DQMP Department of Quantum Matter Physics

Ultracold Fermions: an introduction

T. Giamarchi

http://dqmp.unige.ch/giamarchi/

UNIVERSITÉ DE GENÈVE

FNSNF
Fonds national suisse
Schweizerischer Nationalfonds
Fondo nazionale svizzero
Swiss National Science Foundation

MaNEP SWITZERLAND

Cold atoms

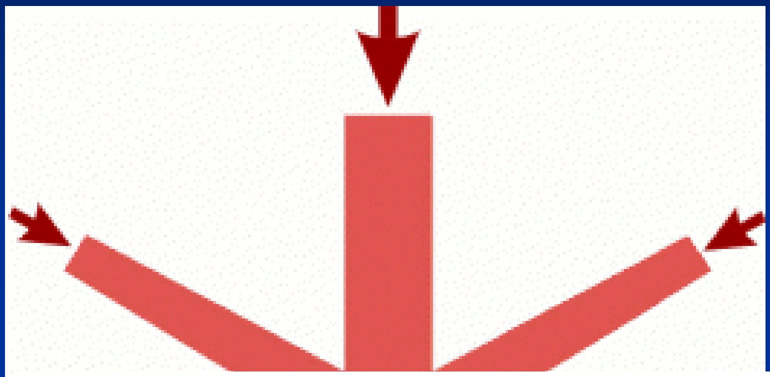
Immanuel Bloch, Jean Dalibard, and Wilhelm Zwerger
Rev. Mod. Phys. **80**, 885 (2008)

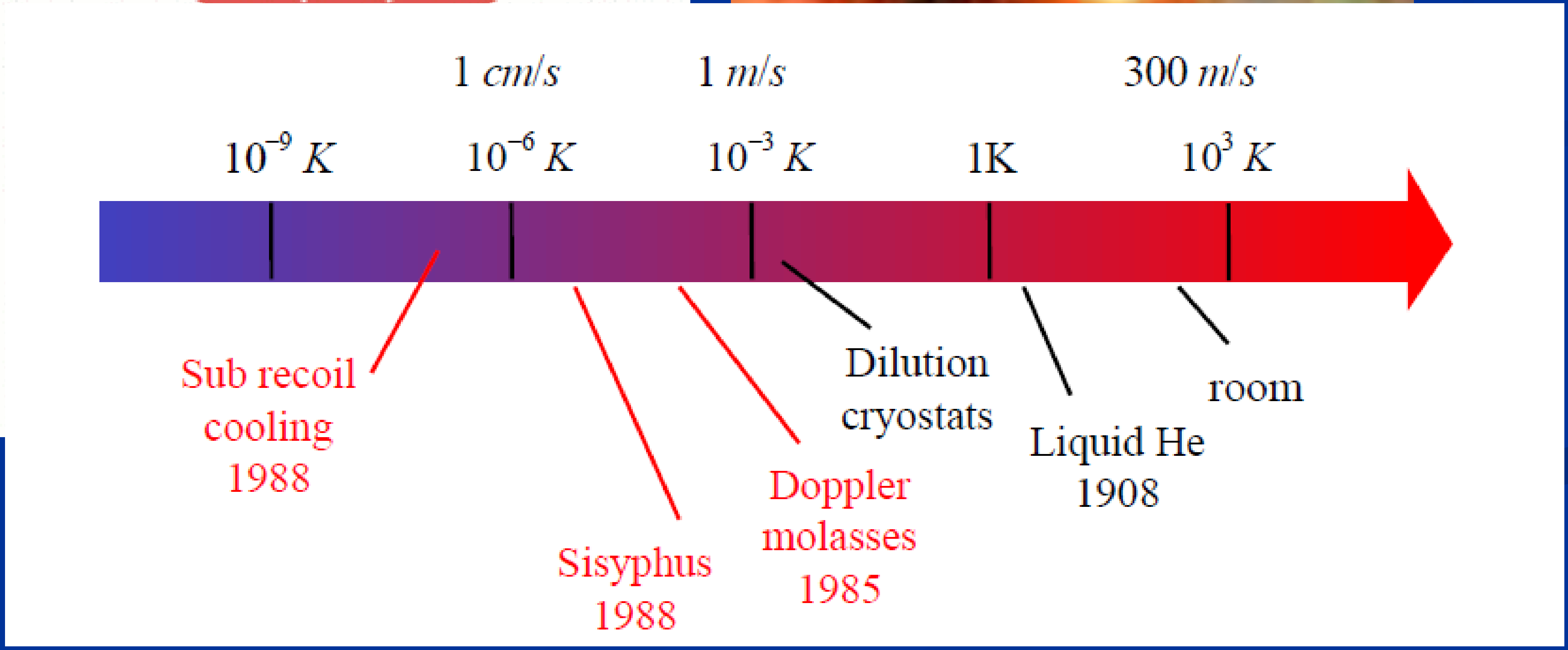
T. Esslinger:
Condensed Matter Physics 1 (2010).

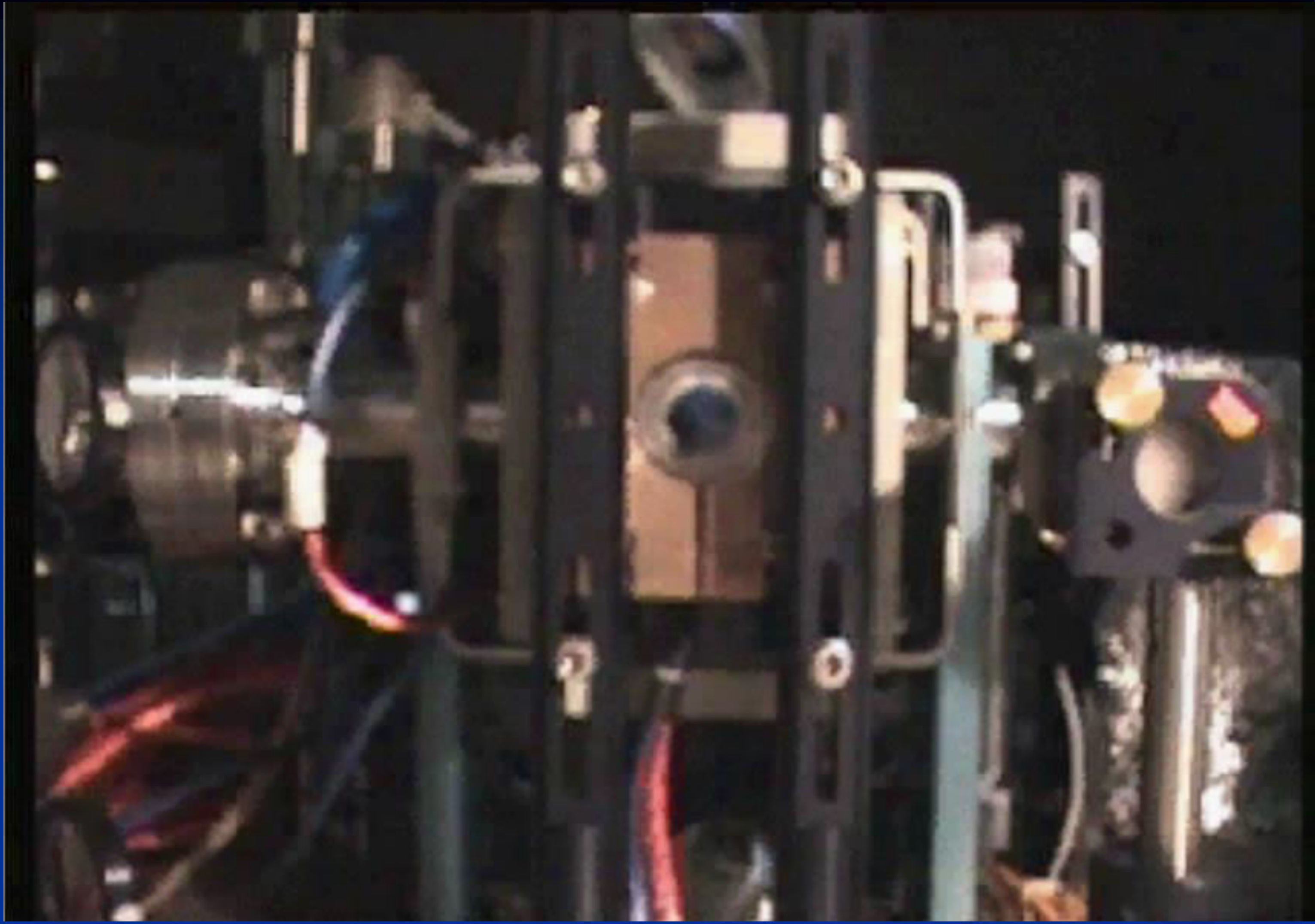
A. Georges, TG
Les houches lecture, arXiv:1308.2684

TG
Proceedings of the International School of Physics
"Enrico Fermi“ Volume 191 (2016)

Atom trapping and cooling

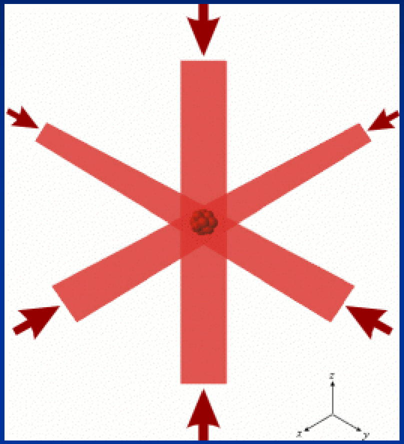






Groupe: I. Bloch (Munich U.)

Cooling and trapping



T_universe = 2.725 K

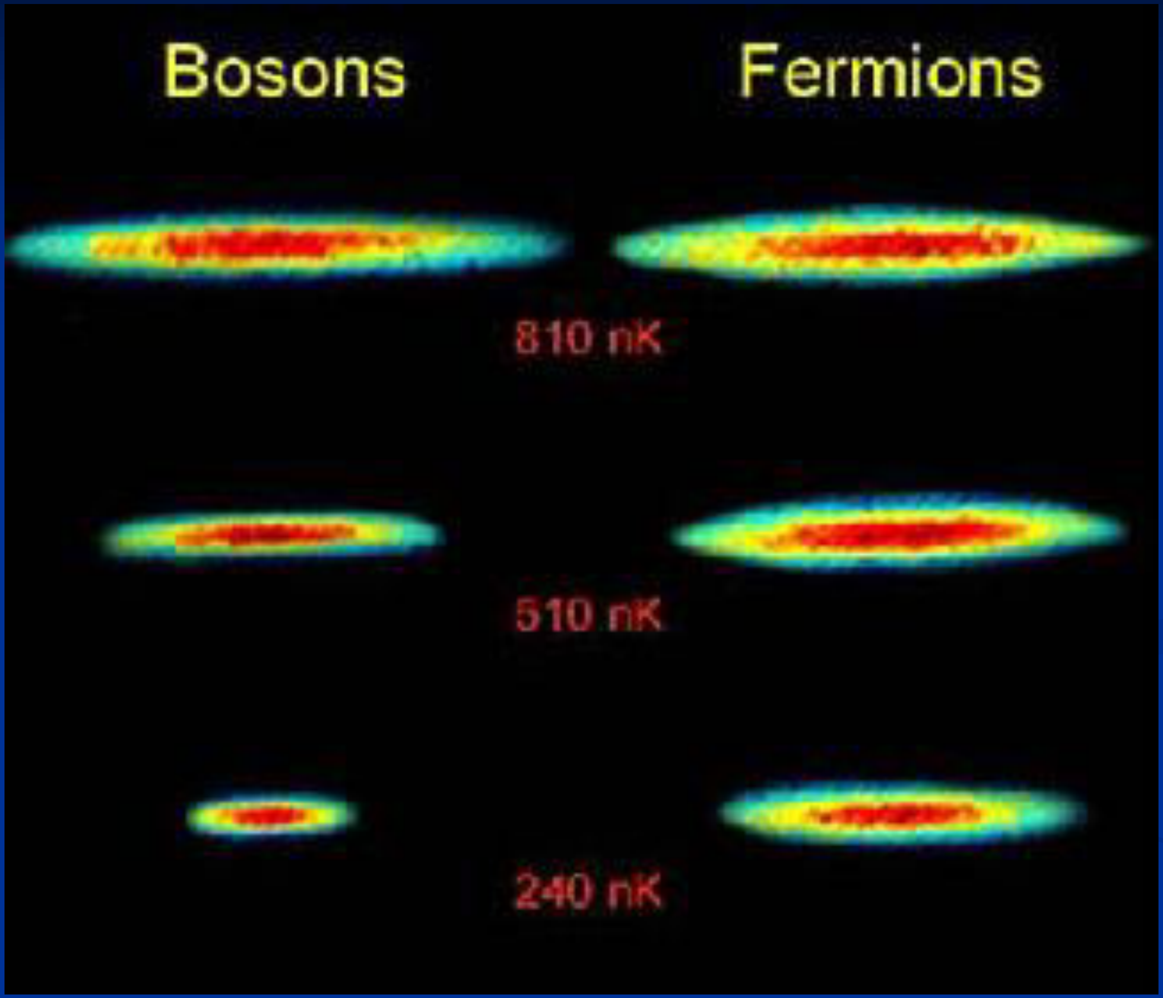
T_at = 0. 000 001 K

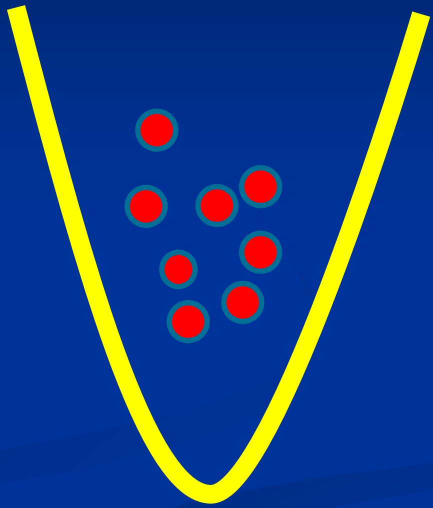
1997

Atomic clocks: 10 seconds error…..

.. since the beggining of the universe !

R. Hulet, Rice university

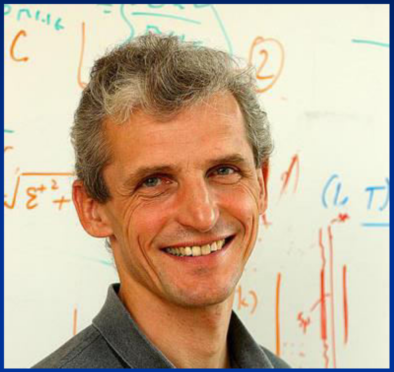




7Li

6Li

Even colder !



$T_{at} = 0.\ 000\ 000\ 001$ K

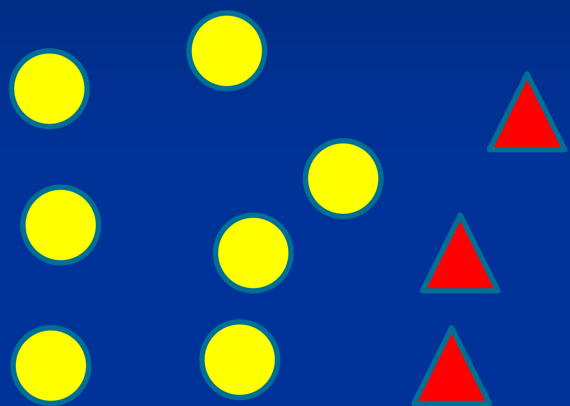
2001: Cornell, Ketterle, Wieman

Group: T. Esslinger (ETH, Zurich)

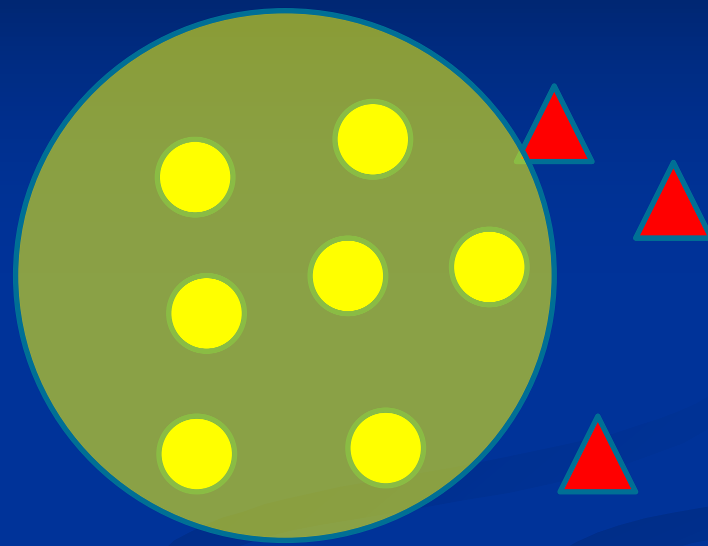
Bose-Einstein condensation

J. Bobroff et al, www.toutestquantique.fr

Special properties



Normal fluid:
“friction” on
impurities



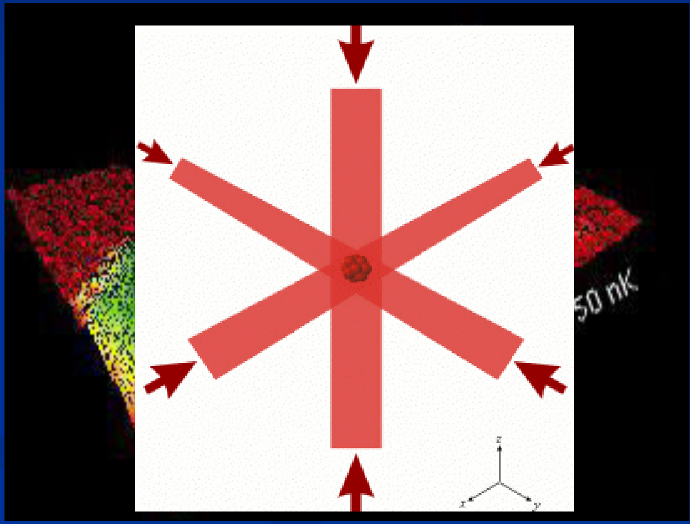
Flow without
“friction”:
Superfluidity

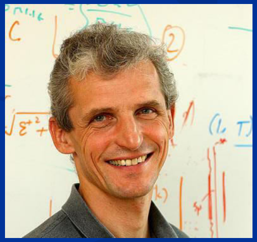
New states of matter

Rb 1995

4He

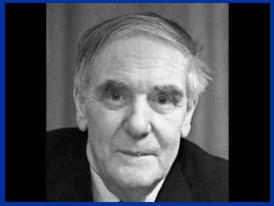
T=2.17K ~-271 C





Cornell Ketterle Weiman

2001



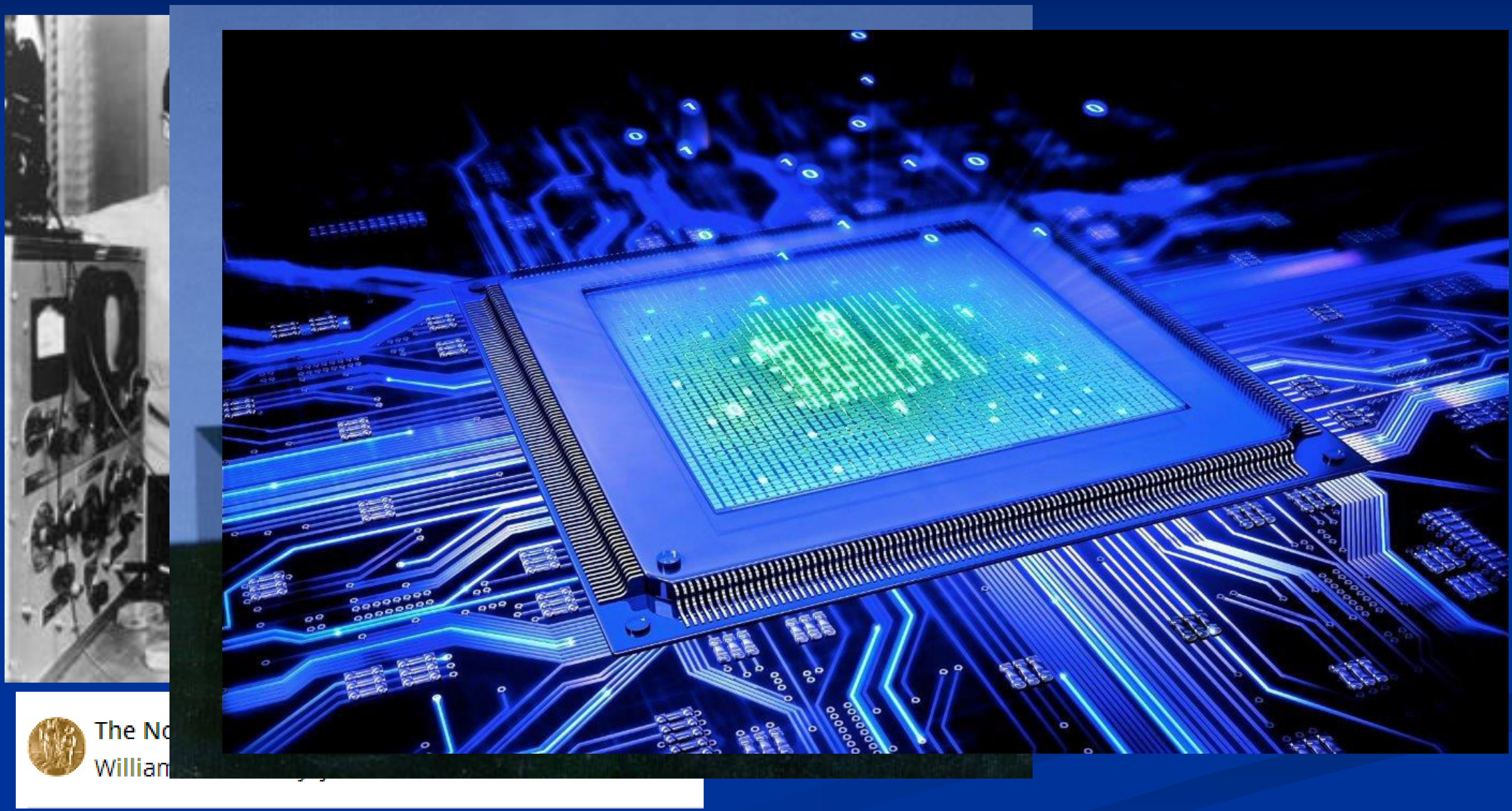
1938

Kapitsa Allen Misener

So what ?

Let us talk about materials (condensed matter physics)

20st century: age of silicon



Complete change of our society

1947 ENIAC

Electronic Numerical Integrator

And Computer

20th century on the ENIAC*:

„Where a calculator on the ENIAC is equipped with 18000 vacuum tubes and weighs 30 tons, computers in the future may have only 1000 tubes and weigh only 1 ½ tons.“

Popular Mechanics, March 1949

POPULAR MECHANICS MAGAZINE

How to master materials ?

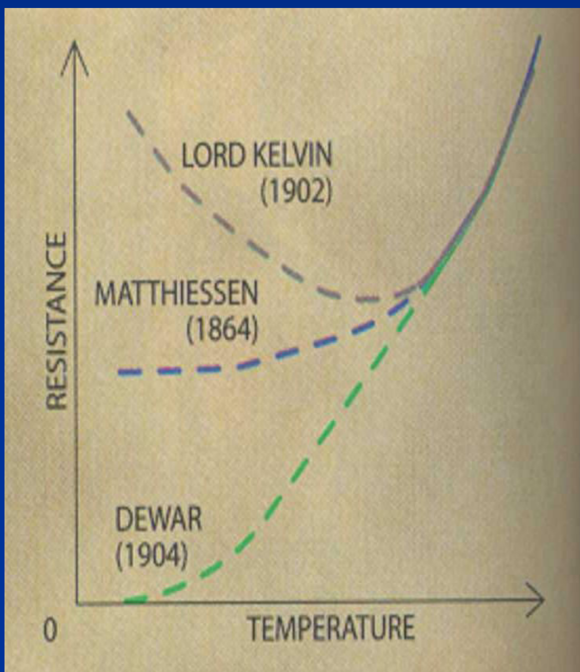
- Understood: free electrons
- Real systems : Coulomb interaction

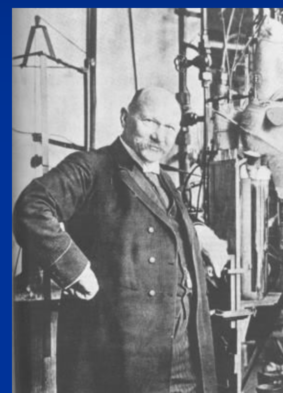
E » 10 000 K !

- Properties of realistic systems ?
- Free electron theory works quite well : Landau Fermi liquid

$$m \rightarrow m^{*}$$

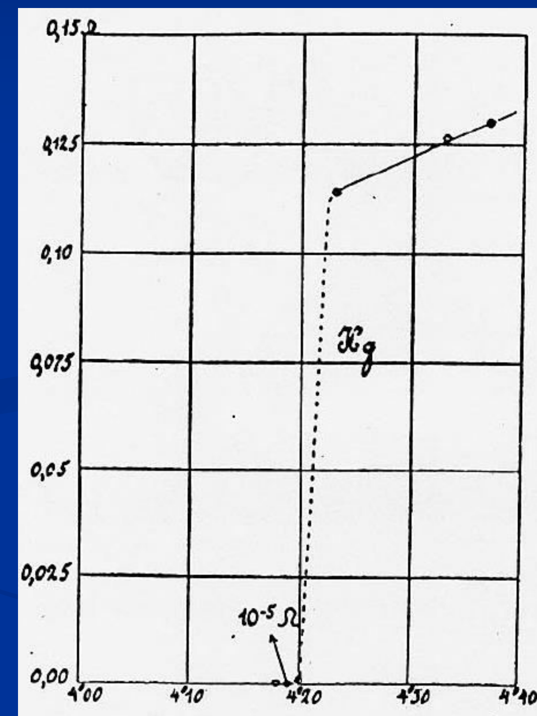
Superconductivity



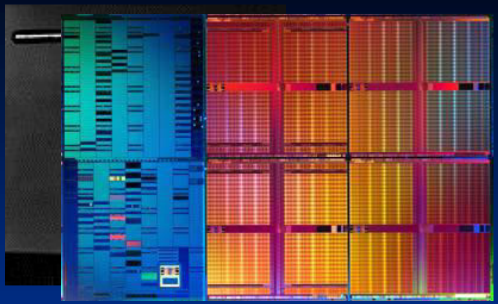


Onnes Holst

1911



- Transistor



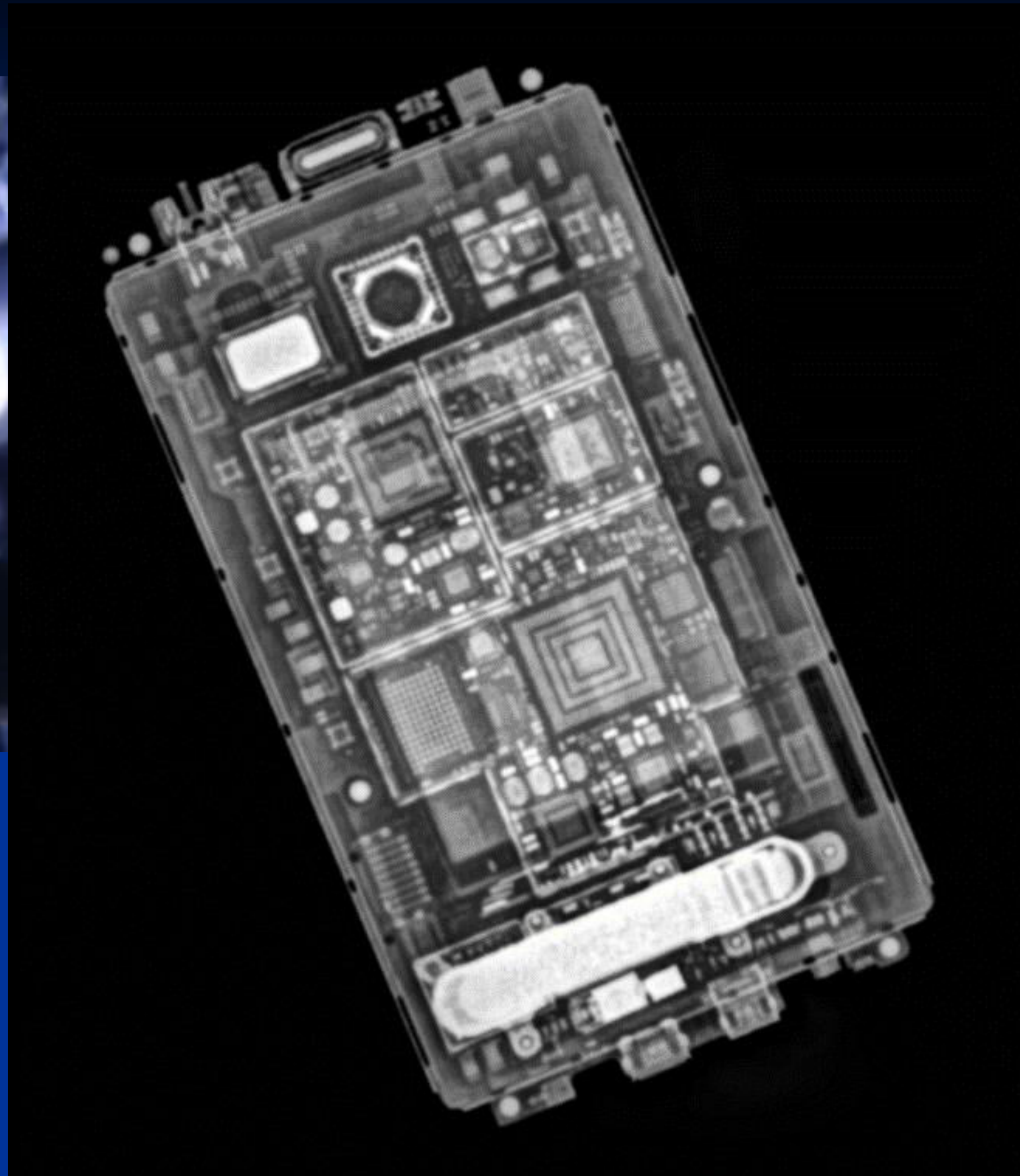
1956

- Superconductivity

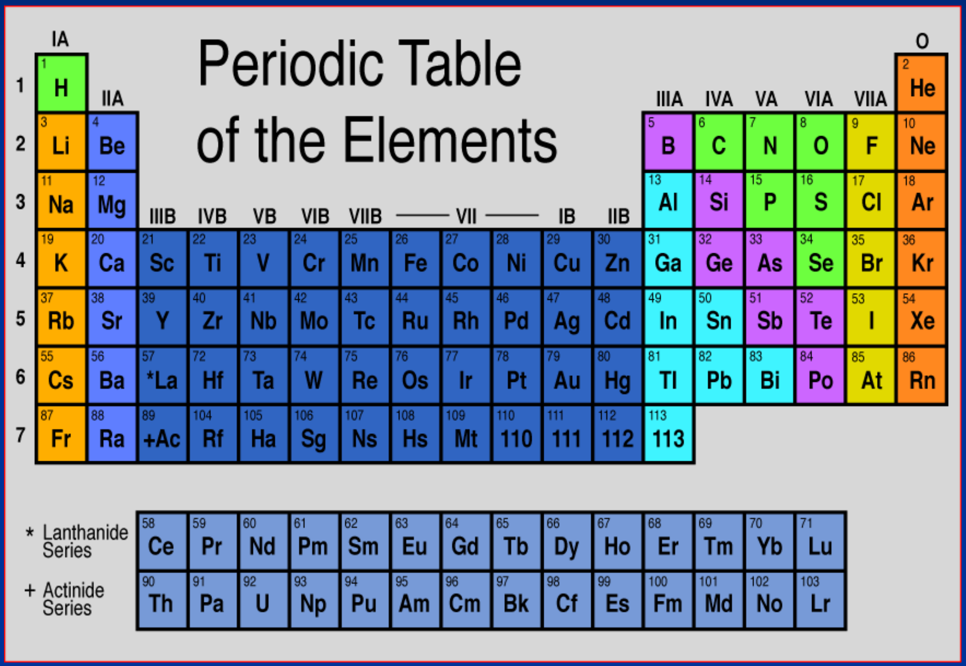
(1913),1972,
1973,1987,2003

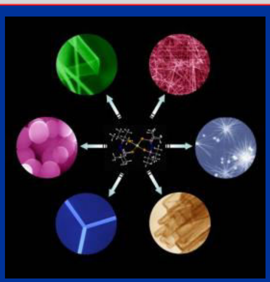
- Giant magnetoresistance

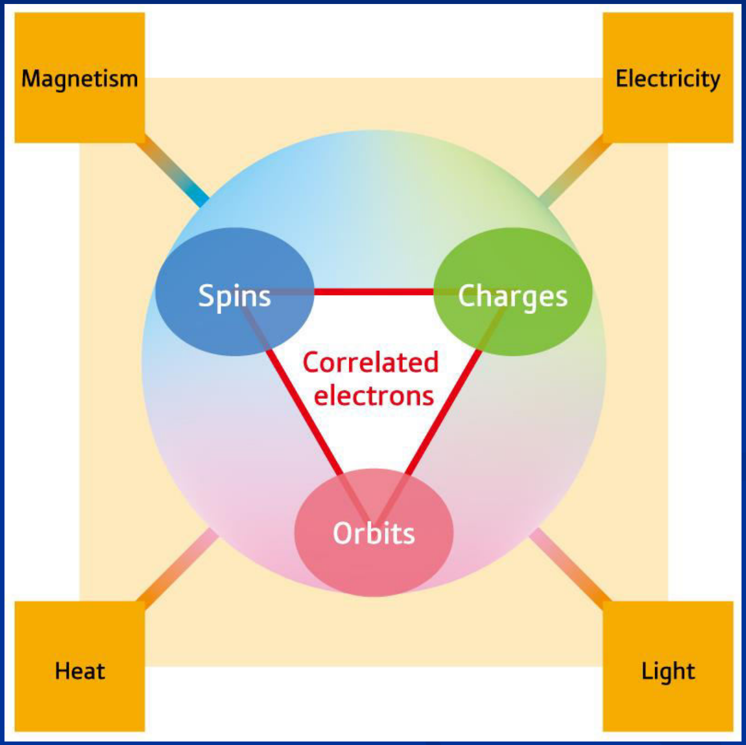
2007


Materials of the future







(Y. Tokura, Japan)

Fundamental ???

- Everything is described by the Dirac / Schrödinger equation

``The general theory of quantum mechanics is now almost complete (…). The underlying physical laws necessary for the mathematical theory of a large part of physics and the whole of chemistry are thus completely known, and the difficulty is only that the exact application of these laws leads to equations much too complicated to be soluble."

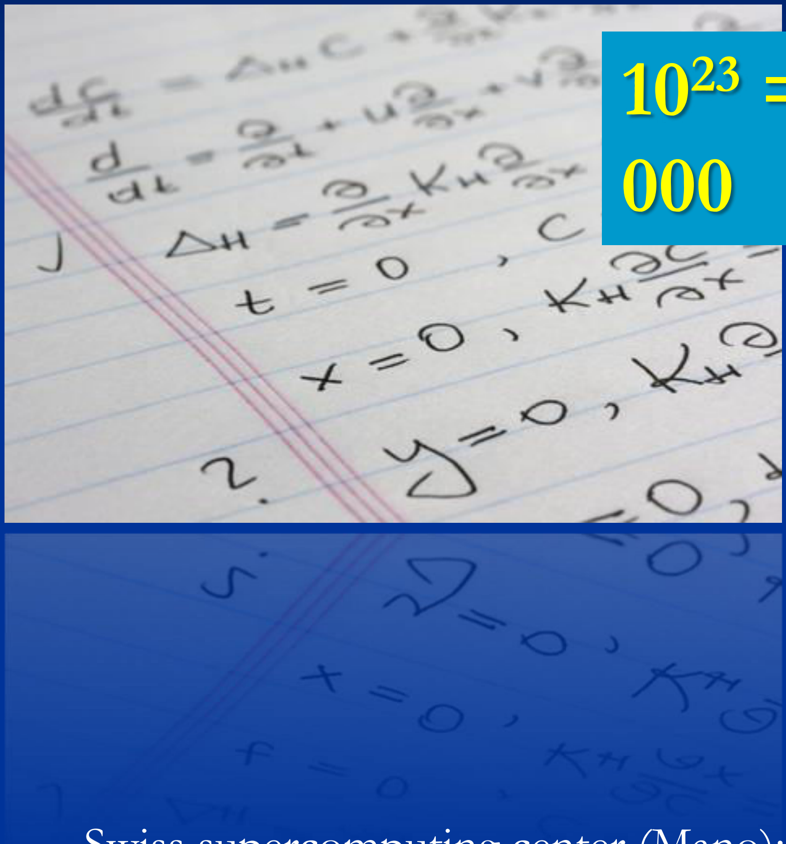
P. A. M. Dirac, "Quantum Mechanics of Many-Electron Systems“, Proceedings of the Royal Society of London, Series A, Vol.123, April 1929, pp 714.

Quantum mechanics / Complexity

- More atoms in a 1 mm^3 system than stars in the universe
- Quantum degenerate (Pauli or Bose statistics) : $T_F \sim 12000$ K
- Quantum mechanics you can touch !

(D. Eigler et al.)

Need to understand interactions

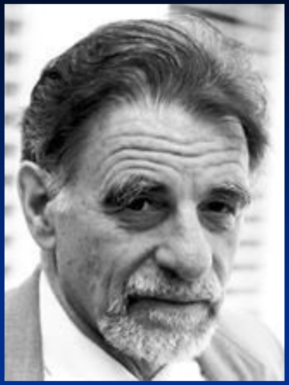


10^{23} = 100 000 000 000 000 000 000 000

Swiss supercomputing center (Mano); machines with 7 10^15 operations per second

Quantum nature of the problem :
numerical instabilities with classical computers

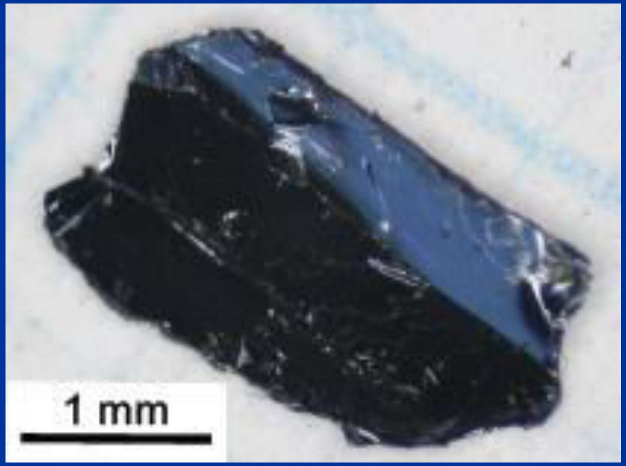
How to study ?

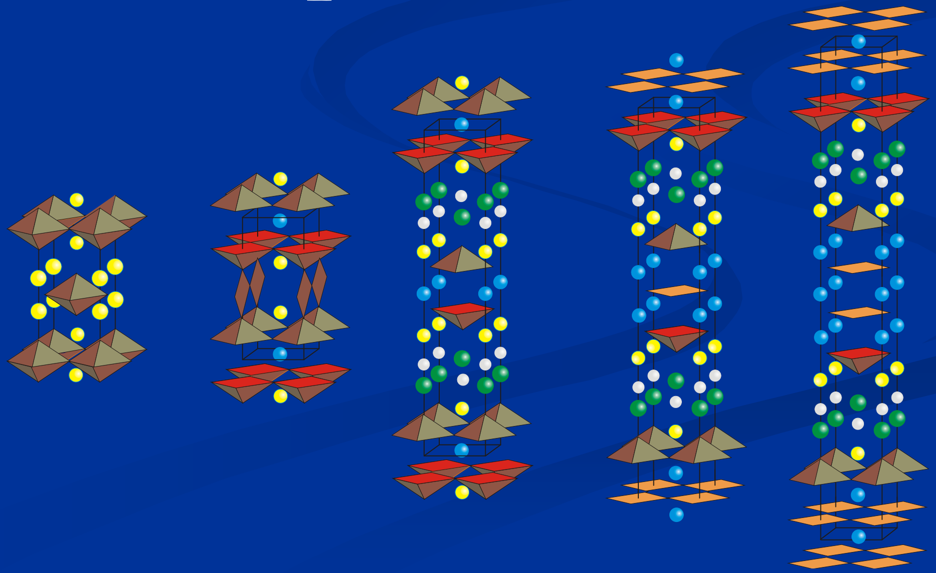


Very difficult !!

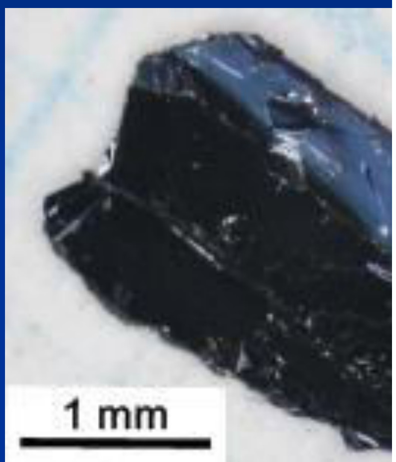
Bednorz Muller

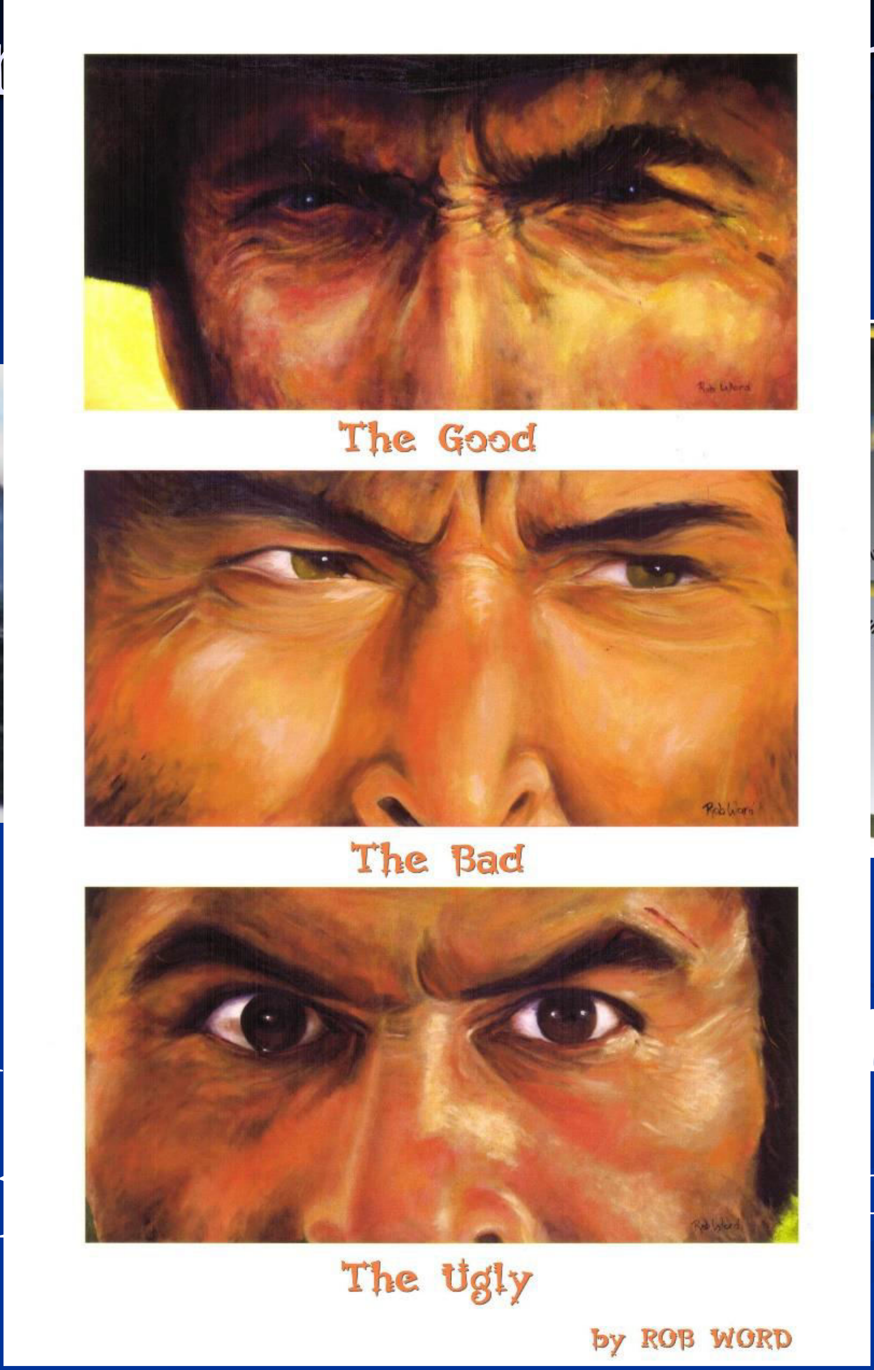
Example of High Tc superconductors (86)

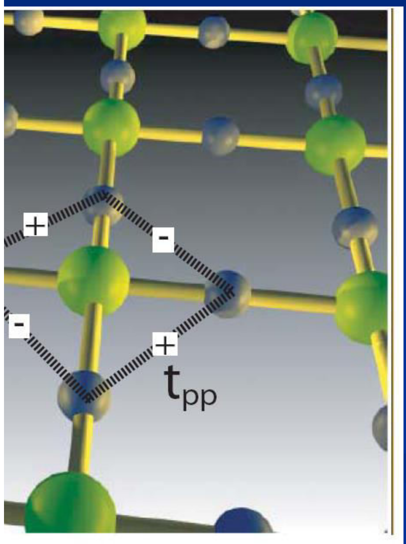




CM: Fr mplified



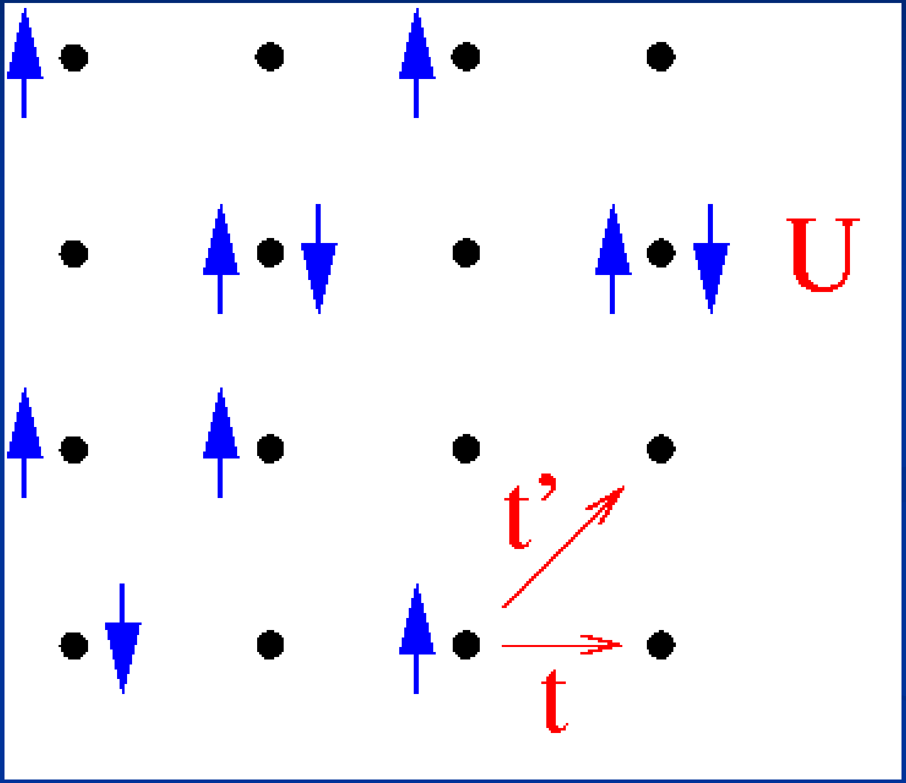




Usually stil lve !

Results: ap odel or reality ?

Hubbard model (1963)



$$H = -t \sum_{<i,j>,\sigma} (c^{\dagger}_{i,\sigma} c_{j,\sigma} + h.c.) + U \sum_{i=1}^{N} n_{i\uparrow} n_{i\downarrow}$$

Methods

- Very difficult analytically
- Novel techniques: many body, field theory, topology concepts, ……. ?????
- Very difficult numerically: fermions, error growing exponentially with the system size
- Novel (approximate or exact) numerical techniques (Monte-carlo, DMRG, DMFT, ….. ????)

How to solve then ?

Quantum simulators

And I'm not happy with the analyses that go with just the classical theory, because Nature isn't classical, dammit, and if you want to make a simulation of Nature, you'd better do it quantum mechanical, and by golly it's a wonderful problem because it does not look so easy.

Richard P. Feynman, "Simulating Physics with Computers"
Int. J. of Theor. Phys. (1981)

Quantum simulators

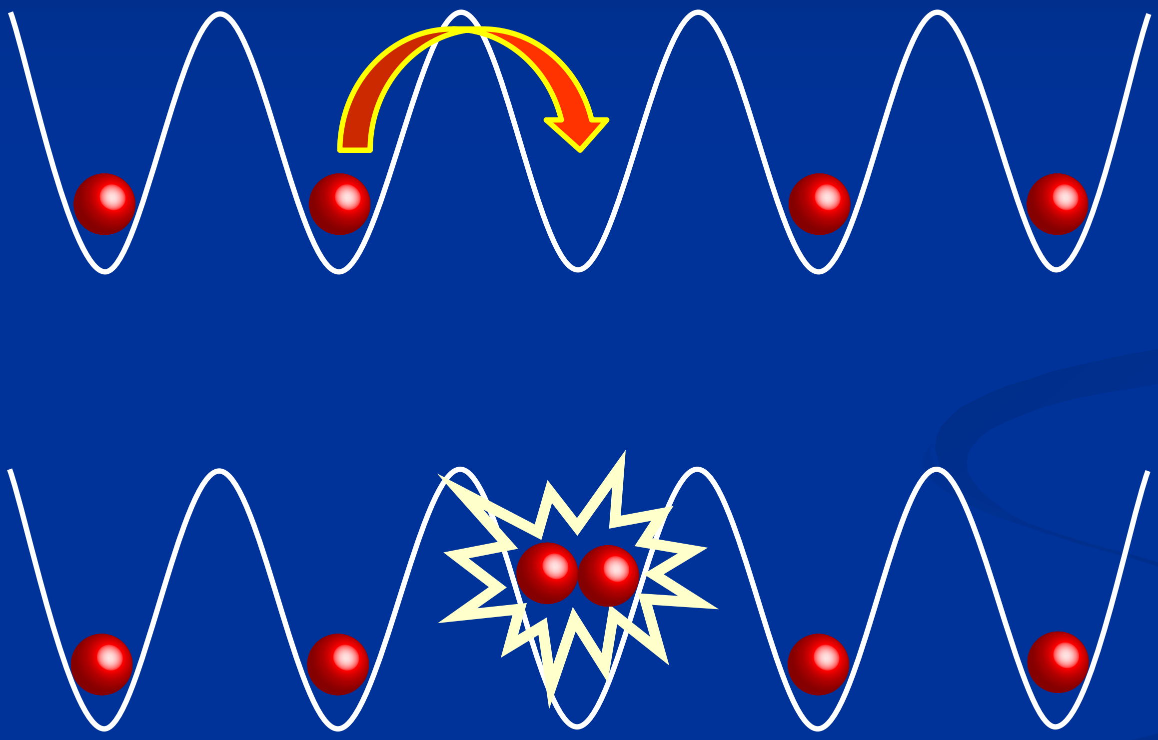
Experimental system that implements as closely as possible one of the canonical models

Read the answer on the experiment (no approximation)

Benchmark some of the theoretical methods

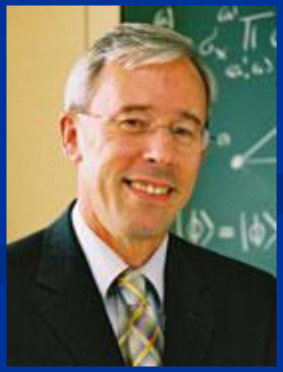
Cold atoms and condensed matter: a love story

Virtual solids



Tunnelling

Short range interaction

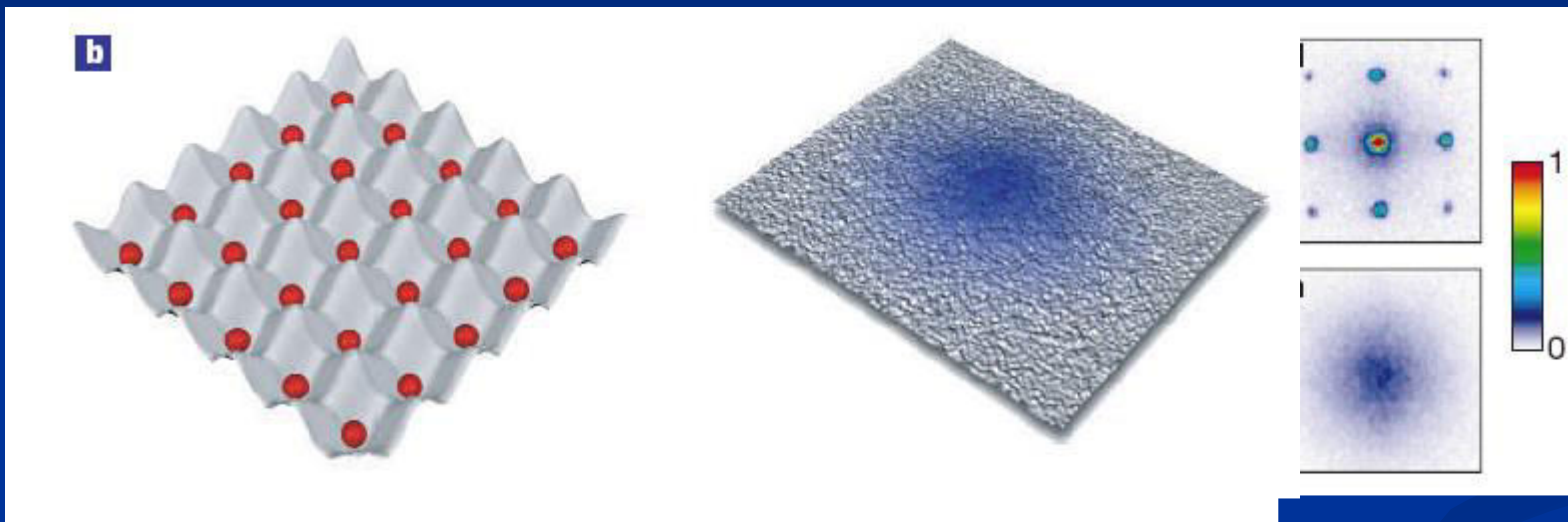


P. Zoller

Proposal: D. Jaksch et al PRL81 3108 (98)

Dream

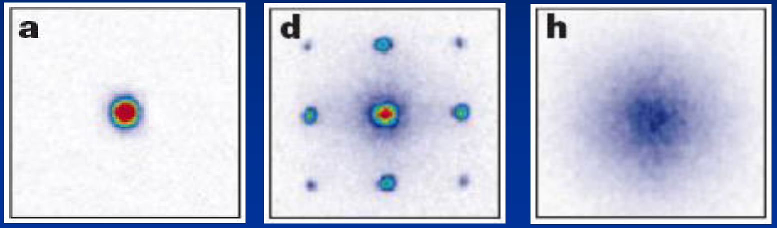
Bosons: from insulator to superfluid



M. Greiner, O. Mandel, T. Esslinger, T. W. Hansch, I. Bloch, Nature 415 39 (2002)

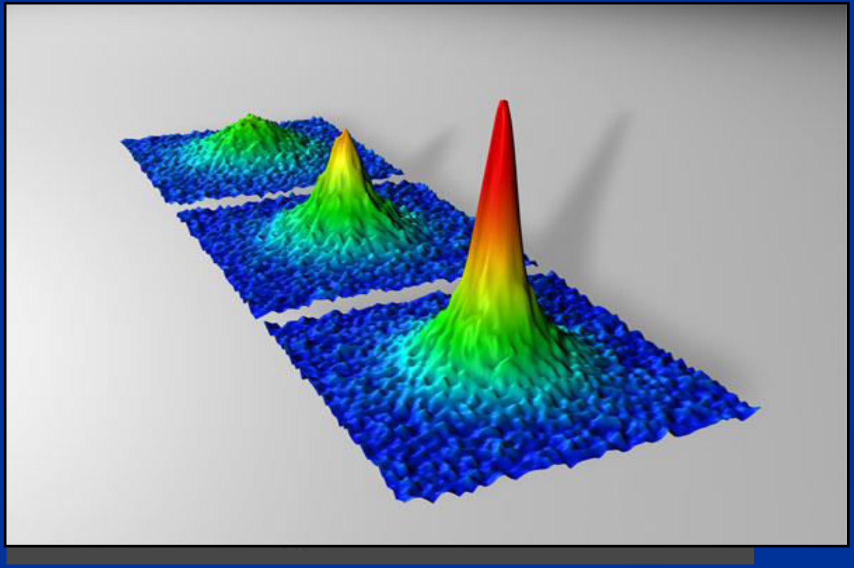
Perfect control on the model

Interactions
(Lattice, Feschbach resonnance)

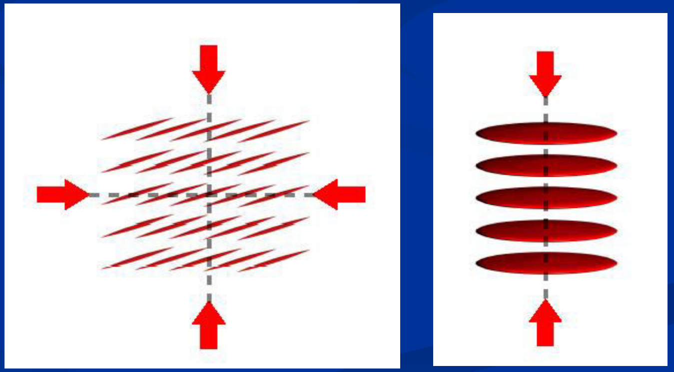


Statistics

Bosons Fermions



Dimensionality



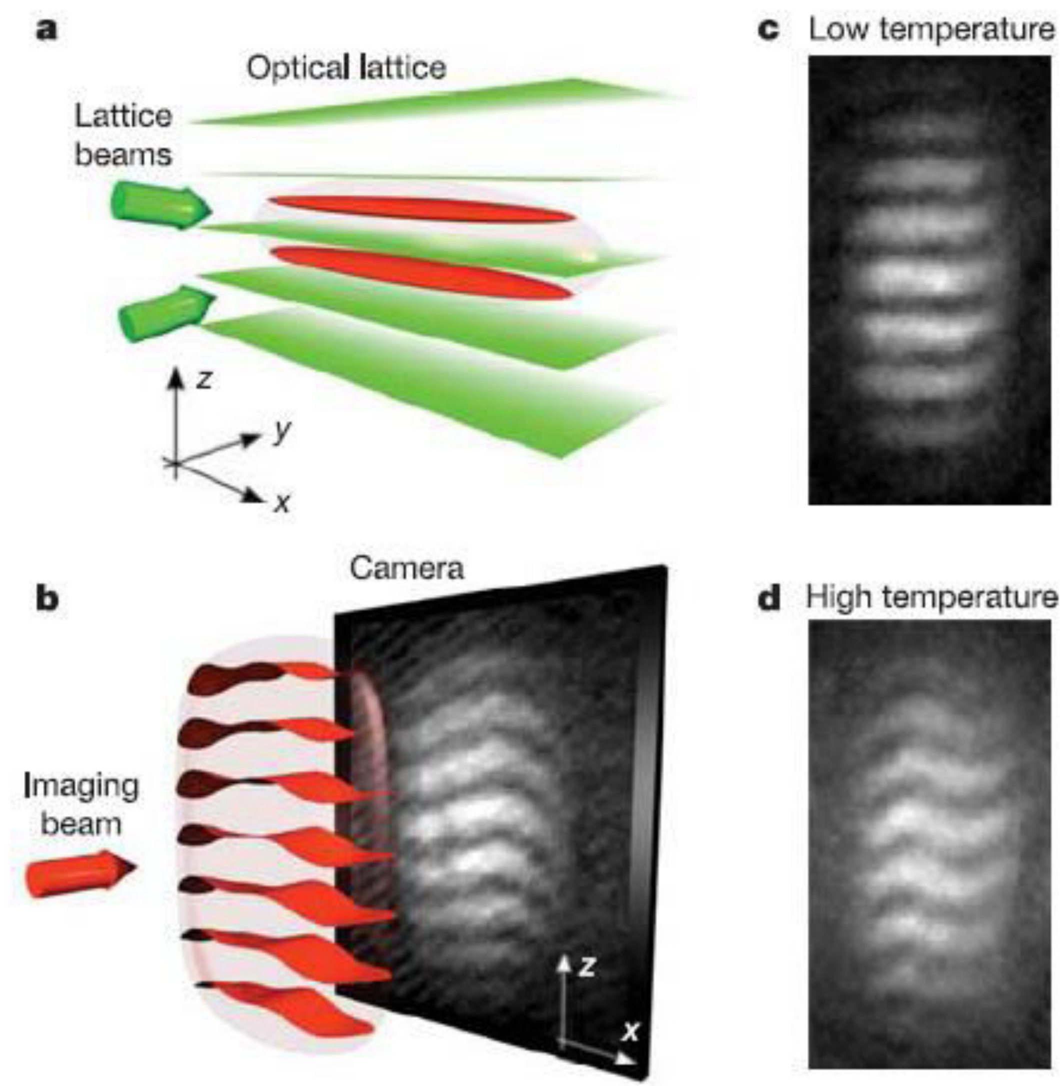
Two dimensional superfluids

nature

LETTERS

Berezinskii-Kosterli
trapped atomic gas

Zoran Hadzibabic[1], Peter Krüger[1], Marc Cl



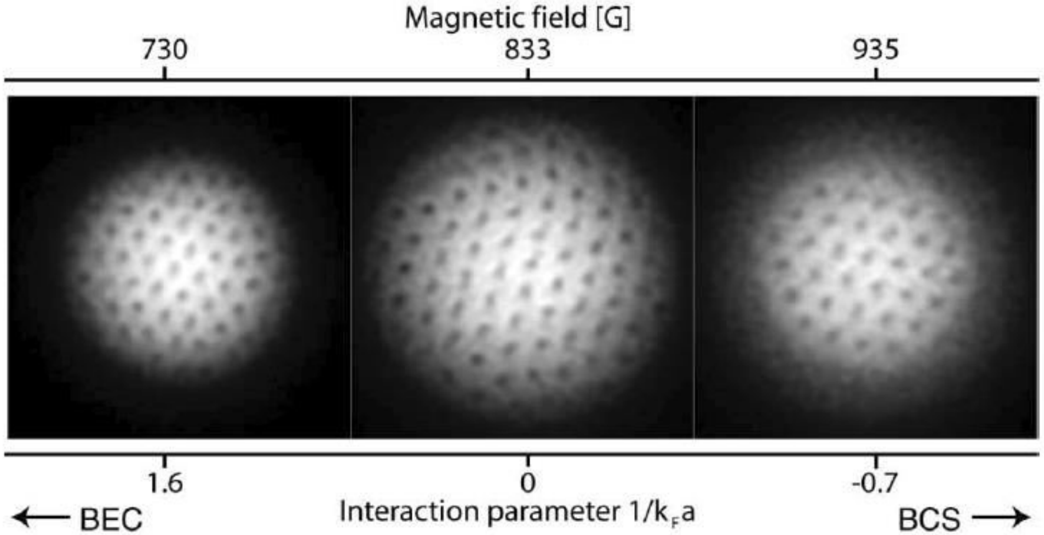


Fig. 59. – Observation of vortices in a strongly interacting Fermi gas, below, at and above the Feshbach resonance. This establishes superfluidity and phase coherence in fermionic gases. After a vortex lattice was created at 812 G, the field was ramped in 100 ms to 792G (BEC-side), 833G (resonance) and 853G (BCS-side), where the cloud was held for 50 ms. After 2ms of ballistic expansion, the magnetic field was ramped to 735G for imaging (see text for details). The field of view of each image is 880 μm x 880 μm. More recent version of Fig. 3 in [68].

Making, probing and understanding ultracold Fermi gases

Wolfgang Ketterle and Martin W. Zwierlein

Department of Physics, MIT-Harvard Center for Ultracold Atoms, and Research Laboratory of Electronics,
Massachusetts Institute of Technology, Cambridge, Massachusetts, 02139, USA

arXiv:0801.2500v1

Hubbard model

nature Vol 455|11 September 2008|doi:10.1038/nature07244

LETTERS

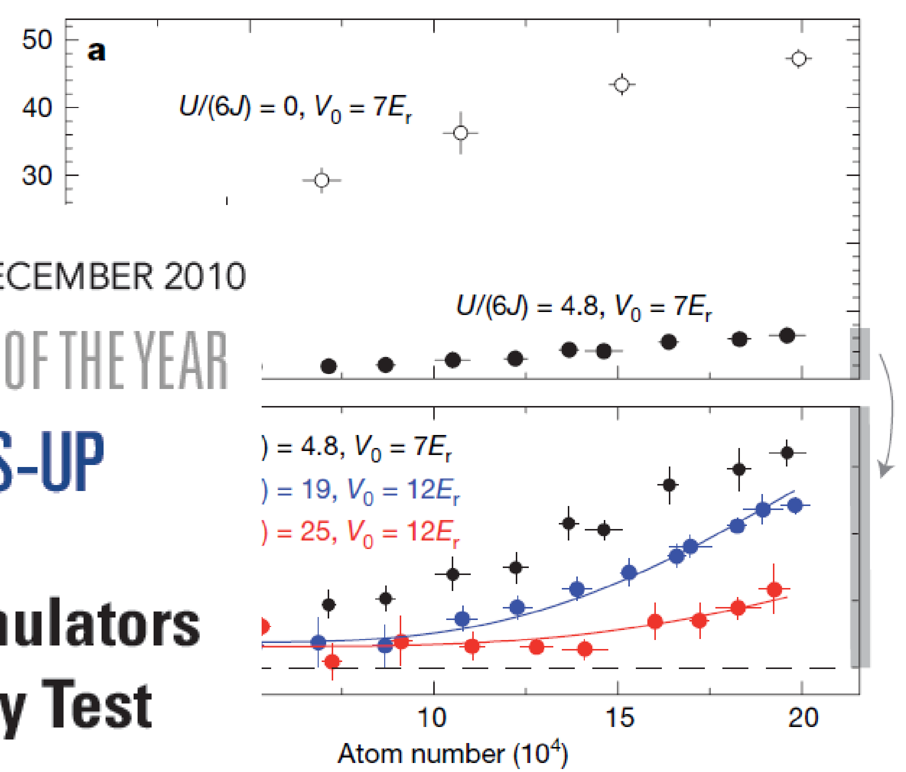
A Mott insulator of fermionic atoms in an optical lattice

Robert Jördens[1]*, Niels Strohmaier[1]*, Kenneth Günter[1,2], Henning Moritz[1] & Tilman Esslinger[1]

Metallic and Insulating Phases of Repulsively Interacting Fermions in a 3D Optical Lattice

U. Schneider,[1] L. Hackermüller,[1] S. Will,[1] Th. Best,[1] I. Bloch,[1,2]* T. A. Costi,[3] R. W. Helmes,[4] D. Rasch,[4] A. Rosch[4]

5 DECEMBER 2008 VOL 322 SCIENCE



SCIENCE VOL 330 17 DECEMBER 2010

BREAKTHROUGH OF THE YEAR

THE RUNNERS-UP

Quantum Simulators Pass First Key Test

Real time observation of the Hubbard model

Letter

Nature **462**, 74-77 (5 November 2009) | doi:10.1038/nature08482; Received 20 July 2009; Accepted 3 September 2009

A quantum gas microscope for detecting single atoms in a Hubbard-regime optical lattice

Waseem S. Bakr[1], Jonathon I. Gillen[1], Amy Peng[1], Simon Fölling[1] & Markus Greiner[1]

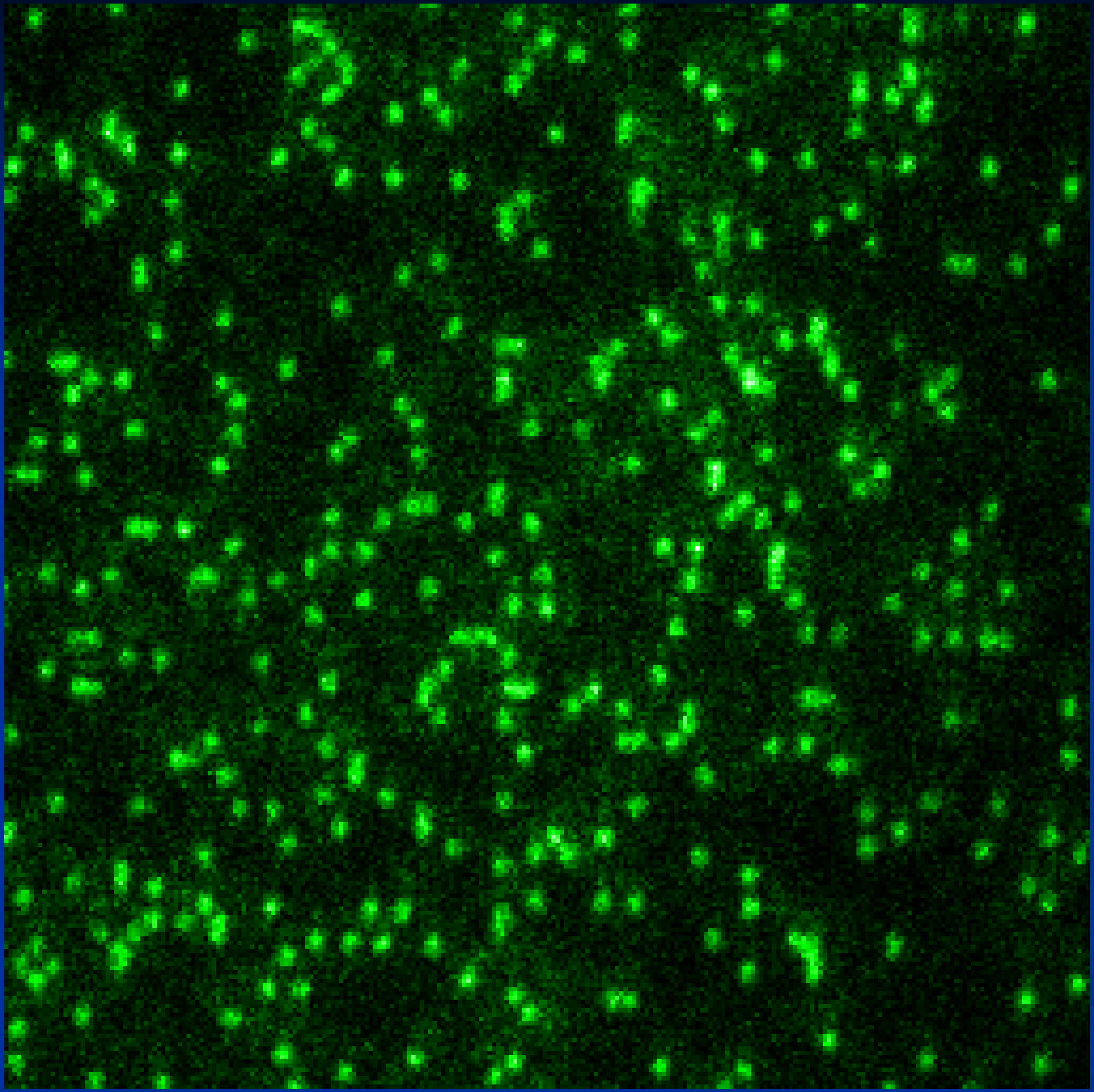
ARTICLE LINKS

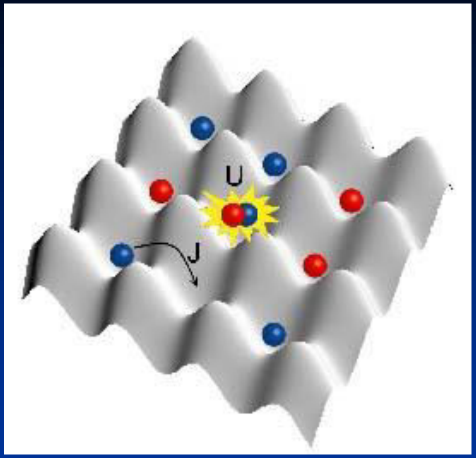
- Figures and tables

SEE ALSO

- Editor's Summary

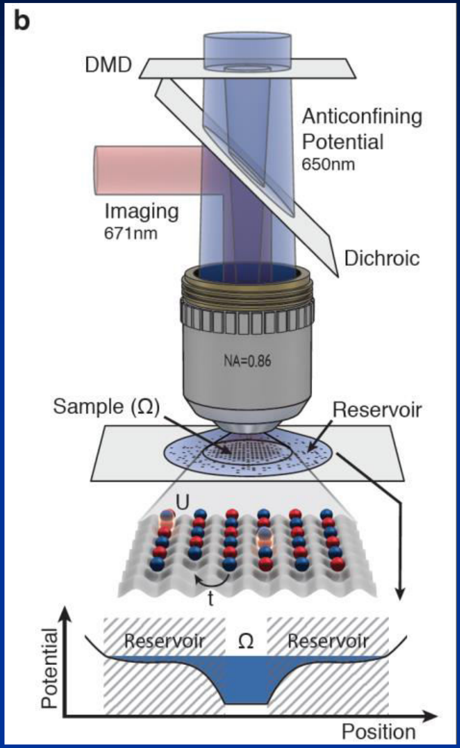
ARTICLE TOOLS

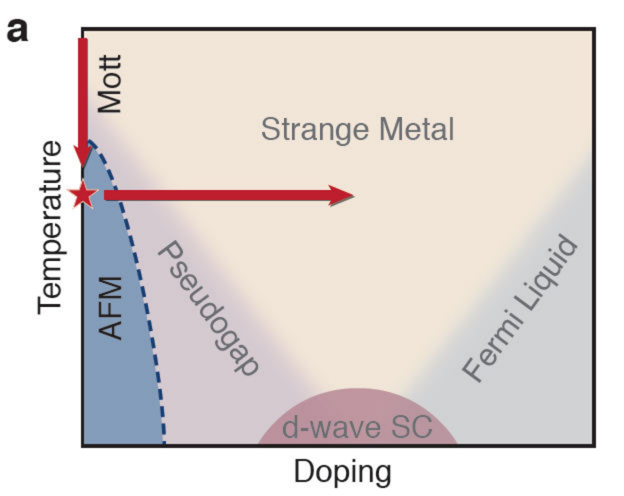


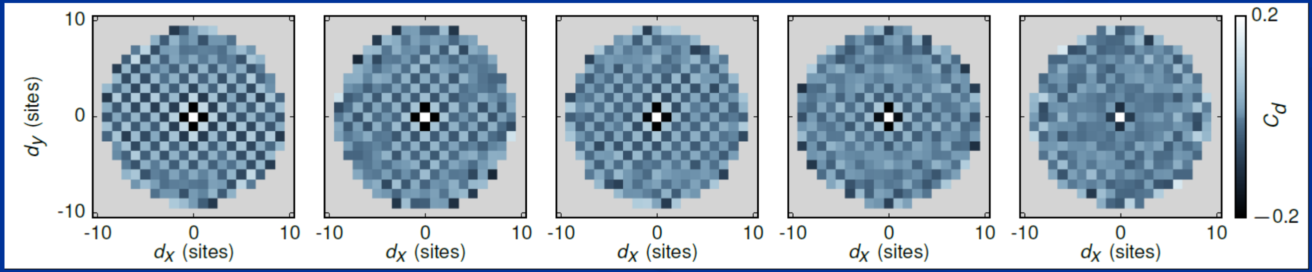


M. Greiner et al.

Mazurenko, A. et al. Nature 545, 462–466 (2017).







QUANTUM PHYSICS

A firmer grip on the Hubbard model

TG Nature 545, 414–415 (2017).

Many additional possibilities

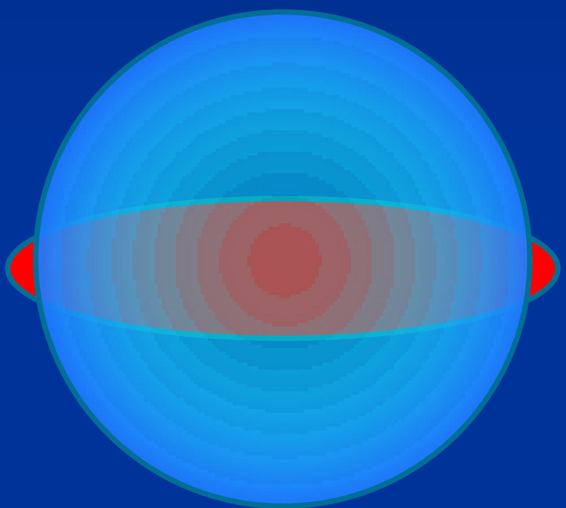
- Exotic lattices
- Novel probes (double occupation etc.)
- Perfectly controlled disorder/ Isolated quantum systems
- Dynamical scales easily accessible
- Long range interactions (dipolar; Rydberg)

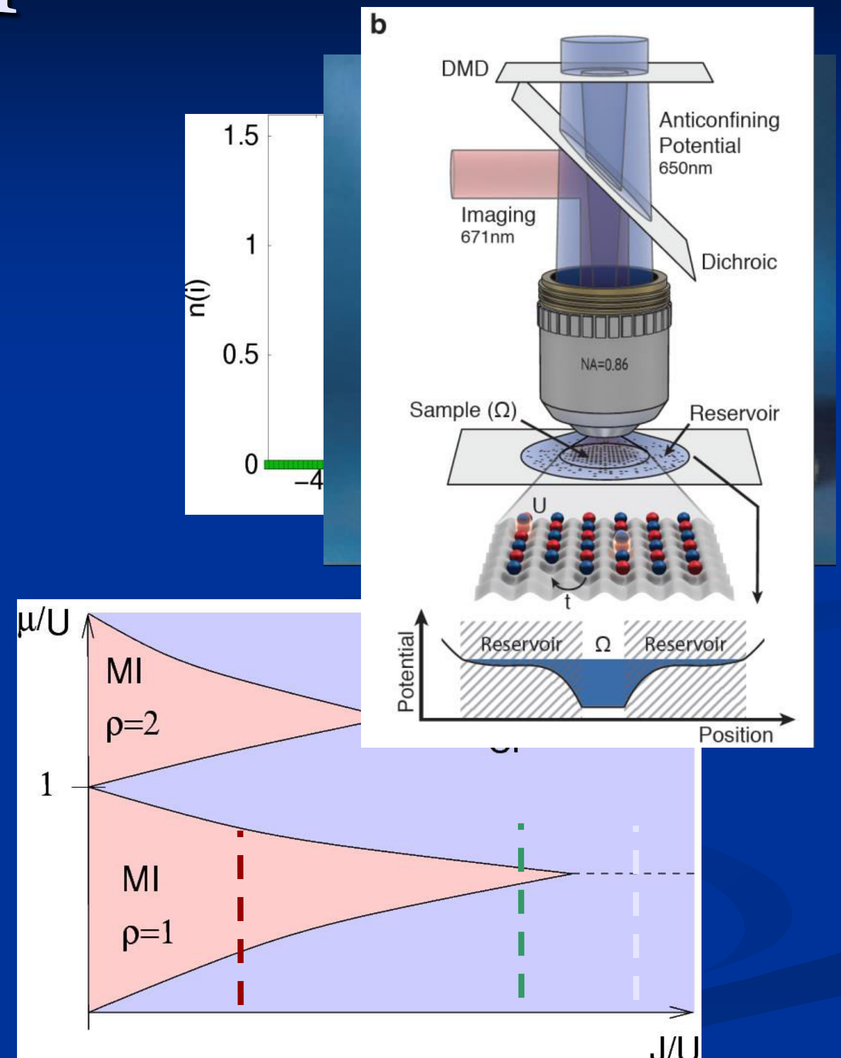
Some imperfections of the simulator (for the moment)…..

I am your nightmare

Confining potential

Confining potential





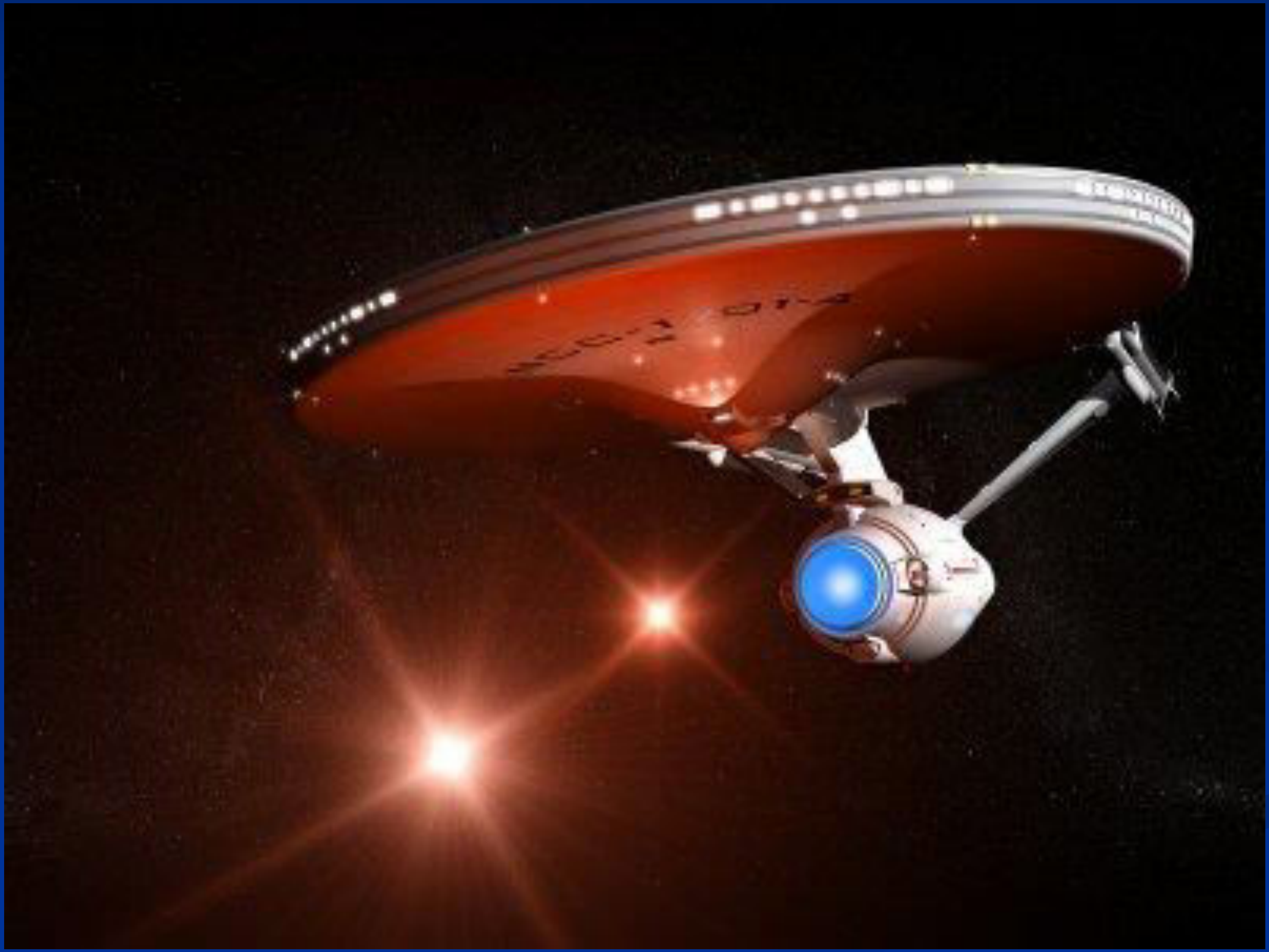
$$H = \int d^3 r \frac{1}{2} \omega_0^2 r^2 \rho(r)$$

- No homogeneous phase !

Main points to improve

- Inherent inhomogeneity
- Fermions: temperature between T_F/20 and T_F/6 (2000 K !)
- In some occasions: Probes

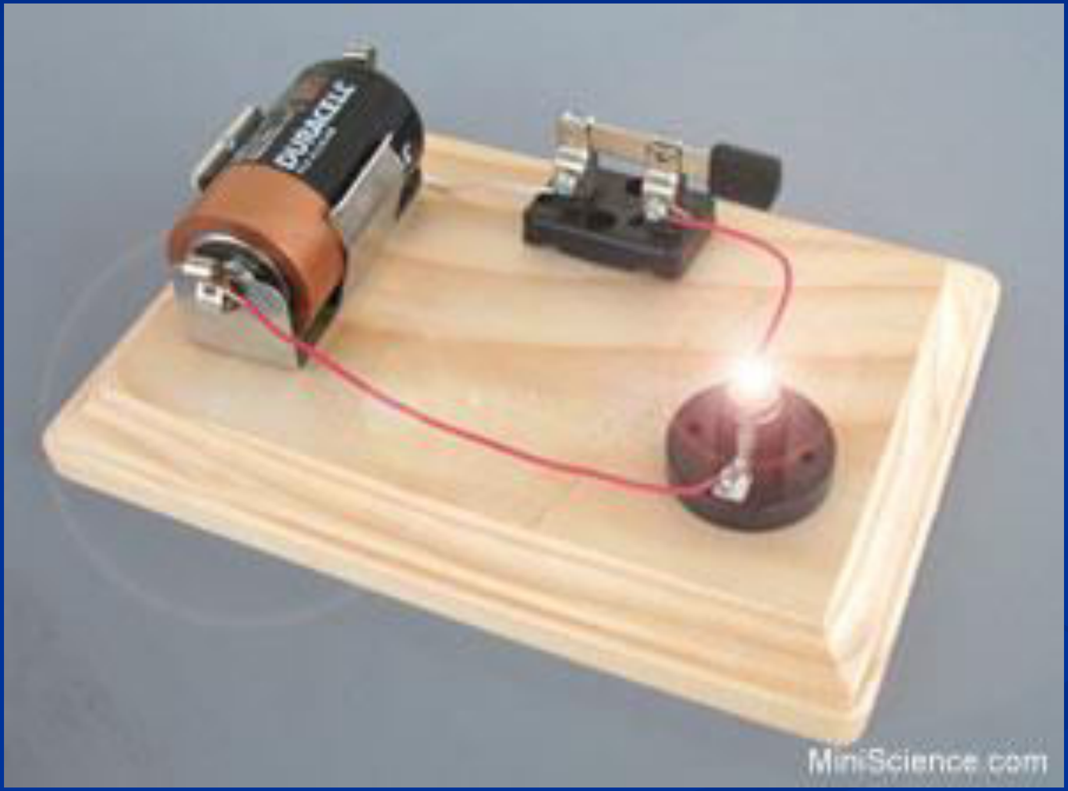
Beyond quantum simulators



Many possibilities

- Out of equilibrium physics (isolated systems)
- Artificial gauge fields (A); very large fields
- Novel matter (mixtures, bosons with “spin”, SU(N) etc.)
- Weird potentials (quasicrystals etc.)

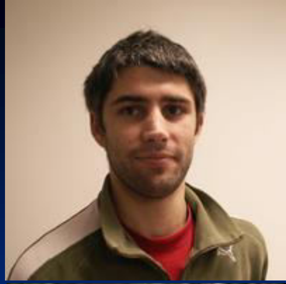
Transport

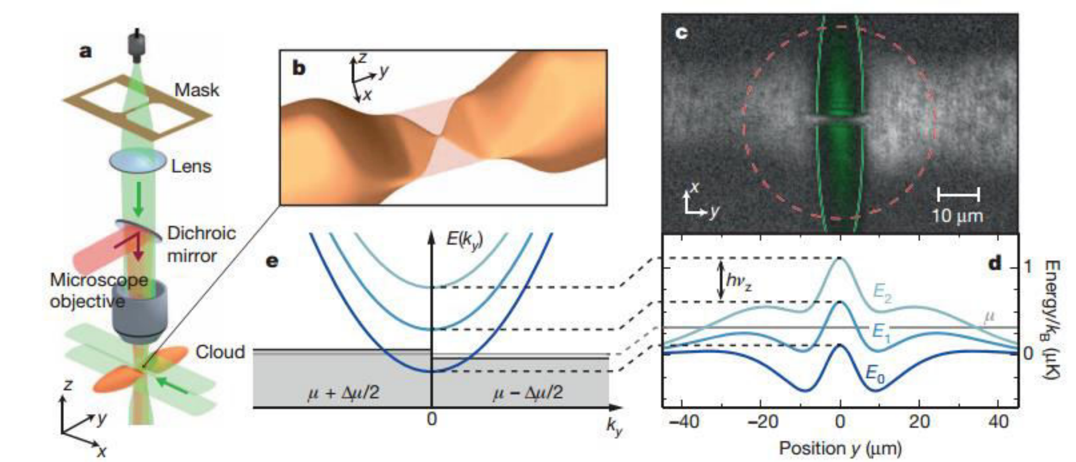


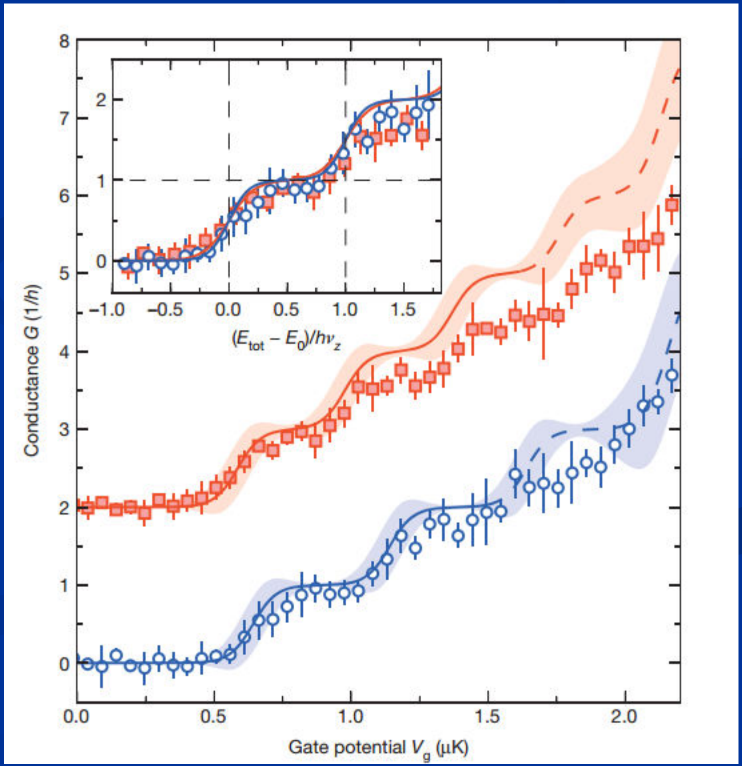
Observation of quantized conductance in neutral matter

Sebastian Krinner[1], David Stadler[1], Dominik Husmann[1], Jean-Philippe Brantut[1] & Tilman Esslinger[1]

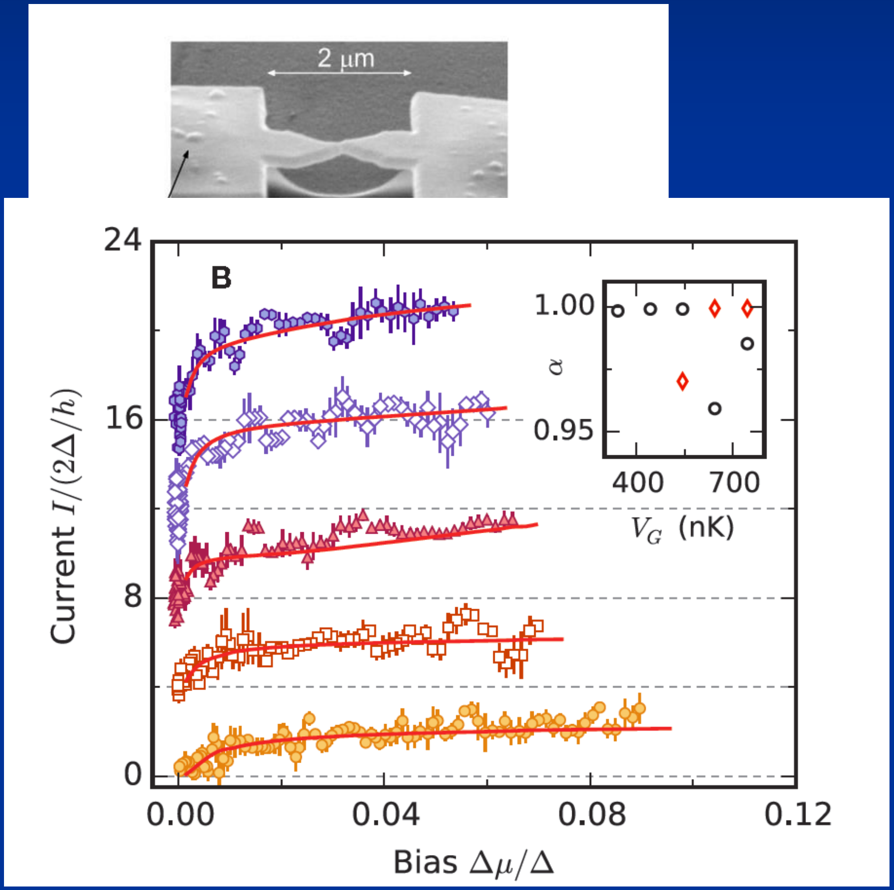
64 | NATURE | VOL 517 | 1 JANUARY 2015

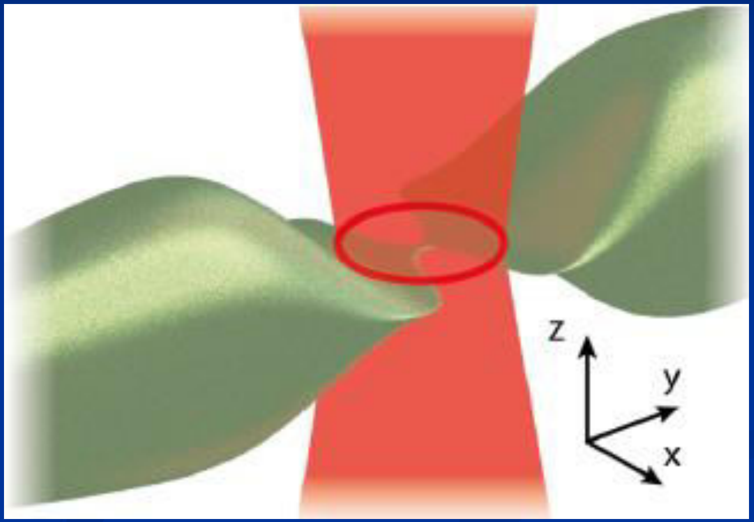






Transport between superconductors

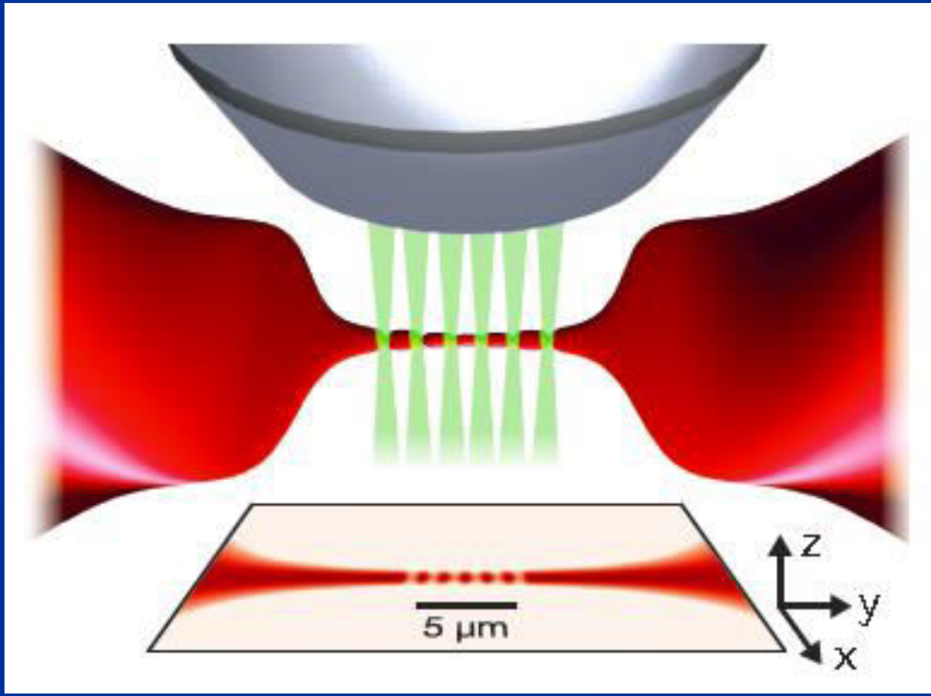


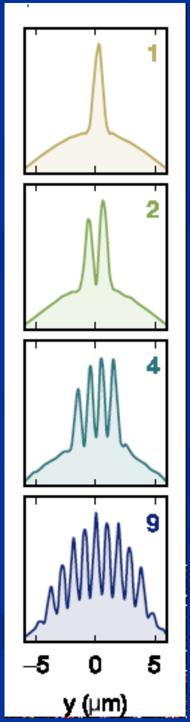


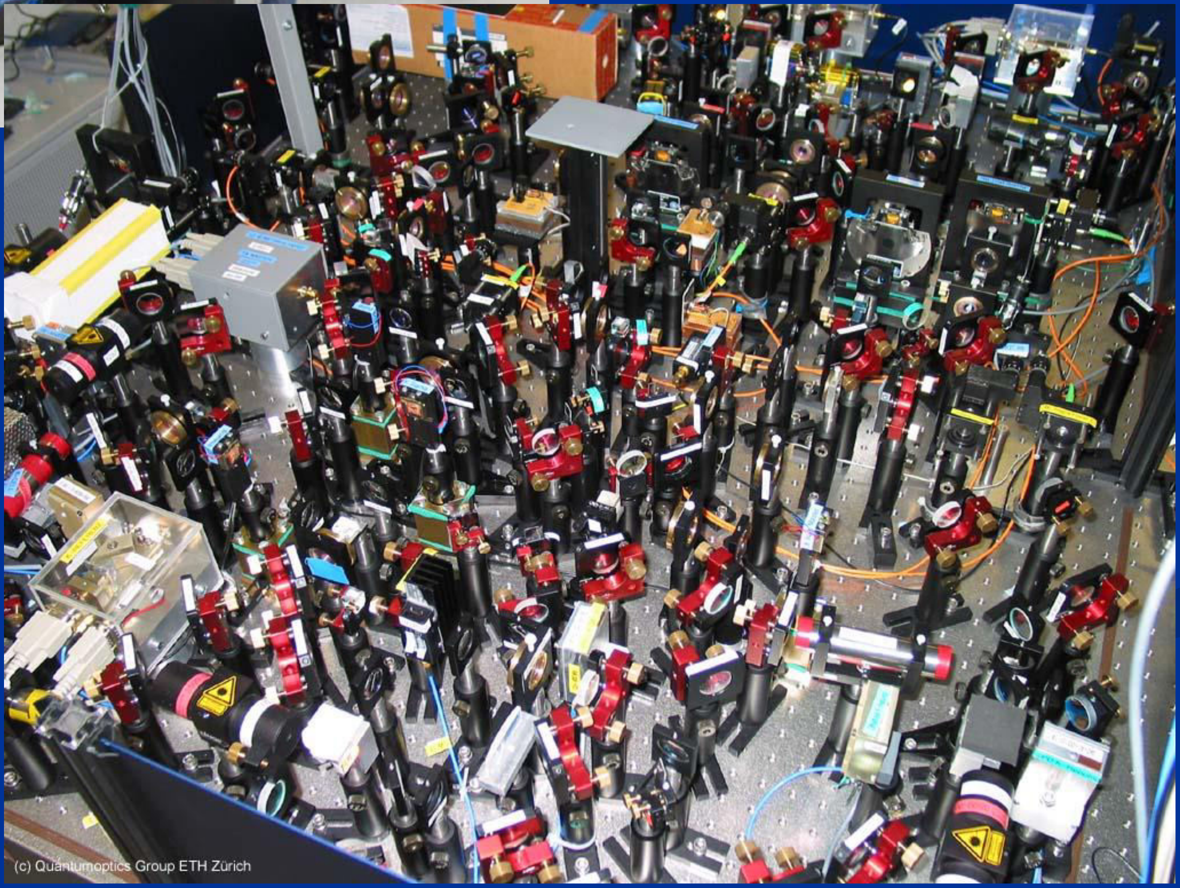
D. Hussmann al. Science 350 62667 (2015).

Periodic one dimensional structure

M. Lebrat, P. Grisins et al., Phys. Rev. X 8, 011053 (2018)

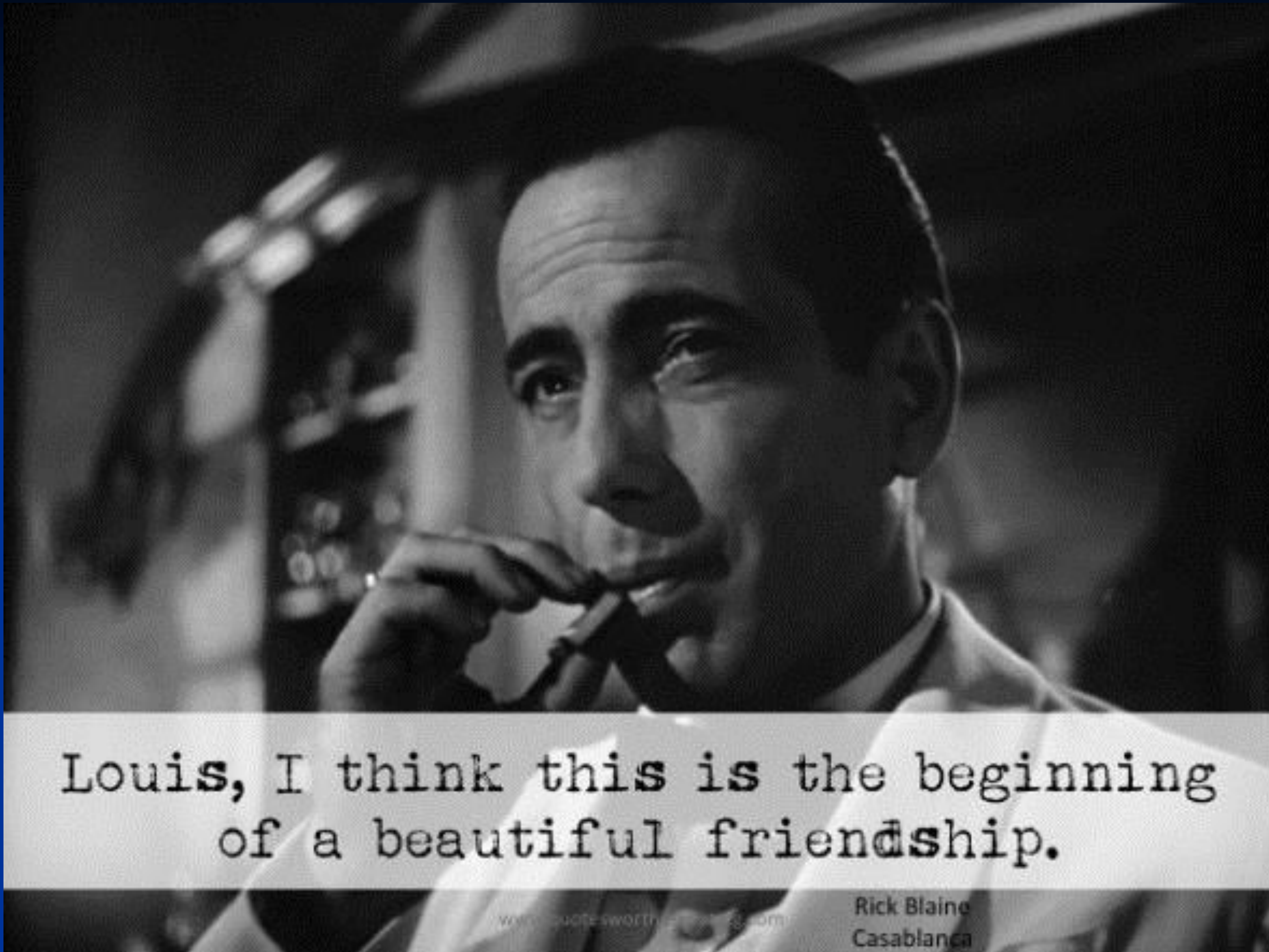





CRAY
CRAY
CRAY
CSCS
C3
B

(c) Quantumoptics Group ETH Zürich

Conclusions / Perspectives

- Remarkable CM-CA interplay
- Quantum simulators and beyond
- Remarkable new way to think/measure
- [Many important developments coming soon]


Louis, I think this is the beginning of a beautiful friendship.
Rick Blaine
Casablanca