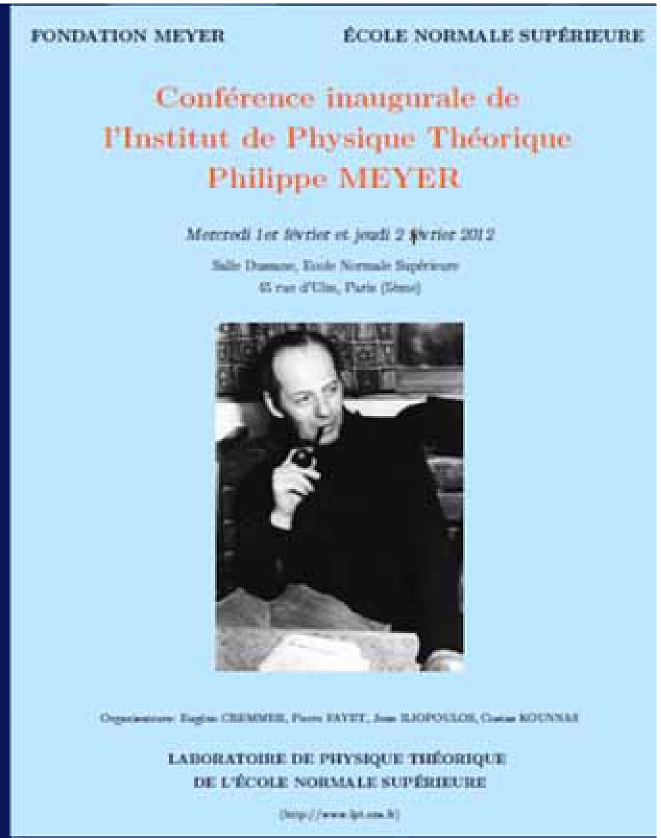
Open questions in condensed matter

T. Giamarchi

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



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P. Bouillot

A. Tokuno

A. Kozenkov

T. Ewart

T. Jarlborg

E. Agoritsas

P. Chudzinski

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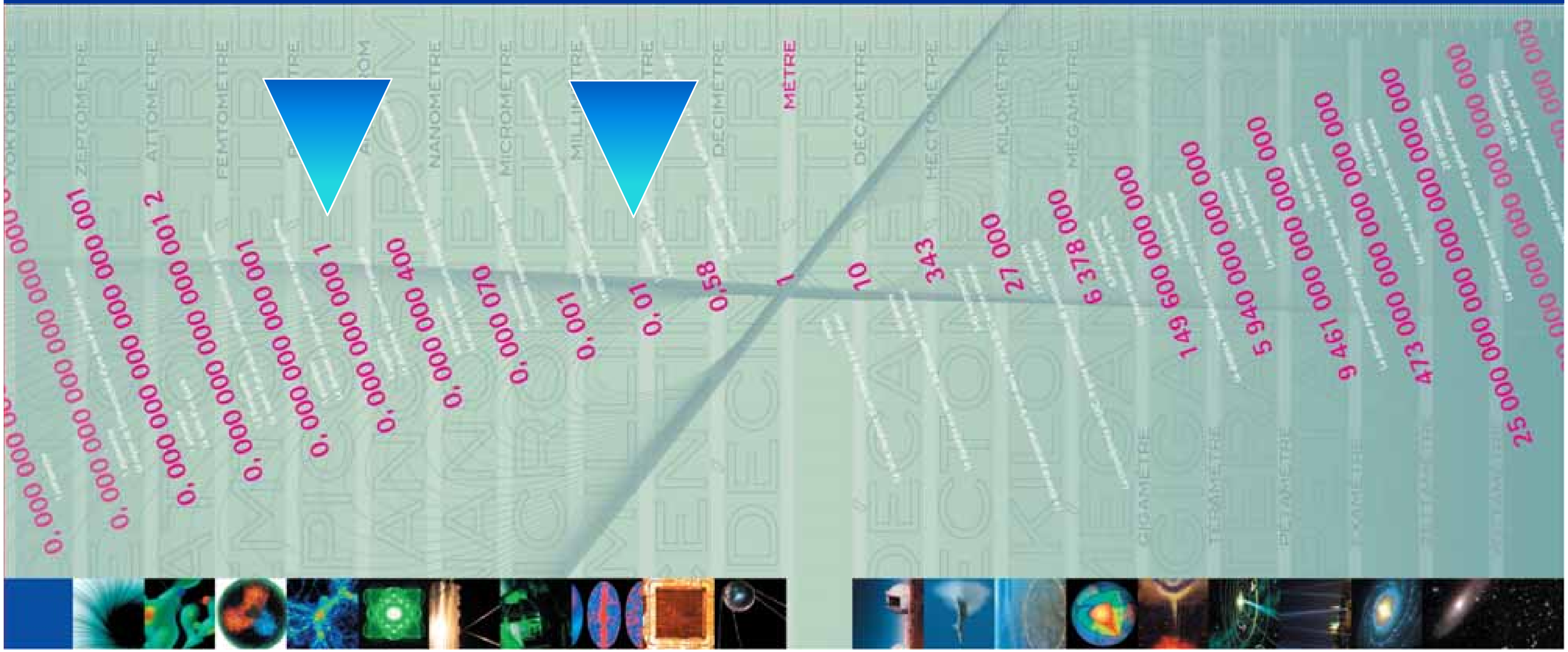
H. J. Schulz

P. Le Doussal
(ENS, Paris)

A. Georges
(X, Collège Fr.)

Condensed matter physics



Understand, prédict

and control

the properties of

materials

Fundamental research

Applied research

Applied

Are not just the results of engineers and corporations

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."

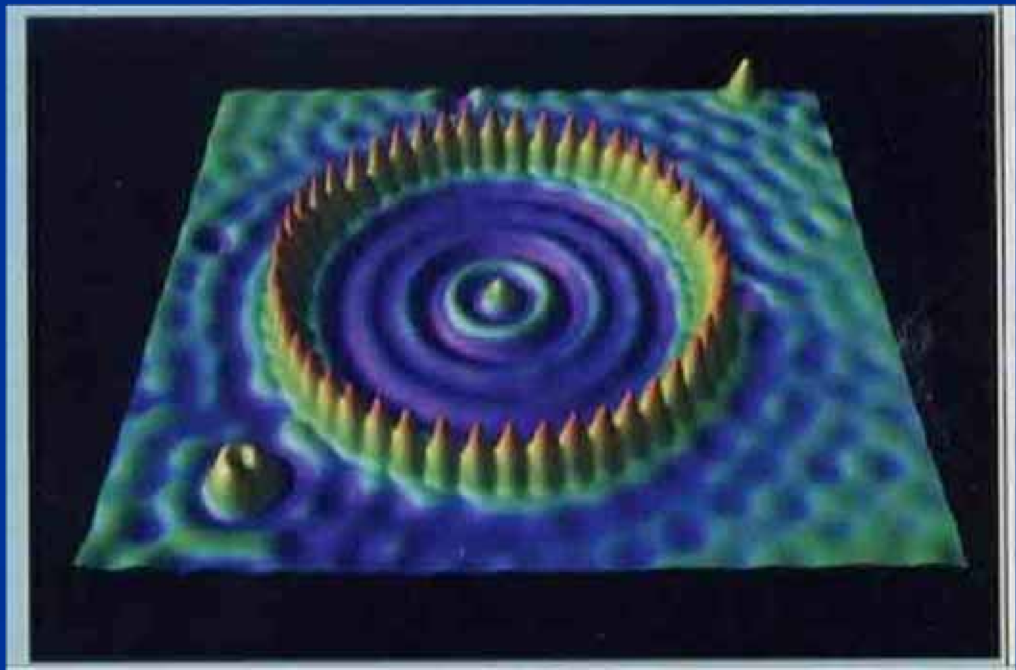
P. A. M. Dirac, "Quantum Mechanics of Many-Electron Systems“, Proceedings of the Royal Society of London, Series A, Vol.123, April 1929, pp 714.

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

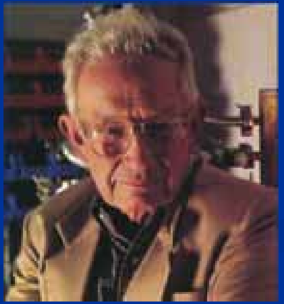
- Quantum mechanics
  you can touch !



(D. Eigler et al.)

Quantum mechanics / Complexity

- Interactions : 10^{23} interacting, degenerate quantum particles (at finite temperature)
- Collective phenomena ``More is different'' (Anderson) :



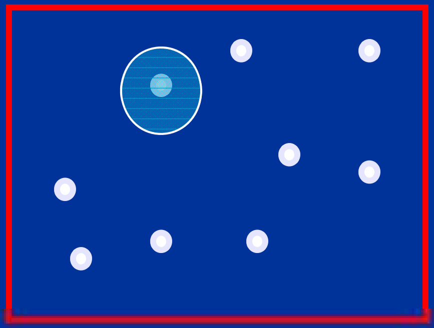
- Superconductivity, Superfluidity, Charge density waves, Josephson effect, Haldane gap, Laughlin quasiparticles, …….

How to attack such a problem ?

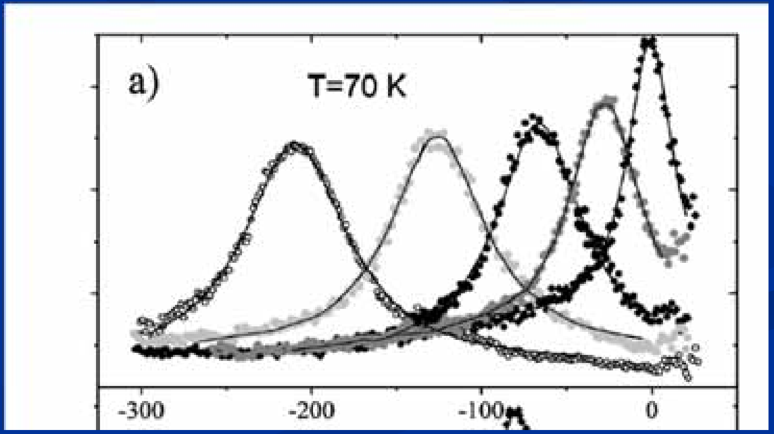
Effect of interactions

- Landau Fermi liquid

- Individual fermionic excitations exist (quasiparticles)



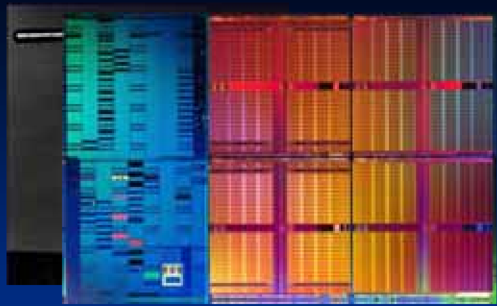
$$m \to m^*$$

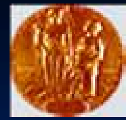


T. Valla et al. PRL 83 2085 (1999)

One electron physics

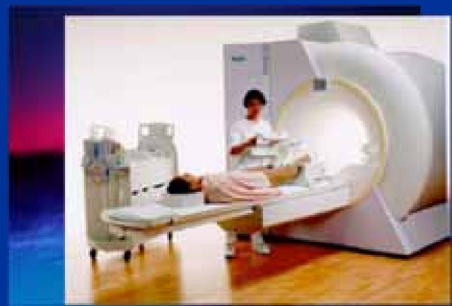
- Transistor





1956

- Superconductivity



(1913),1972, 1973,1987,2003

- Giant magnetoresistance

2007

But….

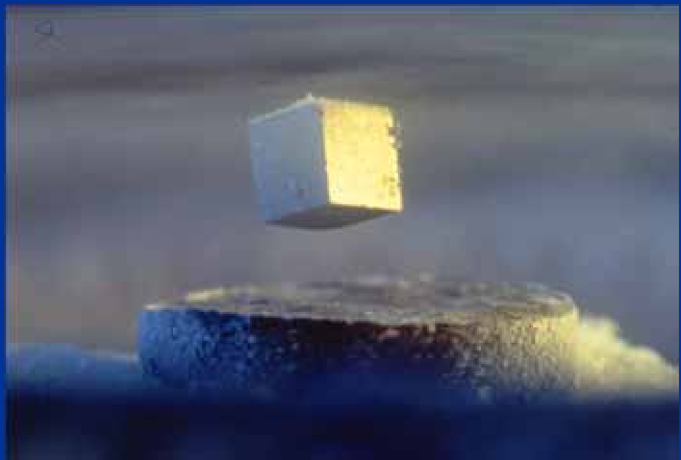
Need to understand interactions !

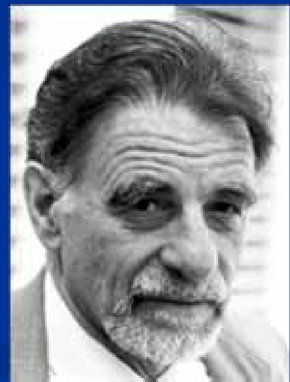
- Conceptual level:
  - 1 e physics easy to solve (numerically)

- Applications: limits of current technologies
  - electronic [density of energy in a processor 1/10 of the one of a nuclear power plant
  - memories
  - energy efficient systems (thermopower, solar cells etc.)

New interesting materials

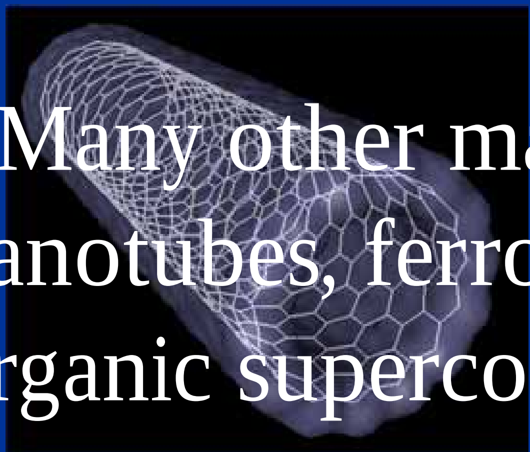
- Superconductivity in oxides (1986):



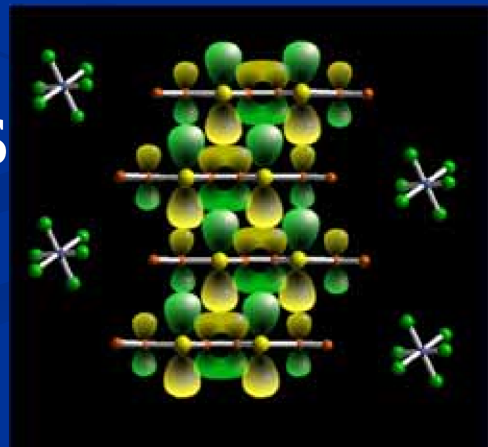


Tc ~ 130 K

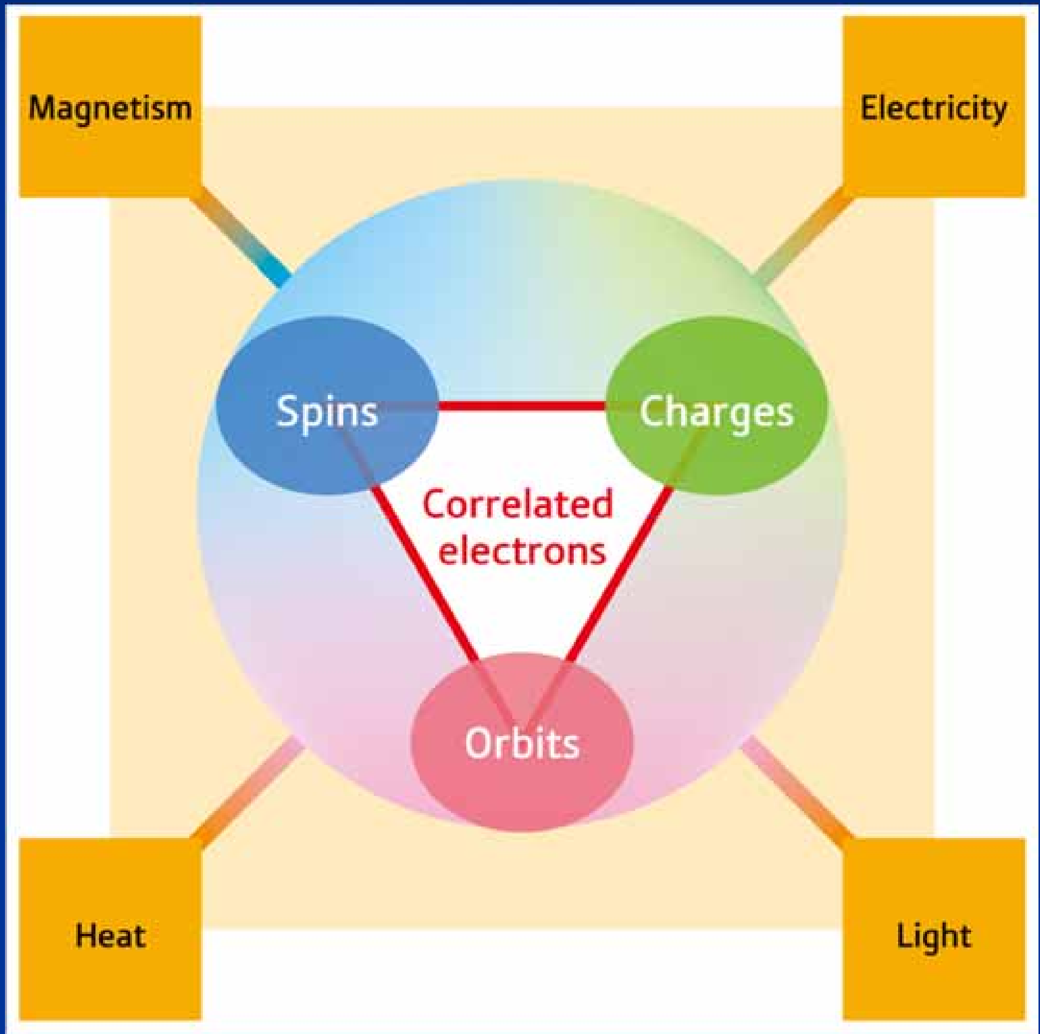
Bednorz Muller



- Many other materials: (manganites nanotubes, ferroelectrics, organic superconductors….)



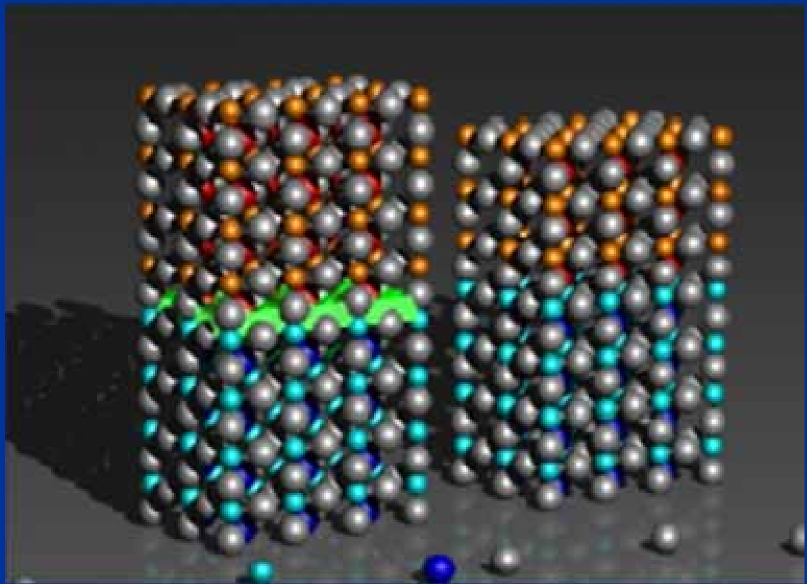
Finding new functionalities /physics

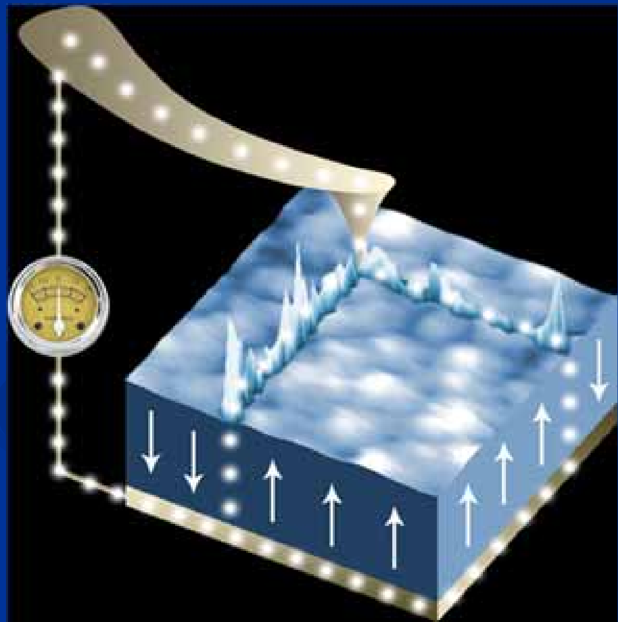


(Y. Tokura, Japan)

Physics at the edge

- New functionalities at interfaces:

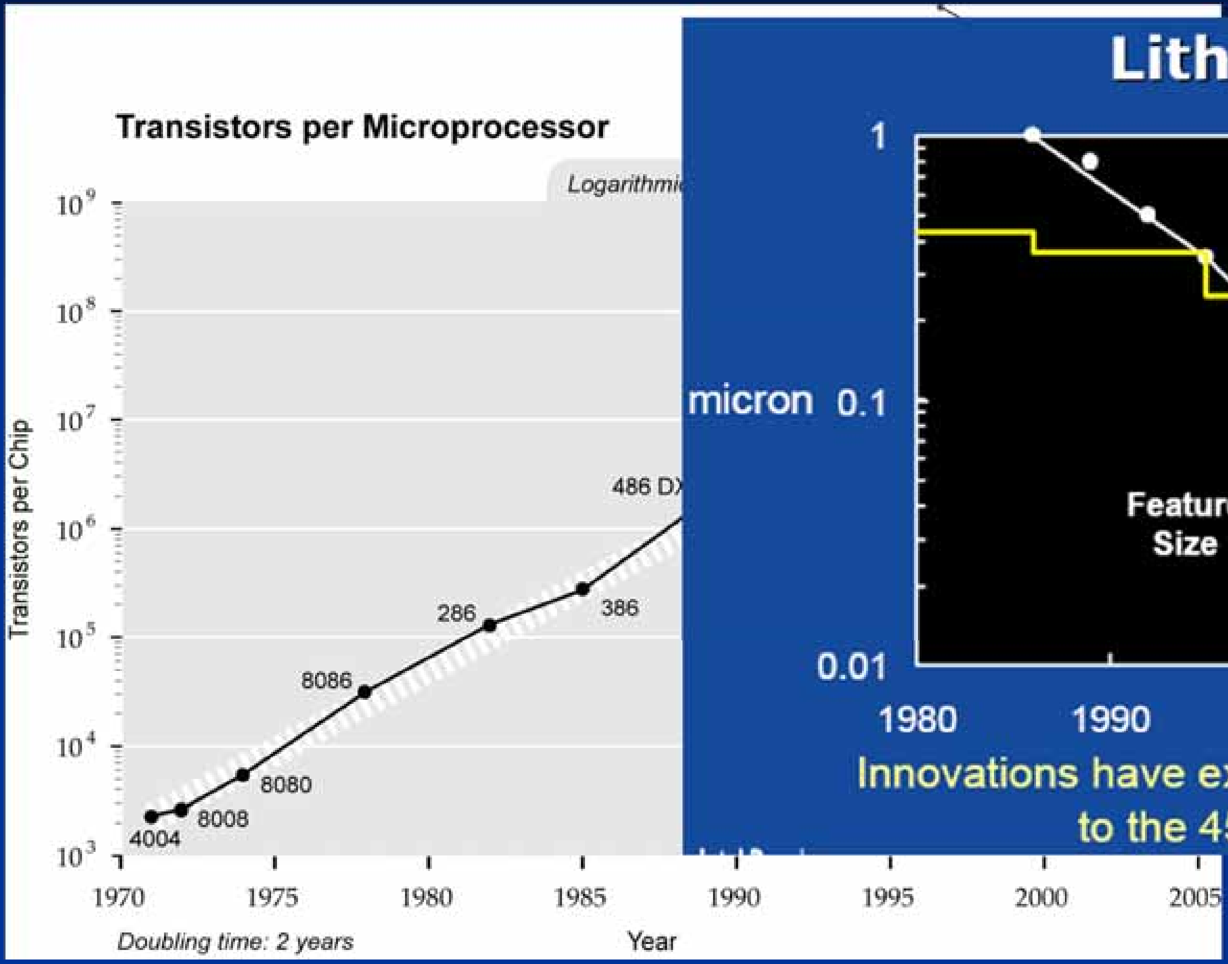


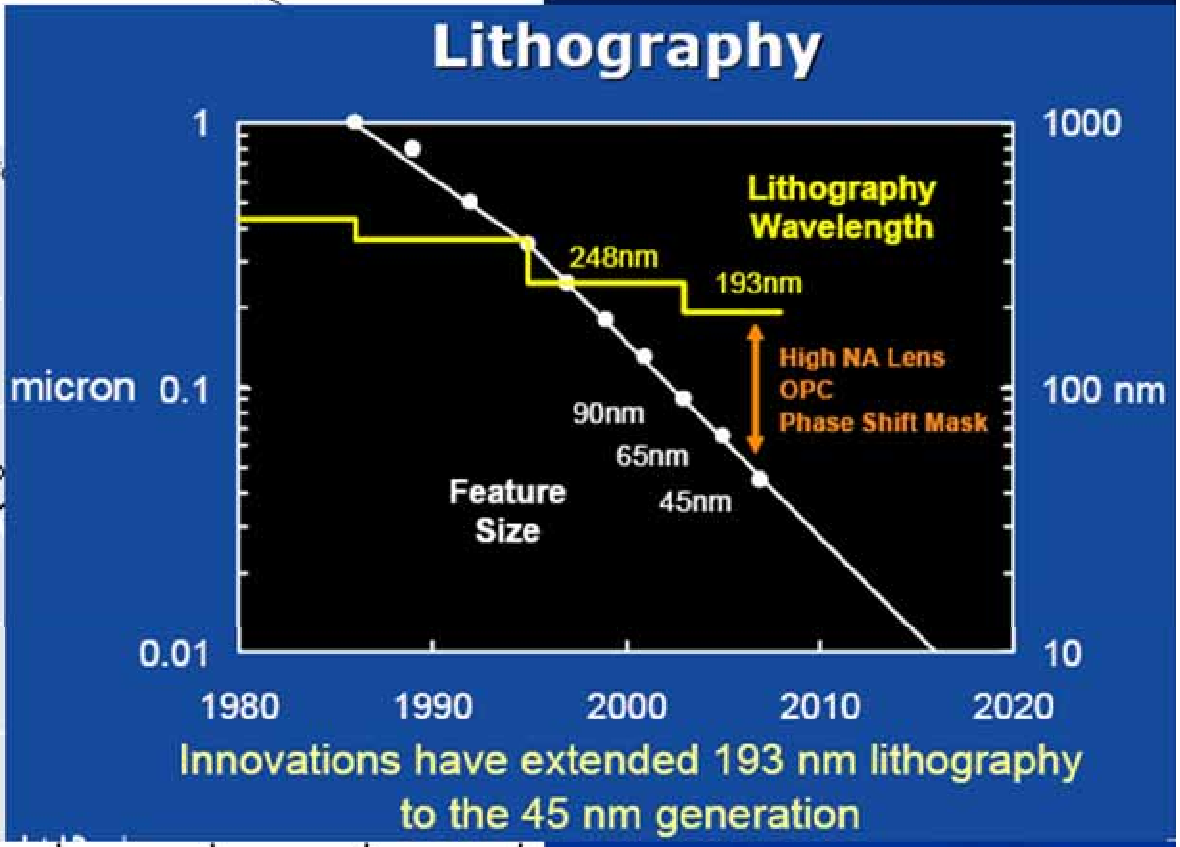


LaO / StO interface
(JM Triscone et al.)

Conducting domain walls
(P. Paruch et al.)

Future electronic

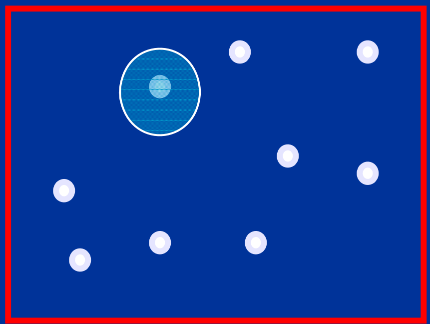




Need to worry about reduced dimensionality

Reduced dimensionality: interactions

- No individual excitation can exist (only collective ones)



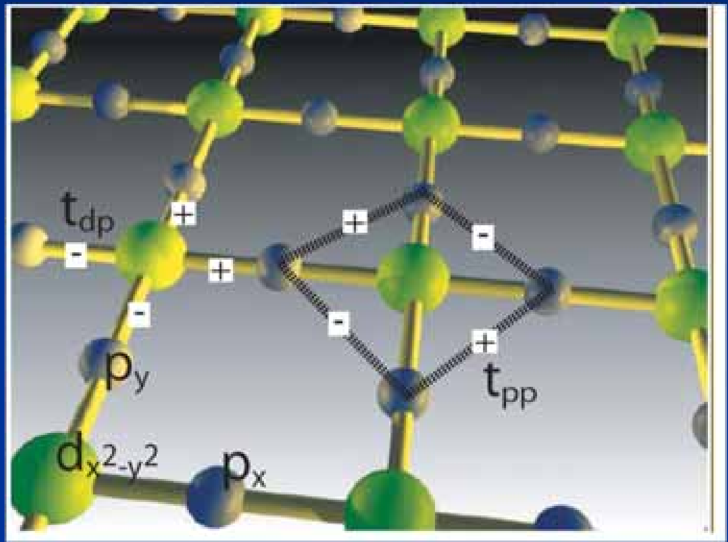
- Strong quantum fluctuations

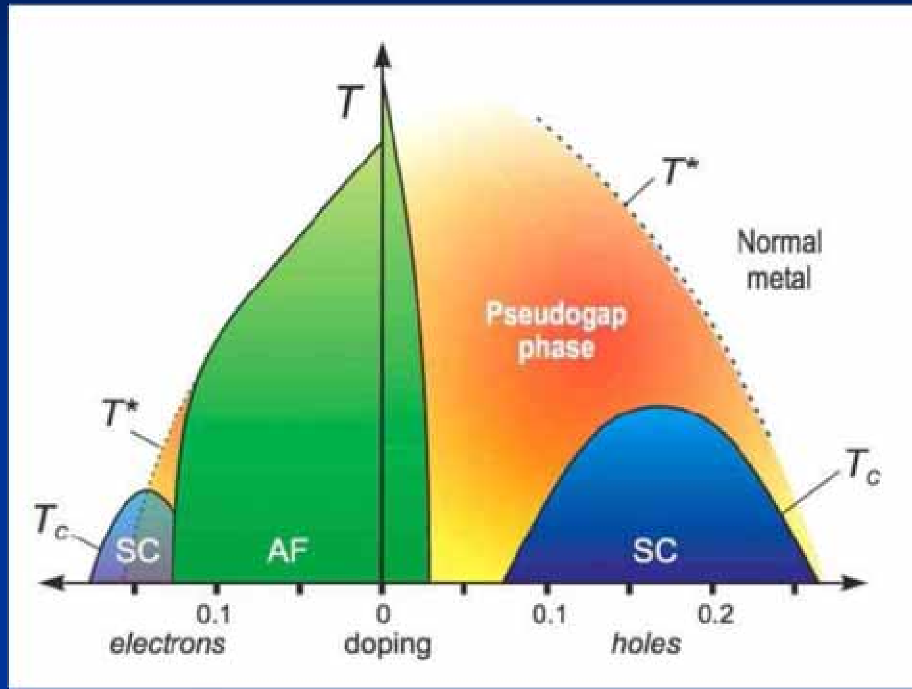
$$\langle \psi \rangle = \rho_0^{1/2} e^{i\theta}$$

Difficult to order

Strategies ?

Find a simplified model

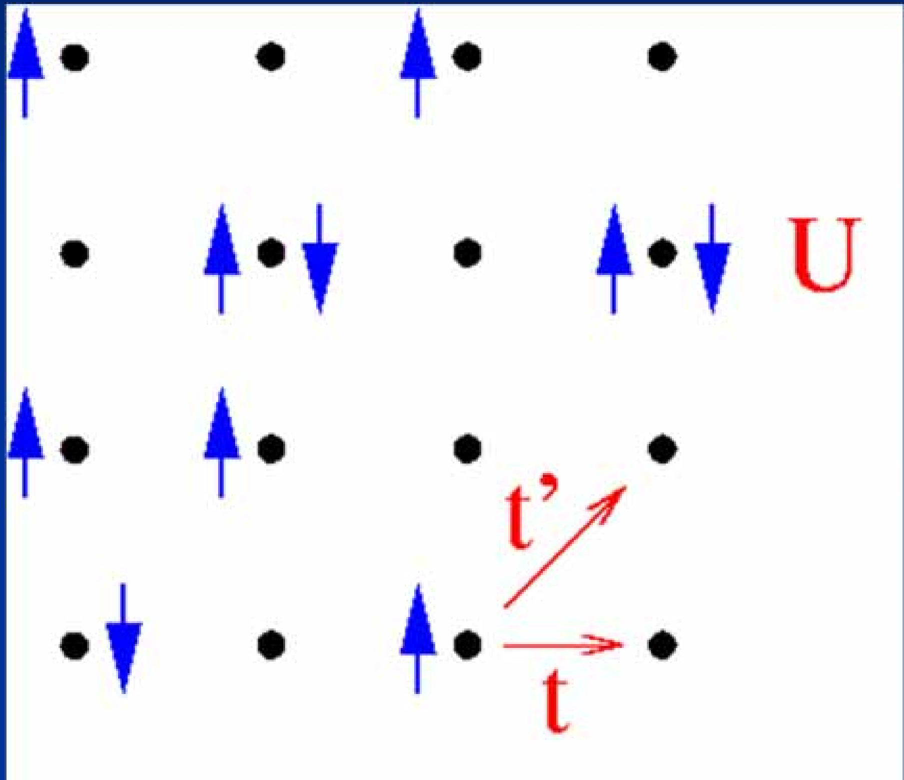




Simplest model with:

- Kinetic energy of the electrons
- Interactions

Hubbard model (1963)



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

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, ….. ????)

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

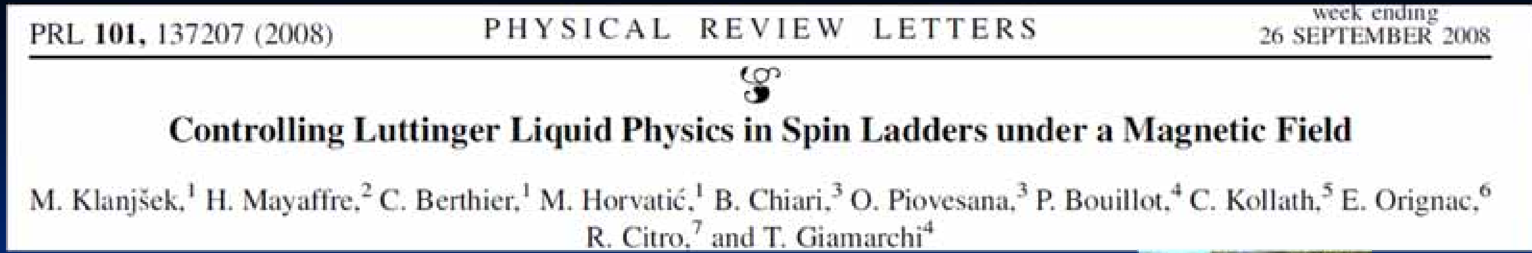
Quantum spins

- Spin ½ : hard core boson (spinless fermion)

- Magnetic field : chemical potential
  Magnetization: number of ``particles''

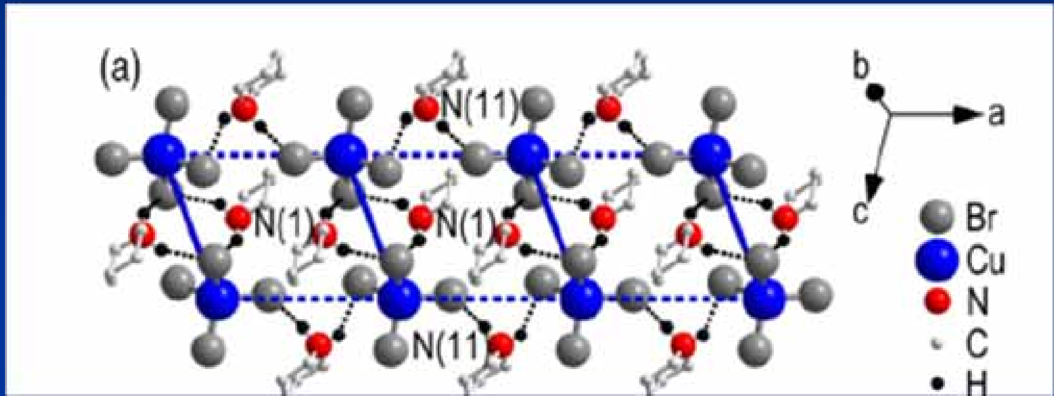
- Simulation of interacting itinerant quantum particles

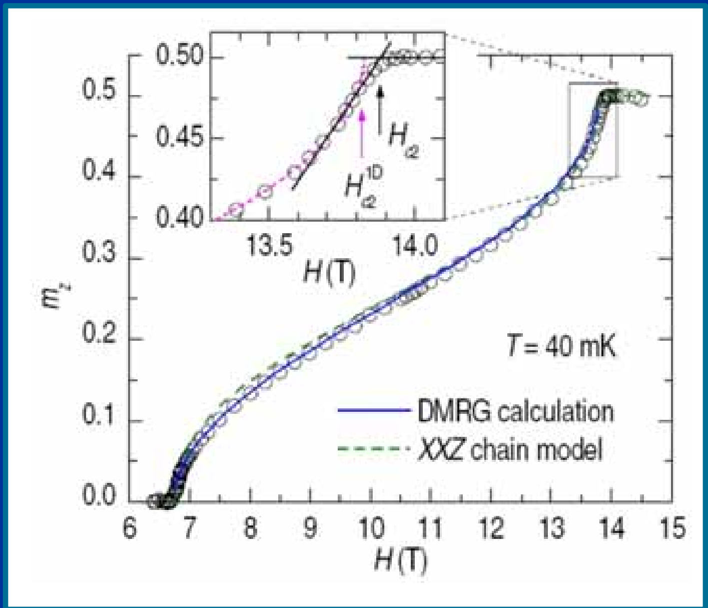
TG, C. Ruegg, O. Tchernyshyov, Nat. Phys. 4 198 (2008)

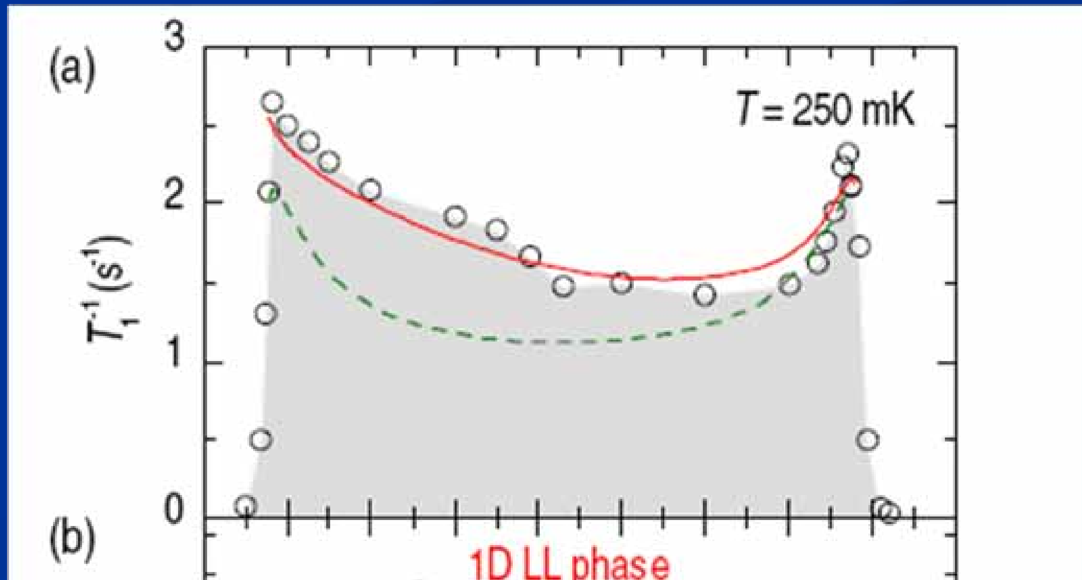

PRL **101,** 137207 (2008) PHYSICAL REVIEW LETTERS week ending 26 SEPTEMBER 2008

Controlling Luttinger Liquid Physics in Spin Ladders under a Magnetic Field

M. Klanjšek,[1] H. Mayaffre,[2] C. Berthier,[1] M. Horvatić,[1] B. Chiari,[3] O. Piovesana,[3] P. Bouillot,[4] C. Kollath,[5] E. Orignac,[6] R. Citro,[7] and T. Giamarchi[4]

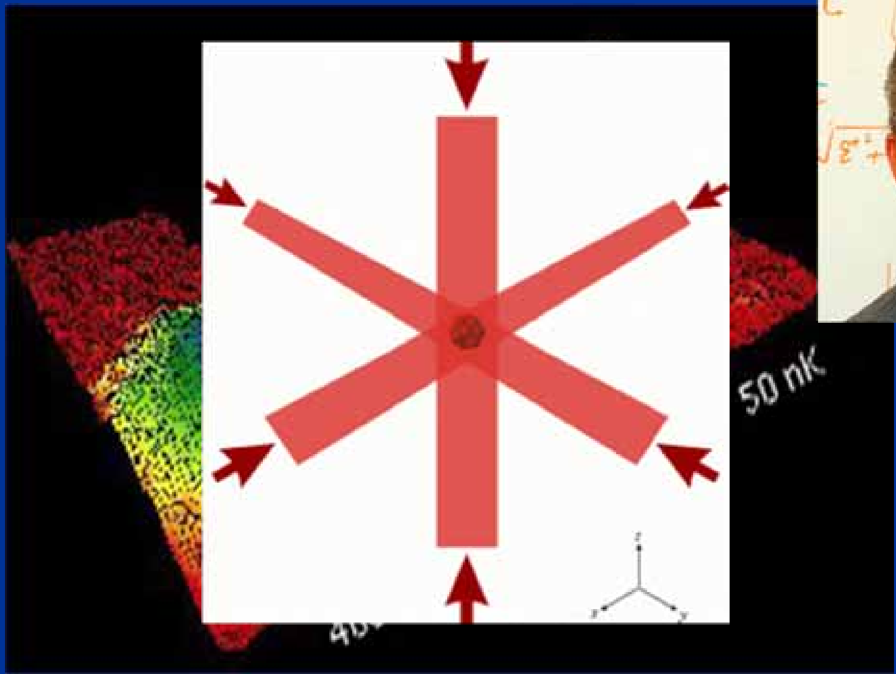


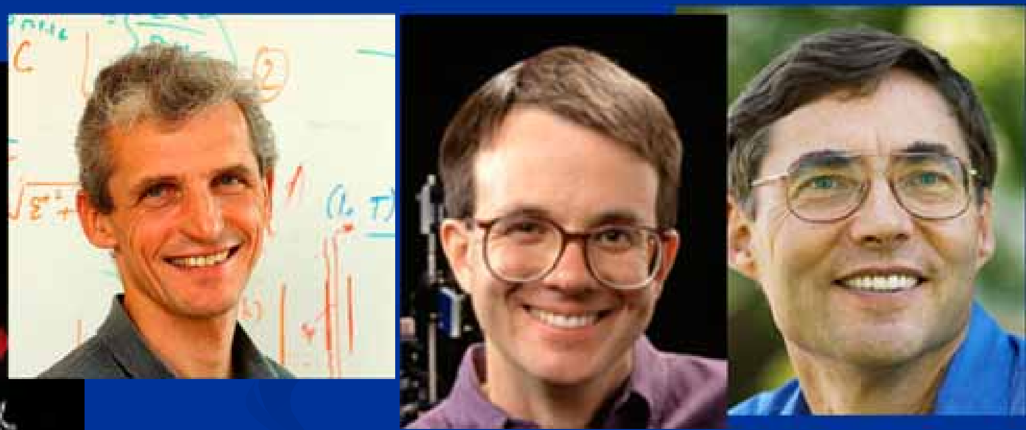




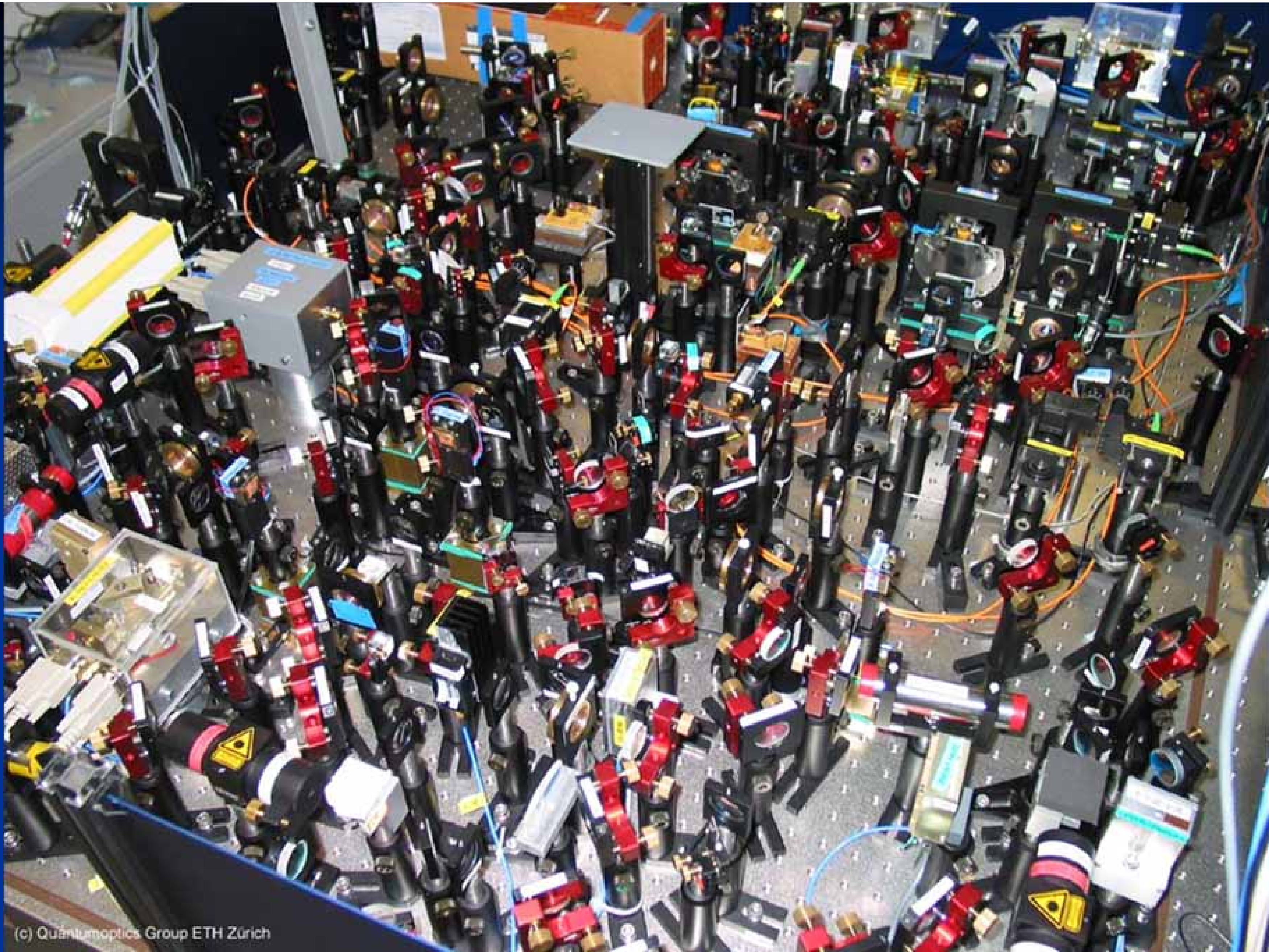
Help from another field of physics

Cold atomic gases



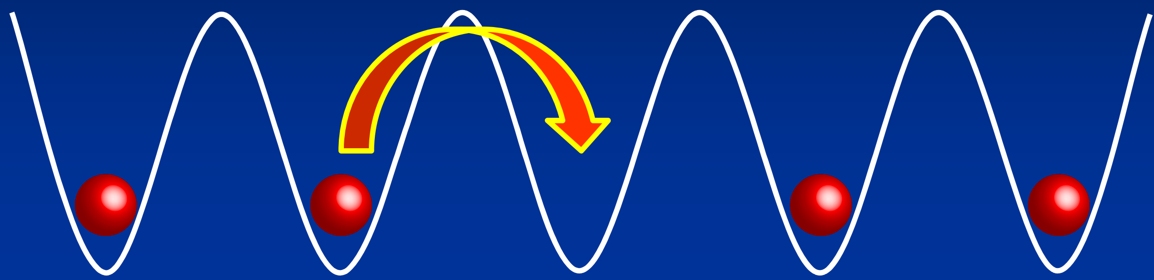


2001: Cornell, Ketterle, Wieman



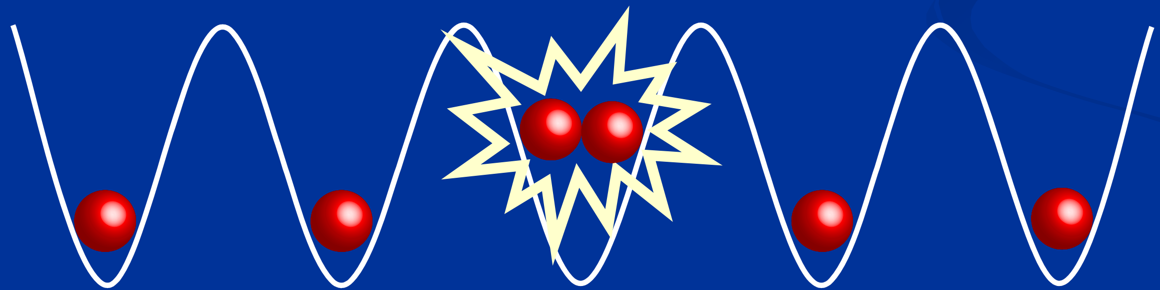
Groupe: T. Esslinger (ETH, Zurich)

Use light to make an artificial solid

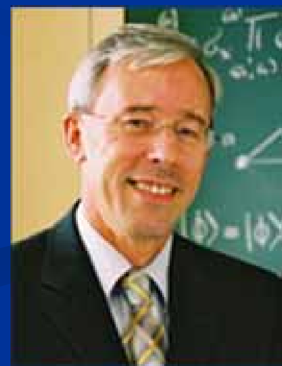


Tunnel barrier

Short range interaction

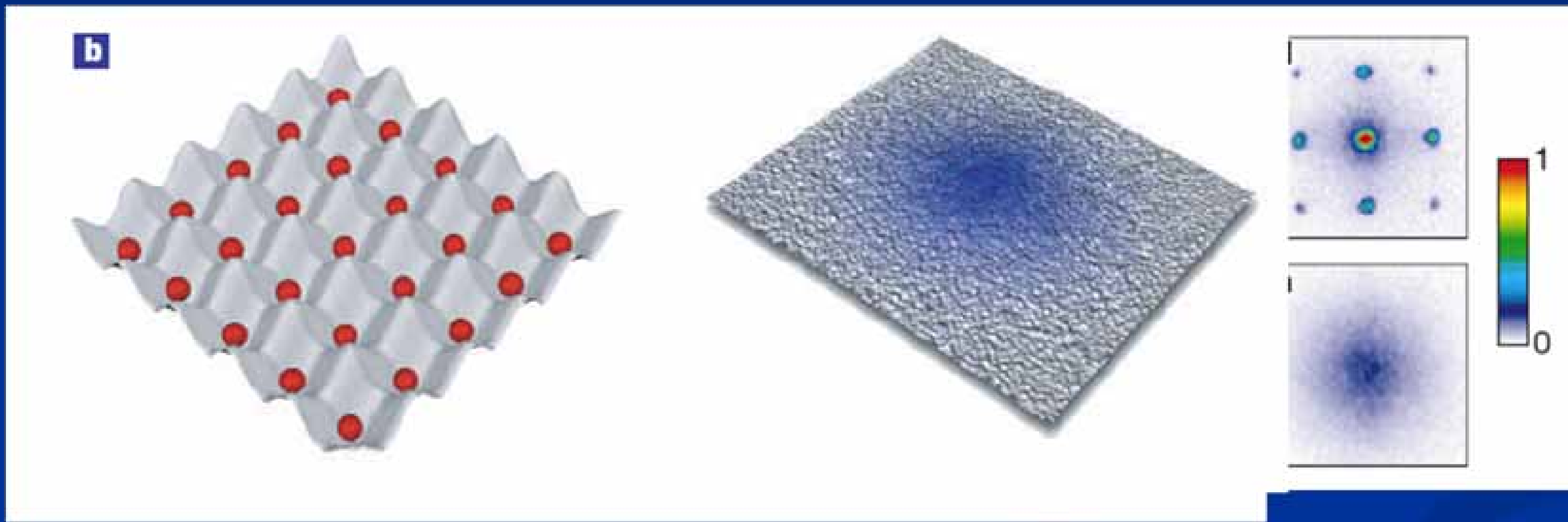


Idea: D. Jaksch et al PRL81 3108 (98)



P. Zoller

Quantum simulators for condensed matter

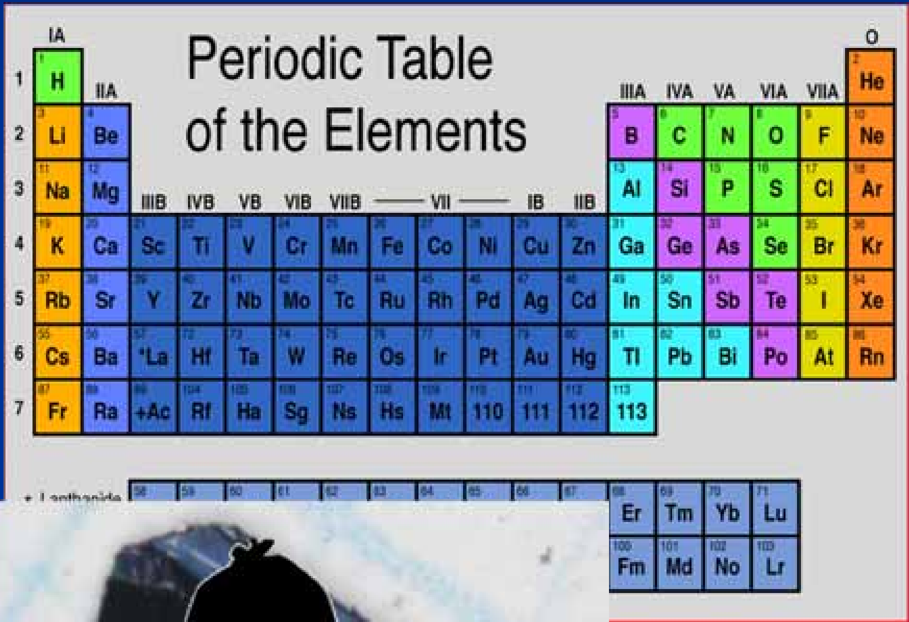


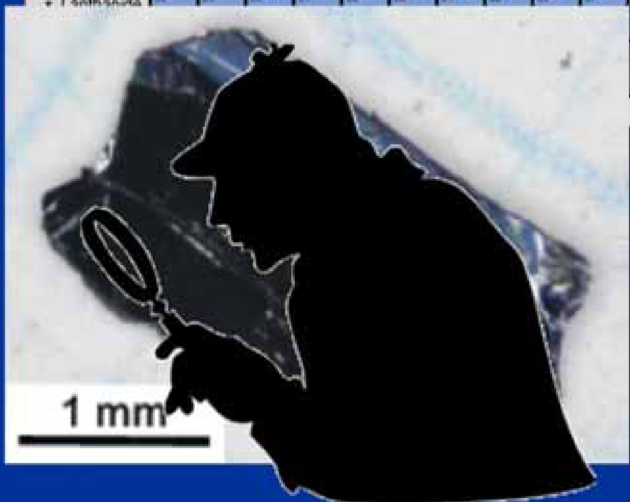
M. Greiner, O. Mandel, T. Esslinger, T. W. Hansch, I. Bloch, Nature 415 39 (2002)

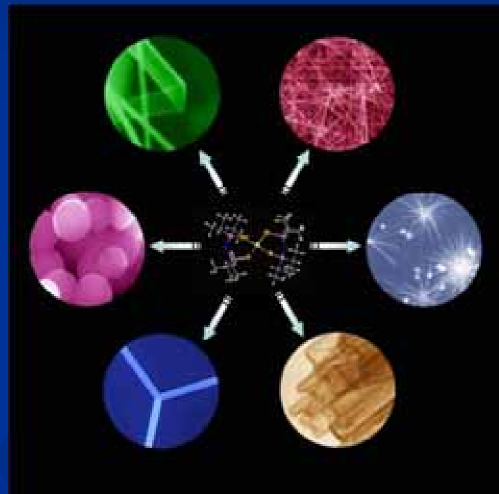
Future….

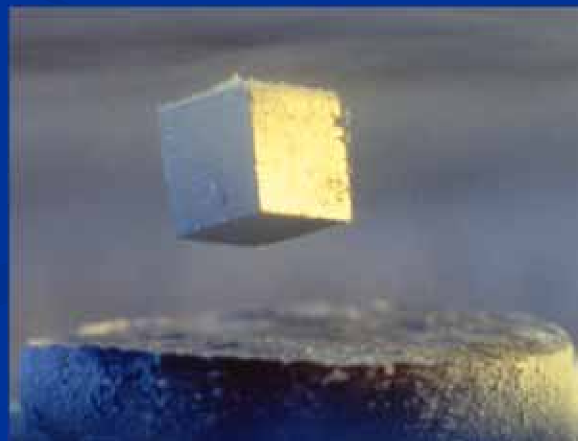
Complexitiy of combining elements

www.manep.ch

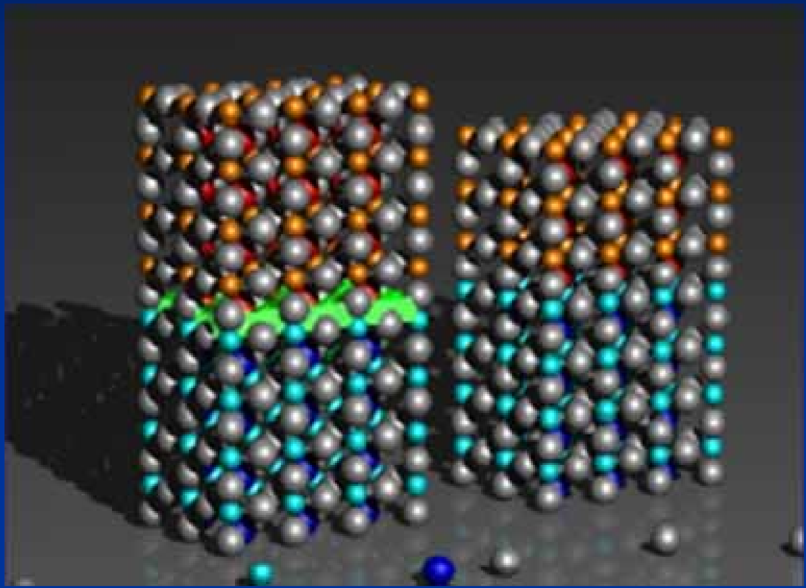


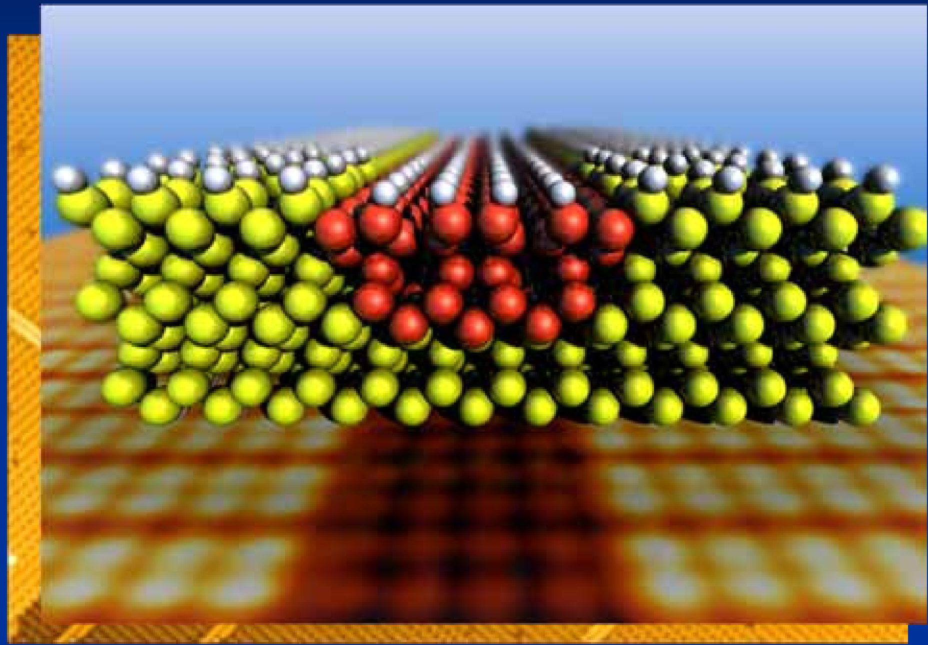






Solid state ``haute couture''





LaO/StO interface
(JM Triscone et al.)

Superconductors

Bi- nanolines
(C. Renner et al.)

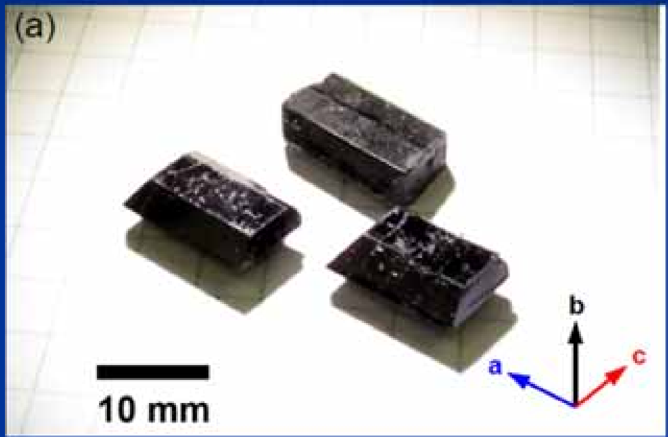
1D wires

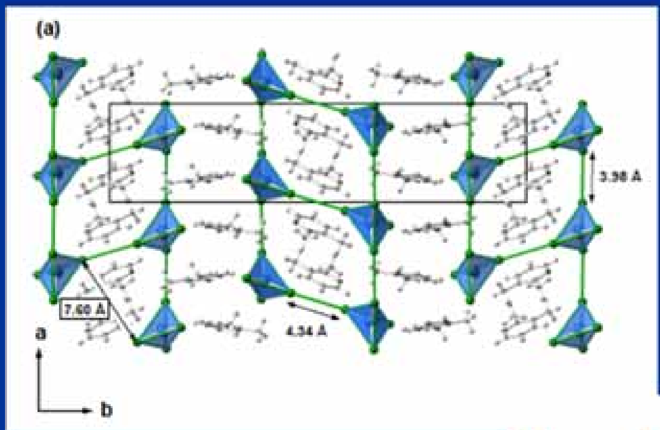
Theorist

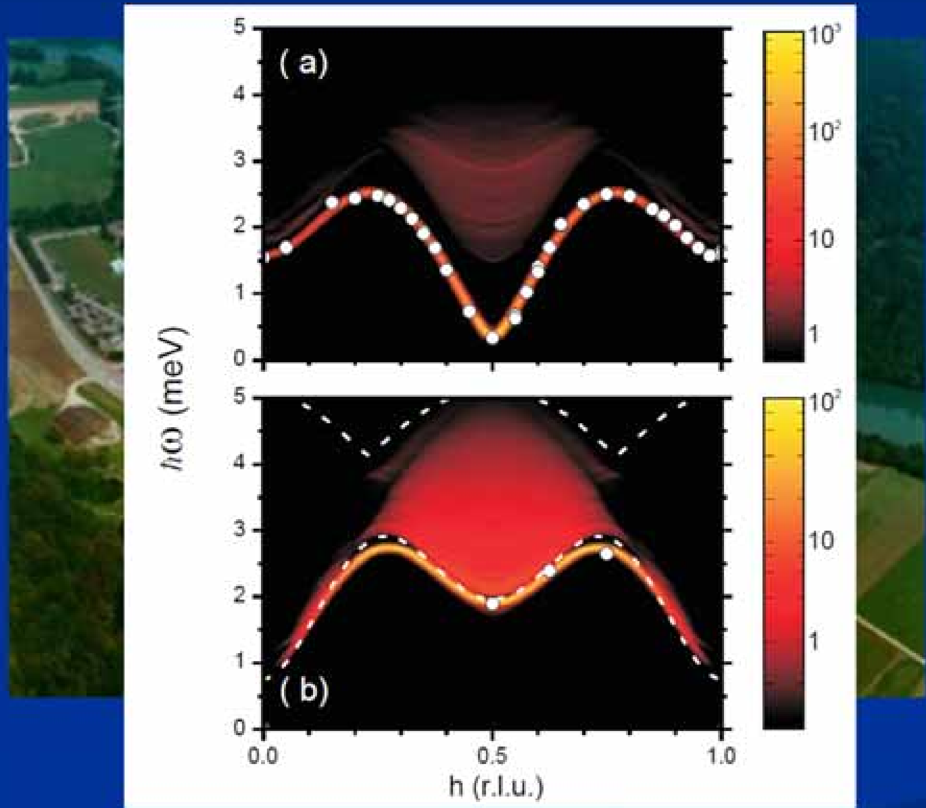
- Numerical design (ab initio calculations); Novel numerical techniques….
- Parameters control / determination
- Novel concepts and physics: new excitations, new phases, etc. ……..

One example

D. Schmidiger et al. arxiv:1112:4307







$$\mathcal{H} = J_{\text{leg}} \sum_{l,j} S_{l,j} \cdot S_{l+1,j} + J_{\text{rung}} \sum_{l} S_{l,1} \cdot S_{l,2} - g\mu_B H \sum_{l,j} S^z_{l,j}.$$

Conclusions / Perspectives

- Strong correlations at the heart of today's condensed matter (but remarkable exceptions)
- Reduced dimensionality more and more important; physics at the edge.
- Novel analytical and numerical approaches needed; Quantum simulators.
- Material design and prediction

Condensed matter theory