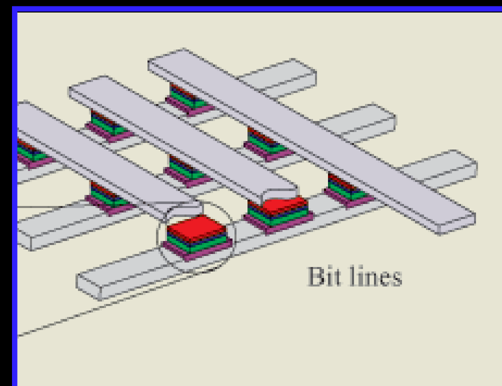
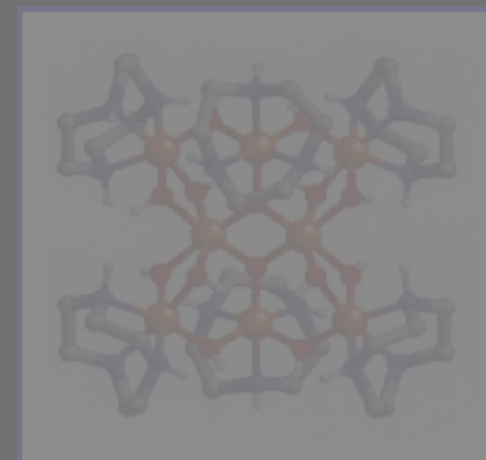
The Quantum and Classical Properties of Spins on Surfaces

Andreas Heinrich
IBM Research, USA

Quantum or Classic: that is the question



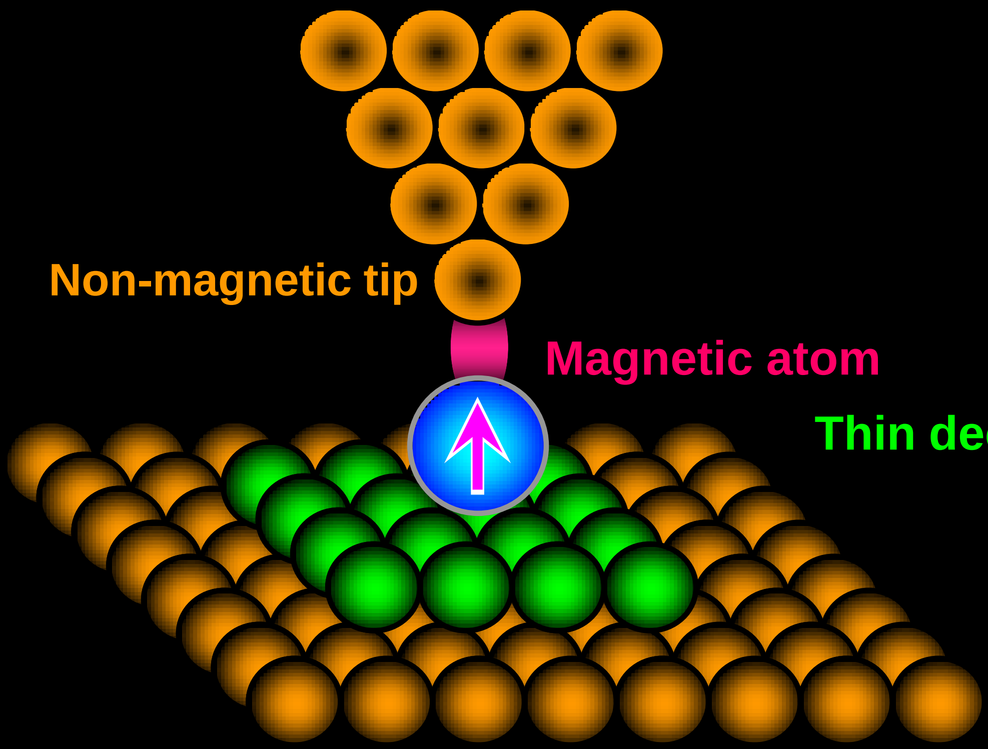


	Top-down	Bottom-up
Address individual structure	✓	✗
Quantum vs. Classical	C	Q
Atomic-scale control	✗	✓

Quantum or classic

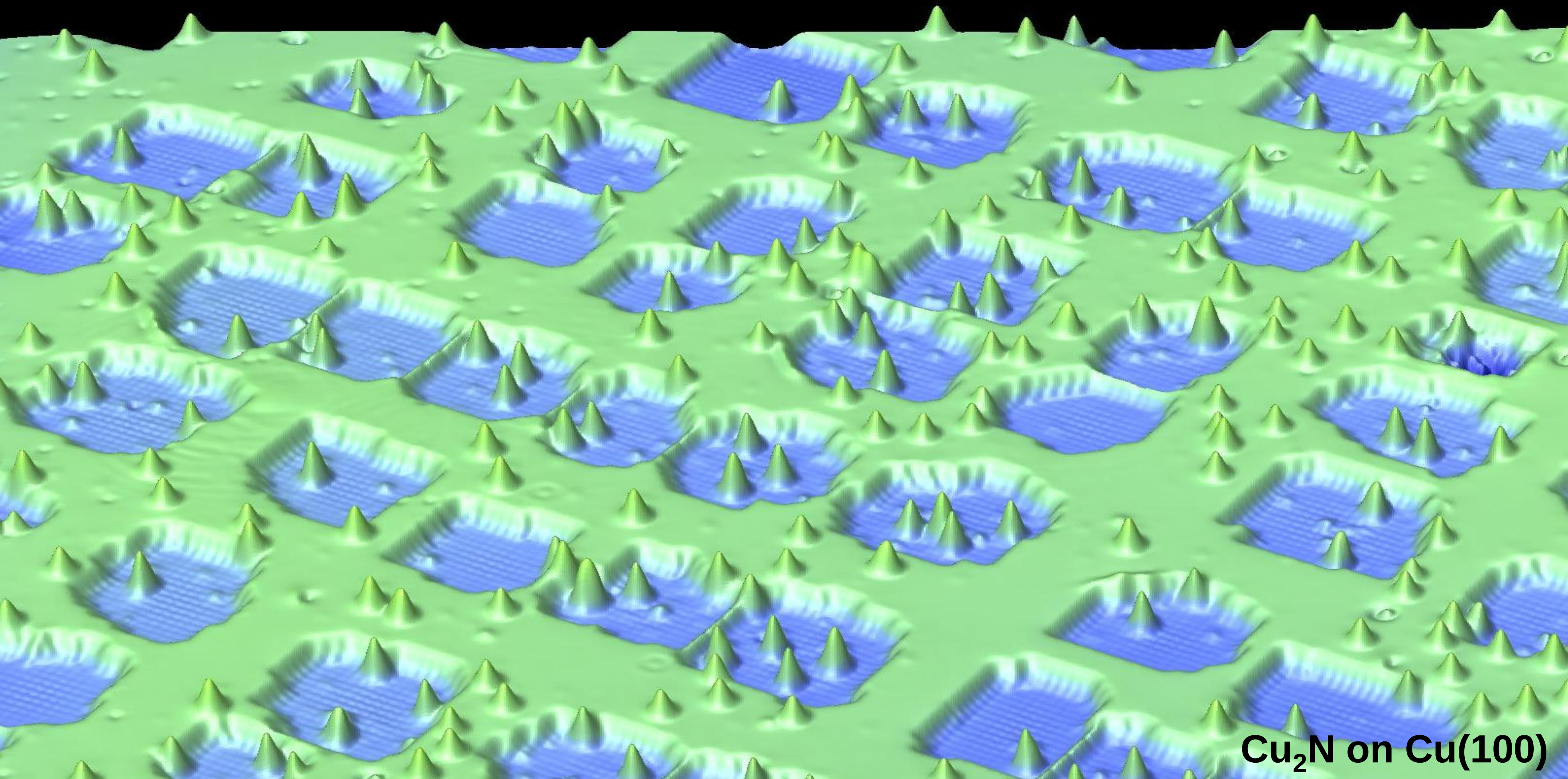
- **Spin excitations in STM**
  Science (2004)
- **Quantum spins:**
  A quantum antiferromagnet
  Science (2006)
- **Classical spins:**
  The smallest classical antiferromagnet
  Science (2012)

Scanning Tunneling Microscopy of Spins

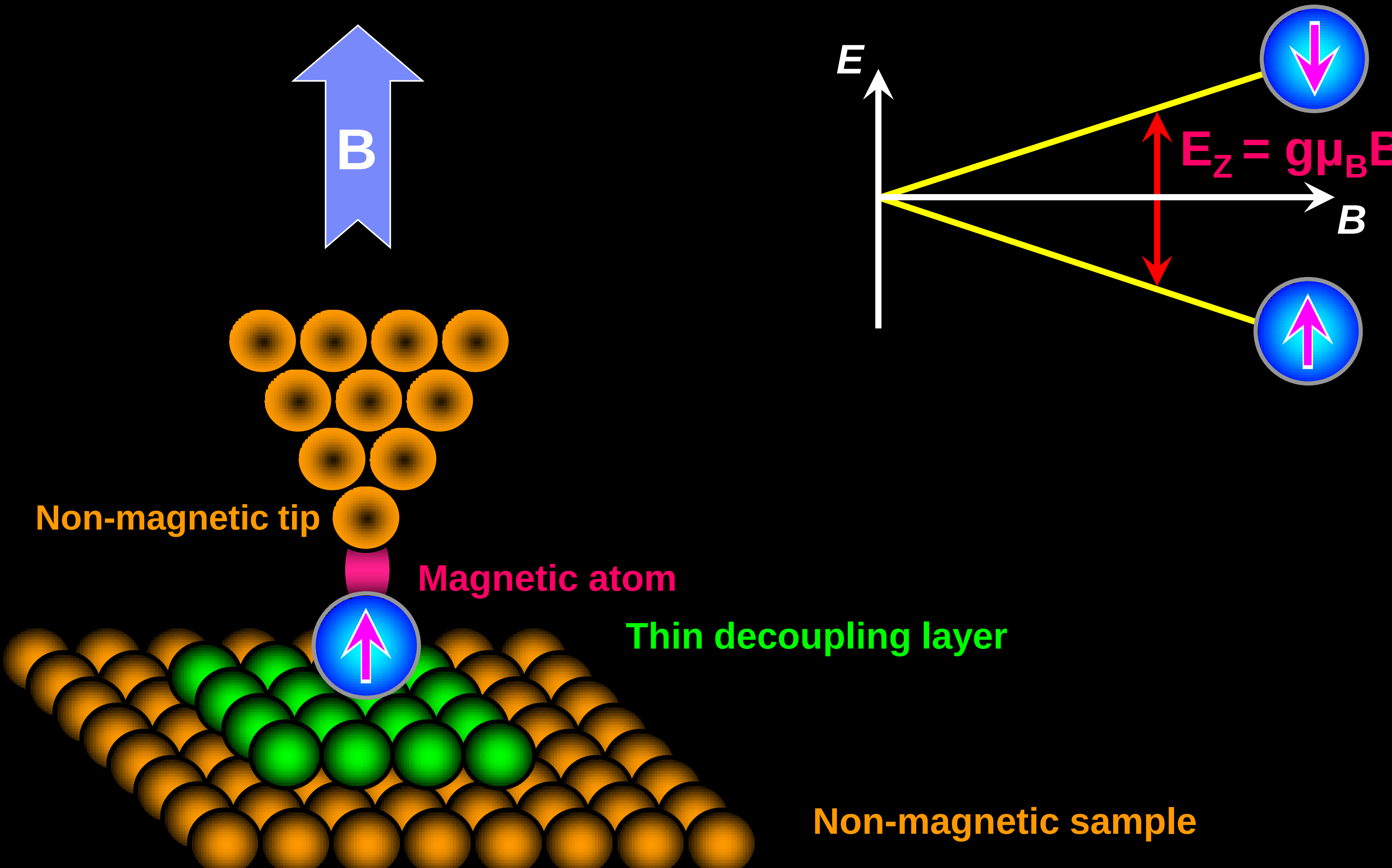


Imaging with STM: Mn, Cu, and Fe on Cu_2N

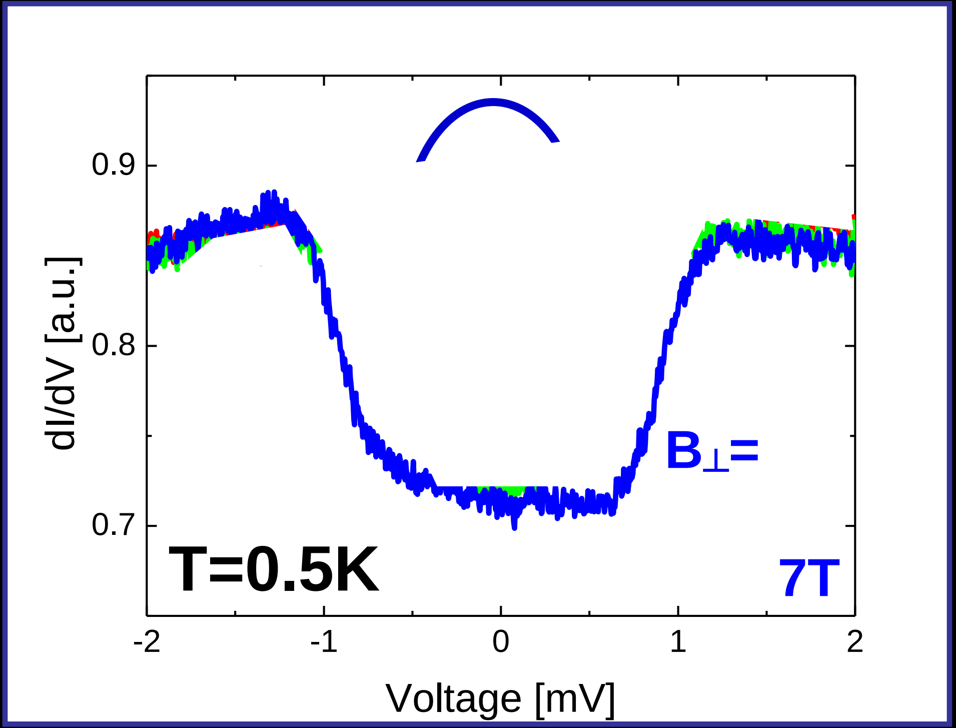
- Isolated magnetic atoms on patches of Cu_2N on Cu(100)
- Atoms are hard to distinguish

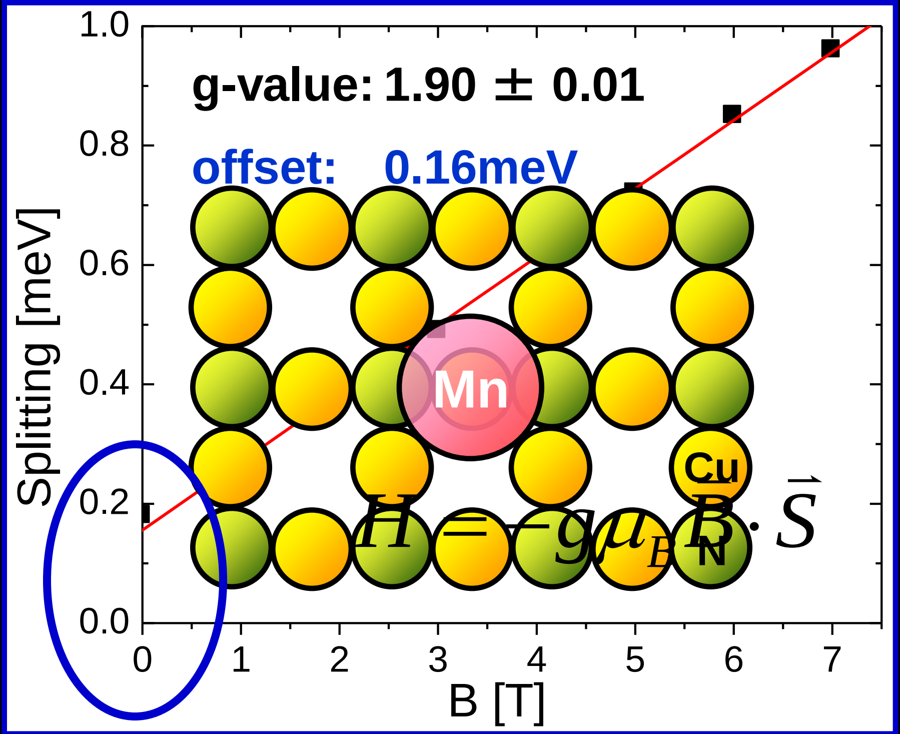


Spin excitation spectroscopy



Mn on Cu_2N: An almost pure spin

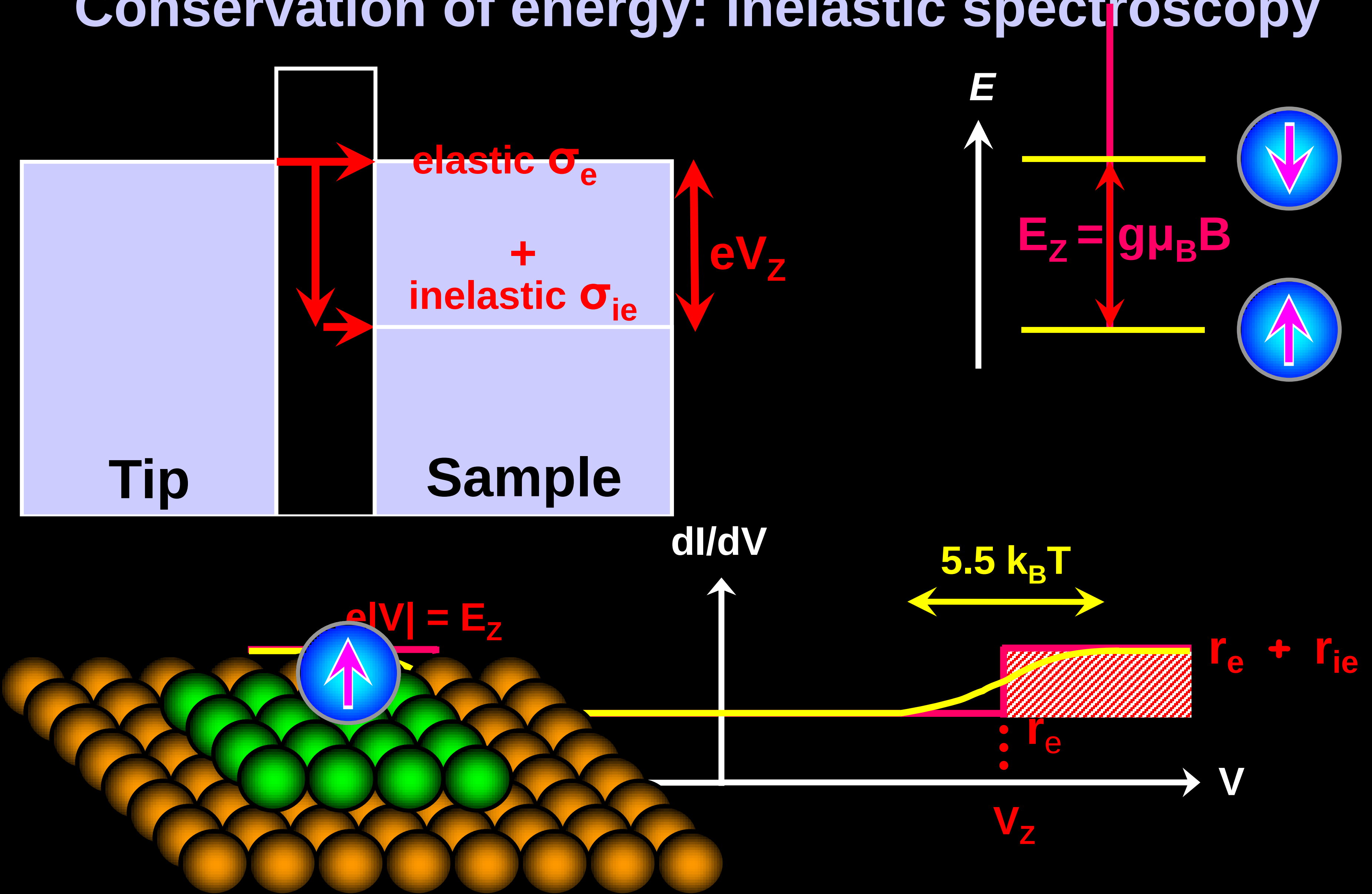




Mn atom on CuN exhibits magnetic behavior:

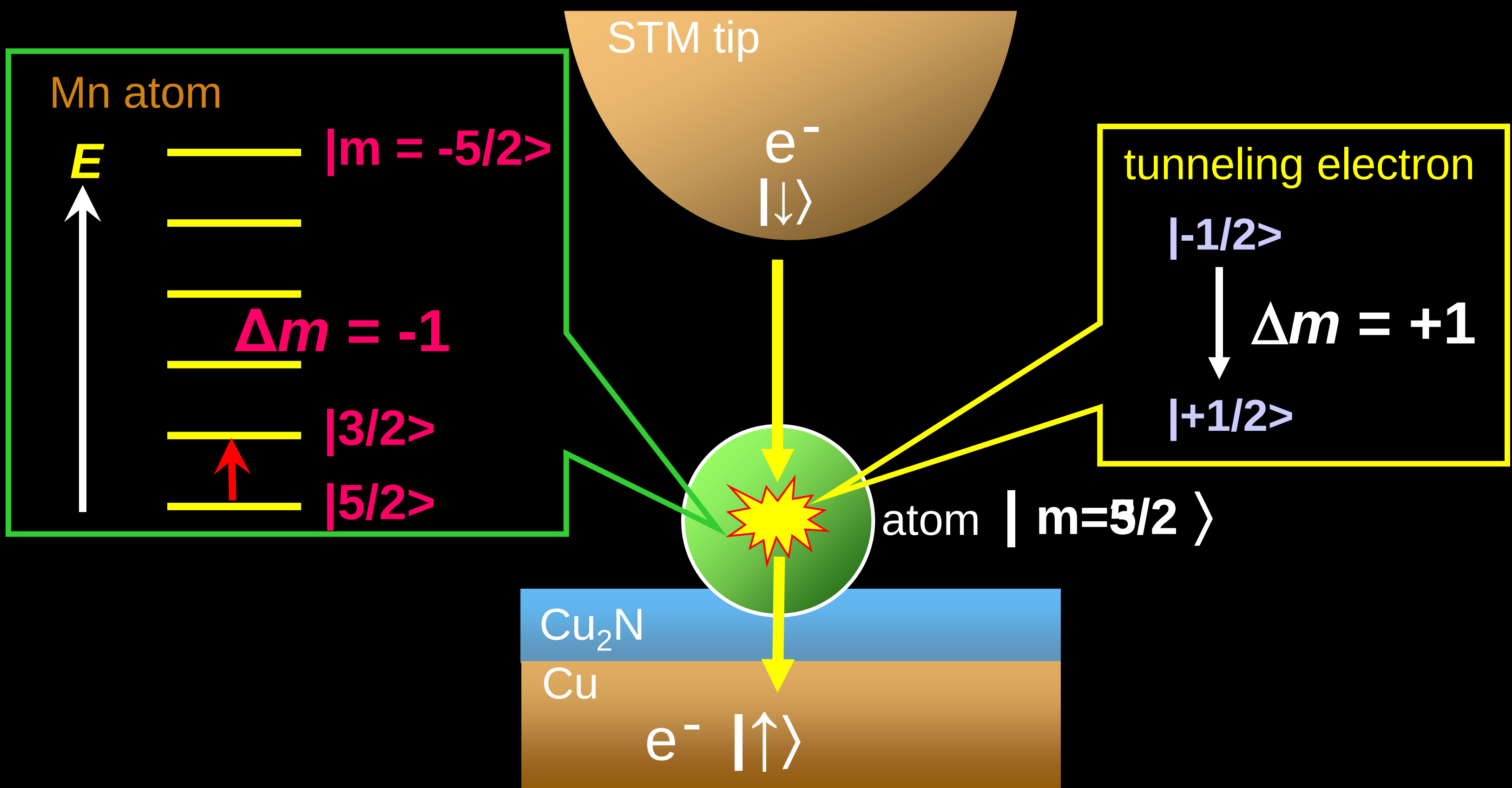
- **spin-flip excitation in *S* = 5/2 system**
- **small amount of zero-field splitting**

Conservation of energy: inelastic spectroscopy

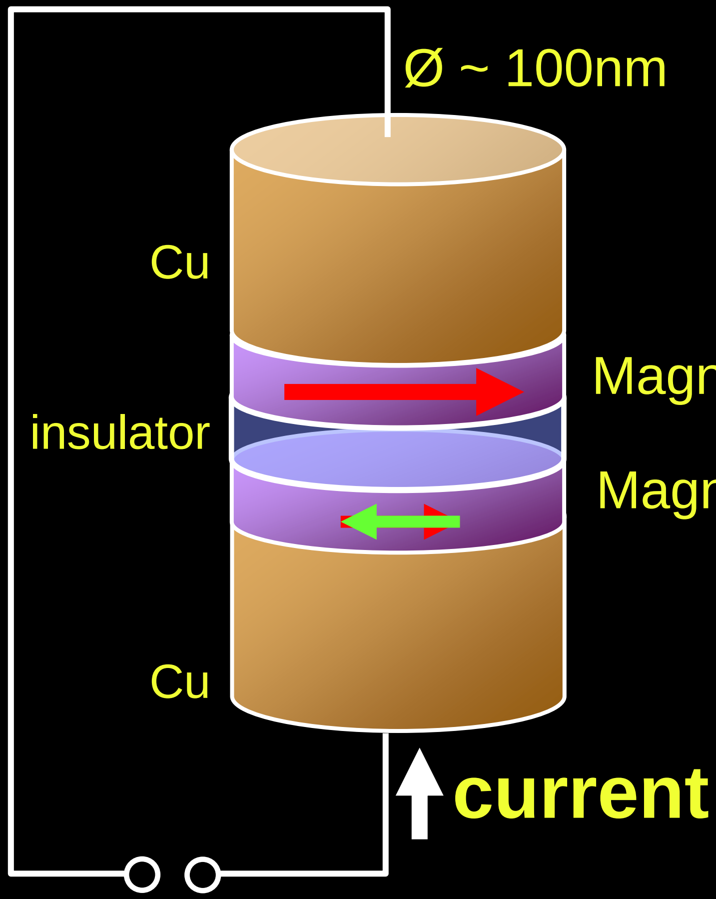


Conservation of spin-angular momentum

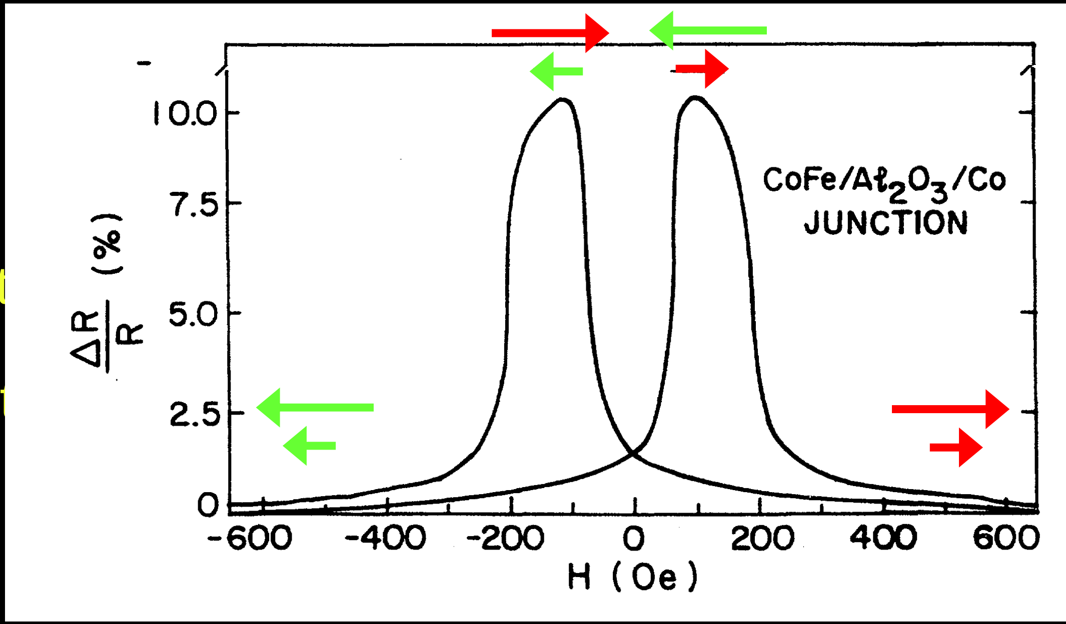
$$\left|\left\langle \sigma_f , m_f \left| \vec{\sigma}\cdot\vec{S} + u \right| \sigma_i , m_i \right\rangle\right|^2$$



Classical magnets in spintronics

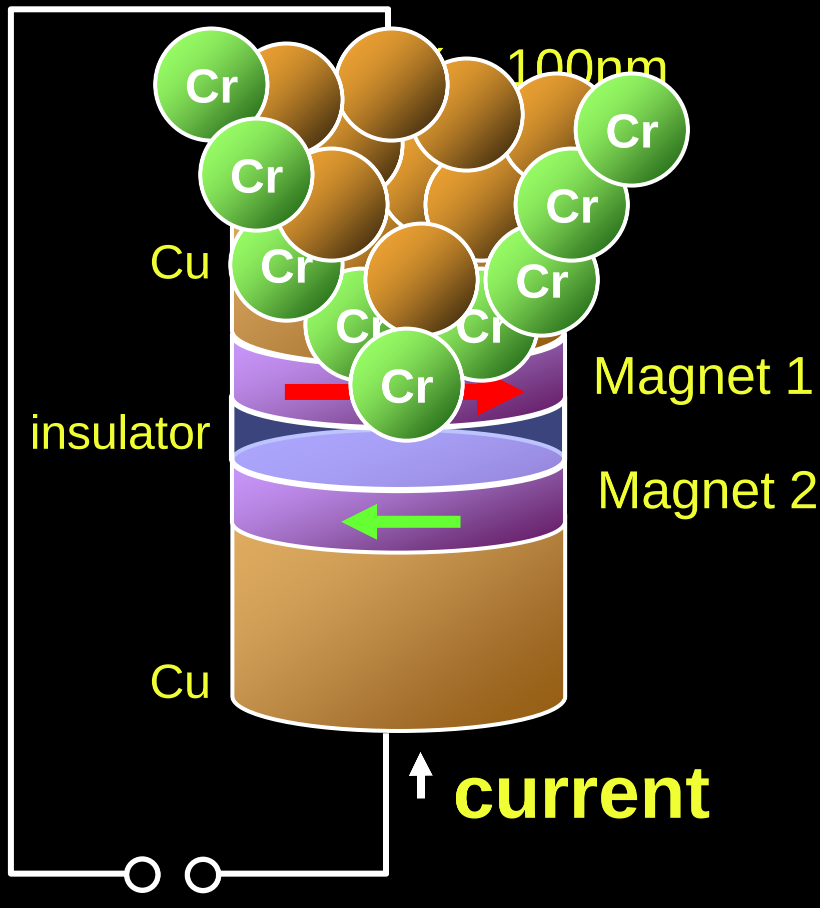


J.S. Moodera, *et al*. PRL (1995)

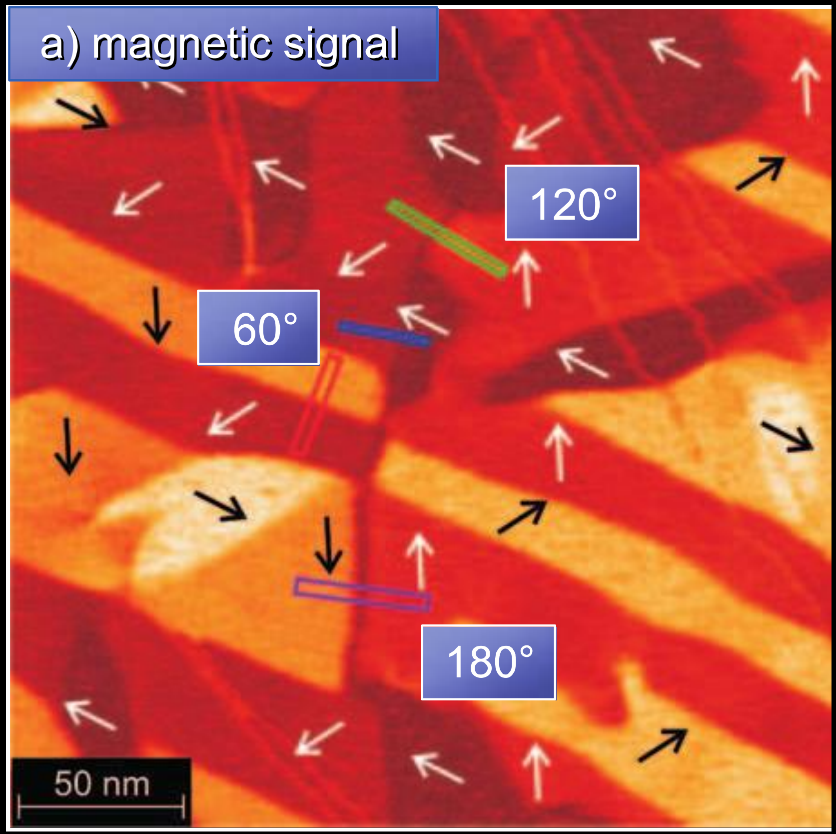


- **Tunnel junctions show Tunneling Magneto Resistance.**
- **TMR can be used to electrically switch nanomagnets.**

STM as a magnetic imaging tool



60 ML Dy(0001) with spin-polarized tip



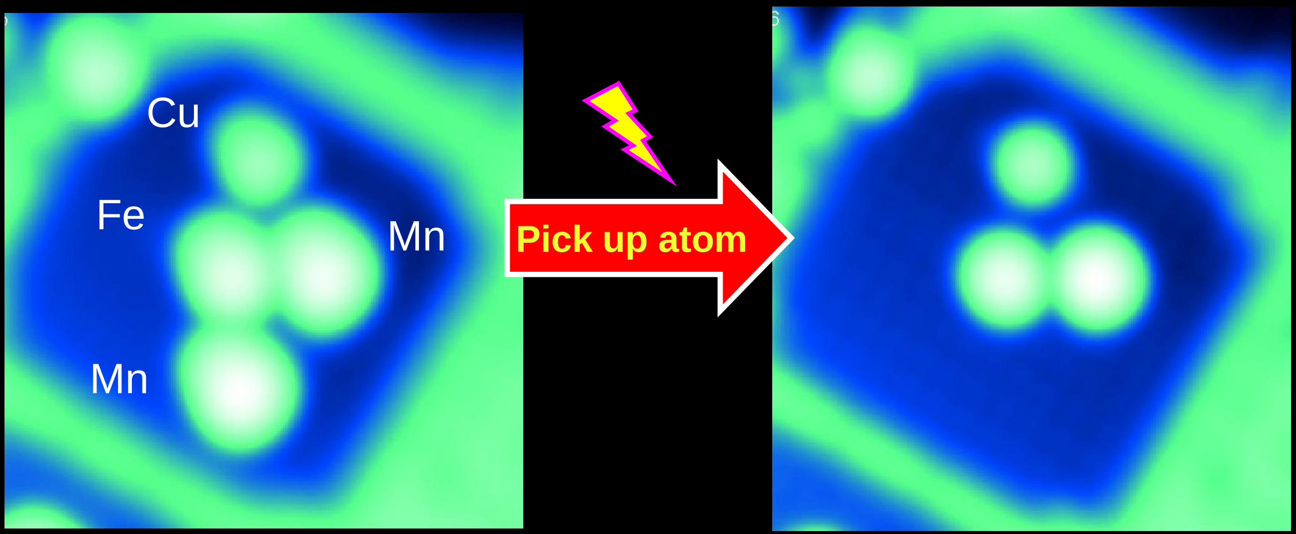
Berbil-Bautista, *Phys. Rev. Lett.* (2007)

- **Tunnel junctions show Tunneling Magneto Resistance**
- **Similar mechanism works on the atomic scale in STM**

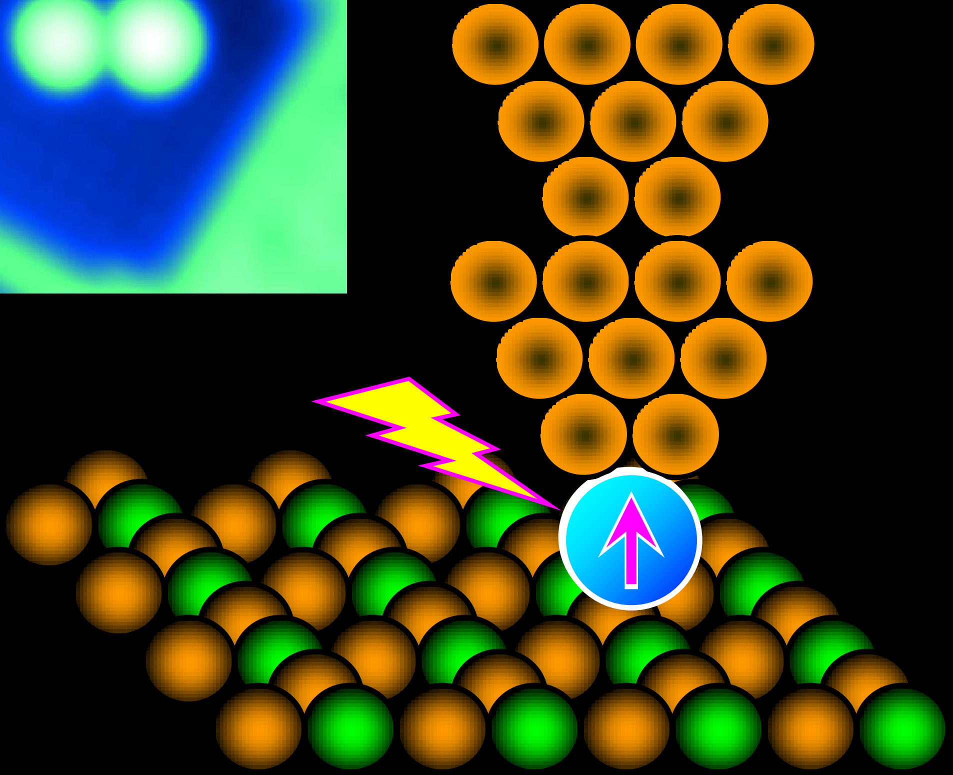
Quantum or classic

- **Spin excitations in STM**
  Science (2004)
- **Quantum spins:**
  A quantum antiferromagnet
  Science (2006)
- **Classical spins:**
  The smallest classical antiferromagnet
  Science (2012)

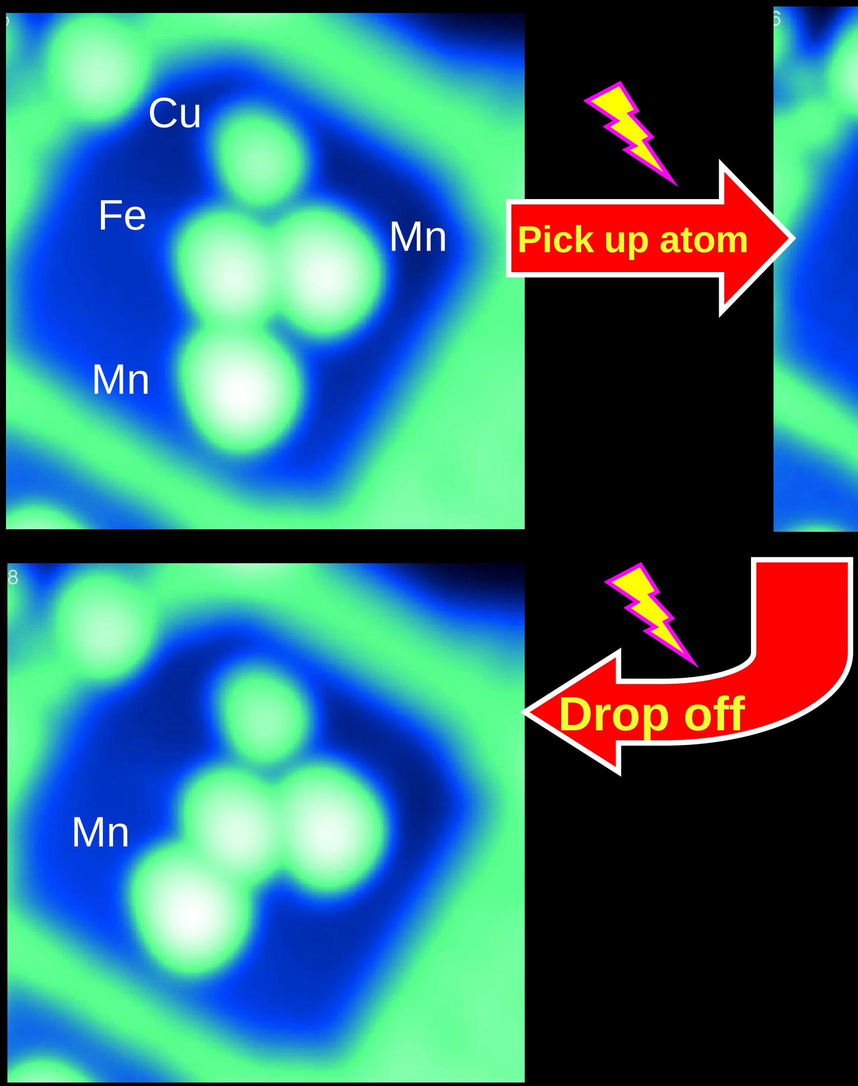
Atom manipulation on Cu_2N



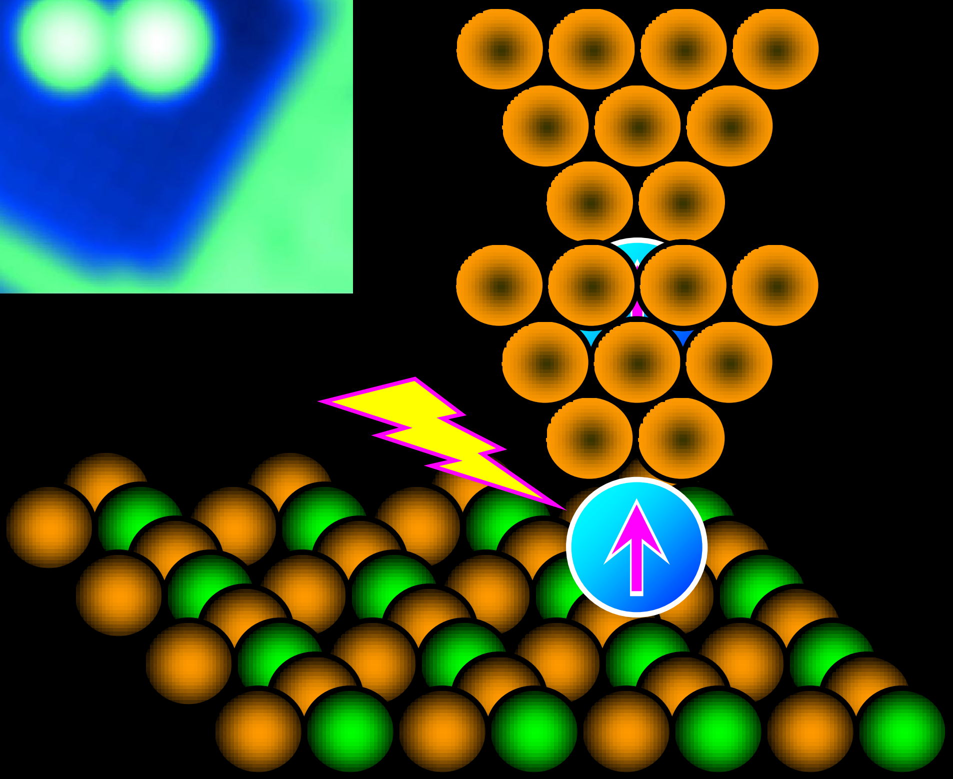
- Move tip in
- Apply 2.0V
- Pull tip back



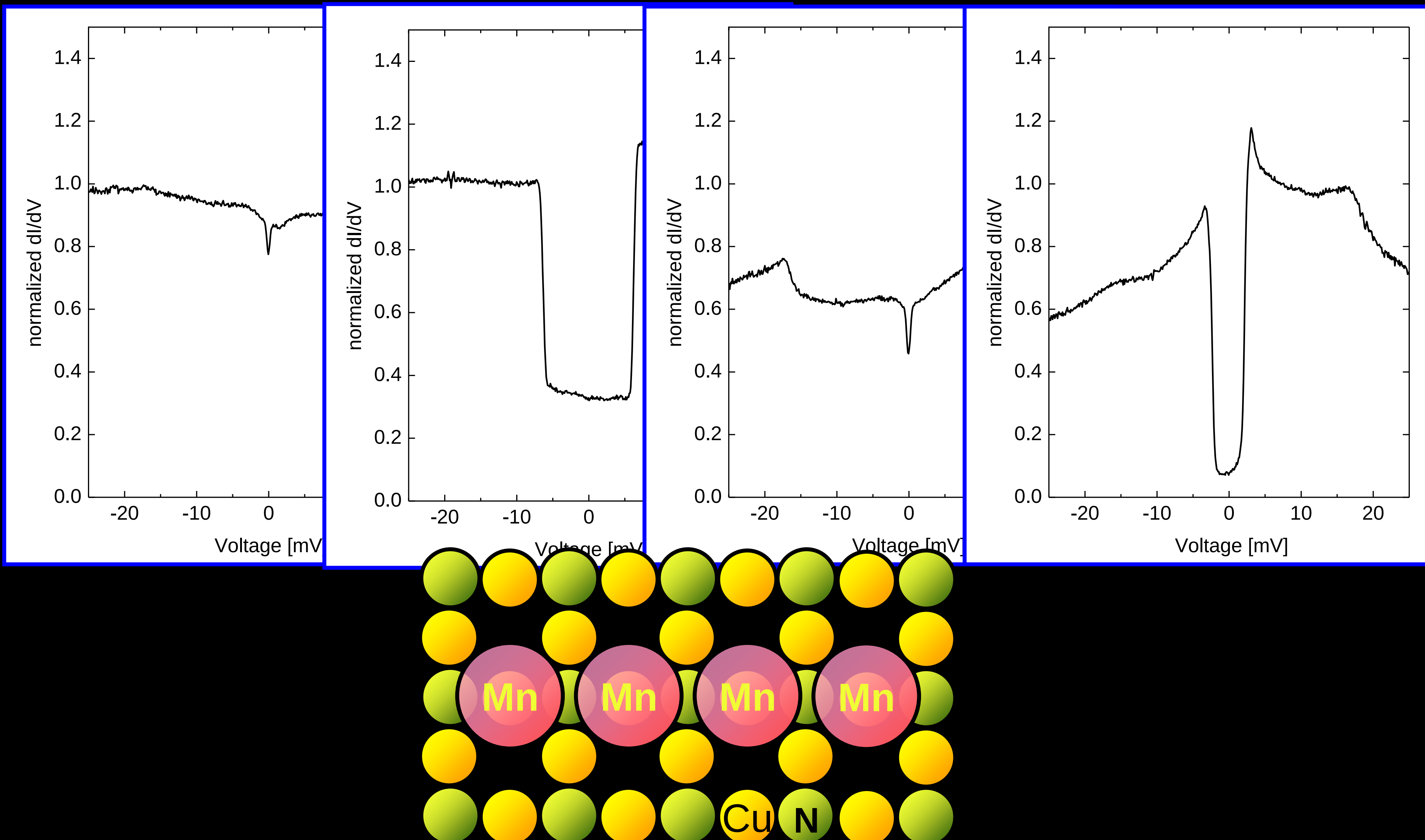
Atom manipulation on Cu_2N



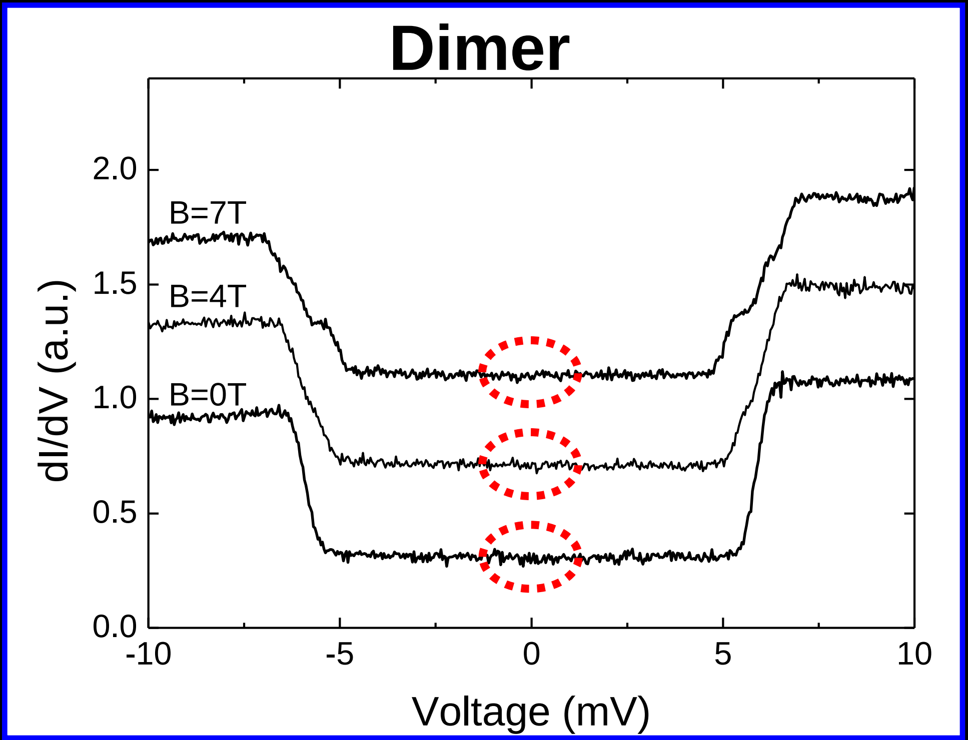
- Move tip in
- Apply -0.5V
- Pull tip back



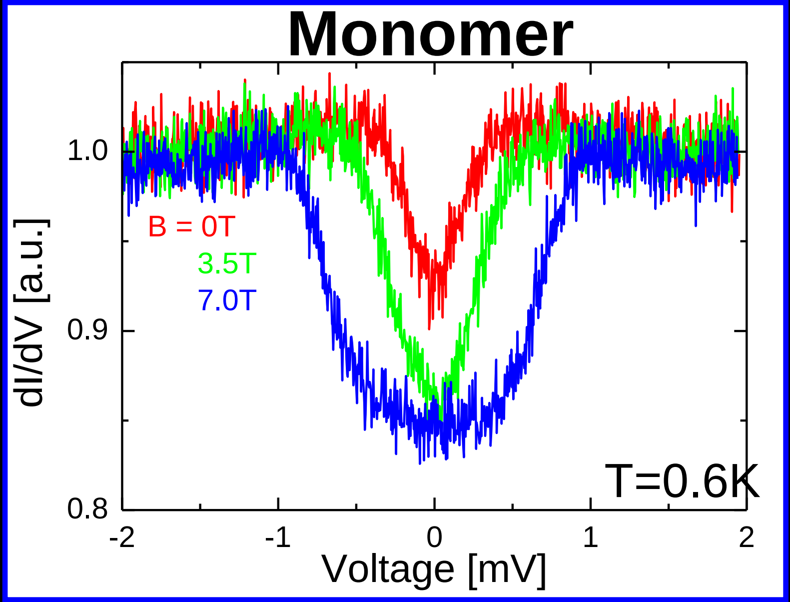
Spin-excitation spectroscopy of Mn chains

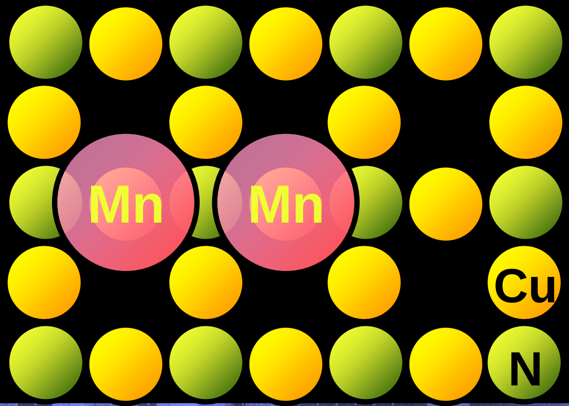


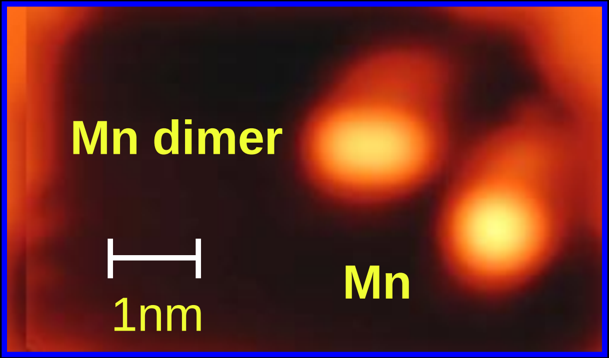
Strong spin-coupling in Mn-N-Mn dimers



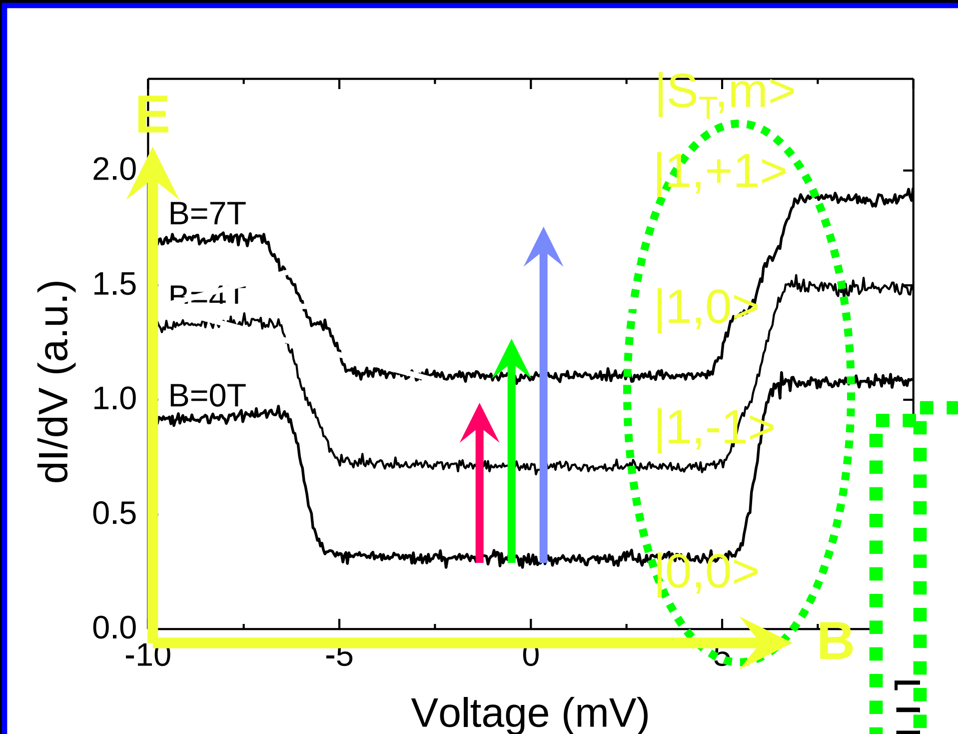
- Dimer has no zero-bias feature



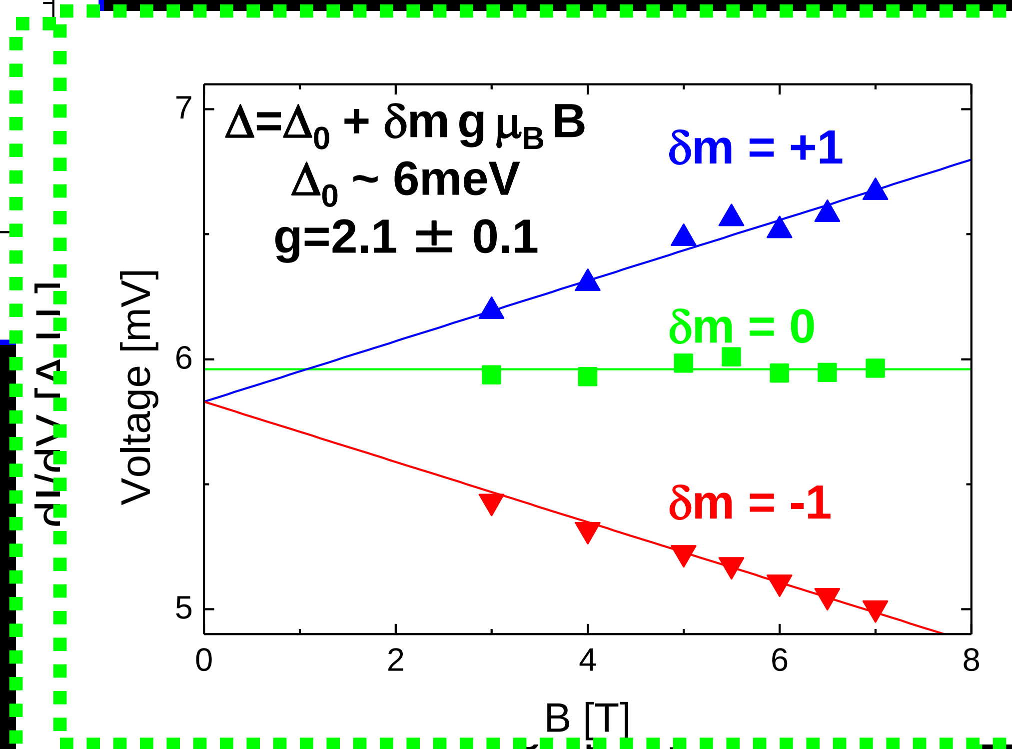


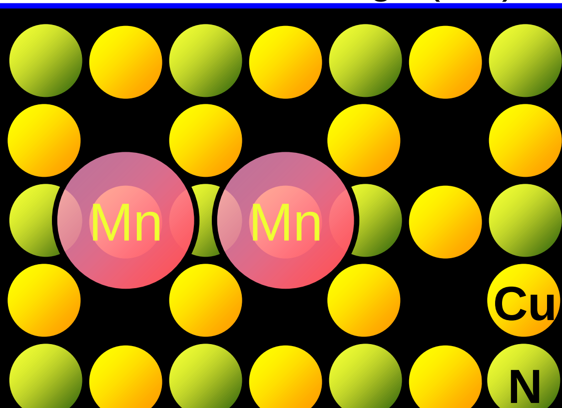


Strong spin-coupling in Mn-N-Mn dimers

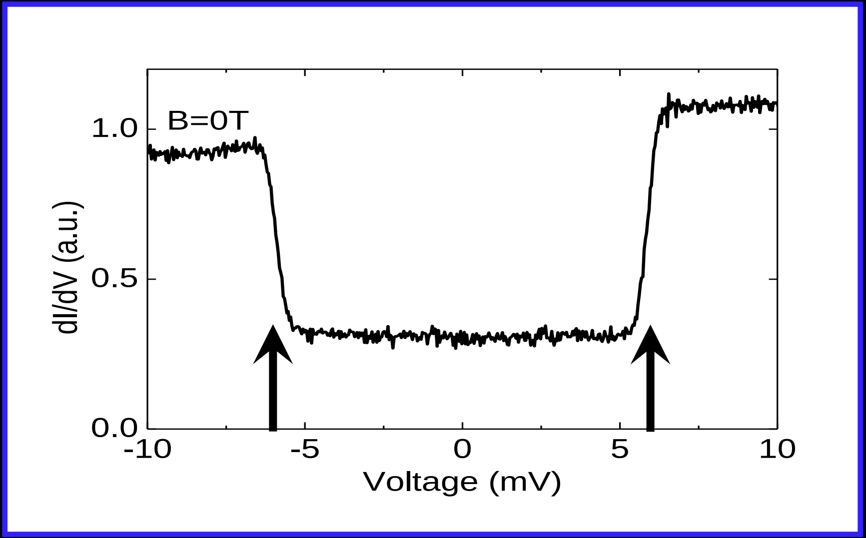


- **Dimer has no zero-bias feature**
- **Large step at ~6mV splits into three distinct steps at high fields**





Heisenberg spin coupling for dimer



$$\hat{H} = J\, \hat{\vec{S}}_1 \bullet \hat{\vec{S}}_2$$

$$\hat{H} = \frac{1}{2} J\, S_T^2$$

- **Antiferromagnetic coupling: *J* > 0**
- **Ground state: $S_T = 0$**
- **First excited state: $S_T = 1$, energy: *J***
- ***NOT* dependent on S**

J = 6meV

What is the singlet wavefunction?

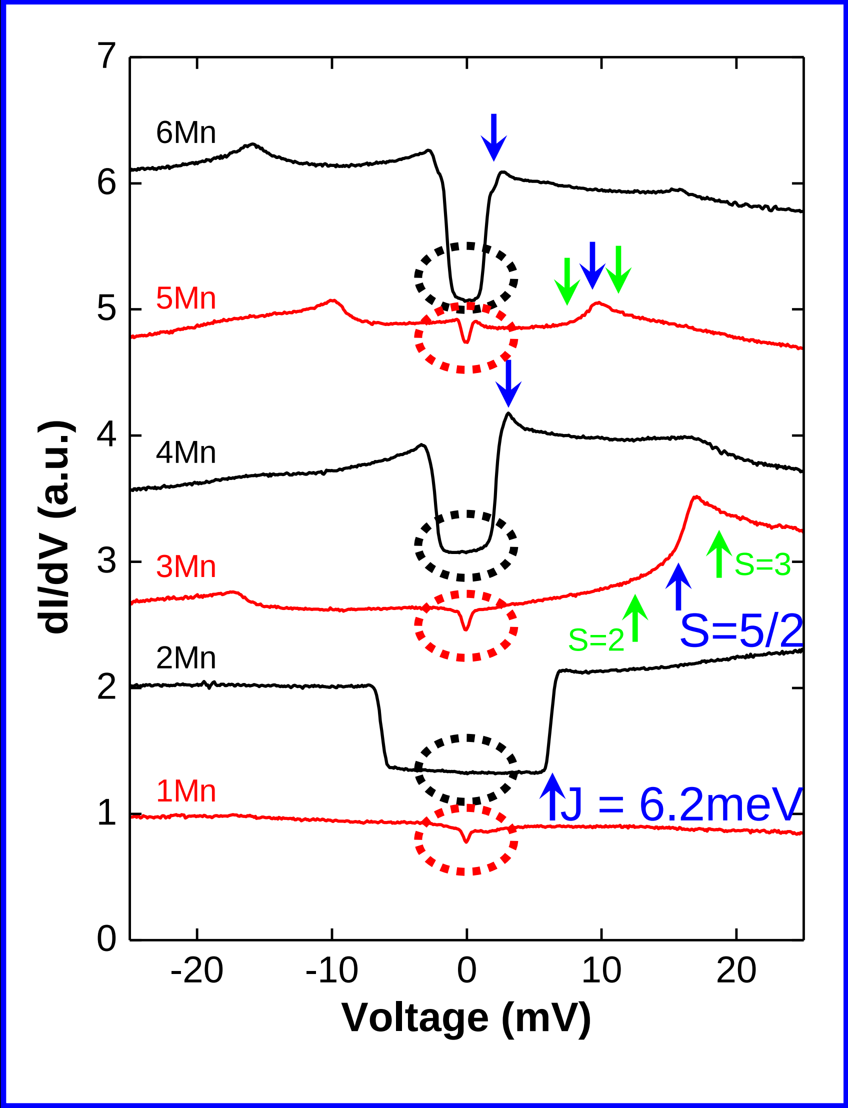
- For two S = ½ you know the singlet state …

$$\left|S_T = 0\right\rangle = \frac{1}{\sqrt{2}}\left(- \overline{} - \overline{} -\right)$$

- For two S = 5/2 it is a bit more complicated:

$$\left|S_T = 0\right\rangle = \frac{1}{\sqrt{6}}\left(\left|\frac{5}{2}, -\frac{5}{2}\right\rangle - \left|\frac{3}{2}, -\frac{3}{2}\right\rangle + \left|\frac{1}{2}, -\frac{1}{2}\right\rangle - \left|-\frac{1}{2}, \frac{1}{2}\right\rangle + \left|-\frac{3}{2}, \frac{3}{2}\right\rangle - \left|-\frac{5}{2}, \frac{5}{2}\right\rangle\right)$$

Heisenberg model for longer chains



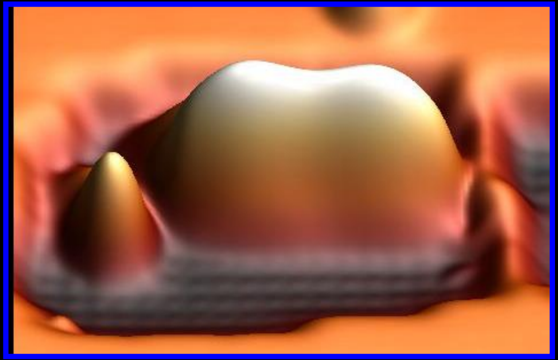
$$H = J\sum_{i=1}^{N-1}\vec{S}_i \cdot \vec{S}_{i+1}$$

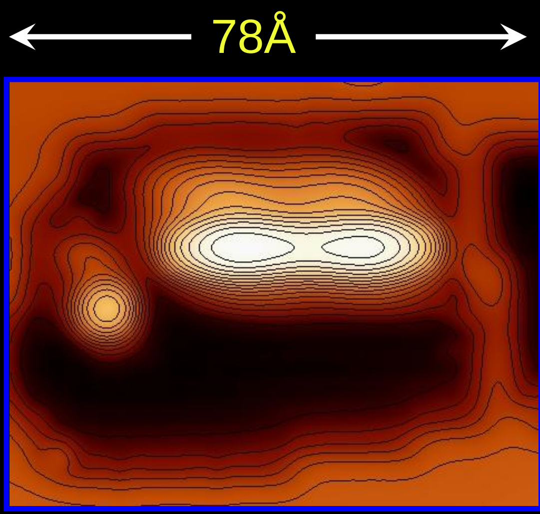
- **Dimer ⇨ J = 6.2meV**
- **Trimer ⇨ S_i = 5/2**

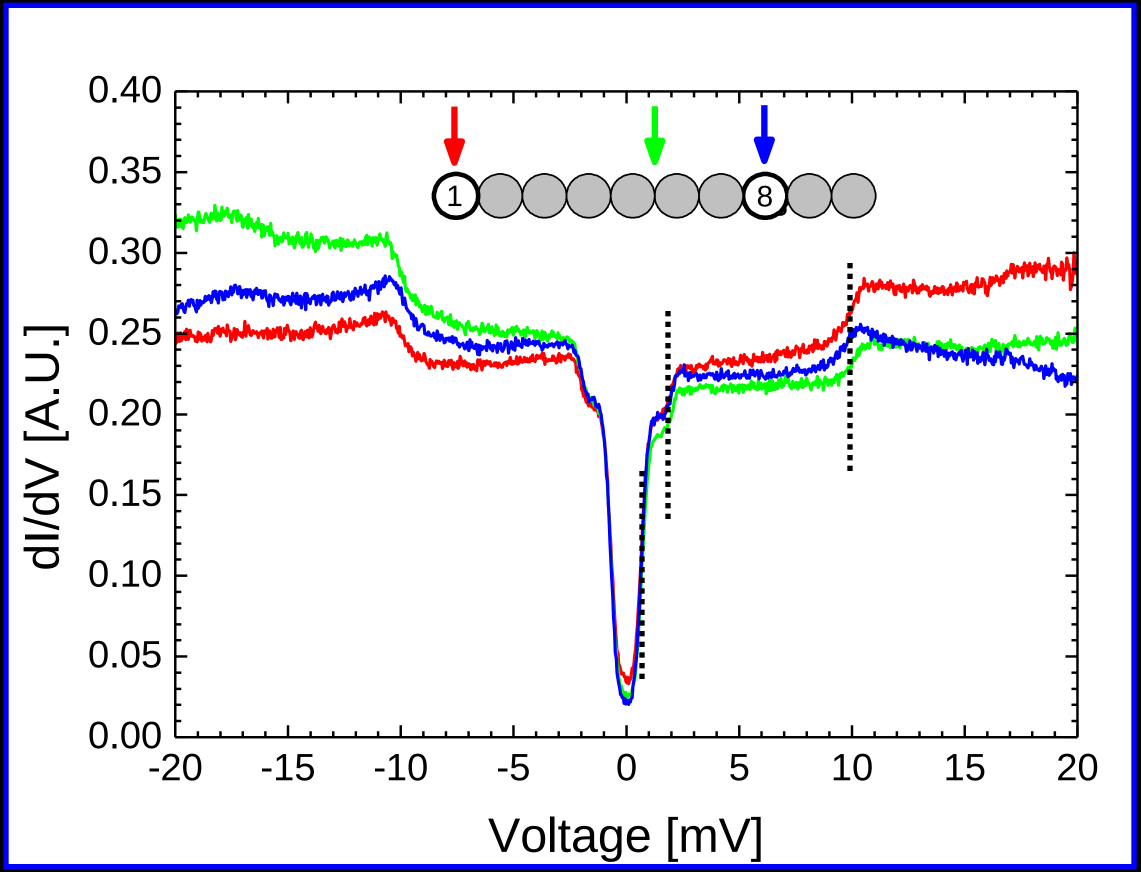
- **Even chains**
  - **ground state spin = 0**
  - **excited state spin = 1**

- **Odd chains**
  - **ground state spin = 5/2**
  - **excited state spin = 3/2**

No changes along the chain

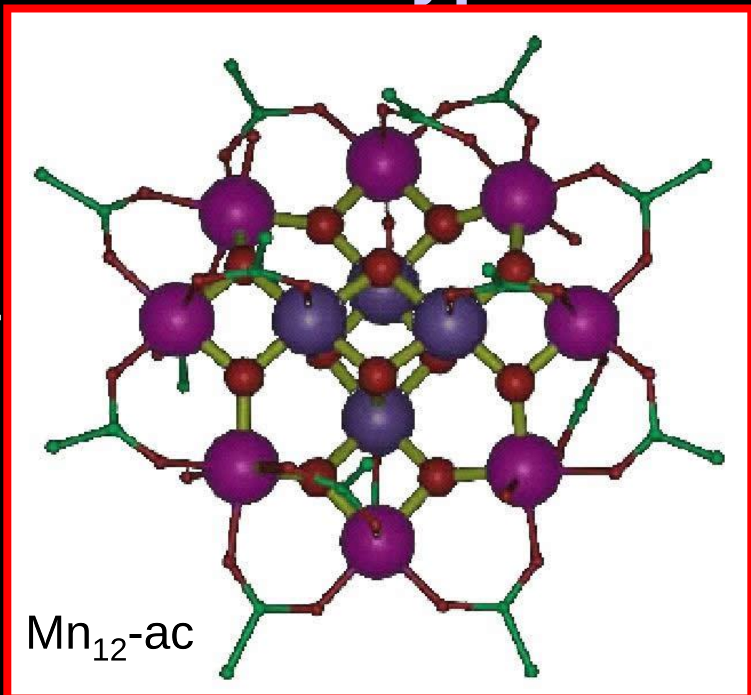






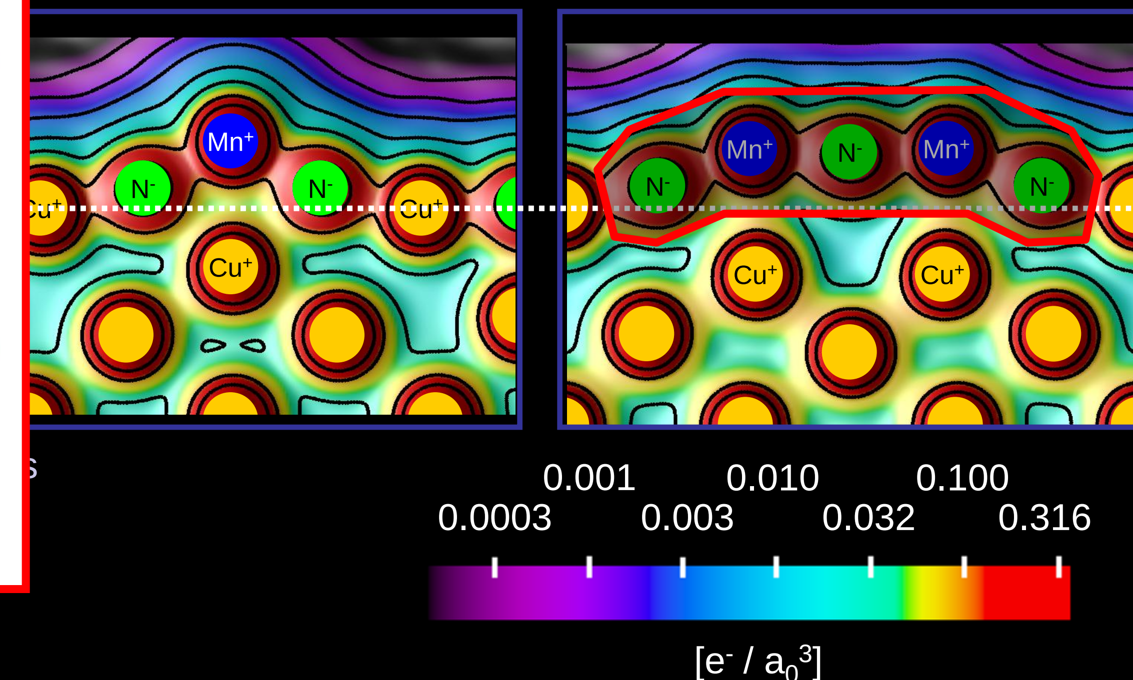
- ➢ **Step energy is independent of location along chain**
- ➢ **Excitation is a property of the chain, not its constituents**

A novel type of atomic-scale magnet?



Mn on Cu-site/CuN

Mn dimer on Cu-site/CuN

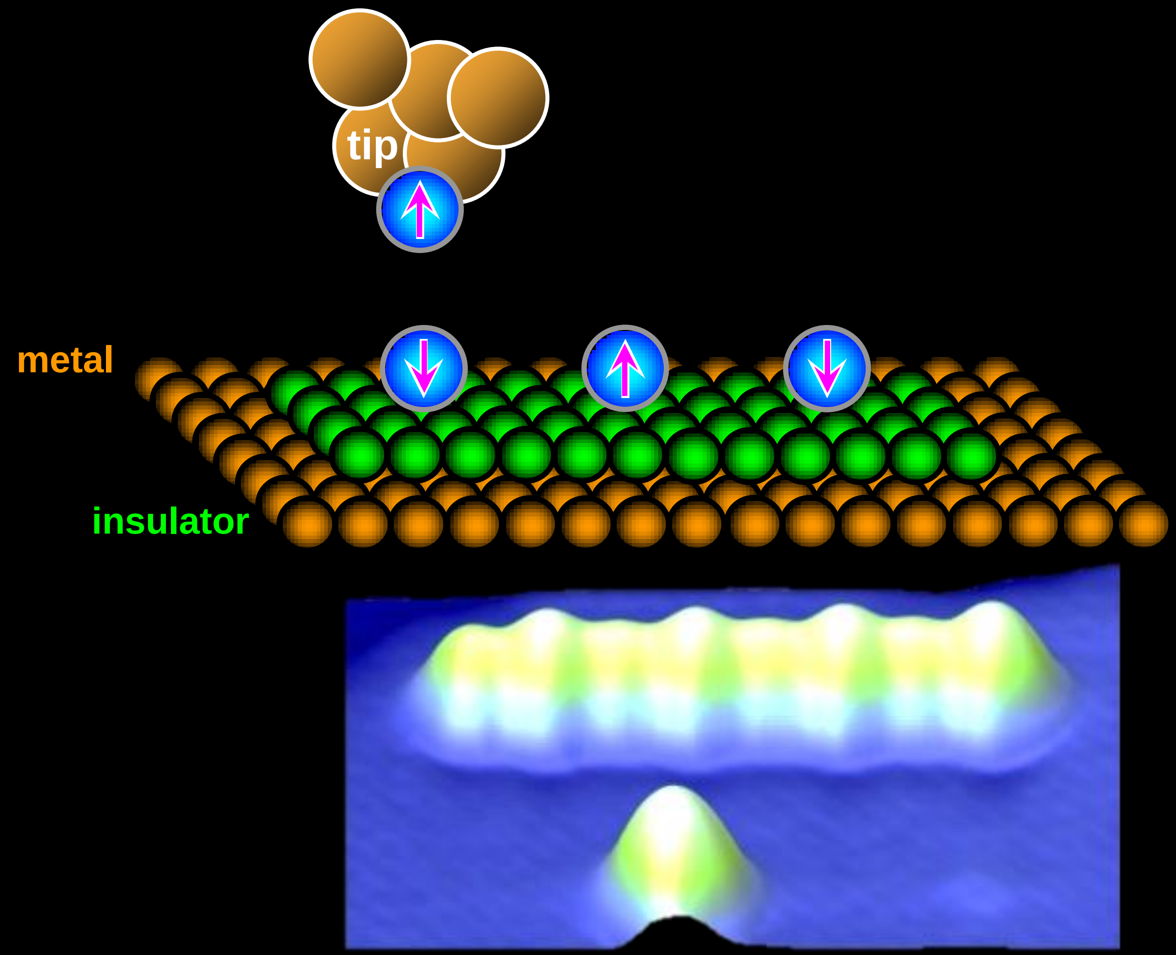


- Cu and N surface atoms form extended molecular bonds
- N atoms are ligands to metals
- N atoms are bridge atoms for superexchange interaction
- A surface-embedded magnetic molecule?

Magnetism on surfaces

- **Spin excitations in STM**
  Science (2004)
- **Quantum spins:**
  A quantum antiferromagnet
  Science (2006)
- **Classical spins:**
  The smallest classical antiferromagnet
  Science (2012)

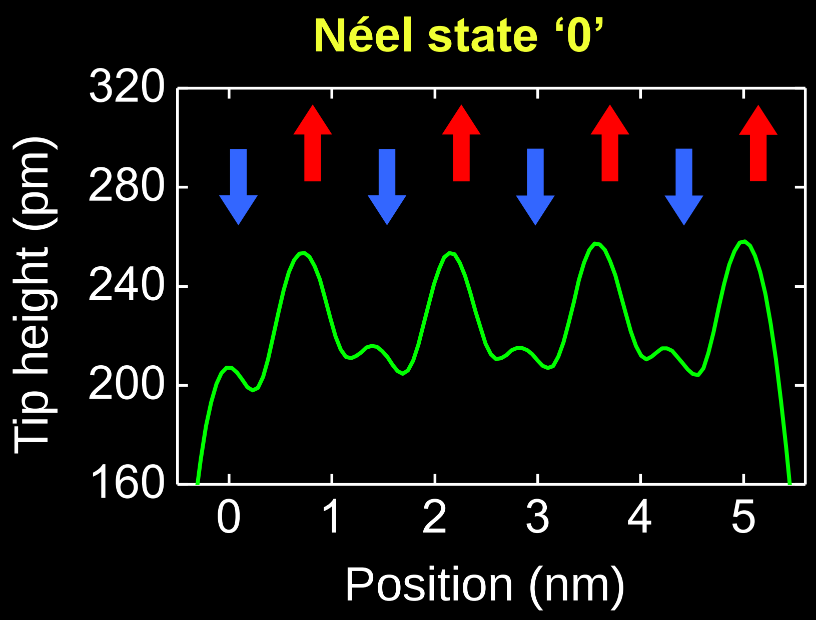
Lateral spin contrast in a chain of Fe atoms?

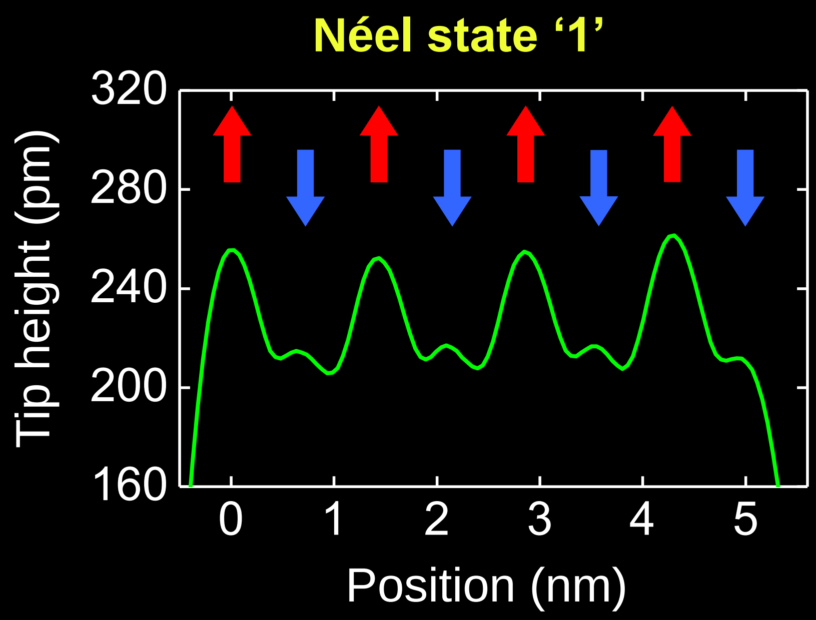


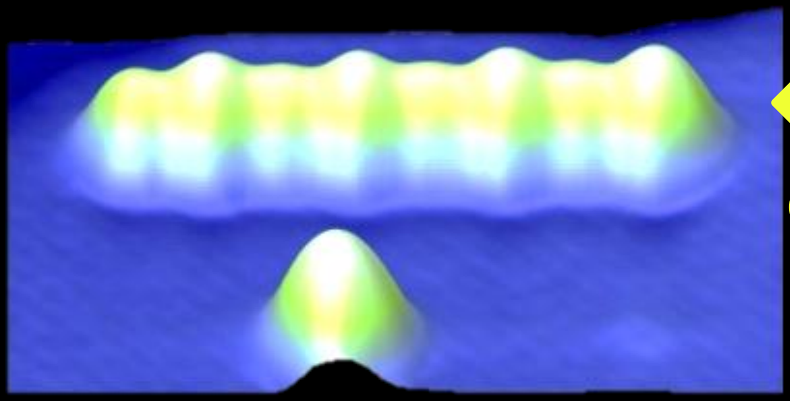
High current: / Low current:
atom appears tall / short

- Atomic-scale Tunneling Magneto Resistance junction.
- Chain of 8 Fe atoms in “classical” Néel states.

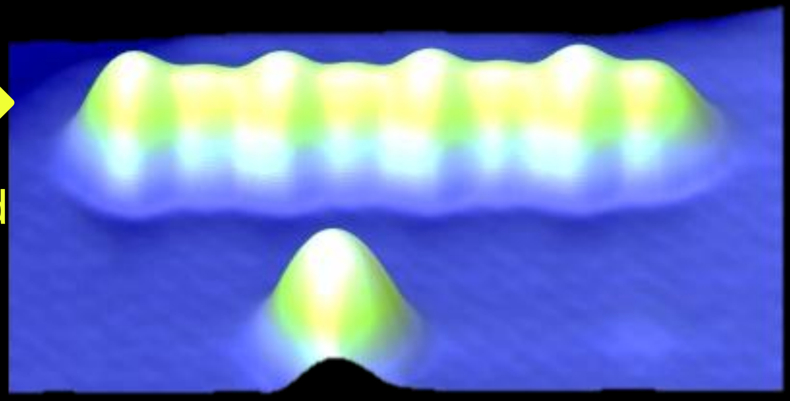
Two stable antiferromagnetic states



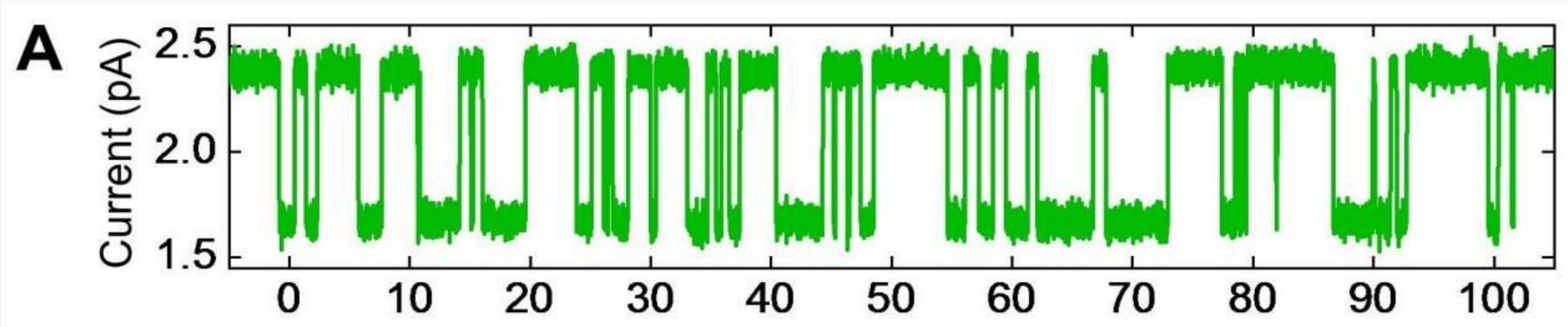




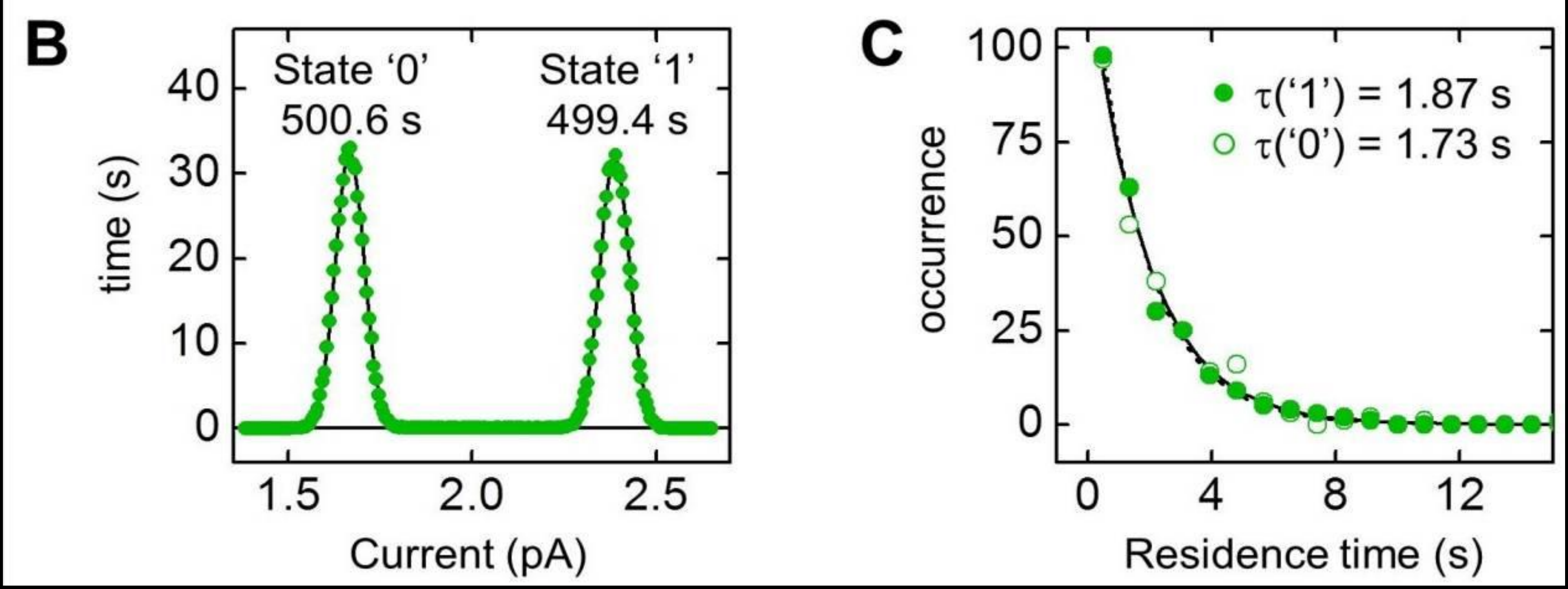
Controlled switching



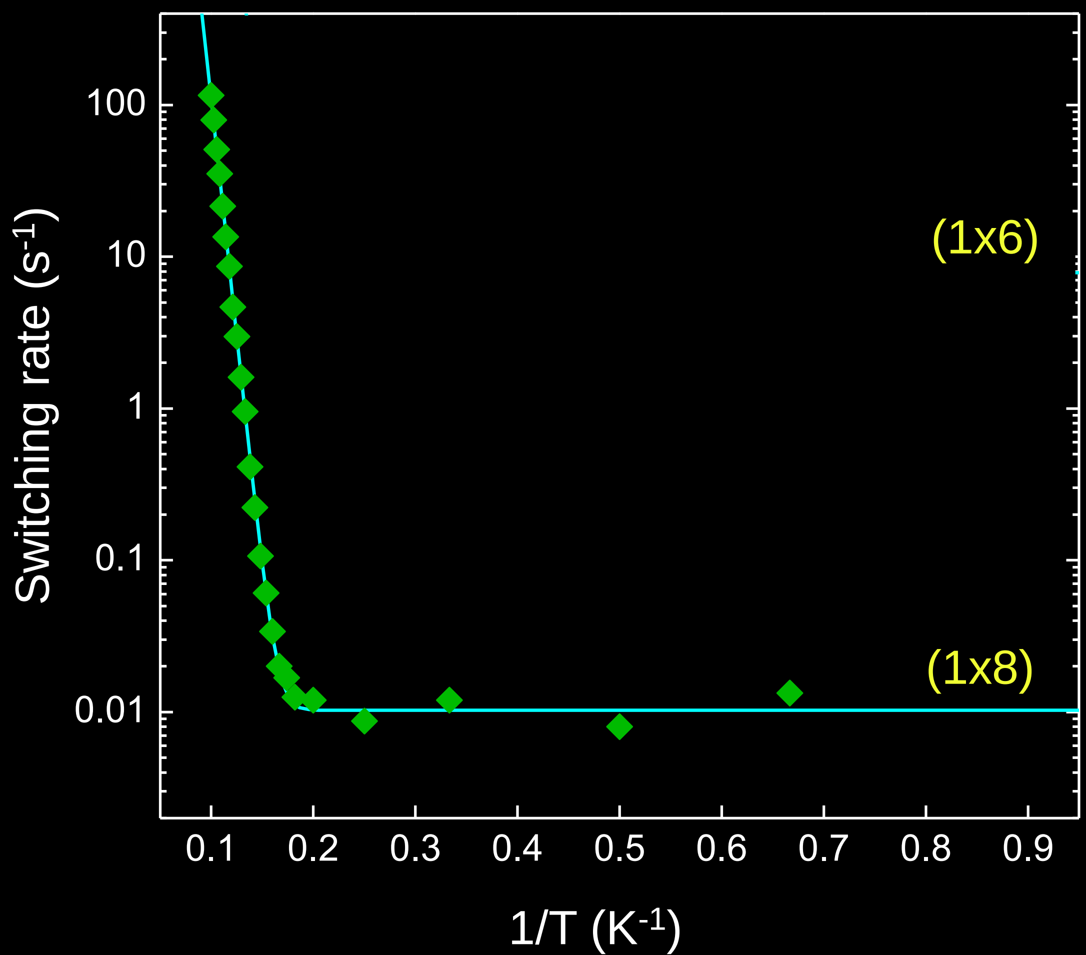
Switching dynamics

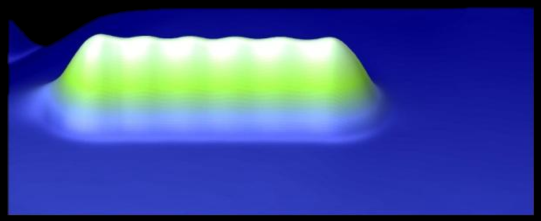


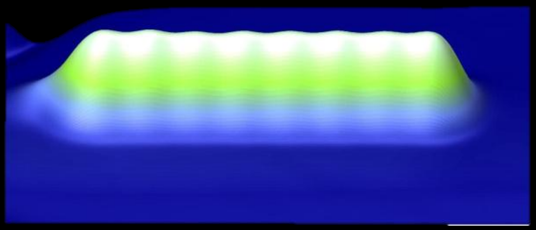
T = 4.75K, B = 3T



Quantum not fully gone – low T switching

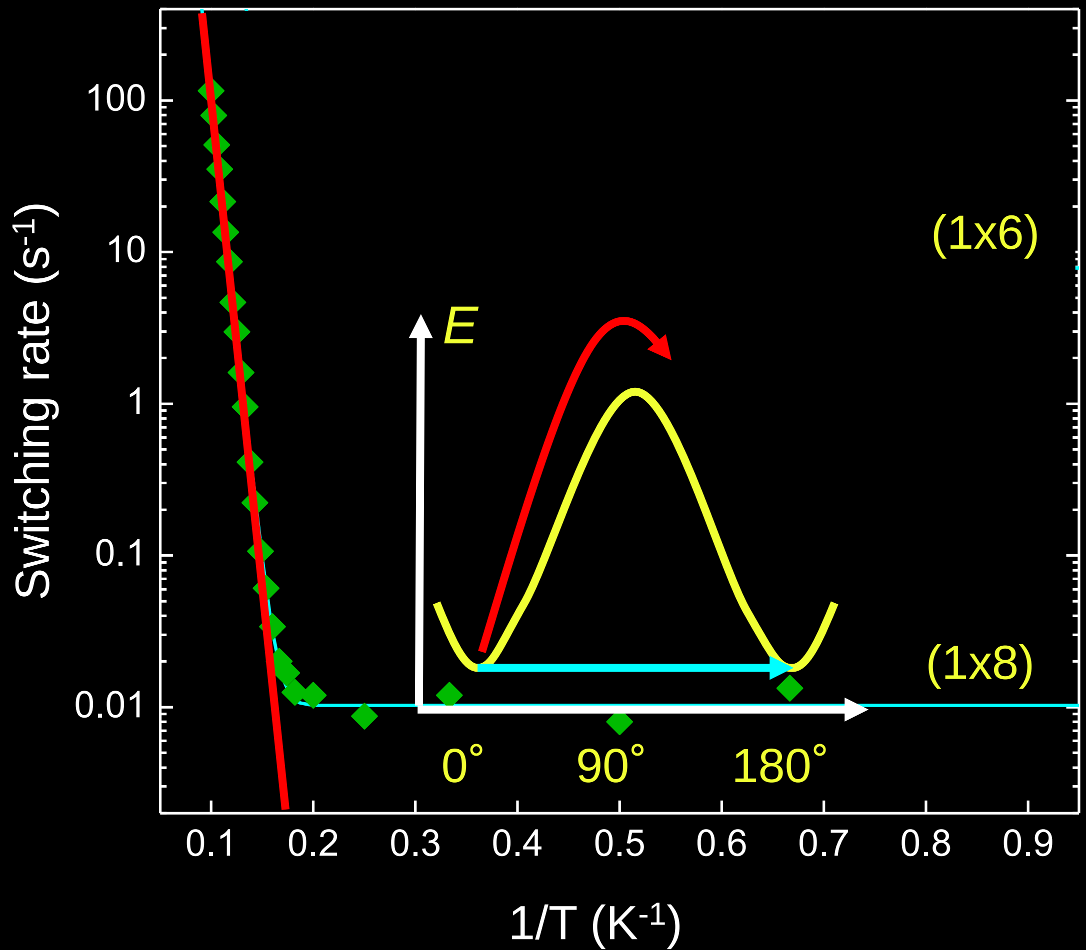


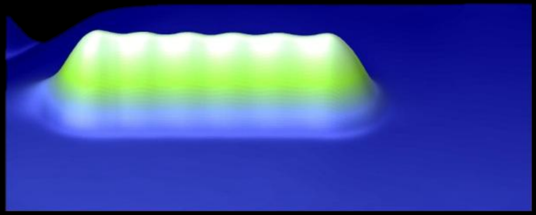


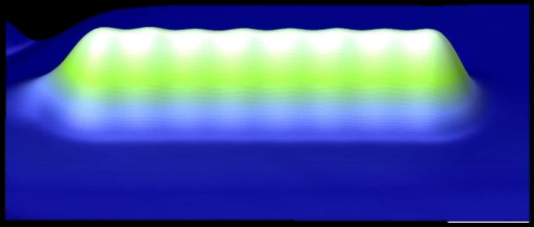


- Removal of 2 atoms increases tunneling by 1000x
- Quantum coherence needed

Switching of Néel vector in AFM chains – high T

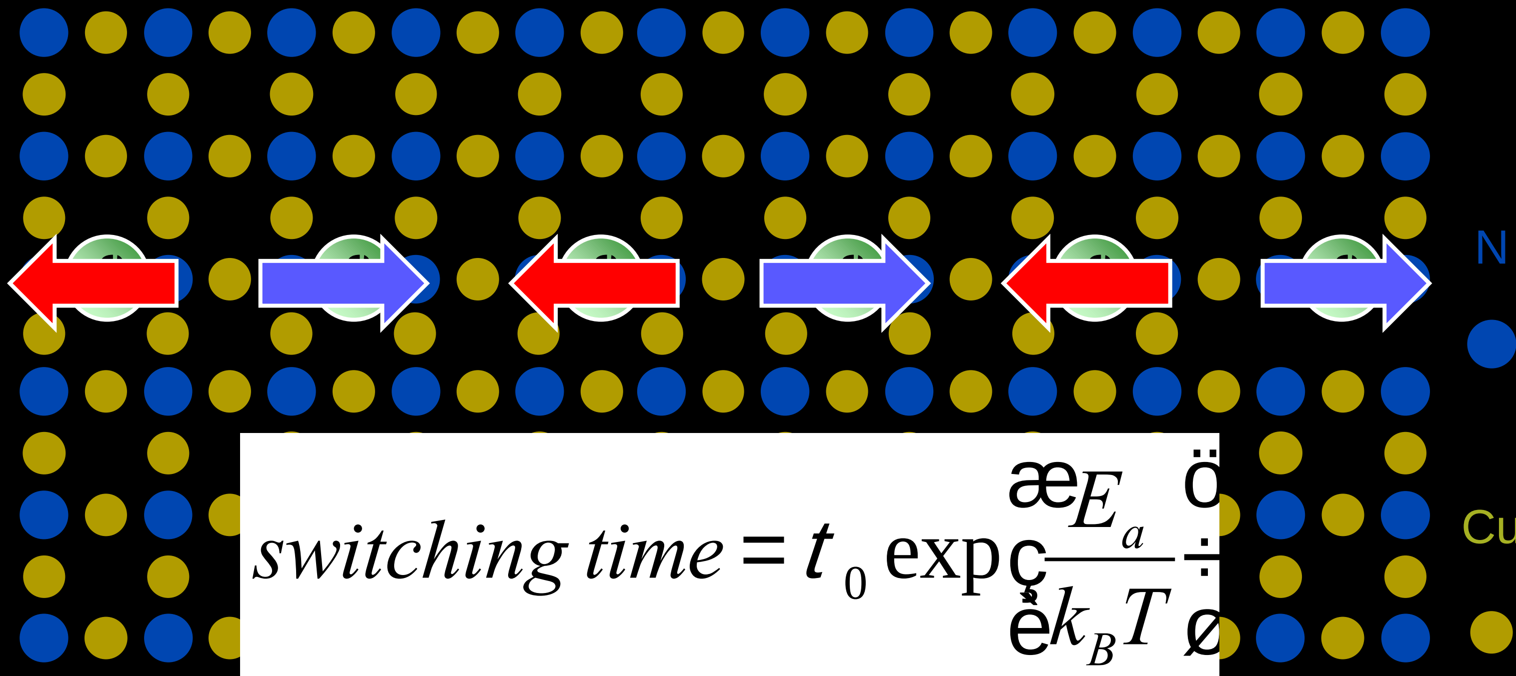






- Removal of 2 atoms increases tunneling by 1000x
- Slope of thermal relaxation gives energetics

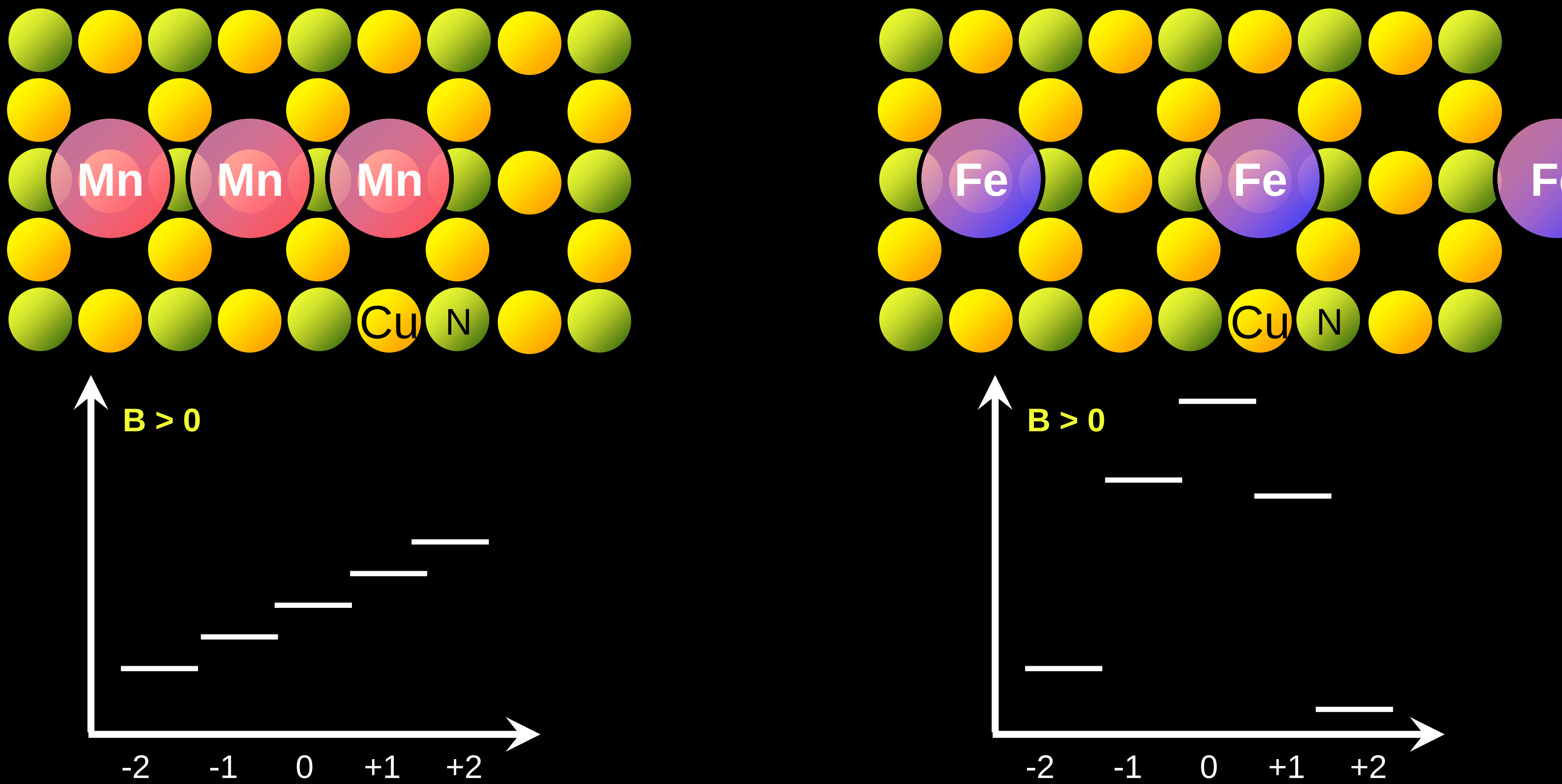
Switching dynamics: high T



$$\textit{switching time} = t_0 \exp\left(\frac{E_a}{k_B T}\right)$$

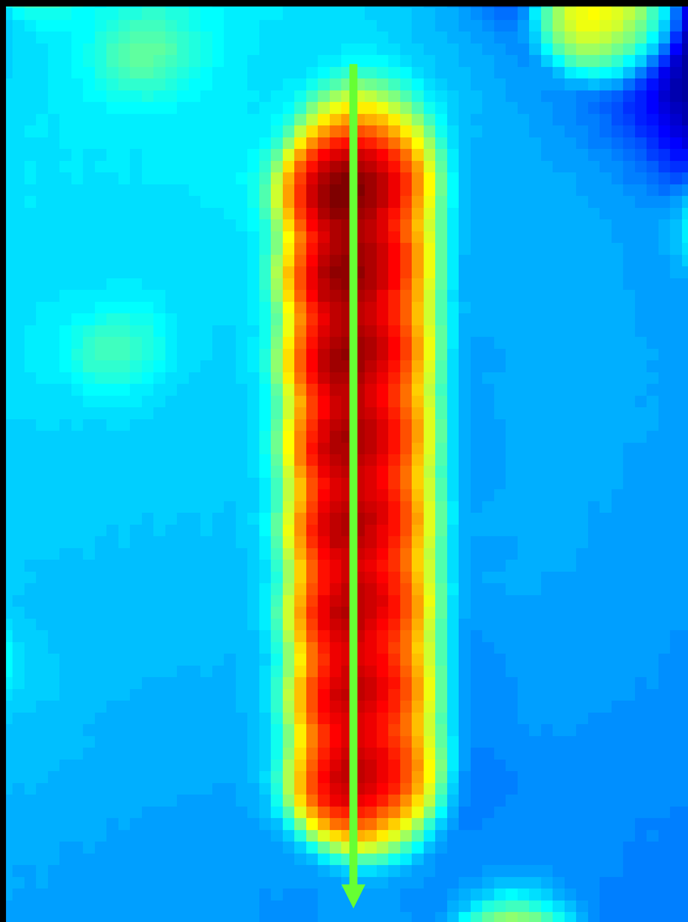
- Domain wall introduced by T fluctuations
- Calculated energy cost is $2S^2J$ = 9.6 meV
- Measured E_a = 12 meV
- Propagation of domain wall costs no energy

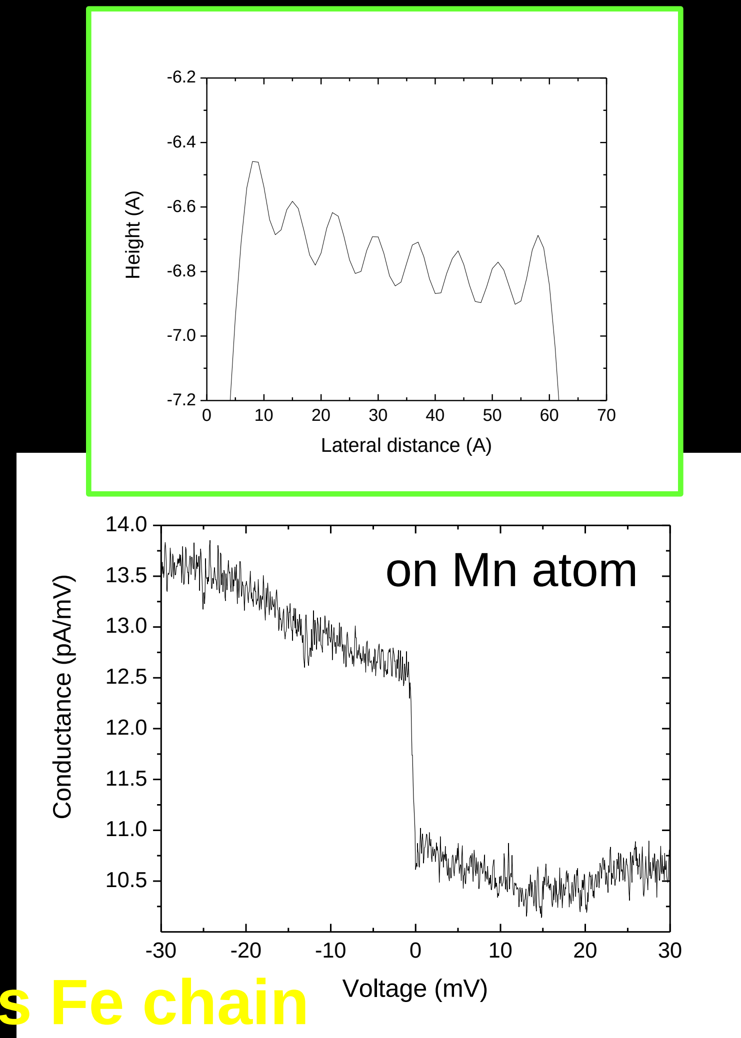
So what is the difference?



- **Fe chain has weaker coupling due to spacing**
- **Fe has strong easy-axis magnetic anisotropy**

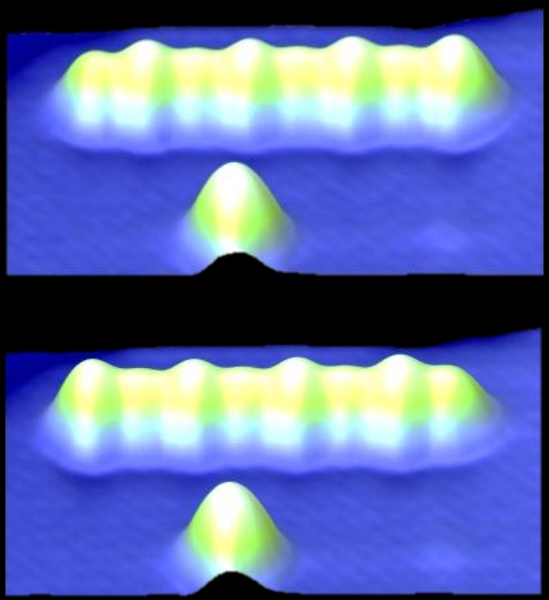
A close-spaced Mn chain

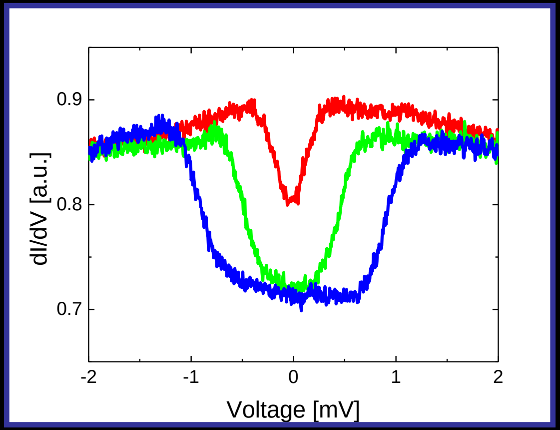




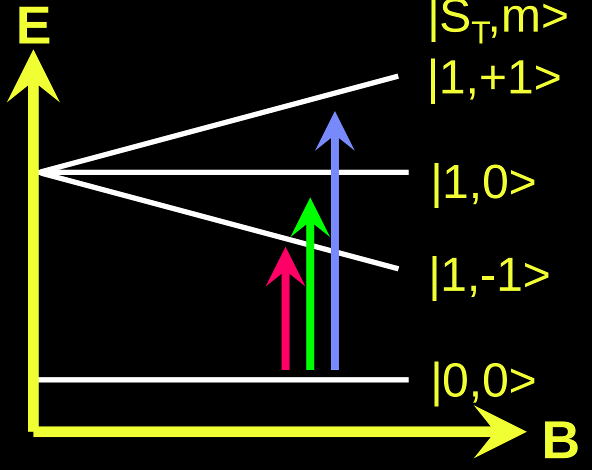
- Mn chain with same spacing as Fe chain
- Tip has very high spin polarization

Summary





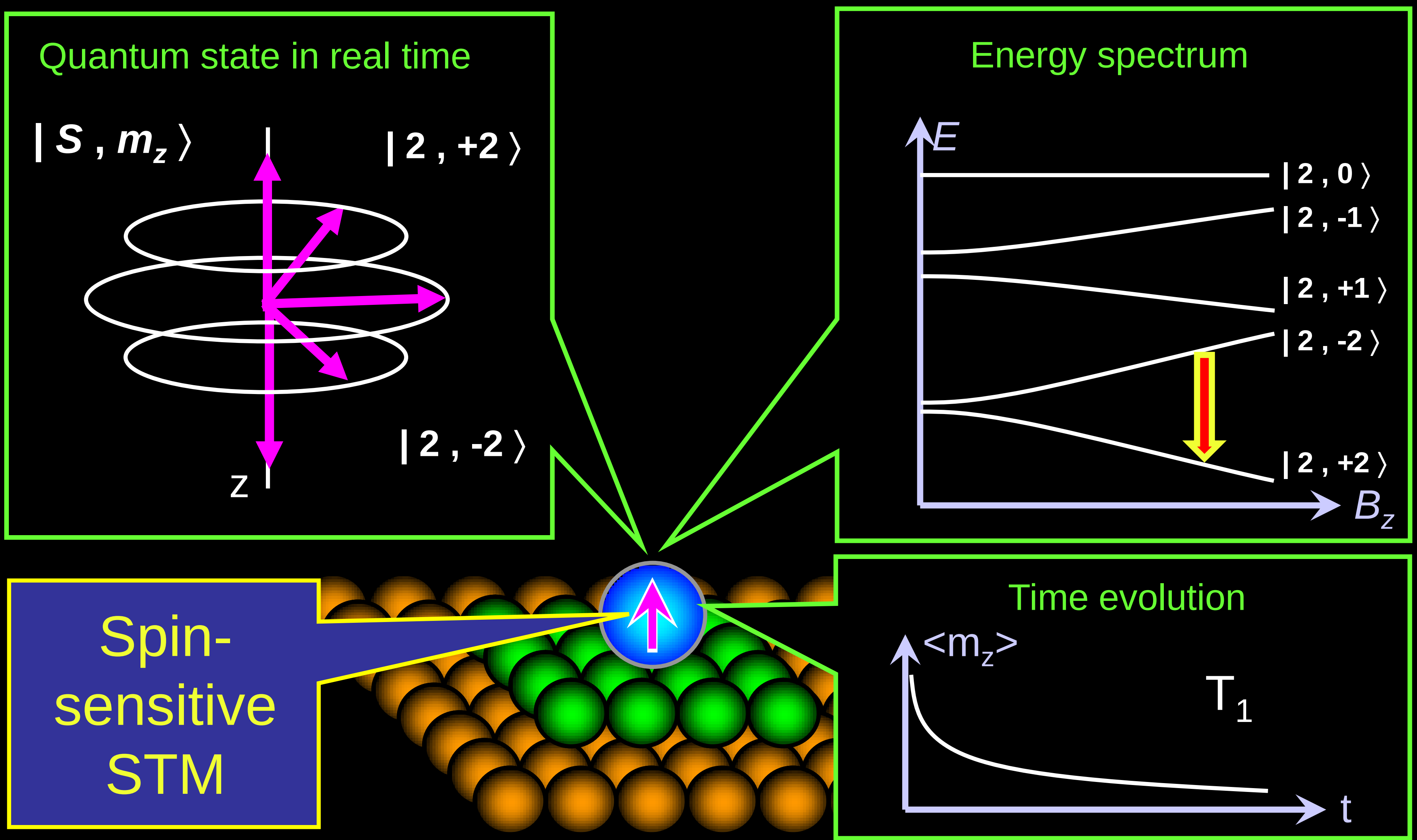
Spin excitation with STM

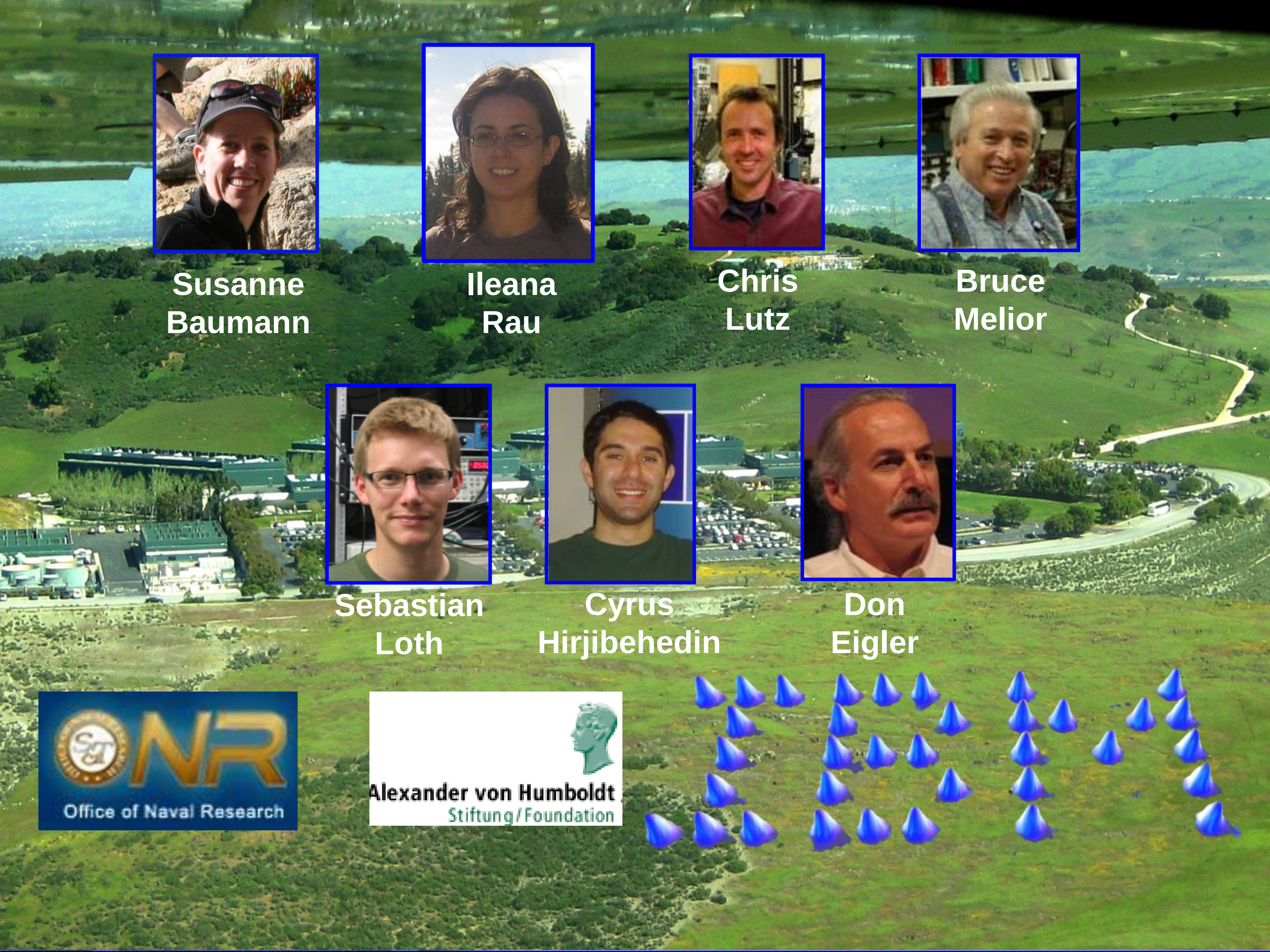


Classical antiferromagnet: two stable states

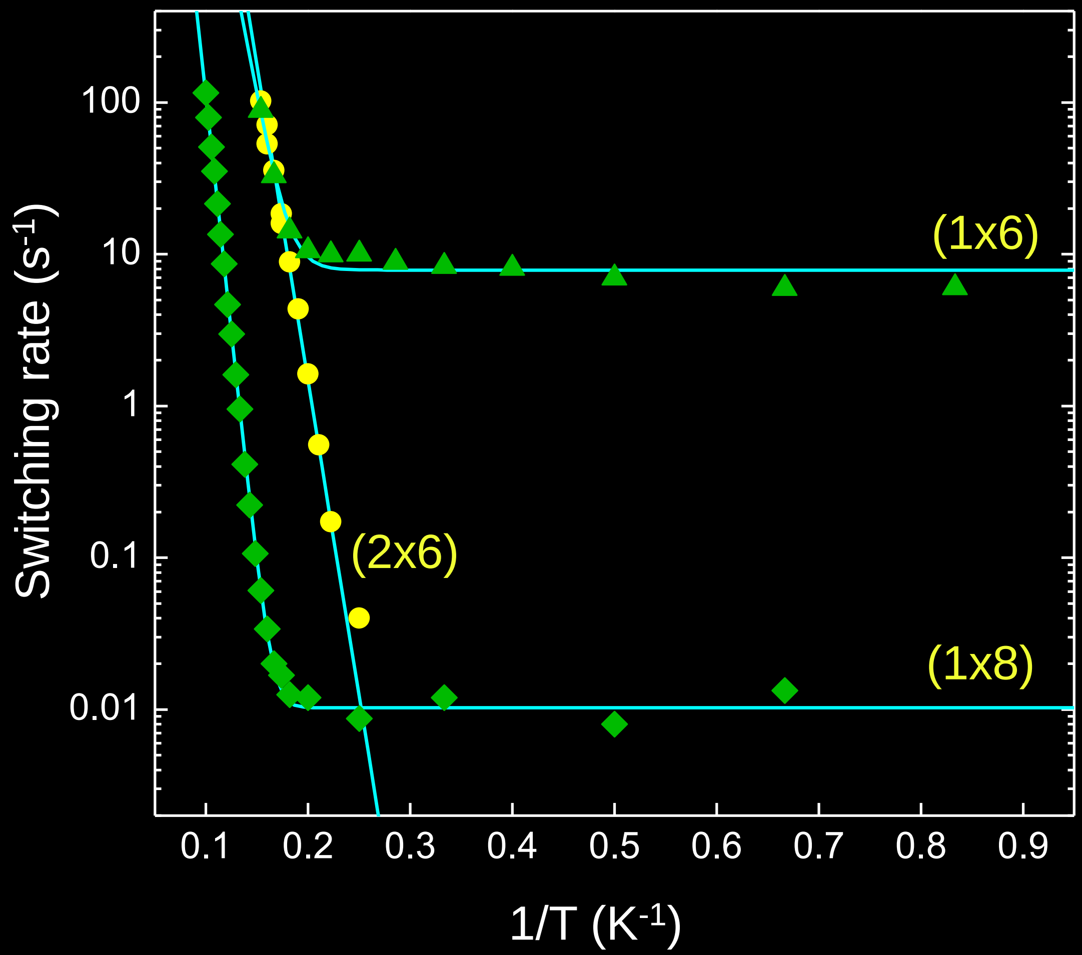
Quantum antiferromagnet: singlet ground state

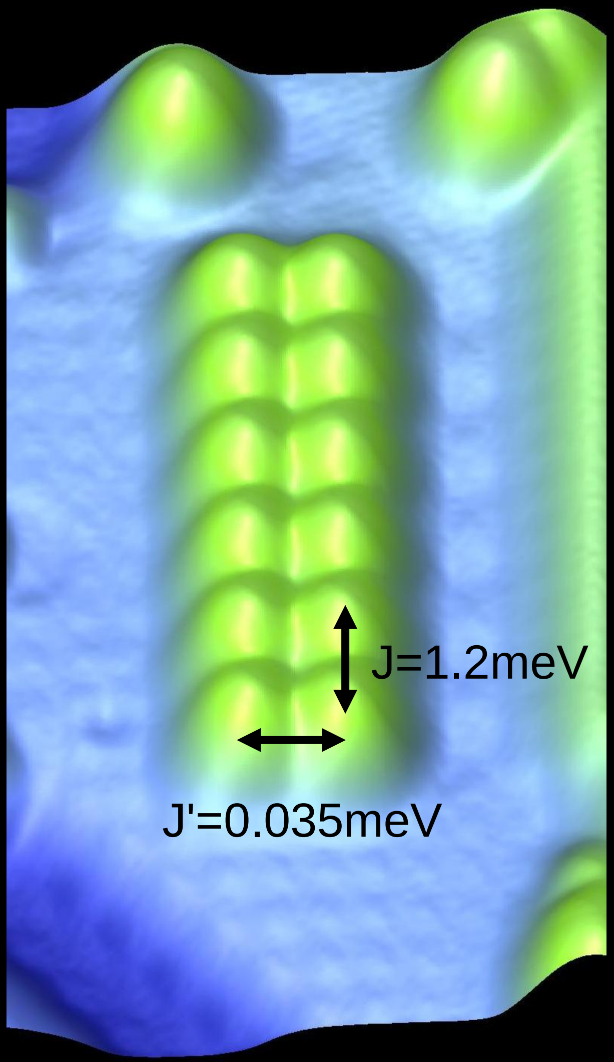
What to learn from quantum spins on surfaces?




Susanne Baumann
Ileana Rau
Chris Lutz
Bruce Melior
Sebastian Loth
Cyrus Hirjibehedin
Don Eigler
Office of Naval Research
Alexander von Humboldt
Stiftung/Foundation

From AFM chains to arrays – kill quantum

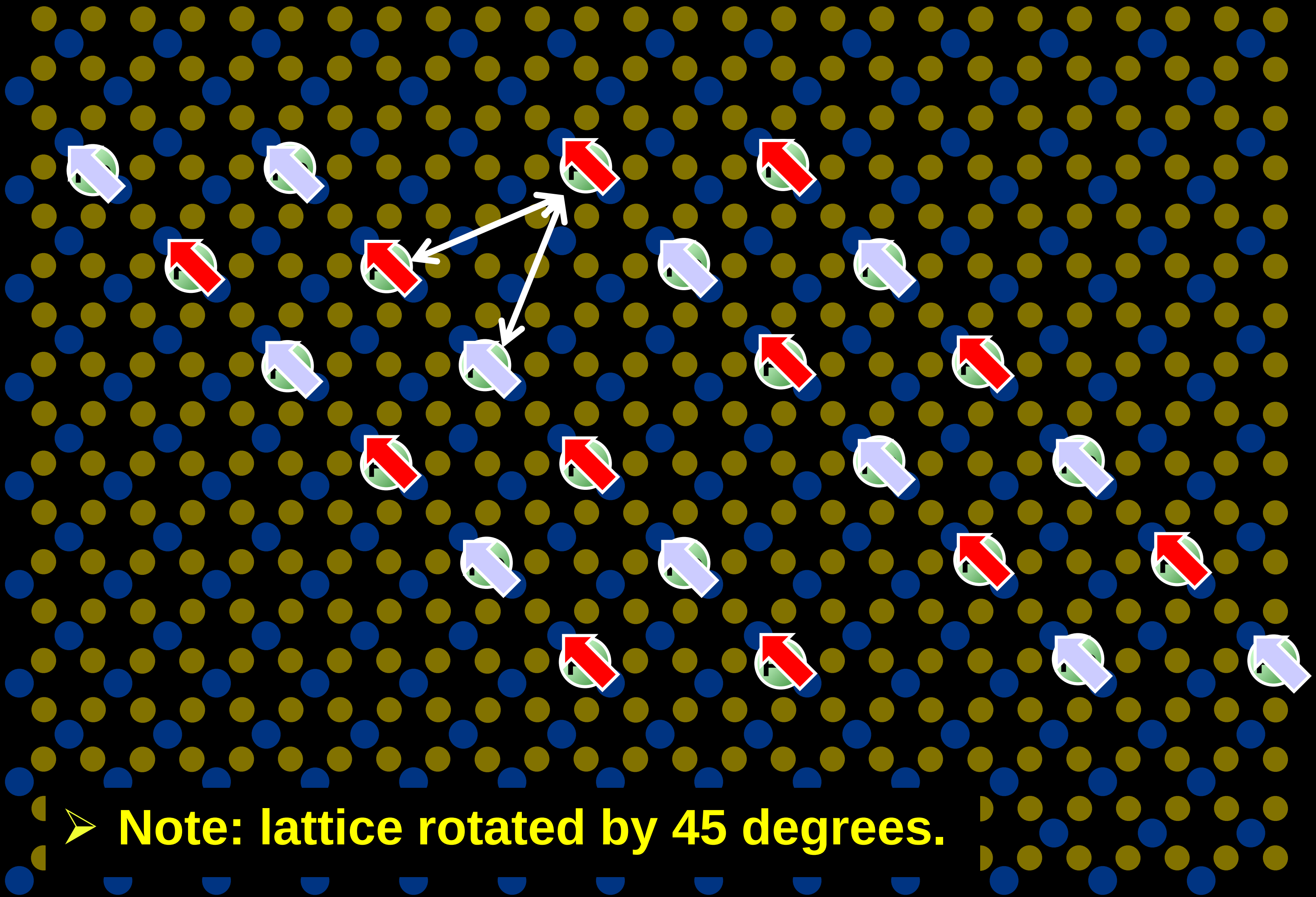




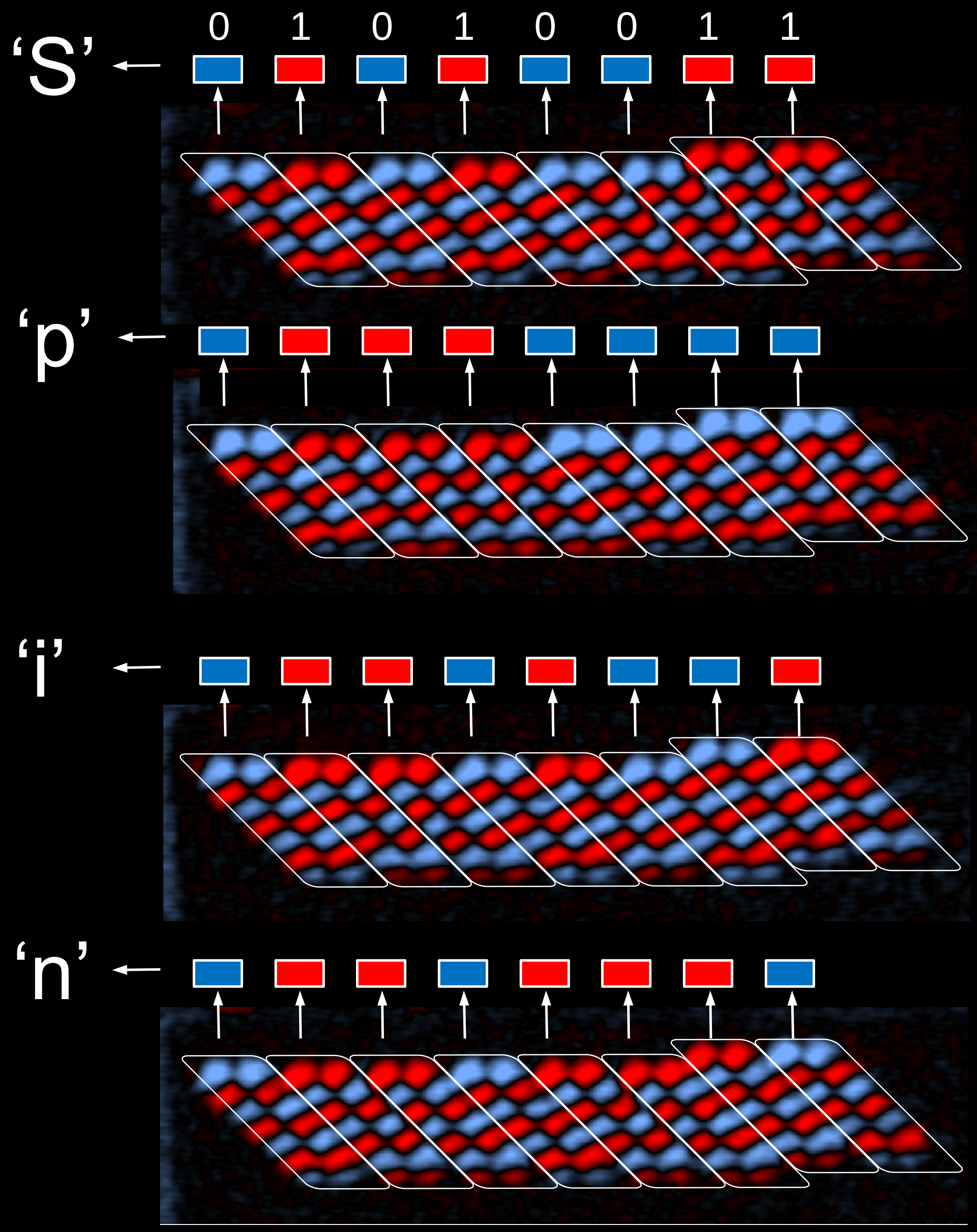
- Weak coupling of 2 chains suppresses tunneling

Stability at 0.5K >17h.

Dense packing: a true advantage of AFM



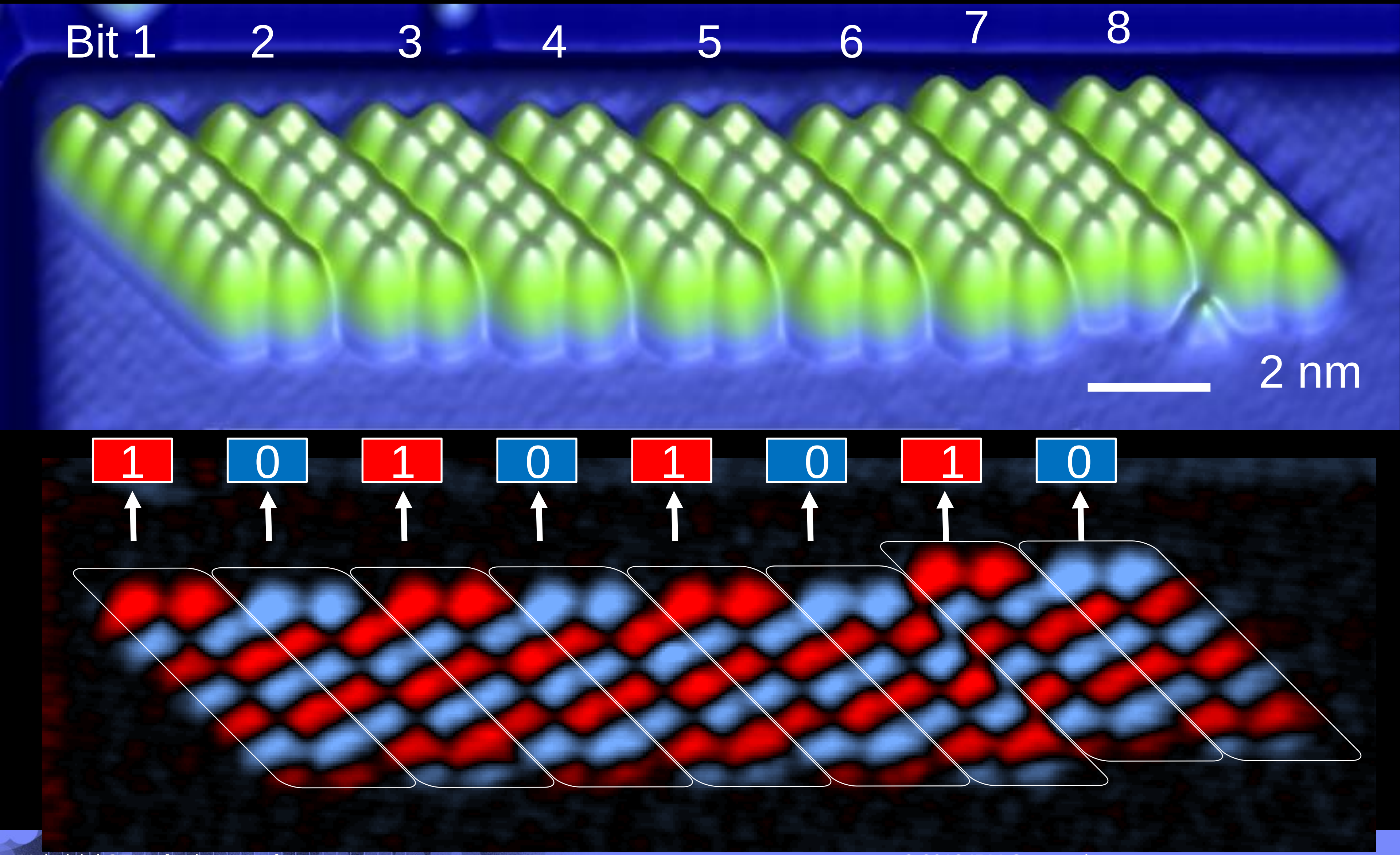
- Note: lattice rotated by 45 degrees.



Antiferromagnetic data storage:

- 12 Fe atoms per bit.
- ~100,000 x fewer magnetic atoms
- Bit density including spacer regions 70 T bit / in^2
- ~100 x denser than current hard disk drive technology

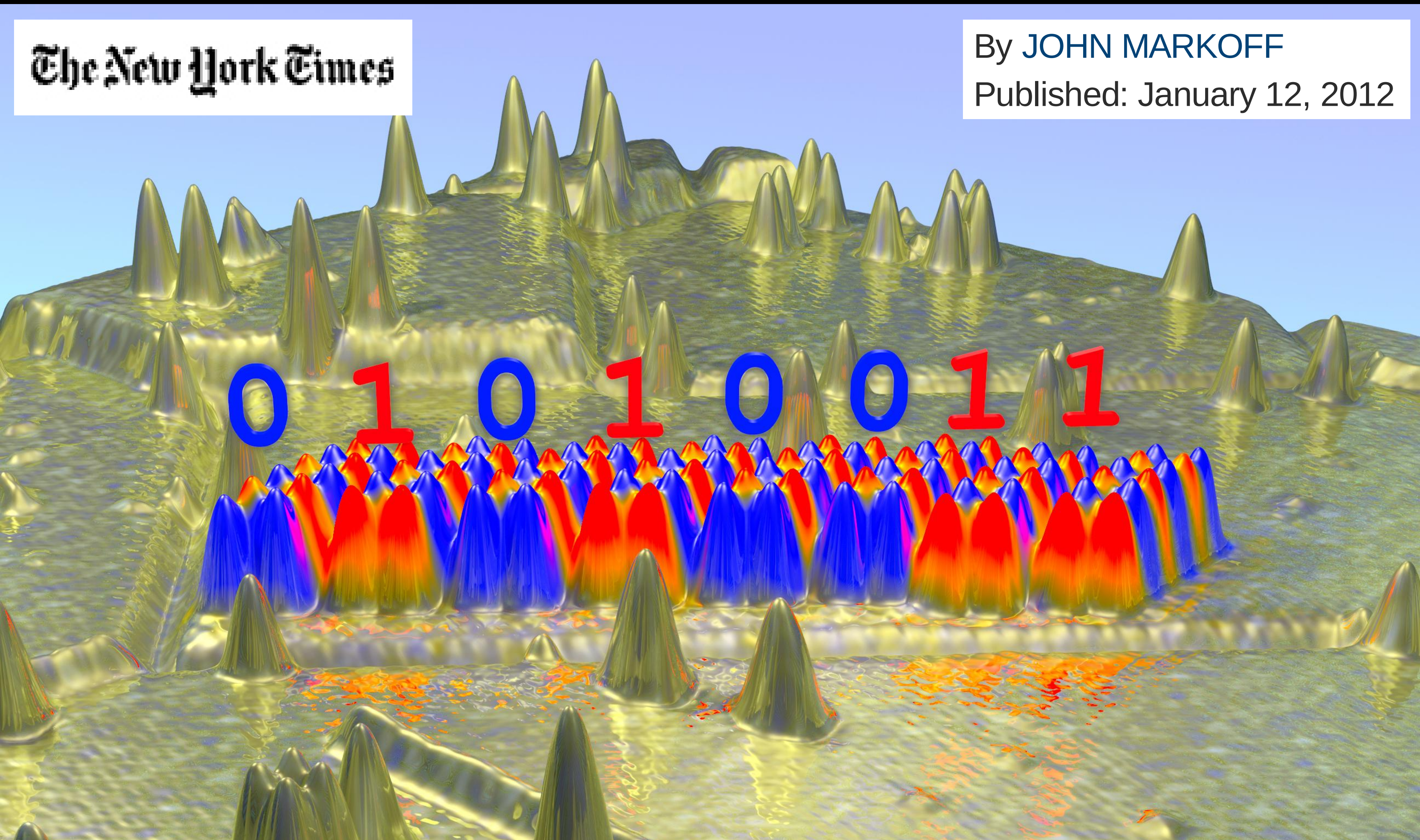
The world's smallest magnetic Byte



New Storage Device Is Very Small, at 12 Atoms

The New York Times

By JOHN MARKOFF
Published: January 12, 2012



What to learn from quantum spins on surfaces?