The Future of Condensed Matter and Materials Physics

Steven M. Girvin

Yale University

APS Meeting
March 3, 2003

Connections

Biophysics, Biologically Inspired Physics

High Energy Theory

Condensed Matter Theory and Expt.

High Energy Expt.

Atomic, Molecular, Optical

Materials Science

Astronomy

CS, EE

Technology ⟺ Fundamental Physics

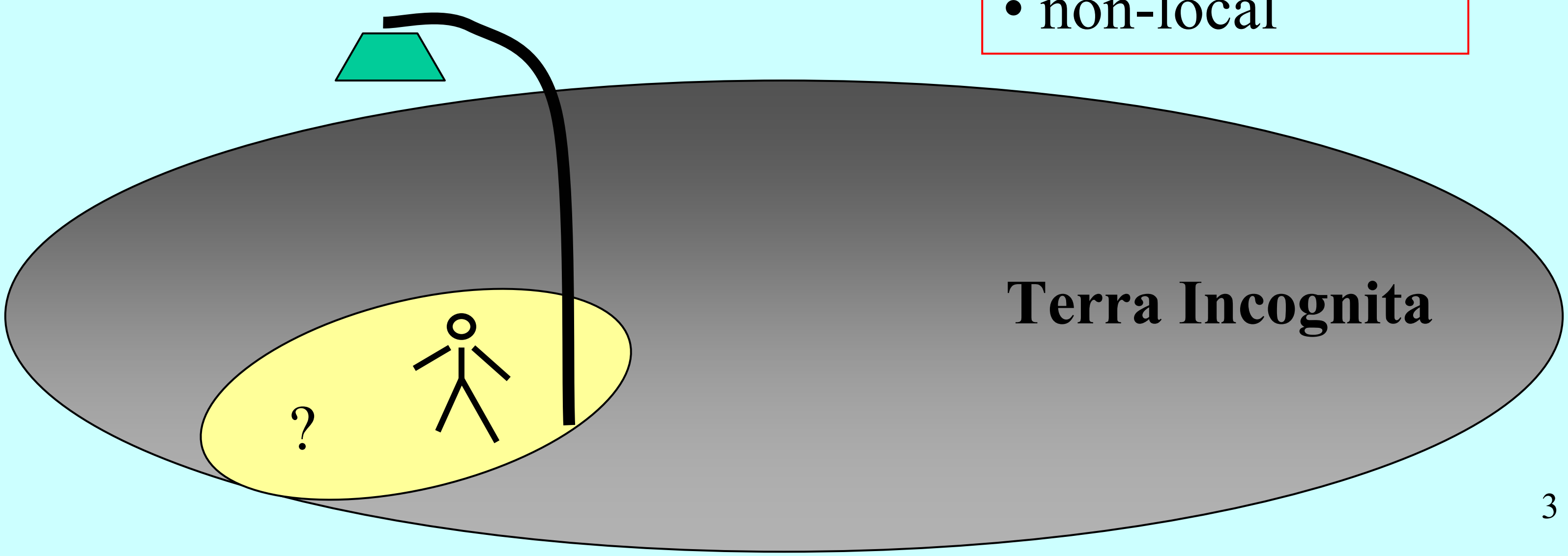
Paradigms

“Spherical Cow” Paradigm

- equilibrium
- linear response
- ordered
- non-interacting
- local

Dark Reality

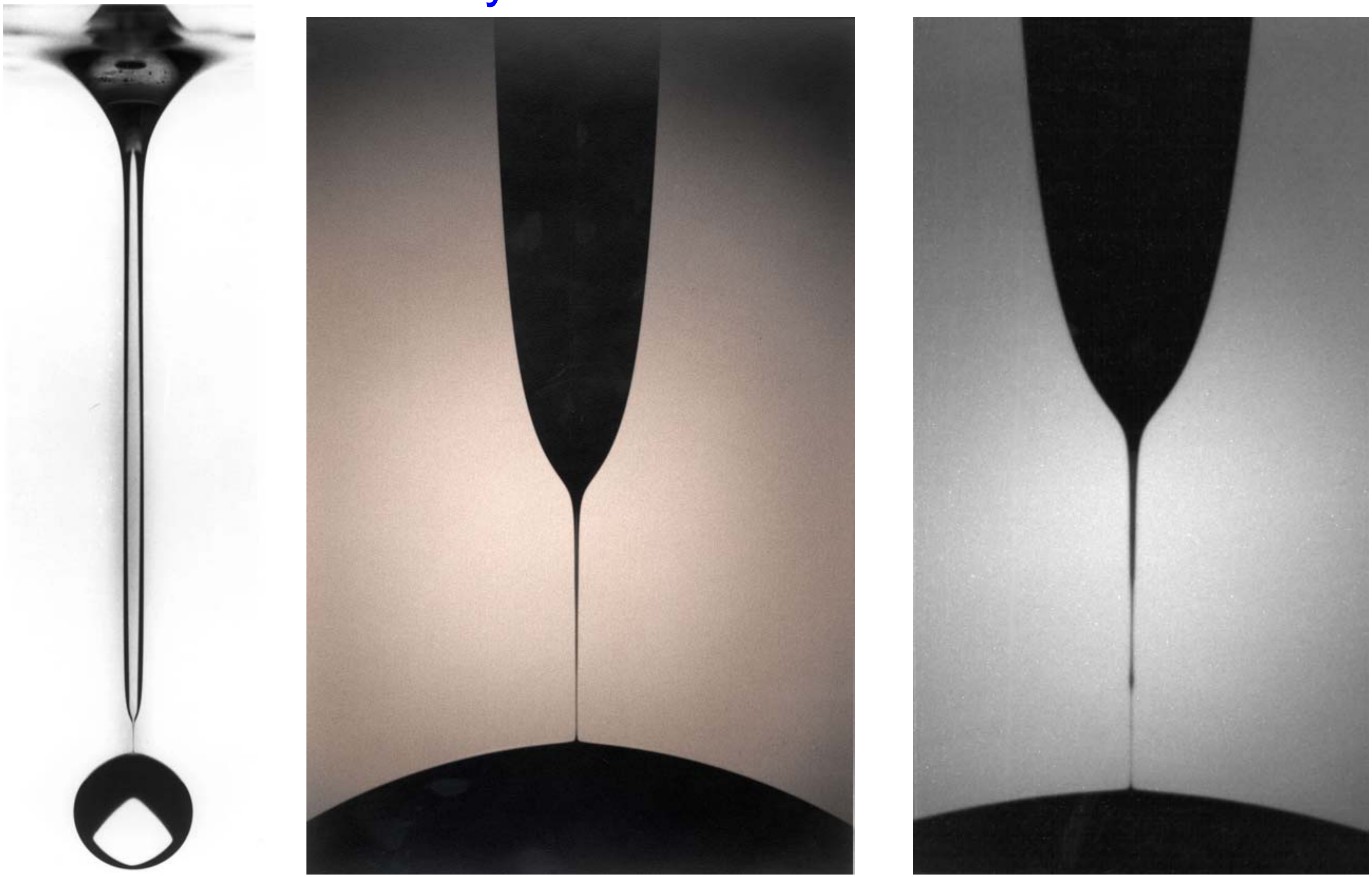
- non-equilibrium
- non-linear
- disordered
- interacting
- non-local



‘Soft-Matter’ and Physics at Human Scales

The World is an interesting and complex place…

Navier-Stokes Equations
Glycerol/water into Air

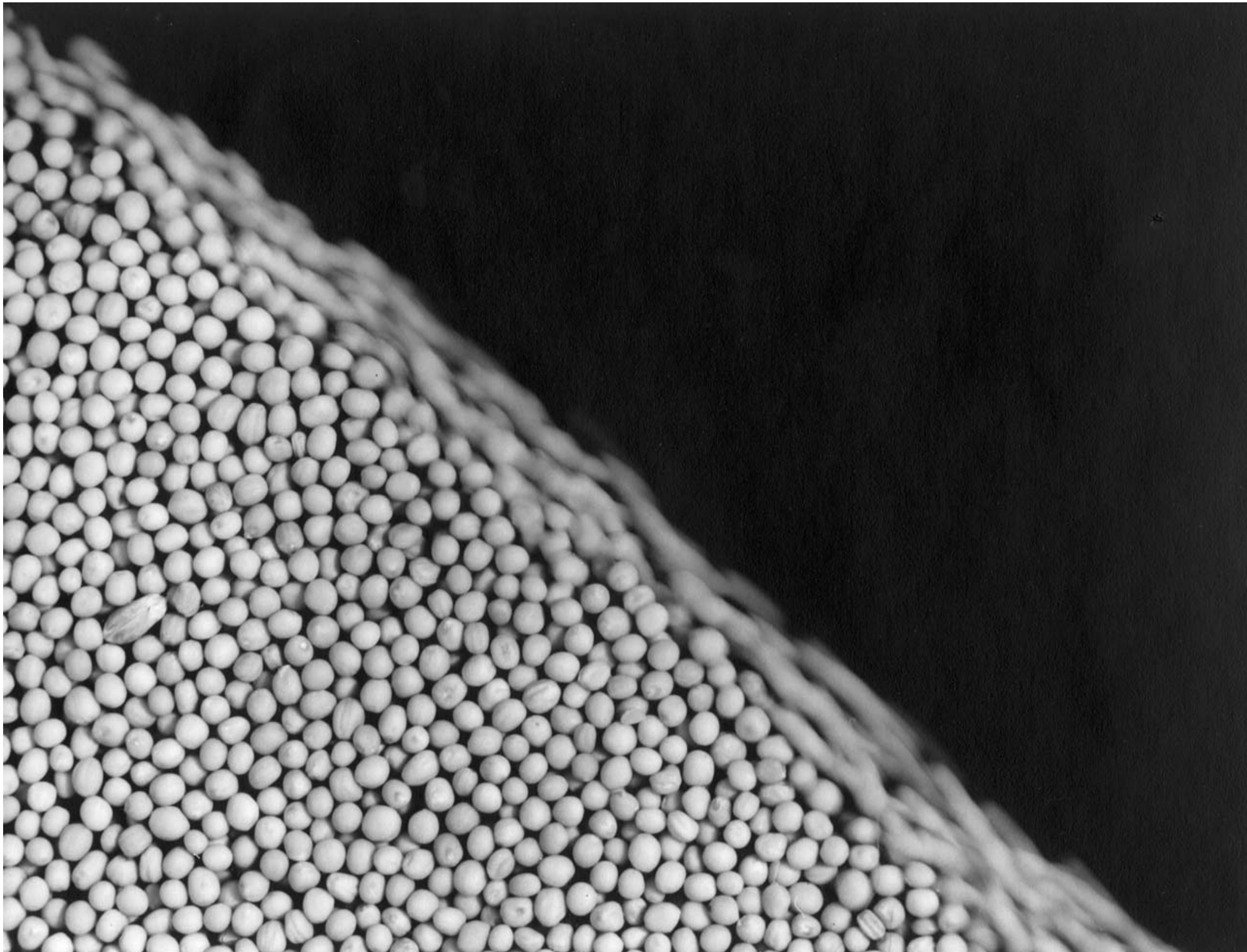


A Cascade of Structure in a Drop Falling from a Faucet ,
X. D. Shi, M. P. Brenner and S. R. Nagel, Science 265, 219-222 (1994).

Crumple

S. R. Nagel

Avalanche:

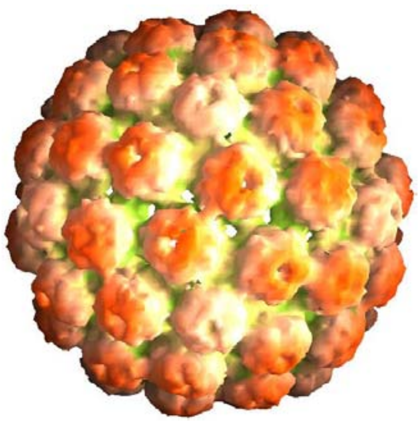


S. R. Nagel

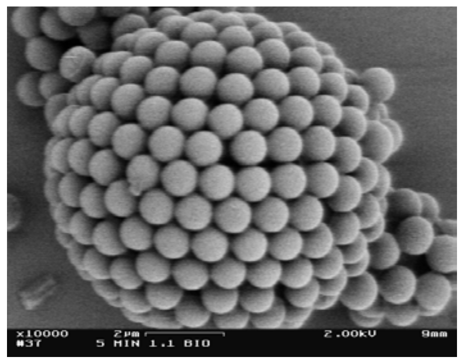
The Thomson Problem and Spherical Crystallography
(Nelson and Weitz groups, Harvard)

1904: J. J. Thomson asks how particles pack on a sphere – relevant to viruses, colloid-coated droplets, and multielectron bubbles in helium

- **Finding the ground state of ~26,000 particles on a sphere is replaced by minimizing the energy of only ~ 250 interacting disclinations, representing points of local 5- and 7-fold symmetry.**
- **Grain boundaries in ground state for R/a > 5-10 have important implications for the mechanical stability and porosity of colloidosomes, proposed as delivery vehicles for drugs, flavors and fragrances.**



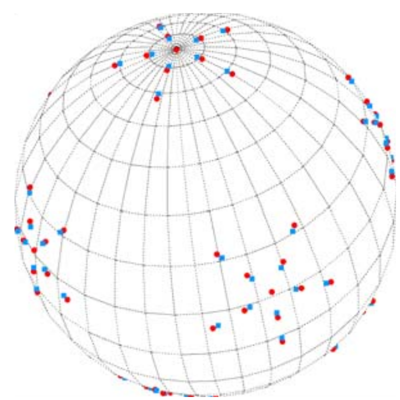
Simian virus SV40

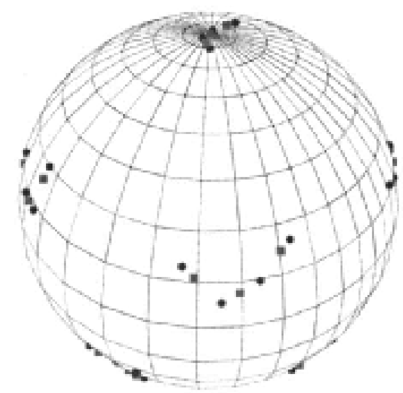


"Colloidosome" = colloids of radius ***a*** coating water droplet (radius ***R***) -- Weitz Laboratory

Bausch et al. *Science* (in press)

Ordering on a sphere ➔ a minimum of 12 5-fold disclinations, as in soccer balls and fullerenes -- what happens for $R/a >> 1$?



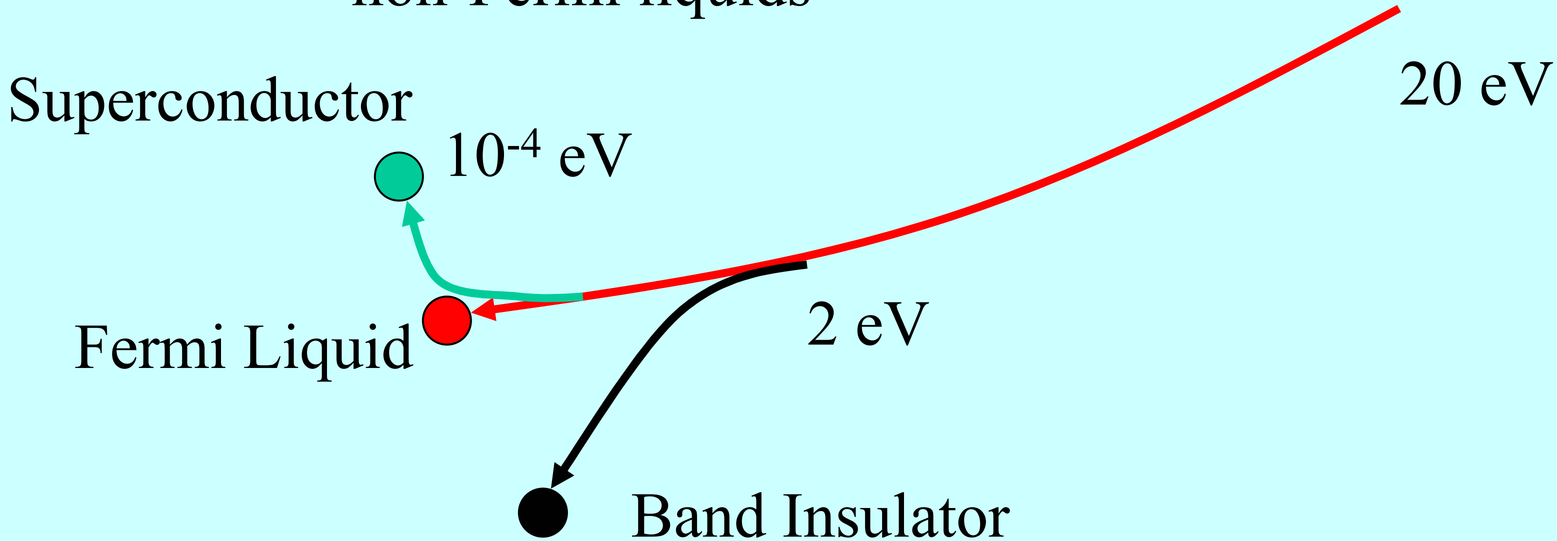


Dislocations (5-7 defect pairs) embedded in spherical ground states

‘Hard Matter’ and the Quantum World of Electrons

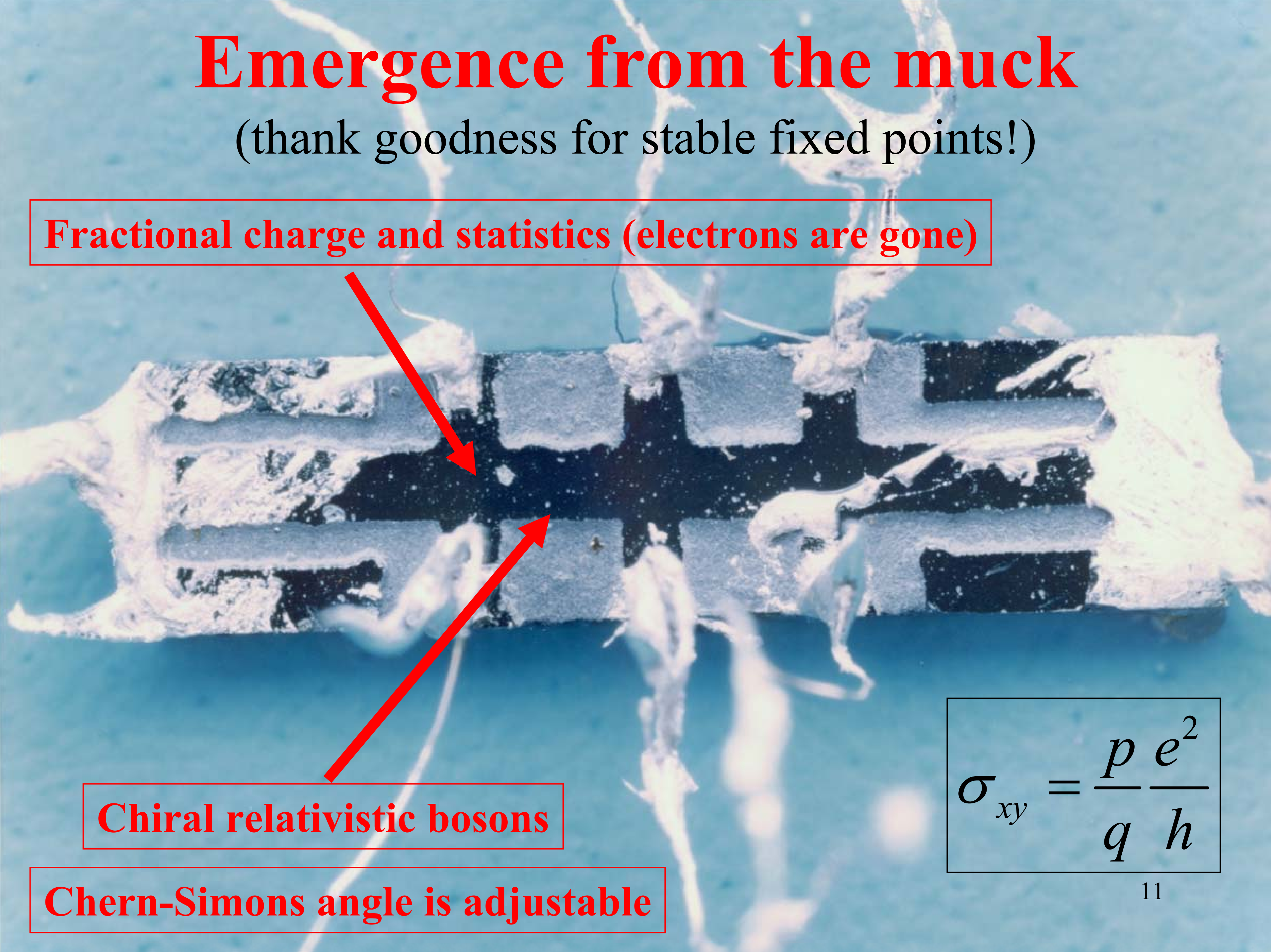
RNG, Field Theory Paradigm

- Powerful ideas and tools
  - quantum criticality
  - stability analysis of fixed points
  - recognize danger of ‘fine tuning’
  - direction of flow hints at strong coupling f.p.
  - broken symmetry
  - ‘emergence’;   new degrees of freedom
  - fractionalization of particles
  - non-Fermi liquids



Emergence from the muck

(thank goodness for stable fixed points!)



Fractional charge and statistics (electrons are gone)

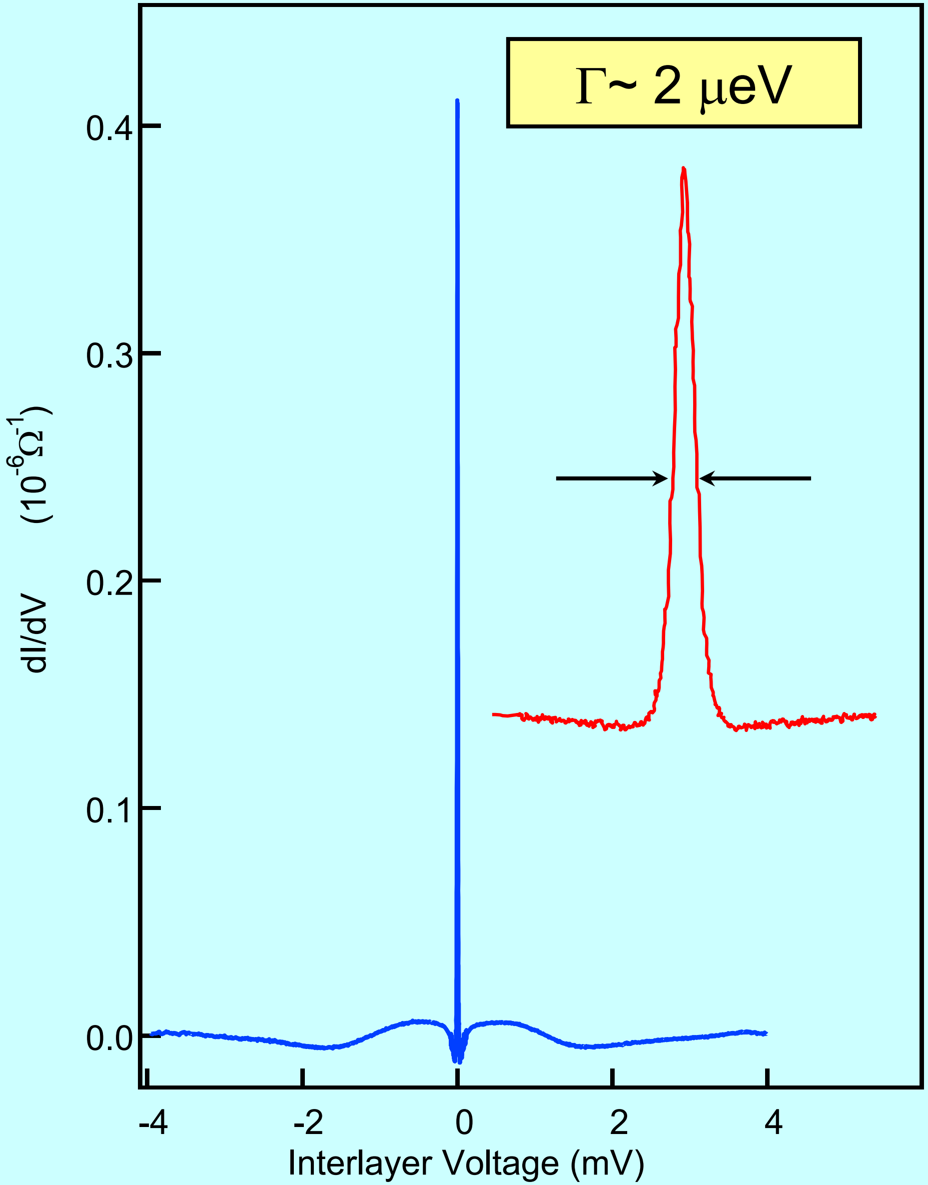
Chiral relativistic bosons

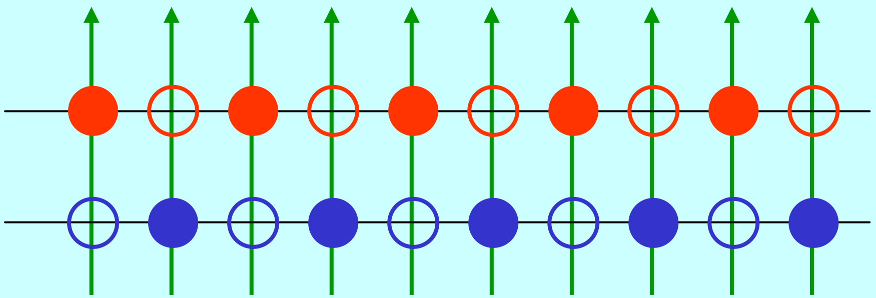
Chern-Simons angle is adjustable

$$\sigma_{xy} = \frac{p}{q}\frac{e^2}{h}$$

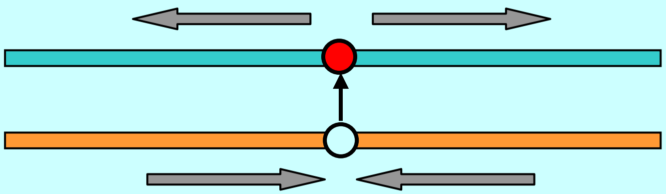
Fractional Quantum Hall State

QHE Bilayer Tunneling





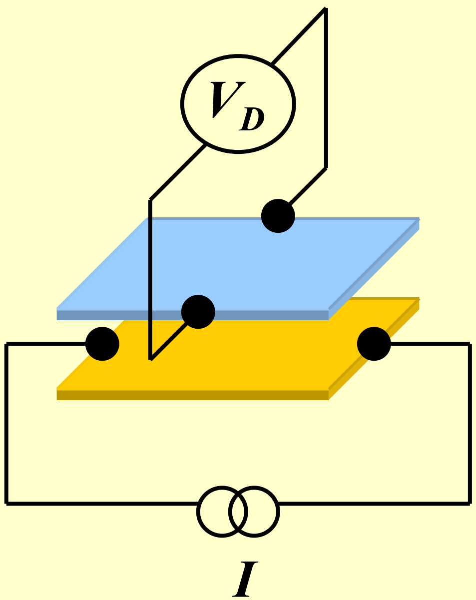
'Which Layer?' Broken Symmetry

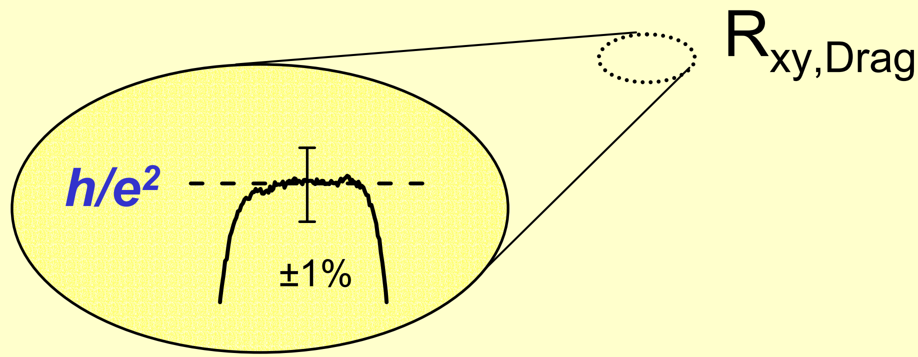


Counter-flow superfluidity rapidly relaxes charge defects created by tunneling.

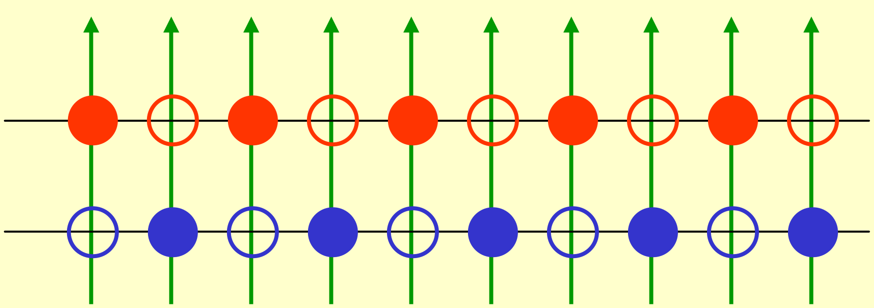
J. Eisenstein

Exact Quantization of “Hall” drag: Hall voltage without current





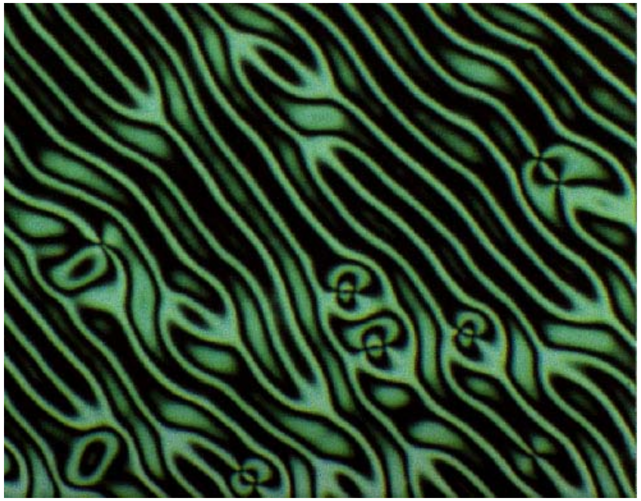
$$V_D = \frac{h}{e^2} I$$



Chern-Simons (Giaver)
Flux Transformer

J. Eisenstein

Electronic Liquid Crystals



Higher Landau Levels

Koulakov, Fogler, and Shklovskii;

Moessner and Chalker 1996

Nematic to Isotropic Transition

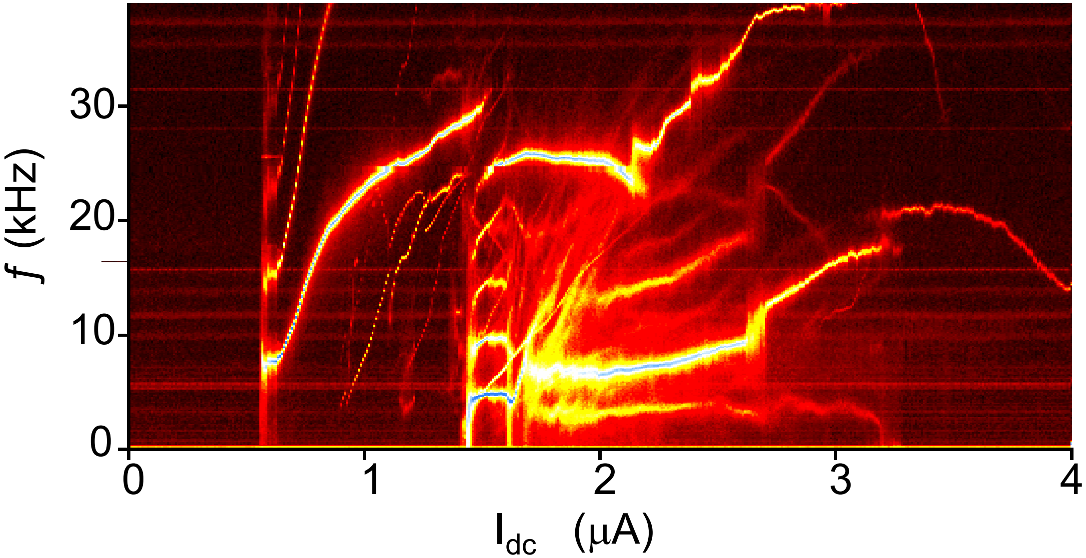
Fradkin and Kivelson

Wexler and Dorsey

Radzihovsky and Dorsey

'Quantum Soft Matter'

Narrow band noise

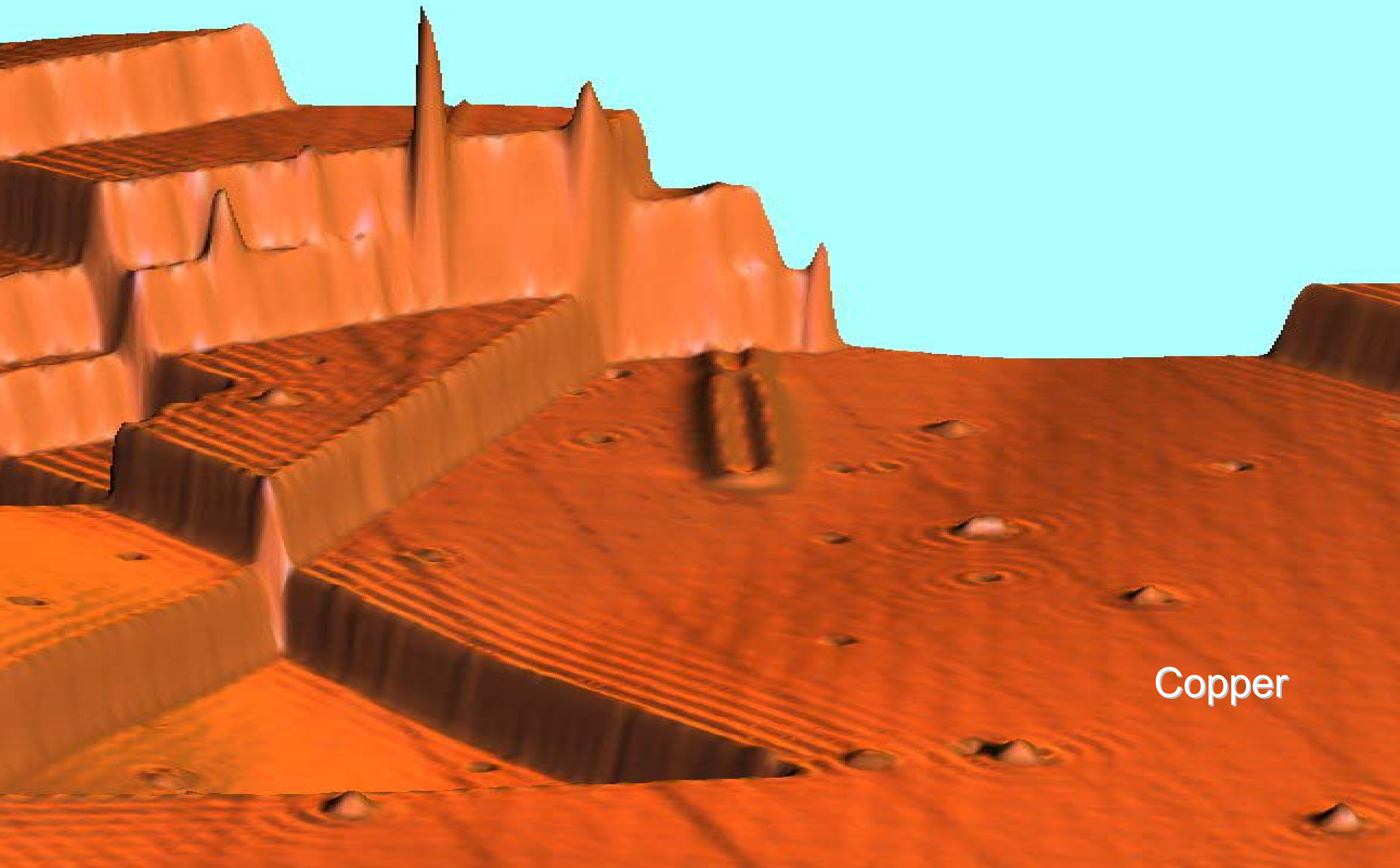


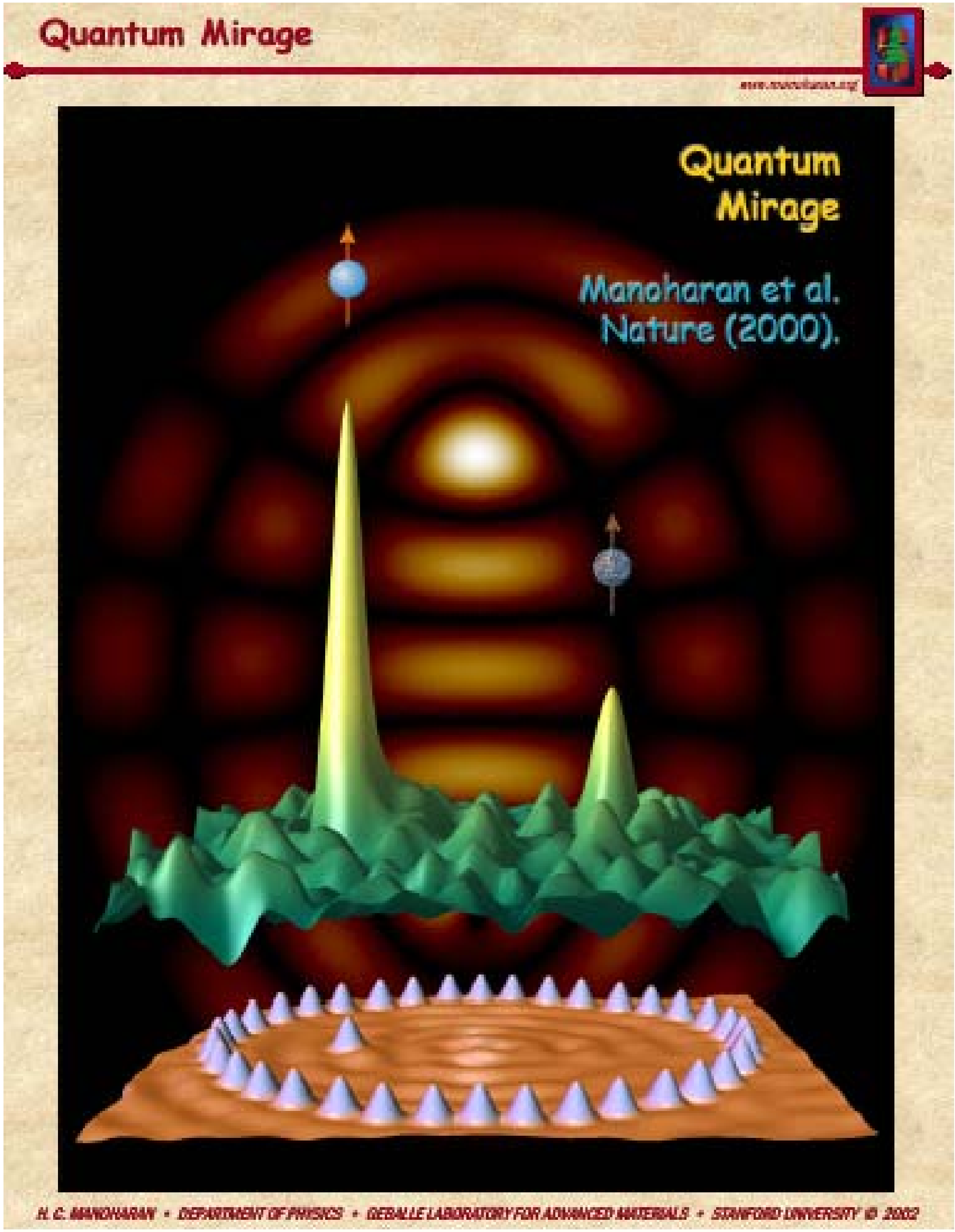
J. Eisenstein

Struggling with other Strongly Correlated Systems is Difficult

- high Tc
- heavy fermions
- oxide magnets, CMR, magnetic SC
- ladders, chains
- organics
- ……

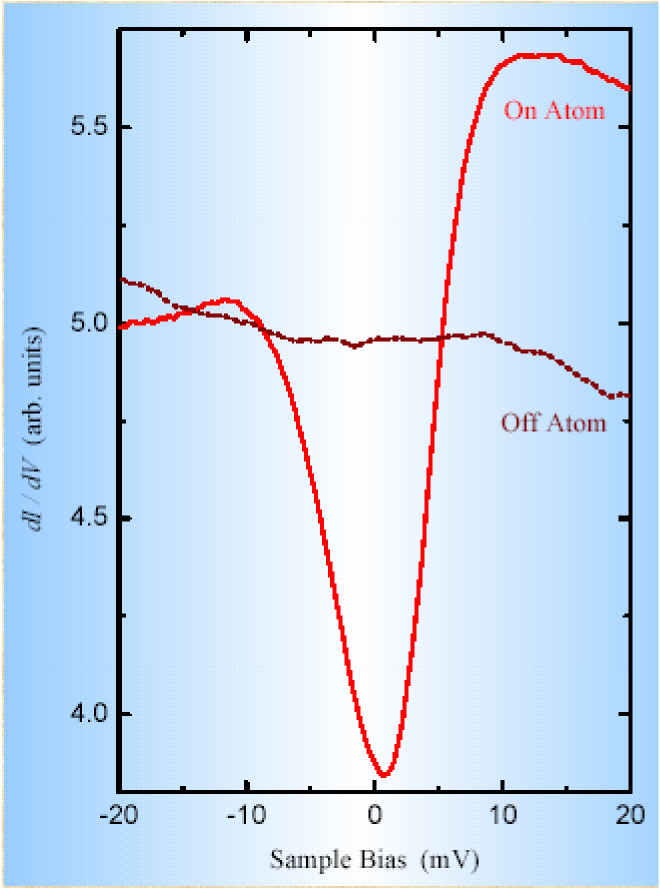
The Nano World



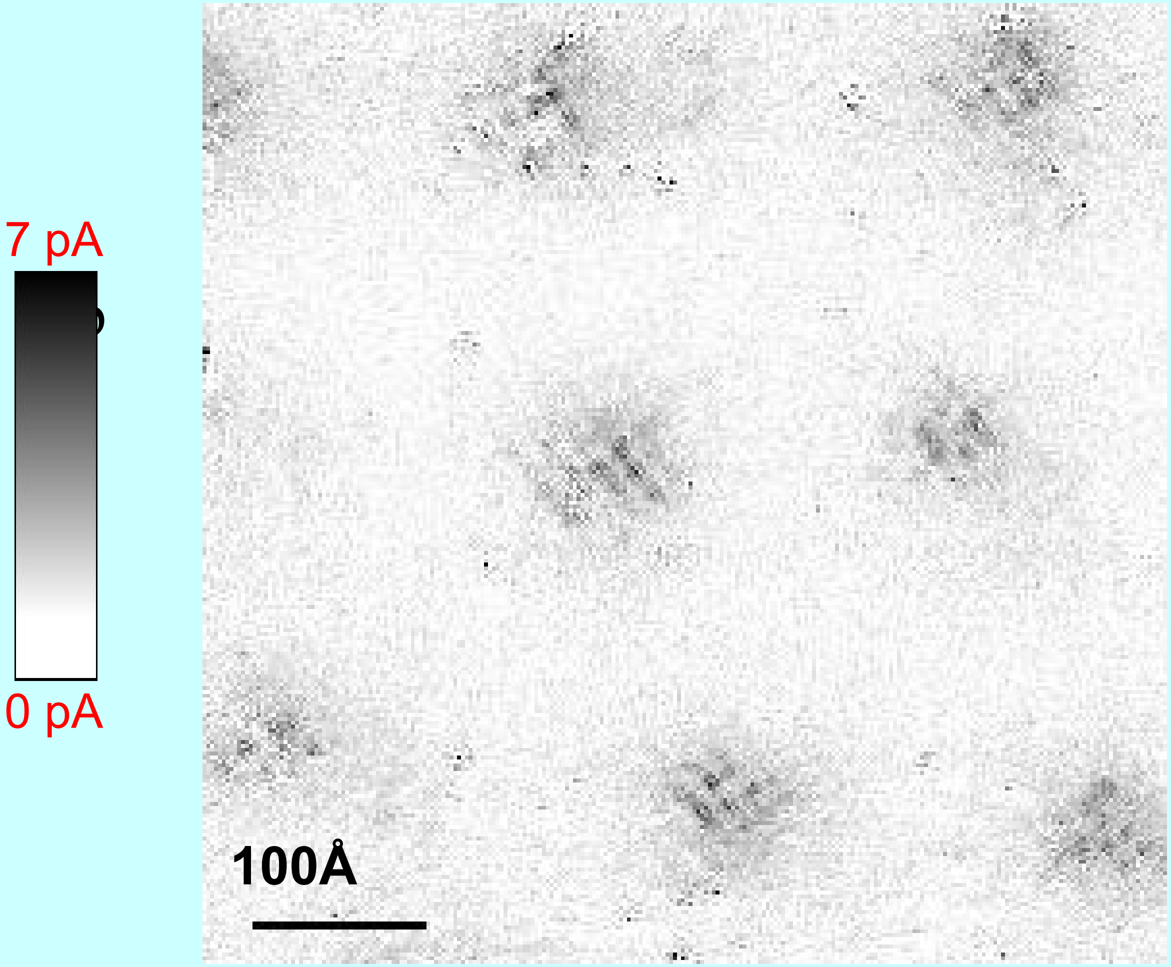


Kondo Mirage in a Quantum Corral

$T_K = 56K$

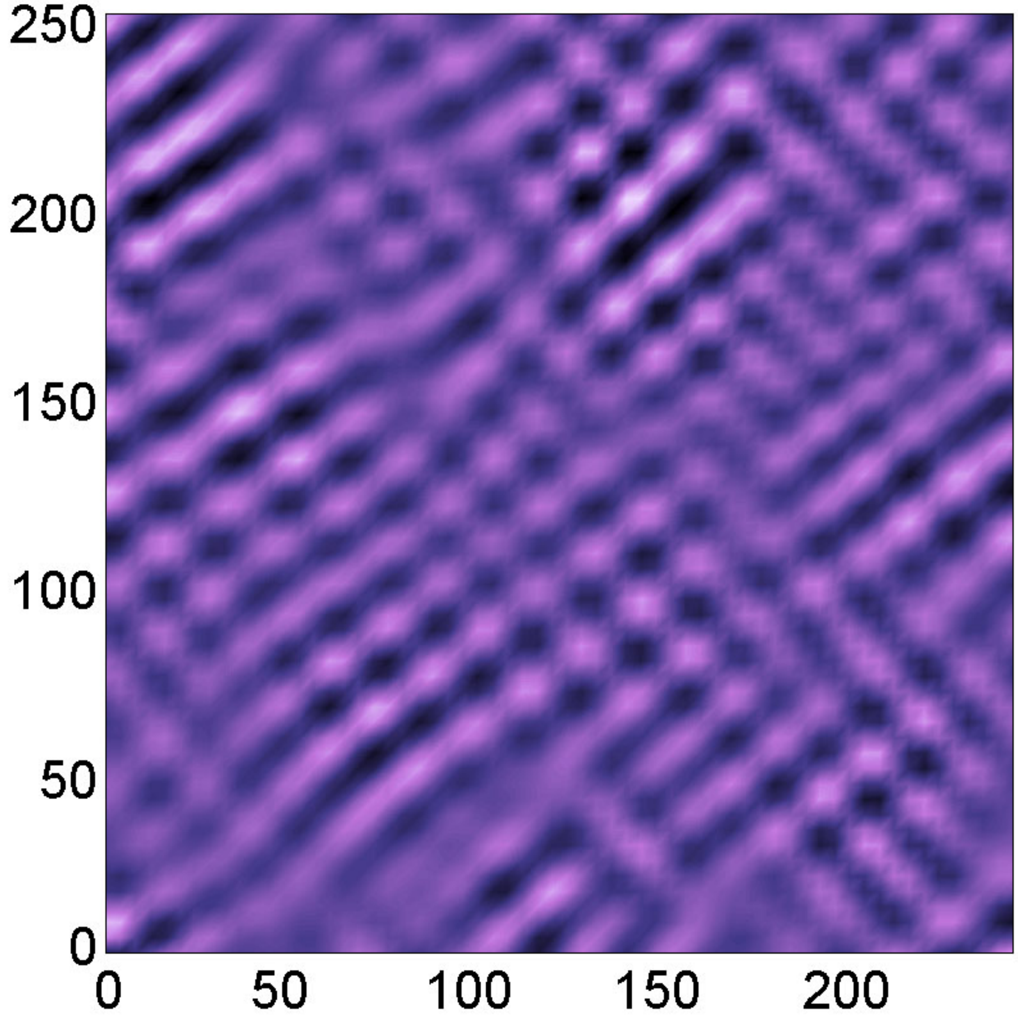


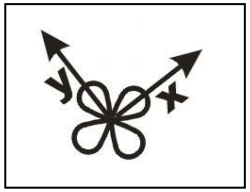
Vortex-induced LDOS of $Bi_2Sr_2CaCu_2O_{8+\delta}$ integrated from 1meV to 12meV



J. Hoffman E. W. Hudson, K. M. Lang, V. Madhavan, S. H. Pan, H. Eisaki, S. Uchida, and J. C. Davis, *Science* 295, 466 (2002).

STM image of LDOS modulations in $Bi_2Sr_2CaCu_2O_{8+\delta}$ in zero magnetic field



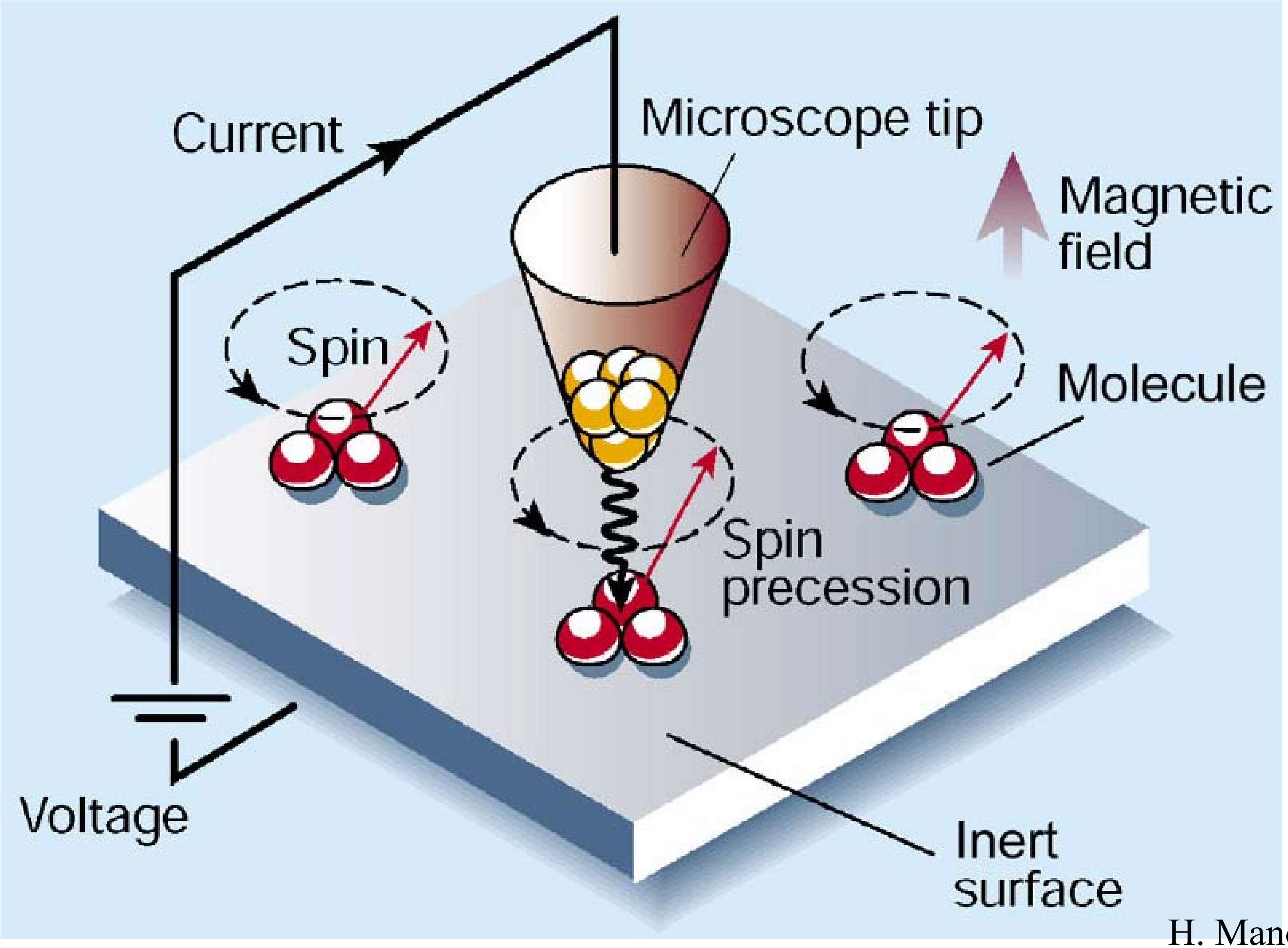


Period = 4 lattice spacings

Energy spectroscopy can be done on the spatial Fourier transform signal

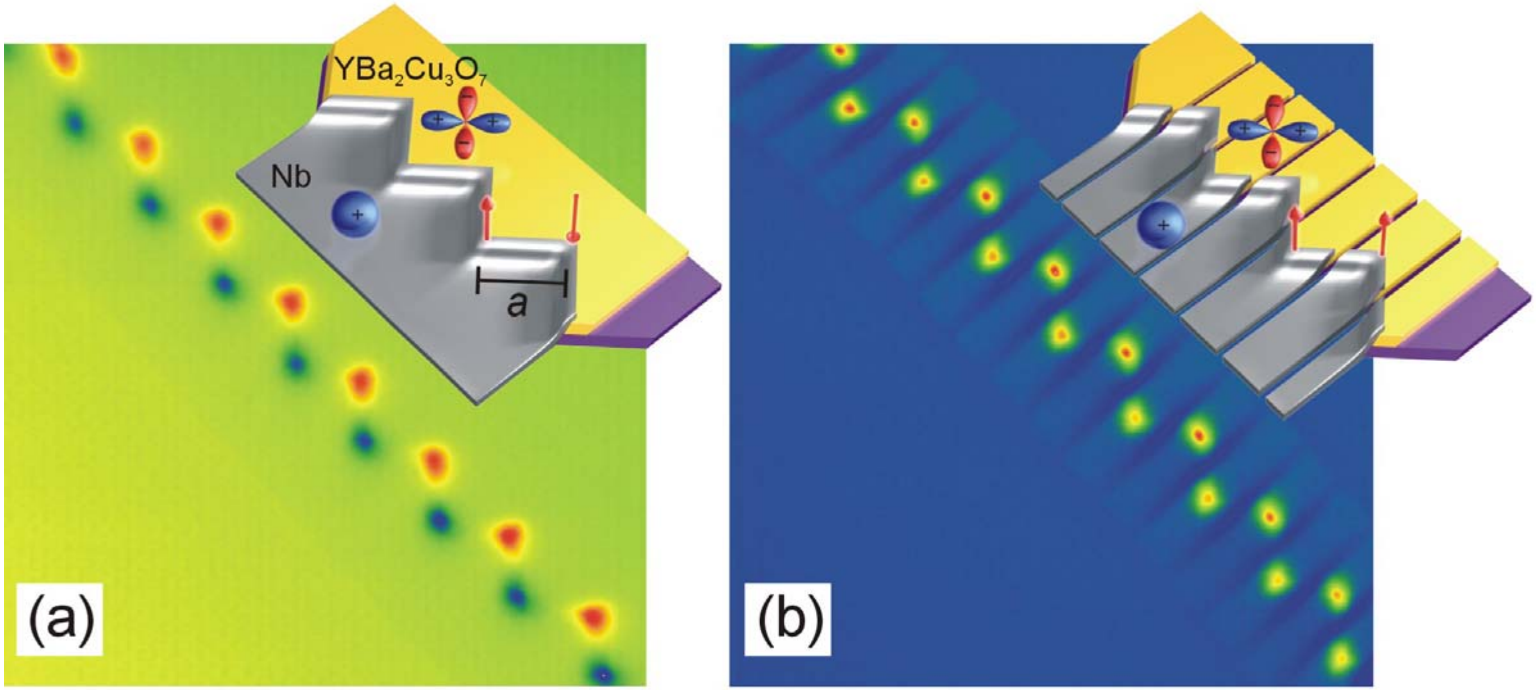
C. Howald, H. Eisaki, N. Kaneko, and A. Kapitulnik, cond-mat/0201546

STM Electron Spin Resonance



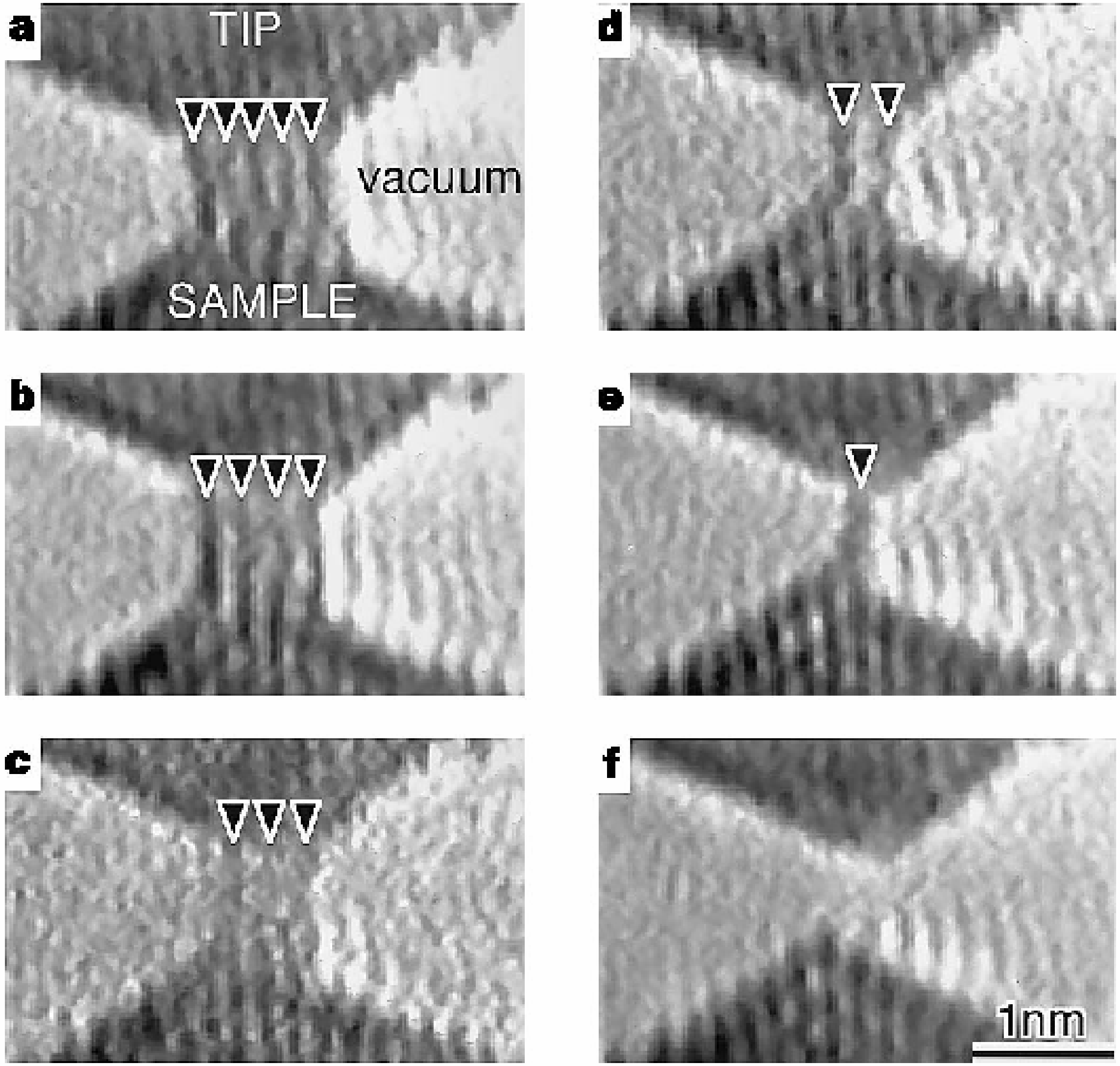
H. Manoharan

Scanning SQUID



Hans Hilgenkamp, Ariando, Henk-Jan H. Smilde, Dave H.A. Blank, Guus Rijnders, Horst Rogalla, John R. Kirtley, and Chang C. Tsuei, Nature, March 6, 2002

Nano-Mechanics



$G = 2G_0$

$G = G_0$

Au bridges

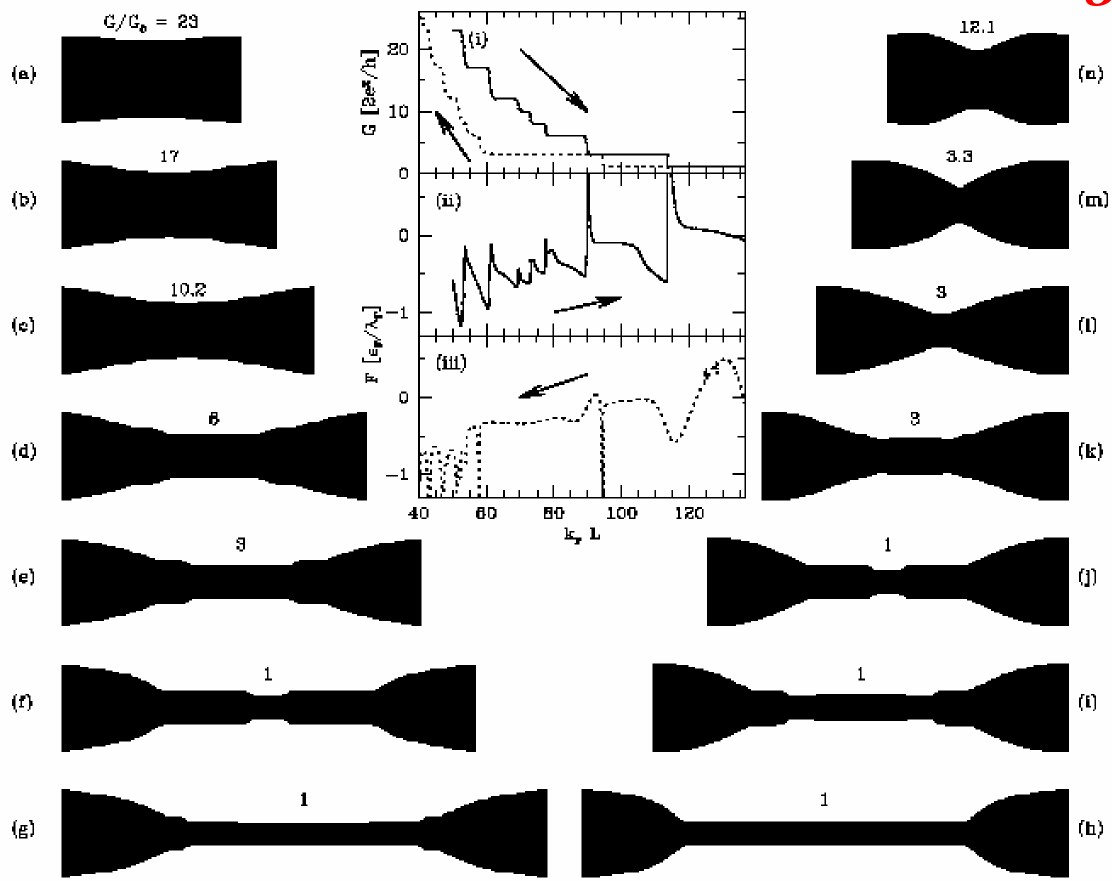
H. Ohnishi et al. *Nature* **395**, 780 (1998)

Free-electron model of a metal nanowire

Structural relaxation due to surface self-diffusion of atoms

Elongation/compression=nucleation/annihilation of kink-antikink pairs

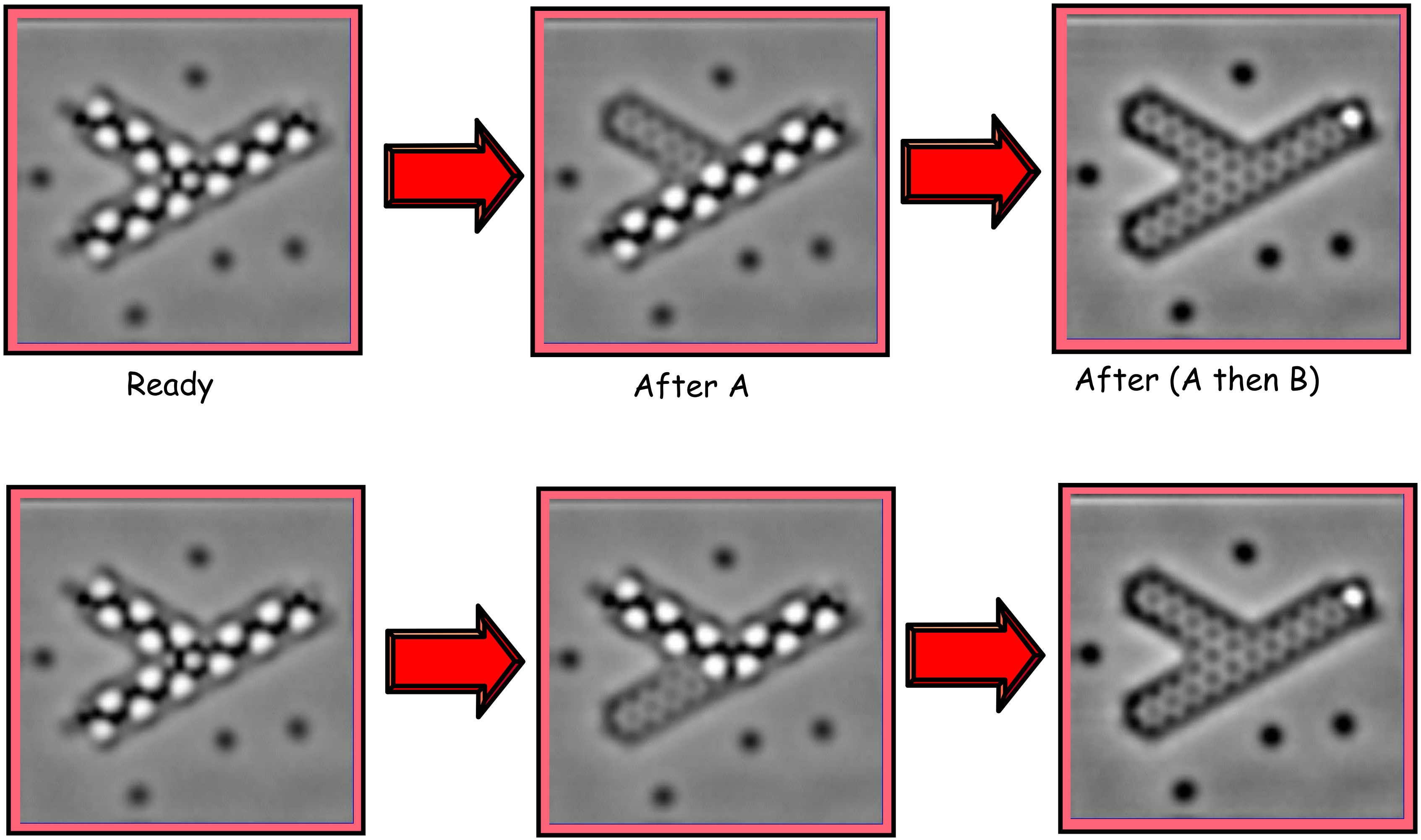
$\varepsilon_F / \lambda_F = 1.7\text{nN}$ in gold



J. Bürki, R. E. Goldstein, and C. A. Stafford, cond-mat/0208540

Nano-mechanical "AND" Gate

Curvature Plots



Ready — After A — After (A then B)

Ready — After B — After (B then A)

D. Eigler

3-Input Sorter Molecule Cascade Logic Circuit

Inputs

Outputs

C

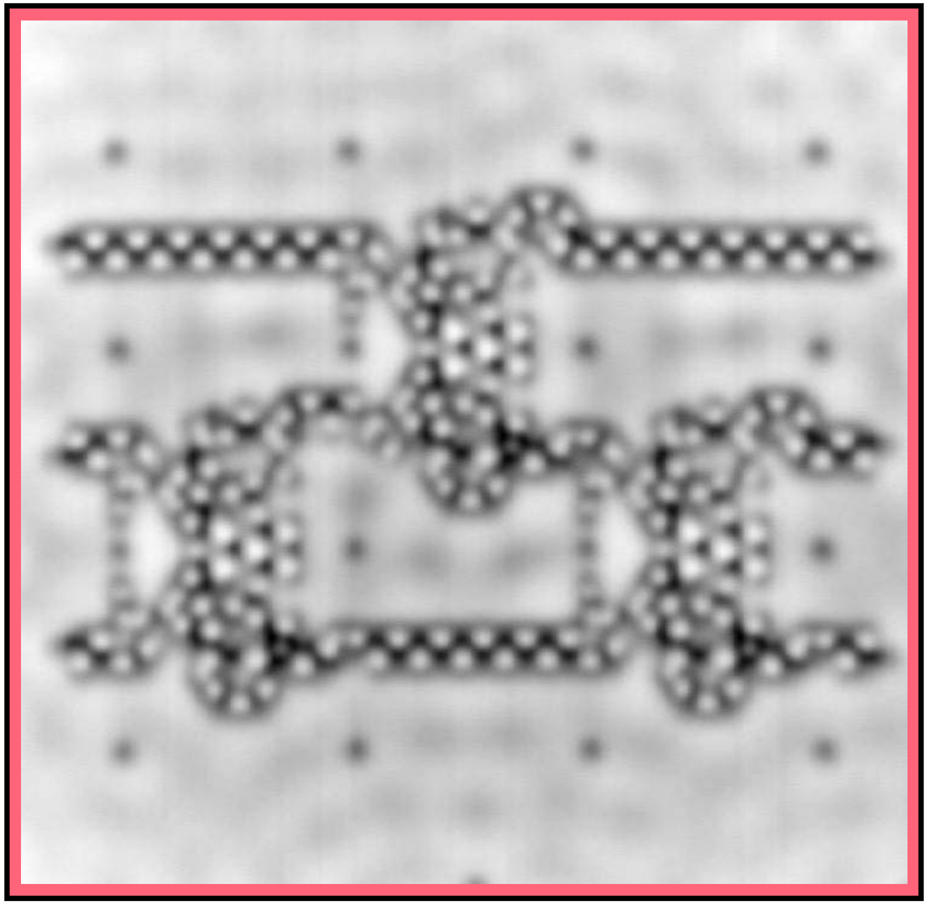
$O_3 = A + B + C$

B

$O_2 = (A * B) + (B * C) + (C * A)$

A

$O_1 = A * B * C$



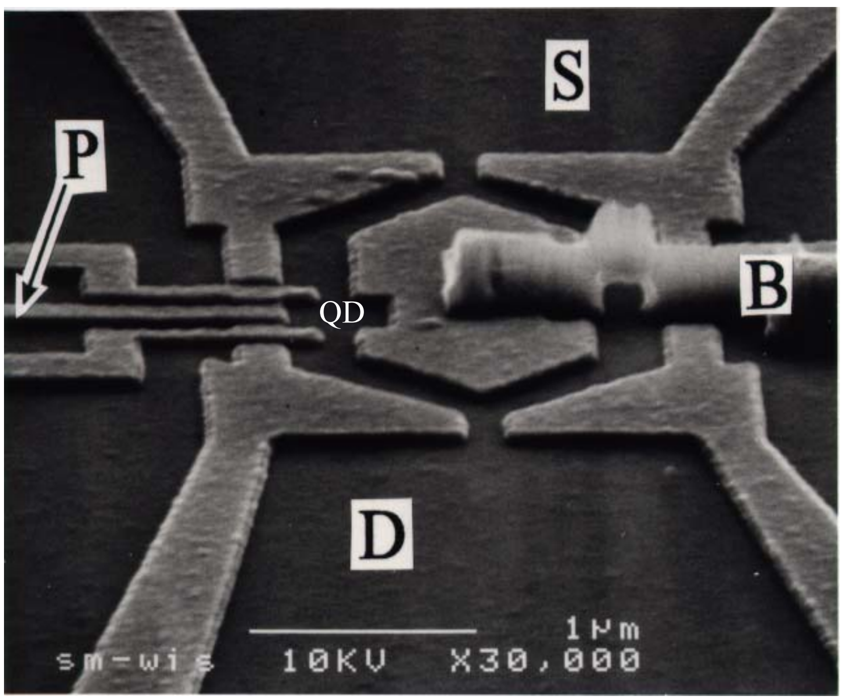
Circuit Dimensions: 12 nm x 17 nm
541 molecules

Circuit Components:
- 3 "And" gates
- 3 "Or" gates
- 6 "Fan-Outs"
- 3 "Cross-Overs"
- + Wiring

D. Eigler

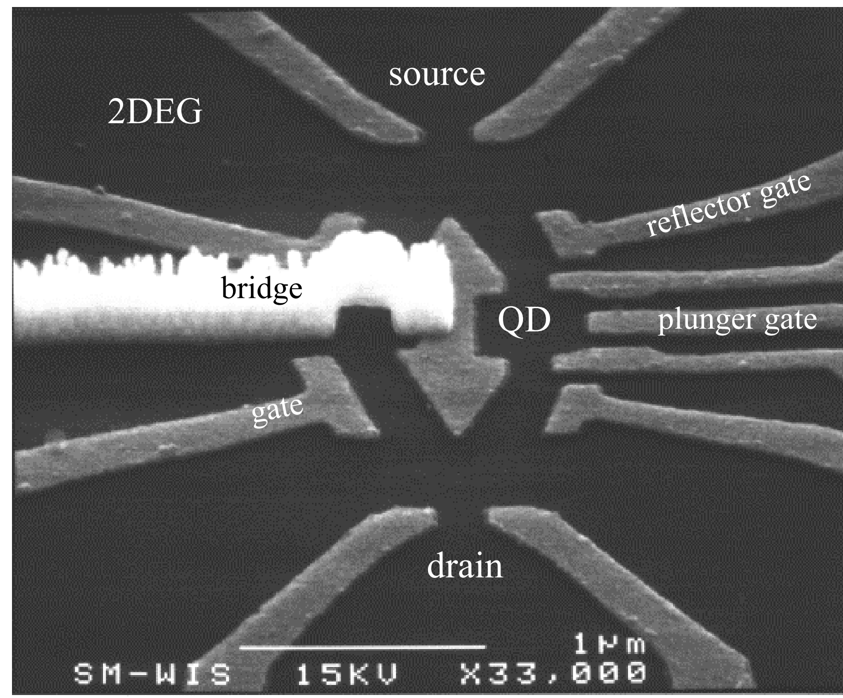
Quantum Dots and Interferometers

two terminal



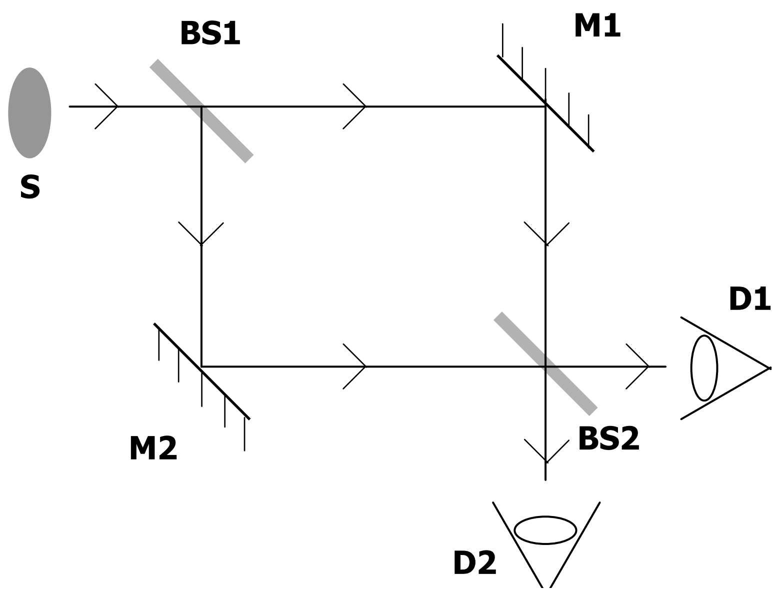
A. Yacoby *et. al.*, PRL **74**, 4047 ('95)

four terminal



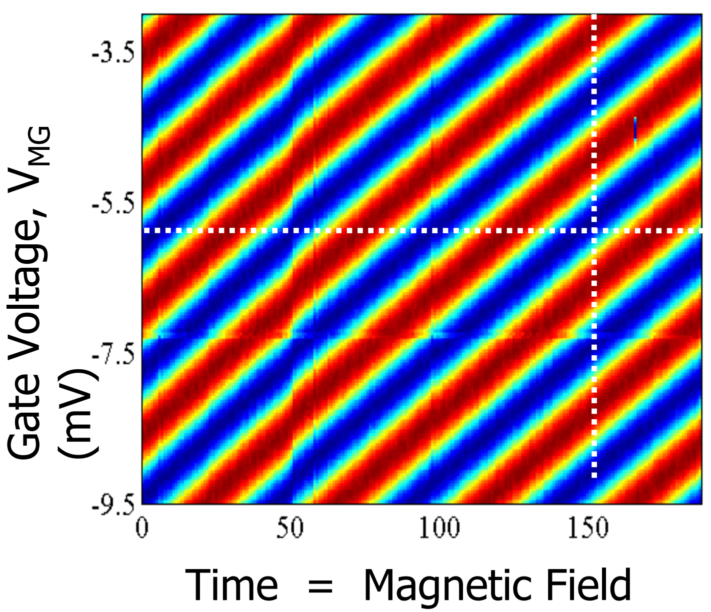
R. Schuster *et. al.*, Nature **385**, 417 ('97)

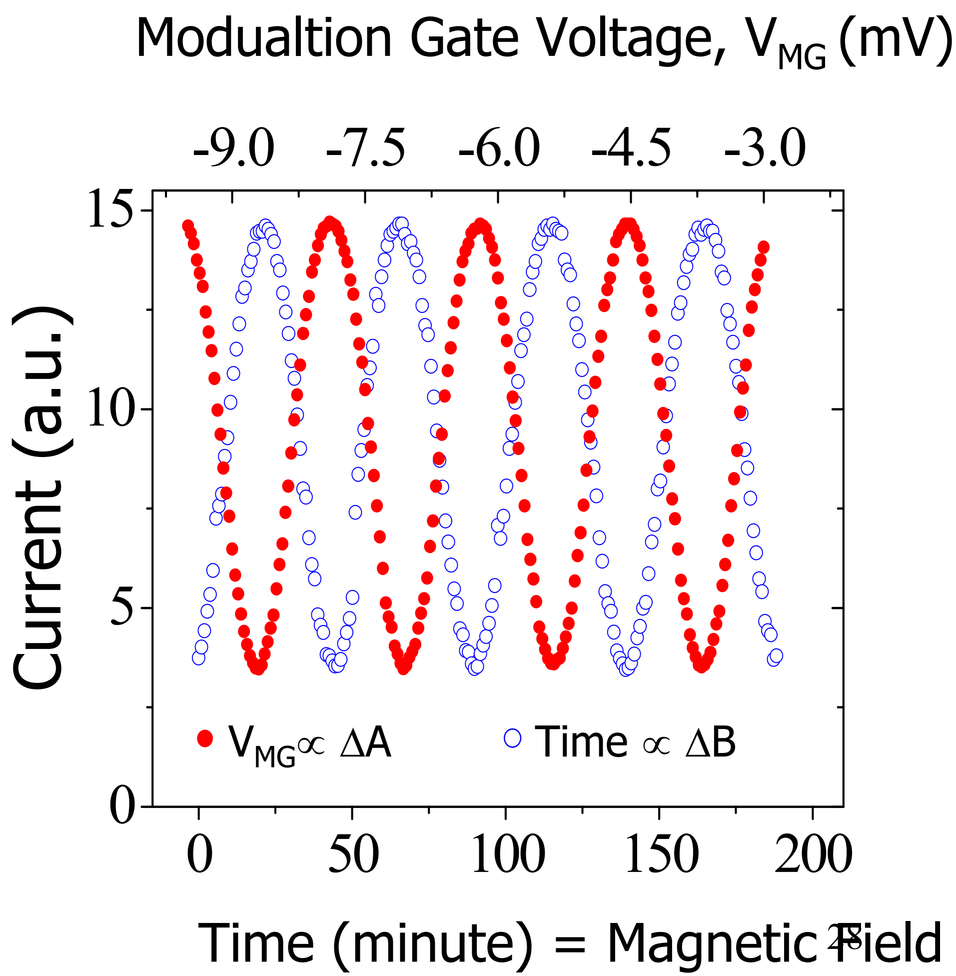
Mach-Zehnder interferometer



Weizmann group

Visibility = 60%

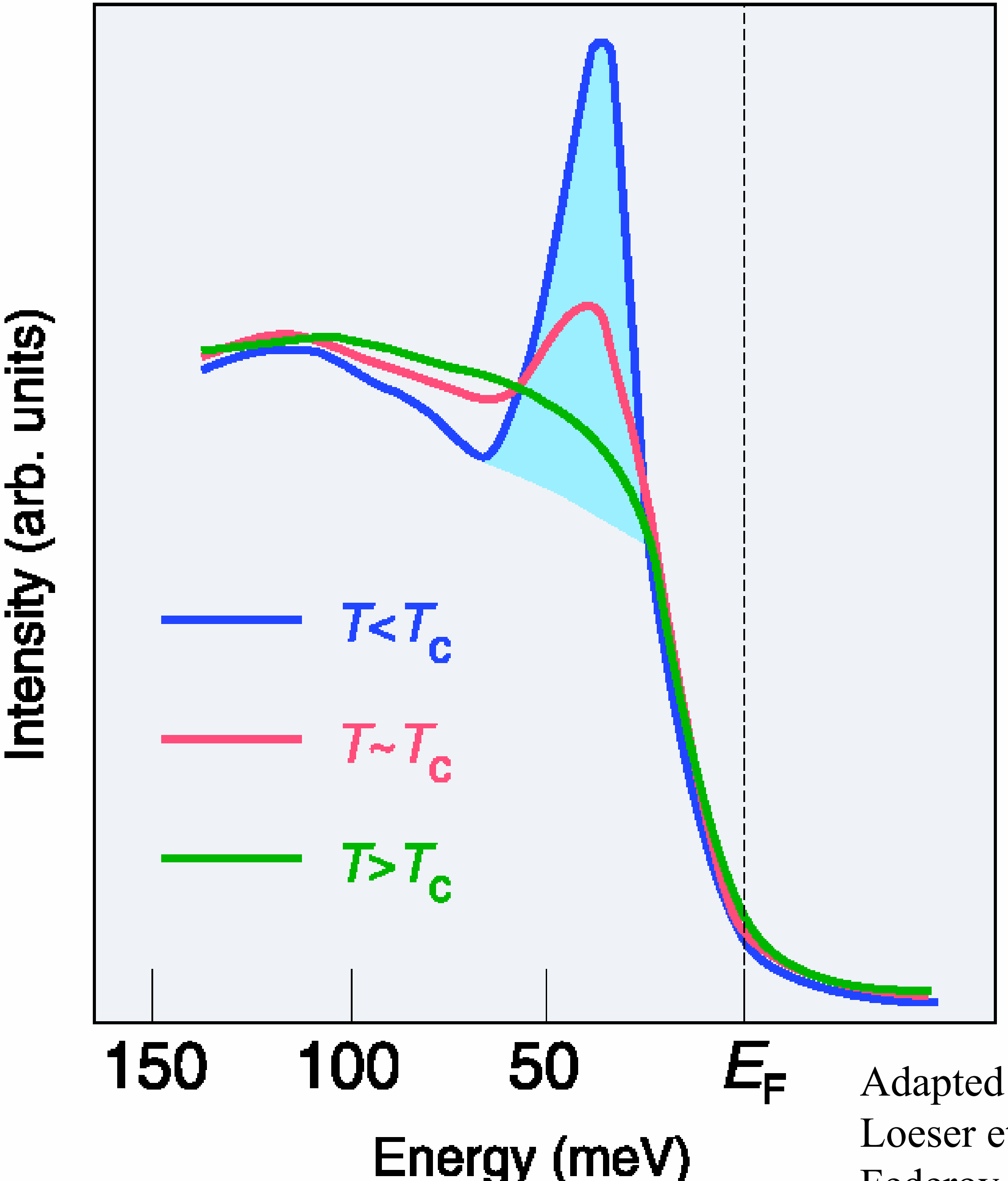




Tools

- Photons
- Neutrons
- Numerics

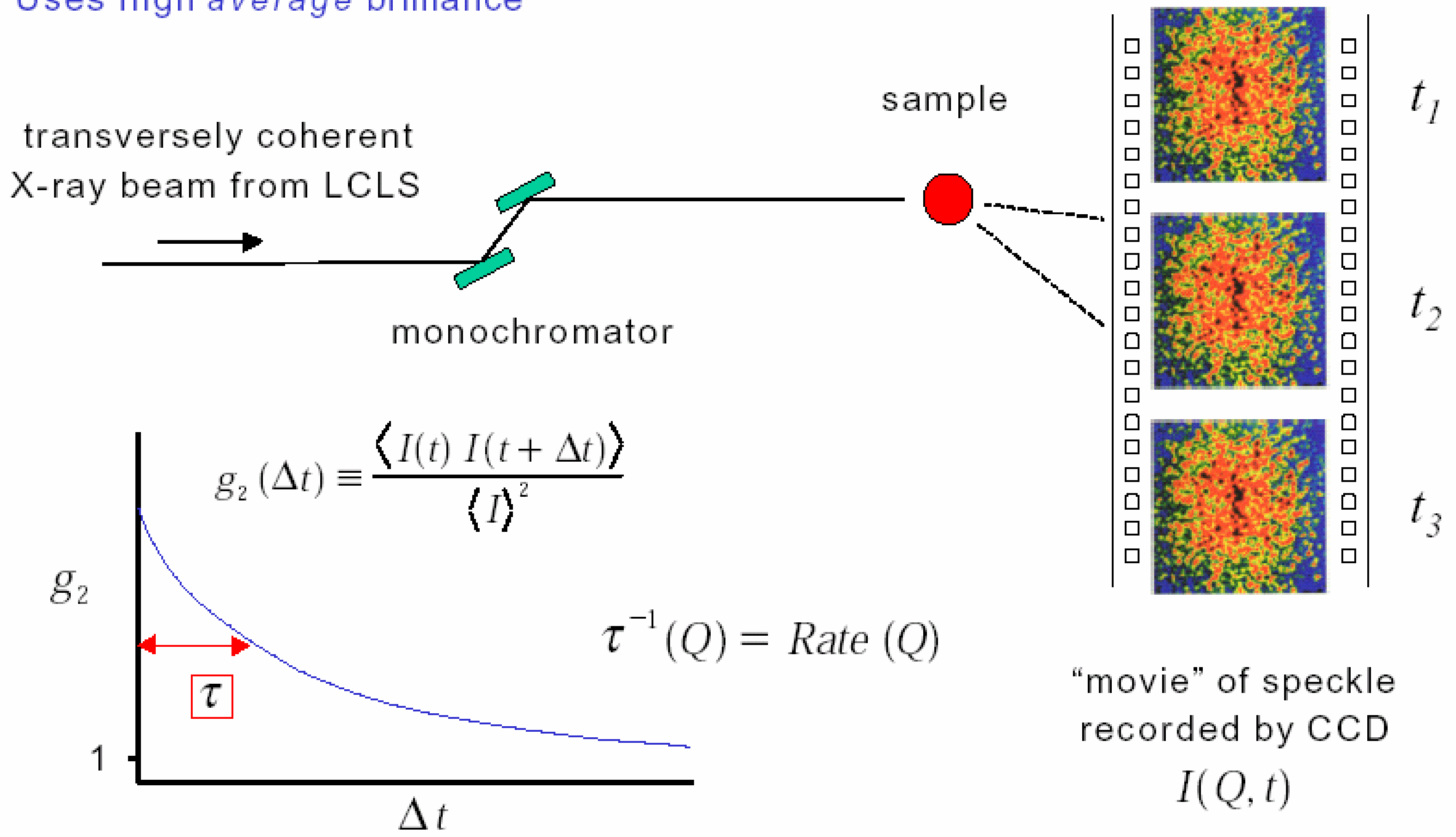
ARPES
pseudogap



Adapted by Millis and Orenstein from:
Loeser et al., *Phys. Rev. B* **56**, 14185 (1997)
Federov et al., *Phys. Rev. Lett.* **82**, 217 (1999)

Coherent Synchrotron Radiation

In **milliseconds - seconds** range:
Uses high *average* brilliance



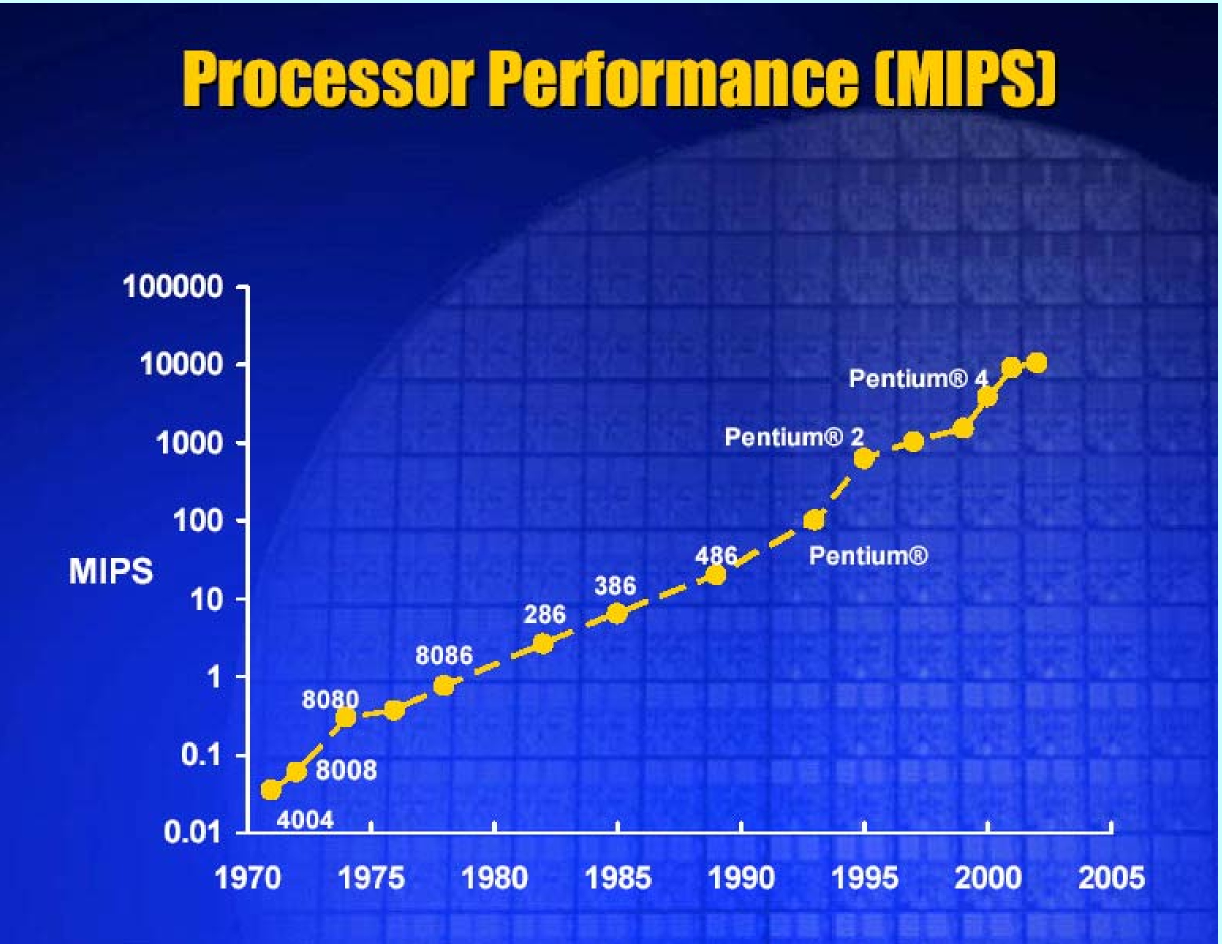
Dynamics: liquids, polymers, bio-molecules, CDWs, glasses, critical phenomena

Spallation Neutron Source

- high intensity
- broad energy range
- pulsed/t-o-f/timing

Numerical Tools

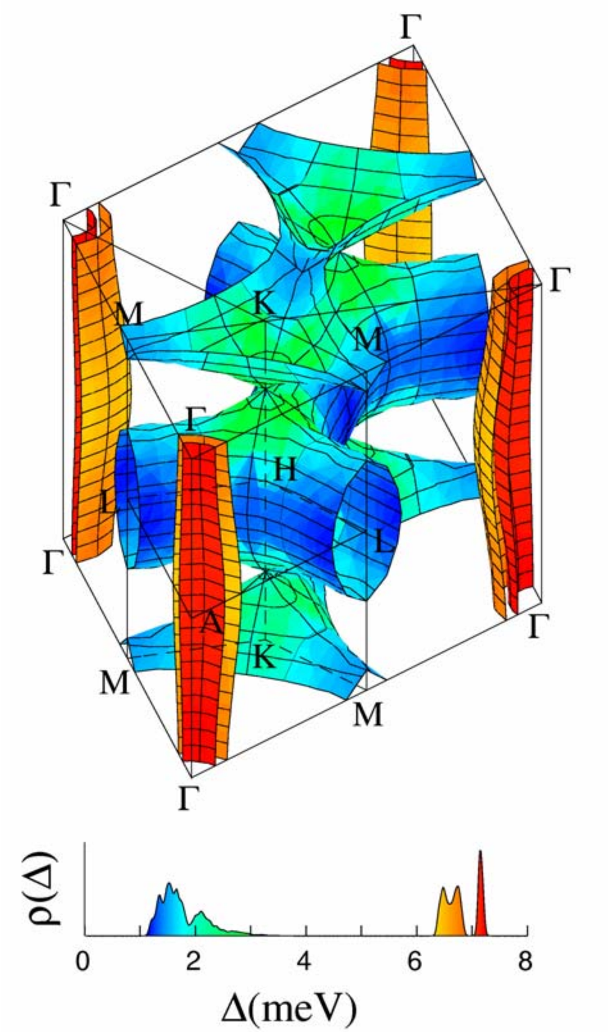
Brute force is not enough…



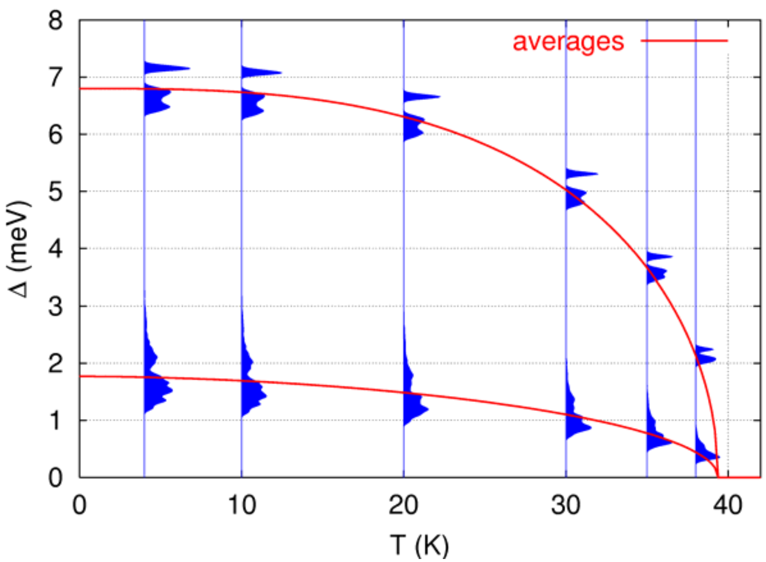
- QMC
  - cluster/loop/worm
  - fermions
- DMRG
  - higher dimensions
- CORE
- LDA (+U)
  - Order N
- DMFT $d = \infty$
  - cluster

Multigap Superconductivity in MgB2

Choi, Roundy, Sun, Cohen & Louie, Nature (2002)



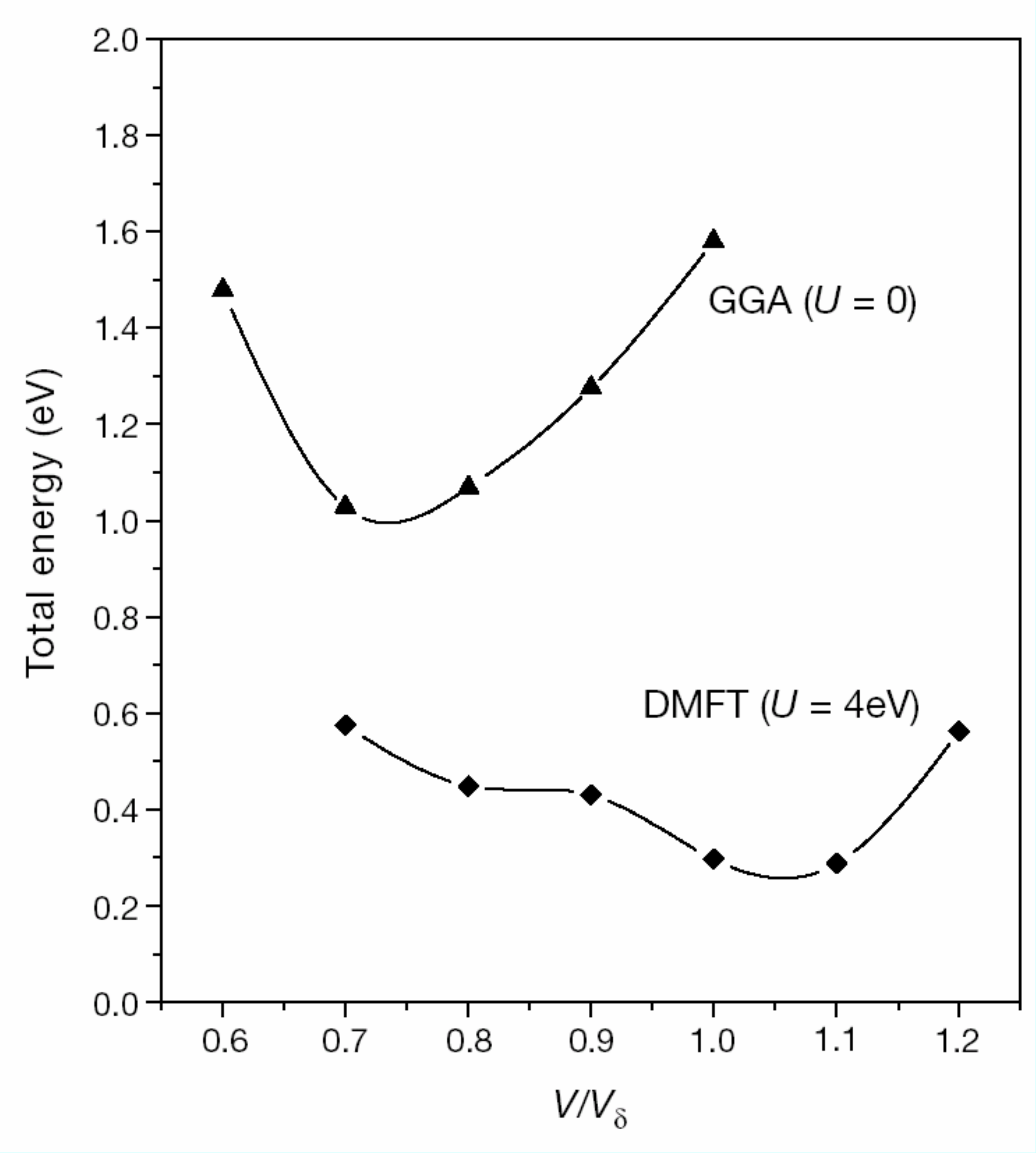
•$\Delta(\mathbf{k})$ on Fermi surface at T=4 K in color scale



- Gap distribution as a function of temperature.
- Expt: $\Delta_1 \sim 2$ meV; $\Delta_2 \sim 7$ meV

Dynamical Mean Field Theory

δ-Plutonium



Realistic band structure
+
local correlations

Volume change 35%

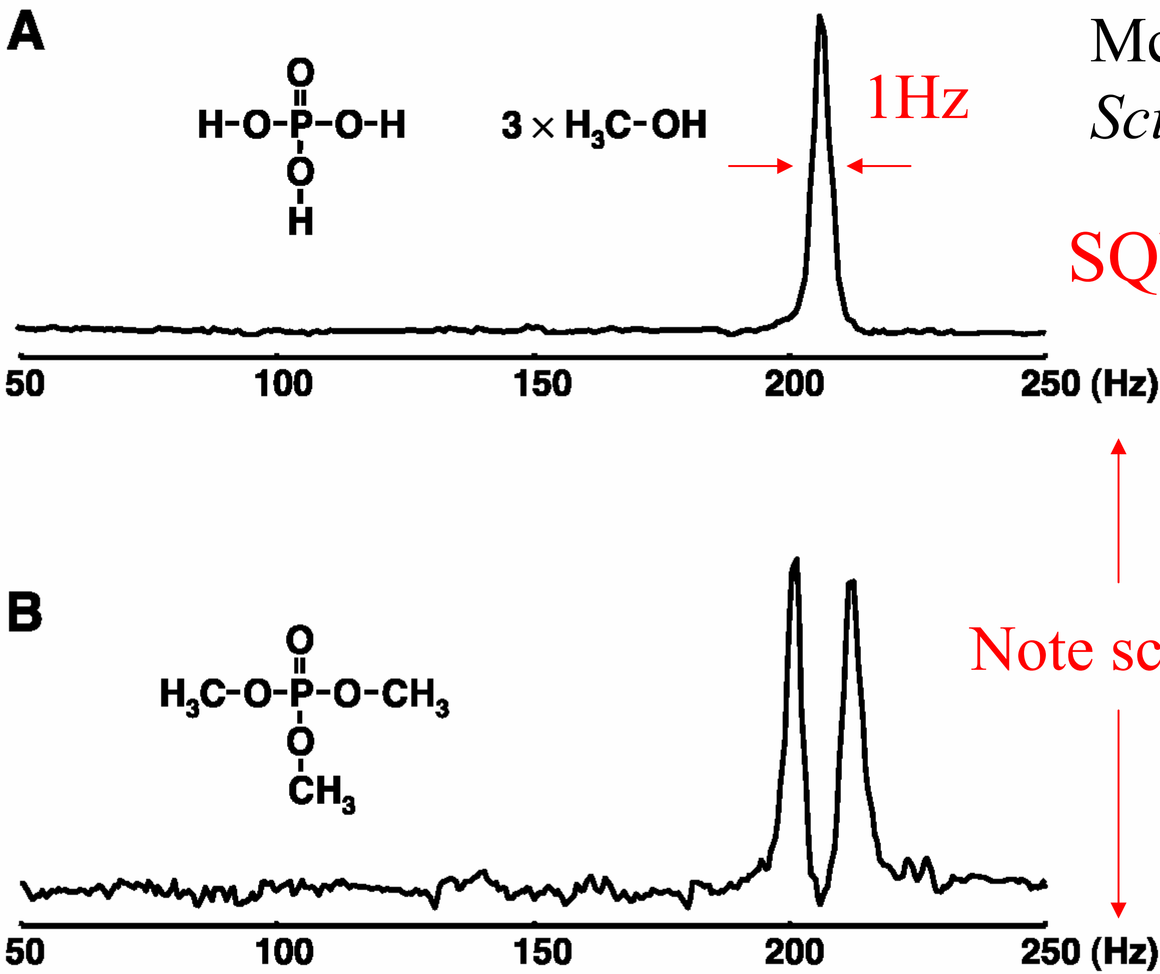
Savrosov, Kotliar and Abrahams
Nature (2001)

Electronic Structure Challenges

- Spectroscopy of real materials
- Many body theory for real materials
- QMC: fermions; real-time vs. Euclidean time
- Prediction, rational materials design
- Multi-scale modeling spanning many decades in length and time

New NMR Tools

‘iron law’ of NMR: signal $\propto B^4$



McDermott et al.
Science **295**, 2247 (2002)

SQUID detects Φ not $\frac{d\Phi}{dt}$

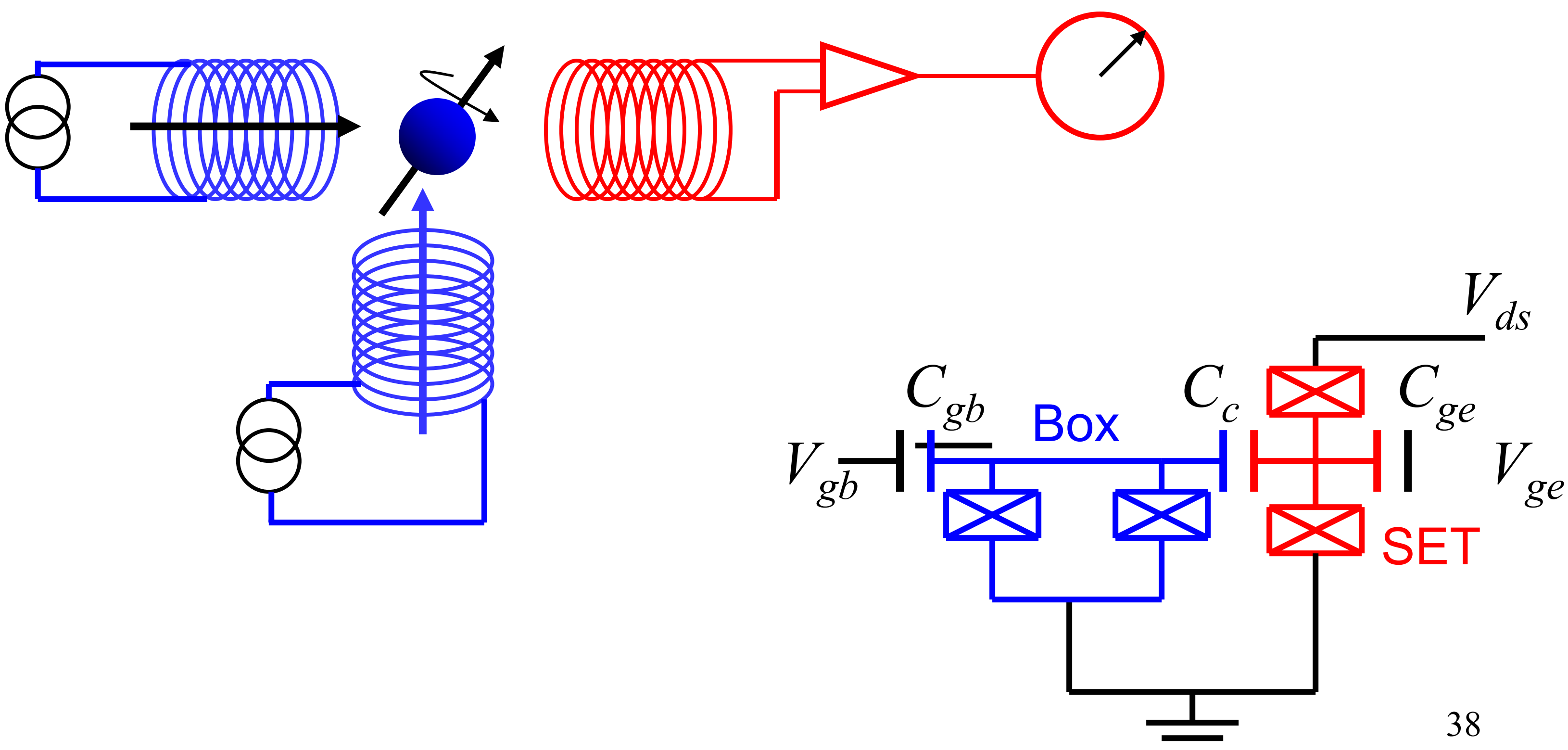
microTesla Fields

Note scale!

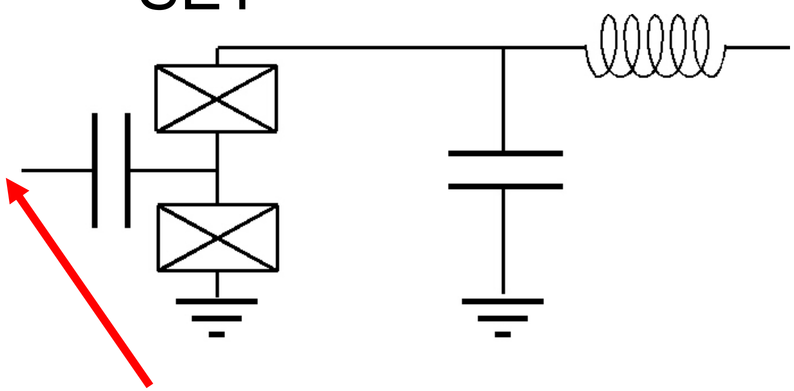
Quantum Computation and NMR of a Single 'Spin'

Single Spin ½

Quantum Measurement



Radio-Frequency Single Electron Transistor (RF-SET)

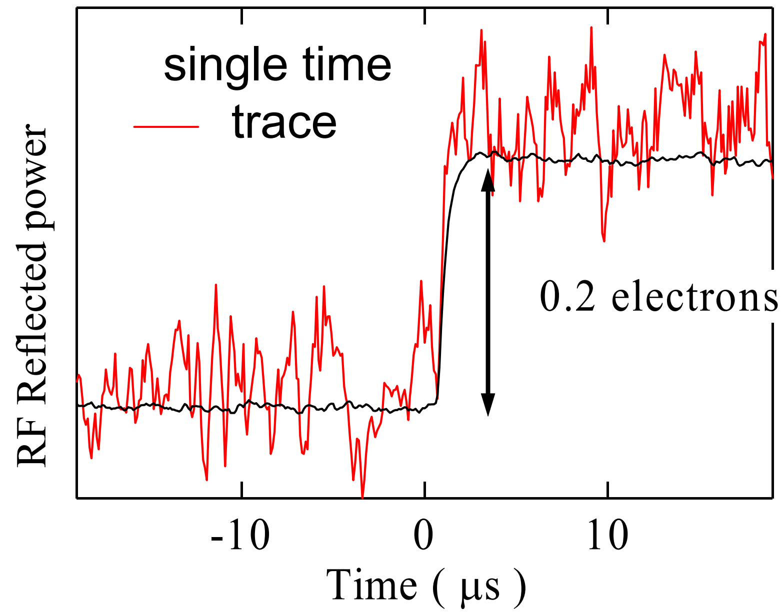


Electrometer
input gate

Measure RF power reflected from LC transformer

Schoelkopf *et al*., (Science 1998)

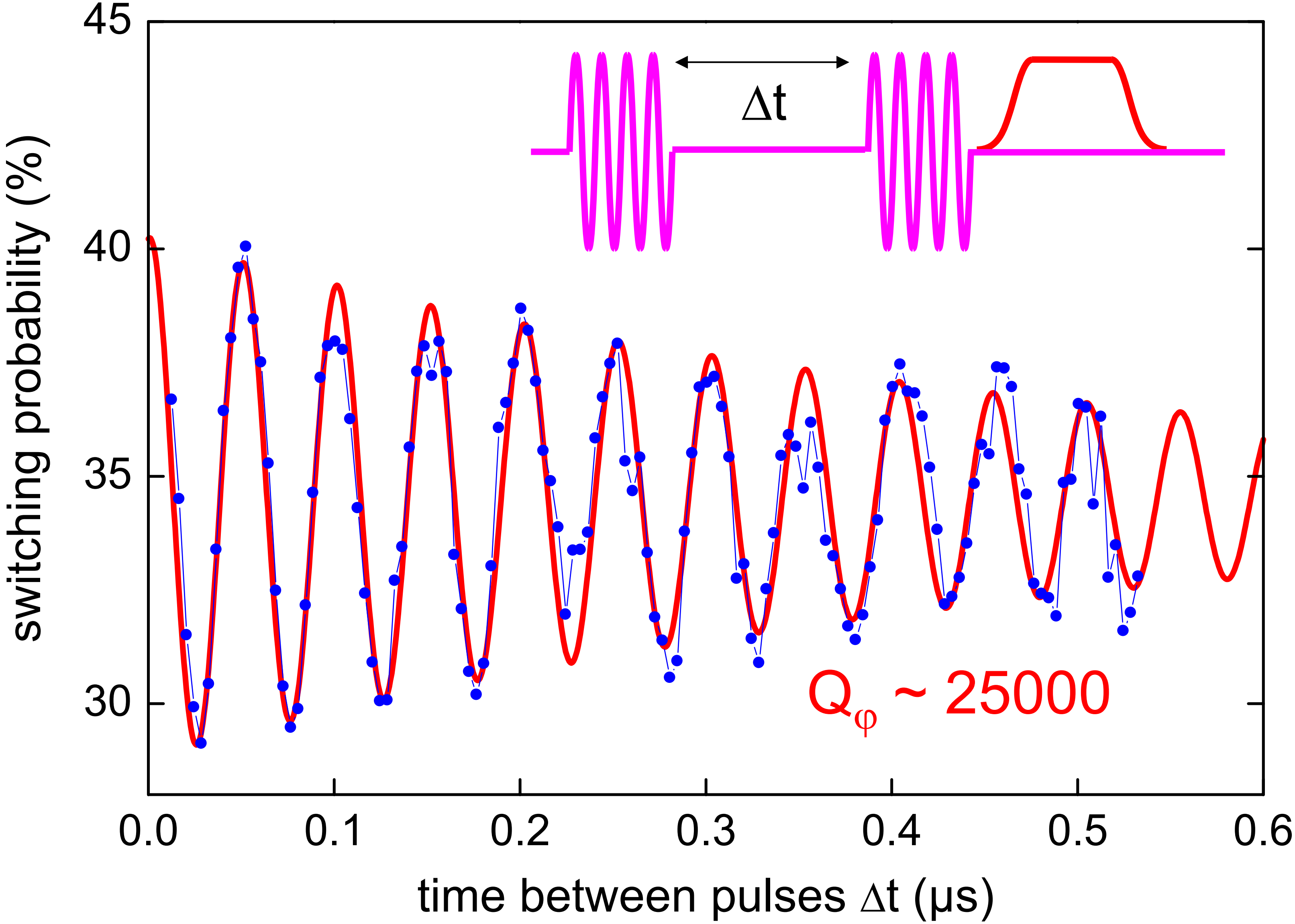
Response to step in V_{ge}



10^{-5} e/Hz$^{1/2}$ charge noise

Sub-electron sensitivity
for > 100 MHz bandwidth

First Observation of RAMSEY FRINGES in a quantum electrical circuit



Courtesy M. Devoret

Vion et al. Science 2002

Future of Quantum Computation

Superconducting Circuits

- Two qubit gates now being established (NEC group Nature 2003)
- crude CNOT gate within 2 years?
- Bell Inequality Test within 5 years?

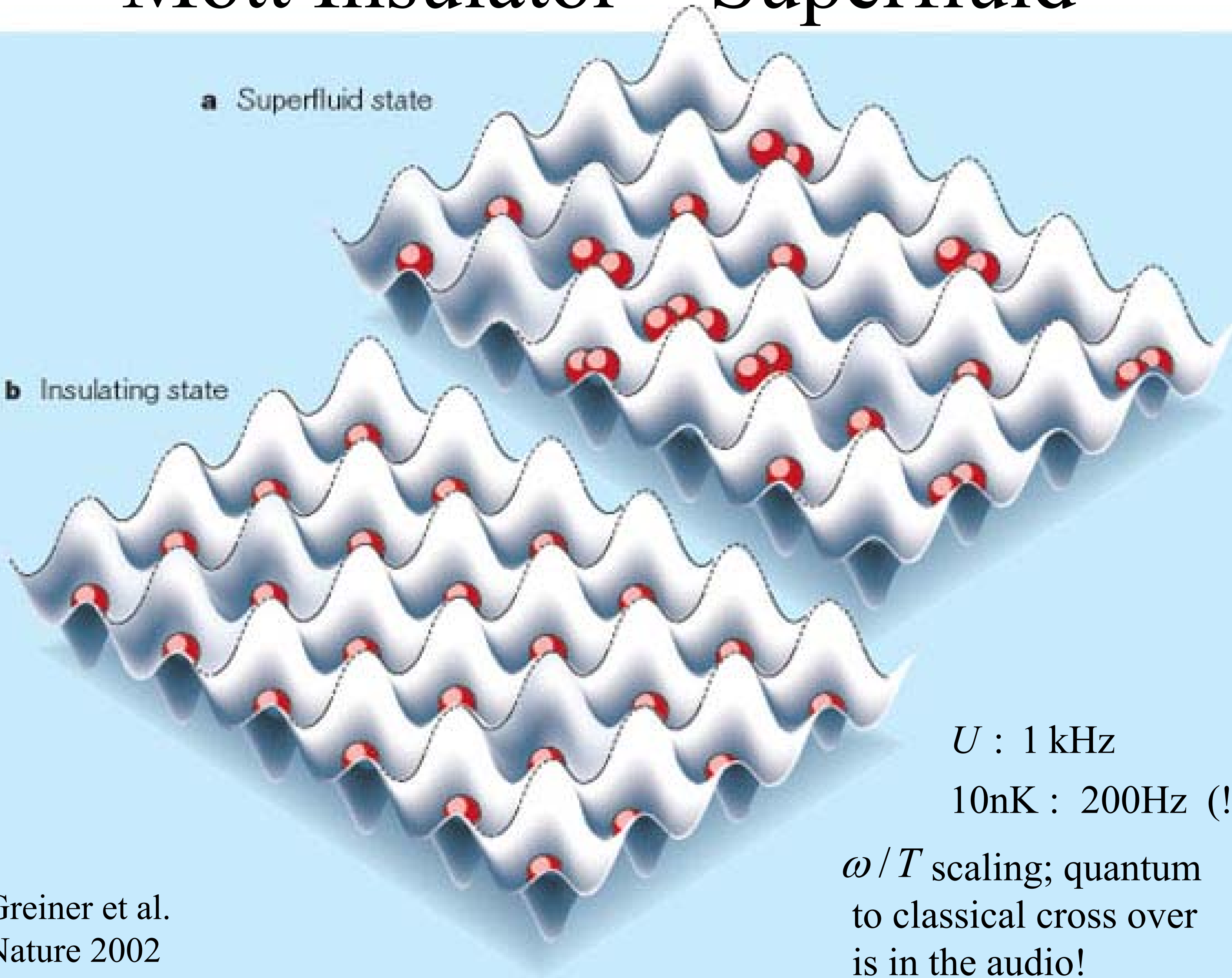
- Quantum Dots
- NMR
- Ion Traps
- Optical Lattices
- Quantum Optics

-quantum encryption will become a practical technology

Convergence of CM and AMO

- optical lattices
- Mott-Hubbard Transition
- Spinor Condensates
- Rotating Condensates = QHE
- Spin waves, vortices, Landau damping
- quantum computation
- many-body effects in condensate clocks
- 1D Luttinger liquids
- quantum chaos in optical ‘billiards’

Mott Insulator – Superfluid



U : 1 kHz

10nK : 200Hz (!)

ω / T scaling; quantum to classical cross over is in the audio!

Greiner et al. Nature 2002

Thanks for slides to:

- C. Kallin
- C. Stafford
- S. Sachdev
- H. Manoharan
- D. Eigler
- S. Nagel
- L. Radzihovsky
- S. Louie
- A. Millis
- M. Devoret
- R. Schoelkopf
- J. Kirtley
- J. Eisenstein
- M. Heiblum

The Future is Bright but will require some **Heavy Lifting**