Cold atoms and condensed matter

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http://dpmc.unige.ch/gr_giamarchi/

http://www.manep.ch

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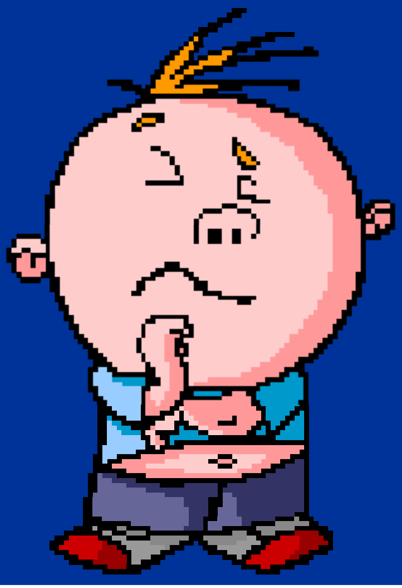
FNSNF
FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

MaNEP SWITZERLAND

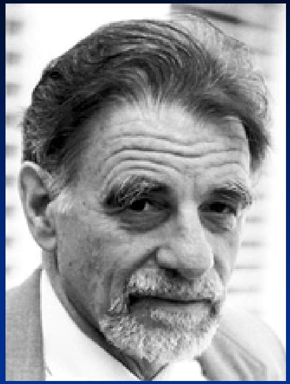
Strong correlations

Still no explanation

Theorists are lazy !!!!



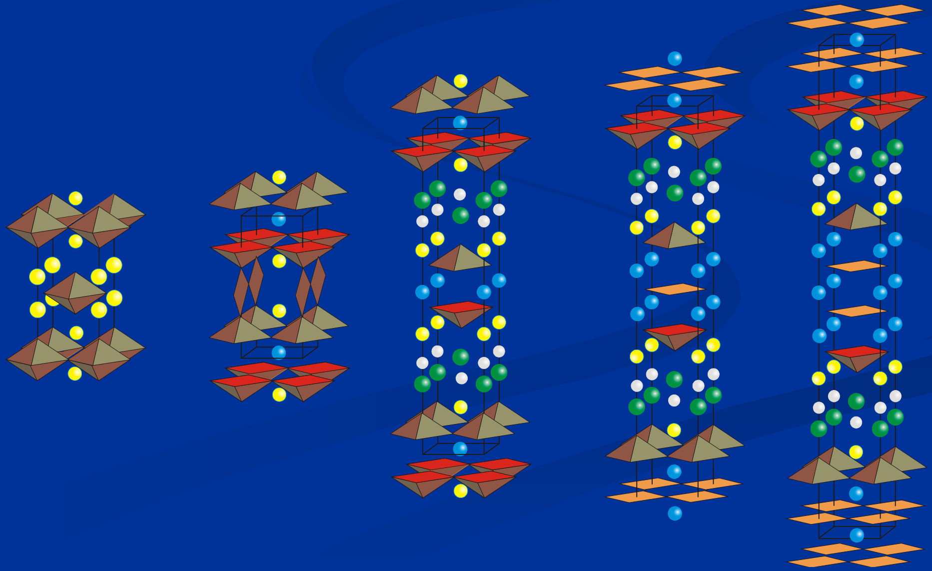
How to study ?



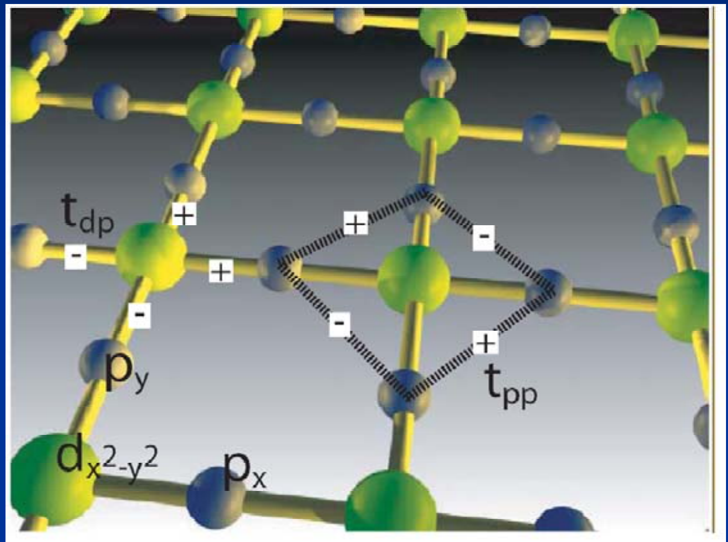
Very difficult !!

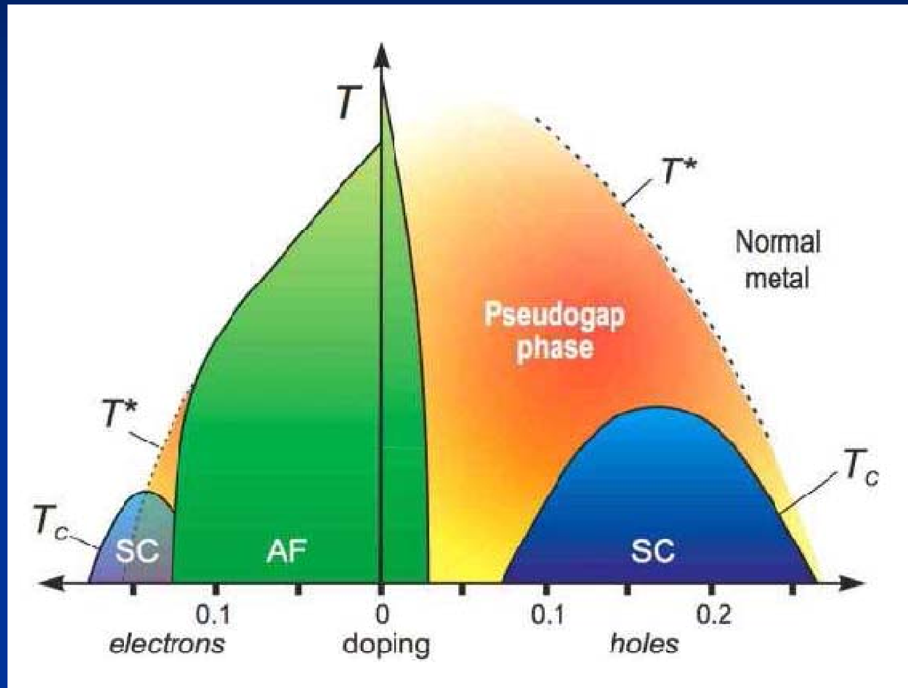
Bednorz Muller

Example of High Tc superconductors (86)



Find a simplified model

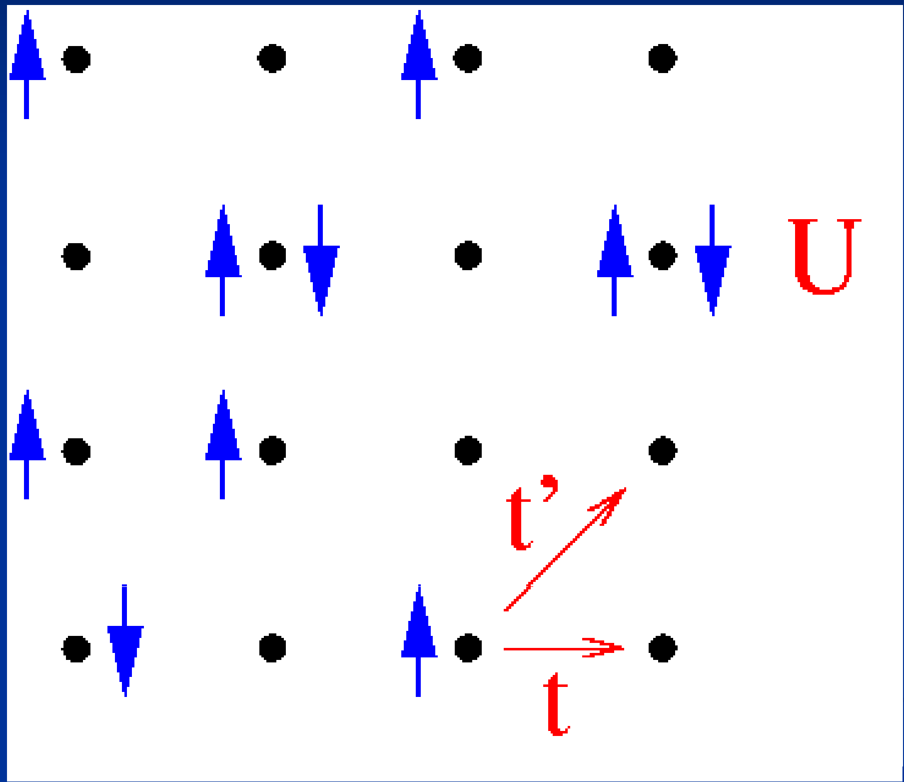




Simplest model containing:

- Bands (filling)
- Interactions

Hubbard model (1963)



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

Analytic calculations

- No good method (except 1d)
- Various approximations to simplify the model
- Never sure whether the results are or are not an artefact of the approximations used

Numerical calculations

- Extremely powerful for classical systems

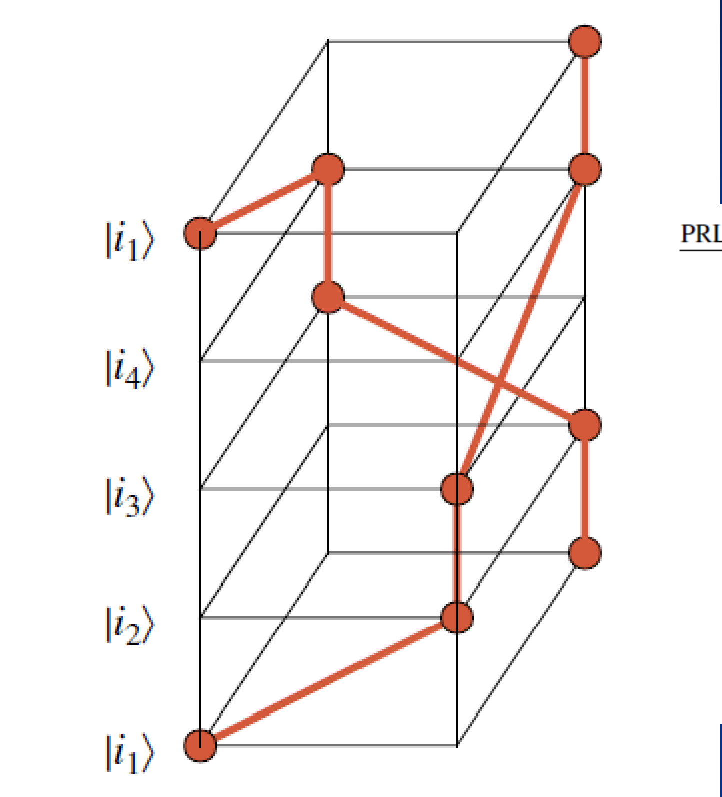
- Quantum systems

Bosons " $(x1,x_2)$ = " $(x2,x_1)$

Fermions " $(x1,x_2)$ = - " $(x2,x_1)$

- Sign problem !!

Configurations: “probabilités” négatives si on veut représenter par des nombres



PRL **94,** 170201 (2005) PHYSICAL REVIEW LETTERS week e[...] 6 MAY

Computational Complexity and Fundamental Limitations to Fermionic Quantum Monte Carlo Simulations

Matthias Troyer[1] and Uwe-Jens Wiese[2]

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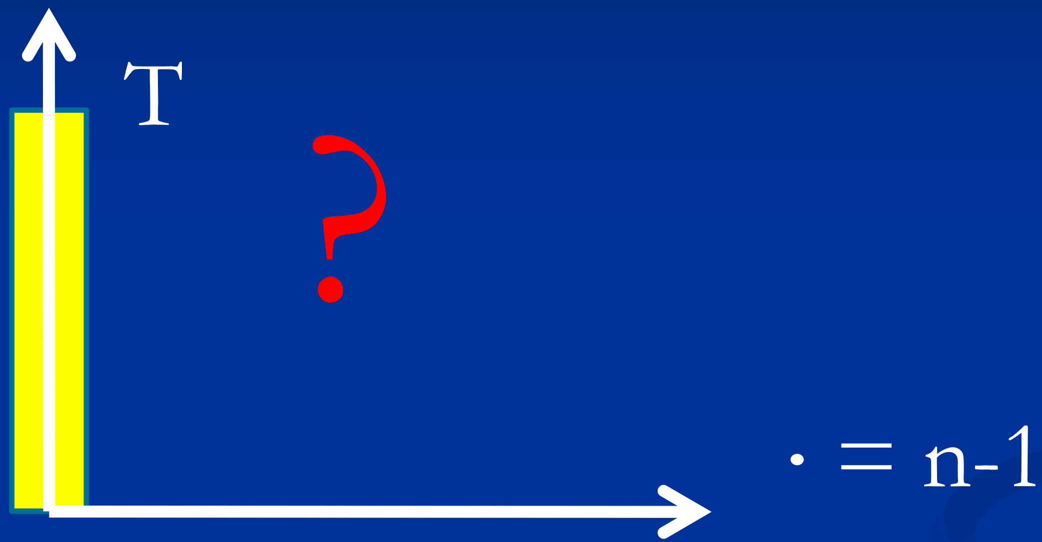
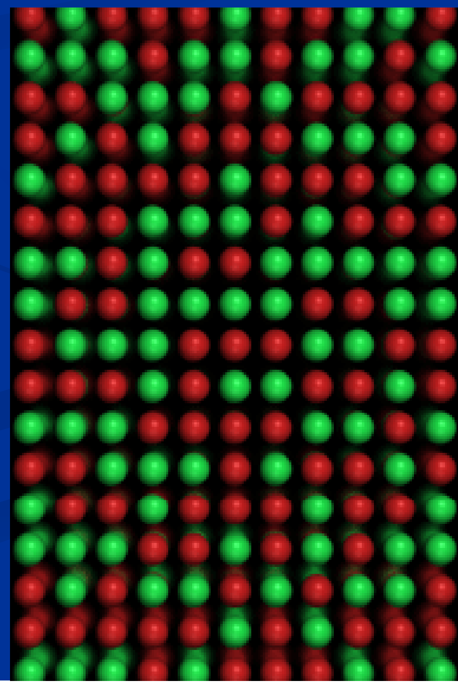
(Received 11 August 2004; published 4 May 2005)

Quantum Monte Carlo simulations, while being efficient for bosons, suffer from the “negative sign problem” when applied to fermions—causing an exponential increase of the computing time with the number of particles. A polynomial time solution to the sign problem is highly desired since it would provide an unbiased and numerically exact method to simulate correlated quantum systems. Here we show that such a solution is almost certainly unattainable by proving that the sign problem is nondeterministic polynomial (NP) hard, implying that a generic solution of the sign problem would also solve all problems in the complexity class NP in polynomial time.

Exponential error with the system size

Properties (U>0)





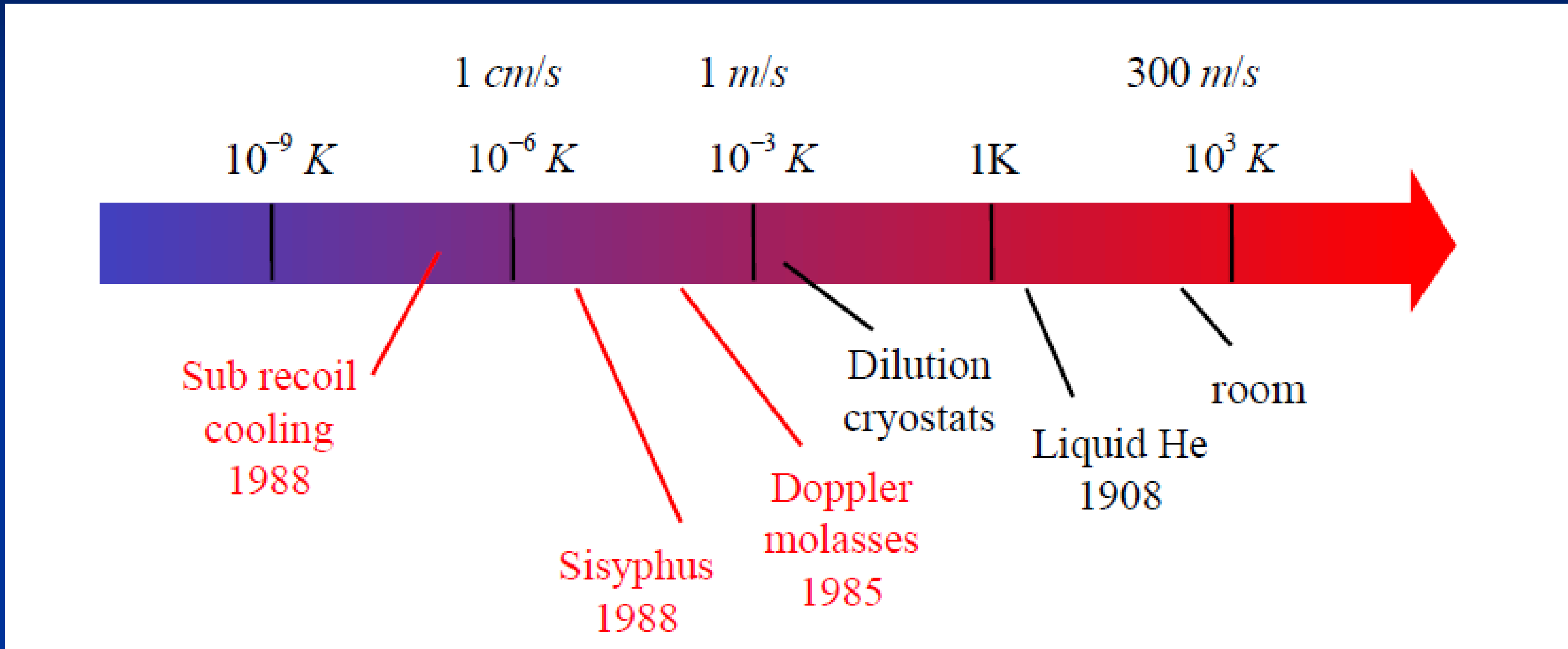
- Mott insulator (n=1)
- T < T_N : Antiferromagnetic phase
- No numerical problem (n=1)

What to do ?

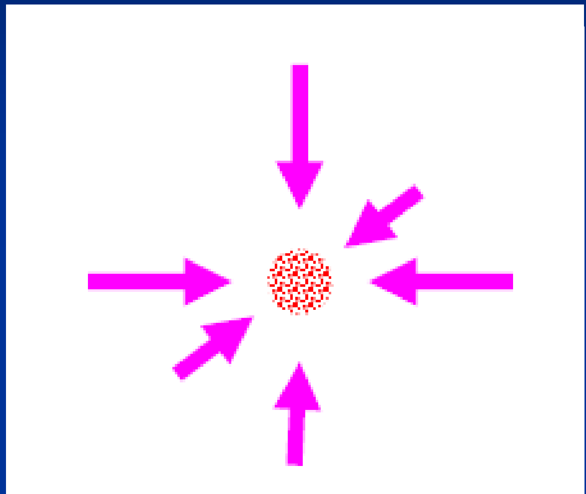
- A genius guess what the right solution is
- Brute force numerical attack
- Find a « computer » that does not suffer from sign problem

Help from another field of physics

Atom cooling

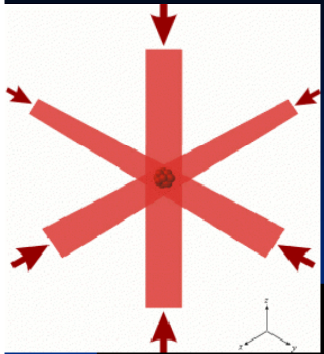


Atom trapping

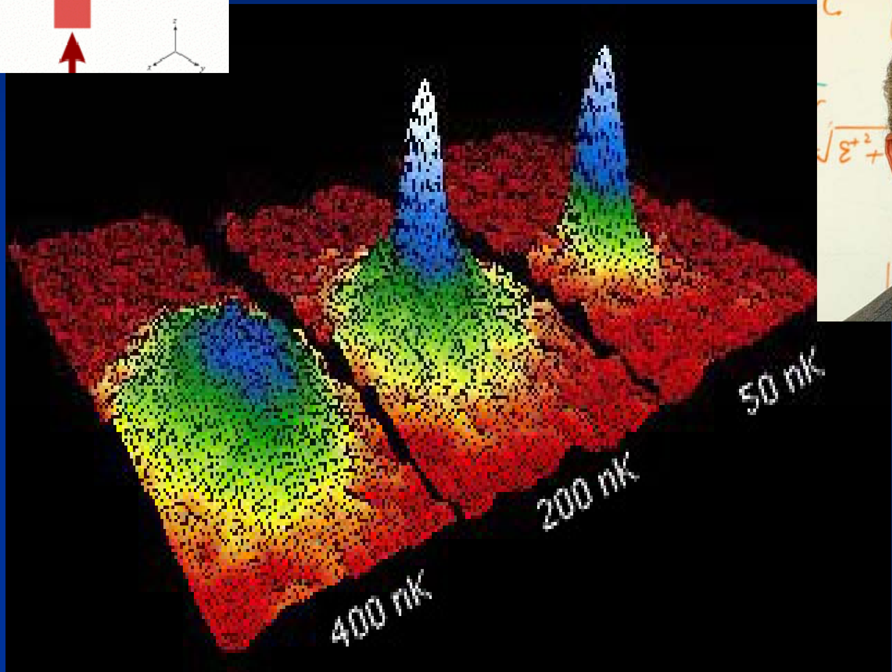


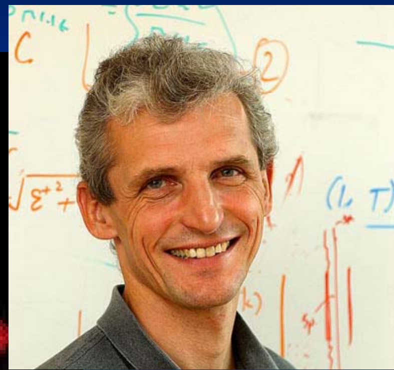
- Evaporative cooling

Group: T. Esslinger (ETH, Zurich)



BEC in cold atomic gases



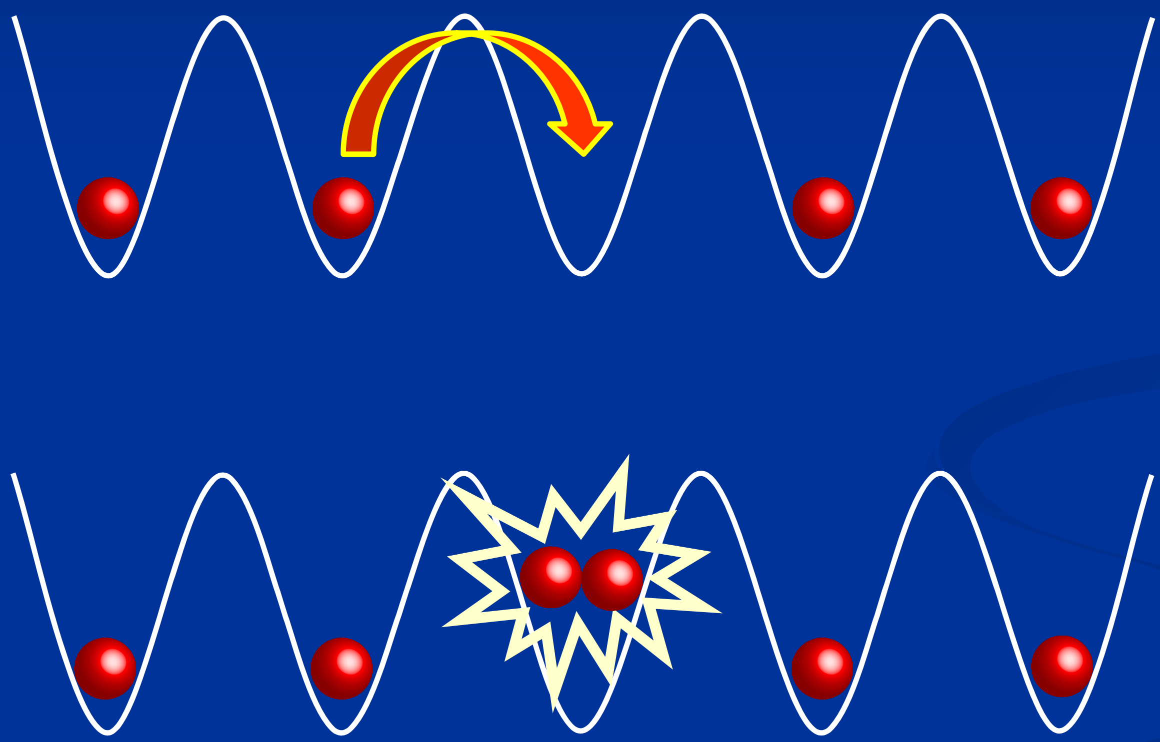


2001: Cornell, Ketterle, Wieman

SO WHAT !

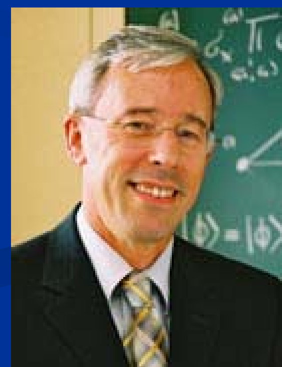
1924: predicted by Bose and Einstein

Atoms in a lattice



Tunnelling

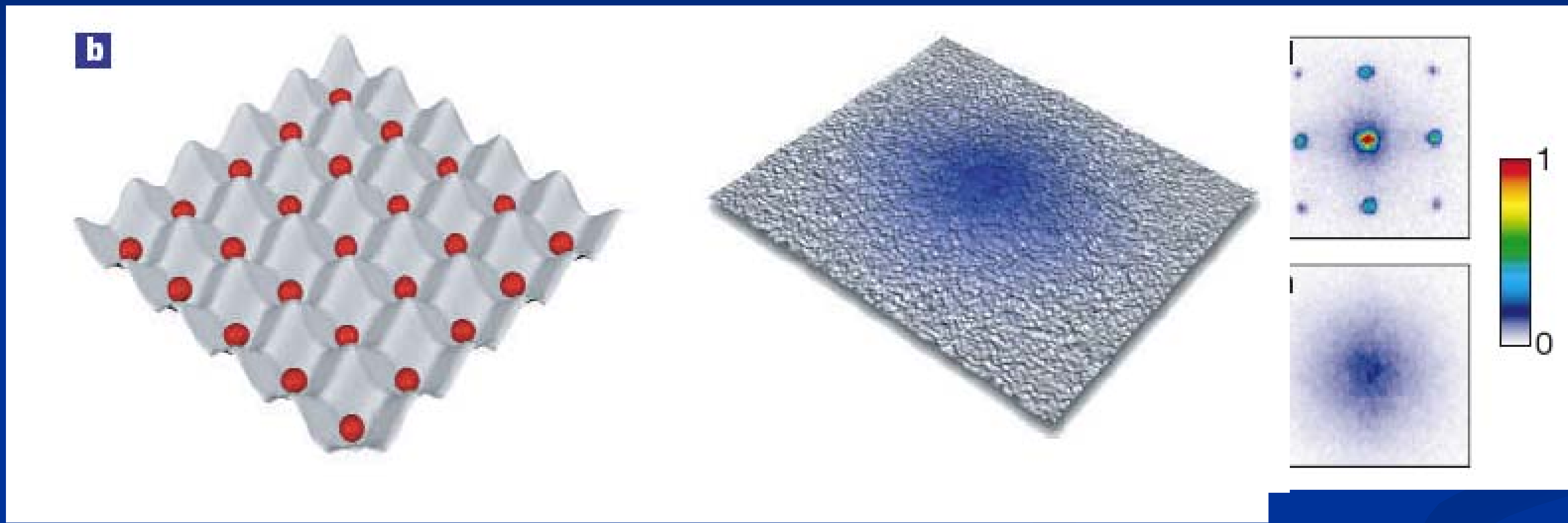
Short range interaction



P. Zoller

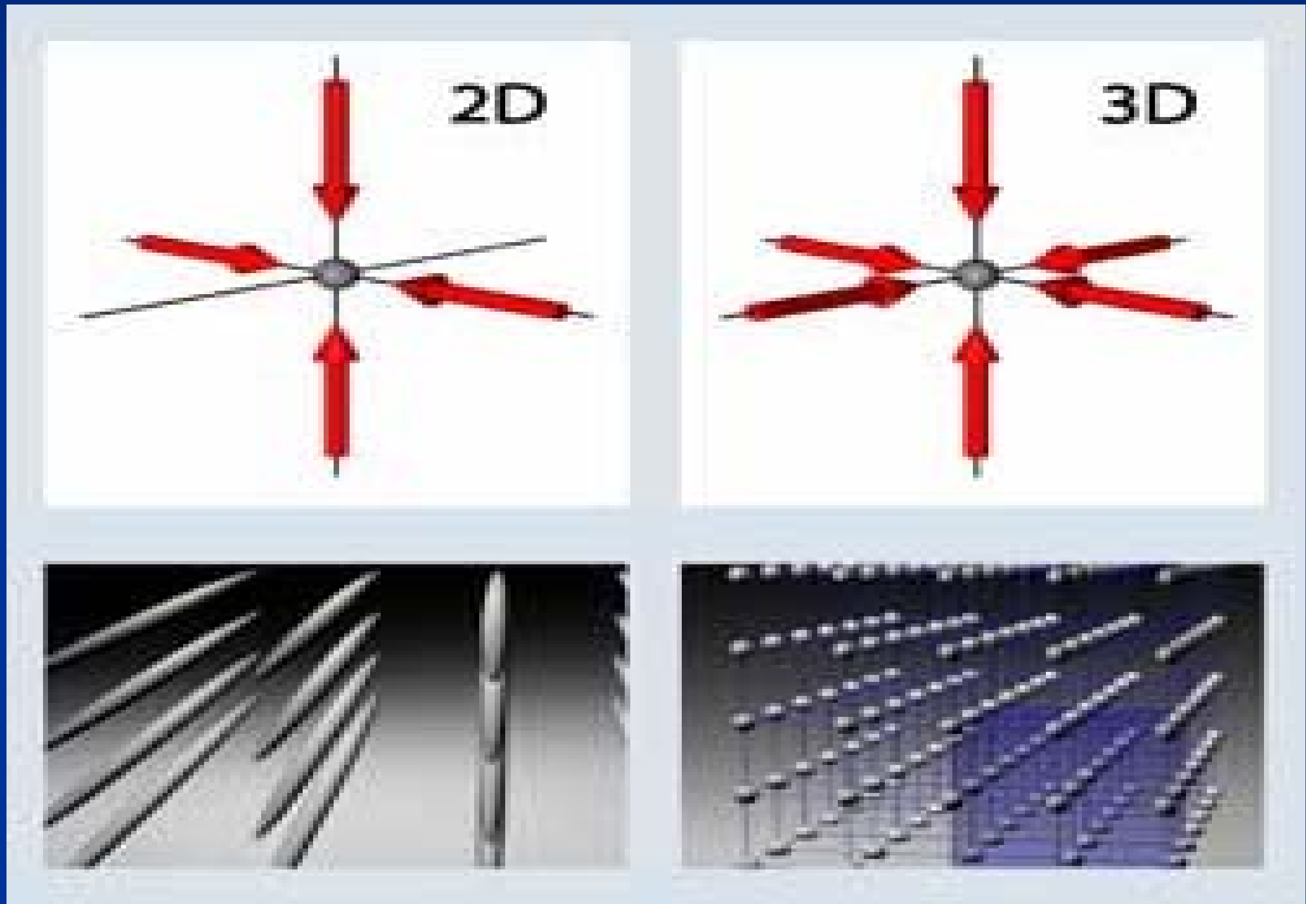
Proposal: D. Jaksch et al PRL81 3108 (98)

Simulators for condensed matter



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

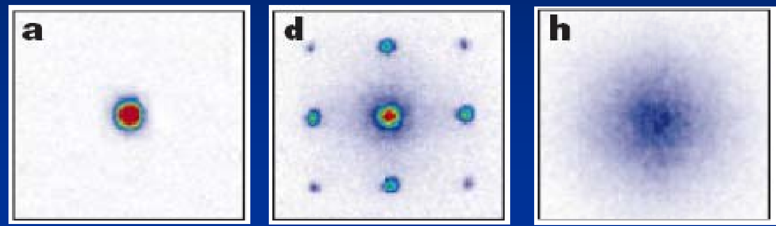
Control on the dimension



I. Bloch, Nat. Phys 1, 23 (2005)

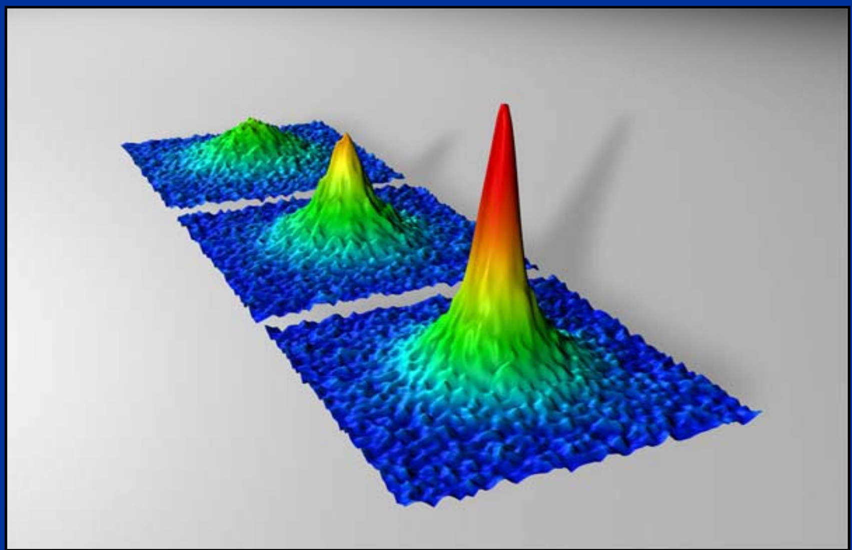
Quantum simulators !

Interactions
(Lattice, Feschbach resonnance)

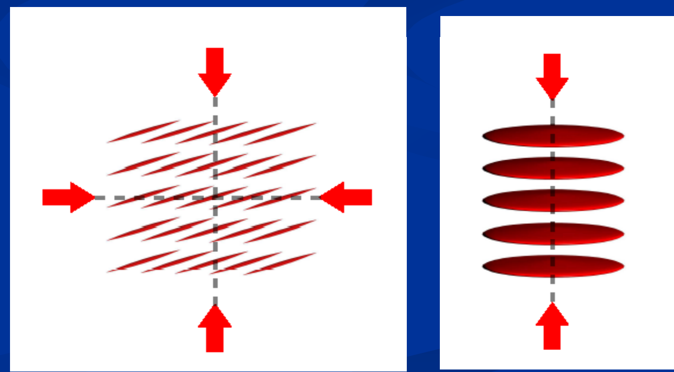


Statistics

Fermions
Bosons



Dimensionality



ENS, ETH, LENS, Mainz, MIT, NIST, Penn State,

Dream ??

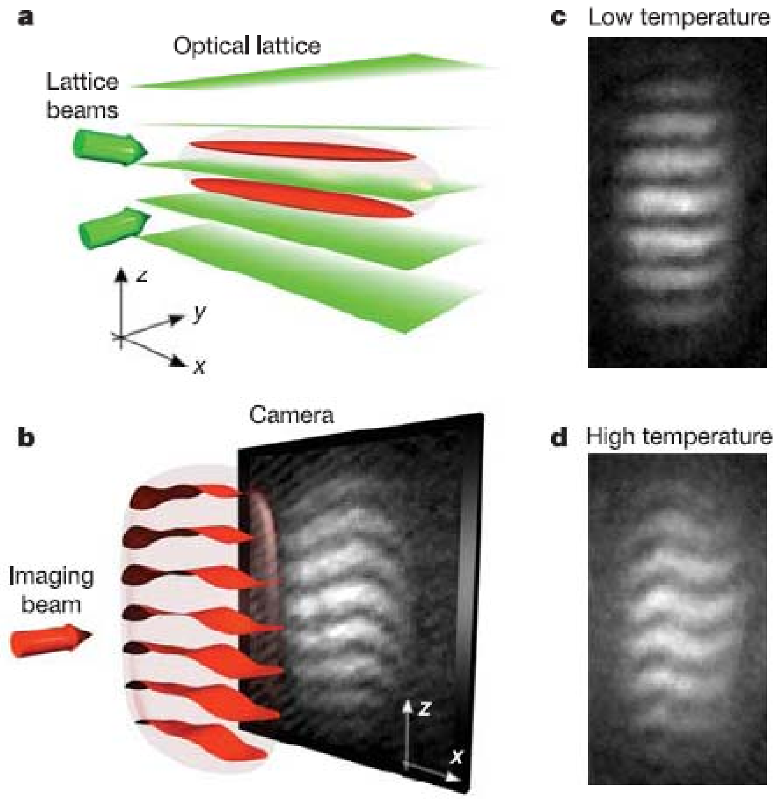
Two dimensional superfluids

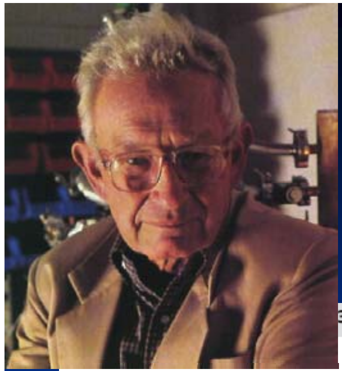
nature Vol 441|29 June 2006|doi:10.1038/nature04851

LETTERS

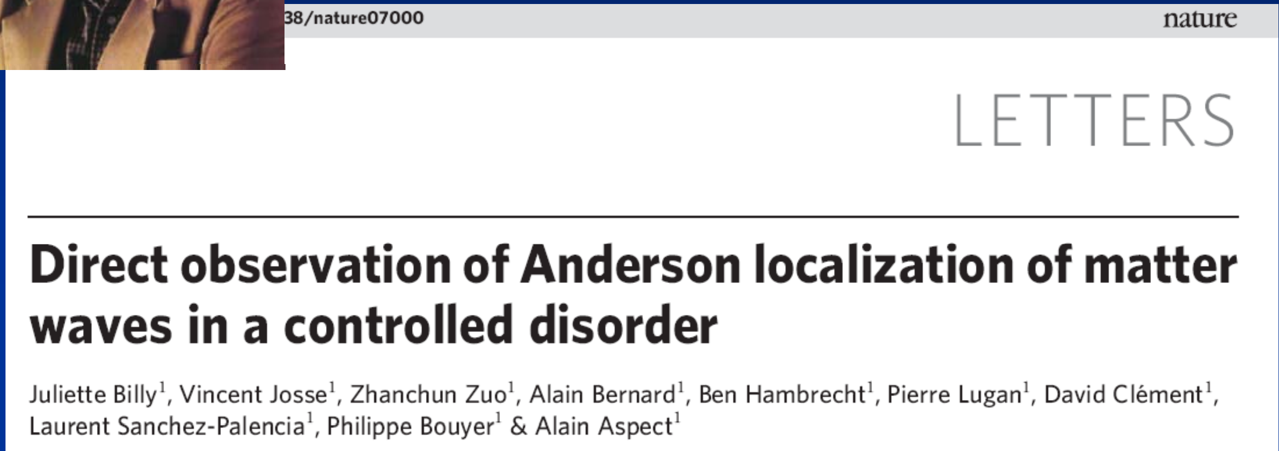
Berezinskii-Kosterlitz-Thouless crossover in a trapped atomic gas

Zoran Hadzibabic[1], Peter Krüger[1], Marc Cheneau[1], Baptiste Battelier[1] & Jean Dalibard[1]





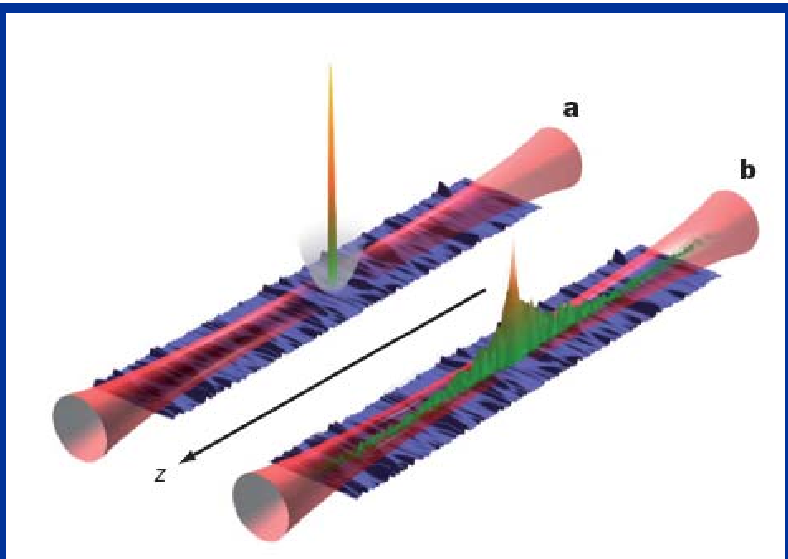
Anderson localization (1958)

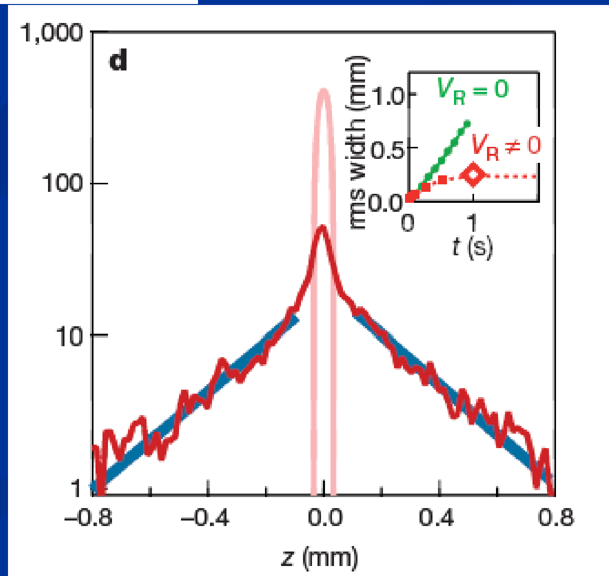

38/nature07000 nature

LETTERS

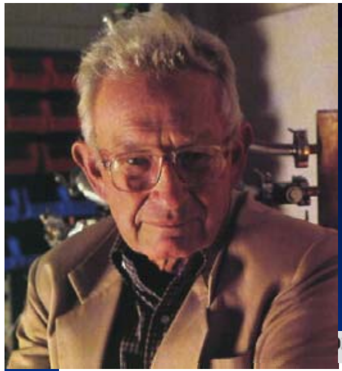
Direct observation of Anderson localization of matter waves in a controlled disorder

Juliette Billy[1], Vincent Josse[1], Zhanchun Zuo[1], Alain Bernard[1], Ben Hambrecht[1], Pierre Lugan[1], David Clément[1], Laurent Sanchez-Palencia[1], Philippe Bouyer[1] & Alain Aspect[1]





Aubry-Andre Model (Ann. Isr. Phys. Soc. **3, 133 1980**)



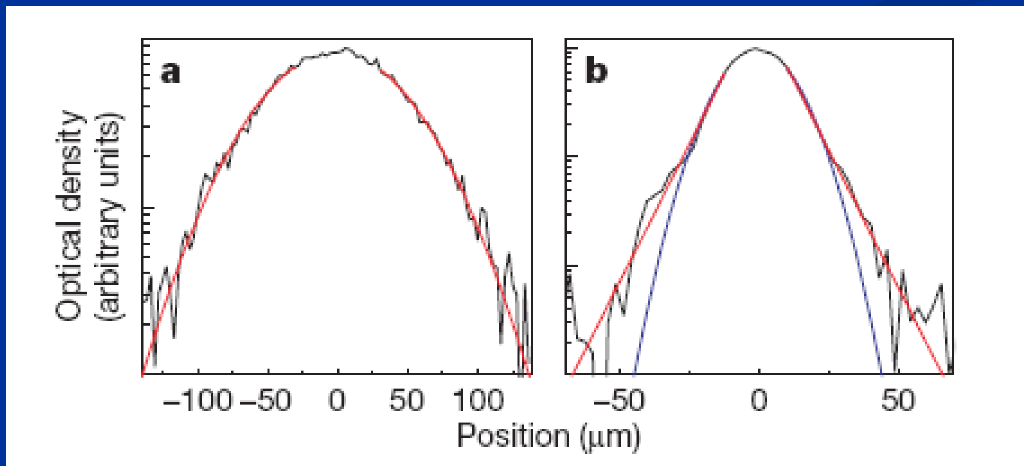
Anderson localization (1958)

)38/nature07071 nature

LETTERS

Anderson localization of a non-interacting Bose–Einstein condensate

Giacomo Roati[1,2], Chiara D'Errico[1,2], Leonardo Fallani[1,2], Marco Fattori[1,2,3], Chiara Fort[1,2], Matteo Zaccanti[1,2], Giovanni Modugno[1,2], Michele Modugno[1,4,5] & Massimo Inguscio[1,2]

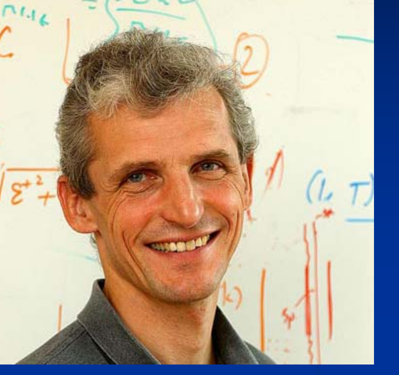


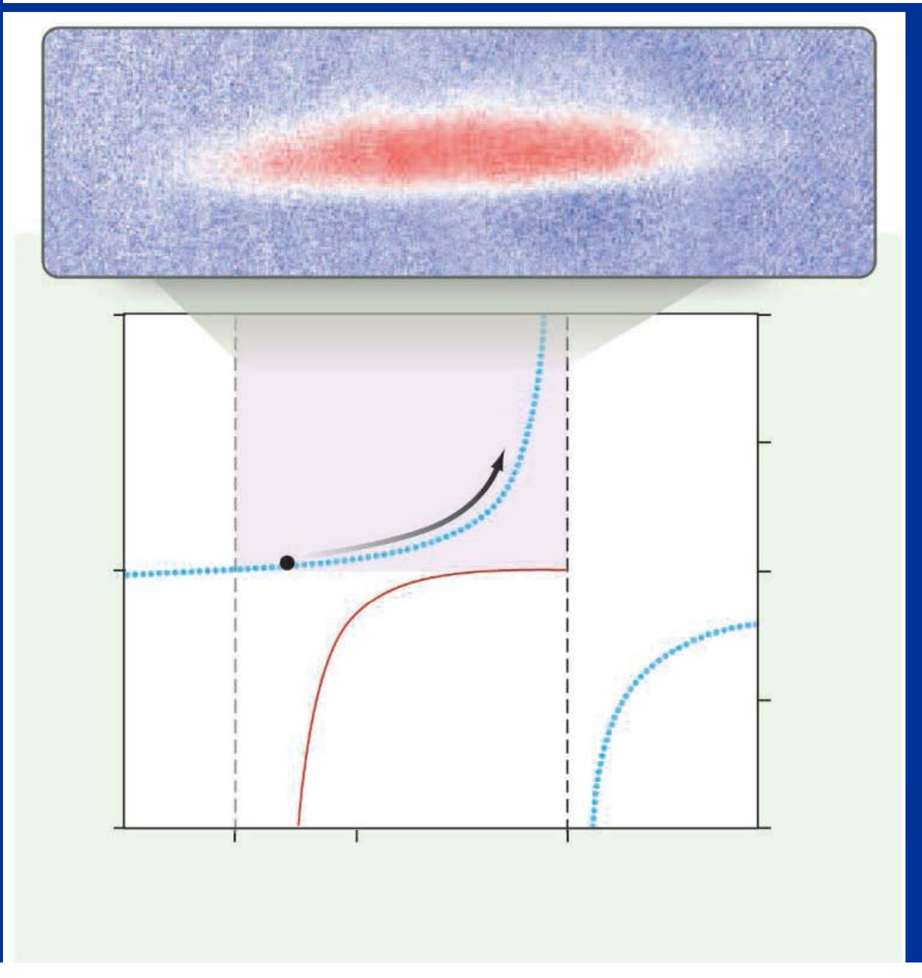
Aubry-Andre Model (Ann. Isr. Phys. Soc. **3, 133 1980**)

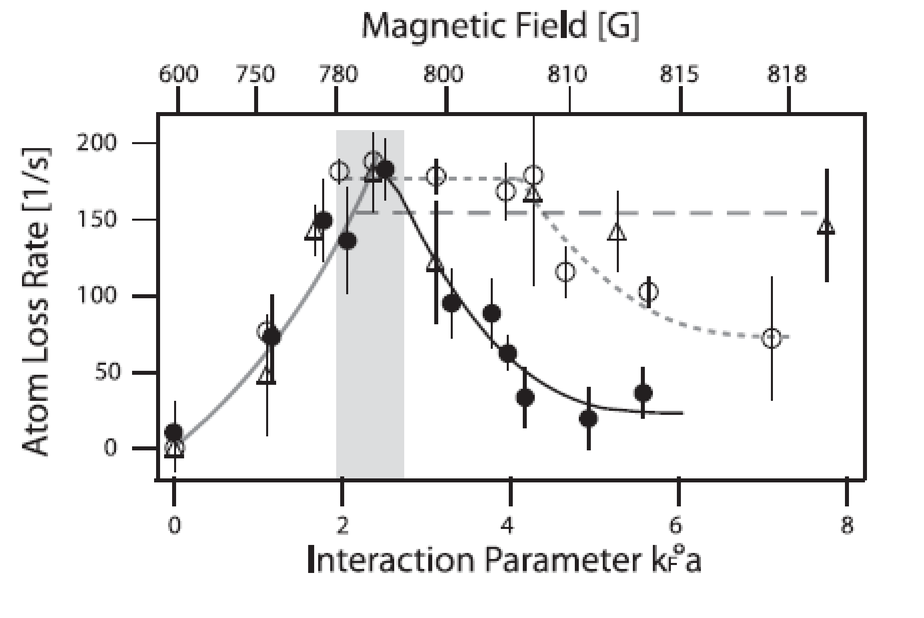
Interactions

Stoner criterion

Itinerant Ferromagnetism in a Fermi Gas of Ultracold Atoms
Gyu-Boong Jo, *et al.*
Science **325**, 1521 (2009);







Hubbard model

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

LETTERS

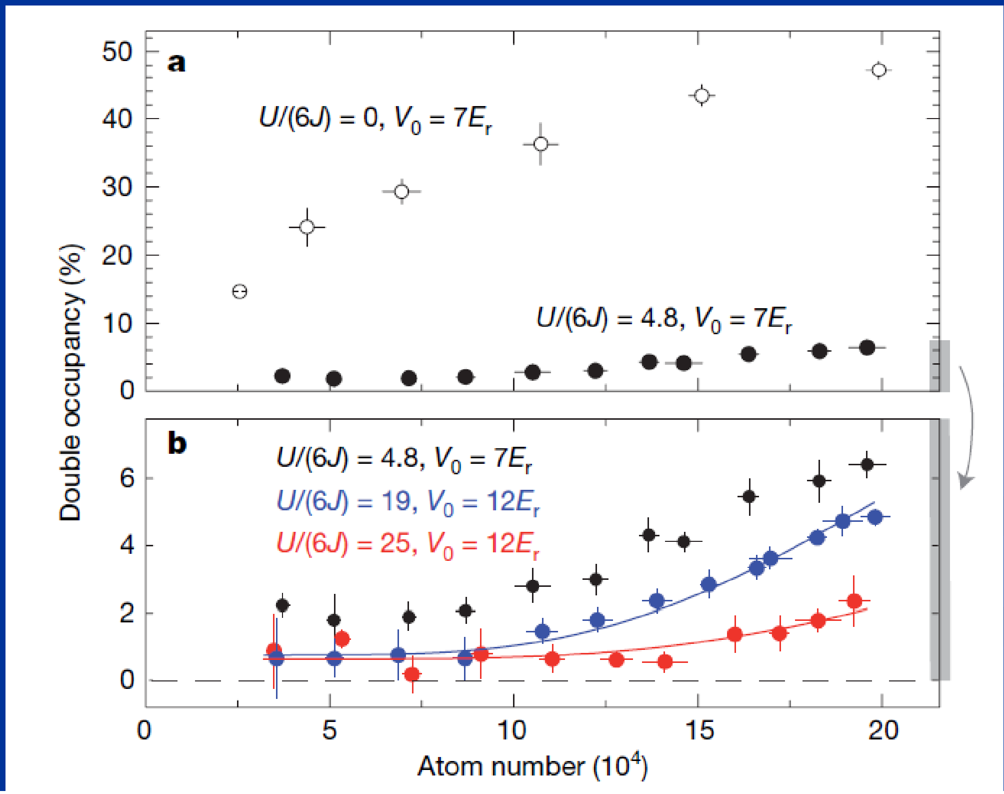
A Mott insulator of fermionic atoms in an optical lattice

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

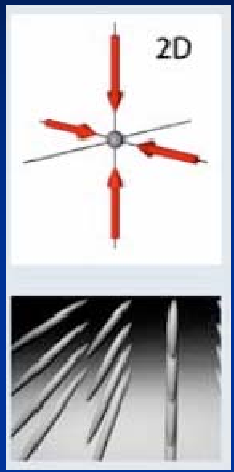
U. Schneider,[1] L. Hackermüller,[1] S. Will,[1] Th. Best,[1] I. Bloch,[1,2]* T. A. Costi,[3] R. W. Helmes,[4] D. Rasch,[4] A. Rosch[4]

5 DECEMBER 2008 VOL 322 SCIENCE

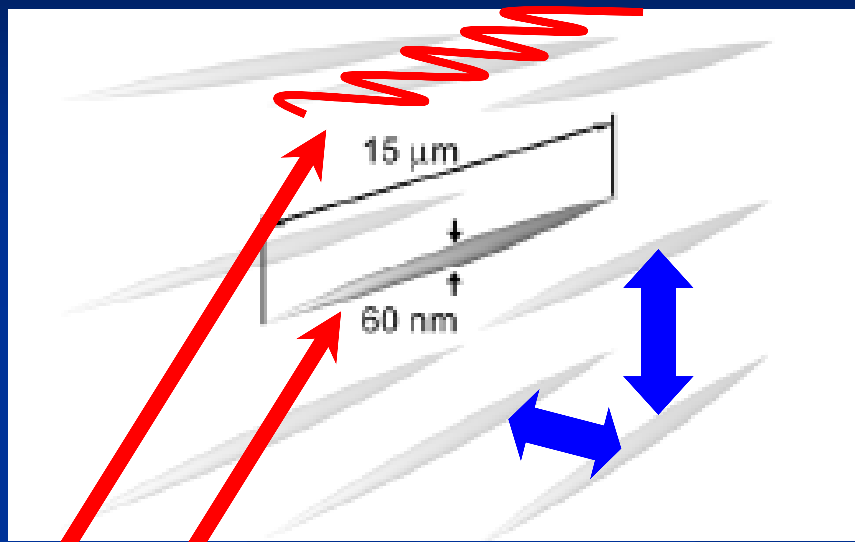


Exotic physics, reduced dimensionality

One dimension: Luttinger liquids



T. Stoferle *et al.*
PRL **92** 130403 (2004)

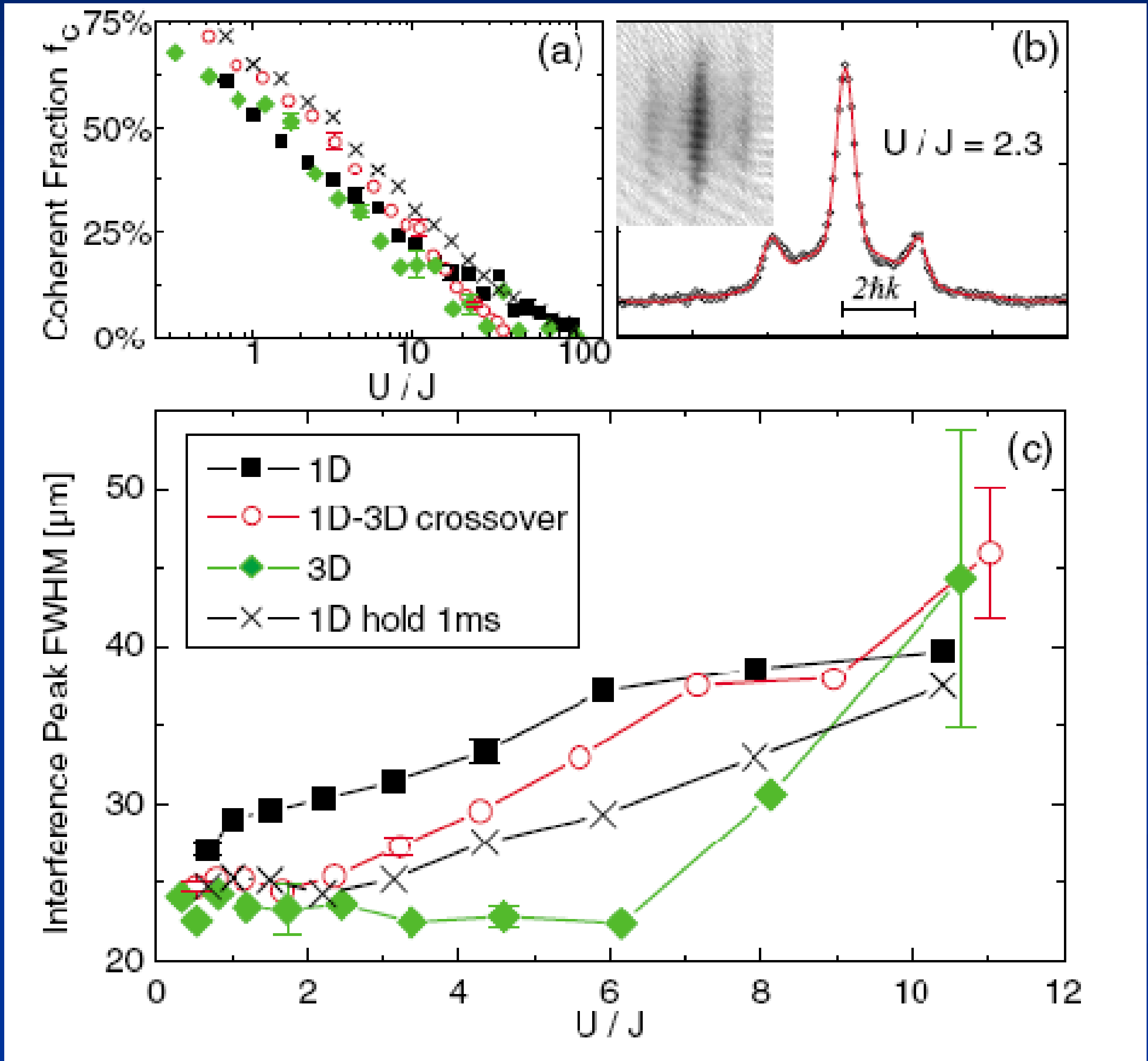


A.F. Ho, M. A.Cazalilla,TG
PRL 92 130405 (2003);
NJP 8 158 (2006)

1D Mott insulator

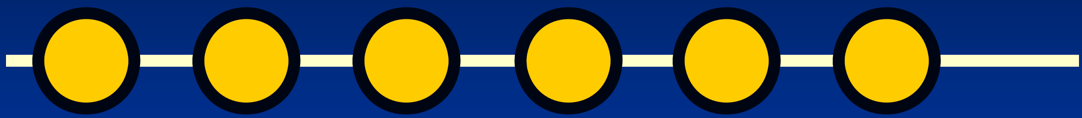
1D physics (Luttinger Liquids)

Experiments



T. Stoferle *et al.*
PRL **92** 130403 (2004)

Tonks limit



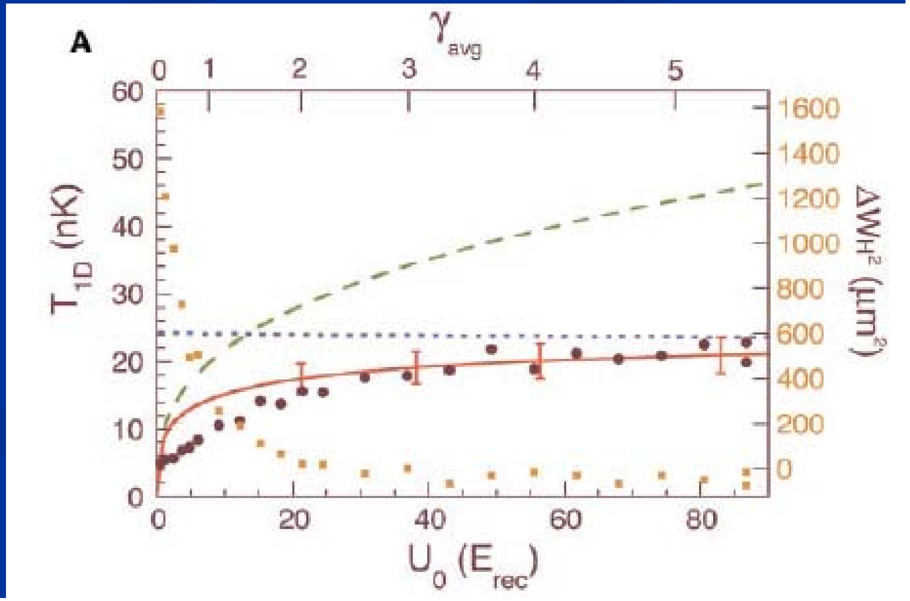
U = 4   : spinless fermions

Not for n(k) : $\psi_F \neq \psi_B$

B. Paredes et al Nature (2004)

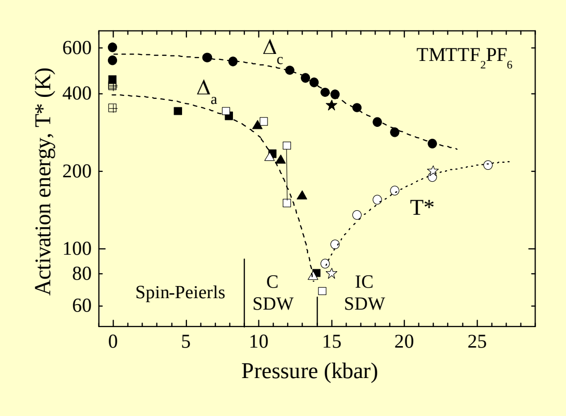
T. Kinoshita et al. Science (2004)

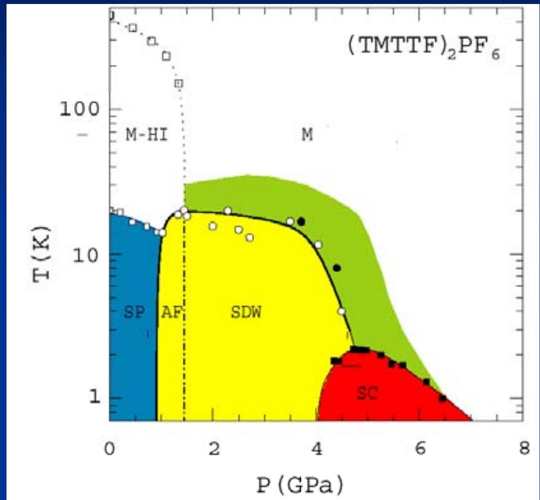
M. Kohl et al. PRL (2004)

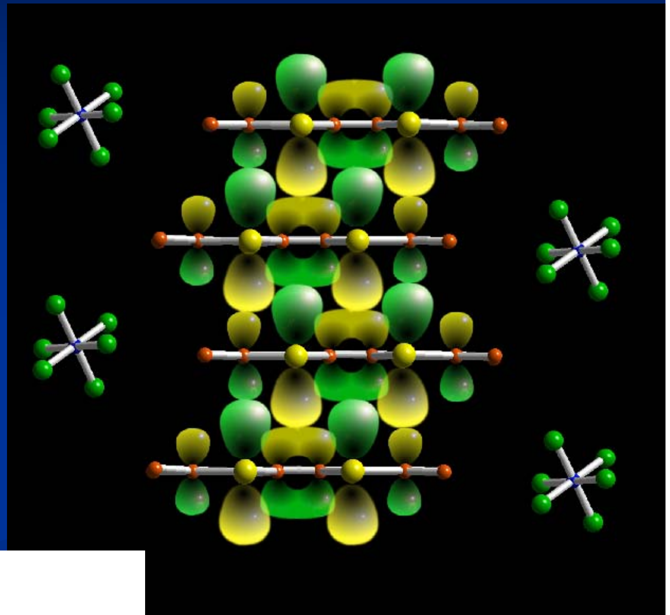


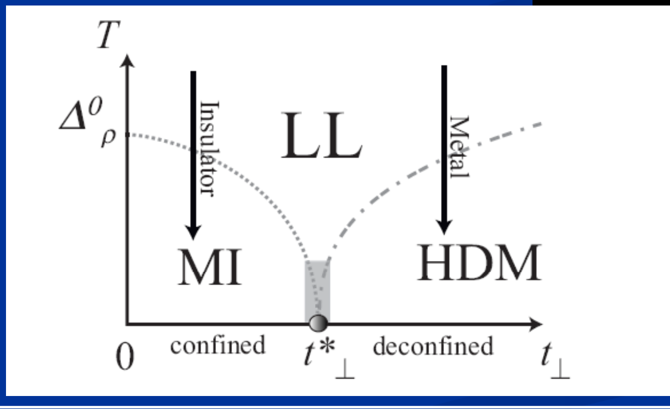
Coupled 1D Fermionic chains: Deconfinement

Deconfinement









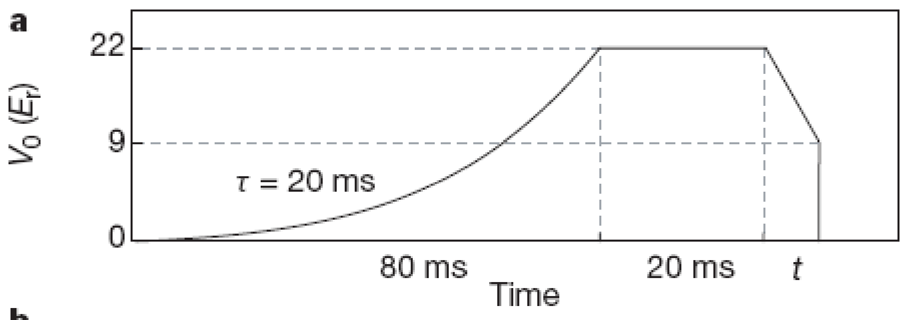
TG Chemical Review 104 5037 (2004)

P. Auban-Senzier, D. Jérome, C. Carcel and J.M. Fabre J de Physique IV, (2004)

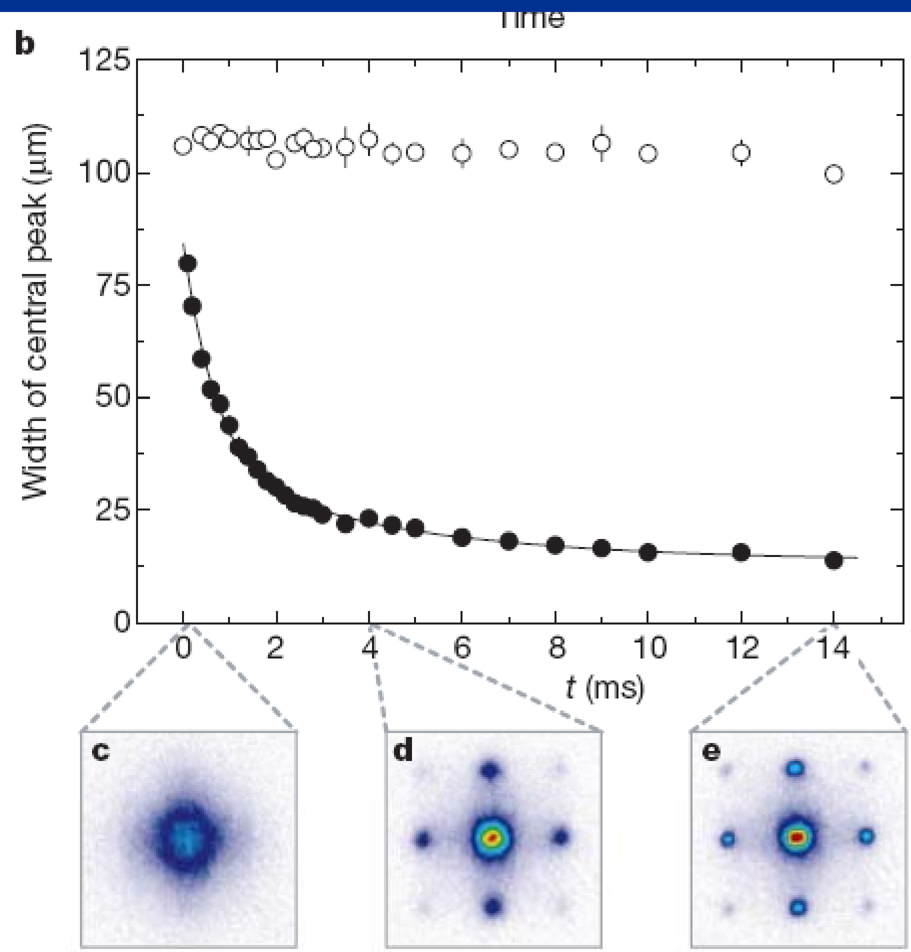
D. Jaccard et al., J. Phys. C, 13 L89 (2001)

New possibilities

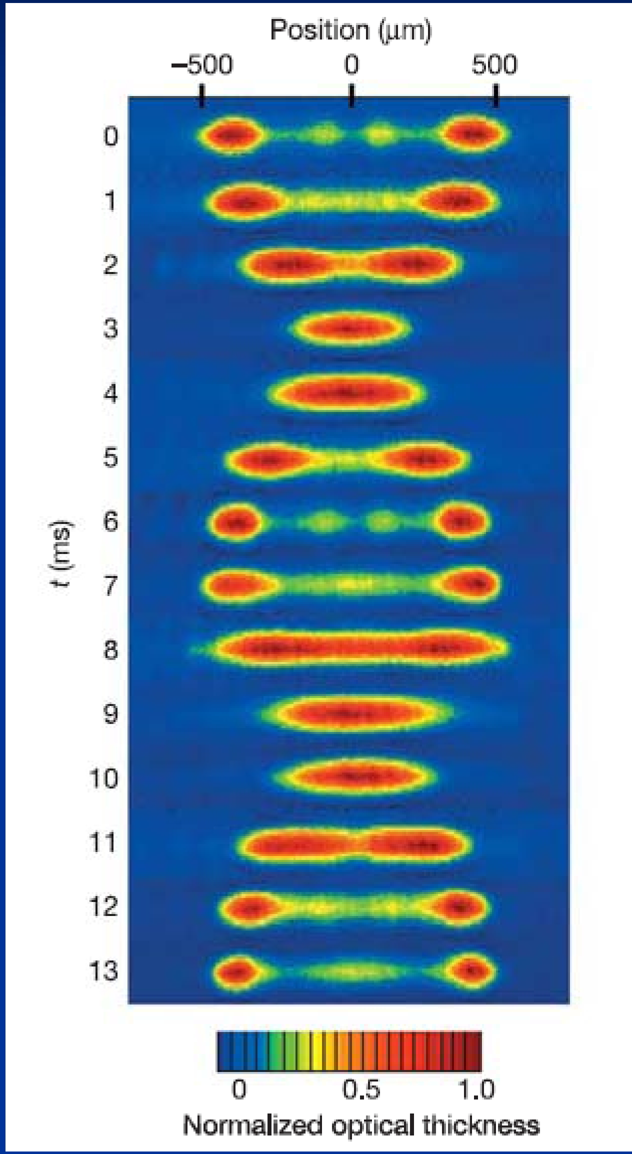
Out of equilibrium physics

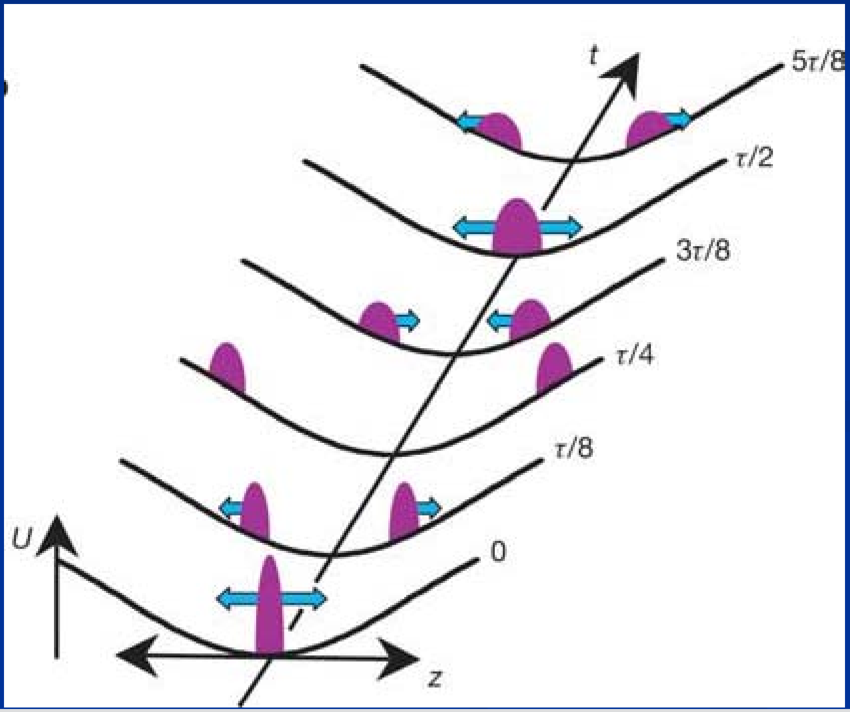


M. Greiner, O. Mandel, T. Esslinger,
T. W. Hansch, I. Bloch, Nature 415 39 (2002)



Quantum dynamics of isolated systems





nature Vol 440|13 April 2006|doi:10.1038/nature04693

LETTERS

A quantum Newton's cradle

Toshiya Kinoshita[1], Trevor Wenger[1] & David S. Weiss[1]

Bosons with "spins"

[L.E. Sadler *et. al.*, Nature **443**, 164 (2006)]

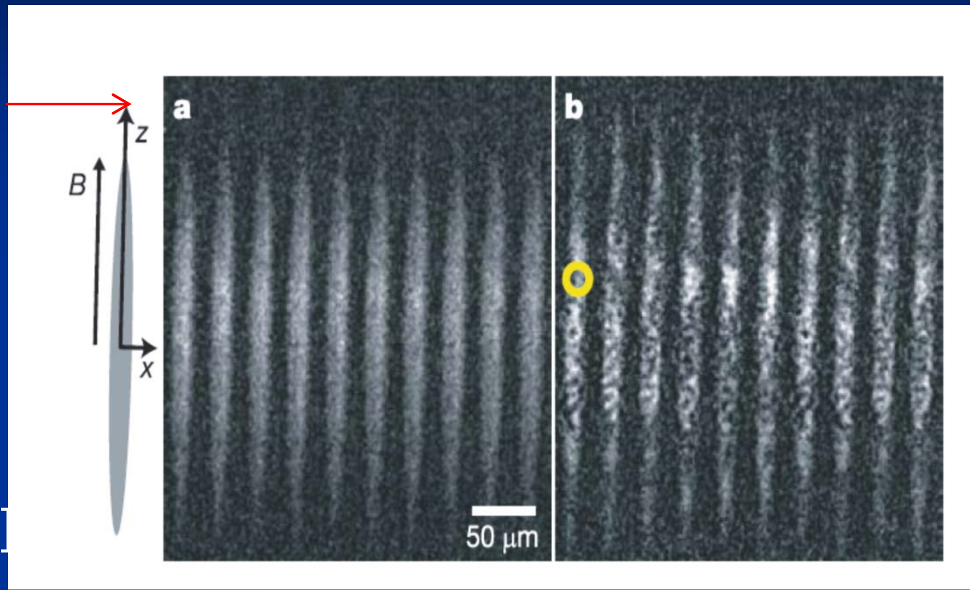
[J.M. Higbie *et. al.*, PRL **95**, 050401 (2005)]

^{87}Rb atoms, F=1 states

⇩

Spin 1 system

[J.M. McGuirk *et. al.*, PRL **89**, 090402 (2002)]



$|F=1, m_F=-1\rangle$ and $|F=2, m_F = 1\rangle$ "spin" ½ system

[M.Erhard *et. al.*, PRA **69**, 032705 (2004)]   [A. Widera *et. al.*, PRL **92**, 160406 (2004)]

Dream ??

The simulator is not perfect (yet)

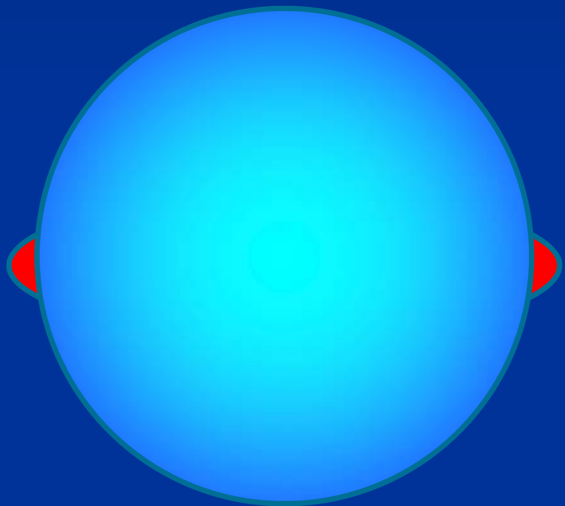
Température (Fermions)

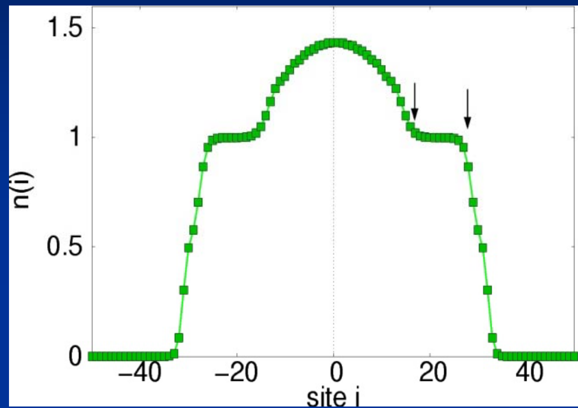
$T = 1$ nK

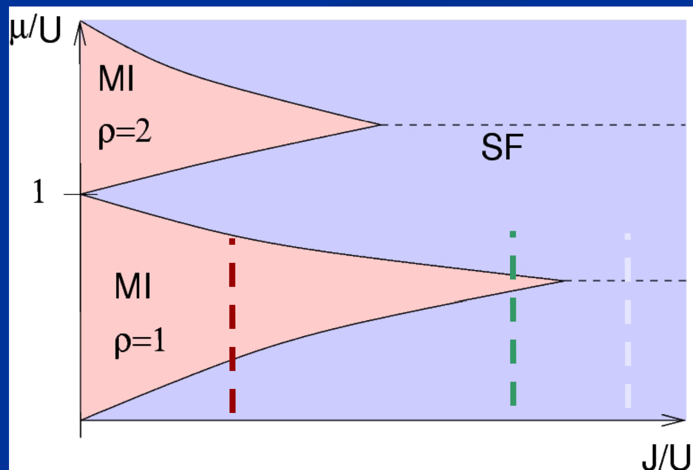
Mais T/T_F = 1/6

$T_{eff} = 2000$ K

Confining potential







$$H = v\, r^2\, \rho(r)$$

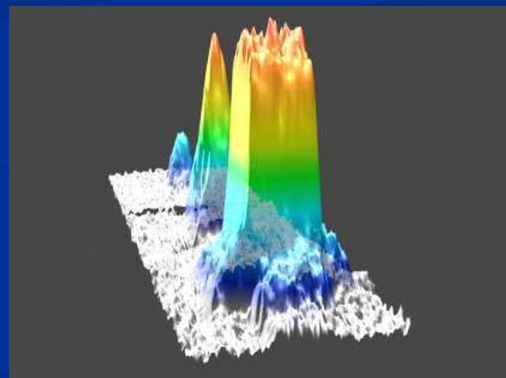
- No homogeneous phase !

Probes !

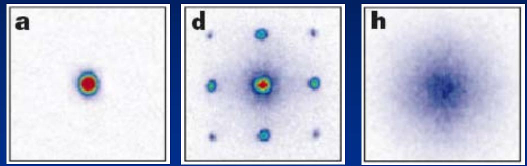
Atoms are neutral !

n(k) (time of flight) useless for fermions !

Need to probe correlations !

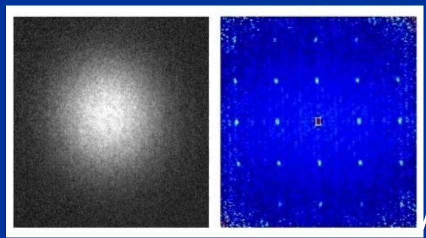


time-of-flight measurement
-> momentum distribution



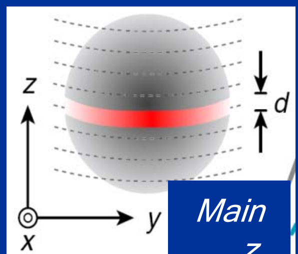
München

noise measurement:
-> density-density correlations



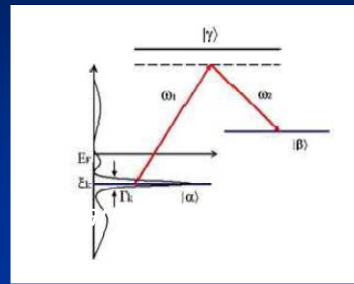
Mainz

microwave spin-changing
transitions
density spatially resolved

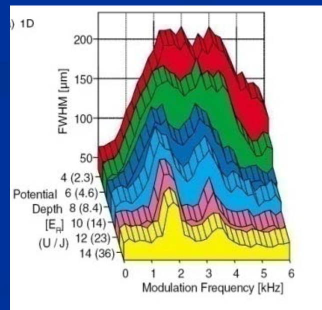


Main z

proposed: Raman spectroscopy
->Green's function, Fermi surface

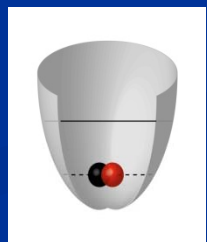


periodic lattice modulation



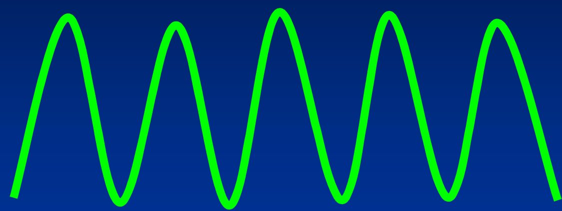
Zurich

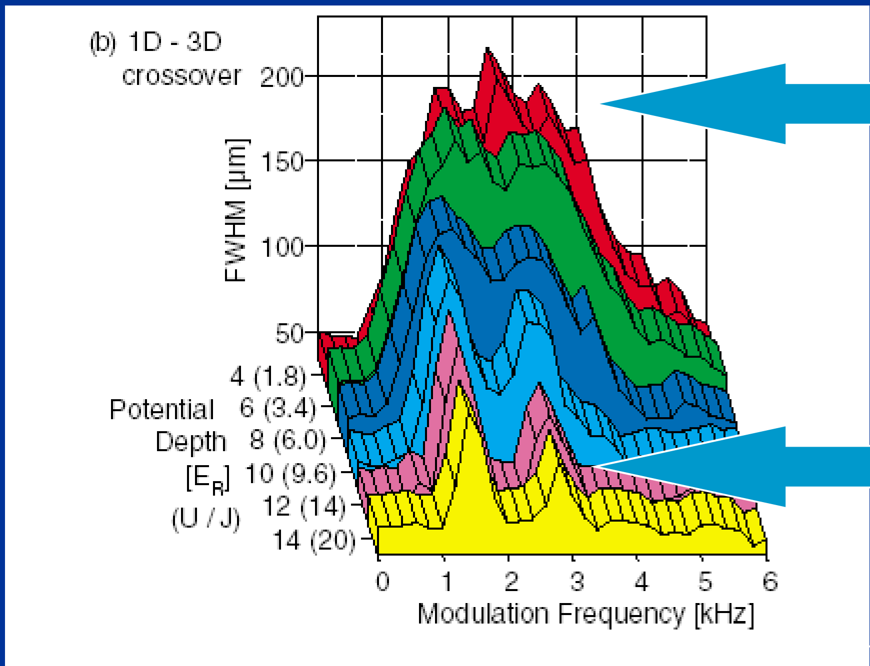
molecule formation
binding energy
doubly occupied sites



Shaking of the lattice

T. Stoferle *et al.* PRL **92** 130403 (2004)





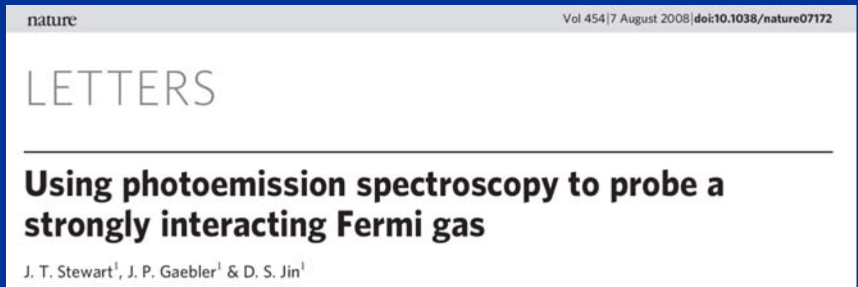
3D superfluid

Not so simple !

Mott ins.

A. Iucci, M.A. Cazalilla, AF Ho, TG, PRA **73**, 041608R (2006);
C. Kollath, A. Iucci, TG, W. Hofstetter, U. Schollwock, PRL 97 050402 (06)
C. Kollath et al. PRA 74 041604(R) (2006):

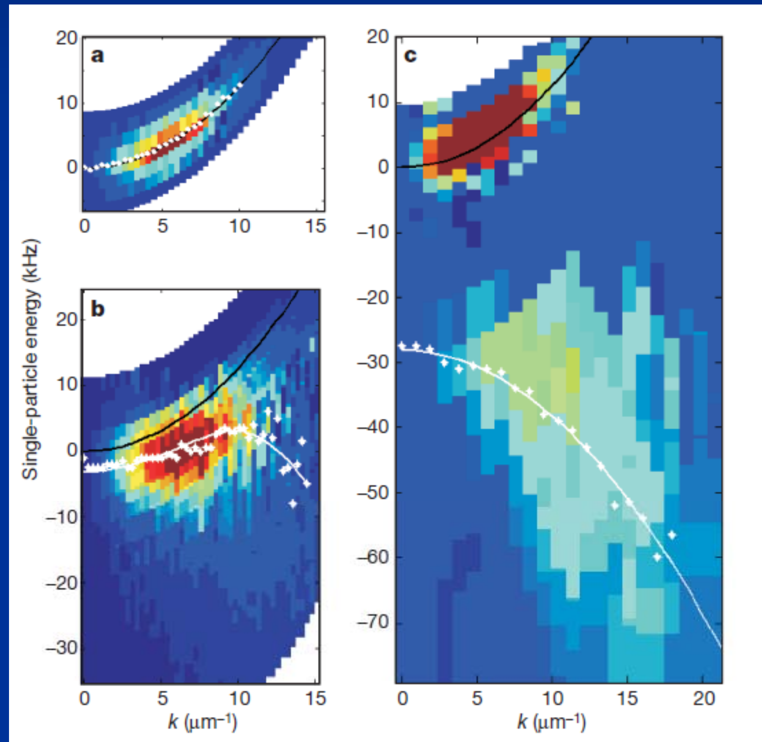
“Photoemission”


nature Vol 454|7 August 2008|doi:10.1038/nature07172

LETTERS

Using photoemission spectroscopy to probe a strongly interacting Fermi gas

J. T. Stewart[1], J. P. Gaebler[1] & D. S. Jin[1]



Observation in "real time" 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]

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- Figures and tables

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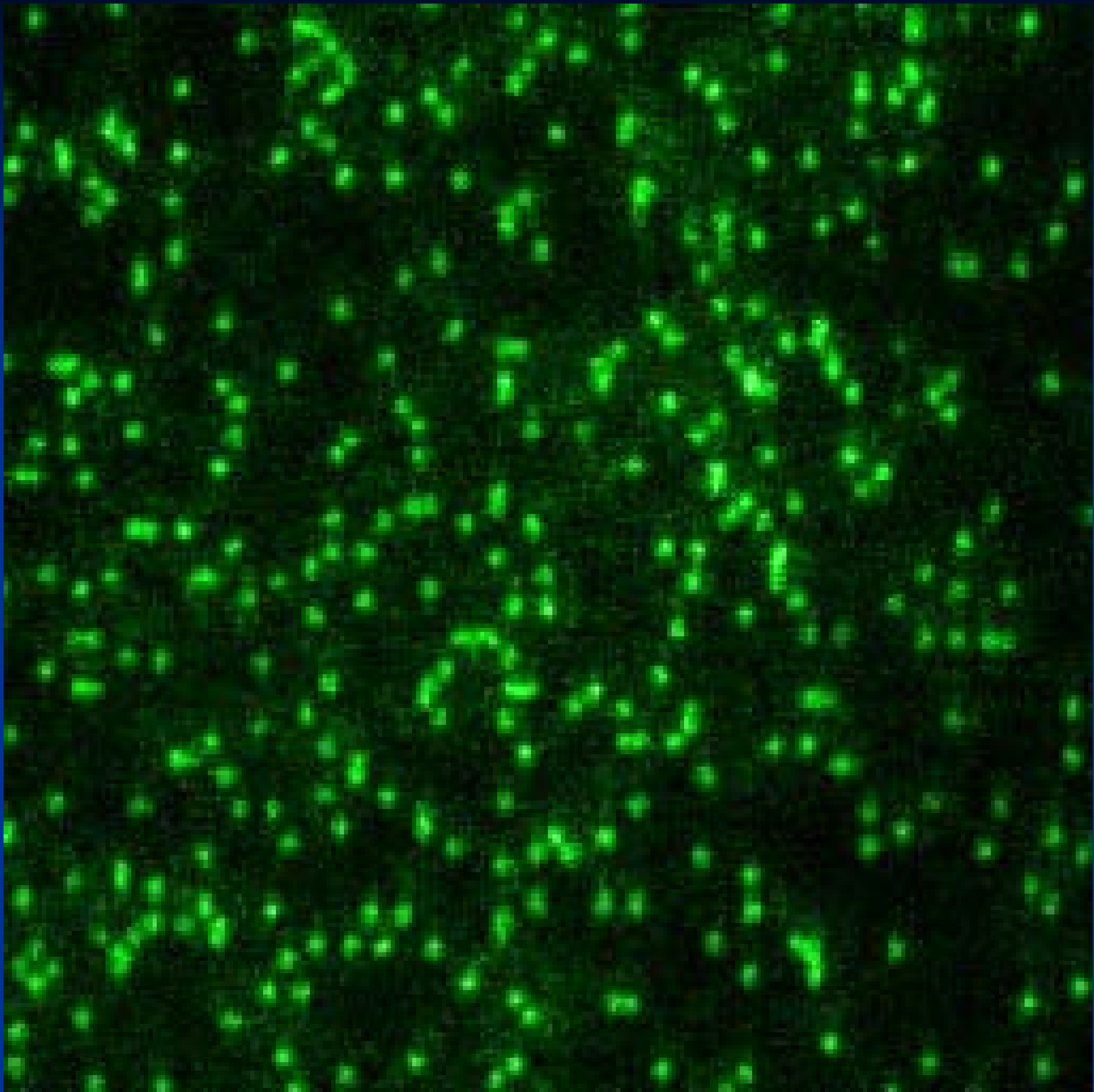
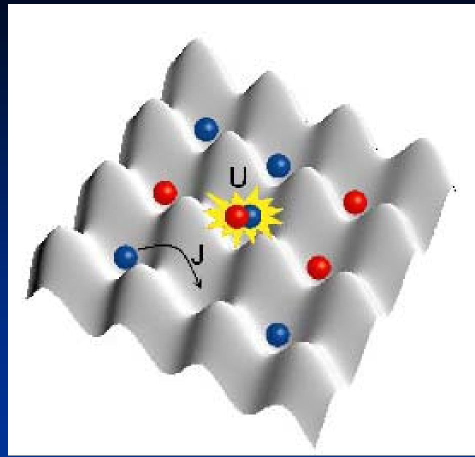
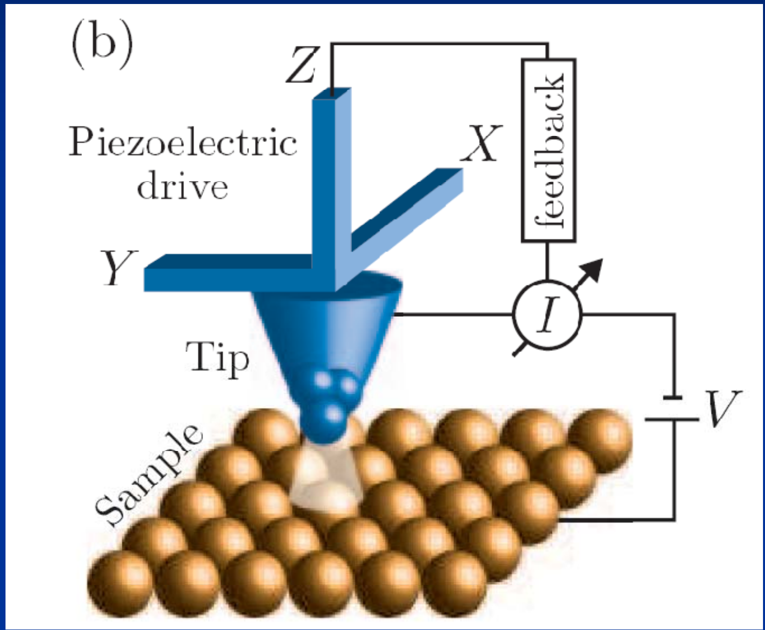
ARTICLE TOOLS





M. Greiner et al.

Need local probes !

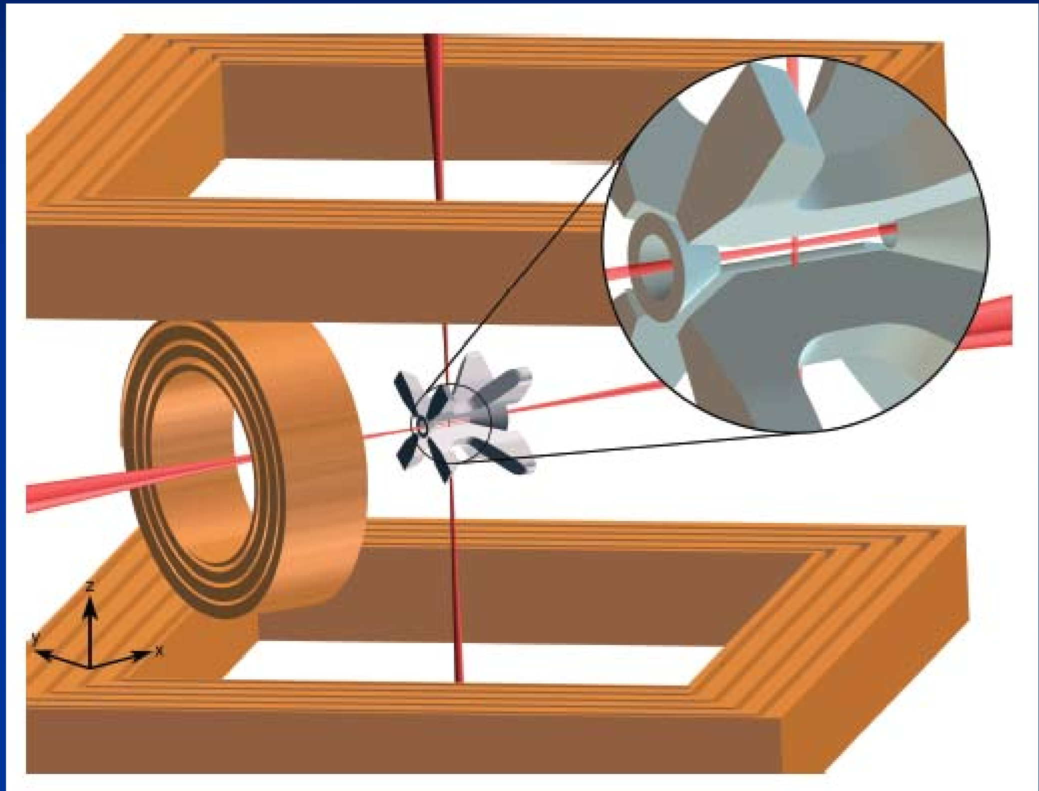


STM

CAT

C. Kollath, M. Koehl, TG PRA 76 063602 (2007)
Physics Web
http://physicsweb.org/articles/news/11/4/13/1

Ions + cold atoms



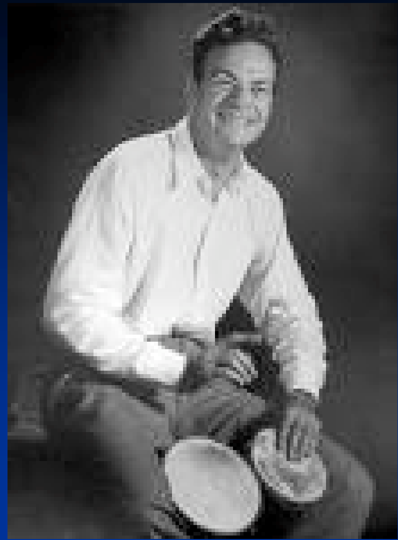
A trapped single ion inside a Bose-Einstein condensate

Christoph Zipkes, Stefan Palzer, Carlo Sias, and Michael Köhl

Cavendish Laboratory, University of Cambridge, JJ Thomson Avenue, Cambridge CB3 0HE, United Kingdom

Conclusions

- Cold atoms/condensed matter: complementary
- Cold atoms: quantum simulators
- Tunability and local interactions. Ideal to explore low dimensional physics.
- Offer new exciting possibilities (out of equilibrium, isolated quantum systems, etc.).
- Inhomogeneous phases
- Probes



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)