History of Scanning Tunneling Microscopy

Roland Wiesendanger

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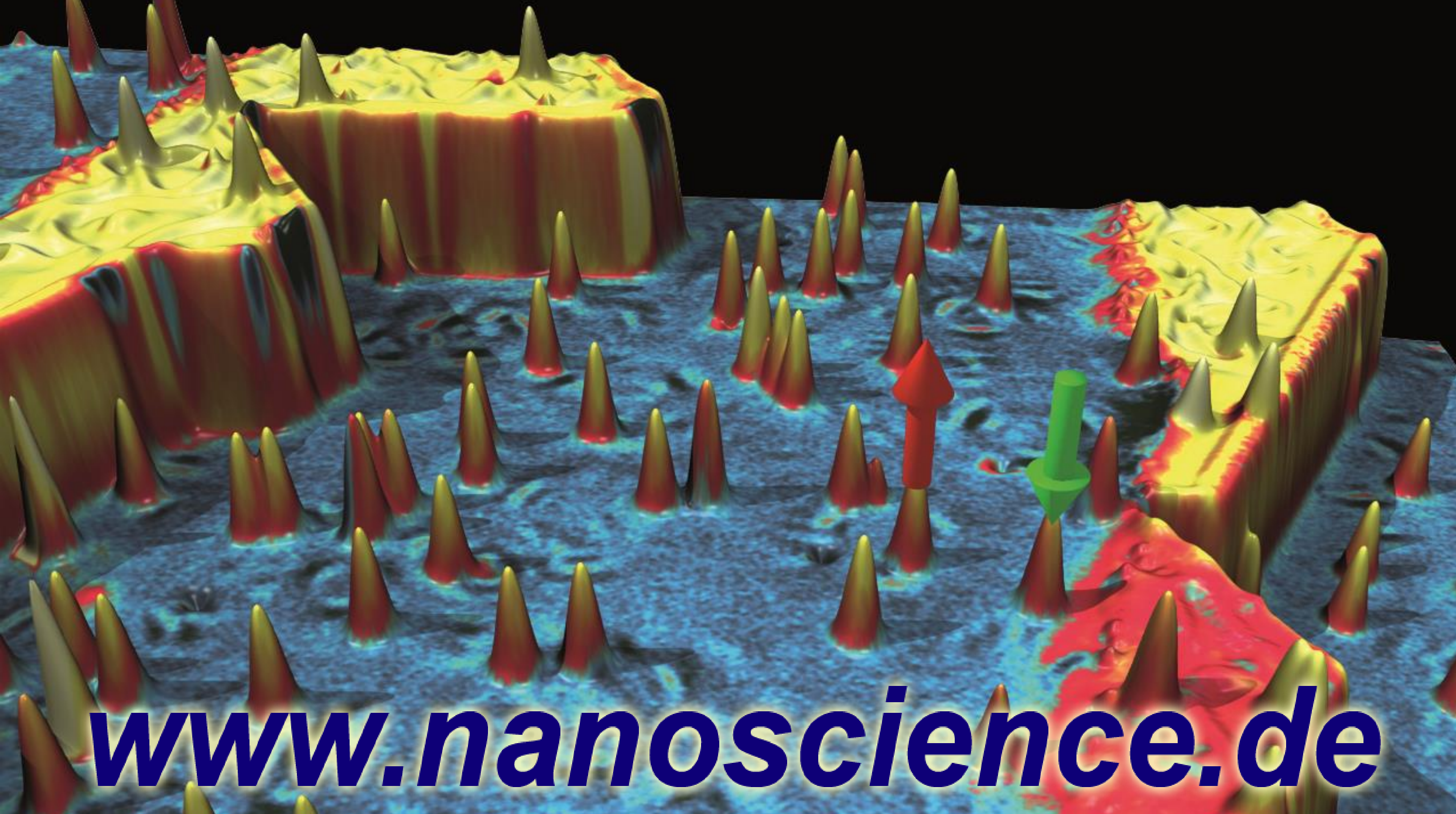
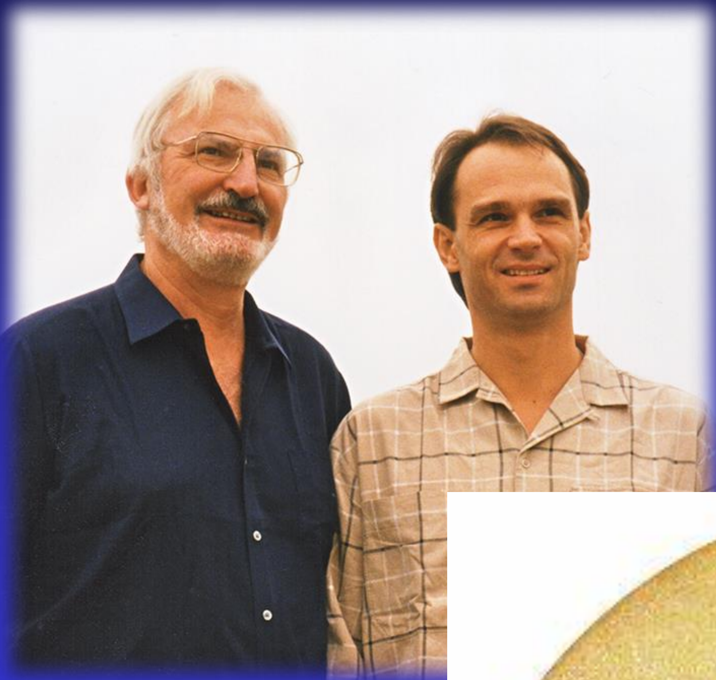
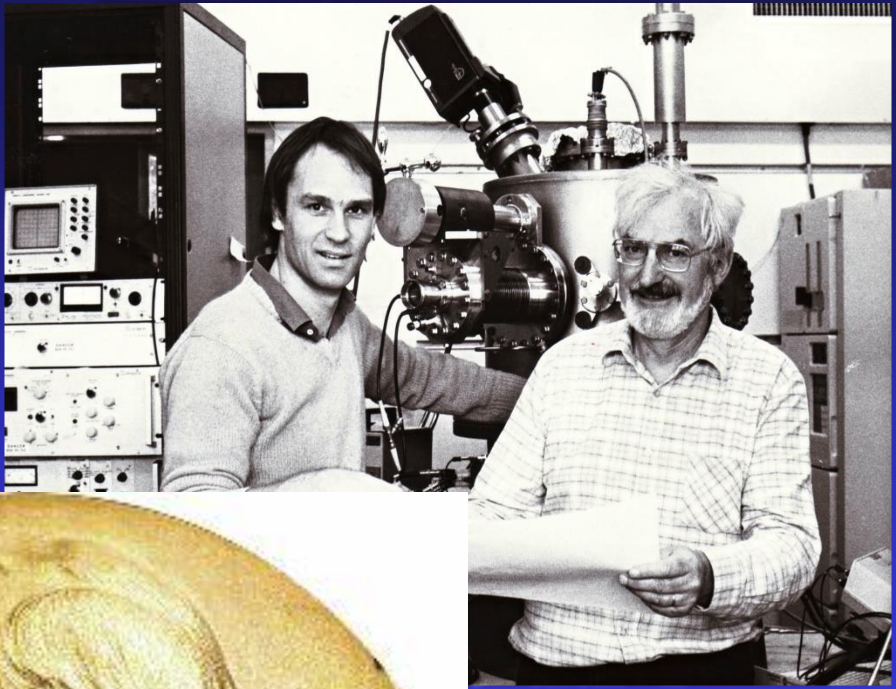
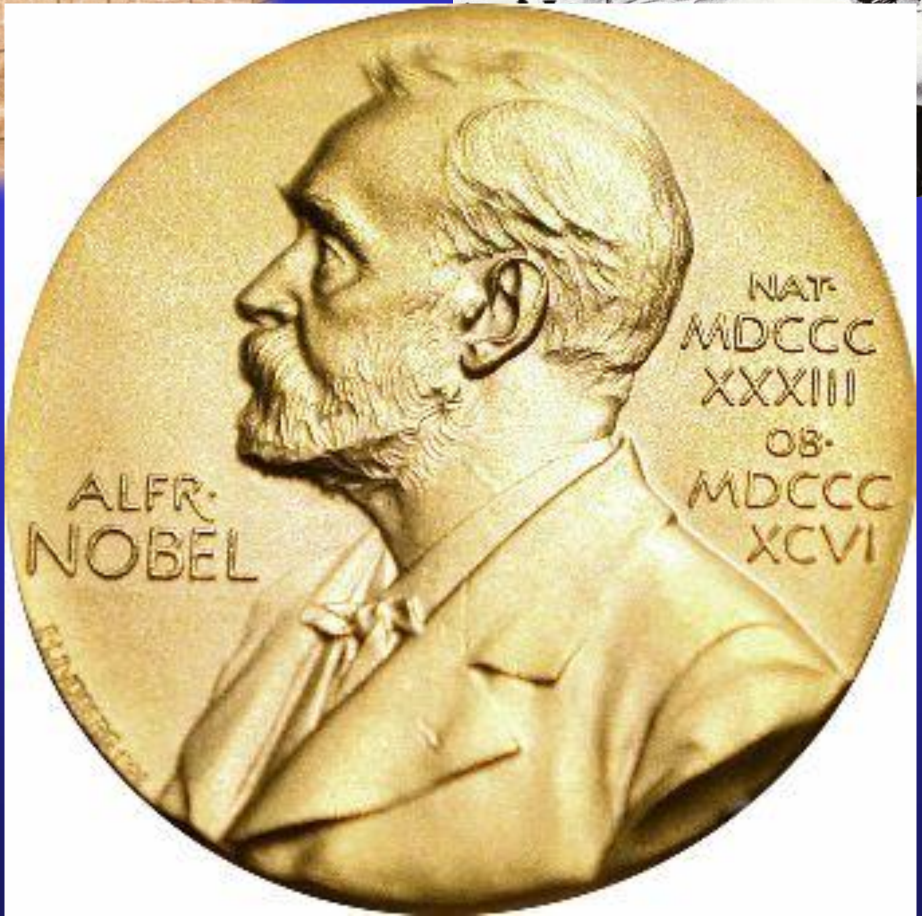








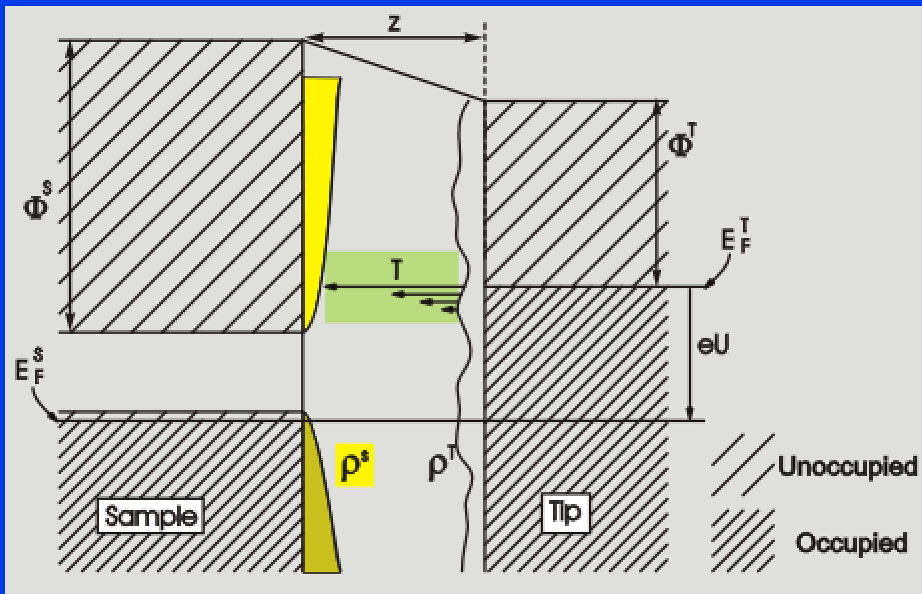
Scanning
Tunneling
Microscopy
(STM)

Vacuum tunneling

Point probing

Scanning

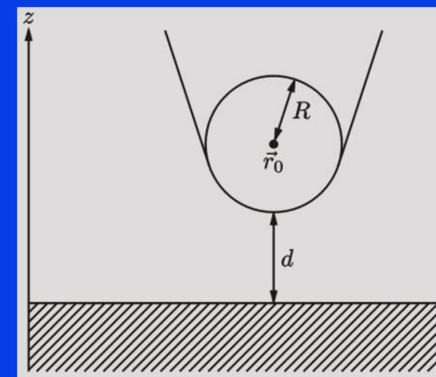
From Quantum Mechanical Tunneling to the Most Powerful Microscopy Technique



$$I \propto \int_0^{eU} \rho^s(eU-E)\cdot\rho^p(E)\cdot T(E,eU,z)\,dE$$

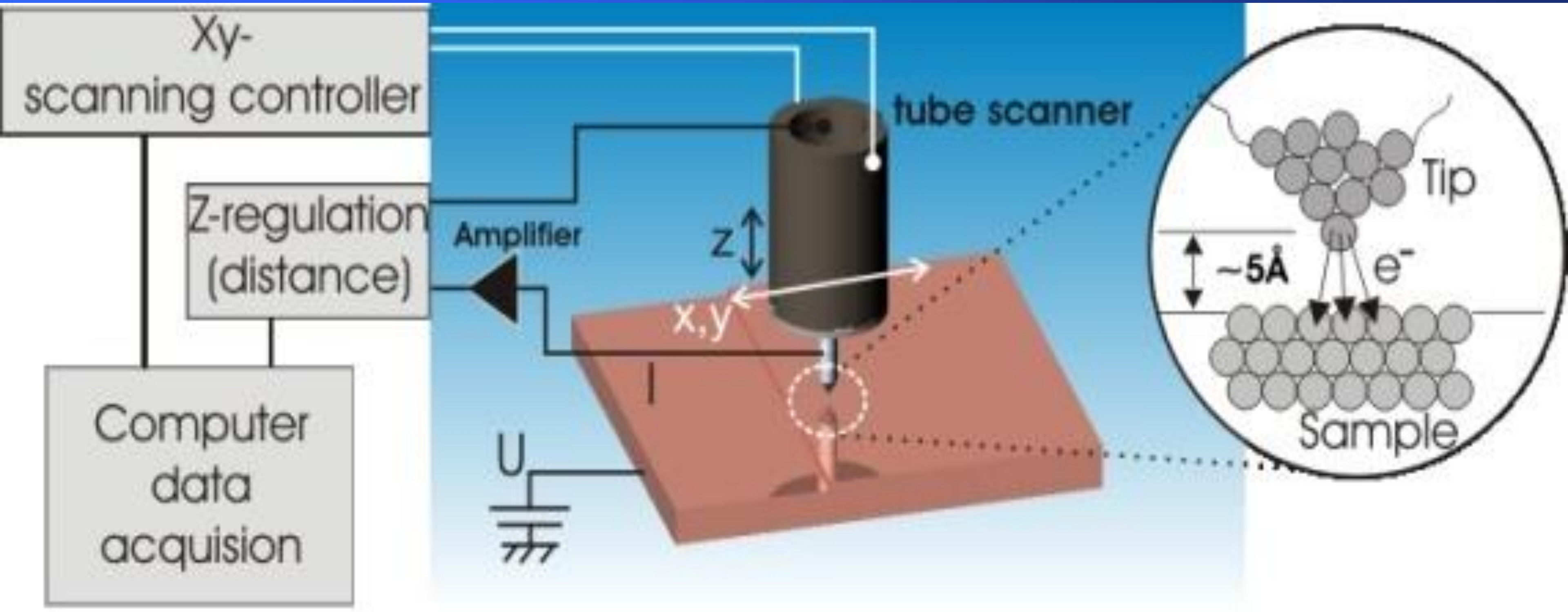
$$T(E,eU,z) = \exp\left\{-z(d+R)\left[\frac{2m}{\hbar}\left(\frac{\Phi^s+\Phi^p+eU}{2}-E\right)\right]^{1/2}\right\}$$

Tersoff-Hamann-Model:



- spherical tip
- s-type tip wavefunction

Scanning Tunneling Microscope (STM)



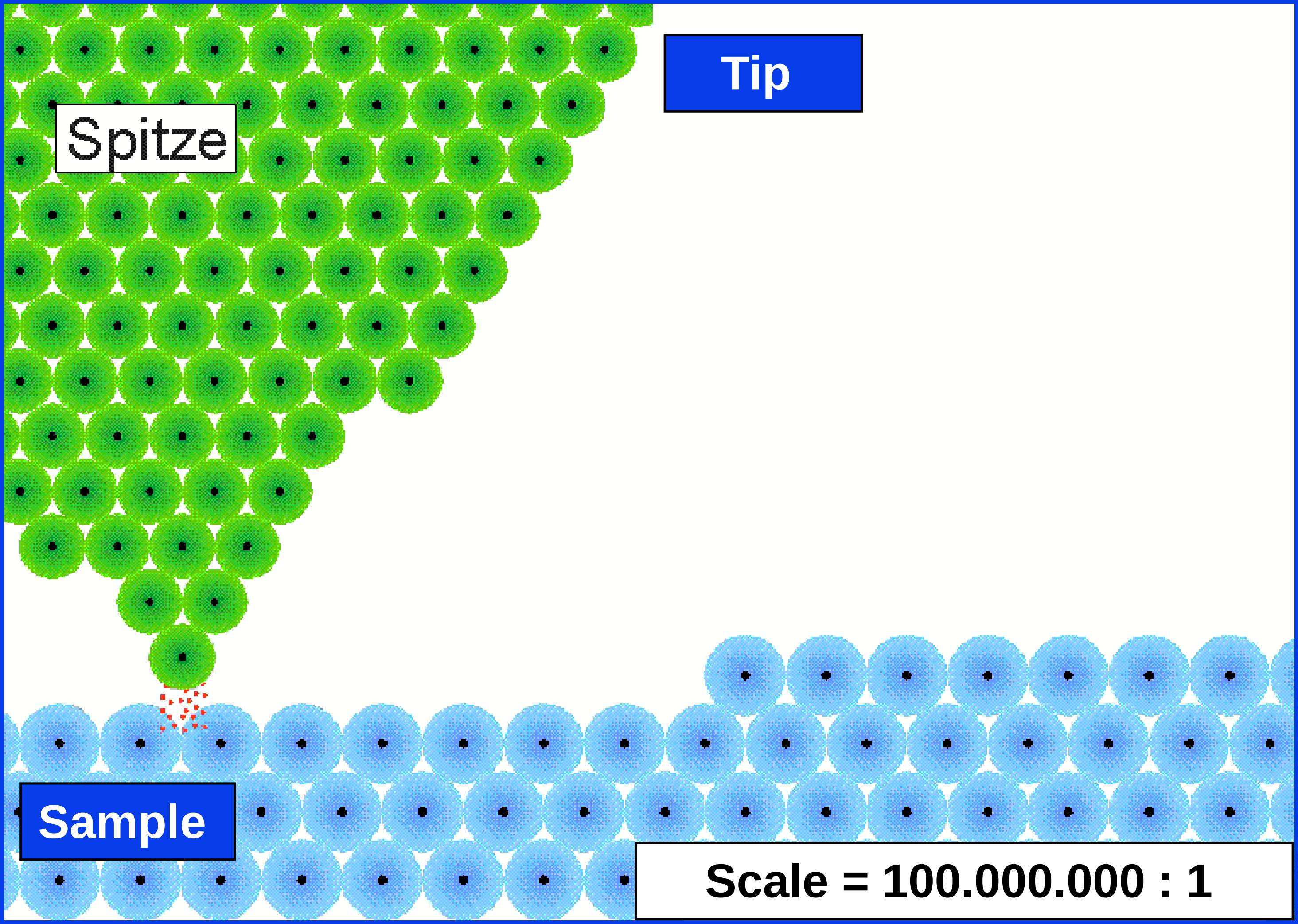
Vacuum tunneling requires extremely small distances between tip and sample

→ **„Near field microscopy“: resolution not limited by electron wavelength !**

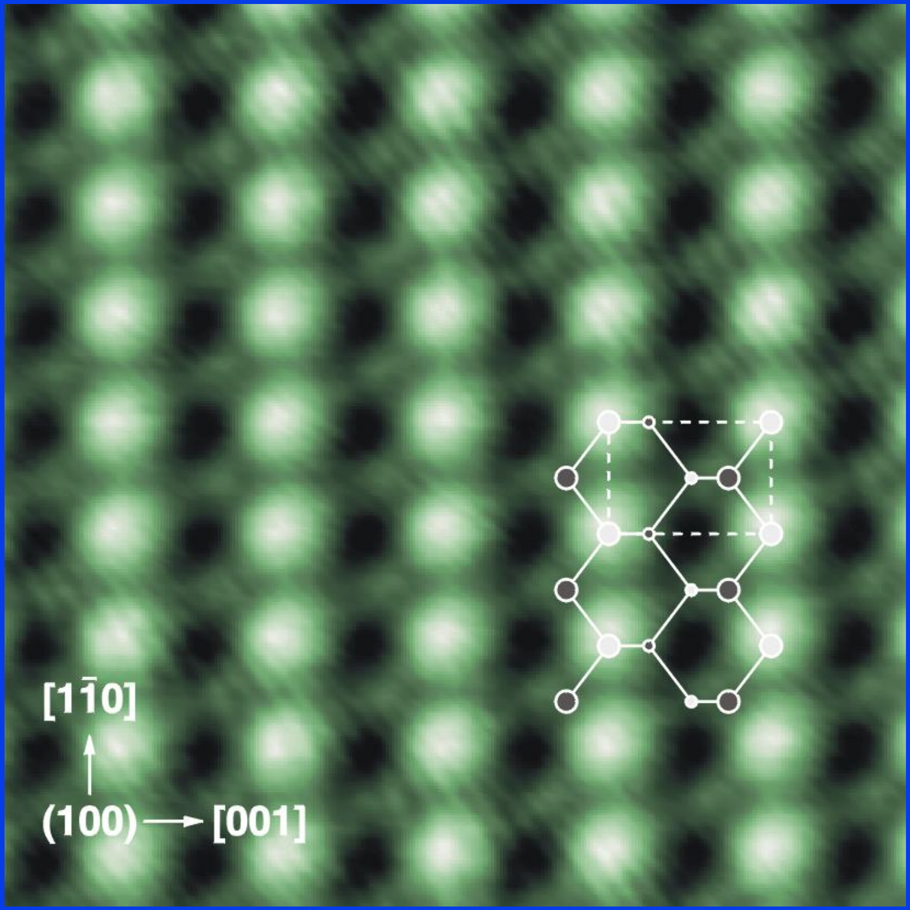
Energy of electrons in the meV-range (<< bindung energies)

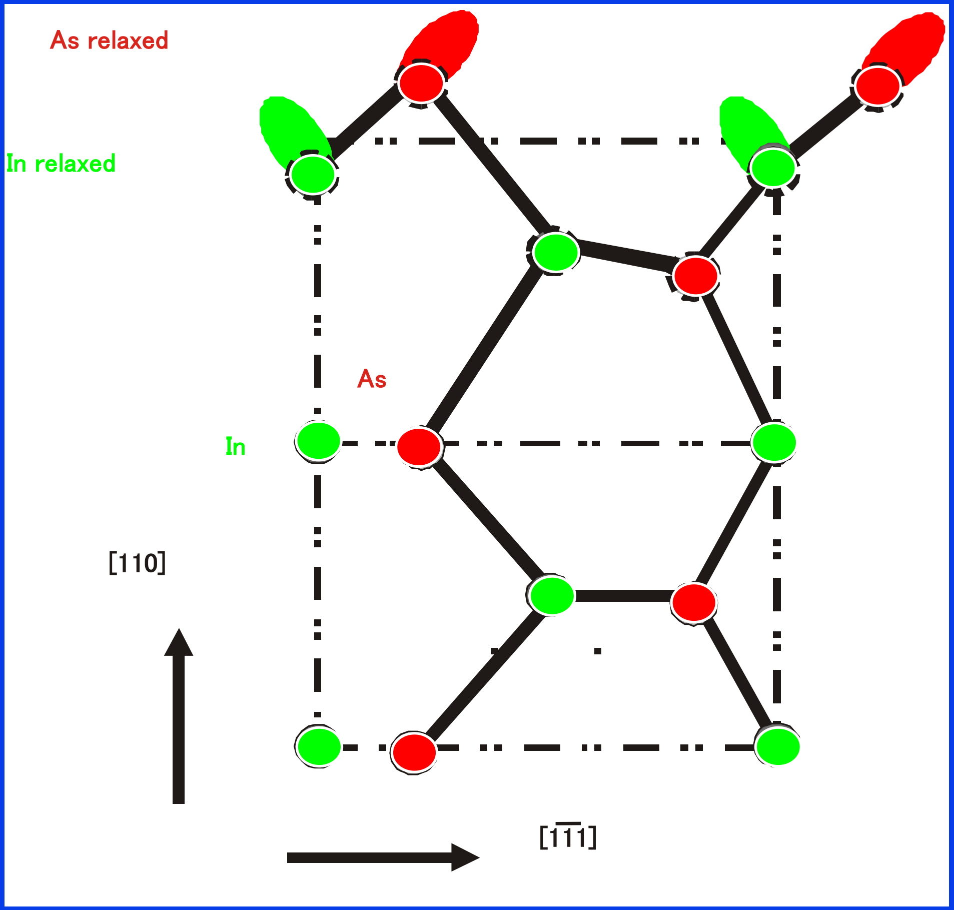
→ **No „radiation“ damage to sample – even on the atomic scale !**

Scanning Tunneling Microscopy: Constant Current Mode

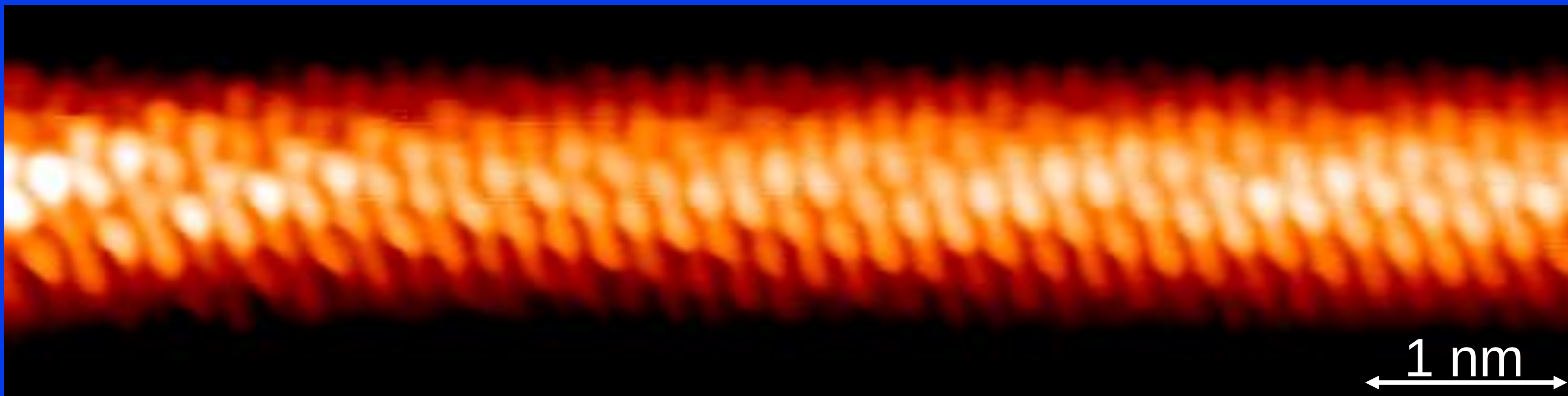


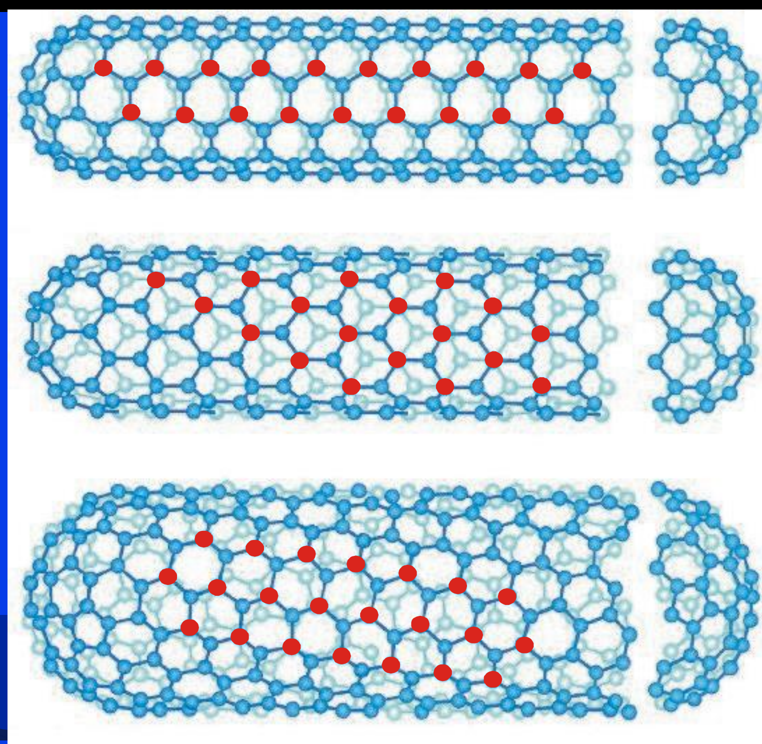
Scanning Tunneling Microscopy of InAs(110)





Atomically-resolved STM on Single Wall Carbon Nanotubes



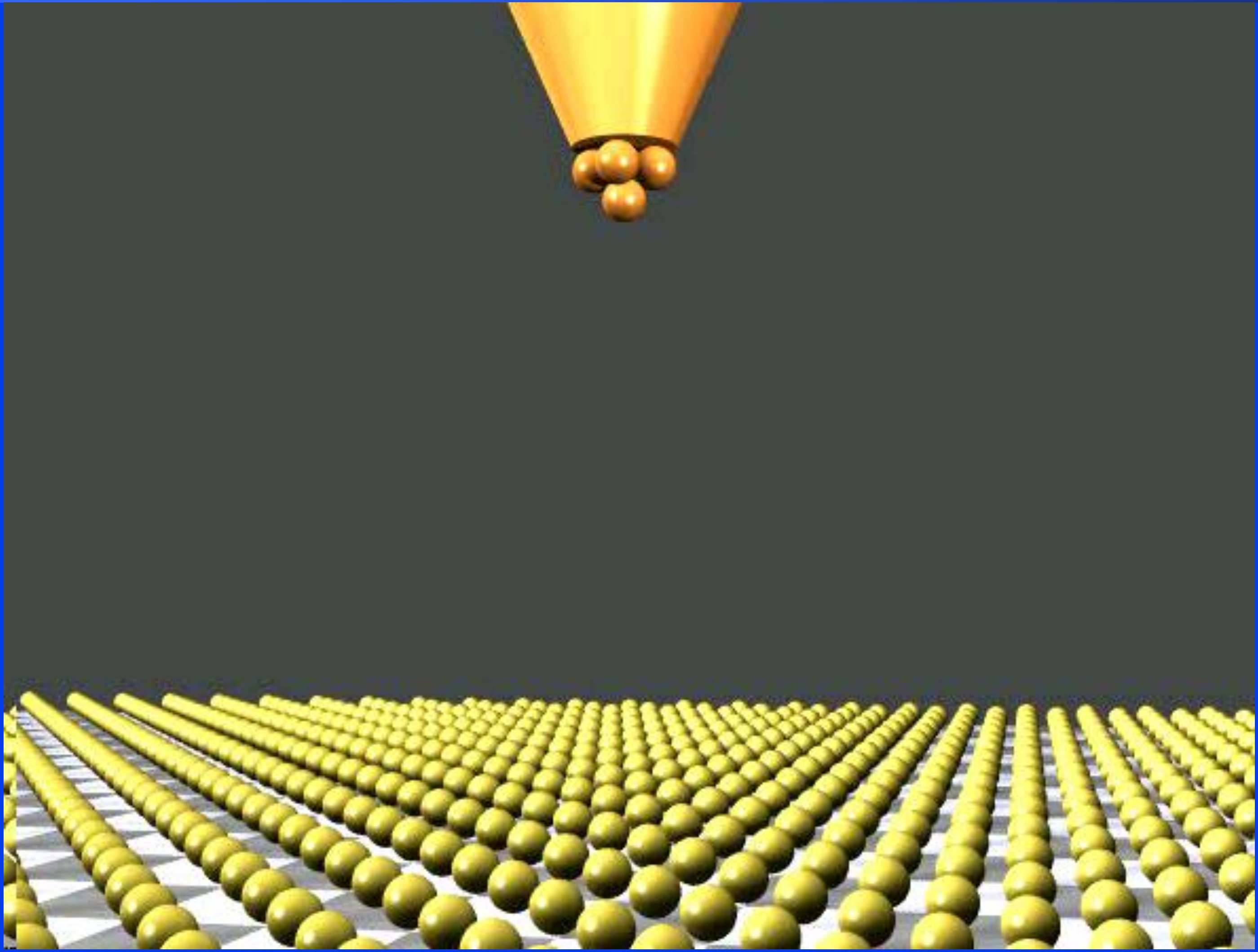


armchair Φ=0° (metallic)

zigzag Φ=30°
(metallic or semiconducting)

chiral Φ=0°-30°
(metallic or semiconducting)

How does Tunneling Spectroscopy work ?



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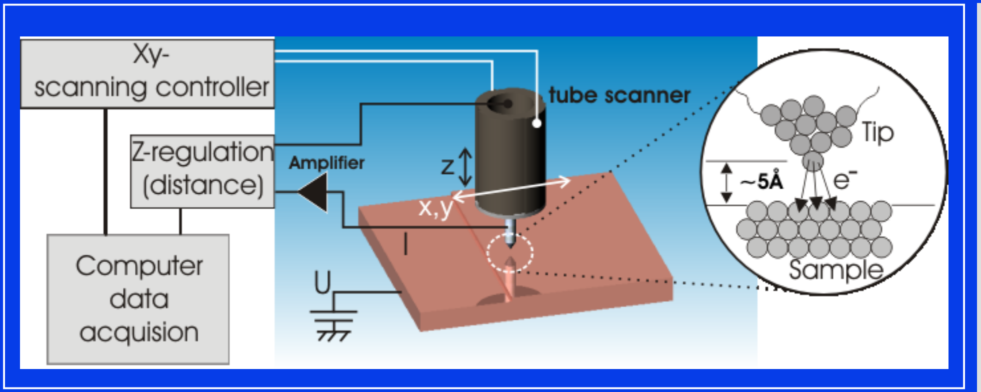
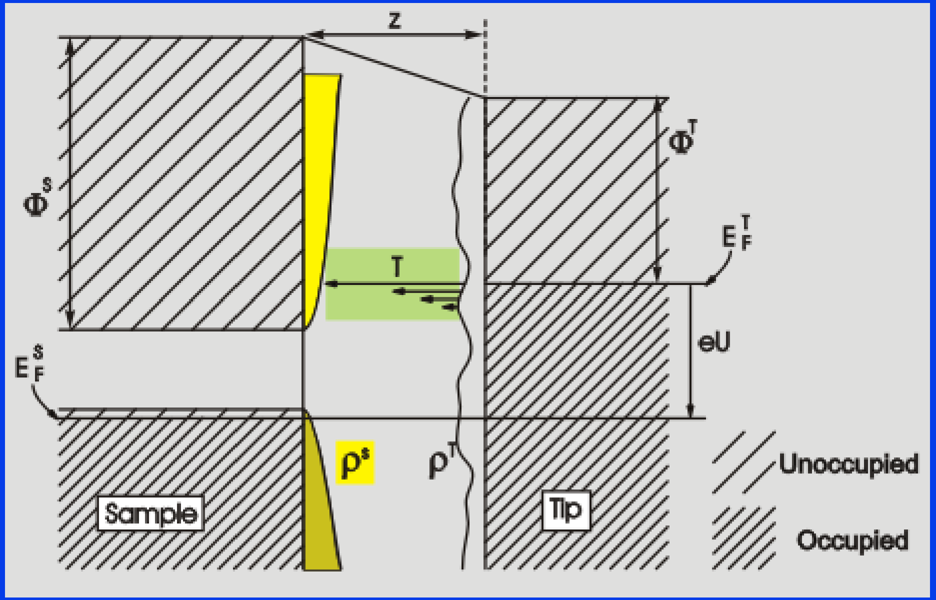
Scanning Tunneling Spectroscopy (STS)





$$I \propto \int_0^{eU} \rho^t(E_F - eU + \varepsilon) \cdot \rho^s(E_F + \varepsilon) \cdot T(\varepsilon, U, z) \cdot d\varepsilon$$

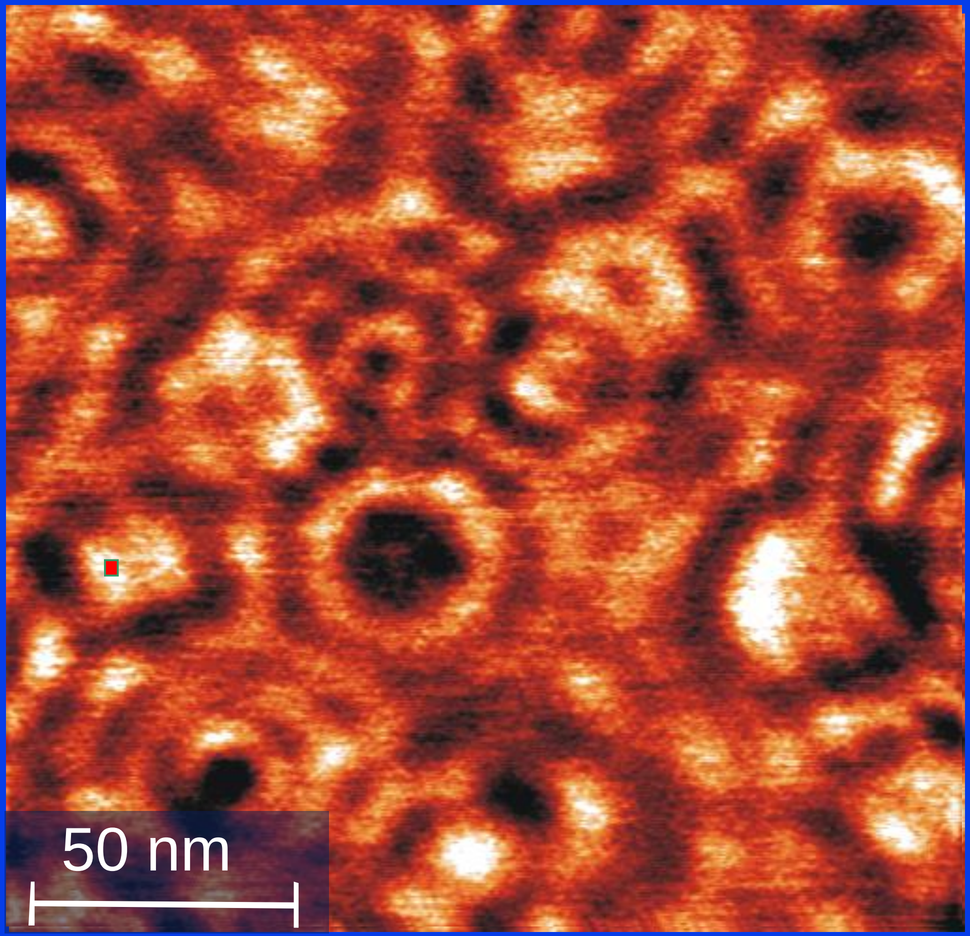
Topography

$$\frac{dI}{dU}(x,y,z)\bigg|_U \propto \rho^t(E_F) \cdot \rho^s(E_F + eU, x, y) \cdot T(eU, U, z) + \cdots$$

Spectroscopy

Local Density of States (E, x, y) $= \sum_{\delta E} \left|\Psi_{i,j}(r,E)\right|^2$

STS revealing electron density distribution at the InAs(110) surface

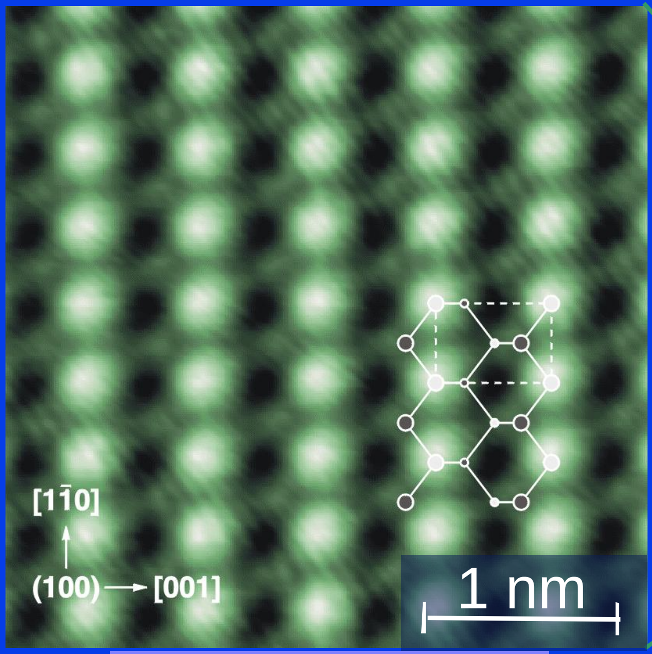


Electronic disorder due to statistical distribution of dopant atoms !

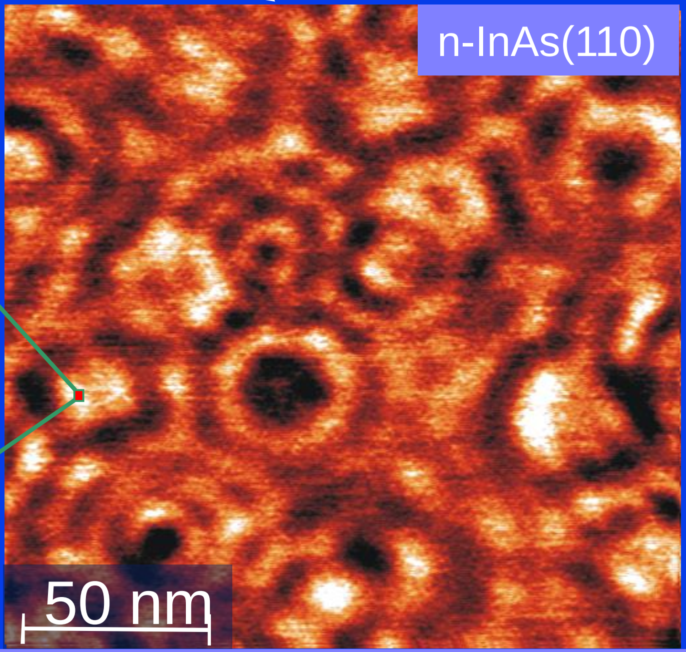
Bloch states in 3D Crystals

$$\Psi_{i,j}(\vec{r}) = A_i(\vec{r})\; e^{i\vec{k}_j\,\vec{r}}$$

$A_i(\vec{r})$: atomically periodic



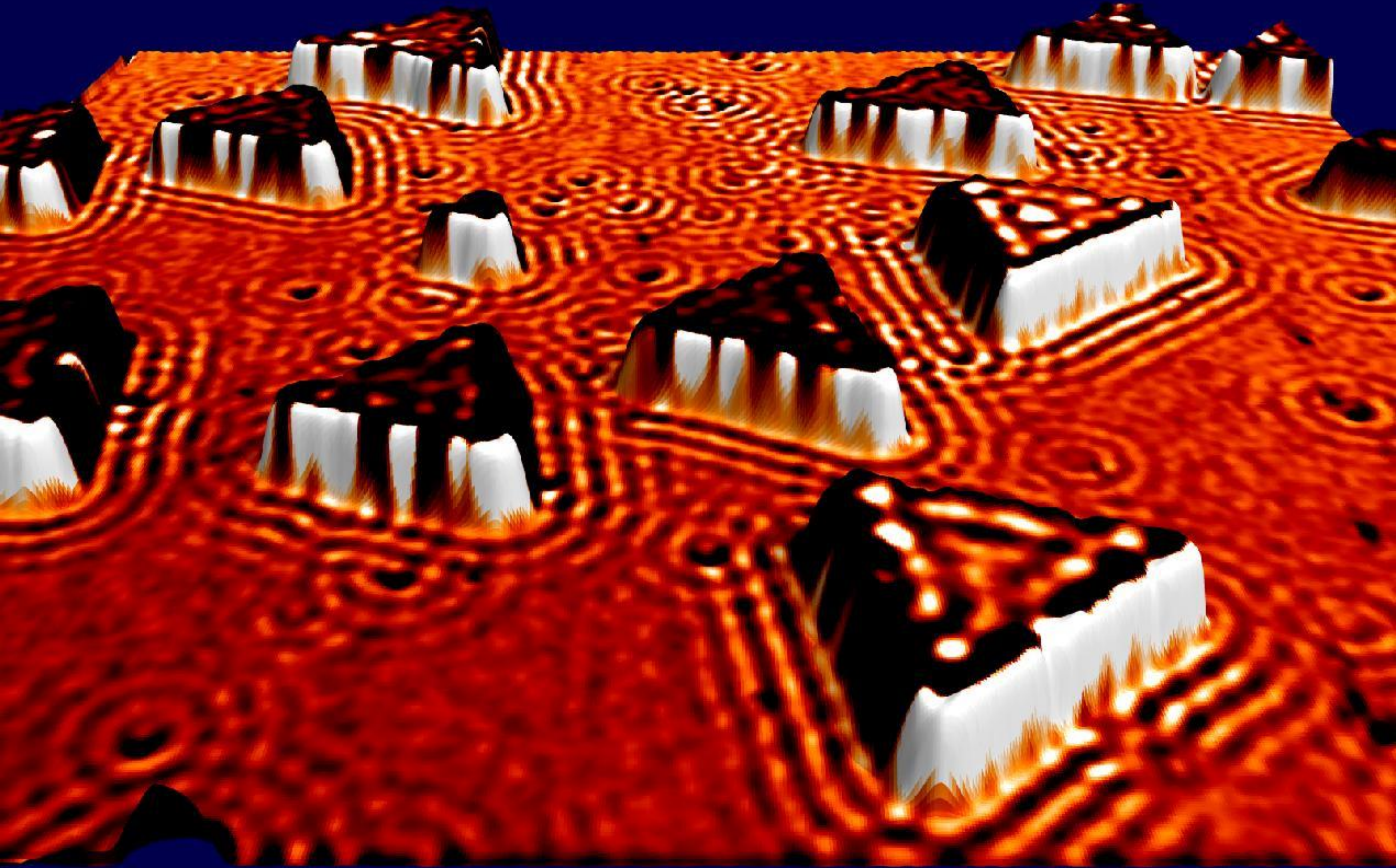
periodic “atomic“ part



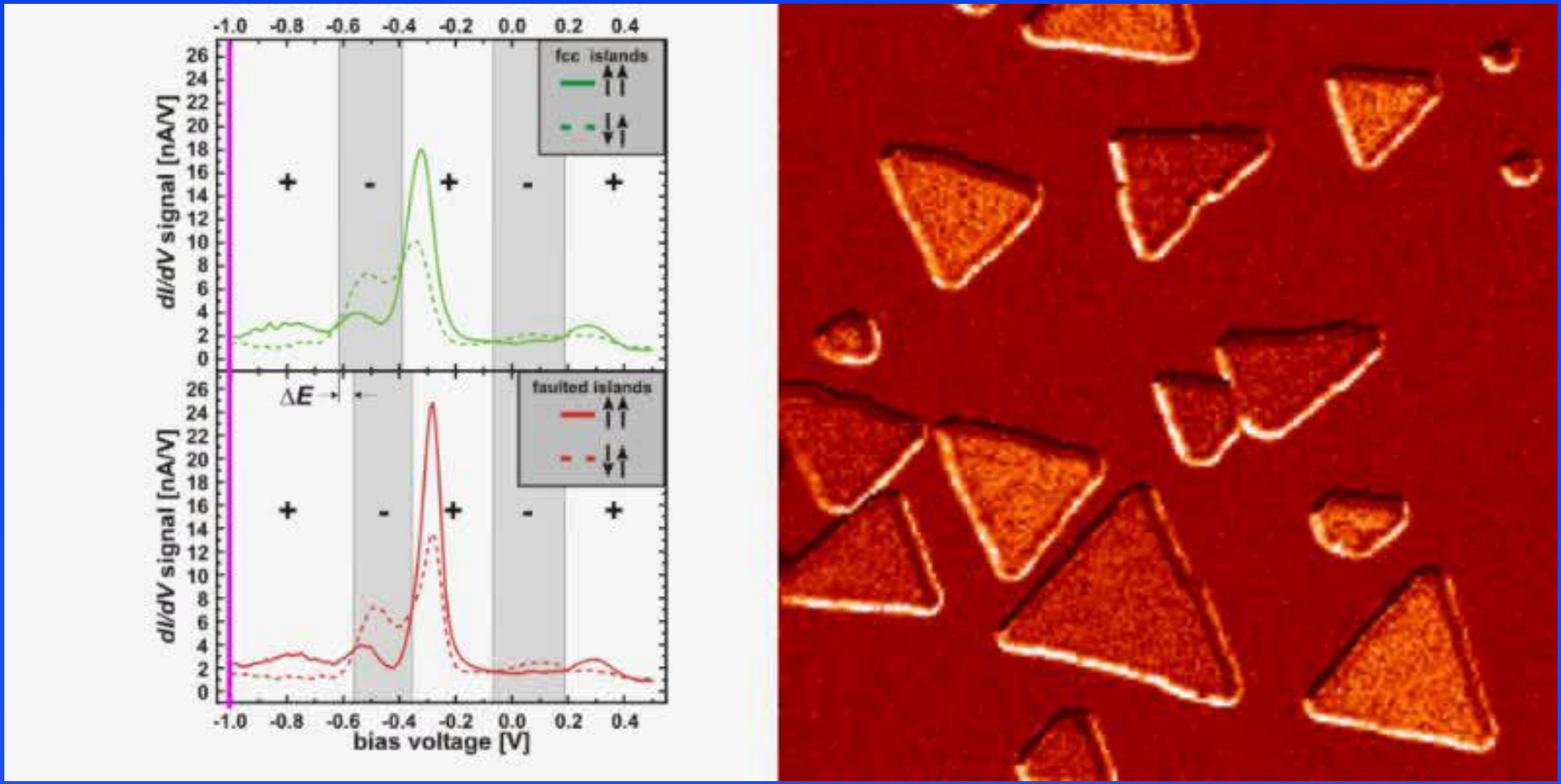
electron waves scattered at dopants

$$LDOS(E) = \sum_{\delta E} \left|\Psi_{i,j}(r,E)\right|^2$$

Nano-scale Co-islands on a Cu(111) surface

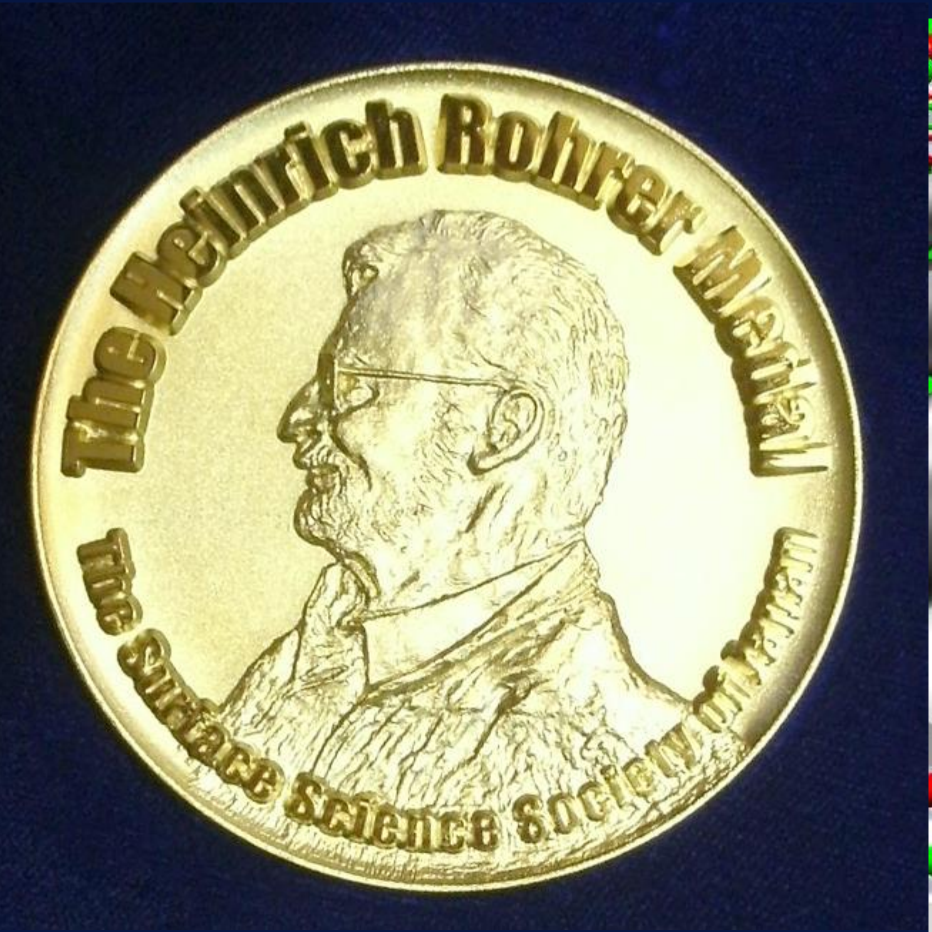


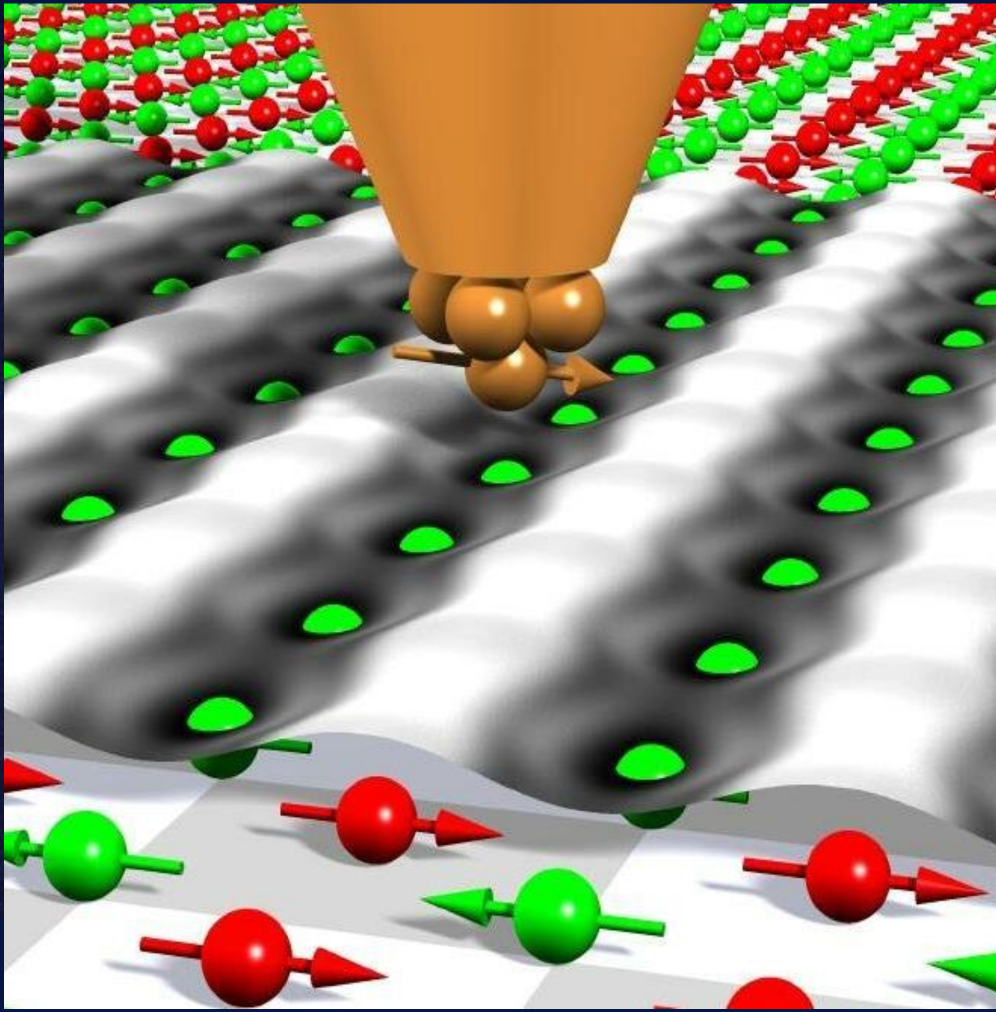
Voltage Dependent STS Imaging



A Quantum Microscope revealing quantum-mechanical phenomena in nanostructures down to atomic scales !

Can one also image magnetic properties of surfaces ?

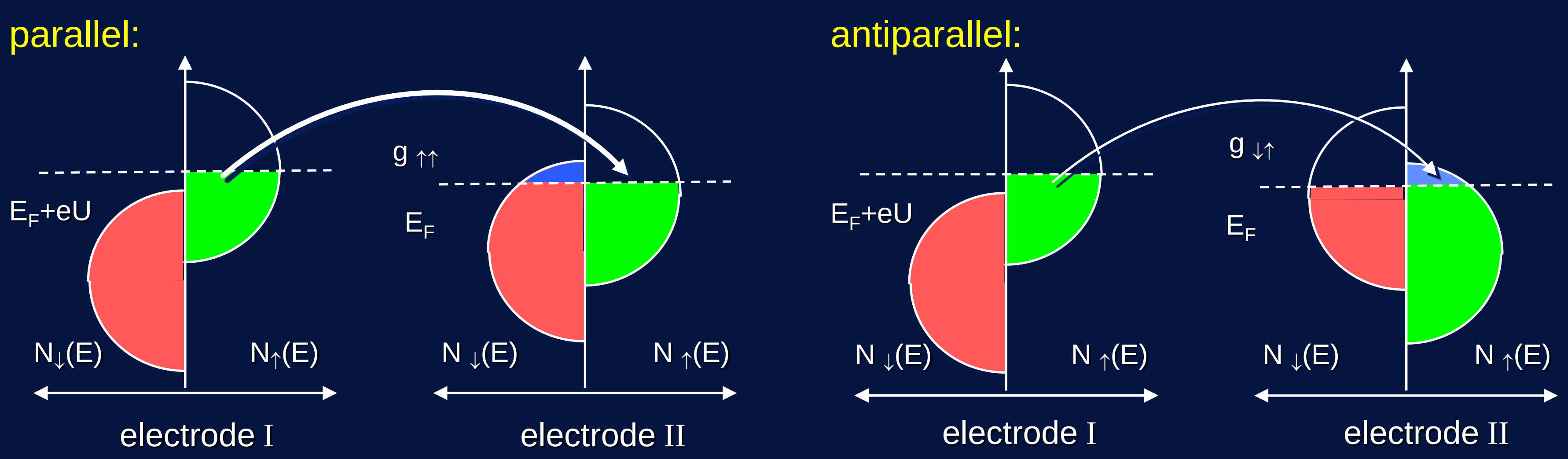


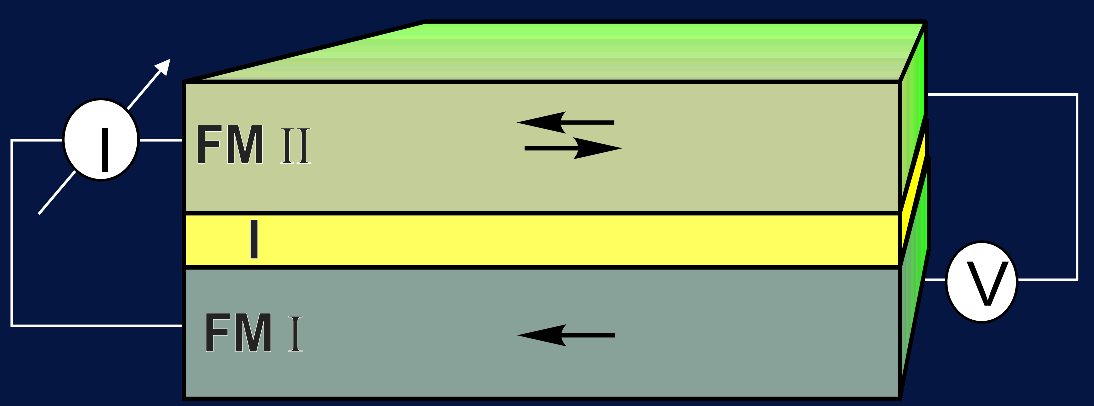


→ Spin-Polarized Scanning Tunneling Microscopy (SP-STM)

Spin-Polarized Electron Tunneling between two Ferromagnetic Planar Electrodes

M. Jullière, Phys. Lett. **54A**, 225 (1975)





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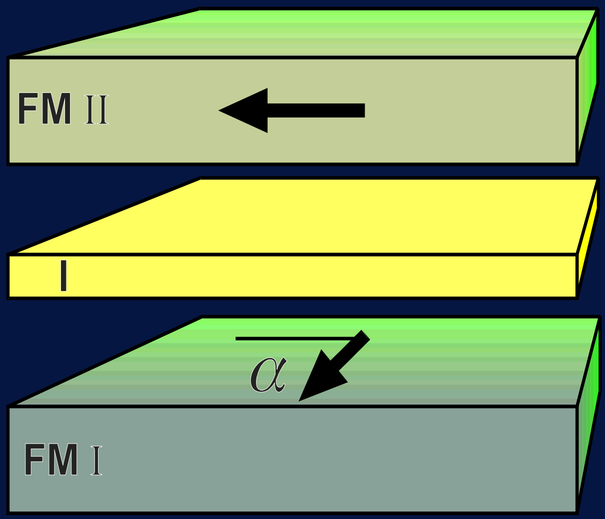
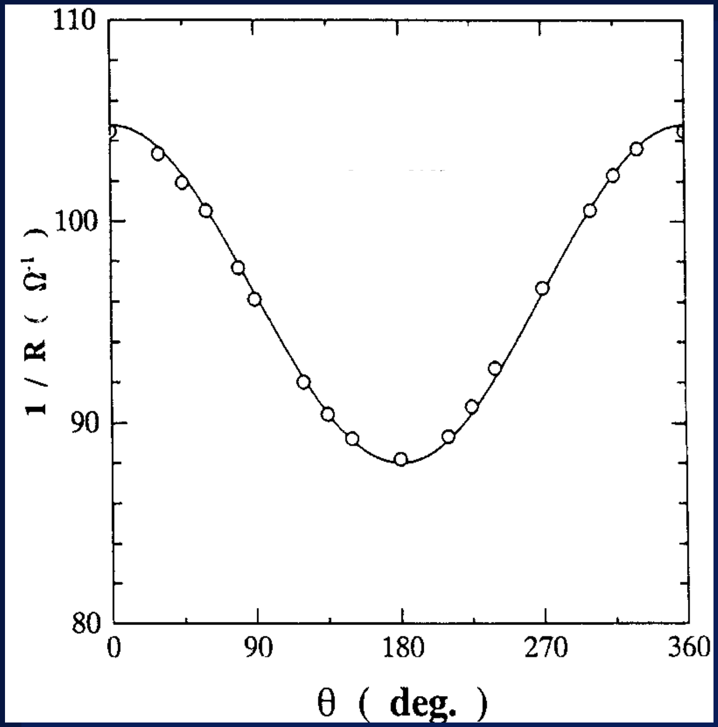
Spin-Polarized Electron Tunneling between two Ferromagnetic Planar Electrodes

Theory: J.C. Slonczewski, Phys. Rev. B **39**, 6995 (1989):

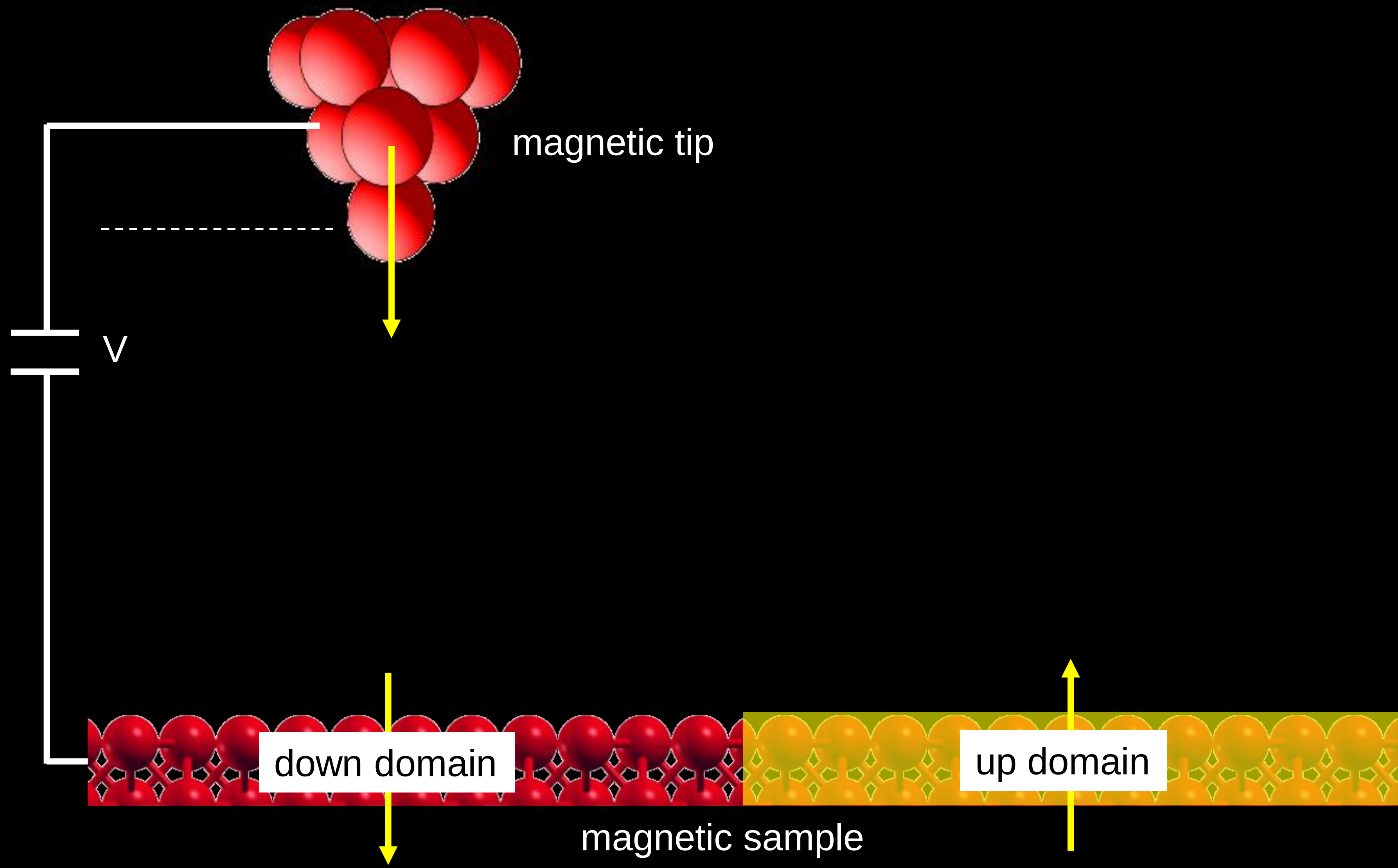
$$I_{sp} = I_0\left[1 + P_I P_{II} \cos\left(M_I, M_{II}\right)\right]$$



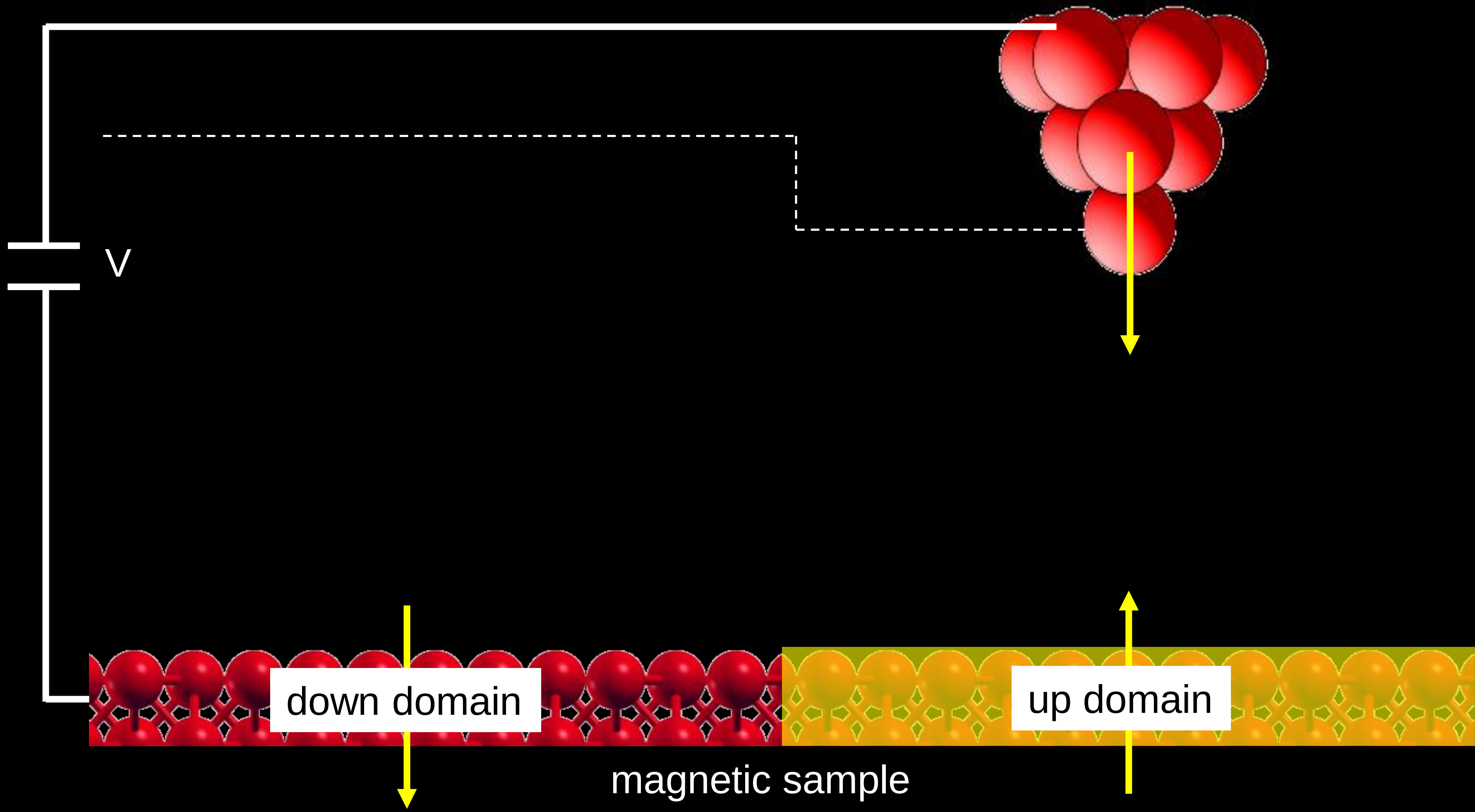
Experiment: T. Miyazaki and N. Tezuka, J. Magn. Magn. Mater. **139**, L231 (1995):



Spin-Polarized Scanning Tunneling Microscopy (SP-STM)

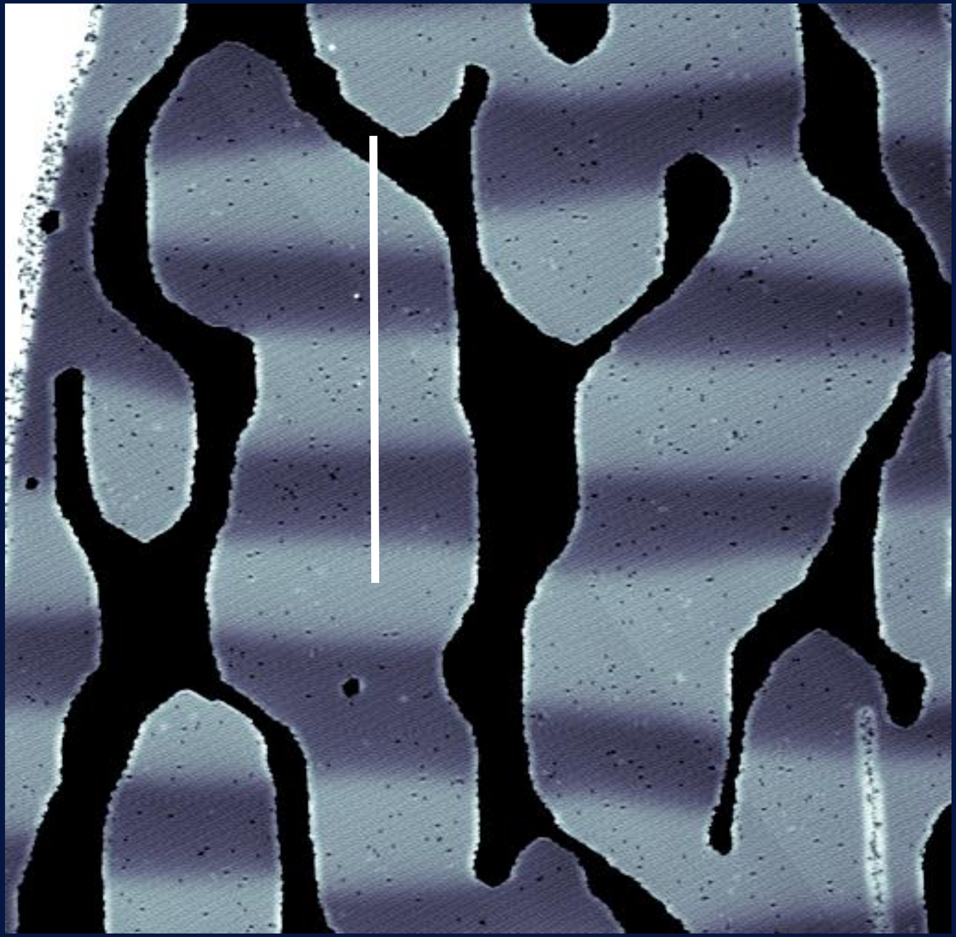


Spin-Polarized Scanning Tunneling Microscopy (SP-STM)

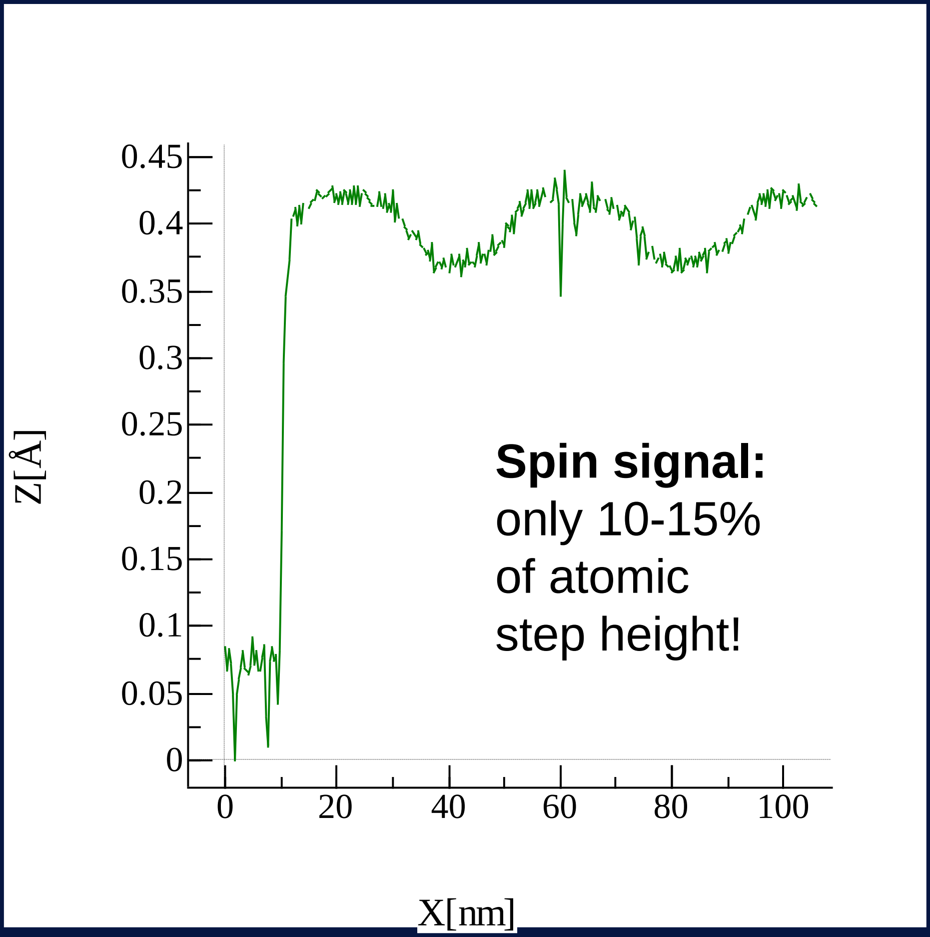


2 atomic layers of Fe on a W(110) surface

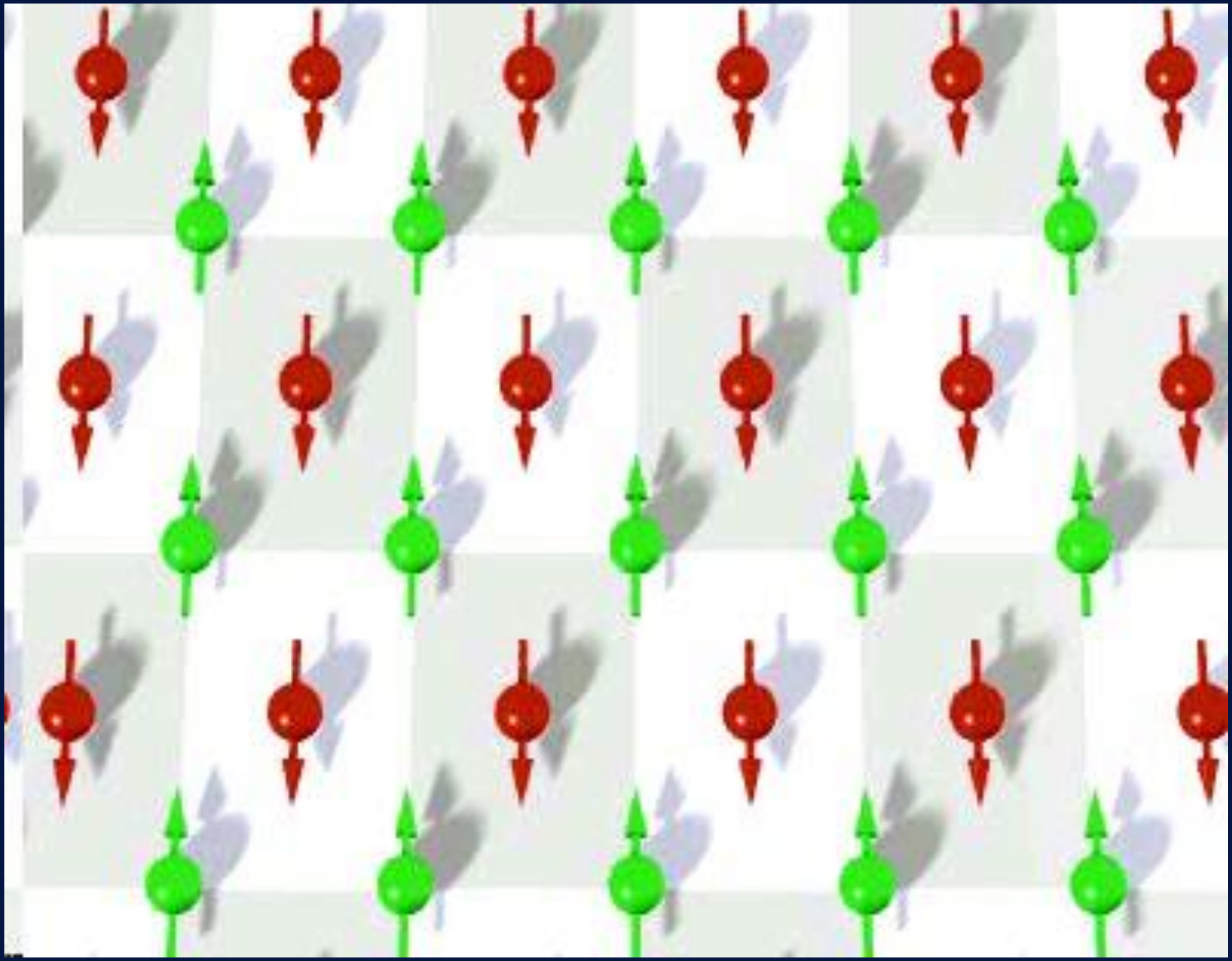
→ Magnetic domain structure clearly visible in constant-current SP-STM images



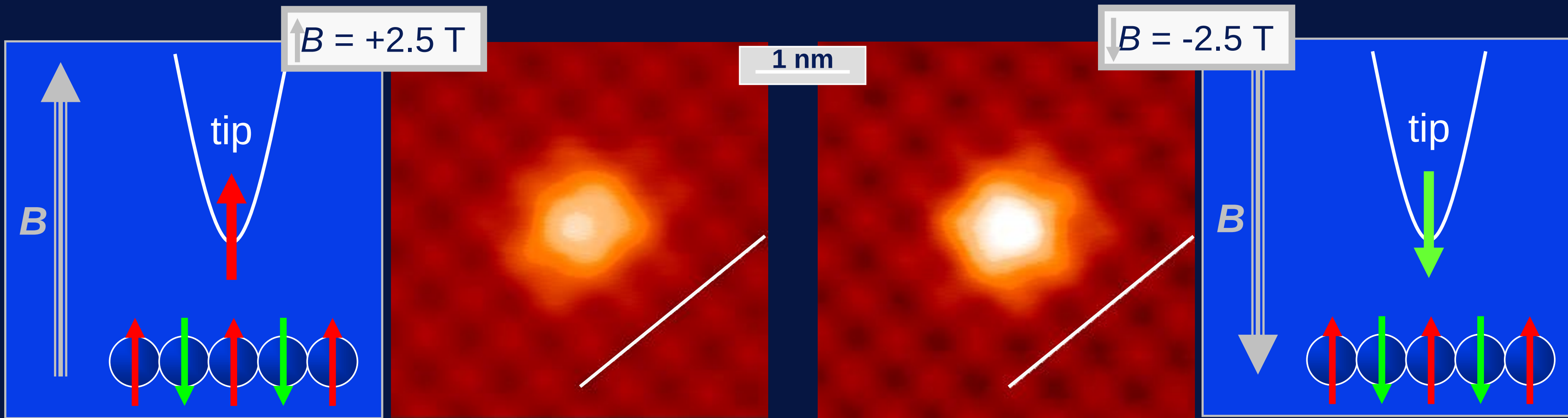
100 nm x 100 nm



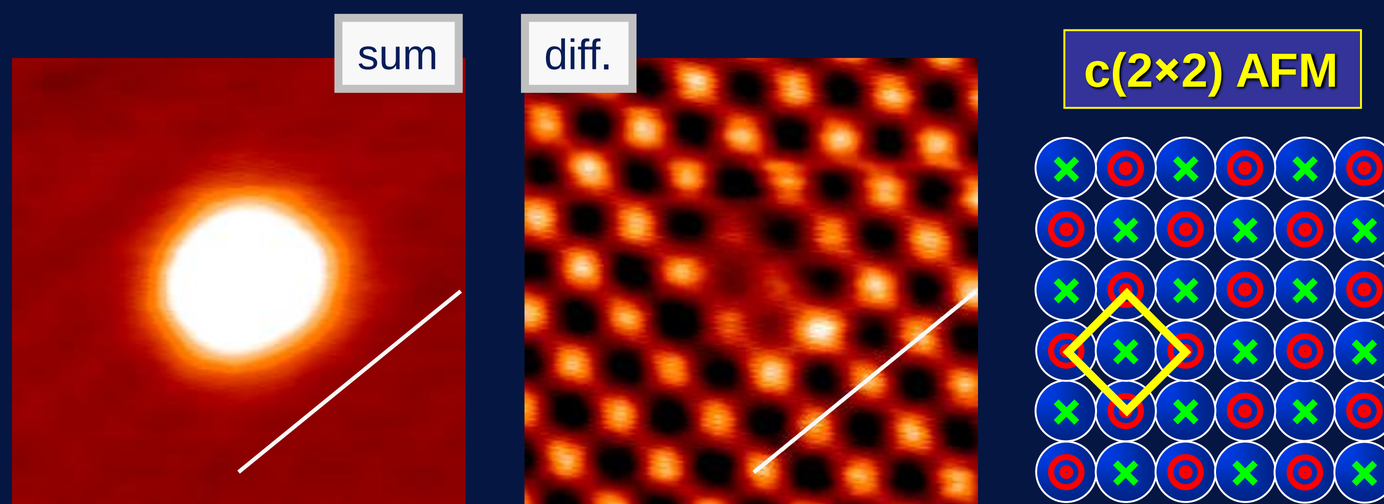
Principle of atomic-resolution Spin-Polarized Scanning Tunneling Microscopy



1 atomic layer of Fe on a W(001) surface: Antiferromagnetic order revealed on atomic scale



First direct visualization of antiferromagnetic Néel-order on the atomic scale



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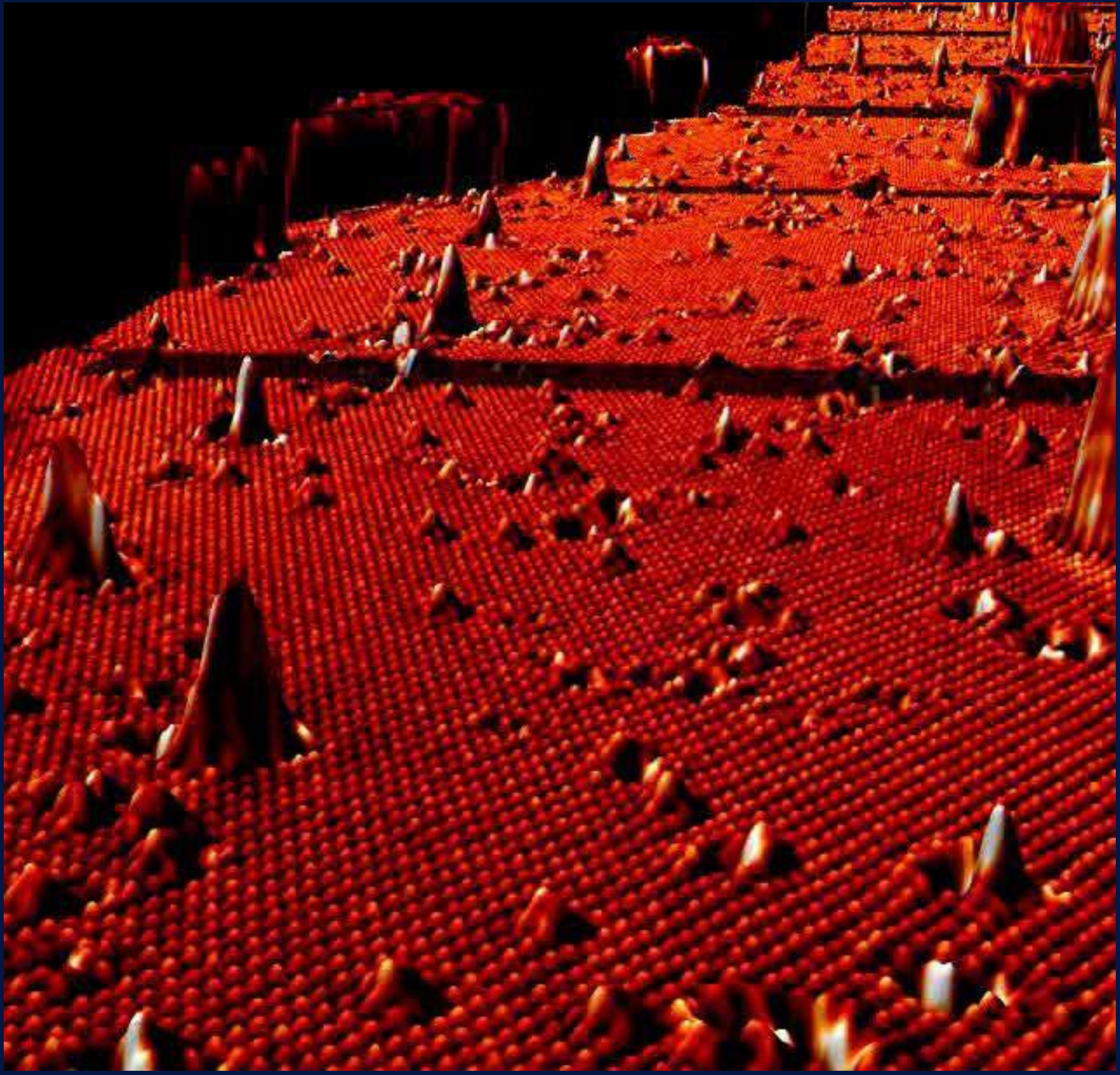
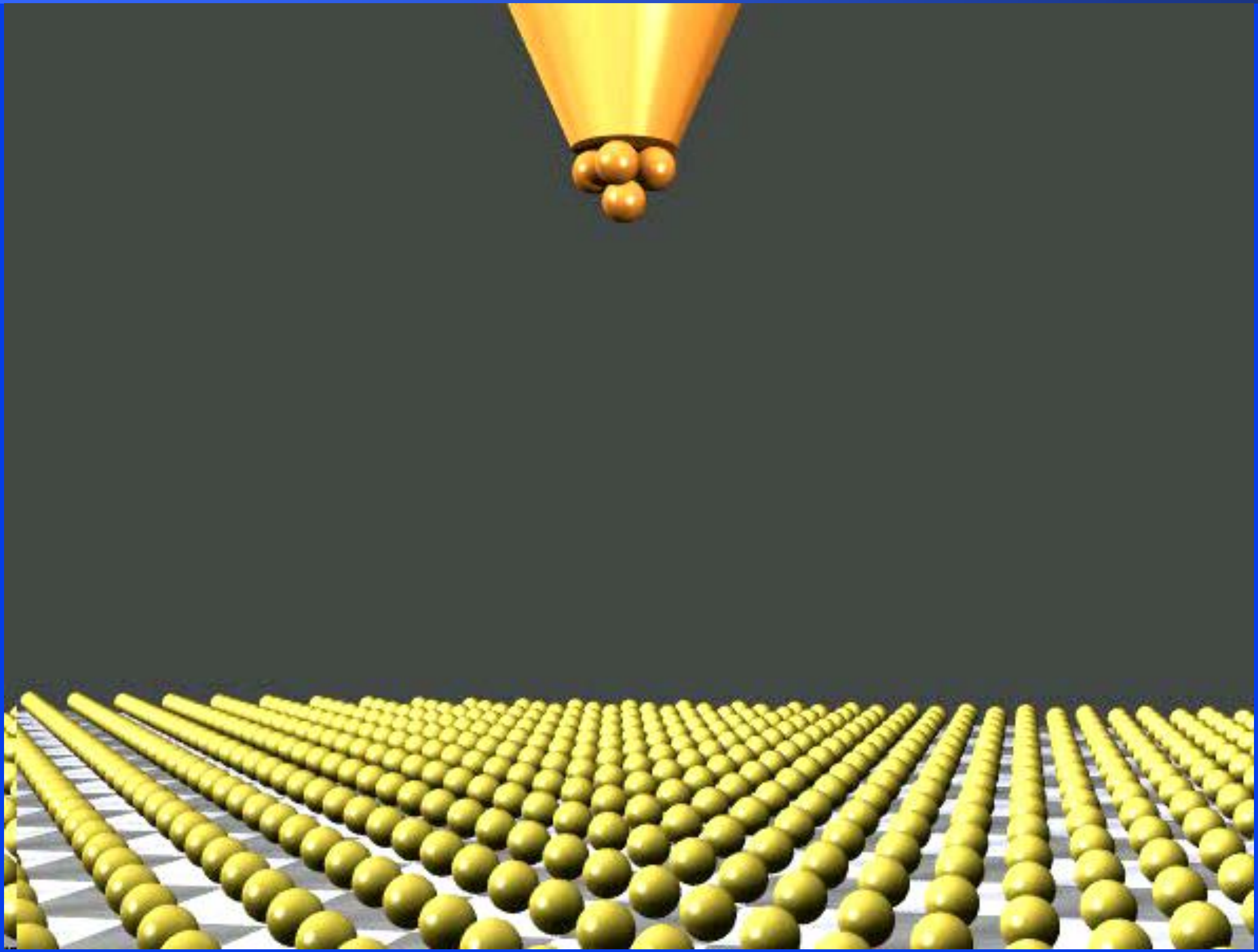
1 atomic layer of Fe on W(001): Spatial coherence of antiferromagnetic order



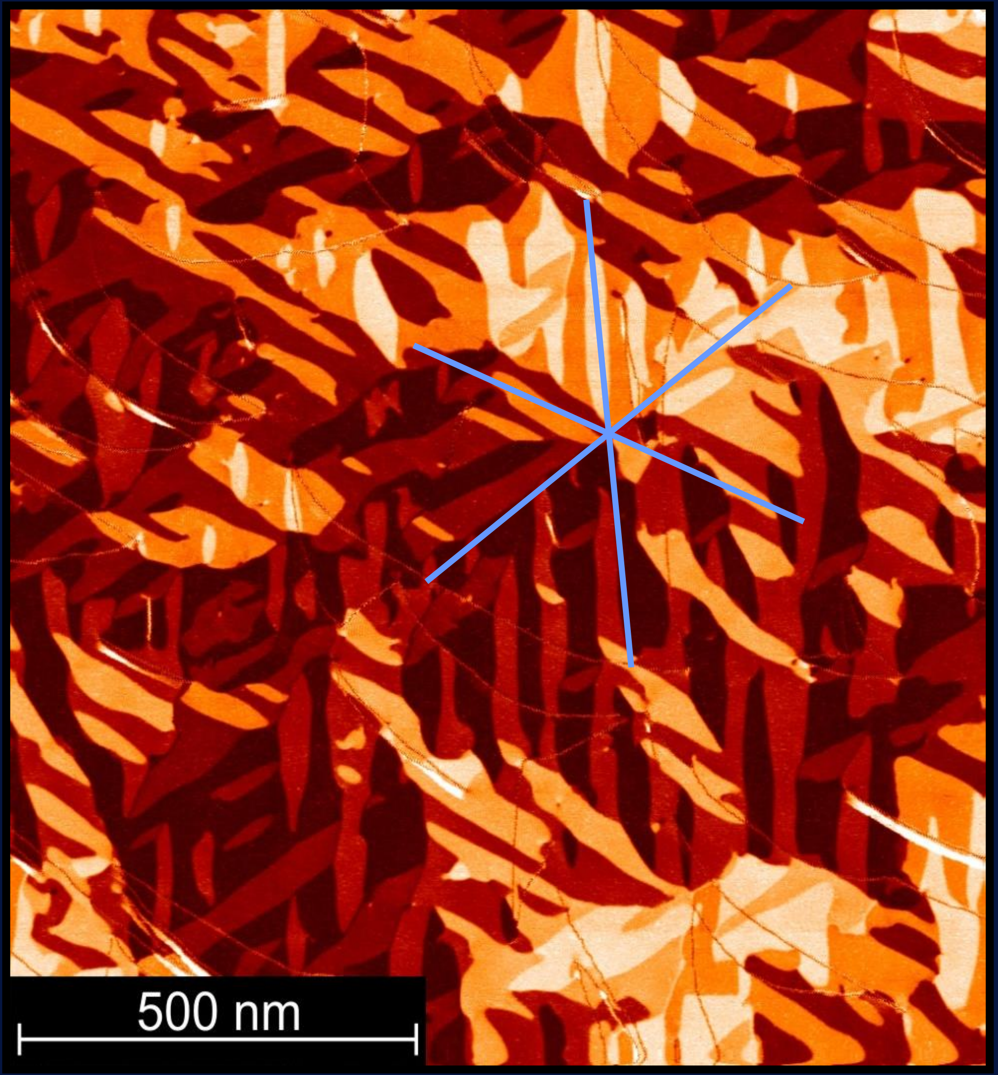
7 SP-RTM Bilder

(50 nm × 50 nm)

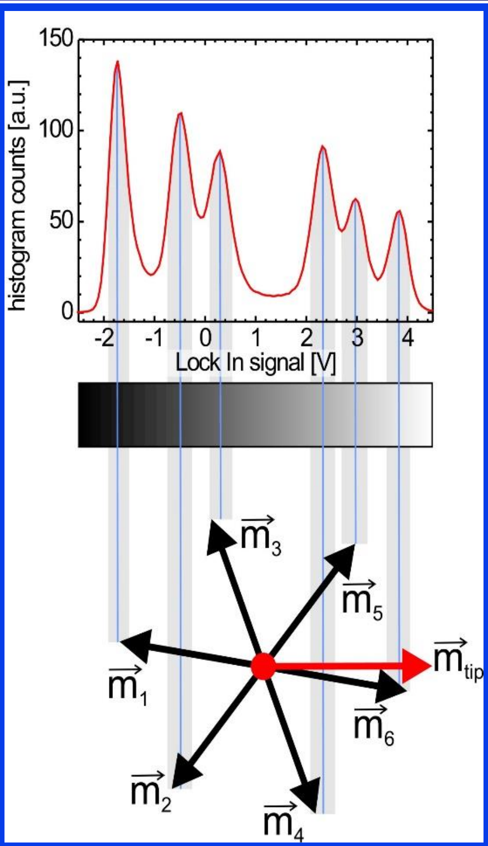
Spin-Polarized Scanning Tunneling Spectroscopy



Magnetic domain structure of Dy(0001) thin film

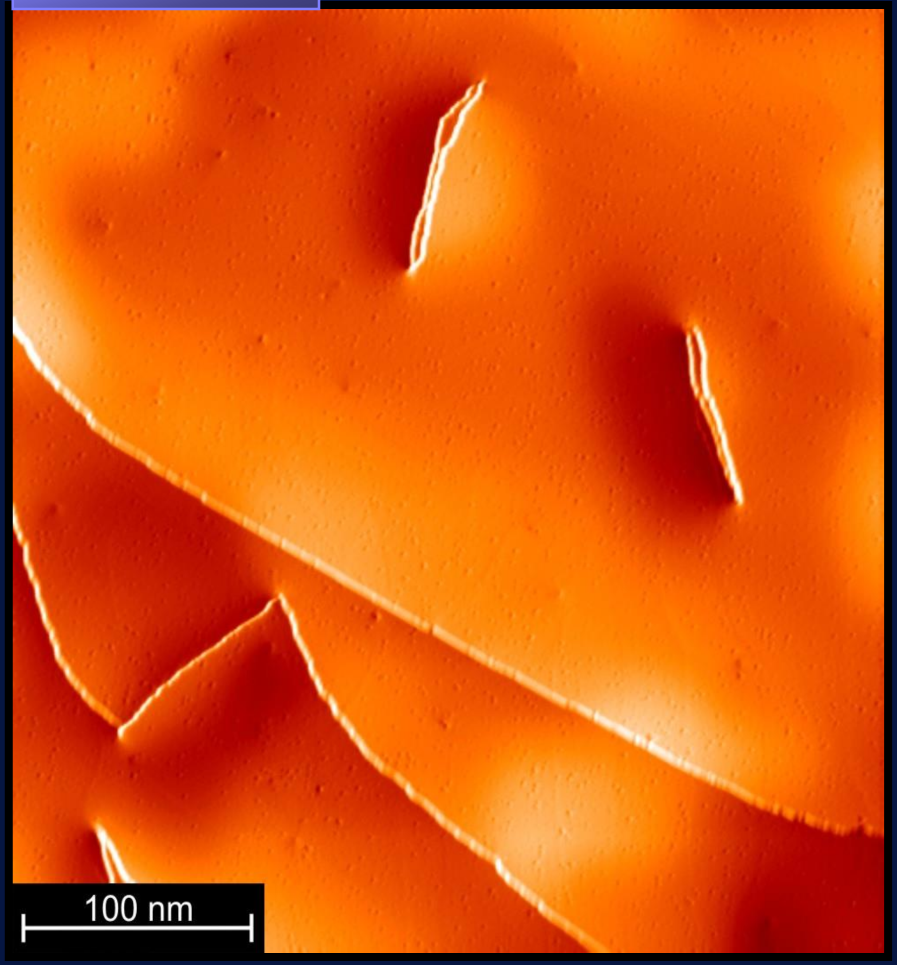


Histogram of magnetic dI/dU signal



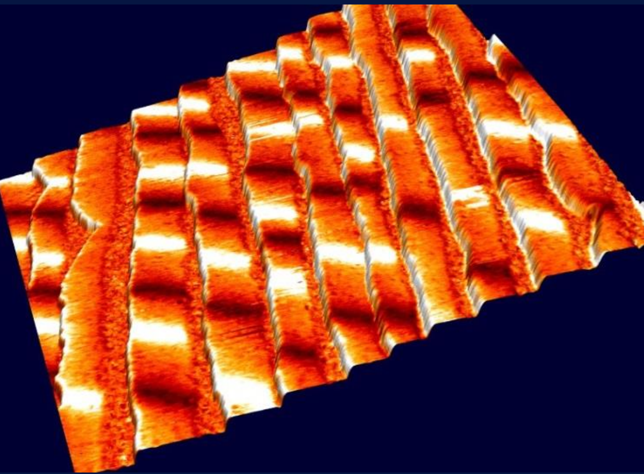
Magnetic domain structure of Dy(0001) thin film

Topography

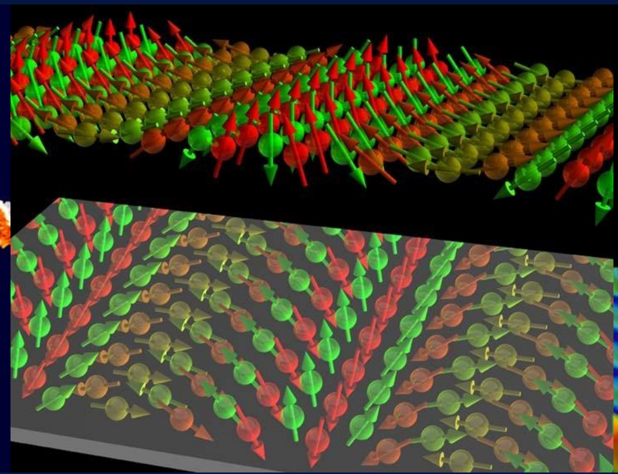


Magnetic structure

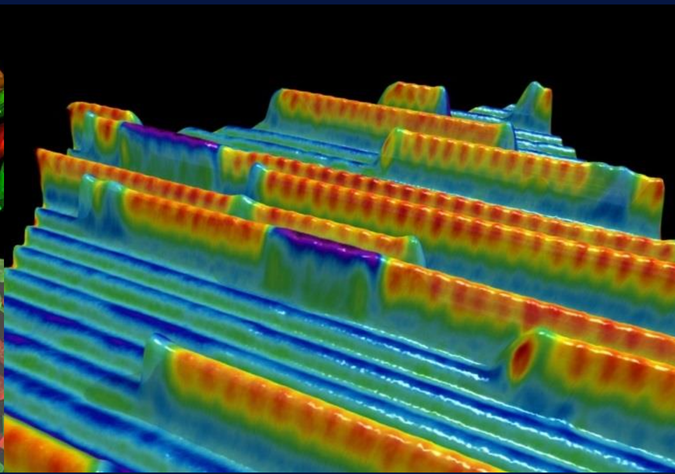
Milestones in the Application of SP-STM to Non-Collinear Chiral Spin States



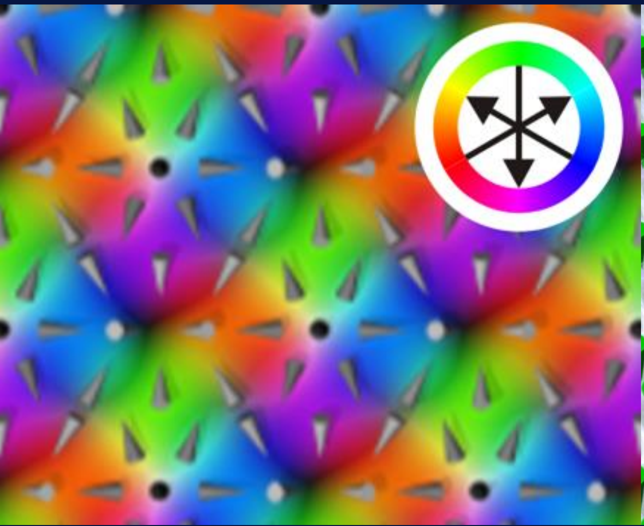
Science **292**, 2053 (2001)
Phys. Rev. Lett. **88**, 057201 (2002)



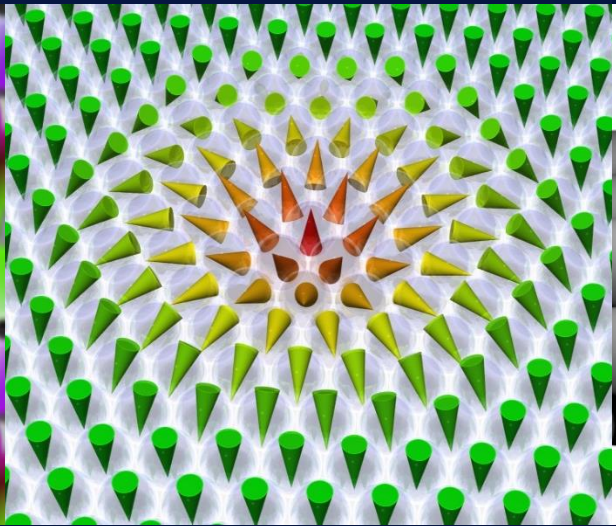
Nature **447**, 190 (2007)
Phys. Rev. Lett. **101**, 027201 (2008)



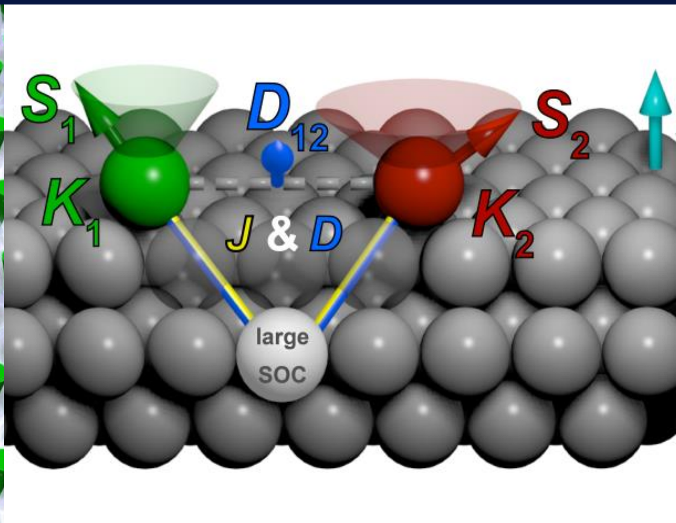
Phys. Rev. Lett. **108**, 197204 (2012)
Phys. Rev. Lett. **112,** 047204 (2014)



Nature Phys. **7**, 713 (2011)
Nature Nanotechnol. **9**, 1018 (2014)



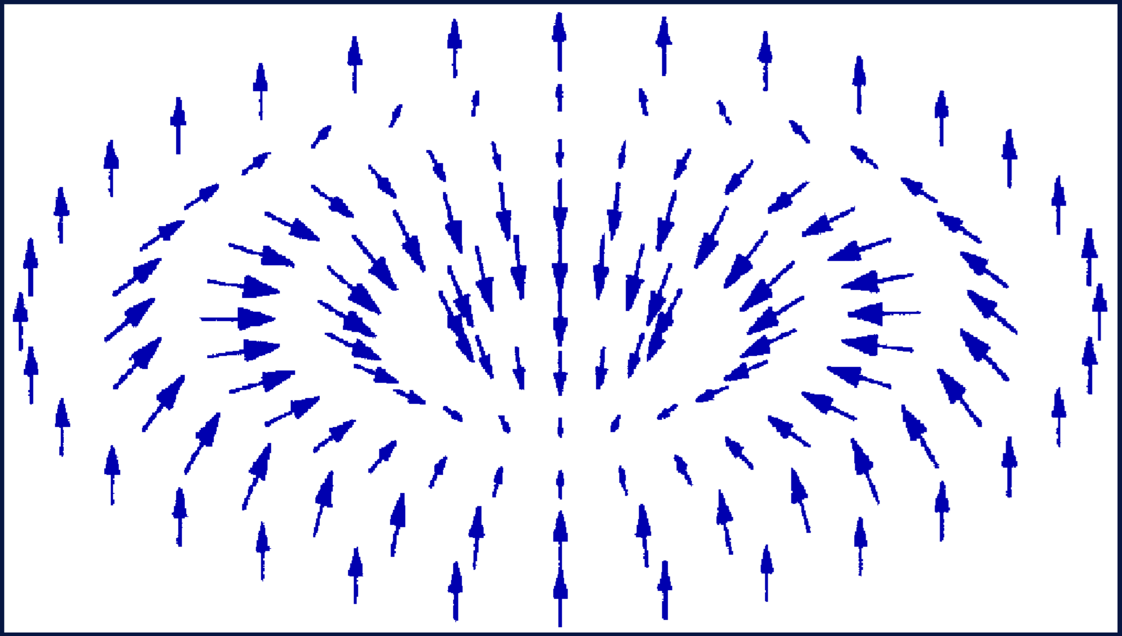
Science **341**, 6146 (2013)
Phys. Rev. Lett. **114**, 177203 (2015)



Nature Commun. **7**, 10620 (2016)
Nature Commun. 9, 2853 (2018)

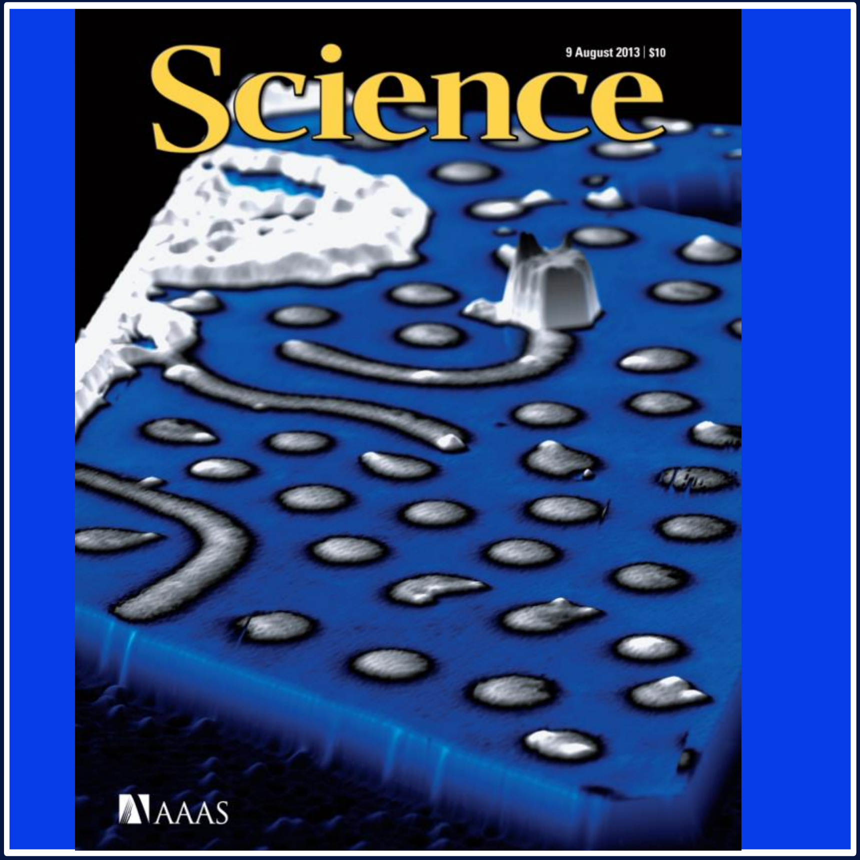
Skyrmions:
Magnetic Knots in the Nanoworld

Particle-like, localized spin structure with a fixed rotational sense:



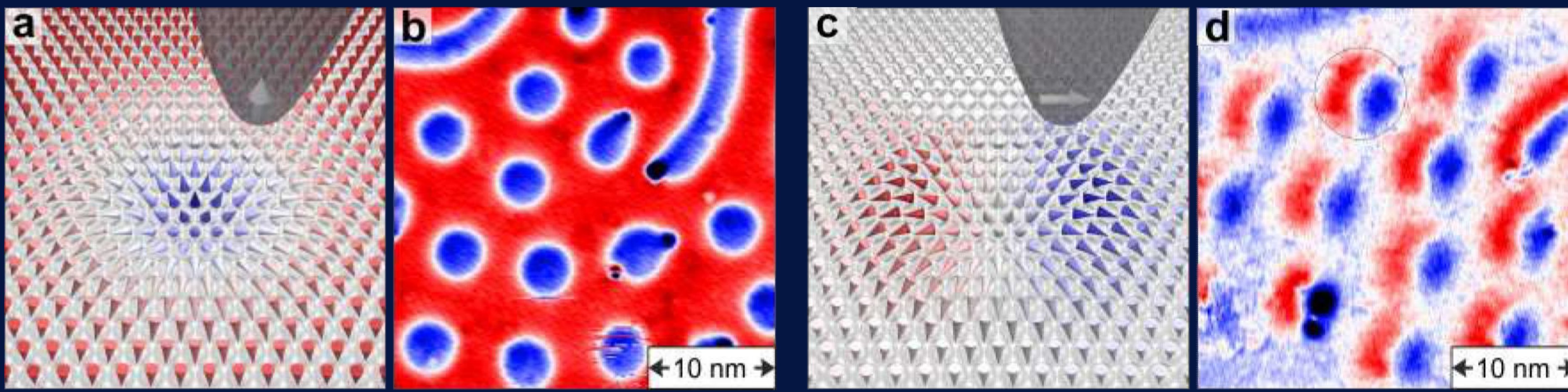
A. Bogdanov & D. Yablonskii,
Sov. Phys. JETP **68**, 101 (1989)

First experimental observation of single magnetic skyrmions in Hamburg



N. Romming et al., Science **341**, 6146 (2013)

3D Spin Texture of Nano-Scale Skyrmions in Pd / Fe / Ir(111)

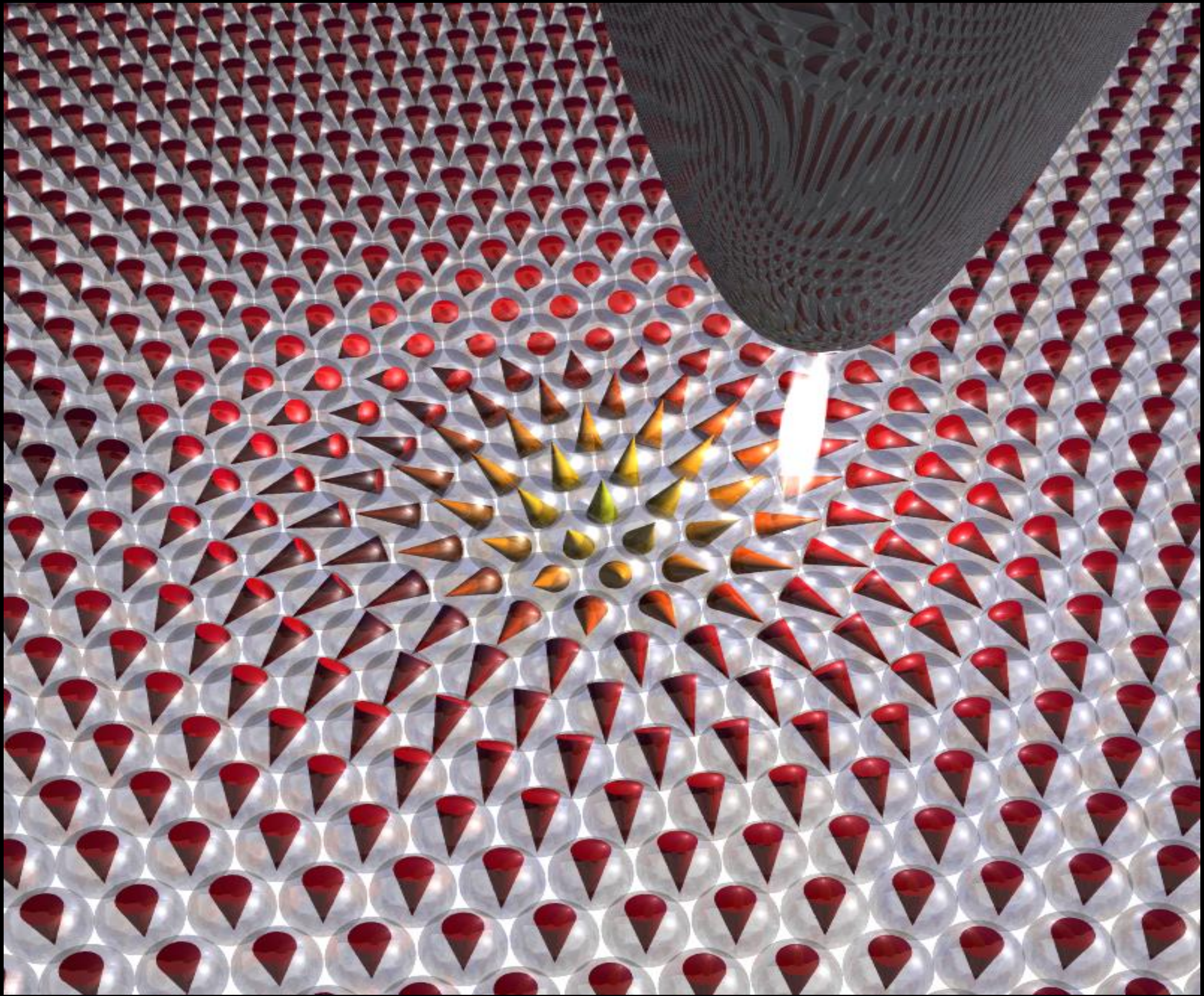


→ axisymmetric appearance of skyrmions with out-of-plane sensitive SP-STM tips

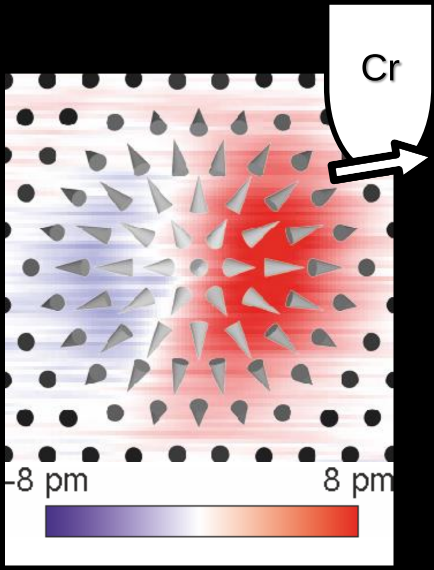
→ in-plane sensitive SP-STM tips reveal unique rotational sense of nanoskyrmions

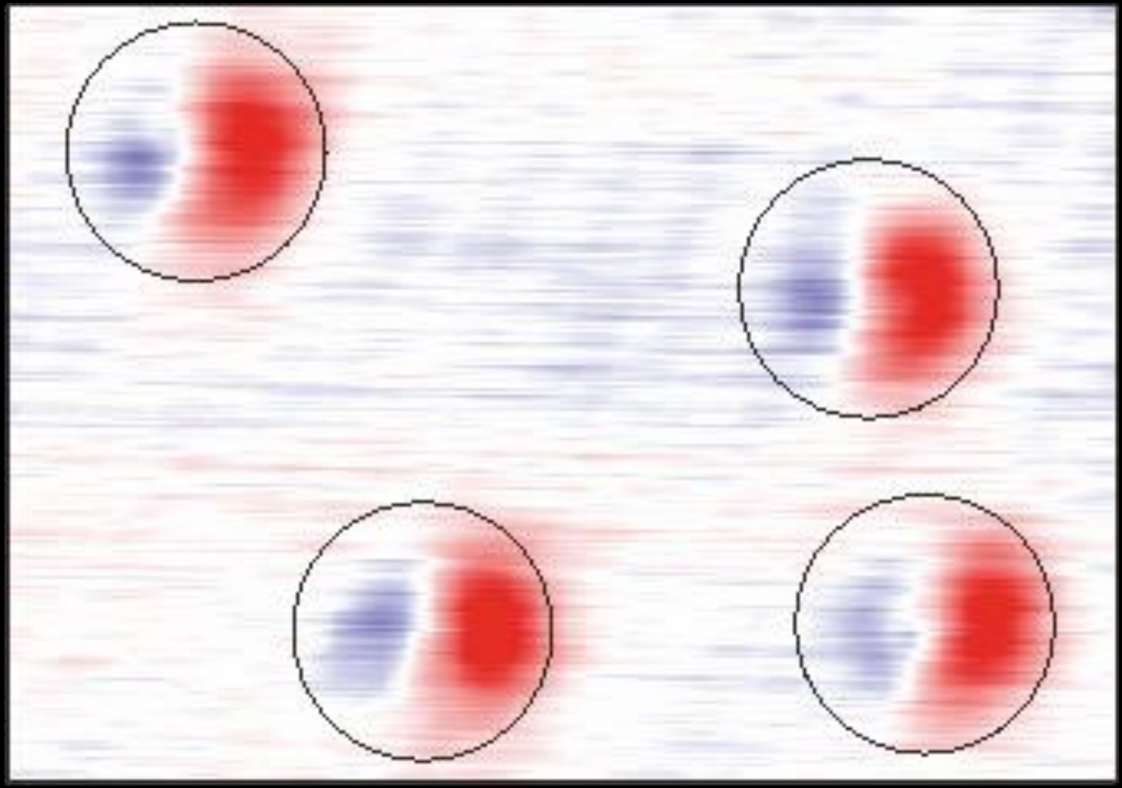
N. Romming et al., Science **341**, 6146 (2013)

From Imaging of Individual Skyrmions to Local Manipulation by Spin-Polarized Current Injection

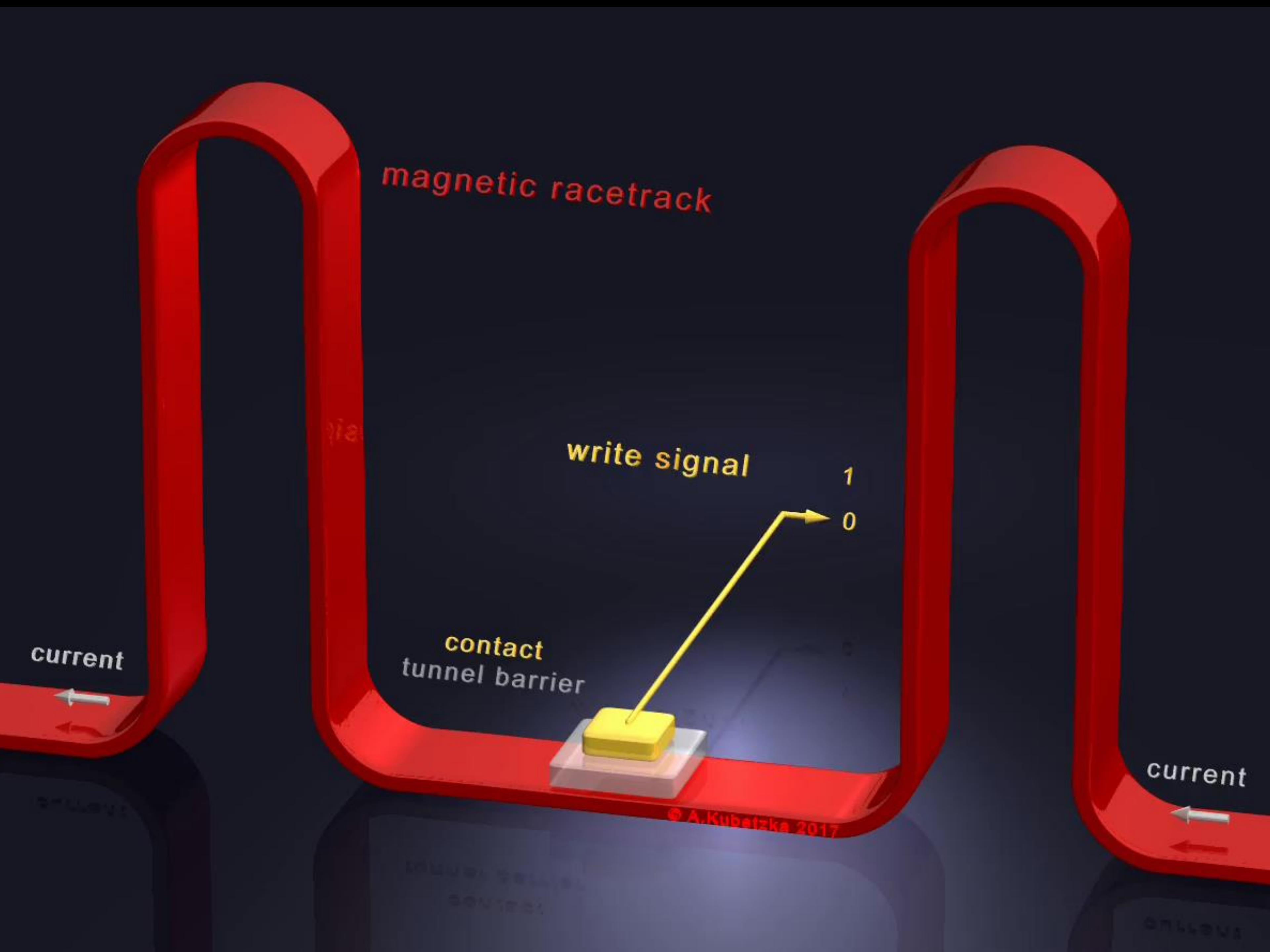


Writing and Deleting Single Chiral Skyrmions (3 nm diam.) by Local Spin Current Injection

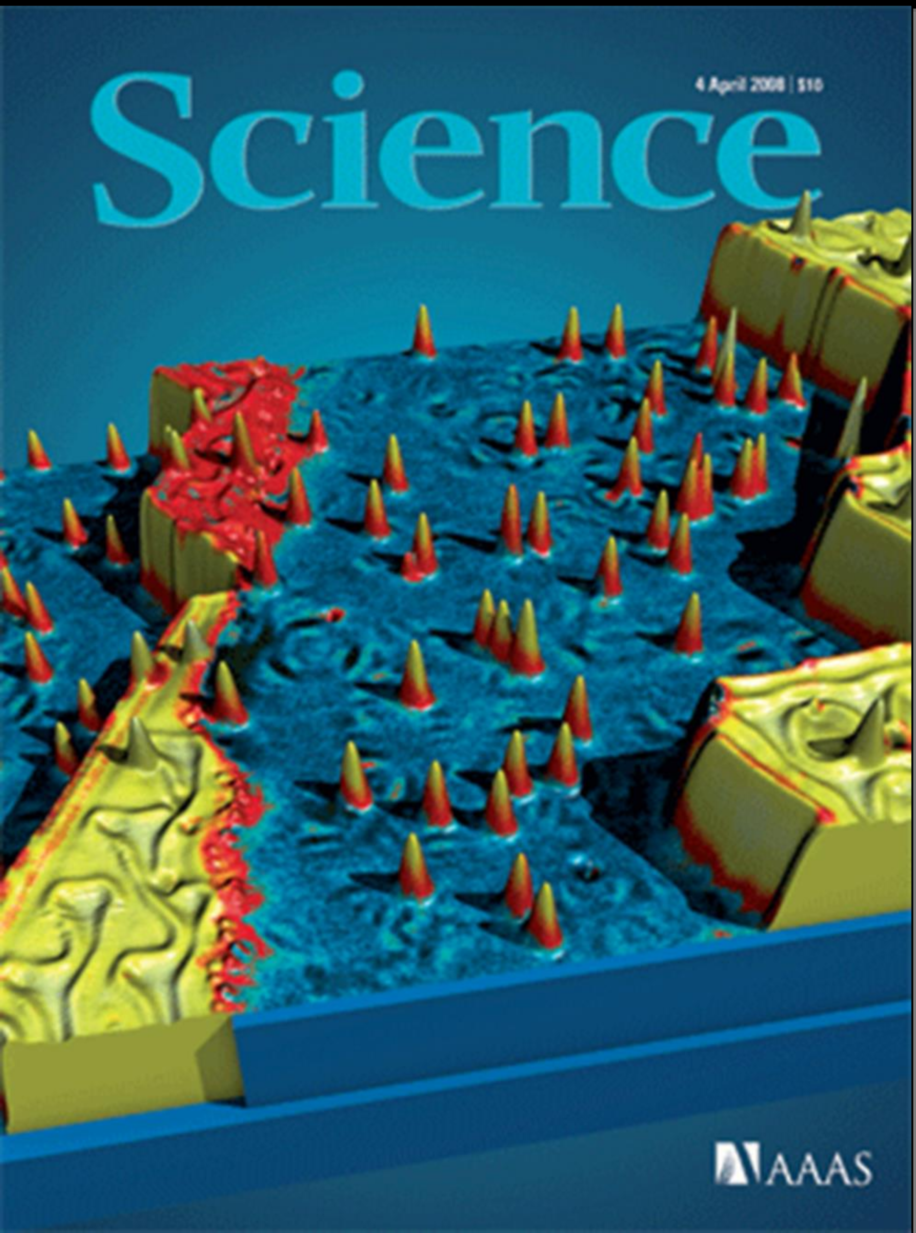


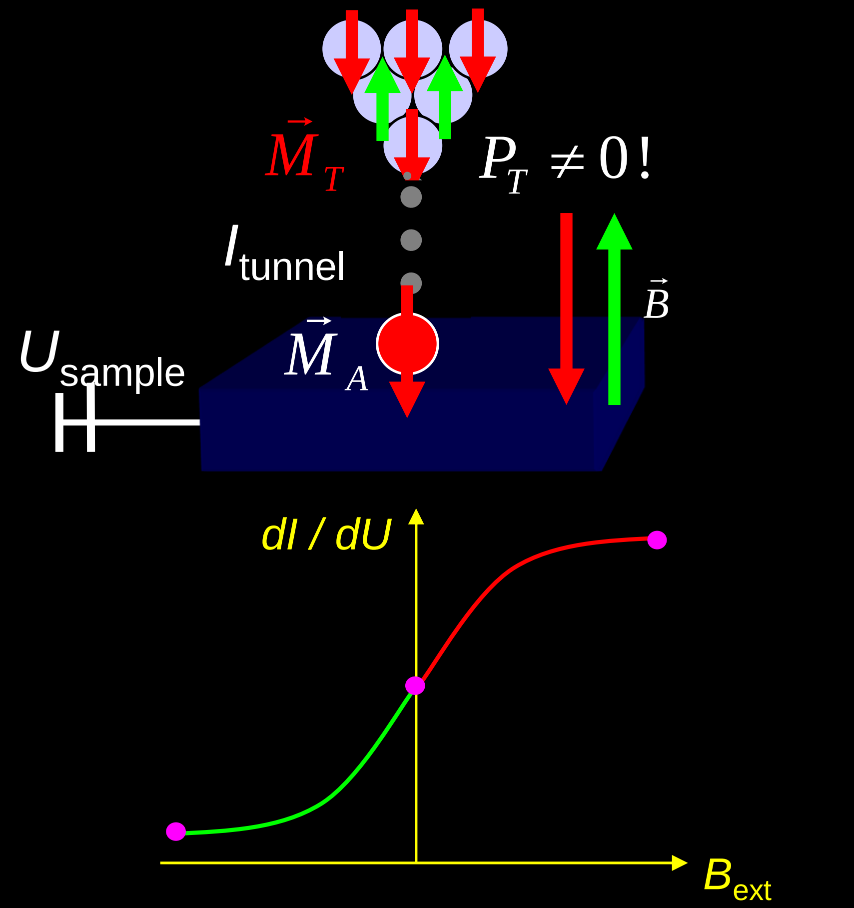


N. Romming et al., Science **341**, 6146 (2013)


magnetic racetrack
write signal
1
0
contact
tunnel barrier
current
current
© A.Kubetzka 2017

Single-Atom Magnetometry based on SP-STM

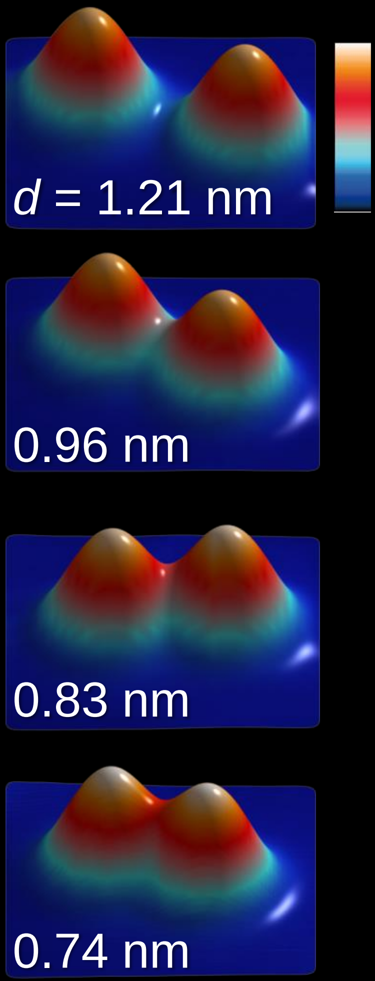


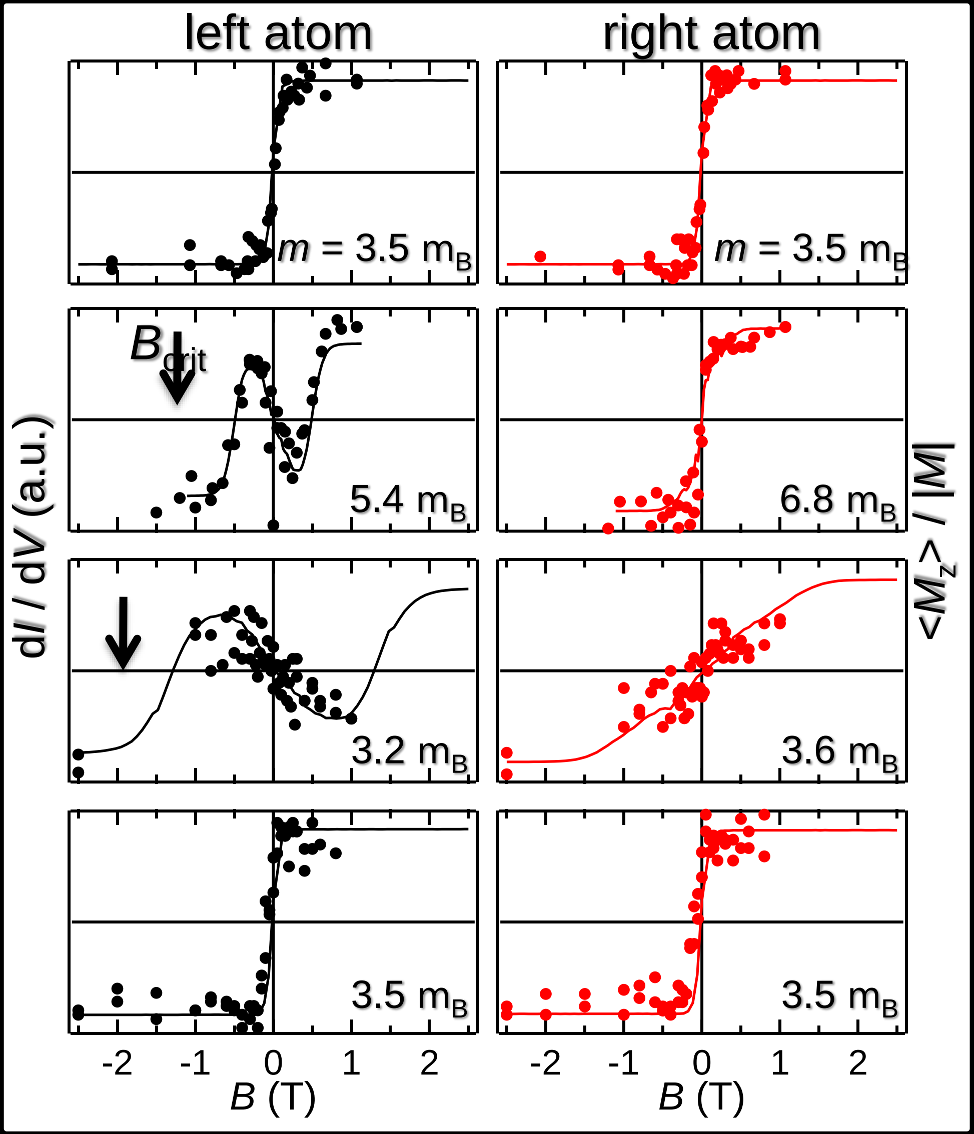


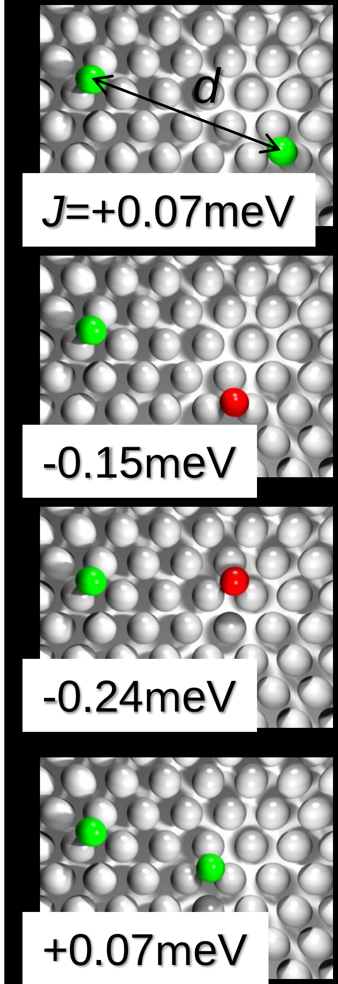
$$I_{sp} = I_0[1 + P_S P_T \cos(\vec{M}_S, \vec{M}_T)]$$

F. Meier *et al.*, Science 320, 82 (2008)

Oscillatory Indirect Magnetic Exchange of Co Pairs on Pt(111)

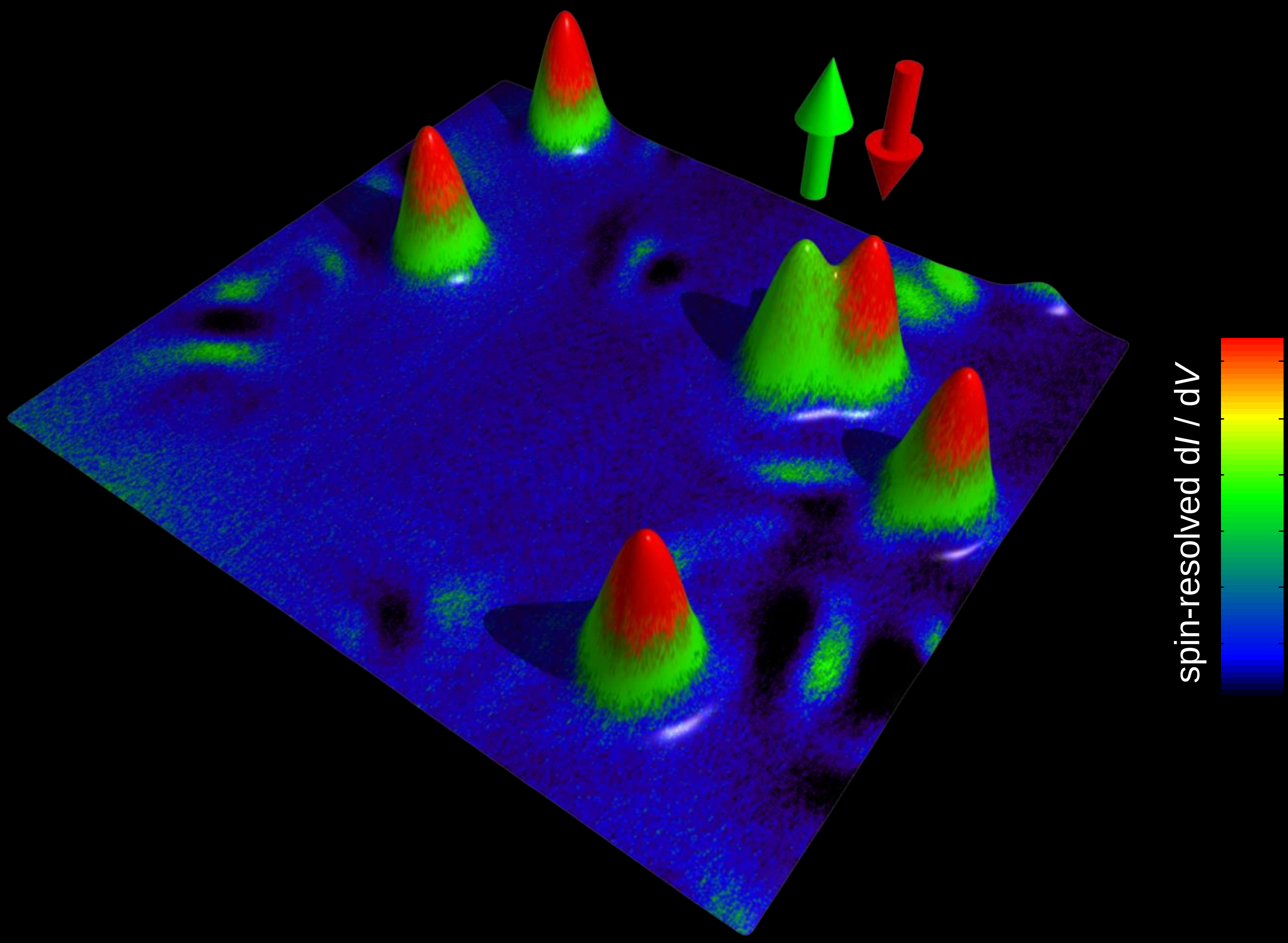


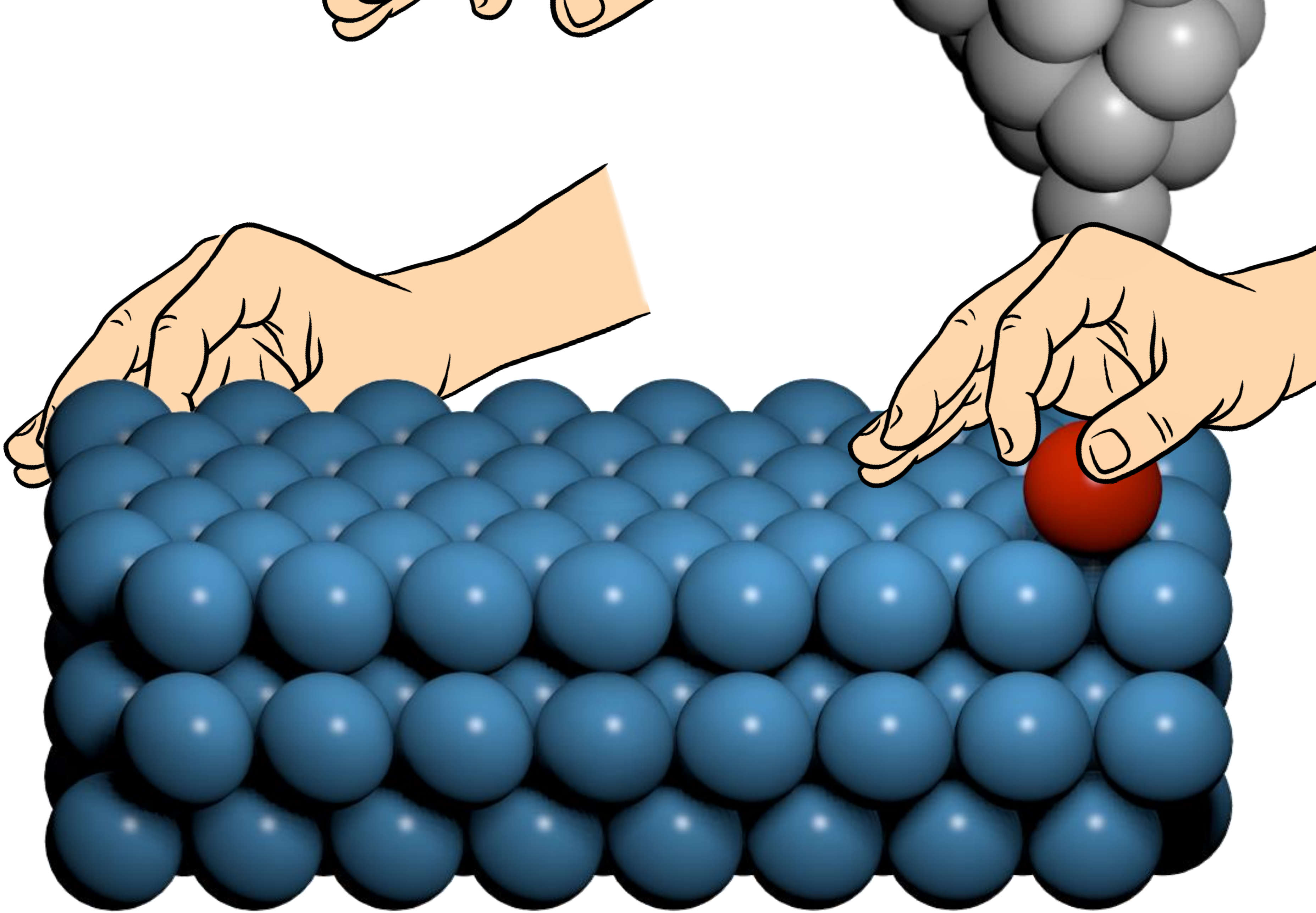




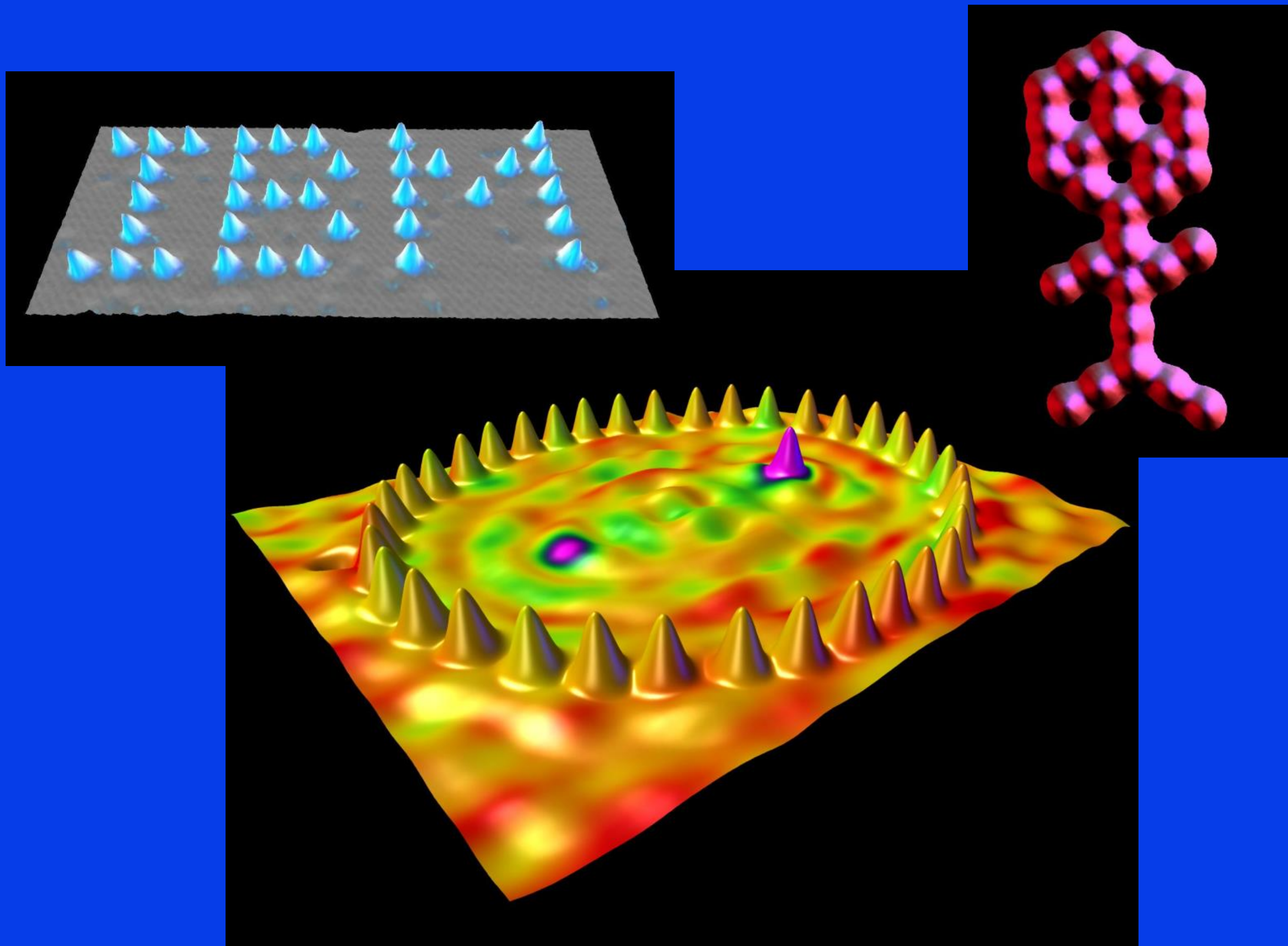
L. Zhou *et al.*, Nature Physics 6, 187 (2010)

Direkte Visualisierung der antiferromagnetischen Kopplung zwischen zwei Kobalt-Atomen auf Pt(111)



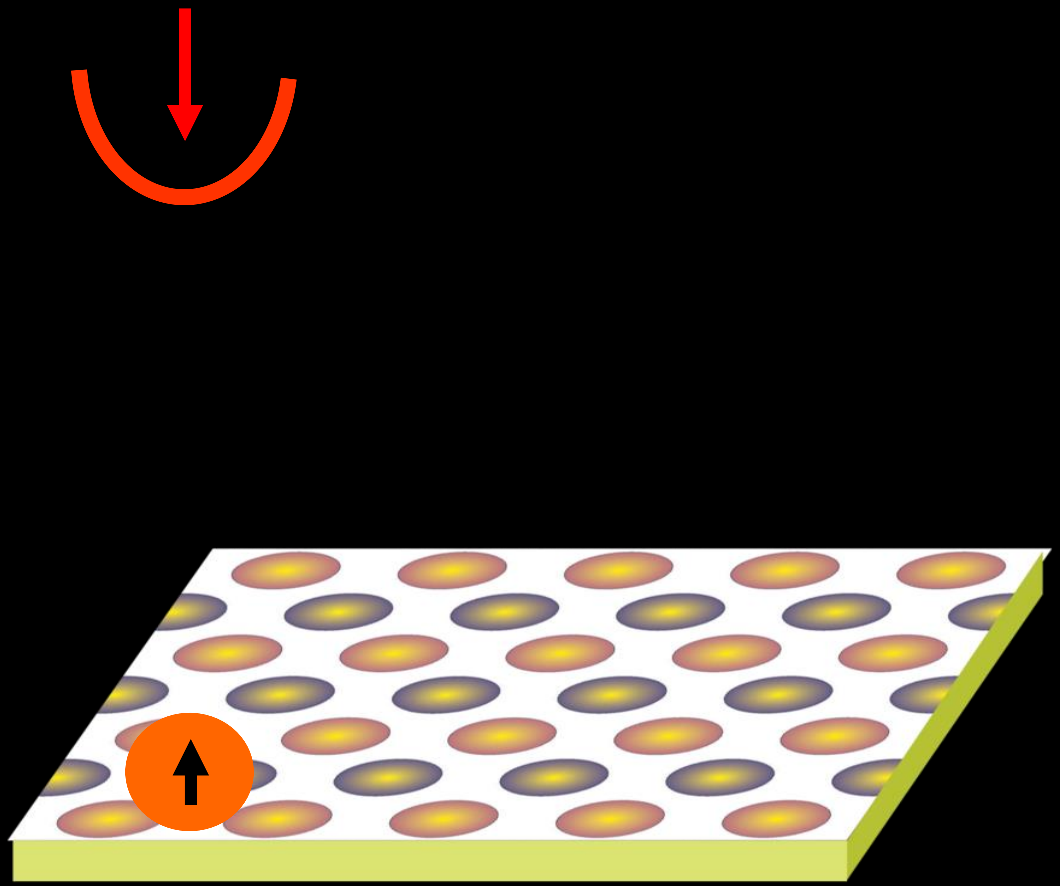


STM-based single-atom manipulation



D. Eigler *et al.*, IBM Almaden Research Center

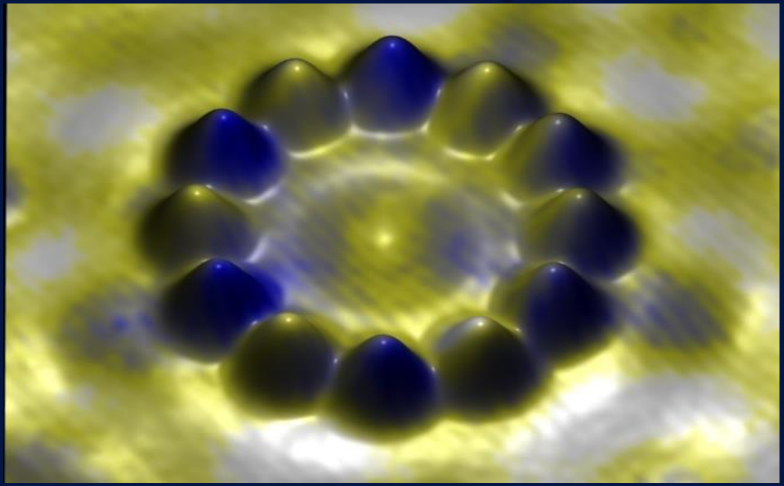
Artificially Fabricated Magnetic Nanostructures by Lateral Manipulation of Single Atoms



D. Serrate *et al.*, Nature Nanotechnology **5**, 350 (2010)

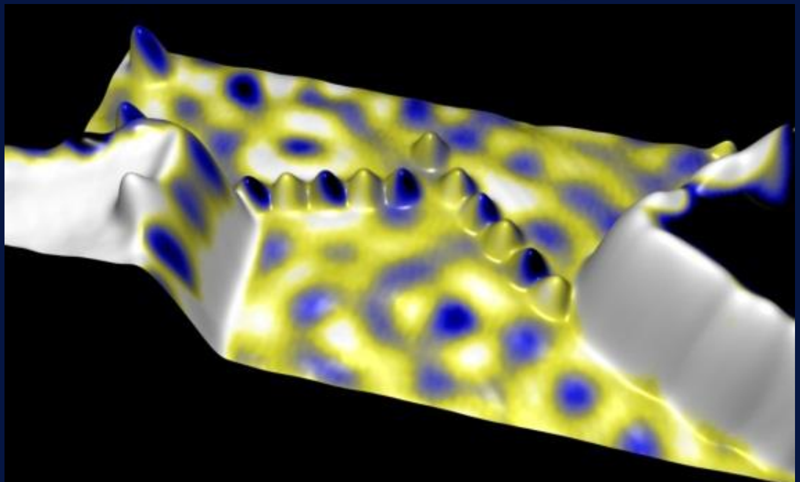
Milestones in Quantum Designer Physics involving Atomic Spin Systems

Tailored Nanomagnets



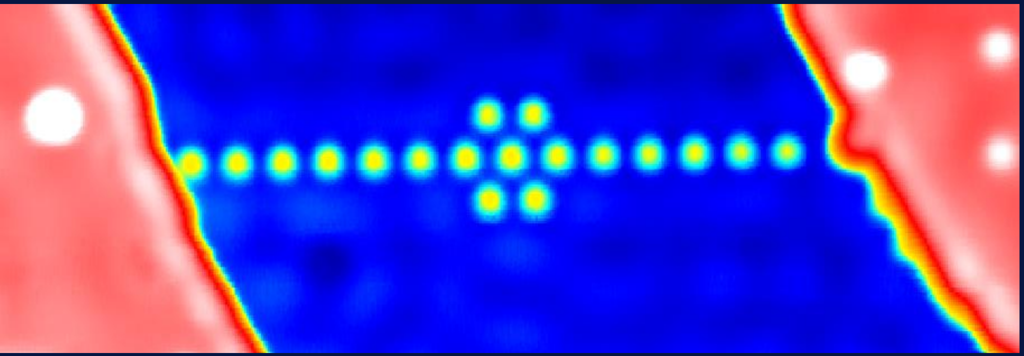
Nature Physics **8**, 497 (2012)
Science **339**, 55 (2013)
Nature Commun. **8**, 41467 (2017)

All-Spin Atomic-Scale Logic Device

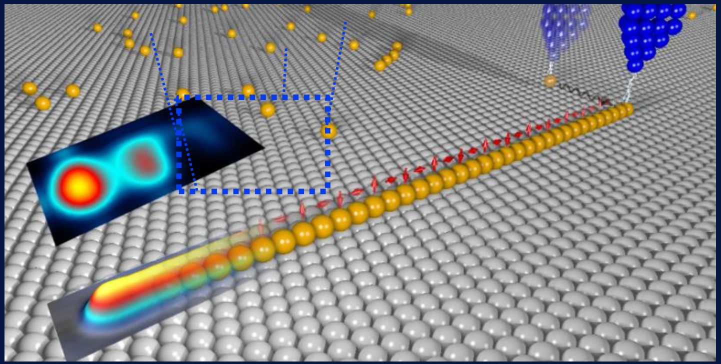


Science **332**, 1062 (2011)

Atomic-Scale Spin Transport Device

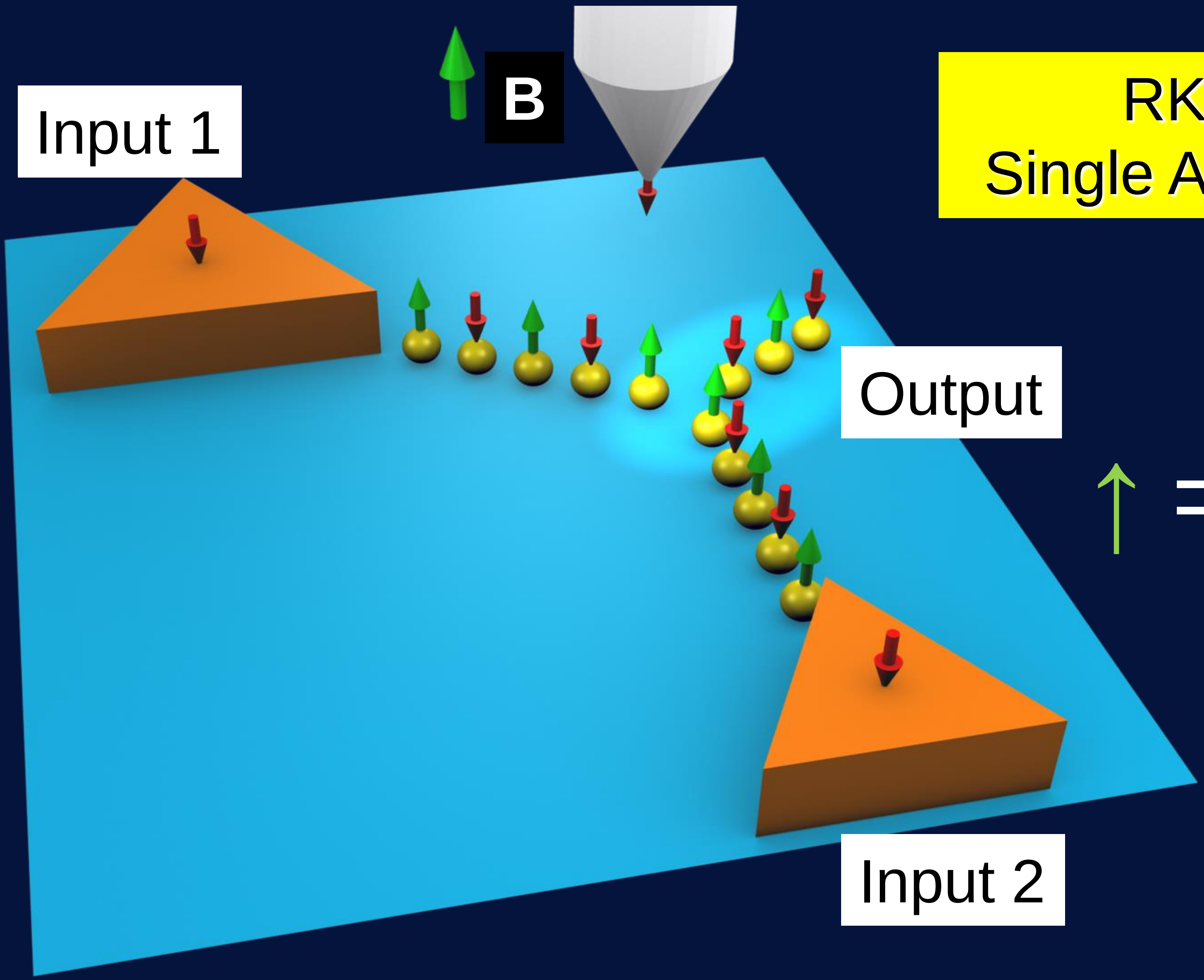


Emergent Majorana States in Atomic-Scale Hybrid Systems



Science Advances **4**, eaar5251 (2018)
Nature Nanotechnol. **17**, 384 (2022)

RKKY-Based Single Atom Spin Logic



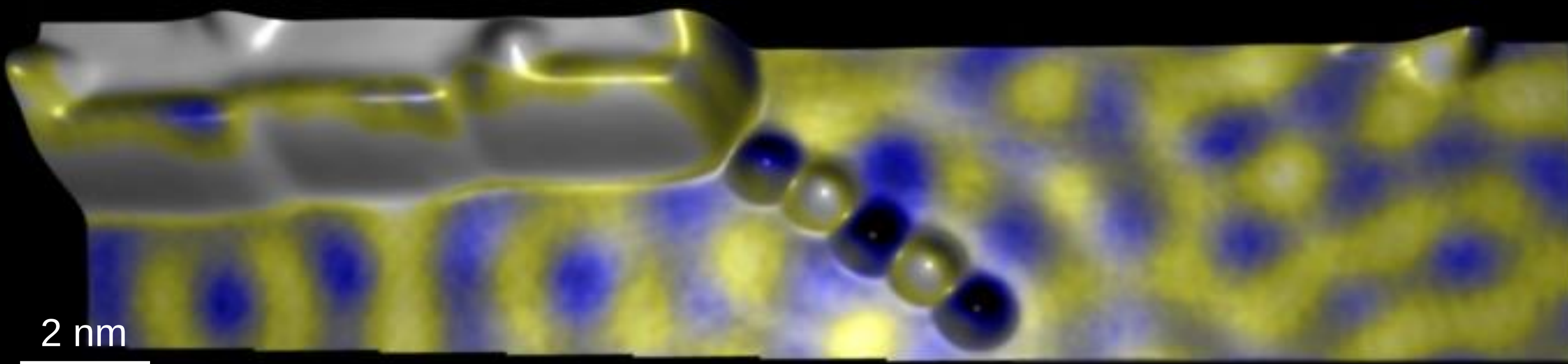
↑ = 1 , ↓ = 0

→ Utilize RKKY-coupling to tailor magnetic state of output !

A. A. Khajetoorians *et al.*, Science 332, 1062 (2011)

Logical Input Negation and Lead Construction

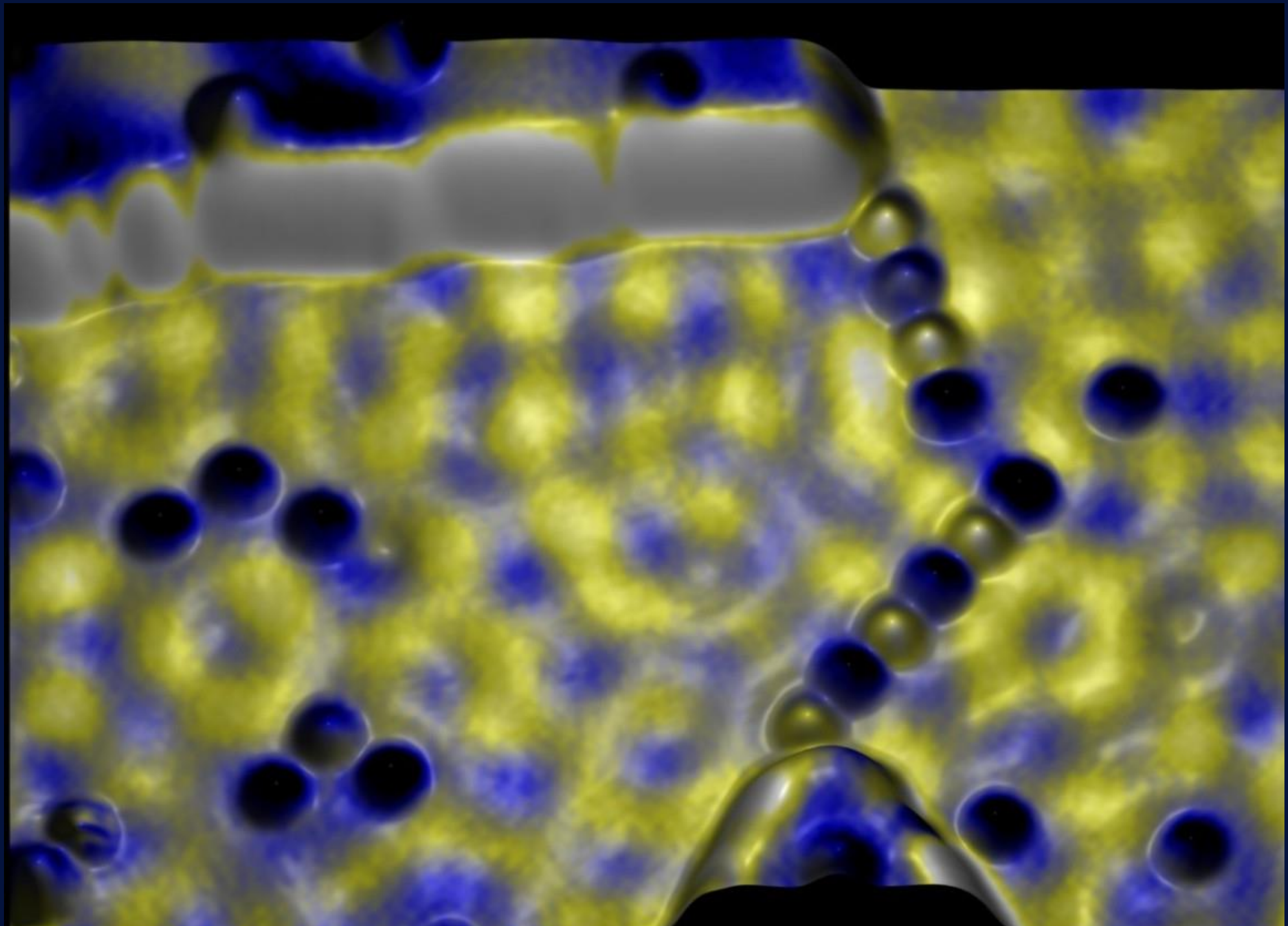
- Tune magnetic coupling ↔ Manipulate inter-atomic distance
- First atom’s spin state stabilized by nanoscale island
- Antiferromagnetic coupling regime



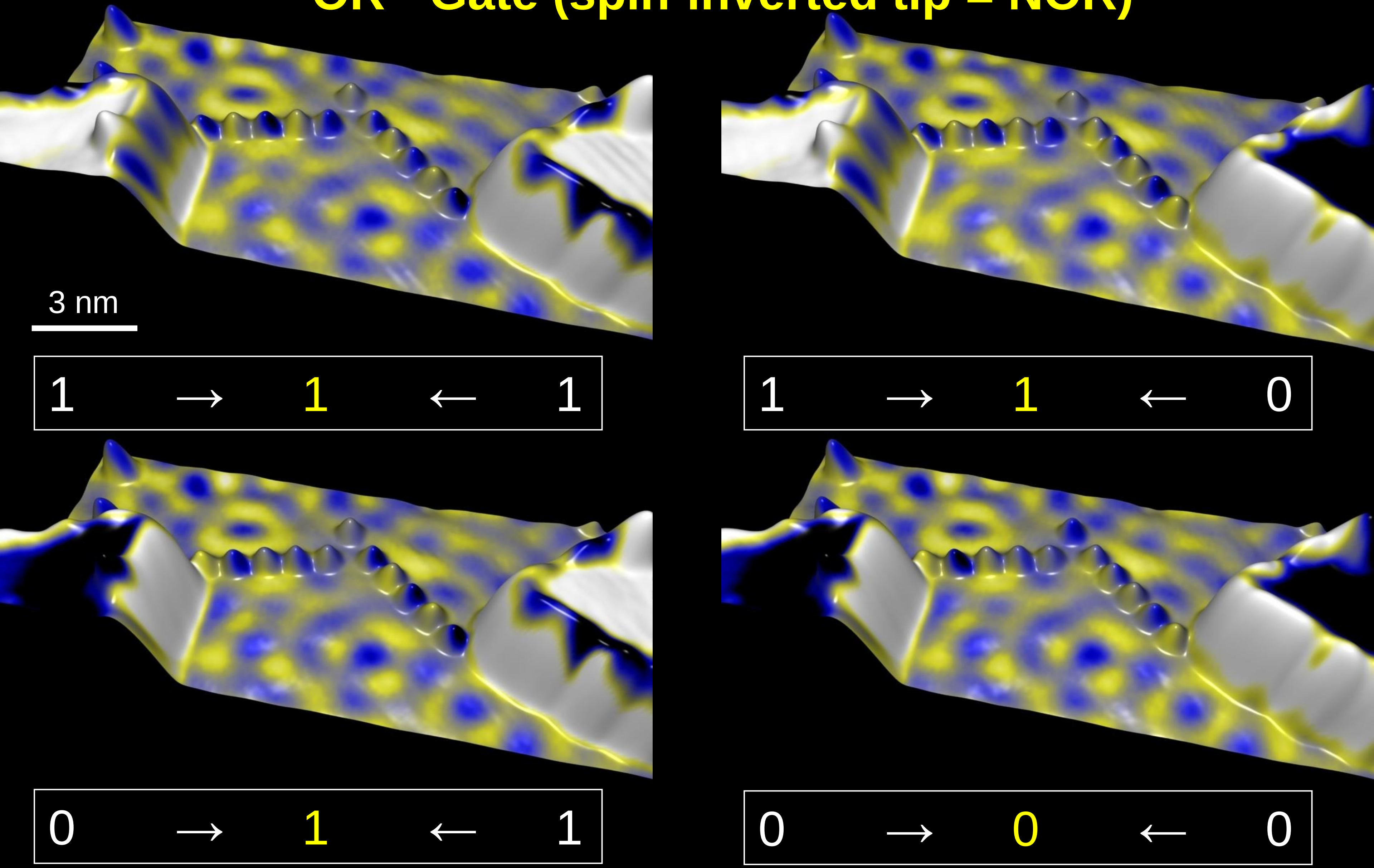
A. A. Khajetoorians *et al.*, Science 332, 1062 (2011)

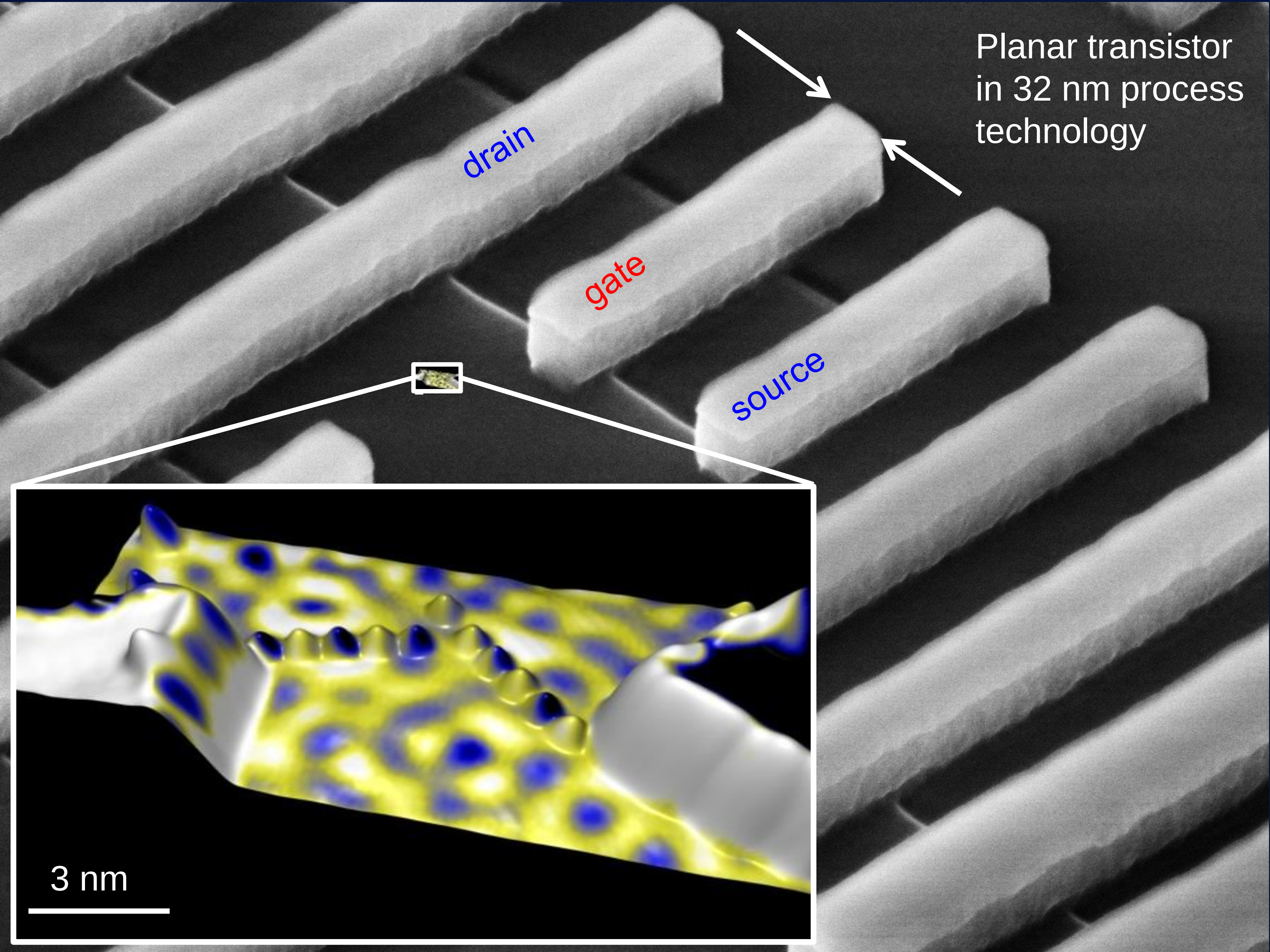
Characteristics of Single Atom Spin Logic

No atom movement involved → Fast switching processes
No charge transport involved → Negligible energy dissipation;
electrical contact properties irrelevant!



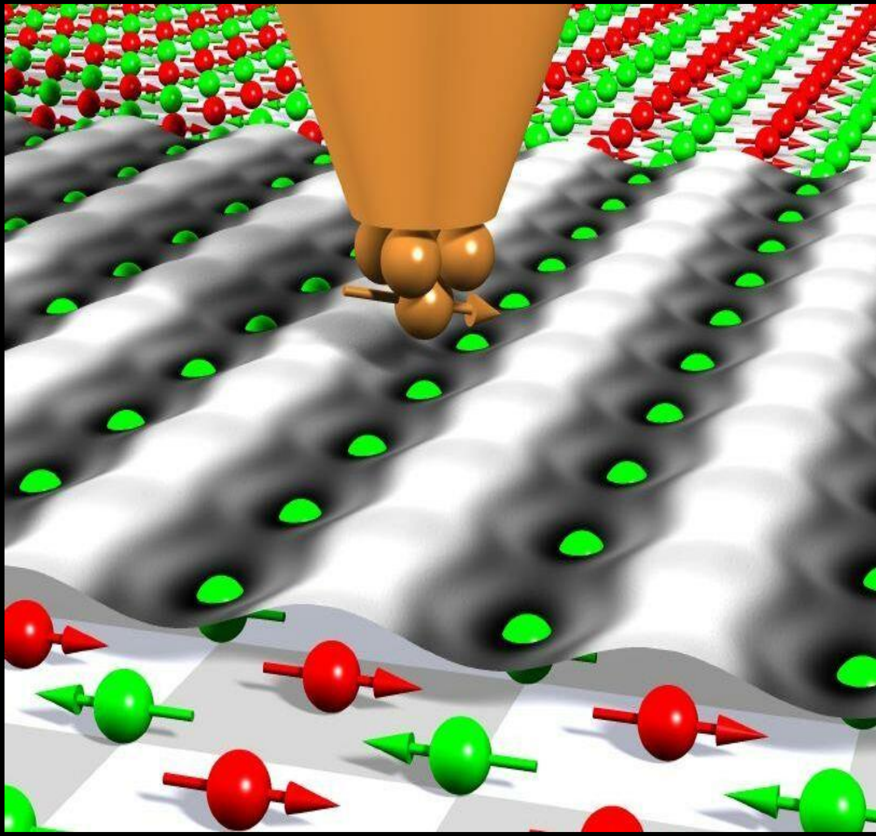
OR - Gate (spin-inverted tip = NOR)



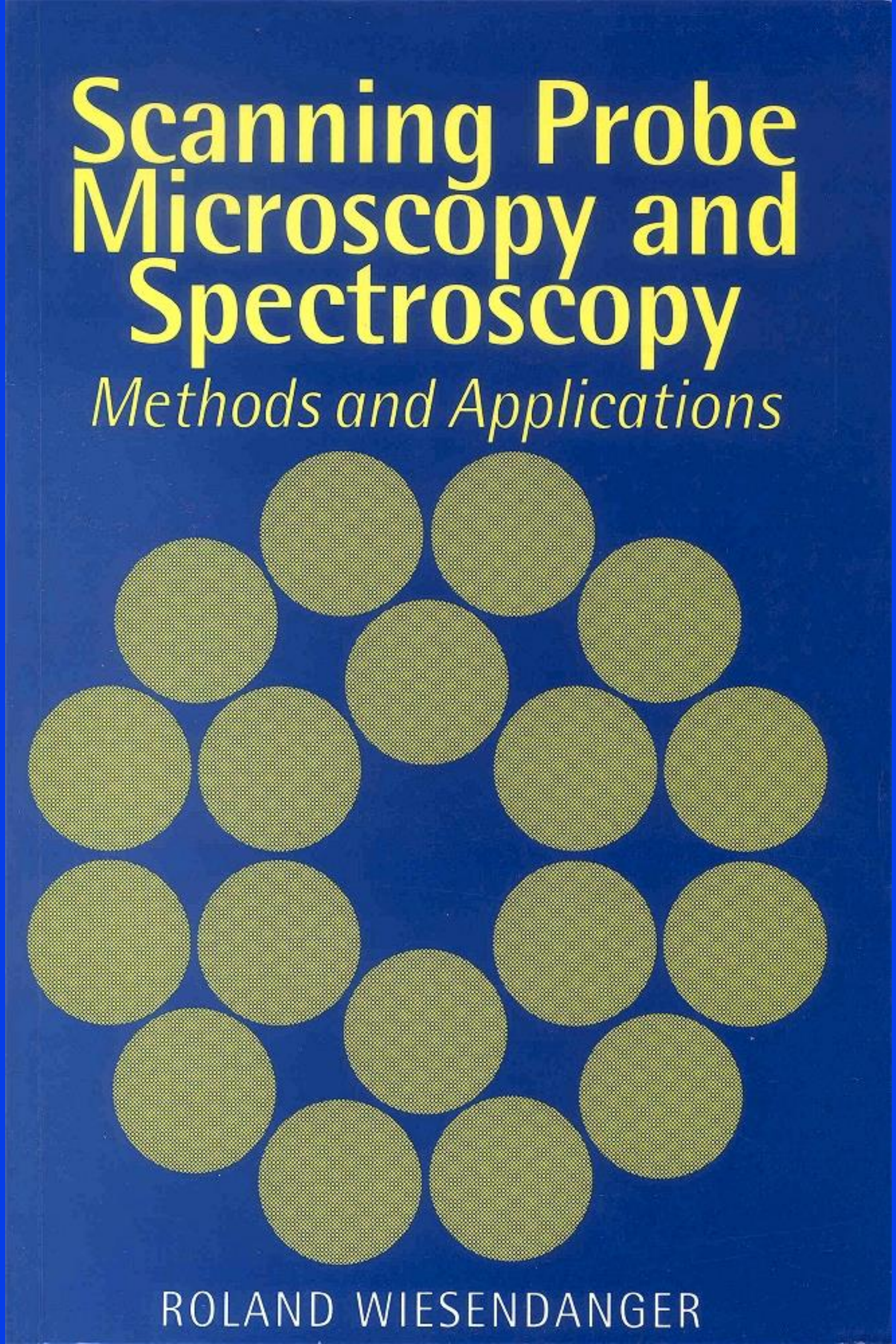

Planar transistor
in 32 nm process
technology
drain
gate
source
3 nm

Tunnelling as One of the Most Powerful Analytical Tools in Nanoscience and Condensed Matter Research

- direct probe of **squared wave-functions** of quantum systems
  (Bardeen)
- probe for **low energy scales**, high energy resolution
  (e.g. superconductivity: Giaever, Josephson)
- local probe at **atomic length scales**
  (STM / STS: Binnig, Rohrer)
- **spin-sensitive probe**
  (atomic-scale magnetism, single spin experiments, spin interactions)



- local probe at **high temporal resolution**


Scanning Probe Microscopy and Spectroscopy
Methods and Applications
ROLAND WIESENDANGER

Acknowledgements

Pin-Jui Hsu

Niklas Romming

Matthias Menzel

Jens Brede

Kirsten v. Bergmann

André Kubetzka

Elena Vedmedenko

Stefan Heinze

Acknowledgements


Howon Kim


Alexandra Palacio-Morales


Manuel Steinbrecher


Khai Ton That


A. Khajetoorians


Jens Wiebe


Matthias Menzel


Thore Posske


Otto Stern Symposium 2013
22. - 23. Mai 2013
Otto Stern Hörsaal, Jungiusstrasse 9, 20355 Hamburg

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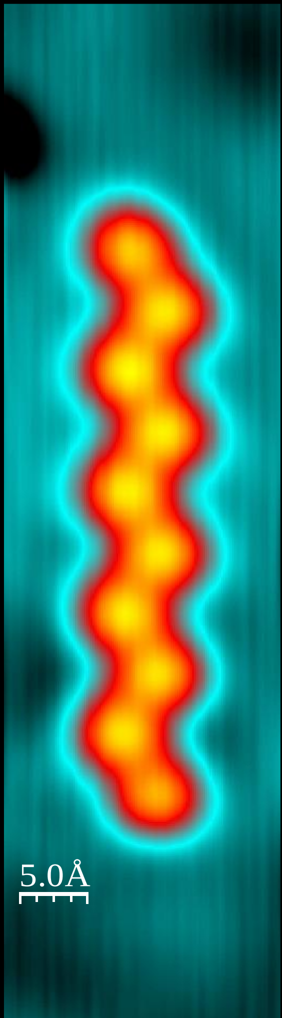
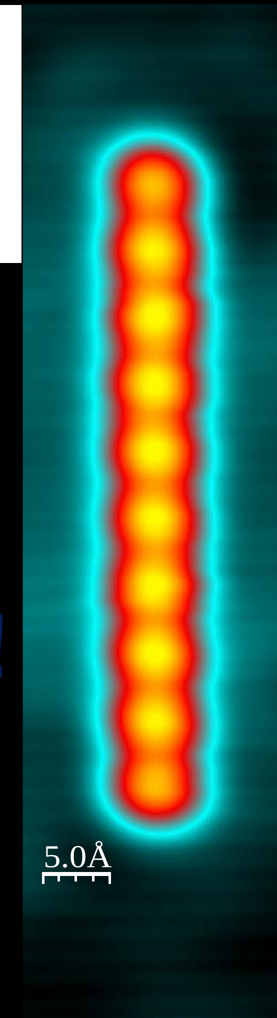
Shaping the Future – Atom by Atom



THANK YOU VERY MUCH FOR YOUR KIND ATTENTION !



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