oxide



Graphite HOPG
Bi-dimensional crystal



Co-TPP on Cu(111)
Functional molecules



H20 on Au (111)
Snowflake :)

Origin

Democritus
460-370 BC

Atomic hypothesis

The theory of Democritus held that everything is composed of "atoms", which are physically indivisible; that between atoms lies empty space; that atoms are indestructible; have always been, and always will be, in motion; that there are an infinite number of atoms, and kinds of atoms, which differ in shape, and size.

Democritus meditating on the seat of the soul by Léon-Alexandre Delhomme. 1868.

The case for the existence of atoms…

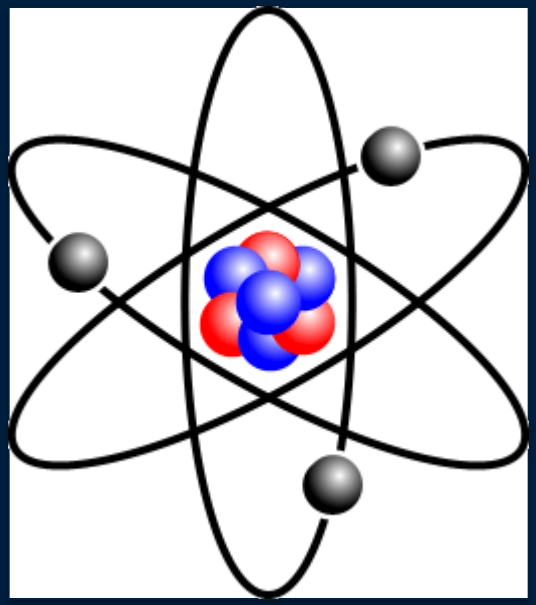
Lavoisier Mendeleev Rontgen

Rutherford Boltzmann Bohr

- The indivisible chemical elements: (1777) Antoine Lavoisier
- The Periodic Table: (1871) Mendeleyev
- Statistical Mechanics: (1890) Boltzmann
- X-Rays: (1895) Röntgen
- Nucleus and electrons : (1910) Rutherford
- Quantum Theory: (1913) Bohr

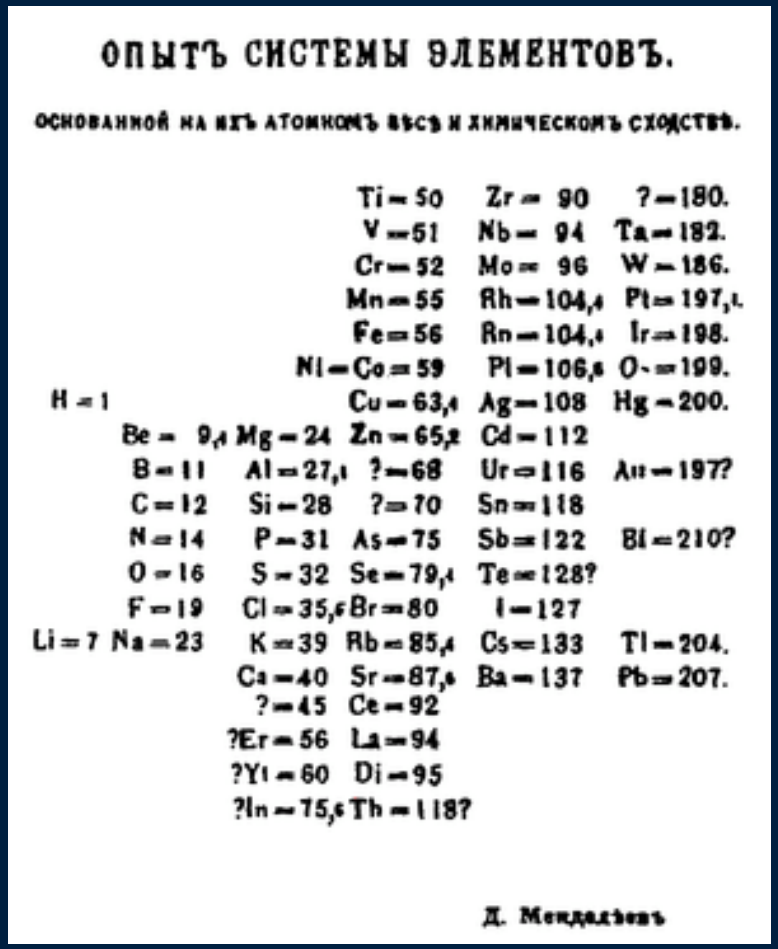
What is an atom?

The “Rutherford” atom.



A lithium atom.
Or three electrons “orbiting” around a nucleus made of three protons and four neutrons.

118 Atoms

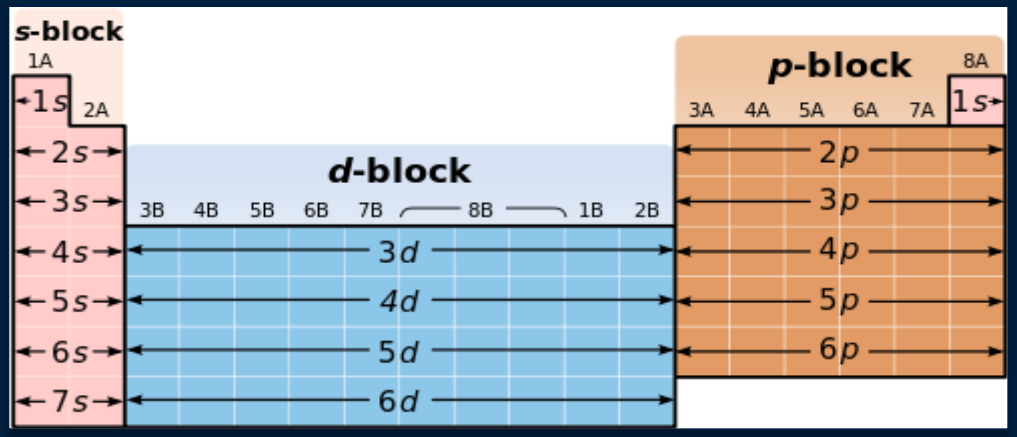


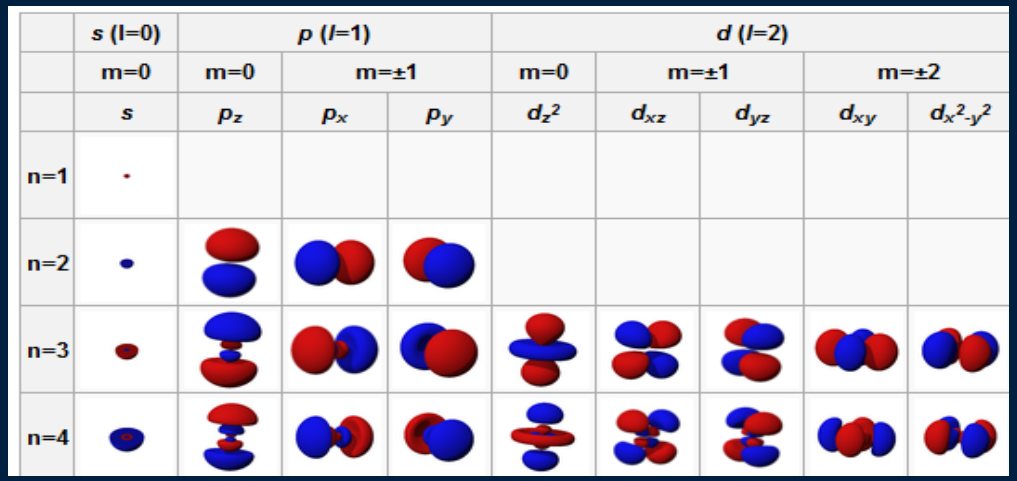
ОПЫТЪ СИСТЕМЫ ЭЛЕМЕНТОВЪ.

ОСНОВАННОЙ НА ИХЪ АТОМНОМЪ ВѢСѢ И ХИМИЧЕСКОМЪ СХОДСТВѢ.

		Ti=50	Zr=90	?=180.
		V=51	Nb=94	Ta=182.
		Cr=52	Mo=96	W=186.
		Mn=55	Rh=104,4	Pt=197,4
		Fe=56	Rn=104,4	Ir=198.
		Ni=Co=59	Pl=106,6	Os=199.
H=1		Cu=63,4	Ag=108	Hg=200.
Be=9,4	Mg=24	Zn=65,2	Cd=112	
B=11	Al=27,4	?=68	Ur=116	Au=197?
C=12	Si=28	?=70	Sn=118	
N=14	P=31	As=75	Sb=122	Bi=210?
O=16	S=32	Se=79,4	Te=128?	
F=19	Cl=35,5	Br=80	I=127	
Li=7 Na=23	K=39	Rb=85,4	Cs=133	Tl=204.
	Ca=40	Sr=87,6	Ba=137	Pb=207.
	?=45	Ce=92		
	?Er=56	La=94		
	?Yt=60	Di=95		
	?In=75,6	Th=118?		

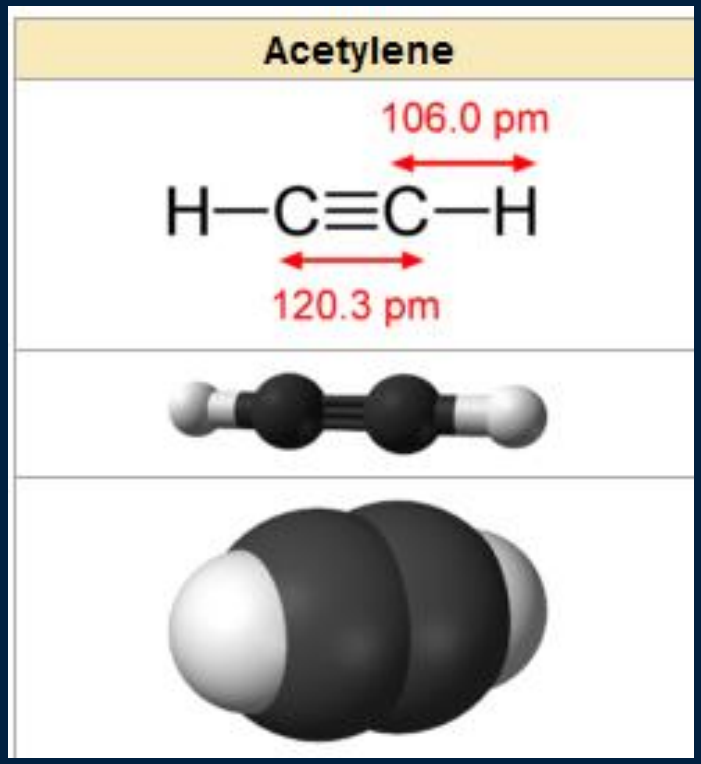
Д. Менделѣевъ





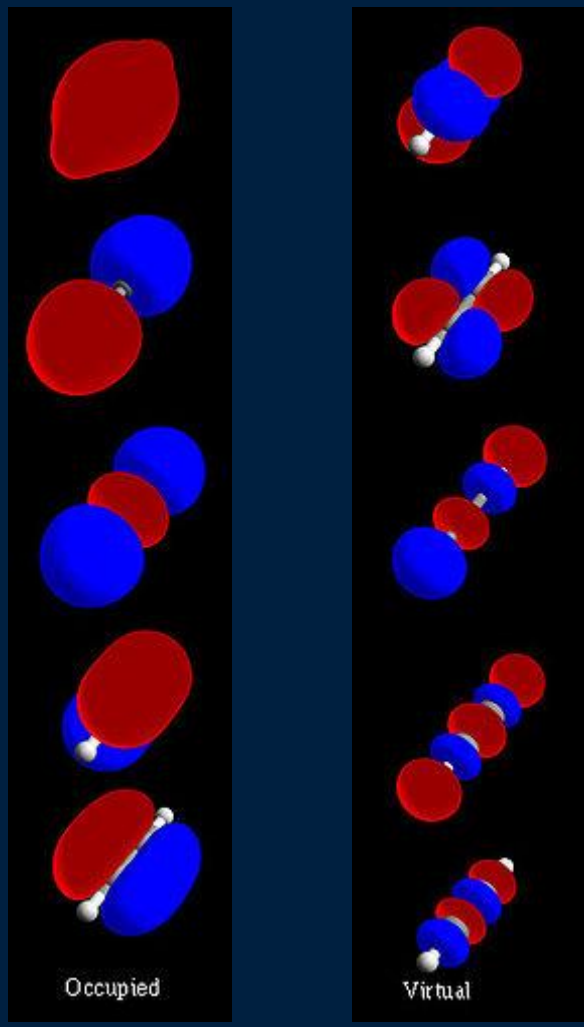
The source of order in the Mendeleyev table originate in the intimate electronic shell of atoms.

From an atom to a molecule



Tight binding description:
New electronic structure is build upon the elemental wave function of each atoms

$$\Psi(\mathbf{r}) = \sum_{n,\mathbf{R}} b_{n,\mathbf{R}} \psi_n(\mathbf{r} - \mathbf{R})$$



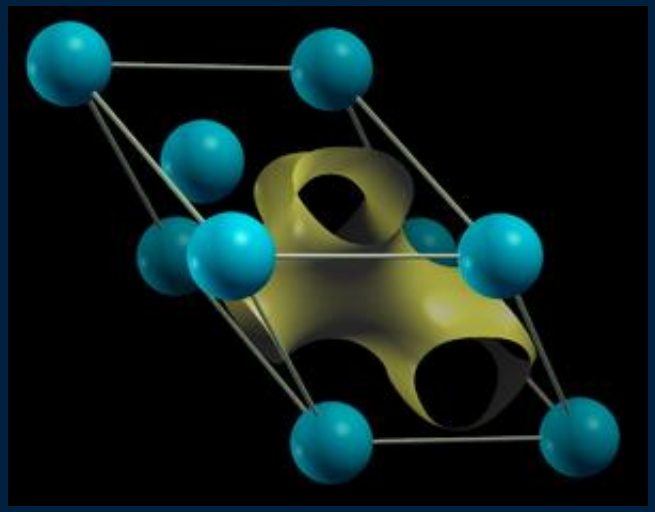
Occupied Un-Occupied

Electronic Molecular Orbitals

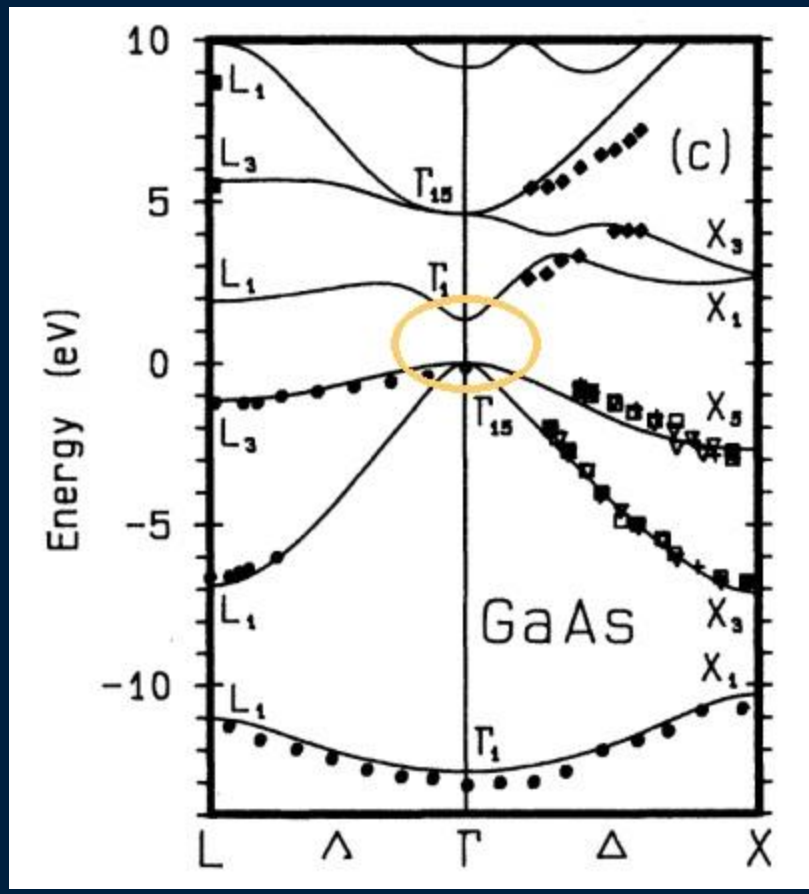
From a molecule to a solid

Electronic wavefunction is build upon the periodicity of the crystal lattice

$$\psi_{n\mathbf{k}}(\mathbf{r}) = e^{i\mathbf{k}\cdot\mathbf{r}} u_{n\mathbf{k}}(\mathbf{r}).$$



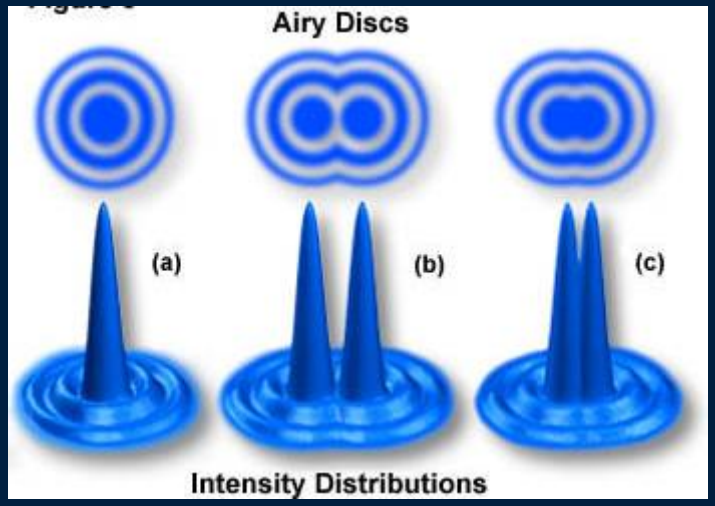
Bloch wave equipotential in AsGa lattice

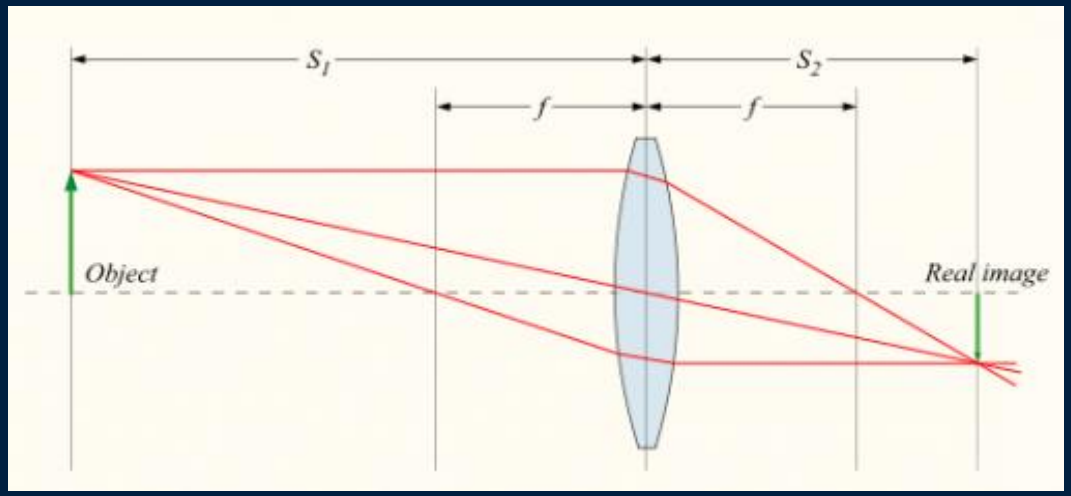


Band structure of GaAs
Note the semiconducting Gap at Ef=0

Can we "see" atoms ?

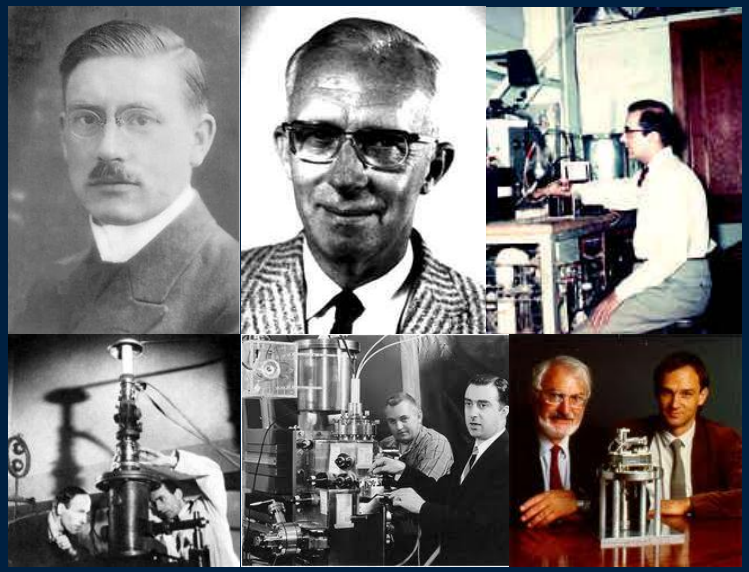
What is seeing?
Projection of an interacting particle from an object onto a detector





Not with usual photons.
Limited by diffraction at 500nm

In touch with atoms



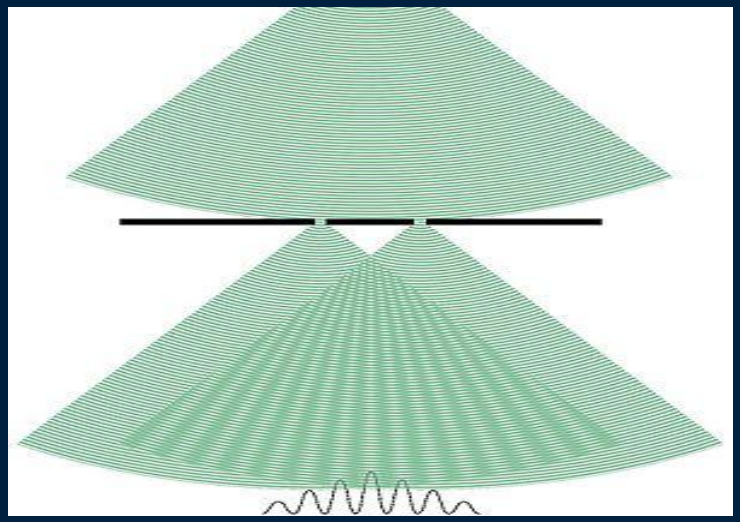
Debye Muller Bahadur

Ruska Crewe Binning & Rohrer

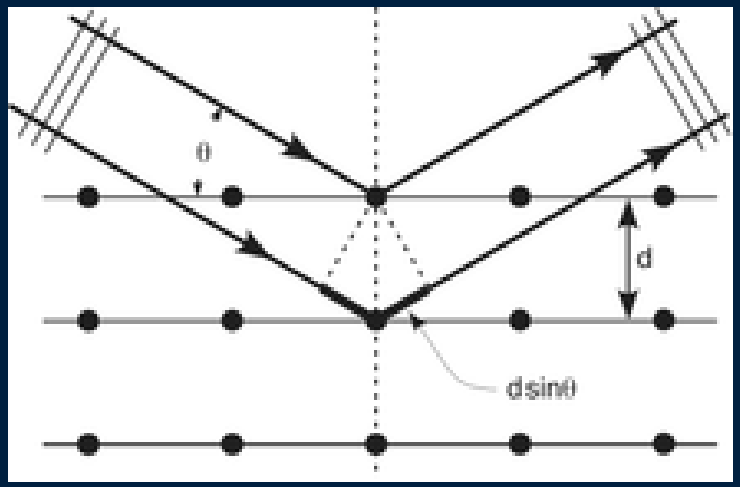
- **X-ray diffraction:** Atoms in the reciprocal space (1920) P. Debye.
- **Field Ion Microscope:** Atoms on a tip (1971) E.W. Muller and K. Bahadur.
- **Transmission Electron Microscope:** 3D sample with atomic resolution (1931-1970) Ruska to A. Crewe.
- **Scanning Probe Microscope:** The almighty microscope for surface (1981) G. Binning and H. Rohrer

Seeing atoms: X-Rays diffraction

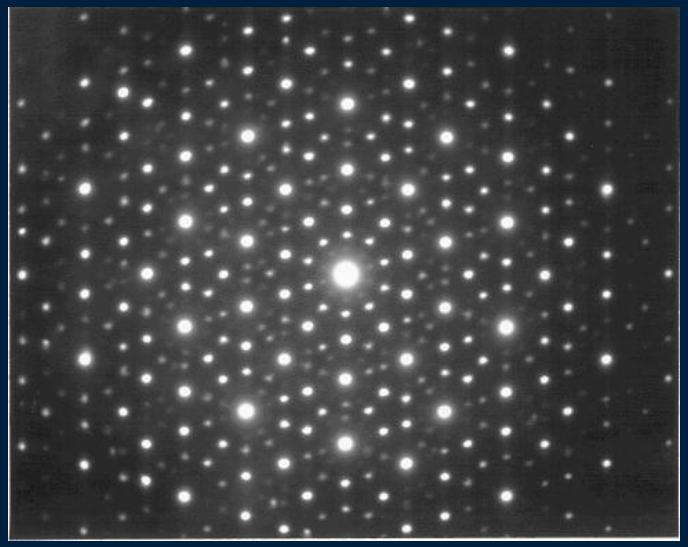
The Fresnel two slit experiment



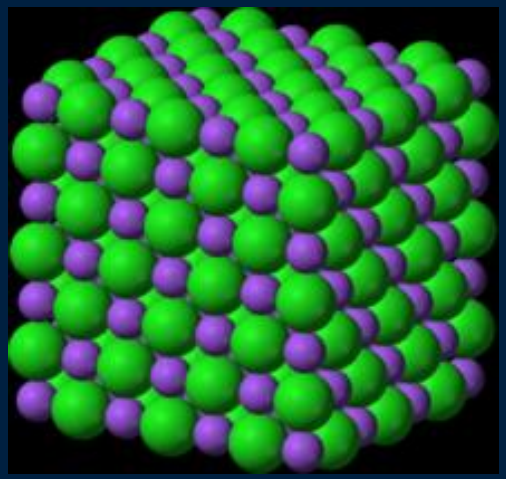
Coherent diffraction of an organized arrays of atoms.



Typical X ray diffraction cliche



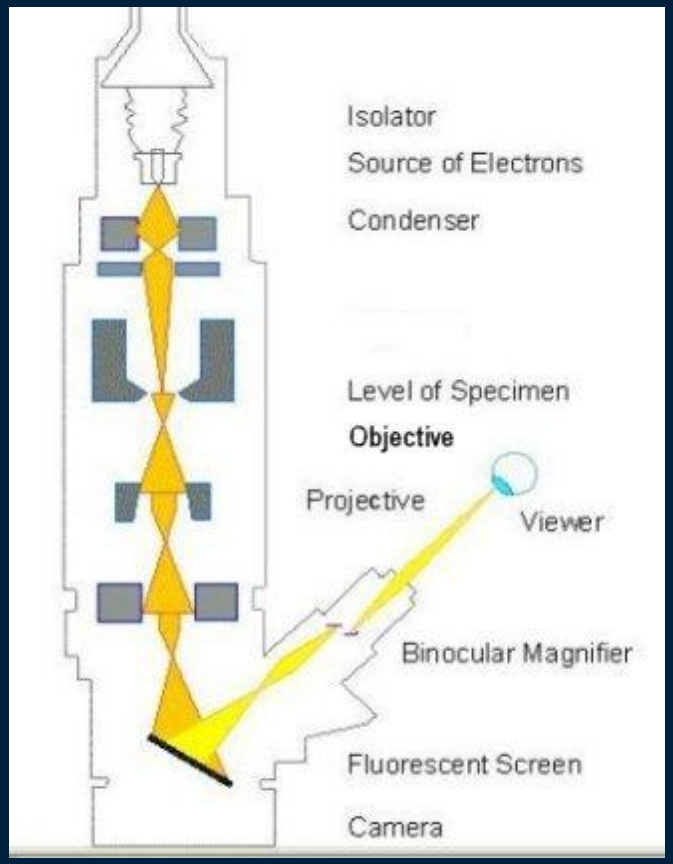
Atoms favor periodic arrangement



Electron Microscope

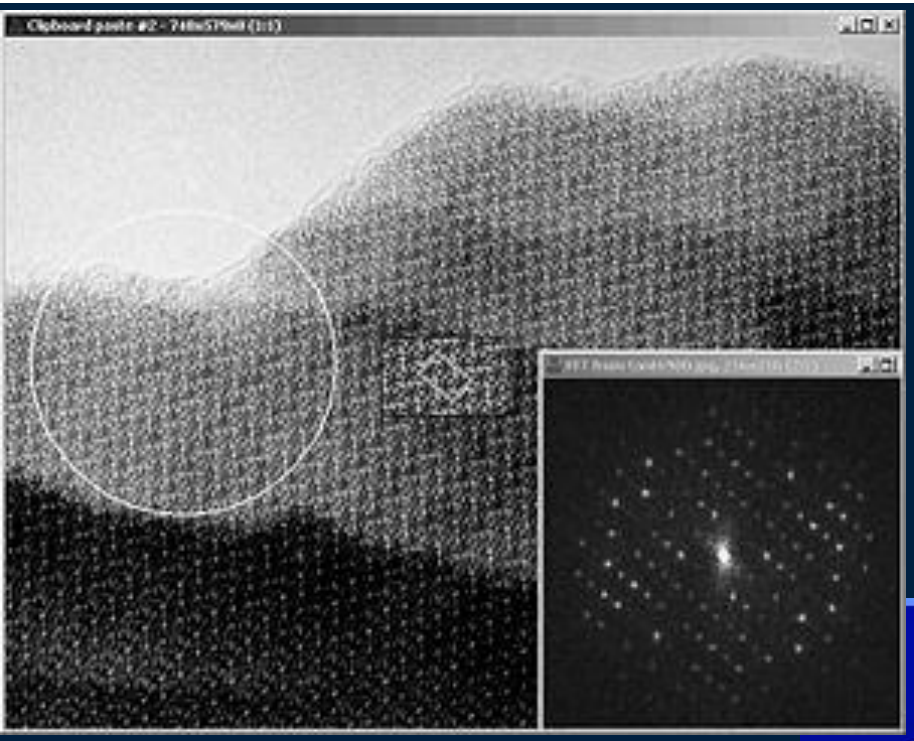
The original (1930)

Principle of operation

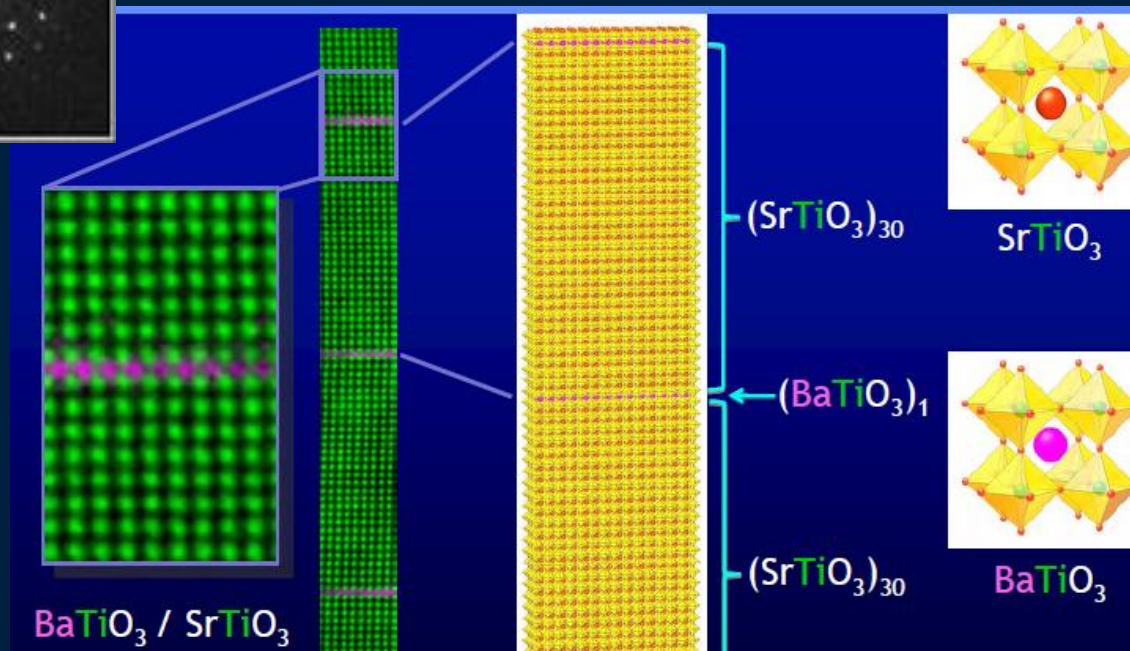


The modern (2010)

Electron Microscope



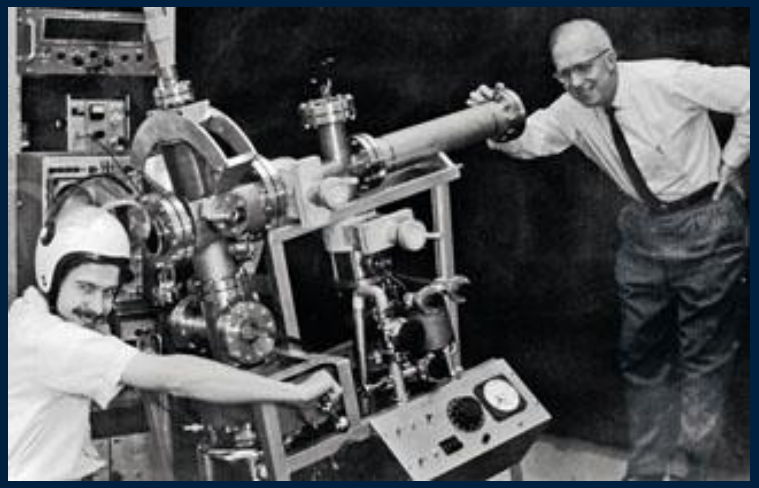
Inverse Fourier Transform of a diffracted electron beam on a crystalline multilayer



High Resolution
Scanning Electron Microscope
Electron Energy Loss Spectrometer

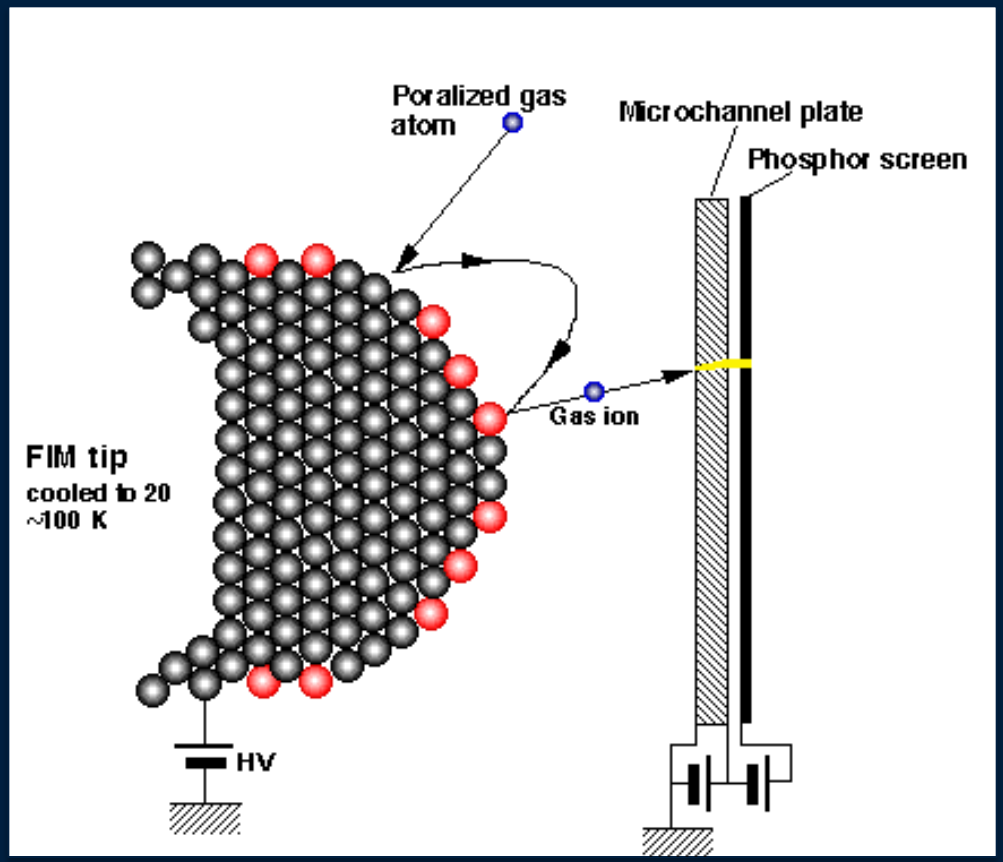
Field Ion Microscope

The Original FIM



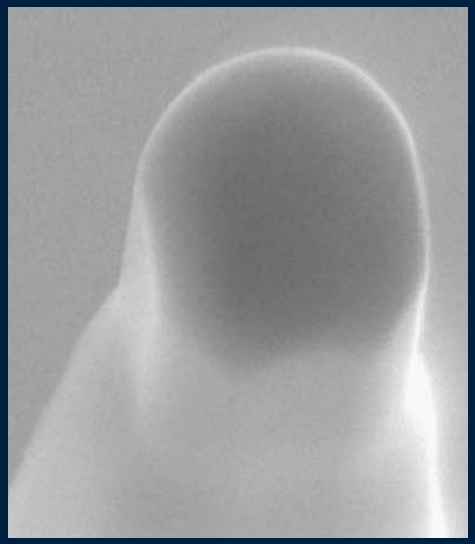
Modern Zeiss FIM

Principle of operation

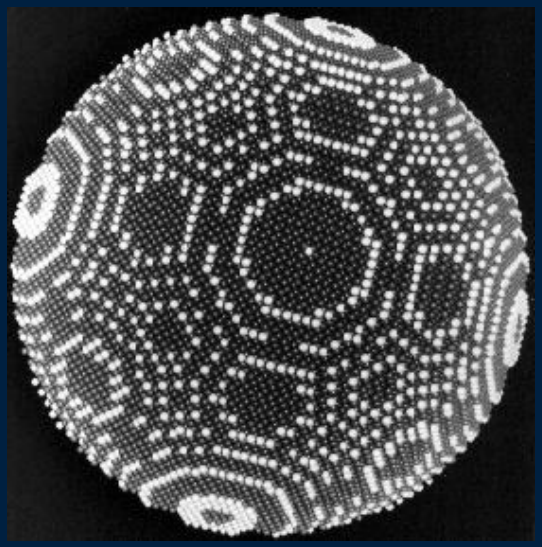


Field Ion Microscope

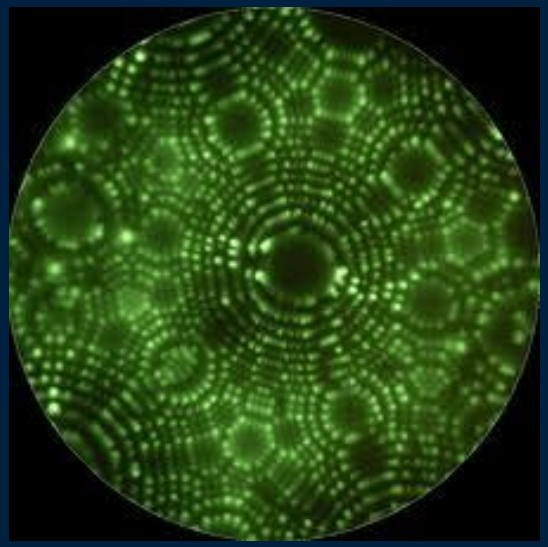
Scanning Electron Micrograph of a W tip



Atomistic modelling of the tip apex

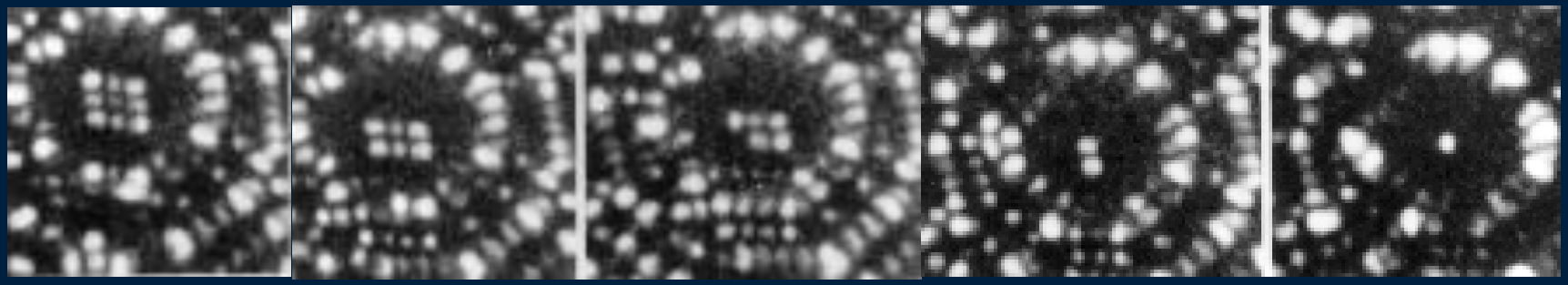


Field Ion Micrograph

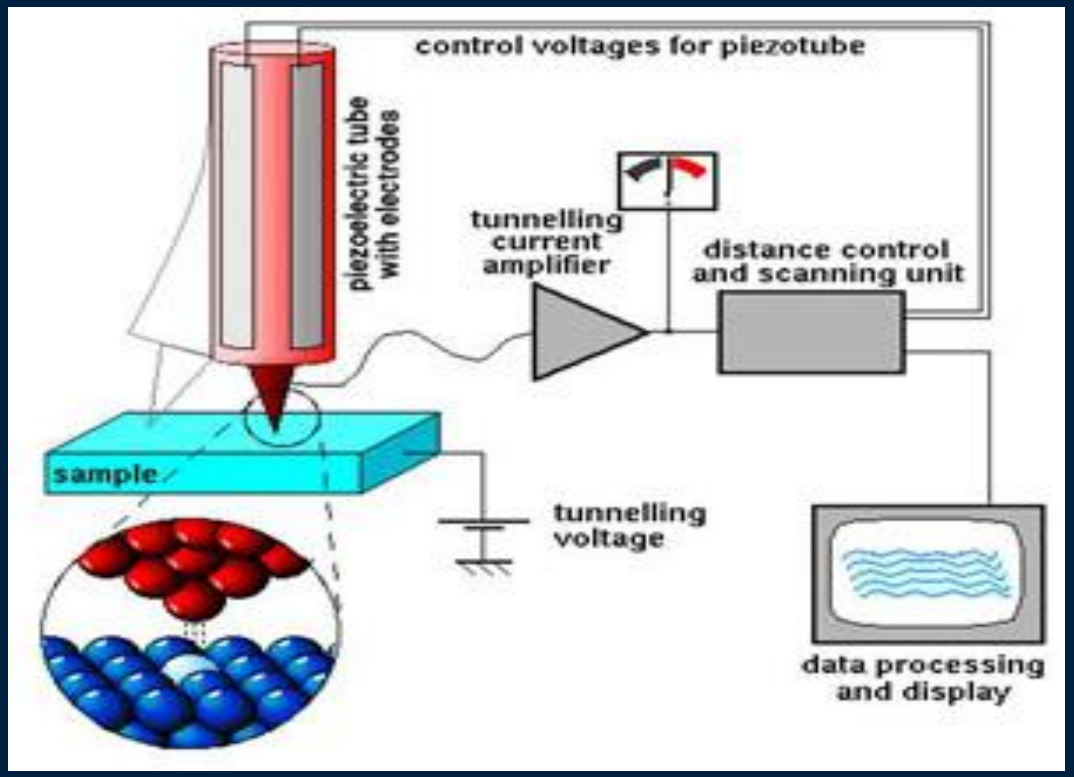


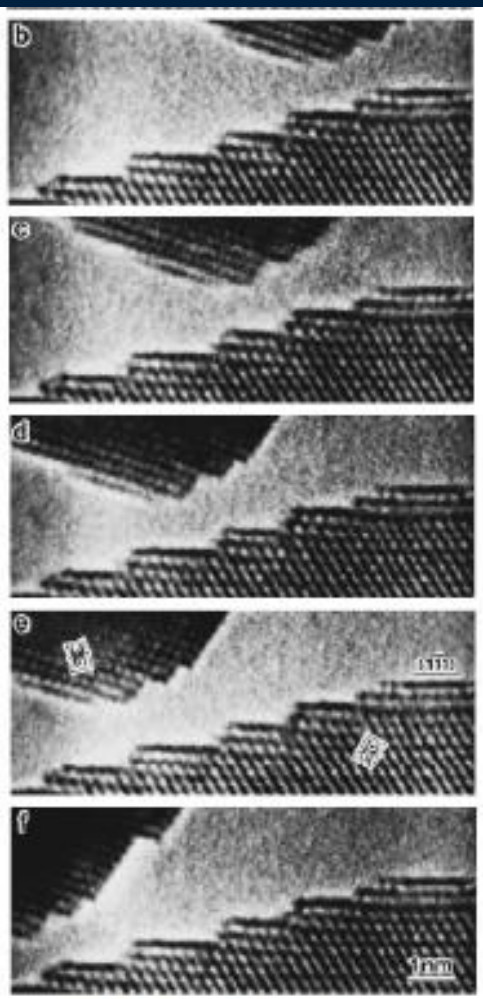
20nm

Sharpening a tip one atom at the time!



The Scanning Tunneling Microscope

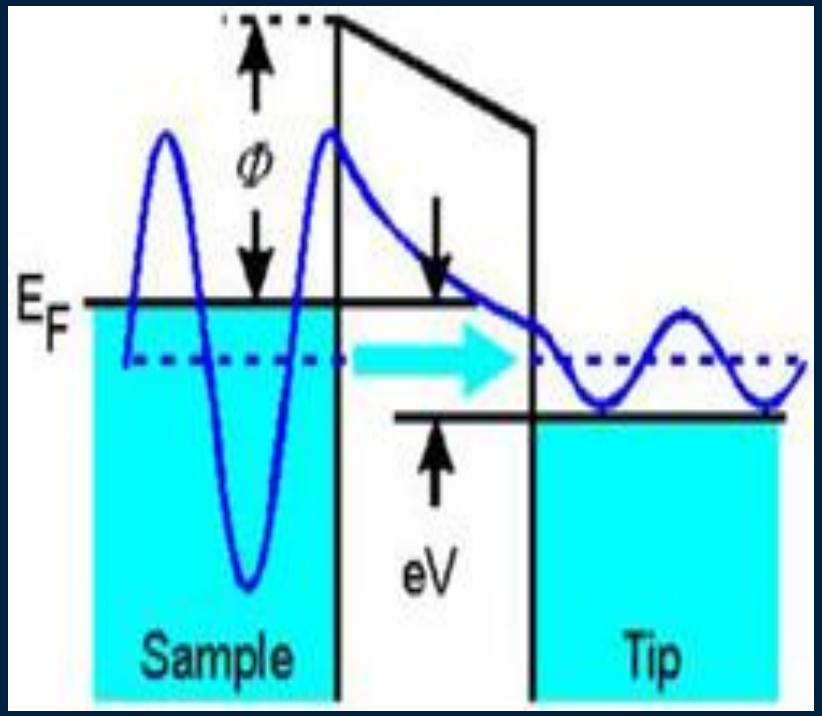




Kizuka et al., Phys. Rev. B 55, R7398 (1997)

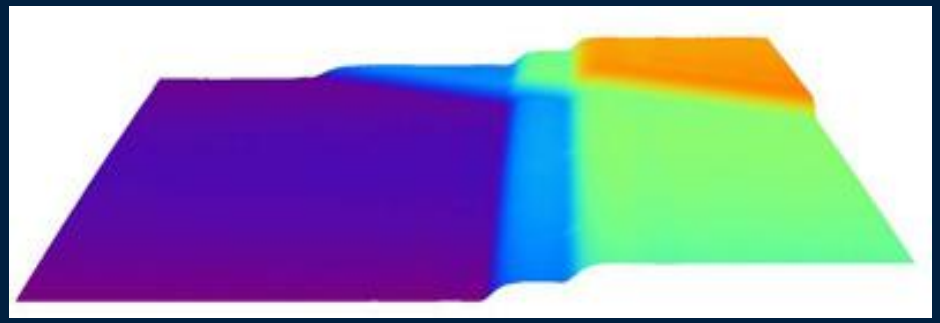
Bring a tip at within atomic reach to a surface
Measure a tunneling current (It) with a high gain amplifier
Stabilize the tip with a feedback loop on It
Track the tip height variation as the tip is raster in the XY plane
Process the signal to form a 3D rendering of the tip trajectory

Electron tunneling 101



$$I \approx Ue^{-2\frac{\sqrt{2m\Phi}}{\hbar}D}$$

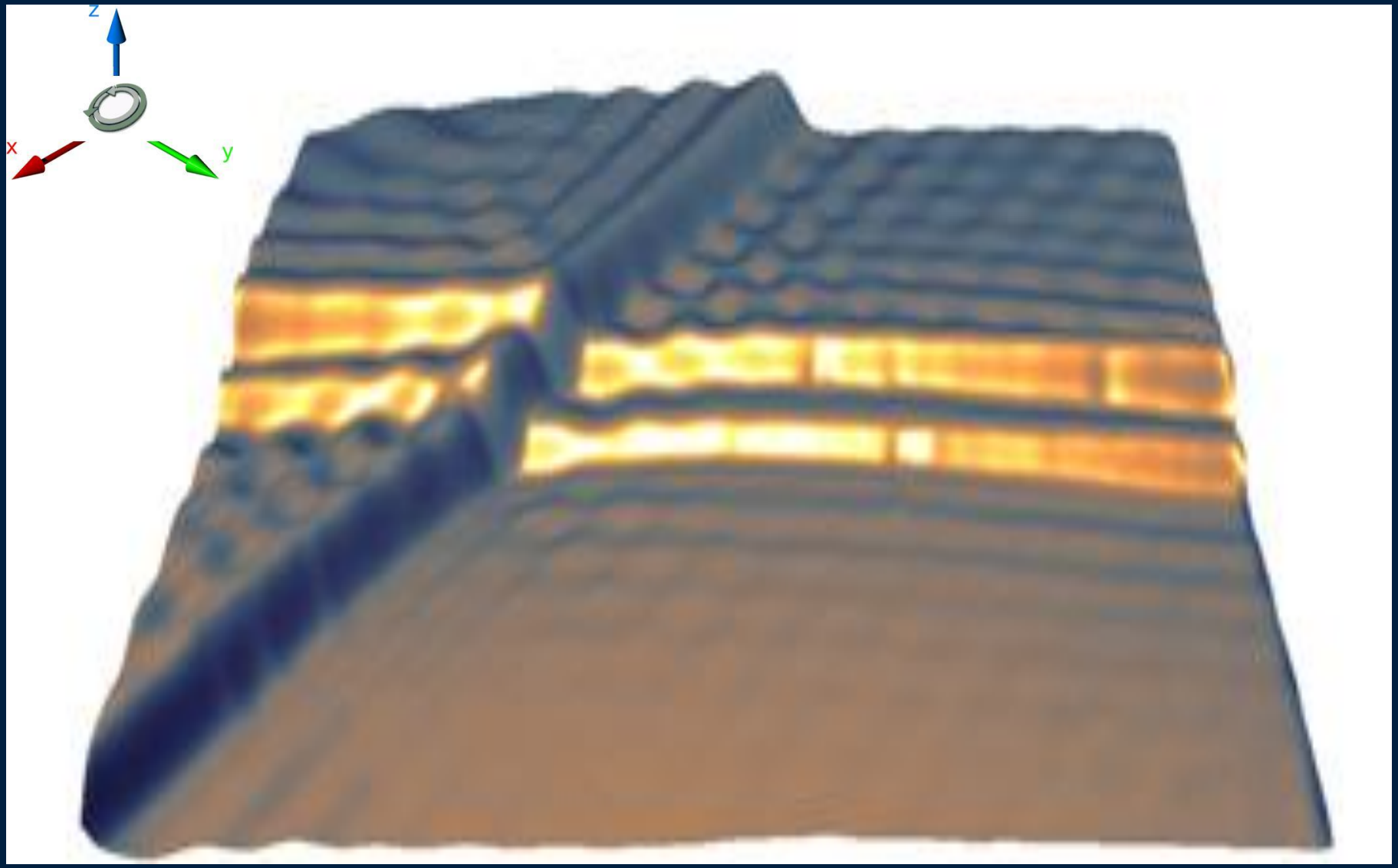
I_t decays exponentially with an increasing barrier width
Characteristic decay length equal 10^{-10}m ,
the size of an atom!



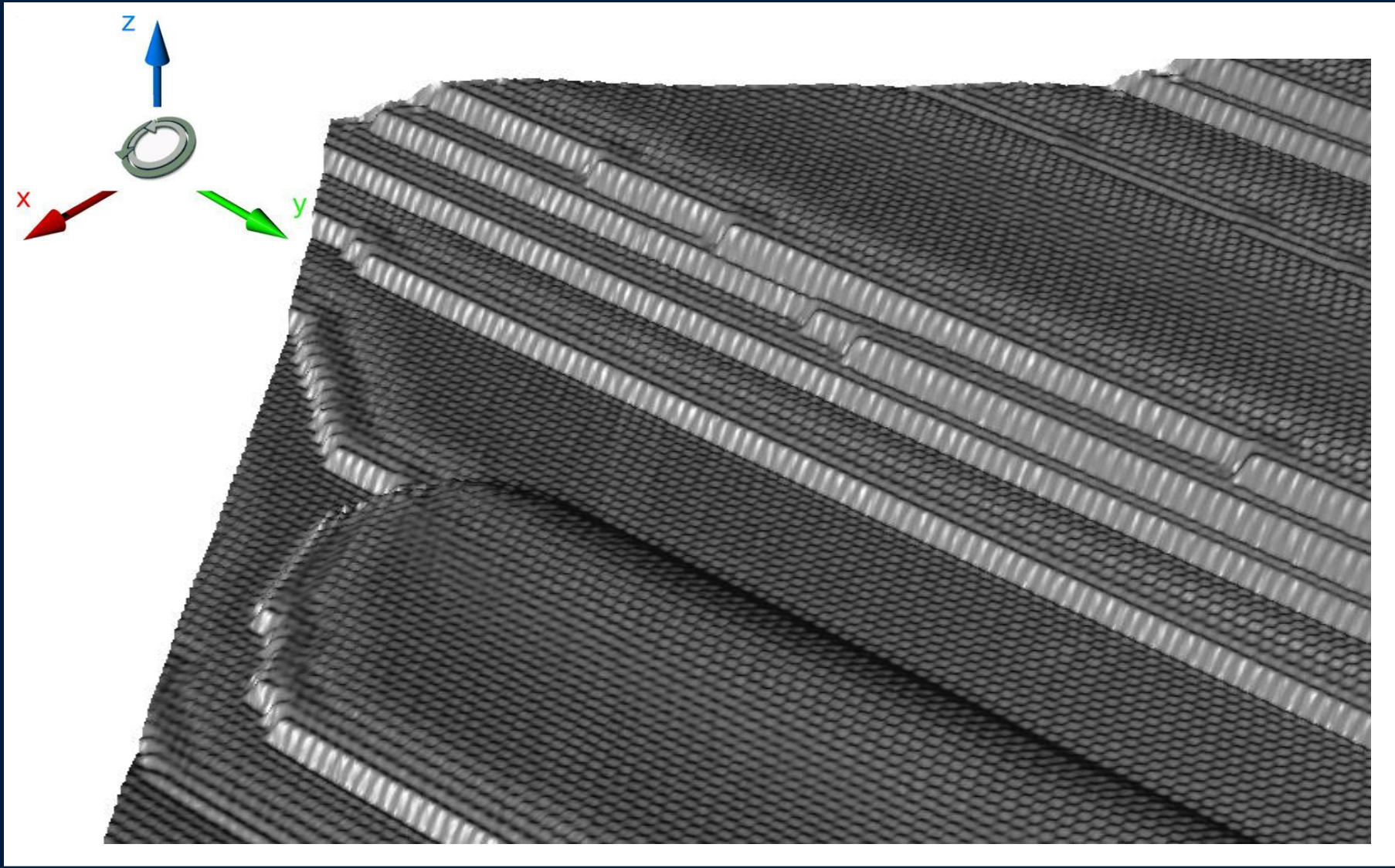
Plane wave travelling trough an energy barrier defined by the work function of the sample from the sample to the tip separated by an external bias eV

40*40nm STM image of the Silver 111 surface showing four distinct atomic terraces.

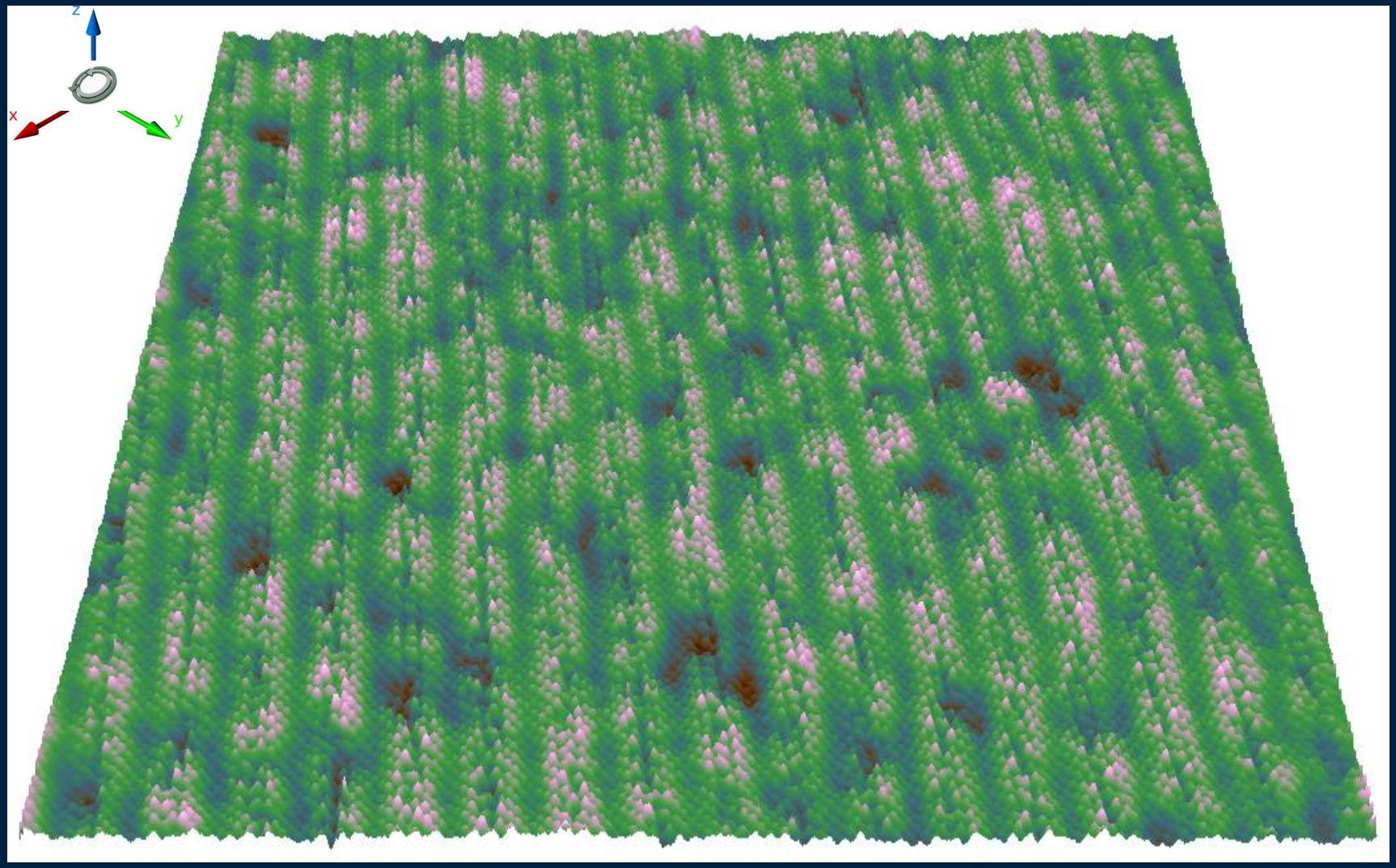
Fermi Liquid Sunset on Ag 111.



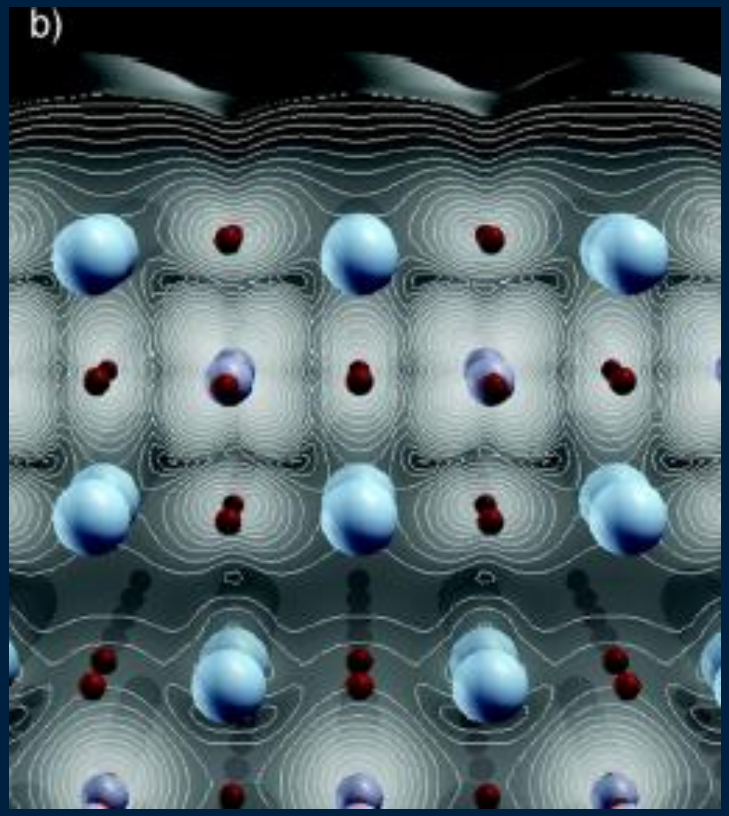
Bi 111 Atomic Landscape by STM (2011)



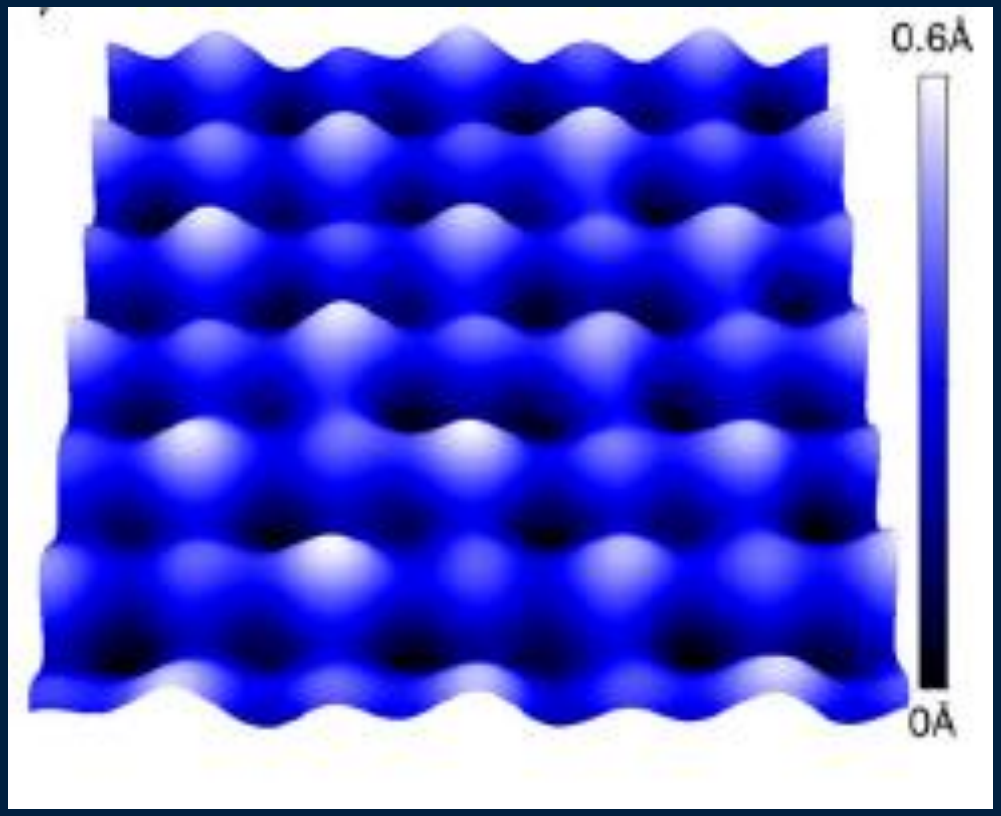
BiSrCaCuO 100 Atomic Landscape by STM (2011)



Density Functional Theory vs. STM on SrRuO



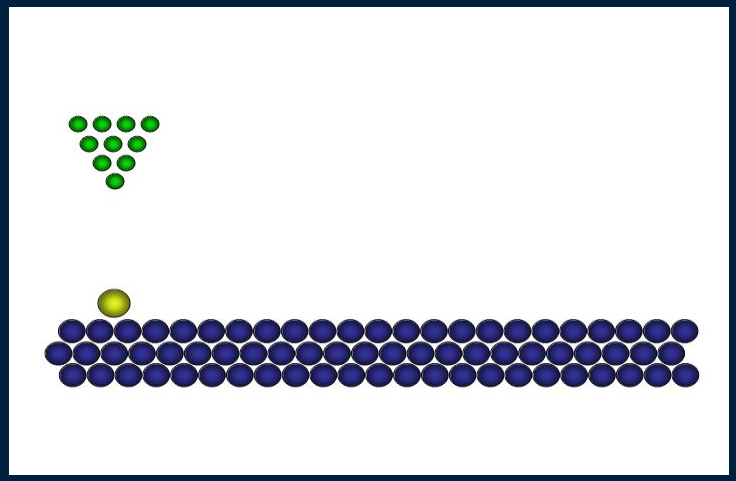
Charge density isolines from DFT at a height of 2.13 A°.

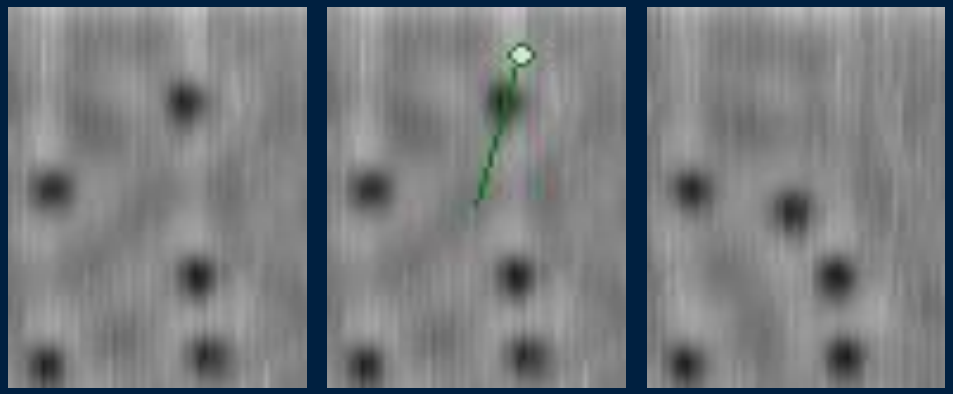


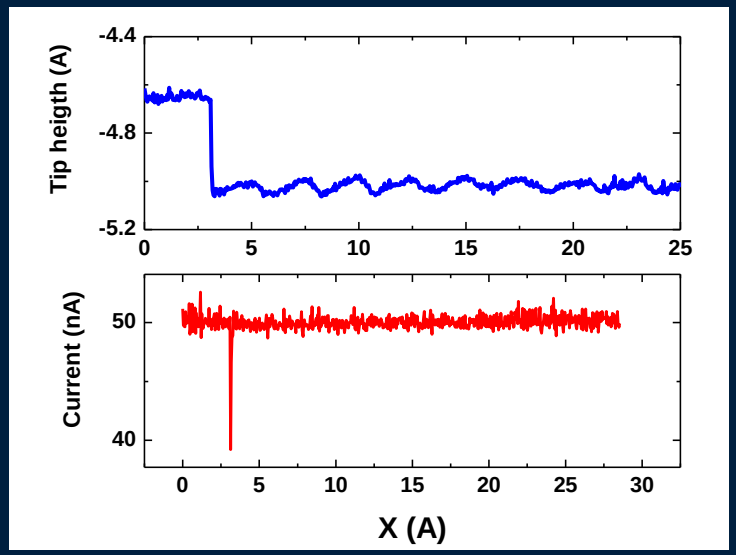
High Resolution STM showing Sr centered resolution

Atomic manipulation

Pushing Carbon Monoxide around

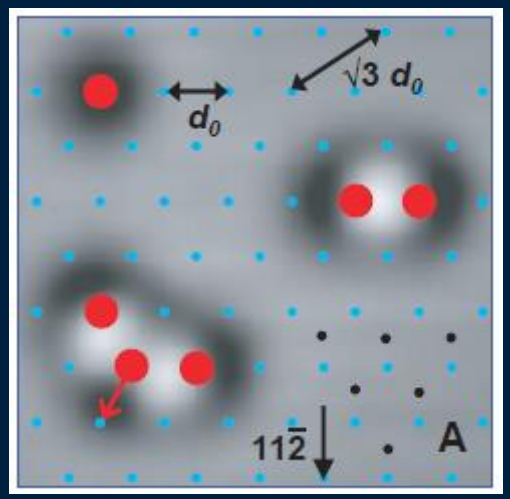




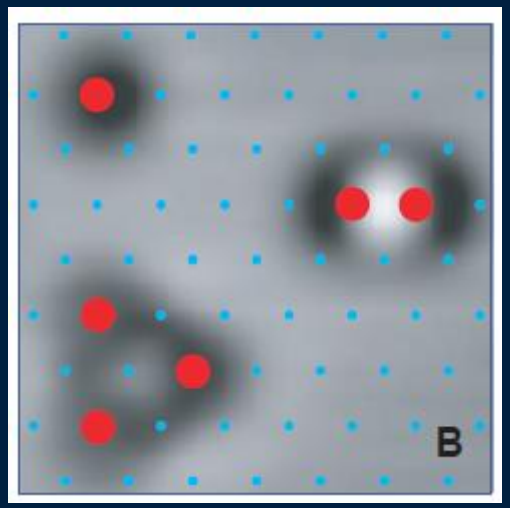


The atomic domino computer I

the tipping point!



few minutes

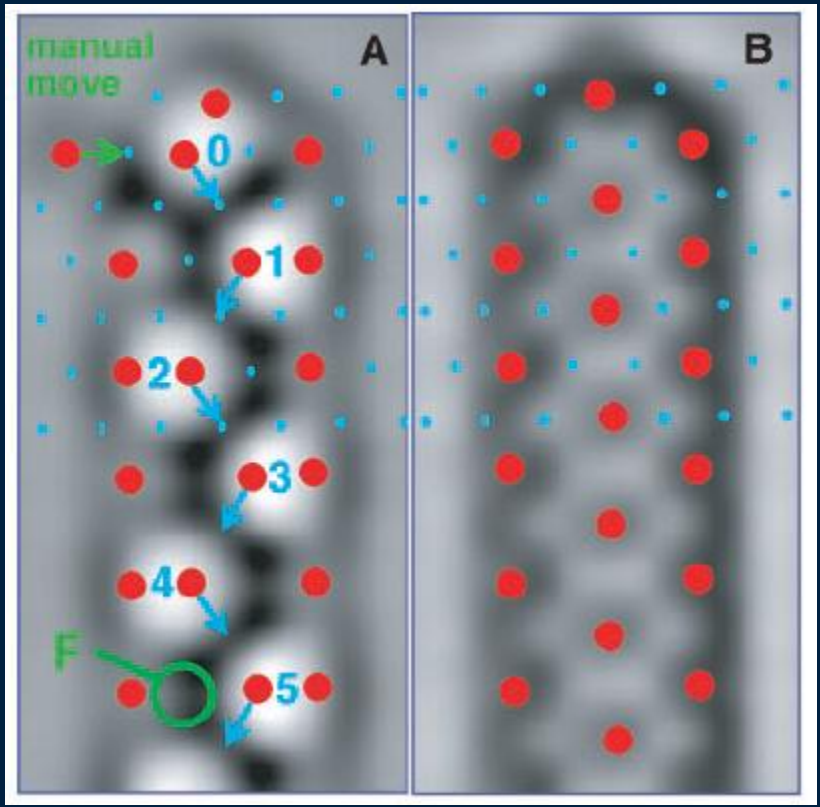


One CO molecule is stable
Two CO molecules are stable
But three CO molecules want to form a perfect triangle

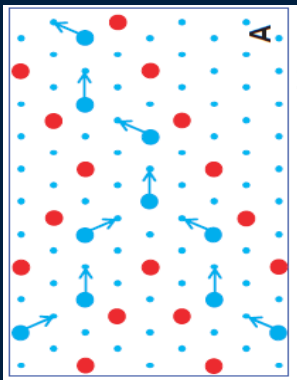
Molecule Cascades
A. J. Heinrich, C. P. Lutz, J. A. Gupta and D. M. Eigler (2002)

The atomic domino computer II

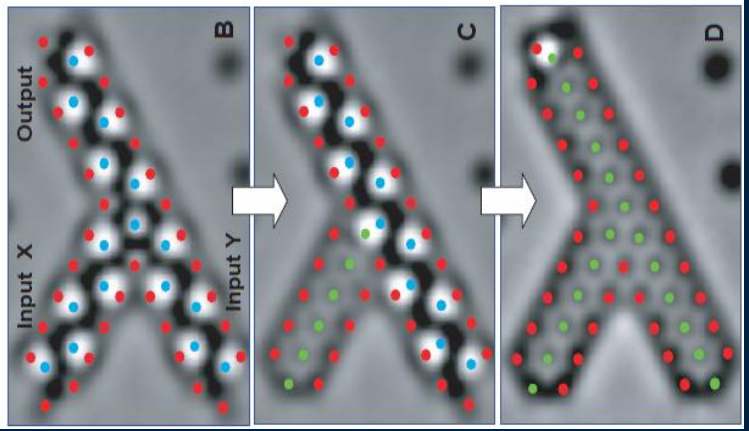
Information transport



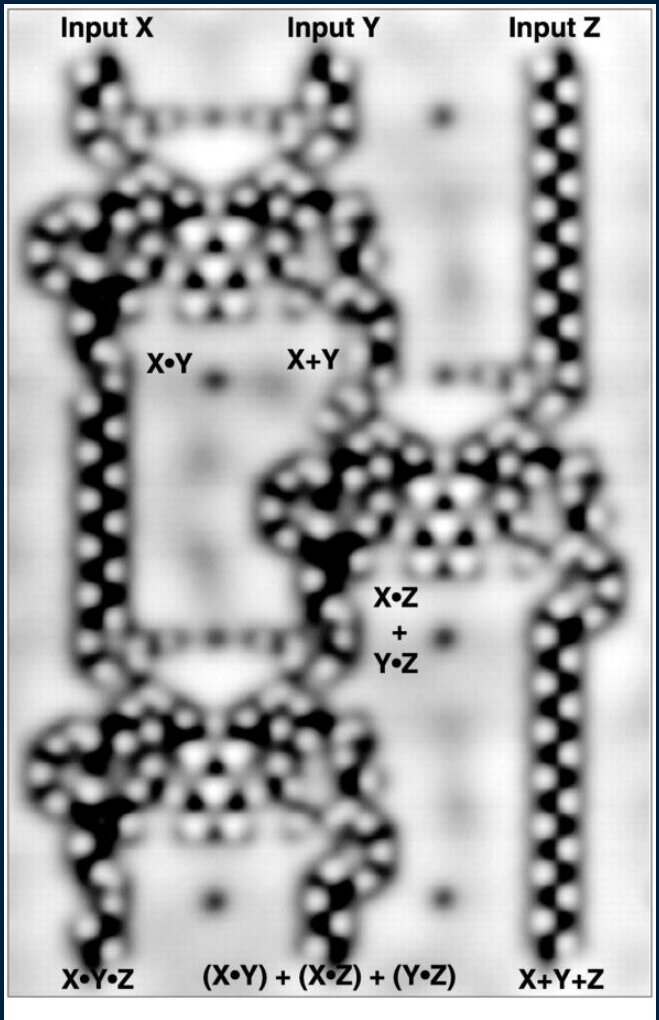
Building an AND gate



A	B	out
0	0	0
0	1	0
1	0	0
1	1	1



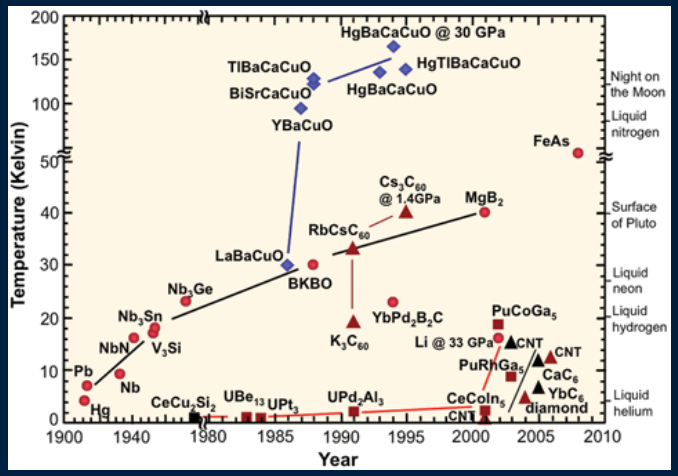
The atomic domino computer III



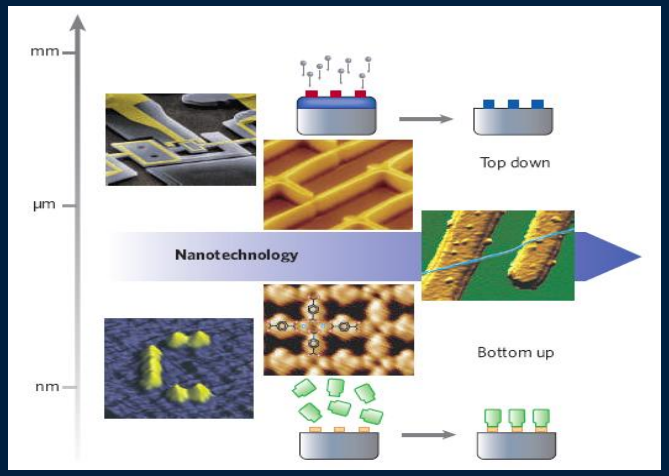
A 200nm^2 three input sorter.
Its CMOS equivalent is 10^5 bigger!

Other fields we are working on.

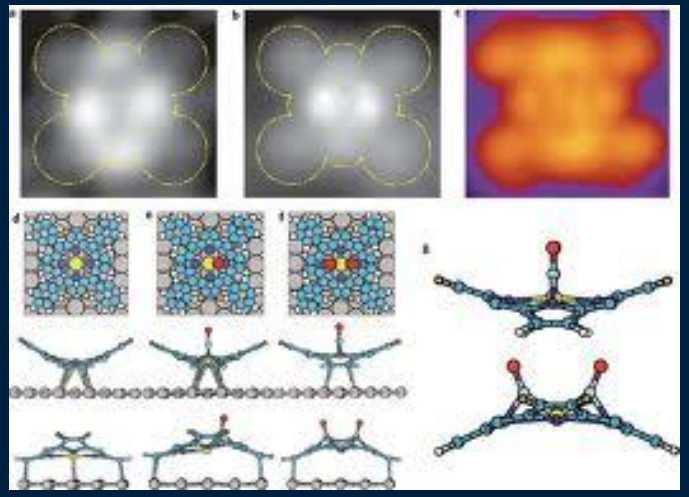
High Tc-superconductivity



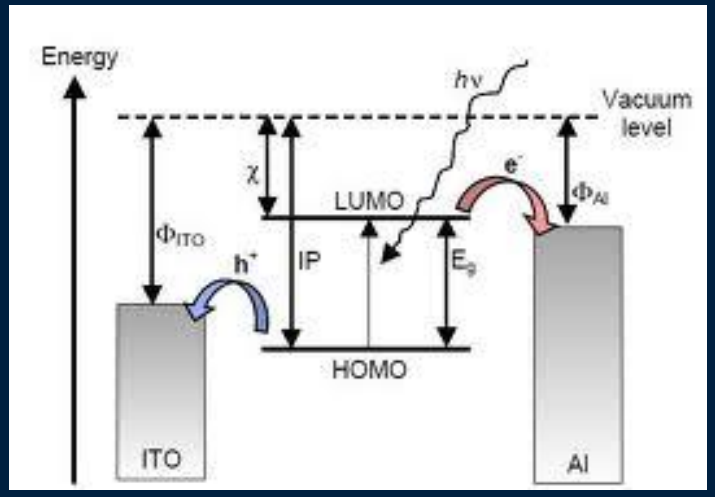
Architecture in the NanoCosmos



Quantum Spintronics

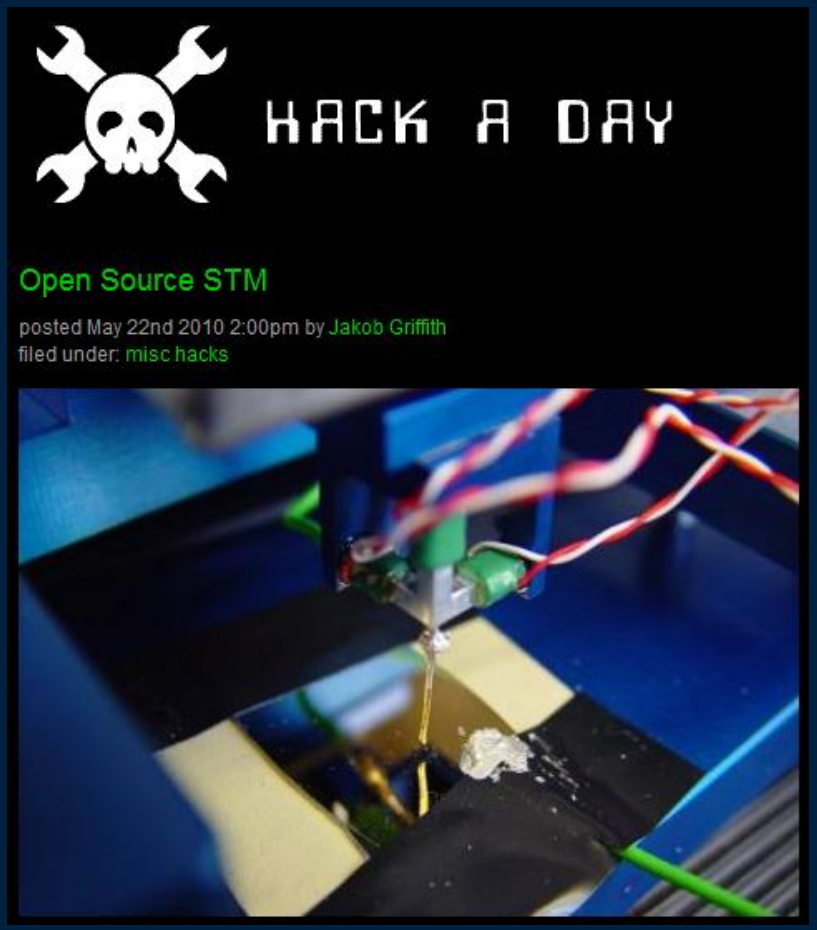


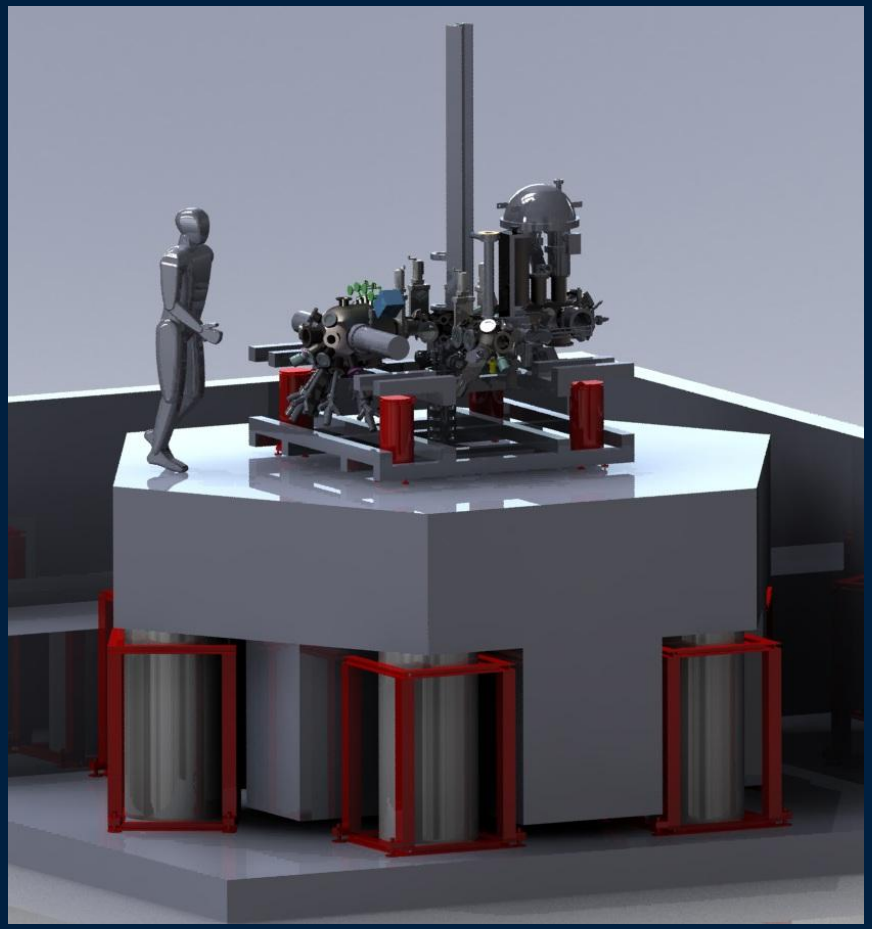
Efficient organics light harvesting device



Building a state of the art STM.

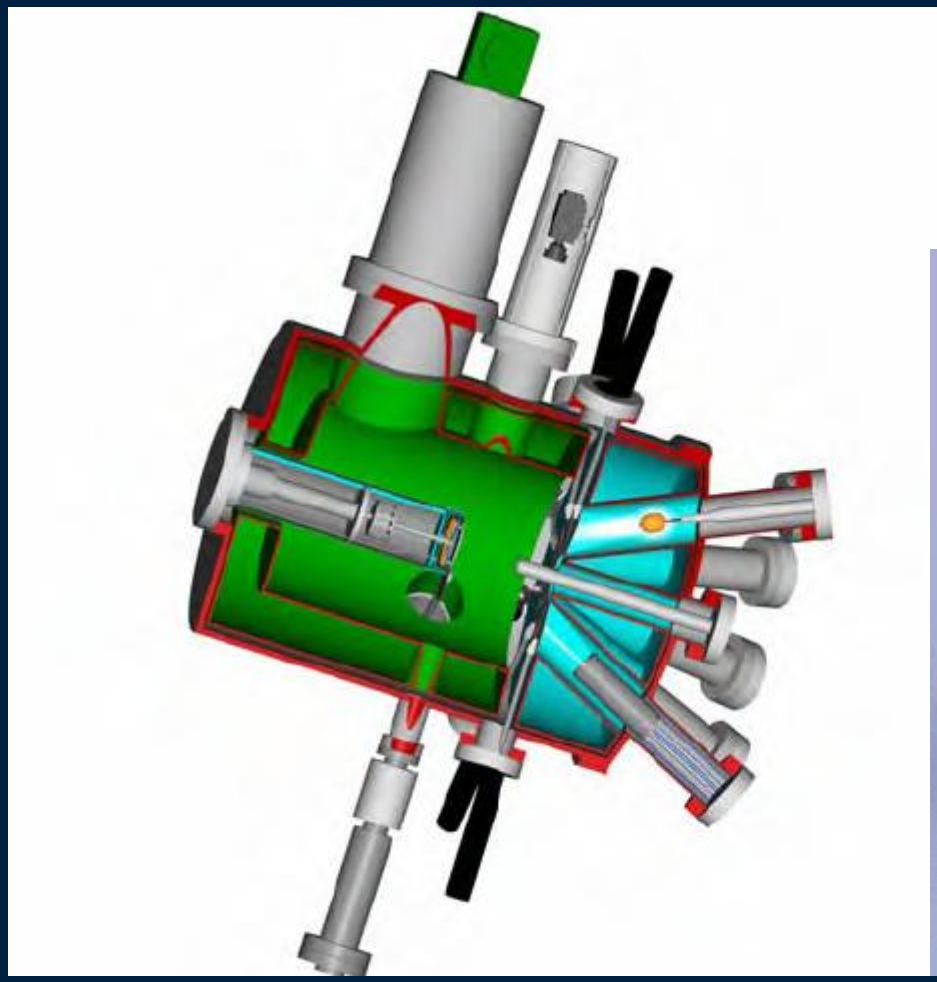
Instrumentation: from a few pennies to M$++

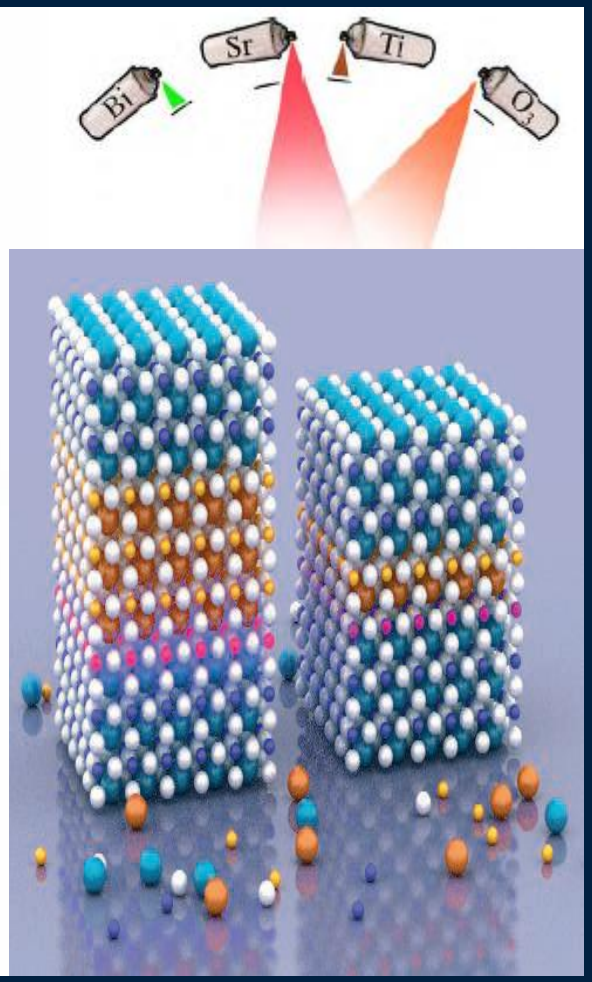




From a single piezoelectric tube to highly controlled environment

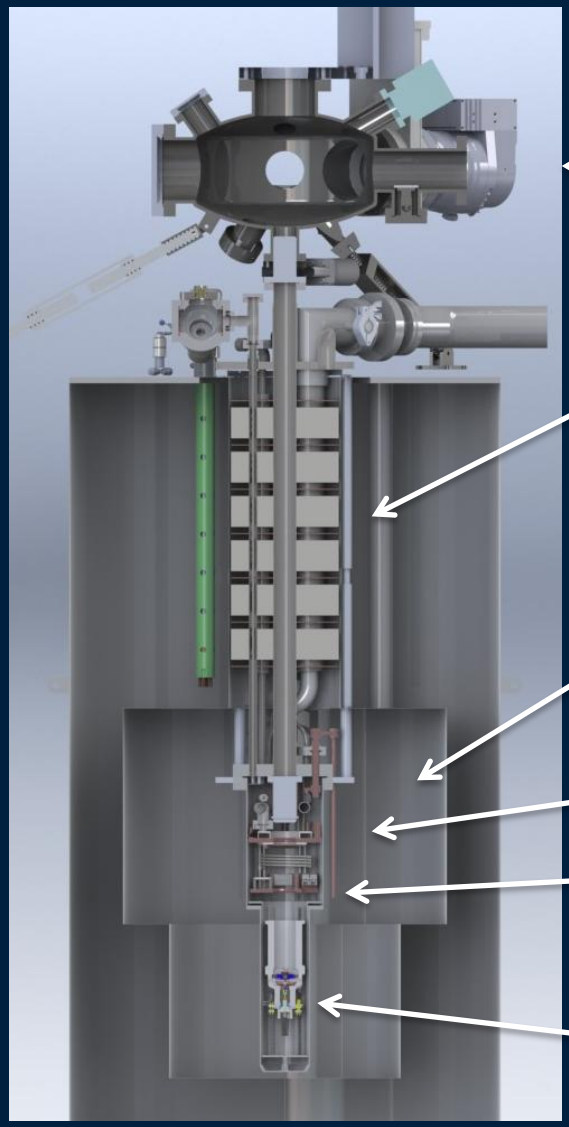
Sample: building one atom at the time





Molecular beam epitaxy in Ultra High Vacuum

A quest for lower temperature



Freeze it!

Room Temperature
300K

Isolation Neck
Vacuum + Radiation shield + low conduction mechanical support

Helium 4 Bath 4.2 K

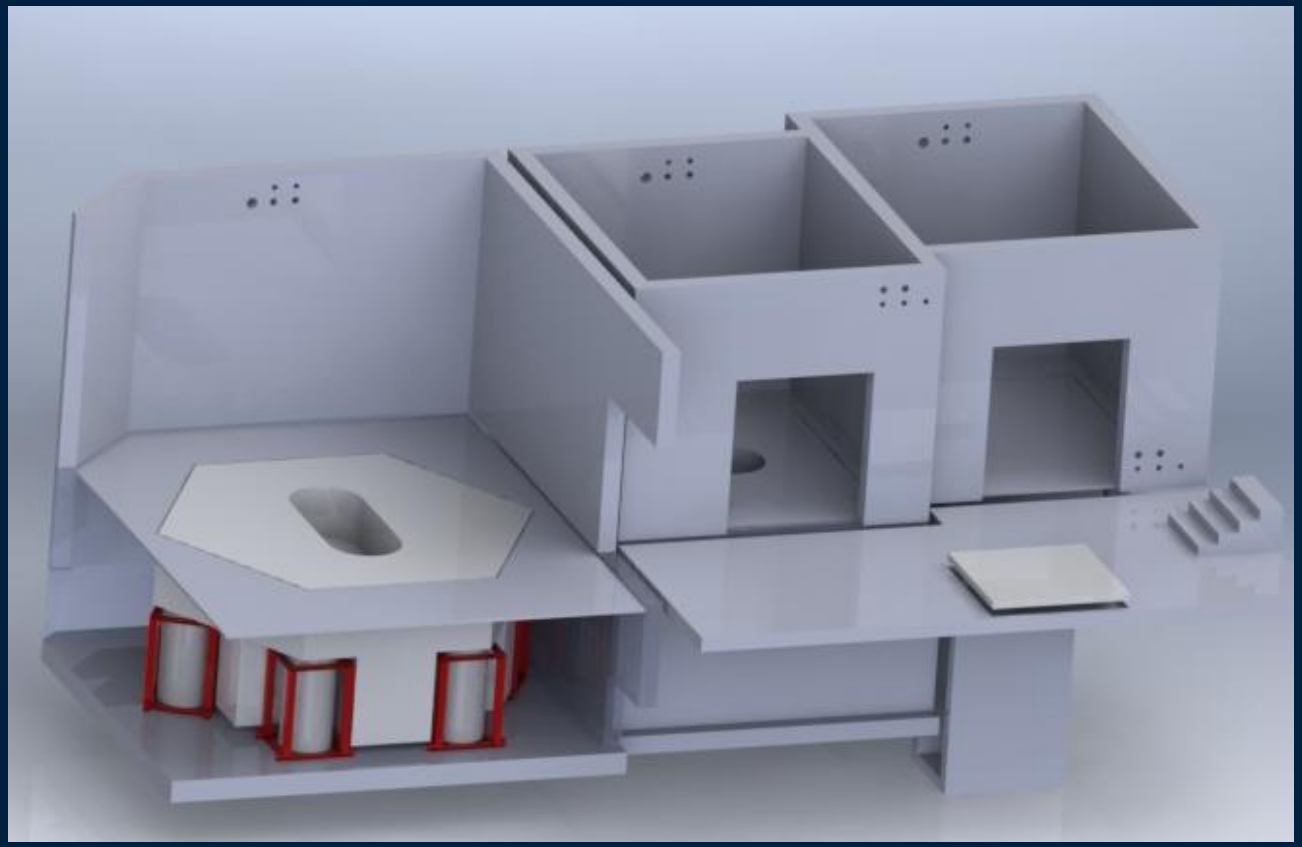
He4/He3 Joule Thompson stage. 1K

He4/He3 Dilution stage 50mK

STM Head
in a 7T magnetic field

A vibration free space

Laboratory for Advanced Imaging Research
State-of-the-art laboratory and scanning probe microscopes for the study of novel quantum materials at the atomic scale.

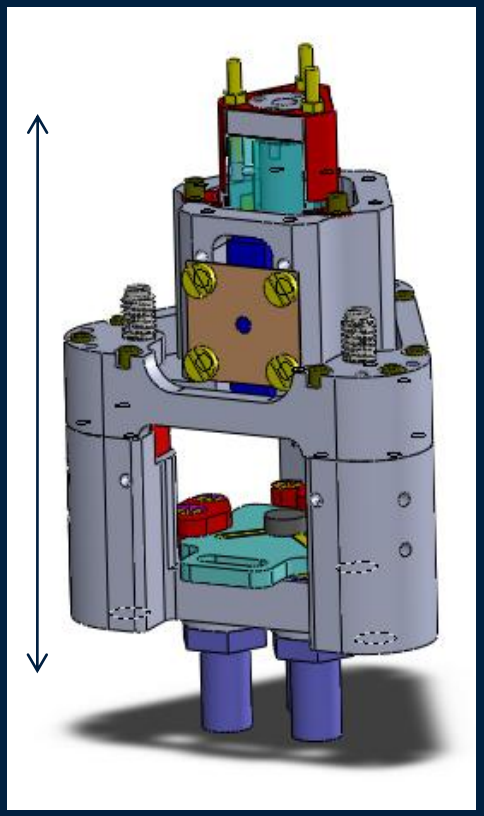


LAIR Construction (Oct 2011)

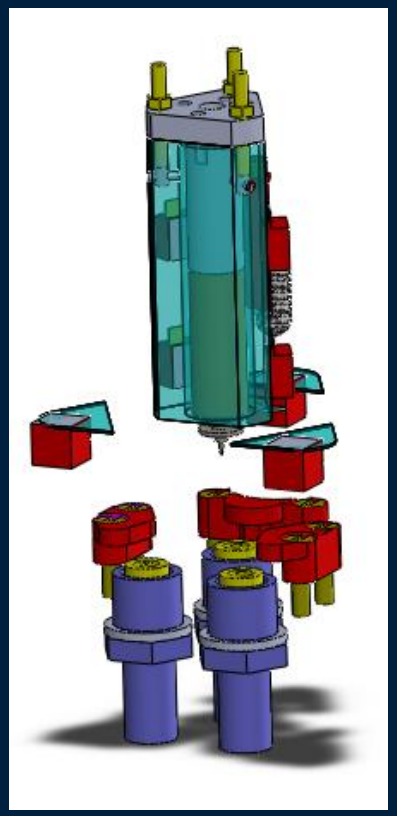
STM head

From millimetres down to angstrom

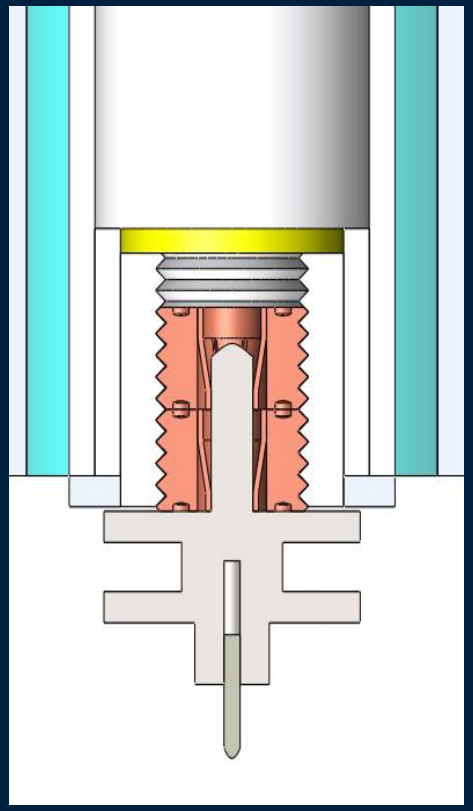
60mm



Body

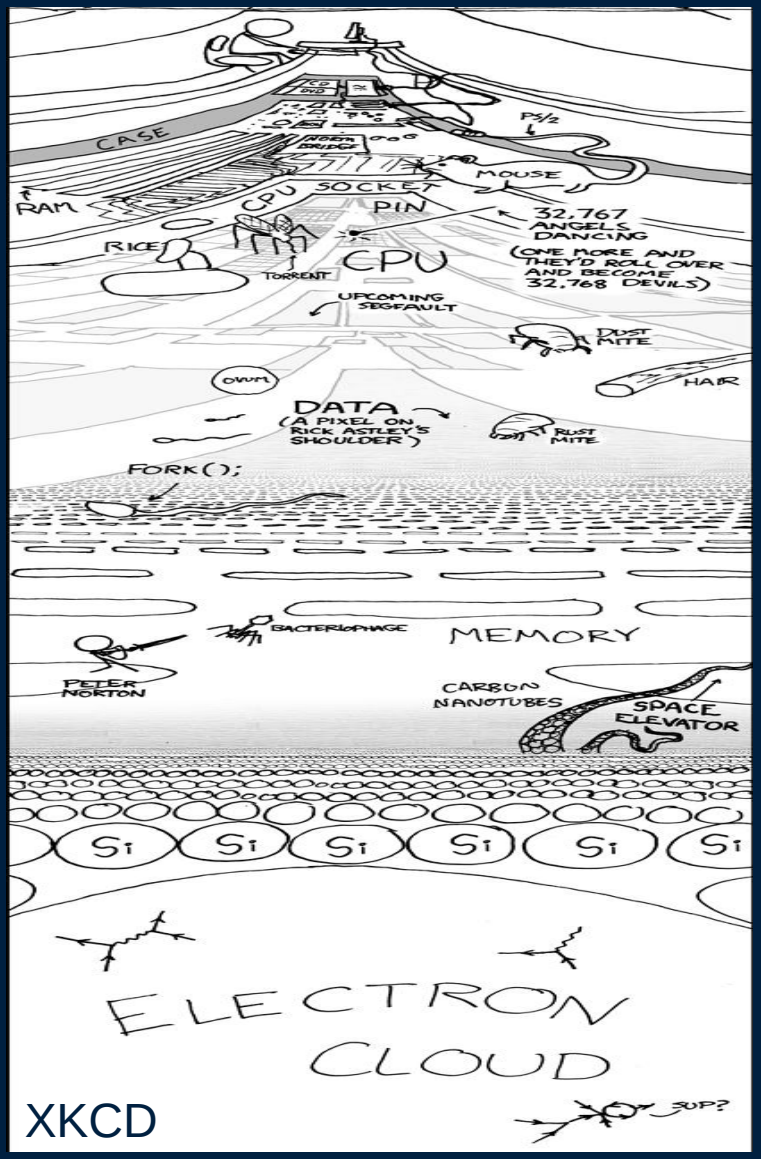


3D Inchworm 10*5*5mm travel
3 S-SMA 40 GHz connectors



In situ
Tip exchange

Conclusion



XKCD

Democritus was right!

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